U. S. DEPARTMENT OF ENERGY
FIELD WORK PROPOSAL

1. WORK PROPOSAL NO.:	2. REVISION NO.:	3. DATE PREPARED:	3a. CONTRACTOR NO.:
12428.1		03-17-11	50341

4. WORK PROPOSAL TITLE:
Dual Readout Calorimetry - LAB 11-438

5. BUDGET & REPORTING CODE:	6. WORK PROPOSAL TERM: Begin: End:	7. IS THIS WORK PACKAGE INCLUDED IN THE INST. PLAN?	7a. PRINCIPAL INVESTIGATORS:
KA-15-01		☒ YES ☐ NO	Demarteau, M.

8. HEADQUARTERS/OPERATIONS OFC PROGRAM MANAGER: Borcherding, F. No. 301-903-6989	11. HEADQUARTERS ORGANIZATION: High Energy Physics	14. DOE ORG. CODE: SC
9. DOE FIELD ORGANIZATION WORK PROPOSAL REVIEWER:	12. DOE FIELD ORGANIZATION: Chicago	15. DOE ORG. CODE: CH
10. CONTRACTOR WORK PROPOSAL MANAGER: Weerts, H.J. No. 630-252-8831	13. CONTRACTOR NAME: UChicago Argonne, LLC	16. CODE: 12

17. IS THIS PROPOSAL TO DO WORK THAT INCLUDES A SECURITY INTEREST? ☐ YES ☒ NO

18. WORK PROPOSAL DESCRIPTION (Approach, anticipated benefit in 200 words or less):

This proposal outlines an R&D program to develop cost-effective crystal scintillators for the HHCAL detector concept with a target mass production price of $2/cc. Providing good resolutions for electrons, photons and hadronic jets to maximizing the physics discovery potential motivates the proposal. The direct goal of this program is to develop large size crystal scintillators with an unprecedented combination of optical and scintillation properties and low cost. Crystal samples will be grown by crystal growers, and will be characterized at Caltech. Part and parcel of the R&D of crystals is the associated photo-detectors, simulation studies and beam tests. This proposal includes a work plan for the development of photo-detectors sensitive in the short wavelength regime, building on the large planar photodetectors currently under development at Argonne and the University of Chicago. Further studies of various hadron shower simulations and evaluation of the uncertainties related to the imperfect knowledge of the shower development will also be carried out. In particular we envisage a detailed comparison of various simulations based on GEANT with the MCNPX code. These studies will be primarily carried out at Fermilab.

19. CONTRACTOR WORK PROPOSAL MANAGER:		20. OPERATIONS OFFICE REVIEW OFFICIAL:	
H. Weerts	03-17-11		
SIGNATURE	DATE	SIGNATURE	DATE

21. DETAIL ATTACHMENTS: (See specific attachments.)

☐ a. Facility requirements	☐ e. Approach	☐ i. NEPA requirements	☐ m. ES&H considerations
☒ b. Publications	☐ f. Technical progress	☐ j. Milestones	☐ n. Human/Animal Subjects
☒ c. Purpose (mandatory)	☐ g. Future accomplishments	☒ k. Deliverables	☐ o. Security requirements
☒ d. Background	☐ h. Relationships to other projects	☐ l. Performance Measures/Expectations	☐ p. Other (specify)

WORK PROPOSAL REQUIREMENTS FOR OPERATING/EQUIPMENT OBLIGATIONS AND COSTS

CONTRACTOR NAME	WORK PROPOSAL NO.	REVISION NO.	CONTRACTOR NO.	DATE PREPARED
UChicago Argonne, LLC	12428.1		50341	03-17-11

22. STAFFING (in staff years)	PRIOR YEARS	FY 2011	FY 2012 ESTIMATE	FY 2013 REQUEST	FY 2013 AUTHORIZED	FY 2014	FY 2015	FY 2016
a. SCIENTIFIC		0.4	0.5	0.5		0.5	0.5	0.0
b. OTHER DIRECT		0.0	0.0	0.0		0.0	0.0	0.0
c. TECHNICAL SERVICES*		0.0	0.0	0.0		0.0	0.0	0.0
d. TOTAL DIRECT		0.4	0.5	0.5		0.5	0.5	0.0
23. OBLIGATIONS AND COSTS (in thousands)								
a. TOTAL OBLIGATIONS		91	150	141		139	126	0
b. TOTAL COSTS		91	150	141		129	126	0
24. EQUIPMENT (in thousands)								
a. EQUIPMENT OBLIGATIONS		0	0	0		0	0	0
b. EQUIPMENT COSTS		0	0	0		0	0	0

25. MILESTONE SCHEDULE (Tasks)	FY 2012 DOLLARS PROPOSED	FY 2012 DOLLARS AUTHORIZED	PROPOSED SCHEDULE	AUTHORIZED SCHEDULE
To be determined by the DOE Program Manager.				

26. REPORTING REQUIREMENTS

*Technical services staffing includes ANL support divisions' scientific effort.

Development of Cost-Effective Crystals with Dual-Readout for for Homogeneous Hadron Calorimetry

Proposal for DOE OHEP Funding Opportunity Number DE-FOA-438

March 15th 2011

Principal Investigators:

Ren-Yuan Zhu (CalTech)
Adam Para (FNAL)
Marcel Demarteau (ANL) **– Lead P.I.**

Collaborators:

Hans Wenzel (FNAL)
Steve Magill (ANL)

Resources Requested:

Year 1: ~$346,000
Year 2: ~$456,000
Year 3: ~$472,000
Year 4: ~$483,000
Year 5: ~$485,000

Contents

Budget Pages(Argonne) 1
Budget Pages(Fermilab) 8
Project Summary 14
1 Introduction 15
2 The HHCAL Detector Concept 16
3 TAHCAL: Total Absorption Hadron Calorimeter 18
4 Development of crystals 19
4.1 Current Crystal Properties 19
4.2 Candidate Crystals for the HHCAL Detector Concept 22
4.3 Development of Scintillating Lead Fluoride 23
4.4 Development of BSO and PbFCl Crystals 26
4.5 Modification of PbWO4 Emission 26
4.6 Proposed Research Schedule and Goals for Crystal Development 27
4.7 Budget and Manpower for Crystal Development 27
5 Development of Photo-Sensors for Dual Readout Hadronic Calorimetry 28
5.1 Motivation 29
5.2 Research Plan for Photodetector Development 29
5.3 Schedule and Deliverables for Photodetector Development 34
5.4 Budget and Manpower for Photodetector Development 36
6 Simulation of Hadronic Calorimetry Cells and Beam Tests 36
6.1 Proposed R&D Program (Fermilab) 37
6.2 Budget Justification 38
References 39
Budget Justification Crystal Development (Caltech) 43
Budget Justification Photo-detector Development (ANL) 45
Budget Justification Simulation and Tests (Fermilab) 47
Biographical Sketches 49

All Other Editions are Obsolete

Budget Page

ORGANIZATION Argonne National Laboratory				Budget Page No.:	1 of 7
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR **Marcel Demarteau**				Requested Duration:	4 (months)
A. SENIOR PERSONNEL: PI/PD, Co-PIs, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos.			**ANL Funds Requested by Applicant**	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. **Sr. Personnel**	1.2			$22,891	
2.					
3.					
4.					
5.					
6. (1) Others (Programmer and ATLAS Integration)					
7. (3) Total Senior Personnel (1 - 6)	1.2	0.0	0.0	$22,891	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	3.0			$16,420	
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$39,311	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$39,311	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment					
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				891	
2. Foreign					
Total Travel				$ 891	
F. Trainee/Participant Costs 1. Stipends (Itemize levels, tuypes and totals on budget justification page) 2. Tuition & Fees 3. Trainee Travel 4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost					
G. Other Direct Costs					
1. Materials and Supplies				$ 29,413	
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					
6. Other					
Total Other Direct Costs				$29,413	
H. **Total Direct Costs (A through G)**				$69,615	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$21,308	
J. **Total Direct and Indirect Costs (H + I)**				$90,923	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$90,923	

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U.S. Department of Energy
Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 2 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Marcel Demarteau

Requested Duration: 12 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**	1.2			$23,816	
2.					
3.					
4.					
5.					
6. (1) Others (Programmer and ATLAS Integration)					
7. (3) Total Senior Personnel (1 - 6)	1.2	0.0	0.0	$23,816	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	4.8			$31,316	
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$55,132	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$55,132	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment					
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				$8,913	
2. Foreign					
Total Travel				$ 8,913	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)					
2. Tuition & Fees					
3. Trainee Travel					
4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost					
G. Other Direct Costs					
1. Materials and Supplies				$ 53,476	
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts				$0	
6. Other					
Total Other Direct Costs				$53,476	
H. **Total Direct Costs (A through G)**				$117,521	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$32,311	
J. **Total Direct and Indirect Costs (H + I)**				$149,832	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$149,832	

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U.S. Department of Energy
Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 3 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Marcel Demarteau

Requested Duration: 12 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**	1.2			$24,938	
2.					
3.					
4.					
5.					
6. (1) Others (Programmer and ATLAS Integration)					
7. (3) Total Senior Personnel (1 - 6)	1.2	0.0	0.0	$24,938	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	4.8			$32,882	
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$57,820	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$57,820	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment					
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				$14,260	
2. Foreign					
Total Travel				$ 14,260	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)					
2. Tuition & Fees					
3. Trainee Travel					
4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost					
G. Other Direct Costs					
1. Materials and Supplies				$ 36,543	
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts				$0	
6. Other					
Total Other Direct Costs				$36,543	
H. **Total Direct Costs (A through G)**				$108,623	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$32,101	
J. **Total Direct and Indirect Costs (H + I)**				$140,724	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$140,724	

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U.S. Department of Energy
Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 4 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Marcel Demarteau

Requested Duration: 12 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**	1.2			$26,113	
2.					
3.					
4.					
5.					
6. ( ) Others (Programmer and ATLAS Integration)					
7. ( ) Total Senior Personnel (1 - 6)	1.2	0.0	0.0	$26,113	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	4.0			$34,526	
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$60,639	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$60,639	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment					
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				$5,347	
2. Foreign					
Total Travel				$ 5,347	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)					
2. Tuition & Fees					
3. Trainee Travel					
4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost					
G. Other Direct Costs					
1. Materials and Supplies				$ 31,194	
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					
6. Other					
Total Other Direct Costs				$31,194	
H. **Total Direct Costs (A through G)**				$97,180	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$31,624	
J. **Total Direct and Indirect Costs (H + I)**				$128,804	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$128,804	

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(04-93)
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U.S. Department of Energy
Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 5 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Marcel Demarteau

Requested Duration: 12 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**	1.2			$27,346	
2.					
3.					
4.					
5.					
6. ( ) Others (Programmer and ATLAS Integration)					
7. ( ) Total Senior Personnel (1 - 6)	1.2	0.0	0.0	$27,346	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	4.8			$36,253	
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$63,599	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$63,599	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment					
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				$1,639	
2. Foreign				$0	
Total Travel				$ 1,639	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)					
2. Tuition & Fees					
3. Trainee Travel					
4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost					
G. Other Direct Costs					
1. Materials and Supplies				$ 28,520	
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					
6. Other					
Total Other Direct Costs				$28,520	
H. **Total Direct Costs (A through G)**				$93,758	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$32,172	
J. **Total Direct and Indirect Costs (H + I)**				$125,930	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$125,930	

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(04-93)
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U.S. Department of Energy

Summary Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 6 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR

Requested Duration: 8 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**					
2. **0**					
3. **0**					
4. **0**					
5.					
6. ( ) Others (List individually on Budget Explanation Page)					
7. (1) Total Senior Personnel (1 - 6)	0.0	0.0	0.0	$ -	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates					
2. ( ) Other Professional (Technician, Programmer, etc.)					
3. ( ) Graduate Students					
4. ( ) Undergraduate Students					
5. ( ) Secretarial - Clerical					
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$ -	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$ -	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment				$ -	
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)					
2. Foreign					
Total Travel				$ -	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)					
2. Tuition & Fees					
3. Trainee Travel					
4. Other (fully explain on justification page)					
Total Participants ( ) Total Cost				$ -	
G. Other Direct Costs					
1. Materials and Supplies					
2. Publication Costs/Documentation/Dissemination					
3. Consultant Services					
4. Computer (ADPE) Services					
5. Subcontracts					
6. Other					
Total Other Direct Costs				$ -	
H. **Total Direct Costs (A through G)**				$ -	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$0	
J. **Total Direct and Indirect Costs (H + I)**				$0	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$0	-

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U.S. Department of Energy
Summary Budget Page

OMB Control No.
1910-1400

ORGANIZATION
Argonne National Laboratory

Budget Page No.: 7 of 7

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Marcel Demarteau

Requested Duration: 60 (months)

A. SENIOR PERSONNEL: PI/PD, Co-Pis, Faculty and Other Senior Associates (List each separately with title; A.6. Show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	ANL Funds Requested by Applicant	Funds Granted by DOE
1. **Sr. Personnel**	6.0			$ 125,104	
2. **0**	0.0			$ -	
3. **0**	0.0			$ -	
4.	0.0			$ -	
5.				$ -	
6. (1) Others (List individually on Budget Explanation Page)				$ -	
7. (3) Total Senior Personnel (1 - 6)	3.6	0.0	0.0	$ 125,104	
B. OTHER PERSONNEL (show numbers in brackets)					
1. (1) Post Doctoral Associates	21.4			$ 151,397	
2. ( ) Other Professional (Technician, Programmer, etc.)				$ -	
3. ( ) Graduate Students				$ -	
4. ( ) Undergraduate Students				$ -	
5. (1) Secretarial - Clerical				$ -	
6. ( ) Others (List individually on Budget Explanation Page)					
Total Salaries and Wages (A + B)				$ 276,501	
C. Fringe Benefits (if charged as Direct Costs)				n/a	
Total Salaries,Wages and Fringe Benefits (A + B + C)				$ 276,501	
D. Permanent Equipment (List item and dollar amount for each item)					
Total Permanent Equipment				$ -	
E. Travel 1. Domestic (incl. Canada and U.S. Possessions)				$ 31,050	
2. Foreign				$ -	
Total Travel				$ 31,050	
F. Trainee/Participant Costs					
1. Stipends (Itemize levels, tuypes and totals on budget justification page)				$ -	
2. Tuition & Fees				$ -	
3. Trainee Travel				$ -	
4. Other (fully explain on justification page)				$ -	
Total Participants ( ) Total Cost				$ -	
G. Other Direct Costs					
1. Materials and Supplies				$ 179,146	
2. Publication Costs/Documentation/Dissemination				$ -	
3. Consultant Services				$ -	
4. Computer (ADPE) Services				$ -	
5. Subcontracts				$ -	
6. Other				$ -	
Total Other Direct Costs				$ 179,146	
H. **Total Direct Costs (A through G)**				$ 486,697	
I. Indirect Costs (specify rate and base) These costs include: (.448) of items A, B, C, E, F, G3 , G6,D, G1,G2 and G5; (.122)					
Total Indirect Costs				$ 149,516	
J. **Total Direct and Indirect Costs (H + I)**				$636,213	
K. Amount of any Required cost sharing from Non-federal Sources					
L. **Total Cost of Project (J + K)**				$636,213	-

DOE F 4620.1	**U.S. Department of Energy**	OMB Control No.
(04-93)	**Budget Page**	1910-1400
All Other Editions Are Obsolete	(See reverse for Instructions)	OMB Burden Disclosure Statement on Reverse

Collider Detector Research and Development Program Lab 11-438 **Year 1 Funding Proposal** 5/1/2011 through 4/30/2012

ORGANIZATION
FERMI RESEARCH ALLIANCE, LLC / FERMILAB

Budget Page No: 1

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Adam Para

Requested Duration: 12 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Hans Wenzel, Computational Physics Developer CD	4.80			$36,400	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.4) TOTAL SENIOR PERSONNEL (1-6)	4.80			$36,400	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$36,400	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$20,442	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$56,842	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)					
2. FOREIGN				$5,000	
TOTAL TRAVEL				$5,000	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$2,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION					
3. CONSULTANT SERVICES				$3,000	
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				$5,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$66,842	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$38,017	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$104,859	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$104,859	

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Budget Page

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OMB Control No.
1910-1400
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ider Detector Research and Development Program Lab 11-438 **Year 2 Funding Proposal** 5/1/2012 through 4/30/2013

ANIZATION
RMI RESEARCH ALLIANCE, LLC / FERMILAB

Budget Page No: 2

CIPAL INVESTIGATOR/PROJECT DIRECTOR
m Para

Requested Duration: 12 (Months)

ENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (ist each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
Hans Wenzel, Computational Physics Developer CD	6.00	0.00	0.00	$46,865	
) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
0.5) TOTAL SENIOR PERSONNEL (1-6)	6.00			$46,865	
OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
0.0) POST DOCTORAL ASSOCIATES	0.00			$0	
0.0) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)				$0	
) GRADUATE STUDENTS				$0	
) UNDERGRADUATE STUDENTS				$0	
) SECRETARIAL - CLERICAL				$0	
) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$46,865	
FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$26,319	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$73,184	
PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$0	
TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$13,500	
TOTAL TRAVEL				$13,500	
TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)				$0	
2. TUITION & FEES				$0	
3. TRAINEE TRAVEL				$0	
4. OTHER (fully explain on justification page)				$0	
TOTAL PARTICIPANTS (0) TOTAL COST				$0	
OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$8,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$10,000	
4. COMPUTER (ADPE) SERVICES				$0	
5. SUBCONTRACTS				$0	
6. OTHER					
TOTAL OTHER DIRECT COSTS				$18,000	
TOTAL DIRECT COSTS (A THROUGH G)				$104,684	
INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$51,643	
TOTAL DIRECT AND INDIRECT COSTS (H+I)				$156,327	
AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
TOTAL COST OF PROJECT (J+K)				$156,327	

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Collider Detector Research and Development Program Lab 11-438 **Year 3 Funding Proposal** 5/1/2013 through 4/30/2014

ORGANIZATION FERMI RESEARCH ALLIANCE, LLC / FERMILAB				**Budget Page No:** 3	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR Adam Para				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Funds Requested by Applpicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. Hans Wenzel, Computational Physics Devel CD	6.00	0.00	0.00	$48,271	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.5) TOTAL SENIOR PERSONNEL (1-6)	6.00			$48,271	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00			$0	
2. (0.0) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	0.00			$0	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$48,271	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$27,109	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$75,380	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$14,500	
TOTAL TRAVEL				$14,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)				$0	
2. TUITION & FEES				$0	
3. TRAINEE TRAVEL				$0	
4. OTHER (fully explain on justification page)				$0	
TOTAL PARTICIPANTS (0) TOTAL COST				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$25,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$10,000	
4. COMPUTER (ADPE) SERVICES				$0	
5. SUBCONTRACTS				$0	
6. OTHER				$0	
TOTAL OTHER DIRECT COSTS				$35,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$124,880	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$55,923	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$180,803	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES				$0	
L. TOTAL COST OF PROJECT (J+K)				$180,803	

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Budget Page

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OMB Control No.
1910-1400
OMB Burden Disclosure
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Collider Detector Research and Development Program Lab 11-438 **Year 4 Funding Proposal** 5/1/2014 through 4/30/2015

ORGANIZATION
FERMI RESEARCH ALLIANCE, LLC / FERMILAB

Budget Page No: 4

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Adam Para

Requested Duration: 12 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Hans Wenzel, Computational Physics Develo CD	7.20	0.00	0.00	$59,663	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.5) TOTAL SENIOR PERSONNEL (1-6)	7.20			$59,663	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES				$0	
2. (0.0) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)				$0	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$59,663	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$33,507	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$93,170	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$14,500	
TOTAL TRAVEL				$14,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)				$0	
2. TUITION & FEES				$0	
3. TRAINEE TRAVEL				$0	
4. OTHER (fully explain on justification page)				$0	
TOTAL PARTICIPANTS (0) TOTAL COST				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$30,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$0	
4. COMPUTER (ADPE) SERVICES				$0	
5. SUBCONTRACTS				$0	
6. OTHER				$0	
TOTAL OTHER DIRECT COSTS				$30,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$137,670	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$66,577	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$204,246	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES				$0	
L. TOTAL COST OF PROJECT (J+K)				$204,246	

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Collider Detector Research and Development Program Lab 11-438 **Year 5 Funding Proposal** 5/1/2015 through 4/30/2016

ORGANIZATION: FERMI RESEARCH ALLIANCE, LLC / FERMILAB

Budget Page No: 5

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR: Adam Para

Requested Duration: 12 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Hans Wenzel, Computational Physics Develc CD	7.20	0.00	0.00	$61,453	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (0.6) TOTAL SENIOR PERSONNEL (1-6)	7.20			$61,453	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0.0) POST DOCTORAL ASSOCIATES	0.00			$0	
2. (0.0) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	0.00			$0	
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$61,453	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$34,512	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$95,965	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$14,500	
TOTAL TRAVEL				$14,500	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)				$0	
2. TUITION & FEES				$0	
3. TRAINEE TRAVEL				$0	
4. OTHER (fully explain on justification page)				$0	
TOTAL PARTICIPANTS (0) TOTAL COST				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$30,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$0	
4. COMPUTER (ADPE) SERVICES				$0	
5. SUBCONTRACTS				$0	
6. OTHER				$0	
TOTAL OTHER DIRECT COSTS				$30,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$140,465	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$68,378	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$208,842	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES				$0	
L. TOTAL COST OF PROJECT (J+K)				$208,842	

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Budget Page
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1910-1400
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Statement on Reverse

Collider Detector Research and Development Program Lab 11- **TOTAL of 5 Year Funding Proposal** ASCR 5/1/2011 through 4/30/2016

ORGANIZATION
FERMILAB Computing Division

Budget Page No: 6

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Adam Para

Requested Duration: 60 (Months)

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Funds Requested by Applpicant	Funds Granted by DOE
1. Hans Wenzel, Computational Physics Developer	31.20	0.00	0.00	$252,652	
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (2.6) TOTAL SENIOR PERSONNEL (1-6)	31.20			$252,652	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0.0) POST DOCTORAL ASSOCIATES	0.00			$0	
2. (0.0) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)	0.00			$0	
3. (0.0) GRADUATE STUDENTS	0.00			$0	
4. ( ) UNDERGRADUATE STUDENTS	0.00			$0	
5. ( ) SECRETARIAL - CLERICAL	0.00			$0	
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				$252,652	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) VACATION+OPTO+FRINGE				$141,889	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				$394,541	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT				$0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				$0	
2. FOREIGN				$62,000	
TOTAL TRAVEL				$62,000	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST				$0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				$95,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				$0	
3. CONSULTANT SERVICES				$23,000	
4. COMPUTER (ADPE) SERVICES				$0	
5. SUBCONTRACTS				$0	
6. OTHER					
TOTAL OTHER DIRECT COSTS				$118,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				$574,541	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) 11.7% on Travel expense and 16.17% on all other M&S expense; 64.43% on SWF					
TOTAL INDIRECT COSTS				$280,537	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				$855,078	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				$855,078	

Project Summary

Total absorption shower counters made of inorganic crystal scintillators have been known for decades for their superb energy resolution and detection efficiency. In high energy and nuclear physics, crystal electromagnetic calorimeters (ECAL) have been constructed for precision measurement of photons and electrons. Because of their good energy and position resolutions and excellent identification and reconstruction efficiencies for electrons and photons, their use has been a key factor in the successful physics programs of many experiments. The physics discovery potential of a crystal ECAL was demonstrated early on by the Crystal Ball experiment through its study of radiative transitions and decays of the Charmonium family.

One of the physics challenges for new detectors is to distinguish W and Z vector bosons in their hadronic decay mode. This requires a di-jet mass resolution of the order of the natural width of these bosons and hence a jet energy resolution of about 3%. For hadron calorimetry this means an energy resolution a factor of two better than previously achieved to date by any large-scale experiment. A novel approach to achieving superior hadronic energy resolution is based on a homogeneous hadronic calorimetry (HHCAL) detector concept, including both electromagnetic and hadronic parts, with separate readout of the Cherenkov and scintillation light and using their correlation to obtain superior hadronic energy resolution. This HHCAL detector concept has a total absorption nature, so its energy resolution is not limited by the sampling fluctuations. It has no traditional boundary between the ECAL and HCAL, so it does not suffer from the effects of dead material in the middle of hadronic showers. With the dual-readout approach, measuring both Cherenkov and scintillator light, large fluctuations in the determination of the electromagnetic fraction of a hadronic shower can be vastly reduced. The missing nuclear binding energy can then be corrected shower-by-shower, resulting in good energy resolution for hadronic jets. Active materials, such as scintillating crystals, glasses or ceramics, may be used to construct an HHCAL.

This proposal outlines an R&D program to develop cost-effective crystal scintillators for the HHCAL detector concept with a target mass production price of $2/cc. Providing good resolutions for electrons, photons and hadronic jets to maximizing the physics discovery potential motivates the proposal. The direct goal of this program is to develop large size crystal scintillators with an unprecedented combination of optical and scintillation properties and low cost. Crystal samples will be grown by crystal growers, and will be characterized at Caltech. Part and parcel of the R&D of crystals is the associated photo-detectors, simulation studies and beam tests. This proposal includes a work plan for the development of photo-detectors sensitive in the short wavelength regime, building on the large planar photodetectors currently under development at Argonne and the University of Chicago. Further studies of various hadron shower simulations and evaluation of the uncertainties related to the imperfect knowledge of the shower development will also be carried out. In particular we envisage a detailed comparison of various simulations based on GEANT with the MCNPX code. These studies will be primarily carried out at Fermilab.

Project Narrative

1 Introduction

We propose to carry out a collider detector research and development program in the next five years to develop cost-effective crystal scintillators of adequate size and density for a homogeneous hadronic calorimeter (HHCAL) detector concept for future high energy physics (HEP) experiments. Total absorption shower counters made of inorganic crystal scintillators have been known for decades for their superb energy resolution and detection efficiency[1]. In high energy and nuclear physics, crystal electromagnetic calorimeters (ECAL) have been constructed for precision measurement of photons and electrons. Because of their good energy and position resolutions and excellent identification and reconstruction efficiencies for electrons and photons, their use has been a key factor in the successful physics programs of many experiments. The most ambitious crystal ECAL is the CMS ECAL which uses 11 m^3 $PbWO_4$ crystals.

The next generation of collider detectors will emphasize precision for all sub-detector systems. One of the benchmarks for new detectors is to distinguish W and Z vector bosons in their hadronic decay mode. This requires a di-jet mass resolution better the natural width of these bosons and hence a jet energy resolution better than 3%. For hadron calorimetry this implies an energy resolution a factor of at least two better than previously achieved to date by any large-scale experiment. A novel approach to achieving superior hadronic energy resolution is based on a homogeneous hadronic calorimetry (HHCAL) detector concept, including both electromagnetic and hadronic parts, with separate readout of the Cerenkov and scintillation light and using their correlation to obtain superior hadronic energy resolution [2, 3]. This HHCAL detector concept has a total absorption nature, so its energy resolution is not limited by the sampling fluctuations. It has no structural boundary between the ECAL and HCAL, so it does not suffer from the effects of dead material in the middle of hadronic showers. It also takes advantage of the dual readout approach by measuring both Cerenkov and scintillation light to correct for the fluctuations caused by the nuclear binding energy loss, so a good energy resolution for the hadronic jets may be achieved [4, 2, 3].

A cost effective active material is crucial for the HHCAL detector concept. Active materials, such as scintillating crystals, glasses or ceramics, may be used to construct an HHCAL. The Caltech crystal laboratory's request of $750k over five years to develop cost-effective crystal scintillators for the HHCAL detector concept with a target mass production price of $2/cc. Crystal samples will be grown by various crystal growers, and will be characterized at Caltech. Studies of the trace element and dopant distribution, the stoichiometry and crystal structure, and the defect distribution will be carried out. Data obtained from specially prepared samples will be cross-correlated with crystal quality, such as light yield, transmittance and radiation hardness, and will be fed back to the crystal growers. This will lead to improved crystal processing technologies. As a result of the improved control of raw material, crystal growth and processing methods, crystals with better quality and lower cost are expected to be developed.

2 The HHCAL Detector Concept

Jet energy is an experimental estimator of the fundamental parton energy. In a hadron collider the jet/parton energy measurement is limited by the jet definition (QCD radiative corrections or gluon bremsstrahlung and underlying event). Jet energy measurements will be important at future lepton colliders, where multi-jet spectroscopy may be the key to understanding of the new physics. Large contributions to the jet energy contribution are induced by the fluctuations in the jet fragmentation if the response of the detector to charged and neutral pions is different and/or by the non-linearity of the response. In the clean environment of a lepton collider the jet energy resolution will be limited by the hadronic energy resolution.

There are many contributions to the hadron energy resolution and non-linearity of the response. The principal ones include:

- Nuclear binding energy loss: fluctuations in the fraction of the hadron energy transferred to the kinetic energy of particles in the shower due to the fluctuations in the nuclear binding energy losses dominate the energy resolution, whereas the very presence of these losses leads to a difference in the response to charged and neutral pions
- Sampling fluctuations: fluctuations in the sharing of the shower energy between the active and passive materials (in sampling calorimeters)
- Difference in the ’sampling fractions’ (i.e. ratio in the effective energy loss) between the different materials in the sampling calorimeters
- Leakage fluctuations due to neutrinos, muons and tails of the hadronic shower escaping the detector volume

Leakage fluctuations, for a given geometrical constraints, can be minimized by maximizing the density of the calorimeter (strictly speaking, by minimizing the absorption length of the detector). This is of particular importance in a collider geometry, where the calorimeter must be placed inside the solenoid and the technical and budgetary concerns place stringent limits on the total thickness of the calorimeter. Sampling fluctuations can be eliminated in a totally active calorimeter. The contribution of differences in response to the energy resolution can be eliminated in a homogeneous calorimeter. This requires, in particular, that the response of the ’electromagnetic’ and ’hadronic’ sections of the calorimeter must be functionally identical.

Dense, uniform and total absorption hadron calorimeters will minimize/eliminate the contribution of the sampling fluctuations to the hadronic energy resolution. Its energy resolution will be limited by the fluctuations in the binding energy losses and the leakage. Further improvement of the calorimetric performance is possible only if the measurement of the total energy deposition is augmented by additional independent information about the actual value of the nuclear binding energy loss in a given hadronic shower. Such a correction will, at the same time, reduce the fluctuation of the measured hadron energy and equalize the response to charged and neutral pions, thus restoring the linearity of the energy measurement. An effective measurement of the nuclear binding energy losses can be realized by a comparison of the scintillation and Cerenkov light emitted in the volume of the calorimeter. The HHCAL detector concept thus offers the best energy resolution, limited principally only by the leakage fluctuations.

Total absorption hadron calorimeter is not a particularly new idea, but it used to be a very impractical one for several reasons:

- Good energy resolution requires a near complete containment of a hadronic shower and this requires at least 7-8λ deep calorimeter. The only active materials of adequate density are inorganic scintillators: crystals or heavy glasses. Most of the available active materials have the interaction length of the order 30-40 cm, making the calorimeter at ;east 210-240 cm deep. While it is conceivable to build a fixed-target type calorimeter of such a depth, it is rather impractical for in the colliding beam geometry, there the tracking detectors and the calorimeters must reside inside a large superconducting magnet.
- Traditional photomultipliers do not function inside the magnetic field
- For a number of reason, from the physics-driven requirements to technical and engineering ones a calorimeter ought to have several segments in depth. This increases significantly the total space requirement for the calorimeter, making it even less practical.
- Cost of inorganic scintillators/crystals is very high

Recent advances in technology have changed the situation considerably. On one hand silicon-based photodetectors (a.k.a SiPM, MPPC) are reaching a very mature state and are becoming potential photo-transducers for hadron calorimetry. One should point out that the Avalanche Photodiodes were not an acceptable solution due to their sensitivity to charged particles. On another hand several new very heavy crystals have been developed with the interaction length of the order of 20 cm. Development of the PbWO4 crystals for the CMS electromagnetic calorimeter is a good example of the success in this direction.

An initial detector design was proposed [2, 3], where homogeneous material of 5 × 5 × 5 and 10 × 10 × 10 cm^3 cubes are used as basic building block. A detailed GEANT simulation carried out at Fermilab shows that a hadronic resolution of less than $\sim 20\%/\sqrt{E}$ may be achieved after corrections with dual readout [3]. Such resolution is more than a factor of two better than what has been achieved by existing hadronic calorimeters to date.

Based upon our experience accumulated in building crystal ECAL, a pointing geometry may provide a better resolutions for both energy and position measurements, and thus a good jet mass reconstruction. Figure 1 shows a schematic of a typical HHCAL cell with pointing geometry [5]. It is similar to a typical calorimeter cell of a crystal ECAL, but has several longitudinal segments with a total length of about 1 m. By using dense active materials such detector depth would provide about 5 nuclear interaction lengths, adequate for the hadronic jet energy reconstruction.

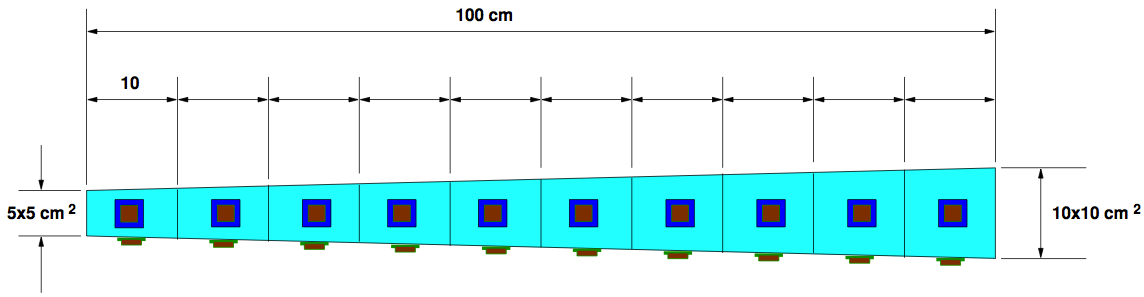

Figure 1: A schematic showing a typical cell for the HHCAL detector concept with pointing geometry [5].

The readout devices are mounted on the side faces of these crystal segments. Due to the recent development in compact solid state readout devices, e.g. silicon PMT, such a readout scheme is now feasible. Because of the unprecedented volume (70 to 100 m^3) foreseen for such a calorimeter the materials used for the HHCAL detector concept must be dense (to minimize the leakage) and cost-effective. It should also be UV transparent (for effective collection of the Cerenkov light) and allow for a clear discrimination between the Cerenkov and scintillation light. The preferred scintillation light is thus at longer wavelength, not necessarily bright or fast. Dense crystals or scintillating glasses offer a very attractive implementation for this detector concept.

3 TAHCAL: Total Absorption Hadron Calorimeter

Further improvement of the energy resolution requires some form of an event-by-event correction for the invisible energy in a given event. Such a correction must exploit some difference in the shower development of the showers where a large number of hadrons is produced or a large number of nucleons is released from the nuclei and the pi-zero reached showers where most of the energy is transferred to the active medium.

In a compensating sampling calorimeter using plastic scintillator as an active medium such a correction can exploit the fact that a number of low energy neutrons is strongly correlated with the invisible energy, that neutrons transfer most of their energy to protons inside the scintillator and that this energy is fully sampled by the active medium (as opposed to the rest of the shower). By a judicious choice of the sampling fraction the small contribution to the observed signal due to slow neutrons can be boosted to correct for the binding energy losses and thus improve the energy resolution [39].

In a total absorption calorimeter, with sampling fractions equal to one, compensation mechanism is not an useful tool to improve the energy resolution, therefore sensitivity, or its lack, of inorganic scintillators to low energy neutrons is of no practical importance; especially as the total kinetic energy of neutrons is very small in comparison with the energy of the shower.

Another correction mechanism for the ‘invisible’ energy was proposed, in fact prior to the compensation mechanism [8]. It exploits the difference in particle composition in different categories of showers: in showers where the invisible energy is small the large

fraction of the energy tends to be deposited by relativistic electrons, whereas in the showers with large number of liberated nucleons a large fraction of energy is deposited by slow, non-relativistic particles.

In a calorimeter with 'dual readout' where both the scintillation and Cherenkov signal are recorded separately one can use the correlation between the total amount of scintillation and Cherenkov light to derive the correction. This technique requires separation of the Cherenkov and scintillation light from a single detector volume. Practicality of such a solution has been demonstrated experimentally over 25 years ago.

4 Development of crystals

4.1 Current Crystal Properties

Table 1 lists the basic properties of the inorganic crystals with mass production capability existing in the world market: NaI(Tl), CsI(Tl), BaF_2, BGO ($Bi_4Ge_3O_{12}$), lead tungstate (PWO or $PbWO_4$), cerium doped lutetium oxyorthosilicate (Lu_2SiO_5 or LSO) [6, 7, 8] or cerium doped lutetium yt- trium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$, LYSO) [9, 7, 8] and lead fluoride (PbF_2). All these crystals, except LSO/LYSO, have been used to construct crystal ECAL in physics experiments as shown in the last row of the table. Several LSO/LYSO calorimeters are proposed, but have yet to be constructed. About 1 m^3 PbF_2 crystals of 20 cm long are used as Cerenkov radiator to construct an ECAL for the A4 experiment at the MAinzer MIcrotron (MAMI) facility in Mainz with excellent energy resolution reported [10].

Because of the huge volume (up to 100 m^3) needed for the HHCAL detector concept, the material used must have high density so that the total volume of the detector can be reduced. This requirement excludes several crystals in Table 1, such as NaI(Tl), CsI(Tl) and BaF_2. Since the crystal price depends heavily on the raw material cost and the crystal melting point, crystals with low raw material cost and melting point are preferred. This requirement excludes the LSO/LYSO crystals in Table 1.

Table 1: Inorganic Crystals for High Energy Physics Experiments

Crystal	NaI(Tl)	CsI(Tl)	BaF_2	BGO	$PbWO_4$	LSO(Ce)	PbF_2
Density (g/cm^3)	3.67	4.51	4.89	7.13	8.3	7.40	7.77
Melting Point (°C)	651	621	1280	1050	1123	2050	824
Radiation Length (cm)	2.59	1.86	2.03	1.12	0.89	1.14	0.93
Molière Radius (cm)	4.13	3.57	3.10	2.23	2.00	2.07	2.21
Interaction Length (cm)	42.9	39.3	30.7	22.7	20.7	20.9	21.0
Refractive Index[a]	1.85	1.79	1.50	2.15	2.2	1.82	1.82
Hygroscopicity	Yes	slight	No	No	No	No	No
Luminescence[b] (nm)	410	560	300	480	560	420	?
(at Peak)			220		420		
Decay Time[b] (ns)	230	1250	630	300	30	40	?
			0.9		10		
Light Yield[b,c]	100	165	36	21	0.3	85	?
			4.1		0.077		
d(LY)/dT[b,d] (%/°C)	-0.2	0.4	-1.9	-0.9	-2.5	-0.2	?
			0				
Experiment	Crystal	CLEO	TAPS	L3	CMS	KLOE	A4 at
	Ball	*BaBar*		BELLE	ALICE	SuperB	MAMI
		BELLE			PrimEx		
		BES III			Panda		

a At the wavelength of the emission maximum.
b Top line: slow component, bottom line: fast component.
c Relative light yield of samples of 1.5 X_0 and with the PMT quantum efficiency taken out.
d At room temperature.

As discussed in Section 2, the dual readout scheme for Cerenkov and scintillation light is effective to achieve good resolution for the hadronic jet measurement. To adapt the dual readout scheme materials used to construct a HHCAL should be UV transparent to effectively collect the Cerenkov light and have a scintillation light easily be separated from the Cerenkov light. The Cerenkov and scintillation light can be separated by several approaches: spectroscopic separation, pulse shape or timing discrimination and light direction separation since Cerenkov light is emitted at a characteristic angle $\theta_c = \arccos(1/\beta n)$ while scintillation is isotropic. To facilitate spectroscopic separation a scintillation emission at a long wavelength is preferred since the Cerenkov light is peaked at the UV. To facilitate pulse shape discrimination a slow decay time of the scintillation light is preferred since the Cerenkov light is instant. Although useful in some laboratory measurement [4], the directional discrimination is not practical for hadronic jets, so is not considered. In a brief summary, the crystal scintillator used for the HHCAL detector concept should have good UV transmittance and a slow scintillation light peaked at long wavelength. Its scintillation light yield is not necessary to be very bright since the energy to be measured in high energy physics experiments is high.

Based upon above consideration our initial investigation was concentrated on three materials in Table 1: PbF_2, BGO and $PbWO_4$ [11]. Samples of $5 \times 5 \times 5$ cm^3 size have been grown at Shanghai Institute of Ceramics (SIC): PbF_2, BGO and $PbWO_4$. Samples of this size may be seen as a basic building block for the HHCAL detector concept. Effective spectral separation between Cerenkov and scintillation light can be realized by using optical filters. Figure 2

(Left) shows the transmittance spectra of PbF_2 (green), BGO (blue), $PbWO_4$ (red) and a UG11 filter (black) as a function of wavelength together with the Cerenkov emission spectrum (dashed blue). A UG 11 filter was used to select the Cerenkov light with small or no scintillation contamination. Also shown in this figure is the normalized figure of merit for the Cerenkov measurement (TWEM) by using the UG11 filter, which is defined as the transmittance weighted Cerenkov emission. The numerical value is 1.0:0.53:0.21 for PbF_2/BGO/$PbWO_4$, which would be 1.0:0.82:0.75 without using the UG11 filter. Among three candidate materials PbF_2 is the one most effective in collecting the Cerenkov light because of its good UV transmission. Figure 3 (Right) shows a set-up used in our investigation for the Cerenkov light collection and its separation from the scintillation light.

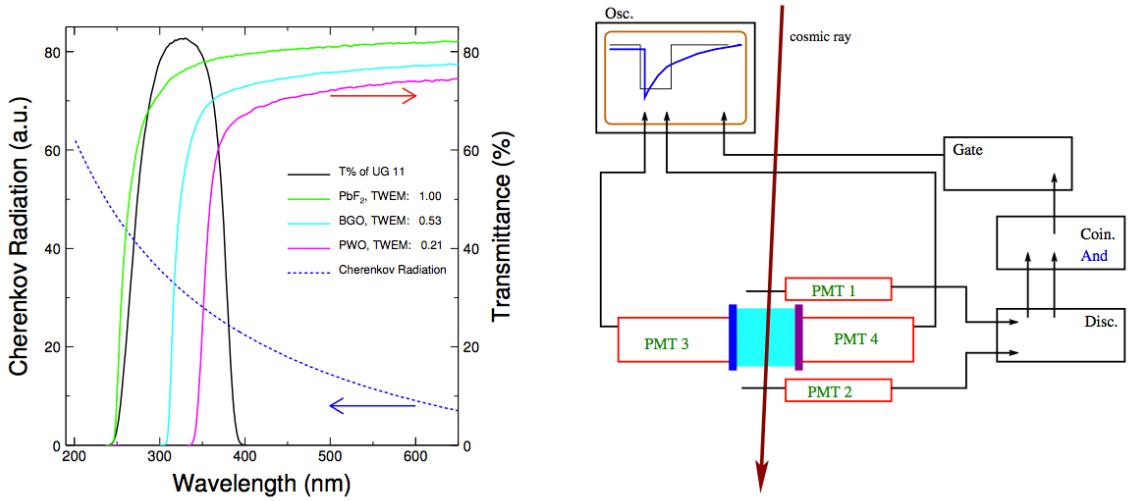

Figure 2: Left: The transmittance spectra of PbF_2 (green), BGO (blue), $PbWO_4$ (red) and UG11 (black) are shown as a function of wavelength. Also shown in this figure are the Cerenkov emission spectrum (dashed blue) and the normalized figure of merit for the Cerenkov light (TWEM) measurement with the UG11 filter. Right: A schematic showing a set-up used to measure the Cerenkov and scintillation light generated by cosmic-rays simultaneously by using two Hamamatsu R2059 PMT with a bi-alkali cathode. The light pulses are recorded by an Agilent 6052A digital scope.

Cosmic-rays were triggered by two finger counters with coincidence. The Cerenkov and scintillation light pulses generated by cosmic-rays were measured simultaneously by two Hamamatsu R2059 PMT with bi-alkali cathode and quartz windows coupled to the sample through optical filters UG11 and GG400. While UG11 is effective in selecting the Cerenkov light as shown in Figure 2 (Left), GG400 is a low-pass filter with cut-off at 400 nm, so is effective in selecting the scintillation light with small contamination of the Cerenkov light. The output of these two PMTs were digitized by an Agilent 6052A digital scope.

All Cerenkov light pulses have consistent time structure in the delay from the trigger (t_d, 6.1 ns), the rise time (t_r, 1.8 ns), the fall time (t_f , 4.2 ns) and the FWHM (3.0 ns). The numerical values of the delay and rise time are 6.2 ns and 1.9 ns respectively for the scintillation pulse, which are consistent with what observed from the Cerenkov light. It is interesting to note that there is no difference observed in the delay and rise time between the Cerenkov and scintillation light, indicating that only the light pulse width and fall time are useful for the

discrimination between the Cerenkov and scintillation light. Integration of the light pulse, starting 15 ns after the trigger, for example, may avoid Cerenkov contamination. A slow scintillator thus may help this discrimination by using time information.

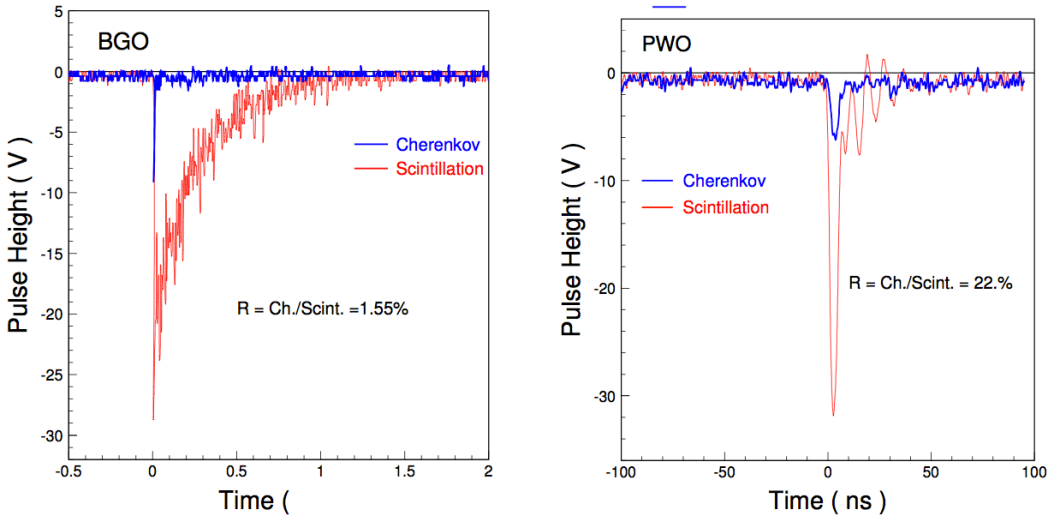

Figure 3: Cerenkov (blue) and scintillation (red) light pulses measured by Hamamatsu R2059 PMTs with UG11 and GG400 filters for the BGO (Left) and $PbWO_4$ (Right) samples.

Figure 3 shows the comparison of Cerenkov (blue) and scintillation (red) light pulses measured by Hamamatsu R2059 PMTs with the UG11 and GG400 filters respectively for BGO (Left) and $PbWO_4$ (Right). The advantage of slow scintillator in Cerenkov/Scintillation discrimination is clearly seen. The ratio of Cerenkov versus scintillation light was determined to be 1.55% and 22% for BGO and $PbWO_4$ respectively for this readout configuration. These values are consistent with the scintillation light yield shown in Table 1, the emission weighed quantum efficiency of the bi-alkali cathode of Hamamatsu R2059 PMT and the TWEM values shown in Figure 3 (Left). Needless to say, this ratio is detector configuration dependent because of the different directionality between the Cerenkov and scintillation light.

4.2 Candidate Crystals for the HHCAL Detector Concept

Summarizing the result discussed in Section 3 it is clear that BGO is better than $PbWO_4$ in both the UV transmittance and the spectroscopic separation of the Cerenkov and scintillation light. BGO would be the choice for this detector concept if financial consideration is not a limiting factor. The high raw material cost, however, makes it unlikely for BGO to meet our target mass production price of $2/cc. We thus have to look for additional candidate materials.

Table 2 lists three candidate materials in a comparison with our reference material BGO: $PbWO_4$, PbF_2 , bismuth silicate ($Bi_3Si_4O_{12}$ or BSO) and lead fluoride-chloride (PbFCl). All mate- rials are high density with short radiation length (about 1 cm) and short nuclear interaction length (about 20 cm). All materials, but PbF_2, are also known crystal scintillators, with their scintillation light properties listed in the table. The UV transmission is represented by the cut-off wavelength in this table, which is defined as the wavelength where the

transmittance of a thin crystal plate falls to the half of its value at a long wavelength, typically at 800 nm. While PbF_2, BSO and PbFCl are potentially better Cerenkov material than BGO, the cut-off wavelength of $PbWO_4$ is about 50 nm worse than BGO. Except BSO and PbFCl, mass production capability exists for these crystals.

Table 2: Candidate Crystals for the HHCAL Detector Concept

Crystal	BGO	$PbWO_4$	PbF_2	BSO	PbFCl
Density (g/cm^3)	7.13	8.29	7.77	6.80	7.11
Radiation Length (cm)	1.12	0.89	0.93	1.15	1.05
Interaction Length (cm)	22.8	20.7	21.0	23.4	24.3
Hygroscopicity	No	No	No	No	No
Cut-Off Wavelength (nm)	300	350	260	295	280
Luminescence (nm)	480	420	?	470	420
Decay Time (ns)	300	30/10	?	100	25
Relative light Yield (%)	100	2	?	20	2
Melting Point (°C)	1050	1123	824	1030	608
Relative Raw Material Cost (%)	100	49	29	47	29

Table 2 also lists two important factors affecting the cost of mass produced crystals: the melting point, which is a dominating factor affecting the crystal growth cost, and the relative cost of the raw materials, which is calculated by using their density and the 2009 market price of the corresponding raw materials. Comparing with BGO the raw material cost of $PbWO_4$ and BSO are about half, but the melting point of $PbWO_4$ is about 100°C higher than BGO. The potential unit price of these four candidate materials is thus in an order of PbF_2, PbFCl, BSO and $PbWO_4$. In addition to materials listed in Table 2, other materials are also being discussed in the HHCAL Workshop series by various developers, e.g. scintillating glasses and ceramics etc. [12]. In the next three sections of this proposal we concentrate on these candidate materials.

4.3 Development of Scintillating Lead Fluoride

Cubic lead fluoride (PbF_2) has a high density of 7.77 g/cm^3 and a short radiation length (X_0 = 0.93 cm) and a short nuclear interaction length (λ_I = 21 cm). It has good UV transparency down to 250 nm. Its low melting point (824°C) and low material cost (less than 1/3 of BGO) makes it potentially a cost-effective material for the HHCAL detector concept. Large size (20 cm long) PbF_2 crystals are available on the market. They were used as a Cerenkov material to construct the ECAL for the A4 experiment at the MAinzer MIcrotron (MAMI) facility in Mainz. Excellent energy resolution was reported [10].

As a Cerenkov material PbF_2 has been studied in detail [13]. The only issue for the HHCAL application is that it is not a scintillator. Effort was made to produce scintillating PbF_2 through phase transition (cubic to orthorhombic) during growth. Positive results were reported by Klassen et al. [14], but were not confirmed by Derenzo et al. [15]. Observation of fast luminescence in Gd doped PbF_2 crystal sample was first reported by Shen et al. of SIC

[16], and was later confirmed by Woody et al. in a beam test at the AGS [17].

Figure 4 shows the γ-ray excited emission spectrum for a Gd doped PbF_2 sample grown at SIC, as compared to a undoped PbF_2 sample. Two clear emission peaks at 280 and 310 nm are observed. Figure 5 shows the pulse height spectrum measured by using a Hamamatsu R2059 PMT doped PbF_2 sample measured at AGS[17] for a Gd doped PbF_2 sample of φ 2.1 × 2.2 cm from SIC. The measurement was carried out by using 1 GeV/c minimum ionizing particles in a test beam at AGS in BNL [17]. About 6.5 p.e./MeV with a decay time of less than 10 ns was observed. This light yield falls short for a precision crystal ECAL.

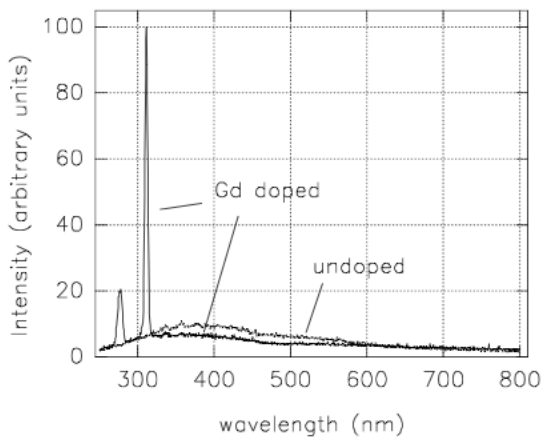

Figure 4: γ-ray excited emission spectrum for Gd doped PbF_2 sample from SIC[17].

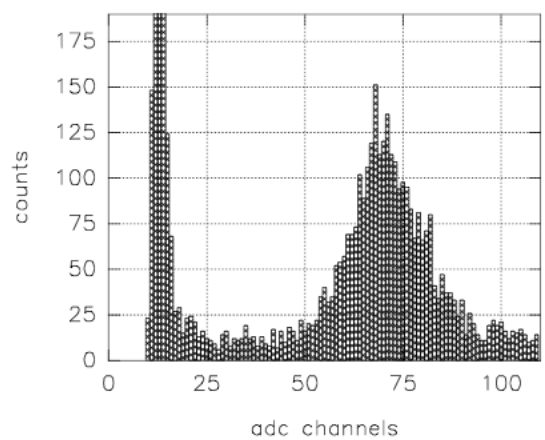

Figure 5: Light yield of a φ2.2× 2.2 Cm Gd doped PbF_2 sample measured at AGS[17].

We have recently investigated PbF_2 samples doped with various rare earth elements [18]. PbF_2 samples doped with various rare earth elements were grown by modified Bridgman method at Shanghai Institute of Ceramics (SIC) and Shanghai Scintibow Crystal Co., LTD. While classical platinum crucible was used at SIC for the crystal growth, graphite crucible was used at Scintibow. The SIC samples are cubes of 1.5 radiation length with six faces polished. Most Scintibow samples are cylinders with two end faces polished and have a dimension of φ 22× 15 mm. Crystals grown in graphite crucible are less transparent that in platinum crucible.

The photo- and X-ray luminescence spectrum was measured with a Hitachi F-4500 fluorescence spectrophotometer. For the X-ray luminescence measurement an AMTPEK E3-T X-ray tube was run at 25 kV and 50 μA. Fig. 6 shows excitation (red) photo-luminescence (blue) and X-luminescence (black) spectra for the PbF_2 samples doped with Er, Eu, Gd, Ho, Pr, Sm and Tb as well as a reference CsI(Tl) sample. Although spectroscopic resolutions are different, the observed photo- and X- luminescence spectra are consistent for all samples. While the scintillation spectra of Er, Ho, Pr and Tb doped PbF_2 samples is peaked at the green (about 500 nm), it is peaked at the red (600 nm) for Eu and Sm doped samples. As discussed above these emissions peaked at a long wavelength is more favorable than that of Gd doped sample for the Cerenkov/scintillation discrimination. The photo- and x-luminescence spectra observed in the Gd doped PbF_2 samples are consistent with previous publications by Shen and Woody [16, 17].

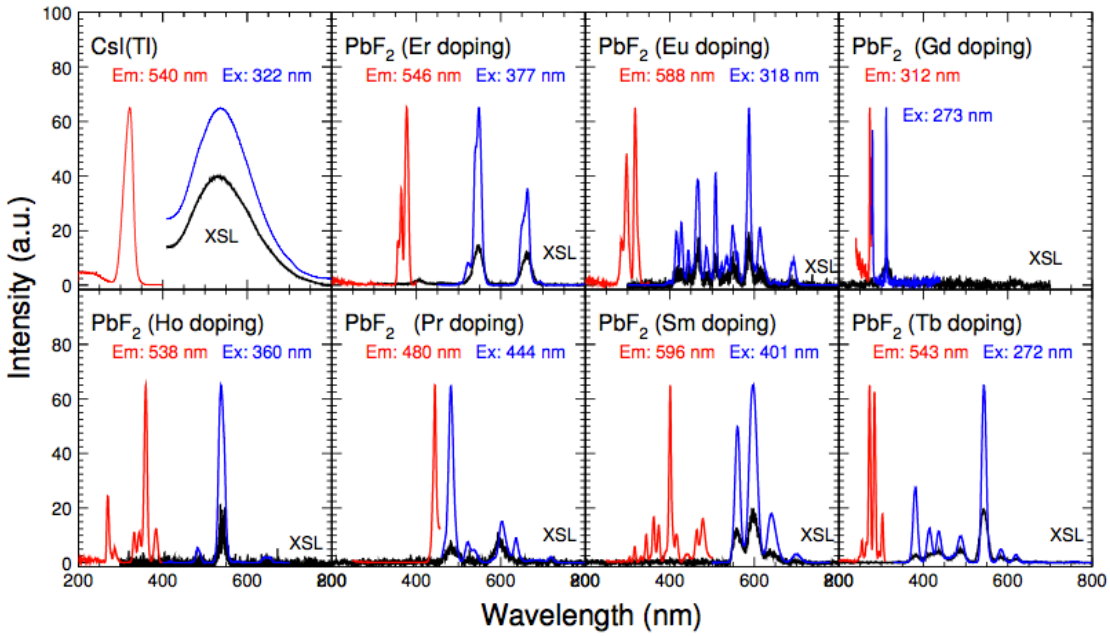

Figure 6: The UV excitation (red) and Photo- (blue) and X- (black) luminescence spectra are shown as a function of wavelength for the PbF_2 samples doped with Er, Eu, Gd, Ho, Pr, Sm and Tb as well as a reference CsI(Tl) sample [18].

The photo-luminescence decay time constant of these doped PbF_2 samples was measured by using a pulsed laser as the excitation source. A UV light pulse of 6 – 8 ns width from an OPOTEK Opolette 355 II + UV tunable laser was used as the excitation source. The photo-luminescence light from these samples went first through an Oriel MS257 monochromator then to a Hamamatsu R2059 PMT. The decay time constants were determined by an exponential fit to the pulse shape in the digital scope. All of the time constants were found at a millisecond scale as expected from the f-f transition of these rare earth elements. These decay times are too long to be useful for the HHCAL detector concept, but may find applications in medical industries.

To summarize, some rare earth doping does introduce luminescence centers into PbF_2 crystal lattice. It seems that the fast luminescence, e.g. d → f transition, is quenched in these samples, and slow luminescence (parity forbidden f → f transitions) are observed. For further development we plan to continue to work on rare earth doping, e.g. Eu^{2+} which is supposed to introduce scintillation light of μs decay time, and also try to introduce other luminescent ions, e.g. transition metal ions or even anion doping etc. As discussed in section 7 below slow scintillation light of μs decay time was observed by anion doping in the $PbWO_4$ crystals. Since fluorides are good hosts for doping ions, scintillation adequate for the HHCAL detector concept is expected in doped PbF_2 based crystals.

4.4 Development of BSO and PbFCl Crystals

As shown in Table 2, BSO are PbFCl are interesting crystals with many properties similar to BGO. Their raw material cost is less than the half of BGO. The light output of BSO and PbFCl is about 20% and 2% of BGO respectively. This is low but should be adequate for the HHCAL detector concept.

Compared to BGO, however, BSO is much more difficult to grow by Czochralski method because its melt is strongly adhesive as compared to BGO. There is no report on the growth of large sized BSO crystals. It is known that different phases exist for different ratios of Bi_2O_3 versus SiO_2. To improve the transmittance of BSO crystals, the dispersed second-phase should be removed from the crystals. It is possible to achieve an entirely $Bi_4Si_3O_{12}$ phase by adjusting the raw material ratio with excessive Bi_2O_3.

BSO crystals cut from φ 30× 200 cm ingots have been grown recently at SIC by a modified Bridgman method. Armed with experience and expertise on mass production of the BGO and $PbWO_4$ crystals by modified multi-crucible Bridgman method, a mass production capability of large size BSO crystals may be developed at SIC.

PbFCl has all the advantages we would like, but it is hard to grow to a large size because of its cleavage surface in the lattice structure [19]. Existing samples are all small with dimension of less than 1 cm. A special effort will be made at SIC to develop technologies to grow large size PbFCl crystals for the HHCAL detector concept.

4.5 Modification of PbWO4 Emission

As shown in Table 1 yttrium doped $PbWO_4$ is widely used in high energy physics experiments. Mass produced $PbWO_4$ crystals doped with yttrium have a low light output peaked at the blue (420 nm), about 10 p.e./MeV measured with a PMT of bi-alkali cathode. Supported by a previous Advanced Detector Research award an effort was made to modify the $PbWO_4$ scintillation. Early Glow Discharge Mass Spectroscopy (GDMS) analysis shows that contaminations of certain impu- rities, especially molybdenum, were responsible for the slow scintillation component in $PbWO_4$, as reported by Kobayashi et al. [20] and Zhu et al. [21]. Following this line, $PbWO_4$ samples doped with PbF_2 and BaF_2 (F^- doping) were grown and it was found that their scintillation properties were significantly modified.

The emission peaks of PbF_2 and BaF_2 doped $PbWO_4$ crystals were found to be moved from 420 nm to 560 nm with luminescence intensity increased by a factor of ten [22]. The corresponding decay time was found to be slowed down from tens of ns to a few μsec. PbF_2 and BaF_2 doped samples have similar photo-luminescence which peaks at 560 nm, while that from an yttrium doped sample peaks at 420 nm. Figure 11 (right) shows a comparison of light output, measured by using a Hamamatsu R2059 PMT with a bi-alkali photo-cathode, for three $PbWO_4$ samples Z24 and Z20 and S762. The photo electron yield of PbF_2 and BaF_2 doped $PbWO_4$ samples were found to be 5 to 8 times of that of the yttrium doped crystal. Taking into account the difference of the quantum efficiencies of the PMT used in this measurement these doped samples produce up to ten times more light than the yttrium doped $PbWO_4$, with decay time of a few μsec. In a brief summary, $PbWO_4$ crystals may also be tuned to have emission light peaked at the green to facilitate the Cerenkov/scintillation

discrimination.

4.6 Proposed Research Schedule and Goals for Crystal Development

The Caltech group has extensive experience in developing high quality scintillating crystals in collaboration with various crystal vendors, such as the BGO crystal for L3 in 1981-85 [23], BaF_2 crystals for GEM in 1988-93 [24], CsI (T1) crystals for *BABAR* in 1994-96 [25], $PbWO_4$ crystals for CMS in 1995 to 2005 [26] and LYSO crystals for SuperB since 2005 [27]. Work was also done to understand radiation damage in halide crystals resulting in improved radiation hardness of CsI (Tl) crystals [28-29].

Crystal development is a costly and time-consuming process. The $PbWO_4$ development for the CMS experiment costed MUSD and a decade to achieve the performance. The effort described in this proposal, however, takes advantage of the previous development programs for PbF_2 and $PbWO_4$ at SIC, recent work for doped PbF_2 at Scintibow. We propose a five year R&D program on doped PbF_2, BSO and doped $PbWO_4$ crystals:

- In the first year, a large number of doped PbF_2, PbFCl, BSO and doped $PbWO_4$ crystals of small size, such as 1.5 X_0 cubes, will be grown by SIC and Scintibow and will be characterized at Caltech. The spectroscopic response (transmittance and emission), light output and decay time will be measured. The goal of this period is to develop a working recipe for doped PbF_2 and $PbWO_4$ crystals as well as PbFCl and BSO crystals with initial quality adequate for the HHCAL detector concept.
- Based upon the result of the first year, in-depth chemical analysis and investigations on structure defects will be carried out for these crystal samples and correlated with their performance and radiation hardness in the following years. Samples with improved performance will be grown, and the work will be concentrated on the crystal quality improvement and cosmic tests. A decision will be made in choosing either doped PbF_2, BSO, PbFCl or doped $PbWO_4$. The radiation hardness of crystal samples of large size, such as $\varphi \times 30 \times 100$ mm or 30 × 30 × 100 mm, will be investigated to find out if it is adequate for the HHCAL detector concept. Various means of cost reduction for the crystal of choice would also be investigated to see if the target price can be met.
- In the last year the crystal of choice will be developed to a size sufficient for the HHCAL detector concept, to further improve the crystal quality and reduce the production cost, and to evaluate mass produced crystals in batches. The final goal of this program is to deliver crystals of adequate quality for the HHCAL detector concept.

4.7 Budget and Manpower for Crystal Development

We request $750k over five years for developing cost-effective scintillating crystals for future HEP experiments. The proposed budget is itemized for 2011-2015. The details of the future budget request will depend on the outcome of the progress of the R&D, and the numbers are the estimates only. The requested funds will cover a partial salary of a staff scientist, a subaward to SIC, travel to crystal growers and necessary material and supplies, covering crystal sample procurement from other crystal growers, such as Scintibow, and material characterization in commercial companies etc. The breakdown of the $150k request

per year is listed in Table 4. In addition to the staff scientist, Dr. Ren-yuan Zhu will oversee its success. As the PI, 1% of Dr. Ren-yuan Zhu's salary is charged to this project according to the Caltech regulation. Dr. Zhu has extensive experience in the development of high quality scintillating crystals. During the last three decades he has been working on a variety of crystal scintillators in collaboration with several crystal growers, including BGO, CeF_3, CsI(Tl) and $PbWO_4$ with SIC, BaF_2 and CsI(Tl) with Beijing Glass Research Institute (BGRI) and LYSO with Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT).
At SIC, Prof. Jianhua Yang, Prof. Jun Fang, Prof. Guohao Ren and Prof. Hui Yuan will participate in this project. Prof. Jianhua Yang is the deputy director of SIC. Prof. Jun Fang is the deputy director of SICCAS. Prof. Dingzhong Shen and Guohao Ren is the leader of the PbF_2 group. Prof. Hui Yuang is the leader of the BSO and $PbWO_4$ group. A subaward of $50k is requested for each year of the project to cover the cost of this effort at SIC.

Table 4: Request for Cost-Effective Crystal Research (k$) in FY11

Item	FY11	FY12	FY13	FY14	FY15
PI salary (0.12 month)†	1.2	1.2	1.2	1.2	1.2
Other Professionals	24.3	27.8	27.8	27.8	27.8
Total Salaries and Wages	25.5	29.0	29.0	29.0	29.0
Fringe Benefits (27.5%)	7.0	8.0	8.0	8.0	8.0
Total Salaries, Wages and Fringe Benefits	32.5	37.0	37.0	37.0	37.0
Travel	6.2	6.2	6.2	6.2	6.2
Materials and Supplies	18.0	22.1	22.1	22.1	22.1
Total direct costs	56.7	65.3	65.3	65.3	65.3
Indirect costs (53.03%)	30.1	34.7	34.7	34.7	34.7
Subaward to SIC	50	50	50	50	50
Indirect Cost of SIC subaward‡ at 53.03%	13.2	0	0	0	0
Total direct and indirect costs	150k	150k	150k	150k	150k

† 1% of PI's salary is charged to this project according to the Caltech regulation.
‡ Only the 1st $25k of a subaward is subject to the indirect cost at Caltech.

5 Development of Photo-Sensors for Dual Readout Hadronic Calorimetry

An integral part of total absorption calorimetry is the photo-detector and its readout. We propose to develop photo-sensors optimized for use in a future dual-readout total absorption crystal calorimeter. Our plan is to optimize existing photosensors, e.g., Silicon Photo-Multipliers (SiPMs) for the detection of scintillating light from a crystal. This requires optimization of collection area while minimizing sensor volume. We plan to test new ideas in thin-film photo-sensors for the detection of Cherenkov light. Developments in UV photon detection using very thin films of silicon nanoparticles [30] make this an attractive option for use in a total absorption calorimeter where minimization of sensor thickness between crystals is desired. Another approach is to

study the applicability of photo-detectors currently being developed by the Large-Area Picosecond Photo-Detector (LAPPD) group at ANL [31]. This development of large-area planar, thin, fast, and economical photo-detectors could be adapted to accommodate the small size crystals anticipated in this application.

5.1 Motivation

The development of clear, dense scintillating crystals presents an opportunity to design a total-absorption crystal calorimeter of similar volume to calorimeters in current HEP collider detectors. With an appropriate choice of crystal, showering particles may adequately produce both visible scintillation light and Cherenkov light in the UV range. Cherenkov light is produced by fast, light particles - so is dominated by the electrons and positrons in the electromagnetic part of a shower. The scintillation response is sensitive to all charged particles in a shower, thus sampling both the electromagnetic and visible hadronic portions. By detecting both scintillation (S) and Cherenkov (C) light separately, the electromagnetic fraction of a particle shower is determined by the C/S ratio. Correcting particle energies using a function based on this ratio can result in significant gains in resolution. Simulations of a total absorption dual-readout crystal calorimeter were developed, replacing the sampling calorimeter in the SiD detector concept. Using a perfect crystal with material properties of BGO, this calorimeter had a thickness of almost 6 interaction lengths and was used to study both single particle showers and e+e- interactions. Using the C/S correction in this simulation, single pion resolutions of <25%/sqrt(E) were obtained [32,33]. The crystals were "pixelated" and in addition to the C/S corrections, particle flow algorithms were also used to enhance the detector performance. For 50 GeV jets, Z dijet mass resolutions of 3.7% were obtained [33], which is almost a factor of 2 better than what the best sampling calorimeters can achieve.

In addition to crystal development, an R&D program is needed to define and optimize photo-sensors for both the scintillation and Cherenkov light. An ideal crystal would propagate a large fraction of prompt Cherenkov signal at wavelengths in the UV range, while the scintillation response would be slower and at longer wavelengths in the blue-green visible range. In a real crystal, a combination of wavelength filtering and signal timing selection could enhance the separation of these responses. An optimal scintillation photo-sensor might not need a large collection area, but would require timing and wavelength capabilities depending on the crystal properties. It may be that existing photo-sensor technologies, e.g., SiPMs can be readily adapted for this use. For the Cherenkov response, total collection area might be critical, covering many faces of the crystal, so to keep the calorimeter as totally absorbing as possible, this sensor must be an extremely thin, as well as a UV-sensitive device.

5.2 Research Plan for Photodetector Development

We propose to develop optimized scintillation and Cherenkov photo-sensors, which would be appropriate for a future dual readout total absorption crystal calorimeter. This would include both response and packaging optimization - we envisage a few square inch, thin-film UV photo-sensor for Cherenkov light detection and a very compact scintillation photon device. The project will draw from expertise gained in the LAPPD

effort at Argonne [31], leveraging existing detector development infrastructure, including lab facilities and testing tools. In addition, the anticipated economy of the LAPPDs could make them very competitive with SiPMs. We will characterize candidate sensors on samples of existing scintillating and Cherenkov crystals and glasses and use optimized sensors to test new crystals as they become available.

Optimization of Scintillator Light Detection

In most scintillating crystals, the amount of light generated is more than adequate for measurement of the energy of showering particles. In this case, optimization of a photo-sensor would involve minimizing its volume-to-collection area ratio and optimizing its location on the crystal. We will first try to adapt existing small photo-sensors, e.g., SiPMs, for this purpose. Our plan is to first characterize SiPM performance on an existing crystal, such as (commercially-available) PbWO - a cubic crystal of approximate size 5 cm x 5 cm x 5 cm would be ideal for these tests. Using both simulations of single crystals and data from cosmics and test beams, we will optimize the collection area and the location of the sensor for this crystal. It is possible that collection areas larger than those commercially available on a single SiPM will be needed - we will optimize this using multiple sensors and then work to minimize the total sensor profile by combining the total collection area into one sensor if practical and/or necessary. We will study and characterize both the timing and wavelength properties of the scintillator light from this crystal using the optimized sensor(s).
We anticipate that an optimized photo-sensor for the scintillation light from a crystal will see only visible light, thus separating it from the Cherenkov detector in wavelength range without the use of external filters. Furthermore, it will probably be possible to make timing cuts to separate the scintillation measurement from the prompt Cherenkov signal while still retaining enough light to achieve the desired energy resolution. Our optimized scintillation photo-sensor for this application will most likely be a modified version of commercially-available SiPM - modified in its collection area and packaging to minimize its profile. If this is the case, we will work with the industry to make our optimized photo-sensors commercially available.

If, however, it becomes clear that an optimized commercial SiPM will not meet our requirements or those imposed by new crystal development, we will investigate other photo-sensors, e.g., LAPPDs. Our ultimate goal is to define and characterize the best sensor for this application.

Optimization of Cherenkov Light Detection

Normally, Cherenkov light is highly directional, being hard to detect unless the direction of the incoming particle is known. In our case, however, there are two factors, which facilitate the measurement of this signal. First, in a particle shower, the direction of the particles is spread over a large angular region, particles entering the crystal from all sides. Second, the crystals under consideration here have an index of refraction of ~2, which means Cherenkov light is emitted at a large angle from the incident particle direction. So, for this application, the produced Cherenkov photons will be incident on all faces of a crystal. The Cherenkov signal is prompt and emitted at wavelengths in the UV range.

An optimized photo-sensor for this would seem to be one which can detect UV photons, be blind to visible photons and have response times in the multi-psec to nsec range. There are reports in the literature of thin-film UV photodetectors sensitive to photons in the wavelength range 200-400 nm and that are only hundreds of nm thick [30]. A thin layer of silicon nanoparticles, deposited on a silicon substrate, changes the energy bandgap from ~1 eV to ~4 eV, consequently moving its response from the visible to the UV range of wavelengths. Being effectively insensitive to visible light, a device of this type would seem to be ideal for this application - no filtering or timing cuts would be required to separate the Cherenkov from scintillator response. It is reported that silicon nanoparticle thicknesses as small as 100 nm can be used, making the total thickness of these devices ~order of a few hundred nm.

First, we will use a commercially available UV photodiode to characterize its performance on a known Cherenkov radiator, e.g., PbF2 or Pb glass. As in the scintillator sensor case, we will use simulations and data from cosmics and test beams to optimize the collection area and locations for detection of Cherenkov light. Since we know that an extremely thin profile is required for this device, once characterization of a crystal sample is complete, we will repeat our measurements with the thin-film devices as mentioned previously. Once this is successful, we will repeat optimization of this device for collection area and sensor location. Ultimately, our goal is to adapt the thin-film UV photodetector to this application, minimizing its thickness while providing adequate collection area. And, since this device is almost blind to visible light, we hope to avoid using additional filters and/or timing cuts to separate the Cherenkov from scintillator light.

Adaptation of LAPPDs

LAPPDs are micro-channel plate (MCP) devices. They combine many of the virtues of photo-multipliers with a relatively simple planar package construction that lends itself to compact embedding in detectors. In addition, the MCP-PMT employs a local amplification construction with very small path-lengths for the photon conversion and electron multiplication, resulting in exceptionally fast rise times. This very fast timing, implemented by waveform sampling, should enable discrimination of Cherenkov and scintillation light.

Since the photo-cathodes are grown at Argonne, we propose to develop inexpensive high quantum efficiency (QE) photo-cathodes for use in Cherenkov-counter particle identification readout. They could also be used in muon trigger systems, segmented calorimeters, time-of-flight systems, and other applications where the high gain, low noise, high-rate capabilities, stability, and ease of use of phototubes makes them a desirable option.

There are many photocathode materials in use in different applications in the larger photo-detector community, with varying wavelength sensitivity, peak quantum efficiency, dark current, growth properties, and robustness. When one surveys the literature of photo-cathodes, one finds two characteristics: there are many one-off studies, and the peak values of desirable quantities are often well above the industrial norm. It is

widely recognized that there are substantial gains to be made in many desirable aspects of photo-cathodes. It will take a systematic effort that is beyond the resources of most institutions, and beyond the scope that industry is willing to commit.

We propose to use `theory-driven design' intended to address the issues of quantum efficiency, dark-current, aging, time-spread, and wavelength response at a fundamental level. To address the often cost-determining problem of production yield we will also investigate the influence of the purity of photocathode materials on the quantum efficiency of the cathodes. Accordingly to our application, we will focus on the wavelength range of 300nm-400nm and on cathodes, which can be produced in cost-efficient thin-film technology. The materials of choice are either CsTe, CsI, or one of the bi- and multialcali cathodes.

Key to the theory-driven approach is the design of device structures with appropriate electric field distributions allowing the conversion of the potential energy of the photoelectron into directed kinetic energy towards the cathode surface. By tuning the surface barrier, e.g. the work function of the surface, we will introduce a filter for low energetic electrons, reducing dark current and providing a low frequency cut-off on the photon detection efficiency.

In any semiconductor, an internal electrical field can be created by an appropriate doping profile or by a combination of bandgap grading and doping profile. This approach is widely used in conventional device and sensor engineering especially in the field of III-V semiconductors and is currently an active research area for GaAs-photocathodes. Simulation frameworks like SILVACO can be used not only to predict the photo-electron behavior in the device but also to simulate the effects of processing.

Our goal is to extend this approach to the multi-alkali and Cs-based photo-cathodes. The rich chemistry of the multi-alkali family allowing ternary components should provide us with the necessary tools to perform bandstructure engineering. In contrast to III-V materials, which need epitaxial substrates, the I-V semiconductors are usually grown in cost efficient thin-film technology directly on the window material. The down side of this approach is the increased defect density caused by the non-epitaxial growth and the resulting electron scattering, capturing, and finally recombination.

The microscopic structure and even the exact chemical contribution throughout the film thickness may vary dramatically and is mainly depended on the used recipe and the experiences of the person who applies the recipe. Years of experiences making these cathodes may give the experimenter an idea which structure or chemical composition is the result of his processing but nearly no systematical investigation has been carried out to study the correlations between process parameters, like substrate treatment, rest gas contributions of the vacuum, evaporation/sputter methods and the resulting film contribution, crystal structure and morphology. X-ray scattering techniques can significantly help to elucidate these correlations. Powerful synchrotron sources and improved detection capabilities provide us today with the opportunity to take movies of structure and chemical composition with a time resolution of about 100ms and with

minimum interference with the recipe itself. The later is a consequence of the large penetration power of x-rays requiring only minimum modifications to the process reactor.

First ex-situ tests have already demonstrated the feasibility of this approach. By comparing various Sb-films which were grown under different growth conditions (substrate, substrate temperature, sputtering and evaporation, and thickness of the film) we were able to detect large variations in the crystalline structure of the material ranging from total random orientation of the individual crystallites to highly textured films. Moreover, we were able to resolve depth dependent changes of morphology and crystalline size. Using the x-ray diffraction technique in an in-situ experiment will also reveal the chemical composition and a possible layering as a result of the evaporation order.

These in-situ experiments will be combined with surface science experiments like X-ray Photoemission Spectroscopy (XPS) to determine the elemental and chemical composition of the surface at different process steps, Scanning Tunneling Microscopy (STM) to characterize the surface morphology, and Low Energy Electron Diffraction (LEED) to elucidate the surface symmetry and possible contaminations. We want to emphasize that the in-situ X-ray experiments and the surface sciences experiments will be performed at DOE user facilities (synchrotrons such as the APS and the Center for Nanoscale Materials (CNM); this allows not only a cost efficient approach, minimize the setup time for the individual experiments, but also builds on the great expertise of staff at these user facilities.

We will perform a systematic search for appropriate substrate layers, which will provide good optical coupling (reduction of reflection losses), and an appropriate growth substrate, which facilitates optimized grain-orientation and grain size. Currently, we evaluate the crystal and electronic structure of various broadband oxides and fluorites. Additionally to the structural requirements, bandstructure and doping profile will have to be compatible with the bandstructure of the cathode itself. Conditioning the substrate layer and optimizing the growth recipe for these growth conditions will be the tools to achieve a QE of 50% or more.

The goal is to develop an understanding and exploitation of the basic underlying physics of photo-cathode chemistry and morphology, based on an understanding of the correlation between microscopic properties of complex heterogeneous materials and the macroscopic behavior. Both the theory and practice of photo-cathodes has not kept up with advances in the development of semiconductor devices; much of the commercially available photo-cathode technology is based on `recipes' that are many decades old. The development of this understanding fully leverages the expertise and infrastructure that exists for the LAPPD project at Argonne. The program of proposed measurements, for example, will be carried out in the photo-cathode growth and characterization facility now being designed at Argonne in the context of the LAPPD project. The effort will include addressing the issues of commercialization, with the goal of renewing the US commercial base in this technology.

Simulations of Light Propagation and Detection

We have used the SLIC Geant4 simulation interface developed at SLAC [34] to study a perfect implementation of dual-readout total absorption crystal calorimetry in a collider detector geometry. Certain parts of this package were modified to include modules necessary for an optical calorimeter and to allow for dual readout of detector elements. Also included is a geometry package which makes the simulation package extremely flexible - perfect for a detector development program. We will use this package to simulate our single crystals in the lab and multiple crystal sets used in test beams. In addition, a digitization package, DigiSim, developed at NIU [35] exists and will be used to simulate response of our readout devices. Since these packages exist and have been used extensively by us, no effort is needed to develop and implement an interface to Geant4 or to handle multiple geometry configurations.

5.3 Schedule and Deliverables for Photodetector Development

This proposal is for a 5-year program with a final goal of defining and characterizing photo-sensors for detection of scintillation and Cherenkov light from crystals.

First year:

- Determine if, in fact, some version of a commercial SiPM sensor could be adapted for detection of the scintillation light from a crystal in this application. If optimization indicates that a non-commercial packaging of this device is needed, we would pursue its development in the industry.
- Characterize the Cherenkov emission of an existing glass or crystal, using commercially available UV photodiodes. Define the optimal placement of sensors on the crystal and the collection area needed for adequate light detection.
- Begin testing of thin-film UV sensors, working with developers to optimize their response characteristics.
- Design, construction and commissioning of mobile in-situ chamber for synchrotron experiments
- Development of texture analysis-software
- First in-situ Sb film experiments

Second year:

- If optimization and/or characteristics of a newly developed crystal indicate that SiPMs are not optimal for this application, we would pursue the development of more suitable sensors for the scintillation light.
- Finalize scintillation readout sensor device, tuning the simulation package to match data from our standard crystal. Begin testing of new crystals with our optimized scintillation sensor.
- Characterize performance of thin-film UV photosensors with our standard crystal, optimizing collection area and detector location.
- Setup of lab system to characterize quantum efficiency and preselect/optimize recipes
- First in-situ experiments with a bi-alkali
- First tests of recipes and new interlayers

Third year:

- Continue testing of newly developed crystals with our optimized scintillation sensor, refining its design if necessary to match ultimate crystal parameters.
- Finalize testing stage of thin-film UV sensors, optimizing its performance and packaging for this application. Work with developers and industry leading to commercialization of the final design.
- Systematic search of appropriate substrate (crystal parameter and symmetry)
- First tests of possible recipes in lab
- Systematic in-situ X-ray experiments and refining recipes

Fourth year:

- Construct first multi-crystal prototype detector with optimized scintillation sensors – in test beam, measure electromagnetic and hadronic showers
- Continue testing of optimized UV sensors, refining the final parameters to match newly developed crystal properties.
- Characterization of surface morphology, symmetry, and chemical composition of selected recipes
- Ongoing search for substrate-layers

Fifth year:

- Equip multi-crystal prototype detector with both optimized scintillation sensors and optimized Cherenkov sensors.
- Test configuration in test beam, measuring electromagnetic and hadronic showers. If enough crystals are available, a multi-interaction length detector should be constructed to study C/S corrections with single particles and calibration methods with muons.

- Lifetime tests of promising candidates
- Investigations of damage with surface sciences tools and X-ray characterization tools

5.4 Budget and Manpower for Photodetector Development

The budget period spans five years, 2011 through 2015. The budget assumes 3% escalation costs in years 2 to 5. The proposed budget is itemized for 2011-2013. The details of the budget request for 2014 and 2015 will depend on the outcome of the first phase of the R&D, and the numbers are estimates only. This program requires 50% of a postdoc at $50K per year ($25K in FY11), $10-11K per year for travel, and other direct costs related to equipment purchases and development averaging ~$20K per year. The total budget for 5 years is estimated at $225K for a Post Doc and $144.5K of direct costs.

6 Simulation of Hadronic Calorimetry Cells and Beam Tests

Detailed simulations of the performance of a total absorption calorimeter with dual readout have been performed using GEANT4 and MCNPX simulation codes. Hadron shower simulation codes are not very reliable, yet, and their predictions differ significantly between different showering codes. Some of the discrepancies reflect our poor understanding of strong interactions, some of them are consequences of demonstrable shortcomings of the simulation codes (like energy non-conservation).
Energy resolution of the TAHCAL calorimeter has been studied in different geometries, with different active components and with different incoming particles spanning the energy range from 1 to 200 GeV. Response to 'jets' composed of particles with different moment has been studied as well.

The correction to the observed scintillation signal can be determined at the test beam experiment by comparison of the scintillation signal with the beam energy as a function of the Cherenkov-to-scintillation ratio. This correction is very weakly dependent on the shower energy. Use of the energy-independent correction instead of the optimal one degrades the energy resolution from ~10%/$\sqrt{E}$ to ~15%/$\sqrt{E}$. In both cases there is no indication of a constant term in the energy resolution [36].

On one hand the simulated response of the calorimeter, both Cherenkov and the scintillation, depends to a disturbing degree on the version of the simulation codes, thus leading to different correction functions within different simulations. On the other hand, the corrected response and the resulted energy resolution is very much the same in all of the simulation codes studied. This is, in fact, quite understandable as the 'invisible' energy is primarily due to nuclear physics processes which are known and understood much better than the high energy interactions.

6.1 Proposed R&D Program (Fermilab)

Given the size of the effort necessary to demonstrate the excellent energy resolution with the full size test beam module we propose to complement the on-going experimental R&D efforts with additional studies focused on the specific issues.

Validation of the Simulation of Hadronic Showers

Detailed Monte Carlo simulation of the performance of TAHCAL indicates that a very good energy resolution can be achieved. Although this conclusion is common to several versions of GEANT4 simulation codes the differences between these simulations are disturbing [37]. We plan to perform a thorough analysis of the physics content of the simulation codes, identify the origin of the differences and evaluate the confidence level in the prediction of the performance of the calorimeter. This work will be carried in collaboration with the GEANT4 group at Fermilab.

We have already identified various shortcomings of some of the simulation codes, primarily related to the lack of energy conservation in the hadron-nucleus collisions. We plan to work with the GEANT4 group to improve the quality of the simulation and investigate the impact on the prediction of the performance of the calorimeter.

The 'invisible' energy in hadronic showers and its fluctuation is primarily related to nuclear processes: spallation and nucleon evaporation. These processes are of critical importance for the design studies in several industrial applications relate to nuclear energy. We plan to perform a detailed comparison of the simulation of the nuclear processes in GEANT4 with the widely used MCNPX code.

Simulation of the performance of the realistic experiments must include proper simulation of the light production and collection processes. We plan to establish a flexible simulation framework for simulation of various geometries of crystals and perform detailed comparison of the simulation results with the light yield observed in the experimental setups. This work will be carried out primarily by Hans Wenzel at Fermilab.

Response of Inorganic Scintillattors to Heavily Ionizing Radiation

All of the simulation studies performed so far assume that the total amount of the scintillation light is directly proportional to the total energy deposition in the scintillator matrix. The scintillation mechanism in different crystals is different, and the understanding of the light generation by slowly moving, heavily ionizing particles is poorly understood. This effect is present also for electrons; topic of 'non-proportionality' of scintillating crystals response occupies a good fraction of sessions devoted to inorganic scintillators.

Good understanding of the low energy response of crystals is especially important for hadron calorimeters as a significant fraction of the energy deposited by hadronic showers is in a form of low energy protons and nuclear fragments. We plan, in collaboration with

JINS Dubna to expose crystals equipped with radioactive source (for calibration) and phototubes to low energy proton beams and nuclear beams at the Dubna phasotron. These data, collected for different crystals, may help with understanding of the non-proportionality of the response of inorganic crystals. Measured saturation effects, if any, will be incorporated into the simulation of the TAHCAL. Different crystals will be exposed, as necessary. This work will be carried out by Adam Para of Fermilab.

Stimulation of Development of Inexpensive Inorganic Scintillators

One of the chief concerns with practical construction of TAHCAL-type detectors, even at the full size test beam prototype scale is related to the cost of crystals. The crystals used in medical applications are expensive. Practical development of hadron calorimetry requires a development of some new inexpensive crystals. Although the task is challenging, it is not hopeless: the requirements for crystals for hadron calorimety are vastly different from those for LHC or PET application in the area of light yield, uniformity, or radiation tolerance.

The progress in the crystal development requires a dialog between the crystal growing industry and the detector builders to identify all critical specifications and to provide a feedback to the industry on one hand and to understand the cost implications of various technological requirements and to optimize the detector design accordingly, on the other hand.

We have established a dedicated series of workshops to discuss the development of inorganic scintillator for hadron calorimetry [38]. Three workshops have taken place so far. We plan to organize a session dedicated to inorganic materials for hadron calorimetry and the SCINT conferences and at IEEE Symposia.

Development of PbWO4 crystals for the CMS experiment would not have been possible without the Crystal Clear Collaboration. It is a large consortium with the research labs as well as academic and industrial centers for crystal development production. It the recent past this consortium focused its attention mostly on medical applications. We plan to initiate close collaboration with Crystal Clear and to use it as a vehicle in engaging the industry into a development of materials suitable for hadron calorimetry. Adam Para will carry out this task.

6.2 Budget Justification

The budget period spans five years, 2011 through 2015. The budget assumes 3% escalation costs in years 2 to 5.

The proposed budget is itemized for 2011-2013. The details of the budget request for 2014 and 2015 will depend on the outcome of the first phase of the R&D, and the numbers are the estimates only.

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Xiangdong Qu, Liyuan Zhang and Ren-yuan Zhu, Radiation Induced Color Centers and Light Monitoring for Lead Tungstate Crystals, IEEE Trans. Nucl. Sci. NS-47 (2000) 1742; R.H. Mao, X.D. Qu, G.H. Ren, D.Z. Sheng, S. Stoll, C. Woody, Z.W. Yin, L.Y. Zhang and R.- Y. Zhu, New Types of Lead Tungstate Crystals with High Light Yield, Nucl. Instr. and Meth. A486, 196 (2002); and R.H. Mao, L.Y. Zhang, R.-Y. Zhu, Quality of Mass-Produced Lead Tungstate Crystals, IEEE Trans. Nucl. Sci. NS-51 (2004) 1777.

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[37] A. Para, Detailed Studies of hadron shower modeling in GEANT4, CALOR2010

[38] 3rd Workshop on Matarials for Homogenous Haron Calorimetry, IEEE NSS, Knoxville, October 2010. List of contributed talks

- Prospects for High Resolution Hadron Calorimetry - Adam Para (Fermilab)
- Studies on Dual Readout Calorimetry with Meta-Crystals - Georgios Mavromanolakis (Conseil Europeen Recherche Nucl. (CERN))
- Degregation of resolution in a homogeneous dual readout hadronic calorimeter Don Groom (LBL)
- High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters - Steve Derenzo (LBL)
- Fluoride Glasses: State of Art and Prospects - Marcel Poulain (Rennes university)
- High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry - Ioan Dafinei (Dipartim.di Fisica G.Marconi RomeI)
- Prospects for Dense Glass Scintillators for Homogeneous Calorimeters -Peter Hobson (Detector Development Group)

- Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry - G Dosovitski (Moscow State University, Moscow)
- Study on Dense Scintillating Glasses -T Zhao (University of Washington)
- BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter -J. T. Zhao (Shanghai Institute of Ceramics, Shanghai, China)
- Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL G.H. Ren (R&D Center for crystals, Shanghai Institute of Ceramics, Shanghai, China)
- Transparent Ceramic Scintillators for Hadron Calorimetry - N Cherepy (Lawrence Livermore National Laboratory, Livermore, CA, USA

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Development of Cost-Effective Crystal Scintillators for Homogeneous Hadron Calorimetry Detector Concept

California Institute of Technology

PI: Ren-yuan Zhu, zhu@hep.caltech.edu

Total Project Budget, in then-year k$. The proposed budget is itemized for 2011-2015. The details of the future budget request will depend on the outcome of the progress of the R&D, and the numbers are the estimates only.

Item	FY11	FY12	FY13	FY14	FY15
PI salary (0.12 month)†	1.2	1.2	1.2	1.2	1.2
Other Professionals	24.3	27.8	27.8	27.8	27.8
Total Salaries and Wages	25.5	29.0	29.0	29.0	29.0
Fringe Benefits (27.5%)	7.0	8.0	8.0	8.0	8.0
Total Salaries, Wages and Fringe Benefits	32.5	37.0	37.0	37.0	37.0
Travel	6.2	6.2	6.2	6.2	6.2
Materials and Supplies	18.0	22.1	22.1	22.1	22.1
Total direct costs	56.7	65.3	65.3	65.3	65.3
Indirect costs (53.03%)	30.1	34.7	34.7	34.7	34.7
Subaward to SIC	50	50	50	50	50
Indirect Cost of SIC subaward‡ at 53.03%	13.2	0	0	0	0
Total direct and indirect costs	150k	150k	150k	150k	150k

† 1% of PI's salary is charged to this project according to the Caltech regulation.
‡ Only the 1st $25k of a subaward is subject to the indirect cost at Caltech.

Summary of proposed activities

Task	FY11	FY12	FY13	FY15	FY16
Crystal Sample Procurement	X	X	X	X	X
Crystal Sample Evaluation	X	X	X	X	X
γ-ray Irradiations			X	X	X
Hadron Irradiations			X	X	X
Cosmic Test Setup		X	X		
Cosmic Test				X	X

FY11 :

Goals and Deliverables In the first year, a large number of doped PbF_2, PbFCl, BSO and doped $PbWO_4$ crystals of small size, such as 1.5 X_0 cubes, will be grown by SIC and Scintibow and will be characterized at Caltech. The spectroscopic response (transmittance and emission), light output and decay time will

be measured. The goal of this period is to develop a working recipe for doped PbF_2 and $PbWO_4$ crystals as well as PbFCl and BSO crystals with initial quality adequate for the HHCAL detector concept.

Based upon the result of the first year, in-depth chemical analysis and investigations on structure defects will be carried out for these crystal samples and correlated with their performance and radiation hardness in the following years. Samples with improved performance will be grown, and the work will be concentrated on the crystal quality improvement and cosmic tests. A decision will be made in choosing either doped PbF_2, BSO, PbFCl or doped $PbWO_4$. The radiation hardness of crystal samples of large size, such as ϕ 30 $\times$ 100 mm or $30 \times 30 \times 100$ mm, will be investigated to find out if it is adequate for the HHCAL detector concept. Various means of cost reduction for the crystal of choice would also be investigated to see if the target price can be met.

In the last year the crystal of choice will be developed to a size sufficient for the HHCAL detector concept, to further improve the crystal quality and reduce the production cost, and to evaluate mass produced crystals in batches. The final goal of this program is to deliver crystals of adequate quality for the HHCAL detector concept.

Personnel Funds are requested for the support of the following personnel. The table below summarizes the costs in k$ and the percent time spent on the project.

Person	Job	Salary	Benefits	FTE On this grant	FTE On other	Total Costs
Ren-yuan Zhu	PI	1.2	0.3	1%	99%	1.5
J. Hanson	engineer	4.4	1.2	6%	94%	5.6
R.H. Mao	engineer	12.4	3.4	25%	75%	15.8
L.Y. Zhang	engineer	7.5	2.1	10%	90%	9.6

Material and Services The Material and Services budget is intended to pay for a subaward to SIC, crystal samples from other crystal growers, such as Scintibow, a cosmic test setup and material characterization in commercial companies etc. Cost estimates are based upon past experience of purchase of similar or like items.

Travel The Travel budget is intended to support two trips each year by the staff to the crystal vendors in foreign countries. Travel cost estimates are based upon past experience of similar number of trips to similar travel destinations with the following break down.

- Airfare round-trip: $1,500;
- Car Rental $50.00 per day for 7 days: $350;
- Hotel $100 per day for 6 days: $600;
- Per diem and Other costs: $650;
- TOTAL average per Foreign trip: $3,100

Indirect costs The indirect costs are collected at a rate of 53.03% for on campus activity less any amounts for capital equipment for the project

Budget Justification Photo-detector Development (ANL)

A. Senior Personnel:

2011: 10%
2012: 10%
2013: 10%
2014: 10%
2015: 10%

B. Other Personnel

2011: Post Doc, 25%
2012: Post Doc, 40%
2013: Post Doc, 40%
2014: Post Doc, 40%
2015: Post Doc, 40%

C. Fringe benefits:

Fringe Benefit Rates

Regular Employees	32%
Post Doc Affiliates	26%

D. Permanent equipment:

E. Travel

2011: Travel to BNL nanocenter and NSLS	$1,000
2012: Travel to IEEE Valencia	$5,000
Travel to CALOR 2012	$3,000
Travel to collaboration meetings	$2,000
2013: Travel to collaboration meetings	$6,000
Travel to BNL nanocenter and NSLS	$5,000
Travel to IEEE Symposium	$5,000
2014: Travel to meetings	$3,000
Travel to BNL nanocenter and NSLS	$3,000
2015: Travel to meetings	$2,000

F. Trainee costs:

G. Other Direct Costs

2011: Commercial Photo-sensors	$8,000
Readout for sensors	$10,000
Pumps, controllers & gages	$15,000
2012: Photo-sensors	$2,000
Readout for sensors	$10,000

	Various sputter targets	$13,000
	Machining of substrates and fixtures	$15,000
	Pumps, controllers & gauges	$20,000
2013:	Photo-sensors	$12,000
	Readout electronics	$2,000
	Ion source for surface preparation	$27,000
2014:	Photo-sensors	$15,000
	Readout electronics	$5,000
	Machining of substrates and fixtures	$15,000
2015:	Sputter targets and evaporation materials	$22,000
	Readout electronics	$10,000

Budget Justification Simulation and Tests (Fermilab)

A. Senior Personnel:

B. Other Personnel

2011: Hans Wenzel, Computing Professional, 40%
2012: Hans Wenzel, Computing Professional, 50%
2013: Hans Wenzel, Computing Professional, 50%
2014: Hans Wenzel, Computing Professional, 60%
2015: Hans Wenzel, Computing Professional, 60%

C. Fringe benefits:

Fringe Benefit Rates	
Regular Employees	31.1%
Post Doc Affiliates	19.8%
Graduate Students	4.4%

D. Permanent equipment:

E. Travel

2011:	travel to Shanghai Institute of Ceramics	$2,500
	Travel to SCINT2011	$2,500
2012:	travel to Shanghai Institute of Ceramics	$2,500
	Travel to IEEE Valencia	$3,000
	Travel to test beam in INR Dubna	$3,000
	Travel to Crystal Clear Collaboration meetings	2x$2,500
2013:	Travel to Shanghai Institute of Ceramics	$2,500
	Travel to Crystal Clear Collaboration meetings	2x$2,500
	Travel to IEEE Symposium	$4,000
	Travel to Test beam in Dubna	$3,000

F. Trainee costs:

G. Other Direct Costs

2011:	Crystal samples	$2,000
	Guests and Visitors	$3,000
2012:	Crystals	$5,000
	Readout for test beam setup	$3,000
	Guests and Visitors	$10,000
2013:	Crystals	$20,000
	Photodetectors	$5,000
	Guests and Visitors	$10,000

H. Total direct costs: Indirect costs:

Current indirect rates are indicated below:

Labor and travel:	52.0%
Procurements:	9.42%

Biographical Sketches

Marcel Demarteau

High Energy Physics Division
Argonne National Laboratory
Argonne, IL 60439

Phone: 630-252-5130
Fax: 630-252-6169
E-mail: demarteau@anl.gov

Education:

Institute of Technology, Eindhoven Undergraduate Studies Physics 1976 – 1982
University of Amsterdam Graduate Studies Physics 1983 – 1986
State University of New York, Stony Brook Postdoctoral Research Physics 1987 – 1992

Professional Employment:

2010 – present Senior Scientist, Argonne National Laboratory
2001 – 2010 Scientist II, Fermi National Accelerator Laboratory
1996 – 2001 Scientist I, Fermi National Accelerator Laboratory
1999 – 2009 Adjunct Professor of Physics ("Bijzonder Hoogleraar"), University of Amsterdam
1992 – 1996 Wilson Fellow (Associate Scientist), Fermi National Accelerator Laboratory

Awards, Memberships and Professional Services:

2011 Member of the BNL Electron Ion Collider Detector Advisory Committee
2011 Program chair for the TIPP 2011conference
2010 – present Member of the KEK BELLE Program Advisory Committee
2010 – present Co-chair, with Prof. Ian Shipsey, of the DPF Task Force on Instrumentation in High Energy Physics
2008 – present Convener of the Detector R&D common task group for the Physics and Experiment Board of the ILC
2008 – present Co-PI, with Prof. Jim Brau, of the university Linear Collider Detector R&D program

Selected Publications:

1. R. Adolphi *et al.* (CMS collaboration), *The CMS experiment at the CERN LHC,* Journal of Instr., JINST **3** S08004 (2008); [http://www.iop.org/EJ/abstract/1748-0221/3/08/S08004/]
2. V.M Abazov *et al* (Dzero collaboration), *The upgraded Dzero detector*, Nucl. Instr. and Meth. **A565,** 463 (2006)
3. W. Cooper *et al.*, *Electrical properties of carbon fiber support systems,* Nucl. Instr. and Meth. **A550**, 127 (2005)
4. M. Abolins *et al., Hadron and Electron Response of Uranium/Liquid Argon Calorimeter Modules for the Dzero Detector*, Nucl. Instr. and Meth. **A280**, 36 (1989)
5. S. Abachi *et al.* (Dzero collaboration)*, Measurement of the W-Boson Mass*, Phys. Rev. Lett. **77**, 3309 (1996)
6. S. Abachi *et al.* (Dzero collaboration)*, Observation of the Top Quark*, Phys. Rev. Lett. **74**, 2632 (1995)
7. B. Adeva *et al.* (Mark-J collaboration), *The production and Decay of Tau Leptons*, Phys. Lett. **179B**, 177 (1986)
8. G.P.A. Berg et al., *High resolution spectroscopy of 102Ru(d,p)103Ru and 104Ru(p,d)103Ru reactions*, Nucl. Phys. **A379,** 93 (1982)

Stephen R. Magill

High Energy Physics Division
Argonne National Laboratory
Argonne, IL 60439

Phone: 630-252-5845
Fax: 630-252-5076
E-mail: srm@anl.gov

Education:

1990 Ph.D. Physics
University of Illinois at Chicago
Chicago, Illinois

1979 M.S. Physics
DePaul University
Chicago, Illinois

1976 B.S. Physics
University of Maryland
College Park, Maryland

Professional Employment:

1998 – Present Physicist
Argonne National Laboratory
Argonne, Illinois

1993-1998 Assistant Physicist
Argonne National Laboratory

1990-1993 Postdoctoral Appointee
Argonne National Laboratory

Awards, Memberships, and Professional Service:

American Physical Society
International Advisory Committee, International Conference on Calorimetry in High Energy Physics

Selected Publications:

1. Innovations in ILC detector design using a particle flow algorithm approach, New J.Phys.9:409, 2007.

2. Measurement of prompt photons with associated jets in photoproduction at HERA, Eur.Phys.J.C49:511-522, 2007.

3. Forward jet production in deep inelastic ep scattering and low-x parton dynamics at HERA, Phys.Lett.B632:13-26, 2006.

4. Jet production in high Q**2 deep inelastic e p scattering at HERA, Z.Phys.C67:81-92, 1995.

Adam Para
Fermi National Accelerator Laboratory

Address: MS234, Fermilab, Pine Street, Batavia IL 60510
E-mail: para@fnal.gov

Education & Training:

Ph.D. in Physics	Warsaw University	1977
M.S. in Physics	Warsaw University	1975

Research& Professional Experience:

Scientist II	Fermilab	1995 – present
Scientist |	Fermilab	1989 – 1994
Associate Scientist	Fermilab	1985 – 1989
Staff Member	CERN	1983 – 1985
Foreign Scientific Collaborator	CEA Saclay	1981 – 1983
Assistant Professor	Warsaw University	1980 -1981
Scientific Associate	CERN	1978 – 1979

Selected Publications:

Total Absorption Dual Readout Calorimetry, Mike Crisler *et al.* FERMILAB-PROPOSAL-1004, Mar 2010. 19pp. Spokesperson: Adam Para.
Summary report of MINSIS workshop in Madrid, Rodrigo Alonso *et al.* Sep 2010. e-Print: arXiv:1009.0476 [hep-ph]
Silicon Photomultiplier Devices and Concept Studies of Readout for Calorimetric Detectors.
G. Deptuch, G. Mavromanolakis, A. Para, P. Rubinov, N. Saoulidou, M. Trimpl, . 2007. 2007 IEEE Nuclear Science Symposium Conference Record, 2007, Honolulu, HA, USA.
Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam. MINOS Collaboration (P. Adamson *et al.*). Phys.Rev.Lett.101:131802,2008.
Muon ID at the ILC. C. Milstene, G. Fisk, A. Para, (Fermilab) . JINST 1:P10003,2006.
Observation of muon neutrino disappearance with the MINOS detectors and the NuMI neutrino beam.MINOS Collaboration (D.G. Michael *et al.*). Phys.Rev.Lett.97:191801,2006.
FLARE, Fermilab liquid argon experiments: Letter of intent.L. Bartoszek *et al.* FERMILAB-PROPOSAL-0942, Spokesperson: A. Para.
Neutrino oscillations experiments using off-axis NuMI beam.A. Para, M. Szleper, e-Print: hep-ex/0110032

Synergistic Activities:

Member of the Instrumentation Panel of the International Committee for Future Accelerators
Member of the Int. Advisory Committee of the EDIT 2011 Instrumentation School
Member of the International Advisory Committee of the International Conference on Calorimetry in High Energy Physics
Member of the Int. Advisory Committee of the Heavy Quarks and Leptons Conference

Ren-Yuan Zhu

California Institute of Technology

Address: 256-48, HEP, Caltech, Pasadena, CA91125, USA

E-mail: zhu@hep.caltech.edu

Education & Training:

Research Associate	Massachusetts Institute of Technology	1983–1984
Ph.D. in Physics	Massachusetts Institute of Technology	1983
B.S. in Electrical Engineering	Tsinghua University, Beijing, China	1968

Research & Professional Experience:

Member of Professional Staff	California Institute of Technology	1996–present
Senior Research Associate	California Institute of Technology	1992–1996
Senior Research Fellow	California Institute of Technology	1987–1992
Research Fellow	California Institute of Technology	1984–1987
Visiting Physicist	DESY, Hamburg	1978–1983

Selected Publications:

All papers can be found on the Web: http://www.hep.caltech.edu/∼zhu

R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *Quality of a 28 cm long LYSO Crystals and Progress on Optical and Scintillation Properties*, Paper N38-2 in IEEE NSS2010 Conference Record.

R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *A Search for Scintillation in Doped Cubic Lead Fluoride Crystals*, *IEEE Trans. Nucl. Sci.* **NS-57** 3841-3845 (2010).

R.-Y. Zhu, *Crystal Calorimeters in the Next Decade*, in *Proceedings of XIII International Conference on Calorimetry in Particle Physics*, Ed. M. Fraternali *et al.*, IOP Conference Series Volume 160 (2009) 012017.

R.-Y. Zhu, *Precision Crystal Calorimeters in High Energy Physics: Past, Present and Future*, Invited Paper in Proceedings of SPIE Vol. 7079, 70790W, (2008).

R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *Optical and Scintillation Properties of Inorganic Scintillators in High Energy Physics*, *IEEE Trans. Nucl. Sci.* **NS-55**, 2425-2431 (2008).

R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *Emission Spectra of LSO and LYSO Crystals Excited by UV*

Facilities/Other Resources and Equipments

The Caltech group has extensive experience in developing high quality scintillating crystals in collaboration with various crystal vendors. The following facilities and equipment exist at Caltech for the characterization of optical and scintillation properties of crystals.

- A 50 Curie ^{60}Co γ-ray source and a 2,000 Curie ^{137}Cs γ-ray source. They provide a well calibrated radiation environment at different dose rates beyond what expected at LHC (1,500 rad/h at the endcaps), and can be used for spectroscopic measurements during irradiations, e.g. the radio-luminescence spectrum with the Oriel 257 monochromator.
- An Am-Be and two Cf-252 neutron sources. They provide fast neutron flux up to 6×10^4 n/s/cm^2 close to the rate expected at LHC (10^5 n/s/cm^2).
- An Amptek ECLIPSE-III x-ray tube. Together with the Oriel 257 monochromator it can be used to measure x-ray excited luminescence.
- An OPOTEK Opollet 355 II + UV tunable pulsed laser with pulse width of 6 to 8 ns as a tunable pulsed excitation light source.
- An Edinburgh Instruments FLS920 Stady State and Fluorescence Lifetime Spectrometer for light output, decay time at various temperatures.
- A Hitachi F-4500 fluorescence spectrophotometer for excitation and emission spectra.
- A PerkinElmer Lambda 950 and a Hitachi U3210 UV/visible spectrophotometers with double beam, double monochromator and a large sample compartment equipped with a custom Halon coated integrating sphere for transmittance measurements up to 30 cm path length with a precision of better than 0.2%.
- A Thermal Electron Corporation Harshaw 3500 Thermal Luminescence Reader for thermal luminescence measurements.
- Several LeCroy QVT and their interface with PC. Together with fast electronics for measurements of crystal's light output, decay kinetics and light response uniformity.
- An Agilent U1071ATM2 Dual channel 8-bit High Speed Digitizer: 500 MHz bandwidth, 1-2 GSa/s 128-256 MS acquisition for fast DAQ.
- An Agilent MS090254A Infiniium MSO: 2.5 GHz, 10/20 GSa/s 4+16 ch for fast DAQ.
- A Neslab temperature stabilizer for crystal measurements at different temperatures.
- A Lindburg Blue-M tube furnace with automatic temperature control for thermal annealing with a defined temperature profile.
- A Sentro Tech STT-1600-3.0-12 High Temperature Tube Furnace 4 Feet Long Extra Thick Rubber Tubing with fittings for connecting Vacuum Pump to SS Seal Plates with a Maximum Continuous Operating Temperature of 1,600°C for various crystal annealing tests.

Light, X-Ray and Gamma-ray, *IEEE Trans. Nucl. Sci.* **NS-55**, 1759-1766 (2008).

J.M. Chen, R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *Gamma-Ray Induced Radiation Damage in Large Size LSO and LYSO Crystal Samples*, *IEEE Trans. Nucl. Sci.* **NS-54**, 1319-1326 (2007).

J.M. Chen, R.H. Mao, L.Y. Zhang and R.-Y. Zhu, *Large Size LSO and LYSO Crystals for Future High Energy Physics Experiments*, *IEEE Trans. Nucl. Sci.* **NS-54**, 718-724 (2007).

J.M. Chen, L.Y. Zhang and R.-Y. Zhu, Large Size LYSO Crystals for Future High Energy Physics Experiments, *IEEE Trans. Nucl. Sci.* **NS-52** 3133-3140 (2005).

R.-Y. Zhu, *Radiation Damage in Scintillating Crystals*, *Nucl. Instr. and Meth.* **A413** (1998) 297.

Synergistic Activities:

Member of the IEEE NPSS RISC/NMISC Oversight Committee.

Member of the International Advisory Committee for the International Conference on Calorimetry in Particle Physics.

Member of the International Scientific Committee for the International Conference on Inorganic Scintillators and Their Use in Scientific and Industrial Applications.

Chair of the 2007 IEEE Nuclear Science Symposium, Hawaii.

Chair of the US CMS Collaboration Electromagnetic Calorimeter Institute Board (1996-2009).

Potential Conflict of Interest or Bias in Selection of Reviewers:

None

Collaborators and Co-editors:

Member of the CMS Collaboration

Graduate and Postdoctoral Advisors and Advisees:

S.C.C. Ting, MIT

H. Newman, Caltech

Other Support

The research work of the Caltech crystal laboratory is partly supported by the DOE detector R&D program. In the last several years the R&D on LSO/LYSO crystals was also supported by the US CMS upgrade program and the DOE advanced detector R&D program. A brief summary of the funds received in the last five years is listed below.

- FY10, $75k, Base support by the DOE detector R&D program.
- FY09-10, $44k, Cerium Doped LSO/LYSO Crystal Development for CMS Calorimeter Upgrade at the SLHC, NSF PHY-0612805.
- FY06-08, $240k, Cerium Doped LSO/LYSO Crystal Development for Future High Energy Physics Experiments, DOE ADR DE-FG02-06ER41427, in Response to the DOE Funding Opportunity Number DE-FG01-05ER05-27.
- FY05-FY10, $600k, Laser Based PWO Crystal Monitoring System Maintenance and Operation for the CMS Experiment at LHC, NSF PHY-0516857 and PHY-0612805.
- FY04-06: $225k, Lead Tungstate Crystal Development for Severe Radiation Environment, DOE ADR DE-FG02-92ER40701, in Response to the DOE Funding Opportunity Number DE-FG01-03ER03-27.