# PIONEER: A next-generation rare pion decay experiment

### David Hertzog; University of Washington

### On behalf of the 74 current Collaborators:

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### The Collaboration has extensive experience in

- Rare π & K Decays; Muon g-2, Muon Lifetime, MEG CLFV, & many PSI experiments
- We have STRONG, YOUNG Leadership at many institutions who will drive this program forward

<sup>1</sup>University of California Santa Cruz <sup>2</sup>University of Washington <sup>3</sup>University of Chicago <sup>4</sup>Brookhaven National Laboratory <sup>5</sup>University of British Columbia <sup>6</sup>TRIUMF <sup>7</sup>Paul Scherrer Institute <sup>8</sup>Tsinghua University <sup>9</sup>Argonne National Laboratory <sup>10</sup>University Zurich <sup>11</sup>Tecnologico de Monterrey <sup>12</sup>Stony Brook University <sup>13</sup>Johannes Gutenberg University <sup>14</sup>Fermilab <sup>15</sup>Cornell University <sup>16</sup>University of Virginia <sup>17</sup>ETH Zurich <sup>18</sup>University of Kentucky <sup>19</sup>University of Bern 20 KEK <sup>21</sup> The University of Tokyo <sup>22</sup>University of Victoria

### **U.S. Institutes**



### **PIONEER** approved at PSI addressing 3 Physics Questions

10 x Improvements in precision

- Lepton Flavor Universality
- Cabibbo Angle Anomaly
- Sterile neutrinos and exotic decays

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2203.05505v1

### Jan. 2022 Approved with high priority @ PSI

#### PSI Ring Cyclotron Proposal R-22-01.1 PIONEER: Studies of Rare Pion Decays

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#### https://arxiv.org/abs/2203.01981

### Snowmass 2022 White Paper

#### Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment

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# Research at PSI Research Divisions and Labs Facilities and Instruments PSI User Services PSI Home Labs & User Services NUM > LTP > PROMEER Experiment First Beam Request-May 2022 PROMEER Experiment PIONEER Experiment

Paul Scherrer Institut PSI PSI Research, Labs & User Services

The PIONEER experiment is a next generation experiment to measure the chargedpion branching ratio to electrons vs. muons. This measurement, which is highly sensitive to new physics at high mass scales, has broad implications for the universality of lepton interactions. Using state-of-the-art instrumentation-learning from the previous generation PEM 2<sup>o</sup> and PIENa 2<sup>o</sup> measurements - and a new high-intensity beam, measurements of the nion decay to electrons vs. muons and nion beta decay will im-

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Documents

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#### PSI Progress Report 2023 R-22-01.1 PIONEER Progress Report

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ABSTRACT: During the past year the PIONEER collaboration has continued to develop the experiment by performing simulations and detector design work. In addition, initial investigations of the  $\pi$ ES beam line were made. The status of the work will be discussed.

#### I. INTRODUCTION

The PIONEER proposal was approved at BV54 in January, 2021 and since then the PIONEER Collaboration has been developing aspects of the experiment. Two weeks of test beam allotted in  $\pi$ E5 offered a first chance for in-person collaboration, and the launching of the experimental campaign. In October 2022, a Rare Pion Decay Physics Case 1: Best Test of Lepton Flavor Universality



### Physics Case 2: High Precision unitarity test with pion beta decay

Tensions in the first-row CKM unitarity test



Pion beta decay offers unique precision to determine V<sub>ud</sub>

Pion beta decay,  $\pi^+ \to \pi^0 e^+ \nu(\gamma)$  provides the theoretically cleanest determination of  $|V_{ud}|$ Dominant uncertainty in  $\delta |V_{ud}|$  associated with hadronic and nuclear corrections

3-fold improvement  $\rightarrow$  improved V<sub>us</sub>/V<sub>ud</sub>

**10-fold improvement** to determine  $V_{ud}$  at the level of  $0^{++}$ , but without nuclear corrections



Eii are possible small corrections to the charged W-l-v couplings,

# Physics Case 3: Sterile neutrinos and exotic decays



Snowmass paper: The Present and Future Status of Heavy Neutral Leptons; Abdullahi et al https://arxiv.org/pdf/2203.08039.pdf

Uniquely sensitivity in the low mass region 1-120 MeV

Heavy sterile neutrino and hidden sector searches improved by factor of 10

 $\pi \to e v_H$  $\pi \to \mu v_H$  $\pi \to e v X$ 

### Example papers published by ൽ PI E NU

A. Aguilar-Arevalo et al. Physical Review D 97(7) 072012 (2018)
A. Aguilar-Arevalo et al. Physics Letters B 798 (2019) 134980
A. Aguilar-Arevalo et al. Phys. Rev. D 102, 012001 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 101, 052014 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 103, 052006 (2021)

# Our strategy for a next-gen pi-e-nu experiment

 $BR\left(\pi^+ \to \mu^+ \nu_{\mu}(\gamma)\right) = 0.999877 = \pm 0.0000004$  $BR\left(\pi^+ \to e^+ \nu_e(\gamma)\right) = (1.2327 \pm 0.0023) \times 10^{-4}$ 

The key to major improvements over current stateof-the-art experiments (PIENU, PEN) is to accurately determine fraction of  $\pi \rightarrow e$  events that hide below the Michel spectrum: "The Tail"

25 X<sub>0</sub> deep calorimeter: *Tail fraction <1%* 

Highly segmented, active target with energy, timing, and topology information to identify events: *Tail fraction uncertainty* <0.01%

Overall uncertainty goal:  

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \pm 0.01\%$$



### **Technical approach (scope) requires** Most intense low-energy pion beamline is at the Paul Scherrer Institute PSI fully supports experiments, installation, etc. KEY Development Active Target $\pi$ Decay at Res $\pi$ Decay at Rest & LGAD 5D-Tracking target (low-gain, avalanche diode) ι Decay at Rest $\rightarrow \mu^+ \rightarrow e^+$ $\pi$ Decay in Flight & High precision tracking Si strip target (Active Target) Decay at Rest Distinguishes events types (unique feature) Decay at Rest & 0->53 MeV u Decay in Flight 5000 channels with time, energy, and position in 2x2x0.6 cm<sup>3</sup> KEY Development • 25 X0 LXe Scintillating Calorimeter • High-resolution, uniform, fast Following MEG II ; <1.5% resolution at 70 MeV</li> State-of-the-art additional instrumentation • + $\mu$ RWell Tracker; fast triggering; high speed digitization and DAQ Many following LHC developments 8

PIONEER Project Costing ... being drawn from full WBS exercise that is in progress

- Total project cost \$26 M + 50% contingency = \$39 M
  - Includes U.S. and International "new-money" contributions
  - Does not include \$10 M worth of *existing* 3 ton LXe and its infrastructure from MEG II
  - Does not include evaluating the value of PSI's full support of beamline, installation, data storage, and general support
- 60% U.S.
- 40% International (Japan / Canada / Swiss)

• Net US Cost: \$16 + \$8 contingency = \$24 M

FYI: We use LXe @ \$2.56 M/ton as quoted to P5 by the XLZD "70 T"

# Needed R&D / Agencies

- R&D funds critically needed for next 2 years
  - Priorities: 5D Active Target development, custom electronics designs, 100 L LXe prototype (10% of TPC is target)
- Multi-Agency support?
  - DOE-HEP is viewed as funding source with BNL as Lead Lab
  - DOE and NSF Nuclear-funded groups have relatively smaller scope (by \$) projects and are assumed to be supported by NP agencies



### Timeline and budget. See backups for finer detail

	2024	2025	2026	2027	2028	2029		2030		2031		2032	
	♦ CD0	♦ CD1	◆ CD2/	PSI Shutdown ,	/ Upgade		•	CD4					
	LXe 100	L	Active Tgt	Test			Run-1	Run-2		Run-3		Run-4	
R&	D	R&D	Large Prototype	Major construc	ction period	Install			<mark>Phy</mark> s		<mark>Phy</mark> s		<mark>Phy</mark> s

Funding						
Profile	Operating grants and small su	pplements	Large purchases:			
	Special R&D award for protot	ypes	LXe procurement			
	Project funds		Photosensors and electronics			
Integral of green			Calibration system			
equals Project		ASIC dev	All electronics	LXe and tanks		
Request	R&D: Active Target, 2nd LXe test			Final install eng	OPERATION SUPPO	ORT OF GROUPS
	LXe Prototype and Electronics	Elect / DAQ				

Physics\* FTEs needed (i.e.; Scientific effort)

- R&D Phase
  - ~10 FTEs presently on Calorimeter, Active Target, Simulations, Electronics, DAQ
    - This will rapidly grow with influx of R&D funding
- Construction Phase
  - ~30 FTEs for testing, building, analyzing, simulations, pre-installations
    - Expect 5-10 graduate students and 5-10 postdocs and more senior scientists who are rolling off present commitments that will have ended
- Commissioning and Running Phase and Online Analysis
  - ~30 FTEs (out of larger 100 person collaboration)
    - Expect more graduate students and postdocs here given the many physics channels and topics that serve thesis and other projects

\*Engineering and technicians are included in R&D, Project, and Operating Grant support, but not counted here

# **PIONEER Summary and Request to P5**

- A Unique Precision Test of Lepton Flavor Universality in a Next-Gen Pion Decay Experiment
  - Unprecedented 0.005% precision on LFU
  - Pion Beta Decay to obtain highest precision on  $V_{ud}$
  - 10-fold improvements in sterile neutrino search
- PIONEER is approved at PSI where it will be strongly supported
  - While it is a US HEP-Led project, there is a significant international component Goal of PIONEER
  - BNL is Lead Lab with very strong young leadership
- P5 Requests
  - Strong support of our physics program and a priority message to Agencies to initiate funding
  - We are "small" but our Physics Reach is large



#### ASIC Active Target (ATAR) ~1 m ~5 cm 120 um Full silicon active target (ATAR): Beam Calorimeter • **High granularity** in (X,Y,Z), fast full collection time, good energy response, high dynamic range inactive angle Crucial to recognize decay chains that cannot be separated with the positron energy only The chosen sensor for the ATAR is a high granularity Low Gain Avalanche Diode (LGAD) technology Wirebond ASIC Why LGADs? High S/N, full fast collection time, great time resolution ASIC Alternative design with standard Silicon being studied as well 48 compact layers of LGAD strip sensors, 2x2 cm wide, 6 mm thick • Complex event reconstruction to detect all types of pion decays Fast electronic readout and fully digitized for each event



## Detailed Notional timeline & funding profile

2022	2023	2024	l 2025	2026	2027		2028		2029		20	30		203	L		203	2		2033		2034
Q2 Q3 Q4	Q1 Q2 Q3 0	Q4 Q1 Q2 Q	3 Q4 Q1 Q2 Q3	Q4 Q1 Q2 Q3	Q4 Q1 Q2 Q3	3 Q4 Q1 C	Q2 Q3 (	Q4 Q1	Q2 Q3 Q4	1 Q1	Q2	Q3 Q	4 Q1	Q2 Q	3 Q4	l Q1	Q2 (	Q3 Q4	Q1 (	Q2 Q3	3 Q4	Q1 Q2 Q3 Q4
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			♦ CD1 / CD	R completed		,																
					PSI Shutdo	own / Upga	ade															
				♦ C	D2/3 nominal	& TDR										_						
										♦ C	D4 I	nomin	al						F	Reque	st pil	peta support
Pio	n Beam Test	#1																				
D: ATAR, Ca	alo, Electronio	s, Tracker																				
		LYSO Test	: Beam at PSI																			
			LXe 100 L Proto	otype Test Beam	at PSI																	
				ATAR pion	stopping test																	
					Develop L	Xe Infrastu	re, inclu	uding	post MEG													
					ATAR + Pa	rtial Calo S	Systems	Test									Targ	et and	Trigg	er up	grade	tests
					Ca	lo Cryo Co	nstructi	on														
								Ins	stallation													
									Run-1	/ Con	nmi	ssionir	ng	Resul	t 1 o	n LFU	J and	exotics	5			
											Run	-2 Ful	Phys	sics Ru	n							
														Run-3	8 Full	Phys	ics R	un <mark>Res</mark>	ult 2	on LF	U an	d exotics
																	Run-	4 Full F	hysi	cs Rur	ו	Final results
		Operating	g grants and small	supplements	Large pure	chases:																
		Special R8	&D award for prot	totypes	LXe procu	rement																
		Project fu	inds		Photosens	ors and ele	ectronic	s														
				ASIC dev	Calibratio	n system																
				ATAR 0.5	All electro	nics		LX	e and tanks													
		R&D f	for ATAR and	2nd LXe tes	t			Fir	nal install en	Ig		OPER		N SUPP	ORT	OF (	GROU	PS				
		LXe Proto	type and Electron	nics Elect / DAC	l																	

# U.S. and International approximate Scope division

### U.S. Scope Management, project costs Active Target development and readout electronics Calorimeter digital electronics • Trigger and DAQ • Calibration system for calorimeter • Tracker system • International Scope (Japan, Canada, Switzerland) Custom beamline elements • Fraction of new LXe purchase Calorimeter photosensors, cabling, and power supplies Cryo-vessel design and construction Cryo infrastructure expansion beyond MEG II • Beamline detectors and LH<sub>2</sub> charge-exchange calibration infrastructure Local installation support at PSI Data storage at PSI

~ 60% ~40%

### $\pi^+ \rightarrow e^+ v$ LFU Tests: Sensitivity to High Mass Scales

### Pseudoscalar interactions





Phase I PIONEER Goal: 0.01 % measurement  $\rightarrow \Lambda \sim 3000 \text{ TeV}$ 

Many others:

- Leptoquarks
- Excited gauge bosons
- Compositeness
- SU(2)xSU(2)xSU(2)xU(1)
- Hidden sector ....

Induced Scalar Currents

Campbell and Maybury (2005), Marciano  $R_{e/\mu}(0.01\%): \Lambda_{S} > 180 TeV(!)$ 

Apparent LFUV could also appear via massive sterile neutrinos (e.g. in  $\pi^+ \rightarrow l^+ v_H$  with implications for leptogenesis (Elahi et al. 2109.09751).

### **Exotic Searches in PIONEER Phase I**

### Searches for Sterile Neutrinos



Also to be improved by an order of magnitude:  $\pi \rightarrow e/\mu v X; \pi \rightarrow e/\mu v v \overline{v}$ 

# Strategy for 10<sup>-4</sup> precision experiment

$$\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}$$

Analysis

$$R_{e/\mu} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

- fit high/low energy  $e^+$  time distributions
  - $\pi e$
  - $\pi \mu e$
  - background, pileup, etc
- Statistics
  - $2x10^8 \quad \pi \rightarrow ev$  events in 2-3 years with  $3x10^5 \quad \pi/s$  beam
- Systematic improvements
  - intense, high quality  $\pi^+$  beam
  - active target with key new ideas and technology
  - calorimeter:  $3\pi$ ,  $25X_0$ , high res., fast



	PIENU 2015	PIONEER Estimate		
Error Source	%	%		
Statistics	0.19	0.007		
Tail Correction	0.12	$<\!\!0.01$		
$t_0$ Correction	0.05	$<\!\!0.01$		
Muon DIF	0.05	0.005		
Parameter Fitting	0.05	$<\!\!0.01$		
Selection Cuts	0.04	$<\!\!0.01$		
Acceptance Correction	0.03	0.003		
Total Uncertainty	0.24	$\leq$ 0.01		

A LYSO based crystal CALO is being investigated to provide a comparison with LXe. To date, no LYSO test array has met our required precision goal but we are testing new crystals to see if improvements have been achieved.



### Two (rather different) Pion Decay Experiments: **PIENU** and **PEN/PIBETA**

Both took data a long ago but have (known) challenges to overcome before final results







- Nal slow, but excellent resolution
- Single large crystal but shower leakage depends on angle changing resolution and tail fraction
- Small solid angle

• Good geometry but calorimeter depth of 12X<sub>0</sub> too small to resolve tail under muon spectrum.

# **WBS Examples**

1	Project Manag	gement		
	1.1	Project Manager/CAM	5a	Calorimeter (LYS
	1.2	Deputy PM		5a.1
	1.3	Controls		5a.2
	1.4	Project ME/EE		5a.3
	1.5	Reviews/travel		5a.4
		,		5a.5
2	Beamline			
	2.1	Management and conceptual design	6	Electronics
	2.2	Instrumentation		6.1
	2.3	Entrance Counters and Readout		6.2
	2.4	Separator		6.3
				6.4
3	Active Target	(ATAR)		6.5
	3.1	Management and conceptual design		6.6
	3.2	LGAD sensors		6.7
	3.3	Frontends, readout, and cabling		6.8
	3.3.1	Frontend		
	3.3.2	Cabling	7	DAO and Compu
	3.4	Power supplies		7.1
	3.5	Calibration		7.2
	3.6	Mechanical support		7.3
	010			7.4
4	Tracker			7.5
•	4 1	Management and conceptual design		7.6
	4.2	Detector		7.7
	43	Frontends readout and cabling		
	4.4	Power supplies	8	Installation
	4.5	Calibration	0	8 1
	4.5	Mechanical support		8.2
	4.0			8.2
5	Calorimeter (I	Ye)		8.4
5	5 1	Management and concentual design		0.4 9 5
	5.2	Xenon procurement		8.J 8.6
	5.2	Chyogonic plant		8.0
	J.J E 2 1			0.7
	5.5.1	Elquid Storage		
	5.5.2	Gas storage		
	5.3.3 E 2 4	Purification		
	5.3.4			
	5.4	Cryo Control/UPS		
	5.5	Priotosensors		
	5.0	Frontends, readout, and cabling		
	5.7	Power supplies		
	5.8	Calibration		
	5.9	Mechanical Support		

Calorimeter (LYSO)	
5a.1	Management and conceptual design
5a.2	Crystals & Mechanical Support
5a.3	Photosensors and frontend
5a.4	Power supplies and cables
5a.5	Calibration
Electronics	
6.1	Management and conceptual design
6.2	Clock and control
6.3	Hardware Trigger
6.4	Calo WFDs
6.5	LGAD WFDs
6.6	Tracker TDCs
6.7	Other backend electronics
6.8	UPS
DAQ and Computing	
7.1	Management and conceptual design
7.2	Control Room
7.3	Computing (Midas level)
7.4	Online (DQM / DB / Nearline)
7.5	Data storage (PSI provide?)
7.6	Offline
7.7	Slow controls
Installation	
8.1	Management and conceptual design
8.2	Beamline
8.3	Calorimeter and tracker
8.4	ATAR
8.5	Alignment
8.6	Counting House (physical)
8.7	Power and grounds

# WBS Examples (WBS 3.1&3.2 ATAR related ...

The Conceptual design costs are those to	o go from the CD-0 Mi	ssion Need Appr	oval in Jan 2024	to the CD-1 Revi	iew in Jan 2025.	Pre-CD0 accon
Conceptual Design (~1 year): C	overs cost to pro	duce concep	tual design n	eeded for CD	-1 review, 1st	pass at eng
Labor table -						
Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	
New FAST board design	Electric •	40	Univer •	DOE P ▼	Rough 🔻	UW
New FAST board design	Electric •	40	Univer •	DOE P ▼	Rough 🔻	UCSC
FAST board assembly	Electric •	40	Univer •	DOE P ▼	Rough 🔻	UW-UCSC
TCAD simulation	Electron •	320	Univer •	Base ( 💌	Rough 🔻	UCSC
BNL sensor design	Scientist 🔹	120	US Lab 🔻	DOE P ▼	Rough 🔻	BNL
BNL sensor production testing	Scientist 🔹	40	Univer •	Base ( 💌	Rough 🔻	UCSC-UW
BNL sensor production testing	Student •	160	Univer •	Base ( 💌	Rough 🔻	UCSC-UW
Sensor-board assembly	Mechan •	20	Univer •	Base ( 💌	Rough 🔻	UCSC
Characterization of board	Scientist 🔹	40	Univer •	DOE P ▼	Rough 🔻	UCSC-UW
FAST on flex design studies	Electric •	100	Univer •	DOE P ▼	Rough 🔻	UCSC-UW
FAST on flex prototype	Electric •	60	Univer •	DOE P ▼	Rough 🔻	
Thermal demonstrator assembly	Mechan •	40	Univer •	DOE P ▼	Rough 🔻	UW
Thermal demonstrator testing	Scientist 🔹	80	Univer •	Base ( 💌	Rough 🔻	UW
PiN readout design	Electric •	60	Univer •	Base ( 💌	Rough 🔻	UCSC
HD-SoC characterization	Scientist 🔹	160	Univer •	Base ( 💌	Rough 🔻	UCSC
Mechanical structure design	Mechan •	60	Univer 🔻	DOE P ▼	Rough •	UW
Mechanical support design	Mechan 🔻	60	Univer •	DOE P ▼	Rough 🔻	UW
Assembly jig design & documentation	Mechan 🔻	40	Univer •	DOE P ▼	Rough 🔻	UW
Assembly jig fabrication	Mechan 🔻	40	Univer •	DOE P ▼	Rough 🔻	UW
Assembly process development	Mechan 🔻	24	Univer •	DOE P ▼	Rough 🔻	UW
Assembly process development	Mechan 🔻	24	Univer •	DOE P ▼	Rough 🔻	UW
Assembly process documentation	Mechan 🔻	24	Univer •	DOE P ▼	Rough 🔻	UW
Mechanical structure assembly	Mechan 🔻	40	Univer •	DOE P ▼	Rough 🔻	UW
Mechanical structure assembly	Mechan 🔻	80	Univer •	DOE P ▼	Rough 🔻	UW
Mechanical structure assembly	Electric •	40	Univer •	DOE P ▼	Rough 🔻	UW
M&S and Contracted Labor table -						
Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.			
FAST board production	6	Base ( 💌	Rough •			
Flex board production	3	Base ( 💌	Conc 🔻			
BNL sensor production	100	DOE P ▼	Vendo •		BNL LDRD	right number?
Thermal demosntrator parts	1	Base ( 💌	Rough •			
TI-LGAD shared production	20	Base ( ▼	Rough •			
Mechanical parts	2	Base ( 💌	Rough •			
Cables	1	Base ( 💌	Rough •			
Travel	5	Base ( 💌	Rough •			

Freiminary Design (~1 year). Con	reis cost nom			ver preninnai	y design, su t	nawings, imp	loveu esuma
Labor table -							
Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	Hourly Rate	Activity Cost
Mask design	Scientist 💌	80	US Lab 🔻	(DOE ▼	Rough 🔻	\$269.75	\$21,580.00
Electrical testing	Student 💌	40	Univer 🔻	Base ( 💌	Rough 💌		\$0.00
Dynamic/TB testing	Scientist 💌	40	Univer 💌	Base ( 💌	Rough 💌		\$0.00
Dynamic/TB testing	Student 💌	160	Univer 🔻	Base ( 💌	Rough 💌		\$0.00
TCAD simulation	Scientist 💌	160	Univer 💌	Base ( 💌	Rough 💌		\$0.00
Sensor assembly	Mechan 💌	20	Univer 👻	Base ( 💌	Rough 🔻	\$60.00	\$1,200.00
M&S and Contracted Labor table -							
Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.	O/H Rate	Total Cost		
AC-LGAD-pin prototype production	100	DOE 👻	Rough 🔻	#N/A			
Readout board production	5	DOE 👻	Rough •				
II-LGAD (alternative tech) prototype produc	100	DOE 👻	Rough •				
Sensor coating or special assembly	2	DOE 🔻	Rough 🔻				
Fravel Contraction of the second seco	5	Base ( 💌	Rough •				
		D 2 laval fina	l deninun für	al ab an alvavi	ana final muat	- <b>f</b> (m - n )	
-inal Design (~1 year): Covers co .abor table -	st to produce (	D-3 level fina	ai design, fin	ai snop drawi	ngs, final prot	otypes)	
Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.		
Aask design	Scientist 💌	80	US Lab 🔻	DOE 💌	Rough 💌		Updated by Vol
Electrical testing	Student •	40	Univer 👻	Base ( 💌	Rough •		
)vnamic/TB testing supervise	Scientist 💌	40	Univer 👻	Base ( 💌	Rough 🔻		
)vnamic/TB testing	Student 🔻	160	Univer 🔻	Base ( 🔻	Rough T		
C supervise	Scientist 👻	40	Univer 🔻	Base ( 🔻	Rough T		
	Student *	160	Univer V	Base (	Rough T		
	Scientist -	80	Univer	Base ( *	Rough -		
Sensor assembly	Mechan ¥	40	Univer •	Base ( *	Rough *		
Sensor assembly	Wechan •	40	Oniver •	Dase ( +	Rough •		
M&S and Contracted Labor table -							
Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.				
Sensor prototype production with full size	100	DOE 👻	Rough 🔻				
Readout board production	5	DOE 👻	Rough 🔻				
Sensor coating or special assembly	2	DOE 👻	Rough 🔻				
Travel	5	Base ( 💌	Rough 🔻				
molemenation (1-2 years): Cover	e cost to build	experiment (i	netallation o	overed in sen	arate W/BS)		
Labor table -	s cost to build	experiment (i	instantation c	overeu in sep			
Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.		
Aask design	Scientist -	80	US Lab 🔻	DOE 👻	Rough 🔻		
QC supervise	Scientist -	40	Univer 👻	Base ( 🔻	Rough •		
20	Student •	160	Univer 👻	Base ( 🔻	Rough 🔻		
Dynamic/TB testing	Student •	320	Univer 👻	Base ( 🔻	Rough •		
CAD simulation	Scientist 💌	80	Univer 🔻	Base ( 🔻	Rough •		
18 S and Contracted Labor table							
vices and contracted Labor table -	Direct Cost (21)	Evendlere Torre	Estimate Her-				
item Descriptions	Direct Cost (\$k)	Lunding Type	Esumate Unc.				
sensor production	100	NSF •	Rougn •				
narrouning devices and supports	10	NSF •	Rough •				
Sensor coating or special assembly	10	DOE •	Rough 👻				
Iravel	10	Base ( ▼	Rough 🔻				
Assumptions: (Document assump	tions that wen	t into these es	stimates, see	examples)			
Assuming AC-LGAD technology, a final PIN	-only production co	sts less (no GL ir	mplantation) but	prototypes will lik	ely all be on share	d wafers	
I-LGAD is more expensive, double sided is	s more expensive						
AC-LGAD charge sharing can be contained	to first neighbor, ve	ery small long ran	ige sharing				
Jain saturation is limited to a reasonable le	vel		Ŭ,				
prototype productions are enough for the	final design						

# WBS Examples (WBS 6.4; Calo digitizers)

Atticity Name         Lakor Type         Hour         Lakor Starse         Funding Type         Extense tools           1 FPGA (a channel prototype VTD         Beletics +         400         Univer -         Beletics +         Monter         Rough, +           1 FPGA (a channel prototype VTD         Builder +         00her         Rough, +         Includes a channels and load design           MAS and Contracted Lakor table - the Decorption         Direct Ces(1b)         Fonding Type         Extense Univ         Prototype VTD         Prototype VTD           Add prototype VTD         Direct Ces(1b)         Prototype VTD         Extense Univ         Prototype VTD         Prototype VTD           Add prototype VTD         Direct Ces(1b)         Conc. +         Prototype VTD         Prototype VTD         Prototype VTD           Add prototype VTD         Direct Ces(1b)         Conc. +         Prototype VTD	Preliminary Design (~1 year): Cov	ers cost from	CD-1 to produ	icing CD-2 le	vel preliminar	ry design, 3d drawings	s, improved estima	tes, prototypes, advanced	
IPR04 (Abusch) protogo VTD         Electron         Other         Obsert         Other         Rough, +         Includes schematics and board deogn           Experimental Interface Firmware, protogo         Stadent, +	Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc			
IPDR unsigned manage         Desker:         Other         Base(         Provide the study -           Experimental interface Finances, pototype         Student, +         500         Univer -         Base(         Rough, +         Interface         Interface           MAS and Contracted Labor table- tem Description         Dired Cost(3k)         Finding Type         Estimate Usc.         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases         This price will come down when I get price beal ADD23 deptases           Proor mezzmine         15         Other         Conce.         Estimate Usc.         Estimate Usc.           Find Design (-1 year):         Conce.         Conce.         Estimate Usc.         Estimate Usc.           Find Design (-1 year):         Conce.         Conce.         Estimate Usc.         Estimate Usc.           Find Design (-1 year):         Conce.         Conce.         Estimate Usc.         Estimate Usc.           Find year down MPT         Externing ''         How ''         How ''         How ''         How ''	1 EPGA (4 channel) protetype WED	Electron Type	640		Othor T	Dough T	includes schoms	atics and board dosign	
The Depring of Laboration Provides	1 EPGA prototype firmware	Electron •	400	Univer •	Other •	Rough V	includes scheine	tics and board design	
Agam Contracted Labor table - Mes and Contracted Labor table - Mes and Contracted Labor table - Mes processing sequences of the sequences o	Eventimental interface Eirmware prototype	Student -	400	Univer •	Base (	Rough -			
MAS and Contracted Labor table - ben Descriptions         Direct Cell (k)         Funding Type Entend to Concernet (spectrame)         Entend	Experimental interface Firmware, prototype	Student •	900	Univer •	Dase ( •	Rougn •			
Item Description         Direct Code (3): CPC balance         Funding Type Code         Extinue Luc.         Code         Code <thcode< th="">         Code         Code</thcode<>	M&S and Contracted Labor table -								
PGB backston       4.5       Other       Catalo       This price will come down when is price backstone         ADS24 digitaria       7.3       Other       Catalo       See L. Gaborn: WFD_prioner spreaduled         ADS24 digitaria       7.3       Other       Catalo       See L. Gaborn: WFD_prioner spreaduled         Non IC components (setImate)       3.0       Other       Catalo       See L. Gaborn: WFD_prioner spreaduled         Sead assembly       3.0       Other       Catalo       See L. Gaborn: WFD_prioner spreaduled         Power mezzanite       1.5       Other       Catalo       Based on g2 WFD5 costs - similar complexity         Field Design (-1 year): Covers cost to produce UP-3 level final design, final shop drawings, final prototypes)       Estimate unc       See L. Gaborn: WFD         Field Design (-1 year): Covers cost to produce UP-3 level final design, final shop drawings, final prototypes)       Estimate unc       See L. Gaborn: WFD         Field Design (-1 year): Covers cost to produce UP-3 level final design, final shop drawings, final prototypes)       Estimate unc       See L. Gaborn: WFD         Power mozanie       Labor Type       Hours       Labor Source       NSF       Rough, *         Field Design (-1 year): Covers cost to produce NSF       Gane       NSF       Rough, *       NSF         Field Testinter       Gane	Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.					
XCU20252 PEQAs         6.3         Other         Catala         This pice will come down when 1 get pice banks           Analysis         Campanets (specified)         2.0         Other         Catala         The pice will come any when 1 get pice banks           Bard assembly         3.0         Other         Catala         The pice will come any when 1 get pice banks           Bard assembly         3.0         Other         Cance         Passembles           Bard assembly         3.0         Other         Cance         Passembles           Analog Ford End (AFE) mezzanine         2.5         Other         Cance         Passembles           Final Design (-1 year):         Concer         Cance         Passembles         Date of the pice of the p	PCB fabrication	4.5	Other •	Conc •					
AD324 digitarin         7.3         Other         Catalo         See L Gibbont WFD_plonear spreadheet           Non IC components (sammal)         0.3         Other         Catalo         See L Gibbont WFD_plonear spreadheet           Non IC components (sammal)         0.3         Other         Catalo         See L Gibbont WFD_plonear spreadheet           Pour mezzanine         1.5         Other         Catalo         Based on p2 WFD5 costs - similar complexity           Print Design (-1 year): Covers cost to produce UD-5 level Intal design, final shop drawings, final prototypes)         Eator Table         See L Gibbont WFD_plonear spreadheet           Final Design (-1 year): Covers cost to produce UD-5 level Intal design, final shop drawings, final prototypes)         Eator Table         See L Gibbont WFD_plonear spreadheet           Final Design (-1 year): Covers cost to produce UD-5 level Intal design, final shop drawings, final prototypes)         Eator Table         See L Gibbont WFD_plonear spreadheet           Final Design (-1 year): Covers cost to produce UD-1 sevel Intal design, final shop drawings, final prototypes)         Eator Table         See L Gibbont WFD_plonear spreadheet           Final Design (-1 year): Covers cost to produce UD-1 sevel Intal design, final shop drawings, final prototypes)         Eator Table         See L Gibbont WFD_plonear Spreadheet           Final Design (-1 year): Covers cost to produce UD-1 sevel Intal design, final shop drawings, final prototypes)         See L Gibbont WFD_plo	XCKU025-2 FPGAs	6.3	Other •	Catalo •			This price will co	ome down when I get price break i	
Open IC components (specifier)         2.0         Other         C conc         Description           Bard assembly         3.0         Other         C conc         Based on p 2 WFDE costs - similar complexity           Power mozzanine         1.5         Other         C conc         Based on p 2 WFDE costs - similar complexity           Analog Front End (AFE) mozzanine         2.5         Other         C conc         Based on p 2 WFDE costs - similar complexity           Field assemblies         3.8         Other         C conc          Based on p 2 WFDE costs - similar complexity           Field assemblies         3.8         Other         C conc          Based on p 2 WFDE costs - similar complexity           Field assemblies         1.5         Other         C conc          Based on p 2 WFDE costs - similar complexity           Field assemblies         1.5         Other         C conc         NSF         Based on p 2 WFDE costs - similar complexity           Field assemblies         1.5         Other         C conc         NSF         Based on p 2 WFDE costs - similar complexity           Field coharol WFD Immare         Electron +         3.20         Univer -         NSF         Based (-         Based (-         Based (-         Based (-         Based (-         Based (-	AD9234 digitizers	7.3	Other •	Catalo 💌			See   Gibbons'	WED pioneer spreadsheet	
Nen IC components (sedimated)         0.3         Other         Conc.         Based on p.2 WFD5 costs similar complexity           Board assembles         1.5         Other         Conc.         Based on p.2 WFD5 costs similar complexity           Availap Font Exp (JFE) resizance         2.5         Other         Conc.         Based on p.2 WFD5 costs similar complexity           Find Design (-1 year): Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)         Image: state stat	Other IC components (specified)	2.0	Other •	Catalo 💌					
Bard seembly         Disk         Conc.         Based on p2 WFPB costs	Non IC components (estimated)	0.3	Other •	Conc 🔻					
Prover mercranne         15         Other         Conce         Based on p2 WFD5 costs - similar complexity.           Analog Front Euro/FE preszranice         3.6         Other         Conce         Based on p2 WFD5 costs - similar complexity.           Find Descip (-1 year): Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)         Image: Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)         Image: Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)           Lator table:         Activity Name         Labor Type         Hours         Labor Source         Funding Type         Estimate Unc.           Activity Name         Labor Type         Hours         Labor Source         Funding Type         Estimate Unc.         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover to produce CD-3 level final design, final broot drawings, final prototypes         Image: Covers cover final design, final broot draw final design, final broot draw final design, final broot draw final design, final broot drawings, final design final broot draw final design, final broot draw	Board assembly	3.0	Other •	Conc •			Based on g-2 W	ED5 costs similar complexity	
Assign From End (AFE) mezzanine         2.5         Other         Canc.         End         Based on g 2 WFDS costs - similar complexity           Find Design (-1 year):         Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)         Image: Similar complexity         Image: Similar complexity           Labor table         Activity Name         Labor Type         Hours         Labor Source         Funding Type         Estimate Unc.         Funding Type         Estimate Unc.         Funding Type         Estimate Unc.         Funding Type         Estimate Unc.         Funding Type         Funding Type         Estimate Unc.         Funding Type         Funding Type         Funding Type         Estimate Unc.         Funding Type         Funding Type         Estimate Unc.         Funding Type         Funding Type         Funding Type         Estimate Unc.         Funding Type         <	Power mezzanine	1.5	Other •	Conc 💌			Based on g-2 W	ED5 costs similar complexity	
Profile according         Differ         Conc         Variable         Conc         Co	Analog Front End (AEE) mezzanine	2.5	Other T	Conc •			Based on g-2 W	ED5 costs similar complexity	
International Context         Difference         Participant           Final Design (-1 year): Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)         Image: Context of Additional Context of Ad	Firefly accomplian	3.9	Other T	Vondo 💌			Dased on g-2 W	Do costa anniar complexity	
Crase     1 S     Outer     Conc       Final Design (-1 year):     Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)       Labor table -     Achtly Name     Labor Type     Hours     Labor Source       Achtly Name     Labor Type     Hours     Labor Source     Funding Type       Exection ×     130     Univer. •     NSF. •     Rough, •       Experimental Interface firmware, revisions     Student. •     500     Univer. •     Base (. •     Rough, •       PCB Indication     Direct Cost (%)     Funding Type     Estimate Unc.     Funding Type       PCB Indication     Student. •     500     Univer. •     Base (. •     Rough, •       Non IC components (selfinal)     0     NSF. •     Conc. •     Conc. •       Non IC components (selfinal)     0.6     NSF. •     Conc. •     Based on g.2 WFD5 costs - similar complexity       Prefit assembly     3.0     NSF. •     Conc. •     Based on g.2 WFD5 costs - similar complexity       Prefit assembly     3.0     NSF. •     Conc. •     Based on g.2 WFD5 costs - similar complexity       Prefit assembly     3.0     NSF. •     Conc. •     Based on g.2 WFD5 costs - similar complexity       Prefit assembly     3.0     NSF. •     Conc. •     Based on g.2 WFD5 costs - similar comple	Crate	1.5	Other •	Conc.					
Final Design (-1 year): Cover scott o produce CD-3 level final design, final shop drawings, final prototypes)         (a)           Labor tabe           Achily Name         Labor tabe           Revisions / full 12 channel prototypes WFD         Election •         (a)         (a)           Revisions / full 12 channel wFD firmware         Election •         NSF •         Rough •           Revisions / full 12 channel wFD firmware         Election •         NSF •         Rough •           Base ( *         Rough •         Rough •           Rough •         Rough •           Statient •         Statient Unc.           Conc •         Rough •           Conc •         Rough •           Statient Unc.         Conc •           Components (pacified)         Conc •         Conc •           Rough •         Conc •           Statient Unc.         Conc • <th colsp<="" td=""><td>Clate</td><td>1.5</td><td>Other</td><td>Conc ·</td><td></td><td></td><td></td><td></td></th>	<td>Clate</td> <td>1.5</td> <td>Other</td> <td>Conc ·</td> <td></td> <td></td> <td></td> <td></td>	Clate	1.5	Other	Conc ·				
Labor table         Labor Type         Hours         Labor Source         Funding Type         Estimate Unc.         Cond           Activity Name         Electron	Final Design (~1 year): Covers co	st to produce (	CD-3 level fina	al design, fin	al shop drawi	ngs. final prototypes)			
Activity Name         Labor Source         Funding Type         Estimate Unc.           Verbians / UL Johannel IVCPD WTD         Electron.         160         Univer+         NSF+         Rough+           Full 12 channel WTD firmware         Electron+         160         Univer+         NSF+         Rough+           Experimental Interface firmware, revisions         Student+         500         Univer+         Base (+         Rough+           M&S and Contracted Labor table - Inter Descriptions         Direct Cost (3k)         Fonding Type         Estimate Unc.         Image: Cost (3k)         Fonding Type           PCB fabrication         5.0         NSF+         Catalo+         Image: Cost (3k)         This price will come down when 1 get price breat ADS234 digitizers           ADS24 digitizers         2.18         NSF+         Catalo+         Image: Cost (3k)         See L Gibbons' WTD gioneer spreadsheet           Non IC components (secfied)         2.00         NSF+         Conc+         Image: Cost (3k)         See L Gibbons' WTD gioneer spreadsheet           Seried assembly         3.0         NSF+         Conc+         Image: Cost (3k)         See Cost (3k) <td>Labor table -</td> <td> p</td> <td></td> <td><b>.</b></td> <td></td> <td></td> <td></td> <td></td>	Labor table -	p		<b>.</b>					
Revision / full / 2 channel prototype WFD         Electron         3.20         Univer         NSF         Rough           Experimental interface firmware, revisions         Student         Student         NSF         Rough         Interface firmware, revisions         Student         Student         NSF         Rough         Interface firmware, revisions         Student         Student         NSF         Rough         Interface firmware, revisions         Student         NSF         Rough         Interface firmware, revisions         Student         Interface firmware, revisions         Interface firmware, revisions         Student         Interface firmware, revisions	Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.			
Full 12 channel WFD firmware         Electron+         160         Univer+         NSF+         Rough+           Experimental interface firmware, revisions         Student+         500         Univer+         Base (+         Rough+         Image: Comparison of Com	Revisions / full 12 channel prototype WFD	Electron •	320	Univer •	NSF 🔻	Rough •			
Experimental interface (imware, revisions         Student+         500         Univer+         Base (+         Rough+           MAS and Contracted Labor table- Nem Descriptions         Direct Cost (\$k)         Funding Type         Estimate Unc.         Image: Cost (Cost (	Full 12 channel WFD firmware	Electron •	160	Univer •	NSF 🔻	Rough •			
M&S and Contracted Labor table - Item Descriptions         Direct Cost (Sk)         Funding Type         Estimate Unc.         Conc.         <	Experimental interface firmware, revisions	Student •	500	Univer •	Base ( 💌	Rough 💌			
Item Descriptions         Direct Cost (sk)         Funding Type         Estimate Unc.           PCB fabrication         50         NSF	M&S and Contracted Labor table -								
PCB faulciation       6.50       NSF	Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.					
XCKU025-2 FPGAs         18.9         NSF	PCB fabrication	5.0	NSF 🔻	Conc 💌					
A09234 digitizers       218       NSF	XCKU025-2 FPGAs	18.9	NSF 🔻	Catalo •			This price will co	me down when I get price break i	
Other IC components (settimated)         0.5         NSF+         Catalo+         Conc+         Conc+         Sade assertion	AD9234 digitizers	21.8	NSF 💌	Catalo •			See L. Gibbons'	WFD_pioneer spreadsheet	
Non IC components (estimated)         0.5         NSF.         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Board assembly         1.5         NSF.         Conc         Image: Complexity         Based on g-2 WFD5 costs - similar complexity           Prefy assemblies         3.8         NSF.         Conc         Image: Complexity         Based on g-2 WFD5 costs - similar complexity           Firefy assemblies         3.8         NSF.         Conc         Image: Complexity         Based on g-2 WFD5 costs - similar complexity           Firefy assemblies         3.8         NSF.         Conc         Image: Complexity         Based on g-2 WFD5 costs - similar complexity           Firefy assemblies         3.8         NSF.         Conc         Image: Complexity         Image: Complexity           Crate         1.5         NSF.         Conc         Image: Complexity         Image: Complexity         Image: Complexity           Labor table -         Image: Complexity         Conc         Image: Complexity         Image: Compl	Other IC components (specified)	2.0	NSF 💌	Catalo •					
Board assembly         3.0         NSF         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Power mezzanine         1.5         NSF         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Analog Front End (AFE) mezzanine         2.5         NSF         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Fired y assemblies         3.8         NSF         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Crate         3.8         NSF         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Crate         3.8         NSF         Vendo         Conc         Conc         Based on g-2 WFD5 costs - similar complexity           Crate         3.8         NSF         Vendo         Conc	Non IC components (estimated)	0.5	NSF 💌	Conc 💌					
Power mezzanine         1.5         NSF+         Conc+         Based on g-2 WFD5 costs - similar complexity           Analog Front End (AFE) mezzanine         2.5         NSF+         Conc+         Based on g-2 WFD5 costs - similar complexity           Firely assembles         3.8         NSF+         Conc+         Image: Costs - similar complexity           Crate         1.5         NSF+         Conc+         Image: Costs - similar complexity           Implementation (1-2 years): Covers cost to build experiment (installation covered in separate WBS)         Image: Costs - similar complexity           Labor table -         Image: Costs - similar complexity         Image: Costs - similar complexity           Revisions / production package         Electron+         Conc+         Image: Costs - similar complexity           Final experimental firmware revisions         Student+         160         Univer+         NSF+         Rough+           MS and Contracted Labor table -         Image: Costs - similar complexity         Image: Costs - similar complexity         Image: Costs - similar complexity           PCB fabrication         Student+         160         Univer+         Rough+         Rough+         Image: Costs - similar complexity           PCB fabrication         Ifrial experimental firmware revisions         Student+         160	Board assembly	3.0	NSF 🔻	Conc 💌			Based on g-2 W	FD5 costs similar complexity	
Analog Front End (AFE) mezzanine         2.5         NSF	Power mezzanine	1.5	NSF 🔻	Conc 💌			Based on g-2 W	FD5 costs similar complexity	
Firefly assemblies       3.8       NSF+       Vendo+         Crate       1.5       NSF+       Conc+       Implementation       Implementation         Implementation (1-2 years): Covers cost to build experiment (installation covered in separate WBS)       Implementation       Implementation       Implementation         Activity Name       Labor Type       Hours       Labor Source       Funding Type       Estimate Unc.       Implementation         Revisions / production package       Electron+       160       Univer+       NSF+       Rough+       Implementation         Final experimental firmware revisions, testing and installat       Electron+       160       Univer+       NSF+       Rough+         M&S and Contracted Labor table -        300       Univer+       Base (+       Rough+         M&S and Contracted Labor table -              Item Descriptions       Direct Cost (Sk)       Funding Type       Estimate Unc.           AD9234 digitzers       371.3       NSF+       Catalo+            Other IC components (specified)       45.4       NSF+       Catalo+            AD9234 digitz	Analog Front End (AFE) mezzanine	2.5	NSF 🔻	Conc 💌			Based on g-2 W	FD5 costs similar complexity	
Crate       1.5       NSF*       Conc*       Implementation       Implementatintit       Implementatintit       Impl	Firefly assemblies	3.8	NSF 🔻	Vendo •					
Implemention (1-2 years): Covers cost to build experiment (installation covered in separate WBS)       Implement (Installation covered in separate WBS)         Labor table -       Implement (Installation covered in separate WBS)         Activity Name       Labor Type         Hours       Labor Source         Final firmware revisions, testing and installa       Electron *         160       Univer *       NSF *         Rough *       Final experimental firmware revisions       Student *         Student *       160       Univer *       Base ( *         Assembly / testing / installation       Student *       300       Univer *       Base ( *         M&S and Contracted Labor table -       Implement firmware revisions       Direct Cost (\$k)       Funding Type       Estimate Unc.         PCB fabrication       17.0       NSF *       Conc *       Implements (conc *       Implements (conc *         AD9234 digitzers       3713       NSF *       Catalo *       Implements (conc *       Implements (conc *         Non IC components (estimated)       85       NSF *       Conc *       Implements (conc *       Implements (conc *         Power mezzanine       9.4       NSF *       Conc *       Implements (conconc *       Implements (conc	Crate	1.5	NSF •	Conc •					
Induction for Lybers (1): Concrete on the concret on the concrete on the concrete on the concrete on th	Implemenation (1-2 years): Cover	s cost to build	experiment (i	nstallation c	overed in sen	arate WBS)			
Activity NameLabor TypeHoursLabor SourceFunding TypeEstimate Unc.Revisions / production packageElectron	Labor table -		experiment (	inotanation o					
Revisions / production package         Electron         160         Univer         NSF         Rough         Ro	Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.			
Final firmware revisions, testing and installa       Electron•       80       Univer•       NSF•       Rough•         Final experimental firmware revisions       Student•       160       Univer•       Base (•       Rough•       Rough•       Accompletee       Image: Completee       Image: Completeee       Image: Completeee       Image: Complete	Revisions / production package	Electron •	160	Univer •	NSF 🔻	Rough 🔻			
Final experimental firmware revisions         Student         160         Univer         Base (         Rough	Final firmware revisions, testing and installa	Electron •	80	Univer •	NSF 🔻	Rough 🔻			
Assembly / testing / installation       Student       300       Univer       Base (       Rough       Court       Court <th< td=""><td>Final experimental firmware revisions</td><td>Student 💌</td><td>160</td><td>Univer •</td><td>Base ( 💌</td><td>Rough 🔻</td><td></td><td></td></th<>	Final experimental firmware revisions	Student 💌	160	Univer •	Base ( 💌	Rough 🔻			
M&S and Contracted Labor table - Item Descriptions         Direct Cost (\$k)         Funding Type         Estimate Unc.         Conc •         <	Assembly / testing / installation	Student •	300	Univer •	Base ( 💌	Rough 🔻			
Item Descriptions         Direct Cost (\$k)         Funding Type         Estimate Unc.         Es	M&S and Contracted Labor table -								
PCB fabrication       17.0       NSF	Item Descriptions	Direct Cost (\$k)	Funding Type	Estimate Unc.					
XCKU025-2 FPGAs         247.6         NSF	PCB fabrication	17.0	NSF •	Conc 💌					
AD9234 digitizers       371.3       NSF •       Catalo •         Other IC components (specified)       45.4       NSF •       Catalo •         Non IC components (setimated)       8.5       NSF •       Conc •         Board assembly       17.0       NSF •       Conc •         Power mezzanine       9.4       NSF •       Conc •         Analog Front End (AFE) mezzanine       17.0       NSF •       Conc •         Firefly assemblies       595       NSF •       Vendo •         Crates       18.0       NSF •       Conc •	XCKU025-2 FPGAs	247.6	NSF 🔻	Catalo •					
Other IC components (specified)         454         NSF •         Catalo •           Non IC components (estimated)         85         NSF •         Conc •           Board assembly         17.0         NSF •         Conc •           Power mezzanine         9.4         NSF •         Conc •           Analog Front End (AFE) mezzanine         17.0         NSF •         Conc •           Firefly assemblies         59.5         NSF •         Vendo •           Crates         18.0         NSF •         Conc •	AD9234 digitizers	371.3	NSF 🔻	Catalo •					
Non IC components (estimated)         8.5         NSF •         Conc •           Board assembly         17.0         NSF •         Conc •           Powr mezzanine         9.4         NSF •         Conc •           Analog Front End (AFE) mezzanine         17.0         NSF •         Conc •           Firefly assemblies         59.5         NSF •         Vendo •           Crates         18.0         NSF •         Conc •	Other IC components (specified)	45.4	NSF 🔻	Catalo •					
Board assembly         17.0         NSF •         Conc •           Power mezzanine         9.4         NSF •         Conc •           Analog Front End (AFE) mezzanine         17.0         NSF •         Conc •           Firefly assemblies         59.5         NSF •         Conc •           Crates         18.0         NSF •         Conc •	Non IC components (estimated)	8.5	NSF •	Conc 💌					
Power mezzanine         9.4         NSF •         Conc •           Analog Front End (AFE) mezzanine         17.0         NSF •         Conc •           Firefly assemblies         59.5         NSF •         Vendo •           Crates         18.0         NSF •         Conc •	Board assembly	17.0	NSF •	Conc 💌					
Analog Front End (AFE) mezzanine         17.0         NSF •         Conc •           Firefly assemblies         59.5         NSF •         Vendo •           Crates         18.0         NSF •         Conc •	Power mezzanine	9.4	NSF •	Conc •					
Firefly assemblies         595         NSF •         Vendo •           Crates         18.0         NSF •         Conc •	Analog Front End (AFE) mezzanine	17.0	NSF •	Conc 💌					
Crates 18.0 NSF • Conc •	Firefly assemblies	59.5	NSF •	Vendo 💌					
	Crates	18.0	NSF 🔻	Conc 💌					