Review of Fermilab Detector Research and Development Relevant to CMS

18 December. 2014

Erik Ramberg
Fermilab

Fermilab Detector R&D Organization

- The **"Detector Advisory Group"** consists of: (PPD unless otherwise noted)

• Technical Point of Contact	Erik Ramberg
• Silicon tracking representative	Ron Lipton
• DAQ and Triggering representative	Alan Prosser (SCD)
• Calorimetry and photodetection representative	Jim Freeman
• Liquid Argon R&D representative	Stephen Pordes (ND)
• Astrophysics detectors representative	Juan Estrada
• Intensity Frontier representative (CD)	Bob Tschirhart
• Head, Particle Physics Division	Patty McBride (ex-officio)
• Assoc. head for Engineering	Eric James (ex-officio)
• Head, Particle Physics Initiatives	Dmitri Denisov (ex-officio)
• Head, New Initiatives R&D	Dave Christian (ex-officio)
• Scientific Computing (CD)	Panagiotis Spentzouris (SCD)
• Ulrich Heintz (Brown University)	(External Representative)

- The group meets twice a month and monitors and reports on the activities in each of their portfolios.
- Members give advice on the future of the program and participate in reviews of projects in each portfolio
- TPOC informs the Division Heads and Offices of Research and Computing of plans arising out of group discussions and reviews.
- After consultation with DOE, Division Heads and CRO then decide on approval of new directions

Detector Research and Development Deliverables (2015)

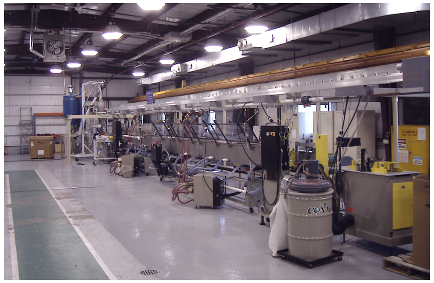
PORTFOLIO	DELIVERABLES	DESCRIPTION	THRUST
* Silicon Tracking	Vertex Sensor/3D ASICS	Collaborative development of 3D ASICs	Sensors
(R. Lipton)	Tracking Mechanical	Low mass mechanical support and cooling designs	Core & Infrastructure
	Pixel Readout	65 micron pixel readout development	DAQ/Trigger Electr.
* Calorimetry &	psec Time-of-Flight	Collaborative LAPPD phototube program at ANL	Sensors
Photodetection	Hadron Calorimetry	Dual readout techniques, QIE10, Phase II CMS endcap	Sensors
(J. Freeman)	SiPM R&D	Testing, fast timing, multi-channel readout	Sensors
	Scintillator R&D	Scintillator/WLS co-extrusion, rad hard, thinned extrusions	Core & Infrastructure
	Calorimetry CDRD	Multi-institution investigations in calorimetry	Sensors
Astrophysics	Bubble Chamber	Acoustic rejection of α background / Recoil calibration	Sensors
Detectors	Silicon Dark Matter	Support of DAMIC technique for dark matter detection	Sensors
(J. Estrada)	CCD R&D	Low noise readout/neutron imaging/CONNIE nu detection	Sensors
	MKID	Multiplexed array for spectrophotometry	Sensor
	CMB	Infrastructure for high channel count - CMB-4	Sensor
Liquid Argon	Materials Test Stand	Testing contamination potential of materials for LAr TPC	Cryogenics
(S. Pordes)	Short Baseline Neutrino	Large scale LAr detector planning and development	Cryogenics
	Low Background Ar	Production of low-background Ar for Dark Matter community	Cryogenics
	Cold Electronics	Collaborative cold electronics development w/ BNL & MSU	Cryogenics
	Test beam for Lar	Develop cryogenics capability at new test beam line	Cryogenics
	Light yield at low E	Small chamber to test light yield in LAr	Cryogenics
	Solid Xenon	New type of dark matter / axion / $\beta\beta$ detector	Cryogenics
	Low Energy Neutrinos	Using Booster Target as a neutrino source	Core & Infrastructure
* DAQ	Sensor DAQ	Radiation hardness testing of new sensors	DAQ/Trigger Electr.
(A. Prosser)	μTCA and ATCA	Evaluation of new data-flow architecture	DAQ/Trigger Electr.
	Optical DAQ	Collaborative development of multi-Gbit data links	DAQ/Trigger Electr.
	VIPRAM	Triggering for CMS using associative memories	DAQ/Trigger Electr.
	CCD R&D	Low noise readout for CCD's	DAQ/Trigger Electr.
	DATA LINKS	High speed DAQ	DAQ/Trigger Electr.
Facilities &	Facilities / Contingency	Facility maintenance & repairs / management reserve	Core & Infrastructure
Community Support	Detector Tools	Upgrade of R&D tools	Core & Infrastructure
(E. Ramberg)	Test Beam Equipment	Pixel telescope support for test beam	Core & Infrastructure
	Workshops / Schools	Conferences, workshops and schools for HEP community	Core & Infrastructure

* = especially relevant for CMS R&D

Fermilab Assets for Detector Research

- Detector R&D program at Fermilab is enabled by our institutional strengths:
  - Presence of research facilities such as:
    - Test beam facility
    - Silicon Detector facility
    - Liquid argon test facility
    - NICADD scintillator extrusion facility
    - CCD characterization facility
    - Thin-Film Facility
    - High power laser laboratory
  - Experienced, well established engineering groups, such as
    - ASIC development
    - Cryogenics
    - Data Acquisition

- We encourage a high degree of collaboration with the university community and other national labs, and we will continue to advertise the capabilities in detector support that Fermilab can deliver



Scintillator extrusion at Lab 5

Clean rooms and metrology at SiDet

CALICE at the test beam

‘KA25’ DOE budget category

- The KA25 budget supports detector R&D at Fermilab that is programmatic to the OHEP mission, including both directed and general detector R&D.
- This B&R funding category supports M&S and SWF of associated technical staff but does not support associated Fermilab scientific effort.
- The KA25 review process includes regular internal reviews, and the OHEP complex-wide triennial reviews organized by OHEP. The next triennial complex-wide review will be held in the summer of 2015.

Collider Detector R&D Funding Opportunity (CDRD)

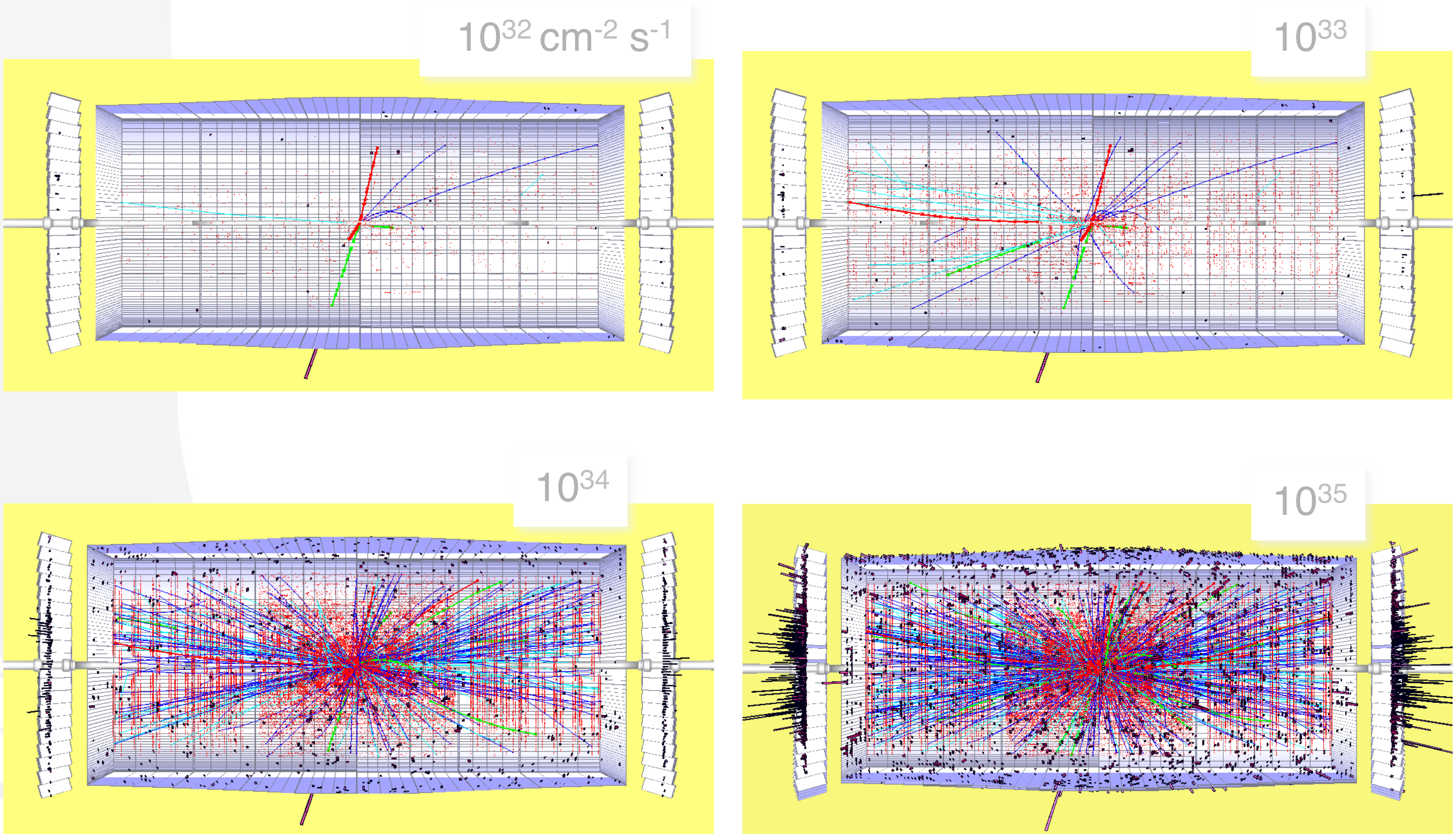
Fermilab was a part of several proposals prepared for the CDRD funding opportunity in 2012. We worked to increase our collaborative efforts with universities, other national labs and industrial partners.

Fermilab participated in several CMS projects selected for funding :

- *A Proposal to Develop a High Speed Data Link for Collider Experiments*
  - *(ANL, U.Mn., OSU., FNAL, SMU, VegaWave)*
  - *$360 K – ($64 K for FNAL)*
- *Development of 3D Vertically Integrated Pattern Recognition Associative Memory*
  - *(FNAL, U.Chicago, ANL, INFN (Padova), Tezzaron)*
  - *$150 K – ($140K for FNAL)*
- *Forward Calorimetry for a High Luminosity LHC*
  - *(Virginia, Notre Dame, Iowa, Florida State, Minnesota, Cal.Tech, Feirald)*
  - *$410 K ($0 for FNAL)*

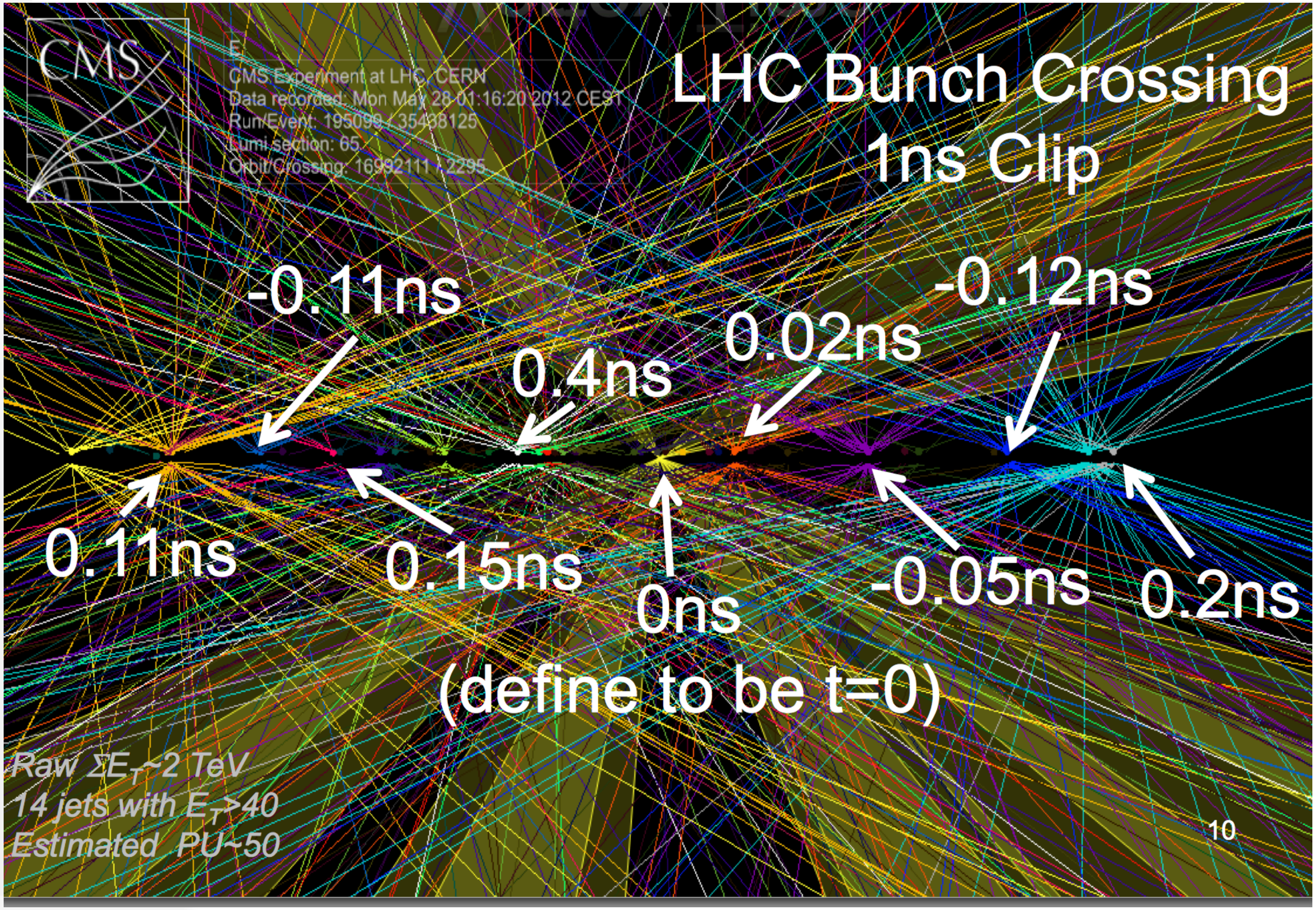
High speed data links and 3D VIPRAM will continue.
How best can Fermilab help the calorimetry research?

The challenge (from simulation) ….



Everything must be fast in CMS Phase II

From Chris Tully SSI lecture, 2012:



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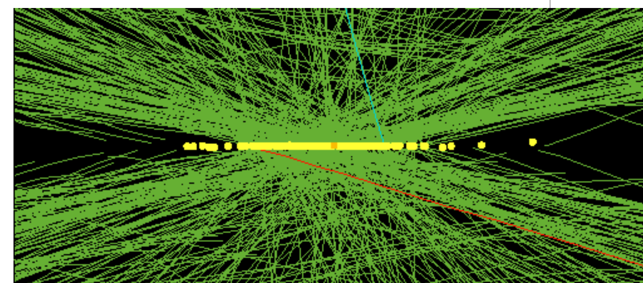
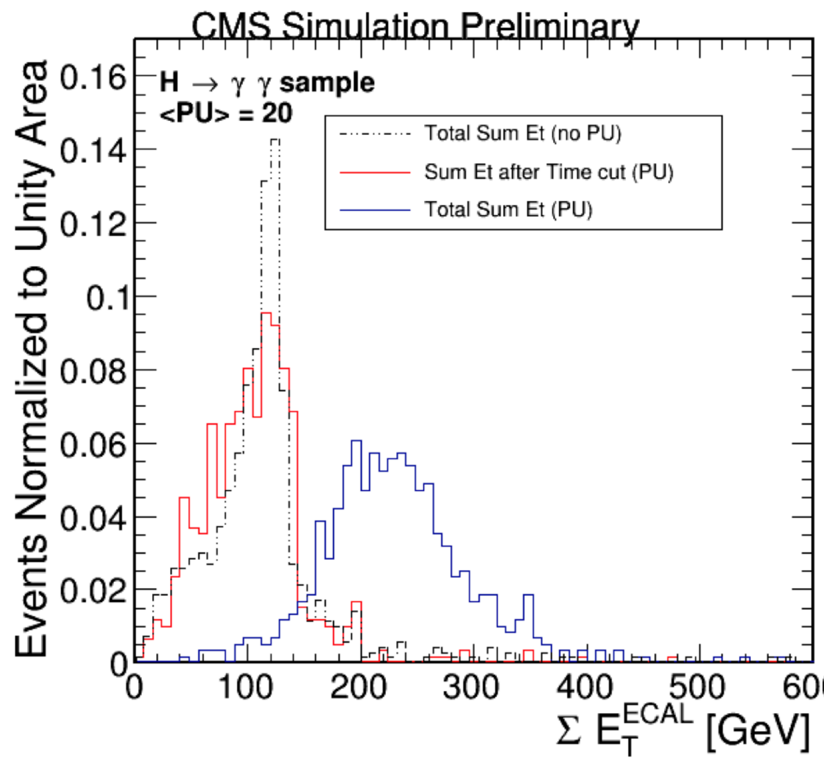
ECAL Clean-up using Timing

- **Effect of timing cut** on ΣE_T^{ECAL} variable
  - sum of all ECAL hits with E > 1GeV.
- O(30 ps) resolution detector simulated



- Require ECAL timing (time-of-flight subtracted) within a **90 ps window**
- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions
- Timing-based selection looks **promising for high PU environment**



- CMS (& ATLAS) require new pixel detector technology (at least for the layers closest to the beam).
  - Both sensor and electronics need greatly improved radiation tolerance:
    - > $10^{16}/cm^2$ n equivalent
    - ~ 1 Grad total ionizing dose
  - And greater rate capability
    - 1 – 2 GHz/cm^2 hit density in inner layer
    - CMS trigger rate will increase by a factor of ten (even as events get larger)
  - Want smaller pixels
  - And longer trigger latency (more memory in ROC)

FNAL Has Had a Comprehensive Approach to Silicon Tracking, Triggering and DAQ R&D for Phase II upgrade of CMS

Creating a tracking and trigger system that can withstand the projected HL-LHC luminosities is arguably the most important detector challenge in the field of High Energy Physics.

There must be a comprehensive approach:

Sensor — Testing radiation hardness in new sensors (3D columnar + Diamond)

↓

Front End — Providing new readout for pixel detectors

↓

L1 Trigger — Track trigger using 3D techniques

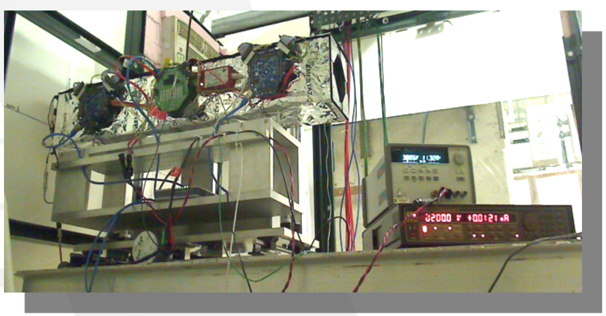
↓

Data Transmission — Multi-wavelength optical DAQ

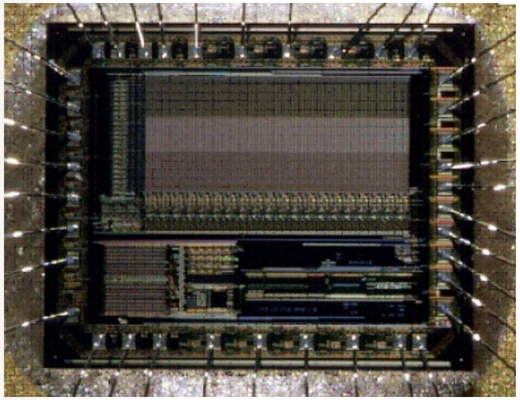
↓

Track Fitting — GPU's and Associative Memory

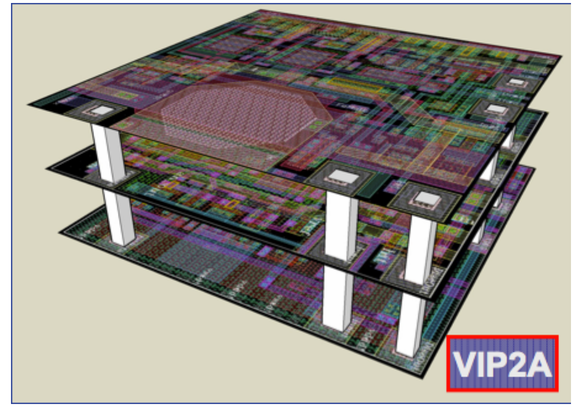
15 US universities
19 foreign institutions
5 laboratories
8 industrial partners



3-Dimensional ASIC program



Conventional Monolithic
Active Pixel Sensor



3 tier 3D stack for FNAL ILC vertex
chip, fabricated by MIT-LL

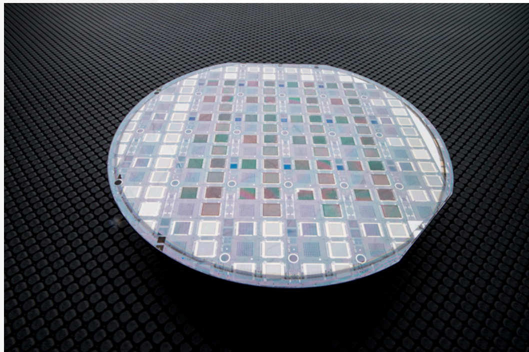
Fermilab has led the formation of a large international consortium (http://3dic.fnal.gov) addressing this technology. This group of 17 members from 6 countries shared a multi-project run in 2009 and we have successfully bonded chips from that run to X-ray sensors

We have established a close working relationship to Tezzaron (located near Fermilab) and the U.S. based firm Ziptronix. The tools and techniques learned from this R&D have been adopted by the major silicon fabrication brokers: MOSIS, CMP and CMC.

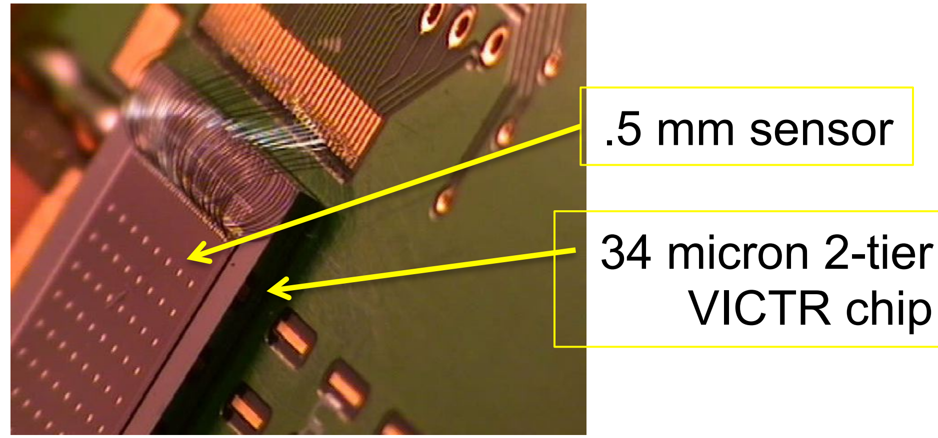
BES has agreed to fund ($2.5M) further 3D development of an x-ray imaging chip in collaboration with BNL and Argonne

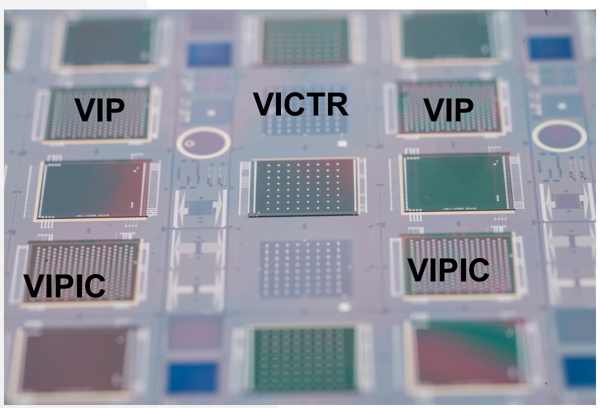
This run will also contain the 3D associative memory chip (VIPRAM) for CMS

Wafer with bonded Chips

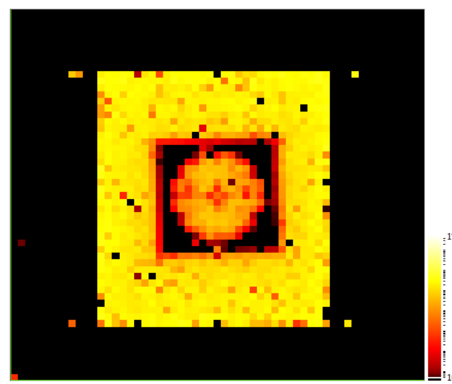


VICTR (CMS Track Trigger Chip)





VIP is very high density, very thin readout chip for ILC



Transmission radiogram of a small W mask (2.5x2.5 mm^2) put on top of the sensor;

VIPIC (X-ray correlation detector)

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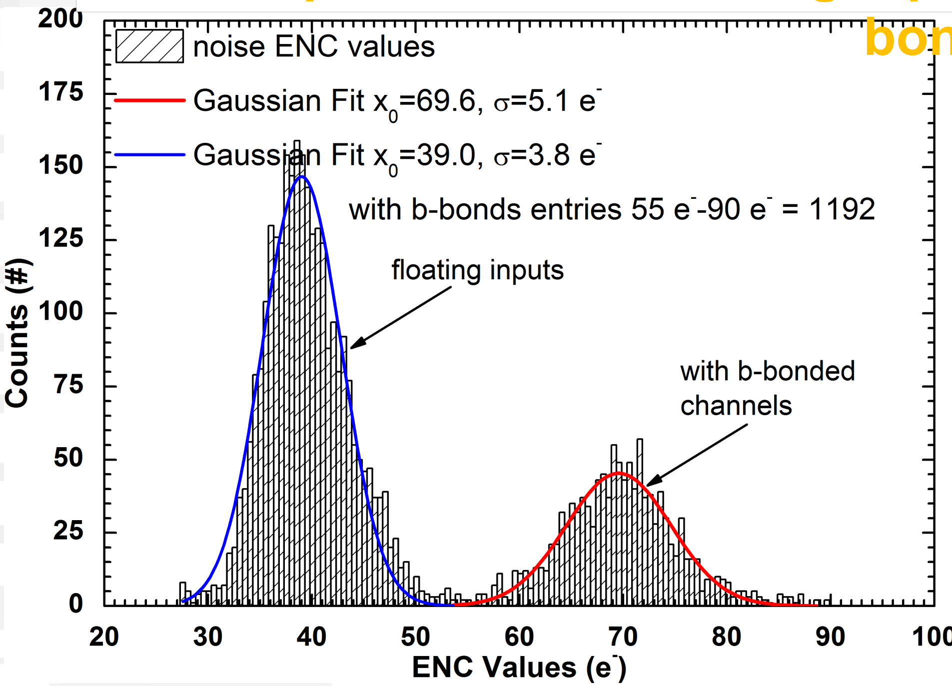
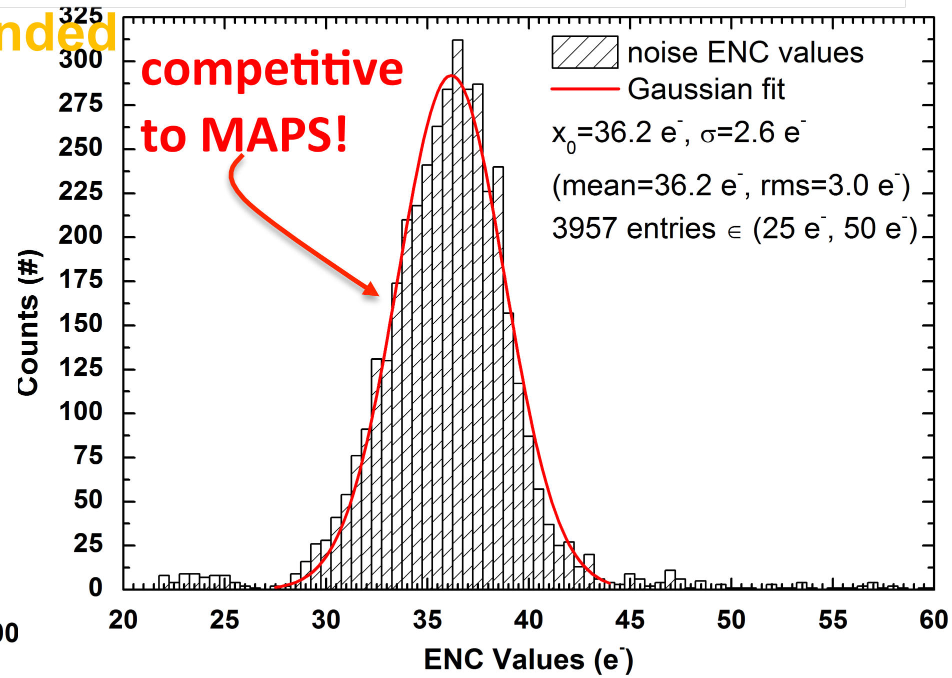
Results: noise comparison fusion-bonded vs bump-bonded

Bump-bonded VIPIC1 larger pitch 100µm vs. 80µm for fusion-bonded





32×38 pixels bonded, 2880 pixels floating

bump-bonded: ENC=69.6 e^- ± 5.1 µV/e^-

larger input capacitance = larger noise, lower gain and more dispersions

LARGE FEEDBACK RESISTANCE

ENC=36.2 e^- ± 2.6 µV/e^-

symmetrical noise distribution with <3.4 % of pixels outside of ±3 σ range

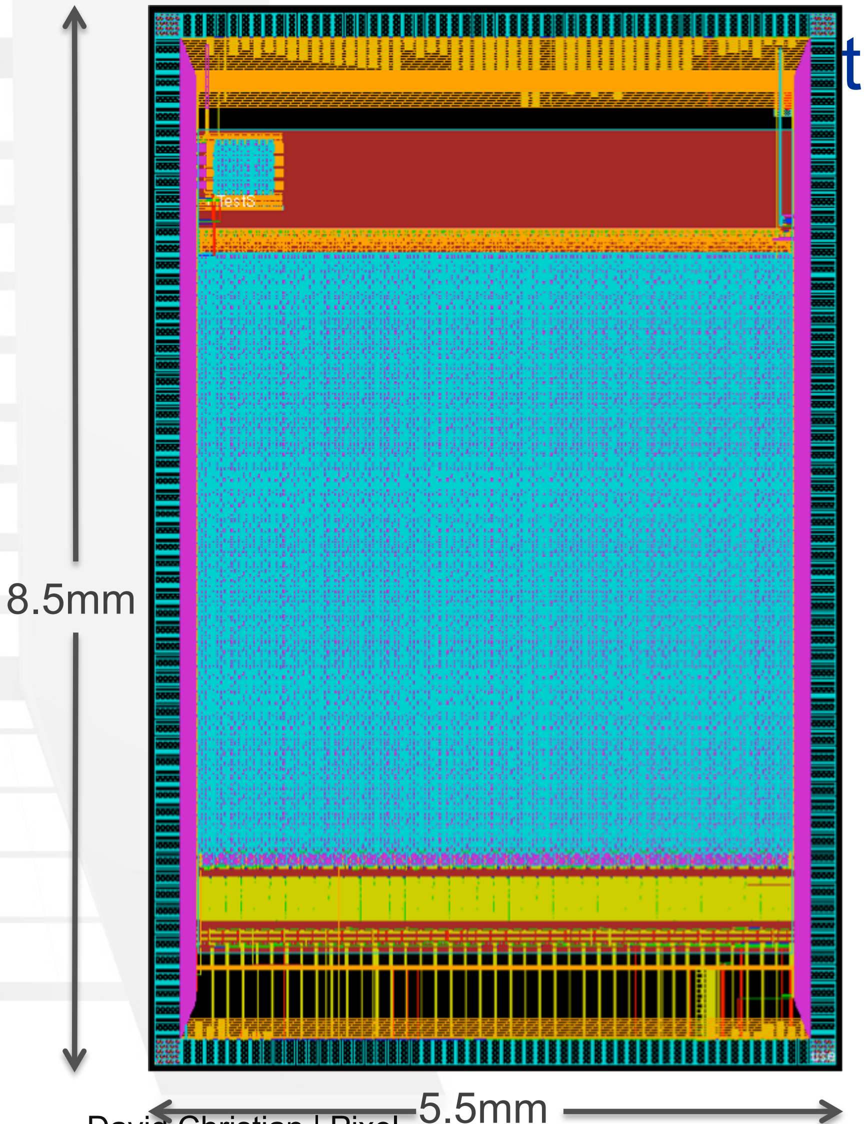
ENC on fusion bonded device is close to that measured for floating inputs!

ENC=40e^- C_{in}<20fF, ENC=70e^- C_{in}>80fF

June Irradiation

- Sandia Gamma Irradiation Facility “Cell 3”
  - 225 kCi of ^{60}Co
  - Dose rate = 5.13 Mrad/hr
  - Total dose = 1.1 Grad
  - Devices kept “cold” except during measurements
- Devices tested:
  - Core NMOS & PMOS
  - Double gate oxide thickness (2.5V I/O) NMOS
  - NMOS bias: Gate = 1.2V, all others ground
  - PMOS bias: ½ with all nodes = 1.2V (substrate gnd) & ½ with Gate (& substrate) = ground, all others 1.2V

A Small-Pixel Readout Chip



- Pixel unit cell = 30μx100μ
- Two types of ADC
  - ½ of array each
- Uses digital logic from other FNAL projects
- Zero-suppressed readout using priority encoder
- Normal readout at bottom; debug at top (including analog from selected cells); side pads accessible only when not bonded to a sensor.
- Fabbed in 130 nm for now

Plans for 2015 & Beyond

- Radiation testing (responding to RD53 priorities):
  - "Warm" irradiation of 65nm transistors at Sandia GIF;
  - If required, design, fabricate, & measure SEU test chip.
- FCP130:
  - Support sensor development.
- Translate FCP130 cells to 65nm:
  - Either prototype cells in small ASIC (only for bare chip testing), or
  - Design & fabricate FCP65 (to be used with test sensors).
- Longer term plans depend on RD53.

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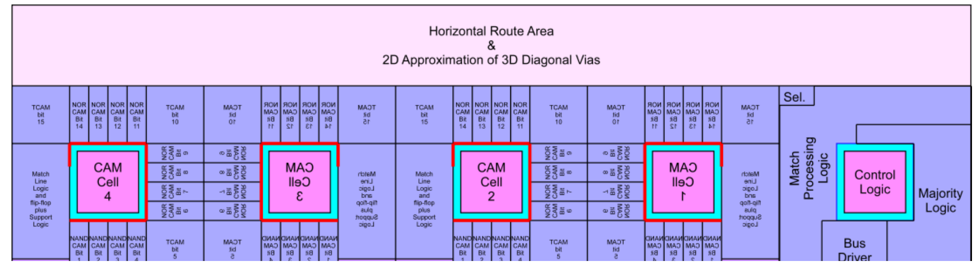
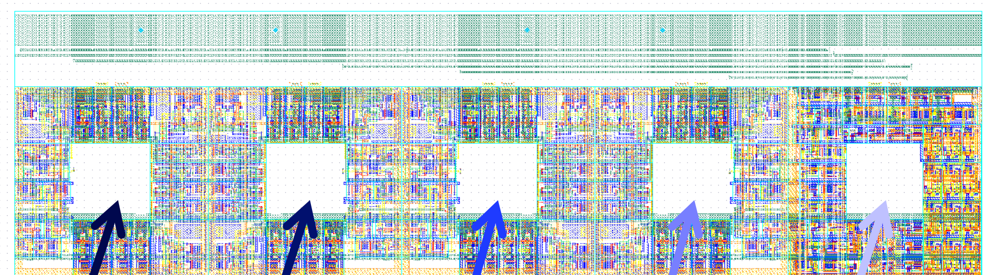
CMS Oriented fast pattern recognition using 3D ASIC

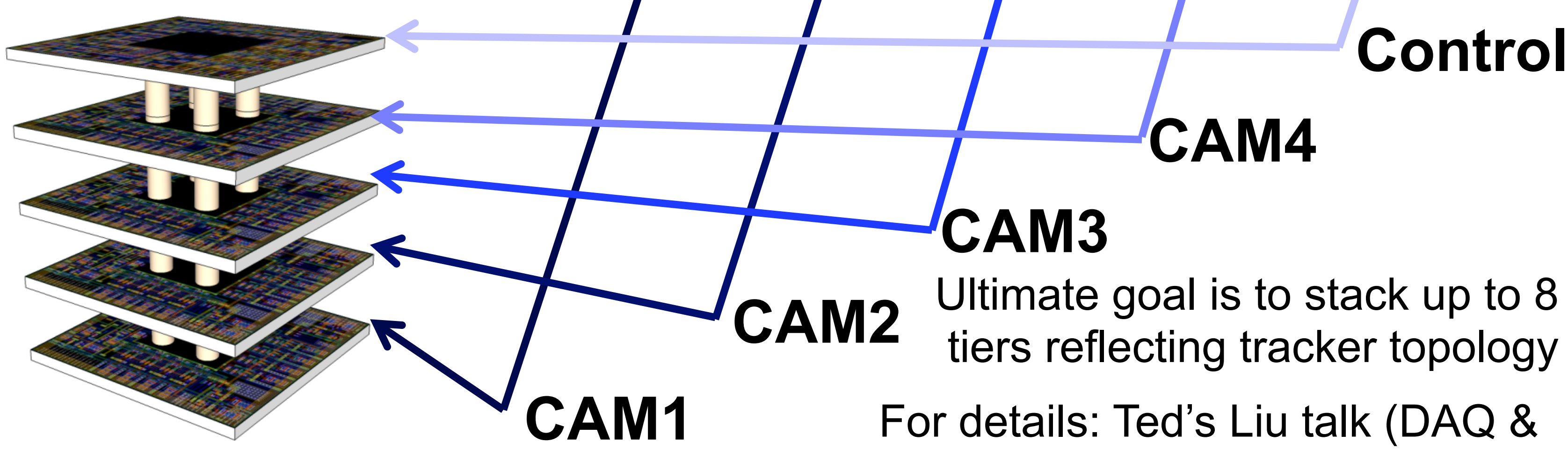
"VIPRAM" = Vertically Integrated Pattern Recognition Associative Memory





VIPRAM_L1CMS

- Pipelined operation between PRAM and Data Output – focus = system
- Significant layout optimizations



Ultimate goal is to stack up to 8 tiers reflecting tracker topology

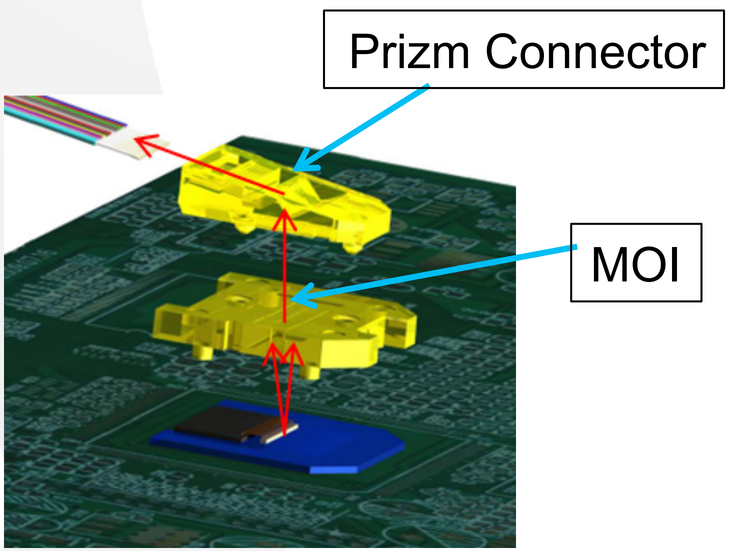
For details: Ted's Liu talk (DAQ & Triggering)

12-channel Array Optical Transmitter Module (ATx)

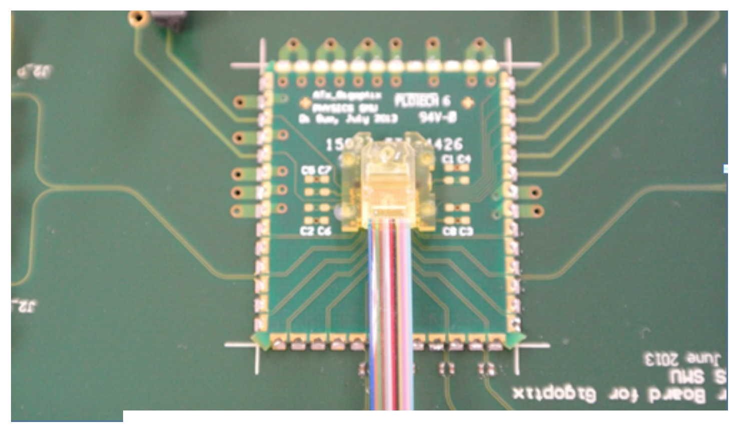
ATx is a compact (1.9 cm x 2.2 cm x 0.44 cm), radiation-tolerant, 12-channel array optical transmitter module towards 120 Gbps optical link, integrating array optical components, a VCSEL array with a driving ASIC in a custom transmitter module.

A custom low-cost and reliable “active-alignment” method was developed to solve the challenging alignment issue in the array optics area.

With a commercial VCSEL array driver, the ATx module successfully operated at 10 Gbps/ch and aggregate data rate of 120 Gbps. The optical transmitter eye diagram passed the eye mask, and the transmitted BER less than 10^{-12} was achieved at 10 Gbps/ch.



Optical Interface



ATx Module with ribbon fiber attached

Calorimetry and Fast Timing research should evolve to more directly support issues relevant to Phase II CMS upgrades:

- Radiation hard scintillators
- Latest version of QIE
- Investigate endcap calorimeter alternatives with test beam studies until downselect in Feb. 2015
  - LYSO/Shashlik
  - High granularity silicon
- Then join succeeding effort?
- Studies of fast timing in showers will continue, to understand how to mitigate pileup difficulties.
  - Should we propose a fast timing pre-shower or shower max insert using MCP or SiPM?

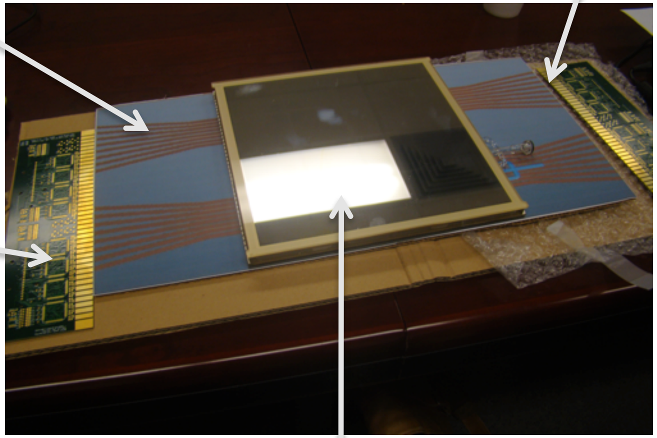
Support of LAPPD ('Large Area Picosecond Photo Detector) Project at ANL and U.C.

A mockup of the 8" MCP/PMT:

Transmission line readout retains superb timing resolution

Readout on both ends gives 1 mm positional resolution

U.C./Hawaii is developing high speed digitizers (10-20 GHz)

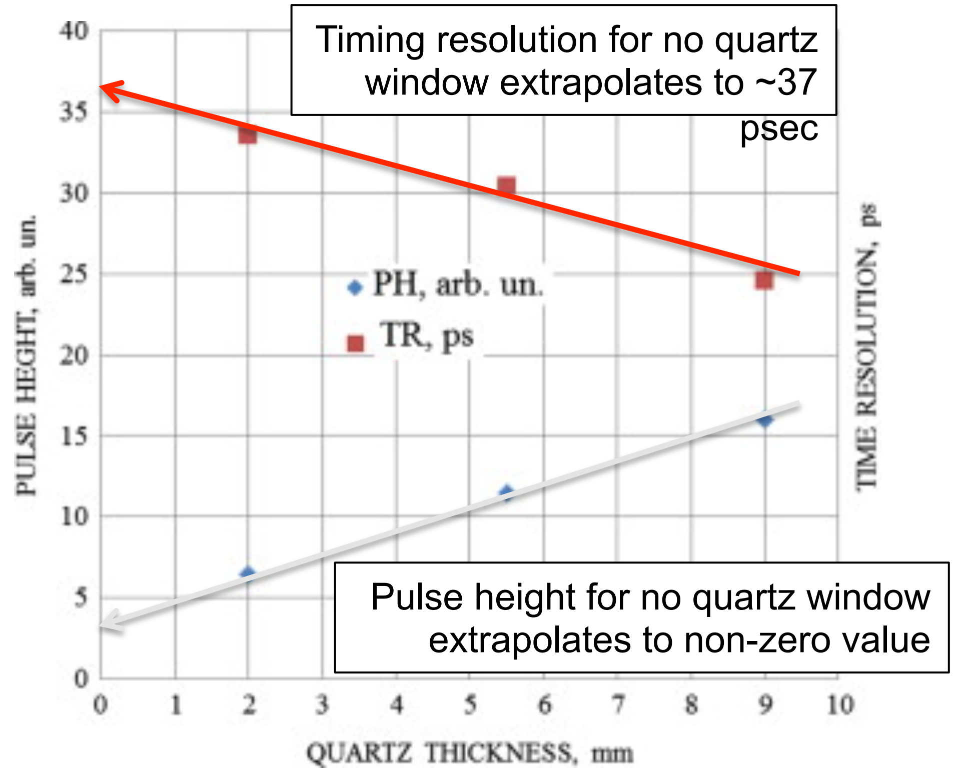


Thin film coating plant for 8" plates

Anatoly Ronzhin holding the 'chalice' for systematic photocathode testing

Fast timing using Secondary Emission in pores of a Microchannel plate

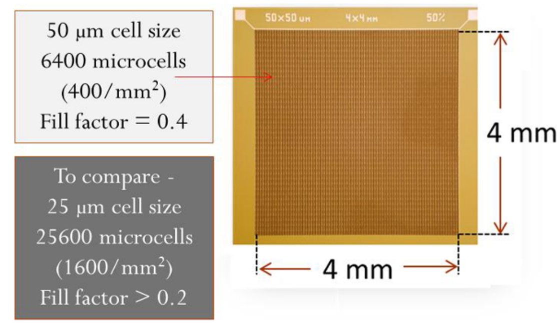
- Goal is to measure timing in showers to 30 nsec, to disentangle pileup effects.
- Propose to use bare MCP in vacuum (no scintillator, no photocathode).
- Our first tests used 16 channels of a Photonis MCP/PMT with photocathode and varying thickness of radiator

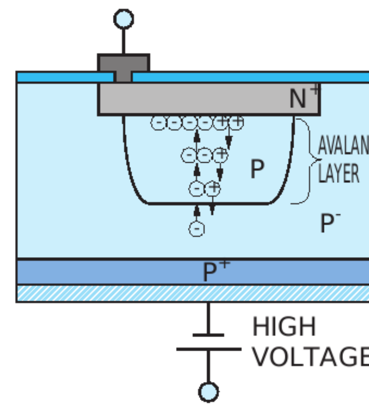


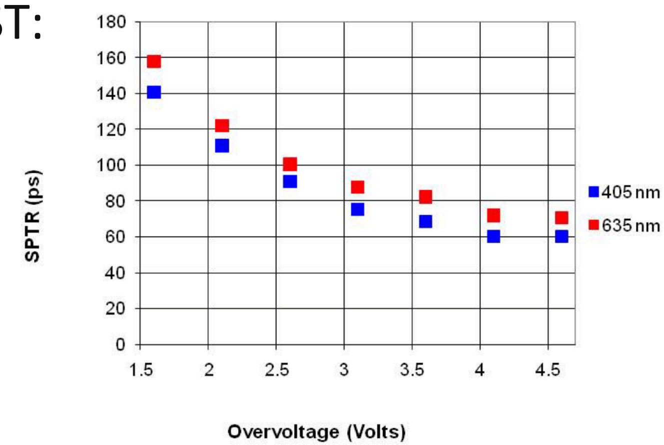
Anatoly Ronzhin (FNAL), Artur Apresyan, Maria Spiropulu, Si Xie and Adi Bornheim (CalTech), Henry Frisch (UC)

Fast Timing in Solid State Silicon Photo-Multipliers (SiPM)

- PN junction reverse biased beyond the Geiger mode breakdown voltage
- Avalanche "quenched" with a series resistor
- Array of thousands of these cells on a single chip that can be tailored for specific purposes
- The avalanche region is very close to the surface (~1 micron), so timing can be excellent
- Note single photon timing resolution of samples from IRST:





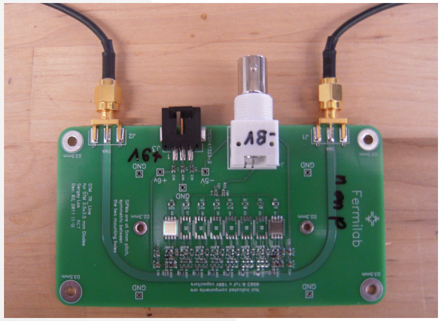


10 photons can give 25 psec resolution (confirmed)

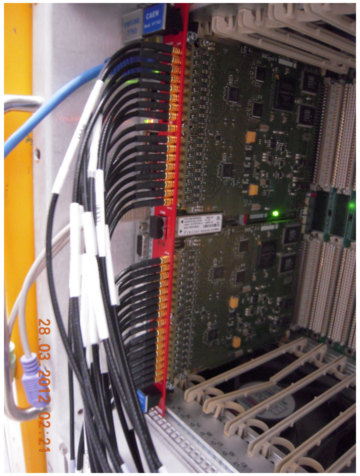
Radiation Soft !!

SiPM's for Time-of-Flight and Calorimetry

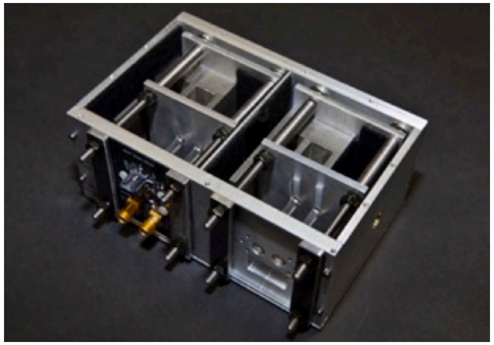
- Silicon PhotoMultipliers are multi-pixel avalanche photodiodes. Pixel sizes on the order of 50 microns and avalanche regions at the micron level.
- Theoretically, they could be one of the fastest particle detectors for HEP (<16 psec seen at FNAL).
- Fermilab has been studying their potential for TOF and calorimetry for many years. Designs developed at FNAL to be used in FP420 forward tracking at CMS.
- DAQ techniques supported by KA25 are being used in Proton Computed Tomography with NIU
- Recently we received a U.Chicago 'seed' grant to apply these techniques to PET-TOF.



Transmission line readout suitable for reading 8 separate SiPM's



CAEN 1742 module digitizes at 5 Gs/s. Good for timing and energy measurement



Example of one geometry of quartz bars and SiPMs for CMS forward region

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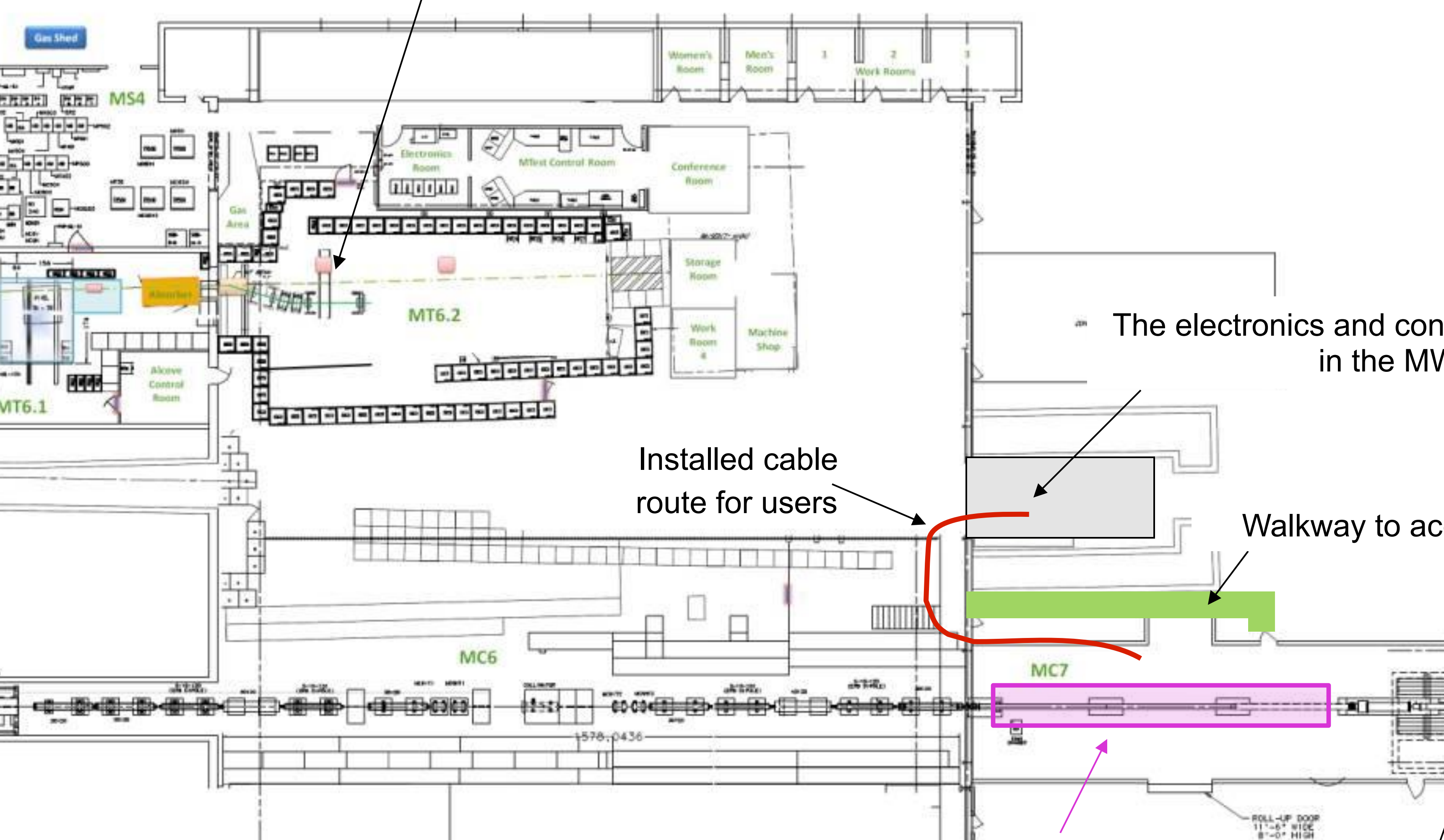
MCenter Beam as part of the Fermilab Test Beam Facility

Tertiary beam moved to MC7



The electronics and control room in the MWest stub

Installed cable route for users

Walkway to access MC7

This section of pipe has been removed.
Tertiary spectrometer for LariaT is here.

Can put another user area near JGG

Facility Details

Beam Details

Drawings & Maps

Layout & Rooms

MTest Beam Areas

MCenter Beam Areas

High Rate Tracking Area

Facility Infrastructure

Instrumentation

Fermilab

Particle Physics Division

Detector R&D

Physics Equipment Pool

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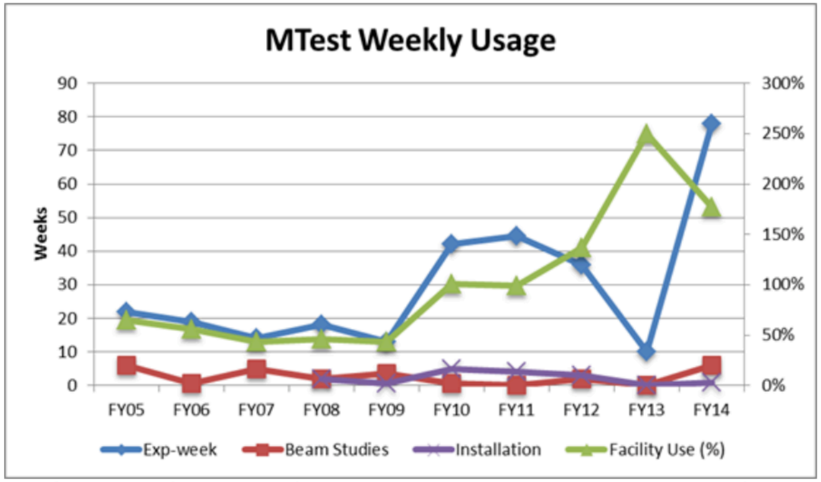
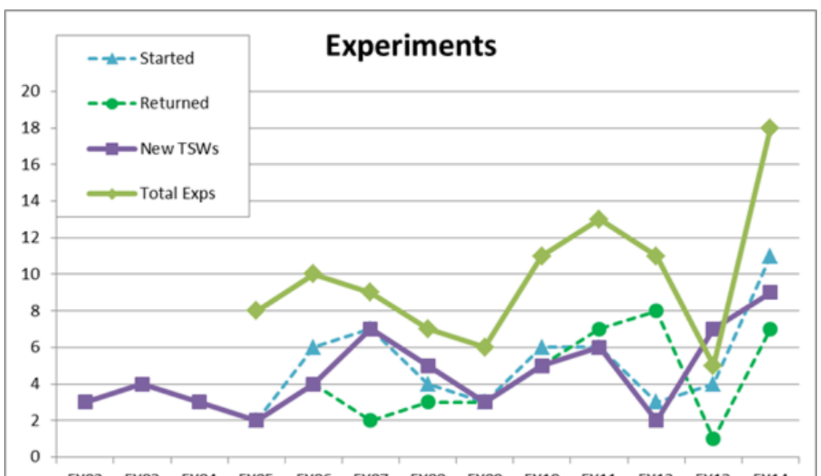
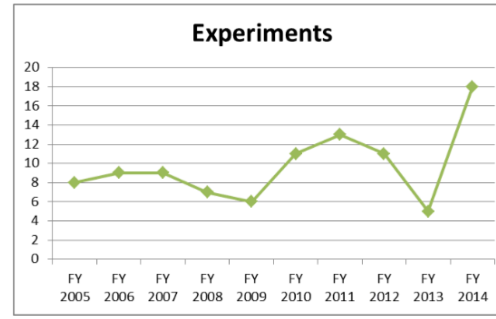


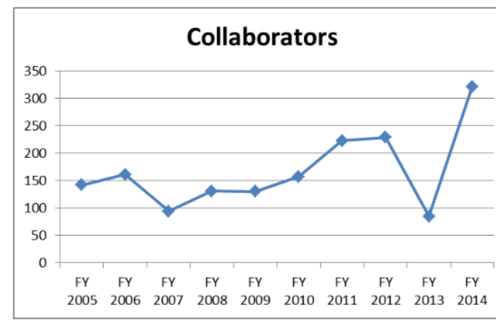
The **Green Line (Facility Use)** is a percentage which includes the number of weeks the facility was being used for data taking by an experiment, and installation of an experiment (some large experiments need several days without beam to install), and beam used for facility tests or outreach. This total is then normalized to the total number of weeks the beam was available, (less than 52).

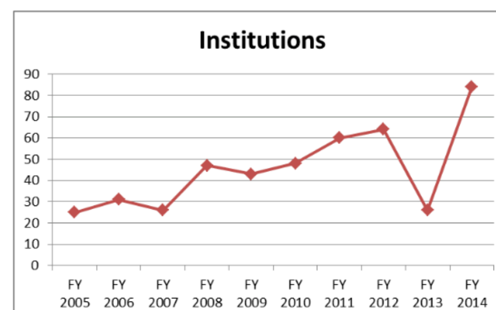
The **Blue Line (Exp-week)** is the total number of weeks the beamline was used by 1 experiment to take data.



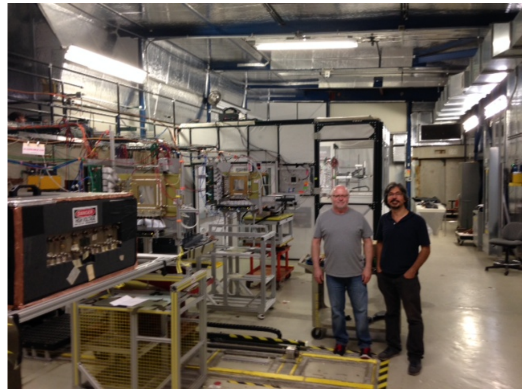
	Exprmnts	Collabrtrs	Institutns	Countries
FY14	18	321	84	20
FY13	5	85	26	3
FY12	11	229	64	14
FY11	13	223	60	14
FY10	11	157	48	12
FY09	6	130	43	15
FY08	7	131	47	14
FY07	9	94	26	6
FY06	9	161	31	4
FY05	8	142	25	4





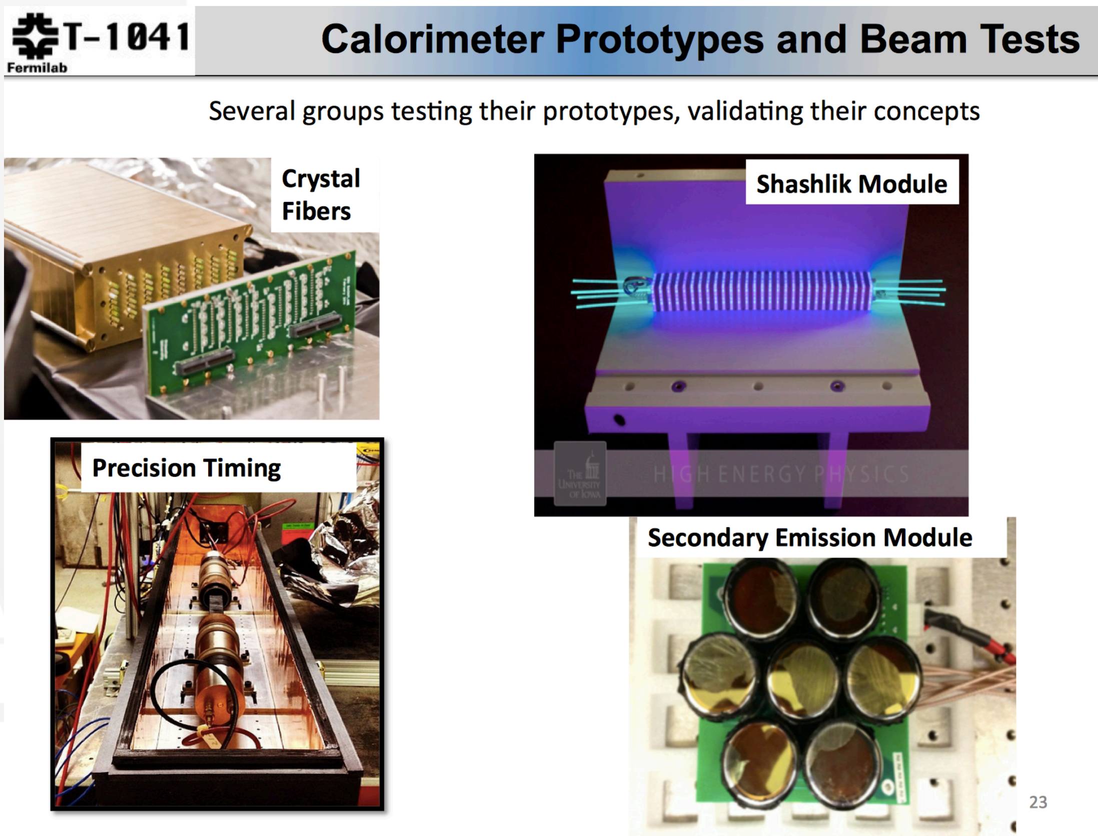


A Day at FNAL Test Beam

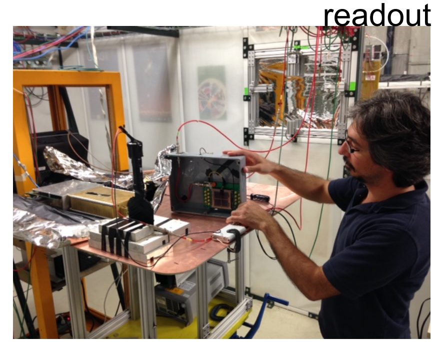


Section 2 of the Fermilab MTest beamline

8/11/2014



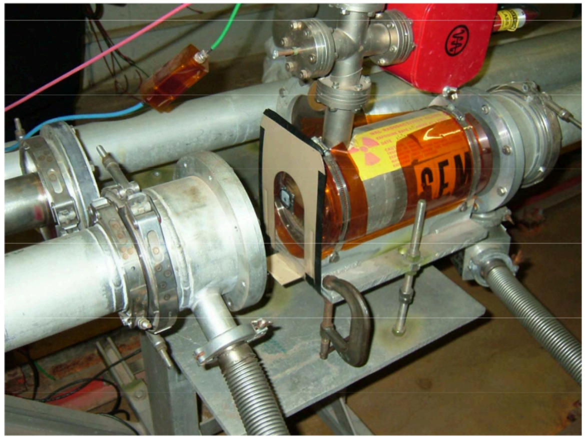
Jim Freeman new rad-hard scintillator studies. Behind him is TTU fiber based dual readout



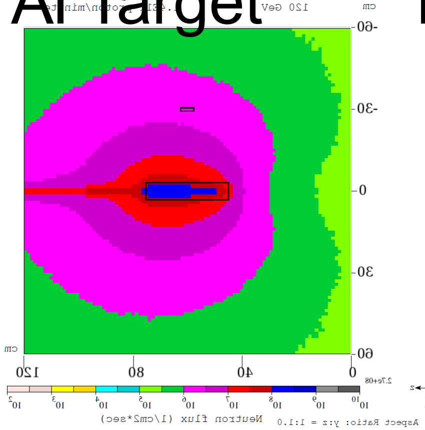
Burak Bilki w/ new ANL MCP. Also studying new scintillators.

MTest irradiation areas

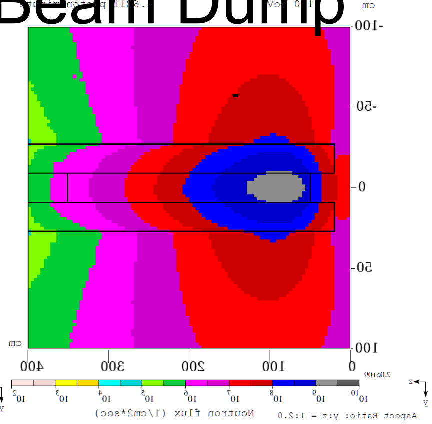
- Have several areas in MTest beamline where high rate studies can take place:
  - M01 has access to primary 120 GeV proton beam at 1E11 per minute.
  - A high rate tracking area with flux of about 1E10 is set up in MT3
  - Near primary target in MT4 you can have a mixed field of radiation that simulates conditions in the LHC halls, for instance.
    - (Calculated dose for a Si sample irradiated @ 30 cm away from the aluminum target and pinhole collimator is ≈ **1.2E4** and ≈ **4.5E3 Gy/yr**, respectively (very similar to LHC cavern)



Al Target



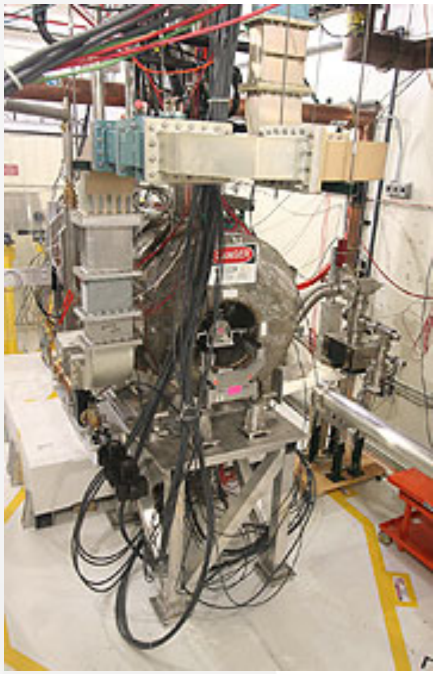
Beam Dump



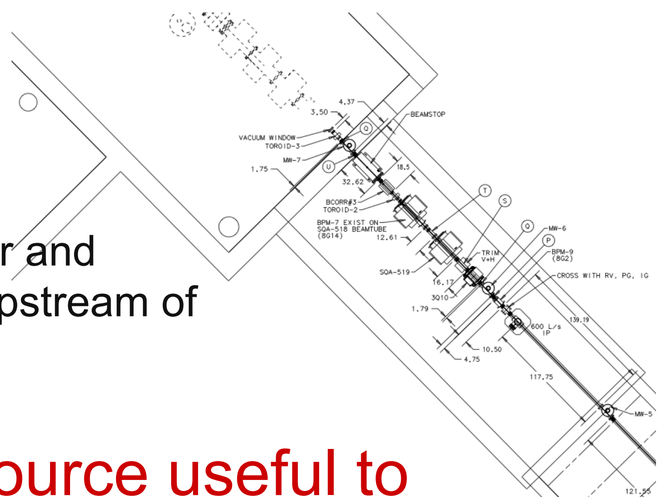
These high radiation areas need further development to have regular use

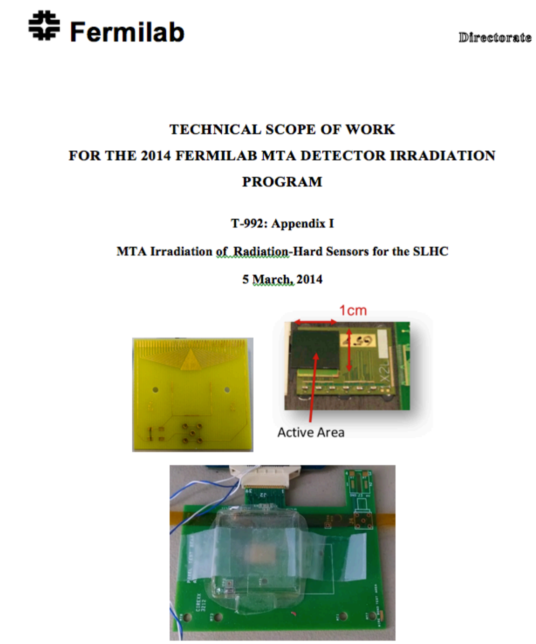
Investigating New Detector R&D Irradiation Capability at MTA in LINAC

- The MTA experimental hall has accepted beam. (400 MeV protons)
- It is possible that we will be able to perform detector irradiation studies there. Safety and scheduling issues being studied.
- The MAP group has installed a table for supporting detector installations
- **Flux as high as 10^{14} / hour** in the experimental hall
- First Statement of Work submitted



Stand for beam stop, collimator and detectors already placed upstream of solenoid




Fermilab Directorate

TECHNICAL SCOPE OF WORK
FOR THE 2014 FERMILAB MTA DETECTOR IRRADIATION PROGRAM

T-992: Appendix I

MTA Irradiation of Radiation-Hard Sensors for the SLHC

5 March, 2014

Is this resource useful to the community?

Summary

- Fermilab has based its detector R&D organization on a "Detector Advisory Group", consisting of representatives of the major detector efforts.
- R&D efforts have been centered on several major portfolios, linked to the highest priorities of HEP:
  - Collider tracking and triggering
  - Liquid argon detectors for neutrino and dark matter experiments
  - High speed calorimetry and photodetection
  - Astrophysics dark matter/dark energy
- Fermilab's resources, facilities and collaborations are crucial in detector research and testing
- From the P5 report, detector R&D is shifting to a more project-directed approach
- We should make sure that Fermilab detector program responds to the needs of CMS Phase II upgrades

Our web site has links to our detector organization and facilities, as well as links to the EDIT school and our detector retreat and reviews:

http://detectors.fnal.gov

Useful Email:

FNAL detector point-of-contact:

ramberg@fnal.gov

Detector Advisory Committee:

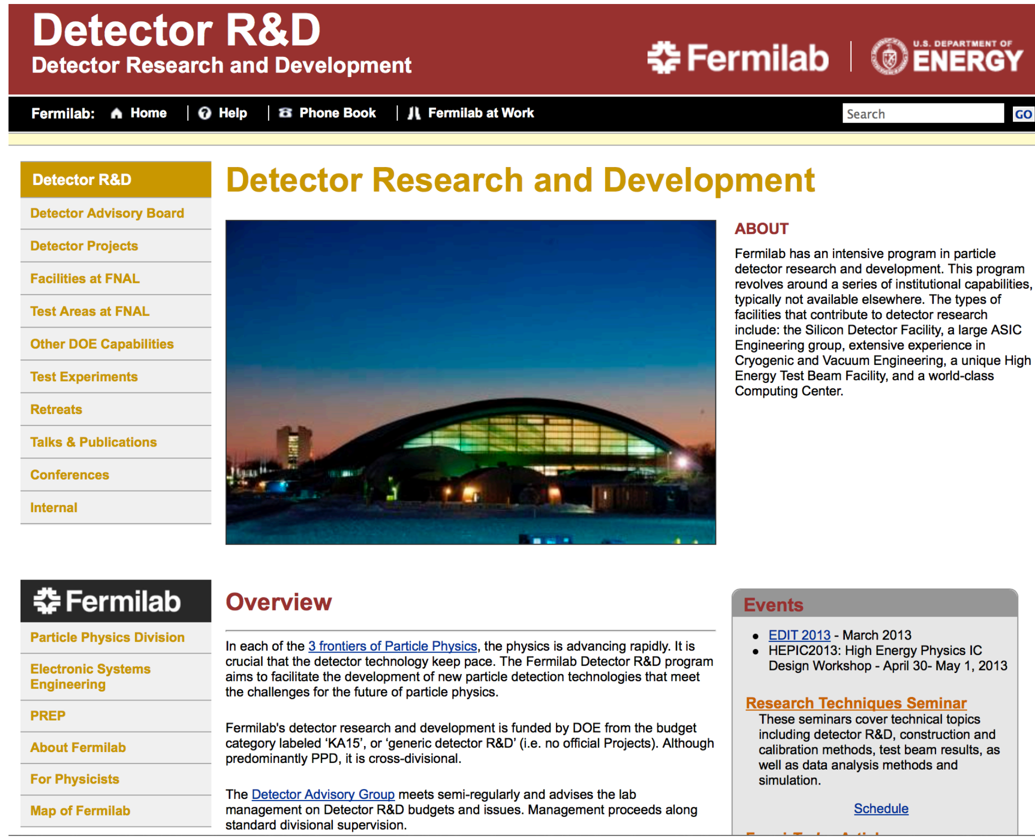
detector-advisory@fnal.gov

Detector R&D mail list:

detectors@fnal.gov

Test beam users:

test_beam@fnal.gov



Detector R&D
Detector Research and Development
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- Detector Projects
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Detector Research and Development

ABOUT

Fermilab has an intensive program in particle detector research and development. This program revolves around a series of institutional capabilities, typically not available elsewhere. The types of facilities that contribute to detector research include: the Silicon Detector Facility, a large ASIC Engineering group, extensive experience in Cryogenic and Vacuum Engineering, a unique High Energy Test Beam Facility, and a world-class Computing Center.

Overview

In each of the 3 frontiers of Particle Physics, the physics is advancing rapidly. It is crucial that the detector technology keep pace. The Fermilab Detector R&D program aims to facilitate the development of new particle detection technologies that meet the challenges for the future of particle physics.

Fermilab's detector research and development is funded by DOE from the budget category labeled 'KA15', or 'generic detector R&D' (i.e. no official Projects). Although predominantly PPD, it is cross-divisional.

The Detector Advisory Group meets semi-regularly and advises the lab management on Detector R&D budgets and issues. Management proceeds along standard divisional supervision.

Events

- EDIT 2013 - March 2013
- HEPIC2013: High Energy Physics IC Design Workshop - April 30- May 1, 2013

Research Techniques Seminar

These seminars cover technical topics including detector R&D, construction and calibration methods, test beam results, as well as data analysis methods and simulation.

Schedule

indico.fnal.gov/event/DetectorR&DReview

Fermilab Detector R&D Program Review

chaired by Mark Oreglia (U. Chicago)

Wednesday, 29 October 2014 from **08:00** to **19:00** (US/Central)
at **Fermilab**

Manage

Description This internal review of Fermilab's detector research will include 5 parallel sessions, corresponding to the 5 thrusts of Fermilab's program: Silicon Tracking, DAQ/Trigger, Cosmic Frontier, Calorimetry/Photodetection and Liquid Argon.

Material: **Charge for the 2014 Detector R&D Review** | **Documents from 2012 review** | **Slides**

Wednesday, 29 October 2014

08:30 - 09:00 Executive session

Fermilab