Silicon Sensors Irradiation Study for ILC Extreme Forward Calorimetry

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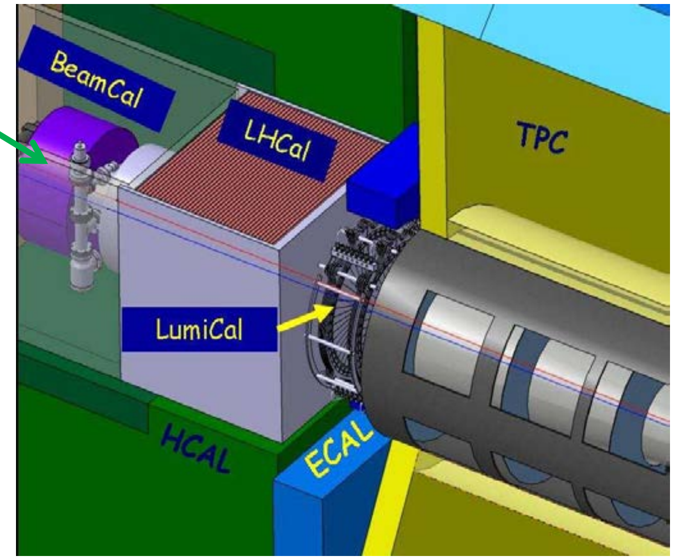
BeamCal Motivation

<u>Basic Idea</u>: At ILC two-photon processes with missing scattered electrons can mimic New Physics phenomena. BeamCal is meant to capture the primary particles scattered at small angles: 5 to 40 mrad. This is a sampling calorimeter with tungsten layers as absorber and sensors in-between.



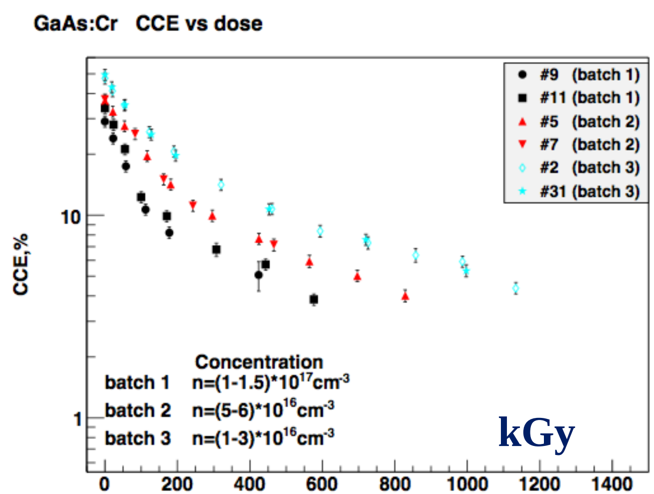
<u>Challen*ge*</u>: GRad of radiation.

<u>Studies of sensor material</u>:

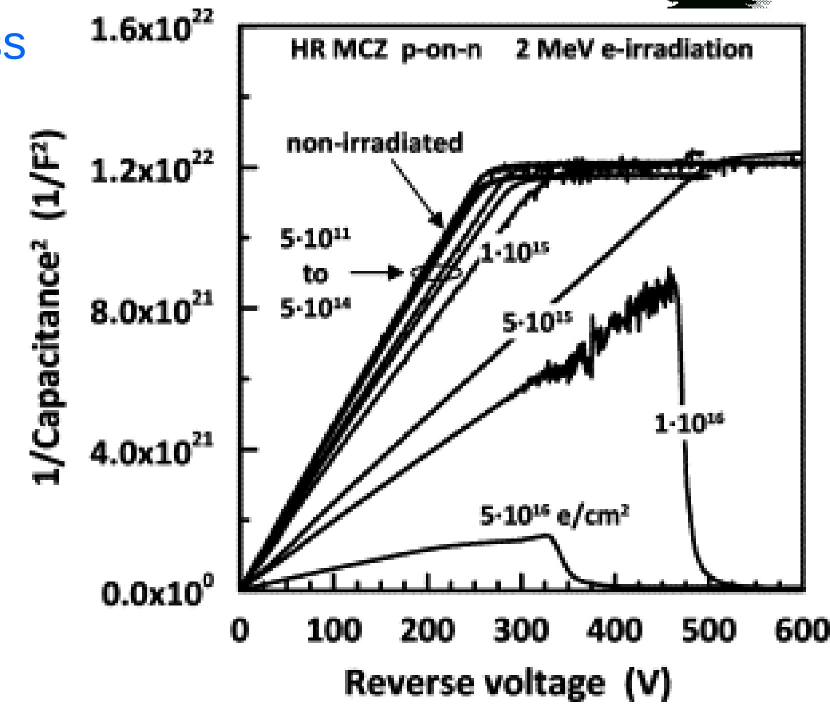
- GaAs
- Diamond
- Saphire
- Silicon Carbide

→ <u>We want to find out suitability of "conventional" Si sensors for this purpose.</u>

GaAs study with ~10 MeV electron beam, K. Afanaciev et al, JINST 7 (2012) P11022 :



Prior Electron Radiation Studies



There were prior studies of Si radiation hardness with electrons:

- J.M. Rafi et al, NIM A 604 (2009) 258: studied HR Si with 2 MeV e- up to 5x10^16 e-/cm^2. They observed *x36* less damage from IV studies than expected from NIEL.
- S. Dittongo et al, NIM A 546 (2005) 300: studied HR Si with 900 MeV e- up to 6.1x10^15 e-/cm^2. Observed *x4* less damage than expected from NIEL.
- S. Dittongo et al, NIM A 530 (2004) 110: studied HR Si with 900 MeV e- up to 2.1x10^15 e-/cm^2. Observed *<3% CCE decrease* after annealing.

→ Is there energy-dependent NIEL hypothesis breakdown with electrons? (Origination of point-like defects rather than clusters at lower energy intuitively makes sense…)

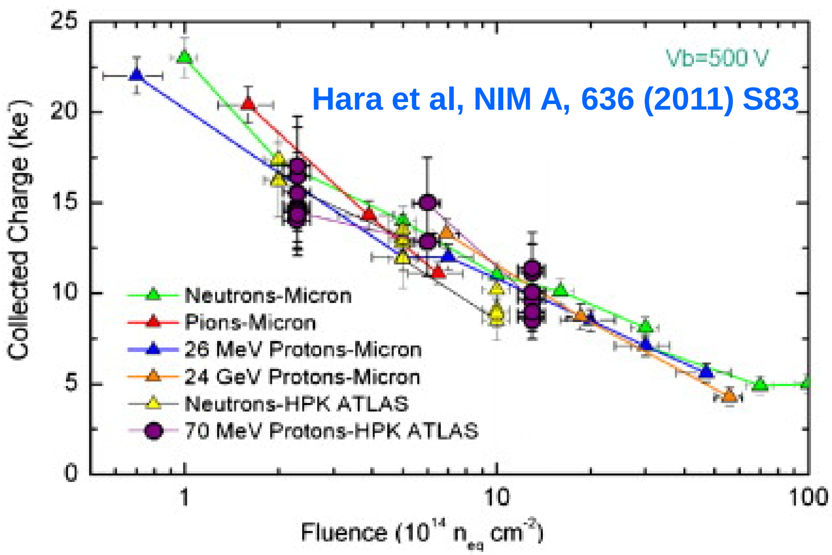
What to study?

Besides EM radiation, there will be a shower => energy spread and potentially a nuclear component:

- Nuclear (“giant dipole”) resonances at 10-20 MeV (~$E_{critical}$)
- Photoproduction: Threshold seems to be about 200 MeV
- Nuclear Compton scattering: Threshold at about 10 MeV; Δ resonance at 340 MeV

→ These are largely isotropic; must have most of hadronic component develop near sample

Want to assess CCE under realistic conditions.
Example from known studies (N-on-p FZ):
- Assuming 50% CCE drop as the FOM (depends on electronics!) => ~0.6x10^15 neq
- NIEL scaling to max D(E, el) => 7.9x10^15 e-/cm^2, or ~260 MRad.



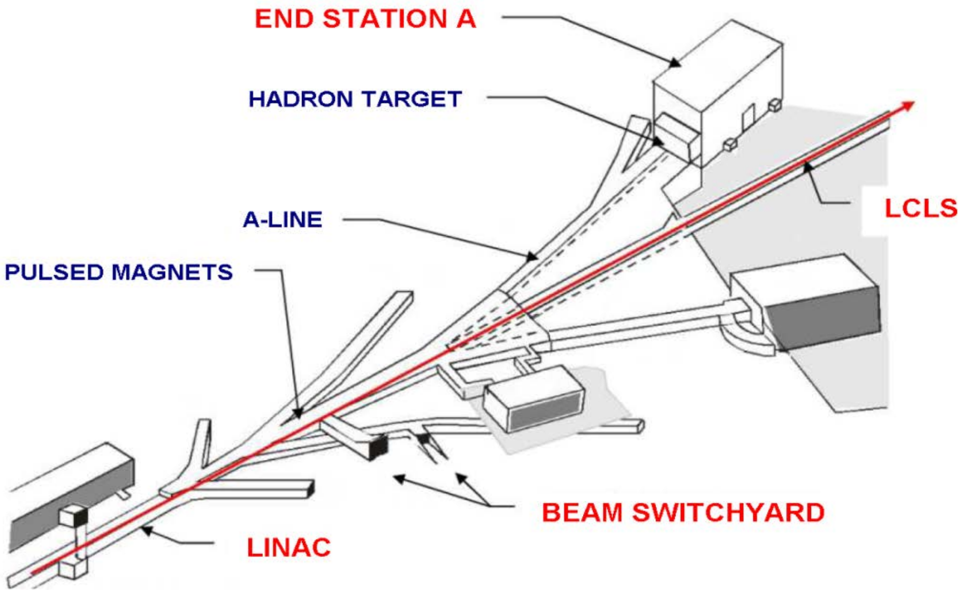
<u>In reality NIEL scaling issue and presence of hadrons can significantly modify the guesstimate.</u>

LCLS and ESTB (FACET)

Want to use > 1 GeV beam to capture the nuclear processes

Table 1: Parameters of the beam delivered by the ESTB facility during the T-506 experiment.

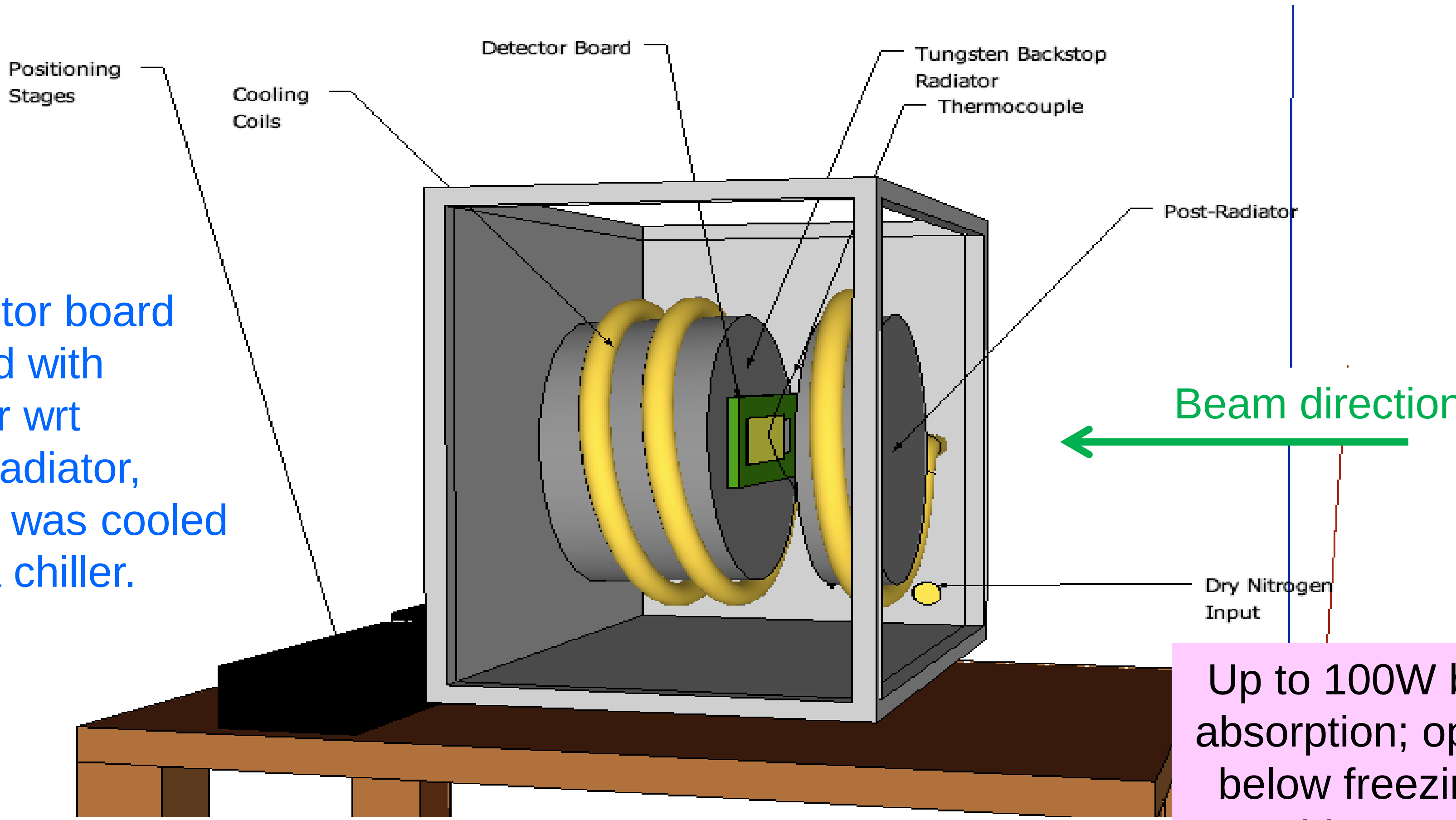
Parameter	Value
Energy	3.5-10.6 GeV
Repetition Rate	5-10 Hz
Charge per Pulse	150 pC
Spot Size (radius)	~ 1 mm



Hadronic Processes in EM Showers

Modeling hadronic components: tungsten pre- and post-radiator
(a stack of 7 mm tungsten plates borrowed from Leszek Zawiejski, INP, Krakow)
Sensors were lightly biased and cooled by Peltier elements to -10 C, 0 C.

Detector board cooled with Peltier wrt post-radiator, which was cooled with a chiller.



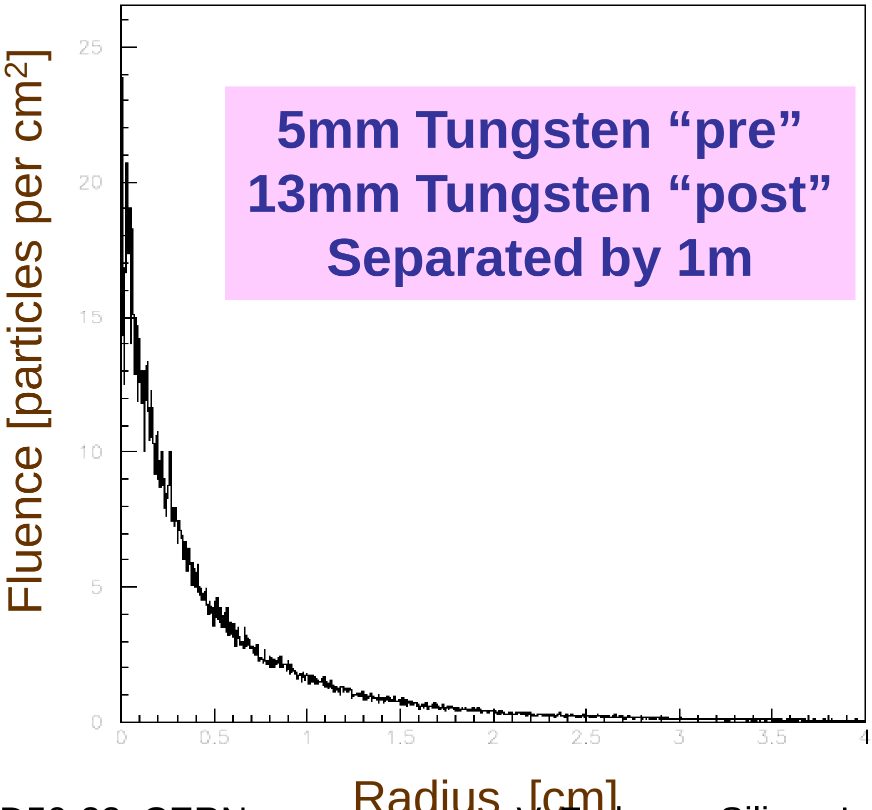
Up to 100W beam absorption; operate below freezing to avoid annealing

Rastering

Want to irradiate a sizable region of the sensor => will use rastering.
Plan on covering 0.6x1.5 cm^2 region with 0.05 cm steps.
Dose rate:

$$1\,GRad \approx \frac{600}{I_{beam}(nA) \bullet E_{beam}(GeV)}\,hours$$

(100 MRad at 1 nA with 13.6 GeV beam in 5 hours)… max rate was 28 MRad/h
Will use CCE with collimated Sr-90 source as a primary observation.
Will need good alignment, dose cross-calibration.



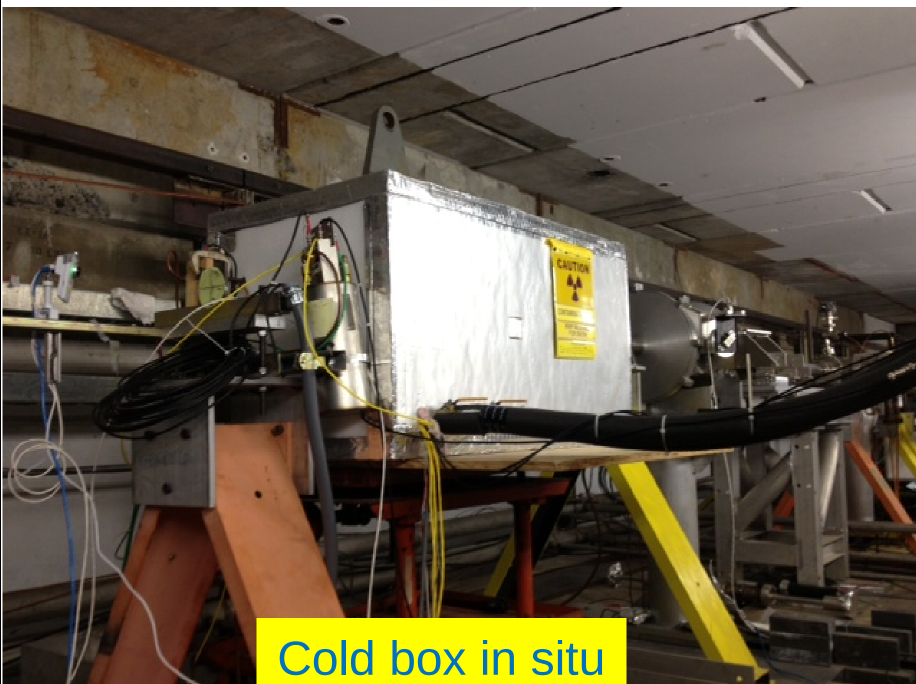
The dose estimates are based on the beam bunch counting and simulation of the shower development. But we did a dedicated run with RADFETs, where the measurements agreed with the estimates within 10%.

Cooling

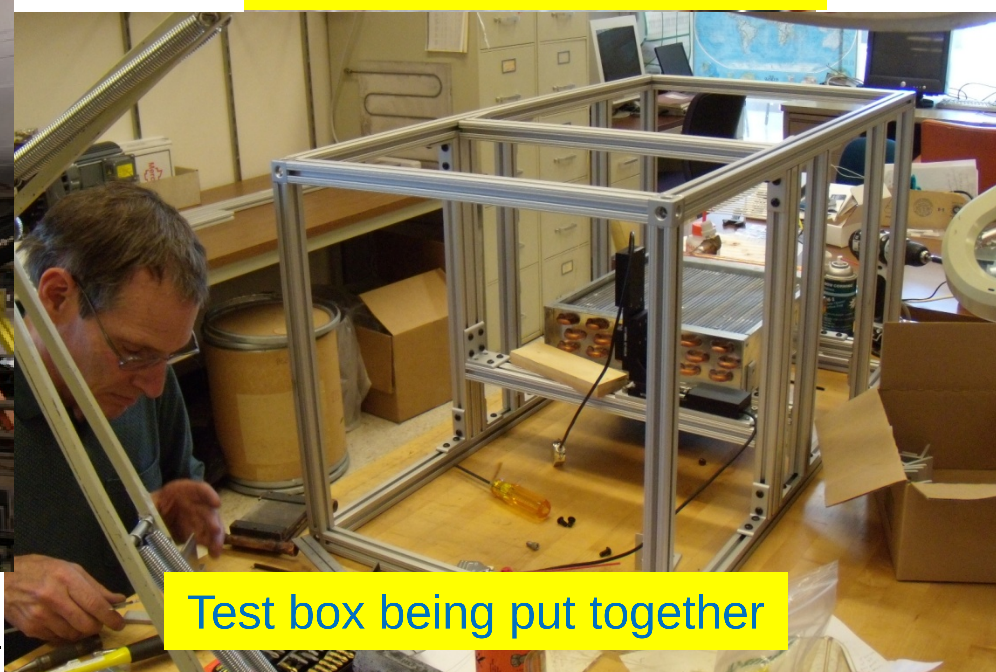
Sizable irradiation duration => Special considerations for cooling and measurements. Target <= -10C:

- Sensors mounted on boards allowing repeated CCE measurements on the same devices at different doses.
- Cooling the devices to avoid annealing (the “quick disconnect” boards avoid warmp-up diruing wirebonding)
- Cooling the tungsten.
- Cold CCE measurements, and transport.

Post-radiator with cooling



Cold box in situ



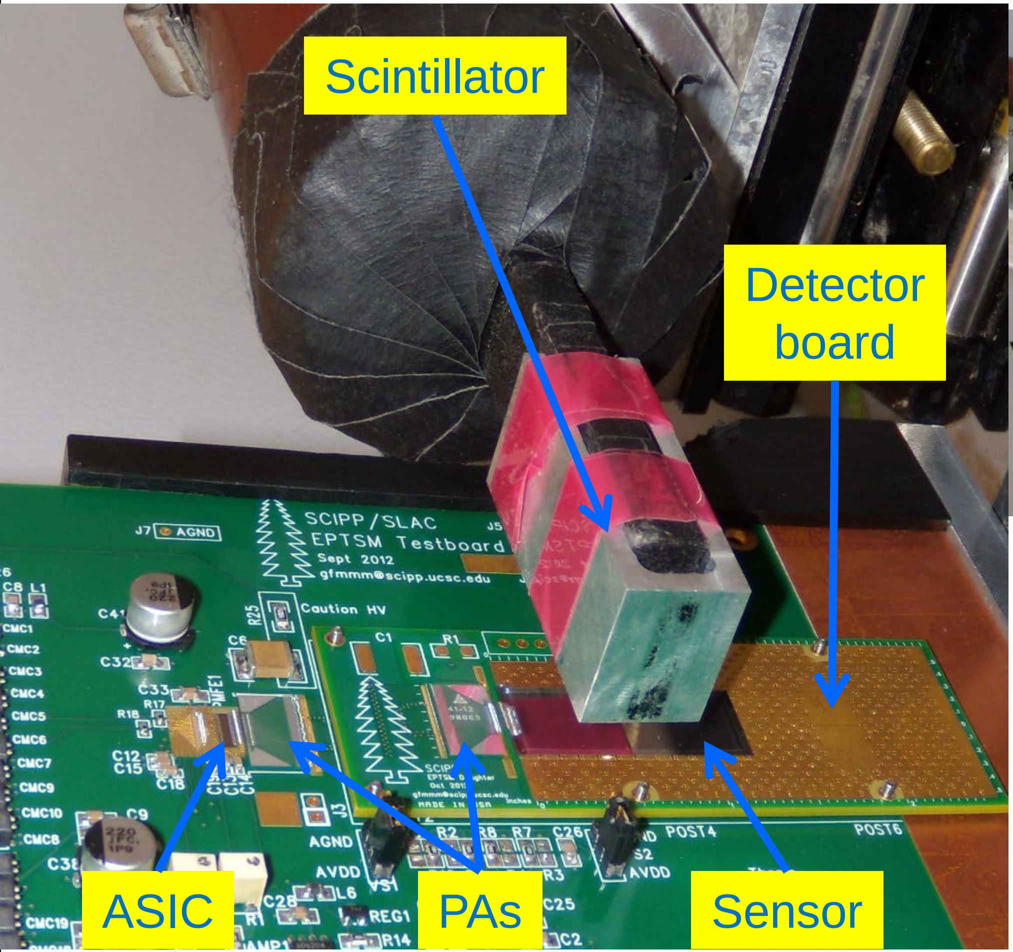
Test box being put together

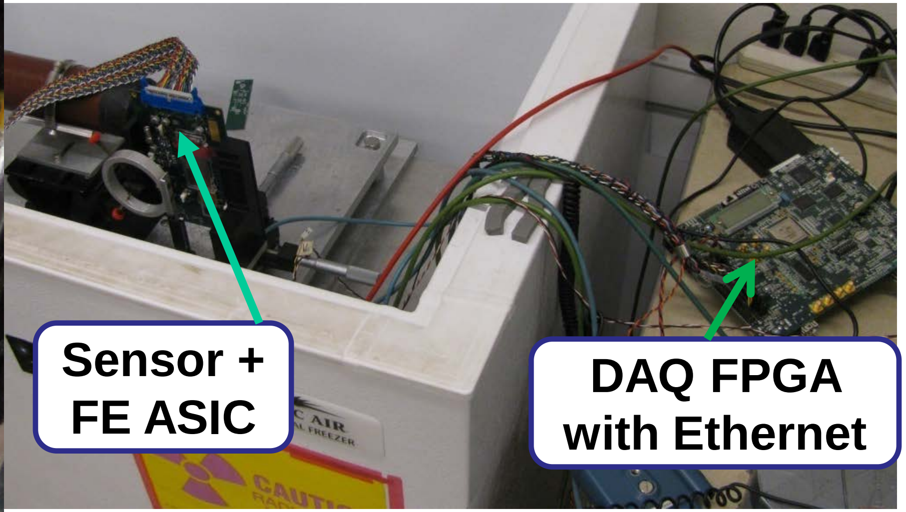
CCE system

Will use binary readout CCE system, that was used in prior irradiation studies. It gives the same answer as AliBaVa within 10%.

Redesigned the FE board to accommodate the “quick connect” detector boards.

The FE and detector boards have permanent pitch adaptors made by AliBaVa.





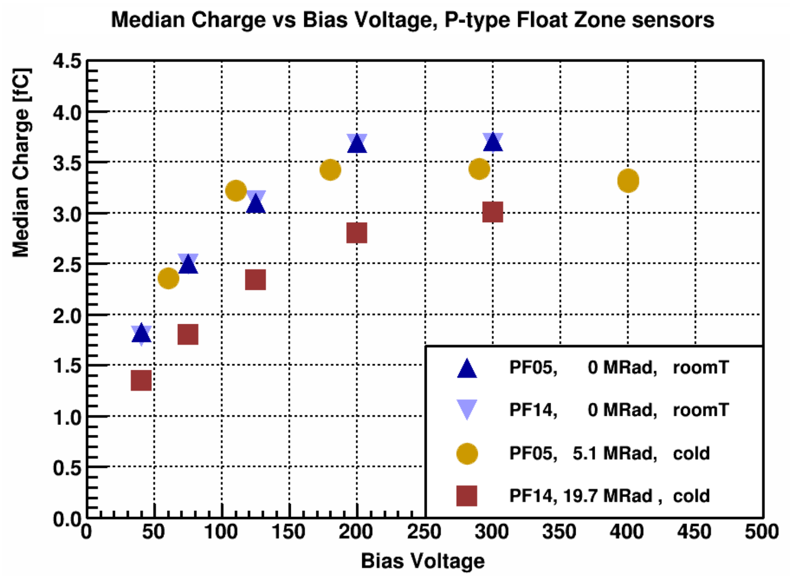
Sensors and Doses

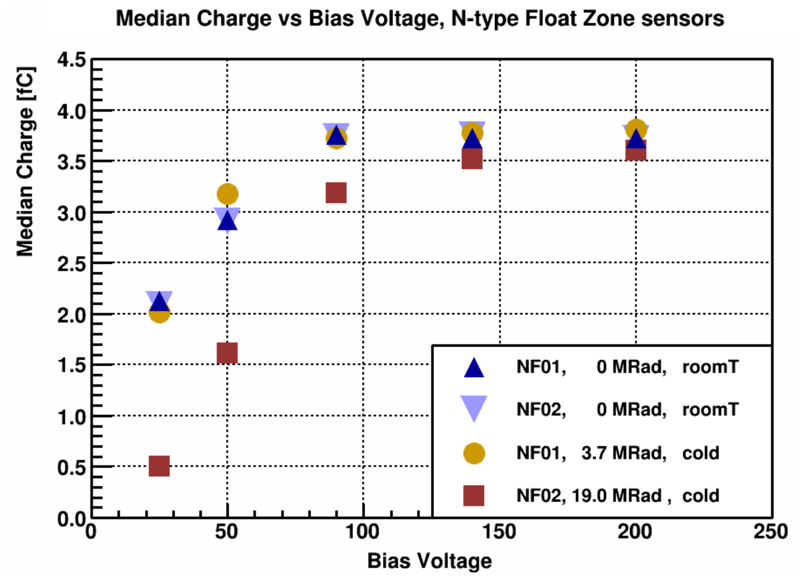
Have used Micron and HPK strip sensors covering 4 technologies.
All devices are ~300 um thick.

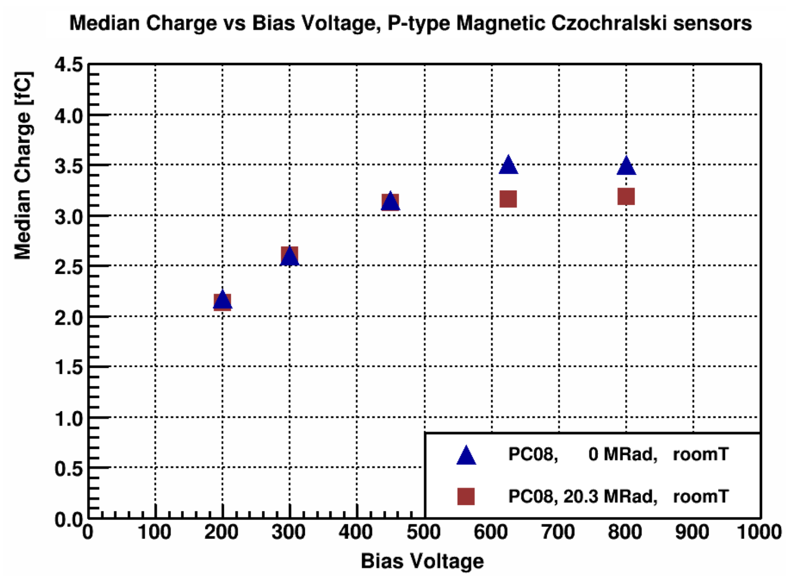
	Sensor	V_{FD}	Irradiation Temp. (C)	Beam Energy (GeV)	Delivered Charge (μC)	Dose (MRad)
HPK, n-on-p, FZ	PF05	190	0	5.88	2.00	5.13
	PF14	190	0	3.48	16.4	19.7
Micron, n-on-p, MCz	PC10	660	0	5.88	1.99	5.12
	PC08	700	0	(5.88, 4.11, 4.18)	(3.82,3.33,3.29)	20.3
Micron, p-on-n, FZ	NF01	90	0	4.18	2.30	3.68
	NF02	90	0	4.02	12.6	19.0
	NF07	100	5	8.20	23.6	91.4
Micron, p-on-n, MCz	NC01	220	0	5.88	2.00	5.13
	NC10	220	0	3.48	15.1	18.0
	NC03	220	5	4.01	59.9	90.2
	NC02	220	5*	(10.60,8.20)	(32.3,13.8)	220

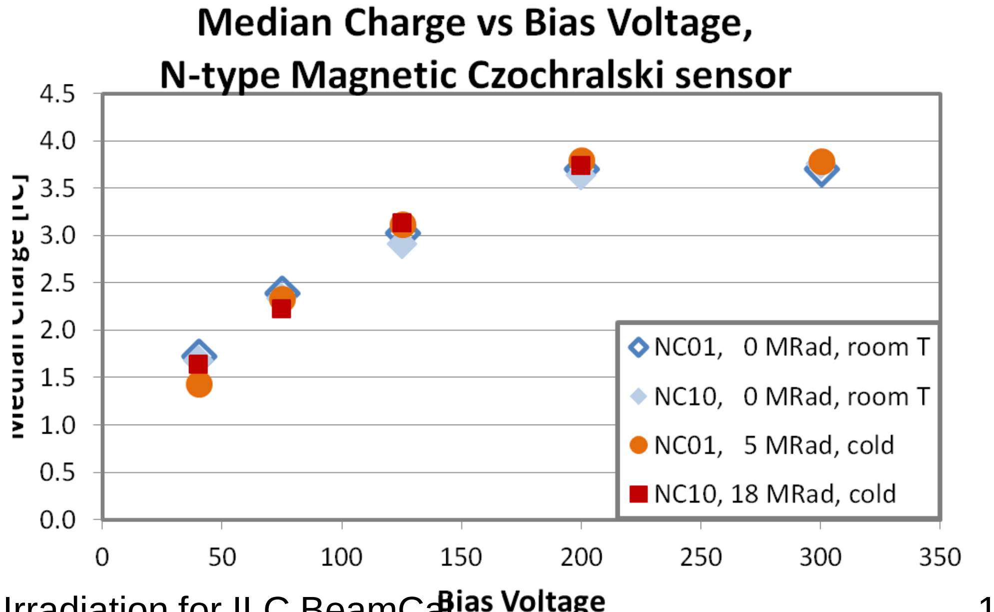
Warmed up to 130 C overnight due to cooling system failure.

Charge Collection vs. Bias Voltage: Lower Dose

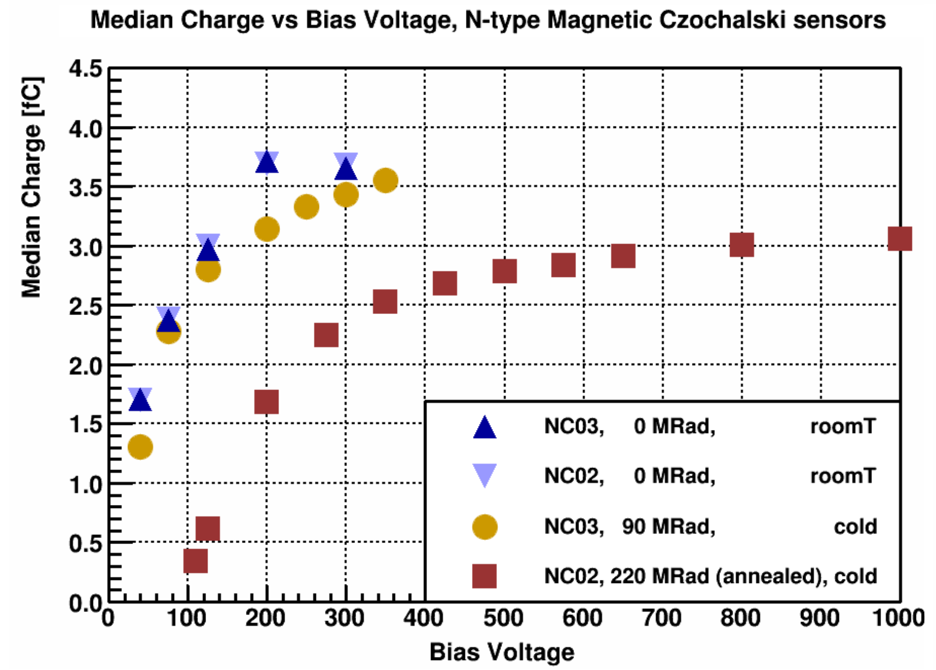


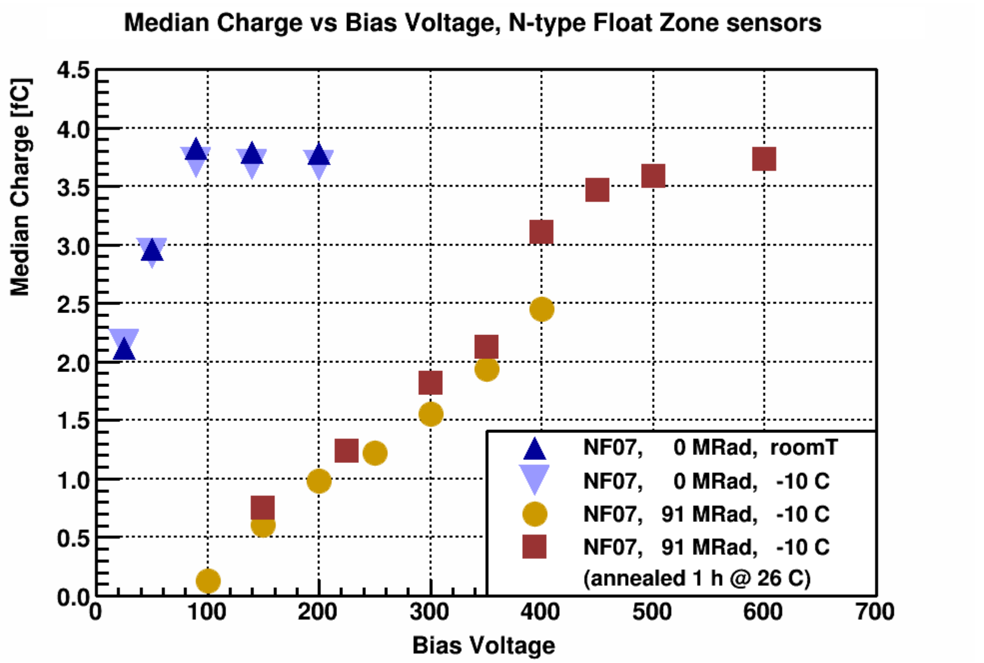






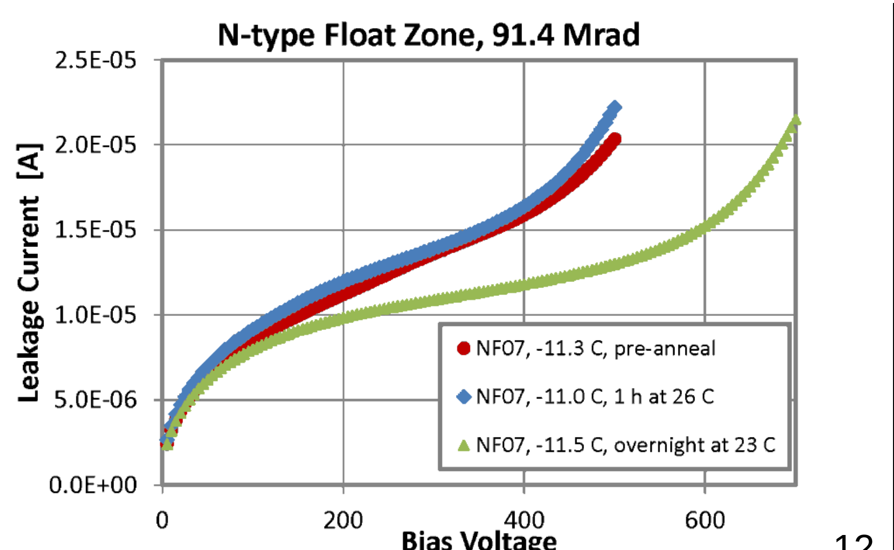
Highest Doses on N-type bulk Si





The plan with N-type Float Zone sensor was to do a series of 1-h long annealing steps: room T, 40 C, 50 C, 60 C…

Room T step is done… twice; the rest is in progress.



Charge Collection Summary

	Sensor	Dose (MRad)	Median CC Before Irradiation (fC)	Median CC After Irradiation (fC)	Fractional Loss (%)
HPK, n-on-p, FZ	PF05	5.1	3.70	3.43	7
	PF14	20	3.68	3.01	18
Micron, n-on-p, MCz	PC08	20	3.51	3.09	12
Micron, p-on-n, FZ	NF01	3.7	3.76	3.81	0
	NF02	19	3.75	3.60	4
	NF07	91	3.75	3.73	1
Micron, p-on-n, MCz	NC01	5.1	3.71	3.80	0
	NC10	18	3.76	3.74	1
	NC03	90	3.68	3.55	4
	NC02	220	3.69	3.06	17

Warmed up to 130 C overnight due to cooling system failure.

Conclusions and Further Studies

We are studying sensor damage with EM radiation for ILC BeamCal. A particular care is taken to model hadronic component. The first results are promising. A paper is submitted to NIM.

So far we have seen only a moderate decrease in collected charge for doses up to 220 MRad. N.B.: The device with highest dose had been un-intentionally annealed.

Studies in progress:

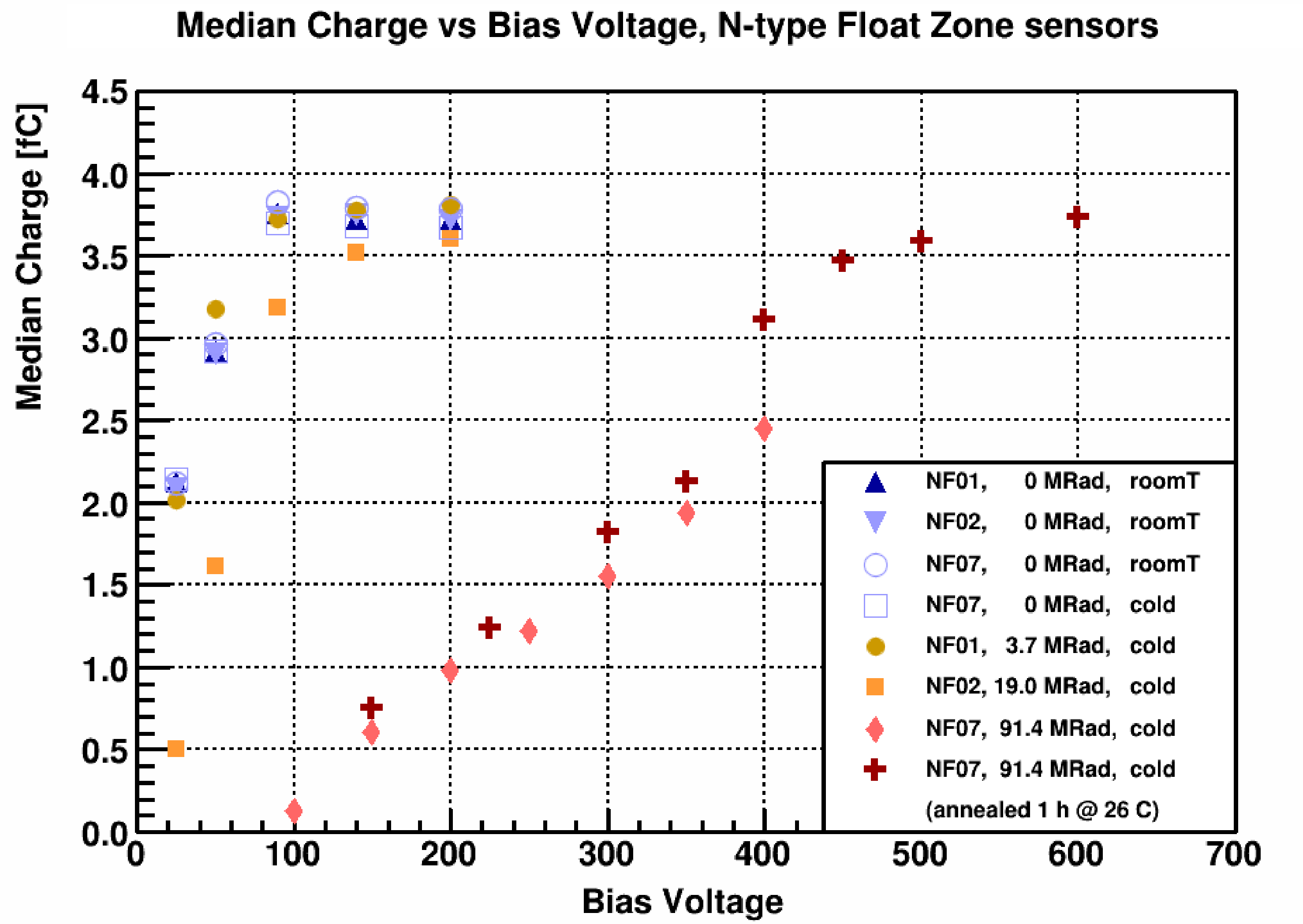
- Annealing effects with IV, CCE.
- Simulation of the hadronic component.

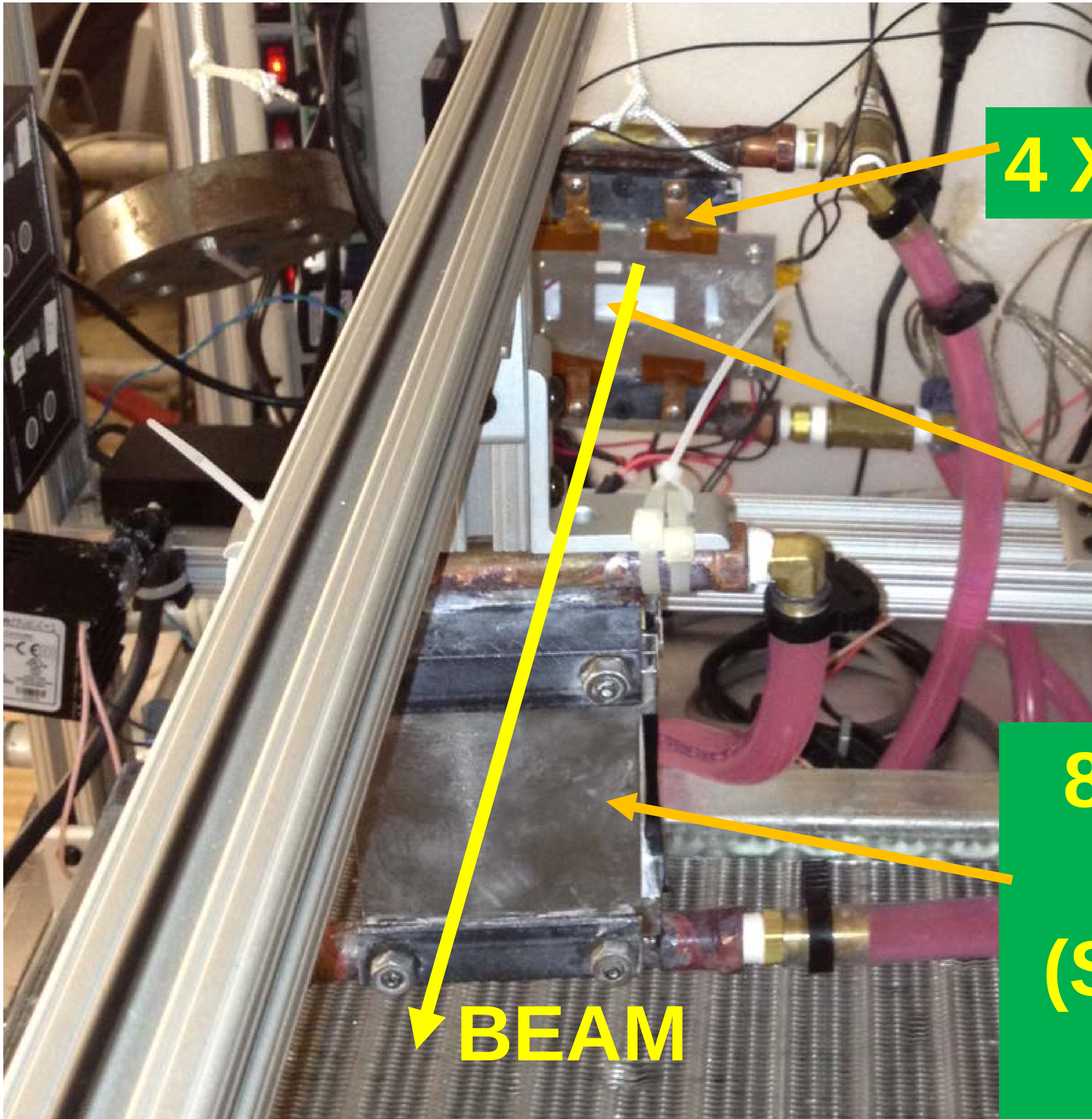
Further studies of radiation damage with SLAC beam is a possibility:

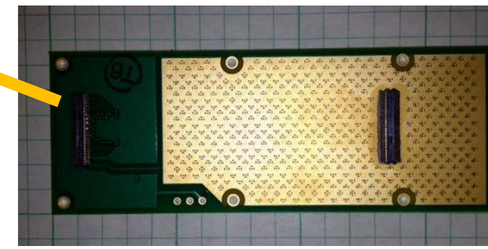
- Higher doses
- Different materials (e.g. direct cross-comparison between Si and GaAs).

Back-Up Slides

N-type Float Zone

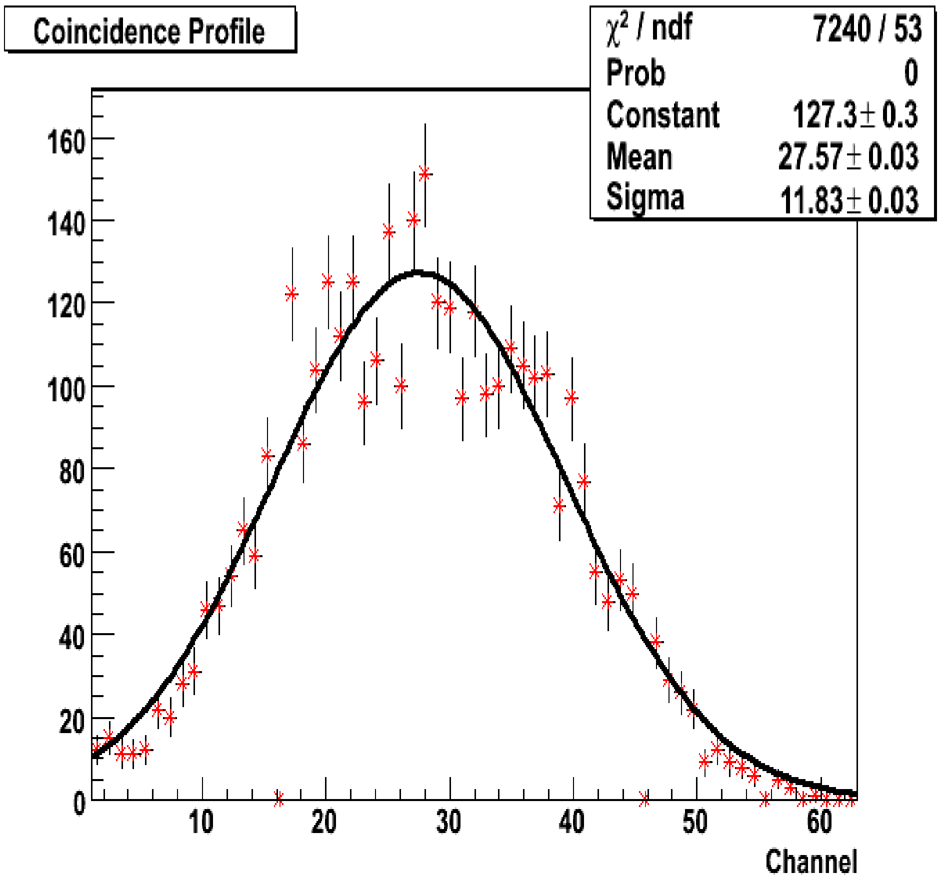


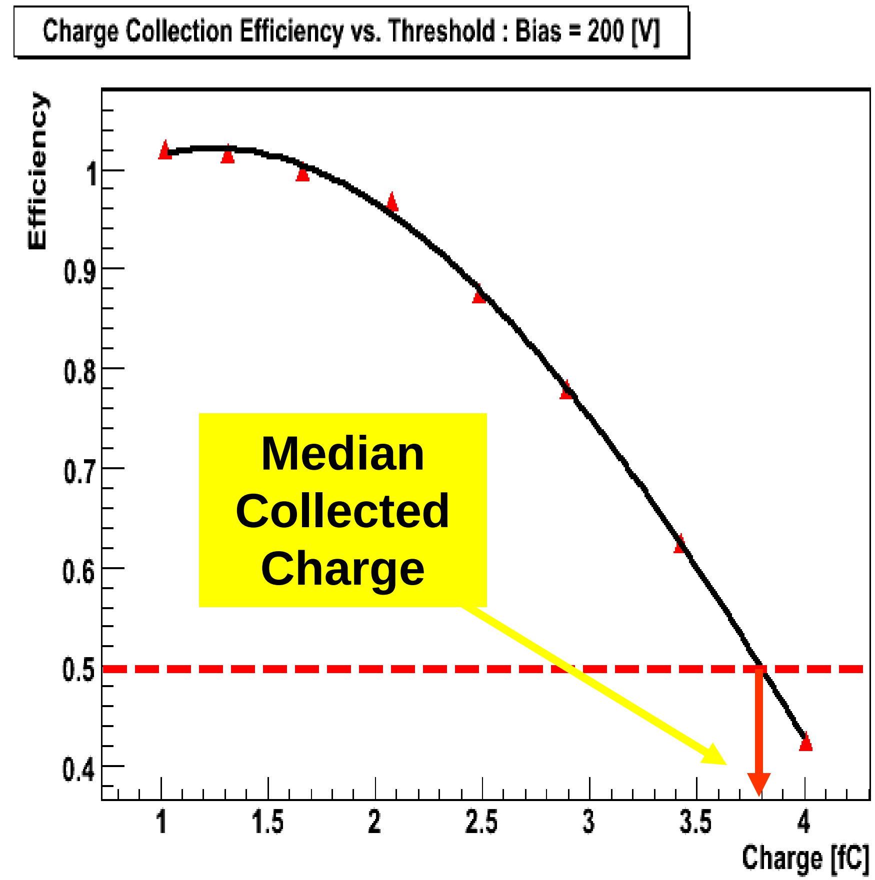

4 X_0 Radiator
8 X_0 Beam Dump (Slides into position)
BEAM



Charge Collection Measurement

2.3 MeV e- through sensor into scintillator

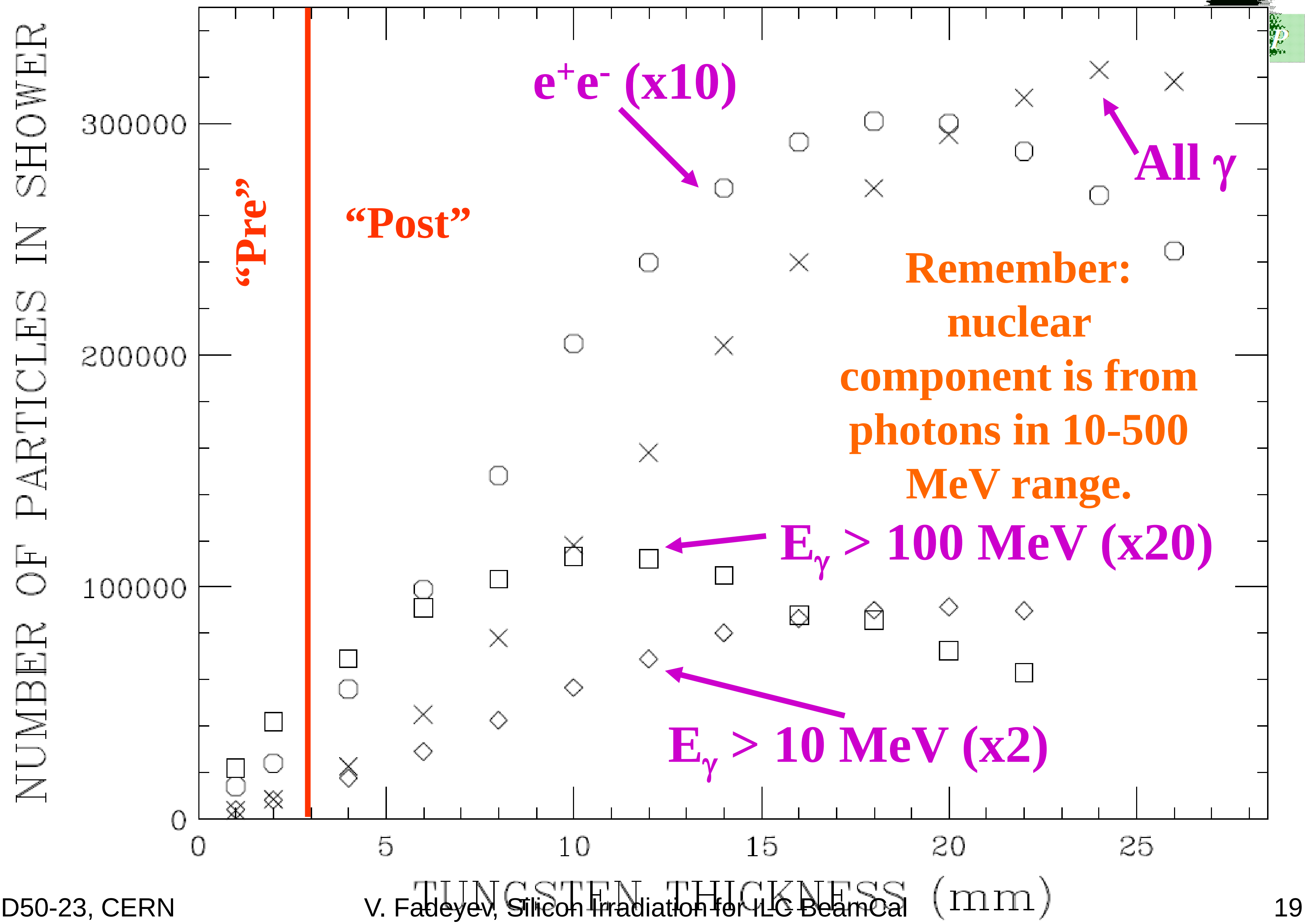




Coincidence Beam profile (Sr90 into Si and Scintillator)

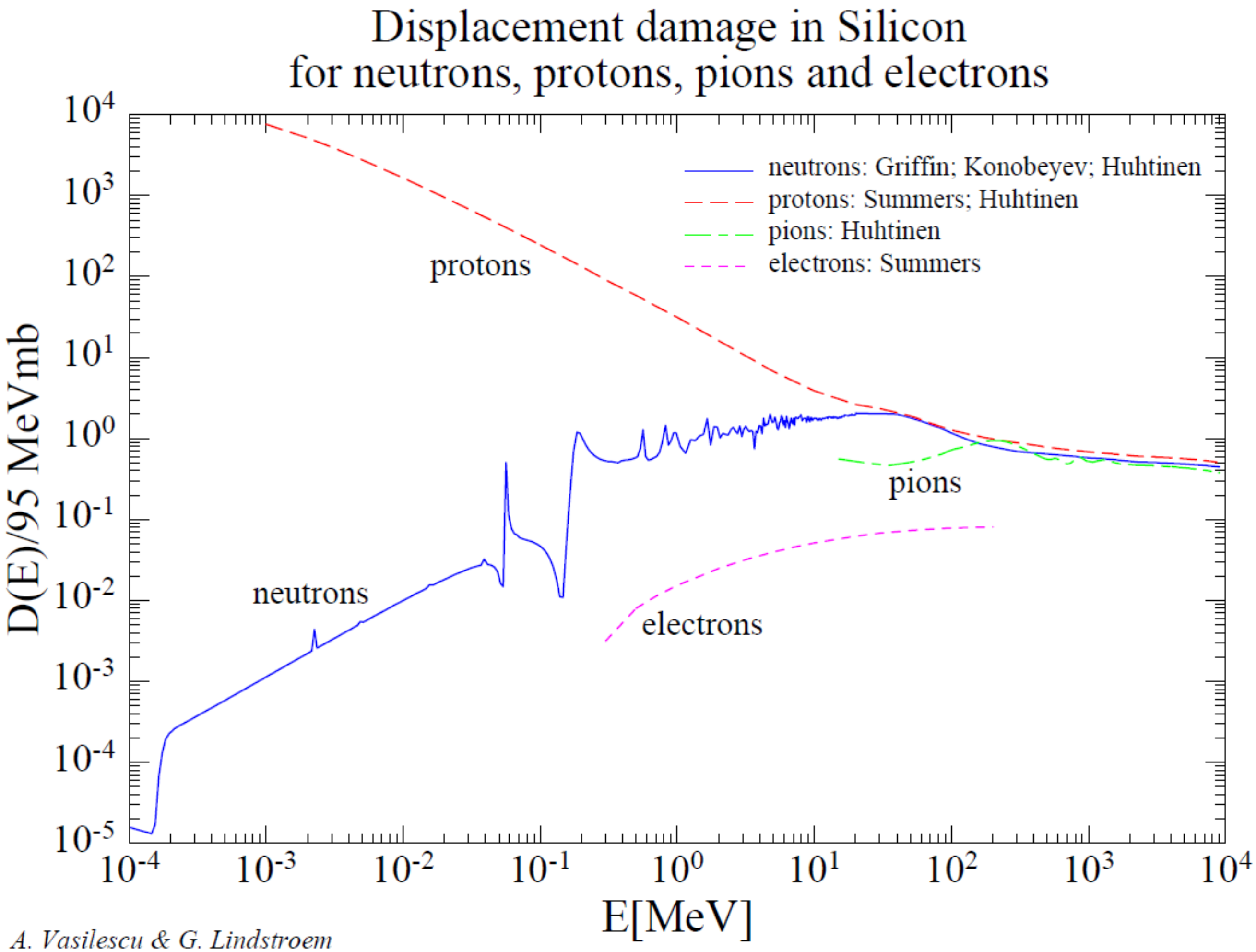
Efficiency vs. threshold

5.5 GeV Shower Profile

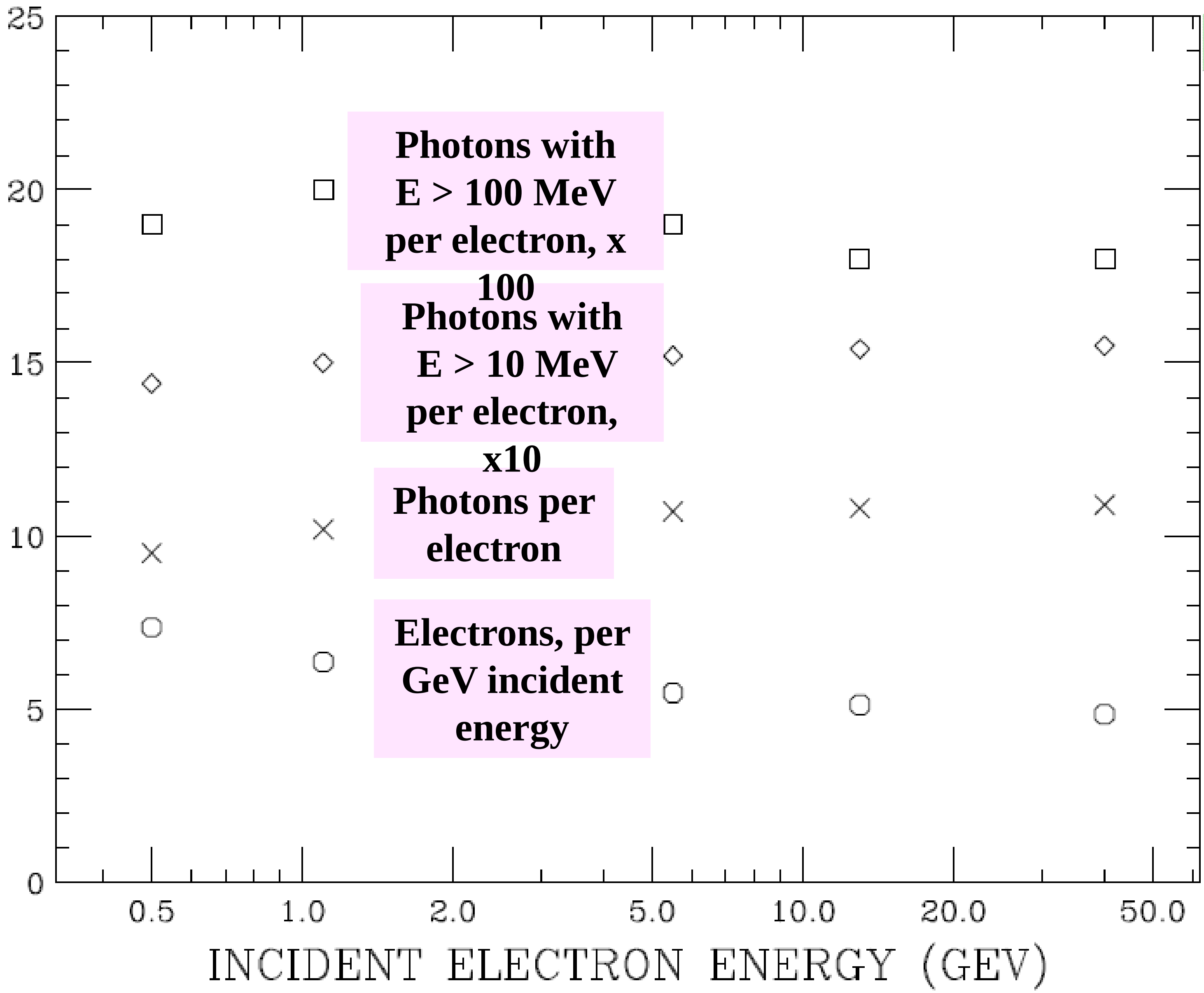


NIEL Plot

D(electrons,max) = (1/13) D(1MeV, n)



Shower Max Results



➔ Photon production ~independent of incident energy!

Fluence (e^- and e^+ per cm^2) per incident 5.5 GeV electron (5cm pre-radiator 13 cm post-radiator with 1m separation)

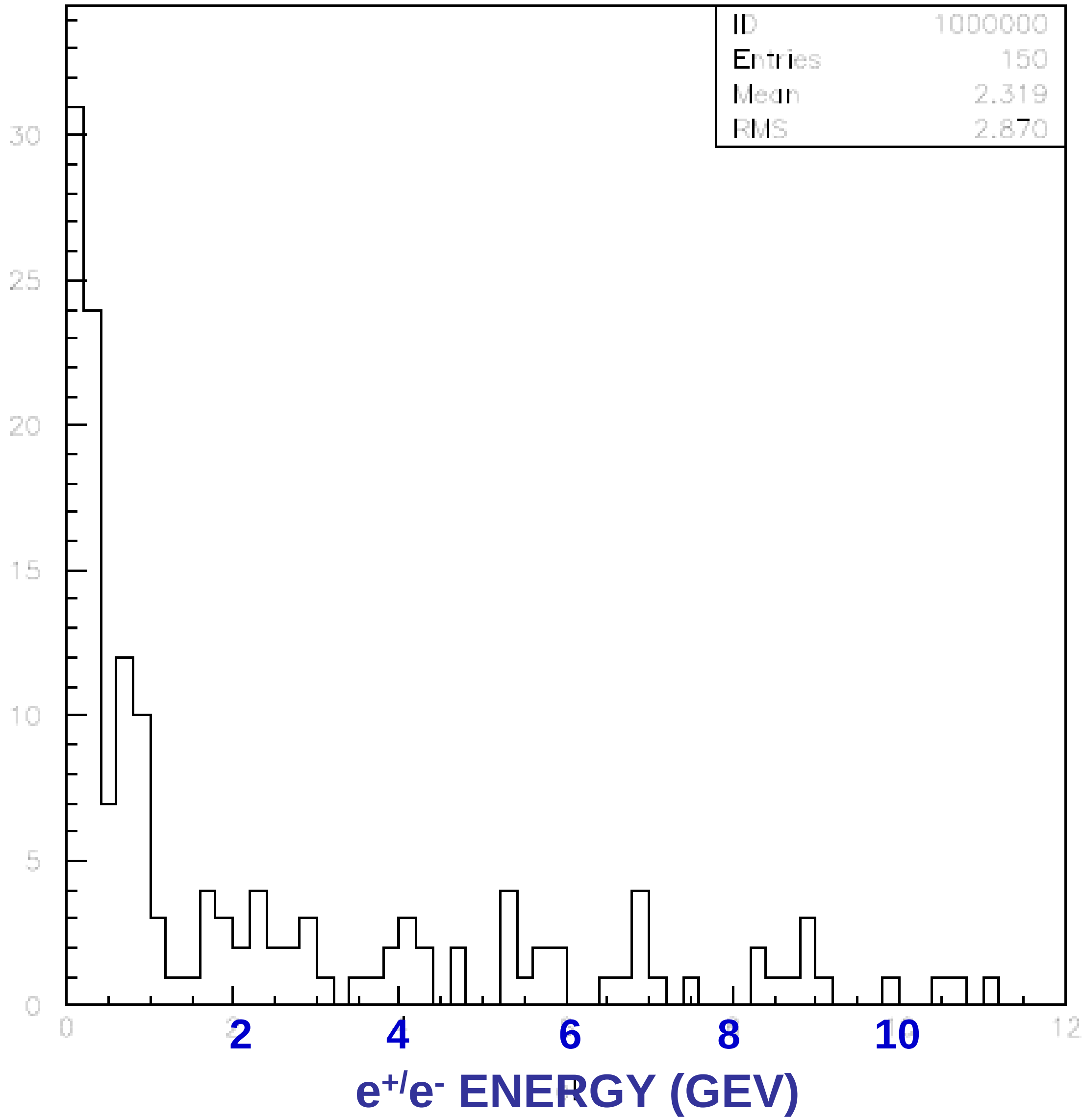
Center of irradiated area

¼ of area to be measured

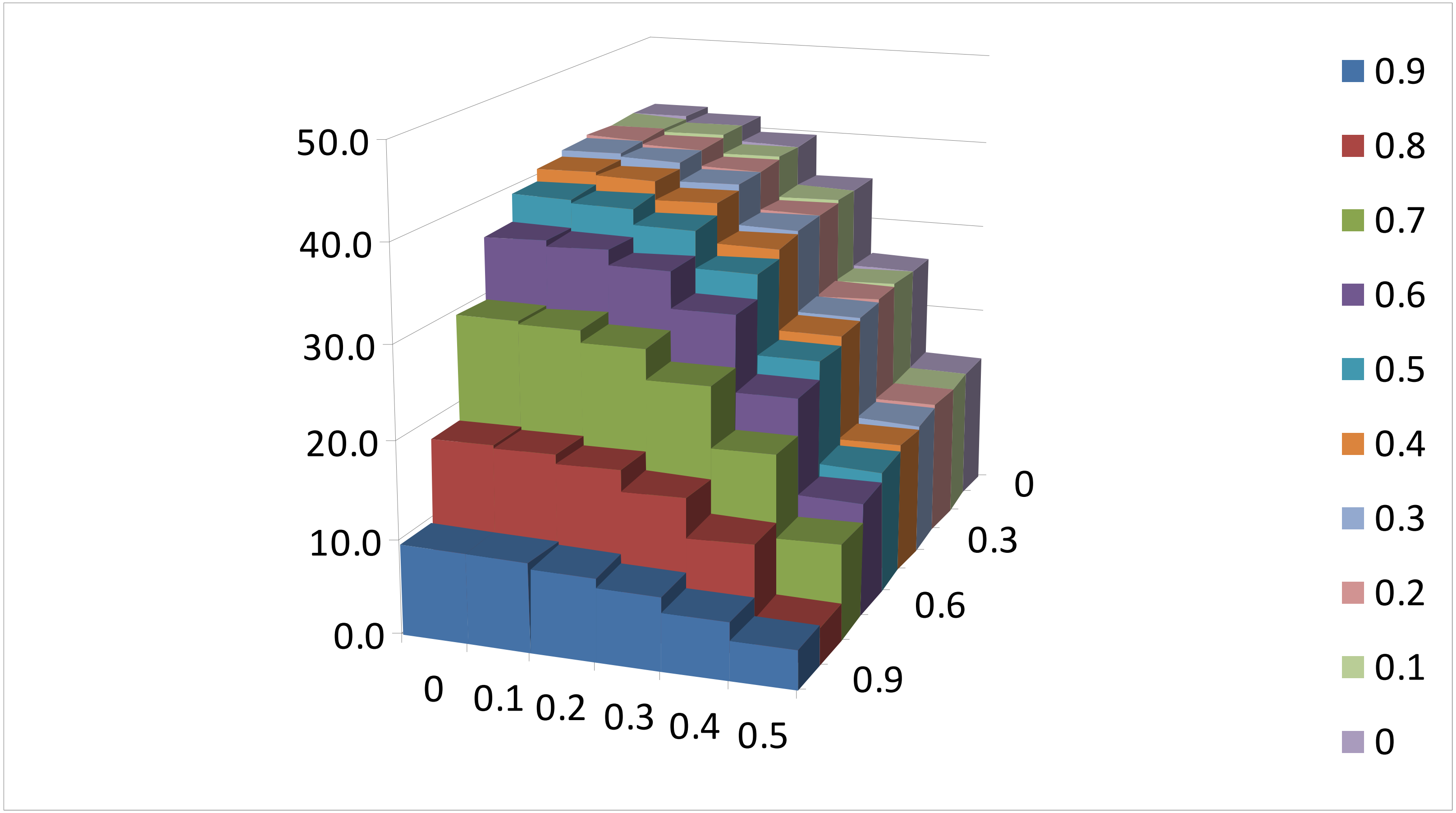
¼ of rastoring area (0.5mm steps)

mm from center	0	1	2	3	4
0	13.0	12.8	11.8	9.9	8.2
1	13.3	12.9	12.0		
2	13.3	12.9	12.0		
3	13.1	12.8	11.8		8.2
4	13.0	12.6	11.7		
5	12.3				
6	11.6		10.7		
7	10.4				
8	8.6		8.0		6.4

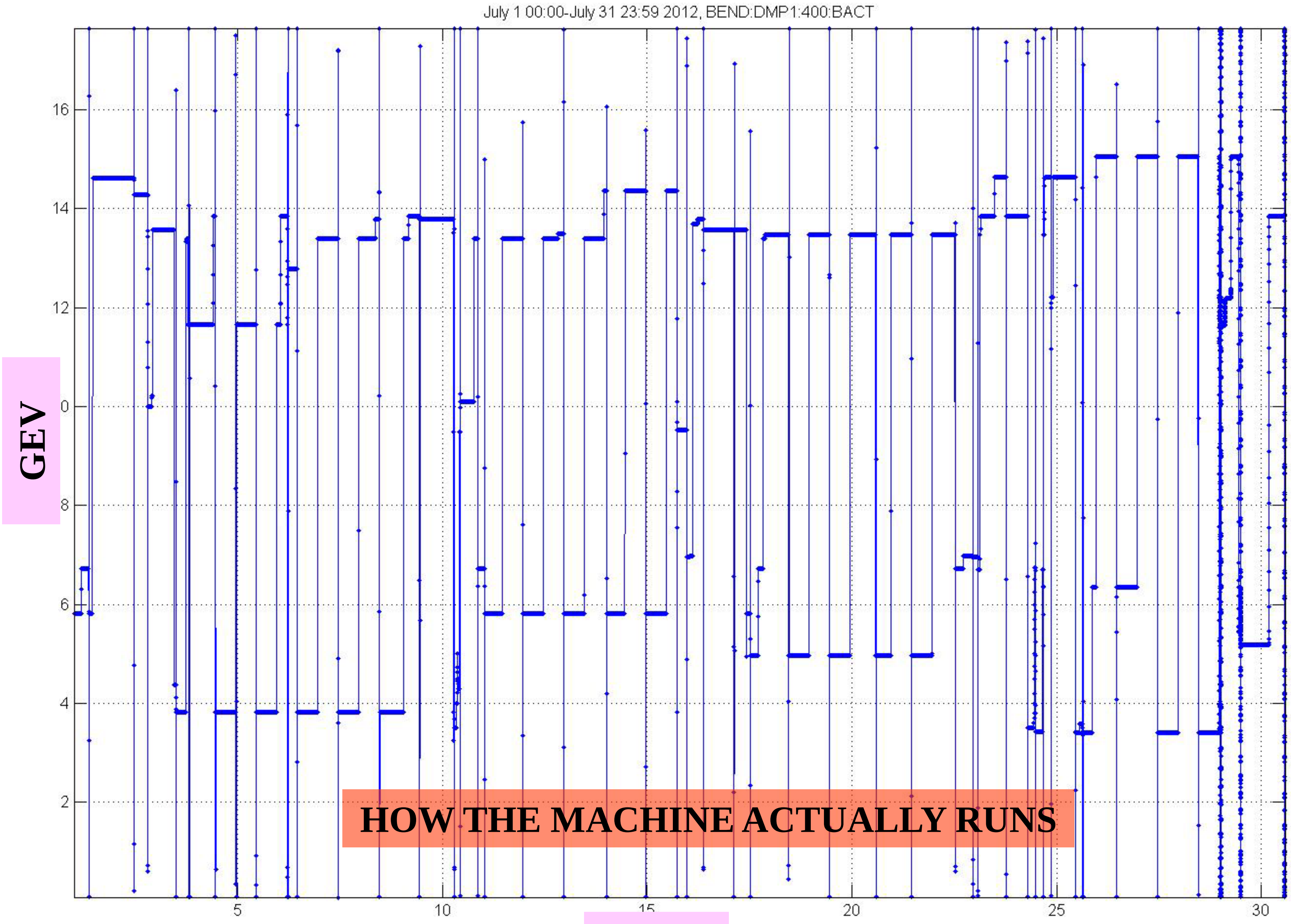
BeamCal Incident Energy Distribution



Illumination Profile



Uniform to ± 10% over (3x6)mm area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HOW THE MACHINE ACTUALLY RUNS