Synthetic Diamonds: Fast, Rad hard particle detectors for ATLAS MiniFCal upgrade

Carleton, Montreal, Toronto, TRIUMF and Victoria

ATLAS groups

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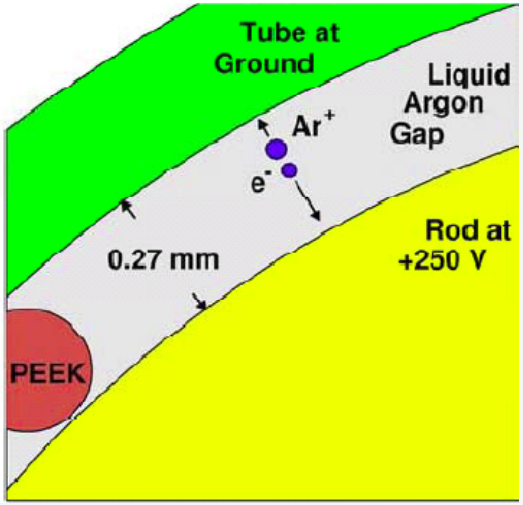
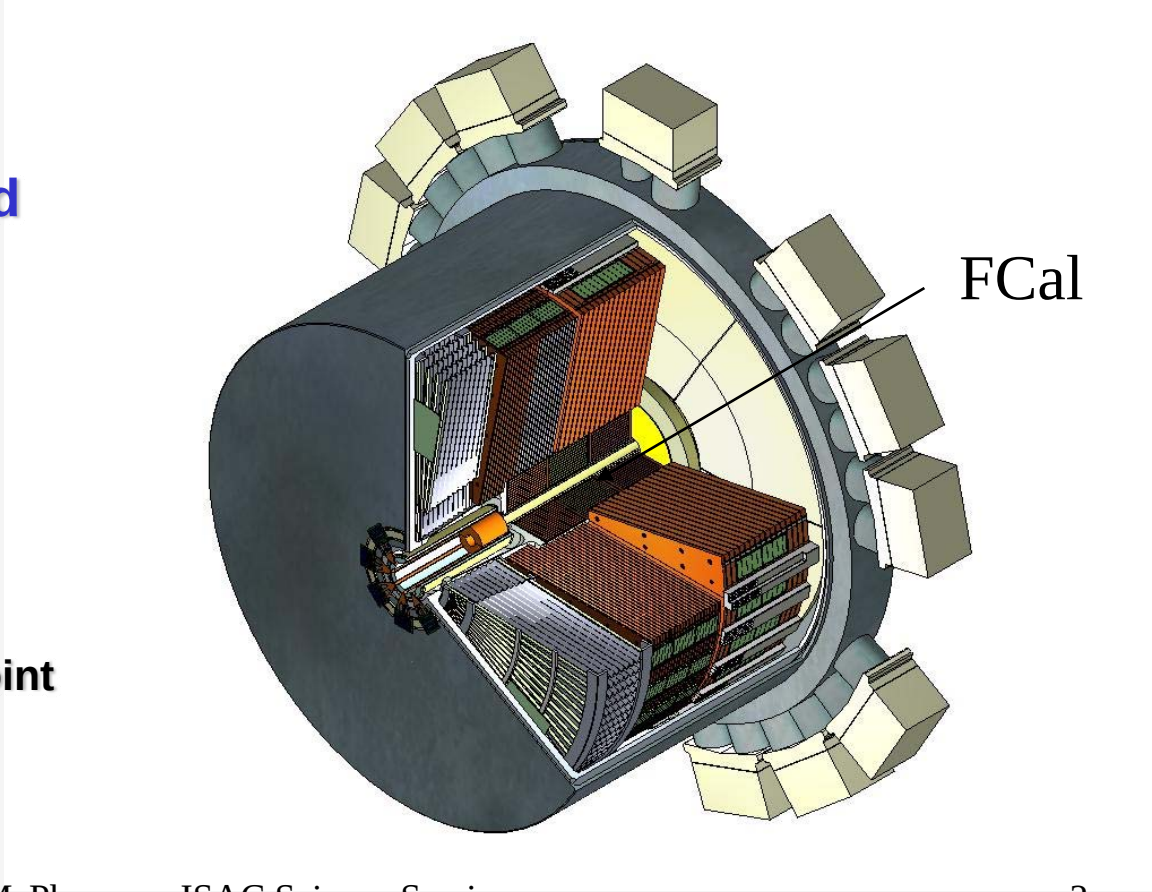
Plus engineering & technical support from TRIUMF: Ray Bula, Dan Gray, Andy Hurst, Scott Kellogg, Roy Langstaff, Brian Minato, Bill Rawnsley

And the cyclotron operation group



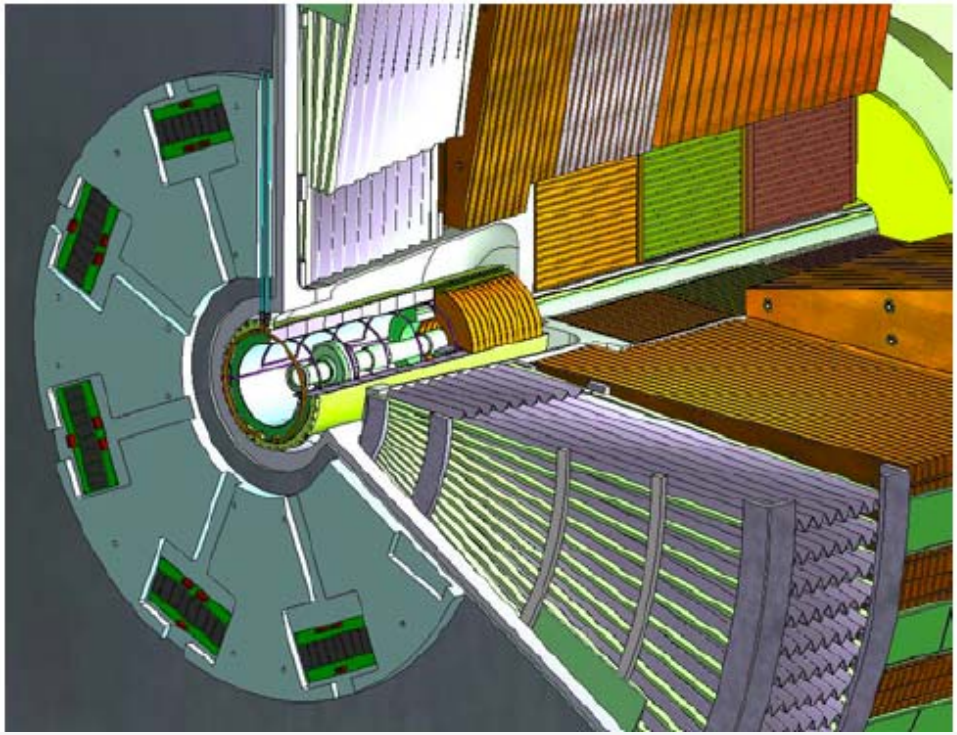
Motivation for MiniFCal: problems in Forward Calorimeters at High Luminosity LHC intensities – exceeding a luminosity of $1x10^{34}$ p cm^{-2} s^{-1}

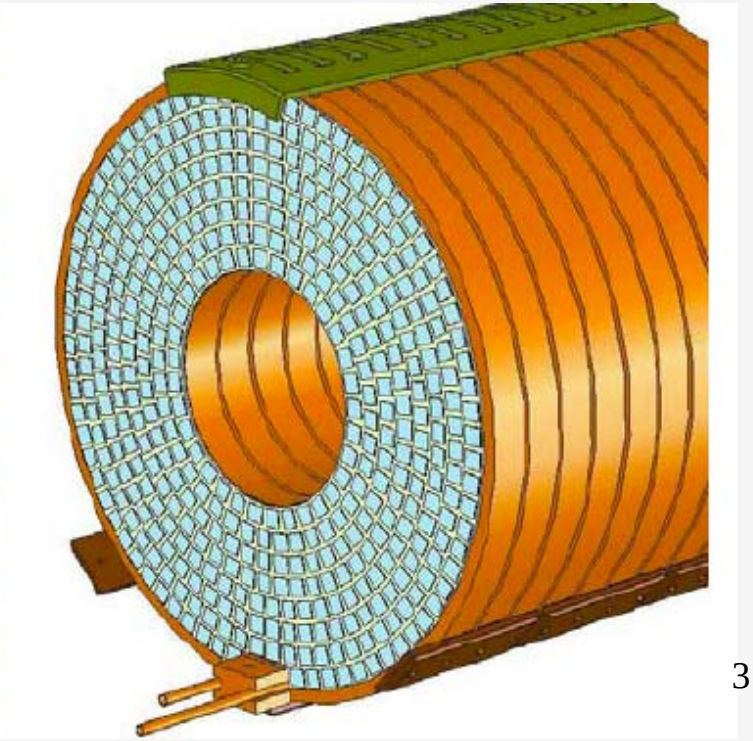
- **Charge build-up in Liquid Argon gap**
  - ⇒ **recombination**
- **HV drop on FCal HV distribution resistors**
  - ⇒ **reduces voltage on gap significantly**
- **Argon beam heating**
  - ⇒ **might exceed boiling point of Liquid**



“Strawman” Mini-FCal design

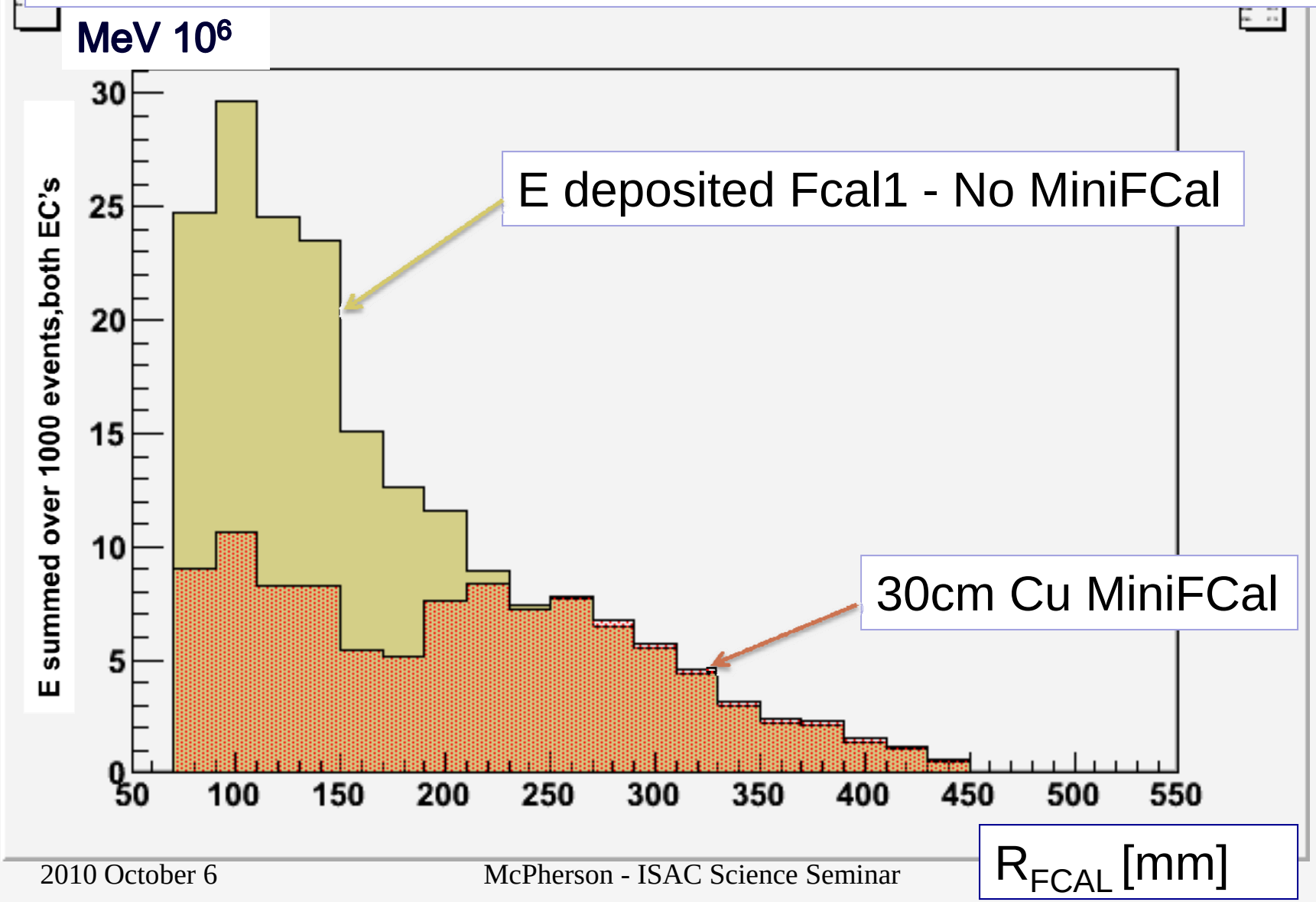
- 12 copper absorber plates with 11 detector planes
- Detector plane:
  - ceramic disc covered with 9 rings of ≈ 1 cm^2 diamond detectors
- Studying optimized tiling, reducing dead regions, …
- Mechanical design by Roy Langstaff, TRIUMF/UVic





MiniFCal Shielding Effect

Radial dependence of energy deposited in Fcal1 without and with a MiniFcal present



Introduction to Diamond Tests

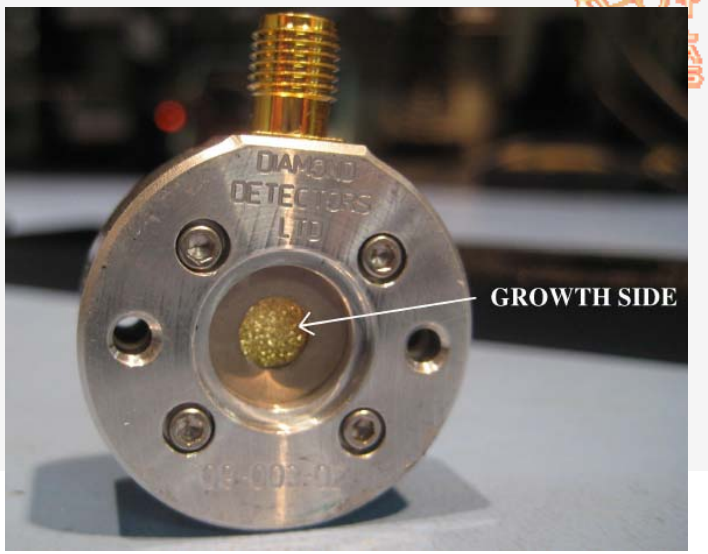
- Synthetic diamonds
  - Attractive possibility for a sensor material in a possible "MiniFCal" for ATLAS high-rate forward calorimetry
    - Large signal
    - Not temperature sensitive
    - Great thermal conductor
    - Sub nanosec timing ⇒ Integrate one bunch crossing
  - Critical worry: radiation damage with fluences above the $10^{17}cm^{-2}$ level expected in MiniFCal in 10 years @ 10^{35} $cm^{-2}s^{-1}$
    - Previous tests (RD42 et al): 20% signal at $16x10^{15}cm^{-2}$ running with protons at the PS
    - Need to push > an order of magnitude

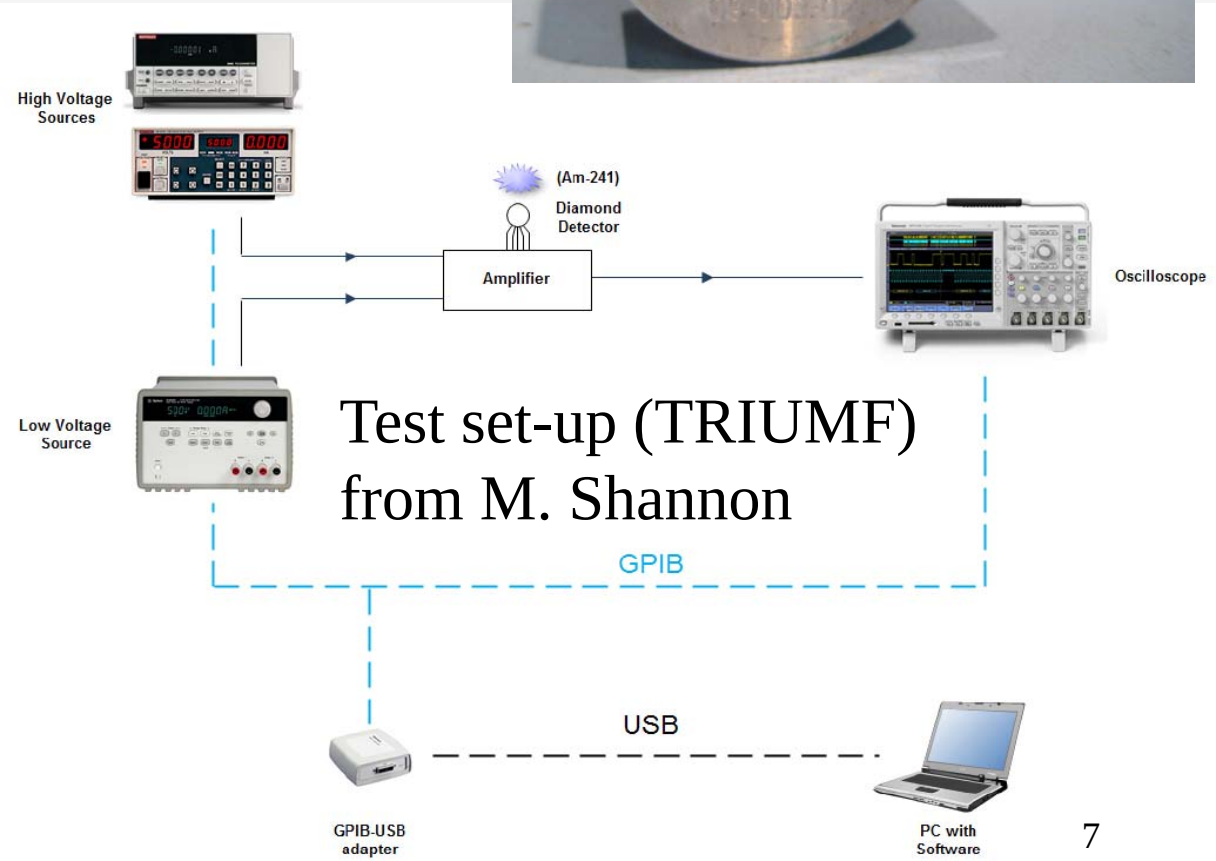
Detectors used in tests

- Detectors purchased from Diamond Detectors Limited (DDL) in U.K.
  - Effectively sole source for packaged diamond detectors
  - Different diamond grades available
    - EL: electronics grade, least nitrogen, largest signal, most £££
    - OP: optical grade, medium signal, middle ££
    - PC: pc grade, most nitrogen, smallest signal, least £
  - Different metalizations
    - Au-Pt has been used more extensively
    - TiW-Al (now TiPt-Au) hoped to be more rad hard
  - NBIF (cyclotron vault) irradiation:
    - 8 mm diameter, 800 μm thick EL-grade with Au-Pt metallization
  - BL1A irradiation:
    - 1) 8 mm dia 200 μm thick EL-grade with TiW-Al metallization
    - 2) 8 mm dia 300 μm thick OP-grade with TiW-Al metallization
    - 3) 8 mm dia 300 μm thick EL-grade with Au-Pt metallization
    - 4) 8 mm dia 300 μm thick OP-grade with Au-Pt metallization

DD Lab Studies

- Started at TRIUMF in 2009 and at Carleton in 2010.
- Summer / term students
  - TRIUMF - M. Shannon and C. David
  - Carleton, C. Collins-Fekete
- Similar set-ups with diamond detector(s) plus preamp/(shaper) and DAQ via digital scopes.
- Control via Testpoint or Labview
- Illuminate detectors:
  - Alpha (^{241}Am)
  - Beta (^{90}Sr)
- Nominal HV of 1V/micron
- Use scintillator to trigger betas, but must use diamond self trigger for alphas.

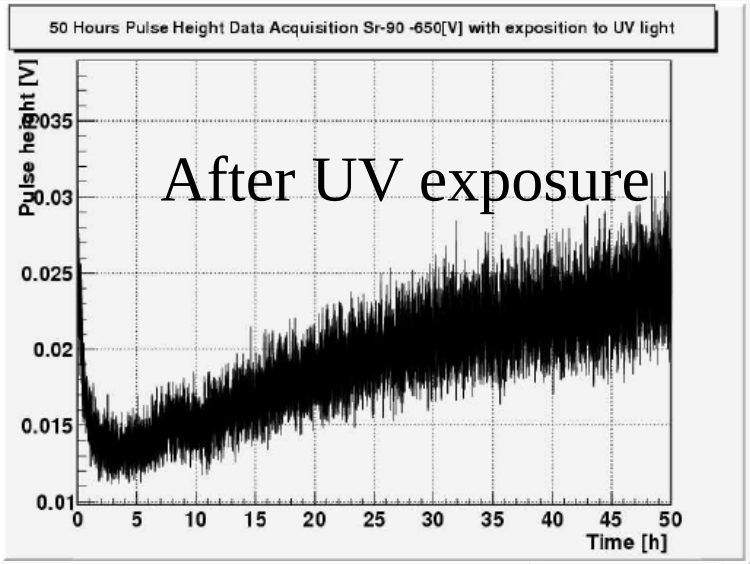


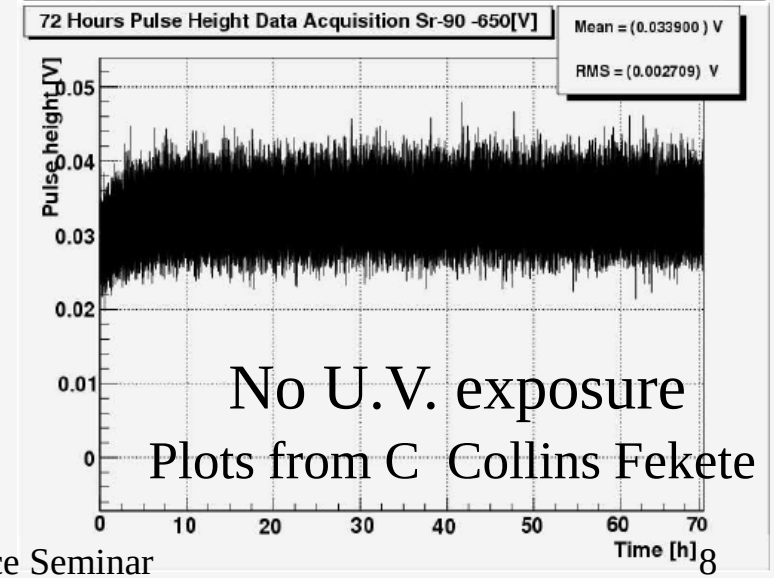


Test set-up (TRIUMF) from M. Shannon

Lab studies: UV history

- Diamond Detector performance affected by exposure to UV light.
- This study with Beta source
- 700 μm EL-grade, Au-Pt
- Top plot after DD exposure to UV
- Lower part after extended operation with beta source and at nominal voltage without UV exposure.
- Current understanding is that UV light clears traps in diamond structure
- Extended operation with source re-fills traps and signal amplitude is regained.
- Time period of days under moderate irradiation to regain consistent output.

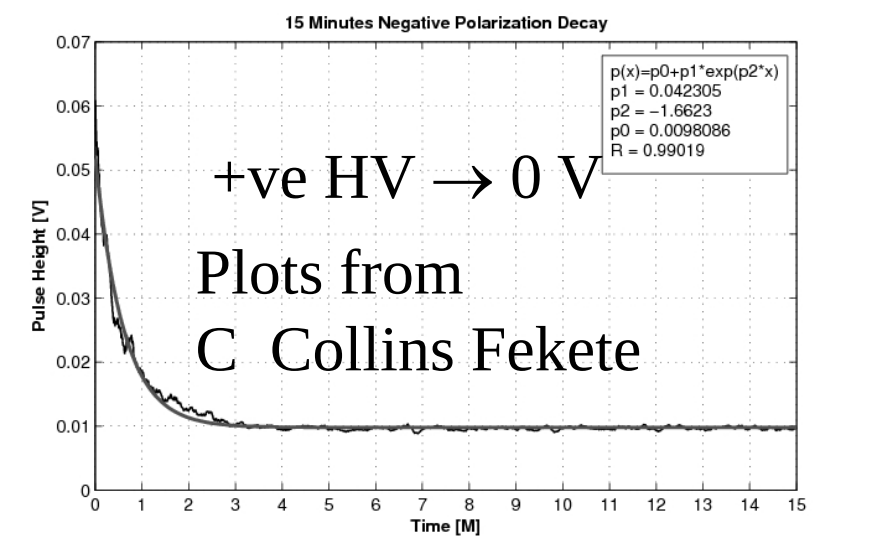


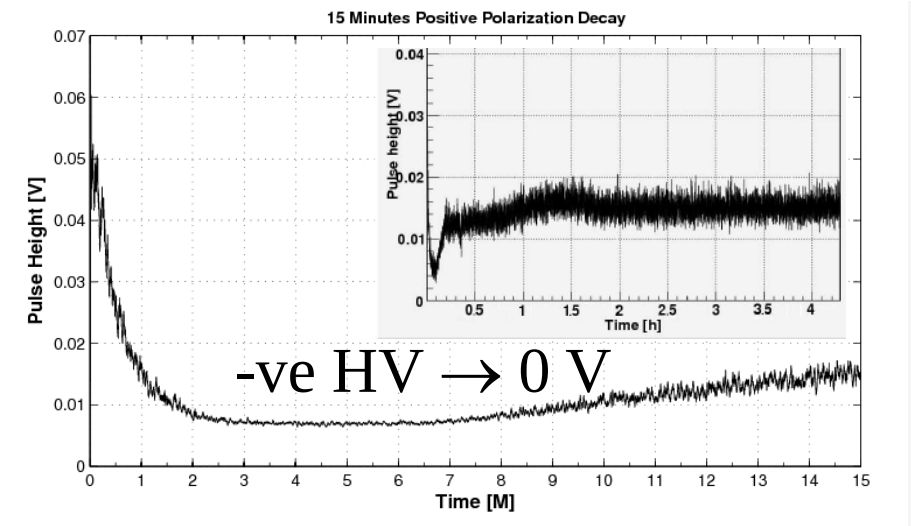


Plots from C Collins Fekete

DD lab studies: Polarization

- There is a polarization effect with DD detectors
- Plots at right are for detector with standard DDL gold metallization.
- They show signal output as function of time over a period of 15 minutes after voltage is turned off.
- The inset in the lower plot is for a time period of 4.5 hours
- Detector outputs stablize after ≈ 1 hour





DD Lab studies: Hysteresis

- 300 μm EL-grade Au-Pt
- Detector keeps some "memory"
  - Same time constants as voltage-off effect
- Alpha sources gives larger pulses than betas
  - Alpha results depend on side of irradiation & HV polarity
  - Presumably due to small differences in electron-hole mobility

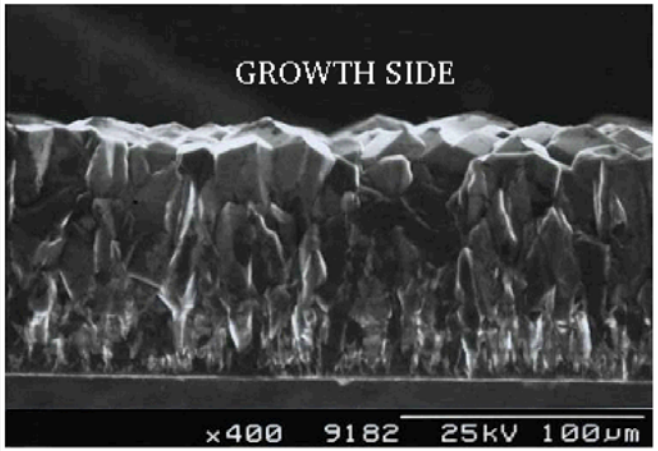
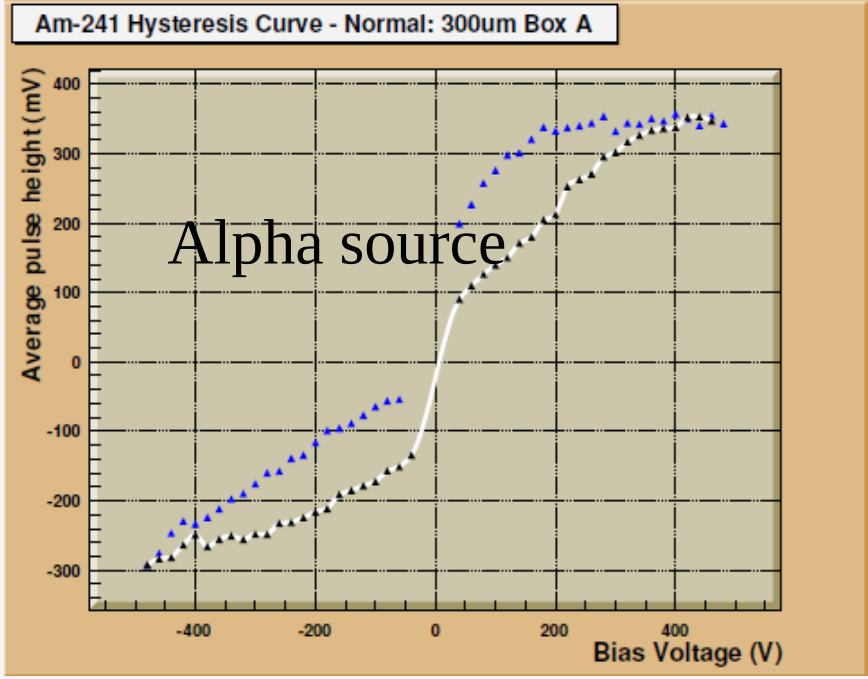
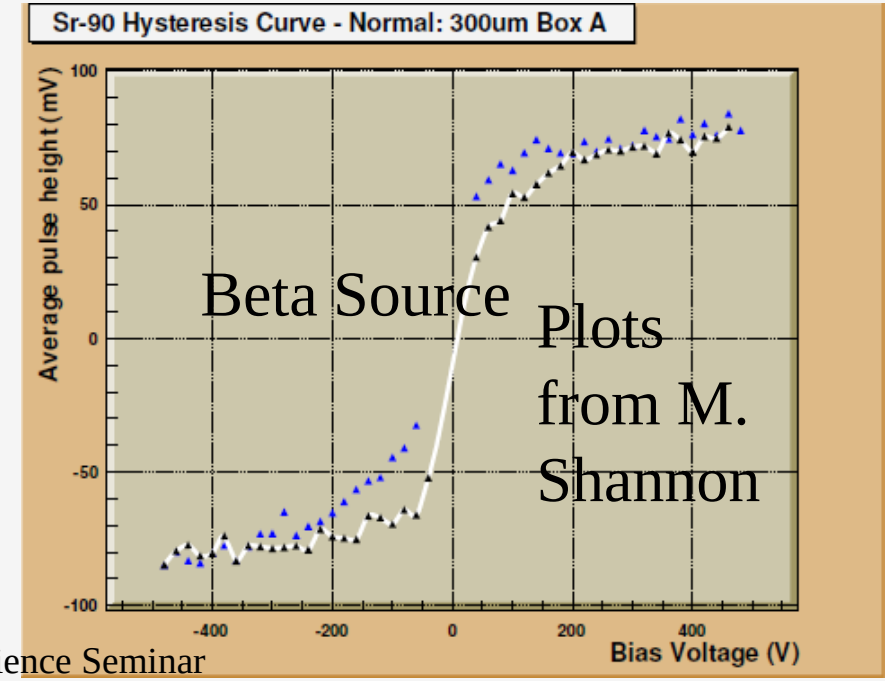


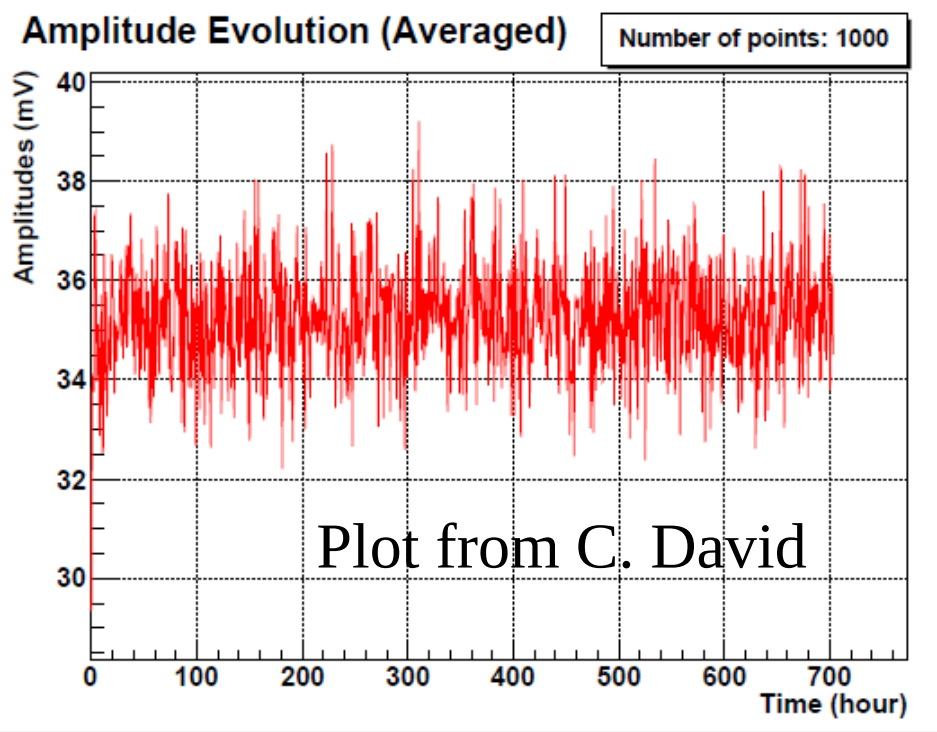
Figure 4: CVD diamond growth, as reproduced with permission from the CVD Diamond Group, School of Chemistry, University of Bristol, UK.





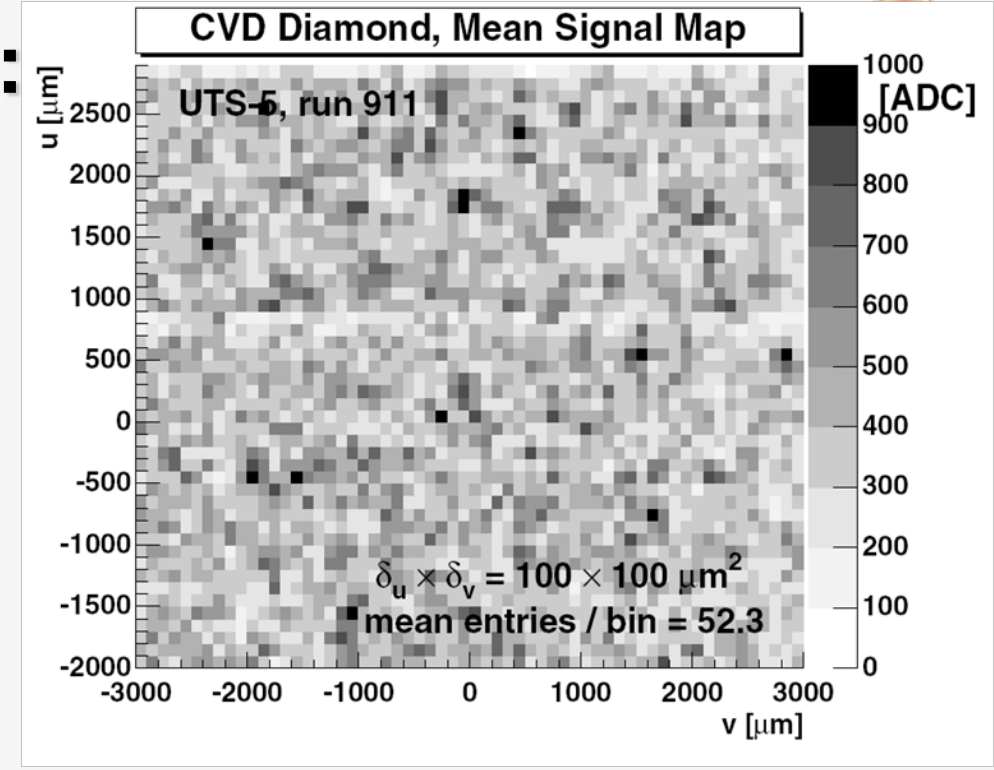
Lab studies: Long term stability

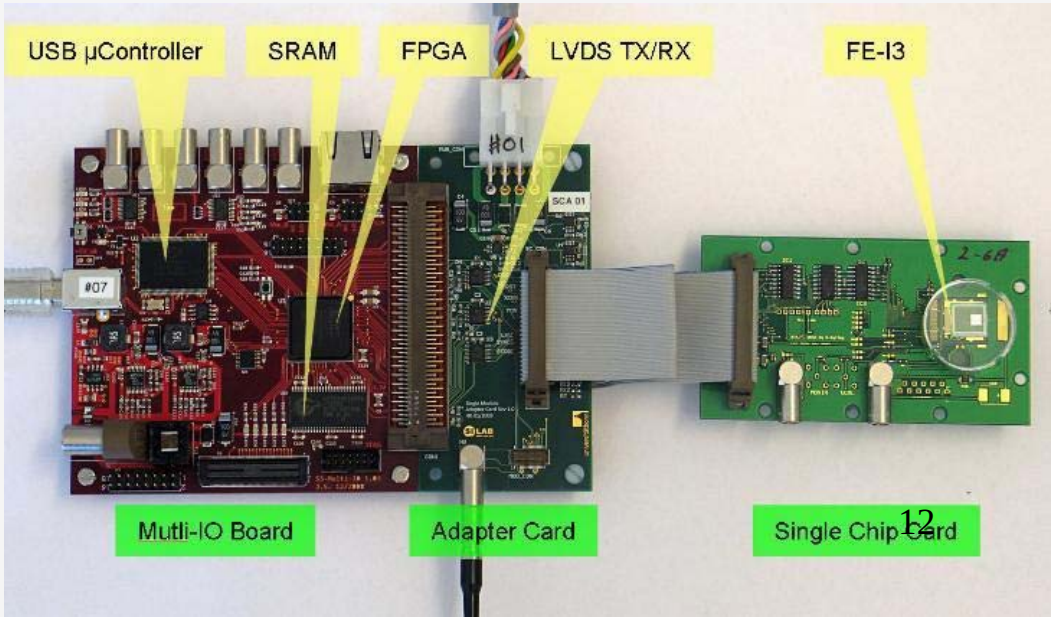
- Initial tests had indicated some problems with detectors ran for extended periods of time (~weeks)
- Test in Spring of 2010
- 200 μm EL-grade TiW-AL
- Irradiated with Alphas
- Run for one month
- No variation in long term signal output.



Lab/beam studies: spatial stability

- Test by (RD42 grad student -?) on spatial response – plot on right →
- Initial lab tests with Alpha and Beta sources and collimators
- Initial test showed variation in response of ± 10%
- Hope is to test spatial response in muon beam with M11 at TRIUMF using DD and USBPix detector from Pixel upgrade work.
- Problem is adapting the USBPix software to work with another detector.
- Timeframe for test at TRIUMF is prior to mid-December
- If we miss this window then TRIUMF beams not available until summer 2011

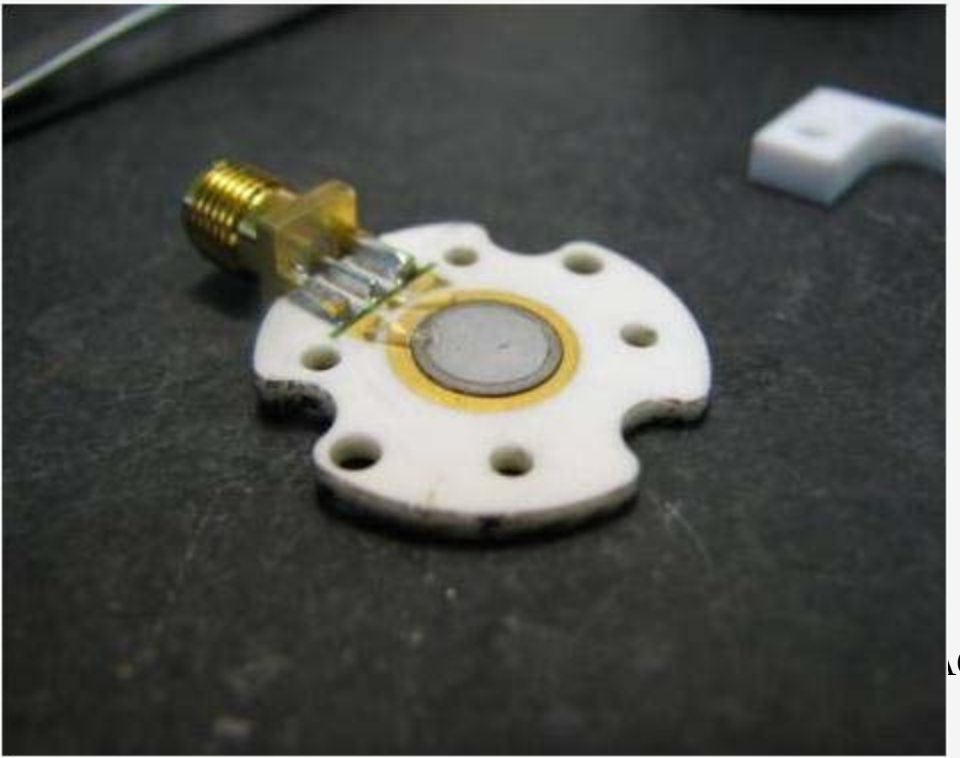




Radiation Tests

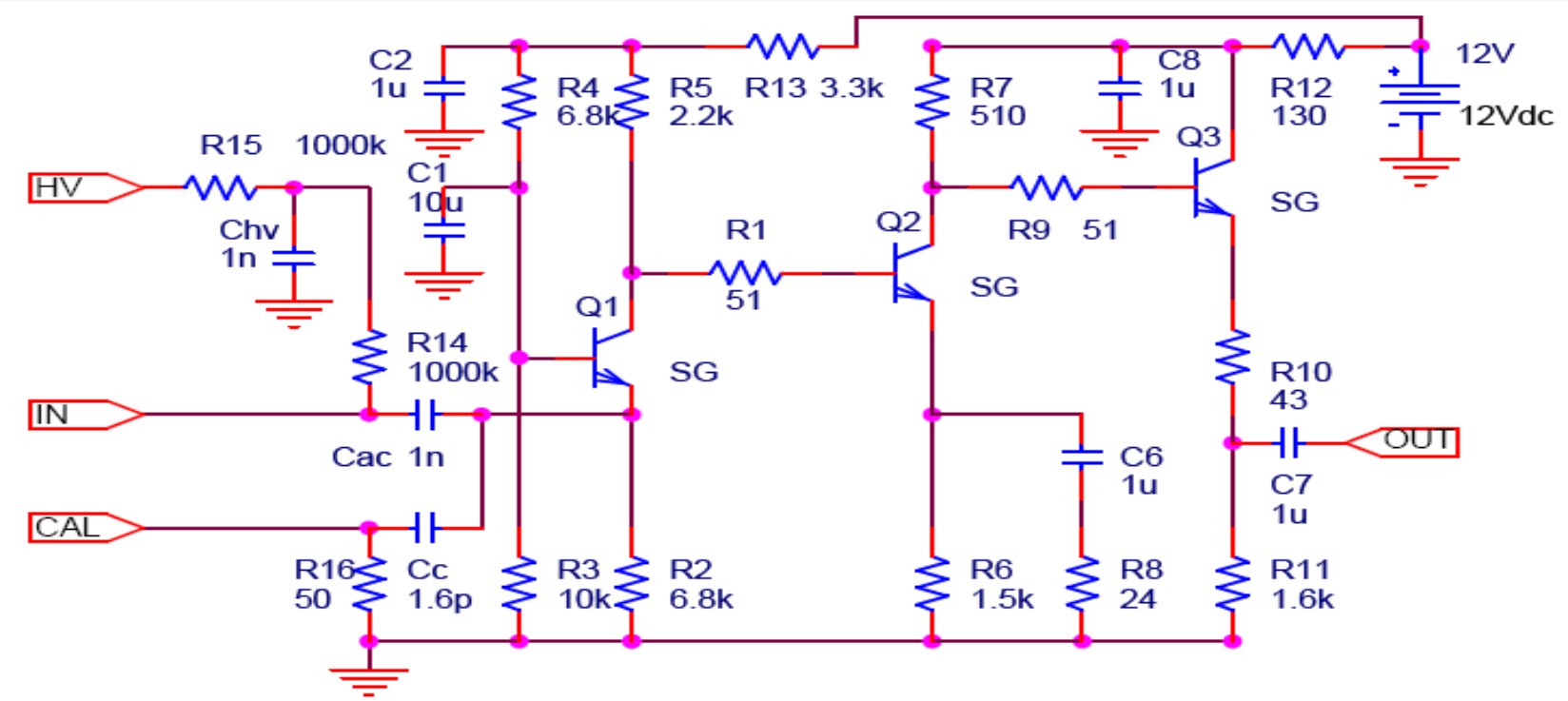
- **Proton irradiation tests at TRIUMF**
  - **1) "Neutral Beam Irradiation Facility" (NBIF) in TRIUMF cyclotron vault**
    - **500 MeV protons, significant neutron backgrounds in vault (preamps also in vault)**
    - **Run: ≈ ½ x 10^{15} p/cm^2 per day, 1 May – 1 Aug 2010**
  - **2) TRIUMF beam line 1A (BL1A)**
    - **500 MeV protons in controlled environment**
    - **Robust tests, but had to wait for beam time**
    - **Run: ≈ 10^{15} – 10^{16} p/cm^2 per day, 1-13 Sep 2010**

Detector packaging for tests



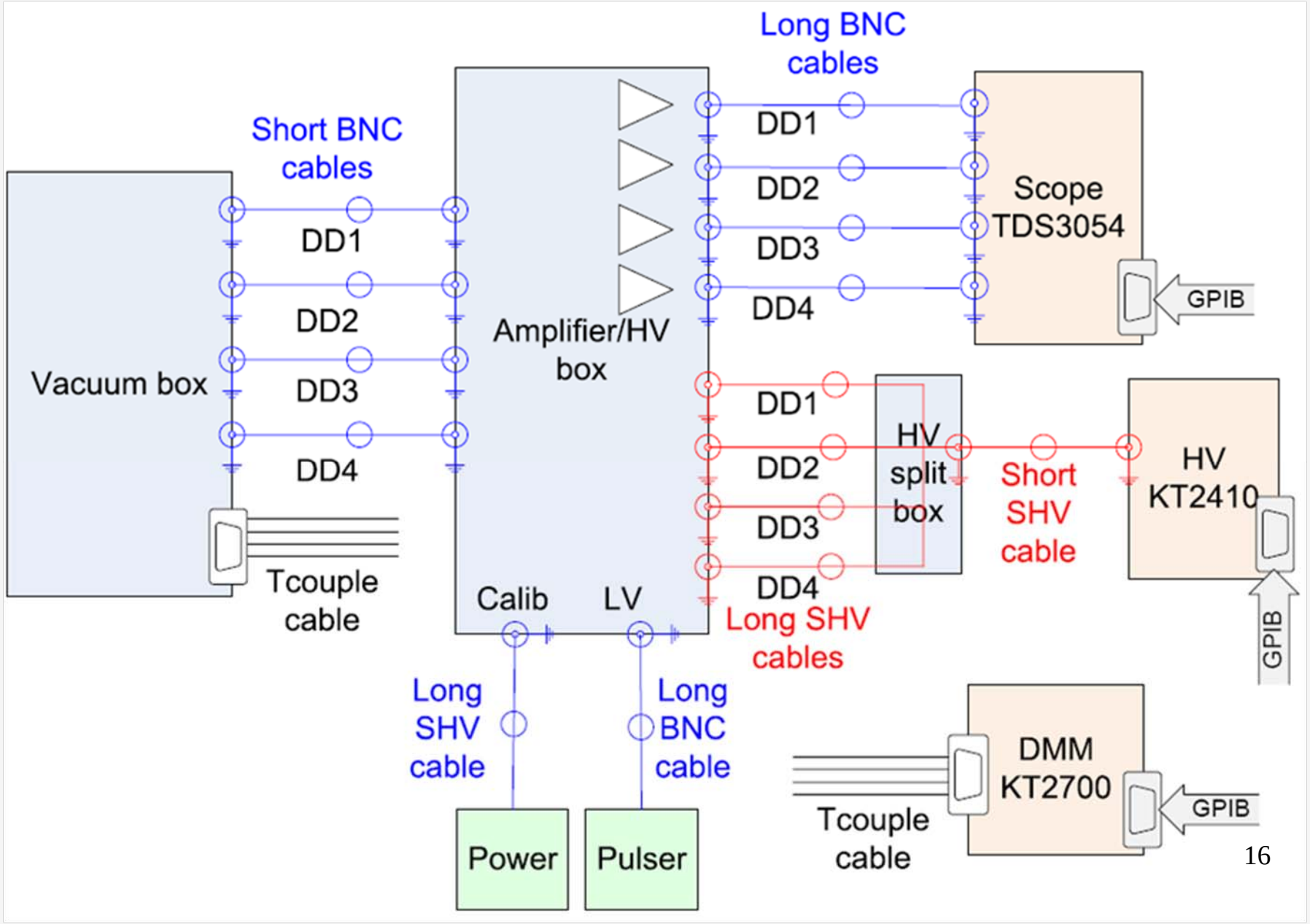
Detector Readout

- Bias detectors with 0.7 – 1 volt/μm
- Preamp locally built with SiGe technology with ~short cable between preamp and detector
- Regular calibration runs to test preamp
- 100'-180' cables to HV, LV, calibration pulser and scope
  - Signal cable: LMR400 (double shielded foam dielectric cable)
- Preamp schematic for NBIF (Leonid):



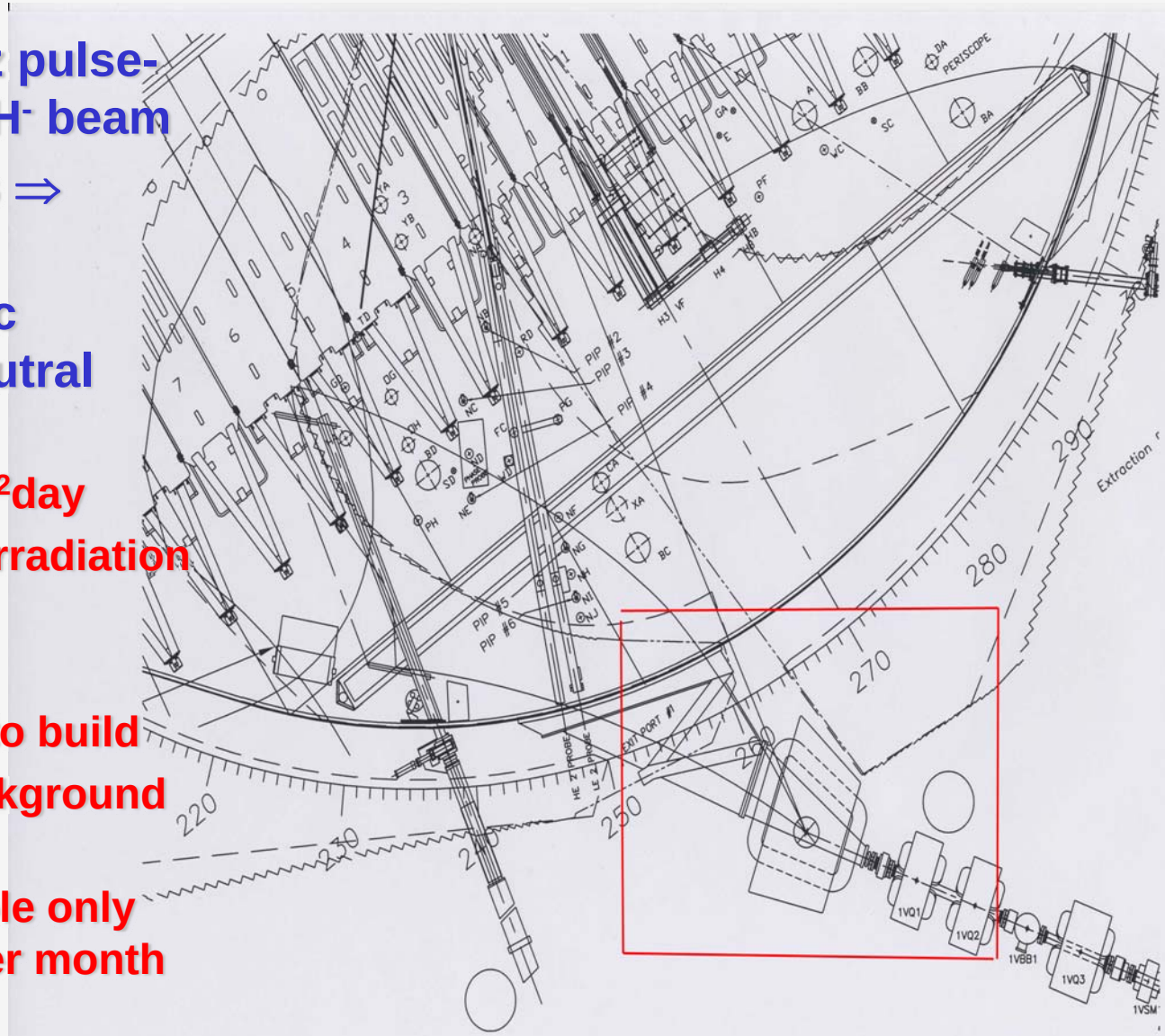
- BL1A preamp improved version (better 50 Ohm match, wider frequency band, larger dynamic range)

BL1A: 4 detector readout

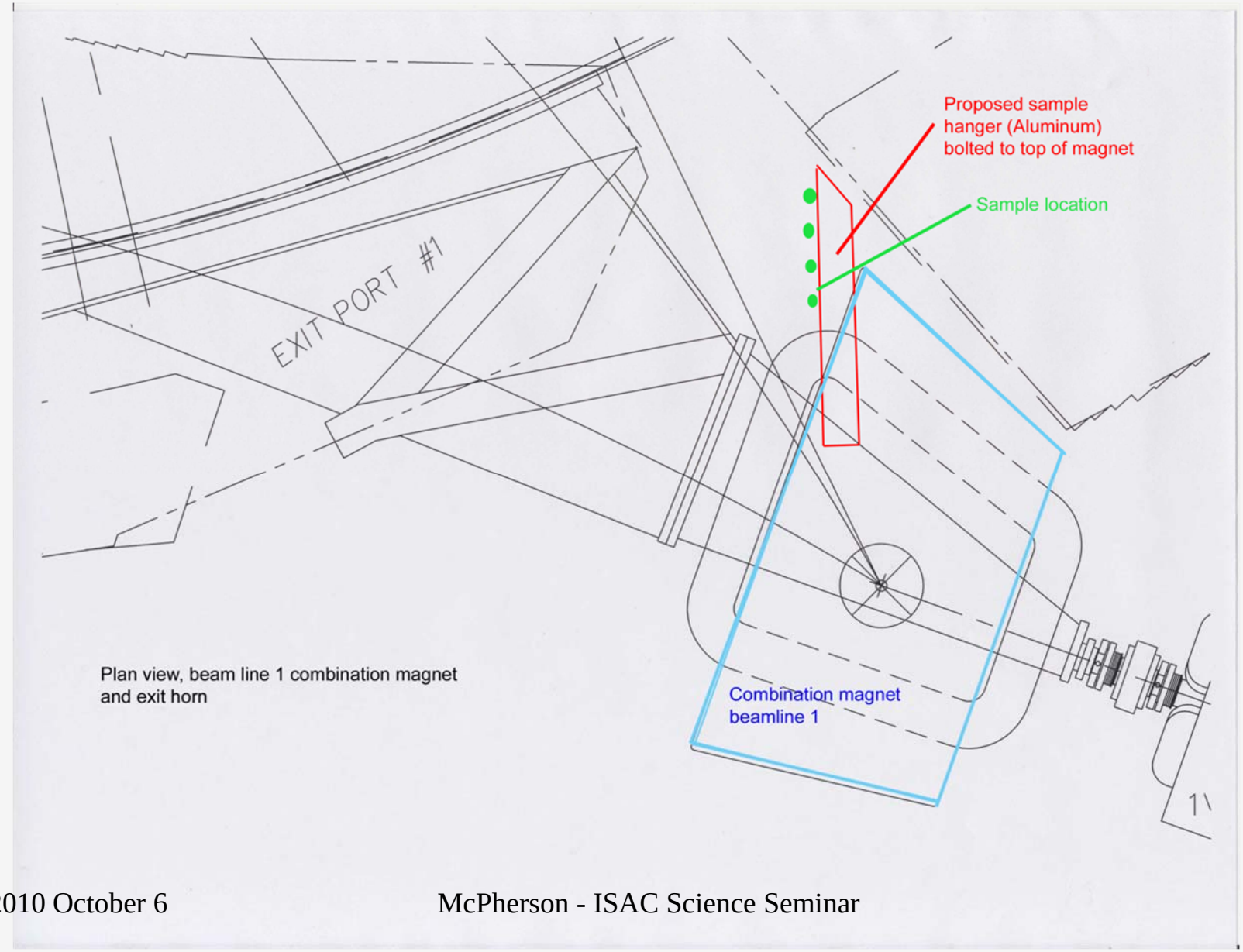


NBIF and BL1A

- TRIUMF 23 MHz pulse-rate cyclotron, H^- beam
- Stripper probes ⇒ multiple beams
- Electromagnetic stripping ⇒"neutral beam"
  - ½ x 10^{15}p/cm^{2}day
  - Can use for irradiation "for free"
  - Downsides:
    - Needed to build
    - high background fields
    - accessible only ~once per month

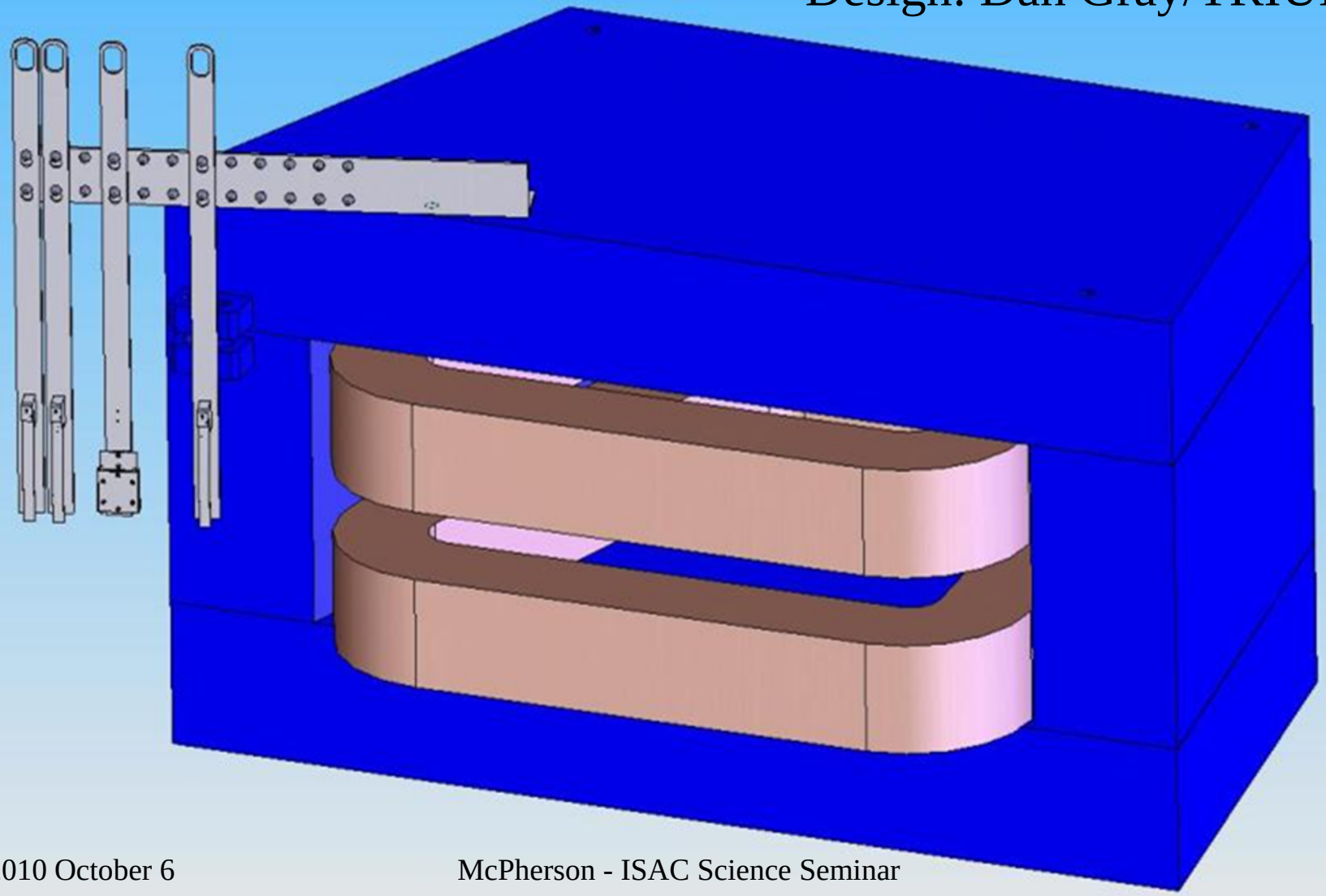


NBIF: layout and beam II



NBIF

Design: Dan Gray/TRIUMF

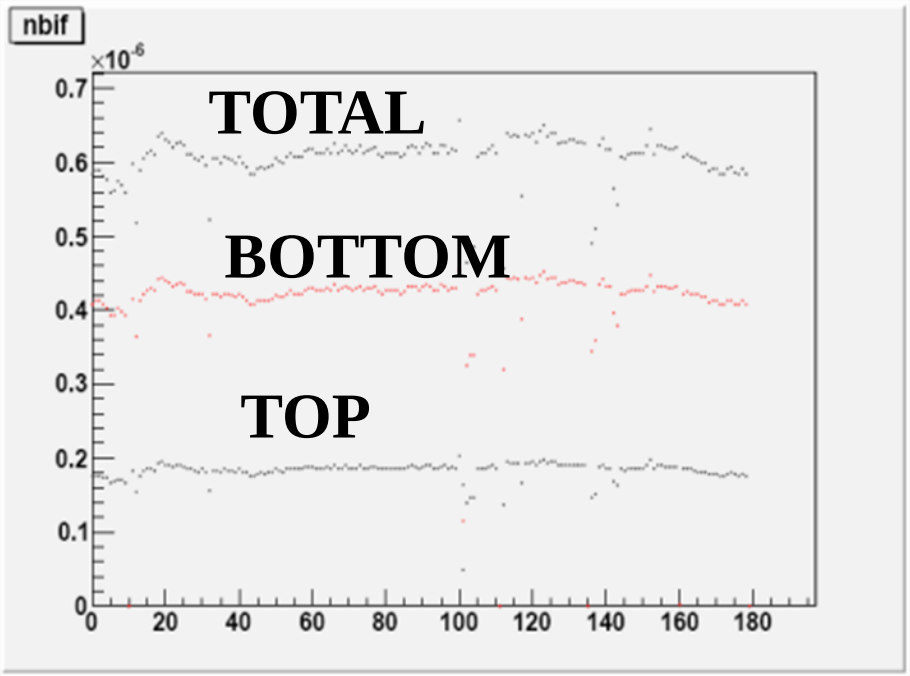


NBIF: installed samples

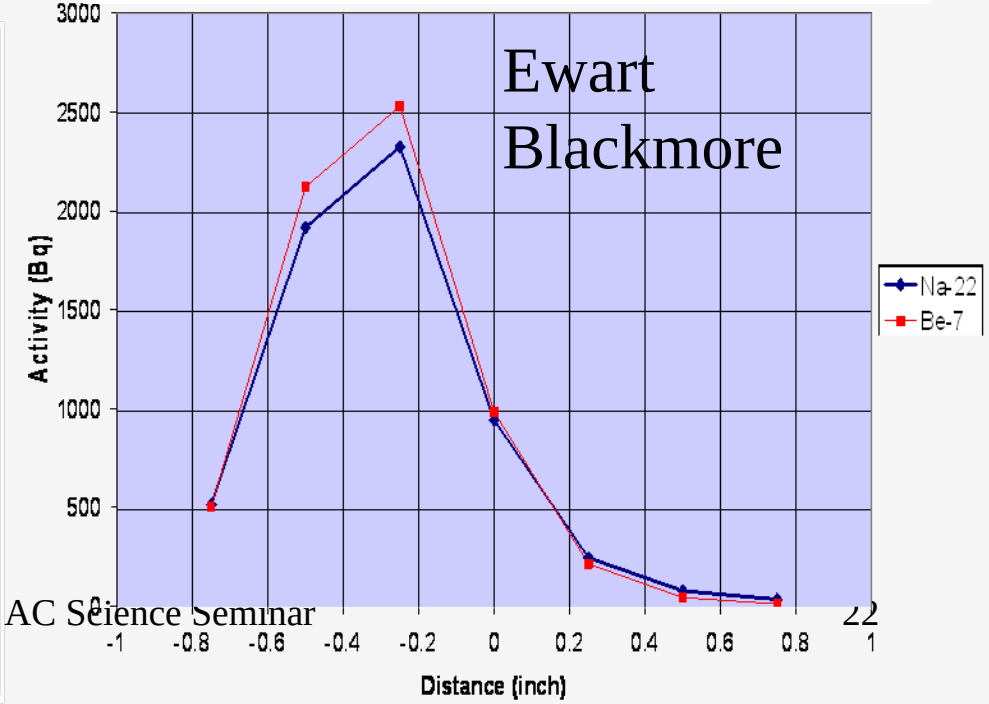
NBIF: Fluence from Air Ionization Chamber

- Simple device, slow but very radiation hard
- Gives absolute ~5% normalization of beam current
- Split into “top” and “bottom” for tracking alignment
- Use this device for O(sec) normalization and integrate for tracking irradiation
- Precision calibration with activation of Al foil (checked once from first month)
- Ran 800 um Au-Pt EL-grade detector to 0.5 x 10^{17} p/cm^2
  - Now drawing too much dark current to run
  - Need to inspect to see if detector or cables/connector are the problem

- Ionization Chamber – first month



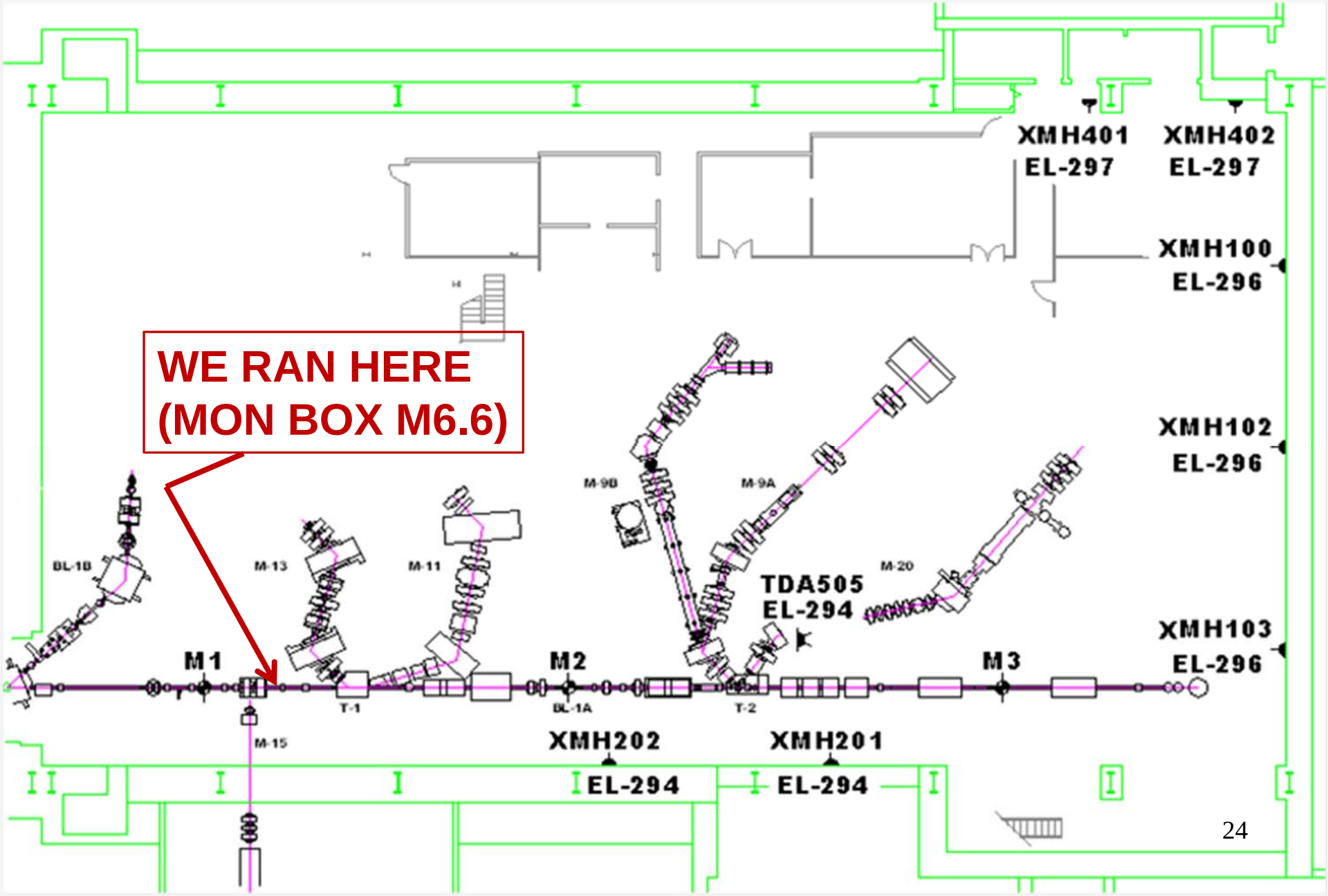
- Activation foil y-profile – first month



TRIUMF Beam Line 1A

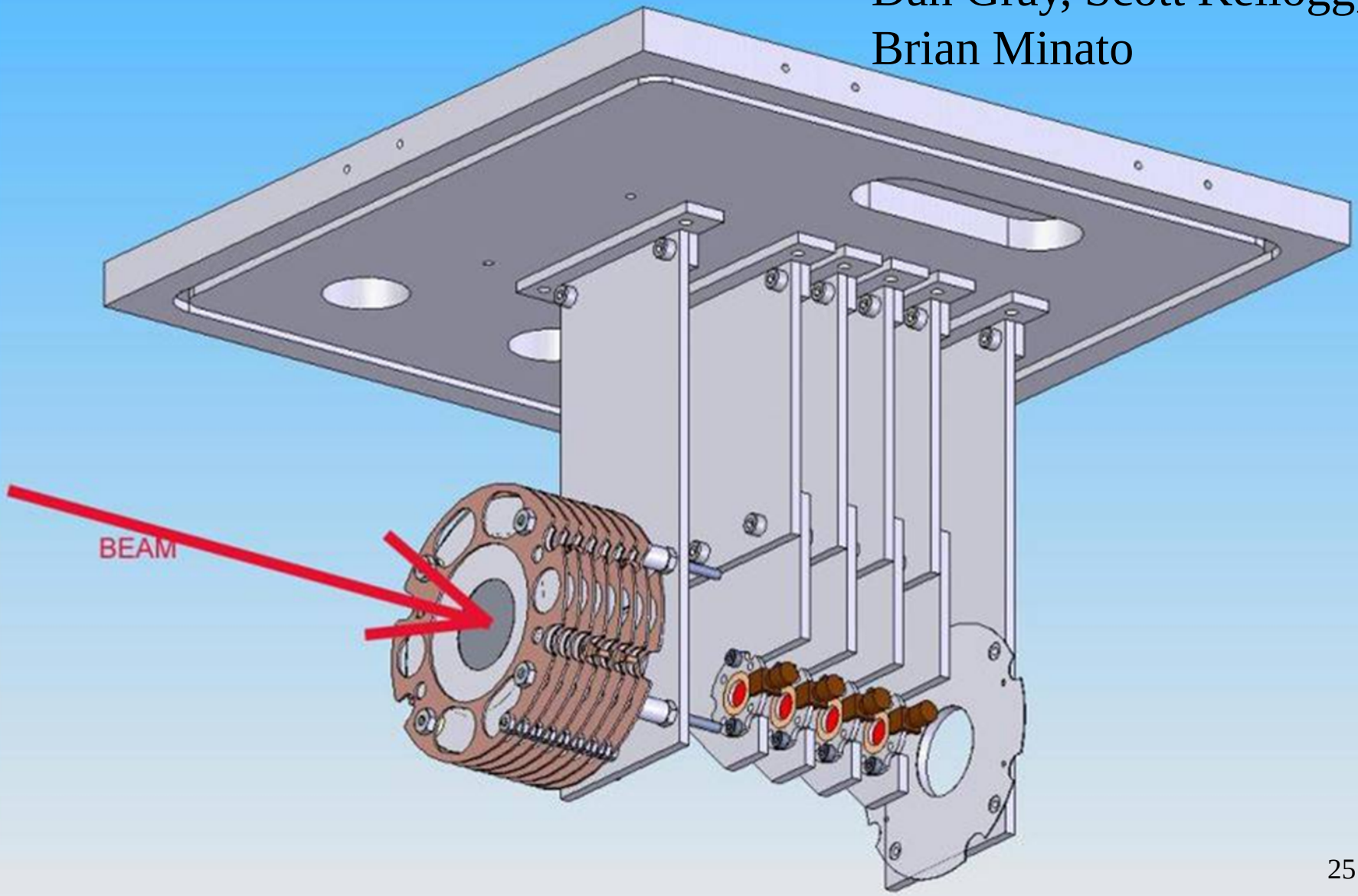
- One of TRIUMF's main beam lines
- Run 500 MeV protons up to 150 μA
- We run at lower beam currents
  - 4 – 40 nA
  - Gives 10^{15} – 10^{16} p/cm^2 per day
- Monitor flux/fluence with secondary emission monitors and Cyclotron "stripper" currents
- Final precise normalization will come from activation of Al foils installed with diamond detectors (in progress)
- 1-13 Sept 2010: ran 4 detectors beyond 2×10^{17} p/cm^2
  - All still alive and giving good signal/noise
  - "flat-line" (not quite) ≈ 5% of initial amplitude

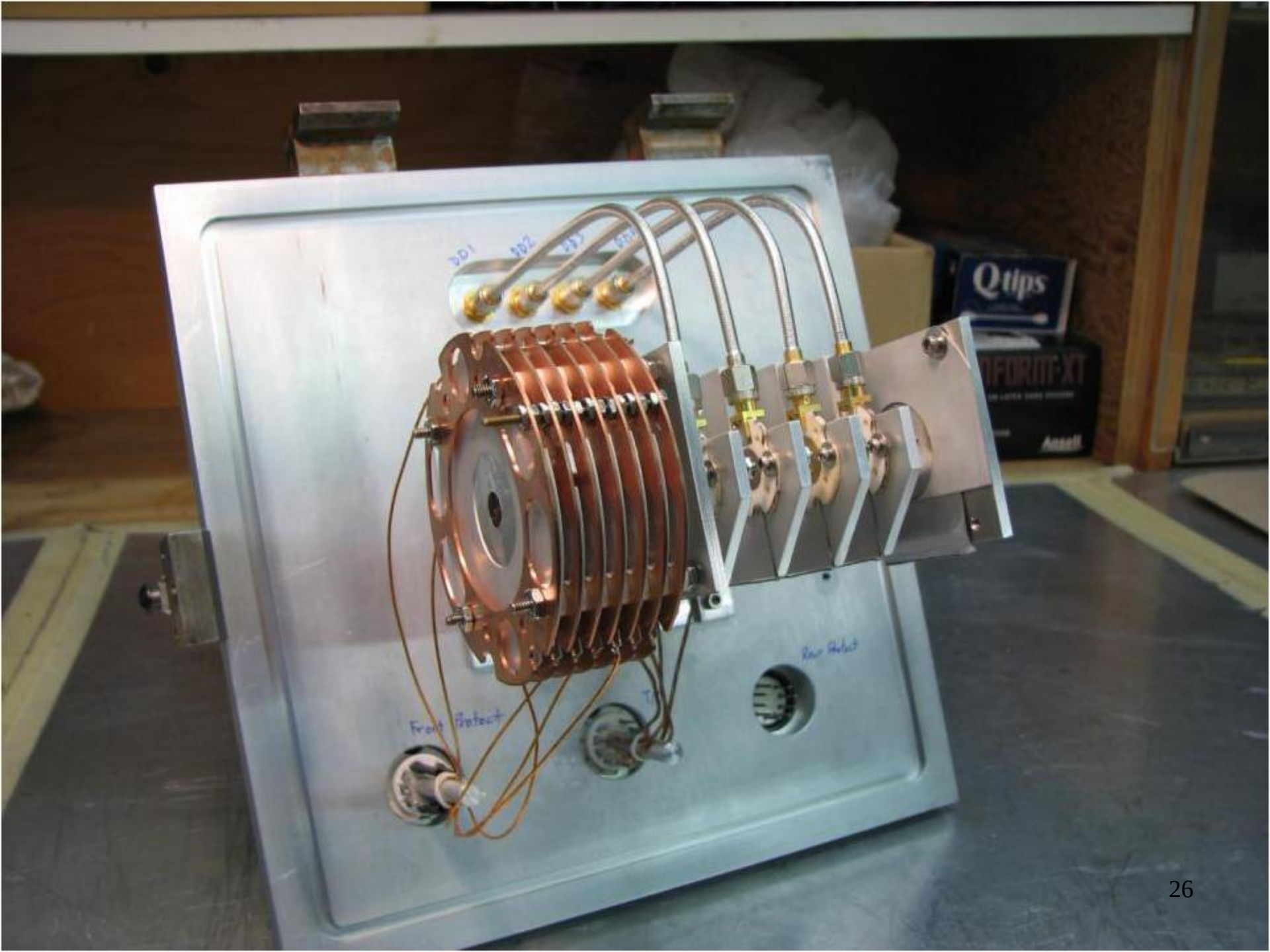
TRIUMF Beam Line 1A



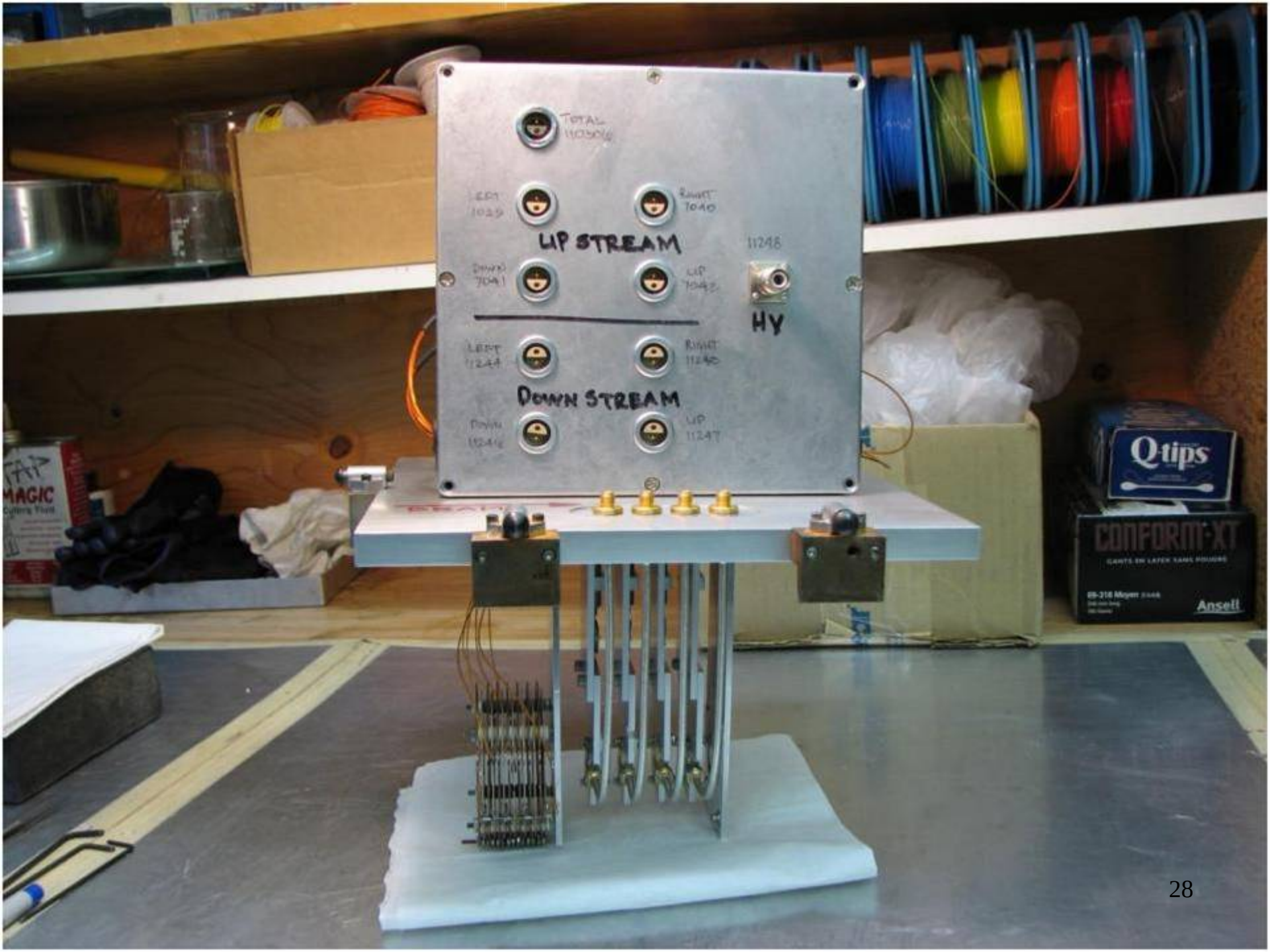
Beam Line 1A Setup

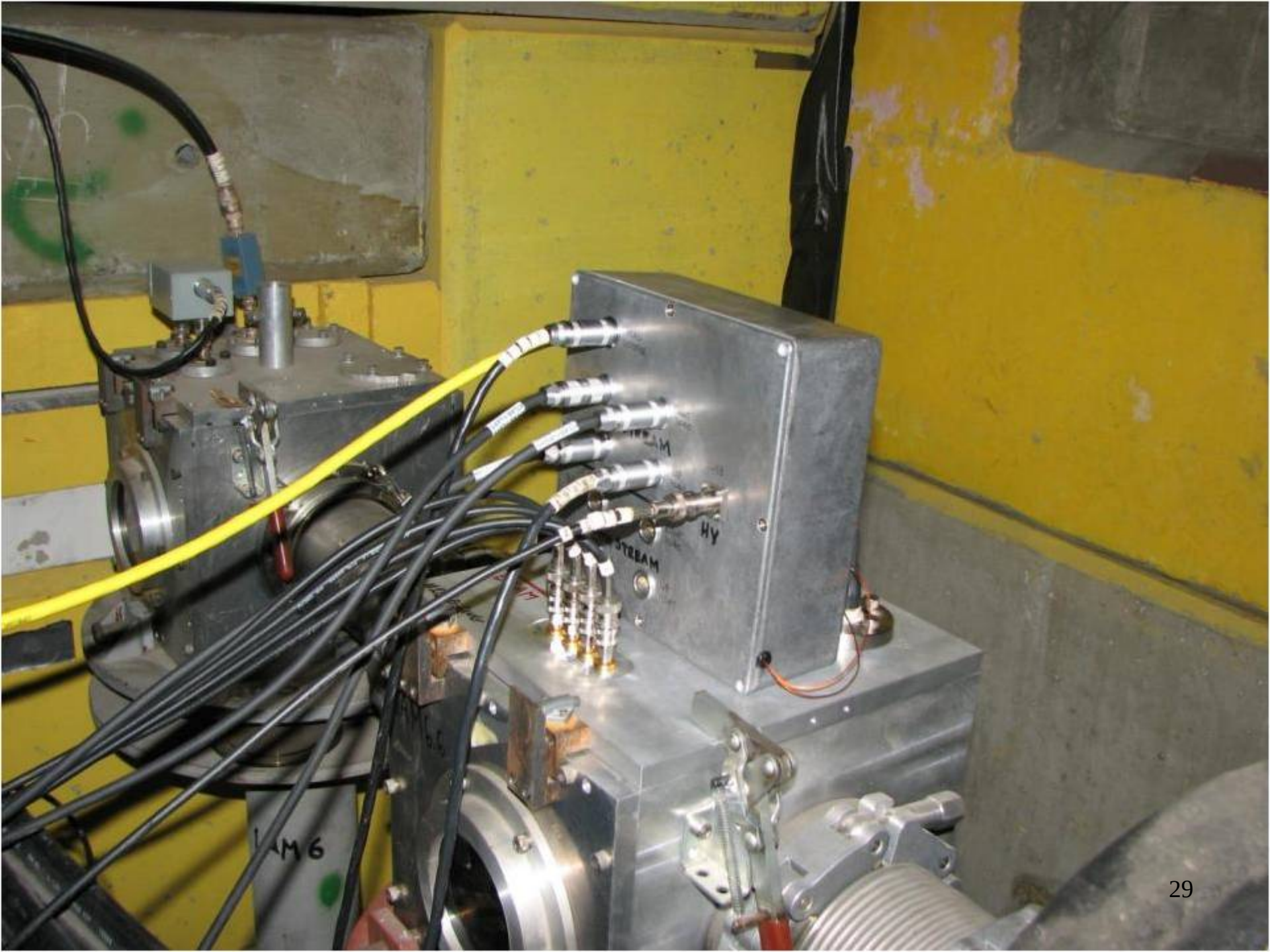
Dan Gray, Scott Kellogg,
Brian Minato



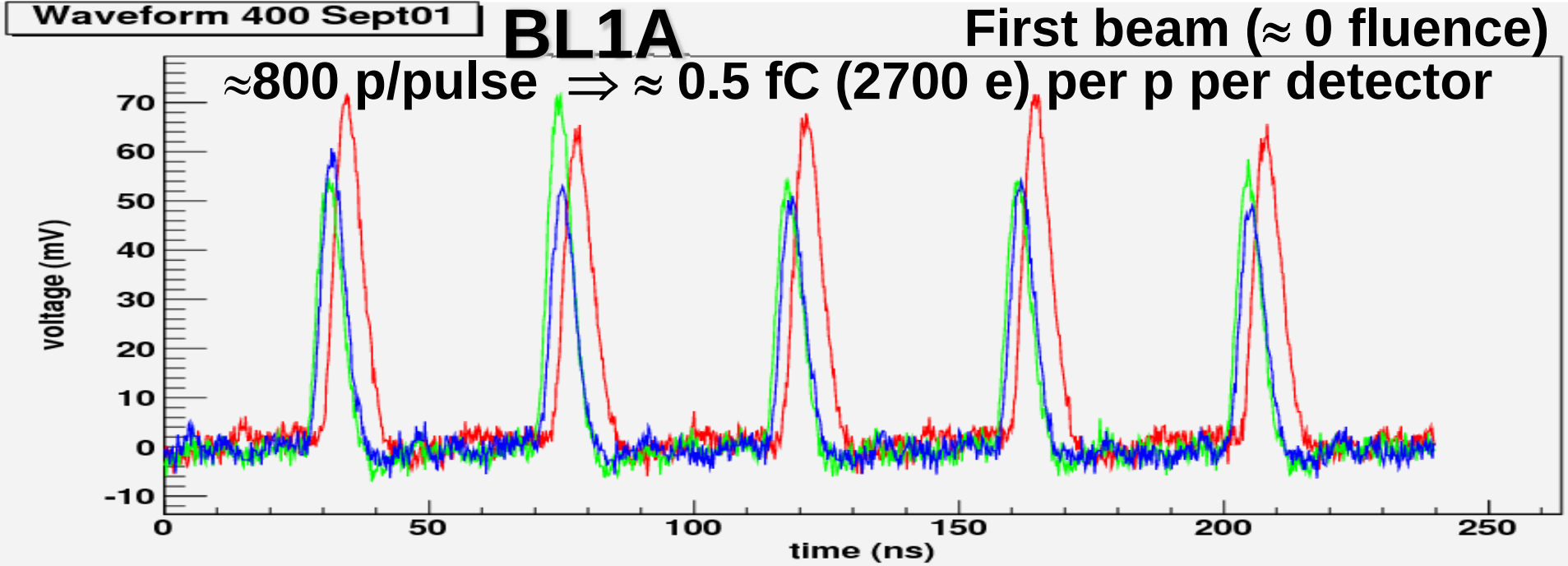

Qtips
Ansell
Front Protect
Rear Protect

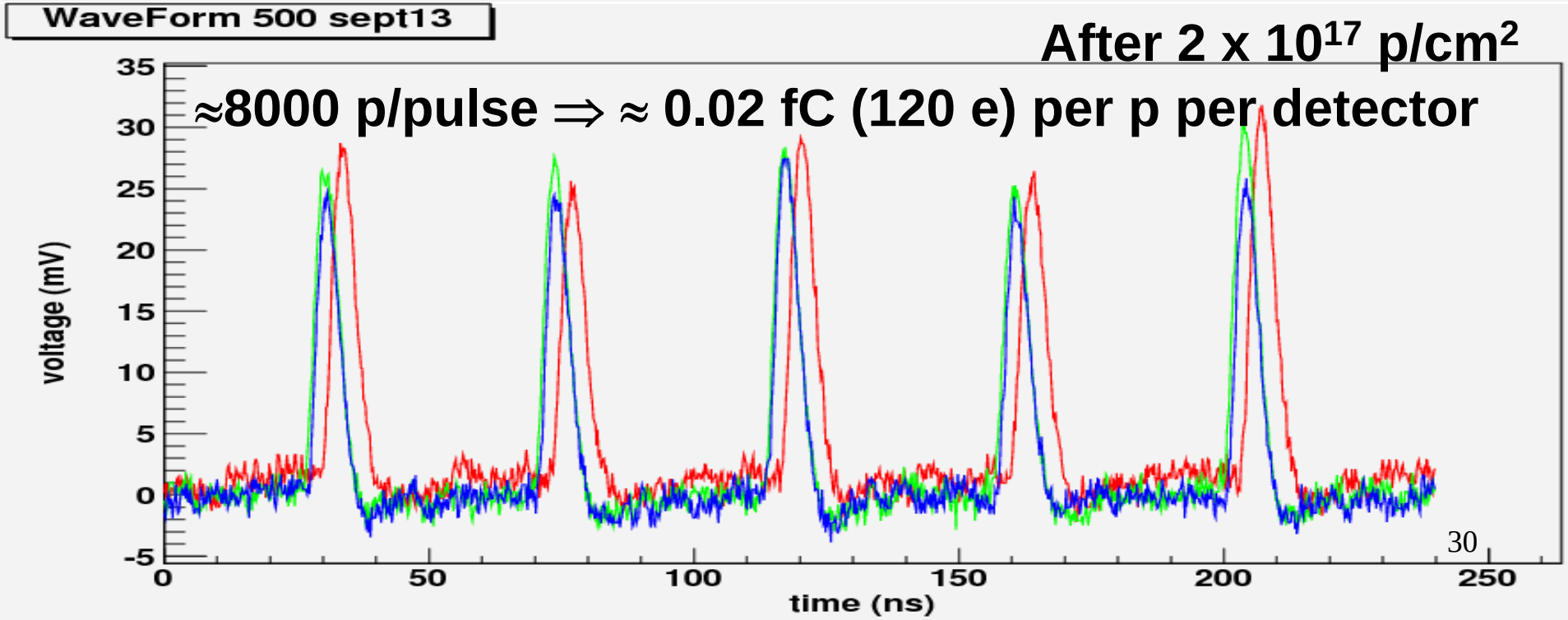

1
2
3
4


TOTAL
LEFT
RIGHT
UP STREAM
11248
DOWN
UP
HV
LEFT
RIGHT
DOWN STREAM
DOWN
UP
Q-tips
CONFORM-XT
Ansell


HY
STREAM
LAM 6

BL1A


Waveform 400 Sept01
First beam (≈ 0 fluence)
≈800 p/pulse ⇒ ≈ 0.5 fC (2700 e) per p per detector
voltage (mV)
70
60
50
40
30
20
10
0
-10
0
50
100
150
200
250
time (ns)

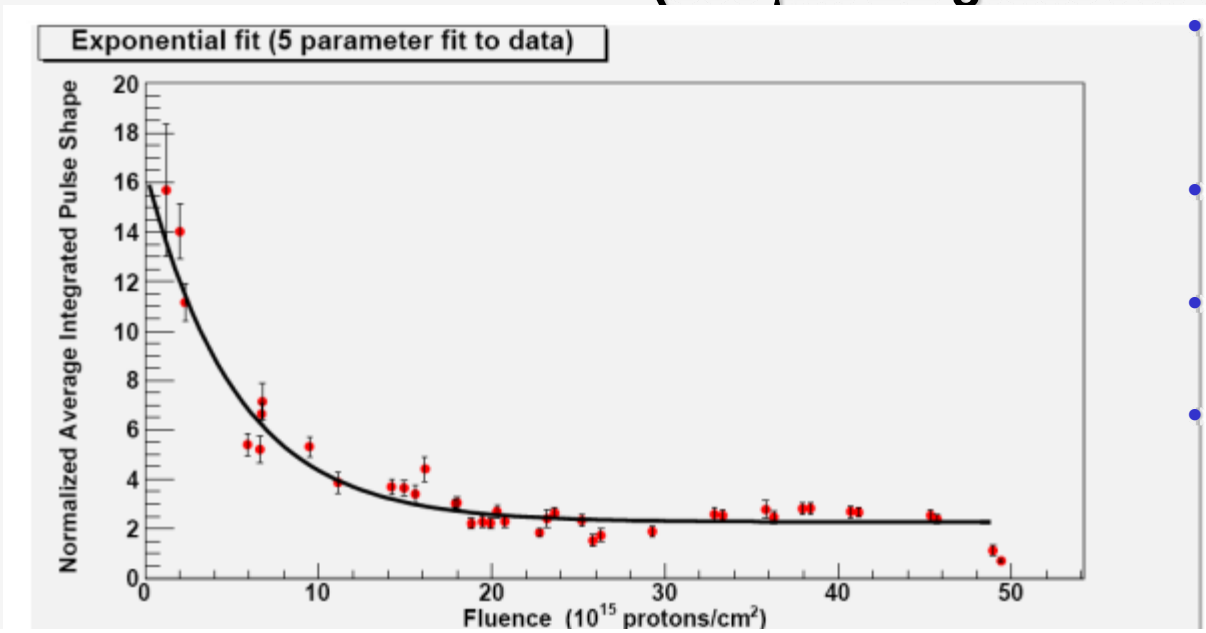

WaveForm 500 sept13
After 2 x 10^17 p/cm^2
≈8000 p/pulse ⇒ ≈ 0.02 fC (120 e) per p per detector
voltage (mV)
35
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
time (ns)

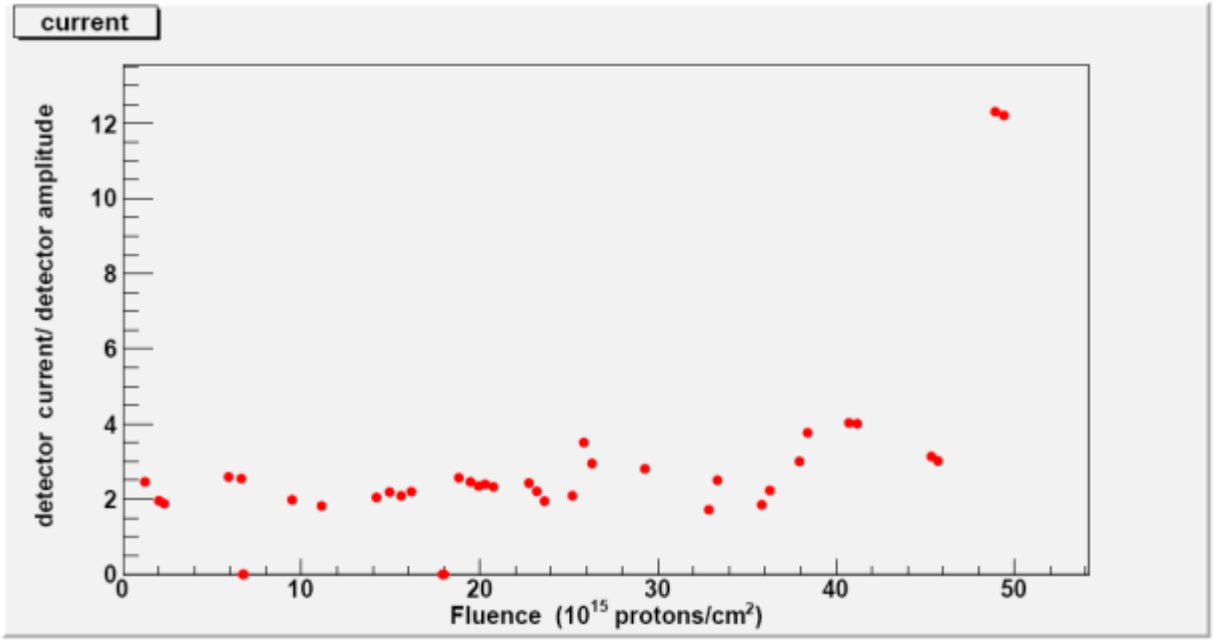
Typical Analysis

- Record both detector data and cyclotron RF clock with digital scope
  - Use relative timing to
    - Measure pedestal where no signal
    - Overlay pulses, build average pulse per channel
    - Measure pulse charge, height, width …
    - And plot normalized:
      - (pulse charge) / beam current vs. fluence
- Also record detector(s) bias (HV) current
  - Compare bias current to average pulse charge
  - Look at
    - bias current normalize to beam current vs. fluence
- Note: BL1A data only 2 weeks old …
  - Analysis is work in progress.

NBIF results

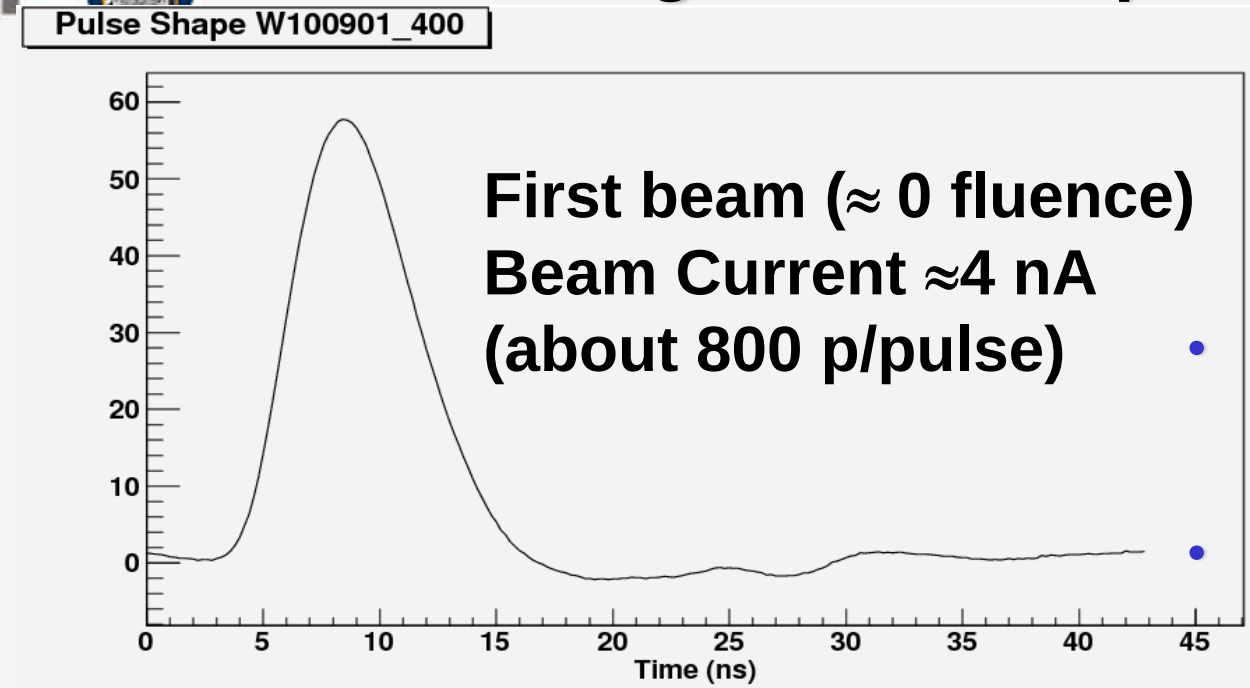
(800 μm EL-grade Au-Pt)

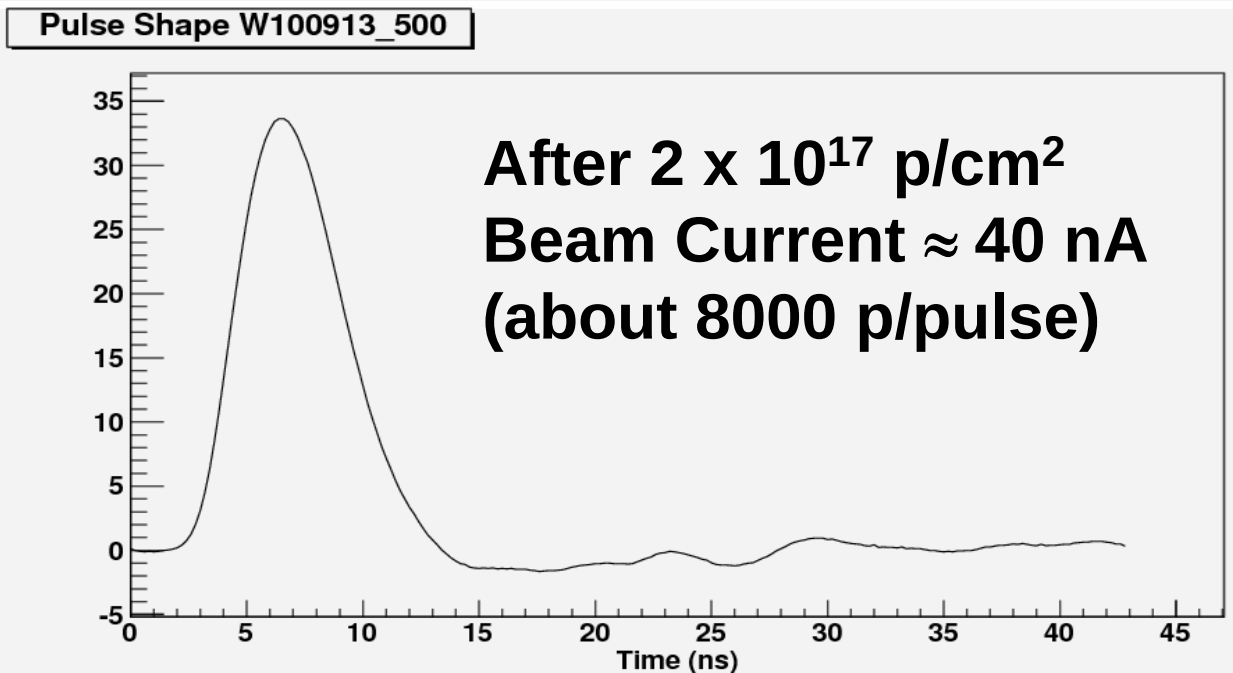




- Detector response reaches ~20% after ~2x10^{16} p/cm^2 (consistent with RD42)
- Response is then ~flat with fluence
- Bias current consistent with pulse charge x rate
- At ~ 0.5x10^{17} p/cm^2 see increase in dark current and now won't old bias voltage
  - Not sure why
  - Eg, cables, connectors in high fluence zone (not rad hard)
  - Also don't really know background field level
  - Will know more after detector assembly cool enough to dismantle for inspection/tests and irradiation foil analyzed

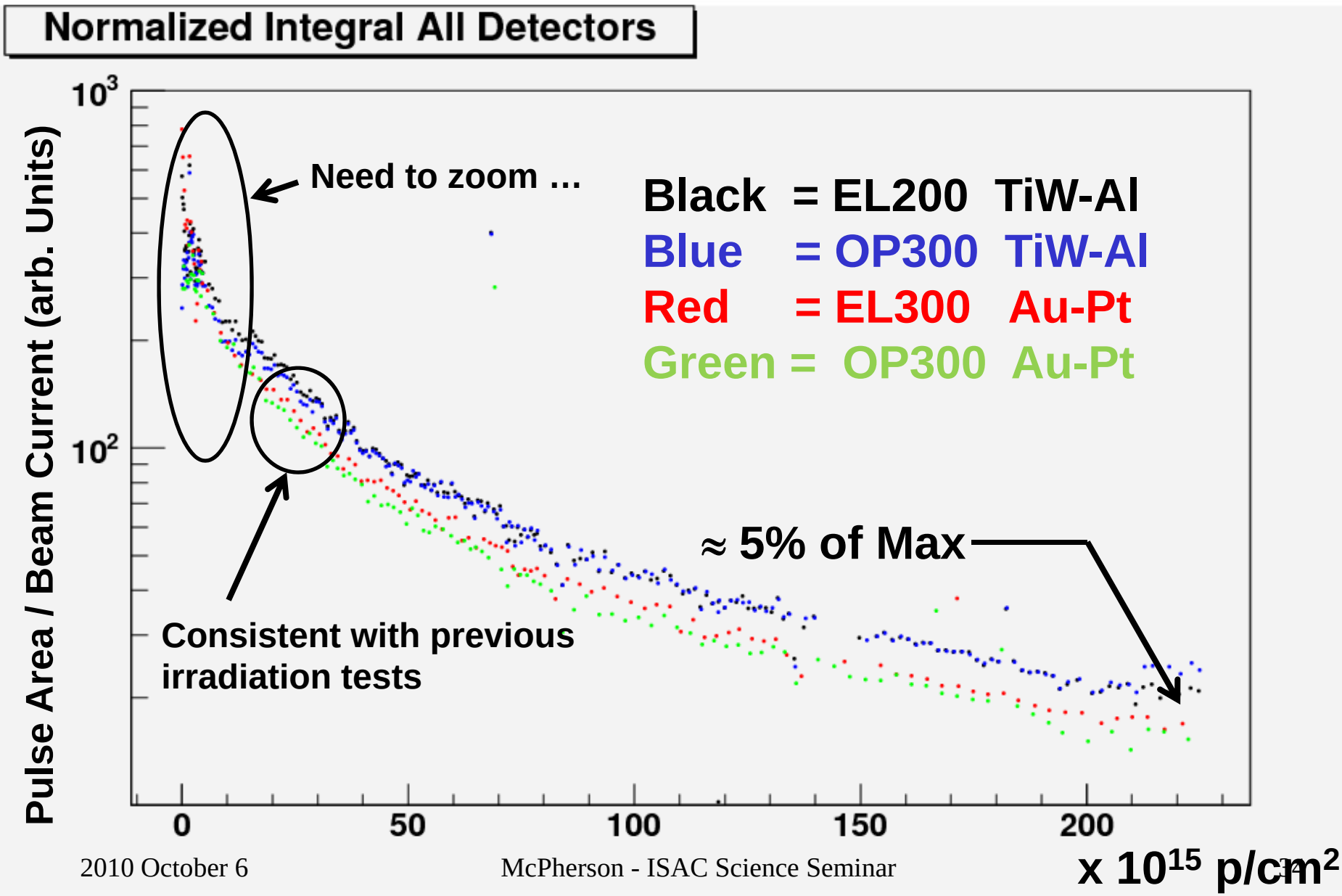
BL1A: Average Pulse Shape EL200 TiW-Al



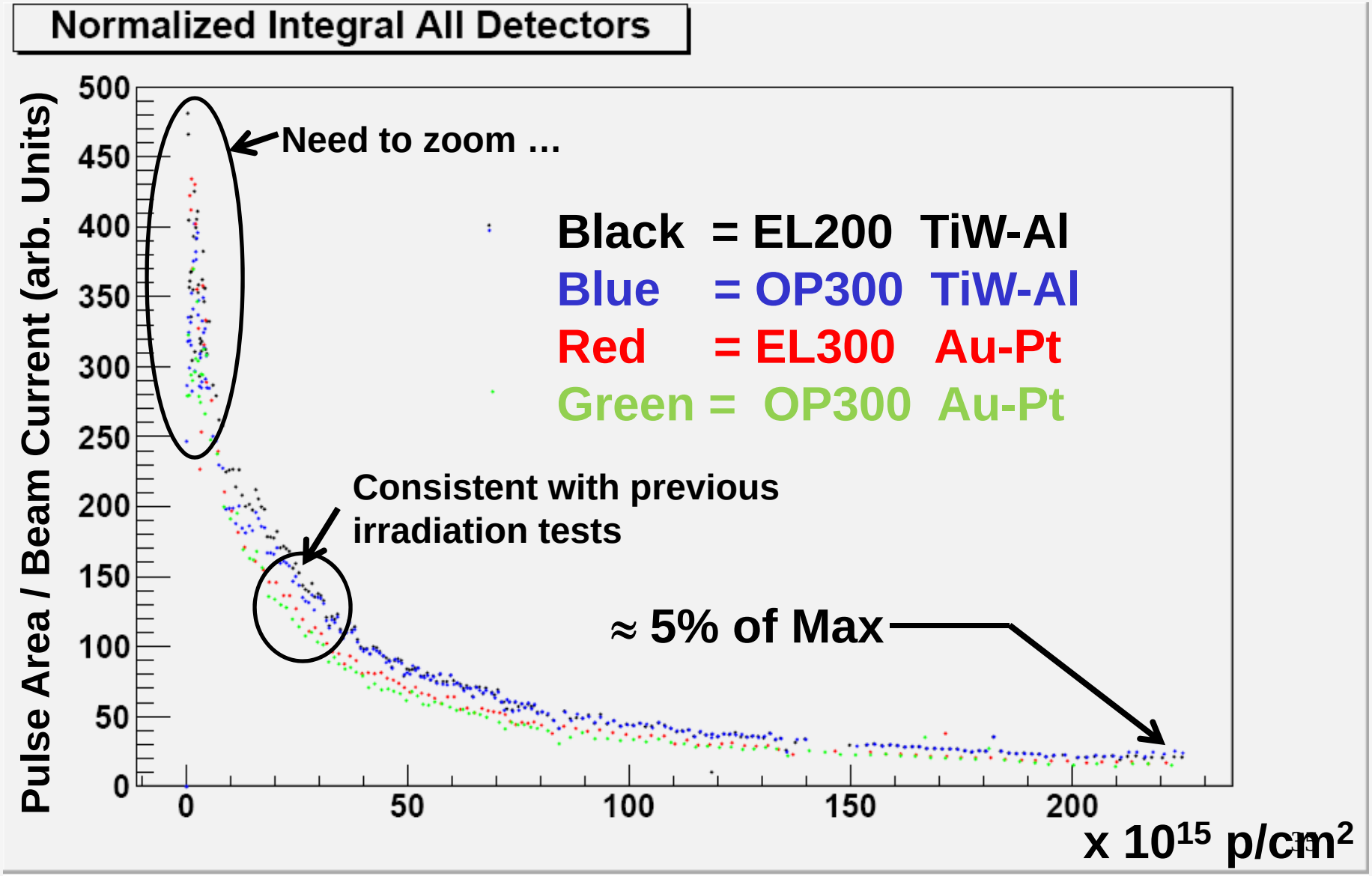


- Some evidence for pulse narrowing with irradiation
- Requires further study
  - Cyclotron pulse width structure
  - Relative phase of signal w.r.t. cyclotron RF
  - …

BL1A: response curve data (log scale)

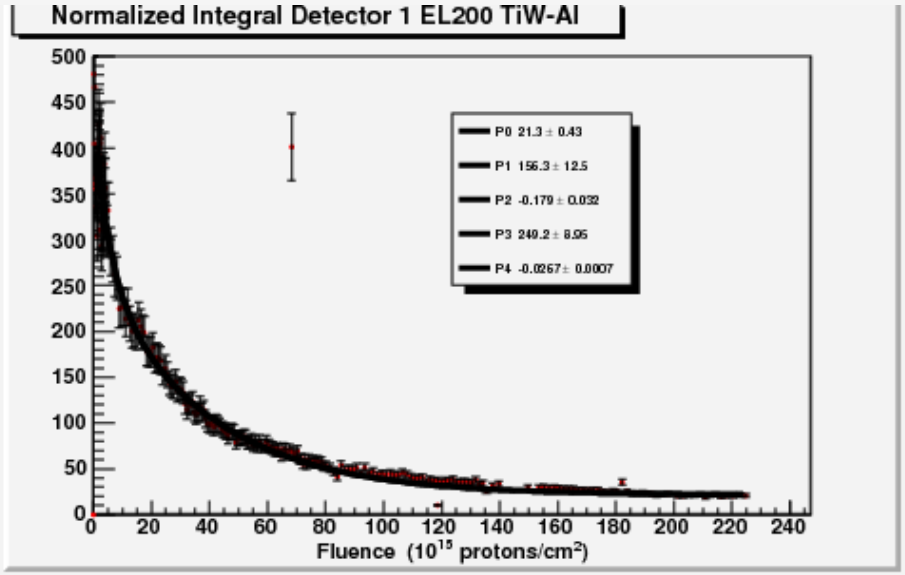


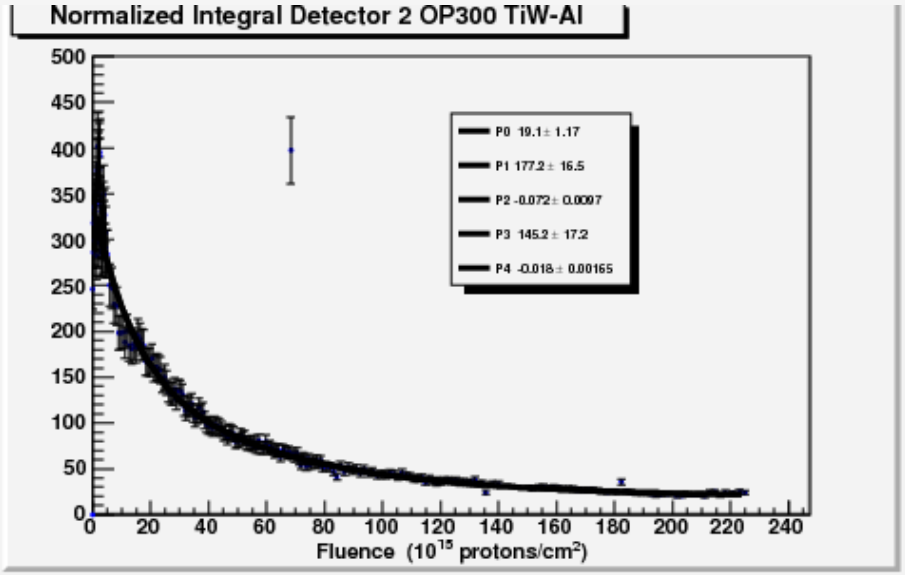
BL1A: response curve data (linear scale)

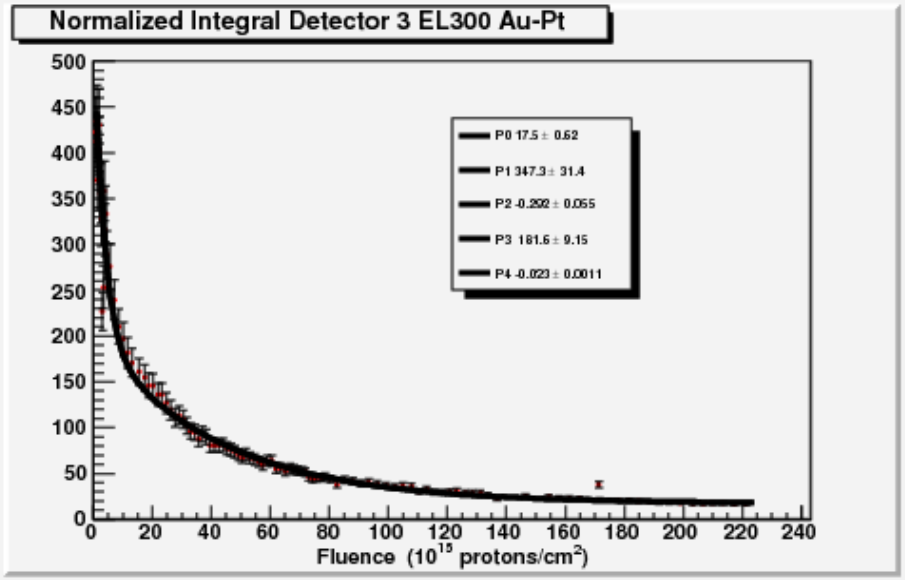


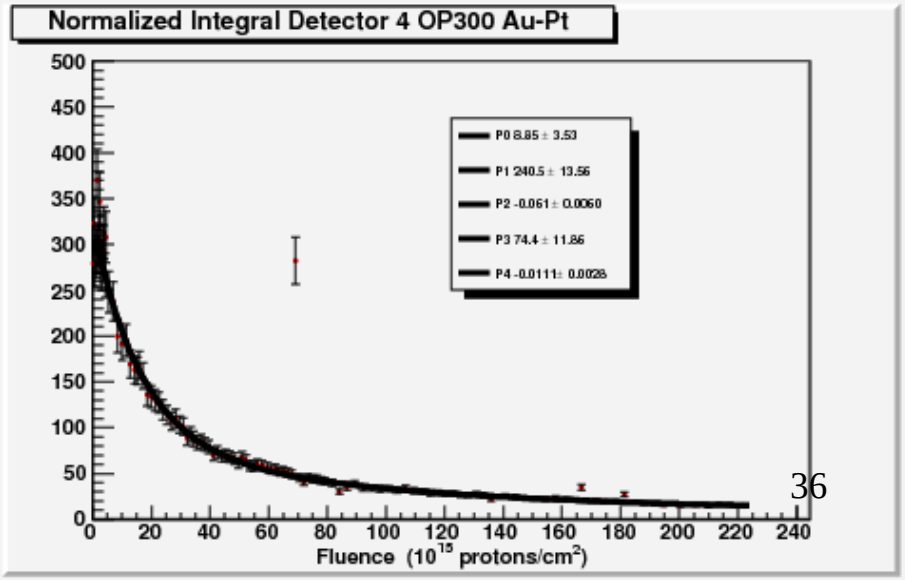
BL1A: fit double exponential

$$p_0 + p_1 e^{p_2 x} + p_3 e^{p_4 x}$$



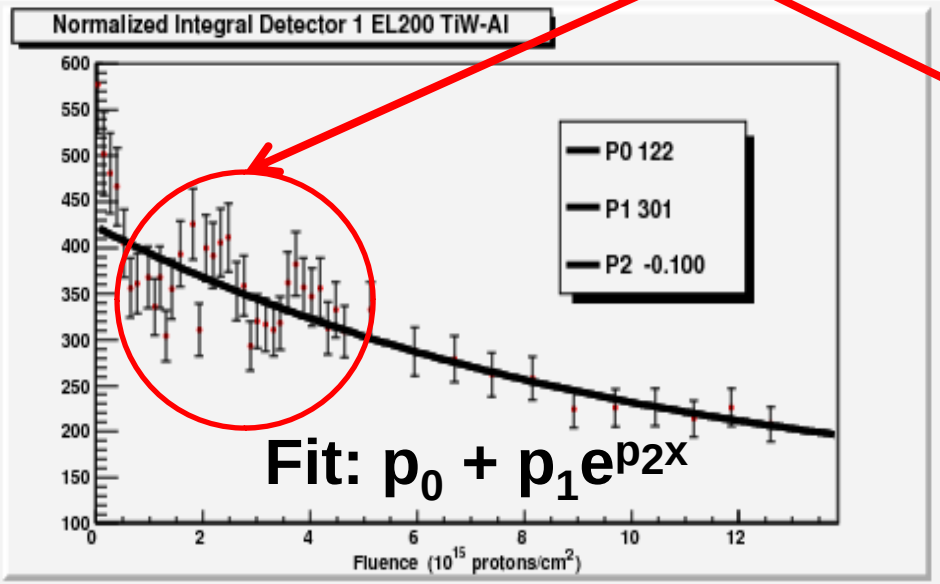


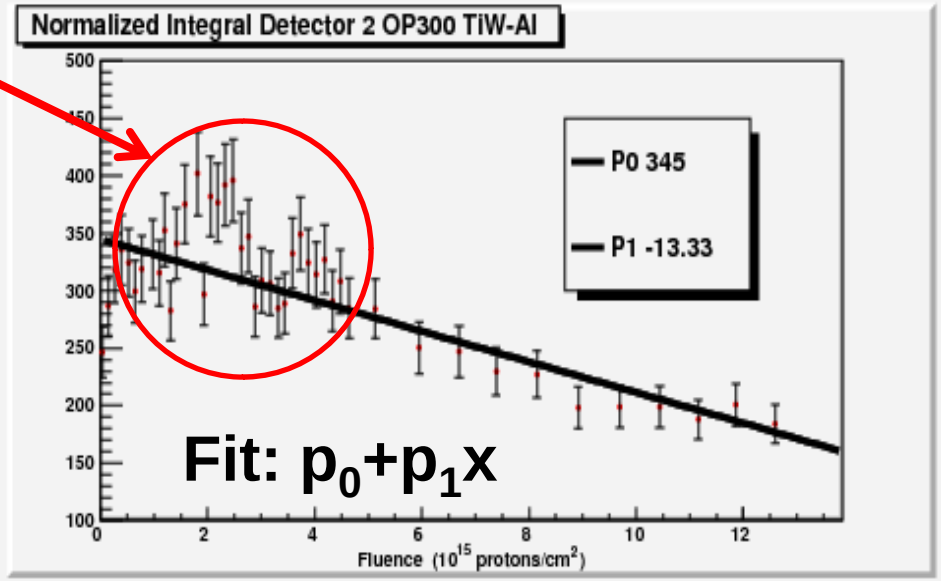


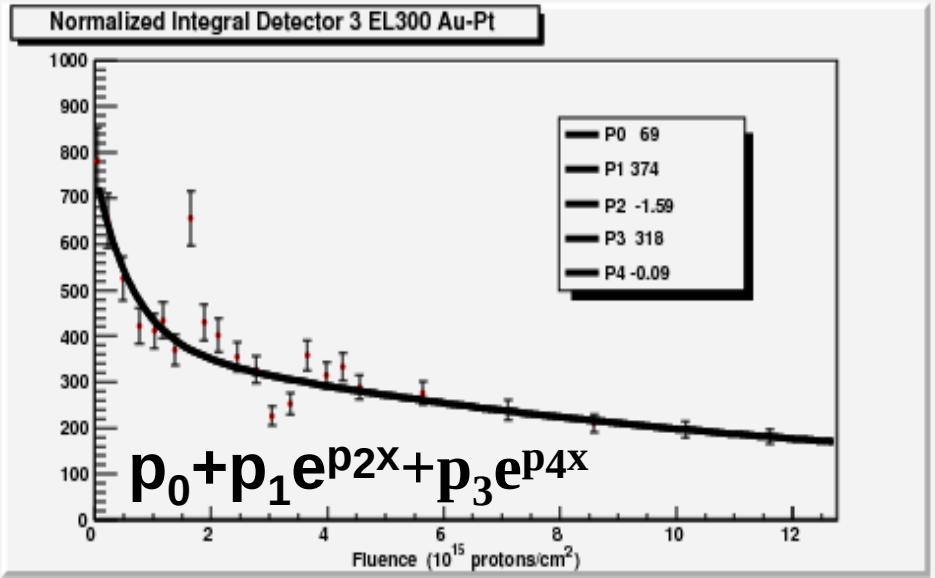


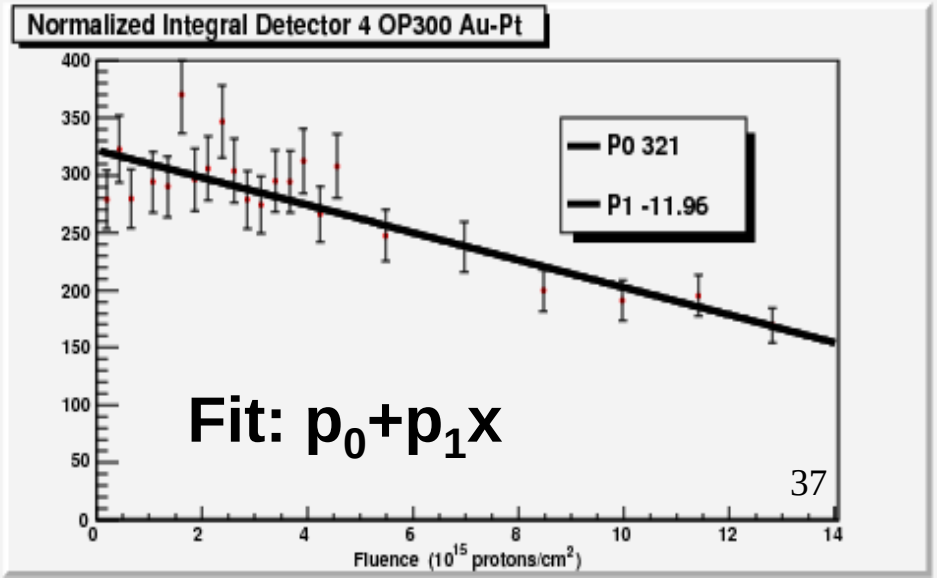
BL1A: zoom 1st 10^{16} p/cm^2

Scatter partly due to beam current logging granularity (in normalization)

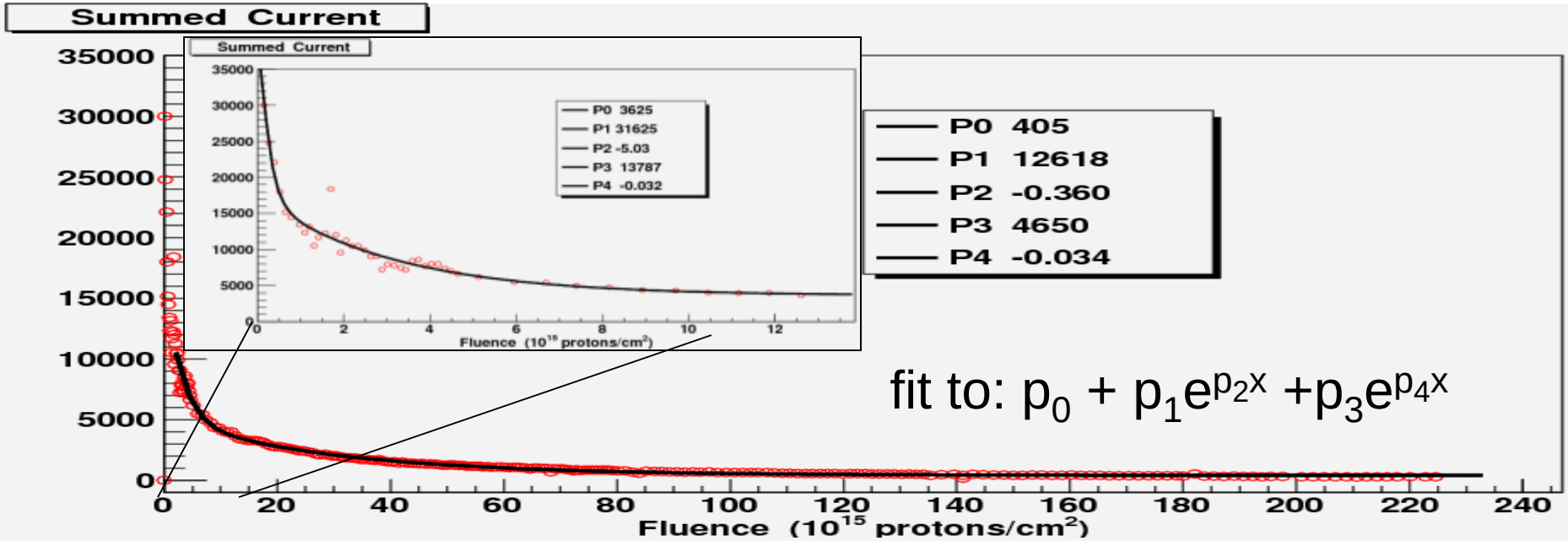




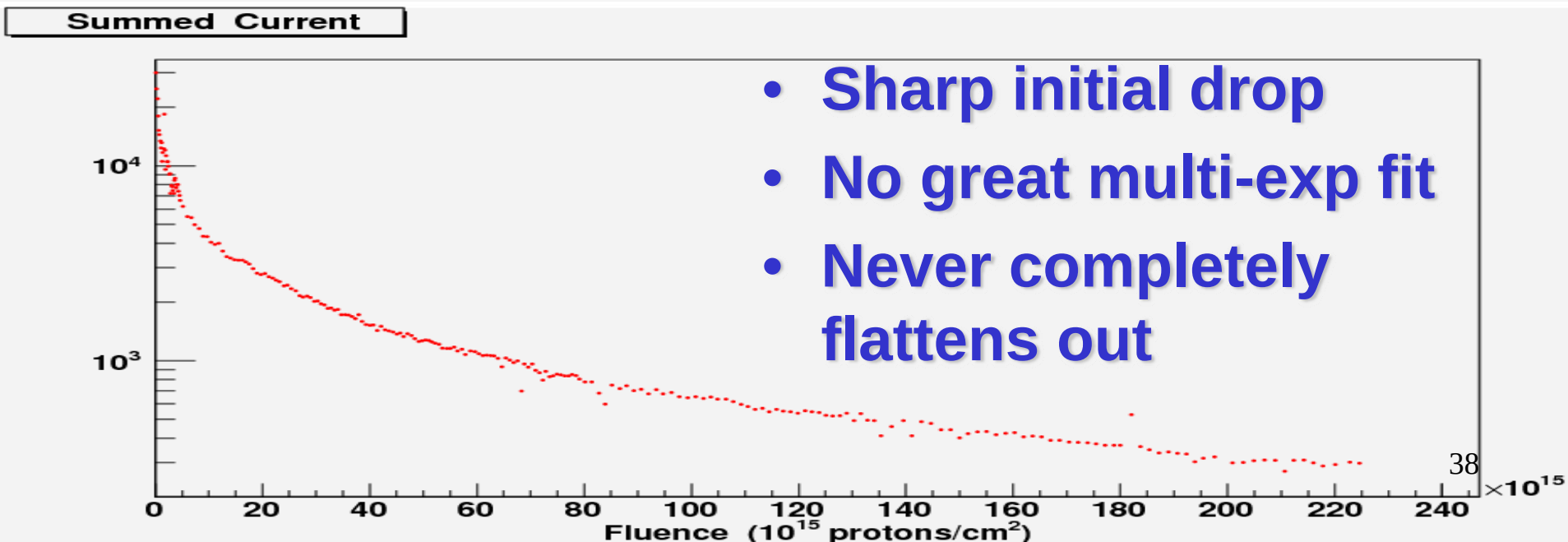




Detector bias current sum

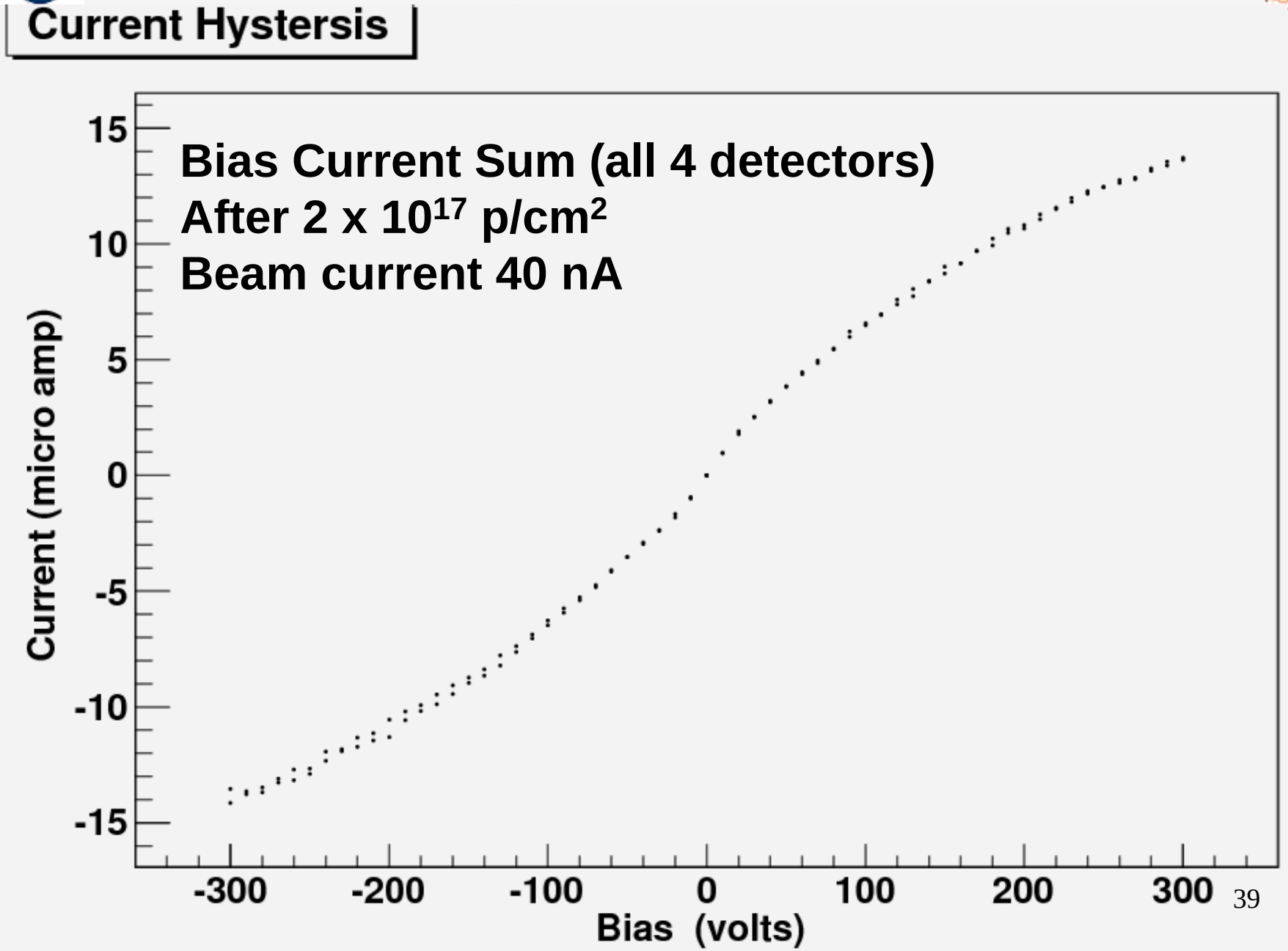


fit to: $p_0 + p_1 e^{p_2 x} + p_3 e^{p_4 x}$



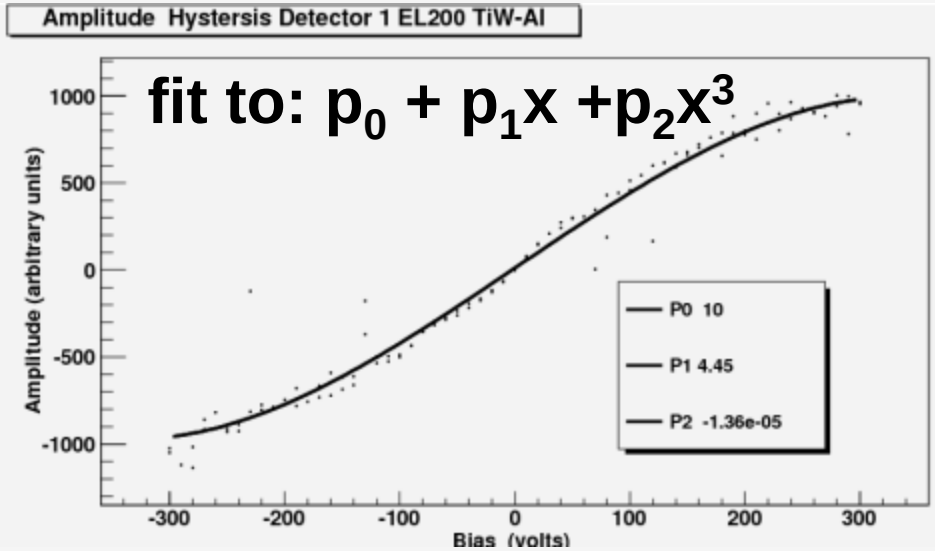
- **Sharp initial drop**
- **No great multi-exp fit**
- **Never completely flattens out**

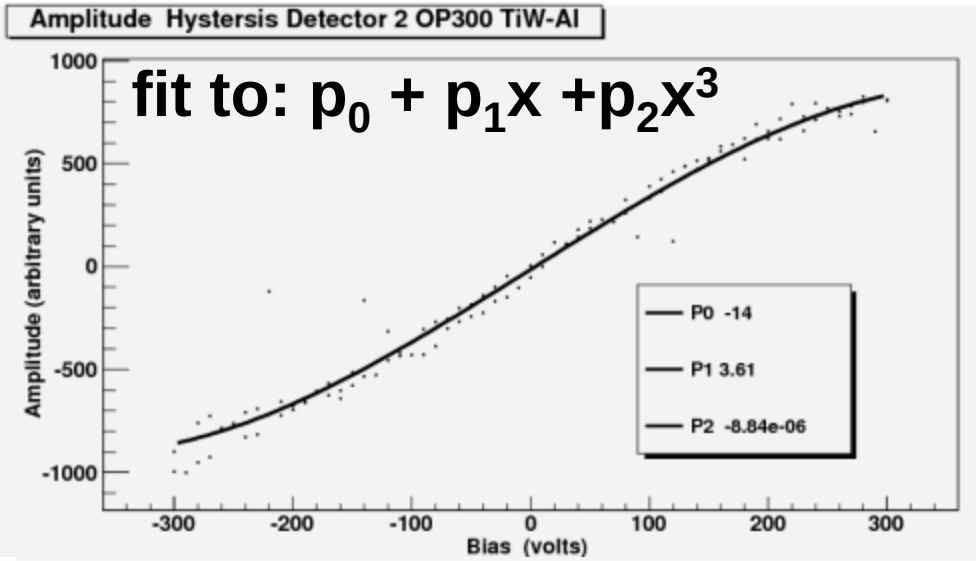
“Hysteresis” (HV scan) Bias Current

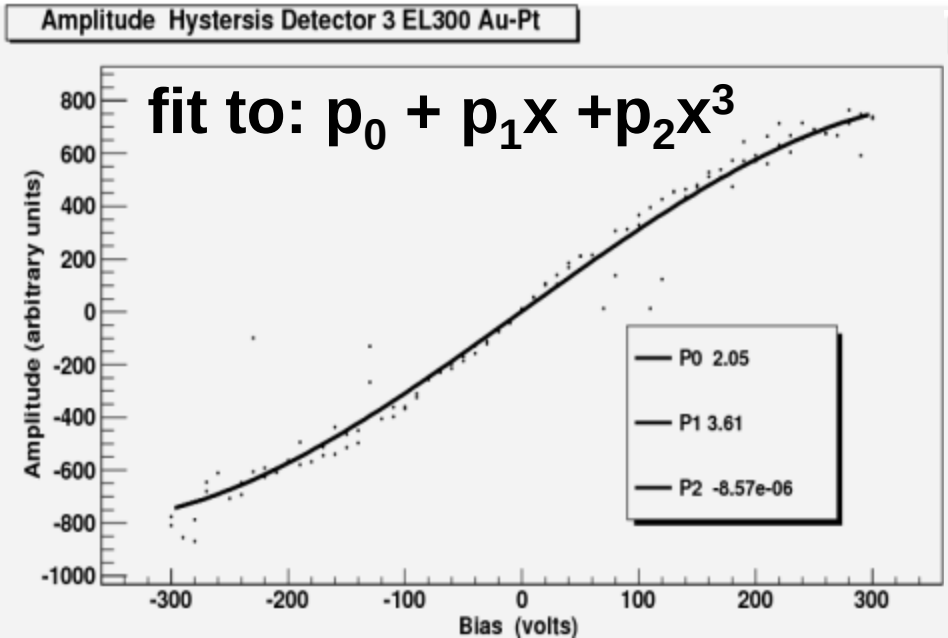


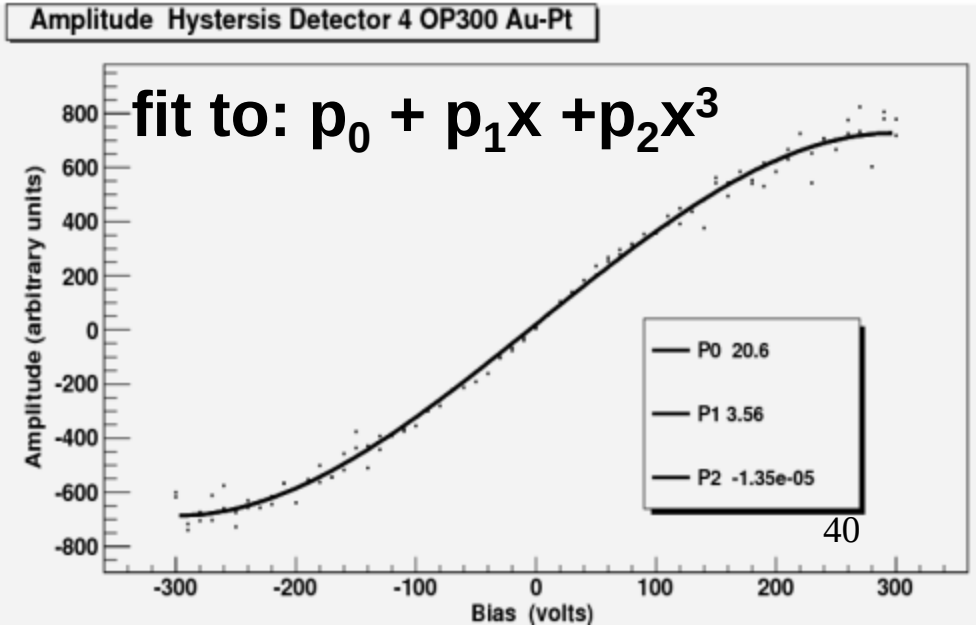
“Hysteresis” (HV scan): Pulse Charge

After 2 x 10^{17} p/cm^2 with Beam current 40 nA

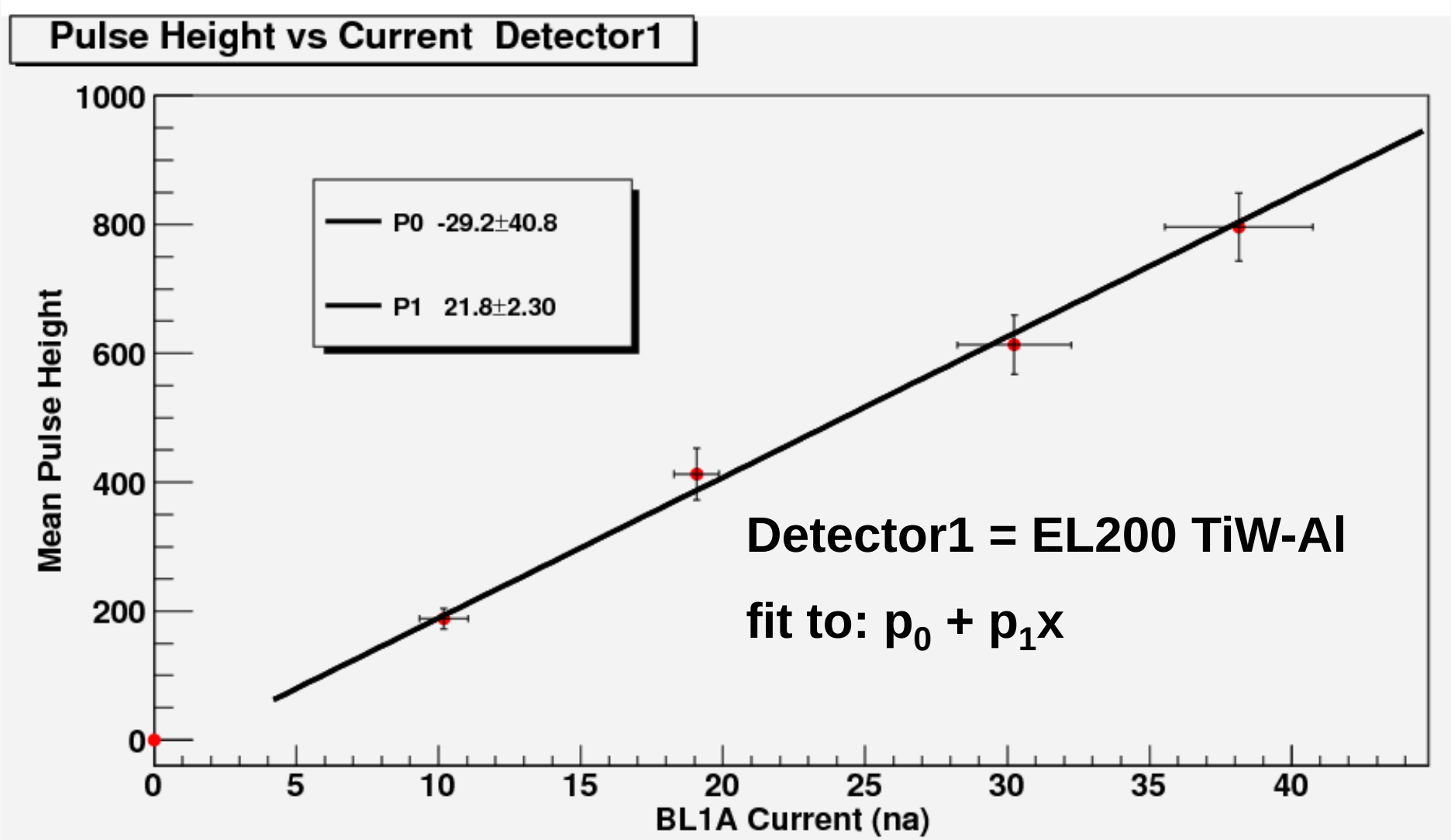






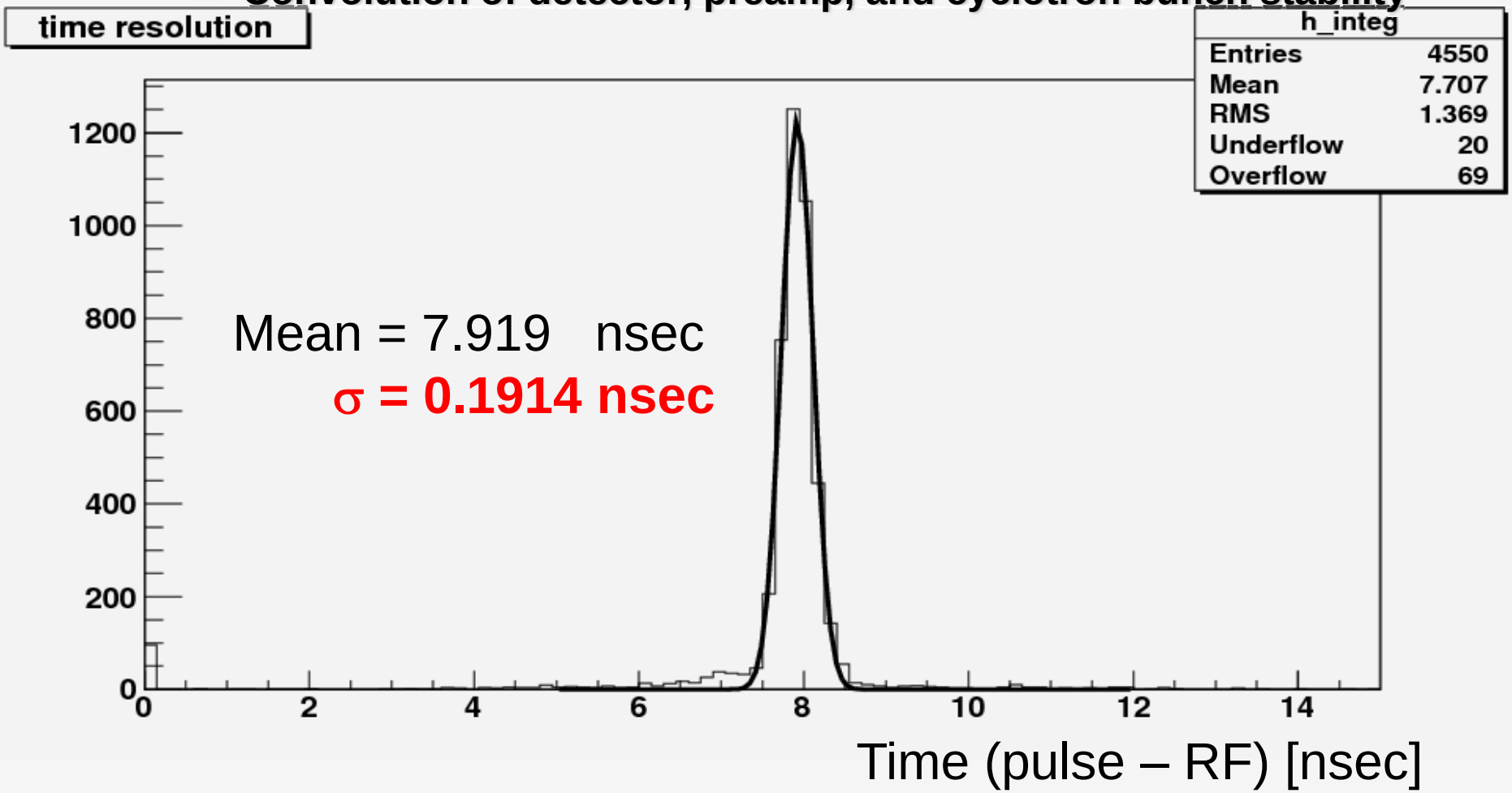


Linearity check: beam current scan after $2x10^{17}$ p cm^{-2} s^{-1} (last day)



Time resolution after 2 x 10^{17} p/cm^2 (last day)

- After full irradiation, check time stability
  - Take 10 "waveforms" (4550 pulses)
  - Plot pulse time – RF time ⇒ Upper limit on diamond time resolution
  - Note: "infinite stats" (≈8000 protons / pulse)
    - Convolution of detector, preamp, and cyclotron bunch stability



Summary

- Diamond irradiation scans to fluences relevant for sLHC ATLAS MiniFCal
- Pushed to proton fluences 10x larger than previous measurements
  - Detectors continued to run above 2 x 10^{17} p/cm^2 (10^{10} RAD, 60,000 kGy)
  - Amplitude ≈ 5% of initial
  - No evidence of heating observed
  - Detector timing remained good (< 200 psec) throughout test
- Do not see enormous differences among different detectors
  - EL seems to have faster initial drop than OP, merging @ high fluence
  - Also that Ti-based metalization a bit more robust that Au-Pt
- Analysis continuing
  - Precise fluence normalization with activation foils, pulse shape/timing evolution analysis, detailed comparisons of different detectors…
- Future tests
  - Monitor detectors from BL1A – look for annealing?
  - Spatial uniformity tests (M11 at TRIUMF?)
  - Multi-detectors running together to test ganging schemes for MiniFCal
  - Lower energy protons to test damage cut-off thresholds, possibly with Montreal van der graaf which runs 1-11 MeV
- Neutron tests: reactor? (exploring use of Dubna reactor)