Diamond Monitors for Beam Monitoring

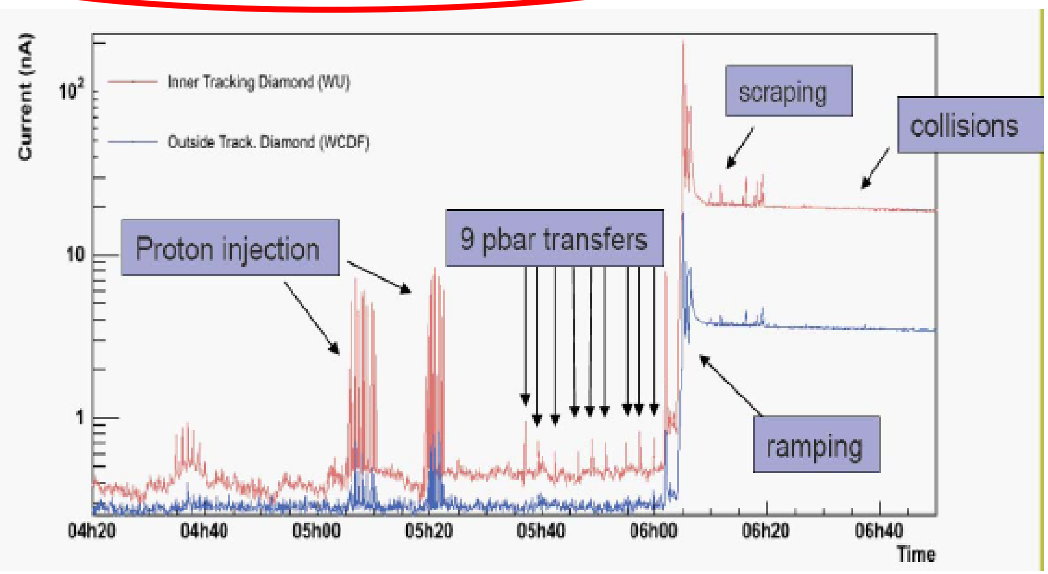
Bernd Dehning

CERN BE/BI

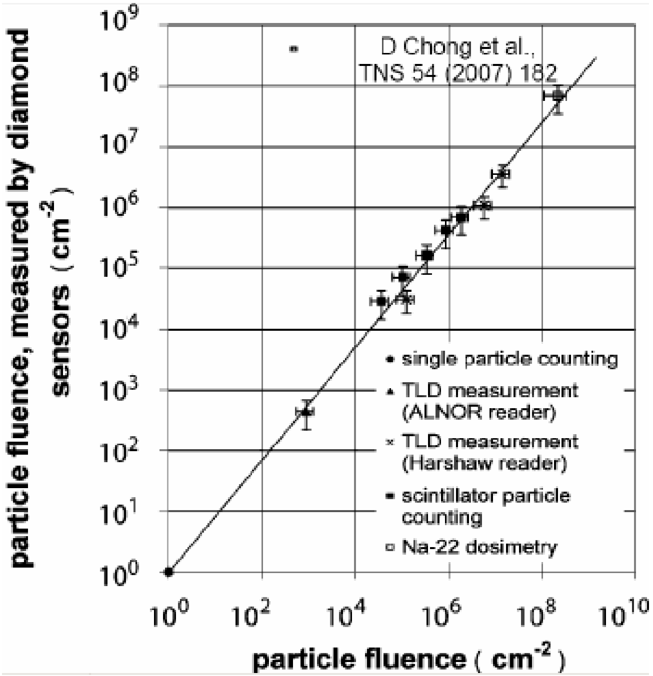
Why CVD Diamond?

- BLM ionisation chambers too big to be installed inside CMS
  - 9cm diameter, 60cm long
- CVD Diamond is now standard choice at other experiments
  - installed in CDF, BaBar, Belle, ZEUS
- Relative flux monitors
- Radiation hard - tolerant beyond LHC nominal luminosity close to IP
- Low maintenance, constant operating conditions, relatively insensitive to environmental conditions, compact size
- Linear response to particle flux

1. **Nano second response time**
2. **Large dynamic range**
3. **Operation at 1.8 Kelvin**

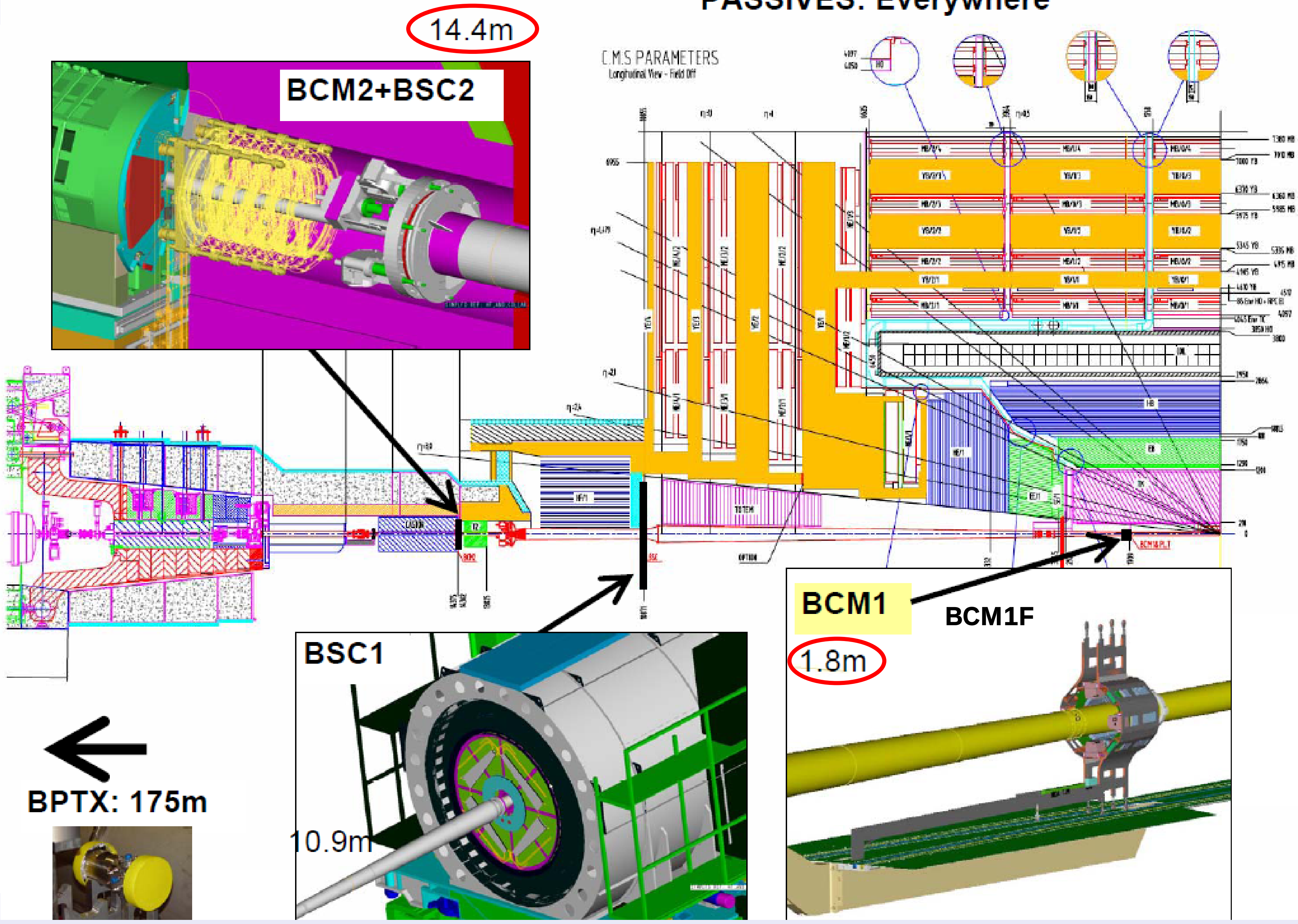


CDF pCVD diamonds at r=3cm and r=10.7cm

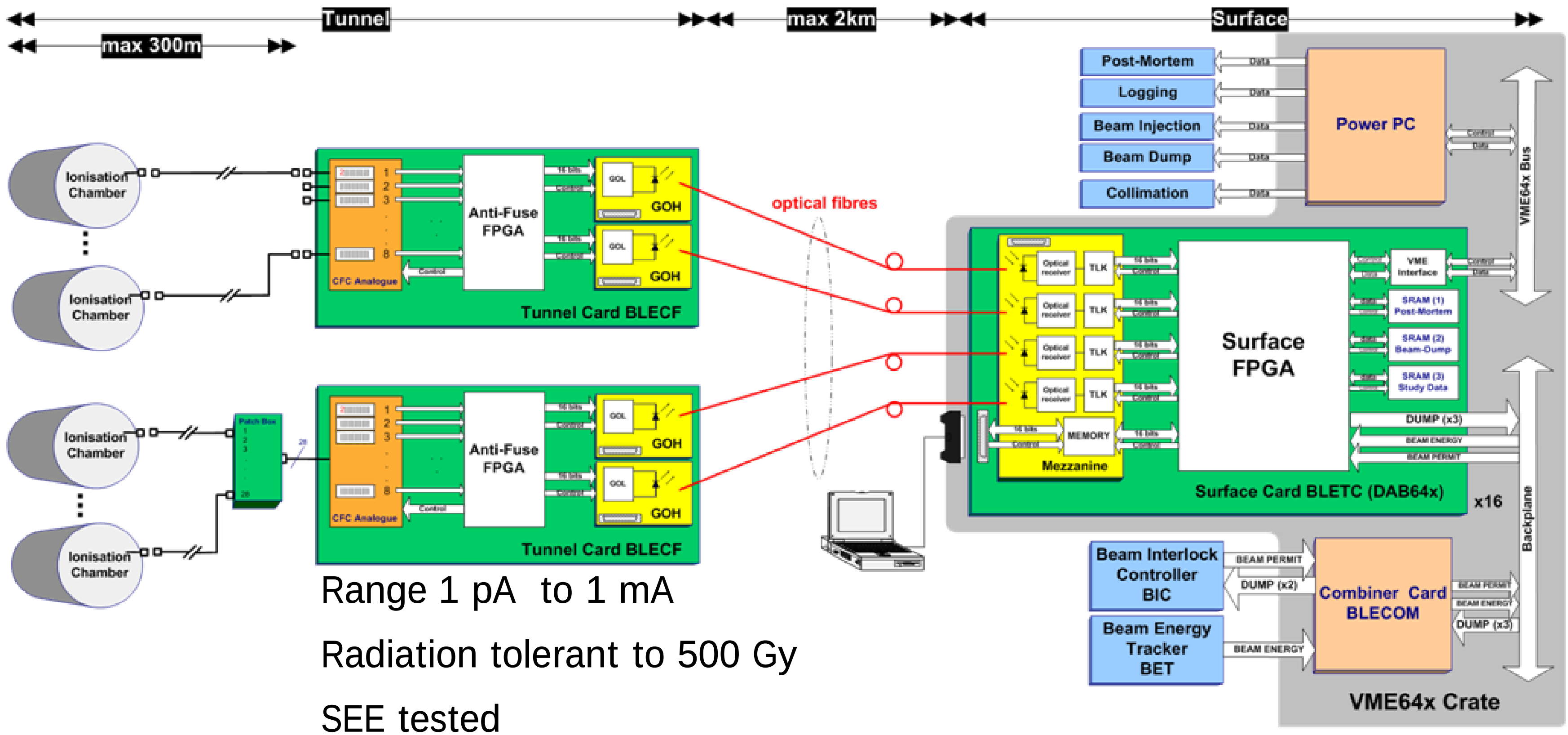


RADMON: 18 monitors around UXC

PASSIVES: Everywhere



The BLM Acquisition System (ALL Experiments and LHC)



Range 1 pA to 1 mA

Radiation tolerant to 500 Gy

SEE tested

Analog front-end FEE

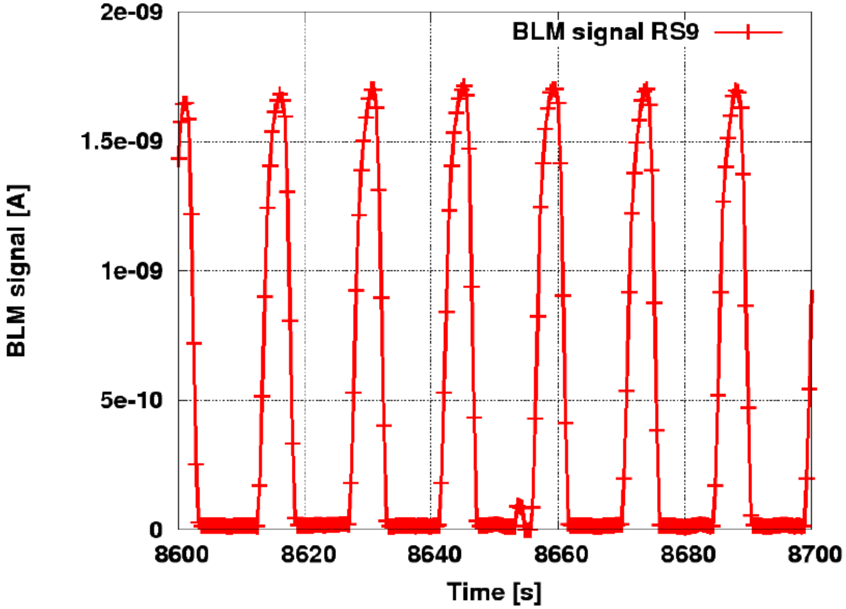
- **Current to Frequency Converters (CFCs)**
- **Analogue to Digital Converters (ADCs)**
- **Tunnel FPGAs:**
  Actel's 54SX/A radiation tolerant.
- **Communication links:**
  Gigabit Optical Links.

Real-Time Processing BEE

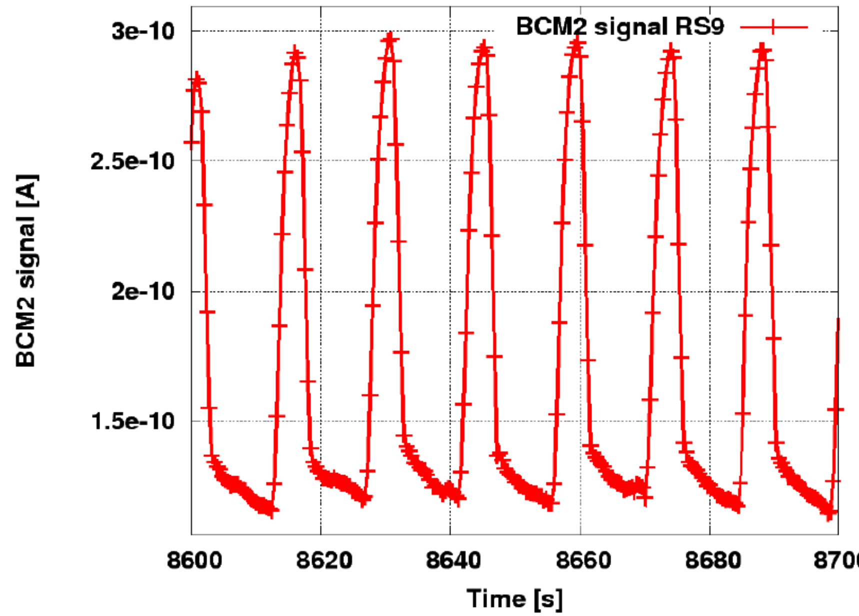
- **FPGA Altera's Stratix EP1S40 (**medium size, SRAM based**)**
- **Mezzanine card for the optical links**
- **3 x 2 MB SRAMs for temporary data storage**
- **NV-RAM for system settings and threshold table storage**

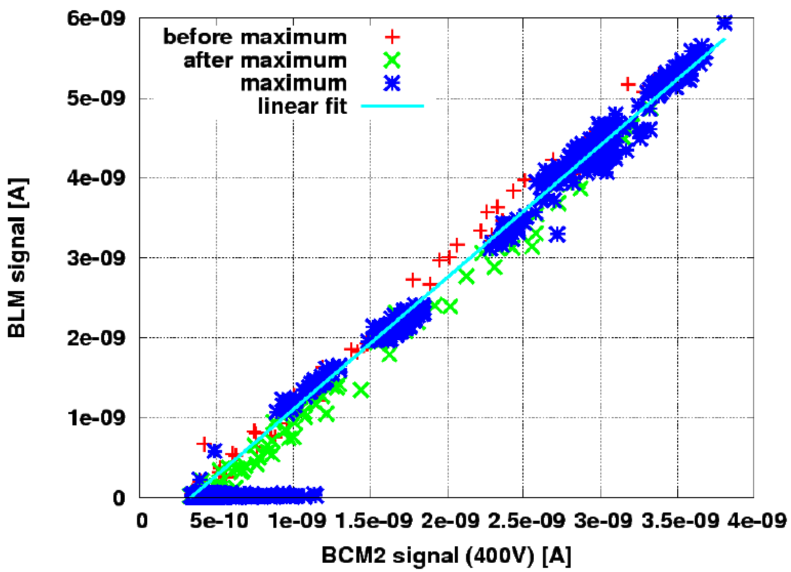
Ionisation Chamber and pCVD Comparison

Ionisation chamber



Diamond

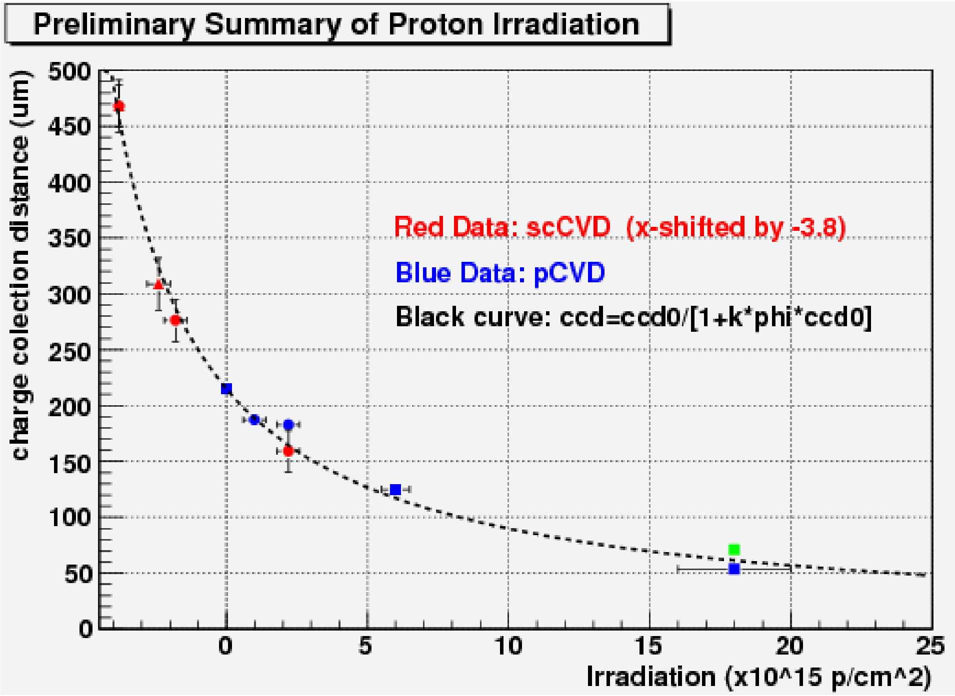


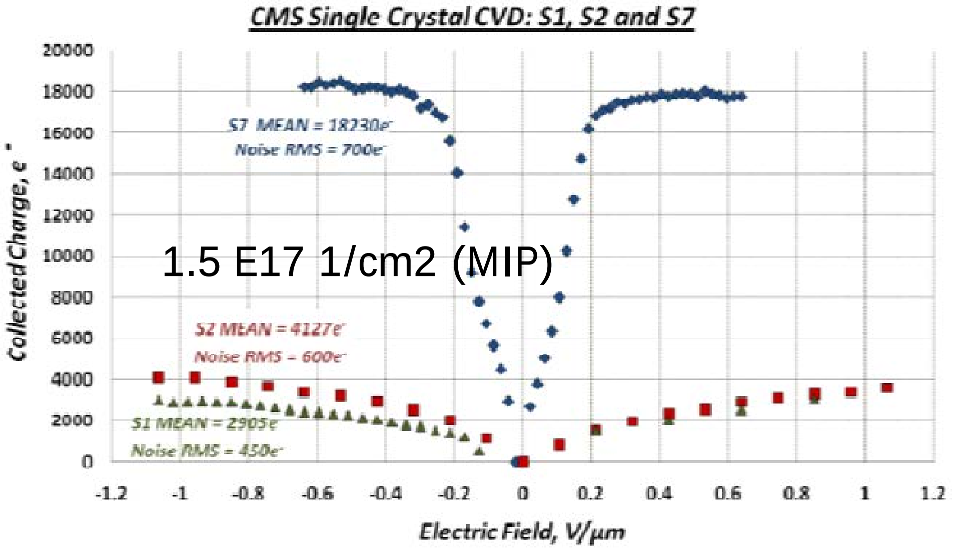


1. pCVD shows after pulse some long tails
2. Ionisation chamber shows no tail
3. Leakage current
   1. Ionisation chamber < 1pA
   2. CMS pCVDs most few tenth of pA one up to 1 nA (S. Mueller)

CMS: S. Mueller

Diamond and Radiation Hardness

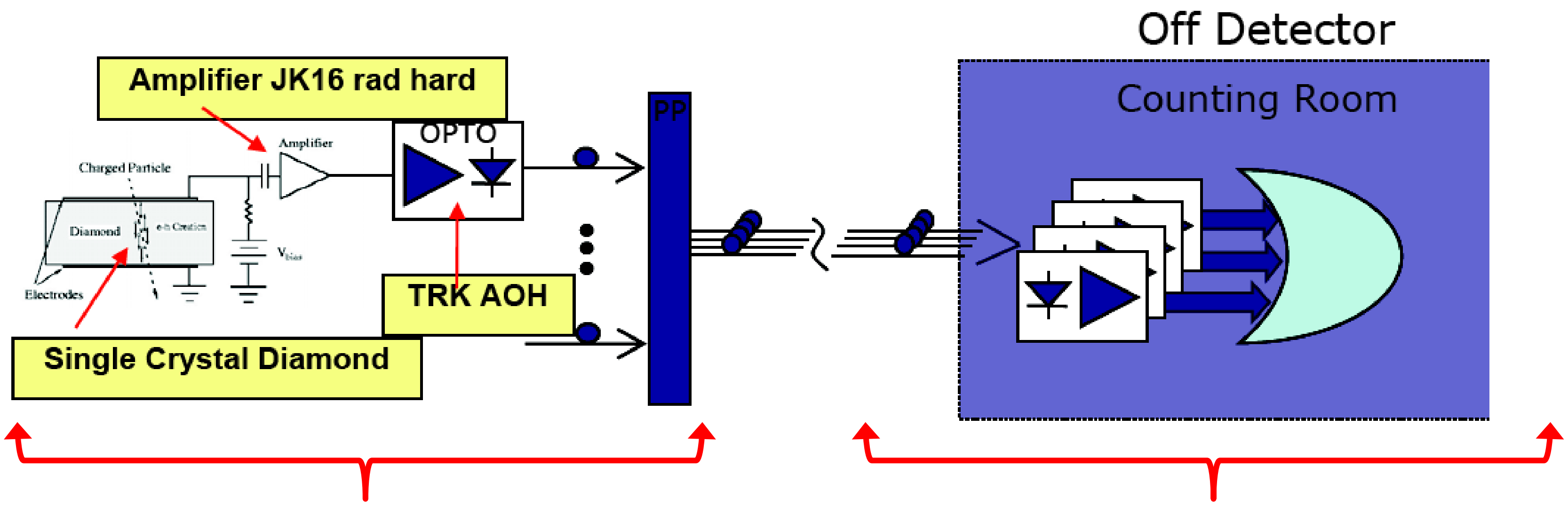




- Top: sCVD shifted to the left to show that it follows the same degradation parameterization as pCVD

- Bottom: sCVD irradiation loss: 20 % of initial signal
- drop of signal to noise from 26 to 7

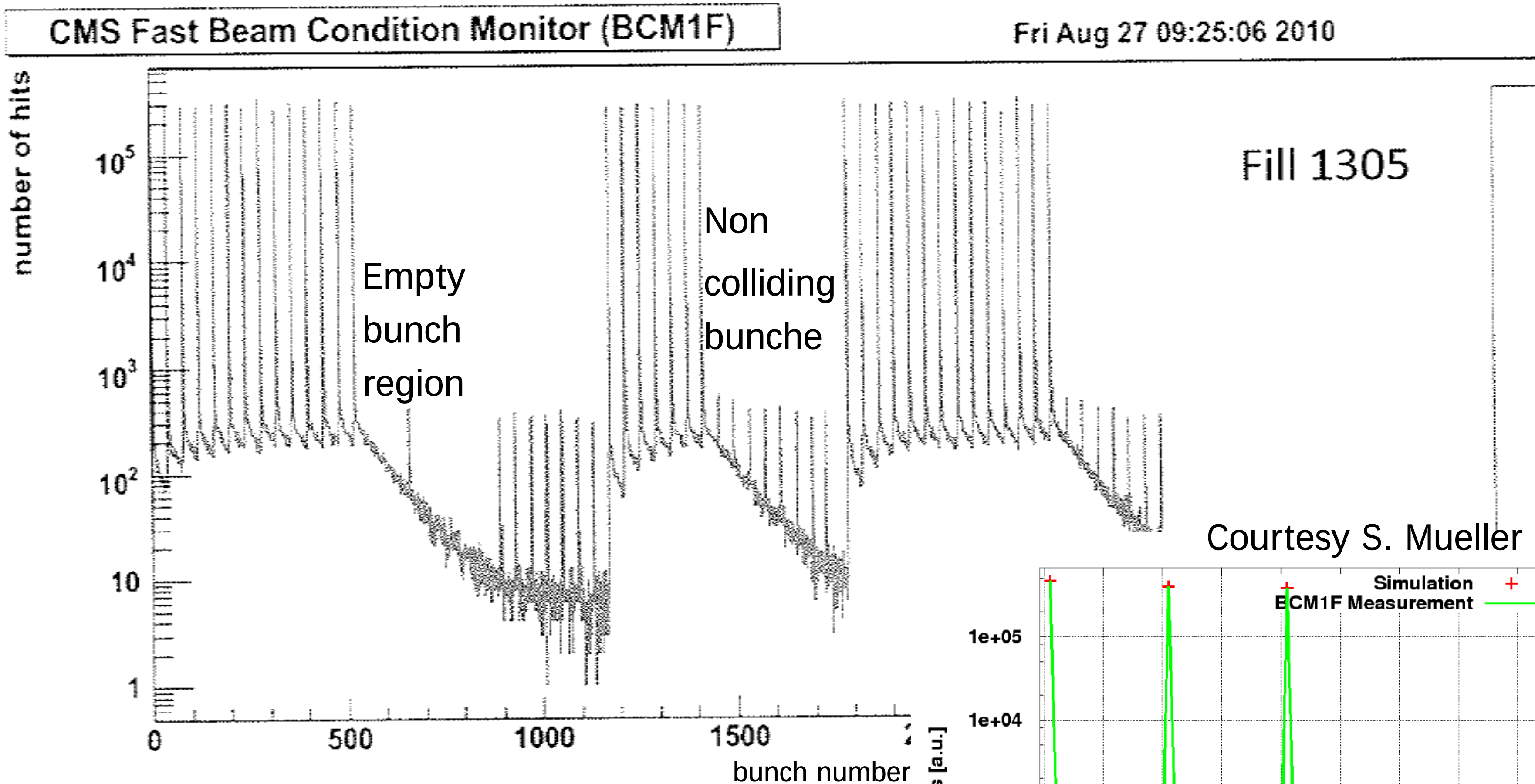
CMS BCM1F Monitor System (histogram of loss arrival time)

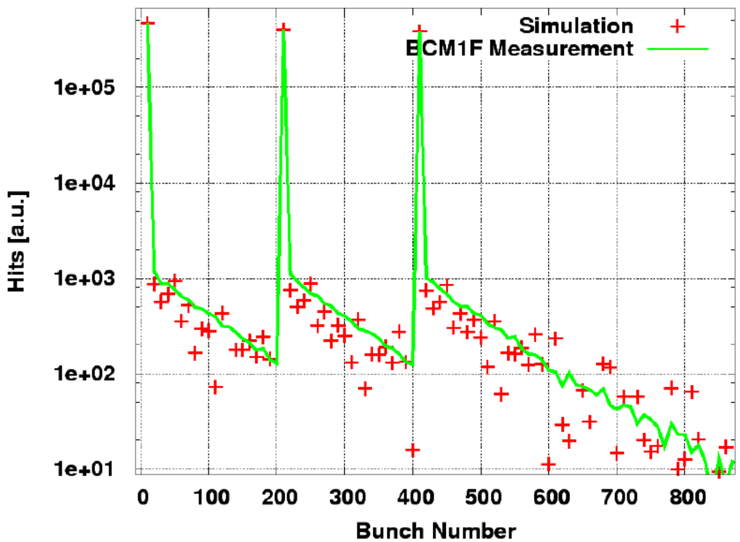


1. Radiation tolerant ASIC amplifier and laser diodes
2. Detector and electronics mounted in a few centimeter case

1. VME based CAEN module acquisition system
   1. ADC 500 MHz
   2. Scalar
   3. TDC

Diamonds Signal over Threshold and Arrival Time Histogram

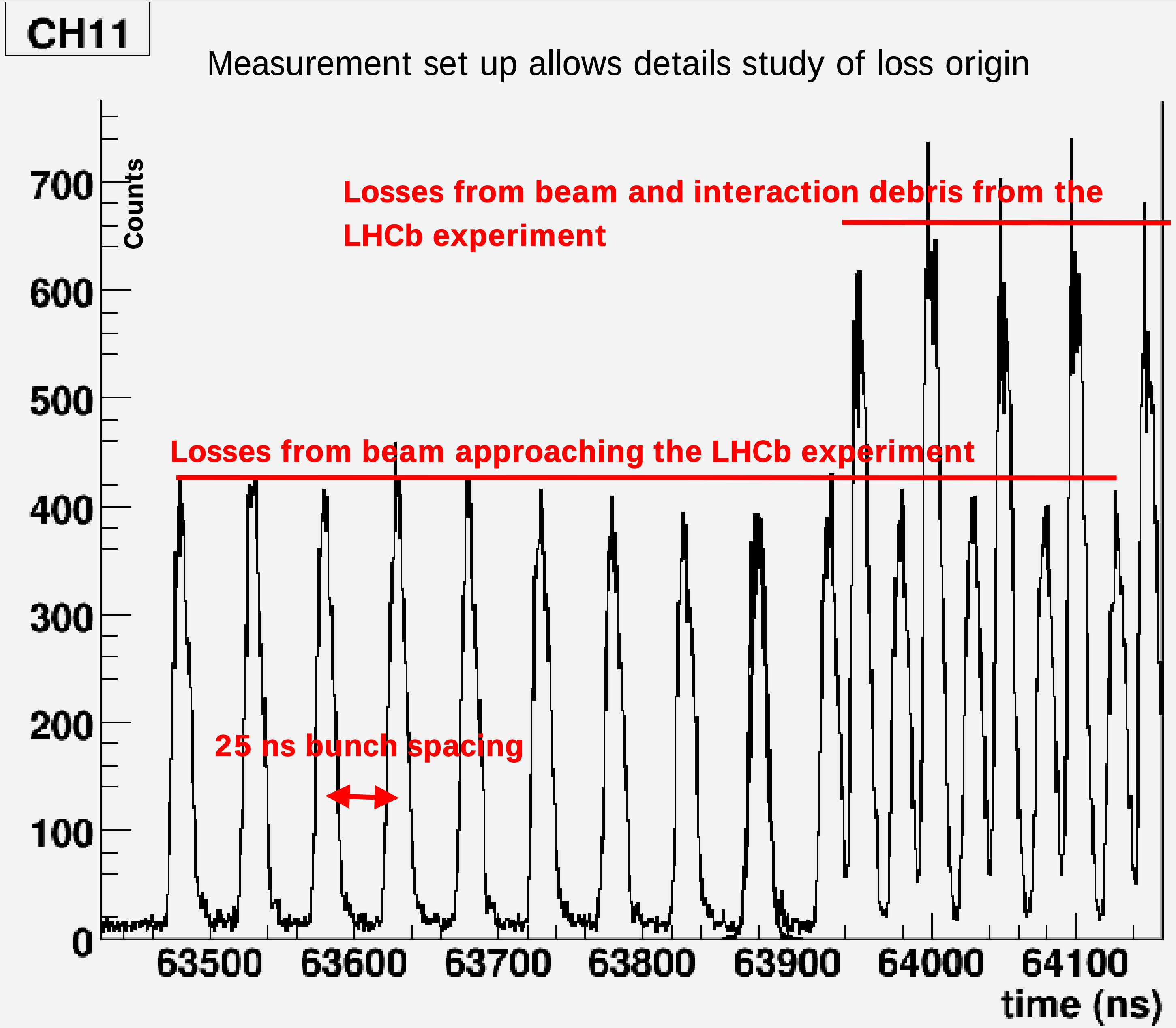




Courtesy S. Mueller

1. **Measurement of bunch filling scheme with high dynamic range**
2. **Model reproduces measurements**

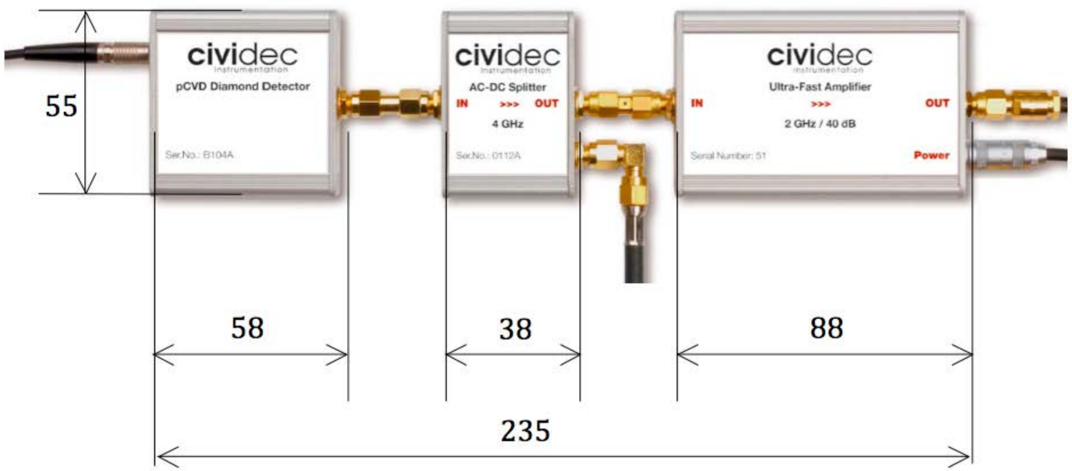
Arrival Time Histogram from Losses downstream of Collimator



4 Diamond BLMs for Observation at LHC (event triggered)

ATS/Note/2011/048 (TECH), B. Dehning et al.

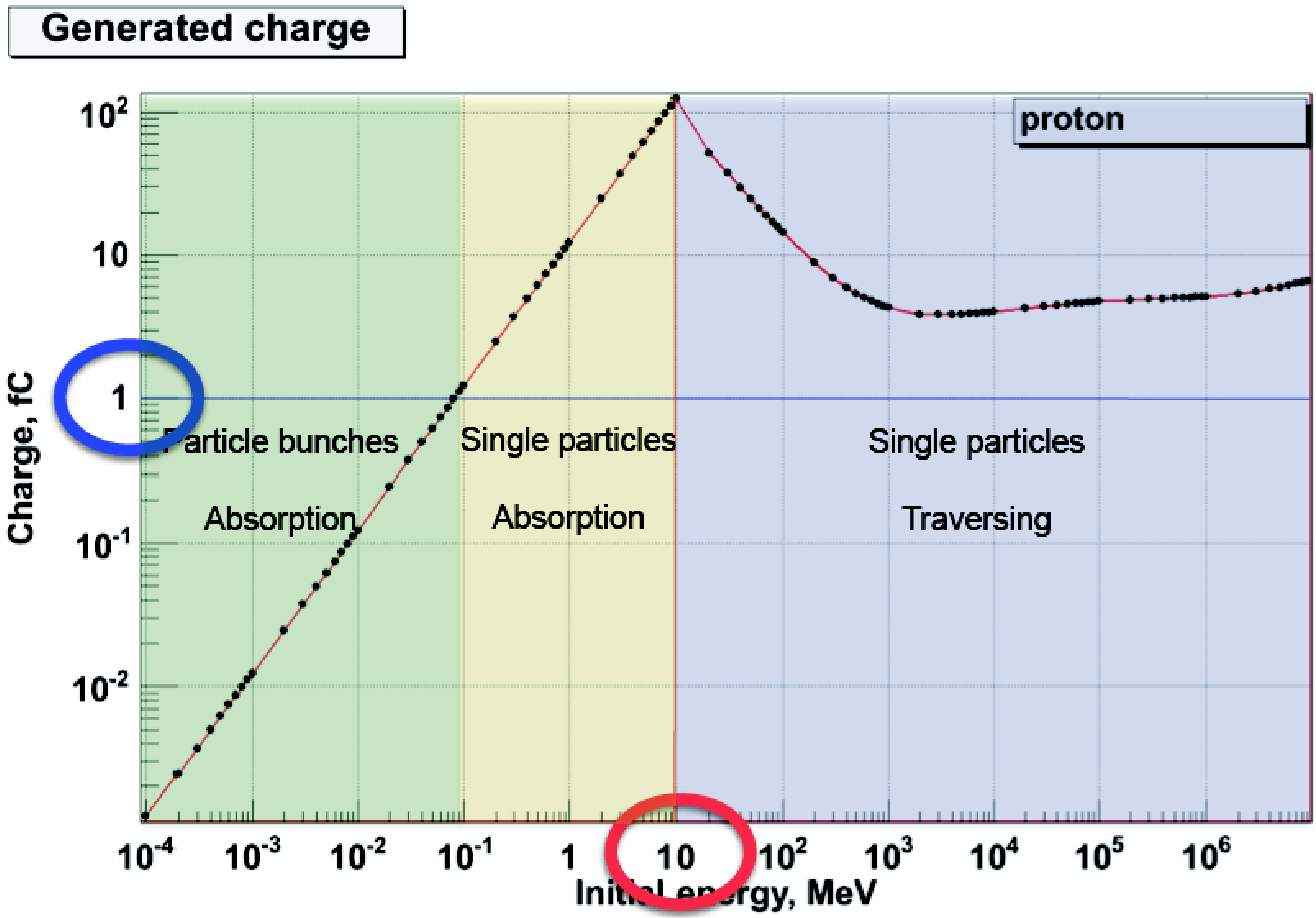
- Chemical Vapor Deposition (CVD) diamond
- IP7 collimators (TCP) – one per beam
    - All sizable local losses are also seen at collimators
- Injection regions – one per beam



Courtesy E. Griesmayer

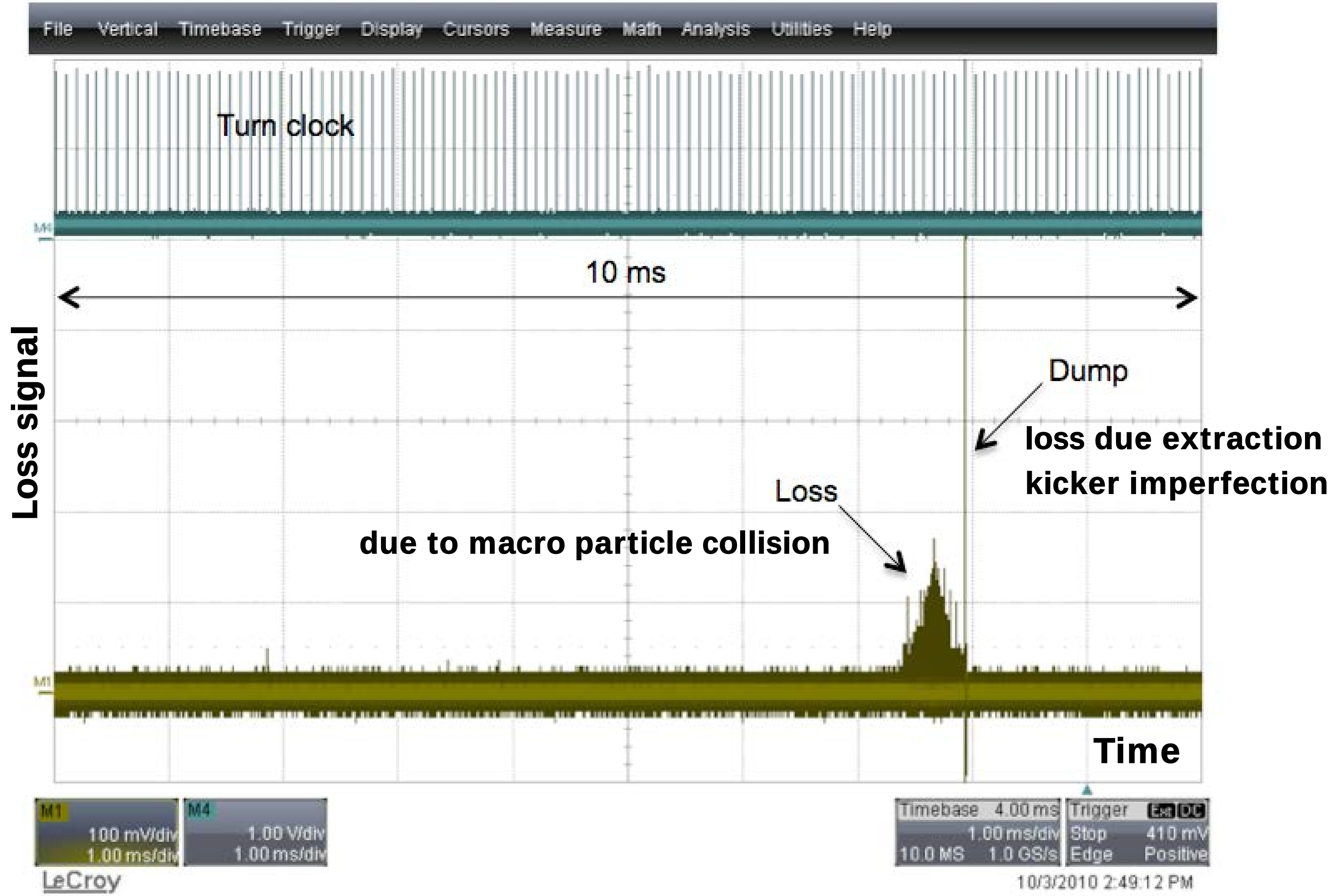
1. 40 dB amplification
2. 2 GHz upper limit
3. Dose up to 1 MGy
4. Rise time 180 ps
5. Pulse width 300 ps
6. Fall time 400 ps
7. SNR of 5 with 1.6 fC

Ionisation Characteristics in 500 um sCVD



Courtesy E. Griesmayer

LHC: 152 bunches, 150ns bunch spacing (3/10/2010 12h48)



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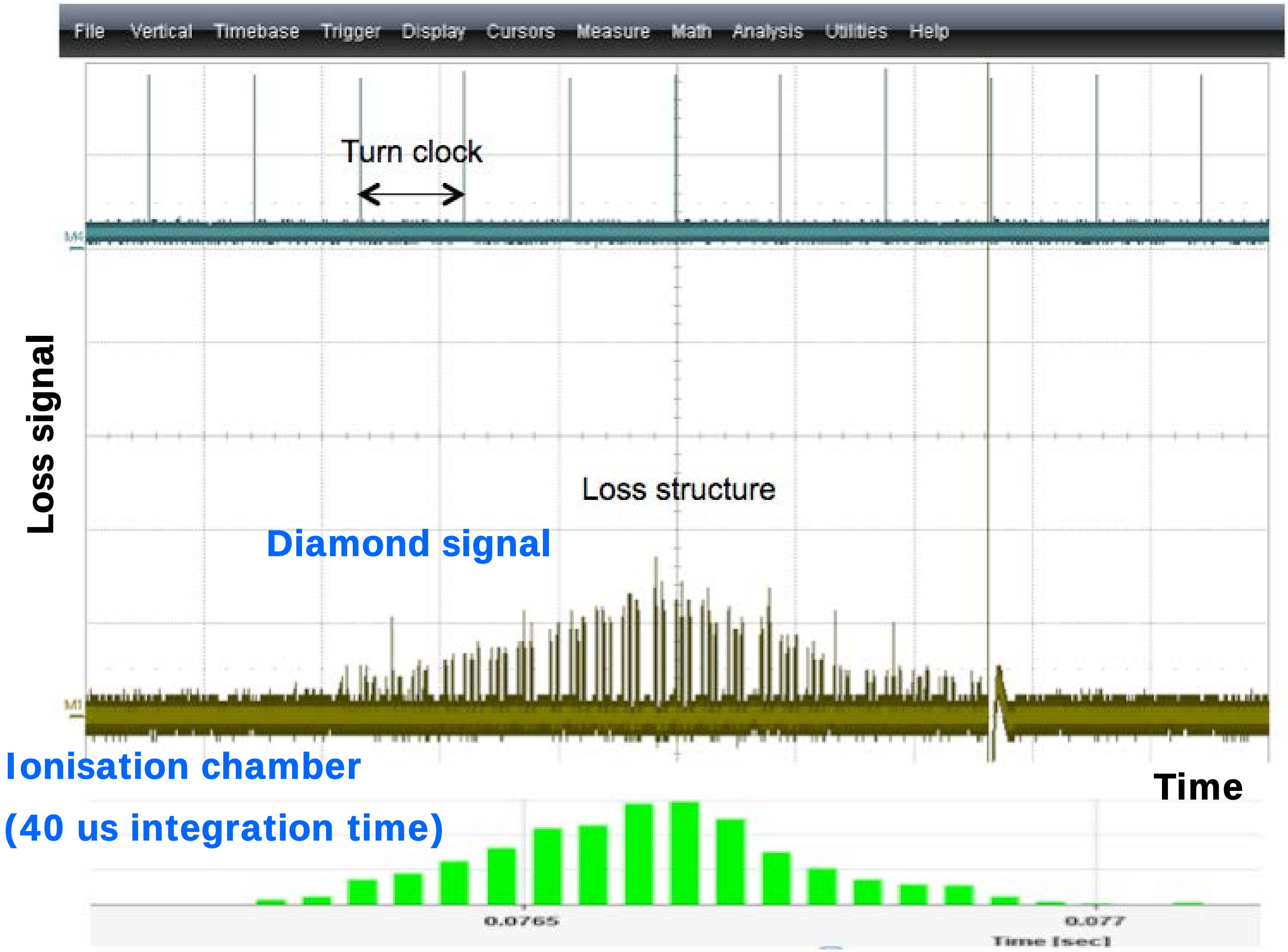

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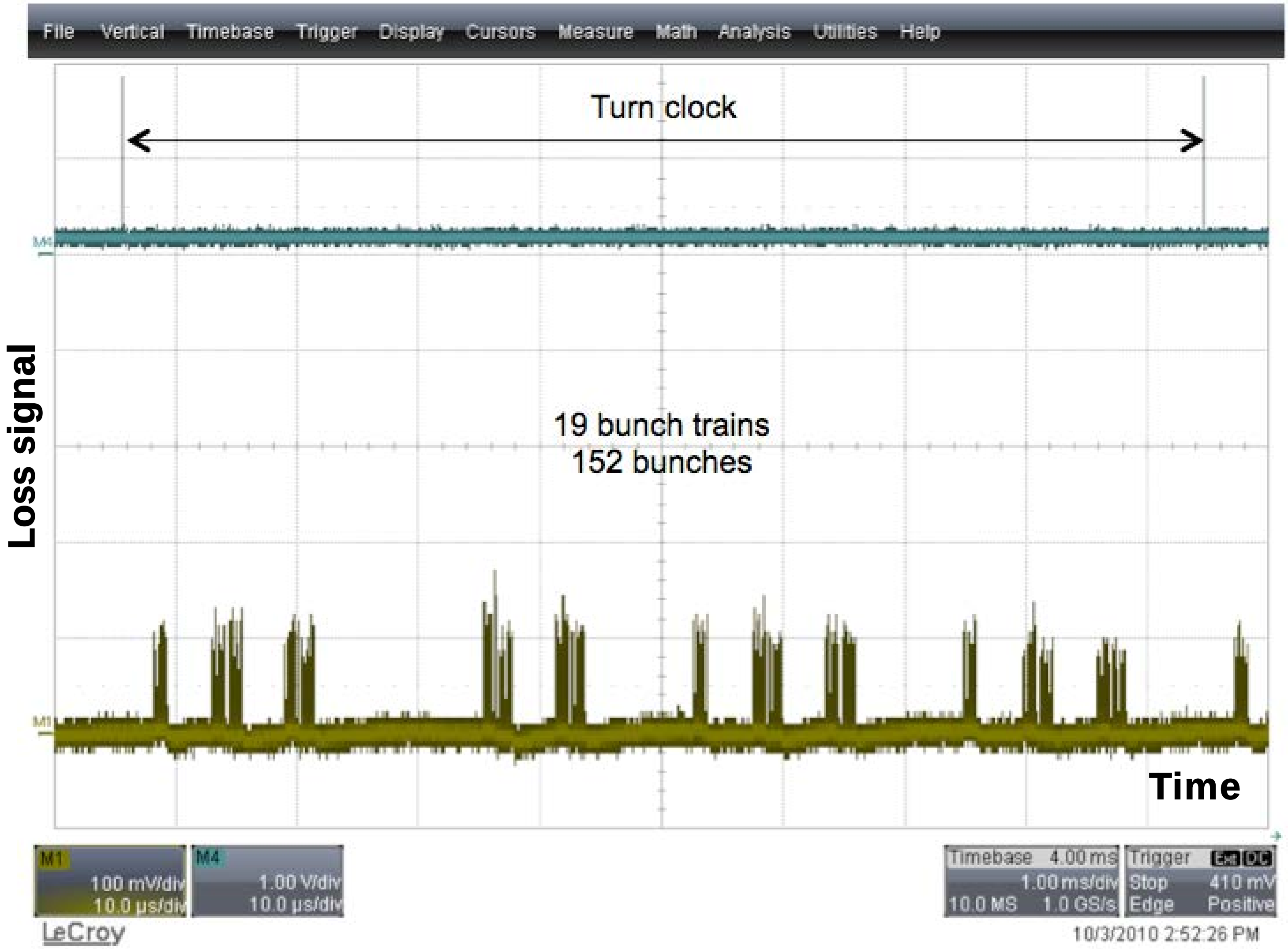

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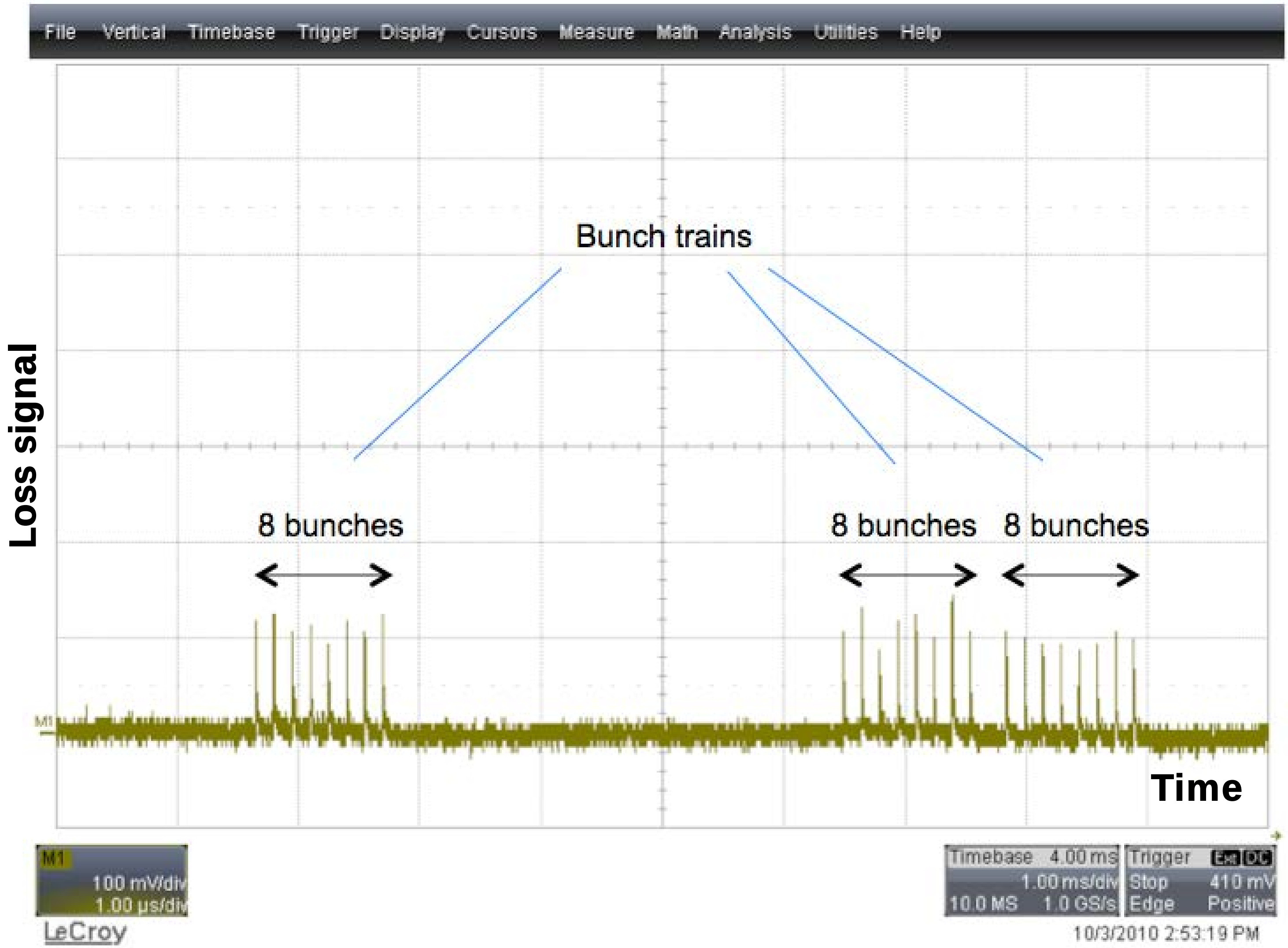

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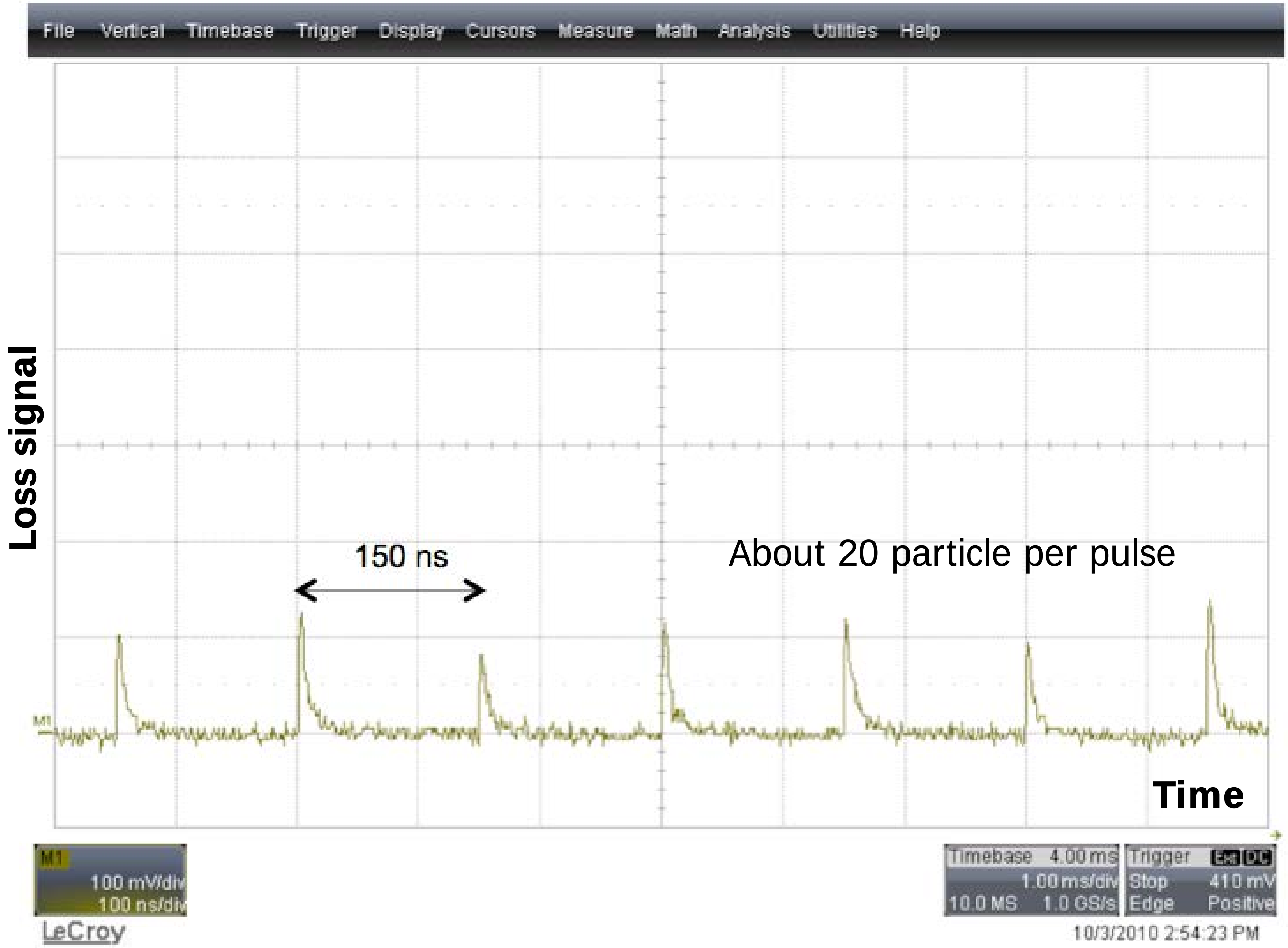
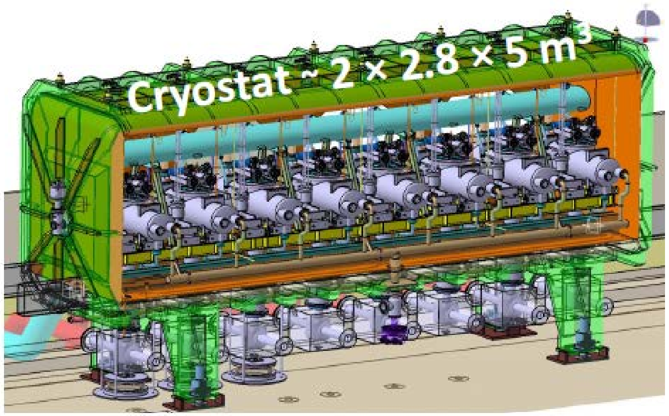
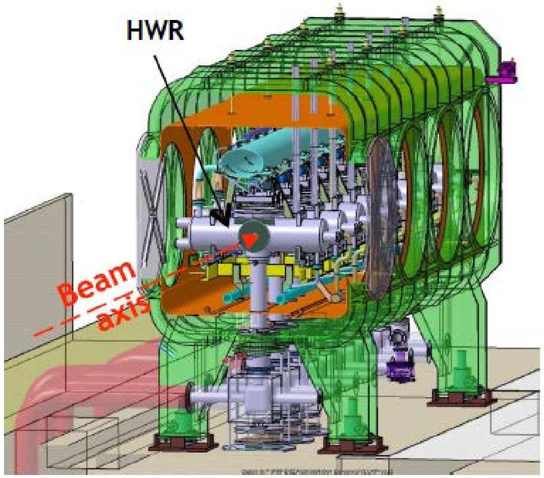


IFMIF (LIRA)

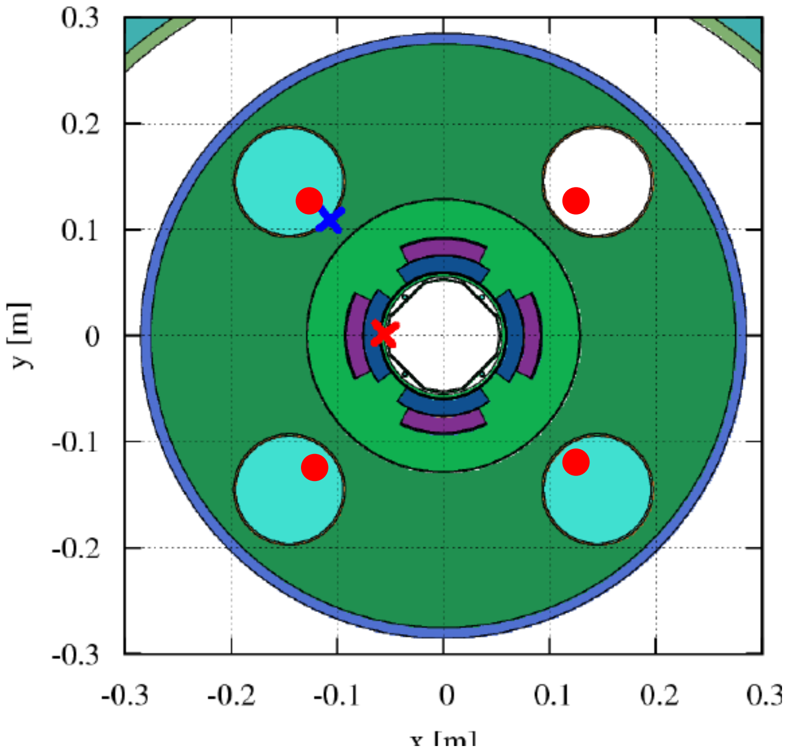
ITER material studies





Steering of beam to minimize energy deposition in cavity (Courtesy J. Marroncle)

New LHC quadrupole magnet



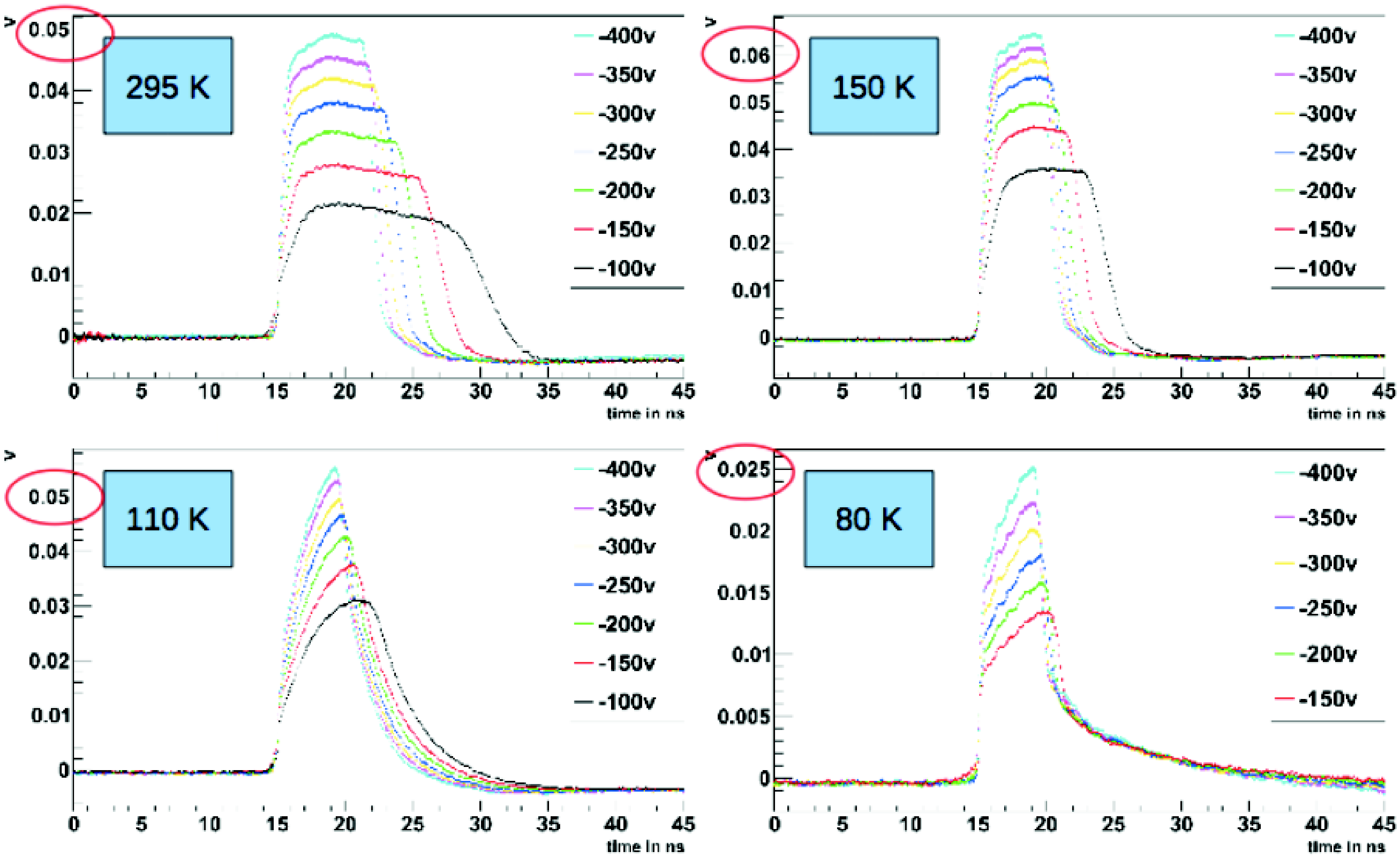
● Location of detectors

Initiating of beam abort trigger

Temperature dependance

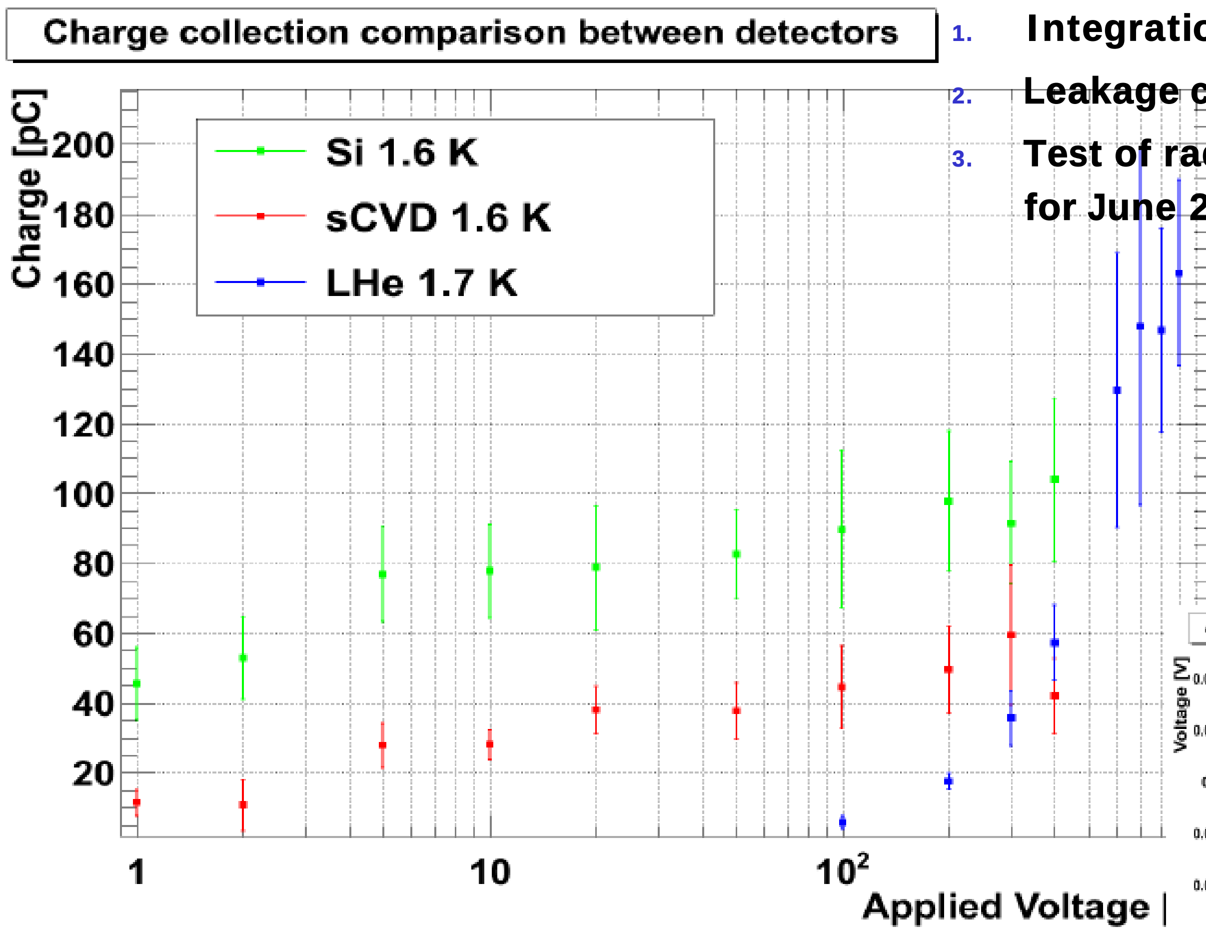
ALPHA source

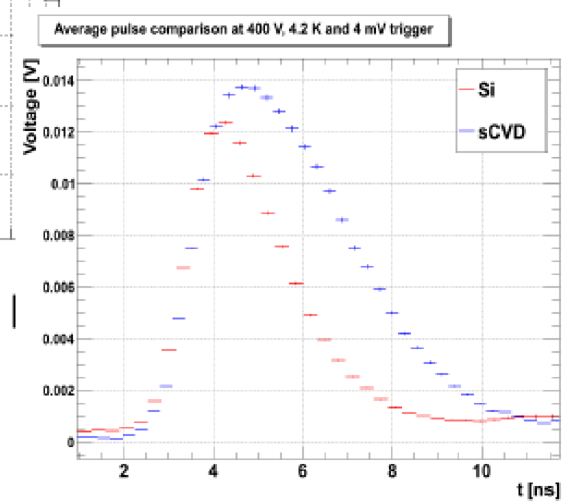
sCVD



Charge collection comparison Plots

1. Integration over length of spill (400 ms)
2. Leakage current below 1 pA
3. Test of radiation tolerance foreseen for June 2011 (dose:1MGy)





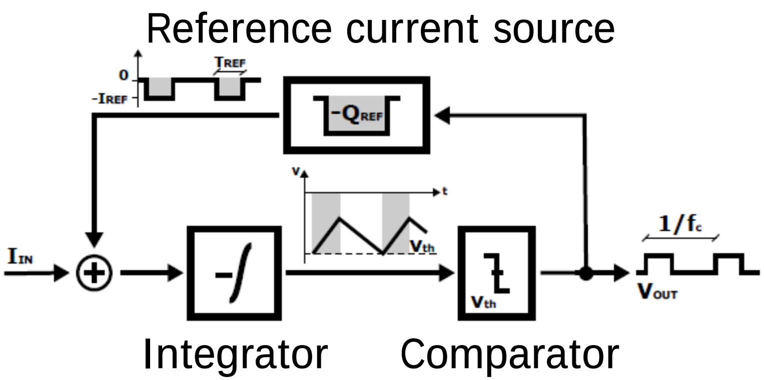
Advanced Current to Frequency Converter Principle

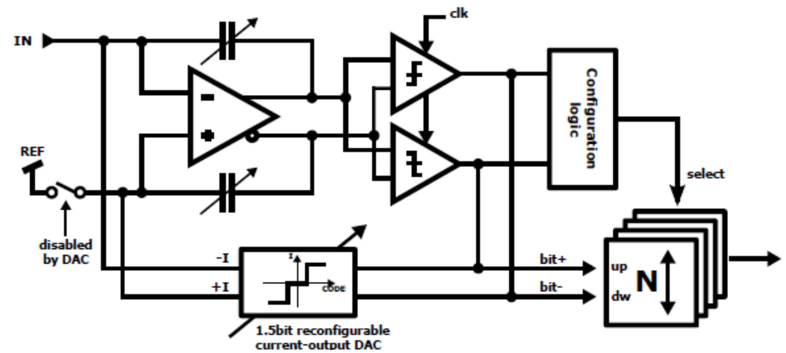
LHC current to frequency converter:

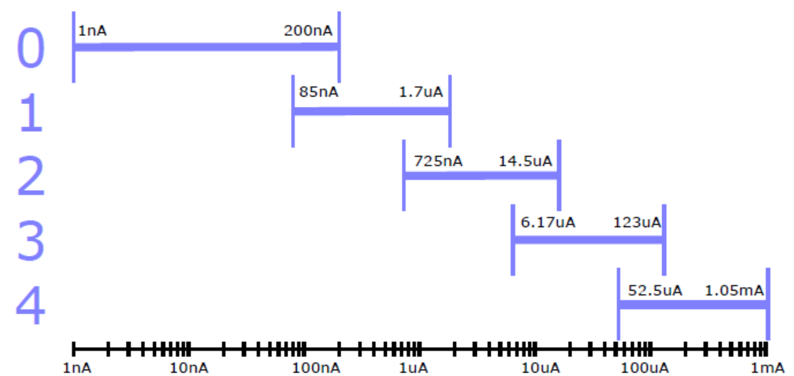
1. only positive signals (limitation in case of signal under shoots)
2. 500 Gy radiation tolerance

	Parameter	Value	Units	Comments
ASIC	Dynamic range	six decades		positive and negative currents
		nine decades		*(indirect measurement)*
	Minimum detected current	1	nA	(user selectable, minimum value)
	Linearity error	$< \pm 10$	%	relative error $\Delta I / I$
	Integration window	40	µs	
	Total integrated dose	1×10^4	Gy	in 20 years
	Target technology	CMOS 0.25 µm		

Six decades to be covered with a direct measurement → 20 bit







$$f = I_{input} / (I_{ref} * T_{ref})$$

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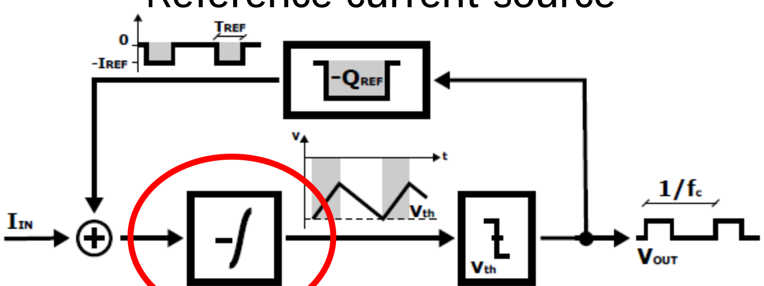
Reference current source



Integrator Comparator

$$f = I_{input} / (I_{ref} * T_{ref})$$

ASIC

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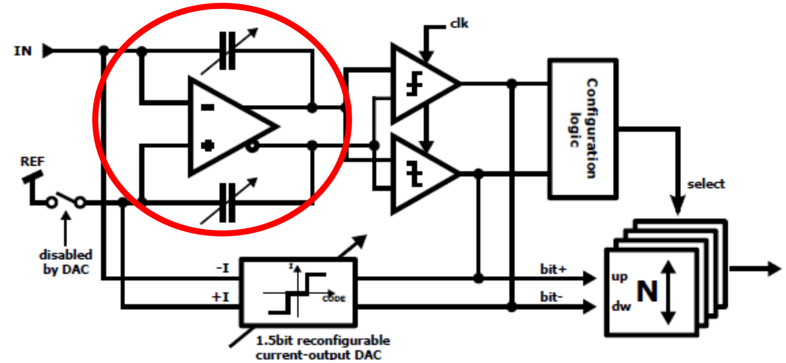

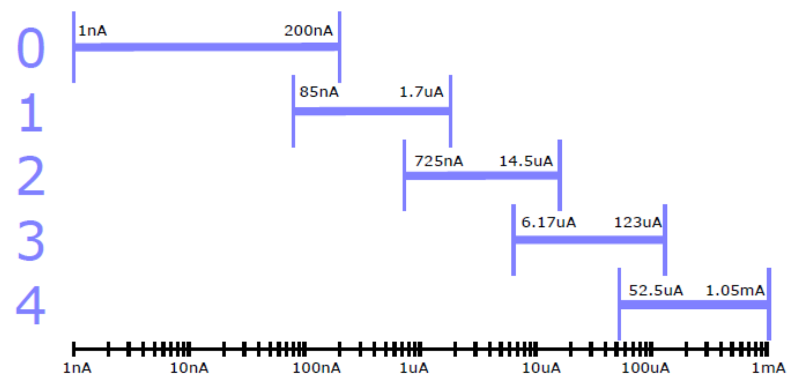

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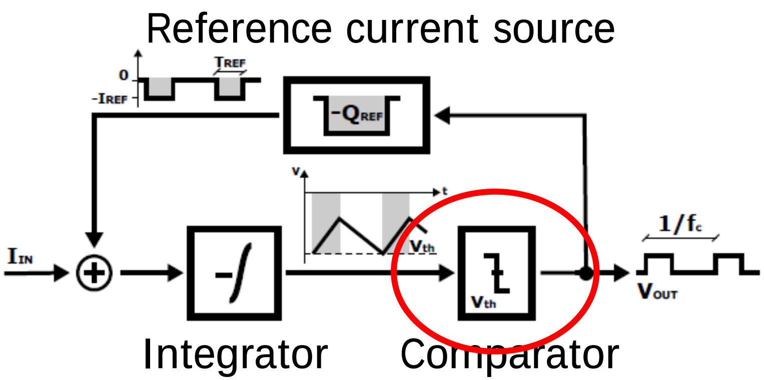

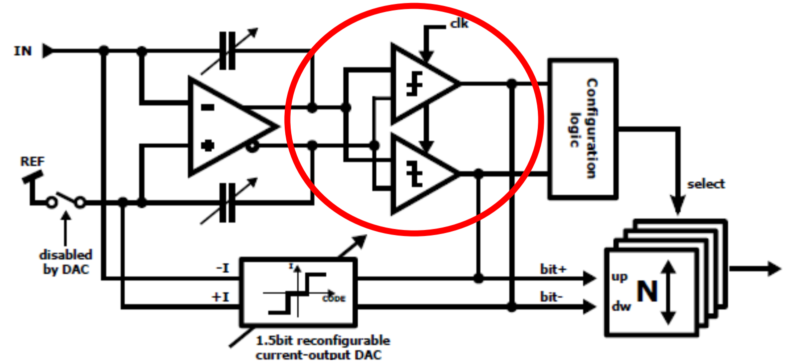

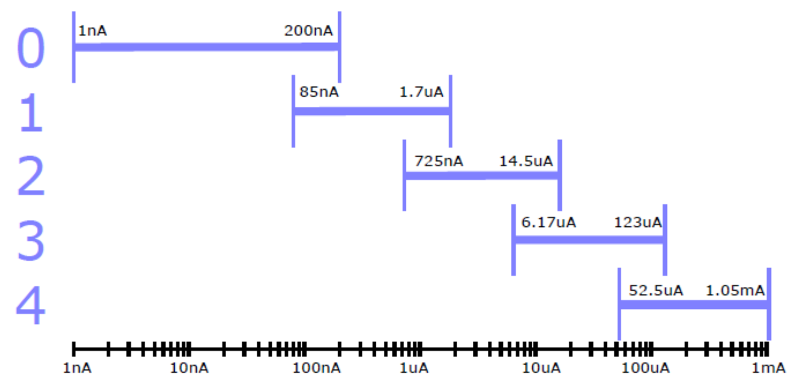

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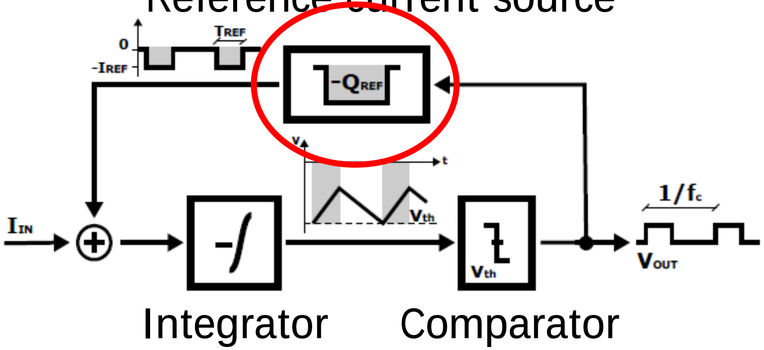
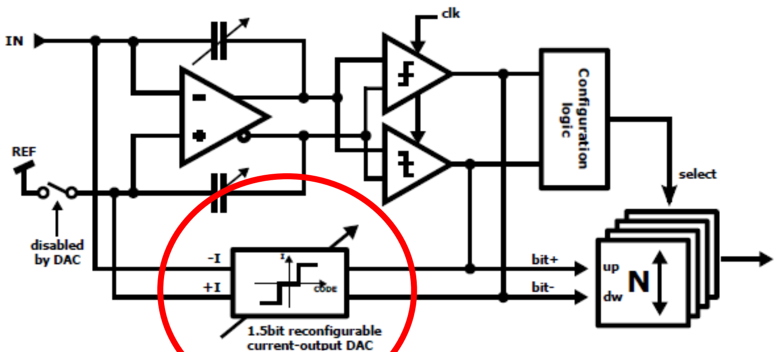
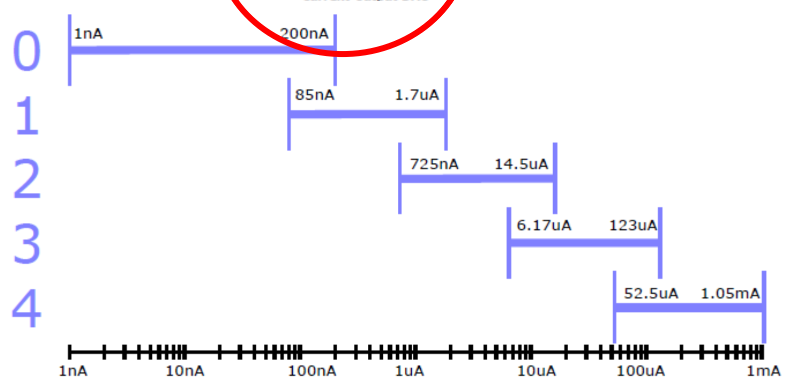


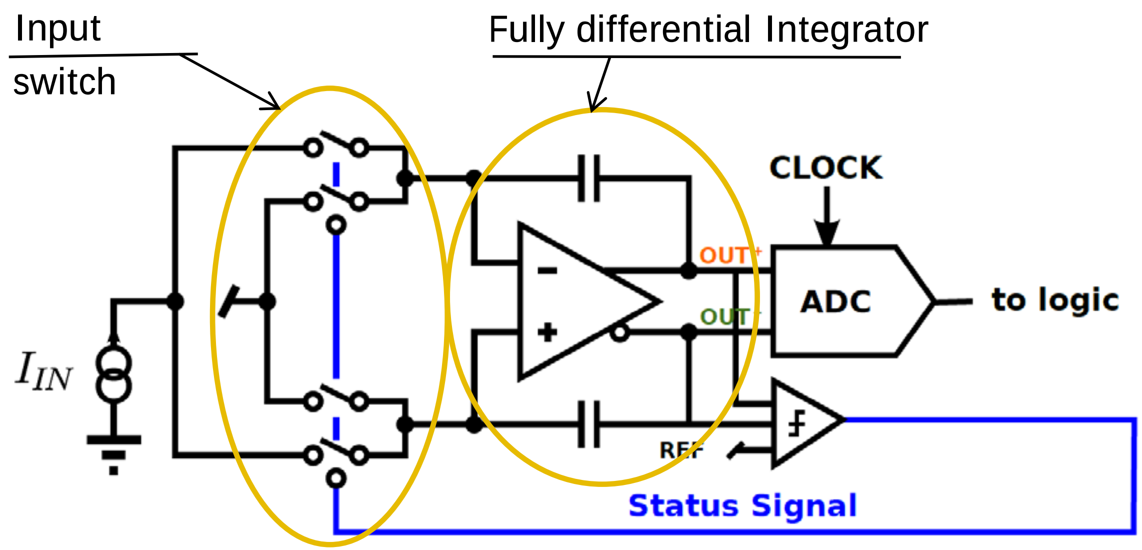


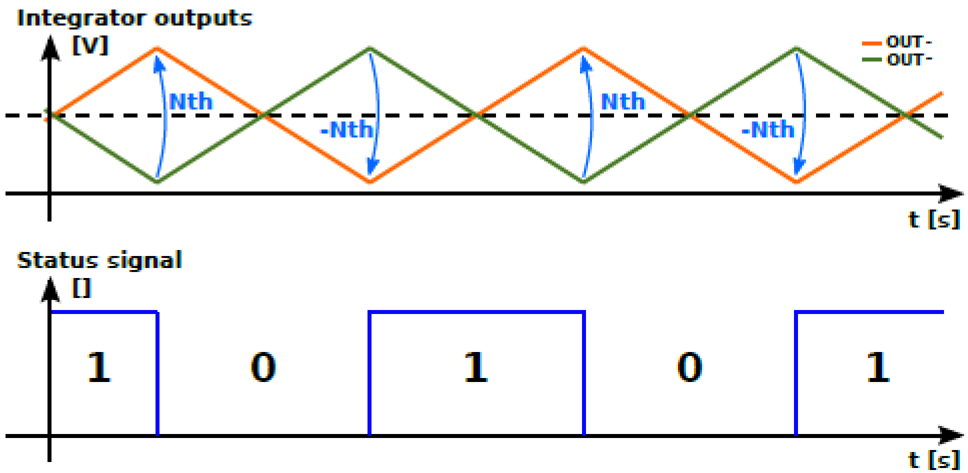


$$f = I_{input} / (I_{ref} * T_{ref})$$

Fully Differential Current to Frequency Converter Principle

Discrete components: not radiation tolerant





bidirectional optical and Ethernet link

1. Specifications:
   1. **Dynamic range 7 orders integration window 2 us 1nA to 200mA**
   2. **Dynamic range 9 orders** integration window 1 s 10pA to 200mA
2. A status signal selects in which branch of a fully deferential stage the input current is integrated.
3. Two comparators check the differential output voltage against a threshold, whenever is exceeded, the status signal changes to the complementary value (0 ! 1 or 1 ! 0) and the input current is integrated in the other branch.

Acquisition System Specification for Diamond Signal

Two data sets should be available:

1. Signal versus time
2. Number of signals over threshold versus arrival time

	Detector			
Pulse	Amplitude	Max.	2	V
		Min.	1	mV
	width		5	ns
	time jitter		1	ns
	noise level	below	1	mV
Double pulse resolution			20	ns

Signal to be measured

	Digitalisation of the signal			
ADC (min)			10	bit
	range	Max.	1	V
	sampling		500	MHz
	bandwidth		250	MHz
Buffer			**1.00E+007**	**words**
Trigger	input		TTL	

Oscilloscope features

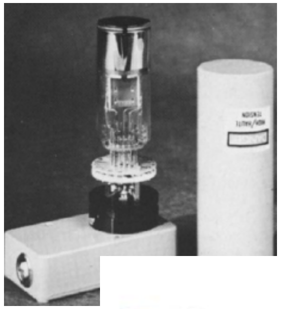
Market survey has been started

	Histogramming of arrival times			
Threshold DAC		min	0.5	mV
			10	bit
Reference frequency		min	10	kHz
		max	2	MHz
			TTL	
Histogram			**5.00E+004**	**bins**
Signal frequency		max	10	MHz

Histogram of time of arrival

Reserve Slides

Beam Loss Detectors used at CERN



Aluminium Kathode

+

PM

ACEM
(current)

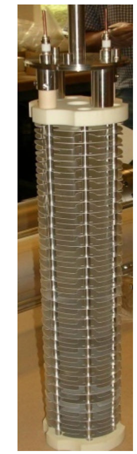
Ionisation chambers

LIC

N2 @ 0.4 bar

LHC BLM

N2 @ 1.2 bar



Optical fibre

+

SiPM (array)

CLIC

+

Proton transfer

Secondary

Emission

effect

SEM

PEP-II BLM

Cherenkov Light + PM

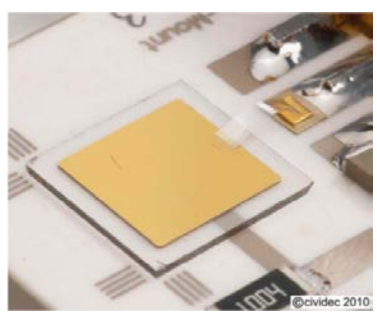
Courtesy of
U. Wienands
(SLAC)

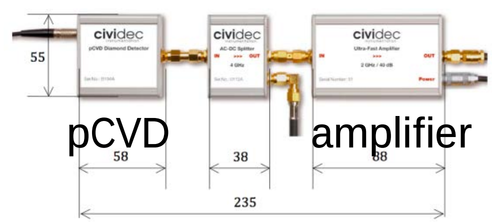
Diamond

pCVD

+

sCVD





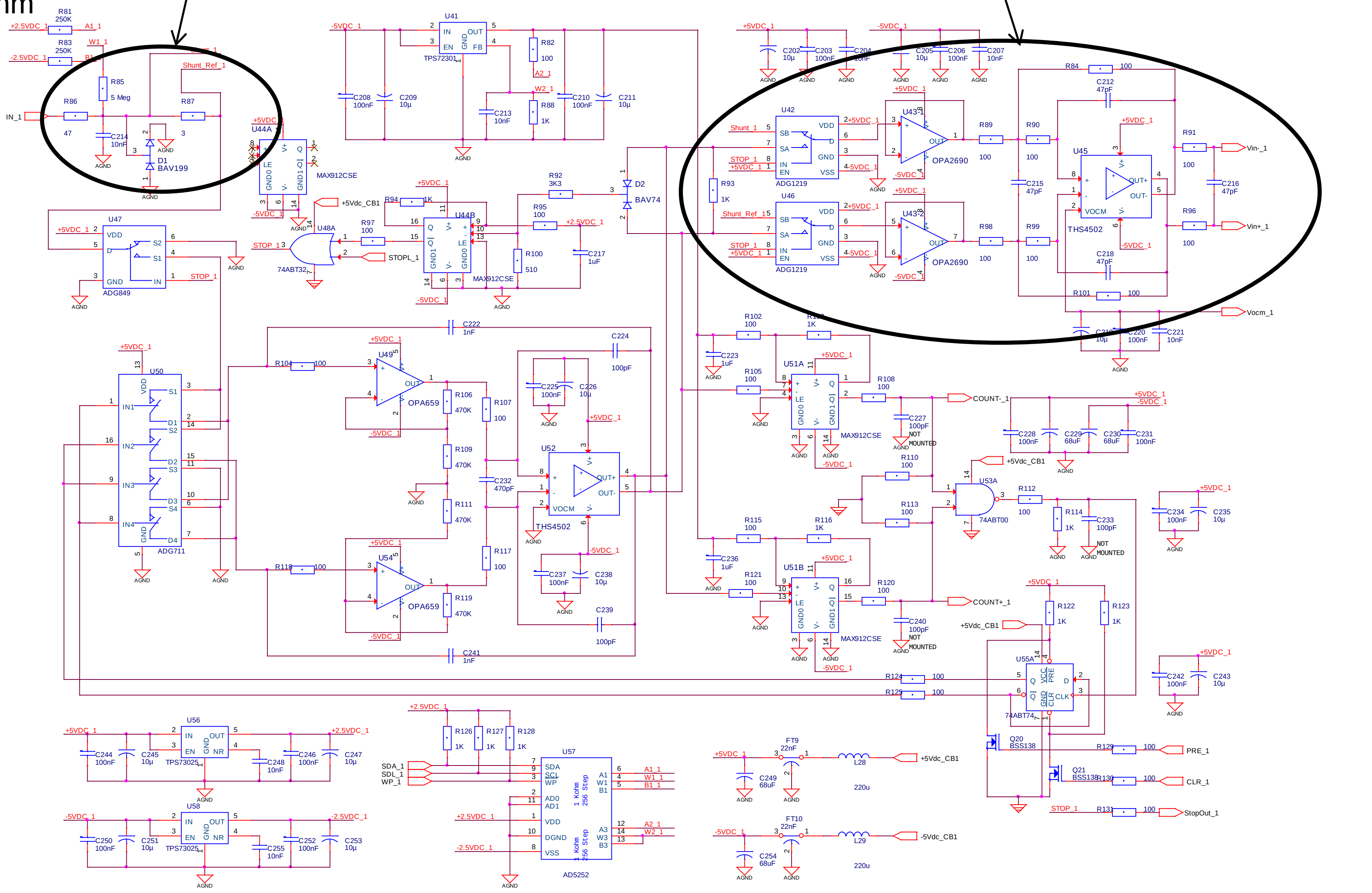
pCVD

amplifier

Fully Differential Current to Frequency Converter Principle

Input 50 ohm resistor split in two: 47 + 3 ohm

Re-routing on the ADC buffer amplifier



Post Mortem Data (some examples)

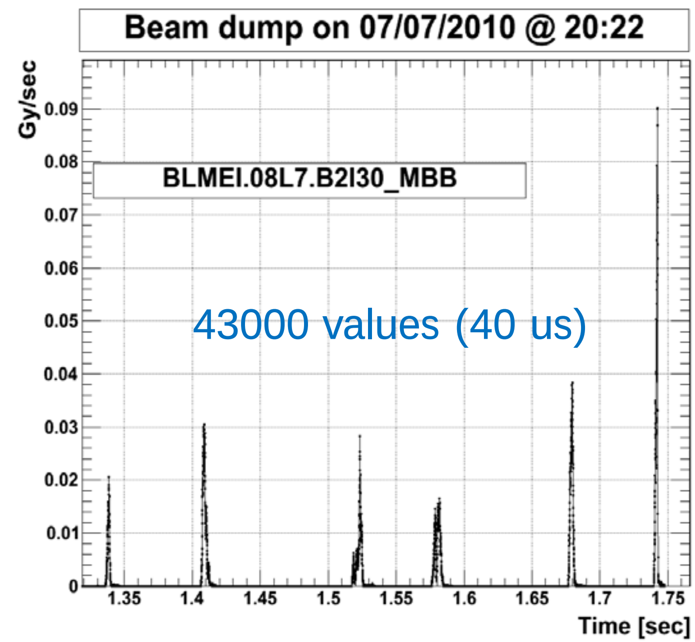
Loss in a bending magnet

PM application: BLM data of 0.082 sec
online available

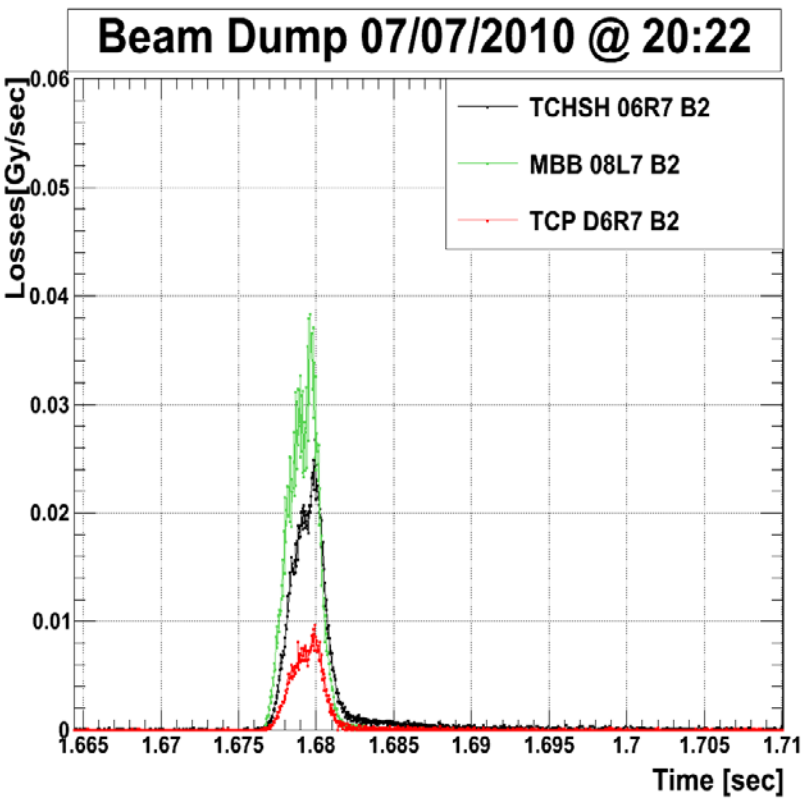
Longer PM buffer: BLM data of 1.72 sec
offline available

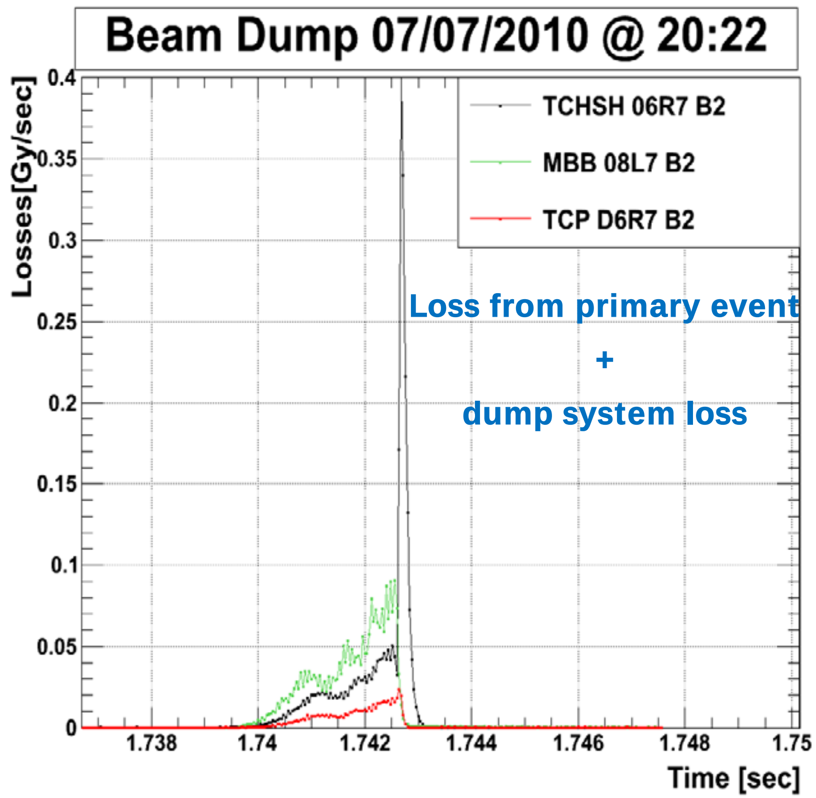
Monitors →

Time →

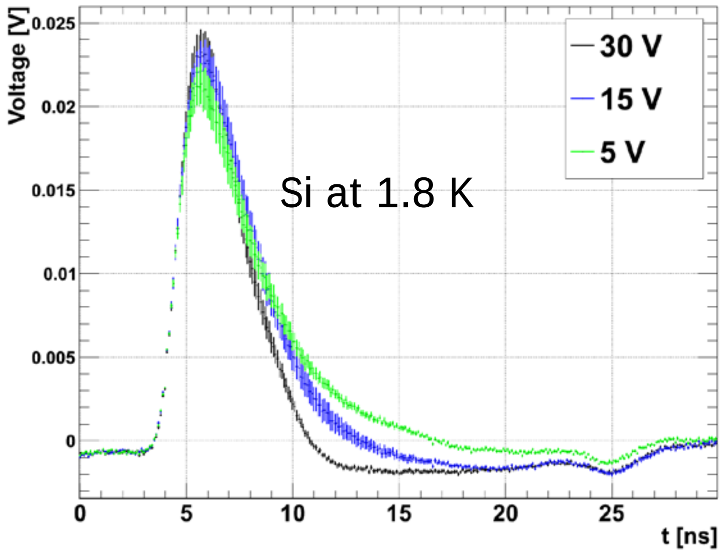


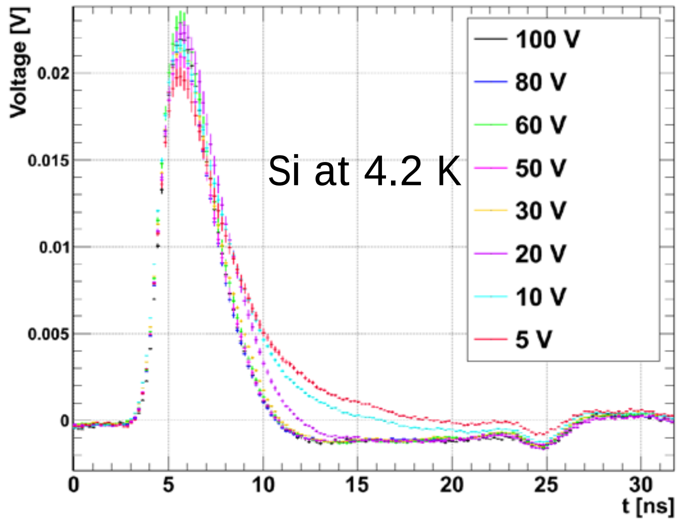
Post Mortem Data (some examples), Zoom

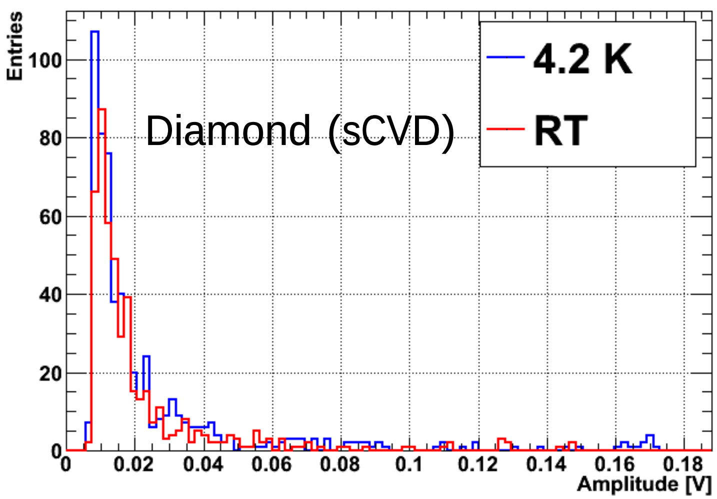


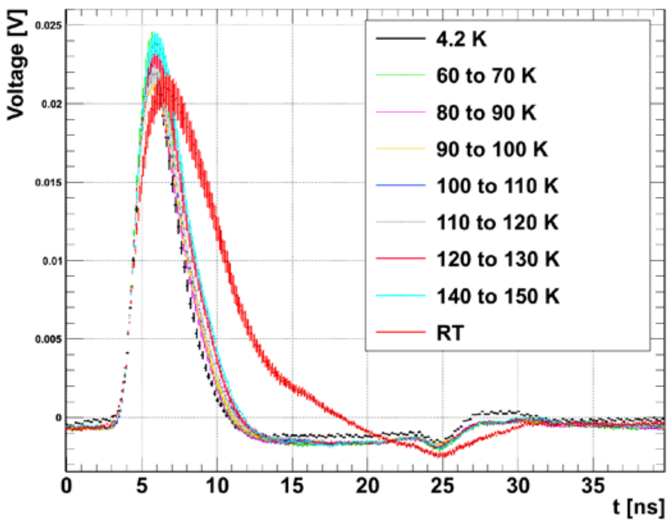


1.8 Kelvin Loss Detection – MIP response (20 GeV Protons)









Open questions: radiation hardness, DC current value, non linearity effects for high losses

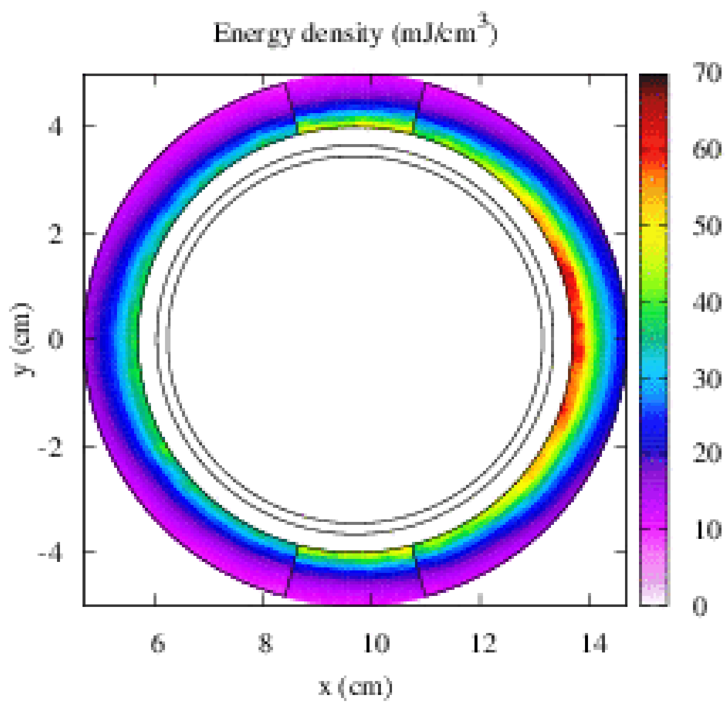
(Roughly) Estimated Sensitivities

- **Ionization chamber:** **70 μC/Gy** — CERN IC 54 uC/Gy
  1 liter argon
  S ≈ active mass · charge per ionization energy ≈ $V \cdot \rho \cdot e/E_{ion}$ ≈ 1 l · 1.8 g/l · e / 26 eV
  LIC 1.4 uC/Gy
- **Long ionization chamber:** **20 μC/Gy**
  1 meter length, 1 cm radius, argon
  S ≈ active mass · charge per ionization energy ≈ $\pi r^2 \cdot L \cdot \rho \cdot e/E_{ion}$ ≈ 314 cm^3 · 1.8 g/l · e / 26 eV
- **PIN diode:** **6 μC/Gy**
  1 cm^2 surface, 100 μm depletion depth
  S ≈ active mass · charge per excitation energy ≈ $A \cdot d \cdot \rho \cdot e/E_{ion}$ ≈ 10 mm^3 · 2.3 g/cm^3 · e / 3.6 eV
- **Secondary emission monitor:** **500 pC/Gy** — CERN
  100 cm^2 surface, 0.01 average secondary emission yield (SEY)
  S ≈ surface · SEY · electron charge · density of primaries per dose ≈ A · SEY · e · (ρ/(dE/dx))
  ≈ 100 cm^2 · 0.01 · e · 1/(2 MeV·cm^2/g)
- **Aluminum cathode electron multiplier:** **5 μC/Gy** — CERN
  10 cm^2 surface, 0.01 average secondary emission yield (SEY), tube gain 10^5
  S ≈ surface · SEY · electron charge · density of primaries per dose · gain ≈ A · SEY · e · (ρ/(dE/dx)) · G
  ≈ 10 cm^2 · 0.01 · e · 1/(2 MeV·cm^2/g) · 10^5
- **PMT with organic scintillator:** **200 C/Gy** ← Radiation damage problematic!
  1 liter scintillator, 60% collection efficiency, 30% photocathode efficiency, tube gain 10^5
  S ≈ active mass · photon yield per energy · collection efficiency · photocathode efficiency · gain · electron charge
  ≈ V · ρ · Y · C · P · G · e = 1 l · 1 g/cm^3 · 1/(100 eV) · 0.6 · 0.3 · 10^5 · e
- **Bare PMT (Čerenkov light):** **4 mC/Gy**
  10 cm^2 surface, 1 mm thick, 30% photocathode efficiency, tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · photocath. efficiency · gain · electron charge
  ≈ A · d · ρ · (ρ/(dE/dx)) · Y · P · G · e ≈ 1 cm^3 · 1/(2 MeV·cm^2/g) · 260/cm · 0.3 · 10^5 · e
- **PMT with Čerenkov fiber:** **2 μC/Gy**
  1 meter length, 100 μm radius, 2% collection efficiency, 30% photocathode eff., tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · coll. eff. · photoc. eff. · gain · electron charge
  ≈ πr^2 · L · ρ · (ρ/(dE/dx)) · Y · C · P · G · e ≈ 31 mm^3 · 1/(2 MeV·cm^2/g) · 260/cm · 0.02 · 0.3 · 10^5 · e

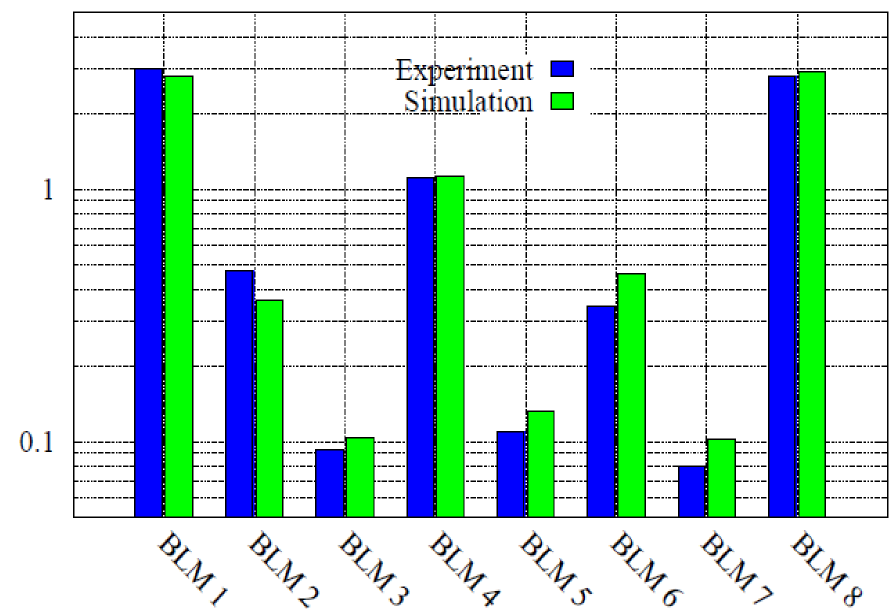
Flexible gain → linearity and calibration problematic!

Particle shower simulations

One of the most spectacular quench tests: generate millisecond scale losses using with Wire Scanner at 3.5 TeV.



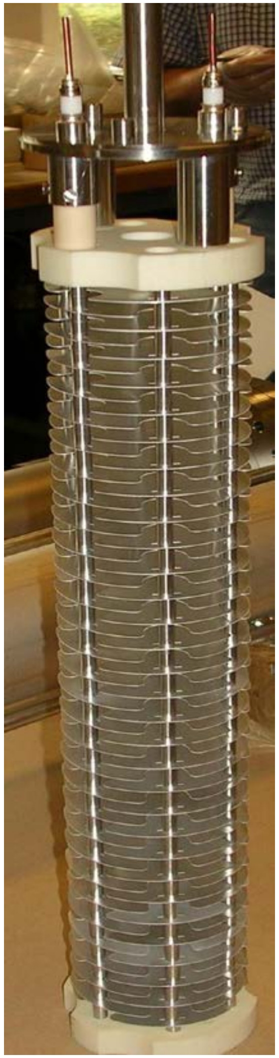
FLUKA simulations



Max E_{dep}
FLUKA: 62.5 mJ/cc
QP3: 38 mJ/cc (preliminary)
we call it a good agreement

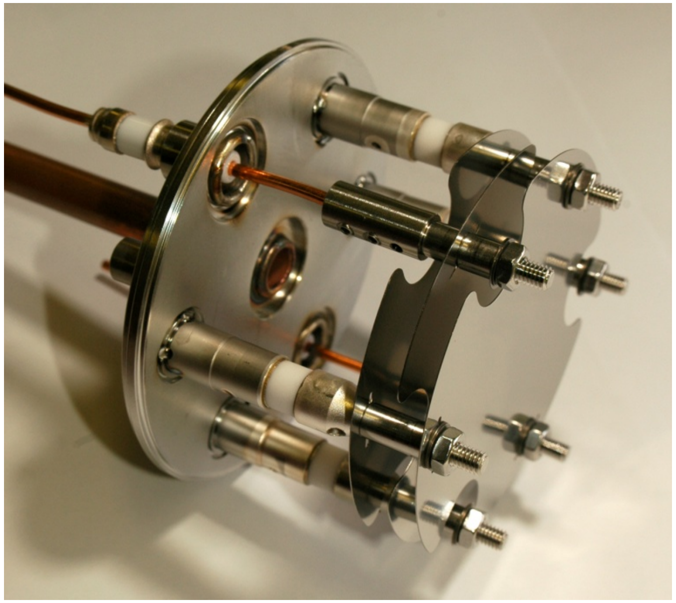
Shower simulation could be accurate to few 10 % in transverse tails of 20 to 30 cm

Ionisation Chamber and Secondary Emission Monitor



- Stainless steal cylinder
- Parallel electrodes distance 0.5 cm
- Diameter 8.9 cm
- Voltage 1.5 kV
- Low pass filter at the HV input

Signal Ratio: IC/SEM = 60000



IC:

- Al electrodes
- Length 60 cm
- Ion collection time 85 us
- N_2 gas filling at 1.1 bar
- Sensitive volume 1.5 l

SEM:

- Ti electrodes
- Components UHV compatible
- Steel vacuum fired
- Detector contains 170 cm2 of NEG St707 to keep the vacuum < 10-4 mbar during 20 years