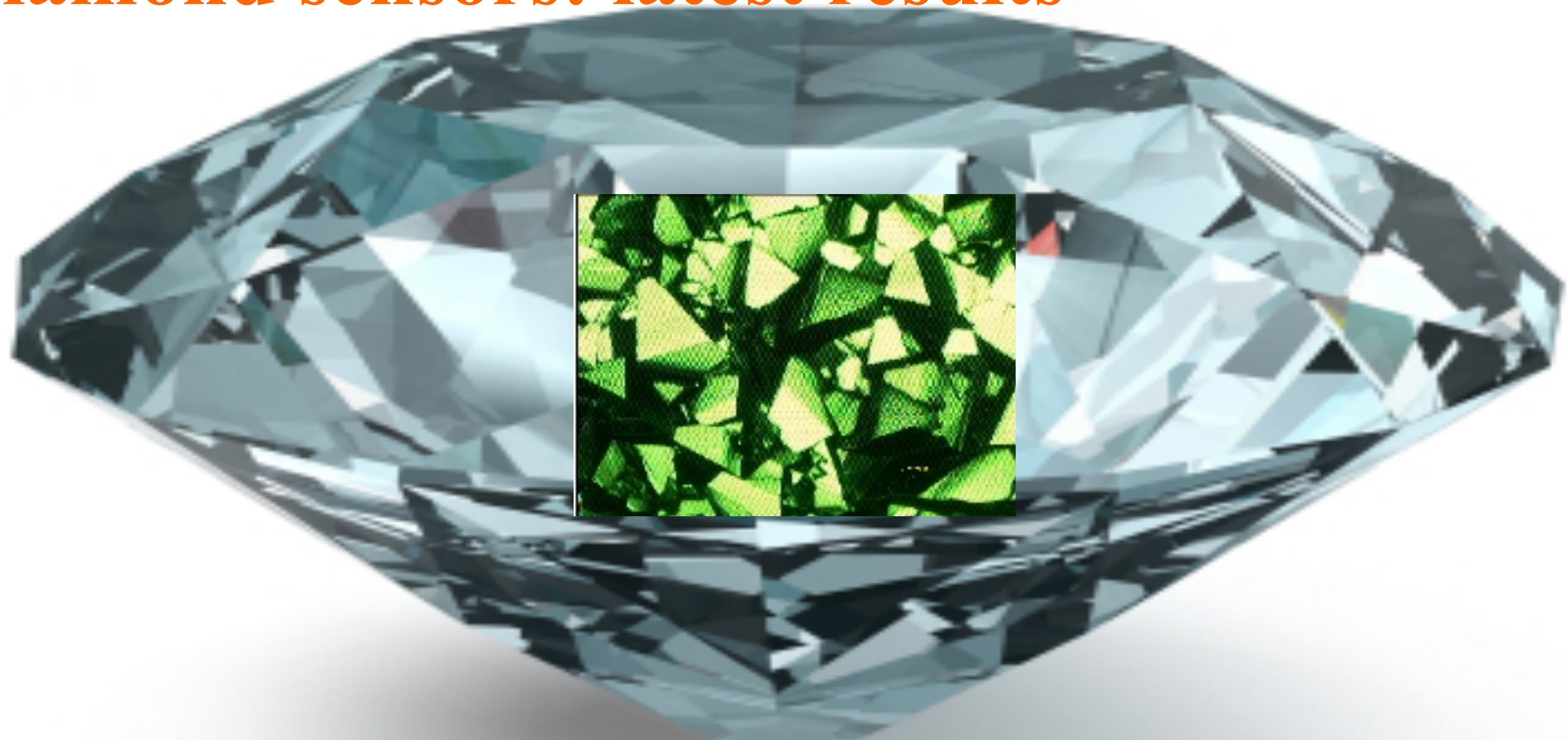
A beam radiation monitor based on CVD diamond sensors: latest results



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LFF Workshop
Luminometry and IP beam monitors for high luminosity Flavour Factories: techniques and detectors
November 22-23, 2012
Napoli

Outline

- Synthetic diamond as sensor material
  - **Diamond properties**
  - **Diamond suppliers**

- Diamond sensor applications in HEP:
  - **Present: radiation detection – beam monitors**
    - Beam Conditions Monitor
    - Beam Loss Monitor
  - **Future: Particle tracking in high radiation environment**
    - Diamond trackers for vertex reconstruction

- R&D work in Roma Tor Vergata University on diamond sensors readout with a fast FE SiGe electronics in view of the SuperB project

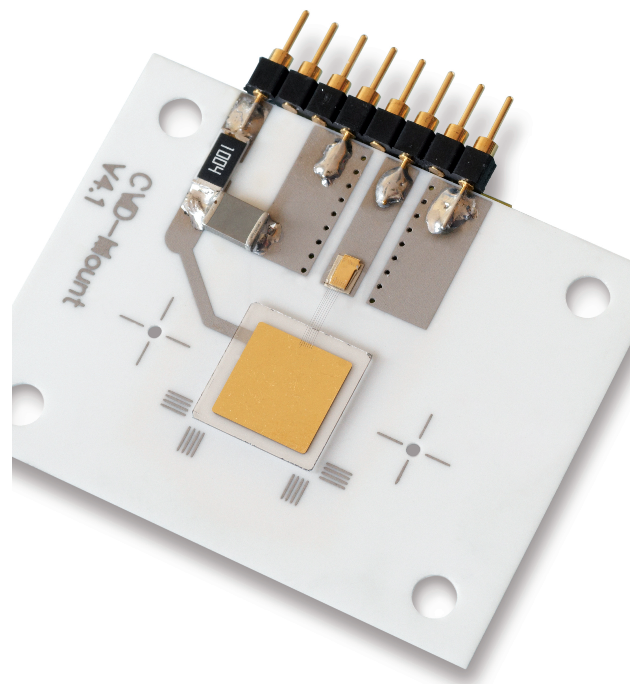
Properties of diamond vs silicon

	Diamond		Si
Band gap [eV]	5.48	Low leakage cur.	1.12
Electron mobility [cm^2/Vs]	2200	Fast signal collection	1450
Hole mobility [cm^2/Vs]	1600		500
Saturation velocity [cm/s]	2×10^7		0.8×10^7
Dielectric constant	5.7	Low capacitance, low noise	11.9
e-h creation energy [eV]	13	Smaller signal (typically 1/5 of Si)	3.6
e-h pairs per MIP [μm^{-1}]	36		89
Displacement energy [eV]	43	High radiation hardness	13 ~ 20
Decrease in charge collection after irradiation with 1×10^{15} proton/cm^2 *	Not observed :by ~40 % at 5×10^{15} p/cm^2		No signal

Diamond in a very high radiation environment is a unique material but need a much more performant FE electronics compared to silicon: low noise (~100e) and low threshold (~1000e)

Main CVD Diamond Properties

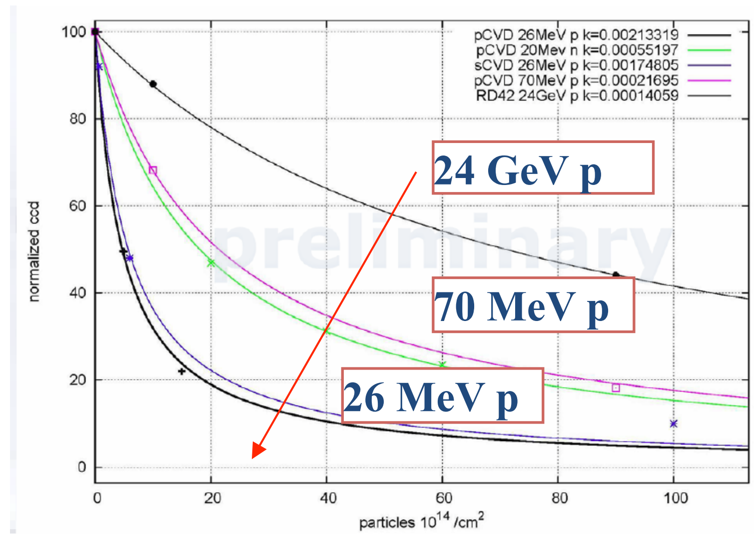
- Fast timing (<1 ns)
- High Radiation tolerante (>1 MGy)
- Single-particle detection and current monitoring
- Efficiency for charged particles practically 100%
- 500 V @ 100 pA, so very low power consumption
- Leakage current of a few pA, do not increase with the accumulated dose
- insensitive to temperature variation



Radiation hardness

- A real challenge : application for 1st (& 2nd) tracking layer of experiments at the LHC and more importantly at the HL-LHC
- Diamond offers:
  - Radiation Hardness
    - ➢ Survive to the end of the experiment
  - Low dielectric constant
    - ➢ Low capacitance → low noise
  - Low leakage current
    - ➢ Low readout noise
  - Room temperature operation
    - ➢ No cooling, Low mass construction
  - Fast signal collection
- Fluence of interest is $O(10^{15\text{-}16})$ cm^{-2}
  - For 1st pixel layer at R ~4 cm

[RD42, LHCC Status Report, Feb. 2010]

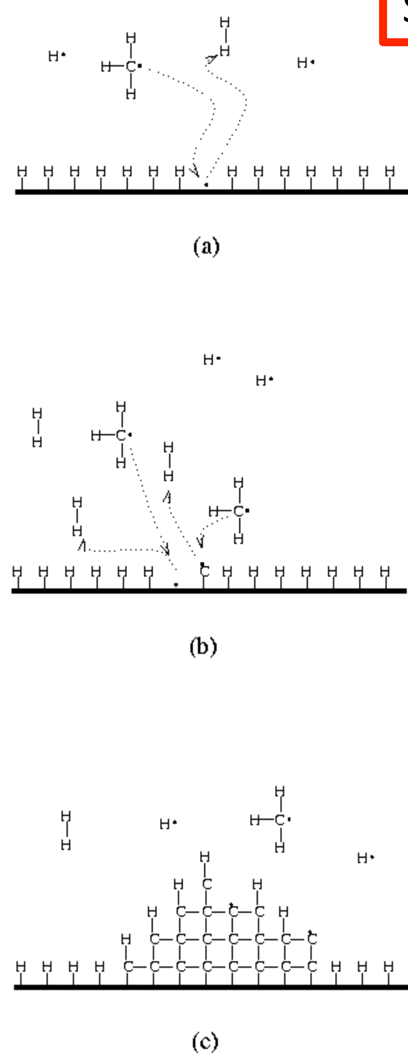


- **70 MeV protons 3 times more damaging than 24 GeV protons**
- **26 MeV protons seem to be even more**

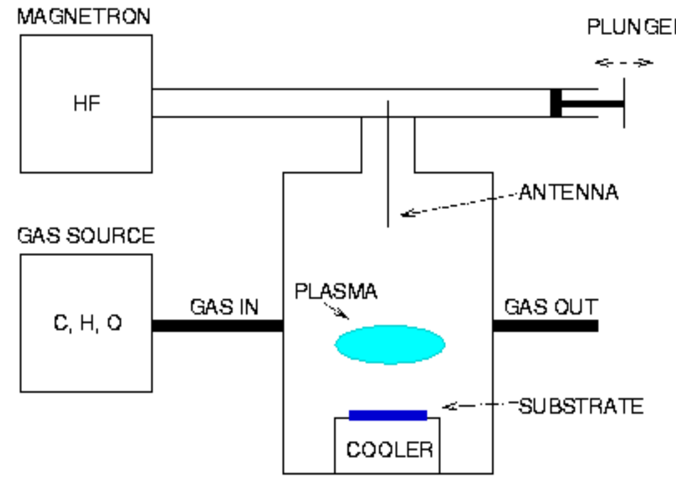
Production of CVD diamond sensors

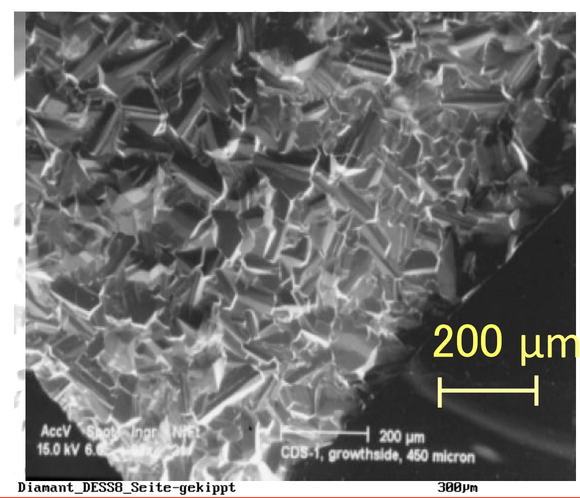
- Chemical Vapor Deposition (CVD) diamond growth:
  - using a gas at low temp. (< 1000 °C) and low pressure (~0.1 atm) in a non-equilibrium process
- CVD diamond grown in μ-wave reactors on non-diamond substrate
  - Allows deposition of diamond on large areas in arbitrary geometries.
- CVD Diamonds are composed of columnar microcrystals.
  - **Growth speed only ≈ μm / h**
  - **Slow=expensive**

CH_4 in form of gas or vapor



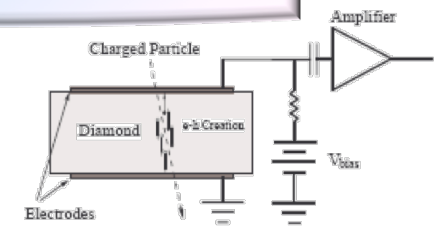
Schematic diagram of a CVD reactor



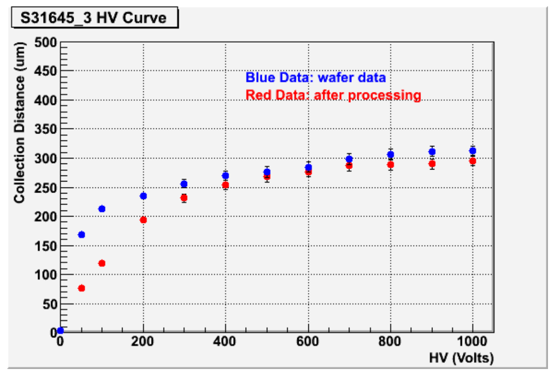


Scanning electron micrograph from the growth side of a CVD diamond sample

Signal from CVD Diamonds



- No processing: put electrodes on, apply electric field. **BUT :**
  - Surface preparation and metallization **non-trivial !**
- 2 types: SsCVD and pCVD sensors
  - For pCVD trapping on grain boundaries and in bulk
    - Very similar to heavily irradiated silicon

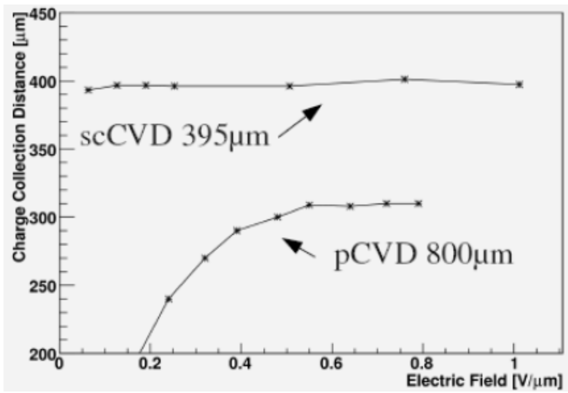


CCD **measured on recent 1.4 mm thick pCVD wafer from E6, and after thinning to 0.8 mm**

- Parameterized with Charge Collection Distance, defined as

$$CCD = \frac{\langle Q_{col} \rangle}{36 \frac{e_0}{\mu m}}$$

✧ **mean** collected charge

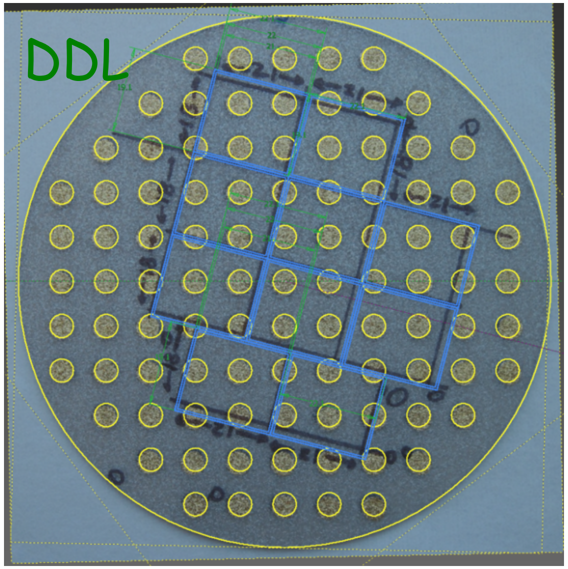


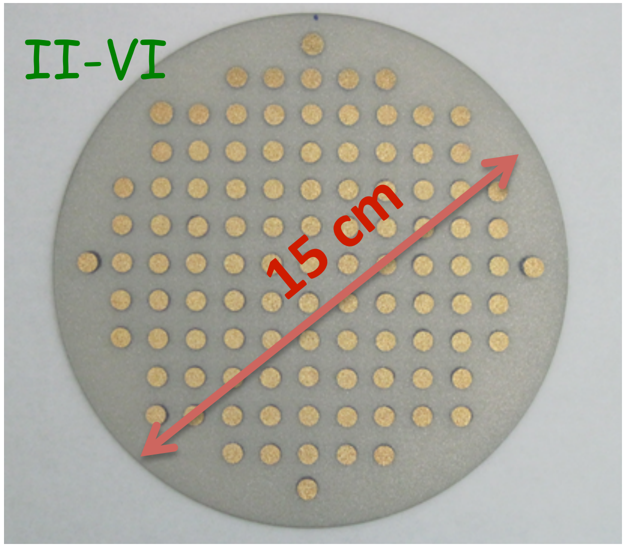
CCD **vs. field for pCVD and scCVD diamond**

- *CCD* = average distance e-h pairs move apart

Diamond Manufacturers

- Several large sensors delivered in the last years :
  - Diamond Detectors Ltd, UK
  - II-VI Infrared, USA
- But DDL this year ending the business!
  - re-structuring from Element Six/DeBeers
- Element Six/DeBeers remains a strong supplier but they do not delivery sensors with metallization, only raw material!





CVD Diamond Sensors application as Radiation Monitor

- Crucial application as radiation monitors to protect Silicon vertex trackers from a high radiation dose due to i.e. beam losses or high background rates
  - Need to abort beam in presence of a current spike or a prolonged radiation dose letal for the SVT
- A fast, radiation hard detector with a low leakage current is therefore required
  - False signals must be avoided.
  - Monitor must be reliable
- CVD diamond sensors already employed for this purpose by several experiments:
    - BaBar, Belle, CDF, ATLAS, CMS, LHC-b, ALICE

Beam loss and conditions monitor in ATLAS e CMS

- CMS and ATLAS use diamond already since a few years as a sensor for a beam loss and conditions measurements close to the beam pipe.
- Same type of device used by CMS & Atlas inside their trackers
  - CMS: ~ z=±1.8m and r=4cm
  - Atlas: ~ z=±3.5m close to beam pipe
- Act as part of a radiation monitoring system for equipment safety and radiation level/beam monitoring
- A beam conditions monitor can in particular address the following issues:
  - Allow to protect equipment during instabilities / accidents
  - Providing feedback to the machine thereby helping them to routinely provide optimum conditions
  - Monitor the instantaneous dose during operation
- Clear advantages of diamond respect to silicon for this application
  - **Radiation hard, low leakage currents at room temperature, fast signal response**

Diamond Sensors @LHC

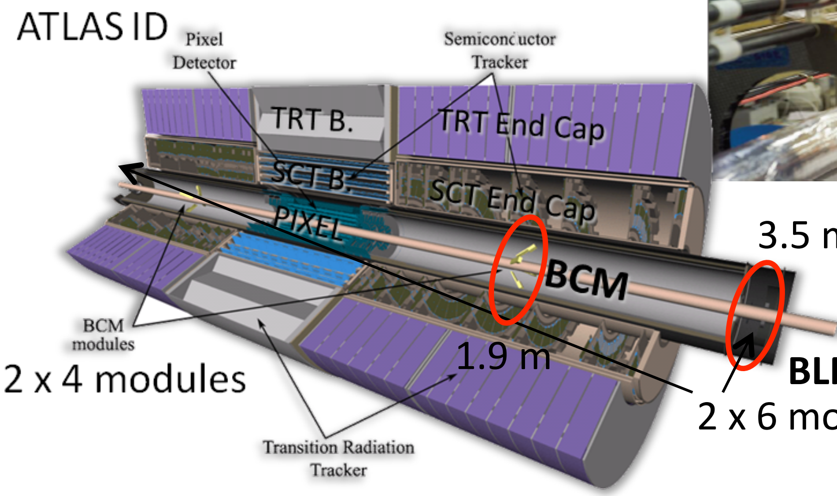
- All LHC exp's use diamonds for beam monitoring & accident protection
  - Current and counting mode operation, TOF capability
  - Today *O*(100) diamond sensors employed
- CMS is building Pixel Luminosity Telescope
  - 48 scCVD pixel modules (5 mm x 5 mm)
- ATLAS is building a new Diamond Beam Monitor
  - 24 pCVD pixel modules (21 mm x 18 mm)
- Upgrade plans for HI-LHC to include diamond as candidate for innermost pixel tracker layer(s)
  - Need ultra-fast FE electronics

Diamond sensors in HEP

Exp.	Application	# ch	cm^2	FE	Year
Babar	BCM	12	12	DC	2002
CDF	BCM	13	16	DC	2006
ATLAS	BCM	8	7.7	MIP	2008
ATLAS	BLM	12	32	DC	2008
CMS	BCM	32	7.7	MIP/DC	2009
CMS	PLT	200 k	30	Pixel	2012
ATLAS	DCM	730 k	90	Pixel	2013

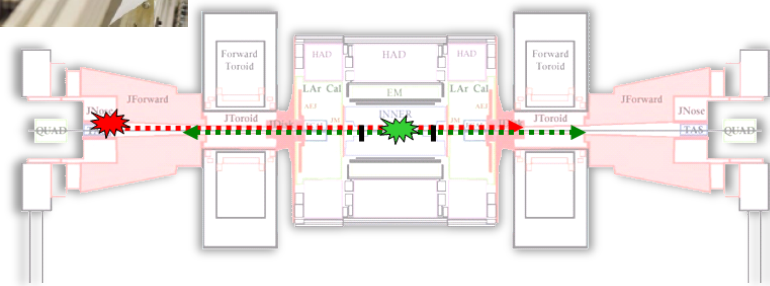
Table 2: Diamond detector built and proposed for beam onitoring and luminosity measurements (PLT and DCM).

Present ATLAS BCM/BLM

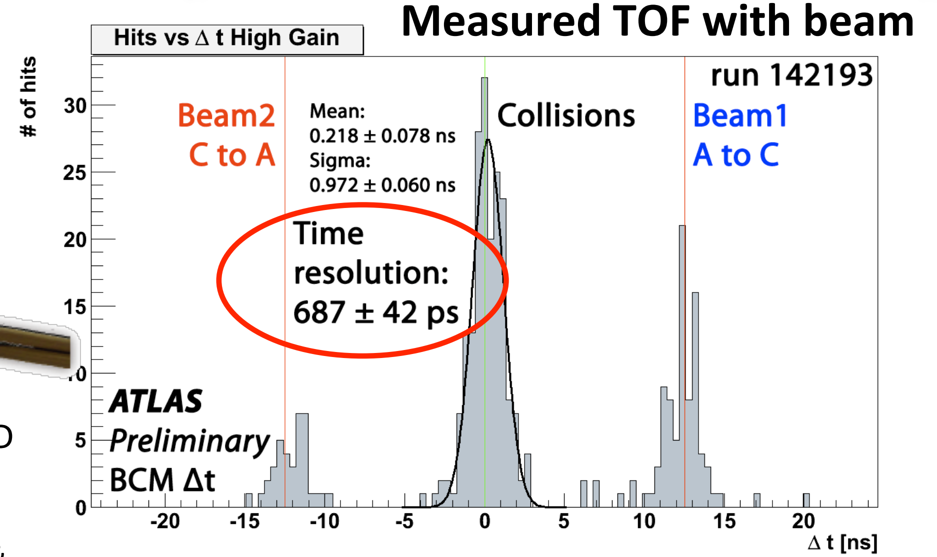


BCM TOF concept

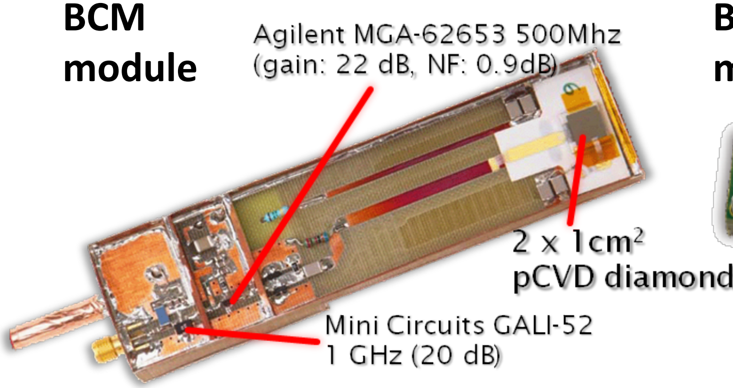
- Collisions: in time
- Background: out of time



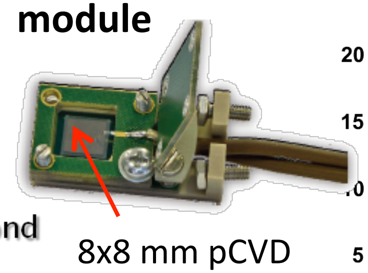
Measured TOF with beam



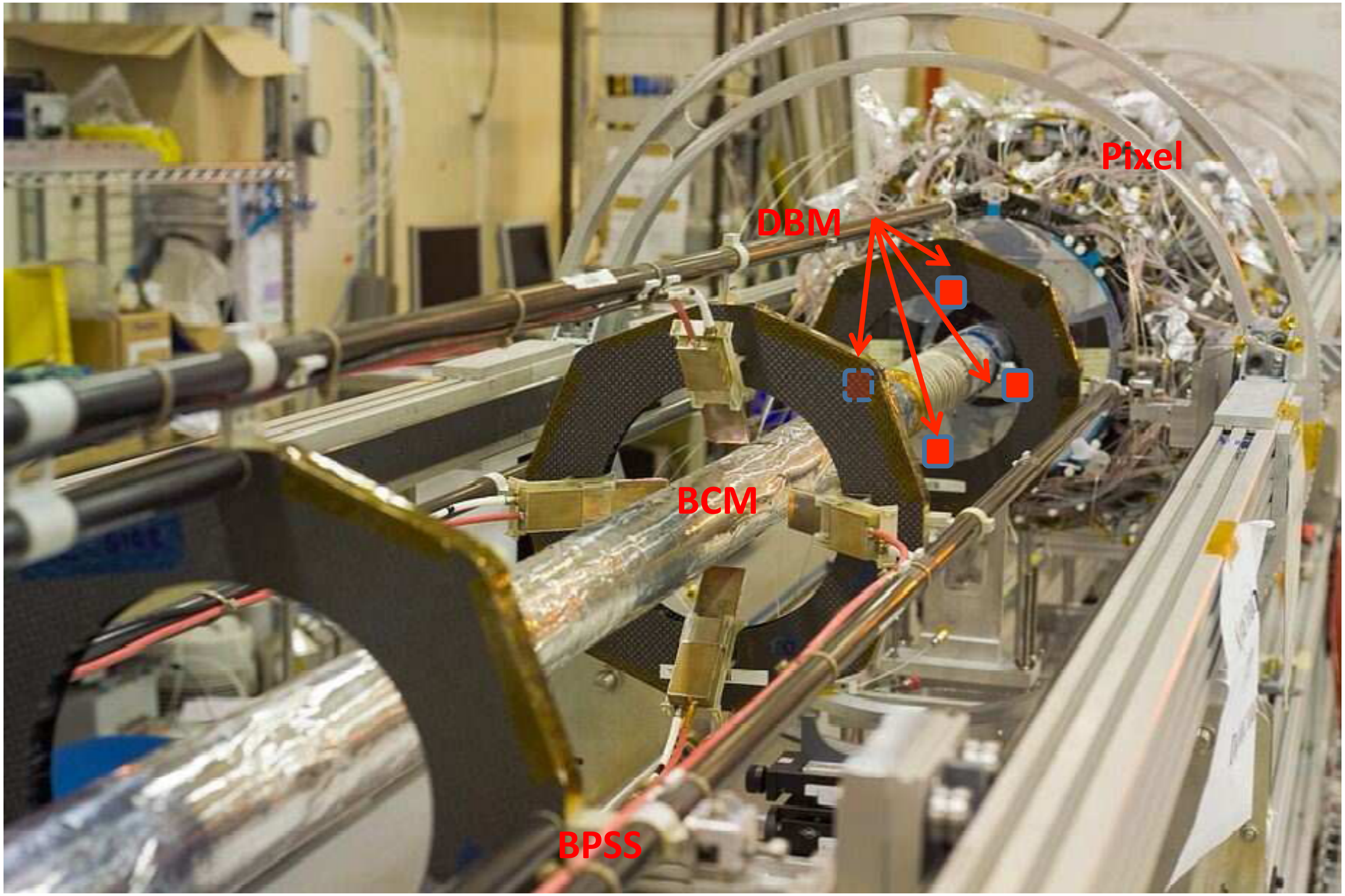
BCM module



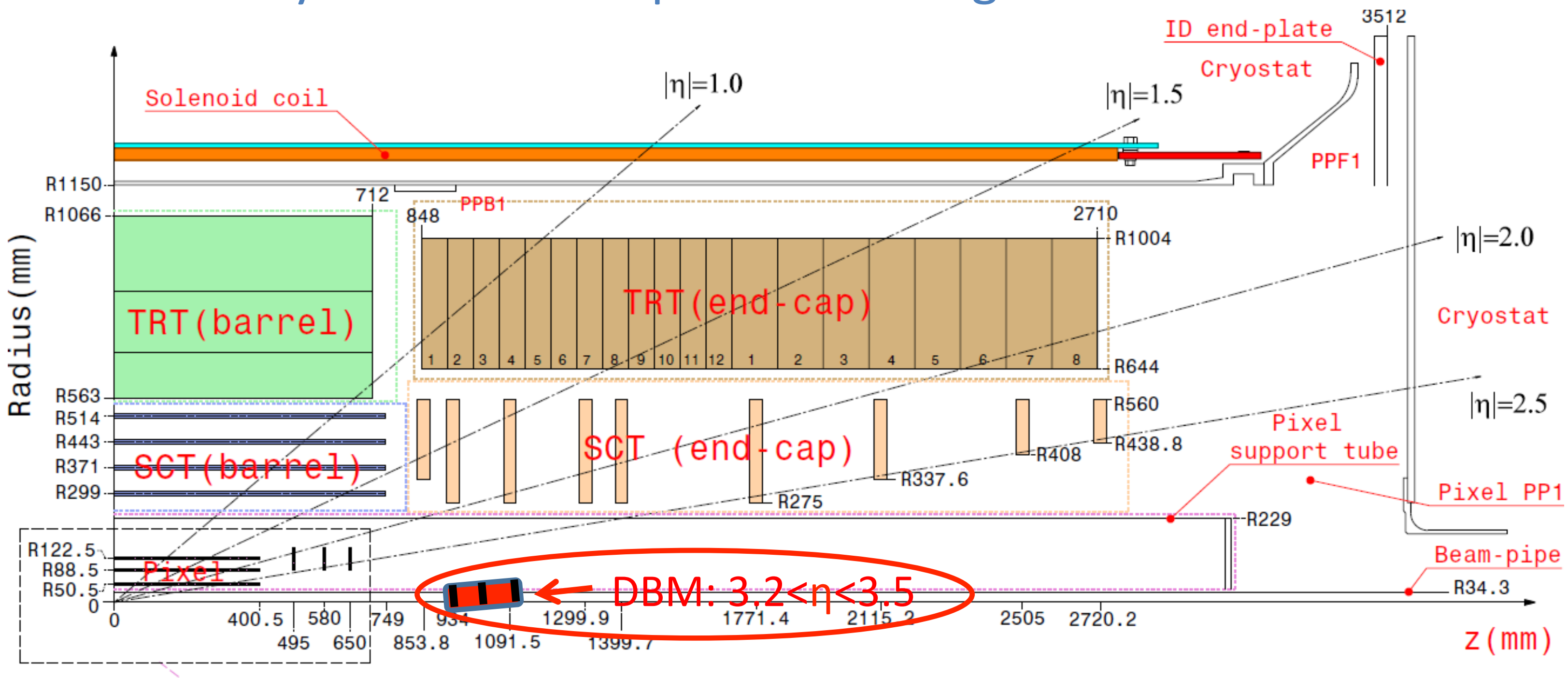
BLM module



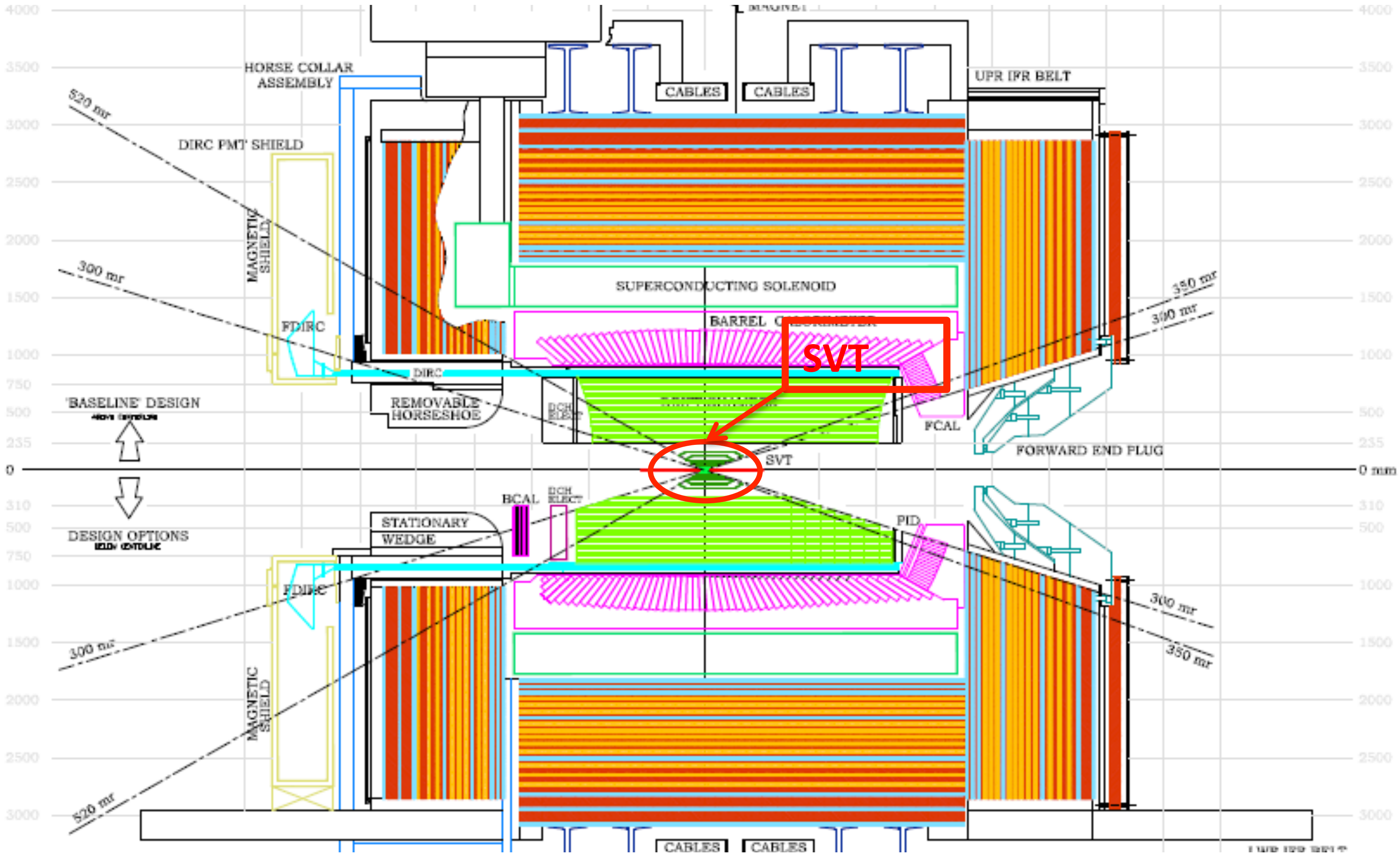
ATLAS- DBM - Installation



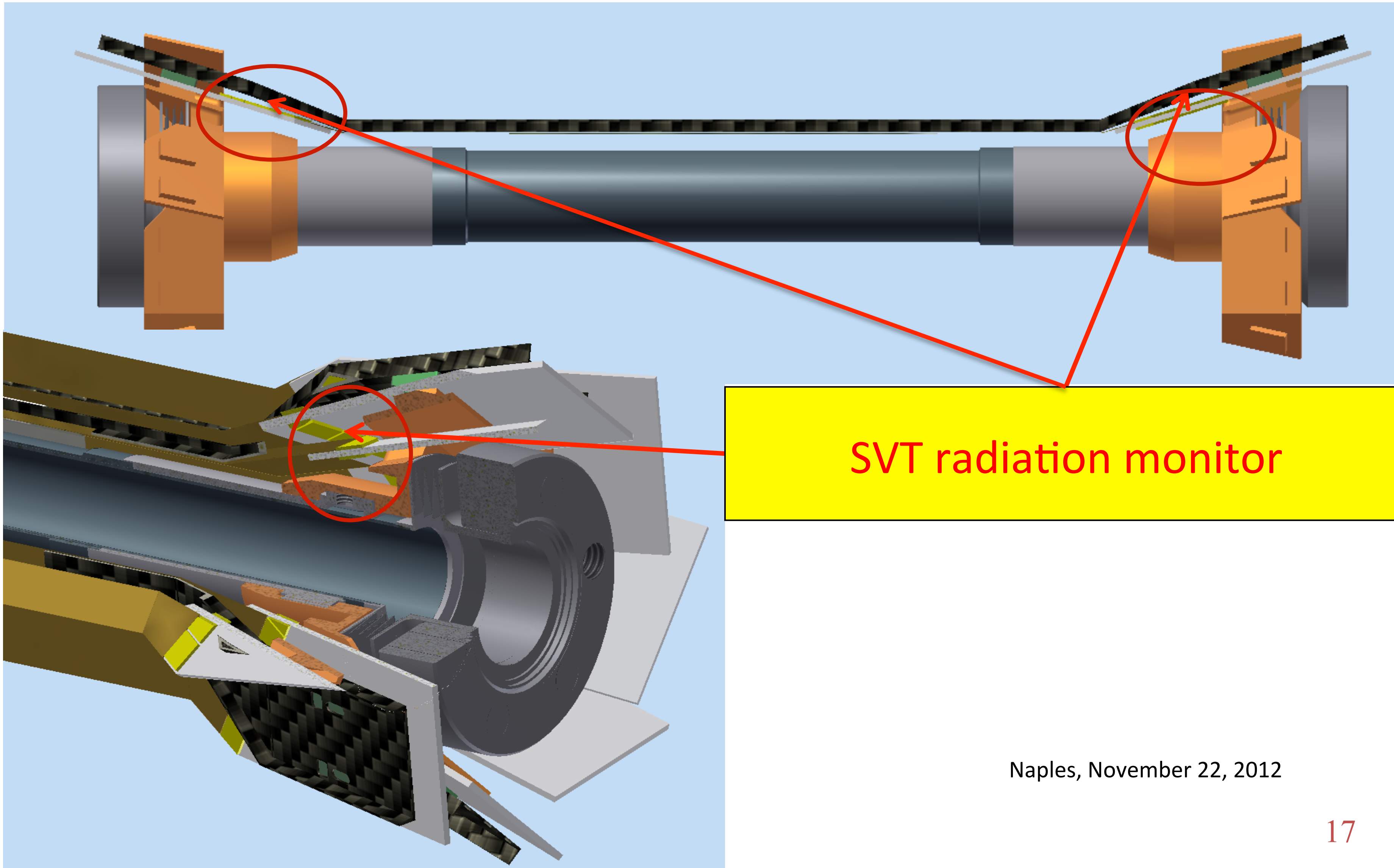
Future ATLAS Diamond Pixel Monitor

- 24 diamond pixel modules arranged in 8 telescopes around interaction point provide
  - Bunch by bunch luminosity monitoring
  - Bunch by bunch beam spot monitoring
- Accepted during last months as add-on to IBL
- 

The SuperB - SVT radmon

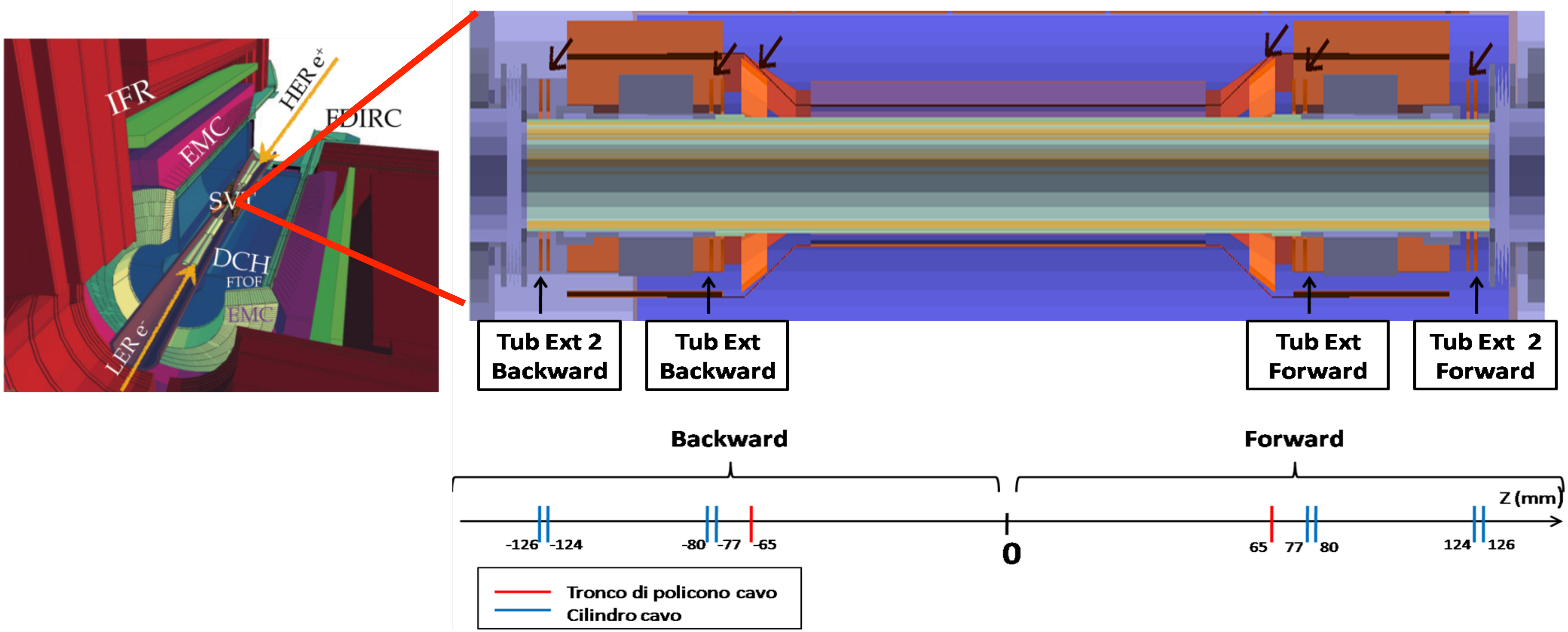


SVT Radiation Monitor



Naples, November 22, 2012

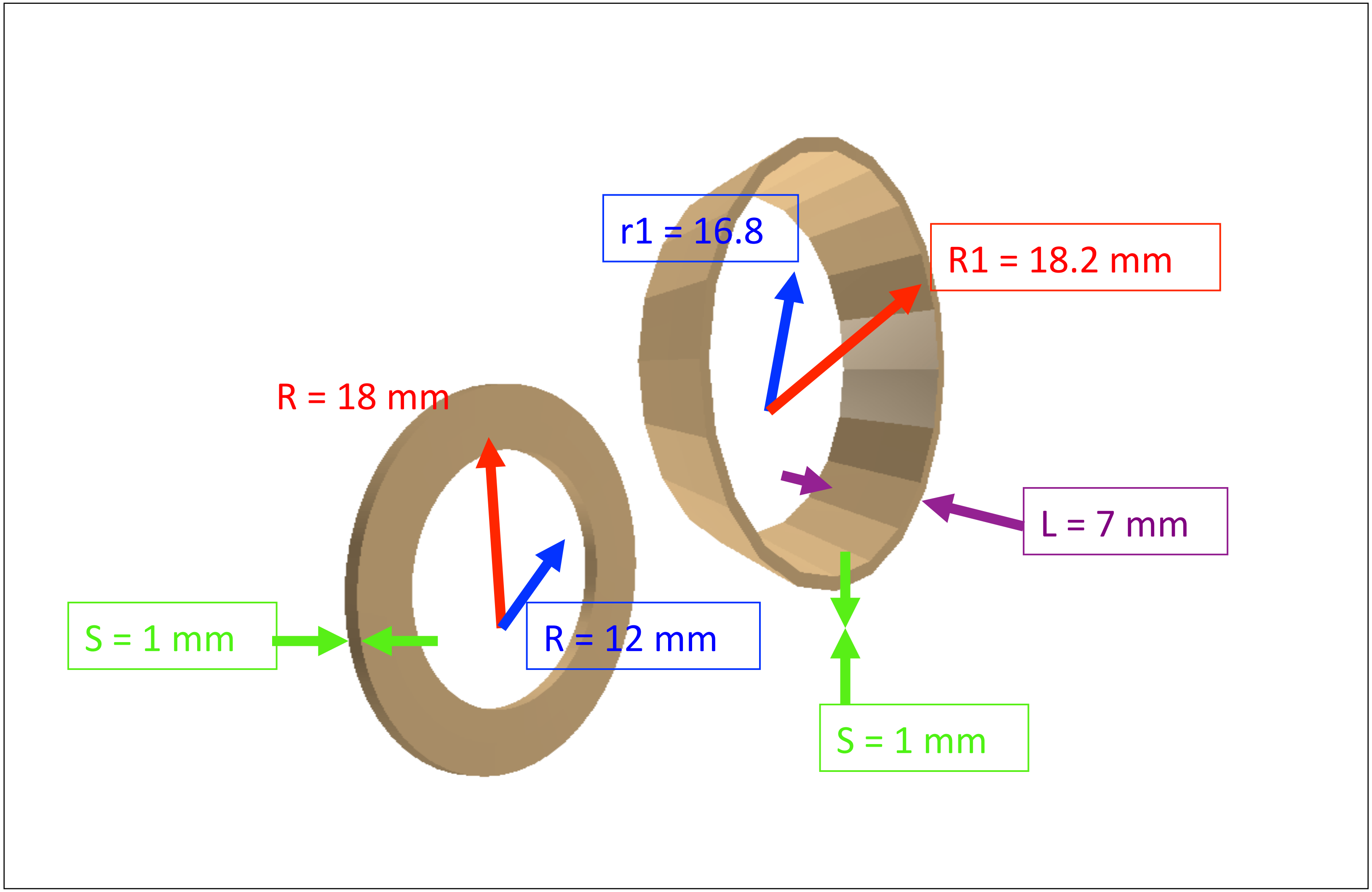
Diamond Rad Monitors in SUPERB



Goals to achieve:

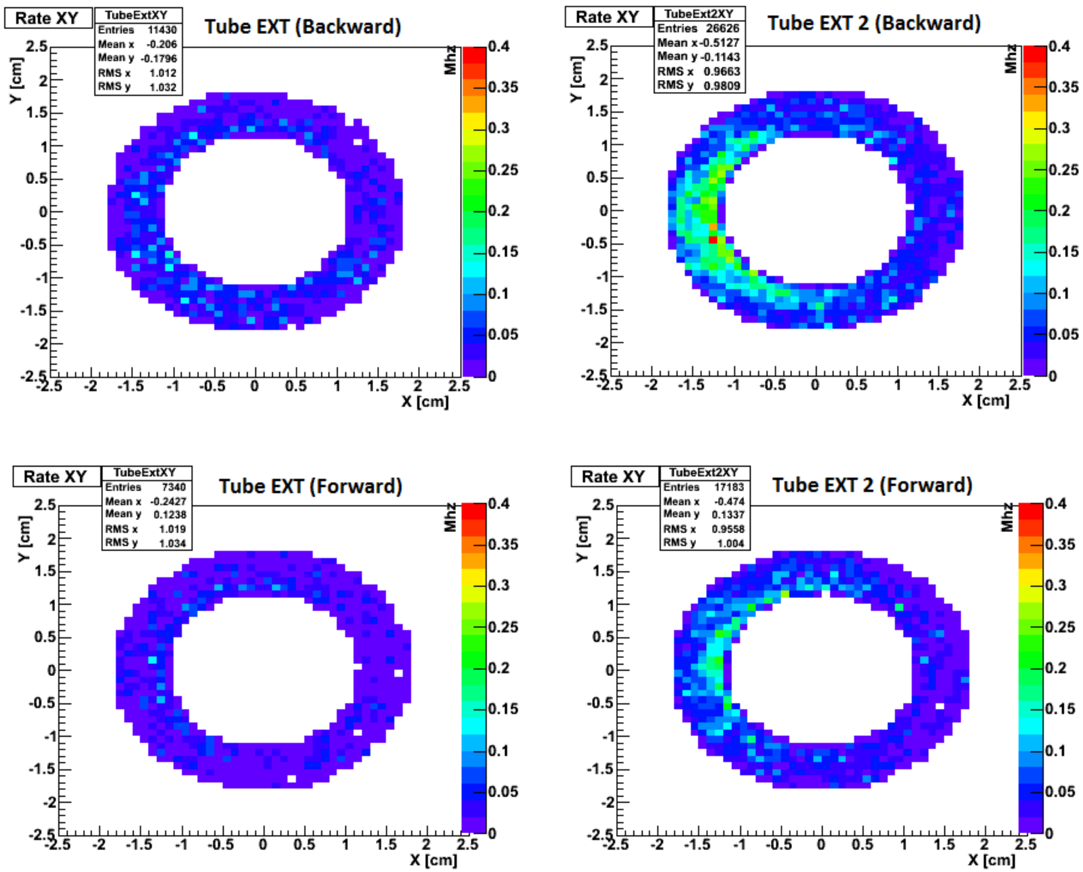
- **protect the SVT from high beam losses**
- **time of flight measurements to distinguish collisions events from background**
- **luminosity measurement**

Tentative detector's support shape



Geant4 results: rate per mm^2 for radiative Babbha

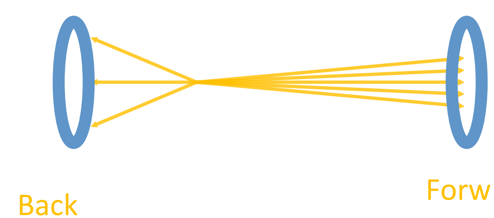
Expected rate on Beam-monitor rings 1, 2



Bins da 1mm^2

- Highest rate about 0.25 MHz / mm^2 (on Backward)

- Possible explanation : SuperB beam asymmetry



S. Tammaro

Geant4 background results @ L = 1 x 10^{36} cm^{-2} s^{-1}

Radiative Babba production

	Rate (MHz)	Edep/sec (GeV/s)	nHits/Event	Edep/Hit (GeV)	Rate/mm^2 (MHz/mm^2)	% Hits (>150KeV)	Z (mm)
Tube Ext (Back)	19.9	1780	0.09	9.0×10^{-5}	0.035	22%	-80
Tube Ext 2 (Back)	46.4	2080	0.20	4.5×10^{-5}	0.082	10%	-126
Tube Ext (Forw)	12.8	1115	0.06	8.7×10^{-5}	0.023	21%	80
Tube Ext 2 (Forw)	30.0	1305	0.13	4.3×10^{-5}	0.053	10%	126

e+e- Pair production : dominant bkgd

	Rate (MHz)	Edep/sec (GeV/s)	nHits/Event	Edep/Hit (GeV)	Rate/mm^2 (MHz/mm^2)	% Hits (>150KeV)	Z (mm)
Tube Ext (Back)	199	16×10^{3}	0.88	8.2×10^{-5}	0.35	19%	-80
Tube Ext 2 (Back)	116	5×10^{3}	0.51	4.2×10^{-5}	0.21	9%	-126
Tube Ext (Forw)	203	17×10^{3}	0.90	8.1×10^{-5}	0.36	19%	80
Tube Ext 2 (Forw)	119	5×10^{3}	0.52	4.4×10^{-5}	0.21	9%	126

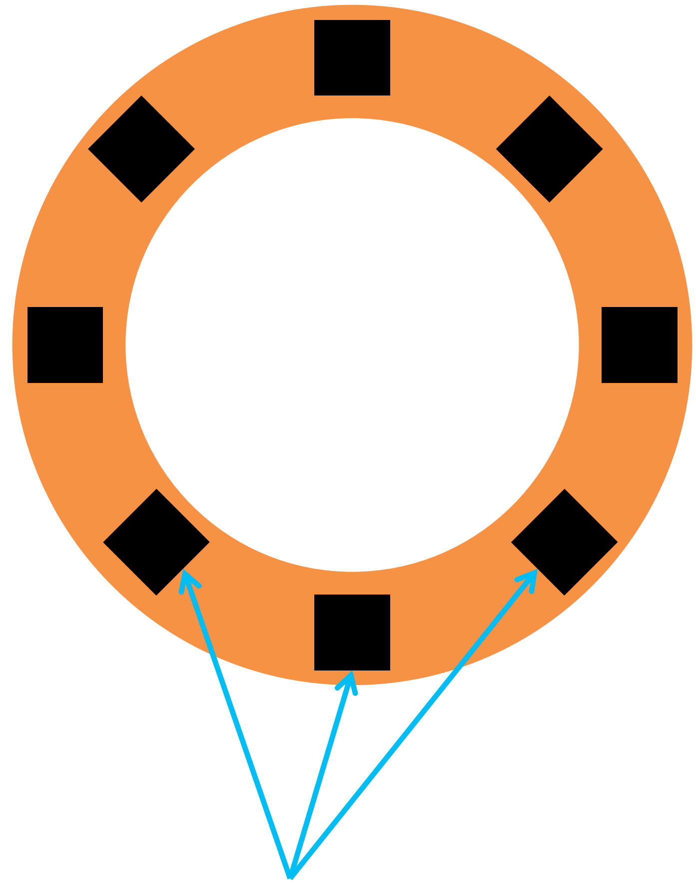
S. Tammaro

Geometry of the detector

Beam monitor caracteristics $L = 1 \times 10^{36}\ cm^{-2}\ s^{-1}$

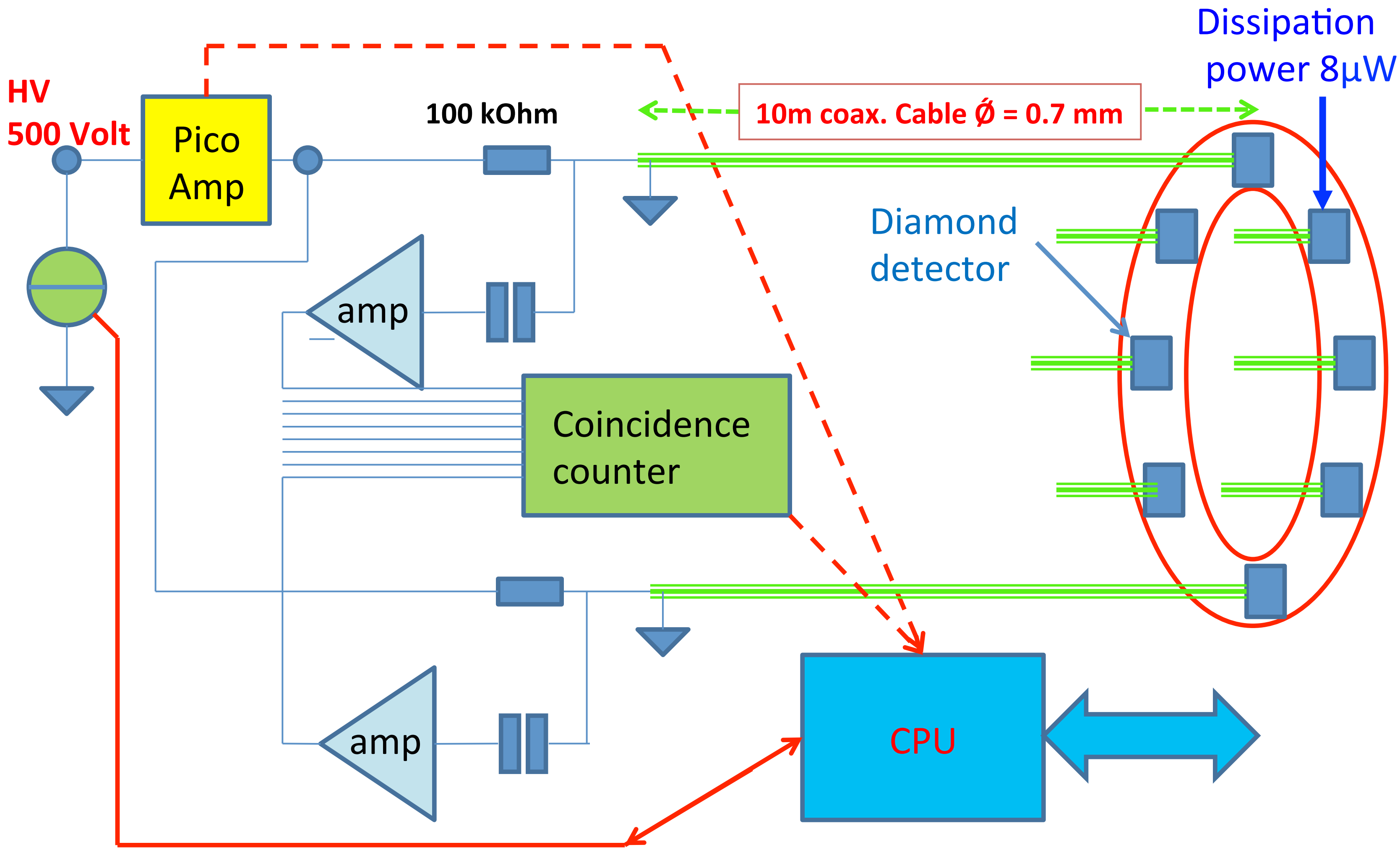
detector sized	8 X16 mm^2
leakage current	8 nA
Ionization current	0.67 nA
hits rate	130KHz
Detector Transit time	20 ns
Electronic Integration time	30 ns
Electric resistance	10^{11} Ωcm
Energy threshold	150KeV

8 diamond detector for ring



Diamond detector
4mm x 4mm

Tentative electronic diagram

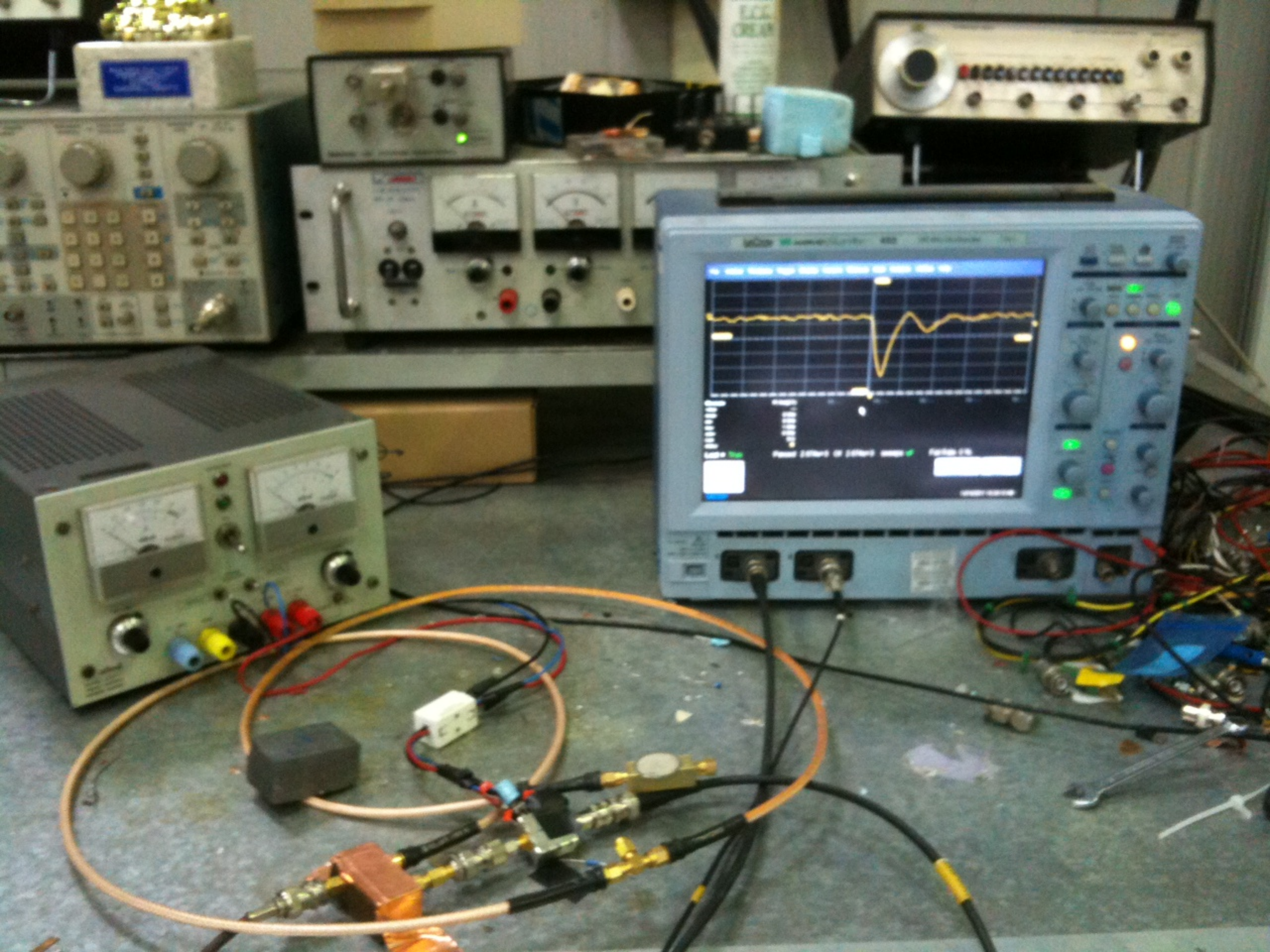


Diamond sensor tested in Tor Vergata laboratoty

- Mono crystal diamond
- thickness 0,5 mm
- Area 4 x 4 mm^2
- HV 400 Volt
- Dissipation power 8 μW

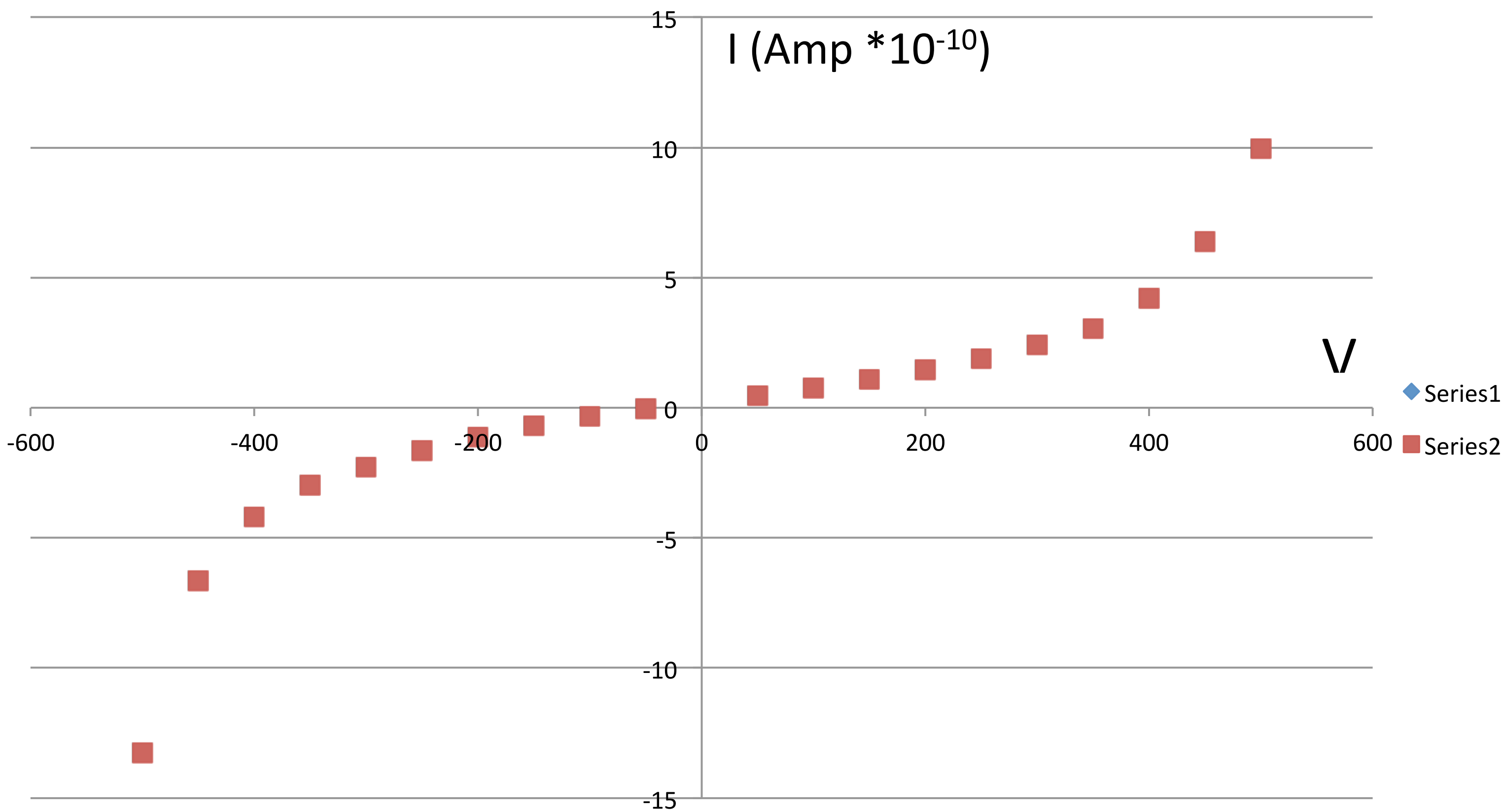
PreAmplifier, AC, (BJT SiGe, BFP740)

• Voltage supply	5 Volt
• Sensitivity	6 mV/fC
• noise	500 e^- RMS
• Input impedance	50 Ohm
• B.W.	30 MHz
• Power consumption	8-10 mW/ch
• Low cost	2 – 3 eur./ch
• Radiation hardness	50 Mrad, 10^{15} n cm^{-2}

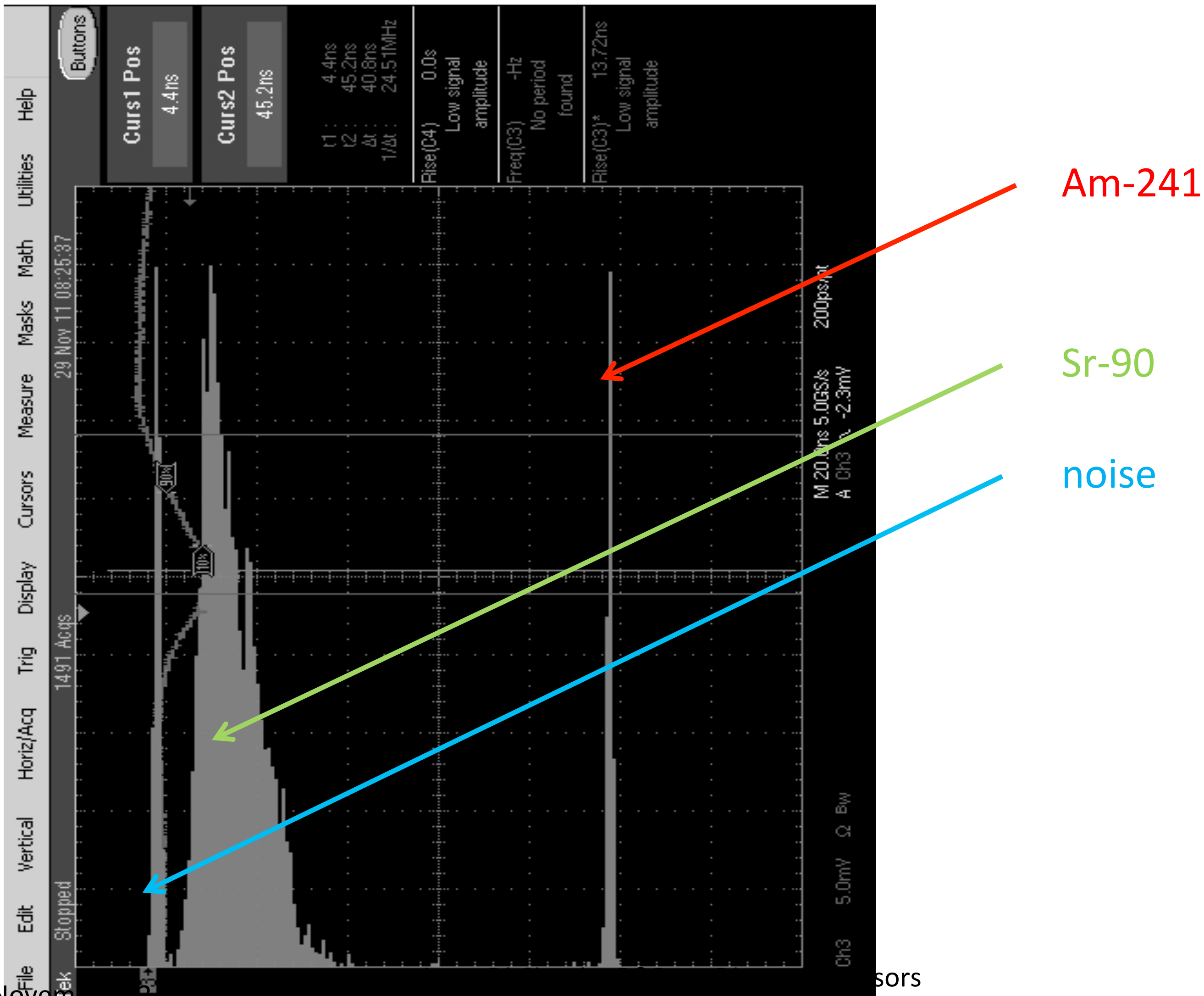


I vs HV (sCVD- diamond detector)

- **Good CVD diamond detectors have a symmetric I–V behavior and can therefore be biased positively or negatively.**



Test with Americium-241 + Sr-90 sources



Coincidence with cosmics

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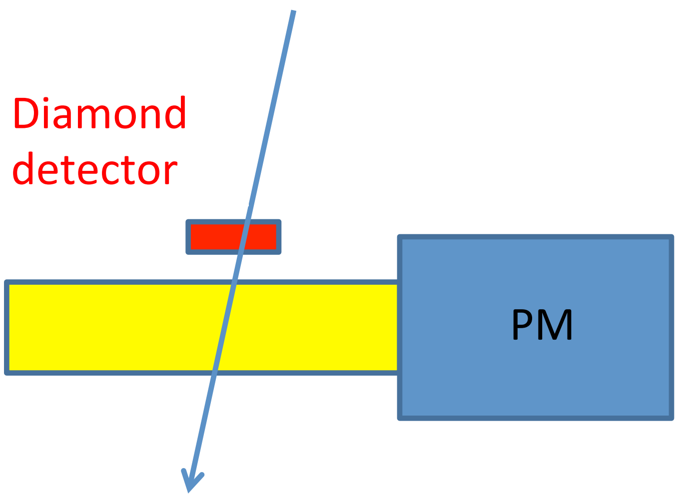
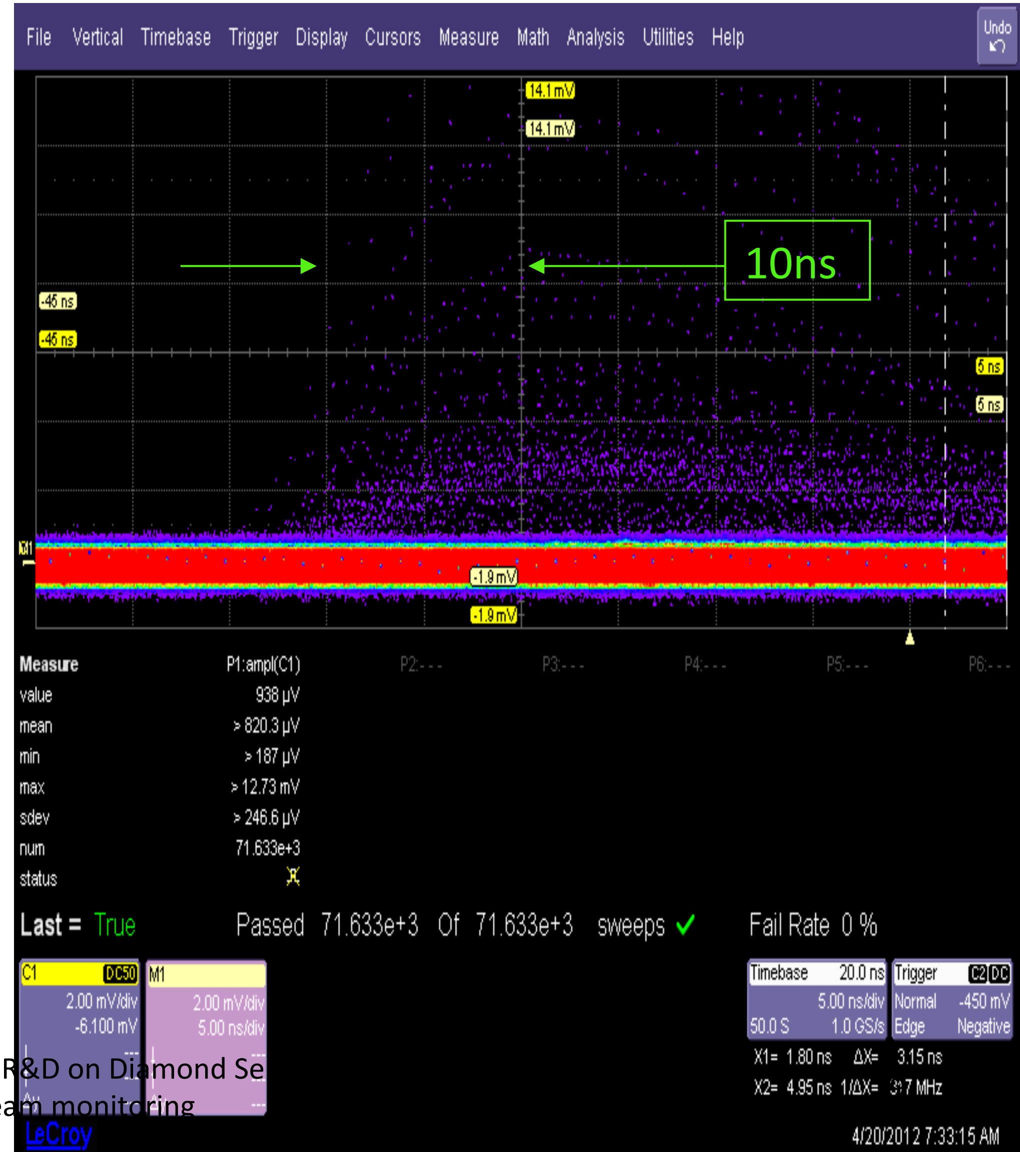
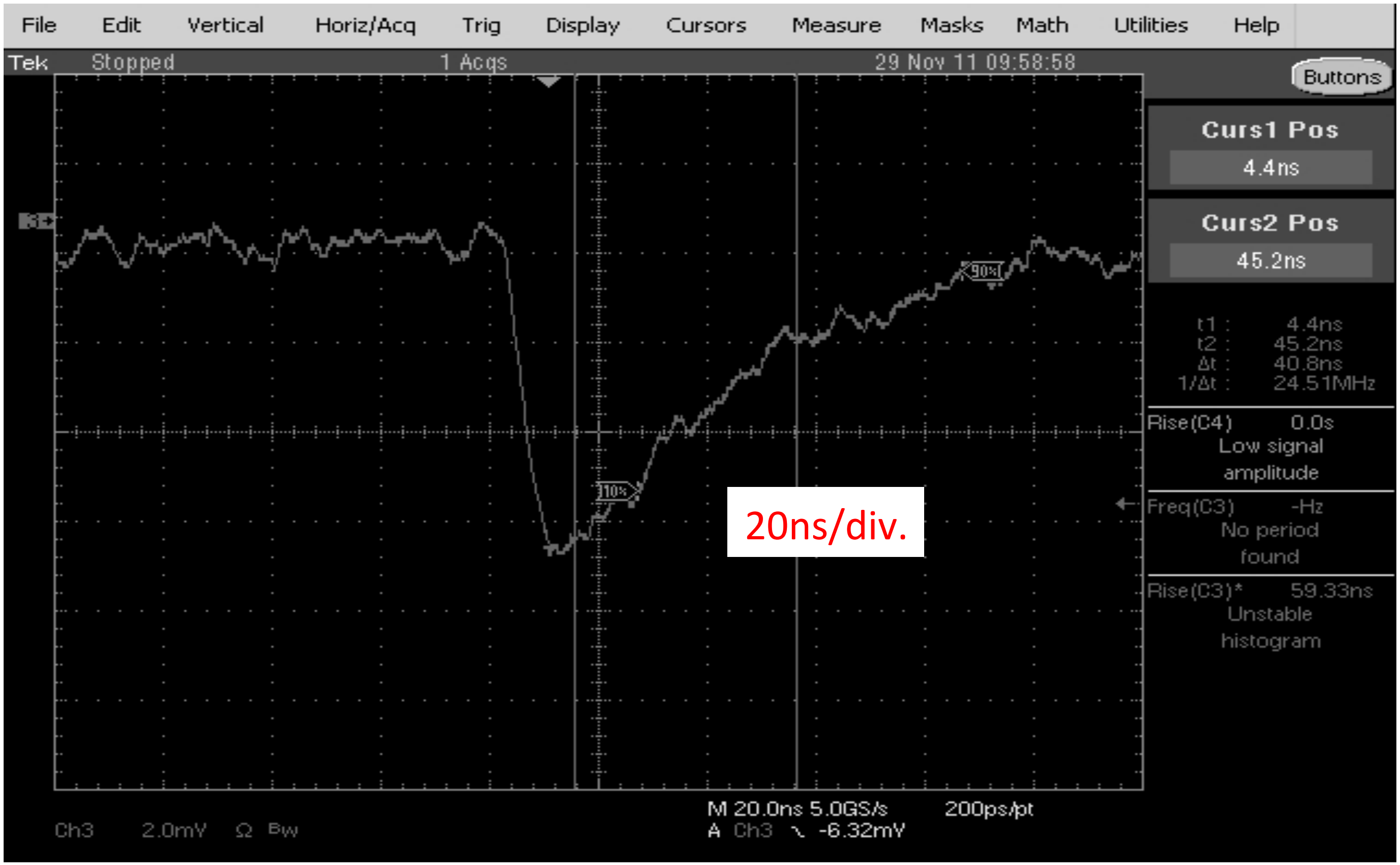




Signal minimum ionization particle

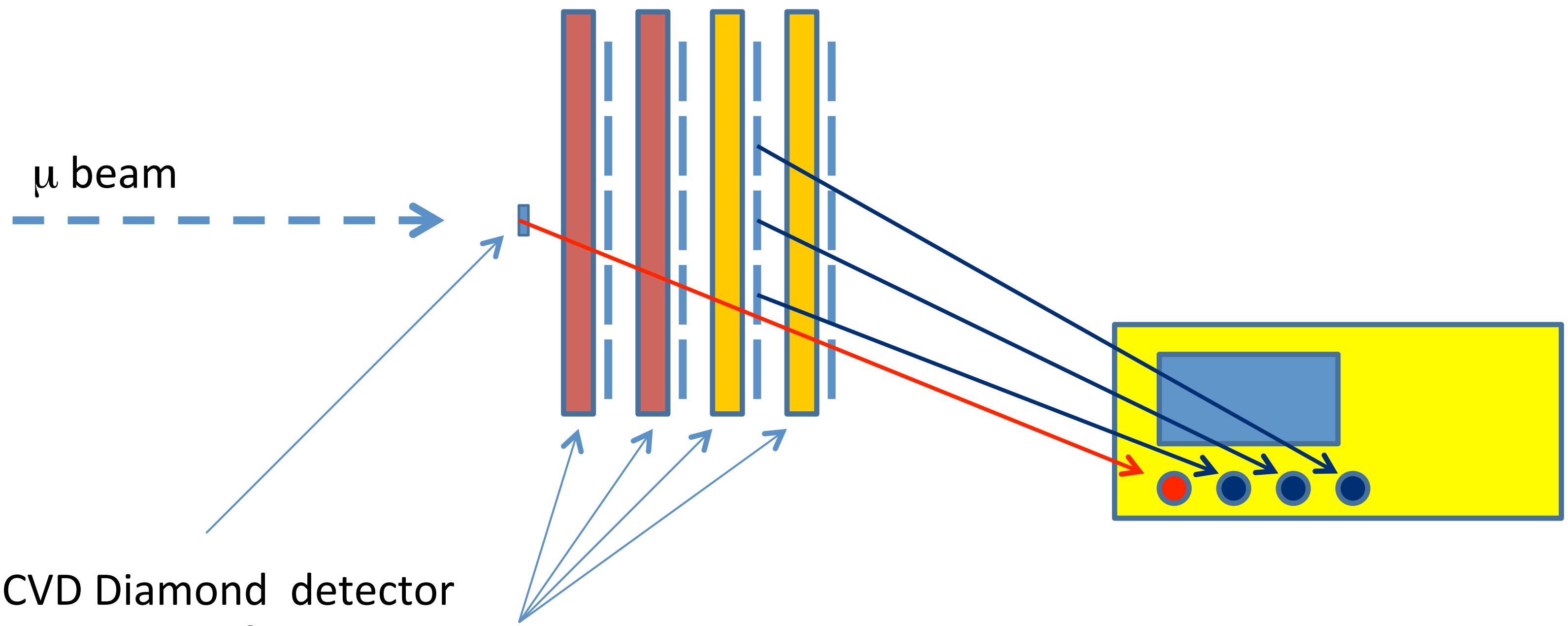


20ns/div.

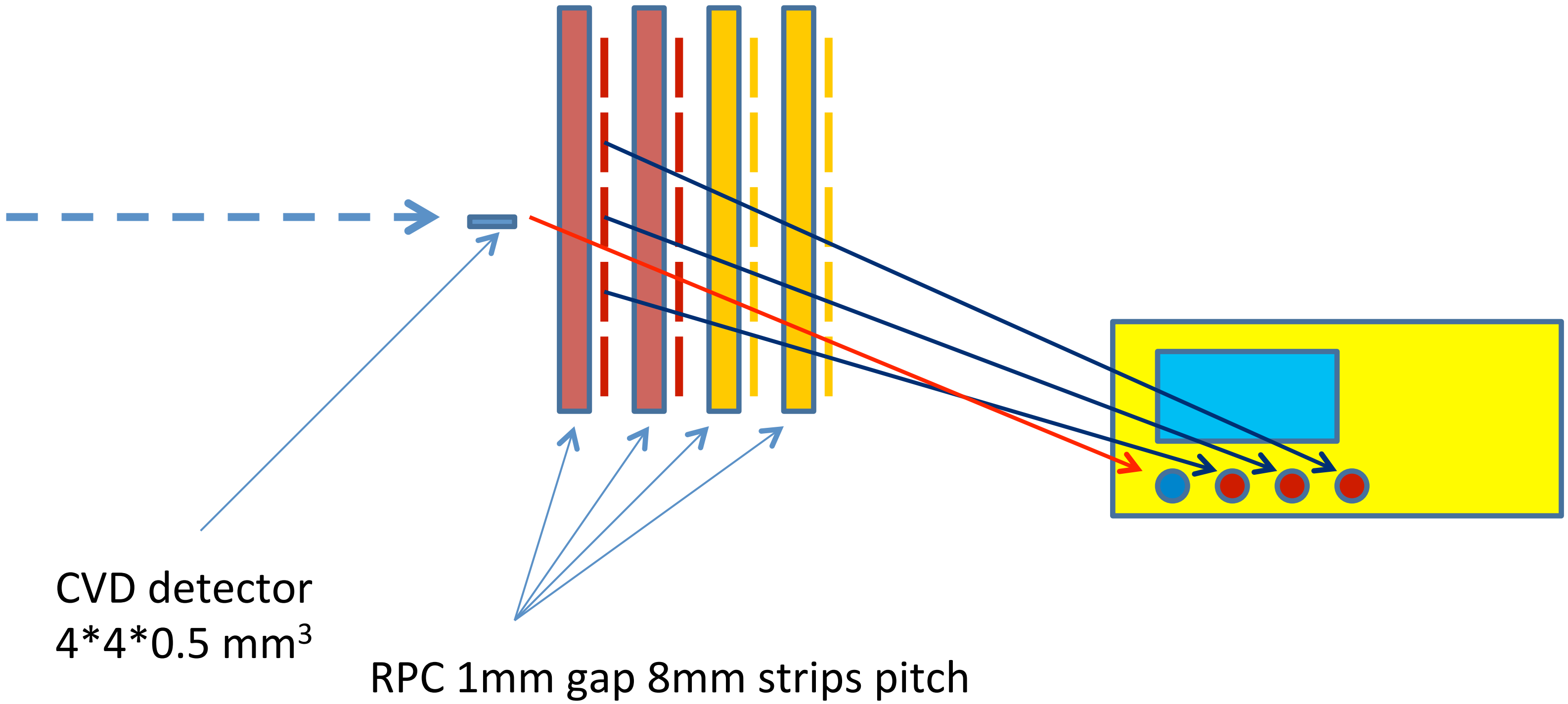
H8 Beam test –beam at CERN: time resolution measurements (Novembre 2012)

- A diamond detector 4x4x0.5 mm^3 with **2 set-up** (see next slides) was tested together with 4 RPC chambers (1mm gas gap each) on a muon beam
- One of the four RPC was used to measure the time of flight with the diamond detector

Experimental H8 test-beam: set up 1 → (Diamond orthogonal to the beam)

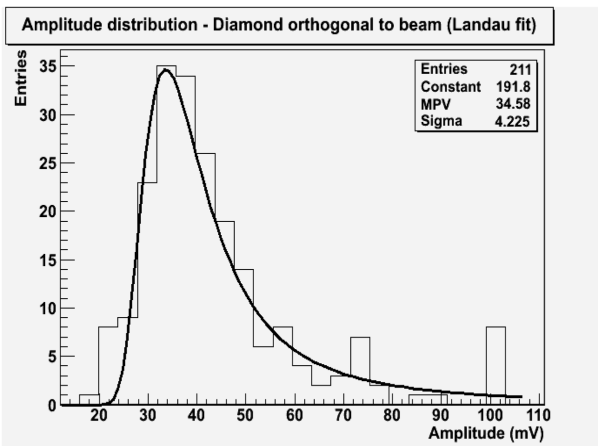


H8 set up 2 (diamond parallel to the beam)



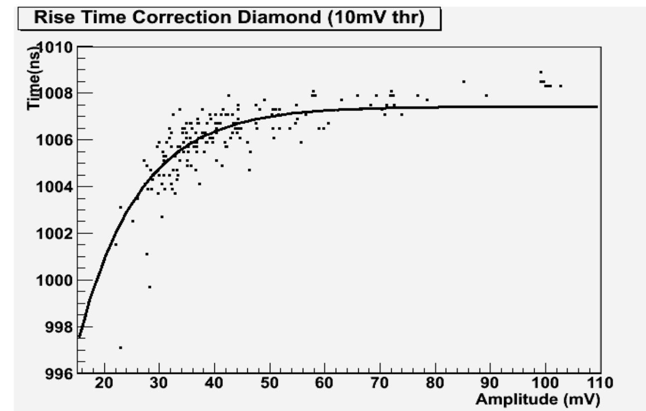
Diamond detector/Front-end electronics consistency checks

Diamond m.i.p. signal distribution

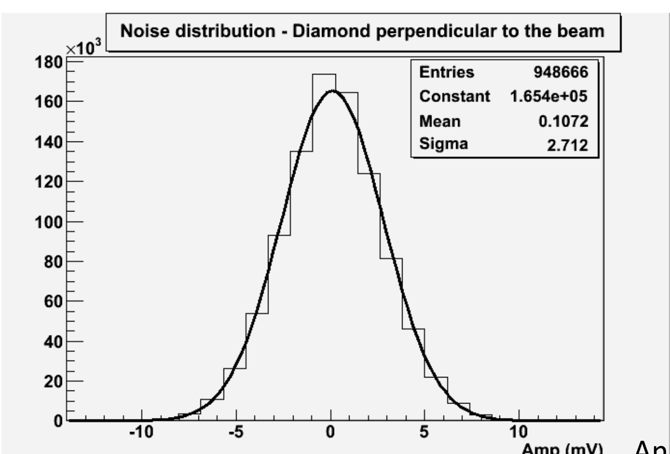


The diamond amplitude distribution, fitting the expected Landau distribution, is used to correct the timing for the signal amplitude

Time vs signal amplitude

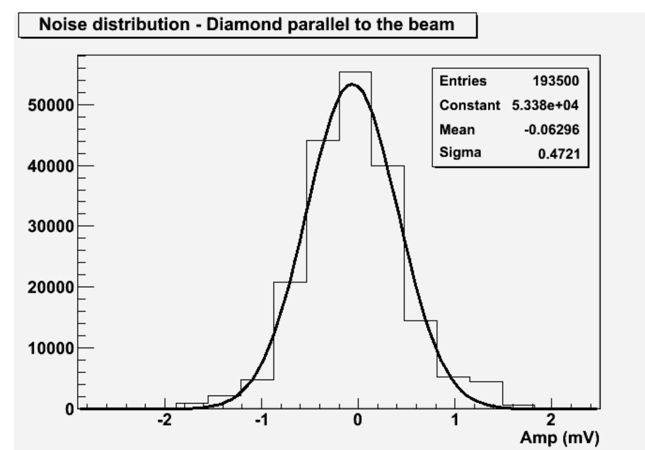


noise for 2 stage +1 stage amp



Front end noise distributions:
- Left plot :2 stage amp followed by 1 stage amp (for ortogonal orient)
- Right plot: only 2 stage amp (for parallel orientation)

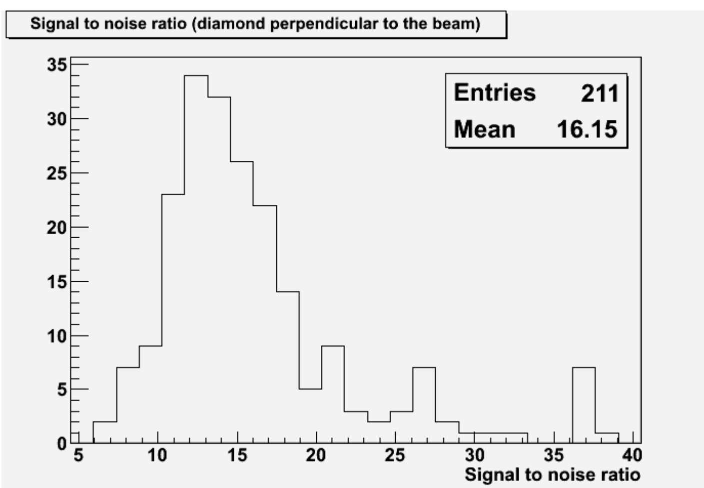
noise for 2 stage amp



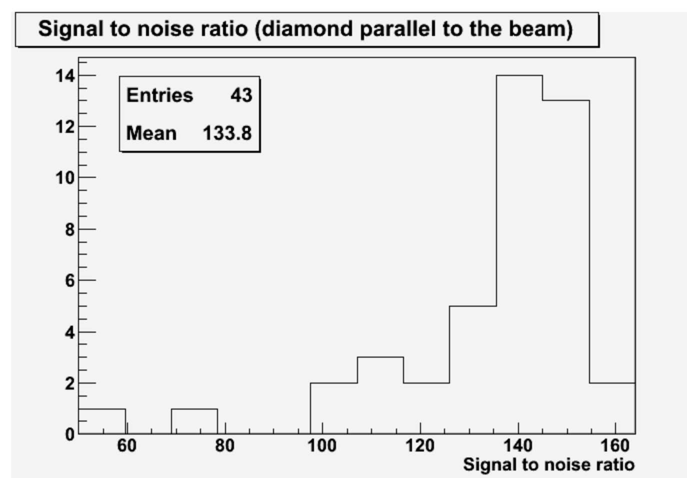
Expected diamond time resolution

- The diamond timing is strongly noise dependent through the relationship
  $\sigma = t_{rise}/(S/N)$ with $t_{rise} = 10$ ns
- The following resolutions are obtained for the two orientations of the diamond
  - Orthogonal orientation (d= 0.5mm) → $(S/N)Diamond_{orthogonal} = 16$ → $\sigma_t = 625$ ps
  - Parallel orientation (d = 4mm)→ $(S/N)Diamond_{parallel} = 133$ → $\sigma_t = 75$ ps

Signal/Noise ratio (orth. orientation)



Signal/Noise ratio (parallel orientation)



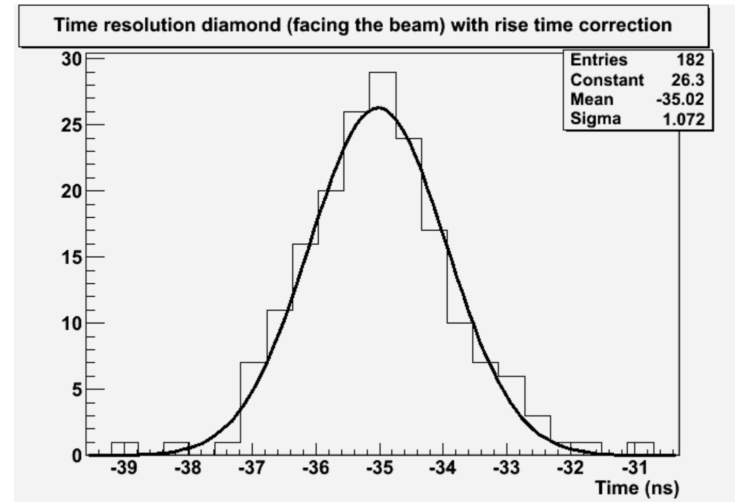
Preliminary results on combined diamond-RPC timing

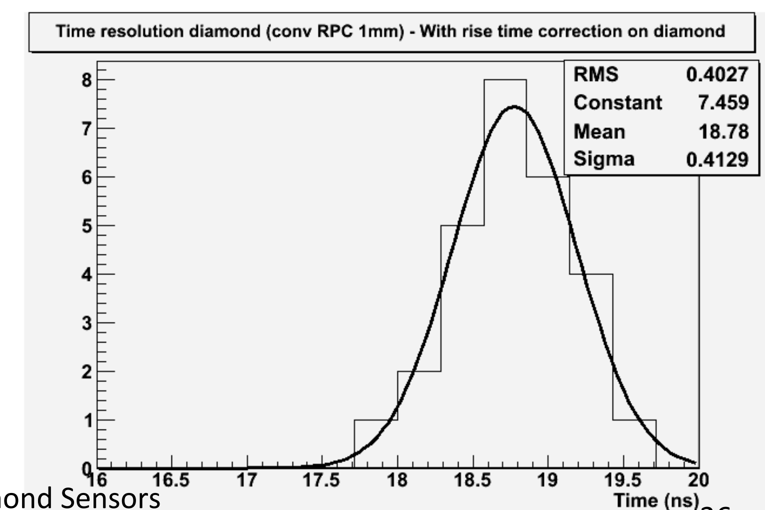
- Assuming $\sigma_{comb}^2 = \sigma_{Diam}^2 + \sigma_{RPC}^2$
- For orthogonal orientation the overall jitter is dominated by the diamond
  - σ_{Comb} = 1 ns
  - σ_{RPc} = 0.42 ns (1mm gas gap)

→ $\sigma_{Diam} \approx$ 900 ps

- For parallel orientation the jitter is dominated by the RPC
  - σ_{Comb} = 0.41 ns

→ σ_{Diam} < 100 ps





Next steps

- First results look very promising: a time resolution of < 100 ps was measured.
  - Further measurements are planned at the H8 test-beam and GIF with several CVD diamonds
  - We plan to make a test of our sensors next years also at the Daphne accelerator in Frascati
- The collected data allow to finalize the design of a new full custom 8 channel FE chip in SiGe technology, in preparation in Tor Vergata.

Summary

- **Many progress in the diamond world**
  - **Successful application in all LHC experiments as radiation monitors**
    - **Diamond trackers is also under way !**
  - **R&D work for the application in SUPERB as radiation monitor is proceeding**
  - **First tests in our laboratory and H8 quite successful**