Development of silicon detectors for Beam Loss Monitoring at HL-LHC

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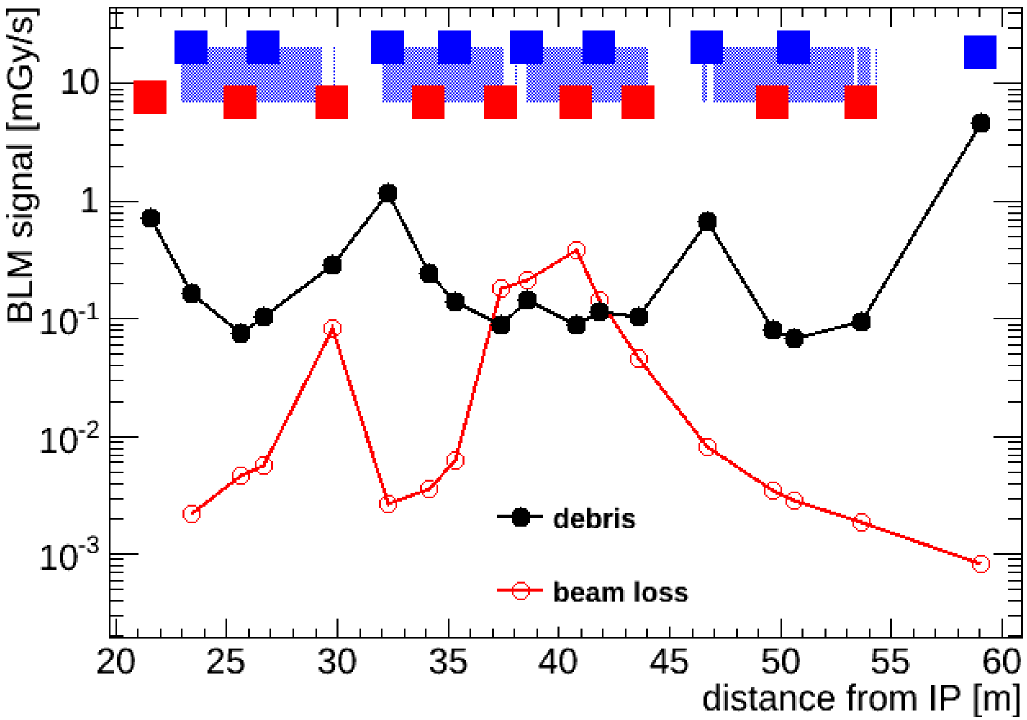
Motivation and background

- **Low beam losses –** ***regular regime for LHC operation.***
- **Increased beam loss -** ***fast pressure increase, particles of dust inside the beam pipe, etc.***
- **Energy deposition** ***from beam loss might heat up LHe magnets and then:***

Beam losses must be carefully monitored



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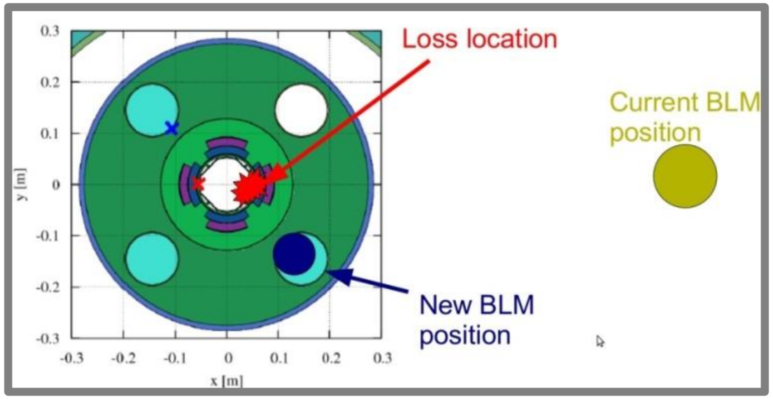
Solution: ***Place BLM sensor close to the magnet coil or integrate it in the coil construction. This requires:***

- **Operational temperature – 1.9 – 4K**
- **No access along the magnet lifetime**
- **Irradiation by debris up to fluence of $10e^{16}$ p/cm^2**

Silicon BLM concept



Operational conditions:

1. Operational temperature – 1.9 – 4K
2. No access along the magnet lifetime
3. Irradiation by debris up to fluence of $10e^{16}$ p/cm^2

Technical requirements

1. *Compactness*
2. *Technology of mass-production*
3. *Reproducibility of characteristics*
4. *Cost effectiveness*

Goal of development

1. *Full prototype of BLM*
2. *Predictable scenario of degradation*

Development under collaboration:

Be-Bi-BL group, RD39 (CERN)**, Ioffe institute** (St. Petersburg)**, HIP** (Helsinki)

Expected problems

1. **Complicate irradiation test:**
   irradiation in super-flued He 1.9K or liquid He 4.3K
   each experiment requires individual cryostat
2. **Limited experimental technique:**
   TSC, DLTS, I(T), C(V) methods are not available
3. **Precise alignment of invisible beam with invisible set of samples**
3. **Non stop data collection for ~ 1 month**
4. **Not enough data on:**
   - ***Radiation induced defects formation***
   - ***Properties of radiation induced defects as a trapping centers at at LHe***
   - ***Simulation tools***

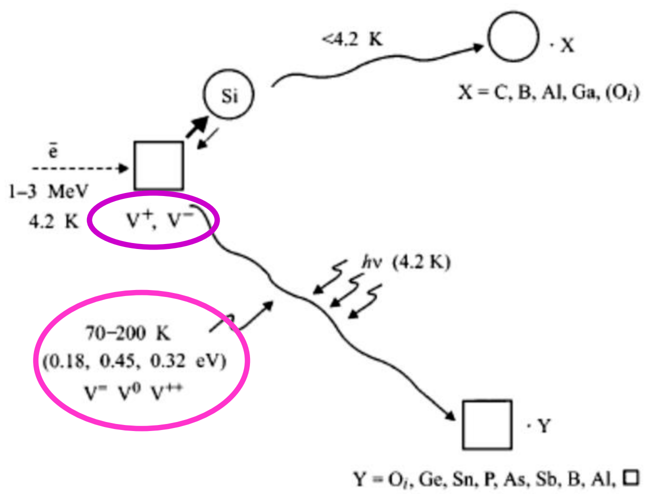
Solution

Application of laser based TCT and CCE vs. V and F analysis

Radiation damage in Si at cryogenic T

Available:

- renewed wide knowledge on radiation damage of **Si detectors at RT** and slight cooling (down to -50°C) – CERN RD collaborations, experiments at LHC



2. Evolution of events after a vacancy-interstitial pair is produced by an electron irradiation event in silicon [11,12].

- *G. D. Watkins, EPR of Defects in* ***Semiconductors: Past, Present, Future,*** *Phys. of Solid State, 41 (1999) 746-750.*
- *G. D. Watkins, Defects and diffusion in silicon processing, Ed. T. D. De la Rubia, et al.; MRS Sypm. Proc. Vol. 469, Pittsburgh (1997) 139.*

- **Low T: <u>raw</u> bulk silicon**

Interstitials – mobile at T~4K

Vacancies (V+, V-) - mobile at:

T~70K (standard n-Si)

T~150K (standard p-Si)

T~ 200K (high resistivity Si)

Expected radiation damage at LHe T: formation of vacancy-related defects critical for degradation <u>is suggested to be suppressed</u>

Milestones and timelines of cryoBLM development

2012 – first test of as-processed Si PIN detector operation at 4 K:
proof of concept , measurements of transport properties

2012 – *in situ* RadTest 1 at 1.9K: standard detectors (300 μm)

2014 – *in situ* RadTest 2 at 1.9 K: first study of thin BLM (100 μm)

2014 – installation of the first Si BLM modules
2015 – *in situ* RadTest 3 at 4.1 K: Improved design of thin BLM
statistics of degradation scenario

In situ RadTests 1:

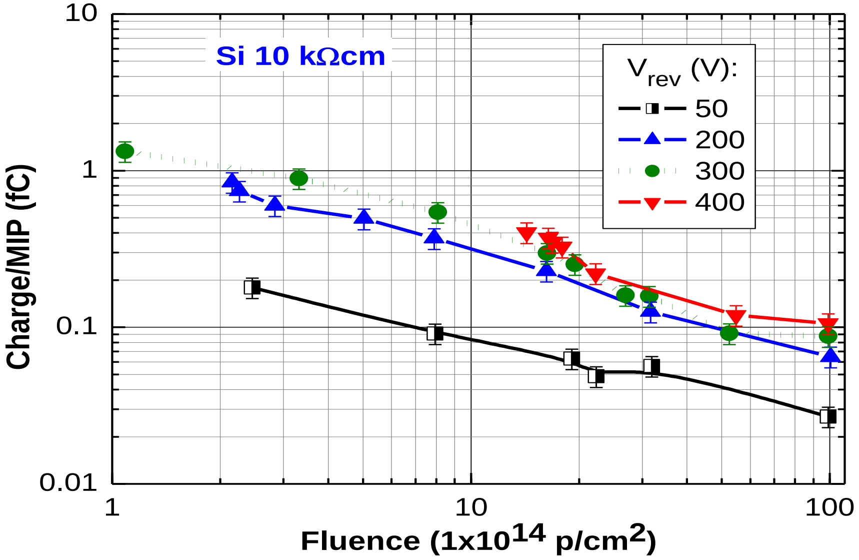
- **P+/n/n+ silicon pad detectors** designed and processed by consortium of the Ioffe Institute, St. Petersburg, and Research Institute of Material Science and Technology, Zelenograd, both Russia
- ρ: 10-15 kΩcm (mostly), 500 Ωcm and 4.5 Ωcm; thickness *W:* 300 **μm**
- Detector operation at reverse and forward bias mode;

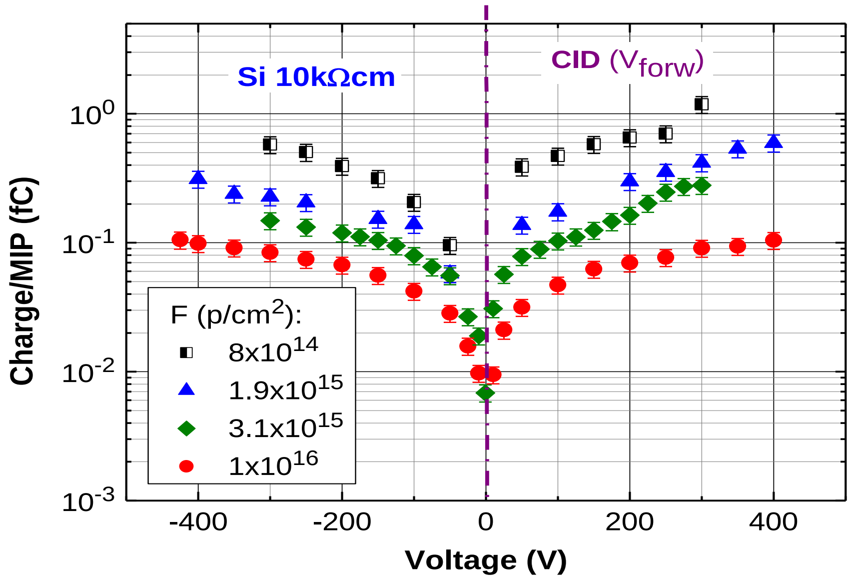
  forward – Current Injected Detectors (**CID**)

Measurements

- **Collected charge Q_c :** ***determined by integrating the detector output current over the 400 ms spill and averaging over a sequence of spills***
- **TCT :** ***LeCroy, 3 GHz bandwidth, 630 nm laser, width 45 ps (1st test)***

RadTest 1 collected charge vs. F and V





300 μm

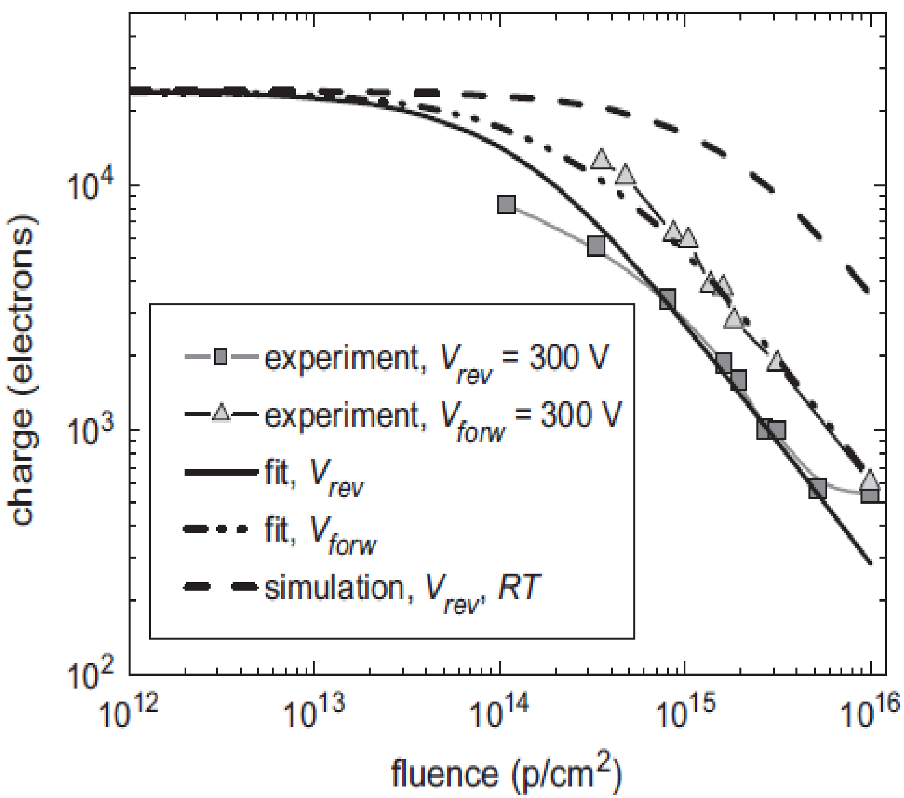
Different silicon resistivity
ρ = 10 kΩcm, 500 and 4.5 Ωcm

All detectors survived irradiation up to 10^{16} p/cm^2
→ no sensitivity to ρ at this F

Unexpected result –
degradation rate higher than at RT

CCE(F) fit with Hecht equation

$$Q_c = e\left\{\frac{v_e\tau_e}{w}\left[1-\frac{v_e\tau_e}{w}\left(1-\exp\left(-\frac{v_e\tau_e}{w}\right)\right)\right]\right\}+\left\{\frac{v_h\tau_h}{w}\left[1-\frac{v_h\tau_h}{w}\left(1-\exp\left(-\frac{v_h\tau_h}{w}\right)\right)\right]\right\}$$



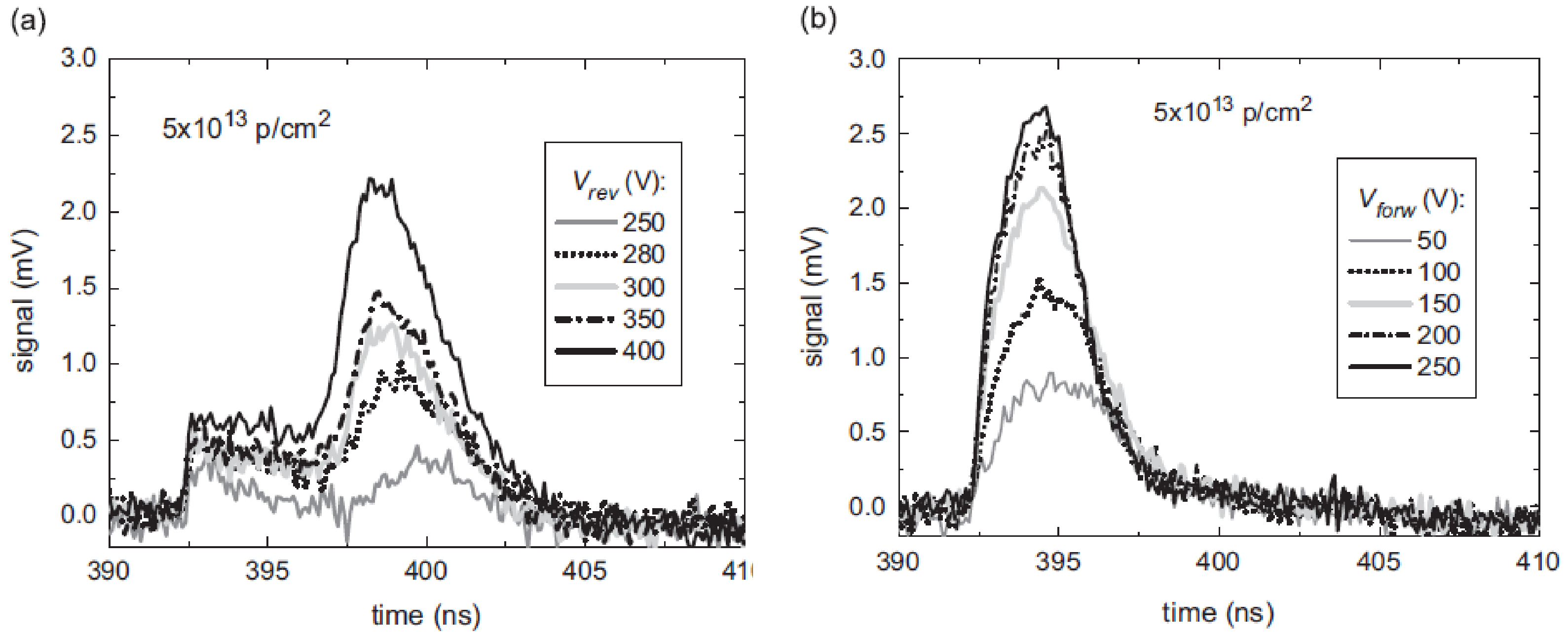
- **1-D approach, *E = V/w*,**
- **2 – levels (EVL) model,**
- **$1/t_{e,h} = b_{e,h}F_{eq}$; *b* – trapping probability constant,**
- **Drift velocities at 4 K (F = 0):**
  v_{es} = 1.2x10^7 cm/s, v_{hs} = 7x10^6 cm/s

CCE degradation at LHe can be explained by trapping

T	**1.9 K**	RT
β_e (cm^{2}ns^{-1})	6×10^{-15}	3.2x10^{-16}
β_h (cm^{2}ns^{-1})	9×10^{-15}	3.5x10^{-16}

β is up to 25 times larger at 1.9K

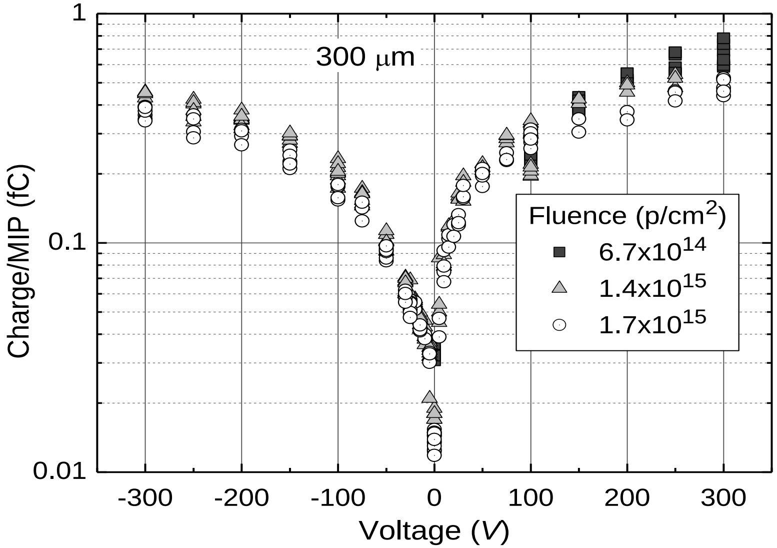
TCT voltage scans at 1.9 K

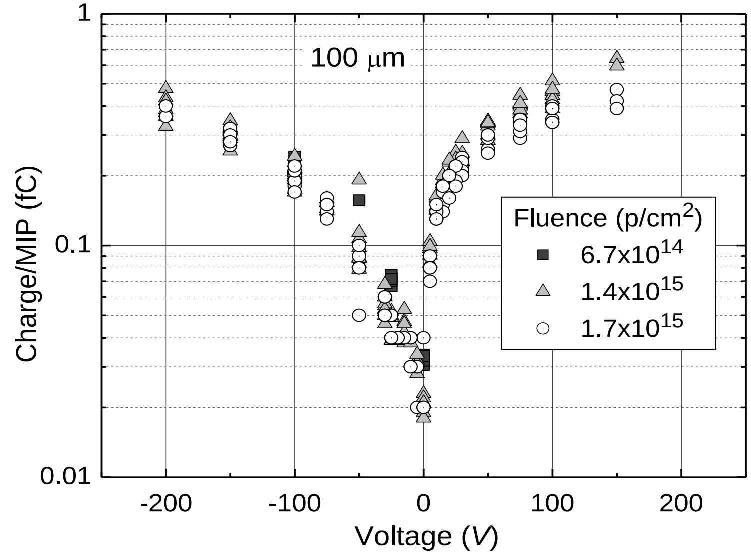


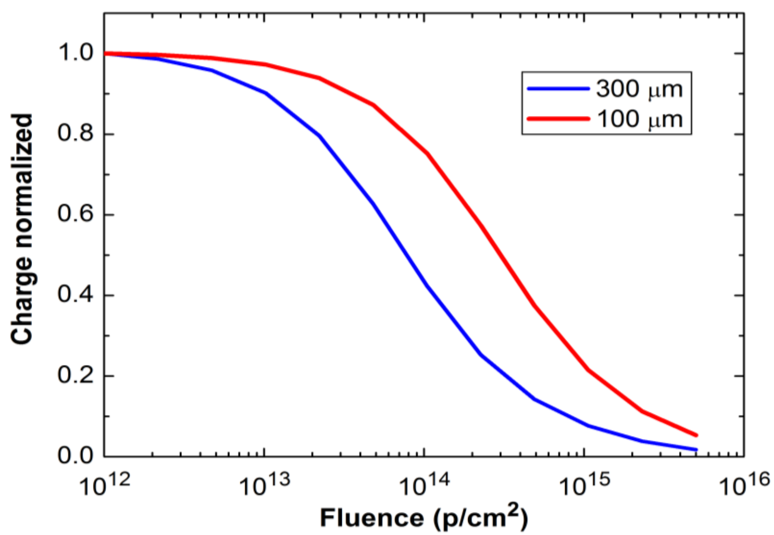
Observation of acceptors domination and DP E(x)

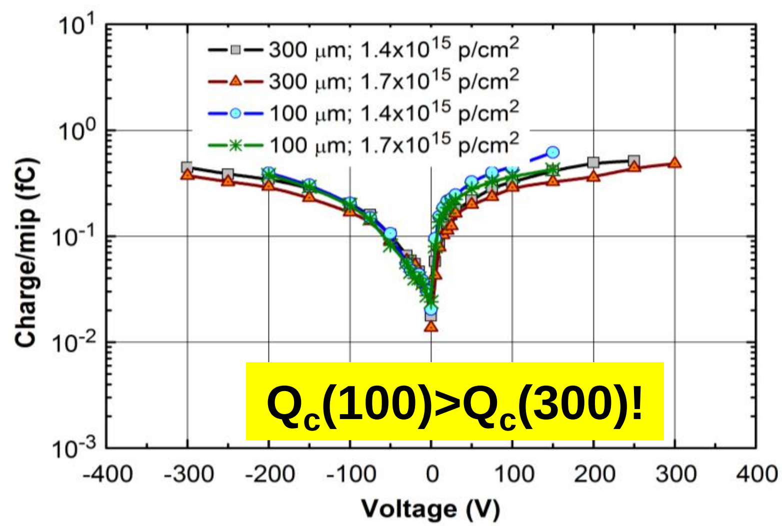
RadTest 2:collected charge vs. F and V

Test 2; 300 and 100 μm









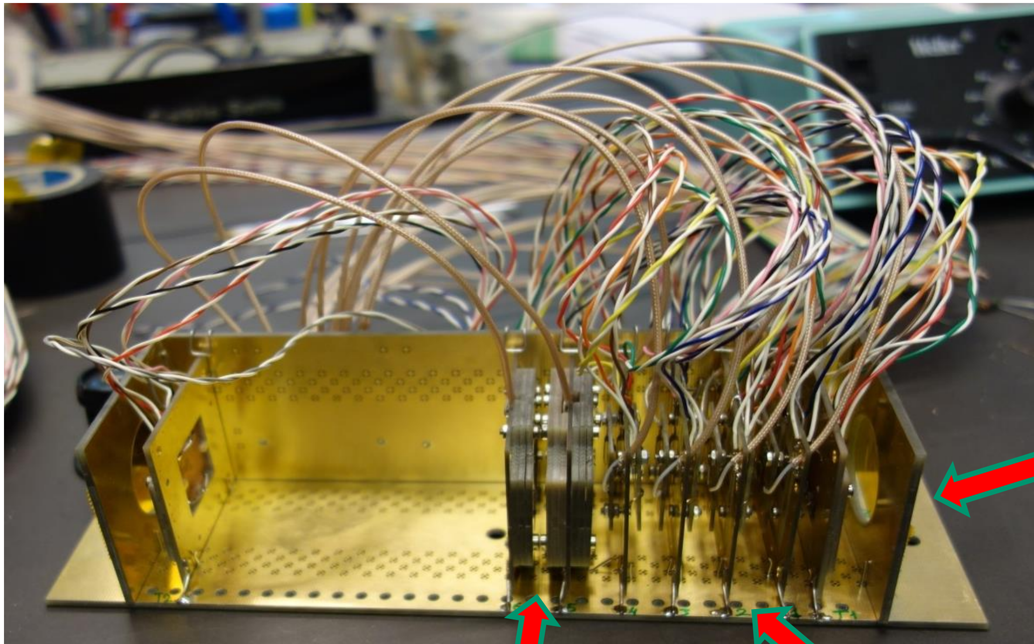
Detectors (modules) for RadTest 3

module	Amount in module	r (kWcm)	d (mm)	area (mm^2)	bias (V)	purpose	readout
TeleIN	4	≥15	300	12×12	200	telescope "IN"	oscilloscope
MM1	4	≥15	300	5×5	400	statistics	Ioffe-DAQ
MM2	4	~0.5	300	5×5	500	statistics	-"-
MM3	4	≥15	100	5×5	500	statistics	-"-
MM4	4	≥15	100	5×5	400	statistics	-"-
Ref1	1	≥15	300	5×5	400	test of DAQ system	CERN-DAQ
Ref2	1	≥15	300	5×5	400	-"-	-"-
TeleOUT	4	≥15	300	12×12	200	telescope "OUT"	oscilloscope

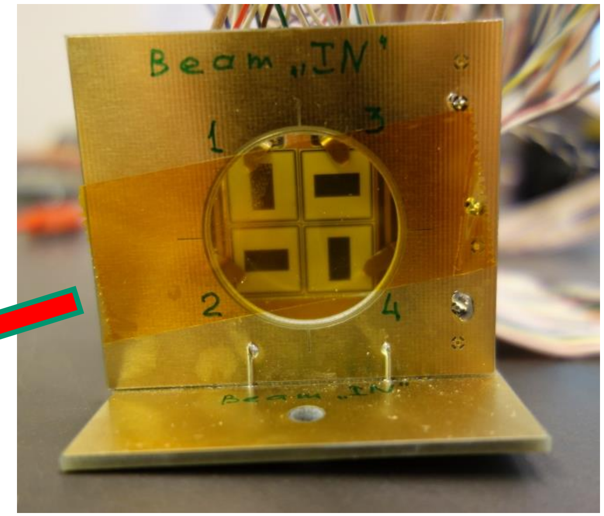
Total detector amount – 26 pcs.

TeleIN and TeleOUT – silicon beam telescopes

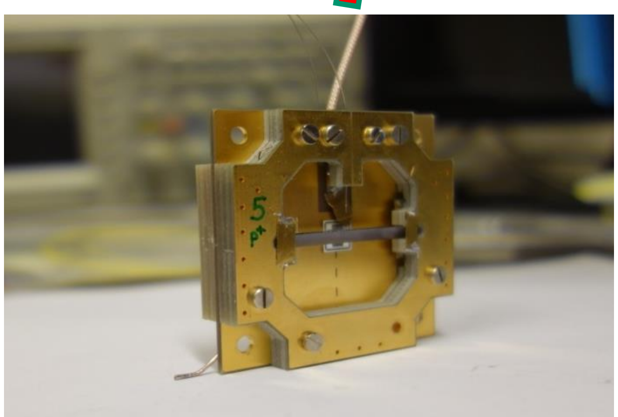
Cassette with detectors modules



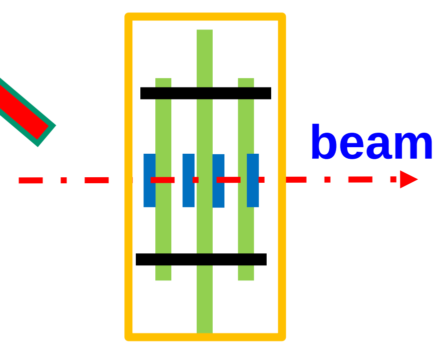
Silicon Beam Telescope module



TCT modules (Ref1,2)



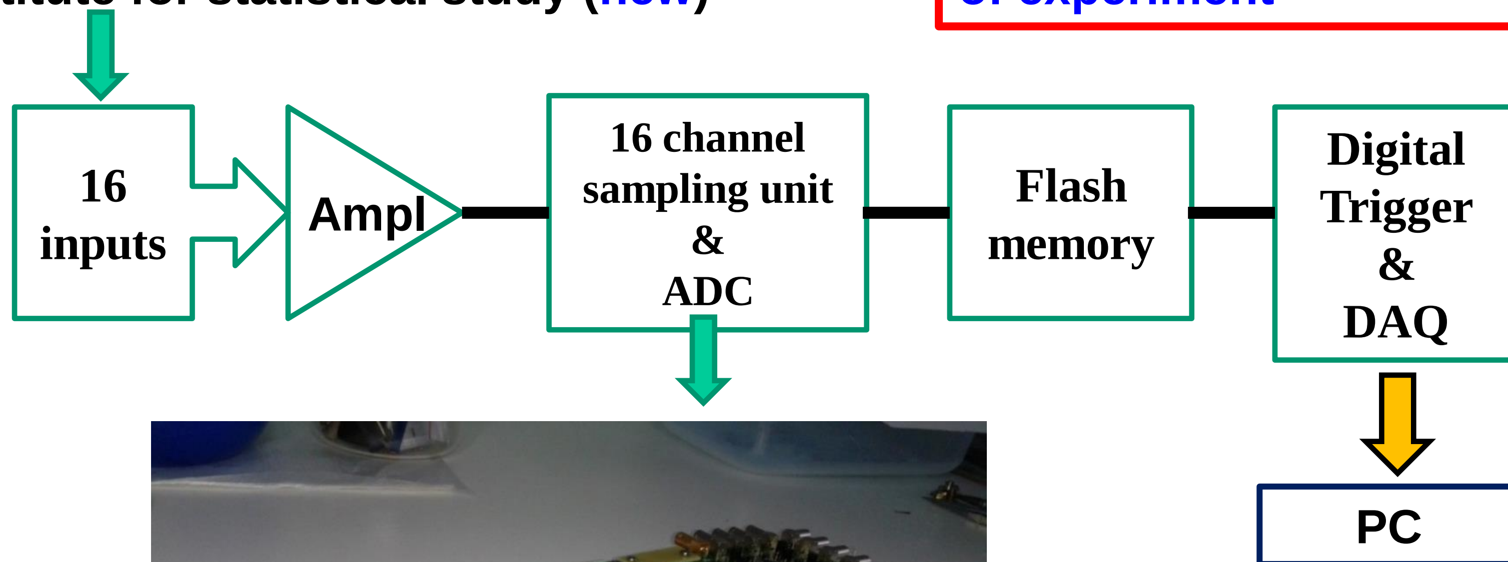
Multi-module construction



Electronics

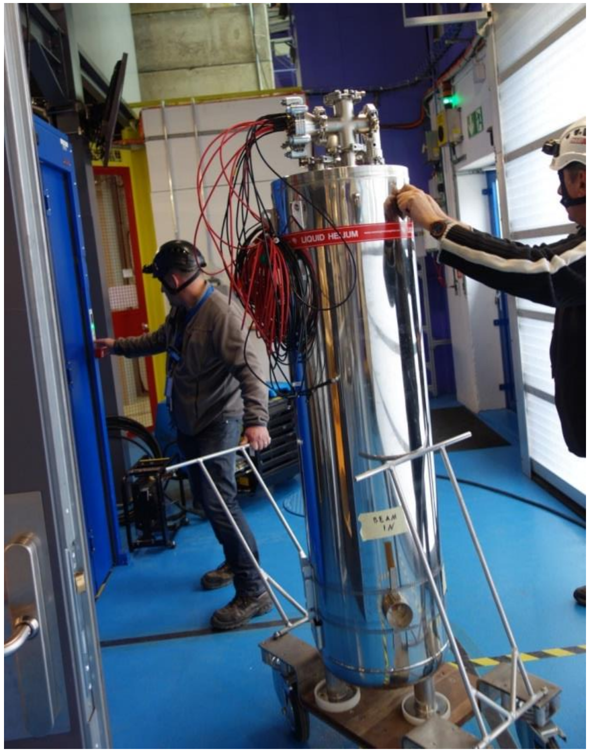
1. Multichannel CERN-DAQ system
2. Multichannel DAQ system of Ioffe Institute for statistical study (new)

Permanent *on-line* registration during 3 weeks of experiment

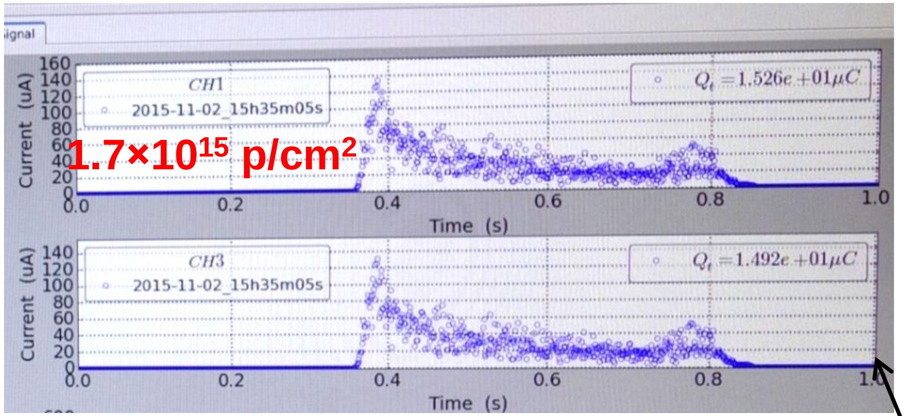


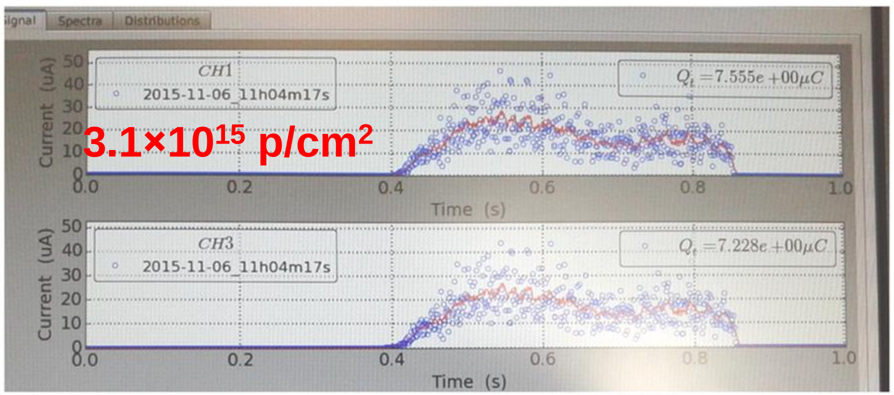
Cryostat for RadTests 3

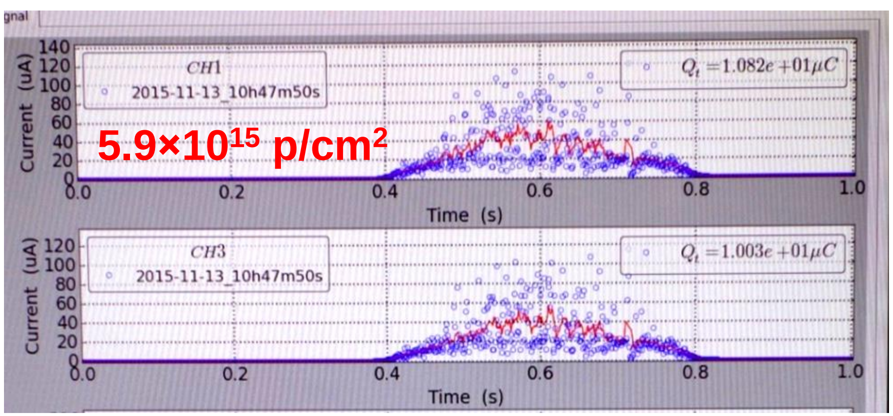
- Cryogenic system for cooling to 1.9K
- Irradiation at CERN PS
- 23 GeV protons, beam diameter ~1 cm at the detector location
- Beam intensity 1.3×10^{11} p/cm^2 per 400 ms spill (~10^{10} p/s on detectors)
- Fluence to 2×10^{15}-1×10^{16} p/cm^2
- Beam position monitoring



Detector signals from spills at $F \sim 10^{15}$ p/cm^2







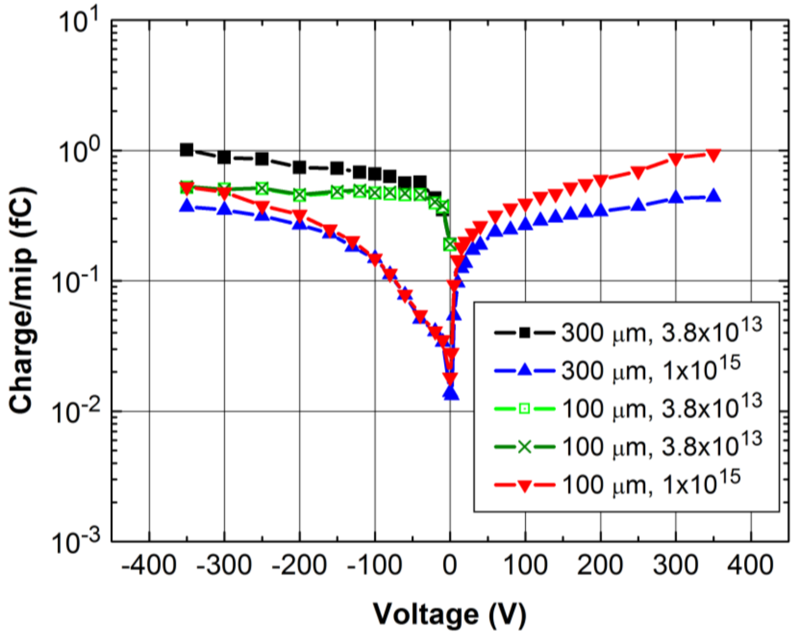
- **Spill:**
  Duration - 400 ms
  Intensity ~ (6-7)×10^{10} p/cm^2

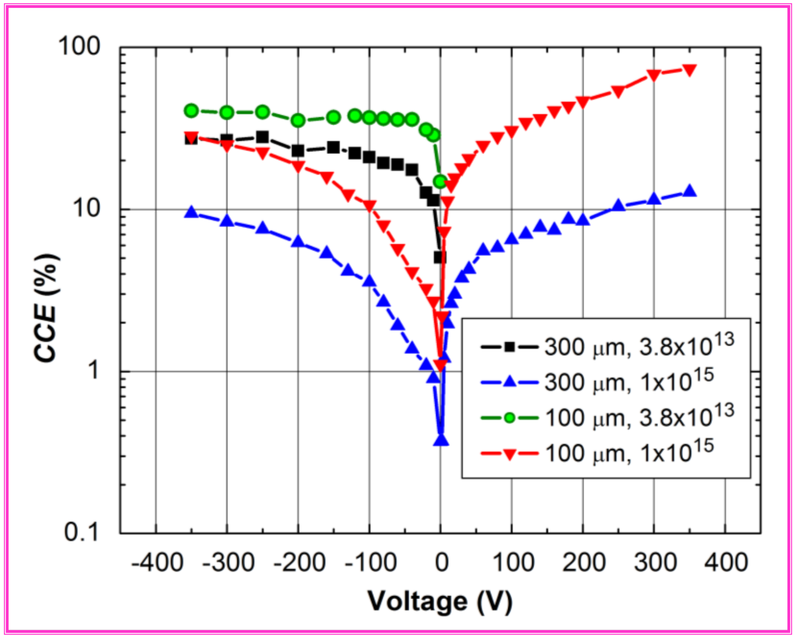
Data from CERN-DAQ system
Detectors:
Ref1 (Ch1), Ref2 (Ch3)
d = 300 μm

Origin of signal fluctuations **is not clear yet.**
This feature is recorded by both DAQ systems.

RadTest 3: CCE in voltage scans

Different thickness





$Q_o(300)/Q_o(100) = 3$

CCE(100) > CCE (300)!

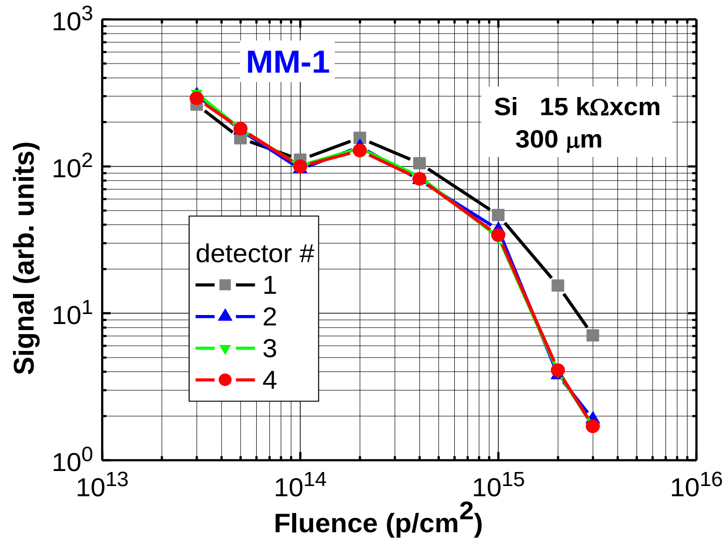
Higher efficiency of thinned detectors is due to two factors:

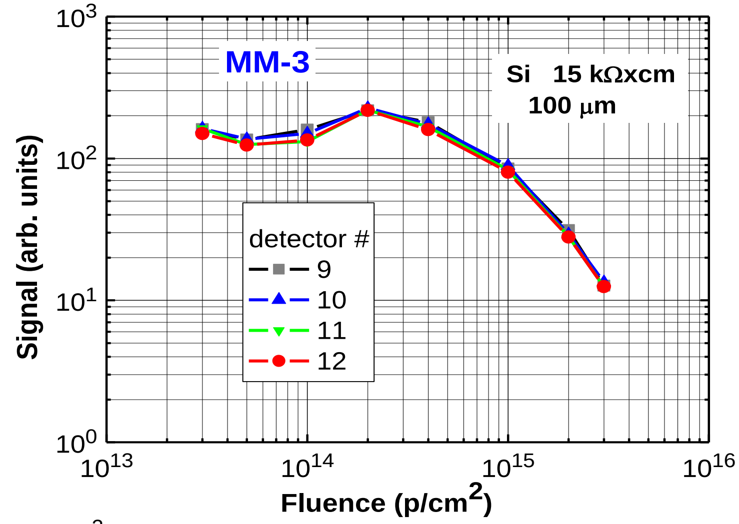
1) E_{mean} is higher,

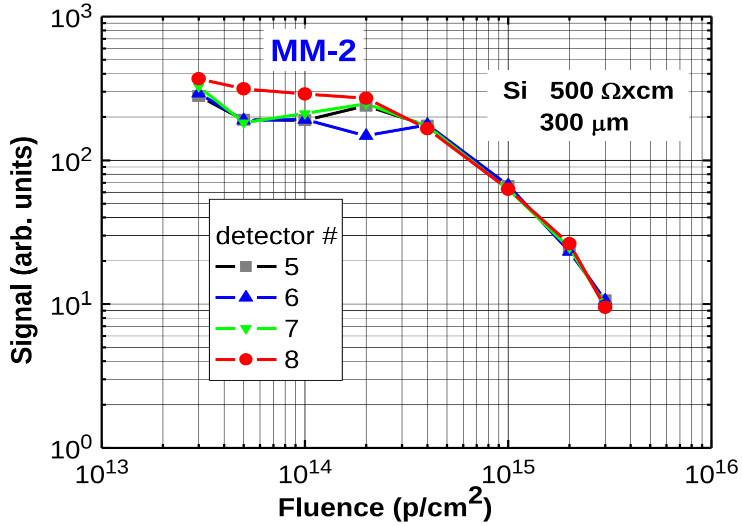
2) Different E(x) distribution

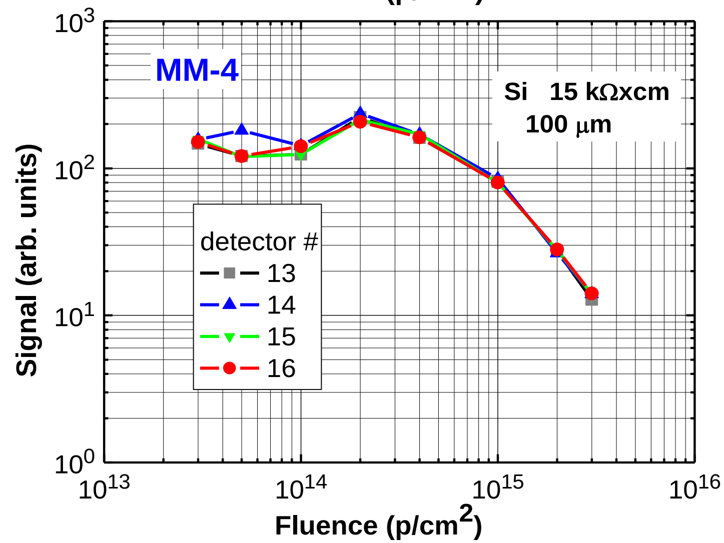
RadTest 3: statistics of signals

Data from Ioffe DAQ system; 16 detectors from modules MM1-MM4









- **100 µm:** minimal deviations (within 10%);
- maximal signal is **not** at F = 0 (non-monotonic signal reduction)

Conclusions

- The rate of signal degradation at 1.9K is higher than at RT.
- Si detectors are appropriate for BLM application at 1.9K and irradiation up to F = 2×10^{15} p/cm^2 .
- Operation in CID mode is advantageous up to F ~ 2×10^{15} p/cm^{2}.
- Thin (100 mm) detectors give lower rate of signal degradation and minimal deviations of the signal.
- Not all is clear!
- 4 Gb data are still under treatment

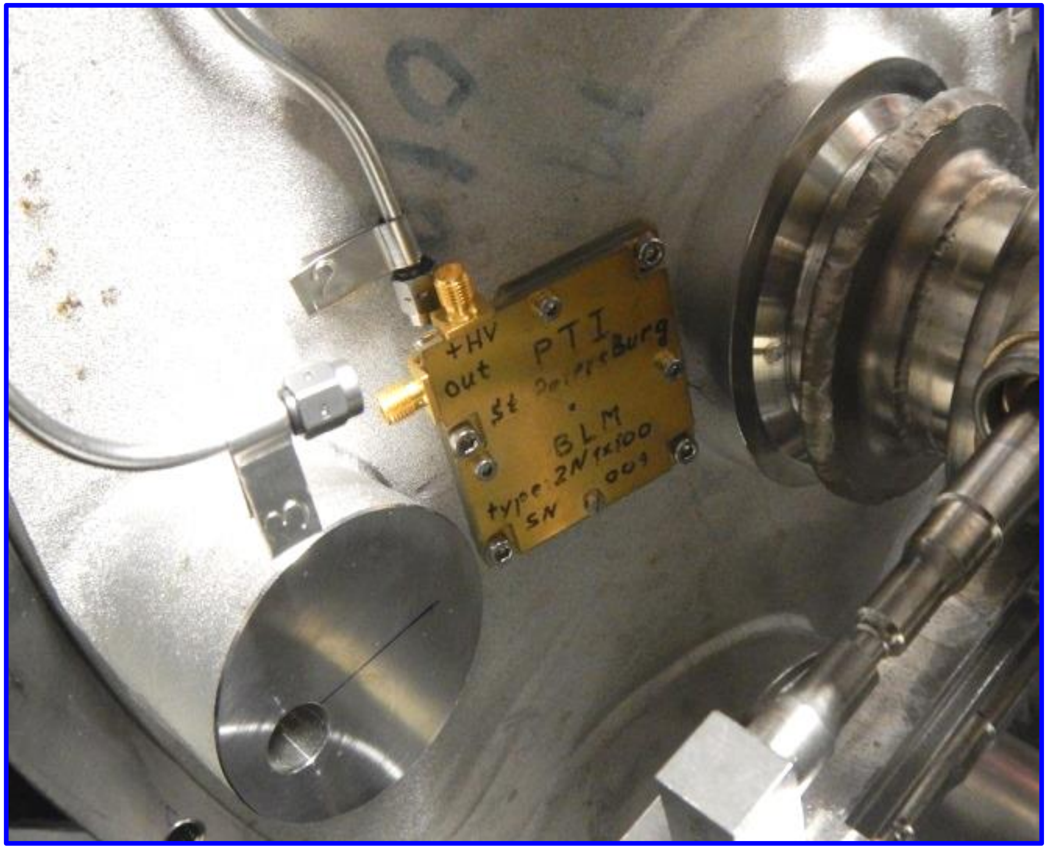
Publications

C. Kurfürst, et al., Nucl. Instrum. Meth. A 782 (2015) 149.

E. Verbitskaya, et al., Nucl. Instrum. Meth. A 796 (2015) 118.

Z. Li, et al., Nucl. Instrum. Meth. A 824 (2016) 476 and references herein.

Most important



2014:

First <u>Si BLM module</u> <u>installed</u>

on the end of the cold mass of LHe vessel of superconductive coils of the magnets

Thank you for your attention