Detector development

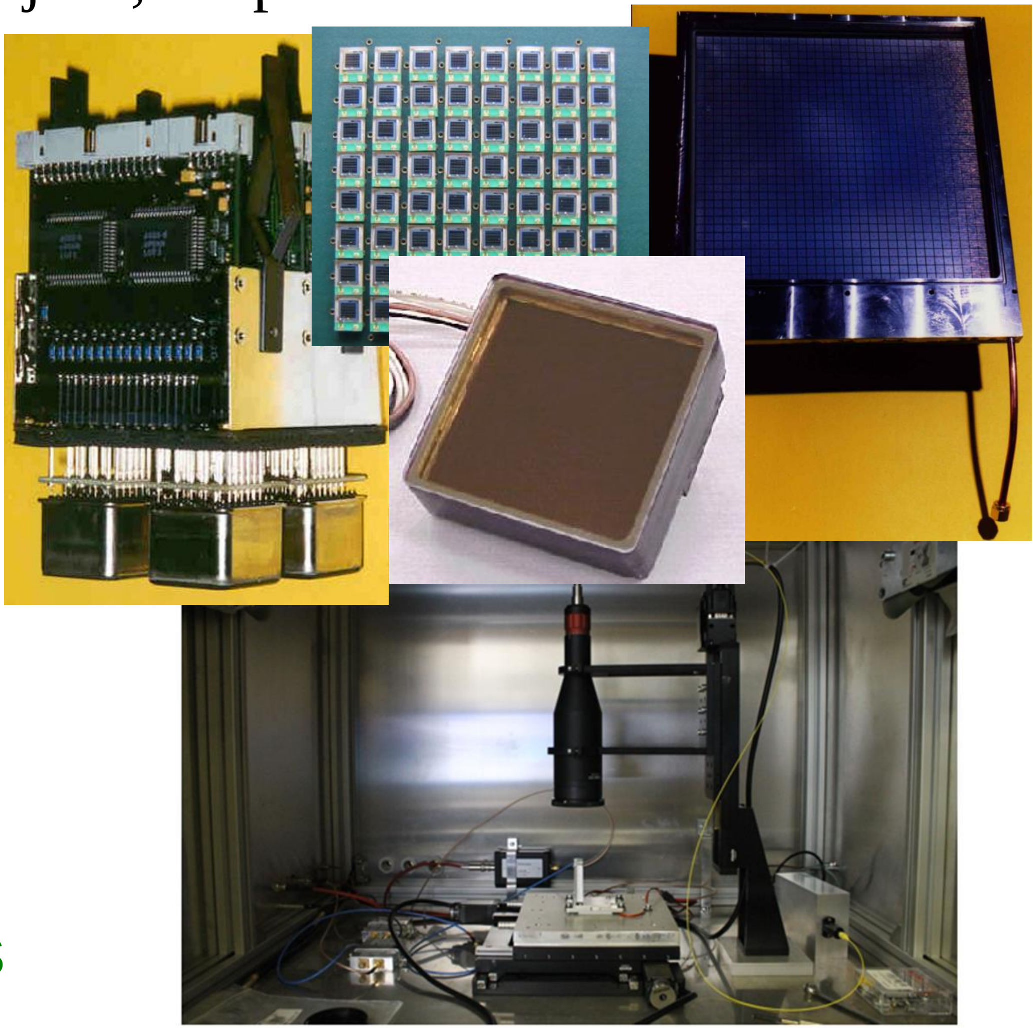
Samo Korpar, Gregor Kramberger

University of Maribor, Jožef Stefan Institute Ljubljana

RECFA visit to Ljubljana, 5 April 2019

Outline:

- A bit of R&D history
- R&D activities
- Photodetector lab
  - RICH detectors development
  - Photodetectors characterization
  - FE electronics
  - Applications
- Silicon detector lab
  - Infrastructure
  - Radiation hard sensors
  - Timing detectors
  - Diamond detectors, depleted CMOS



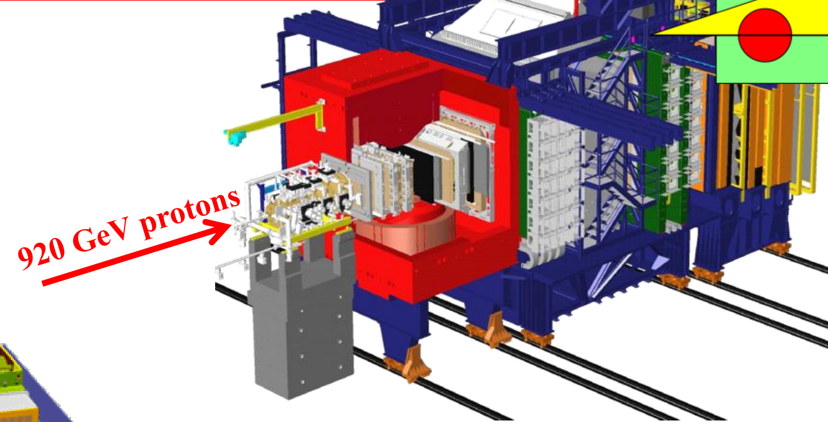
Photodetector R&D and Belle II & LHCb RICH upgrade activities

Photodetector lab R&D

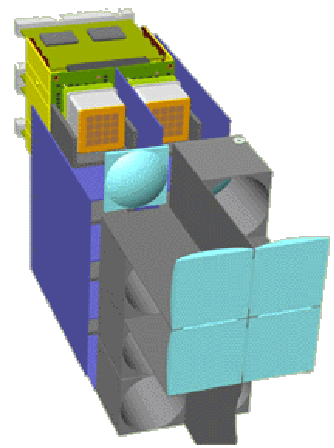
- Development and characterization of photodetectors for particle identification (PID) - Ring Imaging Cherenkov (RICH) counters
- Photon detectors for HERA-B RICH
  - CsI detector
  - TMAE detector
  - multi-anode PMTs
- Photon detectors for Belle II aerogel RICH
  - MPPC (SiPM)
  - HAPD
  - MCP PMT
- Applications (TOF-PET, ^{90}Sr detection)

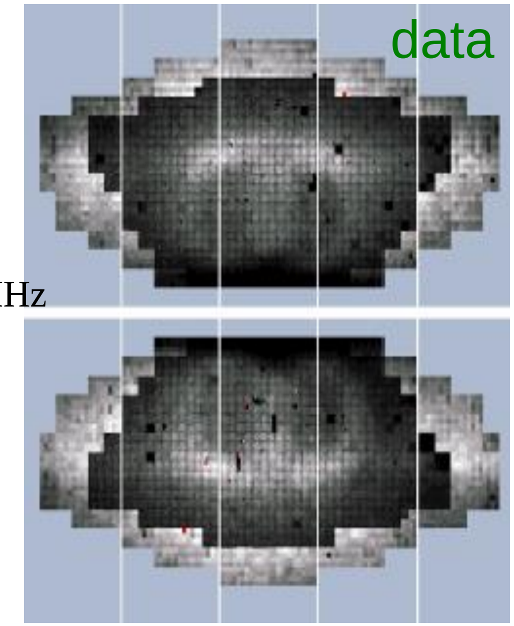
Photodetectors for HERA-B RICH

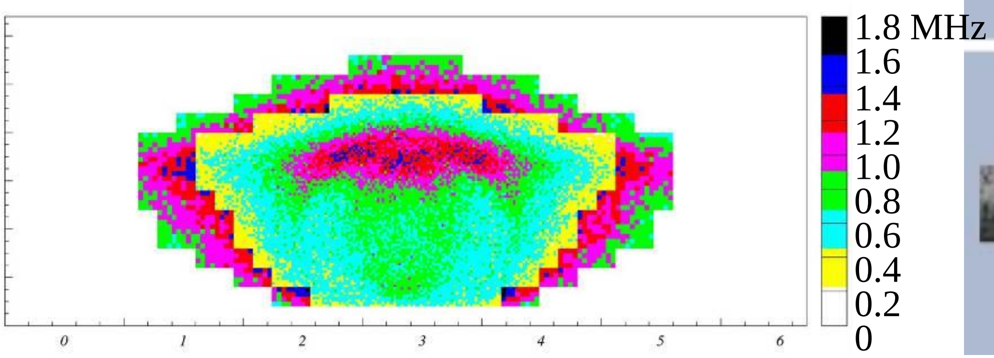
p + A → X @ $\sqrt{s}$ = 41.6 GeV

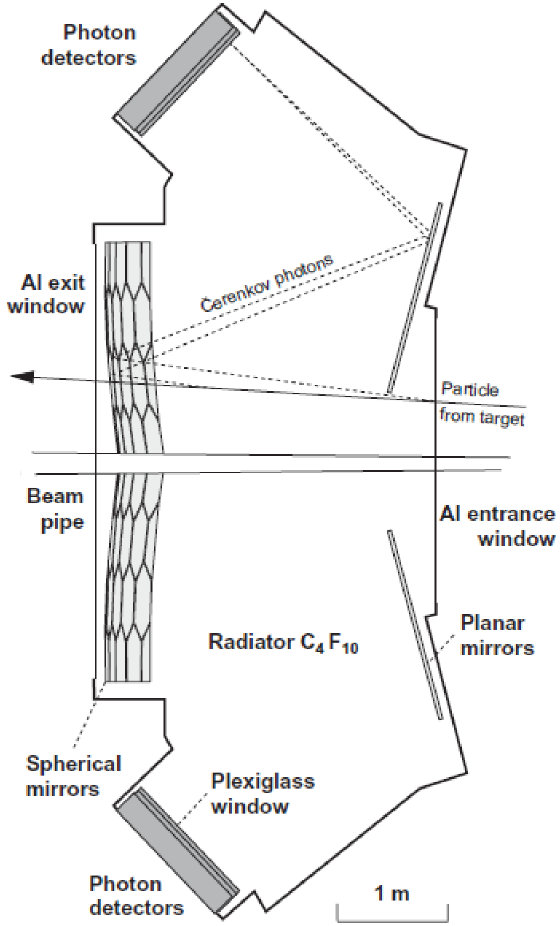


- radiator C_4F_{10} (n=1.00137)
- Cher. angle 52.4 mrad (β = 1)
- π/K Cher. angle difference @ 50 GeV/c → 0.9 mrad
- mirror radius 11.4 m
- Main challenge for photodetectors – high occupancy ≈ 5 MHz/cm^2
- spherical + planar mirrors – move photon detector away from magnet and particle tracs
- optical demagnification – telescope
- use of multi-anode PMTs



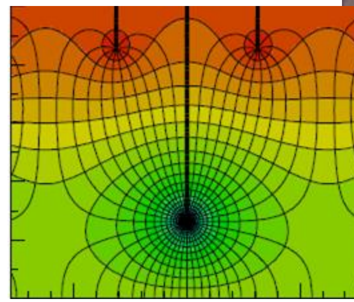


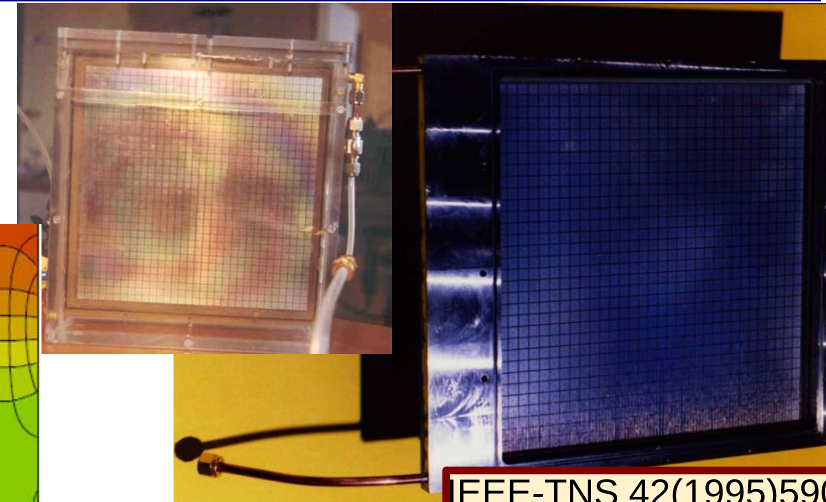




Photodetector R&D for HERA-B RICH

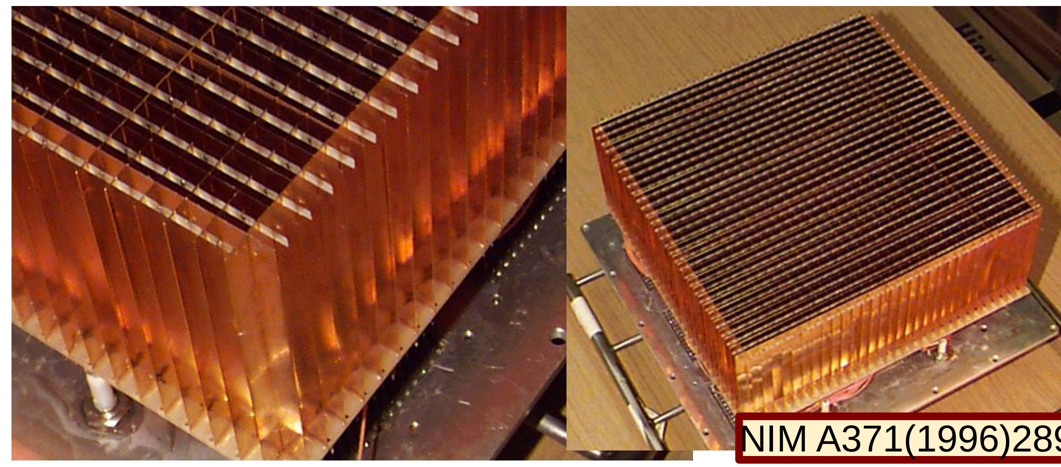
- first large area MWPC with CsI photocathode developed at JSI
- fails at high rate operation by few orders of magnitude





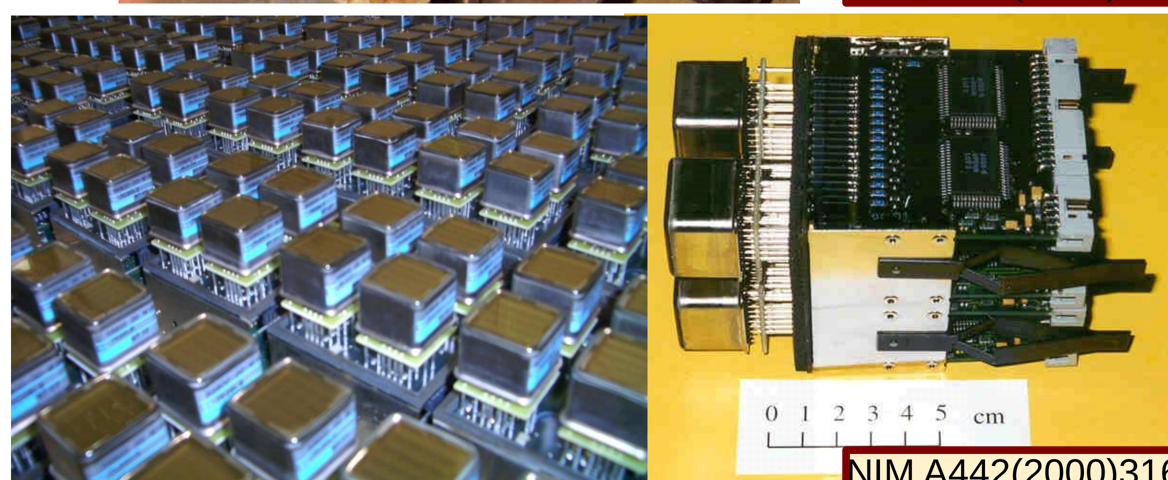
IEEE-TNS 42(1995)590

- tests of proportional counter array with TMAE developed at DESY
- tests of aging and rejuvenation of smaller prototype developed at JSI
- fails at aging by few orders of magnitude



NIM A371(1996)289

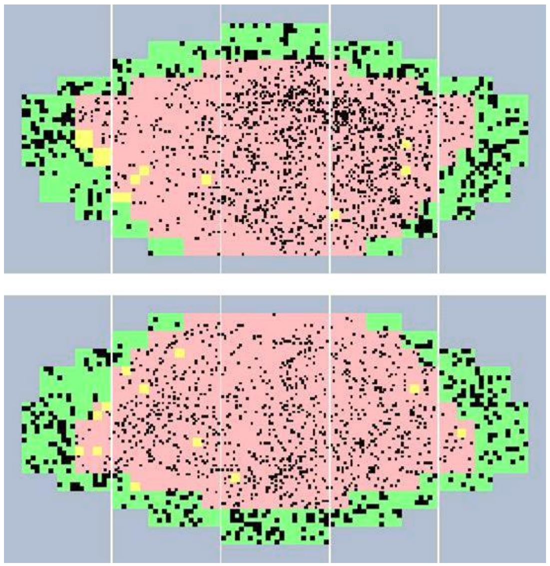
- first large deployment of multi-anode PMTs produced by Hamamatsu
- characterization of MA-PMTs: single photon detection efficiency, aging tests, base board development ...
- selected for the HERA-B RICH

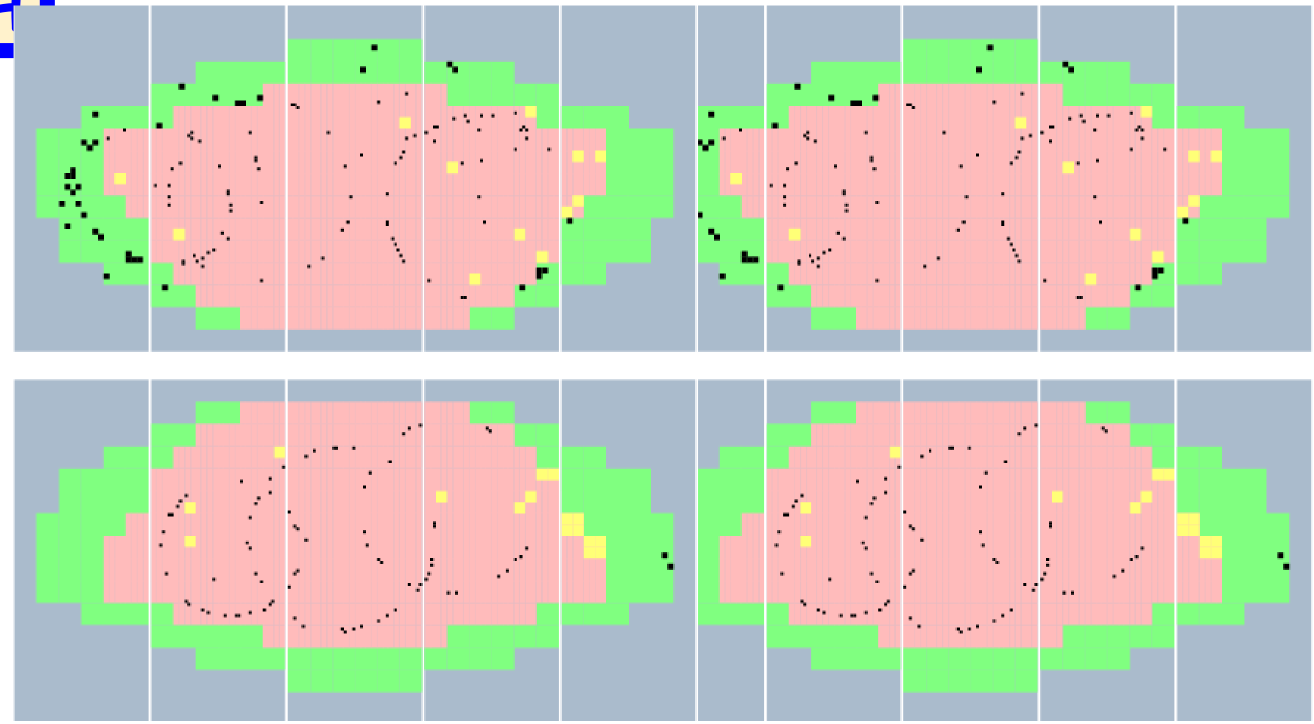


NIM A442(2000)316

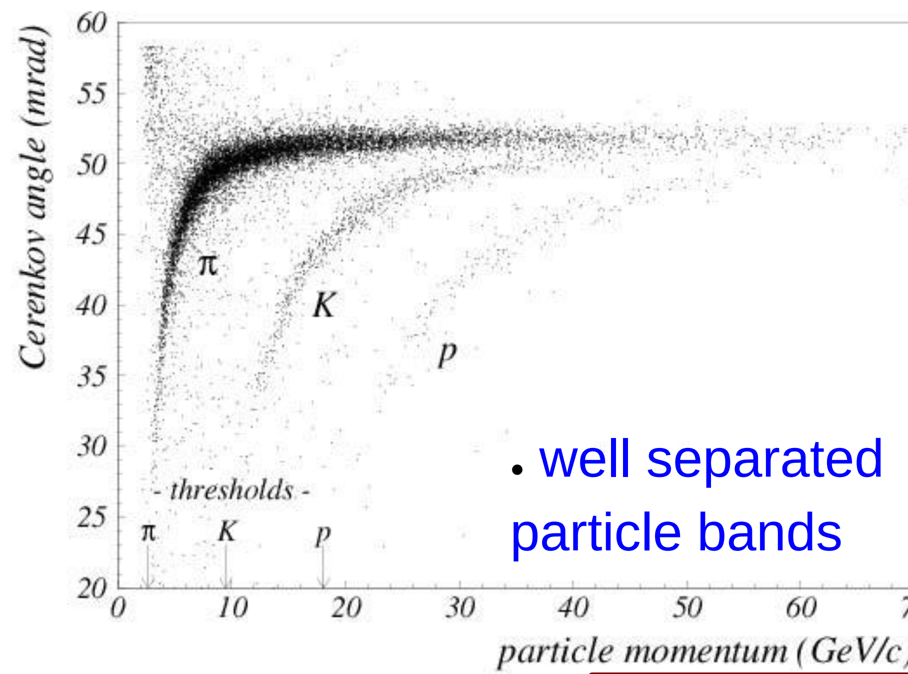
Success of HERA-B RICH

- very clear rings
- only few noise hits with ~30k read-out channels





- Average number of photons per ring: 33
- Single photon resolution:
- σ_0= 0.8 mrad for fine granularity region (R5900-M16 tubes)
- σ_0= 1.0 mrad for coarse granularity region (R5900-M4 tubes)
- **Paved the way for later RICH detectors of COMPASS and LHCb experiments**



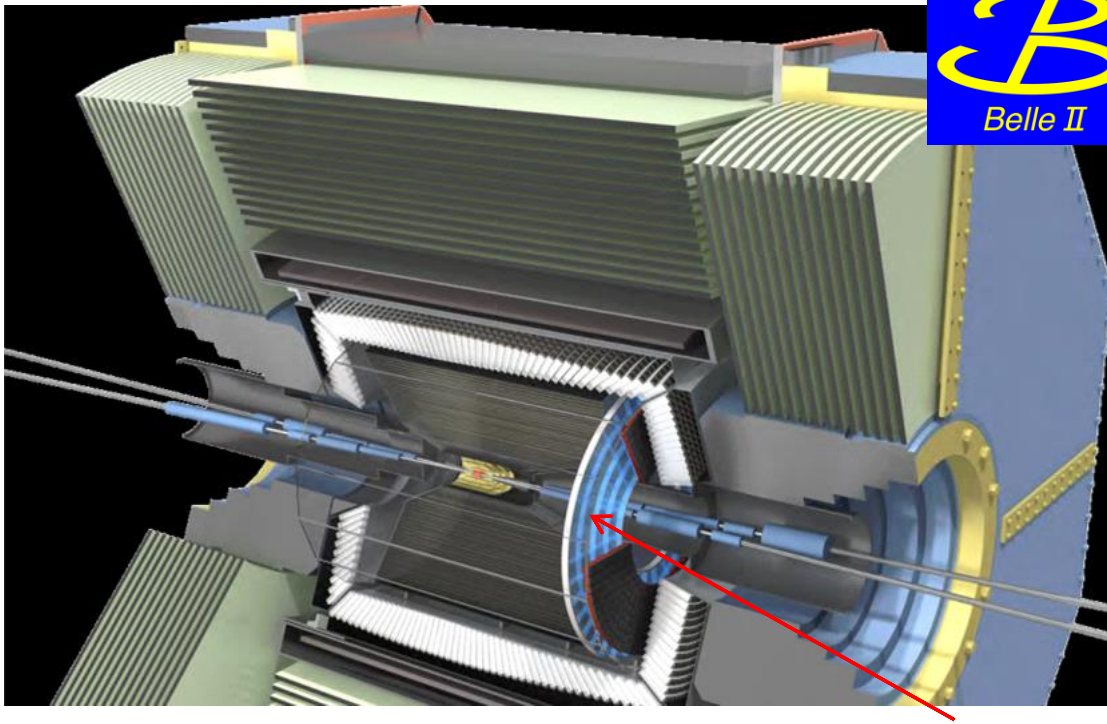
- well separated particle bands

NIM A516(2004)445

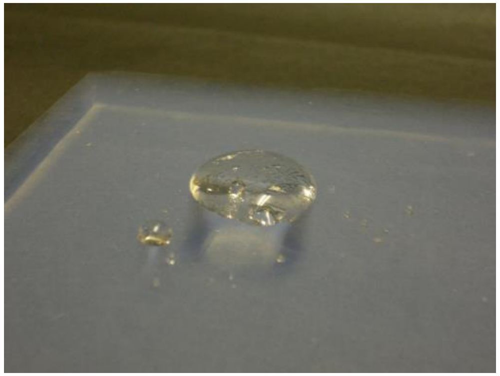
Belle II ARICH detector

- proximity focusing RICH to fit the tight available space
- aerogel radiator, $n \approx 1.05$
- π/K Cher. angle difference @ 3.5 GeV/c → 30 mrad

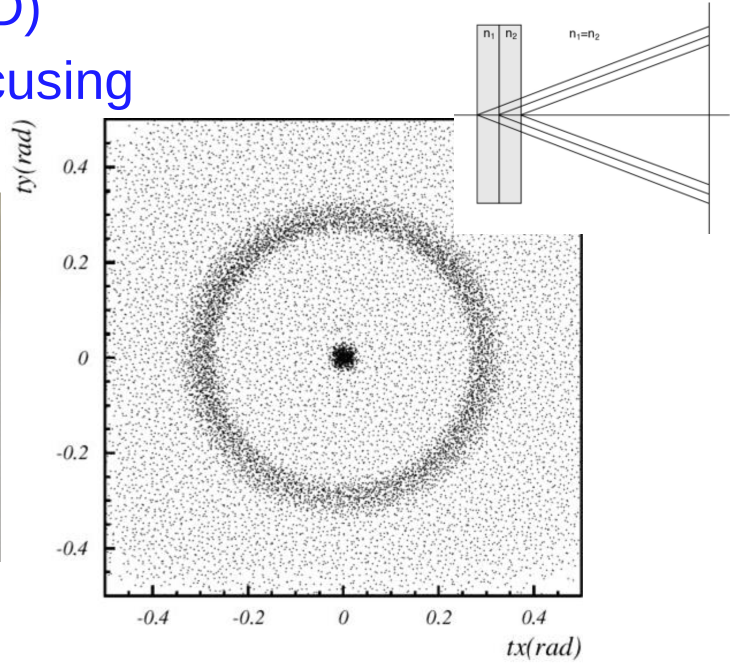
- Main challenge for photodetectors – strong magnetic field $1.5\ T$
- new photosensor – hybrid avalanche photodetector (HAPD)
- new double layer focusing aerogel radiator

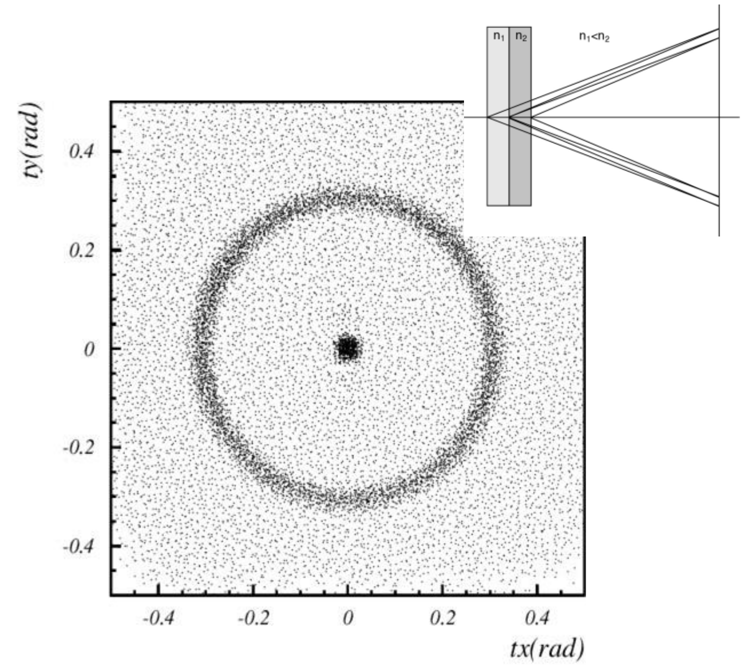


End-cap PID: focusing aerogel RICH - ARICH



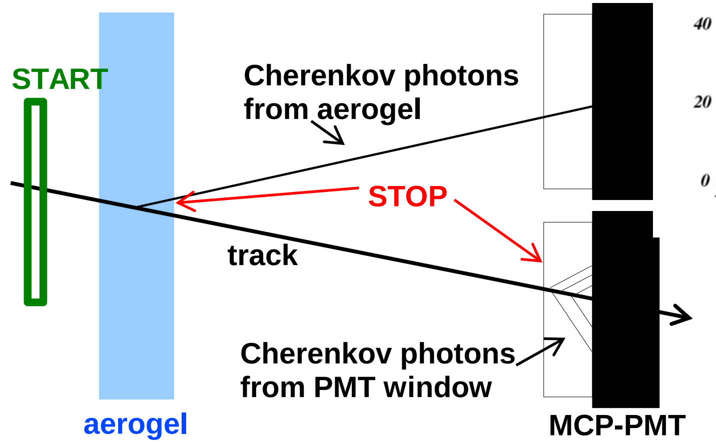
NIM A548 (2005) 383,
NIM A553 (2005) 64

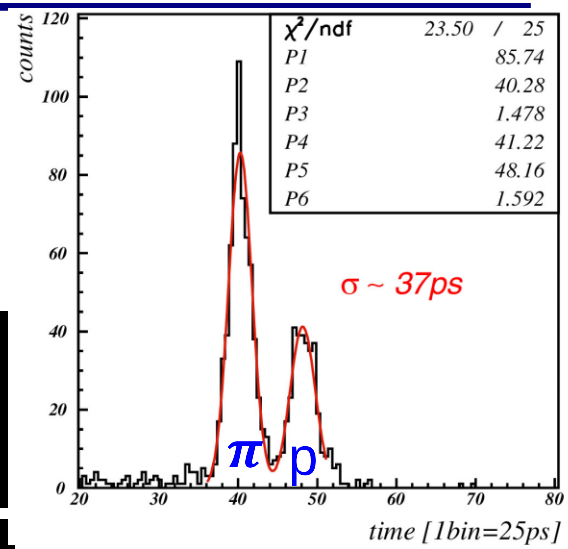




Photodetectors for ARICH

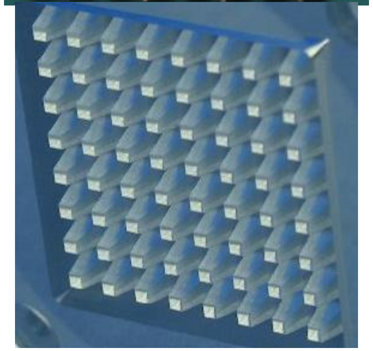
- micro-channel plate (MCP) PMT, planacon from Photonis (Burle)
- study of excellent timing properties → proposed combination with TOF based on Cherenkov light from PMT window
- modest collection efficiency
- concerns about aging at the time

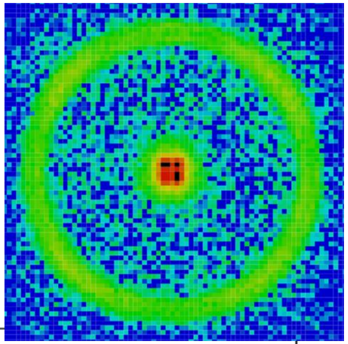




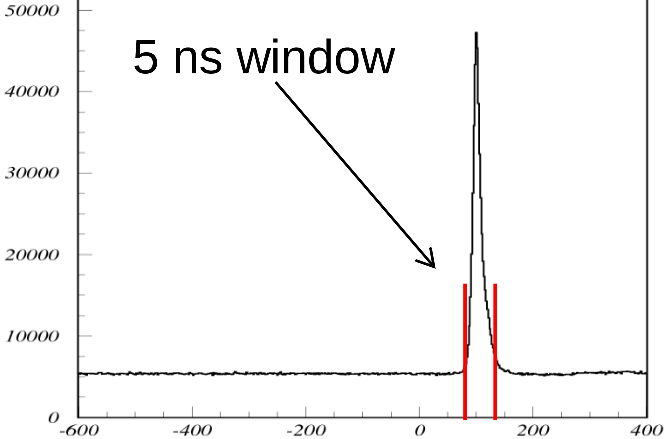
NIM A572 (2007) 432

- silicon photomultiplier – SiPM
- high photon detection efficiency
- excellent timing properties
- large dark-count noise equivalent to single photon signals
- immunity to magnetic field
- first use of SiPM for RICH detector





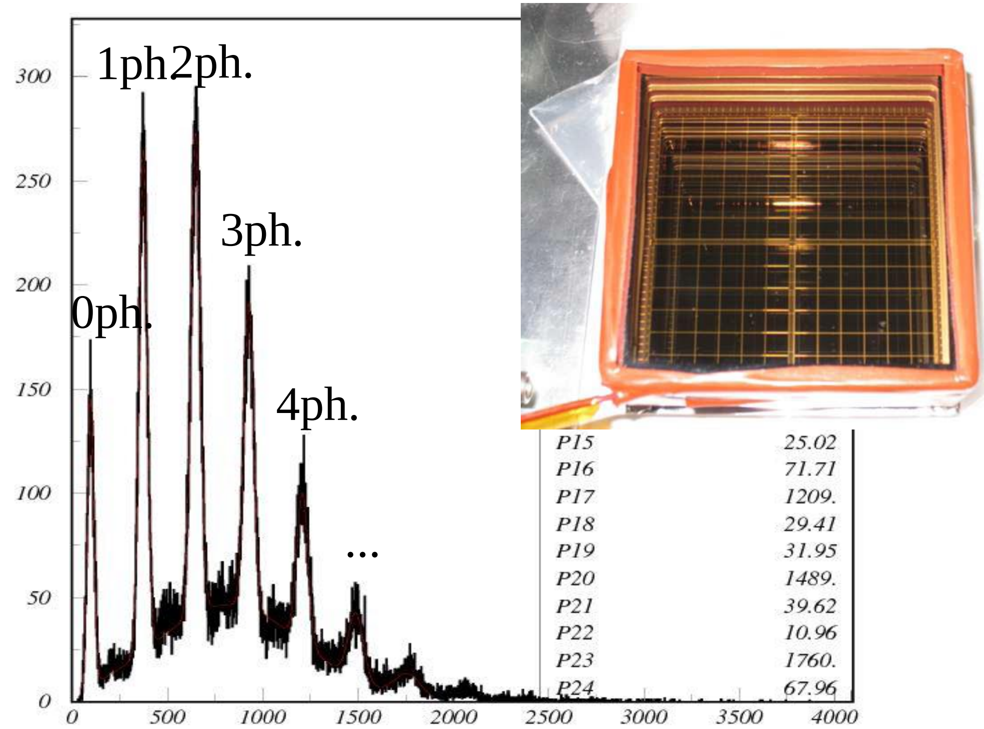
NIM A613 (2010) 195



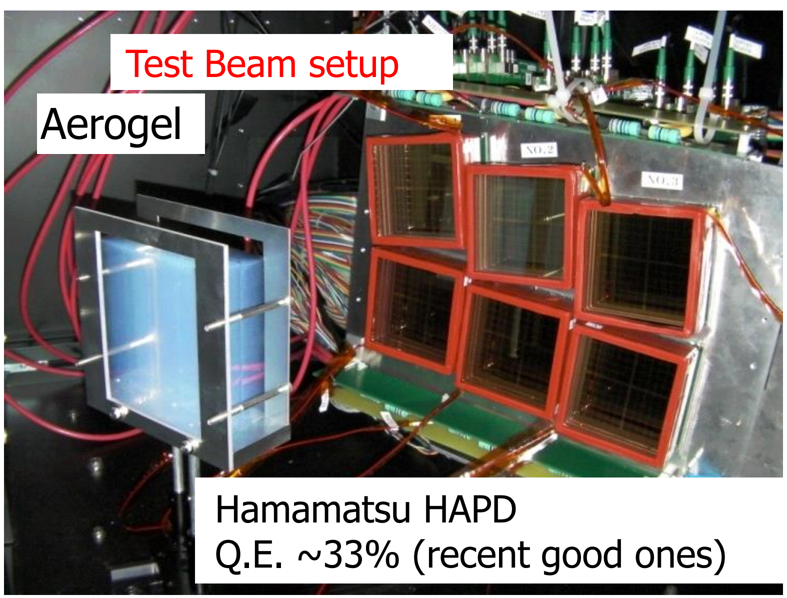
- dark-counts strongly enhanced by nonionizing radiation damage

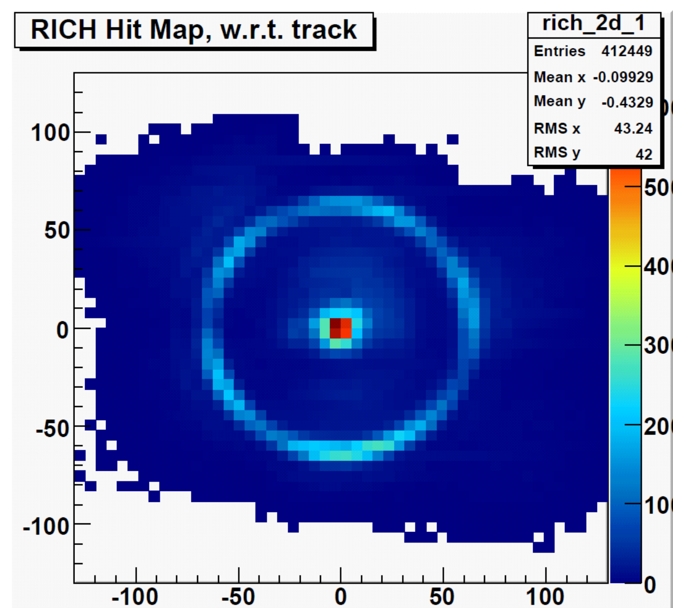
Photodetectors R&D for ARICH

- hybrid avalanche photodetector – HAPD
- high photon detection efficiency
- excellent photon counting
- proximity focusing configuration → operation in the magnetic field with limitation
- APDs sensitive to radiation damage
- new type of photosensor



- selected for the ARICH



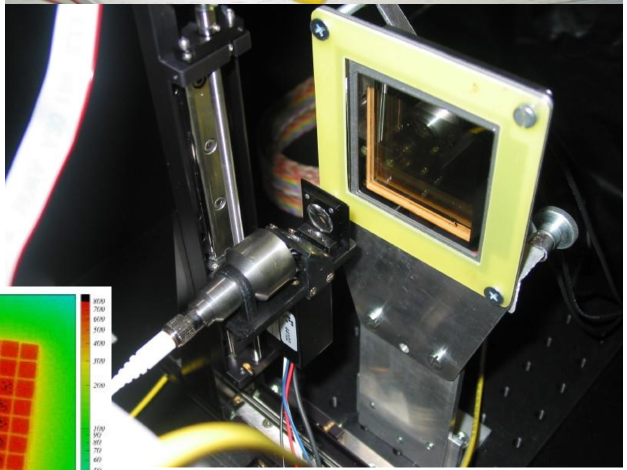


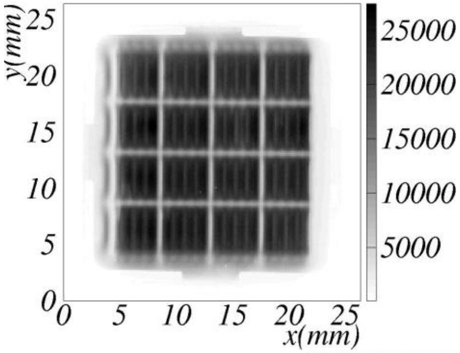
ring image

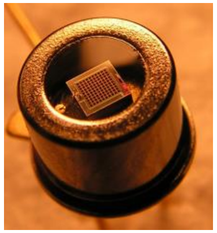
NIM A595 (2008) 180

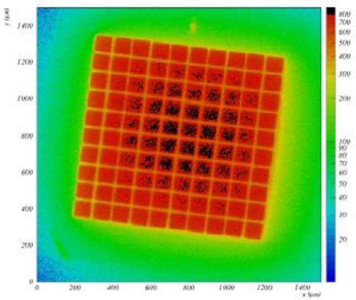
Characterization of photodetectors

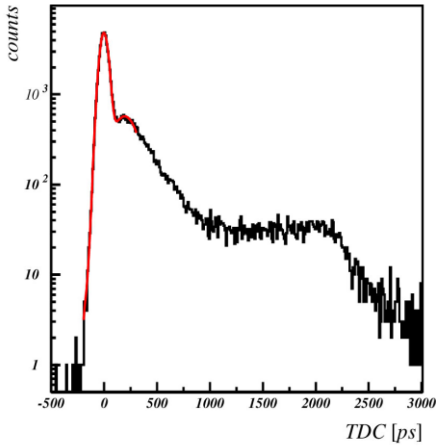
- several setups for photodetector characterization:
- 2D, 3D stages for position dependent characterization
- library of modular electronics (VME, CAMAC) for pulse height and timing measurements
- different types of light sources:
  - pico-second lasers
  - LED sources
  - spectrometers
- climate chamber for tests to -70^oC
- study of position dependent efficiency, timing, charge sharing, cross-talk, photoelectron backscattering ...

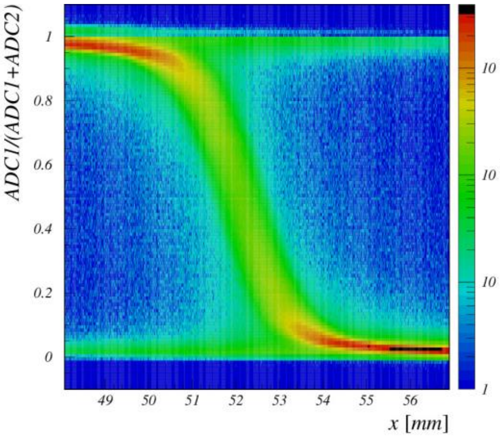


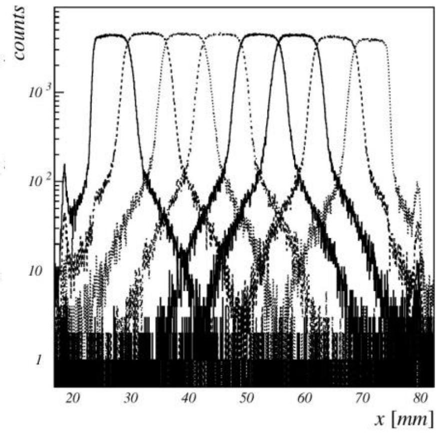


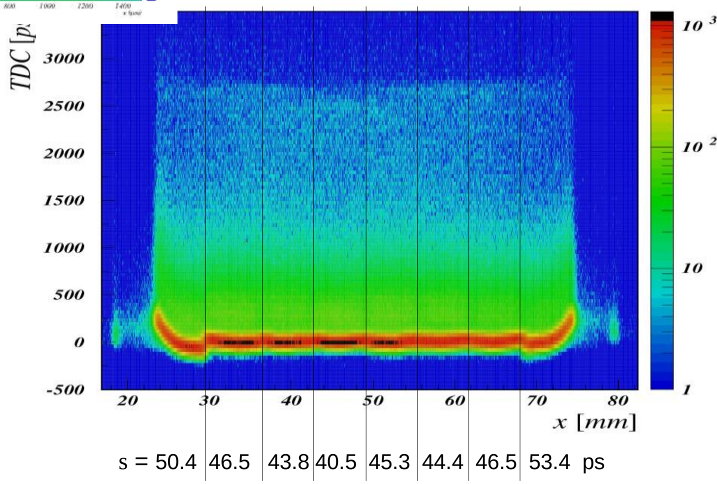






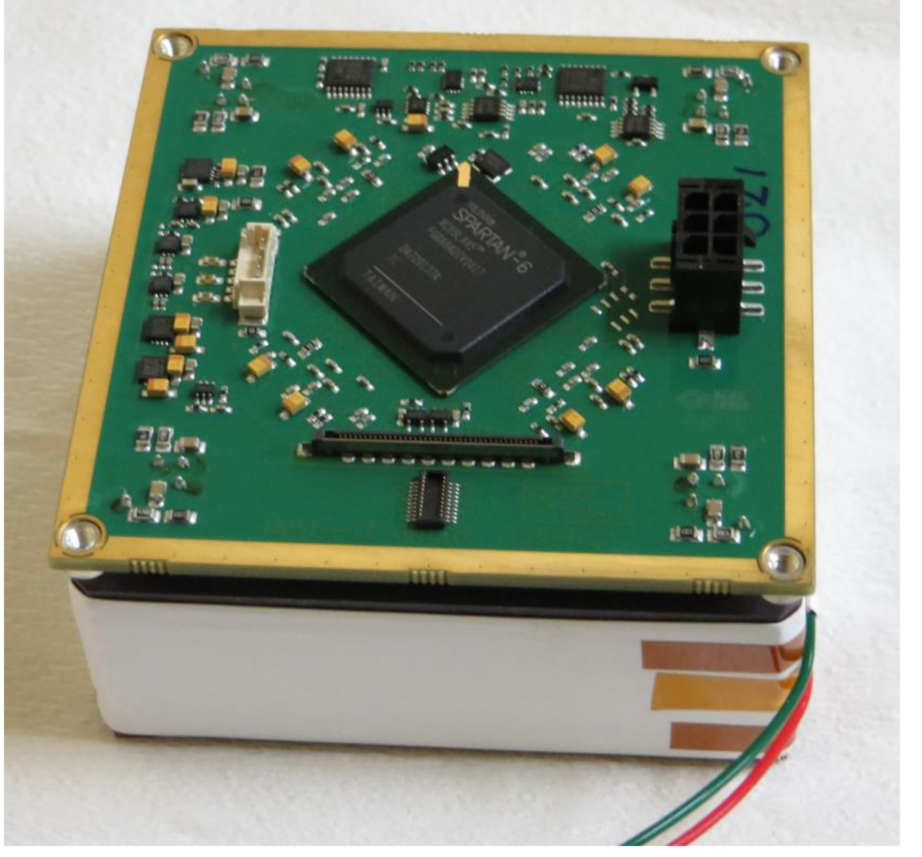






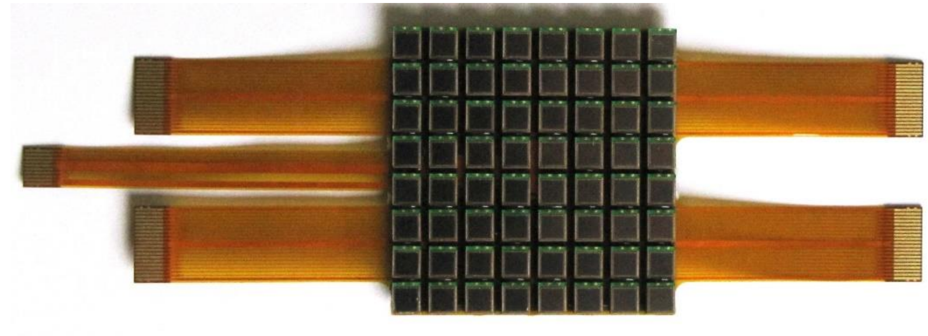
Development of front-end electronics for ARICH

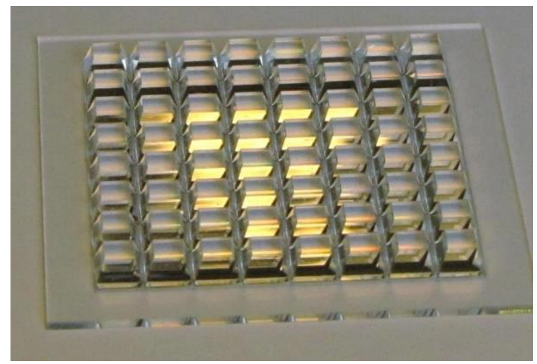
- front-end electronics is an integral part of the detector and we are equipped for design, prototype board assembly, rework and tests (ERSA rework station, manual pick & place, reflow own)
- irradiation tests of the electronics components, boards
- ARICH front-end board was design @JSI and produced at local company KENS
- radiation hardness of the board was tested at the JSI reactor including the tests of SEU in FPGA

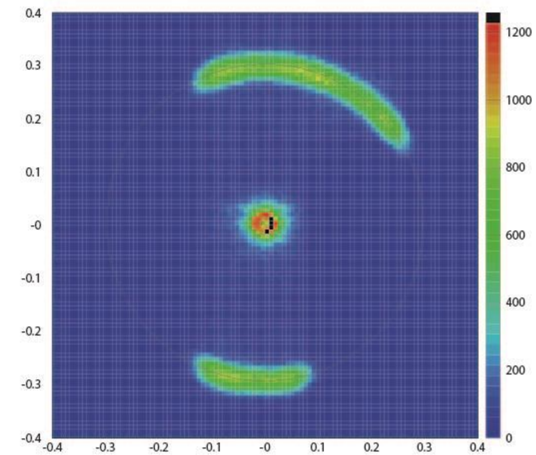


SiPM R&D for future RICH upgrades – Belle II, LHCb

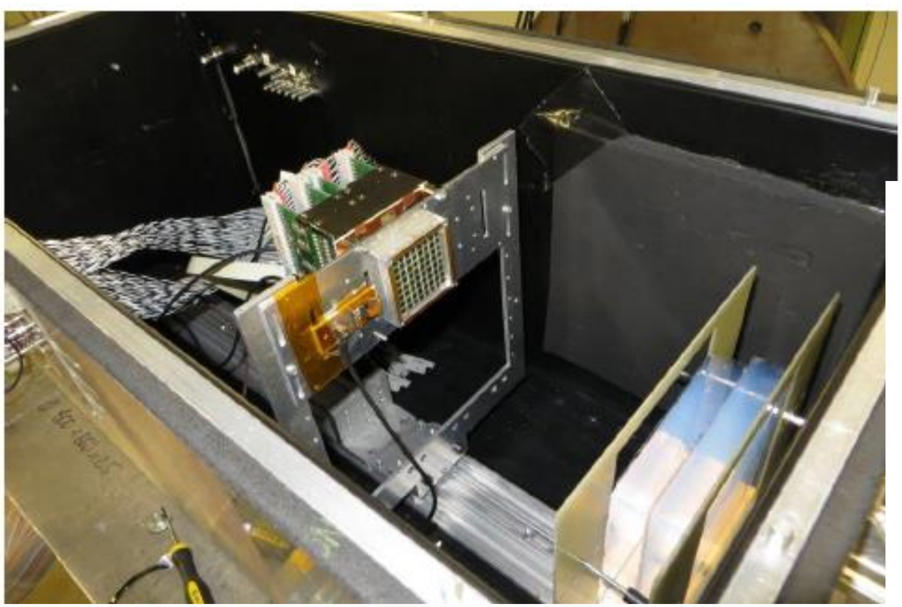
- continuation of development of SiPM photodetector for future experiments
- tests new type of SiPM arrays + light concentrators
- compact module designs
- study of photon detection efficiencies after neutron irradiation
- integration with available electronics
- evaluation in the beam tests

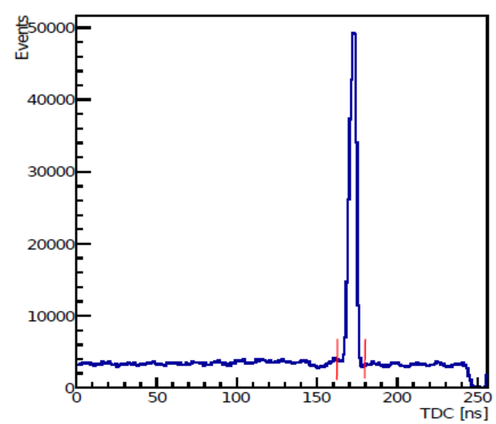


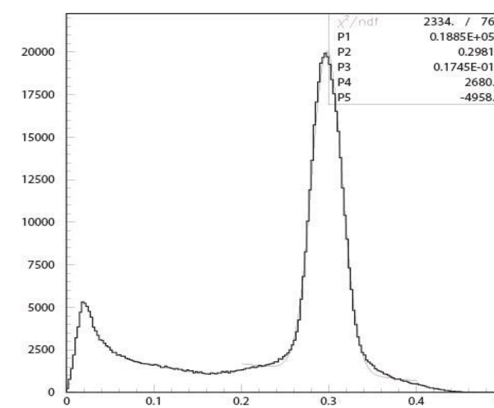




ring in Cherenkov space



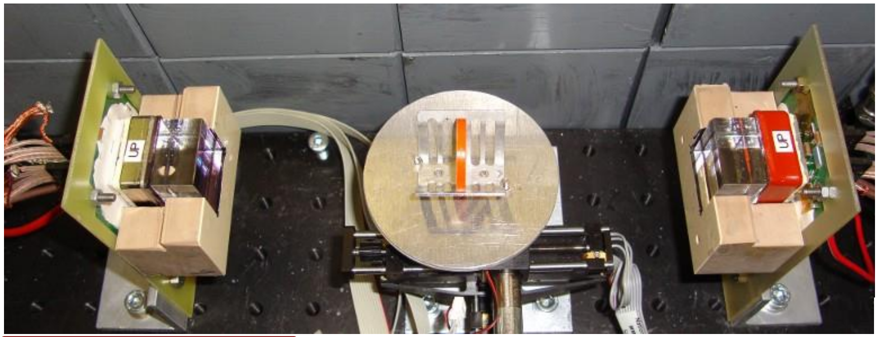




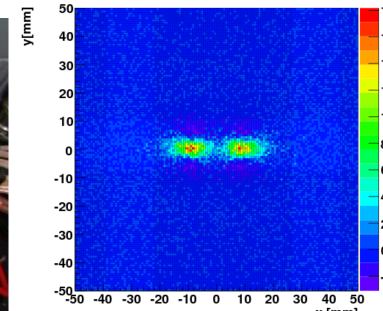
theta Cherenkov

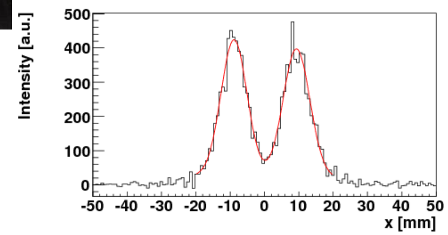
Technology transfer - applications

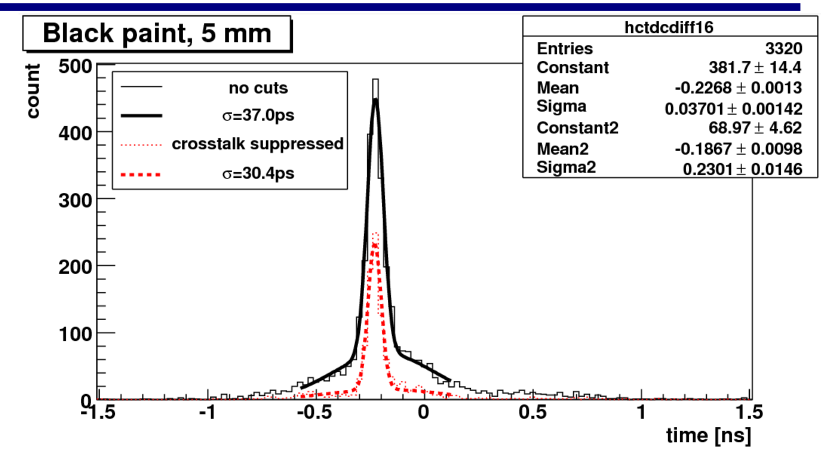
- study of TOF-PET based on Cherenkov light production in PbF_2 and MCP-PMTs, SiPMs
- excellent timing < 100 ps with 15mm crystals

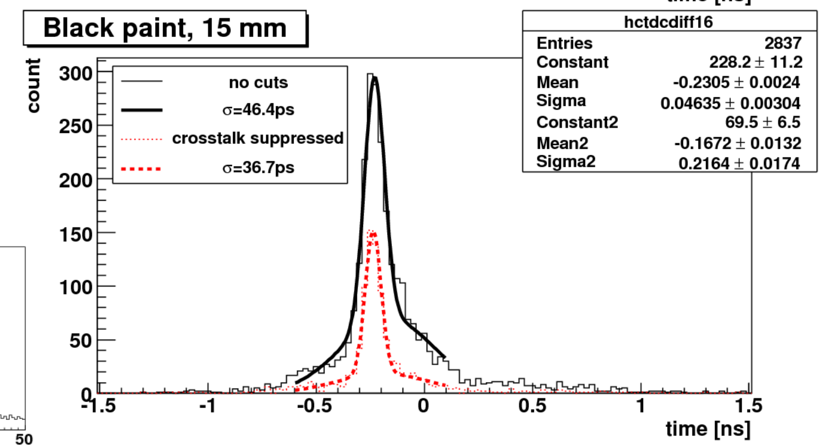


NIM A654(2011)532

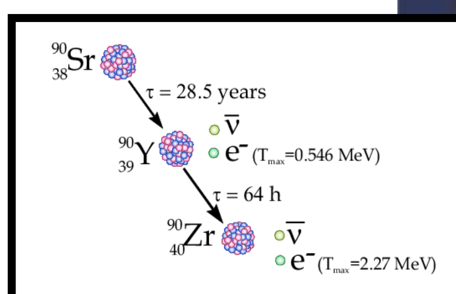


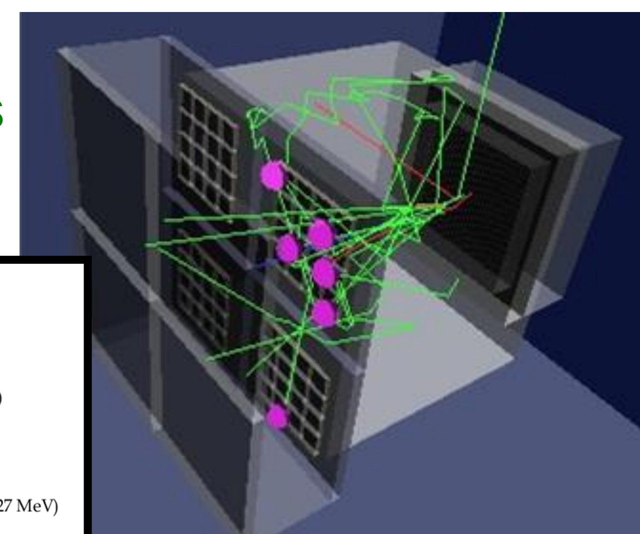






- detection of ${}^{90}_{38}Sr$ through the fast electron from ${}^{90}_{39}Y$
- pure beta emitter – can not b detected by gamma detectors
- coincidence detection with MWPC and Cherenkov light from aerogel to discriminate against background





NIM A353(1994)217;NIM A595(2008)278

Semiconductor Detector R&D and HL-LHC upgrade activities

Activities

Research in semiconductor particle detectors and dosimetry sensors

ATLAS upgrade (JSI activities – covered by ATLAS talk)

- Beam Condition Monitor (diamond detectors)
- Radiation monitoring (dosimeters)
- High Granularity Timing Detector (LGADs)
- ITk (strip sensors, depleted CMOS)

R&D Collaborations for HEP (upgrade of LHC, Future Circular Collider) and Nuclear physics

- RD50 - Radiation hard semiconductor devices for very high luminosity colliders (previously in RD39, RD48)
- RD42 - CVD Diamond Radiation Detector Development
- Dosimetry (PIN, MOS-FET and diamond)

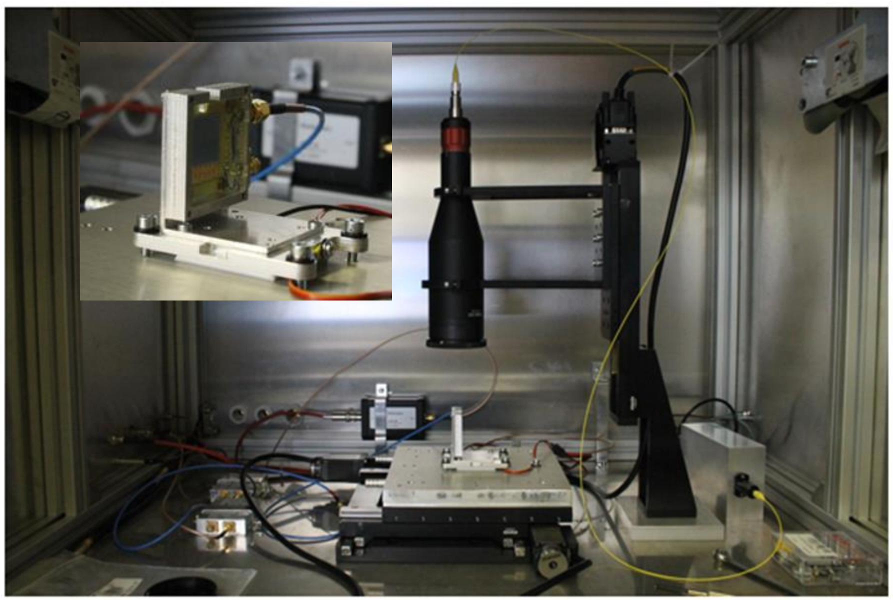
Infrastructure : JSI semiconductor Lab

Established laboratory for studies of position sensitive semiconductor detectors:

- Lab Techniques (probe stations, Scanning-TCT, Cryo-TCT, Timing resolution Setup, Multi-Ch. charge collection)
- Detectors simulation software – KDetSim.org (a 3D ROOT based software)
- KARTEL – “Mimosa” based beam telescope with full software analysis
- Infrastructure (wire-bonders, CAD/CAM workshop, clean room)

Scanning-Transient Current Technique(pioneers)

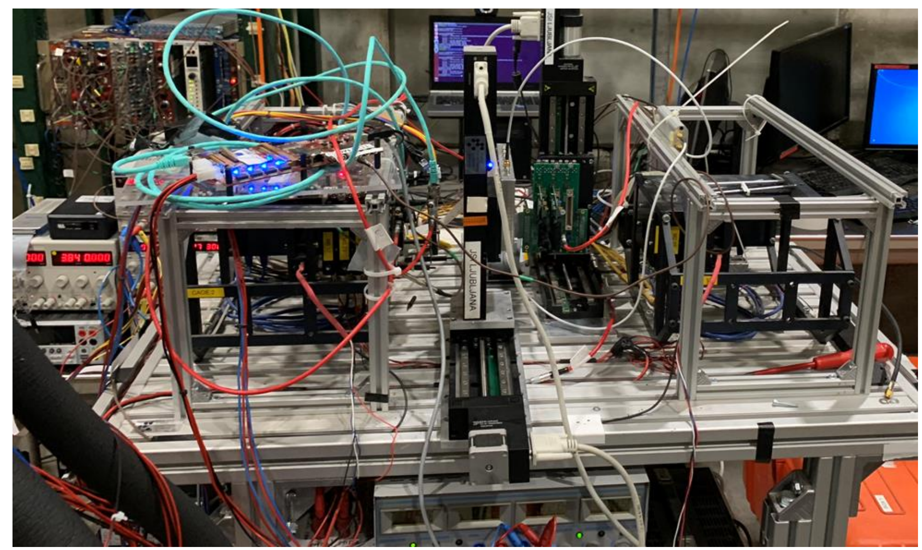
- Used by many laboratories around the world
- Commercialization through Particulars Ltd.



Investigation of Irradiated Silicon Detectors by Edge-TCT, *IEEE Trans. Nucl. Sci.* **57** (2010) 2294.

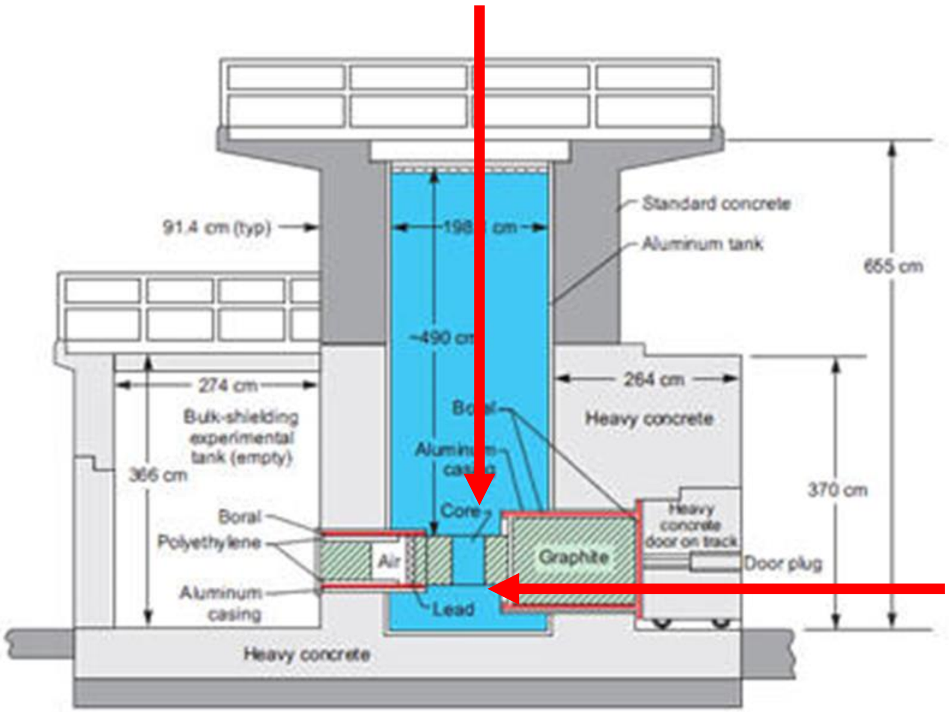
KARTEL Beam Telescope

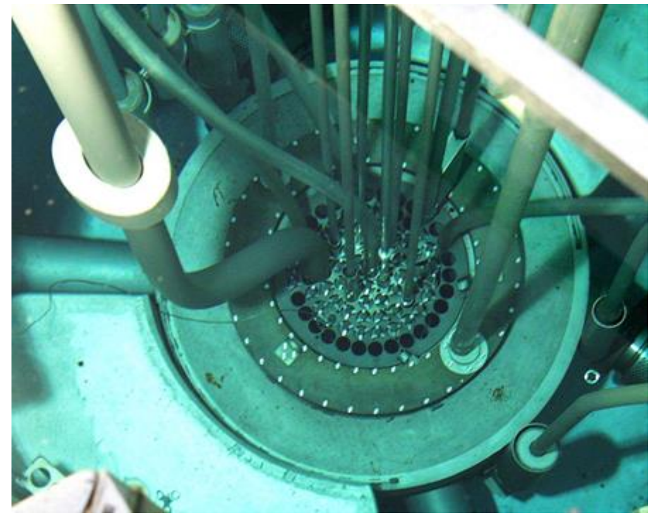
- 6 Mimosa planes with FEI4 for anchoring tracks
- used by RD42, ATLAS (HVCMOS)



***Synchronized analysis of test beam data with the Judith software*,** *NIMA 765 (2014) 140.*

Infrastructure : JSI Irradiation facility





TRIGA Mk. 2 type

- Built 1961
- 250 kW max
- TID at 250 kW

~1 kGy /10^{14} $n_{eq}cm^{-2}$

- well known hardness factor 0.9 (>100 keV)
- <10% accuracy

Reference irradiation facility for HEP – similar spectrum of neutrons than those at LHC

(well known spectrum, regulary calibration checks, known conditions, established procedures)

Different irradiation channels which allow irradiations to extremenly high fluences up to $10^{18}\ neq/cm^2$:

- 3 vertical for samples up to 6 cm in diameter with fluxes: $1.54,\ \ 3.57,\ 6\ \cdot 10^{12}\ neq/cm^2s$
- tangentional channel ($130 \times 200\ mm^2$) - $4 \cdot 10^{11}\ neq/cm^2s$

AIDA 2020

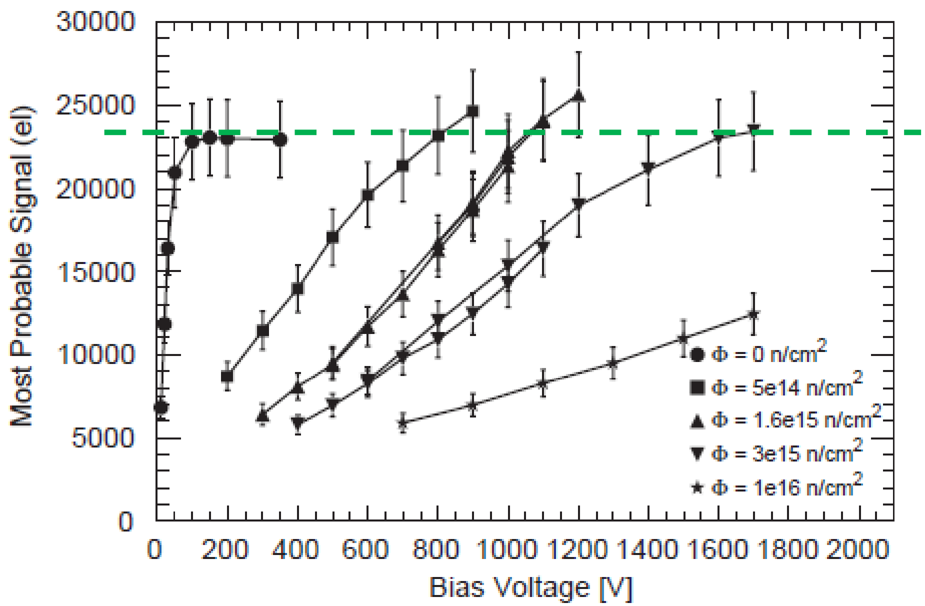
AIDA 2020 facility – widely exploited by all LHC experiments : 514.5 units delivered in 98 projects, approx 580 irradiations (ALICE 1%,LHCB 2%,CMS 18%, ATLAS 26%, RD 49%, 4% others)

R&D: Radiation hardness of position sensitive detectors

Very active collaboration within RD39,48 and 50:

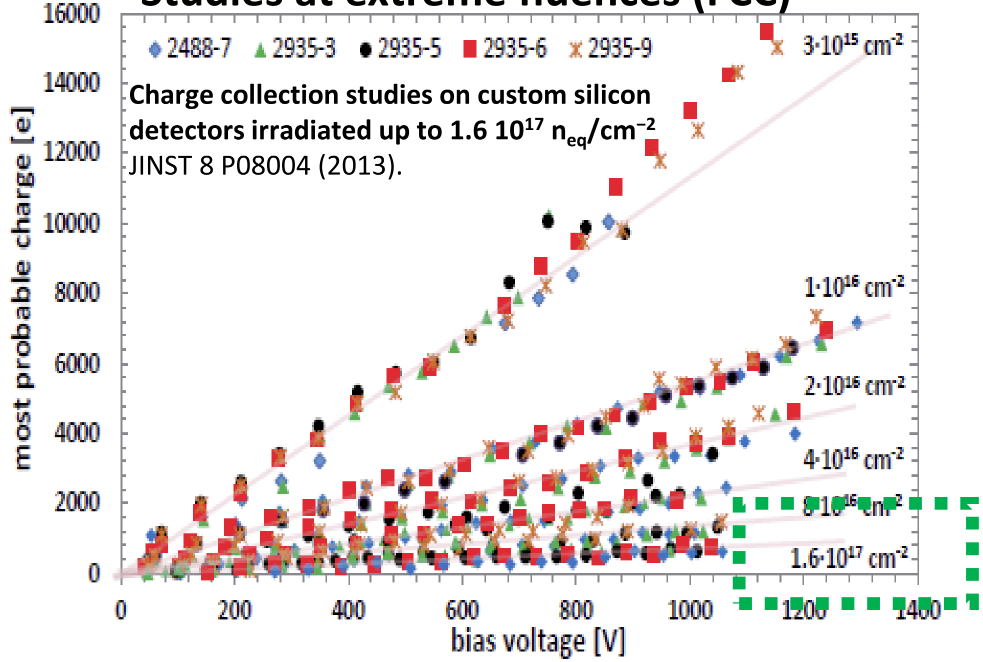
- annealing studies
- trapping measurements in many materials (>150 citations)
- bias effects on long term operation
- studies of multiplication dependence on hit position, electrode configuration, fluence, bias

First direct observation of charge multiplication in irradiated silicon detectors

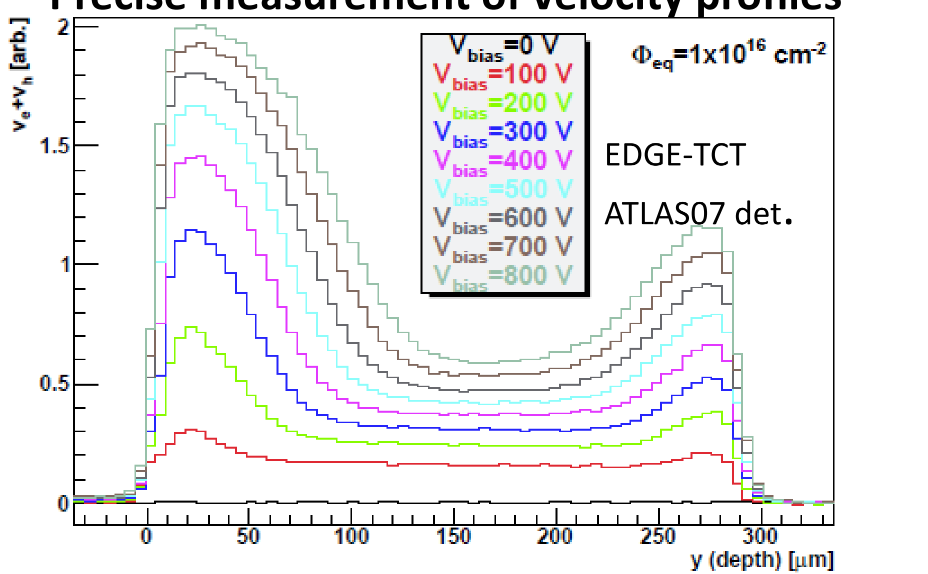


NIM A603(2009)263

Studies at extreme fluences (FCC)



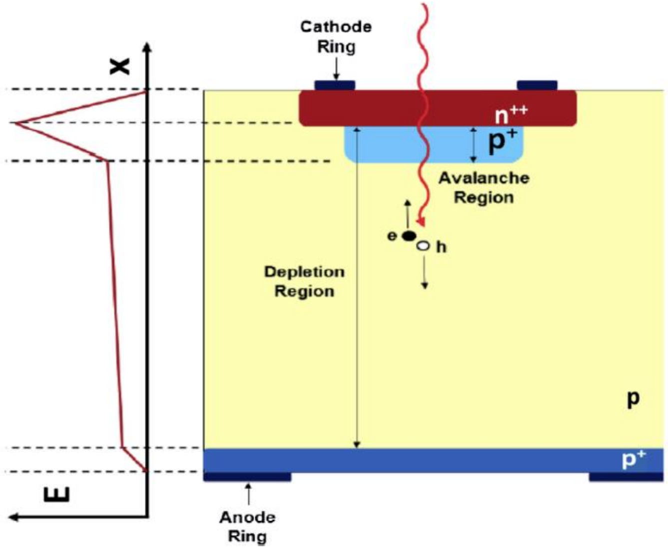
Precise measurement of velocity profiles



Modelling of electric field in silicon micro-strip detectors irradiated with neutrons and pions, 2014 JINST 9 P10016

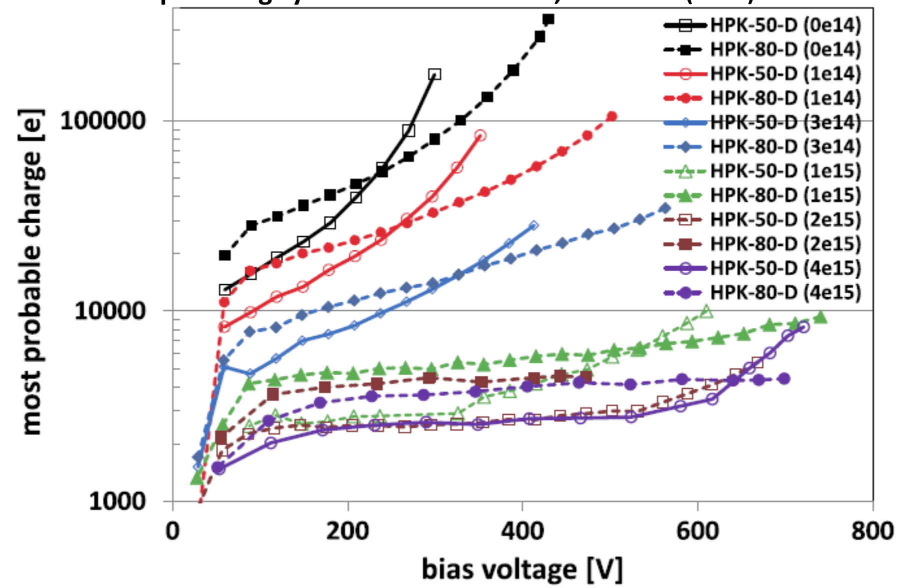
R&D : timing detectors, LGADs and 3Ds

Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications, Nucl. Instrum. Methods Phys. A (2014)



Radiation effects in Low Gain Avalanche Detectors after hadron irradiations, JINST Vol. 10 (2015) P07006.
Radiation hardness of thin low gain avalanche detectors, Nucl. Instr. and Meth. A 891 (2018) 68.

Beam test results of a 16 ps timing system based on UFSD, NIM A850 (2017) .



Development of timing detectors for HGTD of ATLAS – 30 ps time resolution for 1.3x1.3 mm^2 large pads

Low Gain Avalanche Detectors for timing application at very high fluences – two problems:

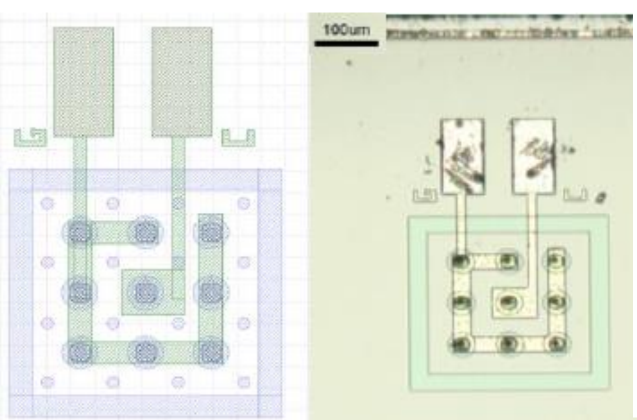
- Gain layer disapperance with fluence in LGADs (acceptor removal identified as the main cause)
- Fill factor importance for small pads (no gain region between pads)

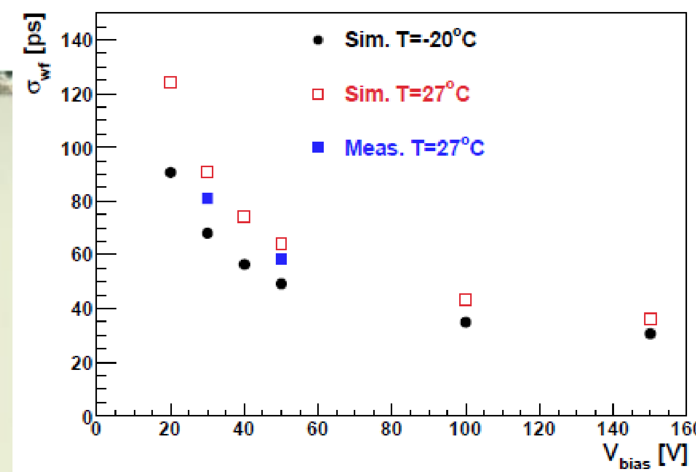
4D tracking detectors utilizing

small cell 3D detectors (RD53, 50x50 μm^2)

-100 % fill factor

-more radiation hard



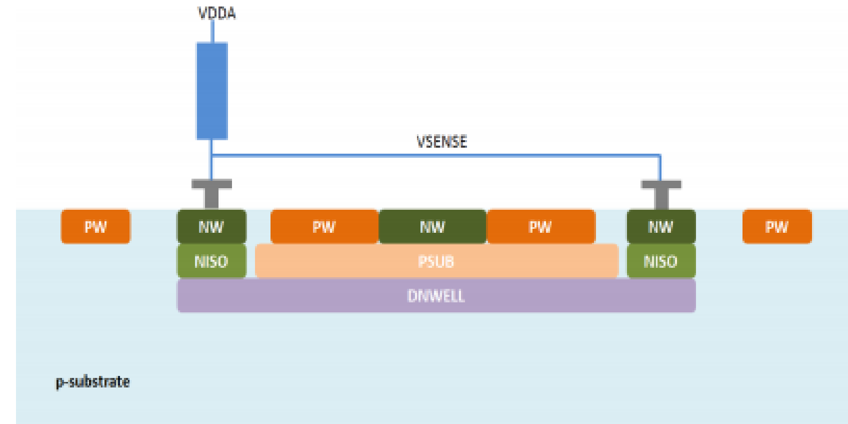


Timing performance of small cell 3D silicon detectors, arXiv:1901.02538v2 [physics.ins-det]

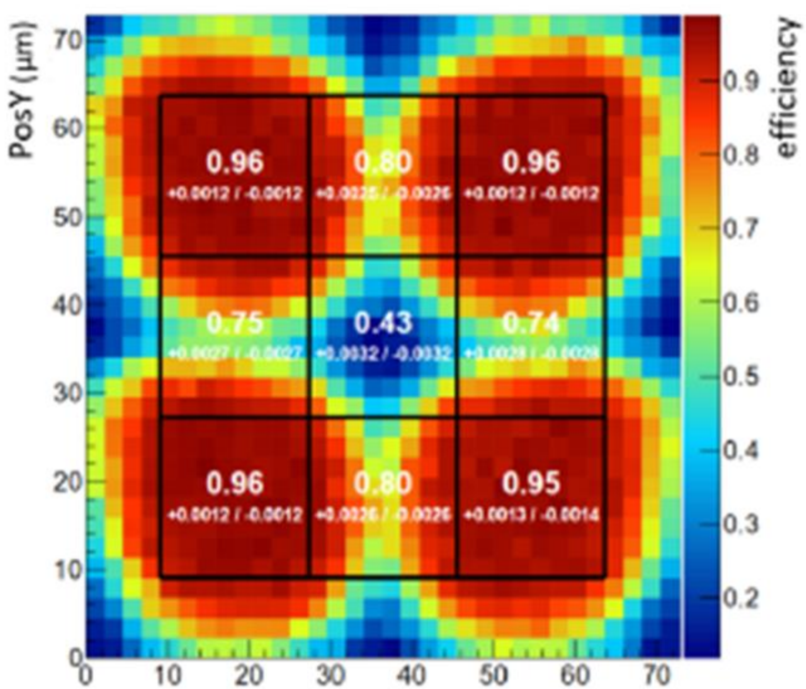
R&D : Depleted CMOS detectors

Active in ATLAS R&D depleted CMOS activities:

- mostly concentrated on radiation effects (acceptor removal, oxide effects)
- studies of passive and active structures (Edge-TCT as a main tool)
- Simulations and test beam studies
- development of readout systems for MAPS

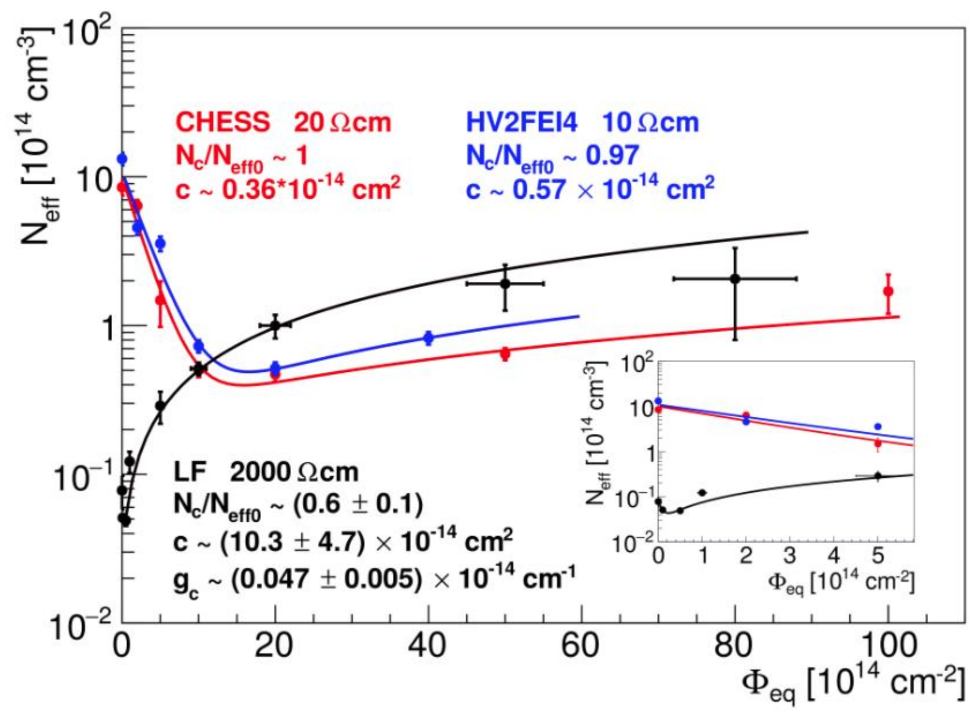


Test beam of irradiated TowerJazz ATLAS prototype



From B. Hiti et al., POS

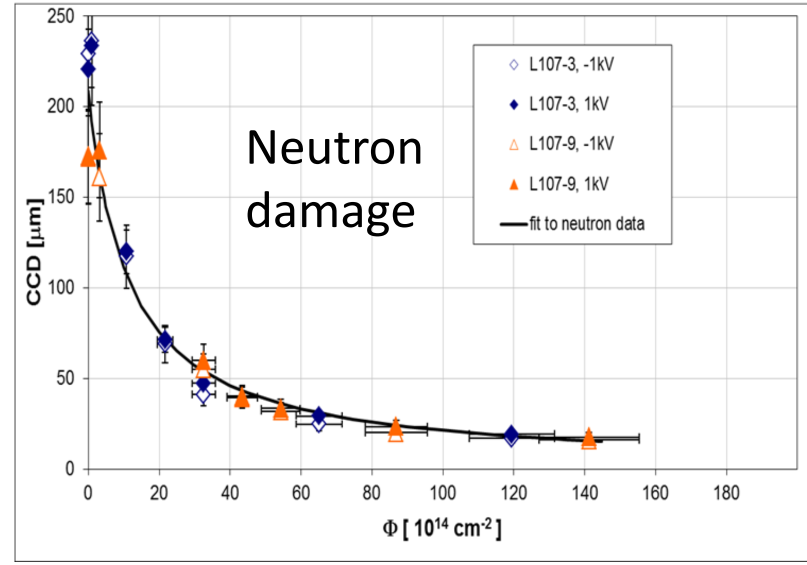
Evolution of substrate properties with



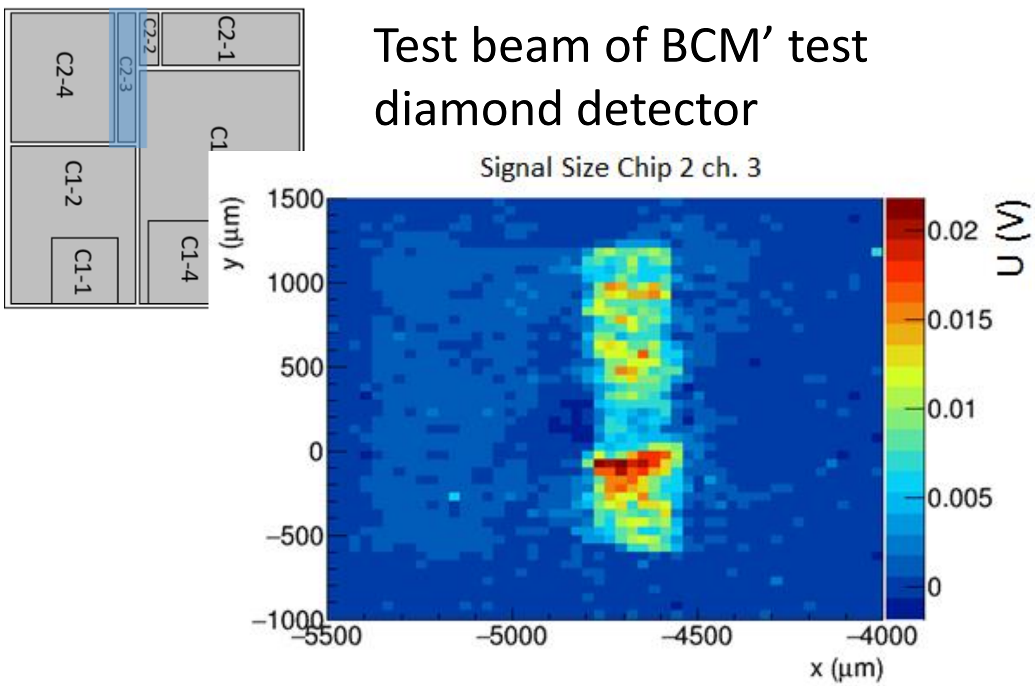
R&D : Diamond detectors

Activities within RD42 collaboration and ATLAS DBM/BCM':

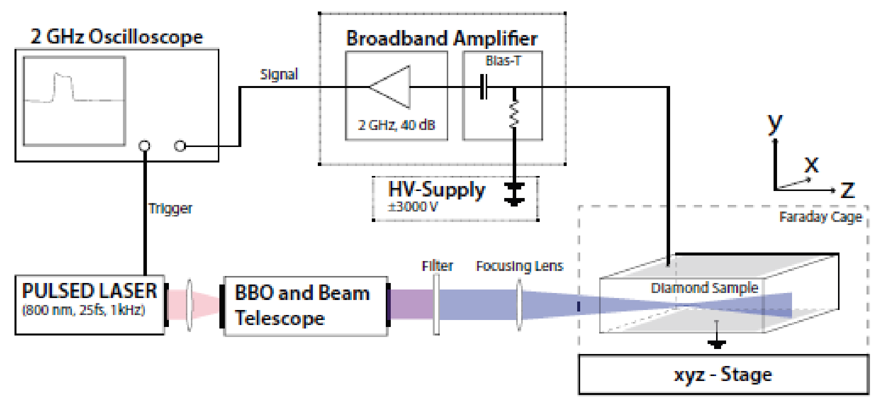
- radiation hardness (mainly neutron damage)
- investigation of charge multiplication in single crystalline CVD diamonds (Nucl. Instr. Meth. Volume 841 (2017))
- Two Photon Absorption TCT studies
- test beam studies for ATLAS-BCM'

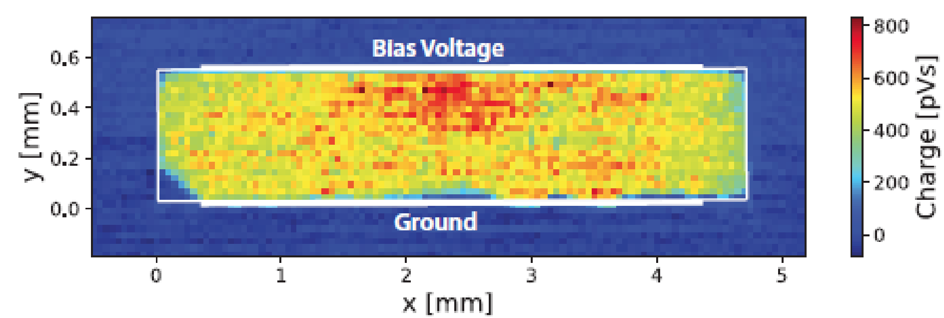


Test beam of BCM' test diamond detector



TPA – TCT in scCVD diamond



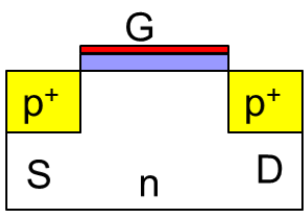


R&D : Dosimetry sensor developments

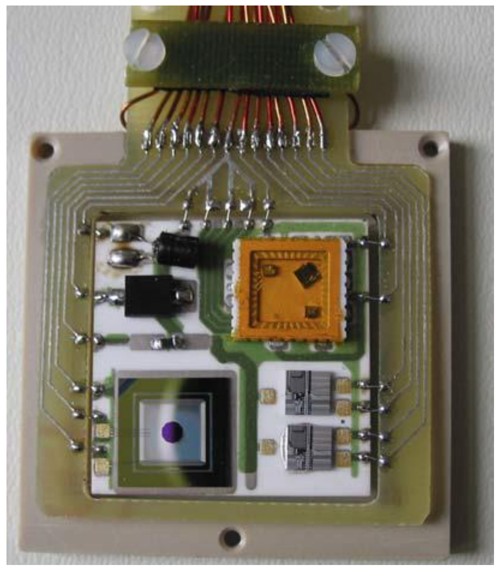
- MOS-FET dosimetry for HL-LHC/ ATLAS and medical applications (with partner Bolu University, Turkey)
- Diamond dosimetry for medical applications – radiotherapies (within RD42)

MOS-FET

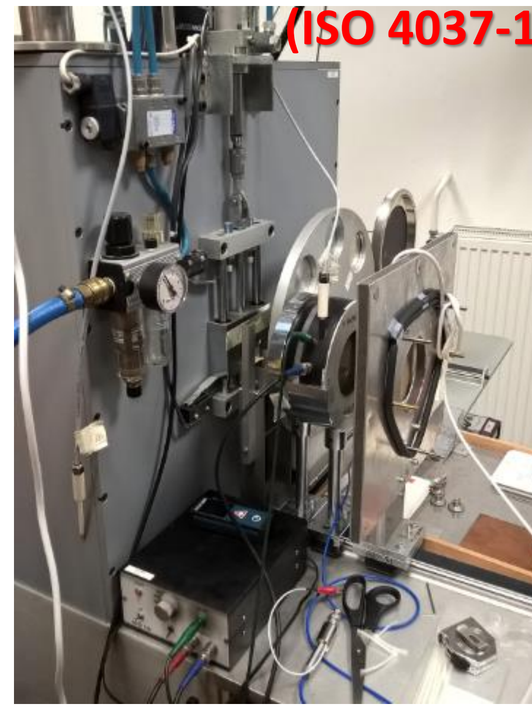
$$V_T \propto t_{OX}^2 \cdot D$$

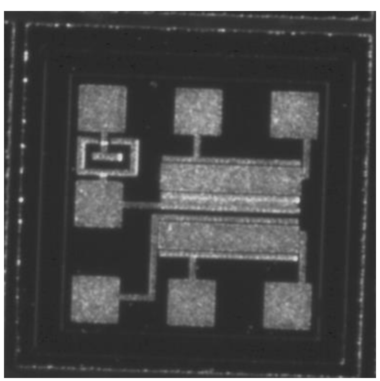


Present ATLAS-ID radiation monitor board



JSI X-ray machine for calibration (ISO 4037-1)





Current R&D: development of dosimetric MOS-FETs (NürFET)

- with different sensitives/ranges (oxide thicknesses 40,60,80,100,400,800 nm), 6” production – several 100k of dosimeters/wafer
- with boron layer above oxide for neutron dosimetry
- with different dielectric materials between the channel and gate (fading/sensitivity)

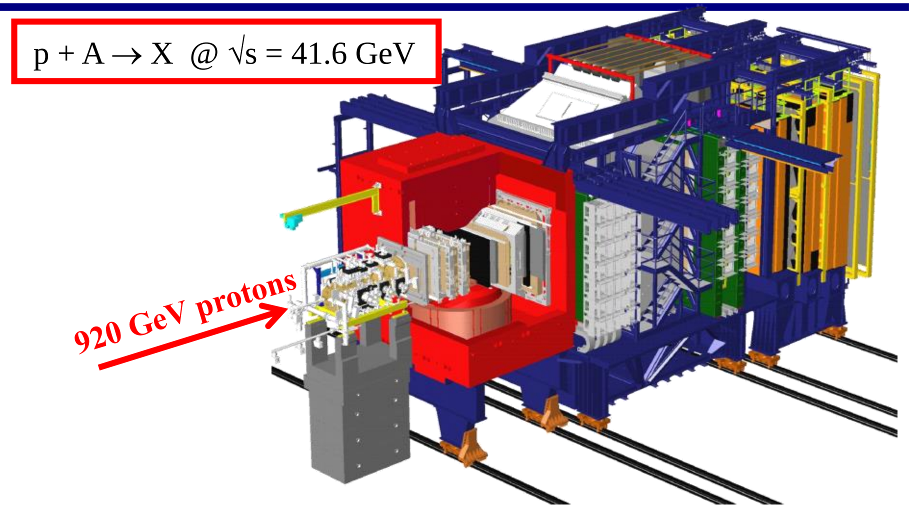
Summary

- Detector R&D for experimental particle physics has a strong tradition.
- At JSI we have set up an infrastructure for R&D of photosensors, semiconductor detectors and neutron irradiation studies
- Contribution to detectors at the energy (ATLAS) and luminosity frontier (Belle II)
- R+D efforts in collaboration with the Slovenian industry, successful transfer of technology
- Applications in medical and environmental physics

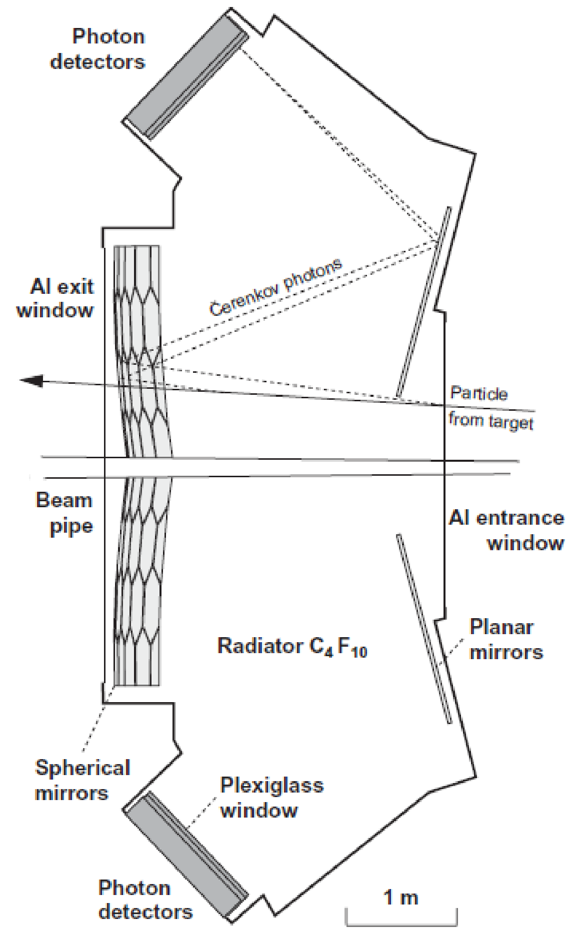
BACKUP SLIDES

A bit of history

Photodetectors for HERA-B RICH



- radiator C_4F_{10}
- ref. index 1.00137
- Cher. angle 52.4 mrad (β = 1)
- π/K Cher. angle difference
  @ 50 GeV/c → 0.9 mrad
- mirror radius 11.4 m



Design and production of ... components