Challenge in beam instrumentation and diagnostics

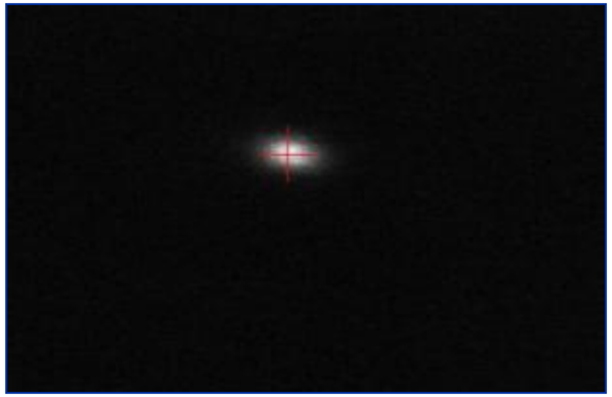
T. Lefevre – CERN

Outline

- Introduction of Beam Instrumentation
- Recent achievements and examples of Key technologies
- Examples of R&D activities
- Conclusions

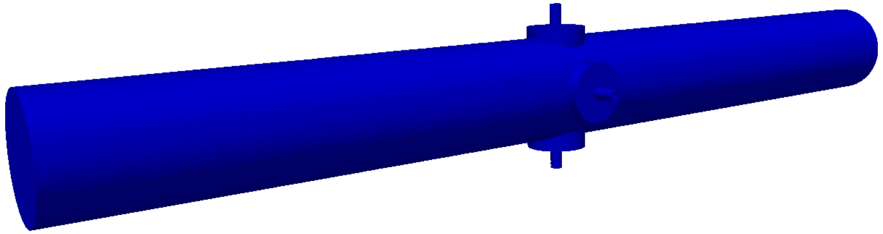
Beam Instrumentation

The EYES



Beam induced Light

The EARS



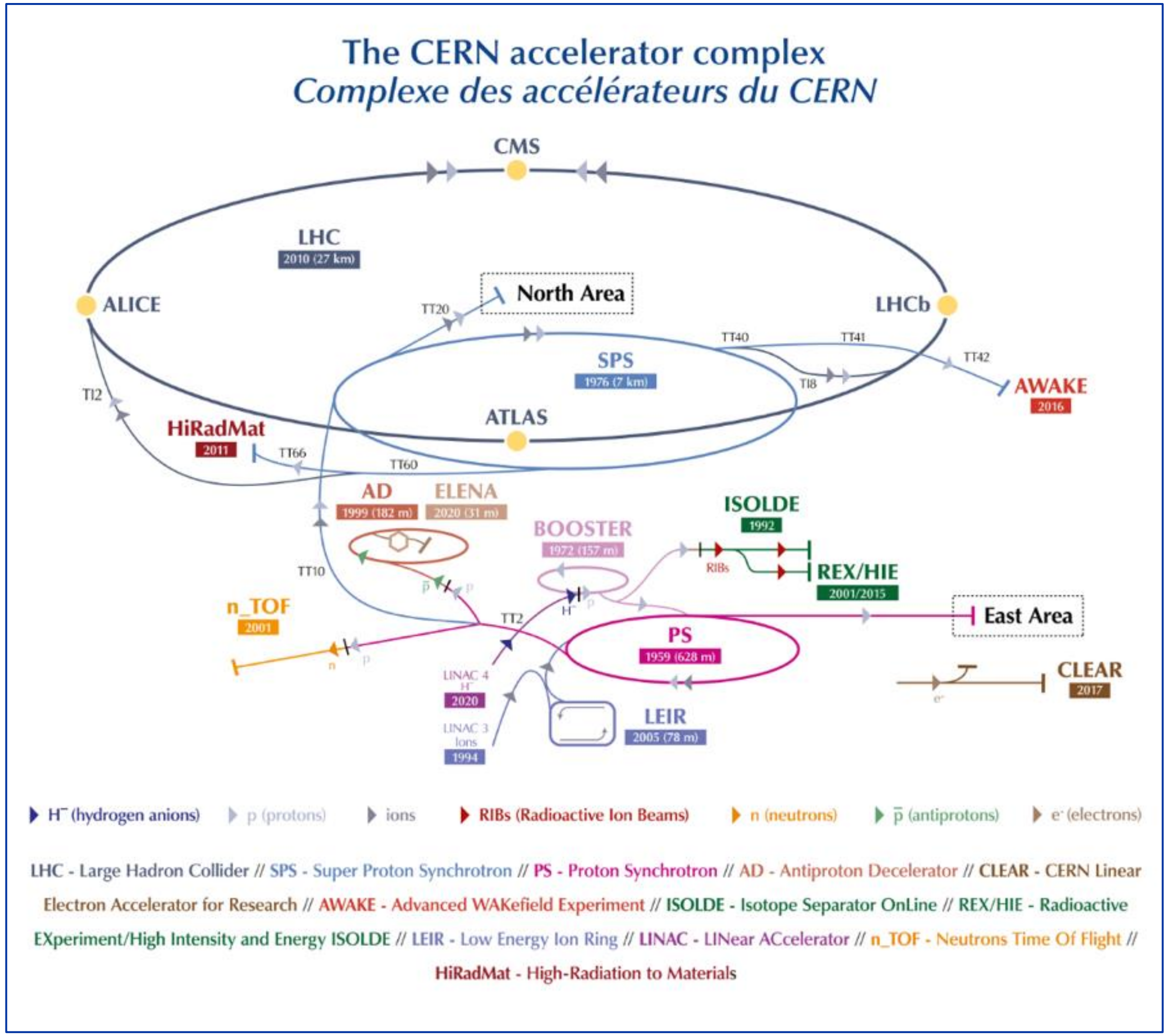
Electro-magnetic field

The HANDS

Beam interceptive devices

Beam instrumentation at CERN

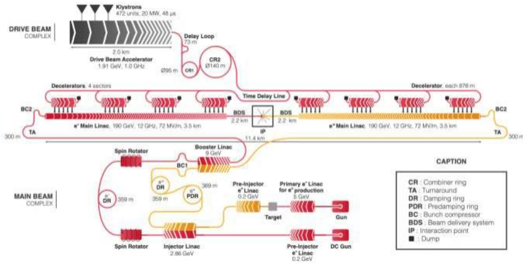
The Beam Instrumentation Group is responsible for designing, building and maintaining the instruments that allow observation of the particle beams and the measurement of related parameters for all CERN accelerators, transfer lines and secondary beam lines. (> 10000 instruments)



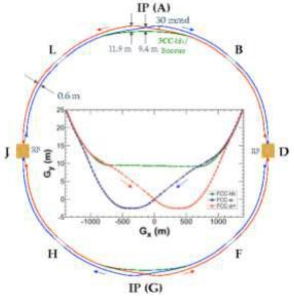
~ 140 people (50% staffs, 50% Students, Fellows and Project associates

Looking forward …

It is engaged in research and development to improve existing detection techniques and explore new avenues to allow further optimization of the current machines and to meet the challenges associated with future accelerators.

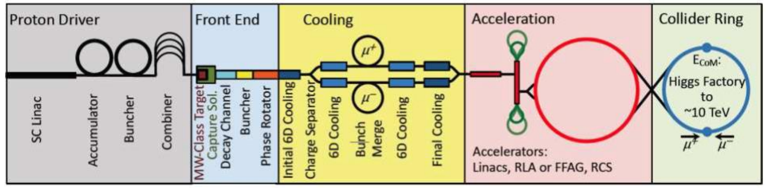


https://clic.cern/



https://fcc.web.cern.ch/Pages/default.aspx

International MUON Collider Collaboration



https://pbc.web.cern.ch/

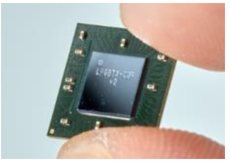
https://muoncollider.web.cern.ch/welcome-page-muon-collider-website

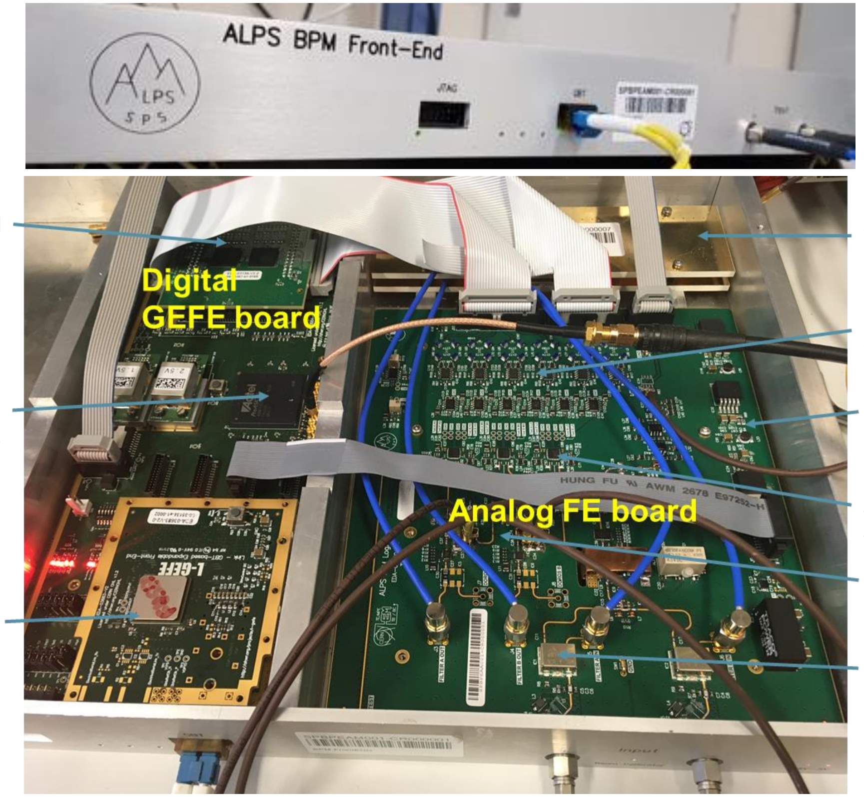
Examples of recent achievements and Key technologies

New acquisition system for SPS Beam Position Monitors

New acquisition system for SPS Beam Position Monitors

- 240 BPMs using a radiation tolerant (10kGy) Front-End electronic installed in the Tunnel
- 75dB dynamic range using logarithmic compression

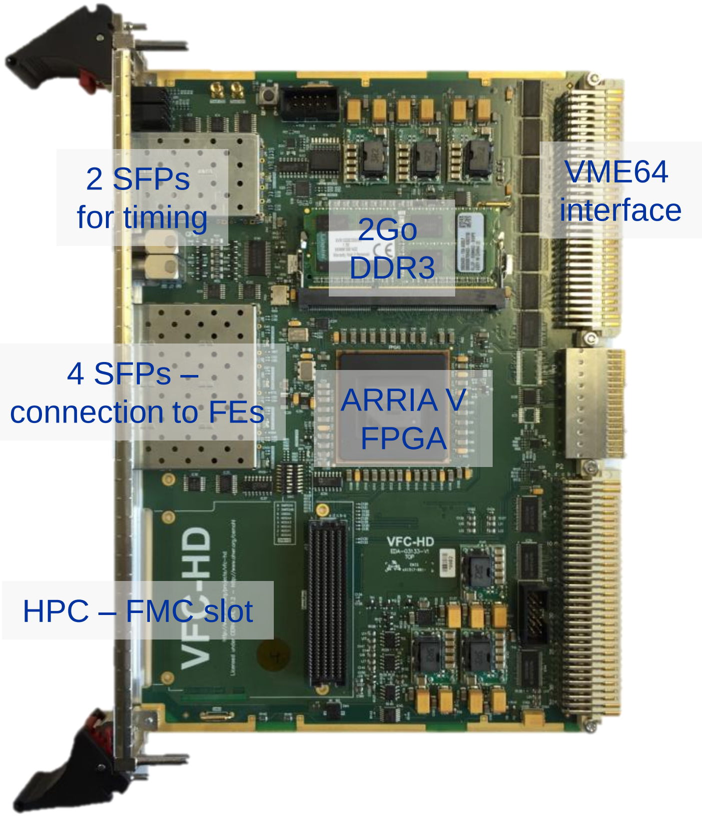




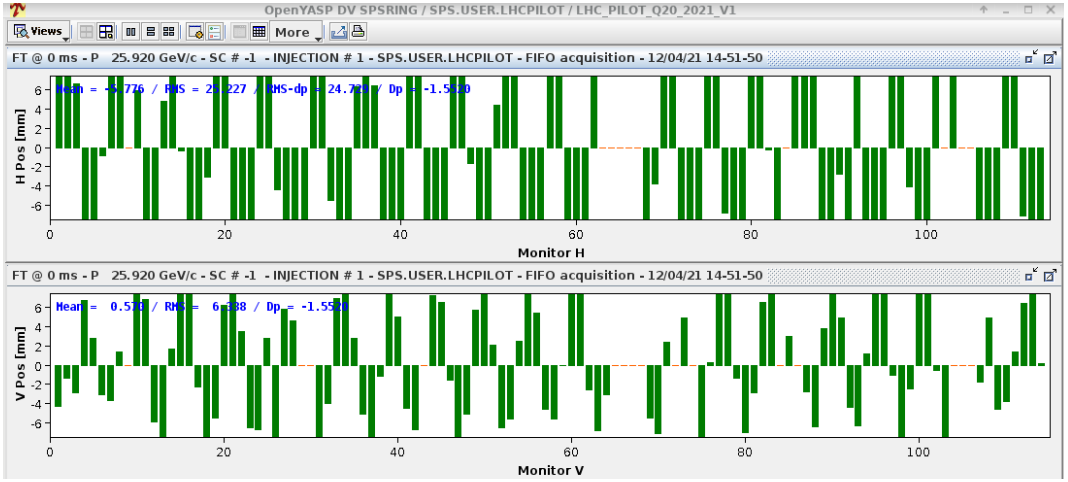
Radiation-hard ASICs and optical transceivers developped by the CERN EP department https://ep-dep.web.cern.ch/organisation/ese

New acquisition system for SPS Beam Position Monitors

- Optical fiber transmission from Front-Ends in tunnel to Back-Ends acquisition system located in Surface buildings
- DAQ based on VME FMC Custom design : open hardware development - VHC-HD



First orbit measurement in SPS in spring 2021



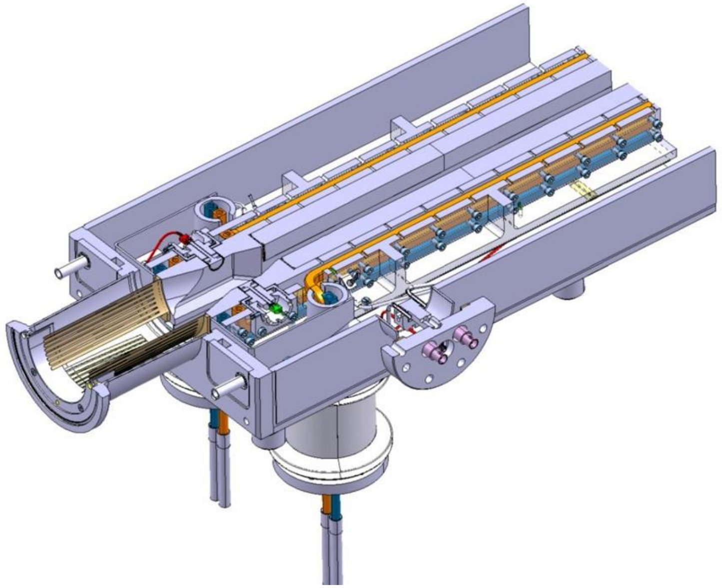
Beam type	Turn by turn resolution
Single bunch	150um
Multi- bunch (10us train)	7um

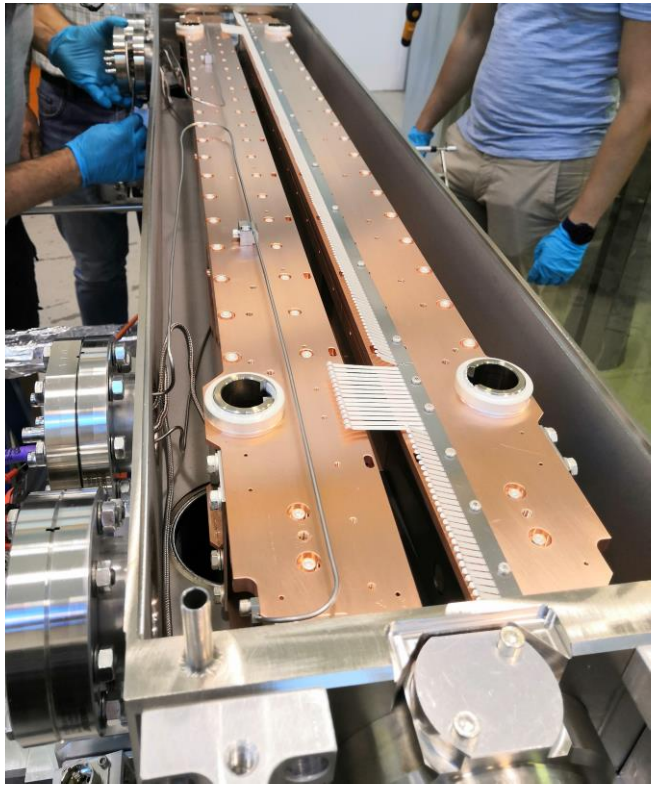
Collimator Beam position monitors

Collimator Beam position monitors

LHC Collimator jaws equipped with 2 BPMs

- Allow the centering and adjutment of each collimator aperture in few minutes
- Allow constant measurements and generate interlock in case of dangerous position drifts

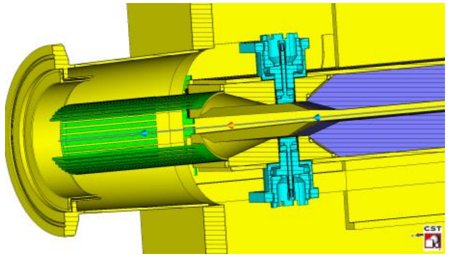




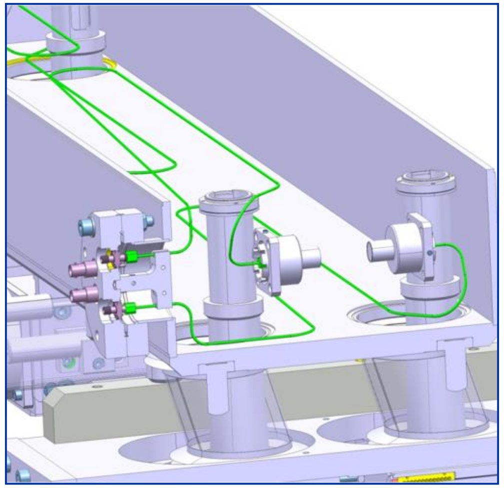
- Should be compatible with UHV conditions and 250C bake-out
- Should withstand high radiation dose (~20 MGy TID)
- Should reach an position accuracy better than 20um with micron resolution

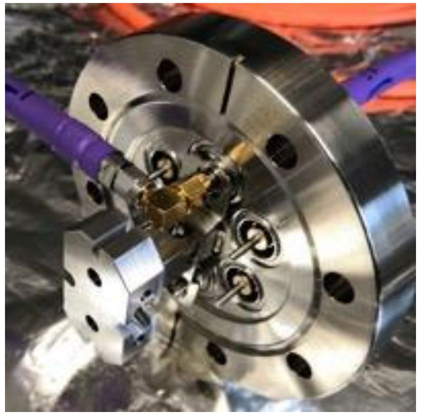
Collimator Beam position monitors

- Electrostatic Buttons



- SiO2 cables to route the cable outside of vacuum
outgassing rate <1e-9 mbar· l/s



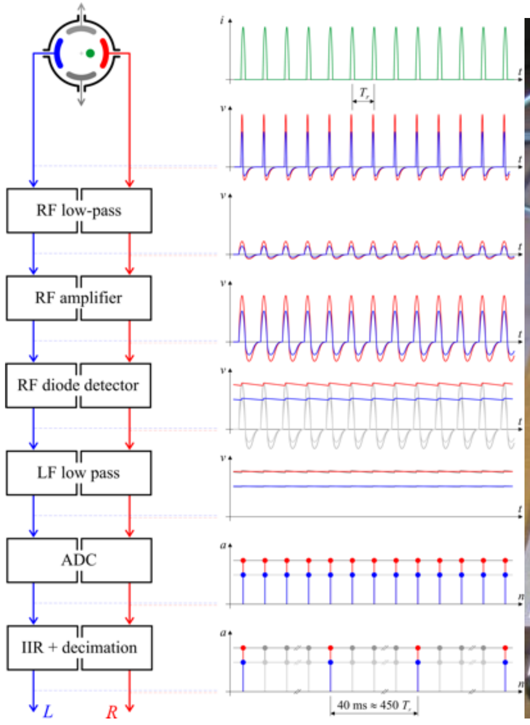


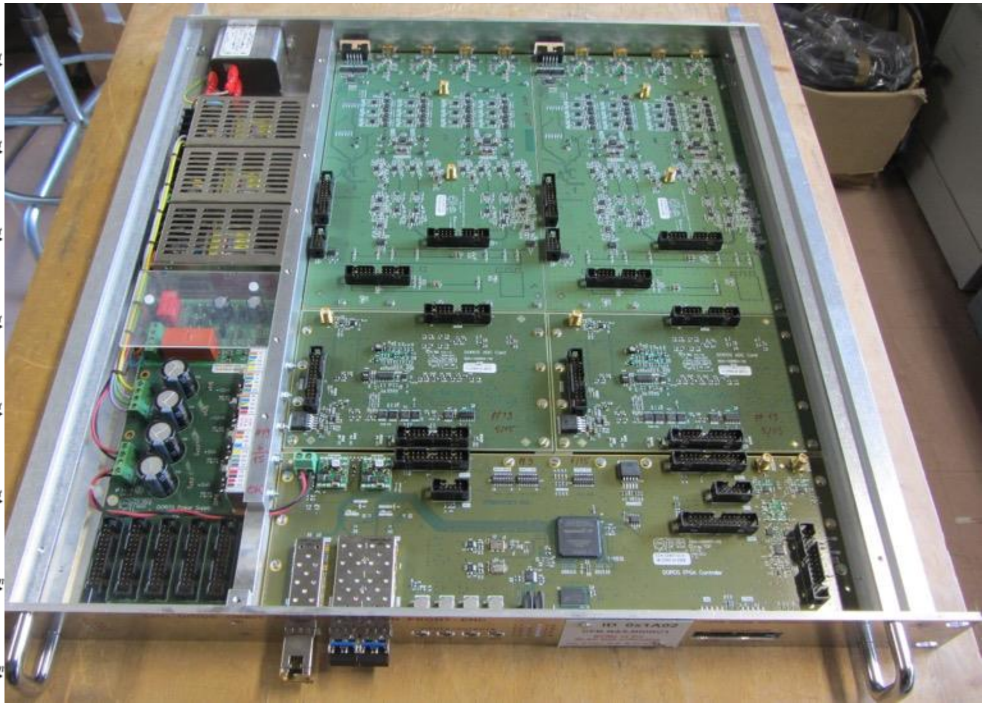
- 8m long Kapton cable followed 50m long cables to acquisition electronic

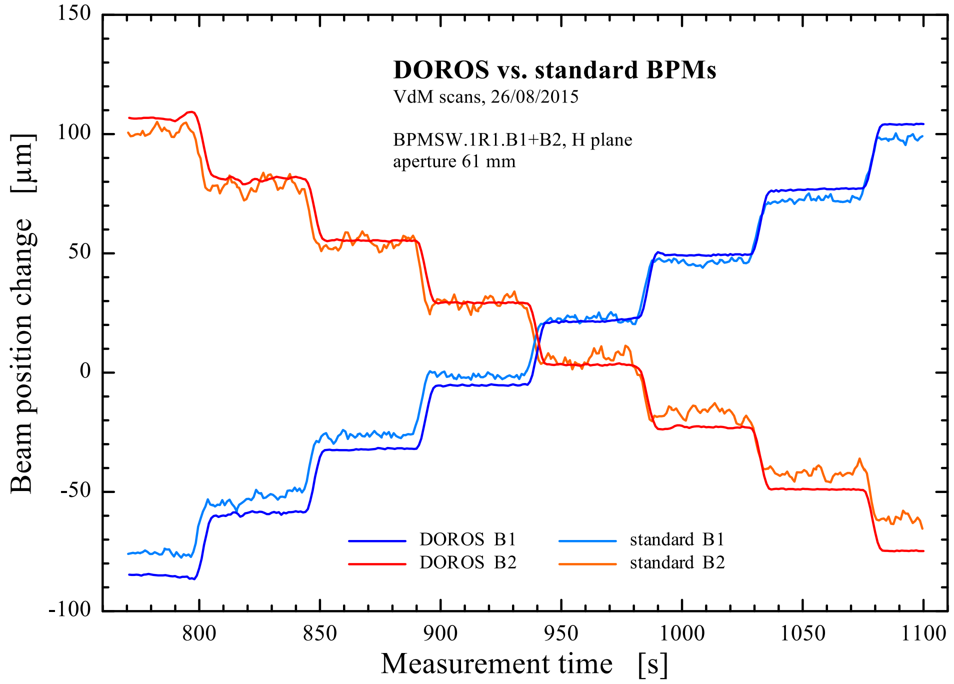
Collimator Beam position monitors

High resolution Orbit measurements

Diode ORbit and Oscillation electronic (DOROS)



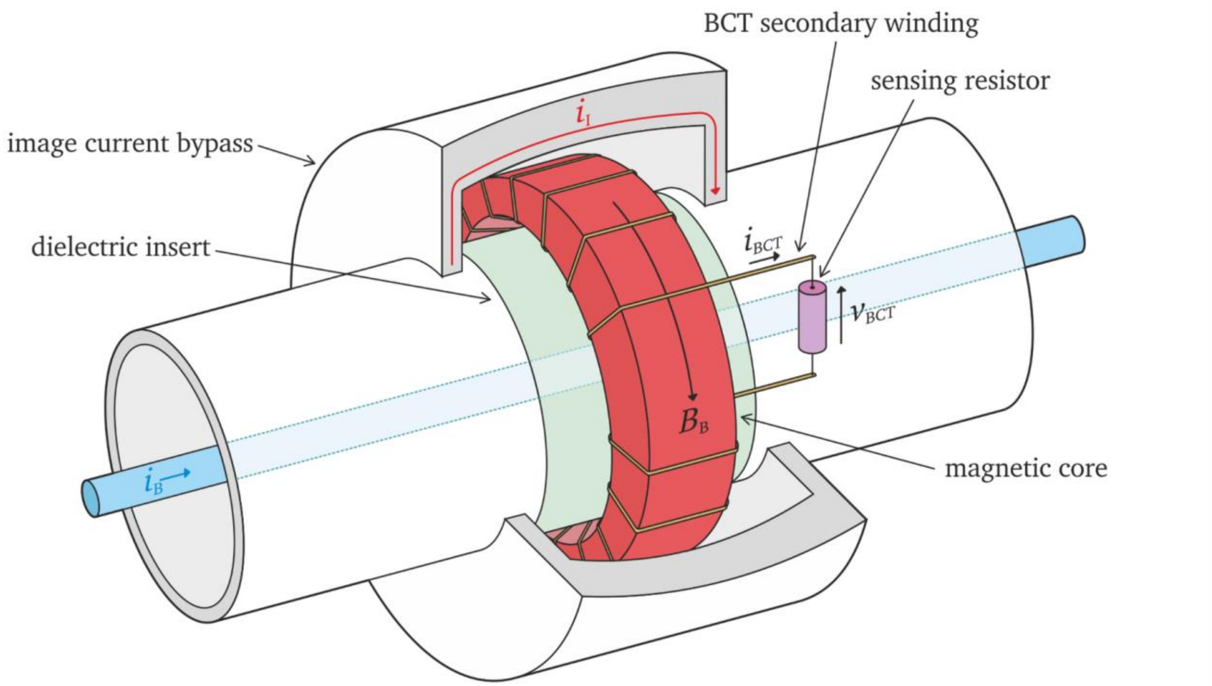




Resolution measured at 100nm

Beam Intensity monitors

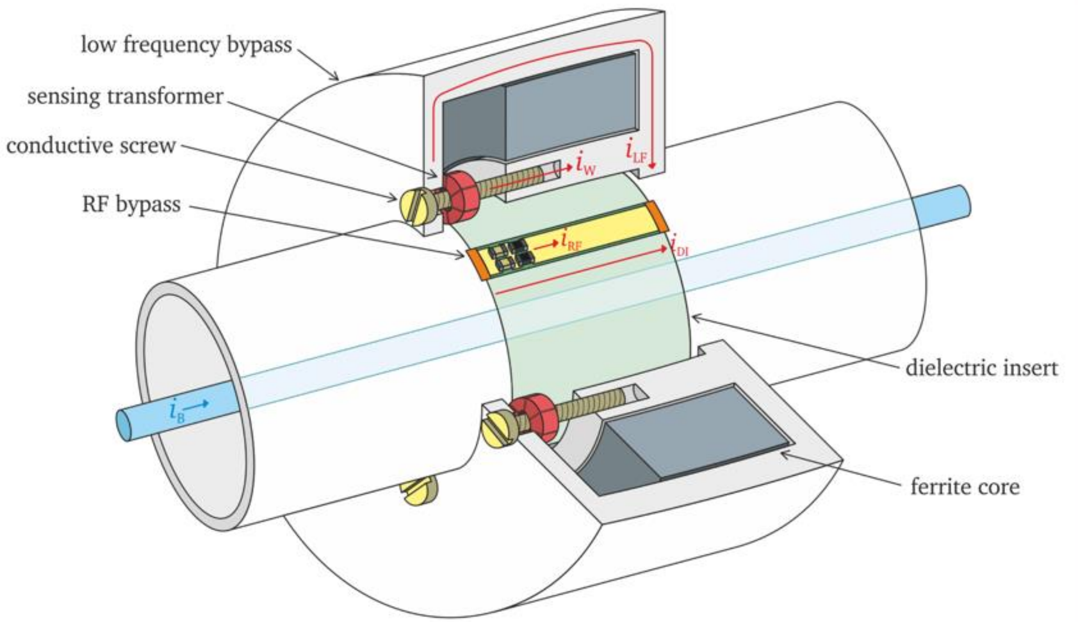
'Classical' Beam Current Transformer

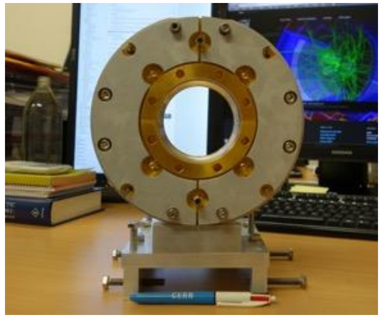


Measuring Beam intensity
with an improved Maintainability and Precision

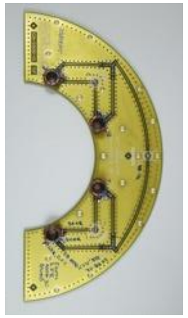
Beam Intensity monitors

Wall Current Transformers (WCT) – LHC & SPS





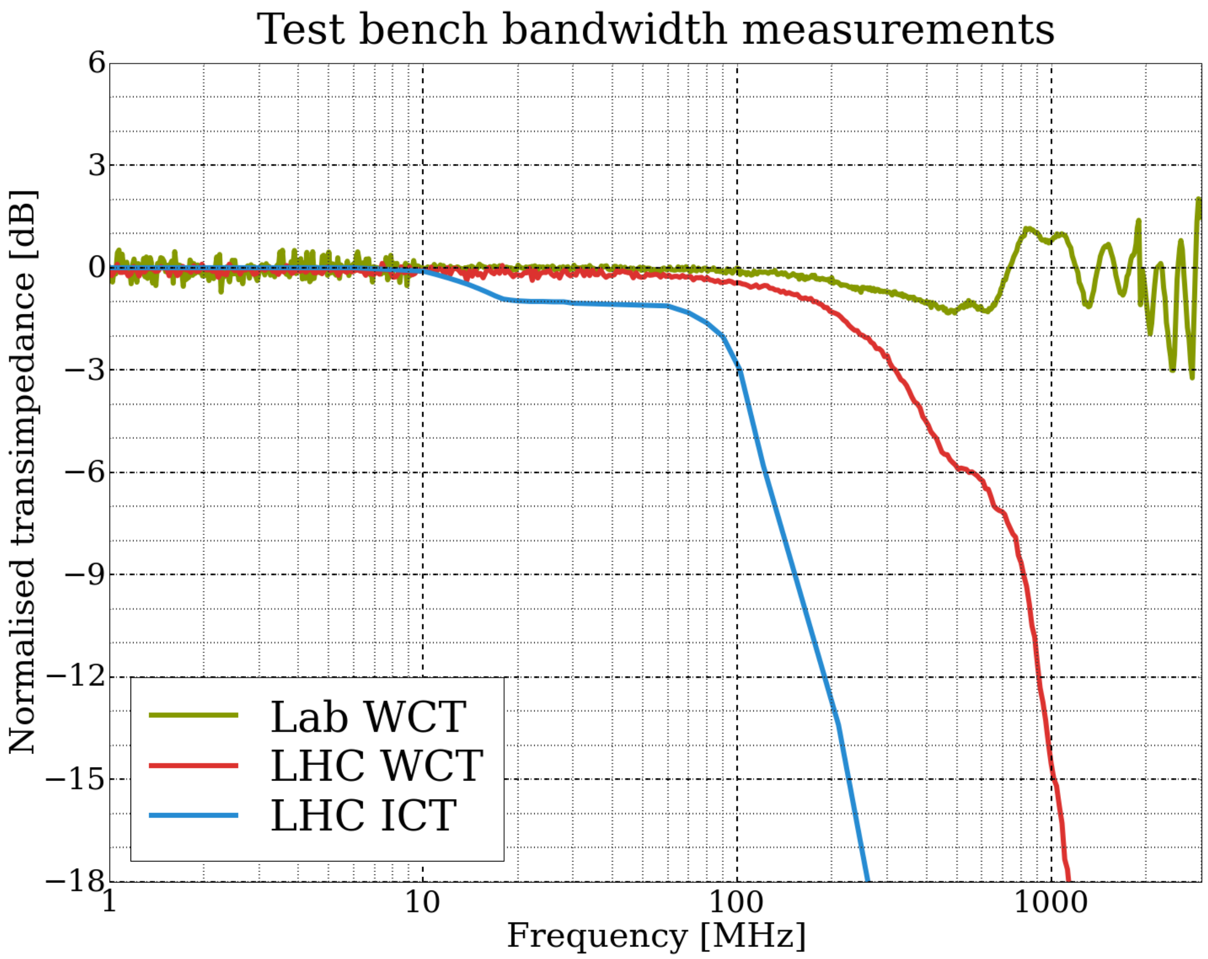
All parts cut in half – installation and removal does not require breaking the accelerator vacuum



Acquisition system based on VFC-HD using 500MSa/s FMC commercial boards

Beam Intensity monitors

Wall Current Transformers (WCT) – LHC & SPS



Lab WCT:
- work in progress
- RF bypass
- 1.1 GHz filter
- low cut-off: 500 Hz

LHC WCT:
- RF bypass
- 400 MHz filter
- low cut-off: 500 Hz

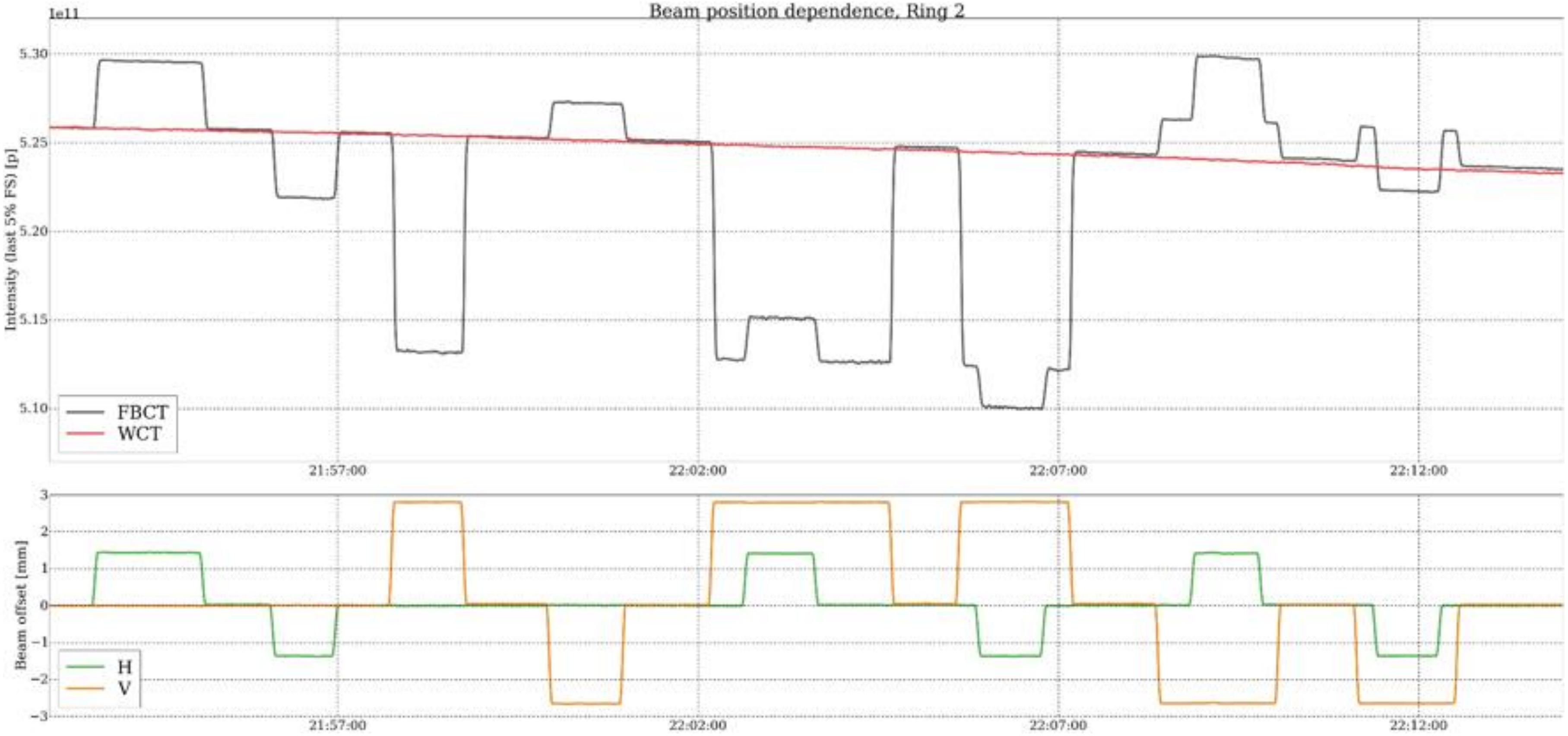
LHC ICT:
- no filter
- low cut-off: 600 Hz

Beam Intensity monitors

Wall Current Transformers (WCT) – LHC & SPS

Beam test at LHC

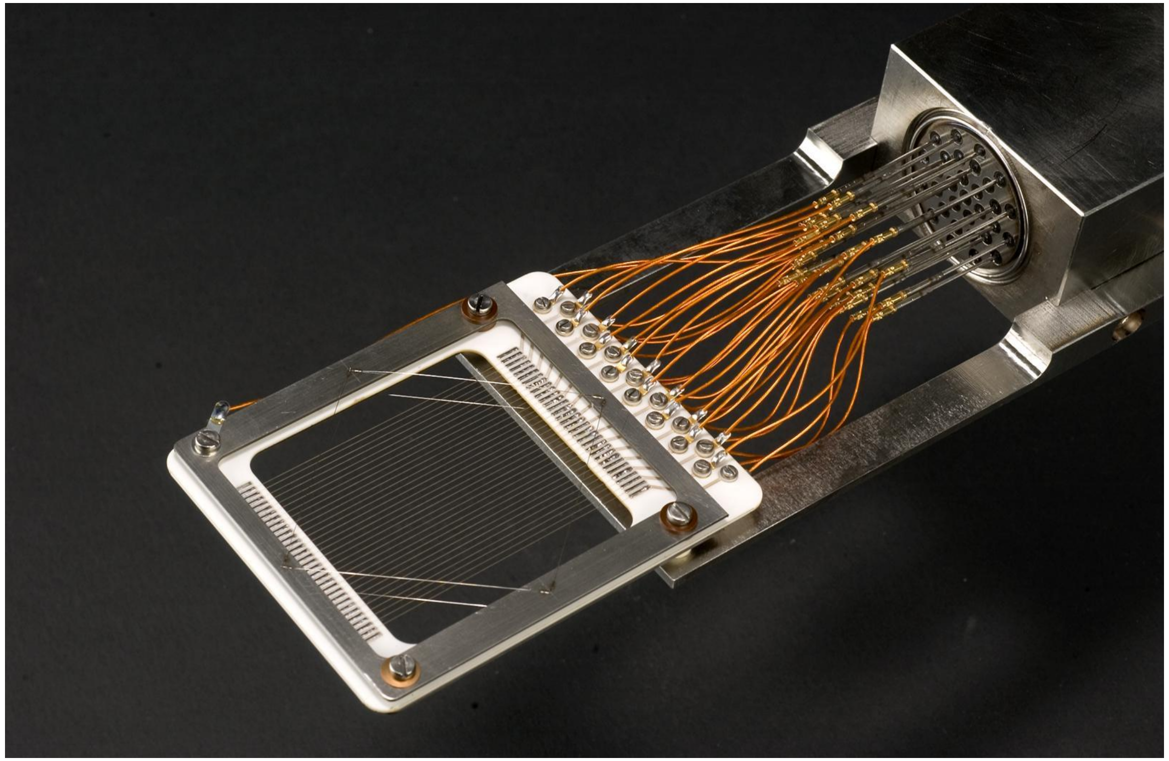
Measuring Beam position dependency



FBCT
ΔI/I ≈ (0.3 – 0.7)% / mm

WCT
ΔI/I < 0.001% / mm

Secondary emission monitors : SEM Grids



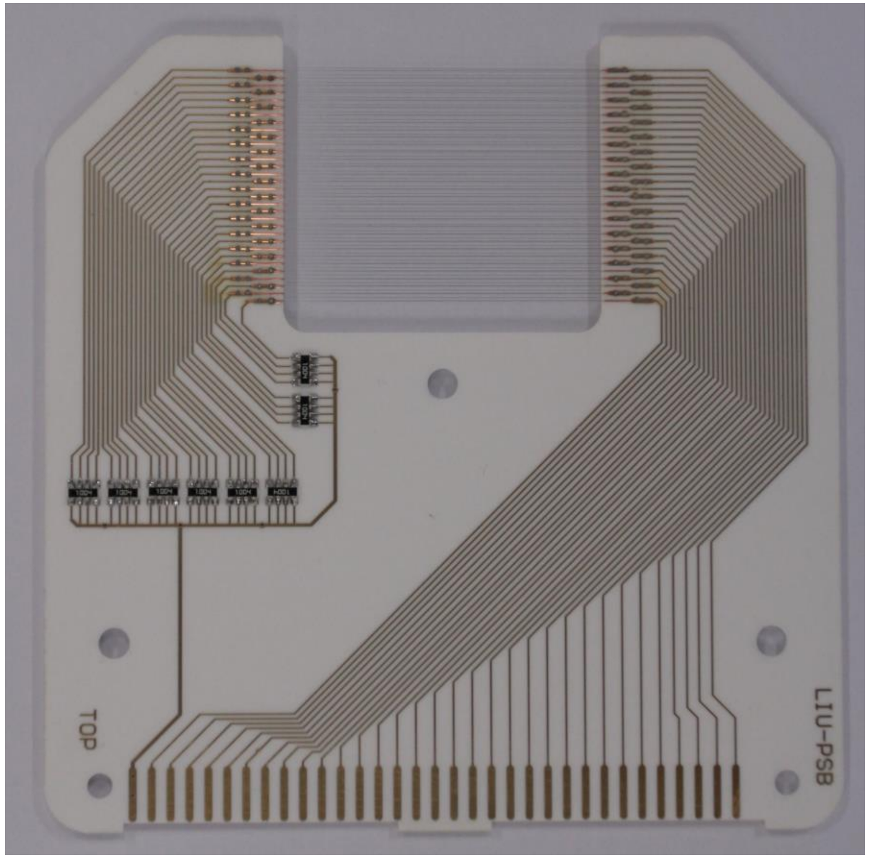
An ‘old’ Concept for measuring transverse beam profiles…

revisited and still usefull !

Secondary emission monitors : SEM Grids

Wire ceramic support evolving with industry standard in PCB manufacturing

Old style……

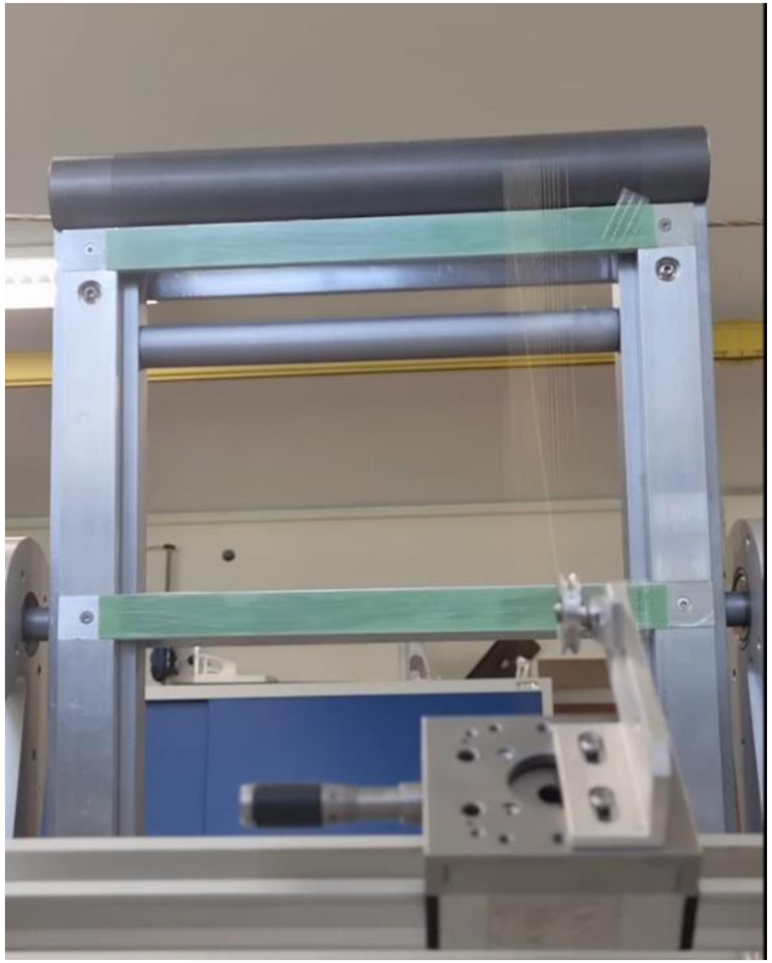


Grid with 0.4 mm spacing

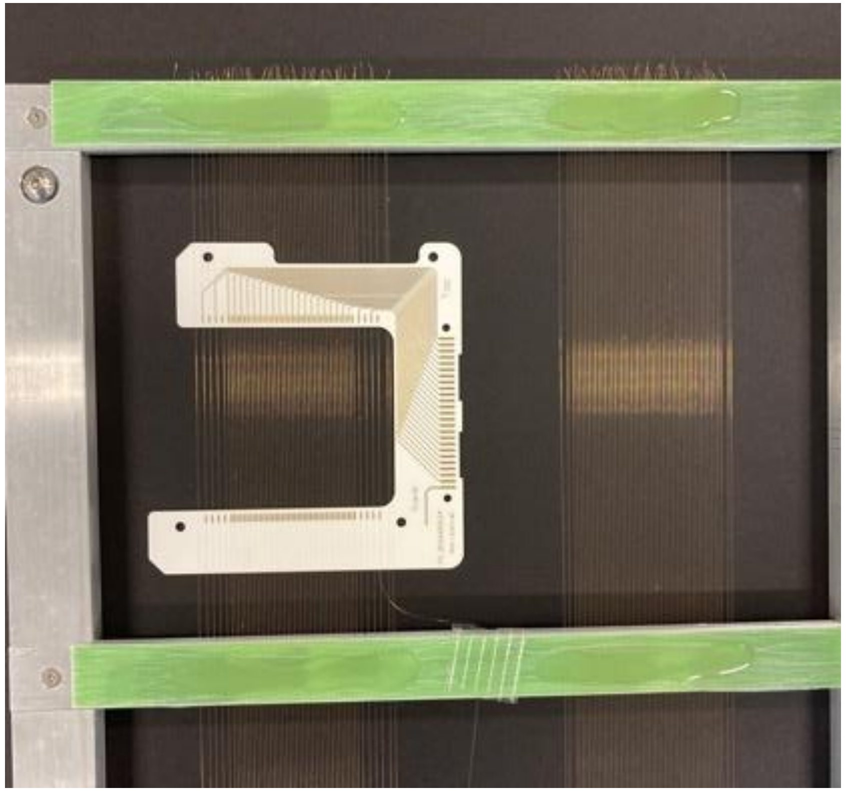
Grid with 1 mm spacing

Secondary emission monitors : SEM Grids

Semi automatic Wire winding machine

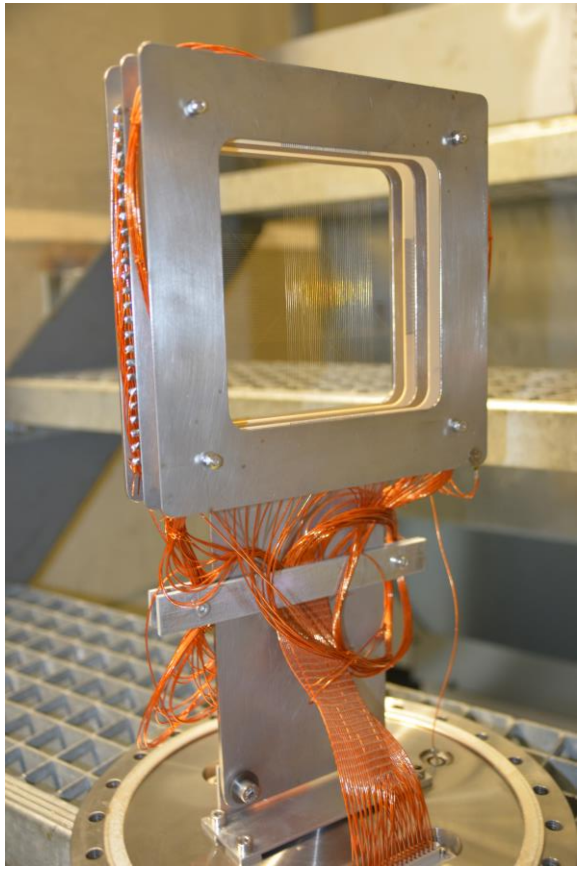


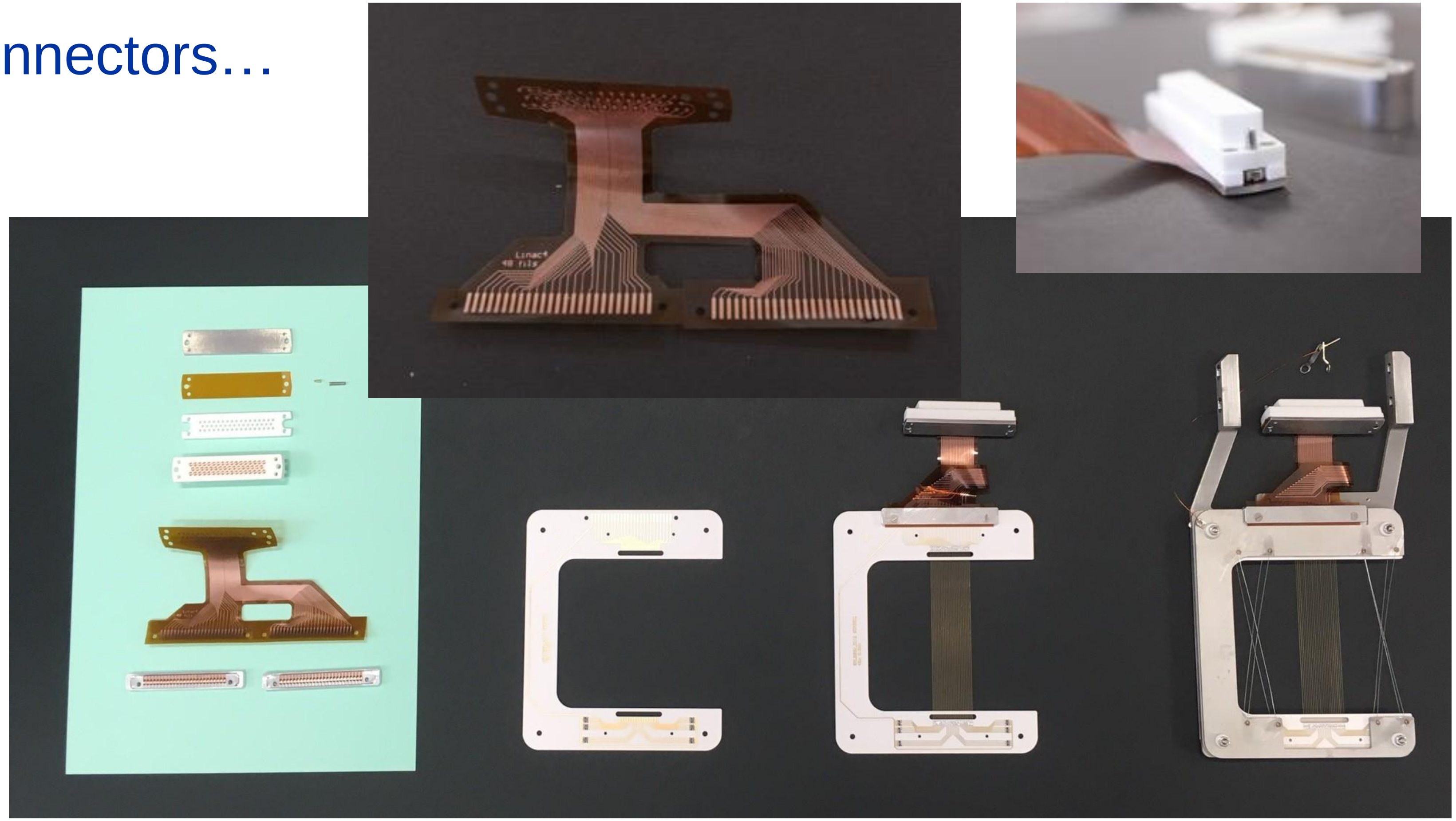
Ready for soldering the wire



Secondary emission monitors : SEM Grids

Improved UHV cabling and connectors…



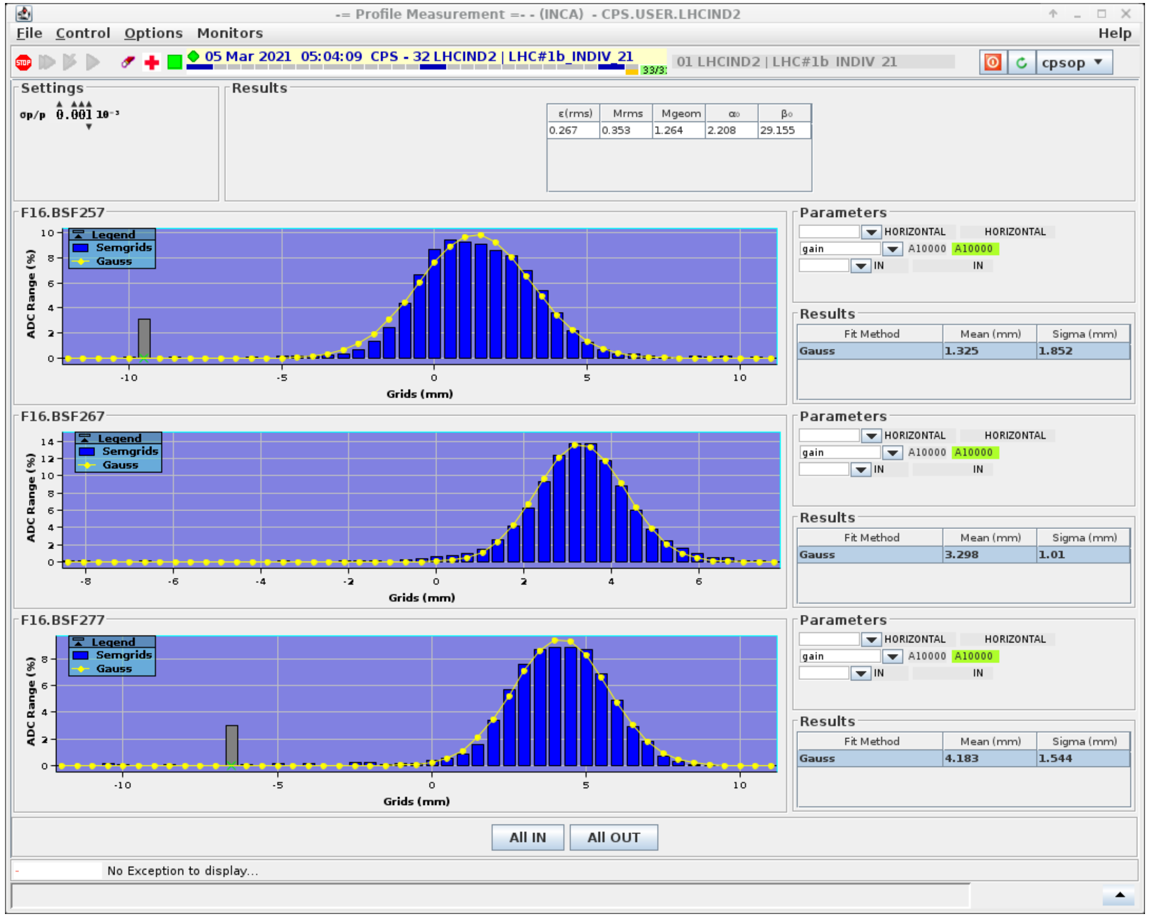


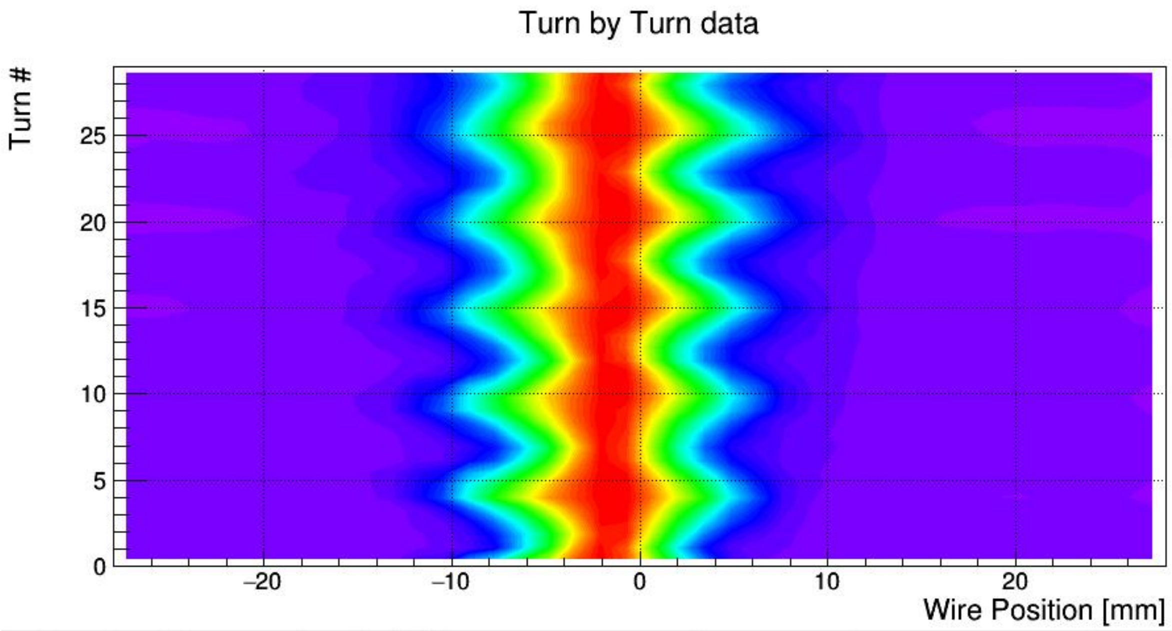
FLEX PCBs and custom ceramic connectors
‘Simpler, faster and more reliable’

Old style… Kapton wire connected manually

Secondary emission monitors : SEM Grids

Measurement in the Transfer line in PS complex





Measurement in the PS ring for injection studies

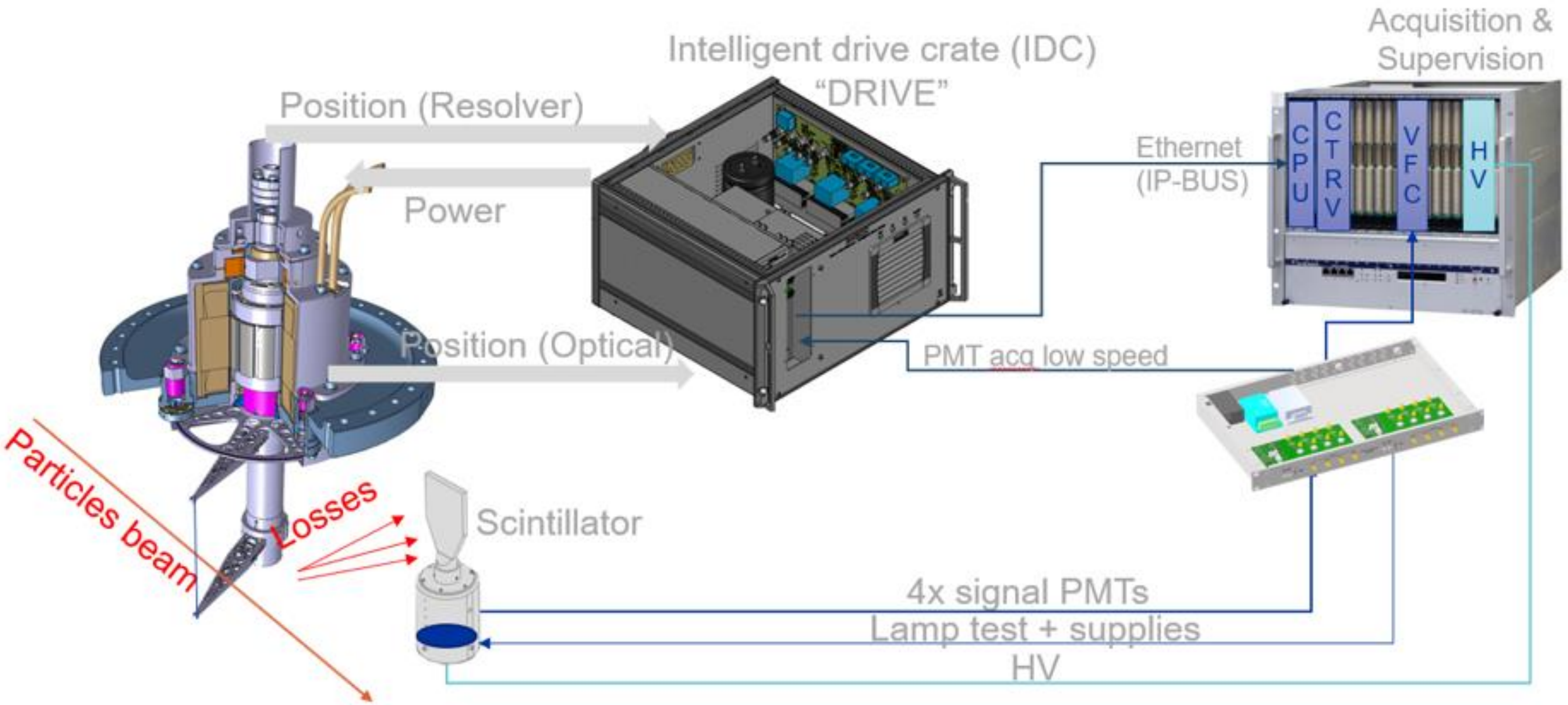
New fast wire scanners in PSB, PS and SPS rings

Scanning fast to measure higher beam intensities

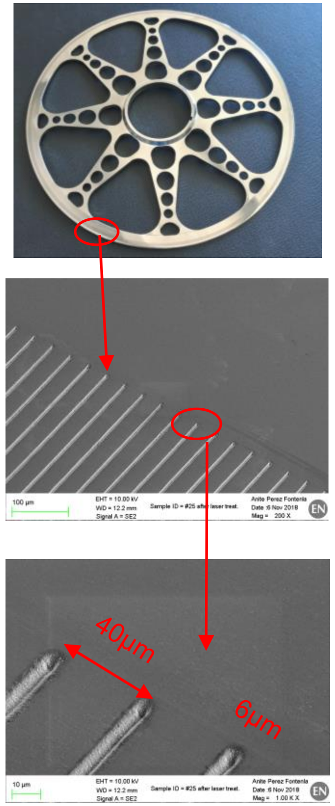
New fast wire scanners in PSB, PS and SPS rings

17 new fast wire scanners installed in 2020 + 5 units for ESS

- Max speed 20m/s
- Wire position from optical disc encoding
- 4 PMTs coupled to same scintillator with different optical density filters
- Fast digital integration (500MS/s) to allow bunch per bunch profile measurement

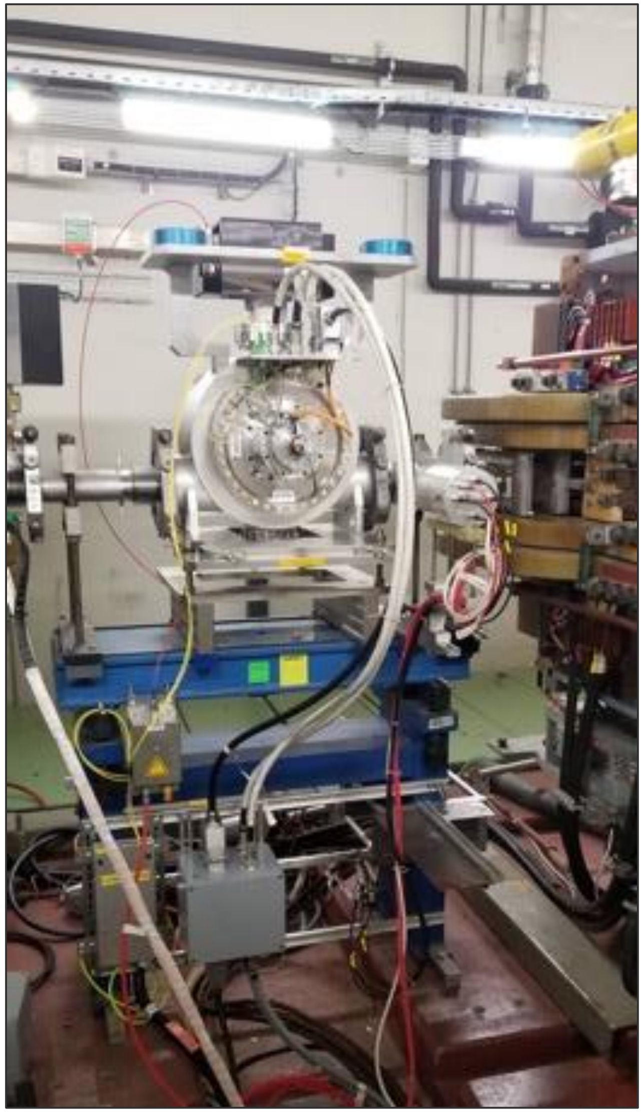


Optical encoder based on a reflective disk engraved with anti-reflective marks



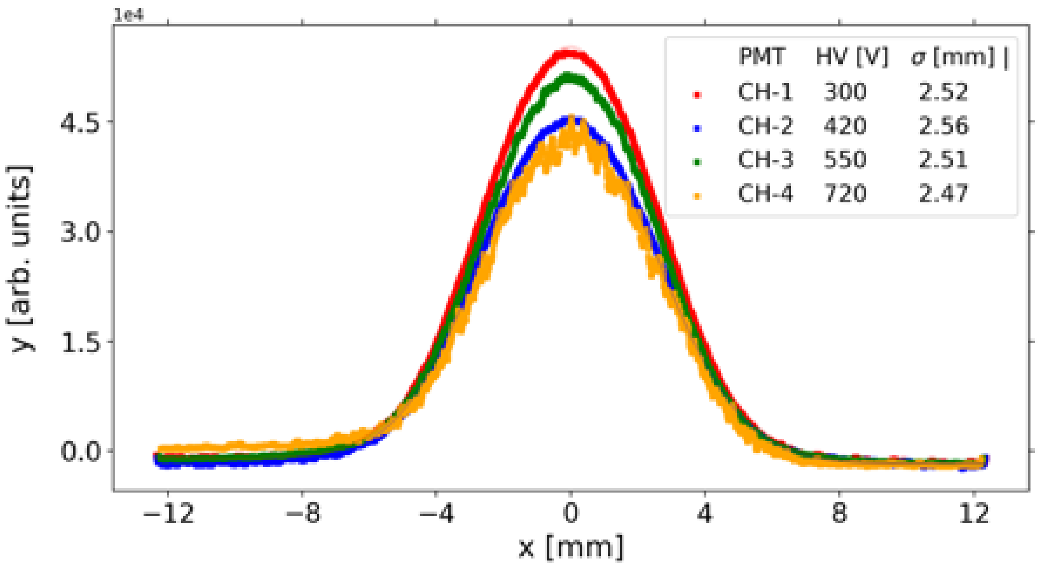
New fast wire scanners in PSB, PS and SPS rings

- 4H, 4V in PS Booster ring
- 3H, 2V in PS ring
- 2H, 2V in SPS ring

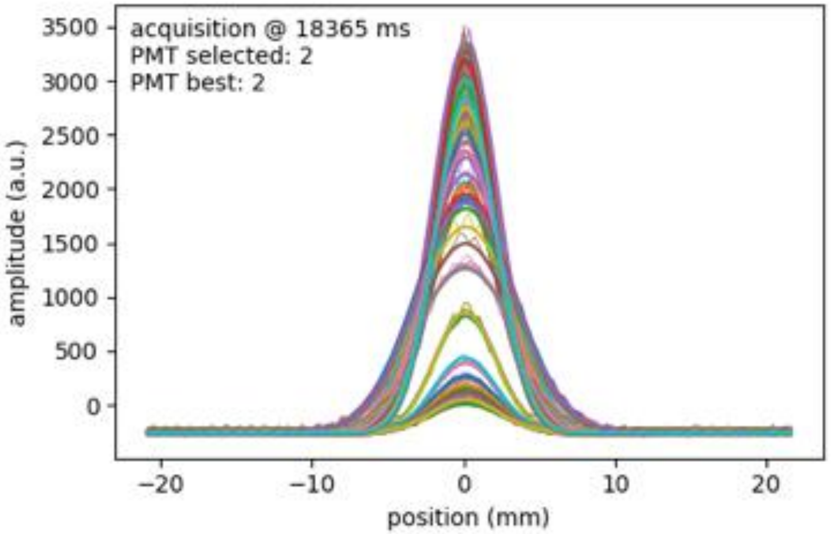


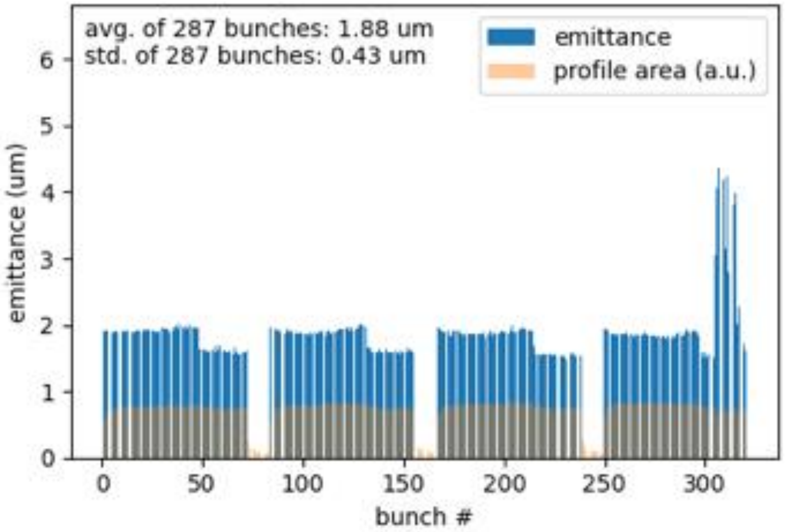
New fast wire scanners in PSB, PS and SPS rings

Beam profile in PS ring



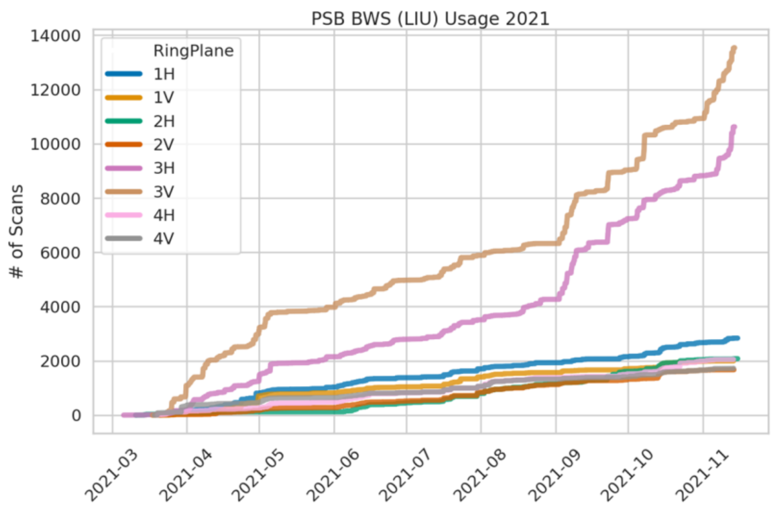
Bunch-by-Bunch profiles in SPS ring



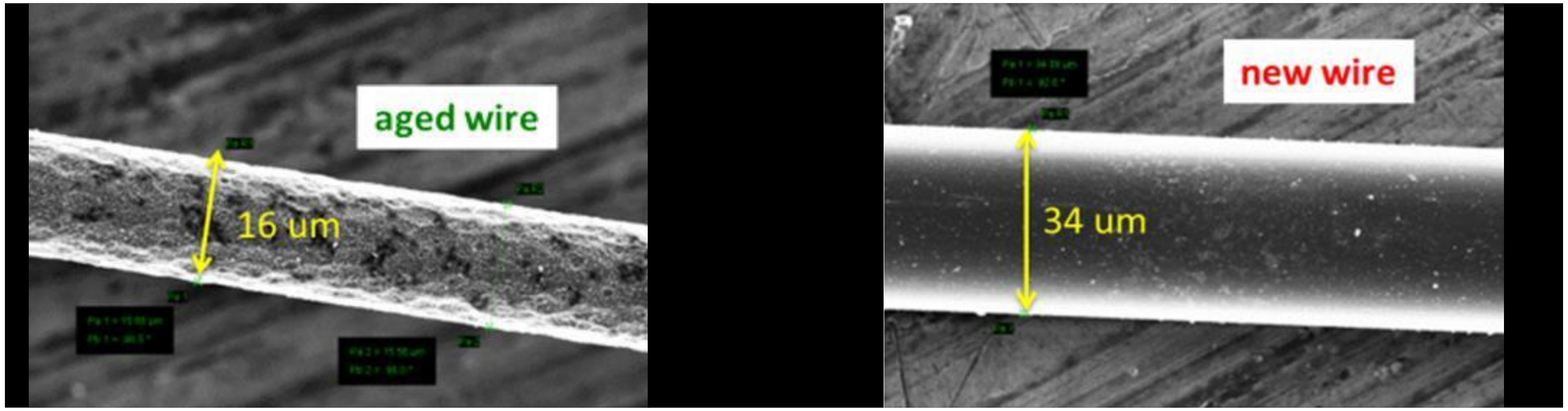


New fast wire scanners in PSB, PS and SPS rings

Intercepting – Fragile



Victims of their own success

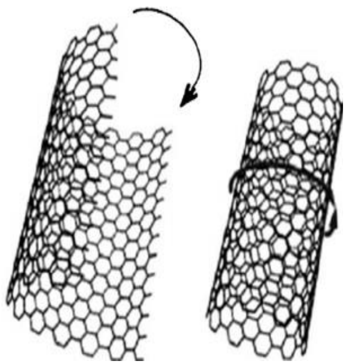


[1] Sapinski, M., J. Koopman, E. Métral, A. Guerrero, et B. Dehning. « Carbon Fiber Damage in Accelerator Beam ». CERN Document Server, 1 mai 2009. https://cds.cern.ch/record/1183415.

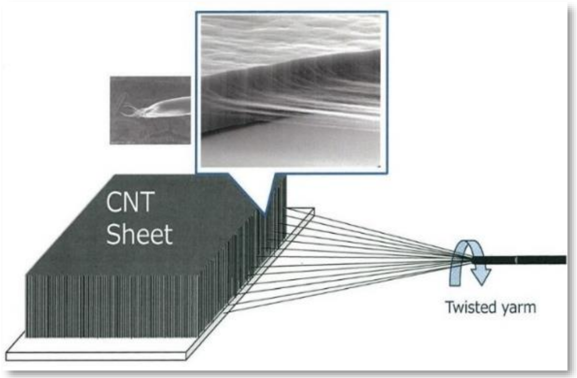
R&D on best possible material for Wire scanner

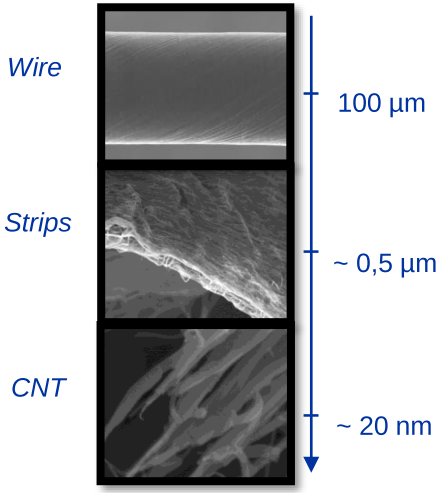
New fast wire scanners in PSB, PS and SPS rings

'Lower density material' for more robust wire – Study on Carbon NanoTubes wires

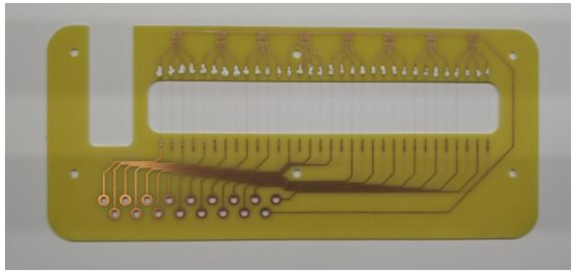


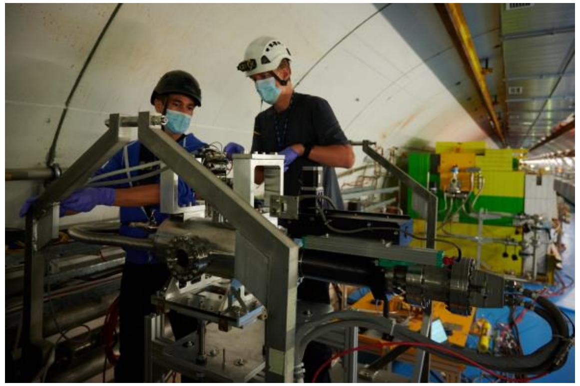
From graphene to Carbon Nano-Tubes

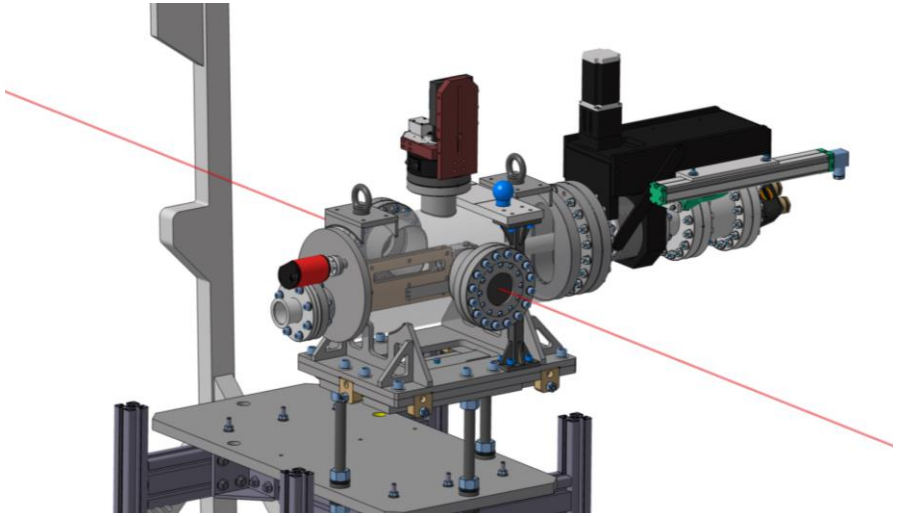




CNTW multi-scale





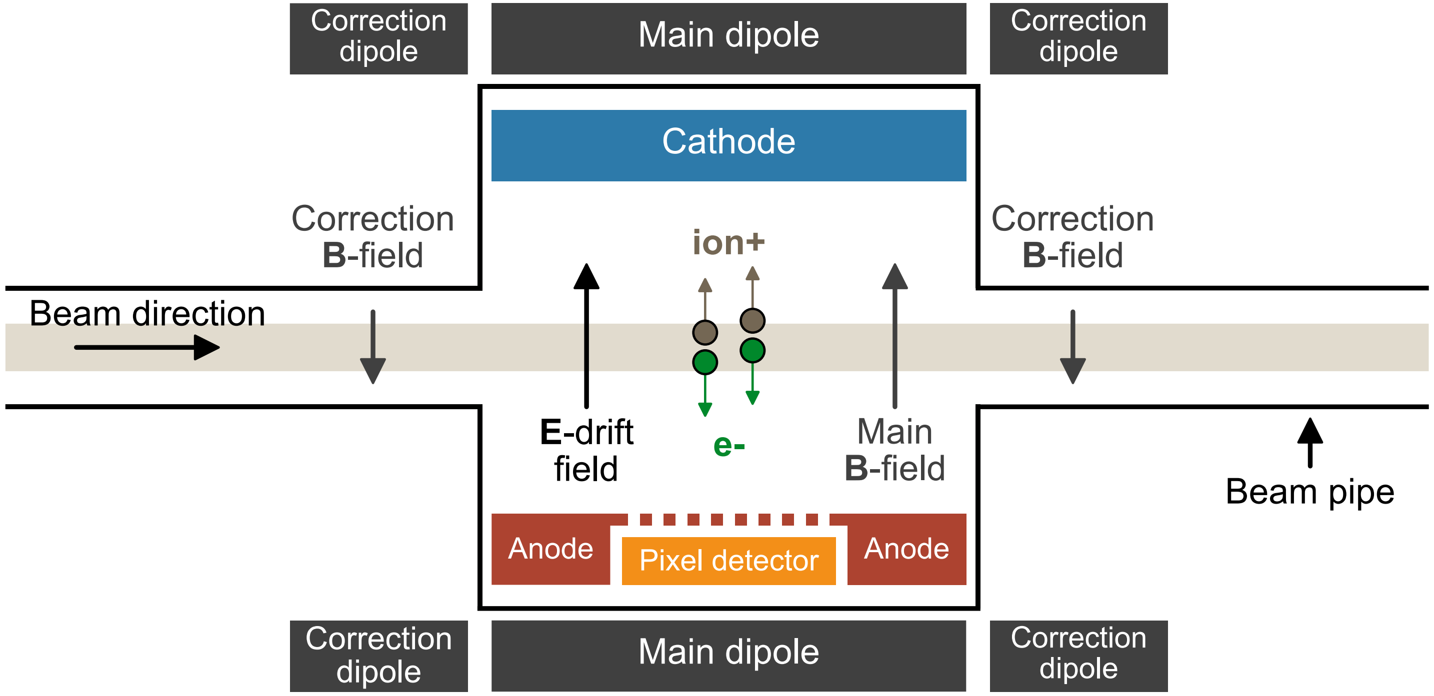


Test of CNT wires at Hiradmat@CERN in 2021

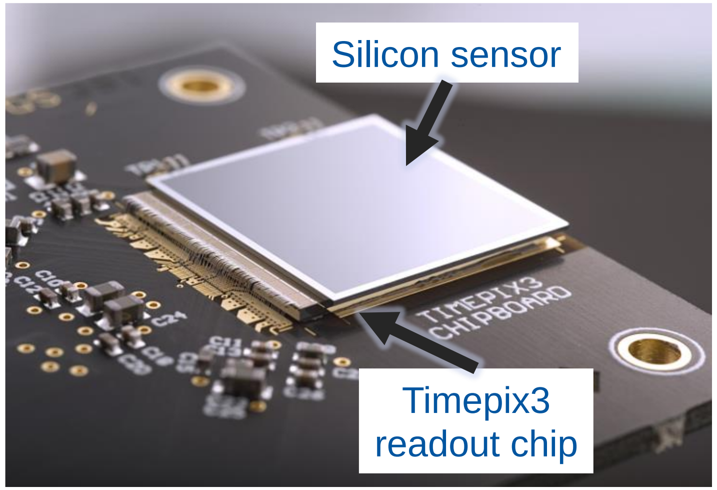
Beam Gas Ionization monitor

Beam Gas Ionization monitor

A new design based on Timepix3 hybrid pixel detector technology



https://medipix.web.cern.ch/technology-chip/timepix3-chip



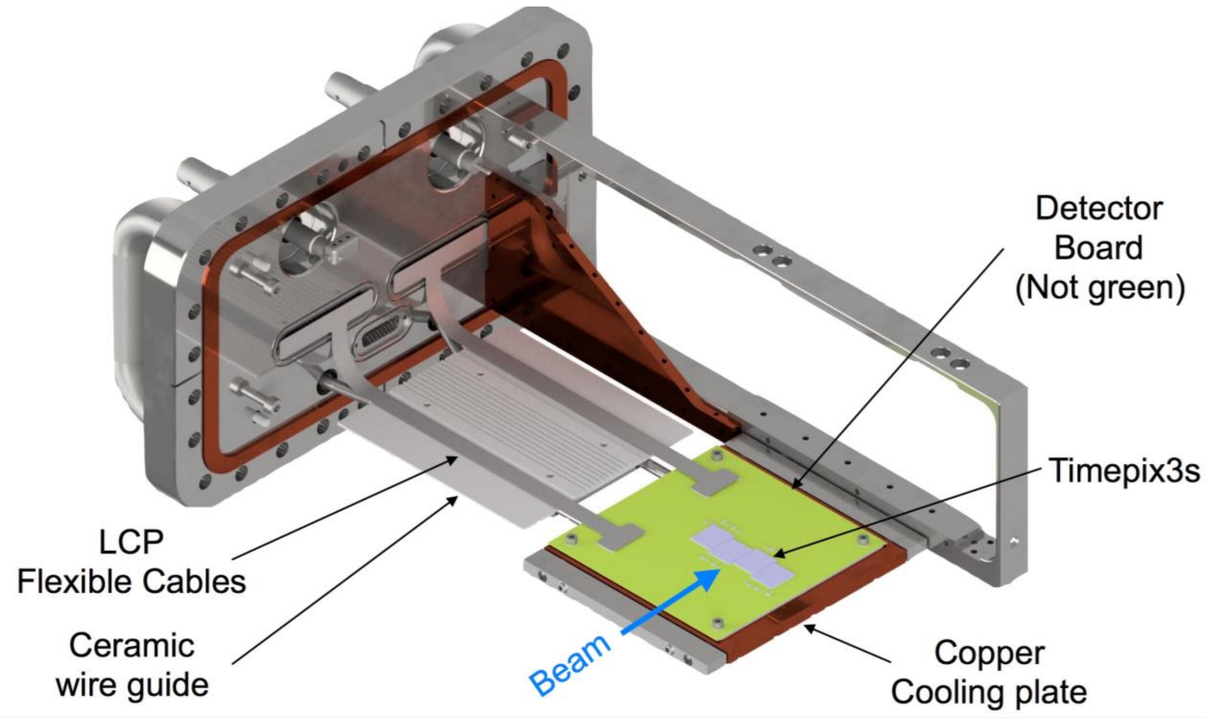
https://cds.cern.ch/record/2253263

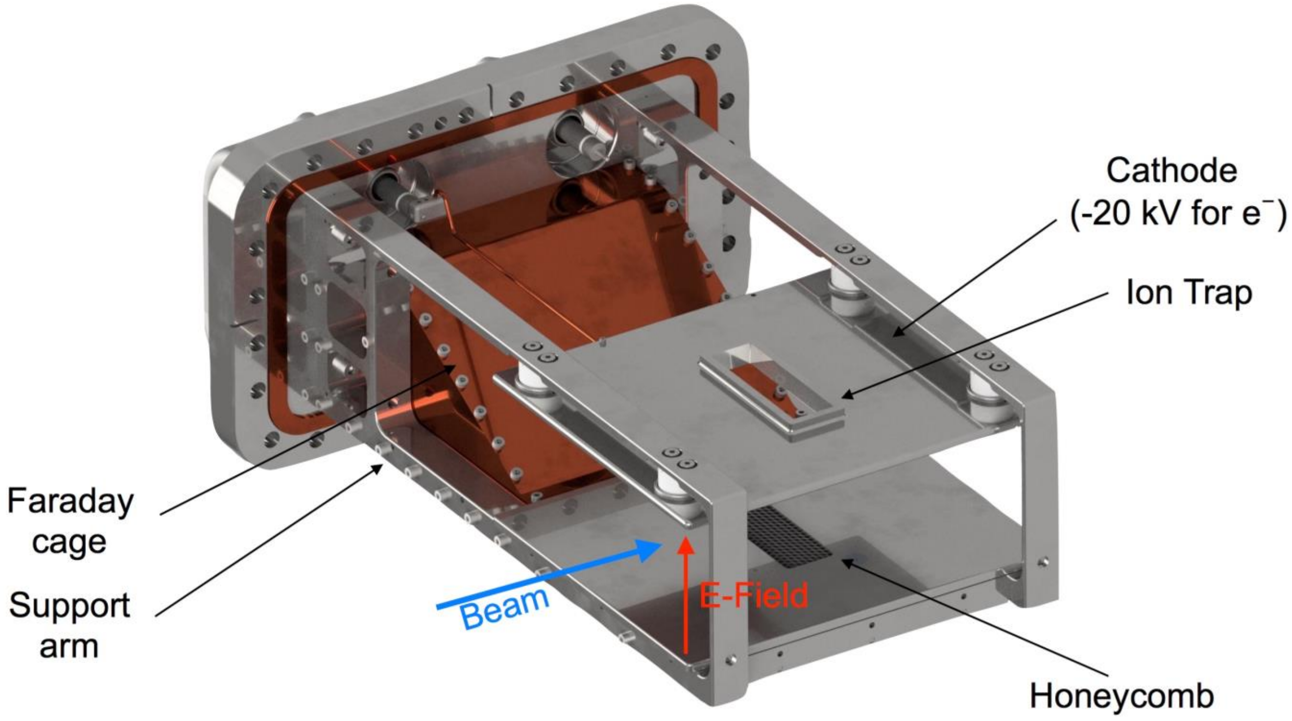
- Sensor and readout are separate
- Readout Chip in Timepix3, CMOS 130nm
- Sensor can be made of Si, GaAs, CdTe, ..

- 256x256 pixels
- 55um pitch
- Timestamp resolution of 1.5625ns
- Time-over-threshold to energy calibration
- 8x serial links up to 640Mbits/s = 5.12Gbit/s

Beam Gas Ionization monitor

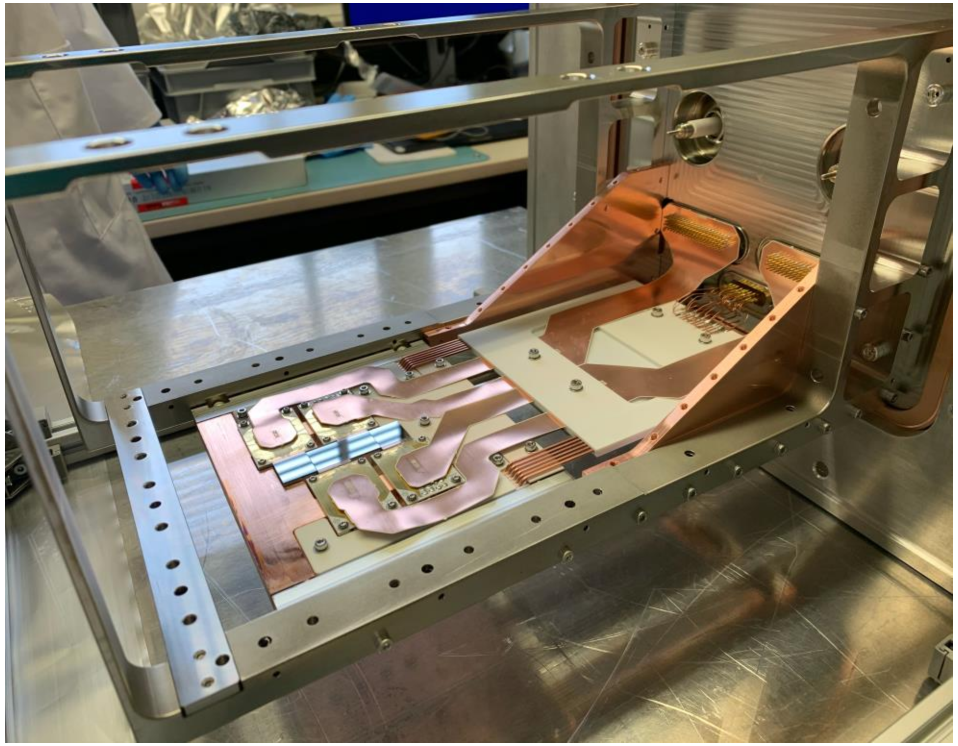
Low impedance design and high vacuum compatibility



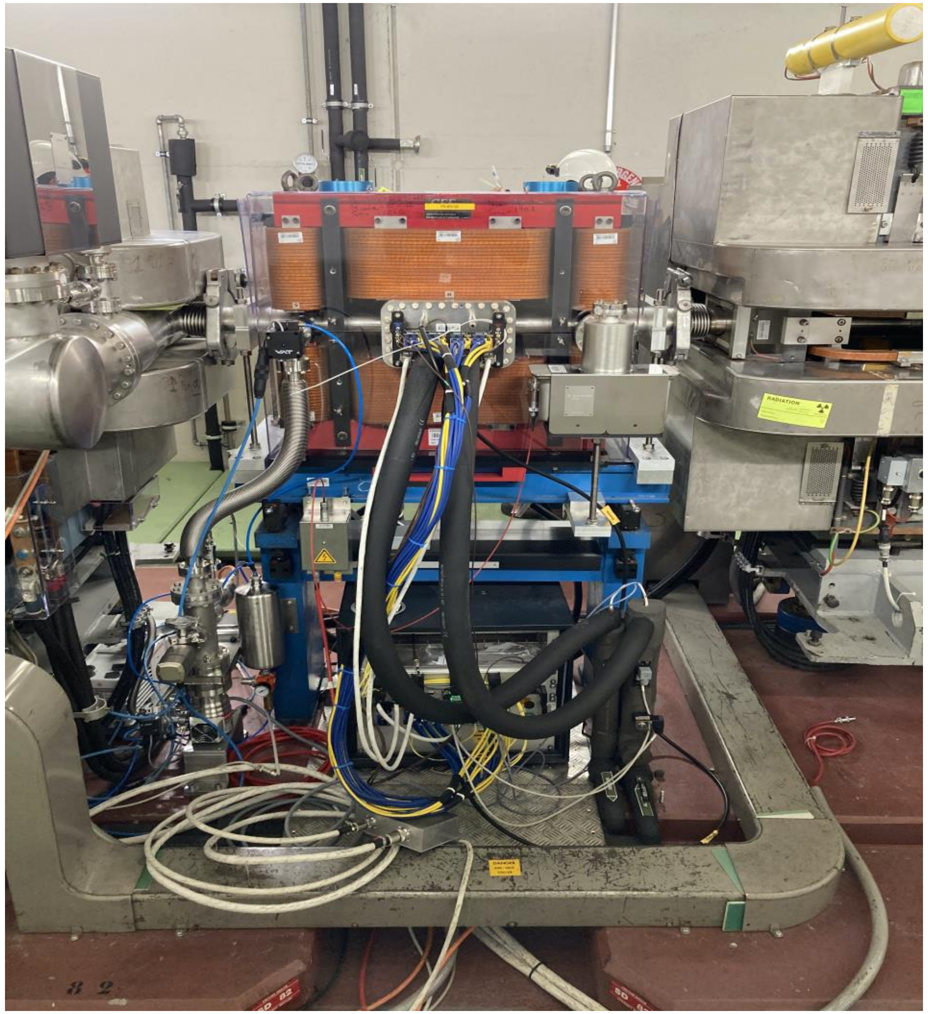


http://bgi-web.web.cern.ch/bgi-web/

Beam Gas Ionization monitor



Timepix3-BGI in-vacuum instrument

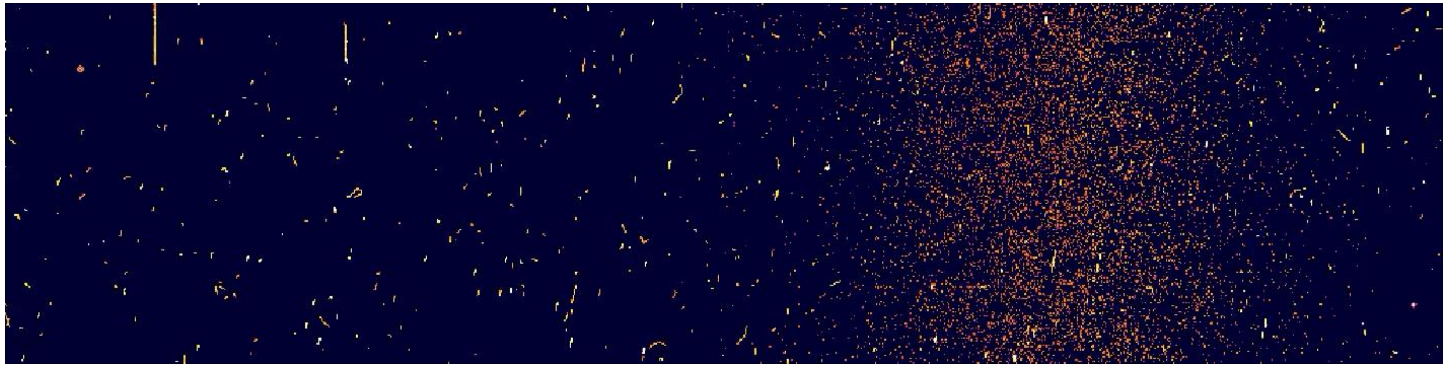


Timepix3-BGI installed in the PS ring

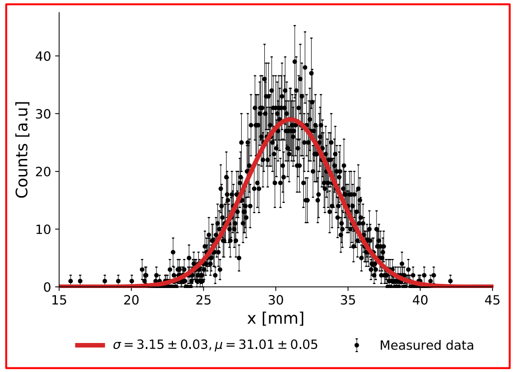
Beam Gas Ionization monitor

Measurement on the PS ring

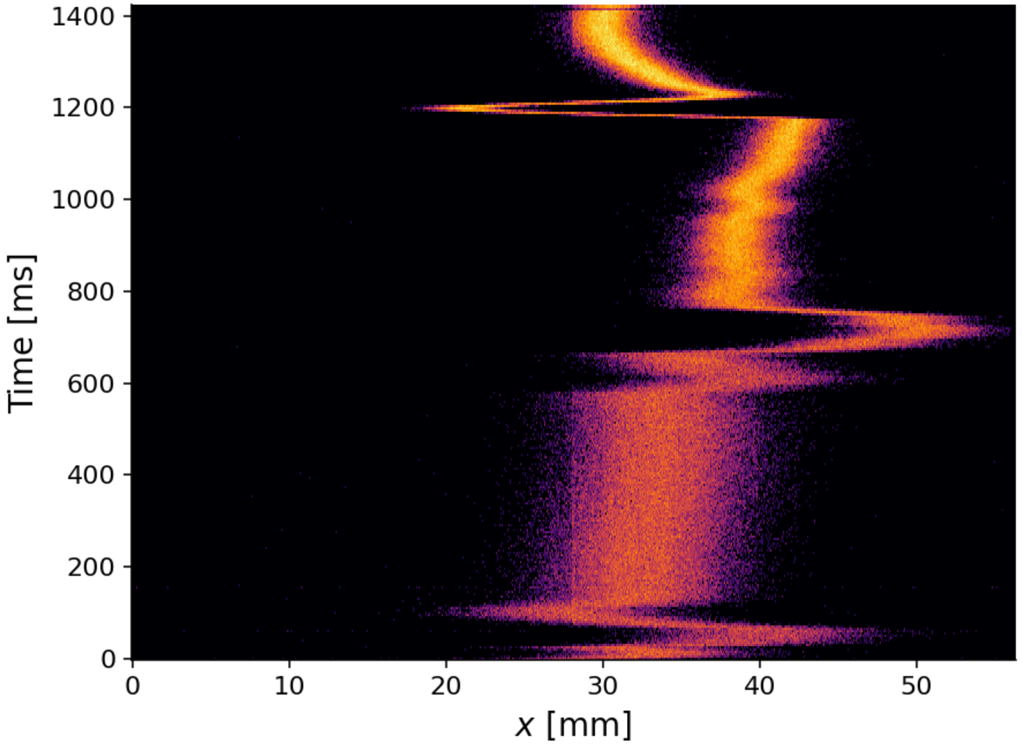
LHC type beam from injection, through acceleration and finally extraction



- 1.5 seconds in real time: slowed down here for viewing purpose.
- Each frame is 10 ms of data
- Not filtered to show background particles.



Beam profile & position through the PS cycle

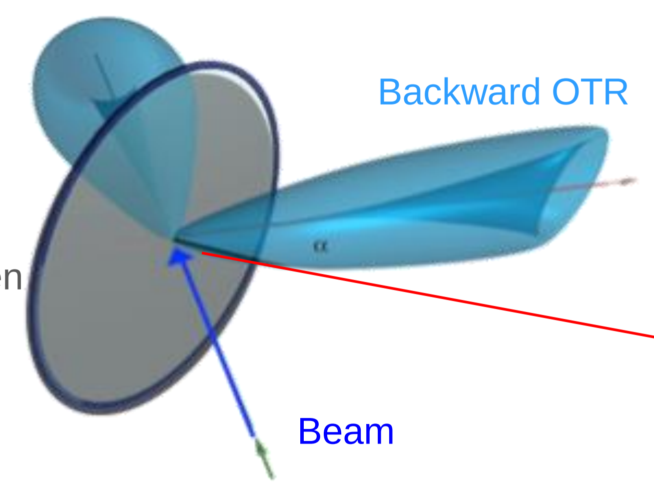


Example of R&D

Measuring small beam sizes ‘single shot’

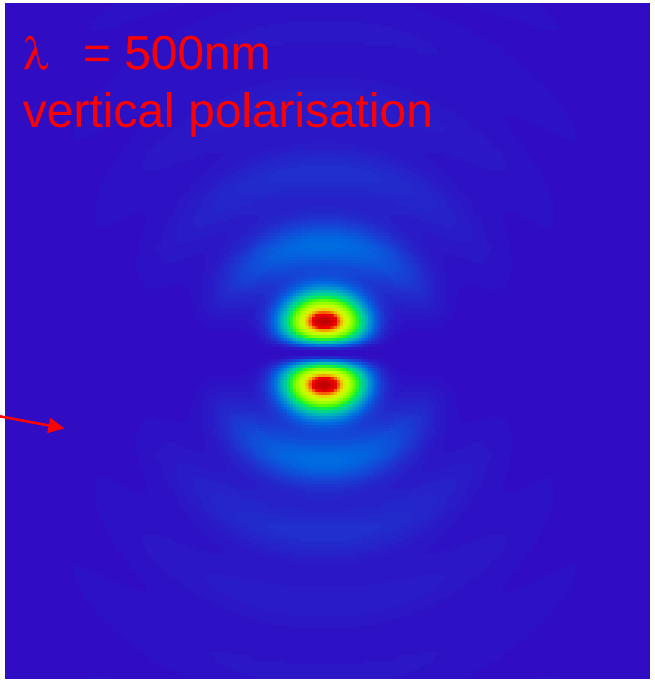
Measuring small beam sizes using Transition Radiation

High magnification / resolution imaging system using Optical transition radiation as a simple solution



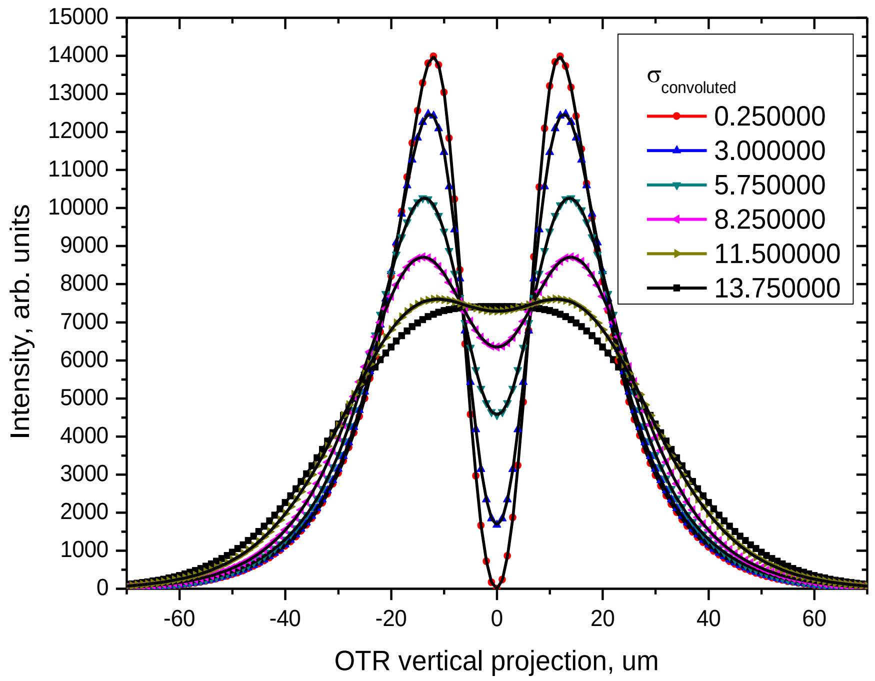
OTR emitted when charged particles cross a dielectric interface

OTR Image from a single particle



'Particle Spread function'

OTR Image from a beam

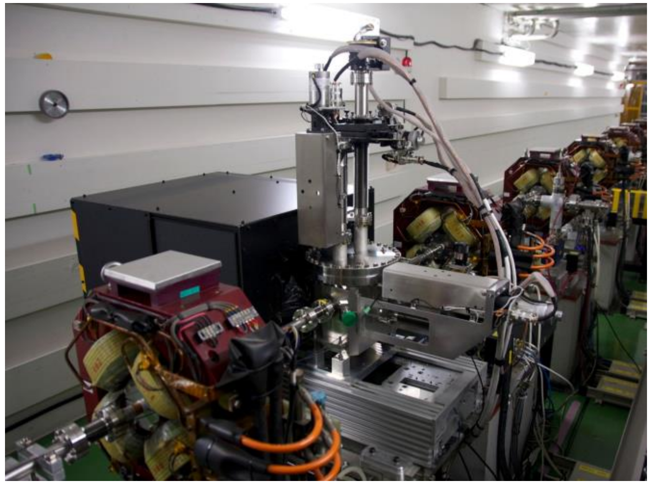


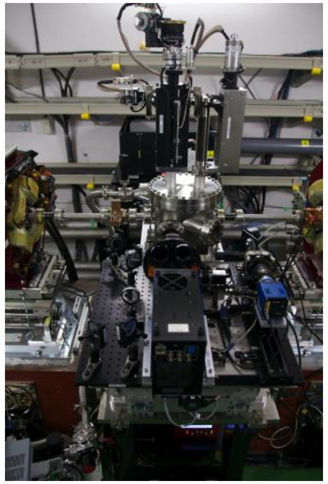
Measuring vert. beam size as visibility of the OTR PSF

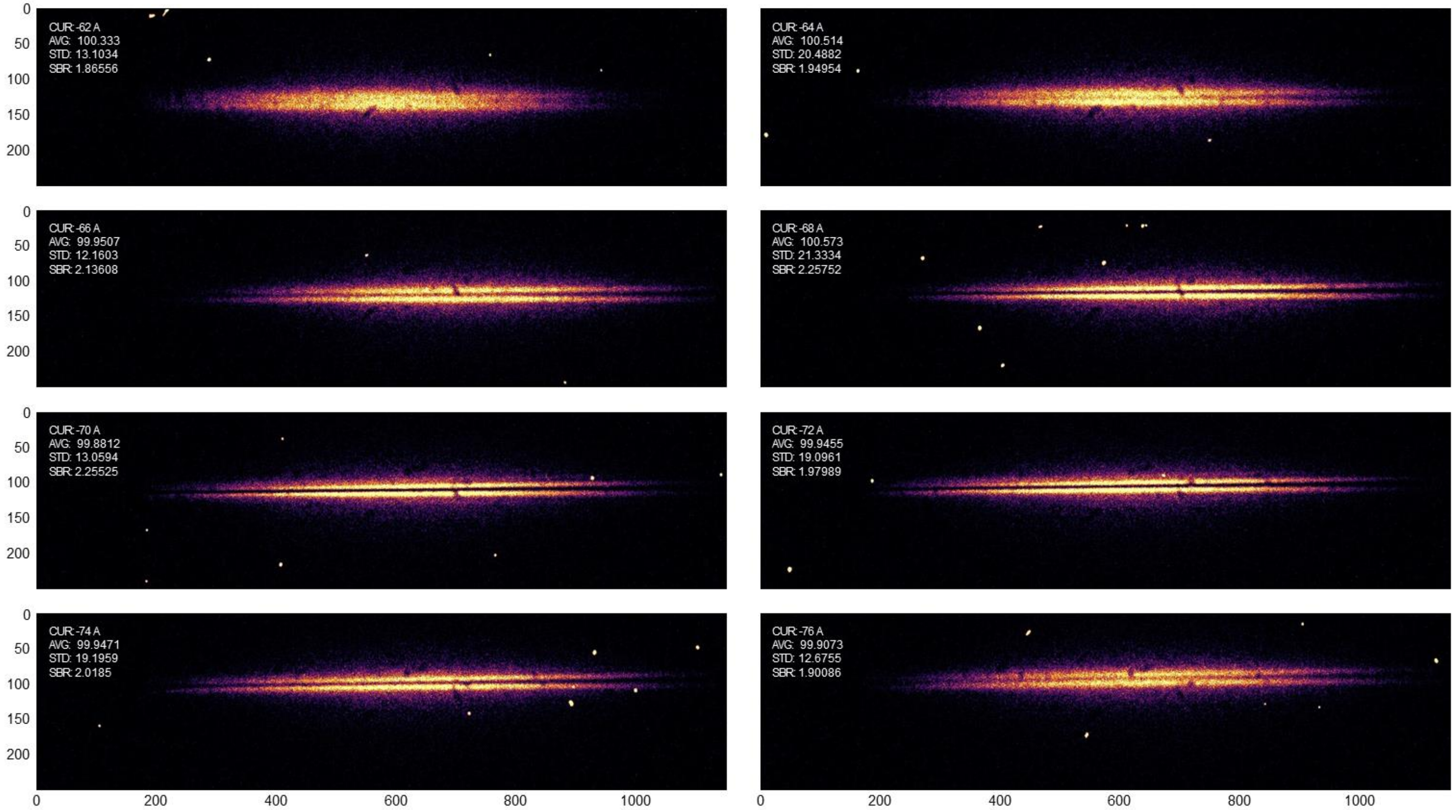
Measuring small beam sizes using Transition Radiation

High magnification / resolution imaging system using Optical transition radiation as a simple solution

Test on ATF2 extraction beam line at KEK





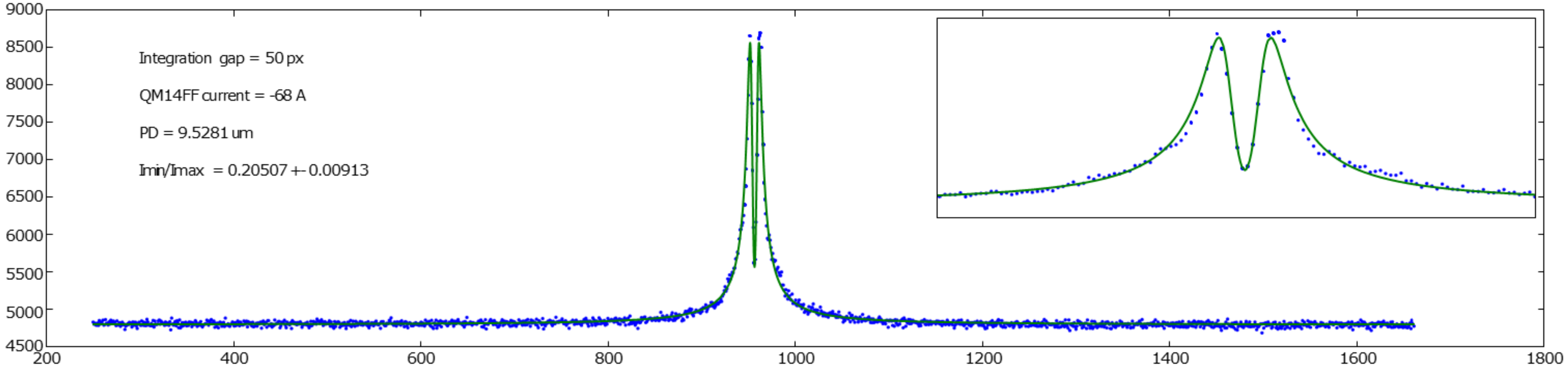


Images acquired during a Quadrupole scan

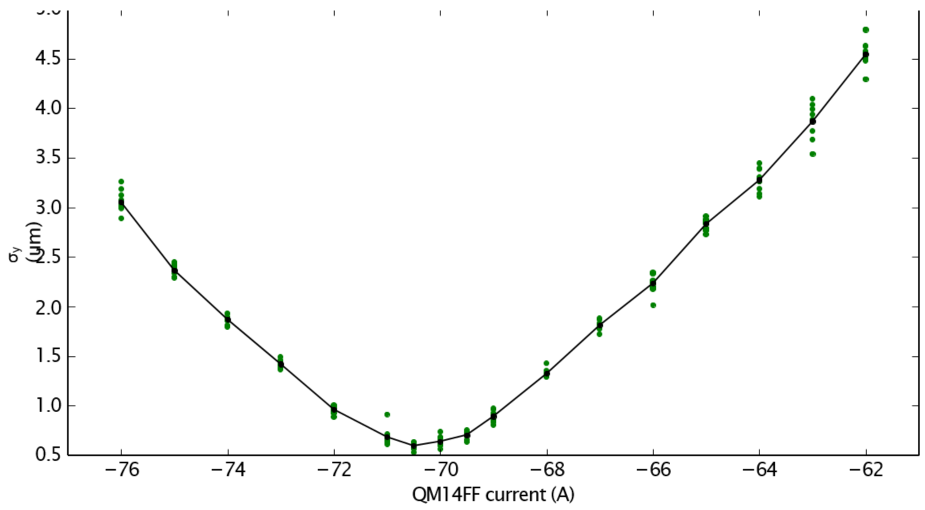
P. Karataev *et al.*, PRL **107**, 174801 (2011)
B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)

Measuring small beam sizes using Transition Radiation

High magnification / resolution imaging system using Optical transition radiation as a simple solution



Smallest beam size measured 600nm

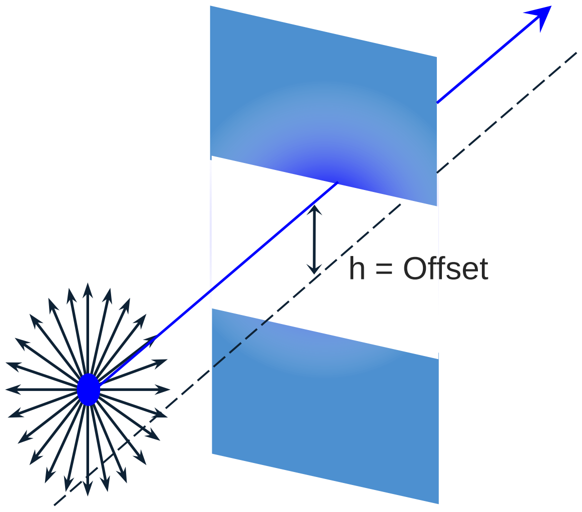


P. Karataev *et al.*, PRL **107**, 174801 (2011)
B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)

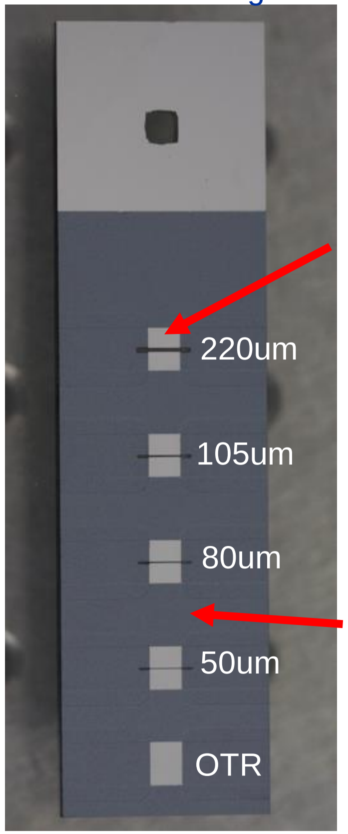
Measuring small beam sizes using Diffraction Radiation

Measuring small beam sizes using Diffraction Radiation

A non-invasive alternative to Transition Radiation using thin dielectric slits



KEK-ATF2 target



Maximizing emission of DR with Al coating around the slit

Minimizing reflection of SR by sand-blasting the rest of the target

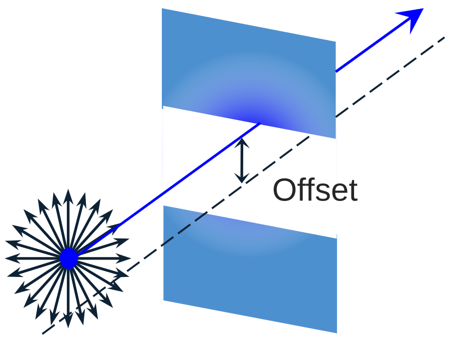
Typically produces radiation for wavelength :

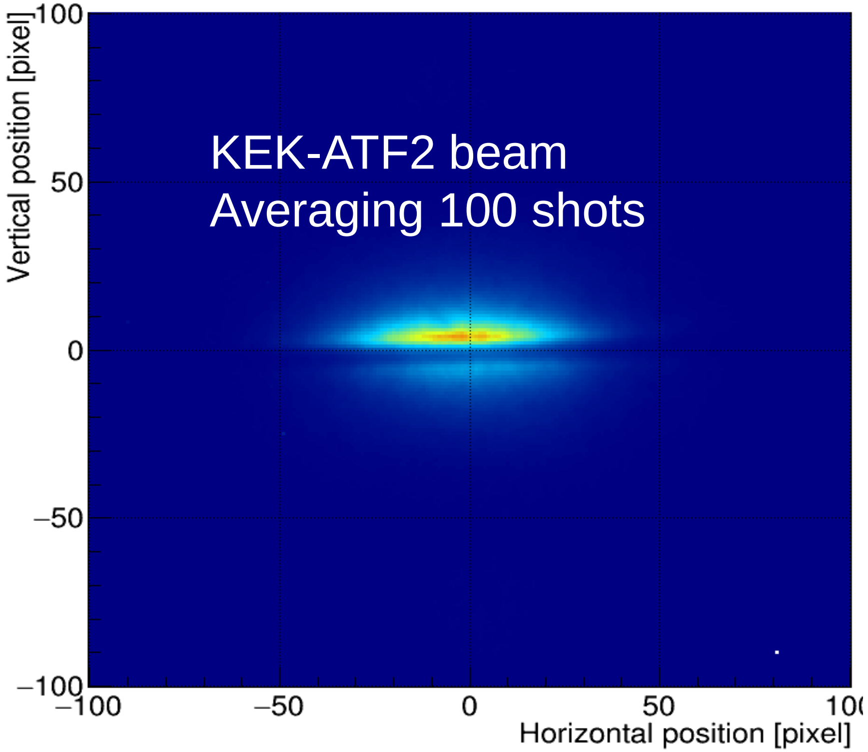
$$h < \gamma * \lambda / 2\pi$$

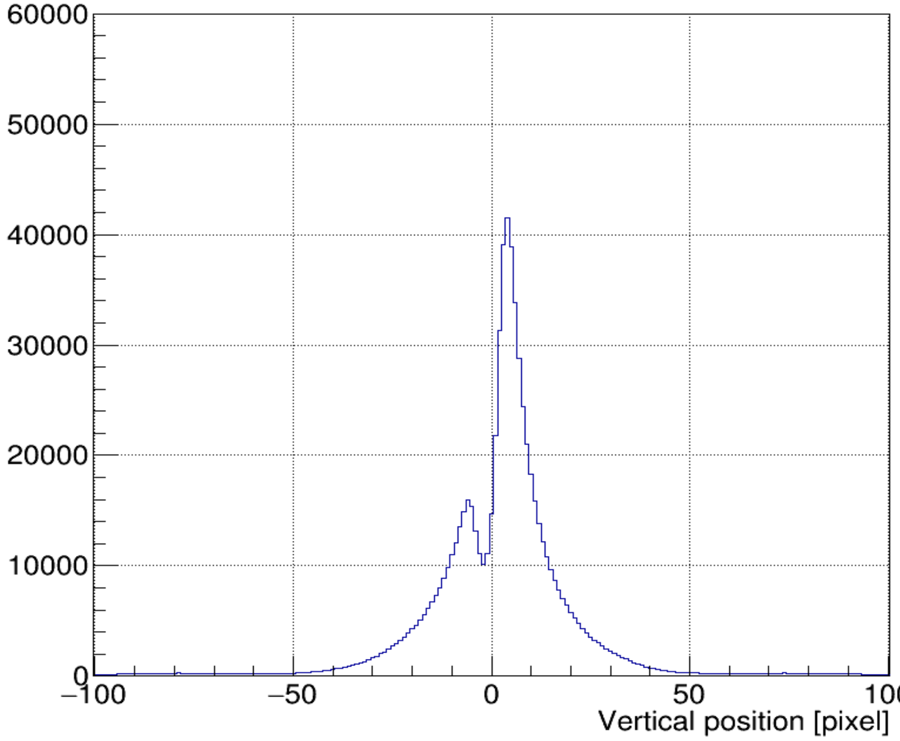
Work for high energy particles : electrons above GeV

Measuring small beam sizes using Diffraction Radiation

Test performed at ATF2/KEK





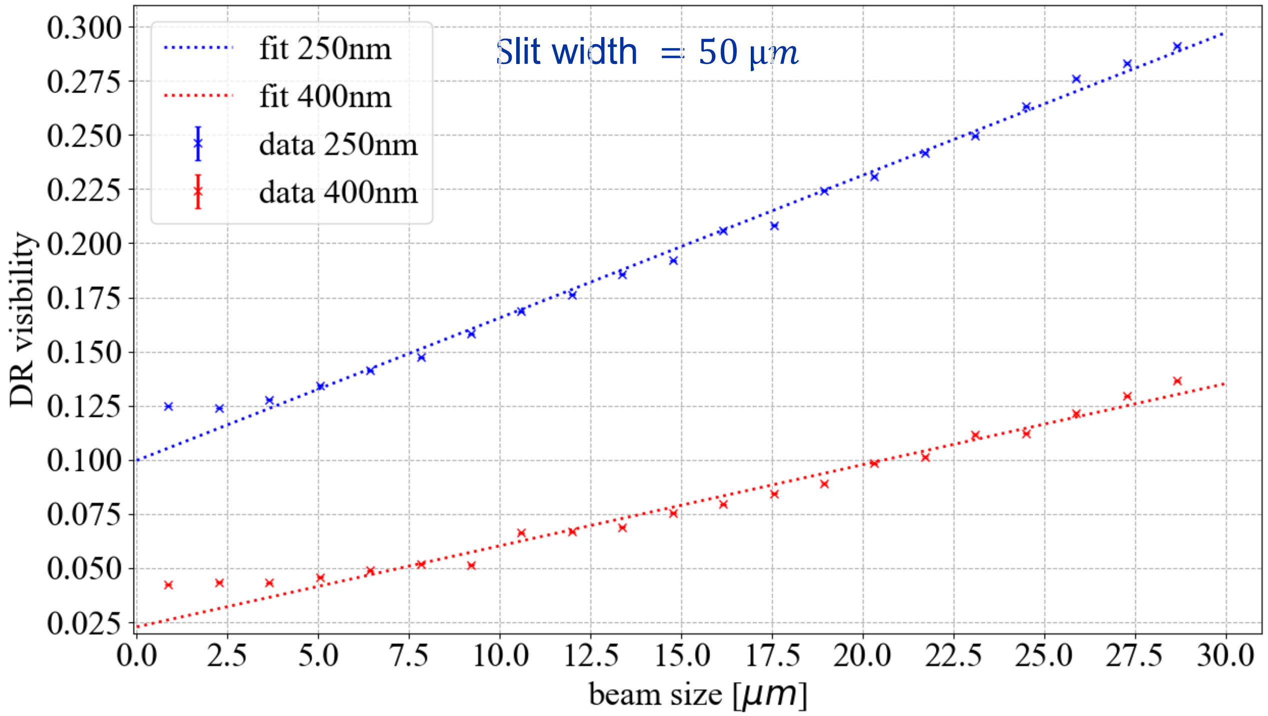


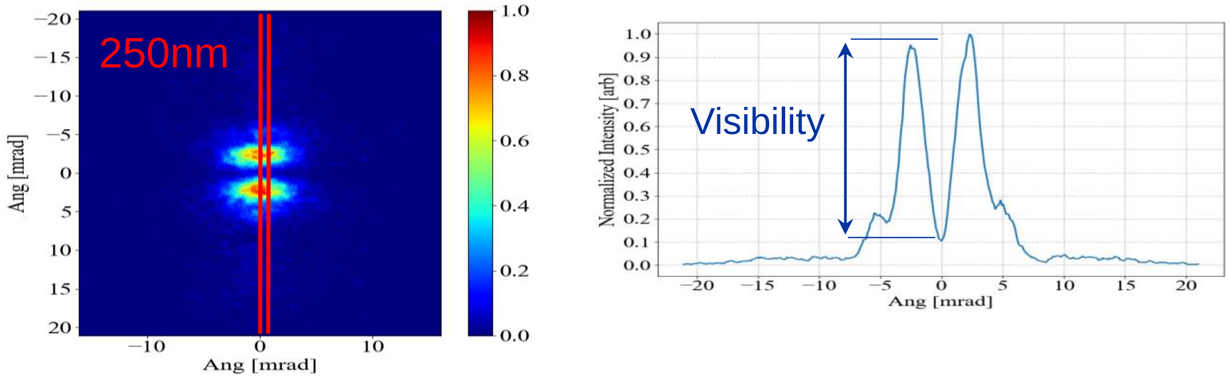
There is **no visible beam size dependency** off the pattern in **imaging**.
But the **vertical position** into the slit change the profile **asymmetry** => **Optical Beam Position Monitor**

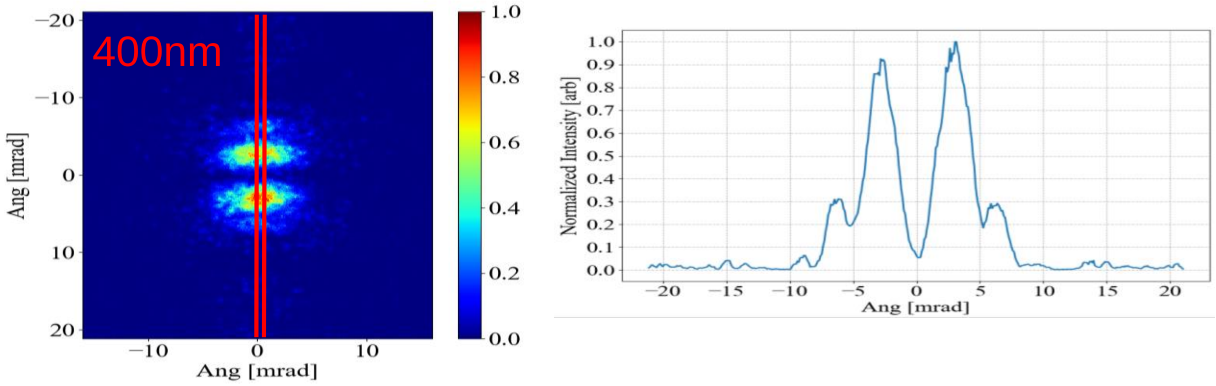
R. Kieffer et al., NIMB 402 88 (2018)

Measuring small beam sizes using Diffraction Radiation

Beam size encoded in the visibility of the angular distribution of DR







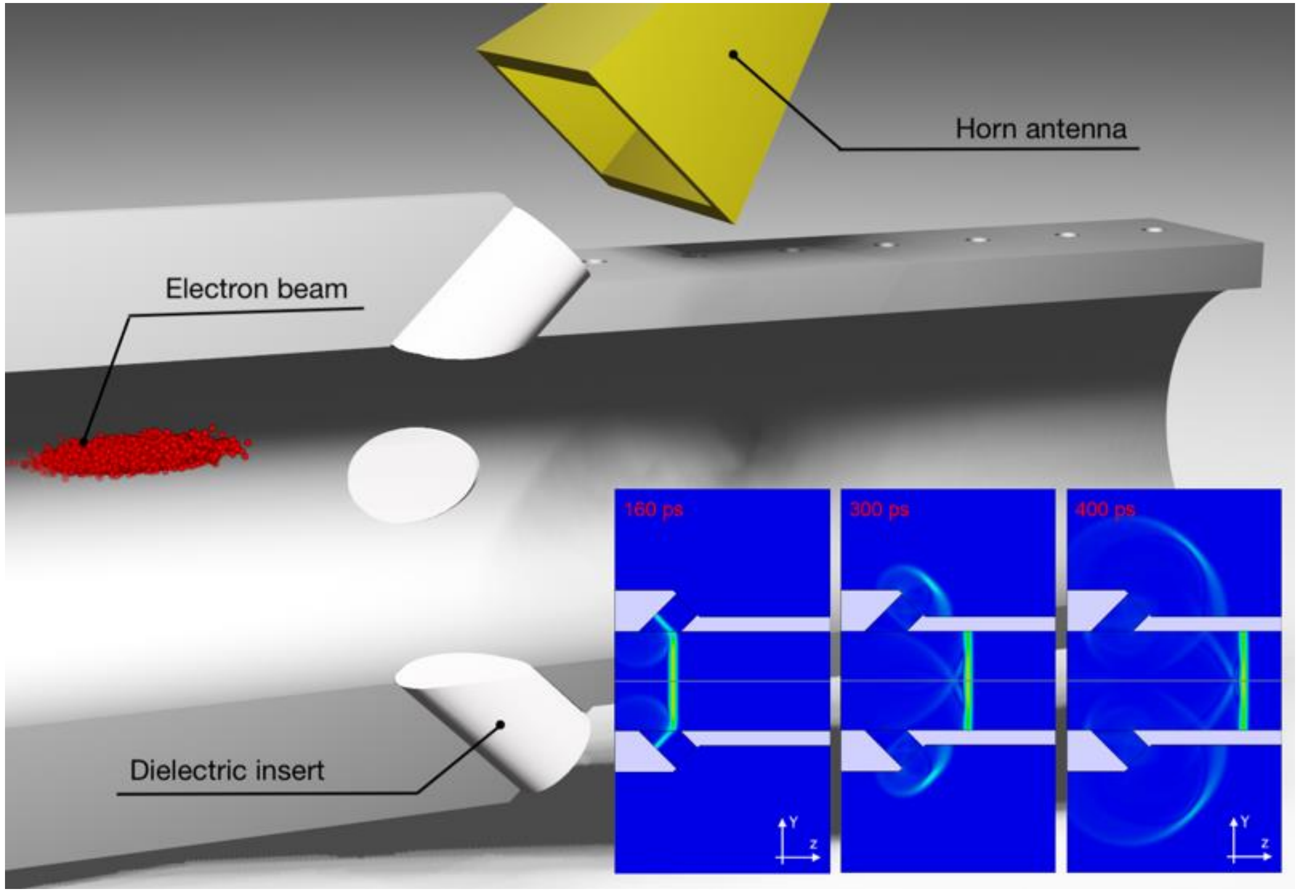
M. Bergamaschi et al., PRA 13 014041 (2020)

As expected sensitivity increase with decreasing wavelength, good sensitivity for UV down to 4-5 micrometers.

Diagnostic using Cherenkov Diffraction radiation

Diagnostic using Cherenkov Diffraction radiation

Cherenkov Diffraction Radiation in dielectric inserts



- Non-invasive version of well-known Cherenkov effect !

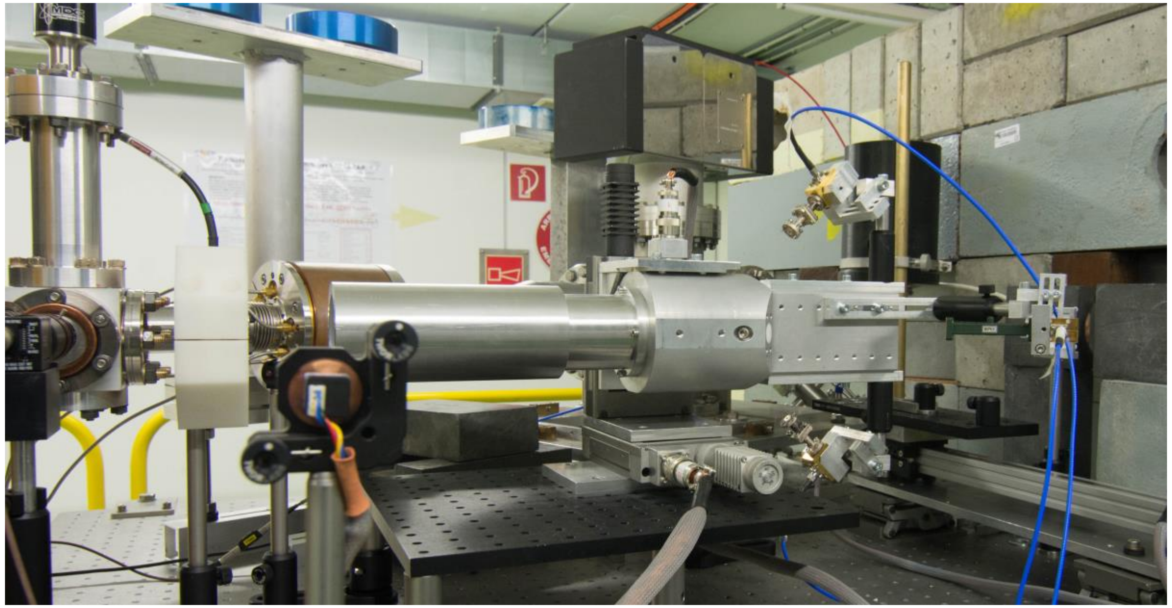
- Radiation spectrum
  - Depends on the dielectric (transparence)
  - Low cut-off frequency depending on dielectric dimension
  - High cut-off frequency depending on dielectric transparency and beam energy

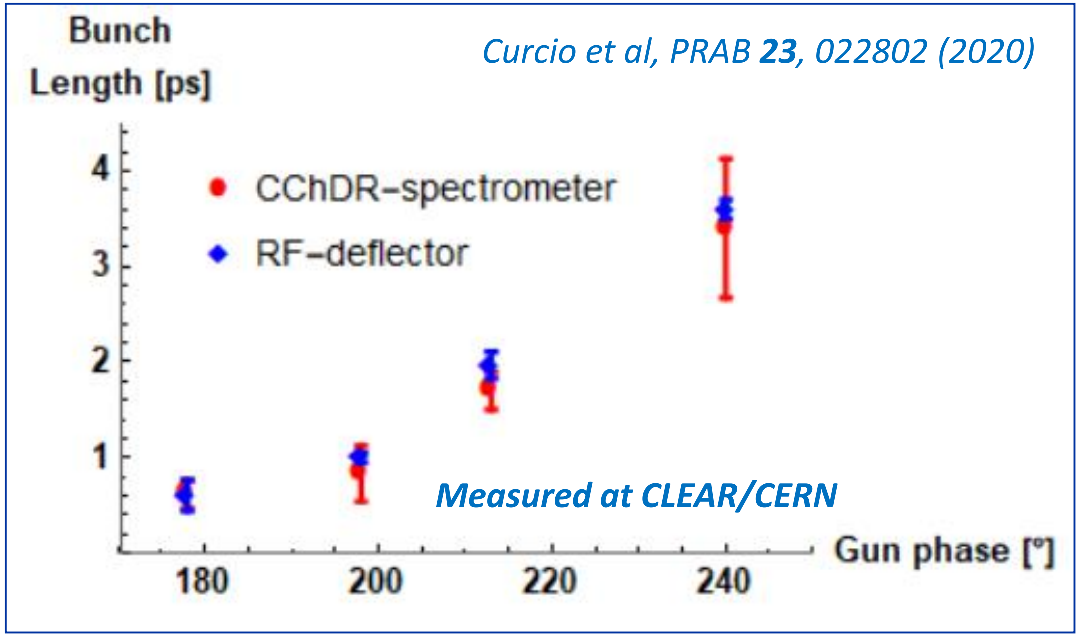
Well adapted for short bunches or high energy particles when measuring at high frequency (>10GHz → UV))

Polarization Current Approach
D. V. Karlovets and A. P. Potylitsyn in JETP Lett. 90 (2009), M. Shevelev, A. Konkov, and A. Aryshev in Phys. Rev. A 92, 053851 (2015)

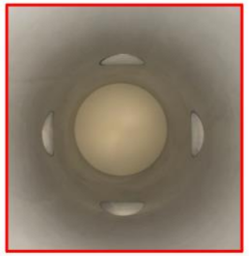
Diagnostic using Cherenkov Diffraction radiation

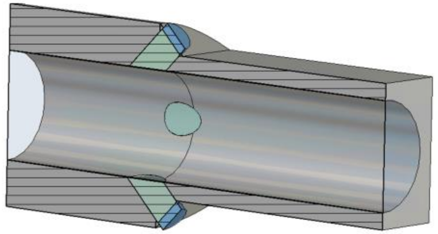
Short bunch length diagnostics using Coherent ChDR





Measuring in 3 frequency bands (30GHz, 60GHz, 90GHz)
Test at CLEAR/CERN using 200MeV e^-

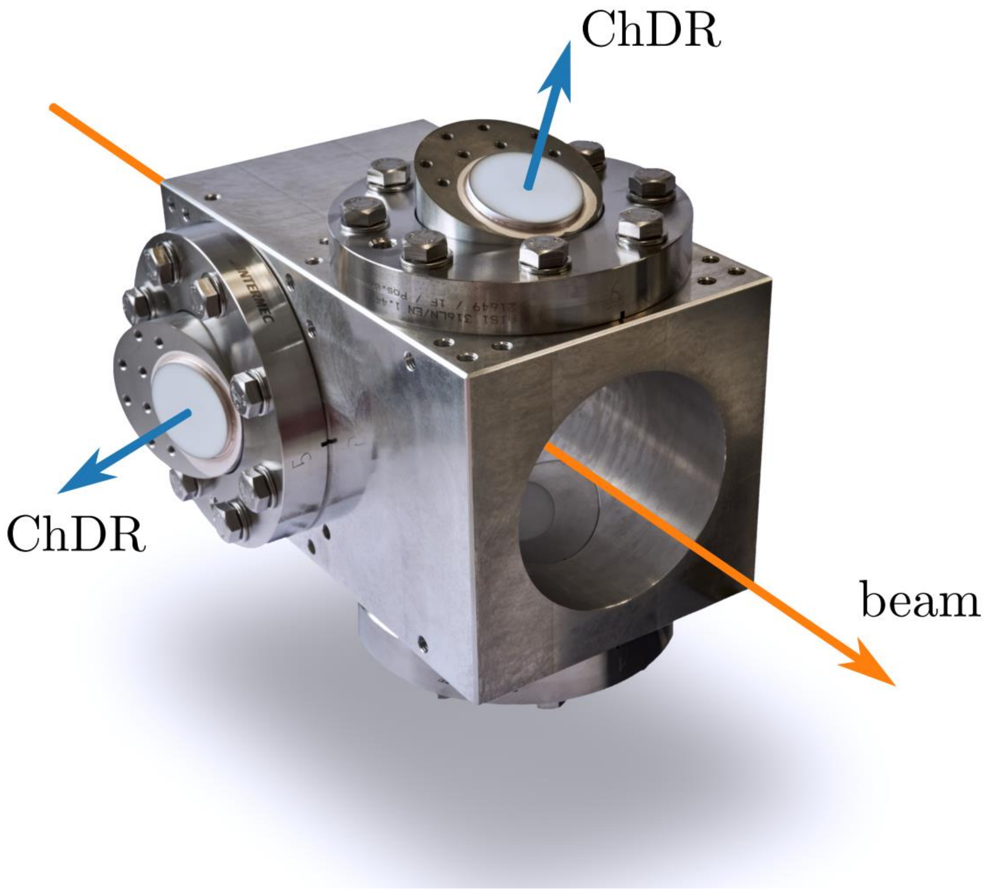


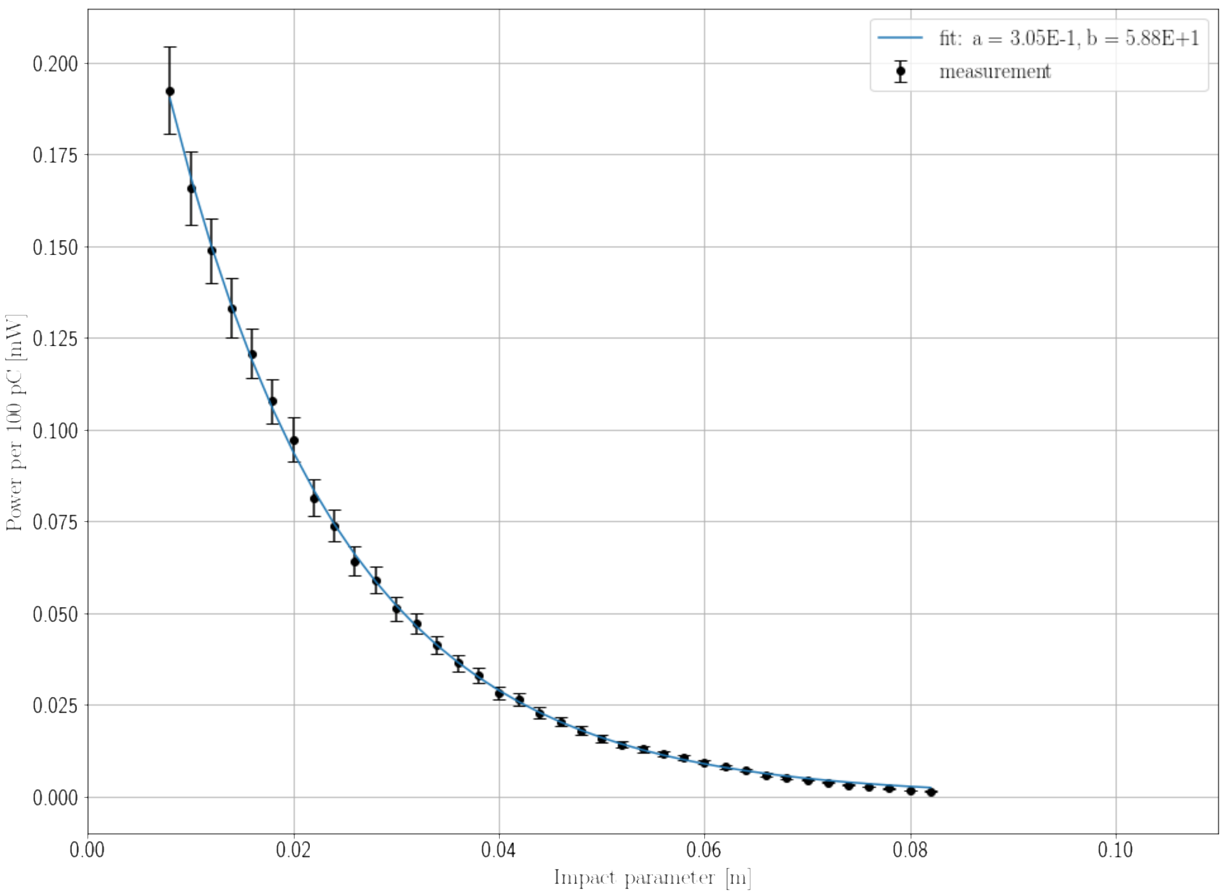


Diagnostic using Cherenkov Diffraction radiation

High frequency BPM using Coherent ChDR

UHV dielectric (alumina) BPM at 30GHz





Position sensitivity studies performed at CLEAR in Sept 2021

Conclusion

- Beam instrumentation is relying on a combination of many exciting fields and expertises.
- It involves innovative detector designs, complex electro-mechanical devices, custom electronic acquisition and control systems (rapidly evolving technologies)
- With increasing intensity, luminosity and brilliance, existing and futur accelerators are challenging our creativity to develop always more performant beam instruments. Non-invasive preferably !
- We can expect an increase in the use of accelerators and related technologies in Industry and Medical field with reliability, maintainability and cost optimization becoming even more important
- Join the BI Tribe !

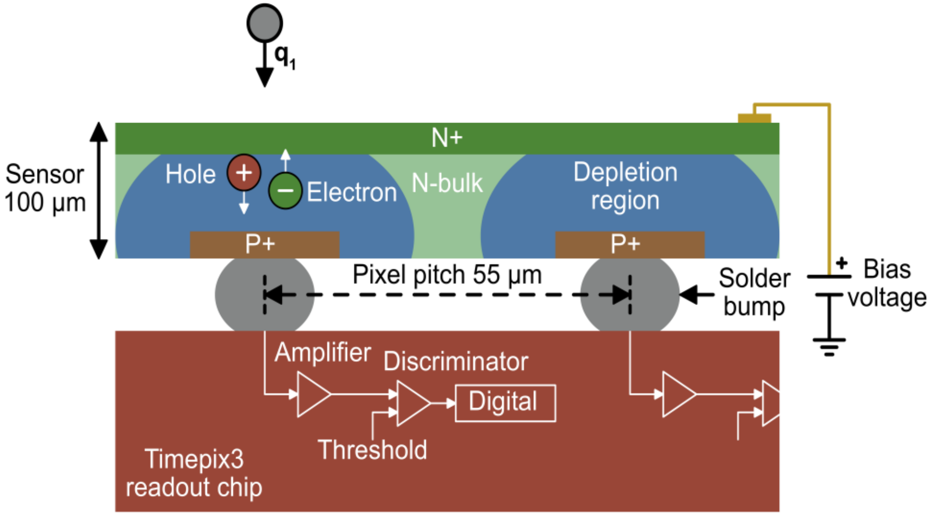
Thanks for your attention

A big thanks to all my colleagues at CERN and elsewhere

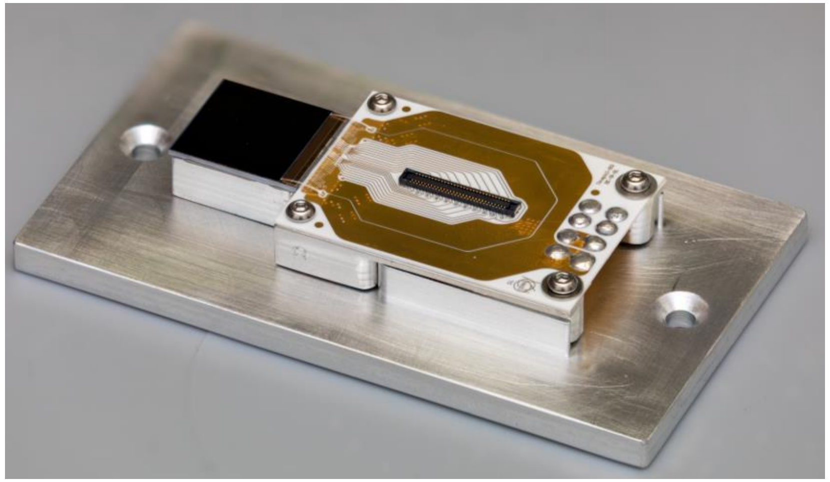
home.cern

Detector based on TPX3 Hybrid Pixel Detector

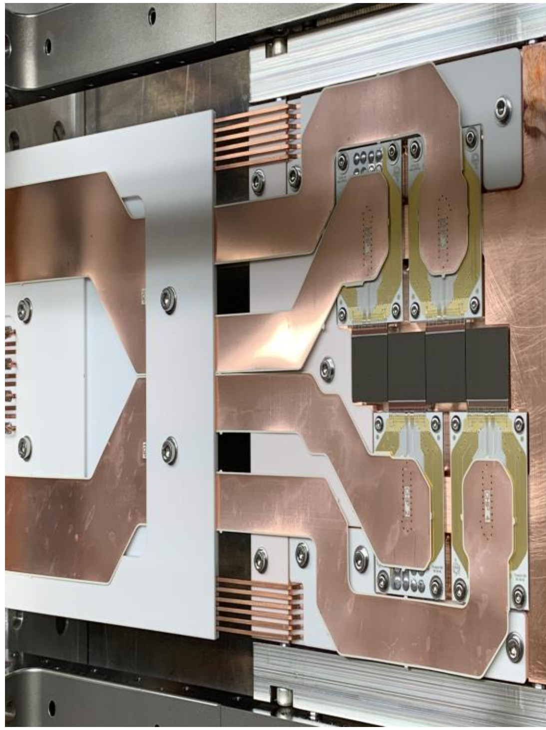
- **Detect ionising radiation (e.g. ionisation electrons, beam loss, etc...).**
- **Measures:**
  - Position (65k pixels with 55um pitch)
  - Time of Arrival (ToA) (1.56 ns resolution)
  - Deposited energy*
- **Virtually 100% detection efficiency.**
- **Virtually noiseless**.**



TPX3 HPD concept



PS-BGI detector module



PS-BGI detector

* Requires extensive calibration.
** Disclaimer: Except when used as a BGI detector.