



Challenge in beam instrumentation and diagnostics

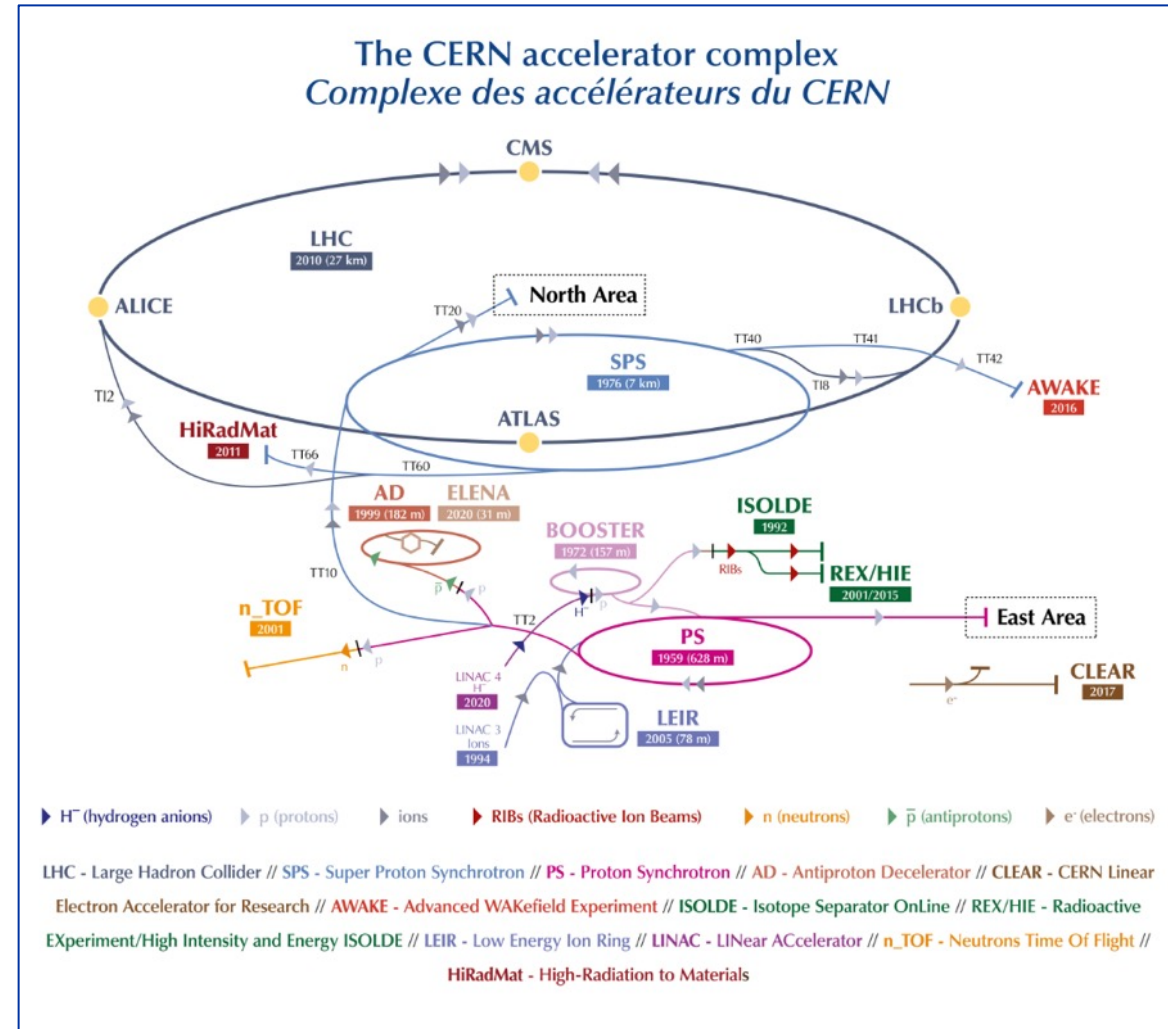
T. Lefevre – CERN

Outline

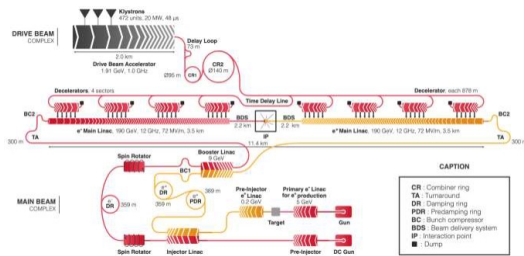
- Main challenges of Beam Instrumentation
- Snapshot of R&D activities and key technologies
- Conclusions

Challenge for Beam instrumentation at CERN – today and tomorrow

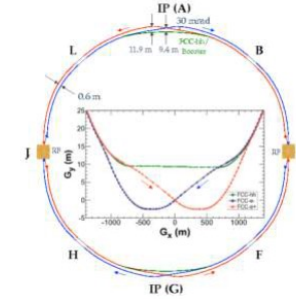
- Maintaining a large (>10000 instruments) and diverse Beam instrumentation system
- Dealing with larger beam intensities in the accelerator complex
- Still a need for consolidation (towards more reliability and efficiency) and improved performance (some missing diag, e.g. beam halo)



Looking forward ... Bigger, Faster, Better !

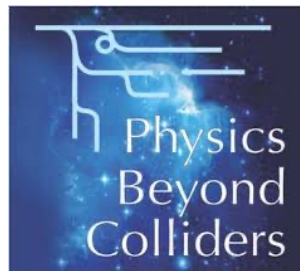


<https://clic.cern/>



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

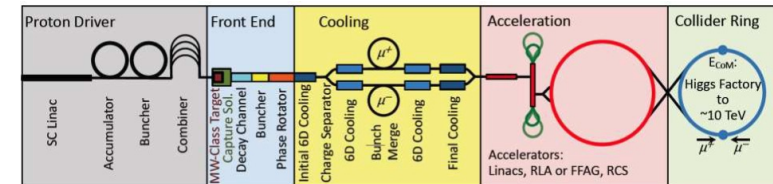
Shorter electron bunches, lower emittance / beam size, very large number of instruments, ..



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



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



Higher beam intensities on target, ..

Launch a bottom-up R&D survey

- Identify state-of-the-art technologies and future trends in our field
- Collect 'all' requirements from Projects and future Studies



- Build a medium to longer term plan of **R&D roadmap** to foster our expertise and maintain top performance
- Identify possible future collaborations – synergies (Group, CCTB)
- Align our Roadmap to the CERN Priorities
 - Future students / Graduates needs

Launch a bottom-up R&D survey

R&D	Challenges	Key Technologies	Status	Funded by	Past achievements (Tests, Publications,..)	Useful for				
						CERN Machines	CERN Projects	CERN Studies	Accelerators outside CERN	Knowledge transfer

Potential quantities	External collaborators	CERN Group involved	SY-BI section and contact persons

Main challenges in Beam instrumentation

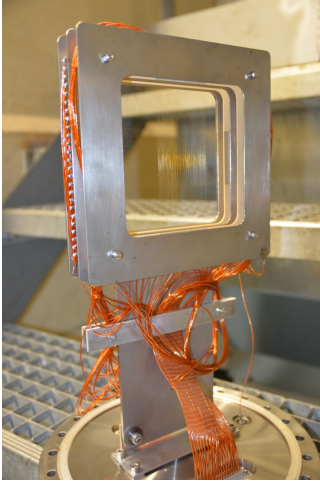
- Dealing with higher beam power
 - Low-impedance design require for all instruments to limit heating problems
 - Higher beam densities putting strong limitations of interceptive diagnostics (screen, wire)
 - Need for robust and reliable machine protection systems
 - Measuring beam quality, tail and halo particles
- Measuring and conserving small beam emittance and small beam size
 - Unprecedented request for higher spatial resolution for position (nanometer) and transverse profile (micrometer) monitors
- Measuring the ultra-short
 - Sub-ps bunches and fast beam instabilities
- Measuring the ultra-low and DC beams
 - Slowly extracted beams and exotic beams, i.e. AD/ELENA and Isolde/REX
- Exposed to higher radiation environment
 - Rad-hard / Rad-tol design
- Treatment of increasingly more data – bunch-bunch everything !
- Cost effective solution for large systems (BPM and BLM)

On-going R&D in the BI group

- Pushing the state-of-the-art in interceptive diagnostics
- Non-invasive beam size monitors
- ‘New’ techniques for short bunches
- Innovative design of Electromagnetic pick-ups
- Techniques for low beam intensity and DC beams
- Robust particle detectors as BLM
- State-of-the-art electronic development

State-of-the-art Interceptive beam diagnostics

Towards a modern optimised design of SEM grids

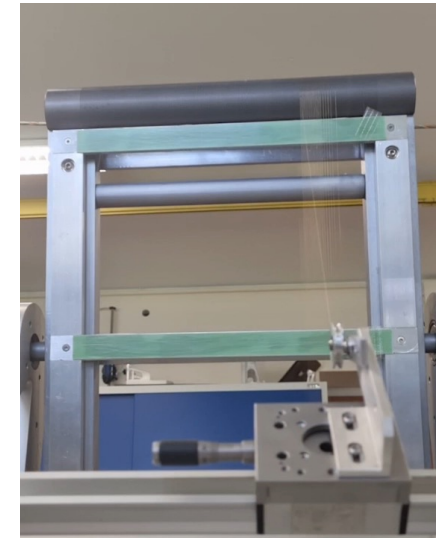
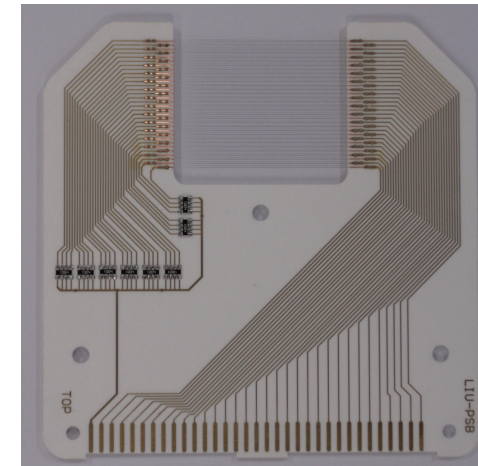


Improved UHV cabling and connectors...

From kapton wiring to Flex cables and connectors



Wire ceramic support evolving towards industry standard in PCB manufacturing : 3 steps in 1



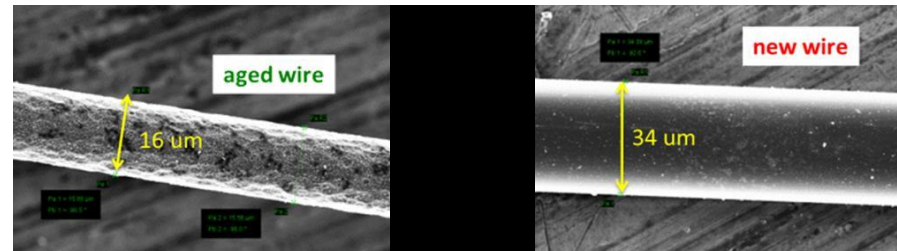
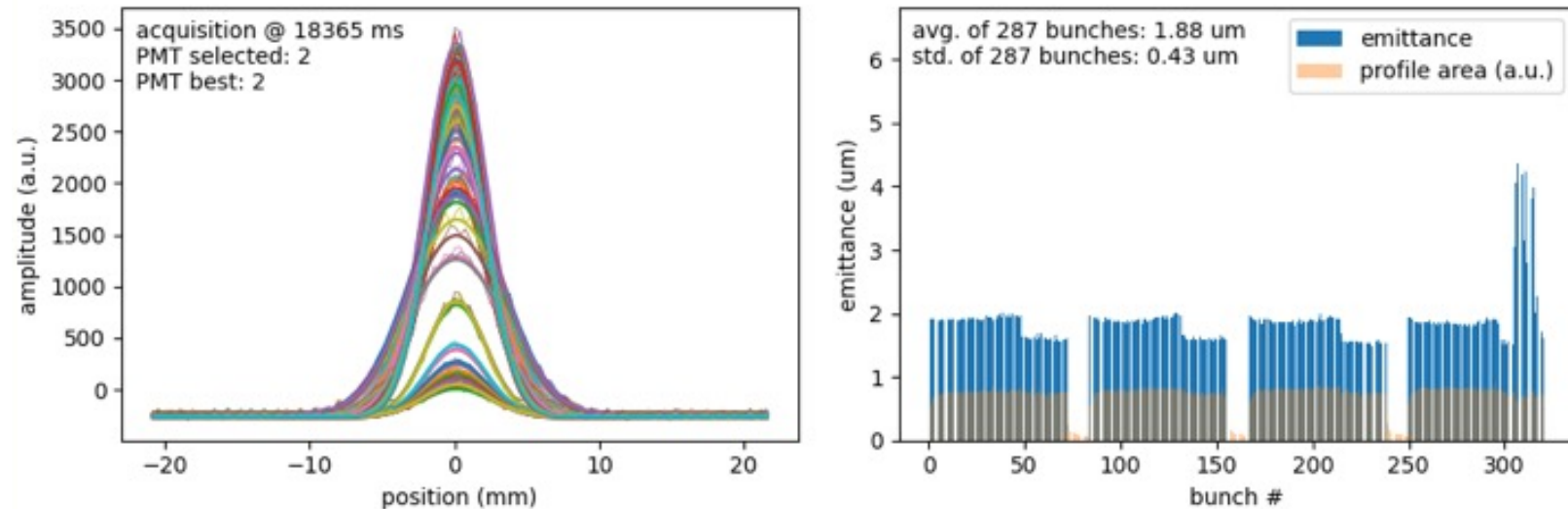
State-of-the-art Interceptive beam diagnostics

20m/s rotational Wire Scanner (LIU project)



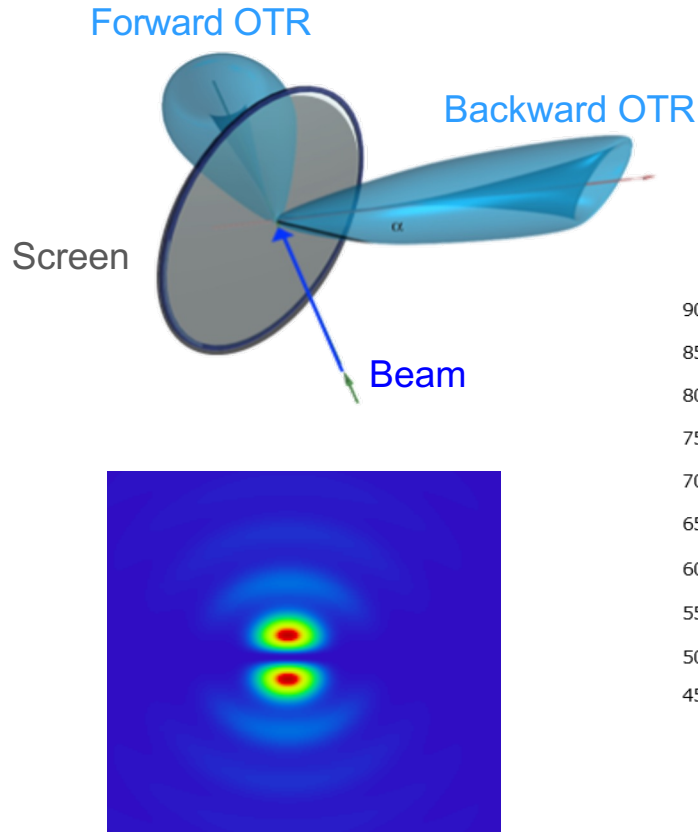
Monitors also produced for ESS

S. Di Carlo et al., IBIC 2022, pp.443

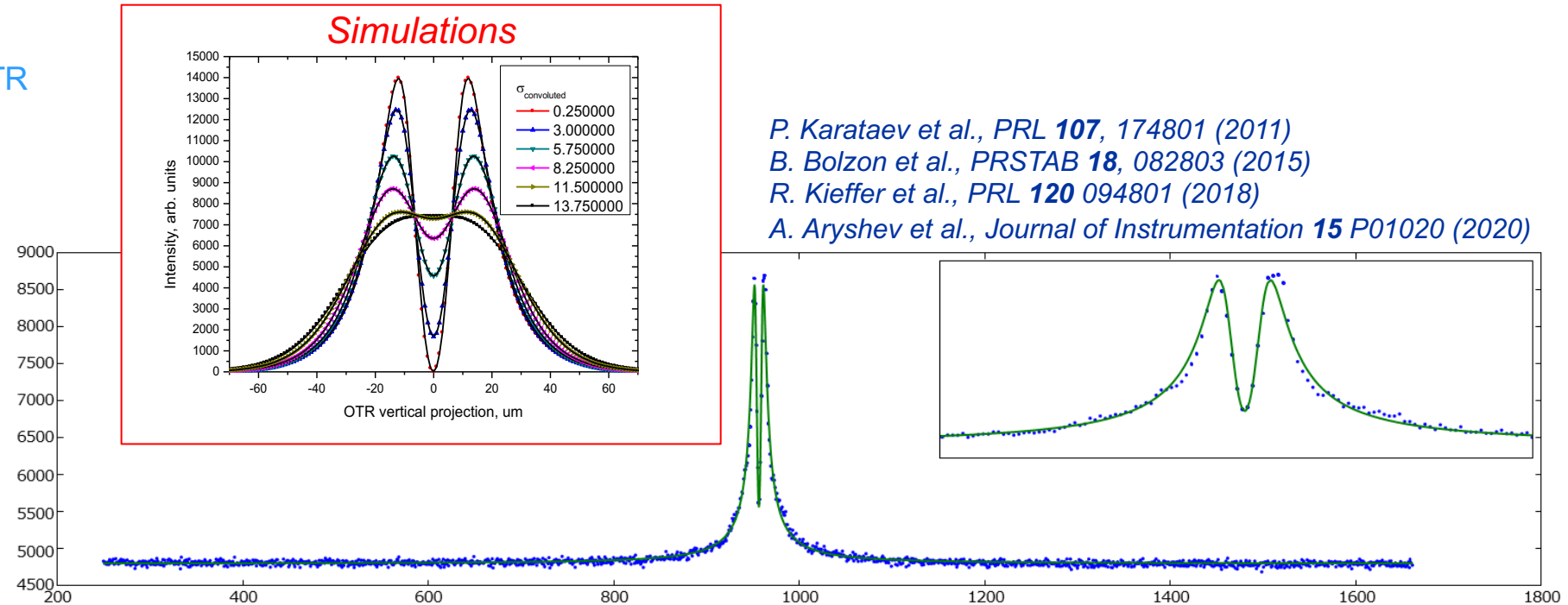


State-of-the-art Interceptive beam diagnostics - Screens

High resolution beam size monitor using **Optical Transition Radiation Point Spread Function (PSF)** with KEK and RHUL



T. Aumeyr *et al.*, PRSTAB **18**, 082803 (2015)



P. Karataev *et al.*, PRL **107**, 174801 (2011)

B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)

R. Kieffer *et al.*, PRL **120** 094801 (2018)

A. Aryshev *et al.*, Journal of Instrumentation **15** P01020 (2020)

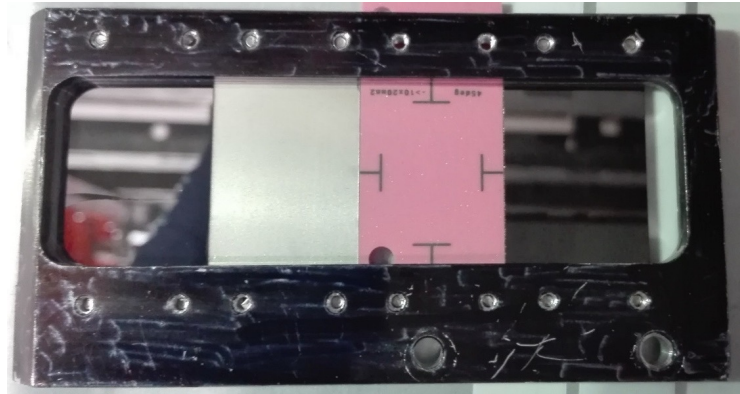
600nm beam size measured @ ATF2-KEK in VUV range
funded by CLIC – stopped now

State-of-the-art Interceptive beam diagnostics - Screens

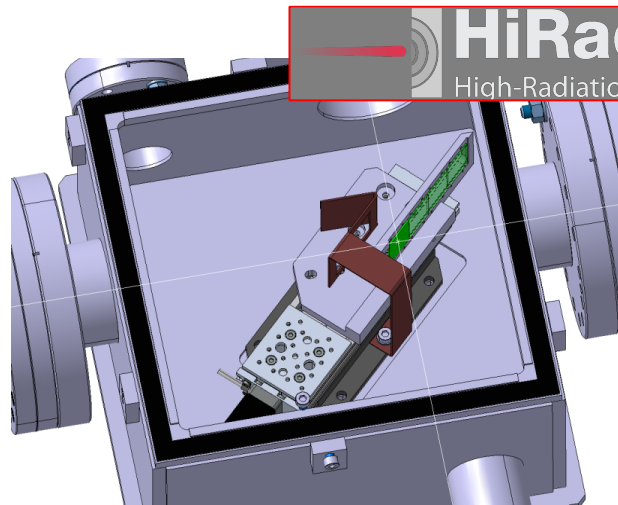
Imaging system for high intensity beams using **Optical Transition Radiation**

Looking for the 'best' thermal resistant material

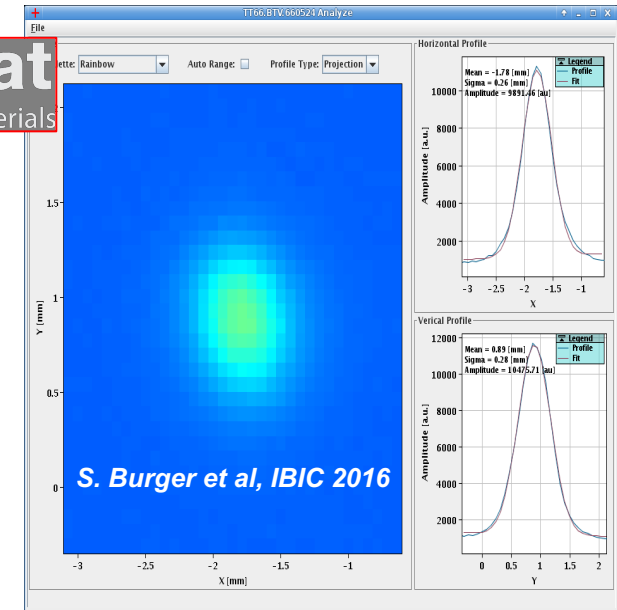
- *Surface homogeneity/flatness/roughness, high reflectivity*



SiC 0.5mm Ti 0.1mm $\text{Al}_2\text{O}_3:\text{CrO}_2$ 0.5mm Sigradur G Glassy C 0.5mm



288 bunches at $1\text{E}11$ with $\sigma_H = 0.26\text{mm}$ and $\sigma_V = 0.28\text{mm}$



CNGS

LHC Dump line

Hiradmat

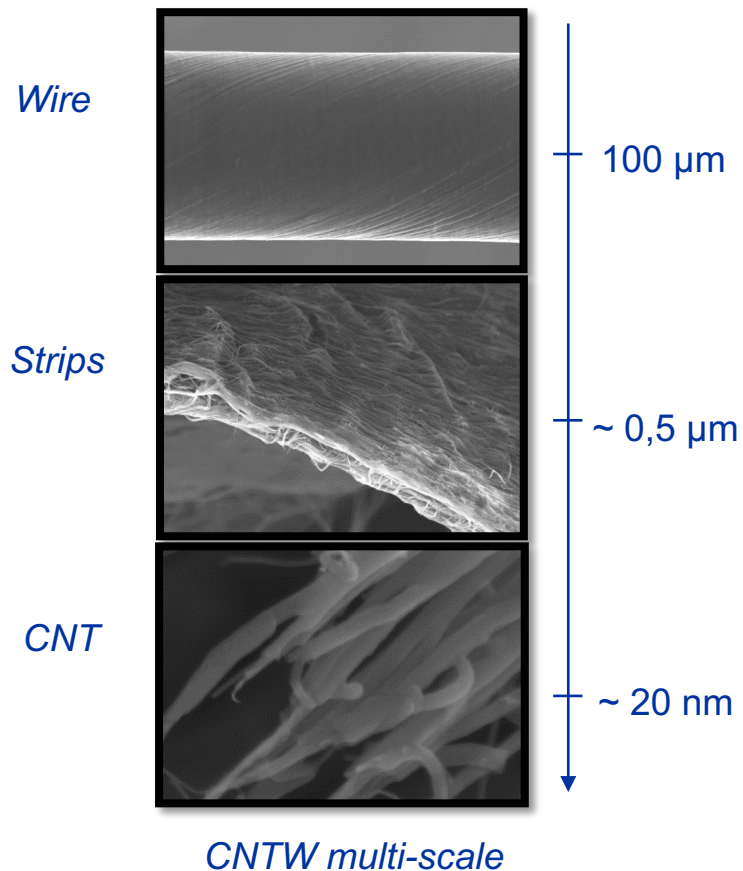
AD target

High power linac and MuC

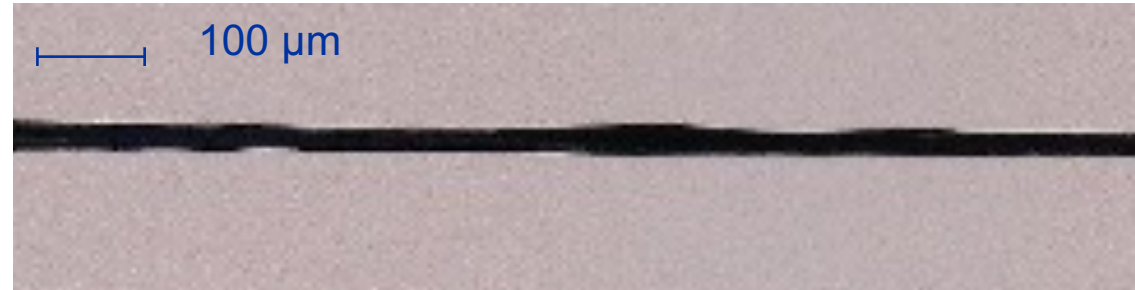
State-of-the-art Interceptive beam diagnostics - Screens

Replacing the best thermally resistant material (carbon wire and glassy Carbon)
by low density materials (CNNT wire and graphene foil)

On-going studies with students (Southampton Uni. and Malta uni.) and Workshop in 2023 <https://indico.cern.ch/event/1275649/>



A. Mariet et al., IBIC 2022 pp.527



CNT yarn before irradiation

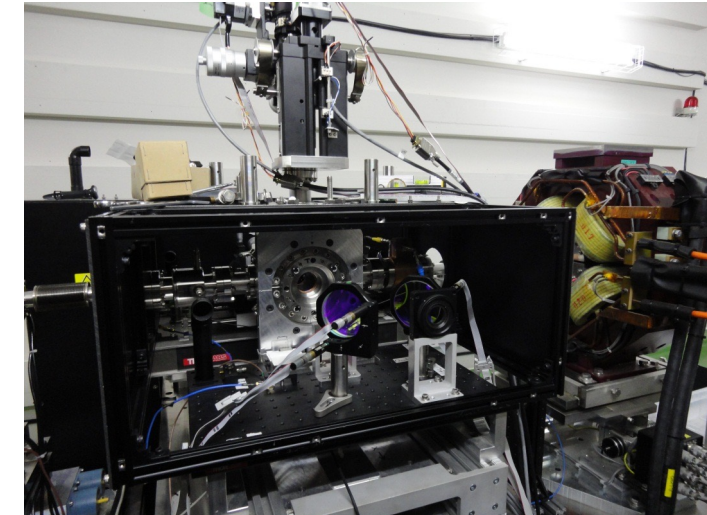
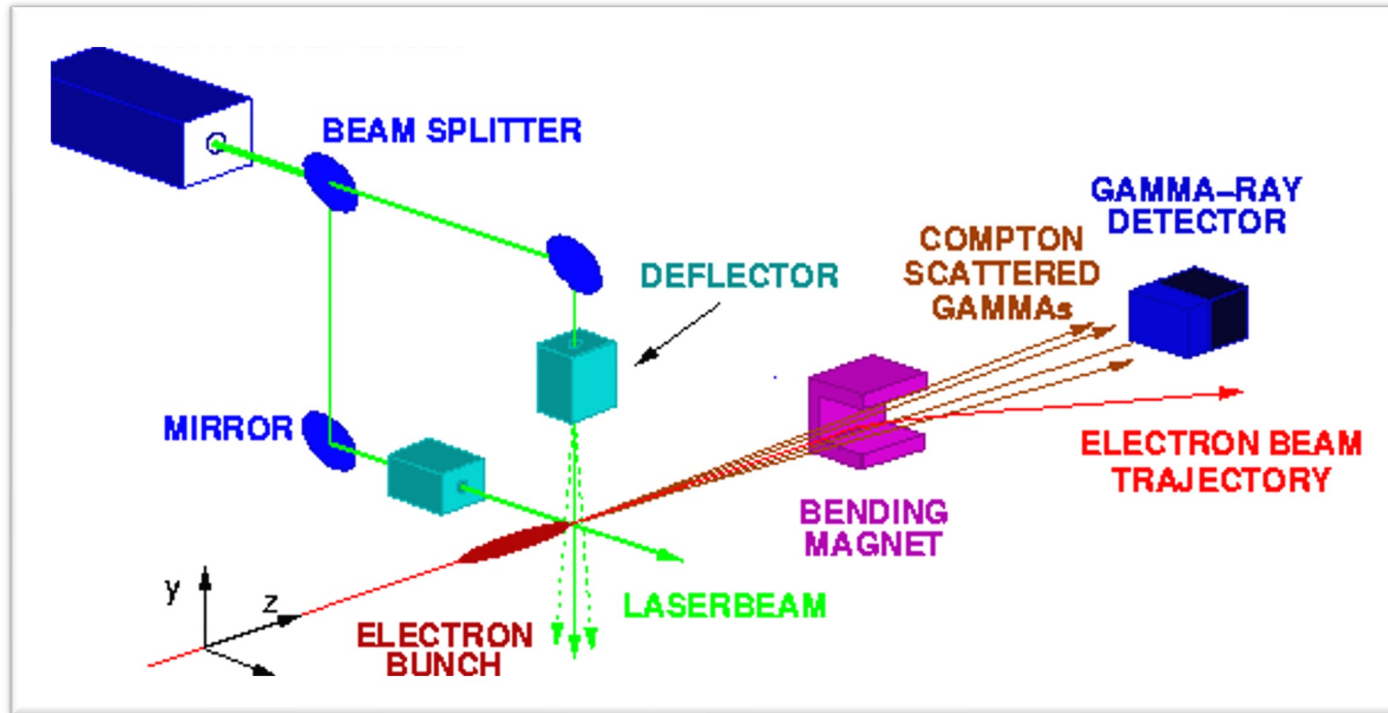


CNT yarn after beam irradiation @ HIRADMAT

Non-invasive beam size monitors

- Laser-based Techniques
- Gas-based Techniques
- Polarisation radiation Techniques
- Synchrotron radiation Techniques

Non-invasive beam size monitors – laser-based



Demonstrated 1 μm measurement resolution

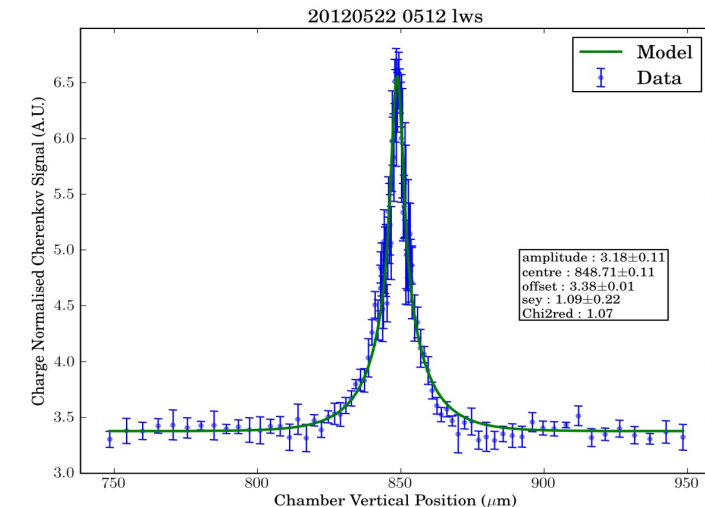
15 years on R&D on ATF2 ring and extraction line with RHUL, KEK

H. Sakai et al, Physical Review ST AB 4 (2001) 022801 & ST AB 6 (2003) 092802

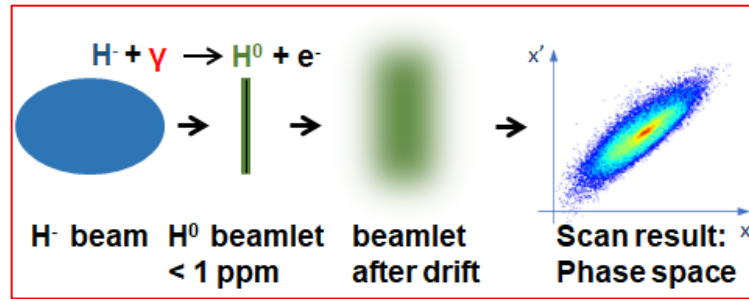
S. T. Boogert et al., PRSTAB 13, 122801 (2010)

L. Corner et al., IPAC, Kyoto, Japan (2010) pp3227

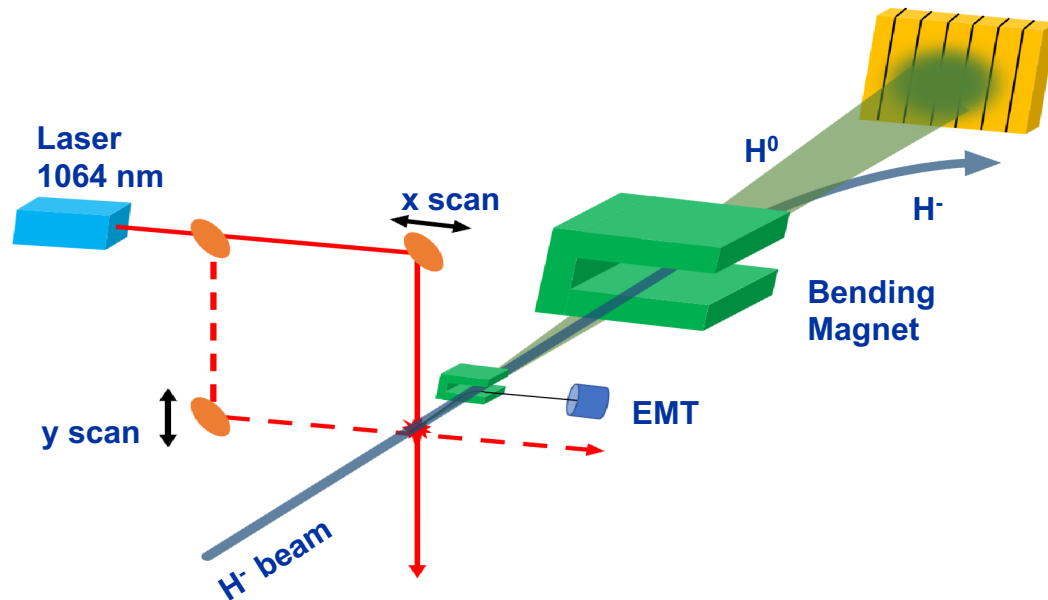
Funded by LC/CLIC → now FCC Polarimeter and transverse beam size (IJCLab)



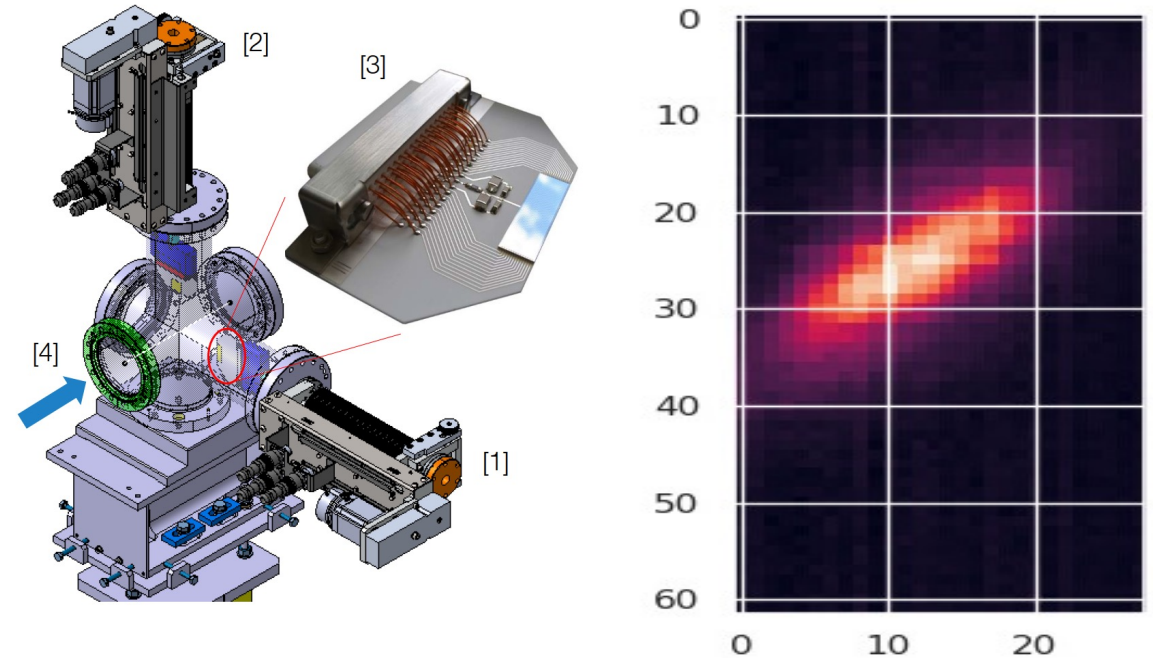
Non-invasive beam size monitors – laser-based



Laser based - Emittance-meter



In-vacuum pixel Diamond sensor



T. Hofmann et al., NIMA 830 (2016) 526

T. Hofmann et al., NIMA 903 (2018) 140

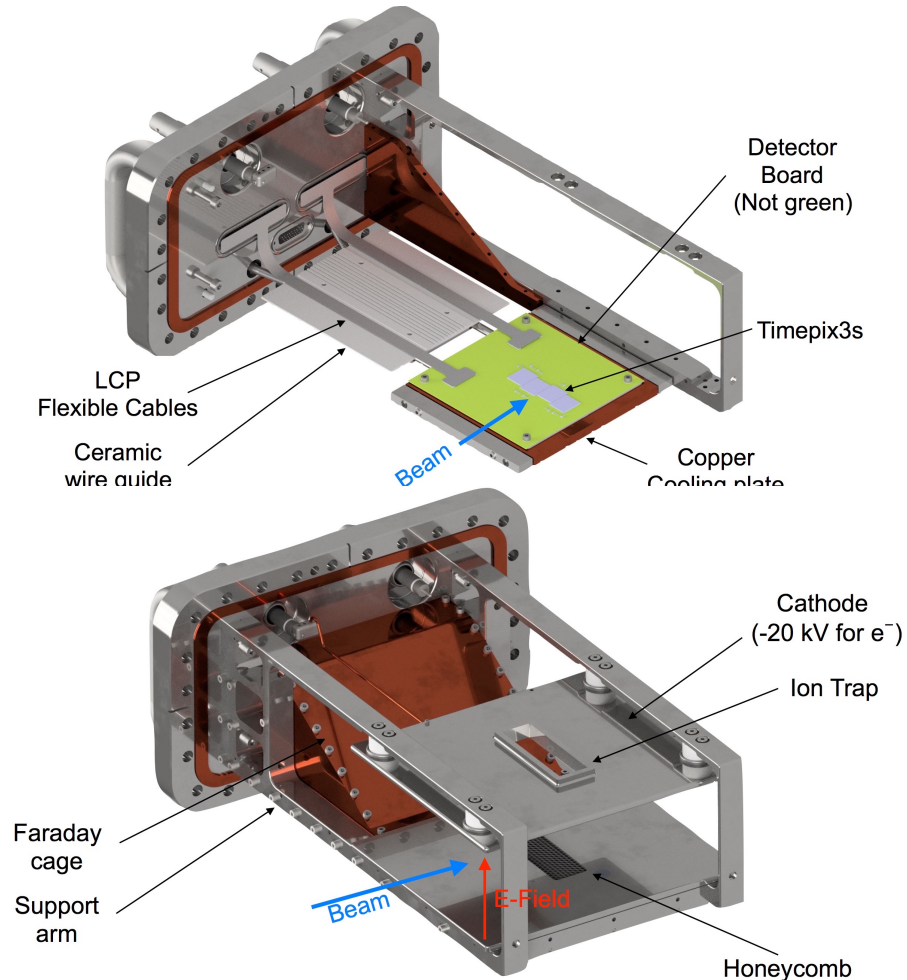
Collab. with RHUL – stopped now

Works only for H^- beams

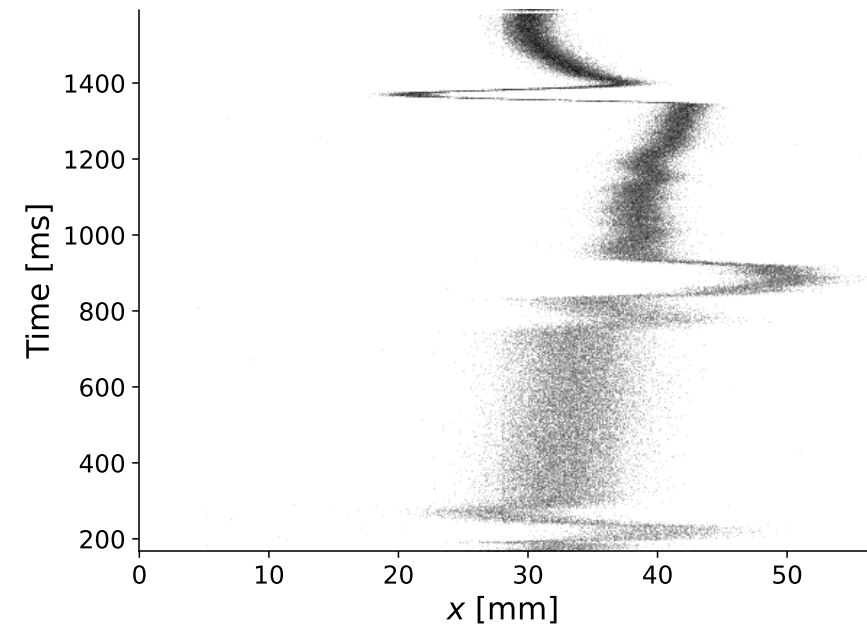
Non-invasive beam size monitors – gas-based

Gas ionization monitor using hybrid pixel detector

S. Levasseur et al., Journal of Instrumentation, 12 C02050 (2017)



*Hor. beam size/position evolution
during 1.2s long cycle @ PS*

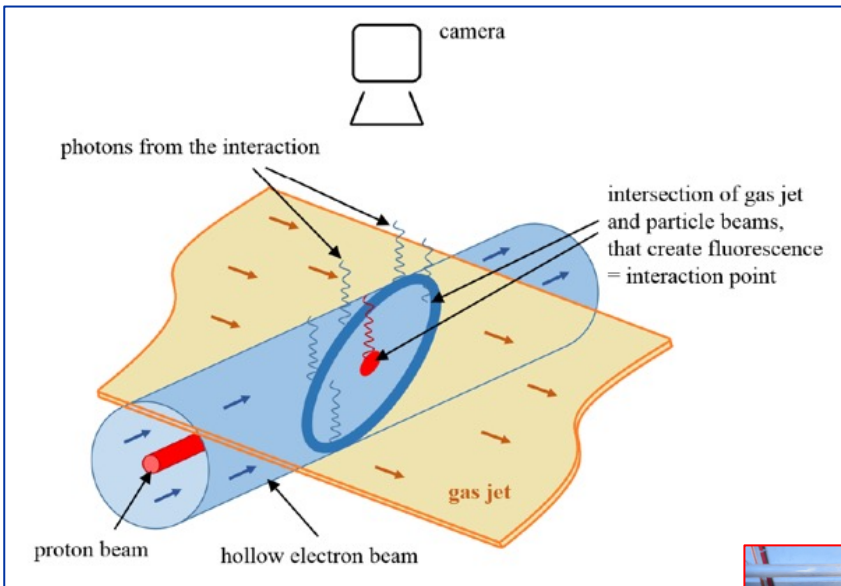


From PS to SPS and LHC, possibly TLs and medical machine

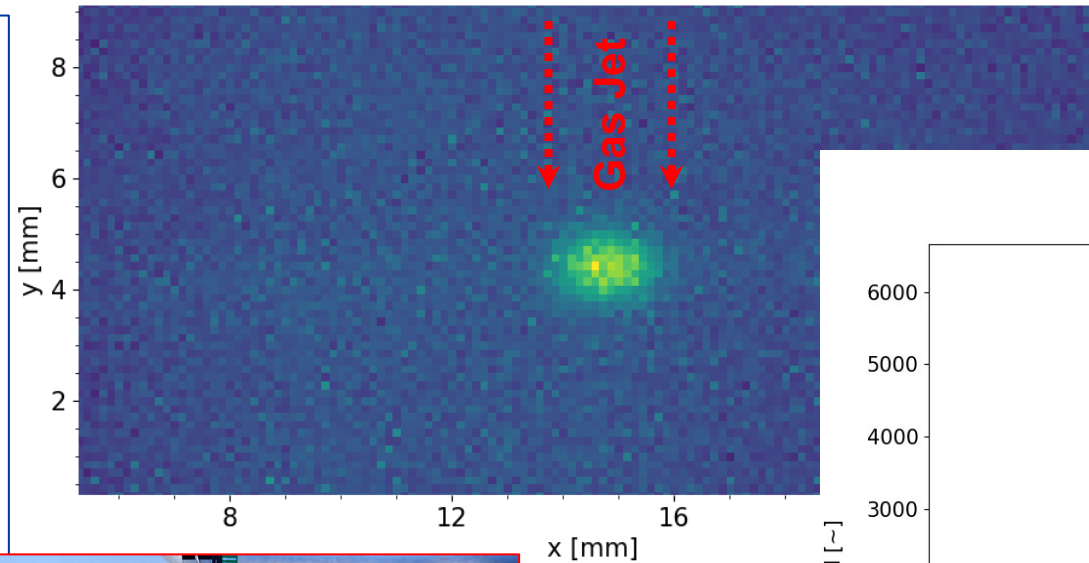
From Timepix 3 to Timepix4

Non-invasive beam size monitors – gas-based

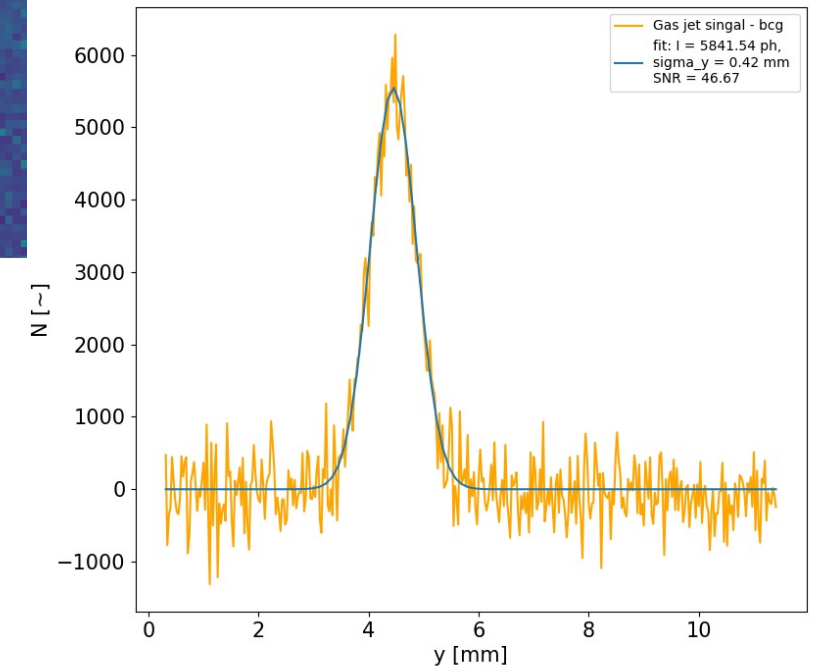
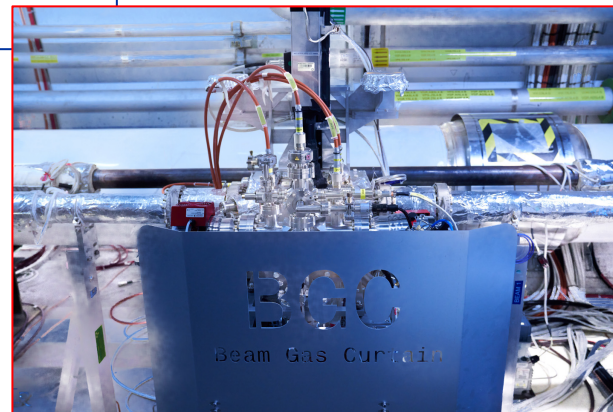
Imaging system using fluorescence of supersonic gas curtain with Uni. Liverpool and GSI



*A.Salehilashkajani et al., APL 120
174101 (2022)*

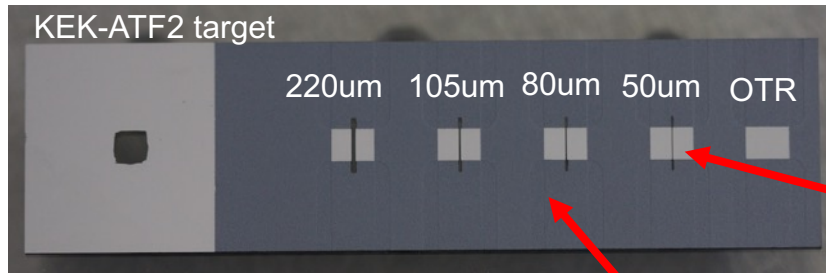


Measurements
performed in 2023



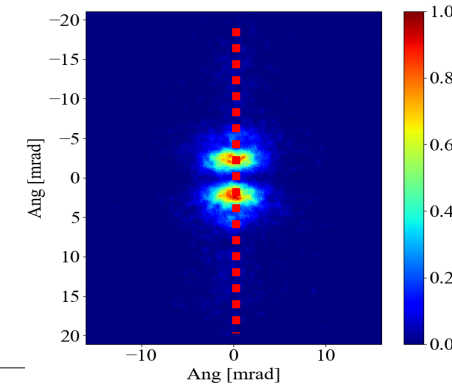
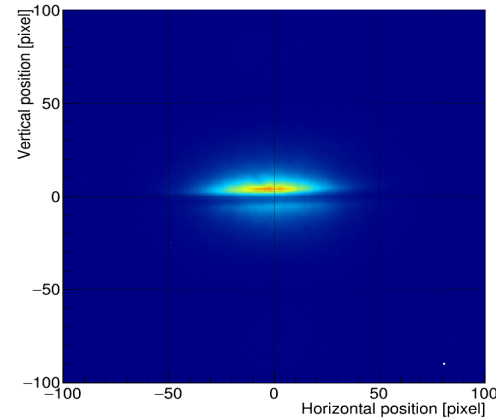
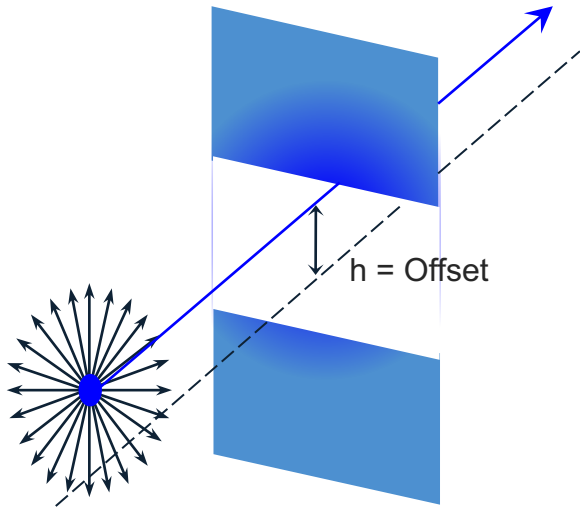
Non-invasive beam size monitors via polarization radiation

Diffraction radiation from high precision slits with KEK and RHUL

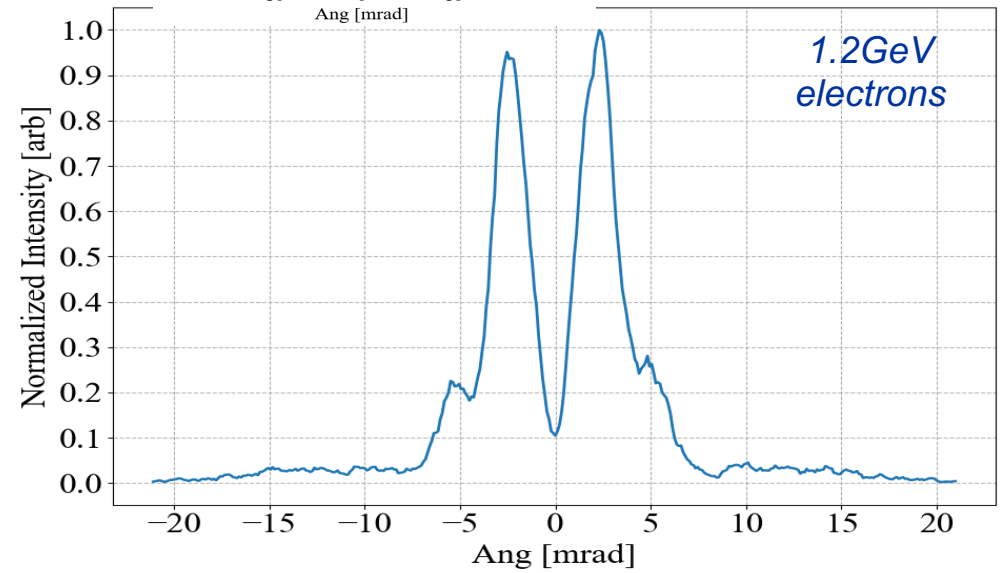


Maximizing emission of DR
with Al coating around the slit

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



*5um beam size measured
@ ATF2-KEK in VUV*



L. Bobb et al., PRAB **21** 032801 (2018)

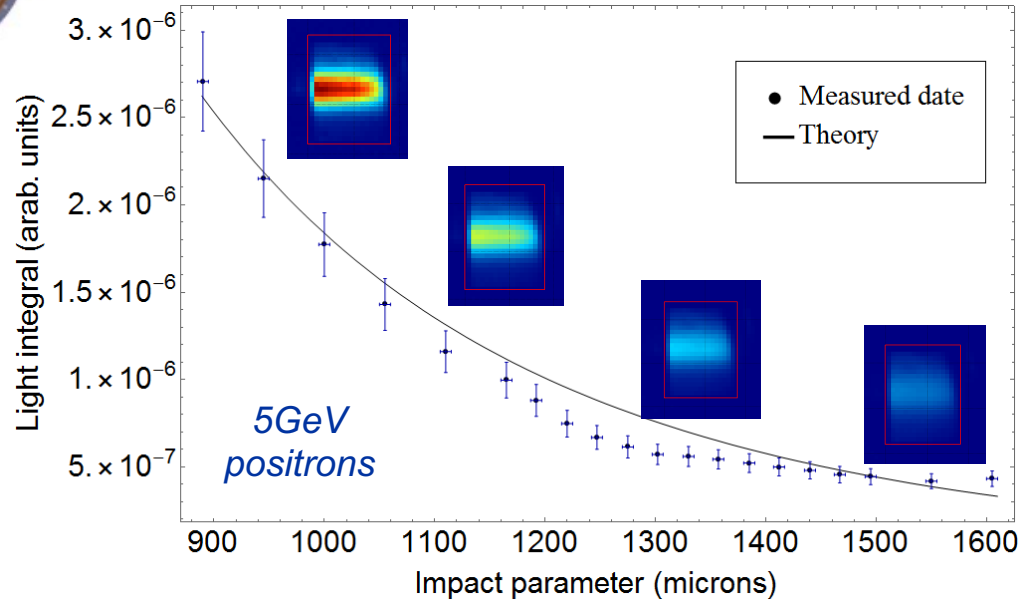
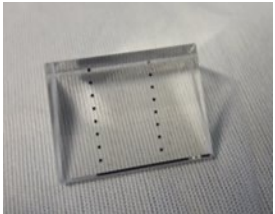
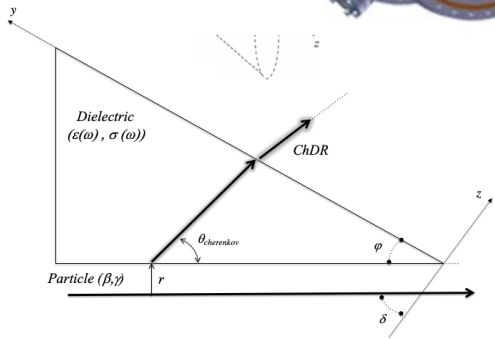
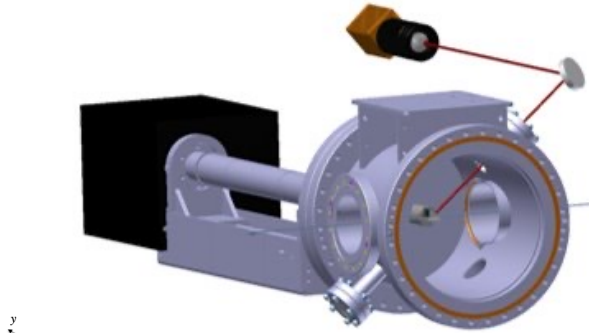
R. Kieffer et al., NIMB **402** 88 (2018)

M. Bergamaschi et al., PRApplied **13** 014041 (2020)

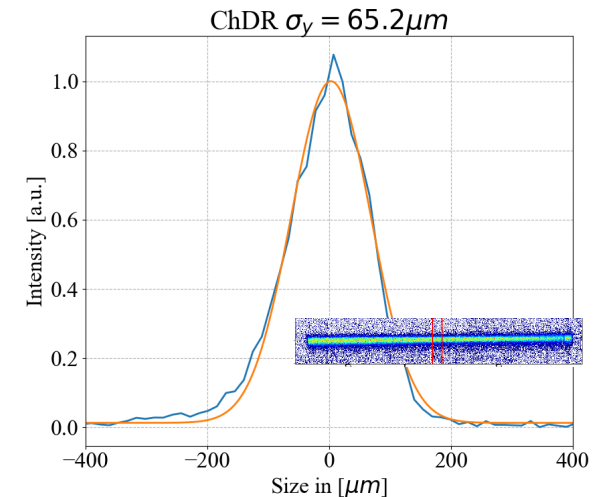
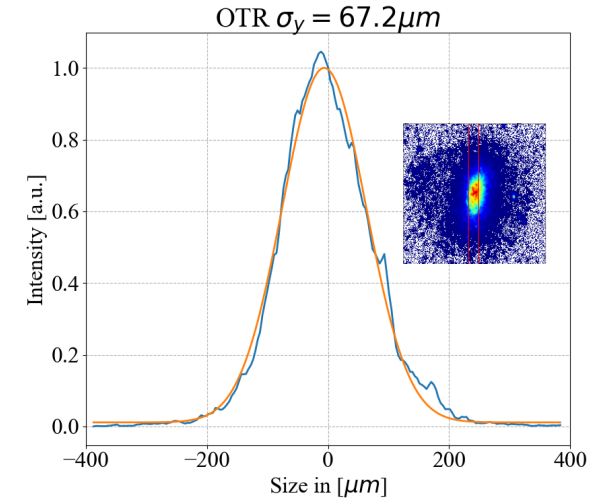
Non-invasive beam size monitors via polarization radiation

Diffraction Cherenkov radiation imaging system with
RHUL, KEK & Cornell Uni.

mm hor. beam size @ CESRTA



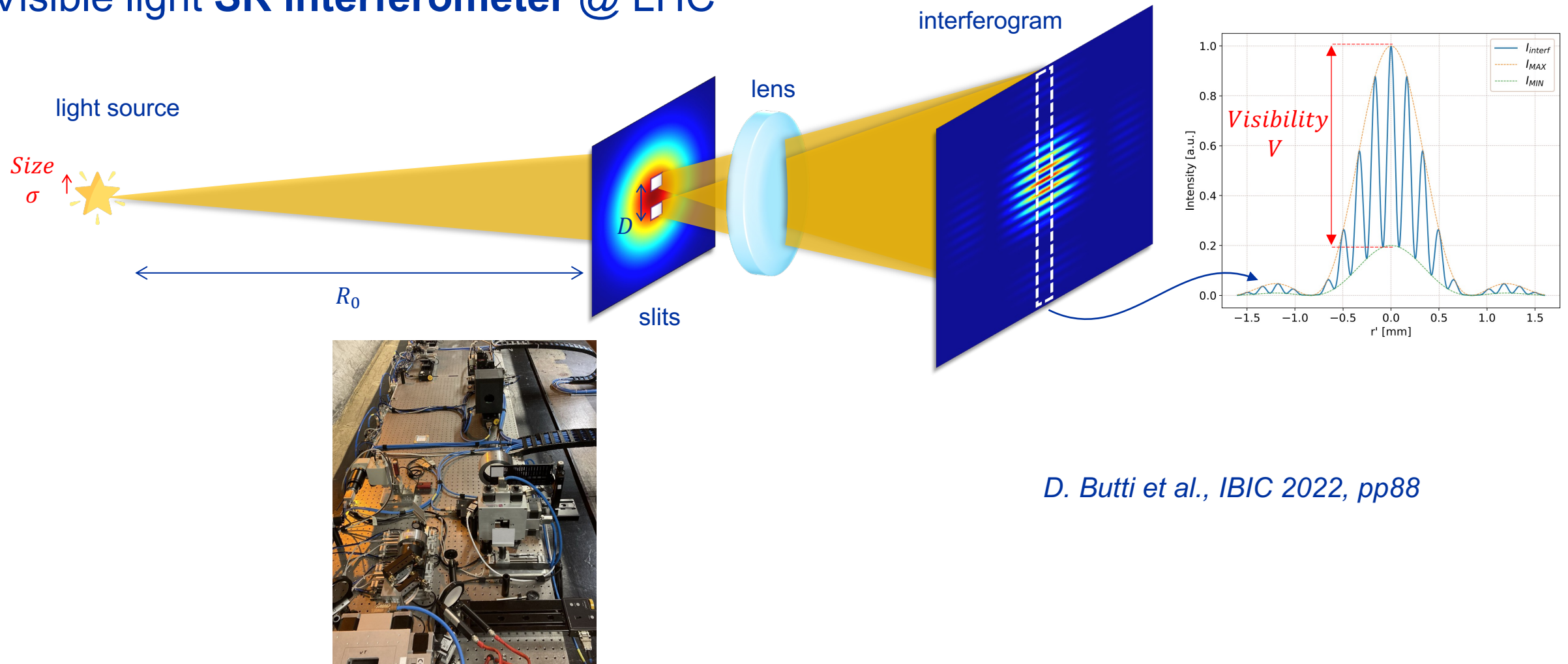
*R.Kieffer et al., PRL **121** 054802 (2018)*
*R.Kieffer et al., PRAB **23** 042803 (2020)*



hor. beam size @ ATF2-KEK
1.2 GeV electrons

Non-invasive beam size monitors via synchrotron radiation

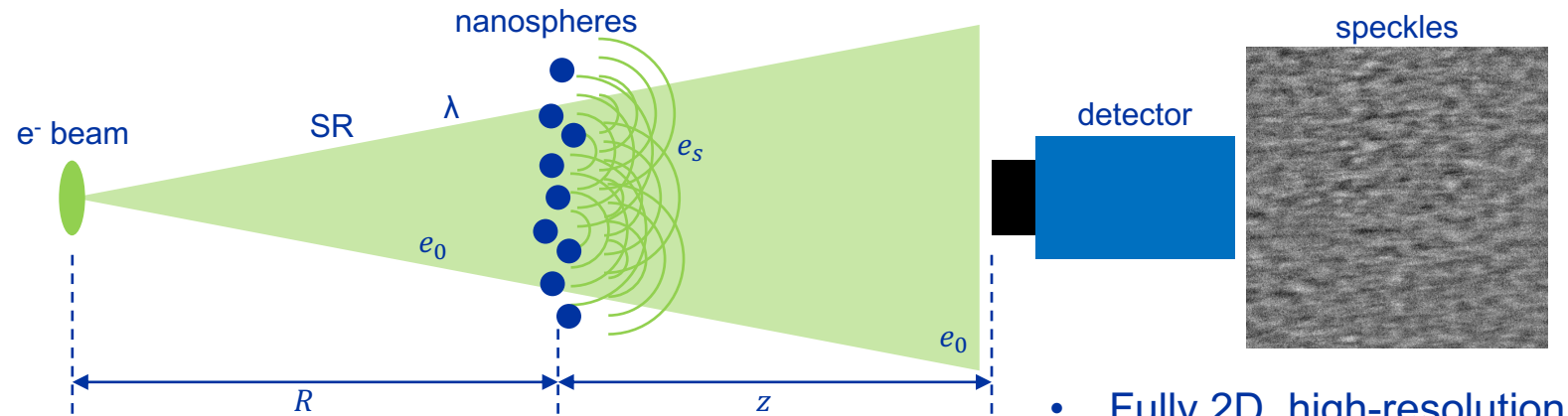
Visible light SR interferometer @ LHC



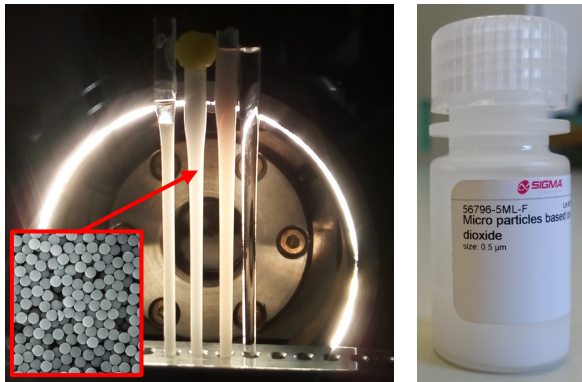
D. Butti et al., IBIC 2022, pp88

Non-invasive beam size monitors via synchrotron radiation

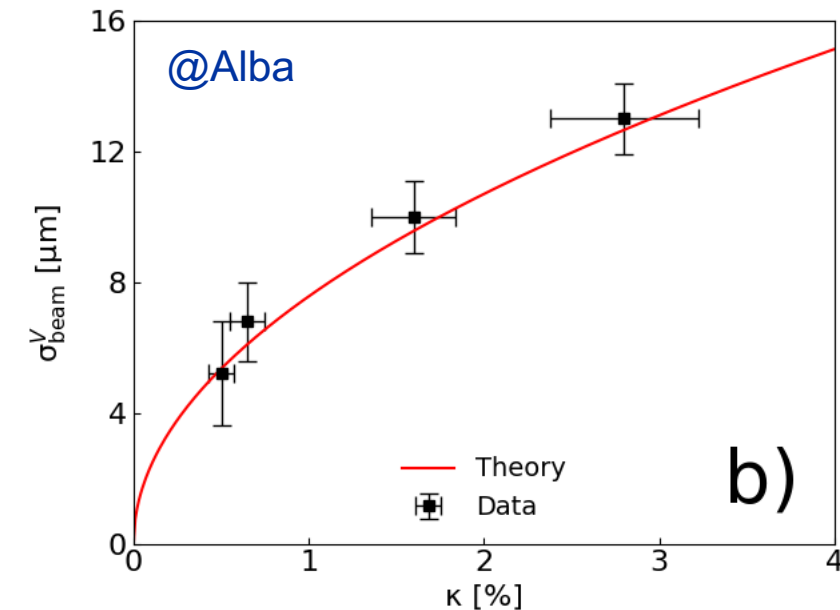
X-ray interferometry using near field speckles with Uni. Milano and Alba



- Fully 2D, high-resolution
- Suitable for X-rays



The probe: silica (SiO_2) spheres, 500 nm, in water



M. Siano et al., PRAB 25 052801 (2022)

Non-invasive beam size monitors

- Laser-based Techniques

LC / CLIC and L4

FCC-ee

- Gas-based Techniques

Proton Synchrotrons

HL, FCC-hh, TLs, ...

- Polarisation radiation Techniques

LC / CLIC

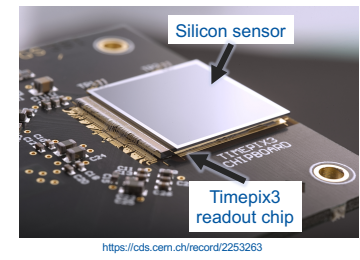
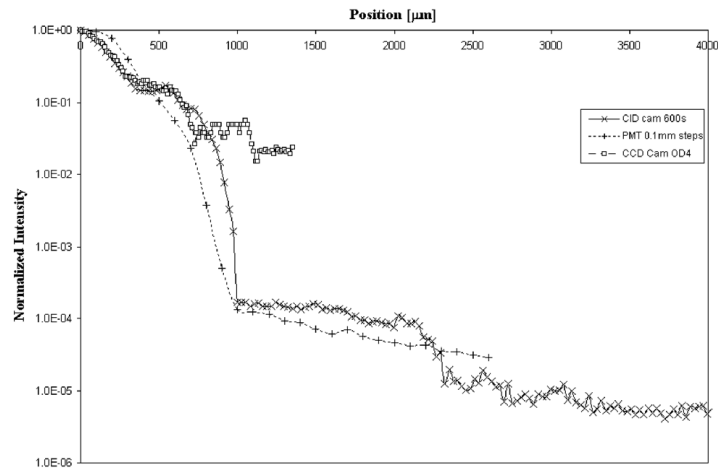
HL, FCC-ee, FCC-hh, MuColl

- Synchrotron radiation Techniques

LC / CLIC

HL, FCC-ee, FCC-hh, MuColl

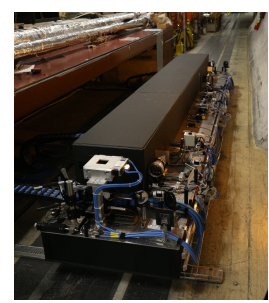
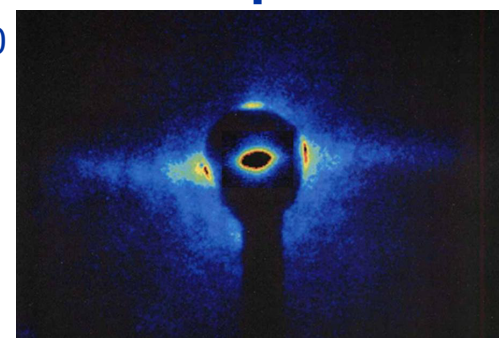
High dynamic range measurements for Beam halo monitoring



A. Fisher et al, IBIC 2015, pp630
Beam halo workshop at SLAC

HL coronagraph and
alternative scenarios
2023

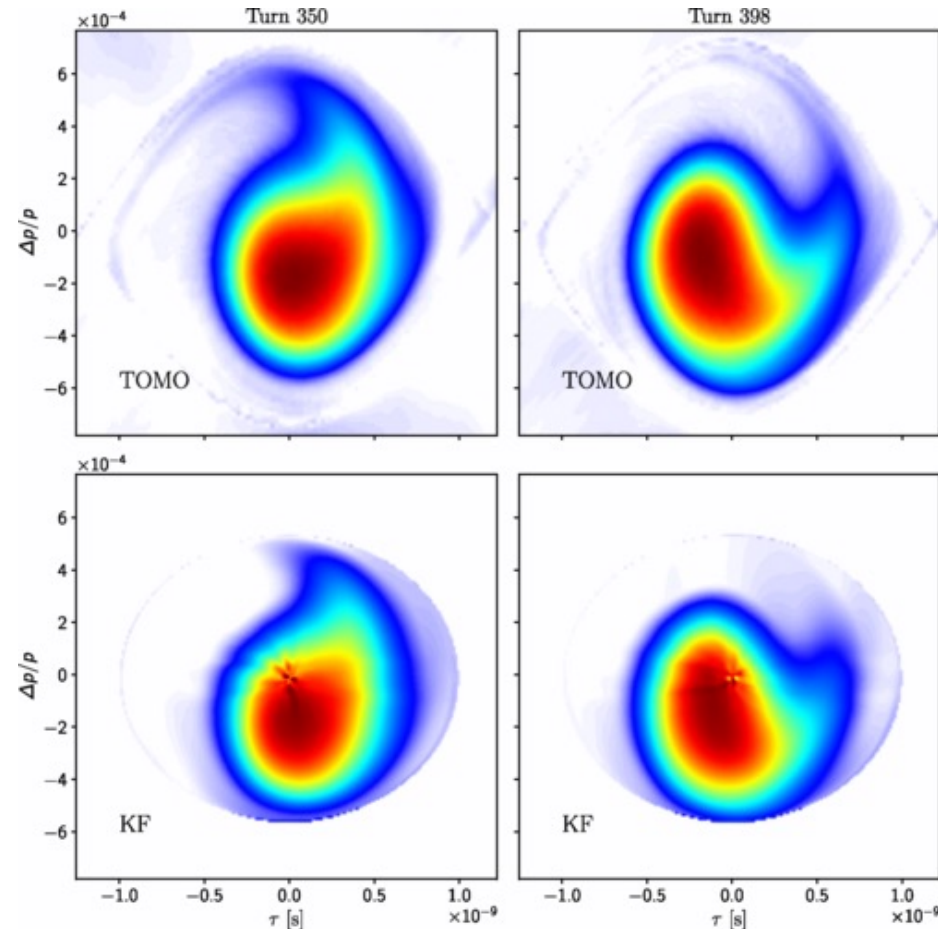
C. Welsch et al, Meas. Sci. Technol. 17 (2006) 2035–2040
funded by CLIC



Longitudinal phase space reconstruction

Kalman filter

D. Alves et al., PRAB 24 (2021) 072801

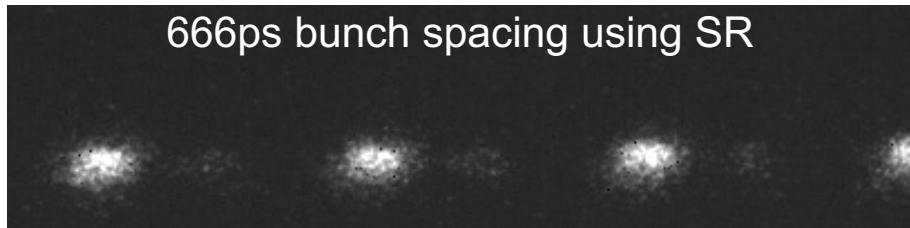


Towards an on-line longitudinal phase space measurements – LHC and others circulation machine

Longitudinal profile of short bunches

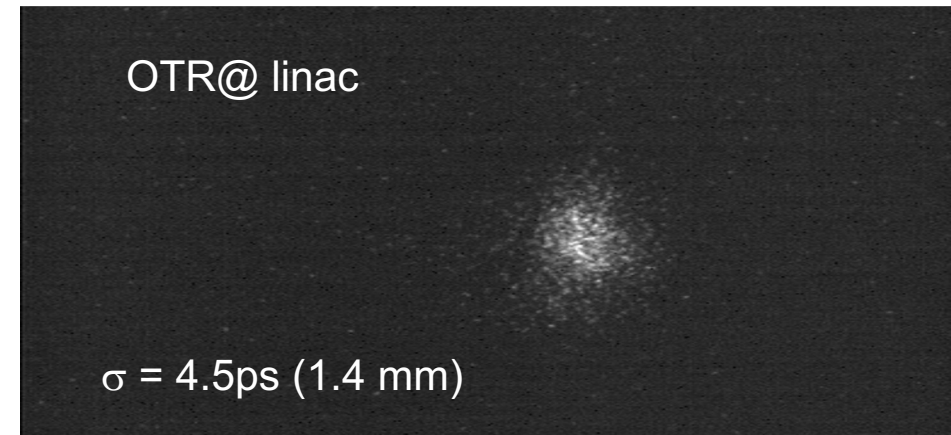
Streak Camera @ CTF3

- Simple but expensive
- Cannot do bunch by bunch measurements



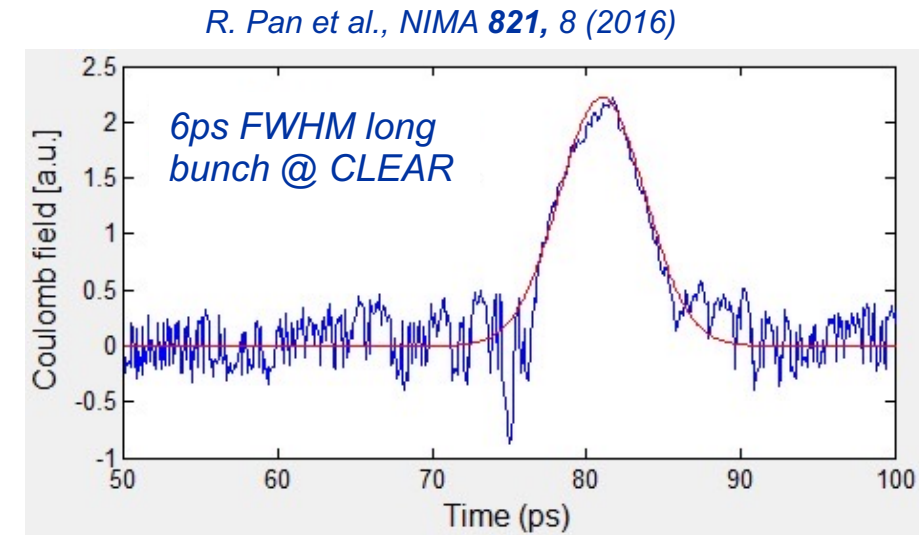
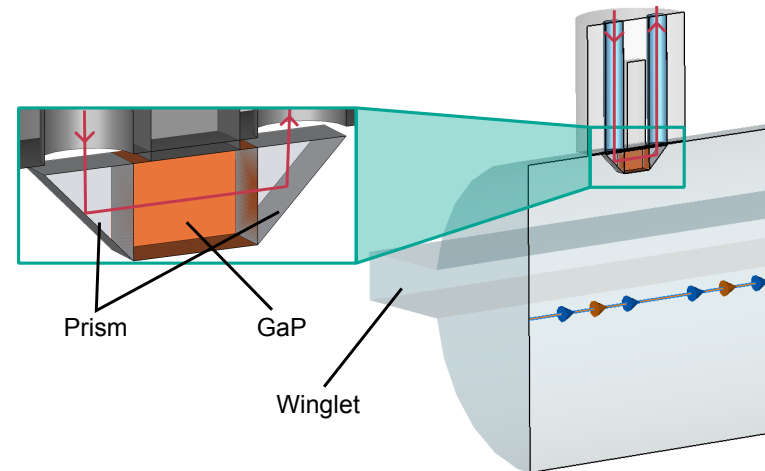
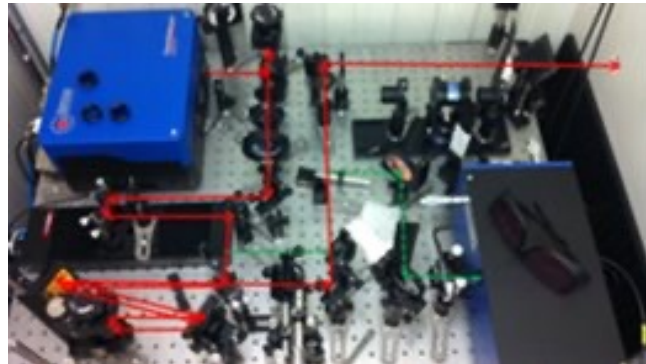
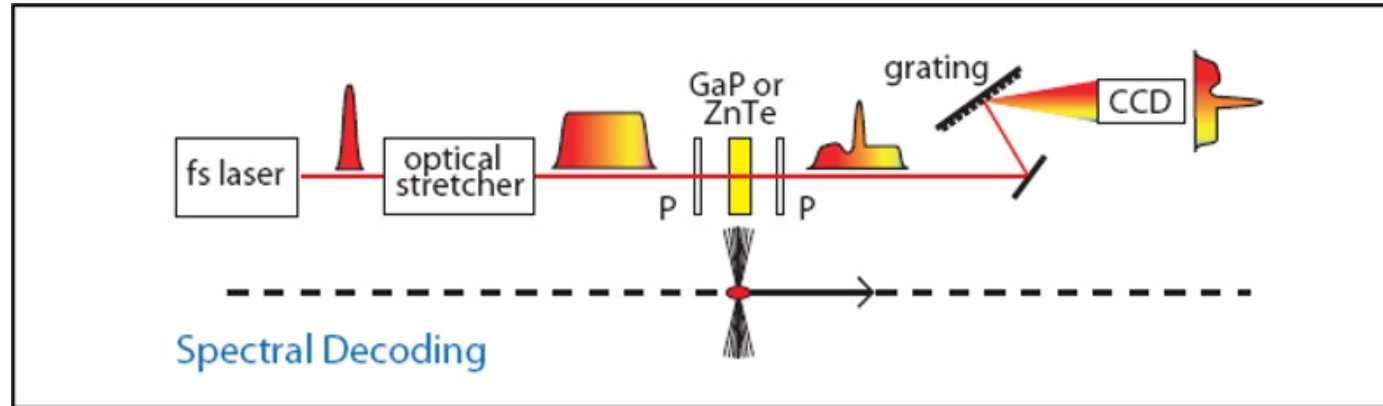
C.P. Welsch et al., Journal of Instrumentation 1 P09002 (2006)

A.E.Dabrowski et al., Journal of Instrumentation 7 P01005 (2012)



Longitudinal profile of short bunches

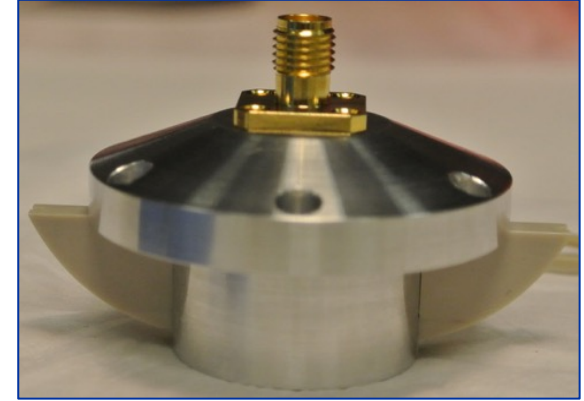
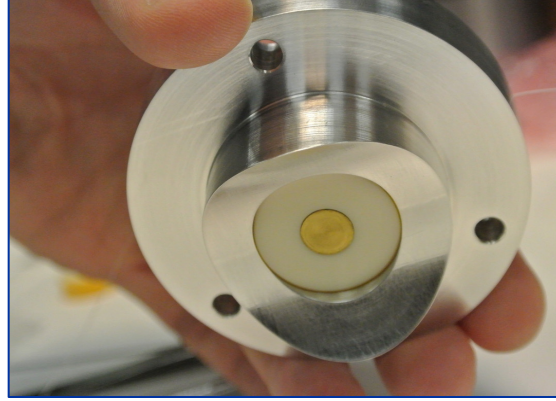
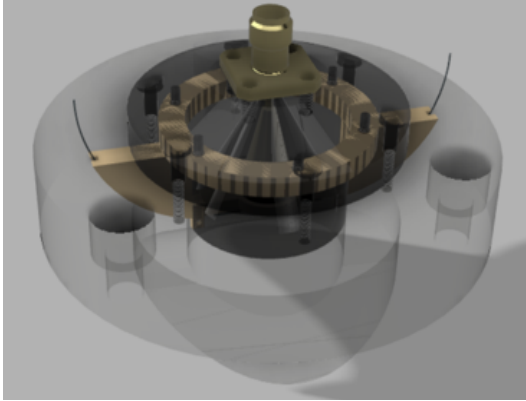
Electro-optical sampling for sub-ps/ps time domain measurement



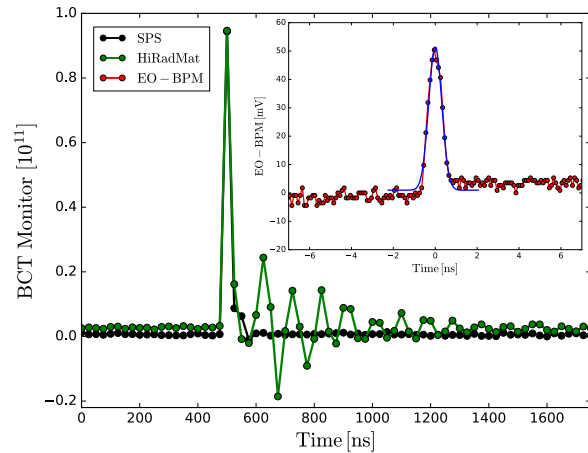
Initiated through CLIC study → FCC study for bunch-by bunch measurement by KIT

Innovative design of electromagnetic pick-ups

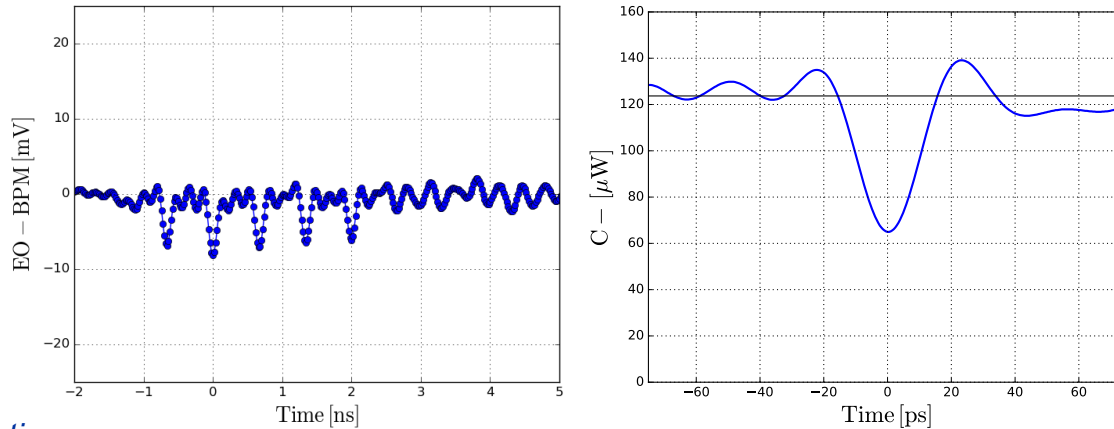
*High bandwidth BPM for HL using **electro-optical pick-up with RHUL***



450GeV protons @ HIRADMAT



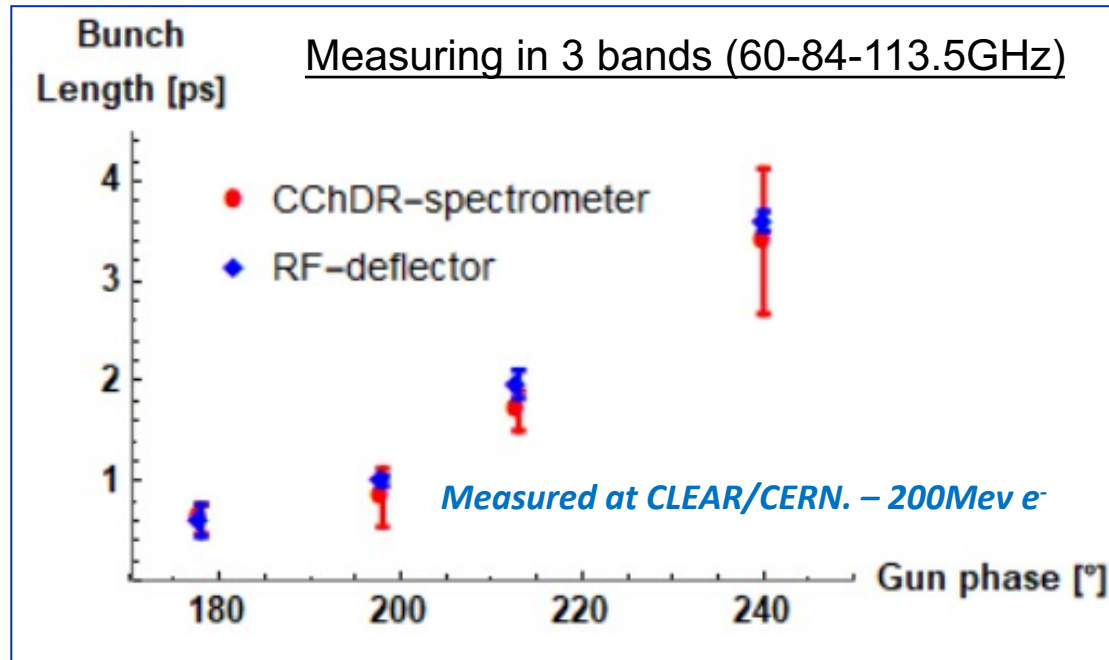
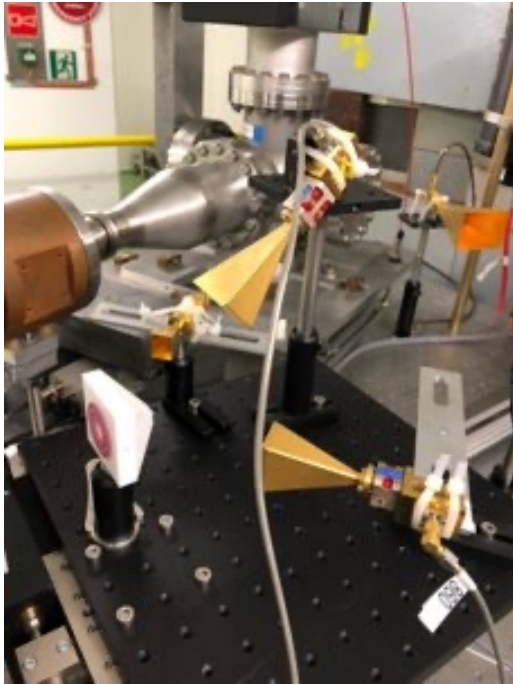
200MeV, ps long electron bunch @ CLEAR



Paper in preparation

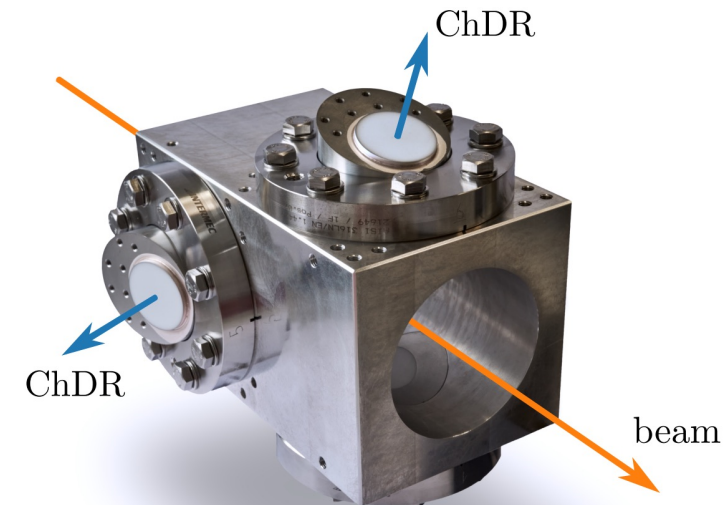
Longitudinal profile of short bunches

Bunch spectrum measurement using **Coherent Cherenkov Diffraction Radiation**



A. Curcio et al, PRAB 23 022802 (2020)

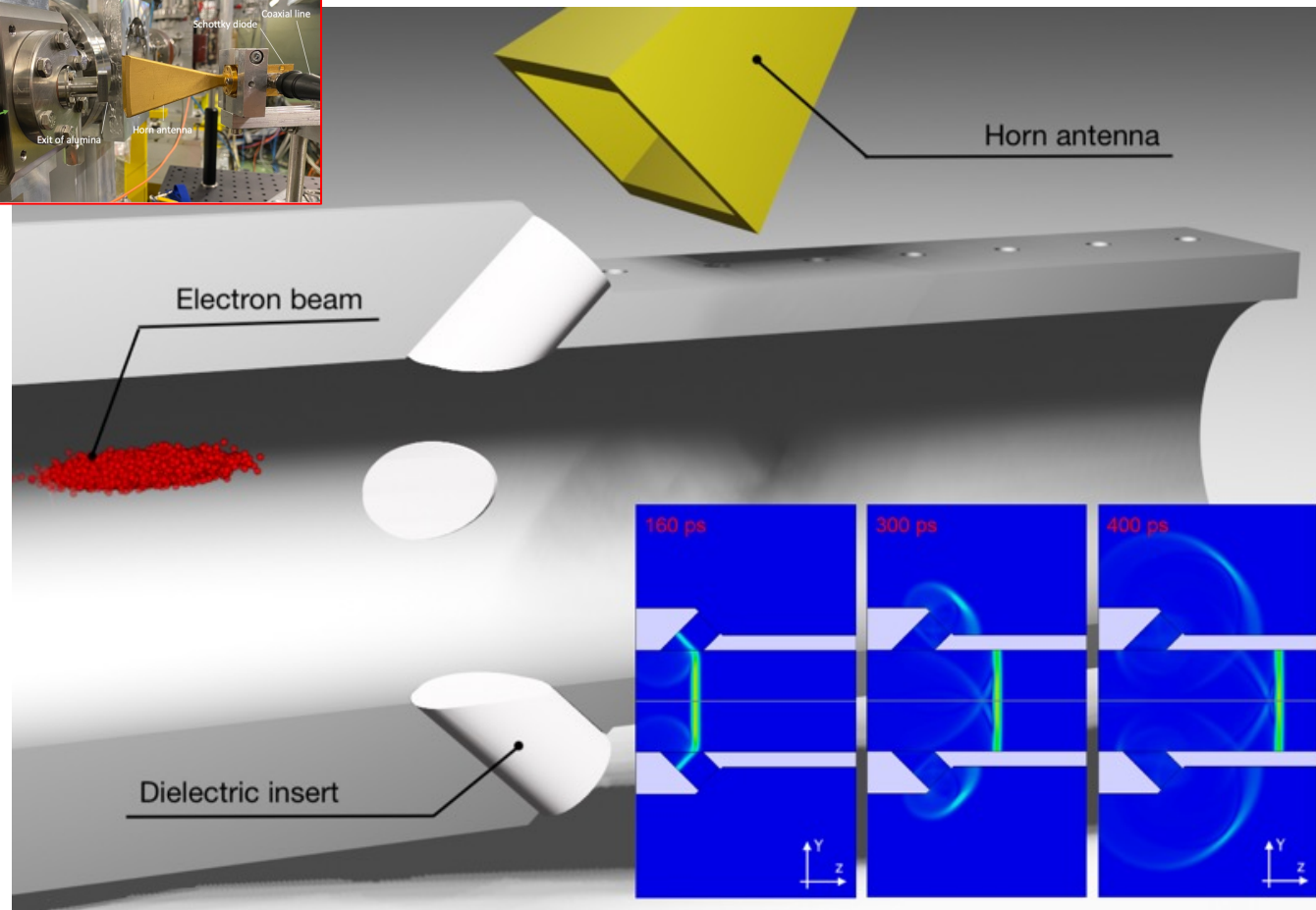
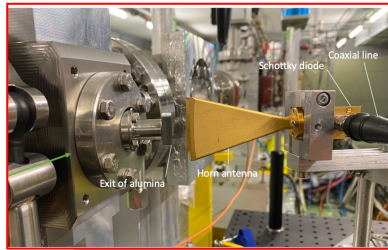
A. Curcio et al, Phys Letters A 391 127235 (2021)



Bandwidth > 1GHz
designed for LHC/SPS

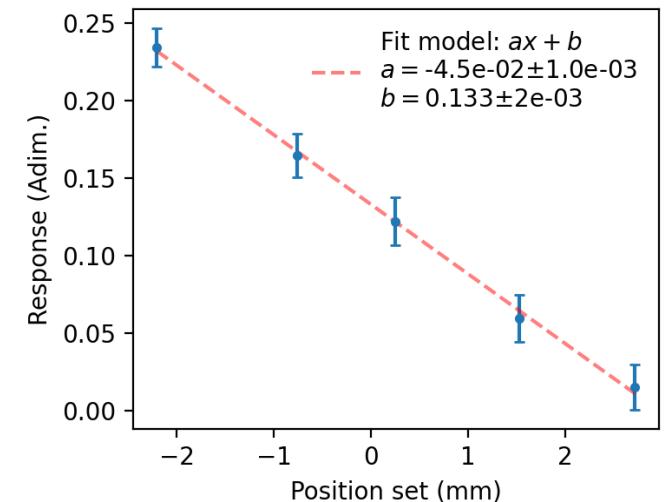
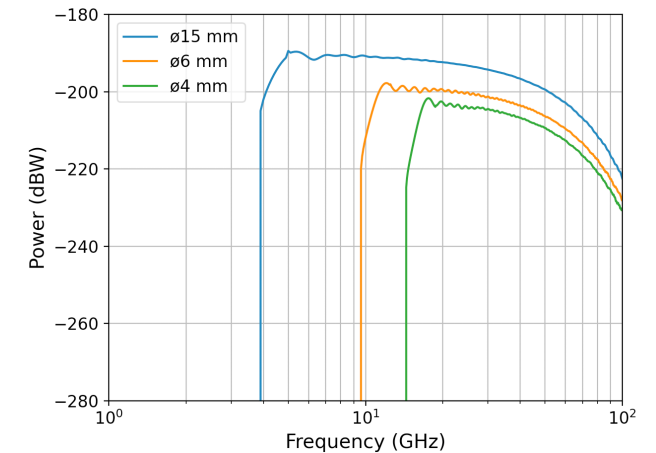
Innovative design of electromagnetic pick-ups

High frequencies BPM using dielectric pick-up with RHUL



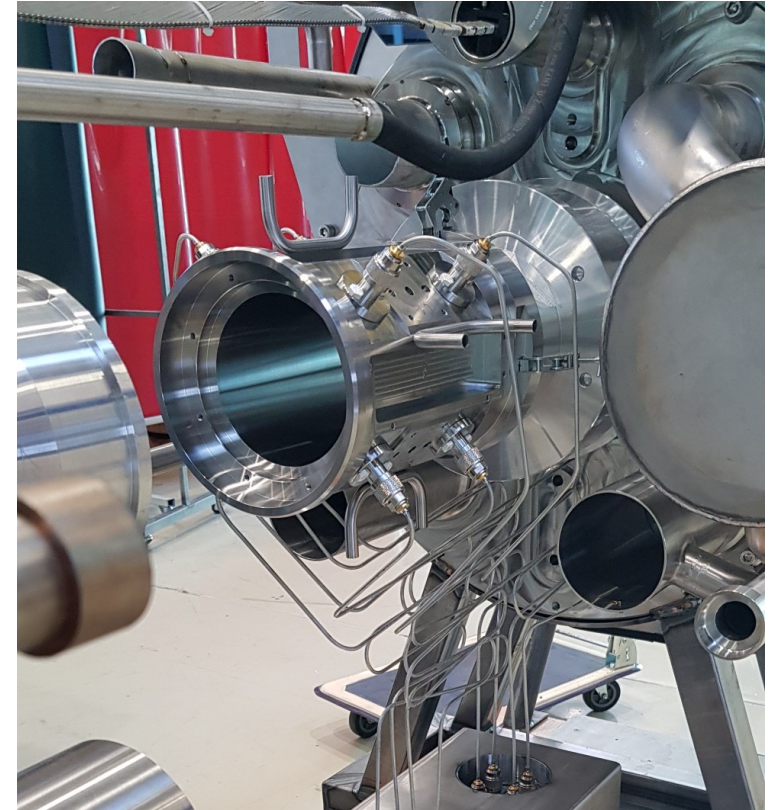
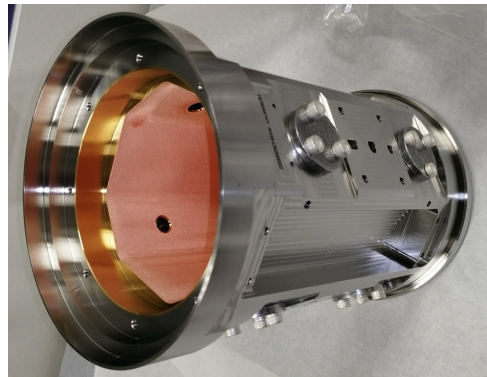
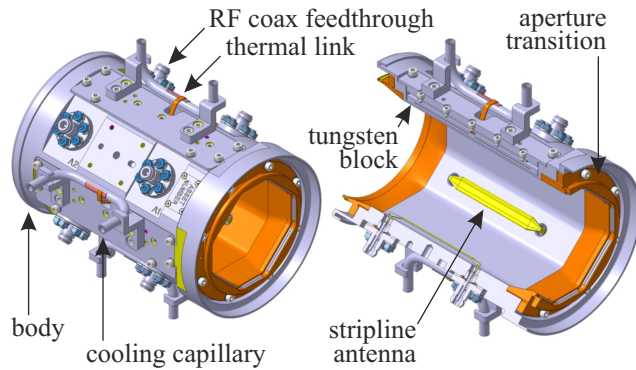
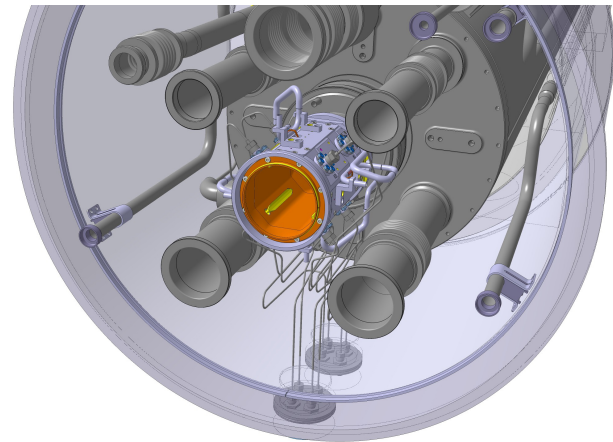
Paper submitted to PRX in Aug. 2023

For electrons @ aWAKE
in presence of Protons



Innovative design of electromagnetic pick-ups

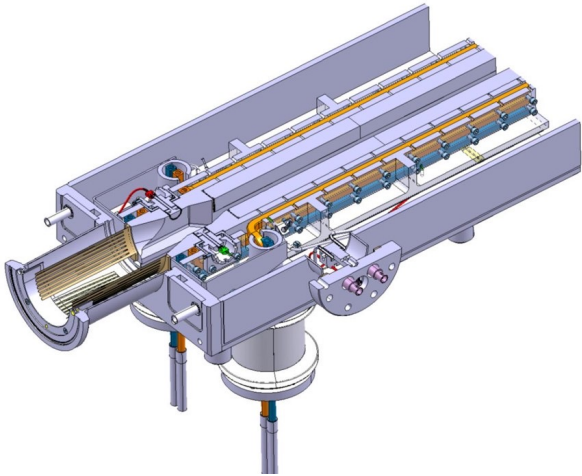
High directivity cryogenic stripline BPM for HL-LHC



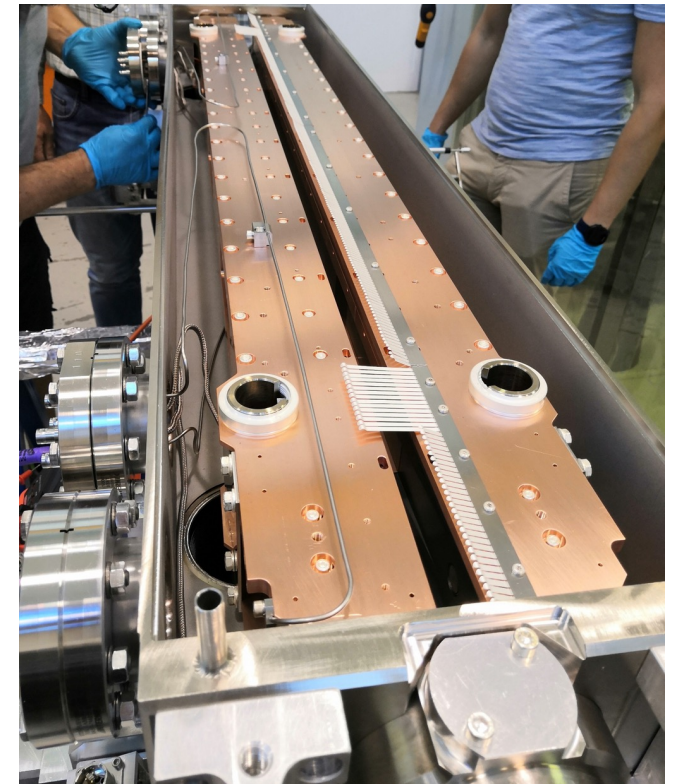
Innovative design of electromagnetic pick-ups

LHC Collimator BPMs

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



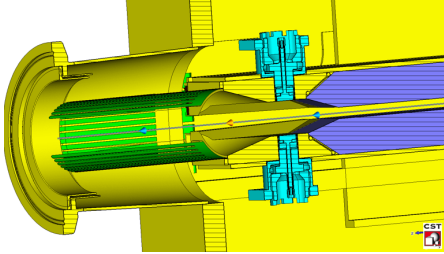
- Should be compatible with UHV conditions and 250C bake-out
- Should withstand high radiation dose (~20 MGy TID)
- Should reach and position accuracy better than 20um with micron resolution



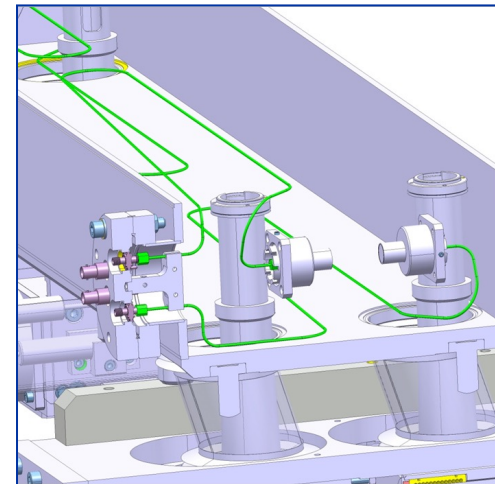
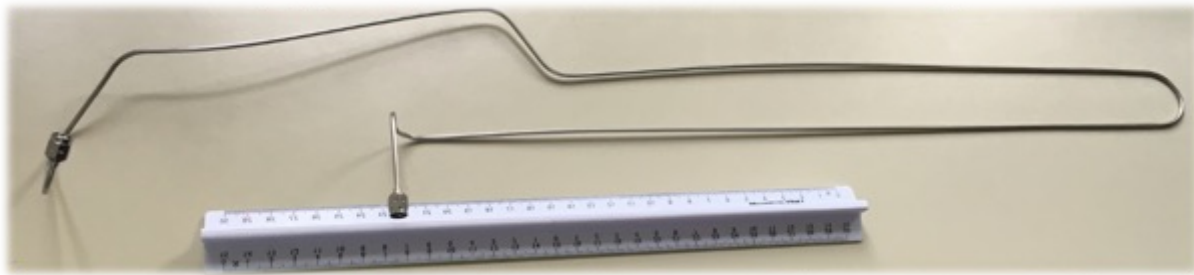
Innovative design of electromagnetic pick-ups

LHC Collimator BPMs

- Electrostatic Buttons

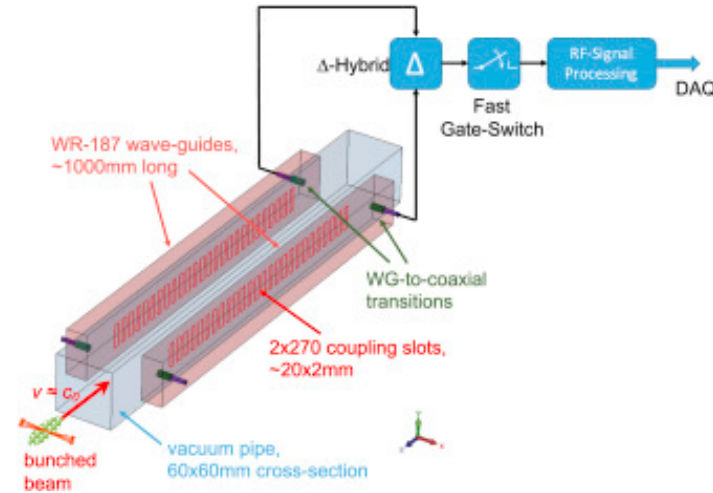


- SiO2 cables to route the cable outside of vacuum
rad-hard, outgassing rate $<1\text{e-}9$ mbar· l/s



BPMs in jaws become a standard for collimation

High sensitivity Schottky monitoring – DC and Short bunches



Long history of CERN contributions in shot noise, schottky signals and stochastic cooling

LHC – high intensities bunches

K. Lasocha et al, PRAB 23 (2020) 062903

K. Lasocha et al, PRAB 25 (2022) 062801

Collab. with ABP, N. Mounet and C. Lannoy Ph.D

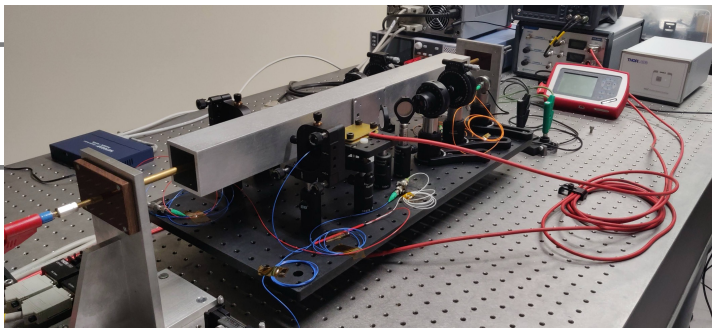
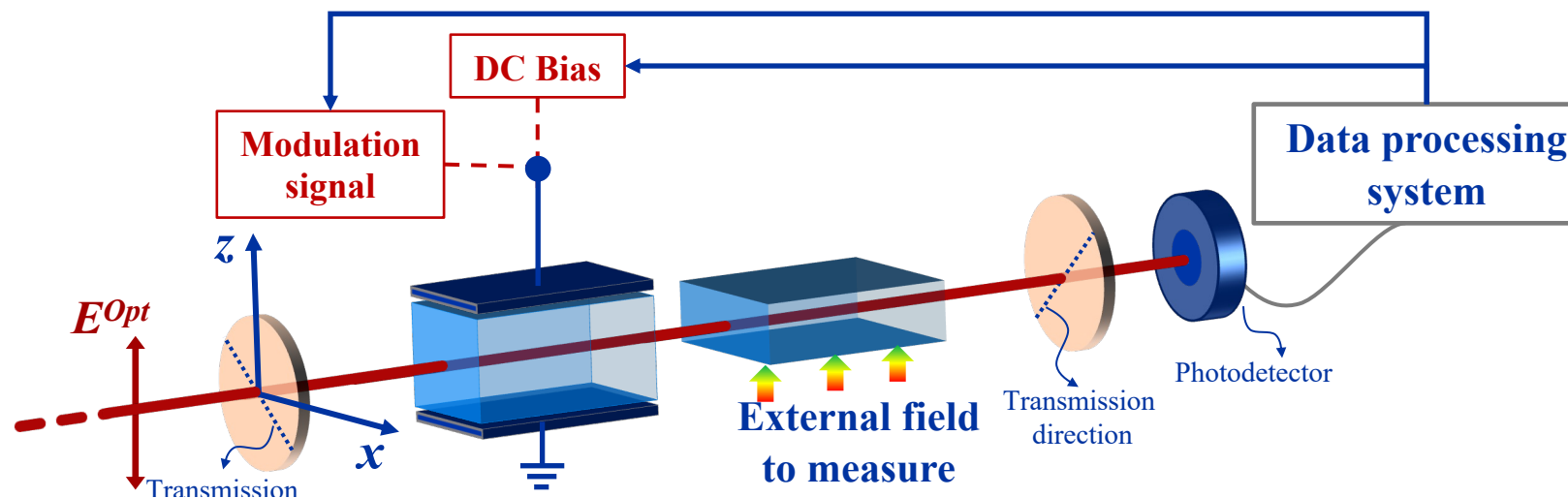
M. Betz et al., NIMA 874 (2017) 113
LHC Schottky for high bunch intensities

Beam position for DC beams using shot noise

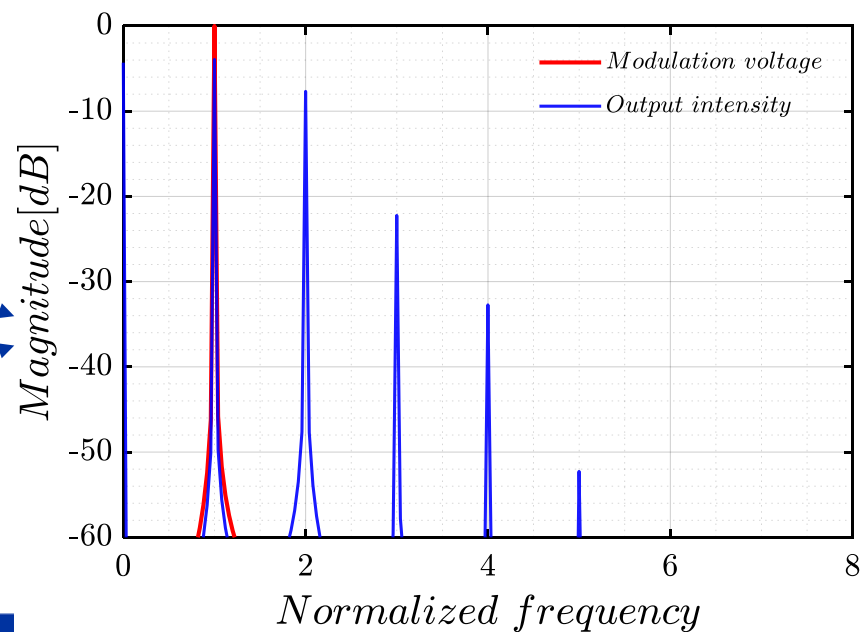
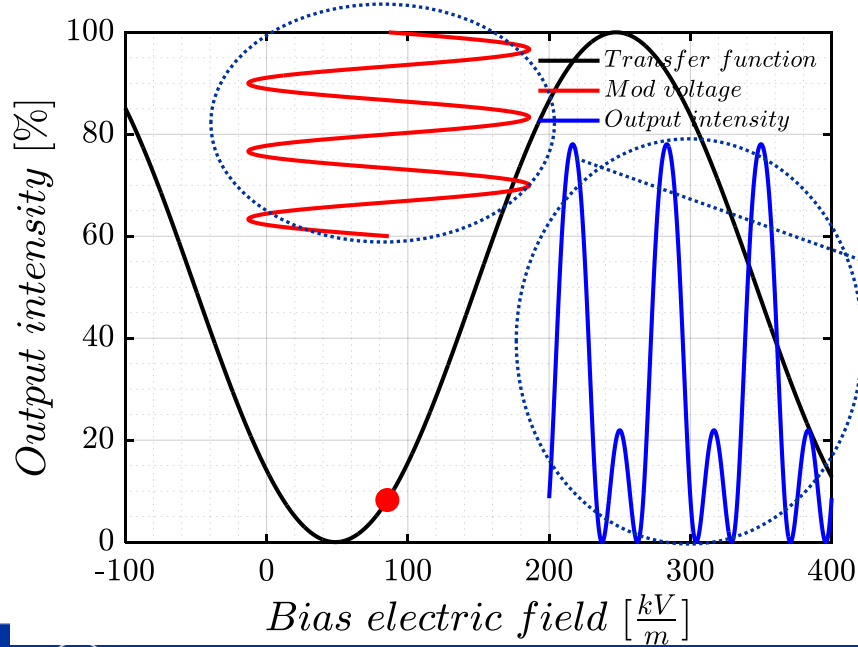
– O. Marquversen, M. Gasior and D. Alves

<https://indico.cern.ch/event/1220800/>

DC beam monitoring – beam position using EO crystal



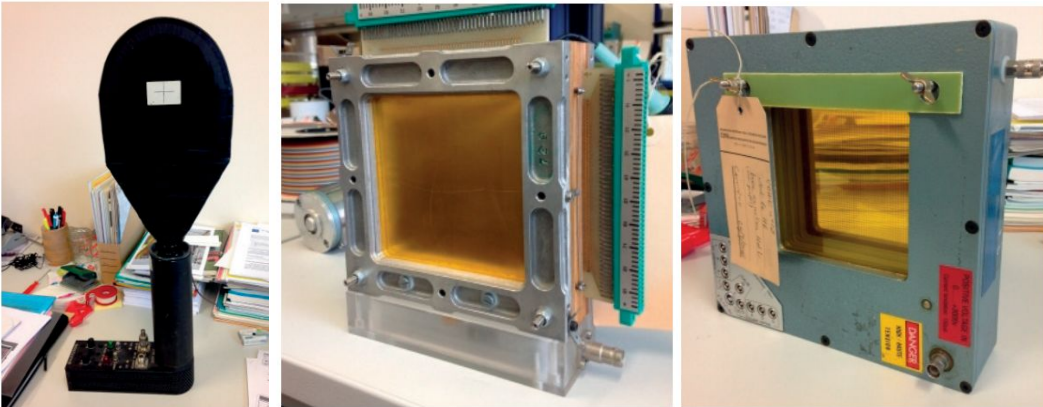
A. Cristiano et al., Appl. Sci. 12(17) 2022, 8544
funded by PBC,



Secondary beams from fixed target

The Past

- Scintillator paddles
- Multi-Wire Proportional Chambers (MWPC)
- Delay Wire Chambers (DWC)
- Filament Scintillators (FISC)



Today ... The Future

Scintillating fibers array

- Plastic fiber (not rad-hard)
- Gas/liquid filled capillary tube

Cherenkov optical fibers array



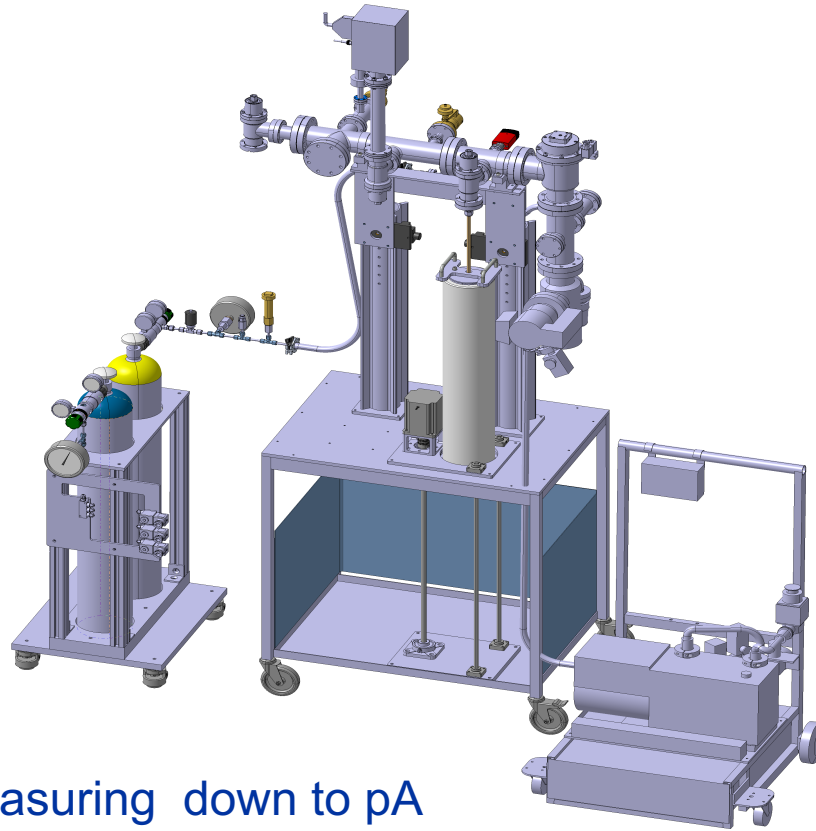
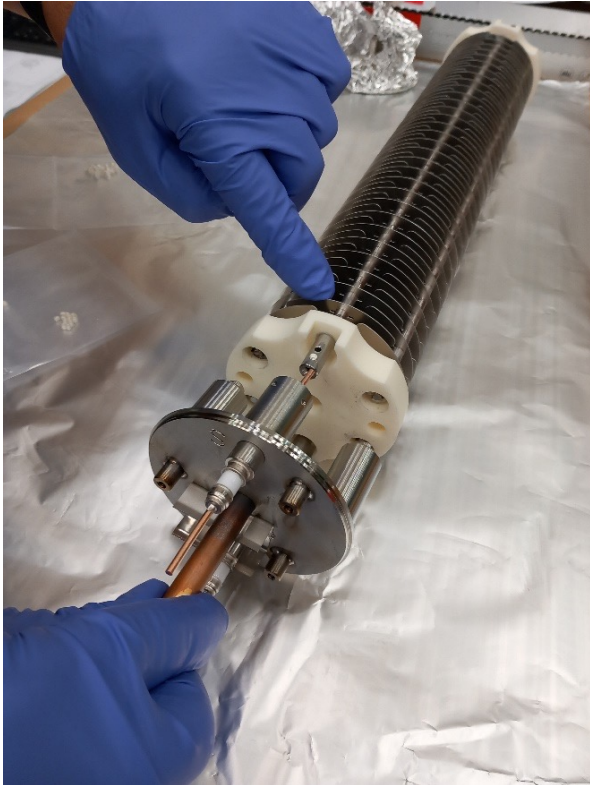
XBPF



Hollow core fiber

Particle detectors for Beam Loss Monitoring

High sensitivity Ionisation chamber

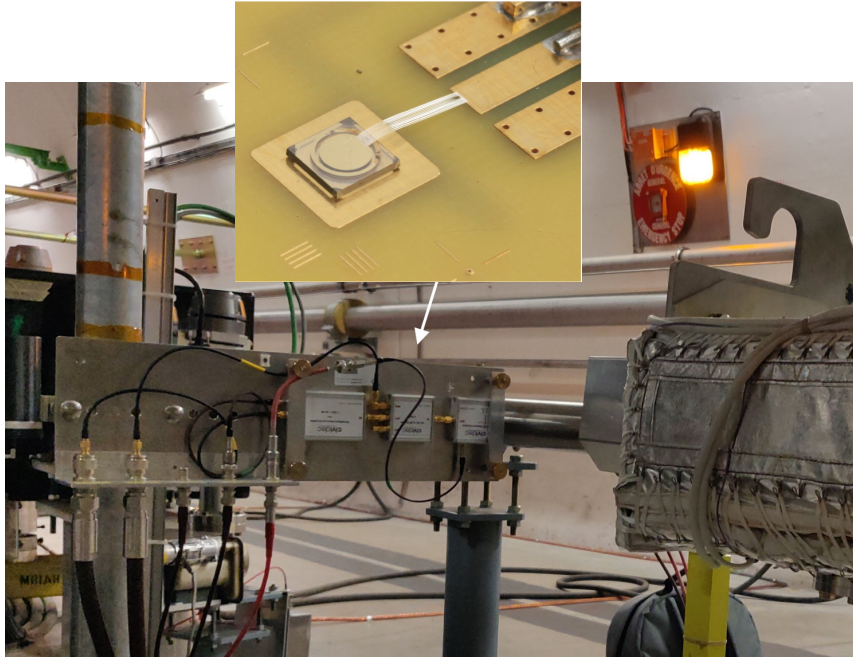


Monitors also produced for
ESS and FRIB

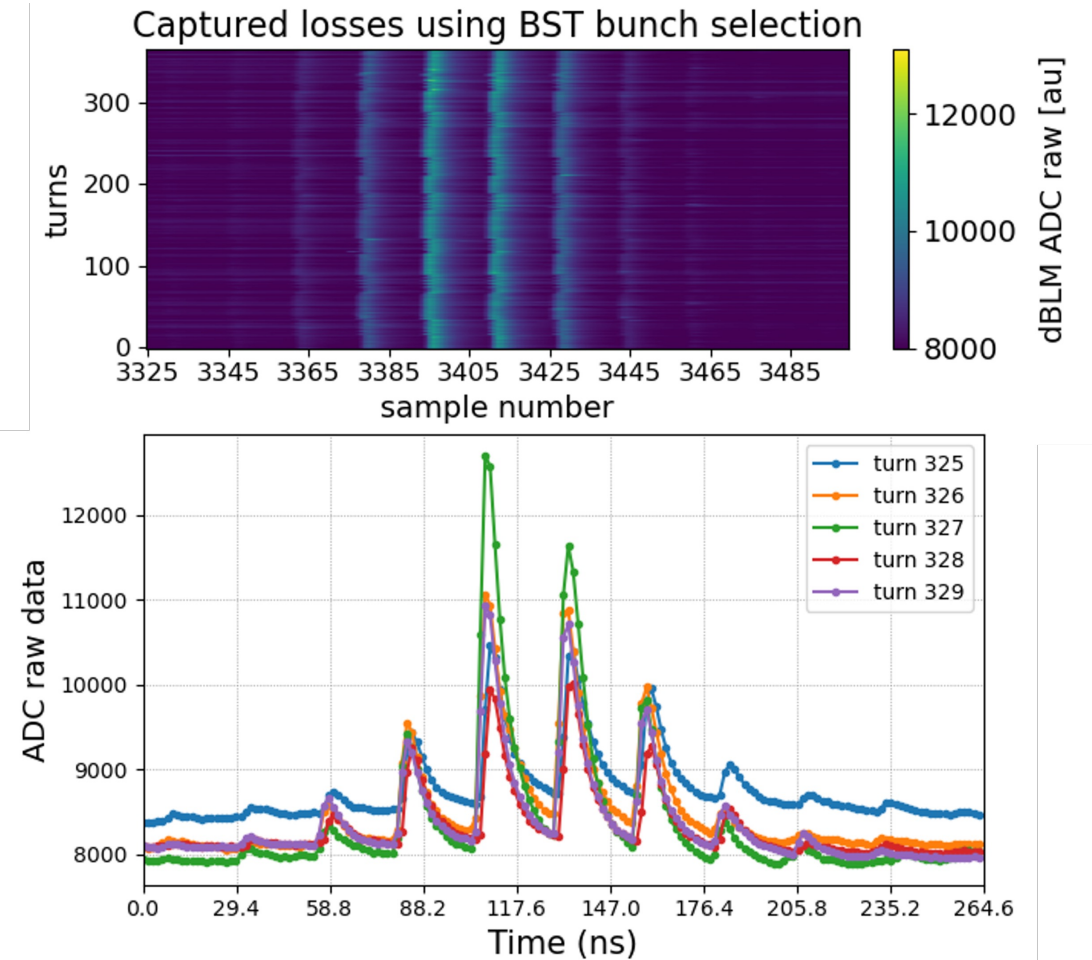
Measuring down to pA

Particle detectors for Beam Loss Monitoring

Semiconductor as fast BLM



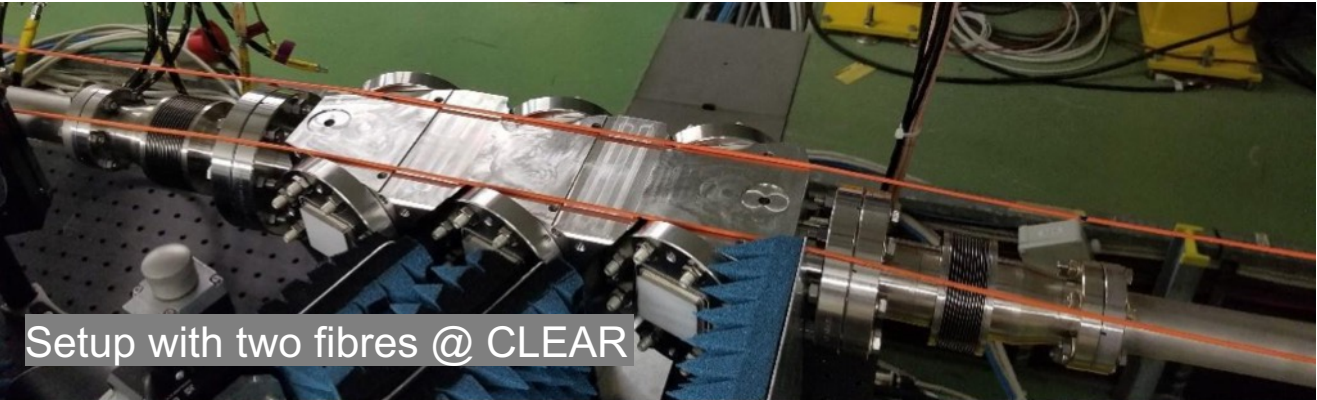
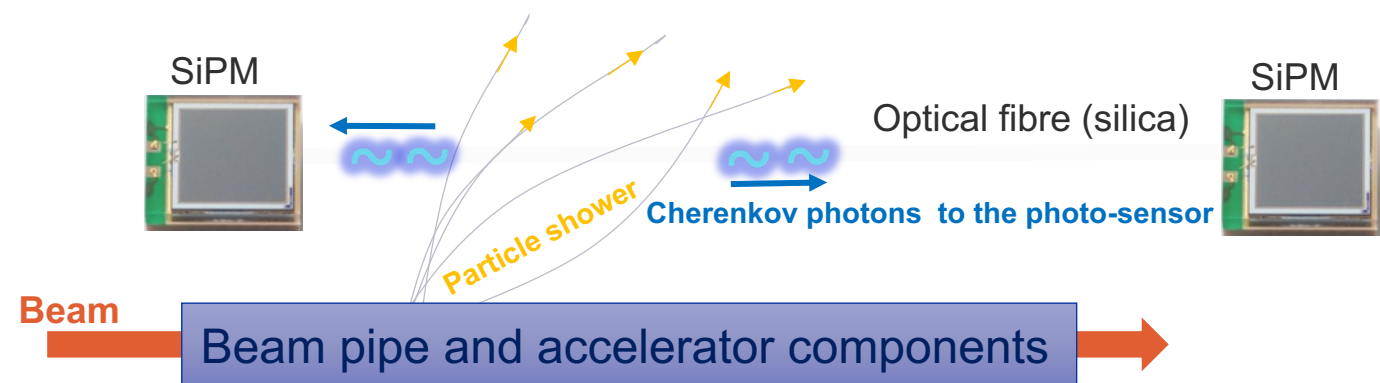
- Diamond sensor today
- Timepix-based BLM under study



E. Calvo et al., IBIC 2022 pp202

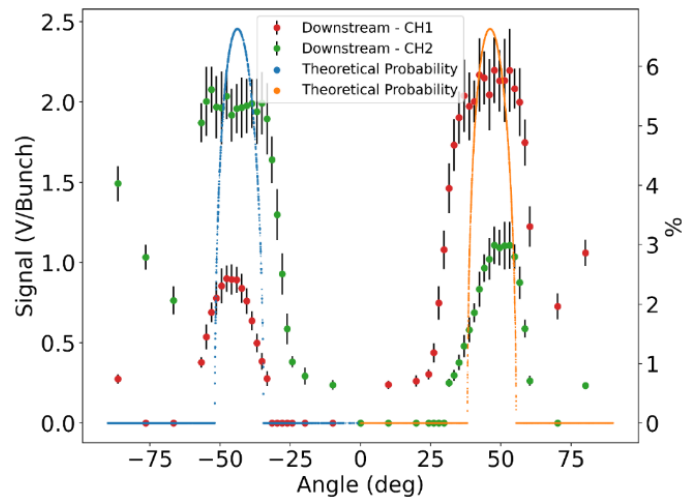
Particle detectors for Beam Loss Monitoring

Cherenkov in optical fiber as continuous BLM

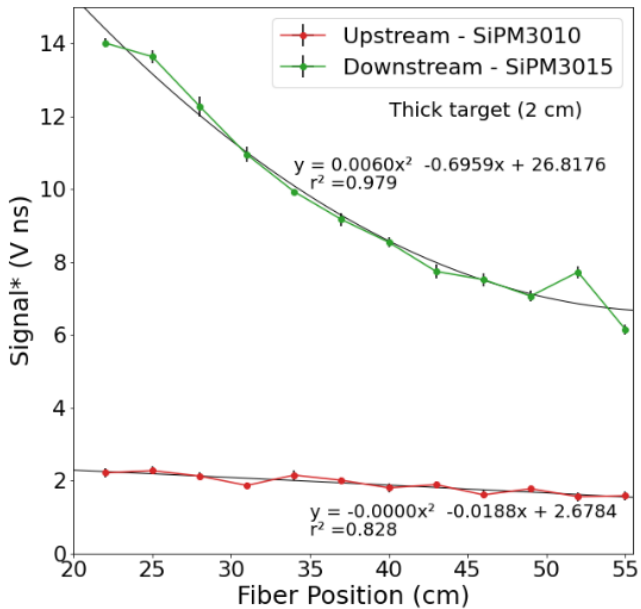


Paper submitted to PRAB in sep 2023
CLIC → NACONS → FCCee

Capture angle



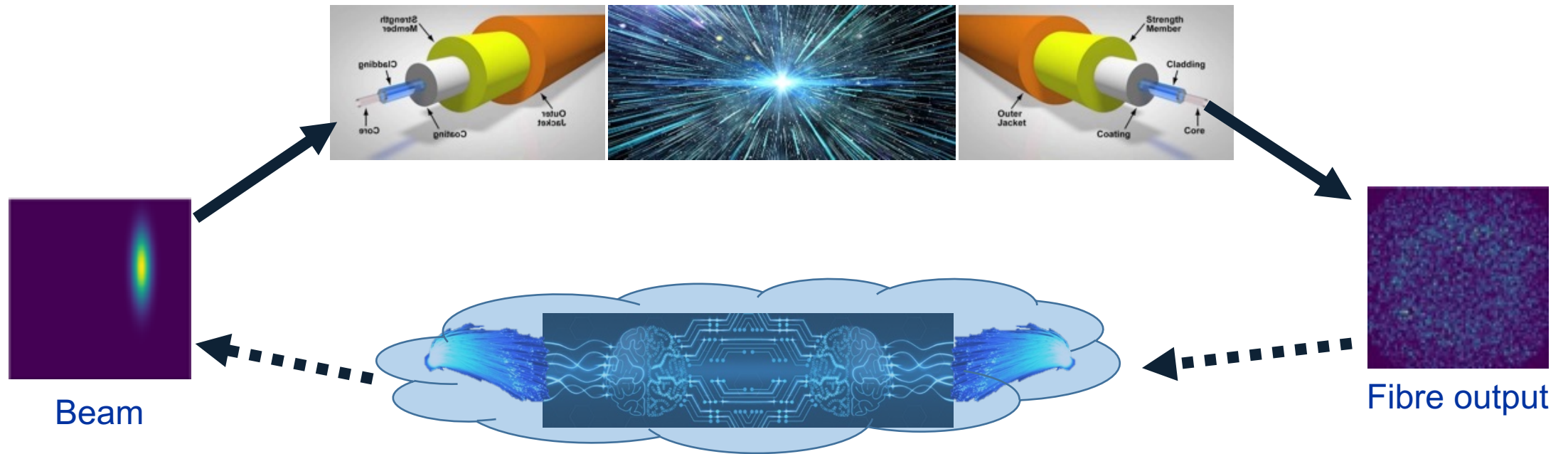
Dependence with fibre distance



R&D on Imaging system using Machine learning

An image will not be preserved at the exit of one fiber

Can it be recovered ?

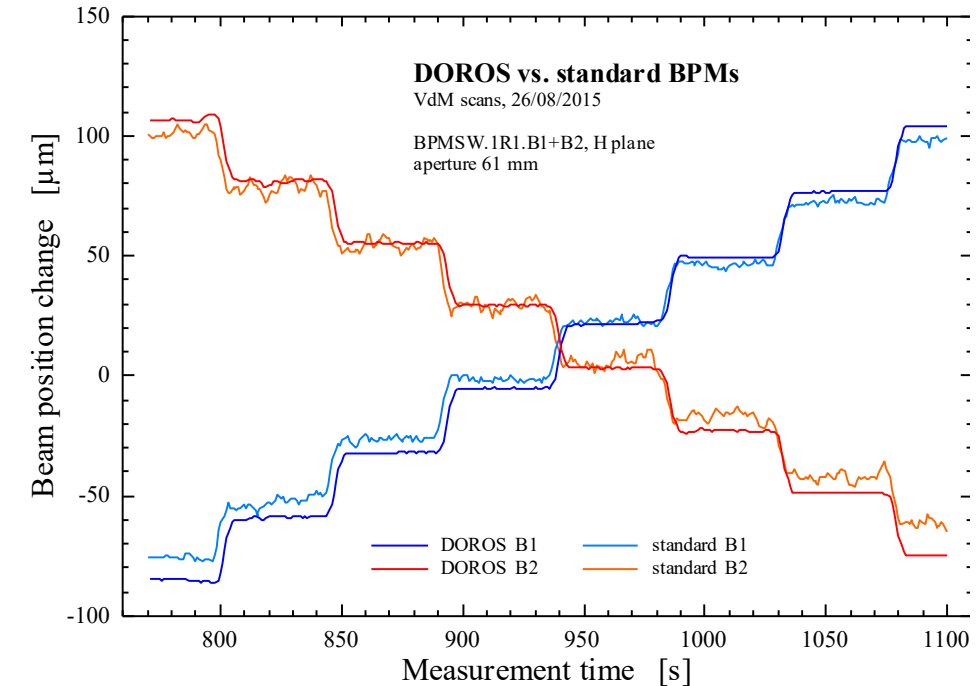
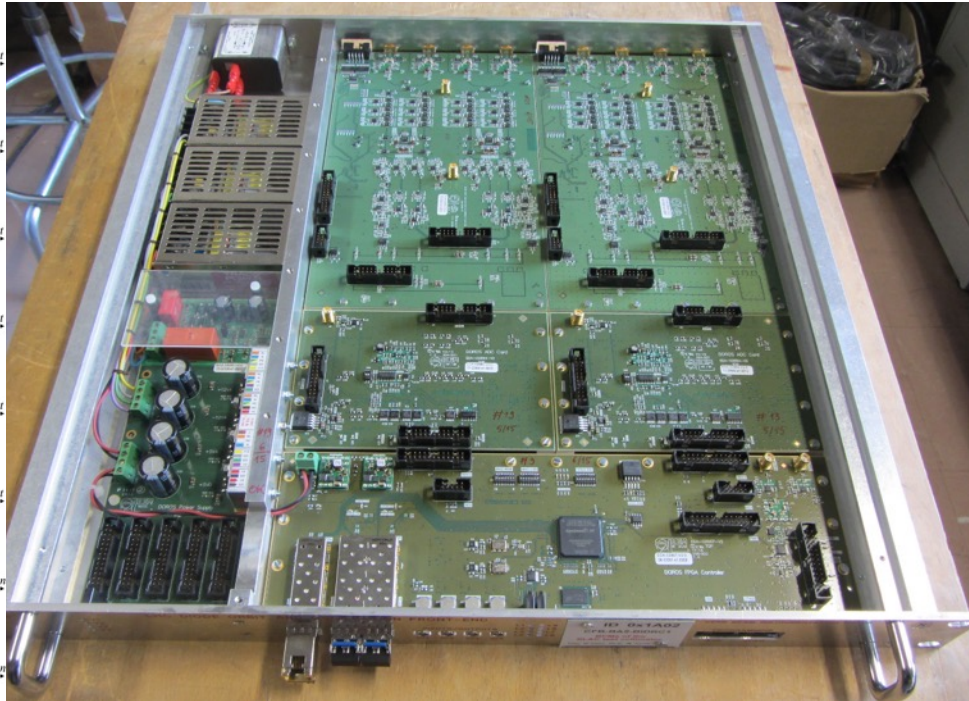
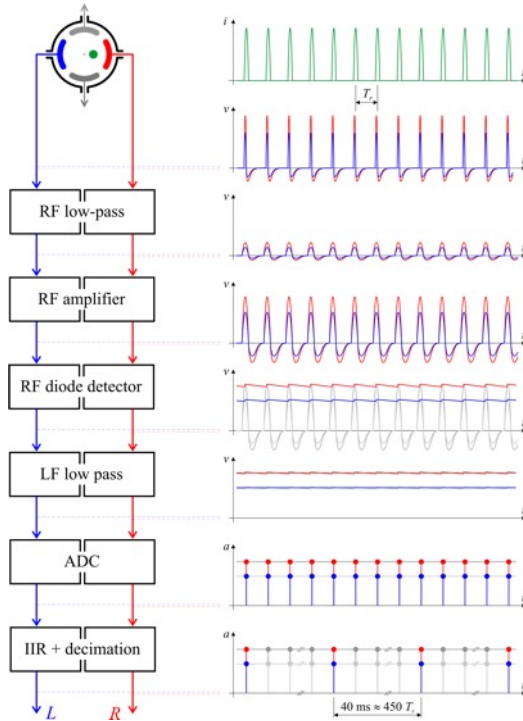


Applying Machine learning algorithms to beam imaging technology

Development of state-of-the-art electronic and DAQ

High resolution measurements for tune and collimator BPM based on diode detection

Diode ORbit and Oscillation electronic (DOROS)

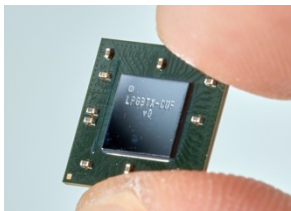
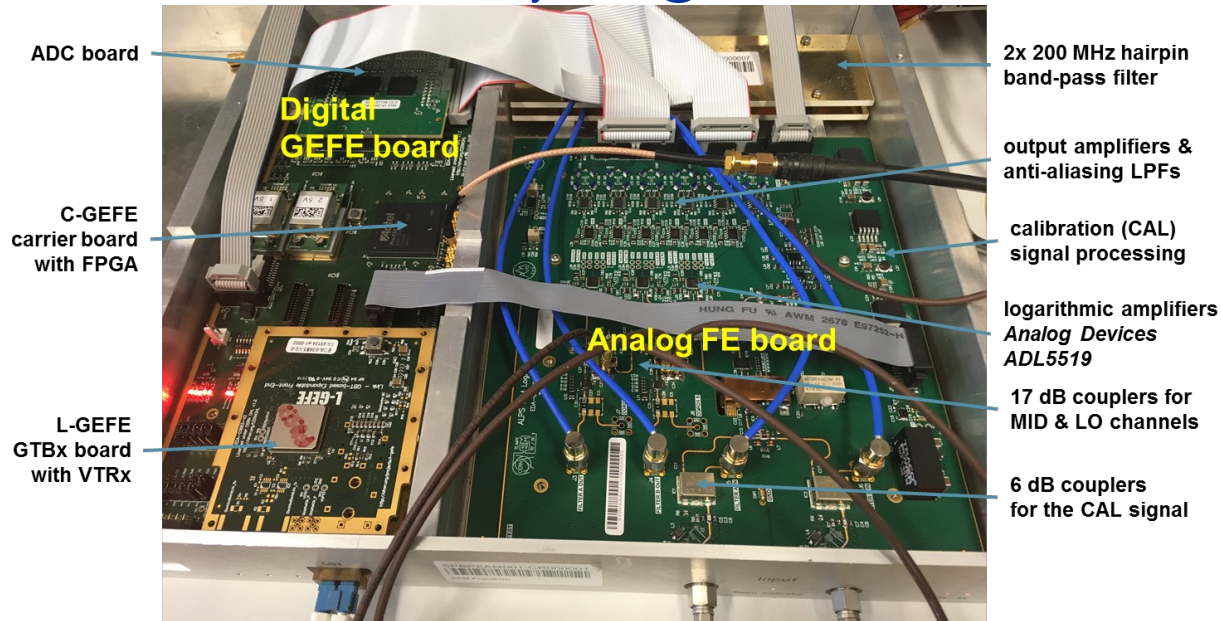


Resolution measured at 100nm for BPM, ~10nm for tune monitors – FCup AWARD to Marek Gasior

Development of state-of-the-art electronic and DAQ

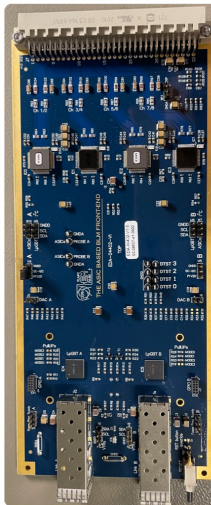
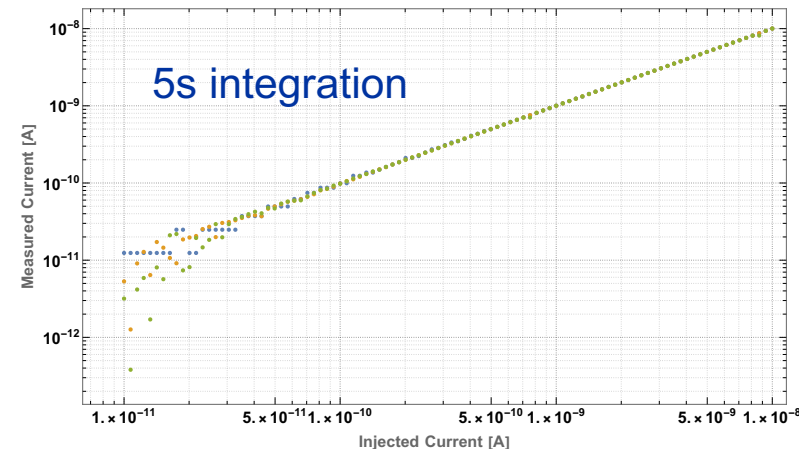
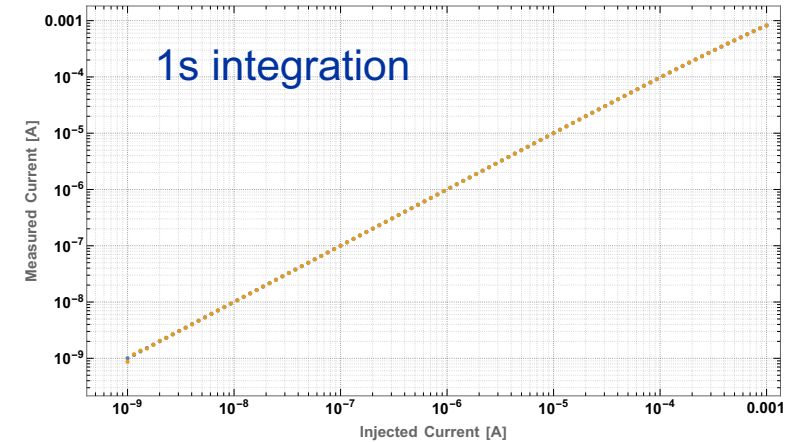
Rad-tol / Rad-hard Front-Ends with EP-ESE

New BPM system @ SPS



M. Barros marin et al, Journal of Instrumentation, vol.11 C02062 (2016)

HL BLM ASIC performance – 10^9 dynamic range



Development of state-of-the-art electronic and DAQ

Standardising read-out platform – performed via LIU project



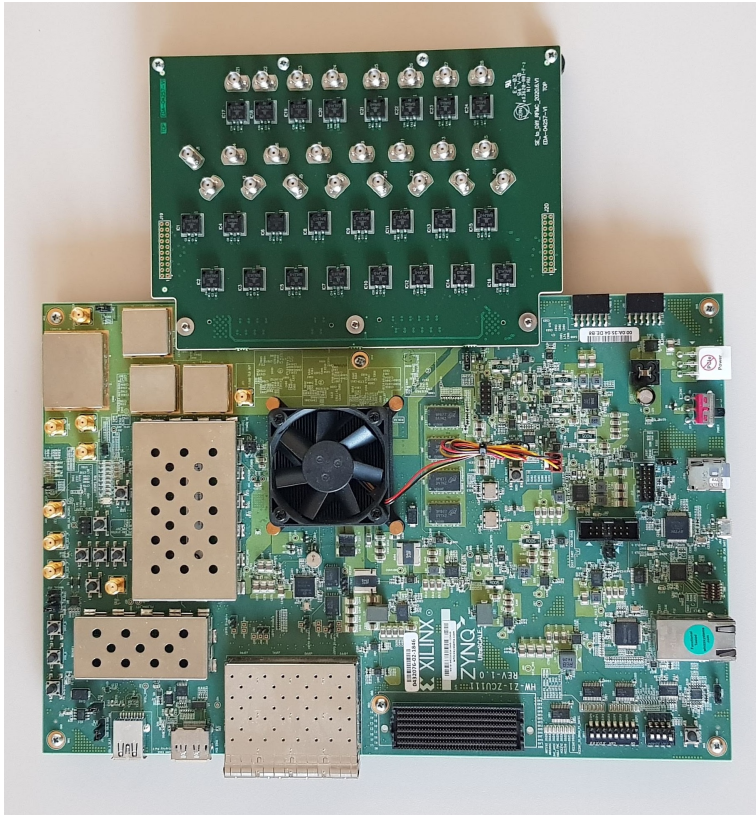
- Wire scanners for all machines
- Fast BCTs for all machines (if included future consolidation for PS complex)
- BLM for all machines
- BPM for SPS and PS-to-SPS TLs
- LHC luminosity monitors

New platform for HL/CONS based on SoM

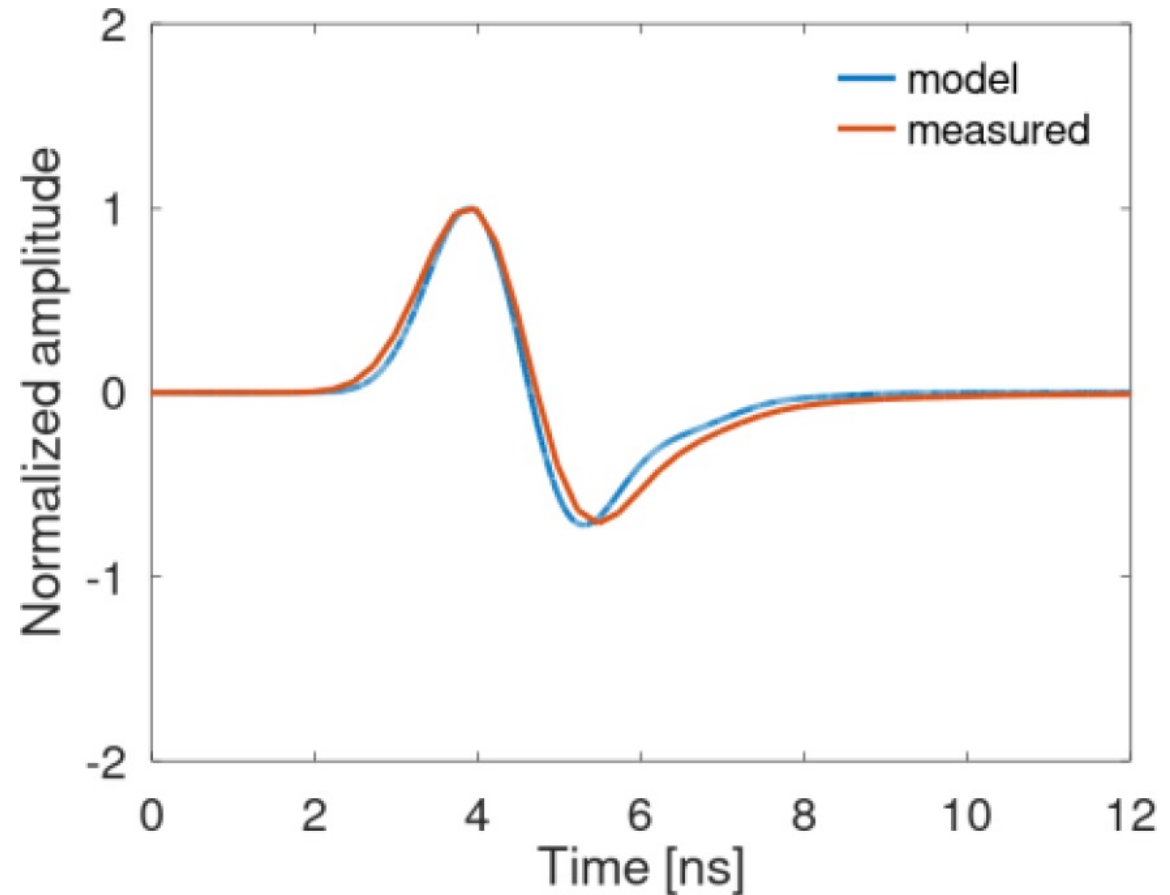
A. Boccardi et al, Journal of Instrumentation, vol.8 C03006 (2013)

Development of state-of-the-art electronic and DAQ

RF System-on-Chip as fast DAQ in the multi GSa/s – developed for HL IP BPMs



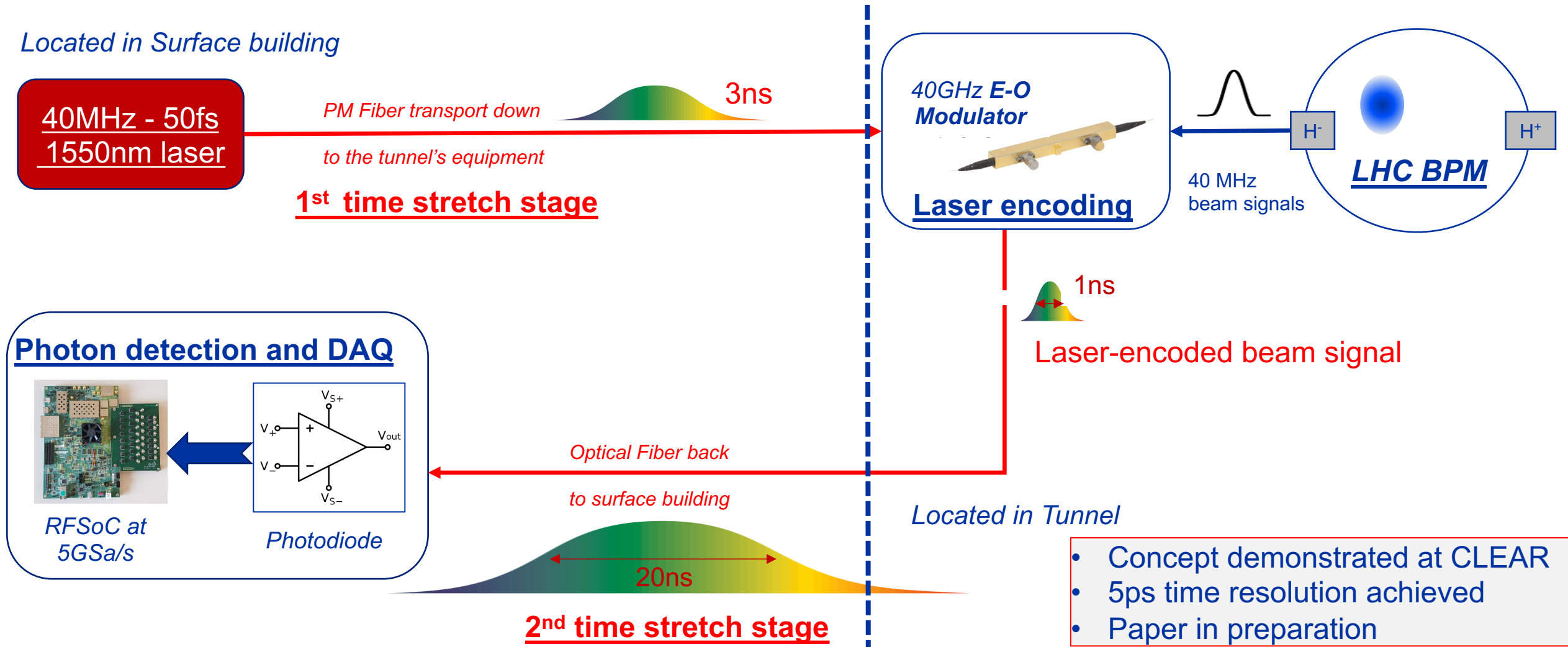
IPAC presentation - Paper in preparation



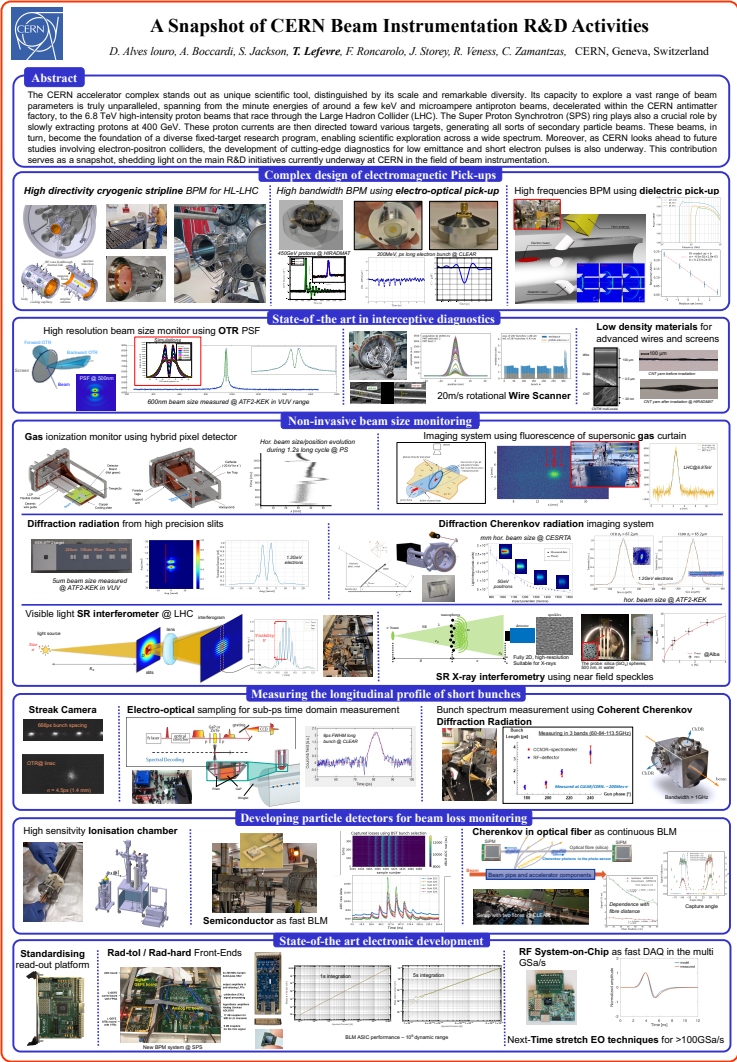
New platform for HL/CONS based on SoM

Development of state-of-the-art electronic and DAQ

Electro-optical time-stretch acquisition system with $>40\text{GHz}$ and $>100\text{GSa/s}$



Poster at IBIC 2023



A SNAPSHOT OF CERN BEAM INSTRUMENTATION R&D ACTIVITIES

T. Lefevre*, A. Boccardi, S. Jackson, D. Louro Alves, F. Roncarolo
J. Storey, R. Veness, C. Zamantzas
CERN, Geneva, Switzerland

Abstract

The CERN accelerator complex stands out as unique scientific tool, distinguished by its scale and remarkable diversity. Its capacity to explore a vast range of beam parameters is truly unparalleled, spanning from the minute energies of around a few keV and microampere antiproton beams, decelerated within the CERN antimatter factory, to the 6.8 TeV high-intensity proton beams that race through the Large Hadron Collider (LHC). The Super Proton Synchrotron (SPS) ring plays also a crucial role by slowly extracting protons at 400 GeV. These proton currents are then directed toward various targets, generating all sorts of secondary particle beams. These beams, in turn, become the foundation of a diverse fixed-target research program, enabling scientific exploration across a wide spectrum. Moreover, as CERN looks ahead to future studies involving electron-positron colliders, the development of cutting-edge diagnostics for low emittance and short electron pulses is also underway. This contribution serves as a snapshot, shedding light on the main R&D initiatives currently underway at CERN in the field of beam instrumentation.

INTRODUCTION

The CERN accelerator complex is a dynamic and continually evolving system. Over a decade ago, an ambitious global initiative was launched to enhance the collision capabilities of the Large Hadron Collider (LHC). This initiative aims to achieve higher collision rates and is executed in phases. The initial phase focused on the LHC Injector Upgrade program [1], which successfully generated higher brightness beams within the CERN injector complex. Building on this achievement, the subsequent stage of the high Luminosity LHC upgrade (HL-LHC) [2] is scheduled for implementation from 2026 to 2028. This phase aims to further elevate beam intensities and reduce emittance, introducing novel challenges to beam instrumentation. These instruments must adapt to unprecedented beam densities while maintaining the highest reliability and precision.

Beyond its contributions to the LHC and its physics endeavors, CERN has embarked on a comprehensive consolidation of the fixed target physics program in the 'North Area' of the Super Proton Synchrotron (SPS). This undertaking necessitates a complete overhaul of the instrumentation employed for extracting continuous beams from the SPS. These beams are subsequently directed towards various targets and experimental zones.

Anticipating the completion of the LHC's scientific program, the scientific community's aspirations encompass the

exploration of $e^- - e^+$ collisions at up to 380 GeV center of mass energies. While the Compact Linear Collider (CLIC) [3] has been under scrutiny for decades, CERN is currently engaged in assessing the feasibility of the 91-kilometer-long Future Circular Collider (FCC). The FCC would initially focus on lepton collisions [4] and potentially accommodate 100 TeV proton collisions in subsequent phases, using the same infrastructure. Although linear and circular colliders differ in their design and implementation, there are notable similarities in terms of beam properties, beam energy, intensity, transverse and longitudinal sizes, as well as the demand for a high level of radiation tolerance within the tunnel. This suggests the prospect of adapting technologies initially developed for CLIC for use in the FCC.

In this paper, we provide a comprehensive overview of the ongoing R&D endeavors at CERN in the realm of beam instrumentation. This encompasses a spectrum of activities, including the design of innovative electromagnetic pick-ups, the refinement of techniques for measuring transverse profiles of high-power density beams, advancements in short longitudinal beam profiling, the optimisation of high dynamic range particle detectors and the latest strides in read-out electronics and digital acquisition systems. By shedding light on these R&D activities, we aim to present the essence of CERN's pursuit of cutting-edge instrumentation techniques.

COMPLEX DESIGN OF ELECTROMAGNETIC PICK-UPS

Within the scope of the HL-LHC program, the demand for large-aperture, high-field quadrupole magnets has surged to compress proton beam sizes during collisions to unprecedentedly minuscule dimensions. This new configuration requires novel cryogenic directional stripline beam position monitors [5], enabling the measurement of counter-propagating beams with a precision surpassing a mere micron. This intricate design encompasses Tungsten alloy inserts, strategically positioned to absorb collision debris and curtail radiation doses to neighboring magnets. Furthermore, these monitors are coated with copper and NEG (Non-Evaporable Getter) coatings, a dual-layer approach that minimizes beam impedance and paves the way for attaining ultra-high vacuum conditions.

Amid recent advancements, beam position monitors (BPMs) with heightened frequency bandwidth have garnered substantial interest. This is not only pertinent to short electron bunches but also to furnish intrabunch monitoring with fast time response for high-intensity proton beams. A range of technologies is presently under exploration, featuring

* thibaut.lefevre@cern.ch

Next Steps

- Provide an Overview of the previous BI R&D achievements
- Provide a Roadmap of BI future R&D activities
 - By Technology
 - By Project
- Provide an updated list of future opportunities
 - For Collaboration
 - For Students (TS and Ph.D) and Graduates

Thanks for your attention



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