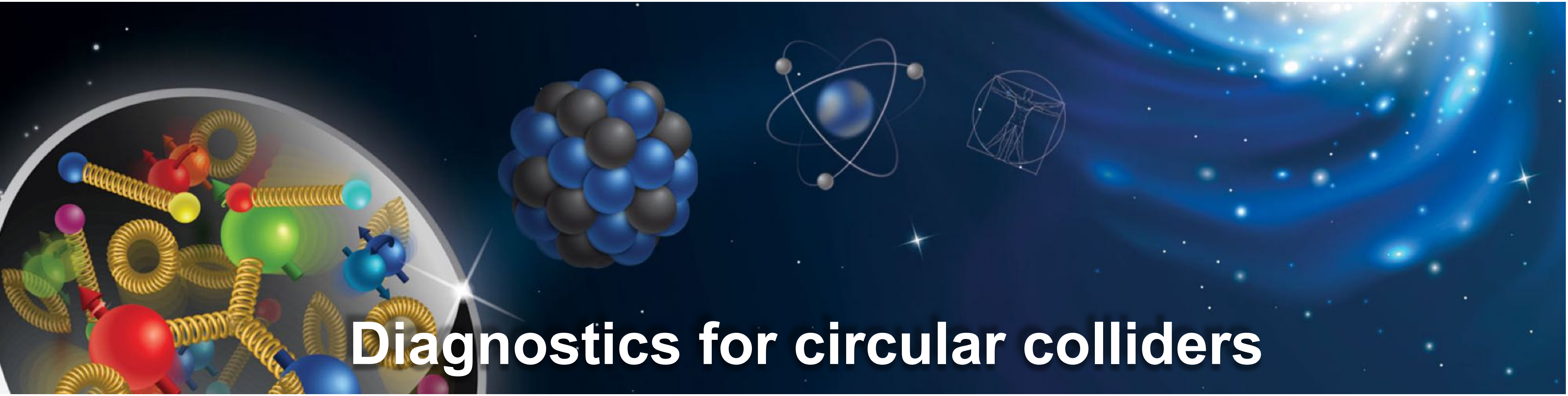


Diagnostics for circular colliders

Stephen Gibson – Royal Holloway

on behalf of JAI & HL-LHC-UK diagnostics team

EIC Workshop –

Promoting Collaboration on the Electron-Ion Collider

9 October 2020

Overview

- ***Brief intro to JAI***
- ***Electron beam diagnostics***
  - ***e- laserwires at ATF2 and DESY***
  - ***Cavity BPMs & fast feedback (see Peter William's talk)***
  - *OTR & Čerenkov diagnostics*
- ***Hadron Beam diagnostics:***
  - ***LHC Injector Upgrade****:*
    - ***Dual H^- laserwire*** *for Linac4, CERN's new injector.*
    - ***Beam Gas Ionisation Profile Monitor*** *at CERN PS.*
  - ***HL-LHC****:*
    - ***Electro-Optical BPMs for crabbed bunches. +*** *IR BPMs*
    - ***Gas-jet Profile Monitor***
    - ***Beam Gas Vertex*** *& Luminosity monitors.*
    - *SR interferometric monitors*

LHC Injectors Upgrade

HiLumi HL-LHC PROJECT

John Adams Institute, UK

"A centre of excellence for advanced and novel accelerator technology, providing expertise, research, development and training in accelerator techniques, and promoting advanced accelerator applications in science and society"

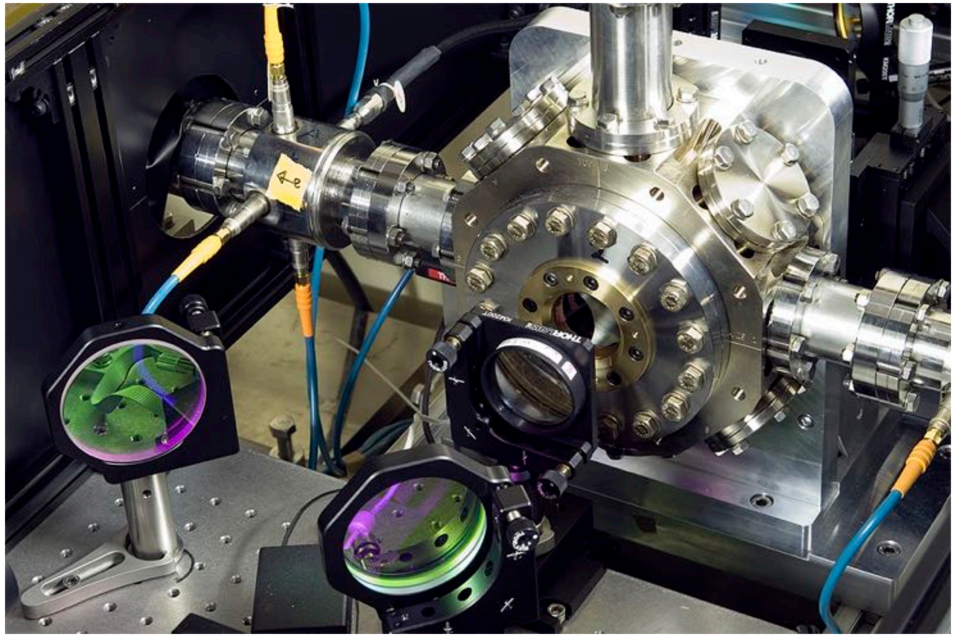
- ***One of two UK national academic centres of excellence in accelerator science, set up 2004.***
  - *20 faculty, 29 staff, 39 PhD students*
- ***Research projects at: CERN, DESY, KEK, Diamond, ISIS …***
  - *HL-LHC, linear & circular e+e-, intense hadrons*
  - *Plasma-based acceleration, medical beamlines*
- ***Expertise includes:***
  - *Beam dynamics, instrumentation, feedback/control:*
  - *Low-latency digital + analogue feedbacks*
  - *High power + bandwidth fast amplifiers*
  - *High-resolution BPMs + signal processing:*
    - *Stripline, cavity & electro-optic BPMs*
    - *Non-invasive transverse beam size diagnostics*
  - *Low-emittance beam transport / tuning…*
- ***Comprehensive PhD training programme.***

Electron Beam Diagnostics

e- laserwires: ATF setup

- Expertise in the development of electron beam laserwires, e.g. first demonstration at ATF in KEK.
- Enables non-interceptive diagnostics of small e⁻ beam profiles by inverse-Compton scattering.

Optics designed to deliver micron-scale focus in vacuum chamber with minimal aberrations:



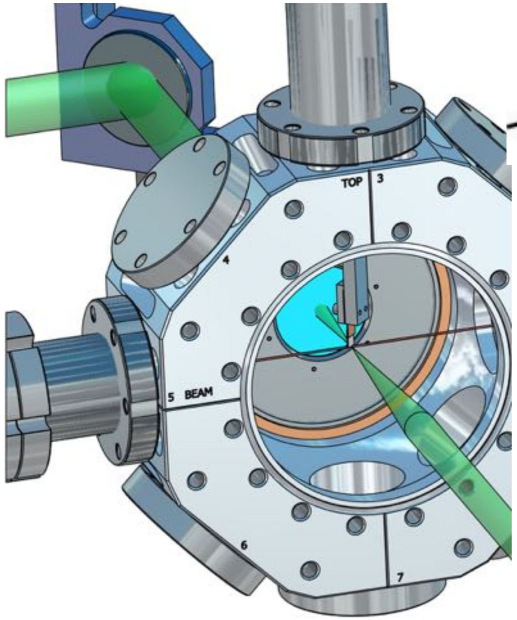
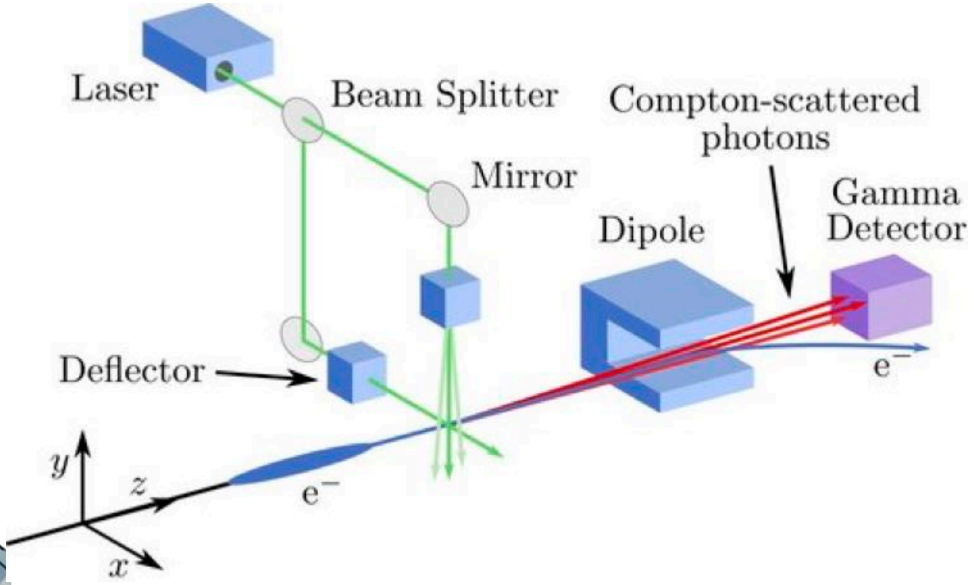


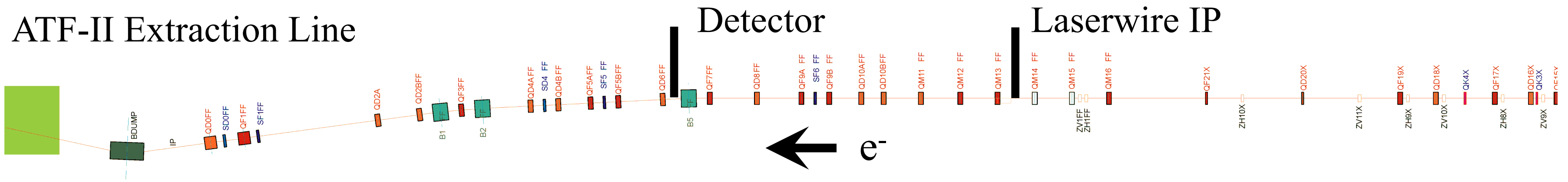
FIG. 10. View of the interaction chamber with the laser exit side flange removed, showing the 45° screen/knife edge.



- S. Boogert et al: Micron-scale laser-wire scanner for the KEK Accelerator Test Facility extraction line PRSTAB 13, 122801 (2010)
- Beam emittance measurement with laser wire scanners in the International Linear Collider beam delivery system PRSTAB 10, 112801 (2007), Issue 11

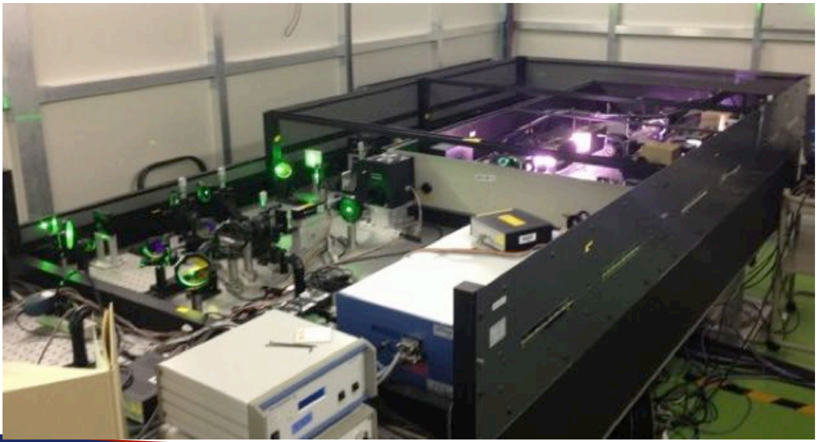
e- laserwires: ATF2 setup

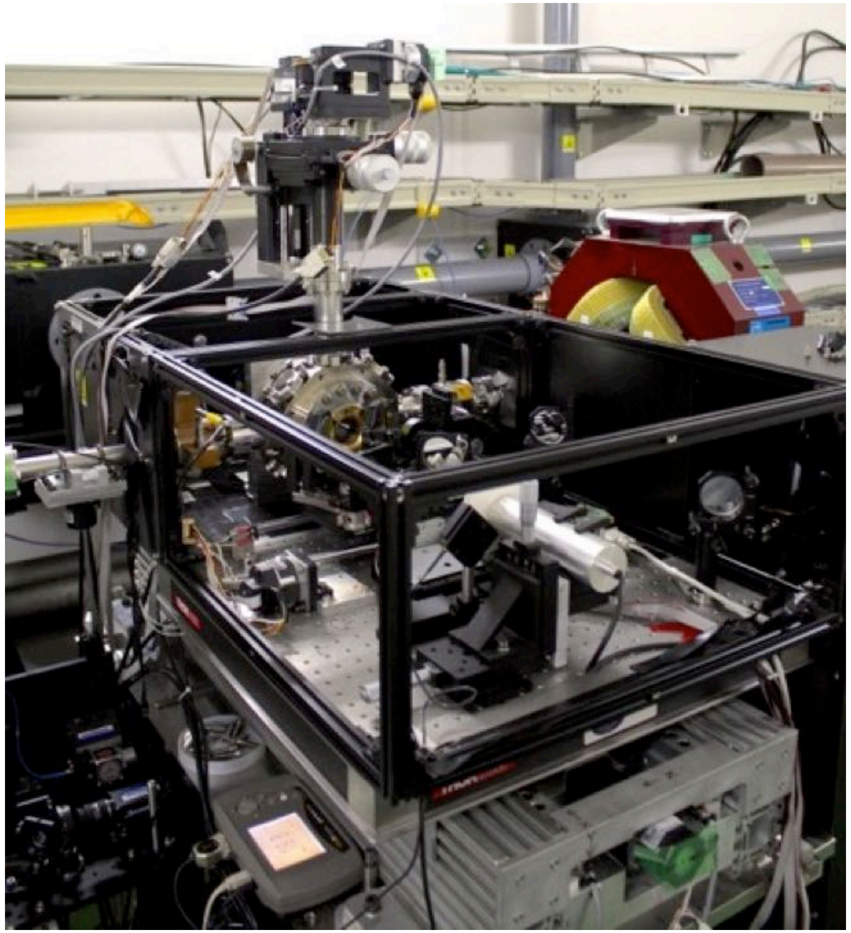
ATF-II Extraction Line

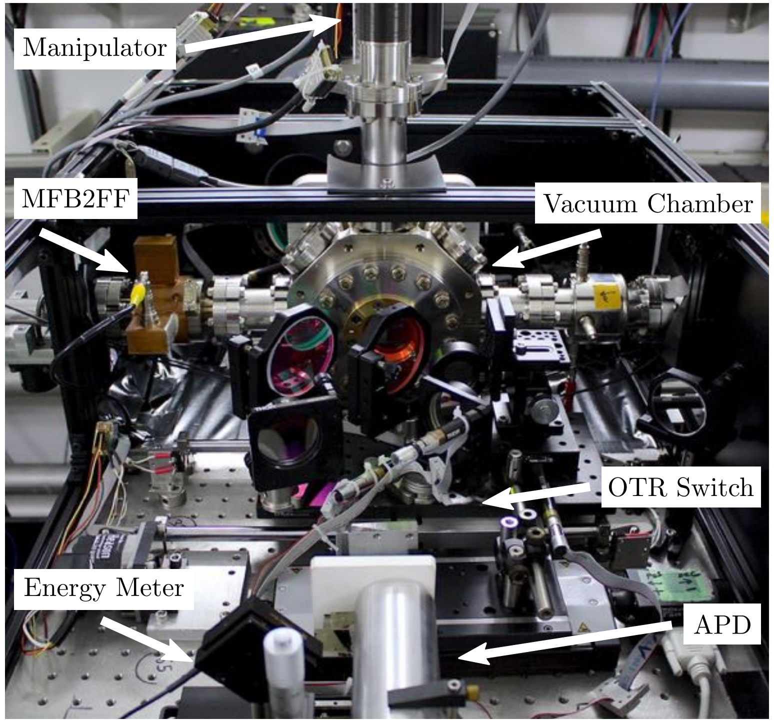


A. Aryshev, S. Boogert L. Corner, D. Howell, P. Karataev, K. Kruchinin, **L. Nevay**, N. Terunuma, J. Urakawa, R. Walczak

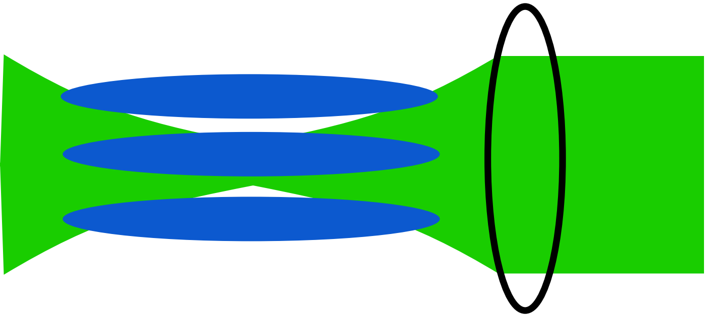
- Goal: Sub-micron resolution laserwire using transmissive optics
- Demonstrate 1μm vertical profile
- Use mode-locked Nd:YAG laser
- 1×10^{10} e^- and ~2GW peak power
- Cherenkov detector for γ-rays

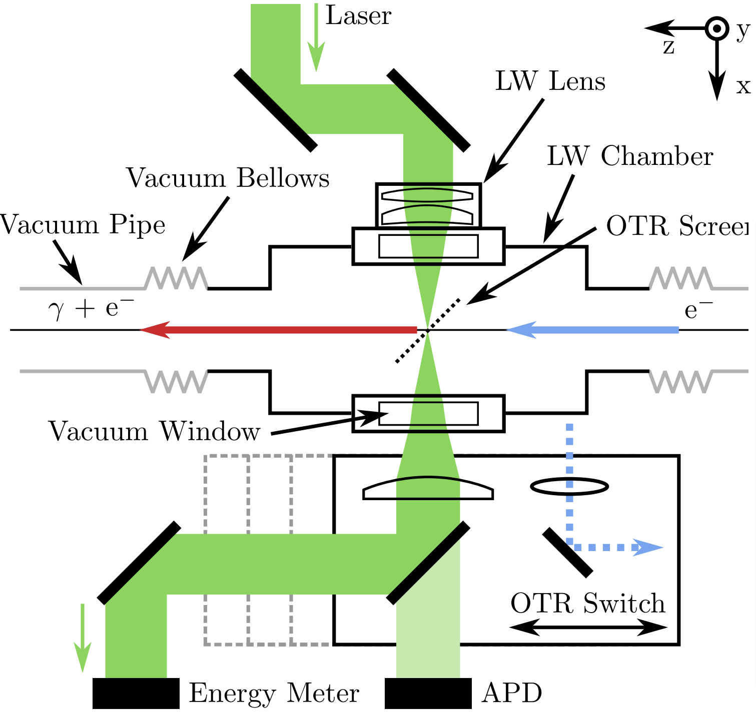






e- laserwires: *ATF2 laser beam characterisation*



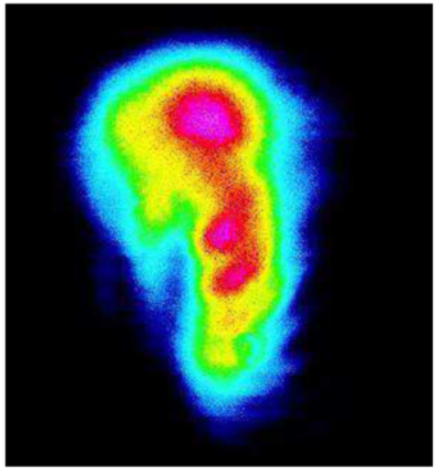


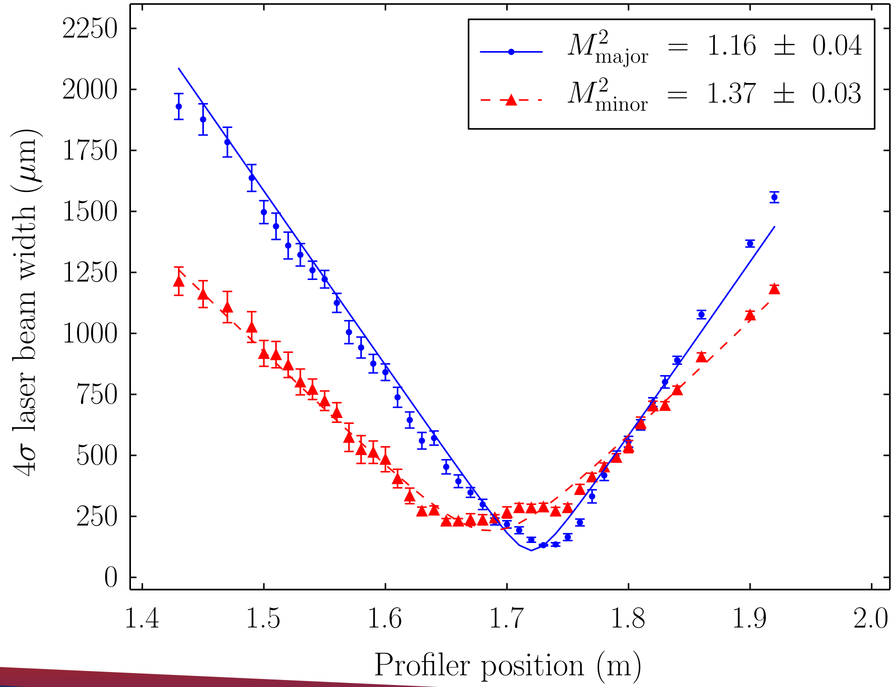
- Electron beam 1 x 250µm
- λ= 532nm laser, σ_0 = 1µm, M^2 (spatial quality) = 1.3
- Rayleigh range = 15µm
- laser σ ~ constant over 30µm << 250µm
- Vertical laserwire scan non-Gaussian
- Use measured laser propagation in overlap integral

A. Aryshev, S. Boogert L. Corner, D. Howell, P. Karataev, K. Kruchinin, **L. Nevay**, N. Terunuma, J. Urakawa, R. Walczak

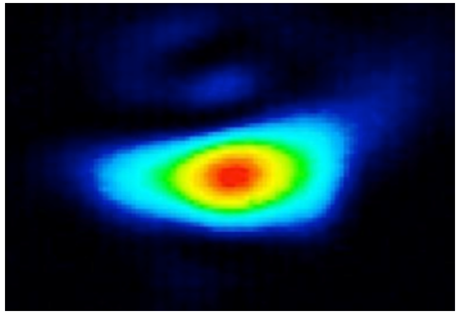
Laserwire at the Accelerator Test Facility 2 with submicrometer resolution Phys. Rev. Special Topics Accel. Beams, 17, 072802 (2014)

Input 4σ = 12mm





Scaled focus
4σ = 50µm



e^- laserwires: ATF2 results

Successful measurement of the 1.07 μm profile electron beam!

A. Aryshev, S. Boogert L. Corner, D. Howell, P. Karataev, K. Kruchinin, **L. Nevay**, N. Terunuma, J. Urakawa, R. Walczak

***L. Nevay** et al: Laserwire at the Accelerator Test Facility 2 with submicrometer resolution*
Phys. Rev. Special Topics - Accel. Beams, 17, 072802 (2014)

Projected laser dimension at interaction point

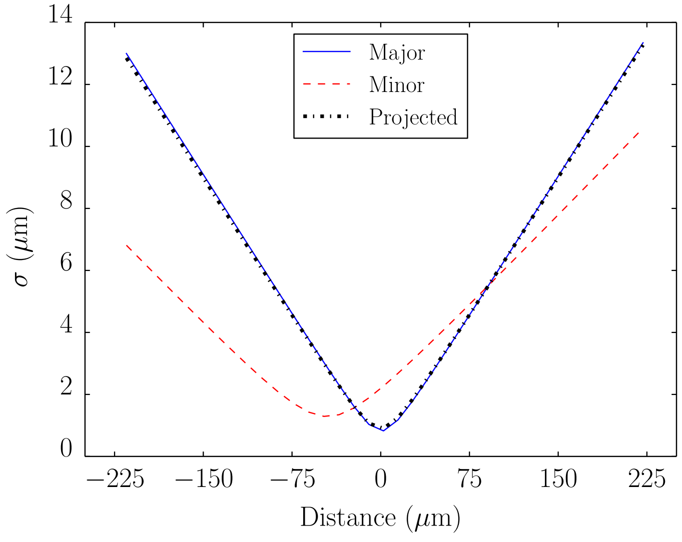


FIG. 12. Calculated projected vertical sigma for the laser as well as the two axes of propagation at the LWIP. The distance is

Measured vertical e- beam profile

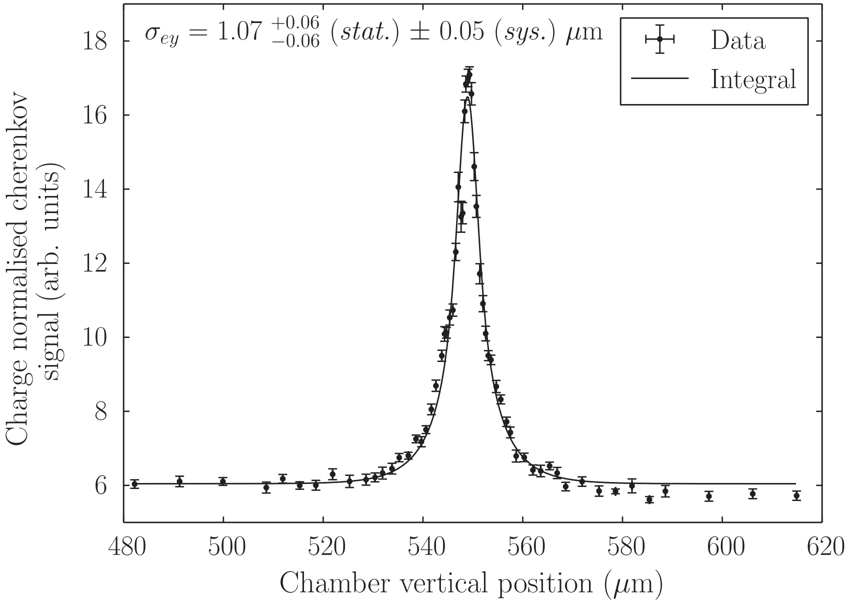


FIG. 19. Nonlinear step size laserwire scan with the smallest measured electron beam size.

Measured horizontal e- beam profile

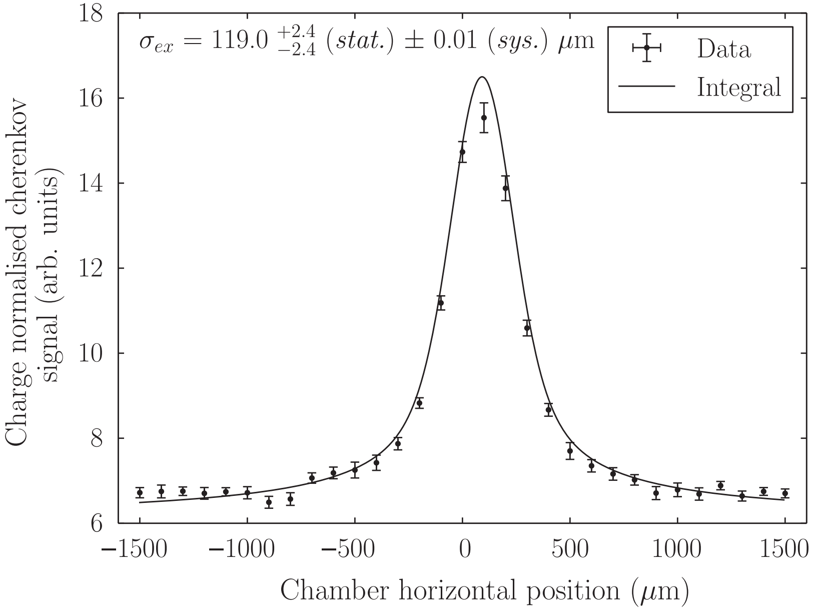
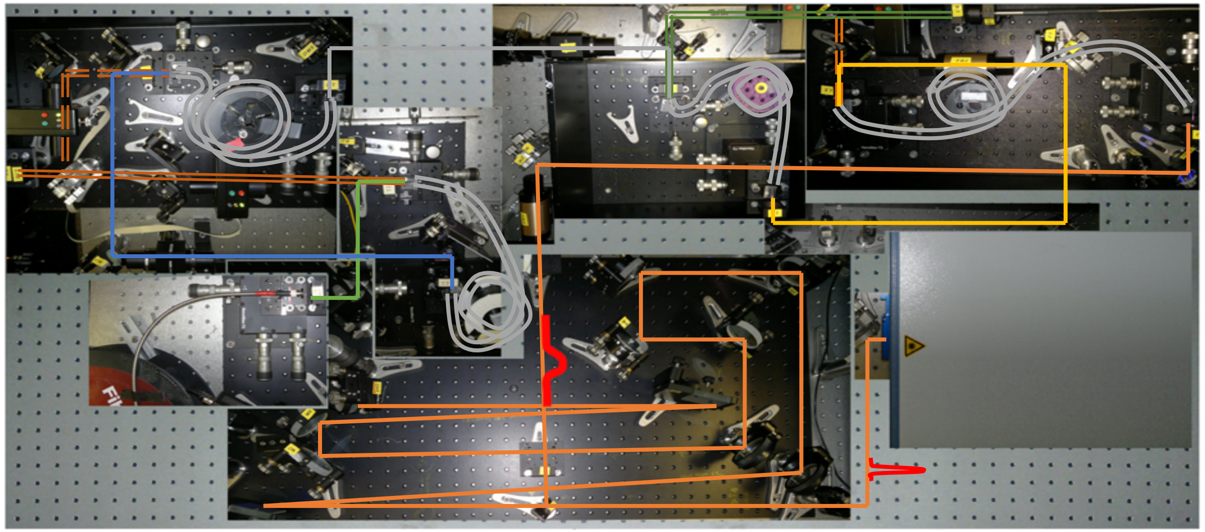


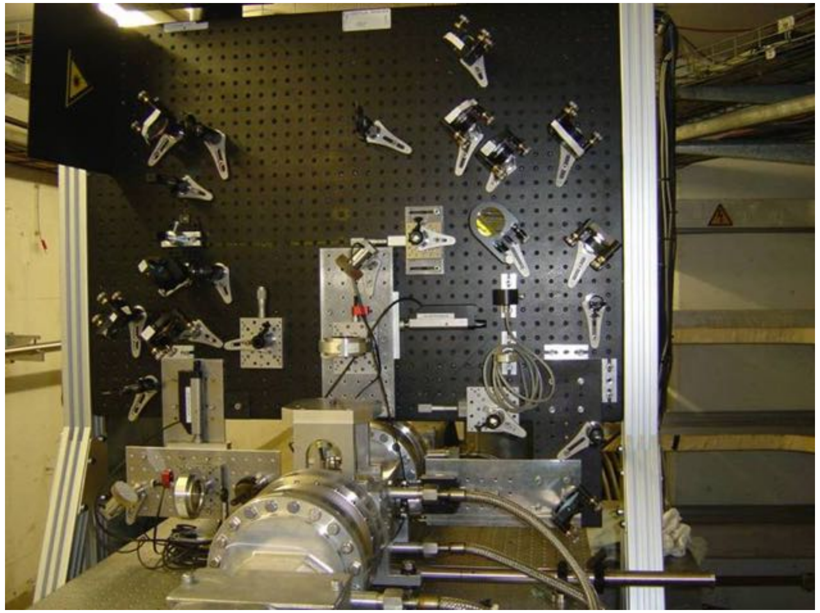
FIG. 20. The corresponding horizontal laserwire scan for the smallest vertical scan, which was required for the combined analysis.

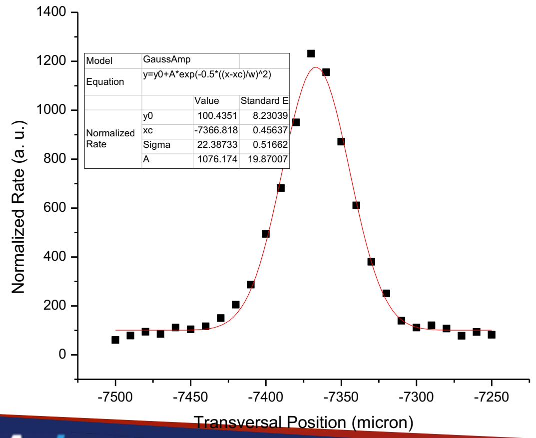
e⁻ laserwires: at PETRA-II & -III

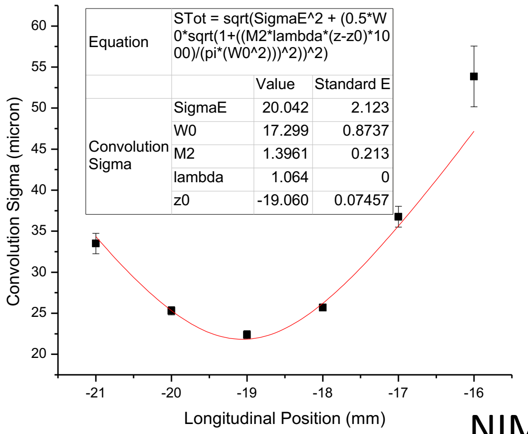
- Laserwire also developed for electron storage ring at DESY
- Chirp pulsed amplified laser synchronised at ps level with bunch RF

Vertical breadboard at beam pipe



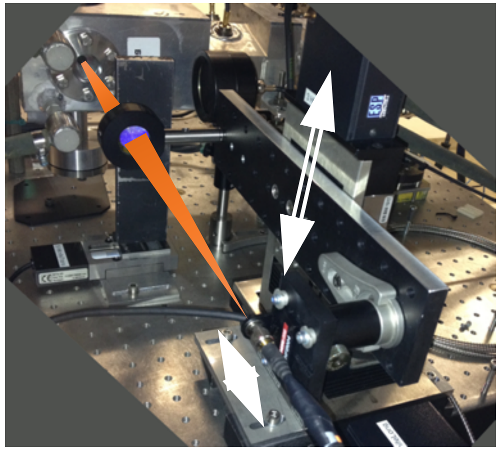






Fibre amplified laser transport to tunnel in photonic crystal fibre – large area single spatial mode.

Beam delivery optics:



NIM in Phys. Res. A 592(3):162-170 · July 2008

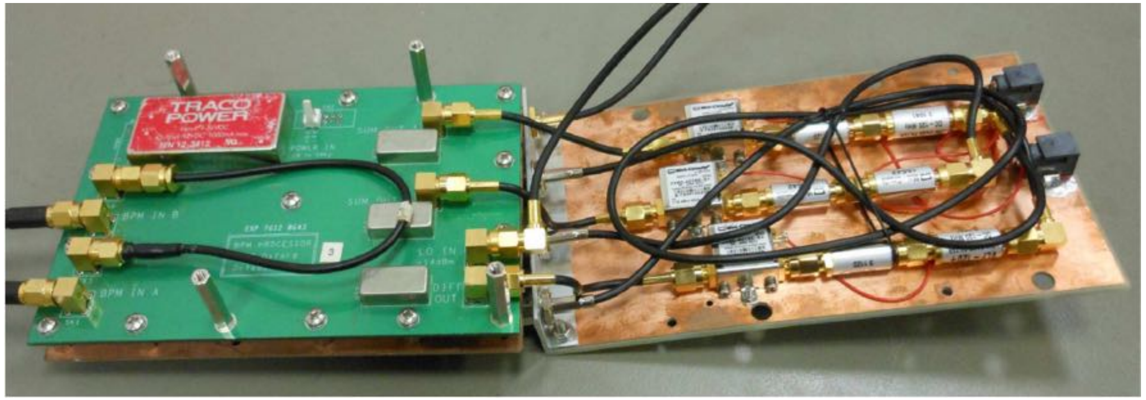
Stripline BPMs

R. Apsimon, D. Bett, P. Burrows et al

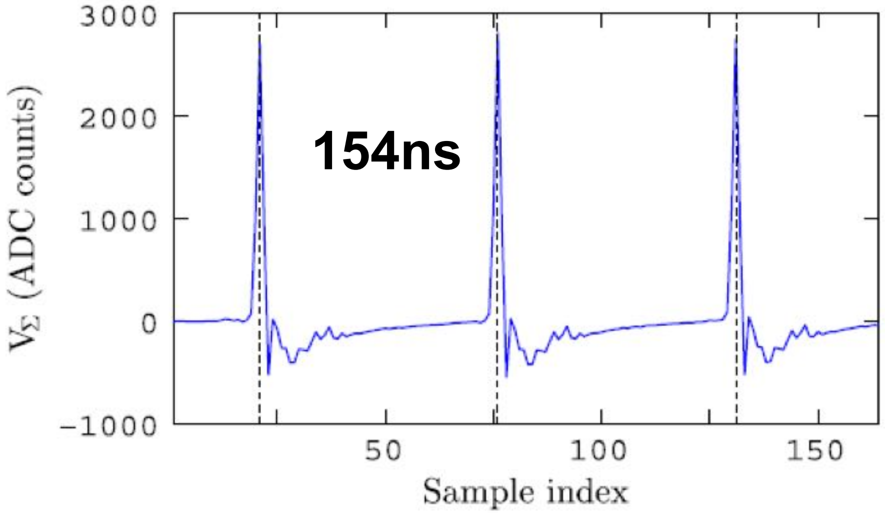
UNIVERSITY OF OXFORD

High resolution, low latency stripline BPMs:

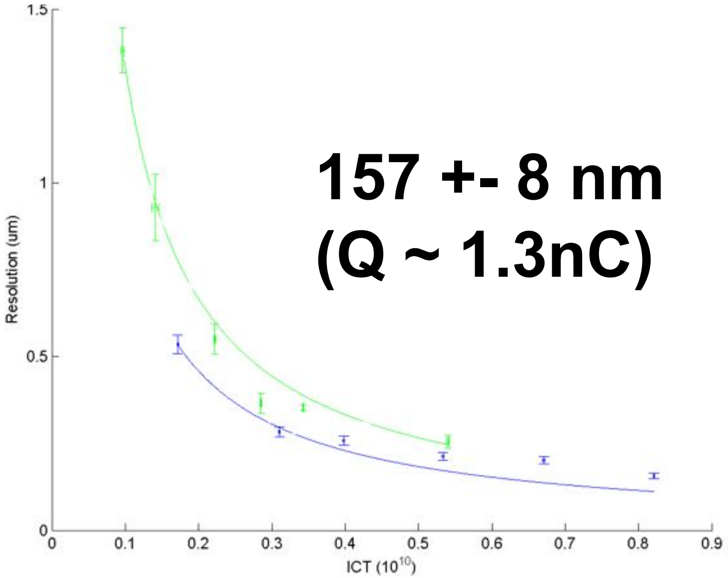
- Three stripline system tested at extraction line of ATF in KEK
- Processor latency: 15.6 ±0.1 ns
- Single-pass resolution of 291 ± 10 nm (at 1nC)



PRSTAB 18 032803 (2015)



Excellent temporal + spatial resolution

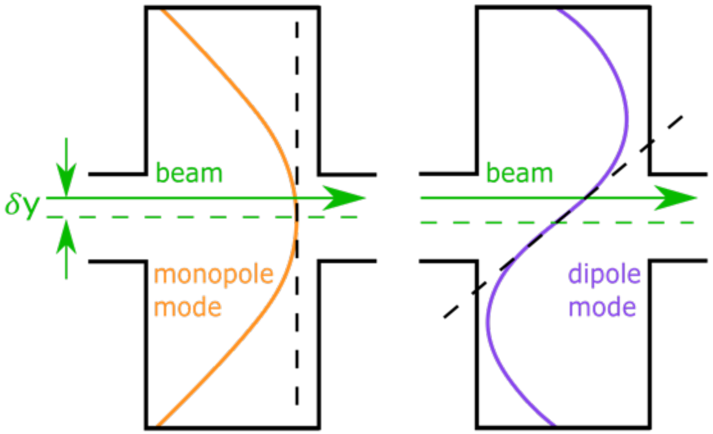


Cavity BPMs & fast feedback

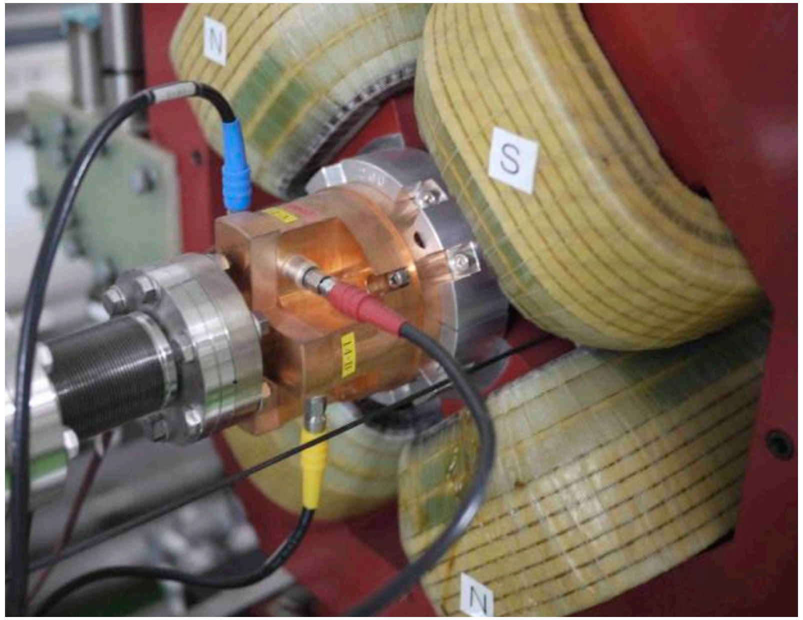
R. Ramjiawan, P Burrows, et al

UNIVERSITY OF OXFORD

Separate cavities for the extraction of the monopole and dipole modes.
These high-frequency signals need down-mixing and mixing to produce a baseband signal proportional to only the bunch offset.



ATF2 (6.5 GHz)



CLIC main beam/CTF3 (15 GHz)

Feedback On Nanosecond Timescales:
Nanometer-resolution cavity BPMs used for fast digital + analogue feedback/feedforward systems

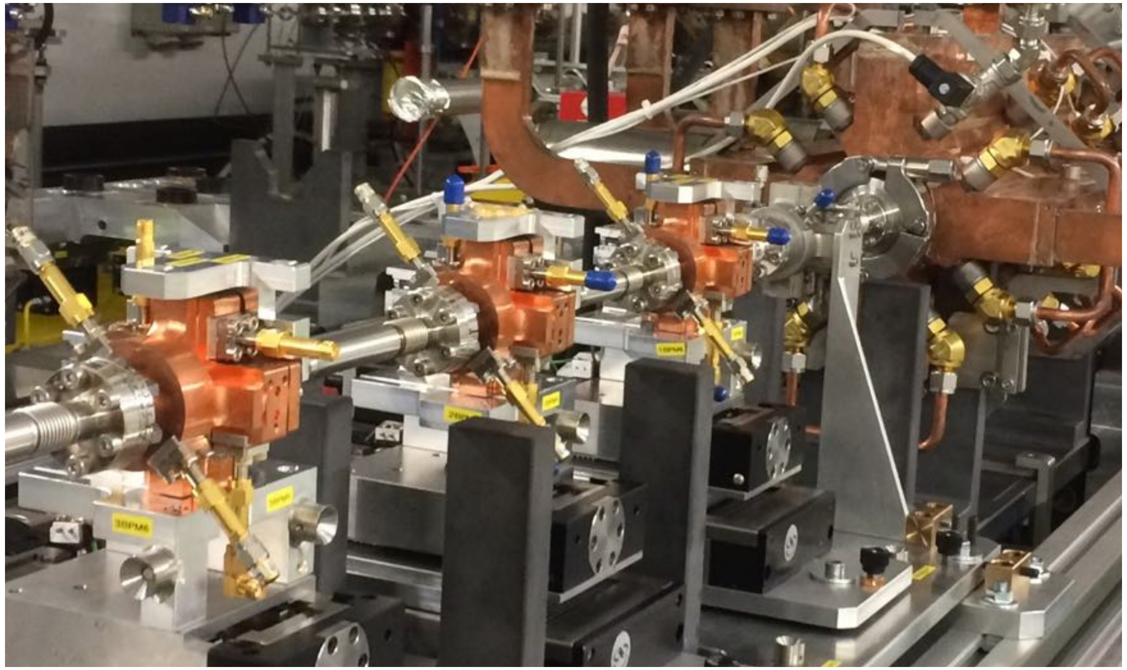
- ADCs to digitise I and Q waveforms at 357 MHz.
- DACs to provide analogue output to drive kicker, with a fast rise time 35 ns

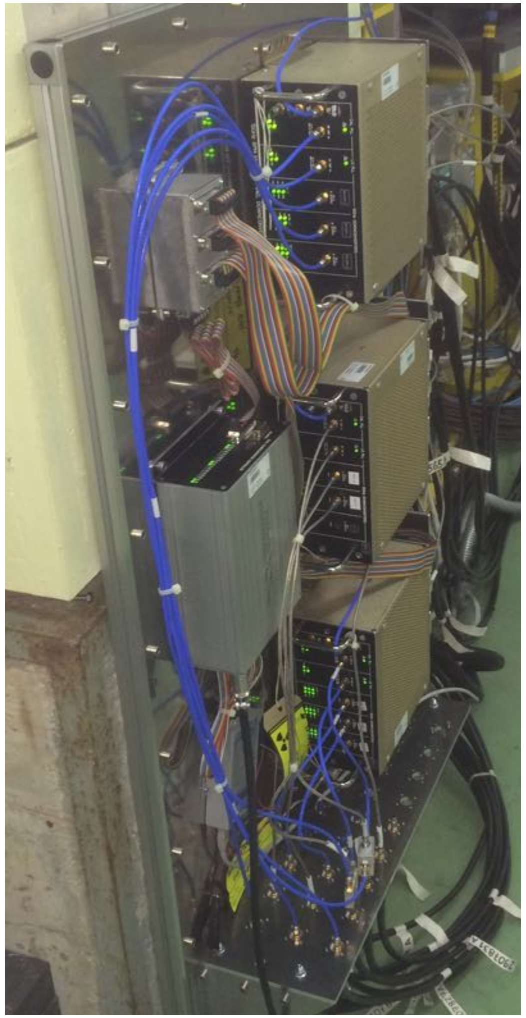
Resolution calculation method	Resolution (nm) Single sampling	Integration sampling
Geometric	49 ± 1	21.5 ± 0.4
Fitting I'	49 ± 1	19.9 ± 0.4
Fitting I', Q'	43 ± 1	19.5 ± 0.4
Fitting I', Q', q	43 ± 1	19.5 ± 0.4
Fitting I', Q', q and x	42 ± 1	19.2 ± 0.4

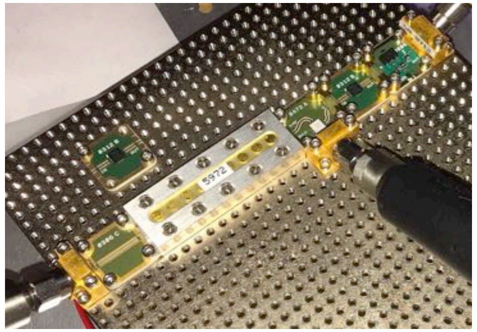
Cavity BPMs at CLEAR

A. Lyapin, M. Cargnelutti (I-Tech)

- A demonstrator system for CLIC main beam cavity BPMs
- High spatial (50 nm) and high temporal (50 ns) resolution needed for beam based alignment, wakefield-free steering and *online dispersion correction* via energy chirped trains
- 3x 15 GHz low-Q (fast decay) position cavities
- Down conversion to a lower frequency for digitization
- Transverse movers for calibration and alignment





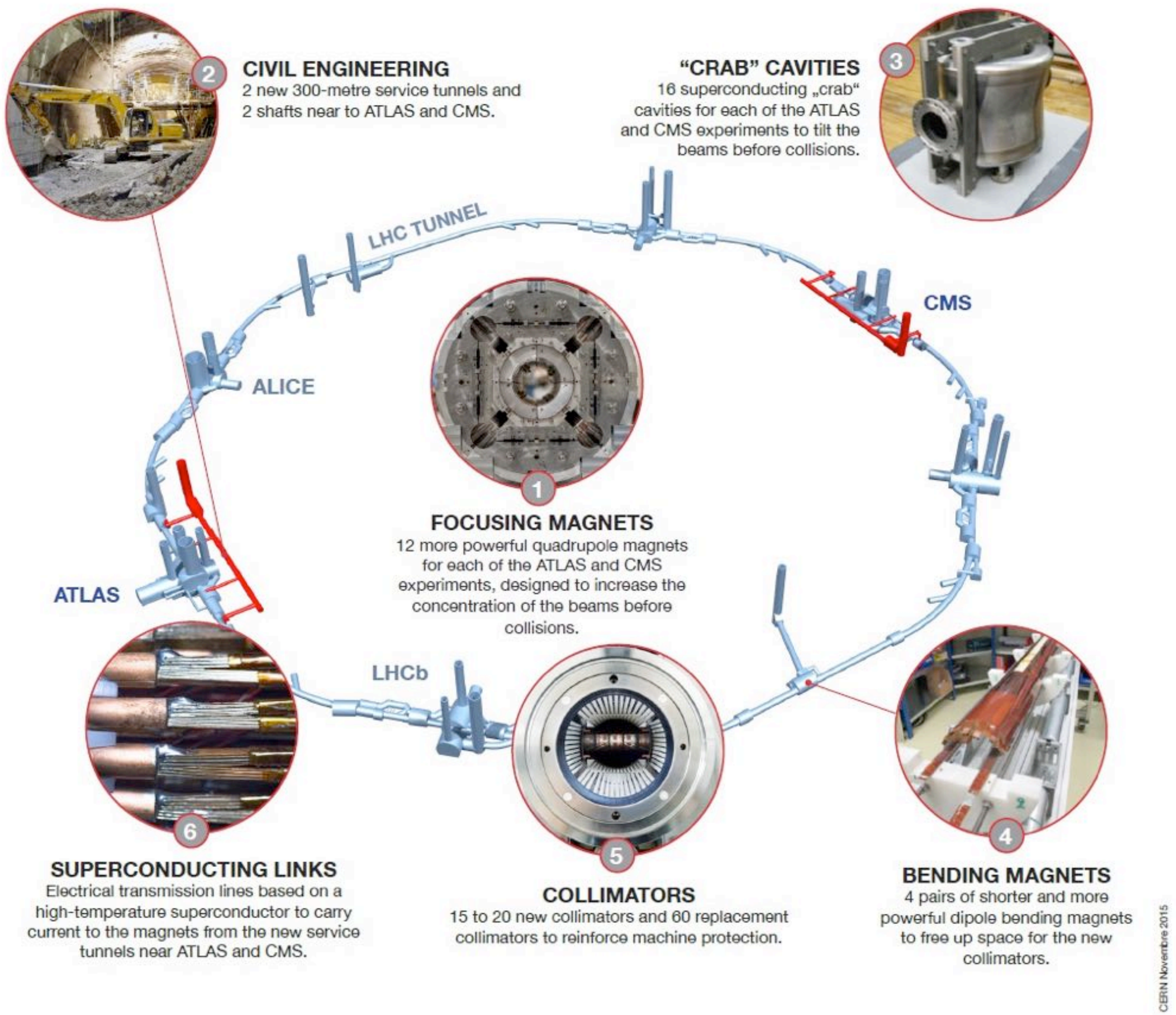


Electronics developed in collaboration with I-Tech (Slovenia)

- 500 MSps – 14 bit
- Bandwidth: 1MHz – 2GHz
- 32 dB variable gain
- Segmented memory with up to 500M ADC samples

Hadron Beam Diagnostics

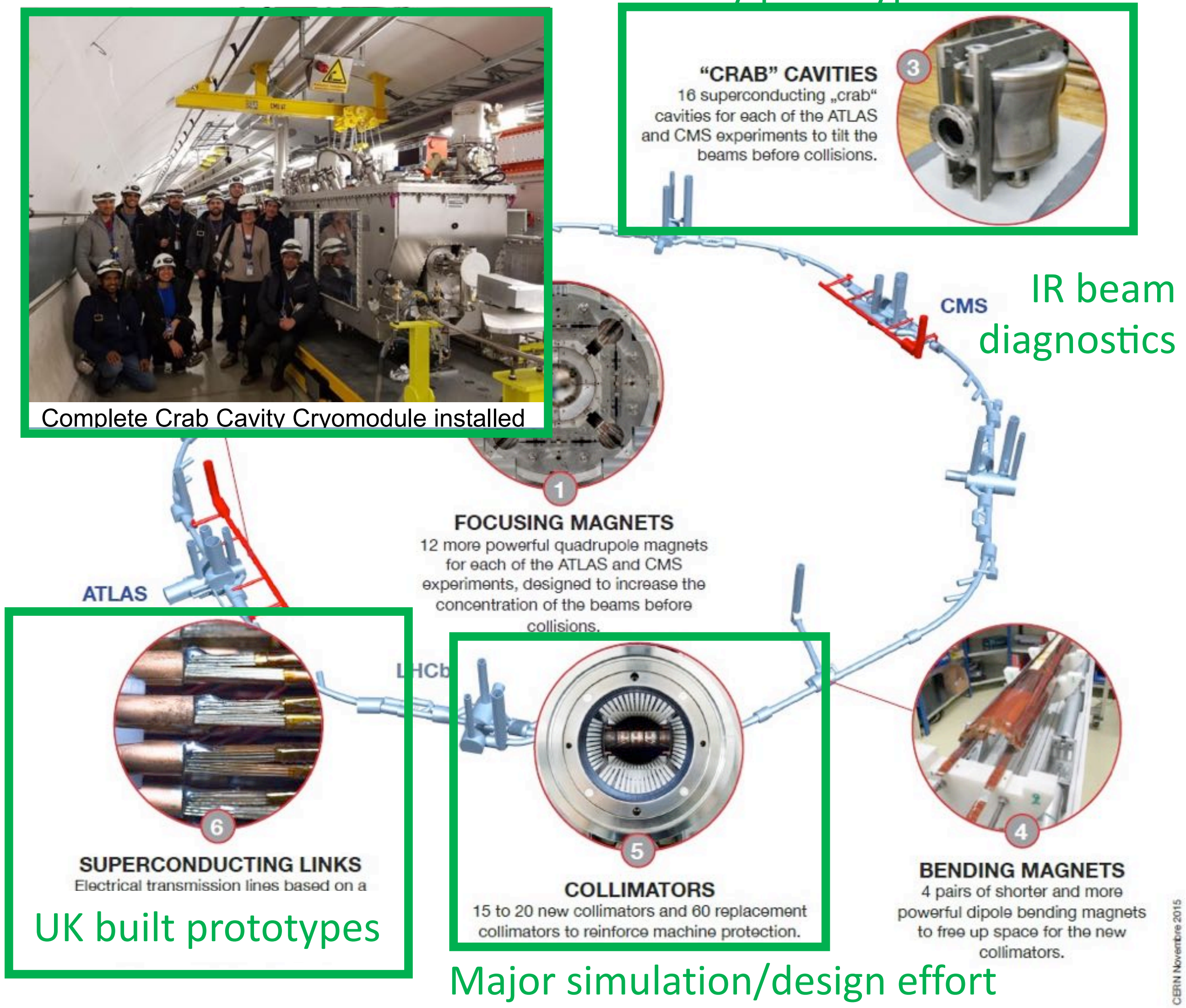
UK contribution to High Luminosity LHC



- **Lower beta* (~15 cm)**
  - New inner triplets - wide aperture Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- **Crossing angle compensation**
  - Crab cavities
  - Long-range beam-beam compensation
- **Dealing with the regime**
  - Collision debris, high radiation
- **Beam from injectors**
  - Major upgrade of complex (LIU)
  - High bunch population, low emittance, 25 ns beam

UK contribution to High Luminosity LHC – phase I

UK delivered crab cavity prototype to SPS



IR beam diagnostics

UK built prototypes

Major simulation/design effort

UK institutes on ***HL-LHC-UK***

£8M CERN-STFC investment in UK

HiLumi HL-LHC PROJECT

- MANCHESTER 1824 The University of Manchester
- The Cockcroft Institute of Accelerator Science and Technology
- Lancaster University
- University of Liverpool
- Royal Holloway University of London
- JAI John Adams Institute for Accelerator Science
- University of Southampton
- University of Huddersfield
- ASTeC

LHC Injectors Upgrade

\+ new injector diagnostics

Linac2:
50 MeV protons

Linac4:
160 MeV H⁻ ions
http://home.cern/about/accelerators/linear-accelerator-4

HL-LHC-UK phase II recently announced by STFC

https://stfc.ukri.org/news/project-to-upgrade-the-large-hadron-collider-now-underway/

Upgrade to Large Hadron Collider underway

11 September 2020

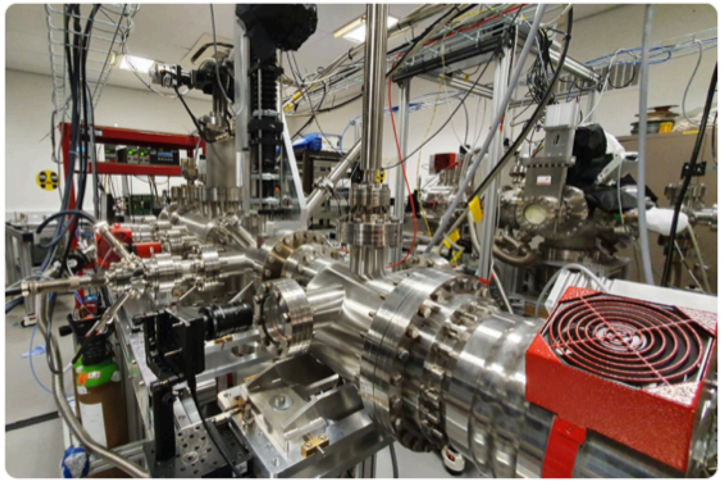
Scientists, engineers and technicians from the UK have embarked on a £26 million project to help upgrade the Large Hadron Collider (LHC) at CERN, on the French/Swiss border near Geneva.

The collaboration is between the Science and Technology Facilities Council (STFC), CERN, the Cockcroft Institute, the John Adams Institute, and eight UK universities. STFC is contributing £13.05 million.

Science Minister Amanda Solloway said:

"Ever since it first switched on in 2008, CERN's Large Hadron Collider has been working to answer some of the most fundamental questions of the universe.

"I am delighted that the UK's science and research industry will play a central role in upgrading what is the world's largest and highest energy particle collider, enabling leading physicists to continue making monumental discoveries."



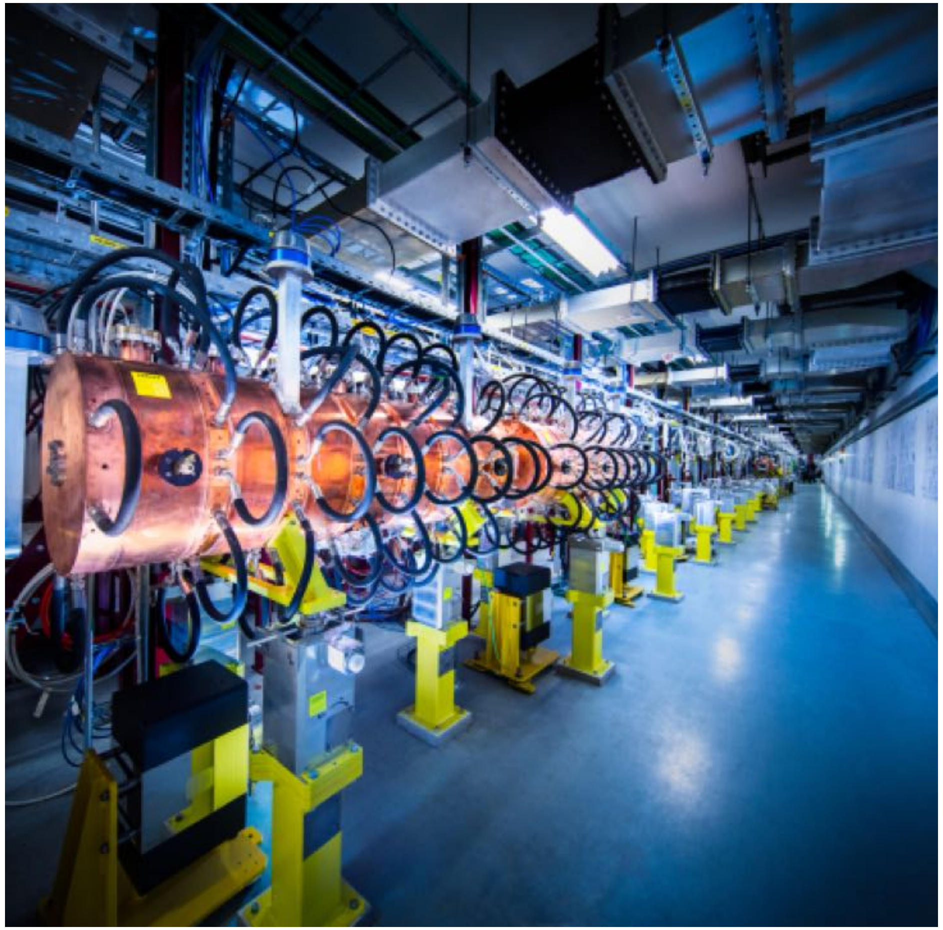
Gas jet beam profile monitor setup at the Cockcroft Institute.

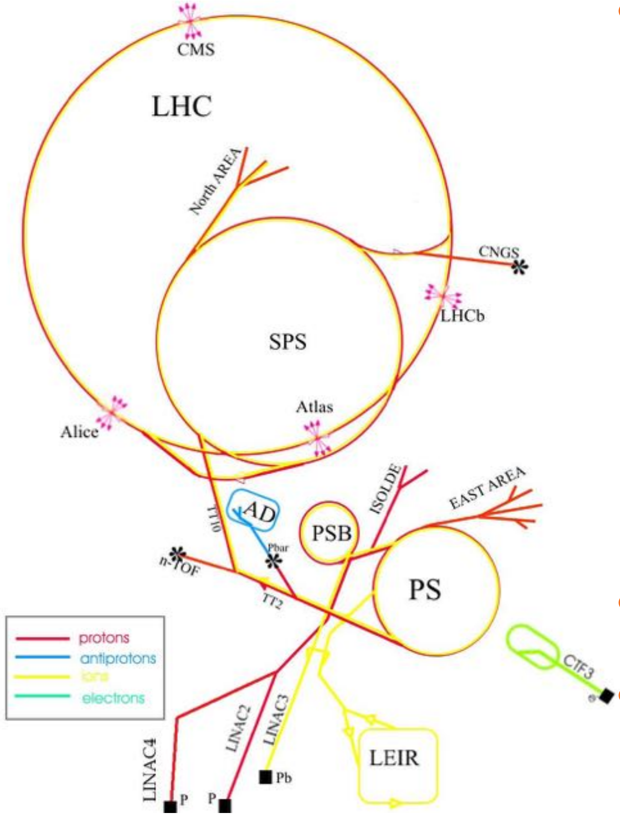
Beam Instrumentation for LIU:

LHC Injectors Upgrade

CERN's Linac2 replaced by Linac4 as main injector

- ***Linac4 is now the main injector for LHC, currently being connected to PSB in LS2 2019/20***



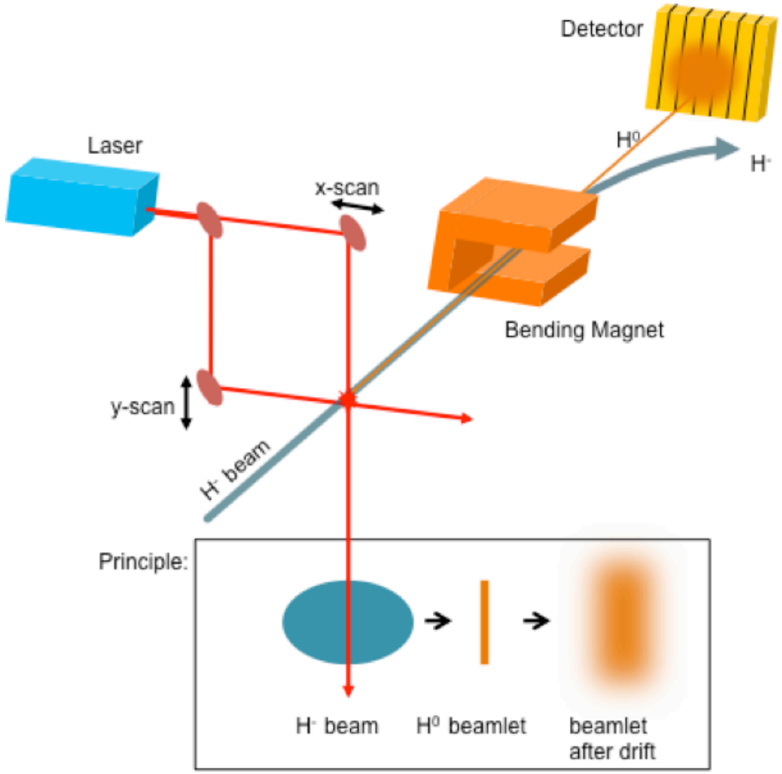


- *H^- ions boosted to 160 MeV*
  - *3 MeV, 352MHz Radio-Frequency Quadrupole (RFQ)*
  - *50 MeV drift tube linacs (DTLs)*
  - *100 MeV coupled-cavity drift tube linacs (CCDTLs)*
  - *160 MeV Pi-mode structures (PIMS)*
- *Commissioned 160 MeV in 2016.*
- *Multi-turn H- charge exchange injection to PSB enables a more brilliant beam for HL-LHC.*

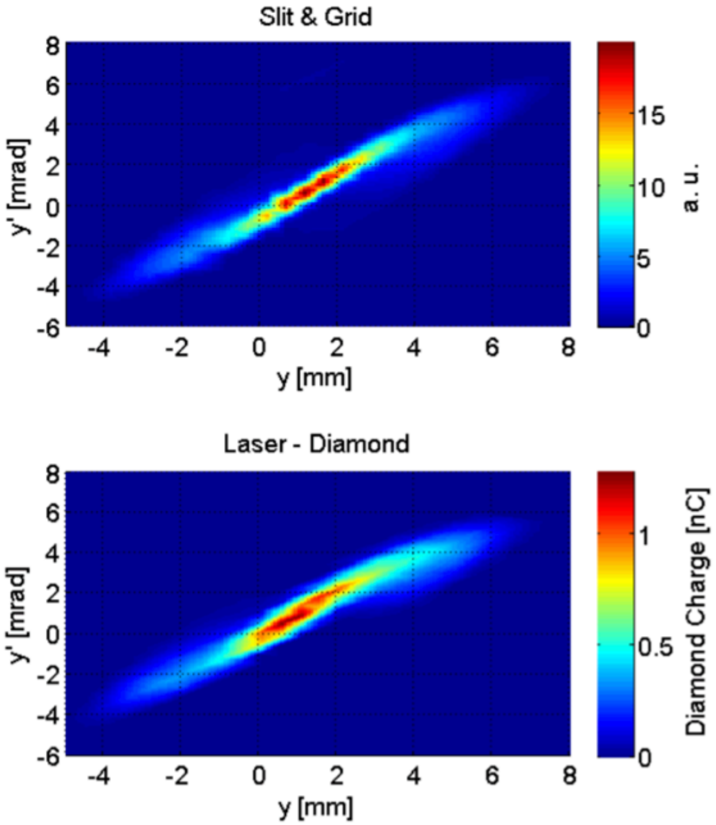
H$^-$ laserwire prototype

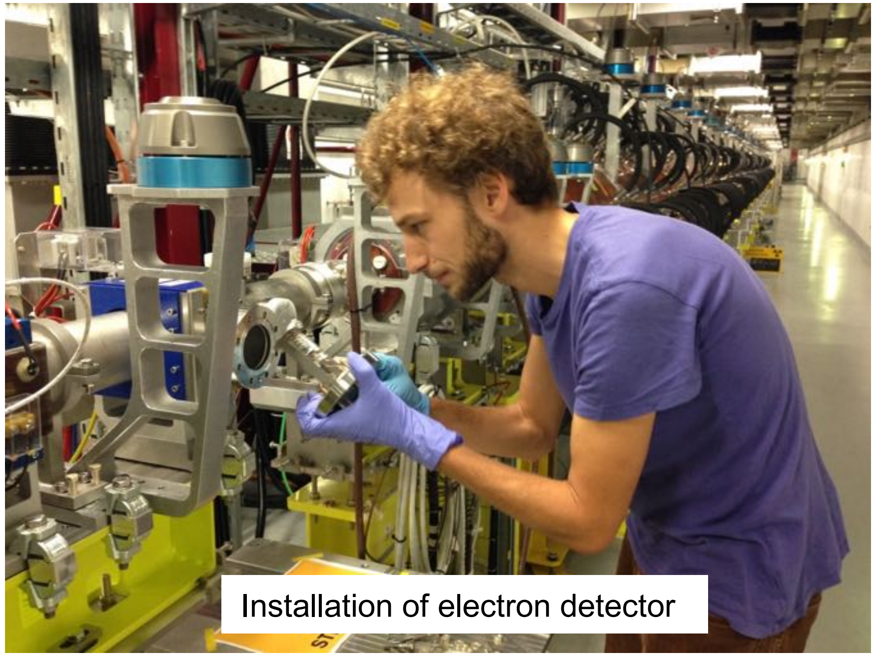
T. Hofmann et al

- ***New instrument to measure the transverse emittance has been demonstrated with RHUL-CERN built prototypes in recent years:***
  - Non-interceptive diagnostics of intense H$^-$ ion beams. In principle applicable to other ion species.



$H^- + \gamma \rightarrow e^- + H^0$

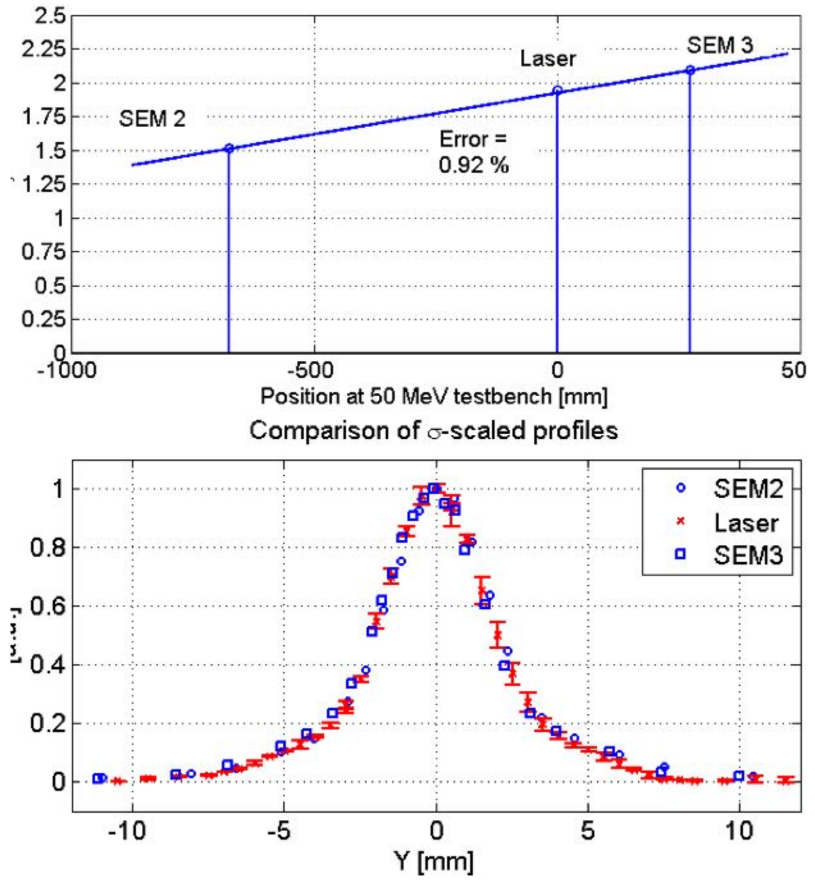




Thomas Hofmann's thesis, July 2017:
https://cds.cern.ch/record/2282569/

H^- laserwire: Linac4 prototype profile scanner results

50 MeV



80 MeV

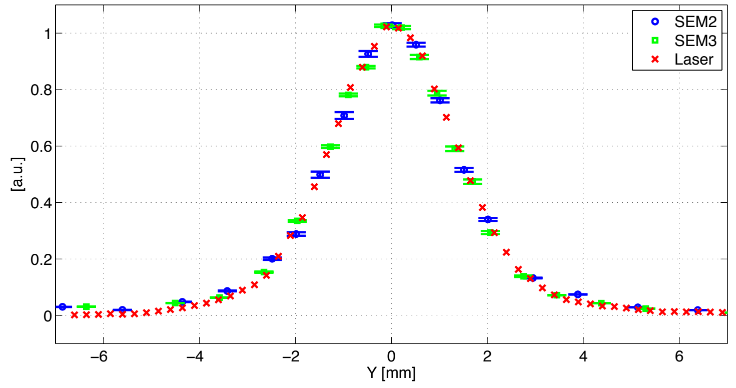


Figure 10: Comparison of SEM-grid σ-scaled profiles with the laserwire profile for the 80 MeV H^- beam.

107 MeV

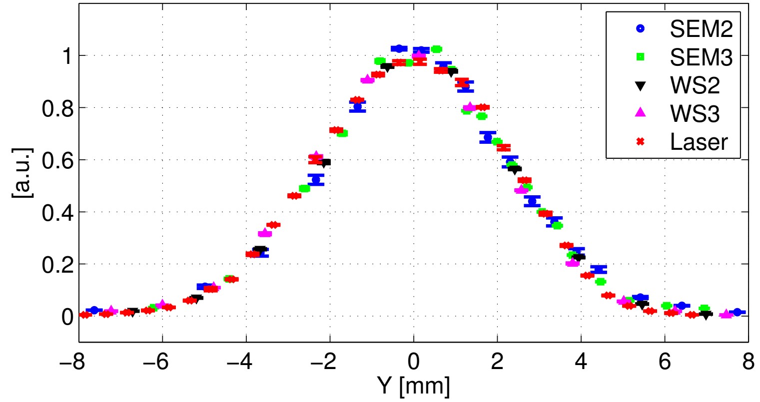


Figure 11: Overlay of 107 MeV H^- beam σ-scaled profiles recorded with different devices.

Laserwire profiles in good agreement (<2%) with nearby conventional diagnostics

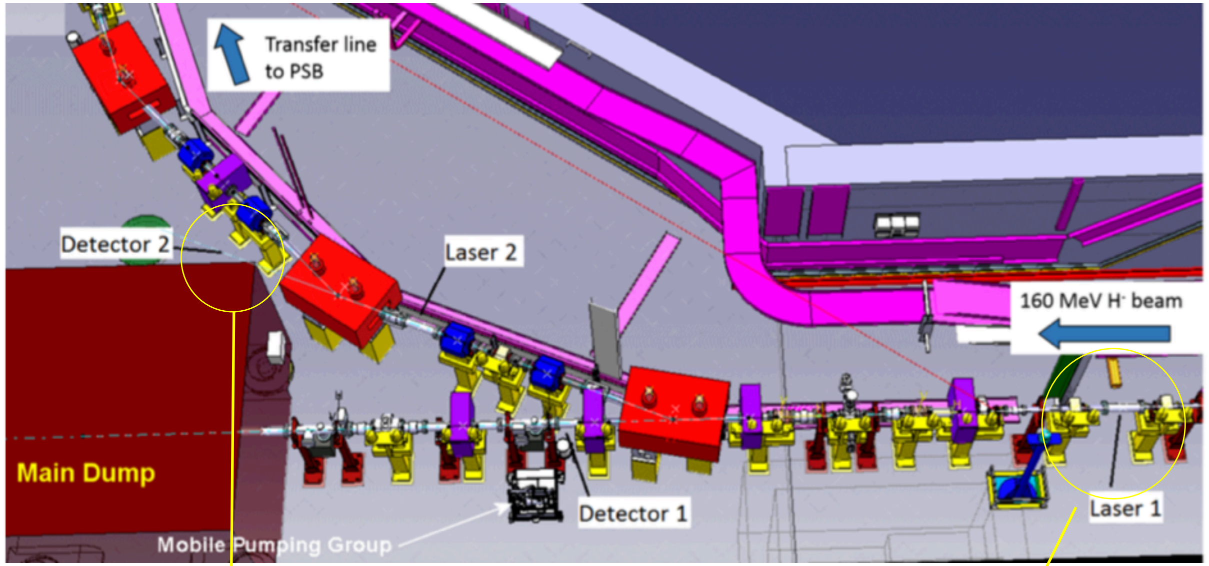
T. Hofmann et al, *'Design of a laser based profile monitor for Linac4 commissioning at 50 MeV and 100 MeV'*, TUPB005, IBIC 2015.

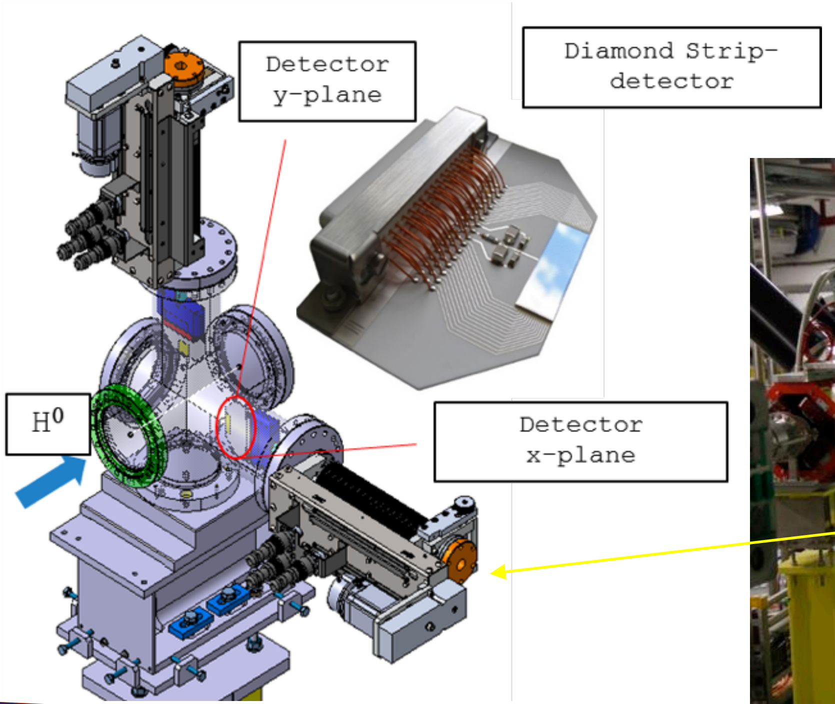
S. Gibson et al, *'Experimental results of a compact laserwire system for non-invasive H- beam profile measurements at CERN"s LINAC4'*, TUPB005, IBIC 2016.

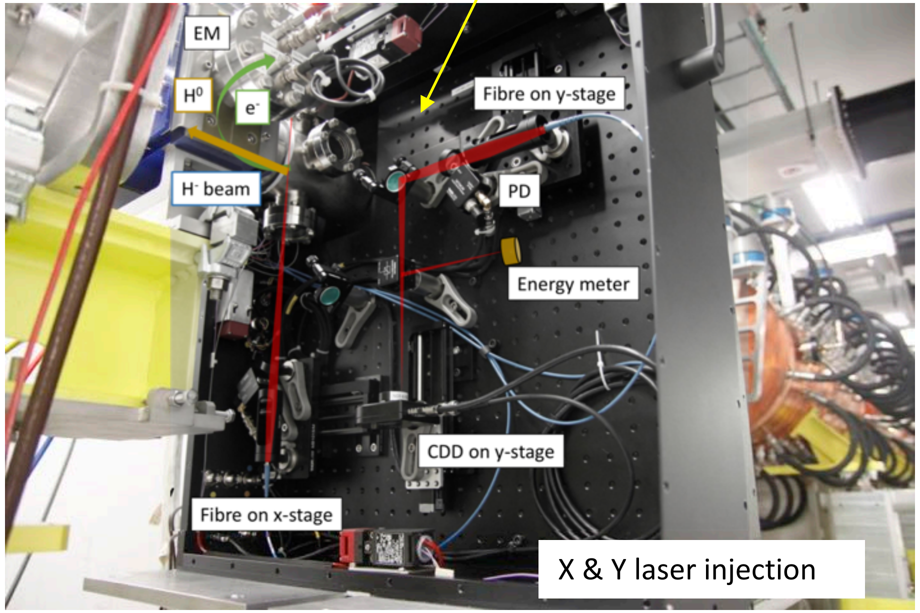
Dual laserwire installed at Linac4

T. Hofmann et al

- ***Non-interceptive emittance monitor***
  - *4 laserwires: in X and Y at two locations*
  - *Commissioned in 2018 at 160 MeV*
  - *Multi-channel diamond strip-detector*



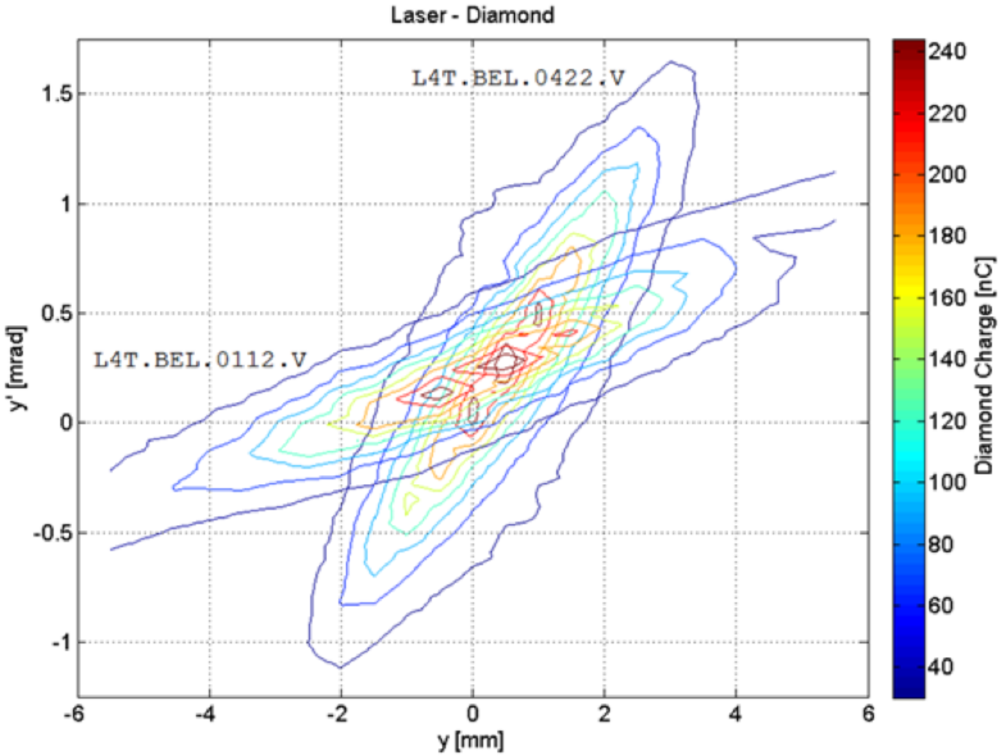




Dual laserwire commissioning results

T. Hofmann, G.E. Boorman, A. Bosco, S.M. Gibson, A. Goldblatt, F. Roncarolo

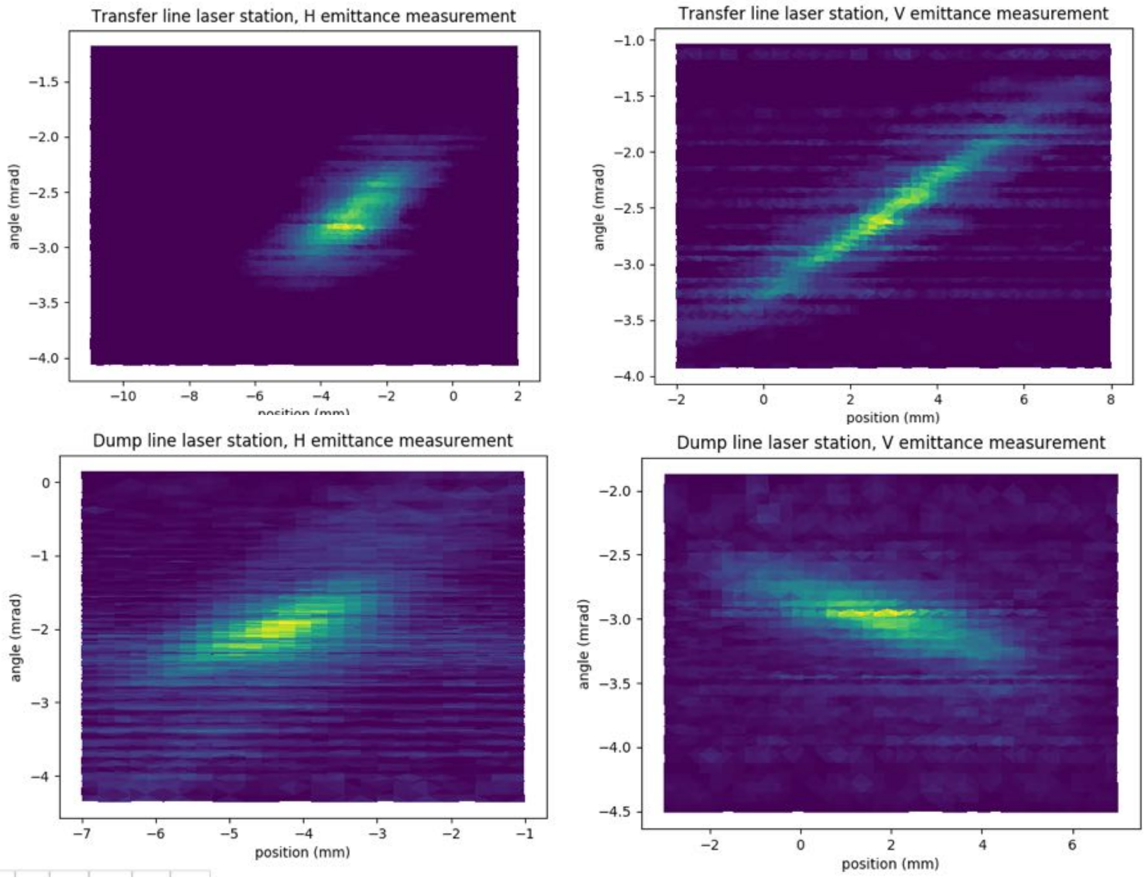
- ***Laserwire Emittance Monitor***
  - *First results showing vertical emittance for two different settings of the line.*



2018 measurements at 160 MeV

New Linac4 run starting now, Oct 2020…

– ***Latest data with 4 diamond detectors fully operational:*** *horizontal and vertical emittance reconstruction from both stations:*



T. Hofmann et al ,'Commissioning of the operational laser emittance monitors for Linac4 at CERN', WEPAL074, IPAC 2018.

PS Beam Gas Ionization (PS-BGI) Profile Monitor

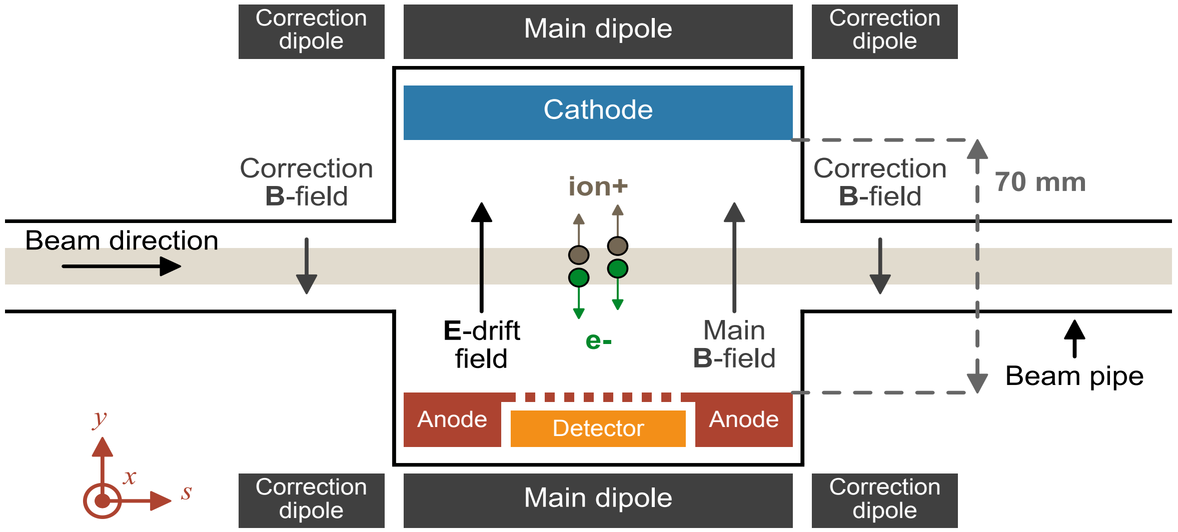
S. Levasseur et al

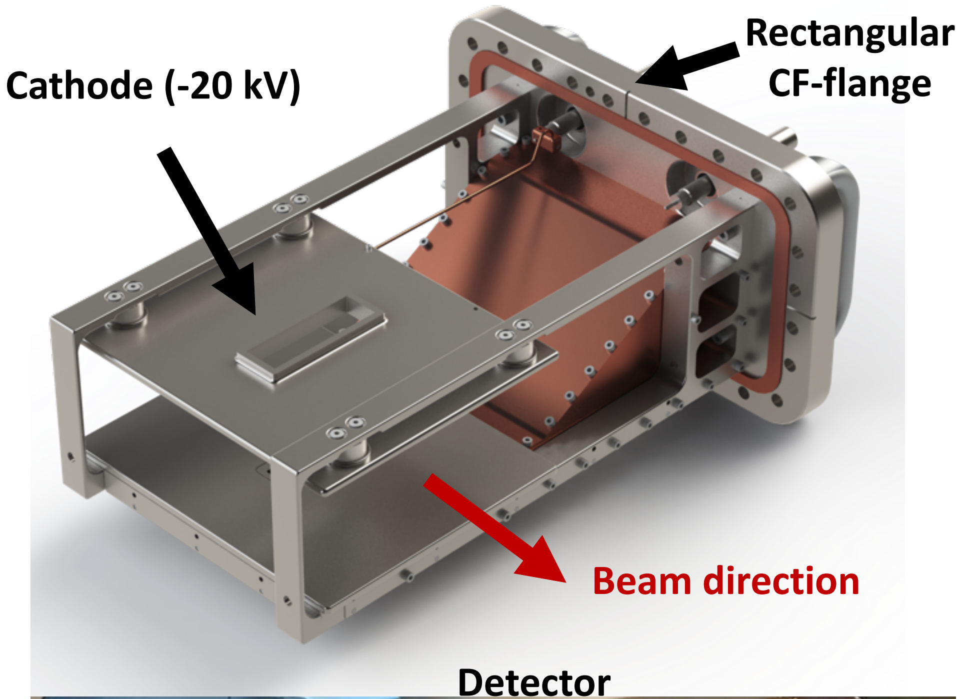
Purpose:

- Measure the transverse beam profile to improve the quality of the beam used for the LHC
- Integrated *non-destructive* beam profile throughout the cycle @ 1 kHz

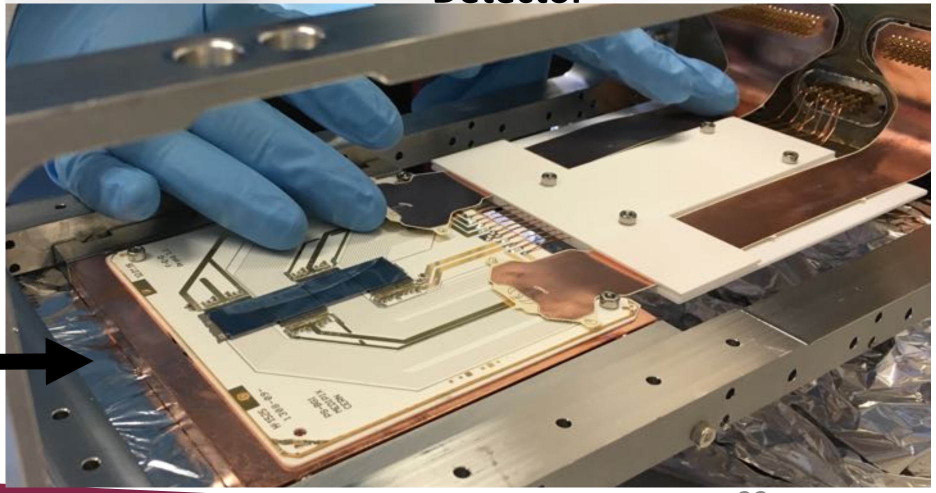
Operating environment:

- Ultra-high vacuum: outgassing ≤ $1 \cdot 10^{-7}$ mbar·l·s^{-1}
- Radiation: 10 kGy/year at beam pipe, 1 kGy/year at 40 cm
- Presence of beam with losses and electro-magnetic interference





Detector



Specifics for the PS-BGI:

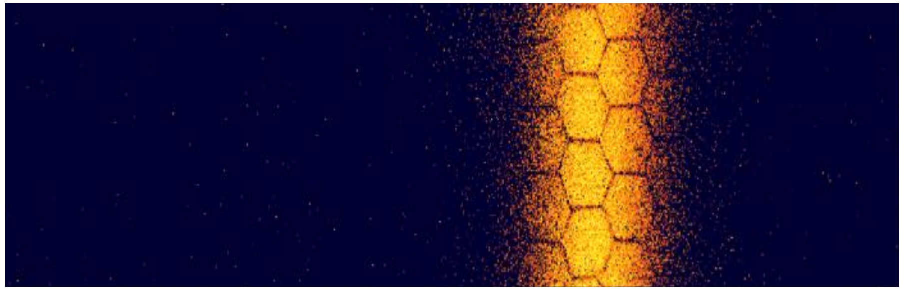
- Imaging of 10 keV ionization electrons using **hybrid pixel detectors**
- 285 kV/m electric field, 0.2 Tesla magnetic field

PS-BGI: transverse beam profile measurement

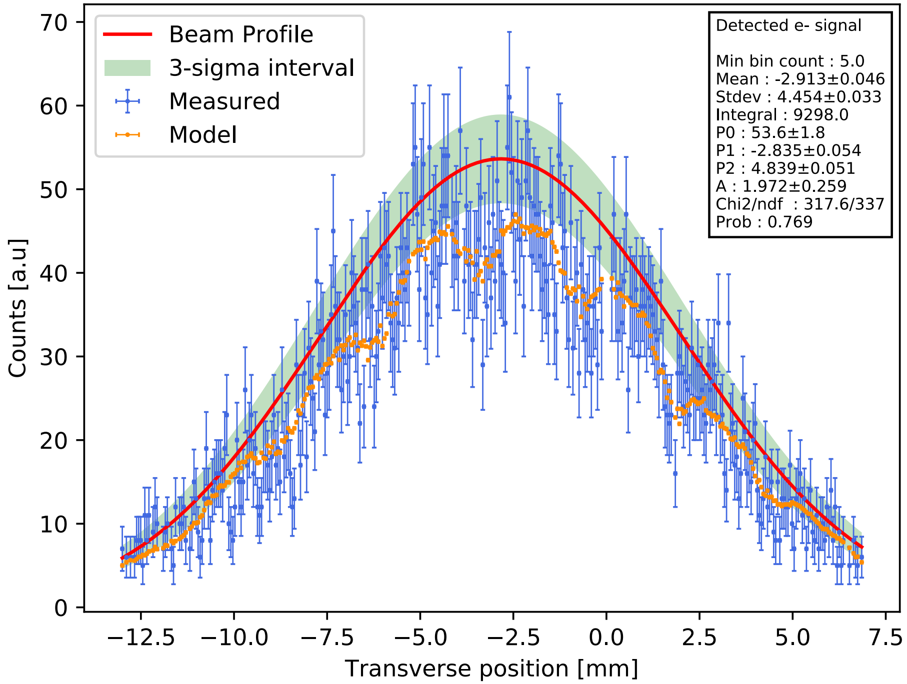
S. Levasseur et al

ROYAL HOLLOWAY UNIVERSITY OF LONDON

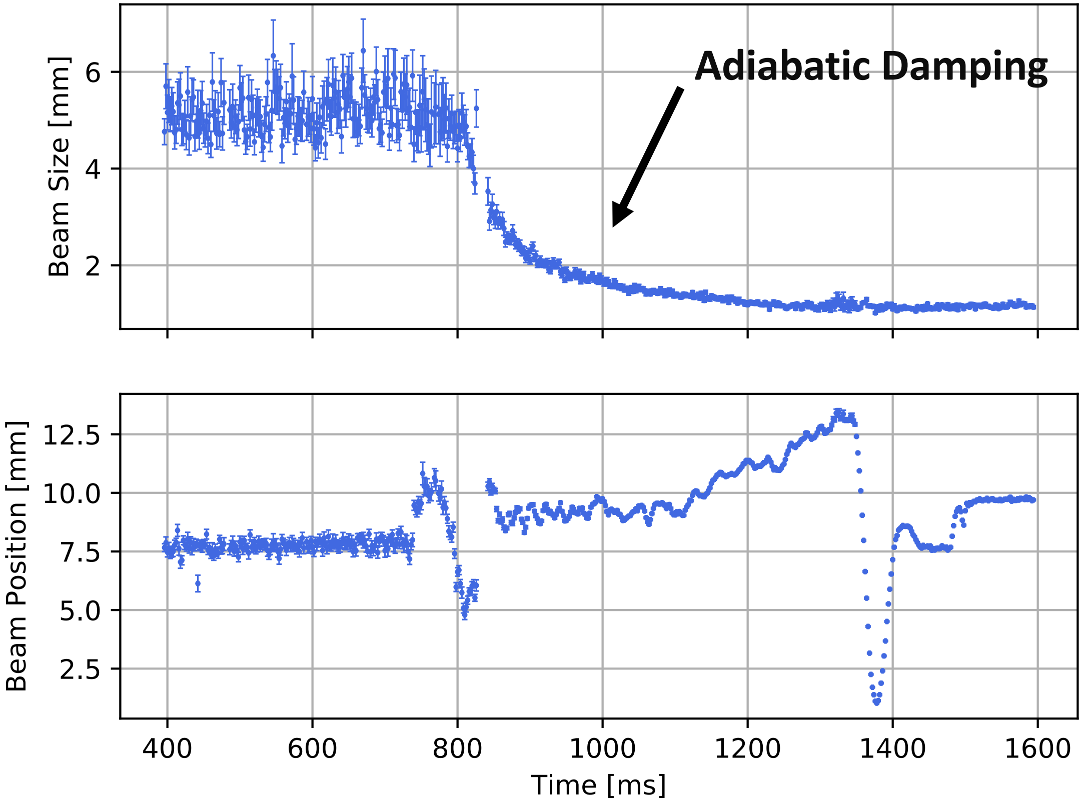
Raw Hybrid Pixel Detector Image



Transverse horizontal beam profile reconstruction



Evolution of beam size & position during the full PS cycle



- Extract beam size & position from fit to beam profile.
- Continuous measurements at a rate of 2kHz per bunch for an LHC-type beam.

PS-BGI: turn-by-turn measurements of single bunch

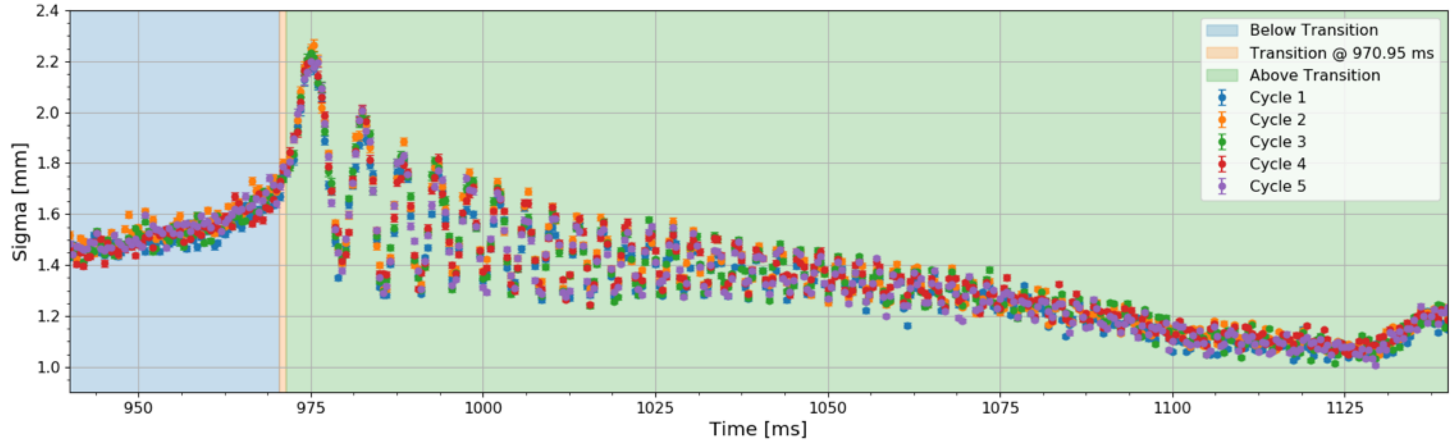
S. Levasseur et al

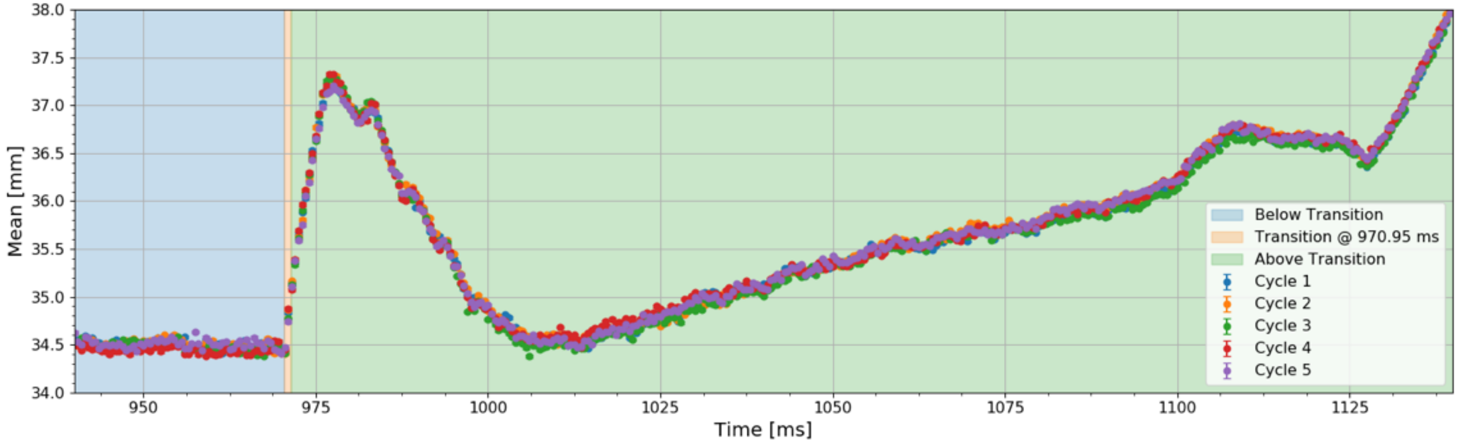
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Practical use case for beam diagnostics - *transition crossing*

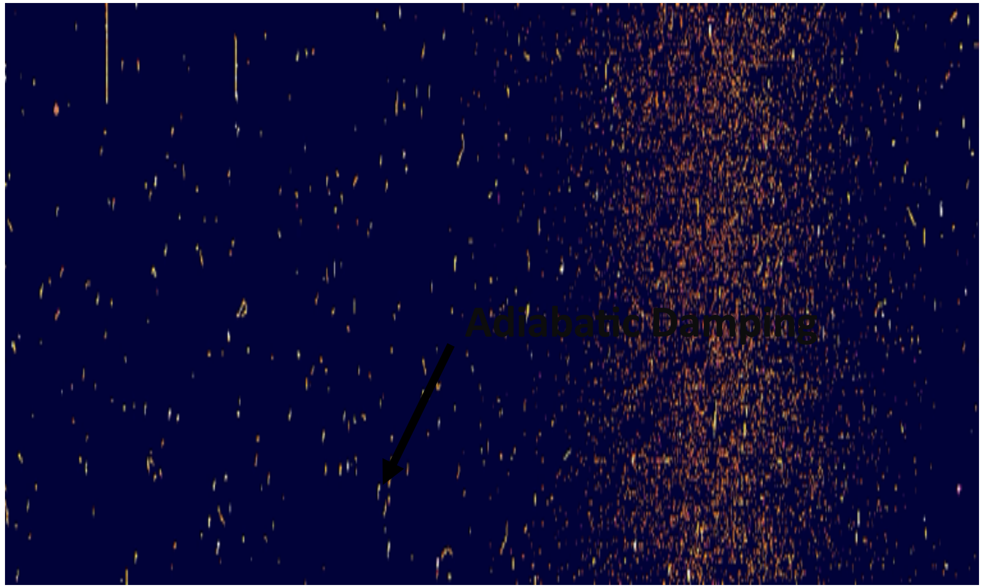
Sigma = width of the beam
Mean = beam centre

Beam sigma/mean measured continuously at 2 kHz
Oscillations within a single cycle can be observed!





CERN-THESIS-2019-354 https://cds.cern.ch/record/2720090



Video of single LHC bunch in the PS as energy ramps from 2.1 GeV to 26.3 GeV

- Slowed down for viewing purposes
- Backgrounds from beam losses not removed

BGI-Timepix3 allows, for the first time, continuous non-destructive turn-by-turn measurement of the transverse beam profile of single bunches.

bgi.web.cern.ch/bgi/papers.html

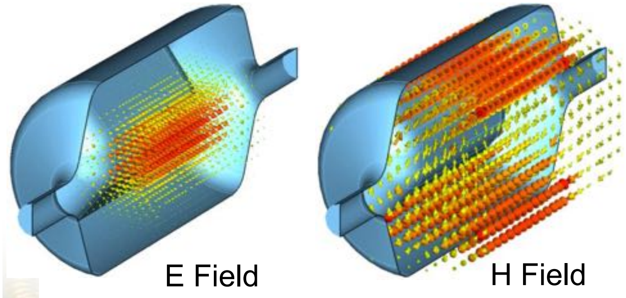
Diagnostics for HL-LHC

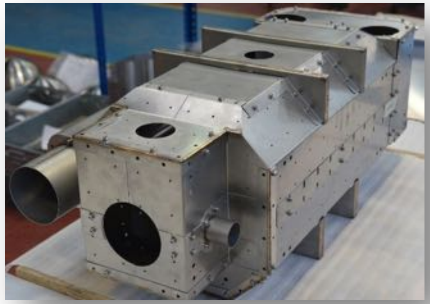
UK Crab-cavity cryomodules for HL-LHC:

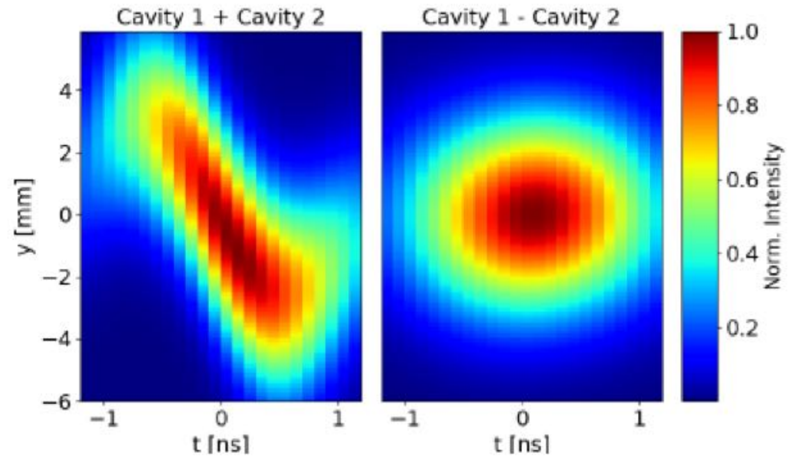
Graeme Burt et al

- First prototype cryomodule (DQW) tests completed on SPS in mid 2018.
- First ever evaluation of crab cavities with a proton beam!
- A 2-cavity pre-series RFD cryomodule in development + providing 4 production DQW cryomodules for LS3

UK team responsible for key elements of the design: cold shield, magnetic shield, thermal shield, vacuum vessel, transport modules, HOM coupler + SPS test: machine physics, impedance, diagnostics and played major roles in other areas (LLRF)

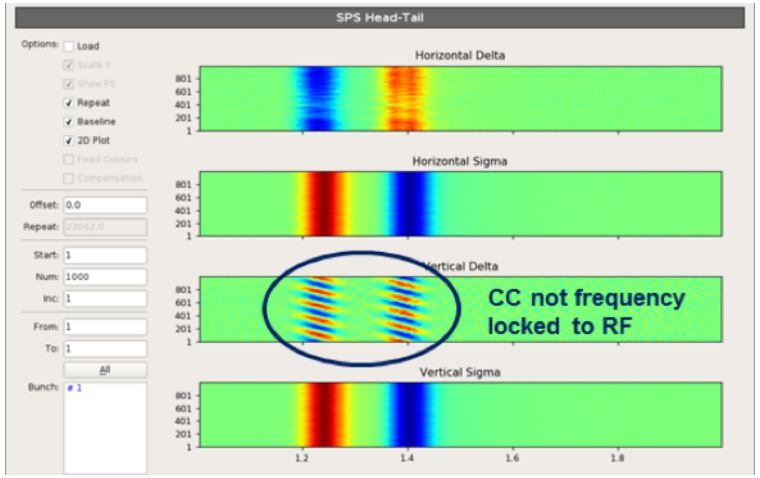




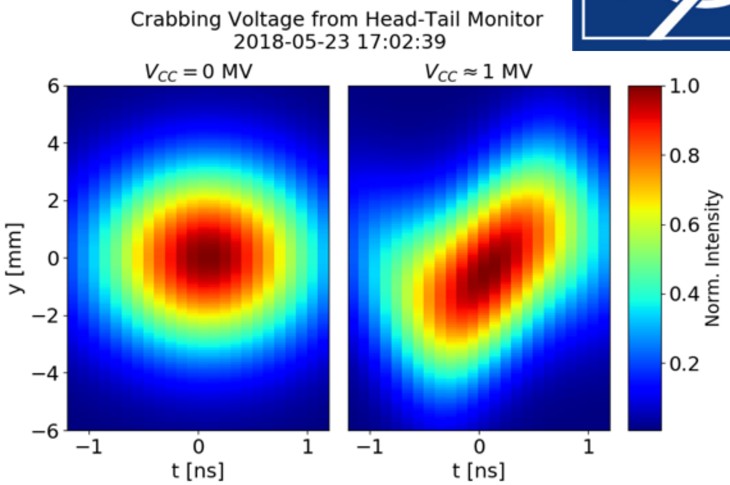


Head-Tail monitors & EO upgrade for HL-LHC

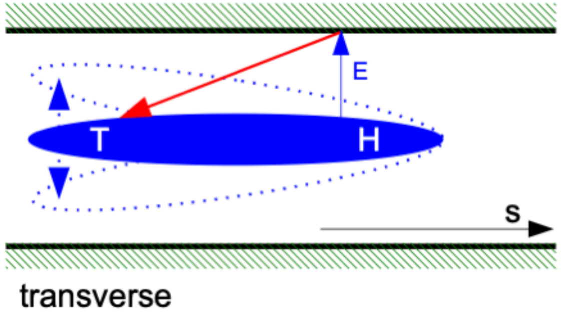
- *CERN's current diagnostics for transverse bunch instabilities.*
- *In 2018, SPS Head-Tail Monitor observed world's first crabbing of a proton beam:*

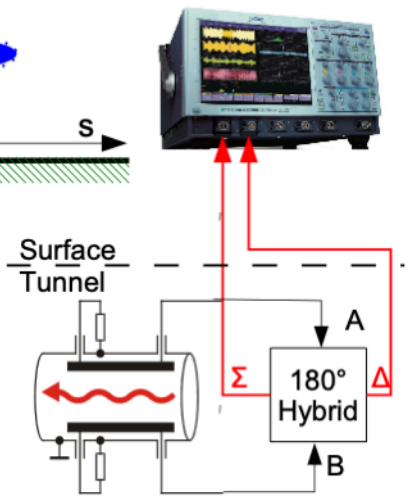


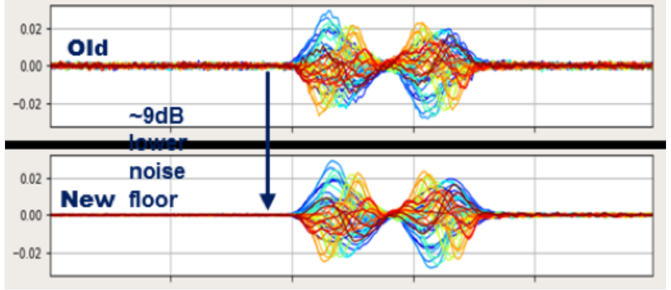
Tom Levens et al

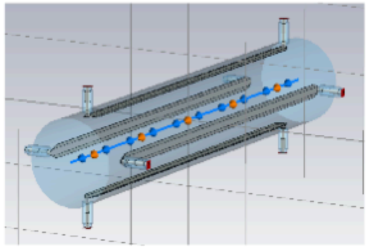


- *HT standard approach:*
  - *Stripline BPMs + fast sampling oscilloscopes*
- *Limitation:*
  - *Bandwidth up to a few GHz, limited by the pick-cables and acquisition system*
- ***For HL-LHC, a new technology is needed**: **fast electro-optic pick-up***





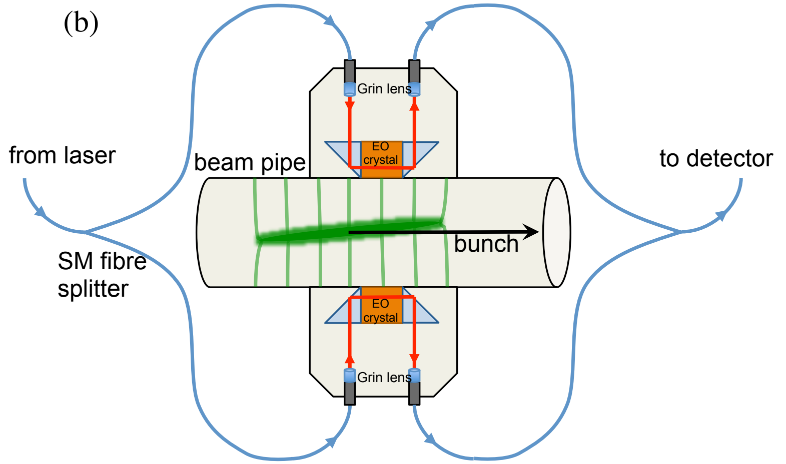




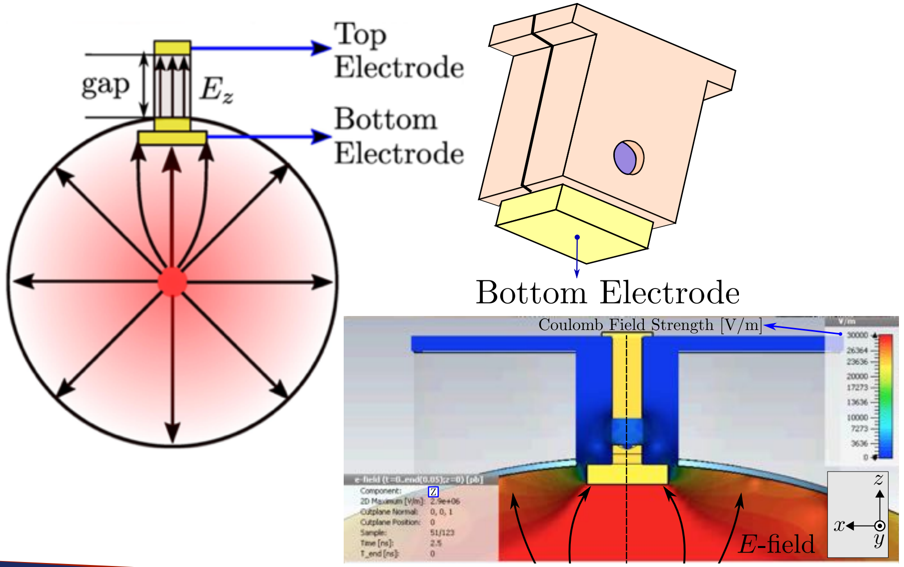
Oscilloscopes with higher resolution installed

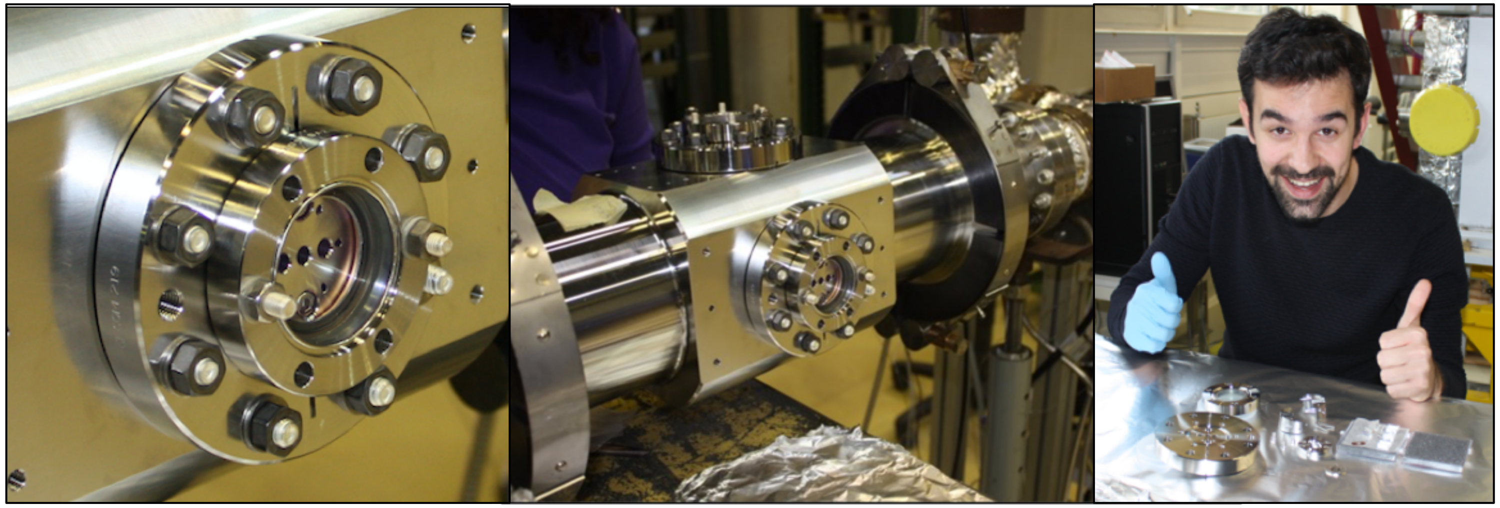
Electro-Optic Beam Position Monitor: SPS prototype

A. Arteche, S. Bashforth,, A. Bosco, S. Gibson, RHUL
M. Krupa, T. Levens, T. Lefèvre, CERN



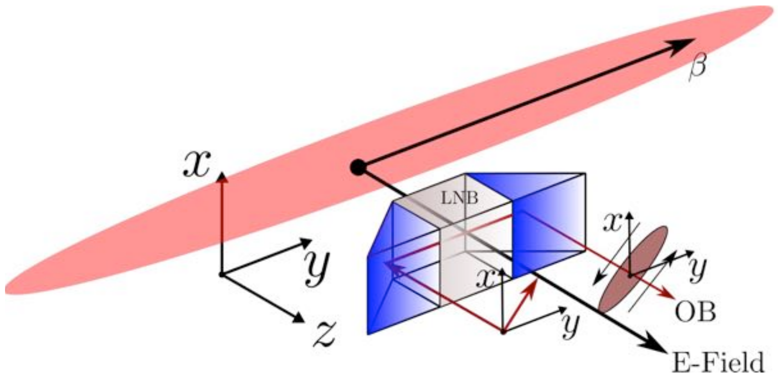
- ***Aim:*** rapid intra-bunch measurement of crabbed bunch shape & instabilities, by replacing BPM pick-ups with ultrafast eo-crystals.
- EO-prototype observed first SPS beam signal in Dec 2016; tune successfully measured in 2017 with electrode pickup.
- Beam signals match well with CST simulations and with results from optical bench tests. See A. Arteche's thesis, 2018.

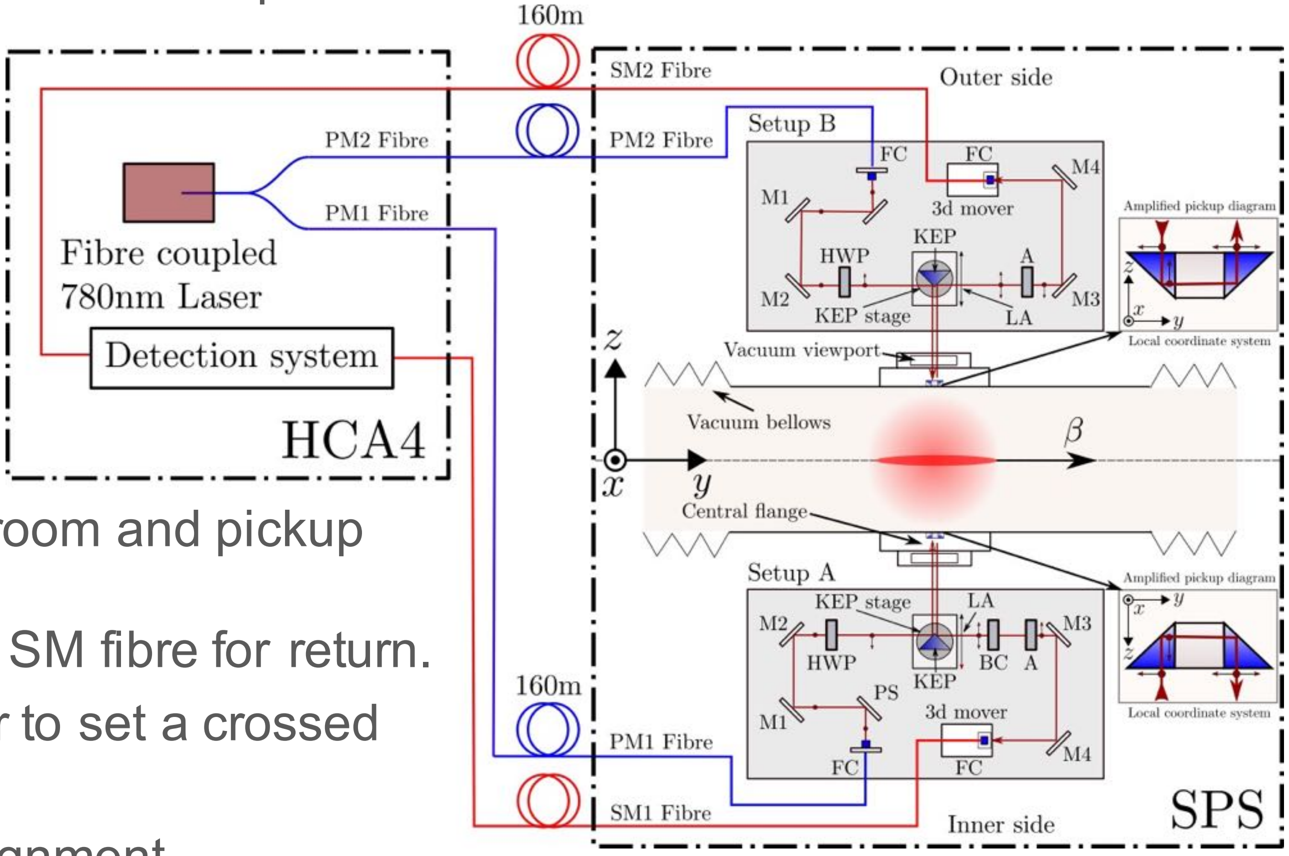




Optical setup

- Bunch Coulomb field as modulating field
- Optical arrangement must replicate an amplitude modulator:





- 160m separation between the rack room and pickup prototype.
  780nm light carried by PM fibre and SM fibre for return.
- Polariser splitter, HWP and Analyser to set a crossed polarisers configuration.
- Arrangement of set of mirrors for alignment.

EO-BPM: compact interferometric design

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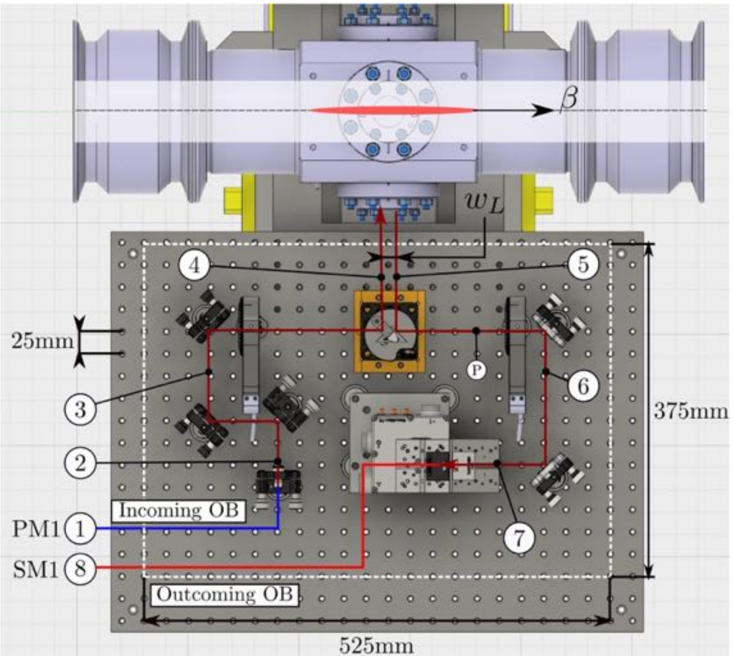
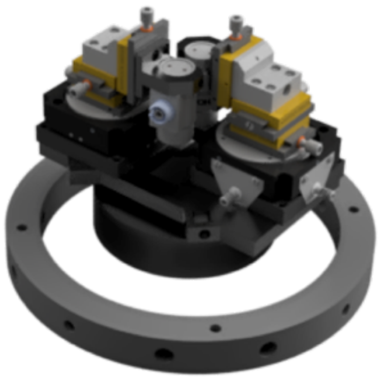
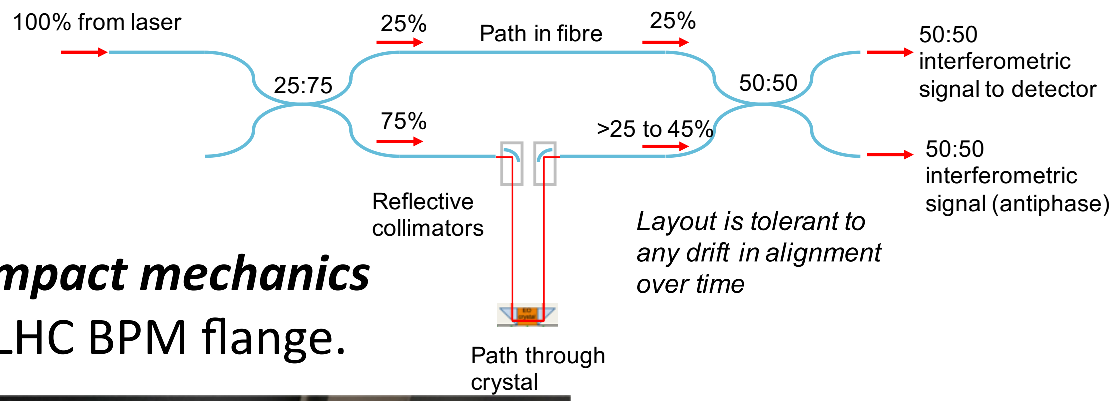
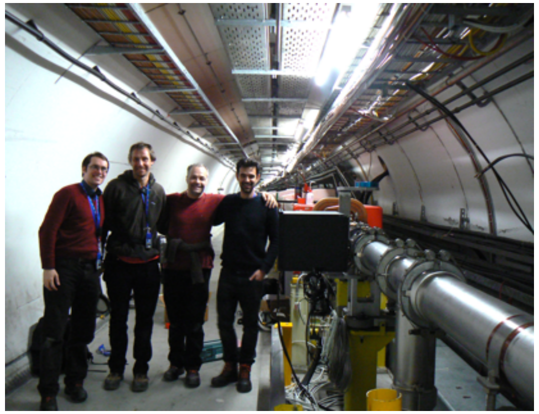


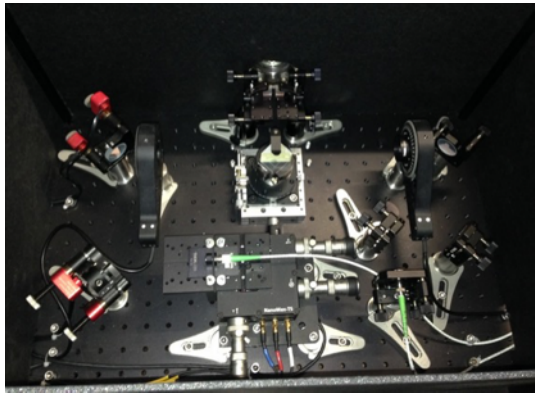
- A pair of fibre-splitters was used to create an interferometer around one EO-crystal as shown.
- Alternatively, as interferometer between opposing EO-pick-ups allows direct optical measurement of the beam position difference signal

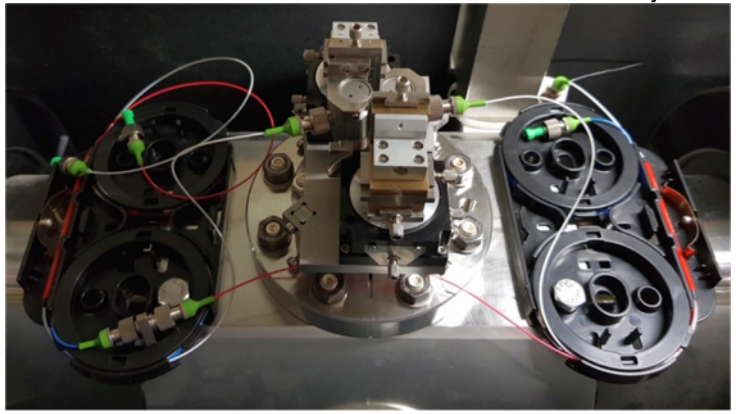


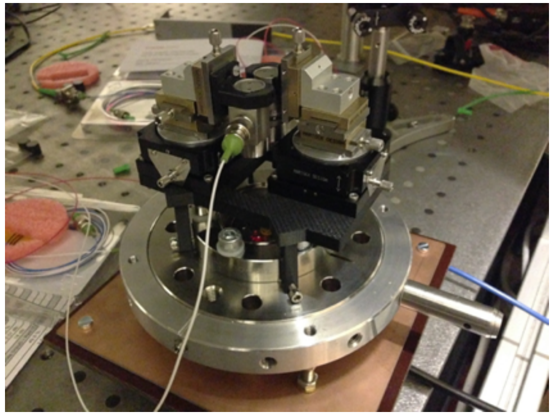
Compact mechanics
fit LHC BPM flange.








Installed on top flange of EO-BPM at SPS


Mounted for bench tests

EO-BPM development for HL-LHC

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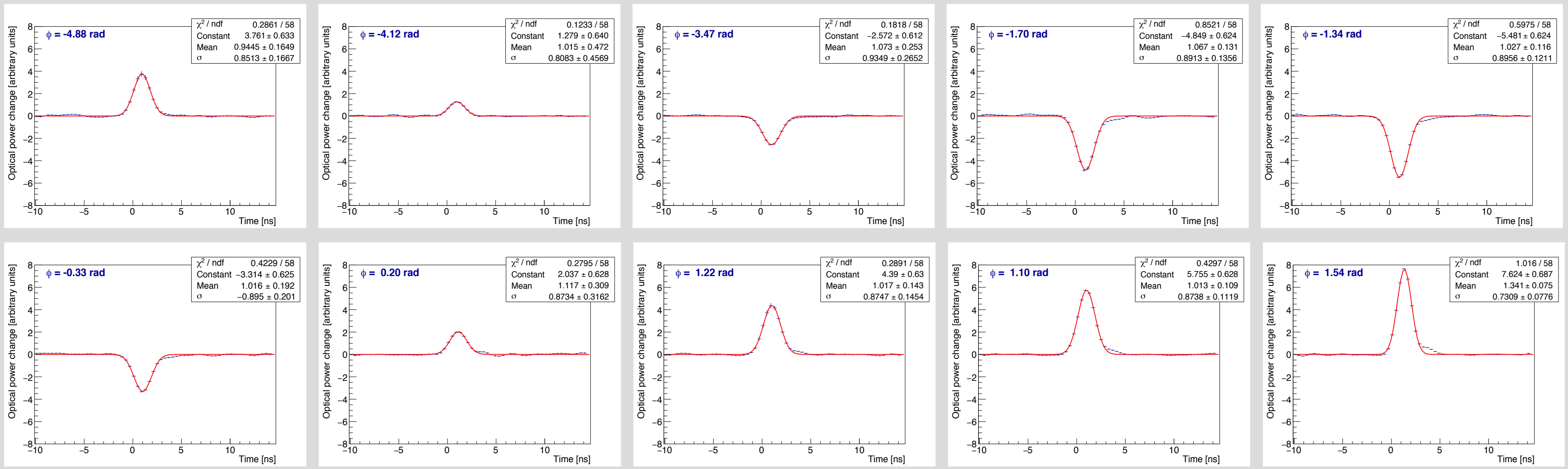
Optical response of the compact EO interferometer to an average SPS bunch as the laser frequency is scanned.

$$\phi(t) = \frac{2\pi}{\lambda} n_e l + \frac{\pi}{\lambda} n_e^3 r_{33} l E_{az}(t)$$



Bandwidth limited by prototype detection system

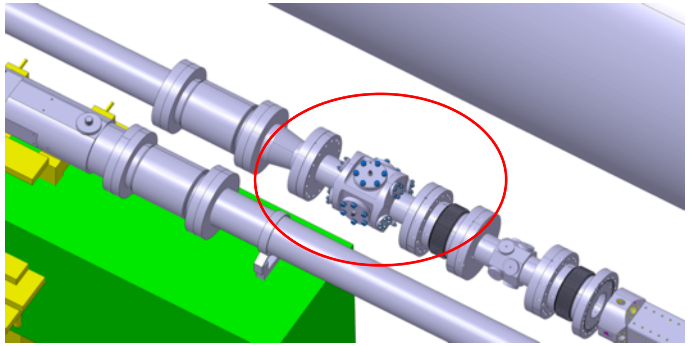
First results from compact setup presented at IPAC18 & IBIC19

S. Gibson et al, Enhanced bunch monitoring by electro-optic interferometric methods, WEP073, IPAC18.

A. Arteche et al, Beam Measurements at the CERN SPS Using Interferometric Electro-Optic Pickups, WEAO04, IBIC19

After SPS run, focus during LS2 is now on RHUL bench tests of LHC compatible design

Space reserved for 4x EO-BPMs in LHC:



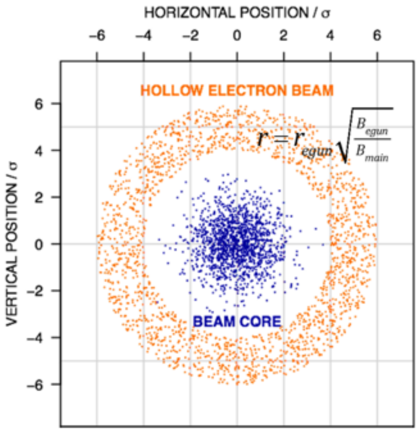
Recent advancements:

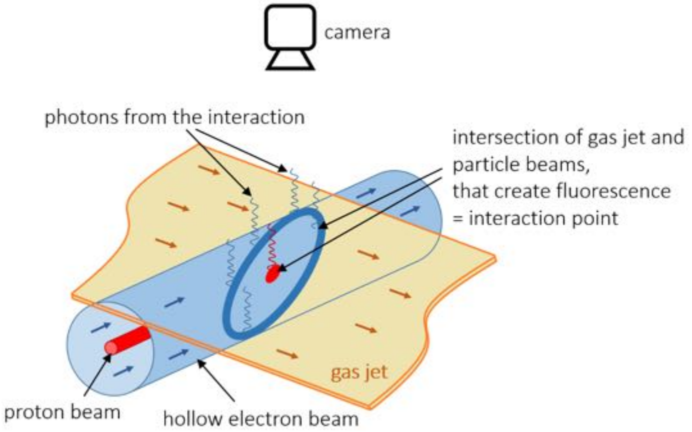
- *Brazed electrode, with crystal outside vacuum*
- *CST simulations with significantly enhanced E-field at crystal*
- *Full fibre-coupled waveguide design*

→ *Beam test of EO-BPM demonstrator planned in HL-LHC-UK phase II project*

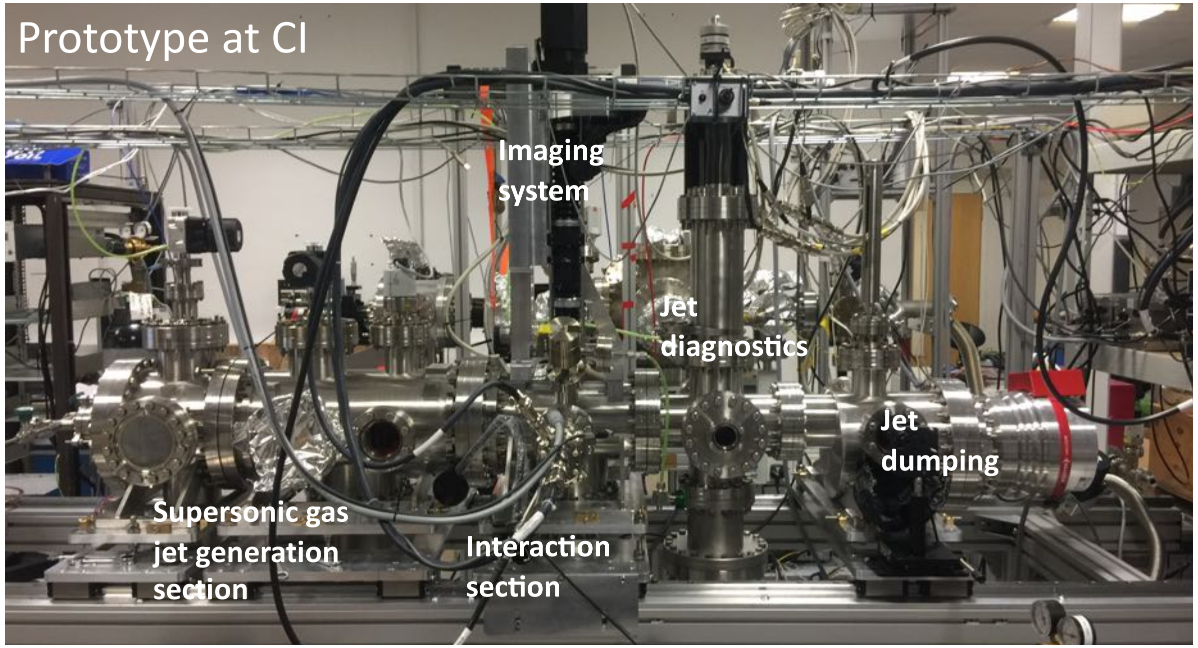
HL-LHC Gas-Jet Profile Monitor

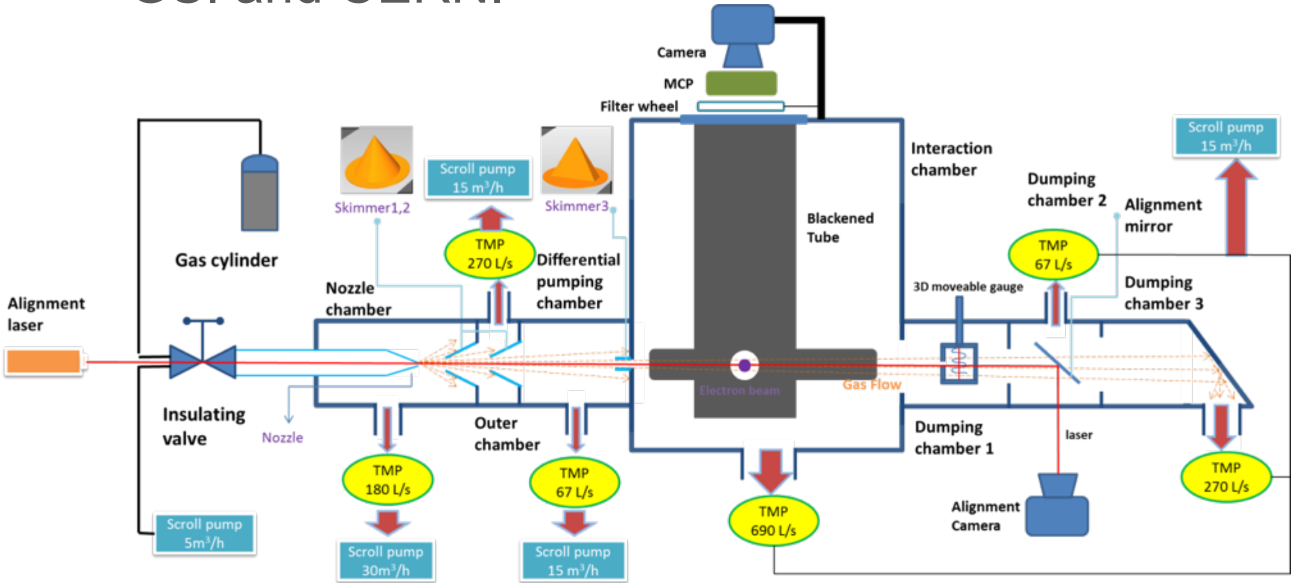
C. Welsch, H. Zhang,
J. Resta Lopez et al
UNIVERSITY OF LIVERPOOL
The Cockcroft Institute of Accelerator Science and Technology





- ***Aim:*** development of a non-invasive beam profile monitor for the hollow electron lens project.
- Beam interacts with gas-curtain formed by supersonic jet of nitrogen passing through the beam pipe.
- Prototypes developed at CI in collaboration with GSI and CERN.



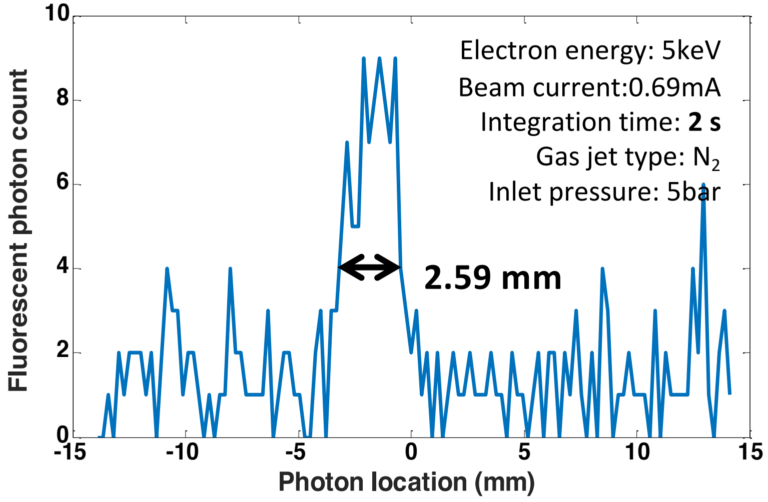


HL-LHC Gas-Jet Profile Monitor

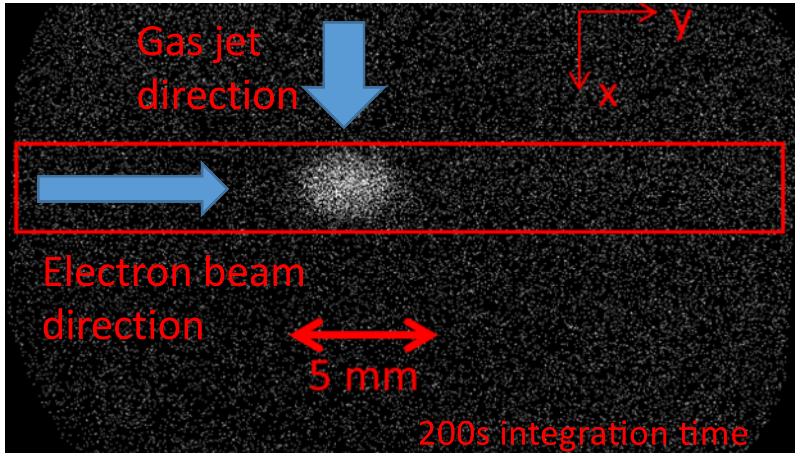
C. Welsch, H. Zhang, J. Resta Lopez et al

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

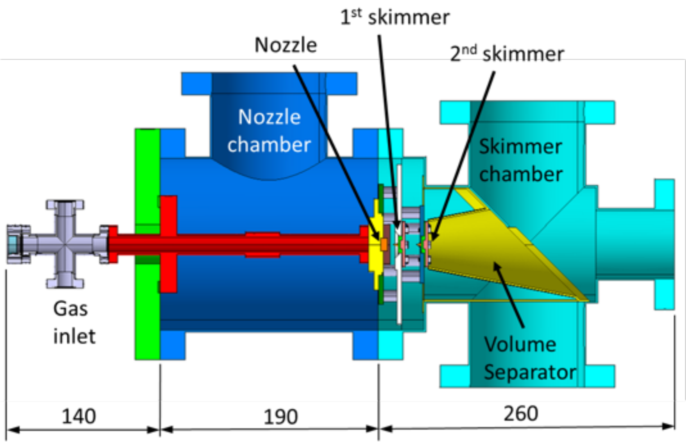


2s integration time to give a profile

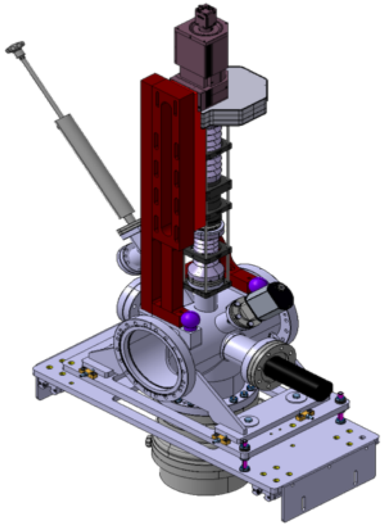


More time to give a 2D detailed image

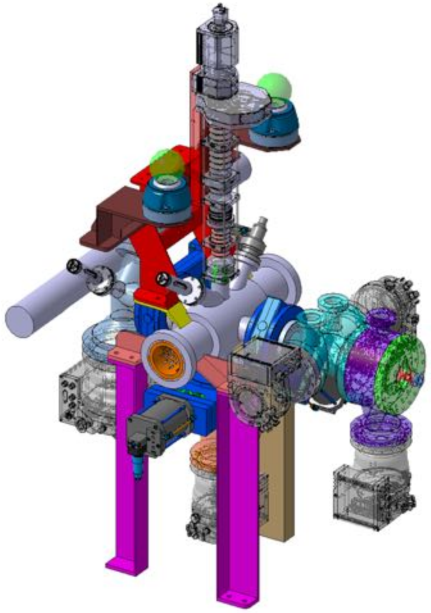
- Promising results with nitrogen gas show improved integration time in low current e-beam tests.
- Expect 2.4 ms for electron beam and 0.3 s for proton beam in hollow electron lens.
- Design in development for LHC:



Section for gas jet generation



Interaction chamber and imaging system

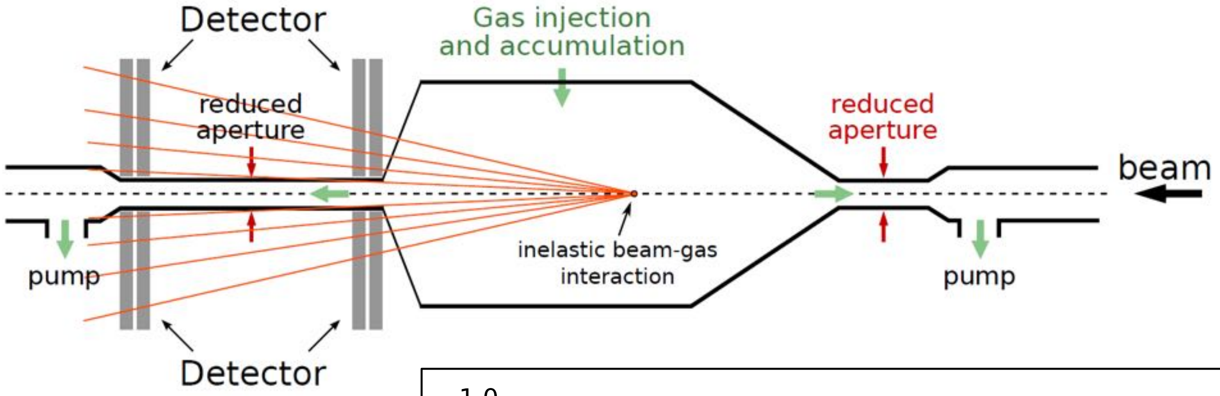


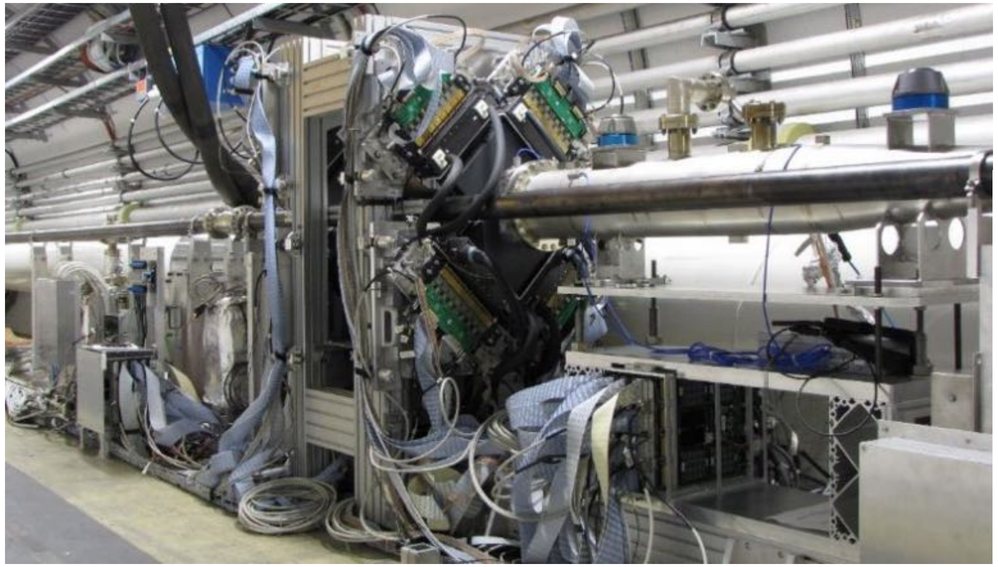
Possible integration in the LHC

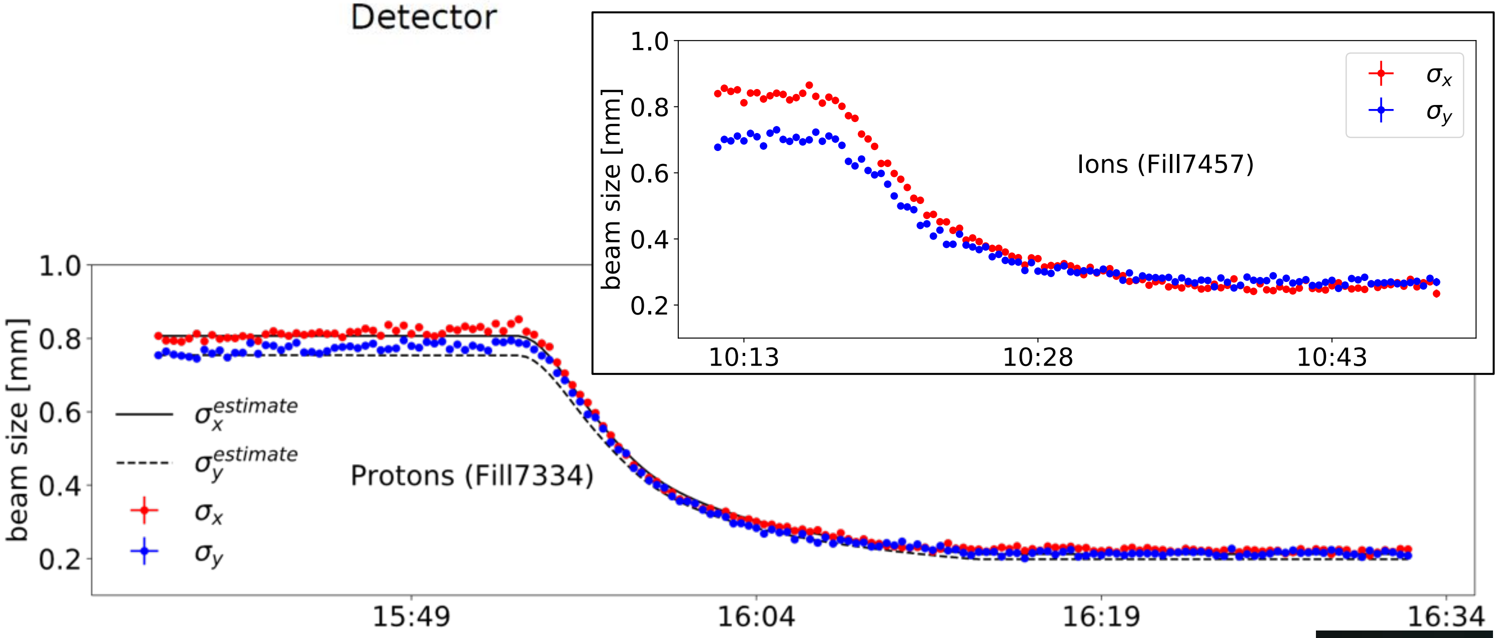
HL-LHC Beam Gas Vertex Detector

R. Kieffer et al

- 2018 Measurements
  - Beam size available in online display
  - Average resolution down to 3 μm
  - Operational measurements during both proton and ion run
  - Being used for emittance studies

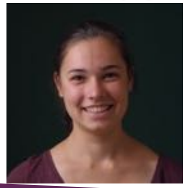






Slide courtesy, R. Jones

…. continued by Hélène Guérin et al, since April 2019.



Potential topics for collaboration at EIC?

- ***Multiple novel beam diagnostics are in development for the HL-LHC that may be synergistic with EIC:***
  - *Beam-Gas Ionisation Profile Monitor – J. Storey & S. Levasseur, CERN / RHUL*
  - *EO-BPM crab cavity diagnostics – S. Gibson, A. Arteche et al, RHUL / CERN*
  - *Gas-jet profile monitor for hollow electron lens – C. Welsch , Liverpool*
  - *BPM readout / fast feedback expertise – P. Burrows, Oxford*
  - *SR interferometric monitor – E. Bravin, Daniele Butti, CERN/RHUL*
  - *Beam Gas Vertex detector – J. Storey & H. Guerin, CERN/RHUL*
  - *Laserwires for electron or ion beams – S. Boogert & S. Gibson, RHUL*
  - *Precise cavity-BPMs – A. Lyapin, RHUL / P. Burrows, Oxford*
  - *OTR & Čerenkov diagnostics – P. Karataev et al, RHUL*
- ***Beyond diagnostics:***
  - *Ion collimation – see EIC workshop talk by Andrey Abramov*
  - *IR design and beam background studies, e.g. with BDSIM – L. Nevay*

Thank you!

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