

Sustainable, Data-Driven Accelerator Infrastructures

Carsten P Welsch, Cockcroft Institute/University of Liverpool



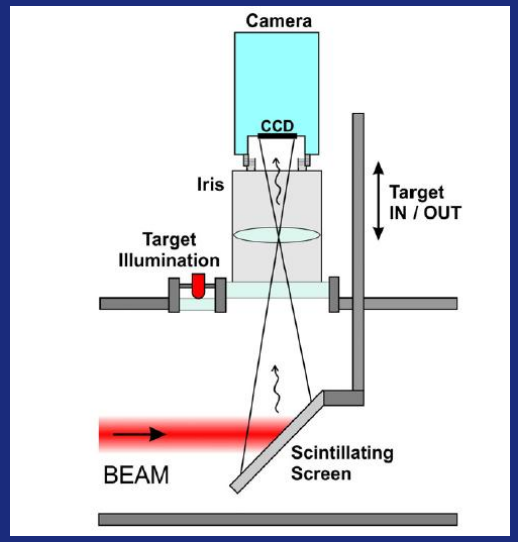
High Luminosity LHC

Enabling scientific discovery

Invasive Methods

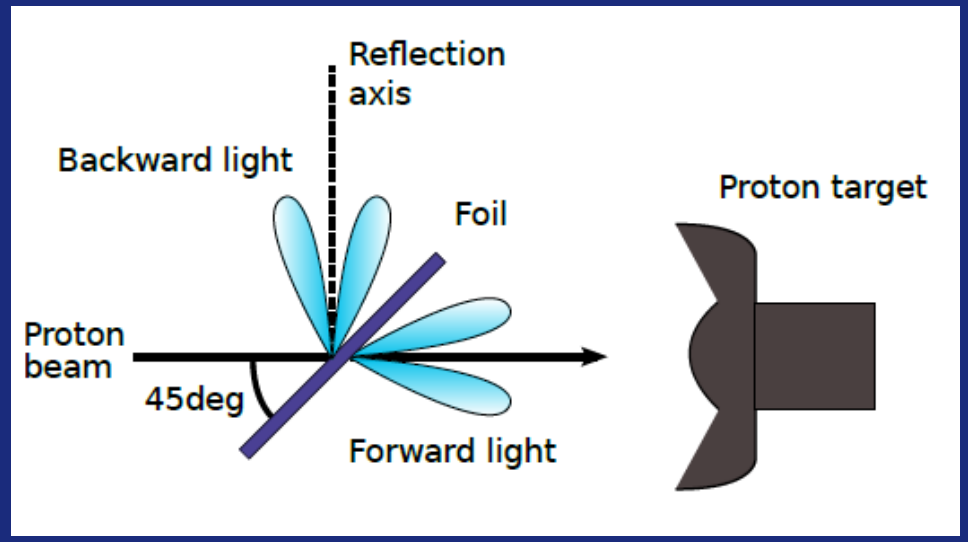
Hadron beams: High intensity and high brightness – high power!

Scintillating screen



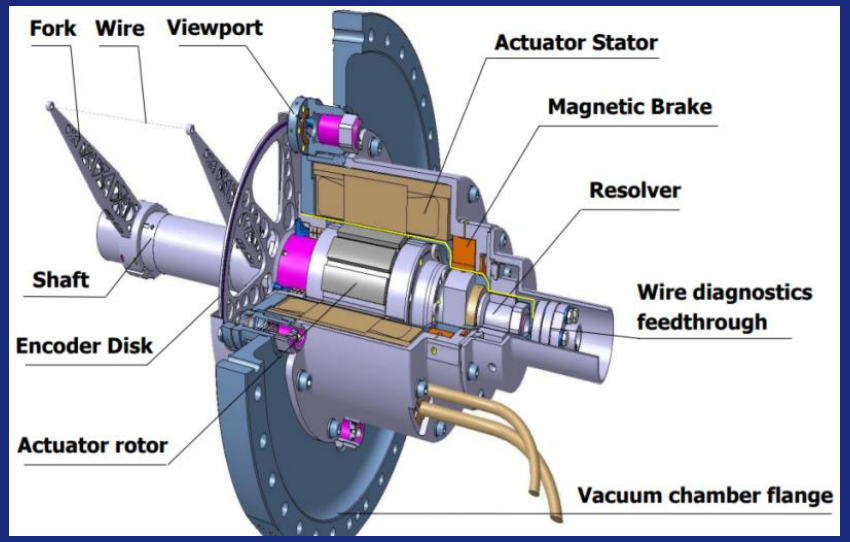
Credit: B. Walasek-Höhne, GSI and G. Kube, DESY

OTR screen



Credit: D. Morris, et al., TRIUMF

Wire Scanner

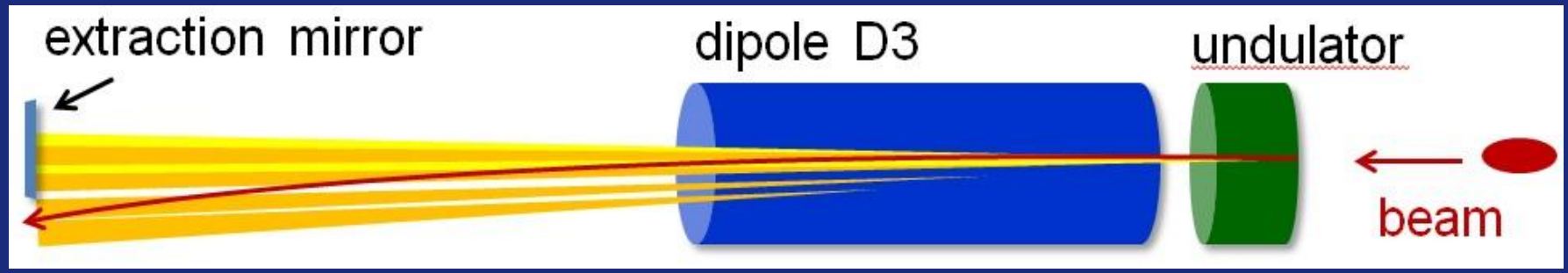


Credit: B. Dehning, et al., CERN

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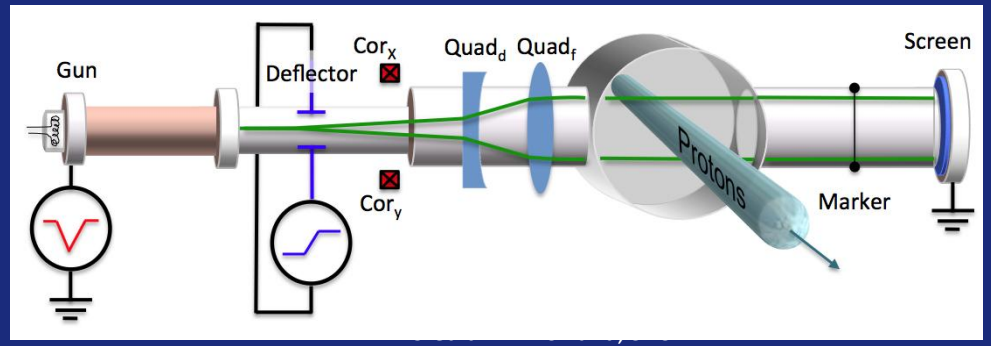
Non-invasive methods

Synchrotron radiation

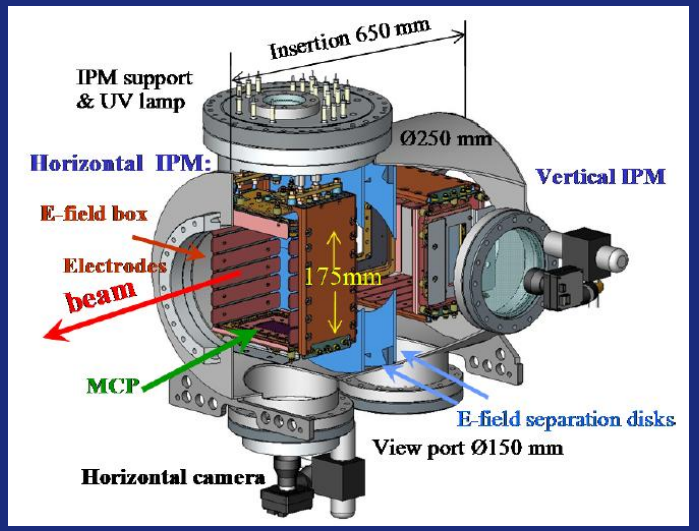


- Signal level
- Space charge distortion

Electron beam Scanner



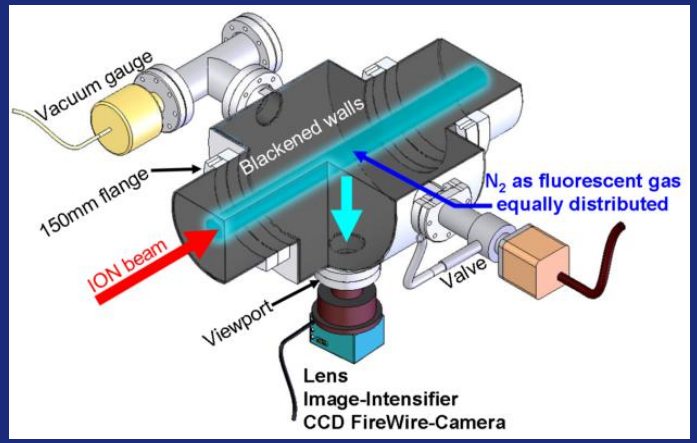
Credit: M. Wendt, CERN



Credit: P. Forck, GSI

Ionization profile monitor

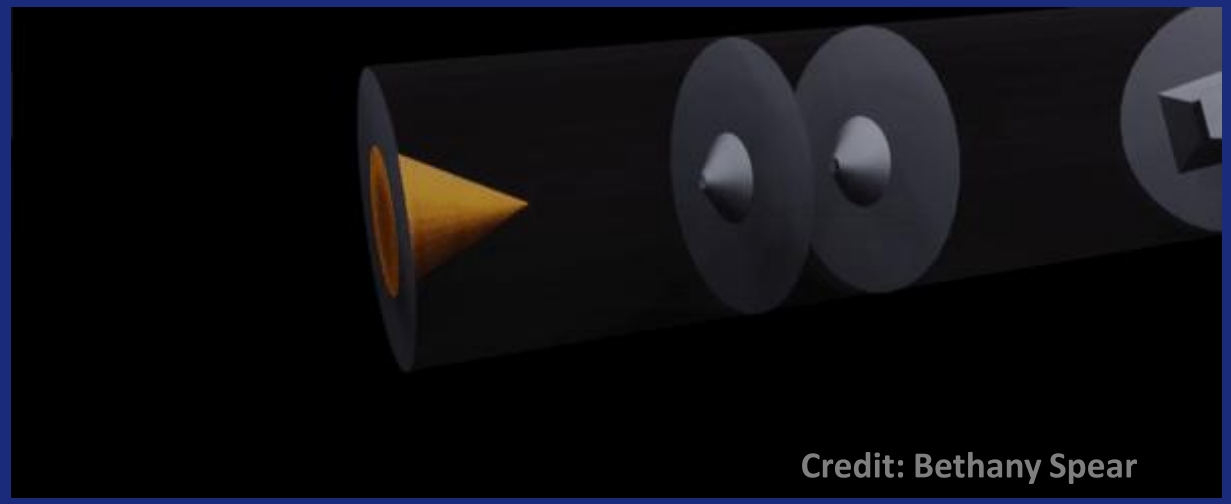
Residual gas-based monitors



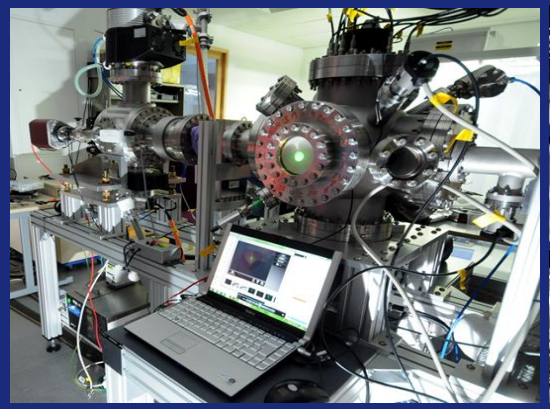
Beam induced fluorescence monitor

Gas Curtain Generation

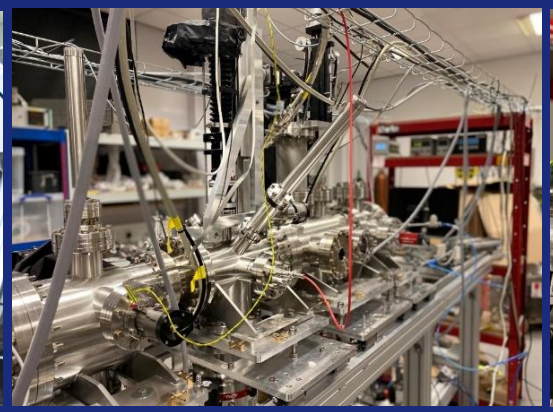
- Accelerate gas to supersonic speeds.
- Collimate the profile using skimmers to a 45 degrees thin curtain.
- 20 years of R&D into gas jet technology.



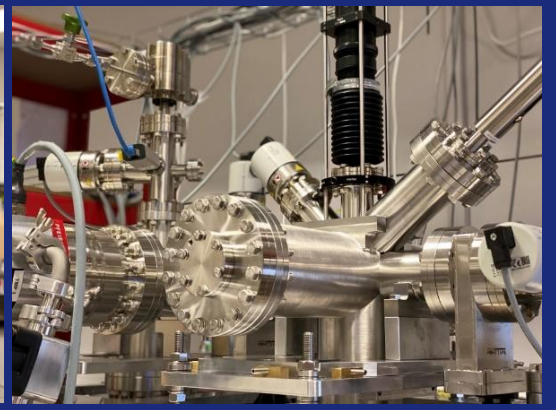
Version 1



Version 2



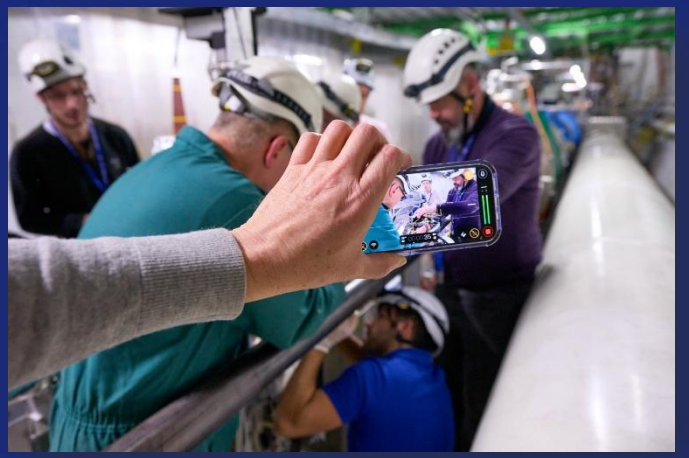
Version 3



UK Prototype Development

- Originally developed as a low energy antimatter physics experiment.
- Changed to non-invasive monitor and focused on HLLHC.
- Extensive testing at the Cockcroft Institute's *DITAlab.*
- Packed and shipped to CERN.
- Installed in the LHC in early 2023.

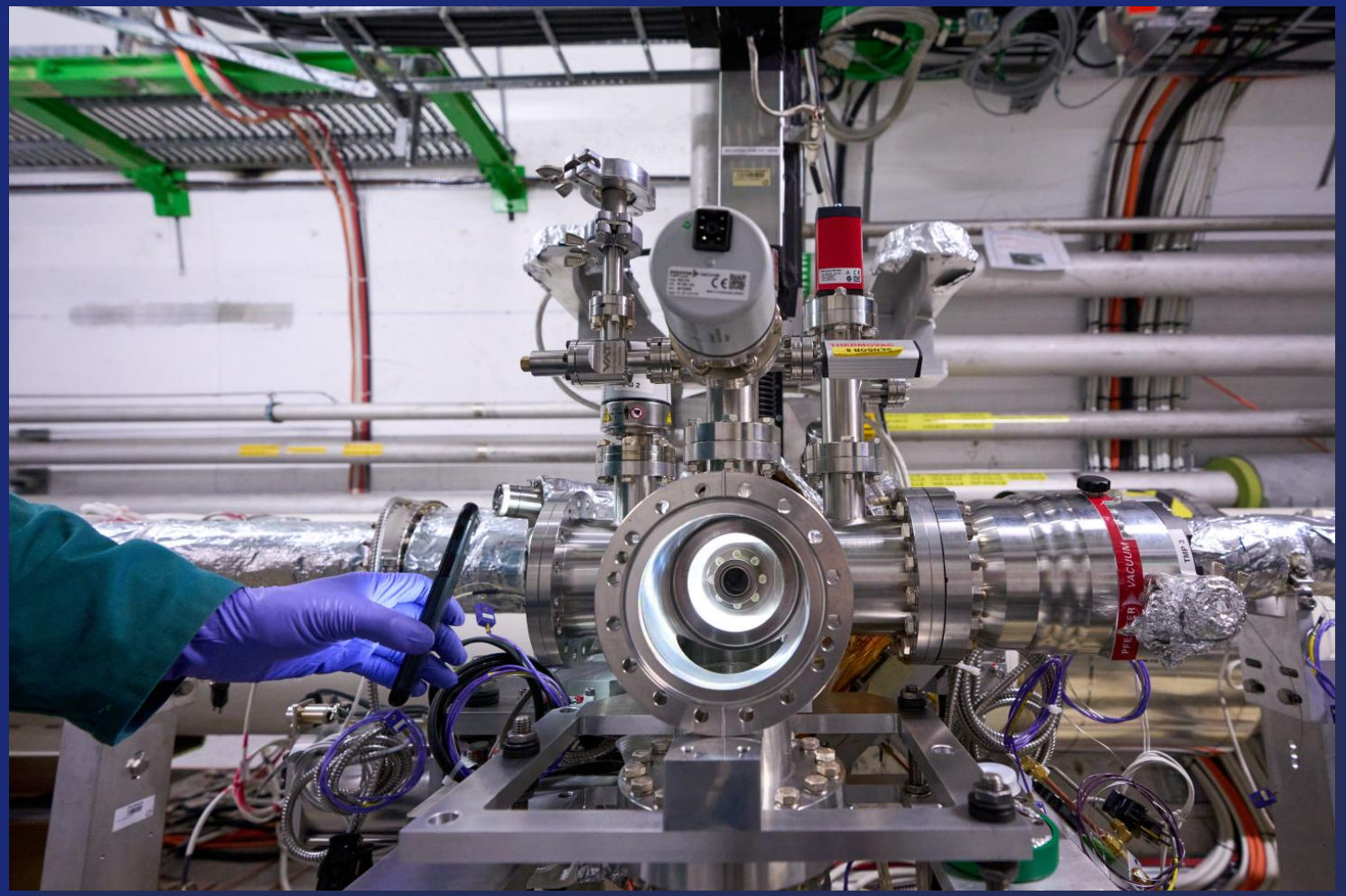




A Welsch, Accelerating News 43 (2023).

BGC installed in the LHC !



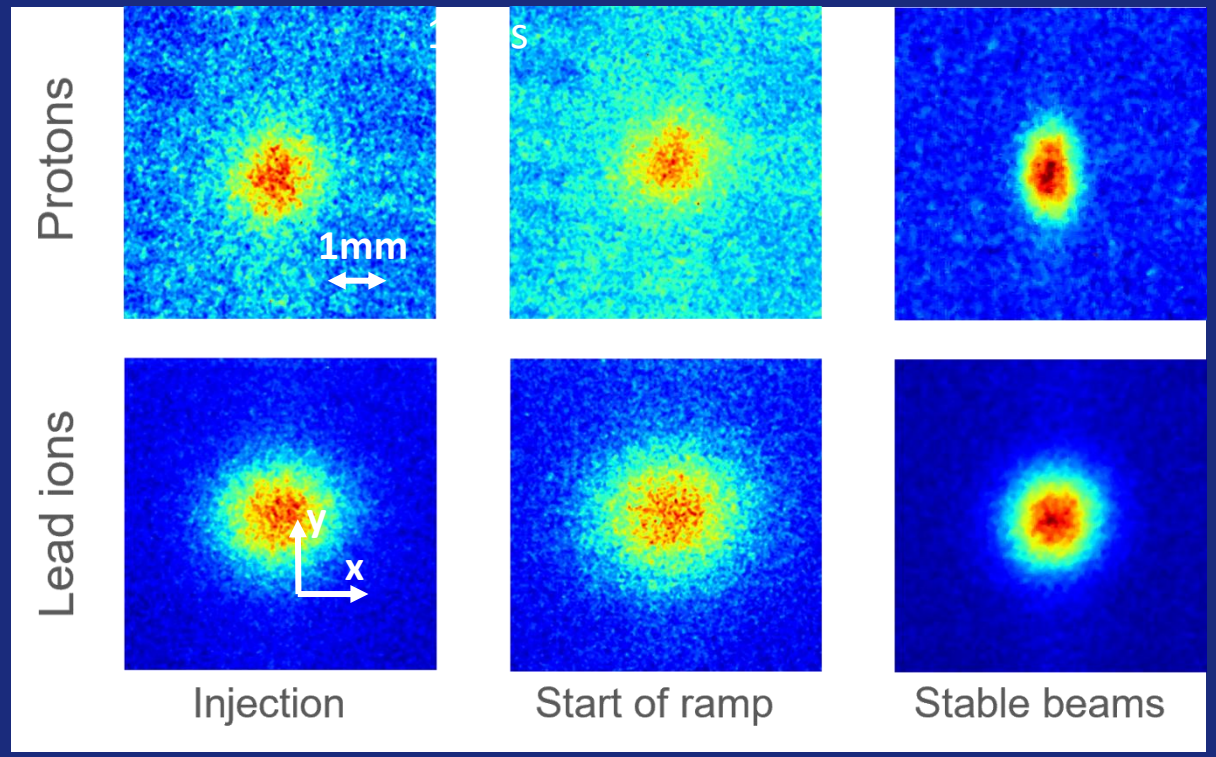


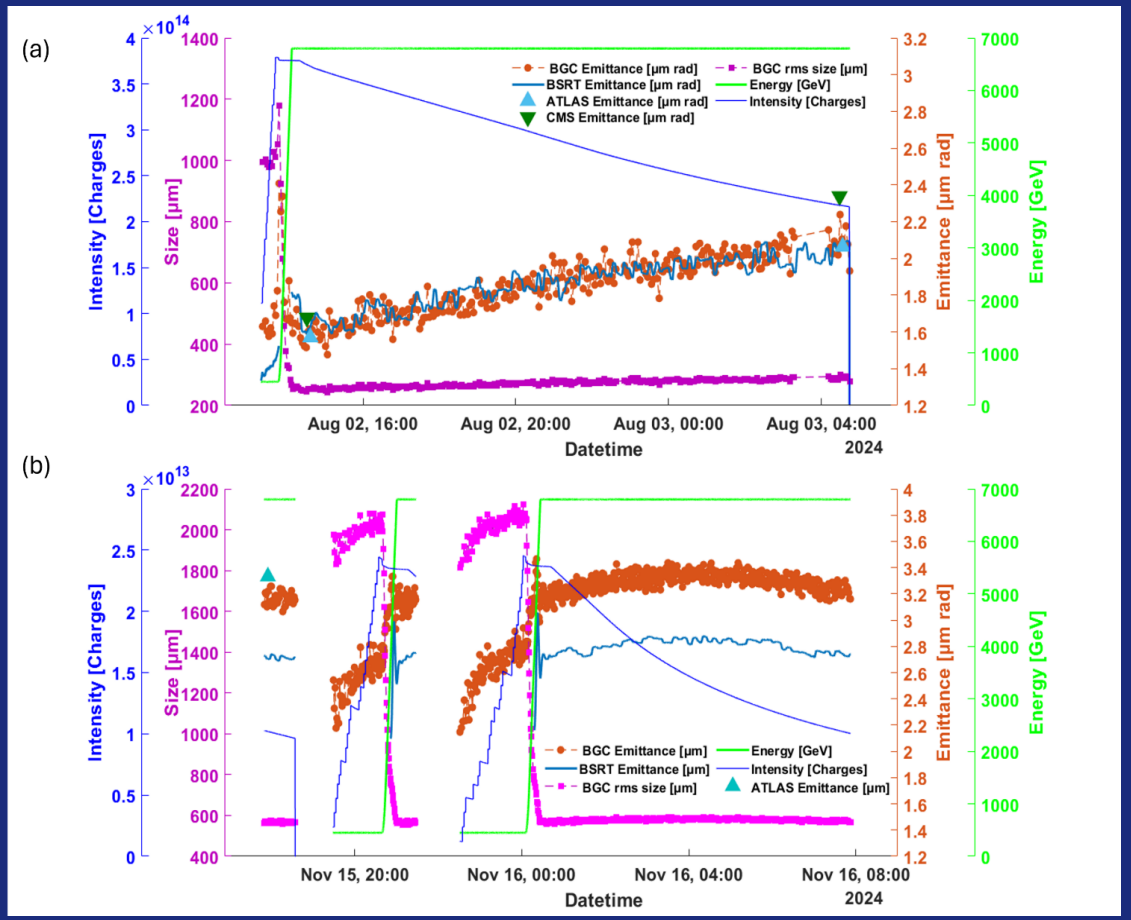
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Physical Review Research **7**, 043144 (2025)


IBGC
Beam Gas Curtain

Beam size and emittance monitor





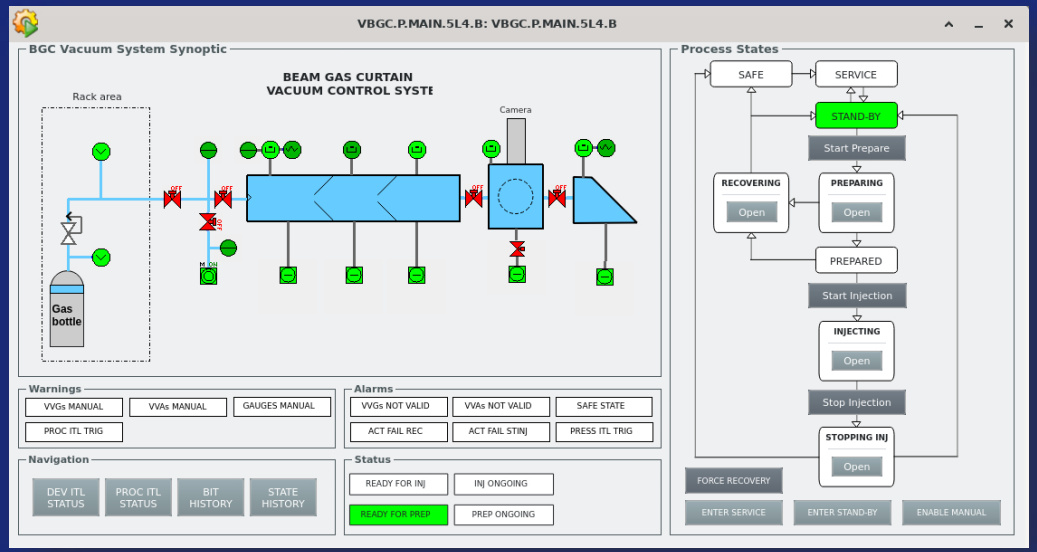
O. Sedlacek et al, *Phys. Rev. Research* 7, 043144 (2025).

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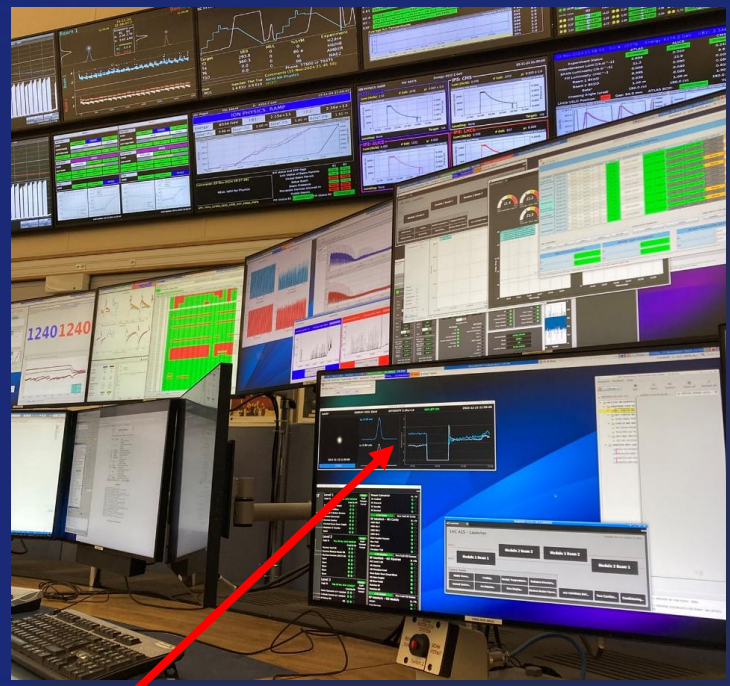
View from CERN Control Center

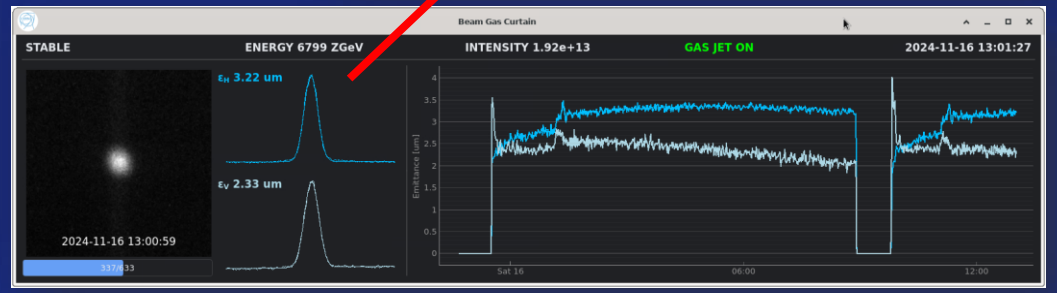
BGC was successfully used throughout the 2024 ion run and the 2025 proton run.

Average emittance measurements are available online.



New BGC vacuum control for operator use.





D. Butti

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Now: award-winning!

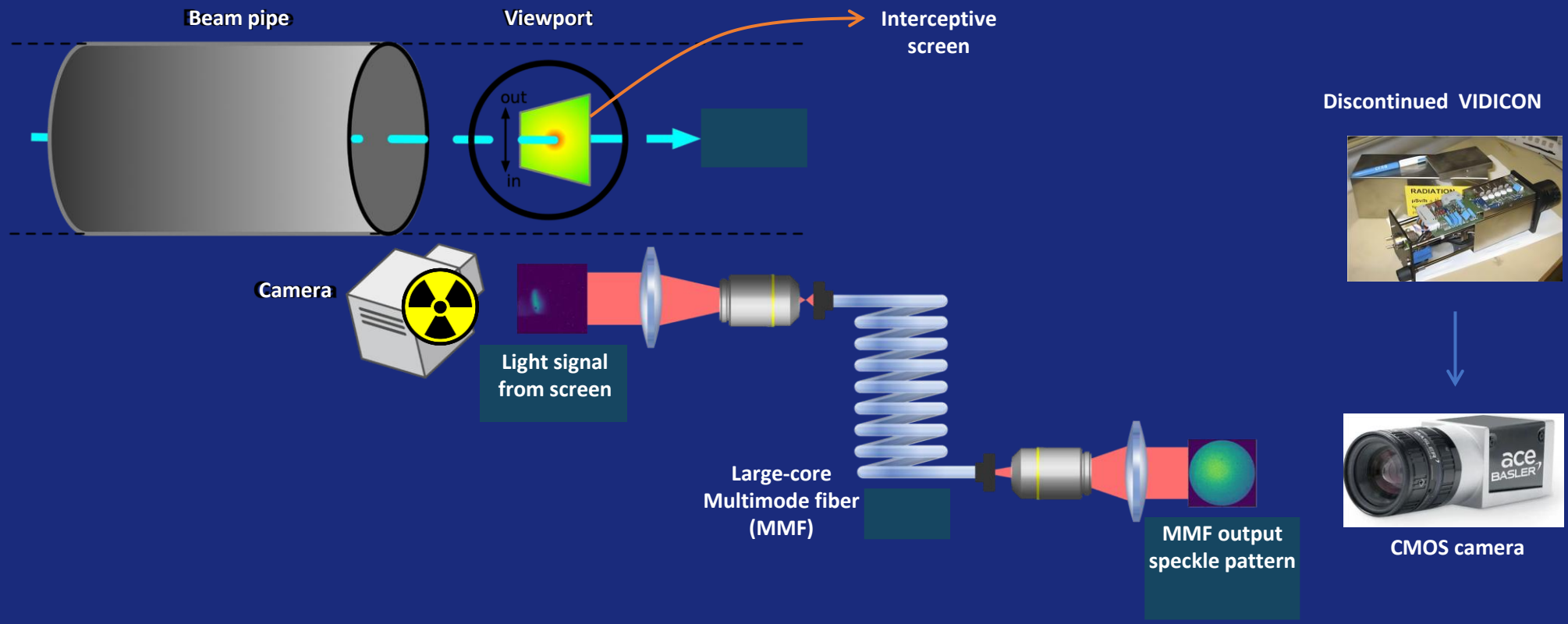
The Beam Gas Curtain monitor won the 2026 Faraday Cup award – the most important international prize for beam instrumentation R&D.



20 years of collaborative development turned an idea into an operational instrument that can characterize *any* beam.

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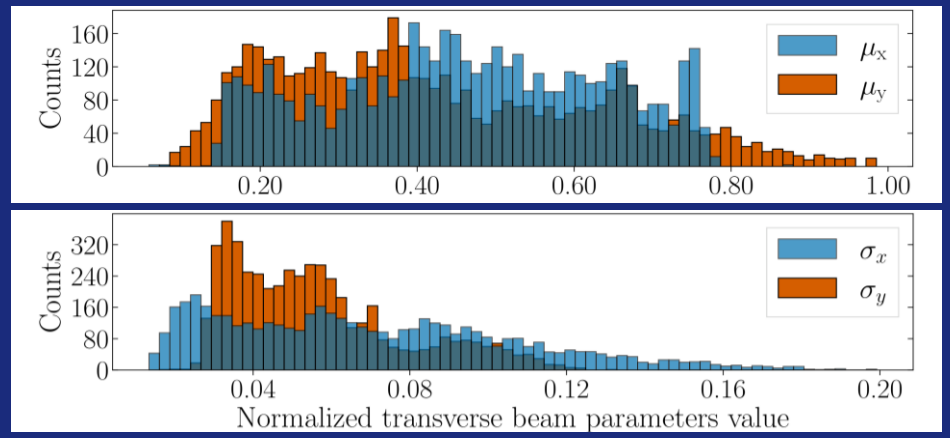
MMF-relayed Transverse Beam Imaging

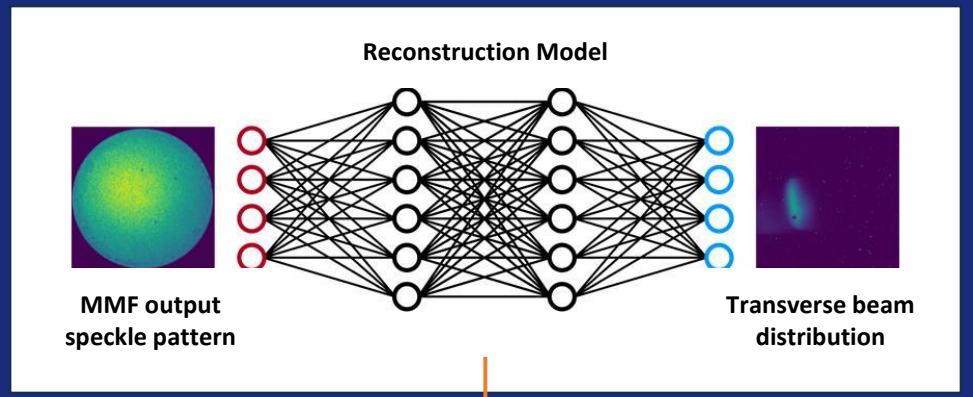


- Screen light is relayed through single Multi-Mode Fiber (MMF) to move camera outside of radiation area.
- <u>Challenge</u>: MMF output is a scrambled pattern requiring reconstruction.

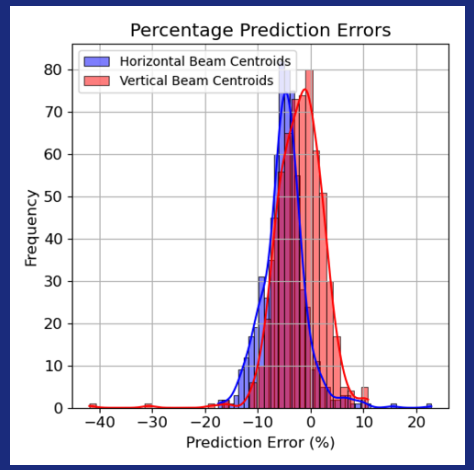
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Training Data is Reconstruction Bottleneck





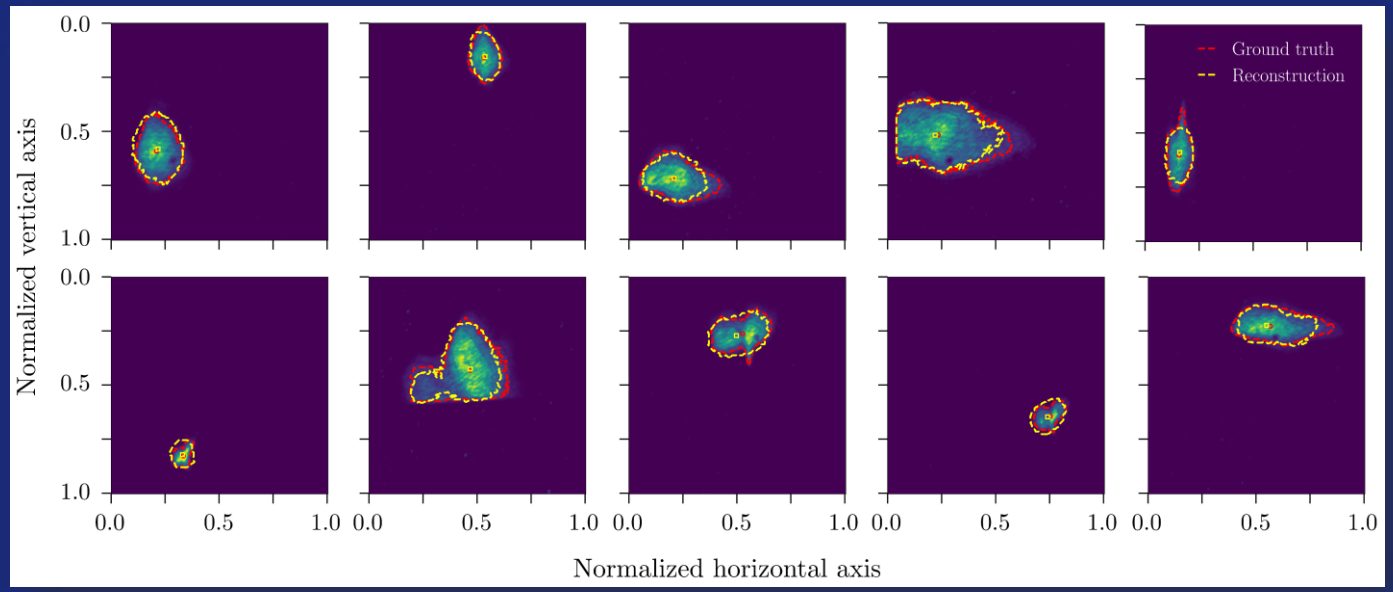
- Beam time and scan constraints limit coverage of beam conditions.
- Collecting more training data risks **degrading the reference camera**.
- Imbalanced parameter coverage **reduces generalization** and introduces **prediction bias**.

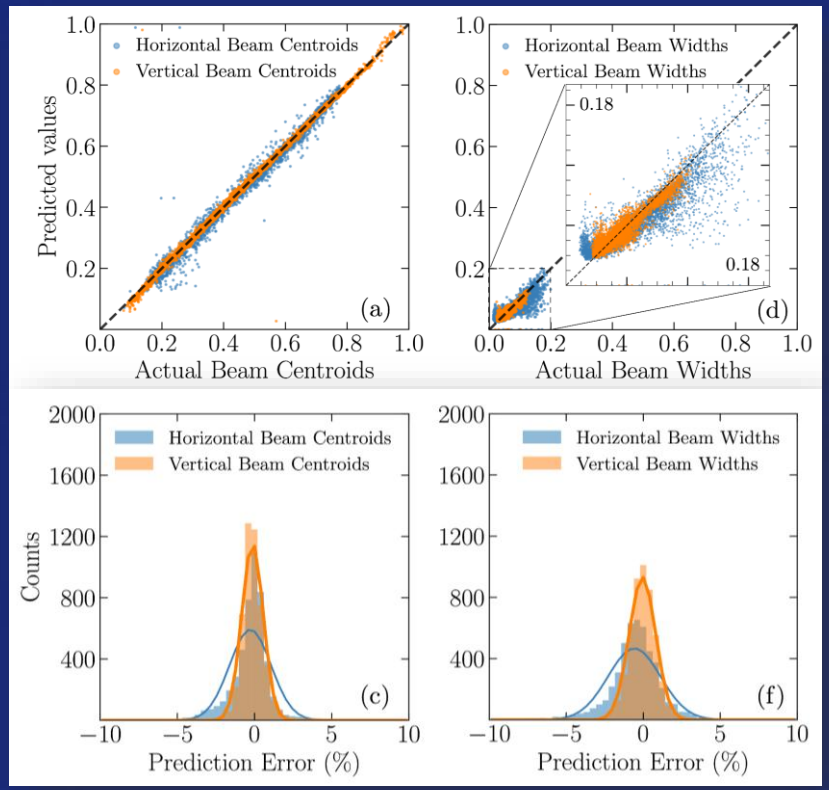


Can synthetic beam-like data provide broader and less biased training coverage?

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Reconstruction of Replayed CLEAR Images



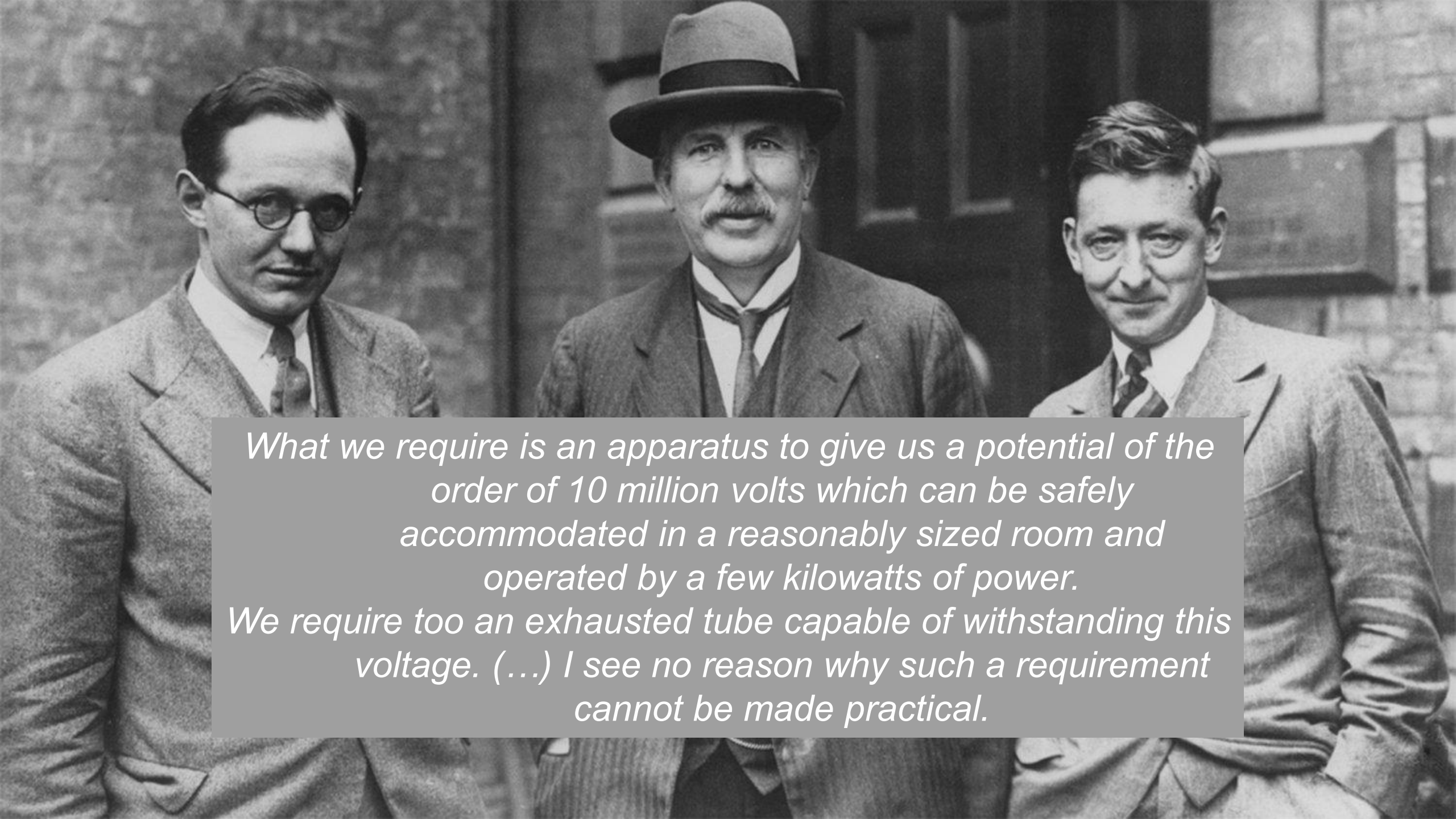


In the controlled DMD–MMF setup, the synthetic Gaussian mixture (SGM)-trained convolution auto-encoder (CAE) reduced the mean relative RMSE over four transverse beam parameters from 5.60% to just 1.49%.

Q. Xu, *et al.*, *Phys. Rev. Accel. Beams* **29**, 032801 (2026).

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This nation should commit itself to achieve the goal,
before this decade is out, of landing a man on the moon
and returning him safely to earth.
J.F. Kennedy
UNITED
STATES



What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accommodated in a reasonably sized room and operated by a few kilowatts of power.
We require too an exhausted tube capable of withstanding this voltage. (…) I see no reason why such a requirement cannot be made practical.

What we require is the design and construction of a laser capable of delivering pulses with a duration of 100 femtoseconds and an energy of 100 joules, at a repetition rate up to 100 Hertz and a user facility build around this technology in this decade.

EuPRAXIA

Accelerating Innovation



FP7 Design Study: 3 M€

Operation: 2030 - 2065

INFRA
3 M€



ERDF
20 M€

Italy
100 M€

PACRI

INFRA
10 M€

ESFRI
European Strategy Forum on Research Infrastructures

EuPRAXIA Doctoral Network

MSCA-DN
3.2 M€

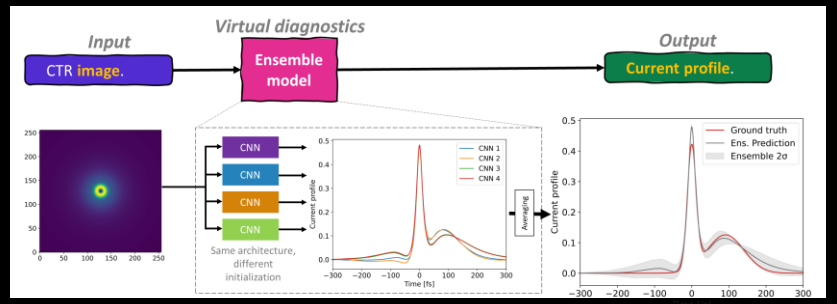
Bunch length measurement with fs resolution

EuPRAXIA Doctoral Network

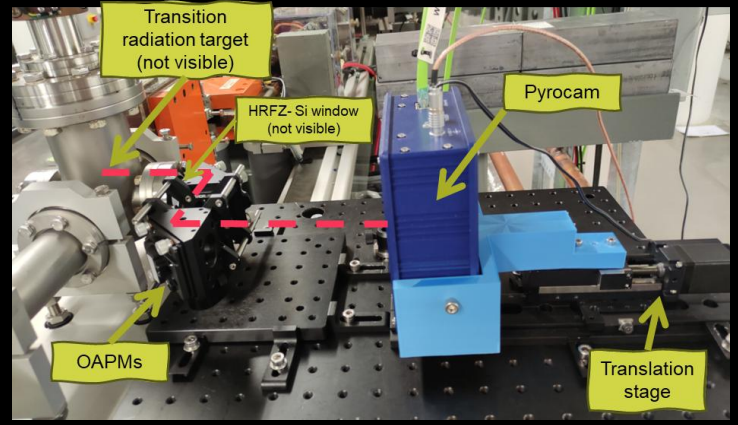
Research focus

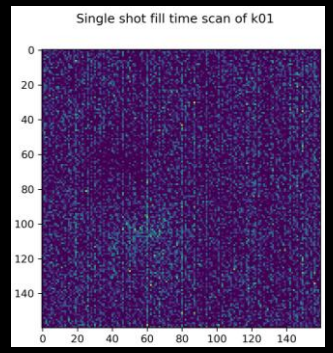
1. Deep learning and data analysis suitable for electron bunch profile reconstruction.
2. Bunch length monitor design, development, and integration.
3. Integration of simulation-experimental results.`

- Deep learning ensemble models applied to simulated CTR images (gaussian and elegant-simulated bunches).
- Talk at ICAP'24 and IBIC 2026



- Optical design simulations and testing in the lab for reflective optics (off-axis parabolic mirrors, OAPMs) for coherent transition radiation (CTR) imaging.
- Beamtime at MAX IV completed in February 2025
- *Instruments* **9**(4), 29 (2025)





- Results of applying transfer learning to deep learning models for evaluating the reconstruction of bunch profiles from experimentally acquired CTR images presented at IBIC 2025.

A glimpse into the future

These are just a few example technologies – there is so much more!

Accelerator-based research infrastructures need a **systems-level approach** to integrate

- Beam diagnostics and advanced sensors
- AI, data and machine learning

for more intelligent accelerator design and operation.

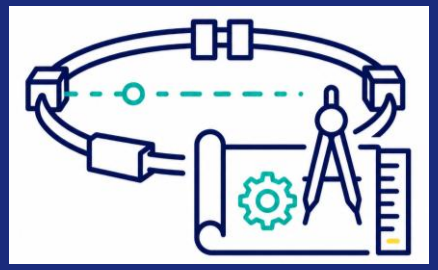
This will enable better science and novel applications.



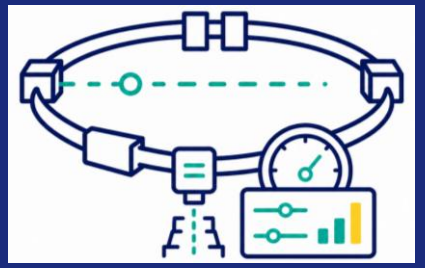
iRIS - expected outcomes



Sustainability analysis Methodology, training and guidelines



Tools to enhance particle accelerator efficiency by design



Tools to enhance particle accelerator operation efficiency



Online materials characterization transferrable to markets



Soil reconstitution procedure transferrable to markets



Non-intrusive load monitoring transferrable To markets

Horizon Europe

- Opportunity to improve the status quo through collaboration
- ARTIFACT, TIARA, RAISE and SCIANCE all helping steer activities

www.irisproject.eu

epita.web.cern.ch

artifact-network.org

EuPRAXIA
Novel Applications

ARTIFACT
Doctoral Network

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Accelerating innovation

International collaboration is key

Summary & outlook

- Future accelerators need to be more sustainable, energy efficient and intelligent.
- Smooth integration of beam diagnostics, machine-learning and AI into accelerator design, optimization and operation will be key!
- Fantastic opportunity to engage with new European initiatives to get the most out of your research.

Let’s design the future – together!



http://www.quasar-group.org