

Status of concepts and main technologies for the FCC-hh beam instrumentation systems

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*on behalf of **BE-BI**. Thanks to R. Jones, T. Lefevre, R. Veness,
F. Roncarolo, T. Mitsuhashi, S. Mazzoni, R. Kieffer, J. Storey.*

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Summary of Beam Diagnostics Requirements and Concepts from FCC-hh CDR

- Beam Position Monitoring
- Beam Loss Monitoring
- Beam Current and Intensity Measurements
- Transverse Profile Measurements

Ongoing R&D

- Beam Synchrotron Light Monitors
- Beam Gas Curtain
- Beam Gas Vertex detector
- Ionisation Profile Monitors
- Future non invasive 'wire' scanner alternative.

| | LHC (HL-LHC) | FCC-hh baseline |
|---|---|--------------------|
| Collision energy [TeV] | 14  | 100 |
| Dipole Field [T] | 8.3 | 16 |
| Luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$] | 1 (5) | 5 |
| Normalised emittance [μm] | 3.5 (2.5) | 2.2 |
| Bunch charge [10^{11}] | 1.1 (2.2) | 1 |
| Bunch spacing [ns] | 25 | 25 |
| Number of bunches | 2808 | 10400 |
| SR power per ring [MW] | 0.0036 (0.0073)  | 2.4 |

Operational scenarios considered:

- Beam commissioning
(low intensity, single bunch)
- Machine protection testing
(nominal intensity, single bunch)
- Nominal beam operation

Table 3.12: Basic FCC-hh parameters of relevance for operation of beam diagnostic devices.

| Particle type | Bunch spacing (ns) | Bunch charge (e) | Number of bunches | Transverse size (μm) $\beta=200\text{m}$ E=3.3 TeV | Transverse size (μm) $\beta=200\text{m}$ E=50 TeV |
|---------------|--------------------|--|----------------------------------|--|---|
| p^+ | 25 (5) | $5 \times 10^8 \rightarrow 1 \times 10^{11}$ ($5 \times 10^8 \rightarrow 2 \times 10^{10}$) | $1 \rightarrow 10600$ (53000) | 350 [$\varepsilon=2.2$] (150 [$\varepsilon=0.44$]) | $90 \rightarrow 30$ [$\varepsilon=2.2 \rightarrow 0.2$] ($40 \rightarrow 10$ [$\varepsilon=0.44 \rightarrow 0.04$]) |

Similar requirements to the LHC.

Dual plane beam position monitors on all quadrupoles - 2000 required.

Higher synchrotron radiation in FCC:

- Sensors placed at 45°. Failure of one sensor leaves both planes unusable.
- Active sensor area is smaller, so less sensitive. Pilot bunch implications?

Accuracy requirements:

(similar to HL-LHC)

- Alignment of 200um or better.
- Sub-micron resolution measurements of closed orbit.
- Fill-to-fill reproducibility of better than 20um.

Real time data for orbit and radial position feedback.

Turn by turn data for injection oscillations, optic measurements.

State-of-the-art BPM acquisition system should meet FCC requirements.

Sensor & front-end electronics (analogue signal processing & digitisation) in tunnel.

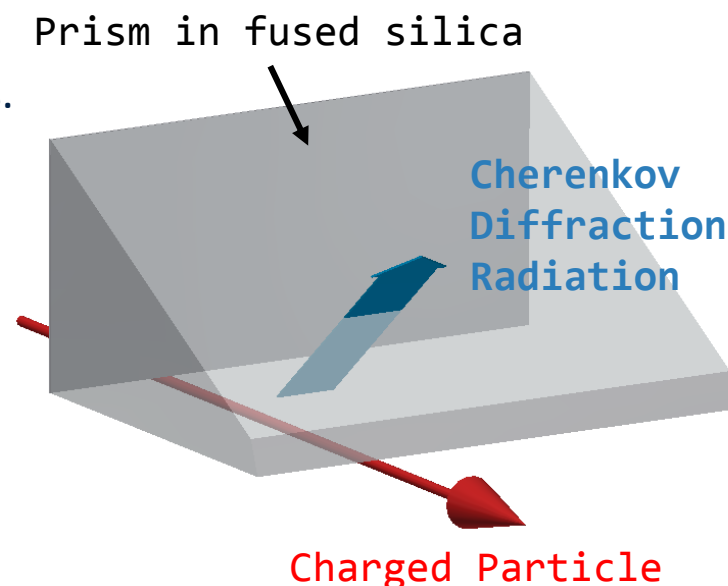
Fibre-optic link (rad-hard, bi-directional) to processing electronics on the surface.

Operational challenges:

- Radiation dose 200x compared to LHC – electronics already proven at these levels.
- High energy hadron fluence is 500x higher than LHC – impact needs study.

Limitation of BPM crosstalk

- Present in common beam pipe regions near IPs.
- Highest precision & reproducibility required
- Optical BPMs using directional Cherenkov diffraction radiation proposed.
- Crosstalk reduction by ~20 times could be achieved, further study needed.



Requirements:

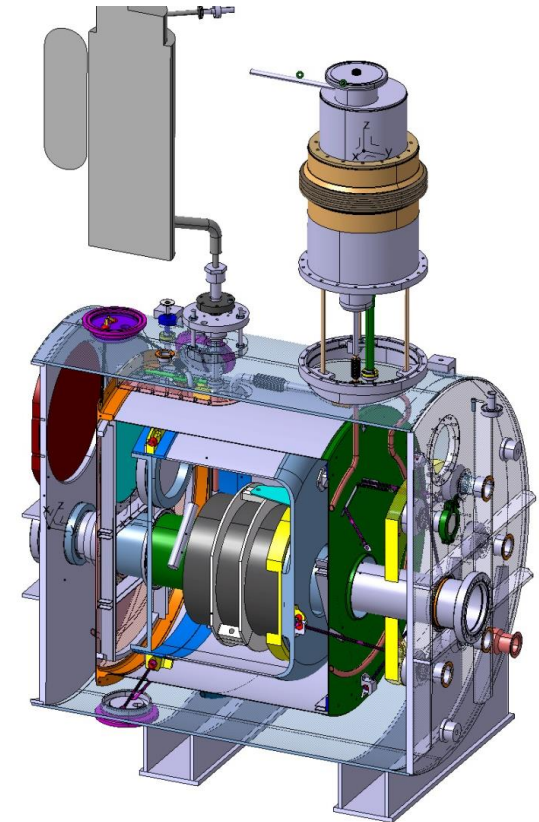
- Circulating current and bunch-by-bunch intensities.
- Beam and bunch lifetimes.

Challenges:

- **Large dynamic range** - 0.25 μA (1 bunch, $5\text{E}8\text{ p}^+$) to 0.5A (10600 bunches, $1\text{E}11\text{ p}^+$)
- **Machine protection interlock** on setup beam (low current, single bunch). Accuracy & resolution $\sim 0.05\mu\text{A}$.

Pilot bunch measurement

- 10pC bunch measurements using inductive pick-ups, done at CLEAR and common at Free Electron Lasers.
- **Cryogenic current comparator** offers best possible beam current resolution – 5nA. Very effective with low intensity beams – further study needed for high intensities of FCC.



AD Cryogenic Current Comparator, BI-EA

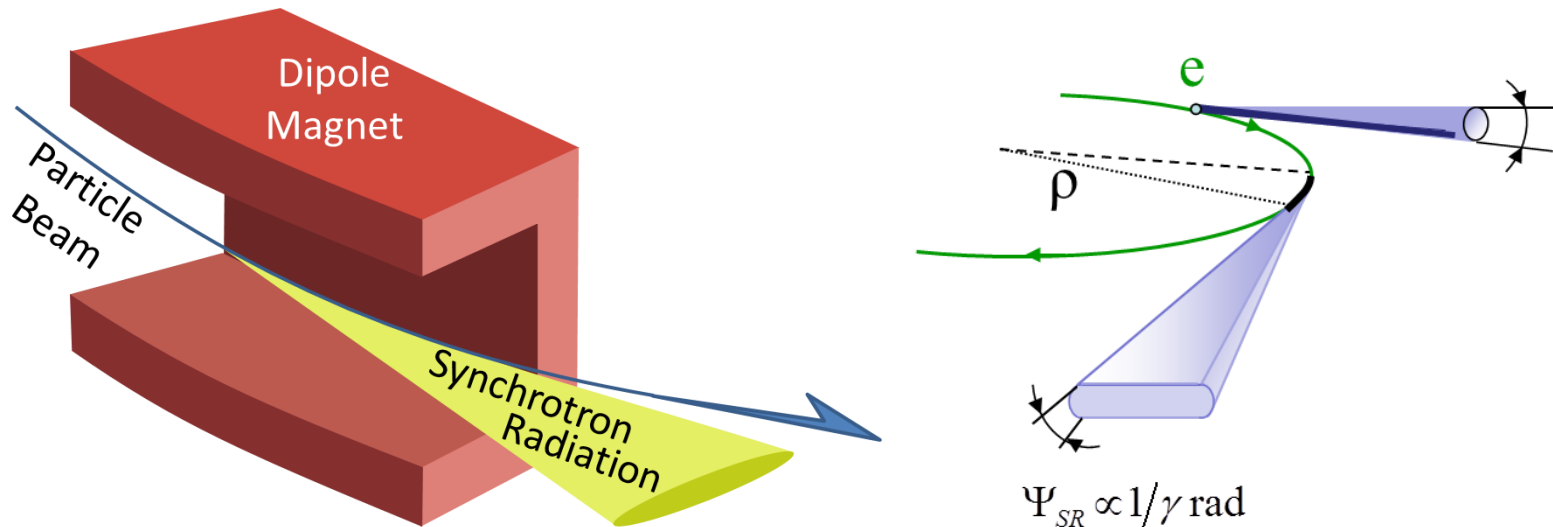
Interceptive devices cannot be used for high energy density beams.

- Several instruments are often used for beam size measurement
- Limitation is calibration of these separate monitors
- Wire scanners are good for calibration - need alternatives for FCC.

Continuous measurements of absolute and bunch-by-bunch emittance.

- Challenge is measurement of the whole beam life-cycle - from injection energy to flat-top run.
- Target 1% accuracy on beam size throughout.
- Main difficulty is for small beam sizes at high energies. (10-30 μm in arcs)

Synchrotron radiation is emitted by charged particles when they are deflected.



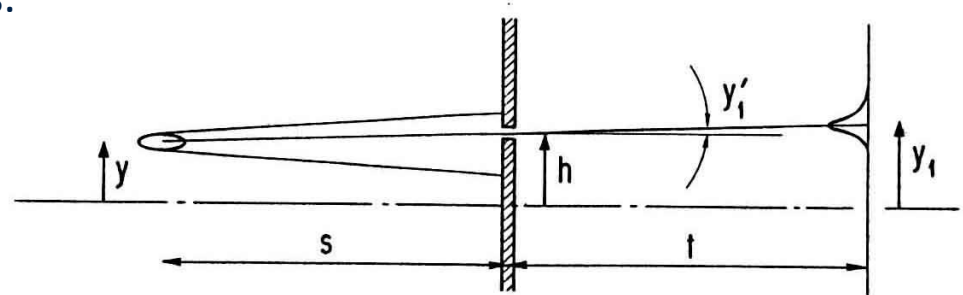
Limitations:

- **Diffraction** effect as light is emitted in a narrow angular cone
- **Field of Depth** effect as the source is extended over the magnet length.

Implications for FCC

- Lots of visible light generated from standard bending dipole at all energies, and X-rays above 30TeV.
- Larger heat deposition on the mirror – compensate with direct cooling.
- X-ray pin-hole camera is proposed to measure small beam sizes at top energies.
- Cross calibration is necessary – wire scanners are currently used with low bunch numbers, these will need alternatives.

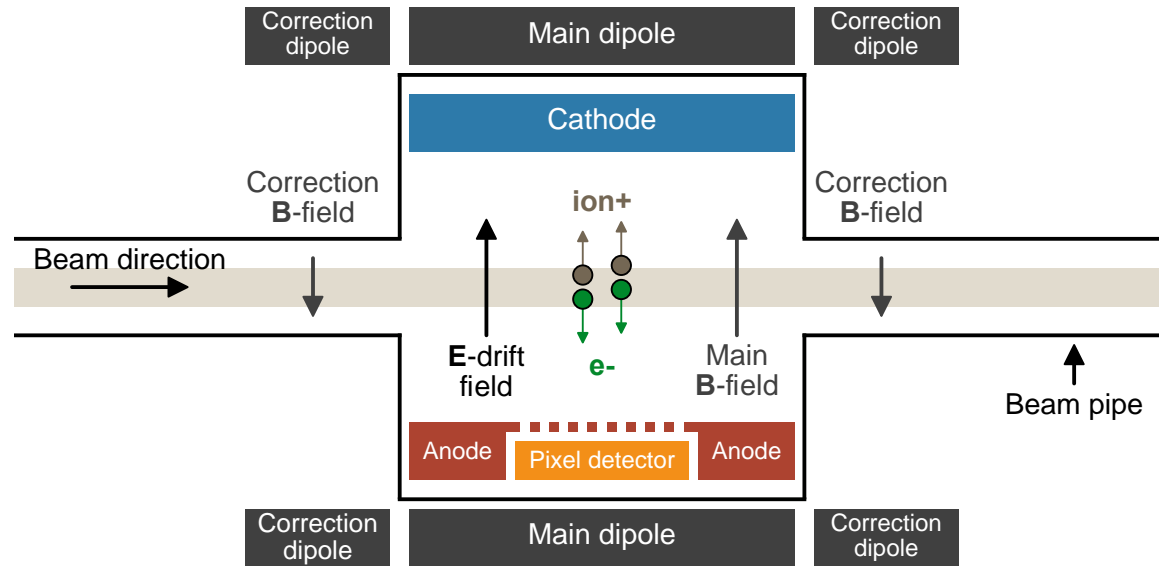
Source points for synchrotron radiation monitors must be taken into account for the lattice design.



Principle of a simple X-ray pinhole camera – this should be convenient for beam profile/size monitor in high energy range

Basic principle of operation:

1. Beam ionizes rest gas particles in the beam pipe vacuum.
2. Transport ionization electrons with E-field and B-field
3. Image ionization electrons with a detector.



- Ionisation electrons detected directly with Timepix3 hybrid pixel detector installed in the PS primary beam pipe vacuum.
- Continuous bunch-by-bunch and turn-by-turn measurements of the beam profile.

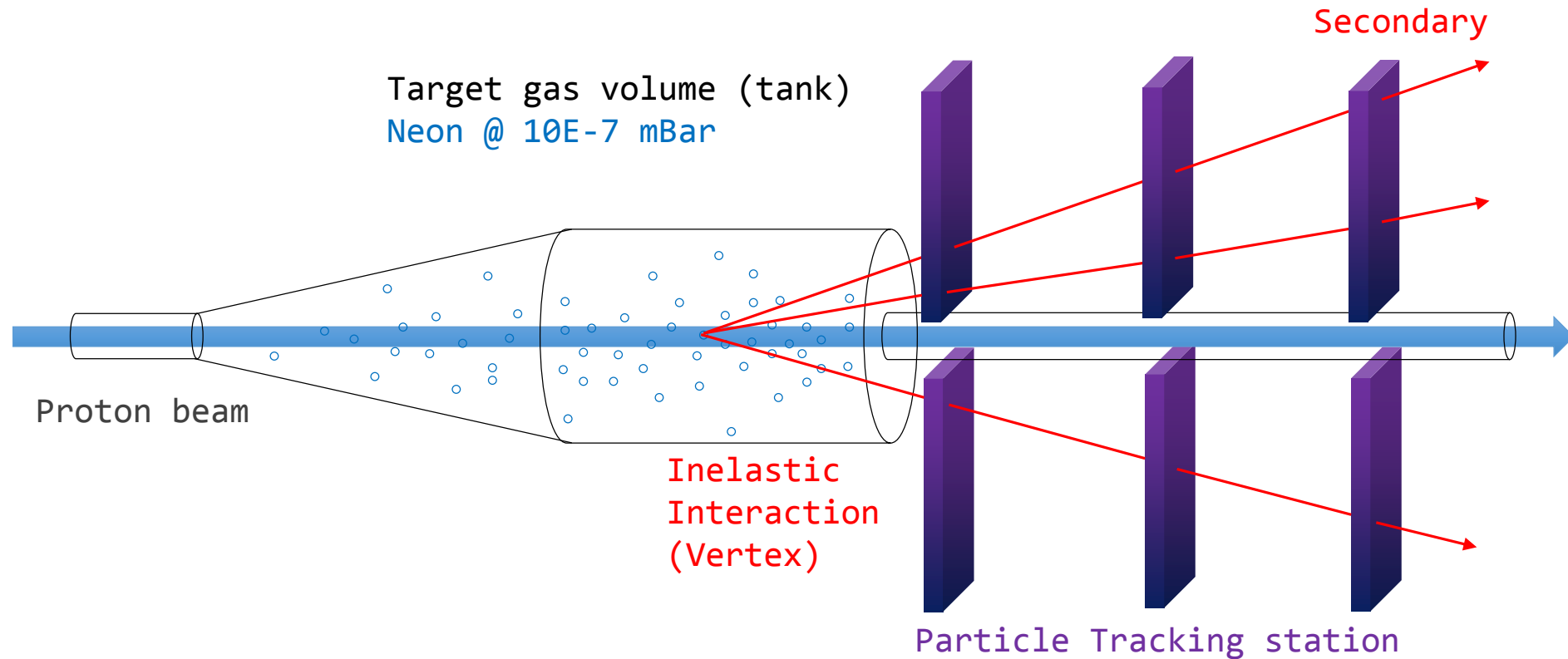
Potential performance (speculative projection from LIU-PS IPM performance):

- Continuous bunch-by-bunch beam profile measurement after each turn.

Issues requiring further investigation:

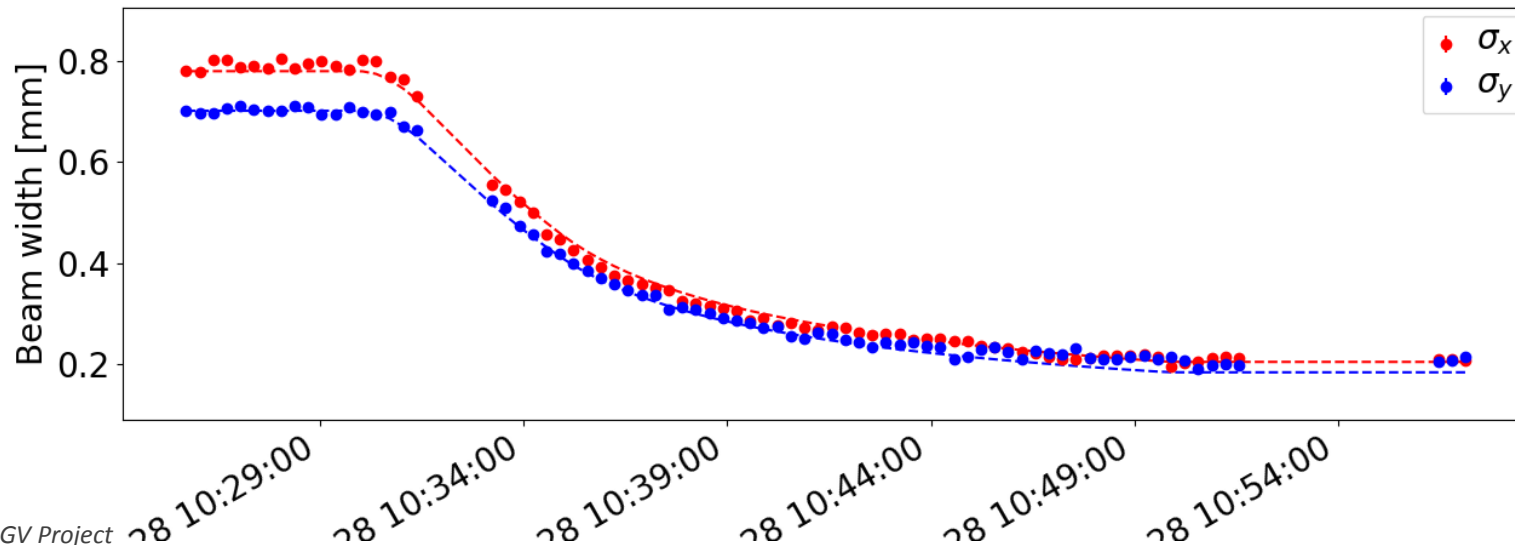
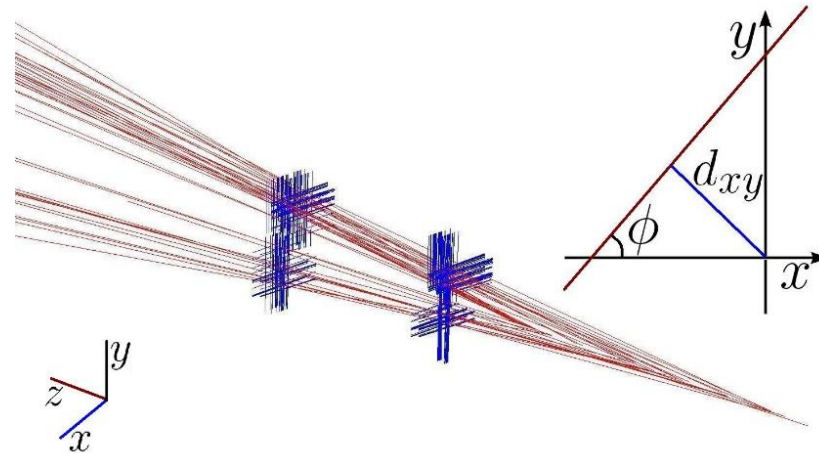
1. Feasibility to use noble gas injection system
 - Ionisation cross section of noble gases at 50 TeV unknown.
 - Effect of beam loss caused by the gas injection needs to be considered.
2. Distortion of the measured beam profile due to the beam electromagnetic field
 - **Resolution limitation for LHC protons is around 200 μ m spot sizes.**
 - Needs very high external magnetic field to limit effect.
 - Most likely impractical for FCC beam intensity and size.
 - Alternatively, significant correction could be done via an on-line algorithm, needs validation.

Beam Gas Vertex detector - principle



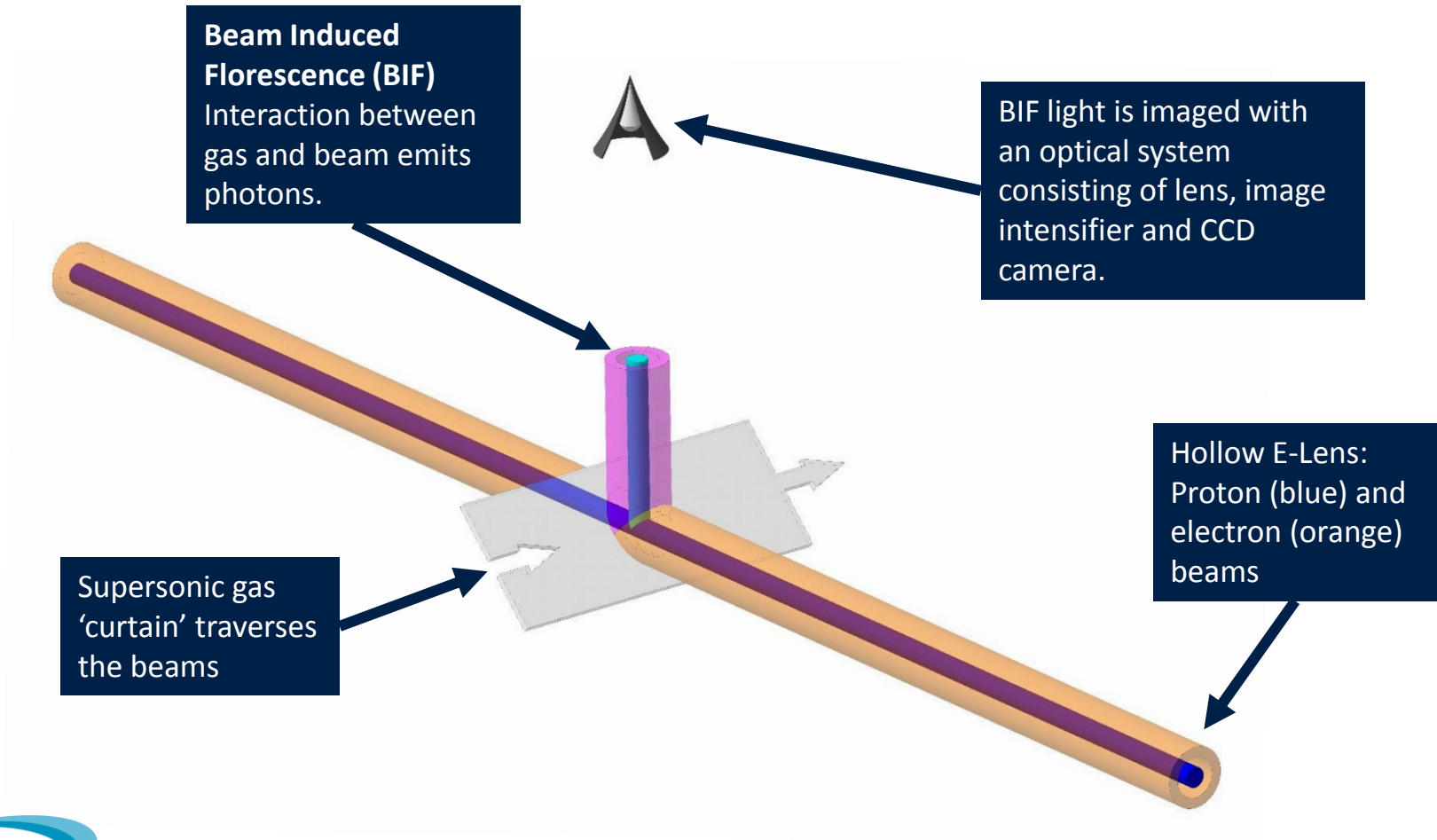
- A few thousand **Beam Gas interaction Vertex events** allows measurement of the **HL-LHC beam size** within desired accuracy.
- Fully **non-invasive method** with no visible effects on the beam lifetime.

- **Demonstrator** in operation in LHC point 4, for full characterisation and as a test bench for online processing development.
- Uses **Scintillating Fibers** (SciFi) detector technology from the **LHCb** R&D.
- Has already provided **beam size measurement in specifications**.



BGV emittance measurements compared to the predicted emittance over beam life - from injection to top energy.

The Beam Gas Curtain - *Principle*



The Beam Gas Curtain - Cockcroft Setup



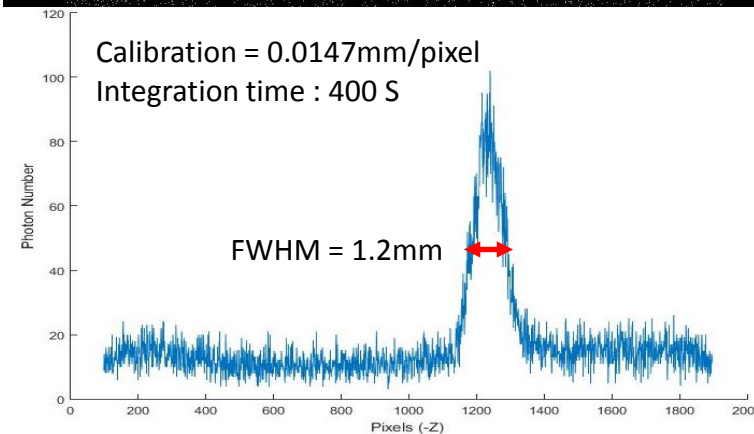
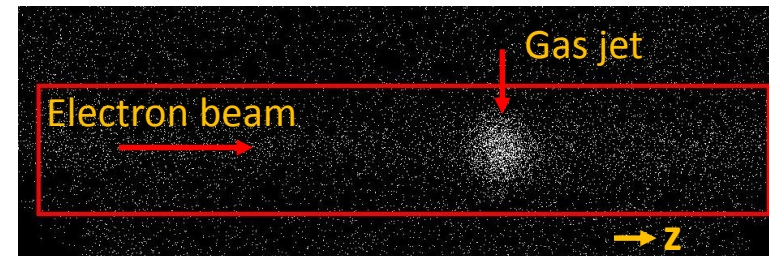
Test setup at Cockcroft Institute, UK.

- Results taken using Nitrogen, Neon and Argon.
- Gas jet densities up to $2.5 \times 10^{15} \text{ m}^{-3}$ ($\sim 1.5 \times 10^{-7} \text{ mbar}$)
- Increased gas density would improve accuracy and reduce integration time.

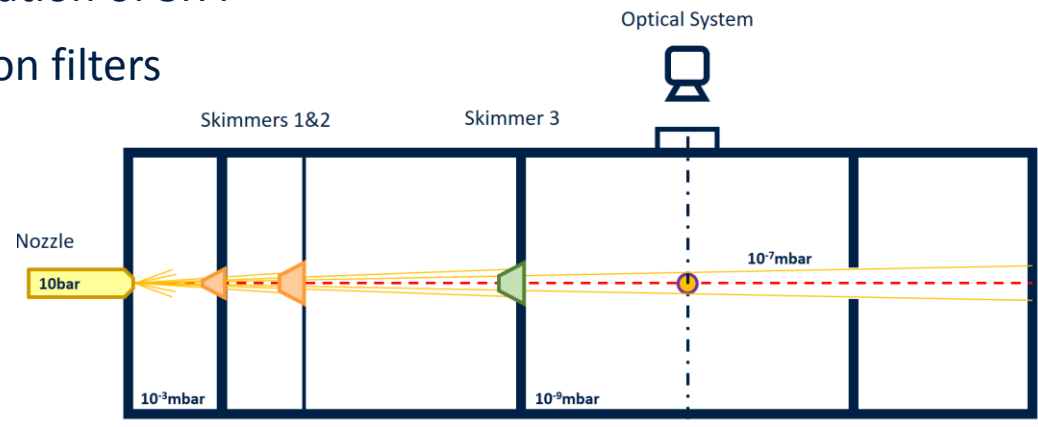
Fluorescence tests in the LHC show background particles and synchrotron light have a big effect.

Significantly higher SR in FCC - mitigation of SR :

- Optics improvements, with precision filters
- Blackening of all chambers
- Selection of a low SR location

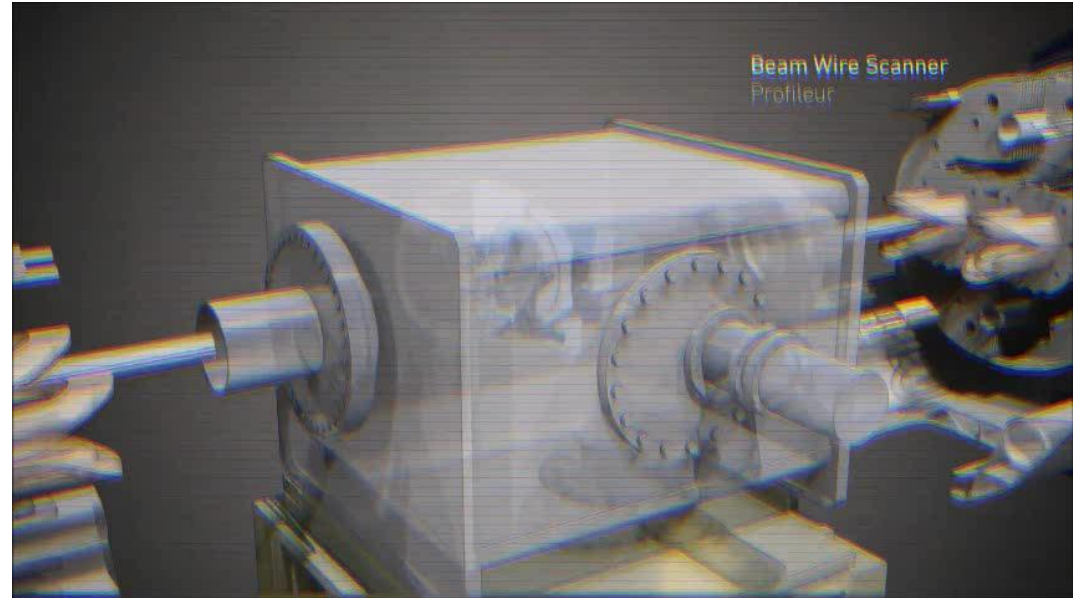


Nitrogen gas jet in the BGC with 0.65mA, 5KeV e-beam



Wire scanners

- Currently used for calibration of different instruments across the beam life cycle.
- Precise position is always known
- High energies will further damage wires, alternatives needed for FCC



THE PROBLEM

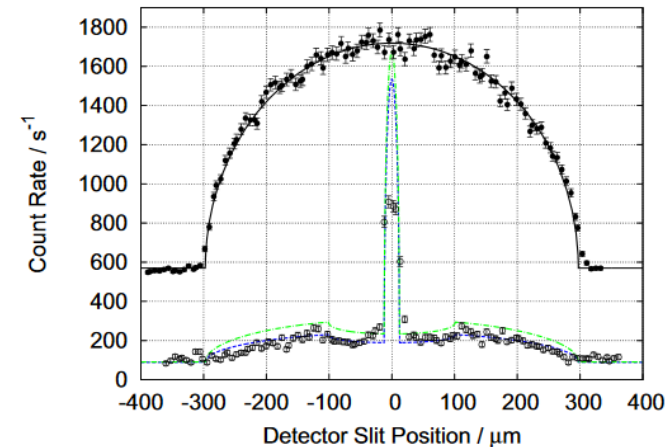
Intercepting devices (screens, wires etc.) will be destroyed.

Higher energy machines need **non-invasive** solutions

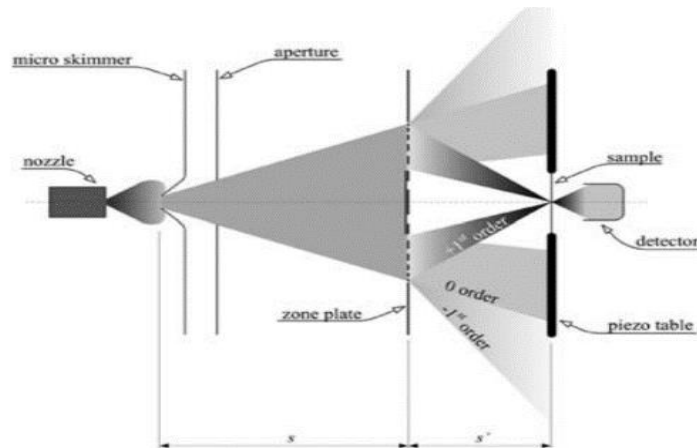
THE CHALLENGE

Can we replace a wire scanner with an scanning gas or ion beam?

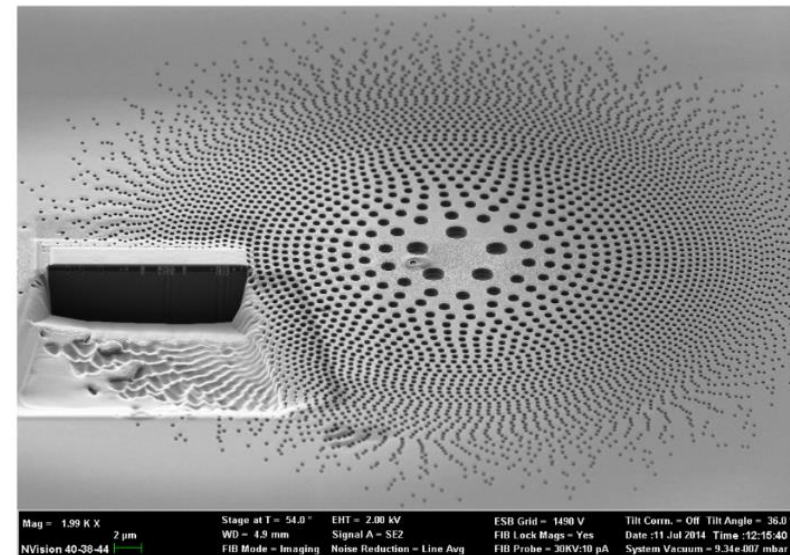
- Aim is to manipulate low energy neutral gas molecules
- Fresnel zone plates use diffraction to focus waves, this also applies to matter such as gas jets.
- Demonstrated at Bergen University using an 'atomic sieve' to focus gas to micron diameter beams.
- Hard to increase jet density due to high losses.
- Next step is to try to simulate gas-focussing and diffraction using MonteCarlo methods.



S D Eder *et al* 2012 *New J. Phys.* **14** 073014



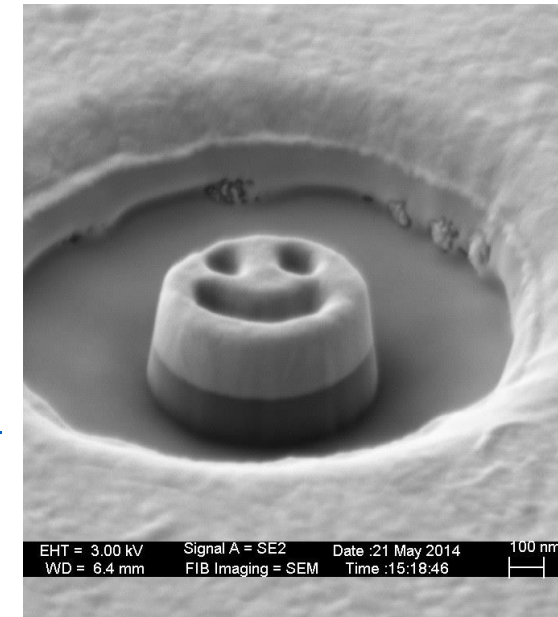
Imaging with neutral atoms—a new matter-wave microscope



SEM Image of an atomic sieve designed and built for a CLIC study at Cockcroft Institute, UK

Can we replace a wire scanner with a scanning ion beam?

- Increasingly high currents from commercial FIBs
 - Used for nanofabrication and microscopy.
 - Xe⁺ ion beam particle density only 40M away from CNT wires
- Space charge has a big effect
 - Working principle of SPS Ion Probe Transverse profile monitor! [\[1\]](#)
 - Can we neutralise the beam? What effect does this have?
- Next Steps
 - Define desired density for specified detection limit.
 - Cross section of collision, what detection technique is best?



Gold Smiley Face, ZEISS Crossbeam FIB-SEM
Todd Simpson, [UWO Nanofabrication Facility](#)

Particle Density Comparison.
BGC gas density vs. Focused Ion Beam alternatives, and particle density of the proposed CNT wire scanner.

| Instrument | Ion Species | Current | Resolution | Current Density | Particle Density |
|------------------|--|-----------|-----------------------|---------------------------------------|-------------------------|
| Beam Gas Curtain | Ne ⁺ (for reference) | 9 μ A | \emptyset 2 mm | 3.0 A.m ⁻² | 2.5 E16 m ⁻³ |
| Zeiss NanoFab | Ga ⁺ (30kV) | 100 nA | \emptyset 4 μ m | 8.0x10 ³ A.m ⁻² | 1.1 E14 m ⁻³ |
| Zeiss CrossBeam | He ⁺ / Ne ⁺ (25kV) | 50-100 pA | \emptyset 4 nm | 1.4x10 ⁷ A.m ⁻² | 1.8 E20 m ⁻³ |
| Tescan iFIB+™ | Xe ⁺ (30kV) | 2 μ A | \emptyset 4 μ m | 1.6x10 ⁵ A.m ⁻² | 4.7 E18 m ⁻³ |
| Wire Scanner | CNT Wire | | \emptyset 30 nm | | 8.5 E22 m ⁻³ |

Many of the standard FCC-hh beam instrumentation system requirements for 25ns spacing **can already be met with LHC or HL-LHC developments.**

- Moving to 5ns spacing would imply the need for significant R&D on all systems.

The **small beam sizes, high energy density** and **large total intensity range** will pose several challenges & require new approaches to be studied.

The main topics identified for further study are:

- High directivity beam position monitors using diffraction Cherenkov techniques
- High accuracy gas jet or ion beam scanner as replacement for solid-wire scanners

Thanks for your attention 😊

Additional Slides

- F. Roncarolo, 2018: [R&D on new concepts for beam instrumentation](#)
- H. Schmickler, 2017: [Summary of the requirements the FCC-hh and FCC e+e- beam instrumentation](#)
- L. Ponce, 2017: [Instrumentation overview and challenges](#)
- T. Mitsuashi, 2017: [Emittance measurement using X-ray interferometer](#)
- Evian 2019: <https://indico.cern.ch/event/751857/timetable/#20190130.detailed>
- Beam Instrumentation, Gorini School PhD School – [F. Roncarolo, 2018](#)



Limited understanding of 16T dipole quench behaviour.

LHC assumed to be adequate for machine protection:

- 6000 ionisation chambers
- 6 per arc half-cell, distributed throughout tunnel.

Verification of functionality of detectors and electronics for loss monitoring:

- 0.2T field outside cryostat of compact 16T dipoles
- Further magnetic shielding around detector could be added.

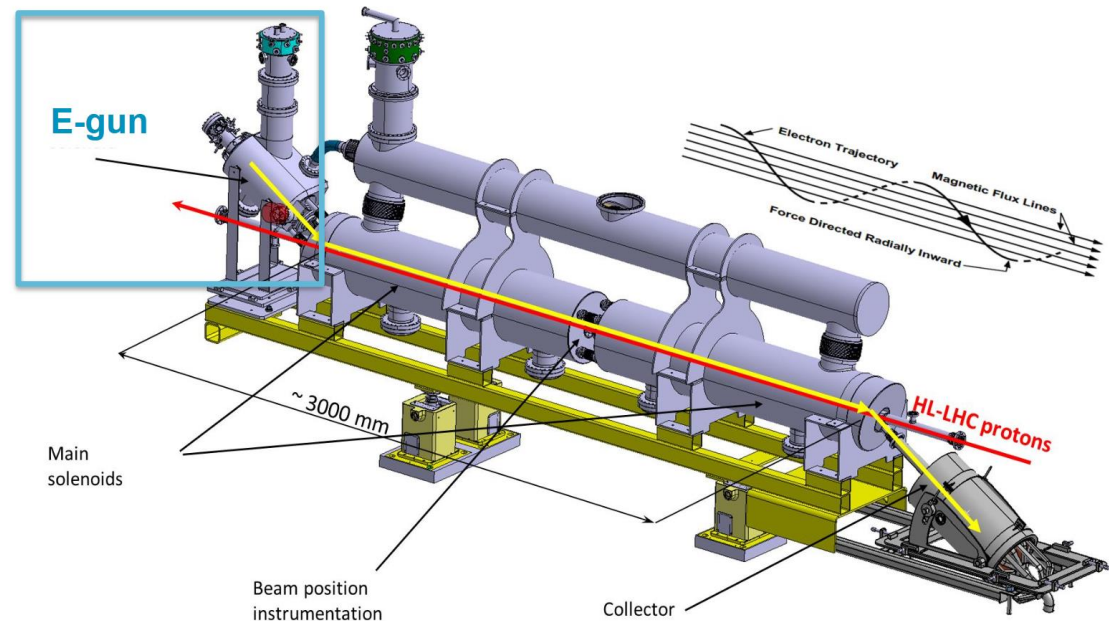
- Identical requirements to the LHC.
- The main problem, as in the LHC, is the tune measurements and their incompatibility with high-gain active transverse damping system.
- The use of a non-linear transfer function for the transverse damper is proposed for study.
- Self-excitation of betatron oscillations at low amplitudes will result in slow emittance growth.
- This can be compensated by FCC-hh radiation damping.

Collimation system of HL-LHC upgrade includes a proposed Hollow E-lens for machine protection from halo particles.

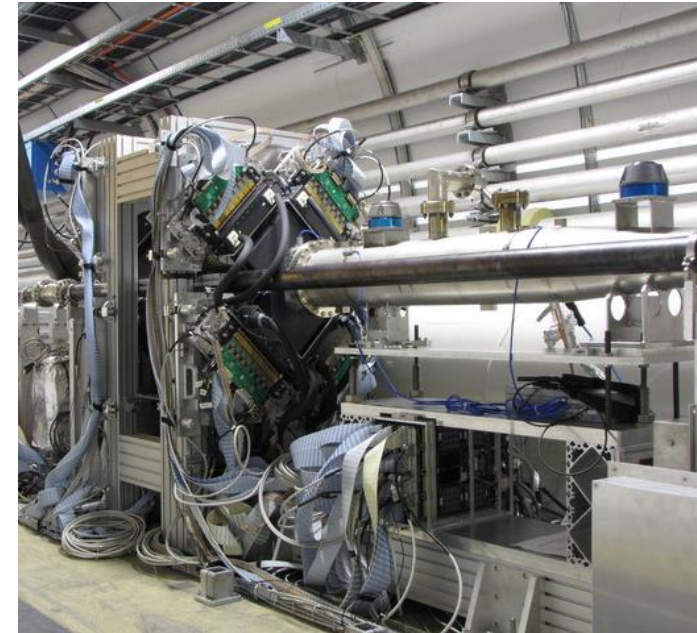
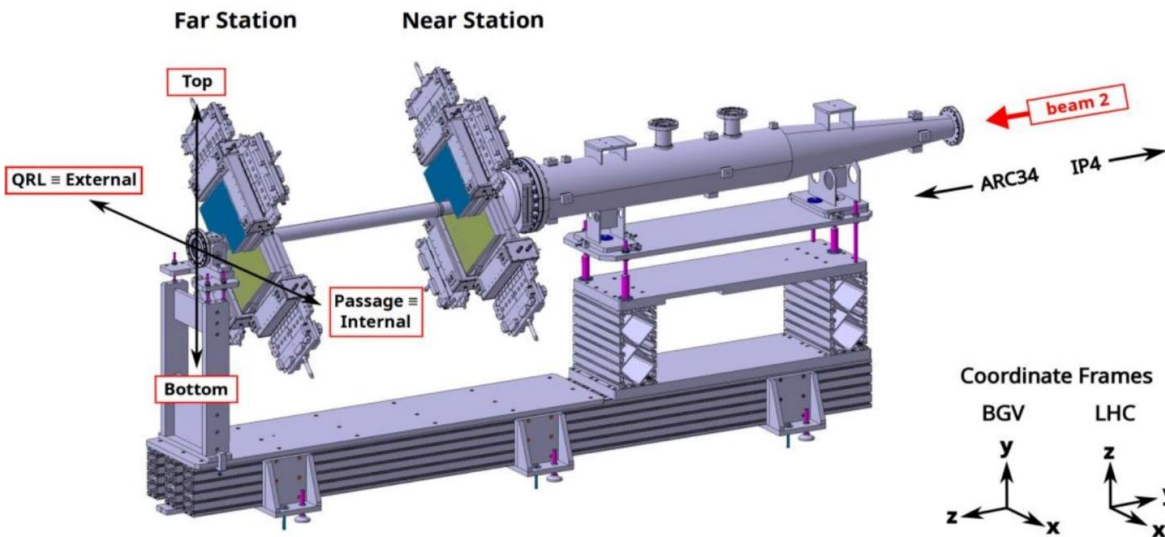
- A hollow electron beam is produced by a cathode in an E-gun
- 4.5K superconducting solenoids are used to tune size and steer the e^- trajectory.

Non-invasive beam diagnostics capable of measuring both the electron and proton beam positions and profiles are required.

Proposed overlap monitor, the Beam Gas Curtain instrument is under development at CERN.



Beam Gas Vertex detector - images



Higher energy particles - Inelastic collisions at higher energies, with more forwards momentum of particles.

Higher proportion of emitted particles close to the beam, so the detector should be moved.

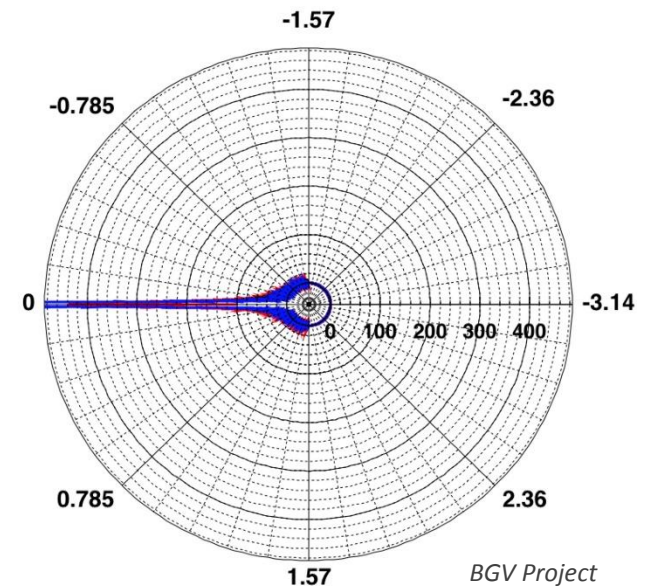
It cannot be placed farther away – error would increase.

Consider sensors inside the vacuum:

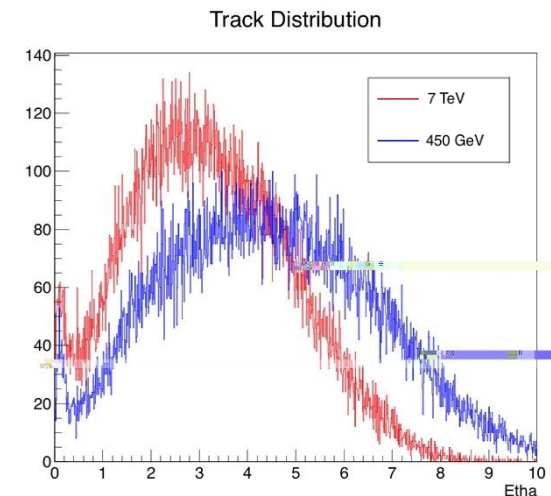
- Already seen on the TOTEM roman pots.
- Smaller sensor could be used
- No additional scattering at the exit window

Overlap with BGC technology:

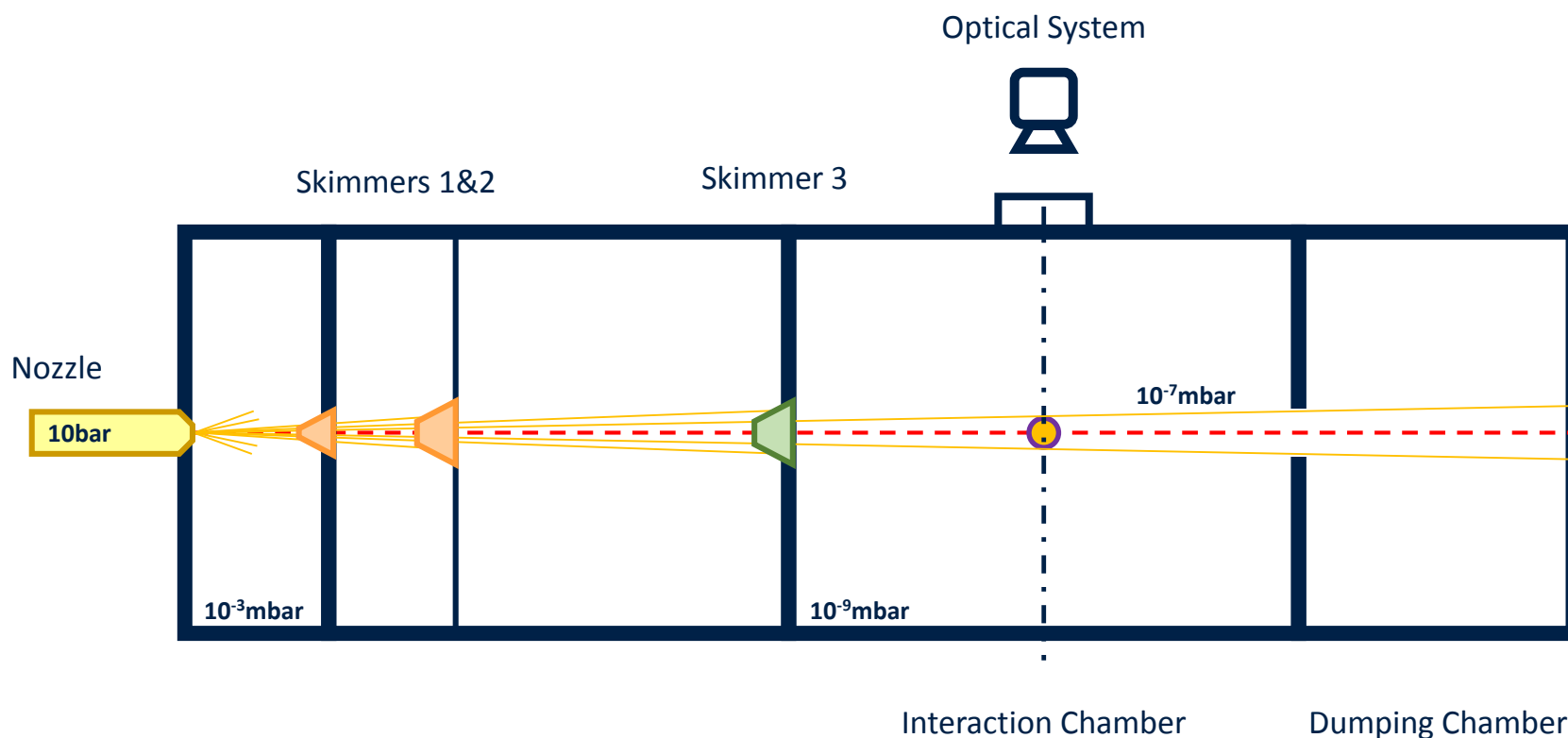
- Consider use of a gas jet some cm in diameter
- Simplifies vertexing capability and cluster association
- Would allow better beam profile reconstruction



BGV Project
robert.kieffer@cern.ch

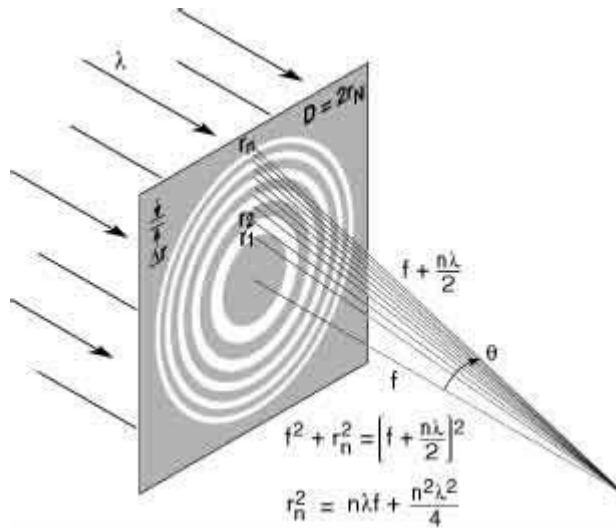
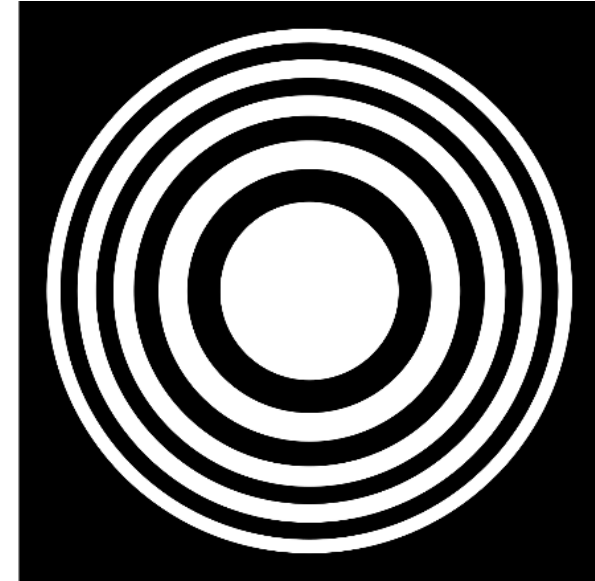
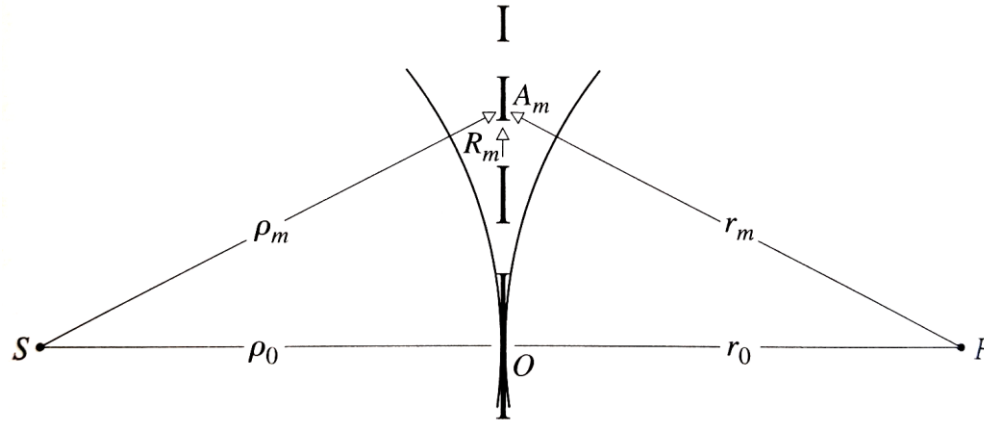


The Beam Gas Curtain - *Principle*



Modified from J. Glutting

Fresnel Zone Plates to focus gas



X-ray Data booklet

http://xdb.lbl.gov/Section4/Sec_4-4.html

