R&D on new concepts for beam instrumentation

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Contents

2017 FCC week beam instrumentation reports:

H.Schmickler: Summary of the requirements the FCC-hh and FCC e+e- beam instrumentation

L.Ponce: Instrumentation overview and challenges

T.Mitsuashi: Emittance measurement using X-ray interferomter

Today will give an update about on going and planned R&D:

Beam Position Monitors	▸ Cherenkov Diffraction Radiation
Transverse Beam Size Monitors	▸ Near field speckles ▸ X-ray interferometer ▸ Optical and Cherenkov Diffraction Radiation ▸ Beam Gas monitors ▪ Beam Gas Vertex detector ▪ Beam Gas Jet

Beam Position Monitors (BPM)

1 BPM H+V per quadrupole → 1000 BPMs per beam

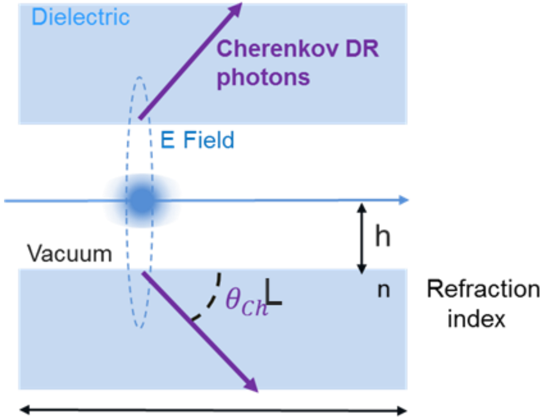
Common beam pipe → need high directivity BPMs

- Standard BPMs feature ~35dB cross-talk
- Next 2 slides: Highly directive Cherenkov diffraction radiation becomes feasible at large distances for the FCC high energies, may go down to ~60dB crosstalk

Cherenkov Diffraction Radiation

Electric field of ultra-relativistic charged particles in the vicinity of a dielectric radiator → photons by Cherenkov mechanism

- Large emission angle: $\cos(\theta_{Ch}) = \frac{1}{\beta n}$
- Photons emitted along the target



For a cylindrical geometry

Cherenkov emission

Exponential decay of the particle field

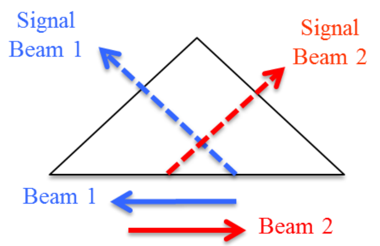
$$\frac{d^2N_{Dcph}}{d\Omega d\lambda} = \boxed{\frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)}\right) sin^2\theta} . \boxed{e^{\left(-4\pi\frac{h}{\gamma\beta\lambda}\right)}}$$

α, fine structure constant
β, normalised beam velocity
γ, beam relativistic factor
θ, angle of observation

-Technology being recently demonstrated at **Cornell**
- Collaboration with **Tomsk Polytechnical Univ**. and **RHUL**
- Possible future tests @ ANKA and collaboration with KIT

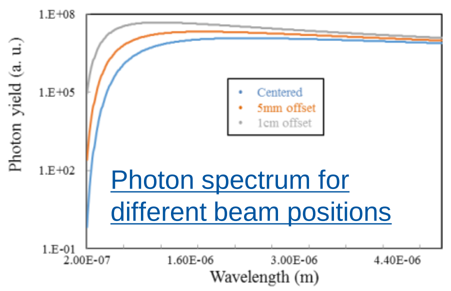
Potential use for:
→ **High directivity BPMs**
→ **Non invasive beam size measurement**

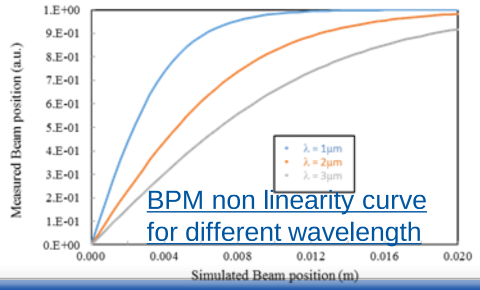
High directivity BPMs



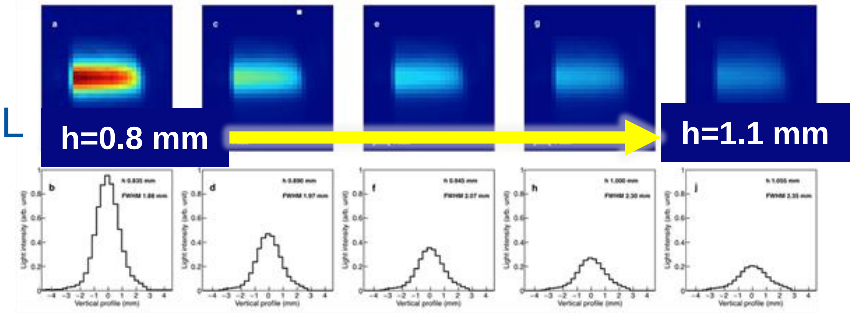
@ FCC energies the order of magnitude of produced photons is expected to be enough for large apertures (~ as standard BPMs)

Example for 50TeV protons – 4cm aperture BPM



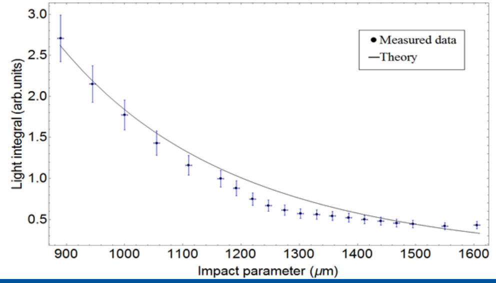


Results of experiment performed @ CORNELL CESR in 2017



Electrons 2.1GeV steered at different offsets from the Cherenkov radiator

Cherenkov photons yield increases for smaller impact parameter



T. Lefevre et al., Non-invasive beam diagnostic with incoherent diffraction radiation, IPAC 2018

Transverse Profile Measurements **FCC hh**

High energy density beams will not allow the use of interceptive devices

Plenty of synchrotron radiation

- In the visible for all beam energies
- Hard X-rays above 40 TeV

Challenges

Small beam sizes at top energy

- Place imaging system (visible) at high beta function (may need at beta=at least 1km)
- X-ray pin hole camera – diffraction limit extremely challenging for FCC, preliminary studies (T.Mitsuhashi) indicate the need of long optical line after the pin hole

Heat deposition on SR extraction mirror → need active cooling

Transverse Profile Measurements **FCC ee**

Main challenge:
measurement of very small beam sizes

On going R&D

- X-ray interferometer
- Near field speckles from nanoparticles suspensions
- Gas jet scanner

Bending magnet length	24.585m
Bending radius	11590.8m
Magnetic field strength	0.0503T
Bending angle	2.144mrad
Beam energy and current	175GeV 6.6mA 45GeV 1500mA
Emittance	1.3pmrad
Estimated vertical beam size	s_y =5.1um with beta_y=20m
Minimum extraction system distance	100 m → 0.05urad minimum angular resolution

T.Mitsuhashi

X-ray interferometer motivation

Method	Wavelength [nm]	Measurable minimum beam size in angular diameter [mrad]	Corresponding size [mm]	
			@ 100m	@ 1 km
Visible light imaging	500	50	500	5000
X-ray pinhole	0.1	0. 5	50	500
FZP imaging of soft X-ray	0.35	0.3	30	300
Visible light interferometry	400	0.47	47	470
Visible light Interferometry with imbalance input	400	0.2 (scaled, No measurement	20	200
Coded aperture	0.3	0.1 … 0.5 (estimation, no measurement)	10 … 50	100 … 500
X-ray Interferometry (new method)	0.1	0.01	1	10

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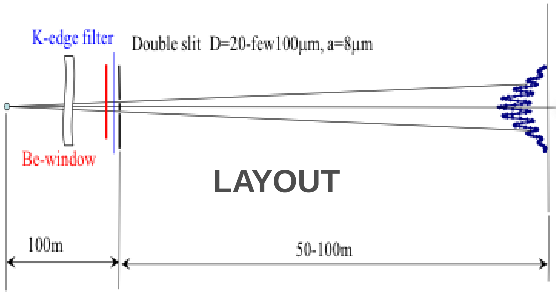
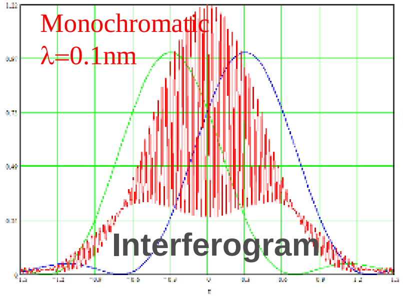
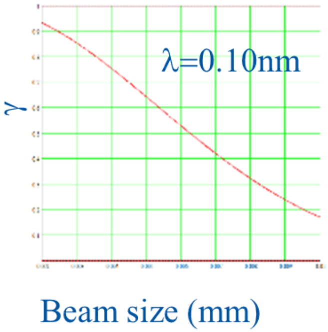
X-ray interferometer





Beam size from fringes visibility



Challenges

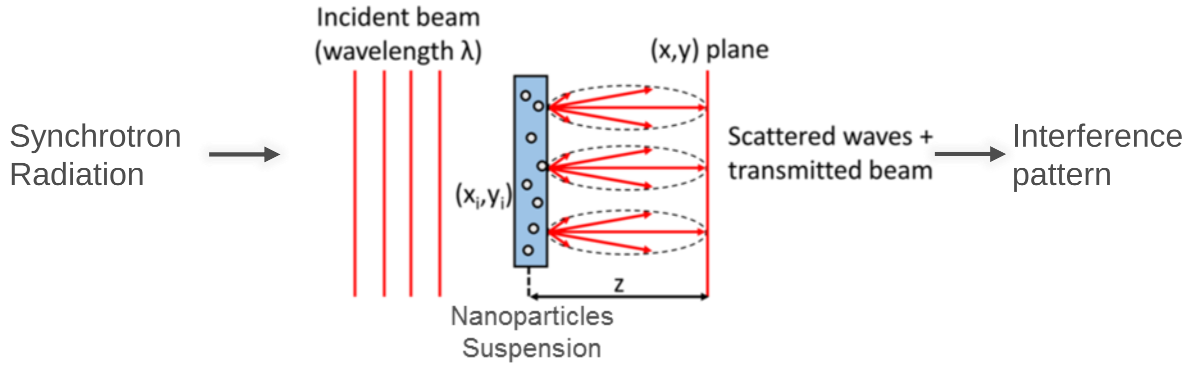
Radiation extraction @ at least 100m from source, Narrow band wavelength selector (not to deteriorate resolution), X-ray high resolution detector, Double slit construction

On going R&D

Extensive studies by T.Mitsuhashi
Setup collaboration between **CERN** and **ALBA (Spain)** for performing experiments

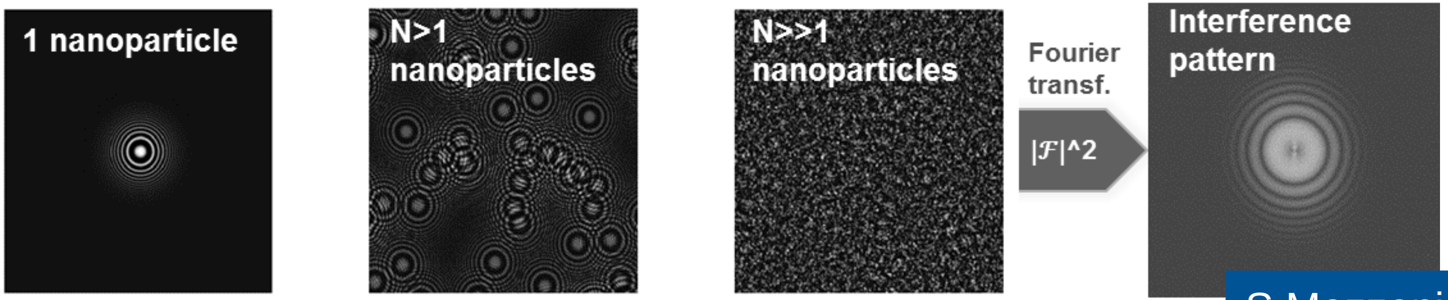
See T.Mitsuhashi's talks @:
2017 FCC week: https://indico.cern.ch/event/556692/contributions/2590167/
2018 FCC week: https://indico.cern.ch/event/656491/contributions/2939188/

Transverse Beam size from near field speckles (I)



Decay of fringes visibility gives transverse spatial coherence, similar to just like two-slit interferometer
→Van Cittert – Zernicke theorem,
→ transverse beam size

Suitable for small electron beam size measurements

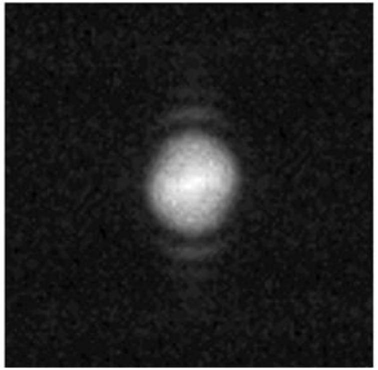


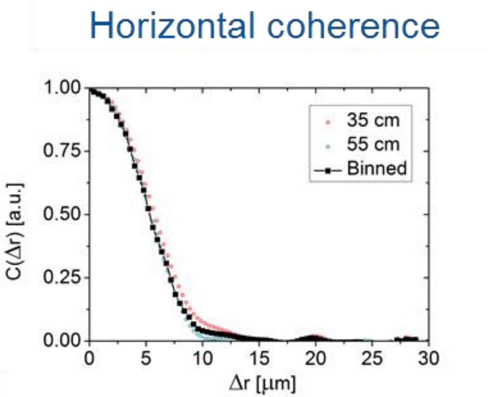
S.Mazzoni, M.Potenza et al.

Transverse Beam size from near field speckles (II)

Advantages
Simple layout (no optics)
2D information

Challenges
From R&D to operation
Data processing
Contrast for hard X ray
Ultimate Accuracy





Courtesy M. Siano, University of Milan

On-going R&D
CERN collaboration with **ALBA** synchrotron radiation facility (Spain), and **University of Milan** (Italy). To be formalized within FCC

Preliminary results from tests in the NCD beamline at ALBA (Dec2016).
- H & V coherence measured.
- H RMS beam size 372 um (309 um from design).

Next tests: 24 April 2018 @ ALBA

Transverse Beam size from near field speckles [REF]

CERN , **ALBA** synchrotron radiation facility (Spain), **University of Milan** (Italy)

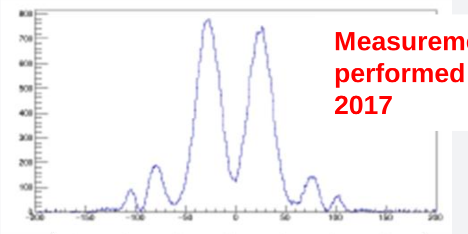
R. Cerbino et al, ‘X-ray-scattering information obtained from near-field speckle’ Nature Physics **4**, pages 238–243 (2008)

M. D. Alaimo, M. A. C. Potenza, M. Manfredda, G. Geloni, M. Sztucki, T. Narayanan, and M. Giglio, ‘Probing the Transverse Coherence of an Undulator X-Ray Beam Using Brownian Particles’ Phys. Rev. Lett. **103**, 194805 (2009)

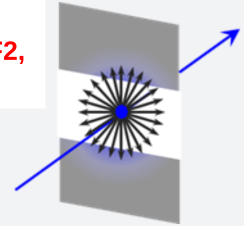
M. Siano, B. Paroli, M. A. C. Potenza, U. Iriso, A. A. Nosych, L. Torino, S. Mazzoni, G. Trad, and A. N. Goldblatt, ‘Characterizing temporal coherence of visible synchrotron radiation with heterodyne near field speckles’ Phys. Rev. Accel. Beams **20**, 110702 (2017)

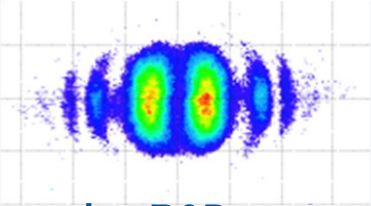
Beam size via ODR and ChDR

Optical Diffraction Radiation (ODR) Non interceptive technique, e.g. for LHC → FCC transf. line



Measurements performed @ ATF2, 2017



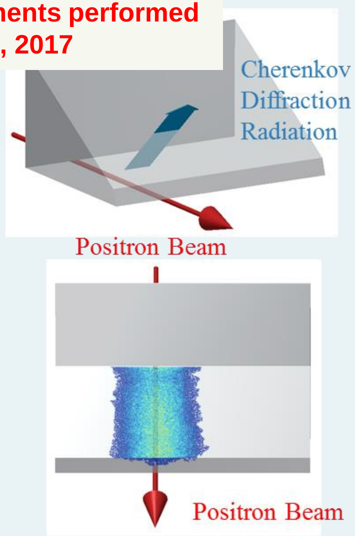


Beam size is extracted from the **visibility I_{min}/I_{max}** of the projected vertical component of the ODR **angular distribution**

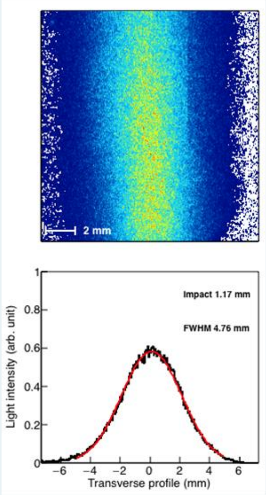
On-going R&D:
@ **ATF2**, in coll. with **RHUL**: demonstrated resolution better than 10um
Collaboration setup with Diamond Light Source (UK)
→ tests on beam line from booster to main ring

Imaging of **Cherenkov Diffraction Radiation (ChDR)**

Measurements performed @ Cornell, 2017



Vertical polarization



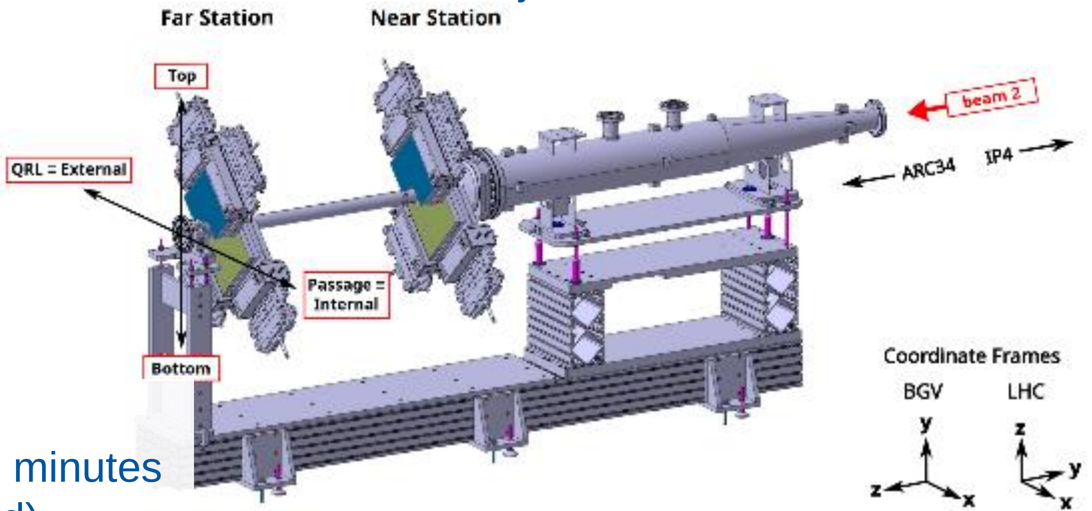
On-going R&D:
Cherenkov radiator being installed at **ATF2**

Beam Gas Vertex detector (BGV) (I)

Beam size measurement based on the tracking of beam-gas interactions to reconstruct beam spot

Demonstrator @ LHC Beam 2, extensively used in 2017

Ne @ 10^{-8} mbar injected at interaction volume



Advantages:
~Non-invasive, suitable for all beam energies including the ramp, bunch-per-bunch, any bunch spacing

Limitations:
Accuracy depends on integration time

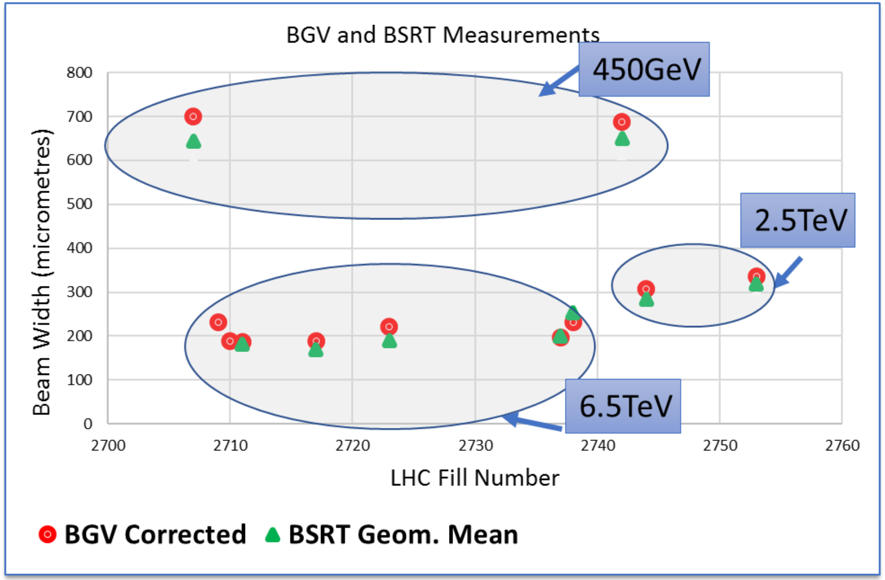
Ultimate Goals, measurement precision:
Relative bunch-per-bunch width : 5% in 5 minutes
Absolute beam width : 2% (already proved)
in 1 min for 10^{11} p/bunch (avg over all bunches)

S.Vlachos et al.

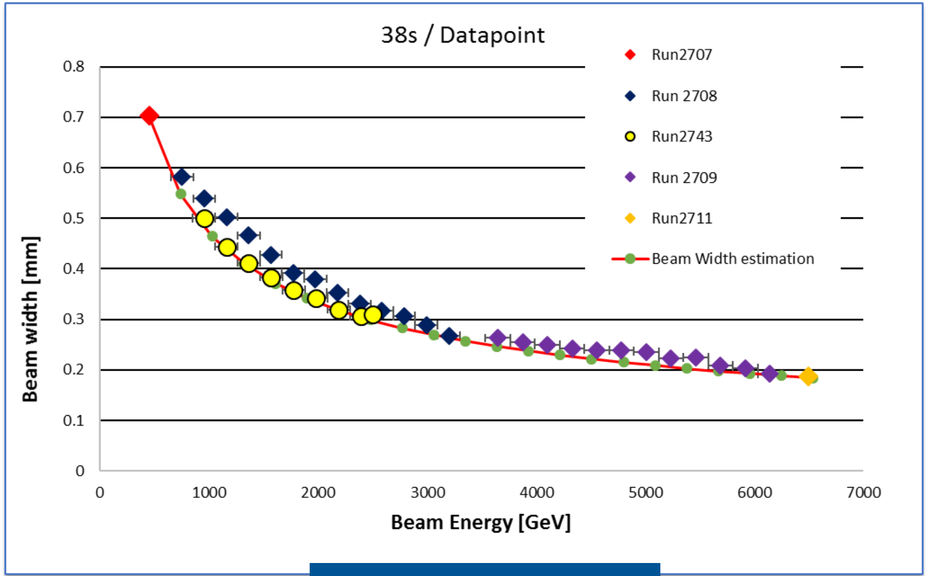
Beam Gas Vertex detector (BGV) (II)

LHC demonstrator 2017 highlights

BGV (10 sec integration) w.r.t. Sync. Light Monitor



Measurements during the ramp



S.Vlachos et al.

Beam Gas Vertex detector (BGV) [REF]

S.Vlachos, Results from the Beam Gas Vertex demonstrator & plans for the future, HL-LHC collaboration meeting, Madrid, 2017

A. Alexopoulos et al., First LHC Transverse Beam Size Measurements With the Beam Gas Vertex Detector, IPAC 2017, Copenhagen

BGV Collaboration:

Alexopoulos, C. Barschel, E. Bravin, G. Bregliozzi, N. Chritin, B. Dehning, M. Ferro-Luzzi, M. Giovannozzi, R. Jacobsson, L. Jensen, O. Rhodri Jones, V. Kain, B. Luthi, R. Matev, M. Rihl, V. Salustino Guimaraes, R. Veness, S. Vlachos, B. Wu ̈rkner, **CERN**, Geneva, Switzerland

Bay, F. Blanc, S. Gian`ı, O. Girard, G. Haefeli, P. Hopchev, A. Kuonen, T. Nakada, O. Schneider, M. Tobin, Q. Veyrat, Z. Xu, **EPFL, Lausanne**, Switzerland

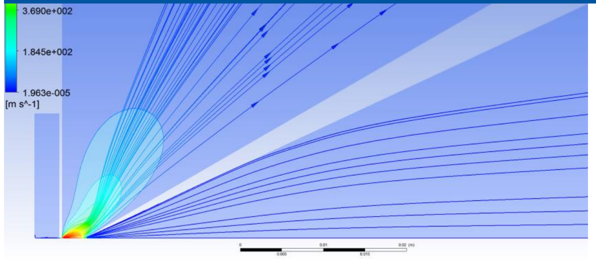
R. Greim, W. Karpinski, T. Kirn, S. Schael, A. Schultz von Dratzig, G. Schwering, M. Wlochal, **RWTH, Aachen, Germany**

Gas Jet for transverse profile

Concept: scan through the particles beam a 'pencil' neutral gas jet

- ► Image the beam-induced fluorescence
- ► Reconstruct beam profile as with standard wire scanners

Computational fluid dynamics (CFX) sim. of high pressure nozzle and first skimmer showing velocity streamlines (P.Magagnin/CERN-BI)



Advantages:

Minimal invasive method, no breakable wire

Not affected by space charge

Potentially suitable for electrons and protons

Challenges

Sensitivity → integration time

Compromise between gas pressure and signal level. Choice of optimal gas species.

Implementation: pencil gas jet production

On going R&D

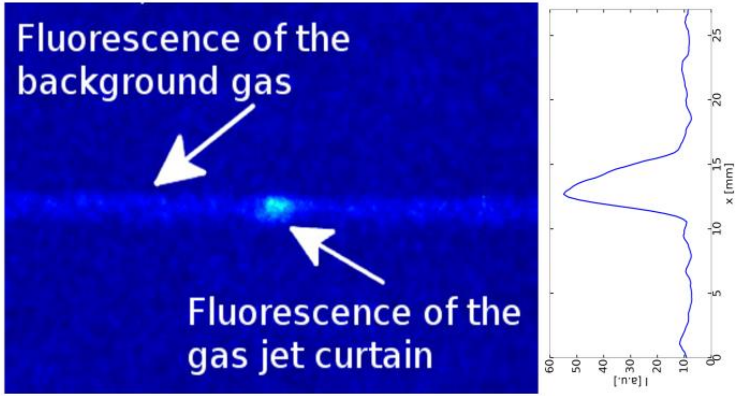
Related to HL-LHC Gas 'Curtain' for Hollow Electron Lens diagnostics

CERN, Cockcroft Institute (UK), GSI (DE), Wroclow University of Science and Technology (PL)

R.Veness et al. , 'Gas Jet Monitor project overview', HL-LHC Collaboration Meeting, Madrid, 2017 2017

Gas Jet – on going activities

Image of fluorescence from a gas jet curtain interaction with 3.5 keV e- beam at the Cockcroft Institute



S.Udrea et al. IBIC 2017

Setup for direct measurement of Ne gas fluorescence cross section of high energy protons recently installed @ LHC

Expected to give results in 2018, very relevant for the R&D in this field since no cross section measurements were performed so far for protons above 450 GeV

Conclusions / Outlook

(Shortly) discussed beam instrumentation challenges and main on-going/planned R&D

Road to FCC will clearly include many other challenges not covered here

- Achievement of requested accuracies/resolutions/reproducibility → e.g. need for BPMs modern electronics, high precision optics for SR detectors, etc..
- 5 ns bunch spacing for beam current and beam size meas.
- Beam loss monitors immunity to dipole fringe field (0.1T >> LHC)
- Radiation hard electronics (200Gy/year ~= 10 LHC case)
- Tune measurement compatibility with high damper gains
- Design of large-scale/limited-cost diagnostics (e.g. thousands BPMs and BLMs)
- Longitudinal beam profile diagnostics to resolve 10ps bunches
- Electron cloud monitoring
- …

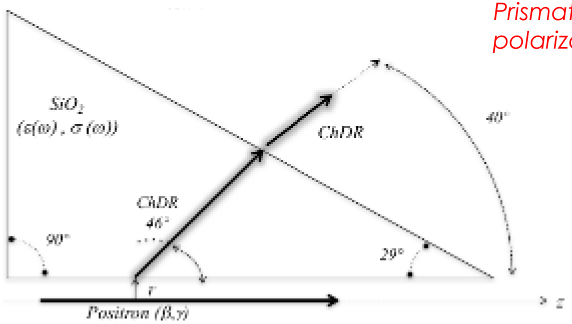
SPARE SLIDES

BPMs (general)

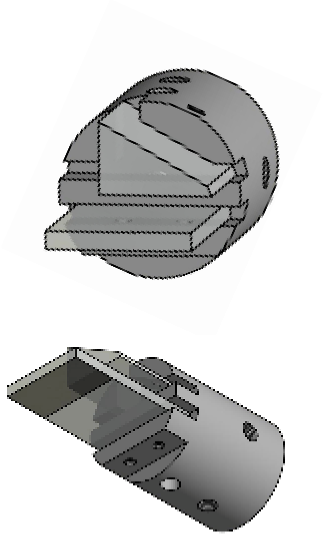
- 1 BPM H+V per quadrupole --> 1000 BPMs per beam
- SR at high energy, an issue for both hh and ee
  - BPM sensors at 45 deg
  - 1 sensor fail --> loose two planes
  - smaller sensor area to avoid SR fan --> less sensitivity --> need to improve of 1 order of magnitude
- need closed orbit with sub-micron repro, 20um reproducibility fill-to-fill
- turn-by-turn for injection oscillation, optics meas. and post mortem
- few BPMs special with bunch-per-bunch turn-by-turn for instabilities and interlock
- sensor + FE electronics in the tunnel --> optical link to non radiation zone
  - expected 500 times higher fluence and 200 times higher total dose w.r.t. LHC. Total dose already tested (SPS) but fluence to be studied
- common beam pipe → need high directivity BPMs
  - highly directive Cherenkov diffraction radiation, something that becomes feasible at large distances at such high energies.

ChDR Results - CESR

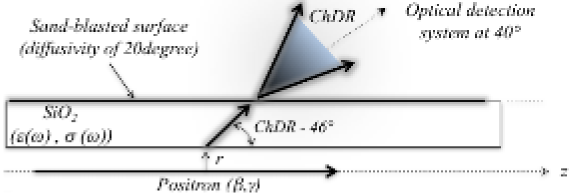
- Two different geometries have been tested at Cornell Storage ring (5.3GeV)
  - **Prismatic radiator**



Prismatic target for polarization studies

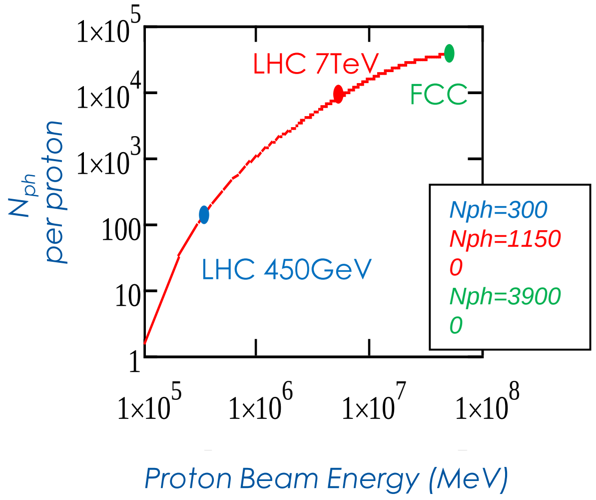


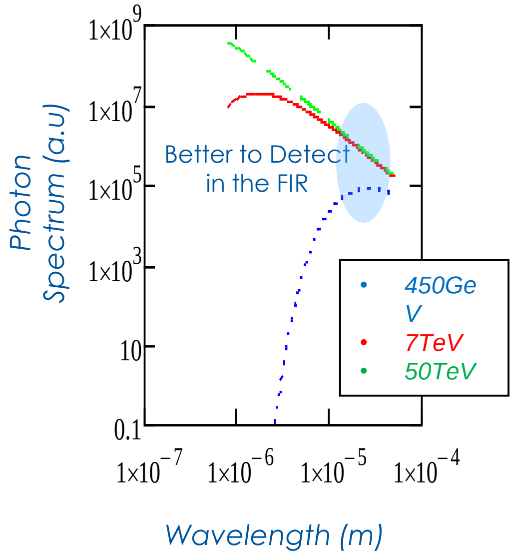
  - **Flat radiator** (simpler and cheaper)



ChDR at FCC

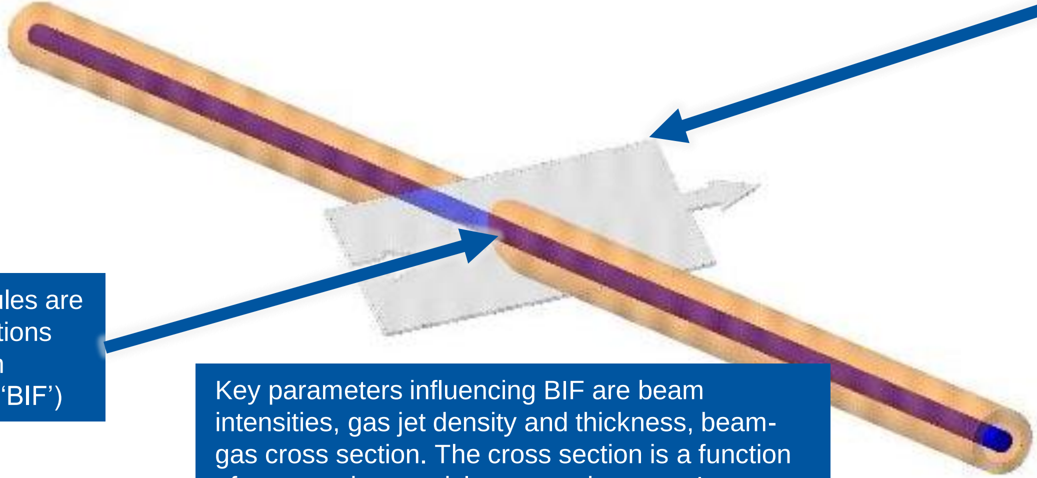
- Number of ChDR photons and ChDR power spectrum as function of beam Energy (LHC-FCC)
  - 1m Si crystal and impact parameter h = 2mm





Beam-Gas Curtain: Principles

Laminar, supersonic gas 'curtain' traverses the beams

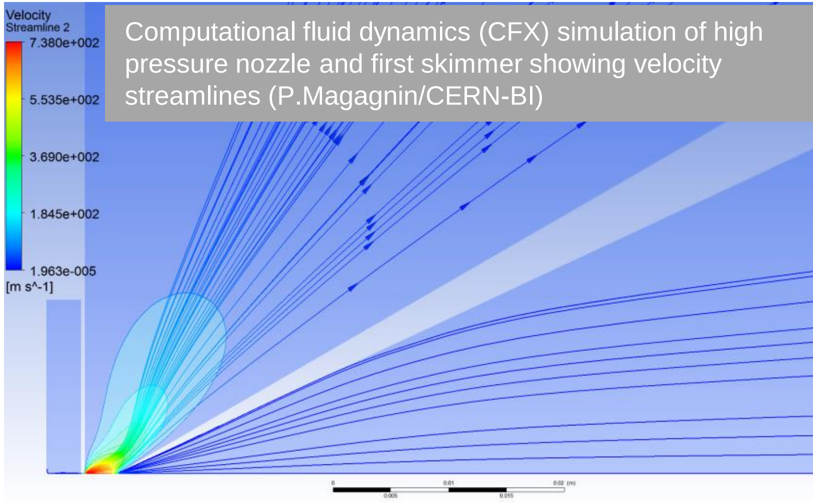


Gas jet atoms or molecules are excited by beam interactions and emit photons (Beam Induced Florescence or 'BIF')

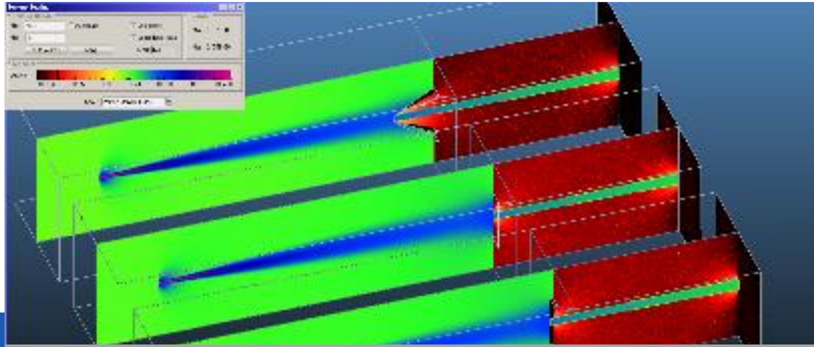
Key parameters influencing BIF are beam intensities, gas jet density and thickness, beam-gas cross section. The cross section is a function of gas species, particle type and energy. In addition, a spectral range of different florescence transitions are excited depending on gas species

Work in progress: Gas jet simulations

- Gas jet simulations span 13 orders of pressure variation
  - The gas is supplied at 10 bar through a 30 µm nozzle
  - The flow is then progressively ‘skimmed’ to select molecules with the required trajectory
  - Base pressure in the beam vacuum chamber ~10^{-9} mbar with ~1×10^{-6} mbar locally in the gas jet
- Gaining predictive power to produce a design optimized for the LHC
  - Maximise the gas density in the curtain at the interaction
  - Minimise the mass flow into the vacuum system
  - Incorporate experience from gas jet targets to improve the nozzle geometry



Computational fluid dynamics (CFX) simulation of high pressure nozzle and first skimmer showing velocity streamlines (P.Magagnin/CERN-BI)



Molecular flow (MOFLOW) simulation through second and third skimmers showing gas density in interaction chamber (M.Ady/CERN-VSC)

CERN FCC hh ee he

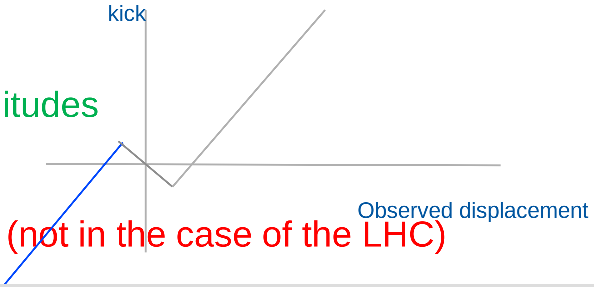
Tune, Chromaticity, Coupling

- Same requests as for LHC, same tools available, nothing new:

  - Excitation of transverse oscillation with the transverse damper
  - FFT analysis,
  - phase-locked loop tune tracking
  - low noise observation of residual beam oscillations with BBQ system
  - Schottky Monitors (OK, but too long integration time for real-time feedback)

  Principal problem: Incompatibility of tune measurements with high gain active transverse damping.

- Already proposed for LHC, but never implemented:
  → non linear transfer curve of transverse damper



- Will lead to self excitation of betatron oscillations at low amplitudes (for tune measurements)
- Will lead to slow emittance growth
- Emittance growth will be compensated by radiation damping (not in the case of the LHC)

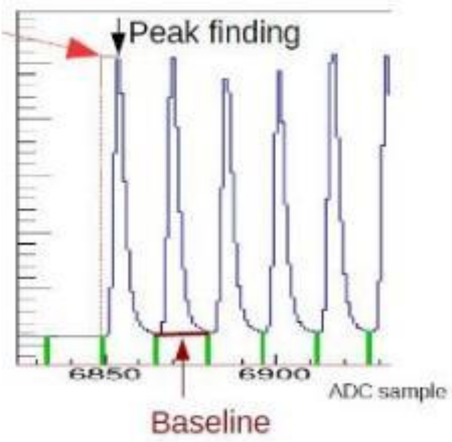
→ Do experiments in the LHC; complement with beam dynamics studies

CERN FCC hh ee he

Beam intensity measurements

- DC-transformers are standard tools in order to capture the total beam intensities
  Expected issues:
  a) One bunch of 5 10 ^{8} is at the sensitivity limit of any DC transformer. Small improvements here and there will help, but no revolution expected.
  Is this an issue? Study on cryo DCCT needed?
  b) Need to check possible interference of modulation frequency with low revolution frequency of FCC (3 kHz)

- Bunch to bunch transformer:
  Recently splendid results with fast bunch to bunch AC transformer (new sensor) and fast digitizer @ 1 GHz and numerical integration. Device directly applicable for FCC.
  Works well for 25 ns bunch spacing;
-
  Study needed: Can this be done for 5 nsec?
  …in principal "yes"; ADC market still evolving….



BGV -Beam width resolution vs integration Time

The longer the integration Time the higher the precision

60 seconds integration
175 ± 4μm

10 seconds integration
174 ± 9μm

2.5 seconds integration
173 ± 17μm