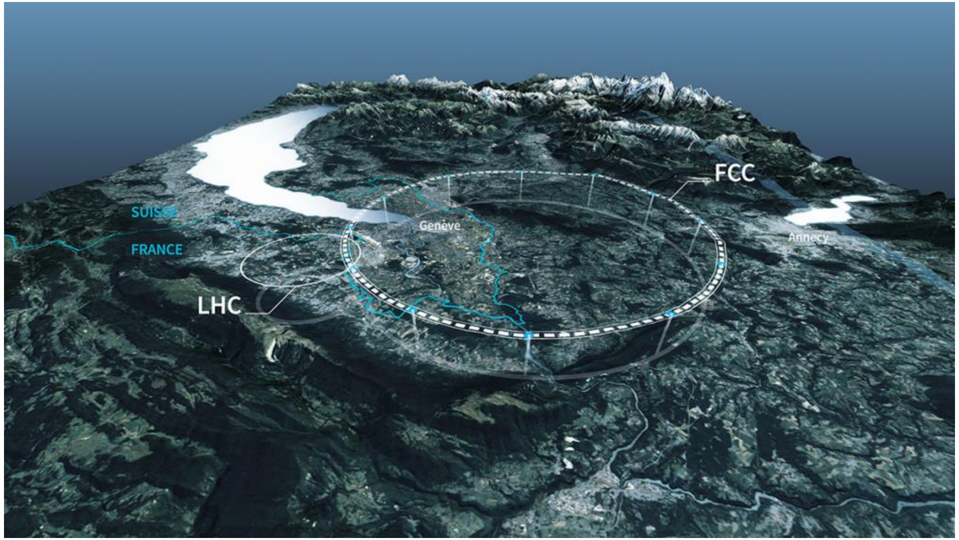
Overview of Beam Instrumentation studies for FCC-ee

T. Lefevre for the FCCee Beam instrumentation team

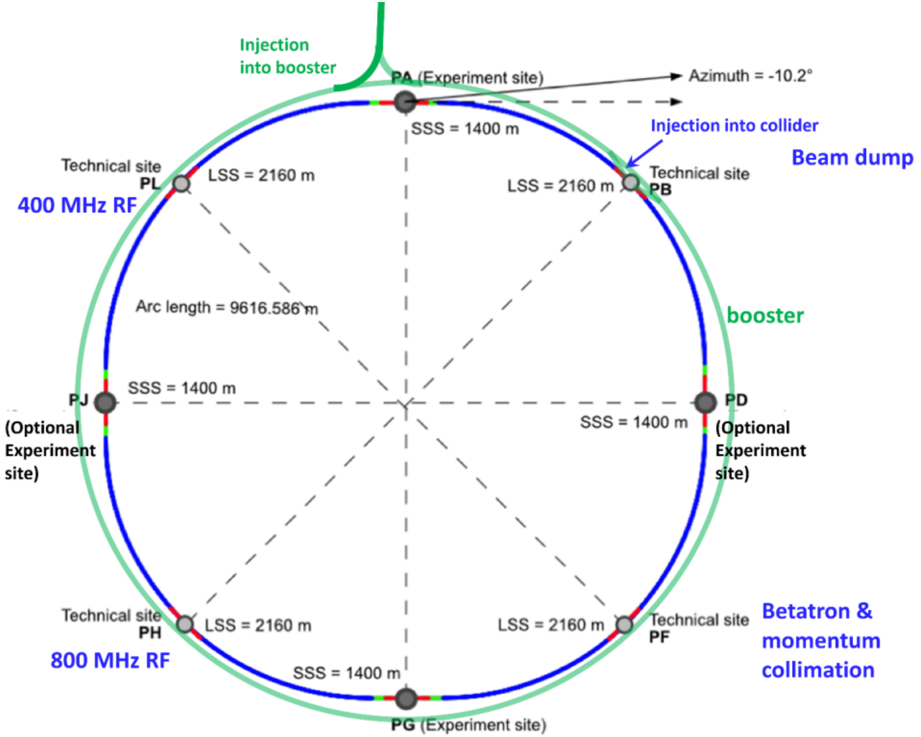
Outline

- FCCee Beam instrumentation in a nutshell
- On-going R&D activities
- Main goals for next years
- Conclusion



FCC-ee in a nutshell (from a BI perspective)

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
circumference [km]	91.18
max. beam energy [GeV]	182.5
max. beam current [mA]	1280
max. # of bunches/beam	10000
min. bunch spacing [ns]	25
max. bunch intensity [10^{11}]	2.43
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42
min. H rms IP spot size [μm]	8
min. V rms IP spot size [nm]	34
min. rms bunch length SR / BS [mm]	1.95 / 2.75



+ injectors and positron source

K. Oide, J. Gutleber

FCC-ee Beam Instrumentation Challenges

- **Technical / scientific challenges**
  - ***Large size / footprint***
    - makes distributed BPM / BLM systems complex, expensive and difficult to maintain, and causes unwanted signal delays for FB applications.
    - High SR power in the tunnel arcs requires radiation tolerant signal processing electronics and X-ray shielding efforts.
  - ***Ambitious beam parameters, similar to 4th generation light sources requirements***
    - state-of-the-art beam instruments for beam size and bunch length / profiles
    - excellent alignment, long term stability
    - low beam-coupling impedance for all devices

FCC-ee Beam Instrumentation Challenges

- **Managerial, manpower and budget challenges**
  - ***Large amount of work to distribute and coordinate between all collaborators***
    - Require good communication between all teams
  - ***Today, with limited resources, we can only follow the most critical R&D activities***
    - Hope that new partners will join and take part in the beam instrumentation development

FCC-ee Beam Instrumentation Challenges

- Beam Position Measurement
- Beam Loss Measurement
- Beam Size Measurement
- Bunch Length Measurement
- Polarisation and energy calibration
- Beamstrahlung photons
- ….

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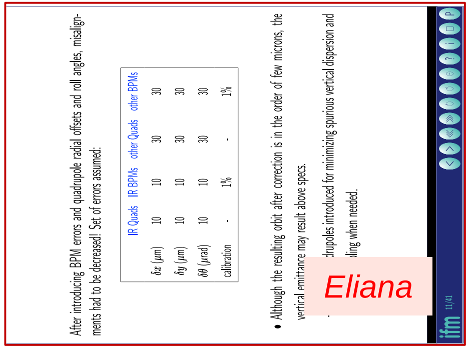
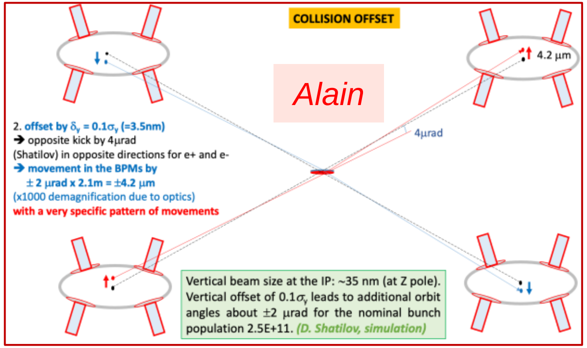
- ….

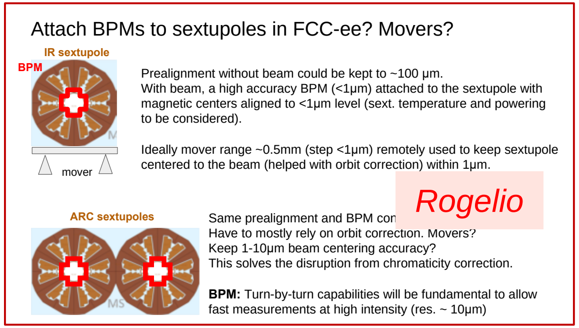
Beam Position Monitors (BPM)

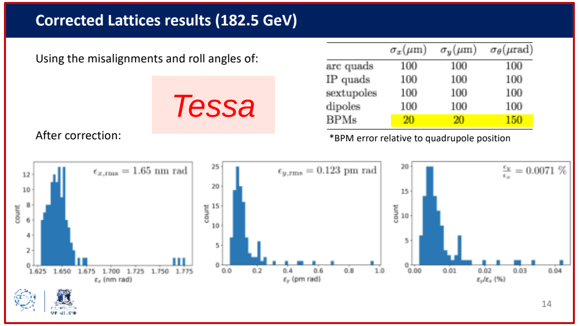
- **> 7000 BPMs in the 91.1 km tunnel**
  - ***2000+2000 BPMs for the main rings, 3000 BPMs for the booster ring***
  - ***Orbit, turn-by-turn, and bunch-by-bunch operating modes, 25 ns signal processing time***
- **BPMs and BPM pickups also will be used for various non-orbit applications**
  - ***Tune measurement, orbit and bunch FB, timing electrodes, instability monitor, etc.***
- **Some of the many challenges**
  - ***Large scale system: infrastructure, segmentation, cost optimization***
  - ***Signal latency (for FB apps), synchronization of turn and bunch data, large data throughput (probably >20 GSPS for each BPM plane) and decimation***
  - ***Radiation tolerant tunnel hardware***
  - ***Low beam-coupling impedance of the BPM pickups (wakefields)***
  - ***Alignment and stabilization (temperature variation) of the BPM pickups***
  - ***Accuracy (non-linearities), resolution (orbit, TxT, BxB), precision (drifts, aging) requirements, which are similar or even more tight then last gen. SL sources.***

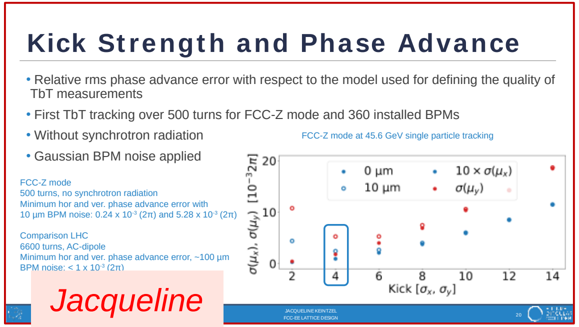
Some BPM Requirements





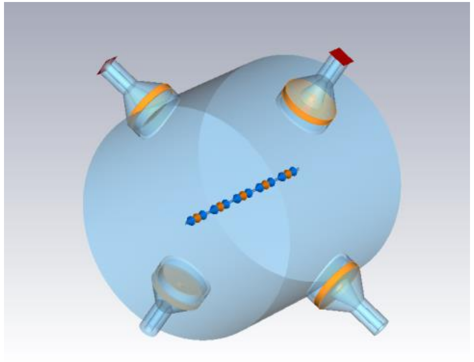


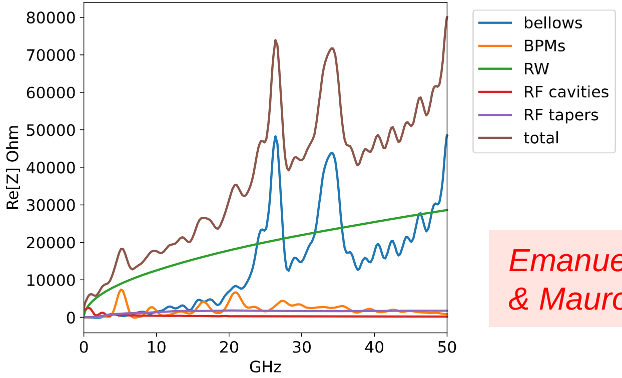




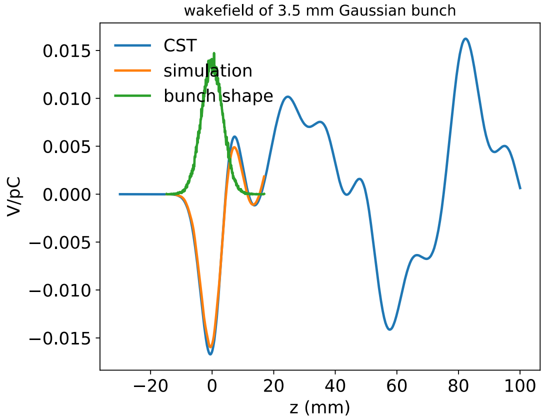
- **Resolution: <1 μm (orbit), <10 μm (TxT)**
  - *However, in a very large beam pipe 70 mm dia. (FCC-ee arcs)*
- **Alignment & accuracy 1-10 μm**
  - *Movers? Pre-alignment accuracy?*
  - *Stretched-wire BPM-quad electromagnetic pre-alignment?*
- **Roll errors 10-30 μrad, calibration errors ~1 %**
- **Long term stability & drifts?**
- **Need to draft a BPM requirements document !**

BPM Pickup R&D: Wakefields





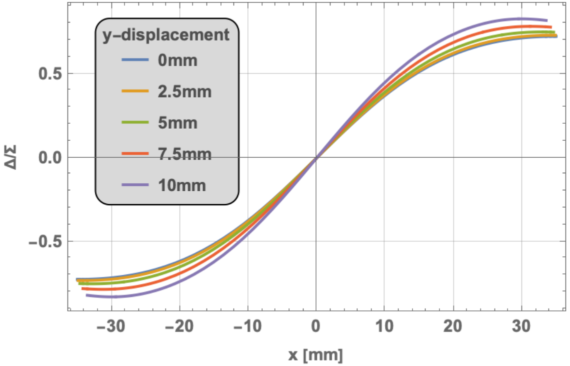
Emanuela & Mauro

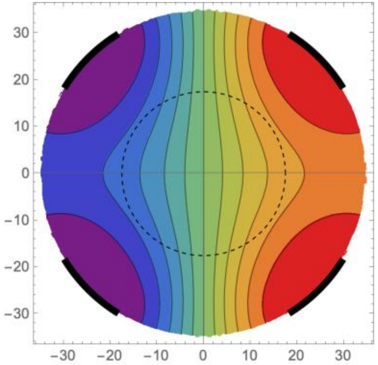


- **Preliminary study by *Emanuela Carideo* and *Mauro Migliorati***
  - ***Simplified button style BPM pickups, pipe with and w/o winglets***
  - $k_{loss} \approx 10mV/pC@\, 3.5mm$ ***RMS bunch length***
  - $Z_{\parallel}$ ***within the regime of other components and resistive wall***
- **More detailed studies are planned in frame of BPM pickup R&D**
  - ***Including beam studies and lab measurement characterization***

Button-Style BPM Position Characteristics

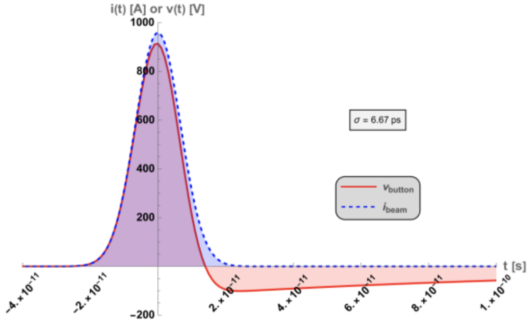
- **Analytical and simplified numerical analysis**

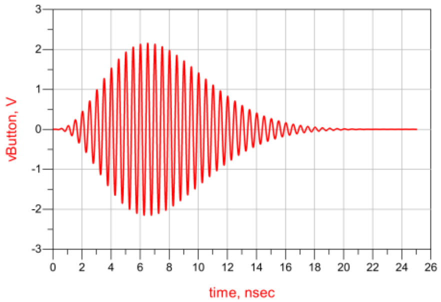




by M. Wendt

- **PU Single bunch response , Band-pass filter: $f_c = 2\ GHz, BW = 80\ MHz$**

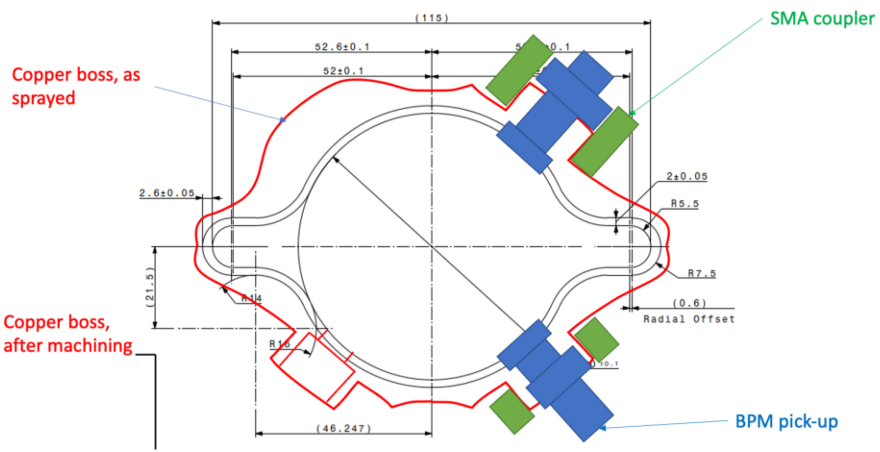




- Theoretical resolution limit ≈ $0.1\ \mu m$!
- Final system typically worse (x10)
- Current technology will do it

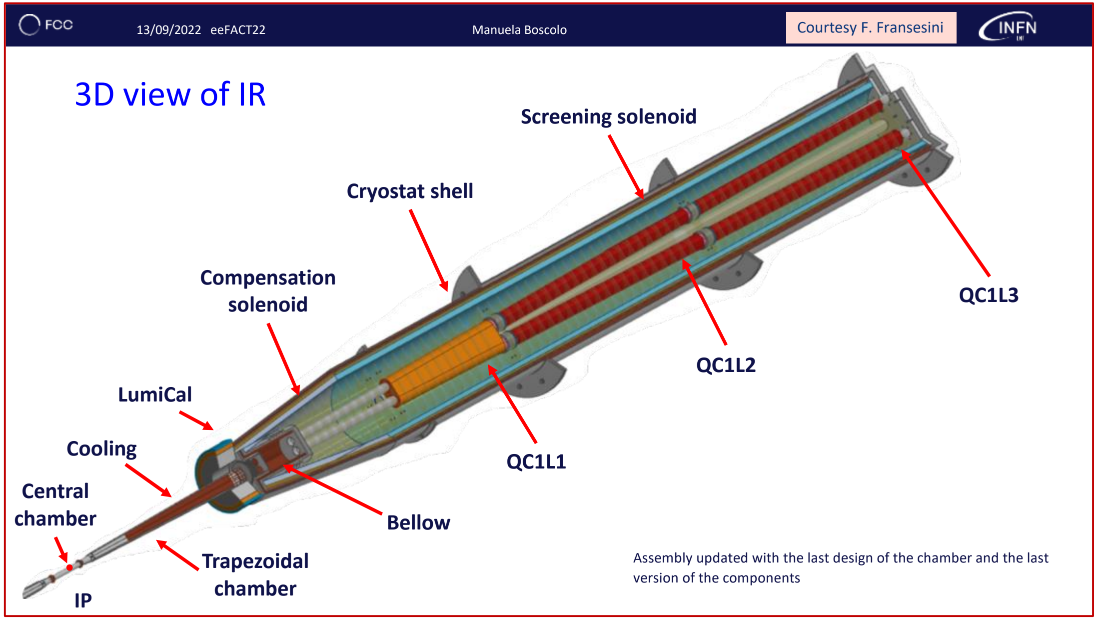
BPM Pickup R&D: Manufacturing & Integration

Button manufacturing and integration



Talk by Cedric

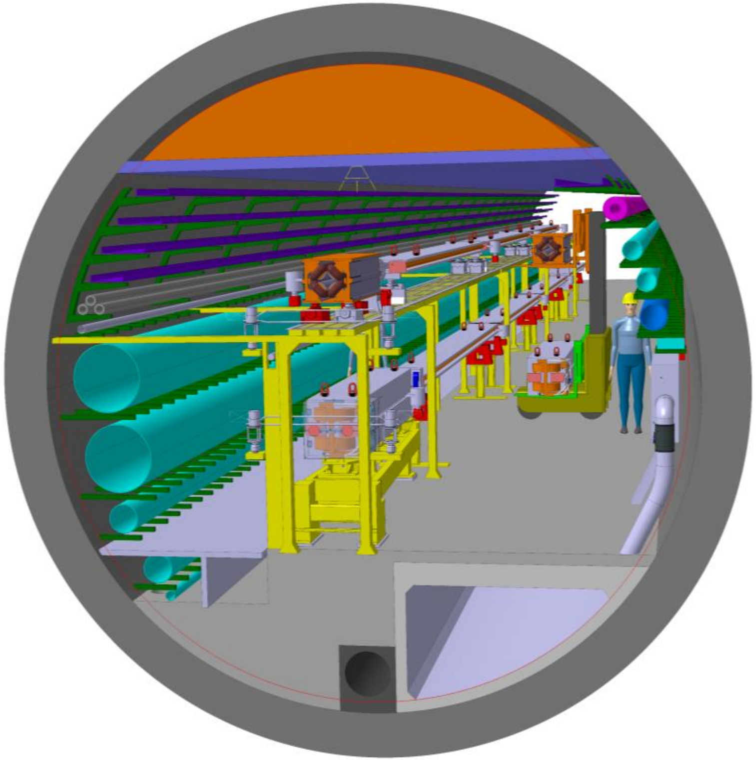
BPMs in Final quadrupole



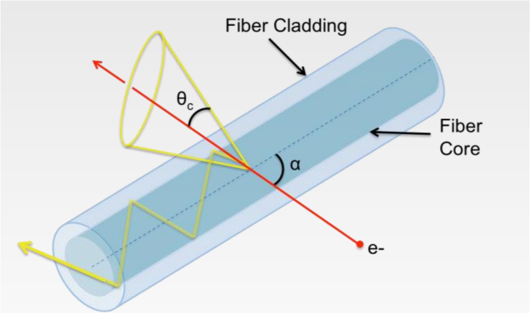
- Challenging BPM integration, accuracy, alignment & stability
- BPM design in Final quadrupole to be studied in more details
- No ressource yet – opportunitites for collaboration !

Beam Loss Monitors (BLM)

- **Large energy stored in both, main rings and booster ring require a machine protection system (MPS), supported by beam loss monitors (BLM)**
  - ***BLMs in the arcs need to be insensitive to X-rays!***
  - ***Identifying losses from the individual rings in the tunnel is difficult!***
    - Between main rings: BLMs with beam directivity
    - Between main and booster rings: staged localization of the quads
- **Specific need in injectors ?**



BLM R&D



Dedicated FCC-ee BLM R&D has not started, but…

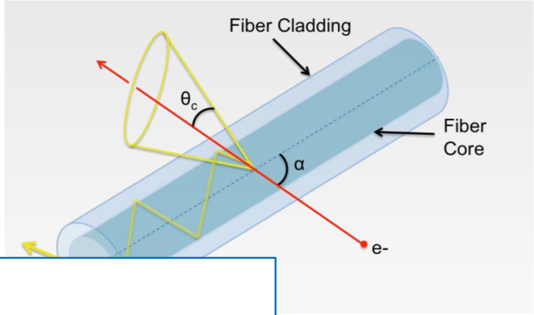
- **Optical BLM system based on *Cherenkov* fibers offer**
  - ***High directivity***
  - ***Only measures charged particles***
  - ***Beam studies at CLEAR and SPS***

- **Many experimental investigations initiated within the Linear Collider study**
  - ***Crosstalk between beam losses from CLIC Drive and Main beams:***
    M. Kastriotou et al, "BLM crosstalk studies on the CLIC two-beam module", IBIC, Melbourne, Australia (2015) pp. 148
  - ***Position resolution of a distributed oBLM system:***
    E. Nebot del busto et al, "Position resolution of optical fibre-based beam loss monitors using long electron pulses", IBIC, Melbourne, Australia (2015) pp. 580
  - ***RF studies (Breakdown and Dark current):***
    M. Kastriotou et al., "A versatile beam loss monitoring system for CLIC", IPAC, Busan, Korea, 2016, pp. 286

BLM R&D

Dedicated FCC-ee BLM R&D has not started, but…

- **Optical BLM system based on *Cherenkov* fibers offer**
  - ***High directivity***
  - ***On***
  - ***Be***



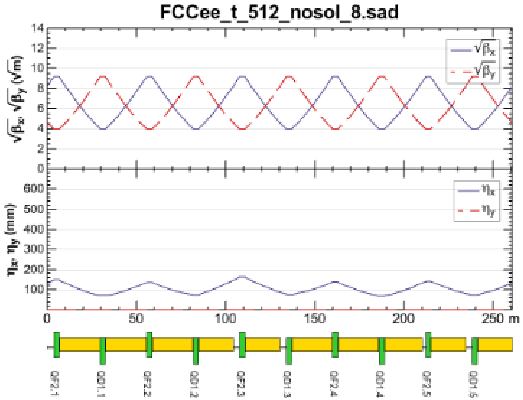
Need to establish a FCCee machine protection and beam loss monitoring working group

- **Many … dy**
  - ***Cr***
    M. … lbourne, Australia (20
  - ***Po***
    E. … ors using long ele
  - ***RF studies (Breakdown and Dark current):***
    M. Kastriotou et al., "A versatile beam loss monitoring system for CLIC", IPAC, Busan, Korea, 2016, pp. 286

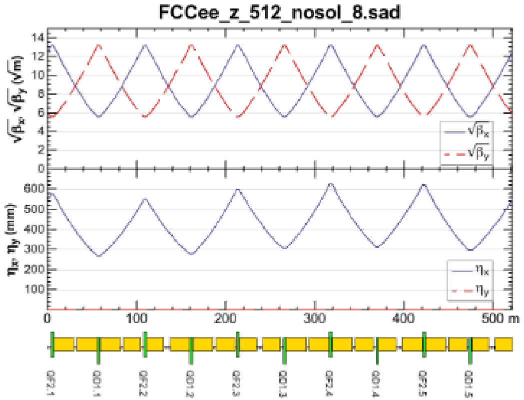
Beam Size Measurement

Parameter [4 IPs, 91.2 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69

90°/90° : $t\bar{t}$, Zh



Long 90°/90° : Z, W

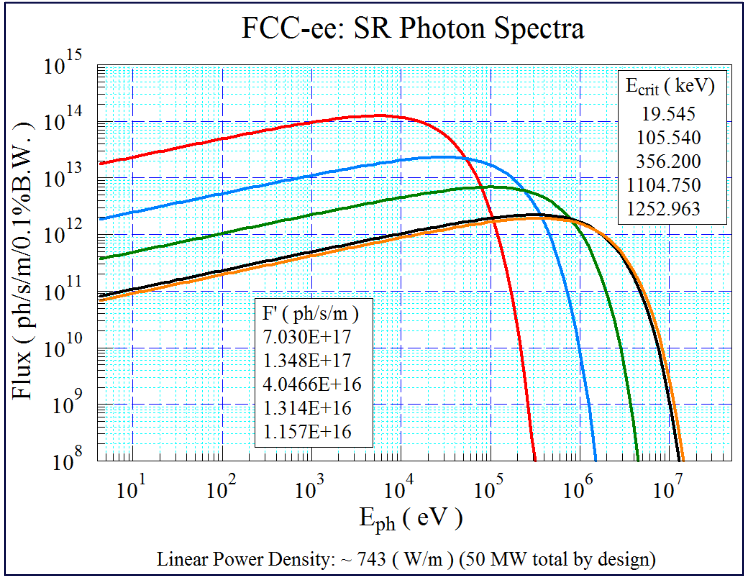


FCC-ee beam size is small!

- ***In the arcs (Zh):***
  horizontal: ~100 μm
  vertical: ~7 μm

Beam Size Measurement based on SR

- Use of synchrotron radiation at high beam energies suffer from diffraction effects!
  - *Requires X-ray interferometric techniques*



$$\sigma_{diff} = \frac{1.22\lambda}{4\sigma_y'} \approx 0.43\gamma\lambda$$

Diffraction limit:
~15 μm @ 0.1 nm (182.5 GeV)

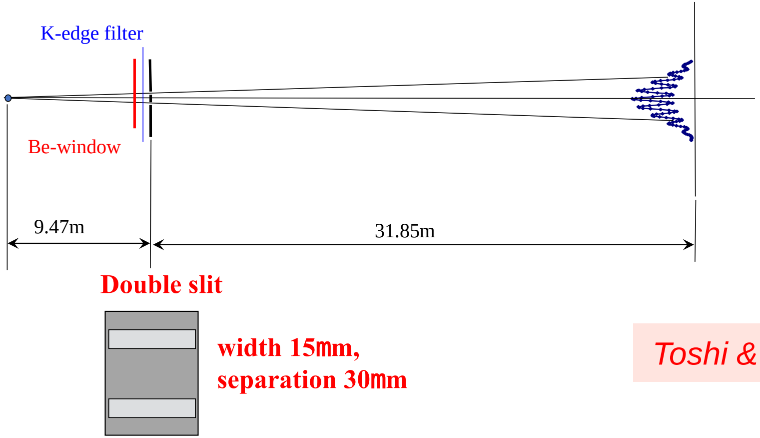
FCC-ee challenge:

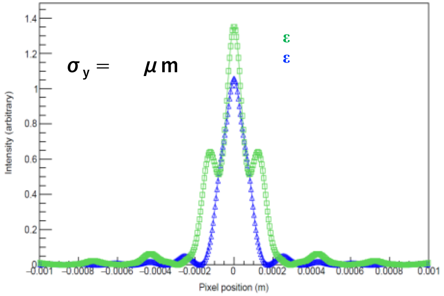
- Large arc radius requires very long, extended SR extraction lines
  - *Need for detailed numerical simulations*

Beam Size R&D: X-Ray Interferometer at KEK

- **Beam size given by the *Fourier* transform of the spatial coherence measured by an interferometer**
  - ***Long light extraction line with critical alignment***
  - ***Single plane***
  - ***Challenging slit design***
  - ***Does not provide the beam profile***

Configuration of X-ray interferometer at SuperKEKB





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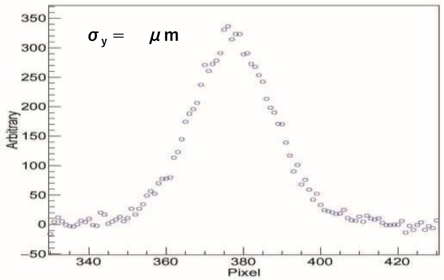
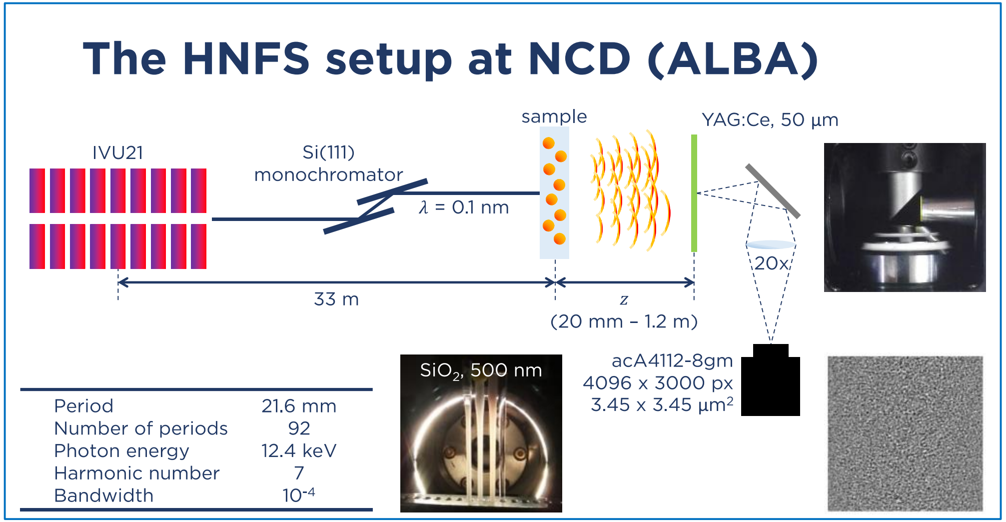


Toshi & Gaku

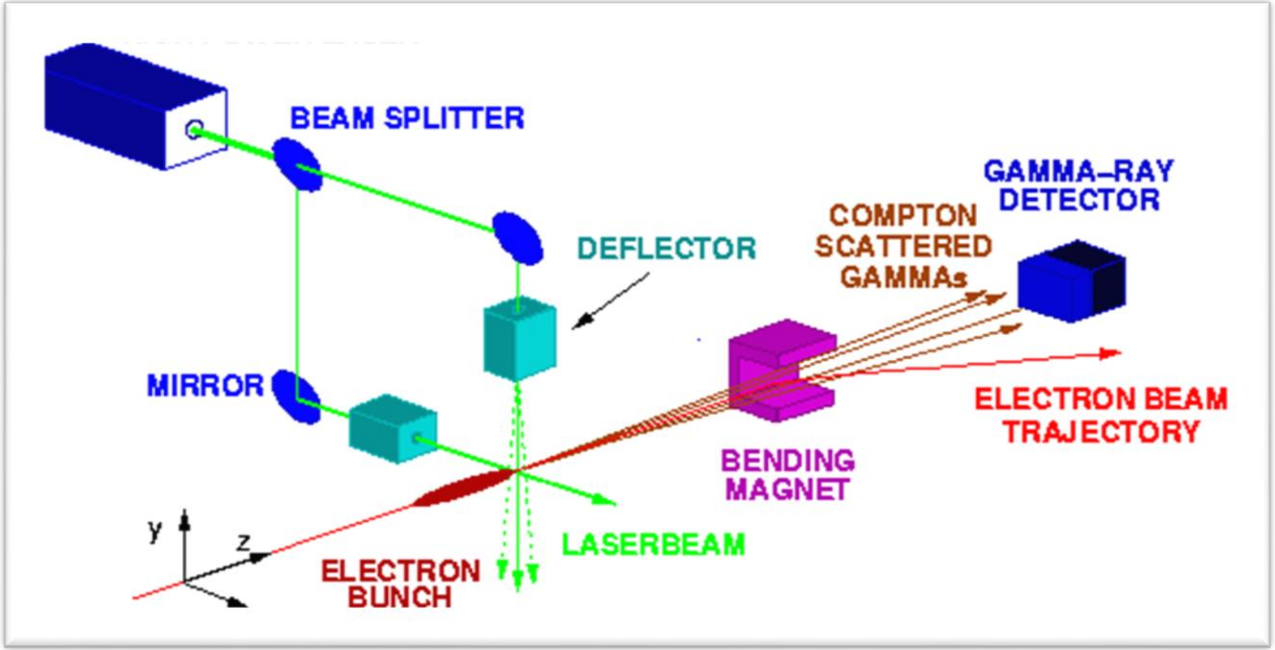
Beam Size R&D: 2D X-Ray HNFS at ALBA



Talk by Ubaldo

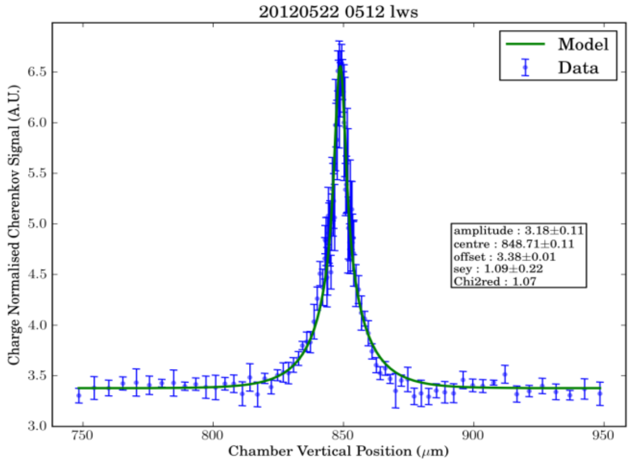
Beam Size alternative : Laser Wire Scanner

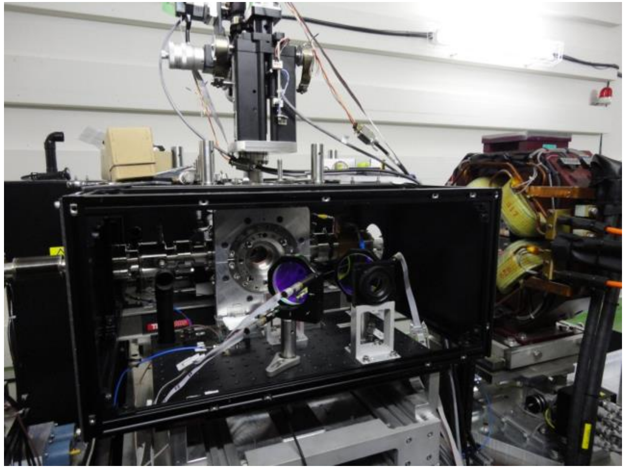
- **Laser wire scanner technology developed for linear colliders**
  - ***Based on Compton scattering using high power laser light***



Beam Size alternative : Laser Wire Scanner

- ***Demonstrated 1 µm measurement resolution!***
  - using a high-power fiber laser
- ***Possibly shares laser technology with the Compton polarimeter***
- ***Not cheap!***





15 years on R&D on ATF2 ring and extraction line

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)

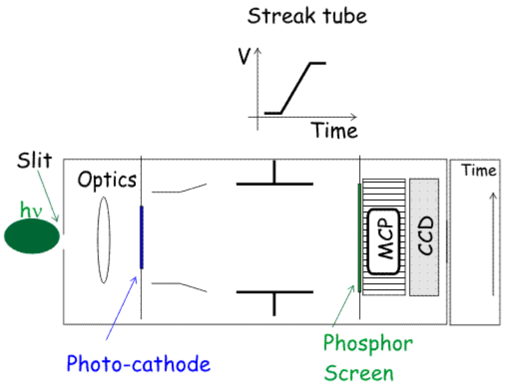
L. Corner et al., IPAC, Kyoto, Japan (2010) pp3227

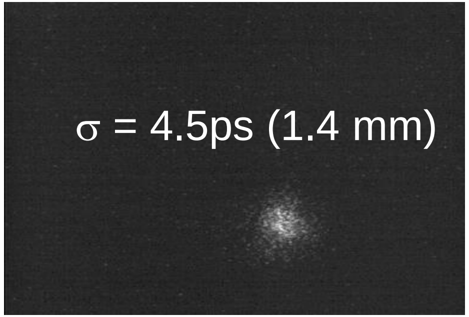
Bunch Length Measurements : specifications

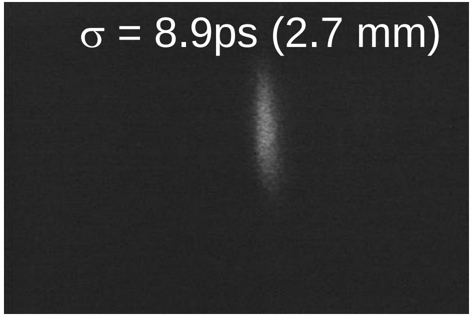
Parameter [4 IPs, 91.1 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75

- “Reasonably” long bunches
  - *2 – 3 mm RMS, or longer*
- Need a bunch-by-bunch measurement system with picosecond resolution to monitor the impact of the Beamstrahlung.
- Need a resolution in the hundred’s femtosecond to estimate the energy spread, required for the energy calibration using the spin depolarization technique

Bunch Length Measurements : Streak Camera



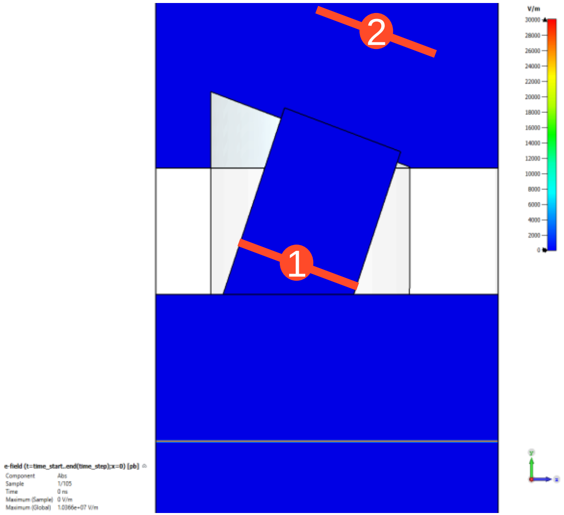




- **200 fs time resolution obtained using reflective optics, a 12.5 nm BW optical BPF (800 nm) and the *Hamamatsu* FESCA200**
  - *M. Uesaka, et.al., NIMA 406 (1998) 371*

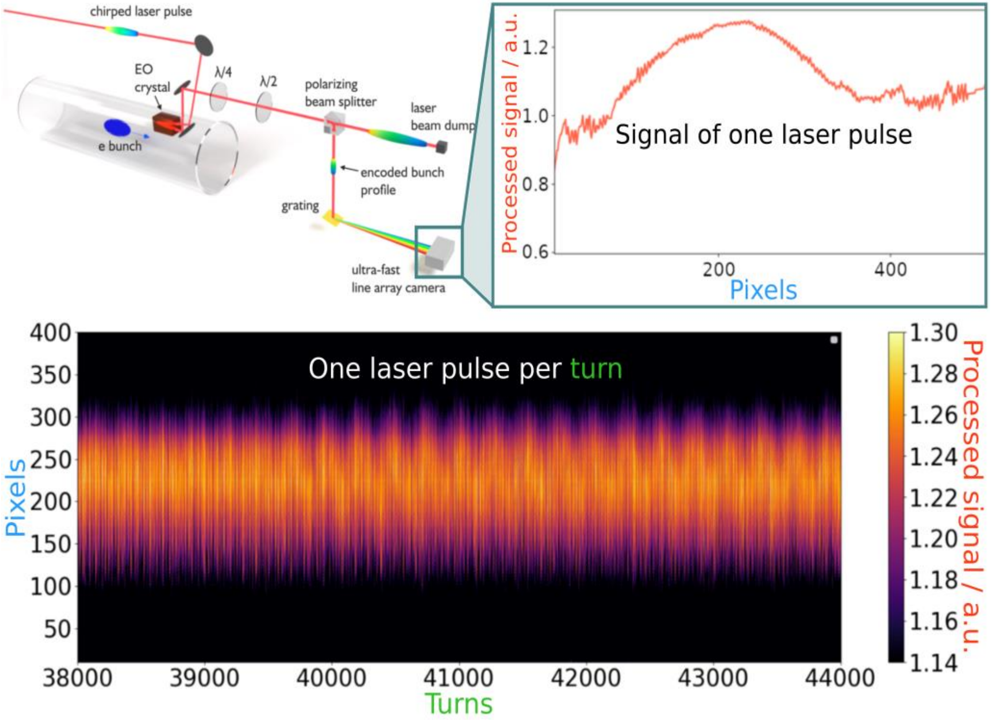
- **Does not provide bunch-by-bunch online monitoring**

Bunch Length Measurements : Cherenkov Diffraction radiation studies at CERN



Talk by Andreas

Bunch Length Measurement: EOS studies at KIT



Talk by Micha

Polarimeter

- Transverse polarimeter for Resonant Depolarisation of pilot bunches
- Longitudinal polarimeter (rate counting) for precession of pilot bunches
- Transverse polarimeter for colliding bunches

Accuracy ~<1e-3 for transverse polarisation (→~<1e-5 longitudinal for physics at IP)

- Use Compton polarimeter using high power laser and measuring the characteristics (amplitude and transverse distribution) of scattered electrons/positrons and scattered Compton photons

https://indico.cern.ch/event/1181966/.
Epol workshop in September 2022

See also the talk from Jacqueline yesterday
And specifications documents in preparation

CERN

Preliminary draft 15:57 21 November 2022

21 November 2022

Energy calibration, polarization and monochromatization - Requirements on alignment, optics, lattice, beam instrumentation and detectors

Polarimeter

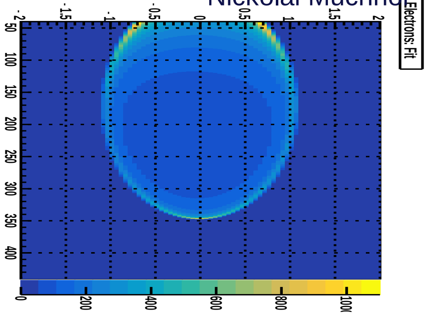
- Laser system
  - *Challenging to control polarisation to high level (10^{-4})*
  - *Preliminary design shows no difficulties as commercial laser exists (would need laser amplification to be able to measure both pilot and nominal bunches)*
  - *Need a dedicated lab to house the laser close to the interaction chamber*

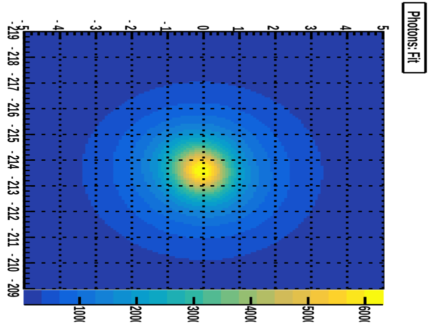
- Laser-beam interaction chamber should have low impedance, to be studied

- Detector technology not studied yet in details
  - *Spectrometer for measuring the energy of the scattered particles*
  - *Calorimeter for photons*
  - *Pixel detectors for charged particles*

- Collaboration with IJCLab

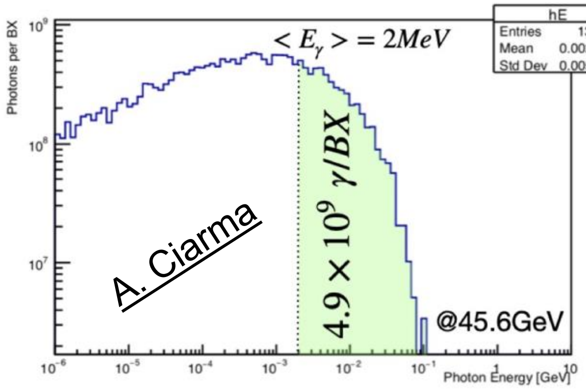
Nickolai Muchnoi





Beamstrahlung photons monitoring

- A **significant fluence of photons is generated at the IPs** in the forward direction by different mechanisms (beamstrahlung, radiative Bhabha, SR, etc.)
  - ±2 MeV average, extending up to 100 MeV
  - **~500 kW** in few cm^2
- To be absorbed reliably and safely



Beamstrahlung photons monitoring

- Measuring the **intensity**, **position** and **size** of high-power densities beamstrahlung photon beams

- Possibly using a **two-step approach** with different diagnostics
  - **Fully characterising the photon beams at low power using, e.g., scintillating screens and cameras (to be studied) that will only be inserted in the photon beam extraction line during single bunch or few bunch operation**
  - Measure the transverse tails of beamstrahlung photon distribution using intercepting sensors (i.e., scintillators, gaseous detectors, pixel detectors..) or developing **fully non-invasive methods** (e.g., using ionisation **or fluorescence of gas jets) that would be able to withstand the full photon beam power**

- Not started yet – possibly looking for external collaborators

Goals for next years

- ***Collect requirements for Beam Instrumentation in the whole complex***
  - Identify all needs – with the aim to minimise number of designs
  - Prepare functional specifications

Instrument	*Accuracy*	*Resolution*	*Bandwidth*	*Beam tube aperture*	*Stability*	*How many?*	*Used in RT Feedback?*	*Machine protection Item ?*
Intensity								
Position								
Beam Size								
Energy								
Energy Spread								
Bunch Length								
Beam Loss								
Beam Halo								
Beam Polarization								
Luminosity								

Goals for next years

- ***Study and Validate prototypes of most challenging technologies***
- ***Launch the study on Beam loss monitoring / Machine protection***
- ***Launch the studies of Beamstrahlung photons detection***
- ***Launch the study on BPM in Final Quadrupole***
- ***Launch the design of Polarimeter (collab. with IJCLab)***
- ***Question on feedback - who does what ?***

Goals for next years

- ***First look on Beam Instrumentation implementation***
  - Needs of radiation-hard, radiation-tol systems integrated in tunnel
  - Infrastructure needs (fiber, cable, racks and laboratory space, ..)
  - Global system design for BPM feedback system – latency ?
  - Define a plausible maintenance strategy
- ***Update on Cost and Optimisation***

Conclusion

- **Huge amount of work:** ***> 20000 Instruments over 300kms of beamlines***
- **R&D on Critical Items has started and is progressing well**
- **Potential for collaborations with other projects (light sources upgrades, FELs, other colliders)**

Thank you for your attention.