Beam Instrumentation WS summary

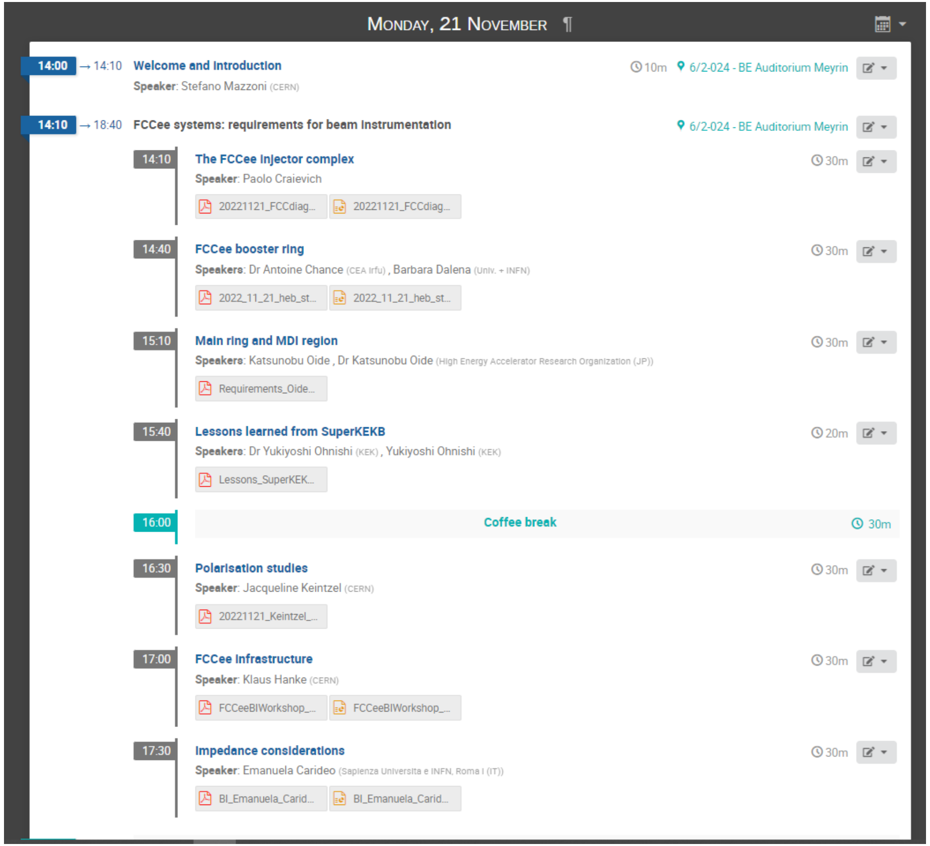
S. Mazzoni, T. Lefevre, M. Wendt, CERN

Workshop

- 1st workshop on Beam Instrumentation for FCC-ee held at CERN on 21-22 November 2022
- 1.5 days, circa 50 participants (20 on site, 30 remote)
- Goals:
  - *To get in contact with all stakeholders involved in defining or developing Beam instrumentation for FCC-ee and possibly identify new collaboration partners.*
  - *To collect an overview of the FCC-ee Beam instrumentation specifications across the full accelerator chain : from source (linac) to FCC-ee storage rings*
  - *To Identify and follow-up on Mission critical R&D on specific BI*

https://indico.cern.ch/event/1209598/

Workshop, day 1



- FCC-ee systems: injector, booster & main ring
- Requirements / considerations from polarization studies, impedance, infrastructures.

Workshop, day 2

TUESDAY, 22 NOVEMBER

09:00 → 12:00 BI studies for FCCee — 6/2-024 - BE Auditorium Meyrin

- 09:00 **Overview of BI studies for FCCee** — 30m
  Speaker: Thibaut Lefevre (CERN)
  BeamInstrumentati... BeamInstrumentati...
- 09:30 **Main ring quadrupole - vacuum chambers and BPM integration** — 30m
  Speaker: Cedric Garion (CERN)
  Vacuum_Developm... Vacuum_Developm...
- 10:00 **Electro-optical Bunch length monitors for FCCee** — 30m
  Speaker: Micha Reißig
  2022-11-22_FCCee_...
- 10:30 **Coffee break** — 30m
- 11:00 **Cherenkov diffraction radiation for bunch length monitoring** — 30m
  Speaker: Andreas Schloegelhofer (Technische Universitaet Wien (AT))
  FCC_BI_ChDR_Schl... FCC_BI_ChDR_Schl...
- 11:30 **Beam size measurements with X-HNFS** — 30m
  Speaker: Ubaldo Iriso
  Ubaldo_Speckles_F... Ubaldo_Speckles_F...

12:00 → 14:00 Lunch break — 2h

14:00 → 16:00 Future lepton accelerators — 6/2-024 - BE Auditorium Meyrin

- 14:00 **CepC beam instrumentation** — 30m
  Speaker: Yanfeng Sui
  CEPC Beam Instru...
- 14:30 **PETRA 4** — 30m
  Speaker: Gero Kube (DESY)
  FCCWorkshop_Kub...
- 15:00 **Diamond-II: Diagnostics and Feedbacks** — 30m
  Speakers: Lorraine Bobb (Diamond Light Source), Lorraine Bobb
  Diamond_II_FCCee... Diamond_II_FCCee...
- 15:30 **EIC beam instrumentation** — 30m
  Speaker: David Gassner (Brookhaven National Laboratory)

16:00 → 16:30 Concluding remarks — 30m — 6/2-024 - BE Auditorium Meyrin

- presentation of current / planned BI studies
- Future lepton machine (4th gen light source upgrades, CepC, superKEKb)

FCC-ee systems

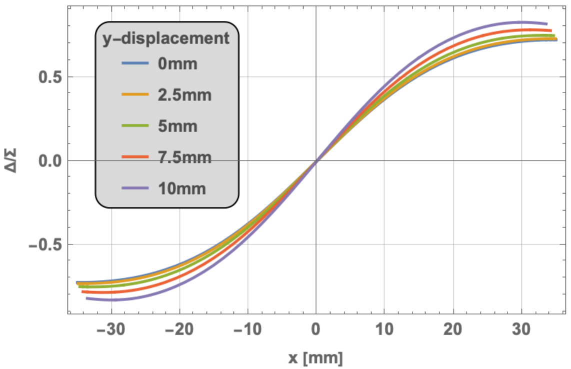
- **(pre) Injector** study - P. Craievich (PSI).
  - *WP contains BI systems and requirements*
  - *Requirements definition is advanced, most BI systems don't represent a challenge.*
  - *Critical point: BI systems based on PSI. Harmonization with other BI systems (eg cavity BPMs) for operation and maintenance. Cost considerations*
- **Booster ring,** A. Chance (CEA).
  - *BI requirements in definition.*
  - *Position, size (emittance), bunch length, energy spread at injection (20 GeV), and extraction energy. During ramp?*
  - *CERN BI to study options. BbB length critical > extraction lines, consequences on tunnel layout (booster / main ring)*
- **Injector to booster / transfer lines** options

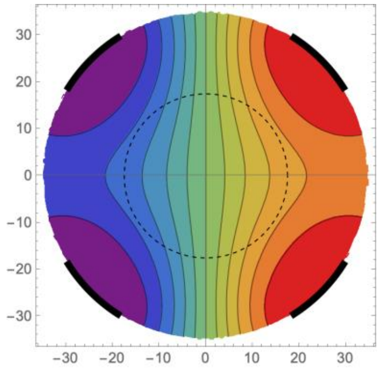
FCC-ee for main ring

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

Arc cell Button-Style BPM

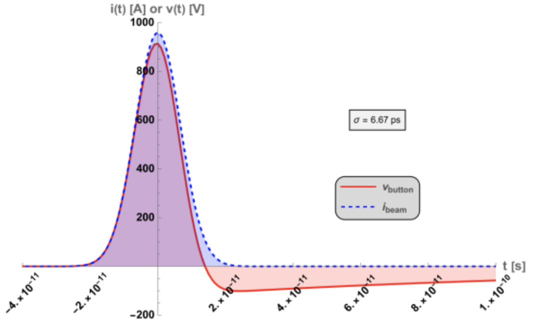
- **Analytical and simplified numerical analysis**

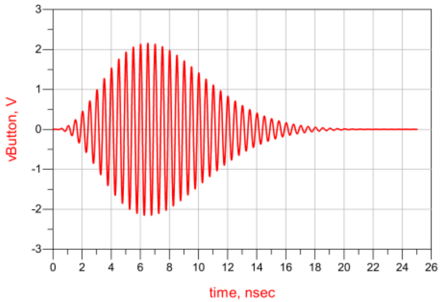




by M. Wendt

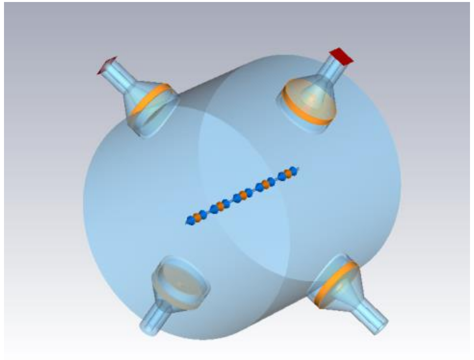
- **PU Single bunch response , Band-pass filter: $f_c = 2\ GHz, BW = 80\ MHz$**

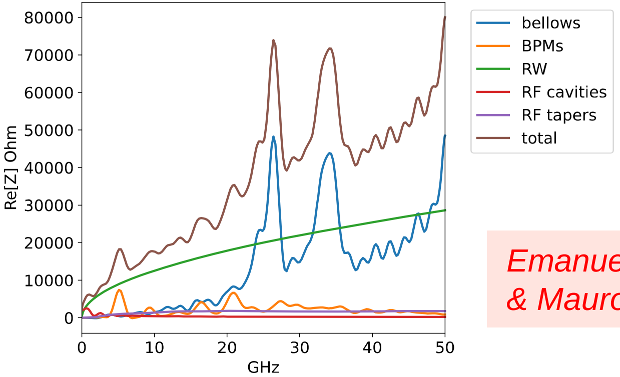




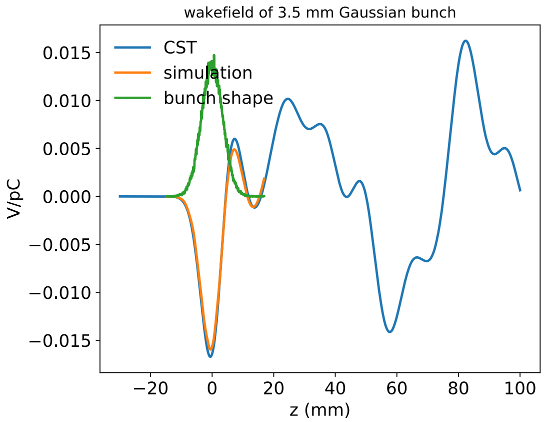
- Theoretical resolution limit $\approx 0.1\ \mu m$!
- Final system typically worse (x10)
- Current technology will do it

Arc cell BPM Pickup R&D: Wakefields



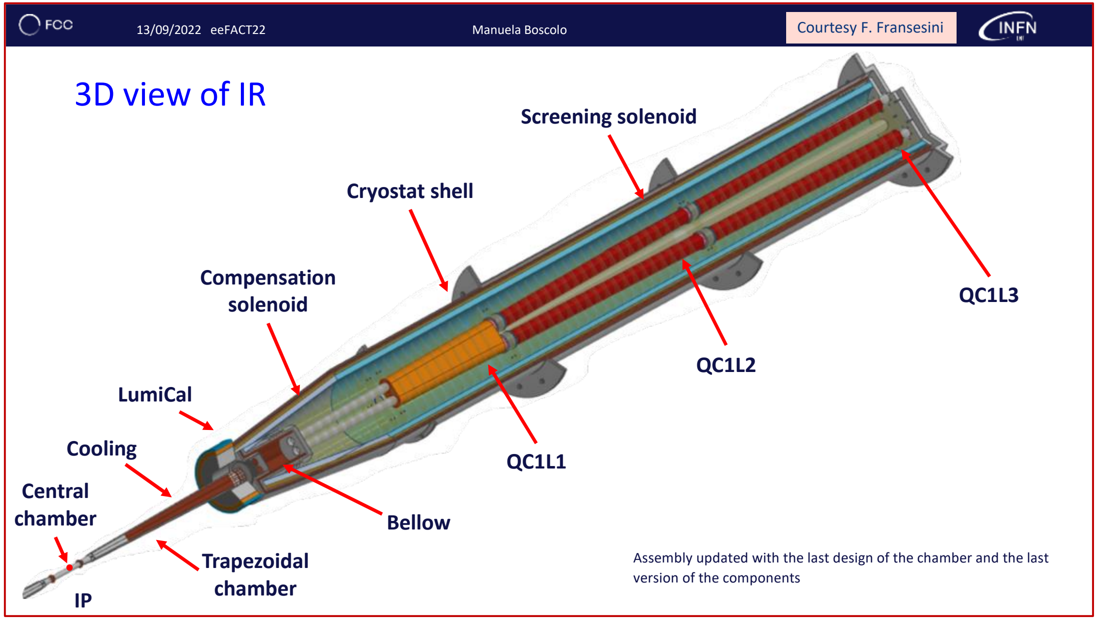


Emanuela & Mauro



- 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*

BPMs in Final quadrupole



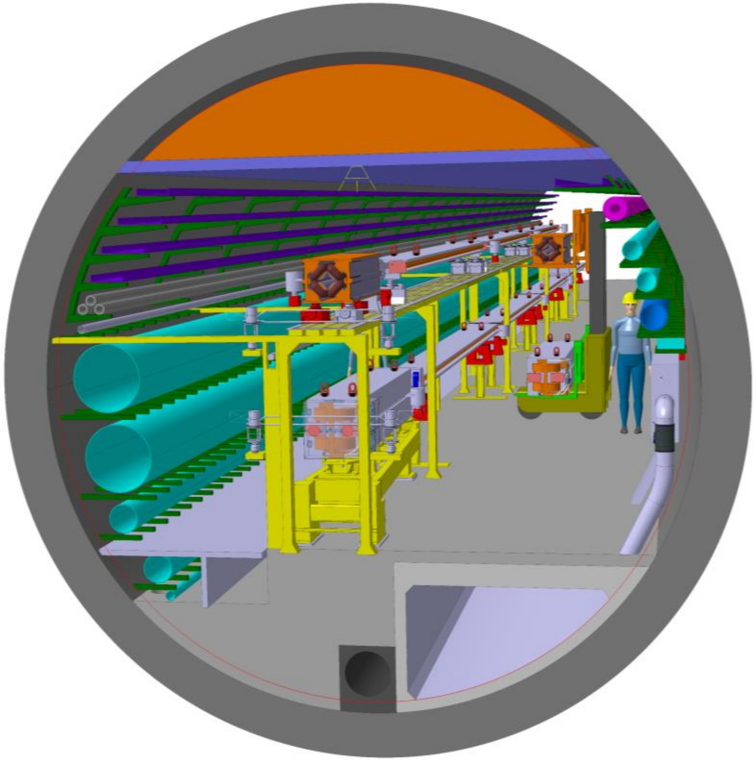
- Challenging BPM integration, accuracy, alignment & stability
- BPM design in Final quadrupole to be studied in more details
- No ressource yet – opportunitites for collaboration !

Beam Position Monitors (BPM)

- **Main challenges – open points:**
  - ***several thousands of BPMs. Try to reduce number of designs***
  - ***requirements for resolution from several WPs seem achievable. This and impedance studies will be part of BI R&D (PhD starting in 2023)***
  - ***Arc cell Accuracy (pre-alignmement) is open point. At present mechanical integration studies do not address this issue.***
  - ***The integration of BPM in final quadrupole should be discussed in a separate working group (control of vibration, temperature etc.). Resources!***

Beam Loss Monitors (BLM)

- Large energy stored in both, main rings and booste 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 tunne is difficult!***
    - Between main rings: BLMs with beam directivity
    - Between main and booster rings: staged localization of the quads
- **Need to establish a machine protection and BLM study WG** (injection / extraction, quench protectic etc.)



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
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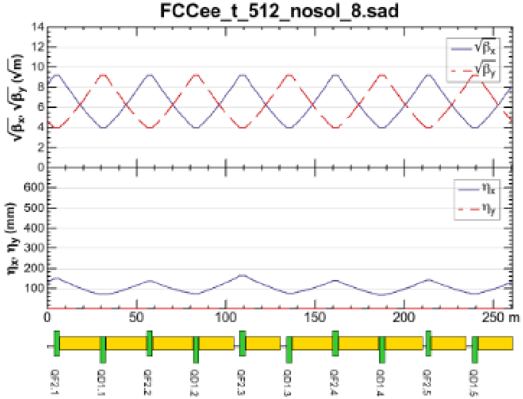
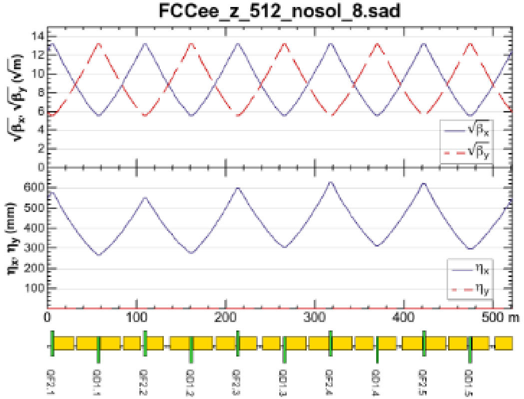
90°/90° : $t\bar{t}$, Zh



Long 90°/90° : Z, W



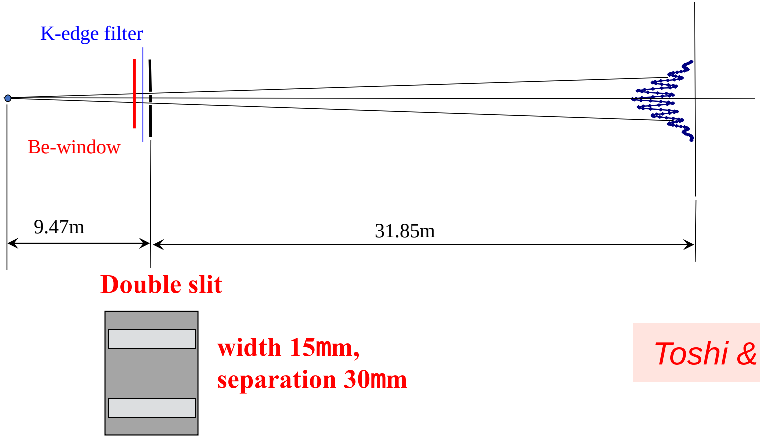
FCC-ee beam size is small!

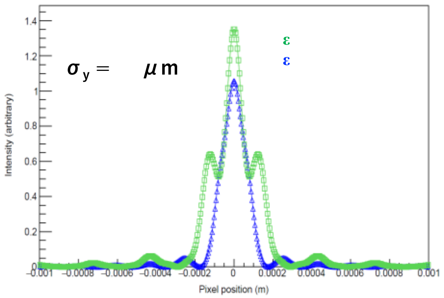
- *In the arcs (Zh):*
  horizontal: ~100 μm
  vertical: ~7 μm

Beam Size 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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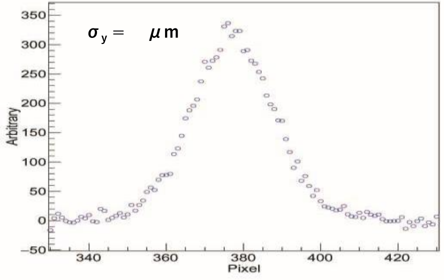
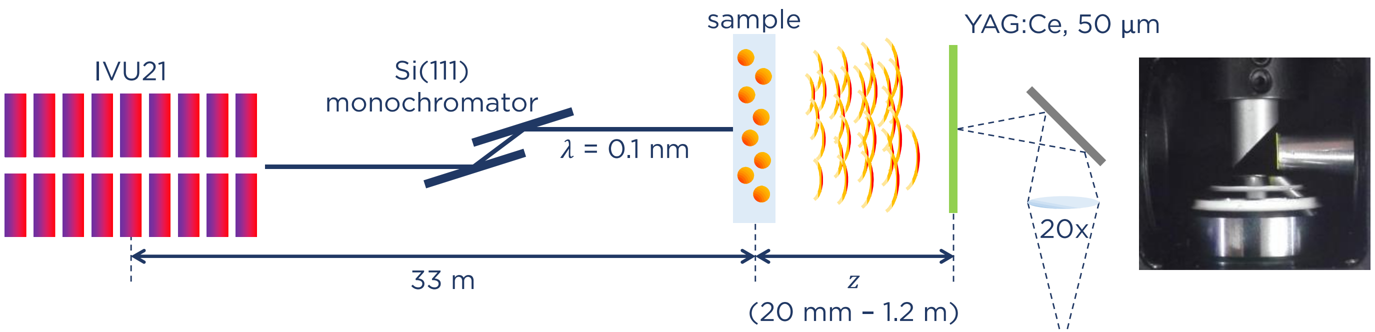
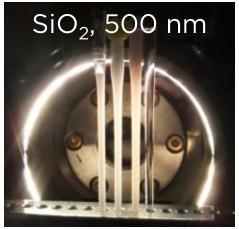


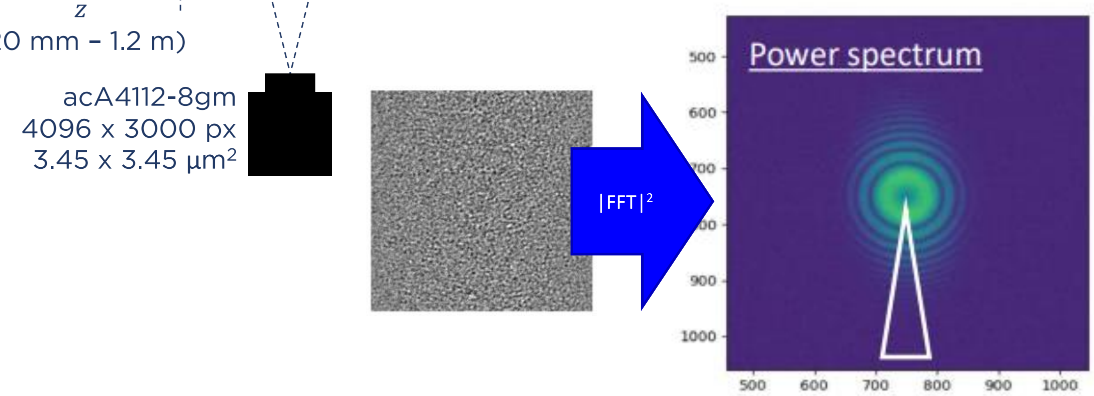
Toshi & Gaku

Beam size R&D: X-HNFS



Period	21.6 mm
Number of periods	92
Photon energy	12.4 keV
Harmonic number	7
Bandwidth	10^{-4}





Beam Size Monitoring

- **Main challenges – open points:**
  - *at present studies for* ***main ring*** *based on SR interferometry based on conceptual requirements (arc dipole)*
  - *BI R&D: definition of source in straight sections. Trade off study of SR- based between techniques ("imaging" vs interferometric), for various machine options (z to ttbar)*
  - *alternative to SR- based: laser wire scanner. Investigate commonalities with polarimeter (studies for linear collider).*

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 monitoring

- **Two studies:**
  - *E-O sampling BL measurements (KIT – see talk B. Haerer)*
  - *BL based on coherent / incoherent diffracted Cherenkov radiation (A. Schloegelhofer, CERN U. Wien). Basic R&D stage*
- **Main challenges – open points:**
  - *stressed the importance of bunch **shape** monitoring (top up). For bunch shape a photon counting method is best (limitations!)*
  - *Different beam parameters (Pilot bunches vs. colliding bunches) can be a challenge.*

More BI challenges

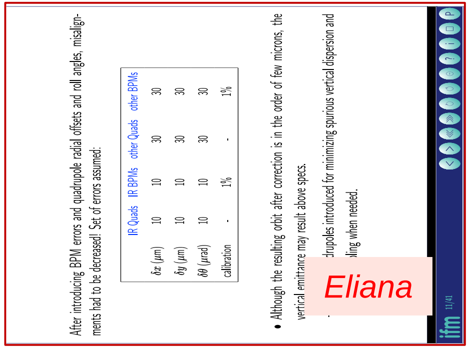
- ***Beam intensity monitoring*** *- possibly not so easy for FCCee. Bunch length dependency for bunch-by-bunch intensity measurement to be checked. Not addressed at present*
- ***Polarimeter*** *design - discussed at EPOL meeting in September. Collaboration with IJCLab for Laser system under preparation to provide a design. Detector part to be defined. Opportunity for collaboration*
- ***Beamstrahlung*** *photons detection. Very challenging due to* ***high photons flux****. Preparation of a Ph.D proposal with University of Malta to design a detector based on (rest) gas ionisation w timepix detector*

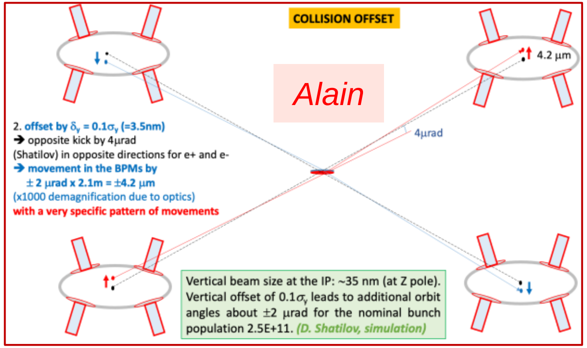
Thank you for your attention

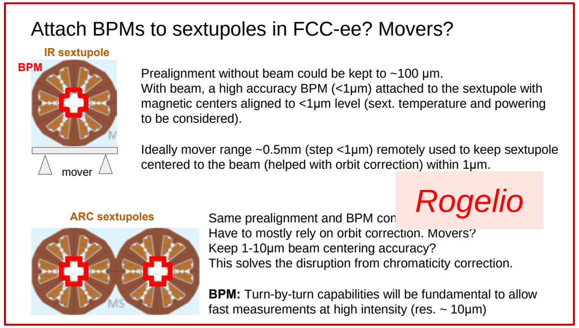
Beam Position Monitors (BPM)

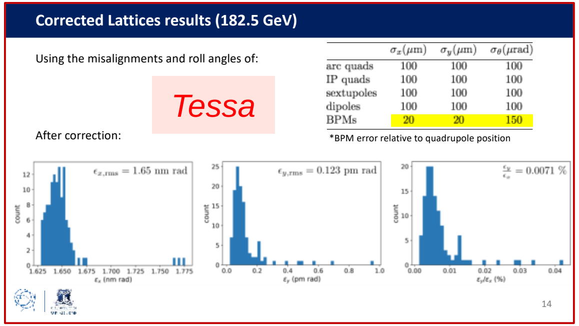
- **> 7000 BPMs in the 91.1 km tunnel**
  - *2000+2000 BPMs for the main rings, 3000 BPMs for the booster ring*
  - *Orbit, turn-by-turn, and bunch-by-bunch operating modes, 25 ns signal processing time*
- **BPMs and BPM pickups also will be used for various non-orbit applications**
  - *Tune measurement, 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.*

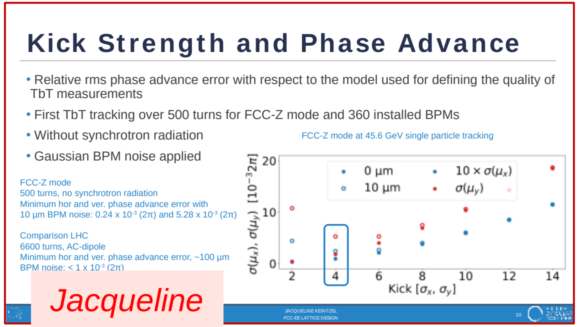
Some BPM Requirements







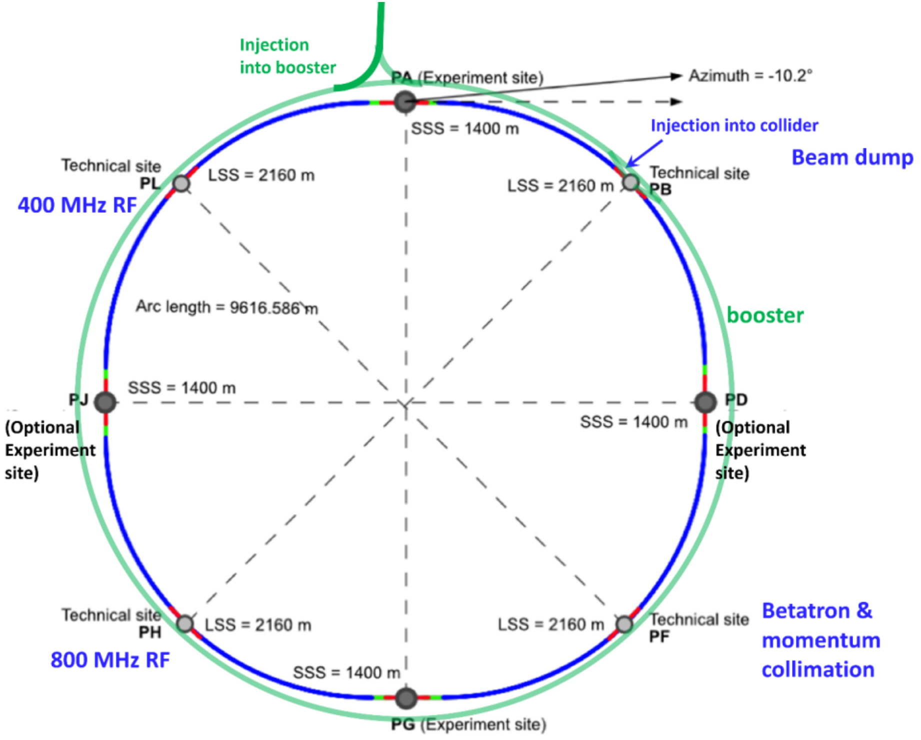




- **Resolution: <1 µm (orbit), <10 µm (TxT)**
  - ***However, in a very large beam pipe 70 mm dia. (FCC-ee arcs)***
- **Alignment & accuracy 1-10 µm**
  - ***Movers? Pre-alignment accuracy?***
  - ***Stretched-wire BPM-quad electromagnetic pre-alignment?***
- **Roll errors 10-30 µrad, calibration errors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

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

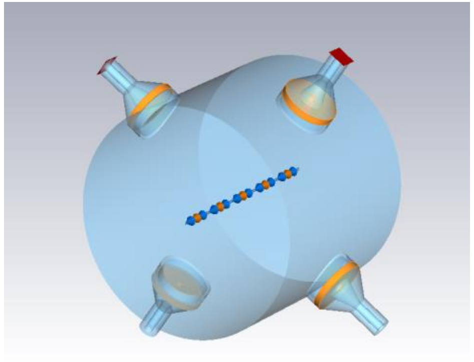
FCC-ee Beam Instrumentation Challenges

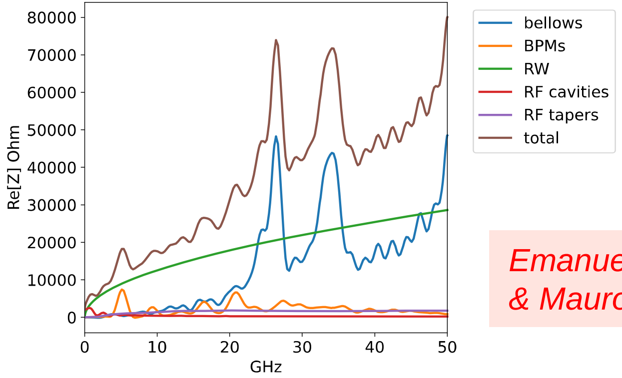
- **Technical / scientific challenges**
  - ***Large size / footprint***
    - makes distributed BPM / BLM systems complex, expensive and difficult to maintain, and causes unwanted signal delays for FB applications.
    - High SR power in the tunnel arcs requires radiation tolerant signal processing 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

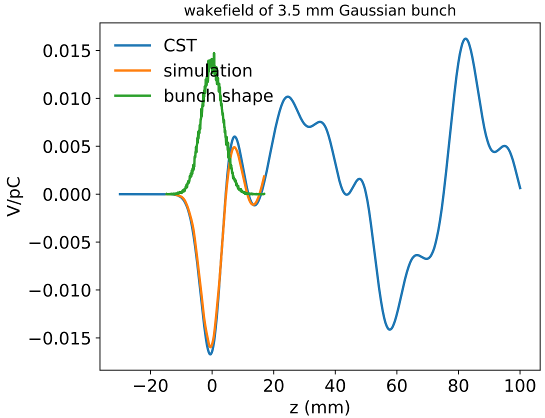
- **Managerial, manpower and budget challenges**
  - ***Large amount of work to distribute and coordinate between all collaborators***
    - Require good communication between all teams
  - ***Today, with limited resources, we can only follow the most critical R&D activities***
    - Hope that new partners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

BPM Pickup R&D: Wakefields





Emanuela & Mauro



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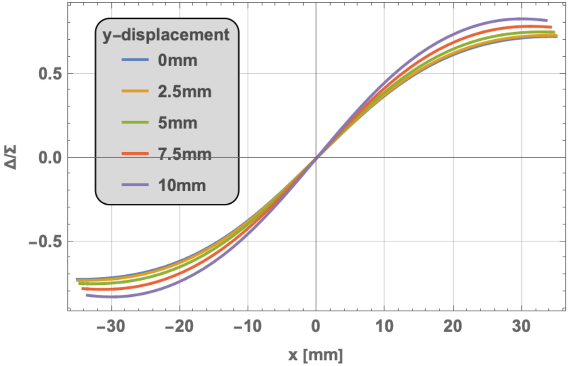
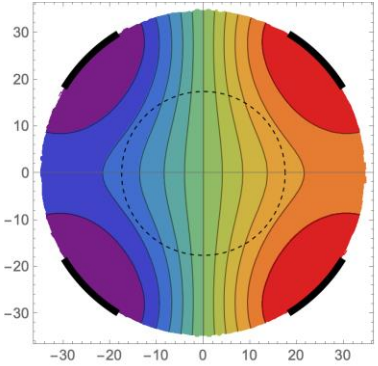
Button-Style BPM Position Characteristics

- **Analytical and simplified numerical analysis**





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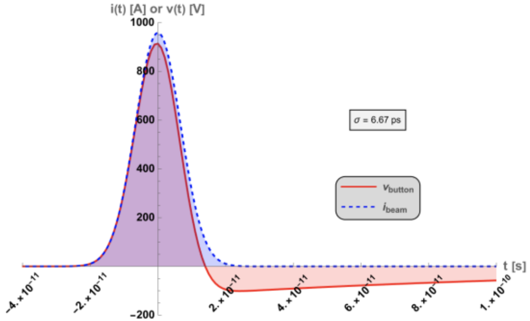

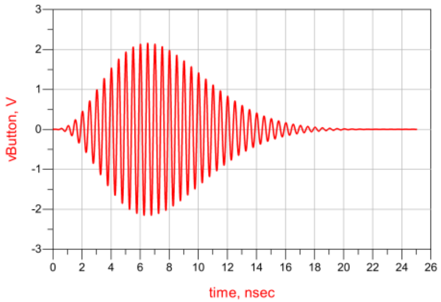

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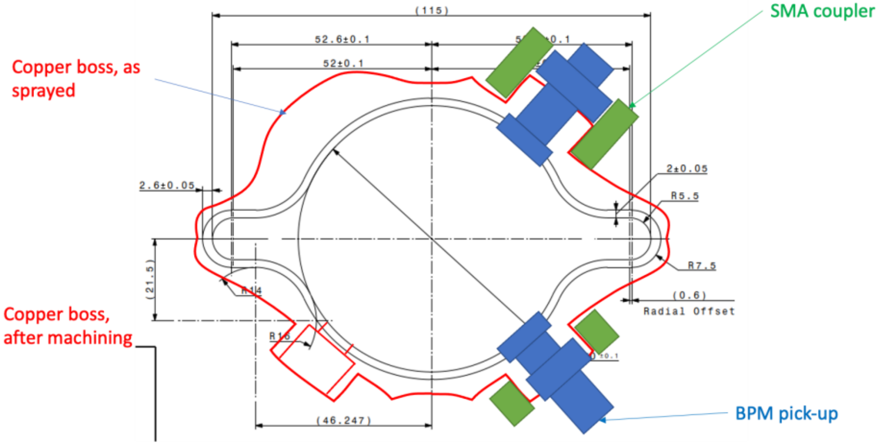
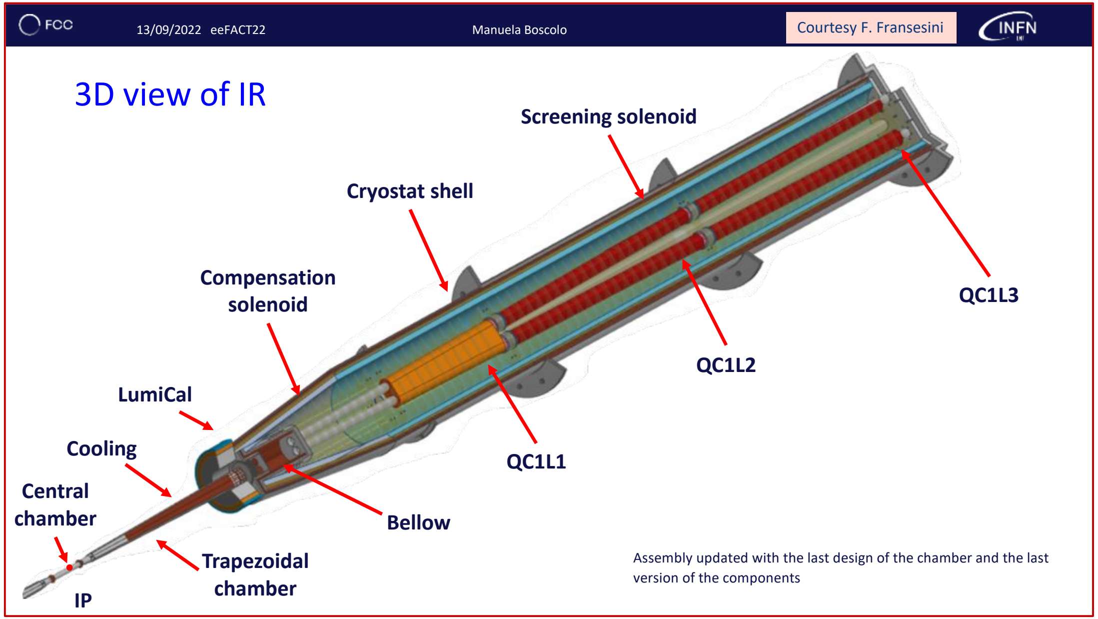
BPM Pickup R&D: Manufacturing & Integration

Button manufacturing and integration



Talk by Cedric

BPMs in Final quadrupole



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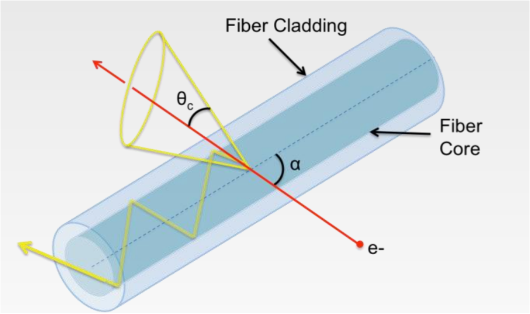
BLM R&D



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

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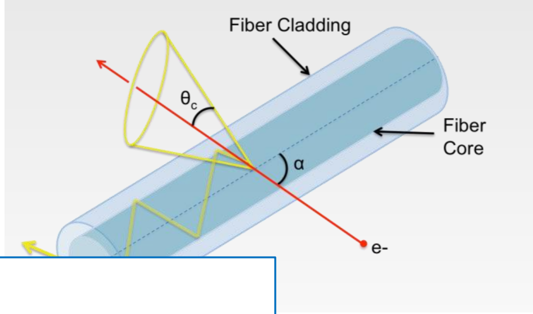

Need to establish a FCCee machine protection and beam loss monitoring working group

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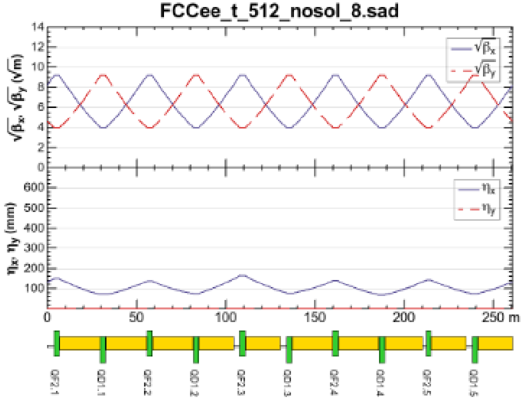
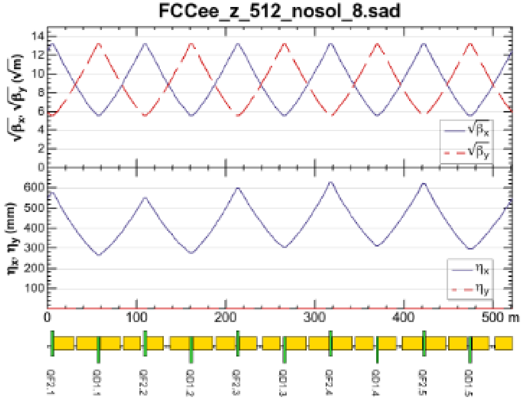
vertical rms IP spot size [nm]	34	66	36	69

90°/90° : $t\bar{t}$, Zh



Long 90°/90° : Z, W

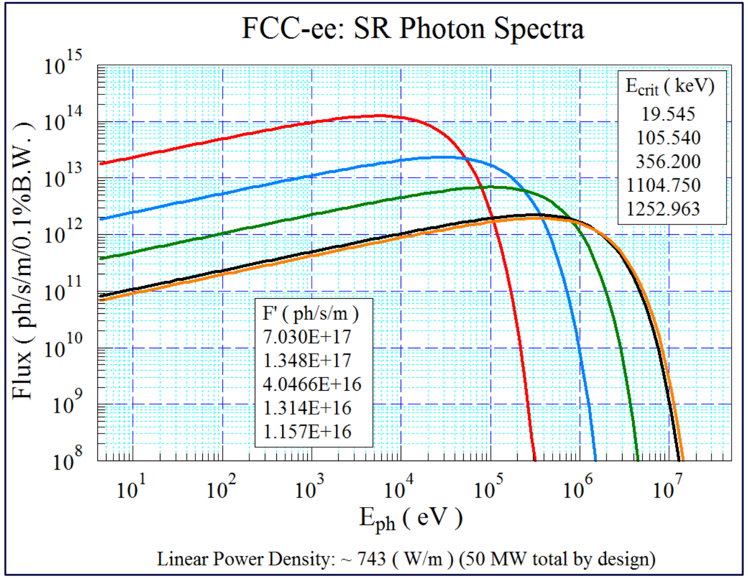


FCC-ee beam size is small!

- *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)

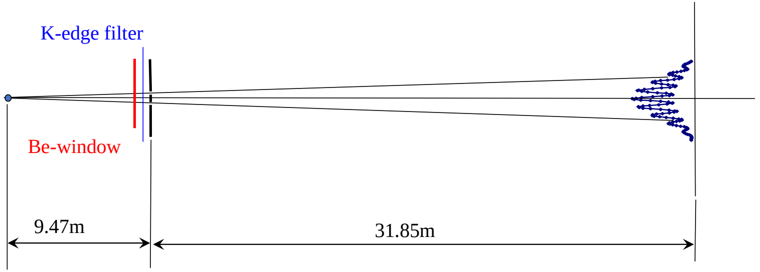
FCC-ee challenge:

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

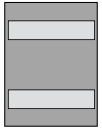
Beam Size R&D: X-Ray Interferometer at KEK

- 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*

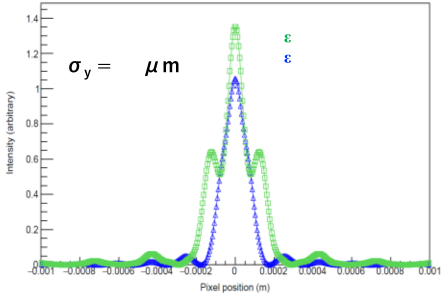
Configuration of X-ray interferometer at SuperKEKB

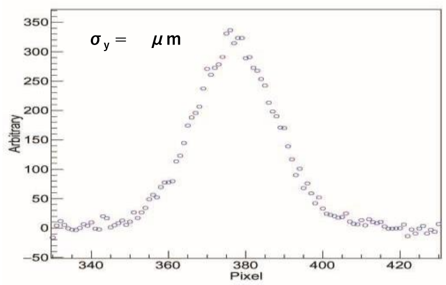


Double slit



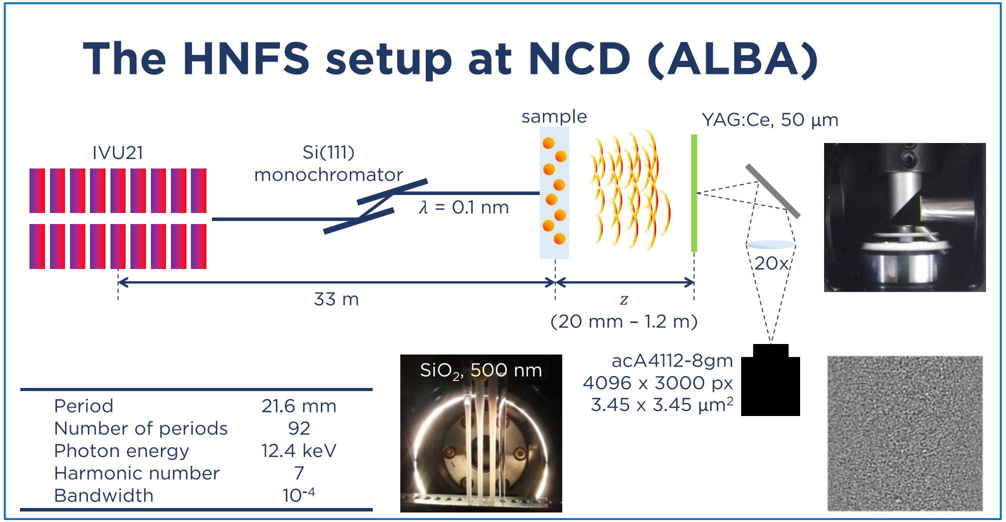
width 15mm, separation 30mm





Toshi & Gaku

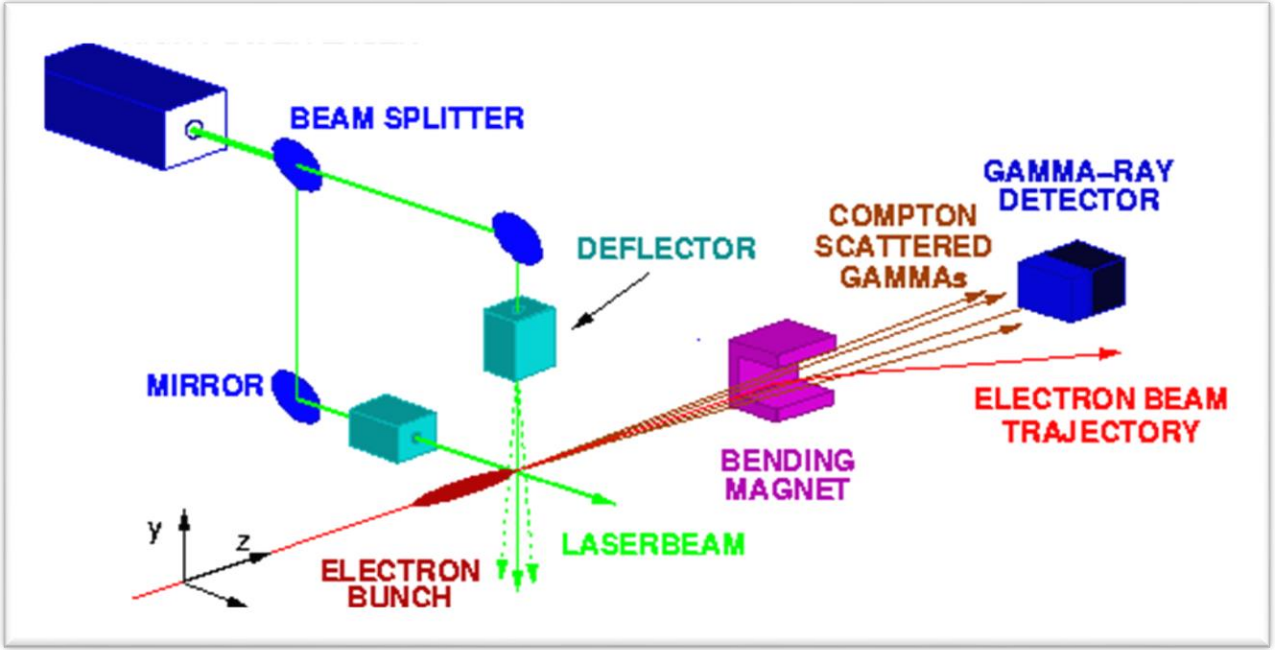
Beam Size R&D: 2D X-Ray HNFS at ALBA



Talk by Ubaldo

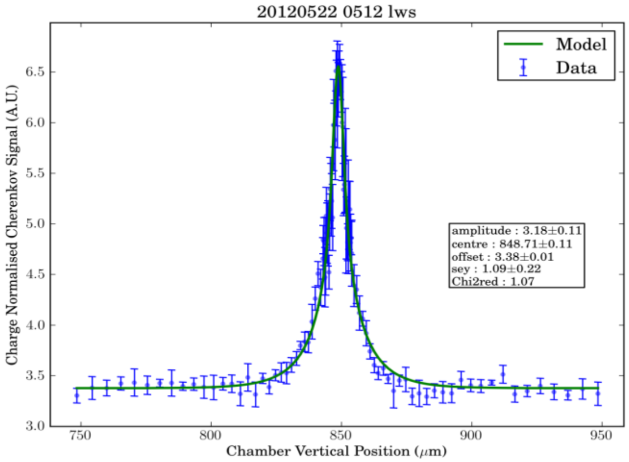
Beam Size alternative : Laser Wire Scanner

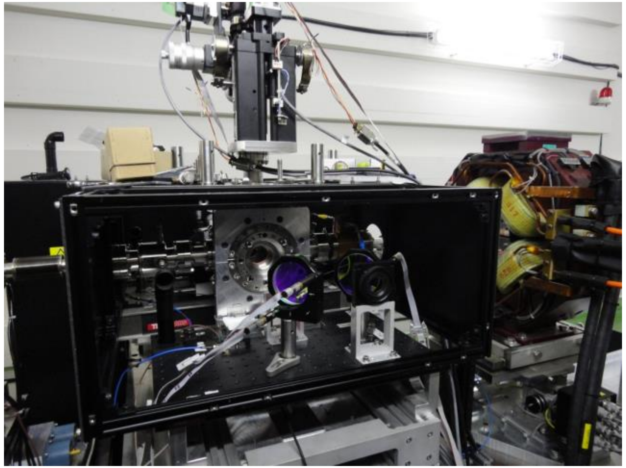
- **Laser wire scanner technology developed for linear colliders**
  - ***Based on Compton scattering using high power laser light***



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

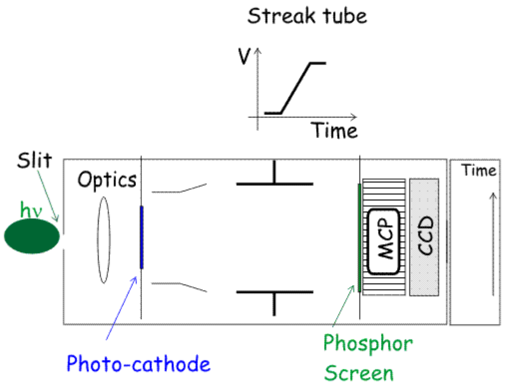
Parameter [4 IPs, 91.1 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75

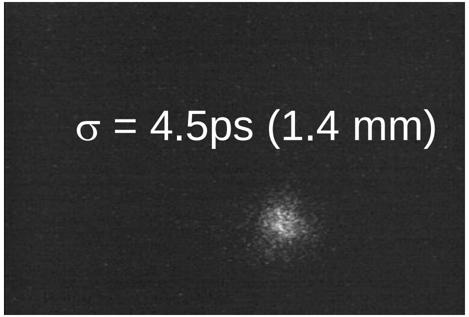
- **"Reasonably" long bunches**
  - ***2 – 3 mm RMS, or longer***

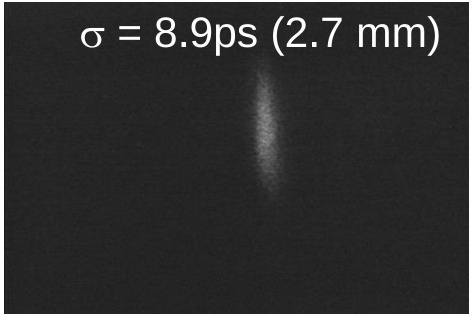
- **Need a bunch-by-bunch measurement system with picosecond resolution to monitor the impact of the Beamstrahlung.**

- **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

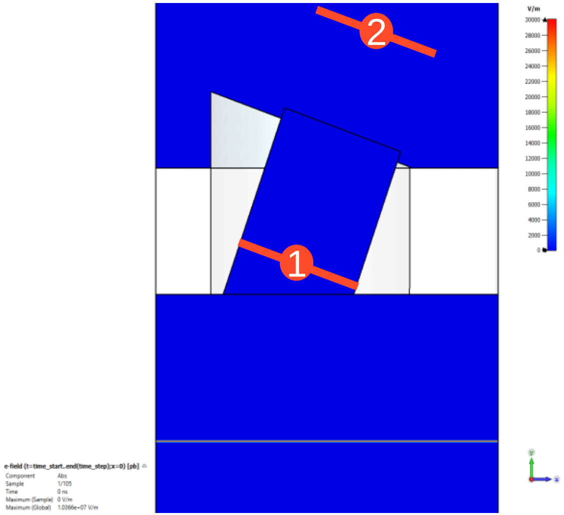






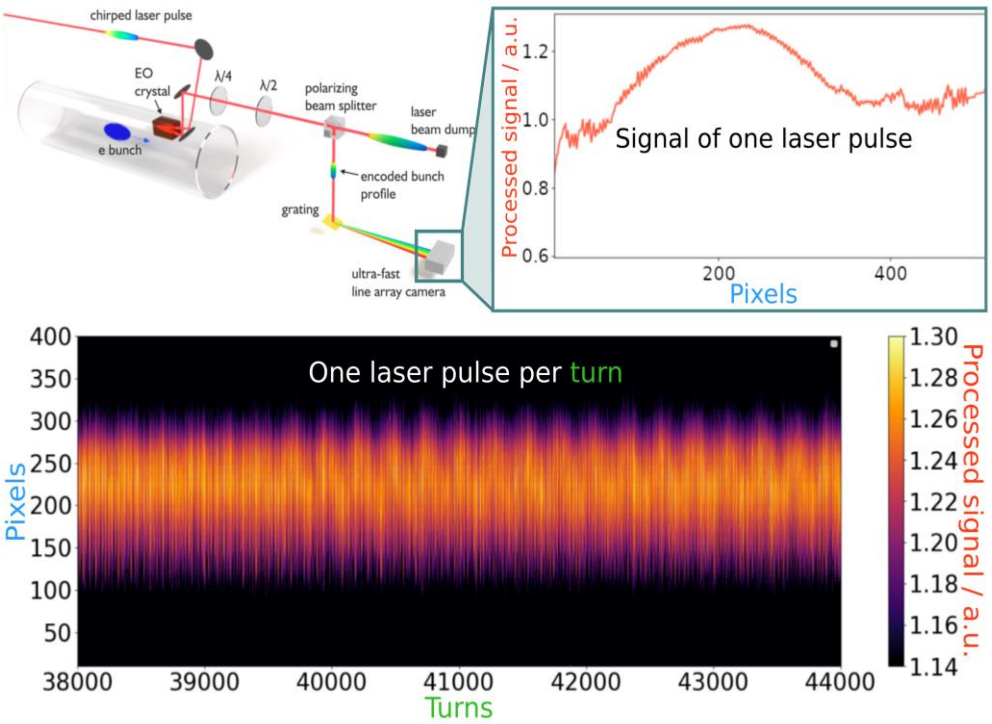
- **200 fs time resolution obtained using reflective optics, a 12.5 nm BW optical BPF (800 nm) and the *Hamamatsu* FESCA200**
  - *M. Uesaka, et.al., NIMA 406 (1998) 371*
- **Does not provide bunch-by-bunch online monitoring**

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

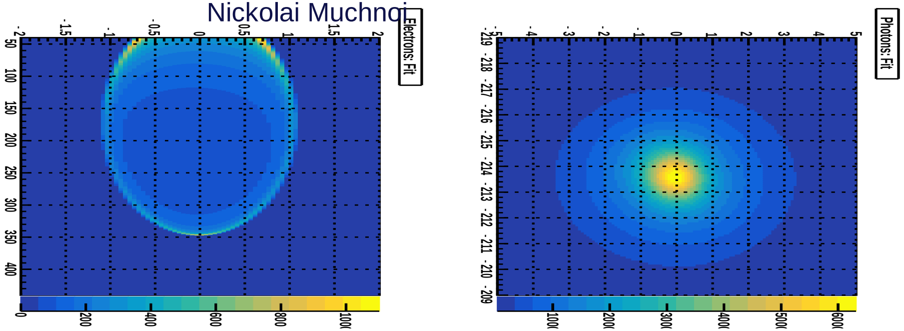
- Laser system
  - *Challenging to control polarisation to high level (10^{-4})*
  - *Preliminary design shows no difficulties as commercial laser exists (would need laser amplification to be able to measure both pilot and nominal bunches)*
  - *Need a dedicated lab to house the laser close to the interaction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

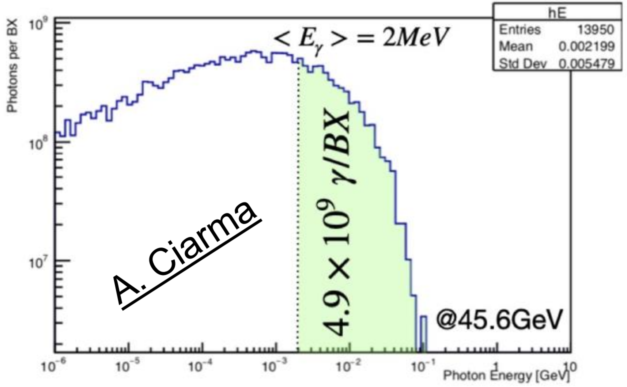
- Collaboration with IJCLab

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.