Overview of Beam Instrumentation studies for FCC-ee

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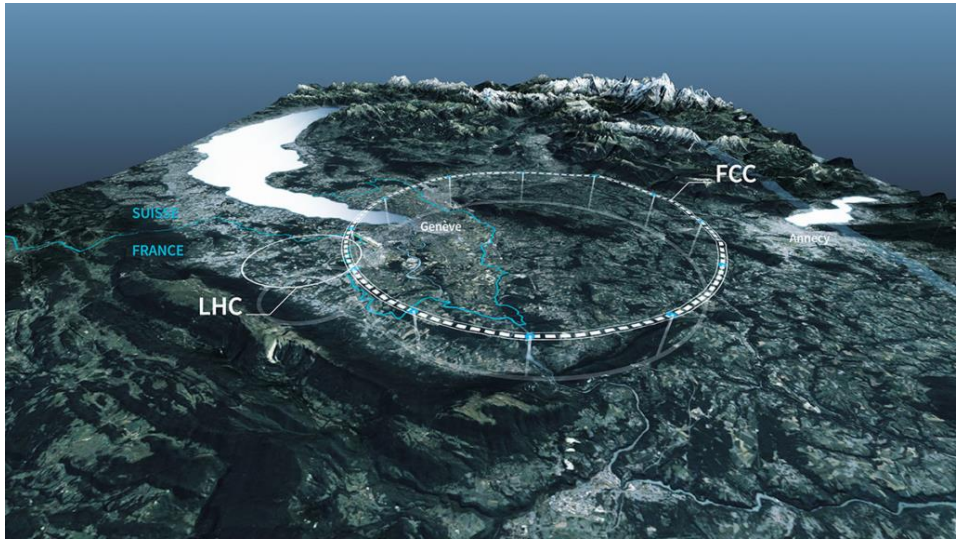
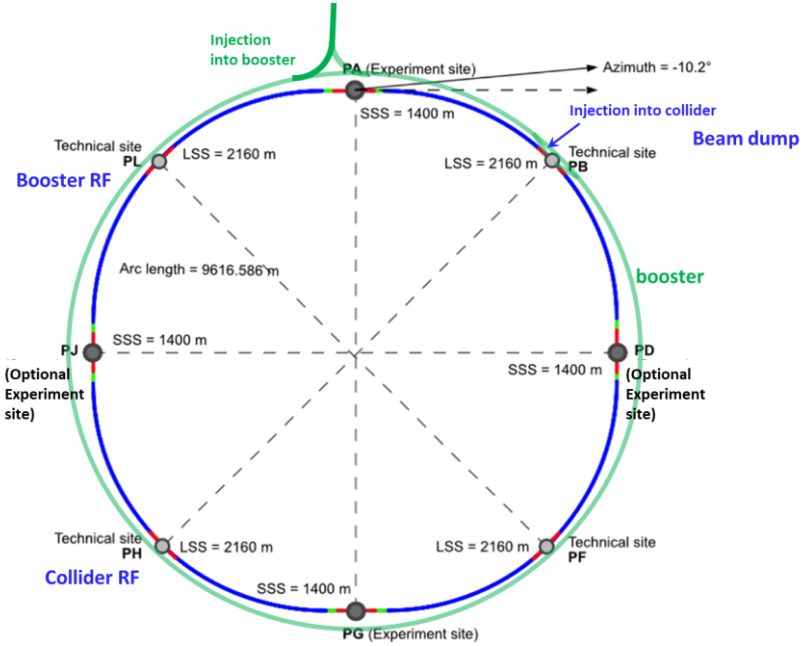
Outline

- FCC-ee challenges from a Beam instrumentation perspective
- On-going R&D activities
- Conclusion



FCC-ee from a BI perspective

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
circumference [km]	90.66
SR power per beam [MW]	50
min./max. beam energy [GeV]	45.6 / 182.5
max./min. beam current [mA]	1270 / 5
max./min. # of bunches/beam	15880 / 40
min. bunch spacing [ns]	15
max. bunch intensity [10^{11}]	1.5
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42
min. rms bunch length SR / BS [mm]	1.95 / 14.45



+ injectors and positron source

FCC-ee from a BI perspective

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
circumference [km]	**90.66**

Large size / footprint

- >300kms of beam lines to equip with a large number of instruments
- Large distance makes distributed BPM / BLM systems more challenging to maintain
- Large distance may cause unwanted signal delays and long latency for Feedback applications. Not been studied yet !

Gathering informations during the 1st FCC BI workshop in Nov 2022 - https://indico.cern.ch/event/1209598/

Instrument	Main tunnel	Injector complex	Total
Position[1]	8855	1492	10347
Losses[2]	1205	200	1405
Intensity	15	15	30
Transverse profile	18	35	53
Longitudinal profile	6	10	16
Beamstrahlung monitors	4	-	4
Polarimeter	2	-	2

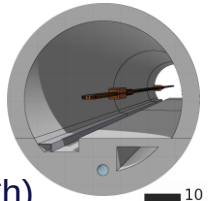
Numbers to be confirmed

Inputs from P. Craievich, A. Chance, C. Milardi, W. Bartmann,..

1 - BPMs on Quadrupole only

2- BLM for collimation, injection, extraction regions only

FCC-ee from a BI perspective

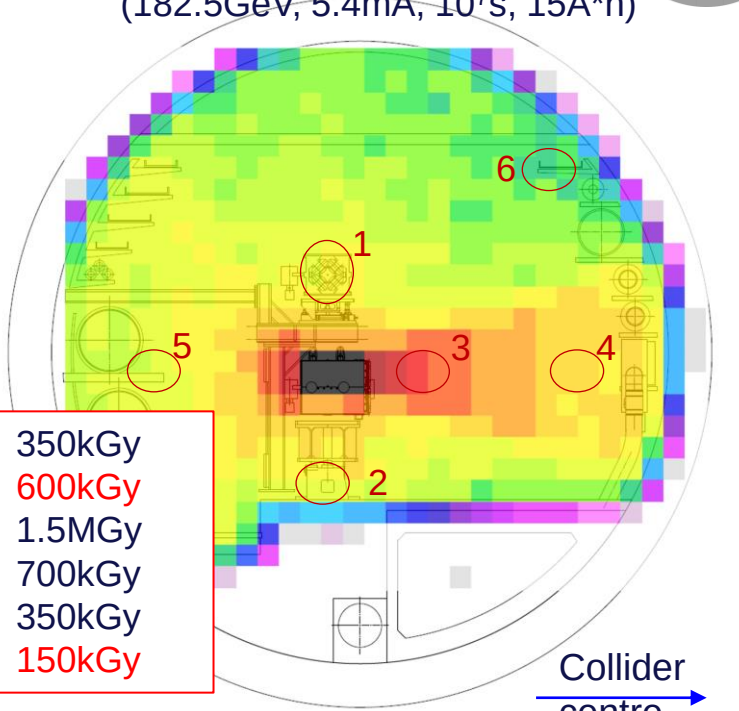


parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
SR power per beam [MW]	50

High Synchrotron radiation power in the arcs

- Would require all monitors in the arc tunnel to be radiation-hard (mainly position & loss monitors)
  - Radiation hard electronic (ASICs)
  - Radiation hard optical fiber for data transmission
  - Specific validation with high energy gamma rays
- Shielding may help … a little

FCC-ee: 1 year of operation
(182.5GeV, 5.4mA, 10^7s, 15A*h)



1) 350kGy
2) 600kGy
3) 1.5MGy
4) 700kGy
5) 350kGy
6) 150kGy

Courtesy of B. Humann, FLUKA team

x100 worse than SPS !

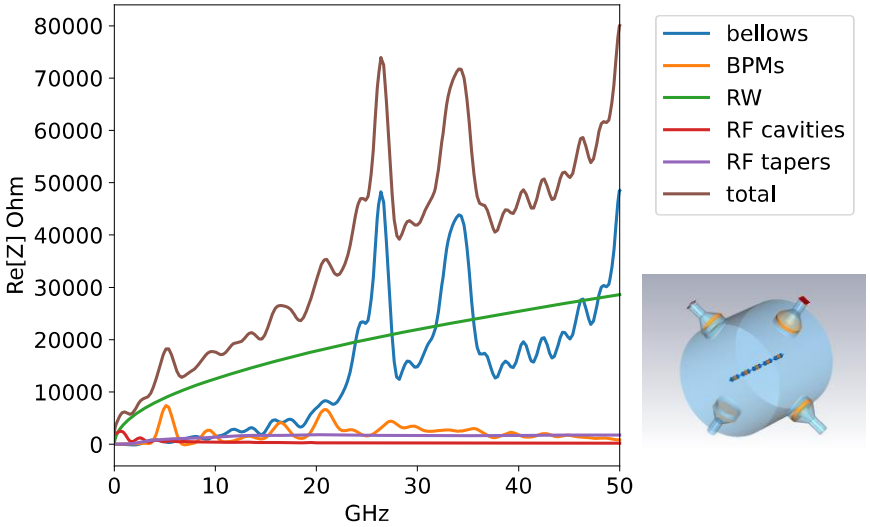
FCC-ee from a BI perspective

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
min./max. beam energy [GeV]	**45.6** / 182.5
max./min. beam current [mA]	**1270** / 5
max./min. # of bunches/beam	**15880** / 40

High beam current / number of bunches when running at Z pole

- Large impact on beam heating related issues
  - Impact on all beam monitor designs, required to have ‘very’ low coupling impedance
  - Impact on stability and precision to be evaluated

Impedance simulation



Courtesy of E. Carideo and M. Migliorati

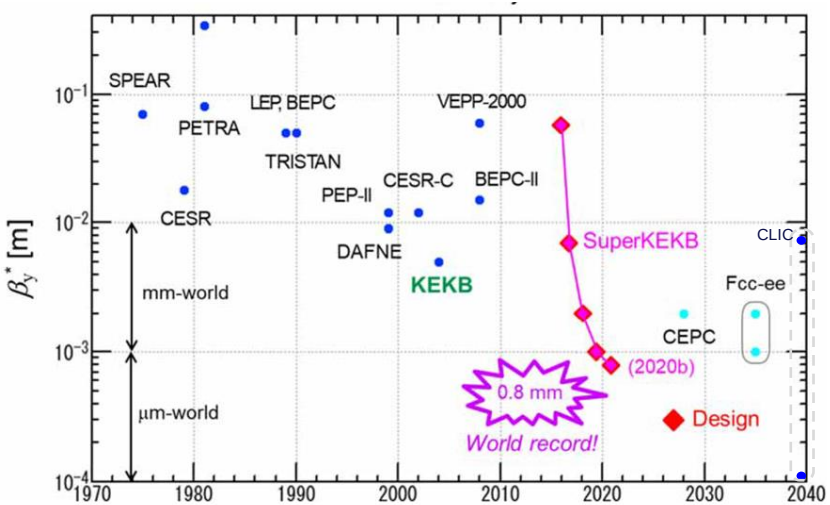
FCC-ee from a BI perspective

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42

Small emittance and small beam size at IP (34nm in V plane)

- challenge in measuring beam profile and emittance (more difficult than in 4th generation light source). *Studies on going..*
- require 'excellent' alignment and state of the art fast orbit feedback system. Not studied yet !

Small beam size chalenge



From Tor's presentation

FCC-ee from a BI perspective

beamstrahlung

parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
min. rms bunch length SR / BS [mm]	5.6 / 12.7
min. rms bunch length SR / BS [mm]	1.81 / 2.17

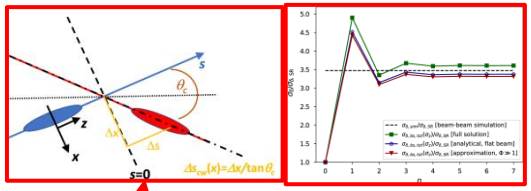
@Z
@top

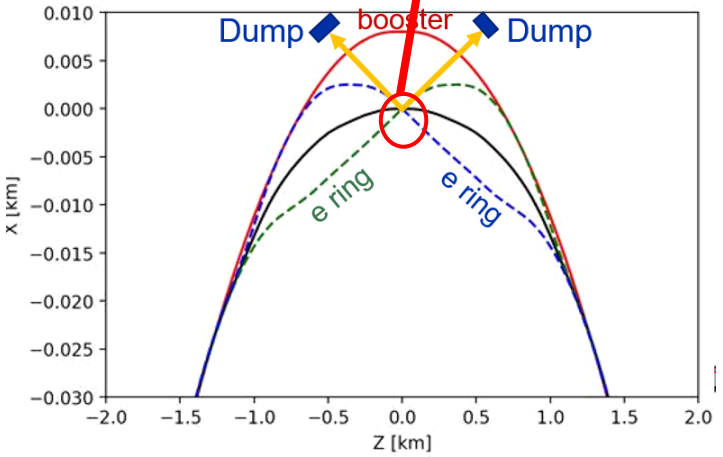
Changes in bunch length due to beamstrahlung generated at IP, combined with top-up operation would result in fast changing beam profiles

- requiring bunch by bunch, turn-by-turn measurements quite challenging to get with ps/sub-ps resolution
- would need to have specifications of realistic transverse/longitudinal beam profiles in top-up mode

+ Challenge of measuring ~ 400kW Beamstrahlung photons as luminosity monitors

Eur. Phys. J. Plus ***136***, *501 (2021)*





On-going FCC-ee BI studies

6 crucial studies identified and being followed up

- **Beam Position Measurement (BPM)**
- **Beam Loss Measurement (BLM)**
- **Beam Size Measurement**
- **Bunch Length Measurement**
- **Polarisation and energy calibration**
- **Beamstrahlung photons**
- **….**

On-going FCC-ee BI studies

6 crucial studies identified and being followed up

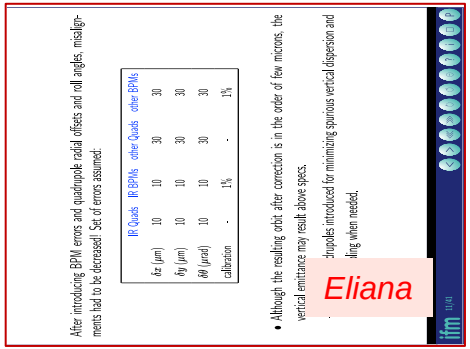
- **Beam Position Measurement**
- **Beam Loss Measurement.. just starting**
- **Beam Size Measurement**
- **Bunch Length Measurement**
- **Polarisation and energy calibration**
- **Beamstrahlung photons**
- **….**

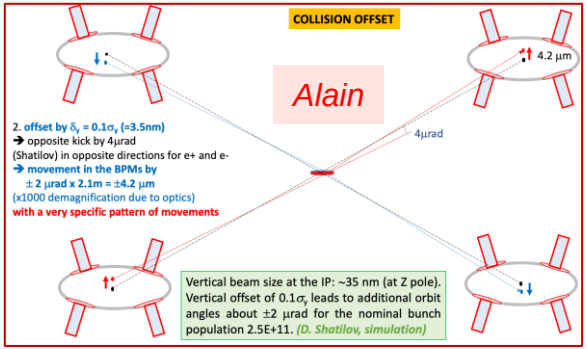
Followed up within Accelerator Technology working group

Followed up within EPOL and MDI working groups

See the talk from Aurelien in this EPOL session this afternoon at 13h30

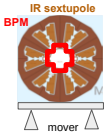
BPM Requirements….





- **Shall provide Orbit, turn-by-turn and bunch-by-bunch data**
  - ***Large data throughput (>20GSPS for each BPM plane)***
- **Resolution: <1 μm (orbit), <10 μm (TxT)**
  - ***challenging when considering large, 70mm, beam pipe diameter***
- **Accuracy 1-20 μm (IP/Arc) (no BPM on sextupoles yet !)**
- **Alignment strategy to be defined globally**
- **Calibration errors ~1 %**
- **Concern on long term stability & drifts (Temperature in the tunnel) ?**
- **Need to draft a complete functional specification for BPM !**

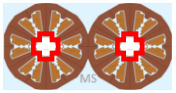
Attach BPMs to sextupoles in FCC-ee? Movers?



Prealignment without beam could be kept to ~100 μm.
With beam, a high accuracy BPM (<1μm) attached to the sextupole with magnetic centers aligned to <1μm level (sext. temperature and powering to be considered).

Ideally mover range ~0.5mm (step <1μm) remotely used to keep sextupole centered to the beam (helped with orbit correction) within 1μm.

Rogelio



Same prealignment and BPM cor
Have to mostly rely on orbit correction. Movers?
Keep 1-10μm beam centering accuracy?
This solves the disruption from chromaticity correction.

BPM: Turn-by-turn capabilities will be fundamental to allow fast measurements at high intensity (res. ~ 10μm)

Corrected Lattices results (182.5 GeV)

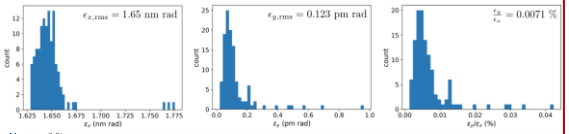
Using the misalignments and roll angles of:

Tessa

	$\sigma_x(\mu m)$	$\sigma_y(\mu m)$	$\sigma_\theta(\mu rad)$
arc quads	100	100	100
IP quads	100	100	100
sextupoles	100	100	100
dipoles	100	100	100
BPMs	20	20	150

*BPM error relative to quadrupole position

After correction:



14

Kick Strength and Phase Advance

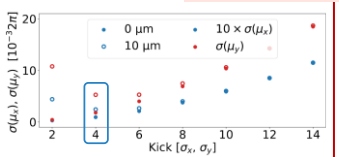
- Relative rms phase advance error with respect to the model used for defining the quality of TbT measurements
- First TbT tracking over 500 turns for FCC-Z mode and 360 installed
- Without synchrotron radiation
- Gaussian BPM noise applied

Jacqueline

FCC-Z mode at 45.6 GeV sing

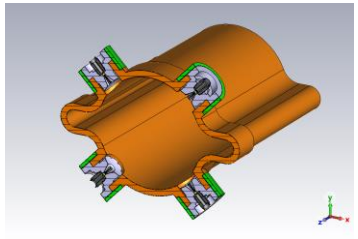
FCC-Z mode
500 turns, no synchrotron radiation
Minimum hor and ver. phase advance error with
10 μm BPM noise: 0.24 x 10^{-3} (2π) and 5.28 x 10^{-3} (2π)

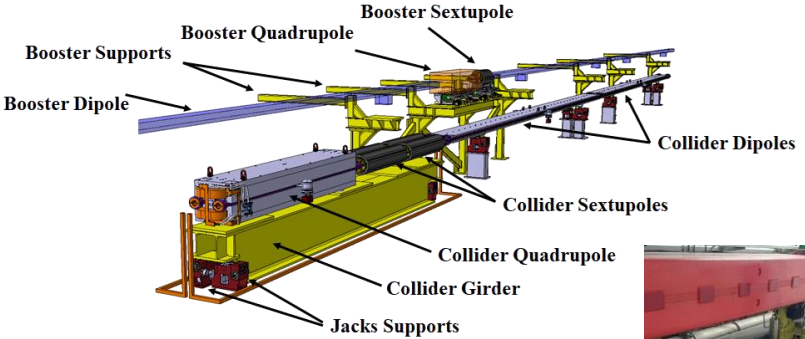
Comparison LHC
6600 turns, AC-dipole
Minimum hor and ver. phase advance error, ~100 μm
BPM noise: < 1 x 10^{-3} (2π)



Arc BPMs

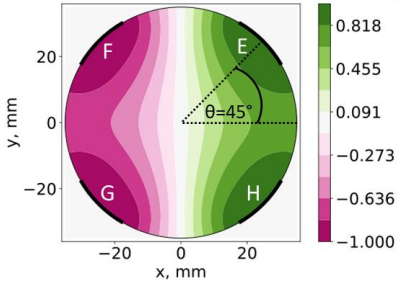
- **Collaboration between different teams to study, impedance, vacuum, integration, magnet and pick-up design for the MR arc half-cell mockup**
  - ***~ 1000 BPMs per arc (incl. Booster ring BPMs)***
  - ***High current inducing high heat load on BPM body and RF Button – Water cooling ?***
  - ***Will make use of the copper cold-spay and shape memory alloy technologies (CERN vacuum group)***

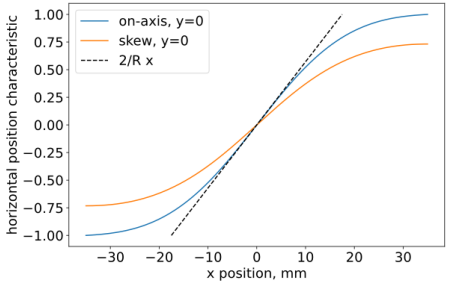


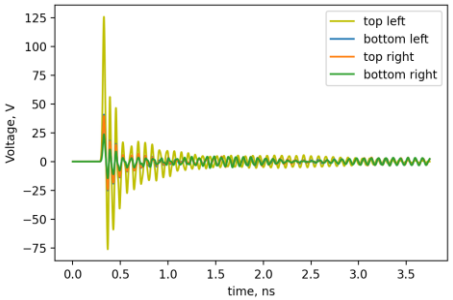


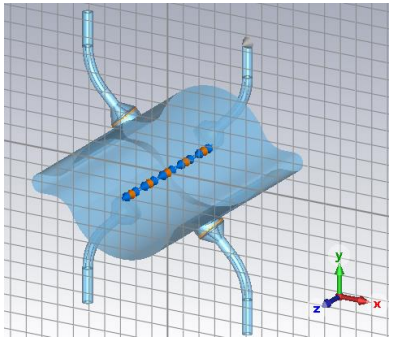
- **Electronic**
  - ***1-2m long SiO2 rad-hard cables from buttons to electronics***
  - ***Radiation-hard conversion of electrical signals into optical signals – two options not studied in detail yet***
  - ***Rad-hard optical fiber to centralised acquisition system either in alcoves or in central shaft/access point***
    - 300 fibers to each alcoves or 2000 fibers to main access gallery (accessible at any time)
    - Keep both options on the table while the orbit feedback system is properly studied

New Workforce on FCC-ee BPM R&D



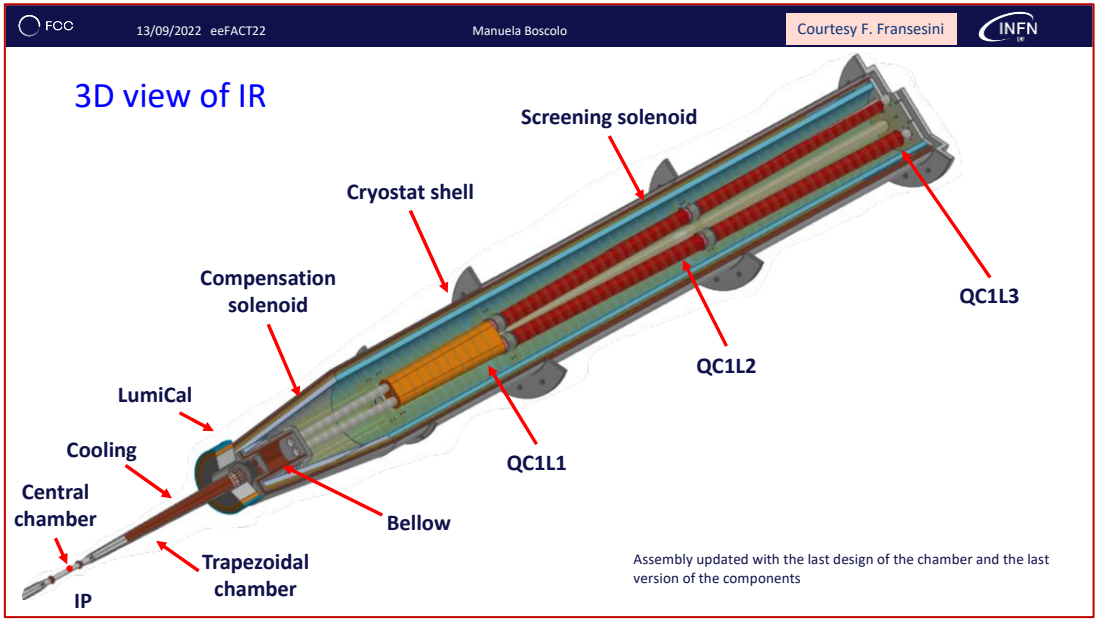






- **New BI Doctoral Student, *Emily Howling*, University of Oxford**
  - ***Started in April 2023, 3-years PhD on FCC-ee BPMs, located at CERN***
  - ***Focus on MR arc BPM pickups, low beam-coupling impedance, prototyping, lab characterization, beam studies at CLEAR***

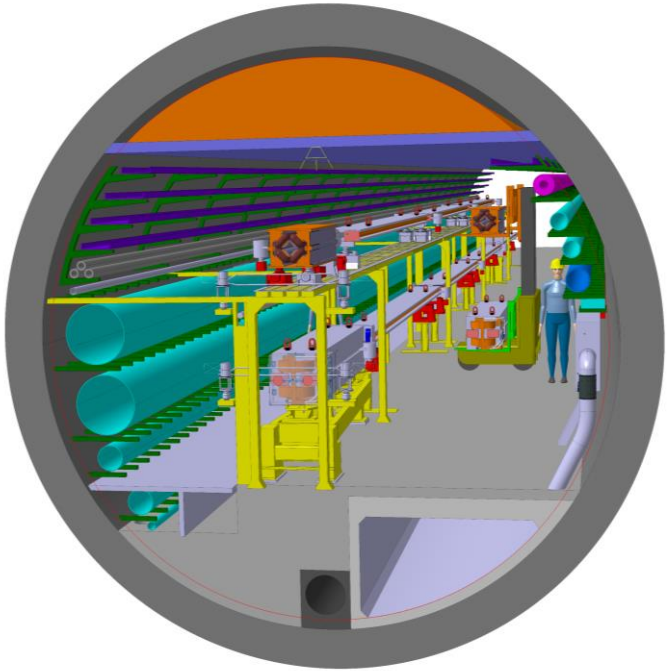
BPMs in final quadrupole



Talk by Manfred Wendt later this afternoon at 14h45 !

Beam Loss Monitors (BLM)

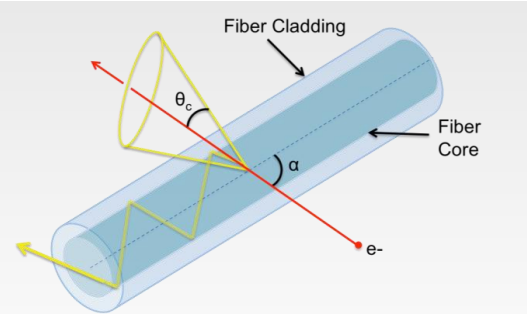
- **Large energy stored in both, main rings and booster ring, would require a machine protection system (MPS), supported by beam loss monitors (BLM)**
  - ***BLMs in the arcs need to be insensitive to X-rays!***
  - ***Identifying losses from the individual rings in the tunnel is challenging !***
    - Between 2 colliding beams - BLMs with beam directivity
    - Between main and booster rings: staged localization of the quads
- **No specific needs in injectors ?**



BLM R&D

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

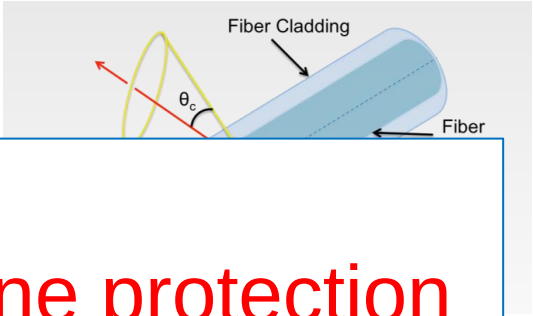
- **Optical BLM system based on *Cherenkov* fibers offers**
  - ***High directivity***
  - ***Only measures charged particles – insensitive to X-rays***



- **Building on existing studies initiated for Linear Collider or SPS slow extraction**
  - ***Development of Cherenkov BLM at CLEAR -*** S. Benitez et al., IPAC, Campinas, SP, Brasil (2021) pp. 2640
  - ***Position resolution of a distributed oBLM system:*** *E. Nebot del busto et al,, IBIC, Melbourne, Australia (2015) pp. 580,* S.Benitez et al. , IPAC 2022, Bangkok, Thailand (2022) pp. 351
  - ***Crosstalk between beam losses from CLIC Drive and Main beams:*** *M. Kastriotou et al, IBIC, Melbourne, Australia (2015) pp. 148*
  - ***RF studies (Breakdown and Dark current):*** *M. Kastriotou et al., IPAC, Busan, Korea, 2016, pp. 286*

BLM R&D

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



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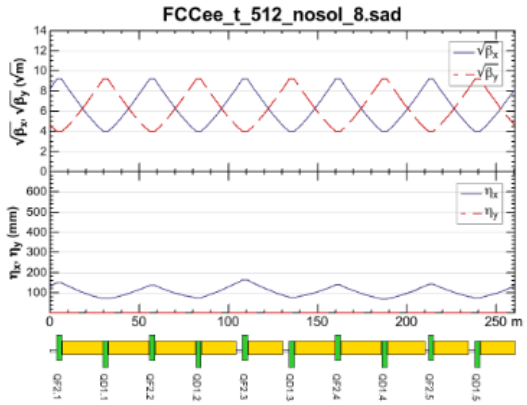
Need to establish a FCCee machine protection and beam loss monitoring working group

New Ph.D student and collaborator starting soon

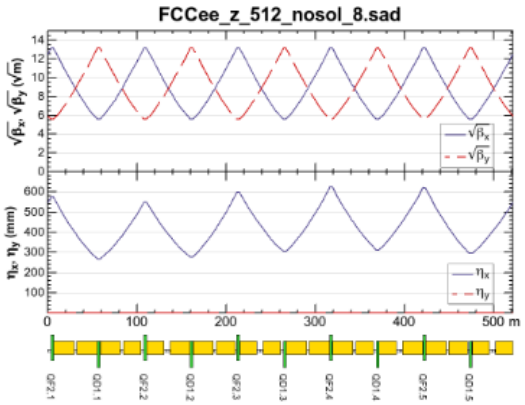
Beam Size Measurement

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	2.16	0.67	1.55
vertical geom. emittance [pm]	1.42	4.32	1.34	3.10
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



FCCee beam sizes are small !

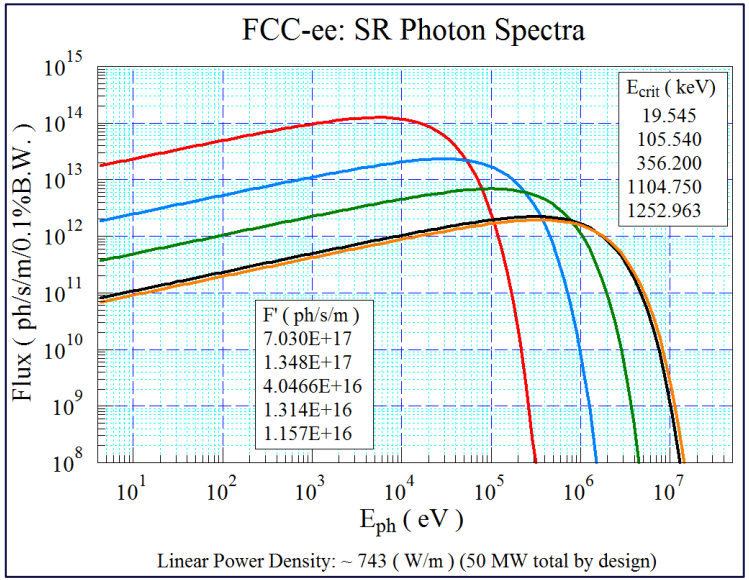
In the arcs (Zh):

horizontal: ~100 μm

vertical: ~7 μm

Beam Size Measurement

- **Use of synchrotron radiation at high beam energies suffer from diffraction effects !**



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

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

FCC-ee challenge:

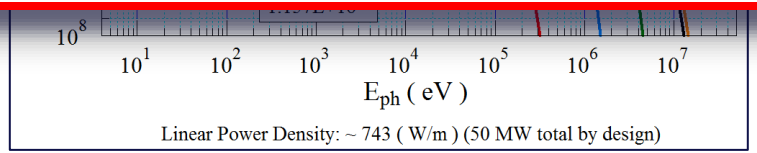
- **Large arc radius requires very long, extended SR extraction lines**
  - ***Need for detailed numerical simulations***

Beam Size Measurement based on SR

- **Use of synchrotron radiation at high beam energies suffer from diffraction effects!**

Requires X-ray interferometric techniques

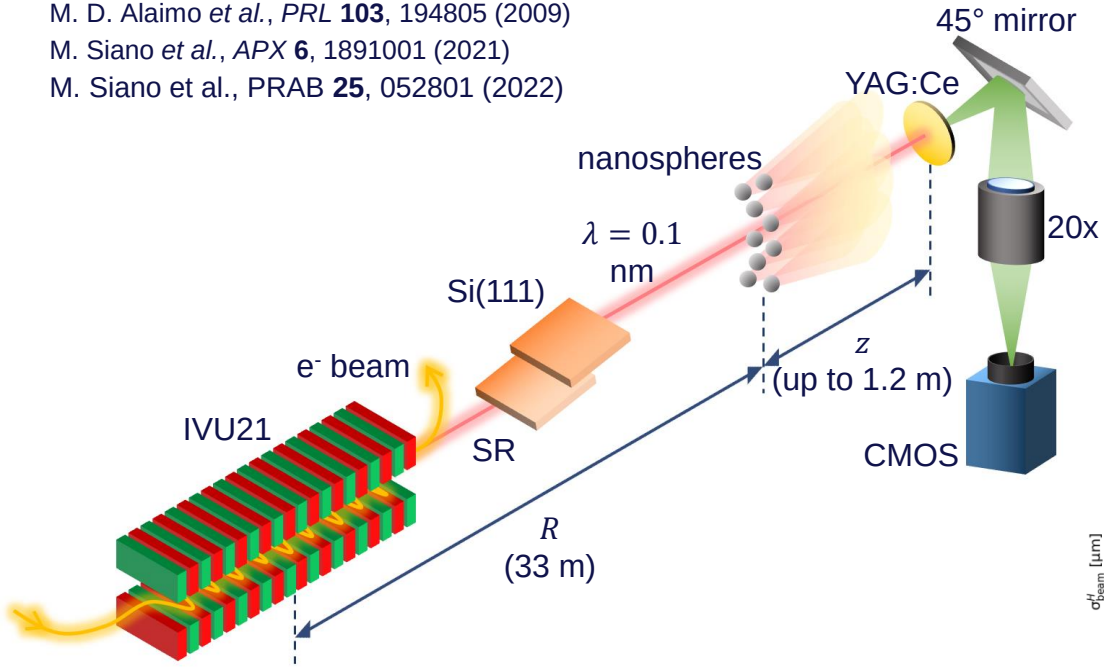
A new Postdoc, Daniele Butti, has just started to study the implementation of SR monitors in FCCee



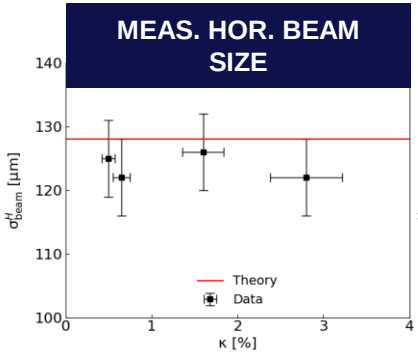
- **Large arc radius requires very long, extended SR extraction lines**
  - ***Need for detailed numerical simulations***

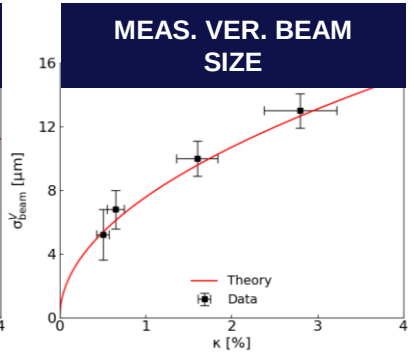
X-Ray SR interferometry studies on-going (U. Milano and ALBA)

M. D. Alaimo *et al.*, *PRL* **103**, 194805 (2009)
M. Siano *et al.*, *APX* **6**, 1891001 (2021)
M. Siano et al., PRAB **25**, 052801 (2022)



Talk by Mirko Siano during Technology session on Thursday afternoon at 14h10





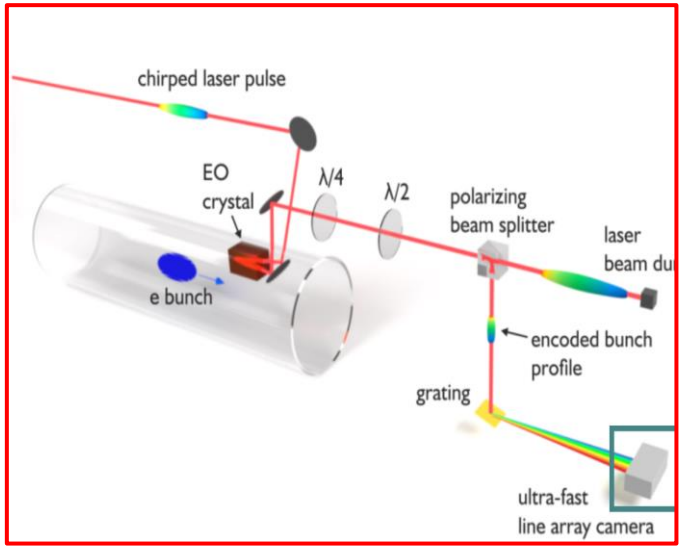
Longitudinal beam profile Measurements

Parameter [4 IPs, 90.6 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
rms bunch length with SR / BS [mm]	5.6 / 12.7	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54

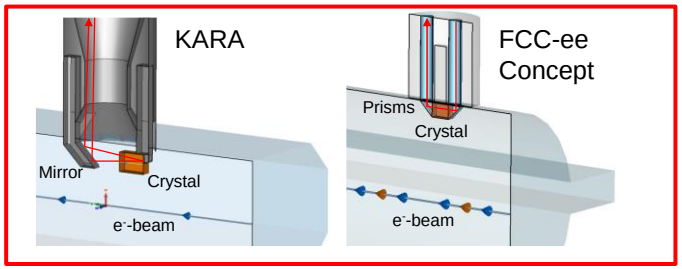
- “Reasonably” long bunches
- Need a bunch-by-bunch measurement system with picosecond resolution to monitor the impact of the Beamstrahlung.
- Need a resolution in the sub-ps range to estimate the energy spread, required for the energy calibration using the spin depolarization technique

Longitudinal beam profile Measurements

Electro-optical Spectral decoding studies at KIT



Poster by Micha Reissig on Thursday

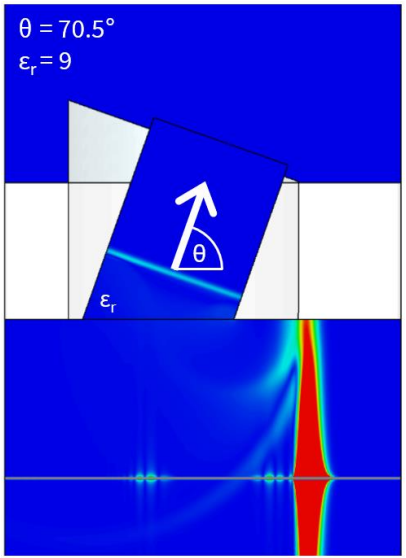


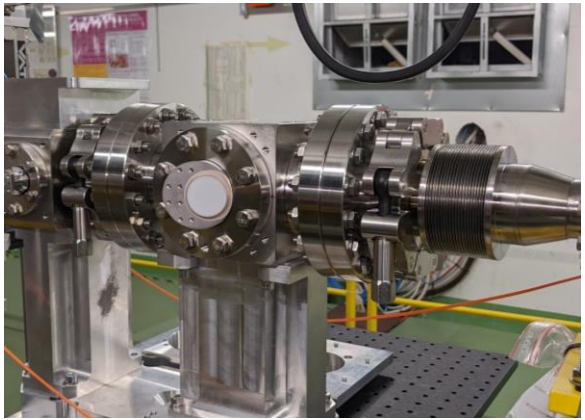
Long term goal

- low(er)-impedance in-vacuum detector
- 67MHz detection system for bunch-by-bunch measurements (today DAQ working at 2.7MHz, moving to 12MHz)

Longitudinal beam profile Measurements

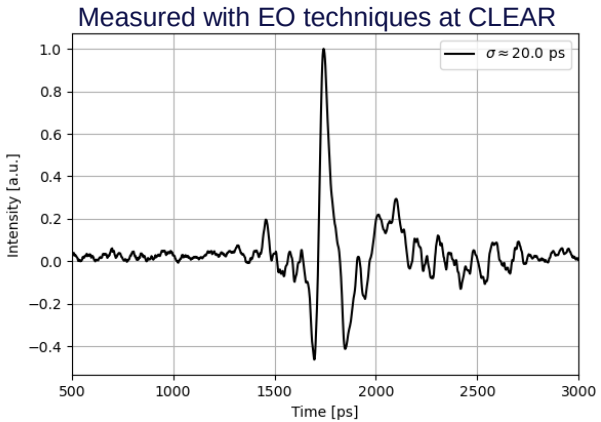
Cherenkov Diffraction radiation studies using dielectric pick-ups at **CLEAR@CERN** and **ATF2@KEK**





Courtesy of A. Schloegelhofer

Generating a radiation replica of bunch profile and measuring it with optical methods



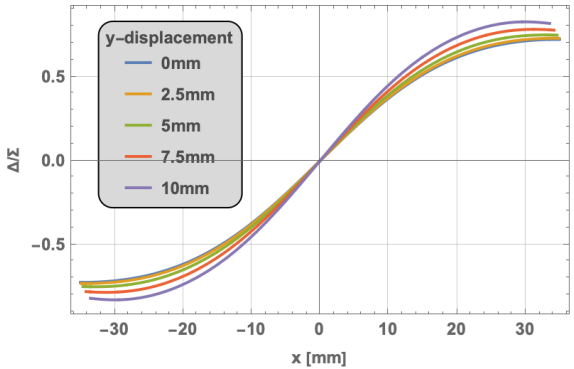
Conclusion

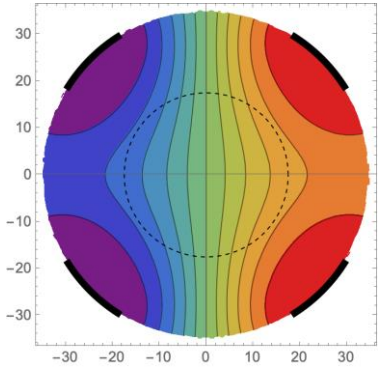
- On-going Beam instrumentation studies for FCC are progressing well
- Relying on a motivated team of young scientists, small for the moment but getting larger and larger …
- Many challenges ahead of us but no show-stopper identified
- Our goal is to provide a conceptual design of a realistic and cost-effective suite of beam diagnostics for FCC-ee by 2025
- Welcoming new collaborators, anybody interested in fast orbit feedback system ?

Thank you
for your attention.

Button-Style BPM Position Characteristics

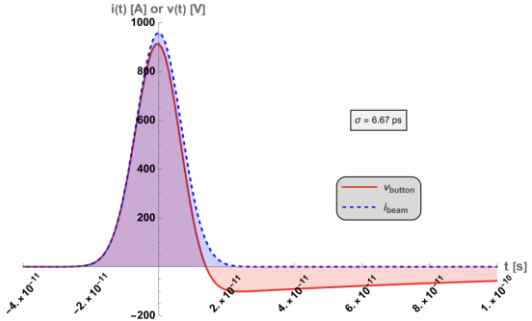
- **Analytical and simplified numerical analysis**

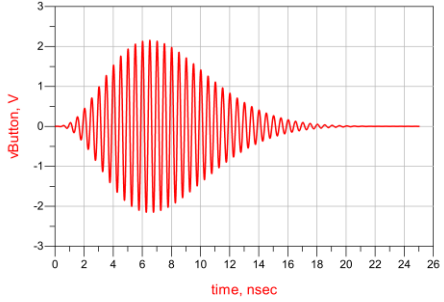




by M. Wendt

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

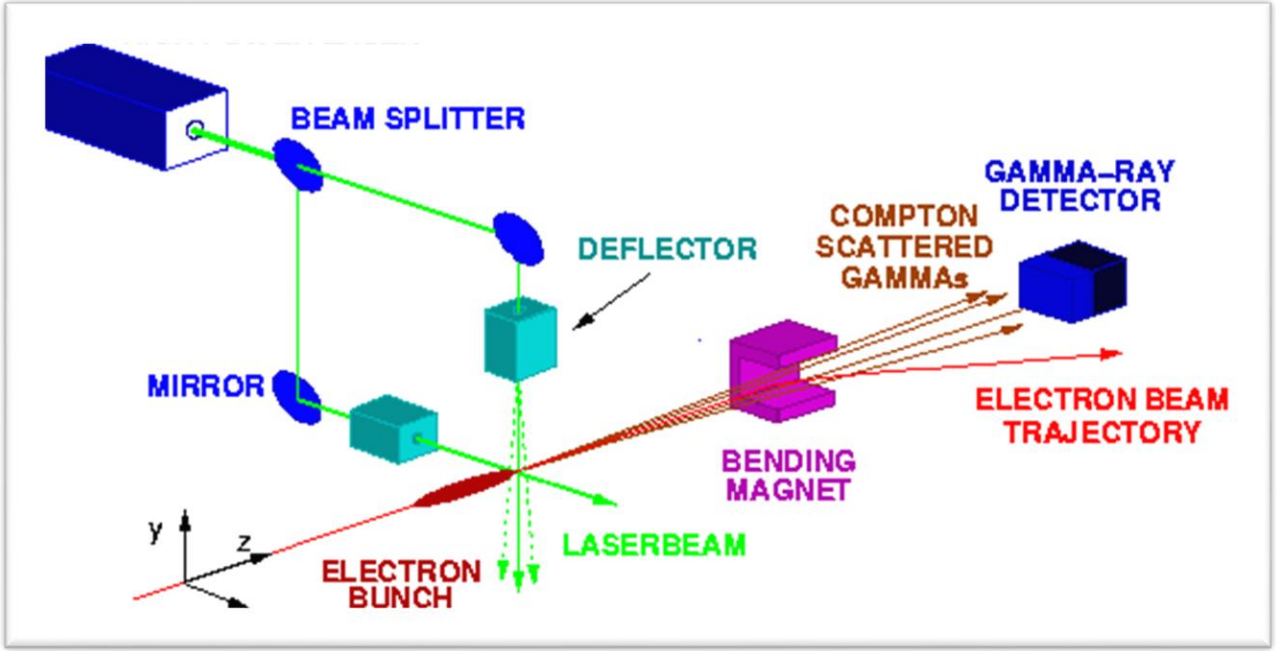




- Theoretical resolution limit $\approx 0.1\ \mu m$!
- Final system typically worse (x10)
- Current technology will do it

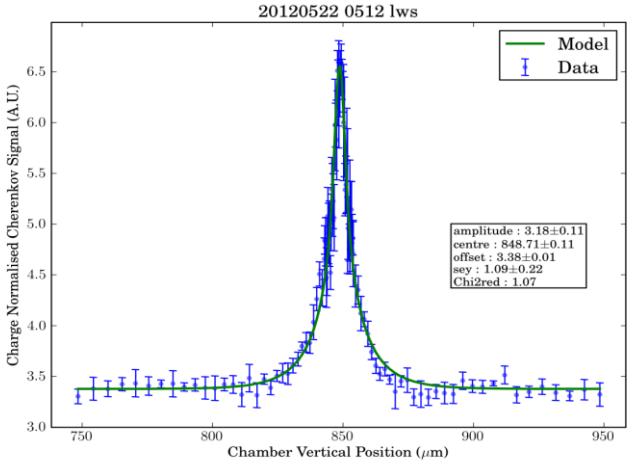
Beam Size alternative : Laser Wire Scanner

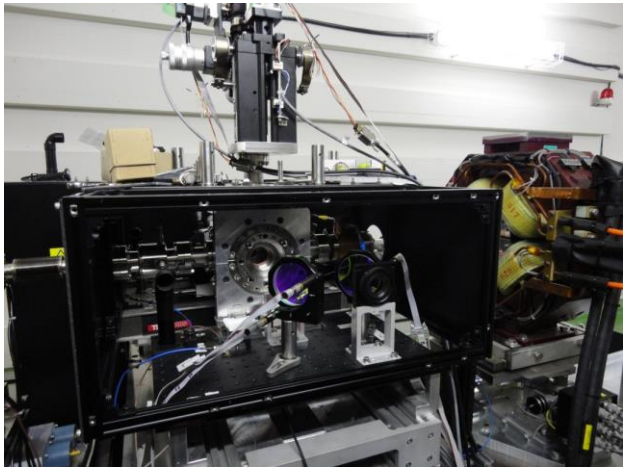
- Laser wire scanner technology developed for linear colliders
  - *Based on Compton scattering using high power laser light*



Beam Size alternative : Laser Wire Scanner

- ***Demonstrated 1 µm measurement resolution !***
  - using a high-power fiber laser
- ***Shares laser technology with the Compton polarimeter***

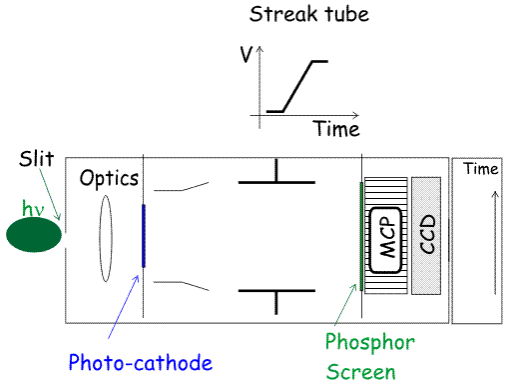


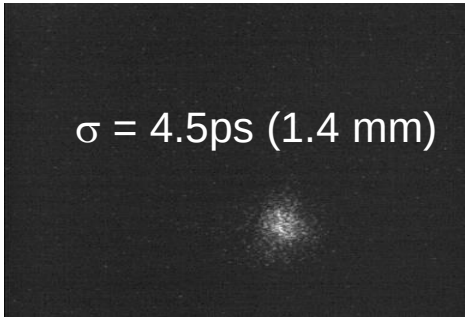


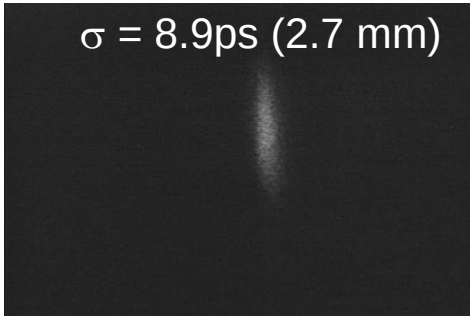
15 years on R&D on ATF2 ring and extraction line

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 : Streak Camera



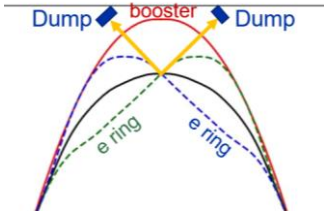


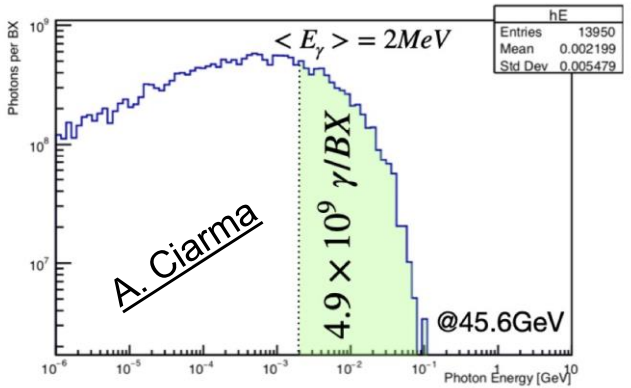


- **200 fs time resolution obtained using reflective optics, a 12.5 nm BW optical BPF (800 nm) and the *Hamamatsu* FESCA200**
  - *M. Uesaka, et.al., NIMA 406 (1998) 371*
- **Does not provide bunch-by-bunch online monitoring**

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
  - **~400 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**

- Detailed study will start soon..