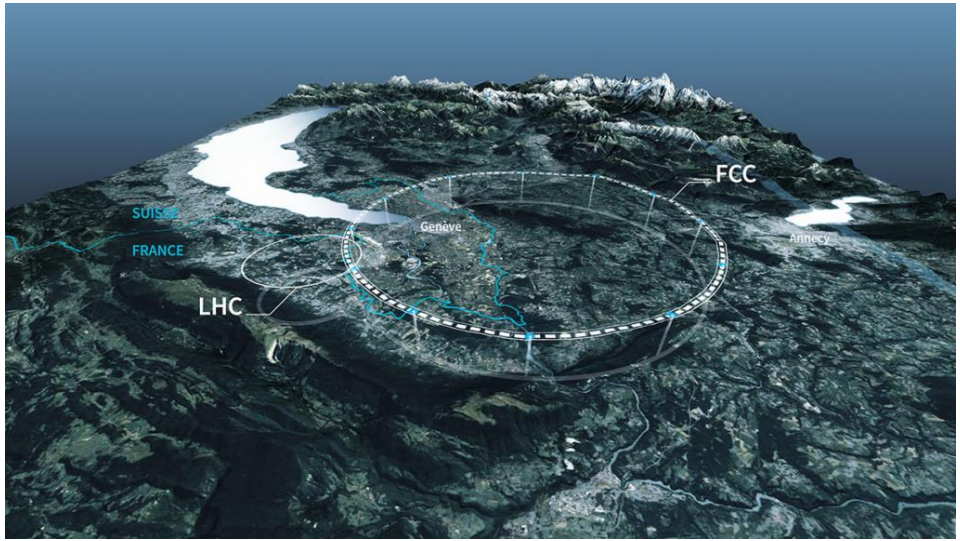
Overview of Beam Instrumentation studies for FCC-ee

D. Butti, M. Gasior, ***T. Lefevre****, S. Mazzoni, B. Salvachua, A. Schloegelhofer, G. Trad, M. Wendt,* **CERN**
E. Howling, P. Burrows, ***Oxford University***
U. Iriso, A. A. Nosych, L. Torino , **ALBA-CELLS**
B. Haerer, A.S. Mueller, G. Niehues, M. Reissig, **KIT**
B. Paroli, M.A.C. Potenza, M. Siano, **University of Milano**

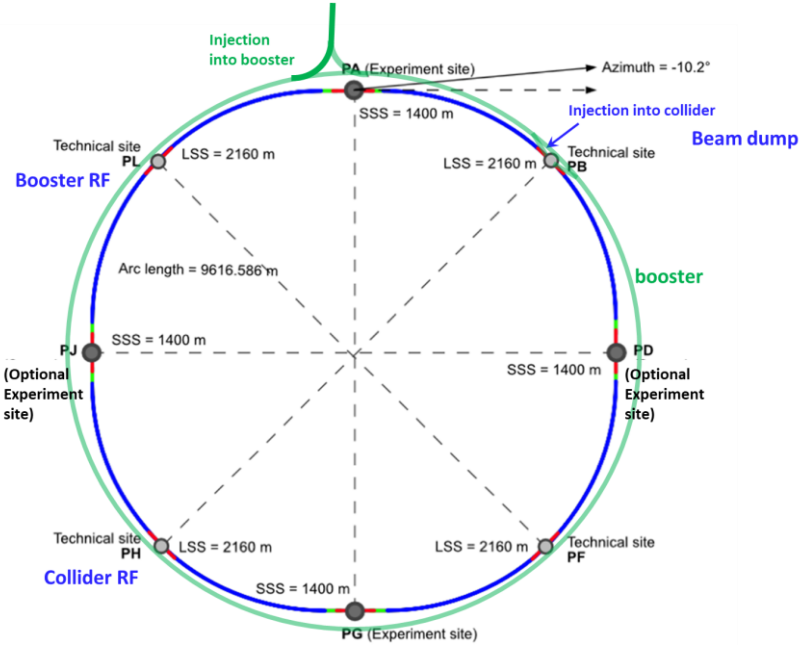
Outline

- 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



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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

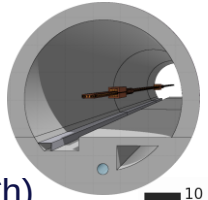
Numbers to be confirmed

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

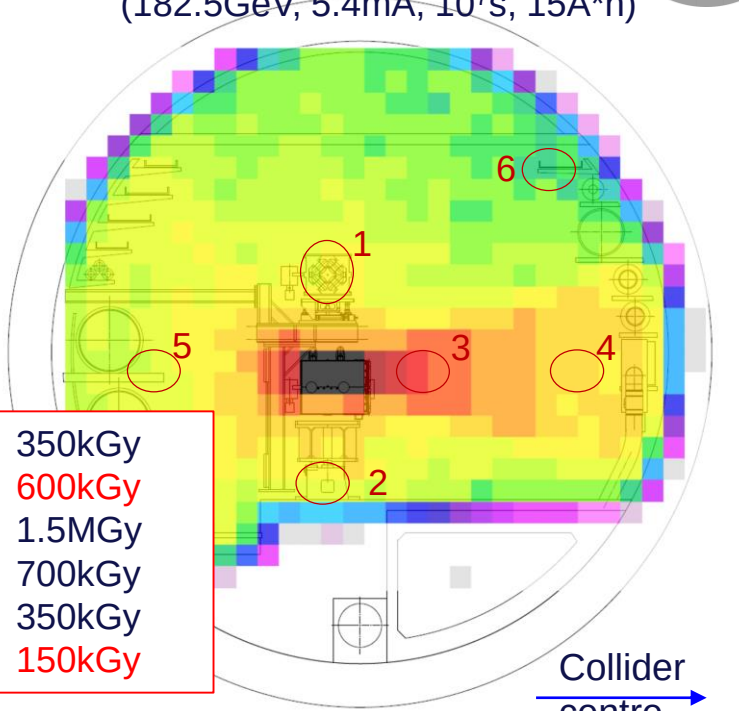


parameter (4 IPs, $t_{rev} = 304\ \mu s$)	value
SR power per beam [MW]	50

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

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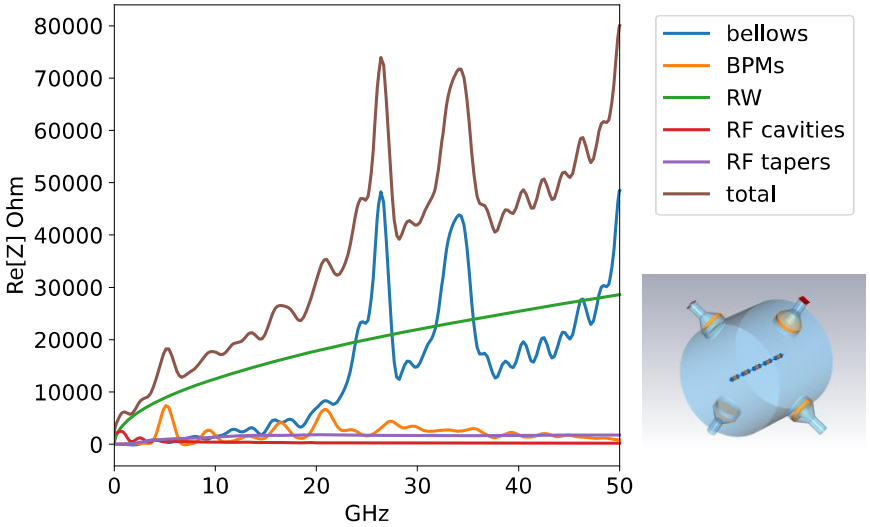
min./max. beam energy [GeV]	**45.6** / 182.5
max./min. beam current [mA]	**1270** / 5
max./min. # of bunches/beam	**15880** / 40

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
    - Ask for Tp evolution in the tunnel during operation

Impedance simulation



Courtesy of E. Carideo and M. Migliorati

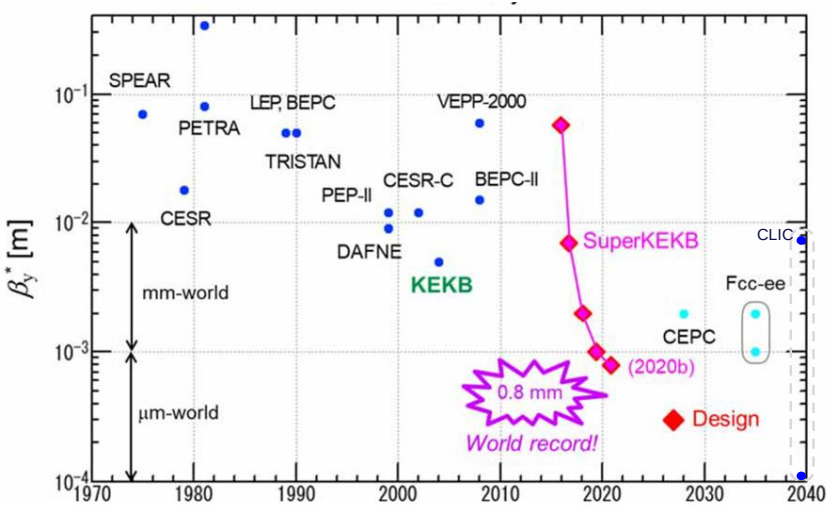
FCC-ee from a BI perspective

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

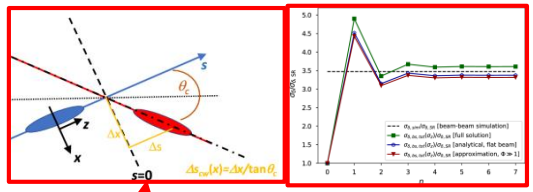
@top

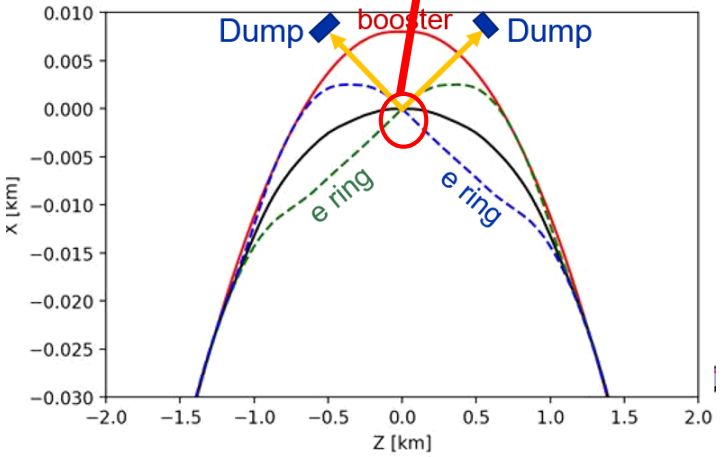
Changes in bunch length due to beamstrahlung generated at IP, combined with top-up operation would result in fast changing beam profiles

- 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

BPM Requirements….

Simone

SUMMARY SENSITIVITY TO ARC ERRORS

HFD61 is less sensitive to errors in the ARCS than the baseline lattice for for all parameters studied.

criteria	E_0	#	orbit H 100 µm	orbit V 100 µm	$\Delta\beta/\beta$ H 1 %	$\Delta\beta/\beta$ V 1 %	$\Delta\eta$ H 1 mm	$\Delta\eta$ V 1 mm	$\Delta\epsilon$ H 1%ϵ_h	$\Delta\epsilon$ V 1%ϵ_h
arc quadrupoles sensitivity [µm]										
V22	Z	1420	1.9	1.9	2.9	0.7	0.1	0.1	3.0	1.0
HFD61	Z	2408	8.4	7.5	>10	3.0	5.0	1.6	>10	2.7
V22	tt̄	2836	1.3	1.5	1.5	0.5	0.12	0.2	0.5	0.17
HFD61	tt̄	2408	2.8	3.1	4.2	1.5	1.9	1.0	>10	0.8
arc sextupoles sensitivity [µm]										
V22	Z	600	>100	>100	17	8.5	3.1	2.6	90	39
HFD61	Z	912	>100	>100	60	26	10	16	>100	>100
V22	tt̄	2336	>100	>100	10	7.0	7.5	10	27	26
HFD61	tt̄	912	>100	>100	19	8	10	11	78	48

SUMMARY TABLE OF ERROR SENSITIVITY: NOT-ARC == FINAL FOCUS AND STRAIGHT SECTIONS

The Final Focus* magnets are more sensible especially in the V plane
Sensitivity to sextupole errors is similar.
Sensitivity to quadrupole errors is better for V22@Z and for HFD61@ttbar

7 nano-meter vertical quad alignment error
1mm rms Hor. Dispersion, 1% hor. Emittance etc. ...

Not-ARC

criteria	E_0	#	orbit H 100 µm	orbit V 100 µm	$\Delta\beta/\beta$ H 1 %	$\Delta\beta/\beta$ V 1 %	$\Delta\eta$ H 1 mm	$\Delta\eta$ V 1 mm	$\Delta\epsilon$ H 1%ϵ_h	$\Delta\epsilon$ V 1%ϵ_h
final focus quadrupoles sensitivity to (hor., ver.) alignment [µm]										
V22	Z	436	0.8	>10	(1.5, 1.2)	0.05	(0.025, 0.025)	0.01	(1.2, 1.0)	0.008
HFD61	Z	524	0.8	0.19	(1.7, 1.0)	0.06	(0.4, 0.007)	0.004	(5.5, 0.007)	0.006
V22	tt̄	480	2.0	0.35	2.1	0.22	0.24	0.04	1.1	0.06
HFD61	tt̄	524	2.8	0.40	4.2	0.3	1.1	0.1	2.1	0.01
final focus sextupoles sensitivity to (hor., ver.) alignment [µm]										
V22	Z	16	>10	>10	>10	0.25	>10	1.2	>10	>10
HFD61	Z	152	>10	>10	>10	0.25	9	2.2	>10	>10
V22	tt̄	16	>10	>10	>10	0.50	>10	2.6	>10	8
HFD61	tt̄	152	>10	>10	>10	0.45	>10	3.7	>10	>10

Sensitivity to sextupole misalignment primarily dominated by the low-beta chromatic correction

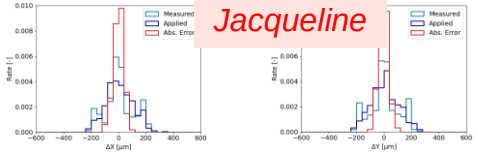
* assuming that the FF focus magnets are the most relevant contributors.

+ BPM Resolution

- Relaxed Z- lattice with $\beta_{x,y}^* = 27$ cm, 2.4 mm
- No synchrotron radiation and sextupoles off
- All quadrupoles misaligned

- $\Delta x = \Delta y =$ Gauss(0, 100 µm)
- COB (u' ~ 10 µrad), including angle, orbit correction and **0.05 µm BPM resolution**

Jacqueline



Resulting alignment: ~**Gauss(0, 35 µm)**
BUT: vertically few outliers (not shown here)

- **Shall provide Orbit, turn-by-turn and bunch-by-bunch data on pilot and colliding bunches**
  - ***Large data throughput (>20GSPS for each BPM plane)***
- **Resolution: 50 nm (orbit), 2 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) ?**
  - ***Tight requirements for IP BPM***
- **Need to draft a complete functional specification for BPM !**

Eliana

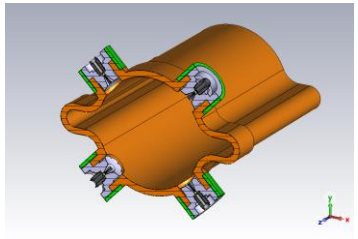
After introducing BPM errors and quadrupole radial offsets and roll angles, misalignments had to be decreased! Set of errors assumed:

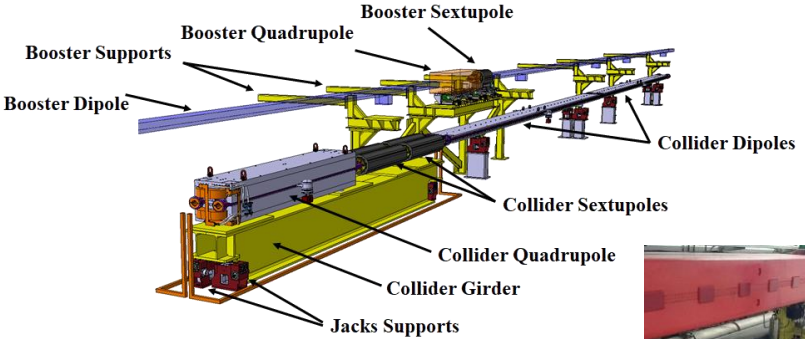
	IR Quads	IR BPMs	other Quads	other BPMs
δx (µm)	10	10	30	30
δy (µm)	10	10	30	30
$\delta\theta$ (µrad)	10	10	30	30
calibration	-	1%	-	1%

- Although g orbit after correction is in the order of few microns, the vertical er / result above specs.
  - 289 sk les introduced for minimizing spurious vertical dispersion and betatro when needed.

Arc BPMs

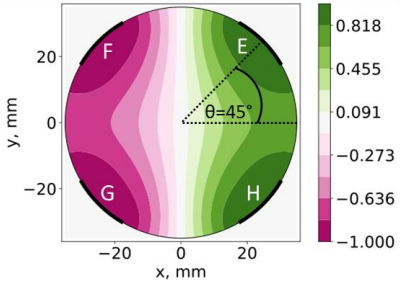
- **Collaboration between different teams to study, impedance, vacuum, integration, magnet and pick-up design for the MR arc half-cell mockup**
  - ***~ 1000 BPMs per arc (incl. Booster ring BPMs)***
  - ***High current inducing high heat load on BPM body and RF Button – Water cooling ?***
  - ***Will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

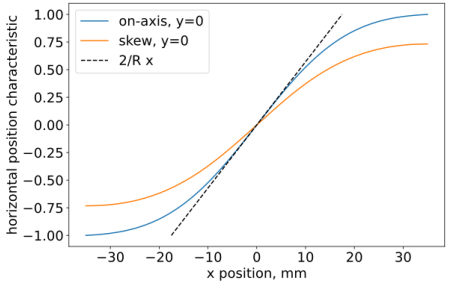


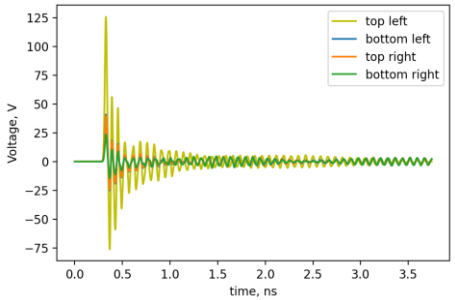


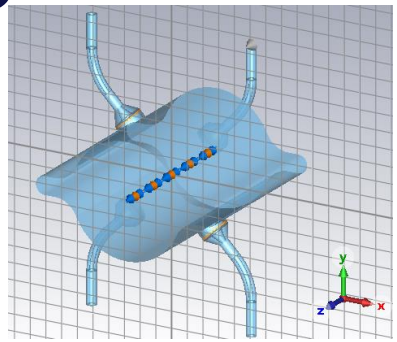
- **Electronic**
  - ***1-2m long SiO2 rad-hard cables from buttons to electronics***
  - ***Radiation-hard conversion of electrical signals into optical signals – two options not studied in detail yet***
  - ***Rad-hard optical fiber to centralised acquisition system either in alcoves or in central 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



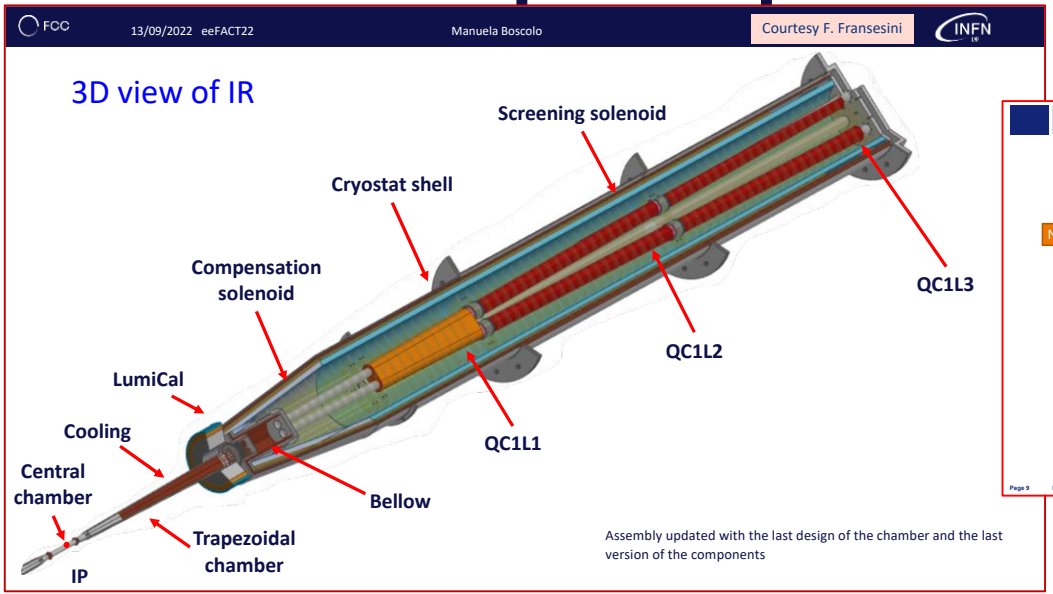






- **New BI Doctoral Student, *Emily Howling*, University of Oxford**
  - ***Started in April 2023, 3-years PhD on FCC-ee BPMs, located at CERN***
  - ***Focus on MR arc BPM pickups, low beam-coupling impedance, prototyping, lab characterization, beam studies at CLEAR***

BPMs in final quadrupole



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Sensitivity to sextupole misalignment primarily dominated by the low-beta chromatic correction

Page 9 | Optics tuning for future circular colliders | 26th June 2023 | S.Liuzzo et al. * ass... the most relevant contributors. The European Synchrotron | ESRF

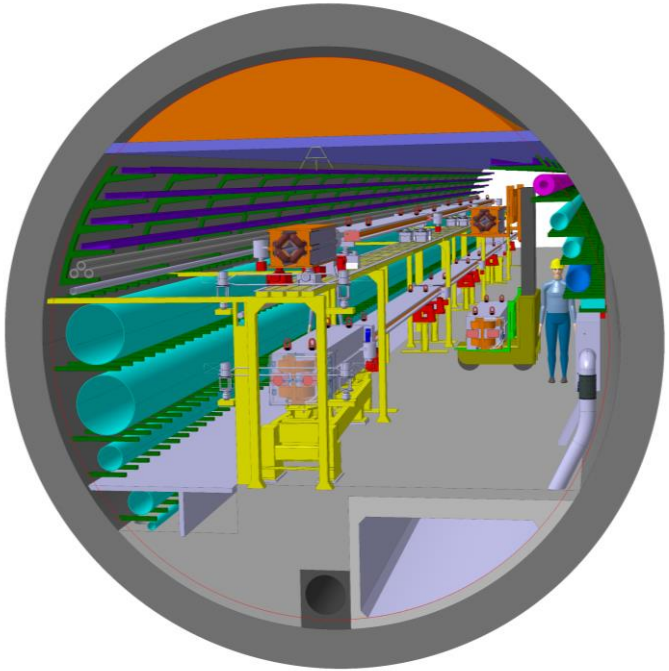
Simone

We need IR BPMs for IP feedback and optic tuning/corrections in the final quadrupole cryostat

- Tightest requirements in terms of accuracy, resolution and stability and worse environment
- Need to work on the detailed engineering of the final quadrupole/cryostat to make sure the BPMs can meet specifications

Beam Loss Monitors (BLM)

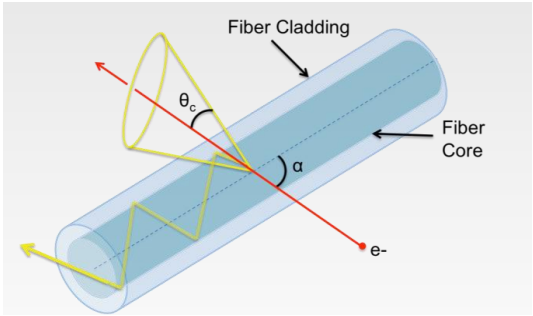
- **Large energy stored in both, main rings and booste ring, would require a machine protection system (MPS), supported by beam loss monitors (BLM)**
  - ***So far BLMs required for injection, extraction, collimatio experimental zones***
  - ***BLMs in the arcs need to be insensitive to X-rays!***
  - ***Identifying losses from the individual rings in the tunnel challenging !***
    - Bunch-by-bunch acquisition required
    - Between 2 colliding beams - BLMs with beam directivity
    - Between main and booster rings: staged localization of the quads ?
- **Need to identify specific needs from injectors ?**



BLM R&D

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

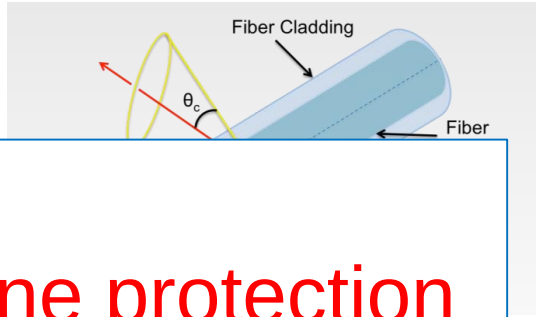
- **Optical BLM system based on *Cherenkov* fibers offers**
  - ***High directivity***
  - ***Only measures charged particles – insensitive to X-rays***



- **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…



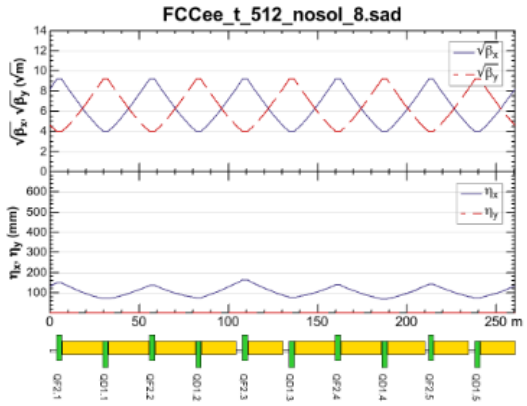
Need to establish a FCCee machine protection and beam loss monitoring working group

New Ph.D student and collaborator starting soon

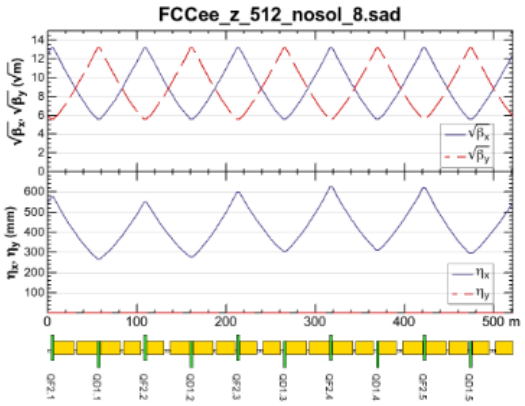
Beam Size Measurement

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 !

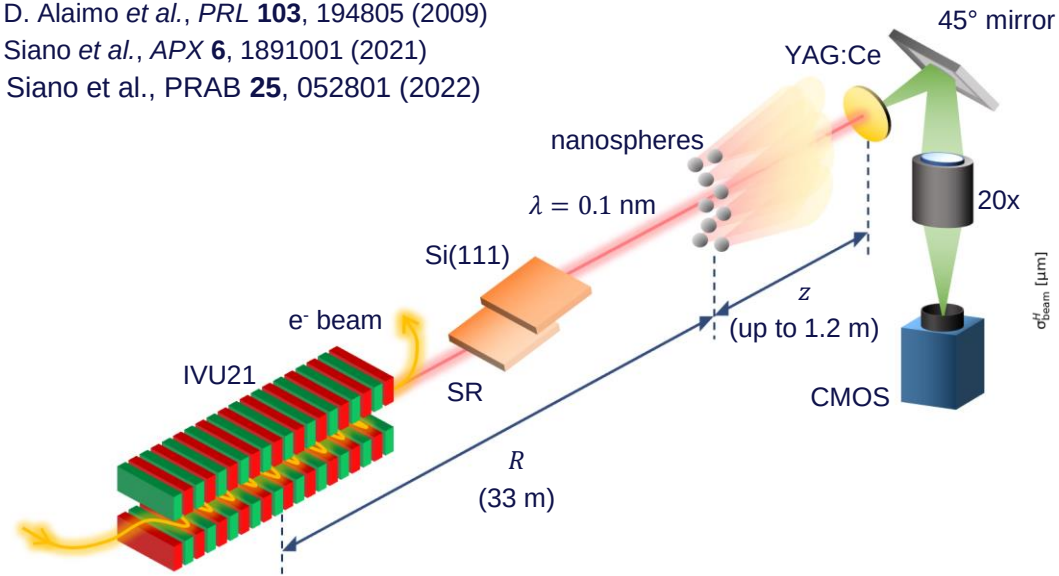
In the arcs (Zh):

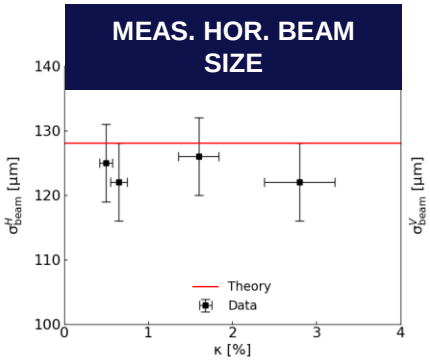
horizontal: ~100 μm

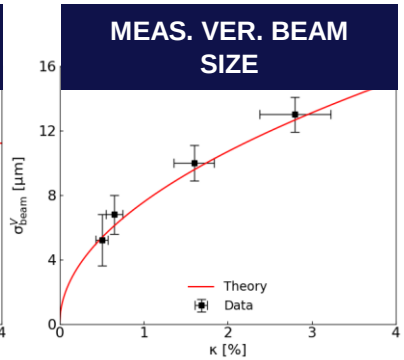
vertical: ~7 μm

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)







- New Postdoc, Daniele to study realistic SR sources in FCCee
- Possibly add. Collaboation with PSI on X-ray imaging systems

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 and top-up injection scheme.
- Need a resolution in the sub-ps range to estimate the energy spread, required for the energy calibration using the spin depolarization technique
- Studies on Electro-optical technique, Optical Cherenkov diffraction radiation monitor using fast time response optical detector.. Collaboration between CERN, KIT, PSI

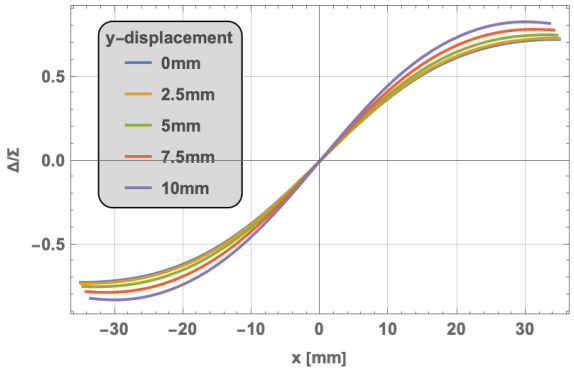
Conclusion

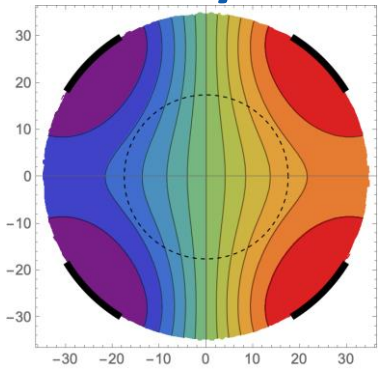
- On-going Beam instrumentation studies for FCC are progressing well
- Relying on a motivated team of young scientists, small for the moment but getting larger and larger …
- Many challenges ahead of us but no show-stopper identified
- Our goal is to provide a conceptual design of a realistic and cost-effective suite of beam diagnostics for FCC-ee by 2025
- Would be great to converge on a draft functional specifications for BPMs

Thank you
for your attention

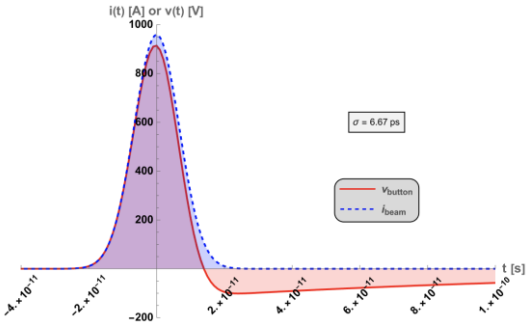
Button-Style BPM Position Characteristics

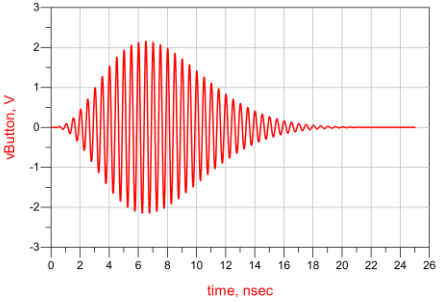
- **Analytical and simplified numerical analysis**





by M. Wendt



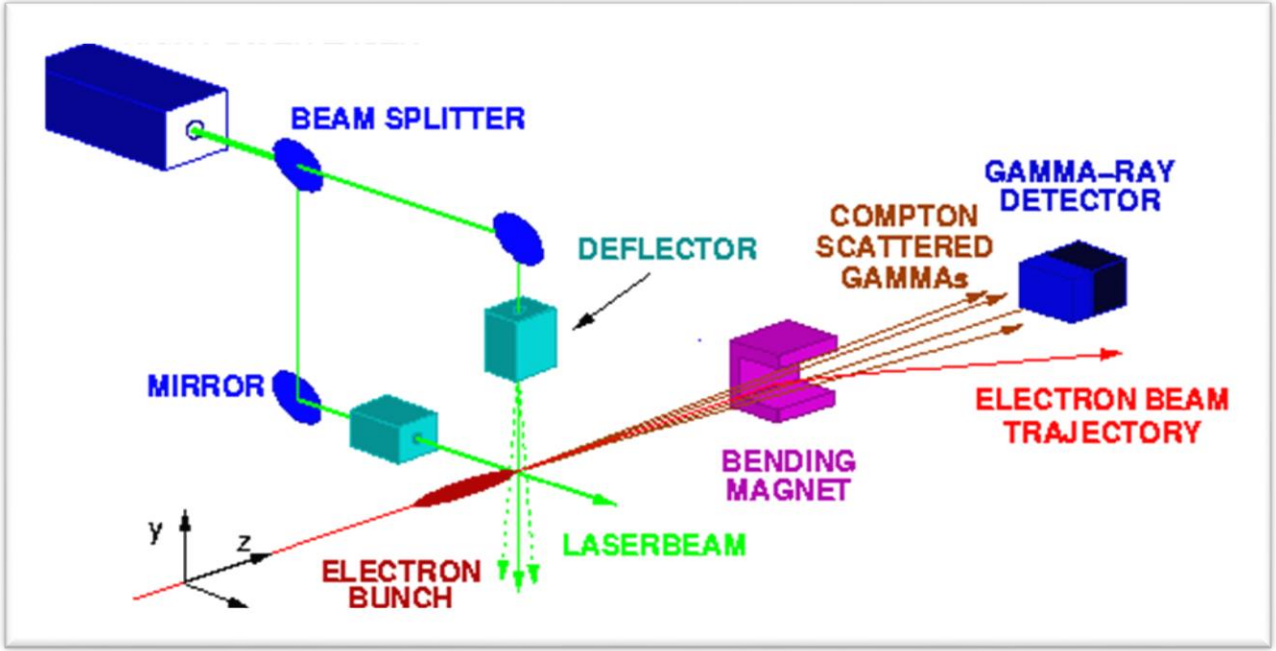


ss filter: $f_c =$

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

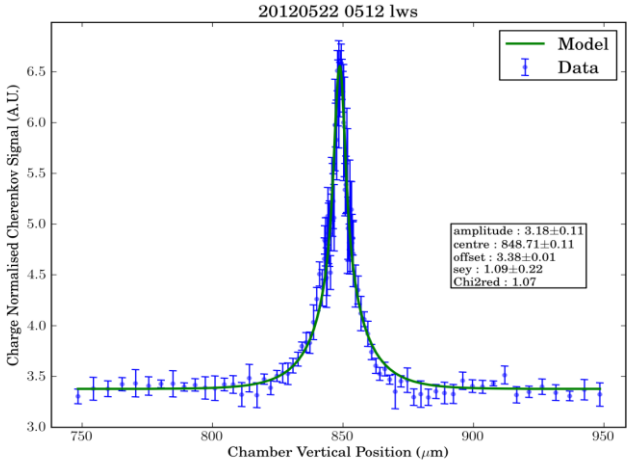
Beam Size alternative : Laser Wire Scanner

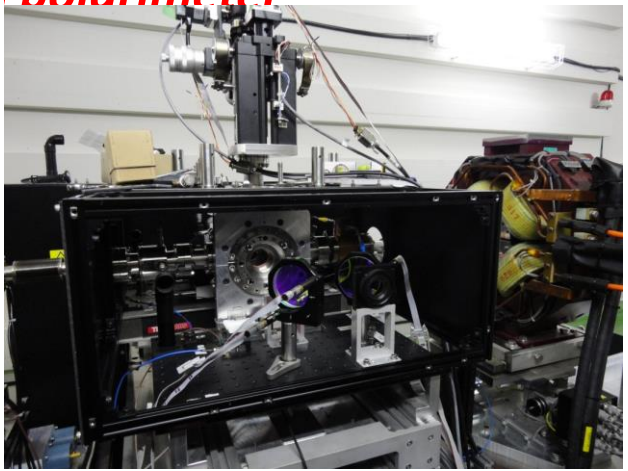
- **Laser wire scanner technology developed for linear colliders**
  - ***Based on Compton scattering using high power laser light***



Beam Size alternative : Laser Wire Scanner

- ***Demonstrated 1 µm measurement resolution !***
  - using a high-power fiber laser
- ***Shares l… polarimeter***



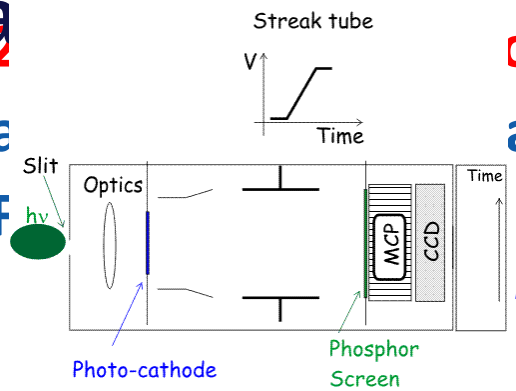


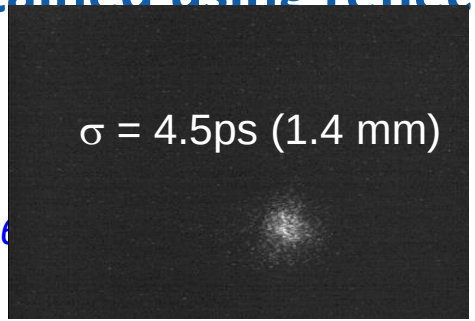
15 years on R&D on ATF2 ring and extraction line

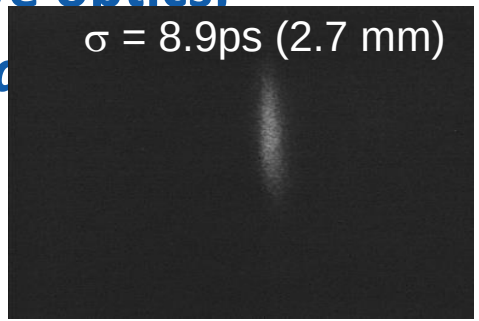
H. Sakai et al, Physical Review ST AB 4 (2001) 022801 & ST AB 6 (2003) 092802
S. T. Boogert et al., PRSTAB 13, 122801 (2010)
L. Corner et al., IPAC, Kyoto, Japan (2010) pp3227

Bunch Length Measurements : Streak Ca

- 2 on obtained using reflective optics,
  a al BPF *Ho*
  F *NIMA 40*
- D unch-by-bunch online monitoring

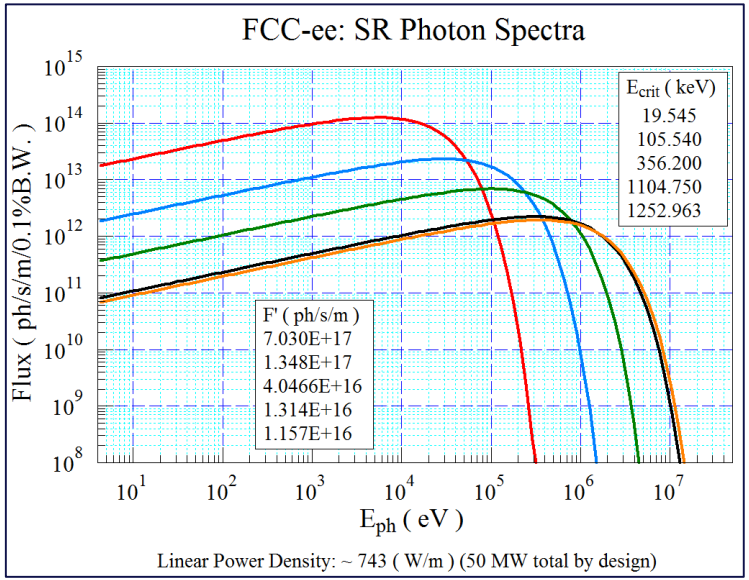






Beam Size Measurement

- **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:

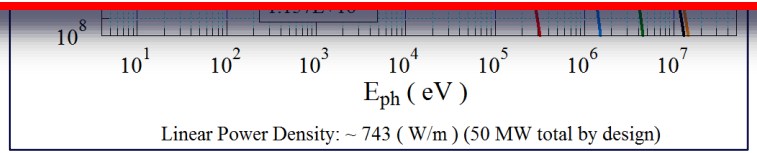
- **Large arc radius requires very long, extended SR extraction lines**
  - ***Need for detailed numerical simulations***

Beam Size Measurement based on SR

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

Requires X-ray interferometric techniques

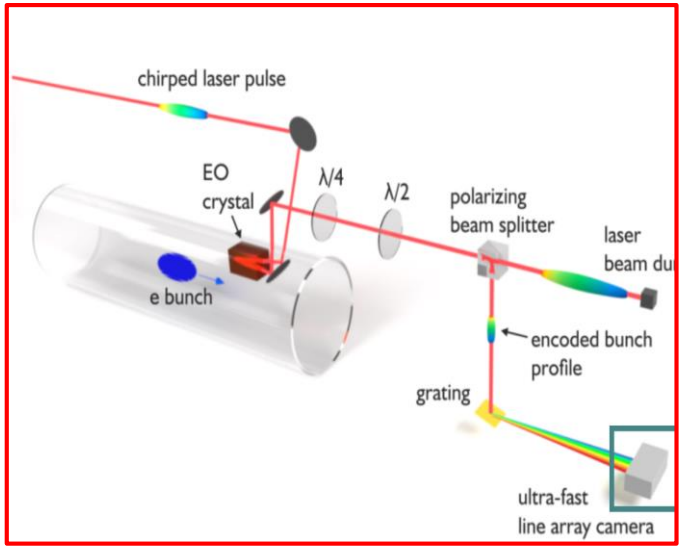
A new Postdoc, Daniele Butti, has just started to study the implementation of SR monitors in FCCee

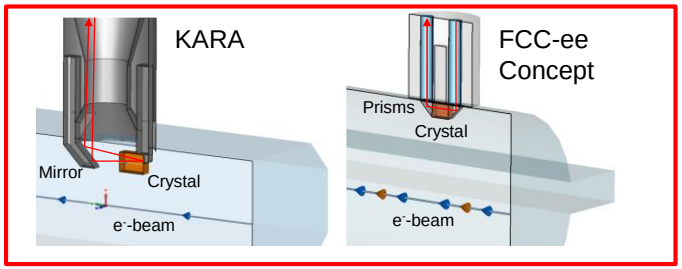


- **Large arc radius requires very long, extended SR extraction lines**
  - ***Need for detailed numerical simulations***

Longitudinal beam profile Measurements

Electro-optical Spectral decoding studies at KIT



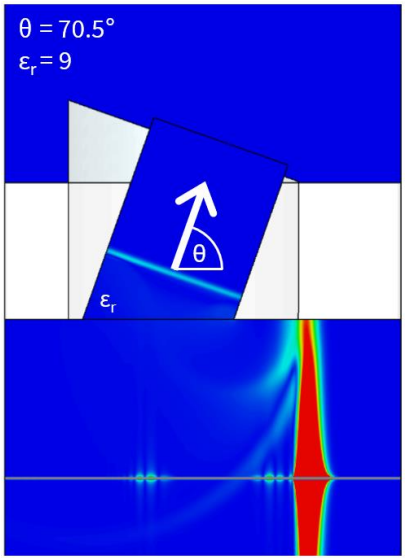


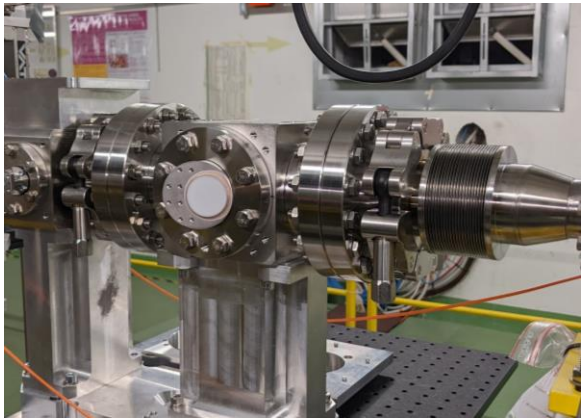
Long term goal

- 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

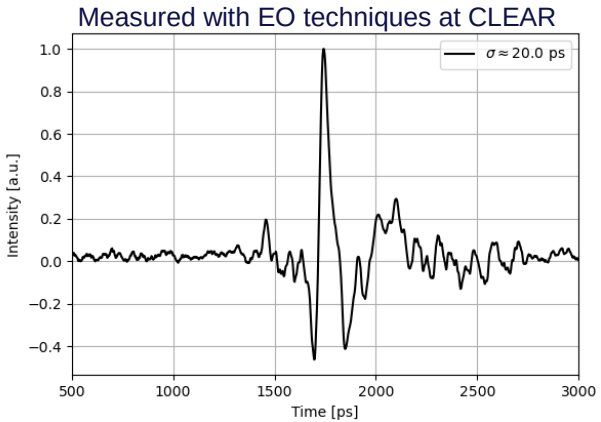
Cherenkov Diffraction radiation studies using dielectric pick-ups at **CLEAR@CERN** and **ATF2@KEK**





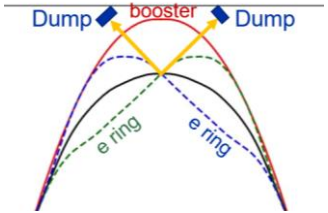
Courtesy of A. Schloegelhofer

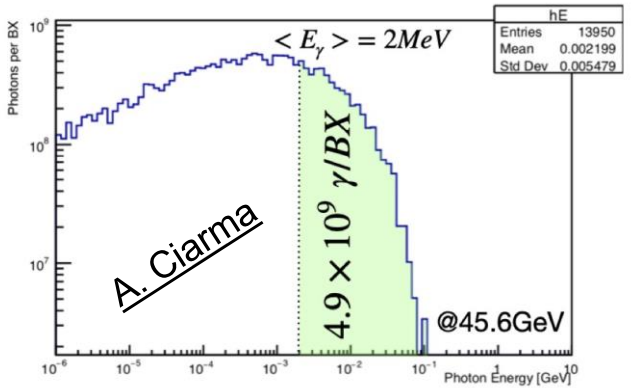
Generating a radiation replica of bunch profile and measuring it with optical methods



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..