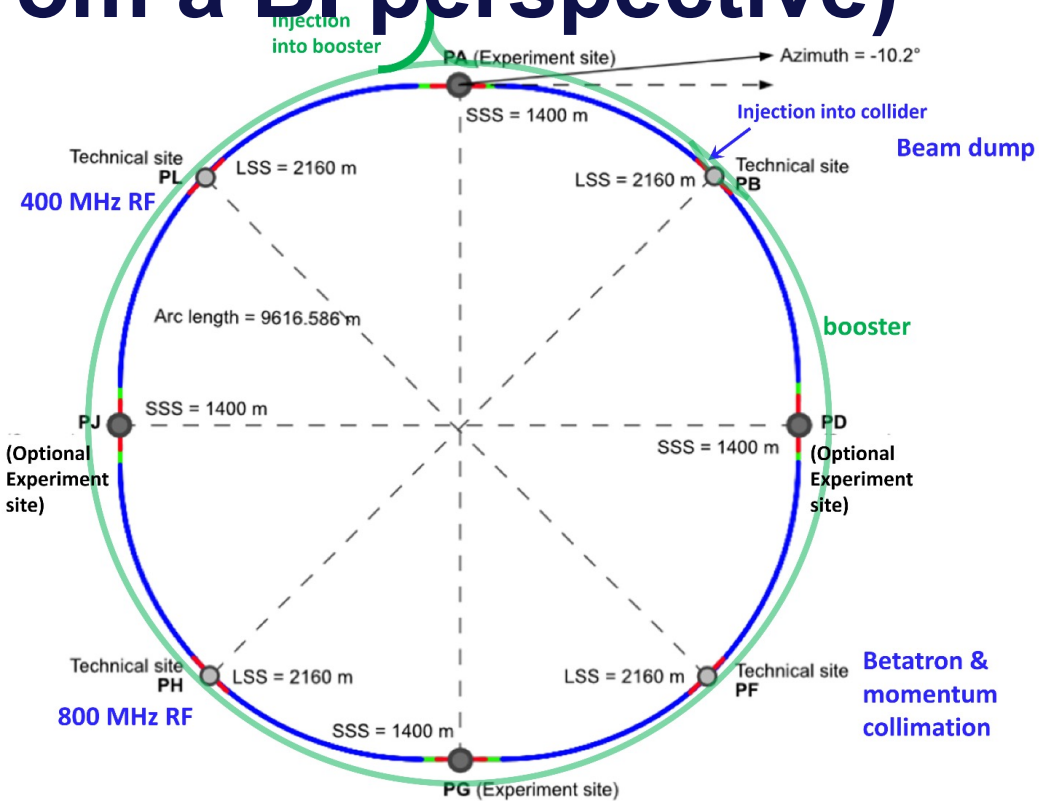
Beam Instrumentation Challenges for FCC-ee

with contributions from
Emanuela Carideo, Ubaldo Iriso Áriz, Gaku Mitsuka, Toshiyuki Mitsuhashi, Gudrun Niehues, Micha Reißig, Mirko Siano, Thibaut Lefevre, Stefano Mazzoni, Andreas Schlögelhofer
and many other colleagues

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

Outline

- **FCC-ee Beam Instrumentation Challenges**
  - ***Some general remarks***
- **Beam Position Measurement**
- **Beam Loss Measurement**
- **Beam Size Measurement**
- **Bunch Length Measurement**
- **Other Challenges**

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, etc. of the BPM system components
    - low beam-coupling impedance for EM beam pickups
- **Managerial, manpower and budget challenges**
  - ***Require good communication between all teams and collaborators***
  - ***Specify and tailor limited resources to the most critical R&D activities***

Beam Position Monitors (BPM)

- **A total of ~6000 BPMs in the 92 km tunnel**
  - ***2000+2000 BPMs for the main rings, 2000 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

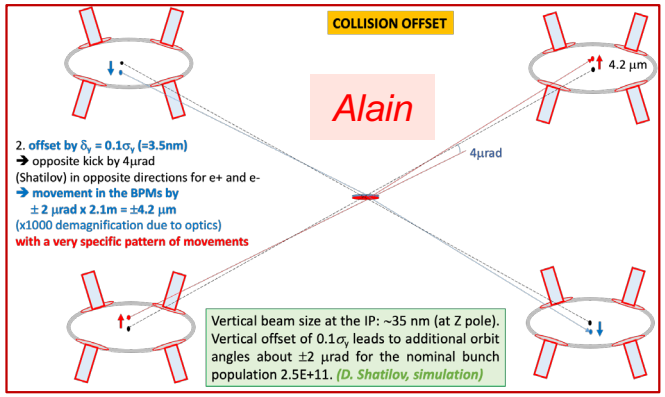
After introducing BPM errors and quadrupole radial offsets and roll angles, misalignments had to be decreased! Set of errors assumed:

	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 the resulting orbit after correction is in the order of few microns, the vertical emittance may result above specs.
  - 289 skew quadrupoles introduced for minimizing spurious vertical dispersion and betatron coupling when needed.

Eliana

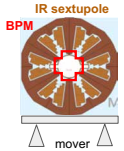
ifm 11/41



Alain

- **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!**

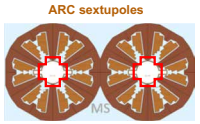
Attach BPMs to sextupoles in FCC-ee? Movers?



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 con
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)

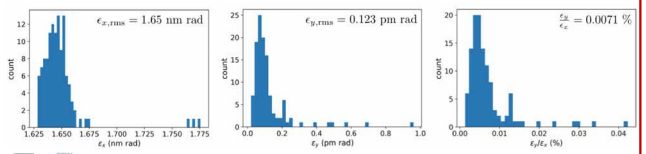
Using the misalignments and roll angles of:

Tessa

	σ_x(μm)	σ_y(μm)	σ_θ(μrad)
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:



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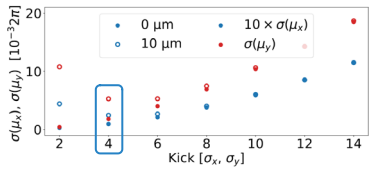
Kick Strength and Phase Advance

- 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 BPMs
- Without synchrotron radiation
- Gaussian BPM noise applied

FCC-Z mode at 45.6 GeV single particle tracking

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)



Jacqueline

JACQUELINE KENTZEL
FCC-EE LATTICE DESIGN
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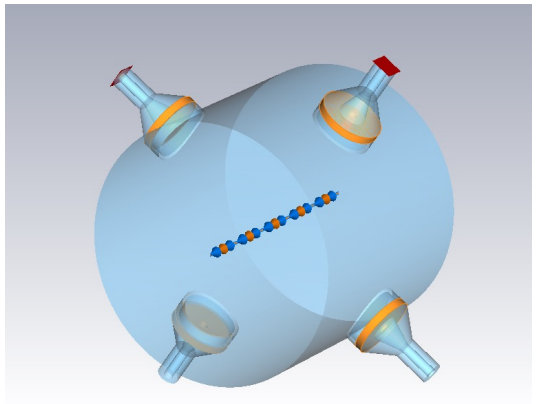
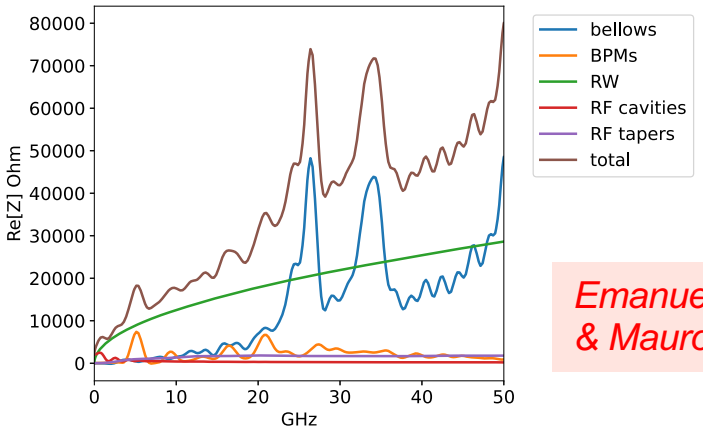
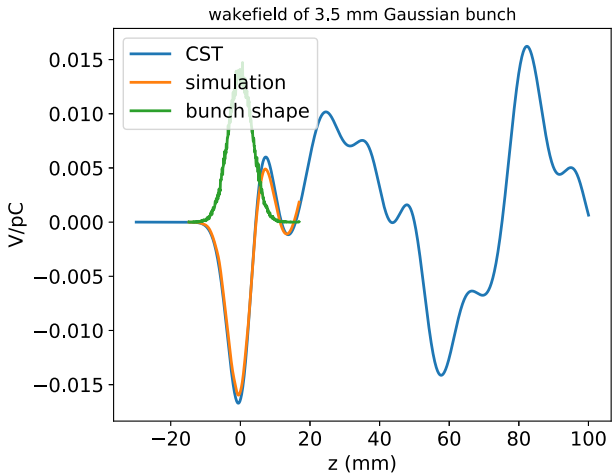
BPM Pickup R&D: Wakefields





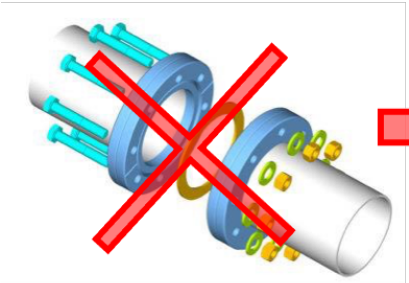
Emanuela & Mauro



- **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***

BPM Pickup R&D: Integration

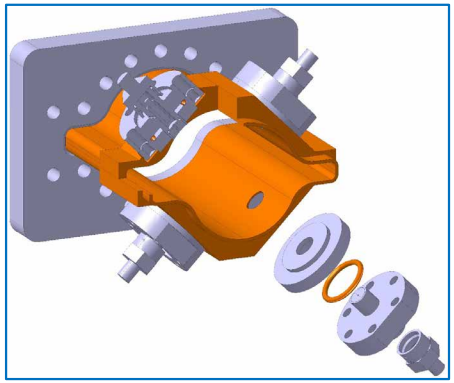
Current system



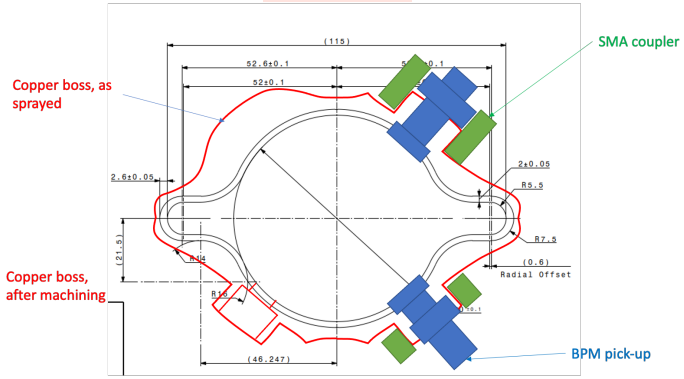
Typical ConFlat flange

New concept

Proof of concept of SMA connectors for Ultra High Vacuum (UHV) chambers.

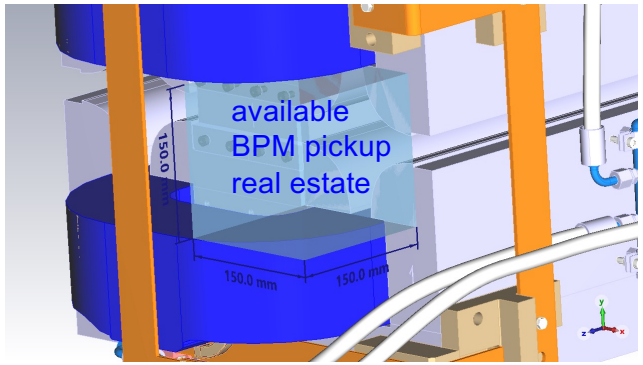


Cedric



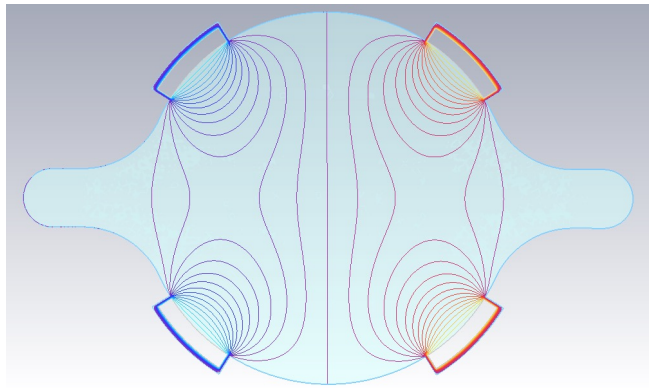
- **CERN vacuum team (*Cerdic Garion*) R&D on additive manufacturing**
  - ***Cost effective method to integrate the UHV BPM button feedthroughts into the vacuum chamber***
  - ***Requires more communication and studies***
    - Feedthrough RF properties, button size and mechanical details, pickup position non-linearities, EM alignment with quad, maintenance, etc.

- **Real estate at the quad**
  - ***Preliminary study hints no "extra" space is required for the BPM pickup***

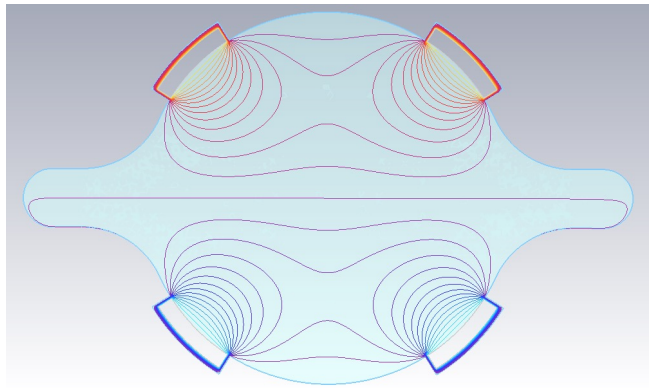


BPM System: Read-out, DAQ, Infrastructure

- **Too early to call**
  - ***With >25 years until installation better wait for technology updates!***
  - ***LHC BPM system (1100 BPMs, all BxB) operates almost unchanged since 15 years***
    - …and probably another 15 years
- **But…**
  - ***Follow technology advances which meets FCC-ee BPM requirements!***
    - Low latency read-out system to meet FB purposes
      - *What kind of DAQ segmentation do we need?*
    - Radiation tolerant hardware for tunnel installation
      - *Data decimation and pre-processing (e.g. correction of position non-linearities) in the tunnel?!*
  - ***Cost optimization and estimation!***



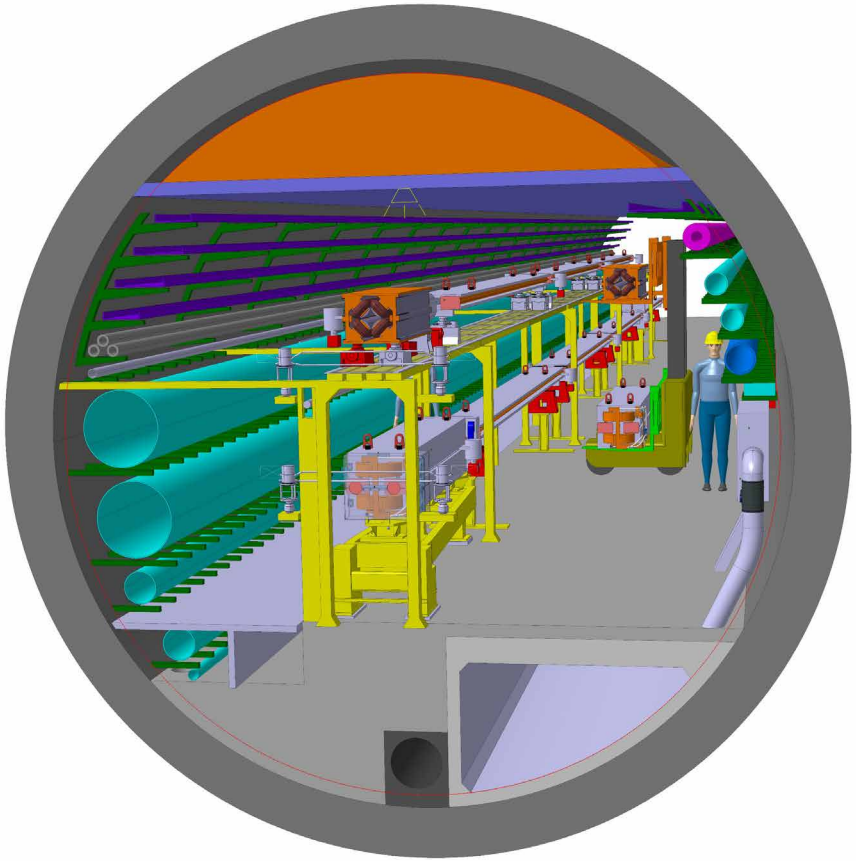
BPM position behaviour: horizontal



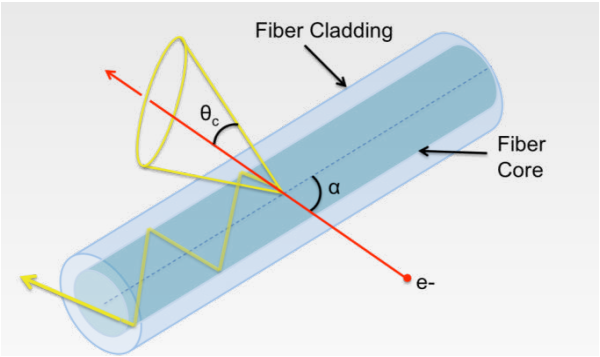
BPM position behaviour: vertical

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



BLM R&D



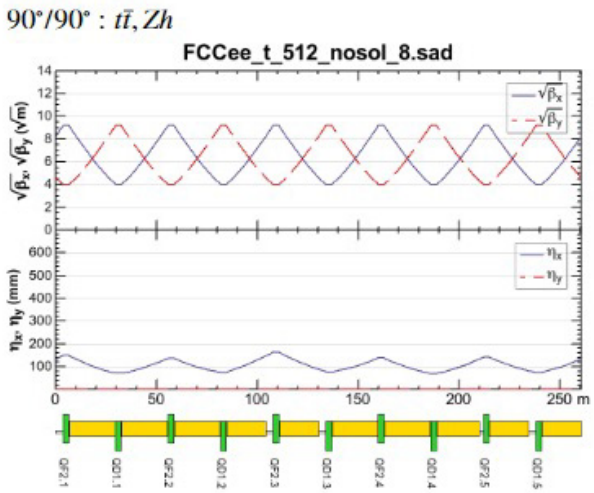
Dedicated FCC-ee BLM R&D has not started, but…

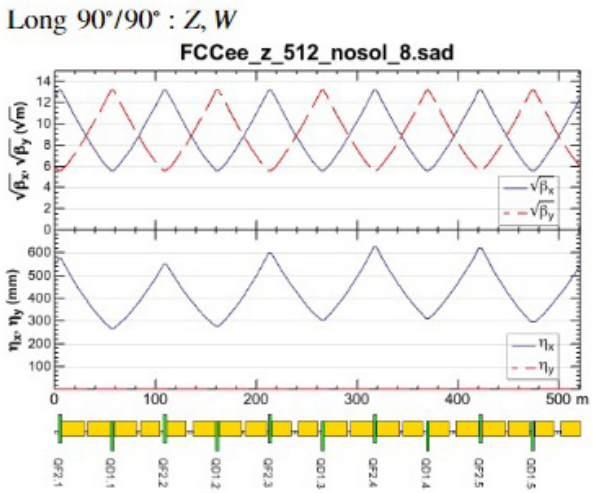
- **Optical BLM system based on *Cherenkov* fibers offer**
  - ***High directivity***
  - ***Only measures charged particles***
  - ***Successful beam studies at CLEAR***

- **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

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



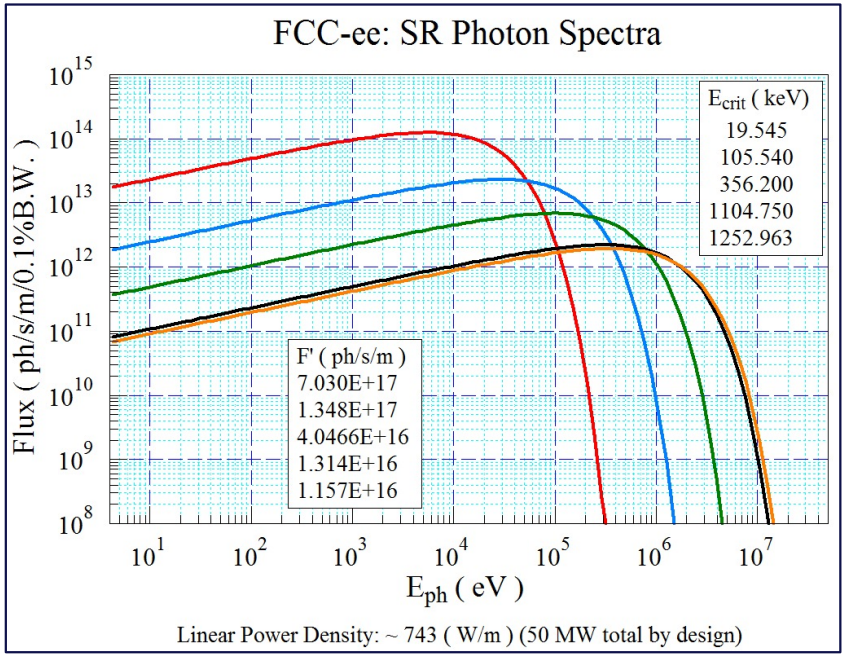


FCC-ee beam size is small!

- ***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)

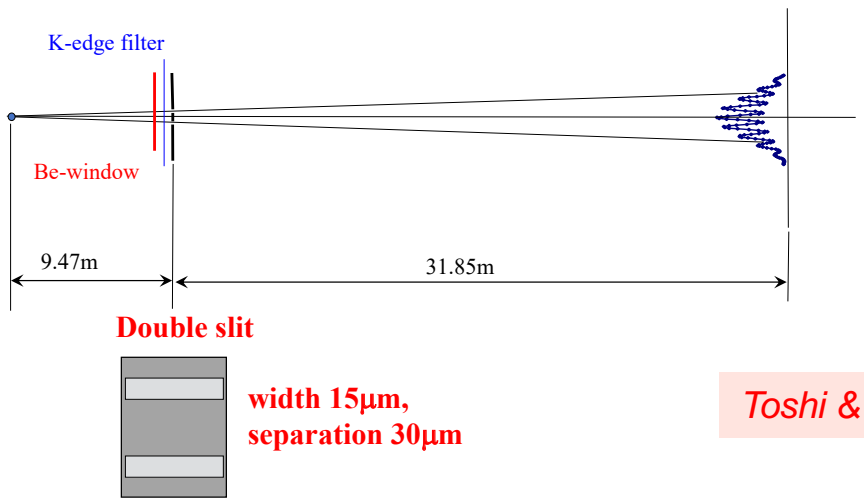
FCC-ee challenge:

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

Beam Size R&D: X-Ray Interferometer

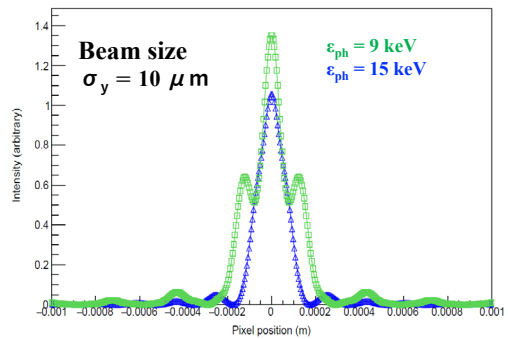
- **Beam size given by the *Fourier* transform of the spatial coherence measured by an interferometer**
  - ***Long light extraction line with critical alignment***
  - ***Single plane***
  - ***Does not provide the beam profile***

Configuration of X-ray interferometer at SuperKEKB

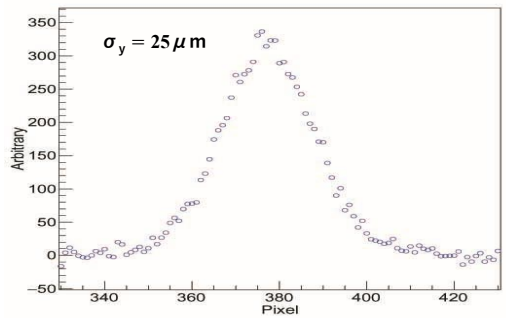


Toshi & Gaku

Simulation of interferogram for X-ray energy of 9, and 15 keV



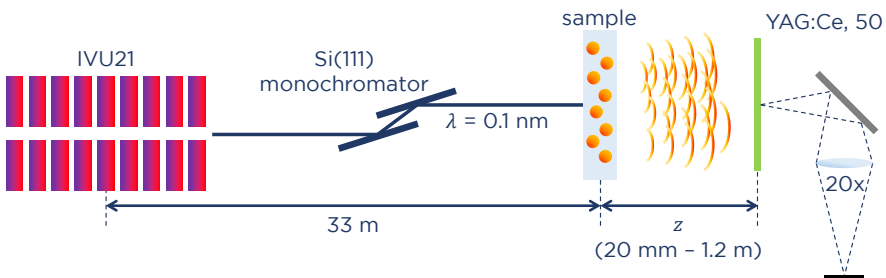
Observation result with beam size of 25µm

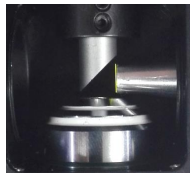


Beam Size R&D: 2D X-Ray HNFS

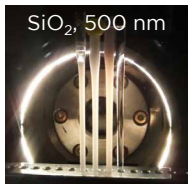
- **Heterodyne Near Field Speckles (HNFS)**
  - ***Interference between the beam's X-ray SR and scattered spherical waves from a colloidal suspension***
    - e.g., nano particle / water mix
  - ***2D beam size measurement, few µm resolution***

The HNFS setup at NCD (ALBA)

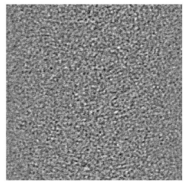




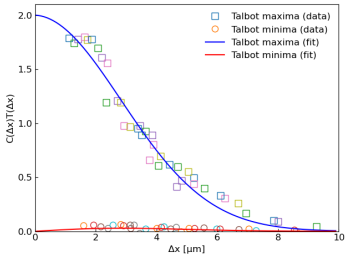
Period	21.6 mm
Number of periods	92
Photon energy	12.4 keV
Harmonic number	7
Bandwidth	10^{-4}

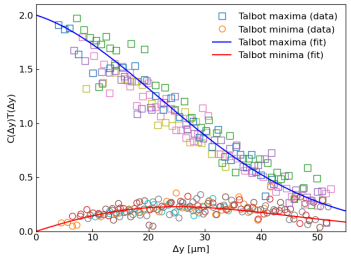


acA4112-8gm
4096 x 3000 px
3.45 x 3.45 µm²



Results: coherence



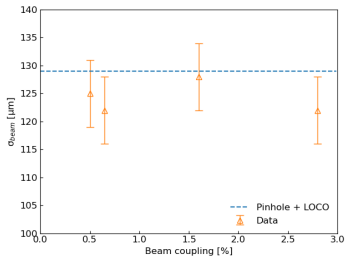


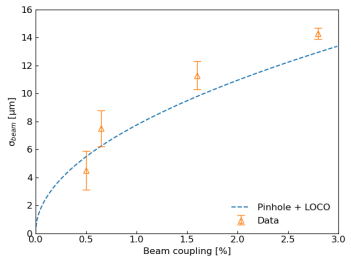
Horizontal coherence length (rms) [µm]			
κ = 0.50 %	κ = 0.65 %	κ = 1.60 %	κ = 2.80 %
4.2 ± 0.2	4.3 ± 0.2	4.1 ± 0.2	4.3 ± 0.2

Vertical coherence length (rms) [µm]			
κ = 0.50 %	κ = 0.65 %	κ = 1.60 %	κ = 2.80 %
105 ± 32	65 ± 11	44 ± 4	36 ± 1

Mirko & Co

Results: beam sizes



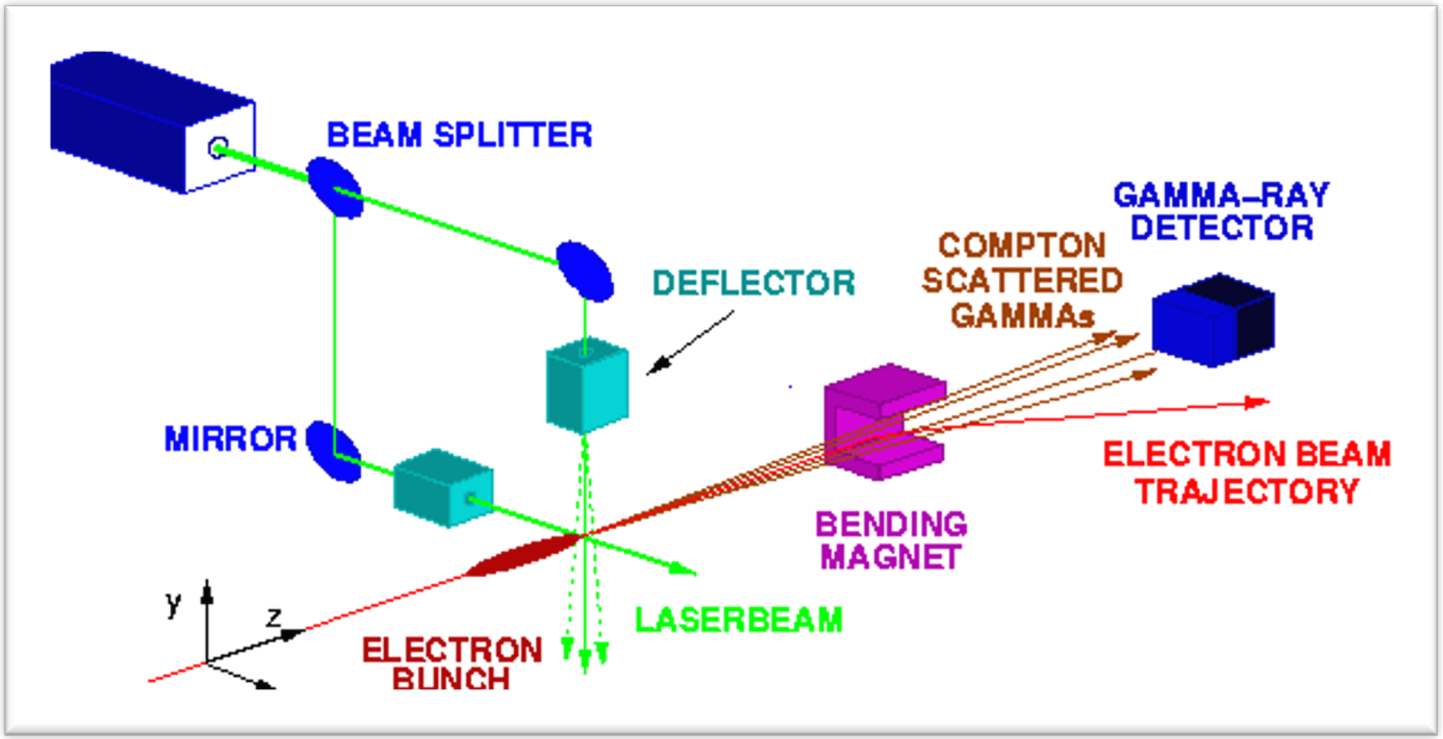


Horizontal beam size (rms) [µm]			
κ = 0.50 %	κ = 0.65 %	κ = 1.60 %	κ = 2.80 %
125 ± 6	122 ± 6	126 ± 6	122 ± 6

Vertical beam size (rms) [µm]			
κ = 0.50 %	κ = 0.65 %	κ = 1.60 %	κ = 2.80 %
4.5 ± 1.4	7.5 ± 1.3	11.3 ± 1.0	14.3 ± 0.4

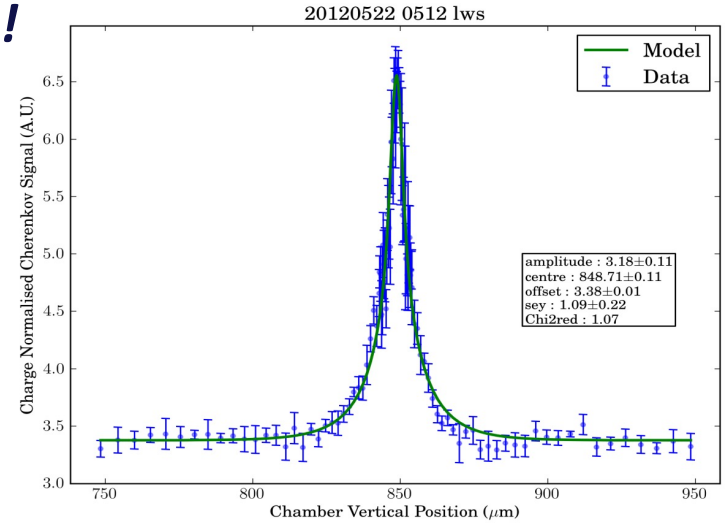
Beam Size R&D: Laser Wire Scanner (1)

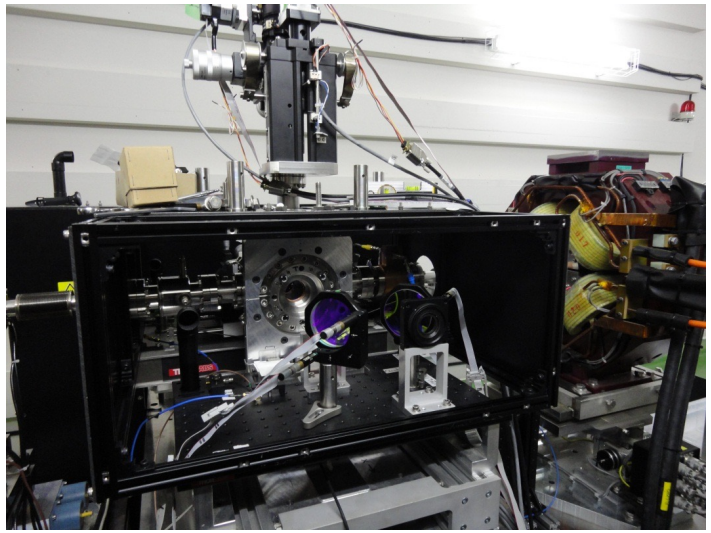
- **Laser wire scanner technology developed for linear colliders**
  - ***Based on Compton scattering using high power laser light***



Beam Size R&D: Laser Wire Scanner (2)

- ***Demonstrated 1 µm measurement resolution!***
  - using a high-power fiber laser
- ***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 Measurement

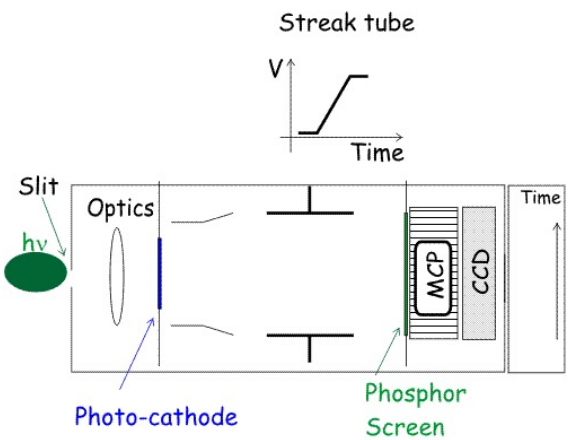
Parameter [4 IPs, 91.1 km]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75

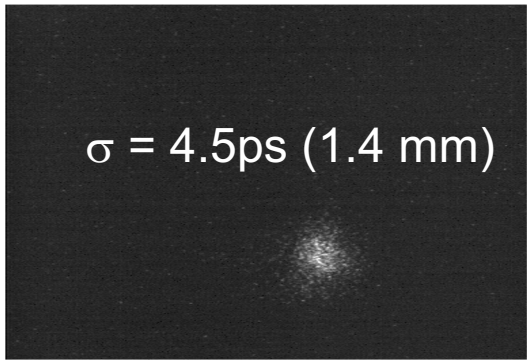
- **"Reasonable" long bunches**
  - ***2 – 3 mm RMS, or longer***

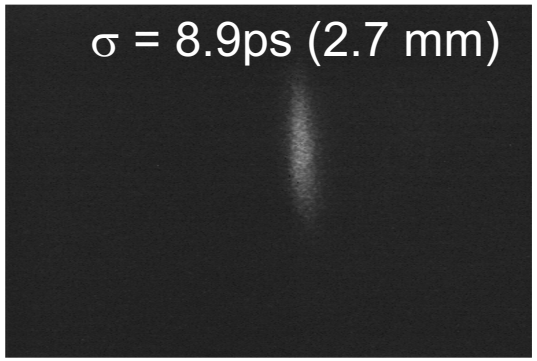
- **Need a bunch-by-bunch measurement system with picosecond resolution to monitor the impact of the Beamstrahlung.**

- **Need a resolution in the 100 fs regime to estimate the energy spread, required for the energy calibration using the spin depolarization technique**

Bunch Length: 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: Radiation-based

Measure the spectrum of coherent radiation $S(\omega)$

$$S(\omega) \approx N^2 S_p(\omega) F(\omega)$$

N – number of particles/bunch

$S_p(\omega)$ – single particle spectrum, of the type of radiation source, e.g., synchrotron, Cherenkov, diffraction, etc.

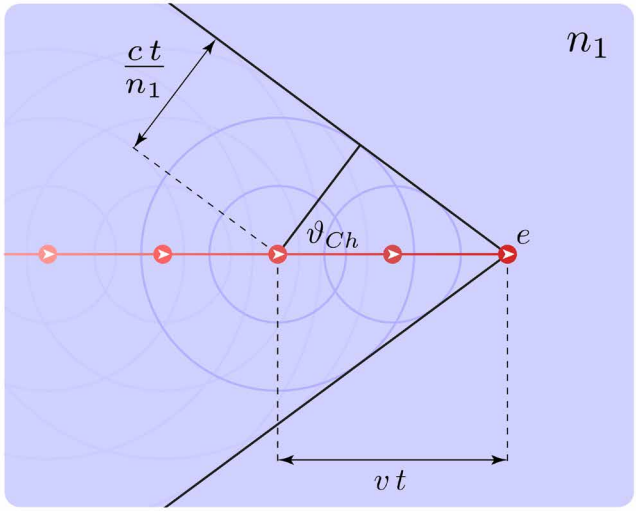
$F(\omega)$ – bunch form factor, e.g., Gaussian particle distribution function

long. bunch profile:

$$\rho(z) = \frac{1}{\pi c} \int_0^\infty d\omega \, F(\omega) \cos\left(\frac{\omega z}{c}\right)$$

Bunch Length: Cherenkov Diffraction

Cherenkov Radiation

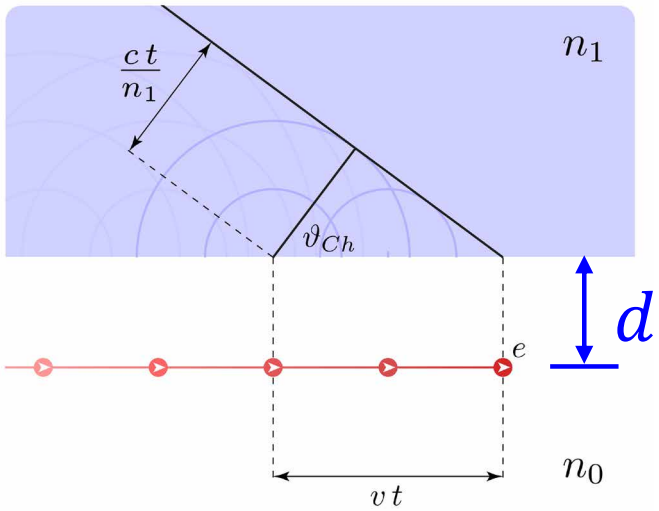


$$v > v_p = \frac{c}{\sqrt{n_1}}$$

$$\vartheta_{Ch} = \frac{1}{n_1 \beta}$$

Andreas

Cherenkov Diffraction Radiation (ChDR)

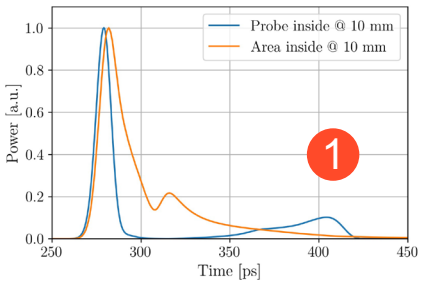


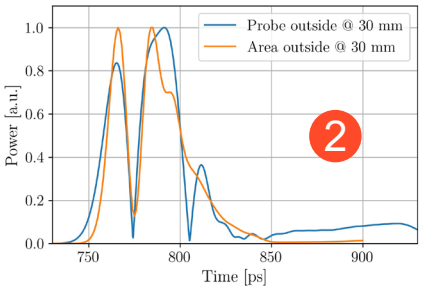
- **ChDR occurs as a charged particle traveling in vacuum (n_0) passes at a distance (d: impact parameter) a dielectric surface (n_1)**
  - ***Beam pickups based on coherent and incoherent ChDR are currently studied for bunch length, beam size and beam position measurements at CERN***

Bunch Length R&D: ChDR BI at CLEAR

- **Numerical analysis with CST Studio**

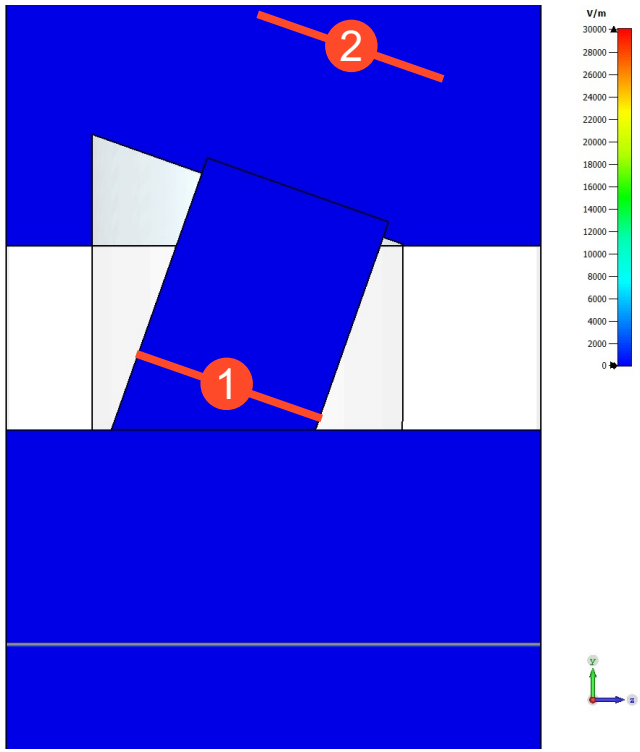
Andreas



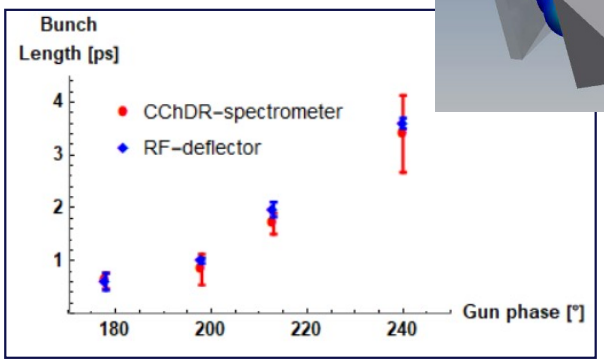


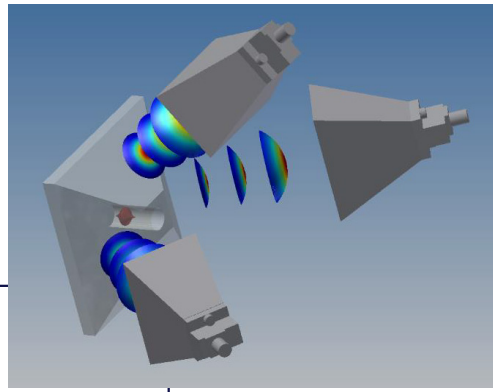
Electron bunch
5 ps Gaussian,
300 pC, 200 MeV

E-field, Median plane (yz-plane)



- **ChDR bunch length measurements at CLEAR**
  - ***Utilizing the radiation at 3 bands, 60 – 90 – 110 GHz***

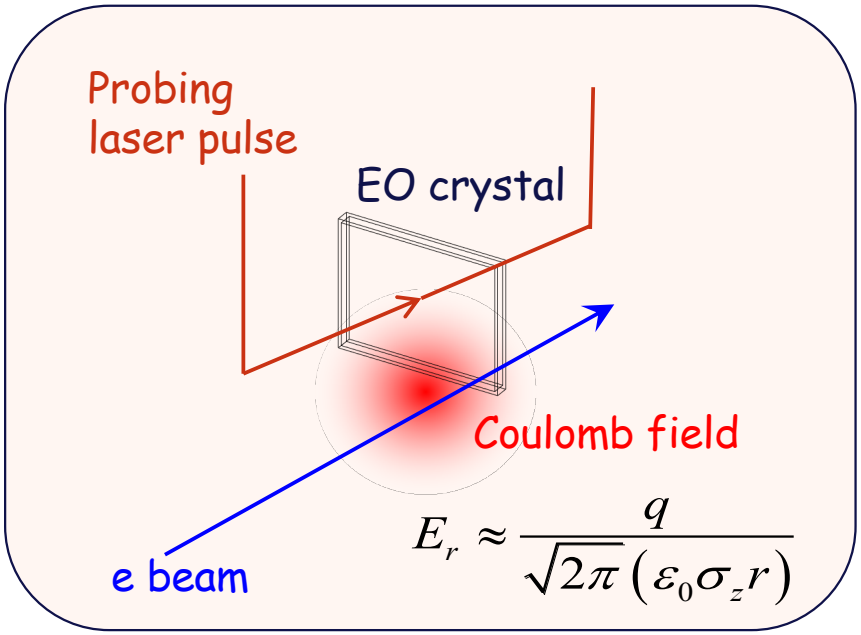




A. Curcio

Bunch Length Measurement: EOS

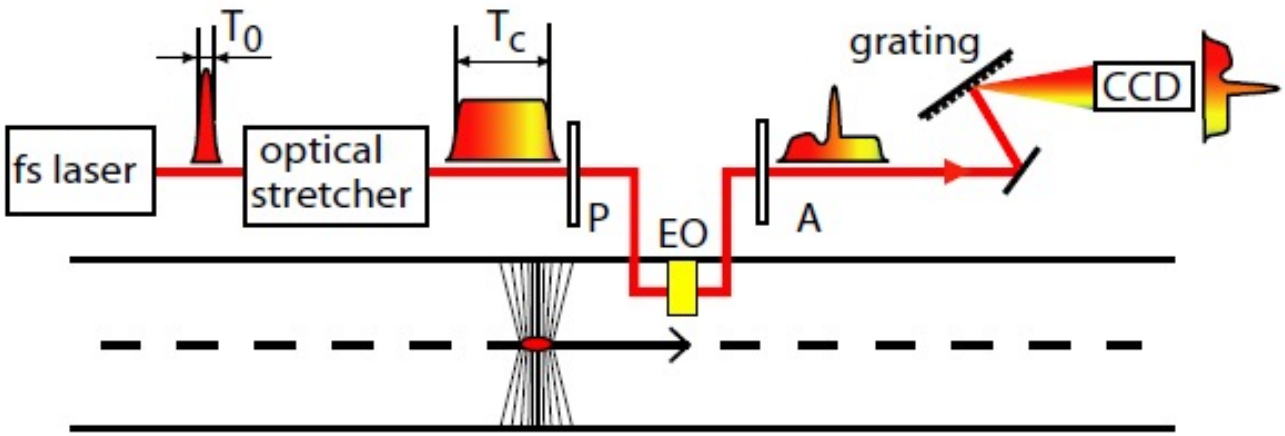
- **Electro-optical sampling (EOS)**
  - ***Encode the bunch EM field onto the laser light, using a non-linear bi-refringent crystal (e.g., ZnTe, GaP)***
  - ***The beam EM field changes the polarization of the laser beam***
  - ***Different EOS methods exist, all of them offer a high time resolution <1 ps***



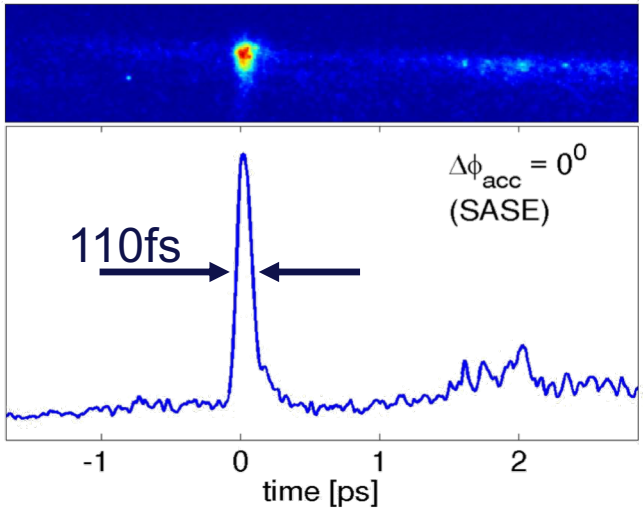
$$E_r \approx \frac{q}{\sqrt{2\pi}\left(\varepsilon_0 \sigma_z r\right)}$$

Bunch Length: EOS Spectral Encoding

- **Single-shot bunch profile measurement**
  - ***by detection the wavelength spectrum in a spectrometer (position vs. wavelength) of a chirped laser pulse (time vs. wavelength)***



Measurement result FLASH (DESY)

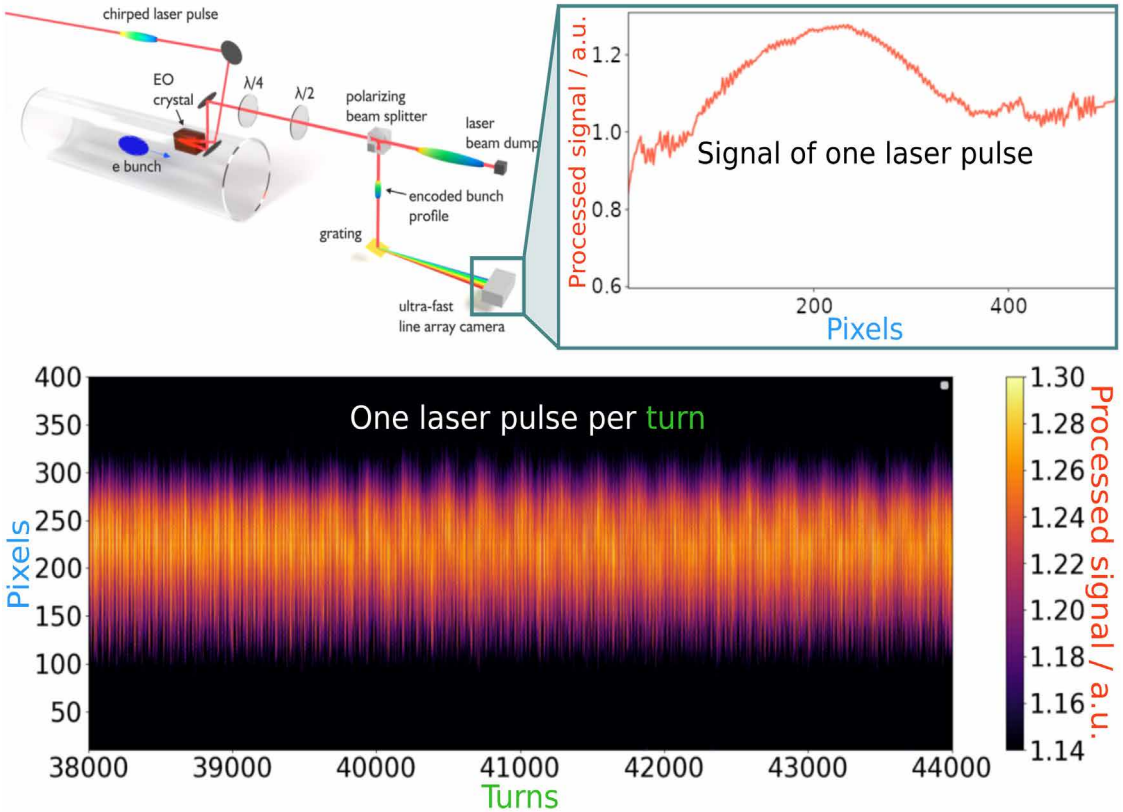


Berden, et.al., Phys Rev Lett. ***99*** *(2007)*

Bunch Length R&D: EOS@KIT (1)

EOS Near-Field at KARA

Turn-by-turn single bunch profile measurements



Challenges for FCC-ee

	KARA low-alpha mode	FCC-ee Z mode*
Beam energy / GeV	1.3	45.5
Bunch charge / nC	2.2	38.9
Bunch length / mm	3	15.4

** K. Oide 2022,151st FCC-ee Optics Design Meeting*

- Bunch-by-bunch measurement necessary
- Higher bunch charge
- Longer bunches

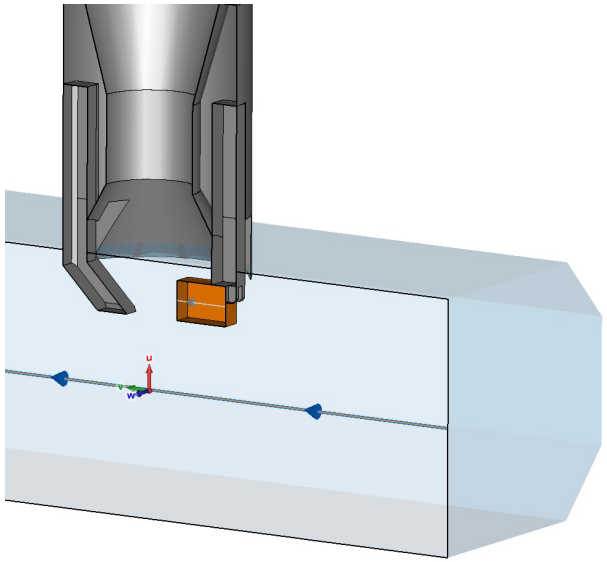
➡ **Monitor design needs to be adapted**

Gudrun, Micha & Co.

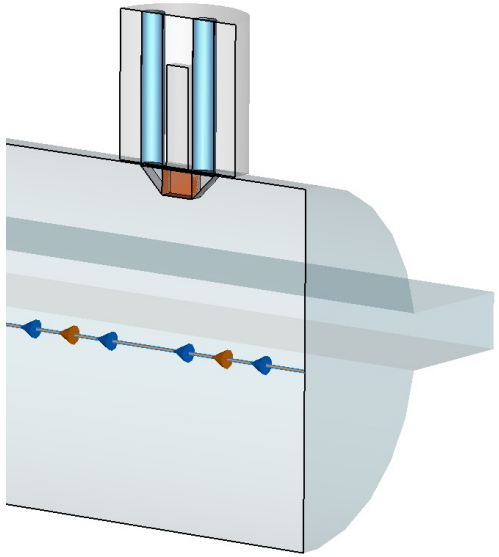
Bunch Length R&D: EOS@KIT (2)

EO Bunch Profile Monitor for FCC-ee

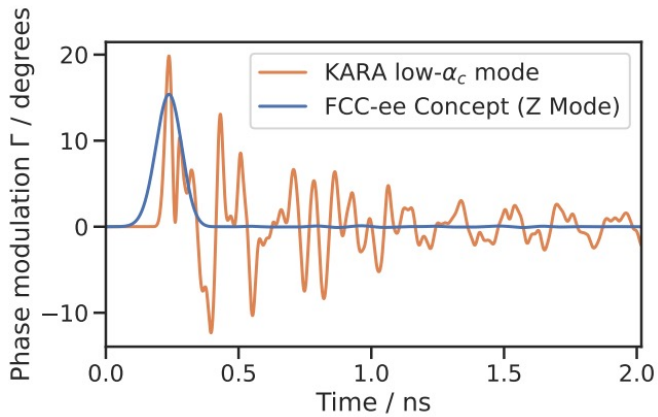
EO Near-Field at KARA



Concept for FCC-ee



Comparison in Simulations



The concept design for FCC-ee achieves a similar signal strength as the monitor at KARA

M. Reissig, et.al., IPAC'22 MOPOPT025
M. Reissig, et.al., IBIC'22 WEP26 (unpublished)

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Other Challenges

- **Communication**
  - ***Many R&D contributions inside and outside CERN***
  - ***Sometimes difficult to follow up, therefore:***
    FCC-ee Beam Instrumentation Mini-Workshop
    Time: 21. – 22. November 2022, Location: CERN – Meyrin
    Contact: Stefano Mazzoni (stefano.mazzoni@cern.ch)
    - Indico link TBD
- **Manpower**
  - ***CERN BI resources are shared between many activities***
    - Maintenance / overhaul of operating CERN beam instruments
    - Various R&D activities and studies, like AWAKE, CLEAR, CLIC, FCC, MC, PBC
- **Budget**
  - ***The FCC-ee BI budget 2023-25 limits our R&D opportunities at CERN***
    - PhD on BPM pickup, ChDR & HNFS beam size, ChDR & EOS bunch length

Thank you for your attention.