Beam instrumentation for FCCee

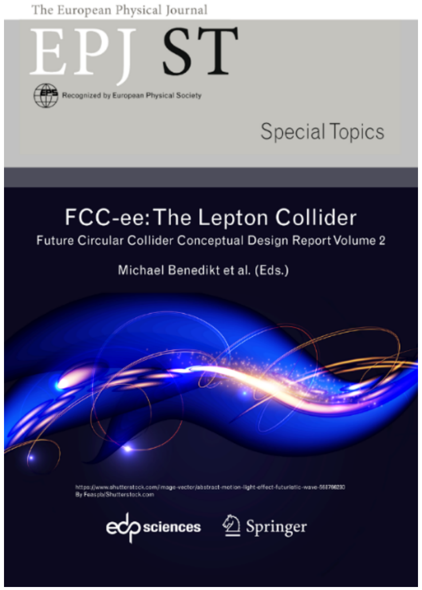
T. Lefevre
CERN

Contents

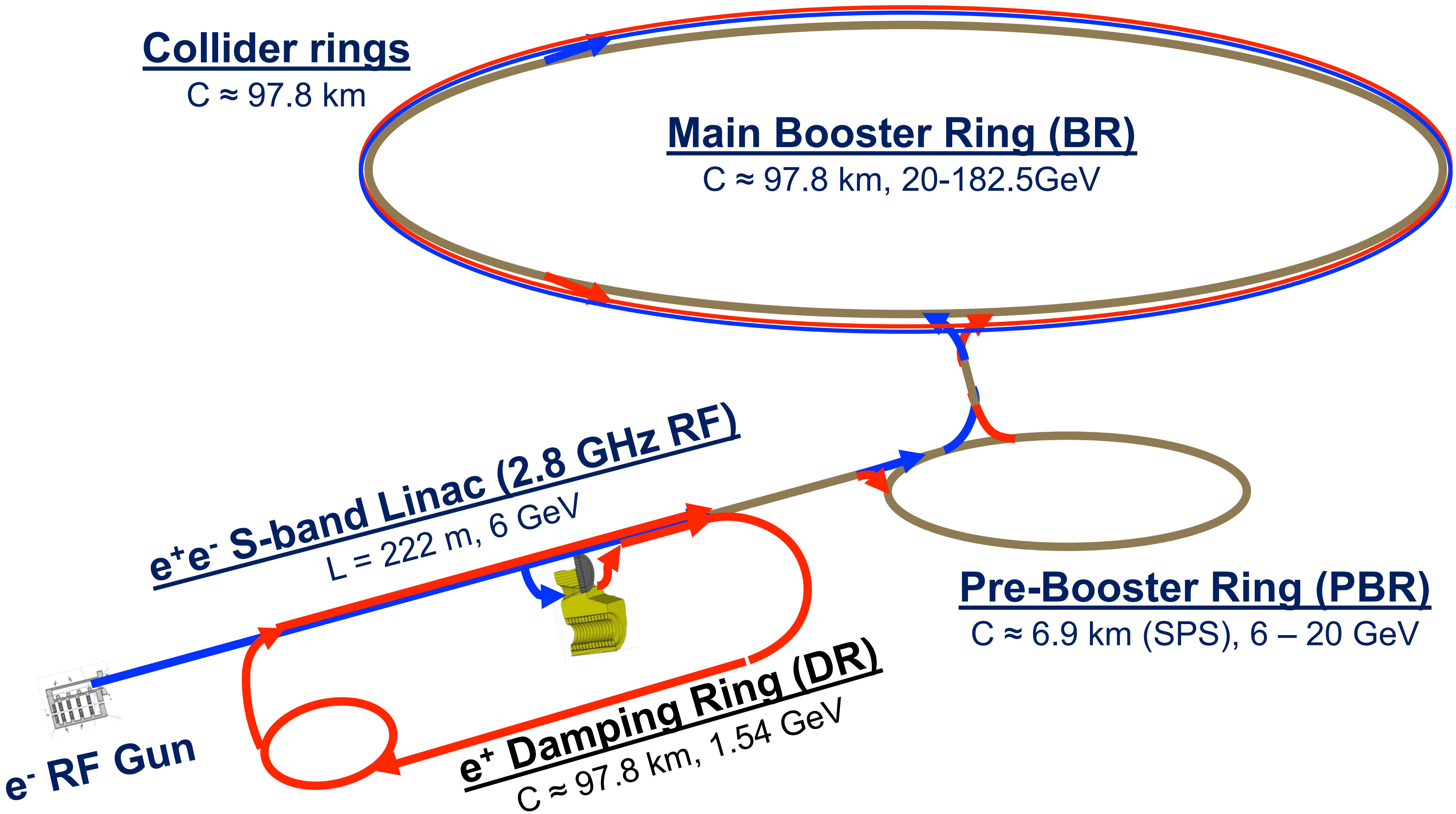
- Introduction

- Overview of Beam instrumentation
  - Main requirements
  - Critical issues
  - Engineering challenges
  - Detector choices

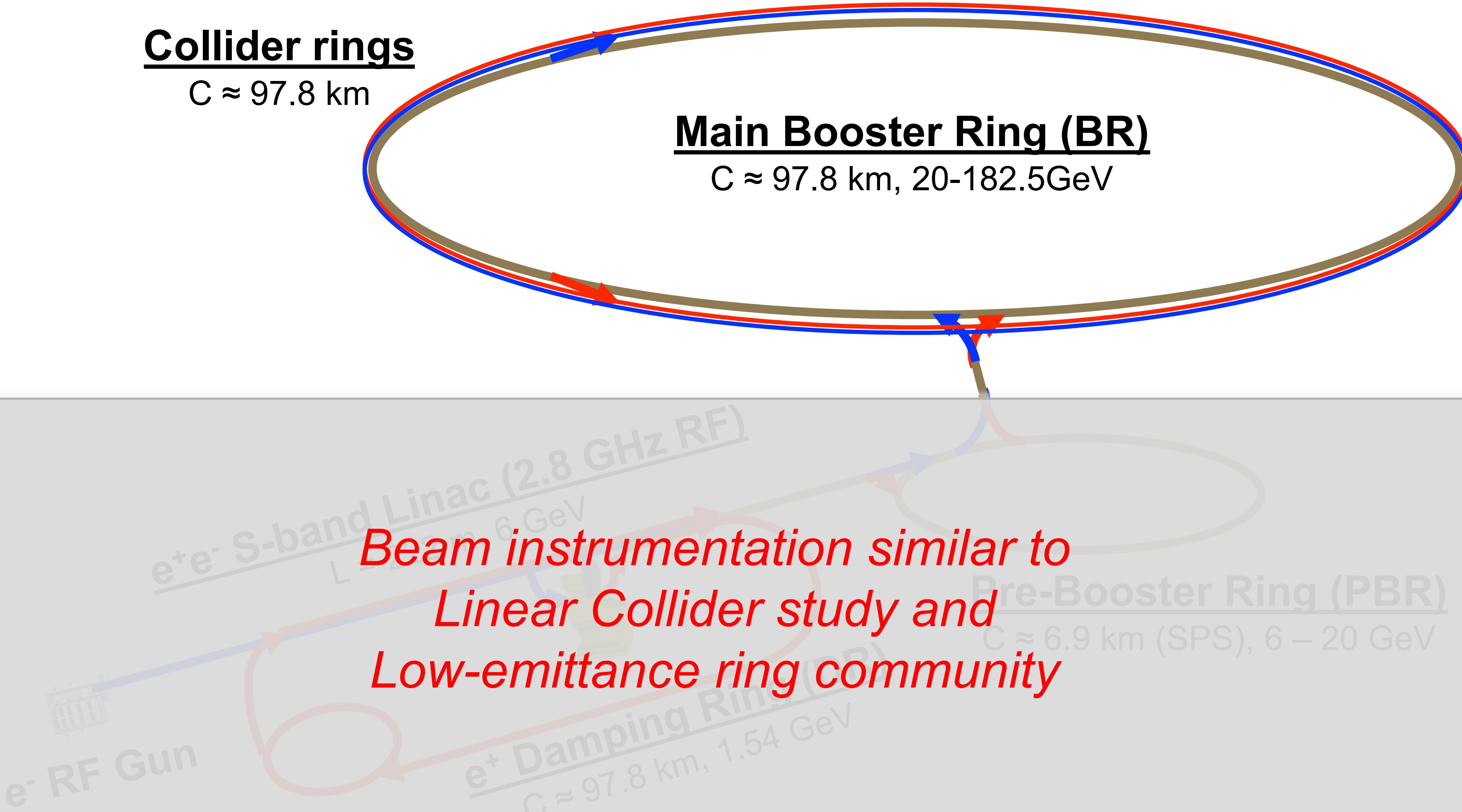
- Future steps and Conclusions



FCCee Layout



FCCee Layout



Beam instrumentation similar to Linear Collider study and Low-emittance ring community

FCCee Beam instrumentation

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5

- **High beam intensity and large dynamic range**

FCCee Beam instrumentation

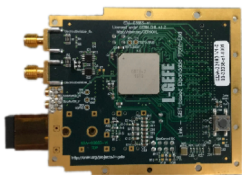
parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5

- High beam intensity and large dynamic range
- **Small Emittances**

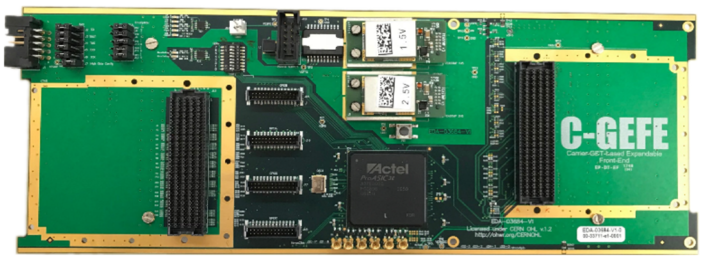
- FCC-ee specifics
  - **High luminosity regions**
    - High radiation level close IP's
  - **High beam intensity**
    - Wakefield effects inducing heat load
  - **High SR power in the arcs** would produce high X-ray dose requiring
    - Shielding (design dependent on beam energy, i.e. SR critical energy)
    - Radiation hard electronic design

Radiation hard design

- **Example of state-of-the-art rad-hard electronic design from SPS@CERN for BPM and BLM**



+

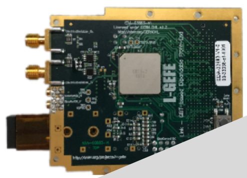


- **Front-end electronic located in the tunnel – Optical fibre connection to surface buildings**
  - Communication ASIC (GBTx) and optical transceiver (VTRx) developed at CERN (EP) that can withstand TID levels higher than >10kGy
  - Mother board with FPGA and ADCs rad-tolerant up to TID levels of 750 Gy
    - Using COTS components (e.g. Proasic3 FPGA)

Courtesy of M. Barros Marin

Radiation hard design

- **Example of state-of-the-art rad-hard electronic design from SPS@CERN for BPM and BLM**



To be further investigated

Impact on cost !

- **Front-end electro… …l fibre connection to surface buildings**
  - Communication AS… …transceiver (VTRx) developed at CERN (EP) that can withsta… …higher than >10kGy
  - Mother board with FP… …ADCs rad-tolerant up to TID levels of 750 Gy
    - Using COTS components (e.g. Proasic3 FPGA)

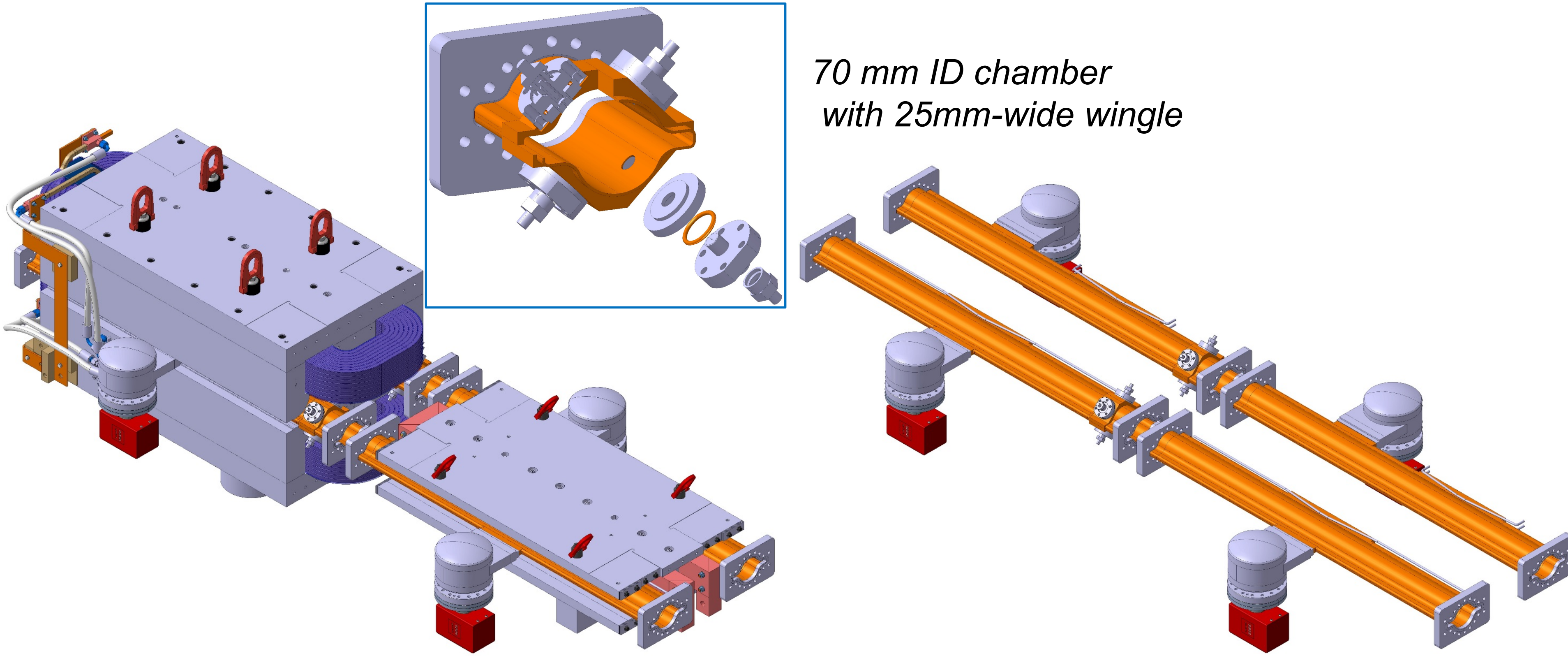
Courtesy of M. Barros Marin

Beam Position Monitoring

Beam Position Monitoring

- **6000 BPMs** required for main (4000) and booster (2000) rings

70 mm ID chamber with 25mm-wide wingle



From Roberto's presentation yesterday

Beam Position Monitoring

- 6000 BPMs required for main (4000) and booster (2000) rings
- **Up to 400W** dissipated in **one BPM – Would need active cooling**

E. Belli PhD thesis

Component	Number	$k_{loss}[V/pC]$	$P_{loss}[MW]$
Resistive wall	97.75km	210	7.95
Collimators	20	18.7	0.7
RF cavities	56	18.5	0.7
RF double tapers	14	26.6	1.0
BPMs	4000	40.1	1.5
Bellows	8000	49.0	1.8
Total		**362.9**	**13.7**

At Z pole

From Mauro's presentation yesterday

Beam Position Monitoring

- 6000 BPMs required for main (4000) and booster (2000) rings
- Up to 400W dissipated in one BPM – Would need active cooling
- **Sub-micron resolution** required for orbit measurements
- Expected misalignment / roll angles / calibration errors
  - Put some **constraints on alignment requirements** (Impact on cost !)

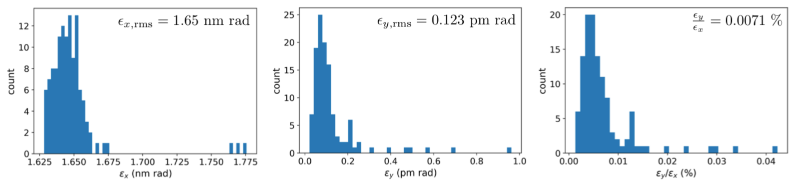
Corrected Lattices results (182.5 GeV)

Using the misalignments and roll angles of:

	$\sigma_x(\mu m)$	$\sigma_y(\mu m)$	$\sigma_\theta(\mu rad)$
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

From Tessa

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.

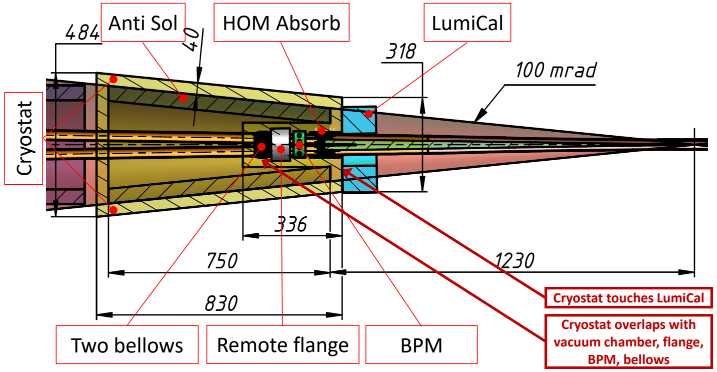
ifm 11/41

From Eliana

Beam Position Monitoring

- 6000 BPMs required for main (4000) and booster (2000) rings
- Up to 400W dissipated in one BPM – Would need active cooling
- **Sub-micron resolution** required for orbit measurements
- Expected misalignment / roll angles / calibration errors
  - Put some **constraints on alignment requirements** (Impact on cost !)
- Question on Cryo BPM in final focus quadrupole

Attempt to look in detail



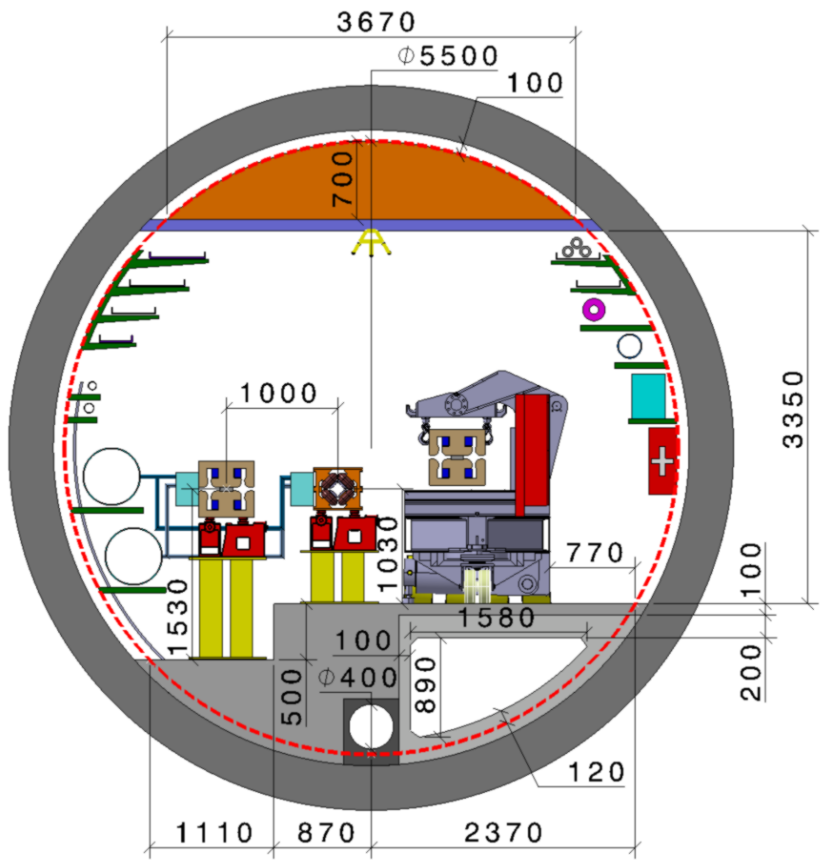
- Good to have BPMs separate beam pipe !
  - No cross-talk between the two beams
- Integration of BPM in cryostat is critical
  - Routing of cryocable towards the coaxial feedthrough
  - Routing of cooling tubes

From Evgeny this morning !

Beam Loss Monitoring

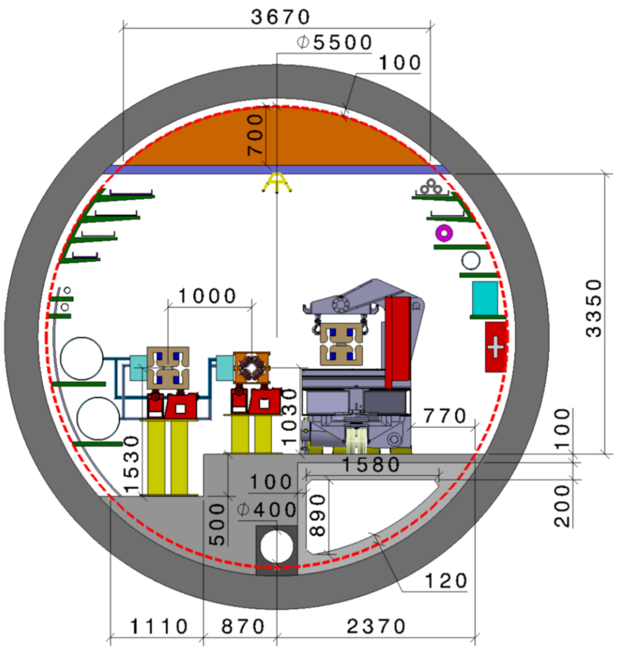
Beam Loss Monitoring

Large energy stored in both Main and Booster beams would require a proper design of the machine protection and beam loss monitoring system



Beam Loss Monitoring

Large energy stored in both Main and Booster beams would require a proper design of the machine protection system and beam loss monitoring system

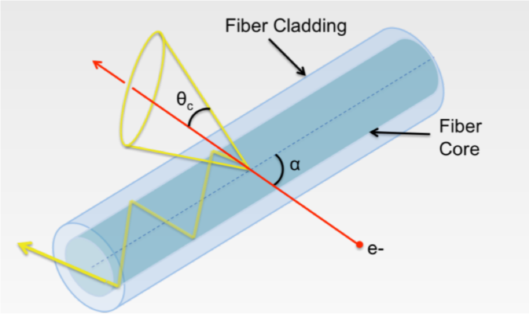


Design considerations

- BLM in the arcs should **not be sensitive to X-ray**
- **Identifying beam losses** from all **different beam lines** may not be trivial
  - Main rings : Detectors sensitive to beam propagation
  - Main vs booster ring : Possibly having quadrupoles at different locations ?

Beam Loss Monitoring

- **Optical BLM system based Cherenkov fibres**
  - High directivity
  - Only measures charged particles



- **Many experimental investigations** initiated within 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*

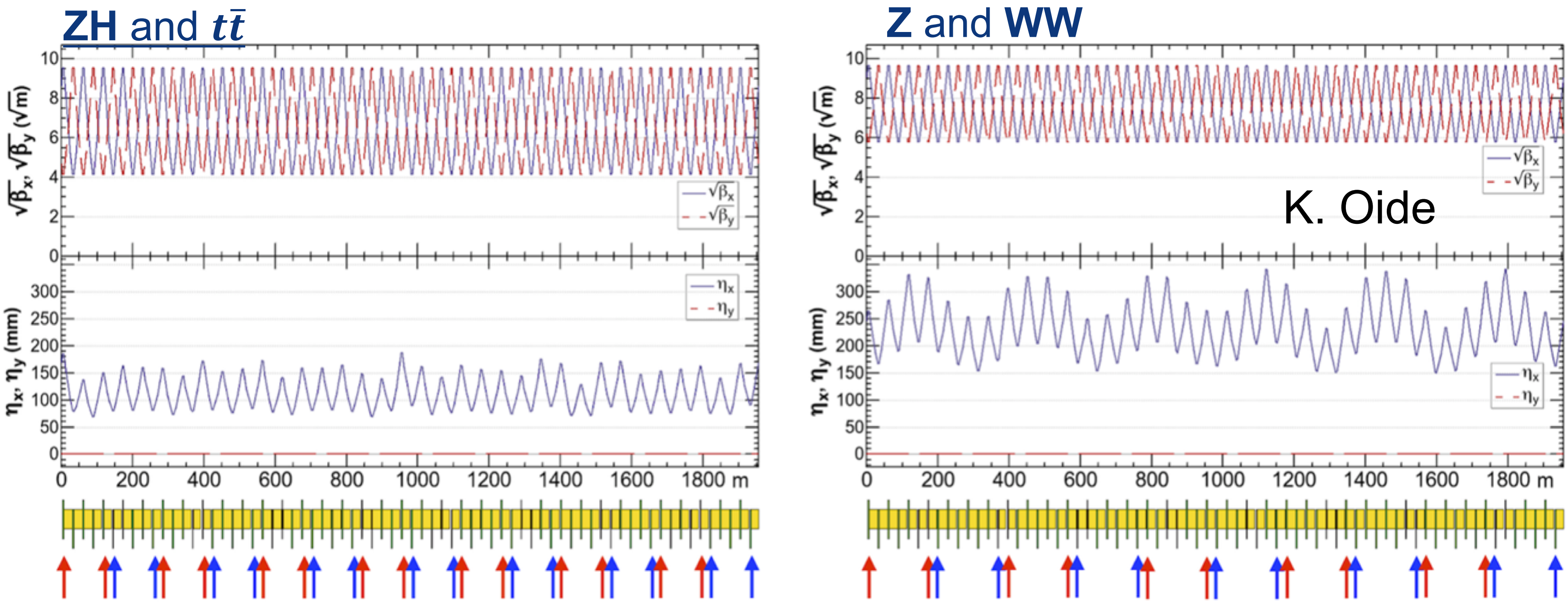
Beam Size Measurement

Small beam emittance

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9

Beam Size Measurement

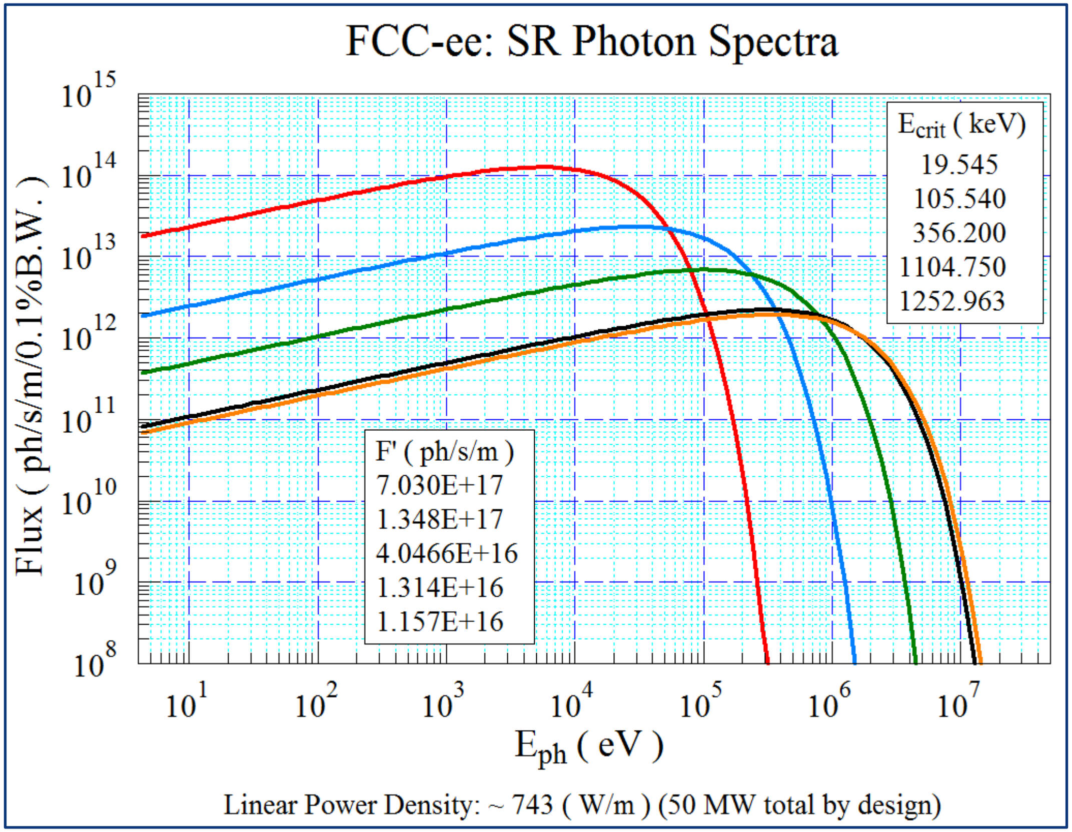
Small beam size



< 10/100um beam sizes in ver/hor planes

Beam Size Measurement

- SR at high energy would suffer from **Diffraction effects** even in the X-ray domain and would require the use of **X-ray interferometric techniques**



From Roberto's presentation yesterday

Diffraction limit !

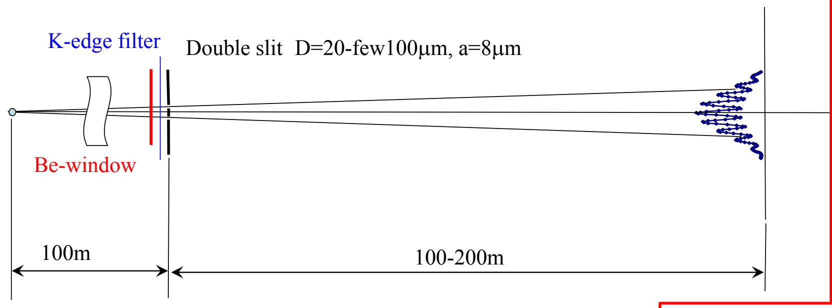
$$\sigma_{diff} = \frac{1.22\lambda}{4\sigma'_y} \approx 0.43\gamma\lambda$$

SR X-ray interferometry

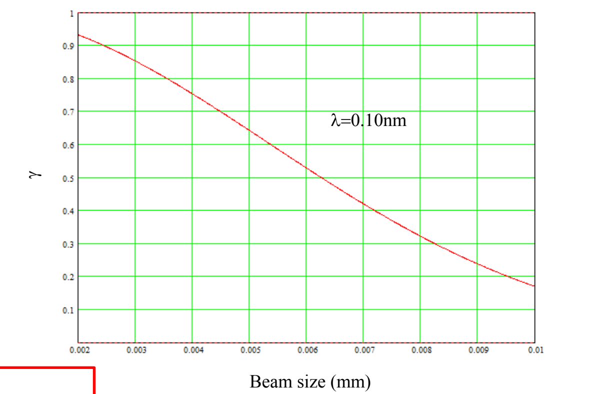
From Toshi's presentation yesterday

- Beam size as the Fourier transform of spatial coherence measured by interferometer

Simple double slit X-ray interferometer (Young type)

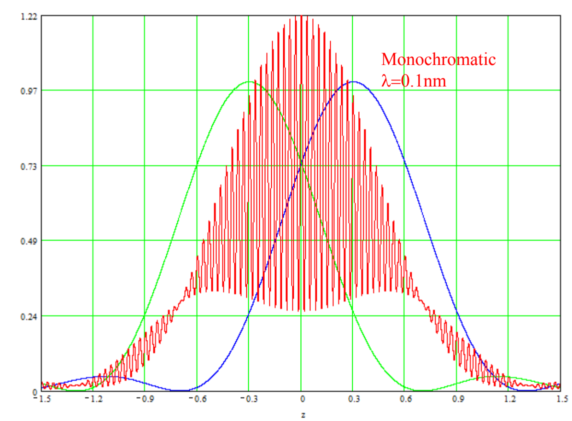


Spatial coherence vs. beam size D=300um, f=100m



Expected interferogram for γ=0.65 (beam size of 5µm at 100m)

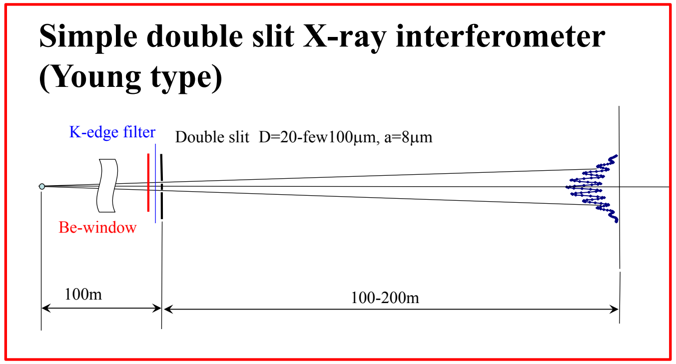
Double slit a=5um, D=300um f=100m

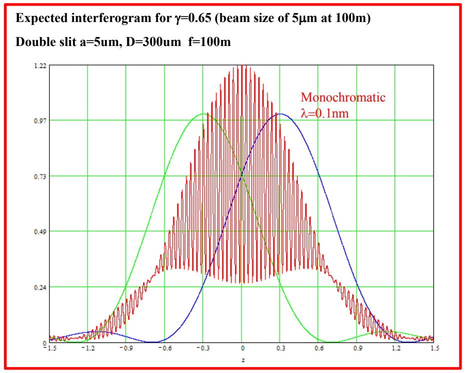


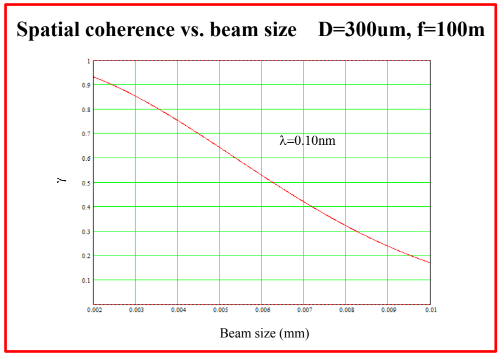
X-ray interferometry

From Toshi's presentation yesterday

- Beam size as the Fourier transform of spatial coherence measured by interferometer



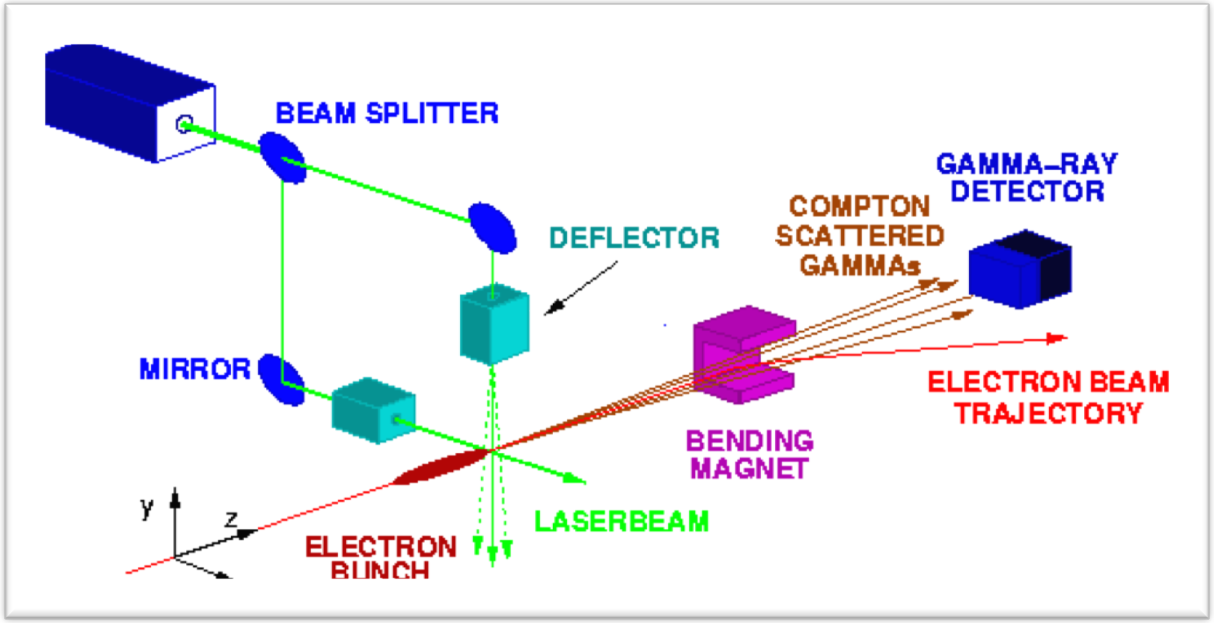




- Long extraction line requiring critical alignment
- Only measure in one plane at the time
- Do not provide a transverse profile !

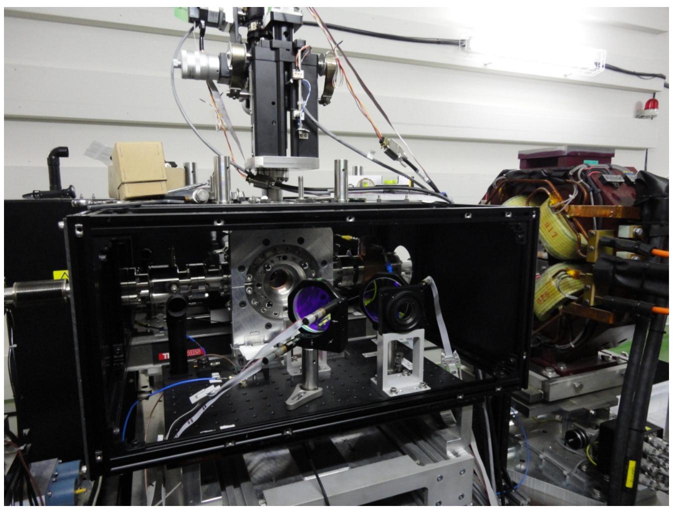
Beam Size Measurement

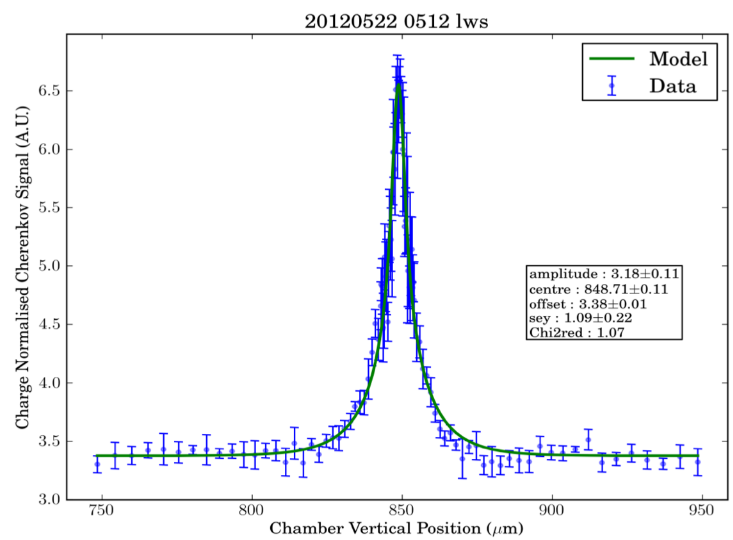
- Laser Wire Scanner technology developed for linear colliders
  - Based on Compton scattering using high power lasers



Beam Size Measurement

- Laser Wire Scanner technology developed for linear colliders
  - Based on Compton scattering using high power lasers
  - Demonstrated measurements of 1 micron beam size using modern laser technology (high power fibre laser)





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

Beam Size Measurement

- Laser Wire Scanner technology developed for linear colliders
  - Based on Compton scattering using high power lasers
  - Demonstrated measurements of 1 micron beam size using modern laser technology (high power fibre laser)
  - Similar hardware used for Compton polarimeter
  - Relatively expensive

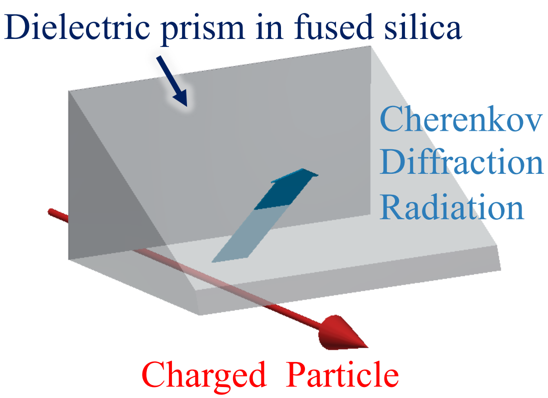
Beam Size Measurement

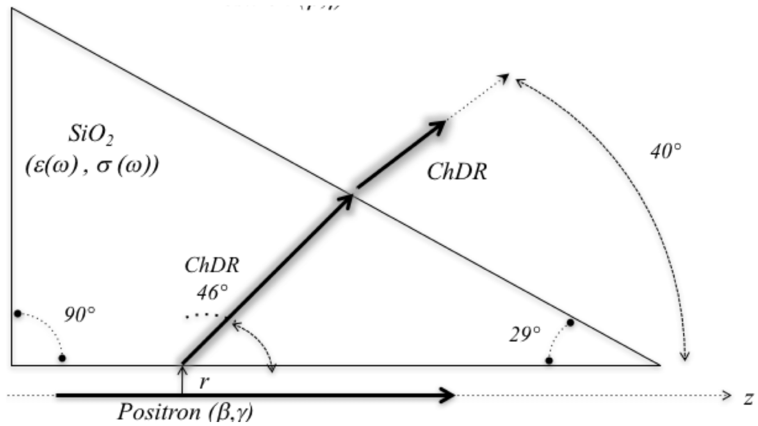
- Imaging Cherenkov diffraction radiation as a simple alternative

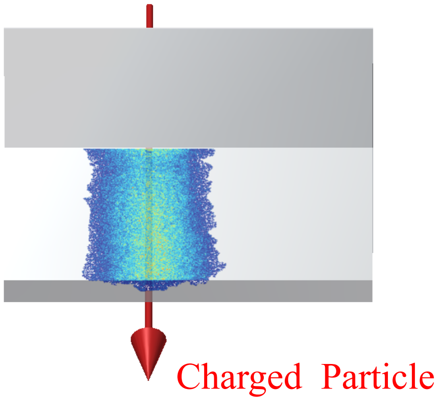
Beam Size Measurement

- Imaging Cherenkov diffraction radiation as a simple alternative

First test on Cornell electron-positron storage ring in 2017-18





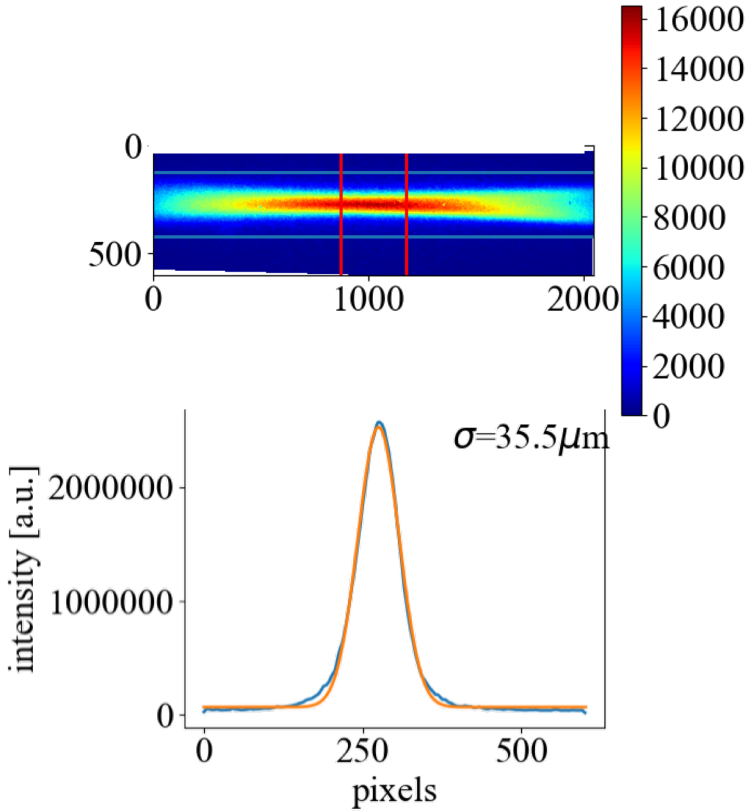


*R. Kieffer et al., "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL **121** (2018) 054802*

Beam Size Measurement

- Imaging Cherenkov diffraction radiation as a simple alternative

Example of direct beam imaging
Using Cherenkov Diffraction radiation
at measured at ATF2/KEK in 2019



Beam Size Measurement

- Imaging Cherenkov diffraction radiation as a simple alternative

- Recent technique
  - Provide transverse profile
  - Very compact (cm) and cheap
  - Can be located anywhere in the ring
  - Resolution better than 30microns – need some more investigations

Bunch Length Monitoring

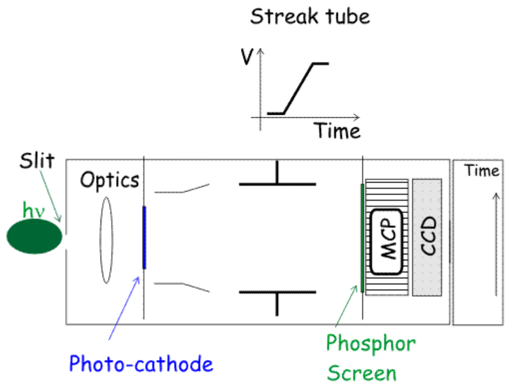
Bunch Length Monitoring

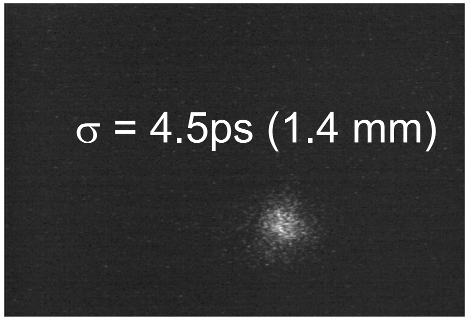
parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5

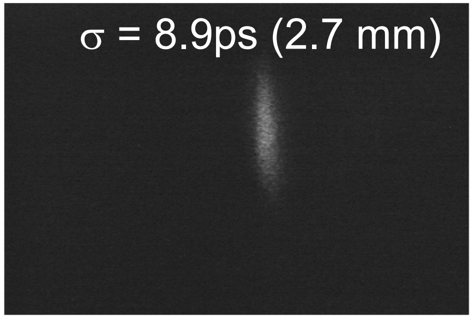
- Relatively **long bunches** !
- Need a **bunch/bunch monitoring system** with picosecond resolution to monitor the impact of Beamstrahlung
- Need **resolution of 100fs** to estimate the energy spread as required for **energy calibration** using spin depolarization technique

Bunch Length Monitoring

Bunch length from streak camera







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

- Do not provide online bunch/bunch measurements

Bunch Length Monitoring

Measured the spectrum of coherent radiation S(ω)

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

N – number of particles / bunch

Bunch Length Monitoring

Measured the spectrum of coherent radiation S(ω)

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

N – number of particles / bunch

$S_p(\omega)$ – single particle spectrum dependent on the source of radiation e.g. Synchrotron, Cherenkov, Diffraction radiation

Bunch Length Monitoring

Measured the spectrum of coherent radiation S(ω)

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

N – number of particles / bunch

$S_p(\omega)$ – single particle spectrum dependent on the source of radiation e.g. Synchrotron, Cherenkov, Diffraction radiation

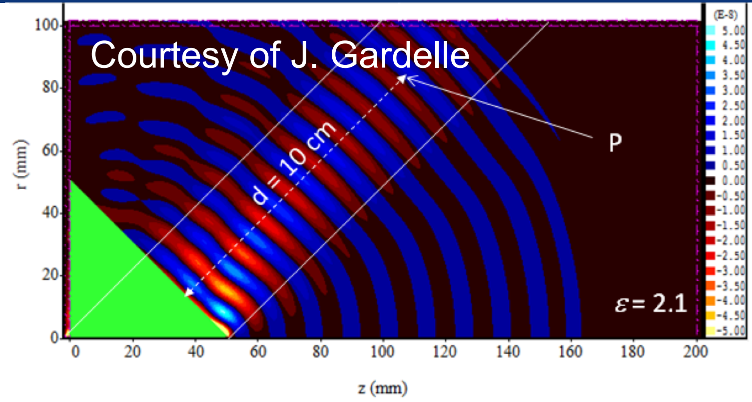
***F(ω)* – bunch form factor**

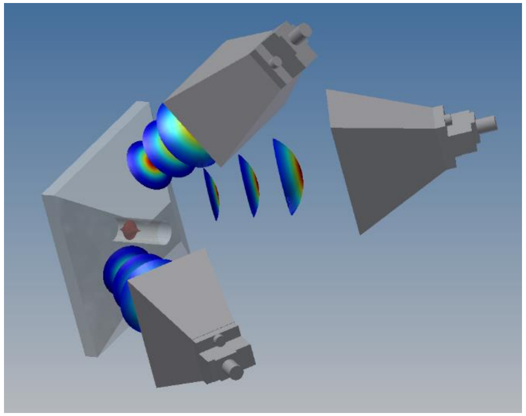
$$\rho(z) = \frac{1}{\pi c}\int_0^\infty d\omega \sqrt{F(\omega)} \cos\left(\frac{\omega z}{c}\right)$$

Bunch Length Monitoring

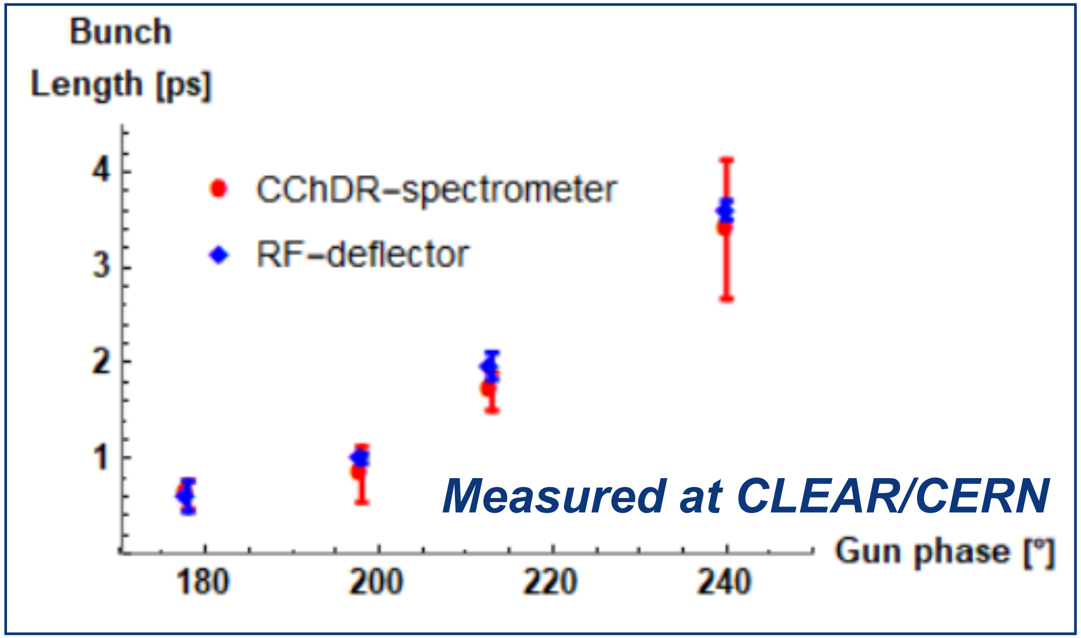
Coherent Cherenkov diffraction radiation
Measured in 3 bands (60-90-110GHz)

Nanosecond time response demonstrated





Courtesy of A. Curcio



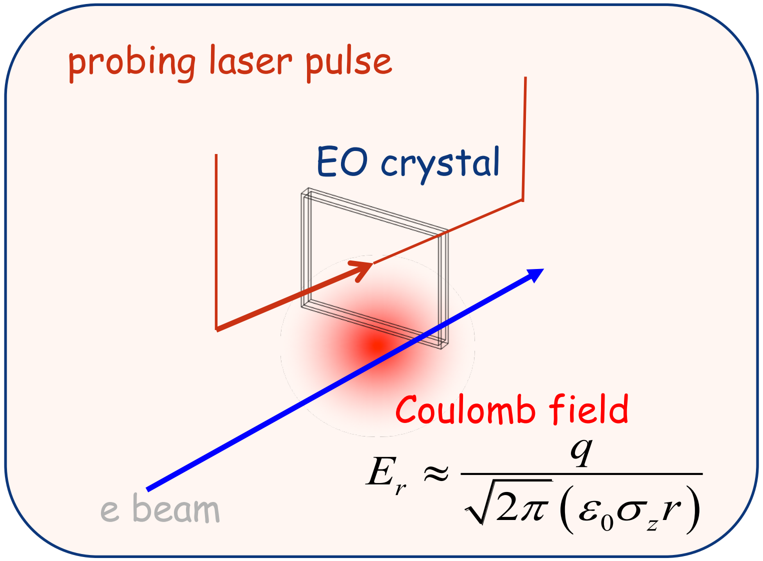
Bunch Length Monitoring

Bunch length from Electro-optical techniques for higher resolution

Bunch Length Monitoring

Bunch length from Electro-optical techniques for higher resolution

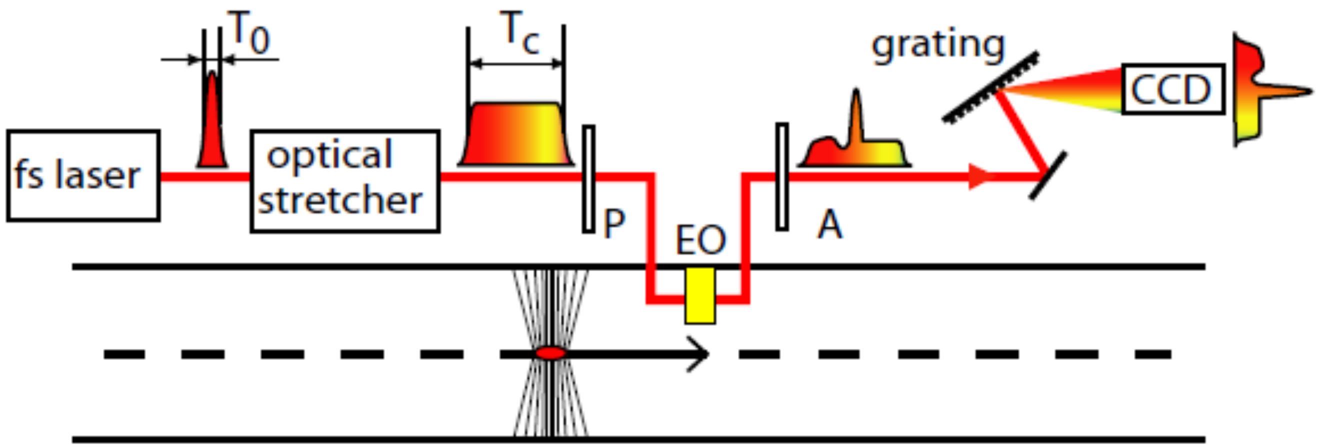
- Encoding the bunch field onto a laser beam using non-linear bi-refringent EO crystals (e.g. ZnTe, GaP) having THz bandwidth



Bunch Length Monitoring

Bunch length from Electro-optical techniques for higher resolution

- Encoding the bunch field onto a laser beam using non-linear bi-refringent EO crystals (e.g. ZnTe, GaP) having THz bandwidth

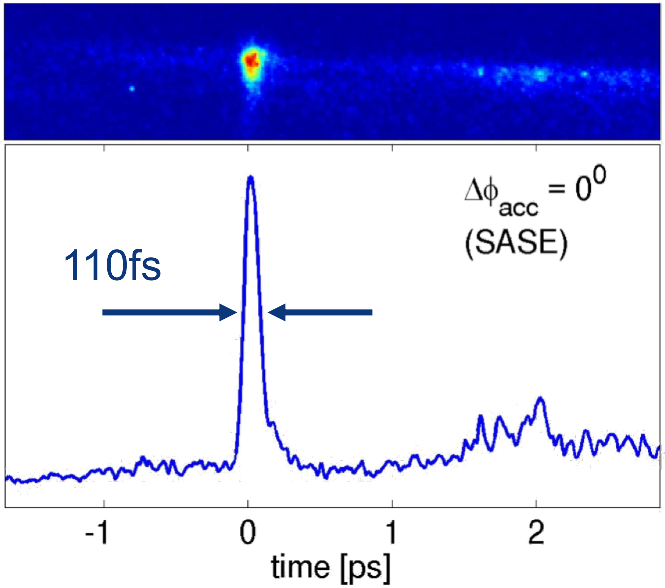


- Single bunch measurements by detection the wavelength spectrum in spectrometer (position vs wavelength) of a chirped laser pulse (time vs wavelength)

Bunch Length Monitoring

Bunch length from Electro-optical techniques for higher resolution

- Encoding the bunch field onto a laser beam using non-linear bi-refringent EO crystals (e.g. ZnTe, GaP) having THz bandwidth
- Single bunch measurements by detection the wavelength spectrum in spectrometer (position vs wavelength) of a chirped laser pulse (time vs wavelength)
- Resolution demonstrated in FEL@FLASH/DESY



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

Conclusion and next steps

- A first conceptual design of the FCCee BI has been performed for the CDR
- No feasibility issues !
- Long list of technological challenges ahead of us
- Benefitting from the R&D done in Low-emittance ring / Linear colliders / FEL communities.
- Next step is to launch the FCCee specific R&D work to provide a realistic suite of beam diagnostic with a more precise cost estimation

Many thanks to all people involved

&

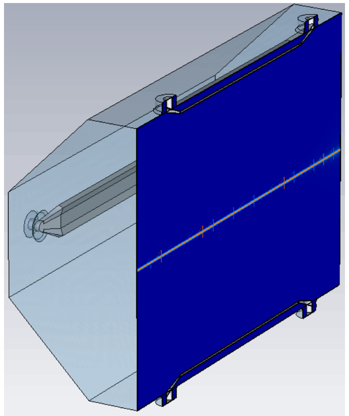
Many thanks for your attention !

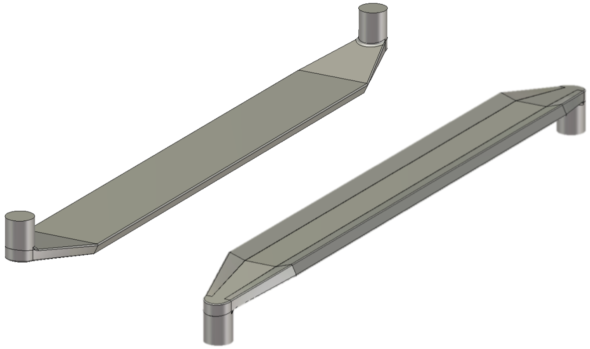
FCCee Beam instrumentation

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

Beam position monitoring

- RF design optimised with 3D EM simulations
  - Achieved very good directivity
- Electrode **prototyping started** with EN/MME
- Purchasing of 400 RF coaxial feedthroughs to be started soon
  - Technical specification ready
- Impedance being validated by WP2





An overview of the Beam instrumentation requirements discussed in the CDR