Transverse beam size monitoring at FCC

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with many thanks to U. Iriso, A. Nosych, L. Torino (ALBA), F. Ewald (ESRF), M. Siano (UniMi)

Outline

Requirements for FCC-ee transverse diagnostics

Synchrotron Radiation based techniques

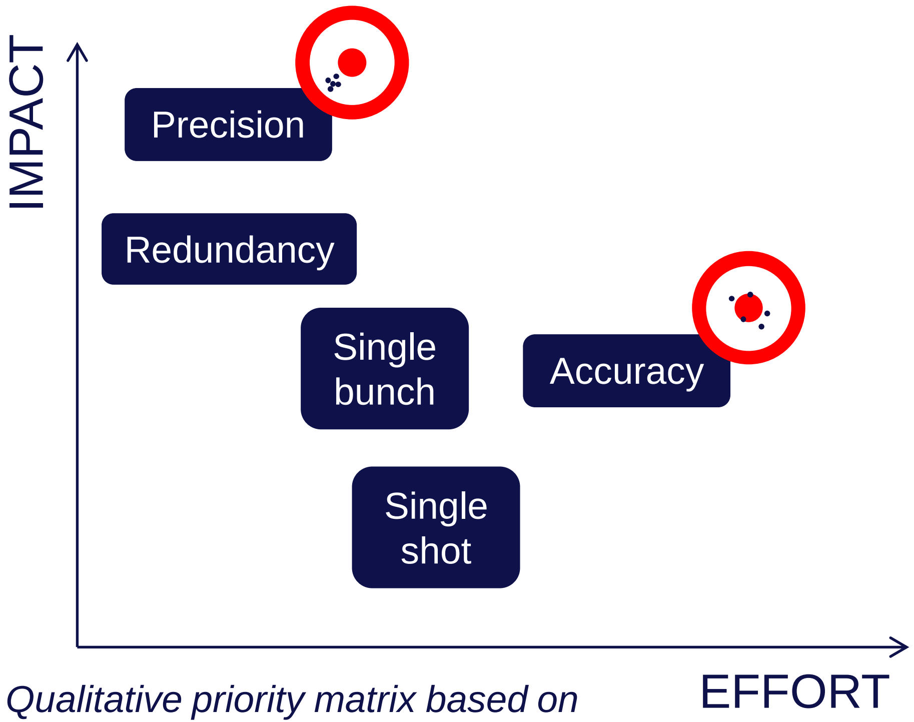
- pinhole camera
- X-ray imaging
- X-ray interferometry

Implementation scenarios

- source options
- extraction lines

Conclusion

Requirements for transverse diagnostics



Qualitative priority matrix based on present understanding of needs

Real-time precise measurement is top priority for commissioning

On-demand accurate measurements required for machine optimization

Multiple systems likely required to meet all specifications

BI specs input spreadsheet

Pinhole camera

$$\sigma^2_{beam} = f\left(\sigma^2_{light}\right) - \sigma^2_{resolution}$$

Standard for X-ray diagnostics

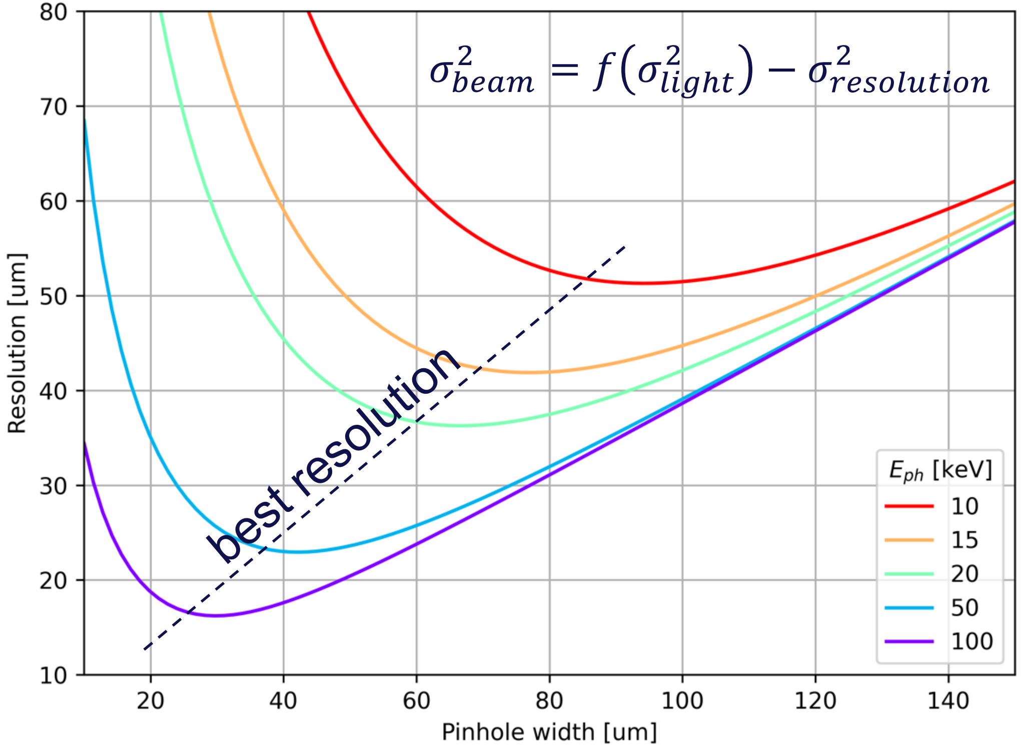
- **robust** and minimal system
- good **precision** <2%
- good **accuracy for** $\boldsymbol{\sigma > 50\ \mu m}$
- possible **bunch-by-bunch**
- typically $\boldsymbol{E_{ph} < 100\ keV}$

Parameters for FCC

- $d \sim 100\ \mathrm{m}$ for beam-light separation
- $D/d \sim 3-4$ for magnification
- w_{PH} to maximize resolution, but $> 10\ \mu\mathrm{m}$ for manufacturing

Resolution of pinhole camera

Ultimate resolution of SR diagnostics is diffraction limit $\sigma_{resolution} \xrightarrow[lim]{diff} \frac{\lambda}{4\pi\vartheta_{SR}} \overset{*}{\approx} 0.2\ \mu m$



Pinhole camera resolution determined by pinhole width

→ accurate for $\sigma_{beam} \geq 50\ \mu m$

Measurements of smaller beam sizes limited by resolution

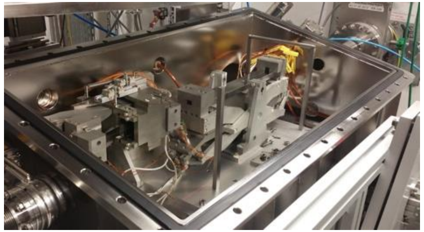
*realistic 50 keV photons and $\vartheta_{SR} \approx 0.1\rho^{1/3}\lambda^{2/3} \approx 10\ \mu rad$

X-ray imaging

$$\sigma_{resolution} \xrightarrow[lim]{diff} \frac{\lambda}{4\pi\vartheta_{SR}} \approx 0.2\ \mu m$$

Upgrade pinhole camera adding X-ray optics

Stack of
Compound Refractive Lenses



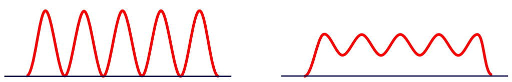
Pair of Kirkpatrick-Baez
focusing mirrors

…allow better resolution but **come with drawbacks**

- suffer from chromatic aberrations
- non-negligible attenuation
- increased setup complexity

X-ray interferometry

Interferometry is complementary technique to imaging
→ **assess beam size from contrast** of interference fringes



Variety of targets

- apertures/slits
- scattering fibers
- nanostructured materials

better resolution than pinhole...

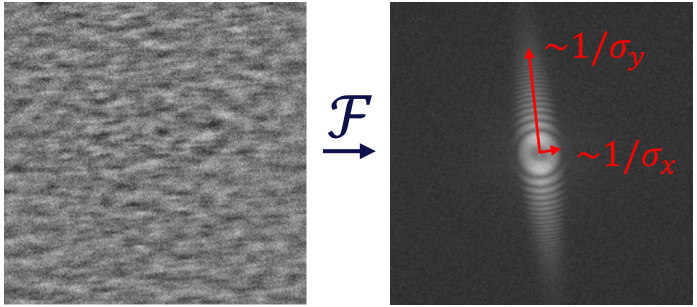
…but with common **challenges**

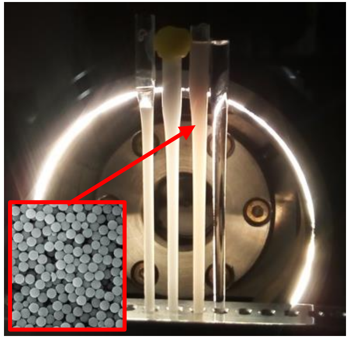
- require monochromatic light
- highly sensitive to distortions
- increased setup complexity

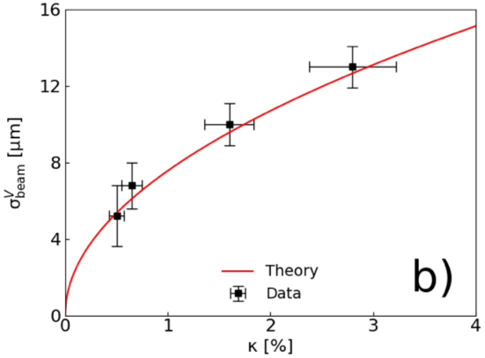
Imaging and interferometry can **coexist** on same extraction line, often with same detector

X-ray Heterodyne Near Field Speckles

Interferometric technique using nanosphere ensemble as interference target







Measurements at ALBA synchrotron (Spain)

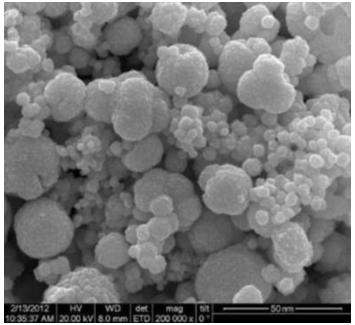
- systematic validation at undulator beamline
- measured beam size as small as 4.5 μm

X-ray Heterodyne Near Field Speckles

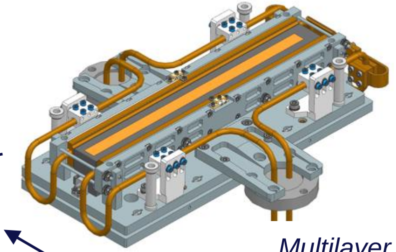
Challenges to deploy technique at FCC-ee

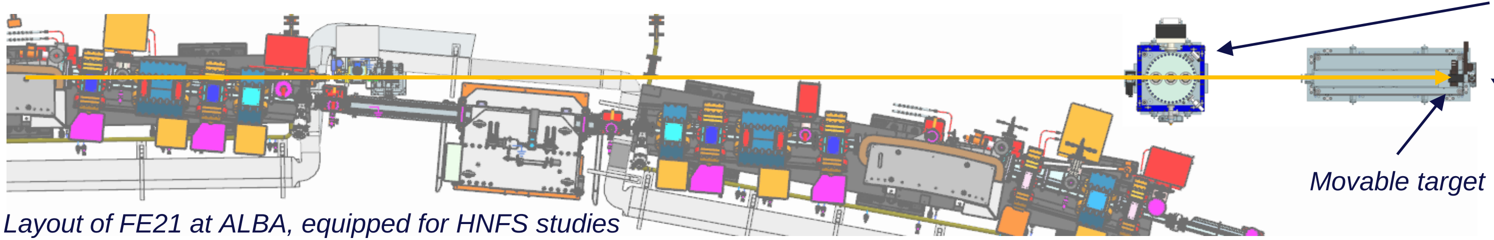
- high energy photons
- broadband (dipole) SR source

→ dedicated R&D studies to develop, characterize and test **target and setup** compatible with FCC environment



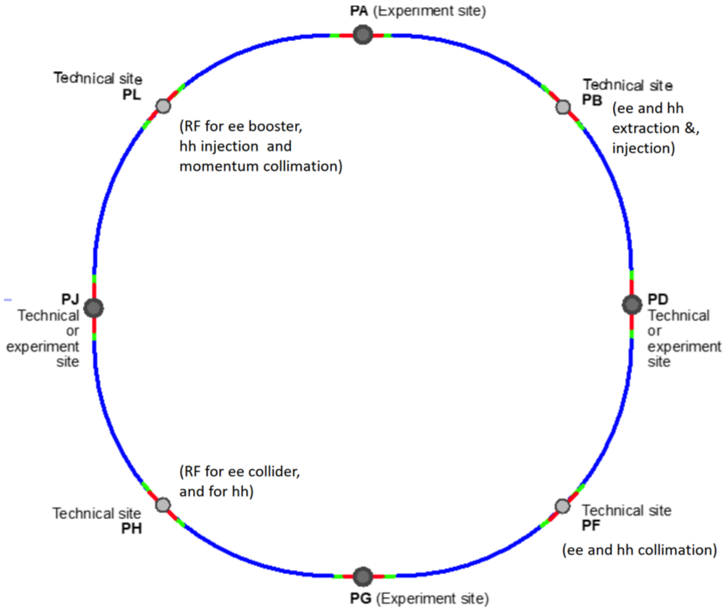
Nanostructured gold target





Layout of FE21 at ALBA, equipped for HNFS studies

Implementation scenarios



Diagnostic challenges

- small vertical beam sizes
- high photon energy

Integration challenges

- high radiation and power load
- large bending radius (long extraction lines)

Options for SR source

- **arc dipole**: maximum flexibility but harsh environmental conditions
- **exp/tech site dipoles**: limited choice but more favorable beam sizes

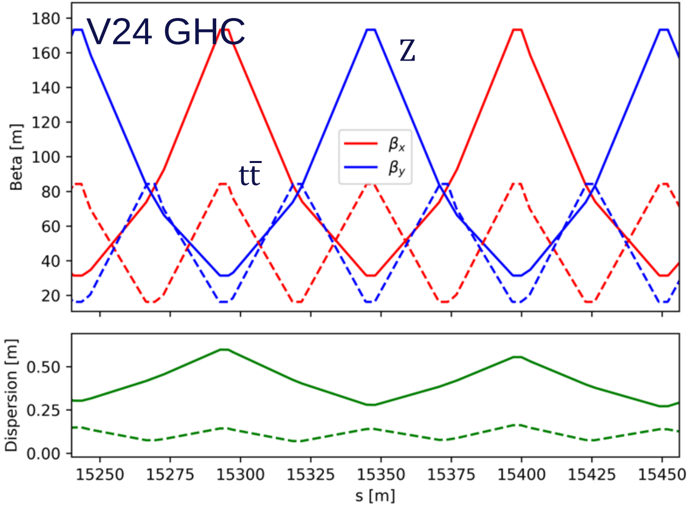
Arc dipoles

Parameter	Z	WW	ZH	ttbar	Unit
Energy	45.6	80	120	182.5	GeV
Current	1283	135	26.8	5.0	mA
Emittance H / V	700 / 1.9	2160 / 2.0	660 / 1.0	1510 / 1.36	pm
ρ / l arc dipole		10000 / ~20			m
λ_c / E_c arc dipole	59.0 / **21.0**	10.9 / **113.6**	3.2 / **383**	0.9 / **1350**	pm / keV

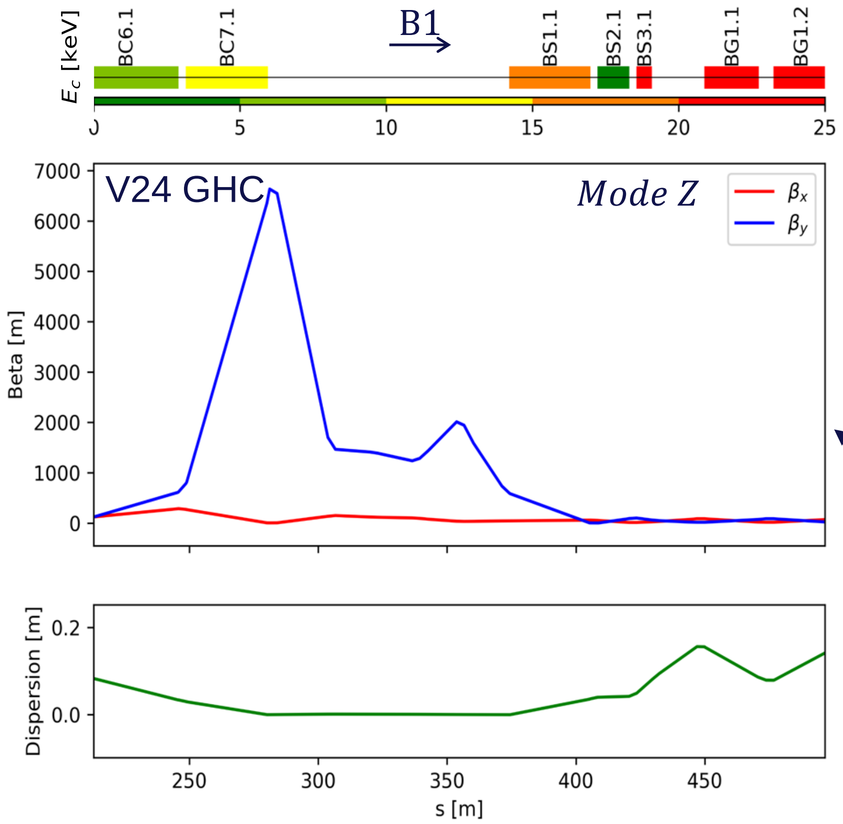
- **radiation power load** ~8kW/mrad
- **photon energy** beyond diagnostics capabilities and destructive for instrumentation in ttbar
- **challenging beam sizes** due to low beta in arcs

Z: $\beta_y \sim \beta_x \sim 100$ m, $\varepsilon_{(y)} \sim 1.9$ pm, $\sigma_{\min\ (y)} \sim 14$ um

ttbar: $\beta_y \sim \beta_x \sim 50$ m, $\varepsilon_{(y)} \sim 1.4$ pm, $\sigma_{\min\ (y)} \sim 8$ um



Magnet downstream of Interaction Points

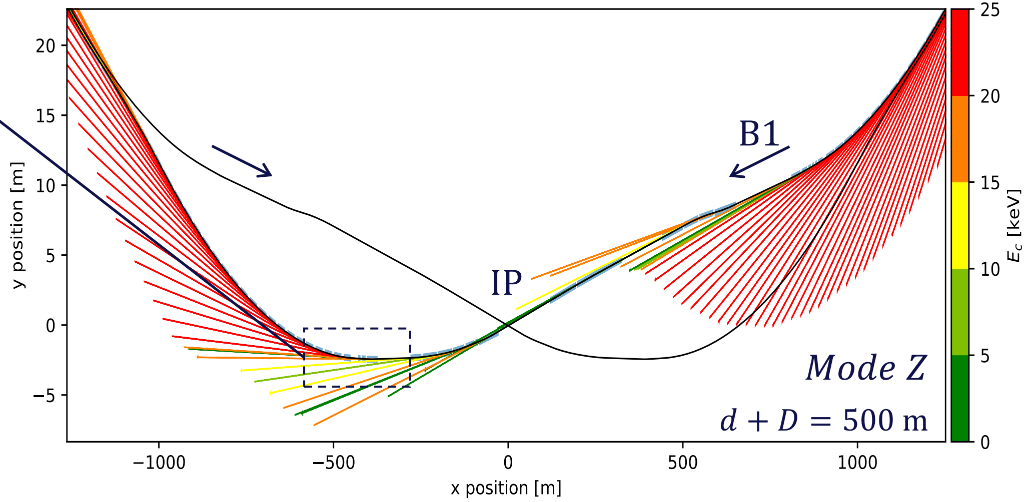


Profit from larger beam size to insert dedicated magnet and provide diagnostics near the IPs, using arcs for light separation

β_y~1000 m

$\boldsymbol{\sigma_y}$**~45 um**

with $\boldsymbol{\sigma_{res}}$**~35 µm** for pinhole at $E_c = 20$ keV

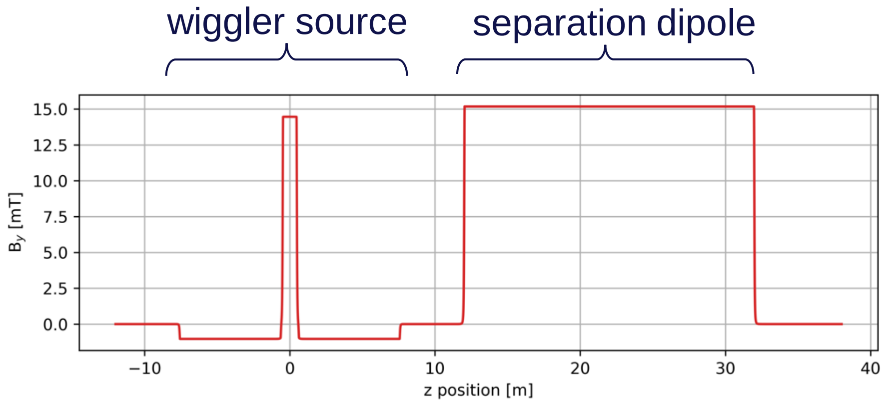


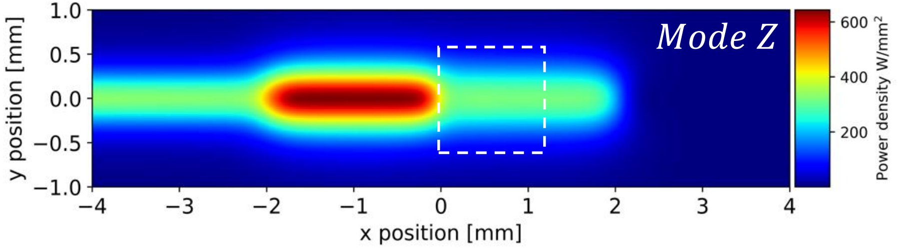
Synchrotron radiation source

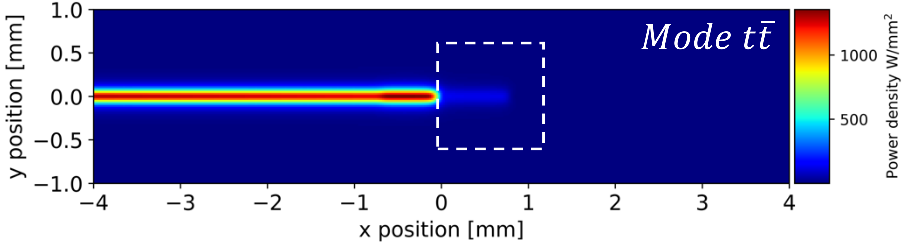
Wishlist

- photon energy in range $\boldsymbol{E_{ph} \sim 20 \div 80\ \mathrm{keV}}$
- within an angle $\sim \mathbf{10\ \mu rad}$ (1 mm @ 100 m)
- location with **beam size $> 40\ \mu m$** in both directions for accurate measurements
- locations w/ and w/o dispersion for **momentum spread evaluation**
- **upstream of strong bends** (e.g. arcs) to separate as quick as possible
- **tunable with energy** to be as constant as possible throughout operation modes

Work in progress…







Extraction lines

Irrespective of the technique, **long extraction lines required** to separate photons from beam

Straight line option

☺ pinhole is straightforward

☹ higher radiation at detector

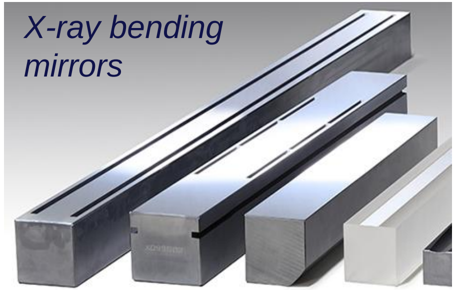
☹ larger transverse extension

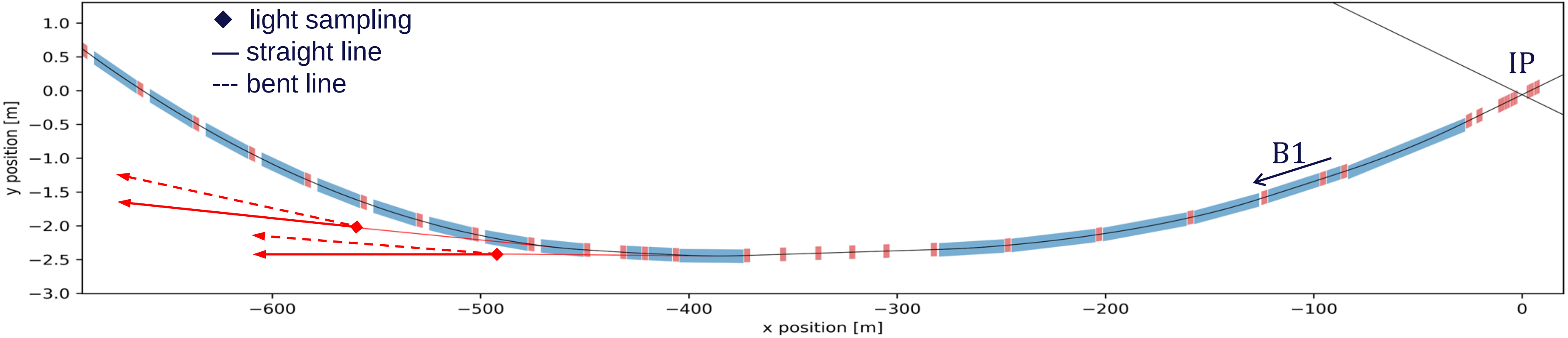
Bent line option

☹ additional mirror for pinhole (monochromator for interferometry)

☺ dilute radiation load on mirror

☺ more compact transversely





Conclusion

Precise and real-time monitoring is priority for commissioning and operation
→ **pinhole camera** baseline for transverse diagnostics

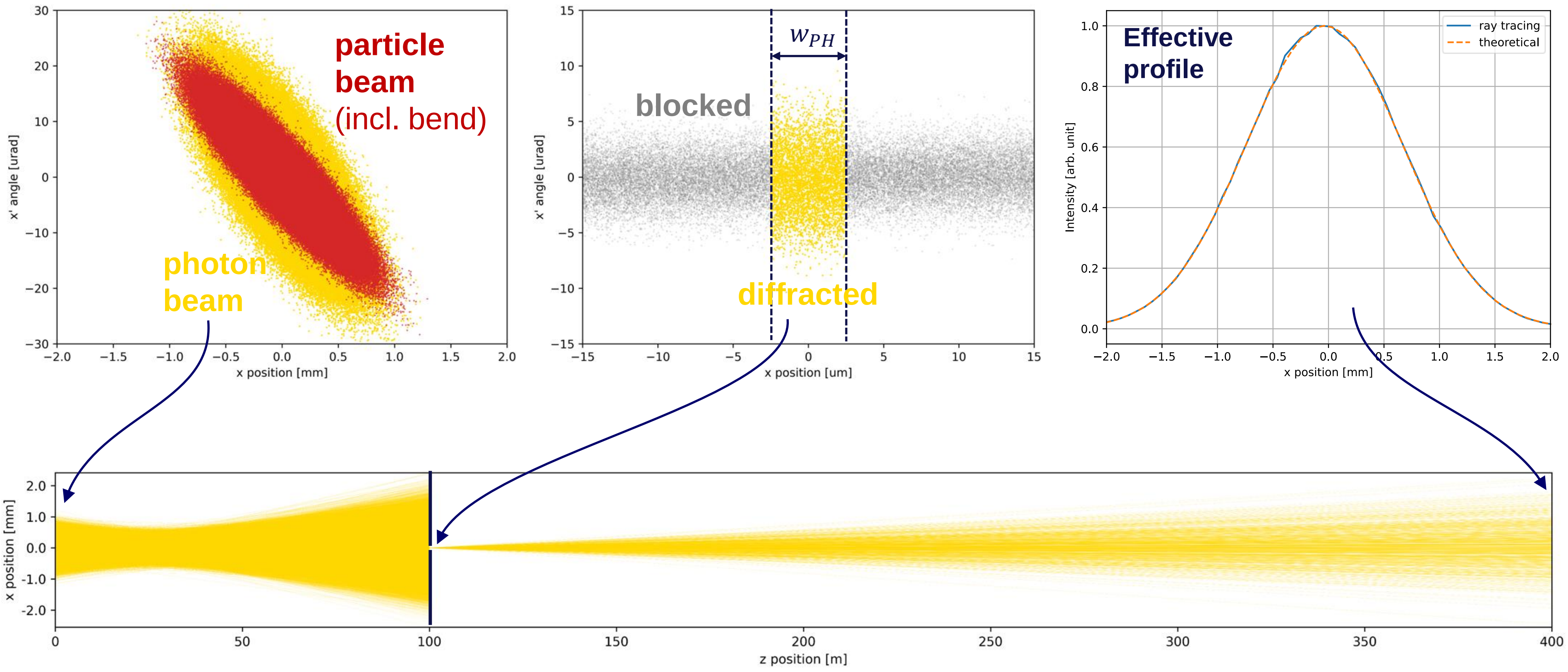
Pinhole alone cannot meet accuracy requirement in vertical direction
→ **X-ray imaging and interferometry** can complement SR-based diagnostics

Experimental sites offer more favorable conditions for beam size measurements
→ work in progress on definition of **SR source and extraction line geometry**

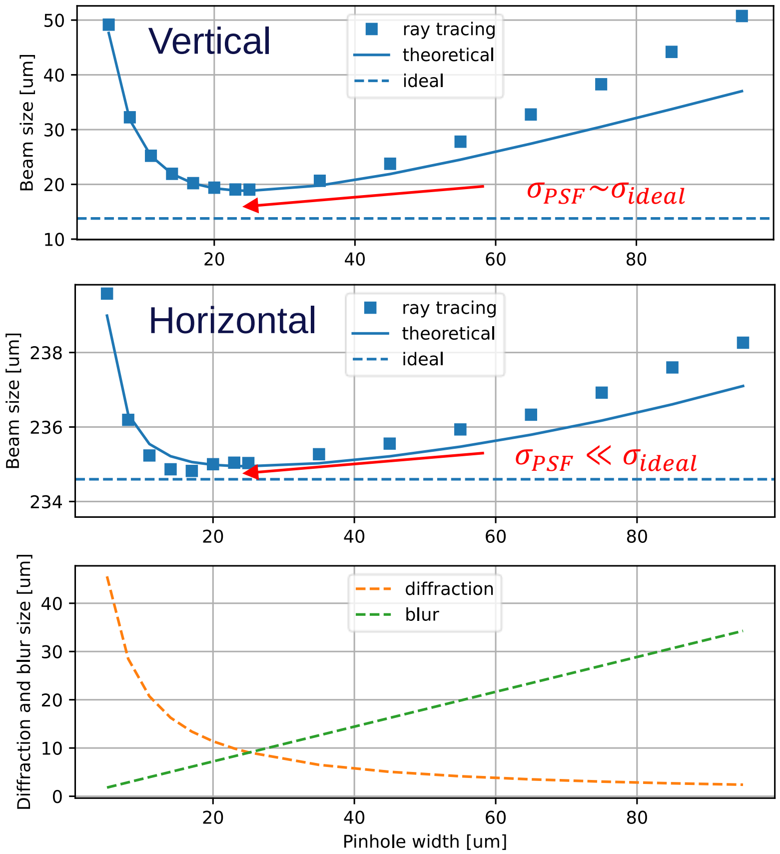
FCC

Thank you for your attention!

Ray tracing


particle
beam
(incl. bend)
photon
beam
x' angle [urad]
x position [mm]
blocked
diffracted
w_{PH}
x' angle [urad]
x position [um]
Effective
profile
ray tracing
theoretical
Intensity [arb. unit]
x position [mm]
x position [mm]
z position [m]

Ray tracing

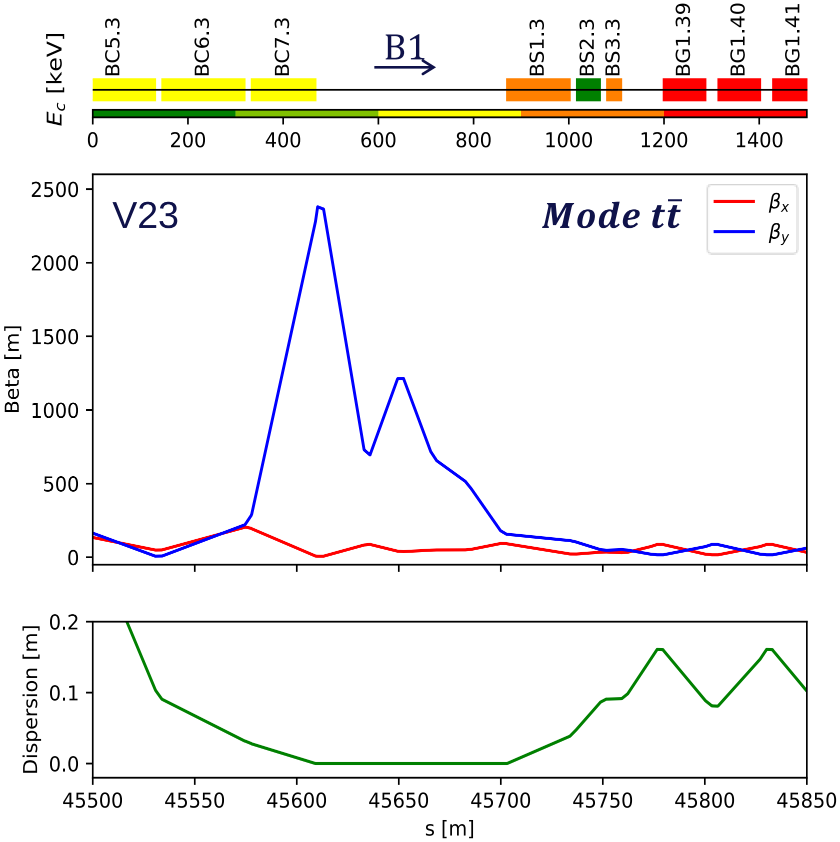


Ray tracing confirms analytical estimation of the Point Spread Function around the optimum w_{PH}

Deviations for large w_{PH} because blur is enhanced by large bending radius

$$\sigma_{eff}^2 = \sigma_{ideal}^2 + \sigma_{PSF}^2$$

Dipole magnets around IPs (ttbar mode)



Critical energies of most dipoles too high (>1 MeV) for diagnostics at tt mode
→ **working in low frequency tail of spectrum**

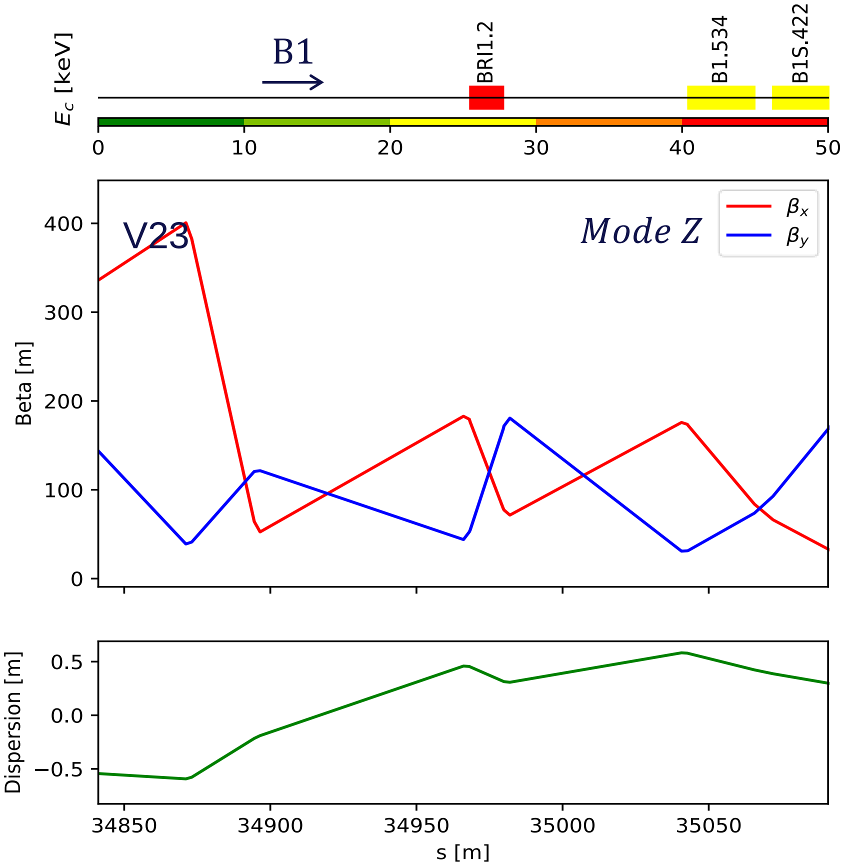
Example centre of BC7 ☺

$\beta_y \sim 1500$ m

$\boldsymbol{\sigma_y \sim 50}$ **um**

with $\boldsymbol{\sigma^2_{PSF} \sim 15\ \mu m}$ for pinhole at $E_{ph} = 150$ keV

Dipole magnets around RF



Pro:

- less SR power

Cons:

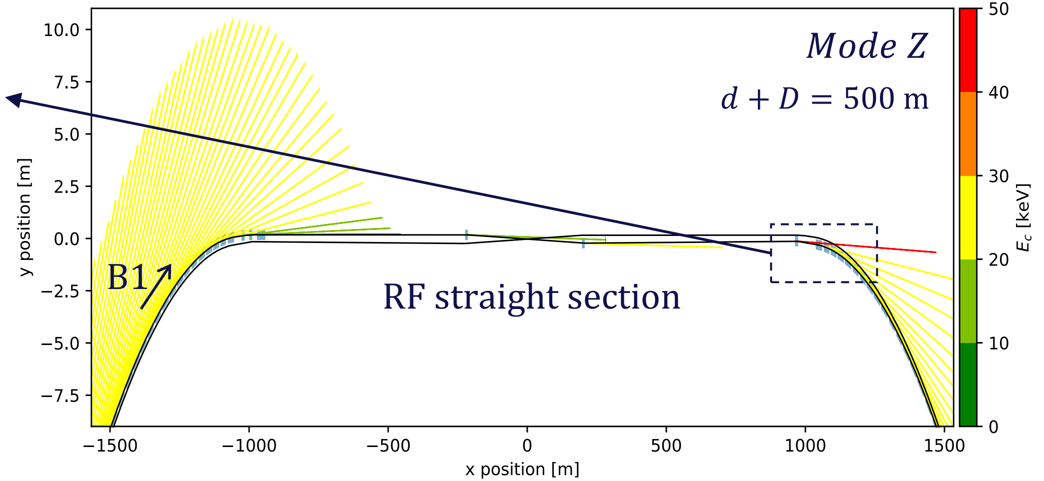
- integration (inside ring and layout changes with mode)
- similar beam sizes as arcs

Example centre of BRI1 ☹

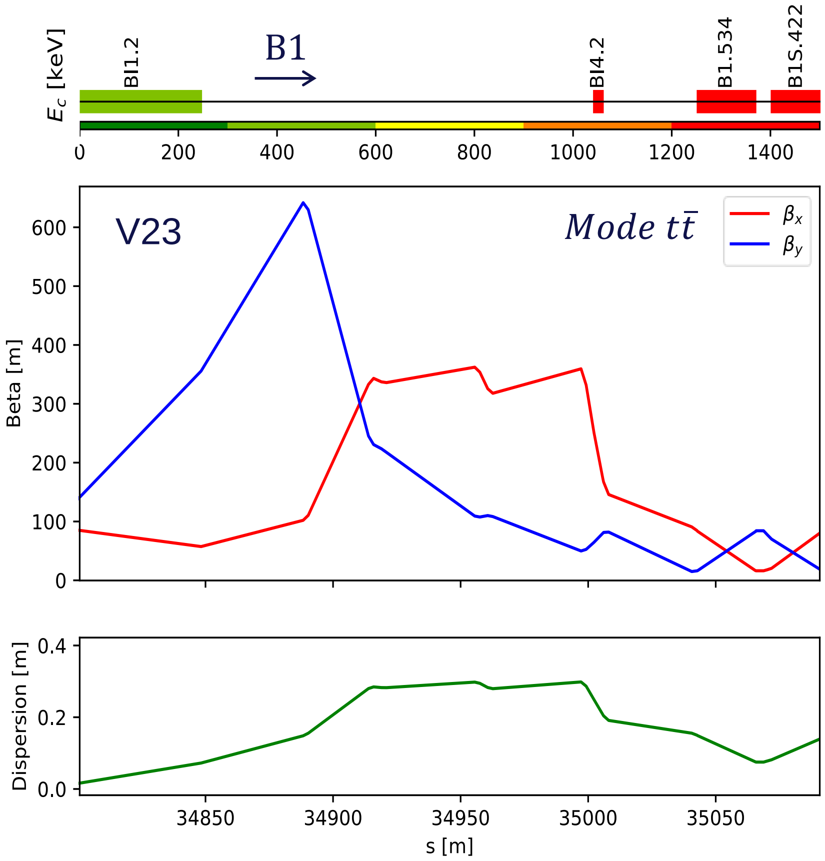
$\beta_y \sim 100$ m

$\boldsymbol{\sigma_y \sim 14}$ **um**

with $\boldsymbol{\sigma^2_{PSF} \sim 25}$ **µm** for pinhole at $E_c = 50$ keV



Dipole magnets around RF (ttbar mode)

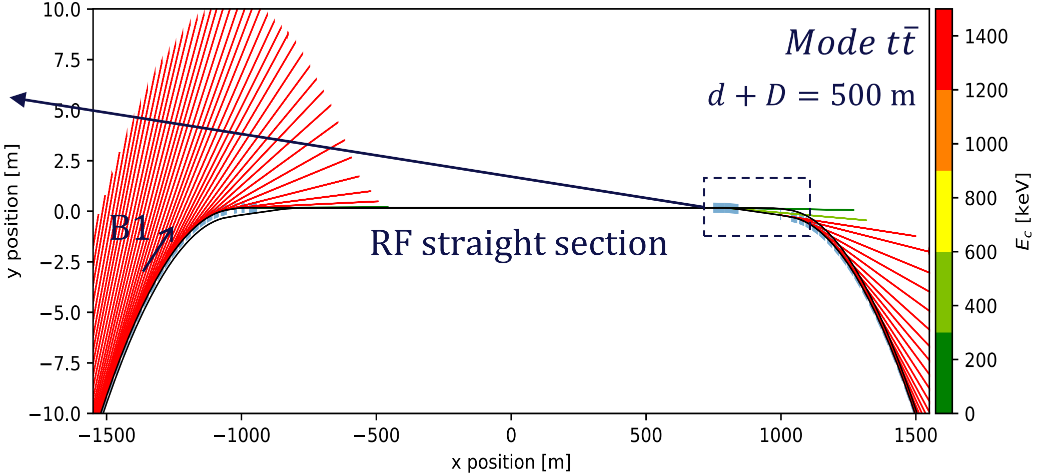


Example centre of BI1

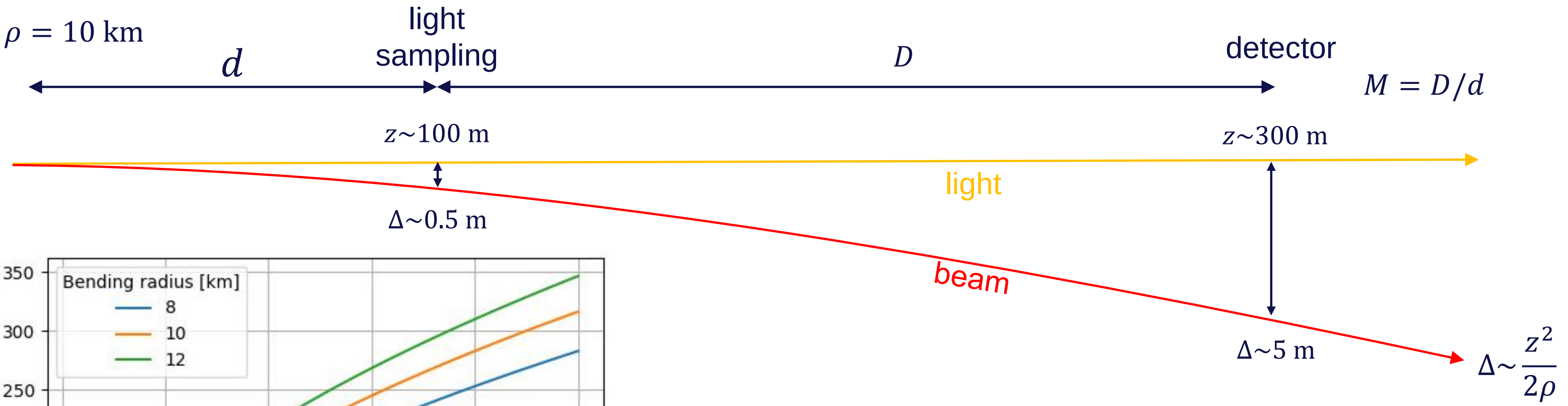
$\beta_y \sim 250$ m

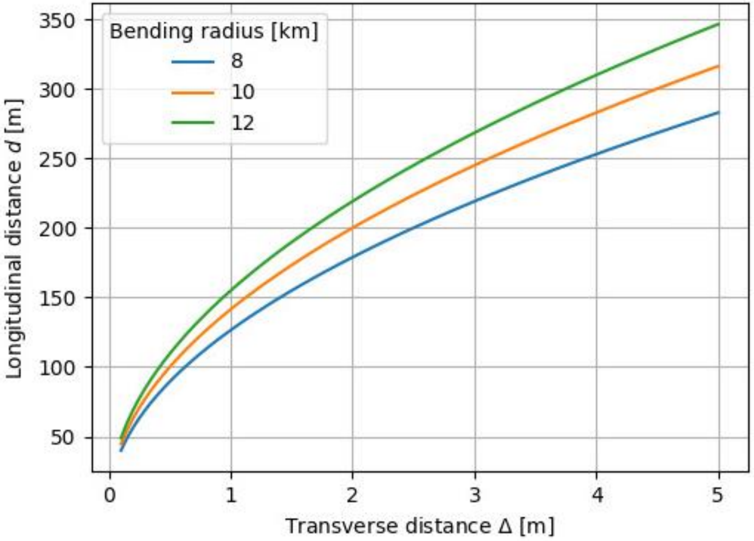
with $\boldsymbol{\sigma^2_{PSF}} \sim \mathbf{15\ \mu m}$ for pinhole at $E_{ph} = 150$ keV

$\boldsymbol{\sigma_y} \sim \mathbf{20\ um}$



Synchrotron radiation extraction geometry

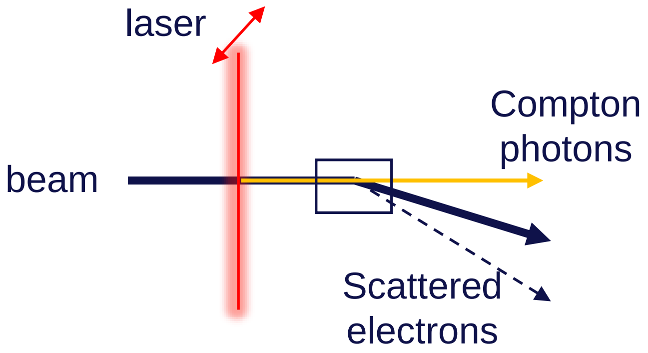


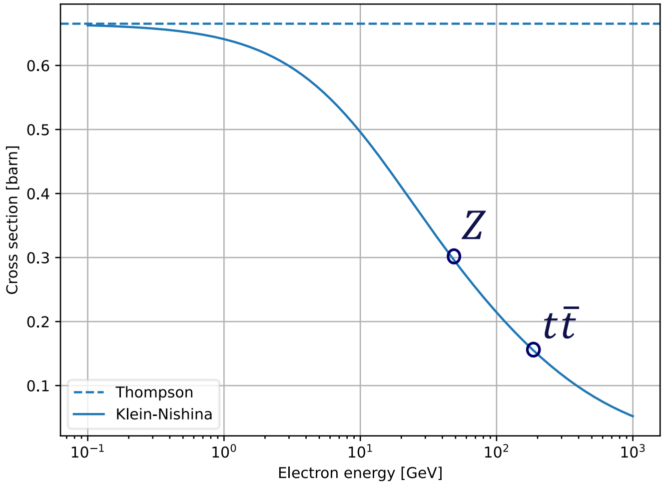


If we assume to measure **source sizes of 50 µm**, we need at least a factor 2 magnification

→ requires $D\sim200$ **m distance from the pinhole,** corresponding to $\Delta\sim5$ **m transverse distance**

Alternative to SR diagnostics: Laser Wire Scanner





LWS can achieve micrometric resolution
→ suitable for **accurate vertical measurements**

Similar hardware as **polarimeter**
→ possible common **integration**

FCC has very high electron energies
→ **lower cross section** and **higher photon energy** than all present applications

Laser technology is quickly advancing
→ higher power laser and better focusing systems likely available by FCC era