The CERN Accelerator School

High Brightness Beam Diagnostics

10 – 22 November 2024

Spa, Belgium

L. Bobb, Diamond Light Source, UK

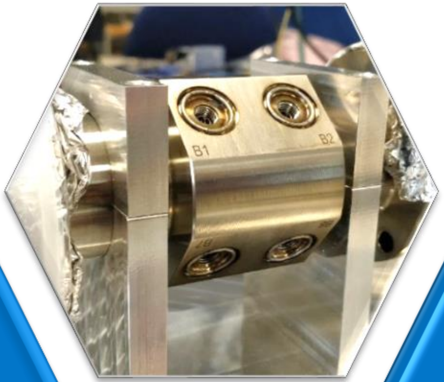
Outline

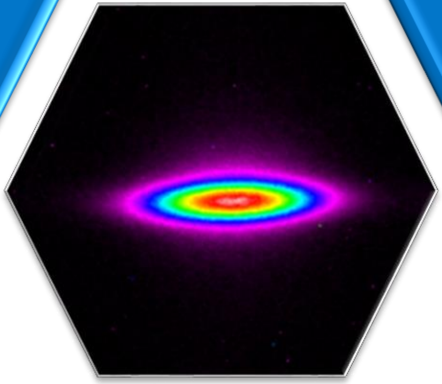
- Aims of Diagnostics
- High Brightness
- Invasive and Non-invasive Techniques for Transverse Measurements
  - Space-charge dominated beams (low energy)
  - Electron LINACS
  - Hadron Synchrotrons
  - Electron Synchrotrons

Aims of Diagnostics Instrumentation

Reliable and robust

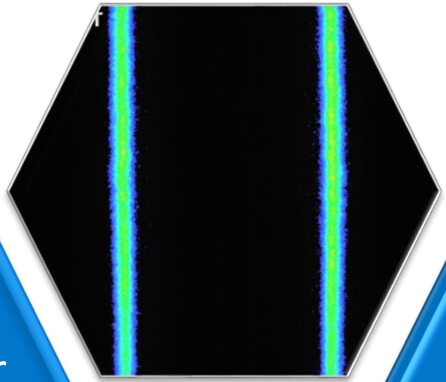
High precision and high accuracy

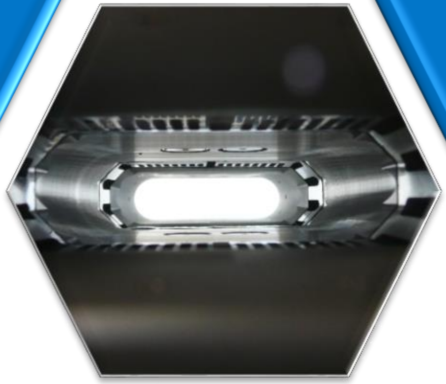




Non-invasive (preferably!)

Compatible for feedbacks





Maintainable and futureproof

Suitable for commissioning and user beam

What is "High Brightness"?

Brightness (4D):

$$B = \frac{dI}{dS d\Omega}$$

Beam current per unit source size and divergence

$$\overline{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$

[A/(mrad)^2]

B = Brightness
I = Current
S = Source size (i.e. area)
Ω = Divergence (i.e. solid angle)
$\varepsilon_{x,y}$ = Horizontal or Vertical emittance

Several authors give different definitions!

- *Brilliance is sometimes used, especially in Europe, instead of brightness*
- *There is also confusion because the same words apply both to particle beams and photon beams*
- *Often the factor $2/\pi^2$ is left out in literature and often the RMS emittance is used in place of effective emittance*
- *The best way is to look to units, which should be unambiguous*

- A. Cianchi, Advanced Accelerator Physics Course 2015

What is “High Brightness”?

$$B = \frac{dI}{dS\,d\Omega}$$

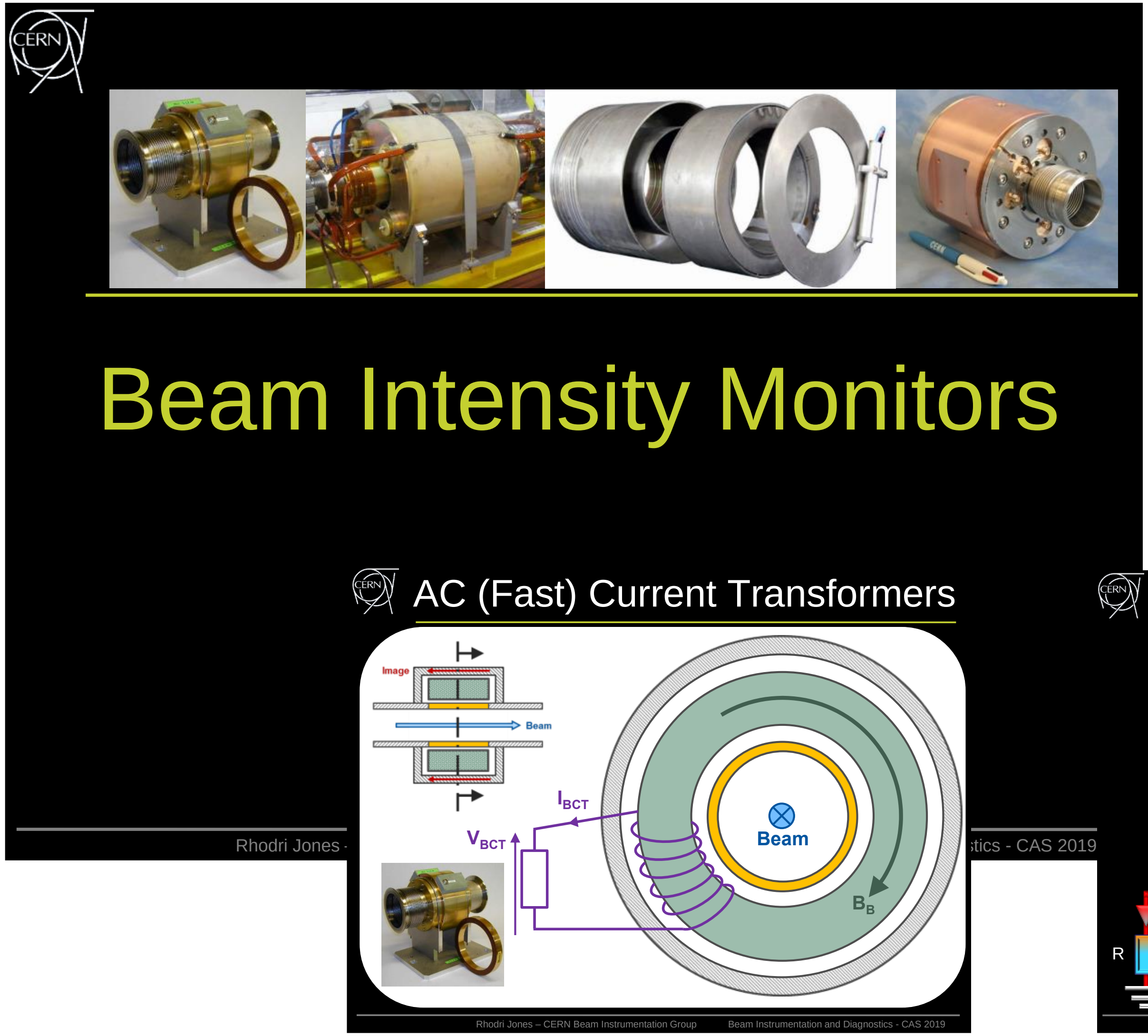
Beam current per unit source size and divergence

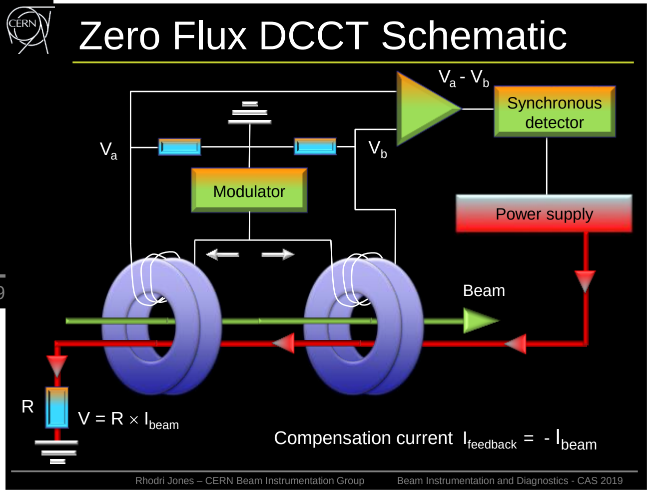
$$\overline{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$

[A/(mrad)^2]

High Brightness generally requires
large beam intensity and/or small beam emittances

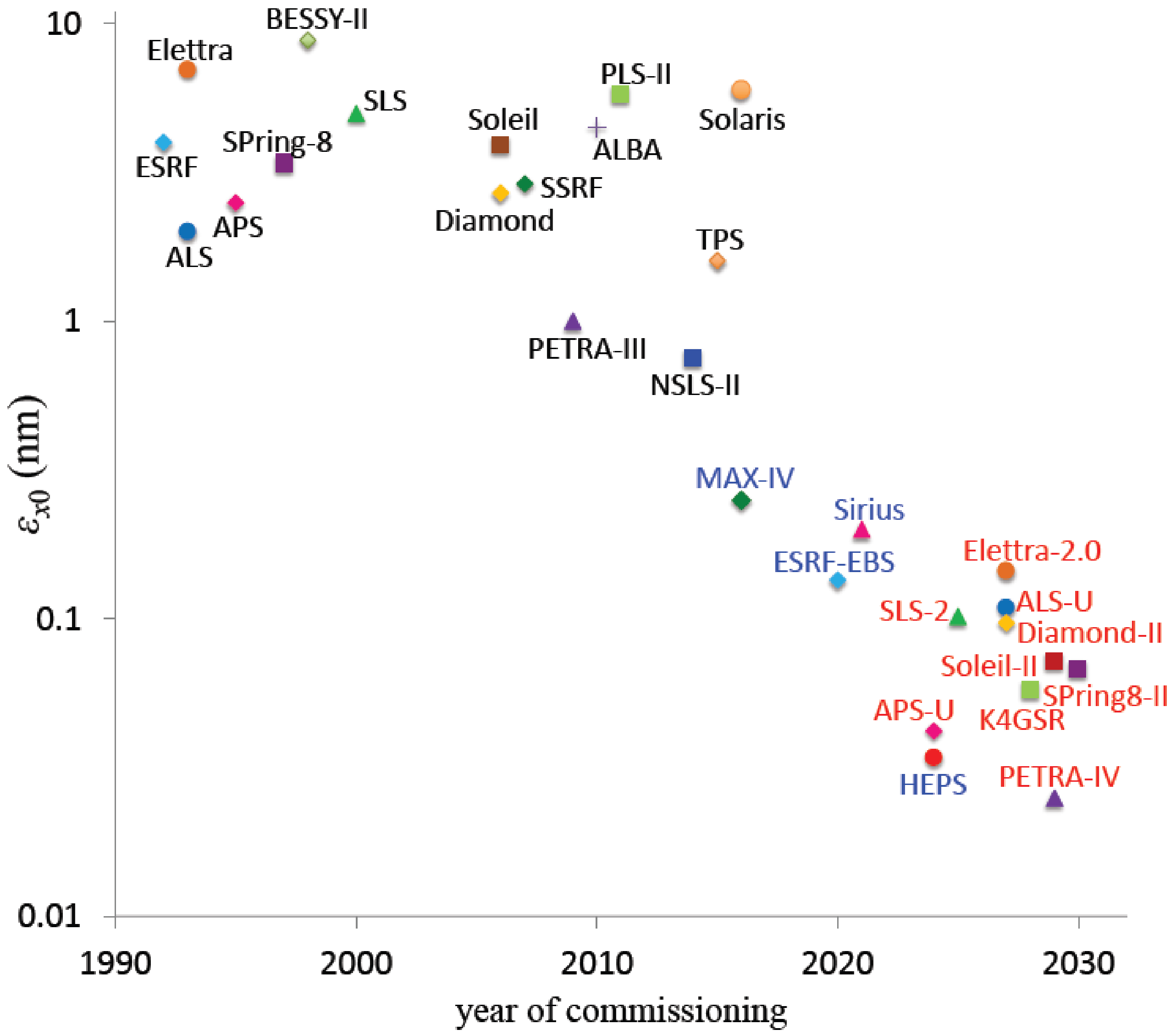
High Beam Intensity





Challenge is measuring low beam intensity ☺

Small Transverse Beam Size

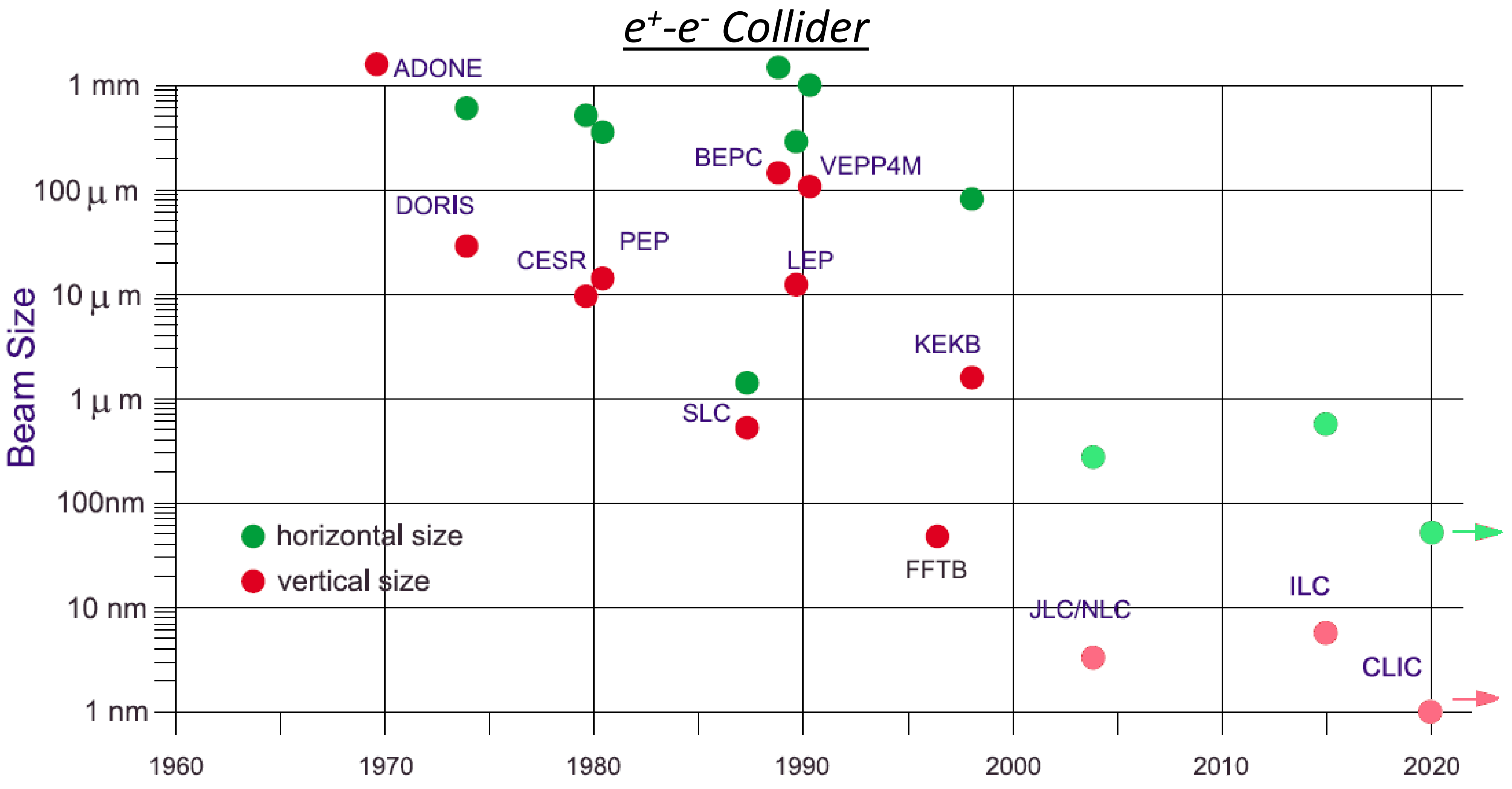


Synchrotron Light Sources

—	3rd gen. in operation
—	4th gen. in operation
—	4th gen. planned/ under construction

V. Smaluk and T. Shaftan, NSLS-II Technical Note, BNL, NSLSII-ASD-TN-403, 2024, (http://arxiv.org/abs/2402.05204)

Small Transverse Beam Size



Adapted from S. Chattopadhyay, K. Yokoya, Proc. Nanobeam `02

Challenges for Beam Instrumentation

- What is the smallest beam size I can measure ?

- Will my device survive such a large beam density ?
  - *Single shot thermal limit for 'best' material (C, Be, SiC)*

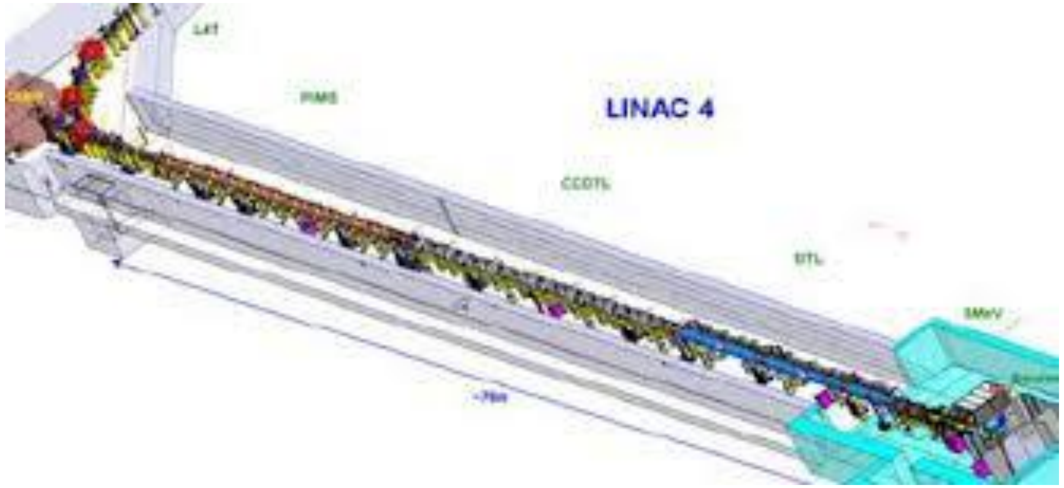
    10^4 nC/mm^2 - 6.25 10^{14} particles/mm^2

  - A limit that is surpassed in most LINACs (not even talking about rings)

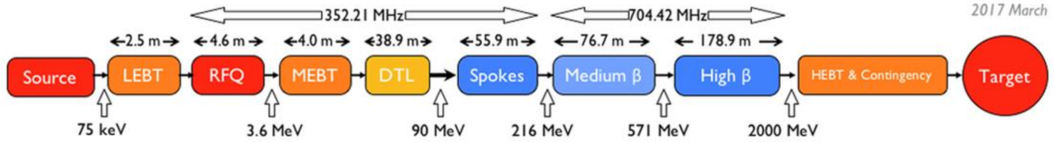
Some Examples of High Brightness Beams

- High intensity Proton LINACs

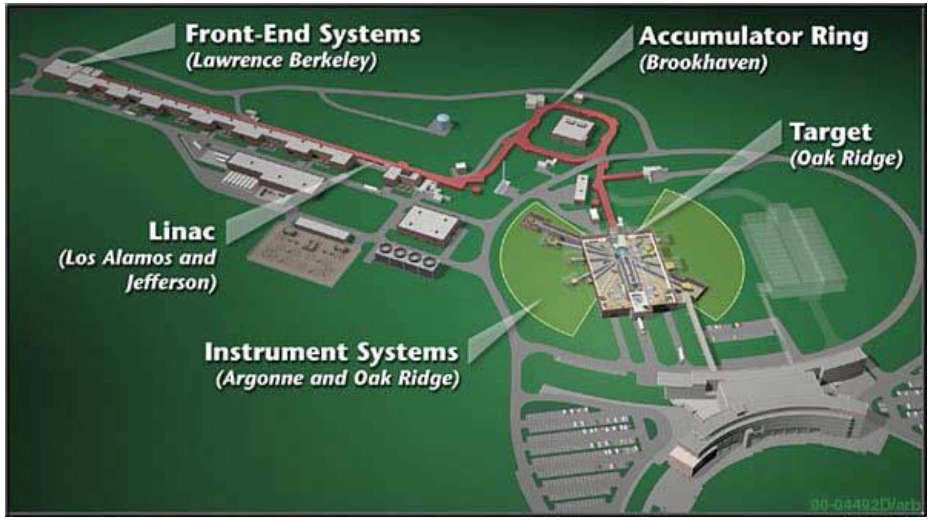
L4@CERN



ESS - https://europeanspallationsource.se/



SNS - https://neutrons.ornl.gov/sns/



Some Examples of High Brightness Beams

- Synchrotrons Light Sources

Image Source ESRF

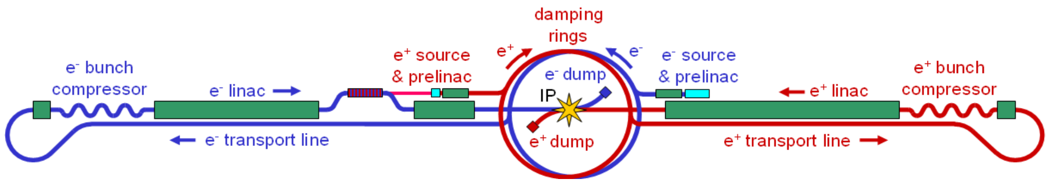
Some Examples of High Brightness Beams

- Free Electron Lasers and Energy Frontier Linear Colliders

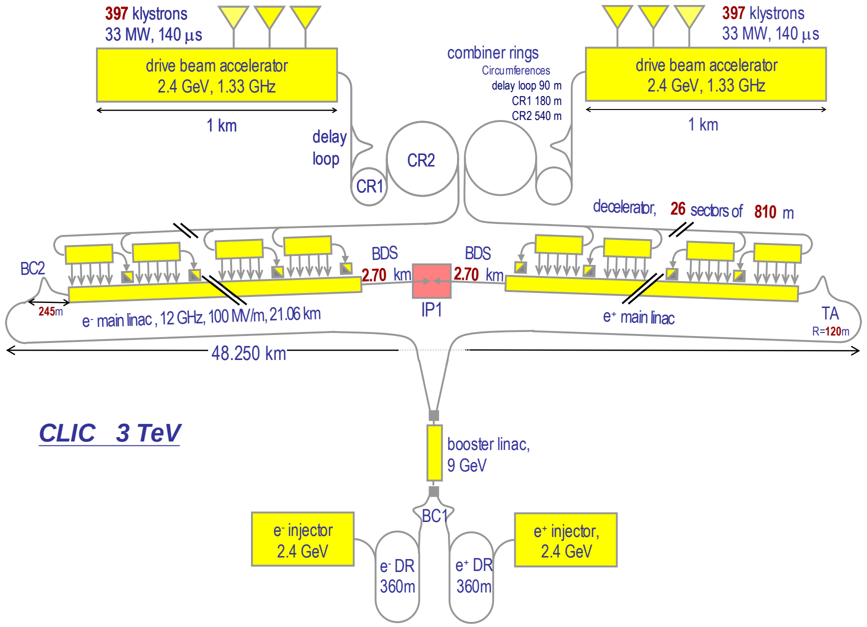
XFEL - https://www.xfel.eu/

LCLS - https://lcls.slac.stanford.edu/

ILC : https://linearcollider.org/



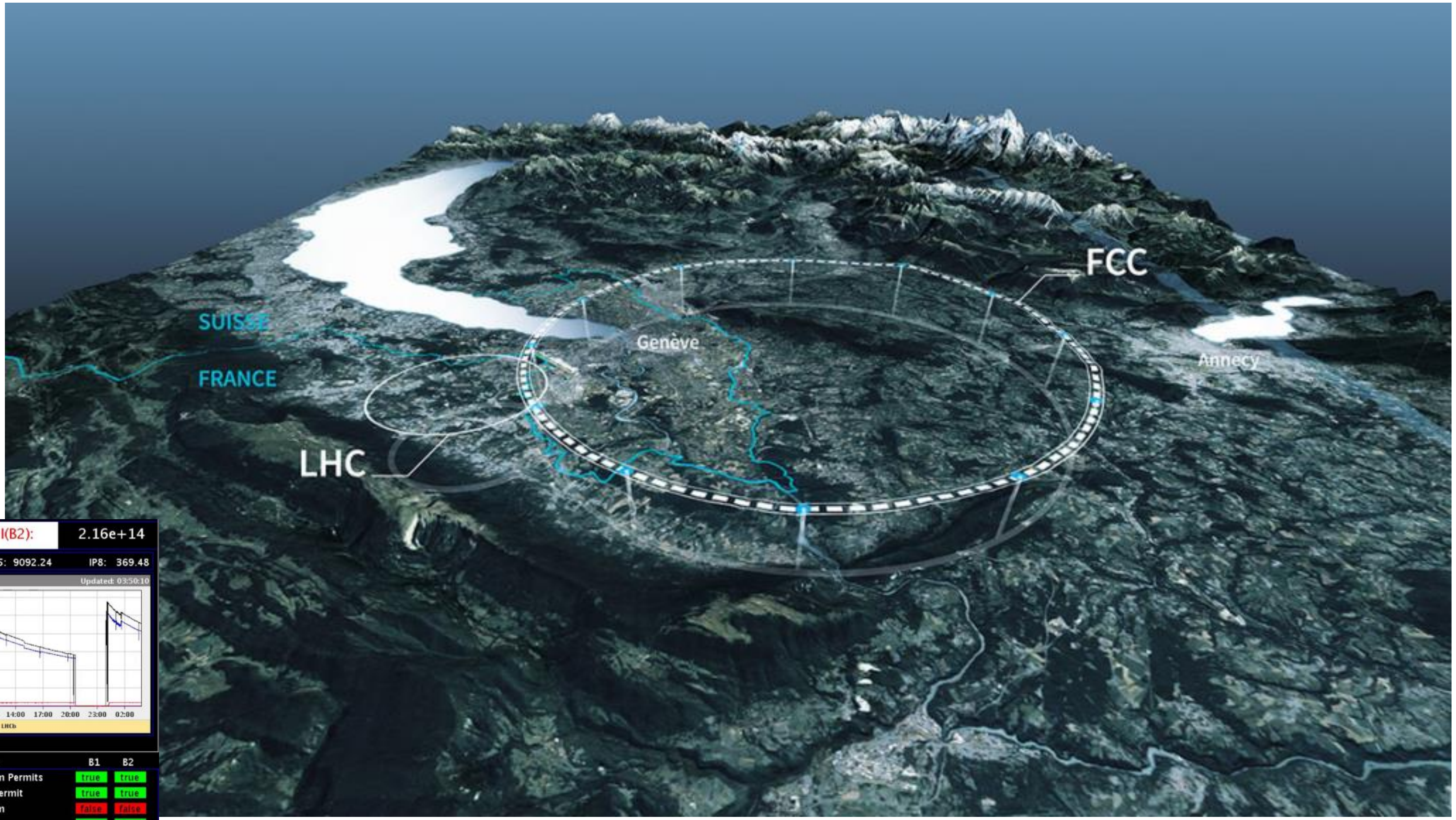
CLIC - https://clic.cern

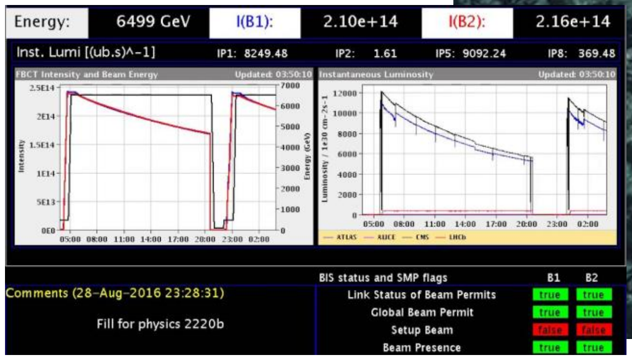


Some Examples of High Brightness Beams

- Energy frontier Circular Colliders

FCC - https://fcc.web.cern.ch/





What Else Determines High Brightness?

$$B_{6D} \propto \frac{Ne}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma}$$

Short bunch length

- Free-Electron Lasers
- Novel Accelerator technologies
  - Dielectric acceleration
  - THz acceleration
  - Plasma acceleration

What Else Determines High Brightness?

$$B_{6D} \propto \frac{Ne}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma}$$

Longitudinal beam diagnostics covered later!

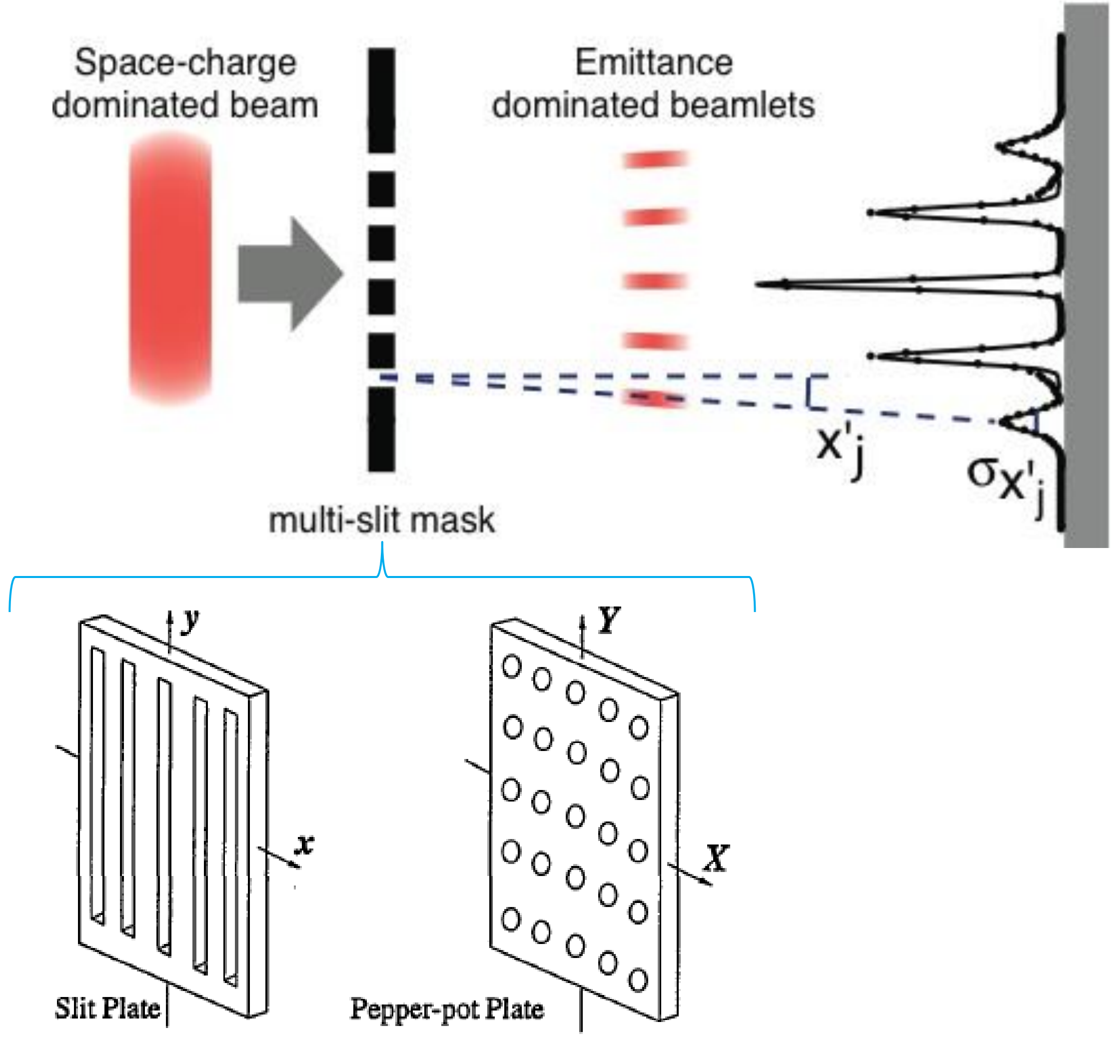
Accelerator technologies

- Dielectric acceleration
- THz acceleration
- Plasma acceleration

Transverse Diagnostics
Space-charge Dominated Beams

high intensity low energy electron/hadron beams

Space Charge Regime



Pepper-pot:

To measure the emittance for a space charge dominated beam.

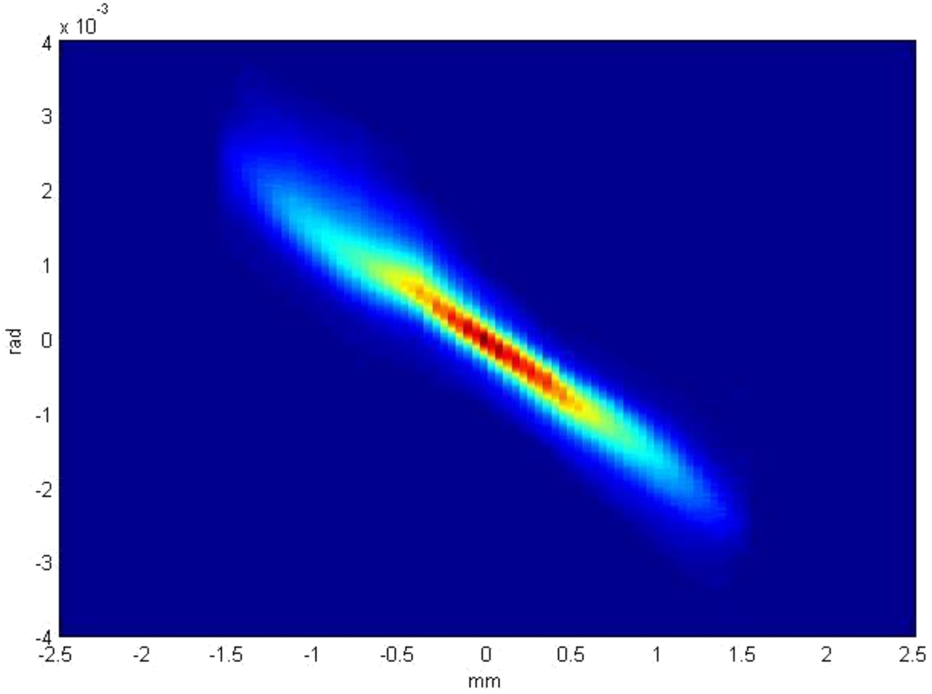
For each transverse part of the beam, divergence of the beam and of individual beamlets are measured.

C. Lejeune and J. Aubert, Adv. Electron. Electron Phys. Suppl. A ***13****, 159 (1980)*

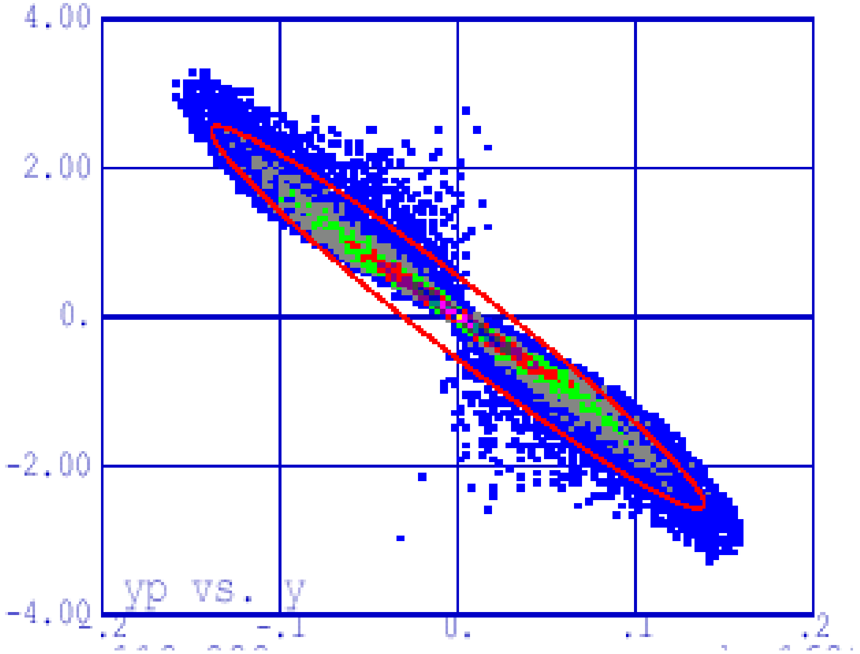
Zhang, M. (1996). Emittance Formula for Slits and Pepper-pot Measurement. *Fermi National Accelerator Laboratory*, (October), 10.

Space Charge Regime

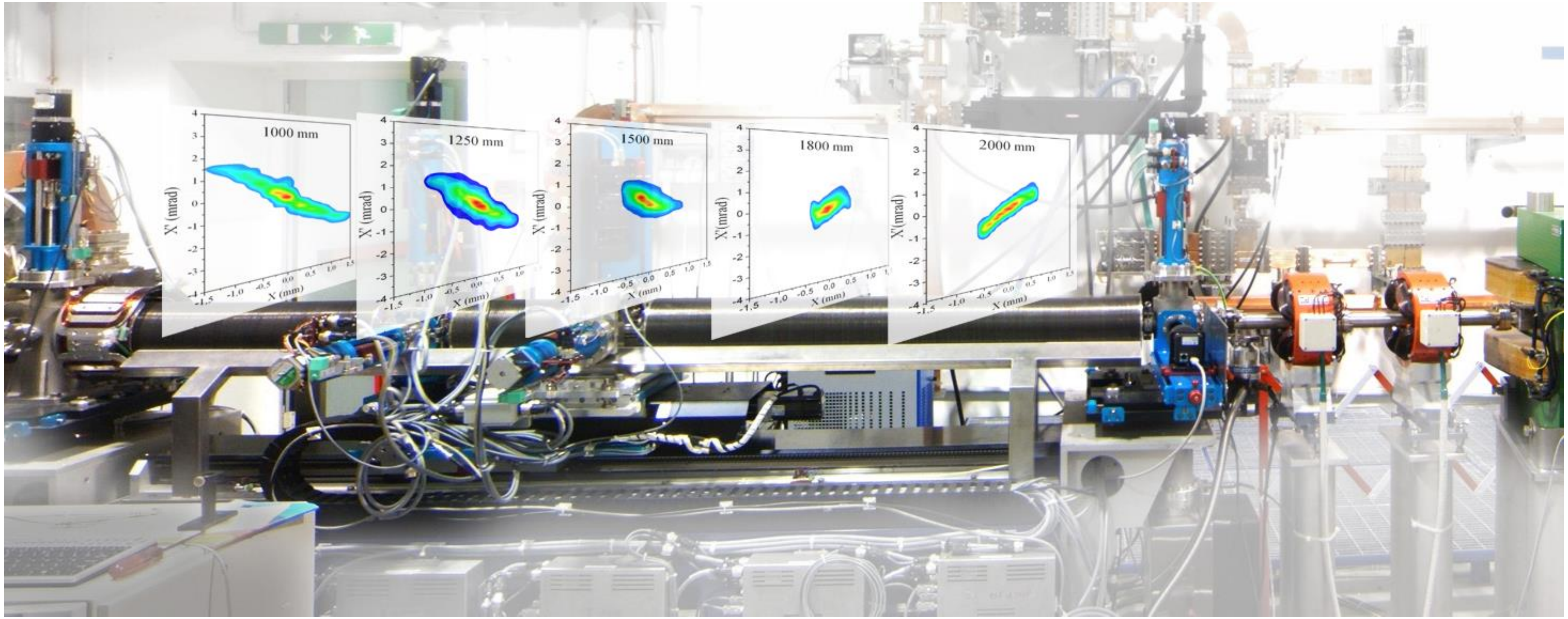
Measurements



Simulations

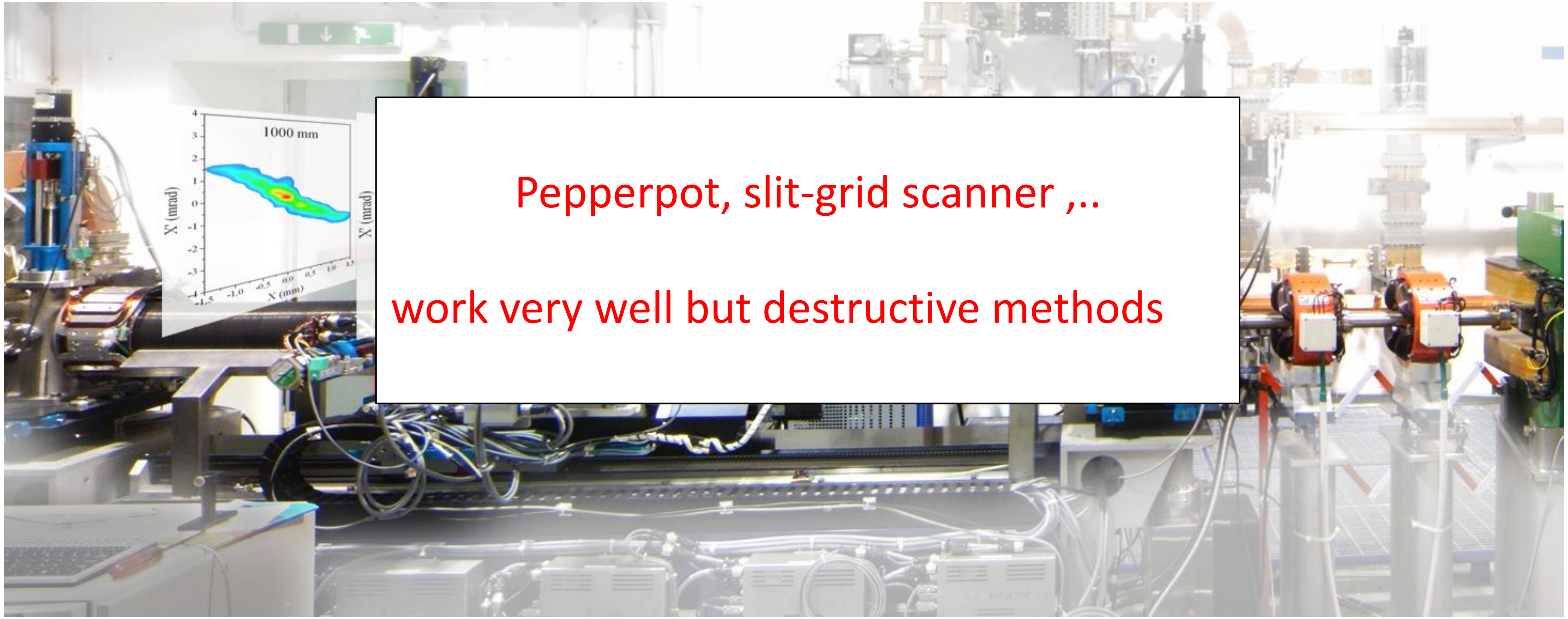


Phase space evolution



A. Cianchi et al., *"High brightness electron beam emittance evolution measurements in an rf photoinjector", Physical Review Special Topics Accelerator and Beams 11, 032801,2008*

Phase space evolution



Pepperpot, slit-grid scanner ,..

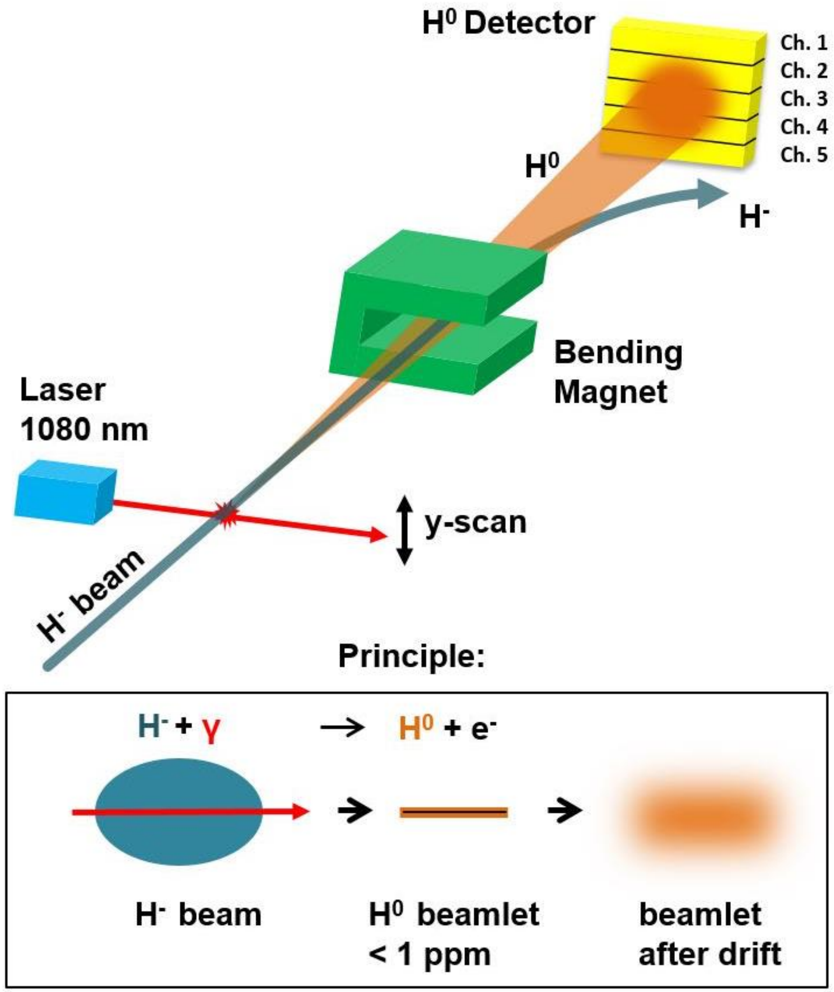
work very well but destructive methods

A. Cianchi et al., "High brightness electron beam emittance evolution measurements in an rf photoinjector", Physical Review Special Topics Accelerator and Beams 11, 032801,2008

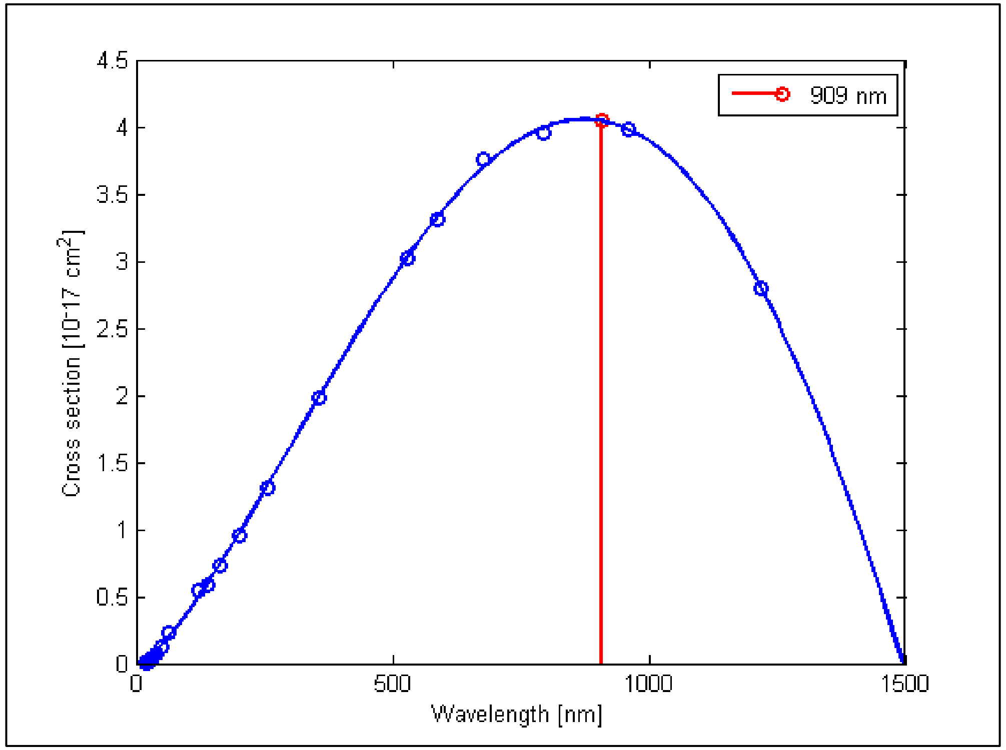
Laser Emittance Meter for H^-

A non-invasive method for H^- beams using electron photo-detachment

Laser Emittance Meter for H^-

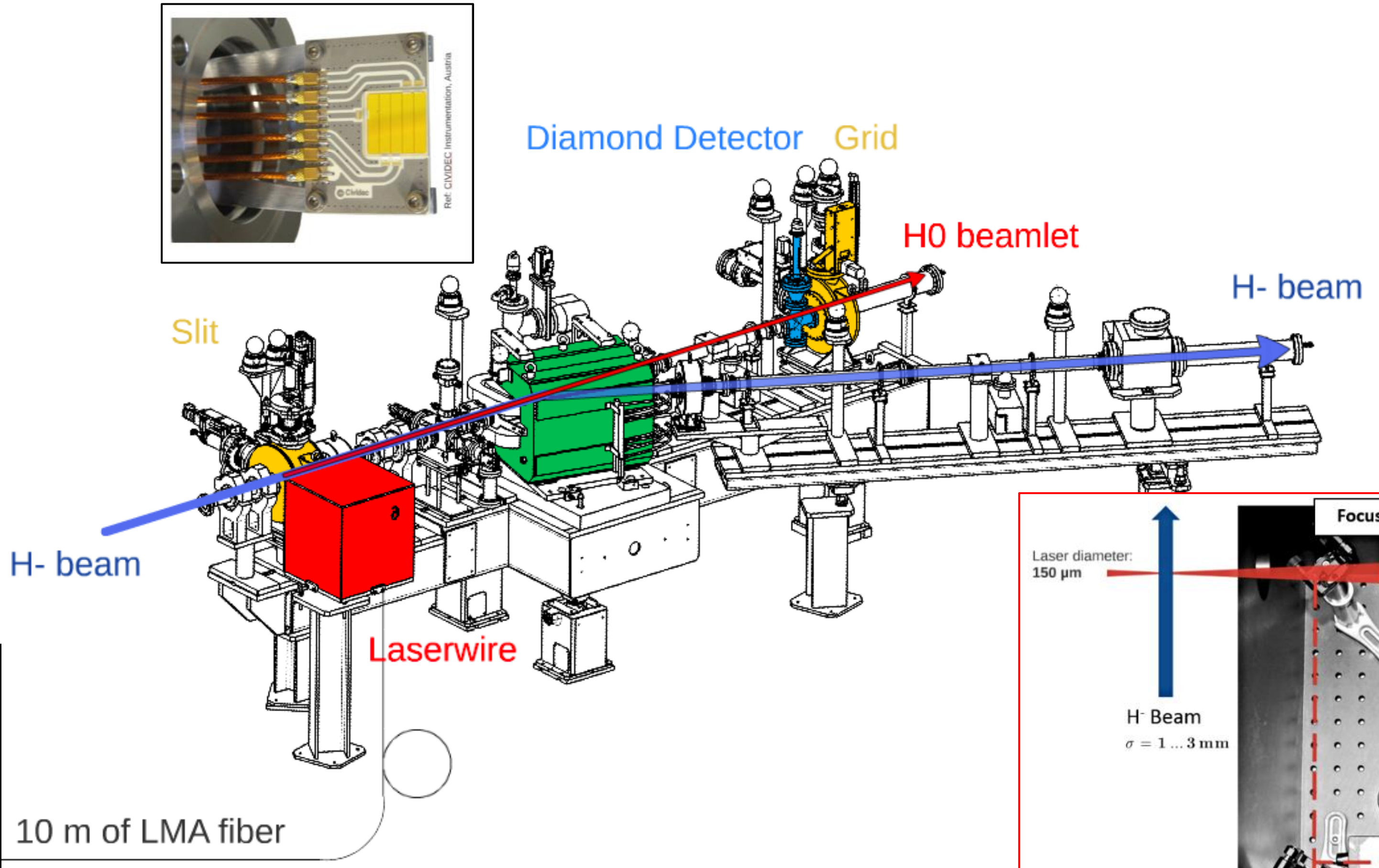


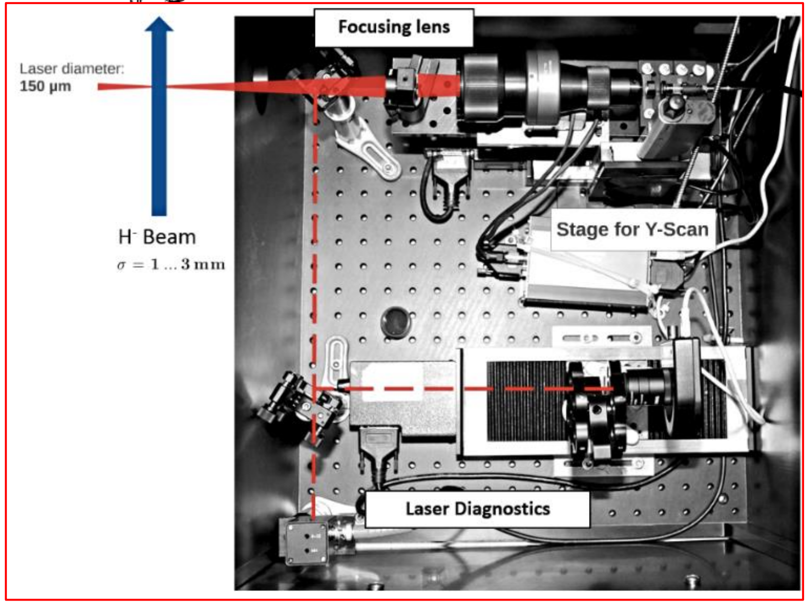
Electron Laser-Stripping cross section



T. Hofmann et al, "A low-power laserwire profile monitor for H- beams: Design and experimental results" Nucl. Inst. and Meth. in Phys. Res. Section A: 903, p. 140-146 (2018)

Laser Emittance Meter for H^-

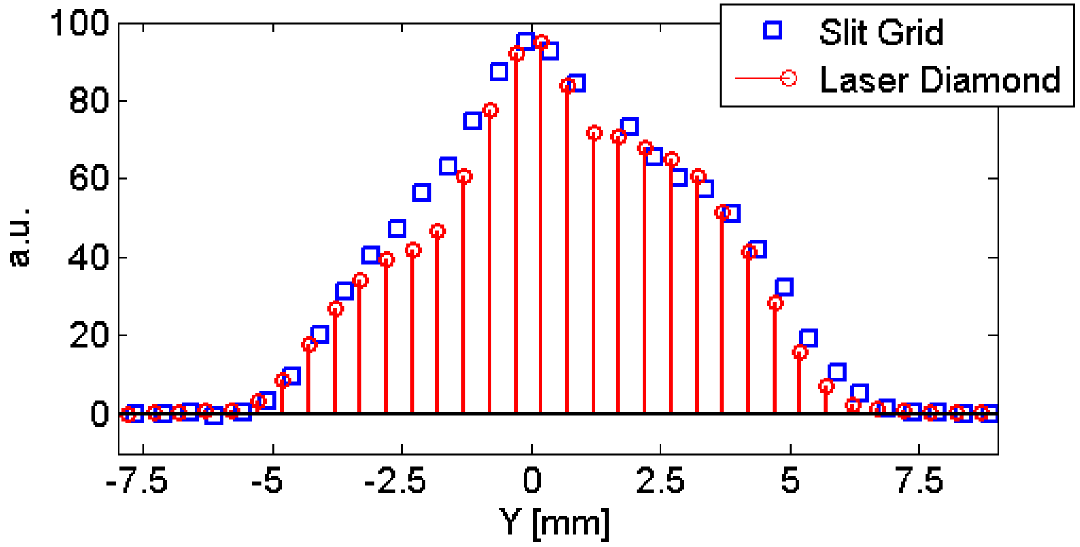


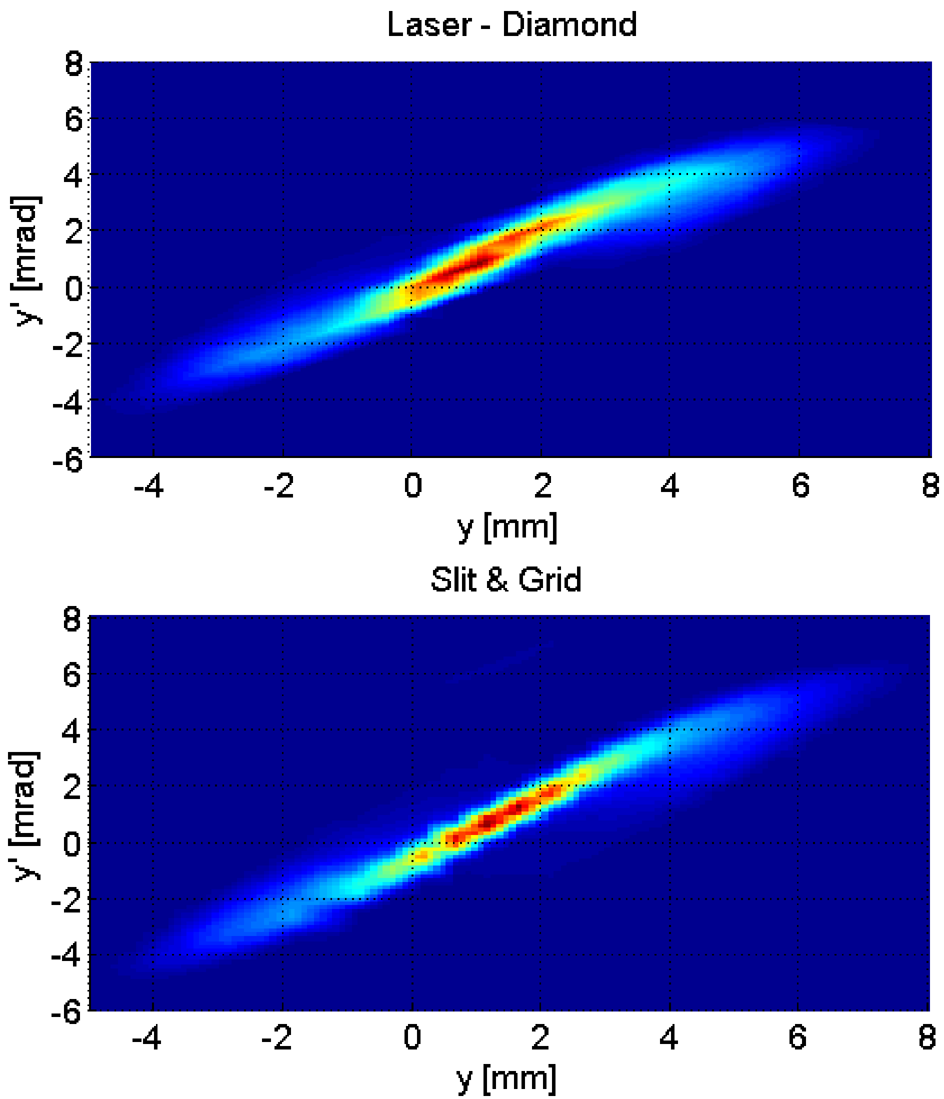


Laser	MOPA	*Nd-YAG*
Pulse Energy	**0.1 mJ**	*50 mJ*
Stripping	**0.1 %**	*> 99 %*
t_{pulse}	80 ns	*5 ns*

Laser Emittance Meter for H^-

- Measurements at 3 and 12 MeV at Linac4/CERN





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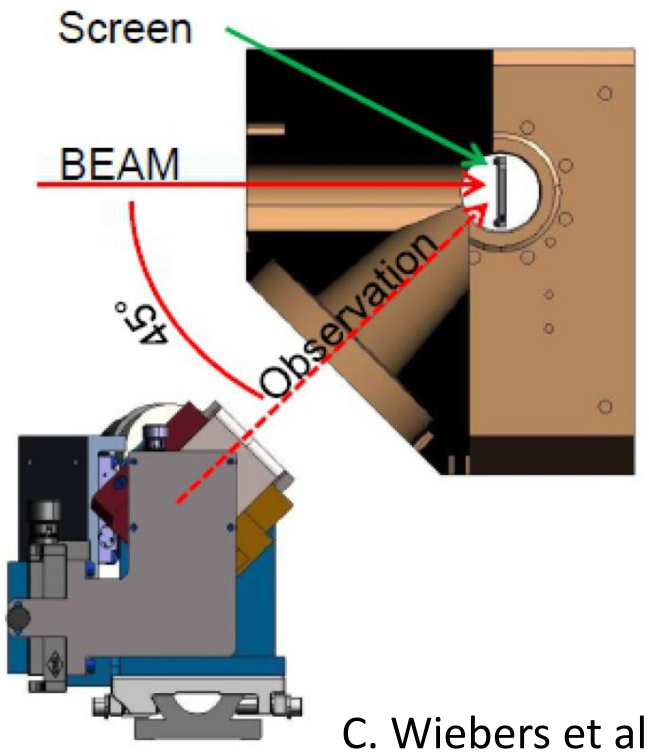
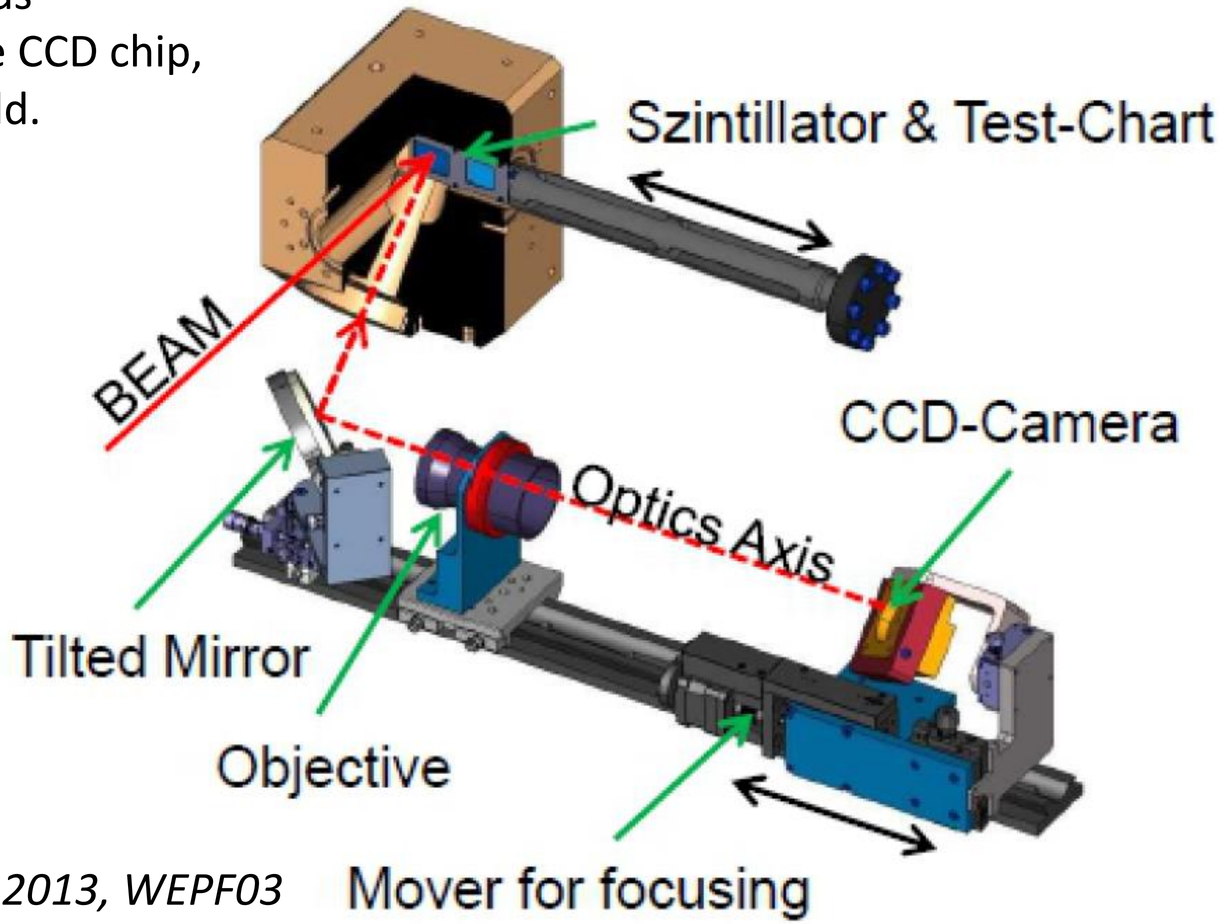
Transverse Diagnostics in Electron LINAC

Electron Linac – Fluorescent (Scintillator) Screen

- Insert screen into beam path
- Photon emission over large solid angle
- Imaging optics operates in Scheimpflug condition, thus adjusting the plane of sharp focus with respect to the CCD chip, and significantly increasing the apparent depth of field.

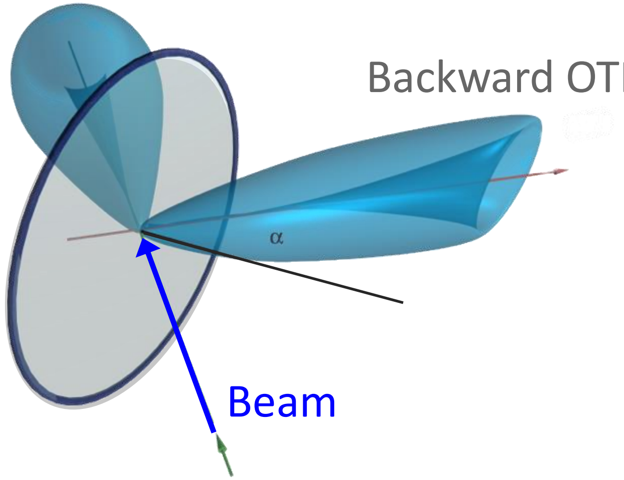




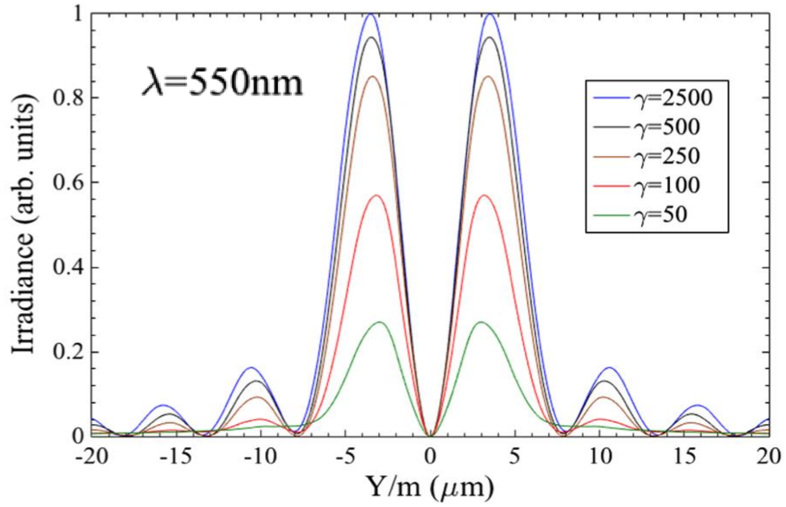
C. Wiebers et al., *Proc. of IBIC 2013, WEPF03*

Electron Linac – Transition Radiation

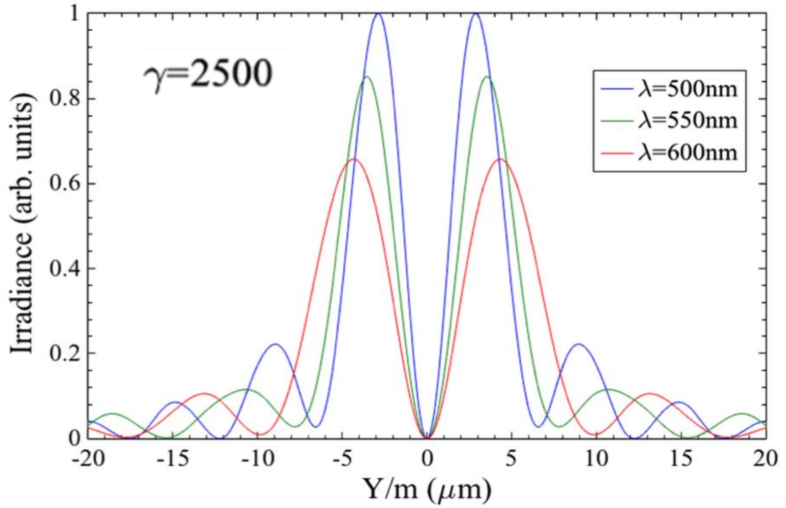
As predicted in 1946 by Frank and Ginzburg, **Transition Radiation** is a broadband electromagnetic field emitted by a relativistic charged particle when it crosses boundary between two mediums of different dielectric constants.



Single particle OTR field distribution at the surface of the screen

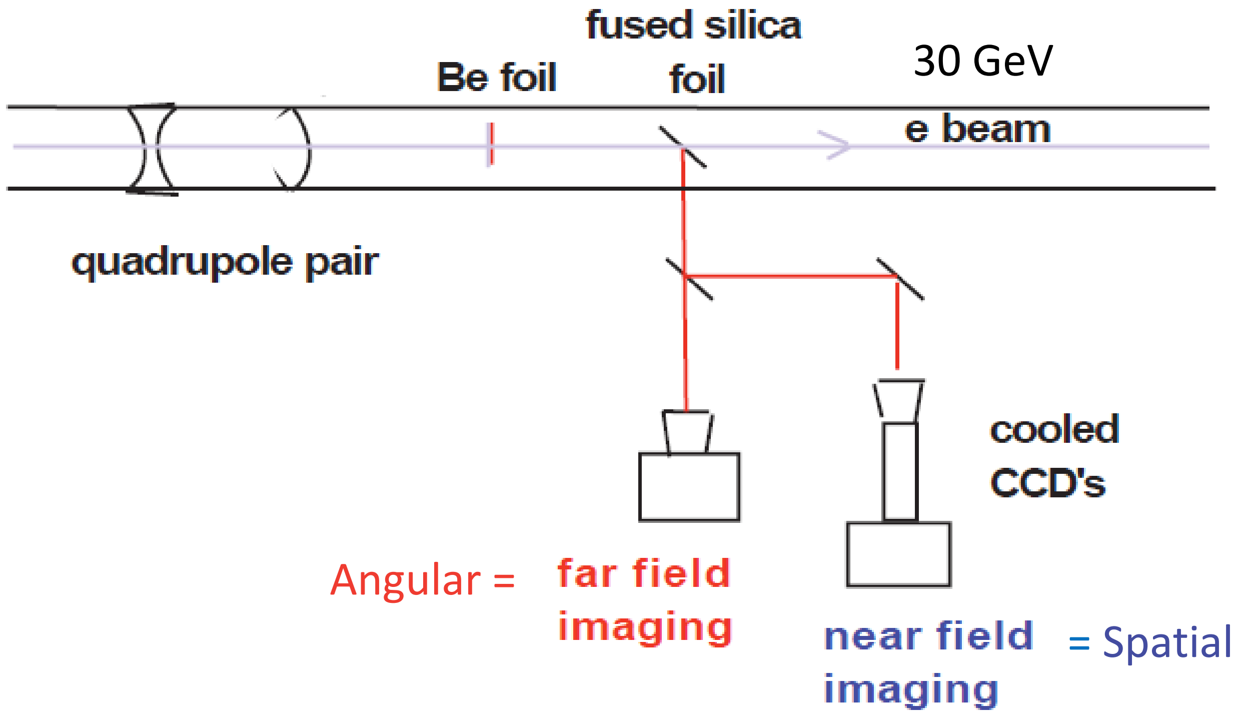


Photon yield increases with energy

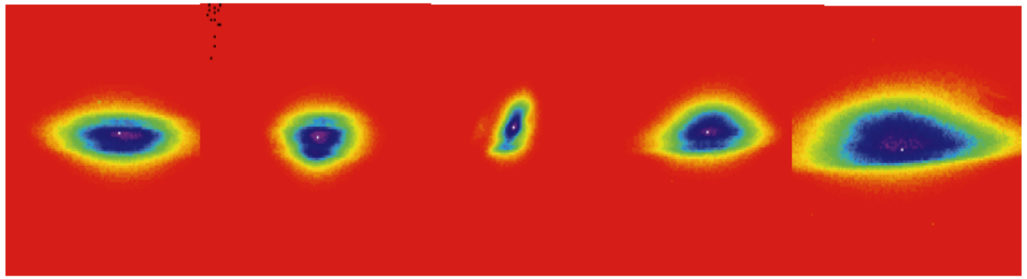


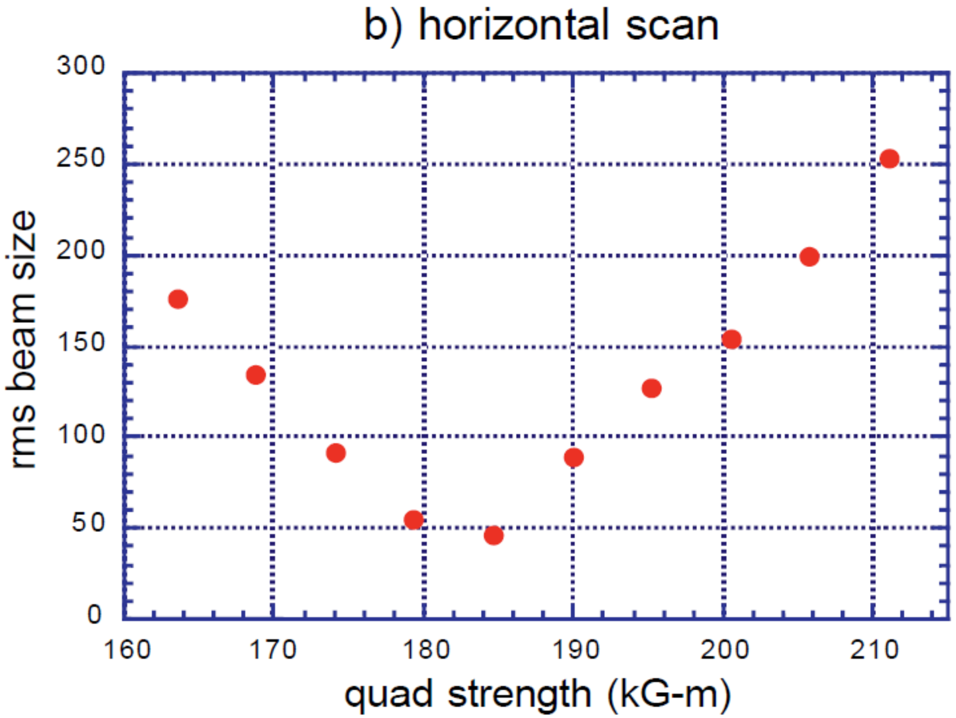
Width increases with wavelength

Electron Linac – Transition Radiation



Near-field imaging:

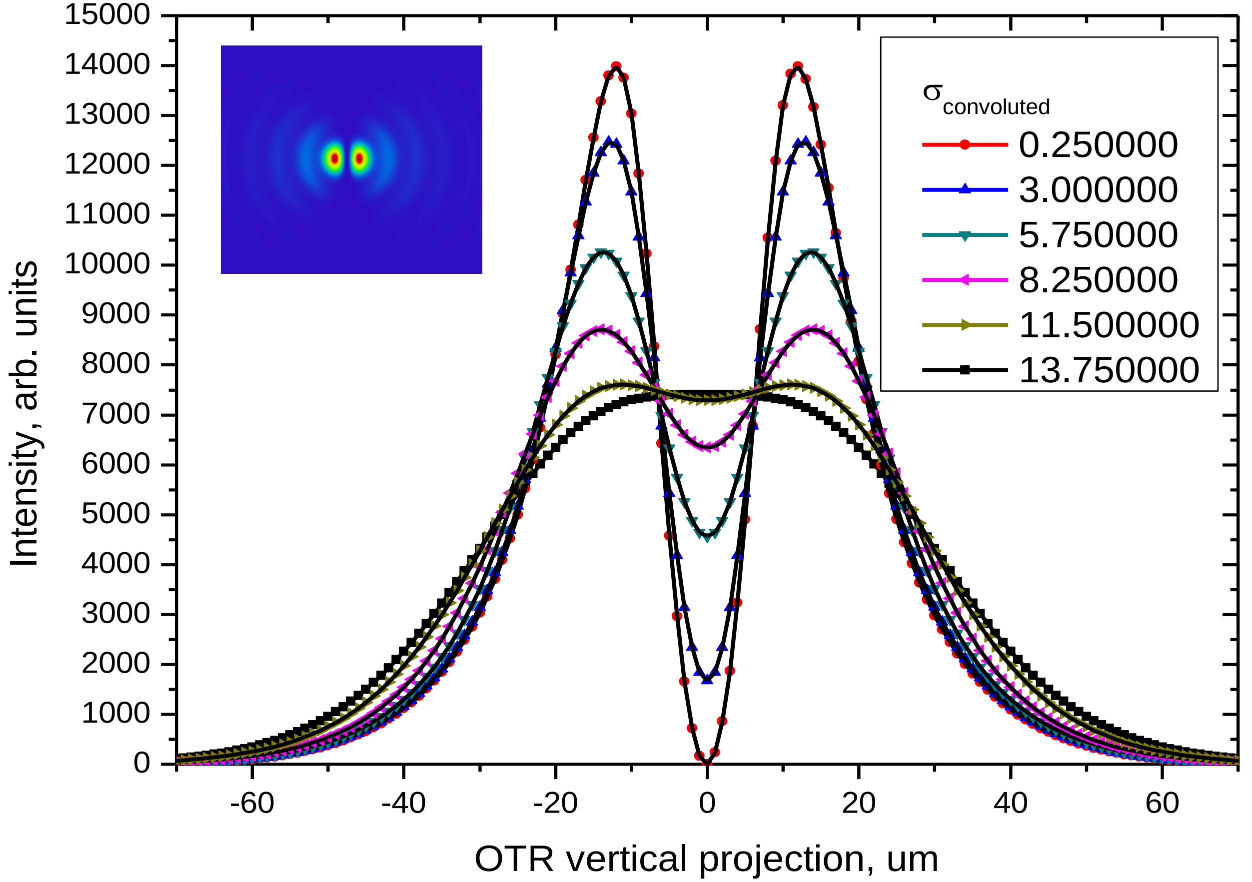




P. Catravas et al.,. (1999). Beam profile measurement at 30 GeV using optical transition radiation, Proc of PAC, *3*(3), 2111–211 (1999) https://doi.org/10.1109/pac.1999.794389

Electron Linac – Transition Radiation

OTR has a double-lobe Point Spread Function i.e. a central minimum.



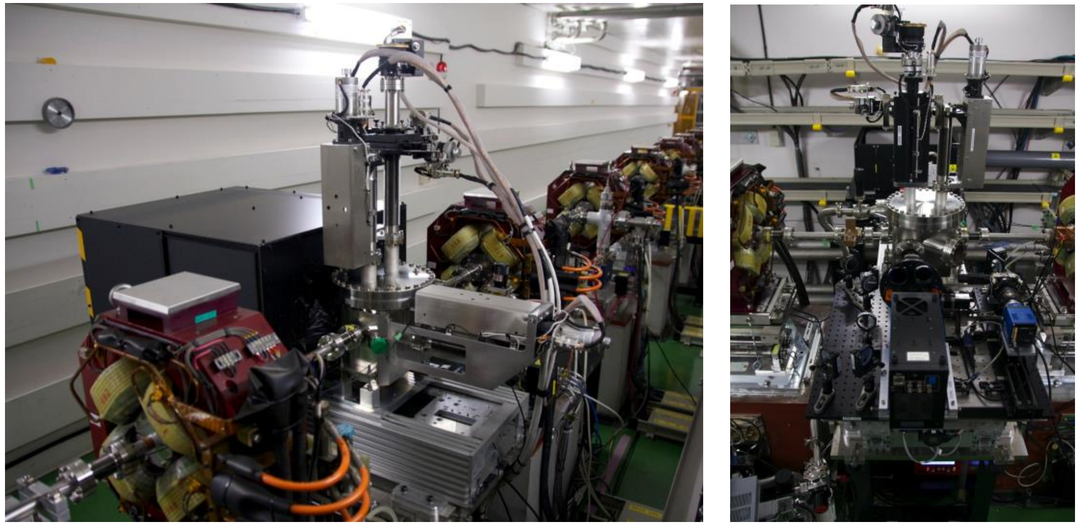
P. Karataev et al., PRL ***107****, 174801 (2011)*

Very small beam size measurement using the visibility of the OTR Point (Particle) Spread Function

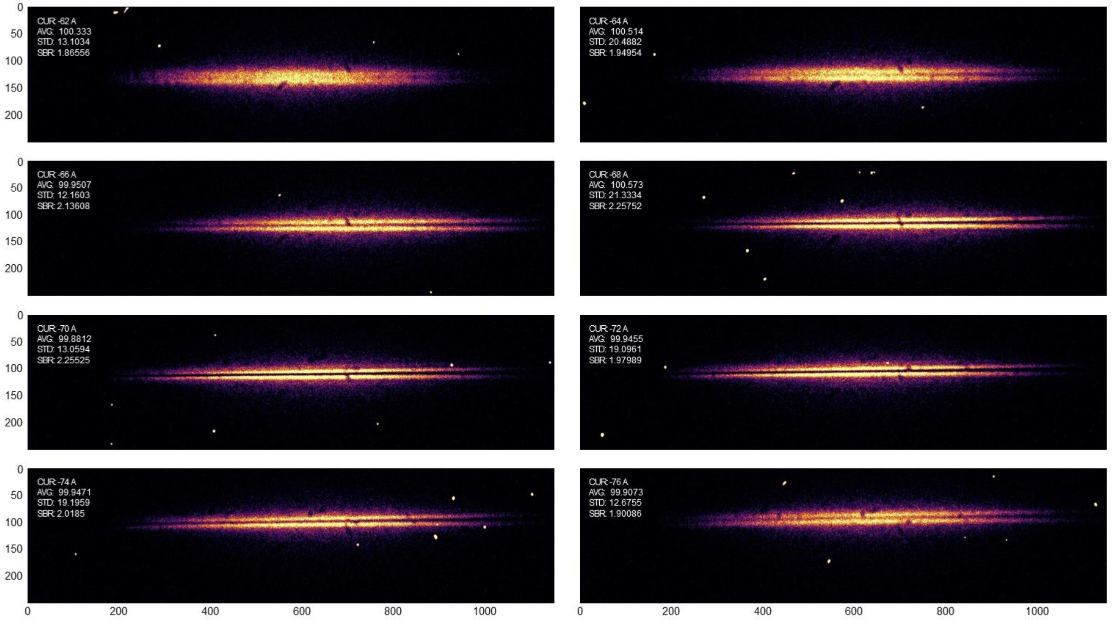
Electron Linac – Transition Radiation

High magnification / resolution imaging system using Optical transition radiation as a simple solution

P. Karataev *et al.*, PRL **107**, 174801 (2011)
B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)



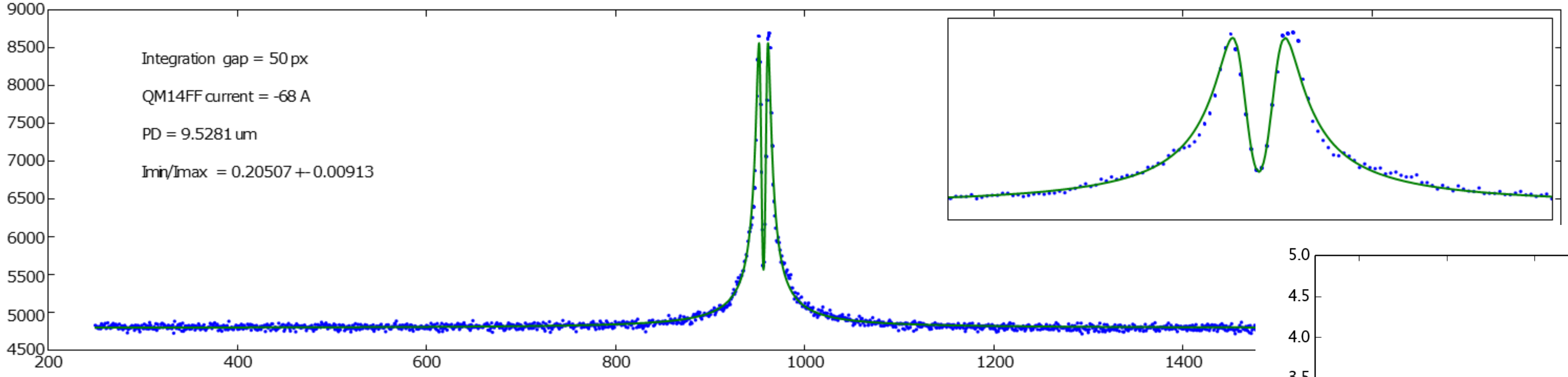
Test on ATF2 extraction beam line at KEK



Images acquired during a Quadrupole scan

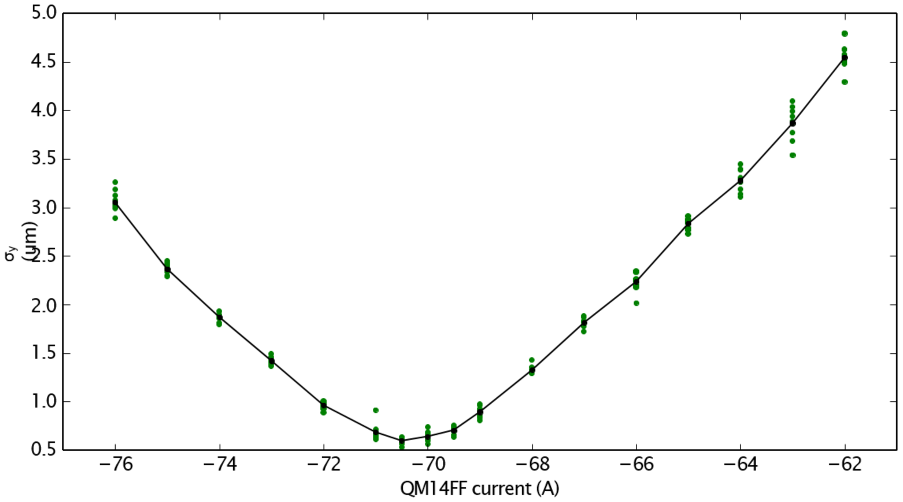
Electron Linac – Transition Radiation

High magnification / resolution imaging system using Optical transition radiation as a simple solution



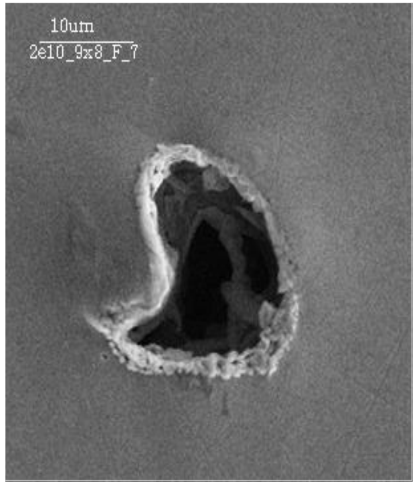
P. Karataev *et al.*, PRL **107**, 174801 (2011)
B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)

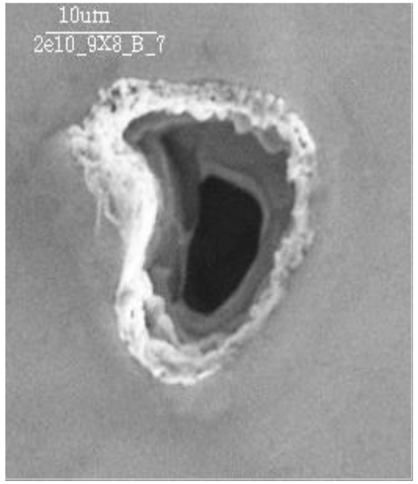
Smallest beam size measured 600nm



Electron Linac – Transition Radiation

OTR, It's all good but….

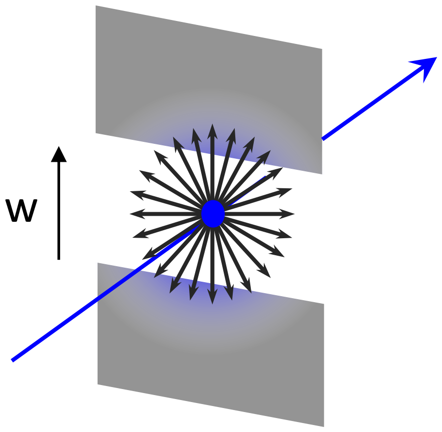




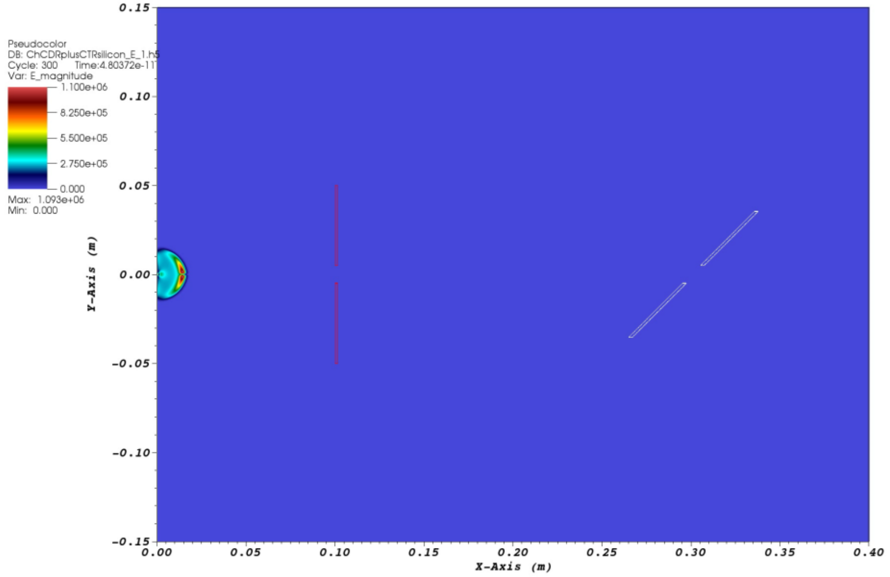
Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using
  Optical diffraction radiation from thin dielectric slits

Optical system here



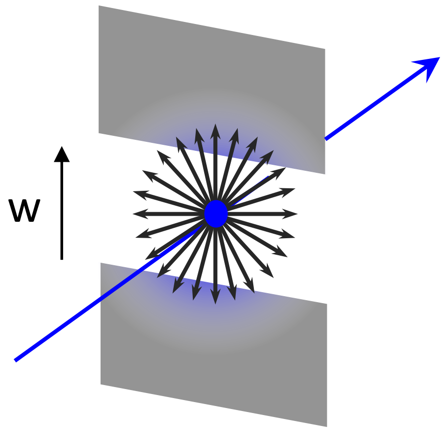
effective electric field radius $\sim\gamma\lambda$

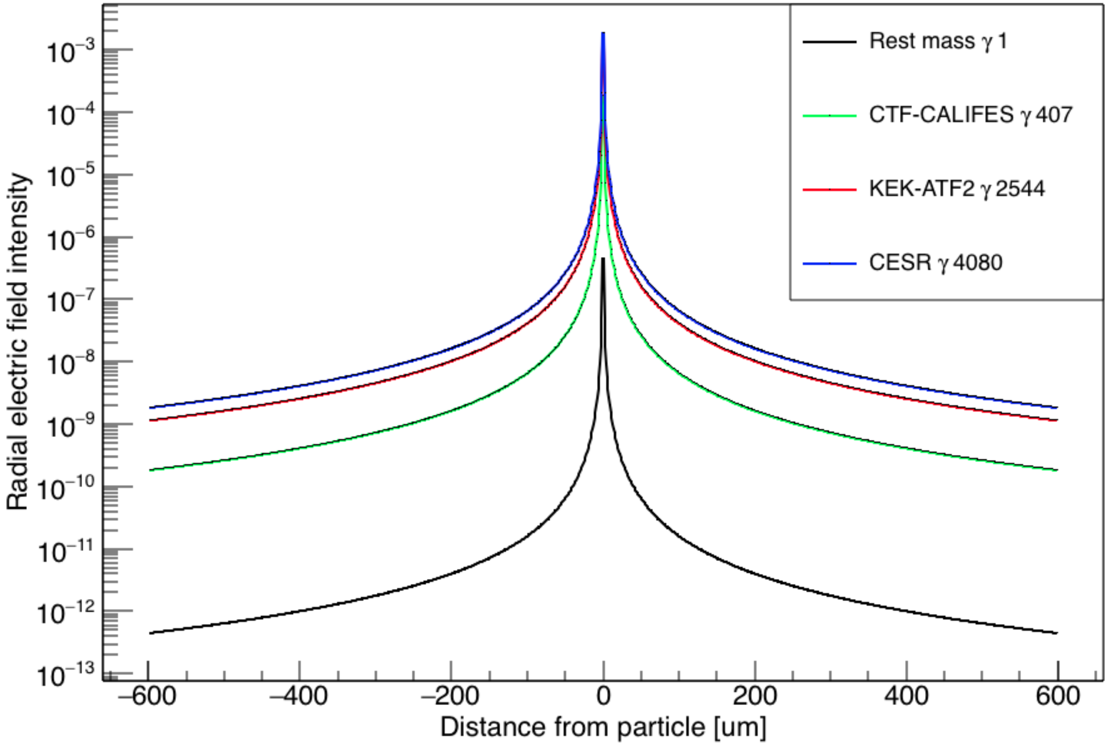


Upstream mask blocks synchrotron radiation

Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using
  Optical diffraction radiation from thin dielectric slits





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Electron Linac – Diffraction Radiation

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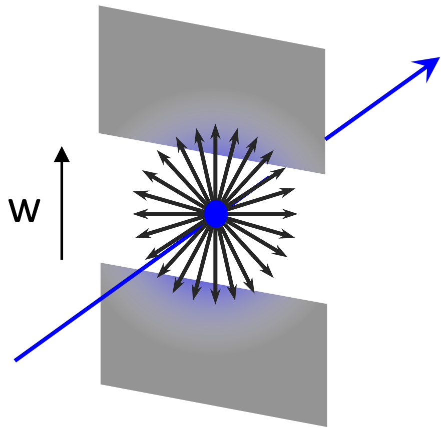
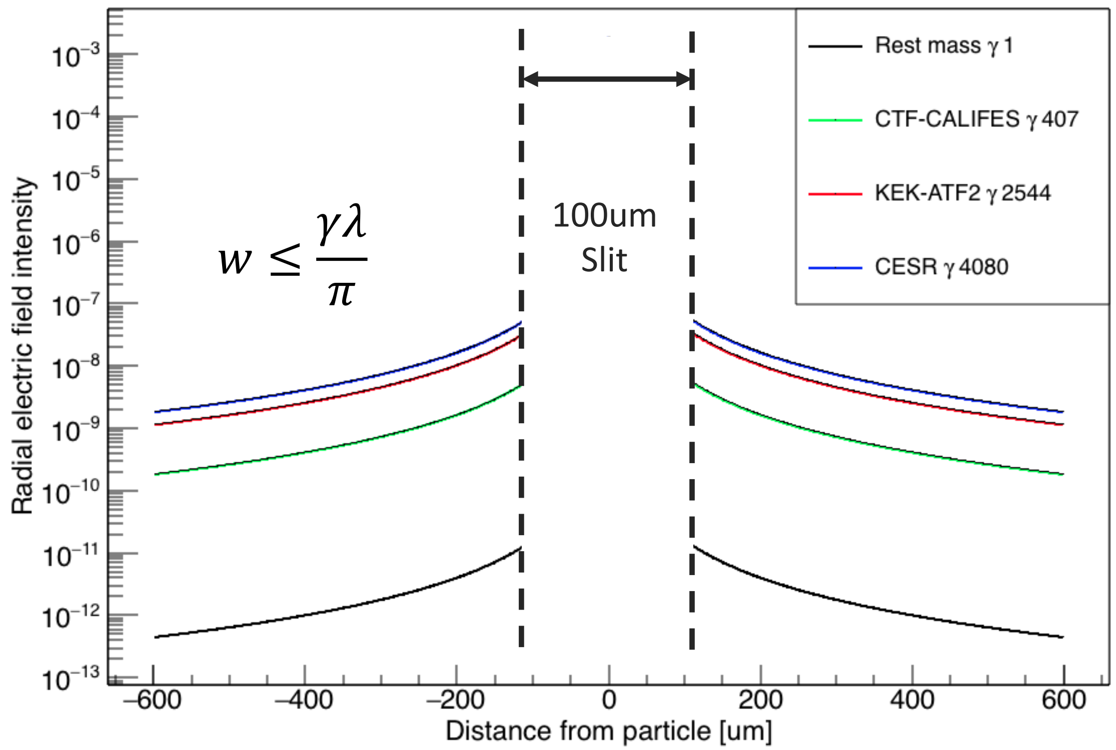
  Optical diffraction radiation from thin dielectric slits





Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using
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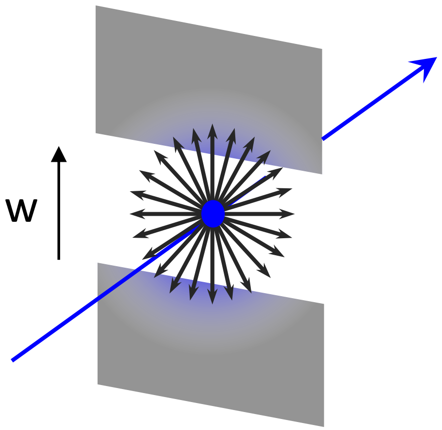
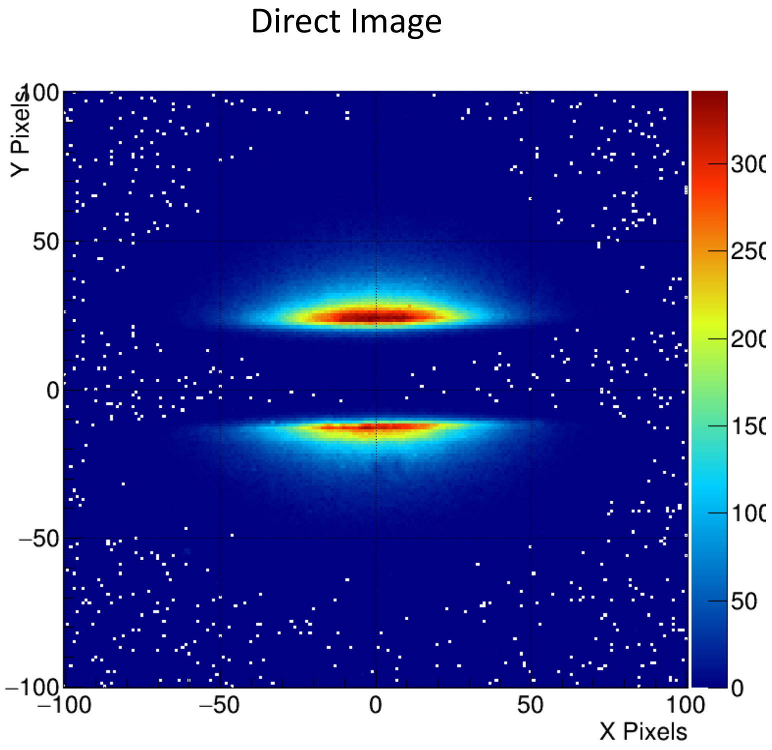
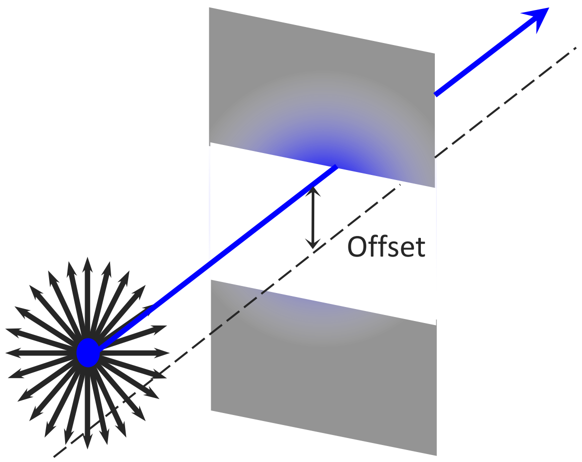
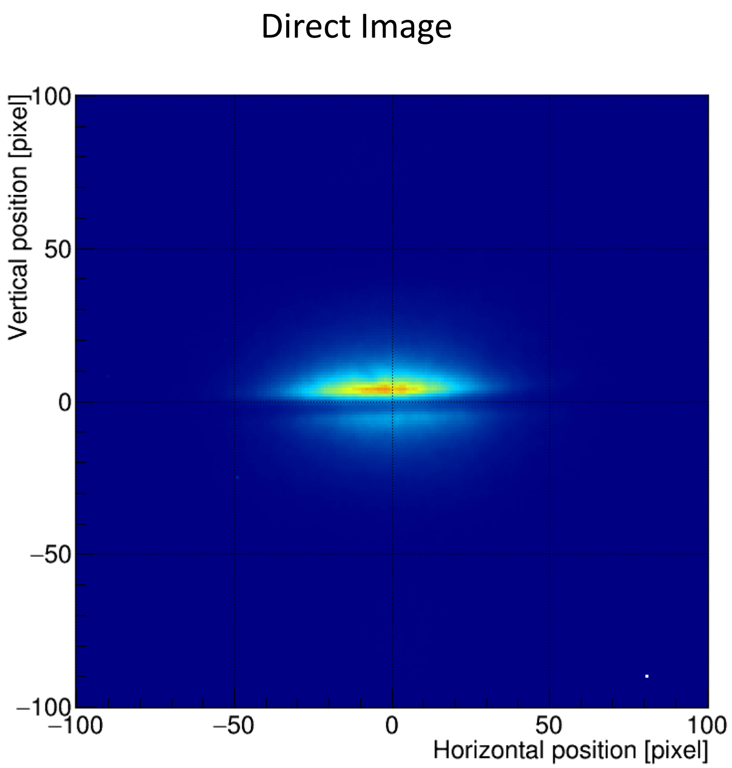




Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using
  Optical diffraction radiation from thin dielectric slits



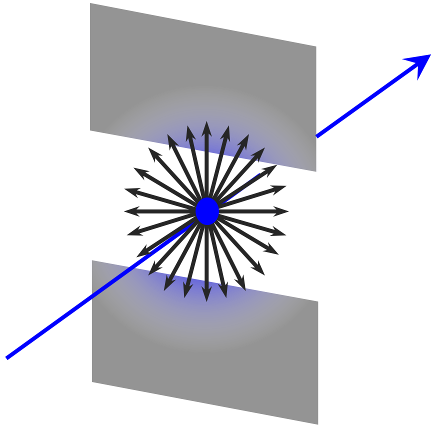


Important to align beam to the centre of the slit!

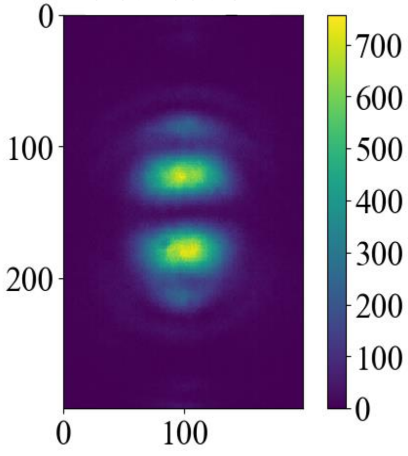
Or can exploit this dependency as a beam position monitor.

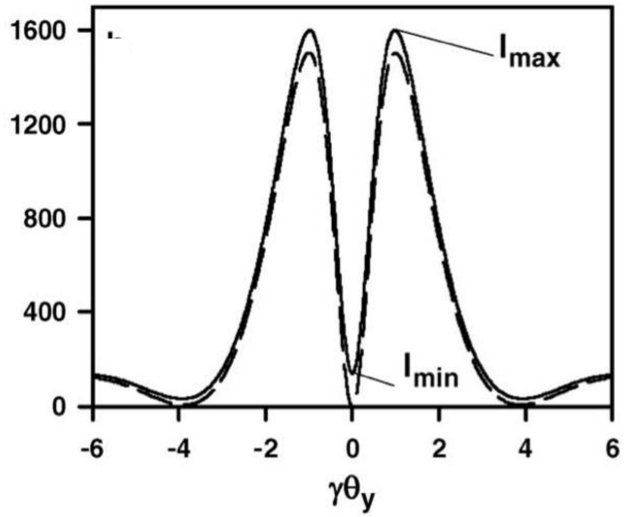
Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**



2D Angular distribution





The **beam size and beam divergence can be** extracted from the **visibility I_{min}/I_{max}** of the projected vertical component of the **ODR angular distribution**

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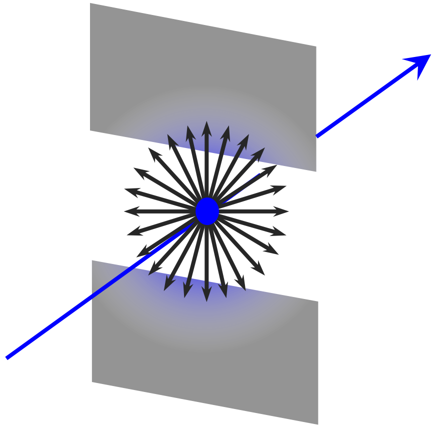
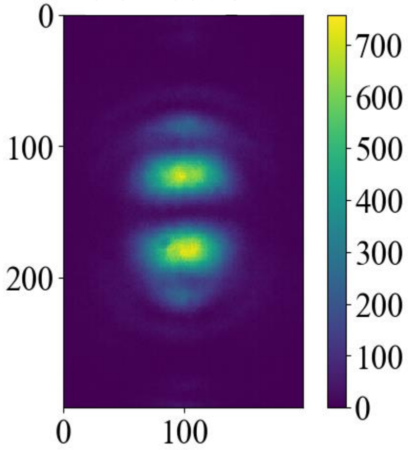
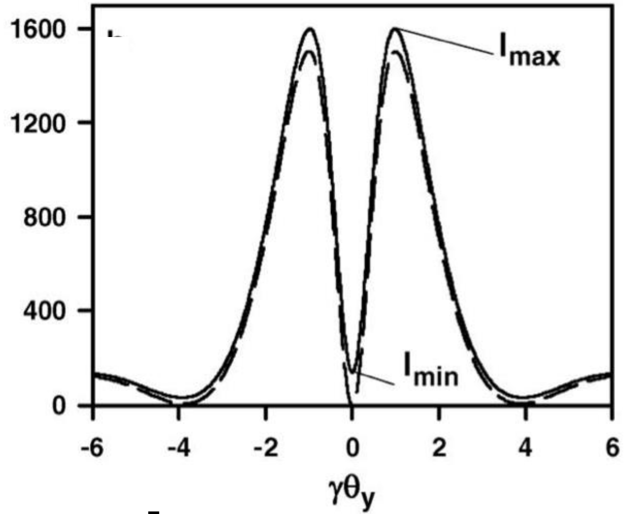
Electron Linac – Diffraction Radiation

- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**



2D Angular distribution



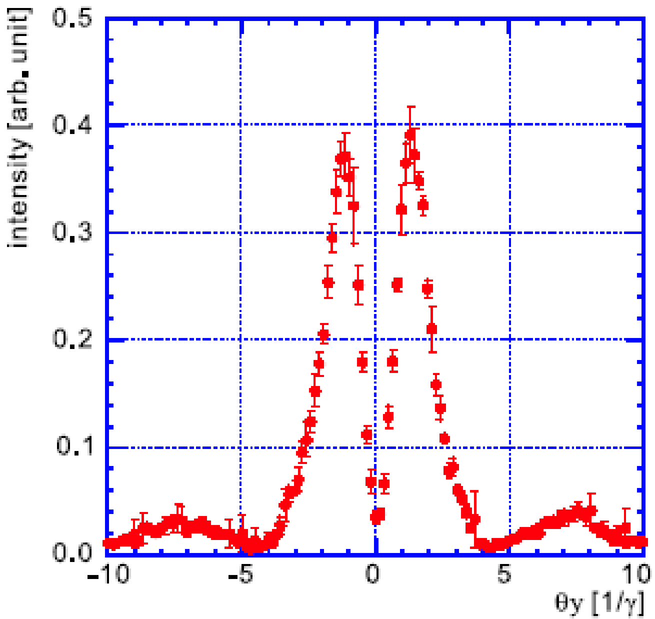


$$\frac{d^2W_y^{slit}}{d\omega d\Omega} = \frac{\alpha\gamma^2}{2\pi}\frac{e^{\left(-\frac{2a\pi\sin\theta_0}{\gamma\lambda}\sqrt{1+t_x^2}\right)}}{1+t_x^2+t_y^2}\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2\gamma^2}\left(1+t_x^2\right)\right]\cosh\left[-\frac{4\bar{a}\pi}{\gamma\lambda}\sqrt{1+t_x^2}\right]-\cos\left[\frac{2a\pi\sin\theta_0}{\gamma\lambda}t_y+2\psi\right]\right\}$$

$$\psi = \arctan[t_y/\sqrt{1+t_x^2}].$$

Electron Linac – Diffraction Radiation

- First Measurements at KEK (Linear collider study)



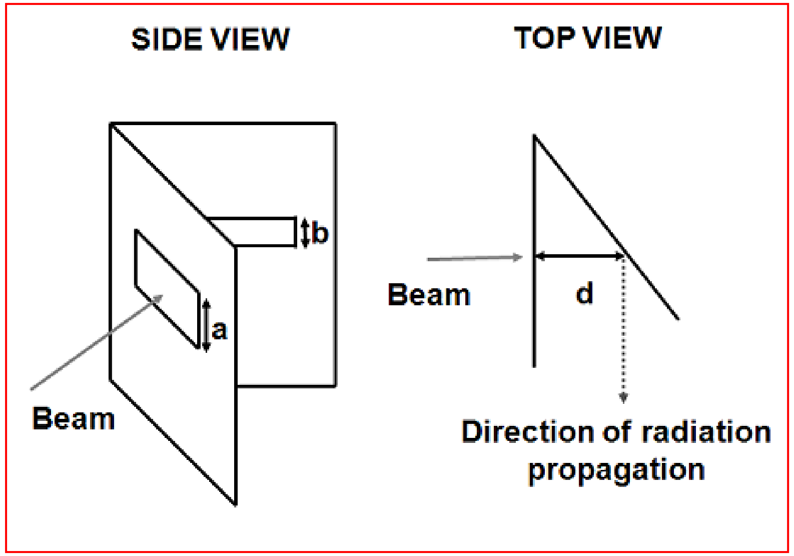
P. Karataev et al., “*Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility*”, Phys. Rev. Lett. 93, 244802 (2004)

  – Weak signal vs strong background, coming mainly from Synchrotron Radiation
  – Smallest beam size observed 14um

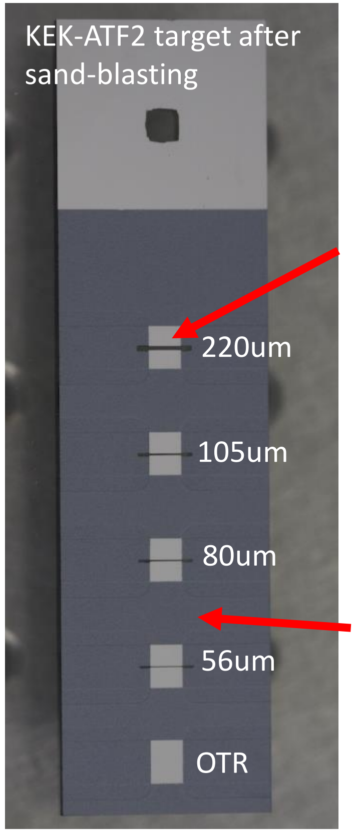
Electron Linac – Diffraction Radiation

- Optimisation on Target manufacturing and SR background suppression

Adding a Mask in front of the slit



A. Cianchi et al. PRSTAB 14, 102803 (2011)
L. Bobb et al. PRAB 21, 032801 (2018)



Maximizing emission of DR with Al coating around the slit

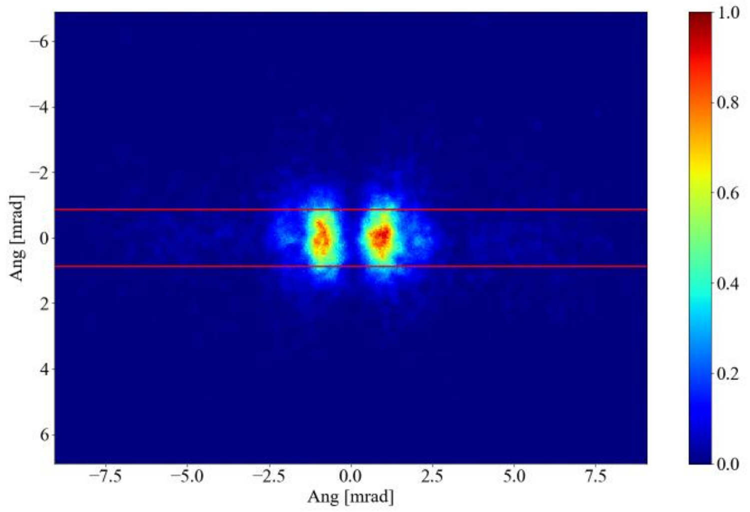
Minimizing reflection of SR by sand-blasting the rest of the target

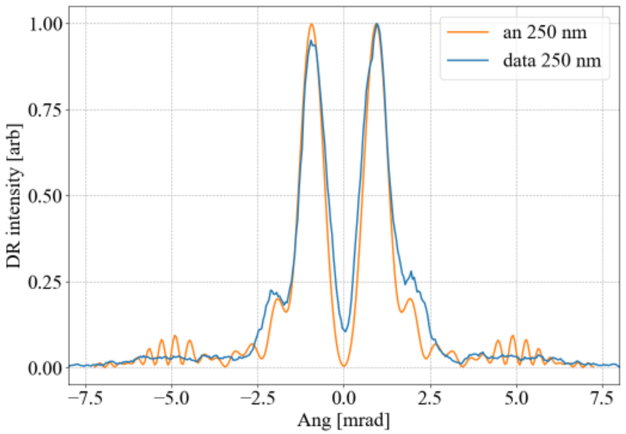
R. Kieffer et al. NIMB 402 88 (2018)

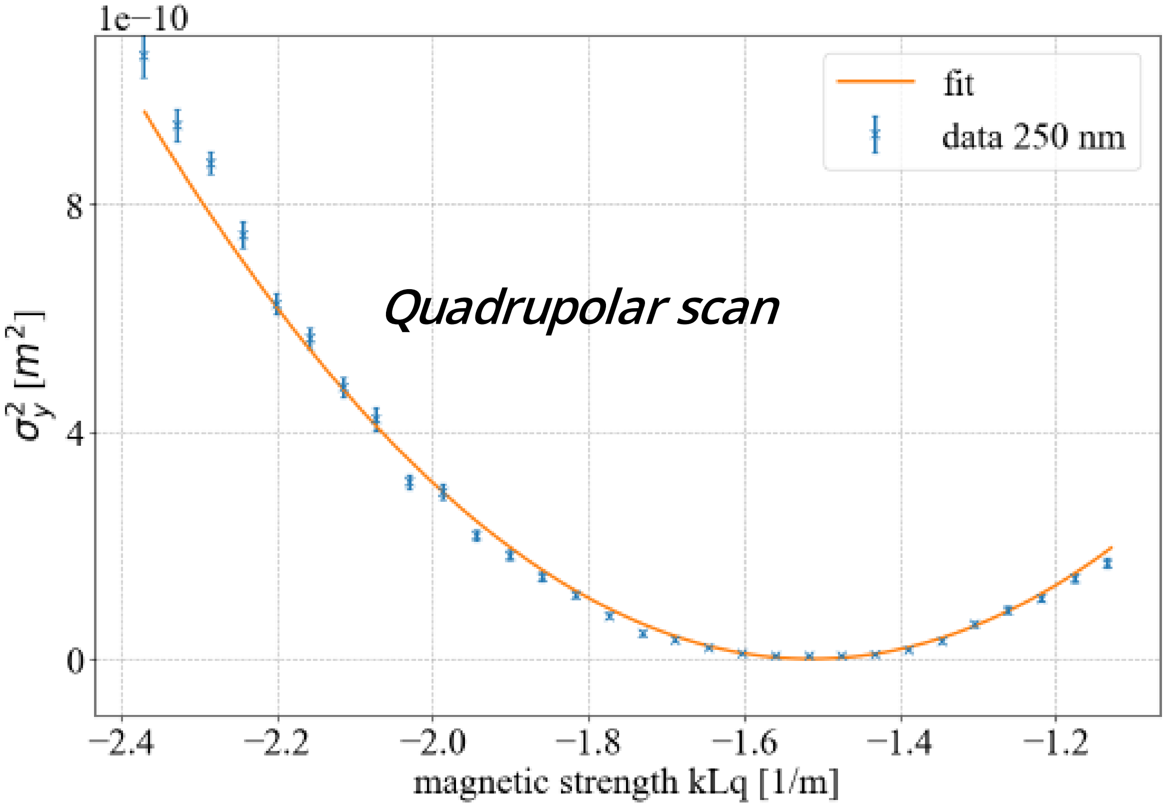
Electron Linac – Diffraction Radiation

- Small beam size of 3um measured using UV light at 250nm

M. Bergamaschi et al., Physical Review Applied 13, 014041 (2020)







Electron Linac – Diffraction Radiation

ODR, It‘s good but....

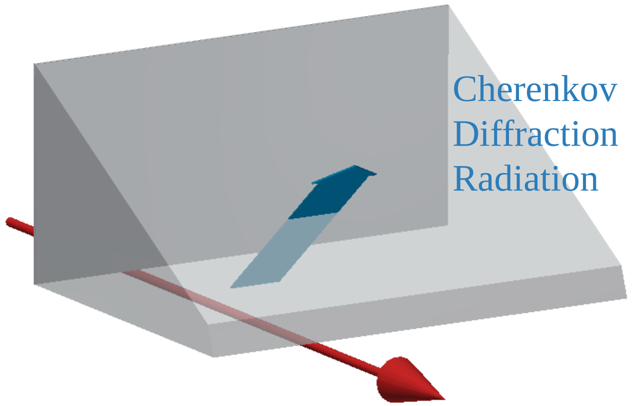
- Looking for higher light yield !
- Getting rid of Synchrotron radiation background

Cherenkov diffraction radiation in longer dielectrics

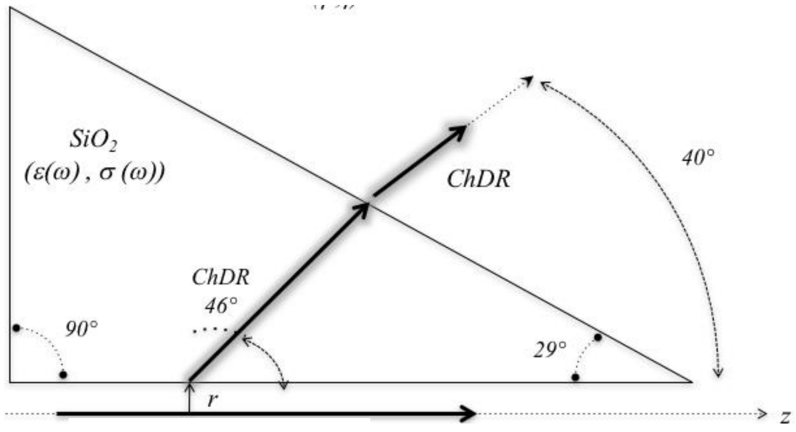
Electron Linac – Cherenkov Diffraction Radiation

- Cherenkov Diffraction Radiation in dielectrics

~~Particle~~ Field goes faster than light $\beta > 1/n$



Charged Particle



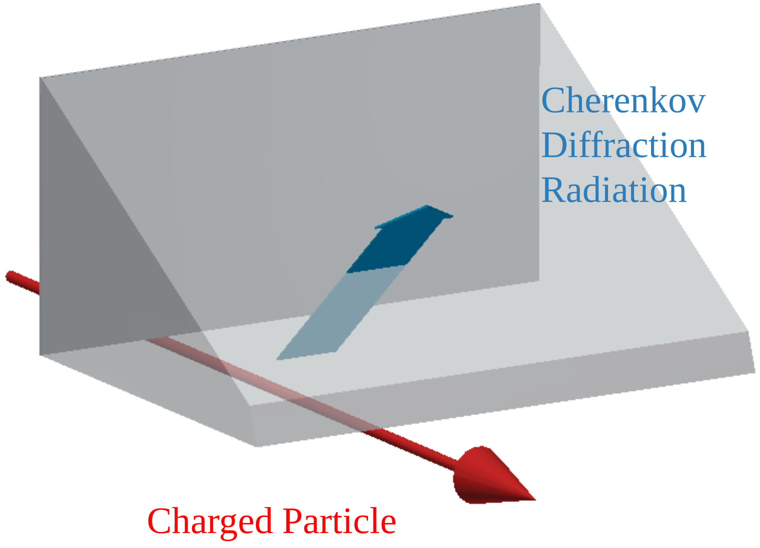
Charged Particle

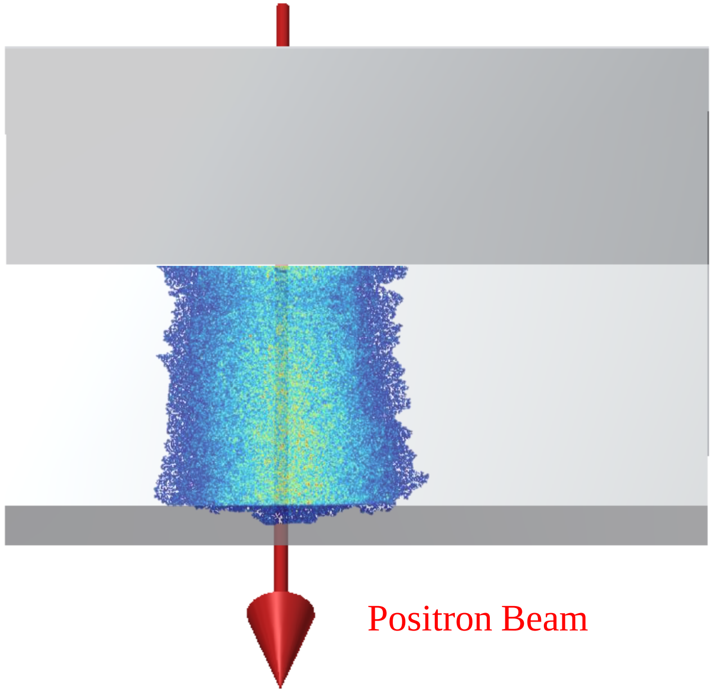
The total number of photons proportional to the length of the Cherenkov radiator

Cherenkov Angle $$\cos(\theta_c) = \frac{1}{\beta n}$$ *n Index of refraction*

Electron Linac – Cherenkov Diffraction Radiation

- Cherenkov Diffraction Radiation first measurement in 2017 using 5.3GeV electron/positrons using direct imaging in visible range



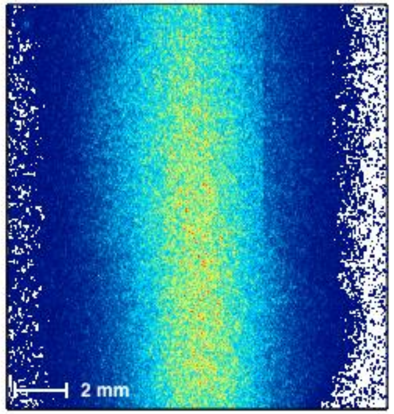


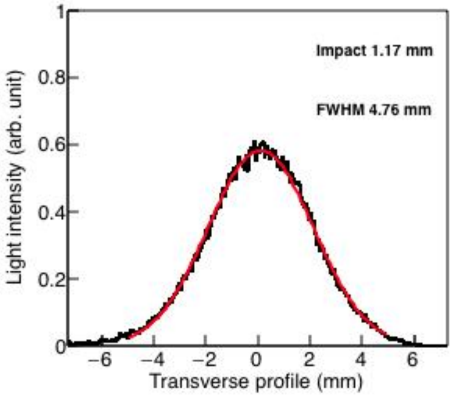
R. Kieffer et al., "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL ***121*** *(2018) 054802*
R. Kieffer et al., "Generation of Incoherent Cherenkov Diffraction Radiation in synchrotrons", PRAB ***23*** *(2020) 042803*

Electron Linac – Cherenkov Diffraction Radiation

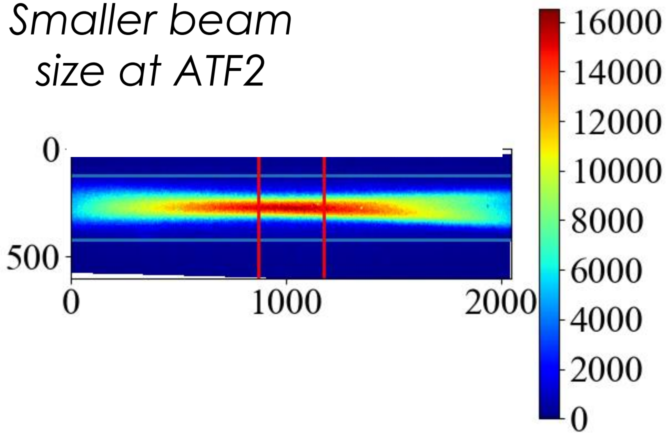
- Measuring beam size using ChDR

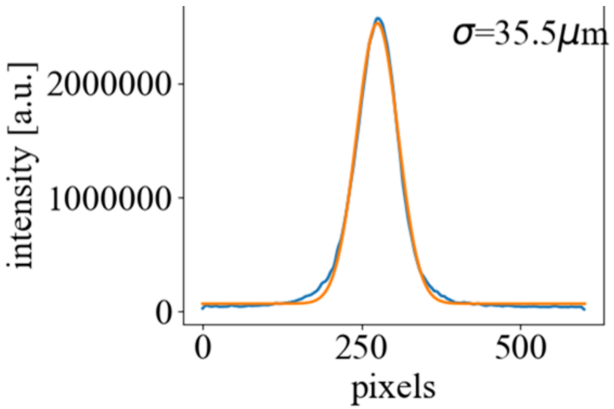
Large beam size at Cornell





Smaller beam size at ATF2





Electron Linac – Cherenkov Diffraction Radiation

- Measuring beam size using ChDR

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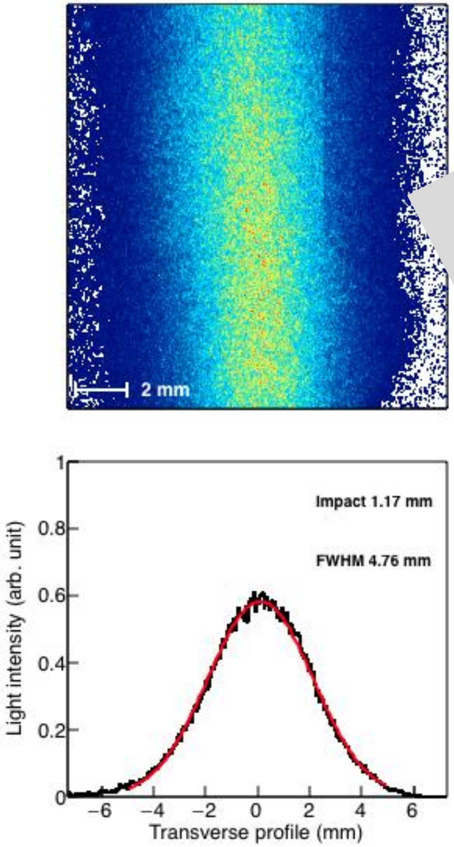
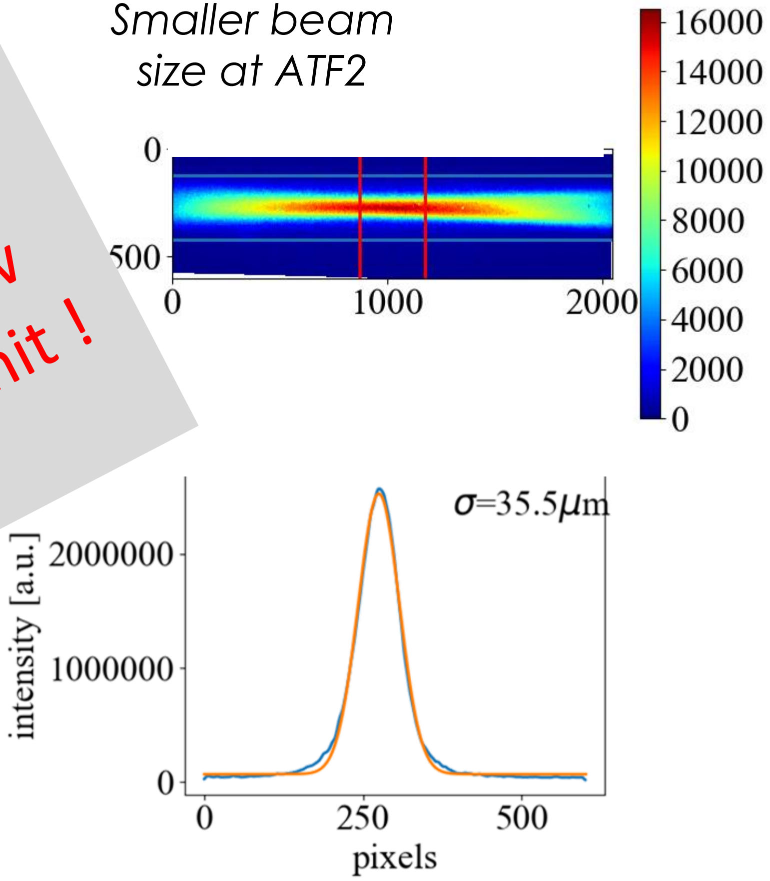
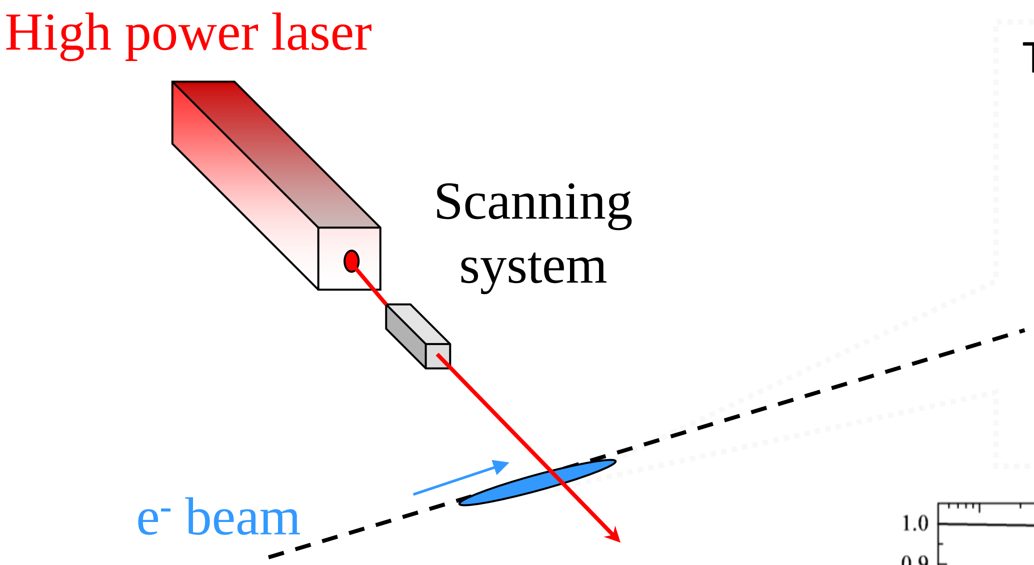


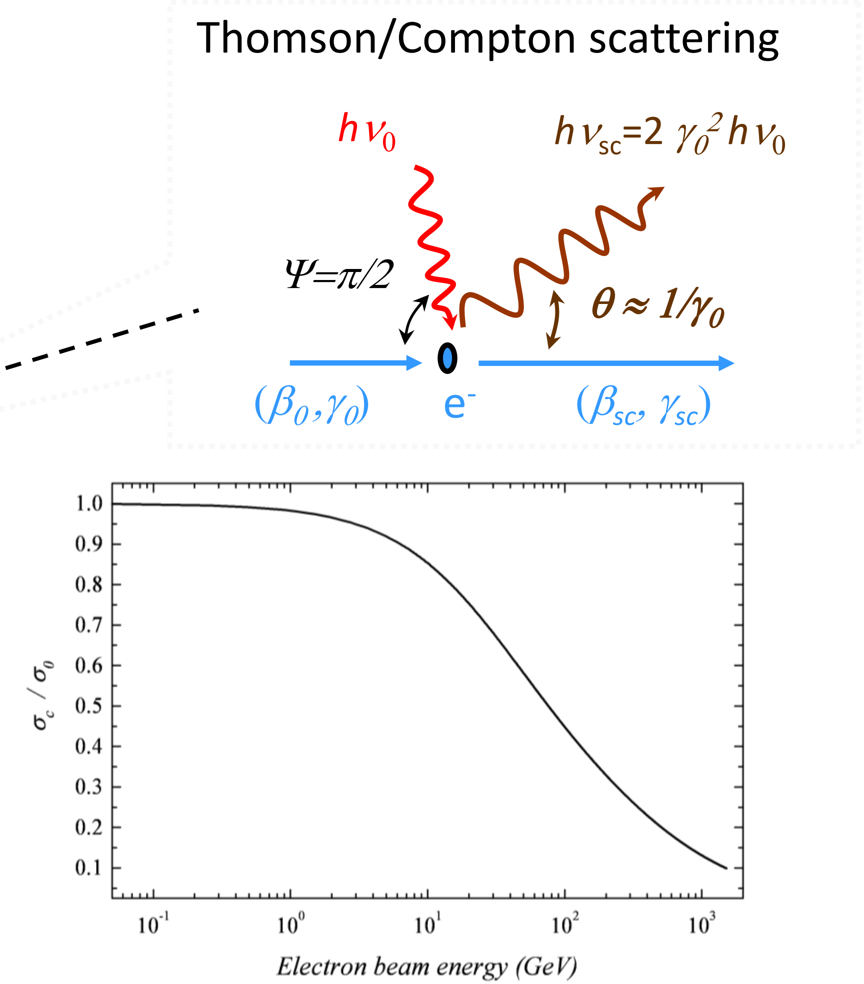
Still preliminary - We do not know where is the limit !

Smaller beam size at ATF2



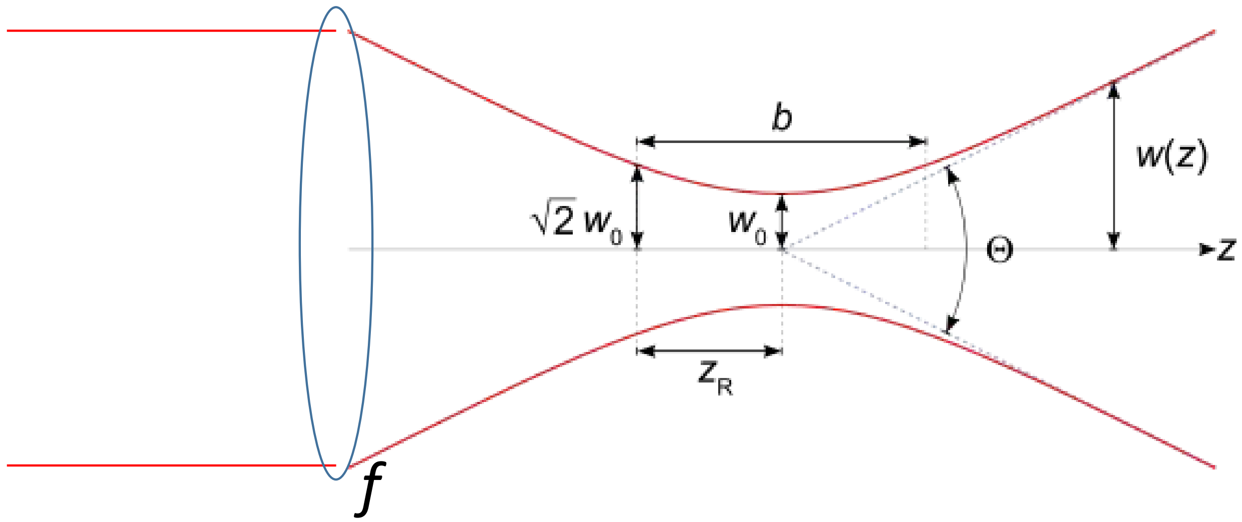
Electron Linac – Laser Wire Scanner





- 10^{-7} smaller than Cross-section for stripping electron from H^-
- Need for high power laser (>10MW)

Electron Linac – Laser Wire Scanner



Can reach beam waist close to the wavelength !

Beam waist

$$w_0 = \frac{\lambda}{\pi} M^2 \frac{2f}{d}$$

Rayleigh length

$$z_R = \frac{\pi {w_0}^2}{\lambda M^2}$$

Beam transverse size (1/e^2)

$$w(z) = w_0 \sqrt{1 + \left(z/z_R\right)^2}$$

M^2 is measure of beam quality (M^2 = 1 would be an ideal Gaussian)

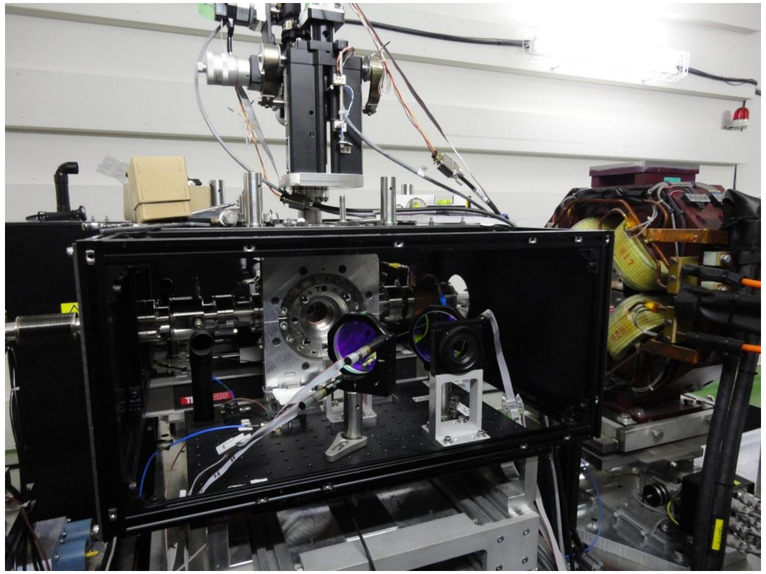
Electron Linac – Laser Wire Scanner

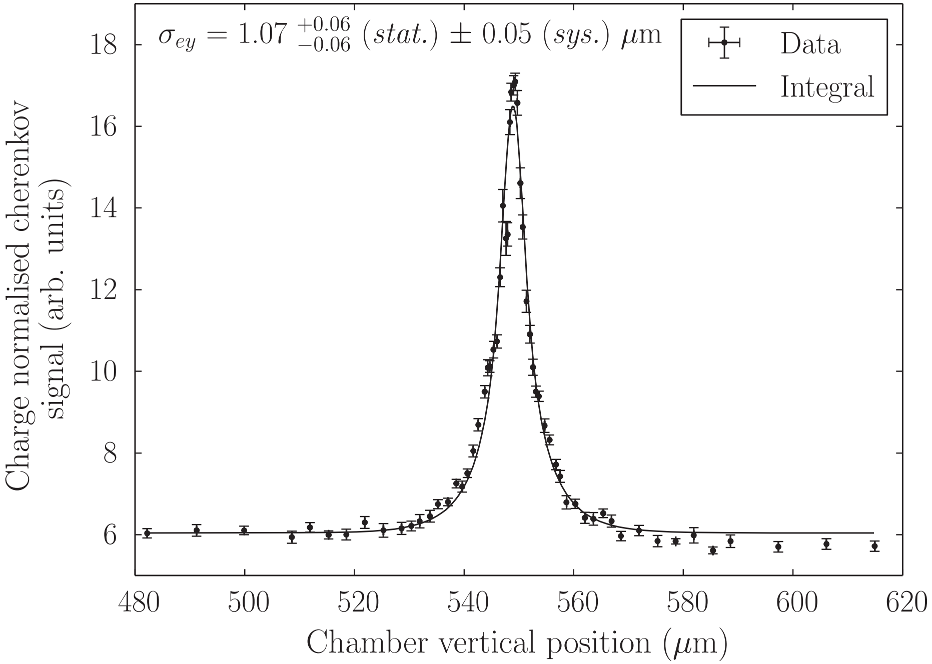
- First tests at SLAC in 90's

R. Alley et al, **NIM A 379 (1996) 363** & P. Tenenbaum et al, **SLAC-PUB-8057, 1999**

- Intense R&D for Linear collider studies

H. Sakai *et al.*, Physical Review ST AB 4 (2001) 022801 & ST AB 6 (2003) 092802
I. Agapov, G. A. Blair, M. Woodley, Physical Review ST AB 10, 112801 (2007)
S. T. Boogert *et al.*, Physical Review ST AB 13, 122801 (2010)





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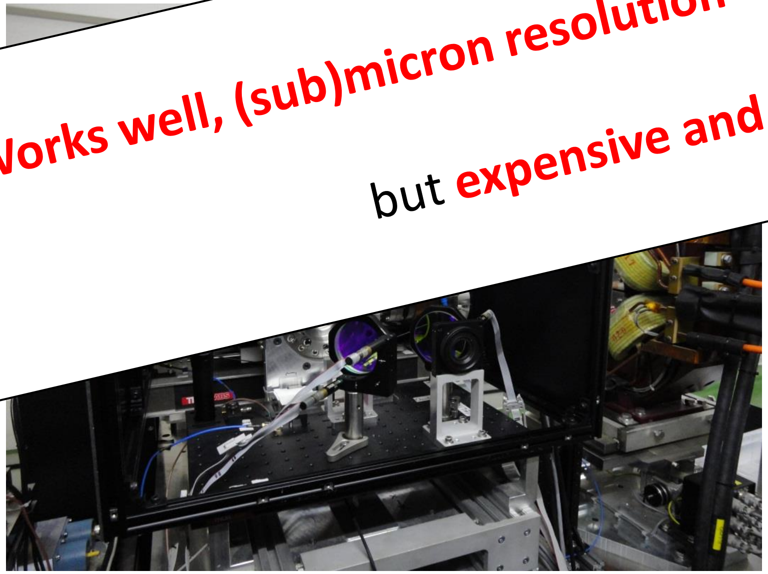
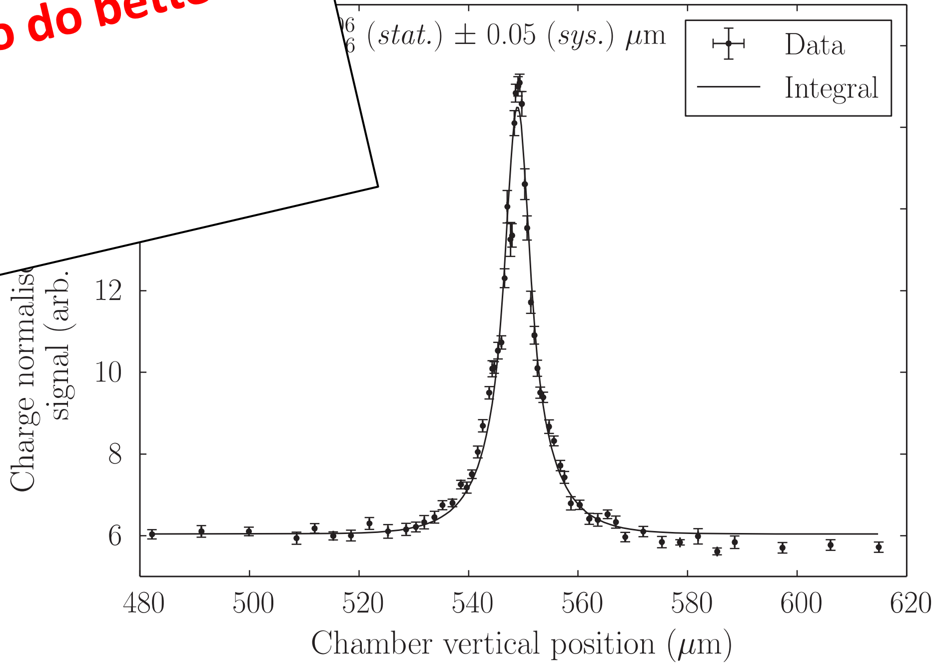
H. Sakai *et al.*, Physical Review ST AB 4 (2001) 022801 & ST AB 6 (2003
I. Agapov, G. A. Blair, M. Woodley, Physical Review ST AB 1
S. T. Boogert *et al.*, Physical Review ST AB 13

Works well, (sub)micron resolution – difficult to do better

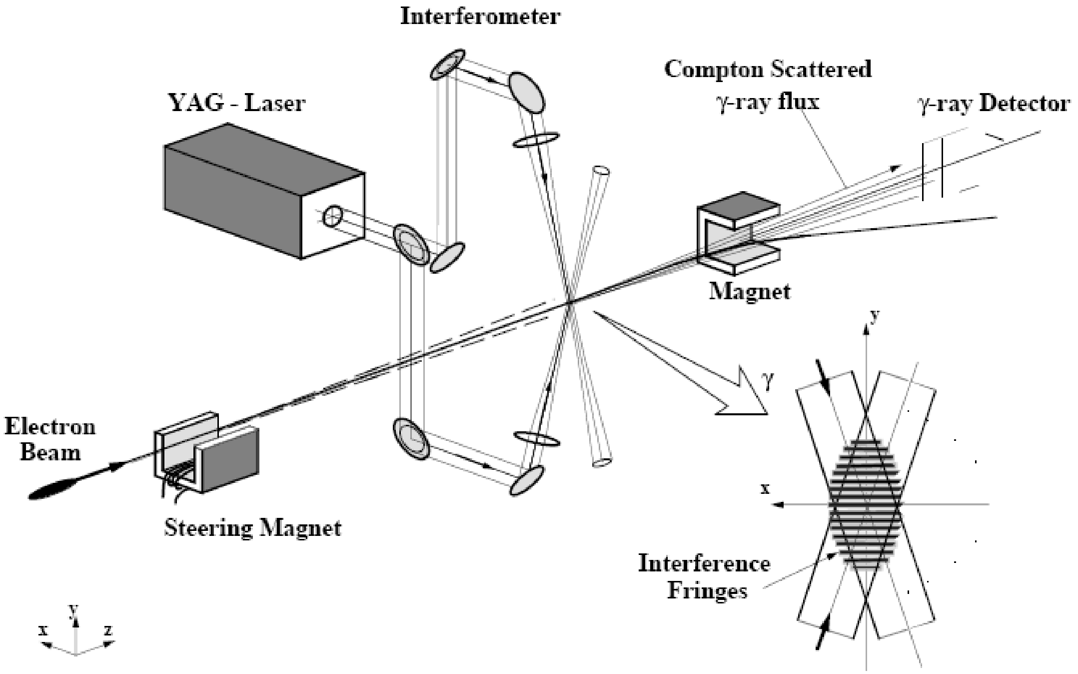
but **expensive and complex**





Electron Linac – 'Shintake monitor'

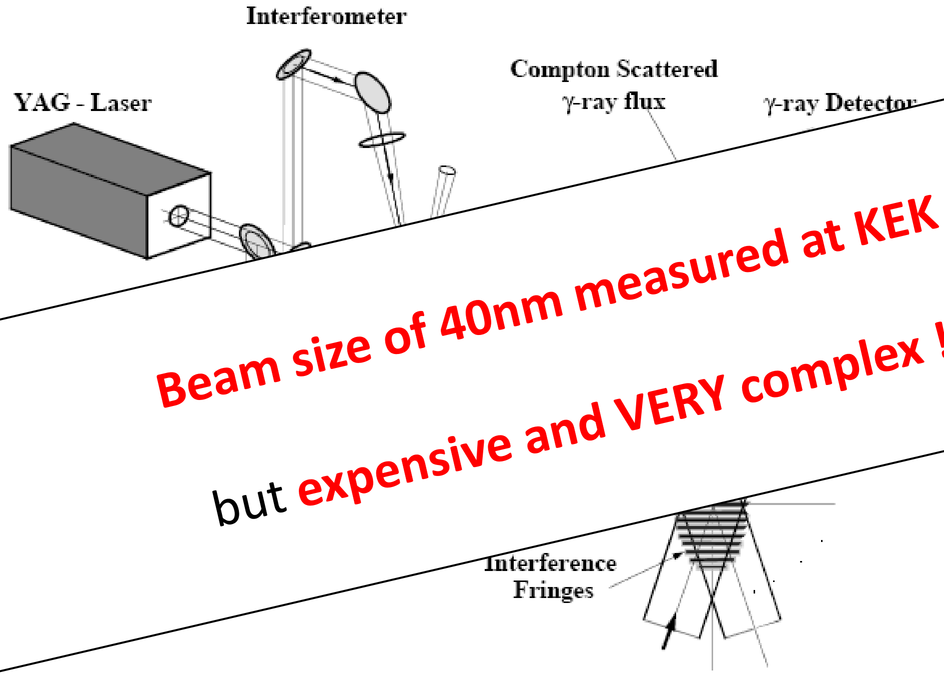
- Measuring nanometer beam size



Tsumoru Shintake, " *Proposal of a nanometer beam size monitor for e^+e^- linear collider*", Nuclear Instruments and methods in Physics Research A311 (1992) 453

Electron Linac – 'Shintake monitor'

- Measuring nanometer beam size



Beam size of 40nm measured at KEK

but expensive and VERY complex !

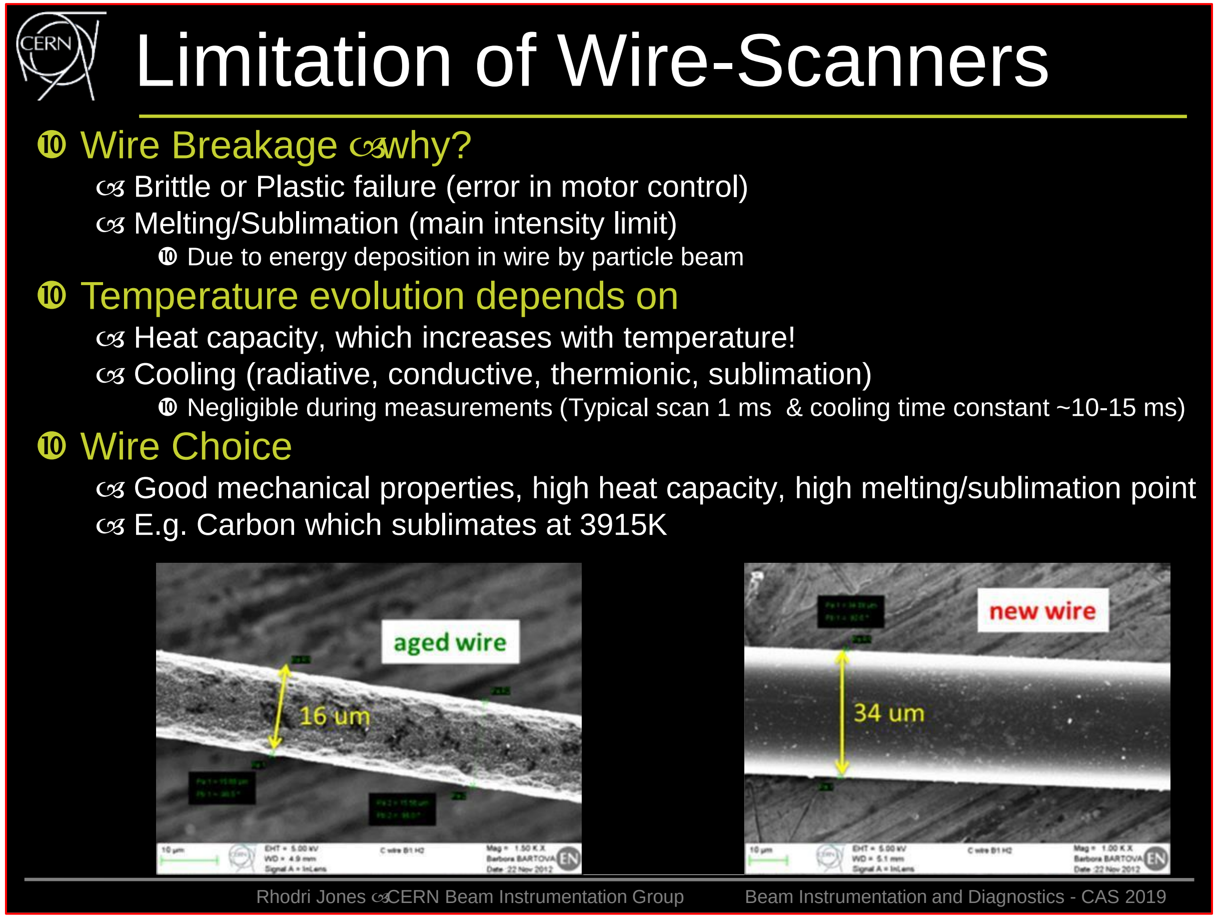
Tsumoru Shintake, " *Proposal of a nanometer beam size monitor for e^+e^- linear collider*", Nuclear Instruments and methods in Physics Research A311 (1992) 453

The CERN Accelerator School

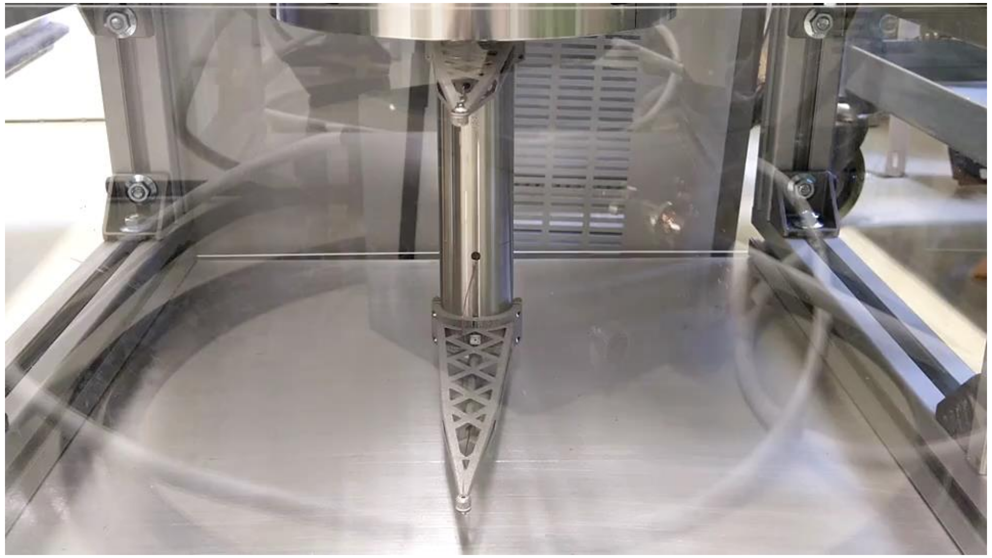
Transverse Diagnostics in Hadron Rings

……higher beam energy

Hadron ring - Wire Scanner

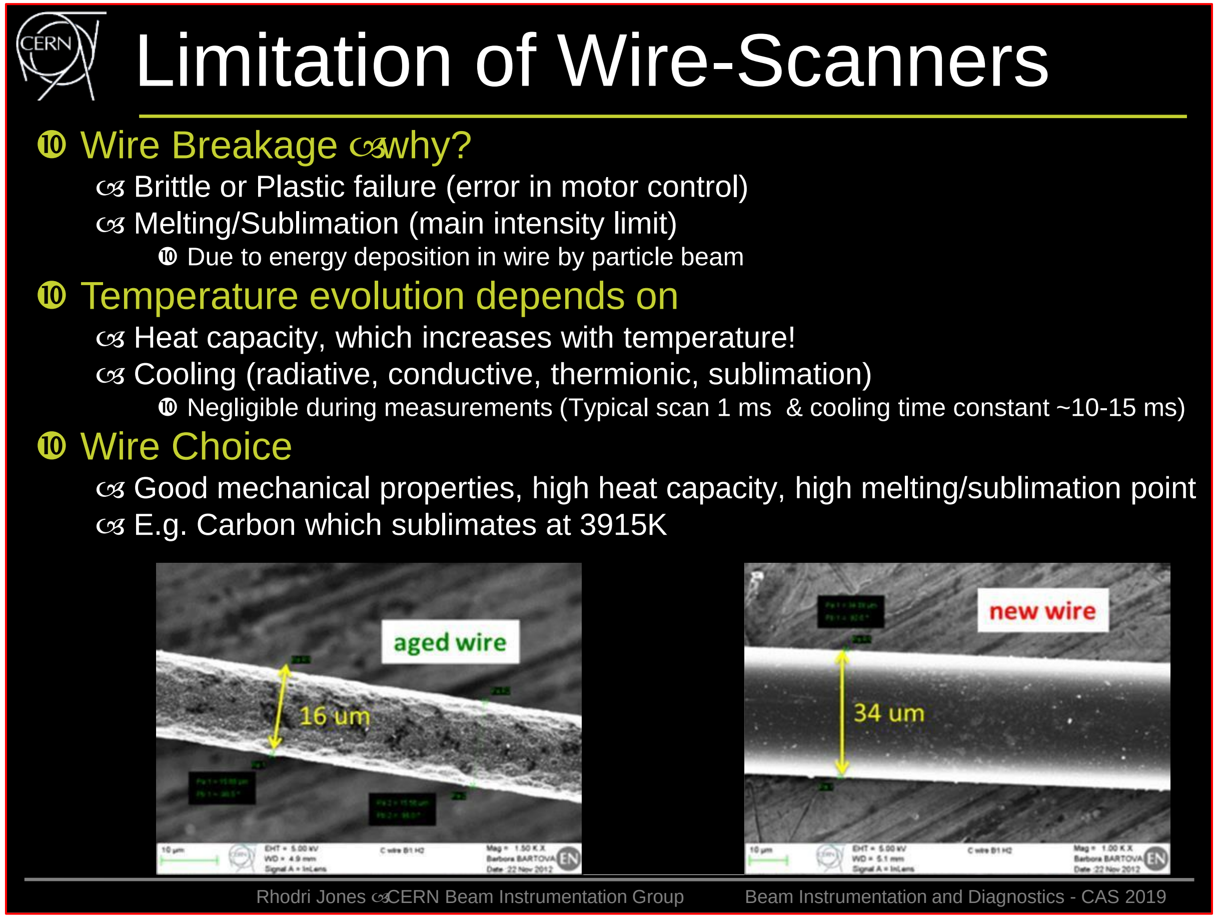


Scanning fast to measure higher beam intensities

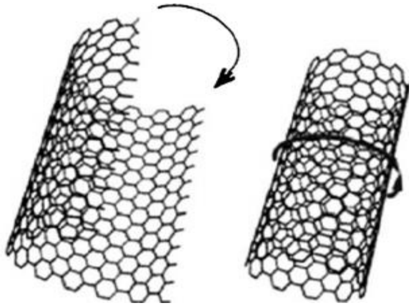


Max speed 20m/s

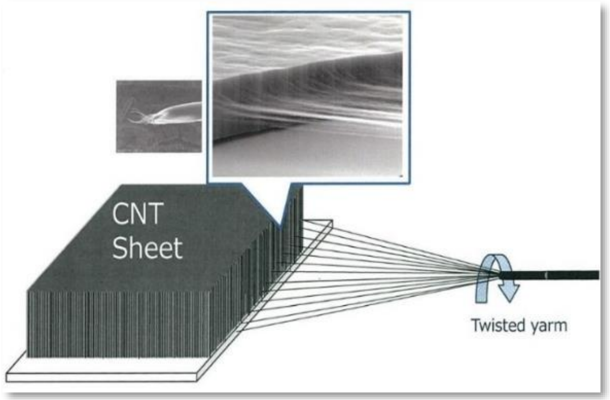
Hadron ring - Wire Scanner

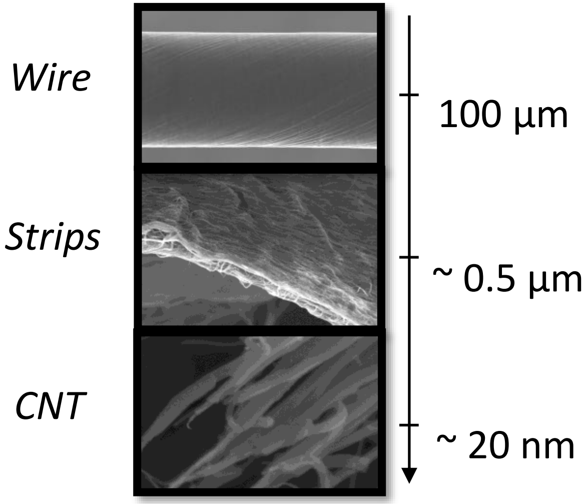


Using better materials for wire – ‘low density’ materials



From graphene to Carbon Nano-Tubes

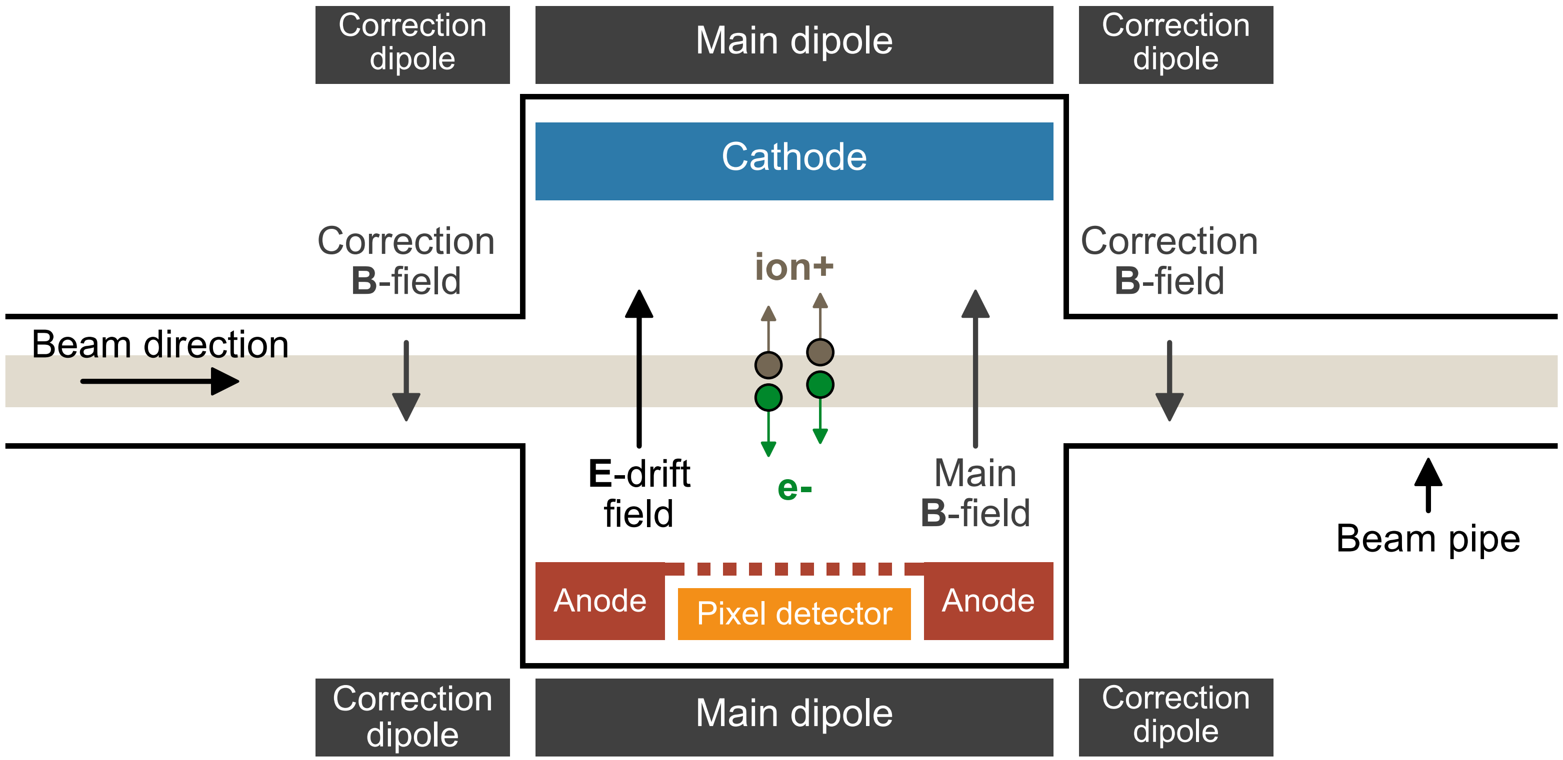


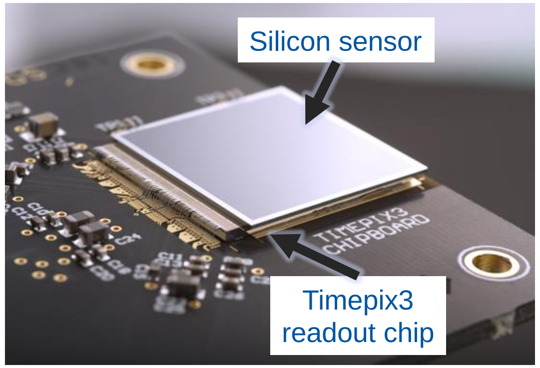


CNTW multi-scale

M. Veronese, et al., A nanofabricated wirescanner with free standing wires: Design, fabrication and experimental results. NIMA, *891*, 32–36. (2018)

Beam Gas Ionization Monitor





https://cds.cern.ch/record/2253263

- Sensor and readout are separate
- Readout Chip in Timepix3, CMOS 130nm
- Sensor can be made of Si, GaAs, CdTe, ..

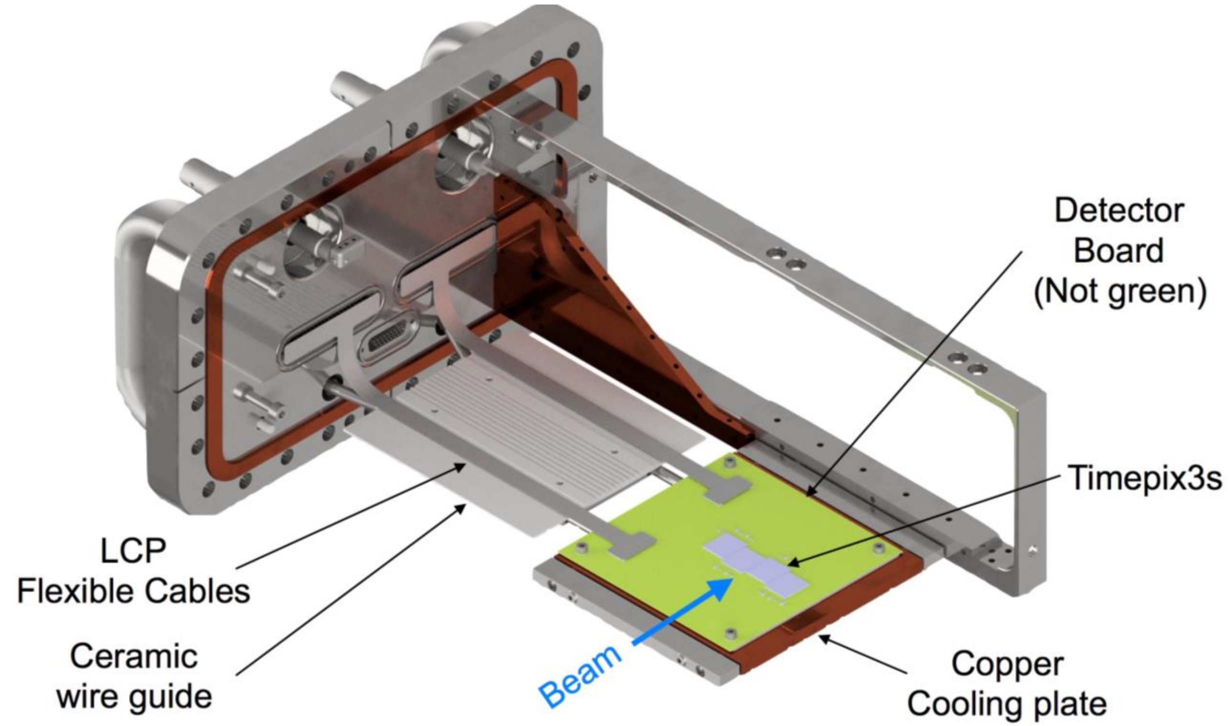
- 256x256 pixels
- 55um pitch
- Timestamp resolution of 1.5625ns
- Time-over-threshold to energy calibration
- 8x serial links up to 640Mbits/s = 5.12Gbit/s

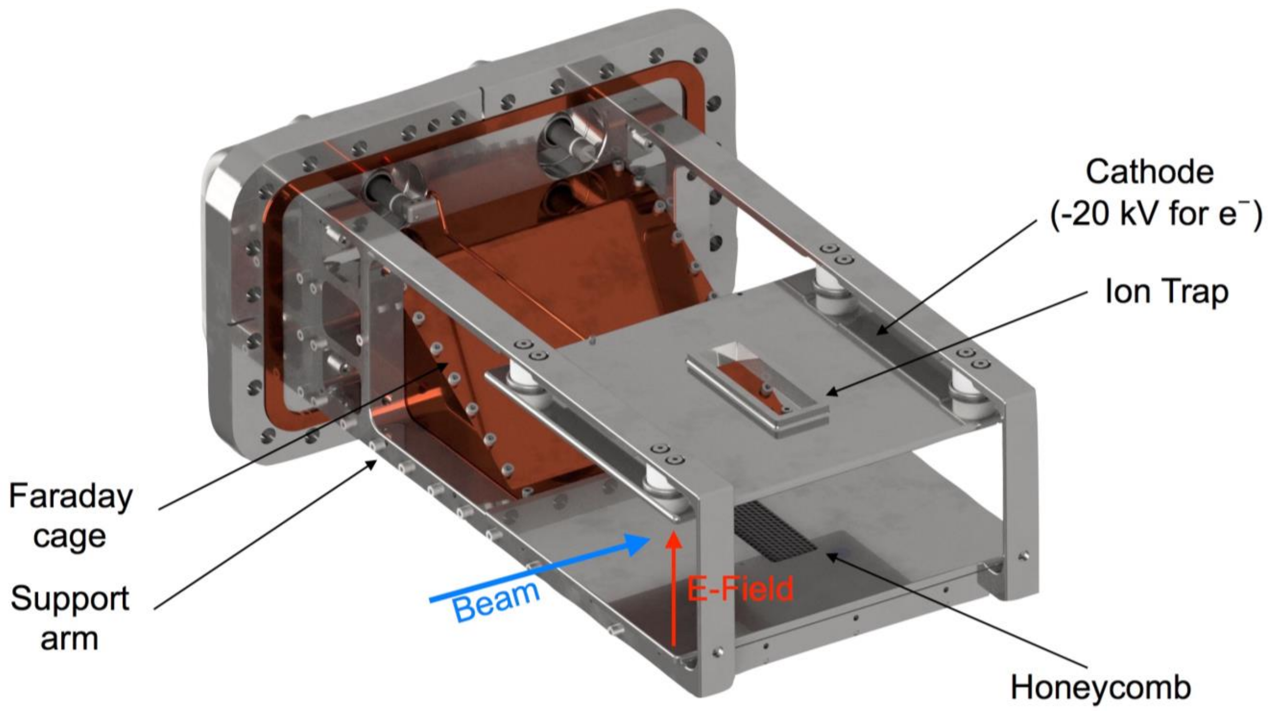
- *Magnet used to guide electrons towards the detector (will play a role on resolution)*
- *Ionization probability proportional to the gas pressure (typically 10^{-7}-10^{-10} Torr) and almost constant for beam energy above 1GeV*

https://medipix.web.cern.ch/technology-chip/timepix3-chip

Beam Gas Ionization Monitor

Low impedance design and high vacuum compatibility

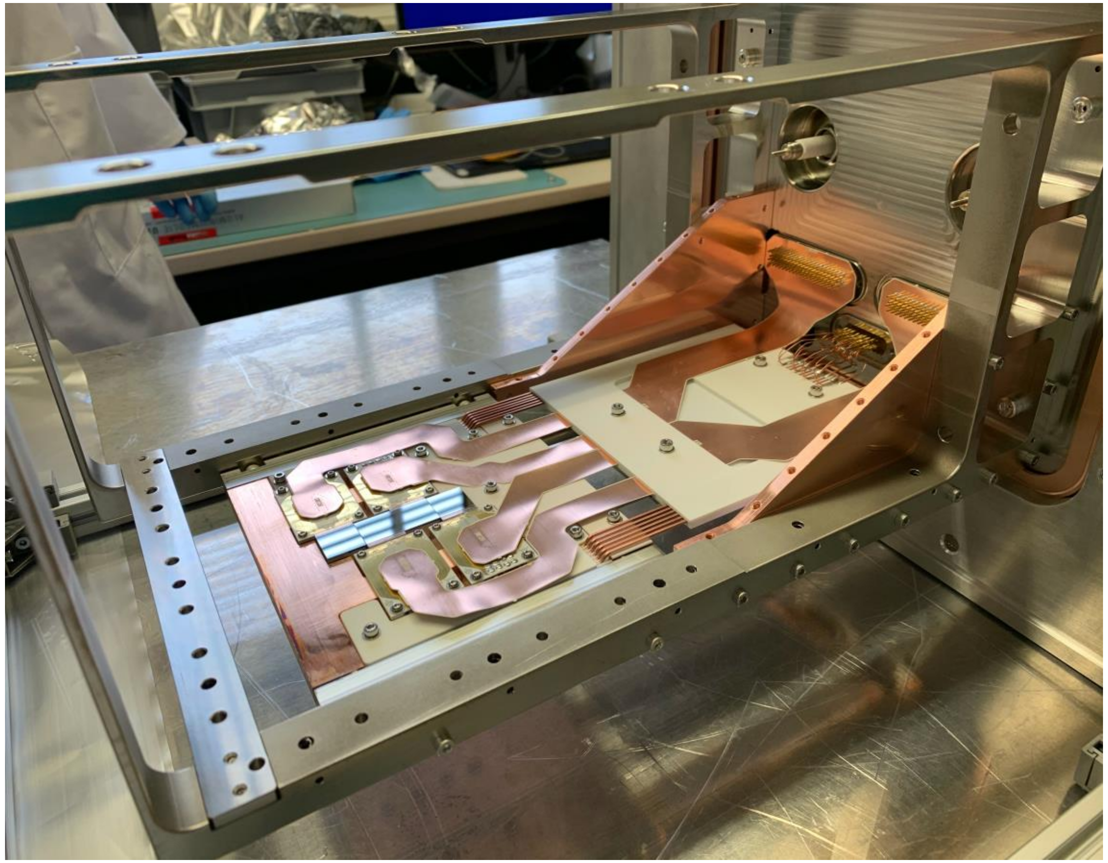




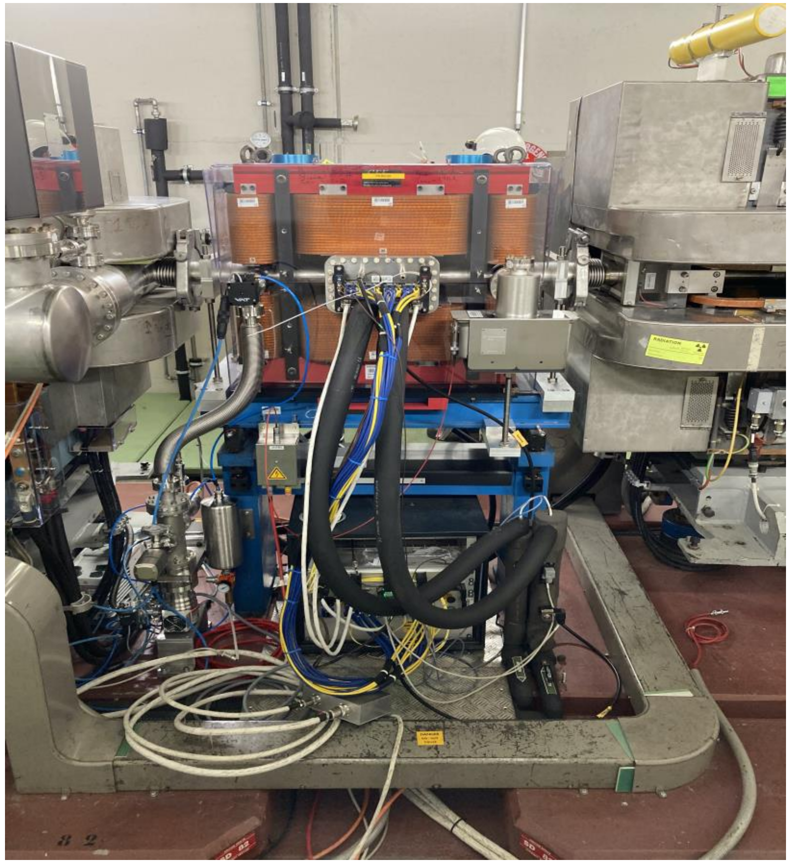
https://bgi-archive.web.cern.ch/bgi-archive/
https://bgi.web.cern.ch/introduction/

The CERN Accelerator School

Beam Gas Ionization Monitor



Timepix3-BGI in-vacuum instrument

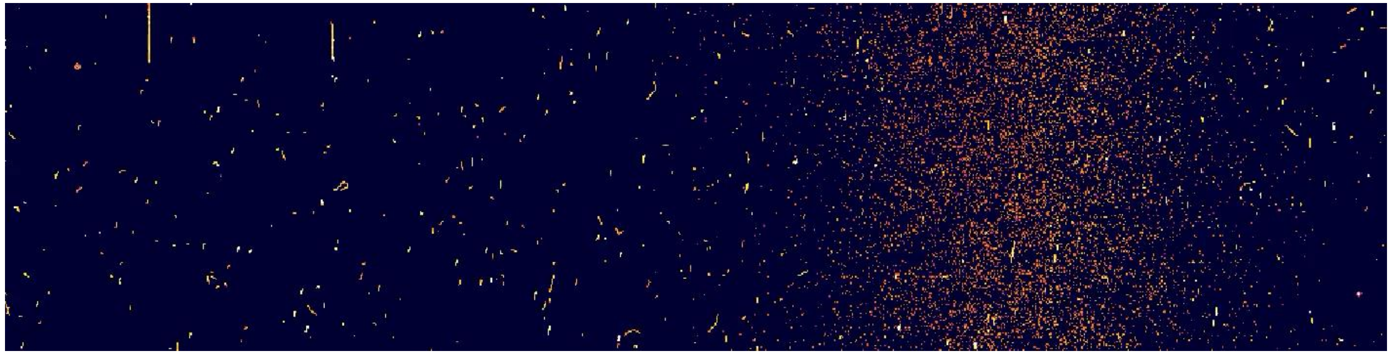


Timepix3-BGI installed in the PS ring

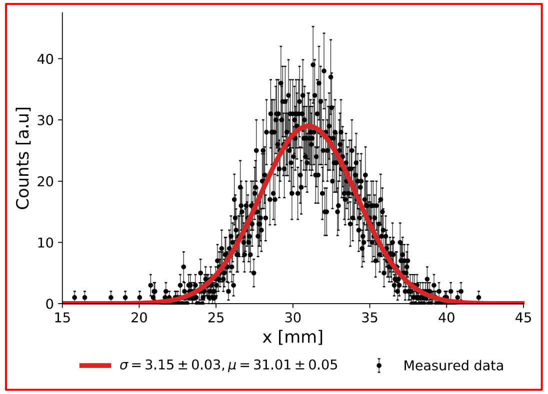
Beam Gas Ionization monitor

Measurement on the PS ring

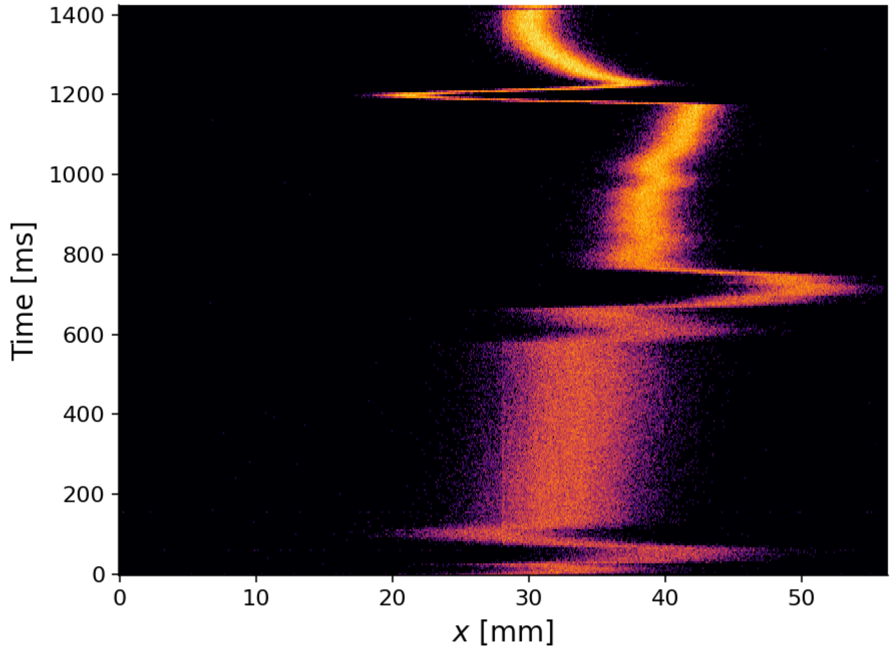
LHC type beam from injection, through acceleration and finally extraction



- 1.5 seconds in real time: slowed down here for viewing purpose.
- Each frame is 10 ms of data
- Not filtered to show background particles.



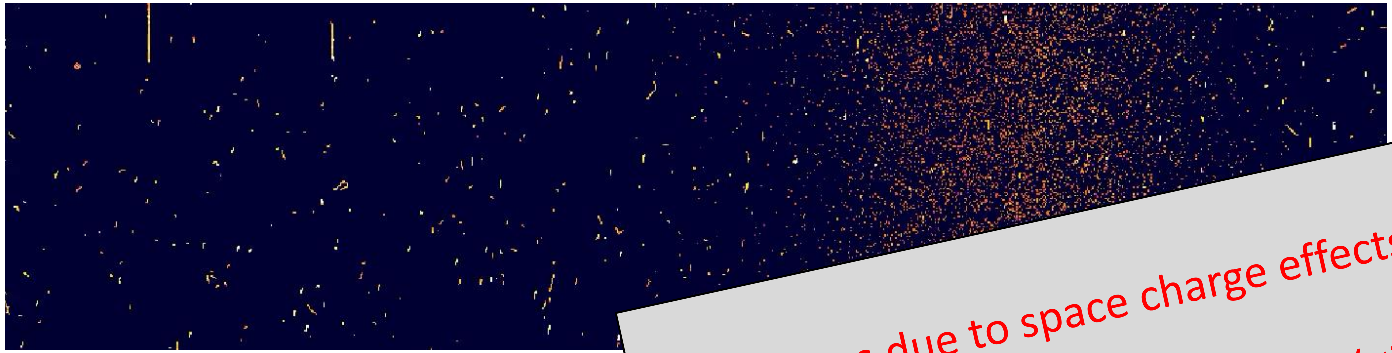
Beam profile & position through the PS cycle



Beam Gas Ionization monitor

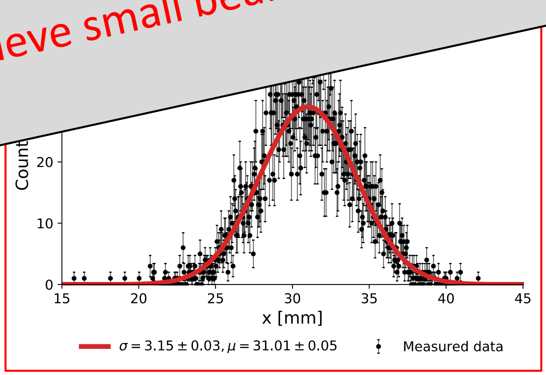
Measurement on the PS ring

LHC type beam from injection, through acceleration and finally extraction

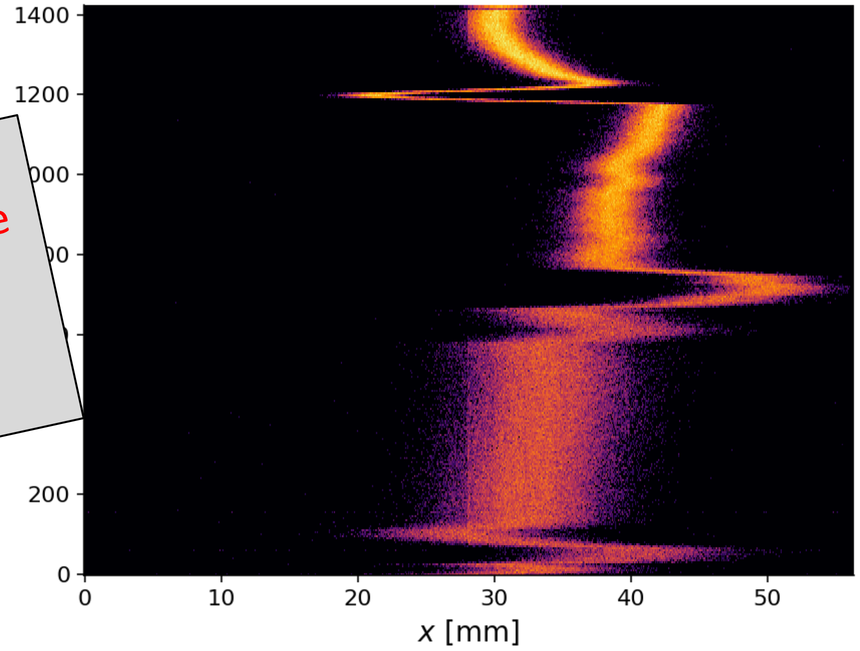


- 1.5 seconds in real time: slowed d
  viewing purpose.
- Each frame is 10 ms of data
- Not filtered to show background particles.

Corrections due to space charge effects need to be applied to retrieve small beam size (<200um)



Beam profile & position through the PS cycle



Beam Gas Fluorescence Monitor

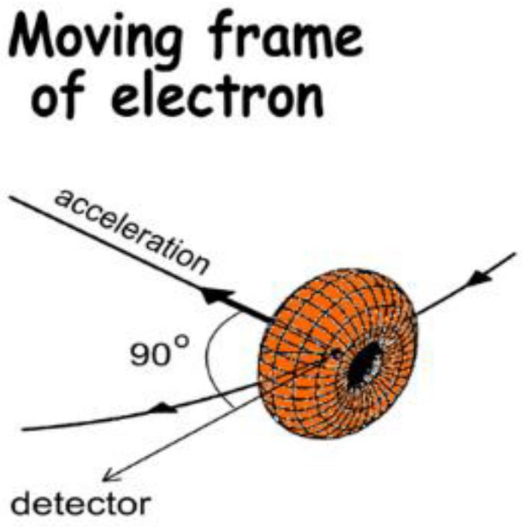
- An alternative to gas ionization is to use **gas induced fluorescence**
  - Using Intensified camera because the light yield is typically low
  - Would require higher vacuum level than gas ionisation
  - More information can be found here :

P. Forck: Minimal invasive beam profile monitors for high intense hadron beams, Proceedings of the International Particle Accelerator Conference, Kyoto, Japan (2010) p. 1261

Hadron ring – Synchrotron Radiation

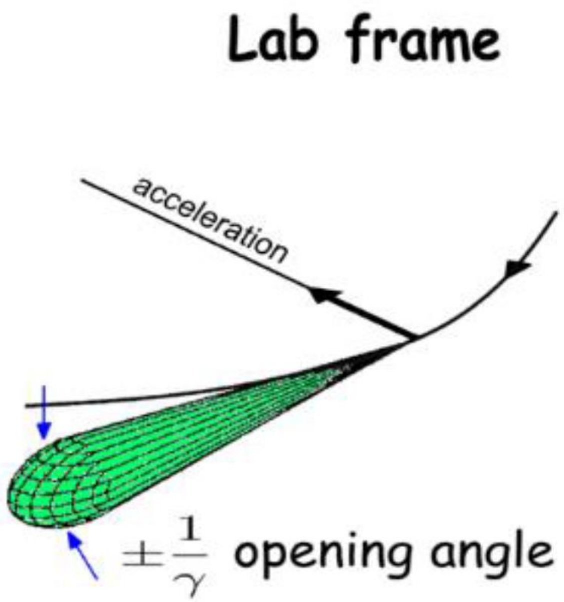
Only relevant for high energy hadron rings like the LHC !
Electrons are much better at emitting synchrotron radiation.

‘Let There Be Light’



$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1 - (\frac{v}{c})^2}$$

Lorentz
Transformation

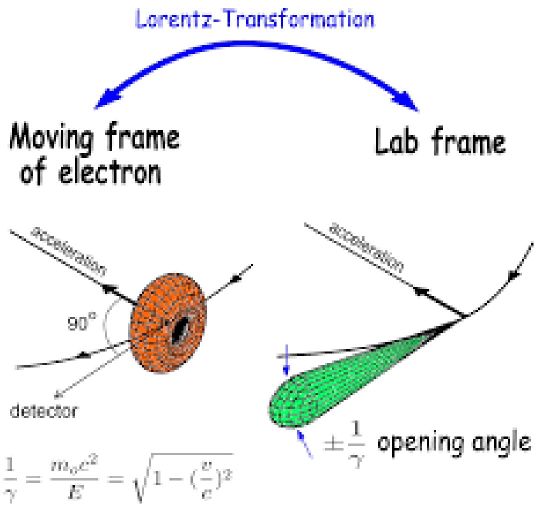


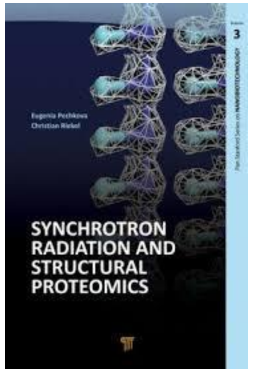
Simone Di Mitri, Elettra Sincrotrone Trieste,
University of Trieste, Dept. of Physics

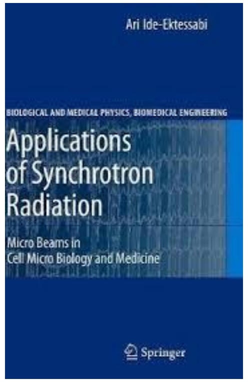
Nothing religious but a great tool for beam diagnostics

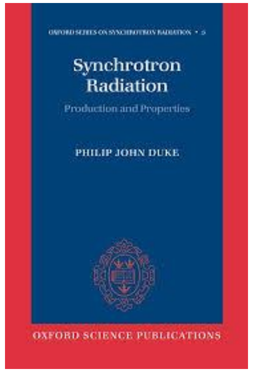
Hadron ring – Synchrotron Radiation

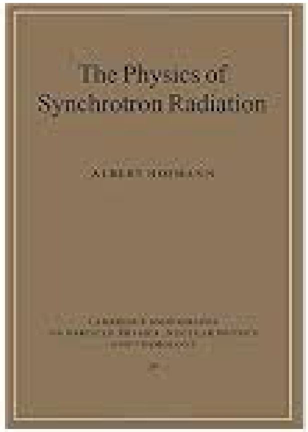
‘Let There Be Light’

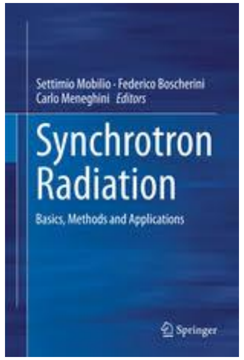


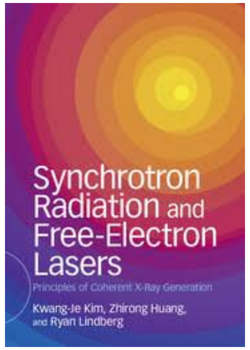


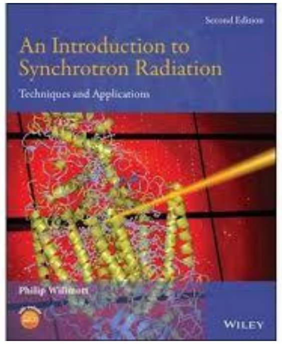












Hadron ring – Synchrotron Radiation

- Power :

$$P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2 c}{\rho^2}\gamma^4$$

- γ charged particle Lorentz-factor
- ρ the bending radius

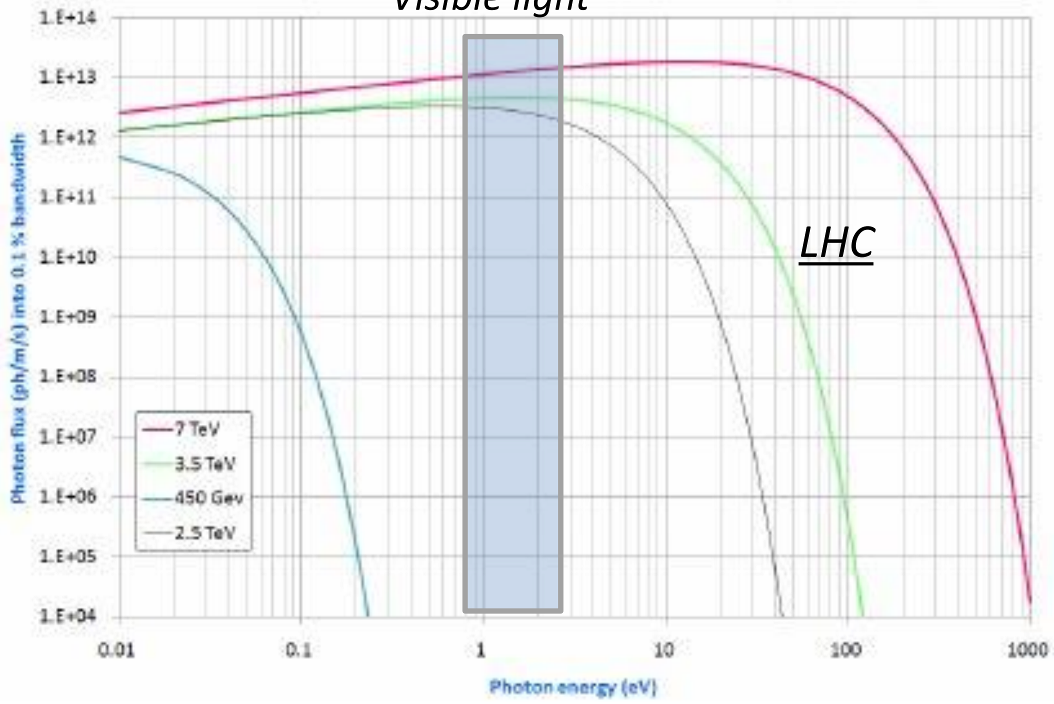
- Critical Frequency :

$$\omega_c = 3\gamma^3 \frac{c}{2\rho}$$

Beam energy

Beam curvature

Visible light



Hadron ring – Synchrotron Radiation

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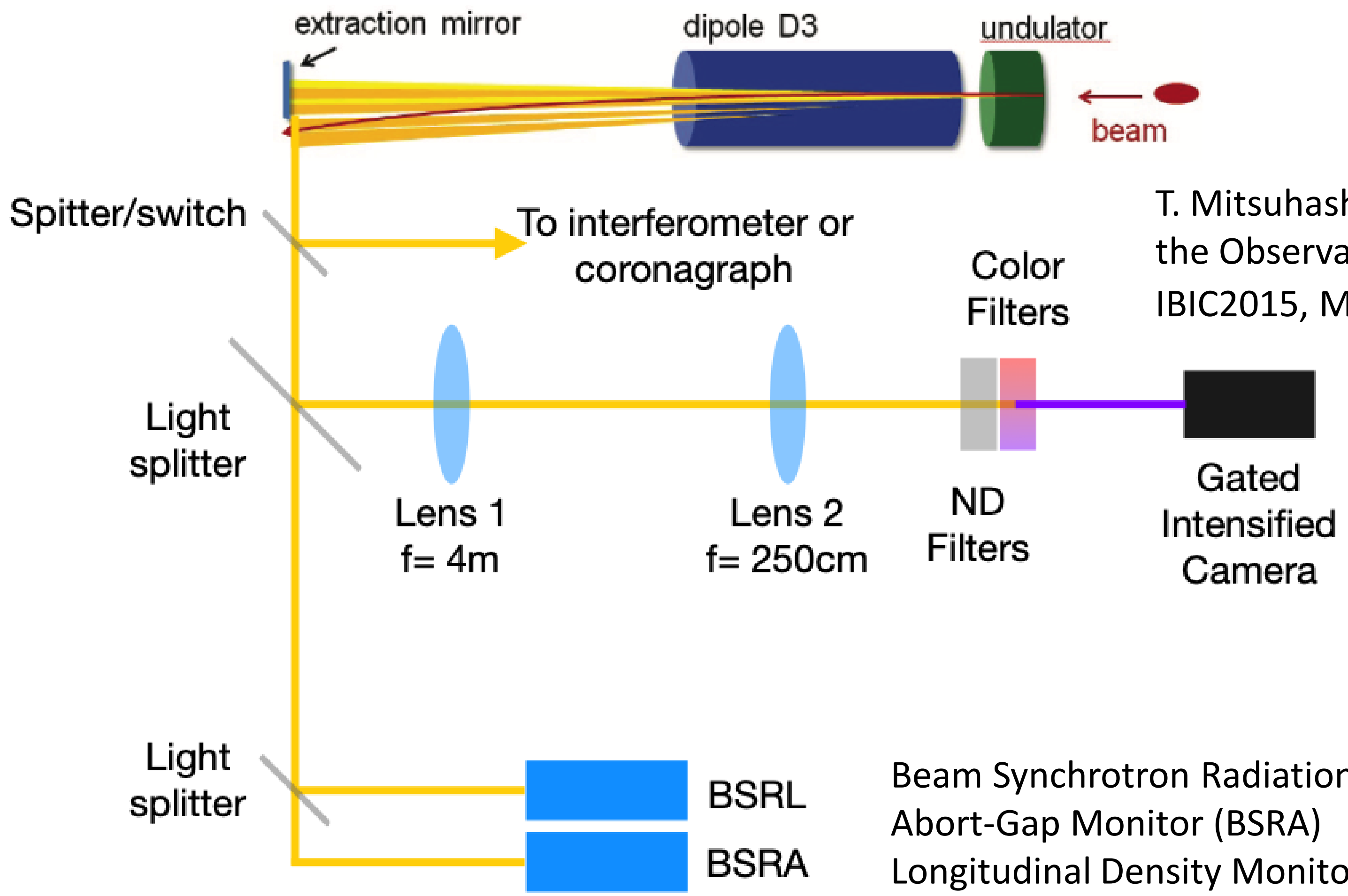
<u>Light is precious and serves many detectors - @LHC</u>

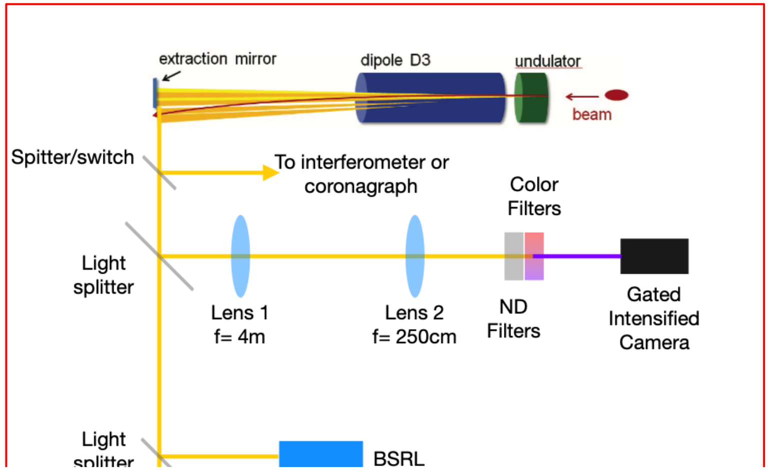


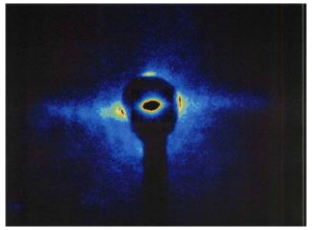
T. Mitsuhashi et al., "Design of Coronagraph for the Observation of Beam Halo at LHC", in Proc IBIC2015, Melbourne, Australia, 2015, p. 288.

Beam Synchrotron Radiation Telescope (BSRT)
Abort-Gap Monitor (BSRA)
Longitudinal Density Monitor (BSRL)

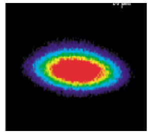
Hadron ring – Synchrotron Radiation

Light is precious and serves many detectors - @LHC

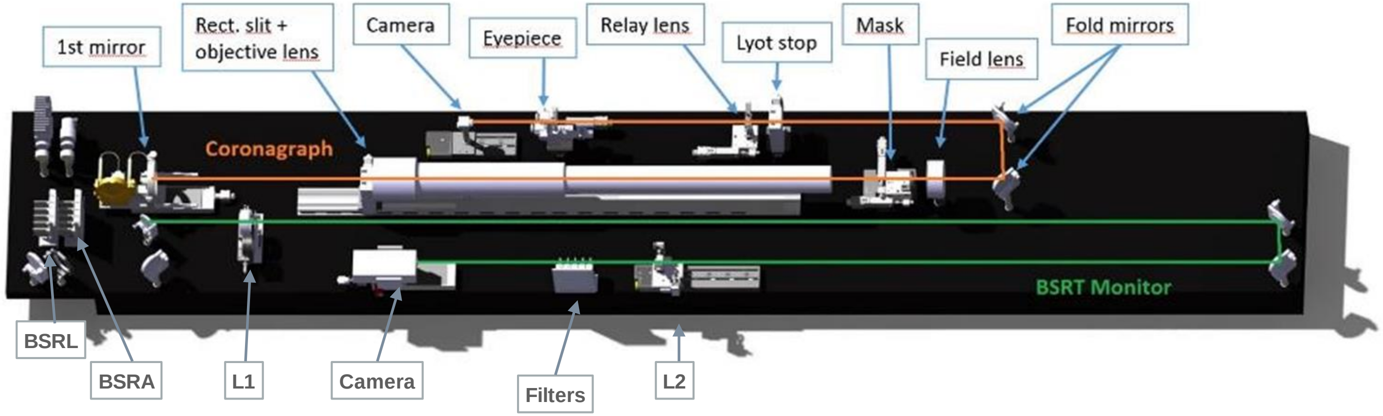




Halo



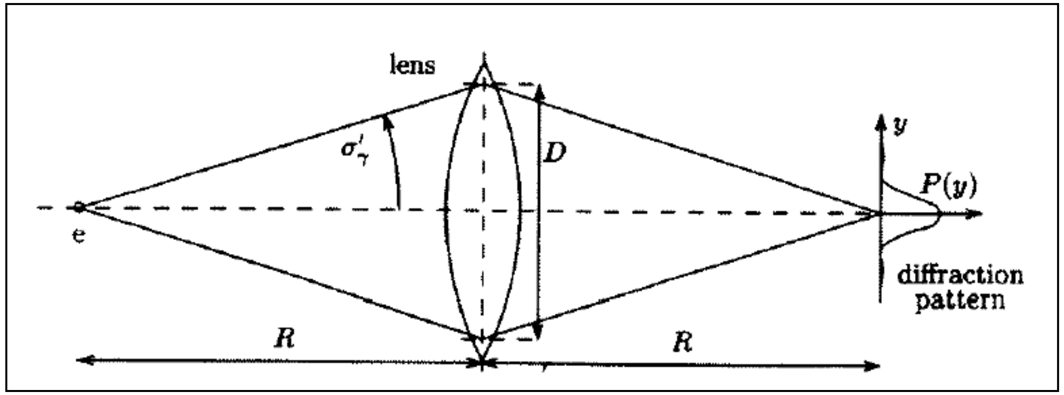
Core



Hadron ring – Synchrotron Radiation

It also suffers from

- Diffraction effects as the light is emitted in a narrow angular cone



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

- Depth of field effect as the source is extended over the length of the magnet

$$\sigma_{DoF} = \frac{\sigma'_y L}{2} \approx 0.36\frac{L}{\gamma}$$

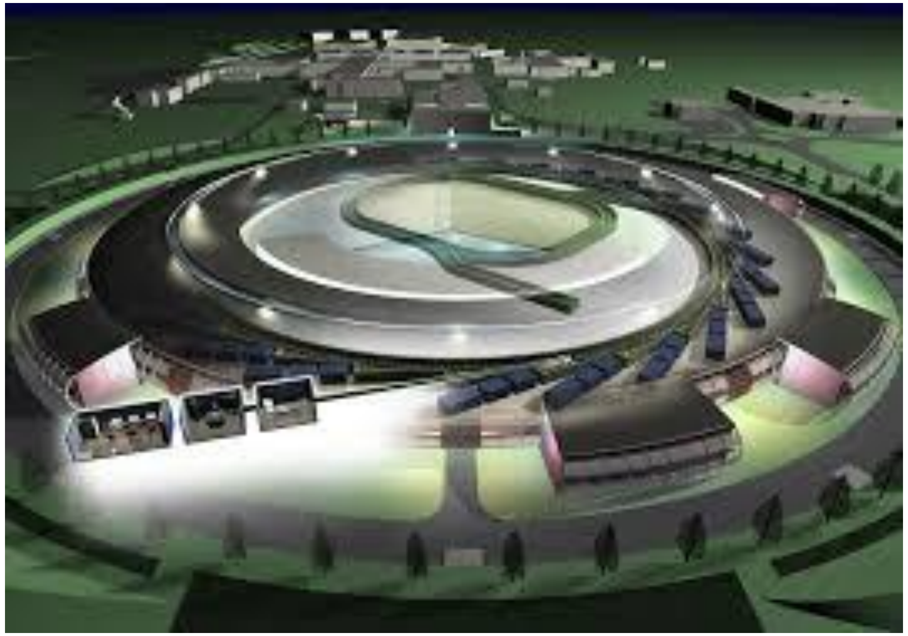
For highly relativistic beams, resolution limit reaches quickly 100's of microns for visible light !!

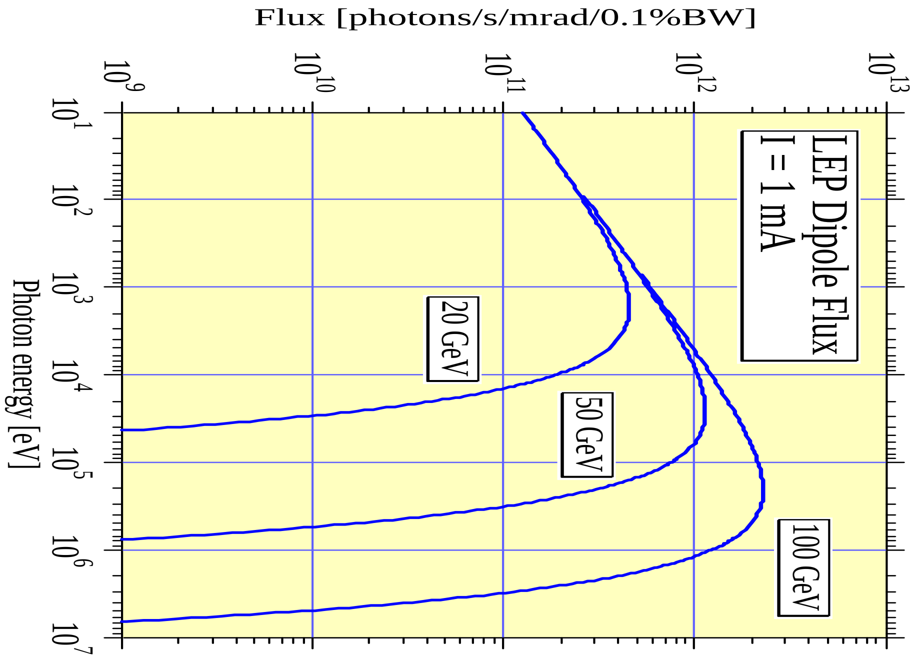
A. Hofmann,(2003). http://cas.web.cern.ch/cas/brunnen/presentations/pdf/cas03dia.pdf

^ Different approximations are often used!

Transverse Diagnostics in Electron Ring

Electron ring – Synchrotron Radiation





Photon spectrum goes in the soft/hard x-ray to γ–ray regimes

Visible photons still available !

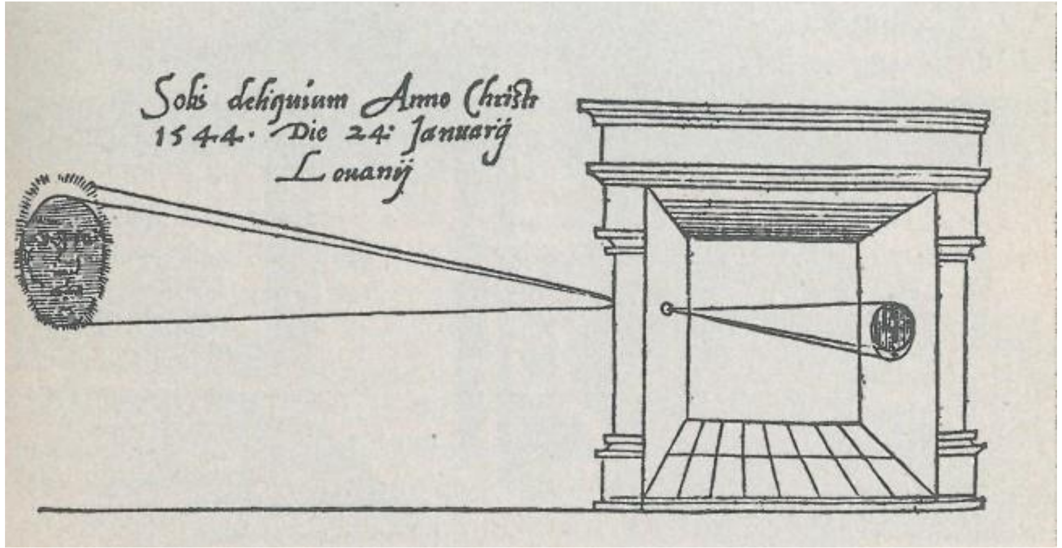
- *Long magnets still an issue !*
- *More SR power - Need to cool extraction mirrors !*
- *Can image X-rays to overcome diffraction limits observed in visible range*

Electron ring – Synchrotron Radiation

Pinhole cameras

≈ 400 – 300 BC : Earliest written observations
Chinese philosopher Mozi.
"Why does the sun penetrating through quadrilaterals form not rectilinear shapes but circles, as for instance when it passes through wicker-work?"
Greek philosopher Aristotle (384-322 BC).

Observation of a partial solar eclipse through overlapping fingers that Aristotle could not explain [3].



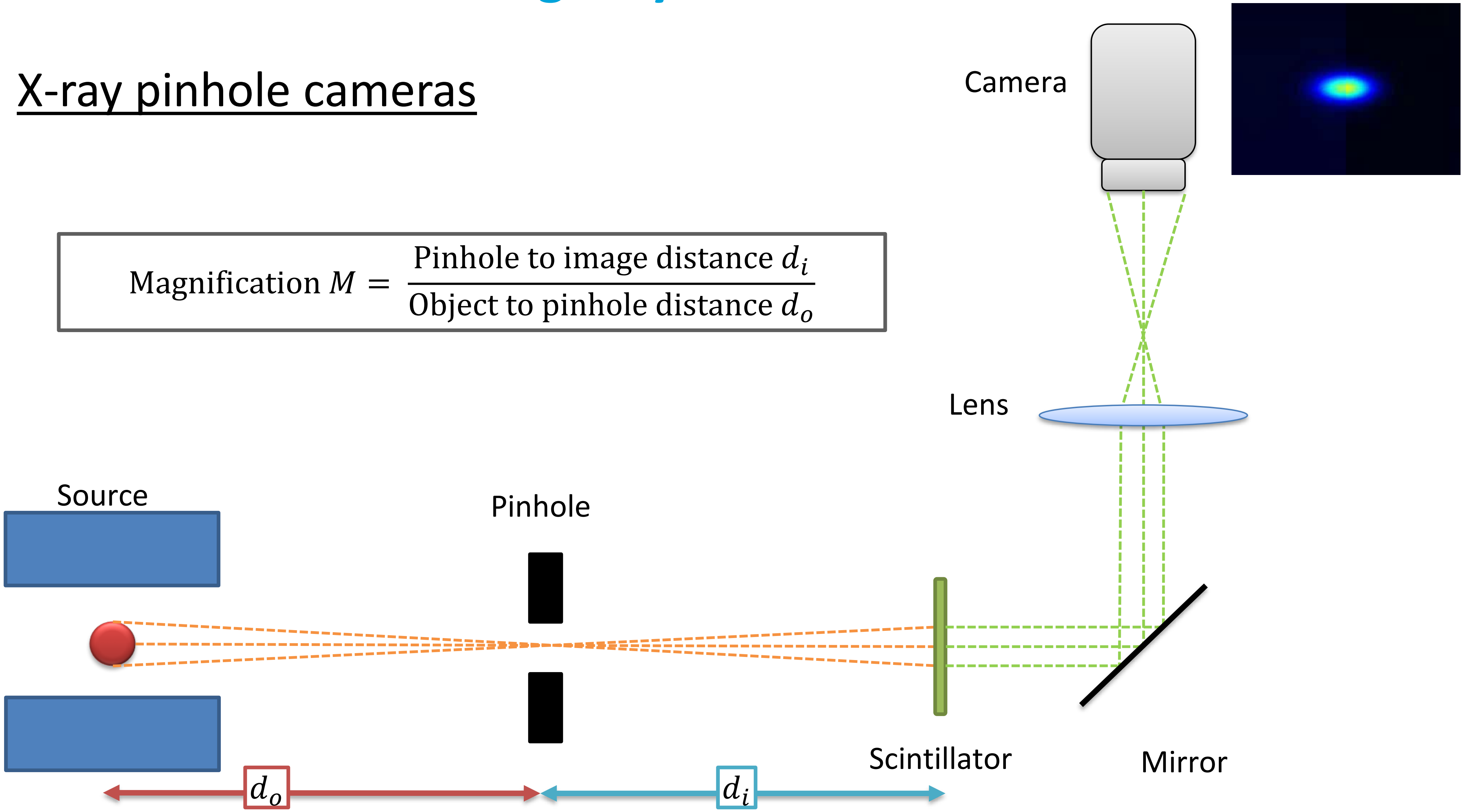
1400 – 1600 AD : Renaissance of human understanding
1545 AD: First published picture of a pinhole camera obscura in the book, *De Radio Astronomica et Geometrica,* by Gemma Frisius.

E. Renner, Pinhole Photography from Historic Technique to Digital Application, Fourth Ed., Focal Press, 2009.

Electron ring – Synchrotron Radiation

X-ray pinhole cameras

$$\text{Magnification } M = \frac{\text{Pinhole to image distance } d_i}{\text{Object to pinhole distance } d_o}$$



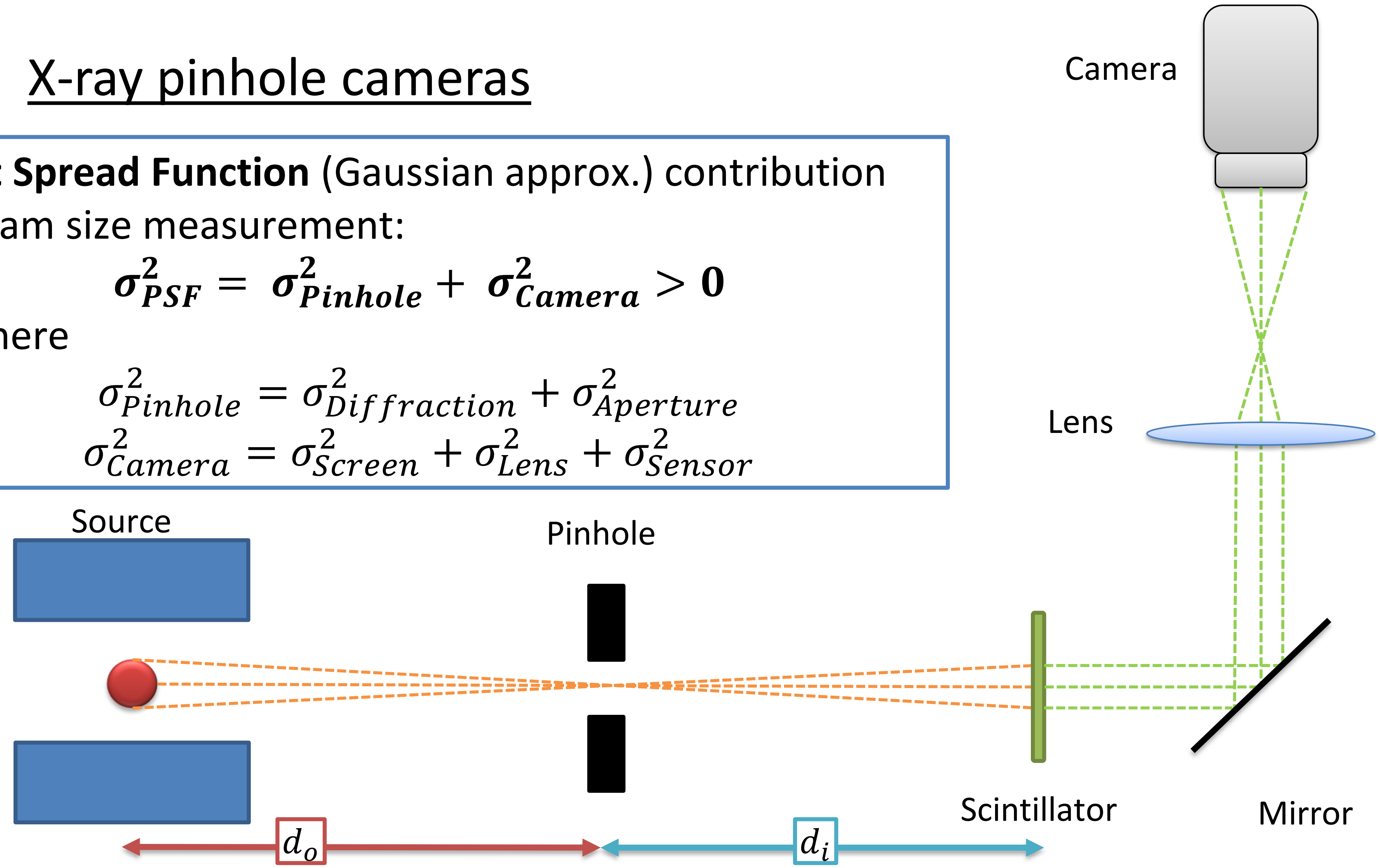
X-ray pinhole cameras

Point Spread Function (Gaussian approx.) contribution to beam size measurement:

$$\boldsymbol{\sigma_{PSF}^2 = \sigma_{Pinhole}^2 + \sigma_{Camera}^2 > 0}$$

where

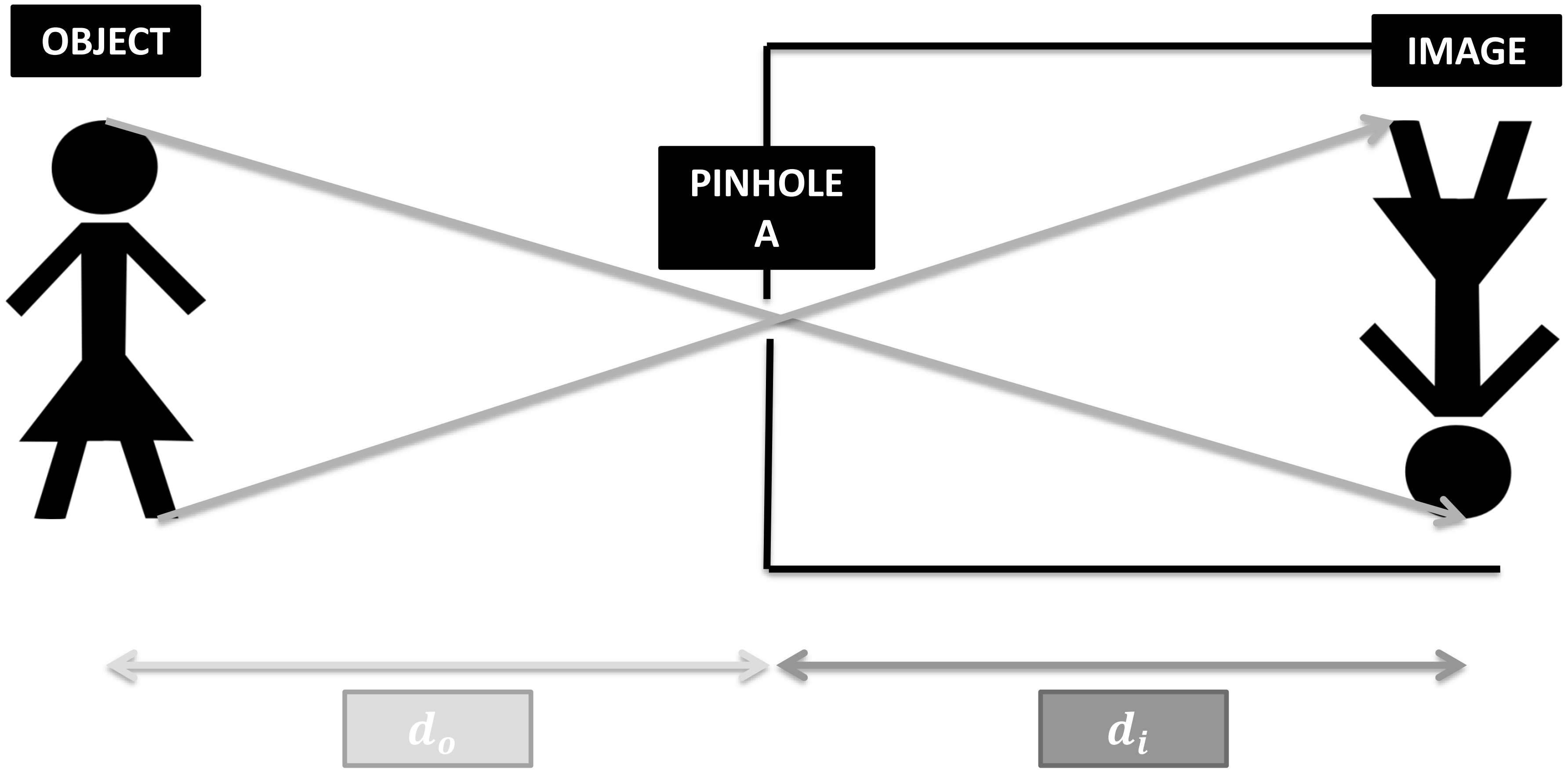
$$\sigma_{Pinhole}^2 = \sigma_{Diffraction}^2 + \sigma_{Aperture}^2$$
$$\sigma_{Camera}^2 = \sigma_{Screen}^2 + \sigma_{Lens}^2 + \sigma_{Sensor}^2$$



Electron ring – Synchrotron Radiation

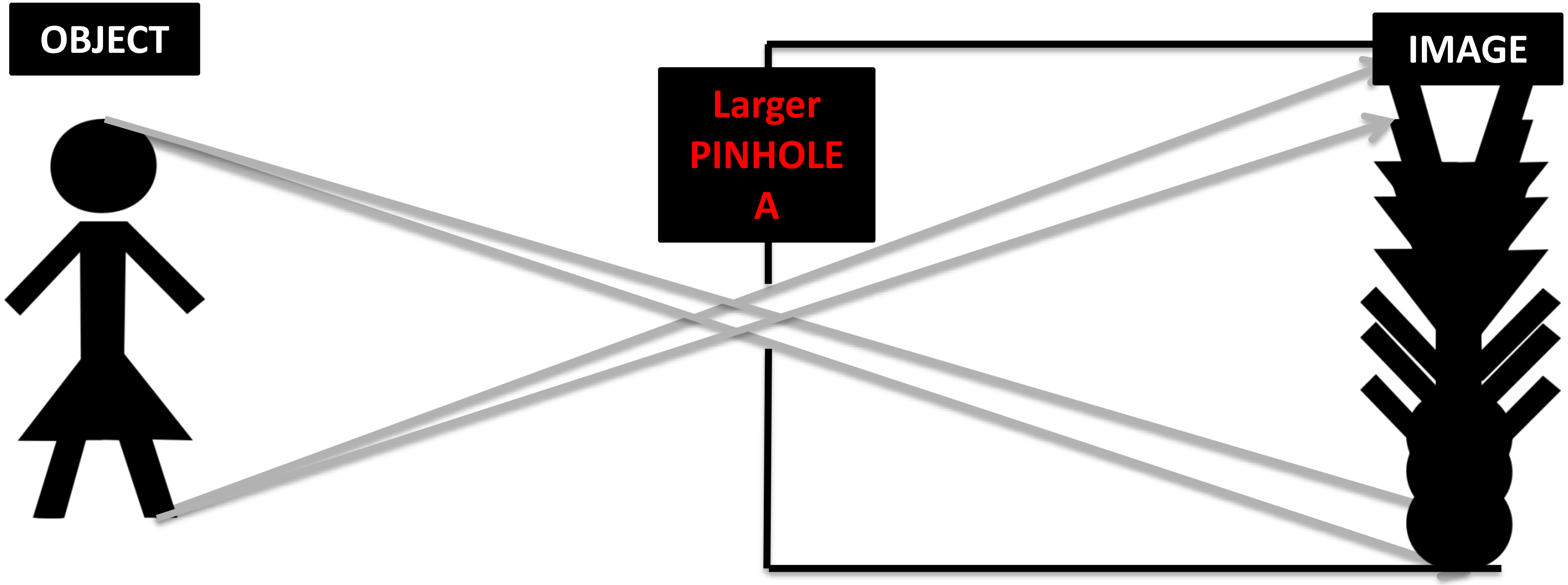
X-ray pinhole cameras

$$\text{Magnification } M = \frac{\text{Pinhole to image distance } d_i}{\text{Object to pinhole distance } d_o}$$



Electron ring – Synchrotron Radiation

X-ray pinhole cameras



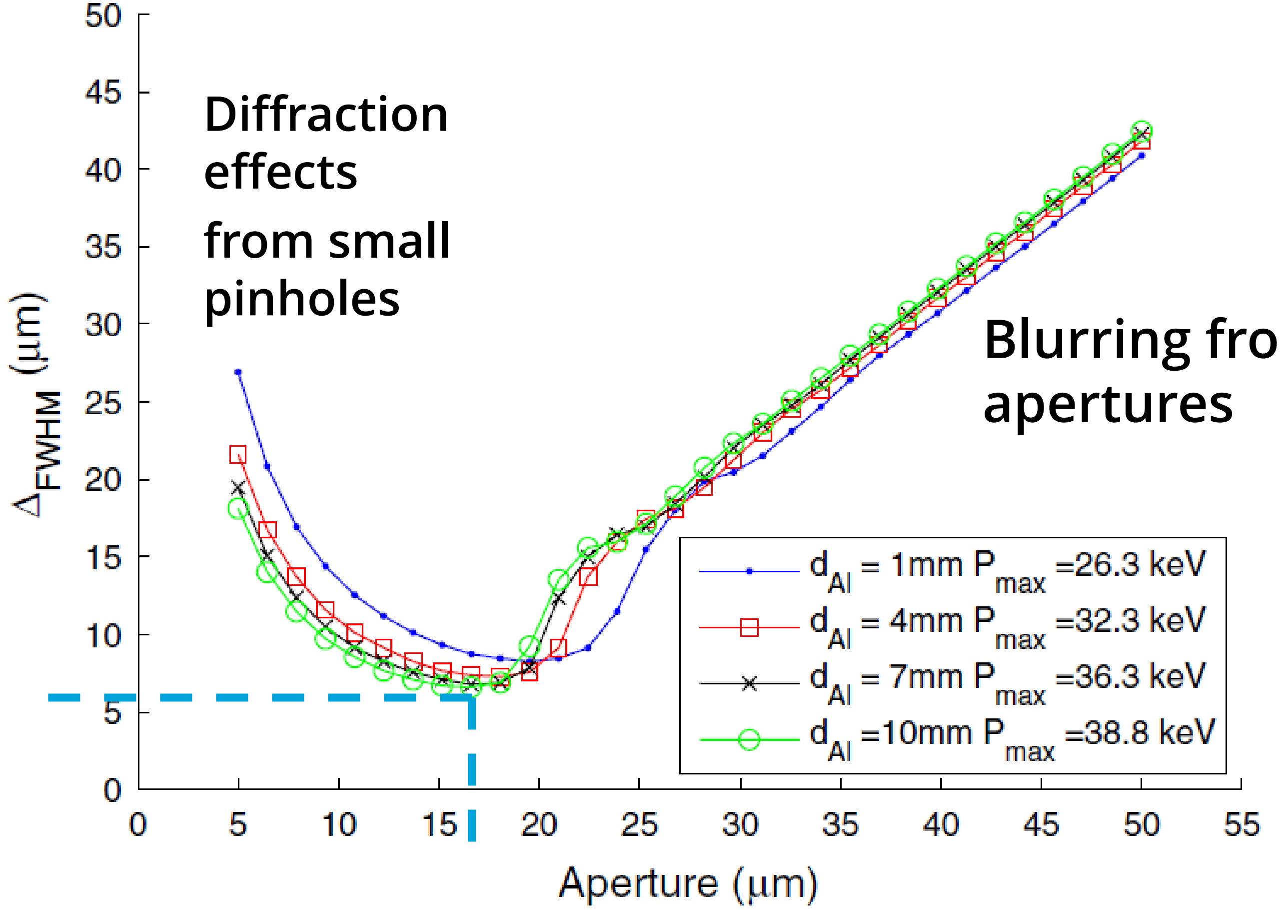
Point Spread Function (Gaussian approx.) contribution to beam size measurement

$$\boldsymbol{\sigma^2_{Pinhole} = \sigma^2_{Diffraction} + \sigma^2_{Aperture}}$$

$$\sigma_{Diffraction} = \frac{\sqrt{12}}{4\pi}\frac{\lambda d_i}{A}$$ for wavelength λ

X-ray pinhole cameras

C. Thomas *et al.*, *X-ray pinhole camera resolution and emittance measurement,* Phys. Rev. ST Accel. Beams **13**, 022805 (2010)



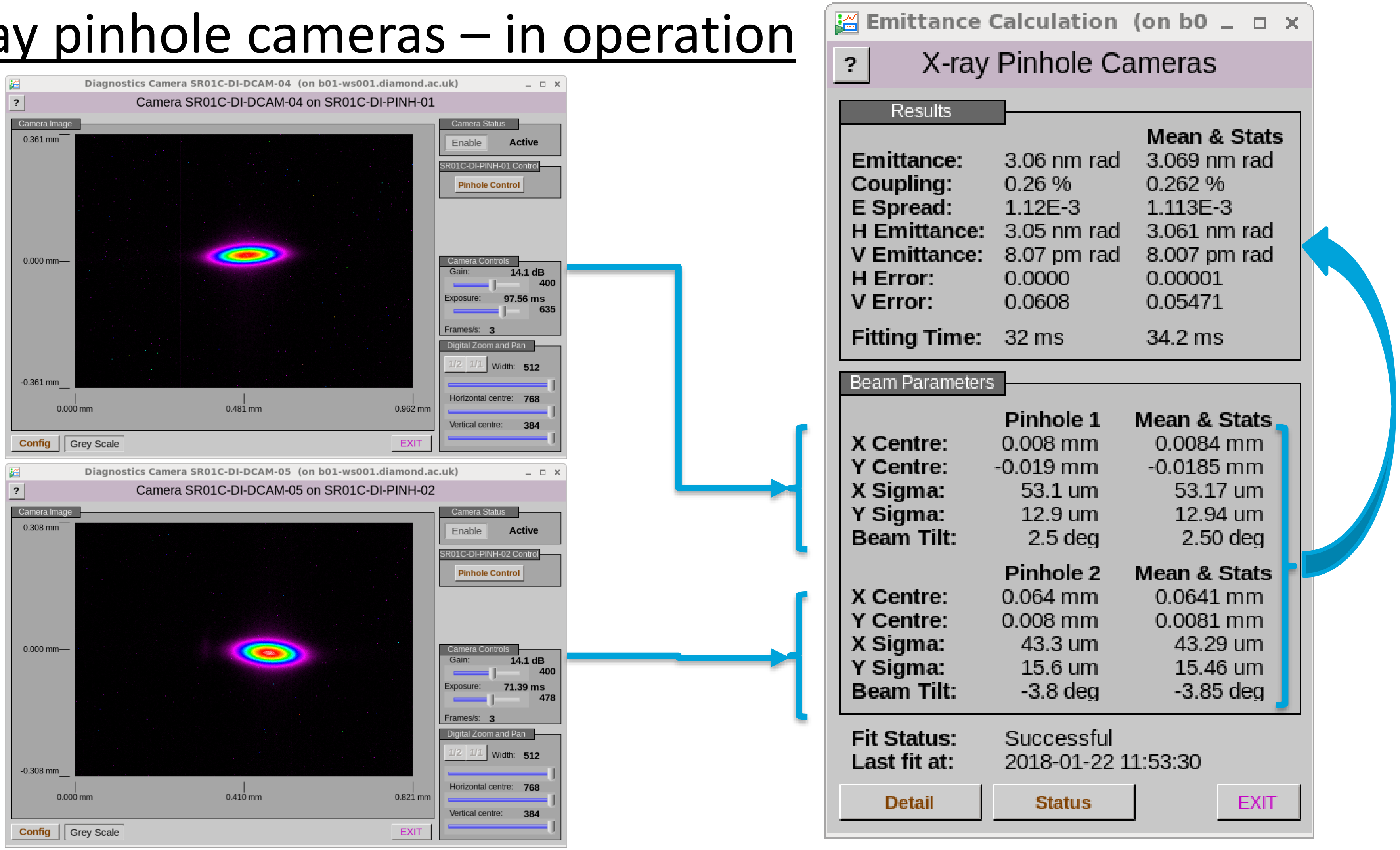
Diffraction effects from small pinholes

Blurring from larger apertures

Optimum aperture size corresponds to minimum PSF

Electron ring – Synchrotron Radiation

X-ray pinhole cameras – in operation



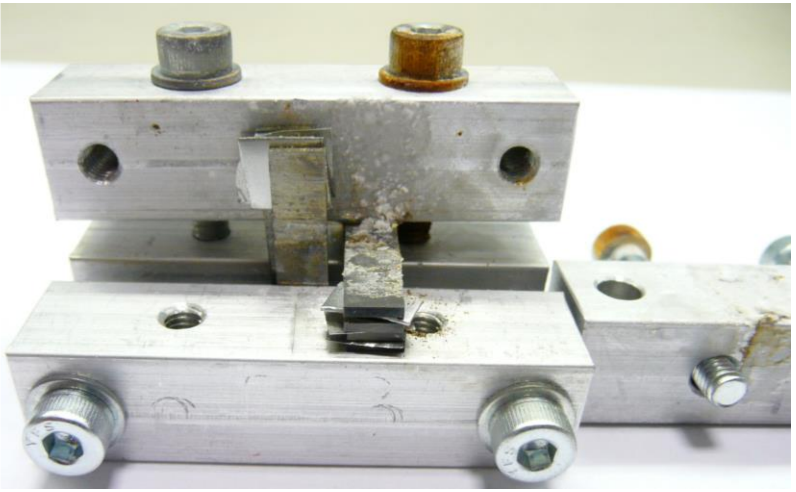
Screenshots from Diamond Light Source

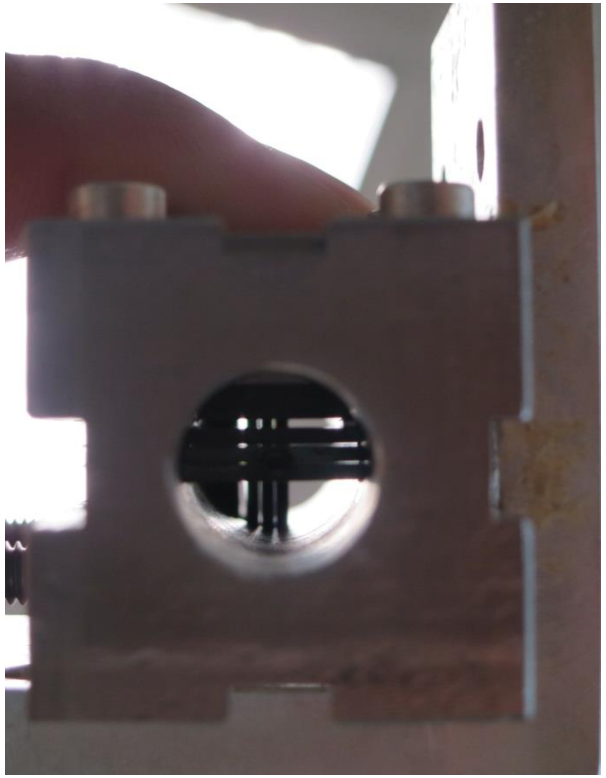
Electron ring – Synchrotron Radiation

X-ray pinhole cameras – additional limitations

- For sufficient source-to-screen magnification ($|M_1| = \left|-\frac{d_i}{d_o}\right| \geq 2$):

  → X-ray path length $(d_o + d_i) \geq 10\text{m}$





- Challenging fabrication for pinholes :

  → pinhole material must be opaque to hard X-rays

  → therefore must use material with high atomic number

  → often hard to machine rectilinear holes of a defined size (nearest micron)

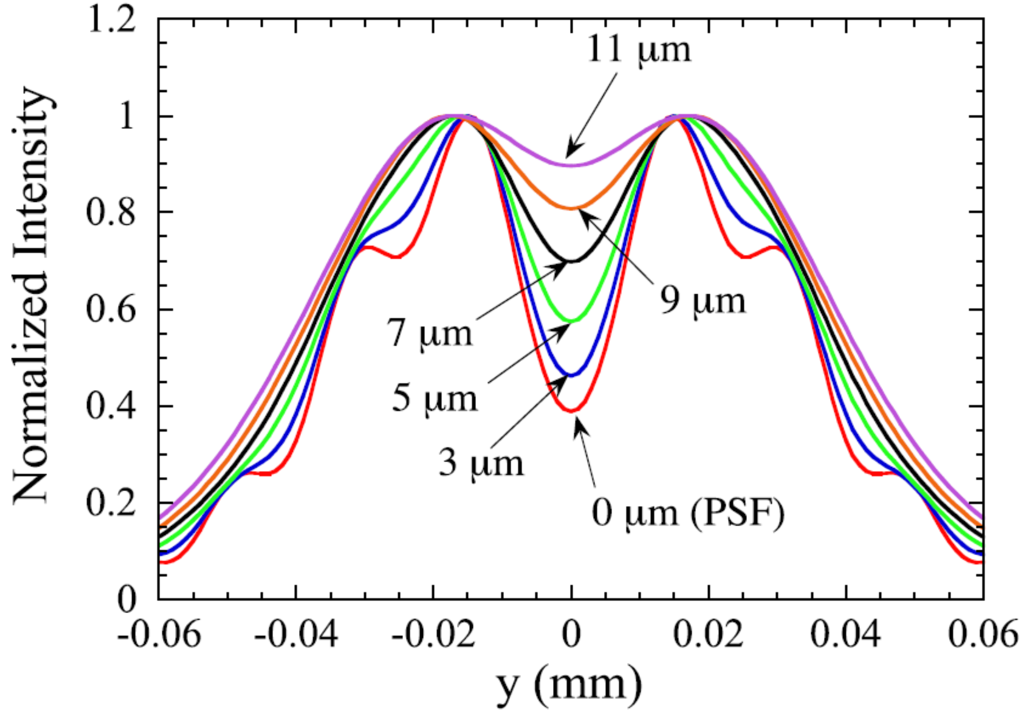
  → often kept under nitrogen or in-vacuum to prevent oxidation

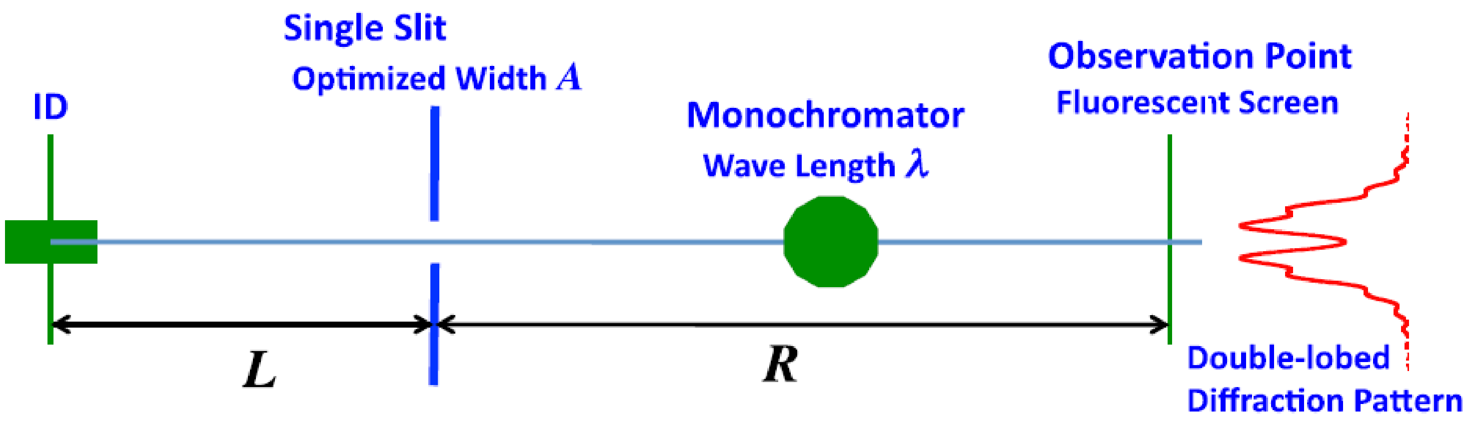
Electron ring – Synchrotron Radiation

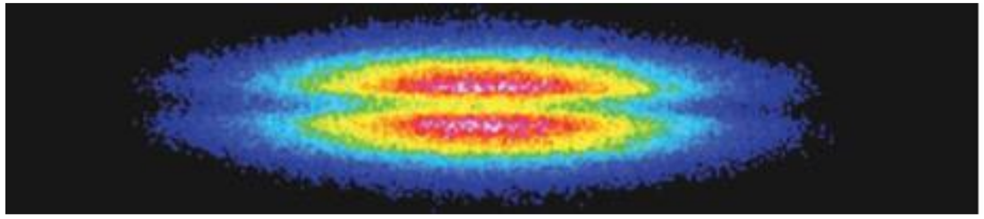
X-ray Fresnel Diffractometry

- Possible upgrade for existing pinhole cameras

$$A \approx \sqrt{7\lambda \frac{LR}{L+R}}.$$







M. Masaki et al., *PRAB*, *18*(4), 042802 (2015).

Electron ring – Synchrotron Radiation

- Interferometric measurement as an alternative to direct imaging
  - Measure the size of object by measuring the spatial coherence of light (interferometry), first proposed by H. Fizeau in 1868 !
  - This method was realized by A.A. Michelson for the measurement of apparent diameter of star with his stellar interferometer in 1921.
  - This principle is known as " Van Cittert-Zernike theorem"

    F. Zernike ***The concept of degree of coherence and its application to optical problems,*** *Physica, 5 (8) (1938), pp. 785-795*
  - Developed for Synchrotron radiation by T. Mitsuhashi during the last 20 years
  - Read as well : *Gianluca Geloni, Evgeni Saldin, Evgeni Schneidmiller, Mikhail Yurkov* ***Transverse coherence properties of X-ray beams in third-generation synchrotron radiation sources,*** *Nucl. Instrum. Methods Phys. Res. Sect. A 588(April (3)) (2008), pp. 463-493*

Electron ring – Synchrotron Radiation

- <u>Van Cittert-Zernike theorem :</u>

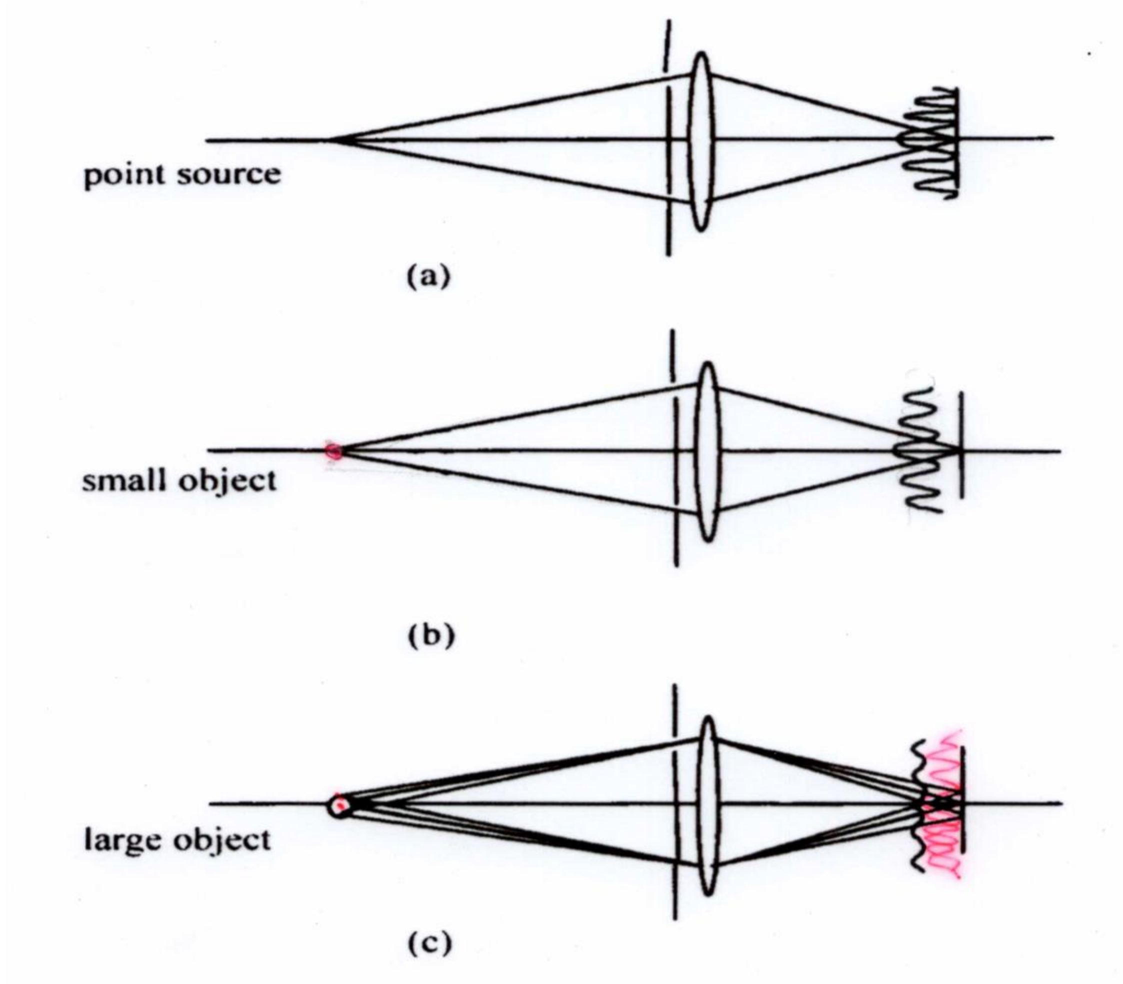
With the condition of light is temporal incoherent (no phase correlation), the complex degree of spatial coherence $\gamma(\upsilon_x,\upsilon_y)$ is given by the Fourier Transform of the spatial profile f(x,y) of the object (beam) at shorter wavelengths such as visible light.

$$\gamma(\upsilon_x,\upsilon_y)=\int\int f(x,y)\exp\{-i\cdot 2\cdot\pi(\upsilon_x\cdot x+\upsilon_y\cdot y)\}dxdy$$

where υ_x, υ_y are spatial frequencies given by;

Electron ring – Synchrotron Radiation

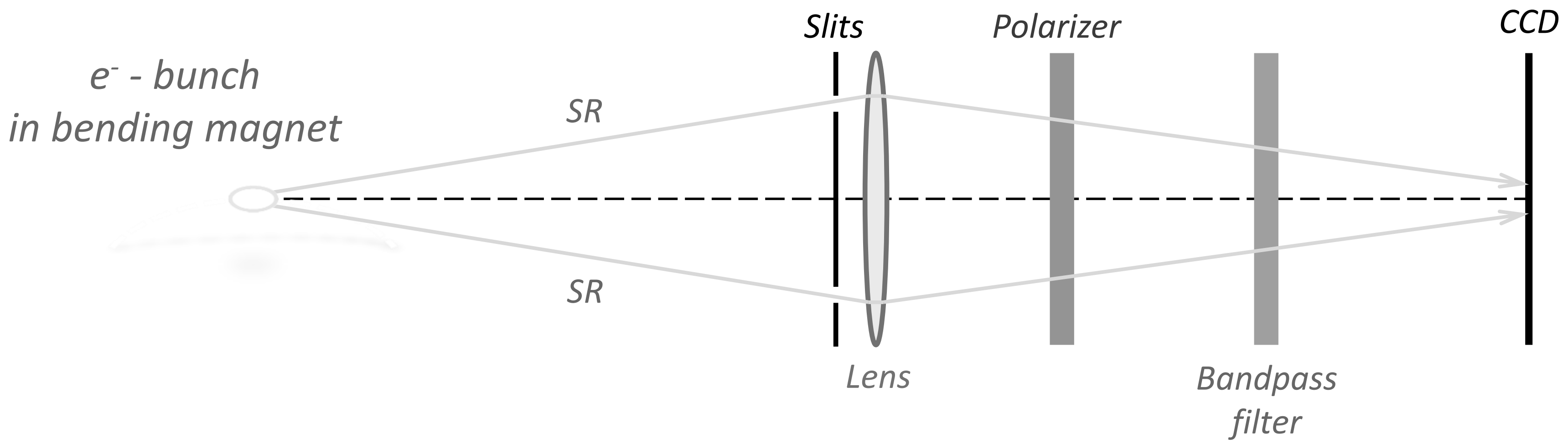
- <u>Van Cittert-Zernike theorem :</u>

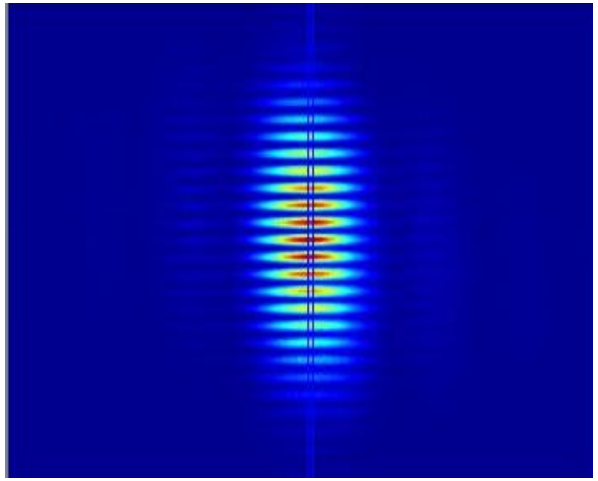


Beam size is inversely proportional to the visibility of the interferogram I_{min} / I_{max}

Electron ring – Synchrotron Radiation

- <u>Interferometer and Interferograms :</u>





$$I(y) = I_0 \left[J_1 \left(\frac{2\pi a y}{\lambda_0 R} \right) / \left(\frac{2\pi a y}{\lambda_0 R} \right) \right]^2 \left[1 + |\gamma| \cos \left(\frac{2\pi D\, y}{\lambda_0 R} + \phi \right) \right]$$

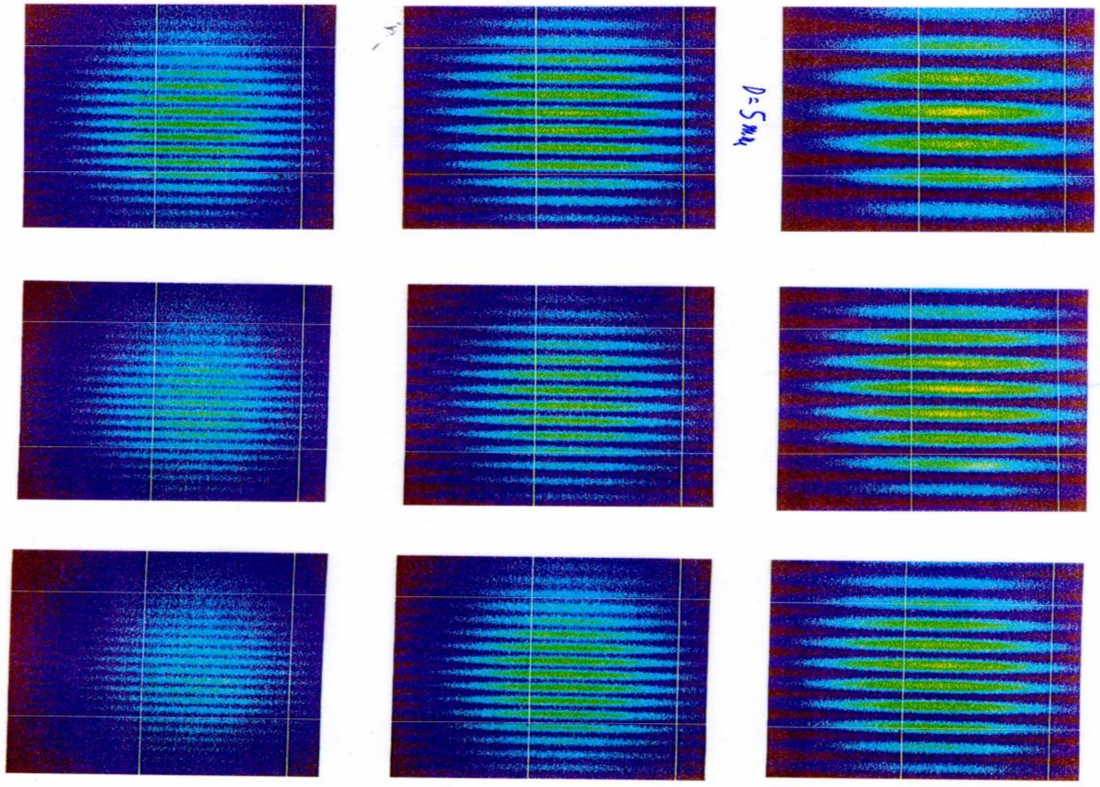
where *a* – half slit size, λ_0 – wavelength of SR, *D* – distance between slits, *R* – distance source– slits, γ – degree of spatial coherence. Getting the parameter γ from the fit, one can recalculate it to the beam size

$$\sigma_y = \frac{\lambda R}{\pi D} \sqrt{\frac{1}{2} \log \left(\frac{1}{\gamma} \right)}.$$

Electron ring – Synchrotron Radiation

- Interferometer and Interferograms :

obtained using visible light for different spacing between slits at ATF-KEK



Small spacing
High visibility

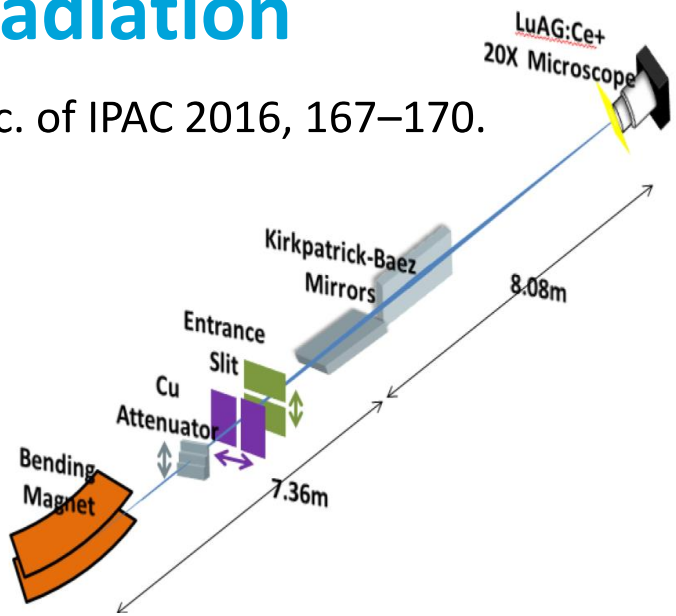
Large spacing
Low visibility

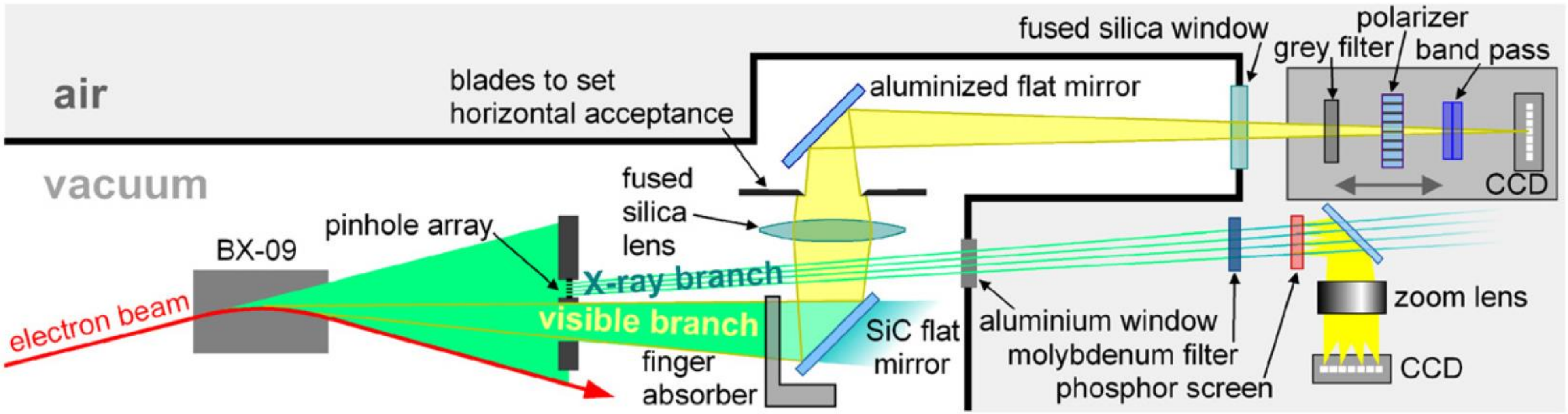
Beam size of 4um

Electron ring – Synchrotron Radiation

- Other techniques:
  - **X-ray lenses**
    - **Fresnel Zone Plate**
    - **Compound Refractive Lens**
  - **X-ray interferometry**
  - **X-ray K-B Mirror**
  - **Pi- polarization using visible synchrotron radiation**

C. D. Zhu et al., Proc. of IPAC 2016, 167–170.





Å. Andersson et al., NIMA *591*(3), 437–446 (2008)

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Conclusions

- High brightness beams put high pressure on diagnostics techniques in order to measure high beam transverse density and very small beam size
- Not-intercepting diagnostics are needed in most cases
- Those diagnostics are using state-of-the-art technologies
- Cost and complexity must be considered
- New techniques are still being developed - An exciting field for R&D !

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Thank you for your attention, and we will continue with the Longitudinal diagnostics later !

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Advanced Accelerator Physics