The CERN Accelerator School

High Brightness Beam Diagnostics

6 – 18 November 2022

Neaclub, Sévrier, France

T. Lefevre, CERN

The CERN Accelerator School

Outline

- What high Brightness means ?

- Invasive and Non-invasive techniques
  - Space-charge dominated beams (low energy)
  - Hadron Synchrotrons
  - Electron Synchrotrons
  - Electron LINACS

What high Brightness means ?

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

Beam intensity per unit source size and divergence

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

[A/(m-rad)^2]

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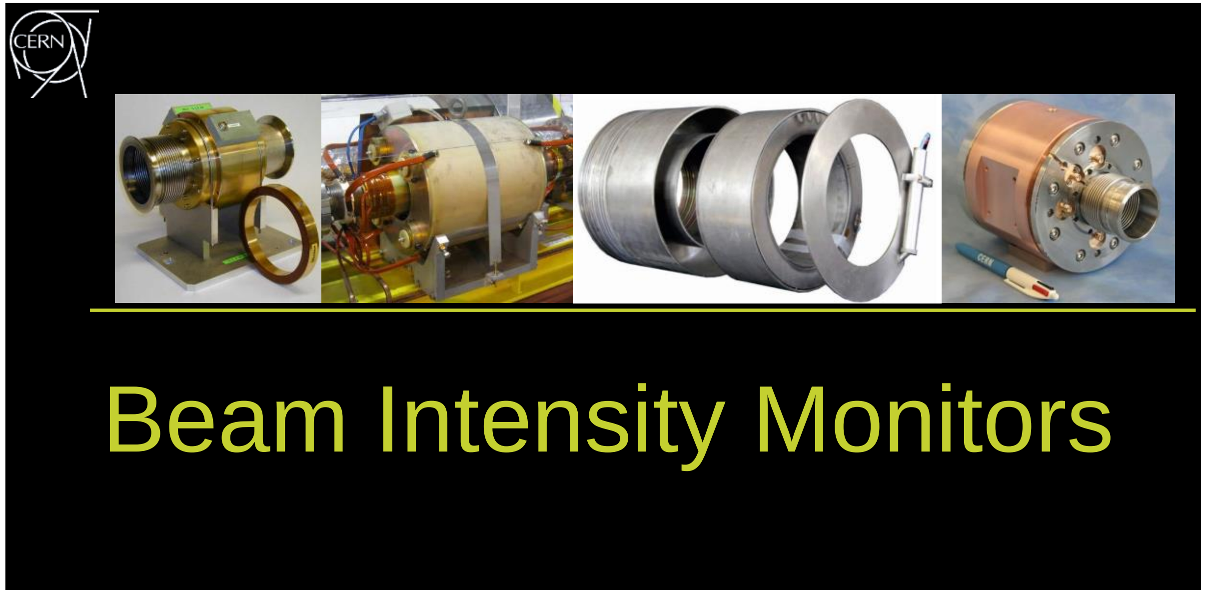
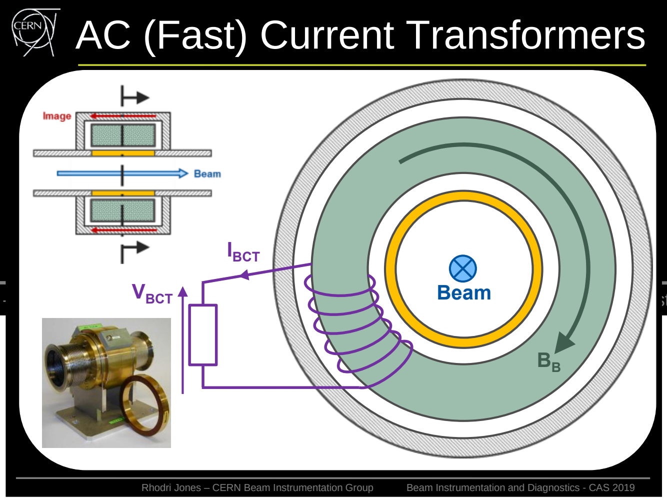
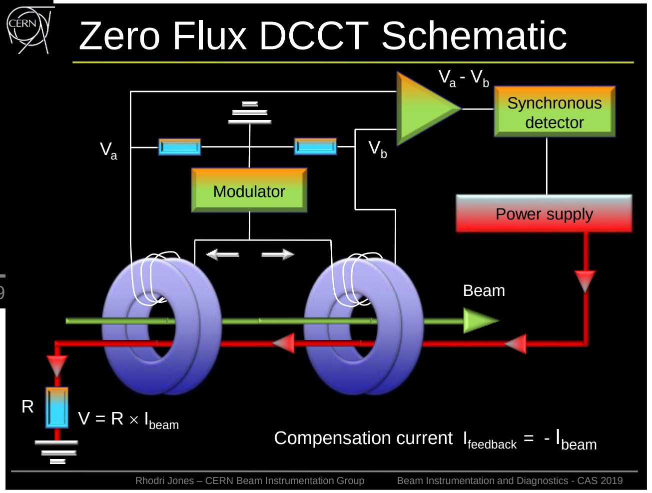
[A/(m-rad)^2]

Measuring large beam intensity and small beam emittances

Measuring high beam intensities





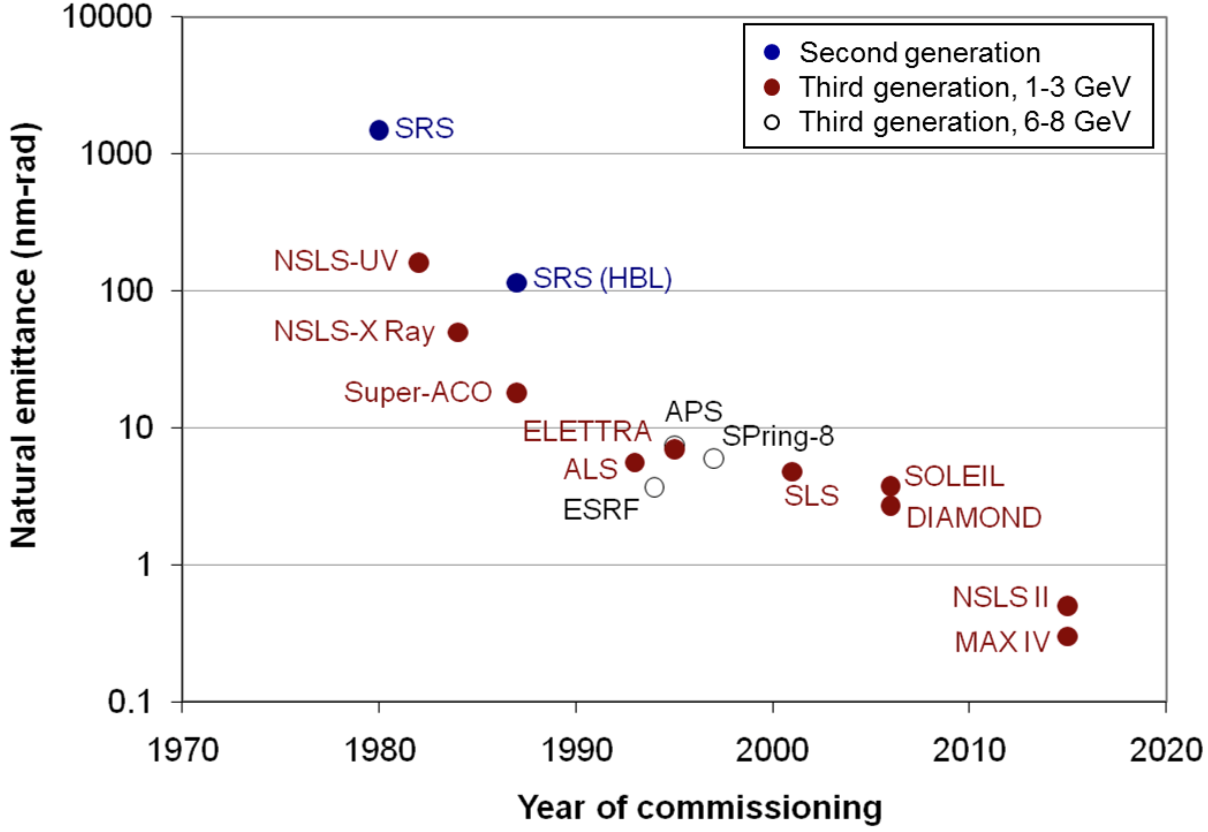


Challenge in measuring
low beam intensity ☺

Measuring small beam size

How small is small ?

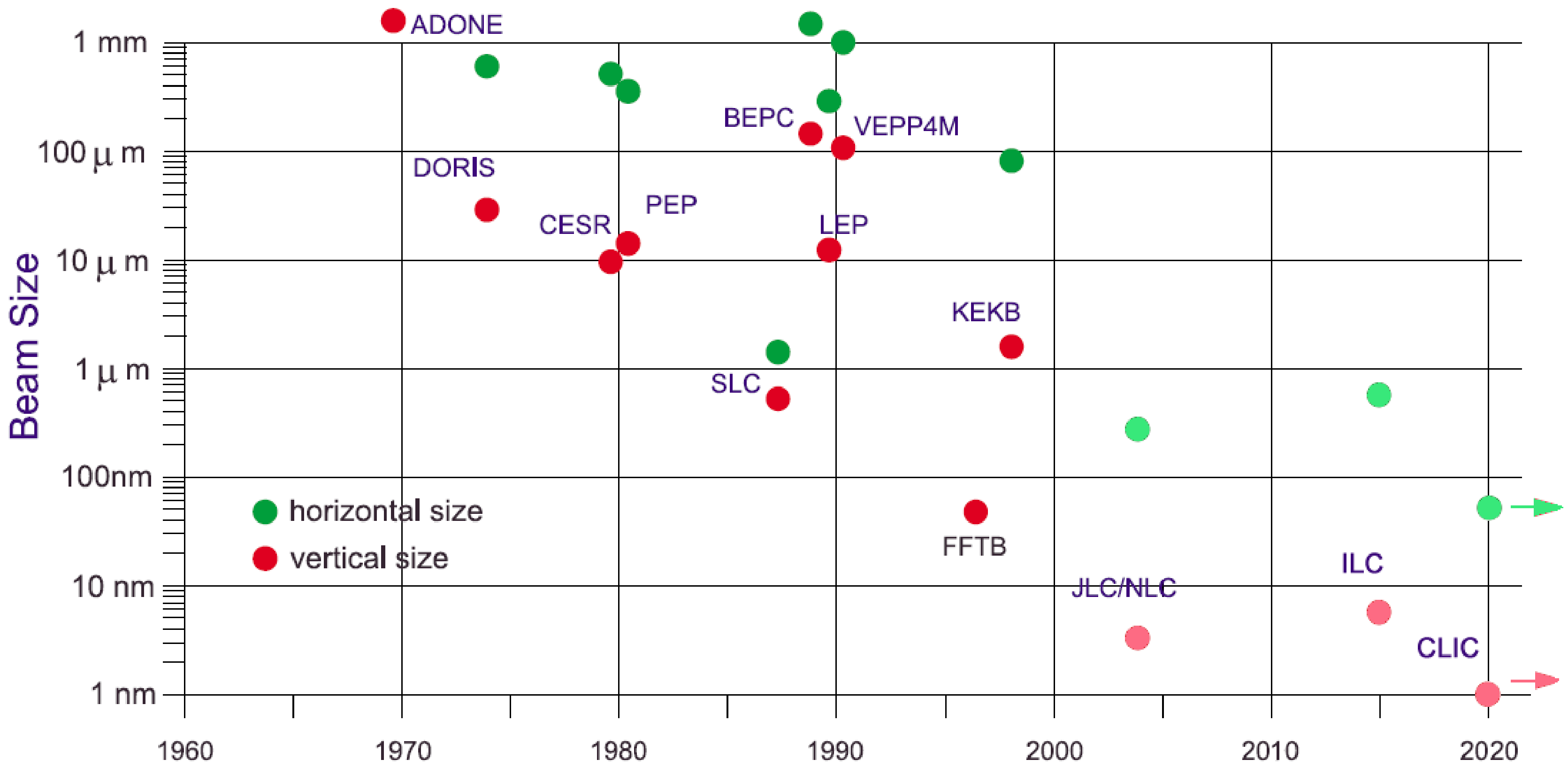
Synchrotron Light Source



Measuring small beam size

How small is small ?

e^+-e^- Collider



Adapded 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)*

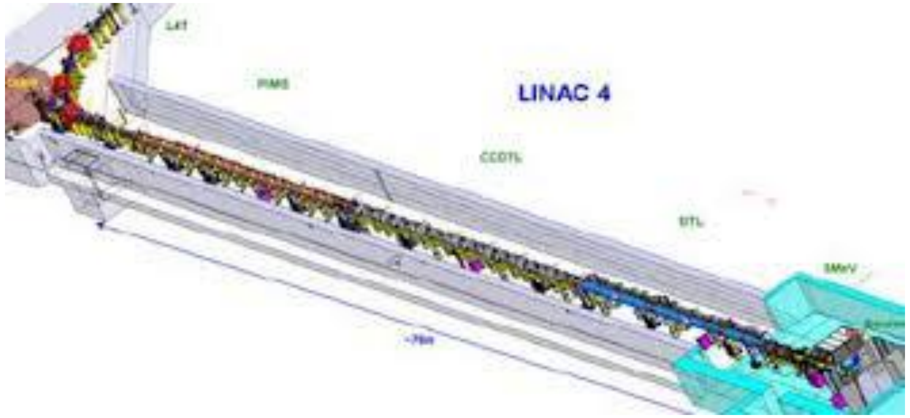
    10^4 nC/mm^2 - 6.25 10^{14} particles/mm^2

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

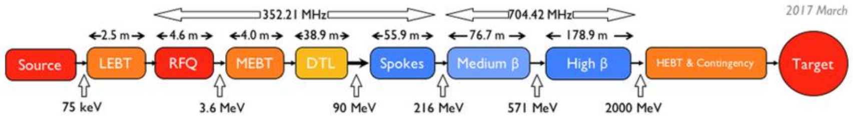
Some example of HB beams

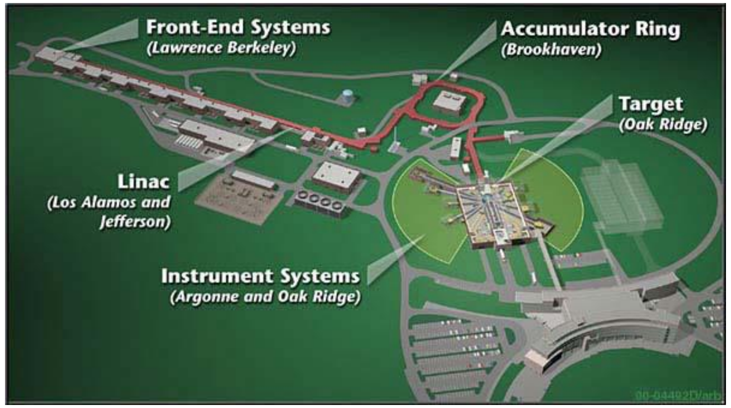
- High intensity Proton LINACs

L4@CERN



ESS - https://europeanspallationsource.se/





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

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Some example of HB beams

- Synchrotron Facility - 3rd generation light sources

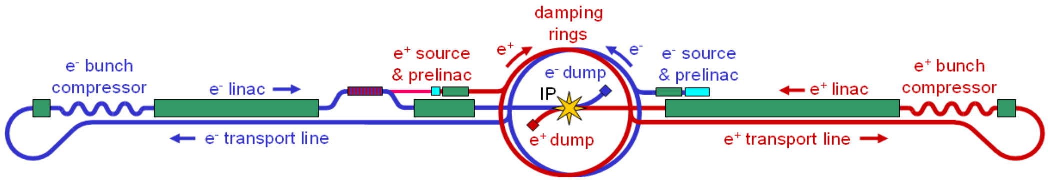
Some example of HB beams

- FEL and Energy frontier Linear Colliders

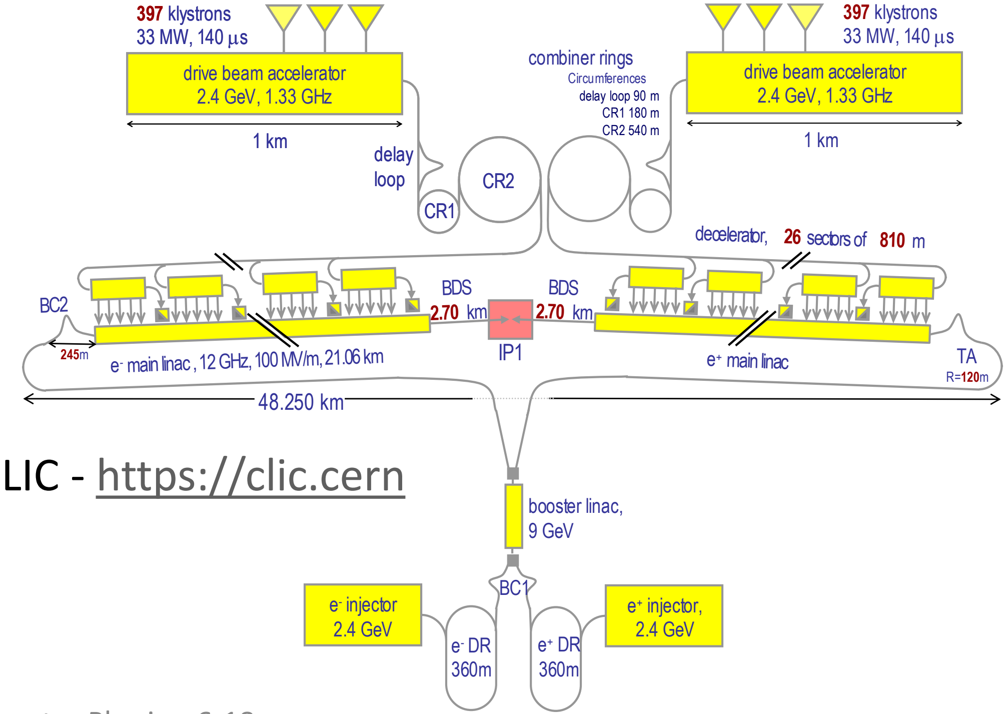
XFEL - https://www.xfel.eu/

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

ILC : https://linearcollider.org/



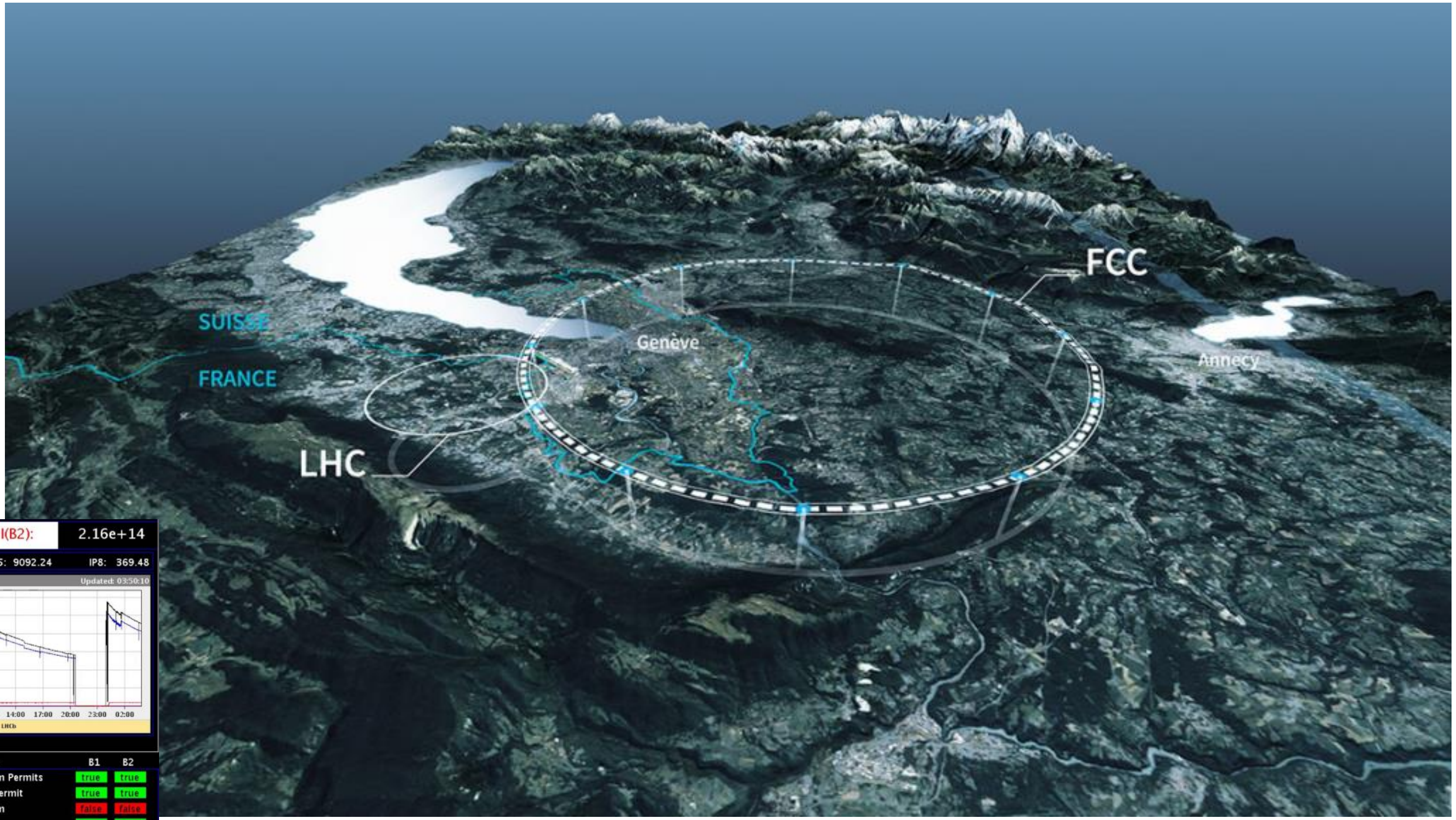
CLIC - https://clic.cern

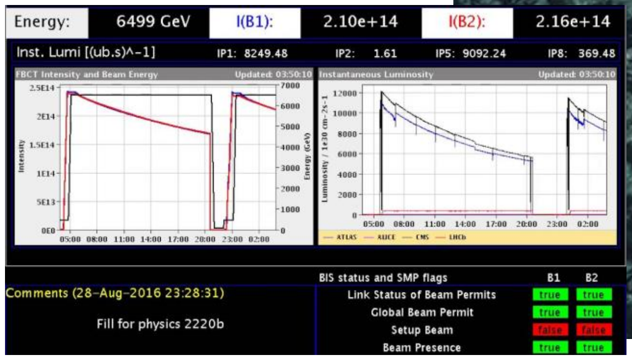


Some example of HB beams

- Energy frontier Circular Colliders

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





What high Brightness means ?

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

Short bunch length

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

What high Brightness means ?

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

Longitudinal beam diagnostics covered tomorrow

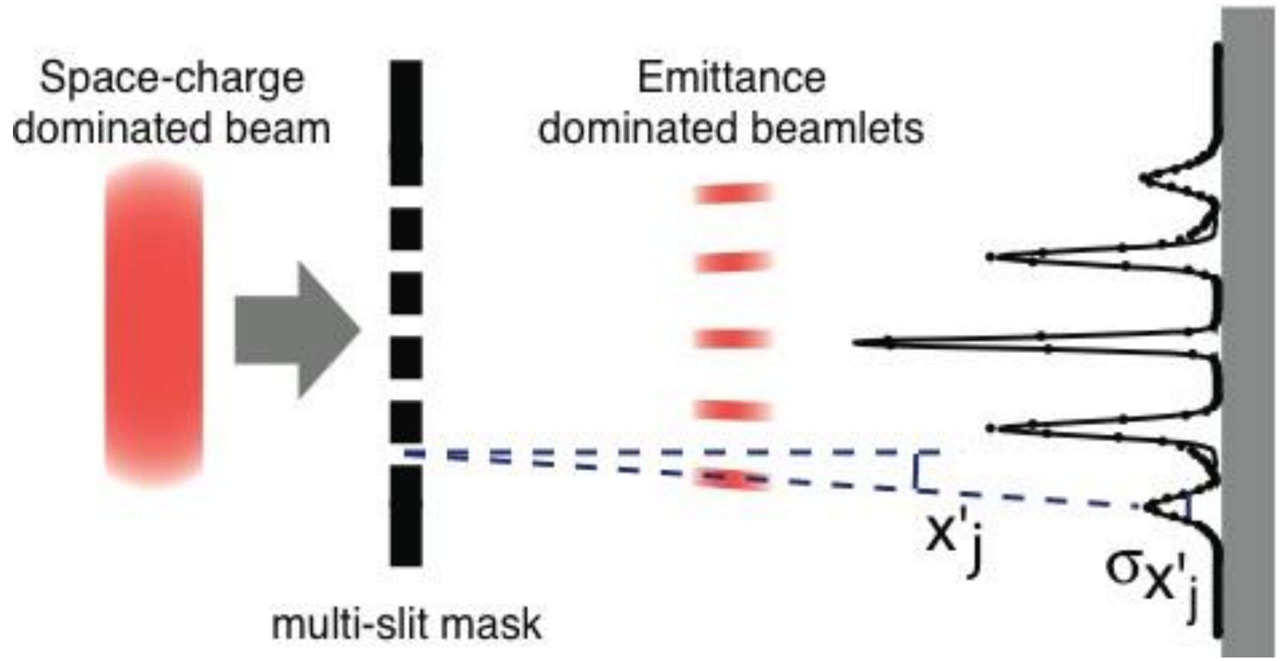
Accelerator technologies

- Dielectric acceleration
- THz acceleration
- Plasma acceleration

Transverse Diagnostics
Space-charge dominated beam

high intensity low energy electron/hadron beams

Space charge regime



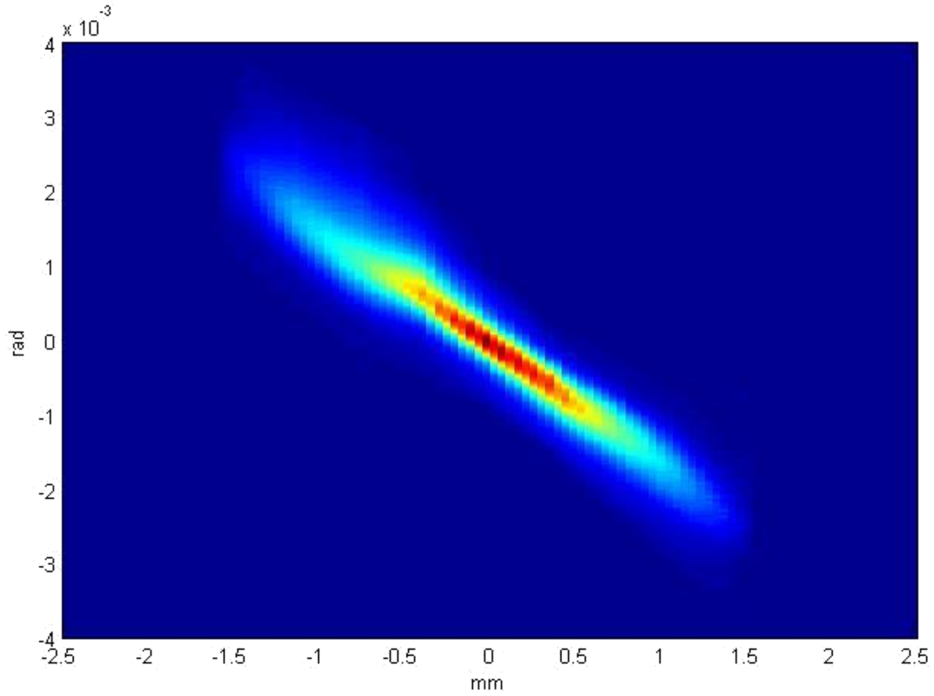
To measure the emittance for a space charge dominated beam the used technique is the well known pepper-pot

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

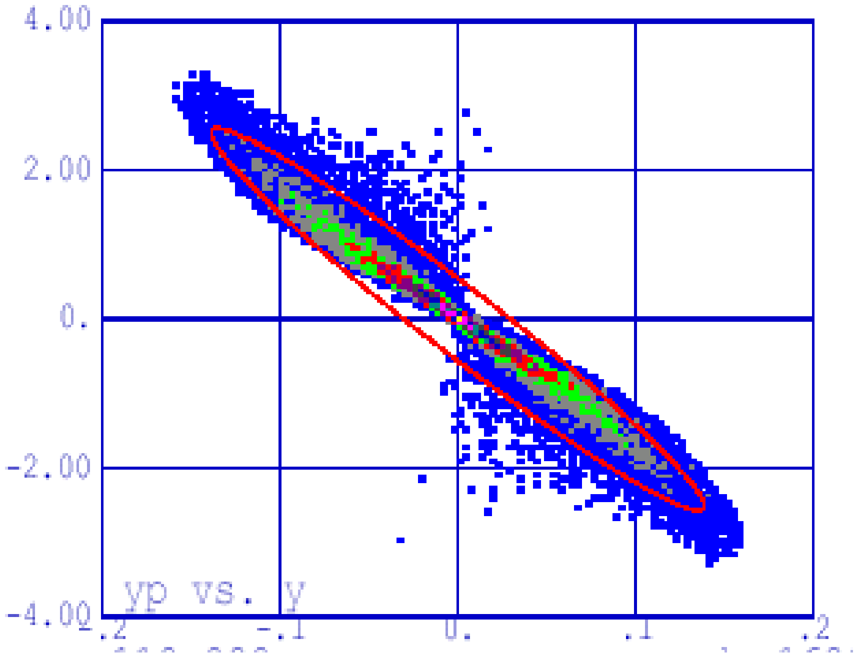
C. Lejeune and J. Aubert, Adv. Electron. Electron Phys. Suppl. A ***13****, 159 (1980)*

Space charge regime

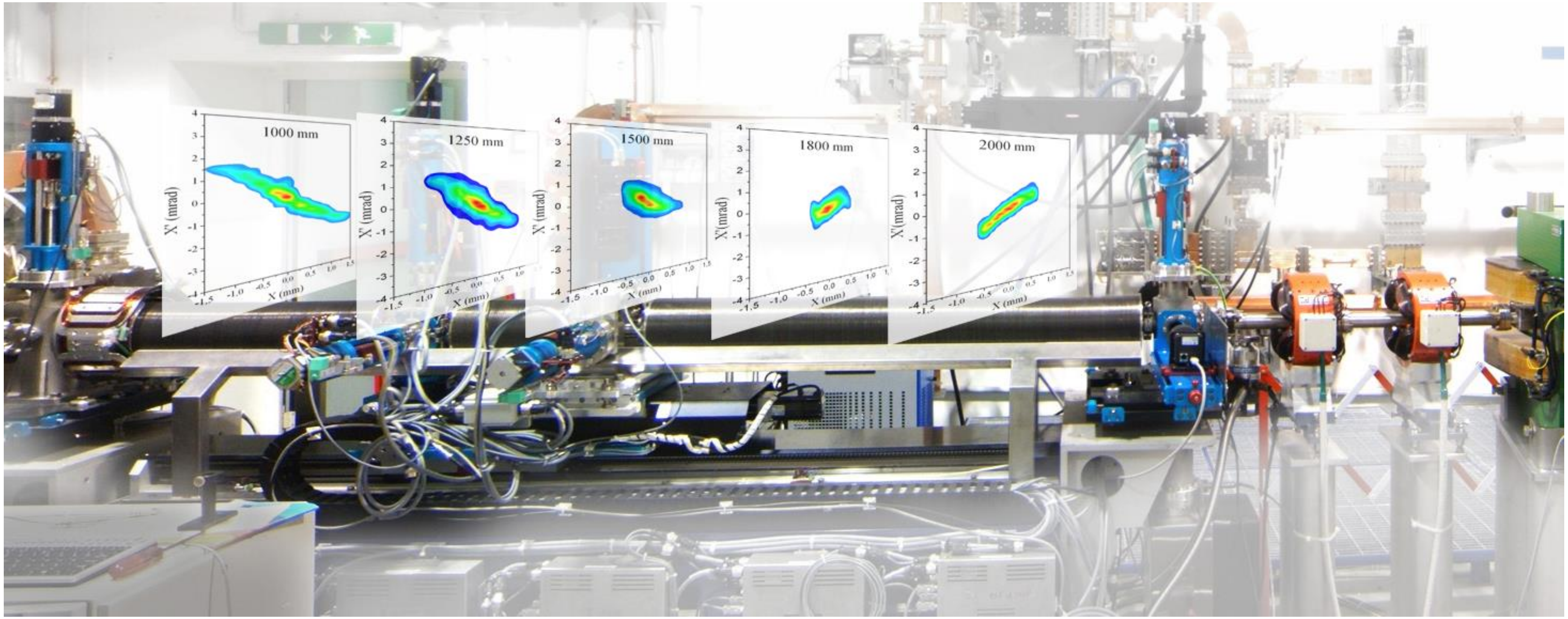
Measurements



Simulations

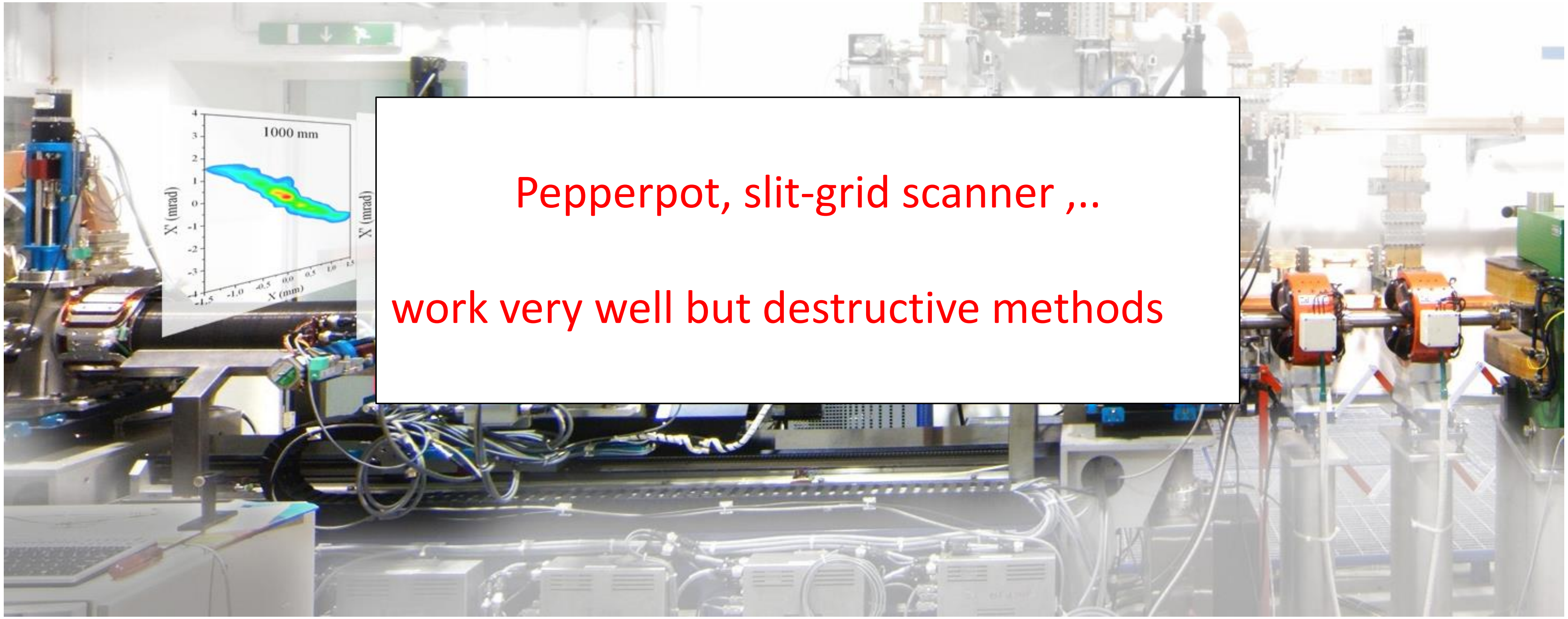


Phase space evolution



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 ,..

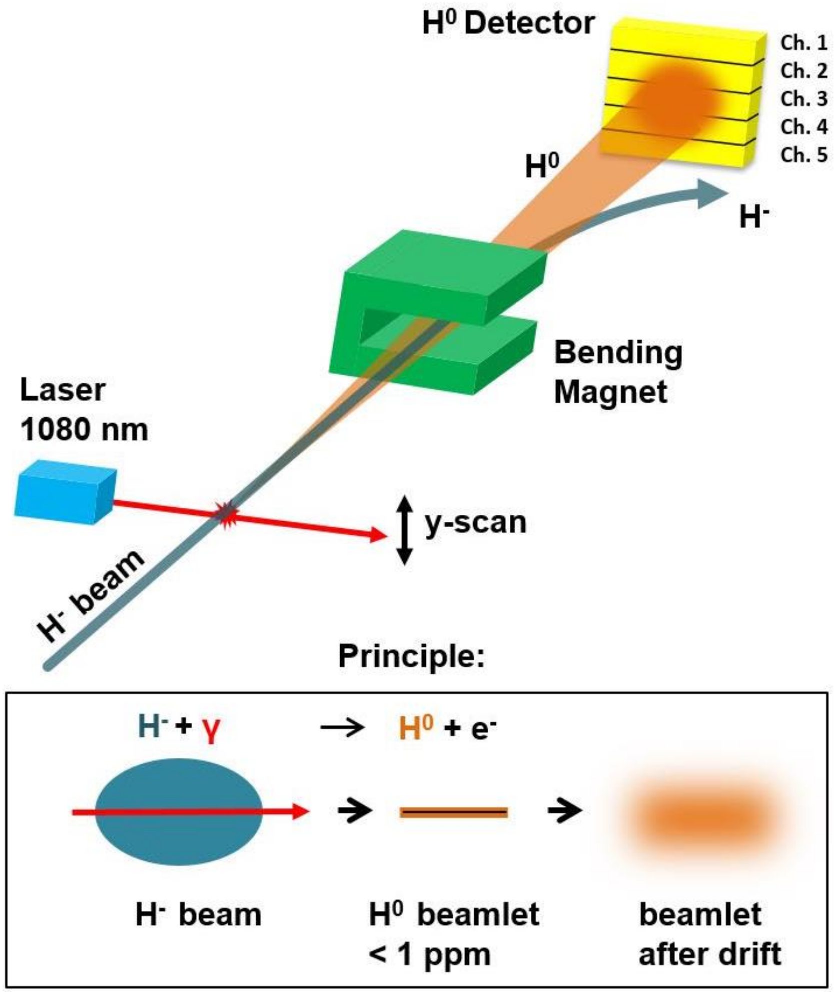
work very well but destructive methods

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

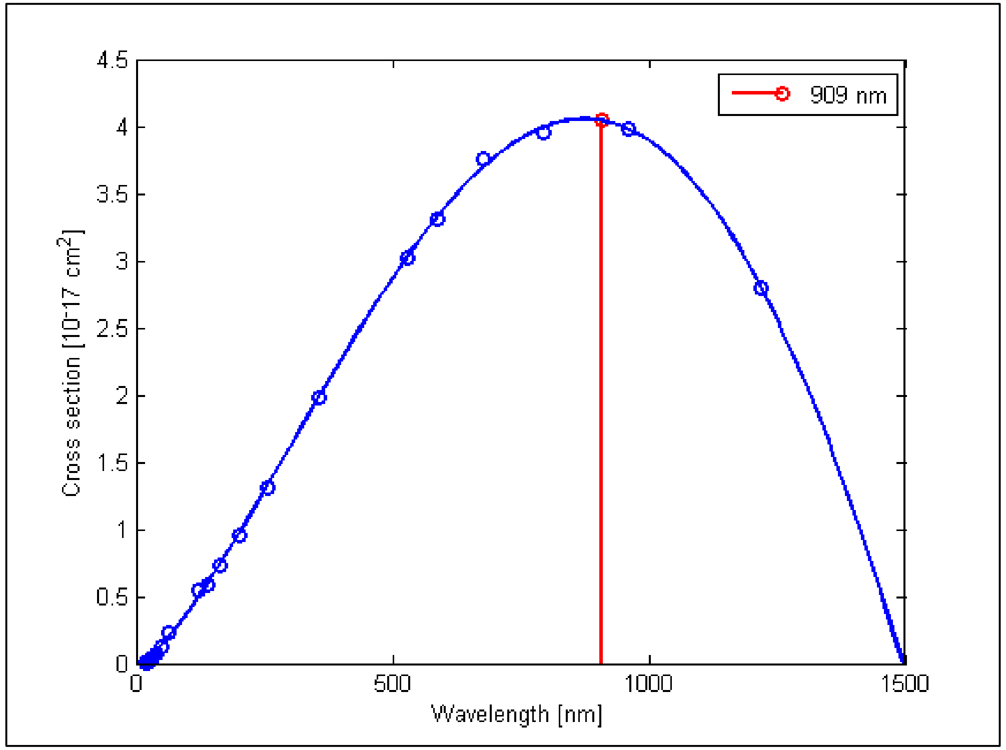
Laser Emittance meter for H^-

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

Laser Emittance meter for H⁻

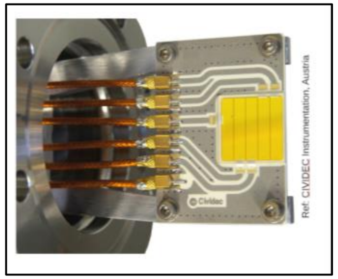


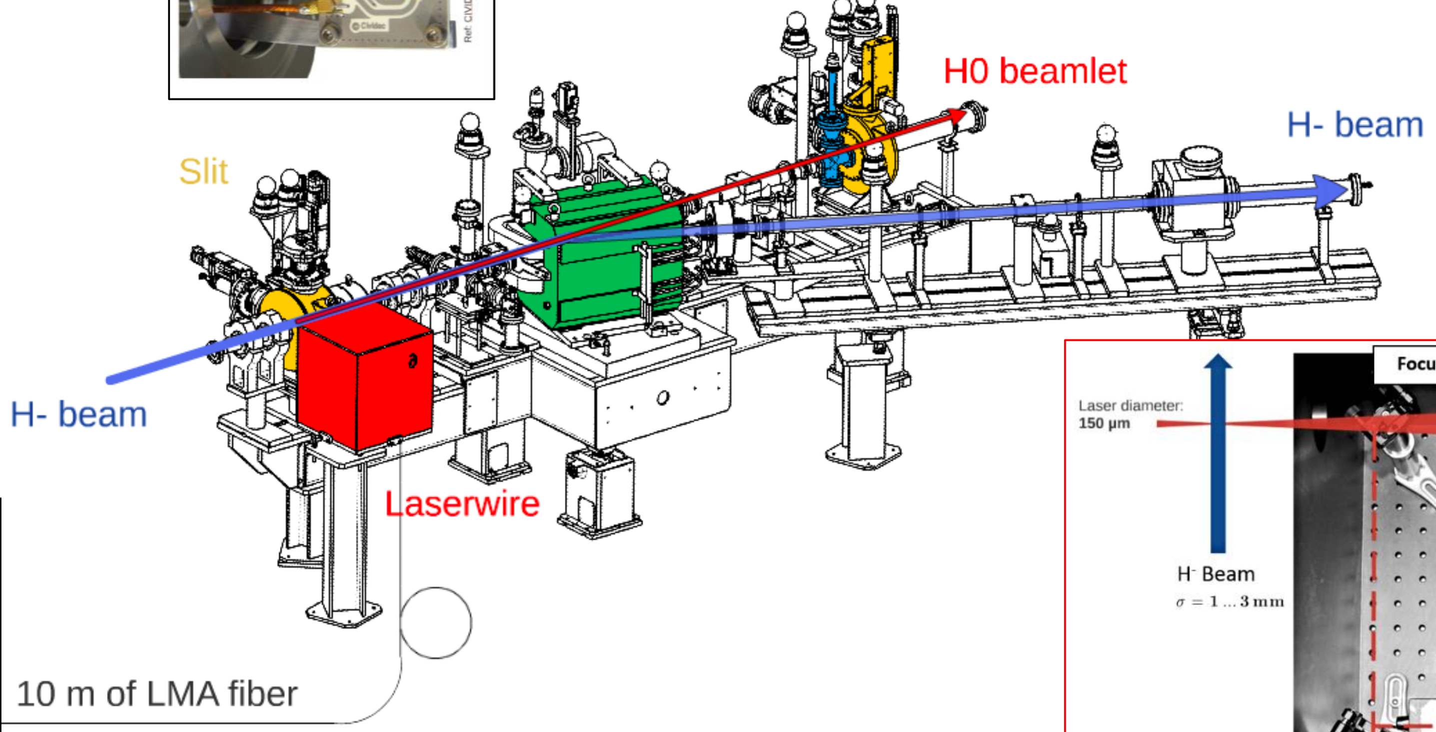
Electron Laser-Stripping cross section

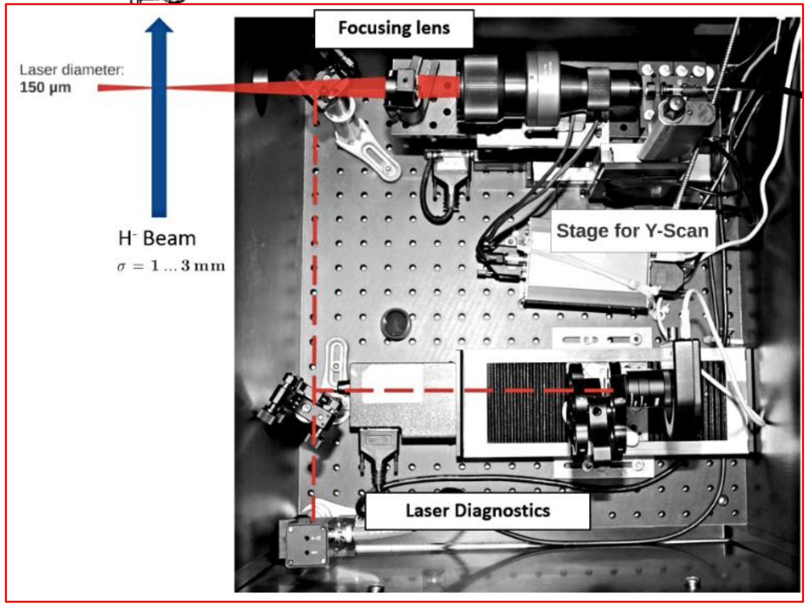


T. Hofmann et al, "A low-power laserwire profile monitor for H- beams: Design and experimental results" Nucl. Inst. and Meth. in Phys. Res. Section A: 903, p. 140-146 (2018)

Laser Emittance meter for H^-



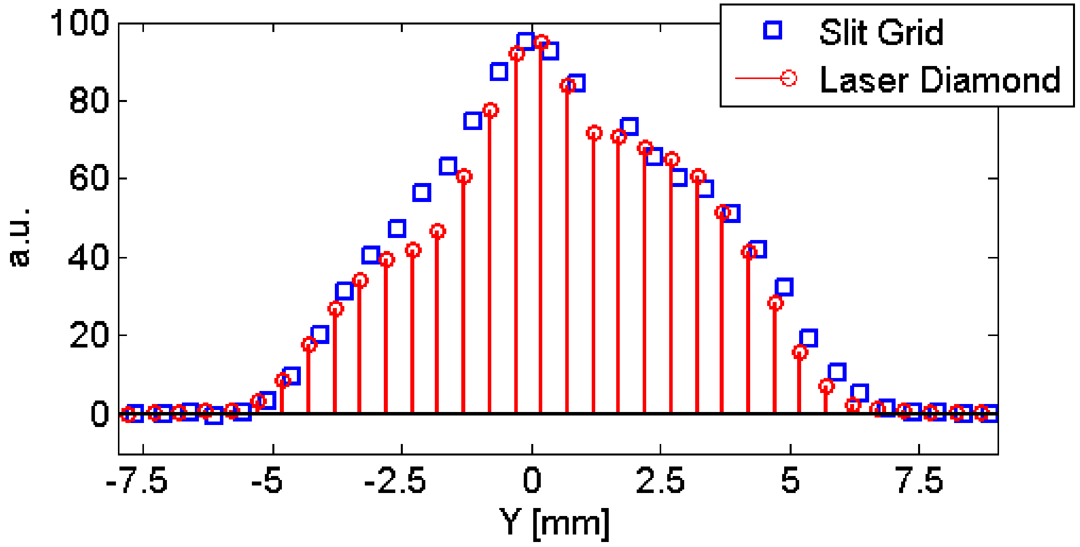


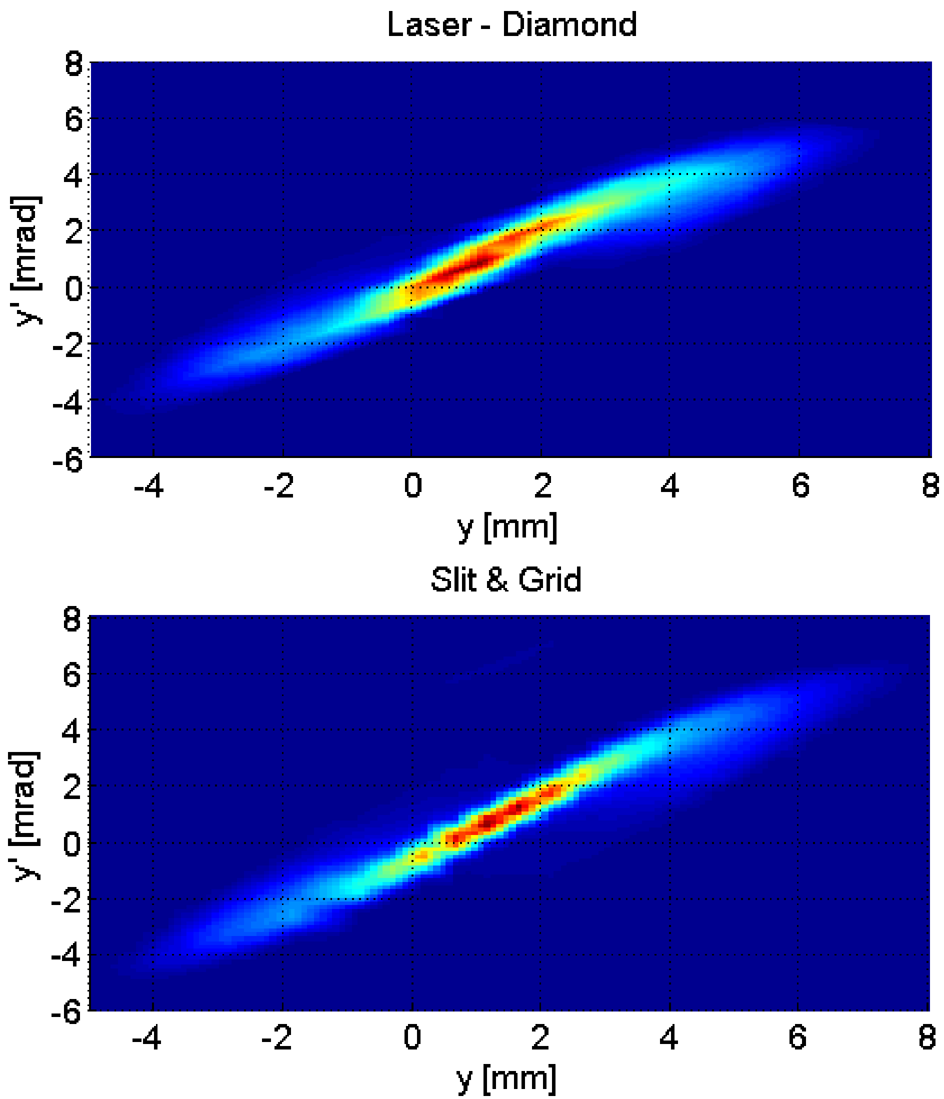


Laser	MOPA	*Nd-YAG*
Pulse Energy	**0.1 mJ**	*50 mJ*
Stripping	**0.1 %**	*> 99 %*
t_{pulse}	80 ns	*5 ns*

Laser Emittance meter for H^-

- Measurements at 3 and 12 MeV at Linac4/CERN

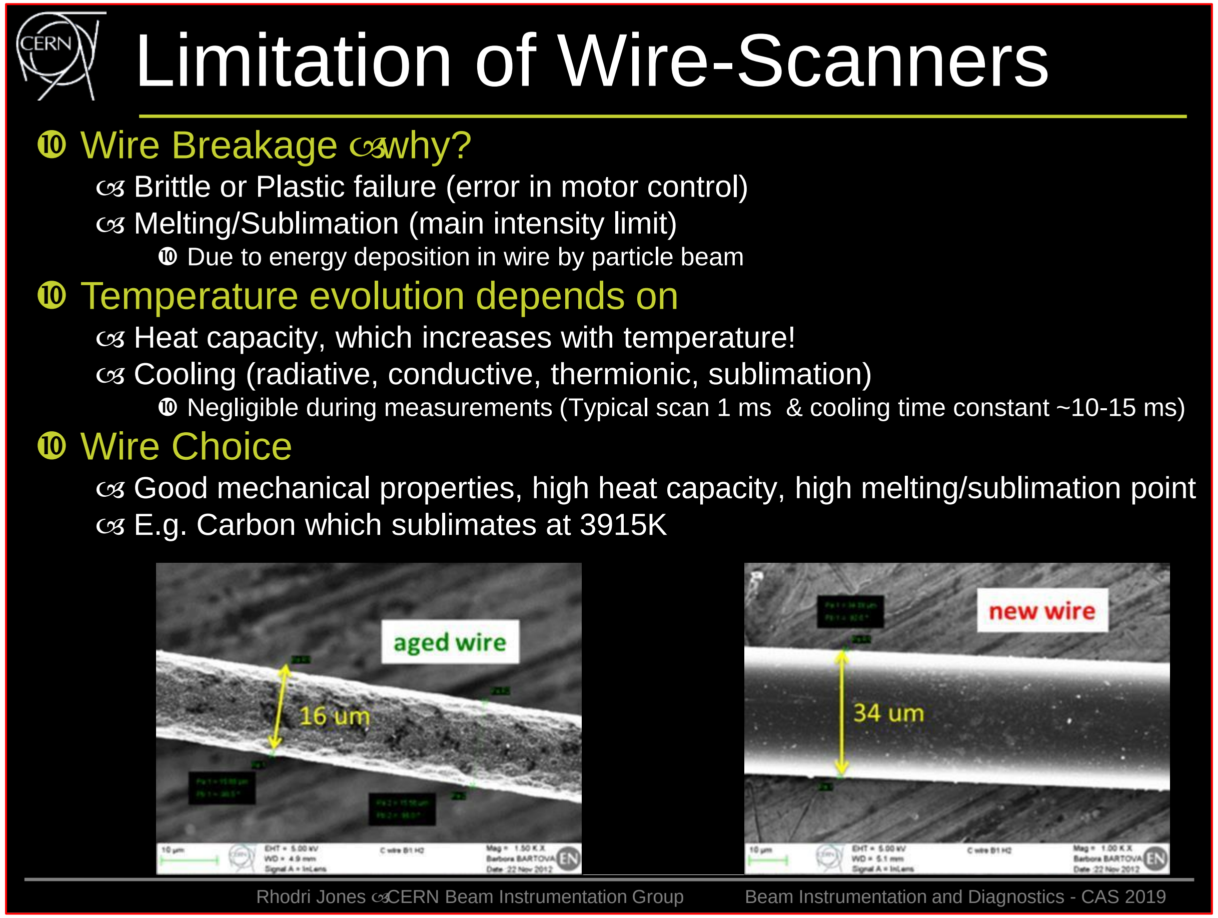




Transverse Diagnostics in Hadron Rings

……higher beam energy

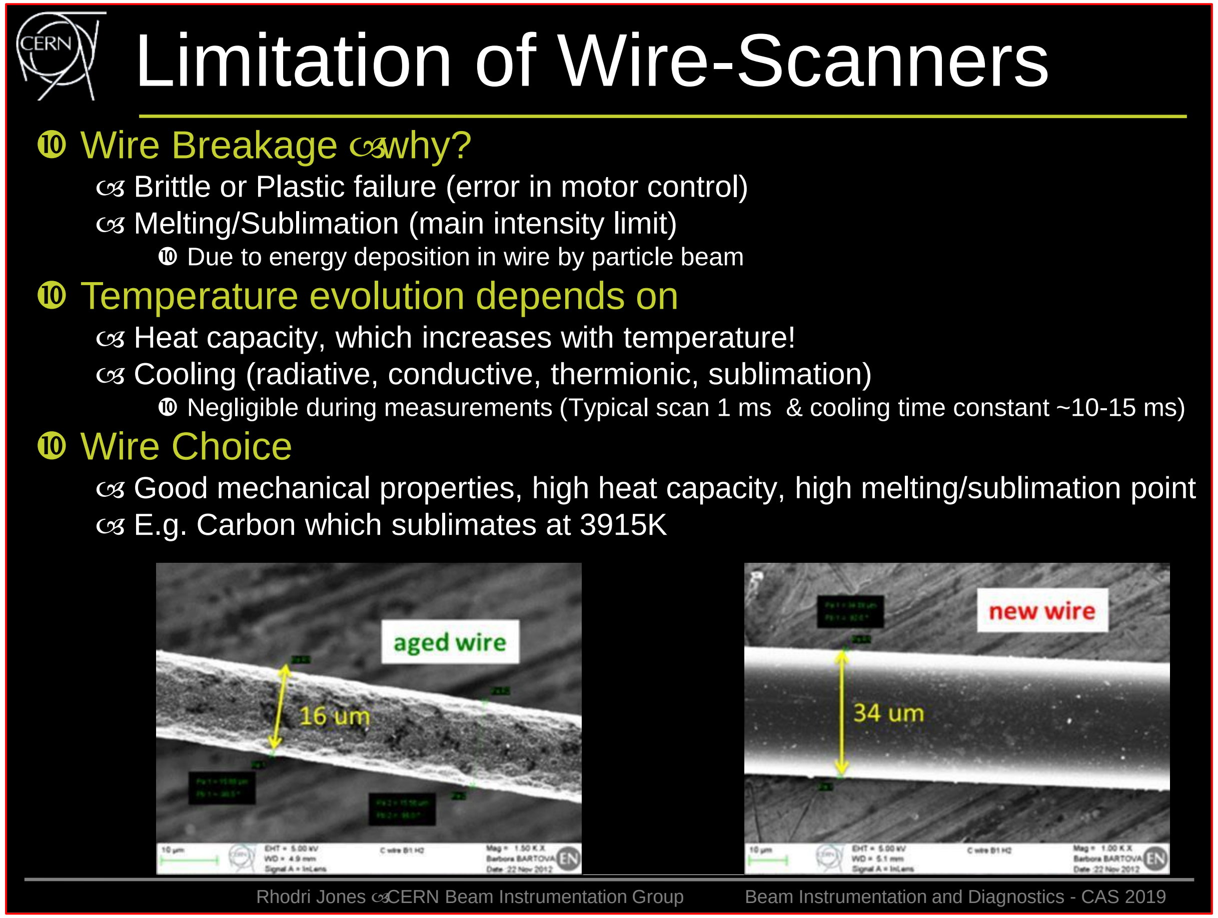
Hadron ring - Wire Scanner



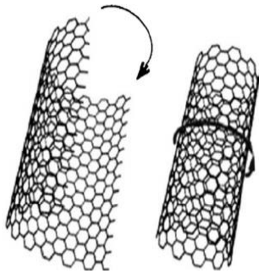
Scanning fast to measure higher beam intensities

Max speed 20m/s

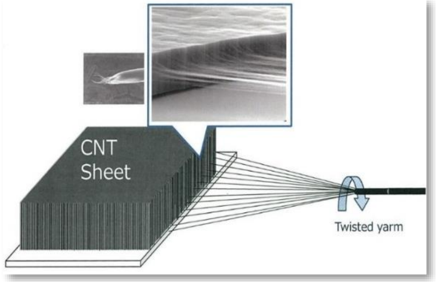
Hadron ring - Wire Scanner

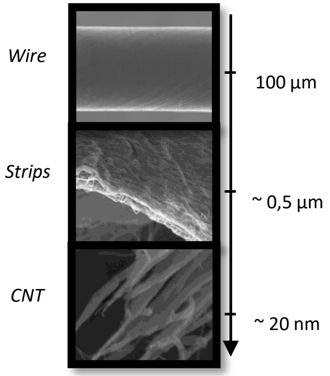


Using better materials for wire – ‘low density’ materials



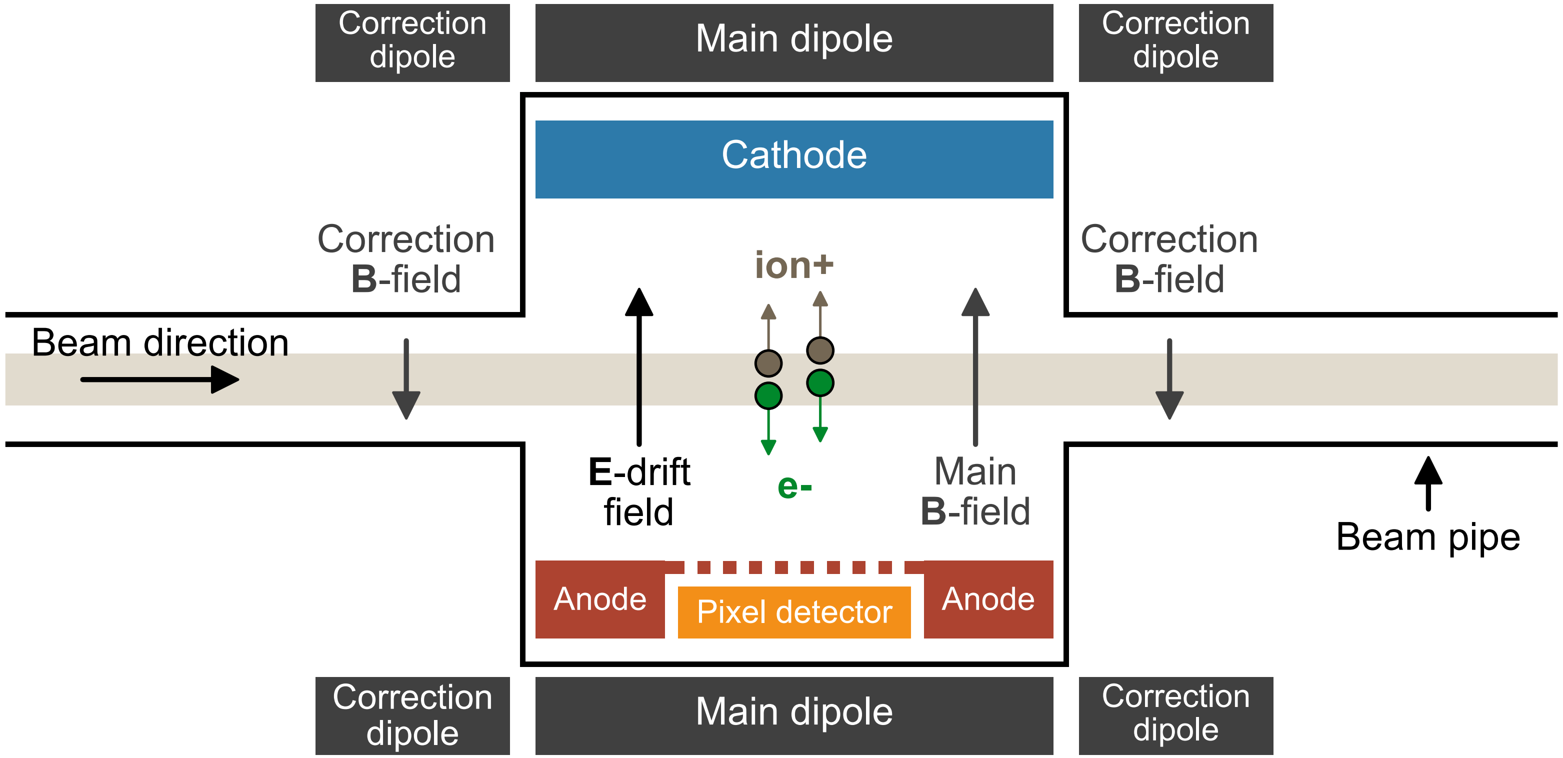
From graphene to Carbon Nano-Tubes

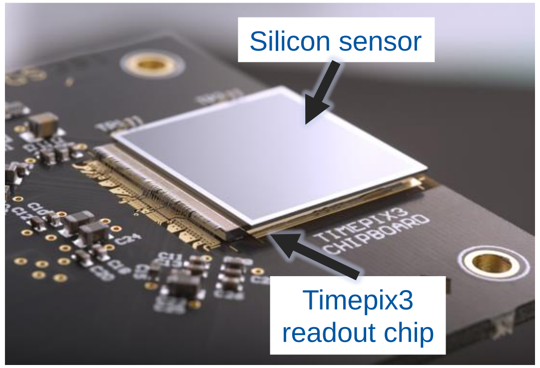




CNTW multi-scale

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, ..

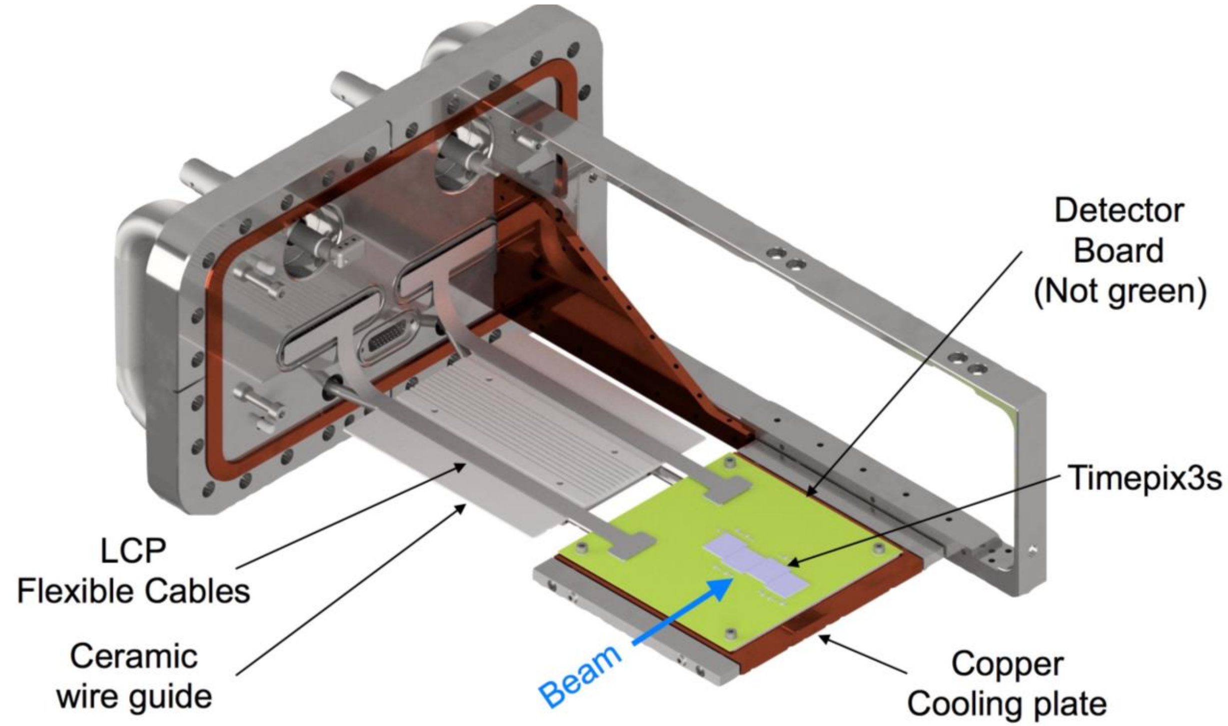
- 256x256 pixels
- 55um pitch
- Timestamp resolution of 1.5625ns
- Time-over-threshold to energy calibration
- 8x serial links up to 640Mbits/s = 5.12Gbit/s

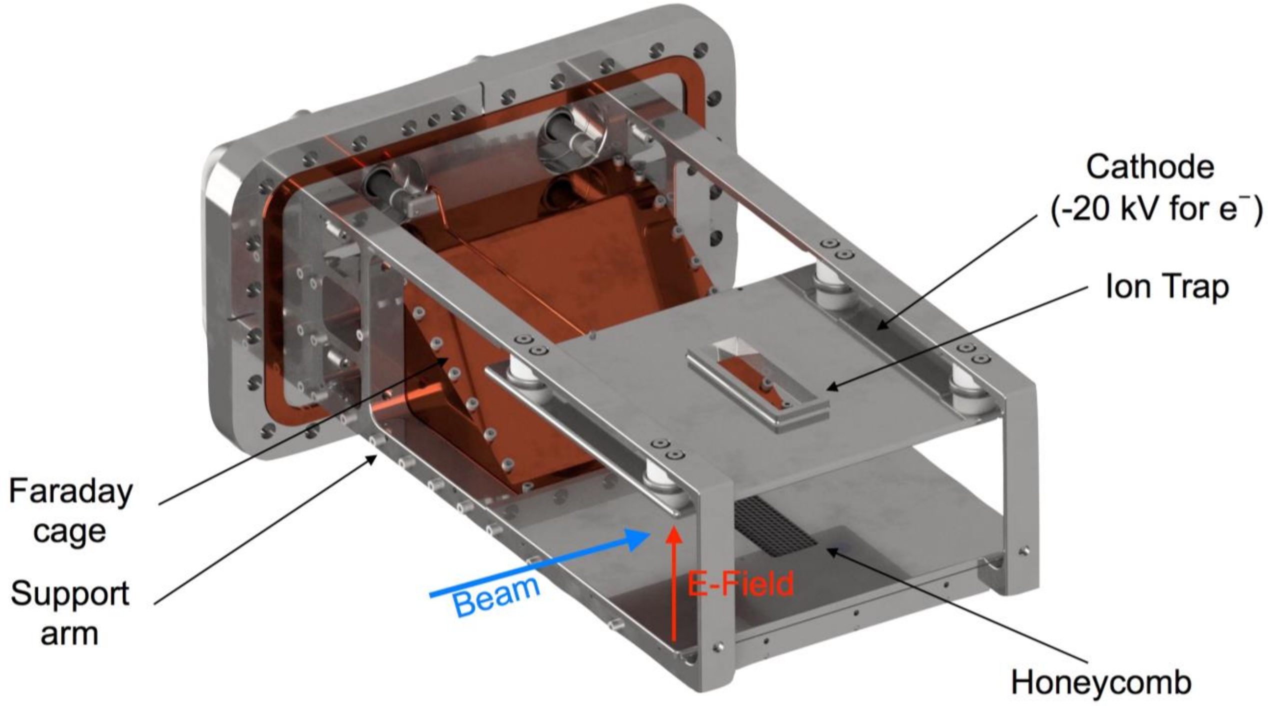
https://medipix.web.cern.ch/technology-chip/timepix3-chip

- *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*

Beam Gas Ionization monitor

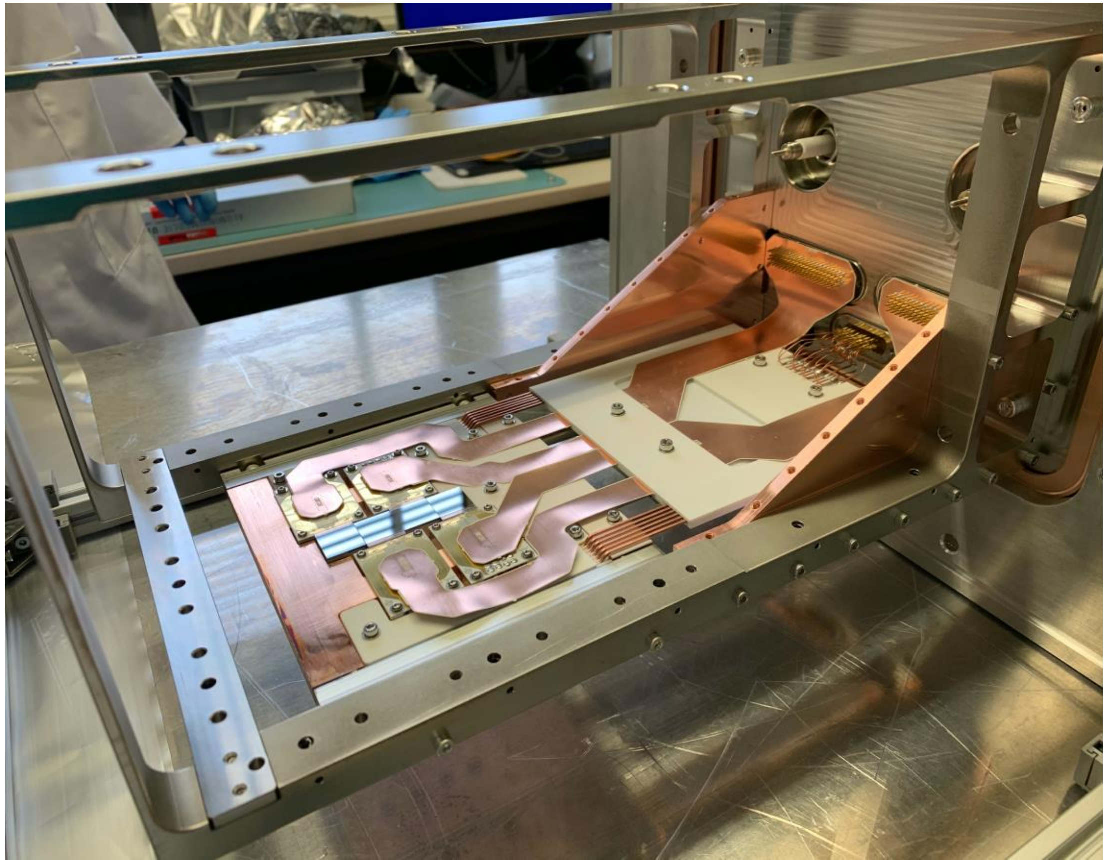
Low impedance design and high vacuum compatibility



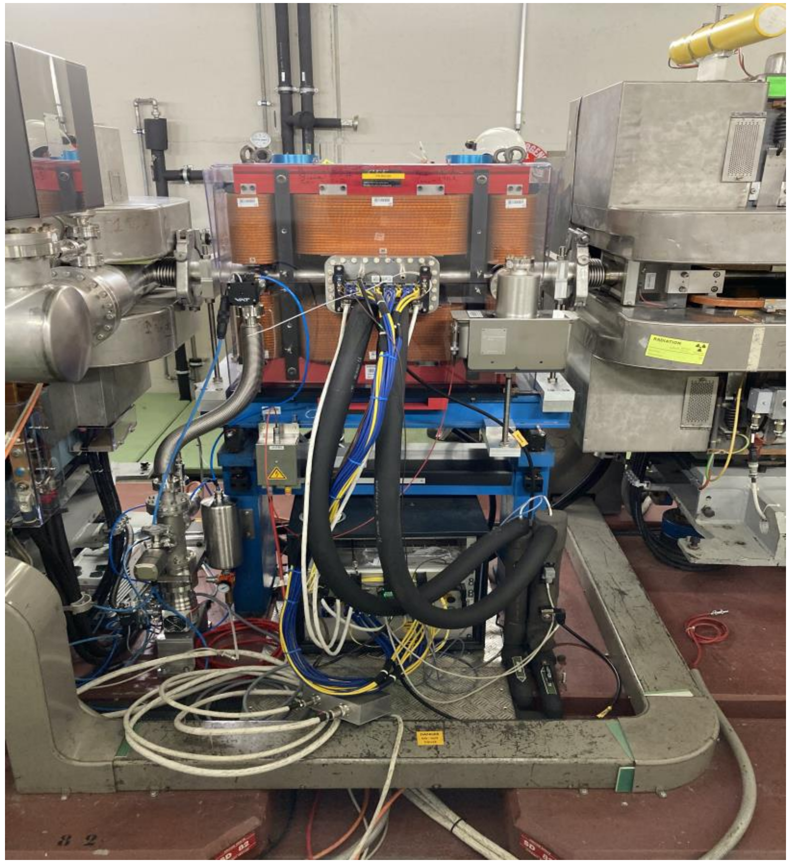


http://bgi-web.web.cern.ch/bgi-web/

Beam Gas Ionization monitor



Timepix3-BGI in-vacuum instrument

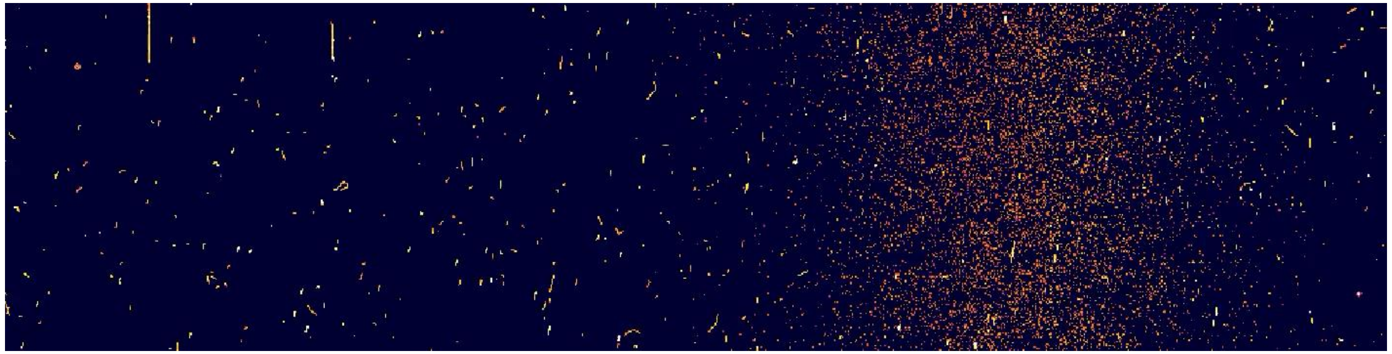


Timepix3-BGI installed in the PS ring

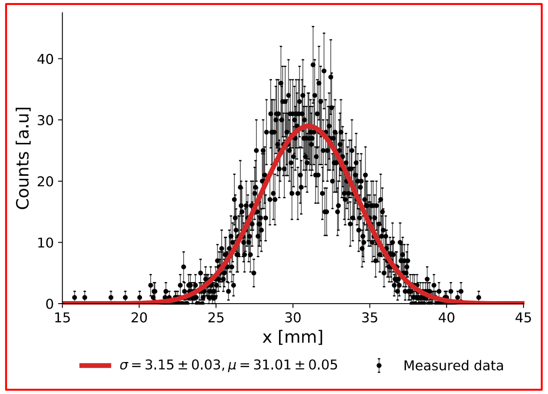
Beam Gas Ionization monitor

Measurement on the PS ring

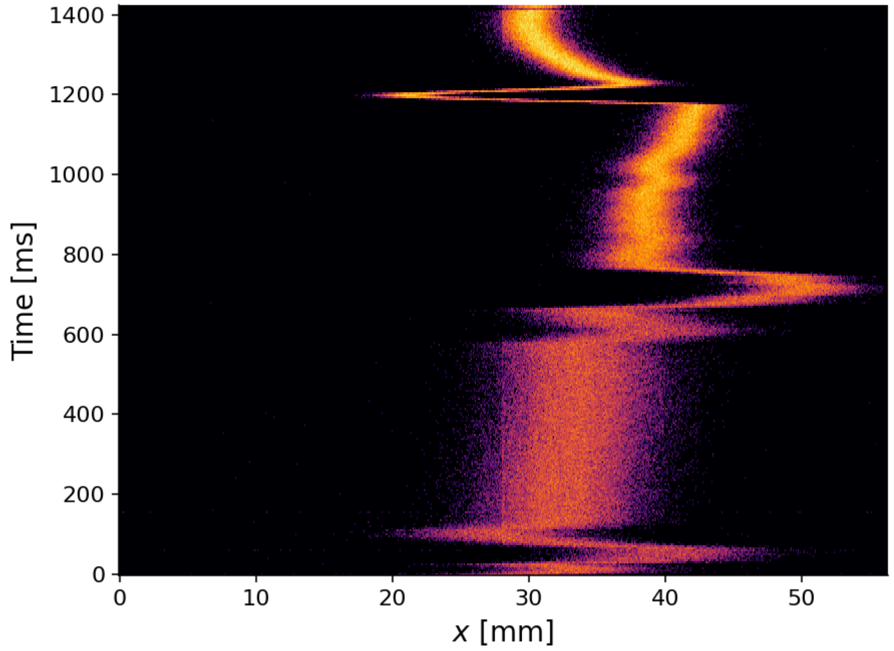
LHC type beam from injection, through acceleration and finally extraction



- 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.



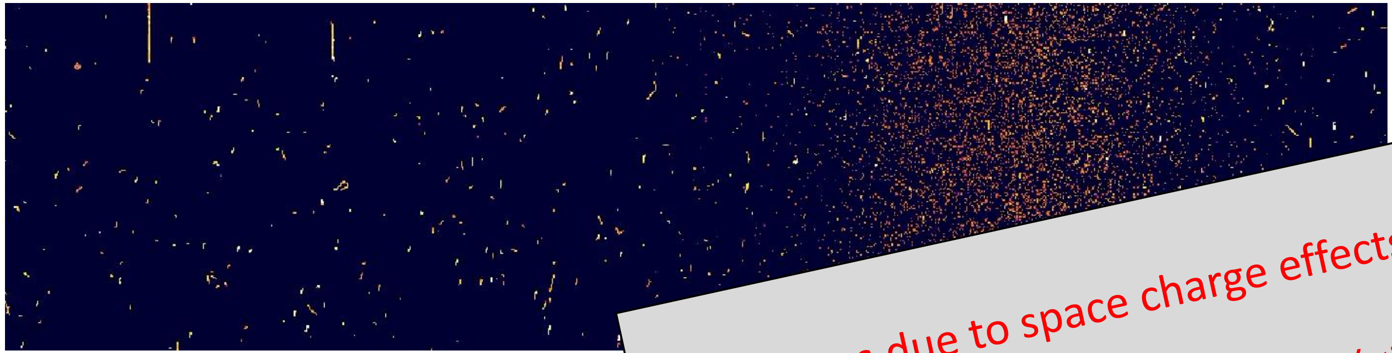
Beam profile & position through the PS cycle



Beam Gas Ionization monitor

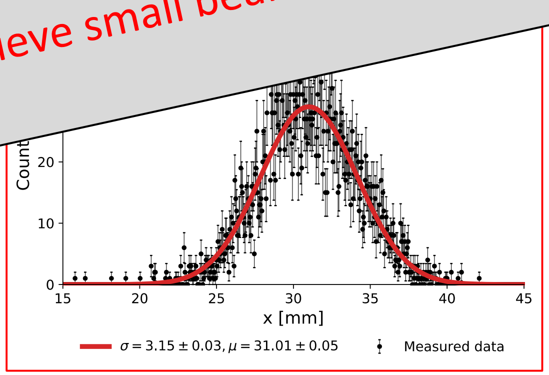
Measurement on the PS ring

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)



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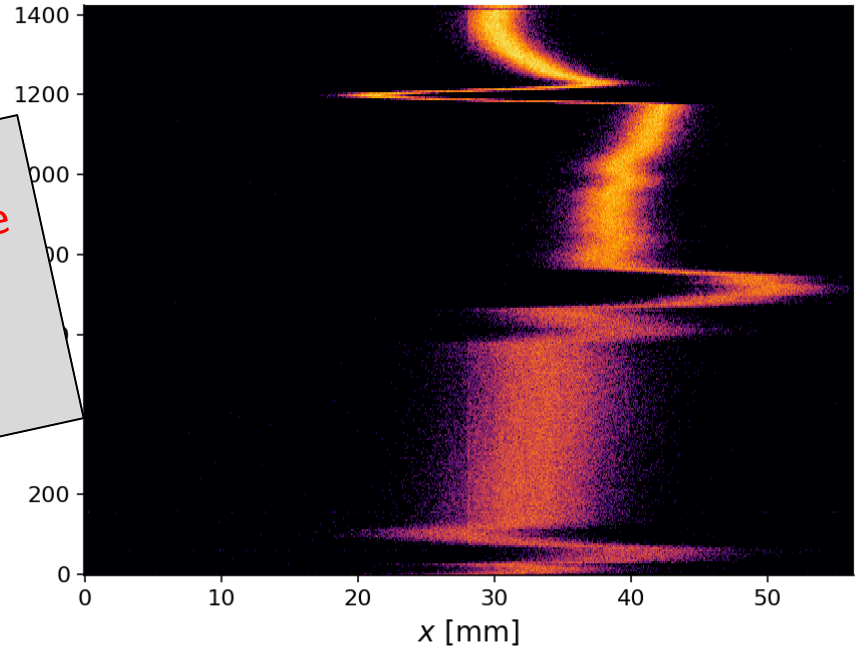


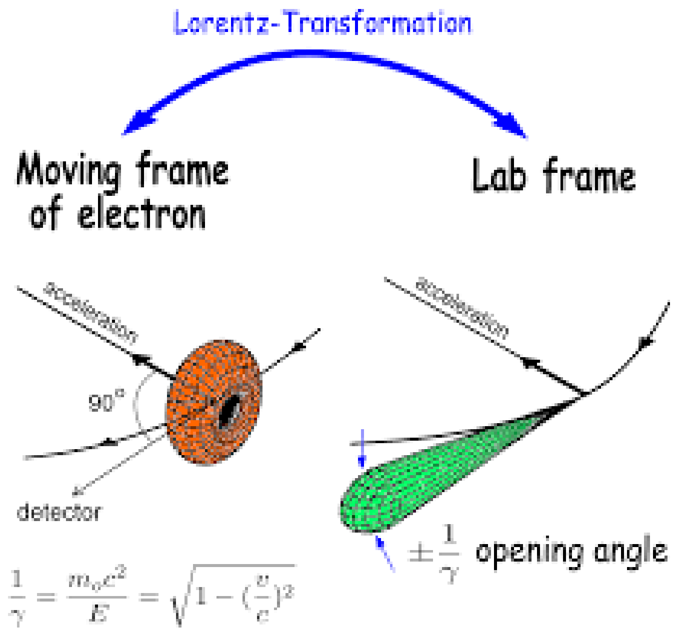
Beam Gas fluorescence monitor

- 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

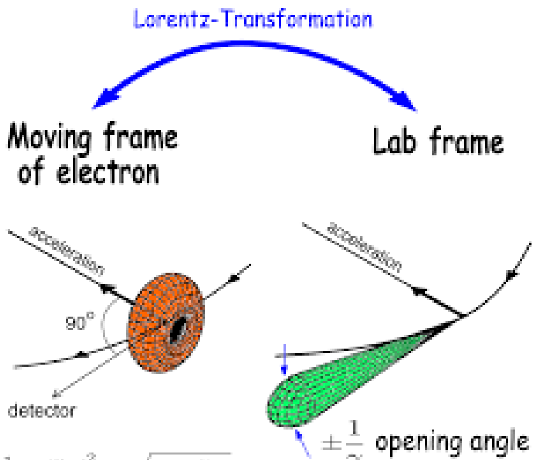
<u>'Let There Be Light'</u>



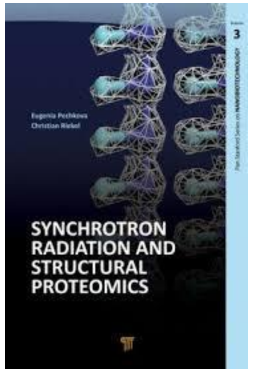
Nothing religious but a great tool for beam diagnostics

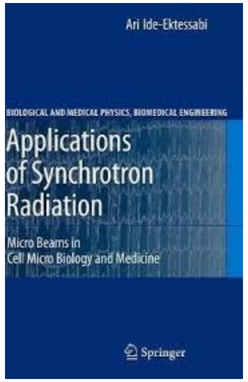
Hadron ring – Synchrotron Radiation

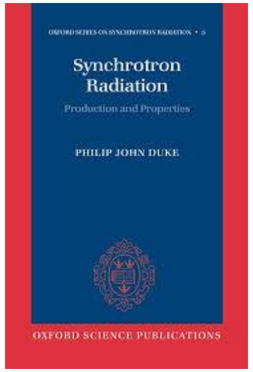
‘Let There Be Light’

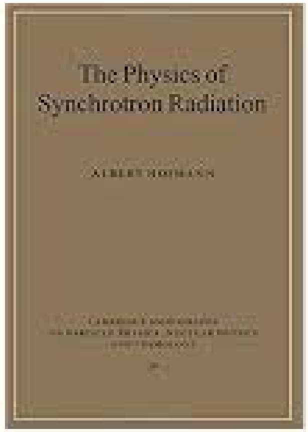


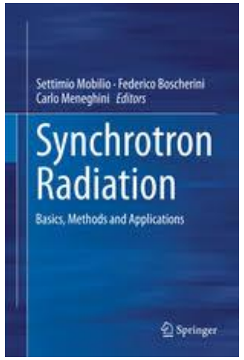
$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1-(\frac{v}{c})^2} \qquad \pm\frac{1}{\gamma}$$

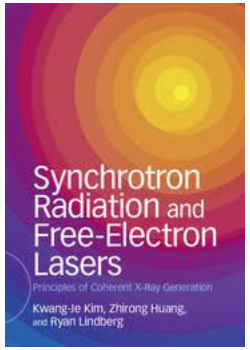


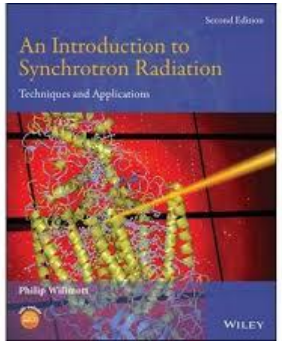












Hadron ring – Synchrotron Radiation

- Power :

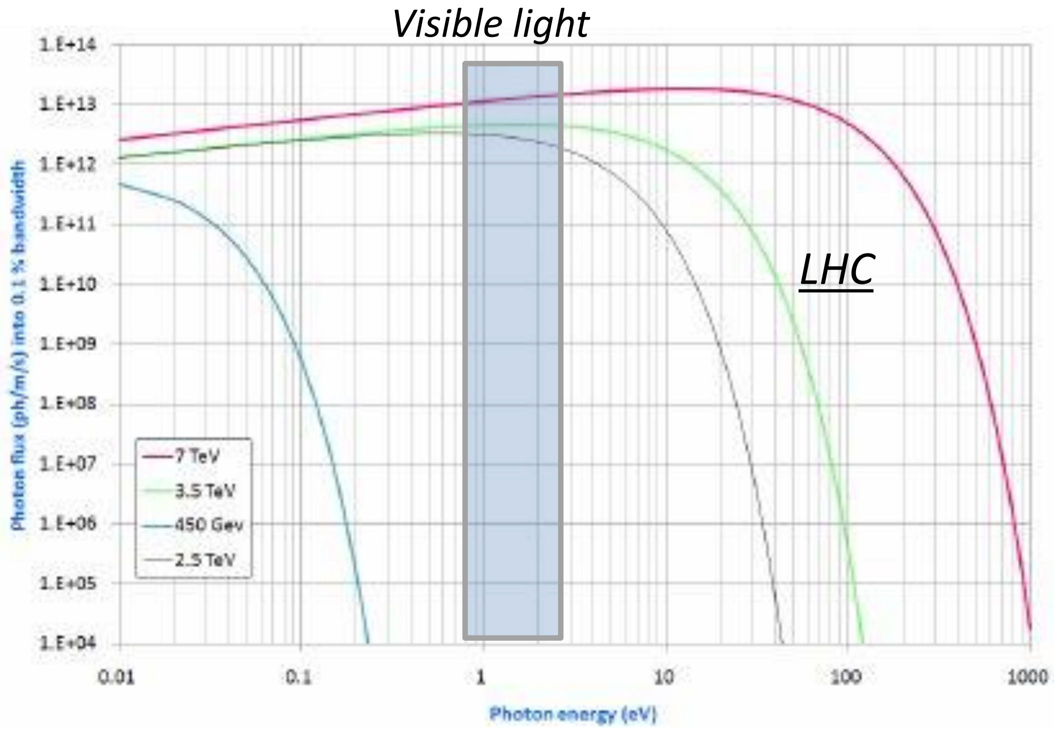
$$P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2 c}{\rho^2}\gamma^4$$

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

- Critical Frequency :

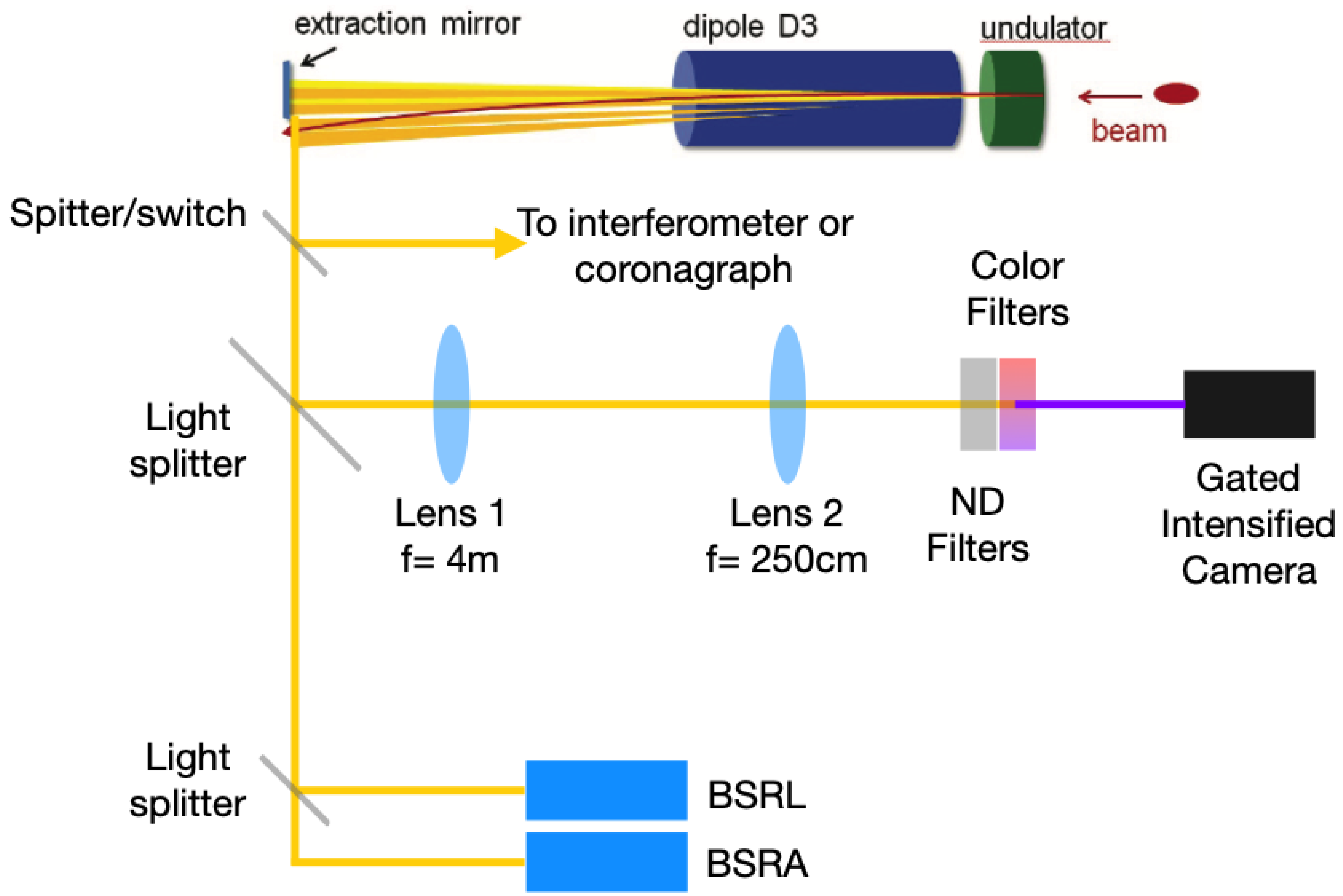
$$\omega_c = 3\gamma^3 \frac{c}{2\rho}$$

Beam energy   Beam curvature



Hadron ring – Synchrotron Radiation

Light is precious and serves many detectors - @LHC



Hadron ring – Synchrotron Radiation

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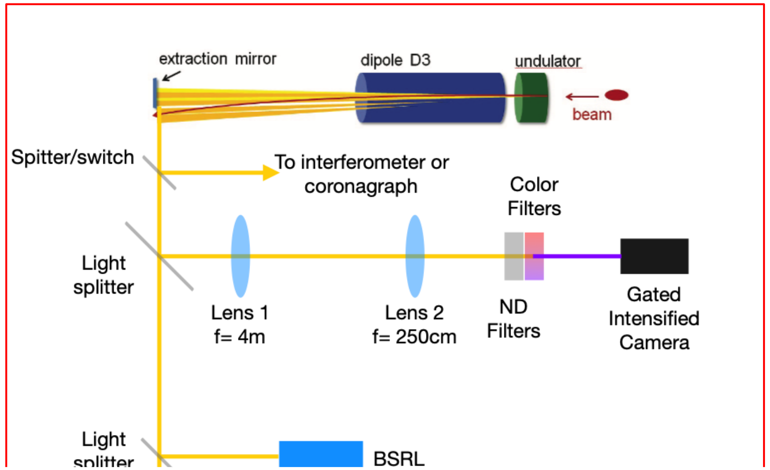
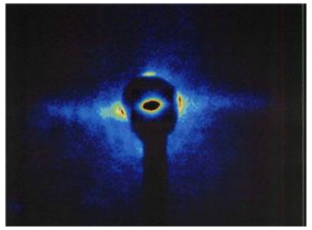
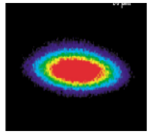
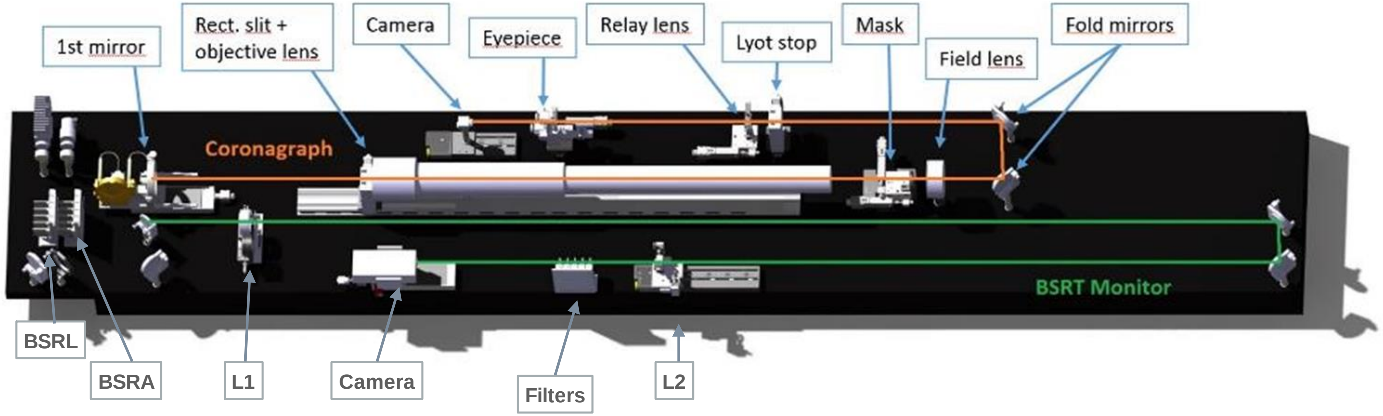




Halo



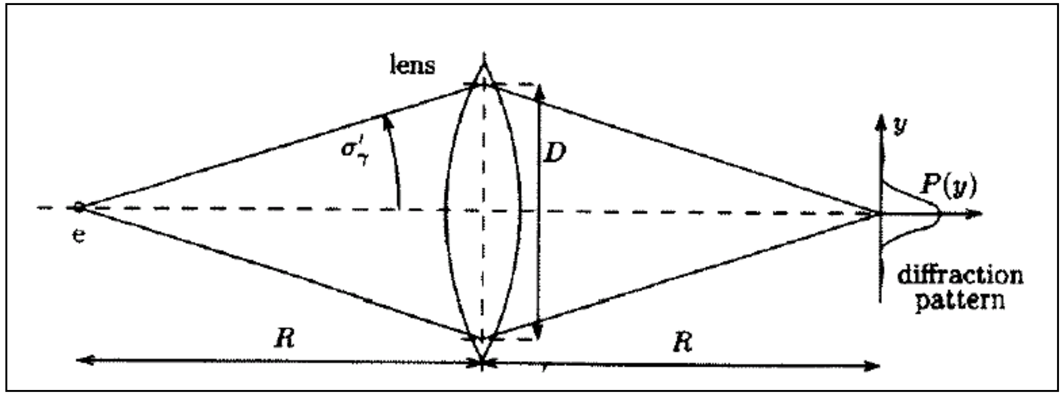
Core



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

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

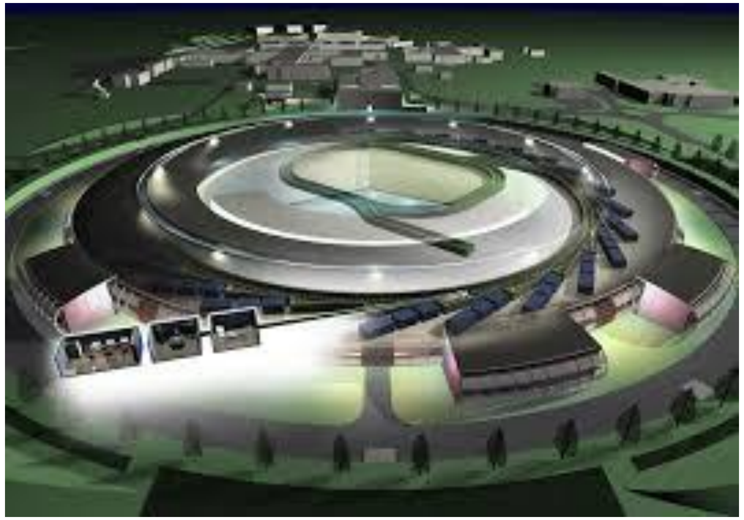
For highly relativistic beams, resolution limit reaches quickly 100's of microns for visible light !!

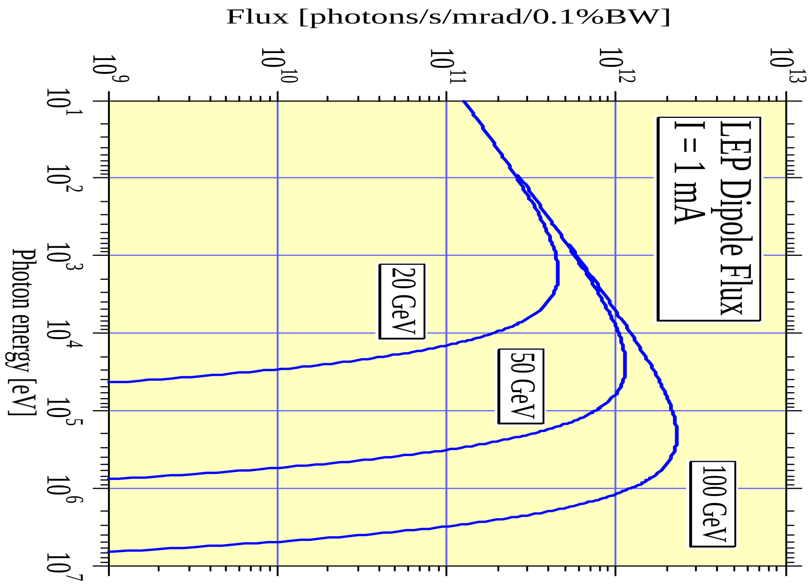
The CERN Accelerator School

Transverse Diagnostics in Electron Ring

Electron ring – Synchrotron Radiation

From Light Sources to Colliders





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

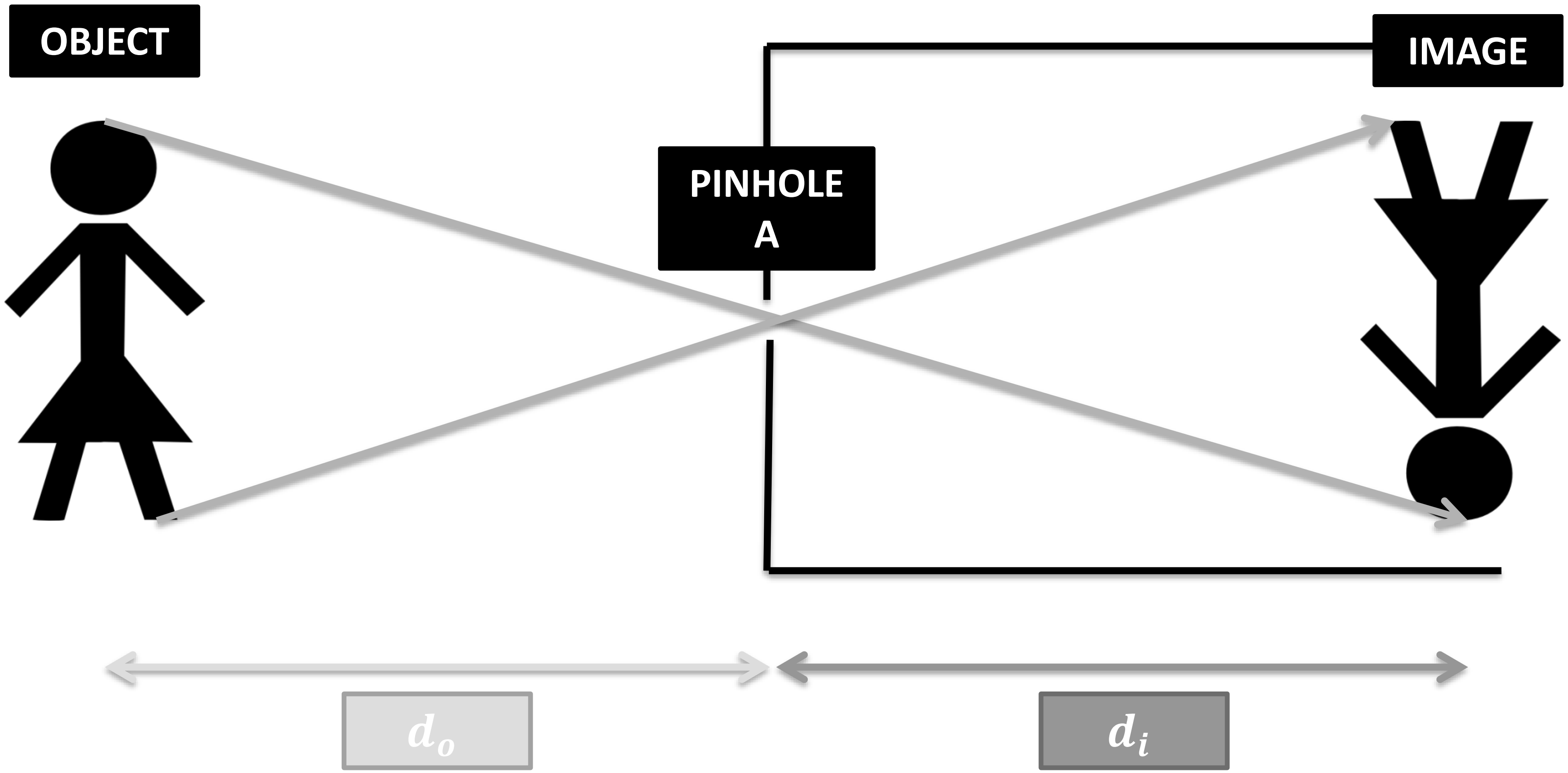
Visible photons still available !

- *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

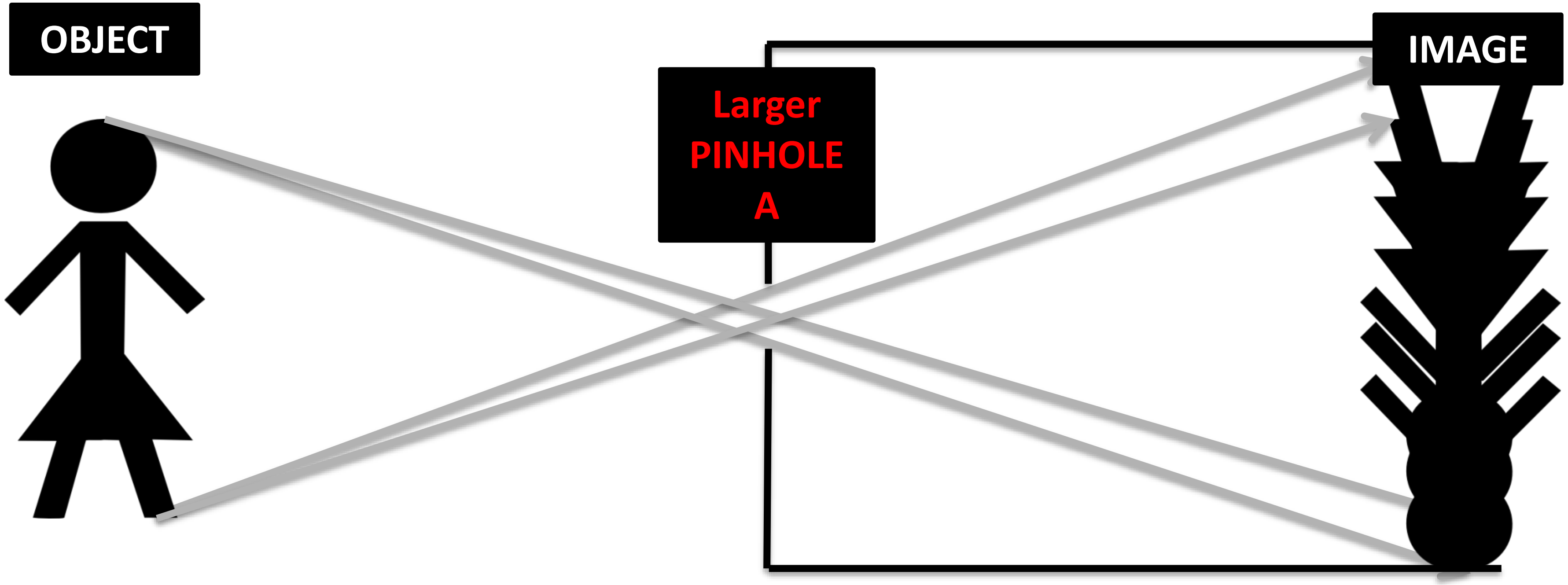
X-ray pinhole cameras

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



Electron ring – Synchrotron Radiation

X-ray pinhole cameras



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

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

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

Electron ring – Synchrotron Radiation

X-ray pinhole cameras

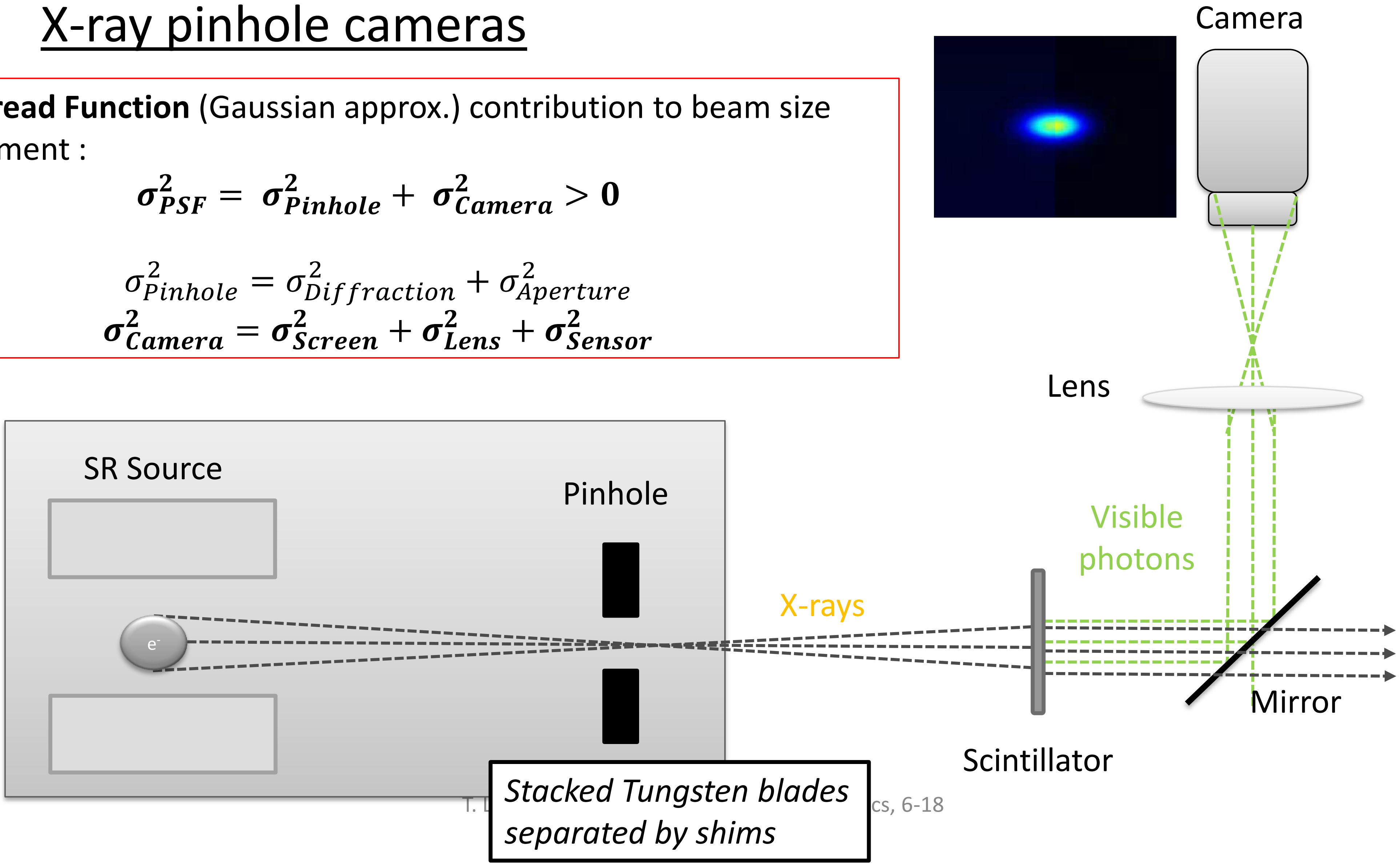
Point Spread Function (Gaussian approx.) contribution to beam size measurement :

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

where

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

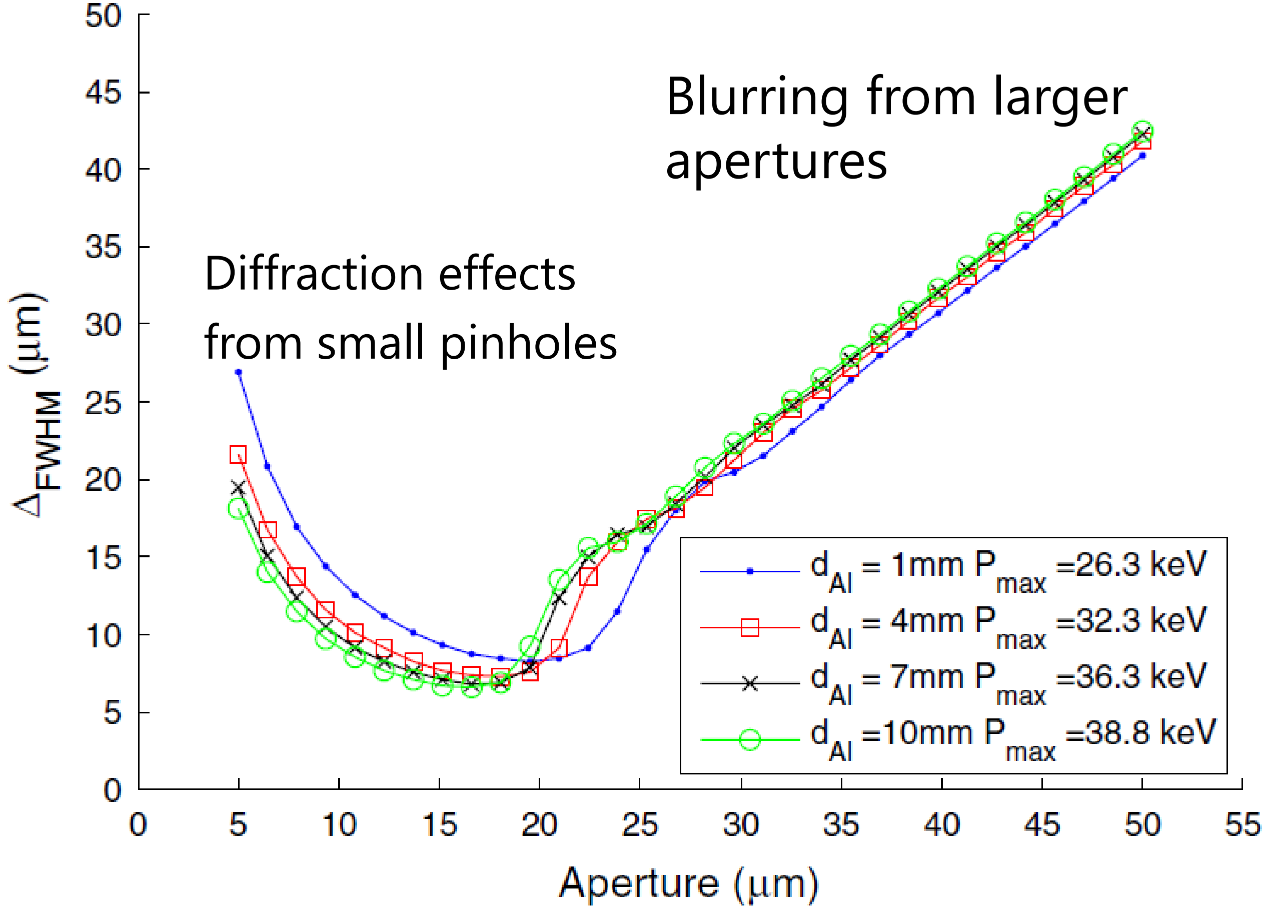
$$\boldsymbol{\sigma^2_{Camera} = \sigma^2_{Screen} + \sigma^2_{Lens} + \sigma^2_{Sensor}}$$



Electron ring – Synchrotron Radiation

X-ray pinhole cameras

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



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 $(d_o + d_i) \geq 10\mathrm{m}$

- Challenging fabrication for pinholes : material hard to machine and suffers from oxidation

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>

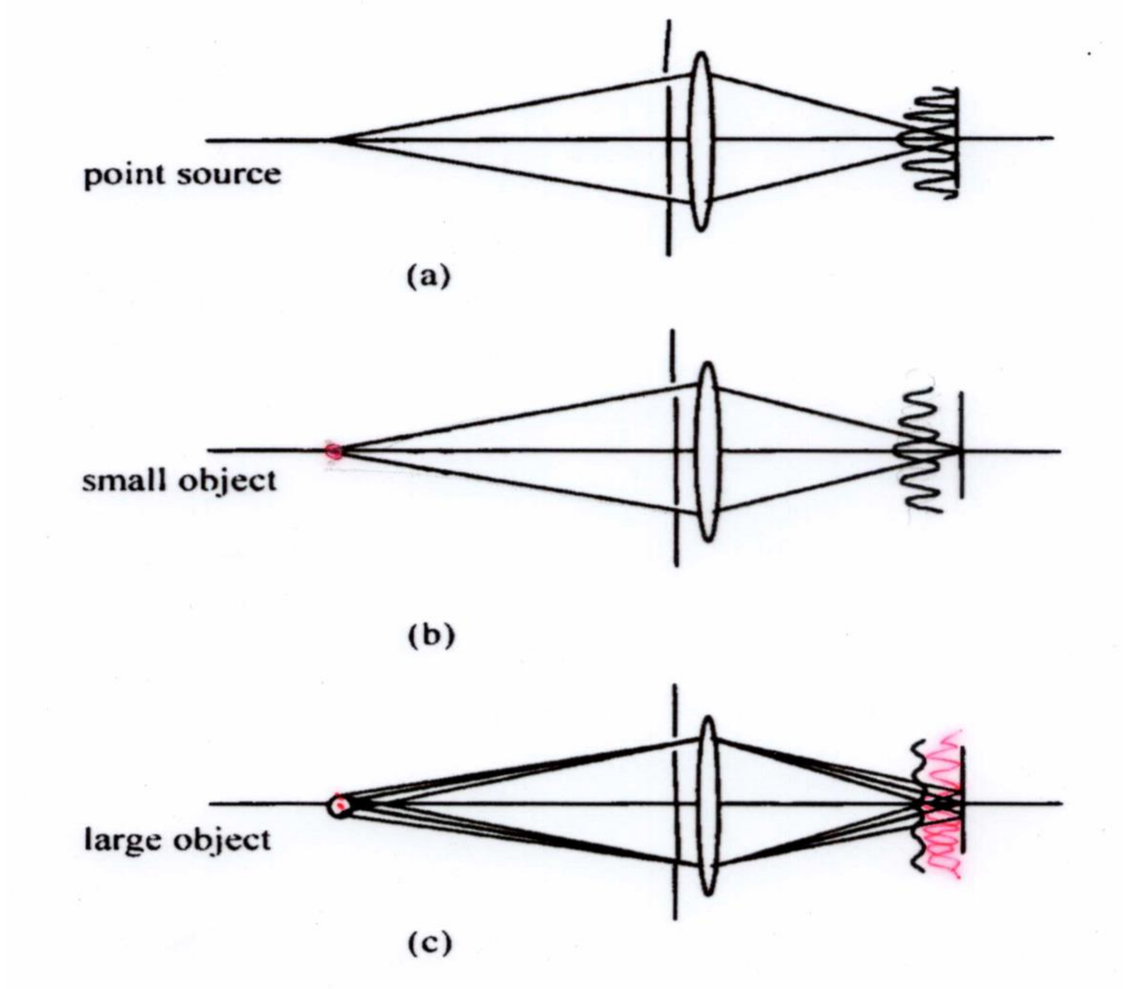
With the condition of light is temporal incoherent (no phase correlation), the complex degree of spatial coherence $\gamma(\upsilon_x,\upsilon_y)$ is given by the Fourier Transform of the spatial profile f(x,y) of the object (beam) at shorter wavelengths such as visible light.

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

where υ_x, υ_y are spatial frequencies given by;

Electron ring – Synchrotron Radiation

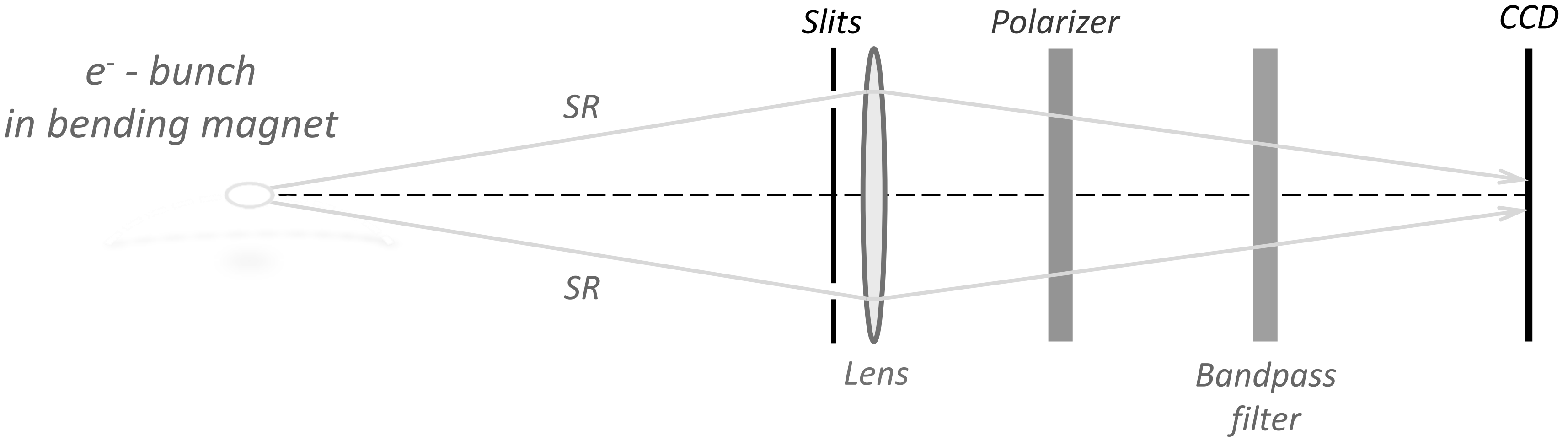
- <u>Van Cittert-Zernike theorem :</u>

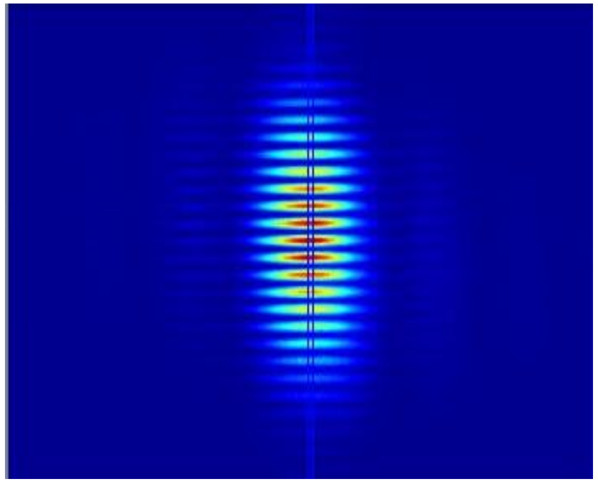


Beam size is inversely proportional to the visibility of the interferogram I_{min} / I_{max}

Electron ring – Synchrotron Radiation

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





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

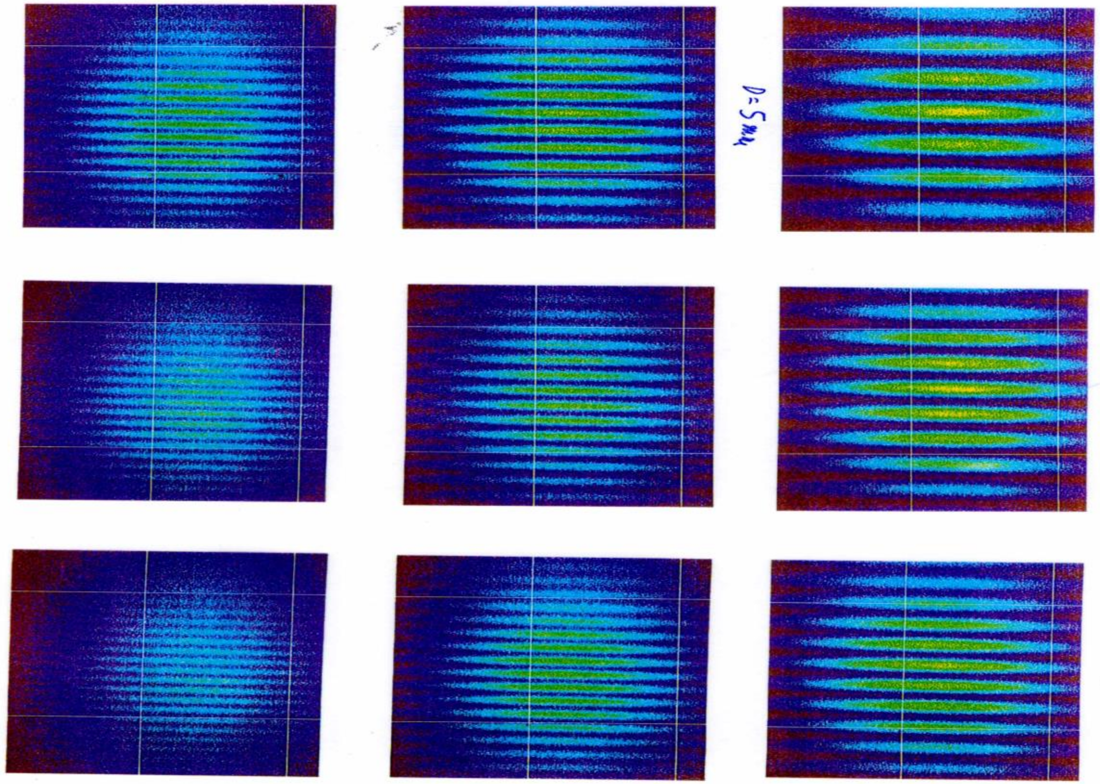
where a – half slit size, λ_0 – wavelength of SR, D – distance between slits, R – distance source– slits, γ – degree of spatial coherence. Getting the parameter γ from the fit, one can recalculate it to the beam size

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

Electron ring – Synchrotron Radiation

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

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



Small spacing
High visibility

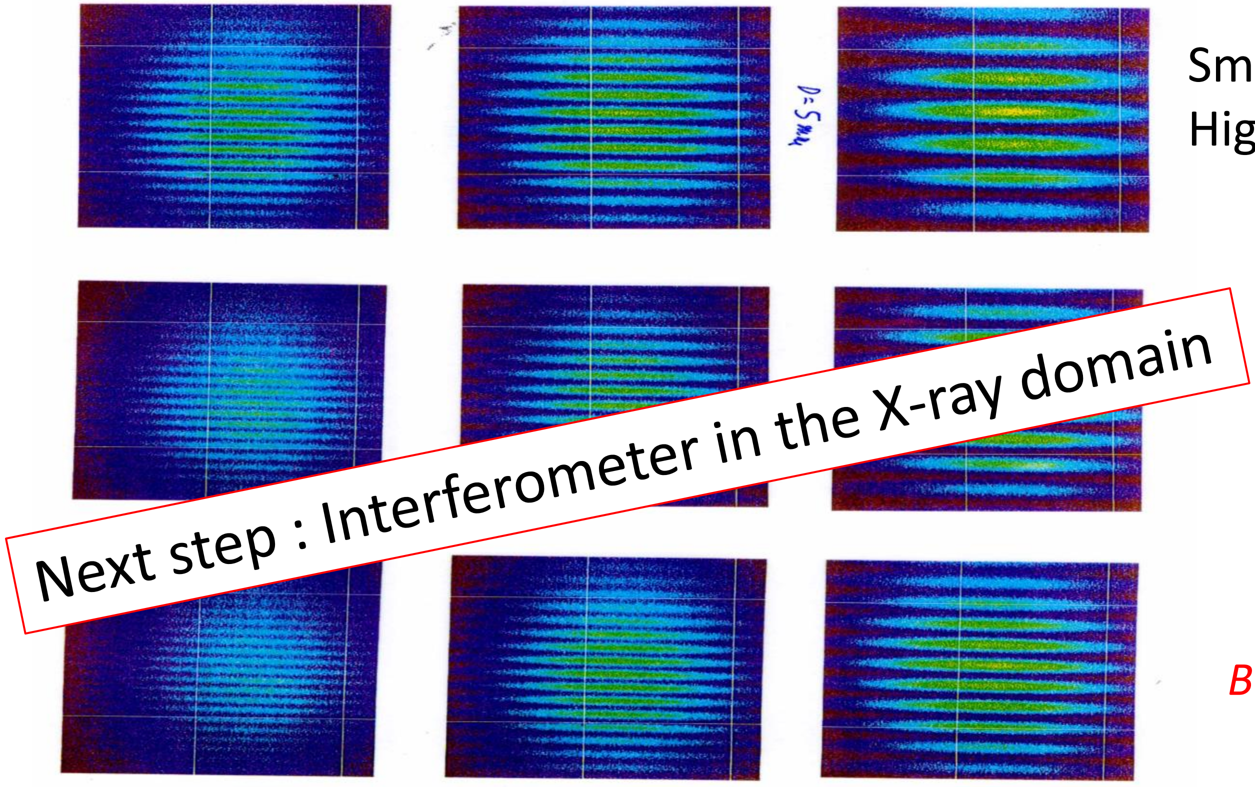
Large spacing
Low visibility

Beam size of 4um

Electron ring – Synchrotron Radiation

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

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



Small spacing
High visibility

Large spacing
Low visibility

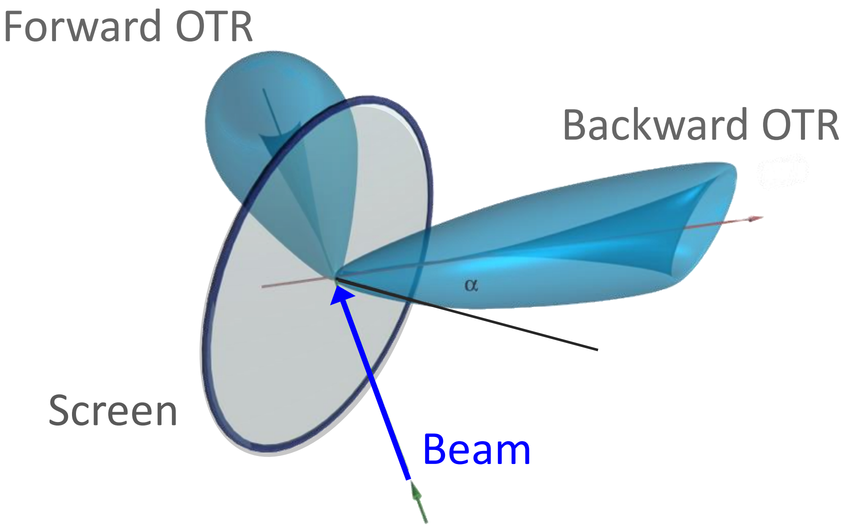
Beam size of 4um

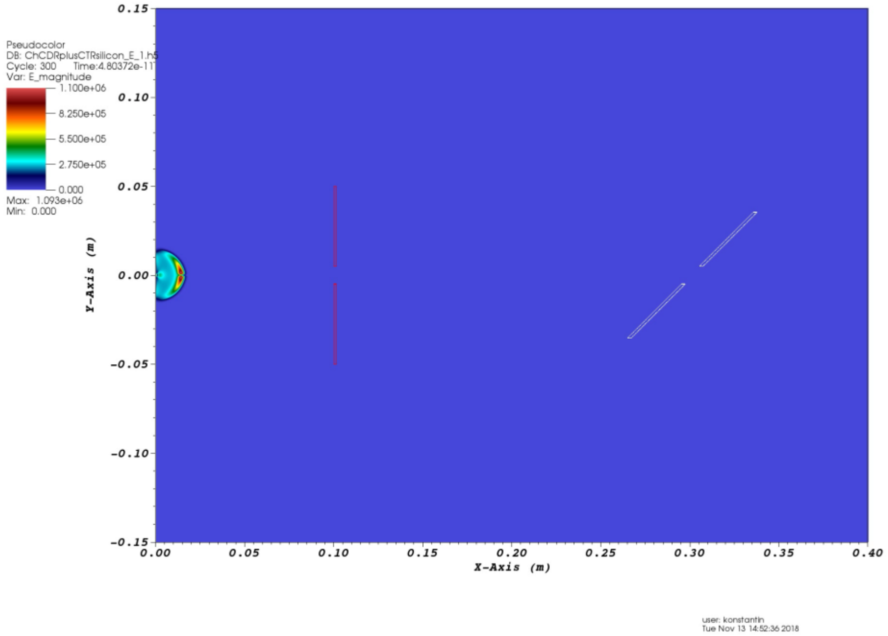
The CERN Accelerator School

Transverse Diagnostics in Electron LINAC

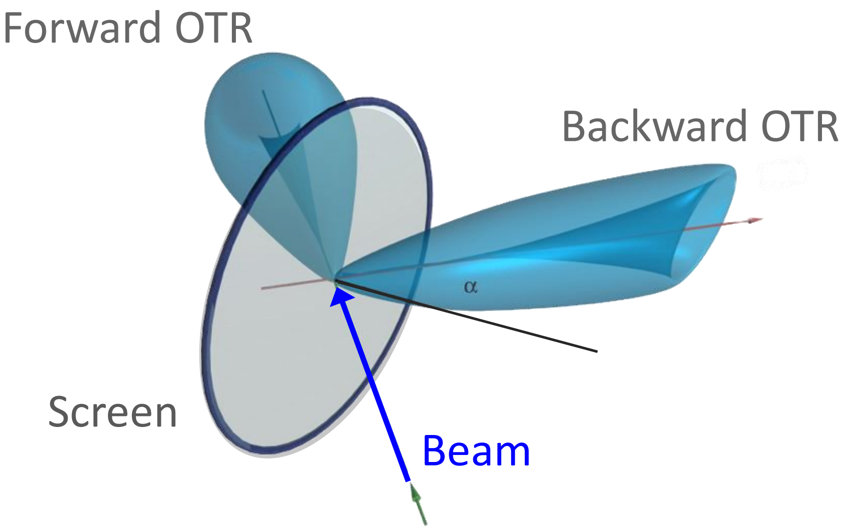
Electron Linac – Transition Radiation

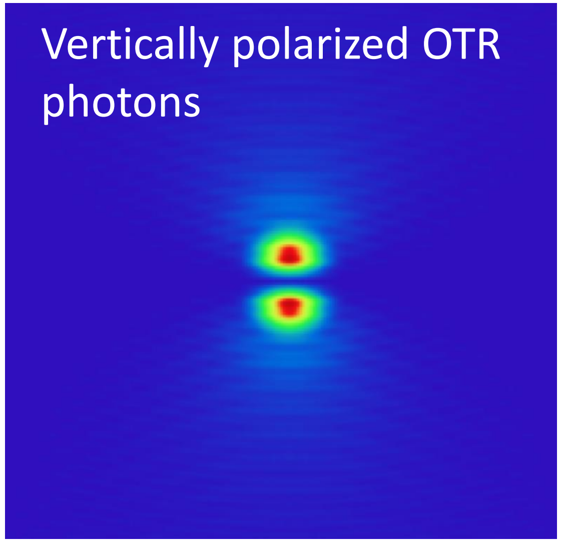
As predicted in 1946 by Frank and Ginzburg, **Transition Radiation** is a broadband electromagnetic field emitted by a relativistic charged particle when it crosses boundary between two mediums of different dielectric constants.

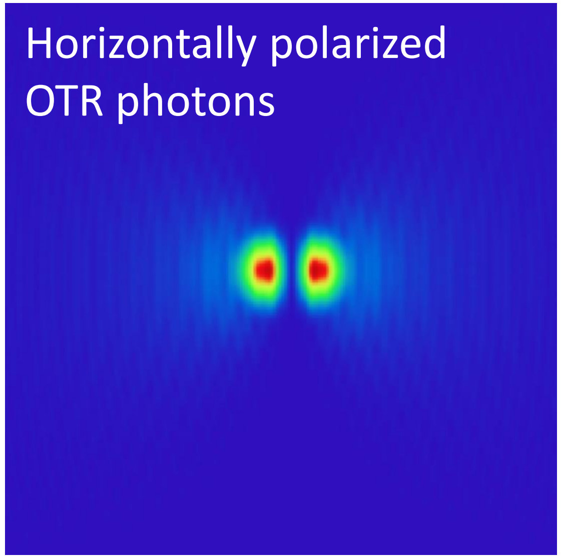




Electron Linac – Transition Radiation





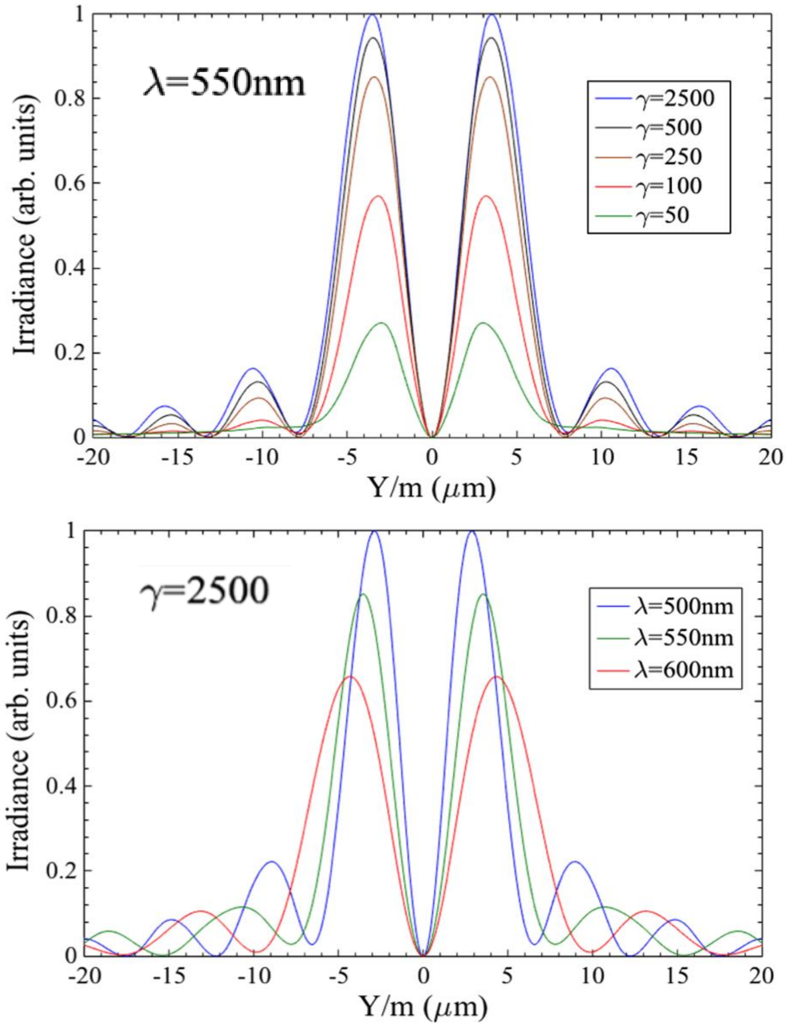


- The OTR field is **radially polarized.**
- Approximation* of the electric field distribution for the **OTR vertical polarization component** induced by a single electron on the target surface (x,y).

$$\mathrm{Re}(E_y) = \frac{y}{\sqrt{x^2+y^2}}\left[\frac{2\pi}{\gamma\lambda}K_1\left(\frac{2\pi}{\gamma\lambda}\sqrt{x^2+y^2}\right) - \frac{J_0\left(\frac{2\pi}{\gamma\lambda}\sqrt{x^2+y^2}\right)}{\sqrt{x^2+y^2}}\right]$$

Electron Linac – Transition Radiation

Single particle OTR field distribution at the surface of the screen



The number of photons is increasing with energy

$$N_{OTR} = \frac{2\alpha}{\pi}\left[\left(\beta + \frac{1}{\beta}\right)\cdot\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\right]\ln\left(\frac{\lambda_b}{\lambda_a}\right)$$

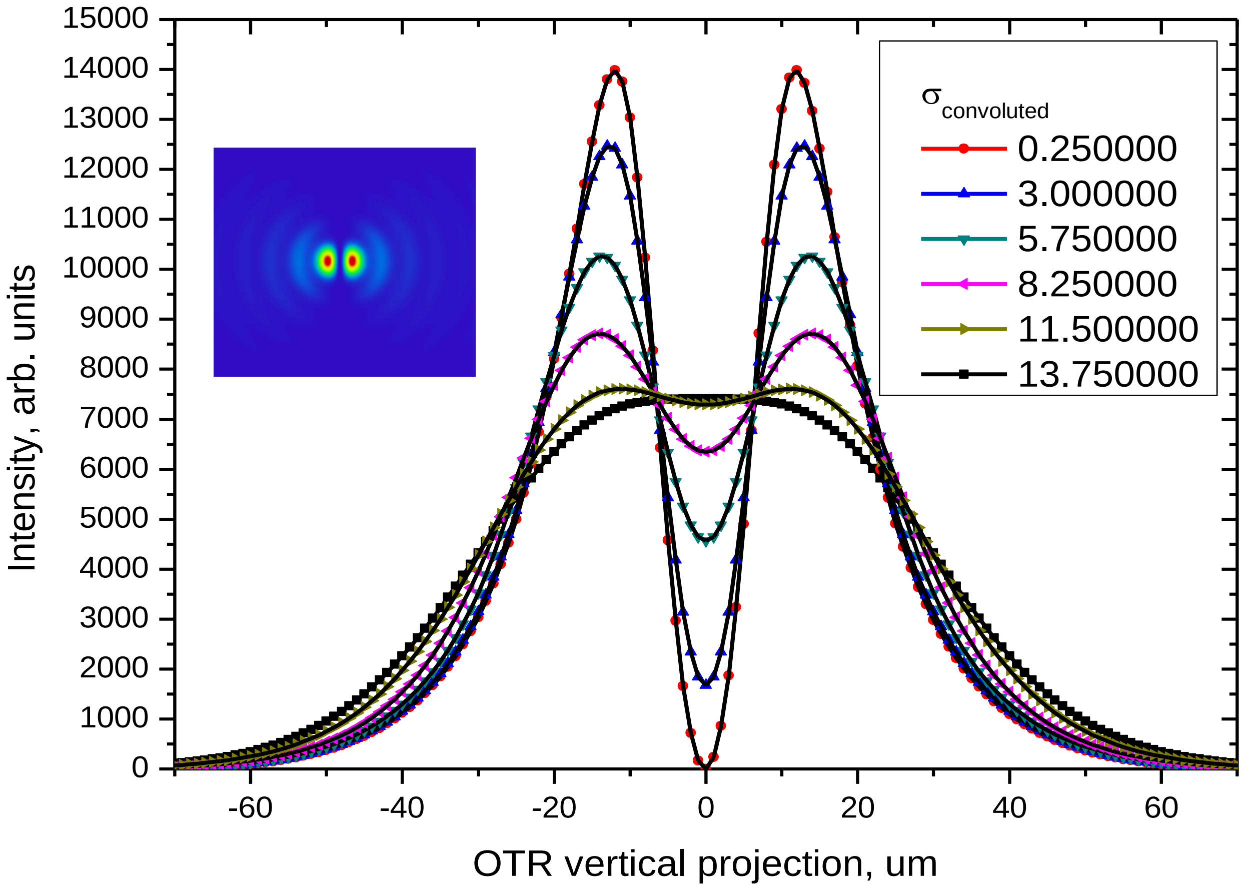
The width of field distribution is wavelength dependent

Distribution
- Zero in center
- Width ~10-20um

Electron Linac – Transition Radiation

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

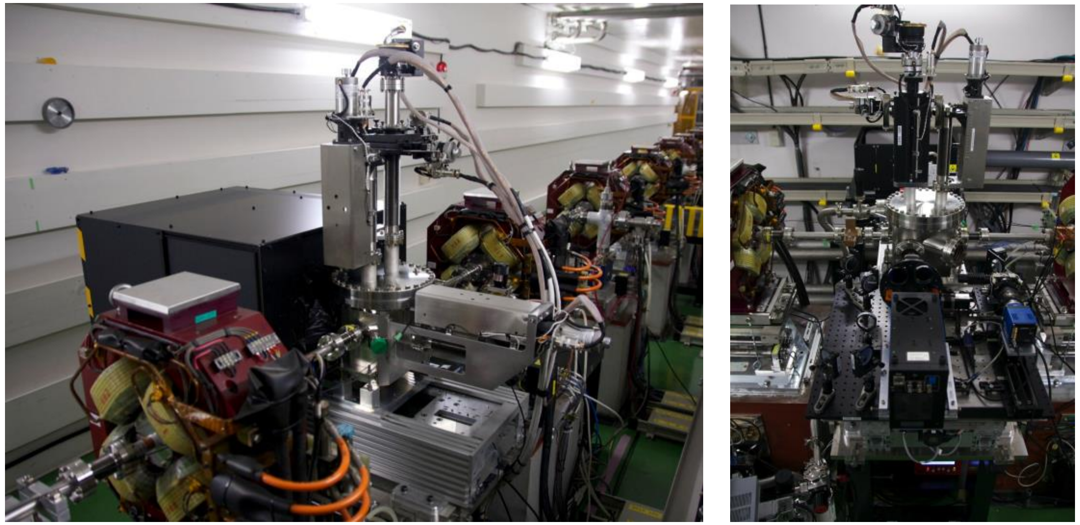
*P. Karataev et al., PRL **107**, 174801 (2011)*



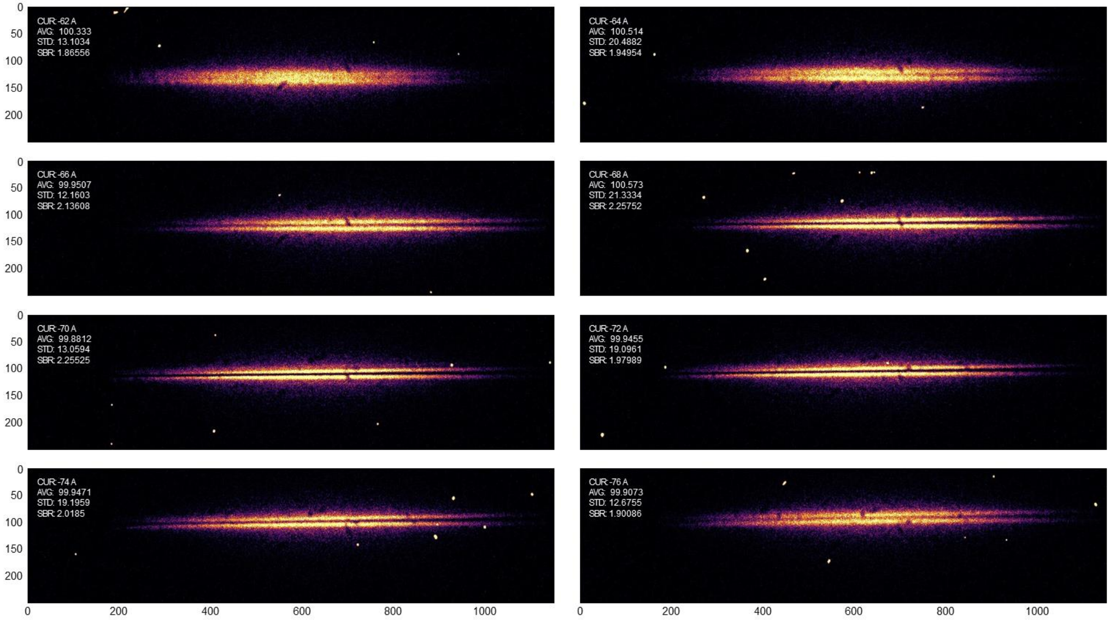
Electron Linac – Transition Radiation

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)



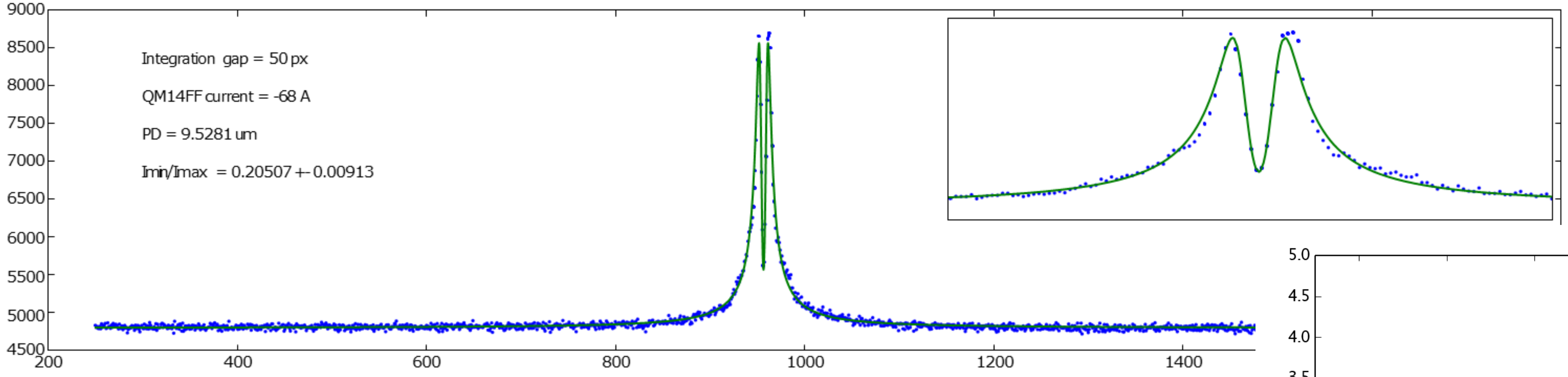
Test on ATF2 extraction beam line at KEK



Images acquired during a Quadrupole scan

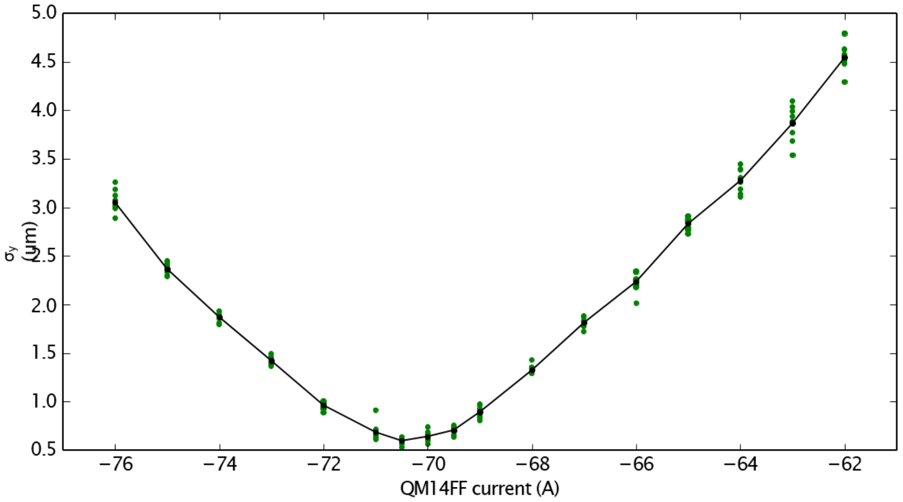
Electron Linac – Transition Radiation

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



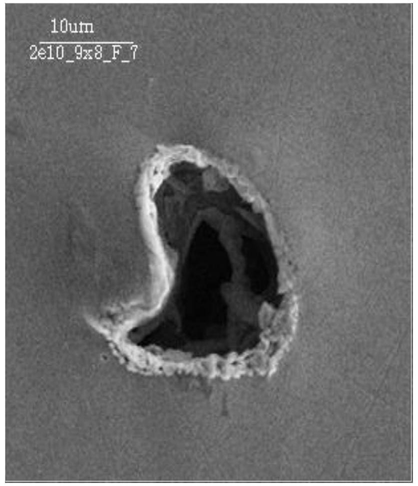
P. Karataev *et al.*, PRL **107**, 174801 (2011)
B. Bolzon *et al.*, PRSTAB **18**, 082803 (2015)

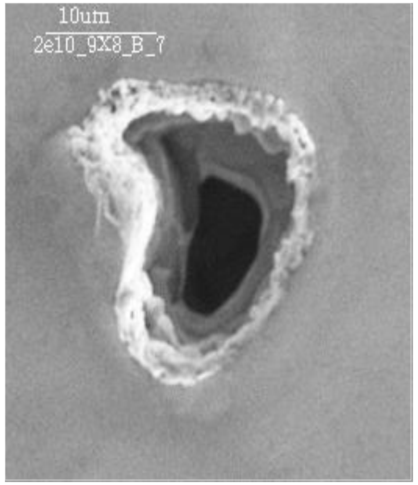
Smallest beam size measured 600nm



Electron Linac – Transition Radiation

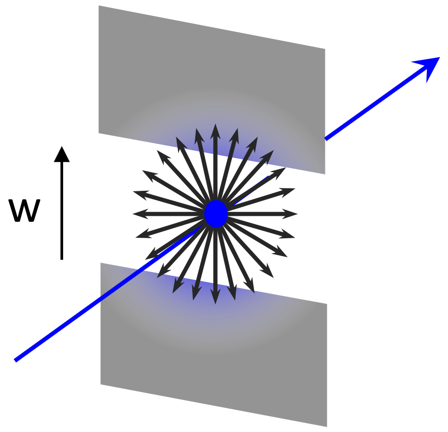
OTR, It ‘s all good but….





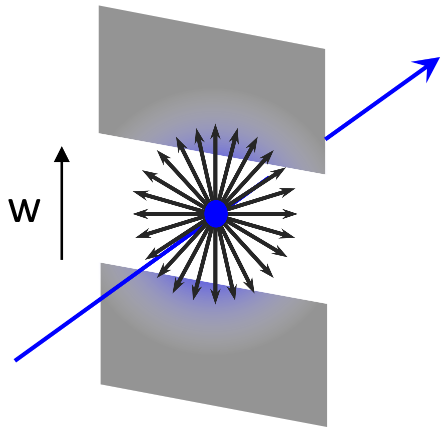
Electron Linac – Diffraction Radiation

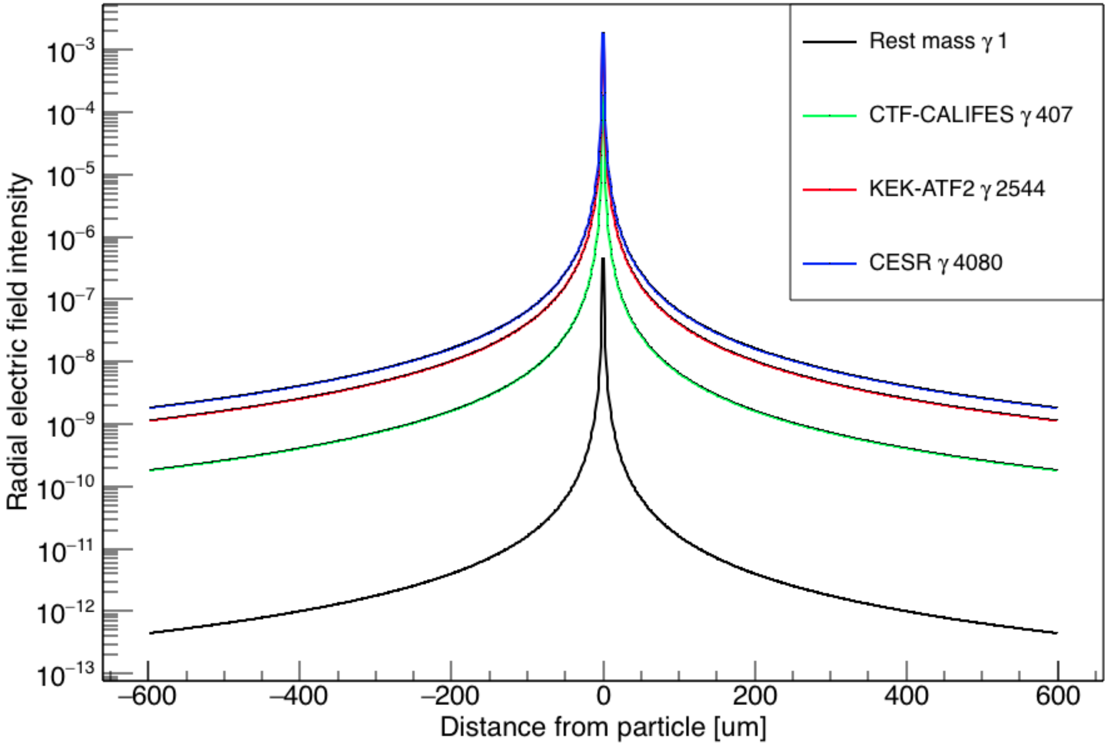
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**



Electron Linac – Diffraction Radiation

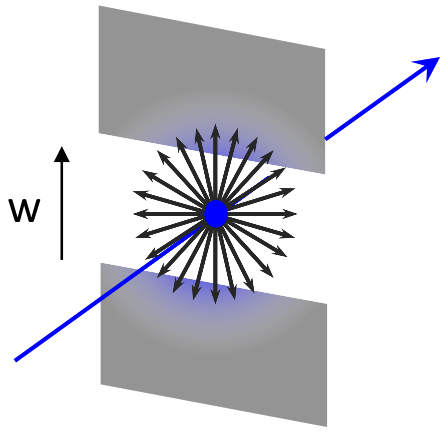
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**



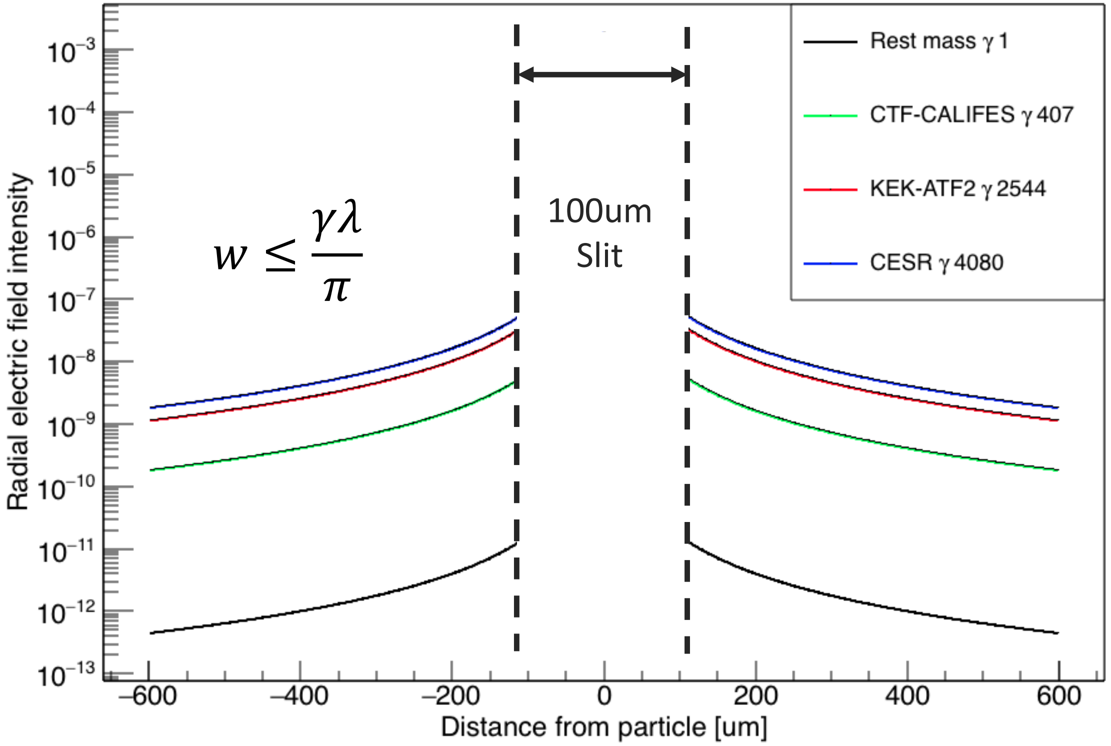


Electron Linac – Diffraction Radiation

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

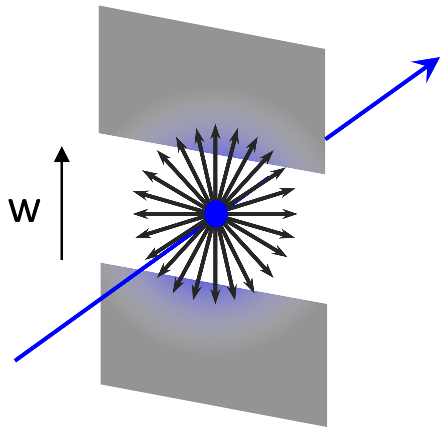


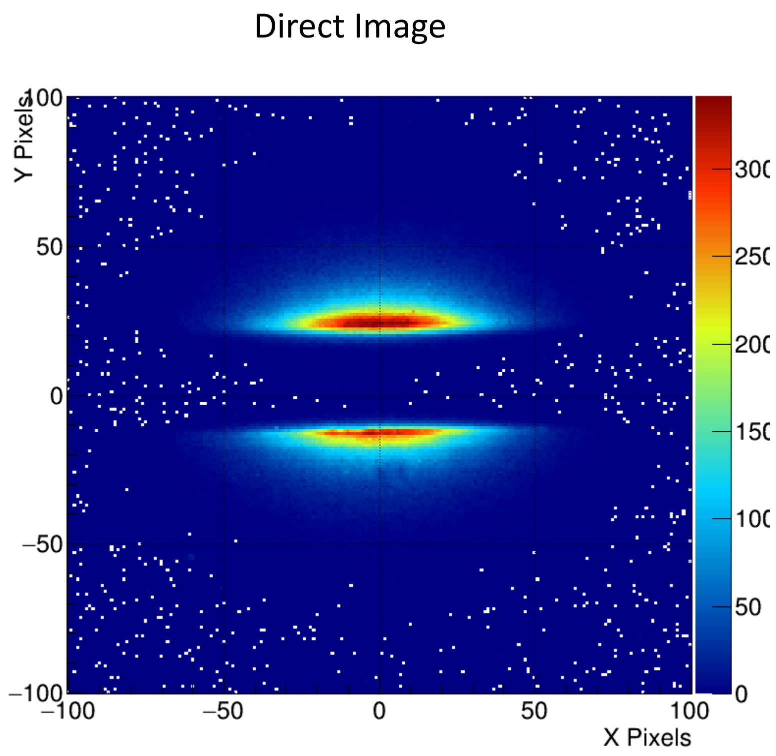
$$w \leq \frac{\gamma\lambda}{\pi}$$



Electron Linac – Diffraction Radiation

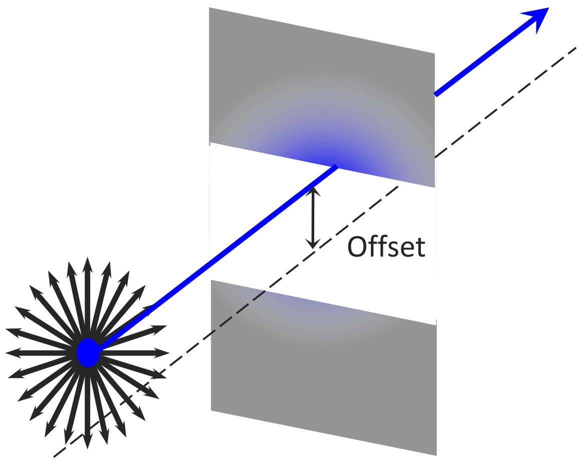
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**

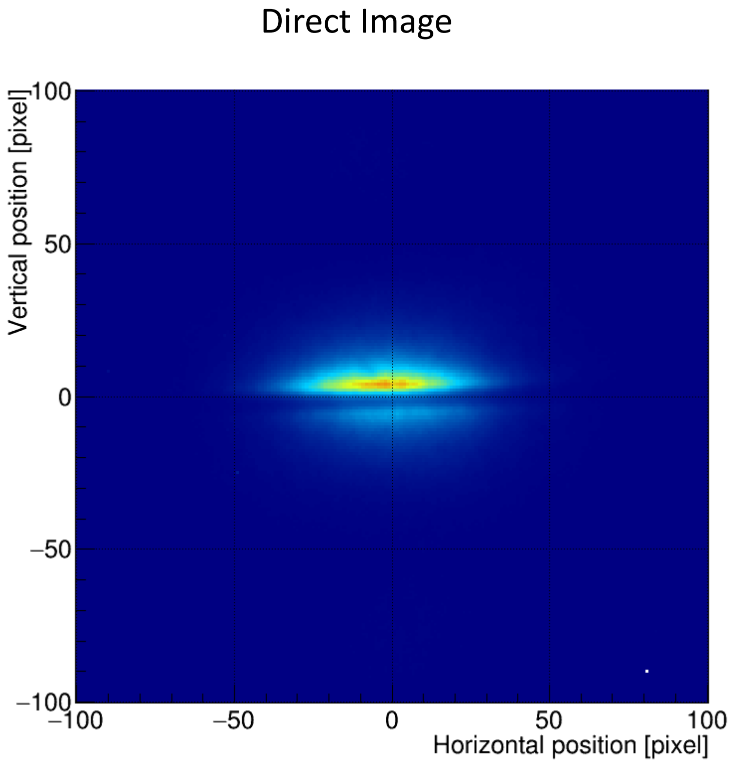




Electron Linac – Diffraction Radiation

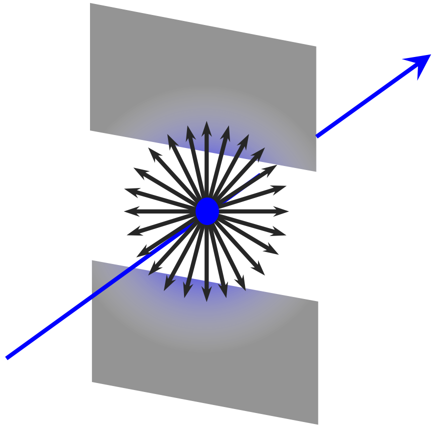
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**



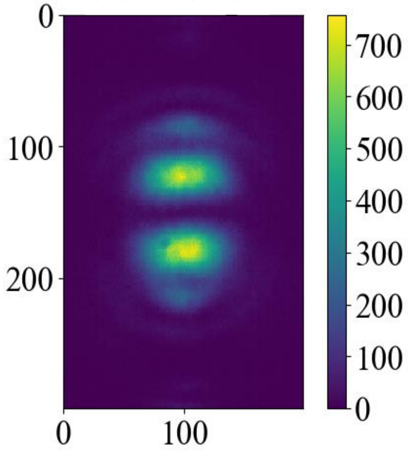


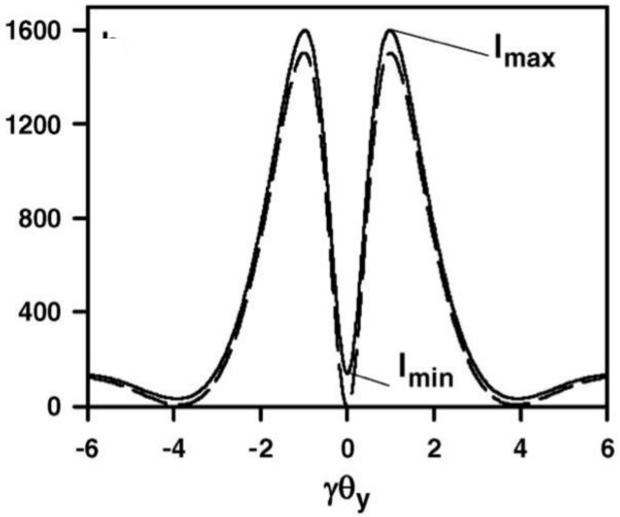
Electron Linac – Diffraction Radiation

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



2D Angular distribution

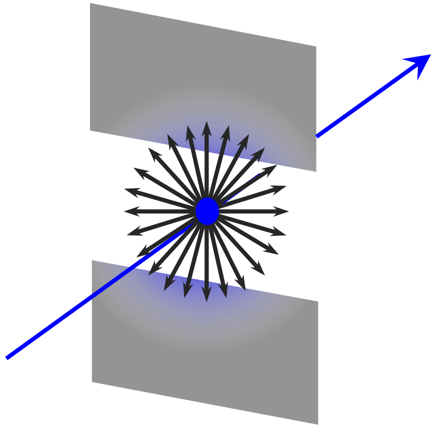




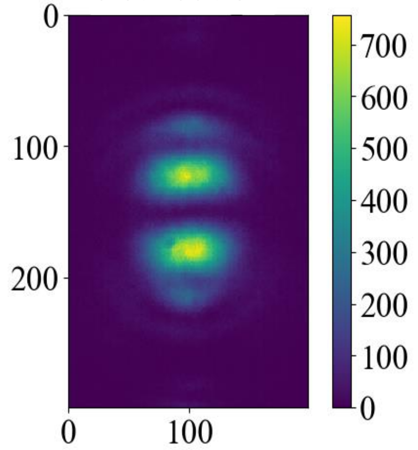
The **beam size and beam divergence can be** extracted from the **visibility I_{min}/I_{max}** of the projected vertical component of the **ODR angular distribution**

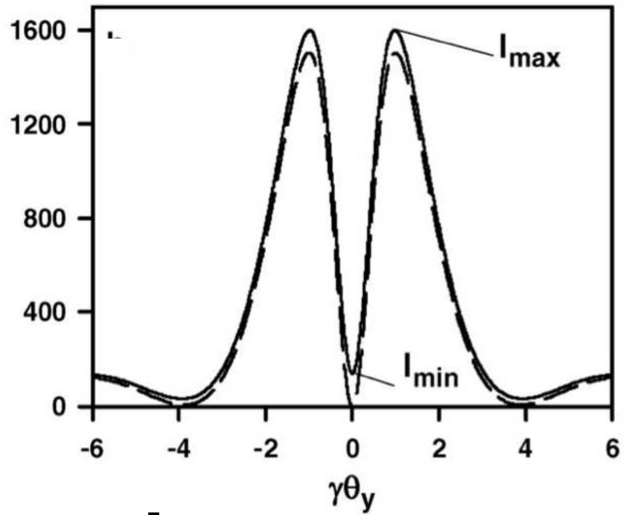
Electron Linac – Diffraction Radiation

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



2D Angular distribution



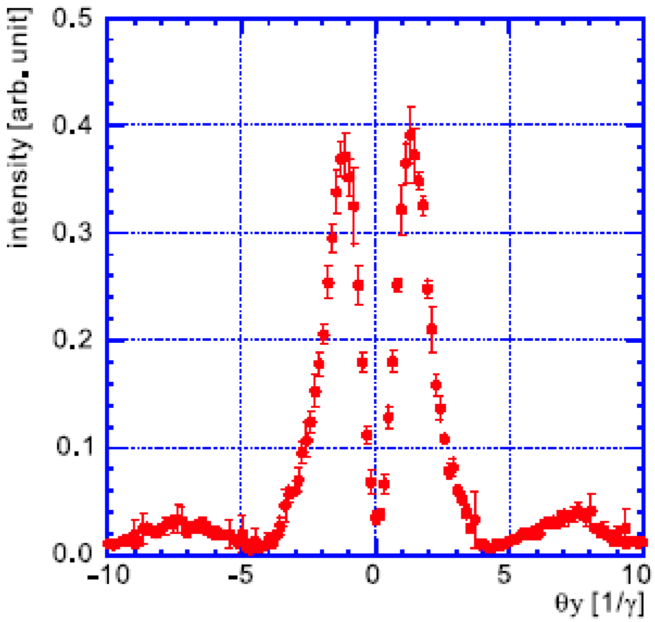


$$\frac{d^2W_y^{slit}}{d\omega d\Omega} = \frac{\alpha\gamma^2}{2\pi}\frac{e^{\left(-\frac{2a\pi\sin\theta_0}{\gamma\lambda}\sqrt{1+t_x^2}\right)}}{1+t_x^2+t_y^2}\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2\gamma^2}\left(1+t_x^2\right)\right]\cosh\left[-\frac{4\bar{a}\pi}{\gamma\lambda}\sqrt{1+t_x^2}\right]-\cos\left[\frac{2a\pi\sin\theta_0}{\gamma\lambda}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

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

Electron Linac – Diffraction Radiation

- First Measurements at KEK (Linear collider study)



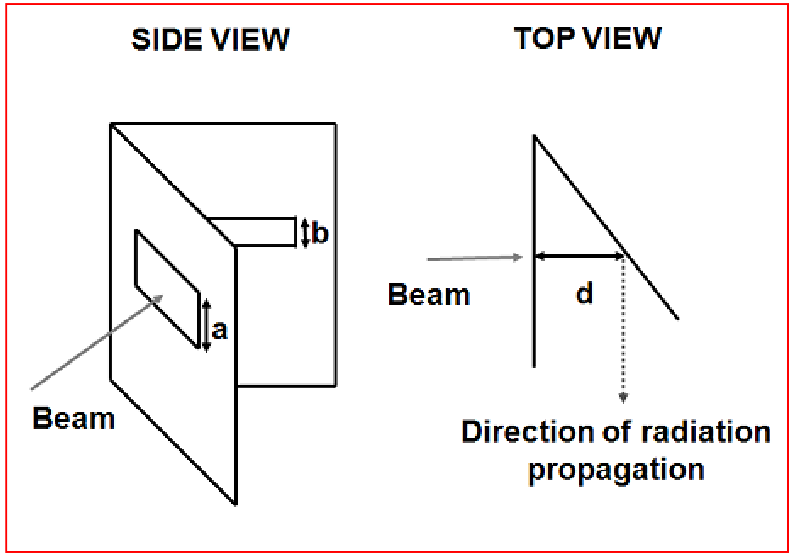
P. Karataev et al., “*Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility*”, Phys. Rev. Lett. 93, 244802 (2004)

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

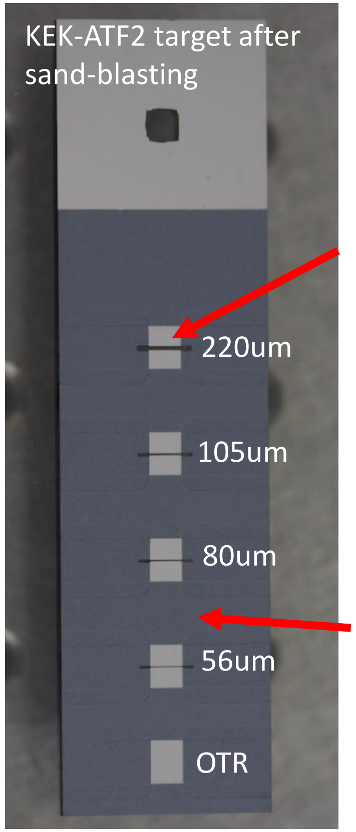
Electron Linac – Diffraction Radiation

- 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

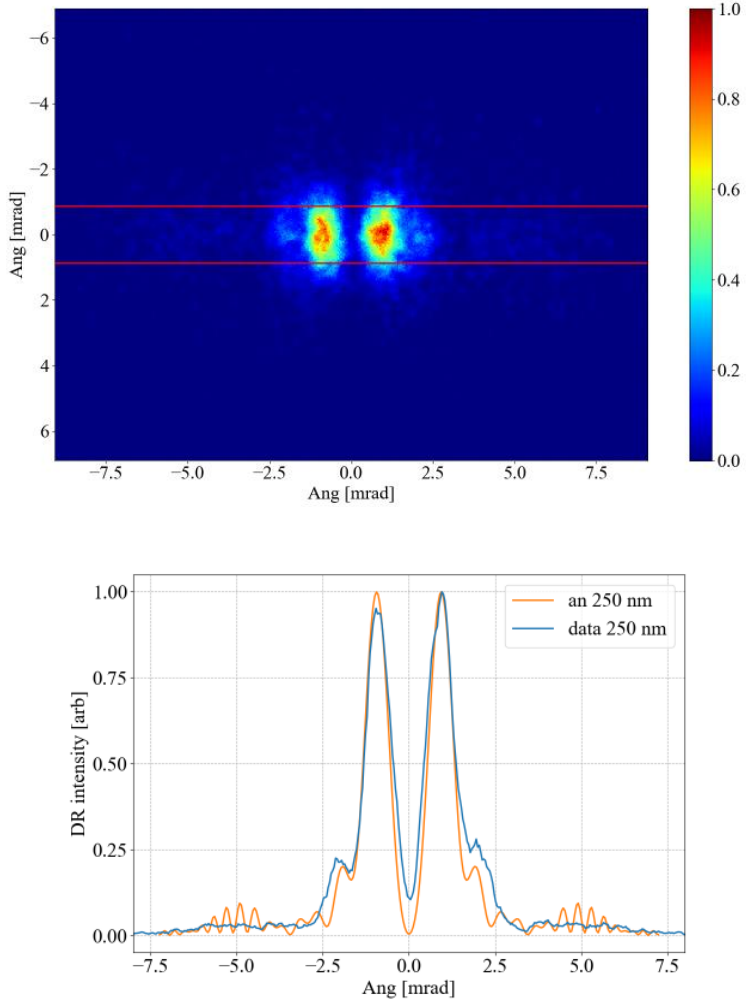
Minimizing reflection of SR by sand-blasting the rest of the target

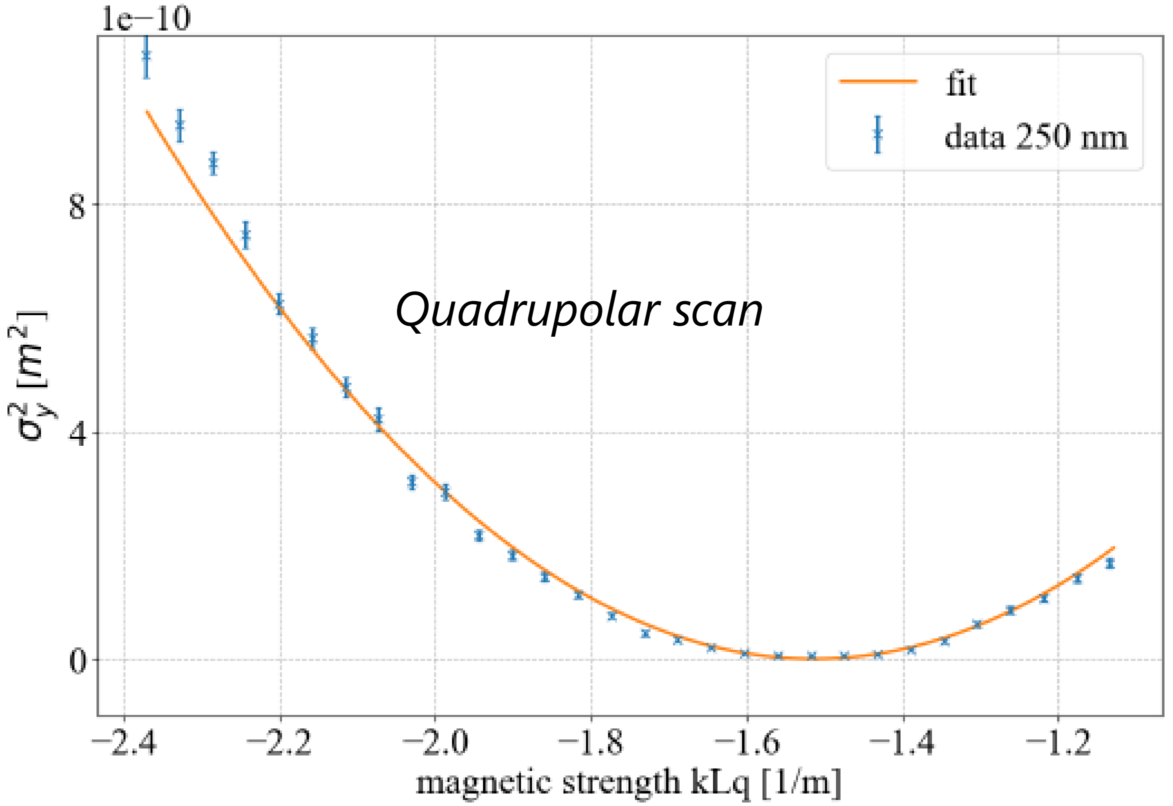
R. Kieffer et al. NIMB 402 88 (2018)

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....

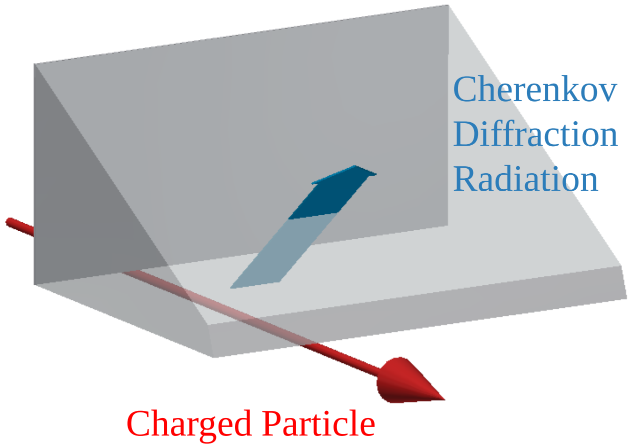
- Looking for higher light yield !
- Getting rid of Synchrotron radiation background

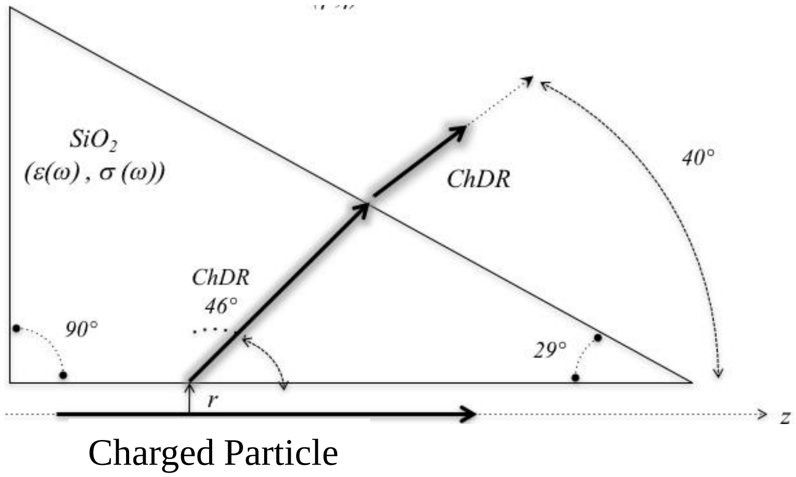
Cherenkov diffraction radiation in longer dielectrics

Electron Linac – Cherenkov Diffraction Radiation

- Cherenkov Diffraction Radiation in dielectrics

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



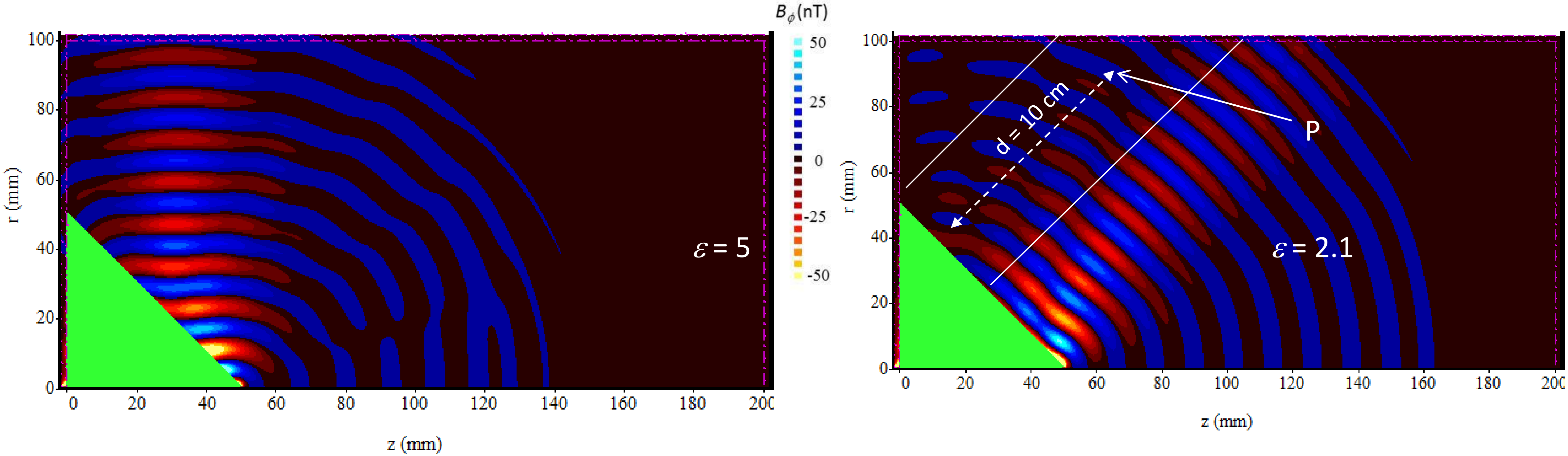


The total number of photons proportional to the length of the Cherenkov radiator

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

Electron Linac – Cherenkov Diffraction Radiation

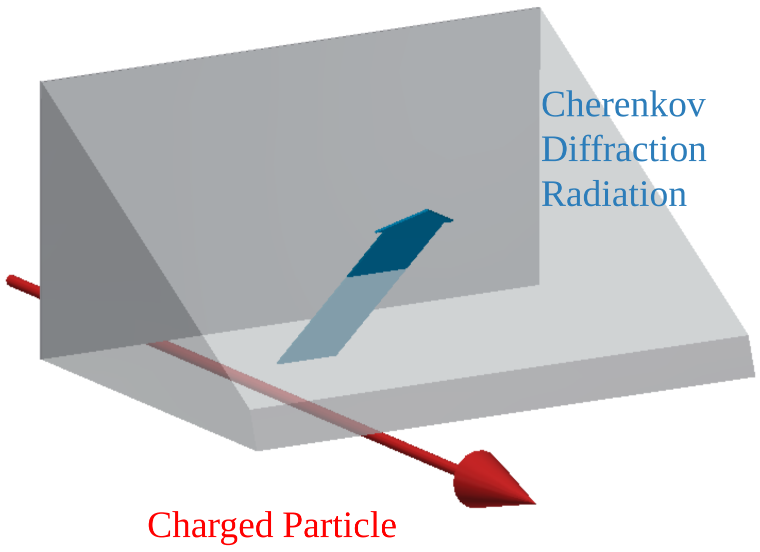
- Cherenkov Diffraction Radiation in dielectrics

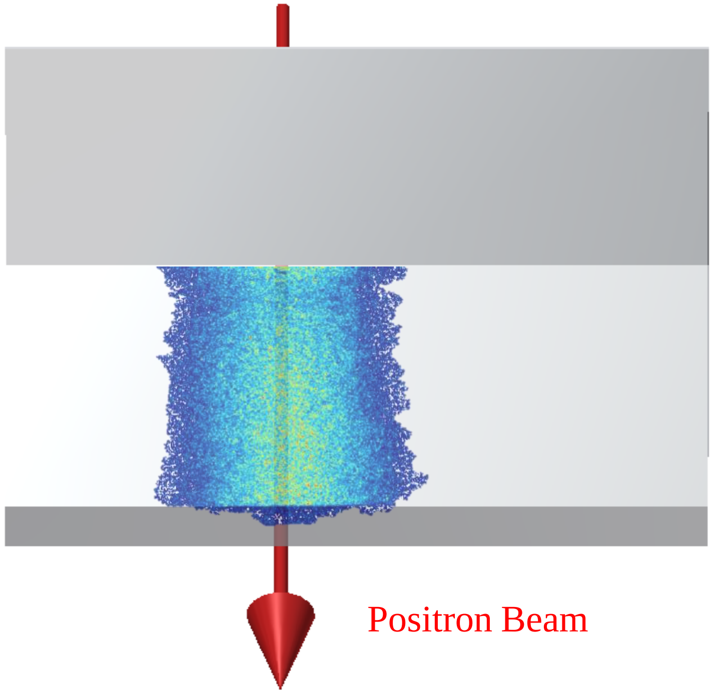


Simulations using Magic

Electron Linac – Cherenkov Diffraction Radiation

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



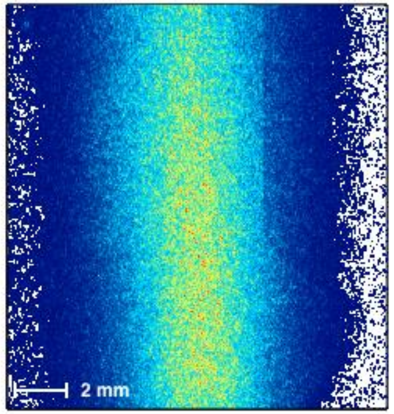


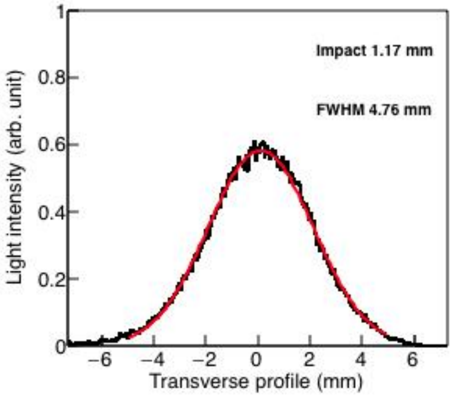
R. Kieffer et al., "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL ***121*** *(2018) 054802*
R. Kieffer et al., "Generation of Incoherent Cherenkov Diffraction Radiation in synchrotrons", PRAB ***23*** *(2020) 042803*

Electron Linac – Cherenkov Diffraction Radiation

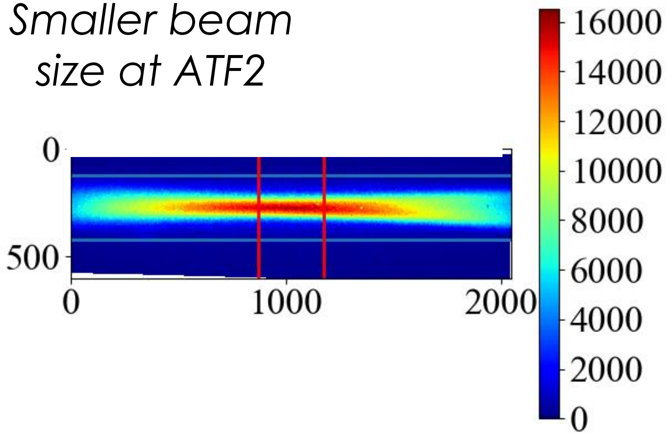
- Measuring beam size using ChDR

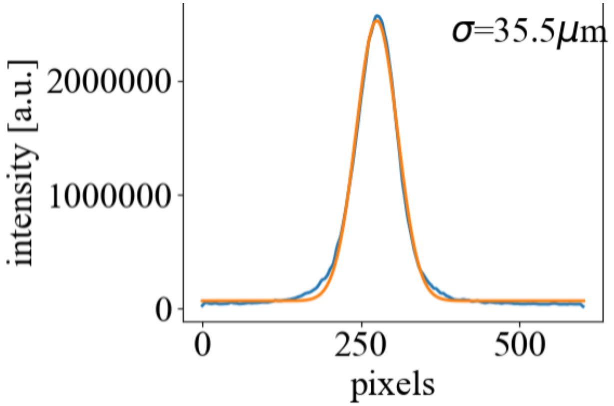
Large beam size at Cornell





Smaller beam size at ATF2

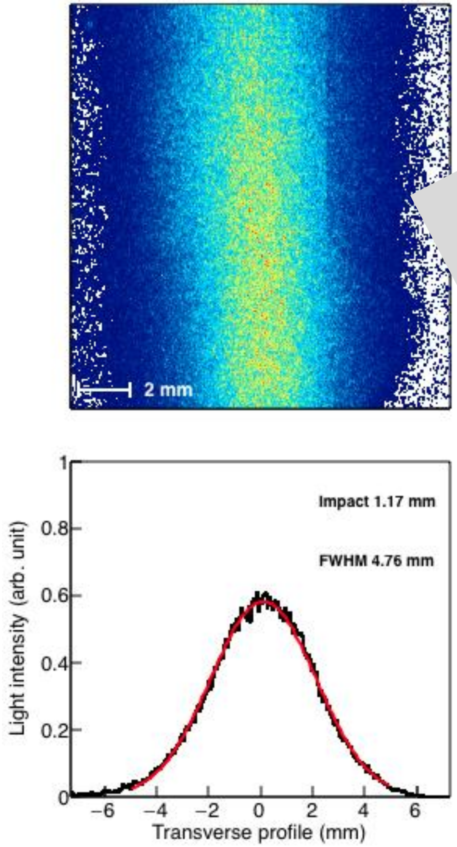




Electron Linac – Cherenkov Diffraction Radiation

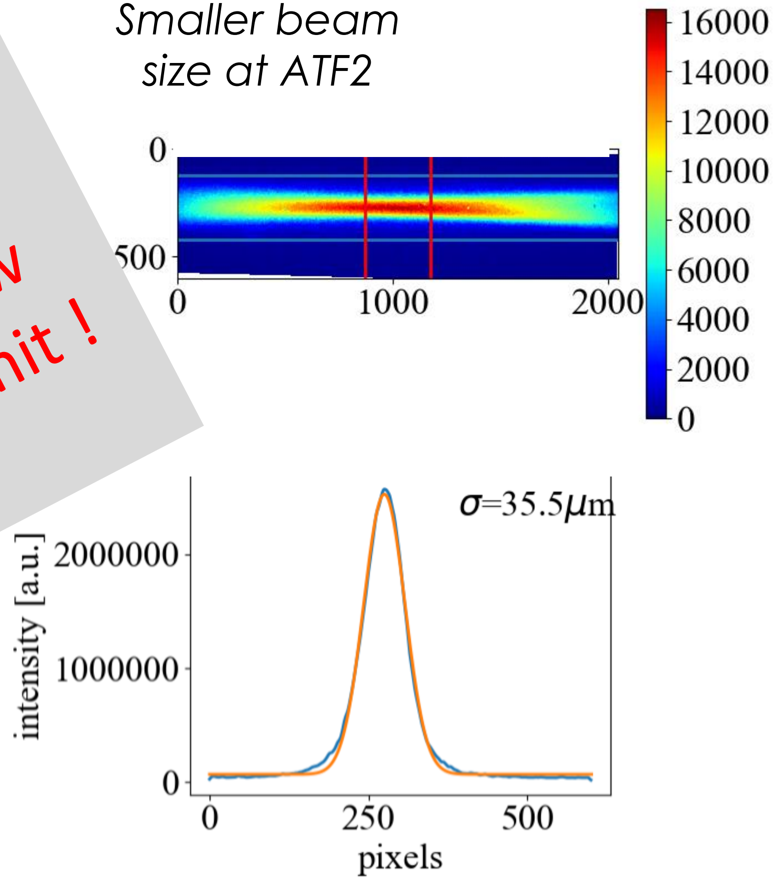
- Measuring beam size using ChDR

Large beam size at Cornell

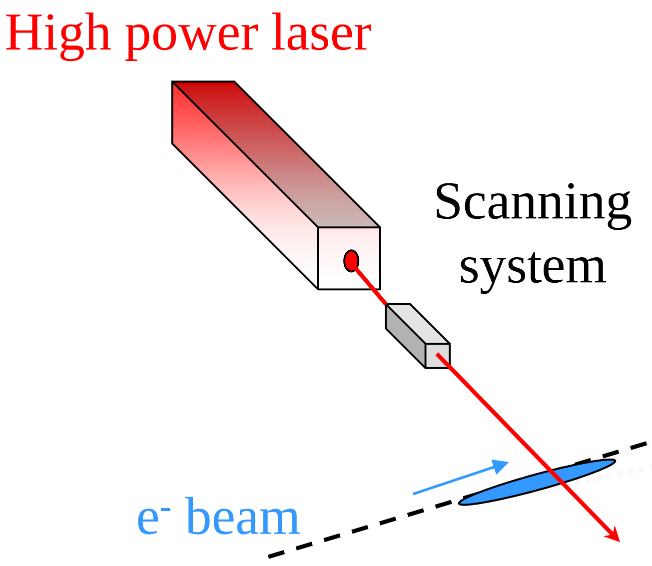


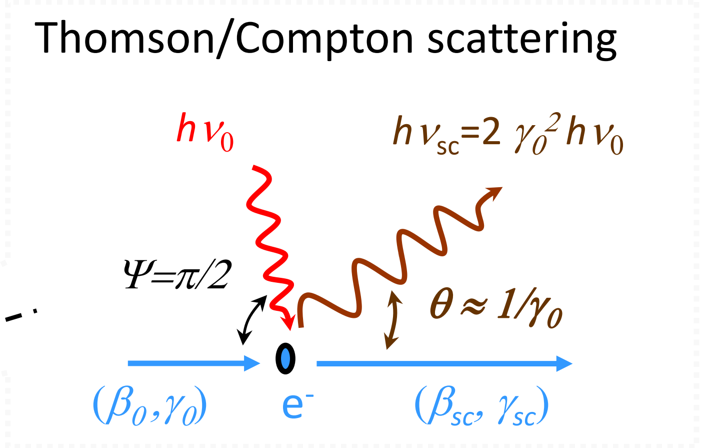
Still preliminary - We do not know where is the limit !

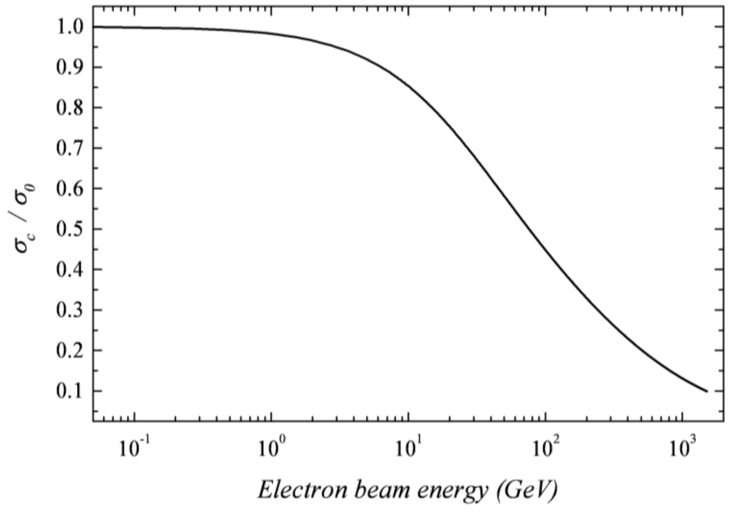
Smaller beam size at ATF2



Electron Linac – Laser Wire Scanner

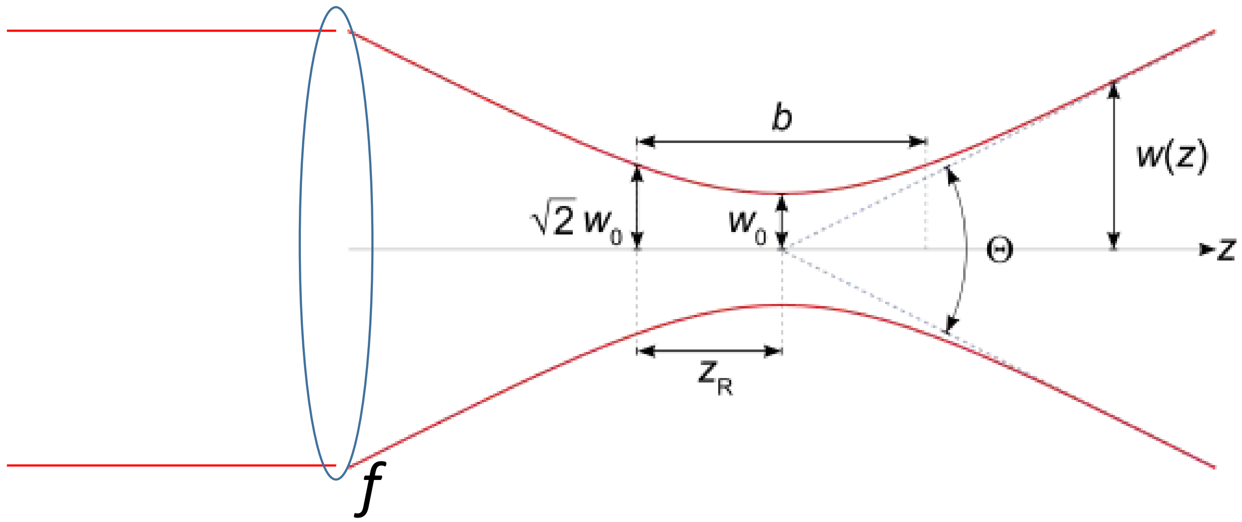






- 10^{-7} smaller than Cross-section for stripping electron from H^-
- Need for high power laser (>10MW)

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/e²)

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

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

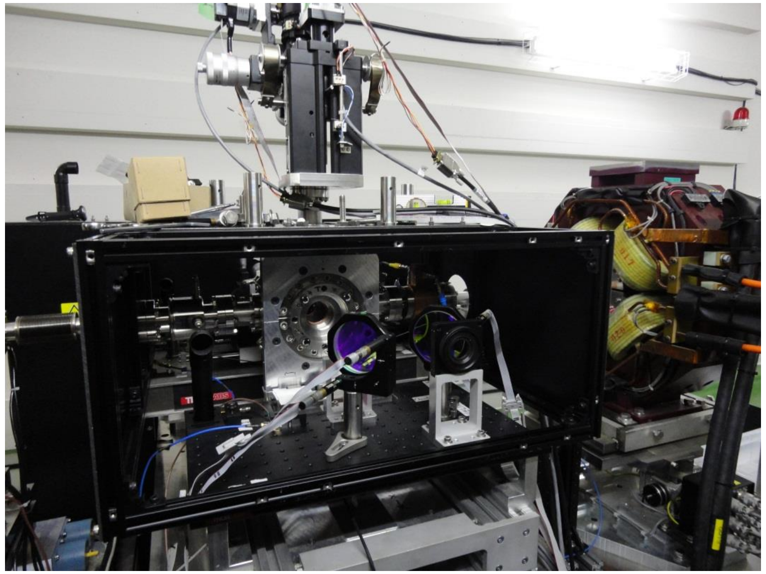
Electron Linac – Laser Wire Scanner

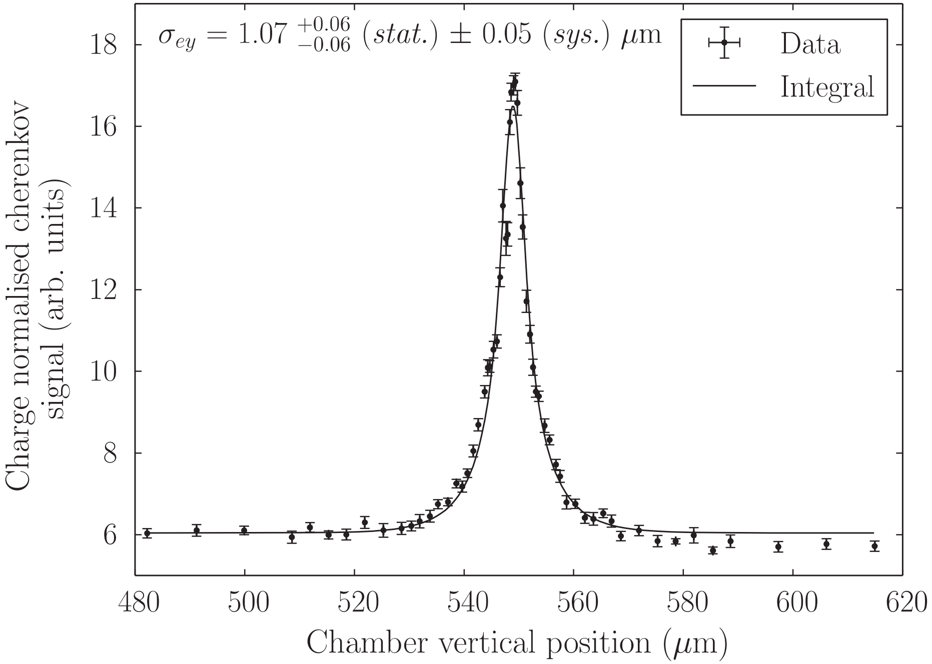
- First tests at SLAC in 90's

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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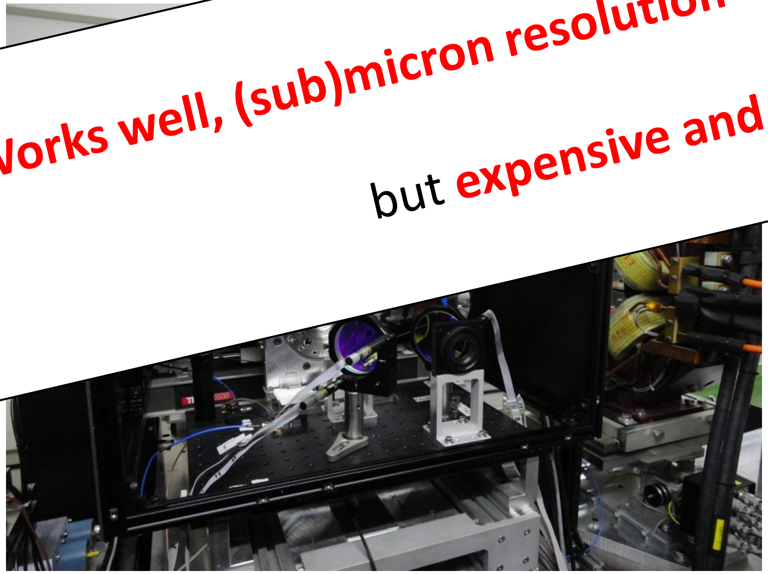
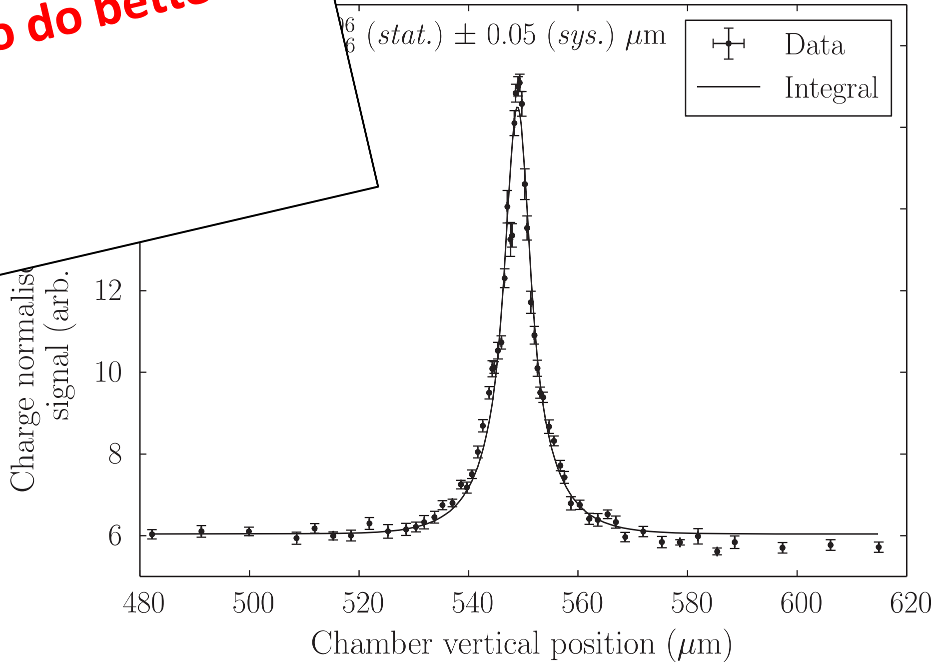


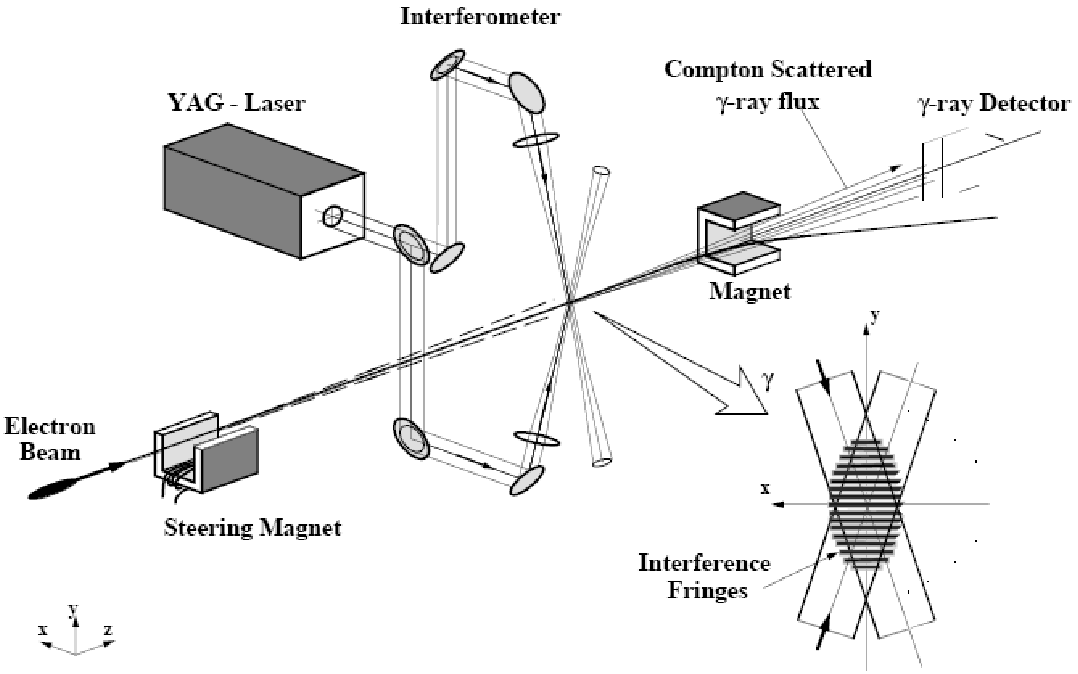


Works well, (sub)micron resolution – difficult to do better

but **expensive and complex**

Electron Linac – ’Shintake monitor’

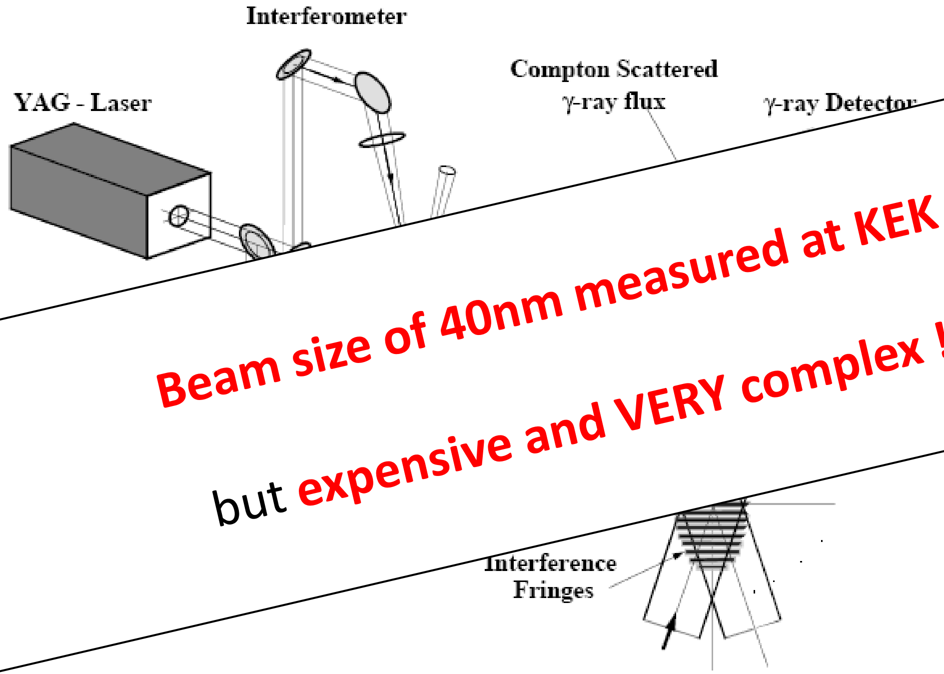
- Measuring nanometer beam size



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

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
- Some are still being developed - An exciting field for R&D !

Thank you for your attention, and it will continue with the Longitudinal diagnostics tomorrow !

The CERN Accelerator School

Advanced Accelerator Physics

The CERN Accelerator School

Extra slides

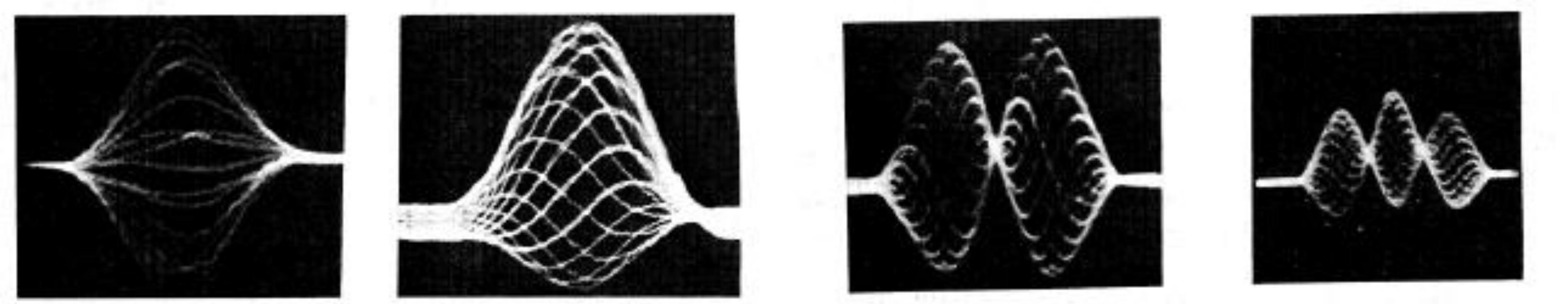
The CERN Accelerator School

Transverse Diagnostics for measuring instabilities

T. Lefevre - CAS Advanced Accelerator Physics, 6-18 November 2022, Sevrier, France

Instability triggering

<u>From Booster in 70's</u>



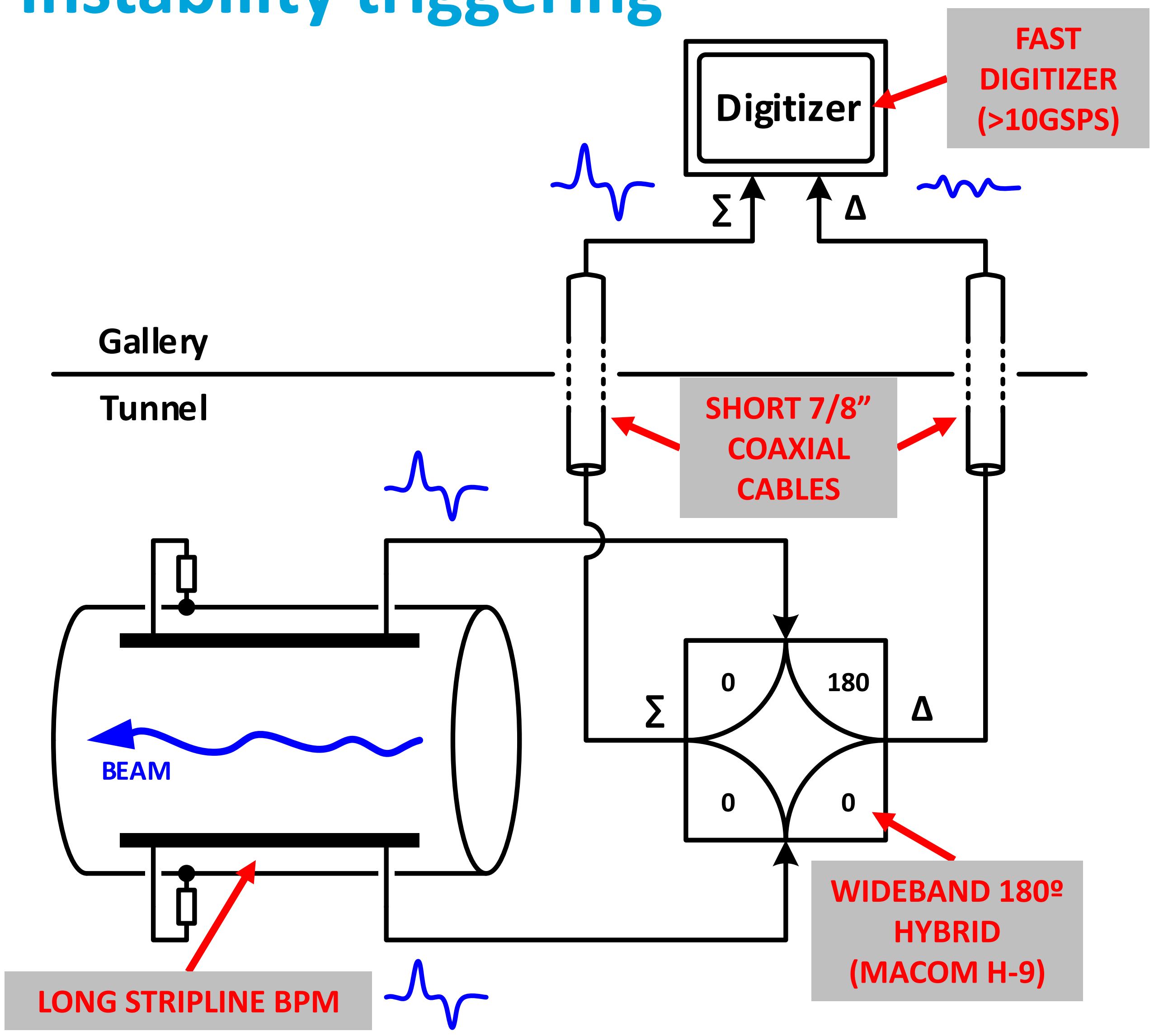
a) mode m = 0, χ = 0 b) m = 0, χ = 2.3 radians b) m = 1, χ = 6.9 radians d) m = 2, χ = 6.9 radians

Very long pulses – 100ns

Instability triggering

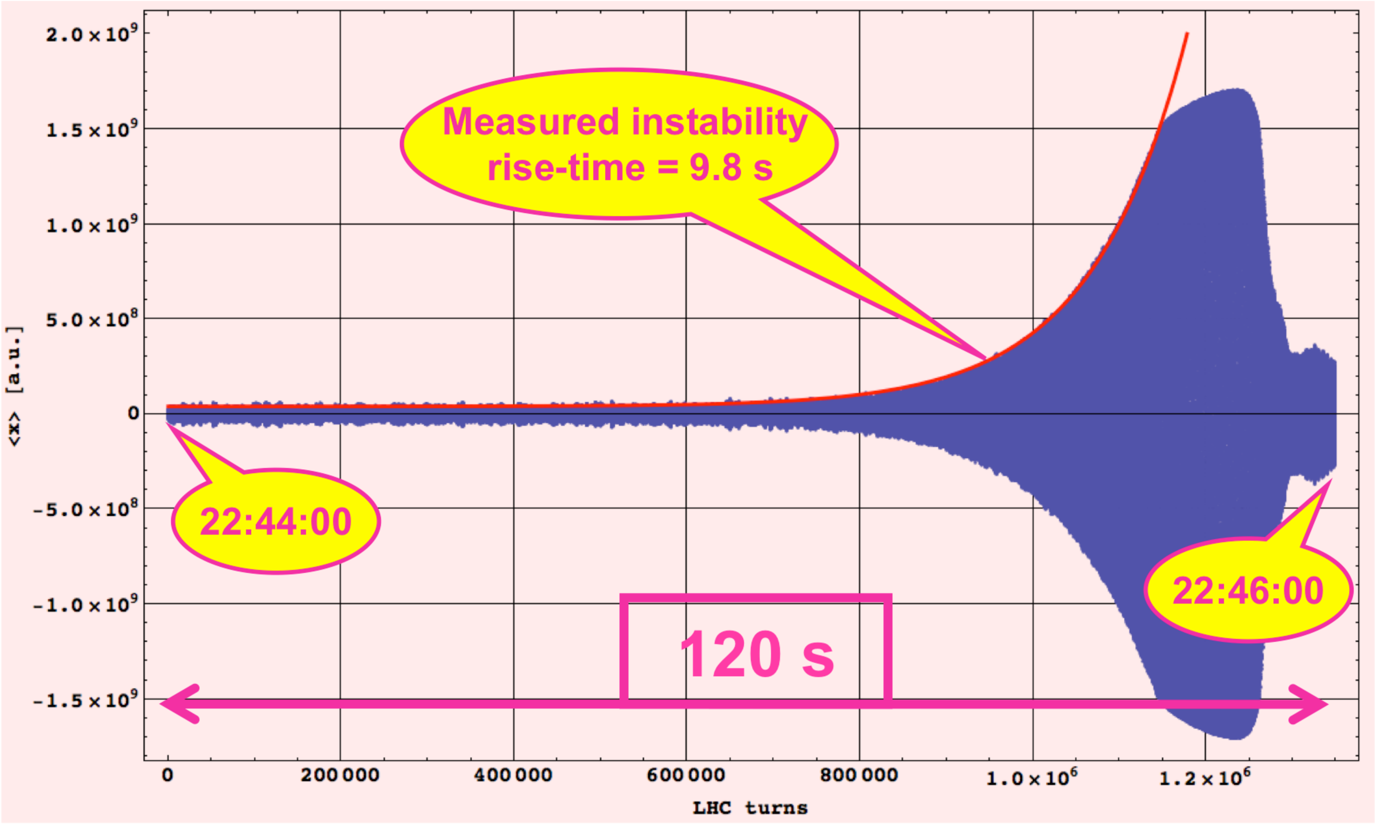
A wideband 180º hybrid calculates the sum and difference of a pair of stripline BPM electrodes.

Signals are directly digitised with a fast (>10GSPS) oscilloscope.



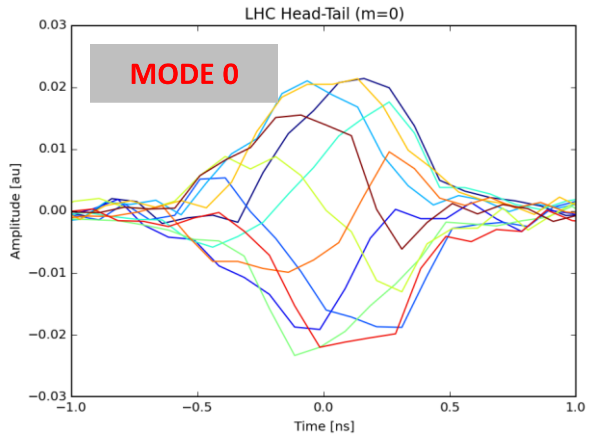
Instability triggering

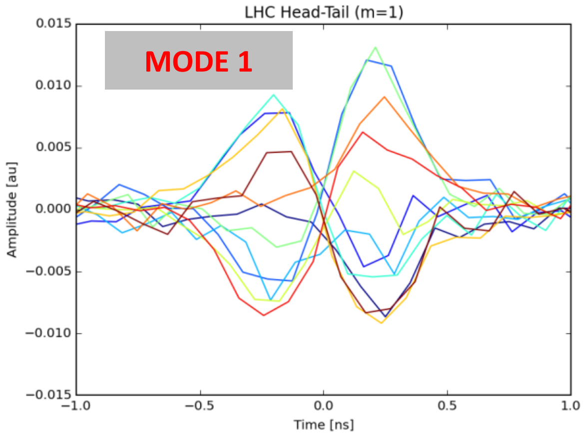
Looking at the beginning of an instability on Large Hadron Collider



The rise time is defined as the time taken for the amplitude of the envelope to increase by: $e^1 \approx 2.7$.

Instability triggering





From LHC in 2018