High Brightness Beam Diagnostics

T. Lefevre
CERN

A big thanks to all the people who provided materials for this lecture !!

L. Bobb, G. Rehm, K. Wittenburg, T. Mitsuhashi, S. Gibson, A. Cianchi, ….

Outline

- What high Brightness means ?

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

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What high Brightness means ?

Definitions of Brightness

$$B = \frac{dI}{dSd\Omega}$$

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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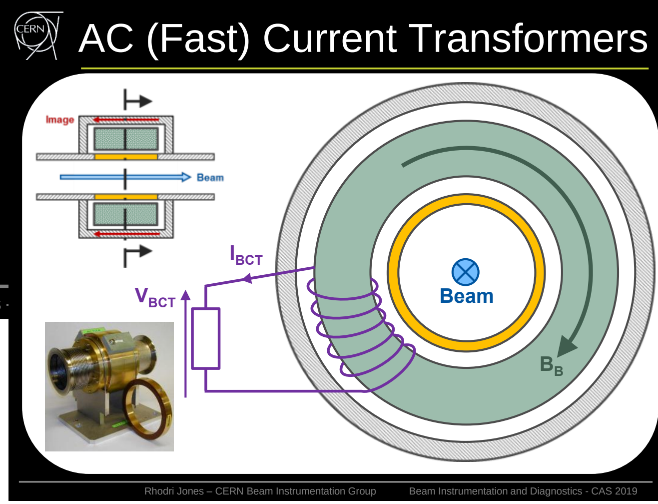
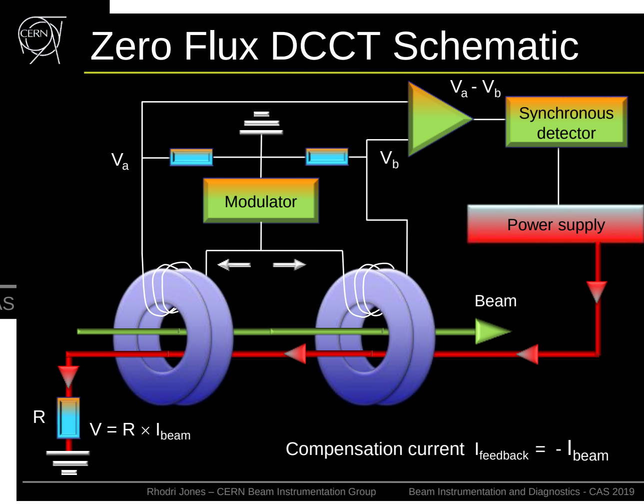
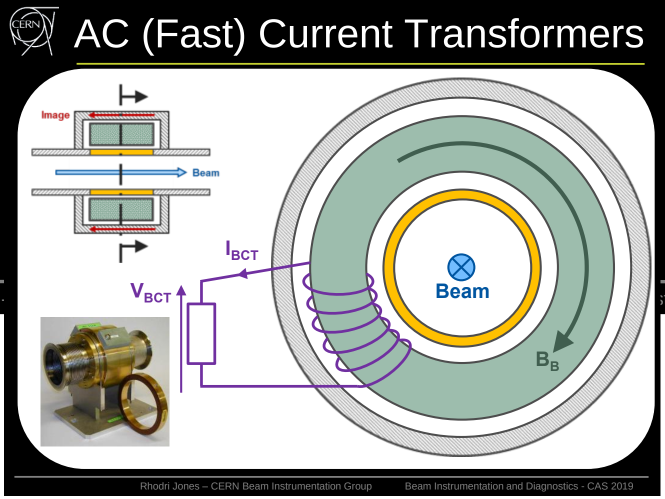
Measuring large beam intensity and small beam emittances

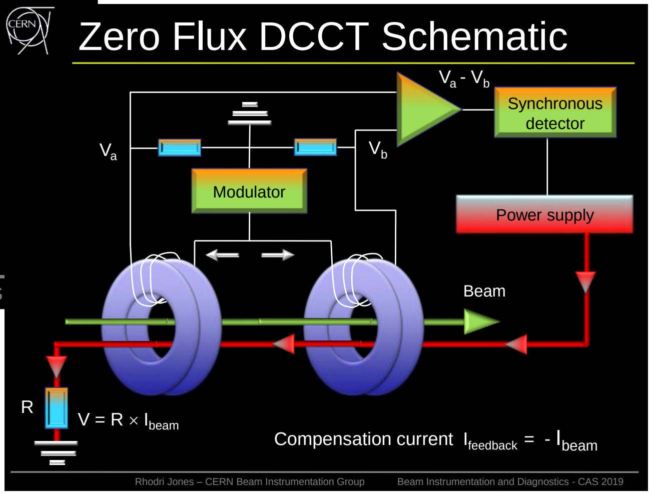
Measuring beam intensity





Measuring beam intensity





Challenge in beam intensity measuring low beam energy

Measuring small beam size

- How small is small ?

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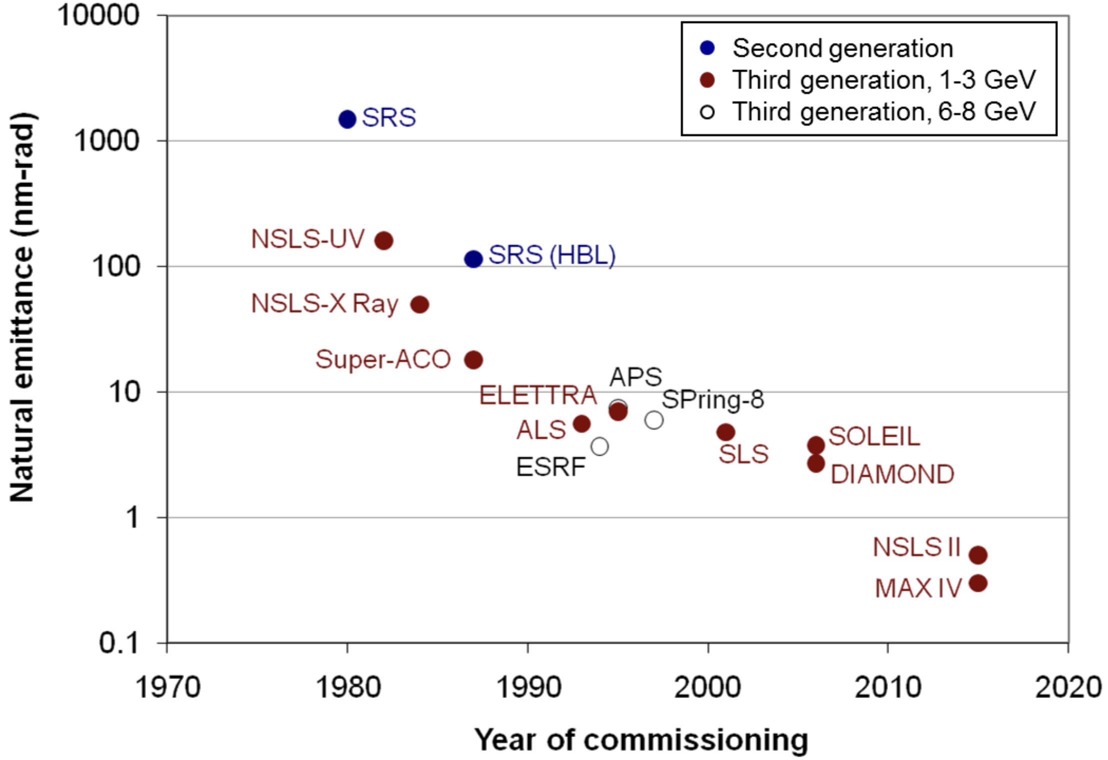
Measuring small beam size

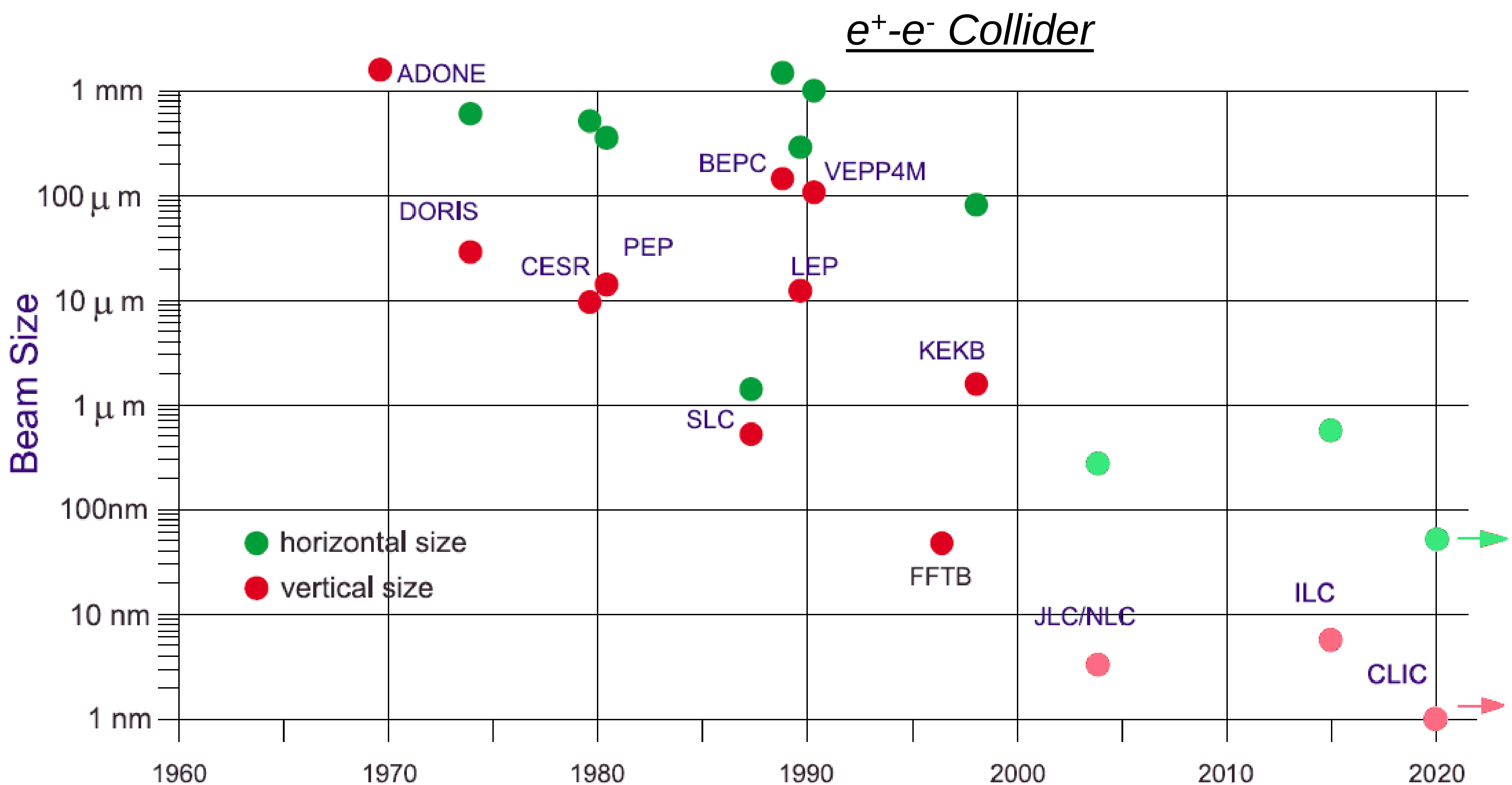
- How small is small ?

Synchrotron Light Source



Measuring small beam size

- How small is small ?



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

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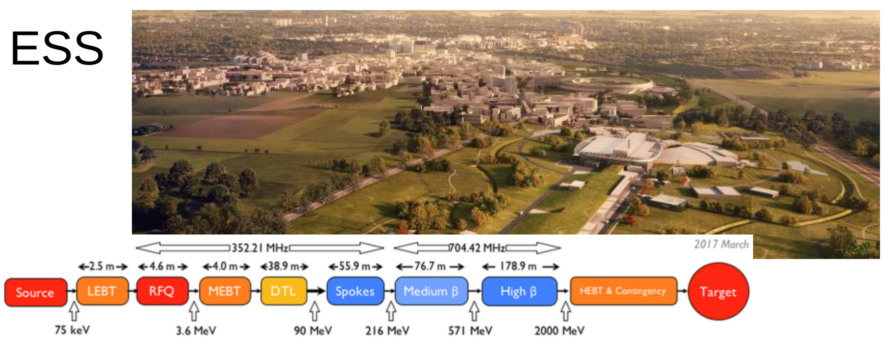

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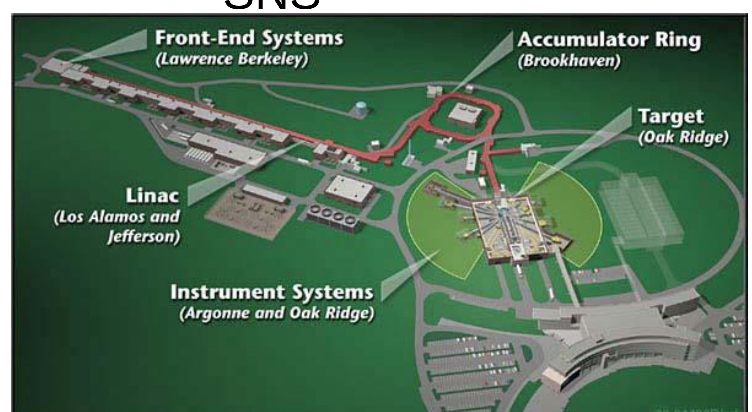
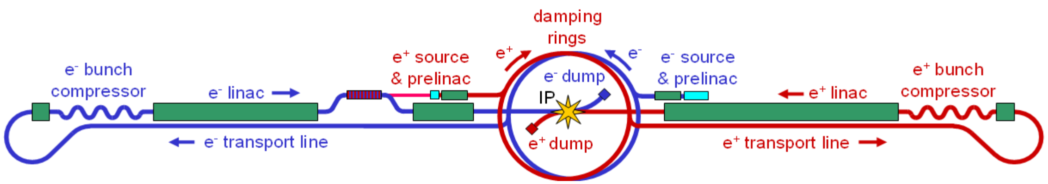


Some example of HB beams

- Synchrotron Facility - 3rd generation light sources

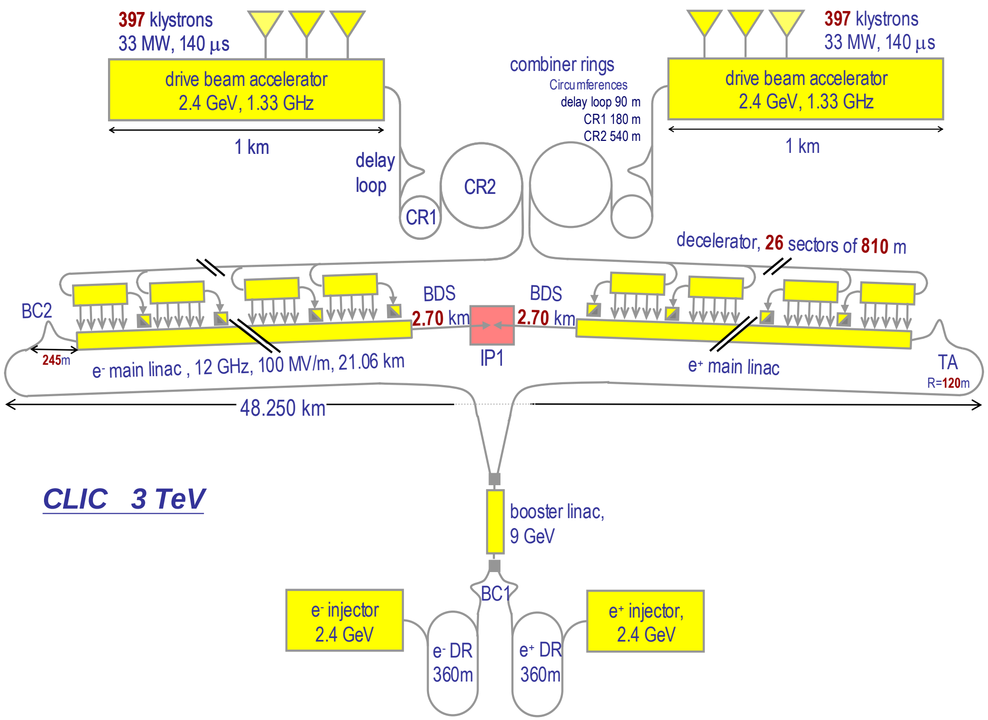
Some example of HB beams

- Energy frontier Linear Colliders



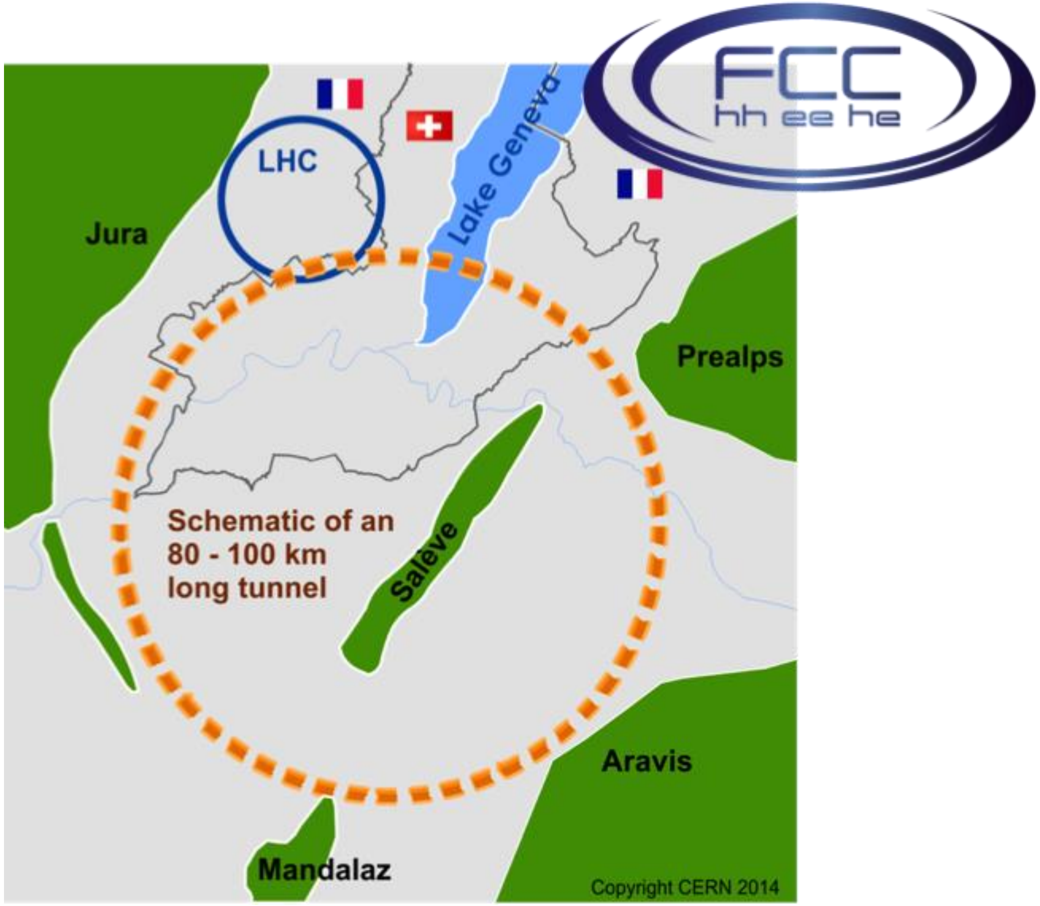
ILC

CLIC



Some example of HB beams

- Energy frontier Circular Colliders



6D brightness

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

Short bunch length (femtosecond)

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

6D brightness

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

Longitudinal beam diagnostics covered tomorrow

... nd)

... Lasers

Novel Accelerator technologies

- Dielectric
- Plasma

Transverse Diagnostics
Space-charge dominated beam

high intensity low energy electron/hadron beams

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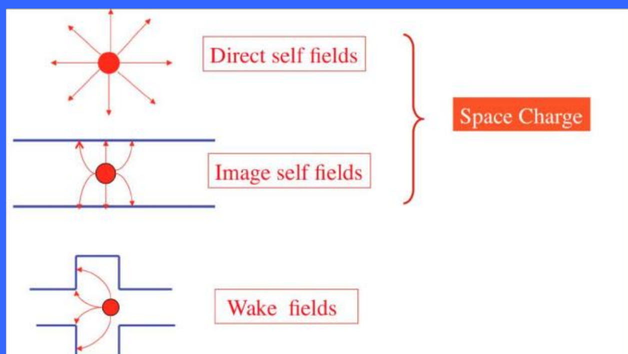
Space Charge in Linear Machines

Massimo.Ferrario@LNF.INFN.IT



Slangerup – June 12 - 2019

Now we can calculate the term $\langle xx'' \rangle$ that enters in the envelope equation

$$\sigma_x'' = \frac{\varepsilon_{rms}^2}{\sigma_x^3} - \frac{\langle xx'' \rangle}{\sigma_x} \qquad \langle xx'' \rangle = \frac{k_{sc}}{\sigma_x^2}\langle x^2 \rangle = k_{sc}$$

Including all the other terms the envelope equation reads:

Space Charge De-focusing Force

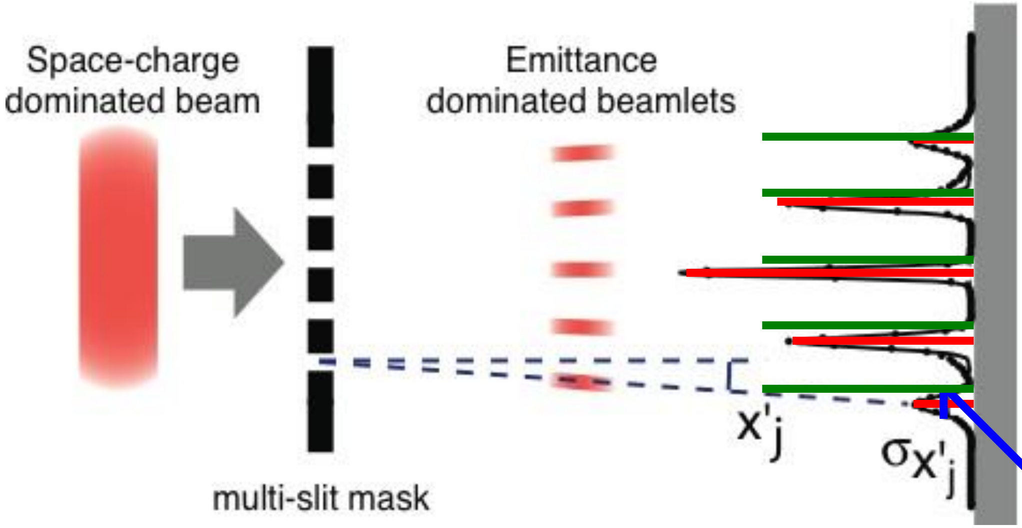
$$\sigma_x'' + k^2\sigma_x = \frac{\varepsilon_n^2}{(\beta\gamma)^2\sigma_x^3} + \frac{k_{sc}}{\sigma_x}$$

Emittance Pressure

External Focusing Forces

Laminarity Parameter: $\rho = \frac{(\beta\gamma)^2 k_{sc}\sigma_x^2}{\varepsilon_n^2}$

Space charge regime



To measure the emittance for a space charge dominated beam the used technique is the well known 1-D pepper-pot

The emittance can be reconstructed from the second momentum of the distribution

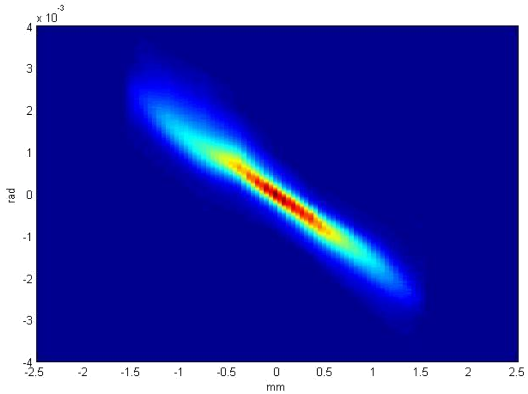
$$\varepsilon = \sqrt{<x^2><x'^2> - <xx'>^2}$$

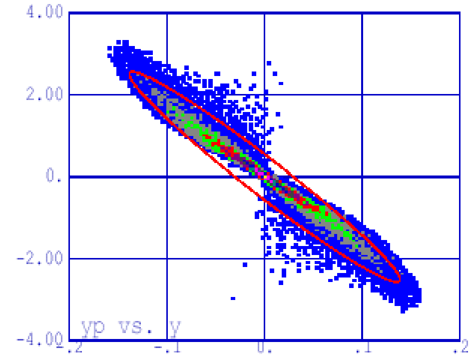
C. Lejeune and J. Aubert, Adv. Electron. Electron Phys. Suppl. A **13**, 159 (1980)

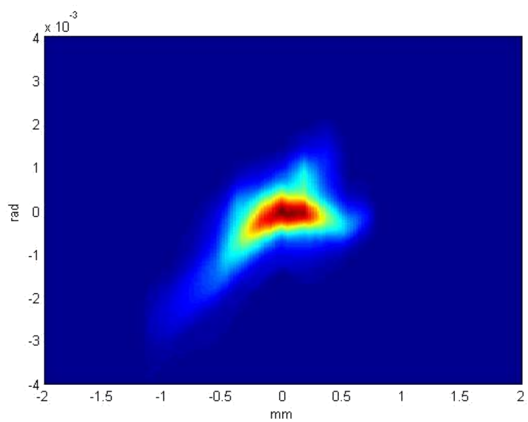
Phase space mapping

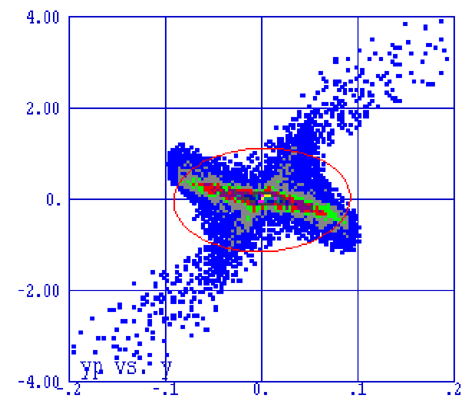
Measurements

Simulations

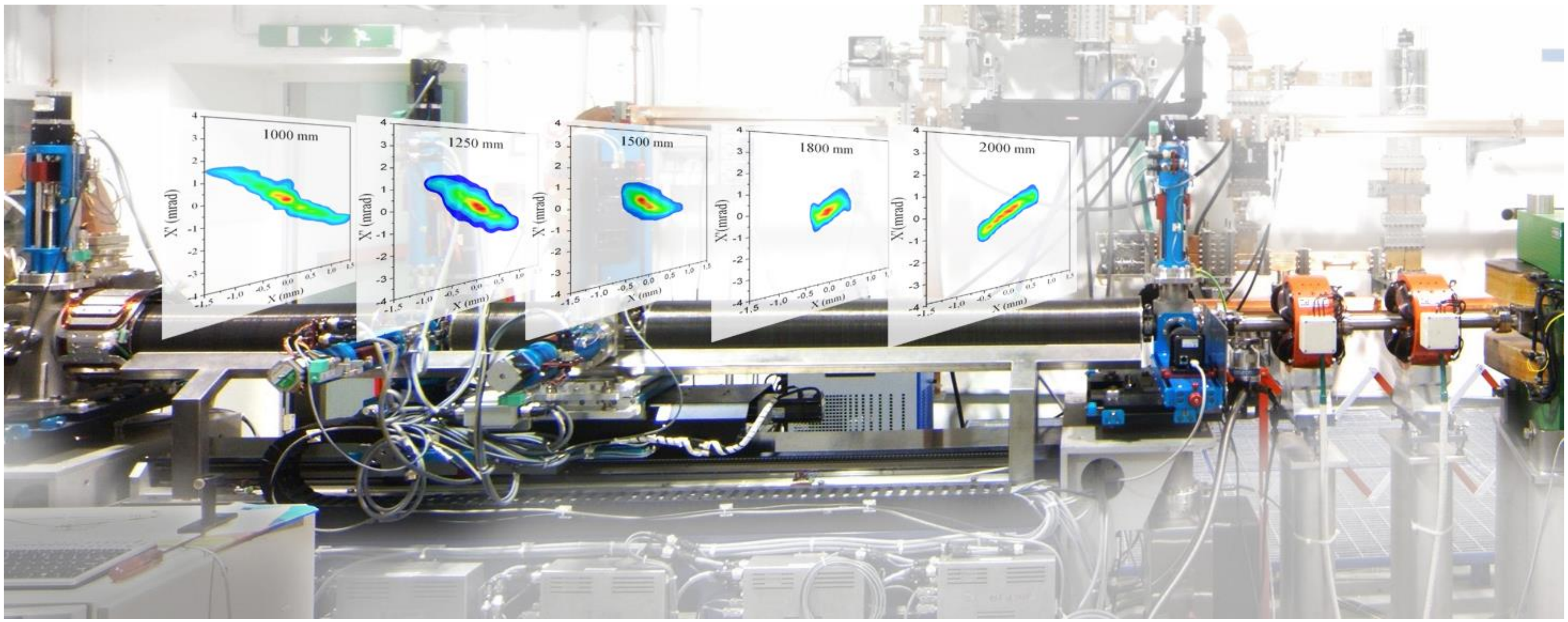








Phase space evolution



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 ,..

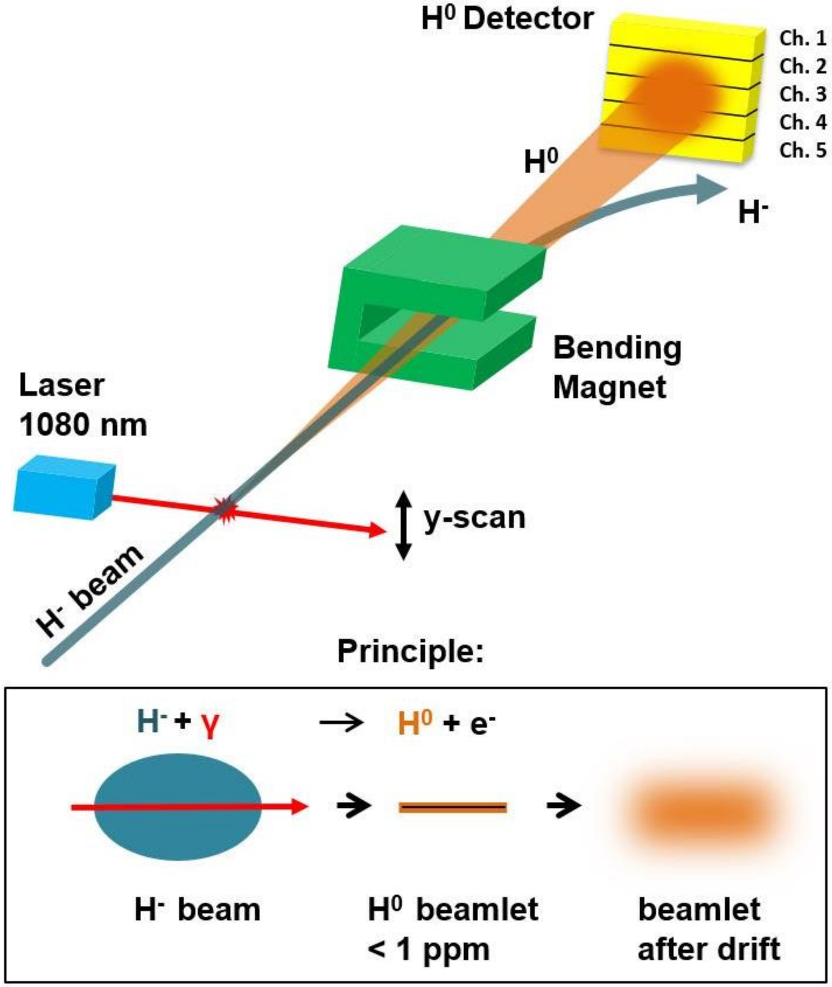
work very well but destructive methods

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

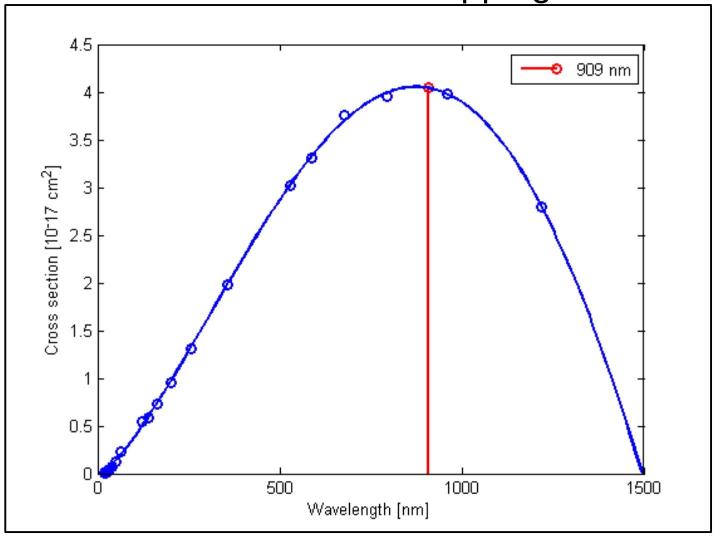
Laser Emittance meter for H^-

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

Laser Emittance meter for H⁻

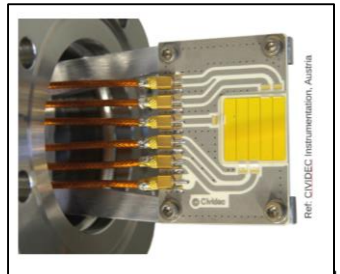


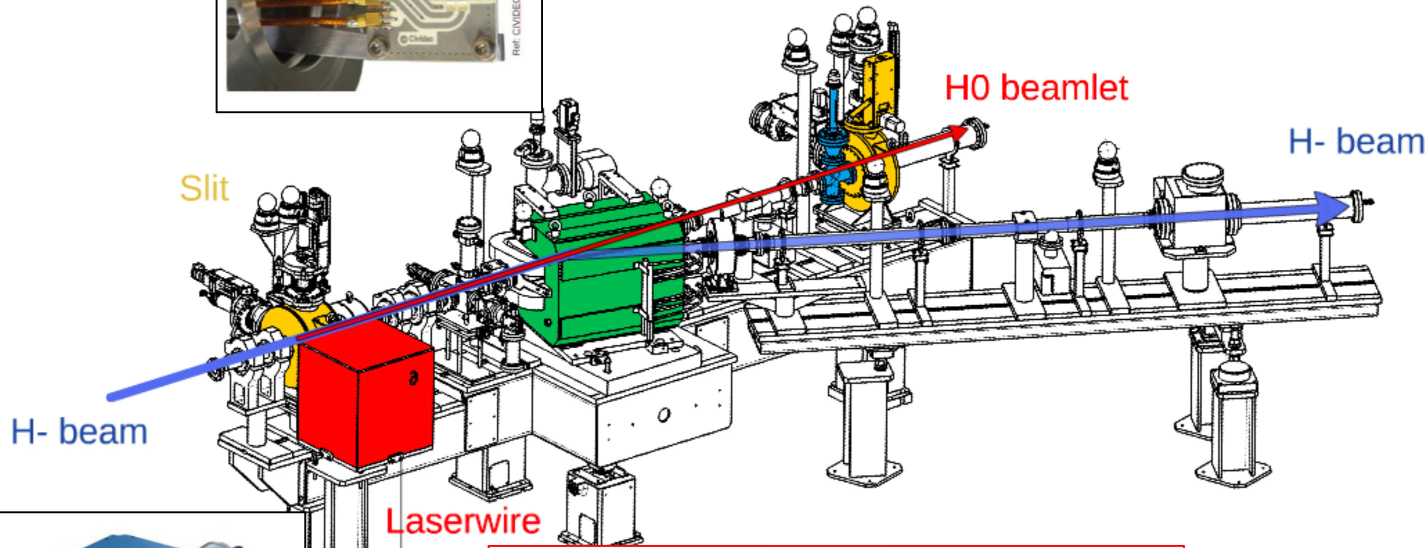
Electron Laser-Stripping



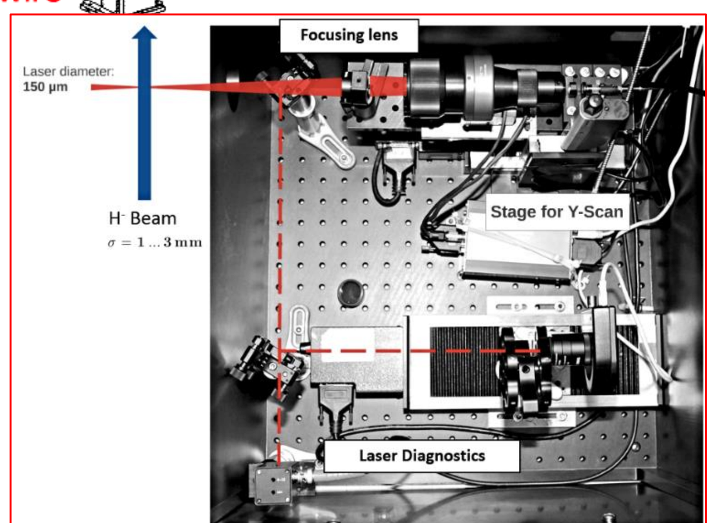
T. Hofmann et al, "A low-power laserwire profile monitor for H- beams: Design and experimental results" Nucl. Inst. and Meth. in Phys. Res. Section A: 903, p. 140-146 (2018)

Laser Emittance meter for H^-



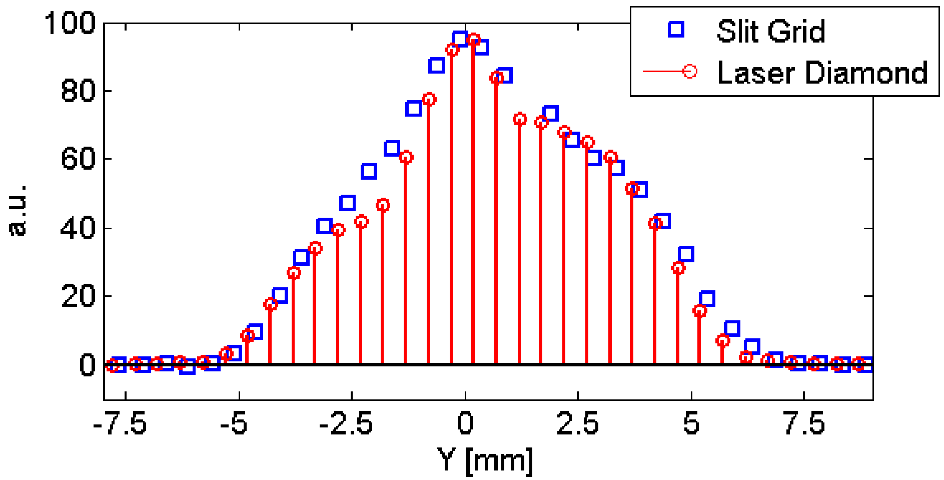


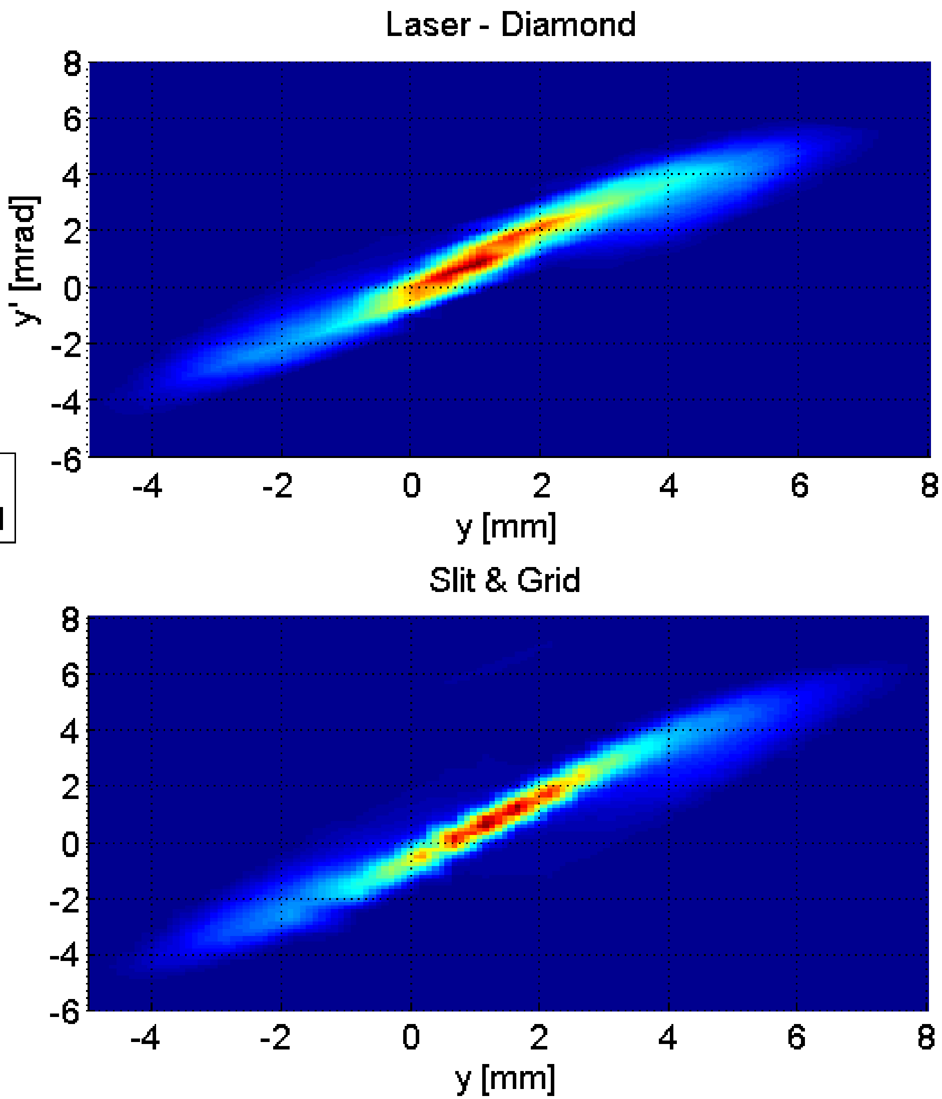
Laser	MOPA	*Nd-YAG*
Pulse Energy	**0.1 mJ**	*50 mJ*
Stripping	**0.1 %**	*> 99 %*
t_{pulse}	80 ns	*5 ns*



Laser Emittance meter for H^-

- Measurements at 3 and 12 MeV at Linac4/CERN





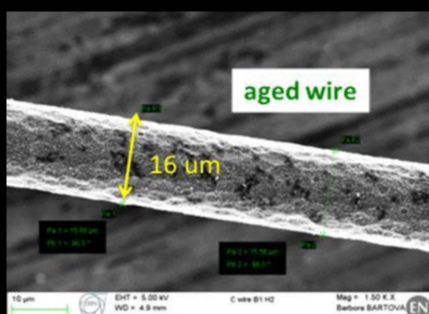
Transverse Diagnostics in Hadron Ring

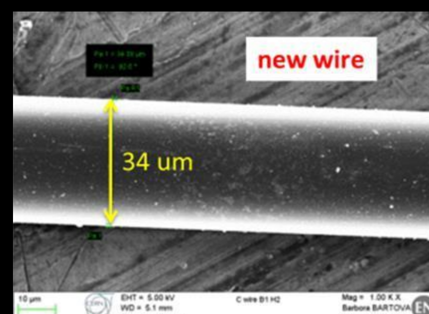
……*higher beam energy*

Hadron ring - Wire Scanner

Limitation of Wire-Scanners

- Wire Breakage – why?
  - Brittle or Plastic failure (error in motor control)
  - Melting/Sublimation (main intensity limit)
    - Due to energy deposition in wire by particle beam
- Temperature evolution depends on
  - Heat capacity, which increases with temperature!
  - Cooling (radiative, conductive, thermionic, sublimation)
    - Negligible during measurements (Typical scan 1 ms & cooling time constant ~10-15 ms)
- Wire Choice
  - Good mechanical properties, high heat capacity, high melting/sublimation point
  - E.g. Carbon which sublimates at 3915K





Rhodri Jones – CERN Beam Instrumentation Group   Beam Instrumentation and Diagnostics - CAS 2019

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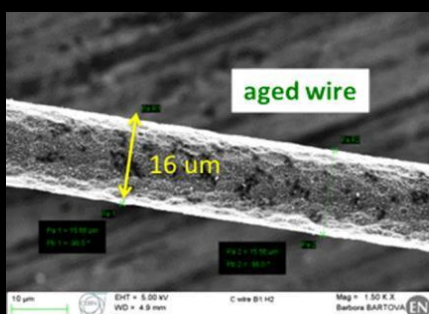

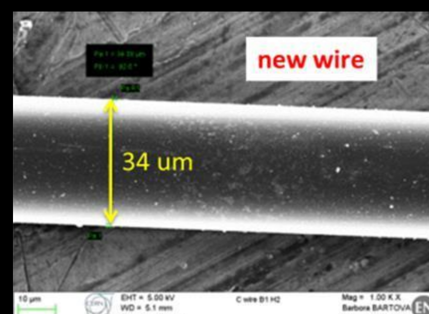

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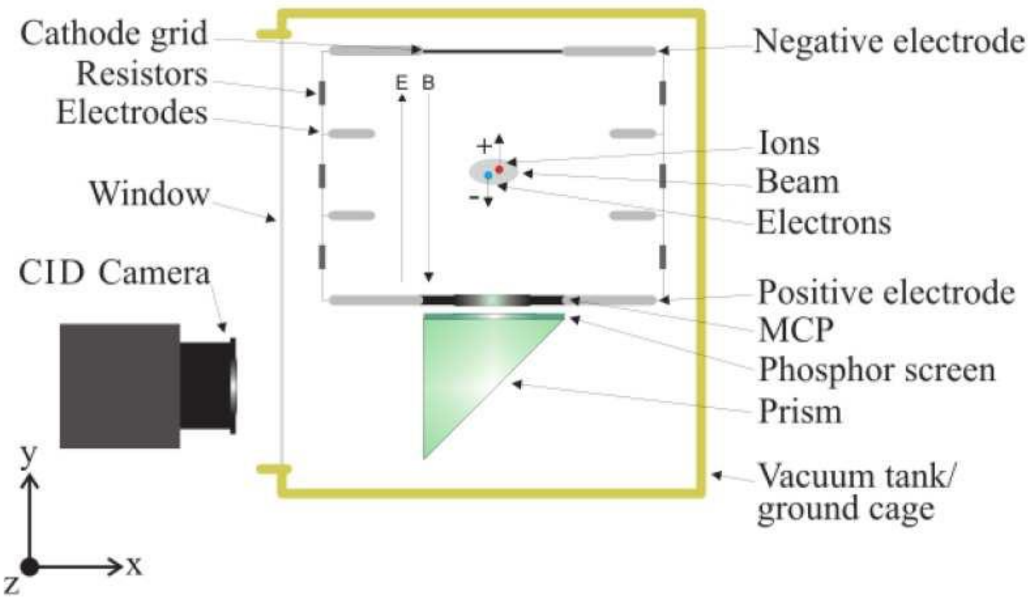
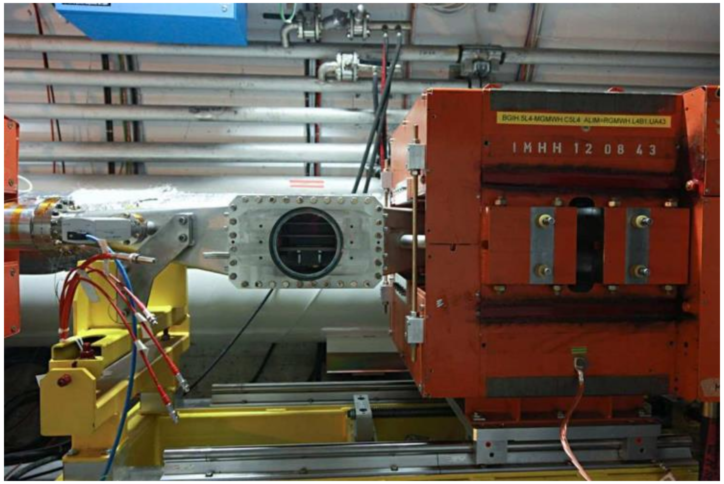
Or worse !

Hadron ring – Beam Gas Ionization

Principle of Operation

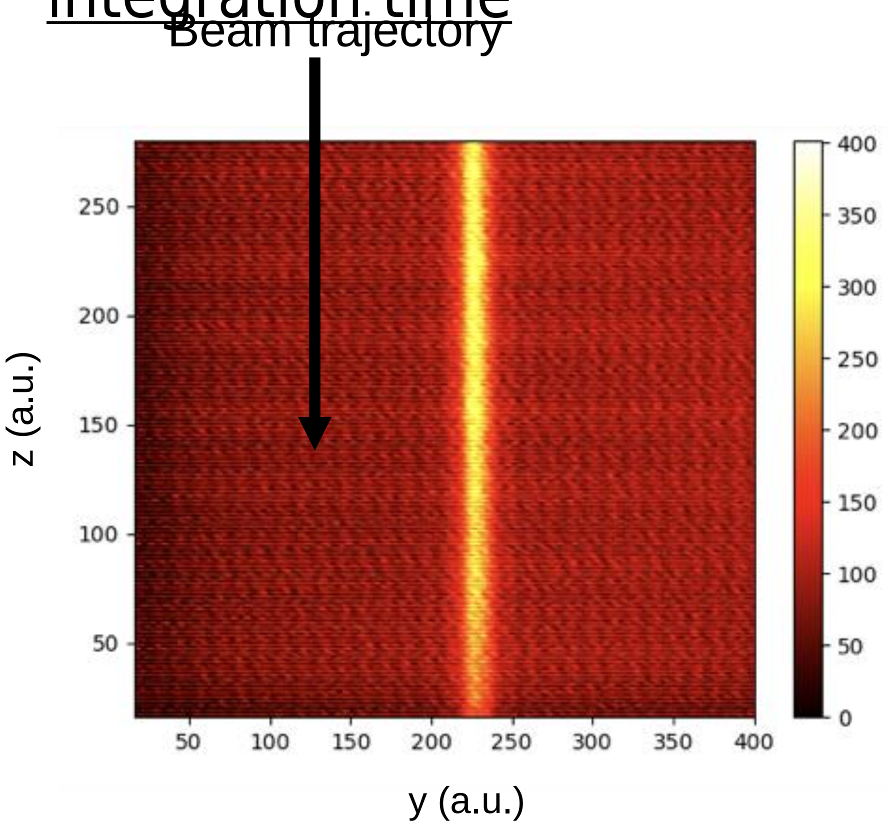


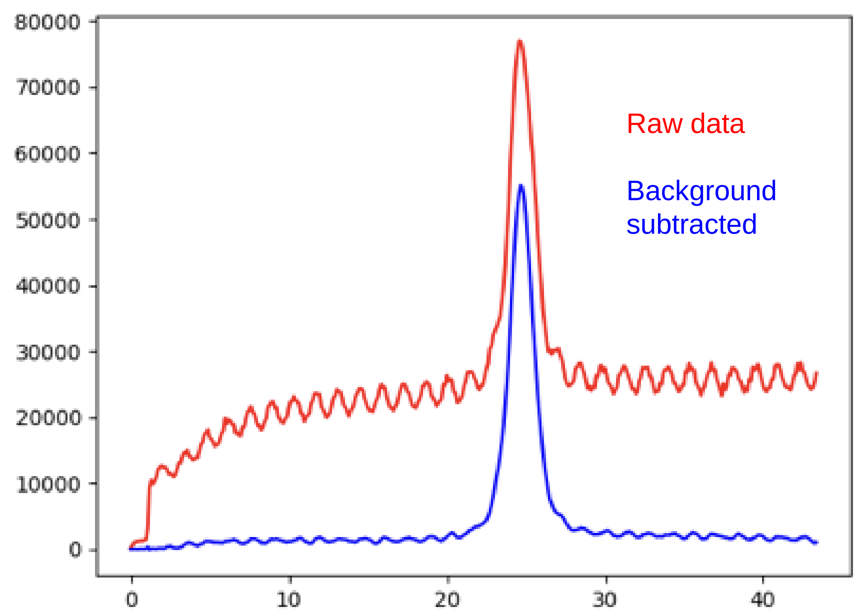


- *Magnet used to guide electrons towards the detector*
- *Ionization probability proportional to the gas pressure (typically 10^{-7}-10^{-10}Torr) and almost constant for beam energy above 1GeV*

Hadron ring – Beam Gas Ionization

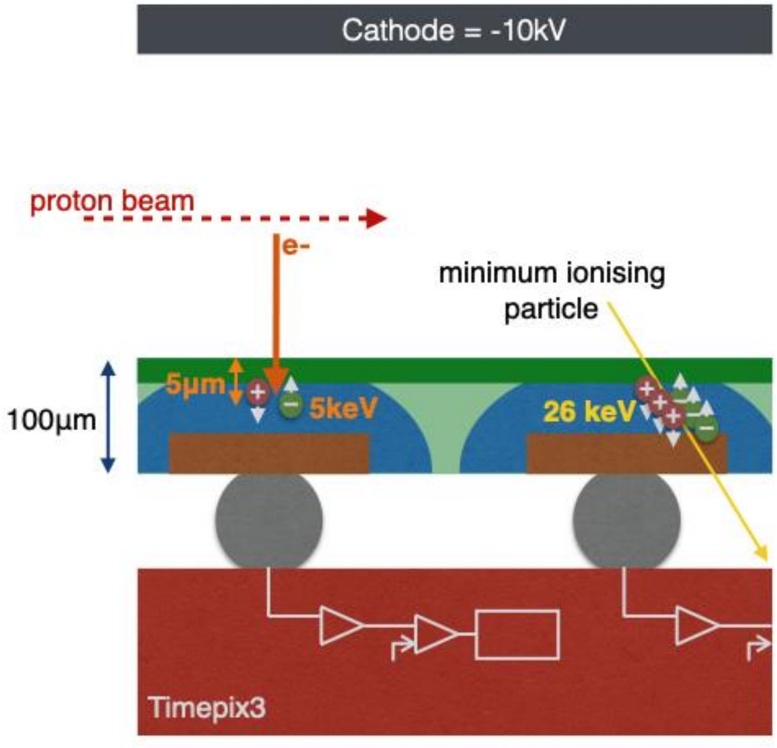
Example at CERN-SPS using 3E11 protons using 1ms integration time

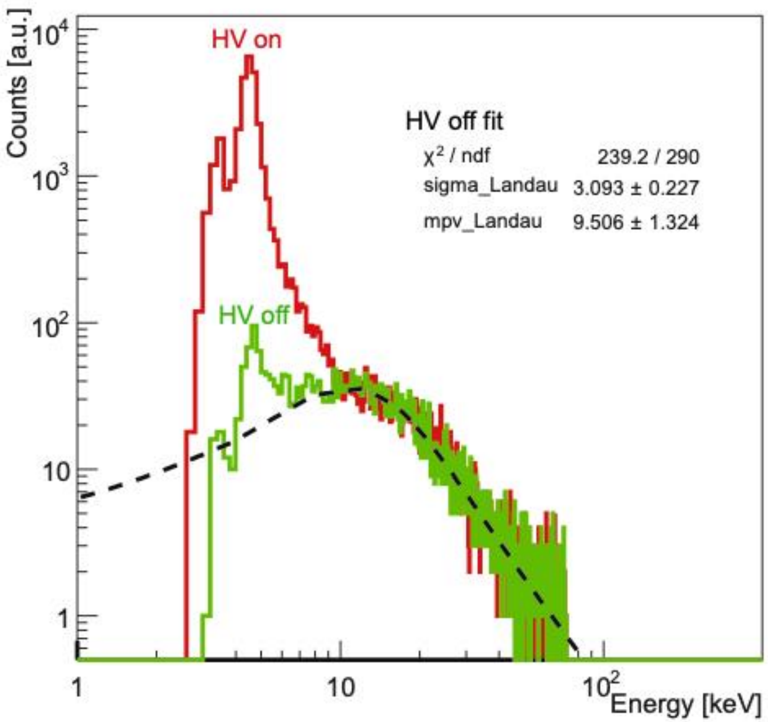




Hadron ring – Beam Gas Ionization

Detection using innovative Pixel detector technology





Charge > threshold → Event

Each events consists of:

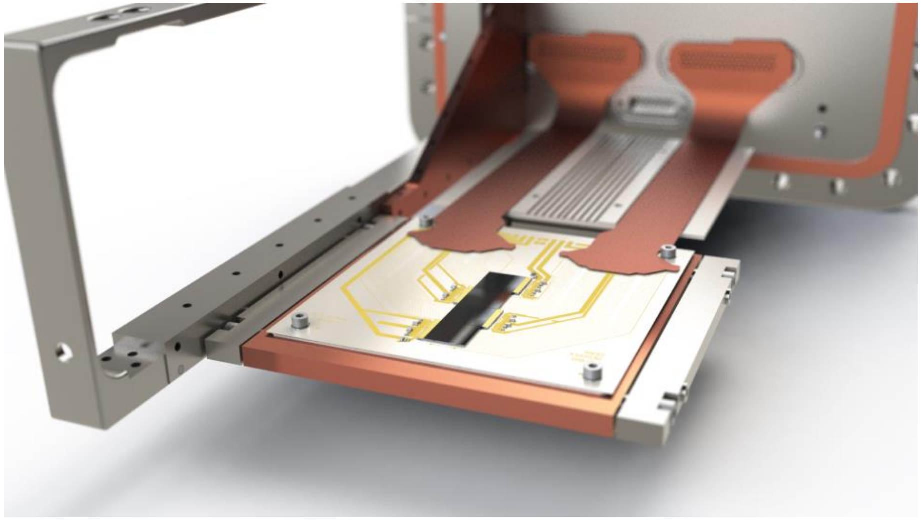
- Pixel position → Where
- Time of Arrival (ToA) → When
- Time-Over-Threshold (ToT) → Energy

Hadron ring – Beam Gas Ionization

Detection using innovative Pixel detector technology

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

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



Timepix3 chip

- CMOS : 256x256 pixels (55umx55um)
- Rad-hard read-out electronic system
- Operational on PS since 2017

Hadron ring – Beam Gas Ionization

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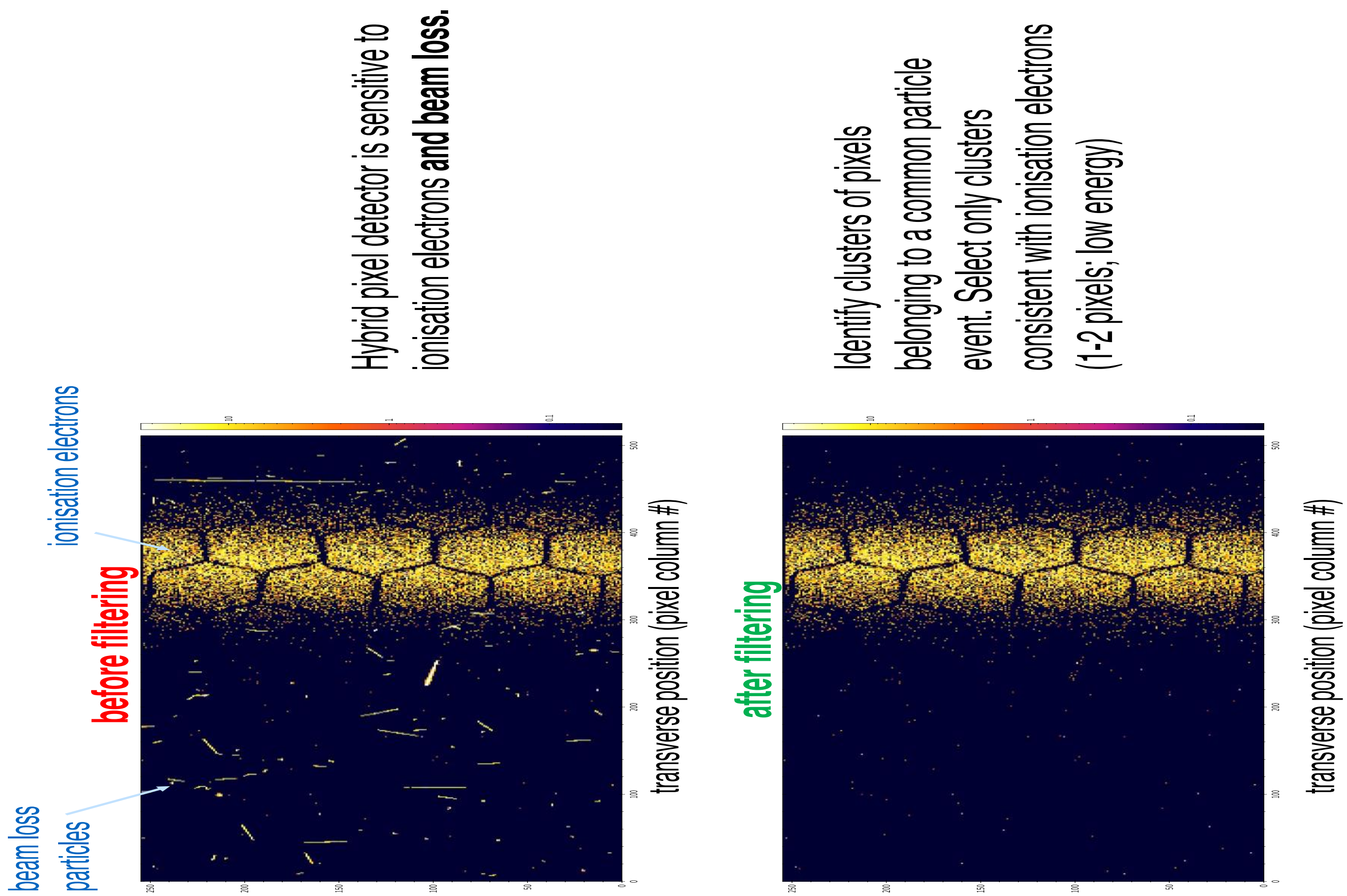
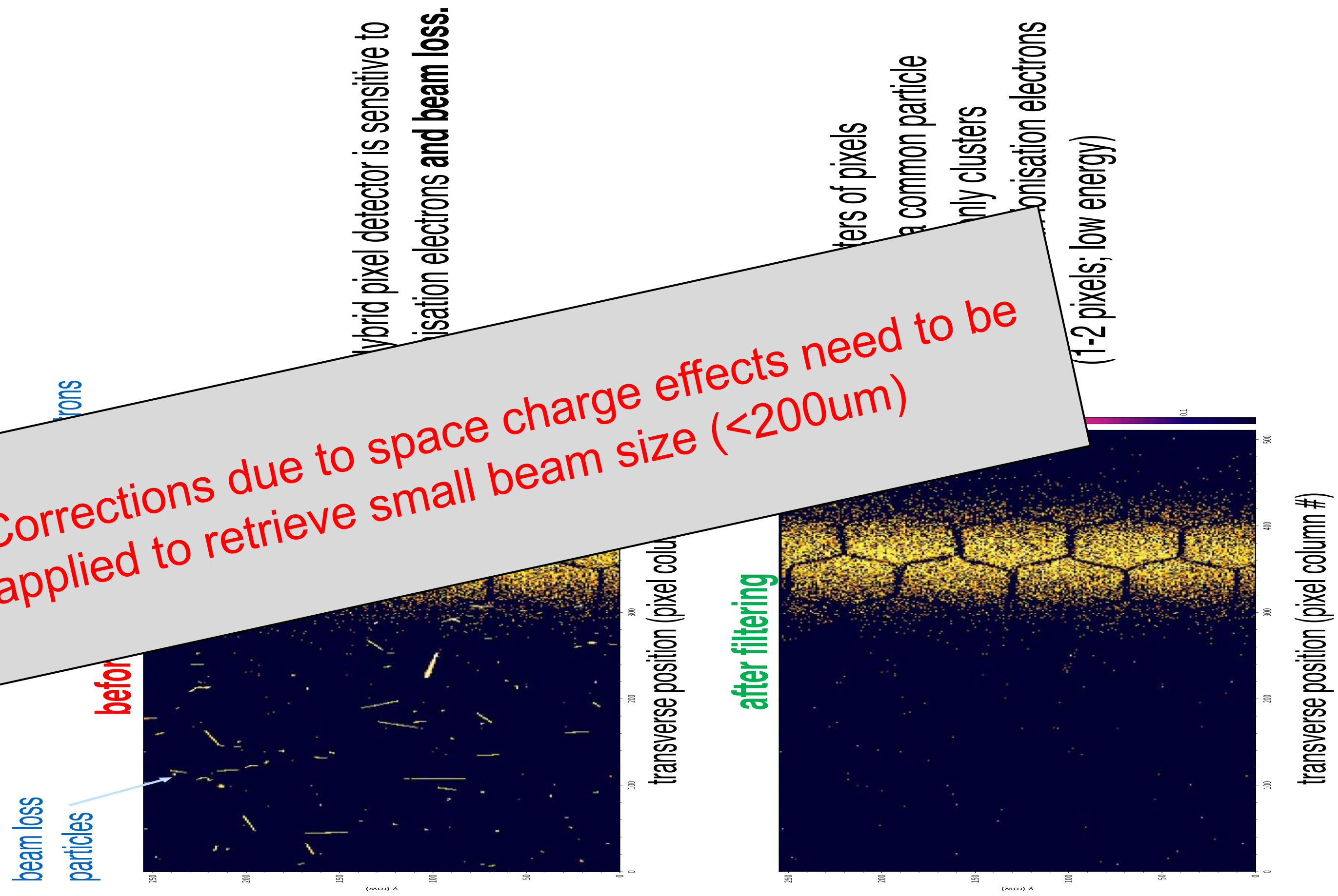
- Example on Proton Synchrotron (PS) at CERN



S. Levasseur et al: Development of a rest gas ionisation profile monitor for the CERN Proton Synchrotron on a Timepix3 pixel detector, Journal of Instrumentation 12 (2017) C02050

Hadron ring – Beam Gas Ionization

- Example on Proton Synchrotron (PS) at CERN



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

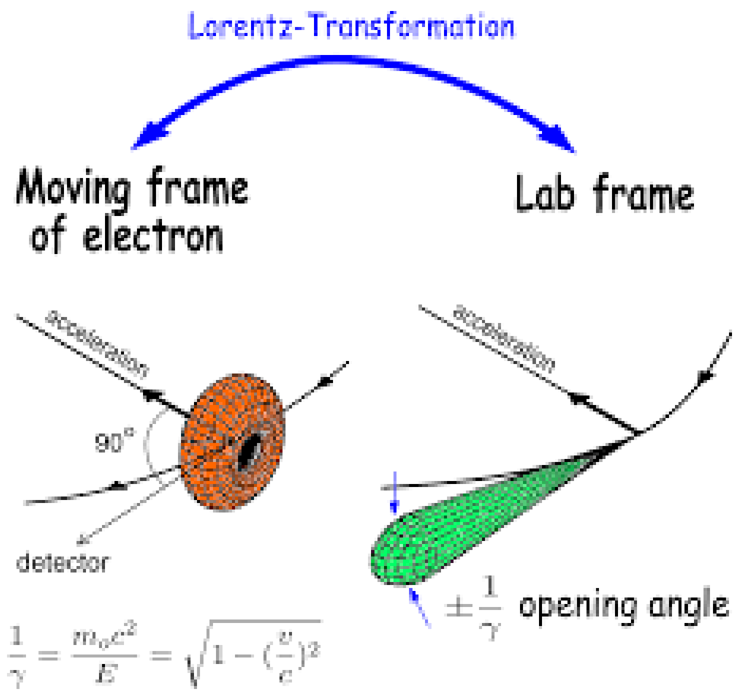
Hadron ring – Beam Gas Fluorescence

- An alternative to gas ionization is to use **gas induced fluorescence**
  - Using Intensified camera because the light yield is typically low
  - 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

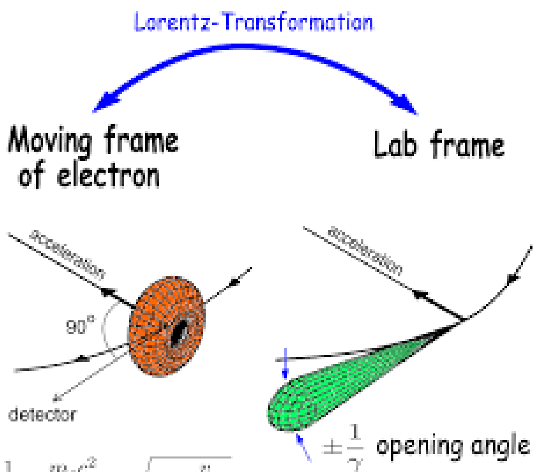
Hadron ring – Synchrotron Radiation

‘Let There Be Light’

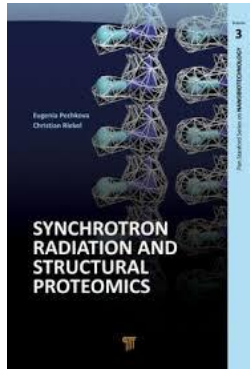


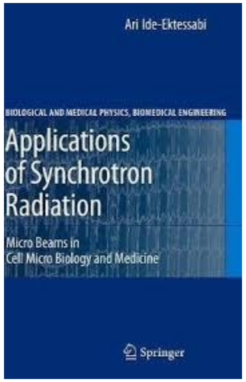
Nothing religious but a great tool for beam diagnostics

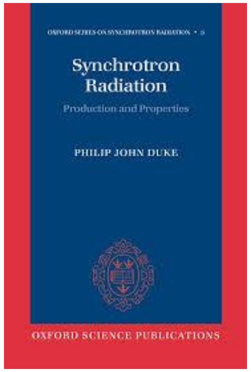
'Let There Be Light'

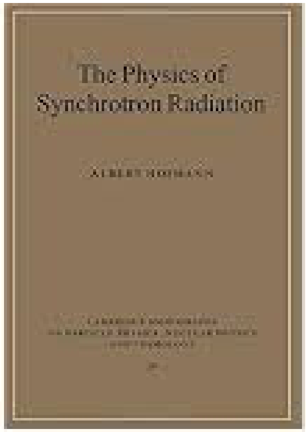


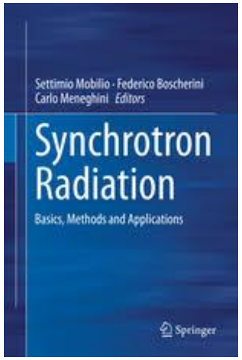
$$\frac{1}{\gamma} = \frac{m_0 c^2}{E} = \sqrt{1-\left(\frac{v}{c}\right)^2}$$

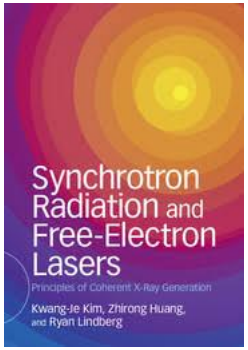


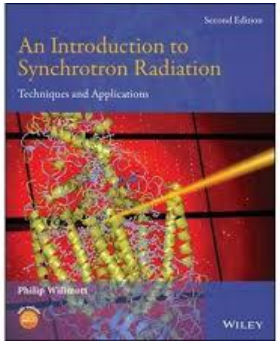












Hadron ring – Synchrotron Radiation

- 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

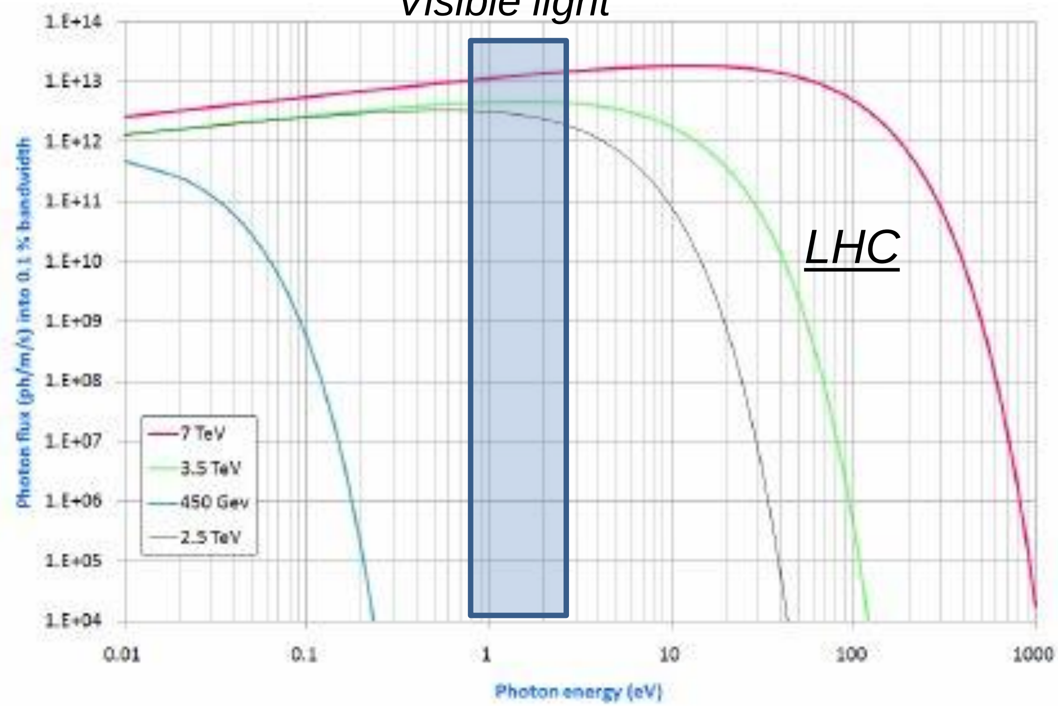
- Critical Frequency :

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

Beam energy

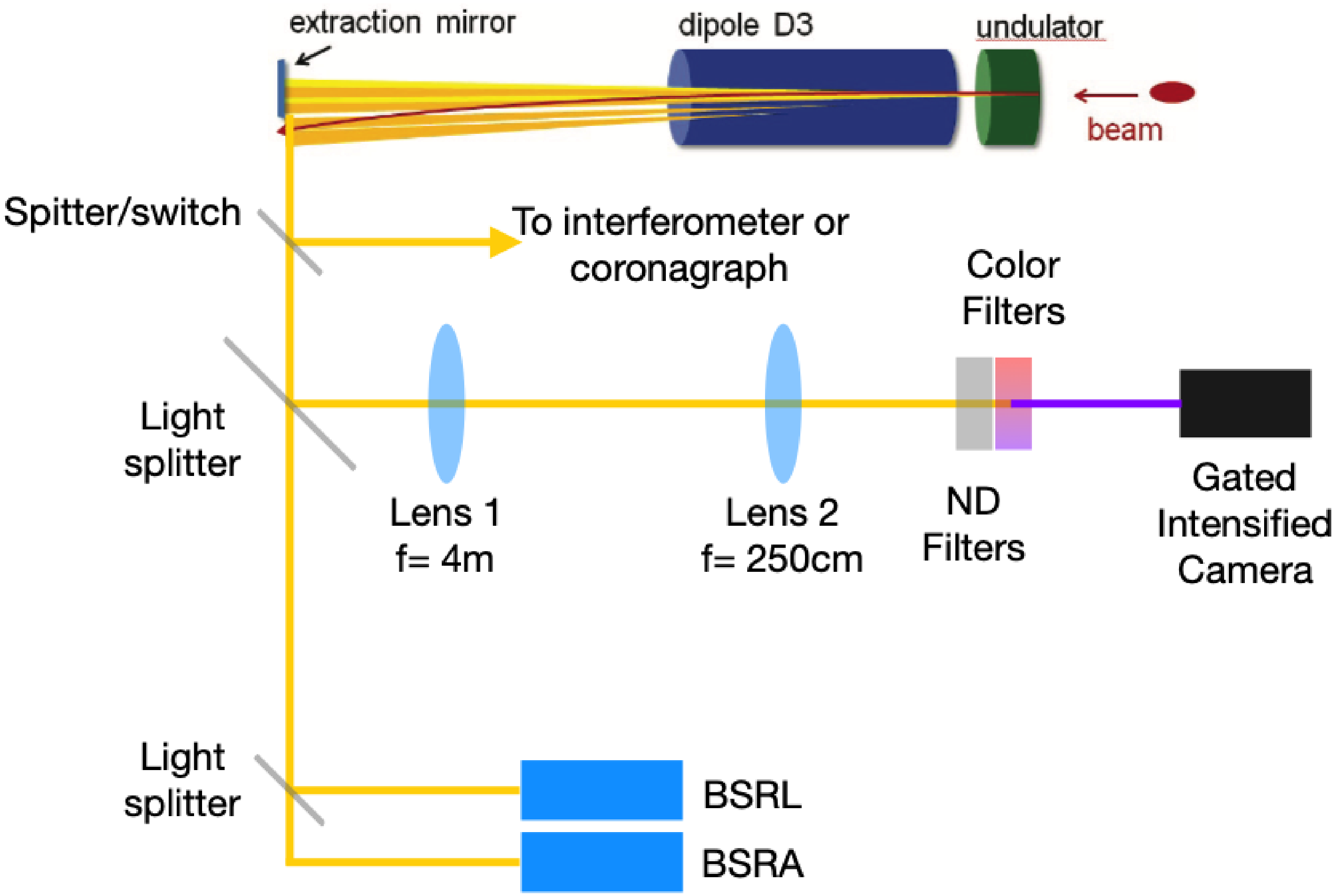
Beam curvature

Visible light



Hadron ring – Synchrotron Radiation

Light is precious and serves many detectors - @LHC



Hadron ring – Synchrotron Radiation

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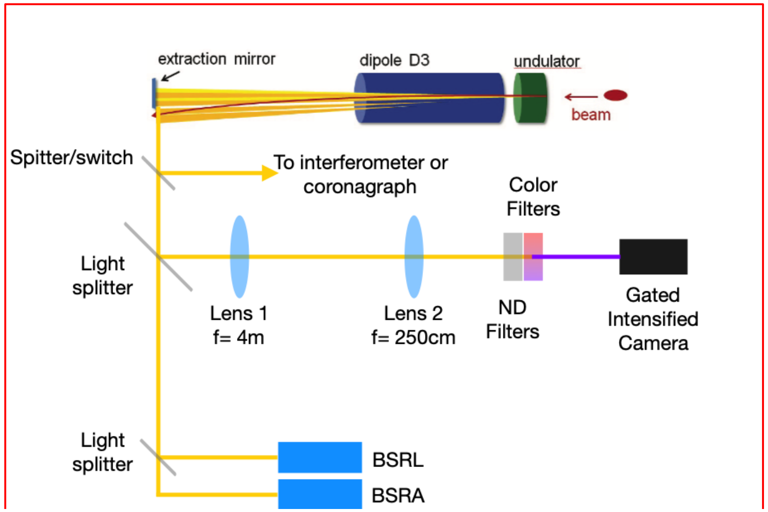
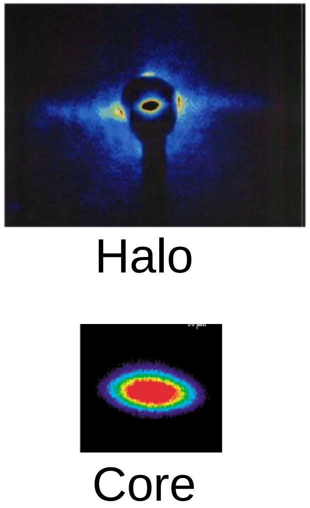
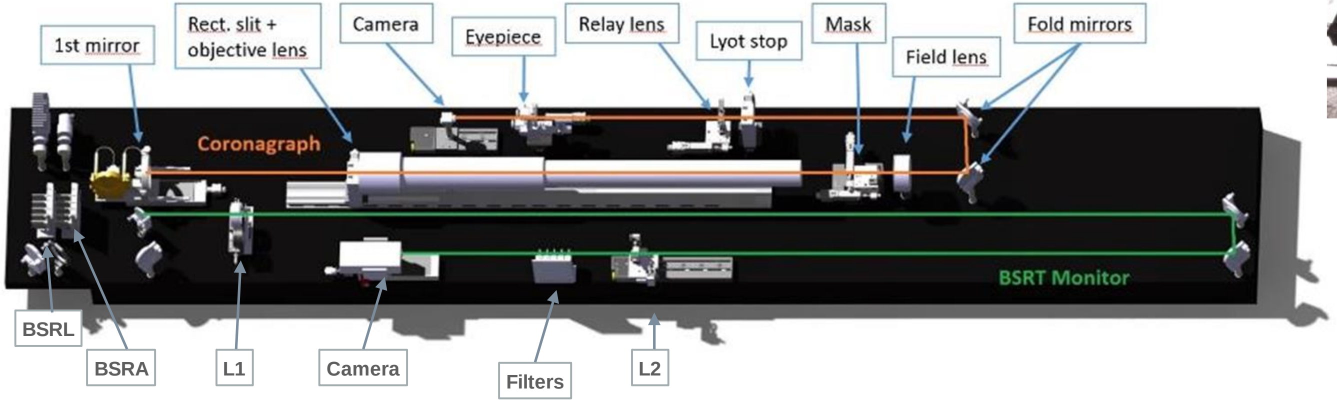
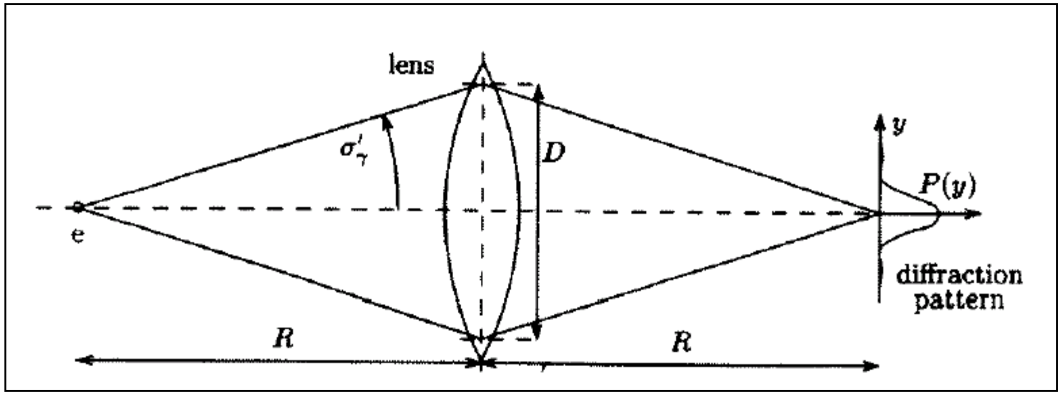






It also suffers from

- 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

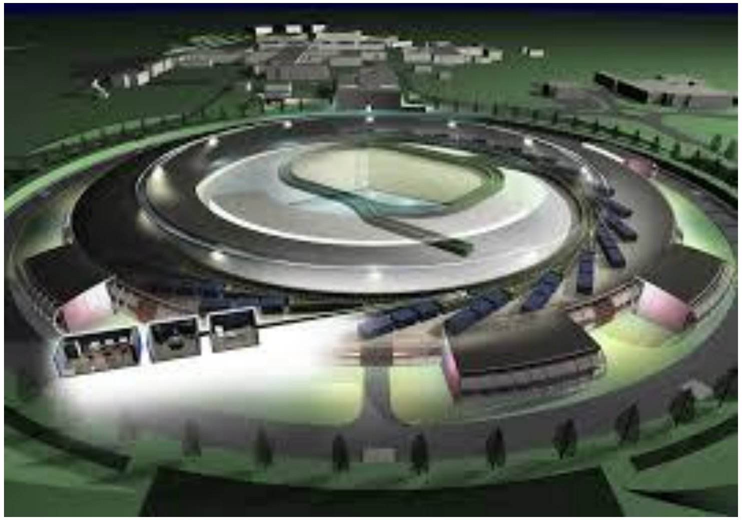
$$\sigma_{DoF} = \frac{\sigma'_y L}{2} \approx 0.36\frac{L}{\gamma}$$

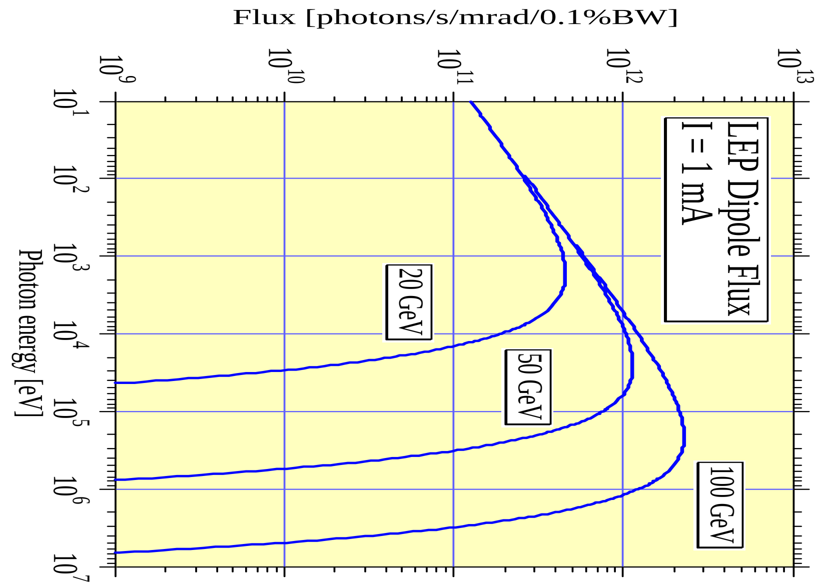
For highly relativistic beams, resolution limit reaches quickly 100's of microns for visible light !!

Transverse Diagnostics in Electron Ring

Electron ring – Synchrotron Radiation

From Light Sources to Collide



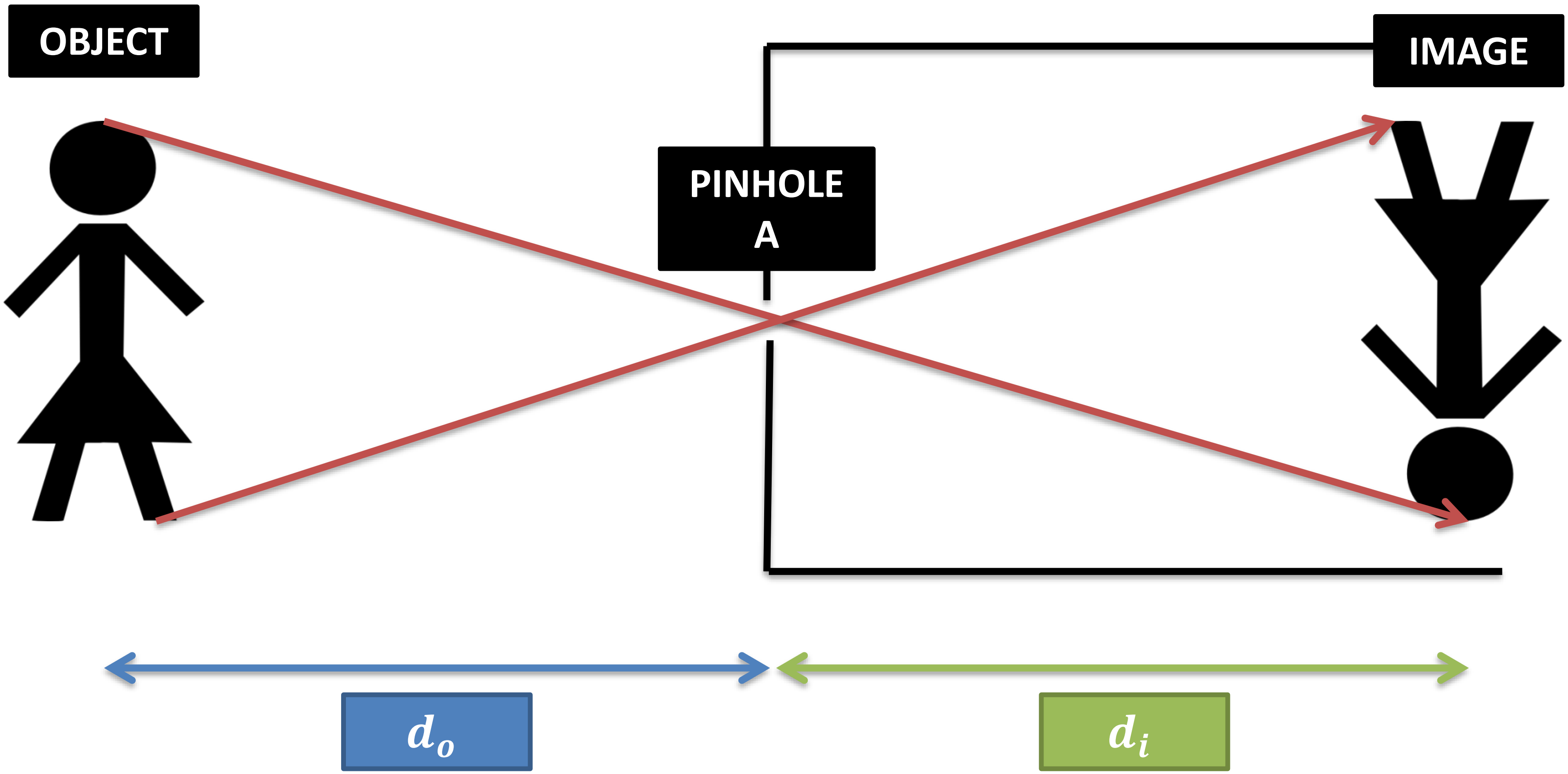


Photon spectrum goes in the soft/hard x-ray to γ–ray regimes

Visible photons still available !

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

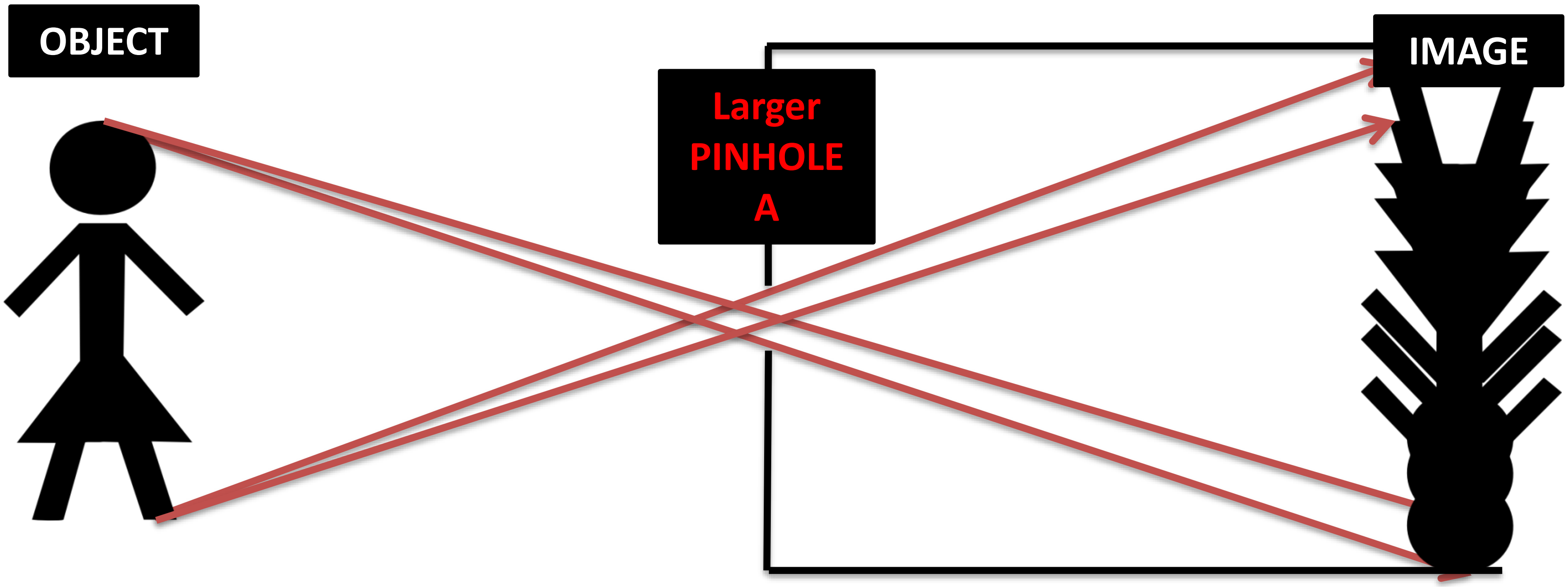
X-ray pinhole cameras



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

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

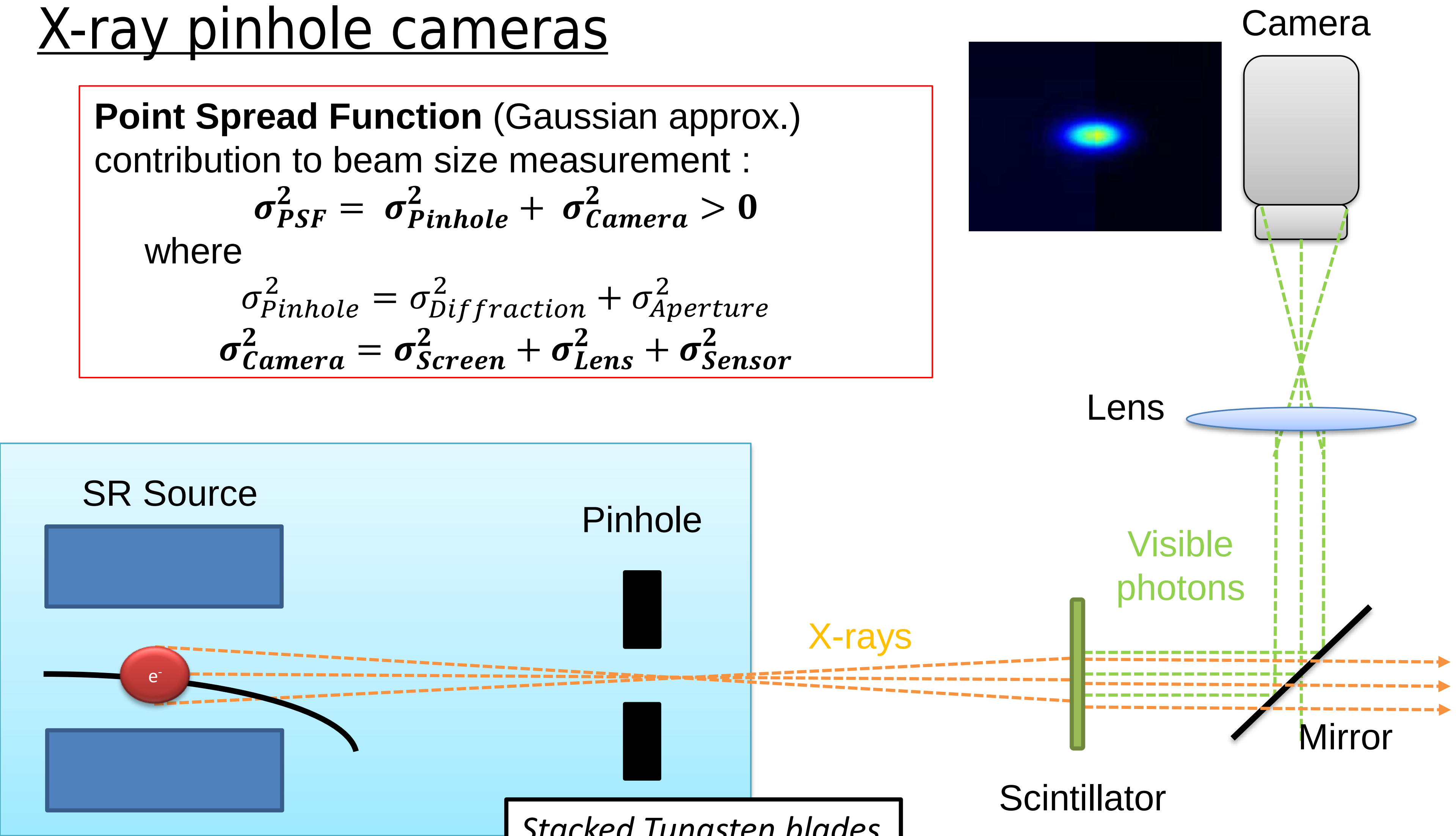
Point Spread Function (Gaussian approx.) contribution to beam size measurement :

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

where

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

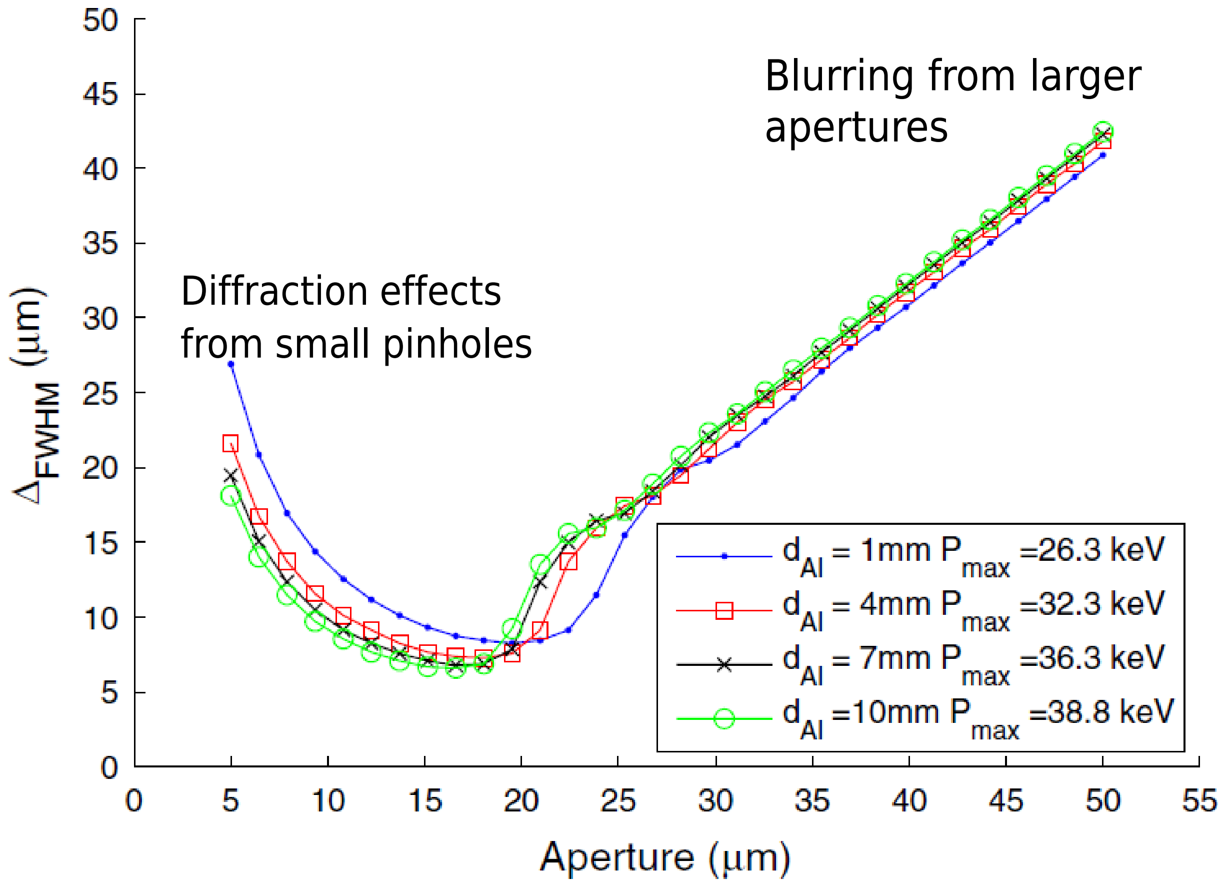
$$\boldsymbol{\sigma^2_{Camera} = \sigma^2_{Screen} + \sigma^2_{Lens} + \sigma^2_{Sensor}}$$



Stacked Tungsten blades separated by shims

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

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

Electron ring – Synchrotron Radiation

- Interferometric measurement as an alternative to direct imaging

  - To measure a size of object by measuring of spatial coherence of light (interferometry) was 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 – SR interferometry

- Van Cittert-Zernike theorem :

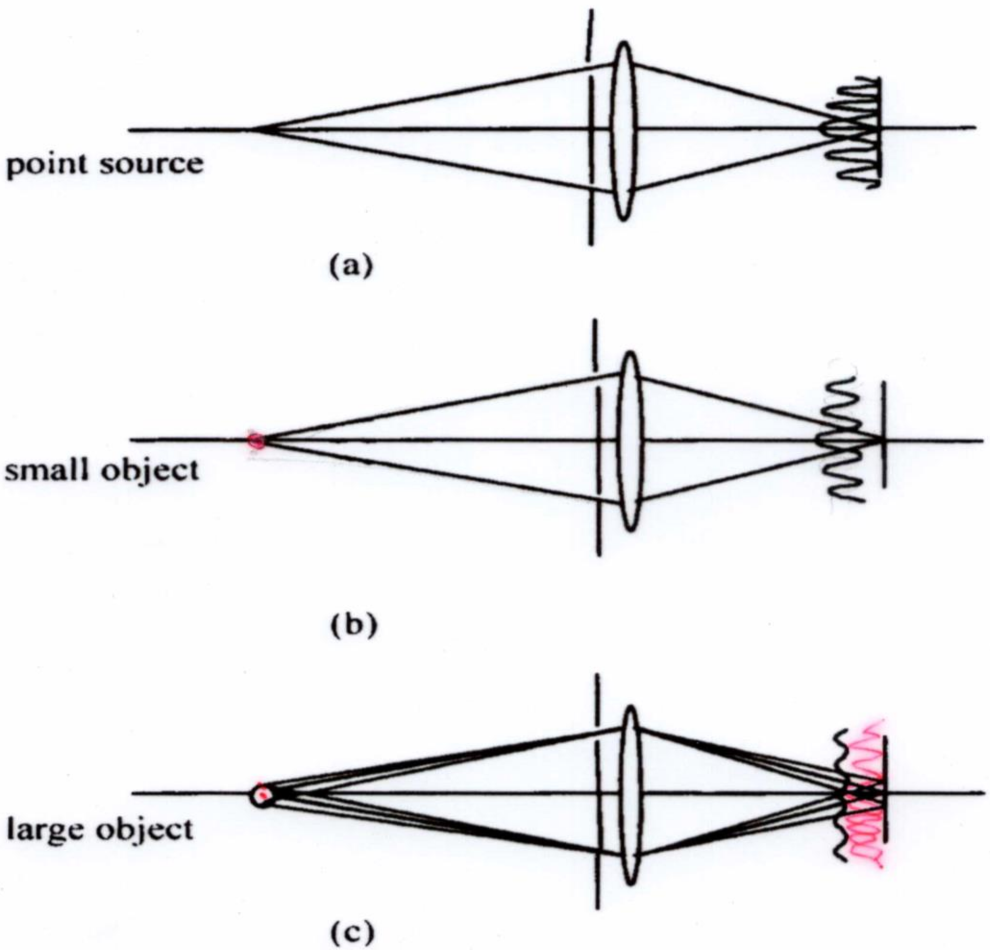
With the condition of light is temporal incoherent (no phase correlation), the complex degree of spatial coherence $\gamma(\upsilon_x,\upsilon_y)$ is given by the Fourier Transform of the spatial profile f(x,y) of the object (beam) at longer wavelengths such as visible light.

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

where υ_x, υ_y are spatial frequencies given by;

Electron ring – SR interferometry

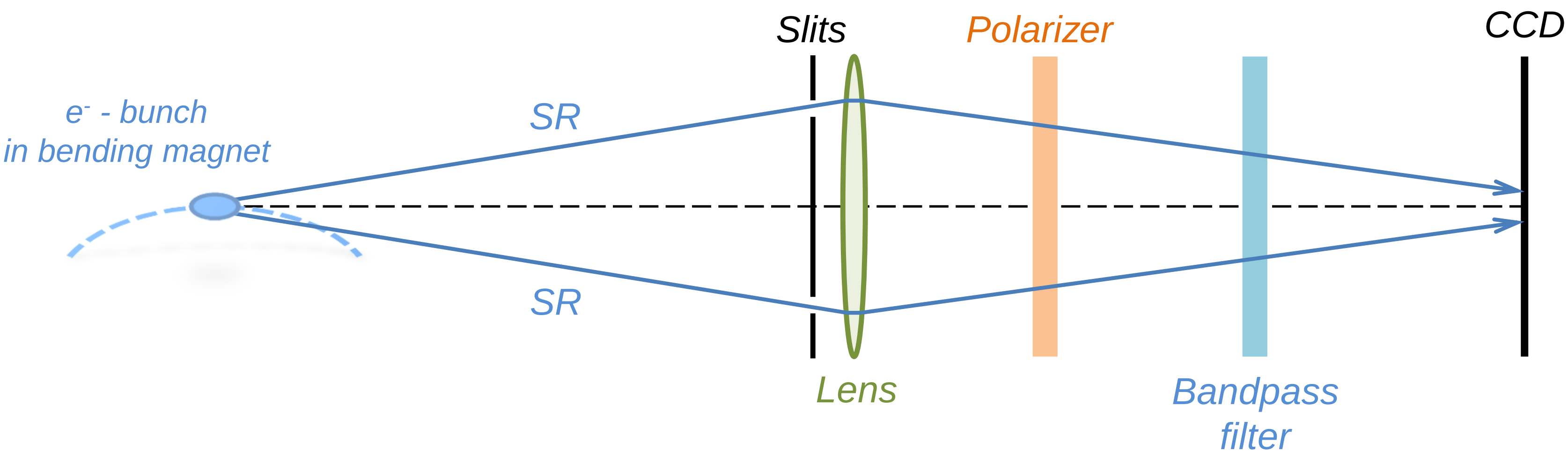
- Van Cittert-Zernike theorem :



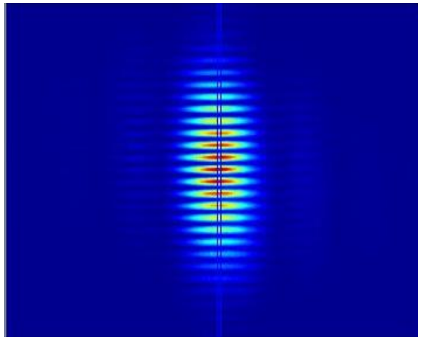
Beam size is inversely proportional to the visibility of the interferogram I_{min} / I_{max}

Electron ring – SR interferometry

- Interferometer and Interferogram:



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



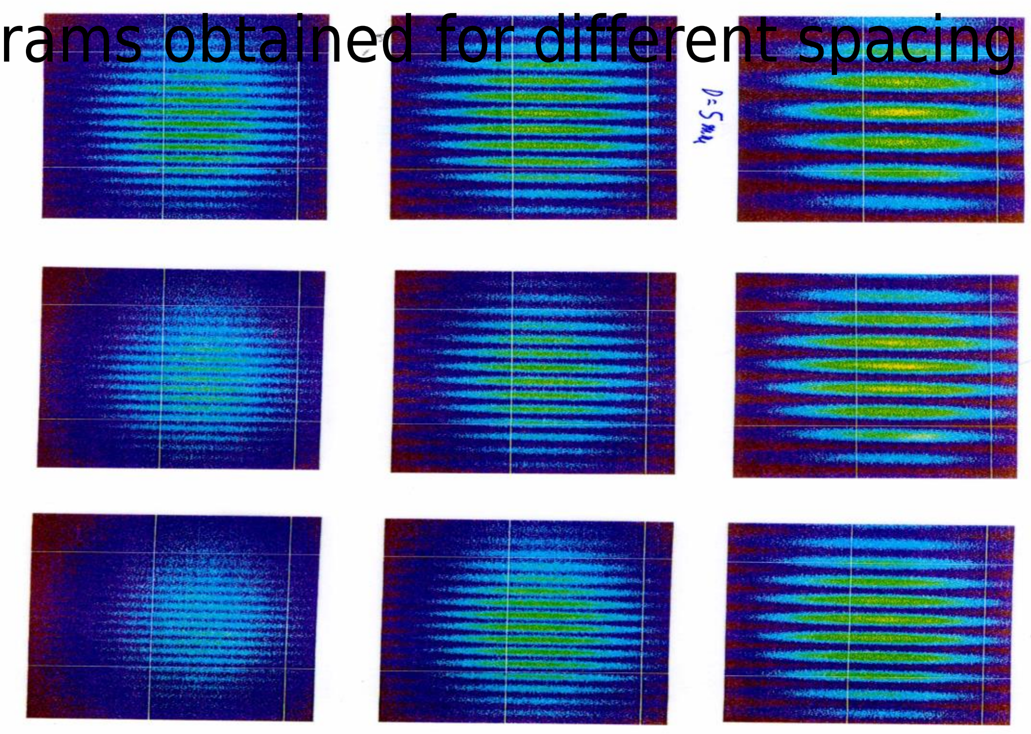
where a – half slit size, λ_0 – wavelength of SR, D – distance between slits, R – distance source– slits, γ – degree of spatial coherence. Getting the parameter γ from the fit one can recalculate it to the beam size

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

Electron ring – SR interferometry

- <u>Measurement of small beam size at ATF damping ring – KEK Japan:</u>

Interferograms obtained for different spacing between slits



Small spacing
High visibility

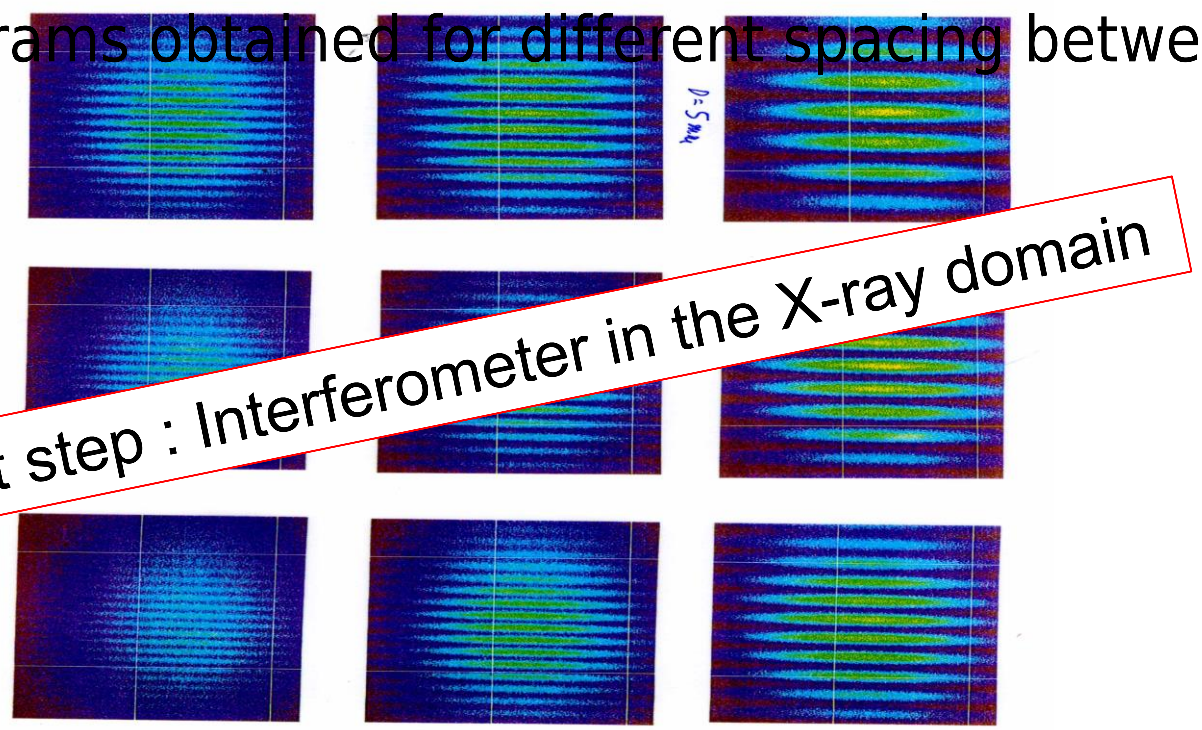
Large spacing
Low visibility

Beam size of 4um

Electron ring – SR interferometry

- Measurement of small beam size at ATF damping ring – KEK Japan:

Interferograms obtained for different spacing between slits



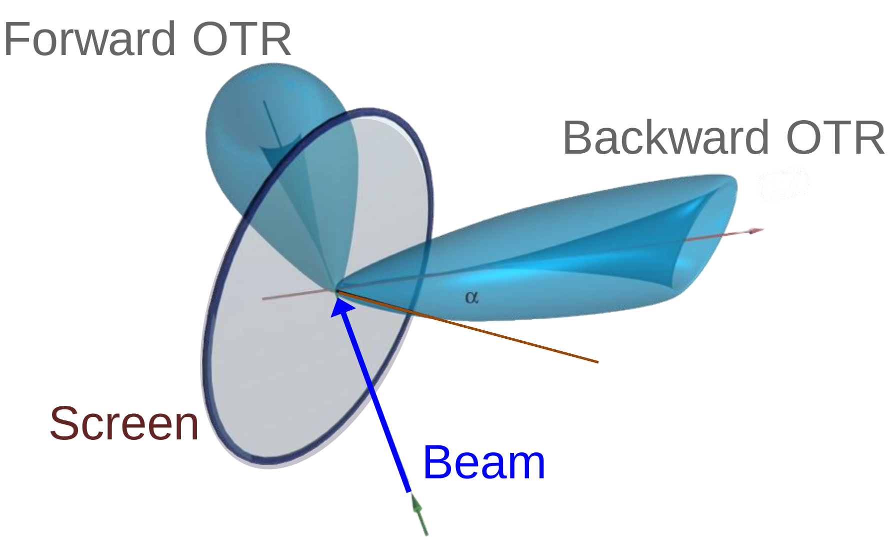
Beam size of 4um

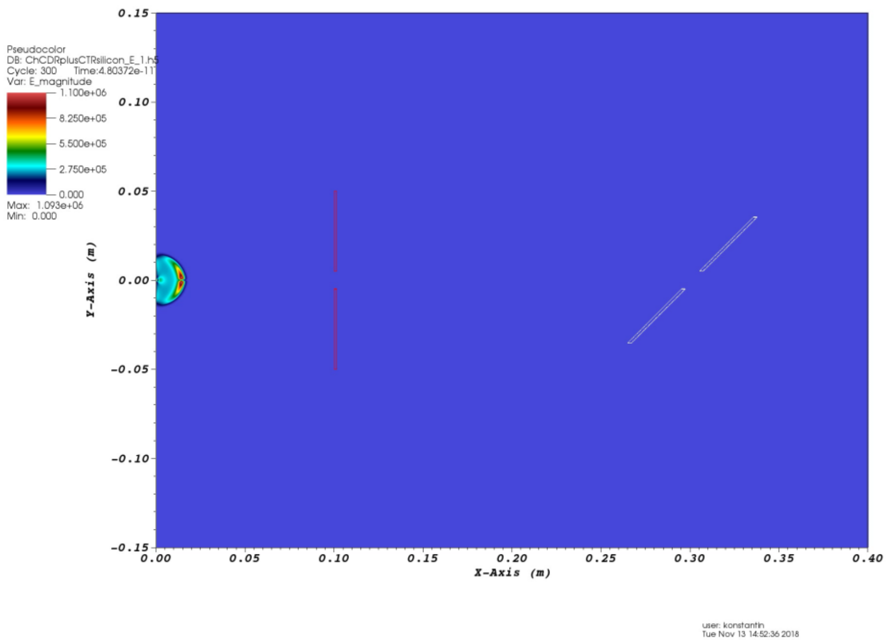
The CERN Accelerator School

Transverse Diagnostics in Electron LINAC

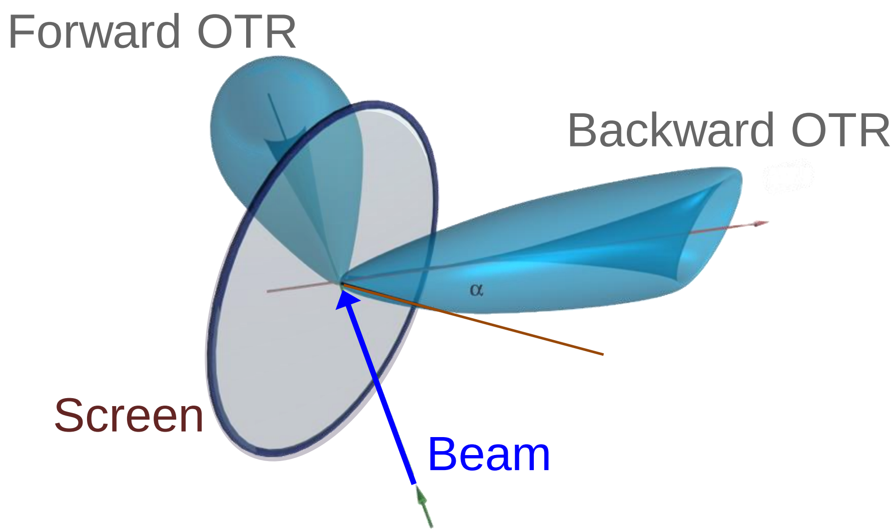
Electron Linac – Transition Radiation

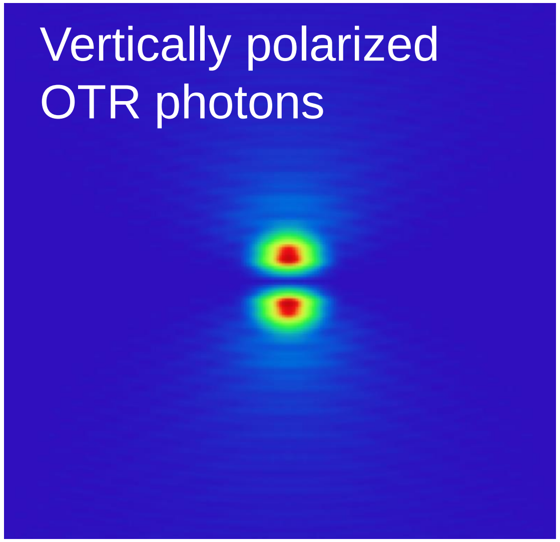
As predicted in 1946 by Frank and Ginzburg, **Transition Radiation** is a broadband electromagnetic field emitted by a relativistic charged particle when it crosses boundary between two mediums of different dielectric constants.

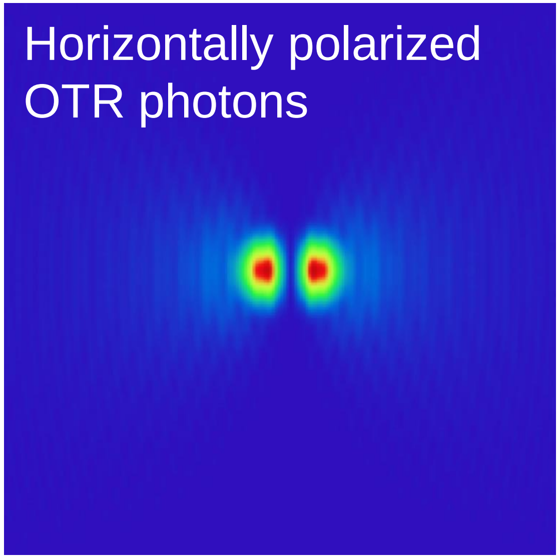




Electron Linac – Transition Radiation





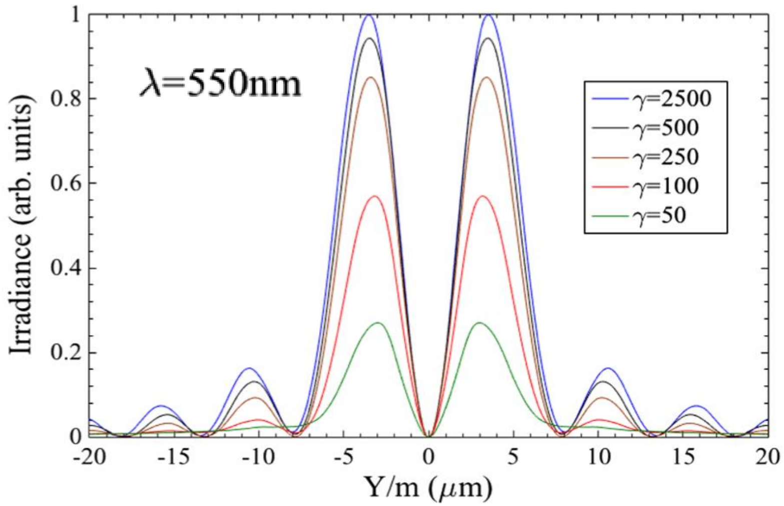


- The OTR field is **radially polarized.**
- Approximation* of the electric field distribution for the **OTR vertical polarization component** induced by a single electron on the target surface (x,y).

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

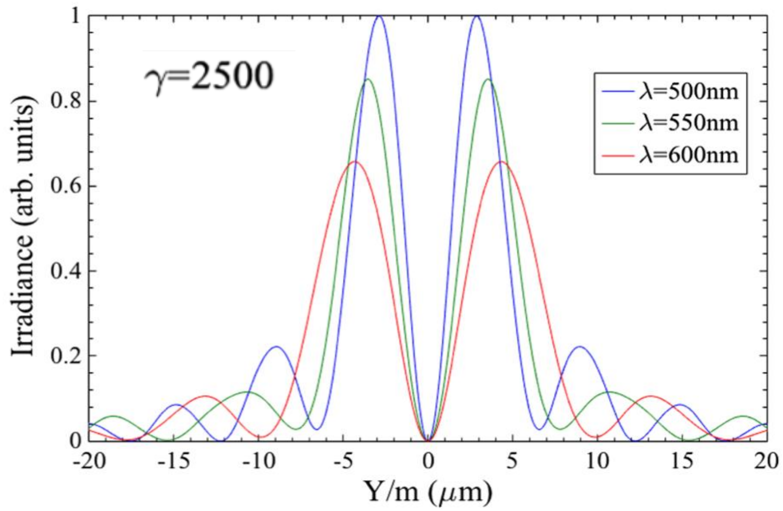
$$\mathrm{Im}(E_y) = 0$$

Single particle OTR field distribution at the surface of the screen



The number of photons is increasing with energy

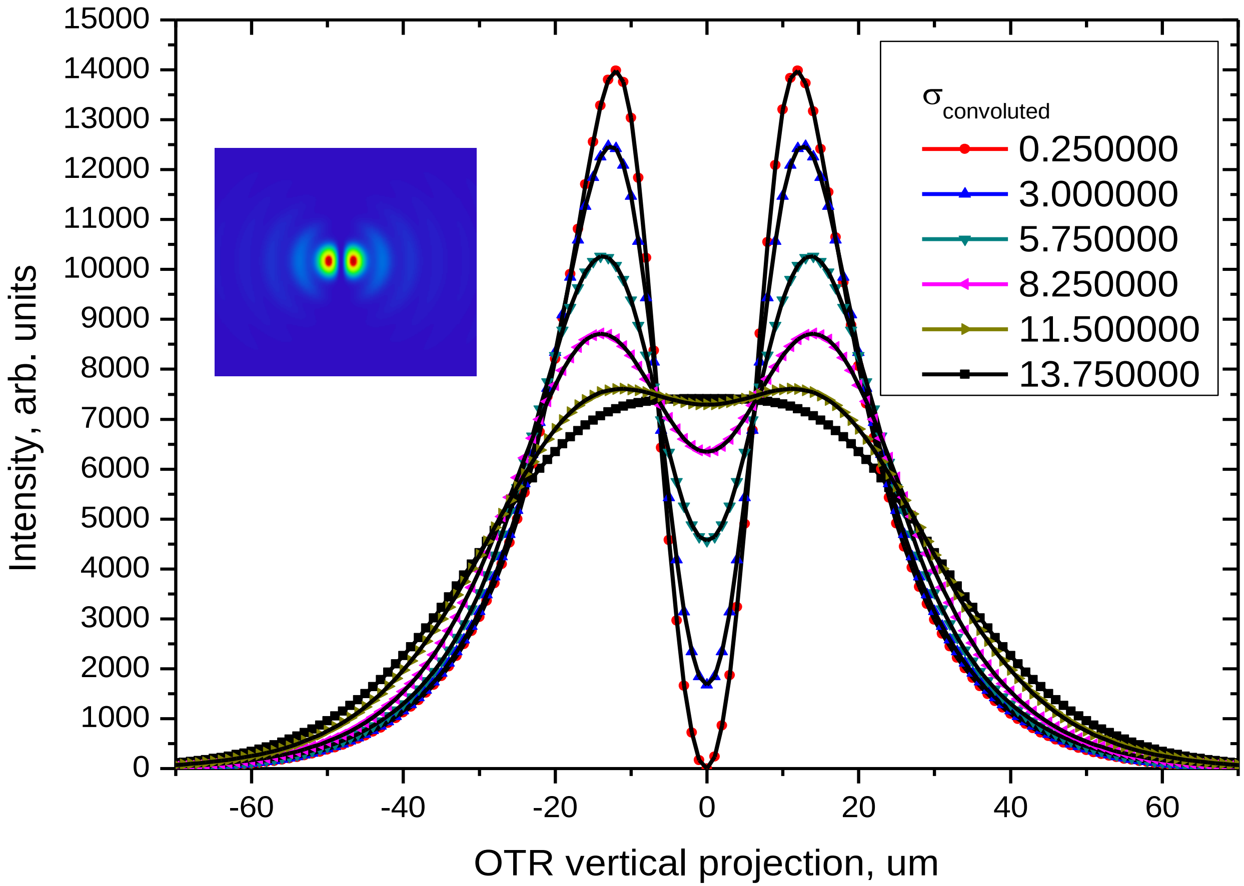
$$N_{OTR} = \frac{2\alpha}{\pi}\left[\left(\beta + \frac{1}{\beta}\right)\cdot \ln\left(\frac{1+\beta}{1-\beta}\right) - 2\right]\ln\left(\frac{\lambda_b}{\lambda_a}\right)$$



The width of field distribution is wavelength dependent

Electron Linac – Transition Radiation

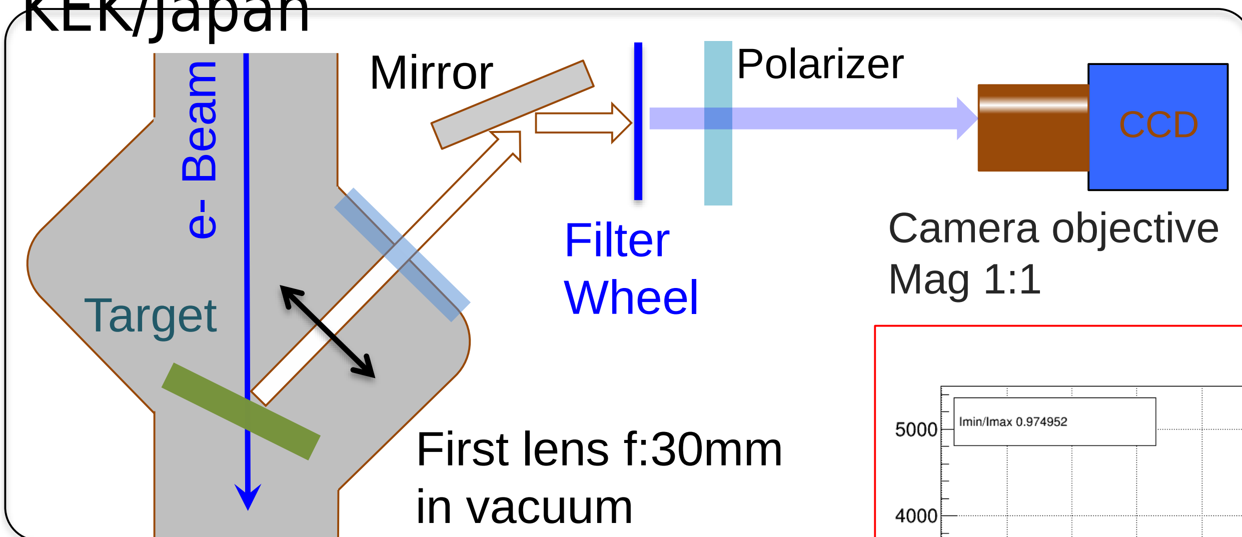
Very small beam size measuring using the visibility of the OTR Point(Particle) Spread Function

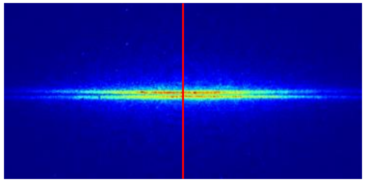


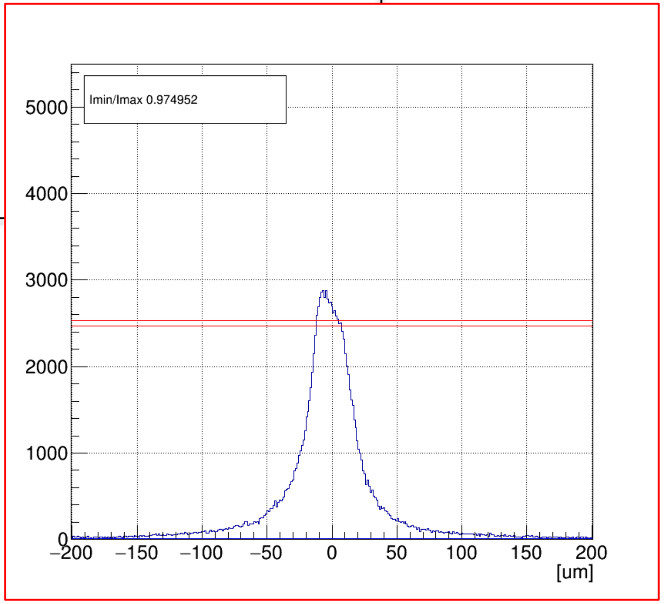
P. Karataev et al., PRL ***107****, 174801 (2011)*

Electron Linac – Transition Radiation

Sub-micron resolution (σ = 0.7um) demonstrated at ATF2 – KEK/Japan



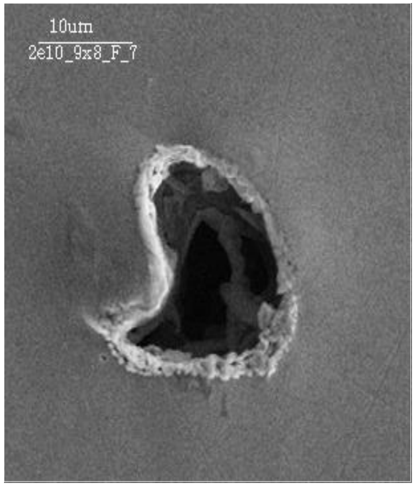


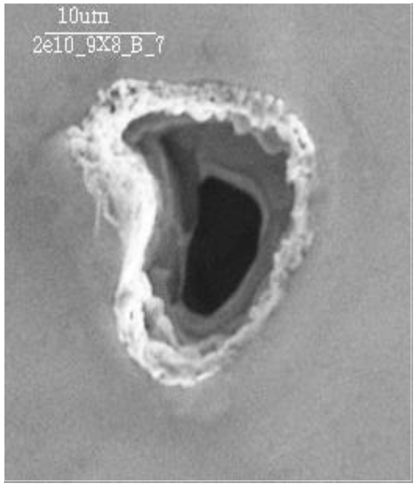


R. Bolzon et al. PRSATB 18 082803 (2015)

Electron Linac – Transition Radiation

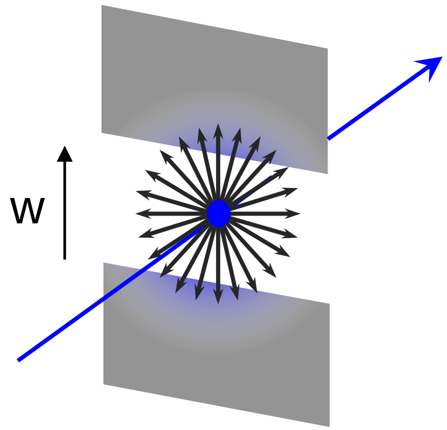
OTR, It 's all good but….



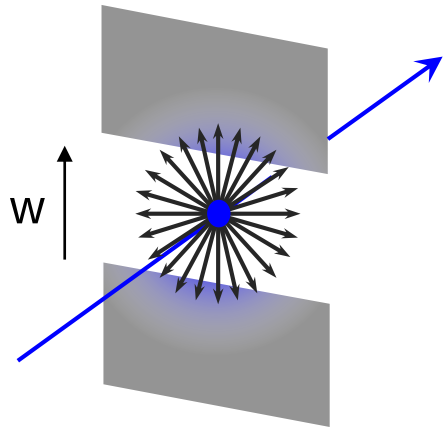


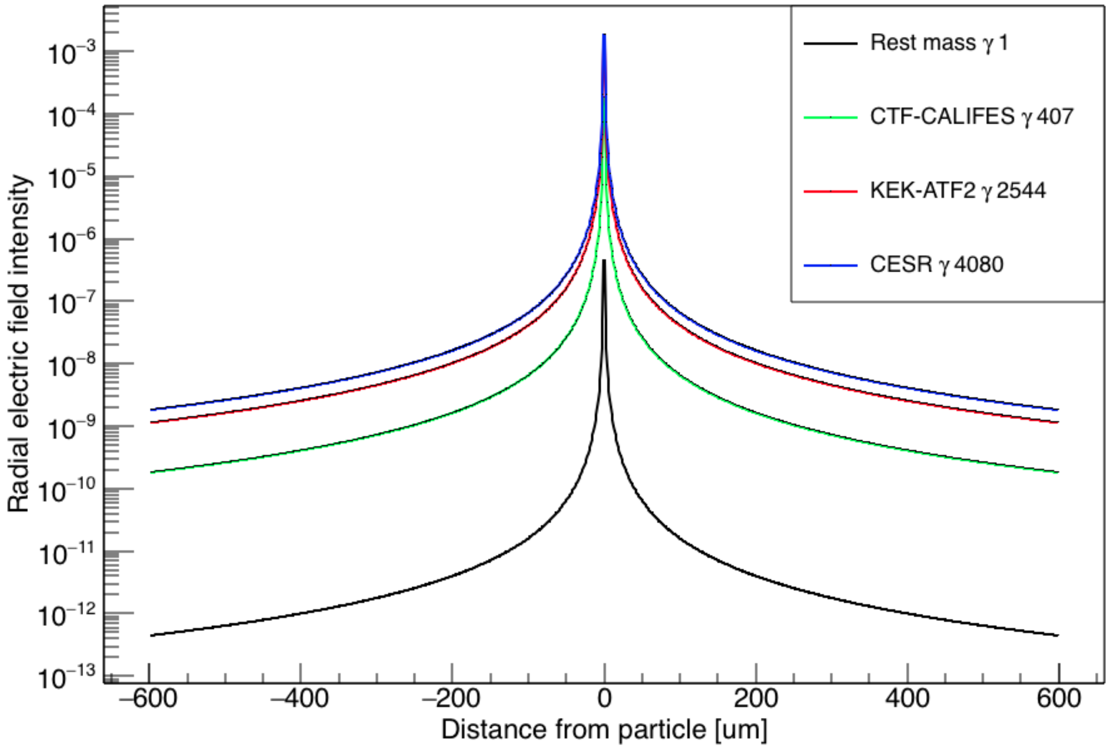
Electron Linac – Diffraction Radiation

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



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





Electron Linac – Diffraction Radiation

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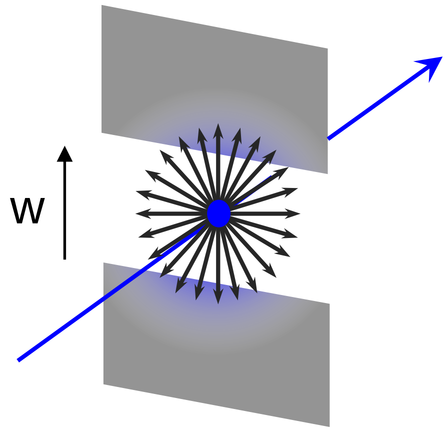
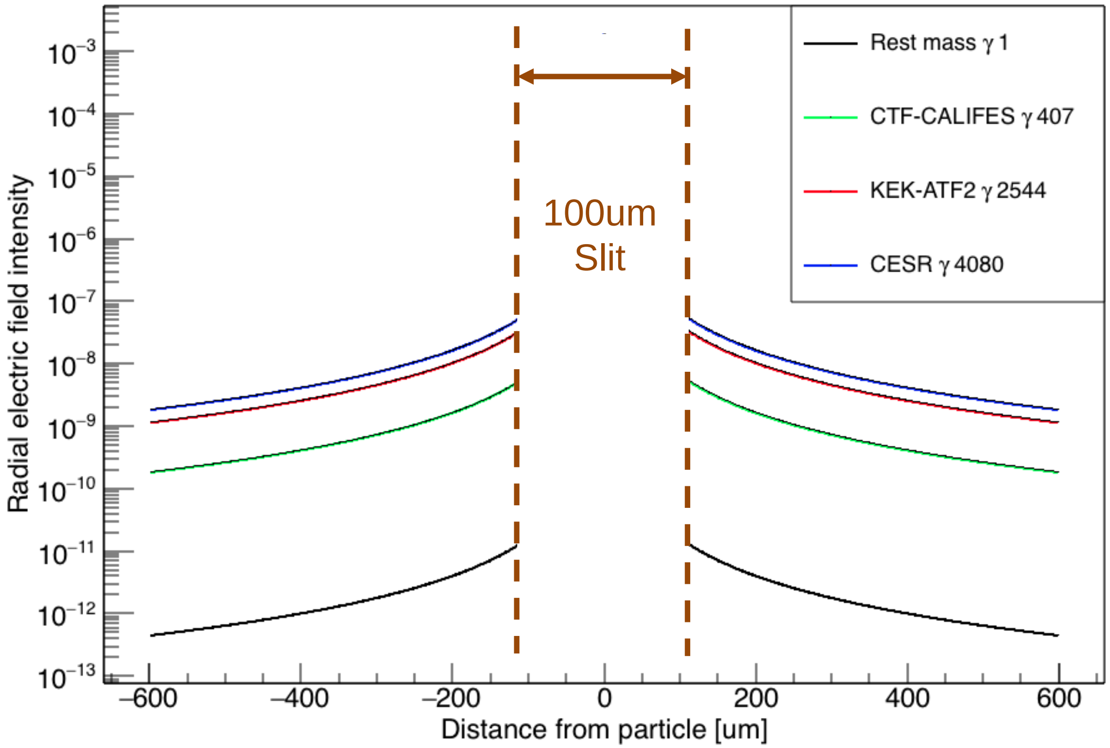
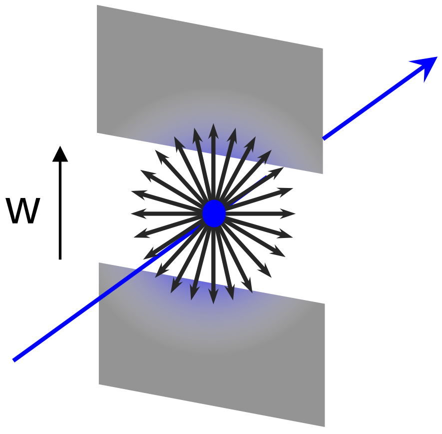
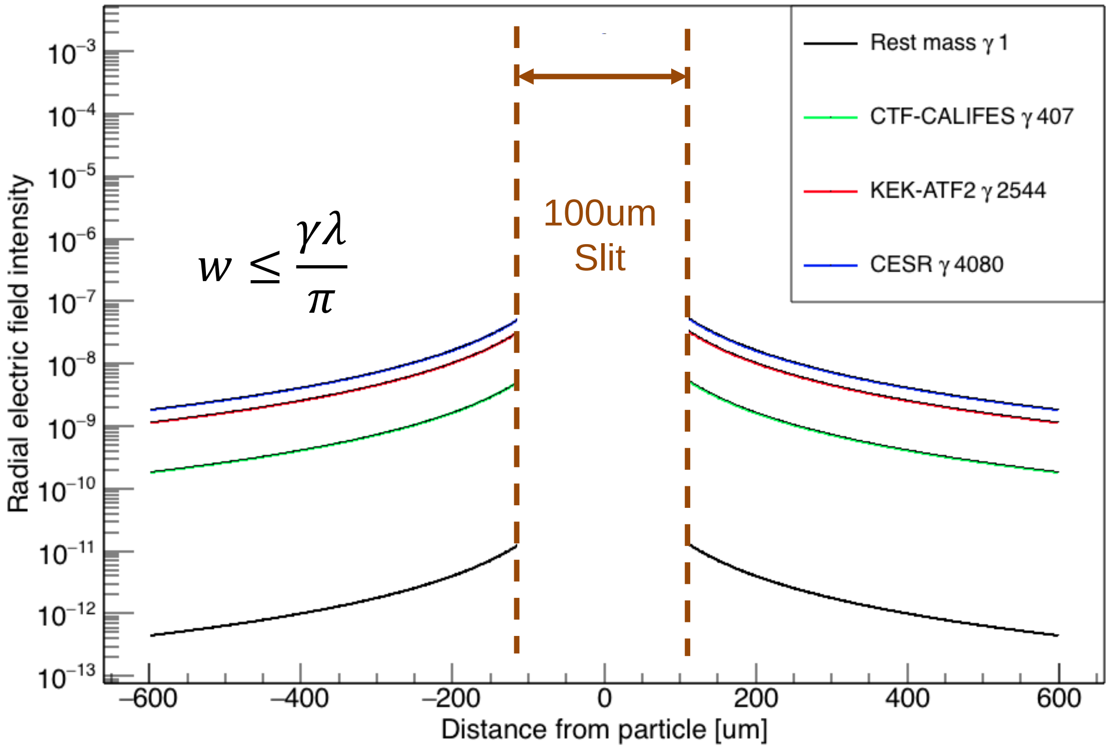




Electron Linac – Diffraction Radiation

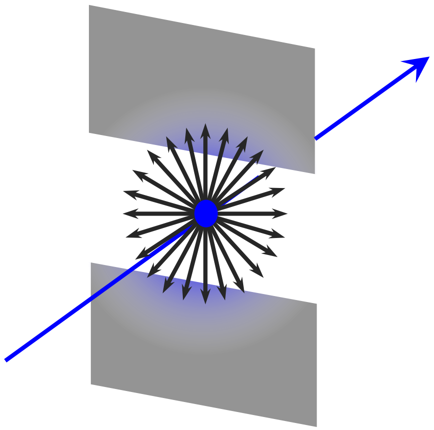
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slit**



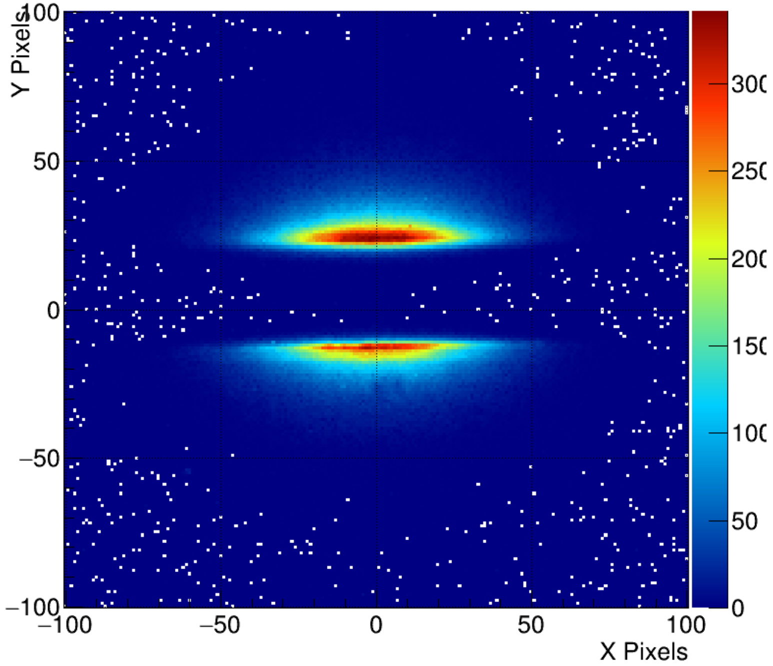


Electron Linac – Diffraction Radiation

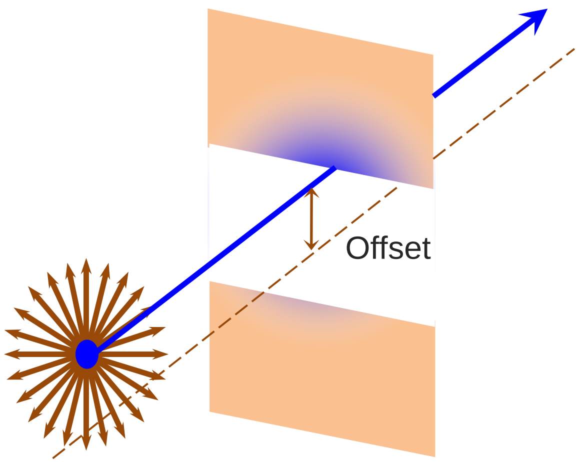
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**

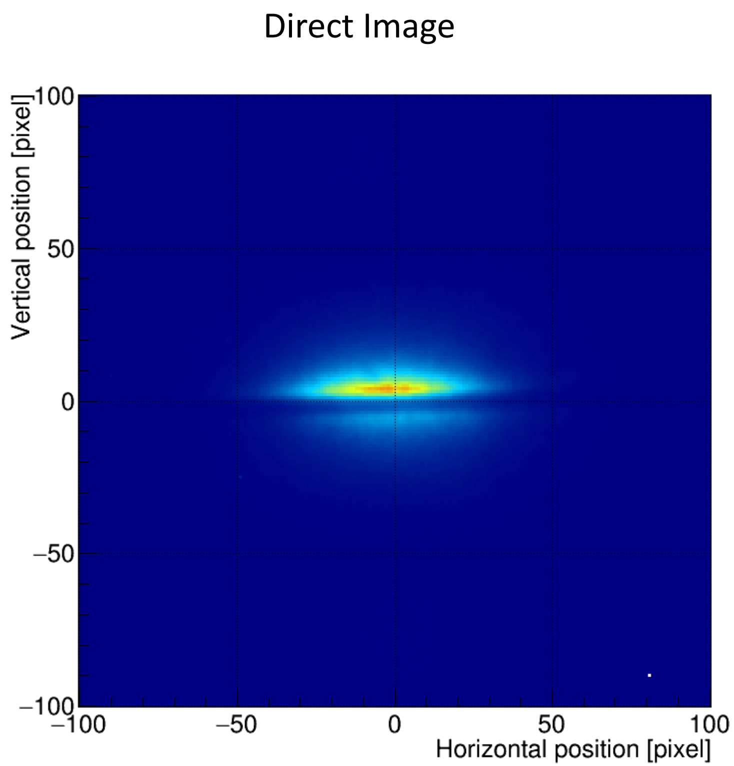


Direct Image

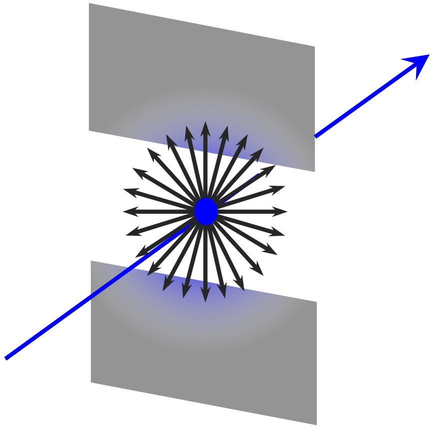


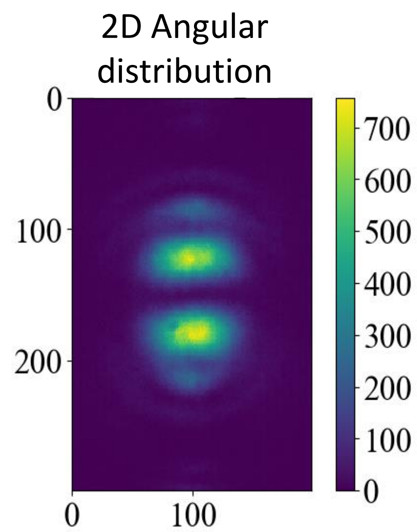
- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**

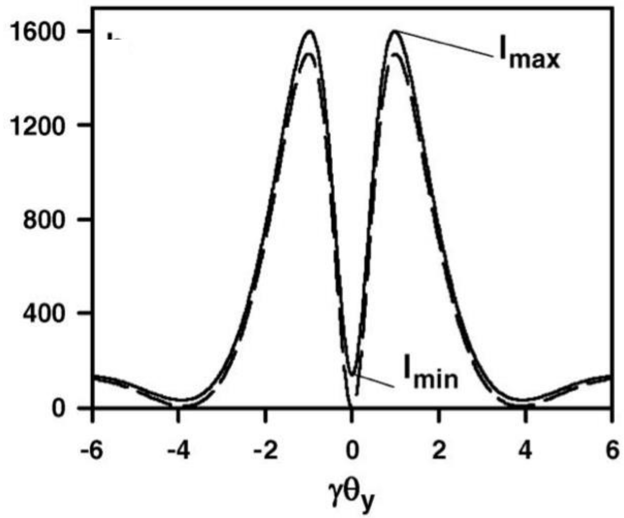




- Non-invasive beam size measurements using **Optical diffraction radiation from thin dielectric slits**





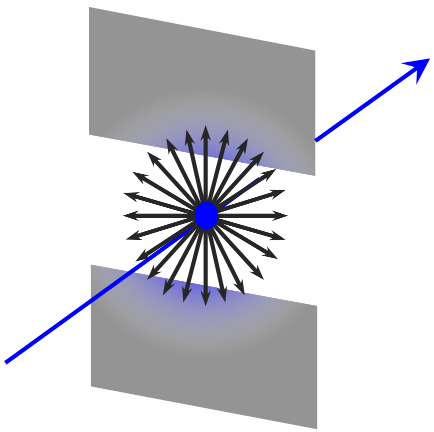


The **beam size and beam divergence can be** extracted from the **visibility I_{min}/I_{max}** of the projected vertical component of the **ODR angular distribution**

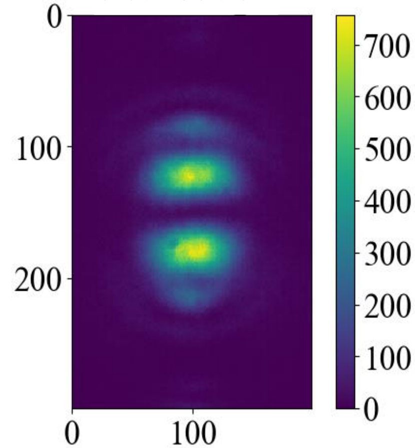
M. Castellano, Nucl. Instrum. Methods Phys. Res., Sect. A ***394****, 275 (1997)*

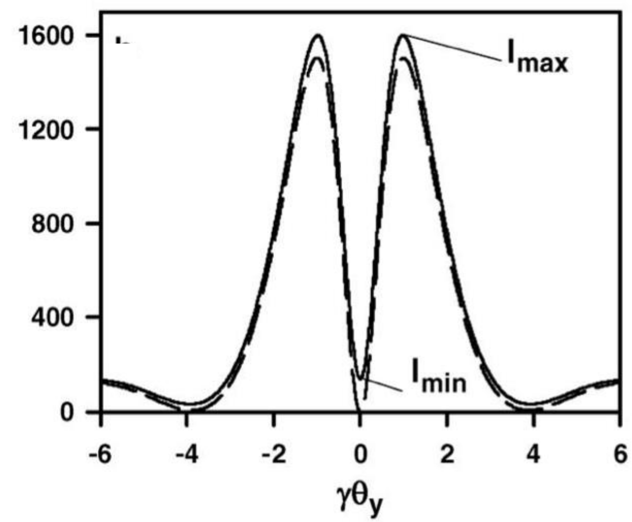
Electron Linac – Diffraction Radiation

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



2D Angular distribution



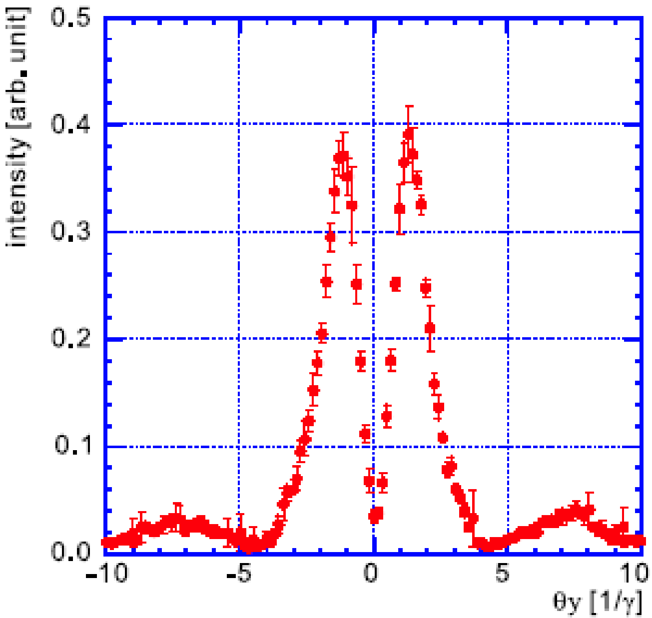


$$\frac{d^2W_y^{slit}}{d\omega d\Omega} = \frac{\alpha\gamma^2}{2\pi}\frac{e^{\left(-\frac{2a\pi\sin\theta_0}{\gamma\lambda}\sqrt{1+t_x^2}\right)}}{1+t_x^2+t_y^2}\left\{\exp\left[\frac{8\pi^2\sigma_y^2}{\lambda^2\gamma^2}\left(1+t_x^2\right)\right]\cosh\left[-\frac{4\bar{a}\pi}{\gamma\lambda}\sqrt{1+t_x^2}\right]-\cos\left[\frac{2a\pi\sin\theta_0}{\gamma\lambda}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

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

Electron Linac – Diffraction Radiation

- First Measurements at KEK (Linear collider study)



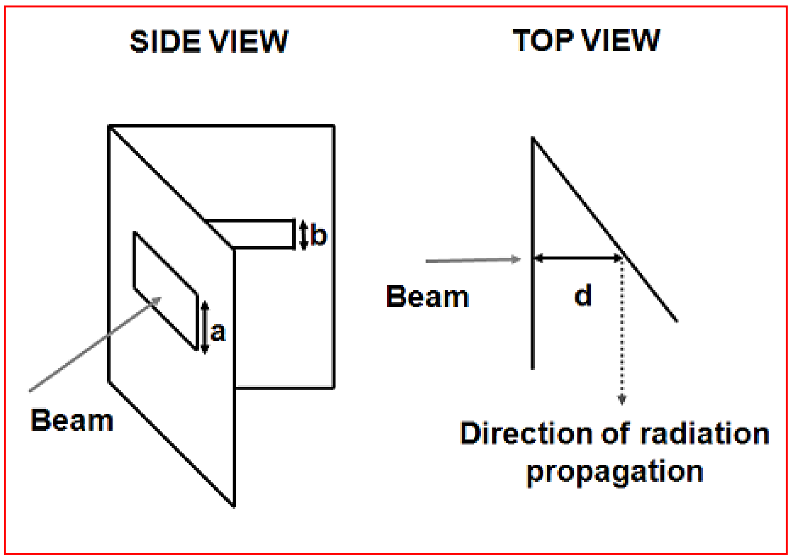
P. Karataev et al., "*Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility*", Phys. Rev. Lett. 93, 244802 (2004)

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

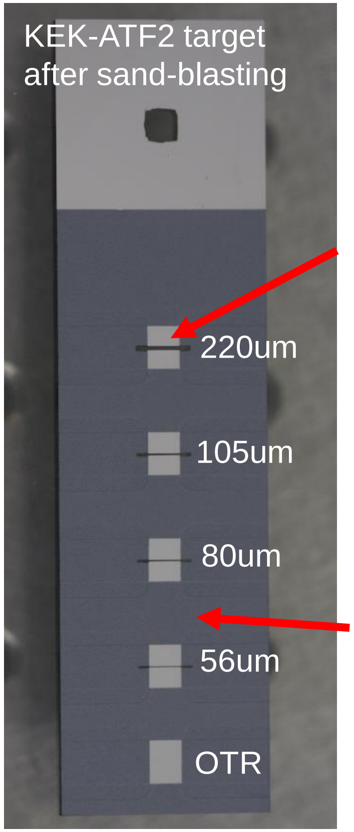
Electron Linac – Diffraction Radiation

- Optimisation on Target manufacturing and SR background suppression

Adding a Mask in front of the slit



A. Cianchi et al. PRSTAB 14, 102803 (2011)



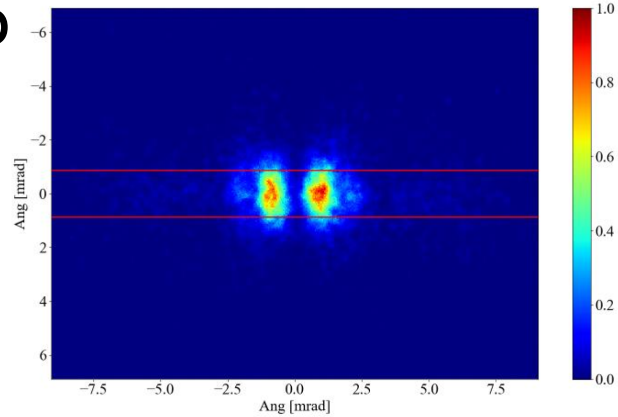
Maximizing emission of DR with Al coating around the slit

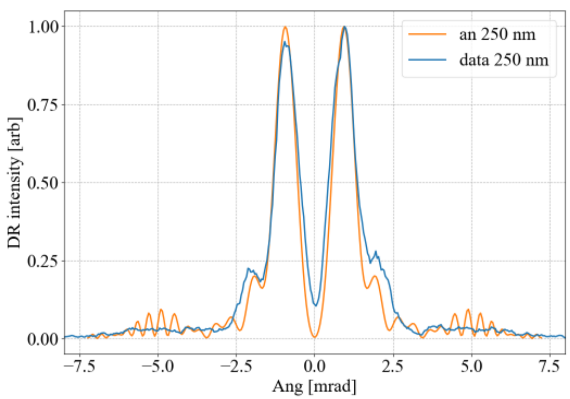
Minimizing reflection of SR by sand-blasting the rest of the target

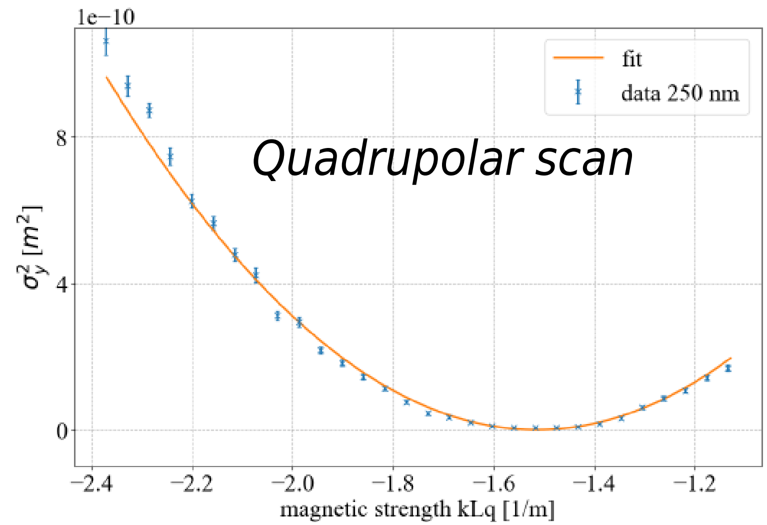
R. Kieffer et al. NIMB 402 88 (2018)

Electron Linac – Diffraction Radiation

- Small beam size of 3um measured using UV light at 25







Electron Linac – Diffraction Radiation

ODR, It ‘s good but….

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

Electron Linac – Diffraction Radiation

ODR, It 's good but....

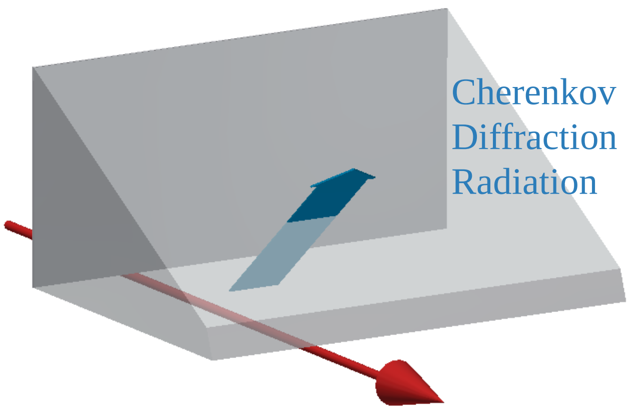
- Looking for higher light yield !
- Getting rid of Synchrotron radiation background

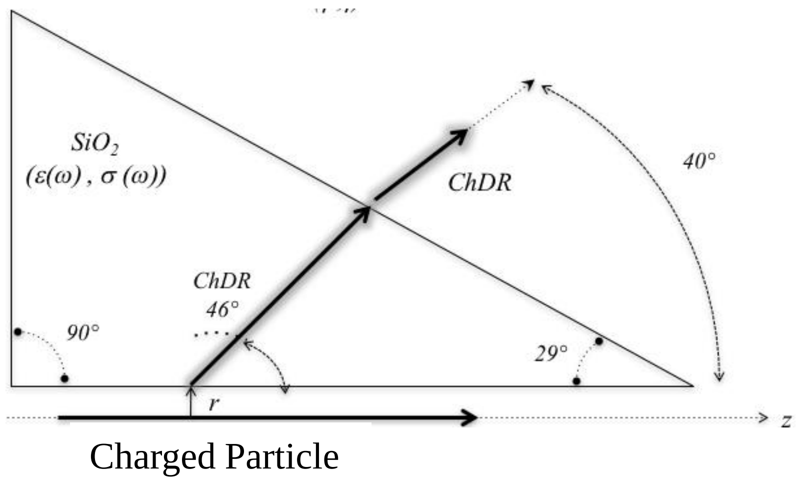
Cherenkov diffraction radiation in longer dielectrics

Electron Linac – Cherenkov Diffraction Radiation

- Cherenkov Diffraction Radiation in dielectrics

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



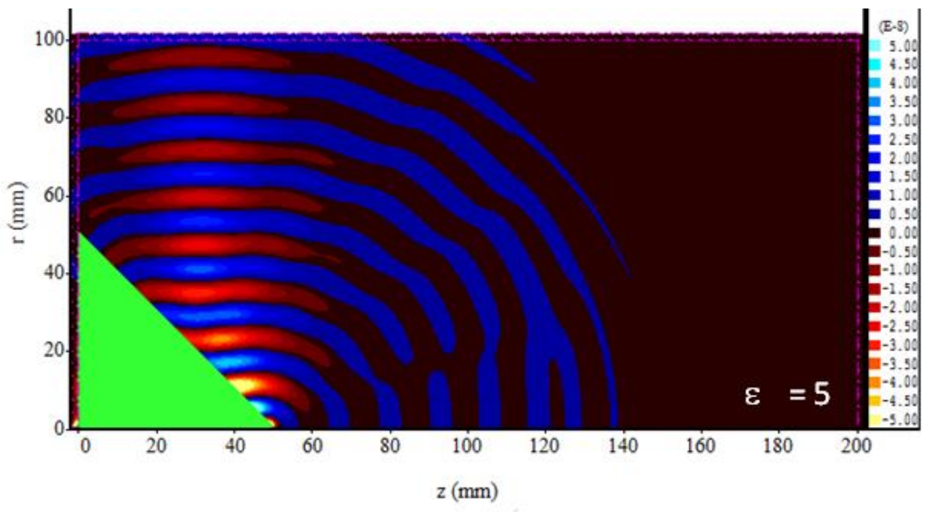


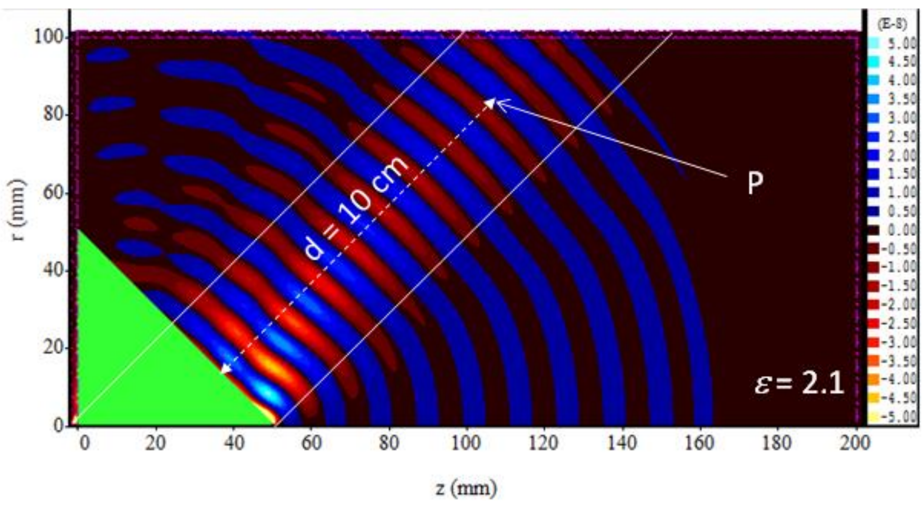
The total number of photons proportional to the length of the Cherenkov radiator

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

Electron Linac – Cherenkov Diffraction Radiation

- Cherenkov Diffraction Radiation in dielectrics

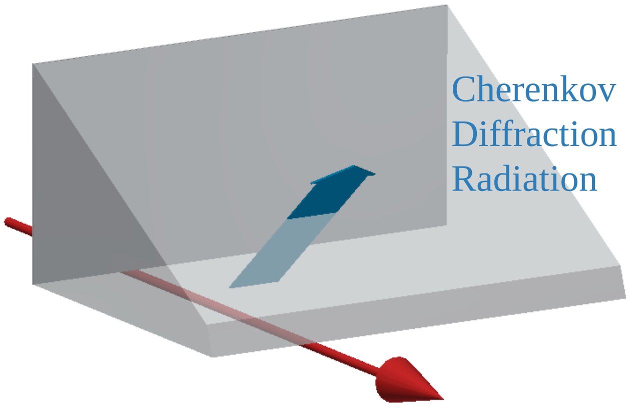


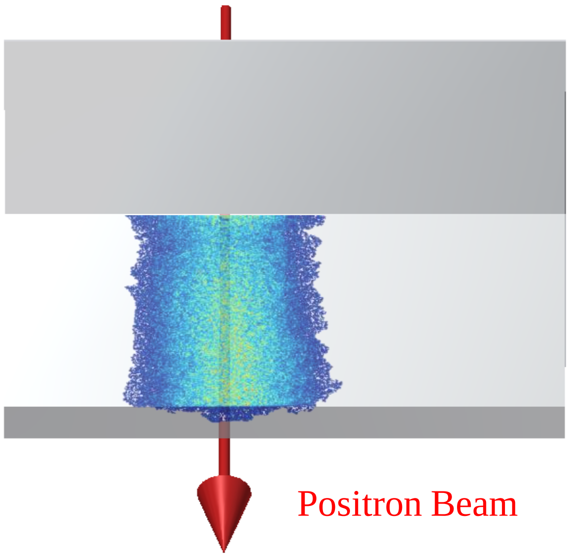


Simulations using Magic

Electron Linac – Cherenkov Diffraction Radiation

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



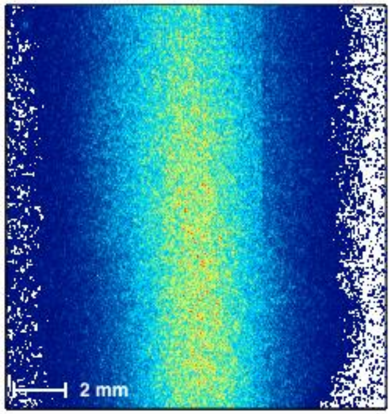


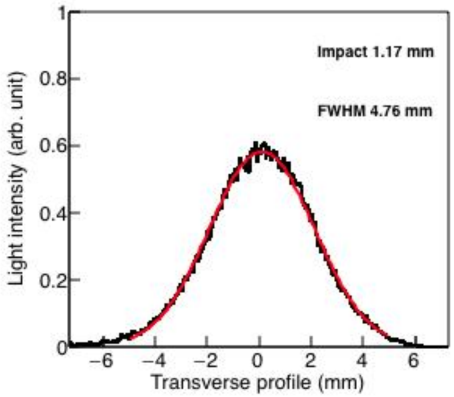
R. Kieffer et al., "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL ***121*** *(2018) 054802*

Electron Linac – Cherenkov Diffraction Radiation

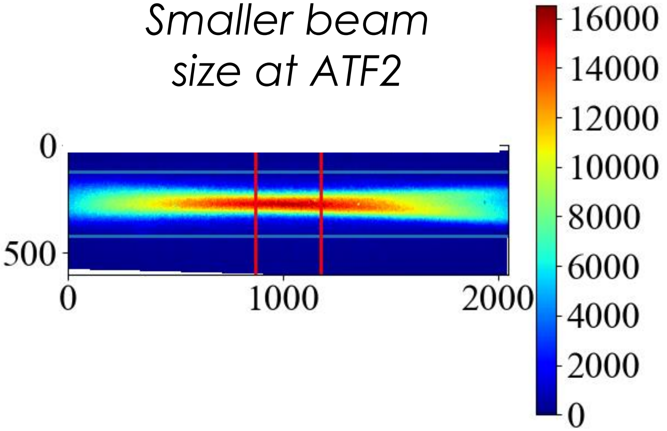
- Measuring beam size using ChDR

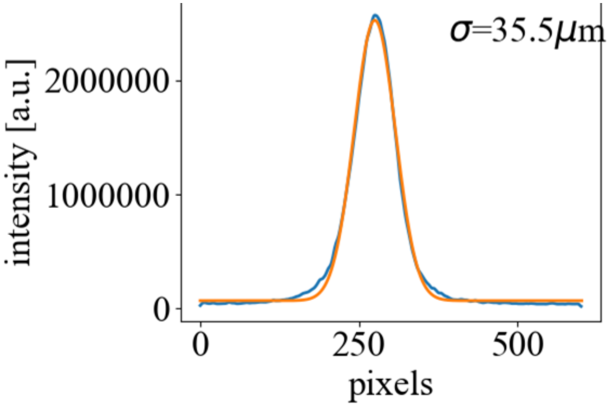
Large beam size at Cornell





Smaller beam size at ATF2

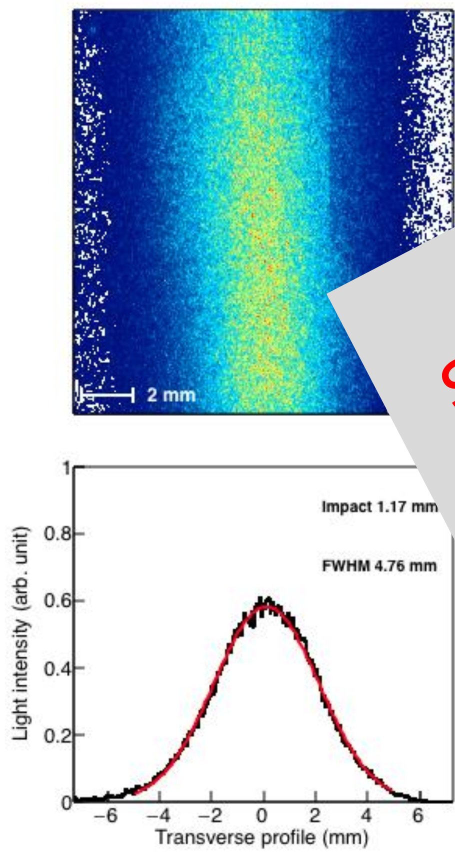




Electron Linac – Cherenkov Diffraction Radiation

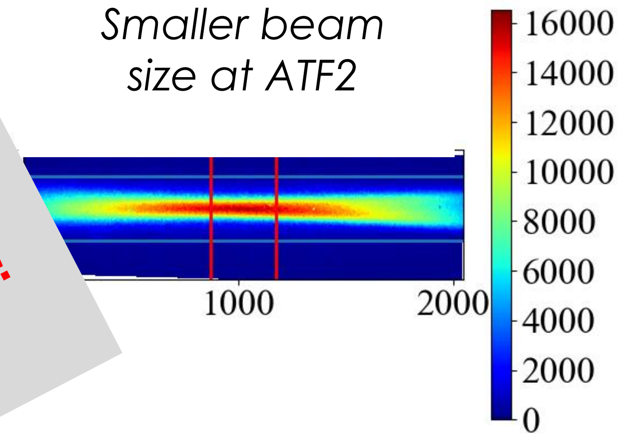
- Measuring beam size using ChDR

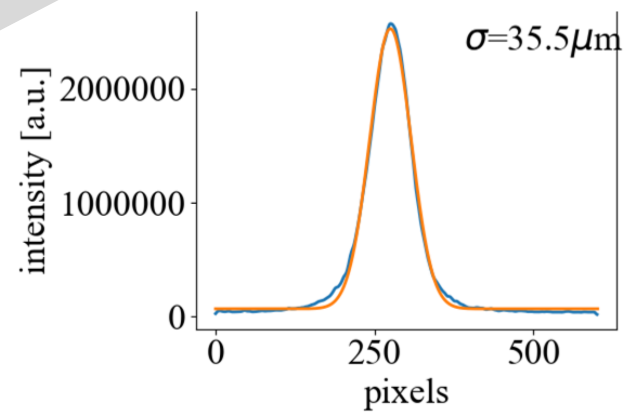
Large beam size at Cornell



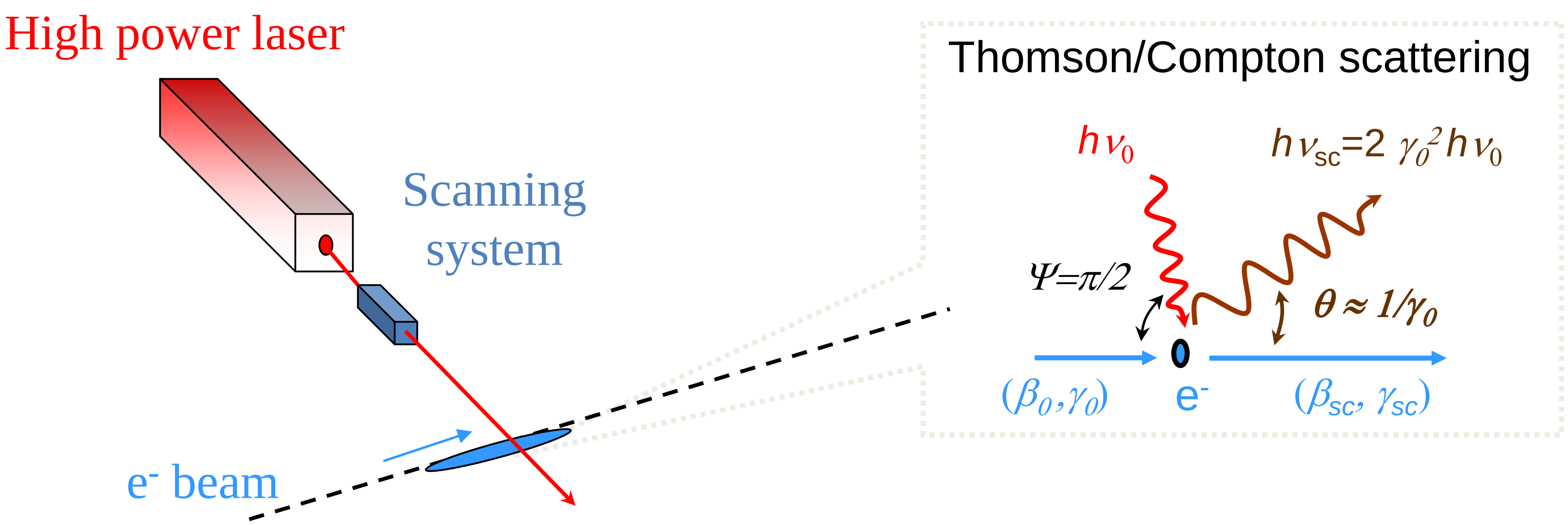
Still preliminary !

Smaller beam size at ATF2

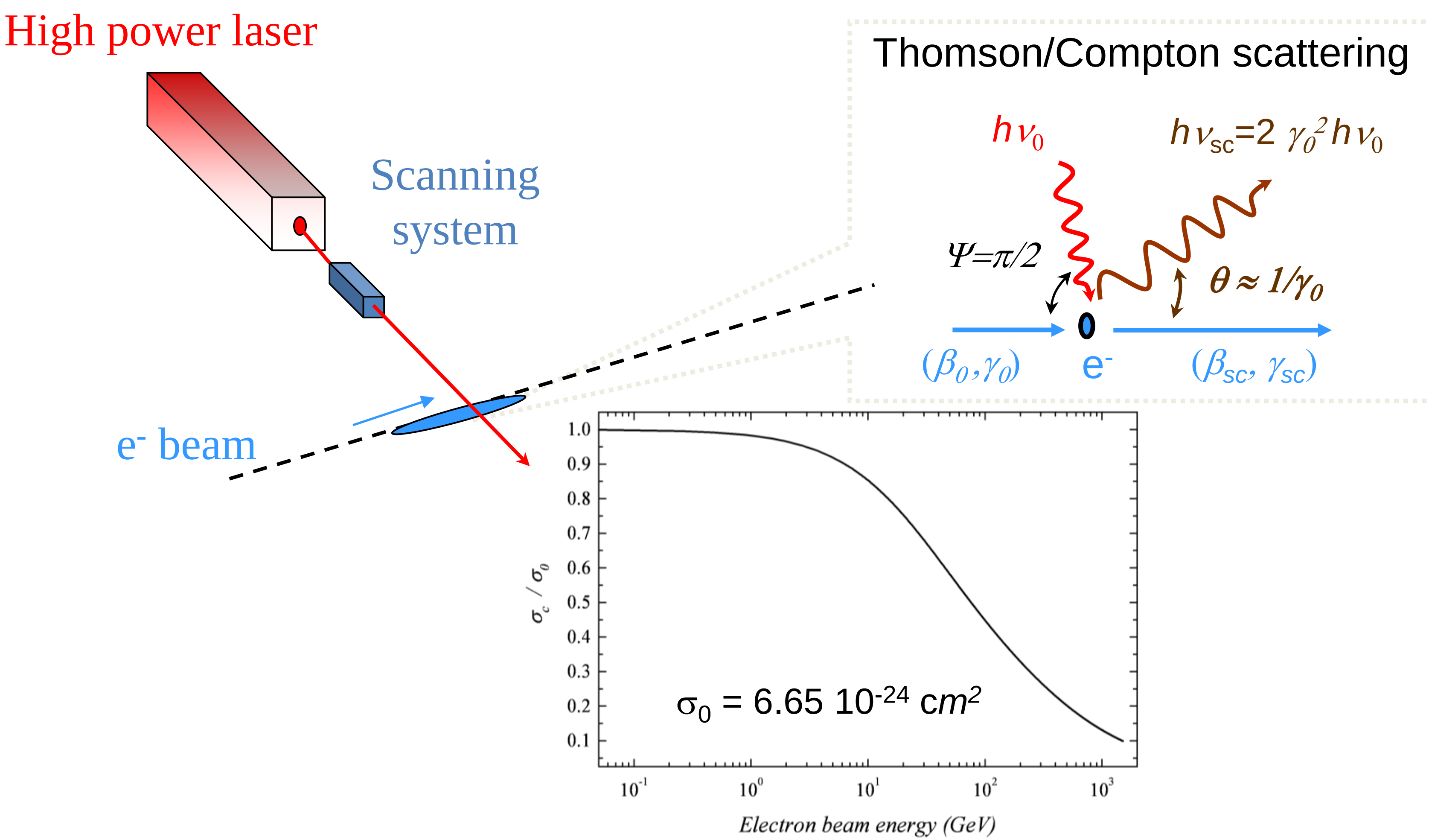




Electron Linac – Laser Wire Scanner

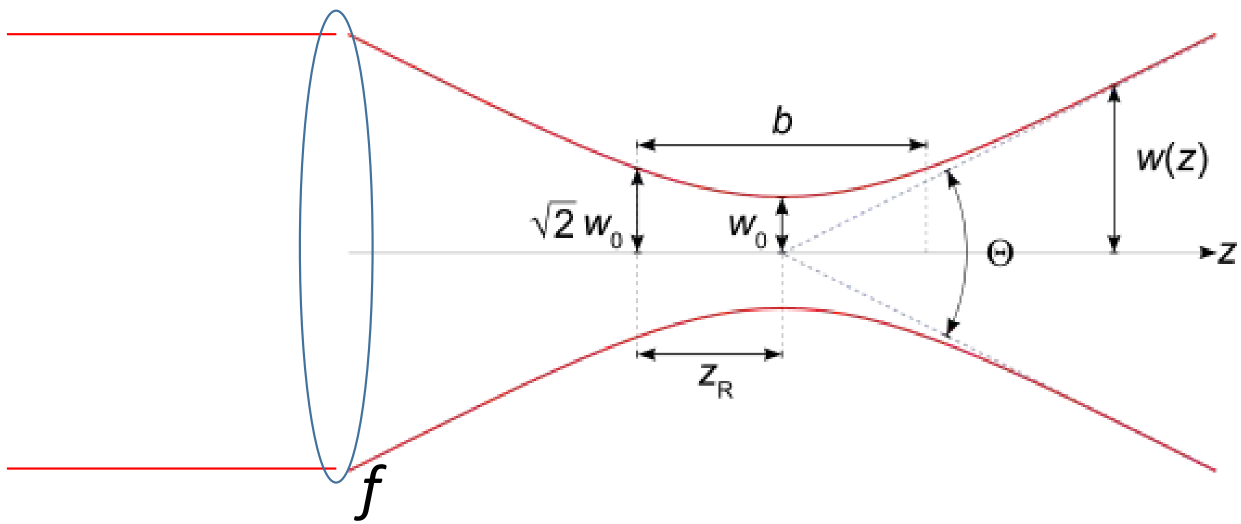


Electron Linac – Laser Wire Scanner



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

Electron Linac – Laser Wire Scanner



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)

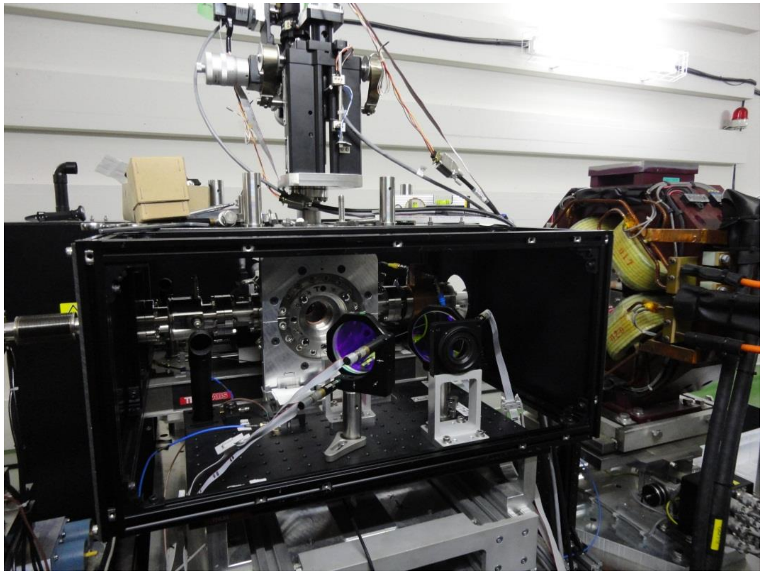
Electron Linac – Laser Wire Scanner

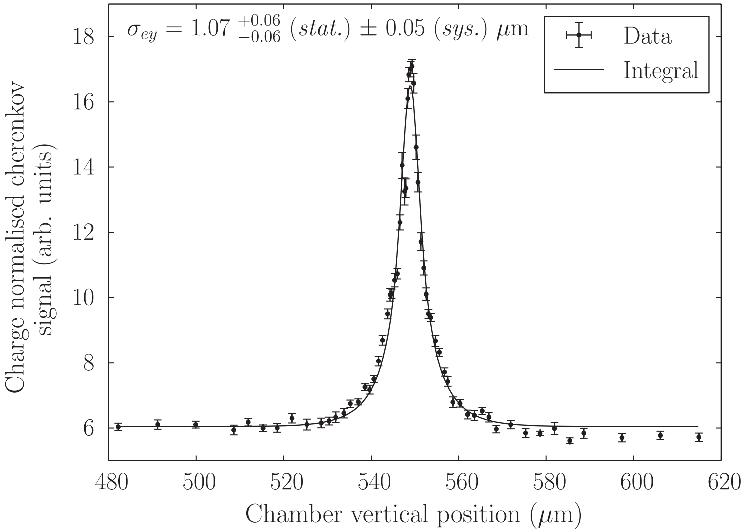
- First tests at SLAC in 90's

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)





Electron Linac – Laser Wire Scanner

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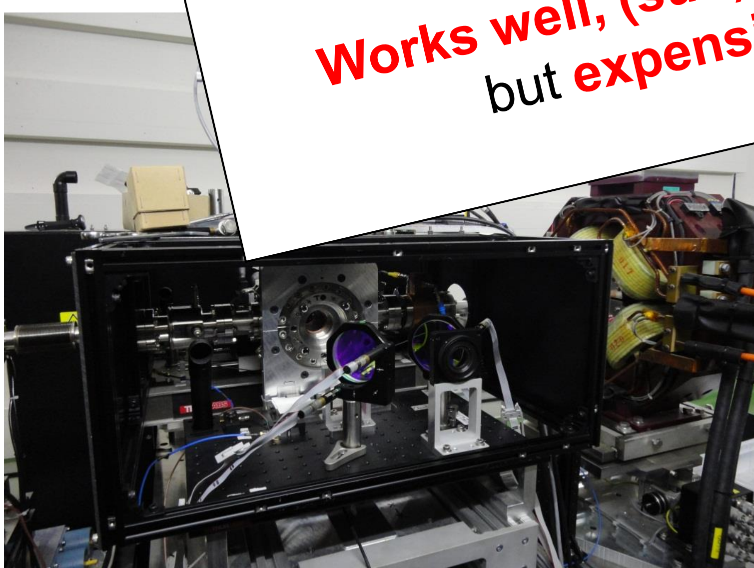
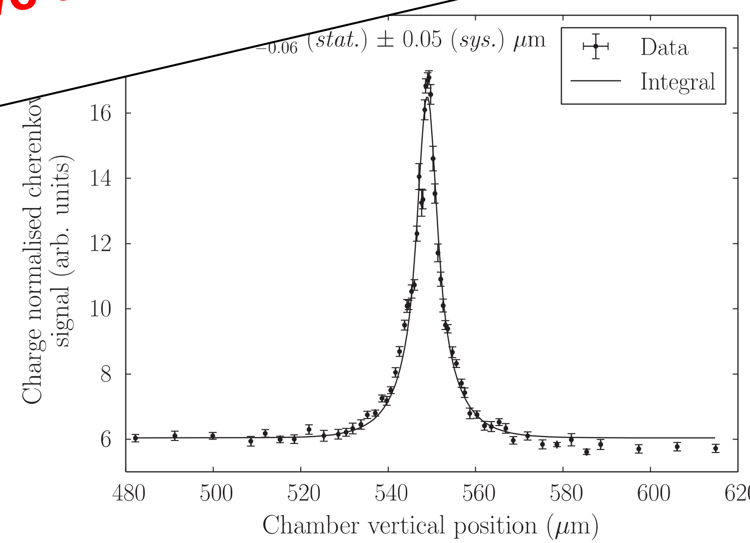
H. Sakai *et al.*, Physical Review ST AB 4 (2001) 022801 ...
I. Agapov, G. A. Blair, M. Woodley, Physical R...
S. T. Boogert *et al.*, Physical Rev...

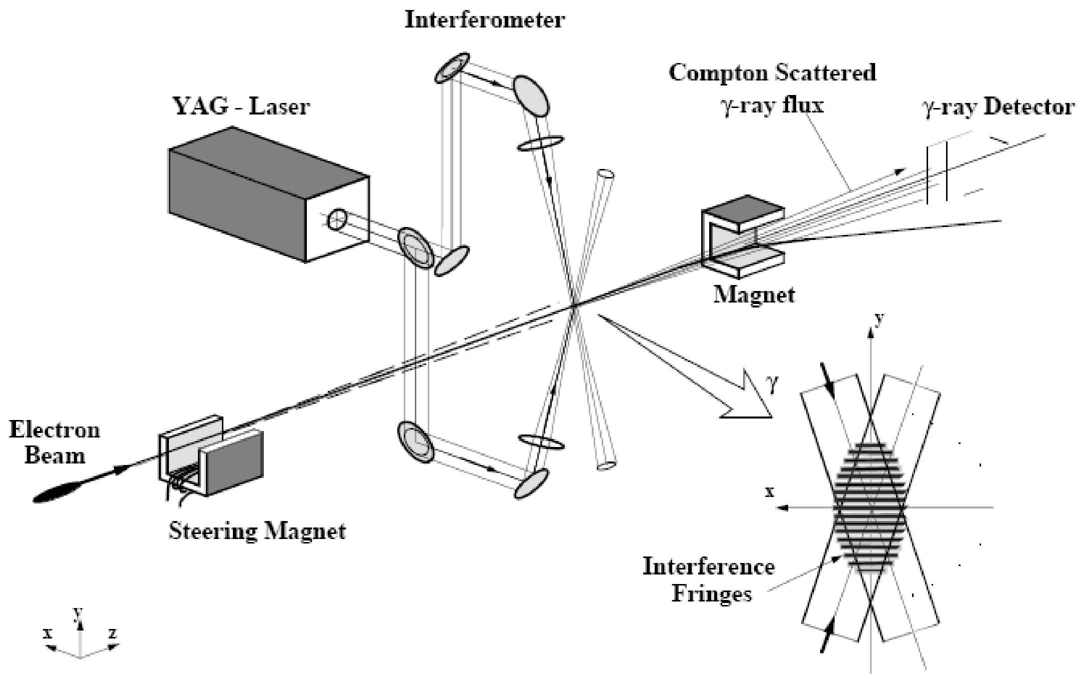
Works well, (sub)micron resolution but expensive and complex





Electron Linac – 'Shintake monitor'

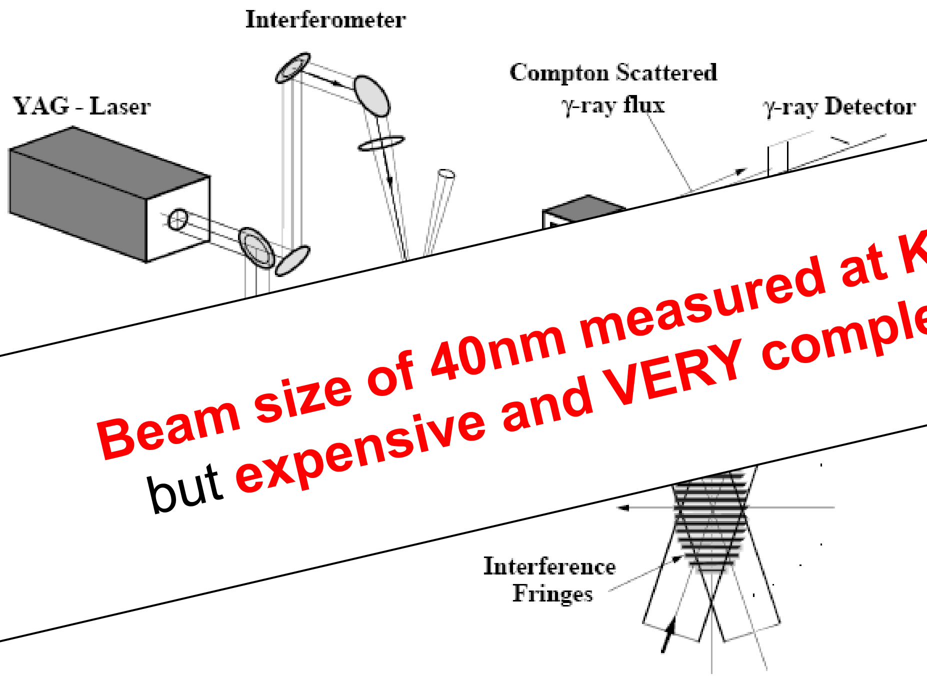
- Measuring nanometer beam size



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 beam demands particular diagnostics techniques in order to measure very small transverse emittance (<1 mm-mrad)
- Not-intercepting diagnostics are recommended in most cases
- Some diagnostics are already state of the art
- Some others are still on-development developing
- An exciting field!

- Thank you for your attention, and be ready for the Longitudinal diagnostics tomorrow !

Extra slides

Spectral Brightness for photons

$$B = \frac{d^4 N}{dt d\Omega dS d\lambda / \lambda}$$

Photons/ (s mm^2 mrad^2 0.1% of bandwidth)

- The term '**spectral brightness**' best describes a photon source, i.e. the **intensity** per unit source **size** and **divergence** in a given **bandwidth**
- J. Synchrotron Rad. (2005). 12, 385

High brightness beams

Machine	ESS	LHC	FCC-hh	DLS	FCC-ee	CLIC
Particle type	H^+	H^+	H^+	e^-	e^-	e^-
Energy (GeV)	2	7000	50000	3	45	1500
Intensity (mA)	62.5	600	500	500	1450	
Rep. rate (Hz)	14	-	-	-	-	50
Pulse length (ms)	2.86	-	-	-	-	0.0002
ε_{nx} / ε_{ny} (m.rad)	1 / 1	1.2 / 1.2	1.2 / 1.2	10 / 2.10^{-2}	10^{-4} / 10^{-6}	10^{-4} / 10^{-6}

The CERN Accelerator School

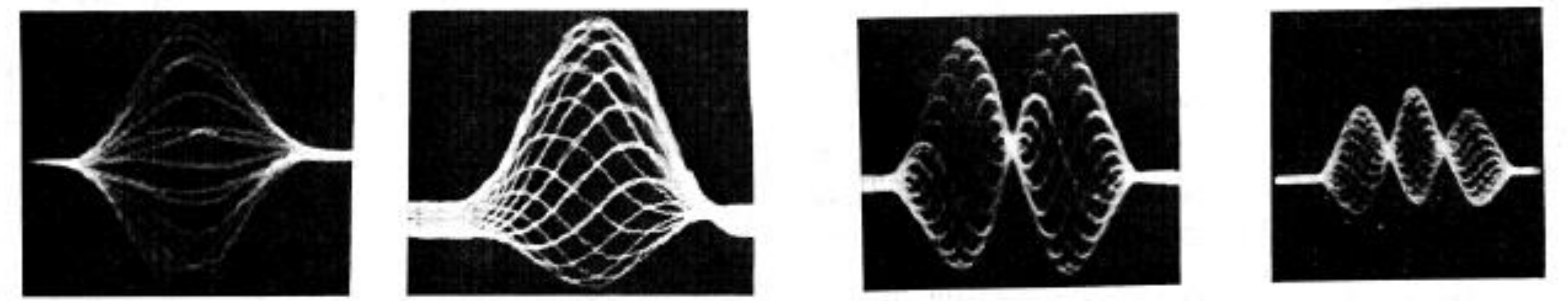
Transverse Diagnostics for measuring instabilities

Transverse instability monitoring

Collection from other lectures

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

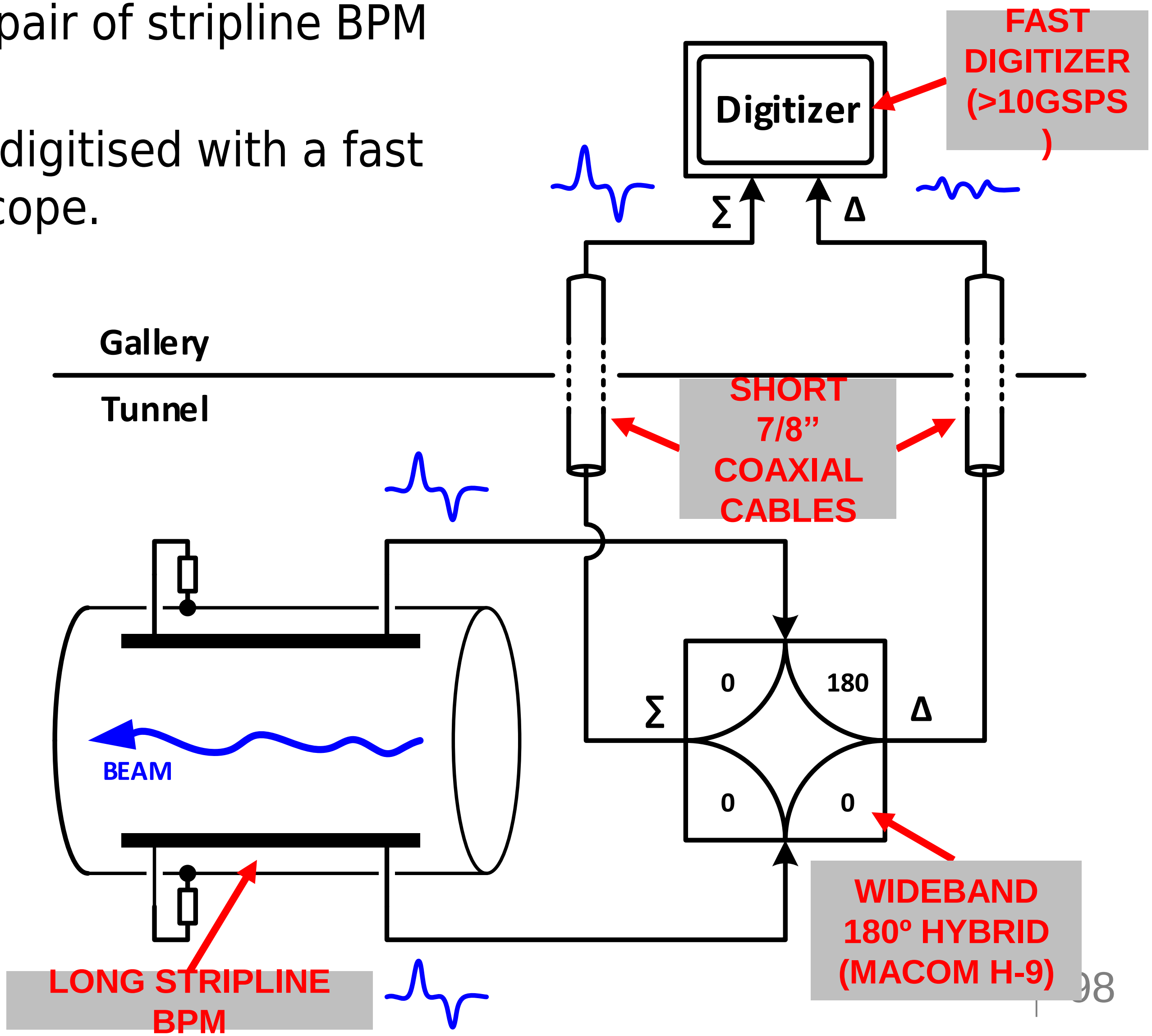
Transverse instability monitoring

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.

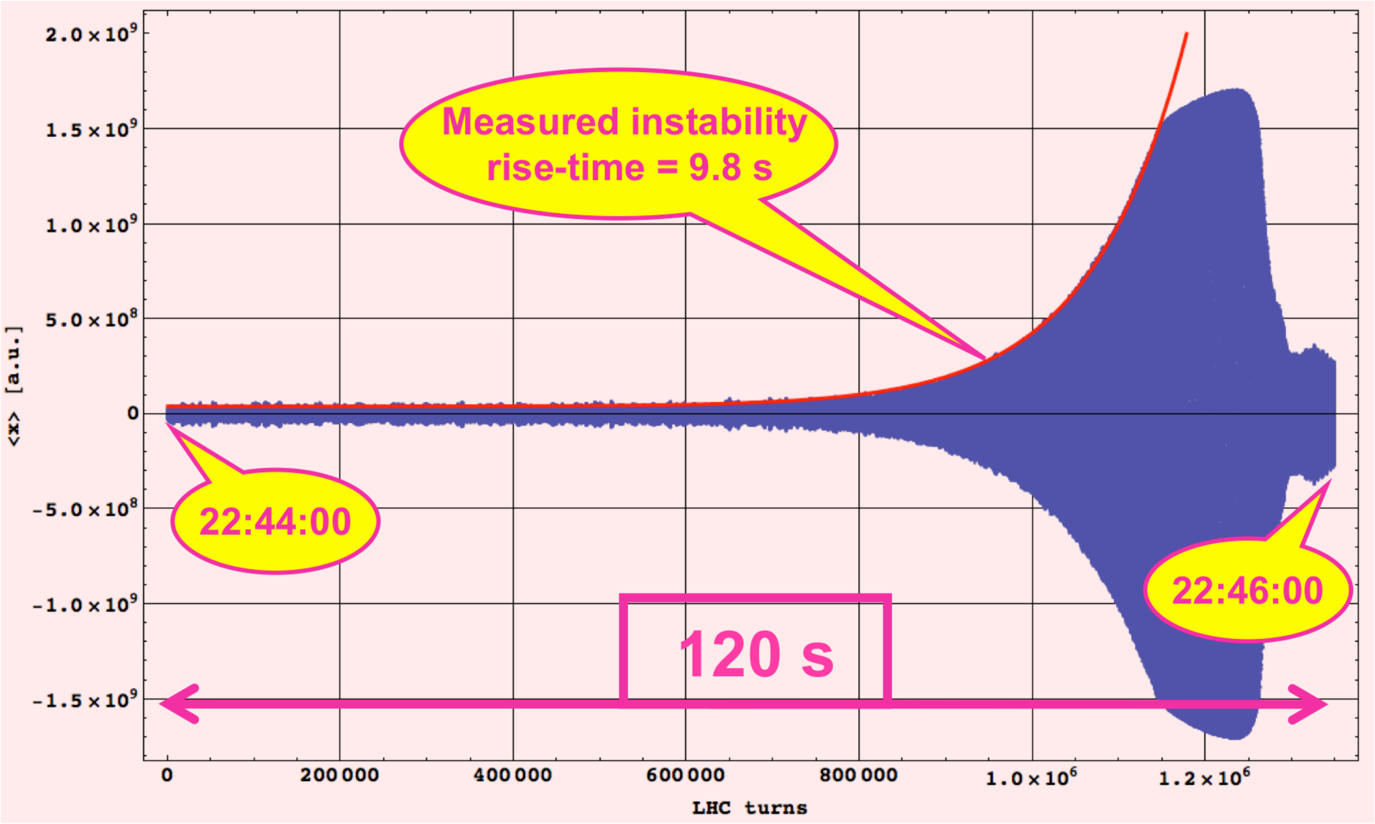
Originally planned for chromaticity measurement (H-T phase shift), but excitation amplitude too large for regular operation.

Now primarily used for measuring intra-bunch instabilities.



Transverse instability monitoring

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: $e^1 \approx 2.7$.

Transverse instability monitoring

The LHC BBQ system is most sensitive instrument available for detecting transverse oscillations. Instability detection can be performed by looking at the growth in BBQ amplitude spectrum. Initial developments of algorithm by J. Ellis. Since 2015 the algorithm has been running online in the LHC (FPGA implementation).

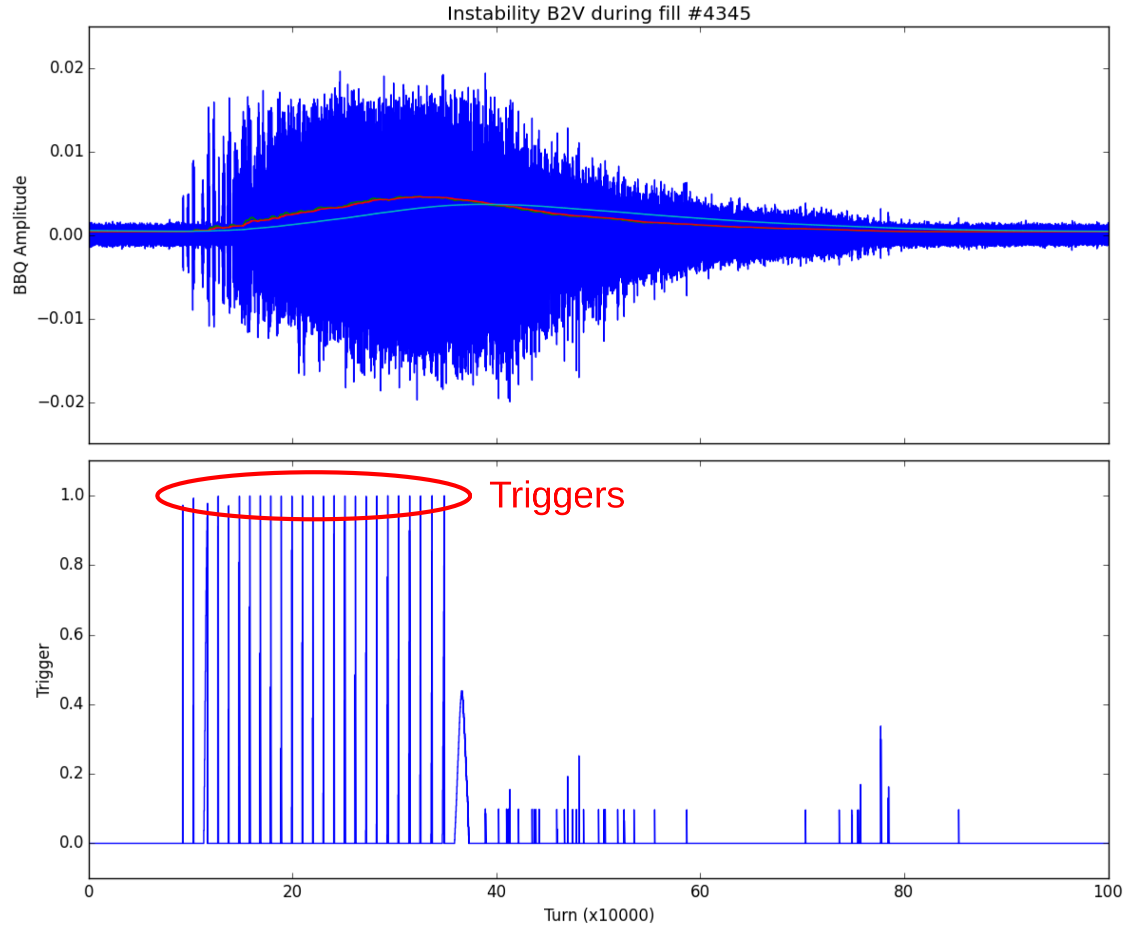
Three moving average filters of different lengths are applied to r.m.s. input signal.

If the condition:

$$\sigma_{short} > \sigma_{medium} > \sigma_{long}$$

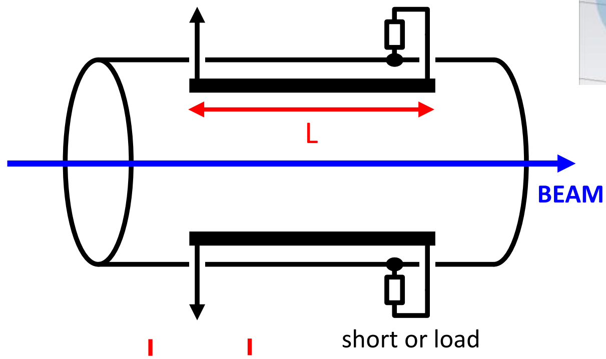
is exceeded for a certain number of turns the trigger is fired.

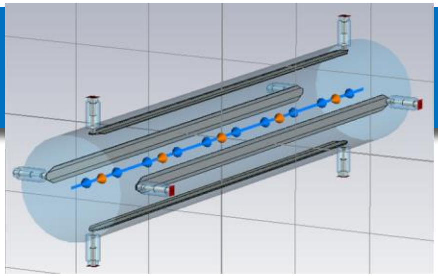
Works reasonably but still being tuned in order to be robust against injection transients, abort gap cleaning excitation, …



T. Lefevre

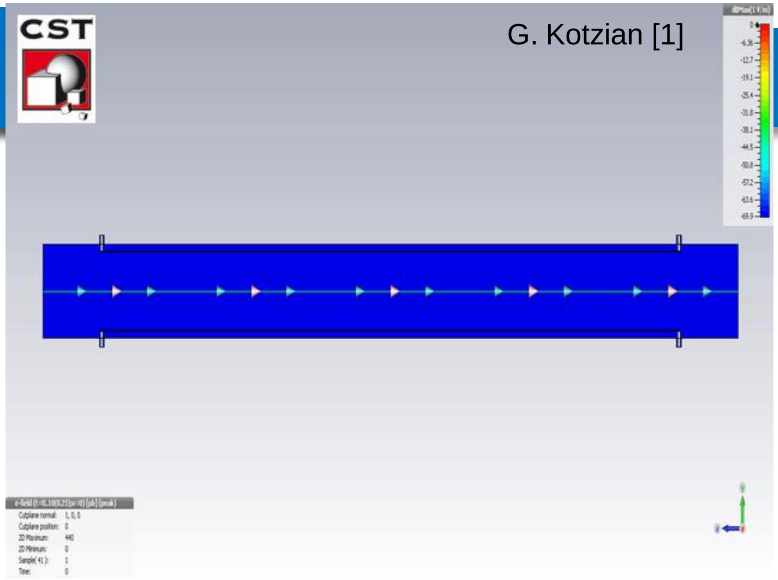
Stripline BPM

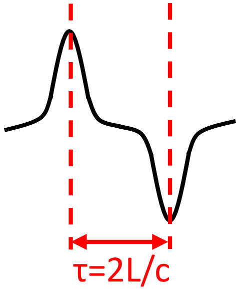




LHC BPLX
L=40cm, τ=2.6ns

SPS BPCL
L=60cm, τ=4.0ns

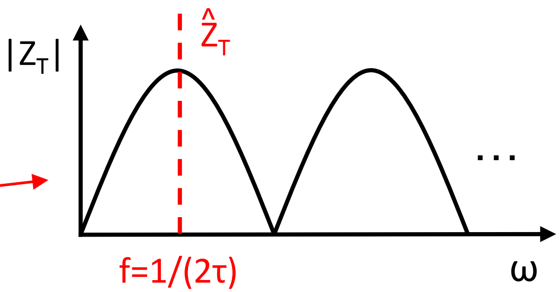




$$V_{PU}(t) = Z_T I_b(t) * [\delta(t) - \delta(t-\tau)]$$

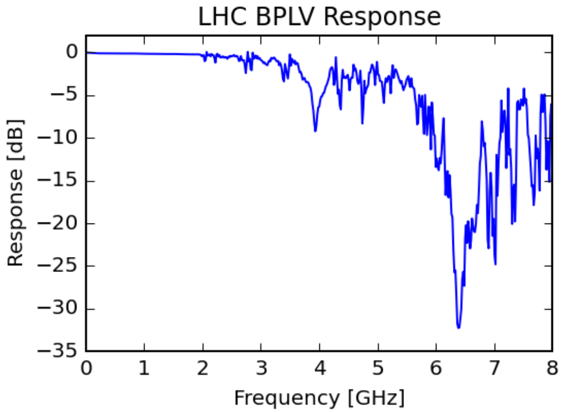
BUNCH PROFILE (under $Z_T I_b(t)$)

NOTCHES IN FREQ. RESPONSE (under $[\delta(t) - \delta(t-\tau)]$)

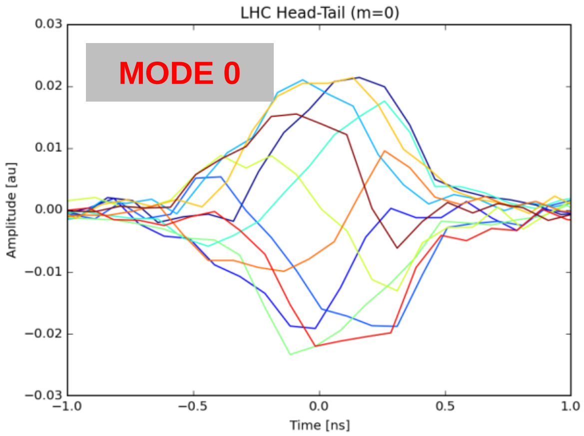


Notches can be removed gating on the initial pulse in the time domain and discarding second pulse. Frequency response is then limited by the BPM structure, feed-throughs, etc.

NB: This requires long BPM and adequate bunch spacing to avoid mixing of the two pulses from the same or subsequent bunches.



Instability triggering



From LHC in 2018