# Diffraction Radiation as a Diagnostics Tool at FLASH

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## Diffraction Radiation

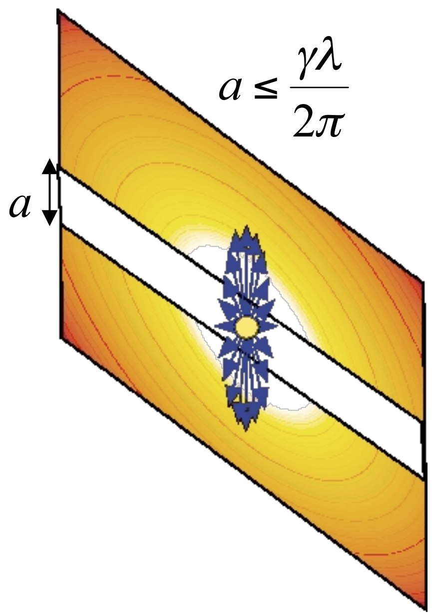
- In this talk we will consider Diffraction Radiation only as a diagnostics tool for high energy electron beams

- When a charged particle crosses an infinite boundary between two different refraction index media, Transition Radiation (TR) is emitted both in forward and backward direction. The backward radiation is typically used for diagnostics purposes.

- When the emitted radiation is produced by only a part of the particle field it is called Diffraction Radiation (DR), in fully correspondence with the wave optics in which only a part of a wave front is allowed to propagate

# Diffraction Radiation

➢ The extension of the electromagnetic field of a relativistic particle is a flat circle of radius $\gamma\lambda$, so that, depending on energy and wavelength, different sources of DR can arise:



# Bunch Length Measurement with Coherent Diffraction Radiation

The total radiation intensity emitted by a bunch of electrons is given by

$$I_{tot}(\omega) = I_{sp}(\omega)[N + N(N-1)F(\omega)]$$

in which $I_{sp}$ is the intensity emitted by a single particle and $F(\omega)$ is the form factor of the bunch, defined as

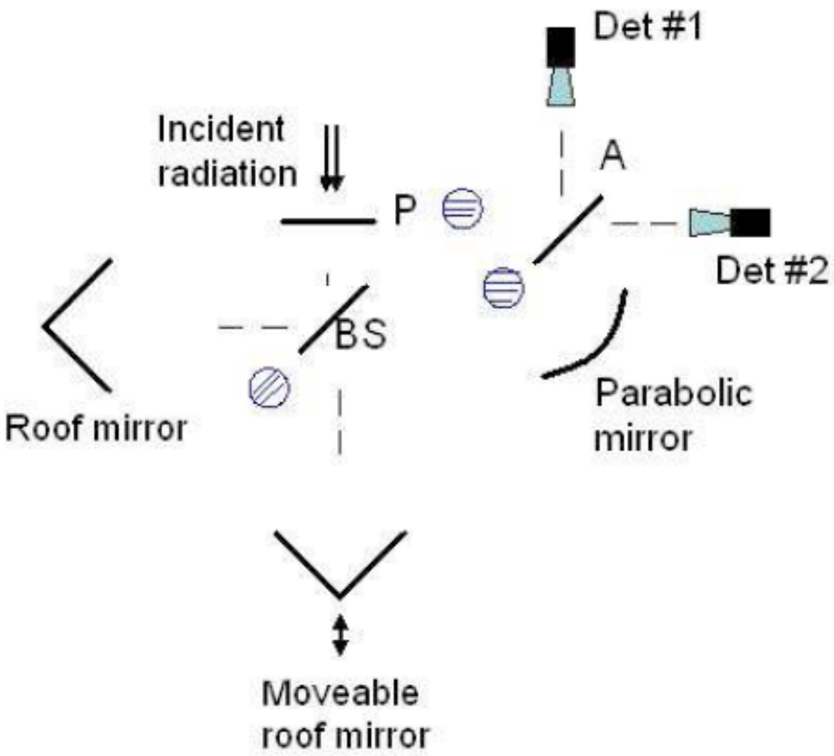
$$F(\omega) = \left| \int_{-\infty}^{\infty} dz S(z) e^{i\frac{\omega}{c}z} \right|^2$$

with $S(z)$ the longitudinal density distribution of the bunch.

The form factor is typically different from zero for wavelengths equal or longer than the bunch length.

Measuring the coherent spectrum it is possible to reconstruct the bunch length and even its longitudinal structure.

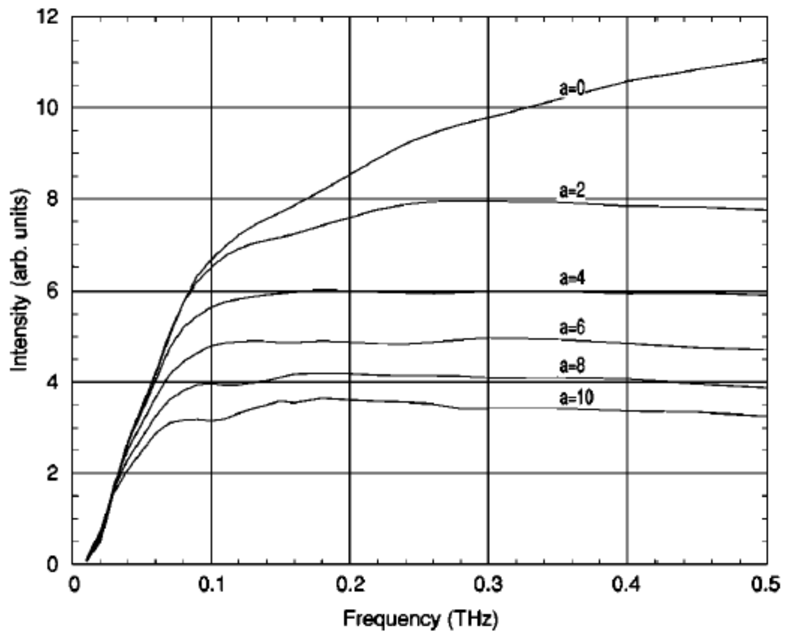
The coherent spectrum is limited at low frequencies by the cutoff introduced by the beam pipe and diffraction losses at wavelength of few millimeters, and at high frequencies by the slit aperture and the vacuum window transmission.




## Experimental Apparatus

In this THz frequency region the spectrum can be measured by means of a Martin Puplett interferometer in which orthogonal polarization states are split, rotated and recombined, resulting in a measurement normalized to the total intensity and free from beam charge fluctuations

At THz frequencies the extension of the particle field ($\gamma\lambda$) is such that even macroscopic slits of mm of aperture can be used without accuracy losses. The high frequency cut introduced by the hole through which the beam passes can even be useful, together with the low frequency cut due to the screen finite size, to flatten the overall frequency response

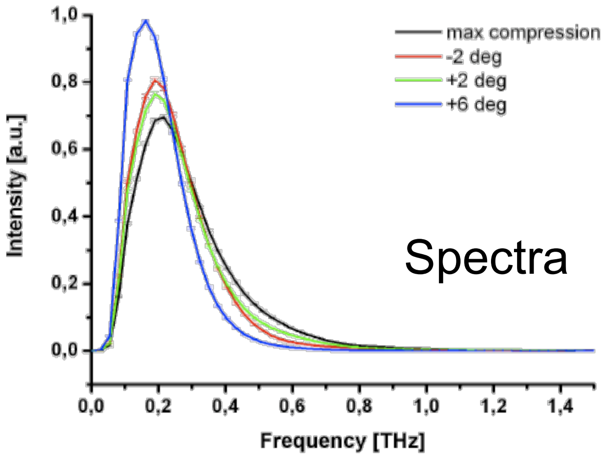


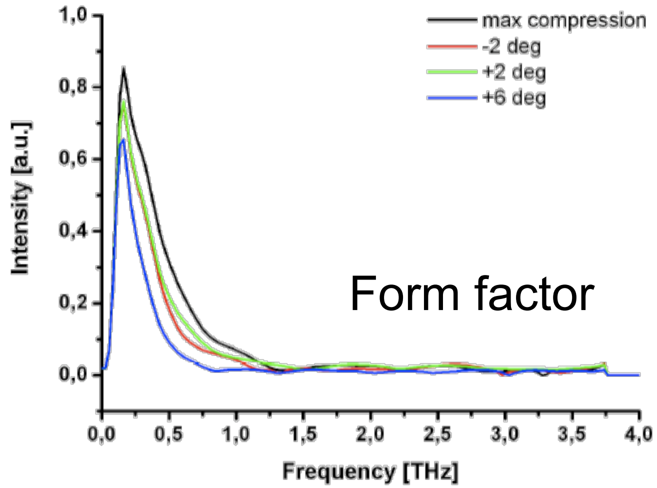

A picture of the variable width slit (0-10 mm) and its frequency response for CDR produced by a 225 MeV electron beam.

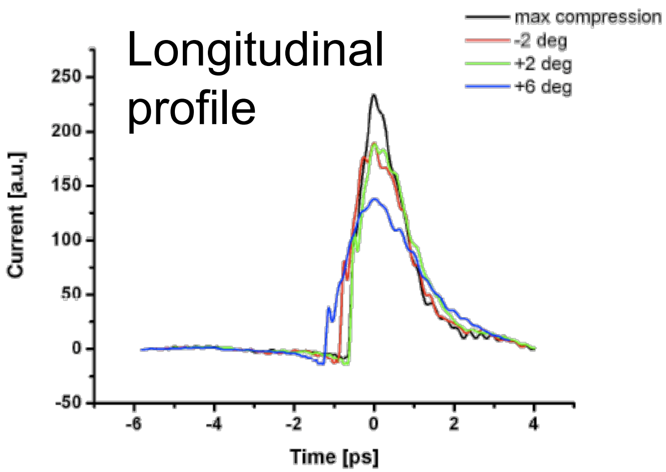
***M. Castellano et al.***,
*Measurements of coherent diffraction radiation and its application for bunch length diagnostics in particle accelerators*
***Physical Review E, vol. 63, 056501 (2001)***

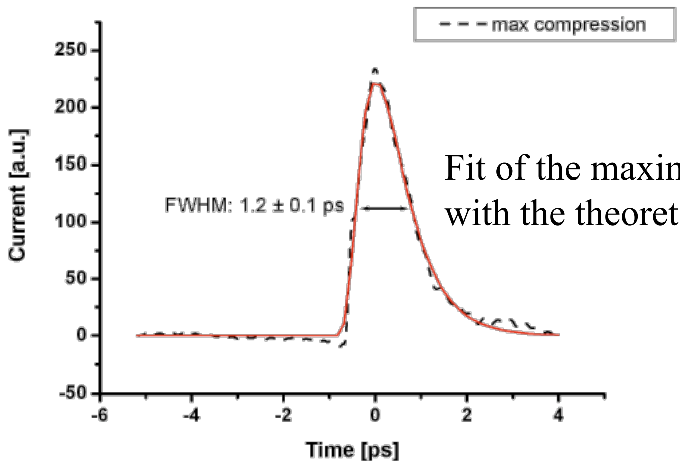
For an accurate evaluation of the coherent spectrum, a detailed analysis of the transfer function of the collection optics and of the spectrometer as function of the radiation wavelength must be performed.

Also a careful calibration of the detectors, in a frequency region in which wide band sources are very poor, is required.



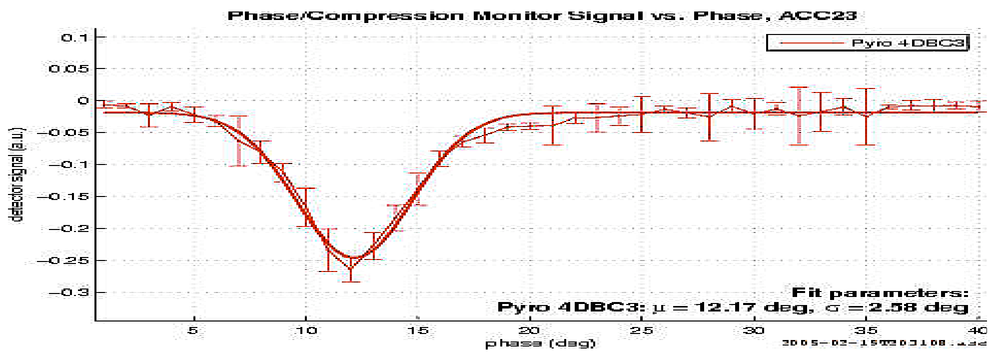



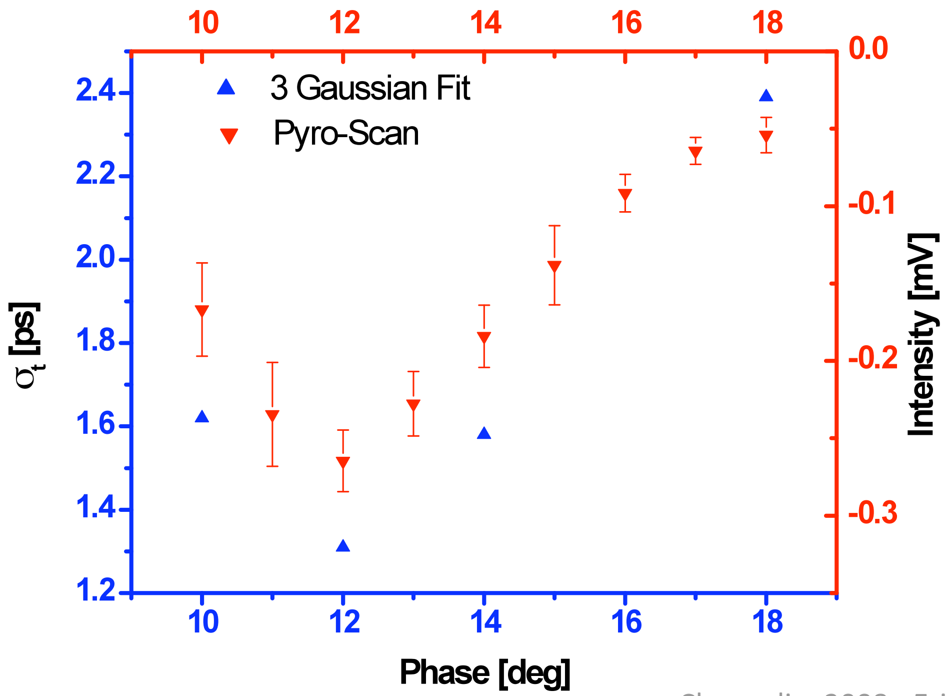




Fit of the maximum compression case with the theoretical structure

# A Fast Bunch Compression Monitor

Accelerating phase scan done to optimize bunch compression

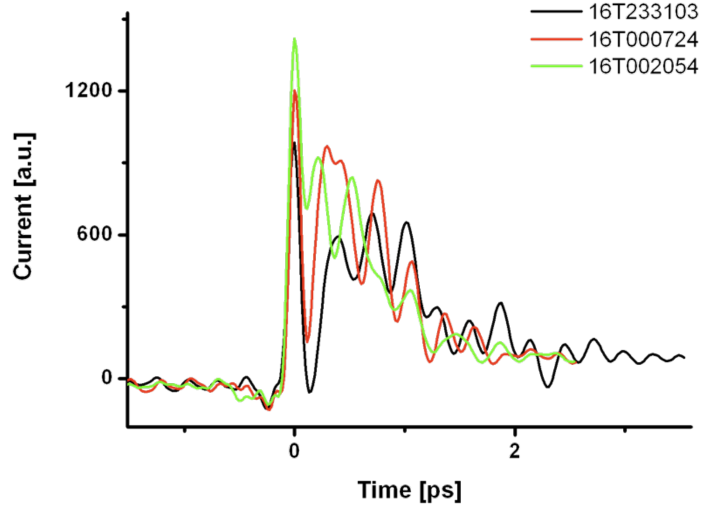


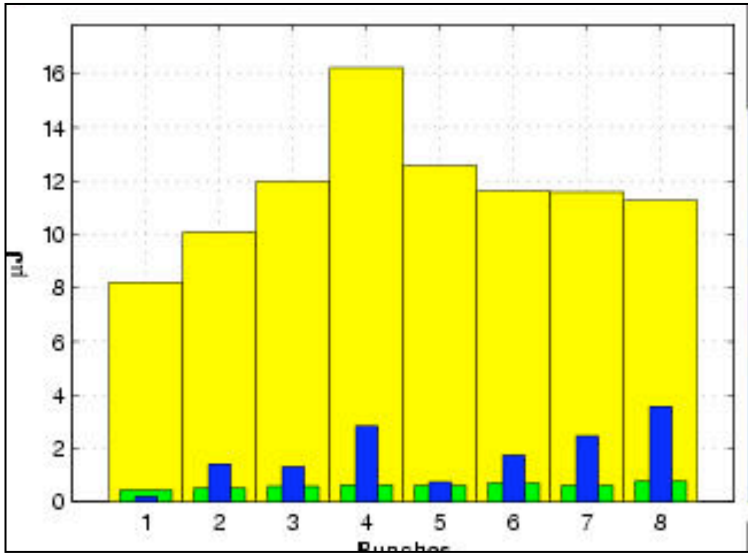



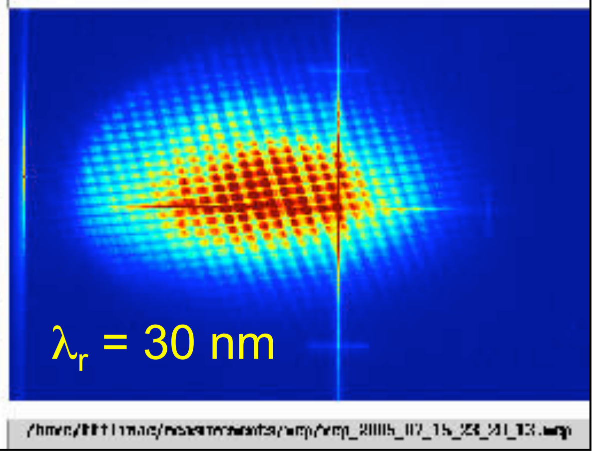

Comparison between the bunch length and the phase scan curve. The bunch length follows very well the phase scan, the maximum registered intensity corresponding to the shortest bunch length.

# A Non-Intercepting Tool

The FEL process would be sensitive to any beam perturbation that can derive from wakefields generated on the DR screen by the very high beam current.
However during the bunch length measurement
**no significant disturbance on the FEL radiation**
has been detected, confirming the effective non-perturbing nature of the technique.



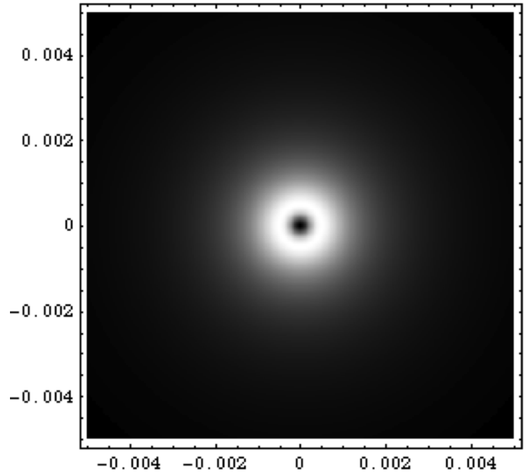

Several measurements were performed when the beam was set up to provide FEL laser radiation close to saturation, in order to demonstrate the **non-intercepting and non-invasive nature of CDR diagnostics**.

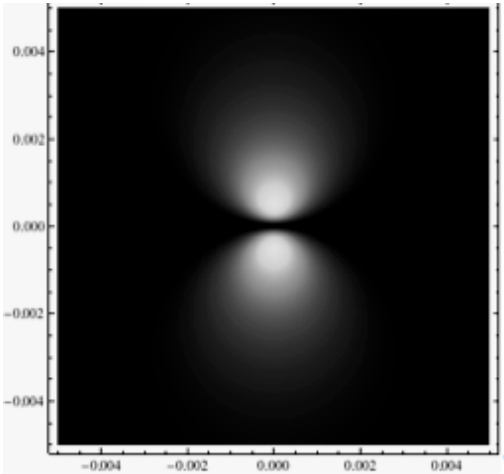
*E. Chiadroni,*
*Bunch Length Characterization at the TTF VUV-FEL,*
***TESLA FEL 2006-09***

# Optical Diffraction Radiation as Beam Size Monitor

**Preface: Optical Transition Radiation as an interference effect**

Angular distribution of backward OTR, around the direction of specular reflection, from a perfect metallic screen emitted by an electron of 1 GeV

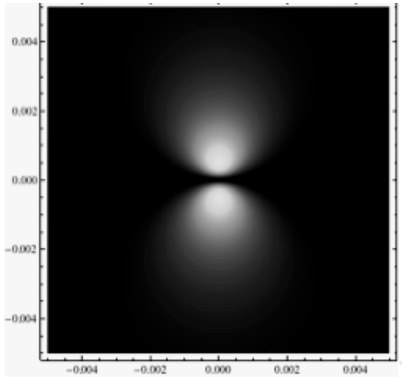


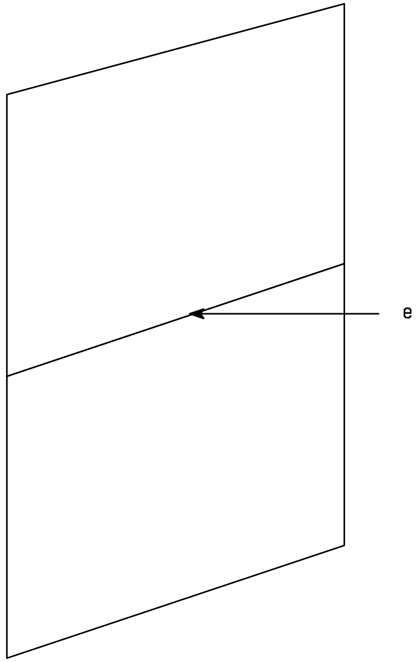




OTR vertical polarization component (the same structure is obtained with respect of any polarization axis)

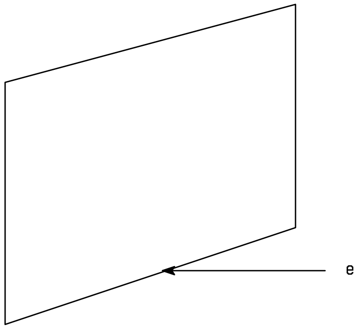
Let us assume the infinite plane composed by two semi-planes divided by a horizontal line passing in the point of the particle impact and let us

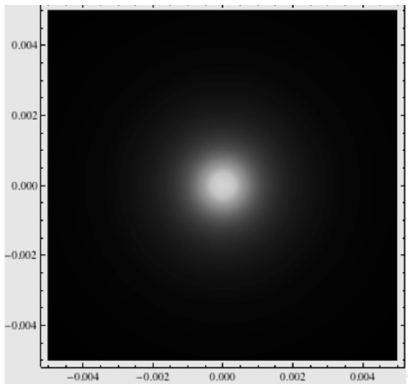
consider the radiation vertical component

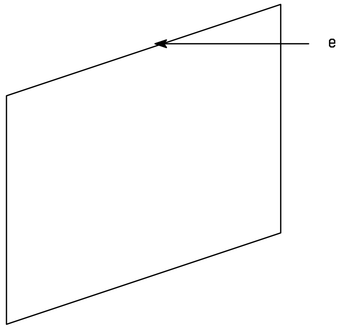



The angular distribution of the radiation vertical component emitted independently by the two semi-planes is equal and centered on the specular reflection direction




The emission from the whole plane is the result of an interference between the amplitude of the two semi-planes

The vertical component of the OTR far field distribution of the upper half plane can be written as
(see M.L. Ter-Mikaelian: *High-Energy Electromagnetic Processes in Condensed Media,* Wiley-Interscience)

$$E_y^+ = \frac{e}{4\pi^2 c}\frac{1}{f - ik_y}$$

with

$$f = \sqrt{k_x^2 + \frac{k^2}{\beta^2\gamma^2}} \qquad k = \frac{\omega}{c}$$

$$k_x = k\sin\vartheta\cos\varphi$$

$$k_y = k\sin\vartheta\sin\varphi$$

While for the lower half plane

$$E_y^- = \frac{-e}{4\pi^2 c}\frac{1}{f + ik_y}$$

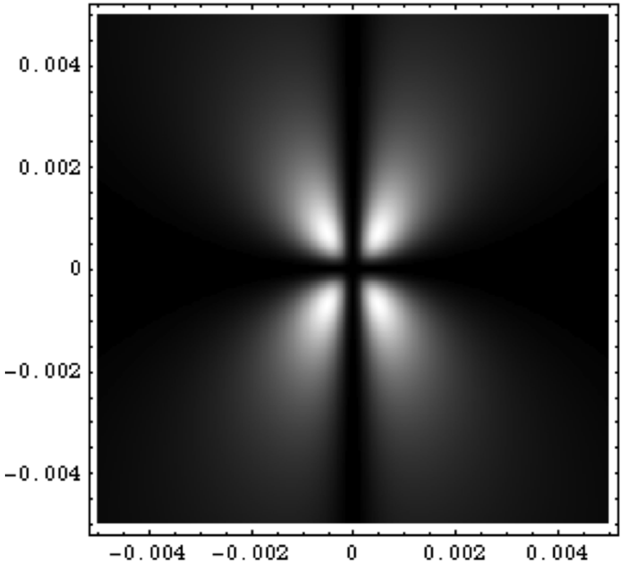
$$E_y^+ = \frac{f + ik_y}{f^2 + k_y^2} = \frac{f}{f^2 + k_y^2} + i\frac{k_y}{f^2 + k_y^2}$$

$$E_y^- = -\frac{f - ik_y}{f^2 + k_y^2} = -\frac{f}{f^2 + k_y^2} + i\frac{k_y}{f^2 + k_y^2}$$

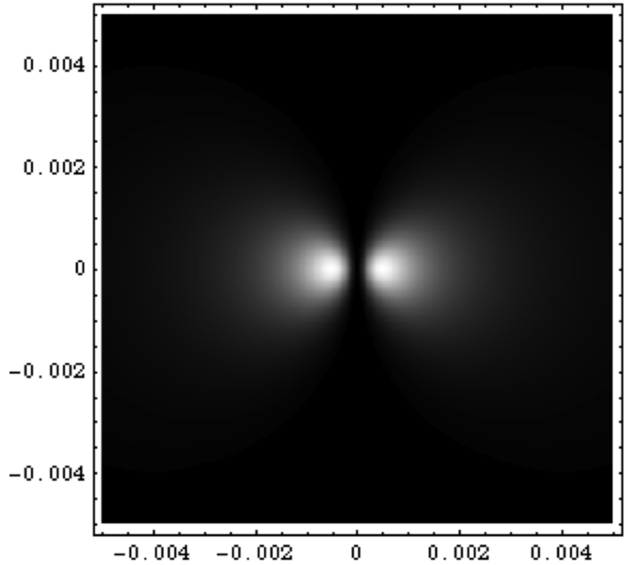
The imaginary parts for the two half plane are equal with the same sign, so they add for the whole plane, while the real parts are equal but with opposite sign, so they cancel. The total amplitude has the angular distribution given by only the imaginary part of a half plane amplitude, the real part being cancelled by the second half plane

The same is true for the horizontal component of the field, for which the distribution due to the real and imaginary parts are

Real

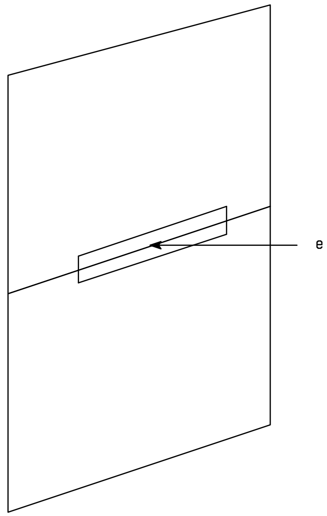



Imaginary

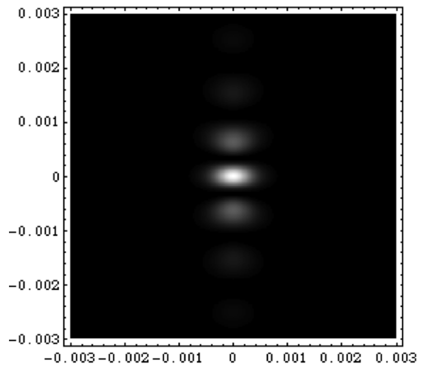


If a slit is cut in the metallic plate with its horizontal dimension large enough to be considered infinite for the particle field, the classical Diffraction Radiation will be produced if the vertical slit width is of the order of $\gamma\lambda/2\pi$.

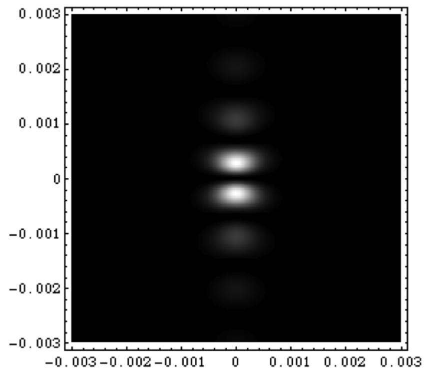
In this case too the radiation is the result of an interference effect between the two half planes, presenting a more complex distribution due to the presence of the cut.




Radiation produced by a single half plane




real part

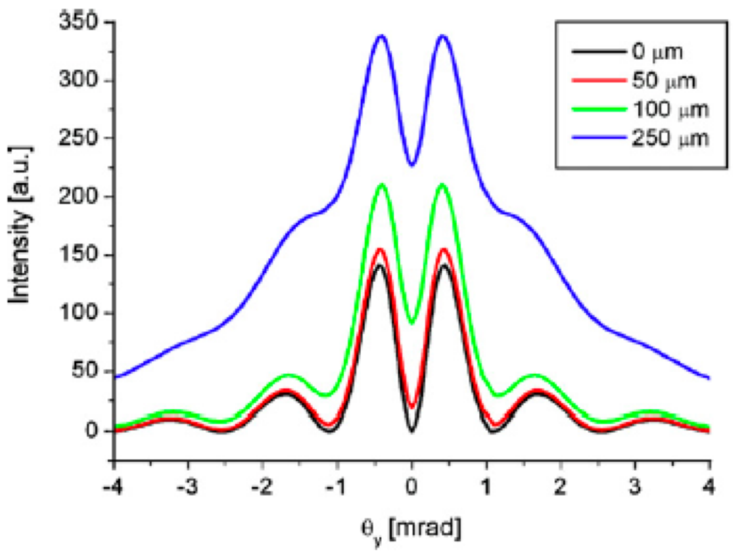



imaginary part

From the whole screen only the imaginary part will be emitted.

In 1997 one of us suggested that the ***visibility*** of the interference fringes could be used to determine the transverse size of a bunch of electrons crossing the slit:

**M. Castellano**,
*A new non-intercepting beam size diagnostics using diffraction radiation from a slit*,
**NIM A 394 (1997) 275**



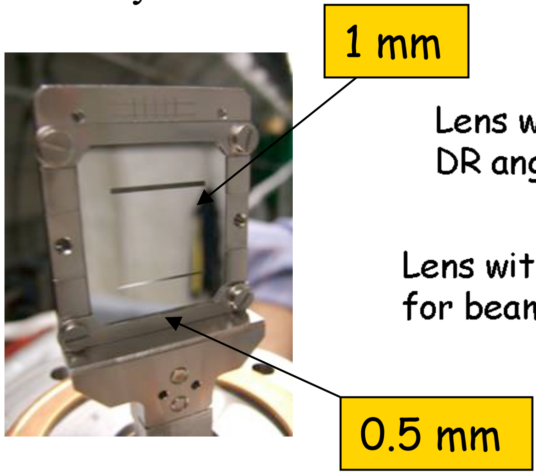

An example of a 1 GeV beam through a 0.5 mm slit for a radiation of 800 nm as function of the beam size.
The beam angular divergence too gives rise to a reduced fringes visibility, but with a slightly different distribution, opening the way to a possible emittance single shot measurement with a very small perturbation of the beam.

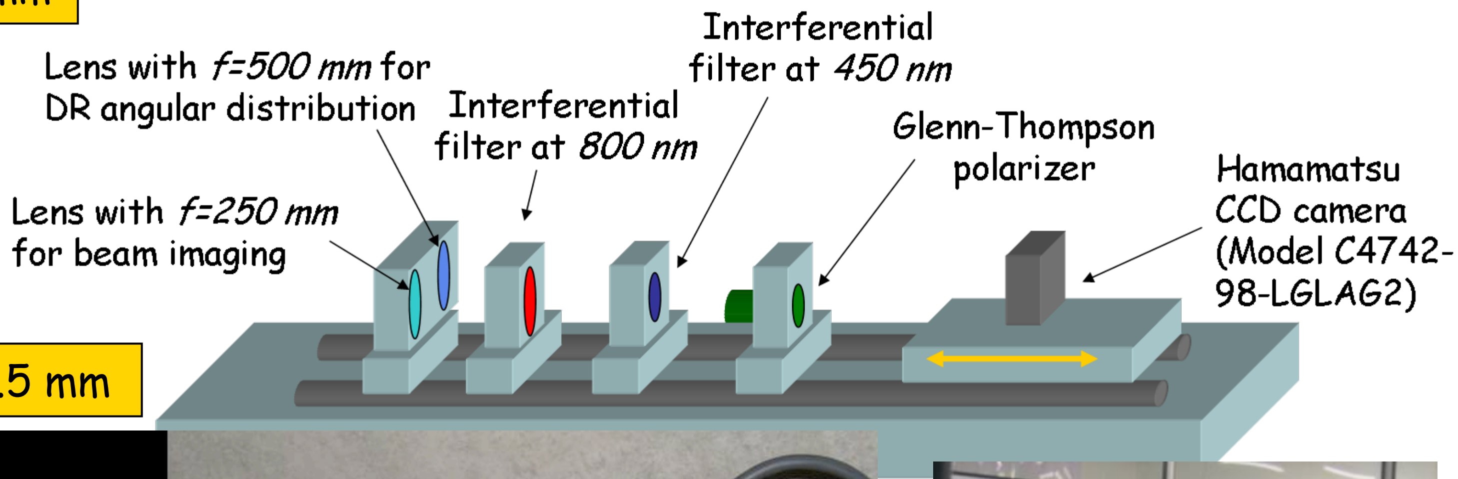
First experimental evidence has been obtained at ATF, KEK:

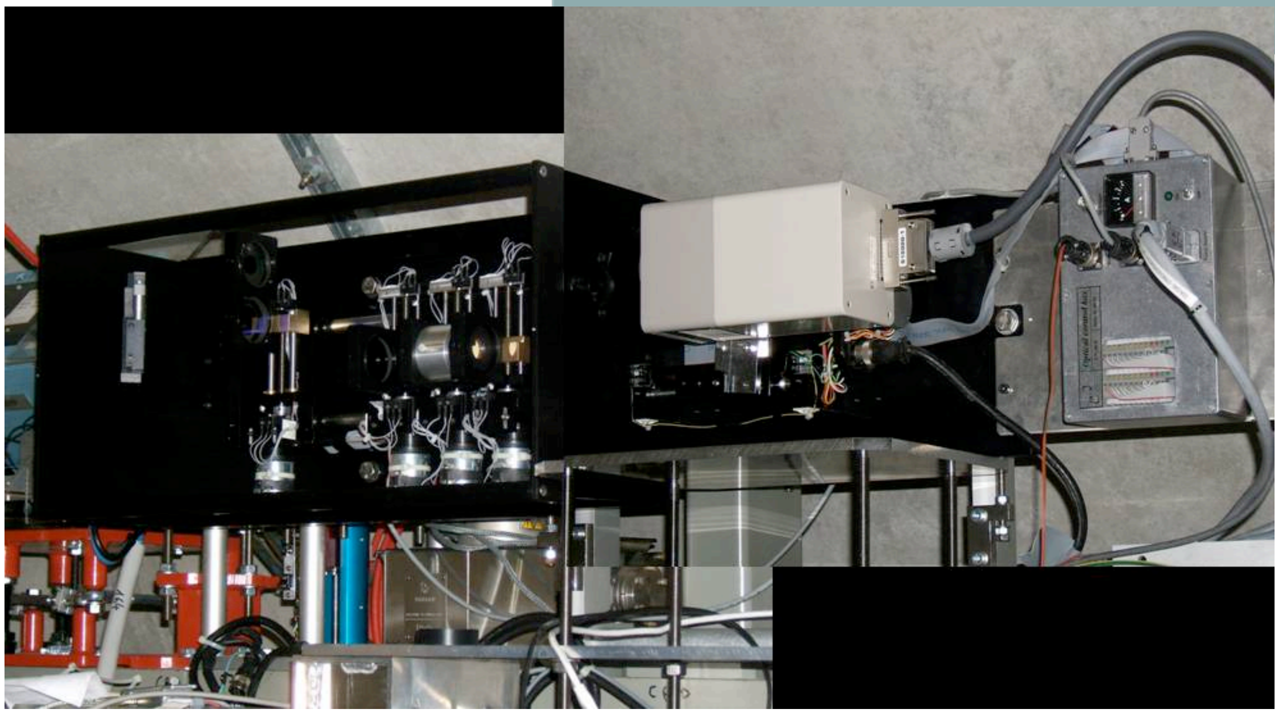
- ***P. Karataev et al.***, *Beam size measurement with optical diffraction radiation at KEK Accelerator Test Facility*, ***Phys. Rev. Lett. 93, p. 244802, 2004***
- ***S. Araki et al.***, *Optical diffraction radiation beam size monitor at KEK accelerator test facility*, *in* ***Channeling 2006 proceedings, 2006***

# ODR Experiment @ FLASH

An experiment based on the detection of Optical Diffraction Radiation has been set up at DESY FLASH Facility.



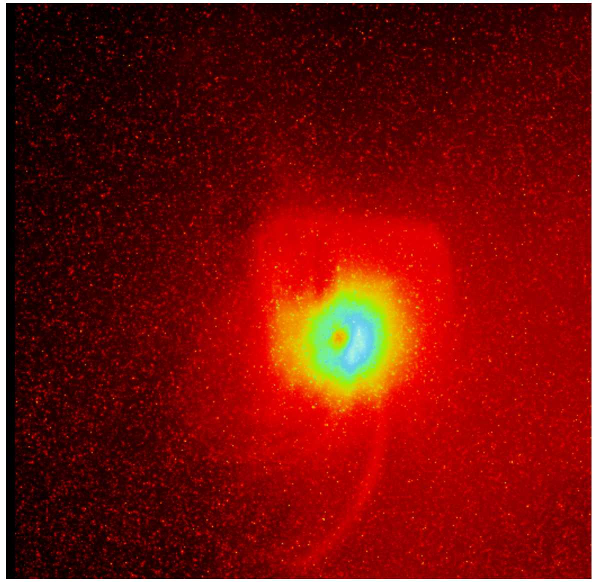



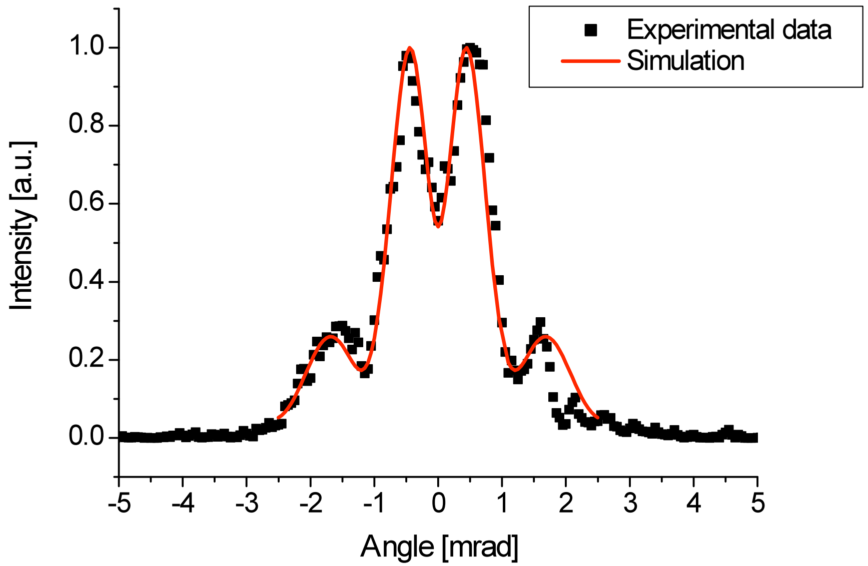



# Phase 1

The background has been a severe limitation for a detailed and quantitative reconstruction of the beam parameters from the ODR angular distribution.
A big effort has been done in order to subtract the SR background via software.

This allowed us to prove a good qualitative agreement between the experimental data and the simulations.






**Beam transport optimization**

- 0.7 nC
- 25 bunches
- 2 s exposure time
- $E_{beam}$ (nominal) = 680 MeV
- 800 nm filter and polarizer in

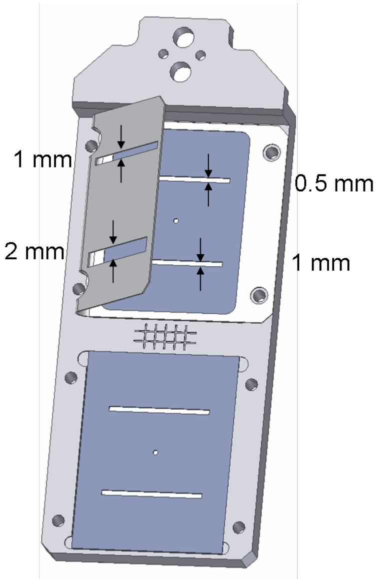
**Simulation parameters**:

- a = 0.5 mm
- Gaussian distributed beam
- $\sigma_y$ = 80 μm
- $\sigma'_y$ = 125 μrad
- $E_{beam}$ = 610 MeV

***E. Chiadroni et al.,***
*Non-intercepting electron beam transverse diagnostics with optical diffraction radiation at the DESY FLASH facility*
***NIM B 266 (2008) 3789–3796***

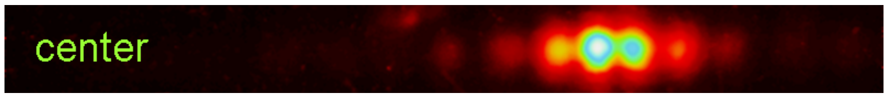
# Phase 2: Optical Diffraction Radiation Interferometry (ODRI)

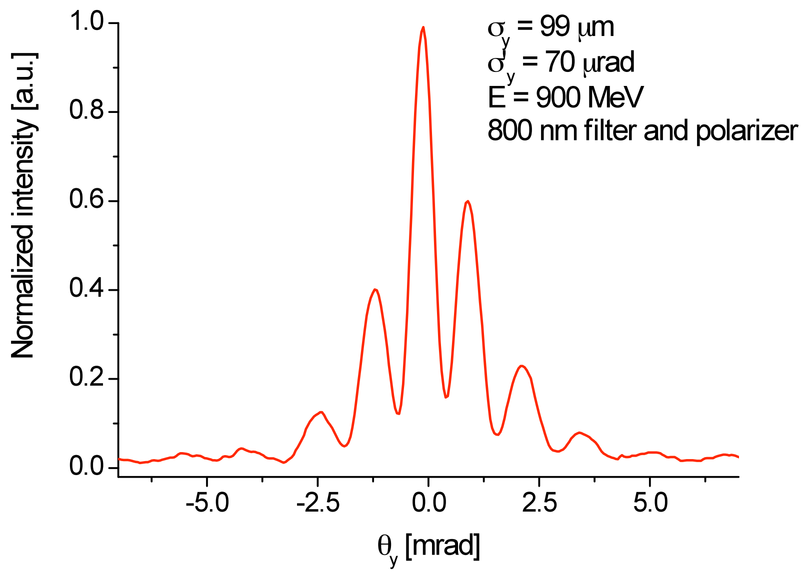
As a tentative to reduce the synchrotron radiation background, we mounted a stainless steel shield in front of our ODR screen, with a larger cut in it.




In the case of a wavelength of 800 nm and 1 GeV beam energy the 1 mm cut is not large enough to prevent the production of ODR in the forward direction, reflected by the screen and interfering with the backward ODR produced by the screen itself.

An ODR analogous of the Wartski interferometer used for OTR, with the difference that in this case the two interfering amplitudes are different in intensity and angular distribution

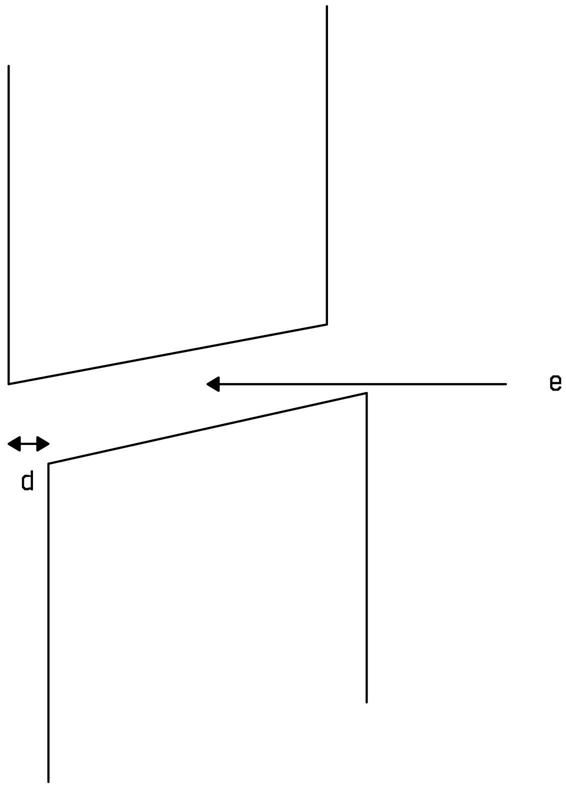



See: *E. Chiadroni et al., Poster Session 2: PS2-4*

The strong asymmetry shown by the ODR experimental distributions can only be explained by considering the previous results on the interference effects between the two half planes.

Suppose that the two half planes are parallel but not perfectly coplanar, as in the picture, the field of a particle incident with angle $\alpha$ will be "reflected" by one half plane earlier than by the other.




The phase difference between the two fields, in the approximation of $d \ll \gamma\lambda$ and $\beta \approx 1$, is

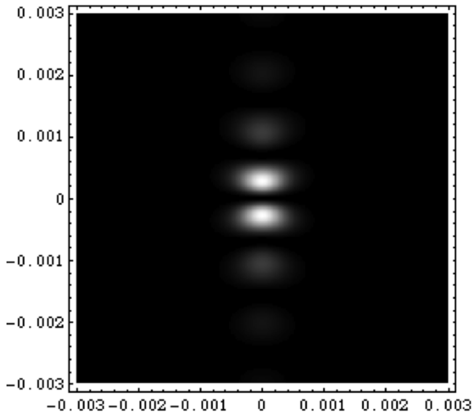
$$\varphi = \frac{4\pi d}{\lambda \cos\alpha}$$

and the vertical polarization component of the total field becomes

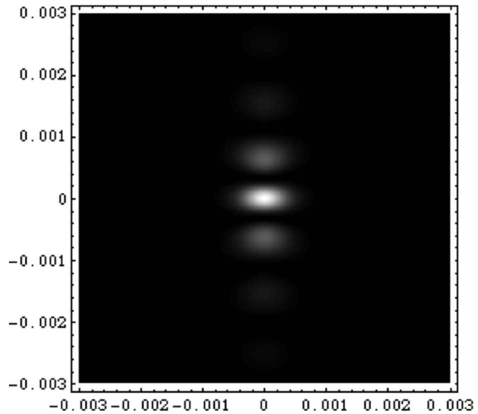
$$E_y = \frac{e^{-a(f-ik_x)}}{f-ik_y} - e^{i\varphi}\frac{e^{-a(f+ik_x)}}{f+ik_y}$$

The effect of the phase factor is of preventing the perfect cancellation of the real part of the field amplitude in the interference effect, resulting in a “mixing” of the real and imaginary parts

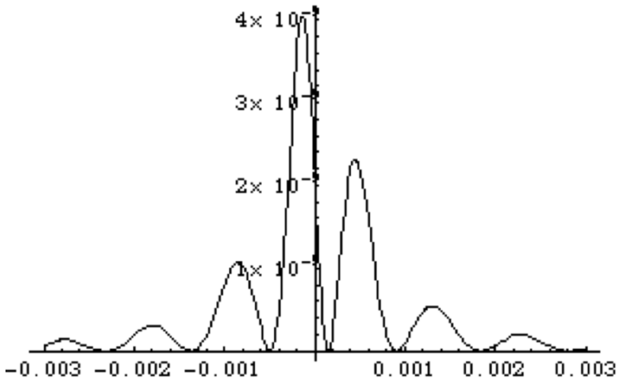
Φ=0




Φ=π




Φ=π/2




For a wavelength of 800 nm and an incidence angle of 45º the phase difference of π/2 is given by a difference in planarity of d = 70 nm.

This means that

- this effect is not completely controllable and must enter in the general fit evaluation
- depending on the thickness of the aluminum layer, the relative phase can be changed as required

# Conclusions

- Diffraction Radiation is a versatile tool for longitudinal and transverse diagnostics of high energy, high density electron beams

- DR is totally non-intercepting, allowing to fully characterize high density electron beams without loosing their quality

- The DR angular distribution is affected, in different ways, both by beam size and divergence allowing a single shot emittance measurement

- DR angular distribution strongly depends on the target
    - Even machining imperfections can be controlled in order to study new effects