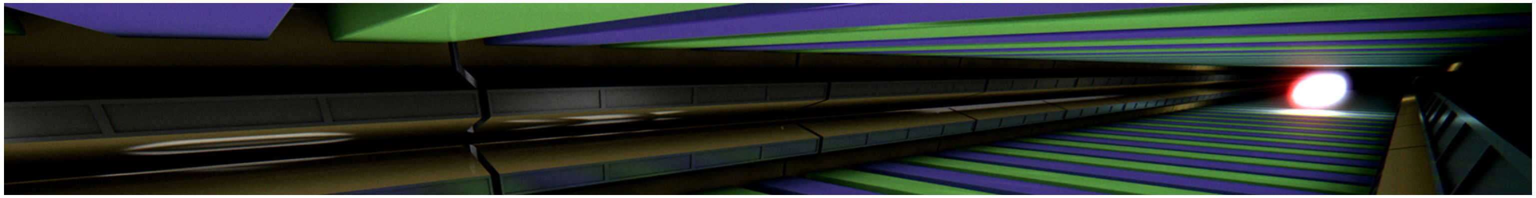


Theory of Edge Radiation. Foundations and applications

Gianluca Geloni

DESY & European XFEL

European XFEL

Theory of Edge Radiation. Part 1 - Foundations and basic applications

Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin, Evgeni Schneidmiller and Mikhail Yurkov

THOB04 (This Talk) - Nuclear Inst. and Methods in Physics Research, A 605 (2009), pp. 409-429

Theory of Edge Radiation. Part 2 - Advanced applications

Gianluca Geloni, Vitali Kocharyan, Evgeni Saldin, Evgeni Schneidmiller and Mikhail Yurkov

WEPC02- Nuclear Inst. and Methods in Physics Research, A 607 (2009), pp. 470-487

Integration of the optical replica ultrashort electron bunch diagnostics with the high-resolution coherent optical transition radiation imager

Gianluca Geloni, Petr Ilinski, Evgeni Saldin, Evgeni Schneidmiller and Mikhail Yurkov

WEPC46 - DESY 069-2009 – To be published

Method for the determination of the three-dimensional structure of ultrashort relativistic electron bunches

Gianluca Geloni, Petr Ilinski, Evgeni Saldin, Evgeni Schneidmiller and Mikhail Yurkov

WEPC47 - DESY 069-2009 – To be published

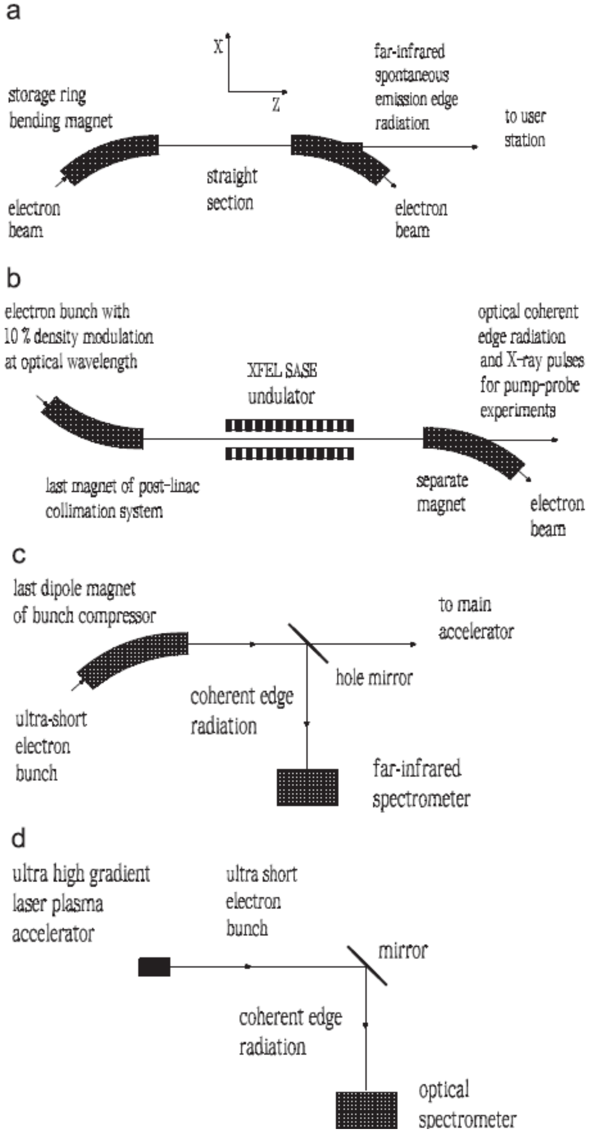
DESY

HELMHOLTZ | ASSOCIATION

Contents

- Basic Theory of edge radiation (single electron)
- Edge Radiation and Optical Transition Radiation
- Coherent OTR for diagnostic purposes: Integration with the Optical Replica Synthesizer (ORS: THOB02)
- Coherent OTR for diagnostic purposes: towards three-dimensional structure determination of ultrashort relativistic electron bunches

Basic Theory of Edge Radiation (single electron)

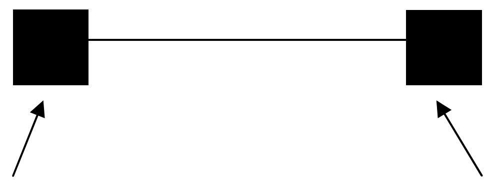


$$\left(\nabla^2 + \frac{2i\omega}{c}\frac{\partial}{\partial z}\right)\vec{\tilde{E}} = \frac{4\pi e}{v_z(z)} \exp\left[i\omega\left(\frac{s(z)}{v} - \frac{z}{c}\right)\right]\left[\frac{i\omega}{c^2}\vec{v}_\perp(z) - \vec{\nabla}_\perp\right]\delta\left(\vec{r} - \vec{r}_0(z)\right)$$

Paraxial Maxwell Equations in the Space-frequency domain

$$\vec{\bar{E}} = \vec{\tilde{E}}_\perp \exp[-i\omega z/c]$$

Sources: $\bar{\rho}(\vec{r}, z, \omega)$ $\vec{\bar{j}}(\vec{r}, z, \omega)$

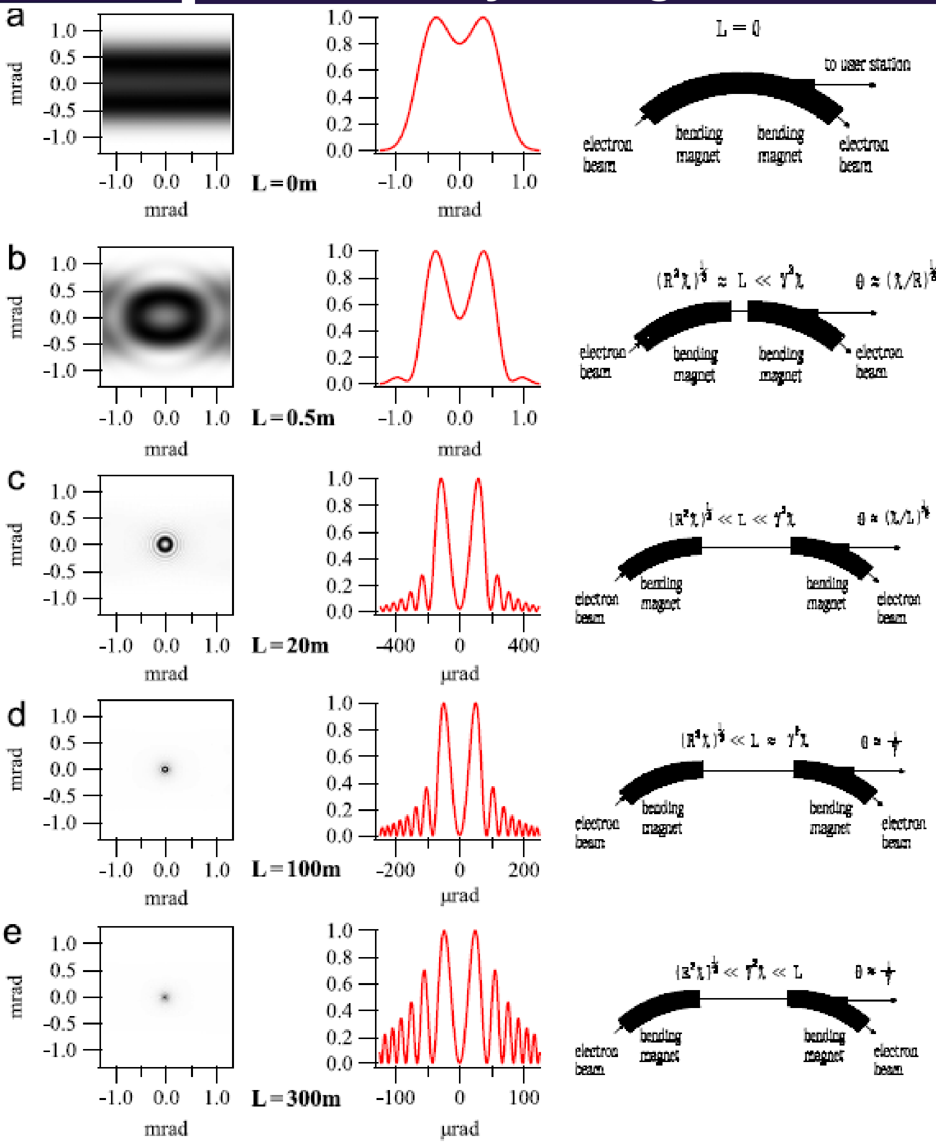


Sources begin to exist here

Sources end to exist here

The way sources begin and cease to exist can include Negligible/non negligible modifications to the field…

Basic Theory of Edge Radiation (single electron)



Synergy with SRW

Similarity techniques can be used to study ER

$$\delta \equiv \frac{\sqrt[3]{R^2 \lambdabar}}{L}, \quad \phi \equiv \frac{L}{\gamma^2 \lambdabar}$$

δ<<1 – can neglect bending magnet contributions

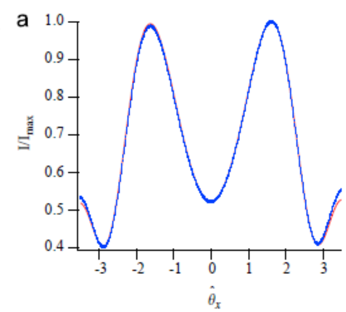
ϕδ<<1 – $\lambda >> \lambda_c$

→Theory of edge radiation

Red: L=0.5m, R=400m, λ=400 nm, @ 17.5 GeV

Blue: L=1 m, R=800m, λ=800, nm @ 17.5 GeV

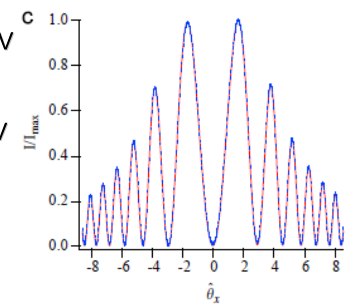
$$\delta \simeq 0.43 \text{ and } \phi \simeq 6.7 \times 10^{-3}$$



Red: L=300m, R=400m, λ=400 nm, @ 17.5 GeV

Blue: L=150 m, R=800m, λ=800, nm @ 8.5 GeV

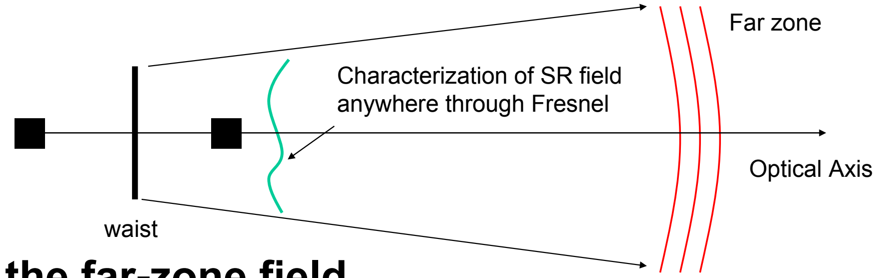
$$\delta \ll 1 \text{ and } \phi \simeq 4$$



Basic Theory of Edge Radiation (single electron)

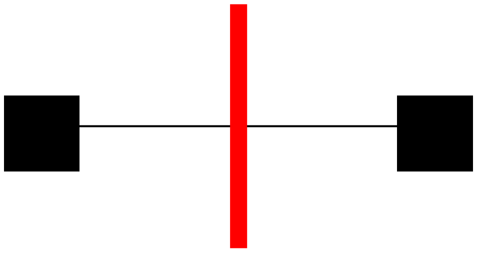
Space-frequency domain

SR beams from single electrons are similar to laser-beams



- **Calculate the far-zone field**
- **The far field completely characterizes radiation at a virtual source = "waist"**
- **Fresnel propagation formula propagates the field from the virtual source**

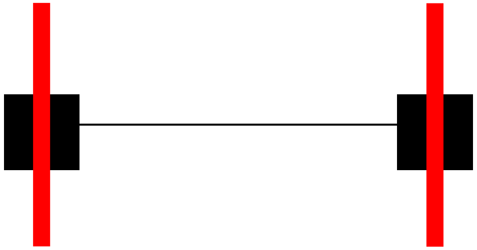
Two equivalent pictures for ER



One source = one laser-like beam

$$\vec{\tilde{E}}(0,\vec{r}) = -\frac{\omega^2 eL}{2\pi c^3}\int d\vec{\theta}\,\vec{\theta}\,\mathrm{sinc}\left[\frac{\omega L}{4c}\left(\theta^2+\frac{1}{\gamma^2}\right)\right]\exp\left[\frac{i\omega}{c}\vec{r}\cdot\vec{\theta}\right]$$

Better applied for $\phi = \frac{L}{\gamma^2 \lambda\!\!\!^{-}} << 1 \quad \rightarrow \vec{\tilde{E}}(0,\vec{r}) = -i\frac{4\omega e}{c^2 L}\vec{r}\,\mathrm{sinc}\left(\frac{\omega r^2}{cL}\right)$

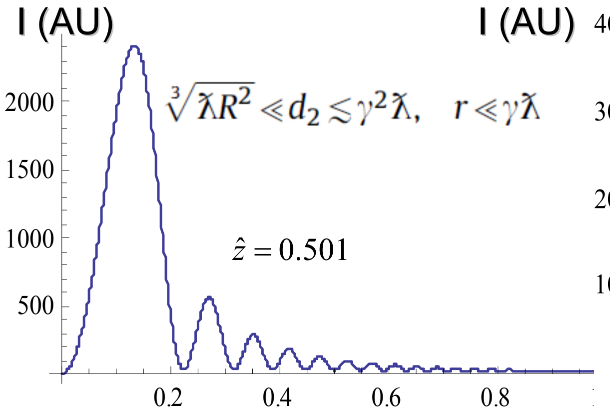


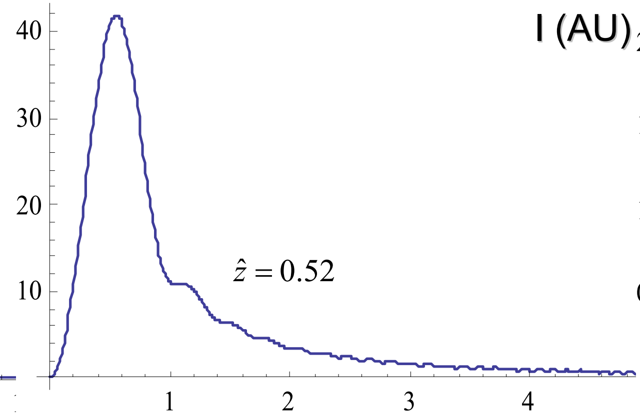
Two sources = two laser-like beam

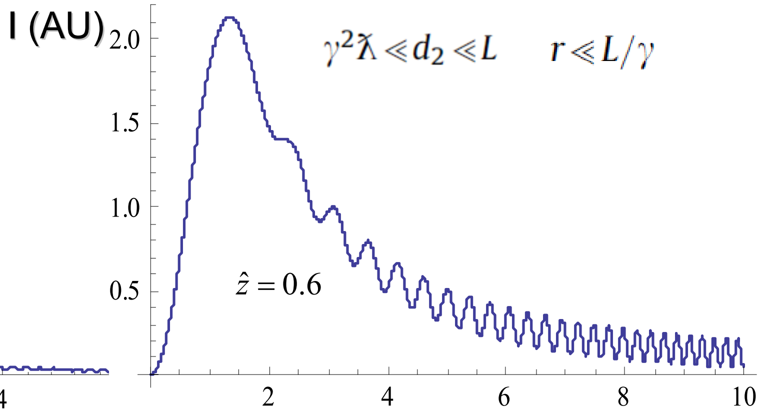
$$\vec{\tilde{E}}_{s1,s2}\left(\mp\frac{L}{2},\vec{r}\right) = \pm\frac{2\omega e}{c^2\gamma}\exp\left[\mp\frac{i\omega L}{4\gamma^2 c}\right]\frac{\vec{r}}{r}K_1\left(\frac{\omega r}{c\gamma}\right)$$

Better applied for $\phi = \frac{L}{\gamma^2 \lambda\!\!\!^{-}} >> 1$

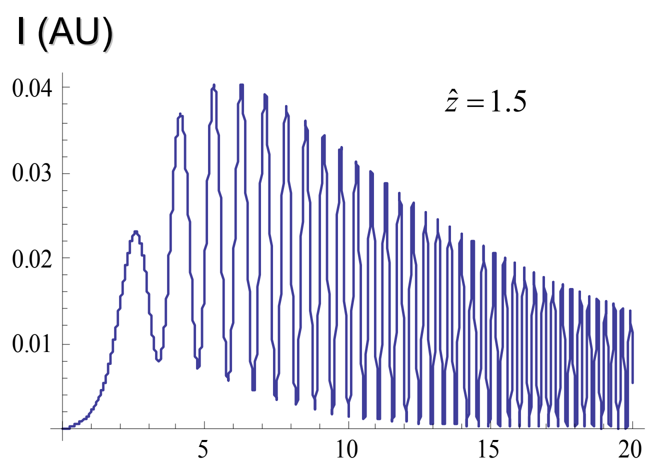
Basic Theory of Edge Radiation (single electron)

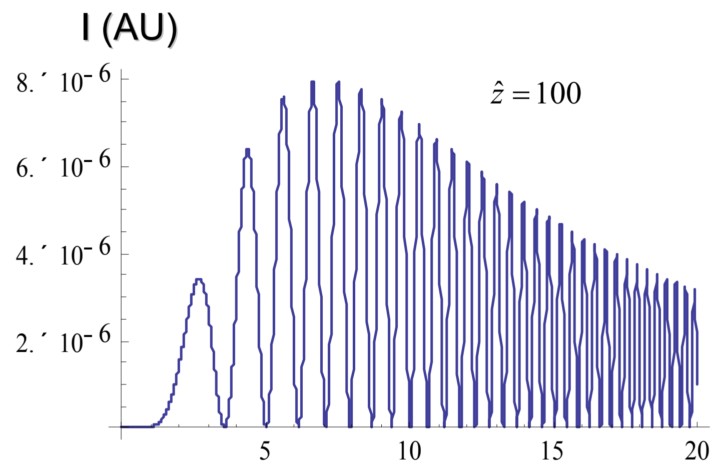






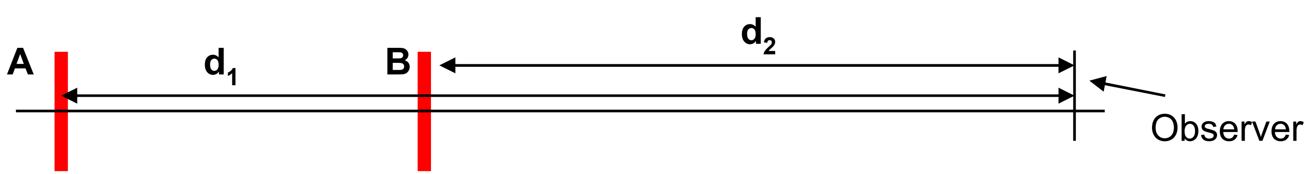
$d_{1,2} \sim L$





$d_{1,2} \gg L$

$\phi = 50$

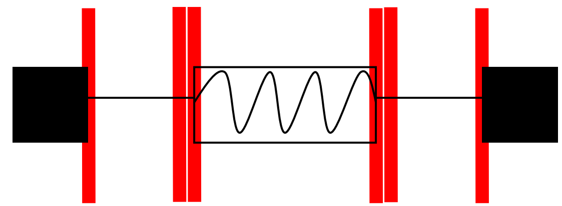


Basic Theory of Edge Radiation (single electron)

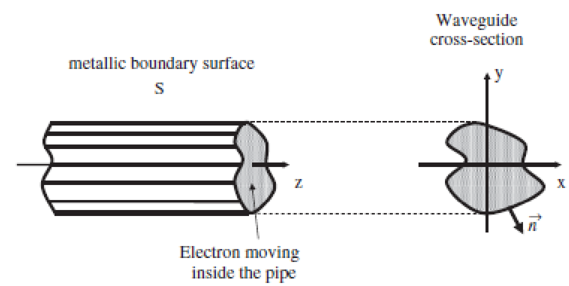
WEPC02

Many possible applications:

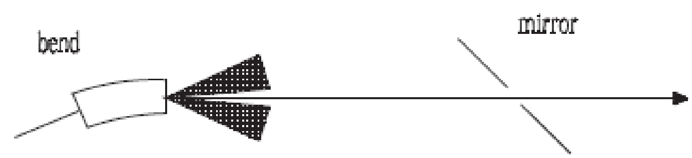
Transition Undulator Radiation



Edge radiation in a waveguide



Extraction of edge radiation from a mirror
(Transition radiation setup)

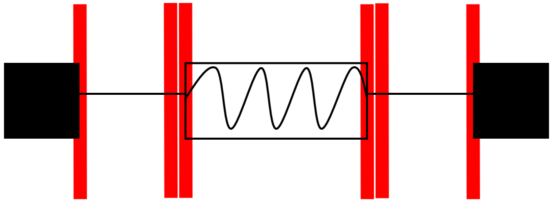


Coherent edge radiation

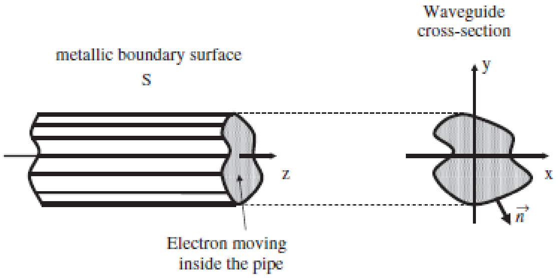
WEPC02

Many possible applications:

Transition Undulator Radiation



Edge radiation in a waveguide



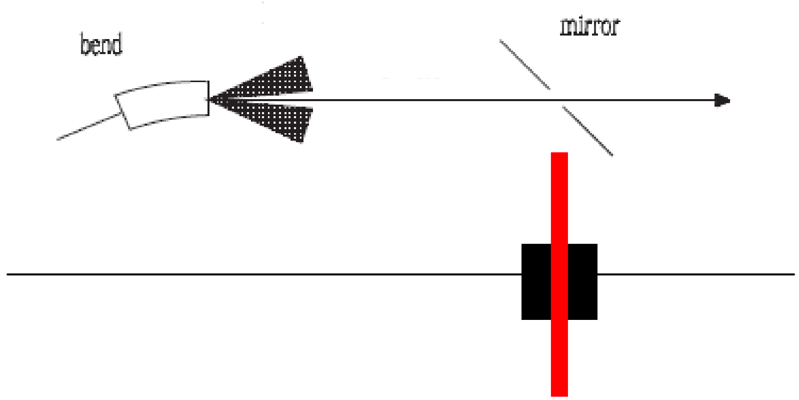
Extraction of edge radiation from a mirror
(Transition radiation setup)

Coherent edge radiation

Edge Radiation and Transition Radiation

WEPC02

Typical treatment of TR uses the Ginzburg-Frank approach



$$\vec{\vec{E}}(\vec{r}) = -\frac{2\omega e}{c^2\gamma}\frac{\vec{r}}{r}K_1\left(\frac{\omega r}{c\gamma}\right)$$

…what about the other edge? And the contribution from the bend?

THz Radiation

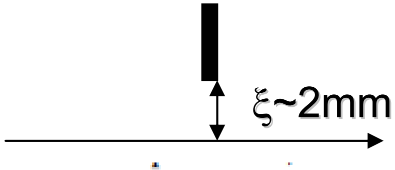
E=500 MeV, R~2 m, L~15 cm, λ=1200 μm

$$\Rightarrow \delta = \frac{\sqrt[3]{R^2 \lambda\!\!\!^{-}}}{L} \sim 0.6$$

Contribution from bend
Cannot be neglected!

High-Energy, Optical diffraction radiation

E=7 GeV, L~5 m, λ=800 nm
→ $\gamma^2\lambda/(2\pi)$~30m i.e. ϕ~0.2

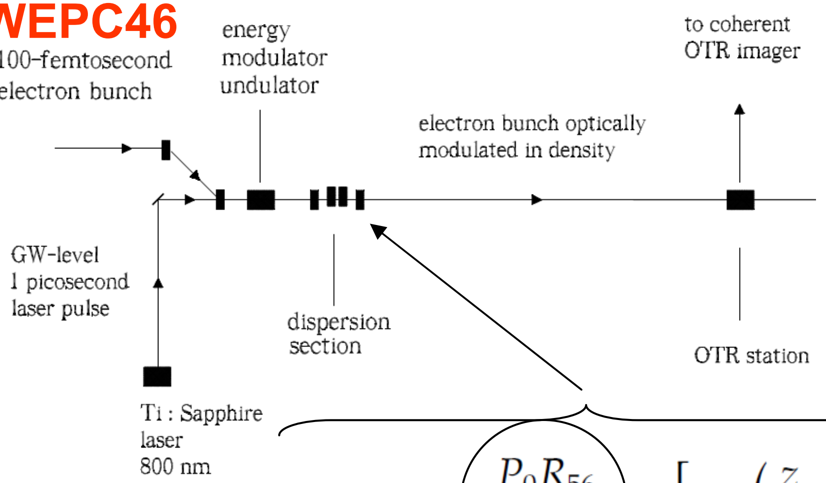


$\xi \sim \gamma\lambda/(2\pi)$
No exponential suppression

$$\vec{\vec{E}}\left(\frac{L}{2},\vec{r}\right) = -\frac{2e}{c}\frac{\vec{r}}{r^2}\exp\left[\frac{i\omega r^2}{2cL}\right]$$

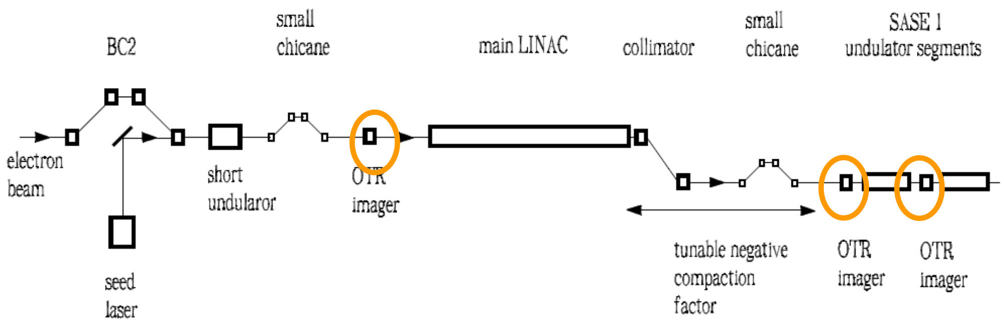
Integration of the OTR imager with the ORS

WEPC46



$$I = I_0 + I_0 \cdot \frac{P_0 R_{56}}{\lambda_m \mathcal{E}_0} \cos\left[\omega_m\left(\frac{z}{v_z} - t\right)\right]$$

a

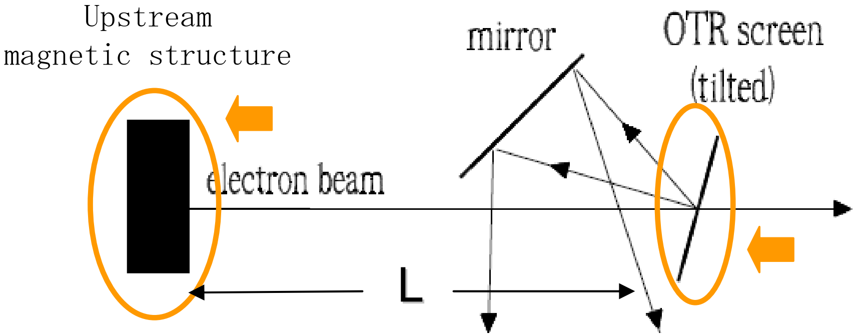


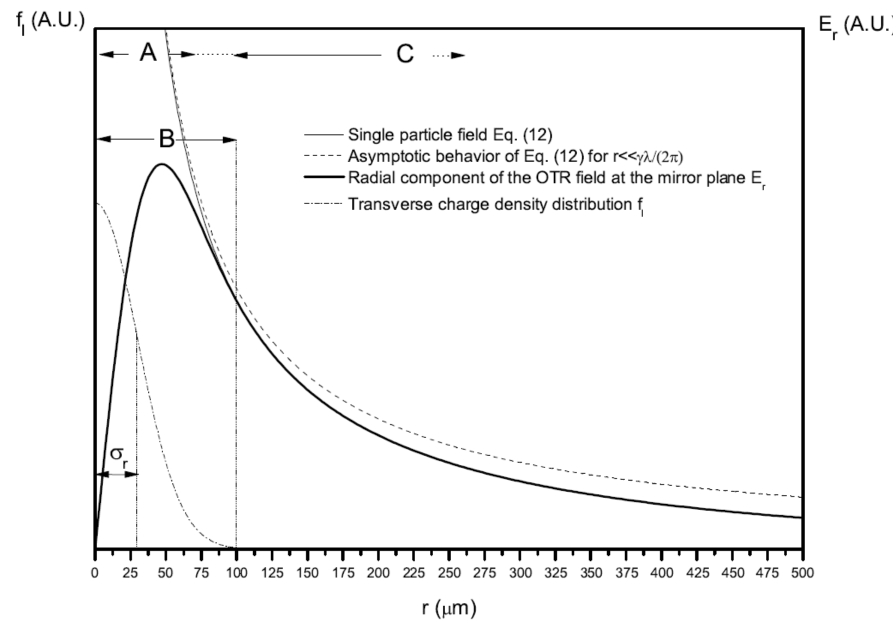
- Seed Laser:
  - λ=800 nm
  - E = 1 mJ
  - Duration (FWHM)= 1 ps
  - Rayleigh length = Lw
  - Waist at the undulator center
  - r (waist) = 20 r (bunch) = 600 μm
- Modulator undulator:
  - L_w=β=1 m ; N_w = 5 ; λ_w = 20 cm)
  - Energy modulation: 500 keV
  - Energy of e^- @ modulation: 2 GeV
  - Modulation energy P_0=500 keV
- Dispersion: R_{56} = 50 μm
  - Initial density modulation a = 10%

European XFEL

Integration of the OTR imager with the ORS

WEPC46





Can neglect upstream source when

$$\phi \equiv \frac{L}{\gamma^2 \bar{\lambda}} \qquad \phi >> 1$$

For us: $\phi \gtrsim 1 \quad \phi \sim 1$ But we are interested in $\sigma_c << \gamma\lambda/(2\pi)$

because the total field is a convolution in space of the FT of the charge density distribution and the FT of the single-electron field

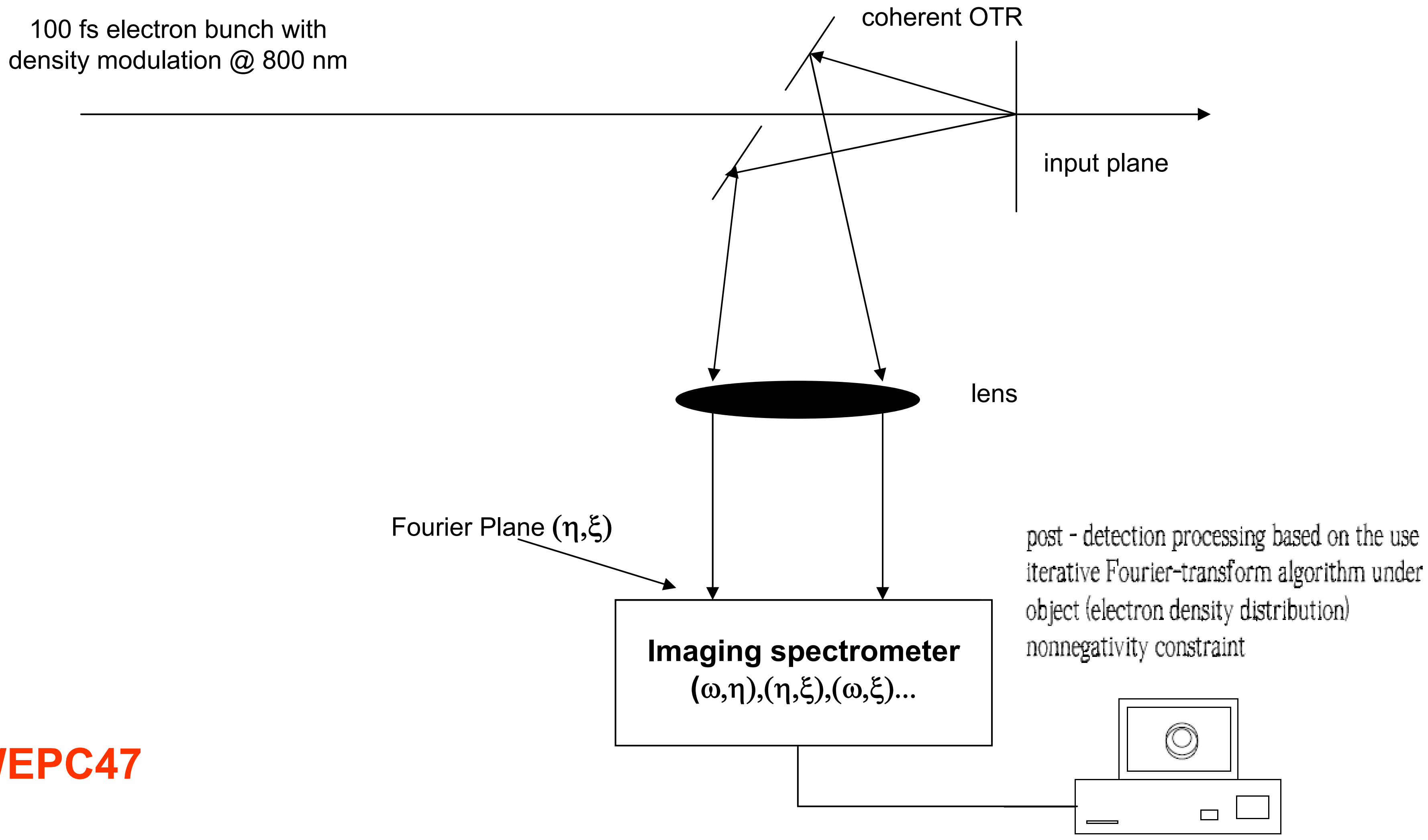
It can be shown that in this case $L_f(\sigma_c) \sim \sigma_c^{\ 2} / \bar{\lambda} << \gamma^2 \bar{\lambda}$

For our parameter choice the G-F description holds for the field (envelope)

$$\vec{\tilde{E}}(\vec{r}) = -\frac{2\omega e}{c^2 \gamma} \frac{\vec{r}}{r} K_1\left(\frac{\omega r}{c\gamma}\right)$$

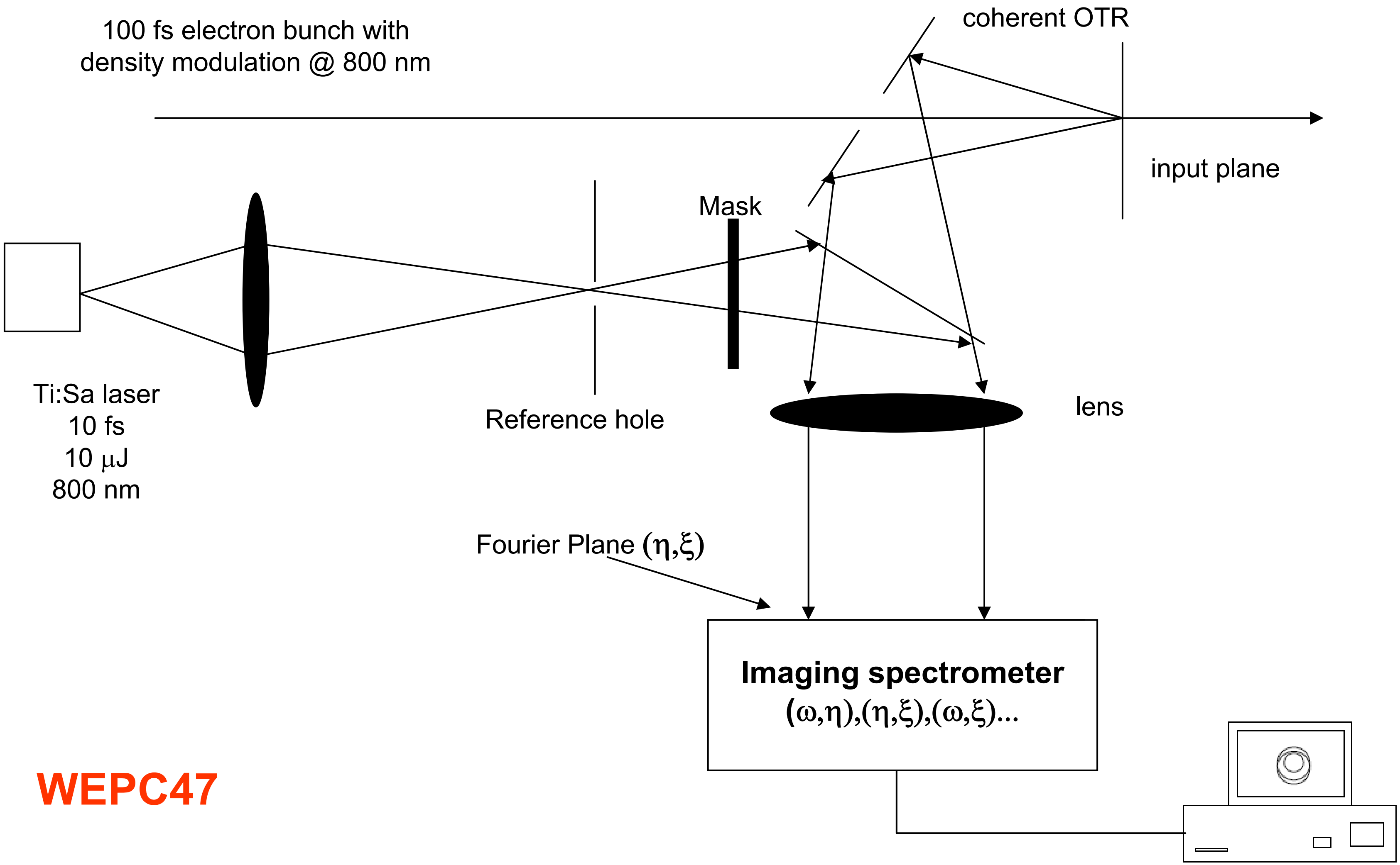
DESY HELMHOLTZ ASSOCIATION

Towards 3D structure determination of ultrashort electron bunches



WEPC47

Towards 3D structure determination of ultrashort electron bunches



WEPC47

European XFEL

Conclusions

- Theory of Edge Radiation important for many FEL-related applications
- Based on two main parameters : δ and ϕ
- Undulator transition radiation, ER in a waveguide, Extraction from a mirror… many possible applications
- In particular, Transition radiation → XFEL diagnostiocs
- New field in e-beam diagnostics using coherent (vs. incoherent) Optical Transition Radiation
- Main advantage exploited: large coherent photon number
- Using imaging spectrometers based on

  - Diffraction Imaging

  - Holography

  towards the 3D structure determination of ultrashort electron beams!

DESY HELMHOLTZ ASSOCIATION