

Michael Scheer, CAoPAC 2015



**WAVE A Computer Code for the Tracking of Electrons through  
Magnetic Fields and the Calculation of Spontaneous  
Synchrotron Radiation**

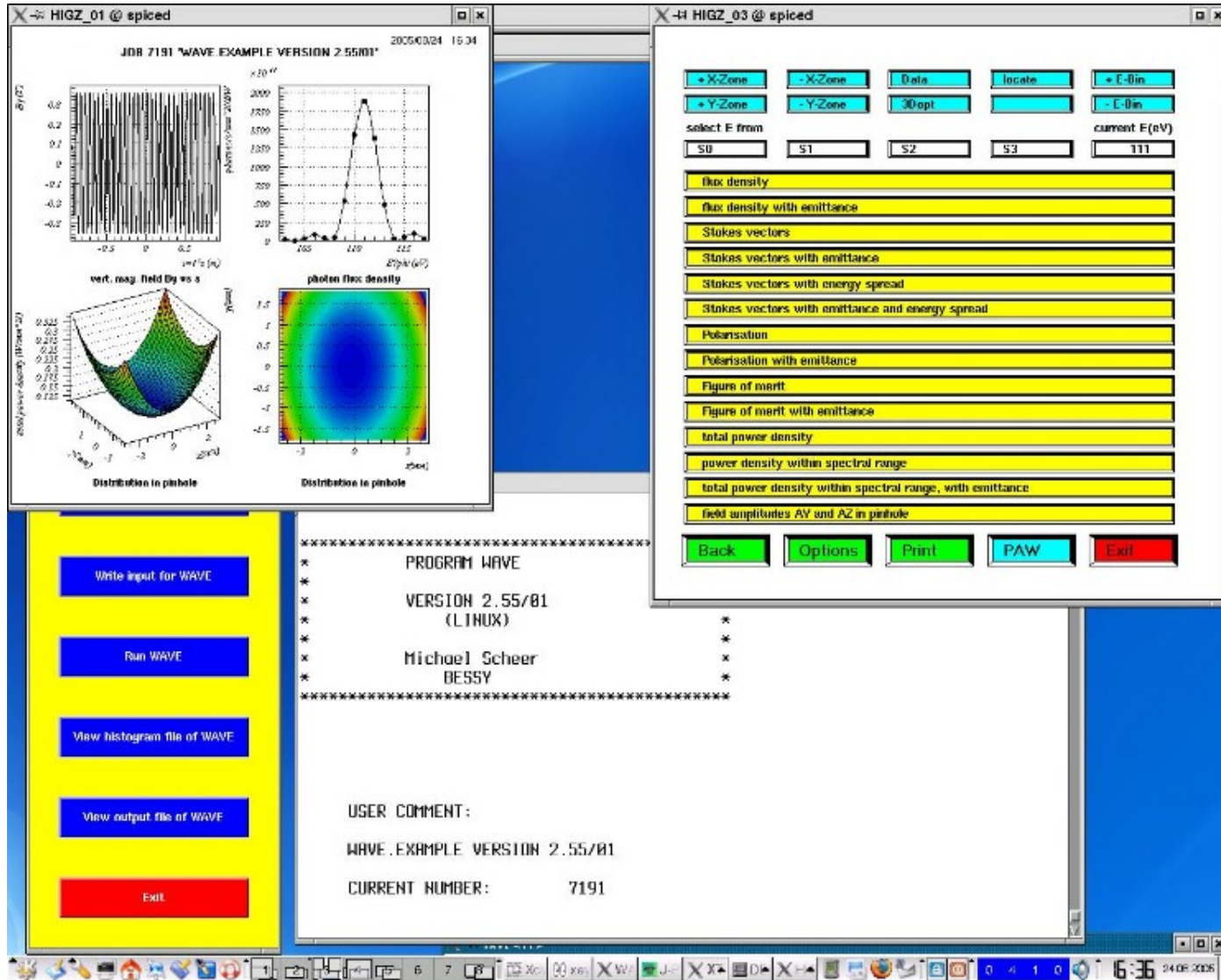
- History
- How to run it
- How it works
  - Tracking
  - Magnetic fields
  - Synchrotron radiation
  - User interfaces
  - Interfaces to other codes
- Synchrotron radiation of IDs
- Accelerator physics
- Status and installation

Developed since 1990 for an expert's report about WLS for metrology in the x-ray regime requiring:

- High accuracy ( $\Delta < 10^{-4}$ ) for the calculation of SR
- Investigation of the impact of the WLS on the machine, with respect to beta-functions, emittance, beam polarization, and dynamic aperture

Since 1993 the emphasis is placed on undulators, both magnetic fields and SR spectra.

Since 2009: Coherent radiation (NOT FEL) of electrons in a phase-space, energy loss, electric fields, CPU cluster



WAVE is controlled by input files to run in batch mode

GUI:

To handle files and visualize results

Based on Perl-Tk and PAW or ROOT

\$Contrl

```
!----- User Comment -----  
      CODE='WAVE.EXAMPLE'  
!----- Main Modes -----
```

! The undulator and wiggler modes should work for standard  
! insertion devices. Reasonable settings for some parameters  
! are taken (mainly in namelist COLLIN).  
! Experienced users might prefer their own settings.

```
IUNDULATOR=1      ! UNDULATOR MODE:  
                   ! whole trajectory is taken as source of  
                   ! synchrotron light (ignoring input of  
                   ! parameters WGWINFC, collimators ...)  
                   ! ISPECMODE = 1  
                   ! IMAGSPLN = -9999  
                   ! NLPOI = -9999  
                   ! WGWINFC = 45.  
                   ! ISPECDDIP = 0  
                   ! IFOLD = 1, if IFOLD.NE.0  
                   ! IEFOLD = 1, if IEFOLD.NE.0  
                   ! IF (IPIN.GT.0) IPIN = 1  
                   ! BMOVECUT = 1.E-7
```

!----- Magnetic Fields -----

KHALBA=0           ! insertion device described by HALBACH's formulas  
                  ! parameter namelist HALBACH  
                  ! magnetic field routine BHALBA  
                  ! KHALBA.lt.0 means zero field outside device

!----- Parameter Namelists -----

\$HALBACH           ! magnetic field defined by HALBACH formula  
                  ! coordinate system here different from the  
                  ! standard of WAVE, HALBACH's convention used  
                  ! i.e. z is longitudinal device axis  
                  ! the system is internally converted to WAVE standard  
B0HALBA=0.5       ! peak field [T]  
XLHALBA=0.0       !  $2\pi/k_x$  (horizontal gradient) [m]  
                  ! XLHALBA=0 means YLHALBA=ZLHALBA (no gradient)  
ZLHALBA=0.04      !  $2\pi/k_z$  [m]  
PERHAL=50         ! number of periods

\$END

## User interfaces:

- Subroutine uname called after initialization
- Subroutine bextern for user-defined mag. fields
- Subroutine ustep to control tracking on step level
- Subroutine ubunch to generate electron distribution in phase-space
- Subroutine uout for user-defined output

## Interfaces to other codes:

- RAY, Franz Schäfers, HZB (BESSY)
- PHASE, Johannes Bahrtdt, HZB (BESSY)
- Generating Functions for tracking codes (e.g. BETA)

## Graphics and data: ASCII, PAW, ROOT, HDF5

## **Magnetic Fields:**

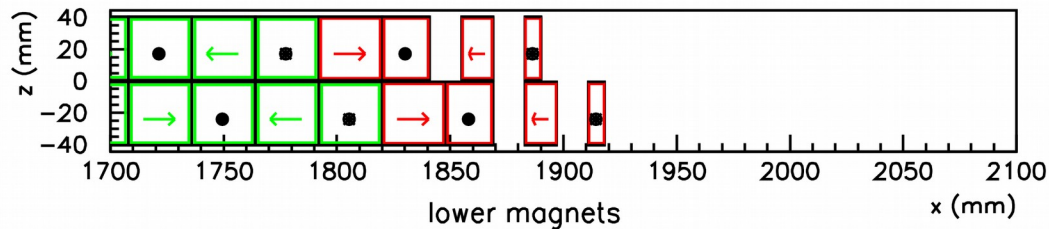
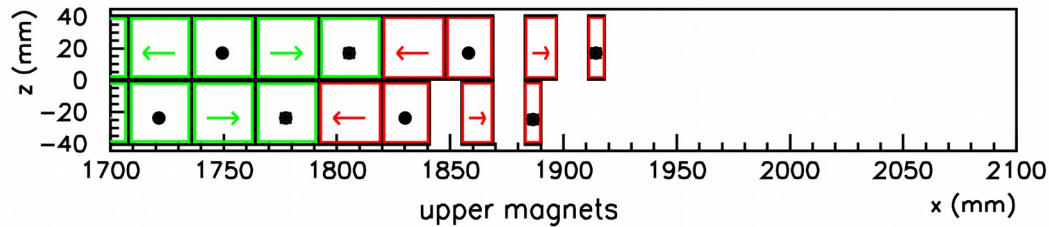
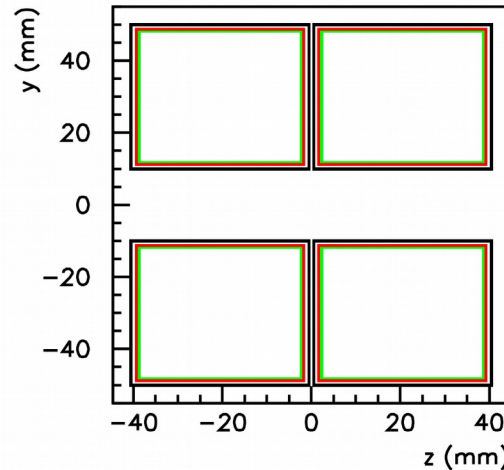
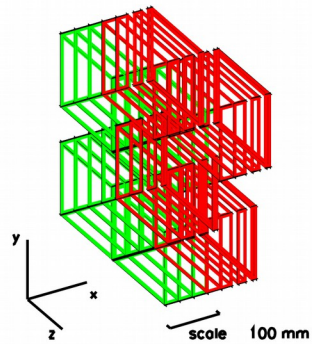
- Planar and helical wigglers and undulators as analytical models of permanent magnet structures
- Tapers and field errors of insertion devices
- Dipoles, quadrupoles, sextupoles with fringe fields
- In- and output of magnetic fields maps or tables
- Maxwell-conform parametrization and interpolation of magnetic fields

## **Tracking:**

- Field is taken as constant for each tracking step
- Continuous or discrete energy loss can be taken into account important for long undulator sections (XFEL)

2009/02/18 14.46

UE112



REC model  
of UE112

Current sheet  
method

Endpole  
configuration

## Maxwell-conform 2D fields as a superposition of functions

$$B_y(y, z) = B_0 \sum_{0 < m, n} C_{mn} \cosh(mk_y y) \cos(nk_z z)$$

$$B_z(y, z) = -B_0 \sum_{0 < m, n} \frac{nk_z}{mk_y} C_{mn} \sinh(mk_y y) \sin(nk_z z)$$

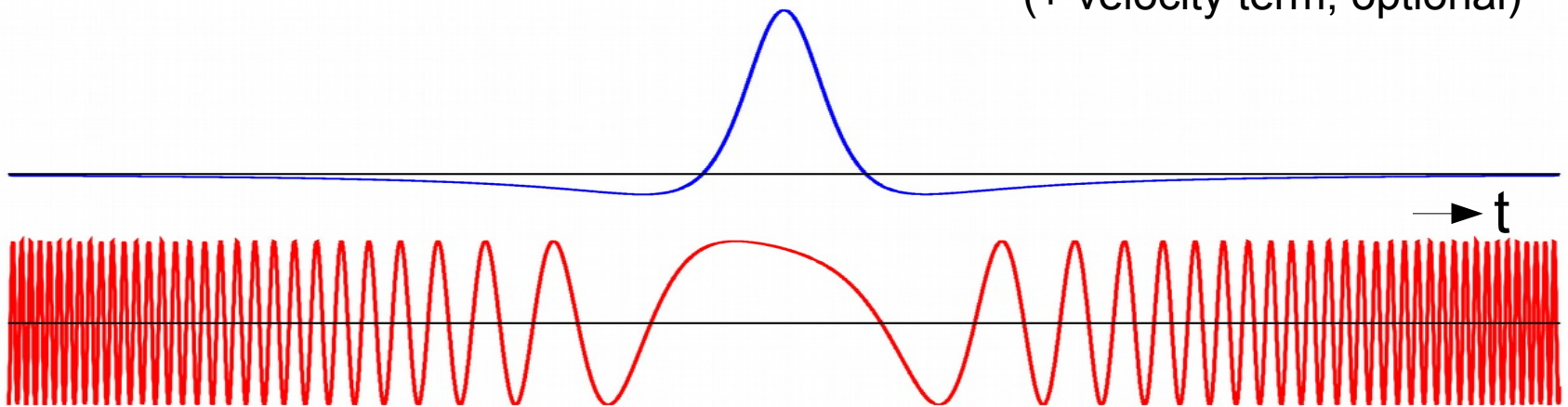
$$nk_z = mk_y$$

3D expansion for undulators are given in, J. Bahrtdt,  
G. Wüstefeld, Phys. Rev. ST Accel. Beams 14, 040703 (2011)

Numerical integration over the steps of the trajectory

$$\int_0^{\Delta T} \frac{1}{R(t)} \frac{\vec{n}(t) \times [(\vec{n}(t) - \vec{\beta}(t)) \times \dot{\vec{\beta}}(t)]}{(1 - \vec{\beta}(t)\vec{n}(t))^2} e^{i\omega(t+R(t)/c)} dt$$

(+ velocity term, optional)



$$\Delta s = c \cdot \Delta T = 6 \text{ mm}$$

Evaluate integral numerically for steps of trajectory

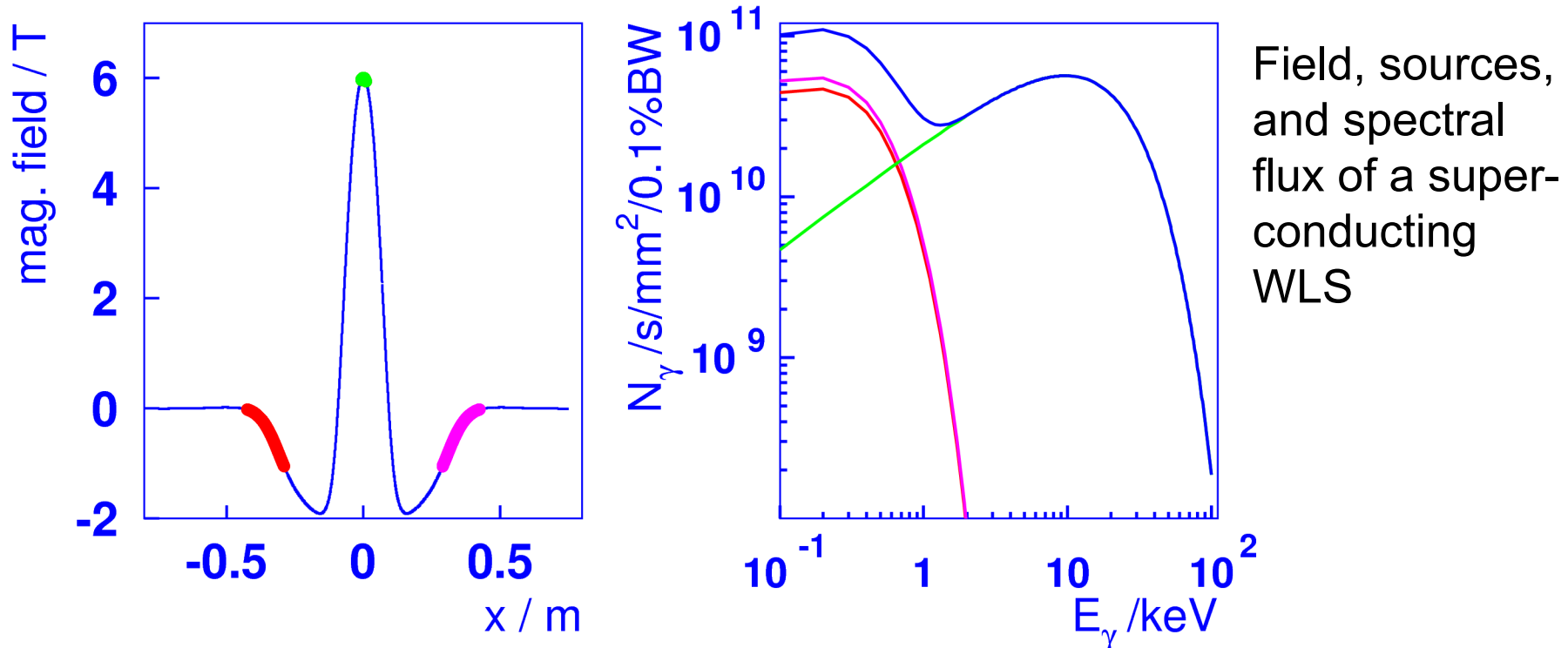
$$\int_0^{\Delta T} \frac{1}{R(t)} \frac{\vec{n}(t) \times [(\vec{n}(t) - \vec{\beta}(t)) \times \dot{\vec{\beta}}(t)]}{(1 - \vec{\beta}(t)\vec{n}(t))^2} e^{i\omega(t+R(t)/c)} dt$$

Treat  $\omega$ -independent part as constant for each integration step and expand phase to first order

$$\sum_{j=1}^N \frac{1}{R(t_j)} \frac{\vec{n}(t_j) \times [(\vec{n}(t_j) - \vec{\beta}(t_j)) \times \dot{\vec{\beta}}(t_j)]}{(1 - \vec{\beta}(t_j)\vec{n}(t_j))^2} e^{i\omega(t_j+R(t_j)/c)} \\ \times \frac{1 - e^{i\omega(1-\vec{\beta}(t_j)\vec{n}(t_j))\Delta t_j}}{(1 - \vec{\beta}(t_j)\vec{n}(t_j))\omega}$$

$$e^{i\omega(t_{j+1}+R(t_{j+1})/c)} \approx e^{i\omega(t_j+R(t_j)/c)} \times e^{i\omega(1-\vec{\beta}(t_j)\vec{n}(t_j))\Delta t_j}$$

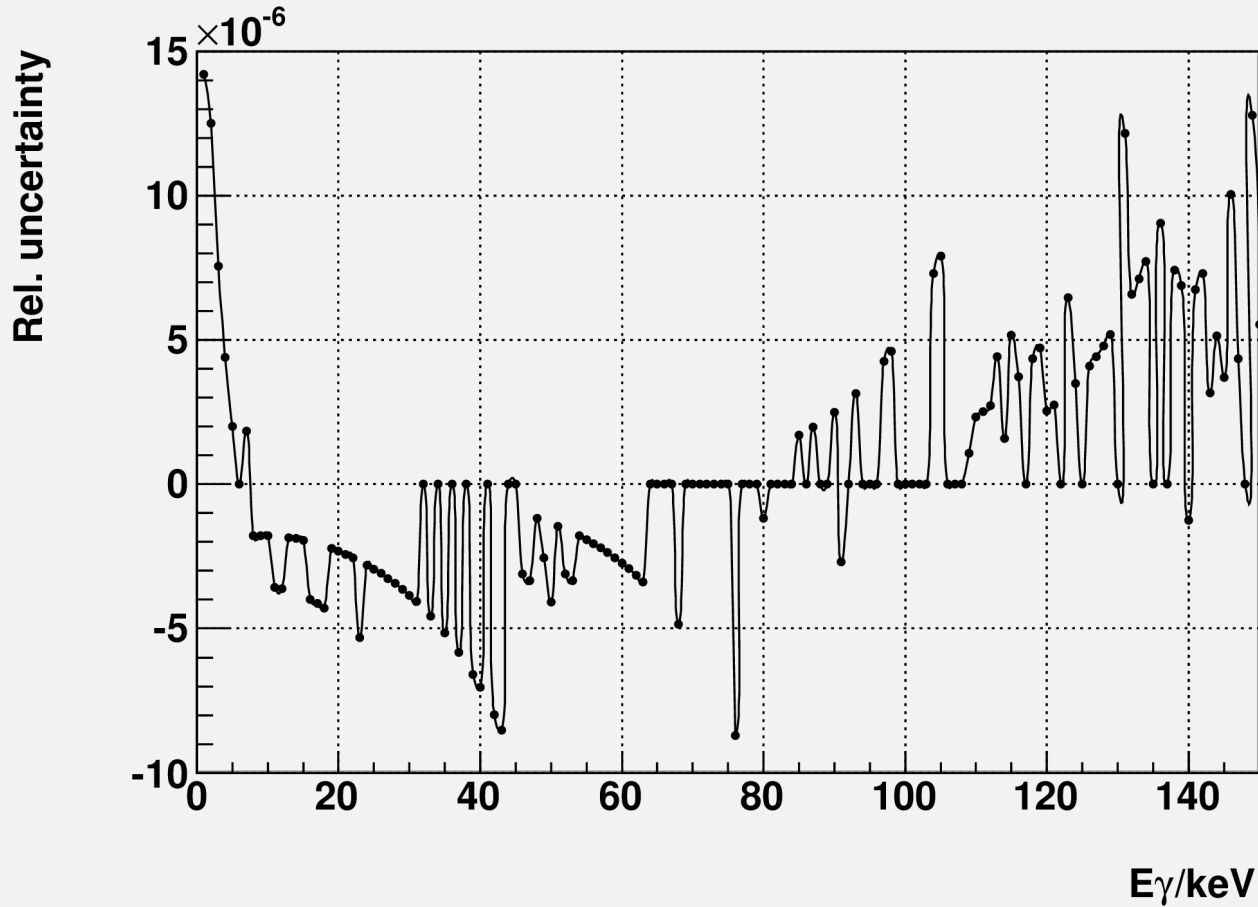
1. Track particle and find sources
2. Calculate radiation coherently for each source
3. Sum up contribution of sources incoherently
4. Apply filters, emittance folding, e-spread folding etc.
5. Integration of flux and power distributions over pinhole

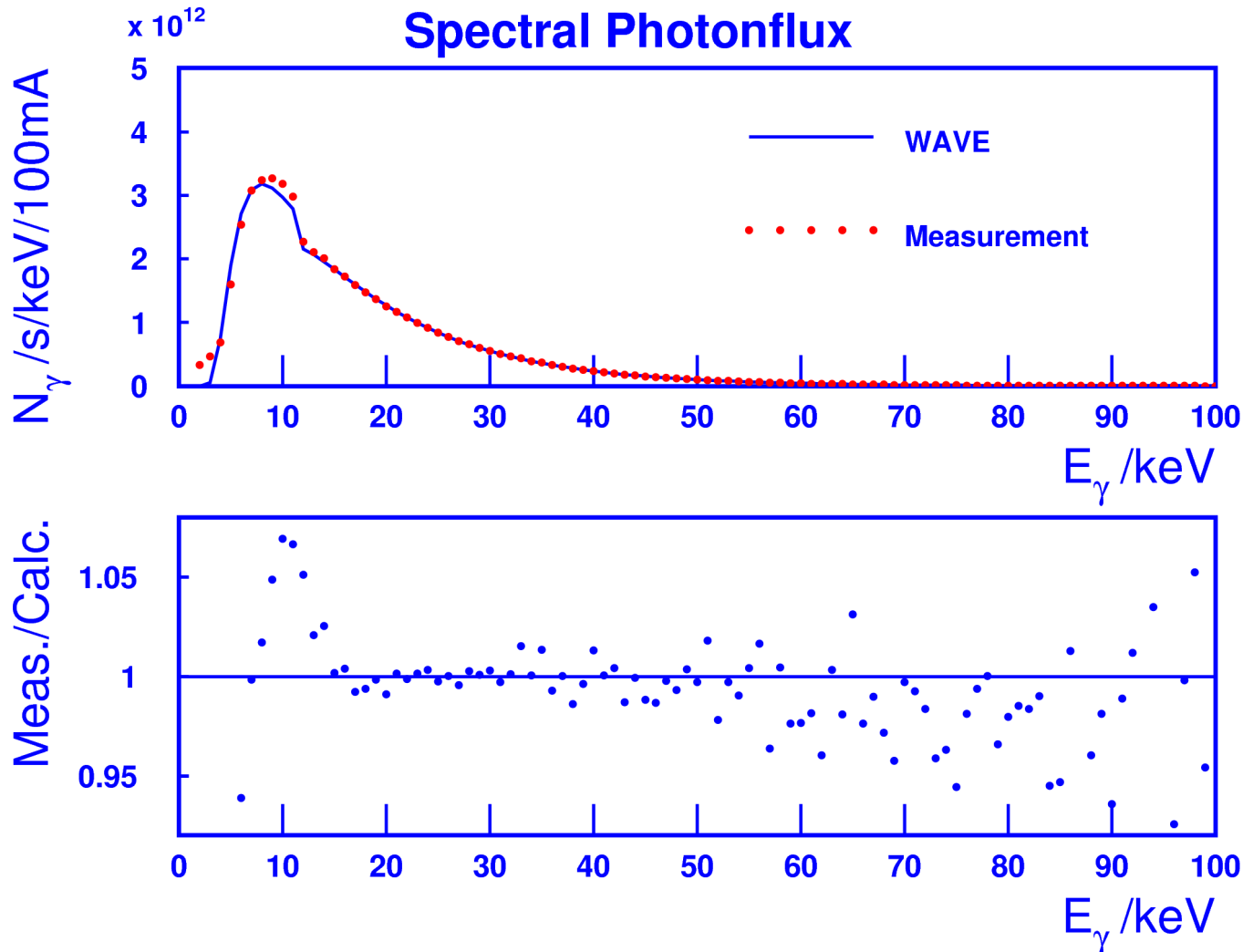


## Options:

- Flux through circular and rectangular pinholes
- Stokes parameters and polarisation
- Influence of beam emittance and energy spread
- Brilliance
- Field amplitudes and their propagation, e.g. to the center of the source
- Discrete and continuous energy loss
- Coherent radiation of particles in a bunch (no FEL!)
- Application of filters
- Radiation dose

Ratio of 6T dipole spectra (WAVE / Schwinger code of PTB)

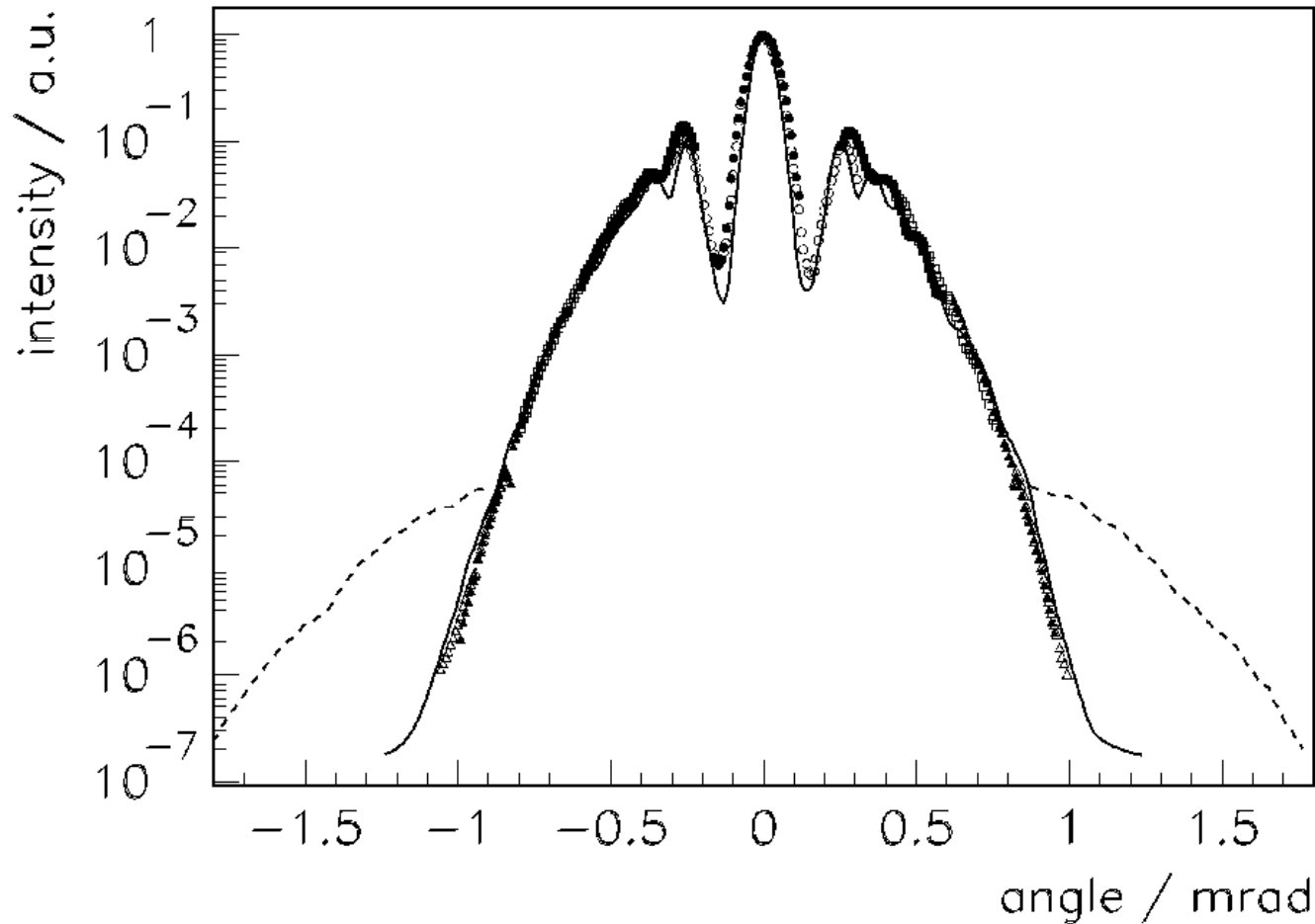




Calculation and Measurement of absolute photon flux of a 6T-WLS

Ratio of measurement and calculation

## Horizontal distribution of synchrotron radiation of the UE56



Comparison of  
measurements  
and WAVE  
calculations

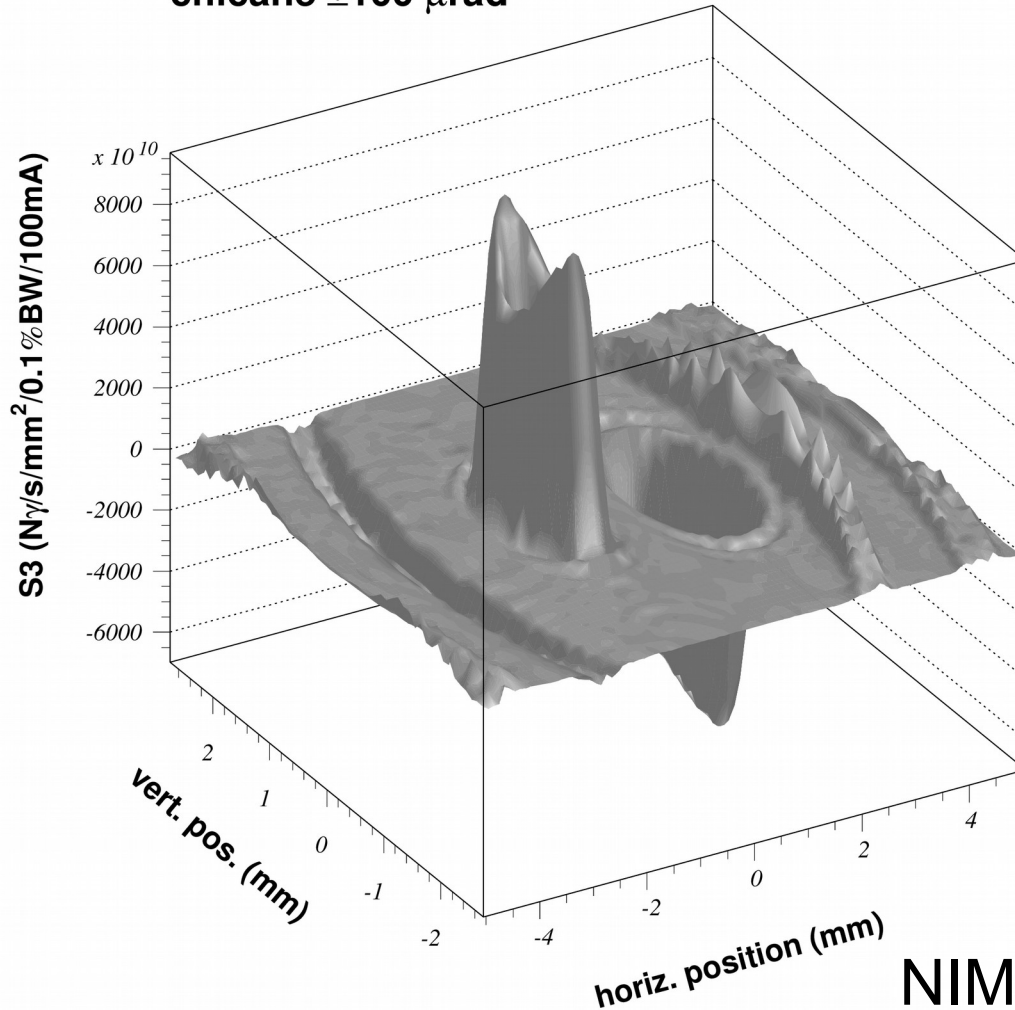
Marker:  
Measurement

Solid line:  
WAVE

Dashed line:  
Slicing signal

<http://cern.ch/AccelConf/p03/papers/mppb005.pdf>

**UE56, 3. Harm.,  $K=2.5$ ,  $E_\gamma=354\text{eV}$ , 13m distance  
chicane  $\pm 100 \mu\text{rad}$**

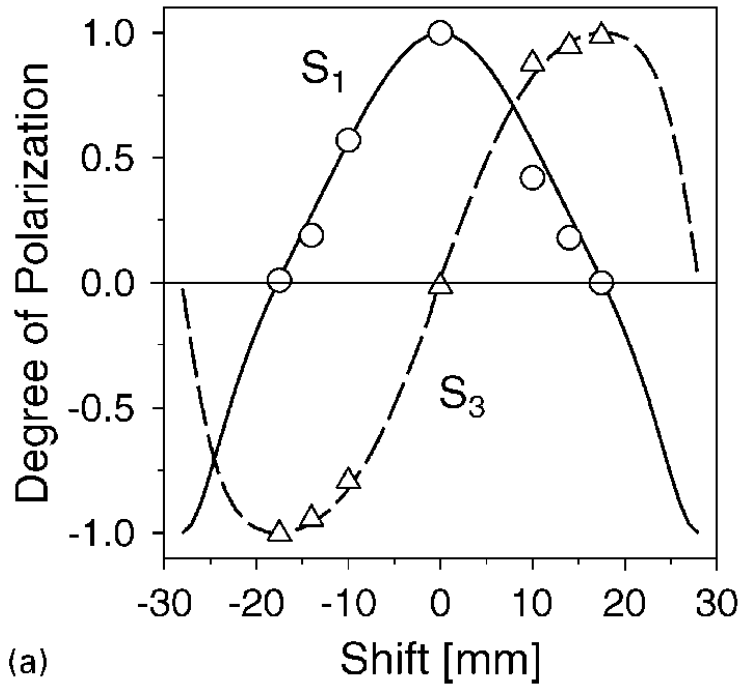


The radiation cones of the two undulators are separated by a  $100\mu\text{rad}$ -chicane

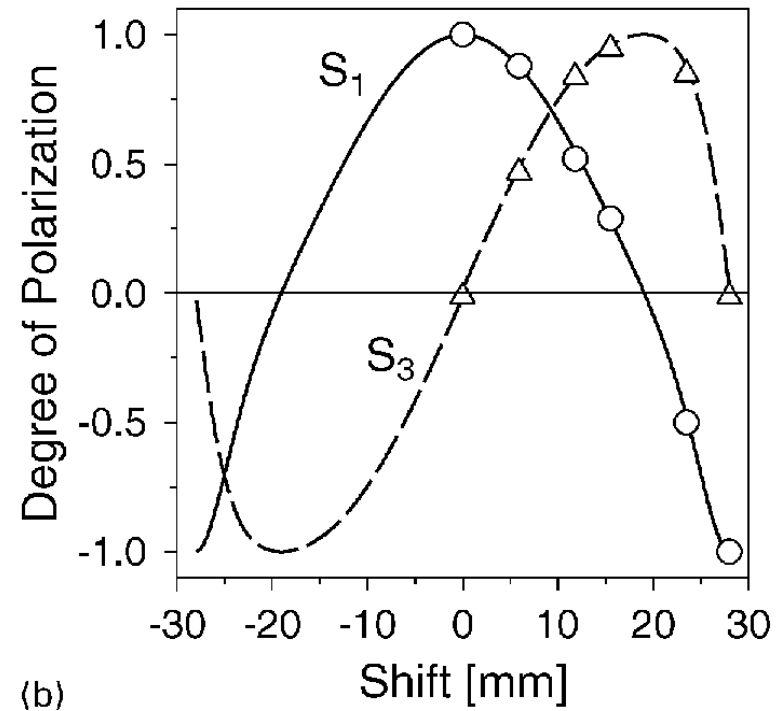
The figure shows the spatial distribution of the circularly polarized radiation

**NIM A 467-468 (2001) 21-29**

DSU: 1. Harmonic (98 eV), PGM1



USU: 3. Harmonic (712 eV), PGM2

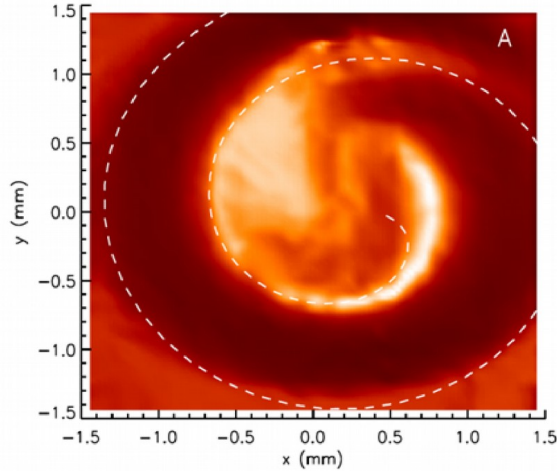


Markers: Measurements    Lines: WAVE calculations

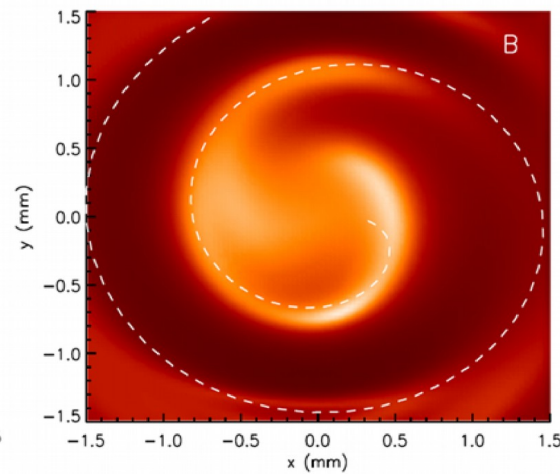
NIM A 467-468 (2001) 21-29

10 degree  
phase shifting

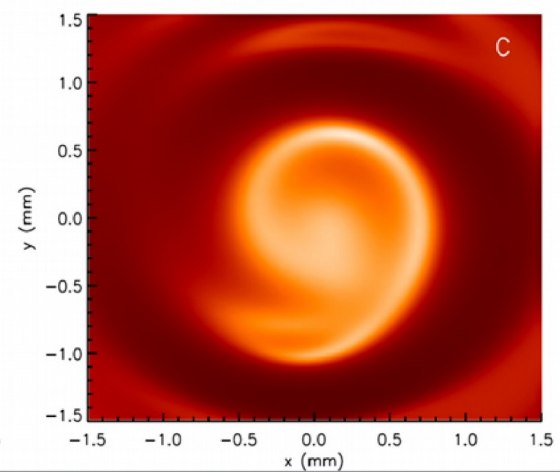
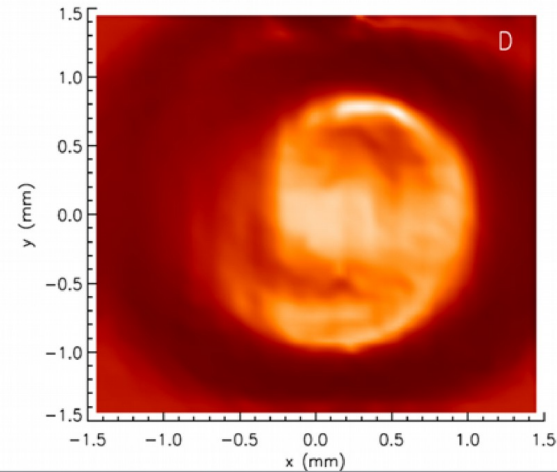
Measurements



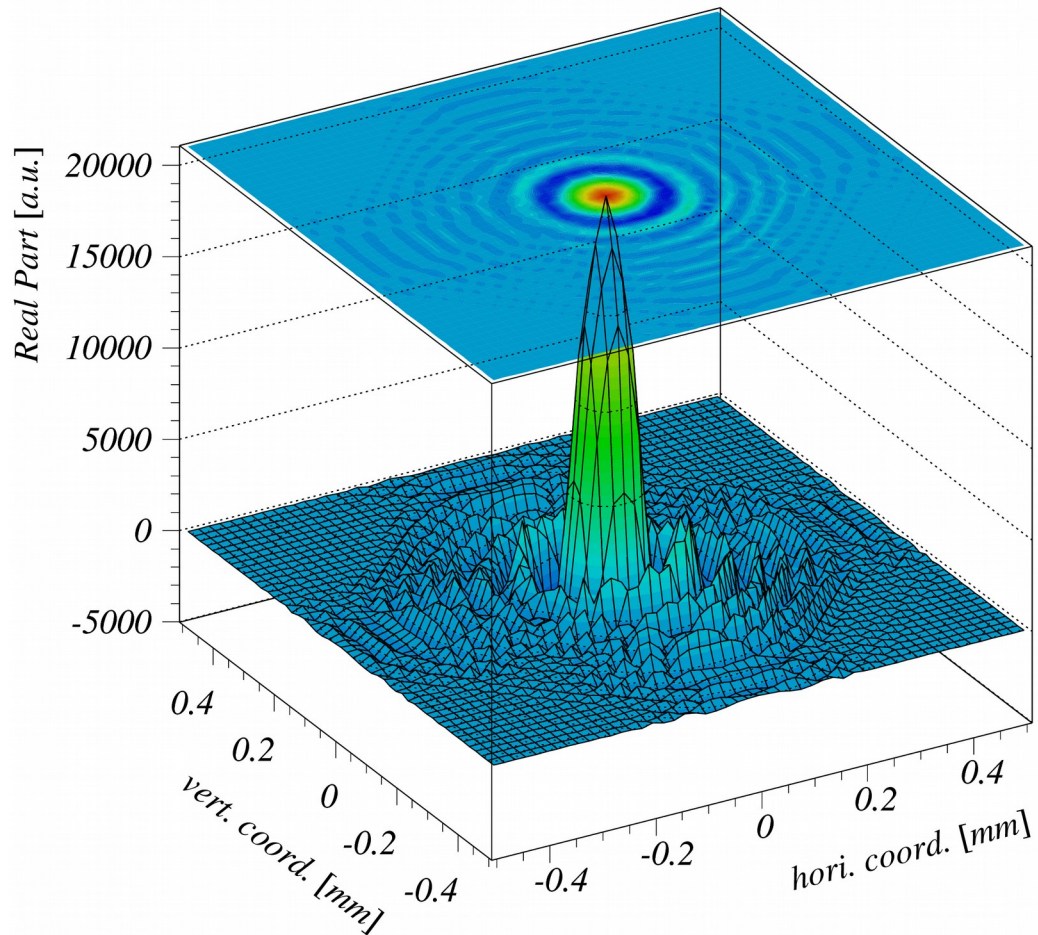
Simulations with WAVE



0 degree  
phase shifting

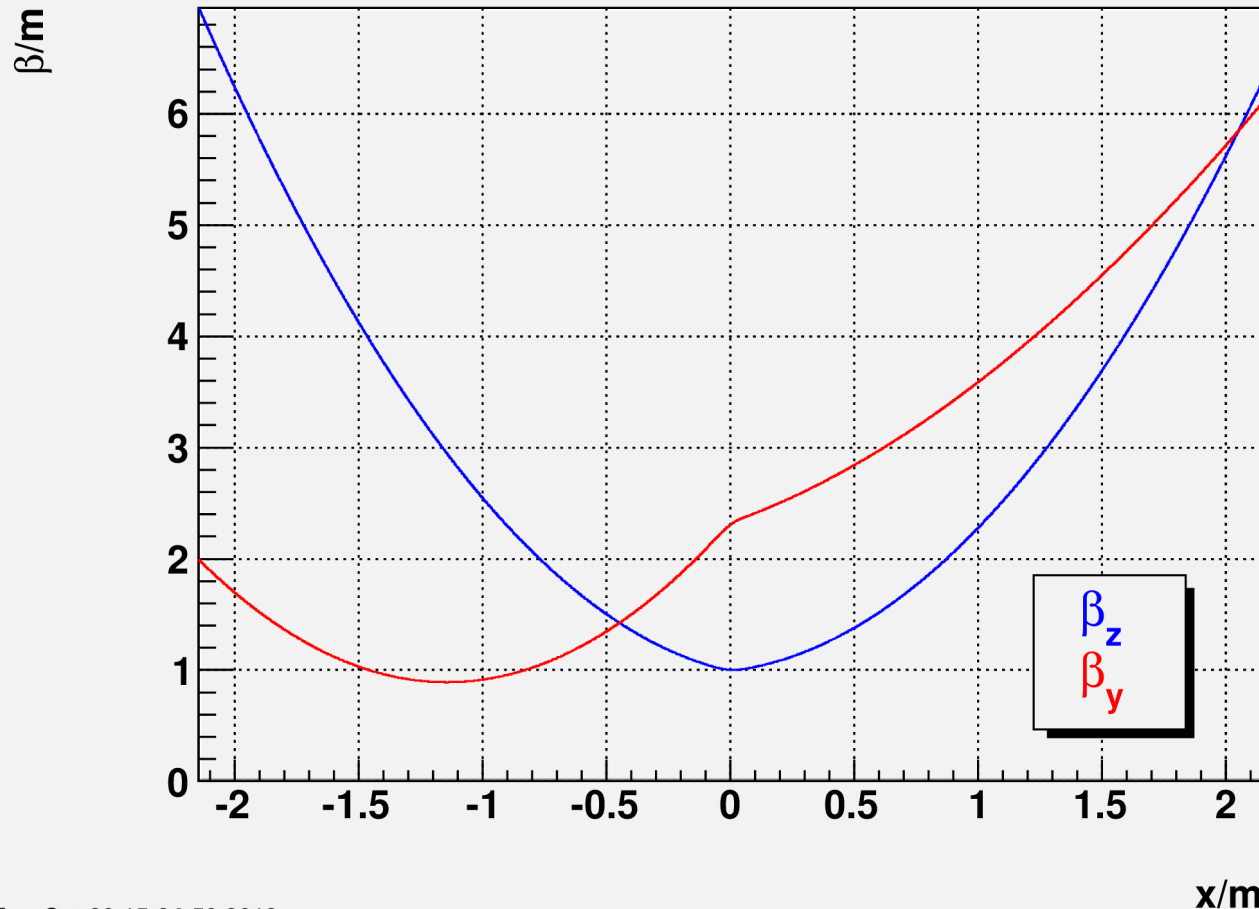


DOI: 10.1103/PhysRevLett.111.034801

**Field Amplitude in the Centre of an Elliptical Undulator**

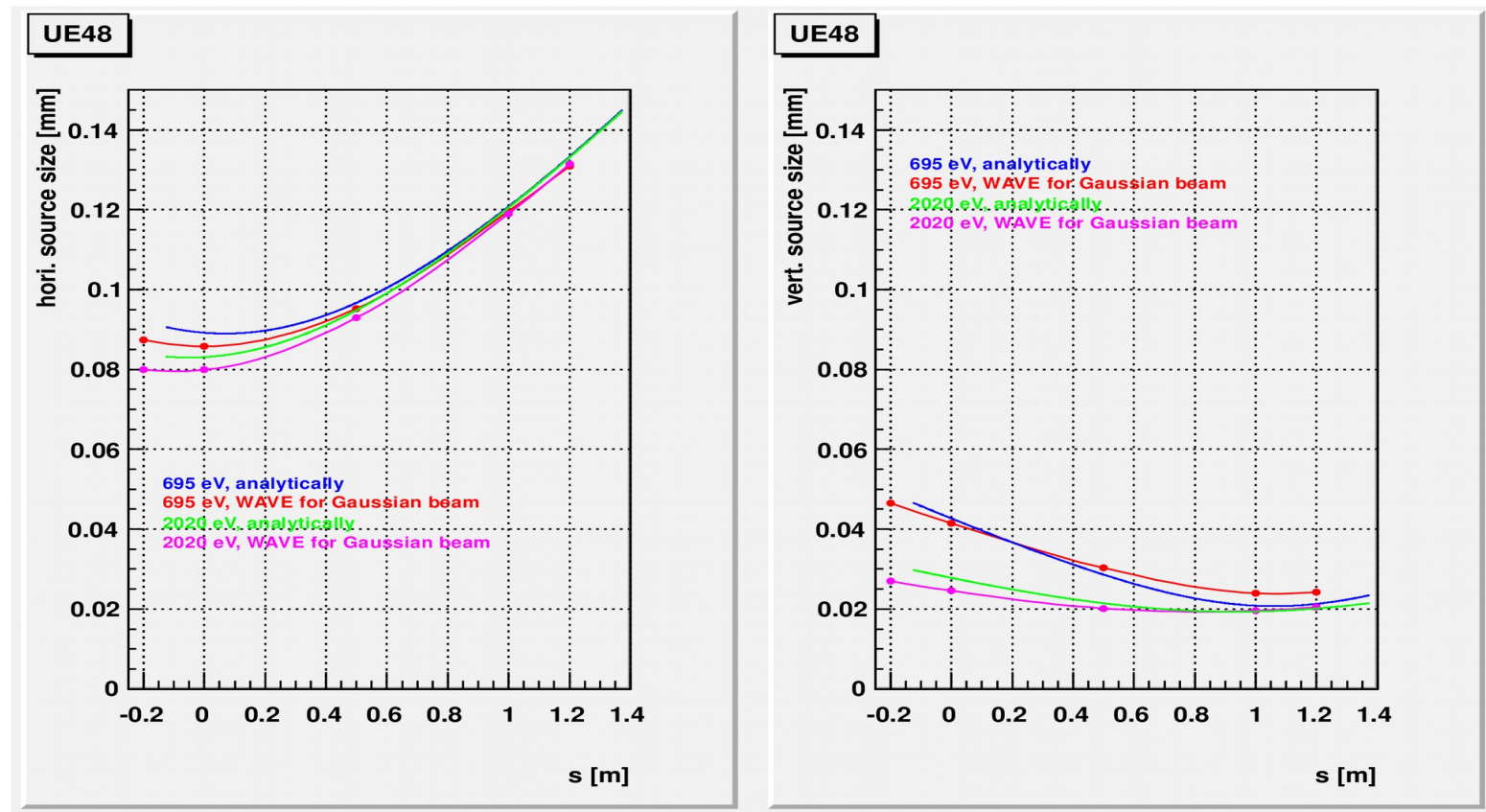
Field amplitude of an elliptical undulator, transformed from 10m down-stream to center of device

## Run 8289: Beta Functions



Mon Oct 29 15:24:59 2012

Where is the source, when the waist of the beta function is not in the center of the undulator?



Analytical approximation of the source size for max. flux at wavelength  $\lambda$ :

$$\sigma(s)^2 = \sigma(0)^2 + \sigma'(0) \cdot s^2$$

$$\sigma(0) \cdot \sigma'(0) = \lambda / (2\pi)$$

$$\sigma'(0)^2 = \lambda / L$$

$$\beta(s) = \beta(s_0) + (s-s_0)^2 / \beta(s_0)$$

Source size:

$$\Sigma(s)^2 = \varepsilon \cdot \beta(s) + \sigma(s)^2$$

Another approach:

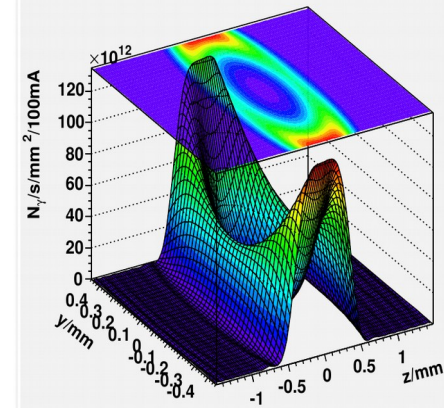
Track many particles according to phase-space and bunch structure

Synchrotron radiation of particles in the same bunch are summed up coherently, of different bunches incoherently.

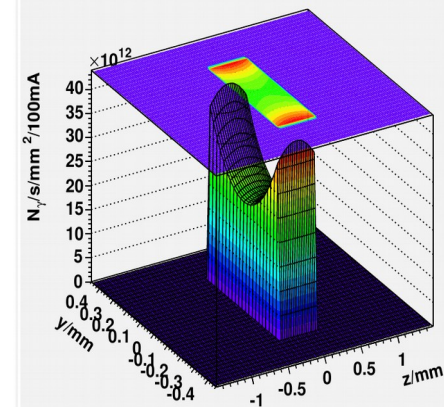
Since position in phase-space and position of observation points are uncorrelated, observation points and electron can be randomized Simultaneously. Can be much faster!

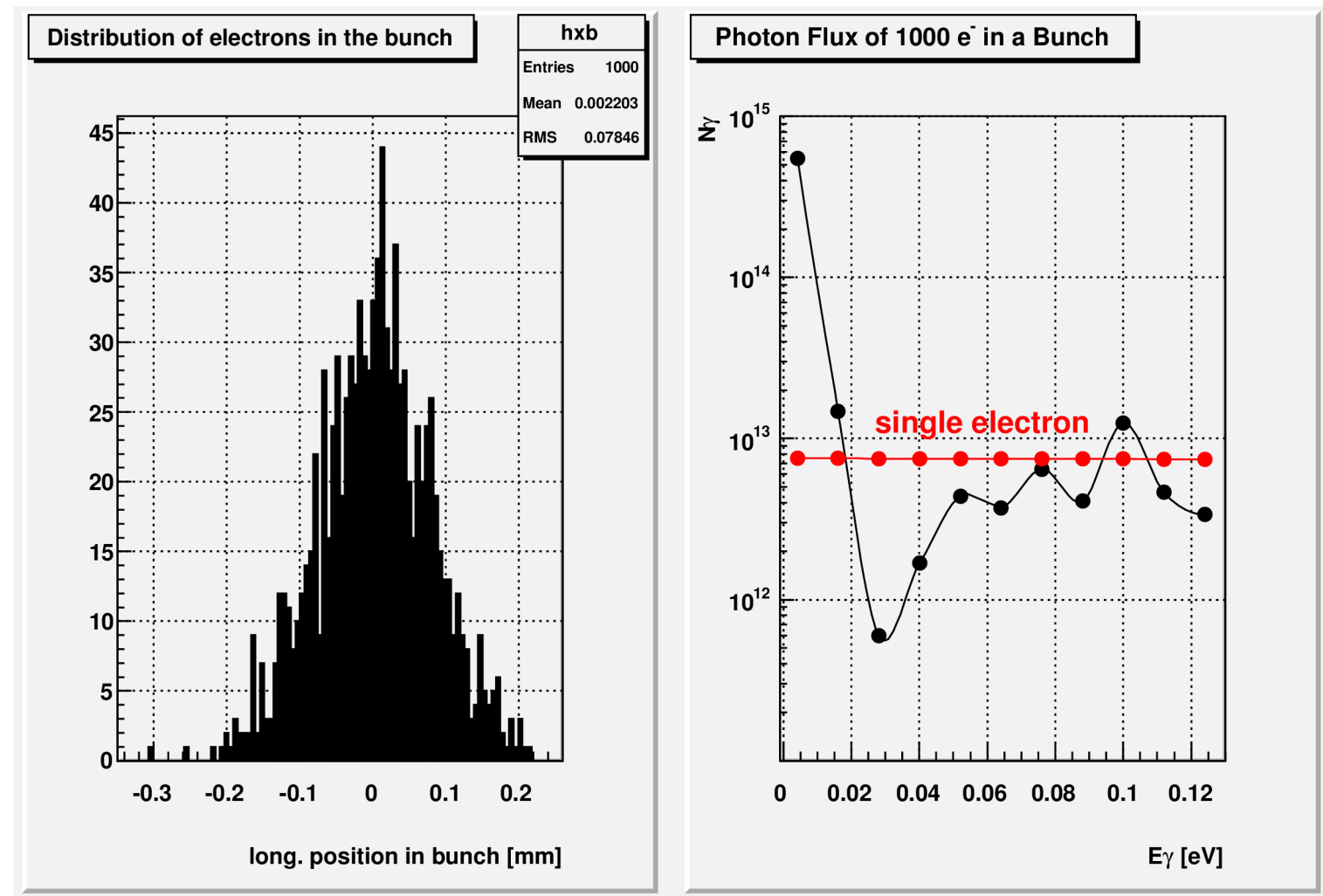
BUT: Statistical noise

Flux-density S0

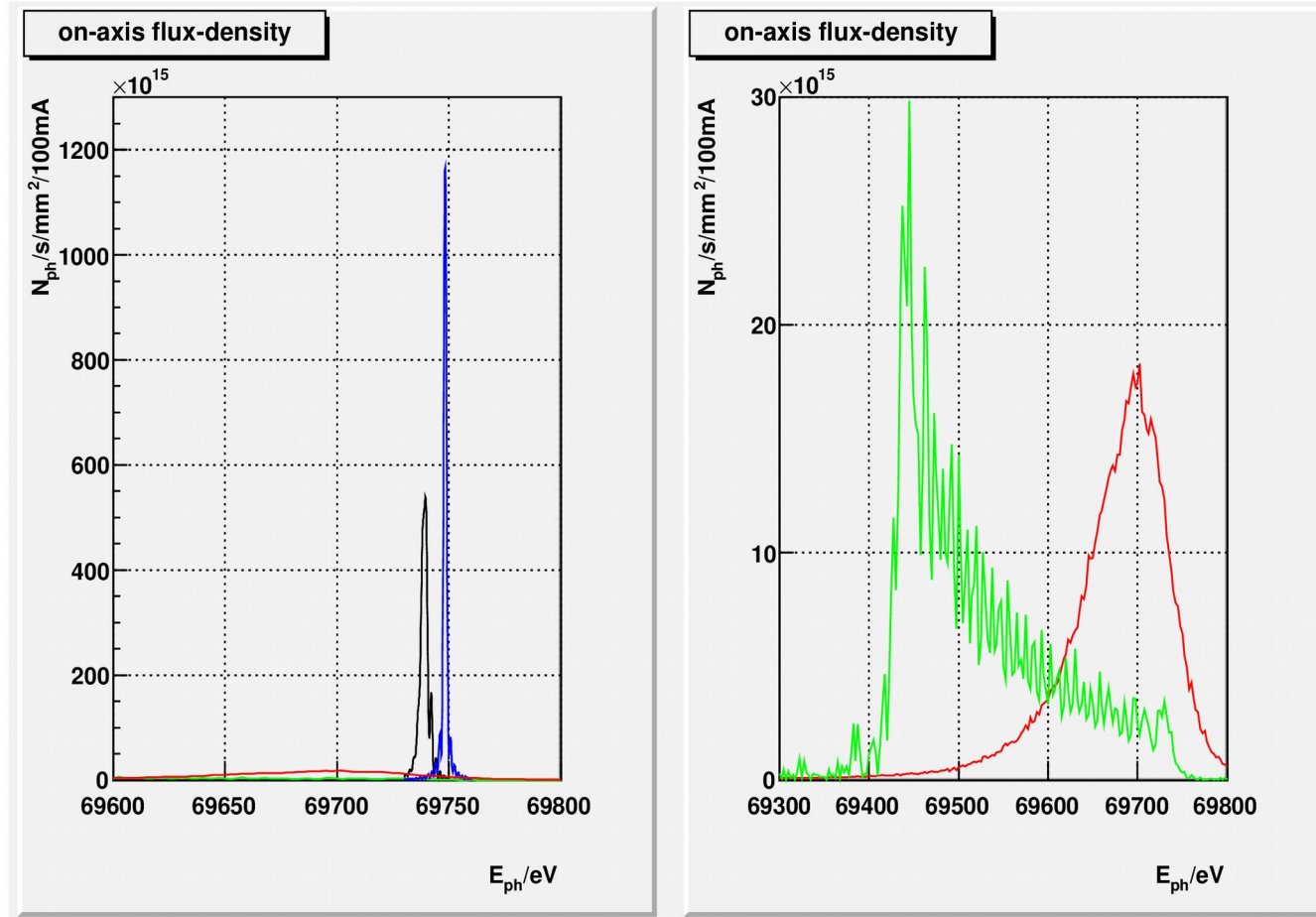


Flux-density S0 with emit. and e-spread





# 17.5 GeV



pencil beam,  
no energy loss

pencil beam,  
cont. ener. loss

pencil beam,  
cont. ener. loss,  
taper

"real" beam,  
taper

Cross-checks pending!

## From tracking results and analytical approximations WAVE can calculate:

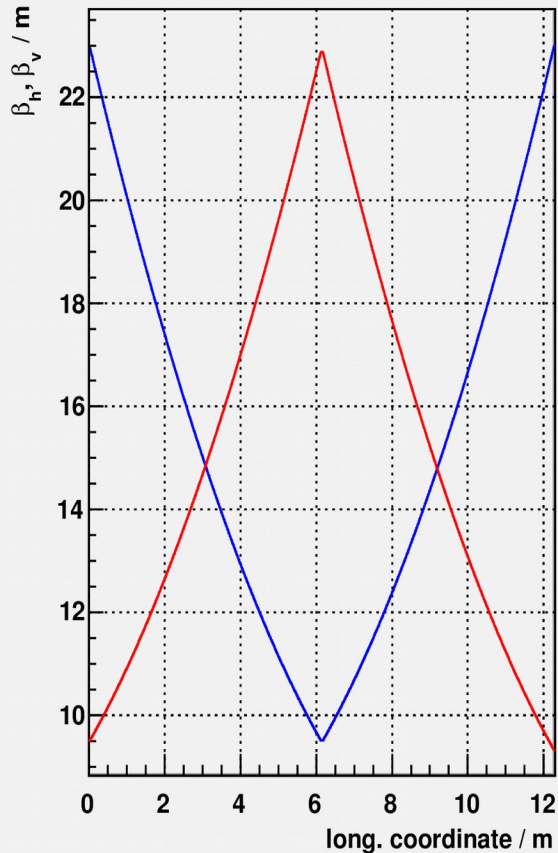
### Effects of IDs on the storage ring:

- Radiation integrals I2, I4 and I5 and change of emittance and energy spread
- Beta functions, optionally a periodic solution form Lin. Trans. Matrices
- Dispersion and optimum dispersion to minimize emittance
- Change of beam polarisation time
- Change of orbit length
- Heat load and photo desorption

### Features of the ID:

- Linear transfer matrices
- Generation Functions for symplectic tracking
- Focal lengths and integrated quadrupole and sextupole terms

$\beta$ -functions of two undulator sections

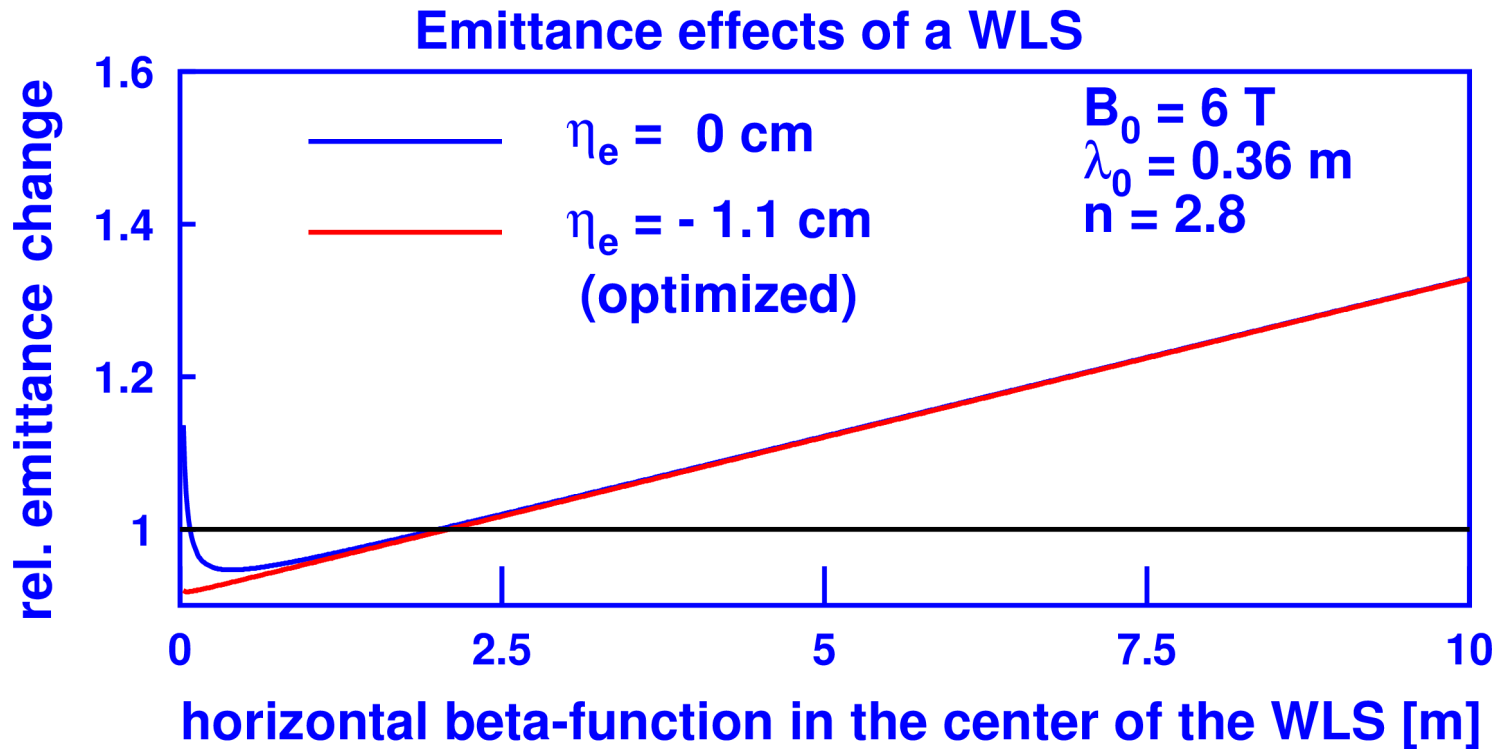


Lattice

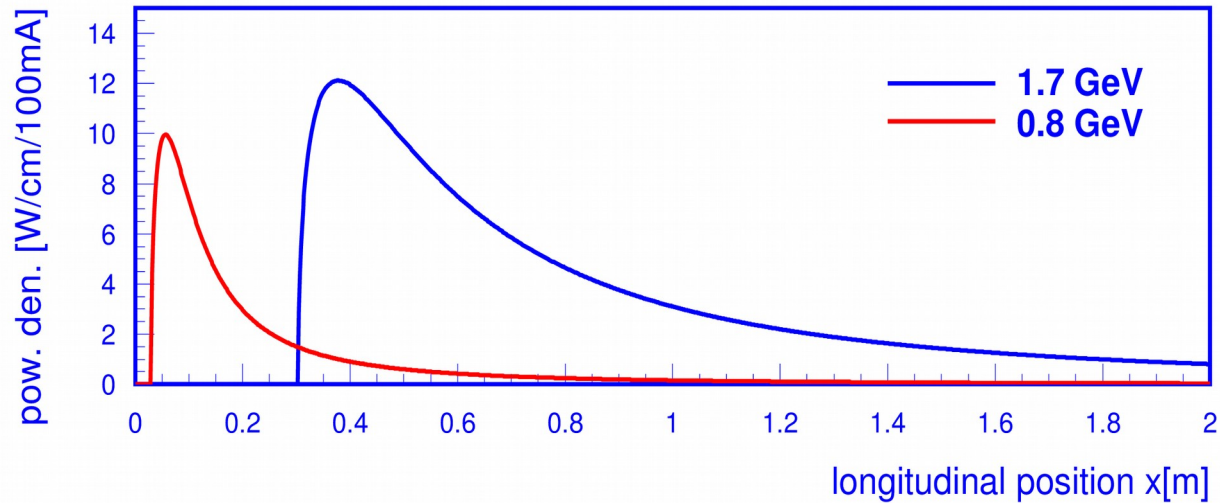
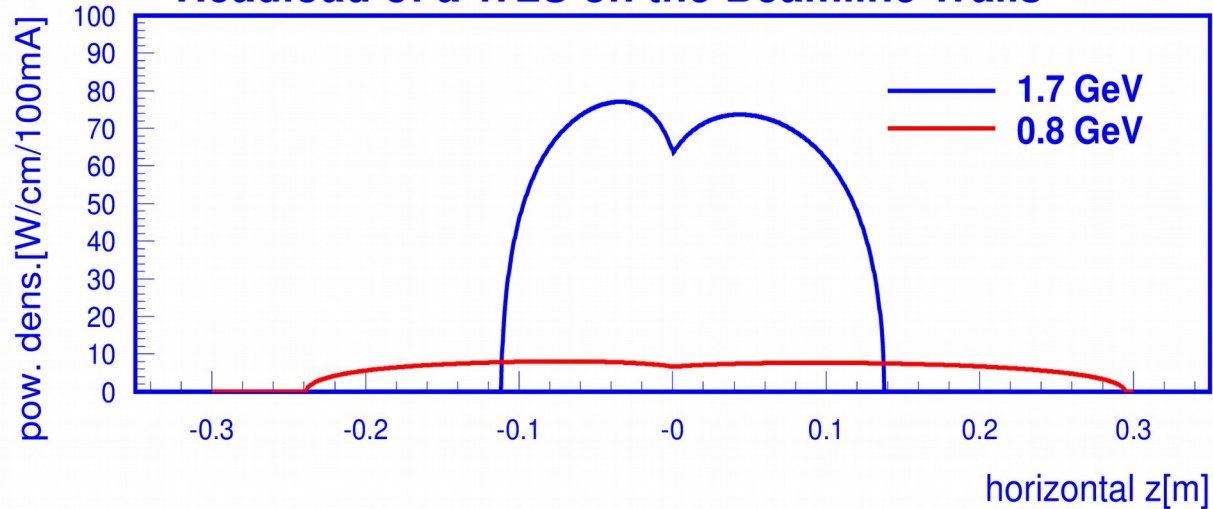


Lattice with  
undulators,  
quadrupoles,  
and dipoles as  
phase-shifters

Field for a  $e^-$   
starting at  
 $z=y=0.5\text{mm}$



## Headload of a WLS on the Beamline Walls



## Stand-alone FORTRAN 95 version

- All CERN-Routines are replaced or build in now
- Should compile on Linux, Windows, Mac, ... with gfortran, ifort, ...
- Histogram file is now pure ASCII. Converter to PAW, ROOT and Hdf5 are available. A ROOT based GUI for plotting is under development.

## Getting WAVE

- License: GPL, i.e. Open Source
- Virtual Linux machine with installation ready to run
- Stand-alone version, ready, but needs testing
- Docker container (planned)

Sometimes, less is more:

```
subroutine urad(  
& gammai,dgamtot,  
& xelec,yelec,zelec,vxelec,vyelec,vzelec,  
& xf,yf,zf,efx,efy,efz,  
& xexit,yexit,zexit,vnxex,vnyex,vnzex,texit,ds,  
& nstep,ndim,traxyz,  
& xobsv,yobsv,zobsv,phelow,phehig,  
& nphener,phener,aradx,arady,aradz,stokes,powden,  
& ieneloss,ivelofield  
& ,istatus)
```

Provide a magnetic field map or subroutine, and you can calculate the trajectory and the radiation at a given point. Maybe, thats all you need!

# Thank you for your attention

More details can be found here:

Michael Scheer, Dissertation, 2008

<http://edoc.hu-berlin.de/docviews/abstract.php?lang=ger&id=29619>

Michael Scheer, ICAP 2012, TUACC2.pdf