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Focus – a new wavefront Propagation Code

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Rationale for new code

Wavefront propagation workshop at Daresbury in Nov 2005.

At that time, could not easily include optics with 'real' surfaces in codes commonly in use in SR community.

New Code

- **Flexible surface description**
- **Keep approximations to the minimum. Simple 'brute force' method – propagate from each point on one surface to each point on the following**
- **Intended for investigating the effect of imperfect surfaces, not for design work**
- **Needs to inter-work with other codes such as PHASE, SRW, Genesis1.3**

Written by Steven Higgins

Code Outline

- The beamline is represented by a set of surfaces; a source surface, any optics and then an image surface

- The Sommerfeld Propagation Integral is used for propagation from every position R on a surface to each point r on the next surface

$$E(\vec{r}) = -\frac{i}{\lambda} \oiint_{aperture} \vec{E}(\vec{R}) \frac{\left[\vec{R}-\vec{r}\right]\cdot \hat{n}\, e^{ik\left|\vec{R}-\vec{r}\right|}}{\left|\vec{R}-\vec{r}\right|^2} \cdot \overrightarrow{da}$$

where <u>da</u> is a surface element on an aperture (surface), λ is the wavelength, n is the normal to the surface, and the dot product gives the obliquity factor.

- The main approximation is that the radiation field and surfaces are represented as values on a grid of points.

Code Outline – source field

Input - the complex values of the field at a grid of point in the input plane which can either be

Read from files

or

Generated internally for a Gaussian source

FILE format.

1) set of ascii files for the real and imaginary parts of the field for orthogonal polarisations for each wavelength– same format as PHASE code Bahrdt [1]
2) binary file, one for each polarisation generated, each record containing the complex field values for a given wavelength

Both types of file can be generated from the 3D fields from Genesis1.3, using an intermediate code which Fourier transforms the input fields to the frequency domain and inversely transforms the fields after propagation to retrieve the 3D field.

*1. J Bahrdt, Appl Optics **34**, 114 (1995), Appl Optics **36**, 4367 (1997)*

Code outline – optical surfaces

Optical elements can be:

Mirrors - the reflected radiation is propagated

Plane windows – the transmitted radiation is propagated

The optical surface is described by either:

a shape - plane, ellipsoid, torroid

or

A 3D grid of points read from file

Reflectivity or transmission efficiency can be included.

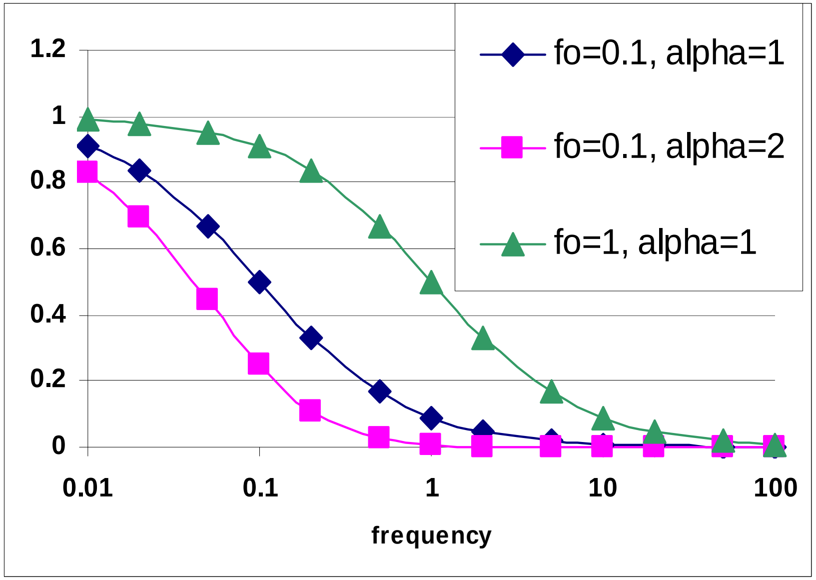
The field cannot be propagated across a thin window as ghosting occurs, so the radiation is ray traced to the exit plane of the window.

A slope error can be added to the perfect surfaces

Slope errors

The deviation from a perfect surface is generated by adding a set of randomly orientated ripples. The amplitude of the ripples is based on the 1-D equation [2]

$$PSD(f) = C\left(\frac{f_0}{f_0 + f}\right)^{\alpha}$$

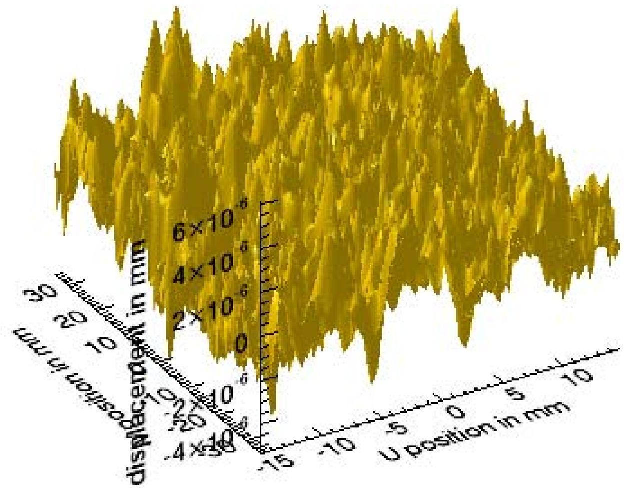


where f0 is the cut-off frequency and α gives the decay. Expect $1<\alpha<2$

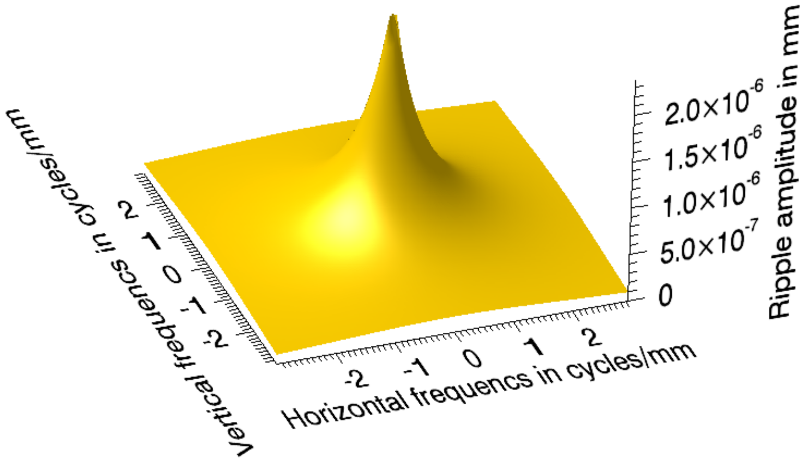
The slope error is obtained by inversely Fourier Transforming a 2-D power spectral density based on the above equation, and adding the result to the surface along the direction of the normal. The overall amplitude of the surface displacement is adjusted to obtain the required rms slope error.

2. J. E. Harvey, Appl. Opt. ***34****, 3715 (1995)*

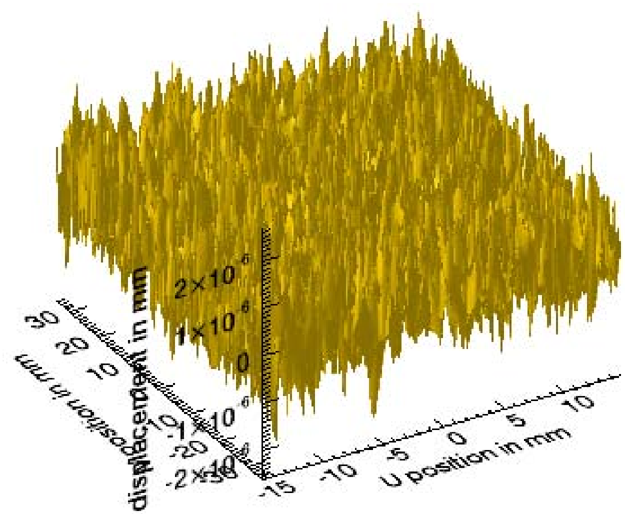
Surface displacements for different f_0 and α with the same rms slope error. Low frequency errors are more important for larger α and smaller f_0



Slope error 2.5 μrad, $\alpha = 2$, $f_0 = 0.16\ mm^{-1}$



2D frequency distribution

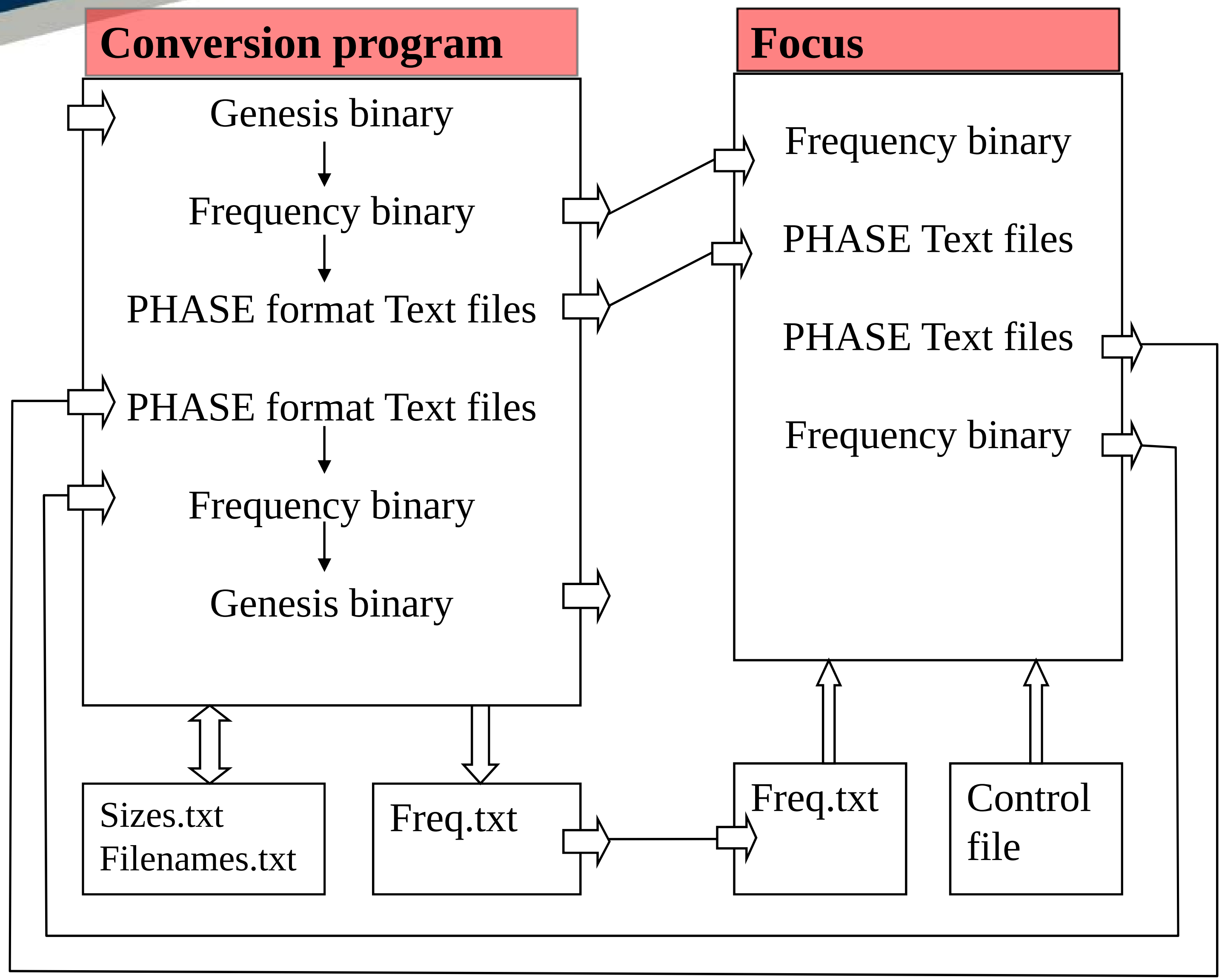


Slope error 2.5 μrad, $\alpha = 1$, $f_0 = 0.33\ mm^{-1}$

Code outline - implementation

- The code is written in standard C++ and runs under windows or Linux
- Simple text control file is used for ease of conversion to other operating systems.
- The visualisation of the output field files has been done using stand-alone IDL codes
- FOCUS can generate report files for the field at each surface
- The grid representing a surface can be output.
- The field at the image plane is output, either to ascii or binary files

```
begin beamline
interpolated phase source
eyre=phase_files\EYRES00001.DA0
eyim=phase_files\EYIMS00001.DA0
ezre=phase_files\EZRES00001.DA0
ezim=phase_files\EZIMS00001.DA0
new u size=151
new v size=151
new width=0.52mm
new height=0.75mm
surface Andy Smith's Mirror
u size=101
v size=201
transverse size=30
longitudinal size=70
refractive indicies=1.0 0.915+i0.0352
x position=50m
y position=0
z position=0
source focal length=50m
image focal length=0.155m
yz rotation=90deg
xz angle of incidence=75deg
elliptical
```


Conversion program
Genesis binary
Frequency binary
PHASE format Text files
PHASE format Text files
Frequency binary
Genesis binary
Sizes.txt
Filenames.txt
Freq.txt
Focus
Frequency binary
PHASE Text files
PHASE Text files
Frequency binary
Freq.txt
Control file

Applications

- High power beamline on an XUV FEL - uses model slope errors
- Test case for XFEL mirror – uses real 1D mirror profile (talk by David Laundy)
- Coherent synchrotron radiation - THz propagation

High Field beamline on XUVFEL

- Aim – to achieve power densities > 10^{16} W/cm^2 at the sample
- Radiation source – 100 eV pulse of radiation from seeded XUVFEL on 4GLS, obtained at end of FEL using Genesis 1.3 [3] (fields supplied by D Dunning)
- Key optic – highly demagnifying elliptical mirror.
- Specification from earlier ray tracing work using SHADOW (A Smith)
  - Source distance - 50 m
  - Image distance - 0.155 m
  - Grazing angle 15°
  - Mirror length - 70 mm
  - Slope error - 2.5 μrad
  - Horizontally deflecting
  - Gold coated
- Focal spot size determined by slope error of mirror – 2.5 μrad thought to be achievable for ‘short’ mirror.

*3. S. Reiche, Nucl. Instr. Meth. **A429**, 243 (1999)*

XUV-FEL - Input field

Input pulse Fourier transformed to get the wavelength components.

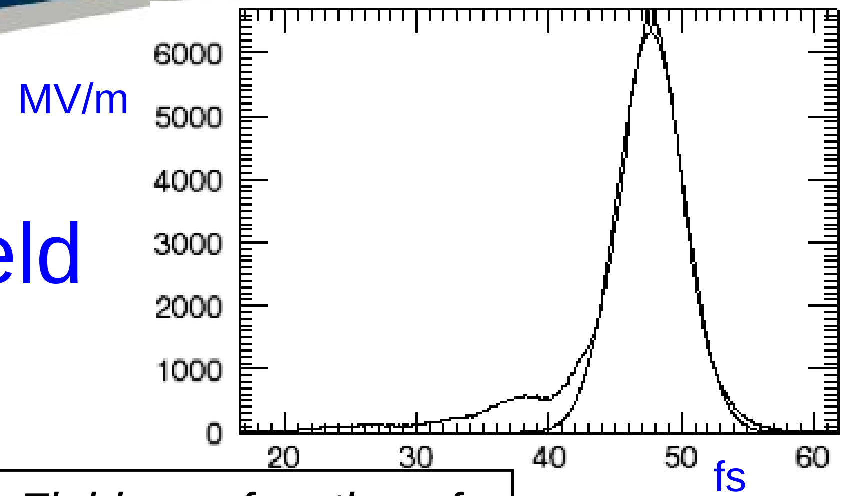
Input field had 2050 ‘time slices’ spaced at 0.0413fs.

Propagated 230 energy ‘slices’ from 90.2376 eV to 101.1416 eV

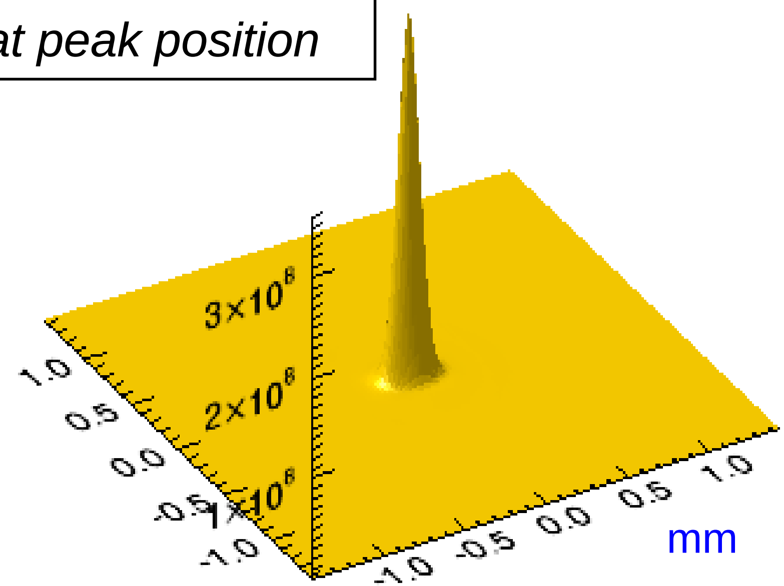
Input grid too coarse - field interpolated using FOCUS to finer mesh.

Interpolated mesh 151*151 points over 0.52 by 0.75 mm^2

Time to propagate each energy approximately 4 minutes



Field as a function of time at peak position



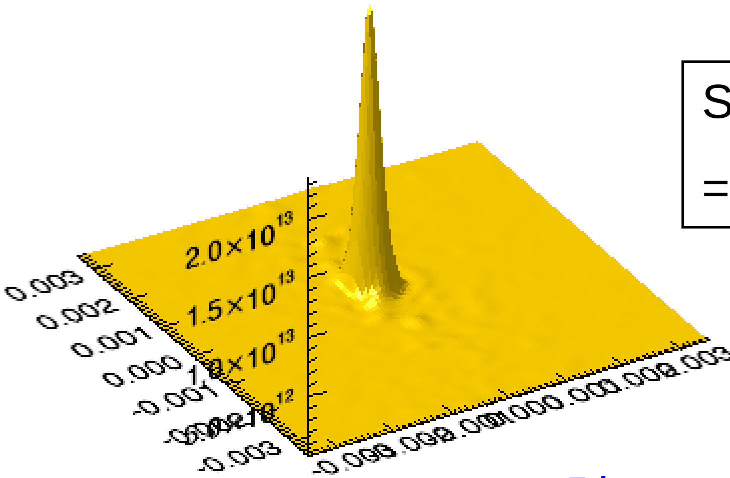
Intensity (a.u.)at 100 eV at exit of FEL

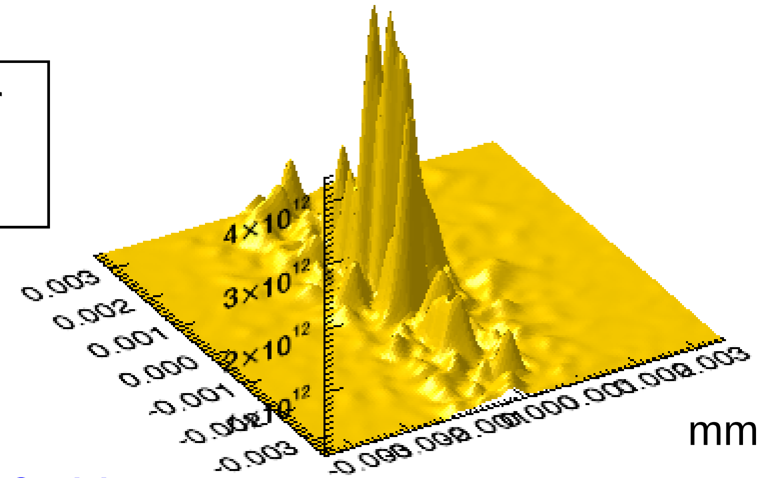
Focal spots for mirrors with different slope errors

f0 =0.33 mm-1 $\alpha = 1$

(~23 periods along mirror)

f0 =0.16 mm-1 $\alpha = 2$

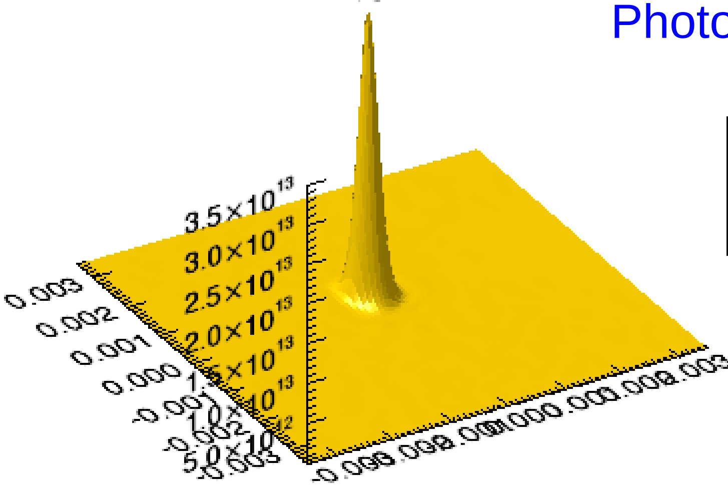




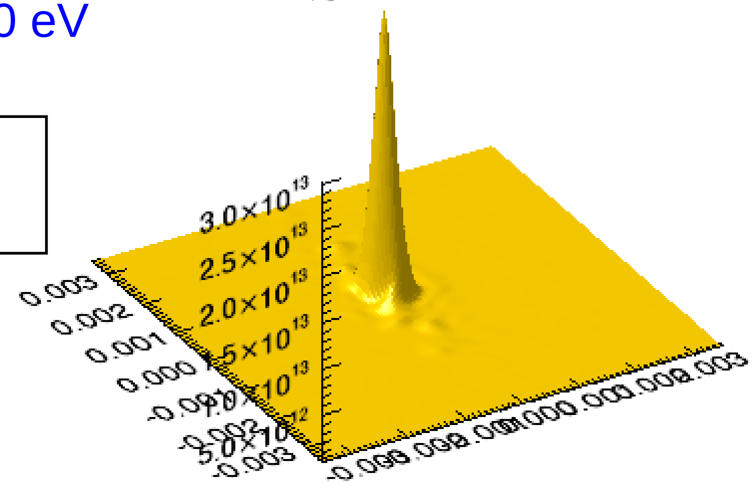
Slope error

=10 μrad

Photon energy 100 eV



Slope error
=2.5 μrad



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Focus properties (100 eV)

f_0 (1/mm)	α	Slope error (μrad)	Power in 7 * 7 μm^2 image plane (a.u.)	Peak value of intensity (a.u.)	Rms size of central peak From Gaussian fit. (μm^2)
-	-	0	8364		0.134 * 0.194
0.33	1	2.5	8277	3.5	0.135*0.195
0.33	2	2.5	8266	3.3	0.135 * 0.202
0.16	1	2.5	8274	3.4	0.135 * 0.196
0.16	2	2.5	8272	3.04	0.137 * 0.21
0.067	2	2.5	8288	2.45	0.141*0.227
0.33	1	10.0	7101	2.4	0.136*0.203
0.16	2	10.0	6898	0.44	0.194* ?

- Slope error of 2.5 μrad does not affect the peak intensity significantly except for slope errors dominated by low frequencies
- Need to know the frequency distribution of the slope error

Comparison with analytical estimates

Input source size 63 * 43 μm^2, demagnification 322

rms image size allowing for slope error δ

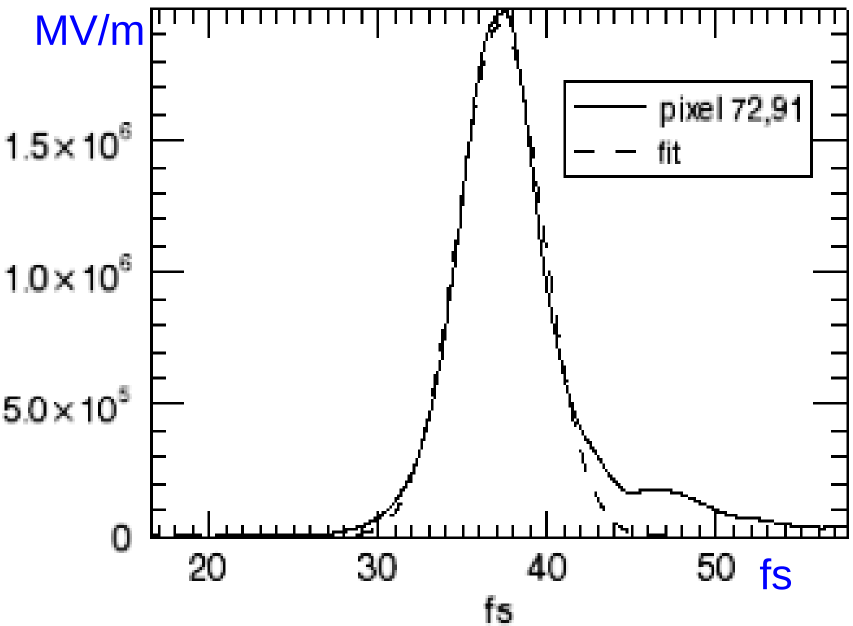
$$\sigma_l = \sqrt{[\sigma_o^2 + (2*r*\delta)^2]}$$ Longitudinal

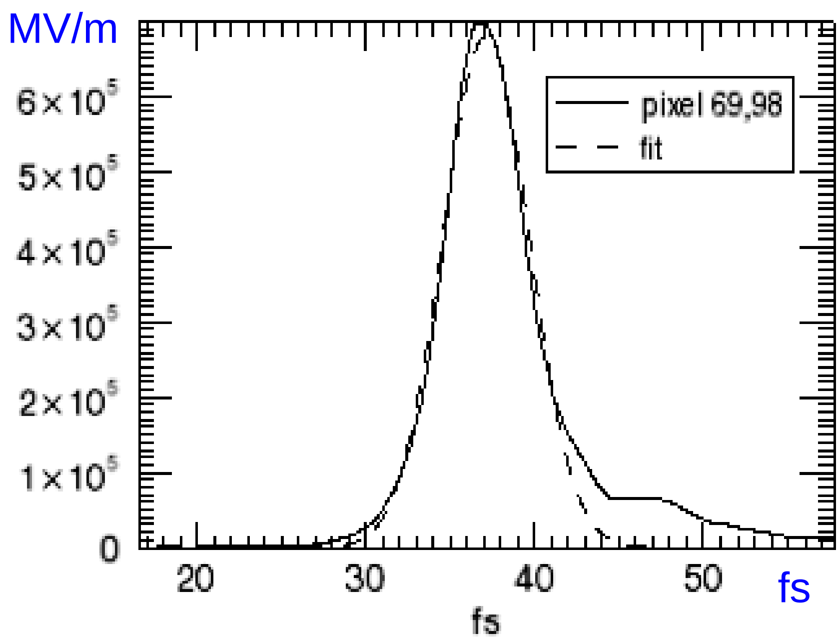
$$\sigma_t = \sqrt{[\sigma_o^2 + (2*r*\delta*\sin\phi)^2]}.$$ Transverse

	Analytical	From FOCUS
rms focus size – no slope error	0.133 * 0.196 μm^2	0.134 * 0.194 μm^2
rms focus size – 2.5 μrad slope error	0.28 * 0.8 μm^2	0.25 * 0.60 μm^2 $

$ *Value found in image plane large enough to capture > 99.9% of radiation*

Pulse length at focus





rms slope error = 2.5 μrad,

f0 =0.33 mm-1, α =2

rms slope error = 10 μrad,

f0 =0.16 mm-1, α =2.

Absolute value of the field in the pixel with maximum intensity

(not including reflectivity of mirror)

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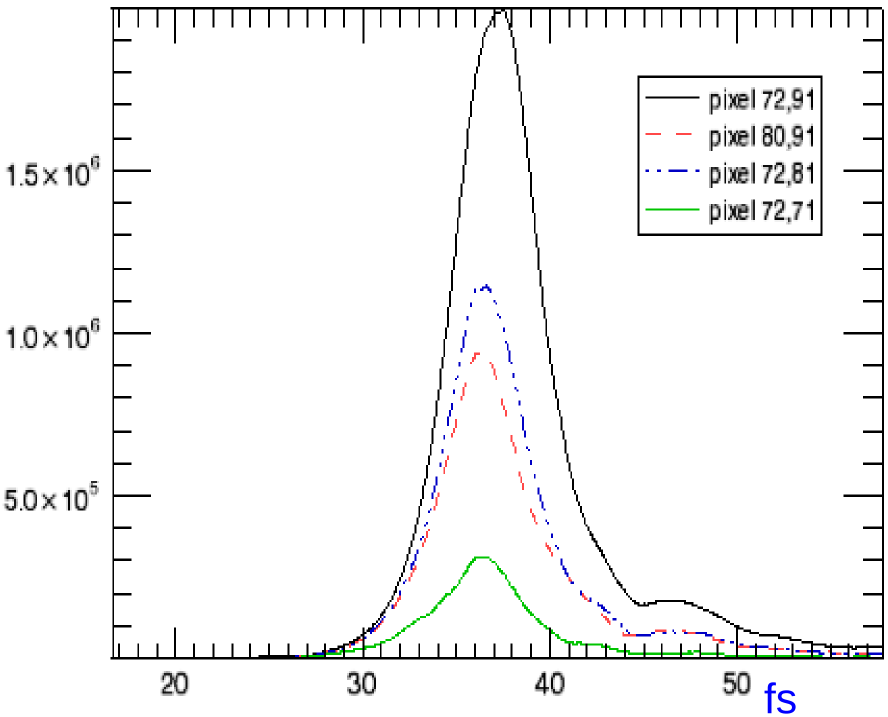
Pulse Properties

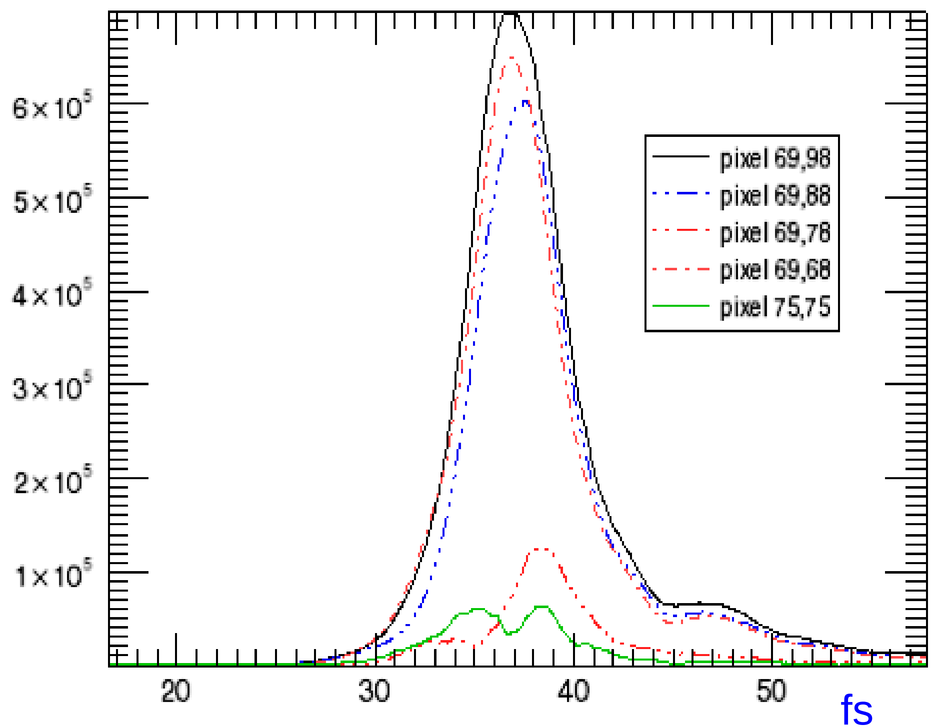
Which pulse	rms intensity pulse length Summed over all pixels (fs)	rms length of abs(field) pulse In pixel of maximum field (fs)	Max Intensity (including reflectivity losses) (W/cm²)
Input	1.64	2.52	$3.1*10^{12}$
At focus, slope error 2.5 μrad	1.64	2.52	$2.7*10^{17}$
At focus, slope error 10 μrad	1.65	2.57	$0.36*10^{17}$

Time profile as a function of position

rms slope error 2.5 μrad



rms slope error10 μrad

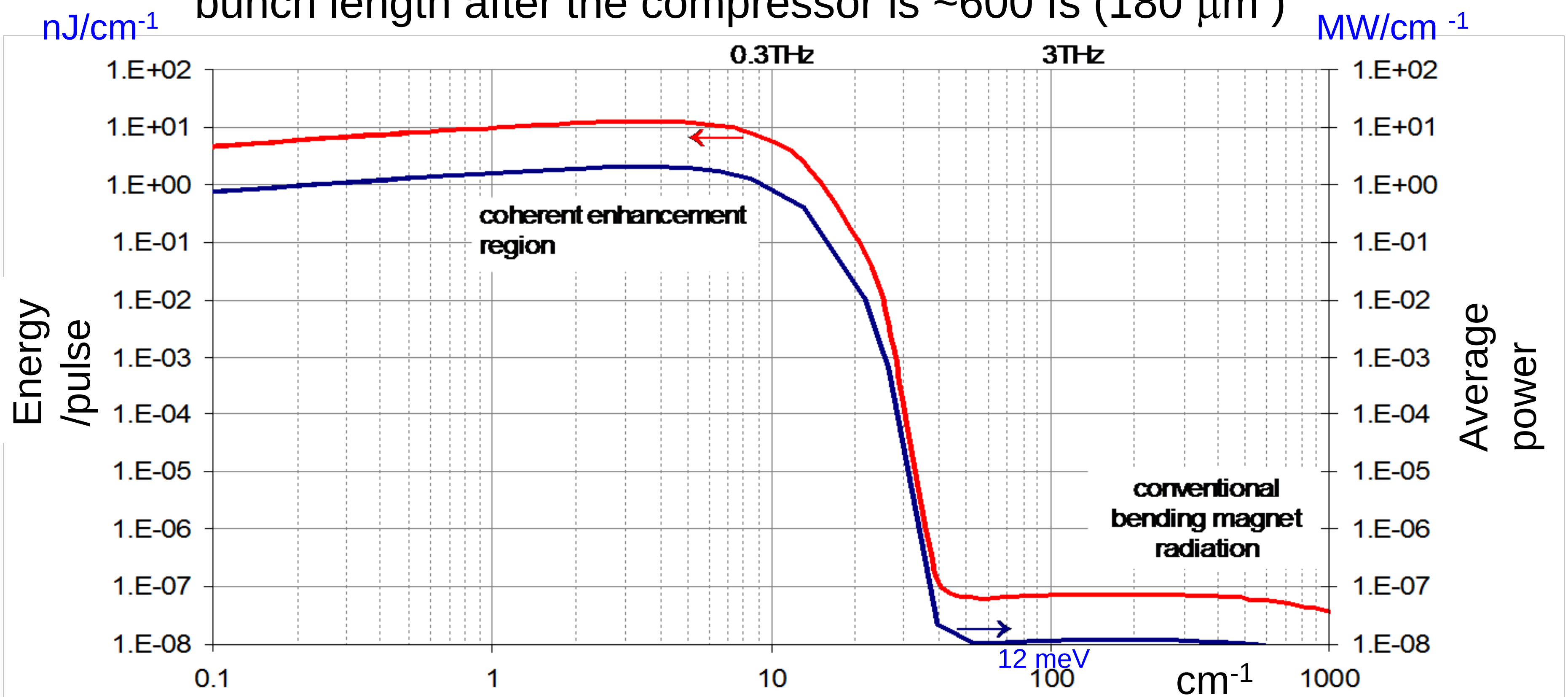


ABS(Field) in MV/m

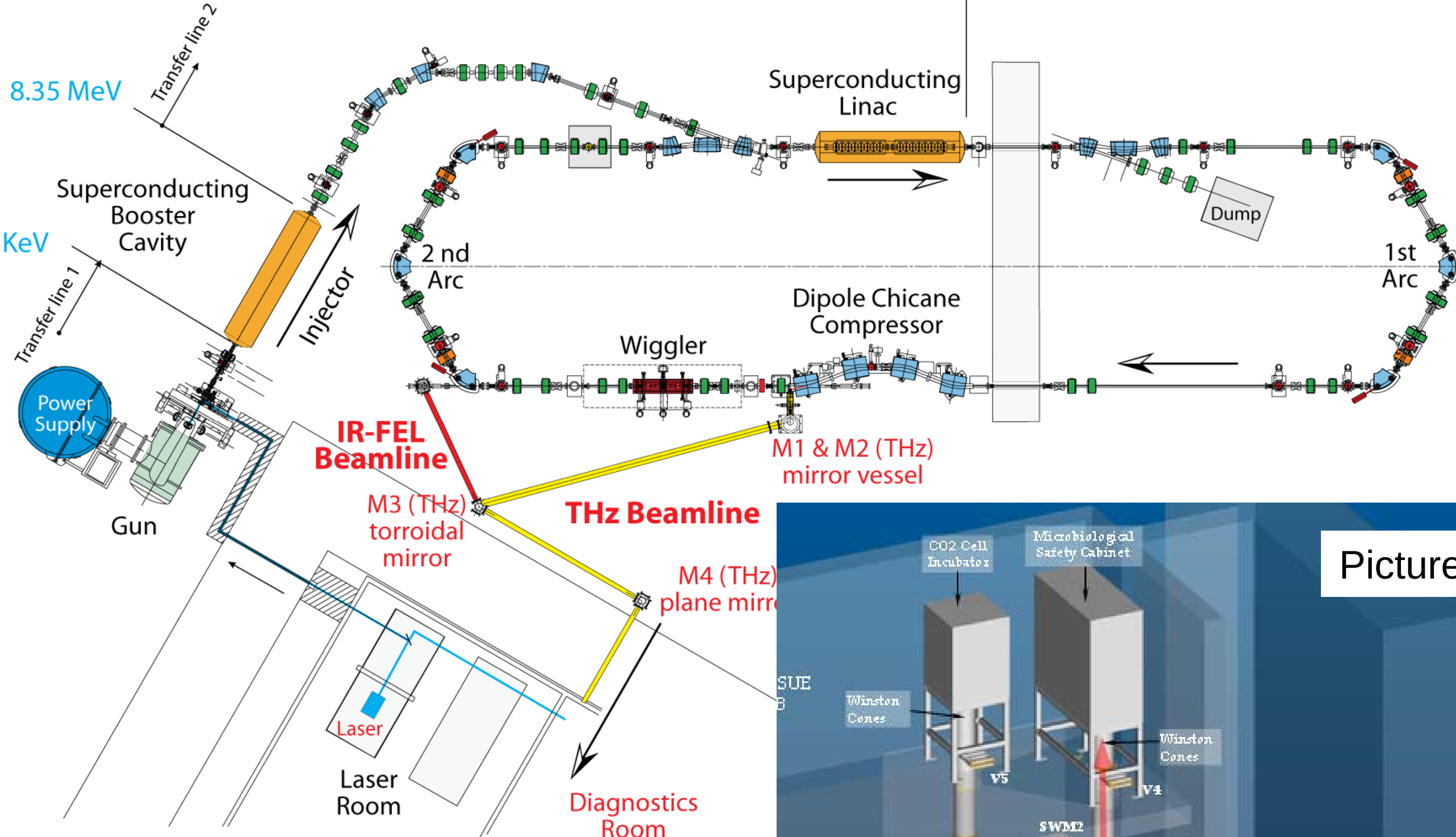
Coherent Synchrotron Radiation.

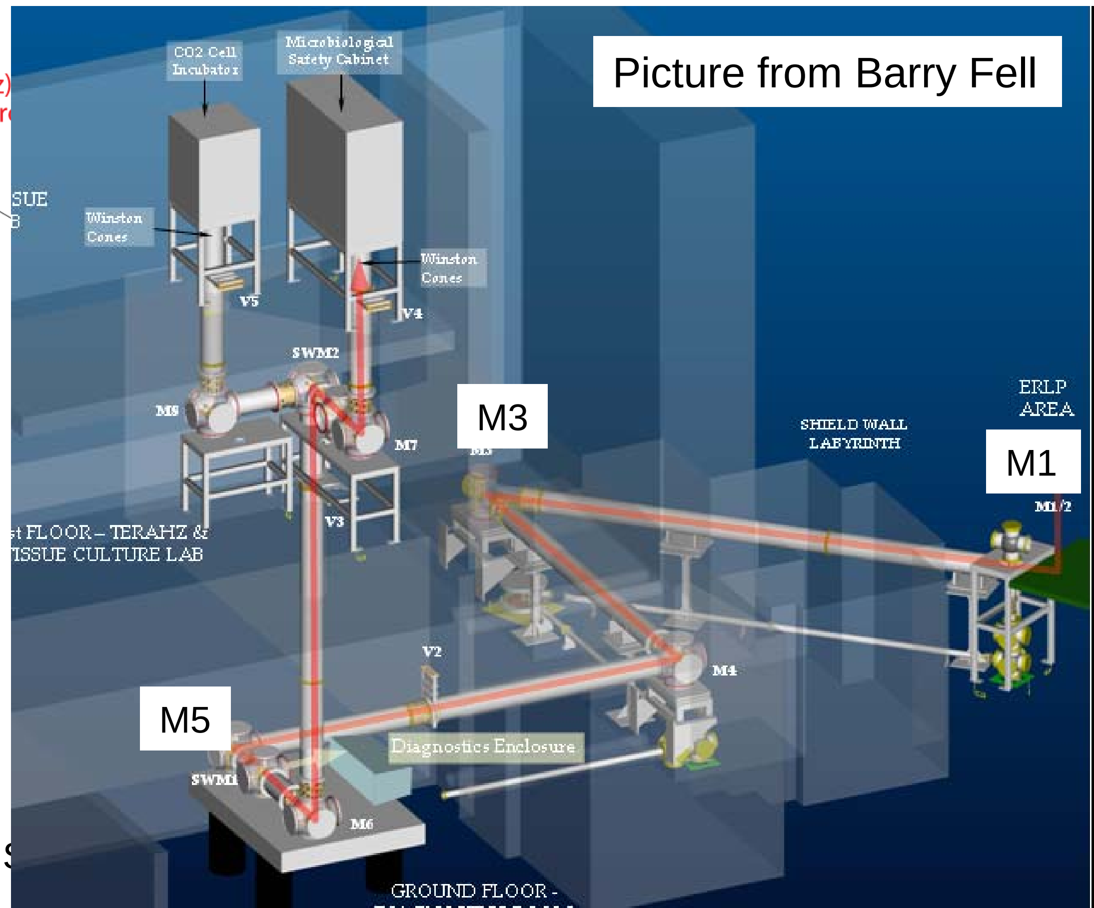
SR coherent at wavelengths longer than the electron bunch

In ALICE, the Energy Recovery Linac at Daresbury, the expected bunch length after the compressor is ~600 fs (180 μm)



Output for a 600 fs 80pC Gaussian bunch





Layout of ALICE and the THz beamline.

M1, M3 M5 are toroidal

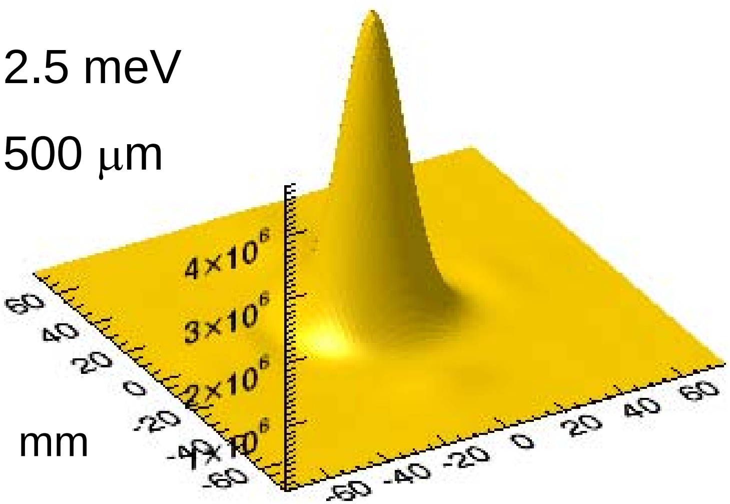
M5 collimates the radiation

Modelling of CSR transport

- Diffraction, at the extraction aperture and mirrors is important.
- The beamline was designed with the tangent point as the source position – waist positions occur at ‘nominal foci’ only for shorter wavelengths
- SRW [4] used to calculate the radiation field distribution at a 36*36 mm^2 extraction aperture, 0.505 m from the tangent point.
- FOCUS used to propagate across M1, M3 and M5 to 2m beyond M5.

2.5 meV

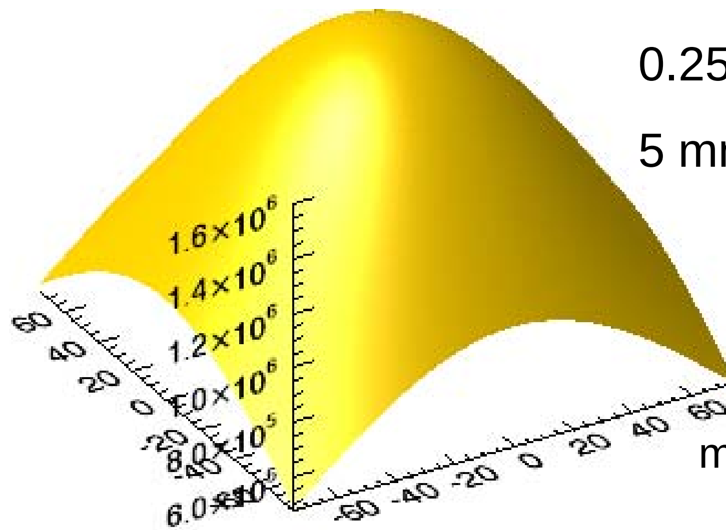
500 µm



mm

0.25 meV

5 mm

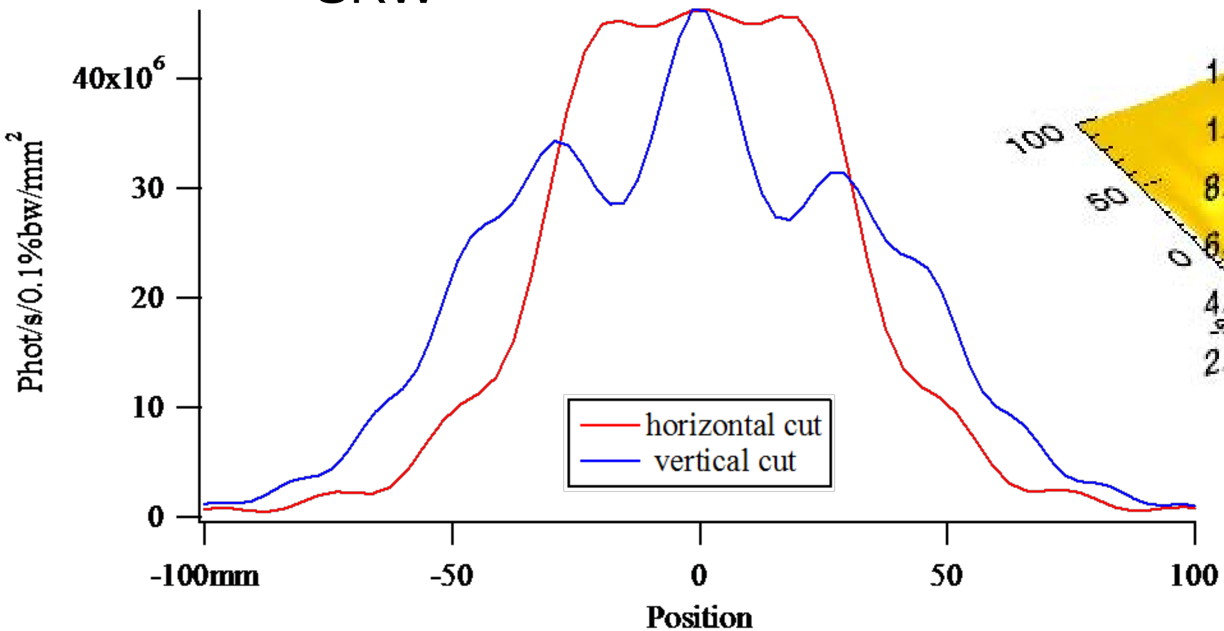


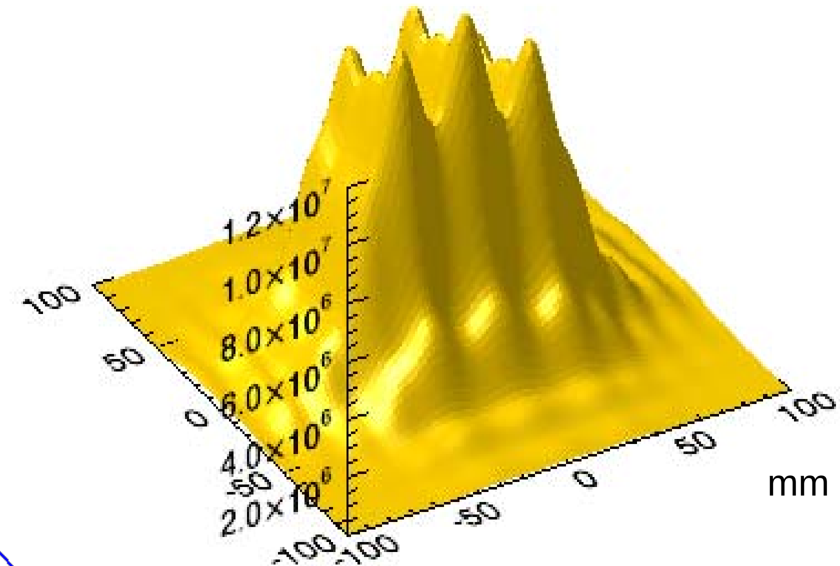
mm

*Intensity (a.u) of horizontally polarised radiation at the **nominal focal position** of M3*

Modelling of CSR transport

SRW





FOCUS

‘Intensity’ of 0.8 meV (1.5 mm) radiation 2 m beyond the collimating mirror.

See edge diffraction from over-filling the collimating mirror.

4. O. Chubar, P Elleaume, EPAC-98 Proceedings, p1177 (1998)

Summary

The code is in the final testing stages
Three different cases have been undertaken so far

- Input fields from Genesis1.3, model slope errors for mirrors
- Internally generated Gaussian field, input 1D mirror profile from metrology
- Input fields from SRW, long wavelength for which diffraction important.

Thank you for your attention