



# **SELECTION OF THE OPTIMUM UNDULATOR PARAMETERS FOR THE NLS: A HOLISTIC APPROACH**

**Jim Clarke, Neil Bliss, Dave Dunning, Barry Fell, Kiril Marinov  
and Neil Thompson, Daresbury Laboratory**

# NLS

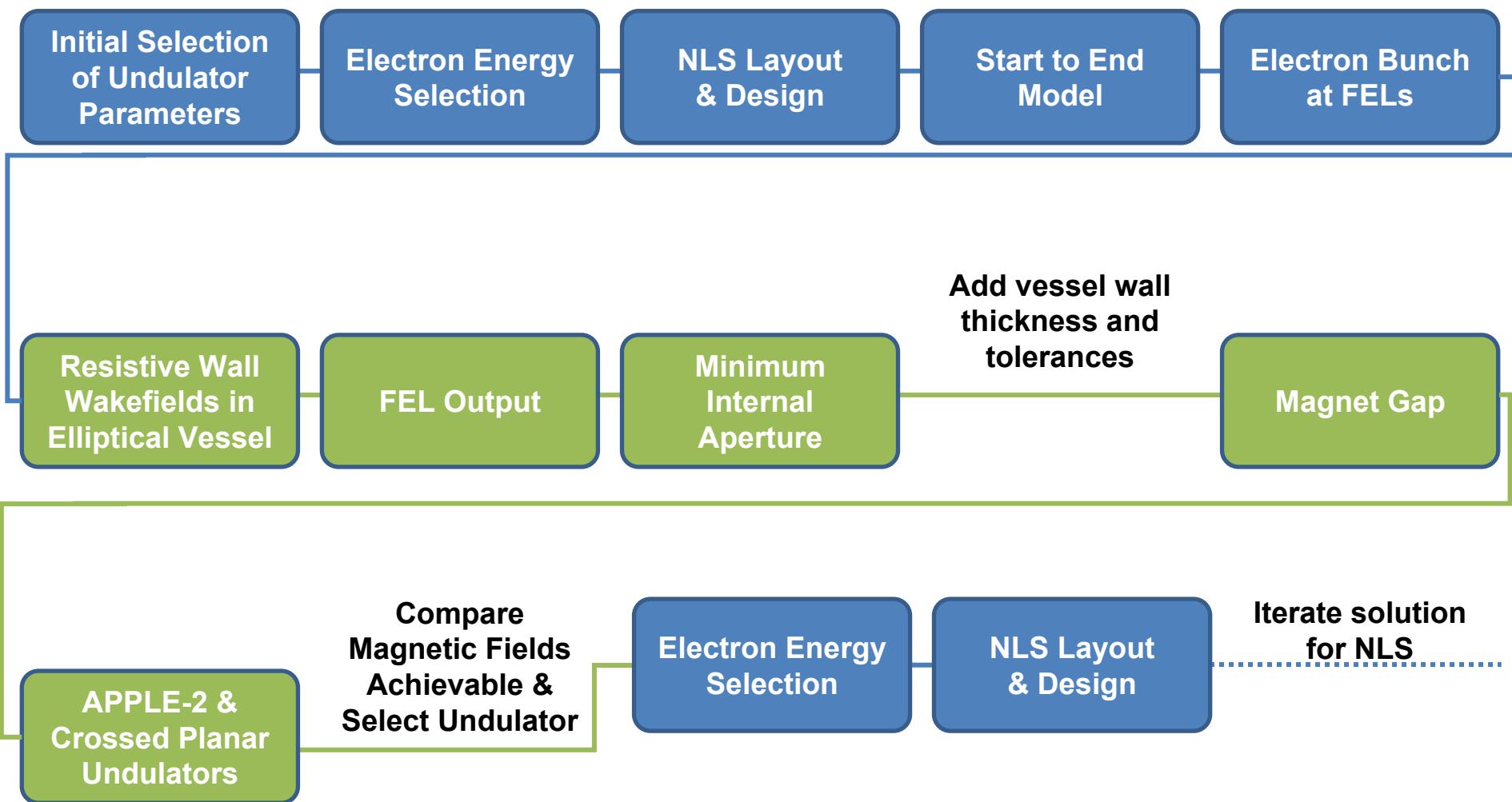
- 4<sup>th</sup> Generation Light Source for the UK
  - High repetition rate (kHz initially, MHz later)
  - Ultrashort, high brightness, high coherence X-rays
  - THz to keV available
- Science Case & Outline Facility Design published
  - Available from [www.newlightsource.org](http://www.newlightsource.org)
- FELs offer complete coverage from 50 eV to 1 keV.
  - FEL-1: 50-300 eV
  - FEL-2: 250-850 eV
  - FEL-3: 430-1000 eV
  - Polarisation control required



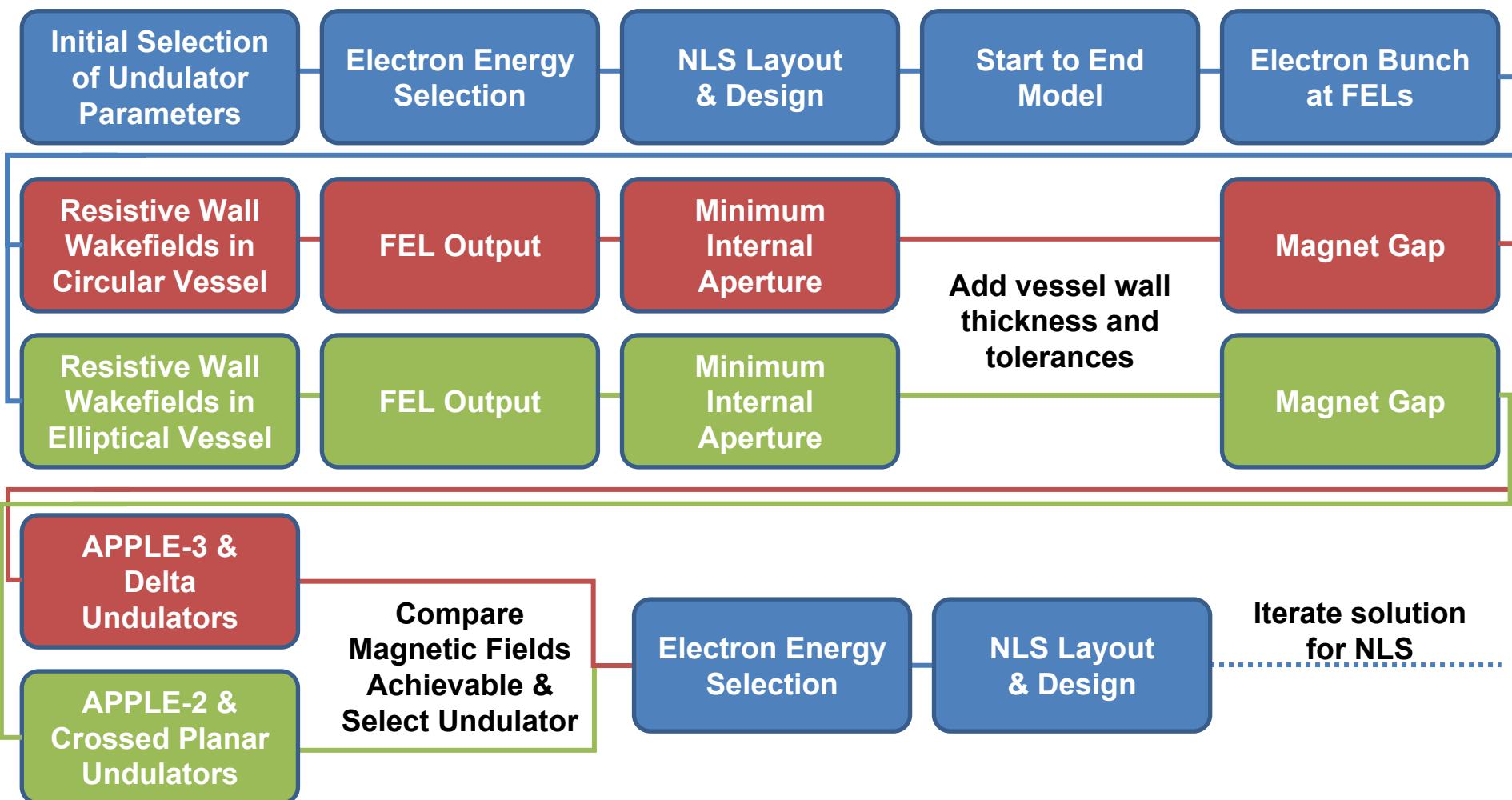
# Design Philosophy for the Undulators

- Often light source projects are forced to make an early decision on undulator type and gap
- Need this to define electron energy to begin accelerator design
- We have made a rapid *second iteration* to avoid project being ‘locked-in’ to initial choice
- Second iteration based on start-to-end model bunches (not Gaussian!), resistive wall wakes, FEA of vessel wall thicknesses, etc
  - Try to be as inclusive as possible

# Design Philosophy for the Undulators

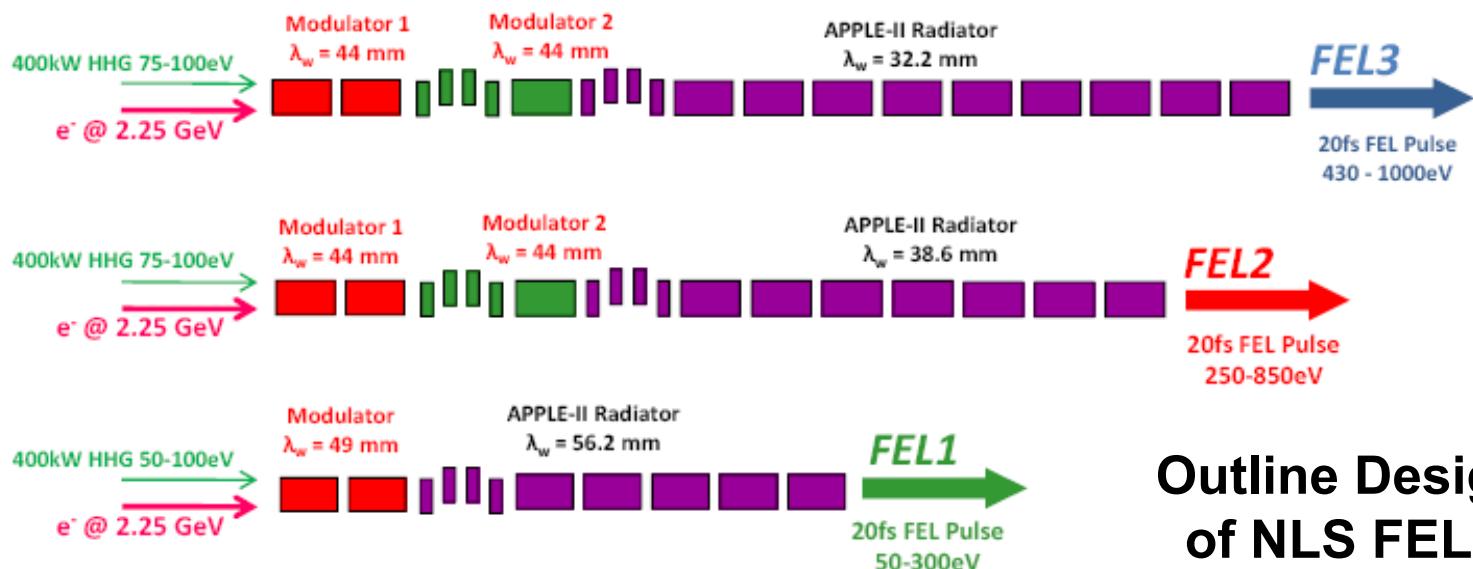


# Design Philosophy for the Undulators



# Initial Selection

- **APPLE-2 undulators with 8 mm magnet gap and internal aperture of 6 mm**
- From photon energy ranges of FELs we need 2.25 GeV electrons



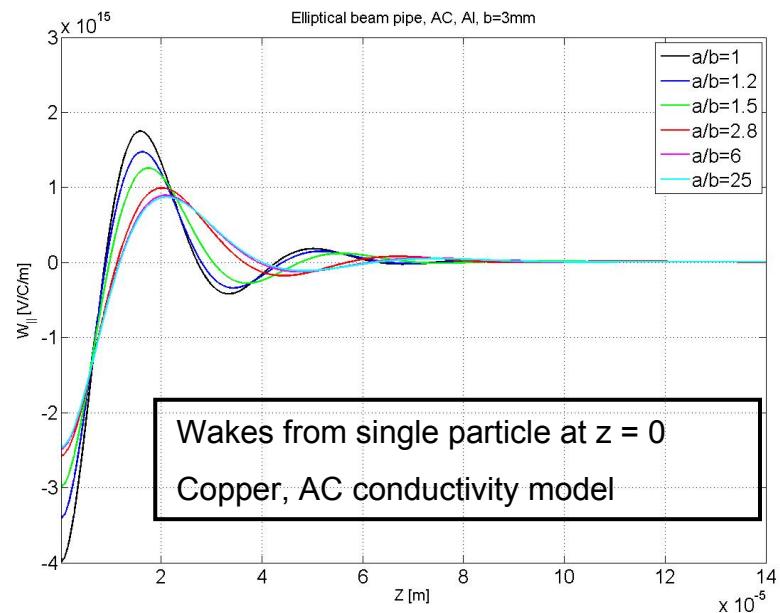
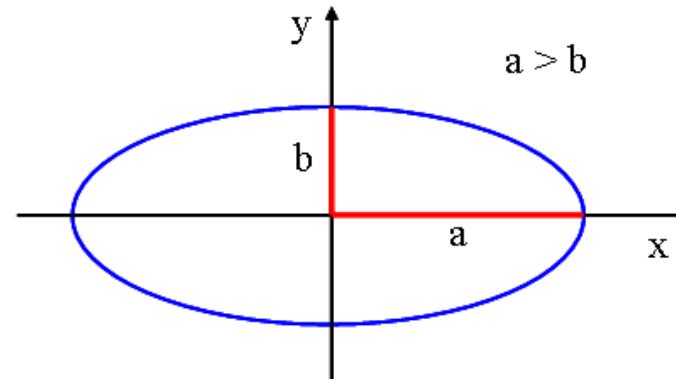
Outline Design  
of NLS FELs

# Wakefields

- Need to consider 3 effects
  - Resistive (image currents)
  - Geometric (changes in vessel cross-section)
  - Surface Roughness (vessel surface finish)
- Resistive is of most concern
  - Other projects have consistently found resistive to be dominant effect
  - Will determine vessel material and inner dimensions
  - Other two can always be made smaller (in principle!)

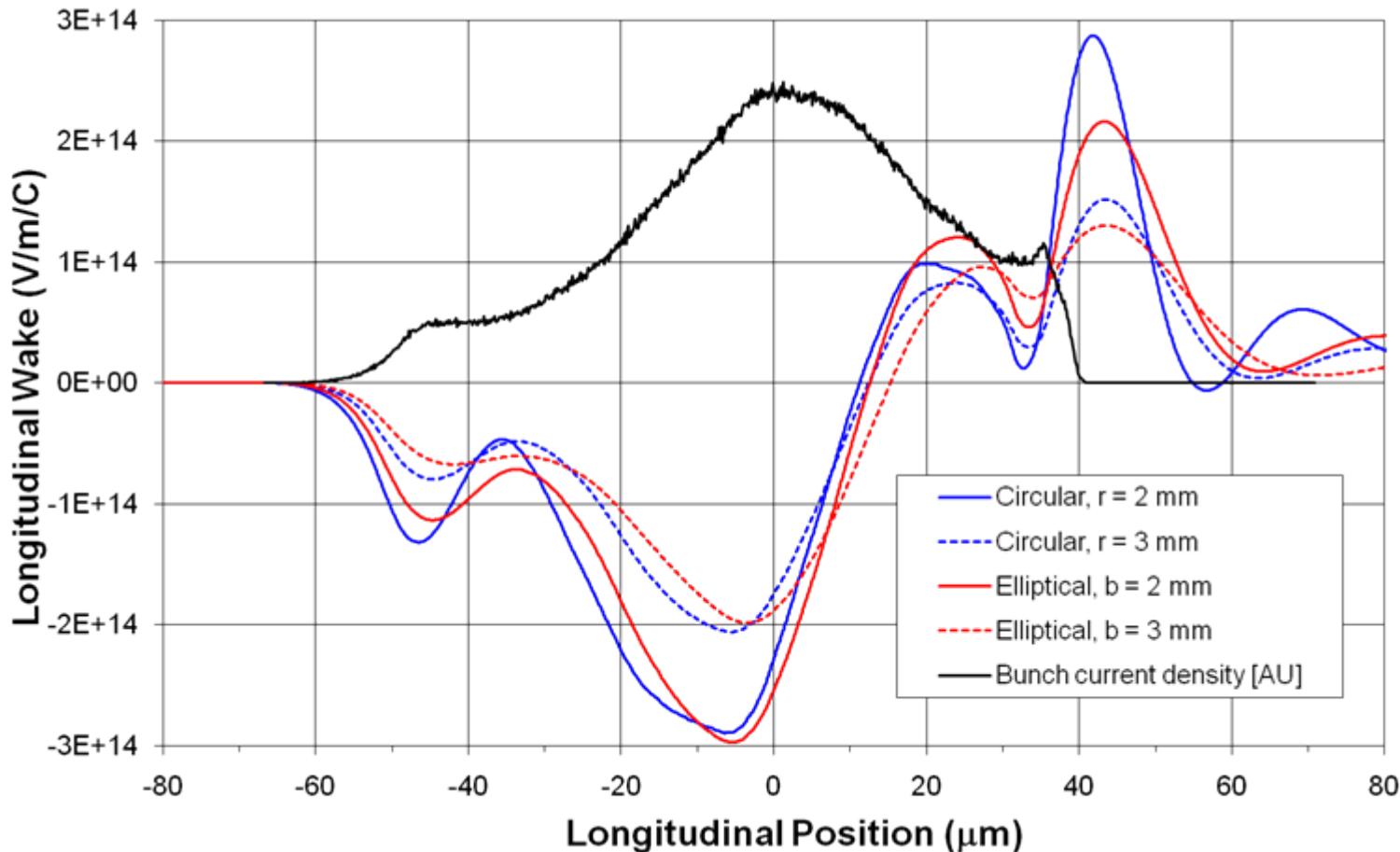
# Elliptical Vessel

- Keep  $b$  fixed at 3mm and vary  $a$
- As  $a$  increases, result tends towards parallel plates result
- Little gain seen when  $a \gg 3b$
- So, set  $a = 3b$  for this study



# Example Wakefields

- Longitudinal wakefields, AC conductivity model, aluminium vessel ( $a = 3b$ ), 200pC

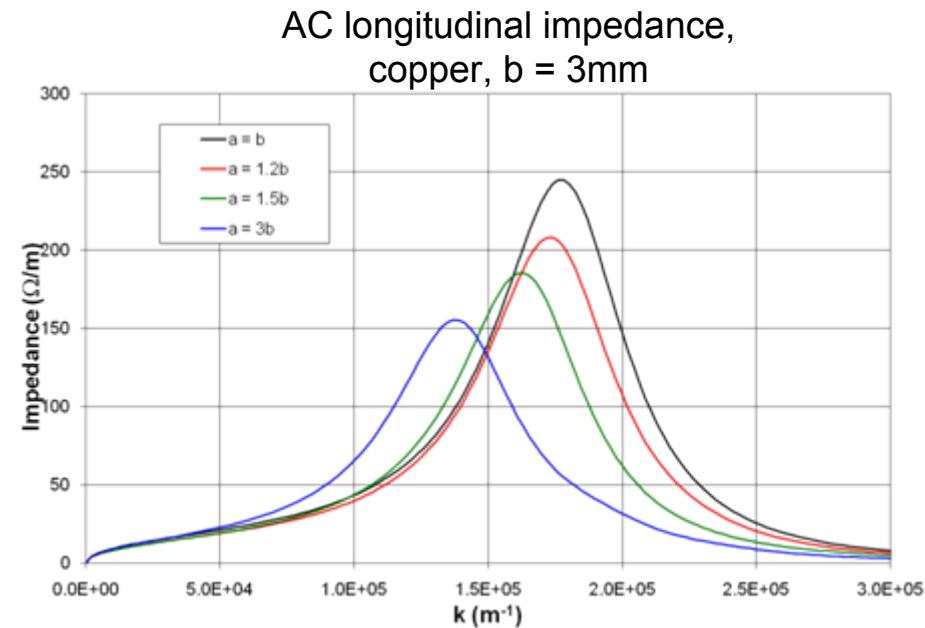
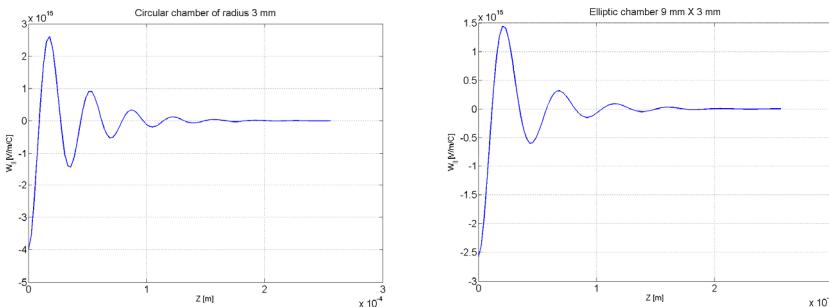


# Circular and Elliptical Vessels

- Differences between circular and elliptical wakes is strongly correlated with bunch length – which frequencies are excited
- For the NLS with FWHM  $\sim 150$  fs there is little difference for the same vertical aperture

Wakes from single particle at  $z = 0$

Copper, AC conductivity model

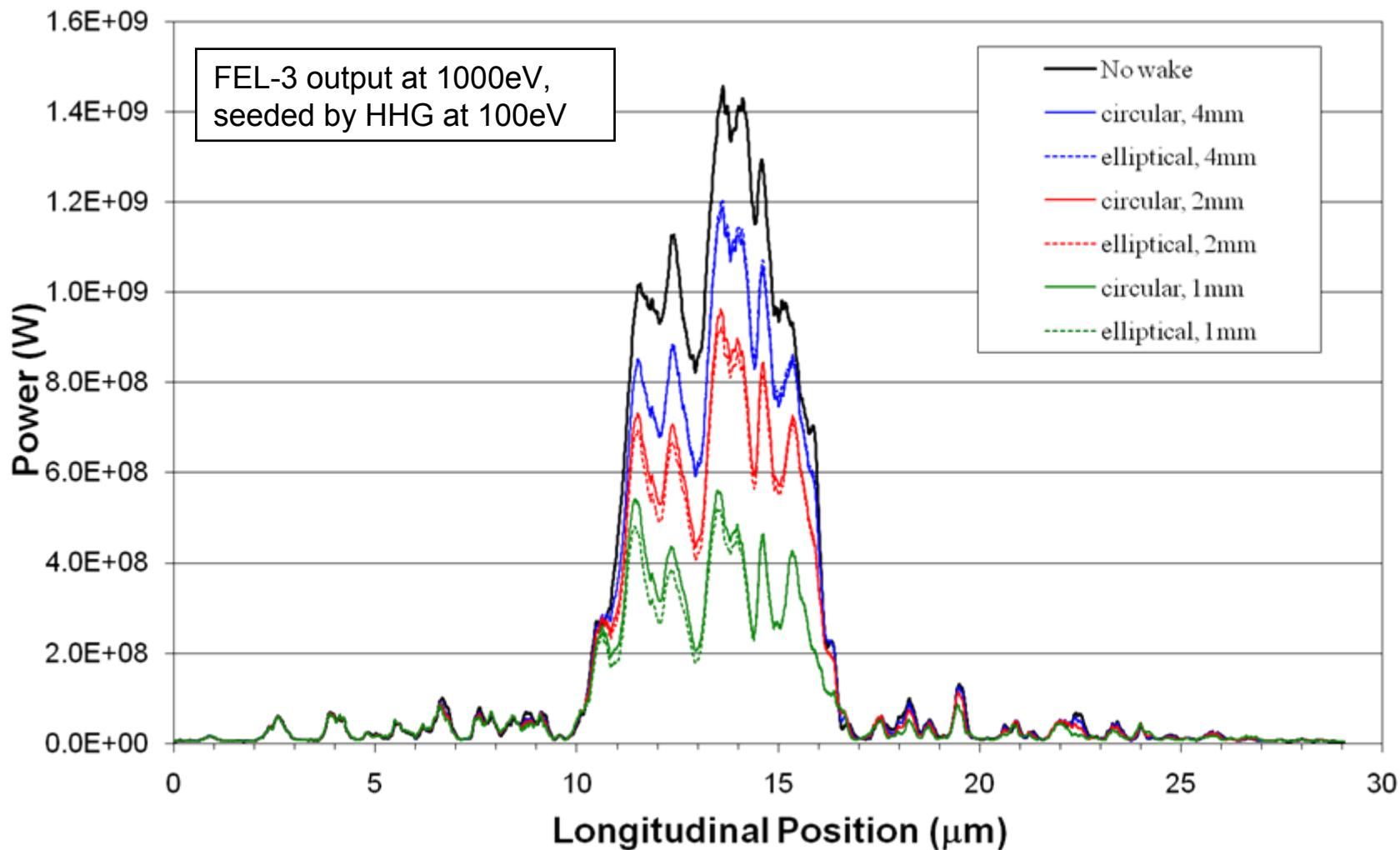


# FEL Performance

- Time dependent modelling carried out for FEL-3 at 1000 eV using Genesis 1.3 – most demanding case
- Resistive wakes were calculated as a function of aperture for circular and elliptical ( $a = 3b$ ) aluminium vessels, AC model
- Only the radiator section has the wake included
- No efforts have been made to regain any loss in output power (eg by tapering or using a longer radiator section)

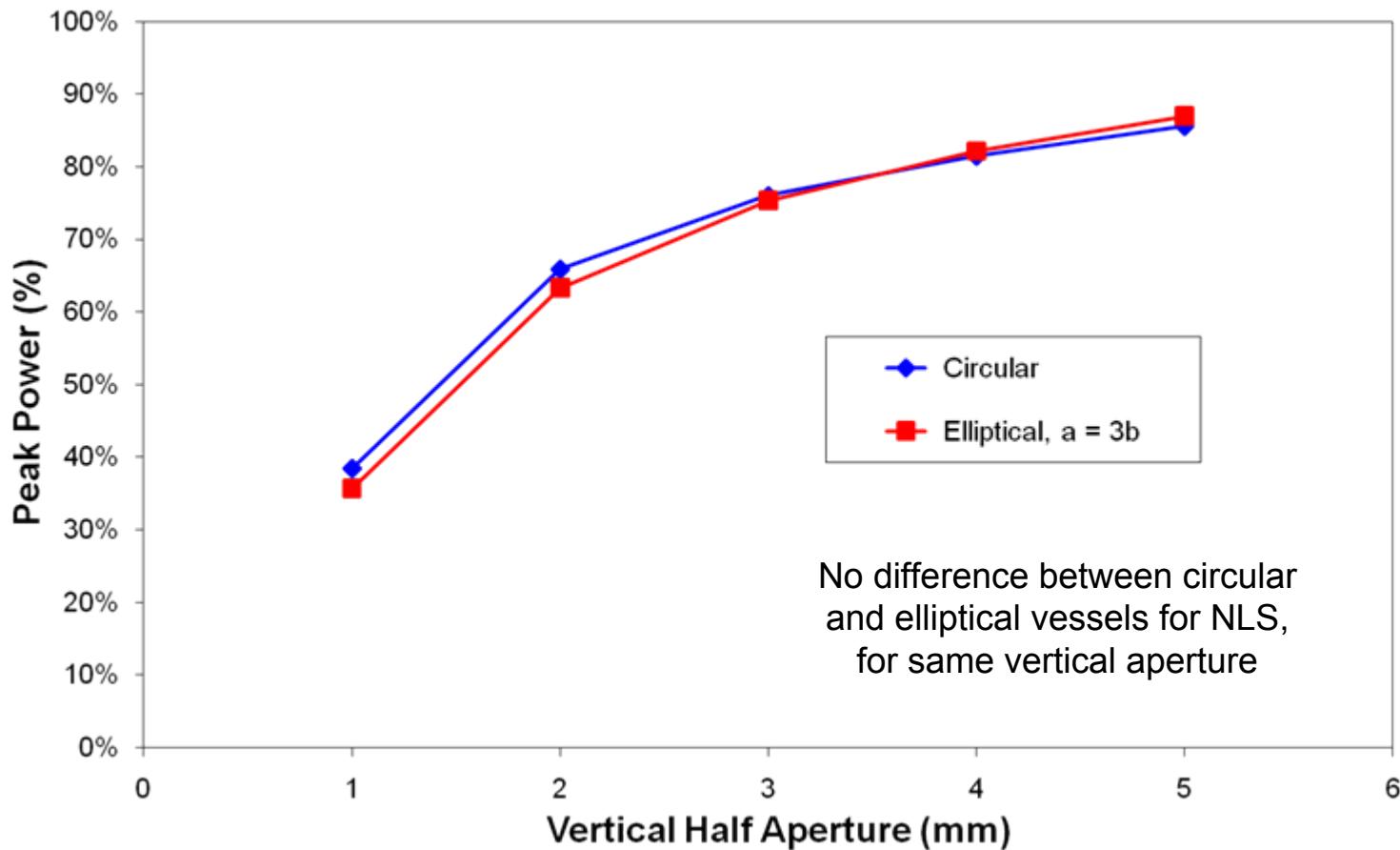
Geometric and surface roughness wakes have been neglected, only on axis effects included

# FEL Performance



# FEL Peak Power

Peak power expressed as a percentage of the value  
with no wake included



# FEL Peak Power

- If peak power is expressed as a percentage of what is practically realisable (ie relative to the 10 mm internal aperture case):
  - 6 mm would give 87%
  - 8 mm would give 94%
- Assume that a 10% loss is acceptable then internal vessel aperture (circular or elliptical) should be **7 mm**
- Need to add allowance for vacuum vessel to understand what the undulator magnet gap can be

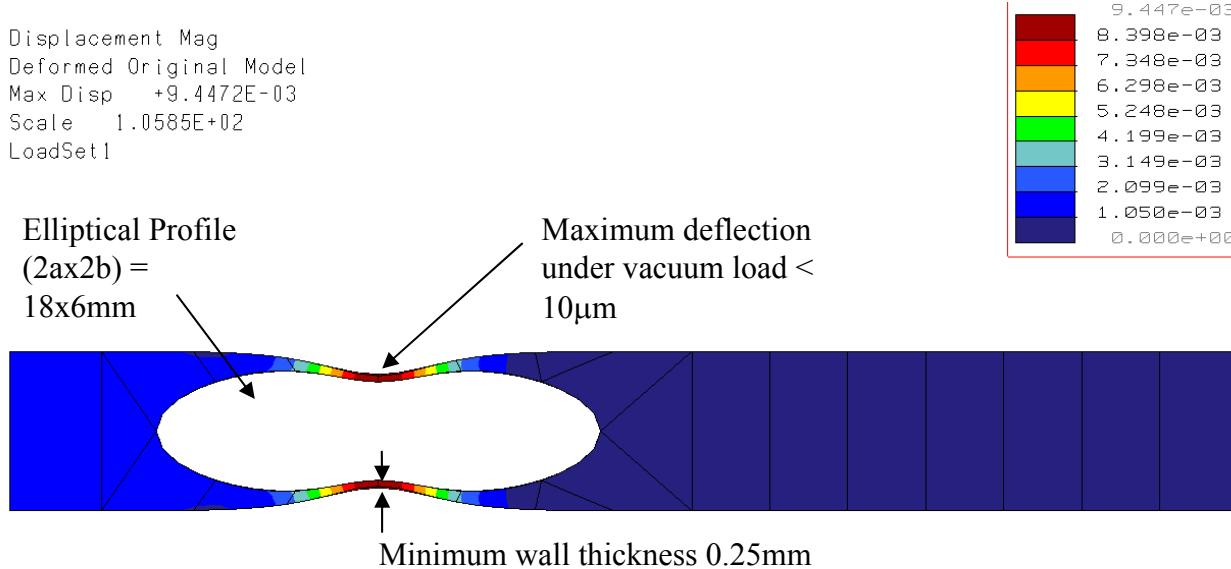
# Vacuum Vessels

- Assessment has been made of wall thickness required for vacuum load by elliptical vessel with  $a=3b$  and also circular vessel (Cu or Al)
  - Elliptical **needs 0.25 mm** thick walls (at thinnest part)
  - Circular **needs 0.1 mm** thick walls
  - Note these are the *maximum* levels required in the gap region of interest for NLS (internal aperture < 10 mm)
- Allowance is added for alignment, vessel straightness, vessel deflection under load

# Vacuum Vessels

- Result shown for Al 6061 alloy extrusion

Displacement Mag  
Deformed Original Model  
Max Disp +9.4472E-03  
Scale 1.0585E+02  
LoadSet1



- Analysis also shows that vessel would be robust under handling and from shock loads
- Vacuum porosity would need to be checked
- Stainless Steel vessel coated with Al or Cu is also possible

# Vessel Examples

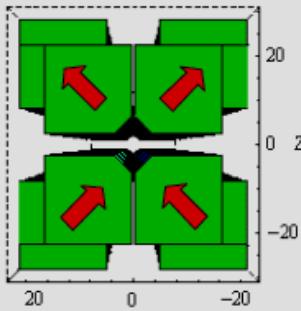
- **Elliptical vessel**, internal height 7 mm
- Width is  $3 \times 7 = 21\text{mm}$
- Add vessel walls & allowances
- **Magnet gap is 8.1 mm**
- **Circular vessel** with same impact on *FEL output* has internal diameter of 7 mm
- Add vessel walls & allowances
- **Magnet gap 7.6mm**
- No difference between Cu or Al

# Undulator Options

- Four options have been considered
  - **APPLE-2**
    - Mature solution, many examples, well understood, low risk
  - **APPLE-3**
    - Fields enhanced ~40%, no practical examples, restricted side access
  - **Delta**
    - Fields enhanced ~70%, only short prototype exists, no side access
  - **Crossed-Planar**
    - Lowest risk magnet, altered FEL configuration, polarisation level vs undulator length for seeded FEL to be studied, fast switching of polarisation

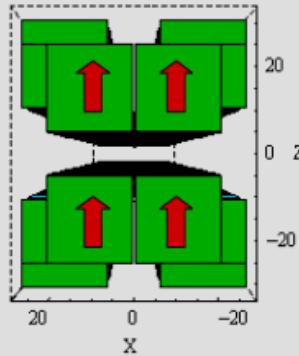
# Undulator Options

APPLE-3



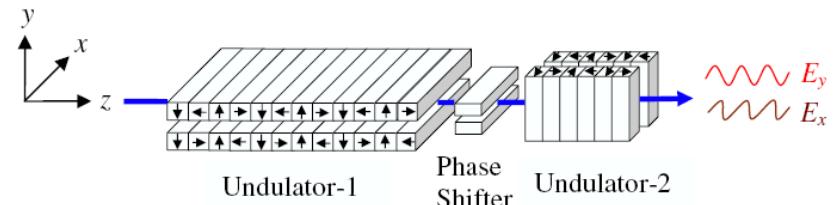
J Bahrdt, FEL04, p610

APPLE-2



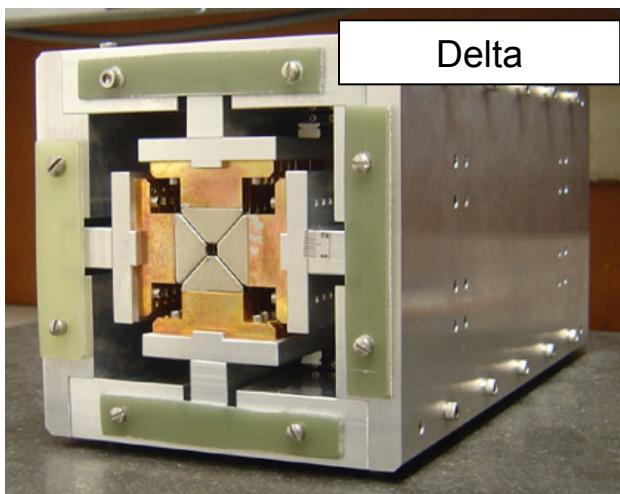
Crossed Planar Schemes

K-J Kim, NIMA 445, p329

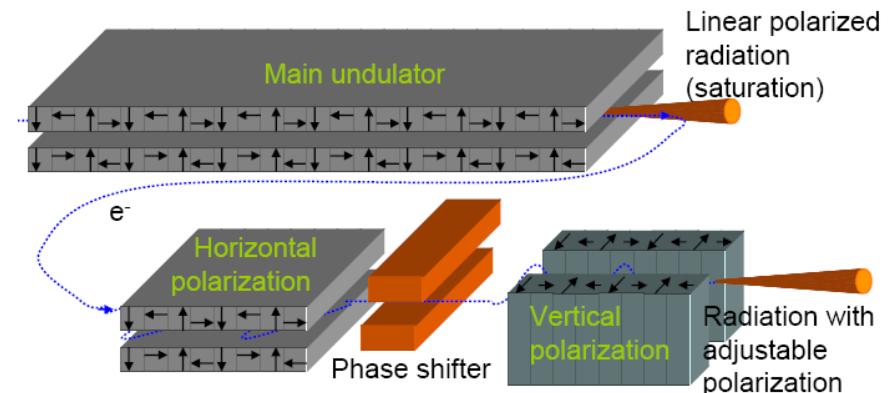


Y Ding, PRST-AB 030702 (2008)

Delta



A. B. Temnykh, PRSTAB 11, 120702, 2008



Y Li, EPAC08, p2282

# Undulator Comparisons

- Assume  $B_r = 1.2\text{T}$  and Period = 32mm

	APPLE-2	APPLE-3	Delta	Planar (Hybrid)
Magnet Gap (mm)	8.1	7.6	7.6	8.1
Vertical Field (T)	<b>0.85</b>	<b>1.09</b>	<b>1.23</b>	<b>1.05</b>
Helical Field (T)	<b>0.51</b>	<b>0.68</b>	<b>0.86</b>	<b>NA</b>
Horizontal Field (T)	<b>0.63</b>	<b>0.87</b>	<b>1.23</b>	<b>1.05</b>
Min Photon Energy (eV) (circular polarisation)	<b>452</b>	<b>293</b>	<b>198</b>	<b>254</b>

Results are from empirical equations except  
Delta which is from RADIA Model

# Undulator Comparisons

- FEL-3 photon energy range determines the NLS electron energy (430 to 1000eV)
- Re-optimise electron energy for these apertures
  - Change undulator period

	APPLE-2	APPLE-3	Delta	Planar (Hybrid)
Internal Aperture (mm)	7.0	7.0	7.0	7.0
Magnet Gap (mm)	8.1	7.6	7.6	8.1
<b>Energy (GeV)</b>	<b>2.25</b>	<b>2.1</b>	<b>1.9</b>	<b>2.1</b>

# Summary

- NLS currently assumes the use of APPLE 2 undulators with an 8 mm magnet gap
- The impact of the resistive wall wakefield has been calculated as a function of aperture and vessel shape using a ‘real’ start to end bunch
- There is negligible difference between circular and elliptical vessels
- A 10% loss in practically realisable power corresponds to a 7 mm internal aperture (relatively slow variation here)
- Four undulator options have been studied
- The APPLE-3 and crossed planar scheme would allow the beam energy to decrease from **2.25 GeV to 2.1 GeV**
- The Delta undulator would allow the beam energy to fall to **1.9 GeV**

# Next Steps

- Study wakes in more detail
  - Look at effect of timing jitter on output
  - Include modulator sections
  - Look at strategies to recover power loss (eg tapering, longer undulator sections)
- Model the crossed planar scheme for FEL-3
  - Polarisation rate as a function of output power
  - Higher harmonic polarisation
  - Optimum configuration
- Carry out a detailed assessment of the Delta design including magnetic forces, support structure, measurement procedure, shimming ideas, etc.
- The vacuum chamber selected must be prototyped to check that the wall thickness, straightness, smoothness, porosity, etc can be achieved

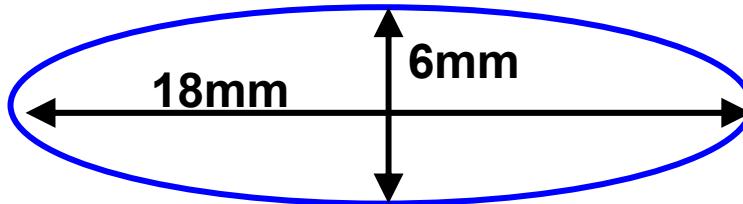
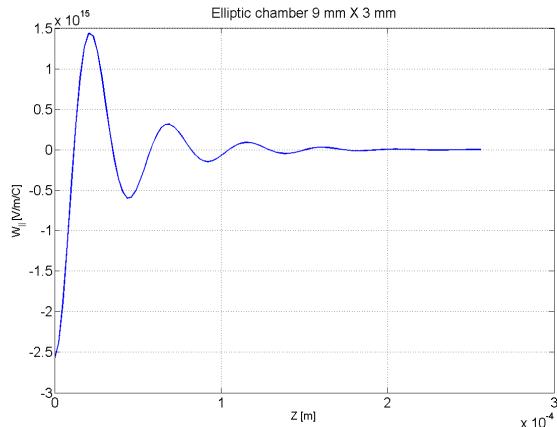
# Extra Slides

# Magnet Gap Comparisons

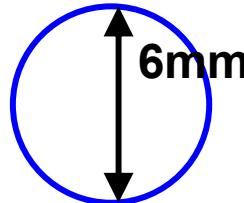
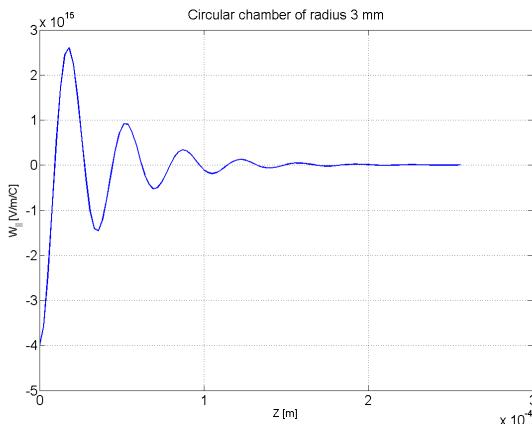
Project	Minimum Magnet Gap (mm)	Vertical aperture for electron beam (mm)
XFEL	10.0	7.6
LCLS	6.8	5.0
SCSS	4.0 nominal (in-vac)	4.0 nominal (in-vac)
PAL FEL (2008)	5.0 nominal (in-vac)	5.0 nominal (in-vac)
FERMI	10.0	6.0
BESSY FEL	10.4 on-axis (circular pipe), 5.4 off-axis	9.0 (diameter)
FLASH	12.0	9.5
<b>NLS (initial working assumption)</b>	<b>8.0</b>	<b>6.0</b>

# Comparing Elliptic and Circular Vessels

- Want to compare elliptical result against “*equivalent*” circular vessel

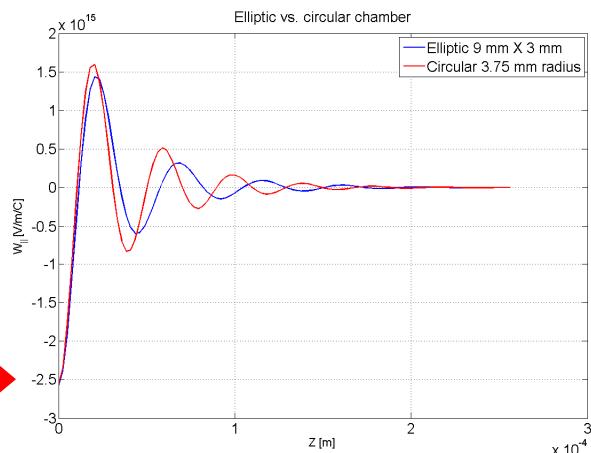
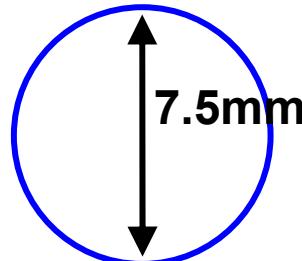
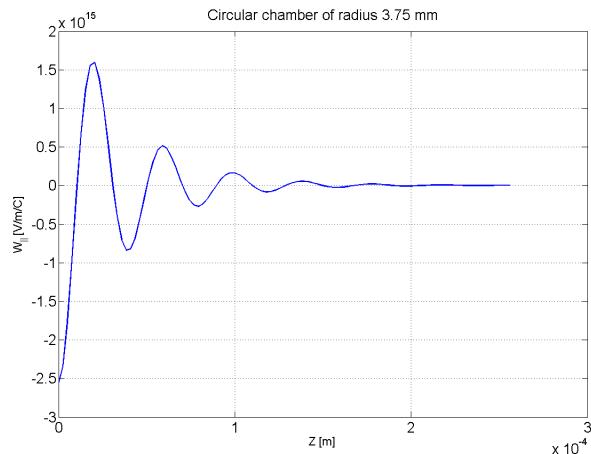


Wakes from single particle at  $z = 0$   
Copper, AC conductivity model



# Comparing Elliptic and Circular Vessels

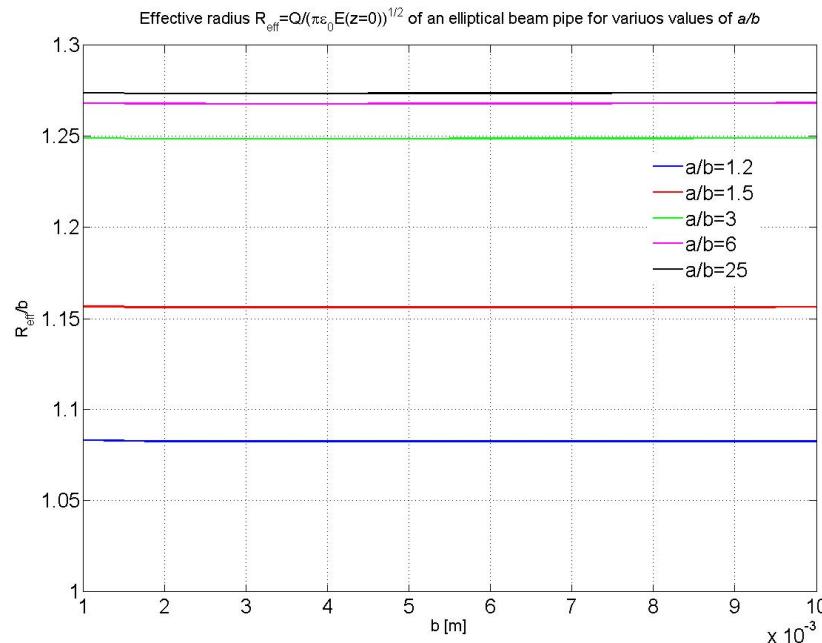
- Adjust diameter of circular vessel to give same field observed by particle (self-field)



Same field at  $z = 0$  but some variation after. This “equivalence” is clearly an approximation but helps develop understanding of how vessel geometries can be compared

# Variation with Aspect Ratio

- Graph shows how effective circular radius varies with elliptical vessel half height,  $b$ , as a function of elliptical vessel aspect ratio ( $a/b$ )
- For  $a = 3b$ , radius =  $1.25 \times b$



# Circular vs Elliptical

- Gaussian bunch, AC, Cu
- $R_L$  = Radius of circular vessel which gives same average **energy loss** per bunch
- $R_s$  = Radius of circular vessel which gives same average **energy spread** per bunch
- Effect of different vessel shape dependent upon bunch length

