Accelerator Science and Technology Centre

Undulator Issues for ERLs

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What do we need to consider?

- Effect of round beams
  - Is this an advantage or disadvantage?
- Can ERLs have undulators with narrower gaps?
- Can ERLs make use of longer undulators?
- Do the undulators have a significant impact on the electron beam itself?
- Will the user of an ERL have a different experience to one on a 3GLS?

Round Beams

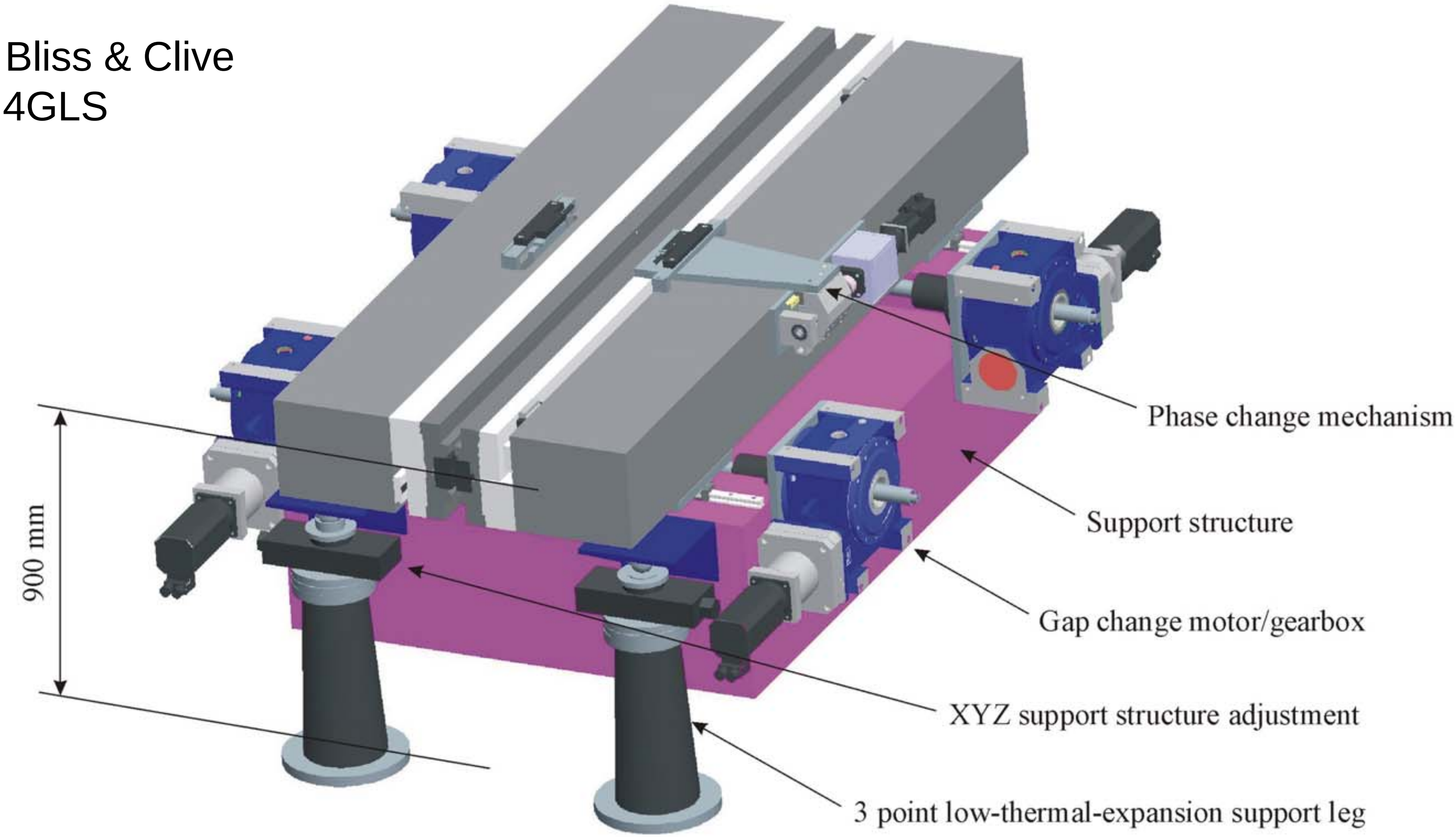
- No need for elliptical vacuum chambers
- No injection process
- Equal emittance in both planes

- Undulator orientation could be horizontal (or arbitrary or even variable?)
- In general this seems to make the engineering easier (& cheaper)
- Several FELs have made use of horizontal undulators

- Can surround the vacuum chamber with the magnet
- Higher on-axis magnetic fields
- Engineering and testing more complex
- Helical fields much easier to generate (but maybe not if variable polarisation needed)

Horizontal undulators – possible APPLE-II design

Neil Bliss & Clive Hill, 4GLS



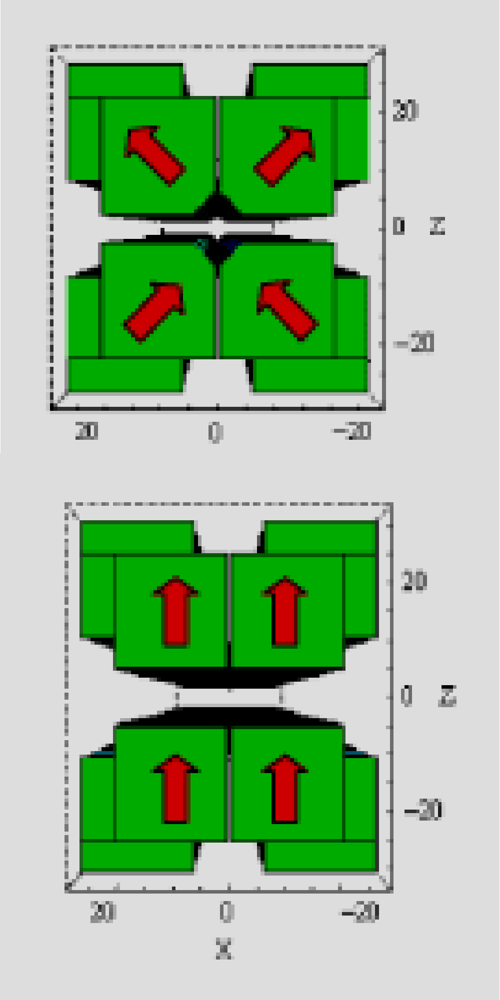
Horizontal undulators - example

Undulator built at Daresbury for Alpha-X laser plasma wakefield/FEL program at Strathclyde University

Delivered Jan 2006

Jim Clarke, Ben Shepherd and Clive Hill

Round vacuum chamber – APPLE-III design



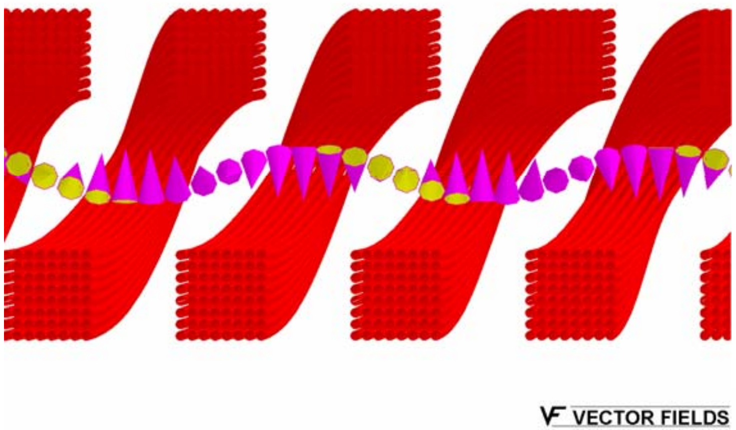
- BESSY FEL Design
- Variable polarisation
- 10.4 mm diameter tube
- 5.4 mm gap at sides
- Field further enhanced by 45 degree magnetisation direction.
- Effective magnetic field ~1.4 times higher than for APPLE-II with 10.4 mm gap

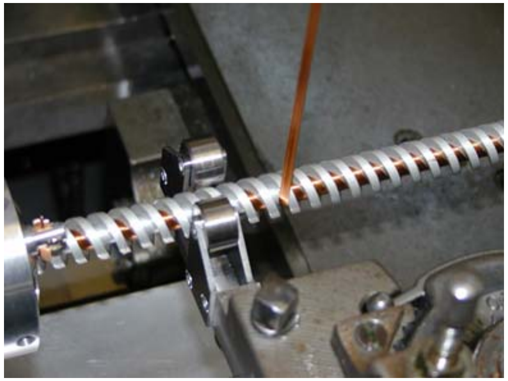
j.b. Bahrdt et al.
Proceedings of the 2004 FEL Conference, 610-613

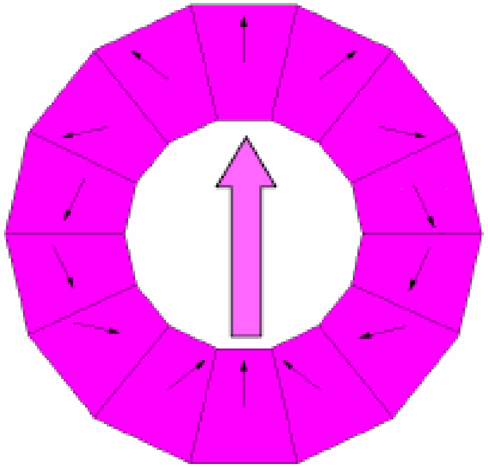
Round vacuum chamber – other options

Bifilar windings.

SC version ~ 1.7 times higher on-axis field than APPLE-II (for 14mm period, 4mm bore example)







Permanent Magnet Halbach Rings

Approx same field as SC for 14mm period, 4mm bore example

Smaller Gaps?

- (Very) Low emittance in both planes
- Can ERLs have smaller gaps over longer lengths than 3GLS ?
- Must keep electron losses very small to avoid radiation damage
  - Typical 3GLS will lose ~5 x 10^{12} e^- per day
  - ERL with 100mA average current will circulate ~5 x 10^{22} e^- per day
  - Must keep losses in undulators extremely low to avoid radiation damage to permanent magnets
  - Say keep losses to 1 in 10^6
  - Undulator could still get equivalent of 20 year lifetime dose in 1 day !

Radiation Damage

- Keep losses ***at undulator*** to 1 in 10^{10}
- Undulator gets same dose as 3GLS ***ring*** each day
- In other words …

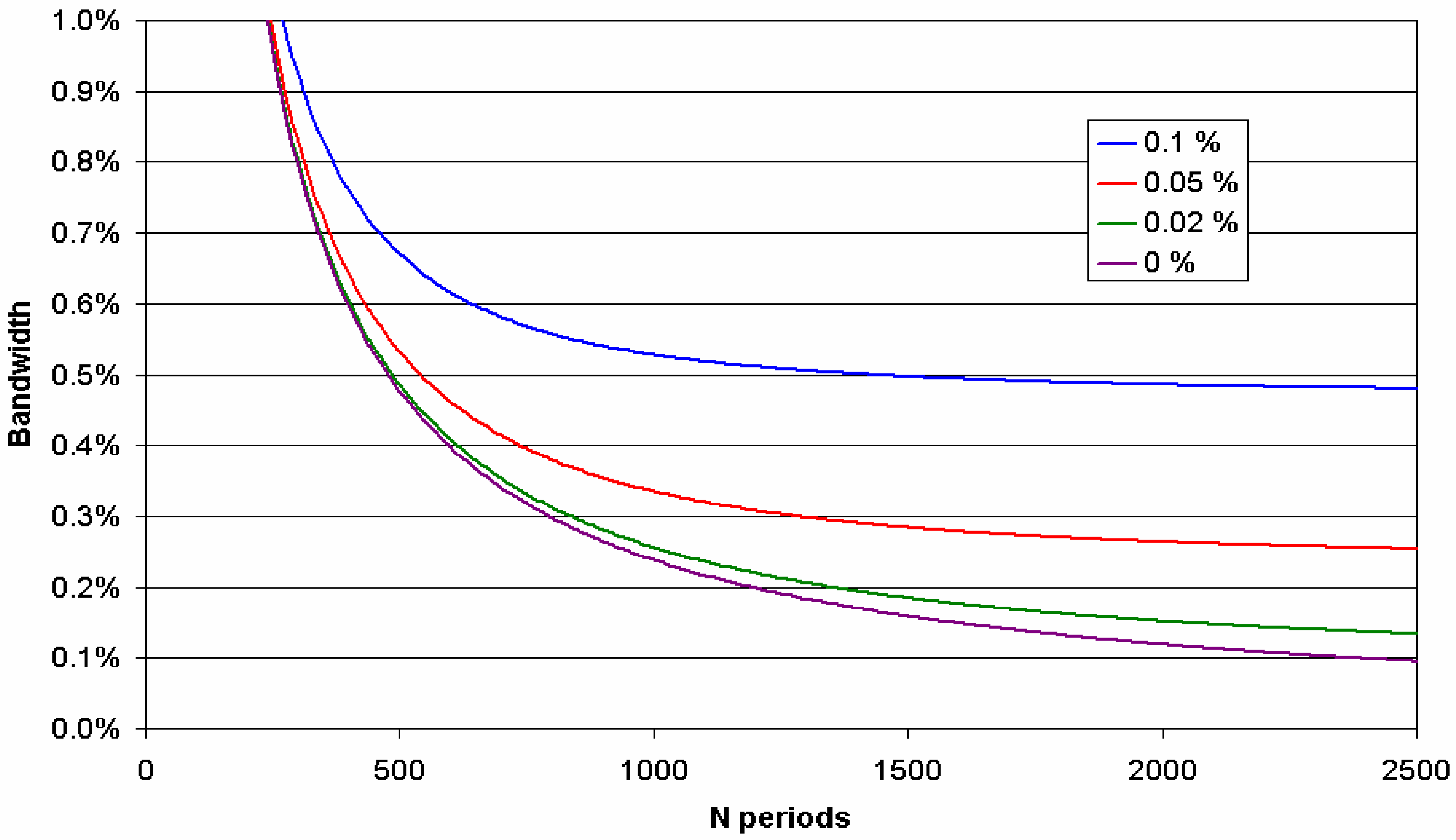
- **We are using the undulator as if it is the only loss point in a 3GLS**

- *Such an approach seems very dangerous*
- Many undulators have been damaged in 3GLS especially at the high energy rings
- Maybe permanent magnets should not be used at all ?
- SC magnets more resistant but quality not as good

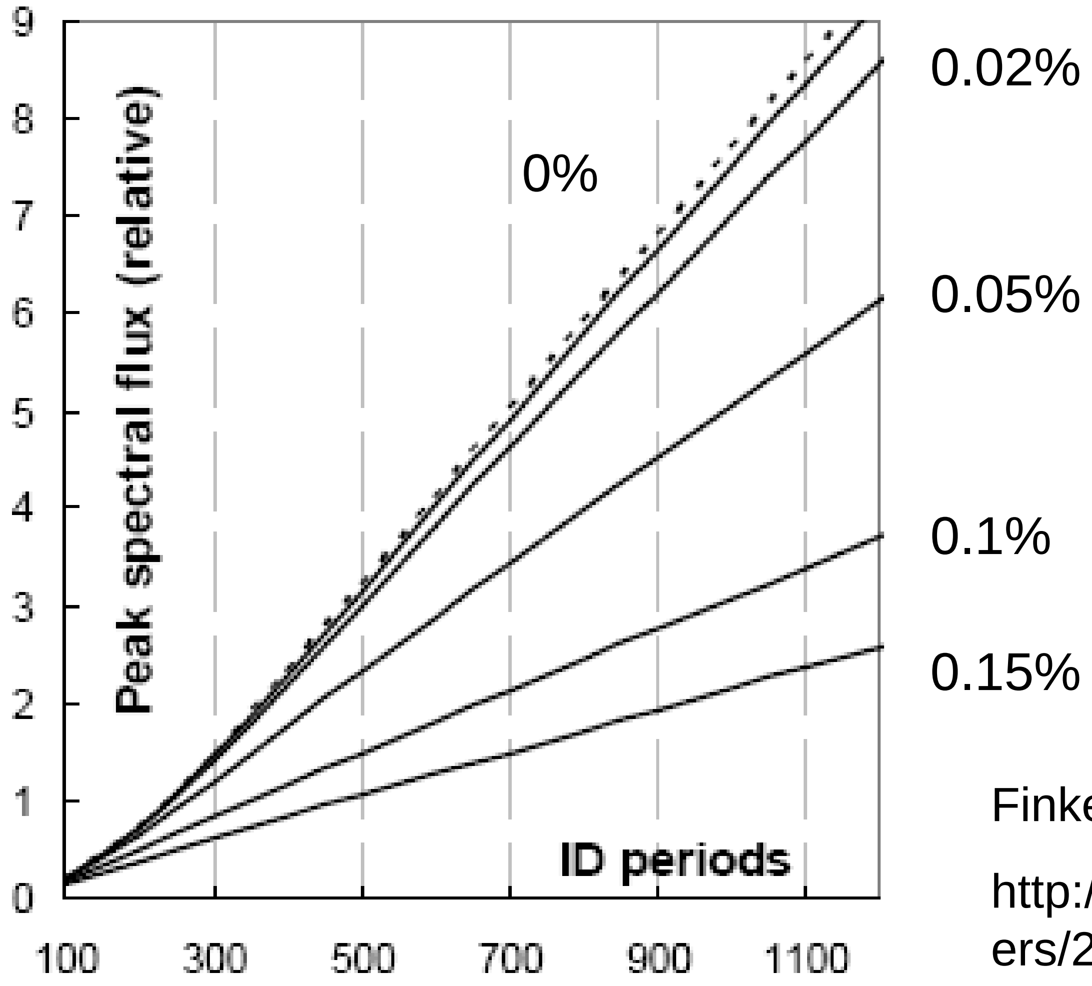
Longer Undulators?

- Undulator linewidth has several contributions
  - Number of periods
  - Energy spread
  - Electron beam divergence
- Storage rings all have energy spread ~0.1%
- ERLs can have lower values – what effect does this have?

Bandwidth vs Number of Periods vs Energy Spread



Spectral flux example



Finkelstein et al

http://erl.chess.cornell.edu/papers/2005/ERLPub05_4.pdf

Wakefields in Narrow Gap vessels

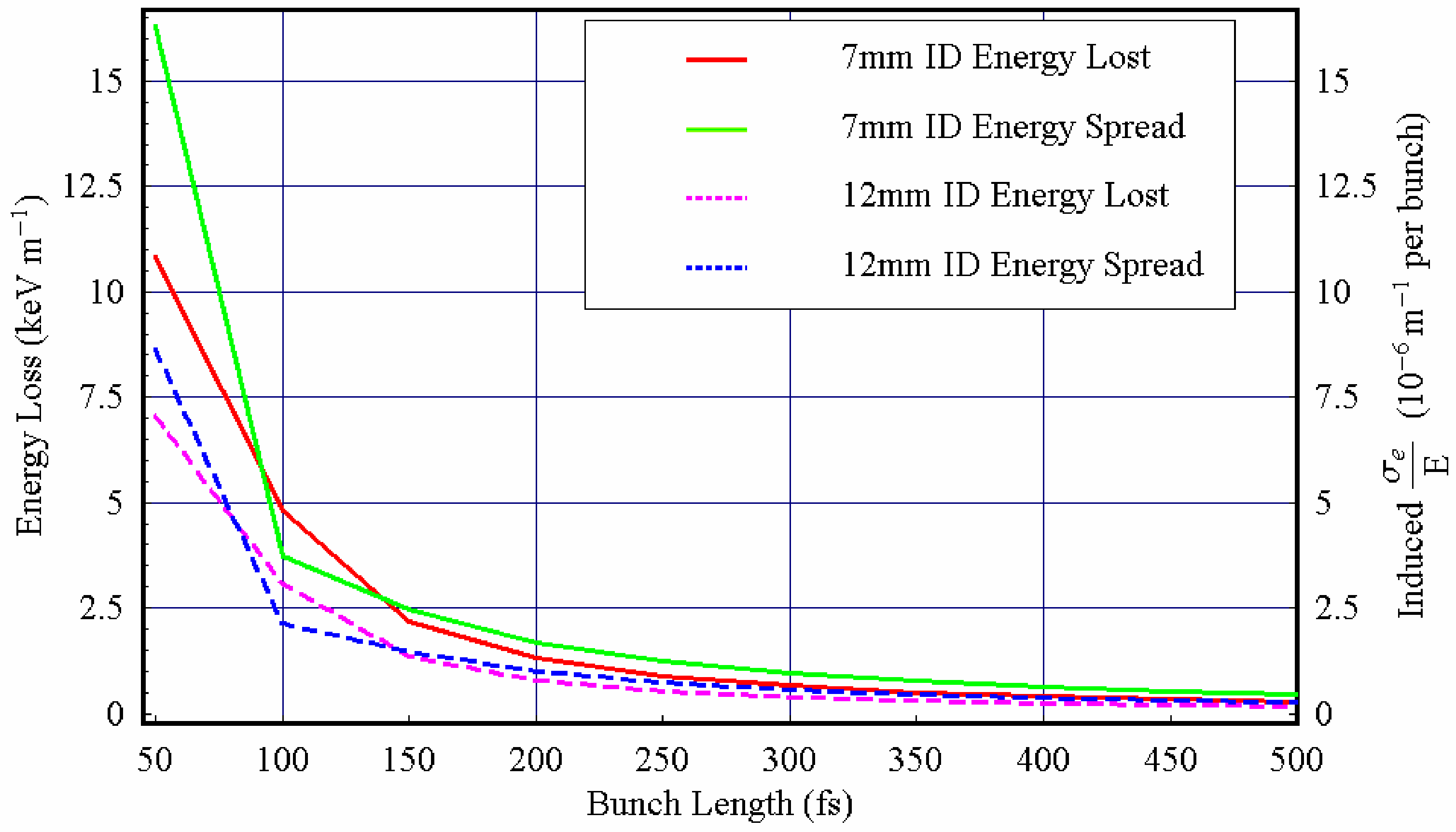
Results for 4GLS: 77pC, 50 fs, 10 m vessel, 273K

Parameter	*Unit*	*Value*					
Vessel Material		**Cu**		**Al**		**SS**	
Vessel ID	mm	7	12	7	12	7	12
Total Energy Lost	**keV**	**81**	**53**	**108**	**70**	**524**	**244**
Relative Energy Lost	10^{-5}	13	8.8	18	12	87	41
Induced Relative Energy Spread	**10^{-6}**	**9.6**	**5.7**	**12**	**7.3**	**60**	**35**
Transverse Kick	keV mm^{-1}	0.21	0.045	0.25	0.054	0.84	0.19

50 keV, 100 mA = 5 kW in vessel walls !

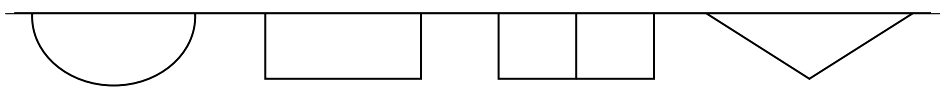
Wakefields in Narrow Gap vessels

Results for 4GLS: Aluminium, 77pC



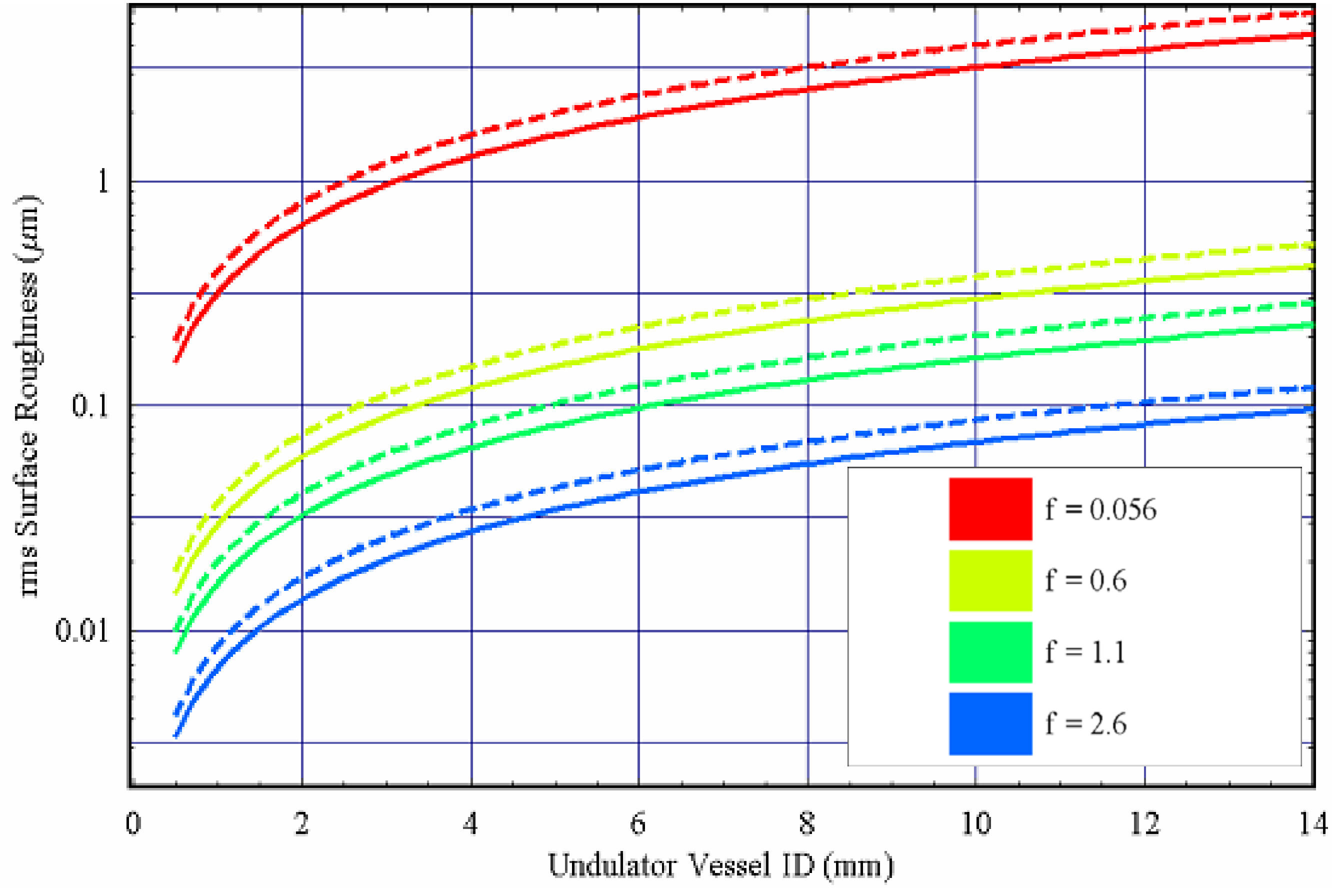
Surface Roughness

- Various bump shapes modelled
- Each has a form factor found from FEA models
- Two ERL examples:



	Unit	4GLS	High Energy ERL
Energy	GeV	0.6	6
Nominal Energy Spread	%	0.1	0.02
Bunch Length	fs	100	100
Bunch Charge	pC	77	77
Undulator Length	m	10	25

Roughness Specification



0.6GeV = dashed line

6GeV = solid line

Energy spread induced set to 10% of nominal

Steel vessels with 125nm roughness are available

Need to take care that coating on vessel wall does not increase roughness

LCLS measured vessel has f = 0.056

Impact of Undulators on Electron Beam

- Emission of SR
  - Electron energy will reduce
  - Energy spread could increase
  - Emittance could increase
- Variable electron path
  - Timing issues?
  - Pulse length variation?

Electron Energy

- Energy loss $$\Delta E = 1265.5 E^2 \int_0^L B(s)^2 ds$$
- For 10m long helical undulator with 1 T field:
- 0.6 GeV = 4.5 keV (< 1 in 10^5)
- 6 GeV = 450 keV (~ 8 in 10^5)
- Energy change of 0.01% gives wavelength change of 0.02%
- Harmonic width ~ 1/nN
  - 1^{st} harmonic ~1%
  - 5^{th} harmonic ~0.2%
- Monochromator bandwidth typically 0.01%
- Wavelength variations due to variable energy could limit number of periods (?) or freedom of users to change undulator gaps (?)

Note - Dipole CSR

- Energy loss dominated by Dipole CSR when bunches short
- Undulator losses maybe irrelevant

- Gaussian bunch length rms = 100 fs
- 0.6 GeV = 80 keV per 10 degrees (0.35T)
- 6 GeV = 230 keV per 10 degrees (0.35T)

- Gaussian bunch length rms = 50 fs
- 0.6 GeV = 200 keV per 10 degrees (0.35T)
- 6 GeV = 490 keV per 10 degrees (0.35T)

- Bunch to bunch (shot to shot) variation ?
- Real longitudinal bunch profile will increase these figures !

Energy Spread

- Analytical solution
- Helical Undulator

$$\sigma_\gamma = 5.02\times10^{-13}\gamma K\left(\frac{F(K)L}{\lambda_u^3}\right)^{1/2}$$

$$F(K) = 1.42K + \frac{1}{1+1.50K+0.95K^2}$$

E. L. Saldin et al, NIM A 381 (1996) p545.

- Example helical undulator with 50mm period, K =5, 10m long
- 0.6GeV = 0.0002%
- 6GeV = 0.002%

Emittance Growth

- Analytic approach assuming zero dispersion in undulator straight and ~constant β

$$\Delta\varepsilon = 1.04 \times 10^{-15} \lambda_u^2 B^5 \hat{\beta} L$$

- Example undulator with 50mm period, K =5, 10m long
- 0.6 GeV ~ 2 x 10^{-7} nm rad, compared with ~1 nm rad
- 6 GeV ~ 2 x 10^{-7} nm rad, compared with ~0.1 nm rad

R. Glantz, DESY-97-201, 1997.

Path length effects

- Undulator gap change implies electron taking different path
  - Could disrupt subsequent timing experiments
  - Example undulator with 50mm period, 10m long
  - Delay between undulator off and on:
  - 0.6 GeV = ~300 fs
  - 6 GeV = ~3 fs
  - If problem then could install simple 3 pole chicane to counteract (?)

- *Also note slippage effects will lengthen output pulse by $N\lambda$*
- *Long wavelength experiments can be significantly affected*

Summary

- Effect of round beams
  - Is this an advantage or disadvantage? Advantage if can make use of it
- Can ERLs have undulators with narrower gaps? Losses critical, wakefields significant
- Can ERLs make use of longer undulators? Losses critical, wakefields significant, low energy spread good
- Do the undulators have a significant impact on the electron beam itself? Energy loss a concern, energy spread might be a problem, path length effects an issue at low energies/long wavelengths
- Will the user of an ERL have a different experience to one on a 3GLS? Main worry is wavelength shift with energy