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Long wavelength free electron lasers: modelling and experiments

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Contents

Books on FELs

- H.P. Freund and T.M. Antonsen, *Principles of free-electron lasers,* Chapman and Hall (London), 2nd Edition 1996.
- P. Luchini and H. Motz, *Undulators and Free-Electron Lasers*, OUP (Oxford), 1990.
- Eds. W.B. Colson, C. Pelligrini and A. Renieri, *Laser Handbook Vol 6 – Free Electron Lasers*, North Holland (Amsterdam), 1990.
- C.A. Brau, *Free-Electron Lasers*, Academic Press, (San Diego), 1990.
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FREE ELECTRON LASERS

1947 V. Ginzburg discusses radiation from undulating electrons

1951 Motz proposes an undulator for producing incoherent radiation

1952-53 Motz measures incoherent radiation using an undulator

1958-60 R Phillips produces coherent radiation in a new device called an ‘ubitron’ which we would now call an FEL or FEM

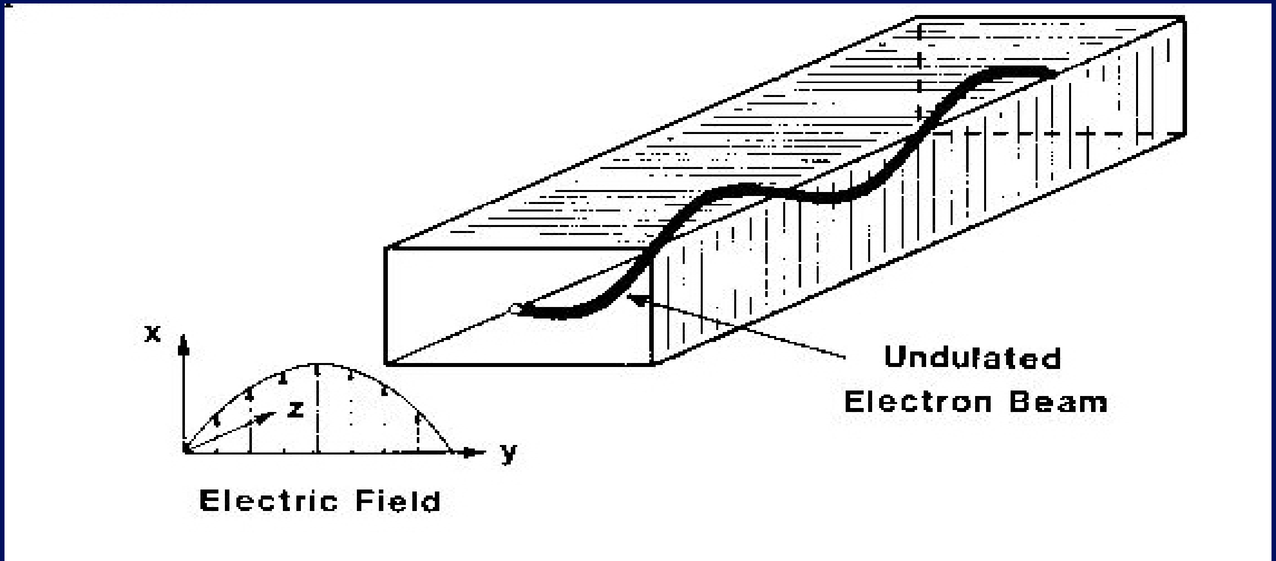
1971-73 Madey introduces the name ‘Free Electron Laser’

1976-77 Madey et al claim the first operating FEL

2009 Many FELs and FEMs worldwide - X-ray to microwave

Ubitron

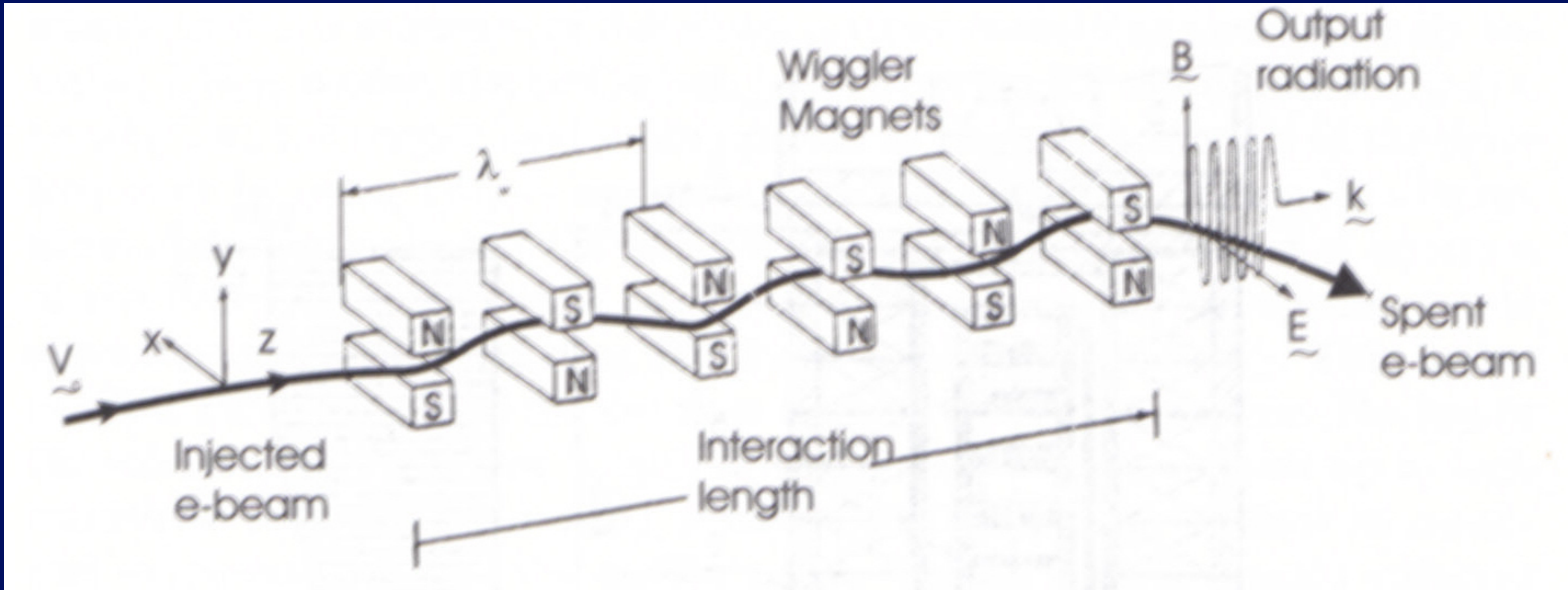
Undulated **b**eam **i**nteraction elec**tron** tube



Phillips IRE Trans Electron Dev, **7**, 231 1960

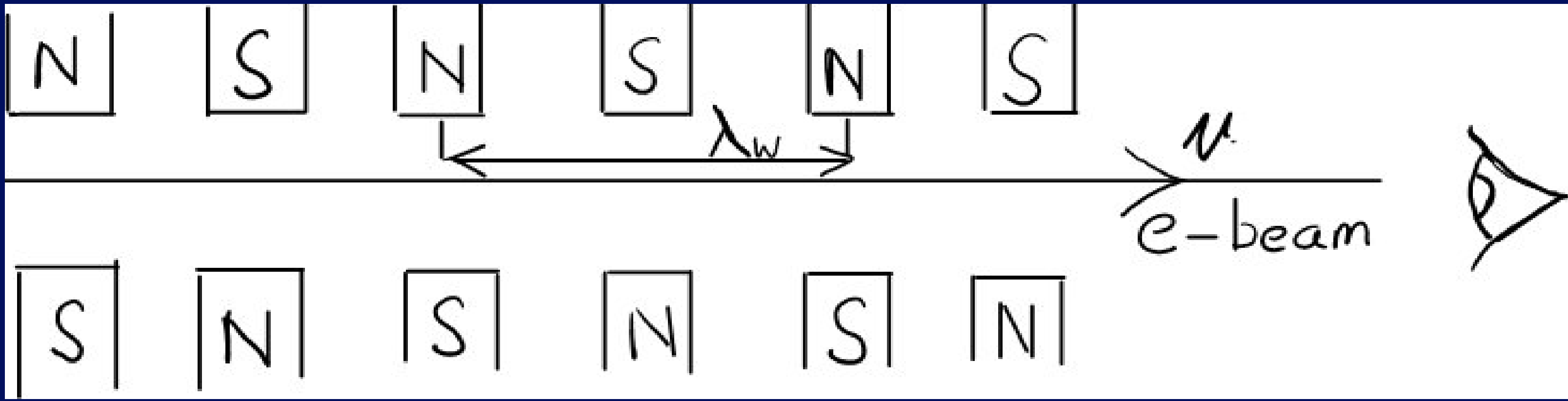
Phillips worked on the ubitron 1958-1965

FREE ELECTRON LASERS



$$\lambda = \frac{\lambda_w (1 + K^2/2)}{2\gamma^2}$$

UNDULATOR STRUCTURE



Spatial period of magnet in lab frame = λ_W

Speed of electrons along the axis towards the observer = v

H. Motz introduced the undulator in 1951 and in 1953 he published observations of incoherent undulator radiation. Madey in the 1970's introduced the name "free electron laser" for an undulator structure placed in an optical cavity. The feedback in the cavity provides coherent radiation.

The bunching of the particles produced by the feedback of the radiation field on the particles can be regarded as the classical equivalent of "stimulated emission of radiation."

APPROXIMATE ESTIMATE of FREQUENCY UPSHIFT

Electron sees magnet structure Lorentz contracted by a factor of γ

Therefore the wavelength seen by the moving electron $= \dfrac{\lambda_w}{\gamma}$

The electron is moving towards the observer so there is a Doppler upshift of the frequency emitted by the electron by a factor of γ and so the frequency observed by the observer = γ x frequency emitted by electron

and since $\lambda \propto \dfrac{1}{\text{frequency}}$

Therefore the wavelength observed should be $\approx \dfrac{\lambda_w}{\gamma^2}$

and the frequency should be upshifted by γ^2

APPROXIMATE ESTIMATE of FREQUENCY UPSHIFT

To get an estimate of the upshift possible, suppose the electrons are accelerated through 10MV to provide an energy of 10MeV.

Then $\gamma = 1 + \dfrac{eV}{m_{e0}c^2}$ where V is the potential difference through which the electron has been accelerated and m_{e0} is the rest mass of the electron.

The rest mass energy $m_{e0}c^2$ is 511keV and so for 10MeV electrons $\gamma \approx 21$

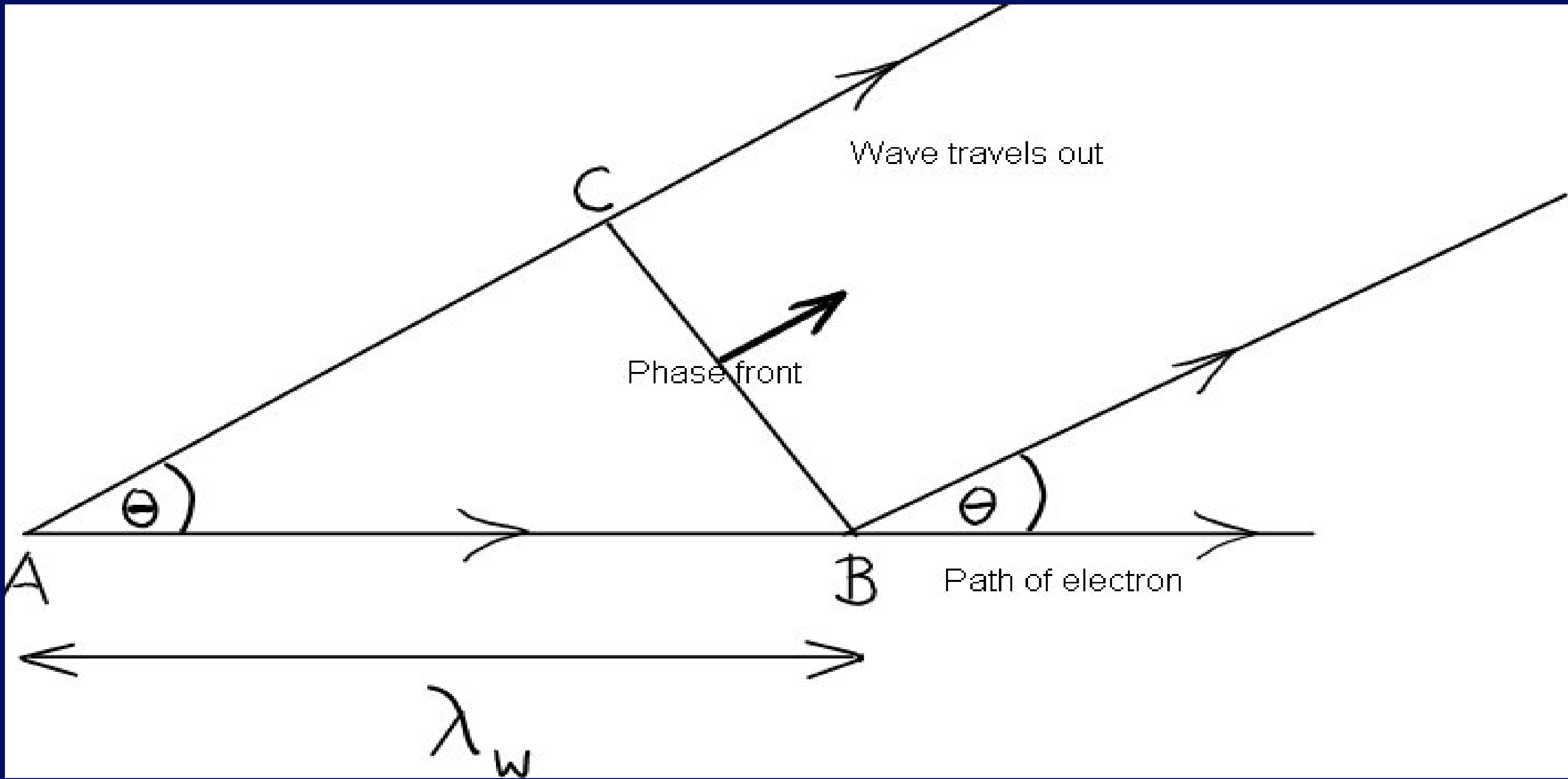
and so if $\lambda_w = 10\text{mm}$ the observed emitted wavelength $\approx \dfrac{10}{21\text{x}21}\text{mm} \approx 23\mu\text{m}$

However this method of obtaining an equation to describe the upshift is not really rigorous and in fact the equation for the upshift in the case of an undulator of <u>negligible magnetic field strength</u> is a factor of 2 different from the above,

Namely $\lambda = \dfrac{\lambda_w}{2\gamma^2}$

The factor of two is associated with the subtle difference between a stationary wave and a travelling wave.

Condition for synchronism



The electron moves from A to B while the electromagnetic wave travels out in the direction AC. Since the wave travels faster than the electron the wave has passed beyond C when the electron reaches B but for synchronism BC should be a phase front.

BC is a phase front if $$\frac{\lambda_w}{v} - \frac{\lambda_w \cos\theta}{c} = n\tau$$

where τ is the wave period and n is an integer

FEL fundamental formulae

The peak of the spontaneous emission spectrum from a magnetic undulator of wavelength λ_w for free relativistic electrons occurs at a wavelength λ given by

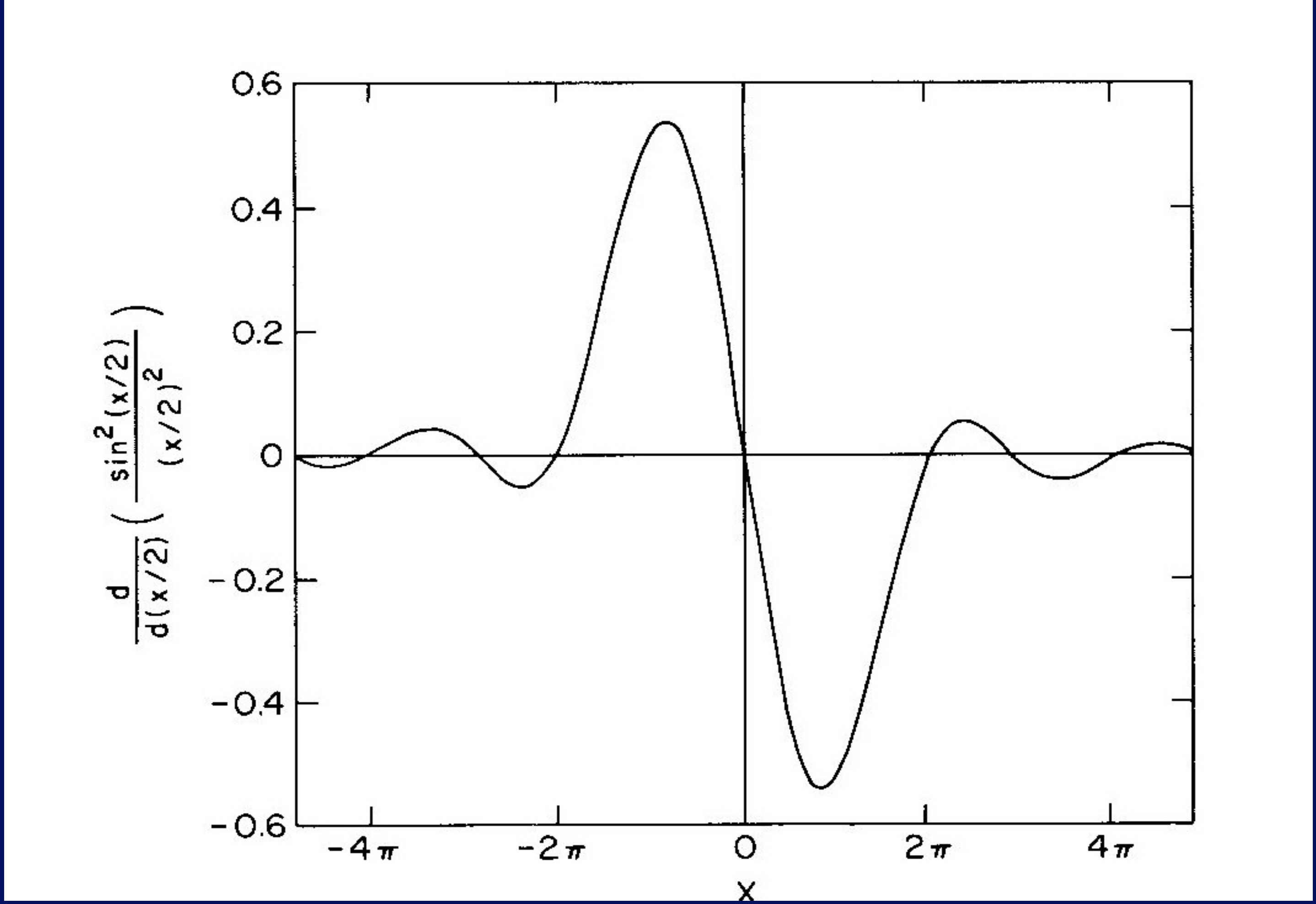
$$\lambda = \frac{\lambda_w (1 + K^2 / 2)}{2\gamma^2}$$

where $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$ and $K = 93.4 \lambda_w B_w$

λ can range from microwave to X-ray wavelengths

The FEL can be tuned by varying the electron beam energy which varies γ or by varying B_w which varies K. It is not so easy to tune by varying λ_w

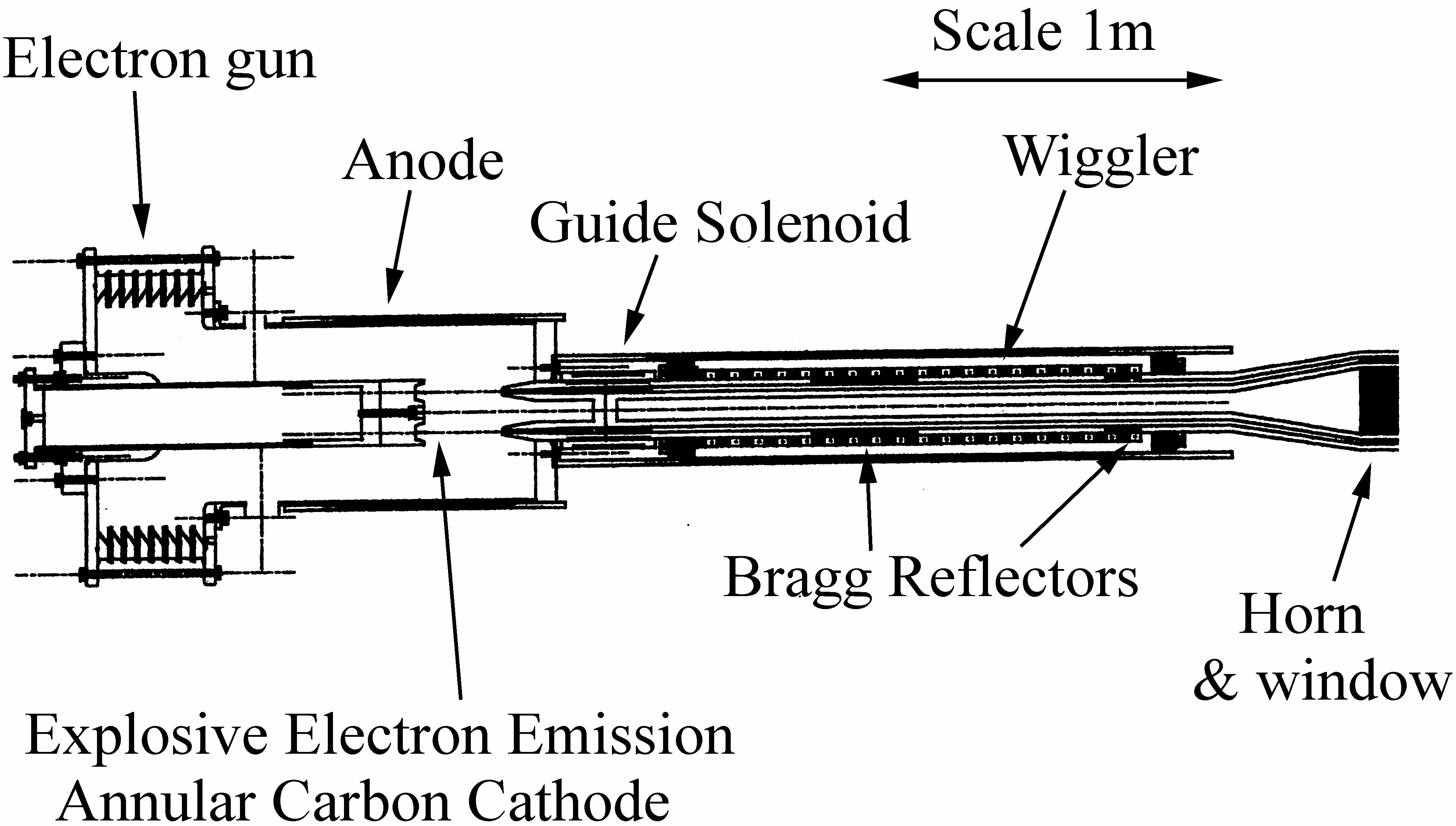
FEL gain curve is asymmetric about resonance frequency



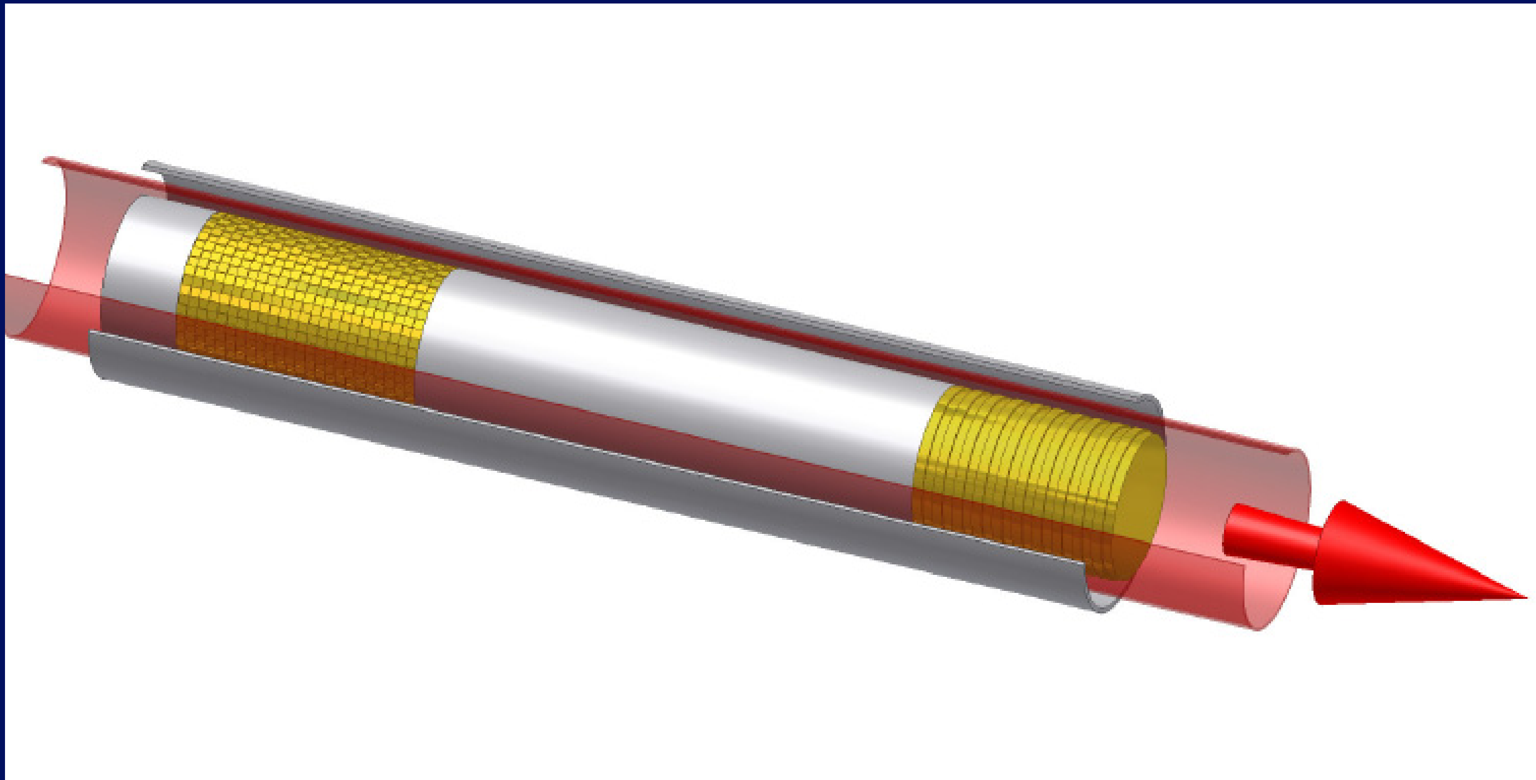
Why introduce 2D distributed feedback?

- Many FEMs have used 1D Bragg structures when D/λ~2-4
- To increase the output power of the coherent radiation
  - increase electron energy
  - increase beam current
- Must increase diameter (D) of the interaction region due to fundamental limitations: if the transverse size of the system is not increased
  - power density becomes high and EM pulse shortening can occur
  - high current densities can lead to instabilities interrupting e-beam
- To retain single mode as size increases we use 2D feedback

Strathclyde ~37 GHz Free Electron Maser

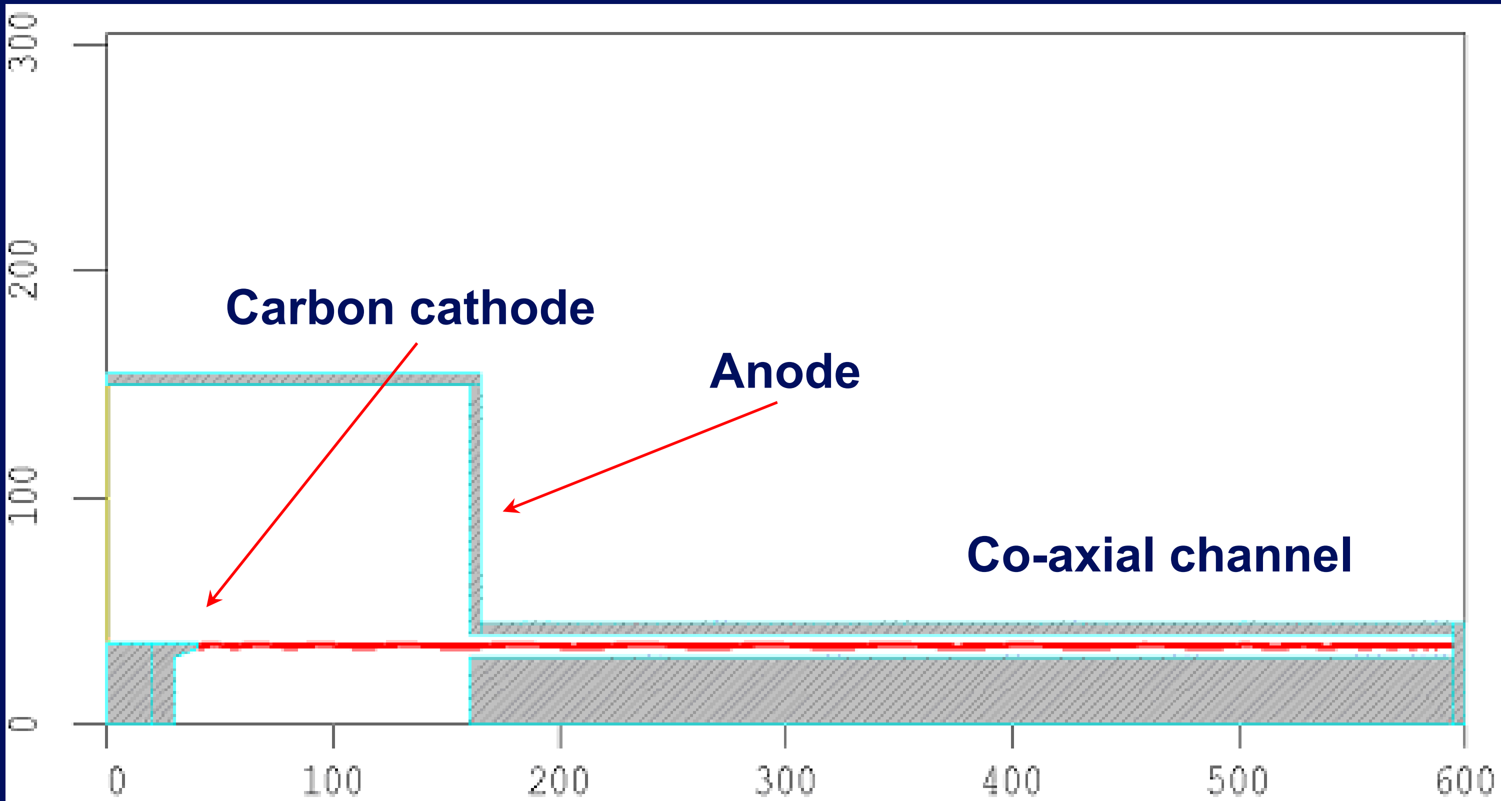


Co-axial FEM with 2D and 1D Bragg mirrors



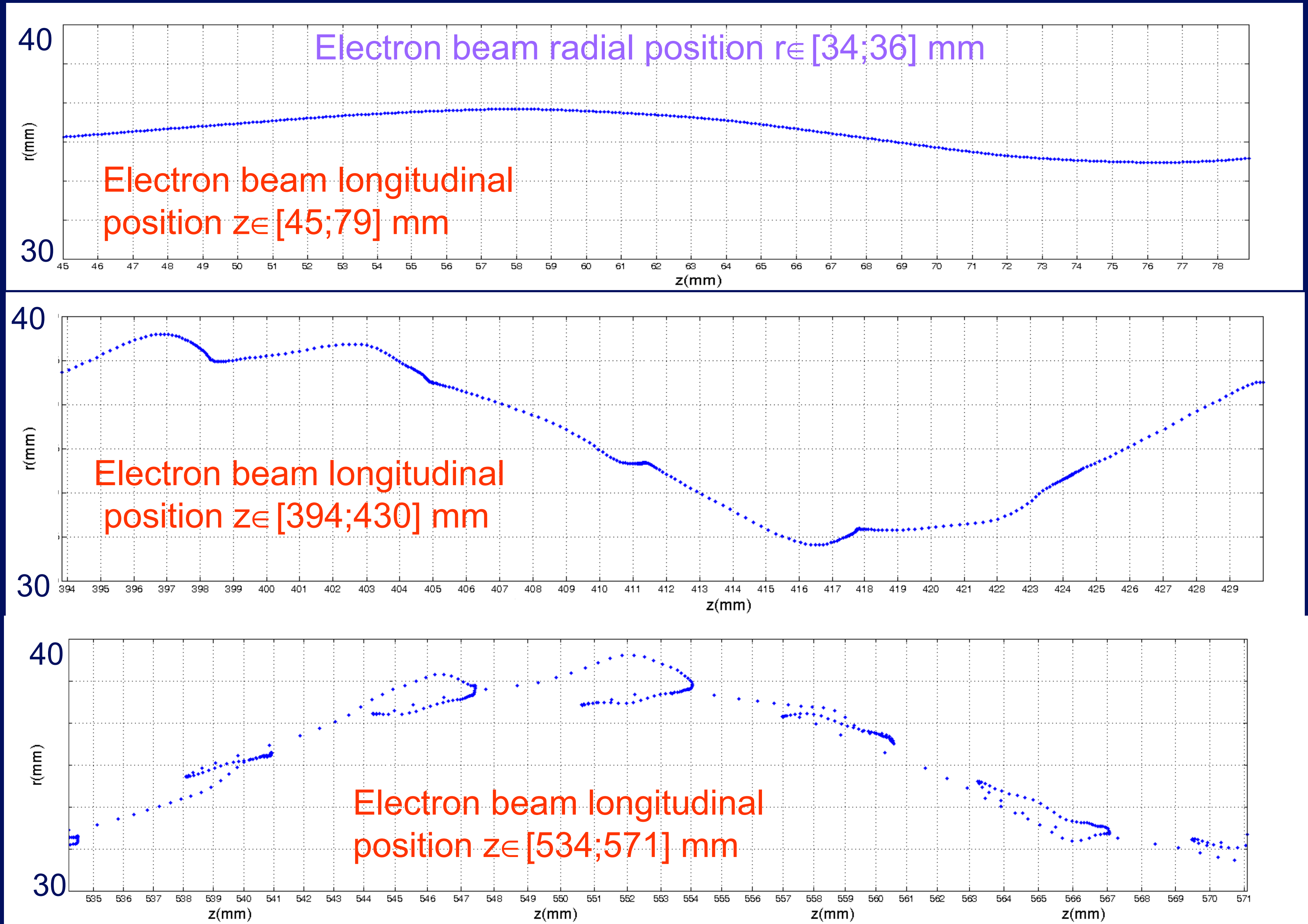
Annular electron beam formation by plasma flare cathode

MAGIC PIC code simulations of electron beam formation from plasma flare cathode

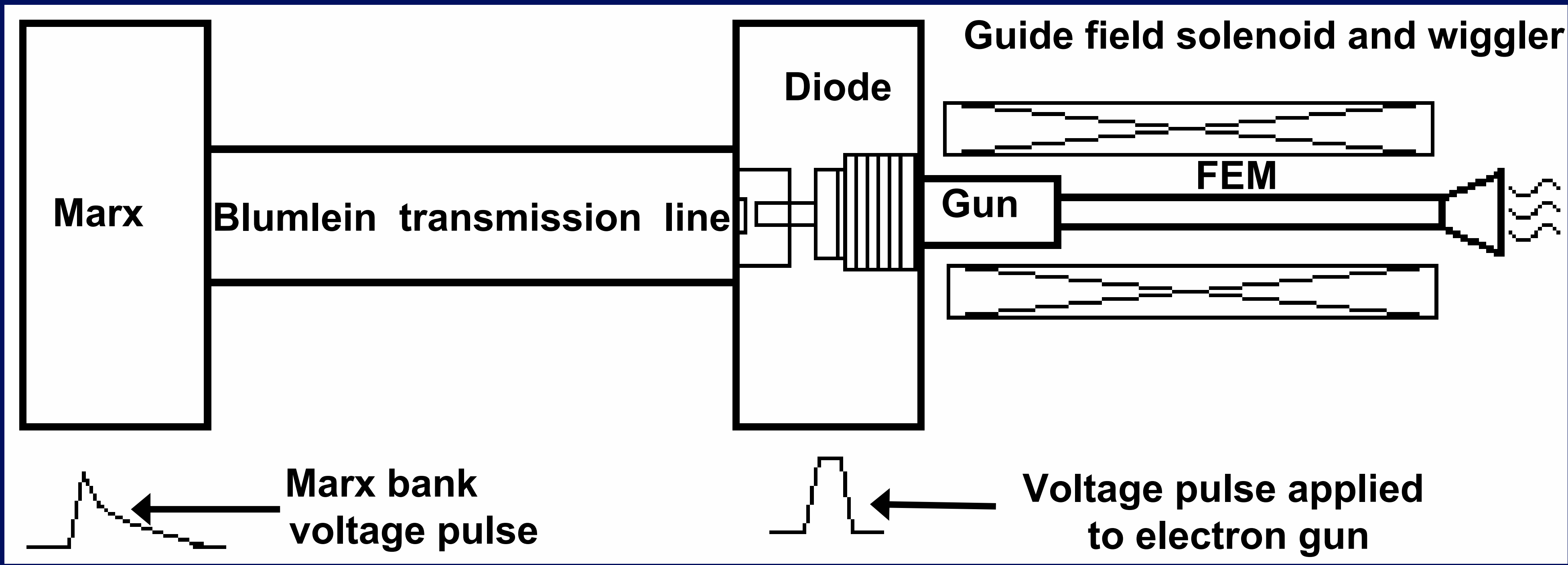


- Electron beam
  - accelerating voltage 450kV
  - beam current ~1.5kA
- Beam power ~ 600MW

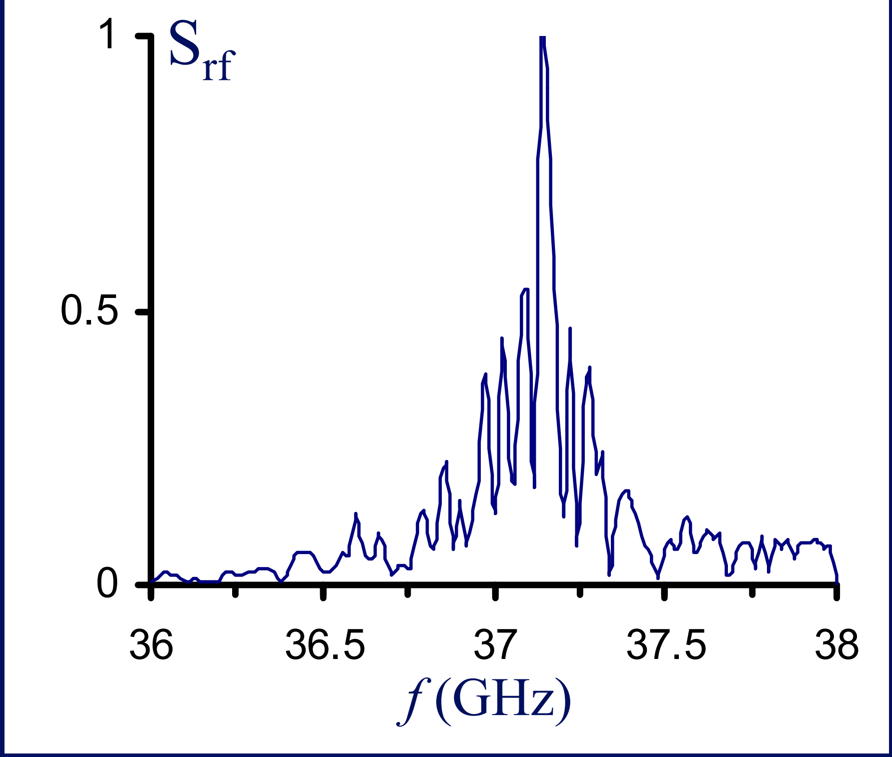
Electron beam bunching inside the FEM



Schematic of Strathclyde FEM & pulsed power system



Heterodyne Frequency Diagnostics



Measured spectrum of the output radiation from the FEM

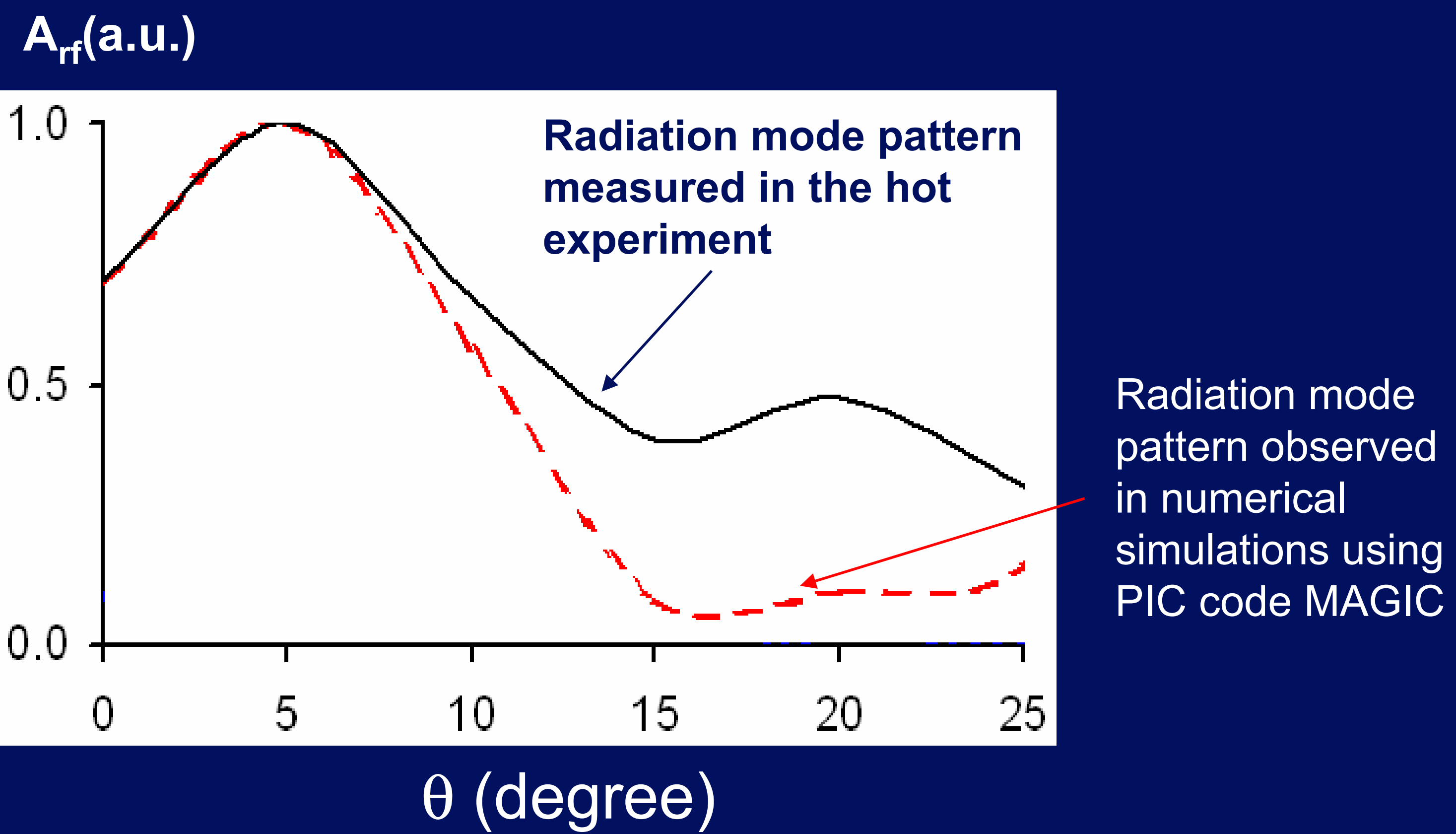
Phys. Rev. Lett., **96**, 035002, 2006

Excitation of Neon Bulb Panel

Excitation of the neon light bulb panel due to the EM field of millimetre wave radiation generated by 2D Bragg co-axial FEM
- neon bulbs are located at ~20 cm from the output window

Mylar co-axial output window - inner diameter 6cm
- outer diameter 20cm

Mode Pattern



- The output radiation pattern
  - measured during “hot” experiments - (electron beam present)
  - predicted using 3D code MAGIC (dashed red line)

Conclusions

- Modelling of FEM based on 2D/1D Bragg cavity achieved
- High current e-beam driven FEM experiment operational
- FEM 60 MW, 200ns, ~9J, ~37GHz, ~10% efficiency measured
- 2D distributed feedback has been successfully demonstrated
- FEM based on 2D/1D Bragg preferable to 2D/2D Bragg

Acknowledgements

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Strathclyde FEM References

Please send an e-mail to: a.d.r.phelps@strath.ac.uk
If you would like to be sent some of these FEL references.
Please give both your e-mail and your paper mail address

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