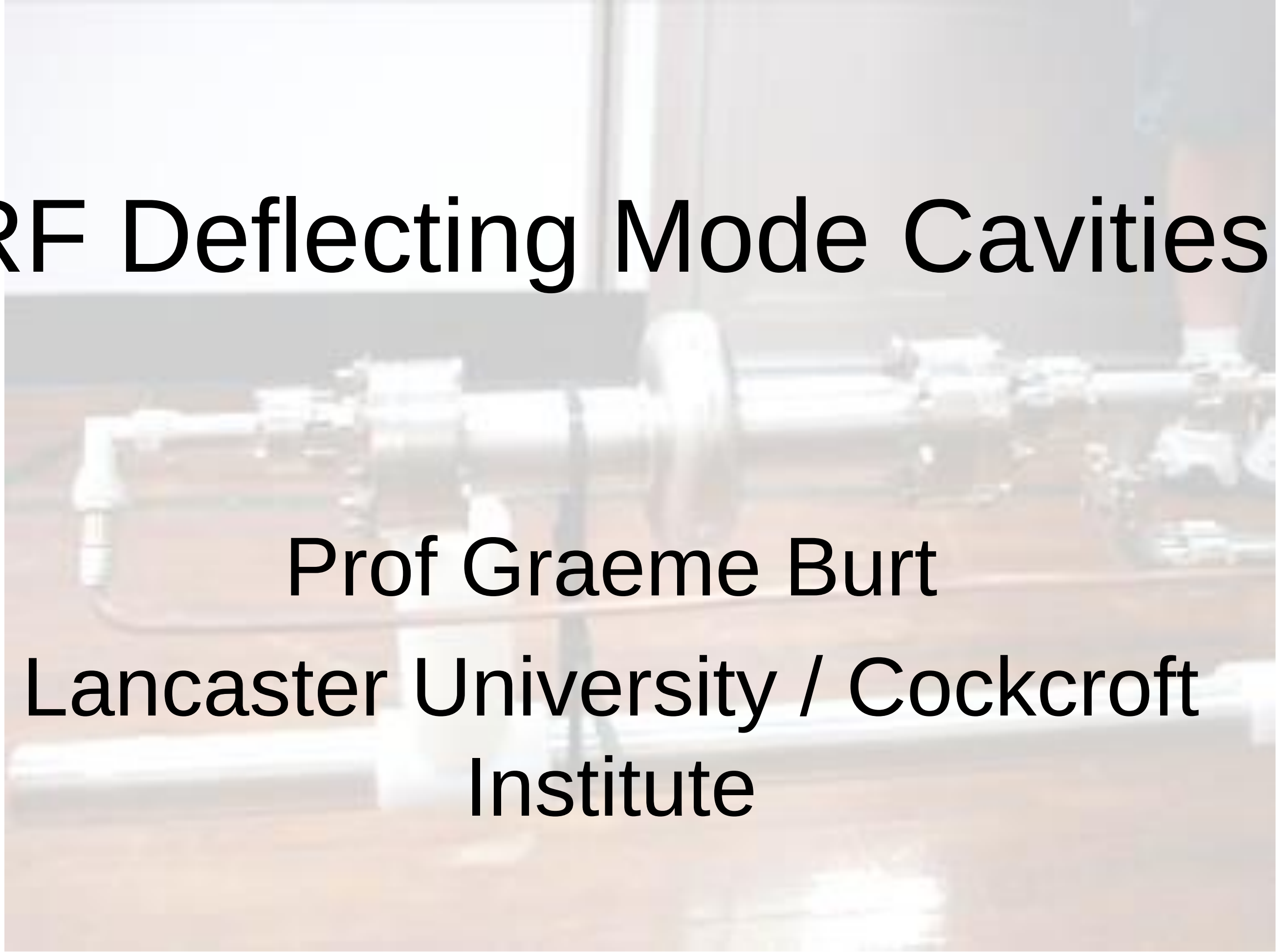
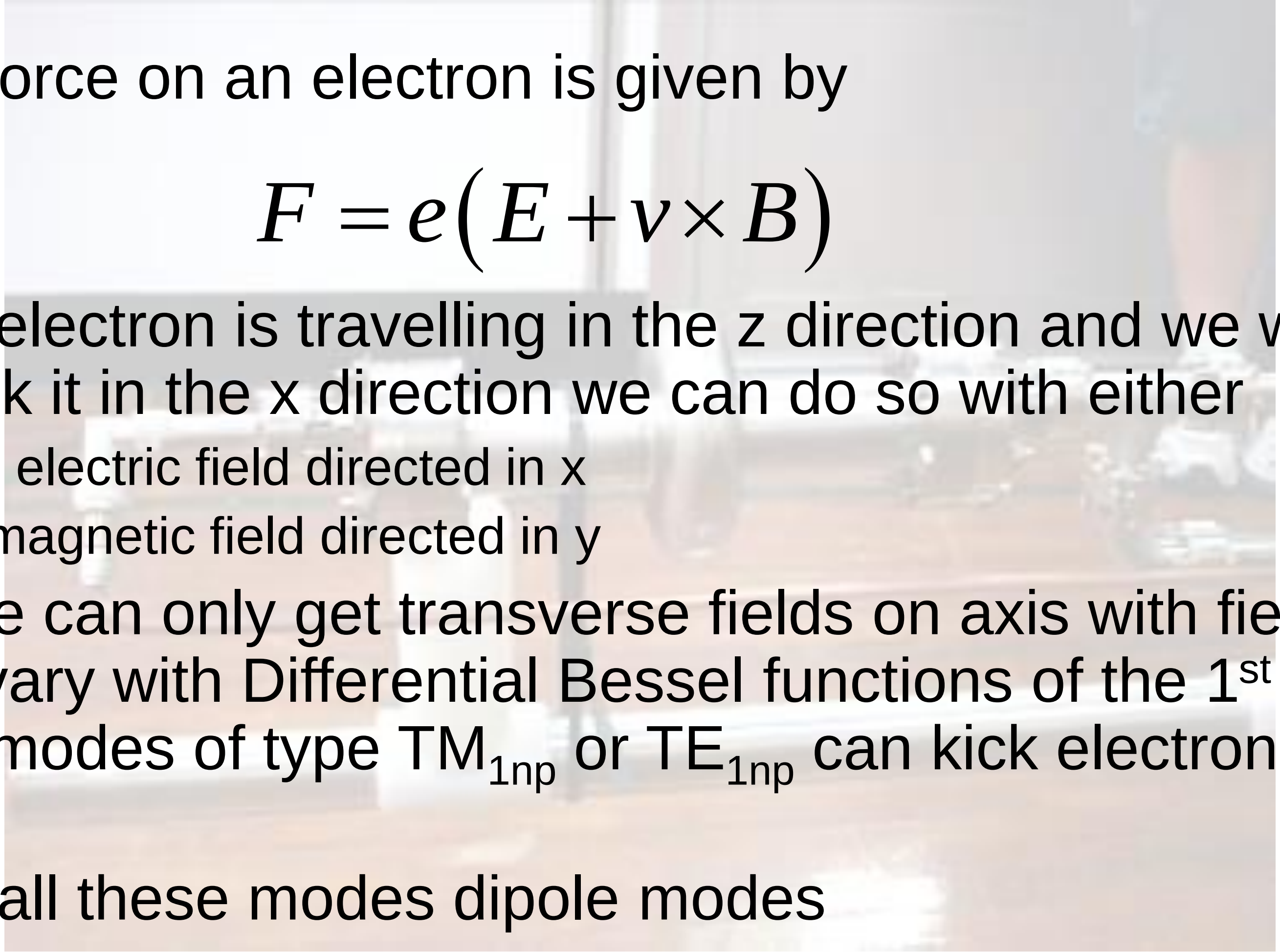


# RF Deflecting Mode Cavities

Prof Graeme Burt

Lancaster University / Cockcroft Institute

# Transverse Kicks



- The force on an electron is given by

$$F = e\left(E + v \times B\right)$$

- If an electron is travelling in the z direction and we want to kick it in the x direction we can do so with either
  - An electric field directed in x
  - A magnetic field directed in y
- As we can only get transverse fields on axis with fields that vary with Differential Bessel functions of the 1st kind only modes of type $\mathrm{TM}_{1np}$ or $\mathrm{TE}_{1np}$ can kick electrons on axis.
- We call these modes dipole modes

# $\mathrm{TM}_{110}$ Dipole Mode

$$E_z = E_0 J_1(k_t r)\cos(\varphi)$$

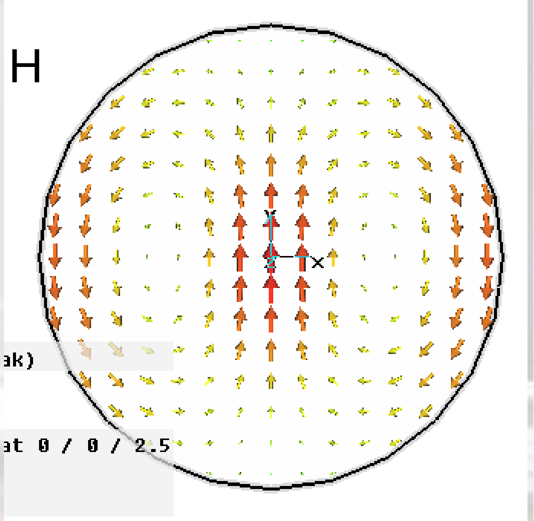
$$H_z = 0$$

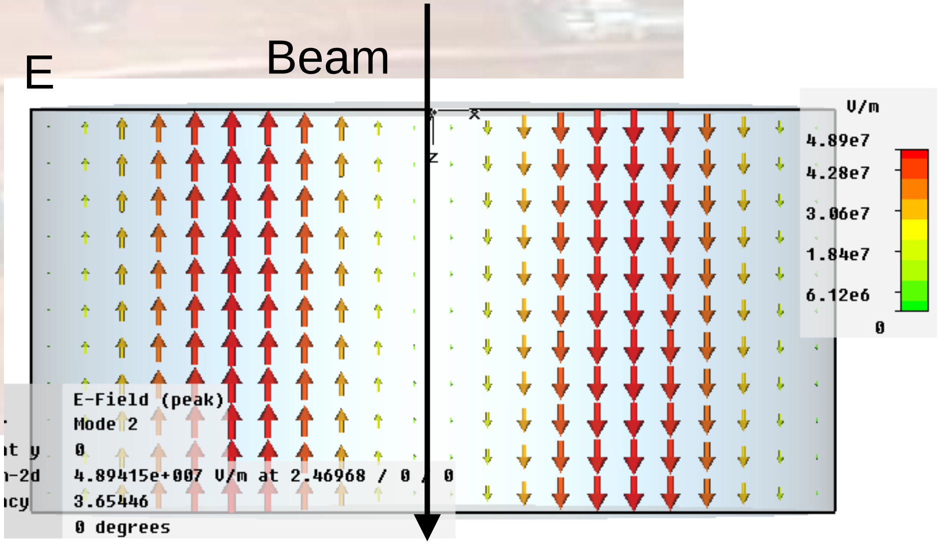
$$H_r = \frac{i\omega\varepsilon}{k_t^{\,2} r} E_0 J_1(k_t r)\sin(\varphi)$$

$$H_\varphi = \frac{-i\omega\varepsilon}{k_t} E_0 J_1'(k_t r)\cos(\varphi)$$

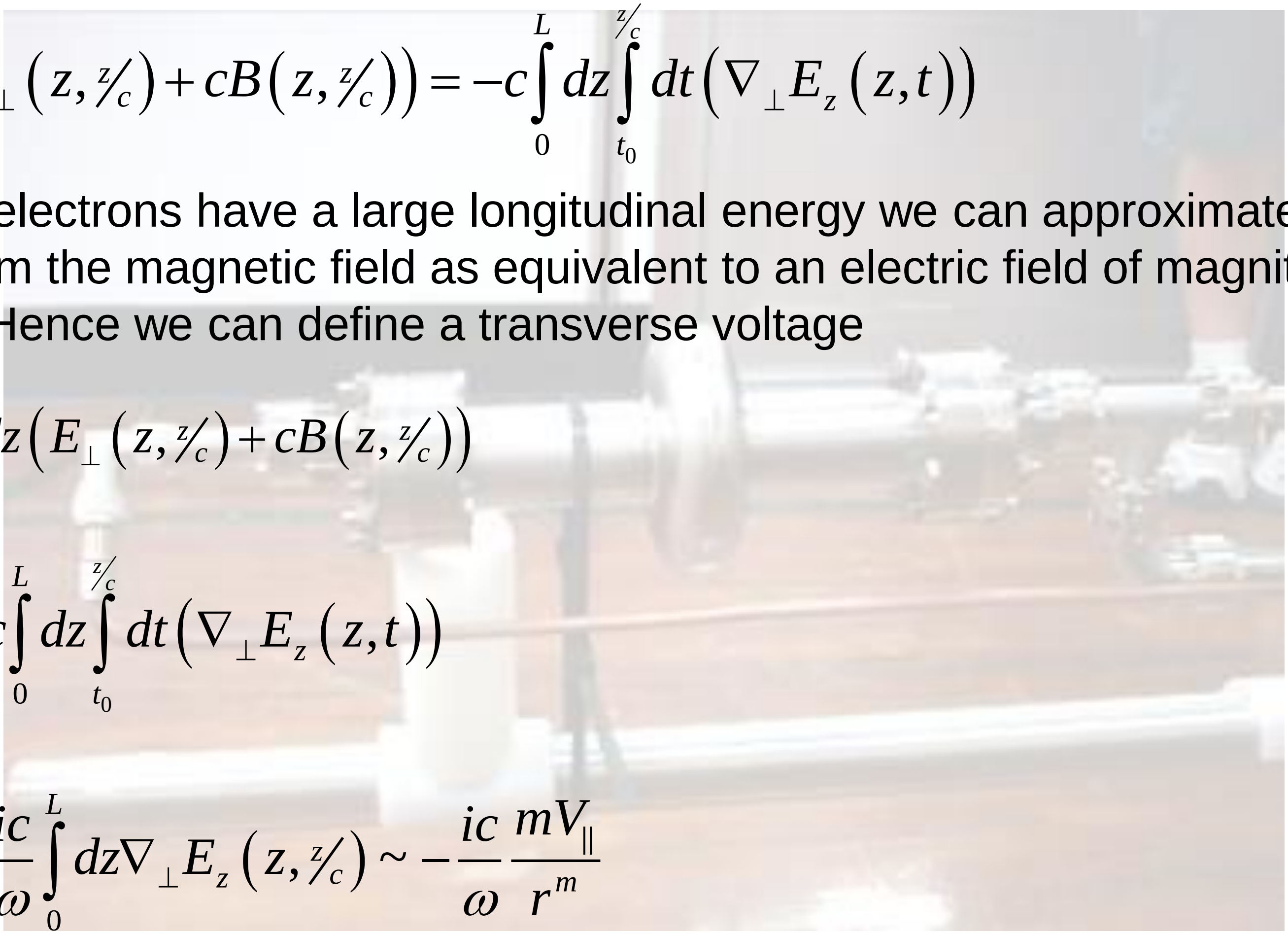
$$E_\varphi = \frac{-ik_z}{k_t^{\,2} r} E_0 J_1(k_t r)\sin(\varphi)$$

$$E_r = \frac{-ik_z}{k_t} E_0 J_1'(k_t r)\cos(\varphi)$$





# Panofsky-Wenzel Theorem



$$\int_0^L dz\left(E_\perp\left(z,{}^{z}\!/_{c}\right)+cB\left(z,{}^{z}\!/_{c}\right)\right)=-c\int_0^L dz\int_{t_0}^{{}^{z}\!/_{c}} dt\left(\nabla_\perp E_z\left(z,t\right)\right)$$

As the electrons have a large longitudinal energy we can approximate the kick from the magnetic field as equivalent to an electric field of magnitude E=cB. Hence we can define a transverse voltage

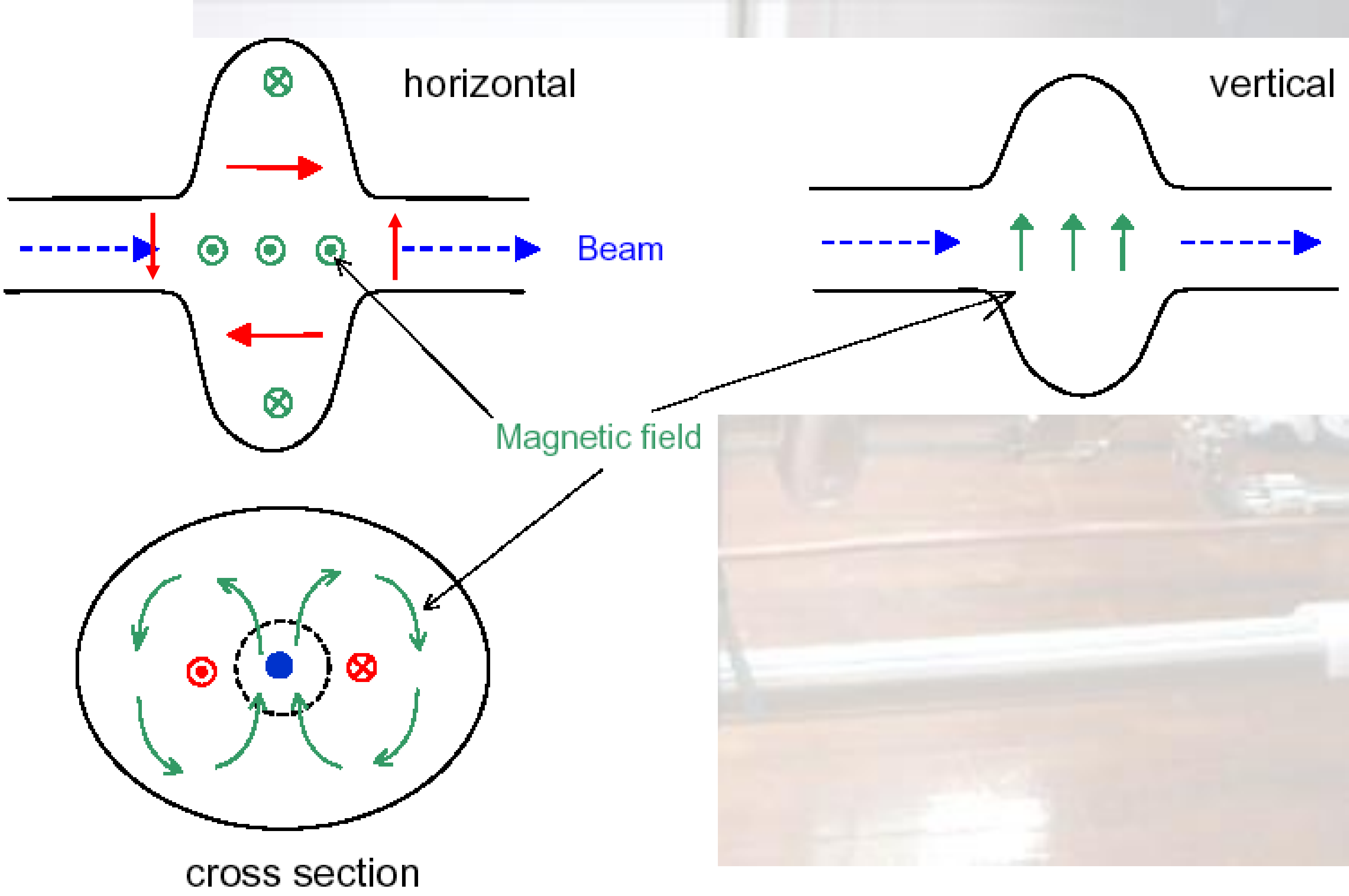
$$V_\perp=\int_0^L dz\left(E_\perp\left(z,{}^{z}\!/_{c}\right)+cB\left(z,{}^{z}\!/_{c}\right)\right)$$

$$V_\perp=-c\int_0^L dz\int_{t_0}^{{}^{z}\!/_{c}} dt\left(\nabla_\perp E_z\left(z,t\right)\right)$$

$$V_\perp=-\frac{ic}{\omega}\int_0^L dz\nabla_\perp E_z\left(z,{}^{z}\!/_{c}\right)\sim-\frac{ic}{\omega}\frac{mV_\parallel}{r^m}$$

This means the transverse voltage is given by the rate of change of the longitudinal voltage (for particles travelling close to c).

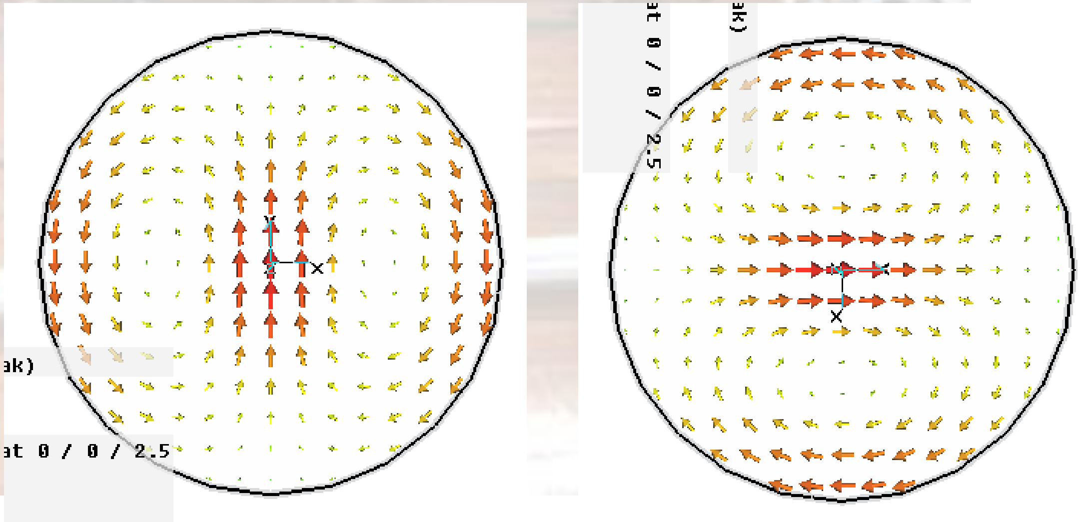
# Single-cell crab cavity



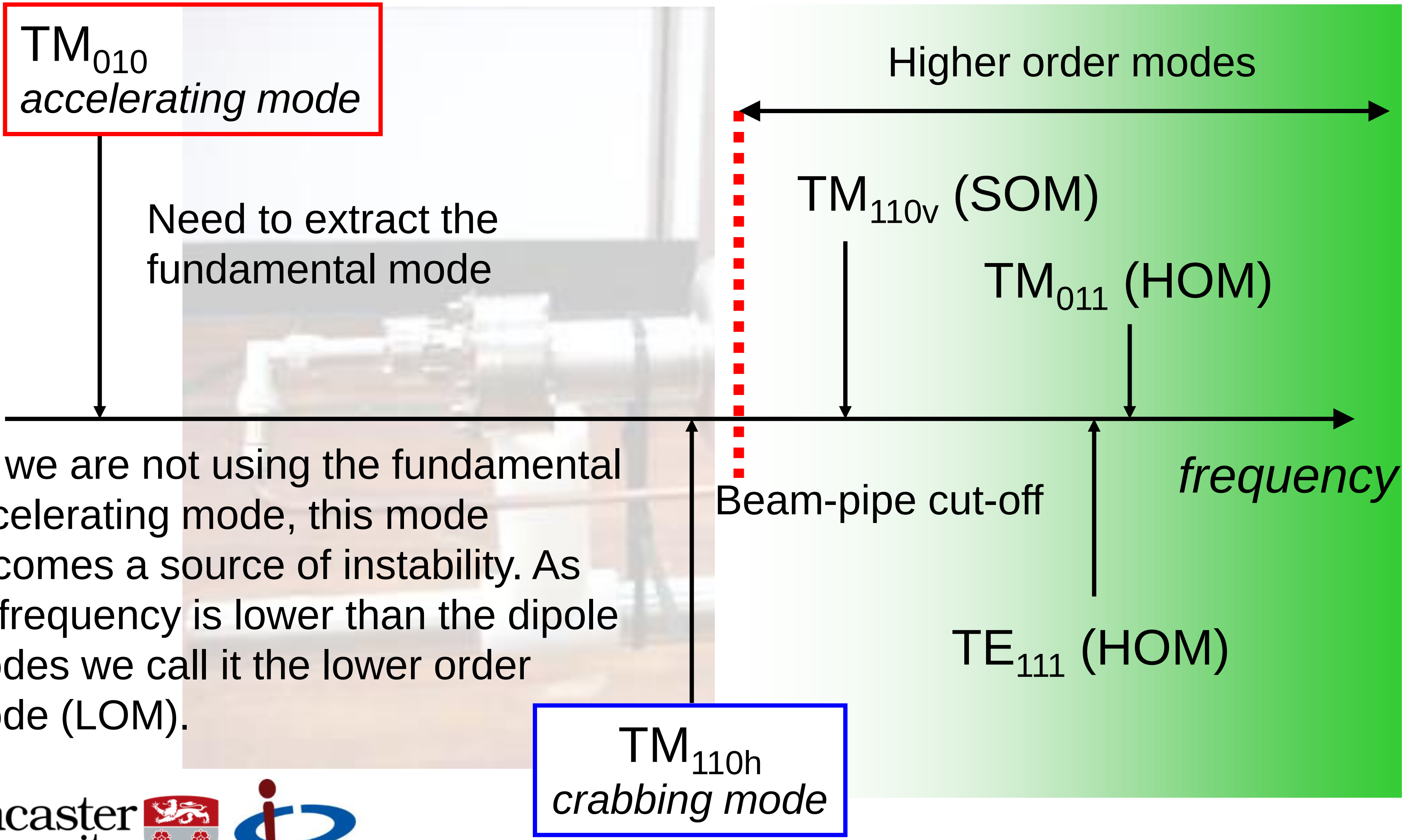
# Mode Polarisation

- Dipole modes have a distinct polarisation ie the field points in a given direction and the kick is in one plane.
- In a cylindrically symmetric cavity this polarisation could take any angle.
- In order to set the polarisation we make the cavity slightly asymmetric.
- This will set up two dipole modes in the cavity each at 90 degrees to each other.

One mode will be the operating mode, the other is refered to as the same order mode (SOM) and is unwanted.



# Lower and Higher Order Modes



TM$_{010}$
*accelerating mode*

Need to extract the fundamental mode

Higher order modes

TM$_{110v}$ (SOM)

TM$_{011}$ (HOM)

*frequency*

Beam-pipe cut-off

TE$_{111}$ (HOM)

As we are not using the fundamental accelerating mode, this mode becomes a source of instability. As its frequency is lower than the dipole modes we call it the lower order mode (LOM).

TM$_{110h}$
*crabbing mode*

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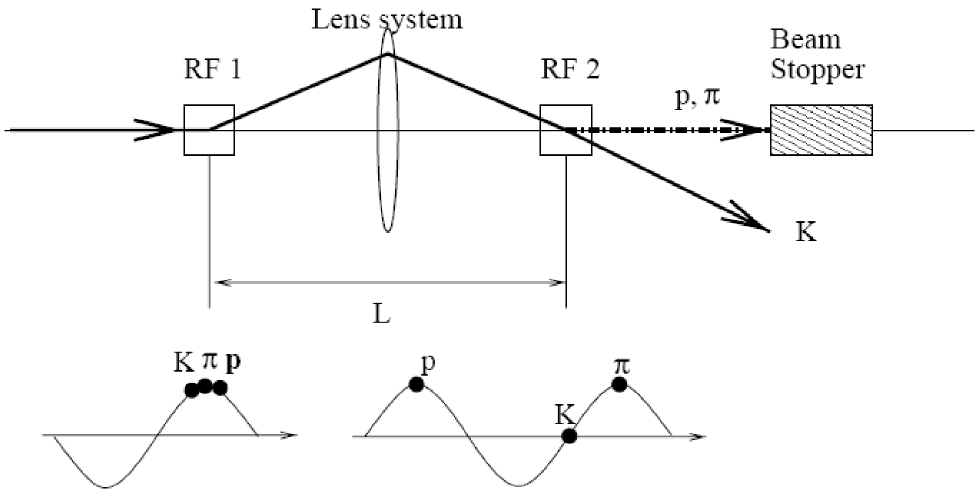
# Particle Separators

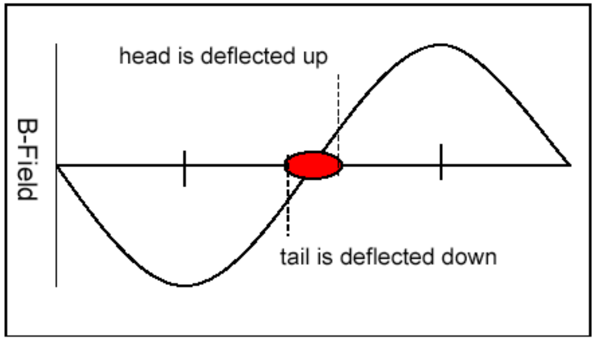
- The earliest use of transverse deflecting cavities were particle separators. There are two different schemes for its use. Can separate out different particle species in a bunch



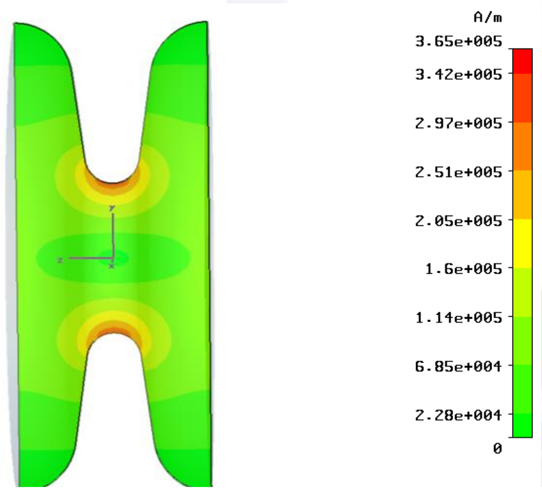
$$\Delta\phi = \omega\frac{L}{c}\left(\frac{1}{\beta_K} - \frac{1}{\beta_\pi}\right)$$

Can we achieve the required ωL?

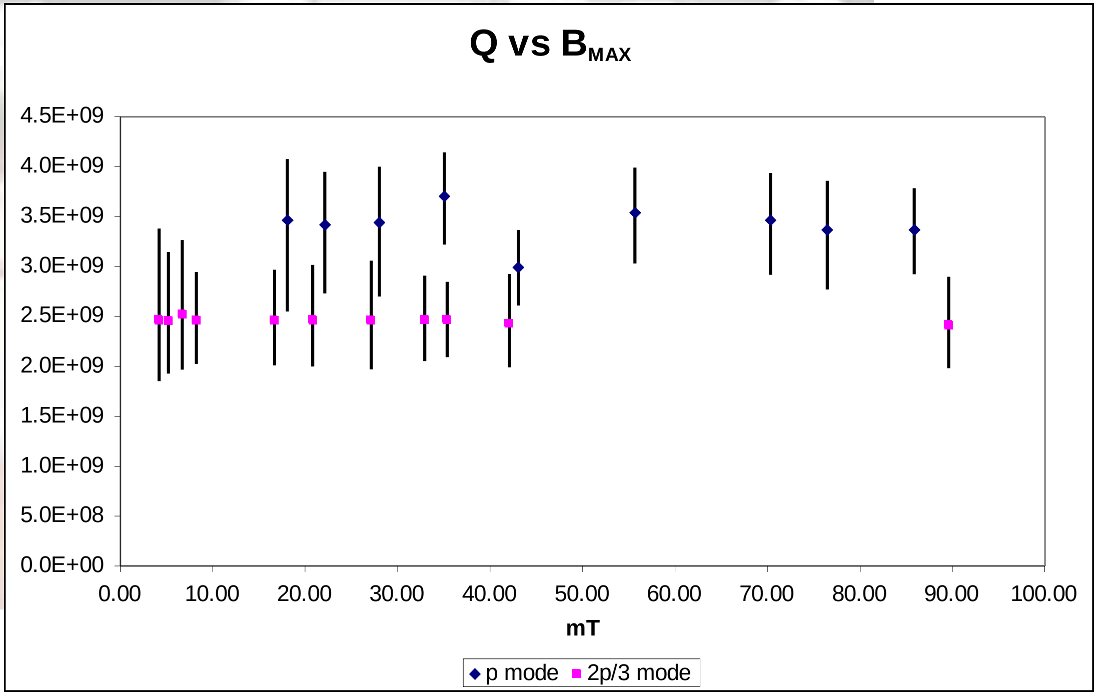
As the field variation with time is proportional to frequency the separation FoM for beamlines shorter than optimum is frequency-gradient product



# Peak Fields



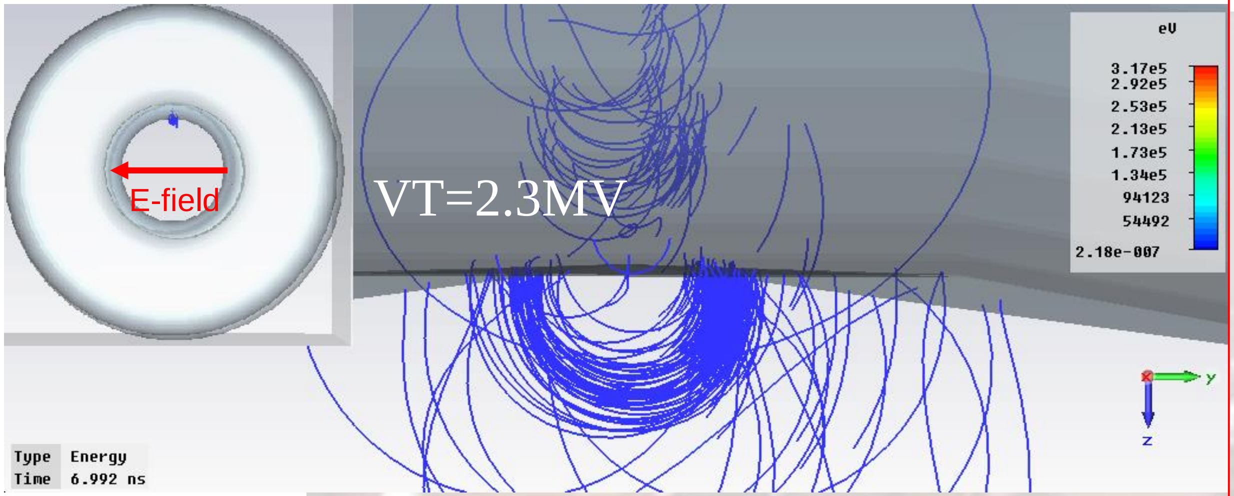
| Cavity type | mode | Frequency GHz | $B_{max}$ mT | $E_{max}$ MV/m |
|---|---|---|---|---|
| TESLA @ 25 MV/m | TM010 | 1.3 | 105 | 50 |
| CKM @ 5 MV/m | TM110 | 3.9 | 80 | 18.5 |

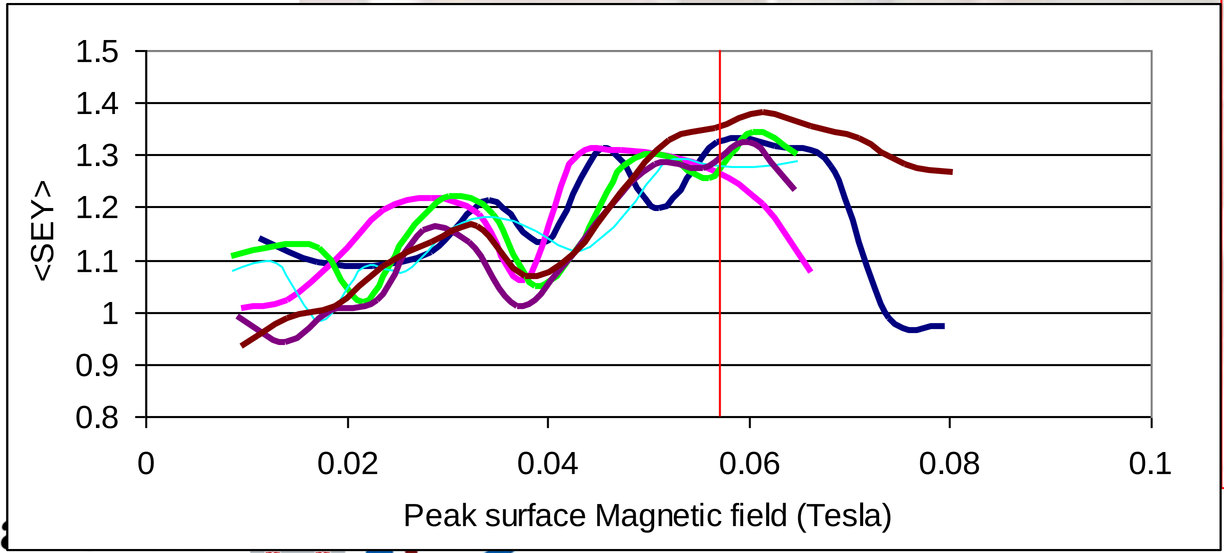


Dipole cavities have much larger peak surface magnetic fields than surface electric fields.

This leads to a much smaller Q drop due to field emission as the deflecting gradient increases.

# Multipacting



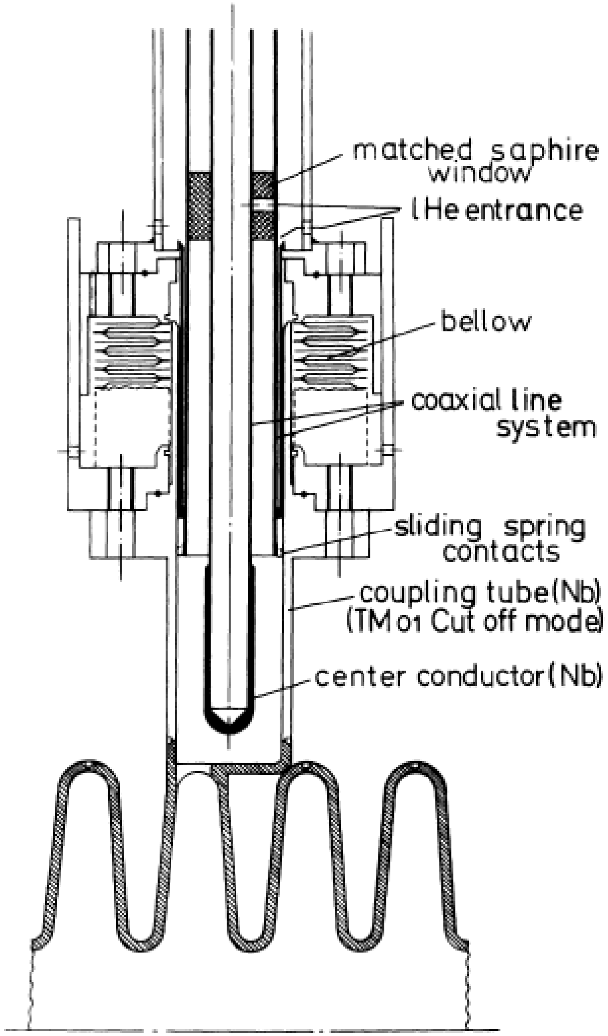


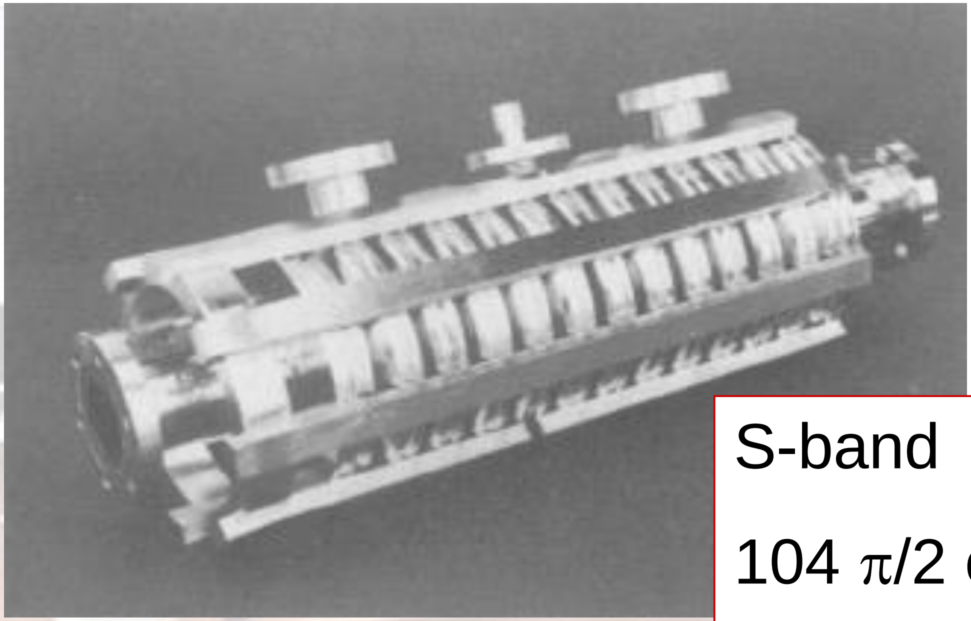
CST-PS simulations clearly show that the multipactor in the iris is directly linked to the cyclotron frequency.

MP always peaks at 57 mT at 3.9 GHz and increases proportional to frequency.

Hence low magnetic field structures suppress multipactor. This means that lower frequency cavities are more likely to multipact as a lower magnetic field is required to have the cyclotron frequency double the RF frequency.

# CERN-Karlsruhe cavity [1970]





S-band

104 $\pi/2$ cells

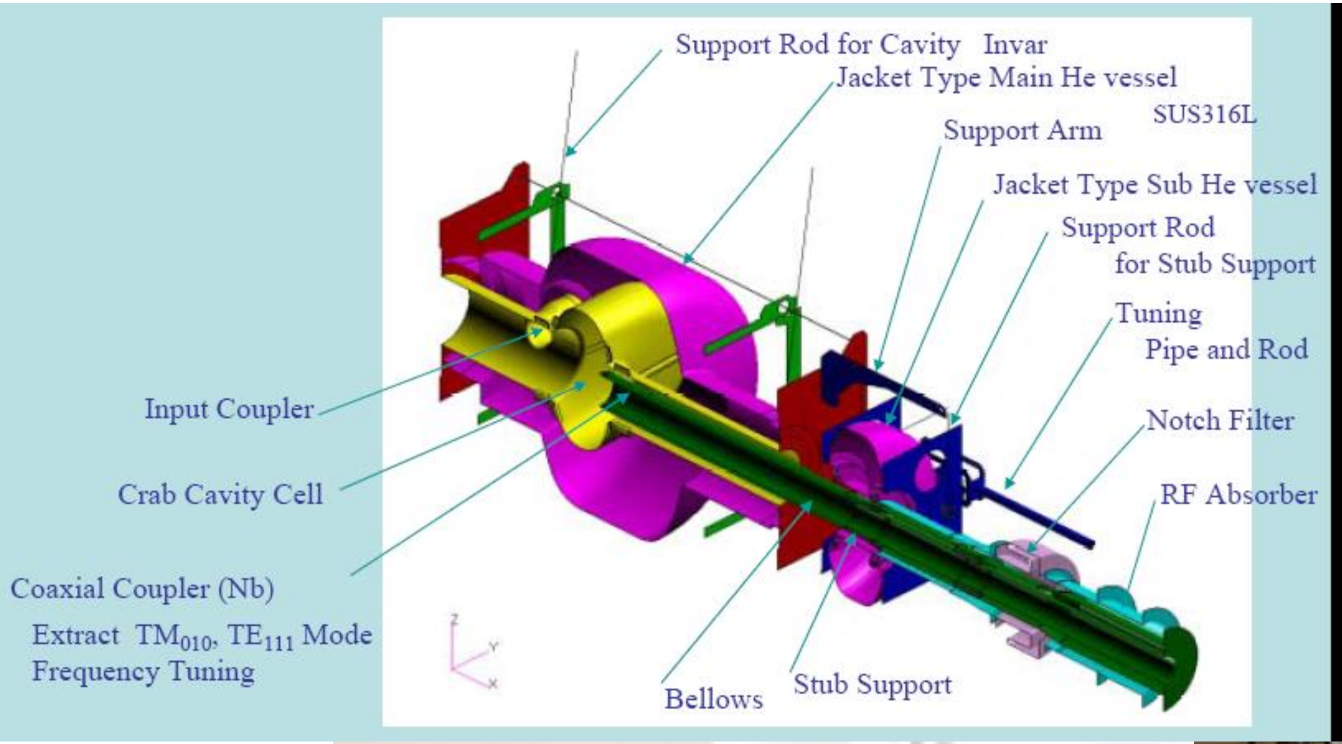
Kick= 2 MV/m

The CERN-Karlsruhe separator was one of the 1st Nb cavities constructed.

The cavity uses a standing wave $\pi/2$ mode to avoid e-beam welds in high field regions

This cavity is still in use at IHEP

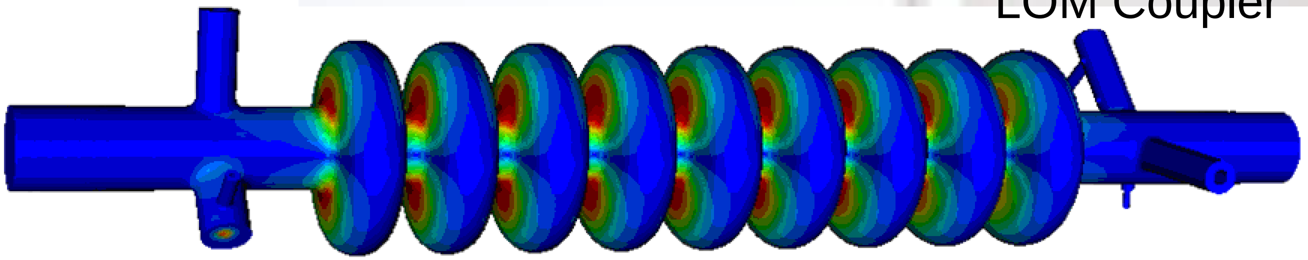
# KEK-B Crab cavity (1991-2009)



- More recently there has been a lot of attention paid to the KEKB crab cavities.
- These 508.9 MHz single cell Nb cavities operate at 1.44 MV

# ILC-CC Design

Based on the FNAL CKM Cavity



Input Coupler

LOM Coupler

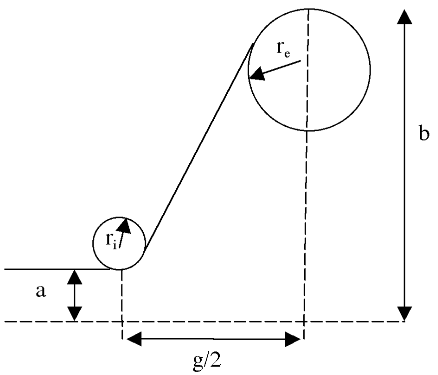
HOM Coupler

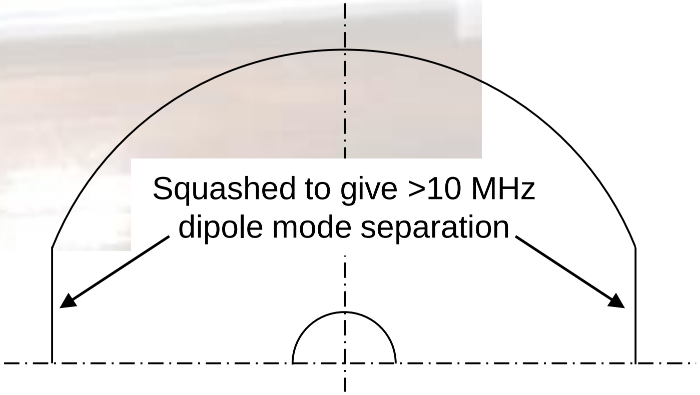
SOM Coupler

| At 5MV/m $P_\perp$: | |
|---|---|
| $B_{MAX}$ | 73 mT |
| $E_{MAX}$ | 16.6 MV/m |
| $U$ | 0.25 J |
| $Q$ (Nb, room temp) | 4780 |
| $\left(R/Q\right)' = \frac{1}{2}\frac{\lvert V_L(r)\rvert^2}{\omega U}\left(\frac{c}{\omega r}\right)^2$ | 235 Ω |
| $G = Q \times R_{SURF}$ | 225Ω |
| $R_{BCS}$(best measurement) @ 1.8K | 30nΩ |
| $R_0$(best measurement) | 40nΩ |
| $Q$ @ 70nΩ1.8K | $3.2 \times 10^9$ |
| Surface power @ 70nΩ | 1.9 W |

Beam-pipe radius = 18mm
Cavity iris radius = 15mm
Equator Radius = 47.37mm

Designed for 5 MV/m @ 3.9 GHz but should be capable of 7 MV/m

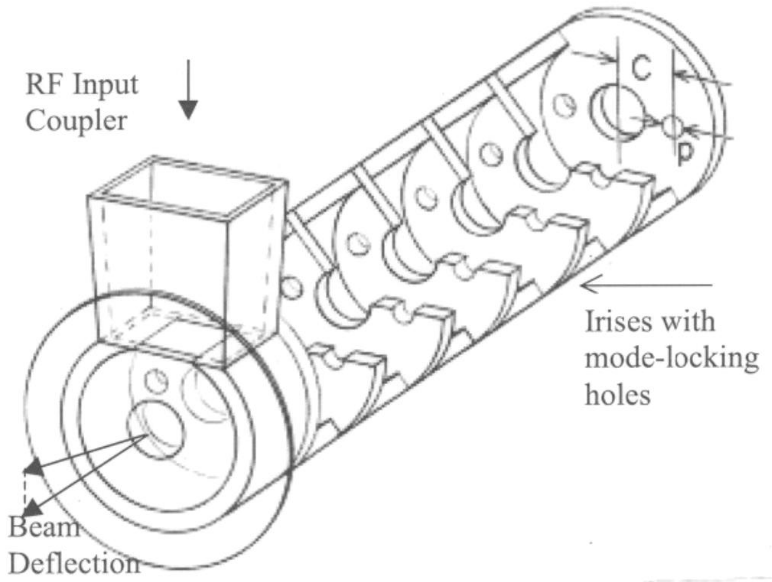




Squashed to give >10 MHz dipole mode separation

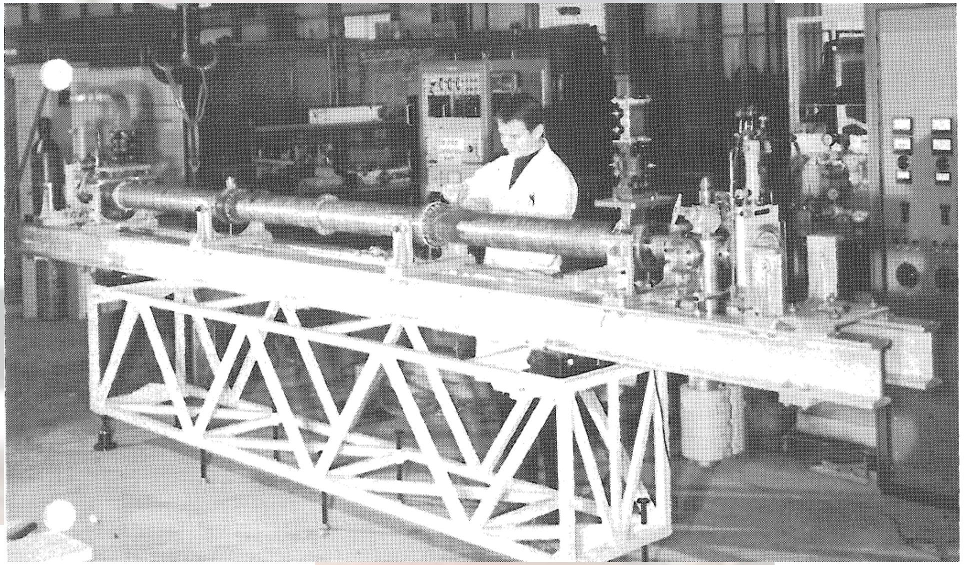
# Travelling wave Cavities

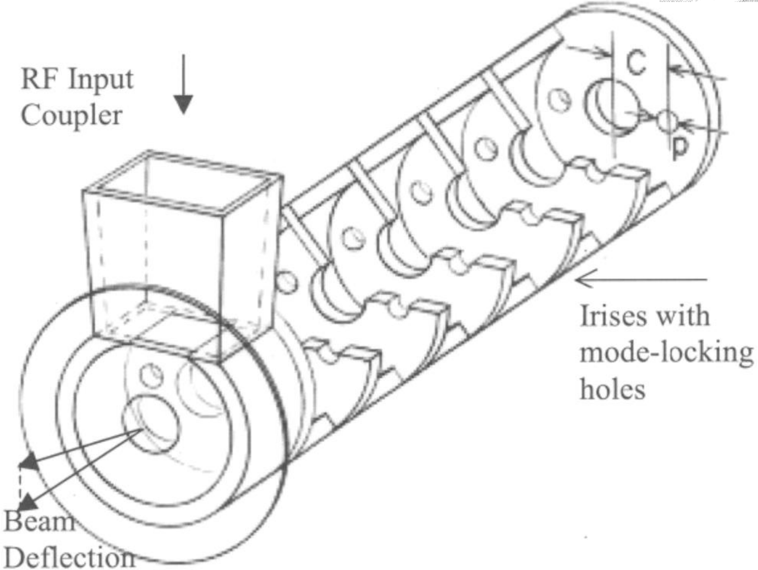
- Like accelerating cavities we can also use travelling wave deflecting cavities.
- These can have more cells per cavity and fill faster.
- The down side is they require more peak RF power.
- Most diagnostic cavities and fast separators are travelling wave to take advantage of fast filling times.



# CERN RF Separators & SLAC LOLA

- Montague Jan 1965 & Loew 1965
- Bernard and Lengler 1969
- $2\pi/3$ 2855 MHz

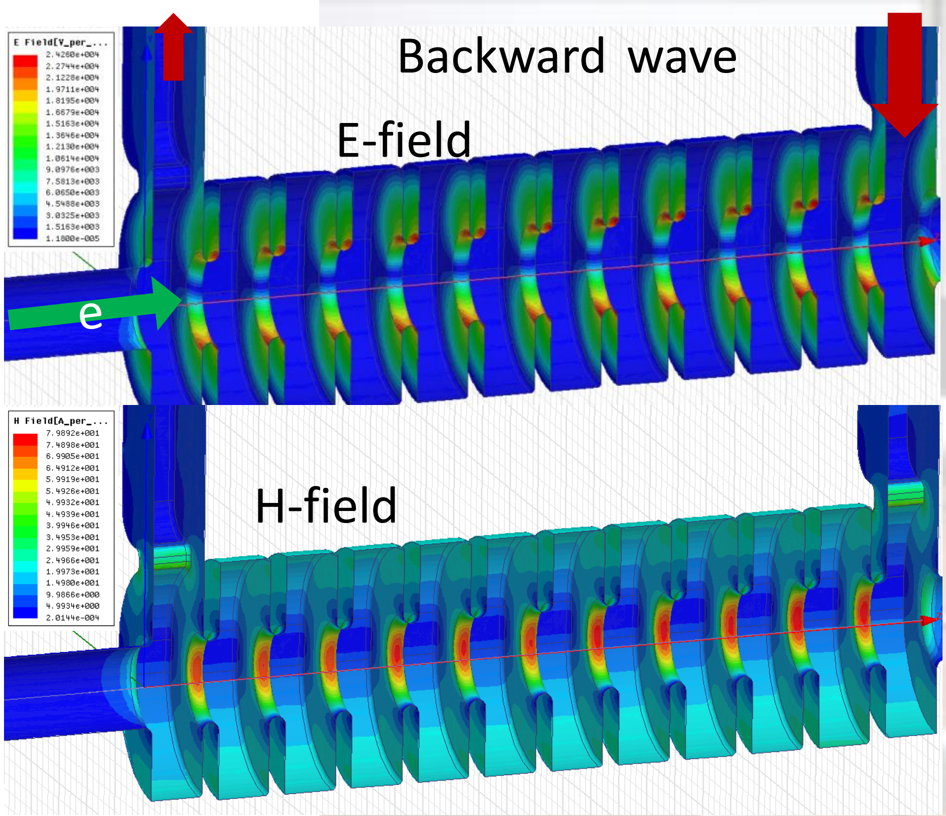




The first RF deflectors were all travelling wave structures with a phase advance of 120 degrees.

They generally had a large number of cells.

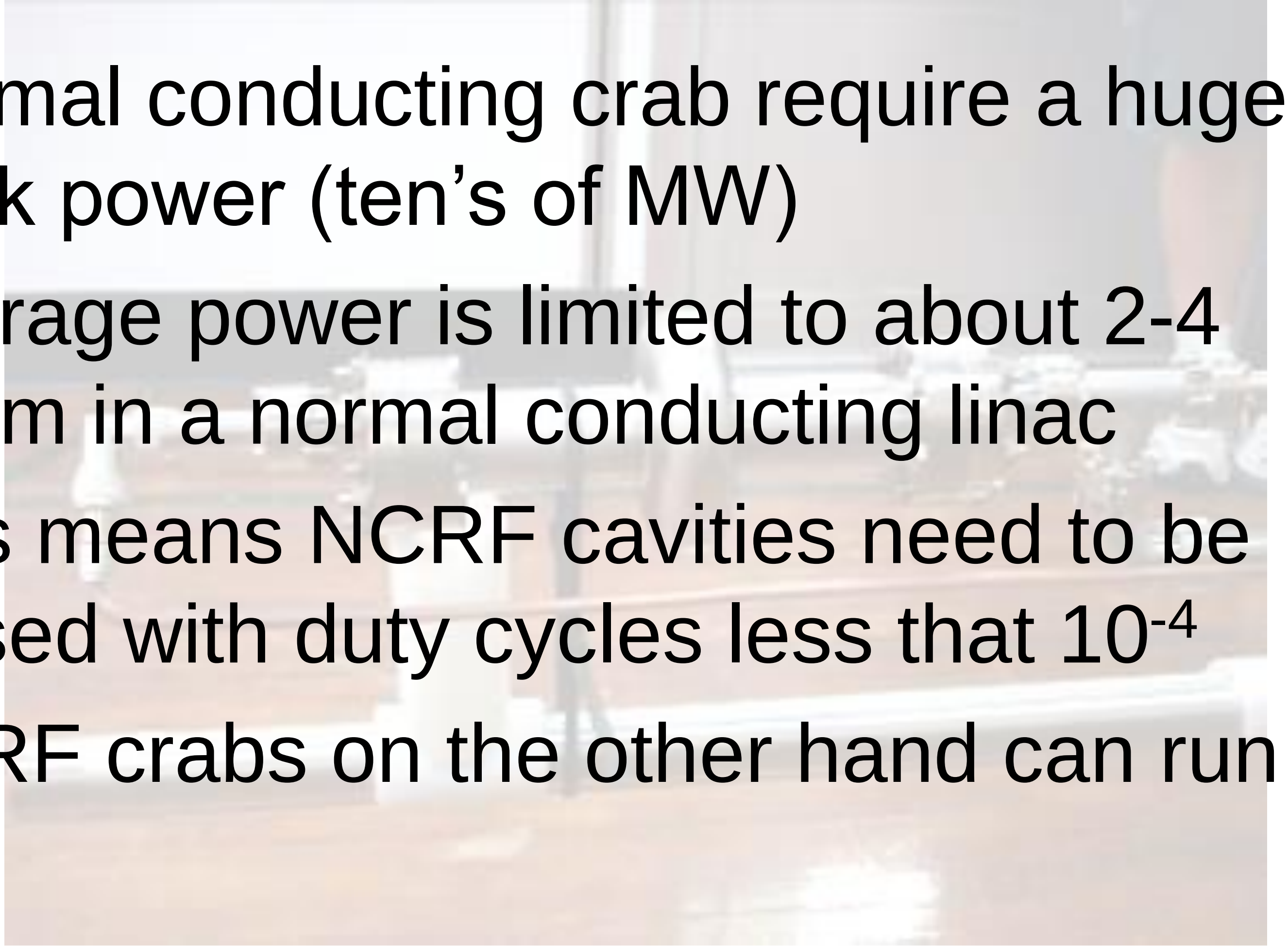
# CLIC Crab Cavity Design



| Property | CLIC T24 (unloaded) | LCLS deflector | CLIC Crab (un-damped) |
|---|---|---|---|
| Input Power | 37.2 MW | 20 MW | 13.35 MW |
| Gradient | 100 MV/m | 22 MV/m | 24 MV/m (tested to 40 MV/m) |
| Peak surf. E-field | 219 MV/m | 115 MV/m | 88.8 MV/m |
| Peak surf. H-field | 410 kA/m | 405 kA/m | 292 kA/m |
| Peak Sc [3] | 3.4 MW/mm$^2$ | - | 1.83 MW/mm$^2$ |
| Group Velocity | 1.8-0.9%c | -3.2%c | -2.9%c |
| # Cells | 24 | 117 | 12 |

CLIC crab achieves a much higher transverse gradient than the ILC cavity, and at a frequency that's 3 times higher (order of mag higher frequency gradient product), but aperture is only 10 mm.

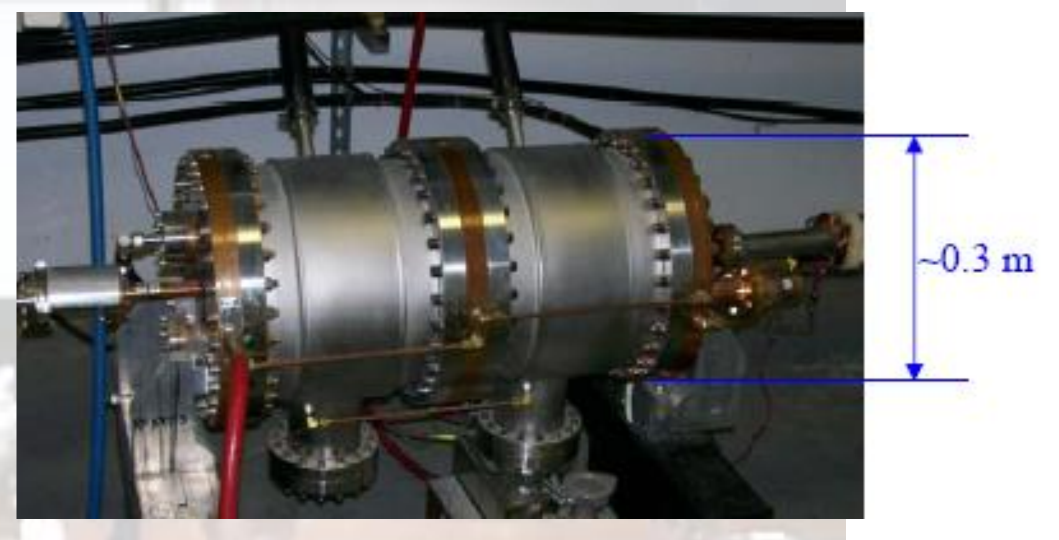
# SCRF vs NCRF crabs

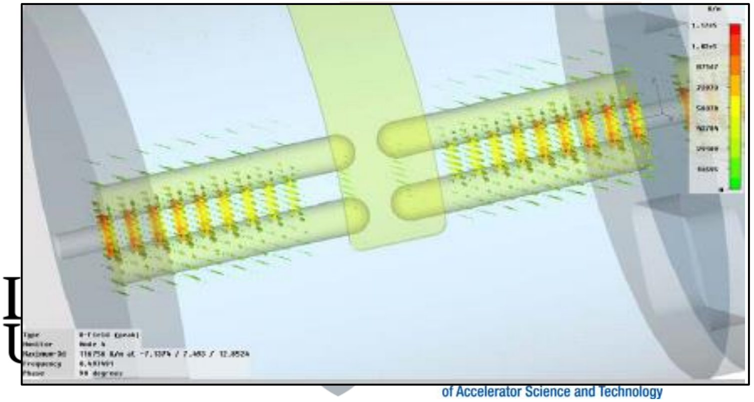


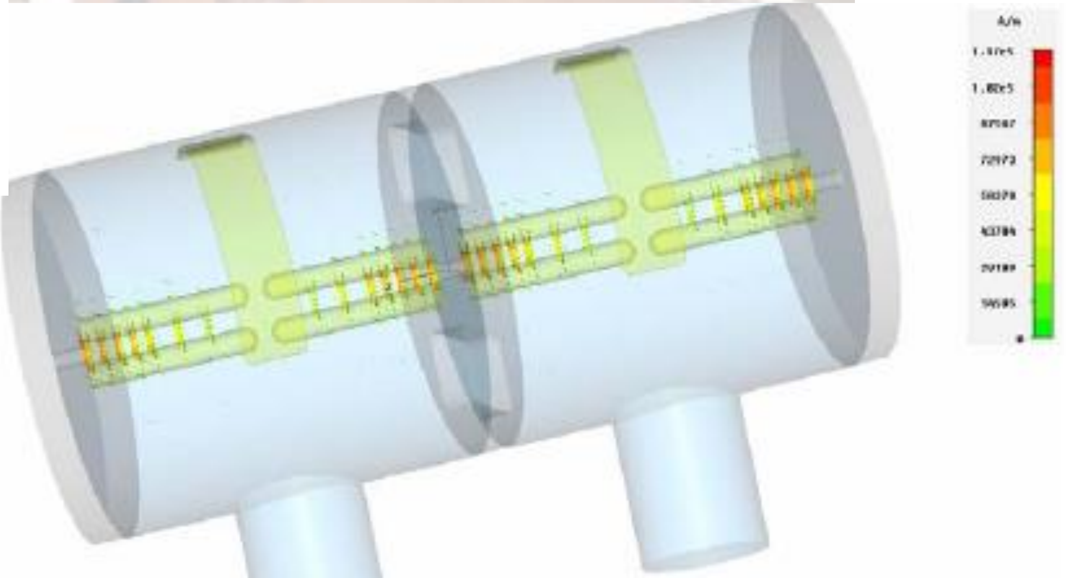
- Normal conducting crab require a huge peak power (ten’s of MW)
- Average power is limited to about 2-4 kW/m in a normal conducting linac
- This means NCRF cavities need to be pulsed with duty cycles less that $10^{-4}$
- SCRF crabs on the other hand can run CW

# CEBAF Cavity (1993)

- CEBAF currently uses a compact normal conducting separator.
- It operates using the TEM mode of four parallel rods (two sets of two co-linear rods).
- To provide the transverse deflection a capacitive gap is placed between the two co-linear rods
- 30 cm diameter at 500 MHz
- **Gradient is below 1 MV/m**

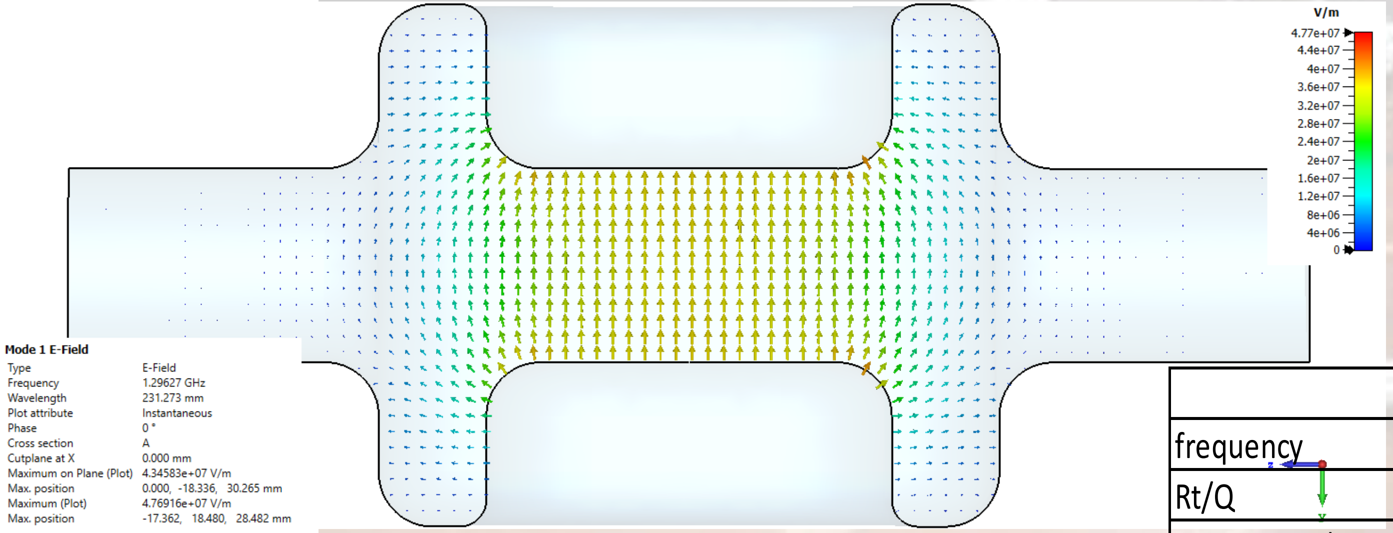






# What about compact crabs?

- Lower peak magnetic fields than the 3.9 GHz elliptical (10 MV/m may be possible)
- Higher Epk but very low in both cases
- But as they are compact they are limited in aperture at high frequencies, not ideal for a separator

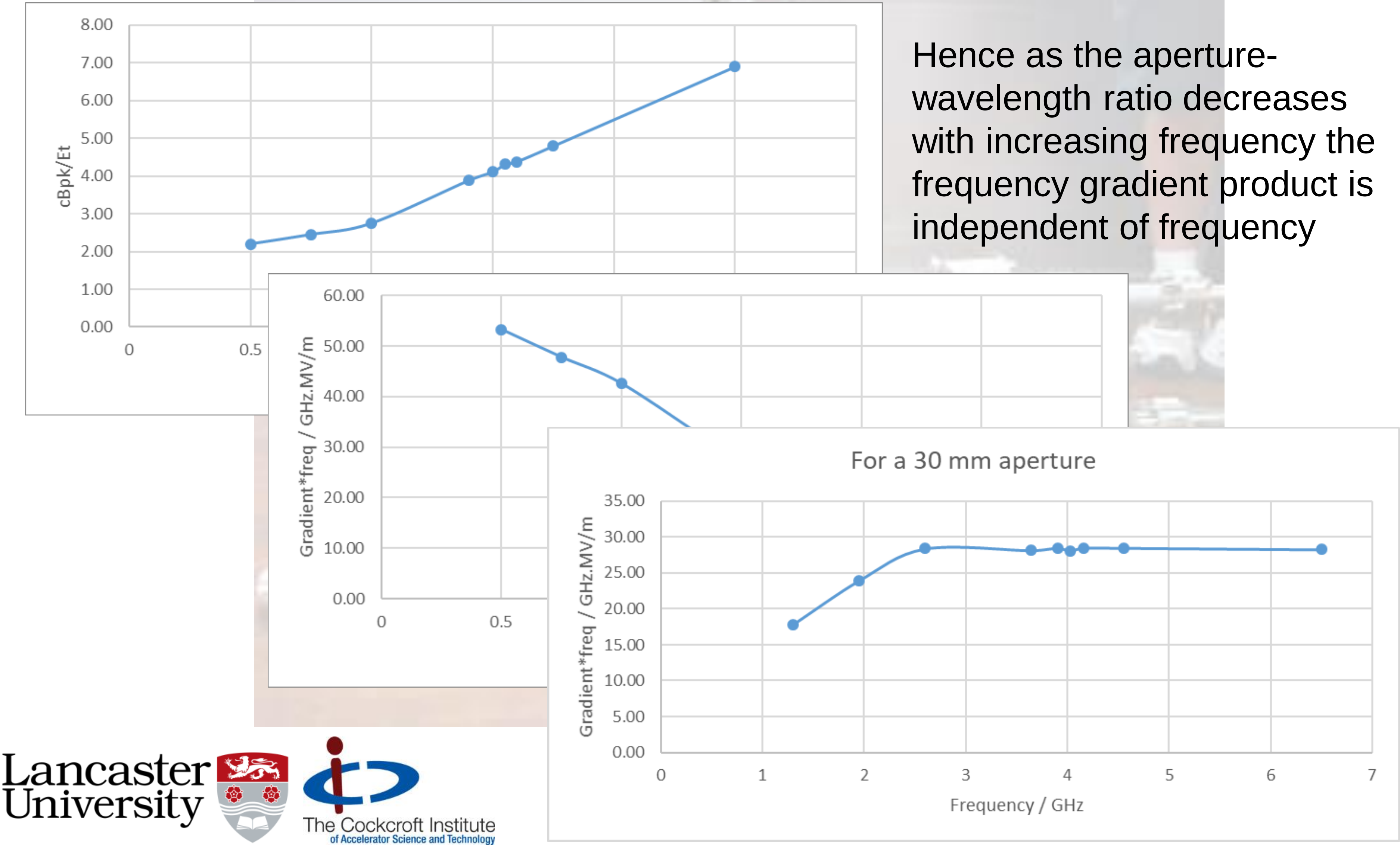


**Mode 1 E-Field**

| | |
|---|---|
| Type | E-Field |
| Frequency | 1.29627 GHz |
| Wavelength | 231.273 mm |
| Plot attribute | Instantaneous |
| Phase | 0 ° |
| Cross section | A |
| Cutplane at X | 0.000 mm |
| Maximum on Plane (Plot) | 4.34583e+07 V/m |
| Max. position | 0.000, -18.336, 30.265 mm |
| Maximum (Plot) | 4.76916e+07 V/m |
| Max. position | -17.362, 18.480, 28.482 mm |

| | RFD | Elliptical |
|---|---|---|
| frequency | 1.3 | 3.9 |
| Rt/Q | 81.27428 | 235 |
| Epk at 5 MV/m | 23.69793 | 16.6 |
| Hpk at 5 MV/m | 54.98273 | 73 |

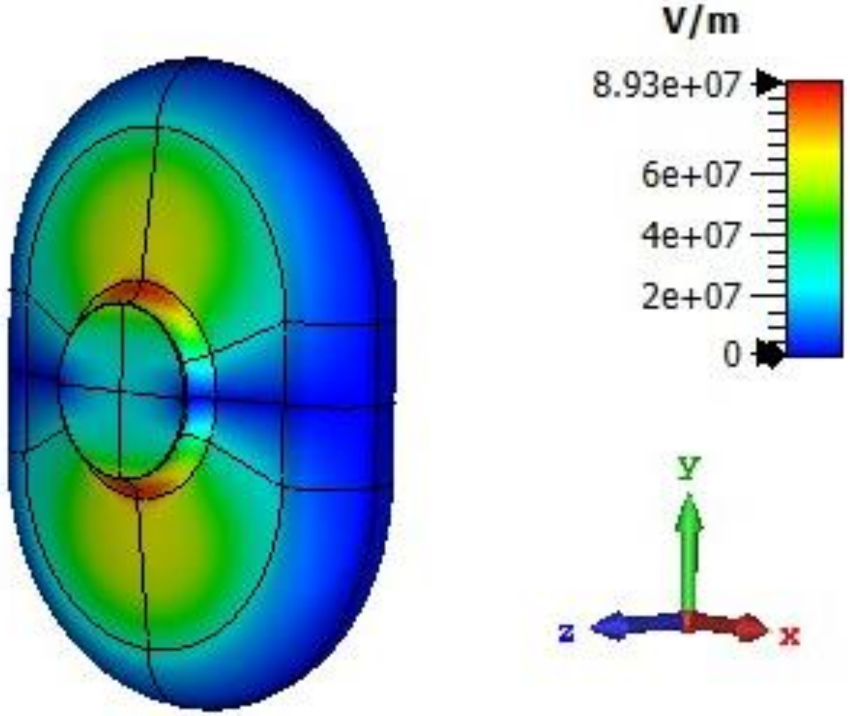
# Aperture limitations



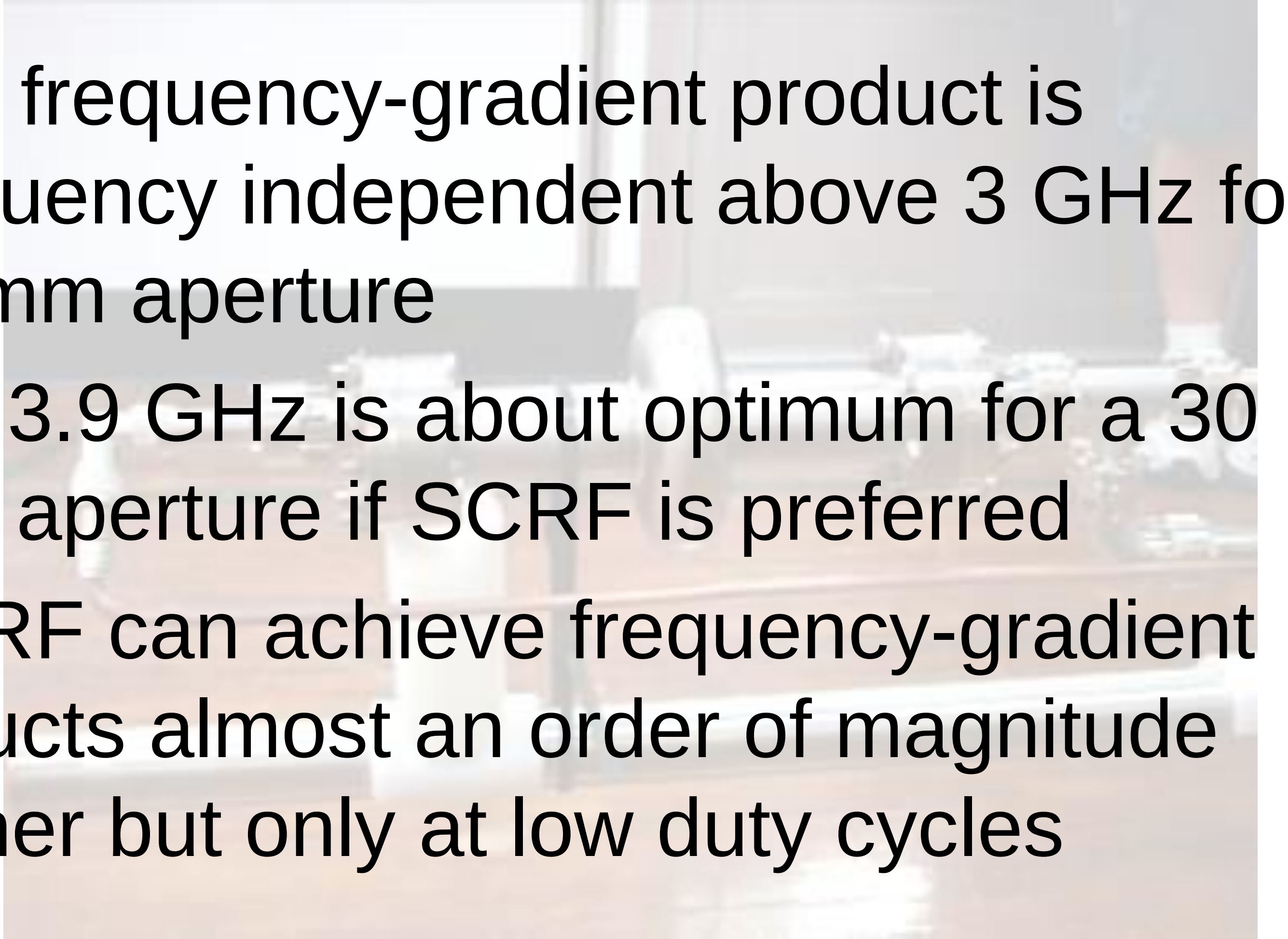
Hence as the aperture-wavelength ratio decreases with increasing frequency the frequency gradient product is independent of frequency

# Improved ILC Design

- A racetrack cross-section seems to reduce the peak magnetic field for a given gradient
- Gradient is 8.5 MV/m for a Bpeak of 100 mT with a 30 mm aperture at 3.9 GHz but is still being optimized.
- Work is ongoing for ILC prelab



# Summary



- The frequency-gradient product is frequency independent above 3 GHz for a 30 mm aperture
- ILC 3.9 GHz is about optimum for a 30 mm aperture if SCRF is preferred
- NCRF can achieve frequency-gradient prducts almost an order of magnitude higher but only at low duty cycles

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