The Cockcroft Institute
of Accelerator Science and Technology

Lancaster University

PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

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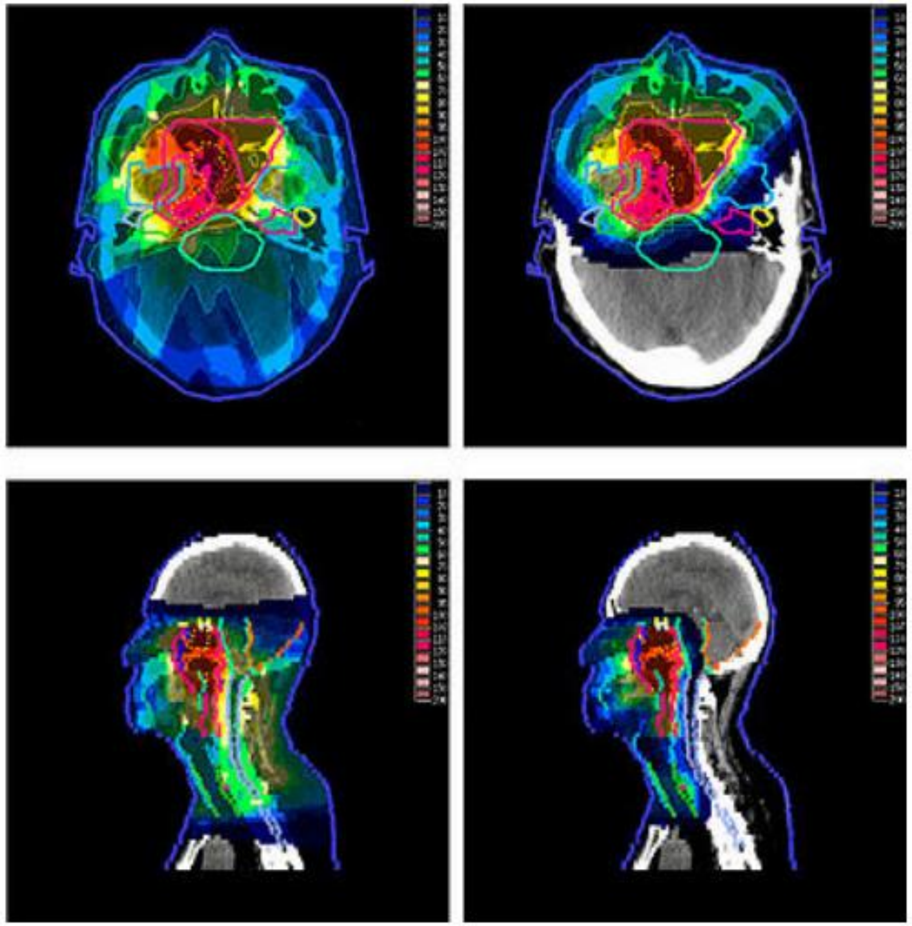
PROTON THERAPY

- Maximum energy is deposited within the tumour site with minimal energy deposited in healthy tissue.
- Treatment currently limited by range verification.
- Several modalities can aid range verification e.g. MRI but conversion produces error.
- Only proton imaging measures proton stopping power.



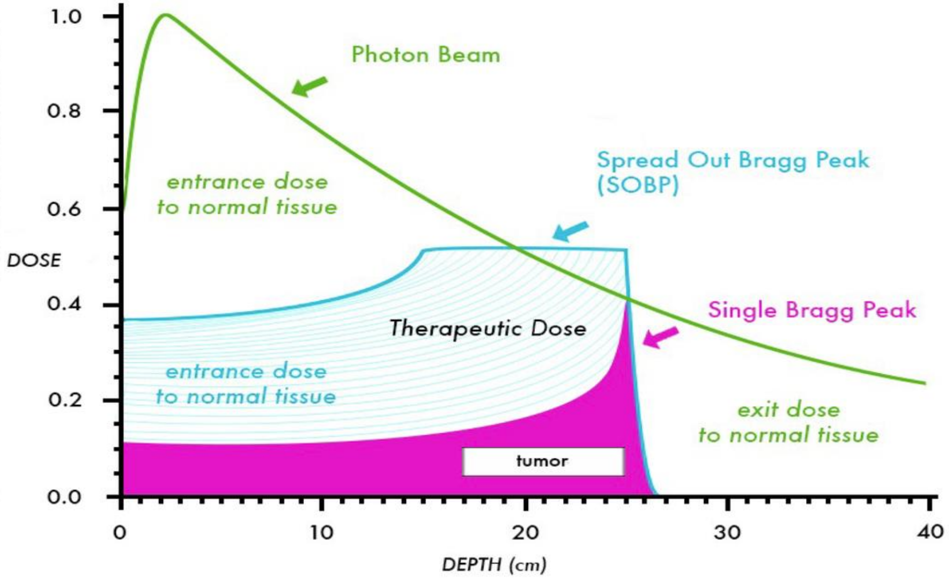


Image from: Ladra, M. and Yock, T, Cancers 2014, 6, 112-127; doi:10.3390/cancers6010112

PROTON RADIOGRAPHY

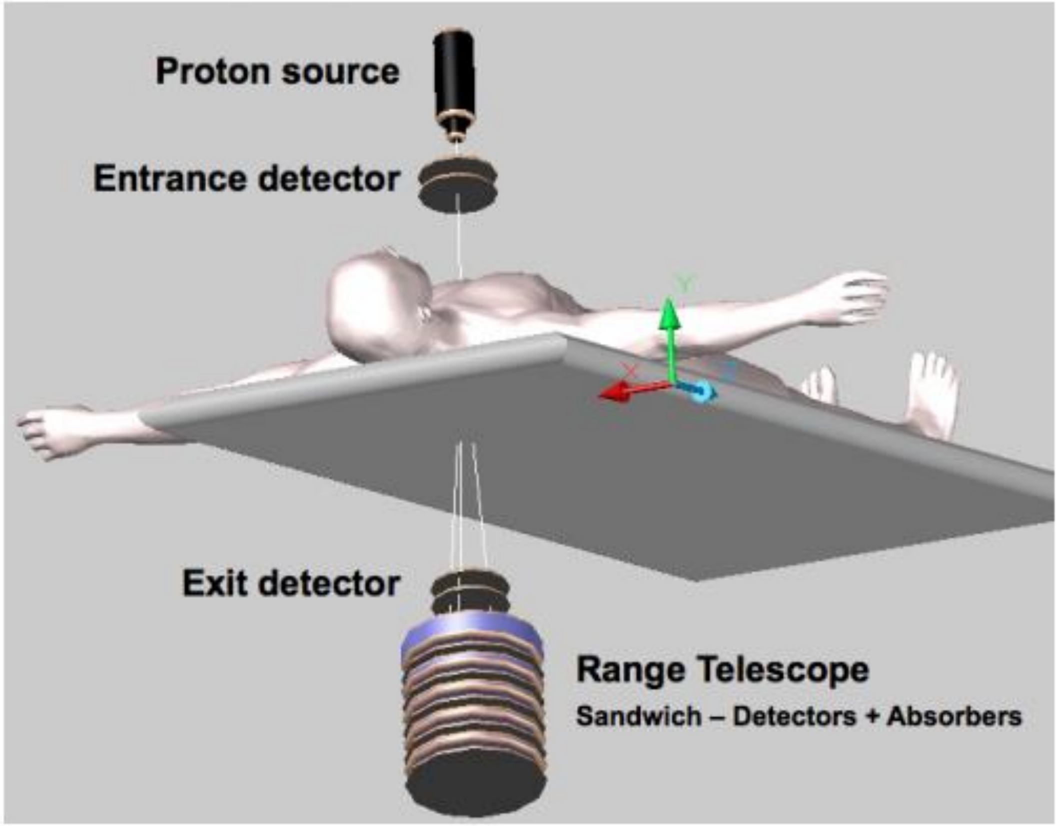


Image courtesy of PRaVDA

- CMOS detectors
- Entrance detector measures angle of incoming protons
- Exit detector measures angle of outgoing protons
- Range telescope measures residual energy of individual protons
- Need 350 MeV protons to image through the body, Bragg peak must not occur inside patient.
- We propose a pulsed linac upgrade to boost protons from the traditional 250 MeV

LAYOUT AT THE CHRISTIE

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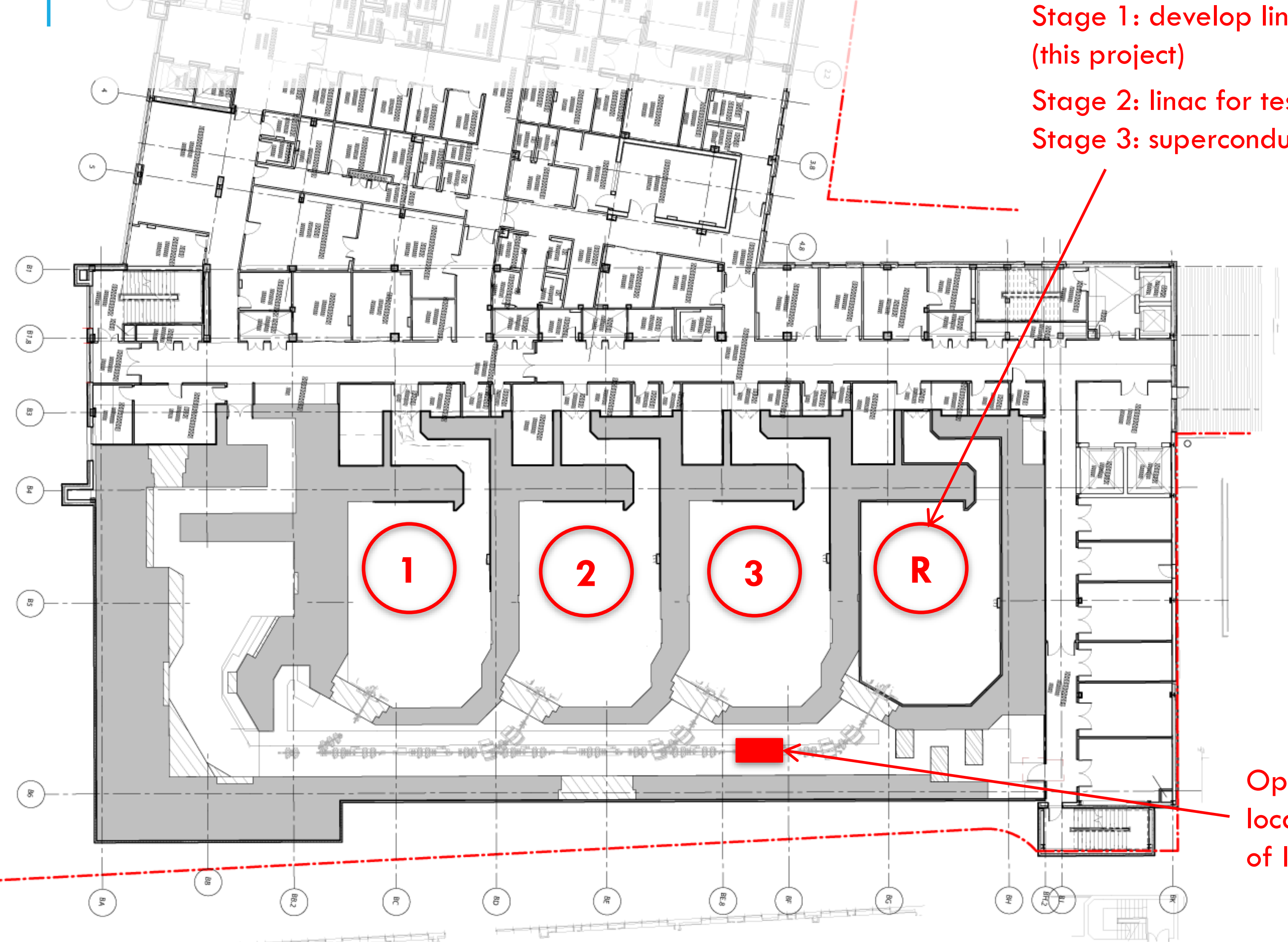
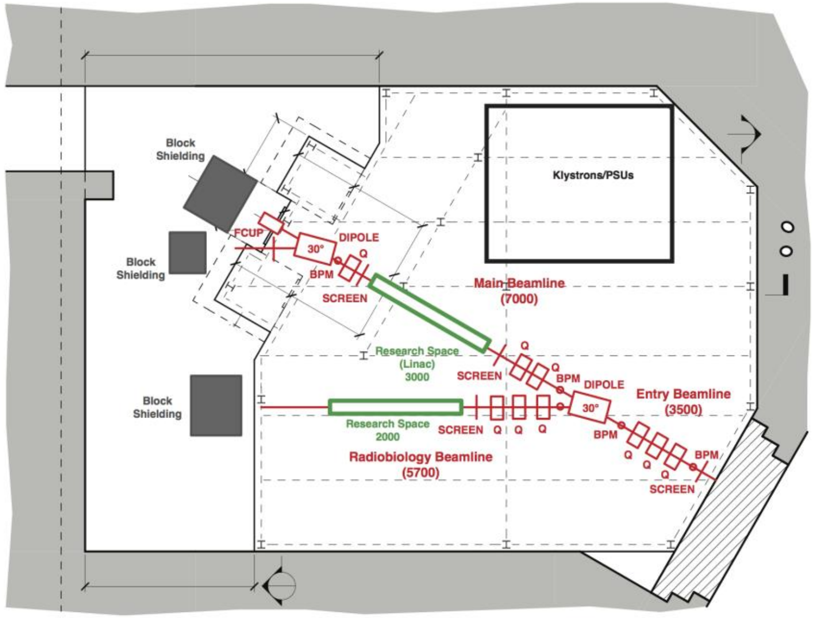
Stage 1: develop linac
(this project)

Stage 2: linac for testing

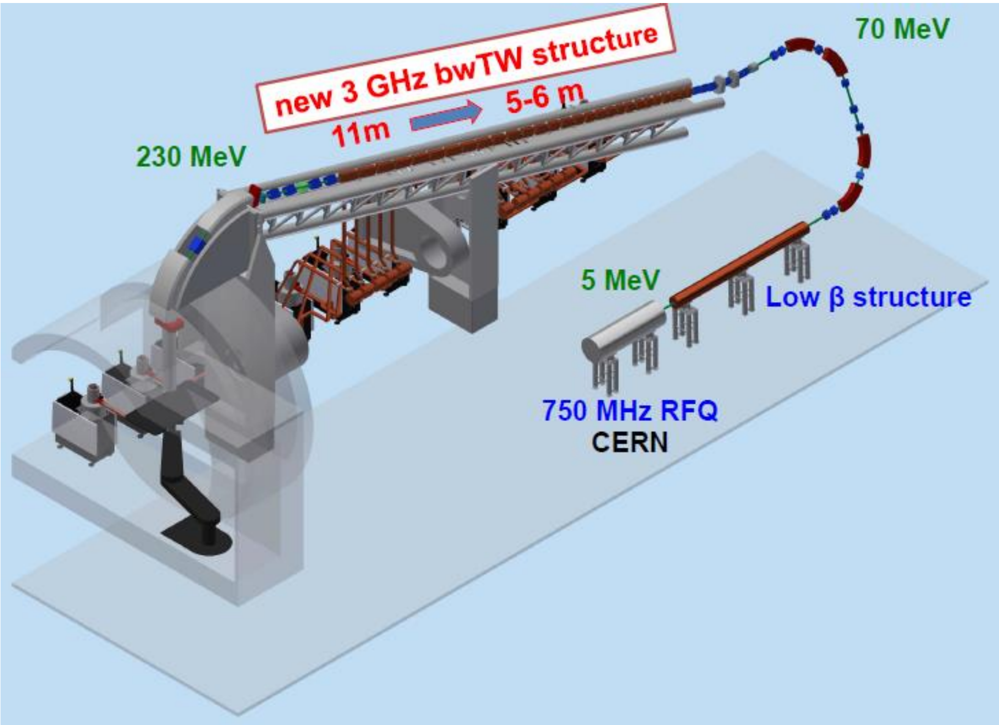
Stage 3: superconducting gantry



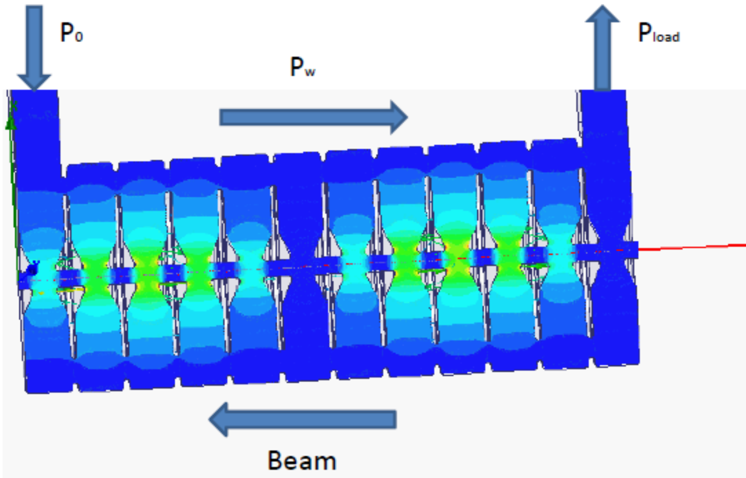
Operational
location
of linac



CURRENT TECHNOLOGY

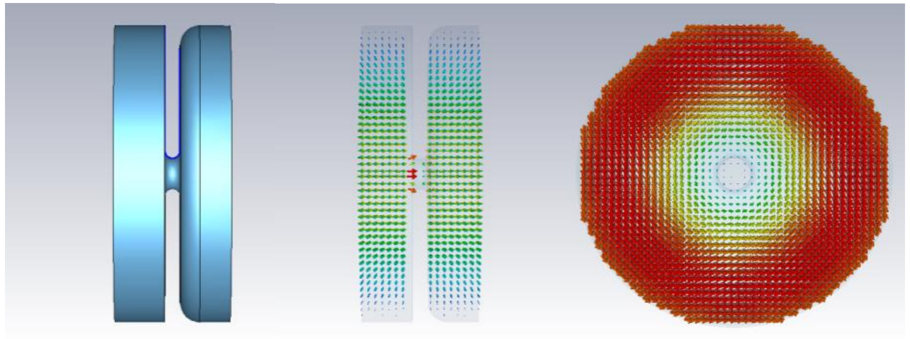


- TERA and CERN have developed high gradient linacs for proton therapy.
- Gradient is not sufficient for this application.
- TERA achieved 50 MV/m (in simulation) at 3GHz.

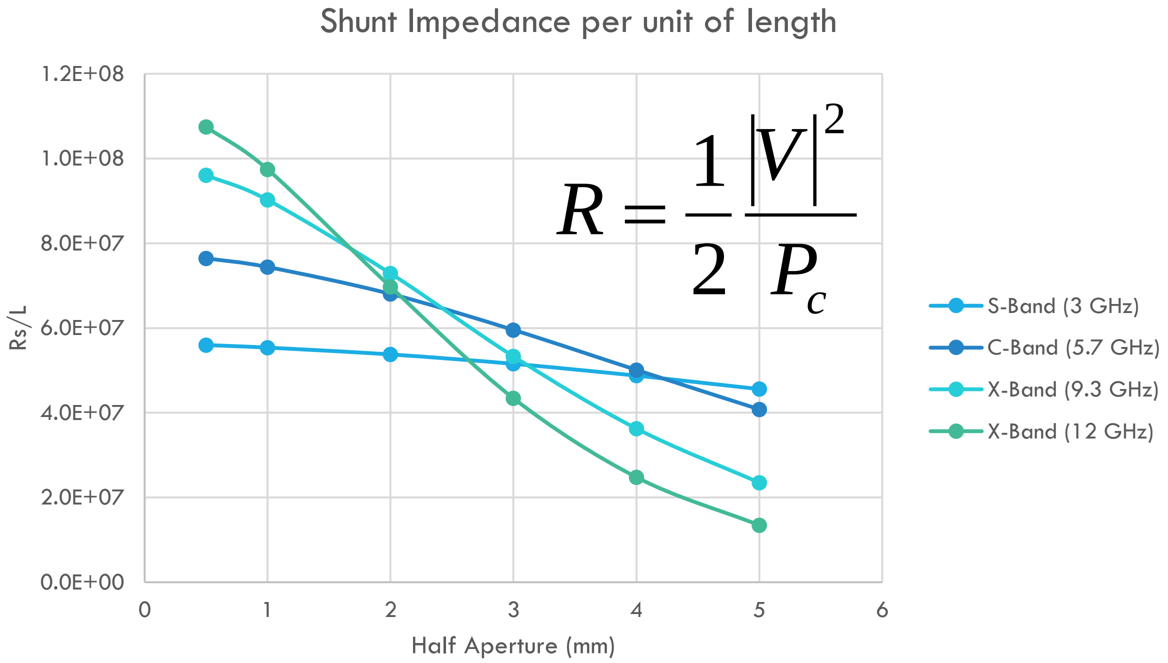


STRUCTURE DESIGN

- Shunt Impedance relates the voltage in the cavity to the power dissipated in the cavity walls
- At small apertures it is an advantage to use X-band.
- We can tolerate lower transmission through a smaller aperture.
- Proton imaging requires low imaging current.
  - mGy not Gy
  - 3.2pA

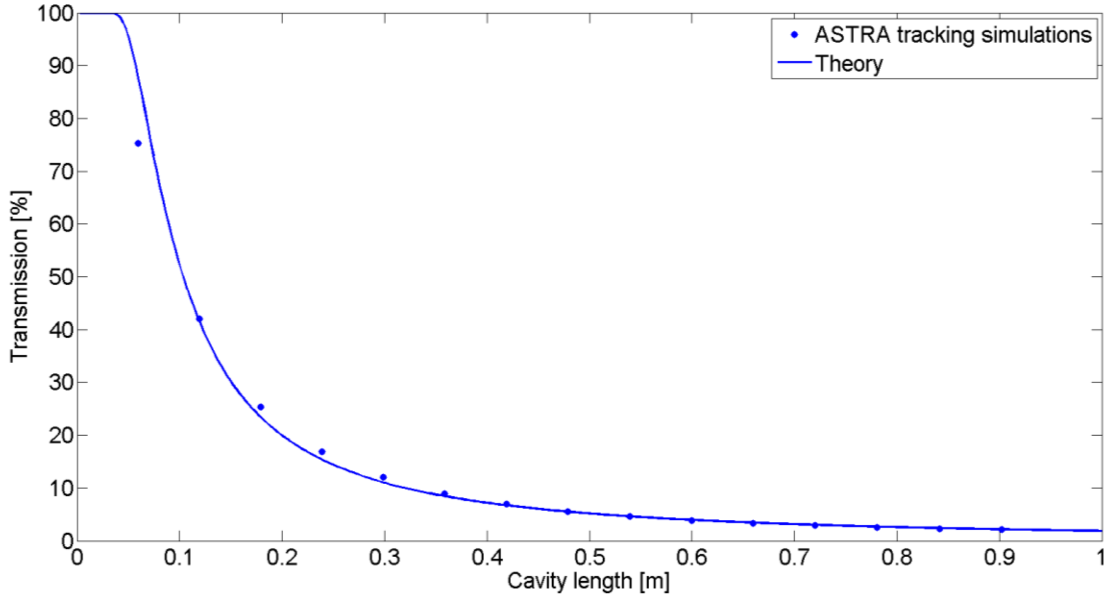


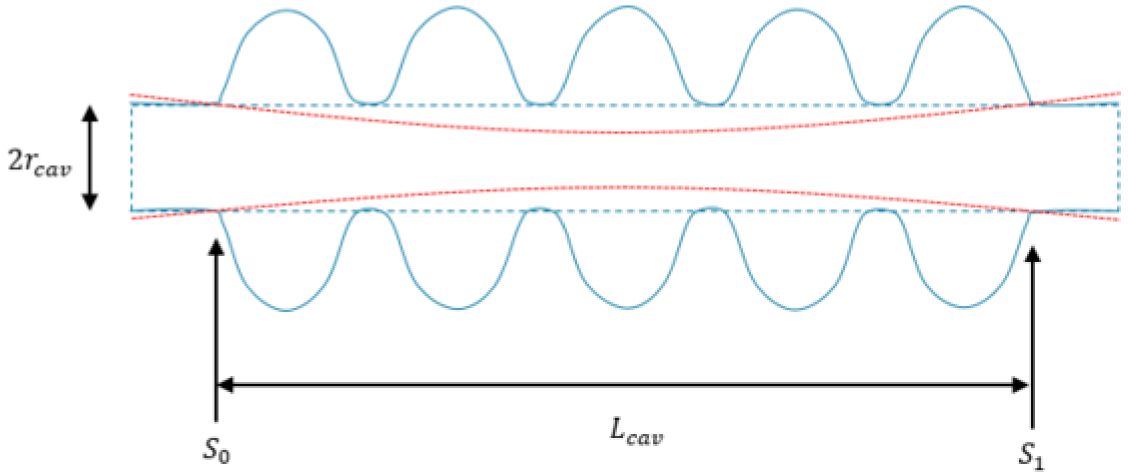
Pillbox Cavity



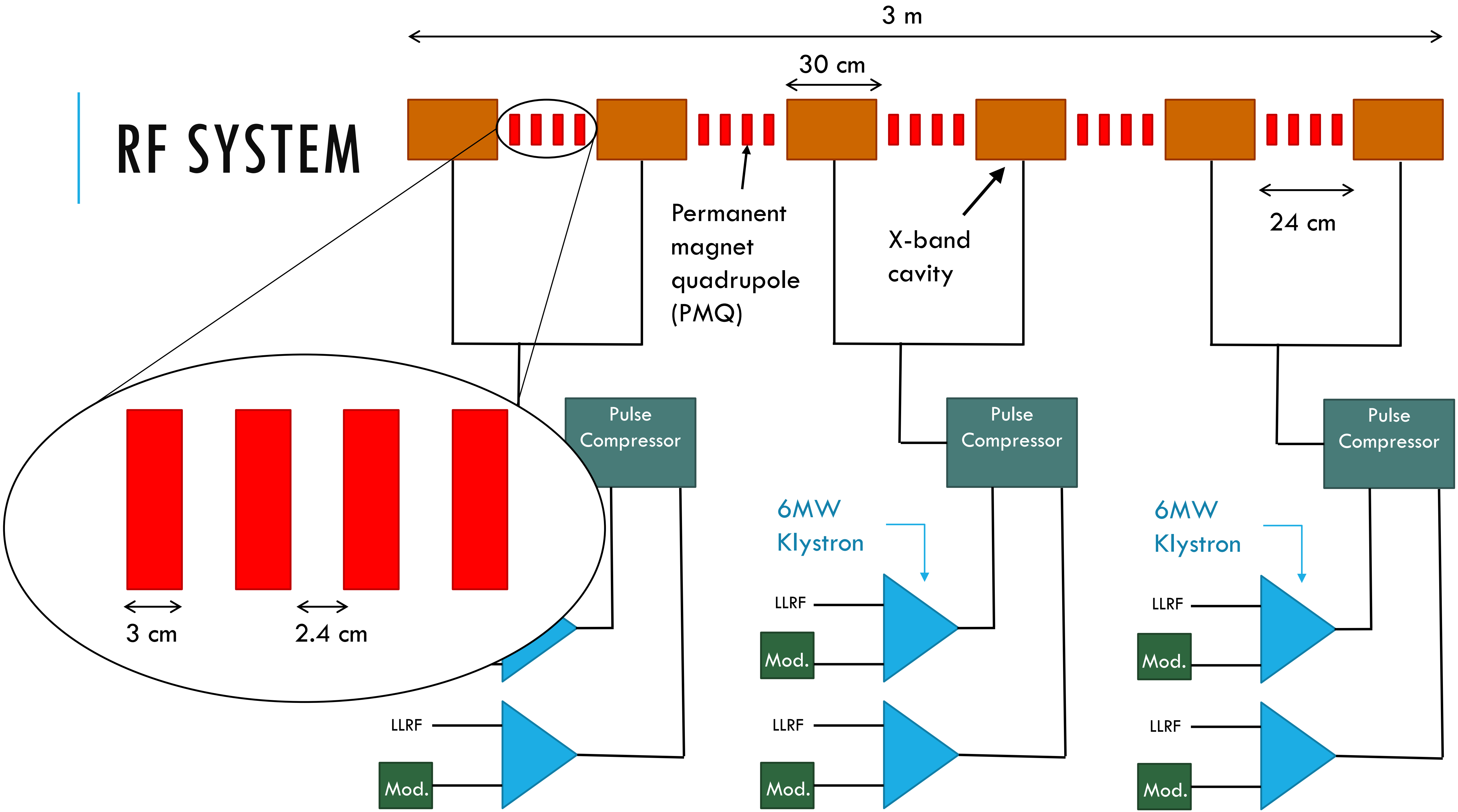
BEAM DYNAMICS

- Studies underway to determine maximum transmission vs. cavity length and iris aperture
- Optimal beam parameters determined to achieve maximum transmission
- 6 30cm cavities should achieve the required imaging current.





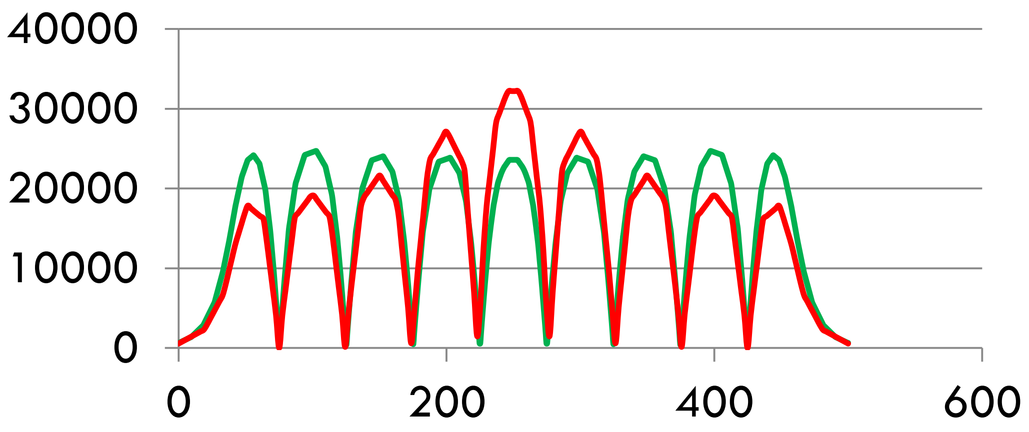
RF SYSTEM


3 m
30 cm
Permanent magnet quadrupole (PMQ)
X-band cavity
24 cm
3 cm
2.4 cm
Pulse Compressor
Pulse Compressor
Pulse Compressor
6MW Klystron
6MW Klystron
LLRF
LLRF
LLRF
LLRF
LLRF
Mod.
Mod.
Mod.
Mod.
Mod.

STANDING WAVE STRUCTURE

- Power is coupled in the middle cell and the amplitude drops off slightly in each cell after.
- Need sufficiently high '*k*' to maintain sufficient power in each cell, and to minimal phase shift.
- At X-band there are significantly more cells to couple together.
- 30cm X-Band structure k≥ 12% whereas S-Band requires k≥ 2%

$$A_{2n} \approx (-1)^{n-m} A_{2m}\left[1-\frac{2\left(m^2-n^2\right)}{k^2 Q_a Q_c}\right]\exp\left[j\frac{4\left(m^2-n^2\right)}{k^2 Q_a}\frac{\Delta\omega}{\omega_a}\right]$$



SIDE COUPLED STRUCTURE

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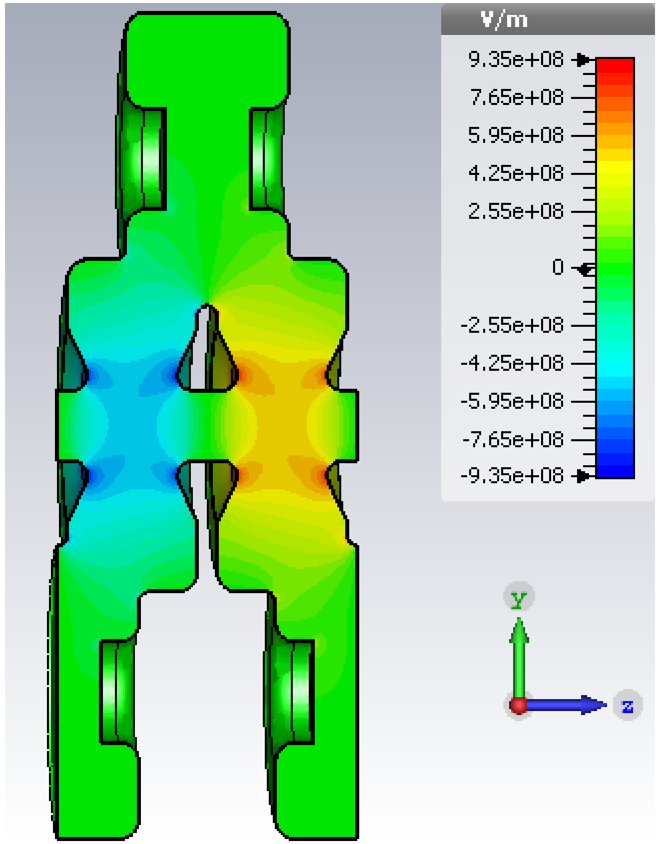
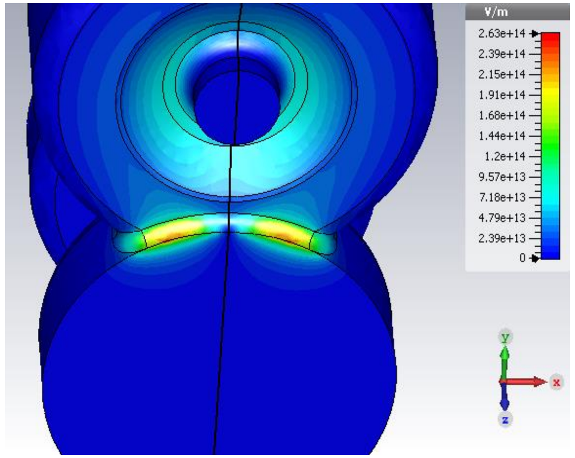
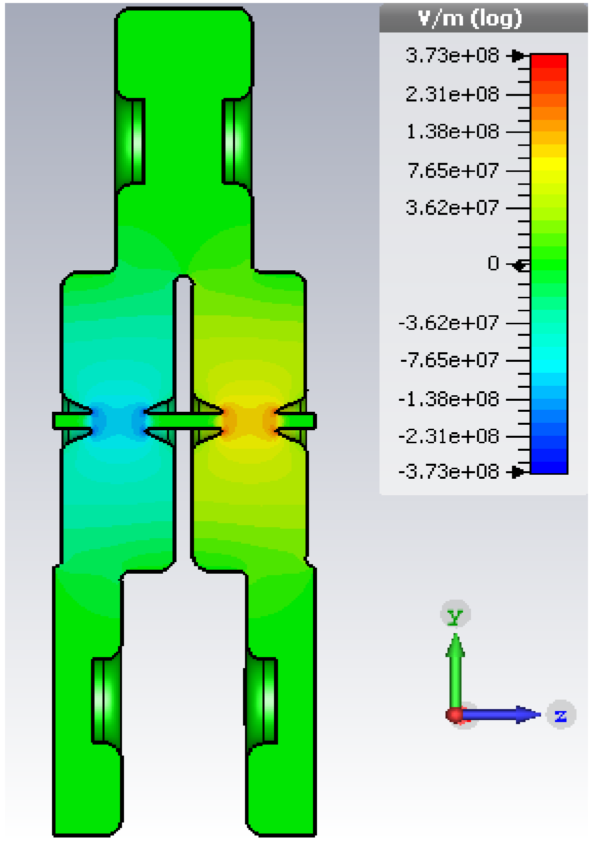
$$S_c = \left\| \Re\{\overline{S}\} \right\| + \frac{1}{6} \left\| \Im\{\overline{S}\} \right\|$$

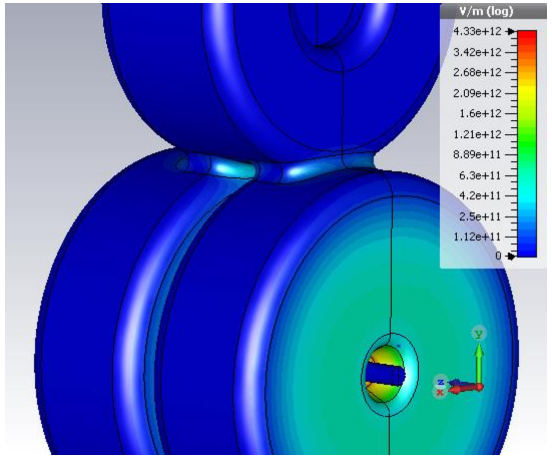


- 30 cm X-Band 12GHz
- Limited by breakdown
- Sc grad. limit 50MV/m
- Sc peaks on the coupling slots



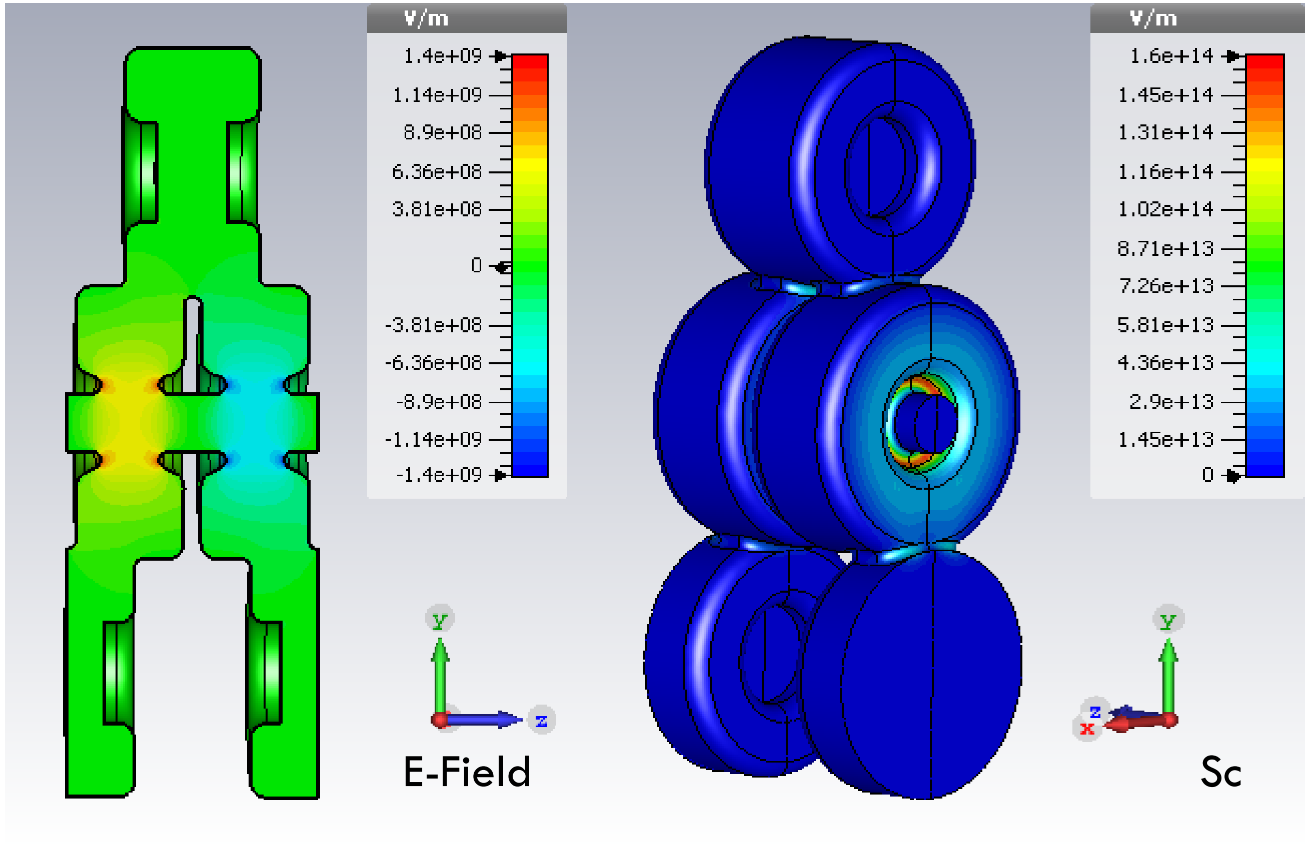


- S-Band 3GHz
- Max. Grad. 68MV/m
- Limited by Sc but peak is on nose cone rather than coupling slot



10CM SIDE COUPLED SW STRUCTURE

- Less coupling required k≥ 3.8%
- Sc Peaking on nose cone rather than coupling slot
- Max gradient ~70MV/m



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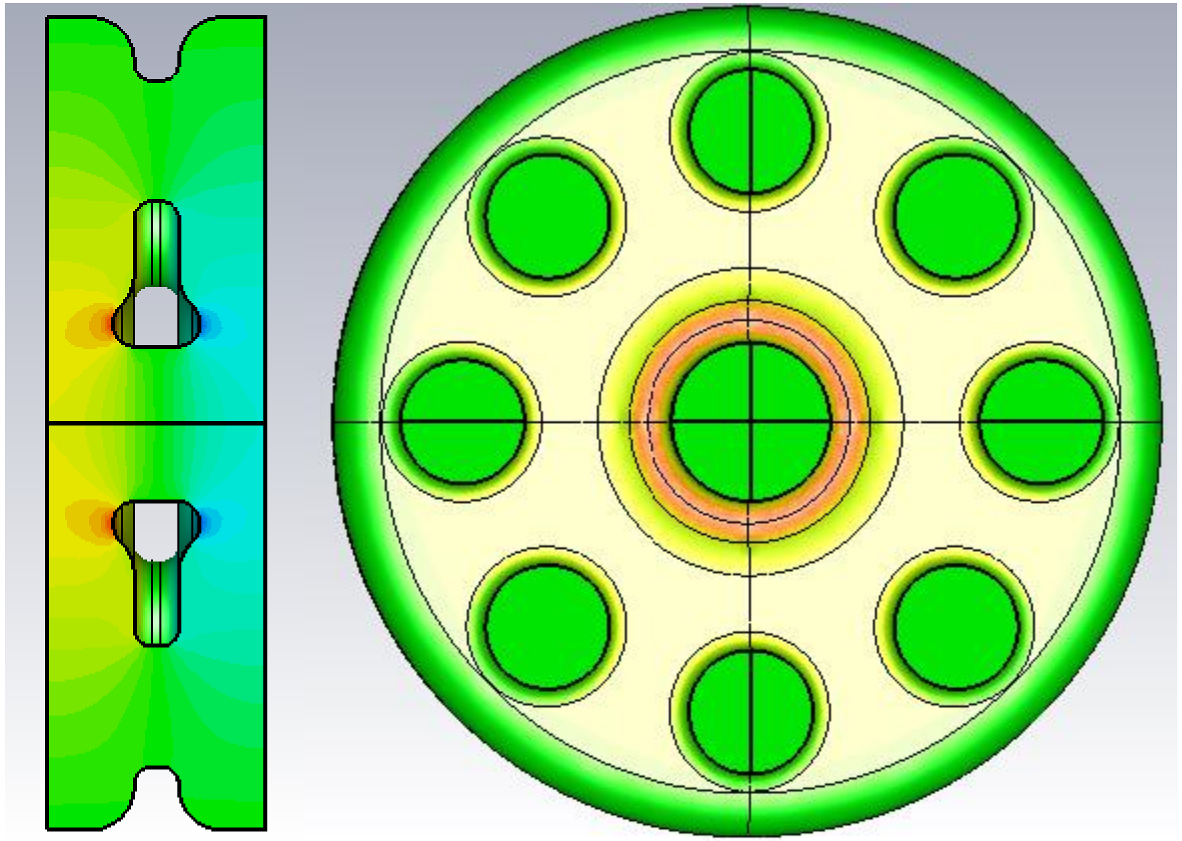
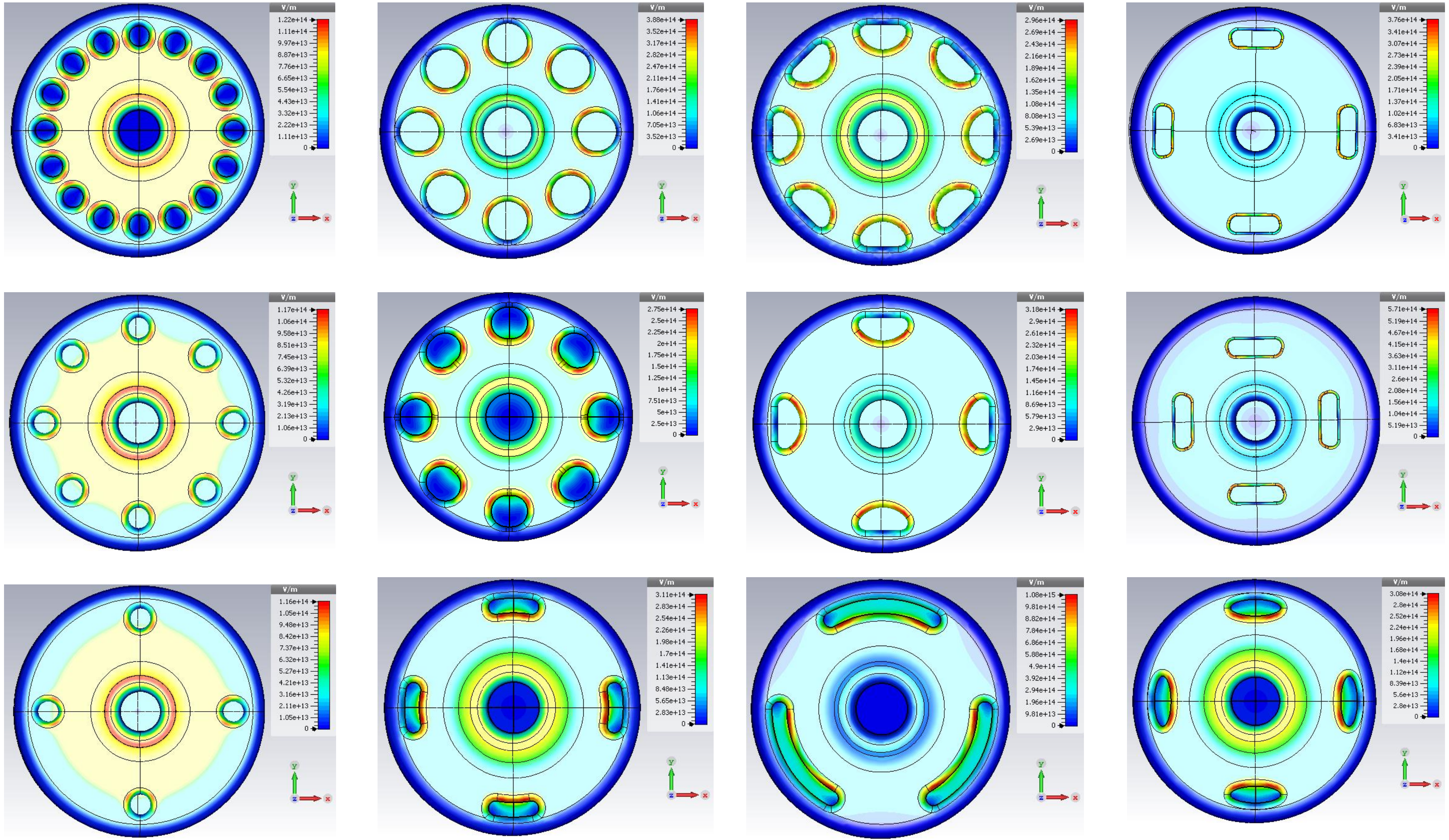
TRAVELLING WAVE STRUCTURE

- Possible alternative to the side coupled structure.
- Power flows though all of the cavities and out the other side.
- Power is coupled through slots in the end caps.
- Average Vg/c>0.65%.
- Coupling slot geometry study.

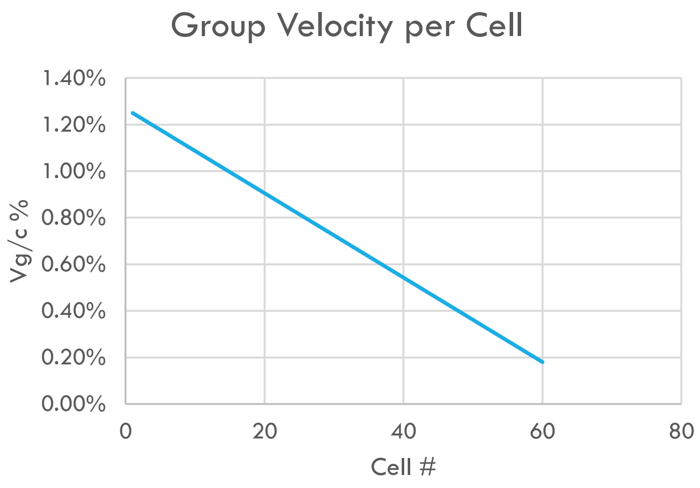


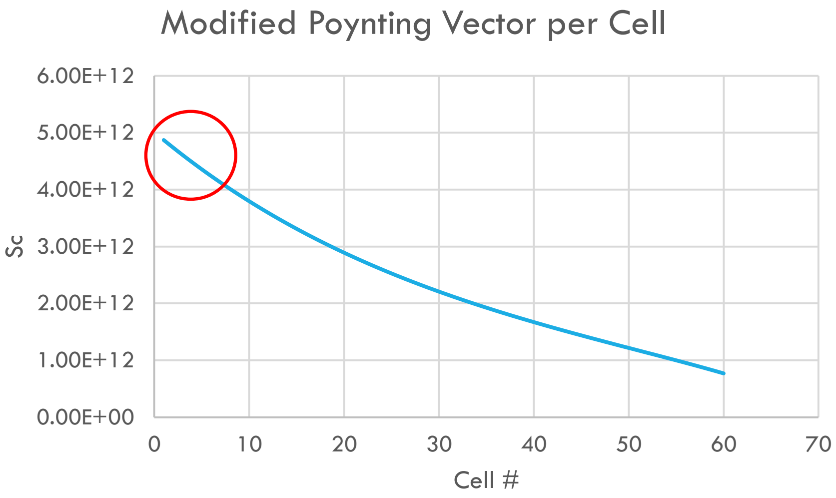
COUPLING SLOT STUDY



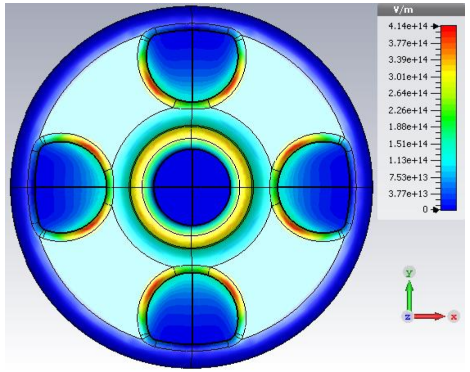
COMPLETE STRUCTURE

- Backwards Travelling Wave Structure with Dee shaped slots and Phase advance of 5π/6
- Hybrid constant impedance and constant gradient structure
- Cant achieve high enough Vg for constant gradient structure (2.2%)
- Sc too high in first 10 cells for constant impedance
- Maximum Gradient 58 MV/m

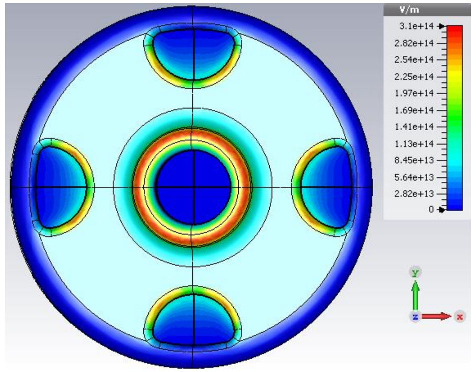




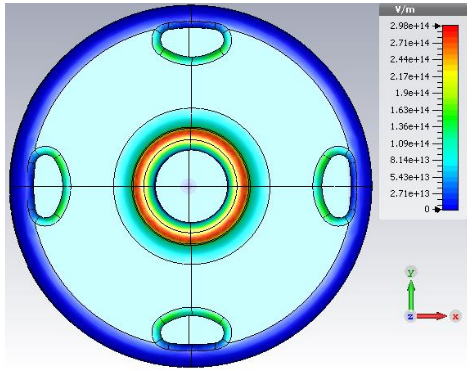
First Cell
Vg= 1.25%



Mid Cell
Vg= 0.69%

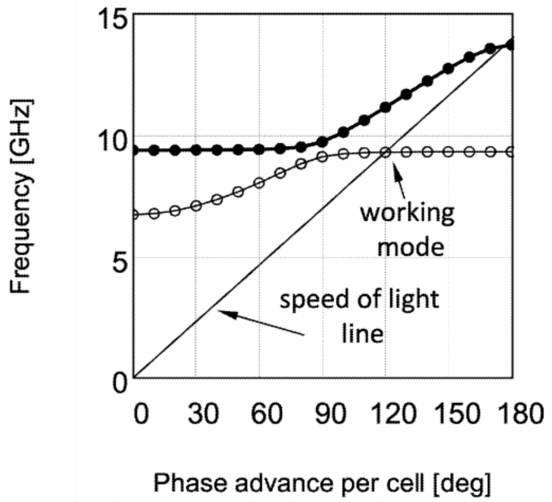


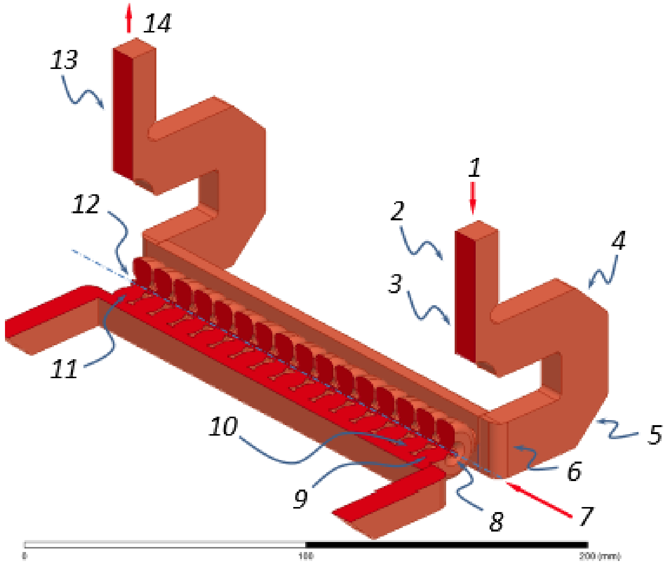
Last Cell
Vg= 0.18%

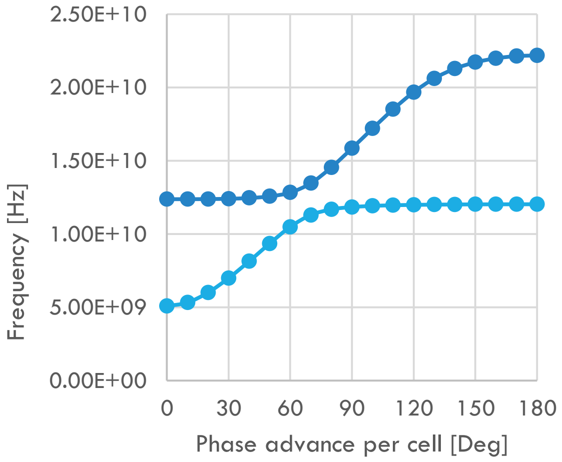


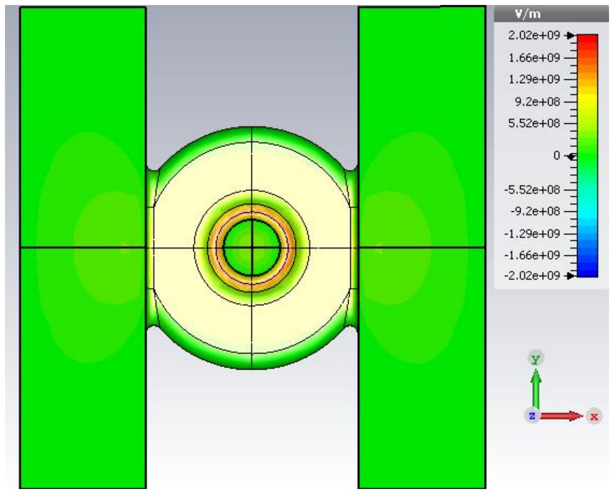
PARALLEL COUPLED TRAVELLING WAVE STRUCTURE

- Based on a ß=1design by V.A. Dolgashev **patent application No.: US 62/007817*
- High shunt impedance of a side-coupled standing wave structure
- At ß=0.6 working mode moves further from the avoided crossing, yielding lower group velocity at the working mode









SUMMARY

- Aim to utilise high shunt impedance of X-Band Structure to achieve high gradient >50MV/m
- A 30cm S-band SC structure reaches higher gradient than X-band structure as it requires less coupling
- A 10cm X-band SC structure looks promising around 70MV/m
- A 30cm bTWS reached 58MV/m slightly higher than TERA 50MV/m
- Potential for a waveguide coupled structure
- Manufacture prototype cavity
- Experimentally verify gradient

Thanks for listening!

Questions?