PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

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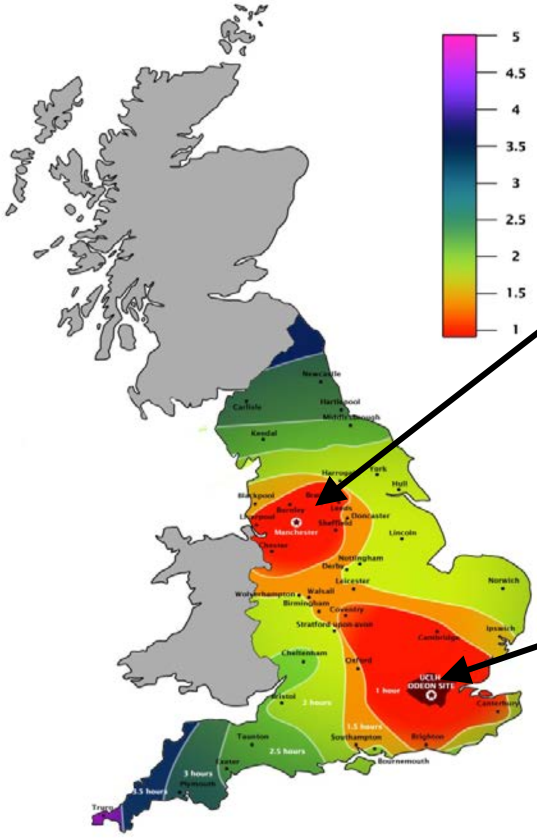
Lancaster University
Cockcroft Institute

PROTON THERAPY IN UK

- Provides UK patients with good access to the service, with limited travel times by car or public transport
- Both sites at the centre of regional public transport links
- Ensures as many patients as possible will be able to return home during their treatment

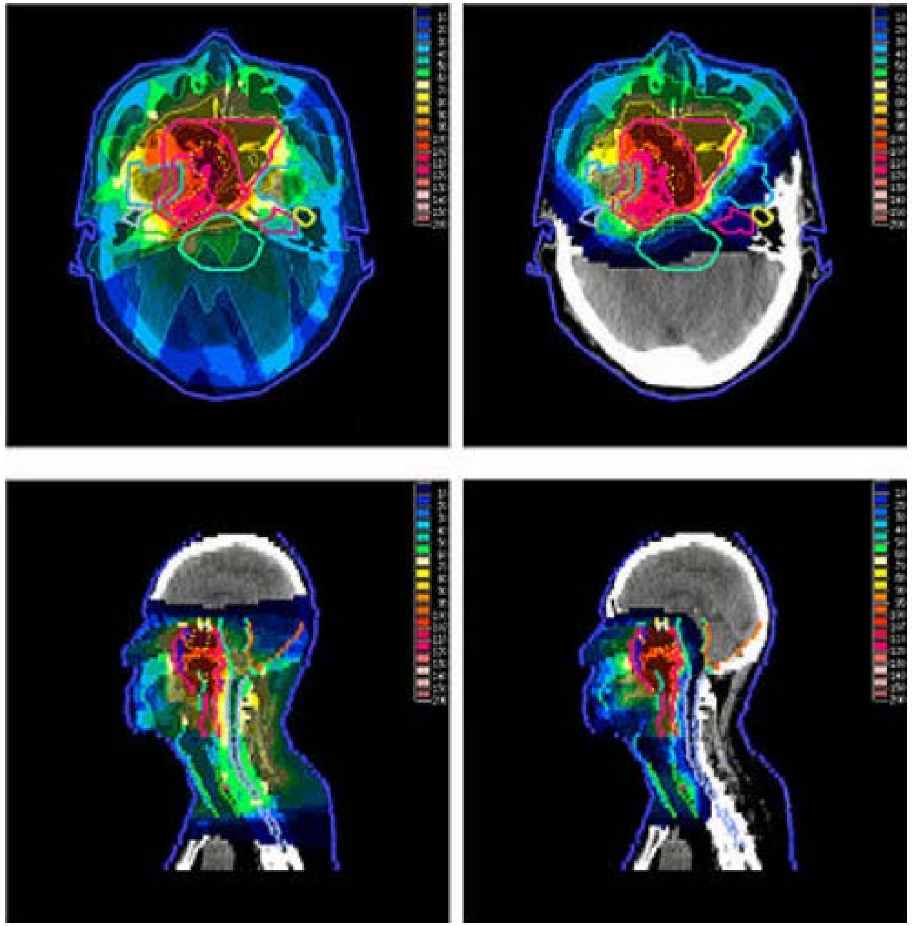


Christie Hospital, Manchester

UCLH, London

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 directly measures proton stopping power.



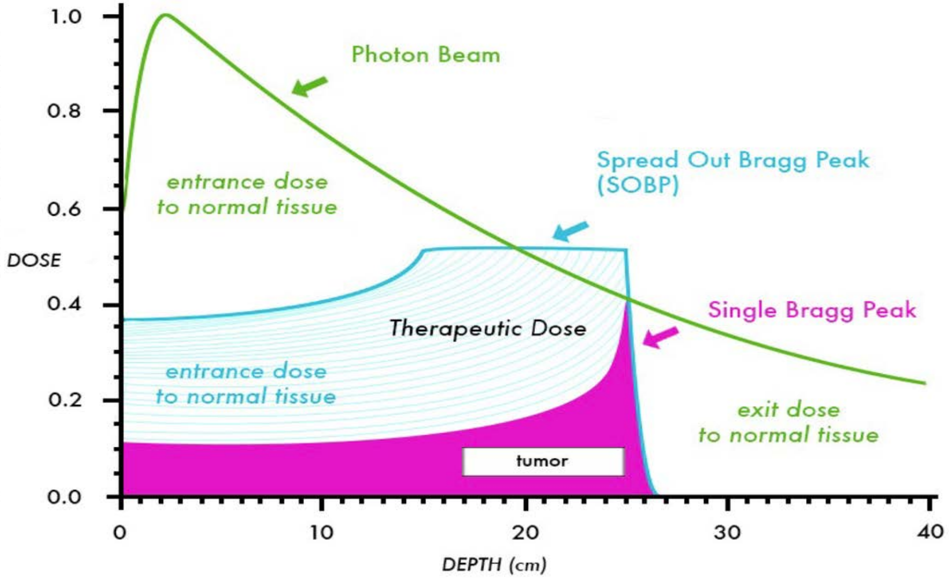


Image from: Ladra, M. and Yock, T, Cancers 2014, 6, 112-127; doi:10.3390/cancers6010112

PROTON RADIOGRAPHY

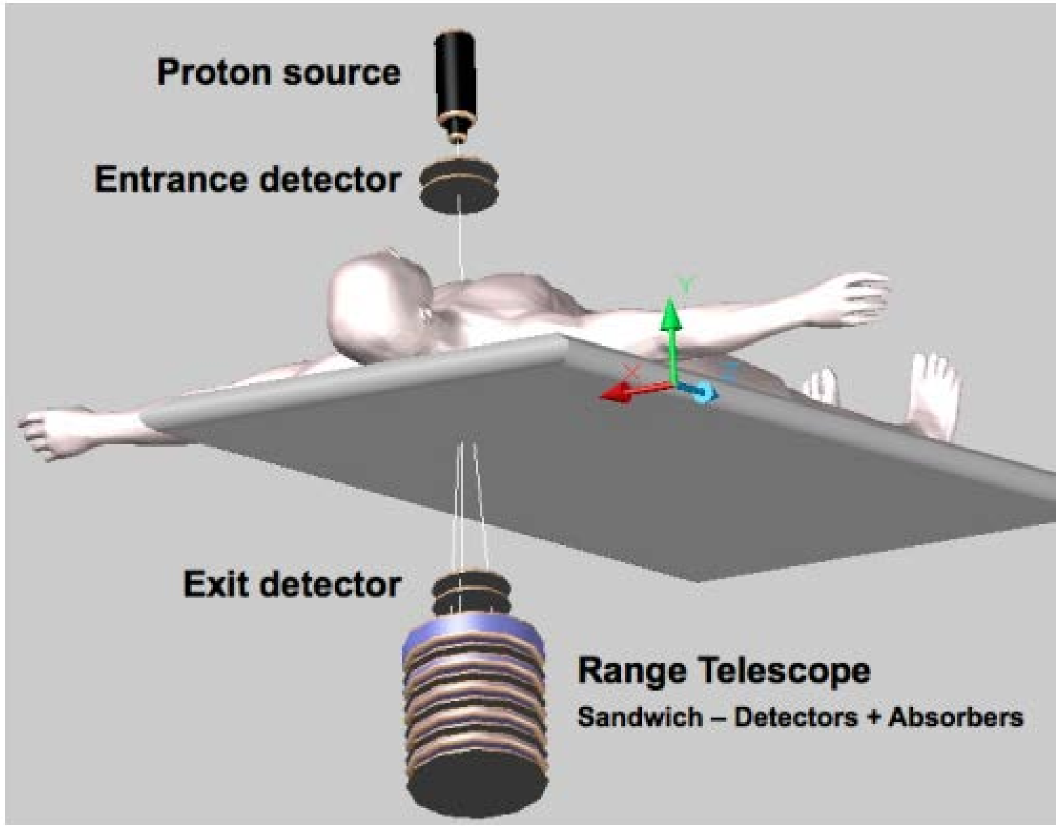
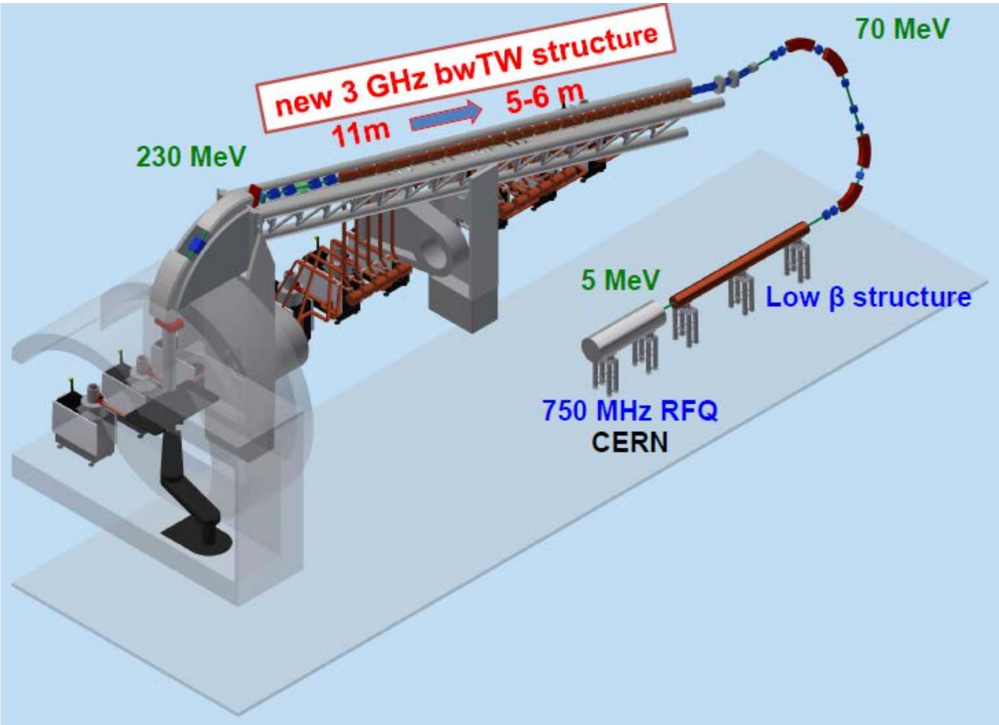


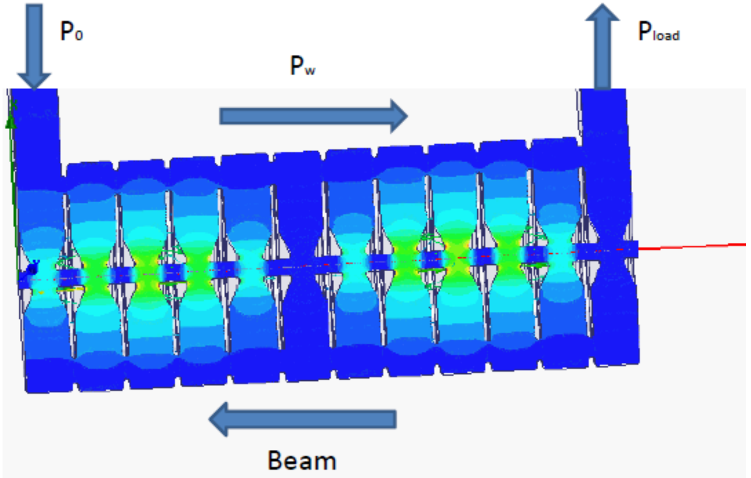
Image courtesy of PRaVDA

- 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 whole body imaging in adults, Bragg peak must not occur inside patient. (250 MeV fine for children or smaller body parts)
- We propose a pulsed linac upgrade to boost protons from the traditional 250 MeV

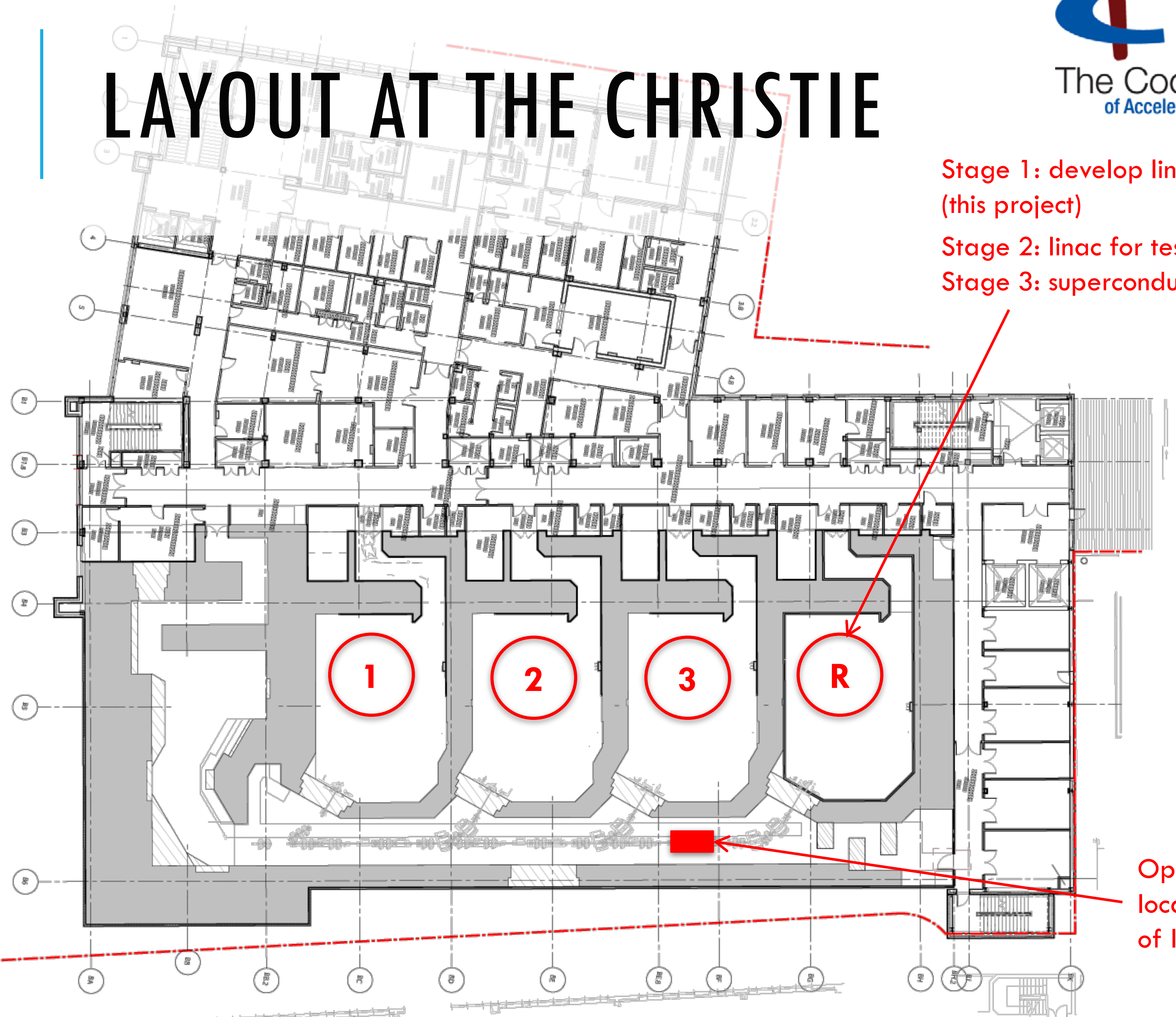
CURRENT TECHNOLOGY



- TERA and CERN have developed high gradient linacs for proton therapy.
- Gradient is not sufficient for this application.
- TERA achieved 45 MV/m (in simulation) at 3GHz.



LAYOUT AT THE CHRISTIE

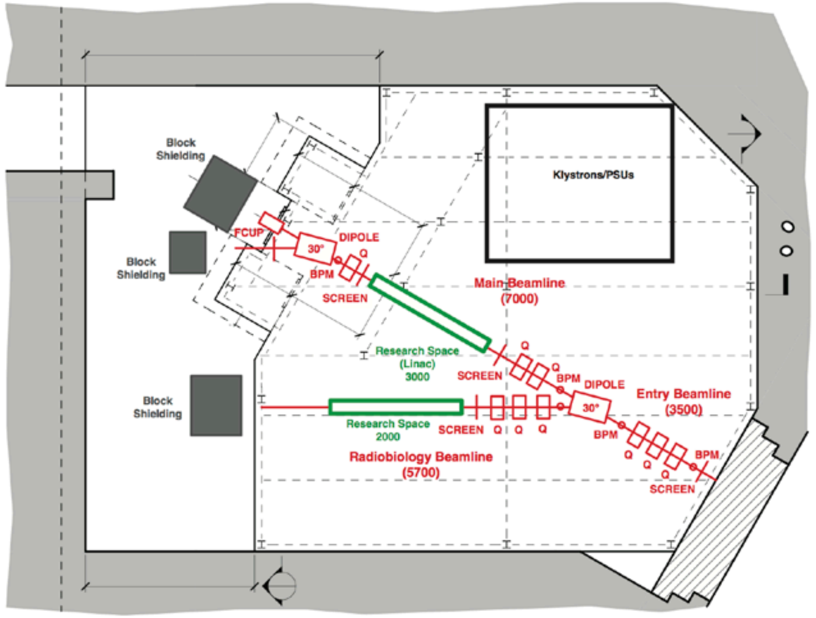


Stage 1: develop linac
(this project)

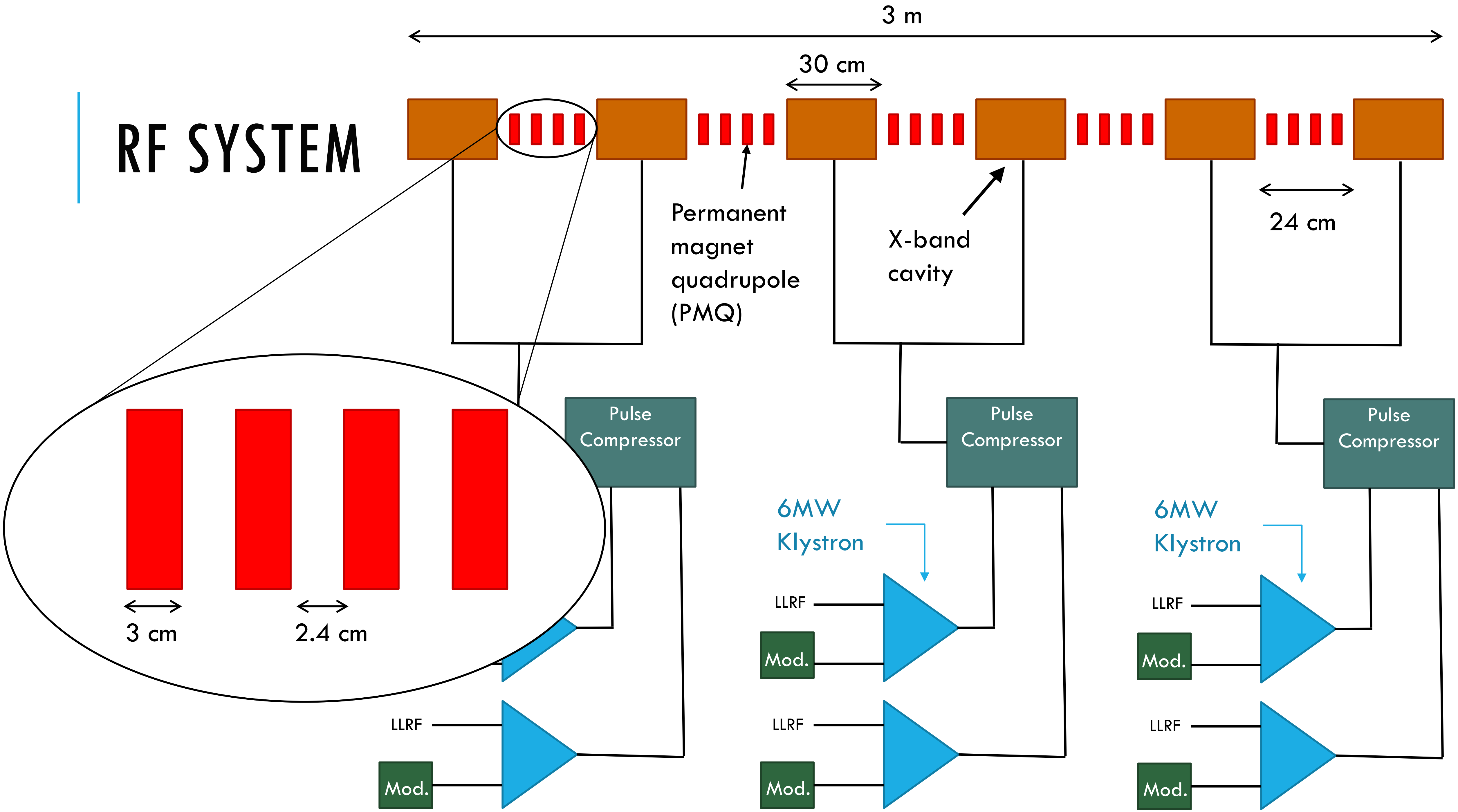
Stage 2: linac for testing

Stage 3: superconducting gantry

Operational
location
of linac



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.

STRUCTURE DESIGN

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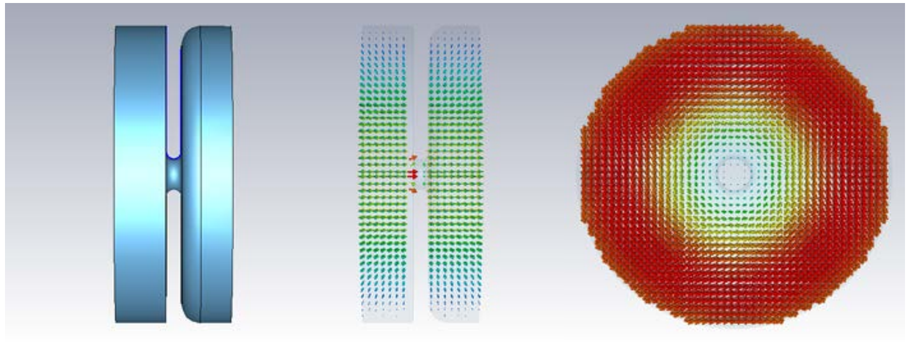
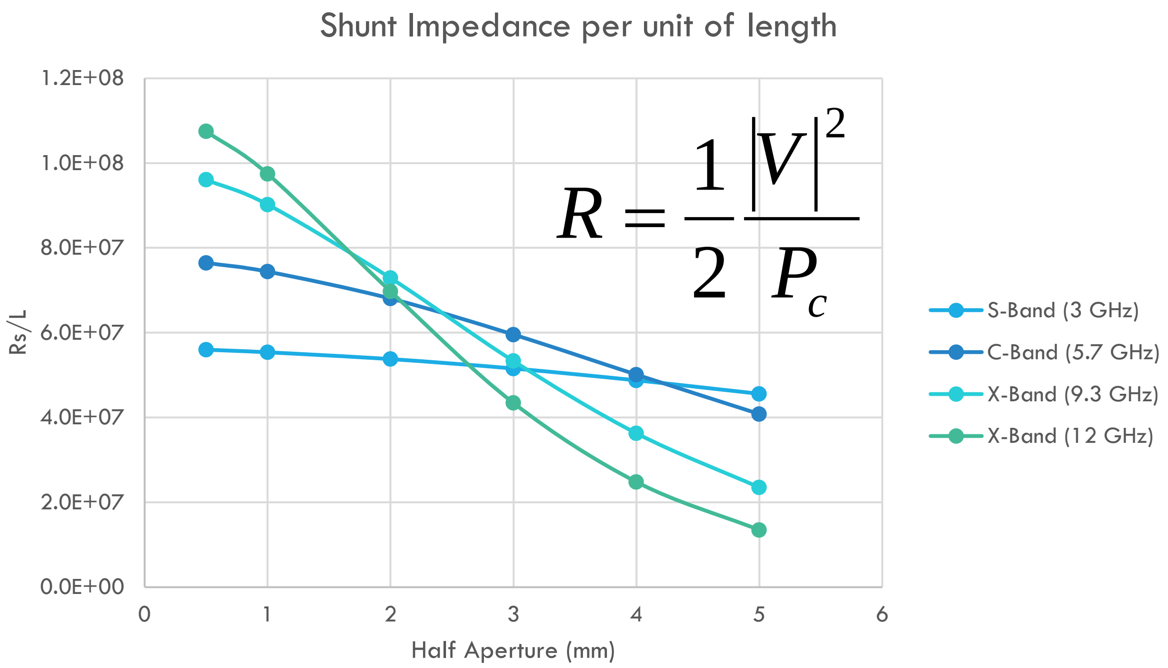
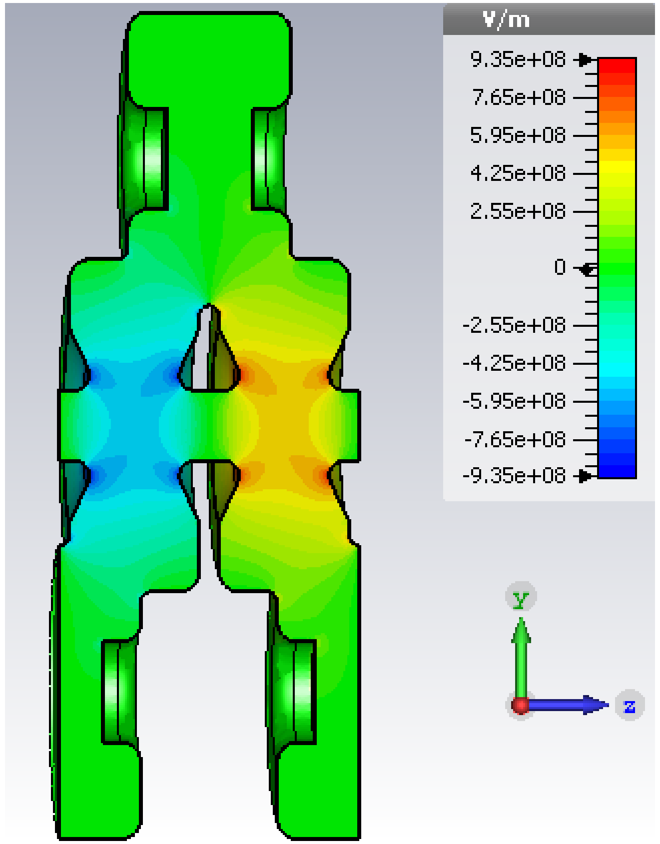
- Shunt Impedance relates the voltage in the cavity to the power dissipated in the cavity walls.
- At small apertures it is an advantage to use X-band.
- We can tolerate lower transmission through a smaller aperture.
- Proton imaging requires low imaging current.
    - mGy not Gy
    - 3.2pA



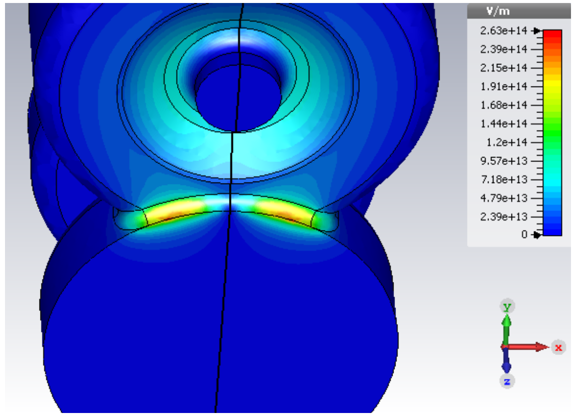


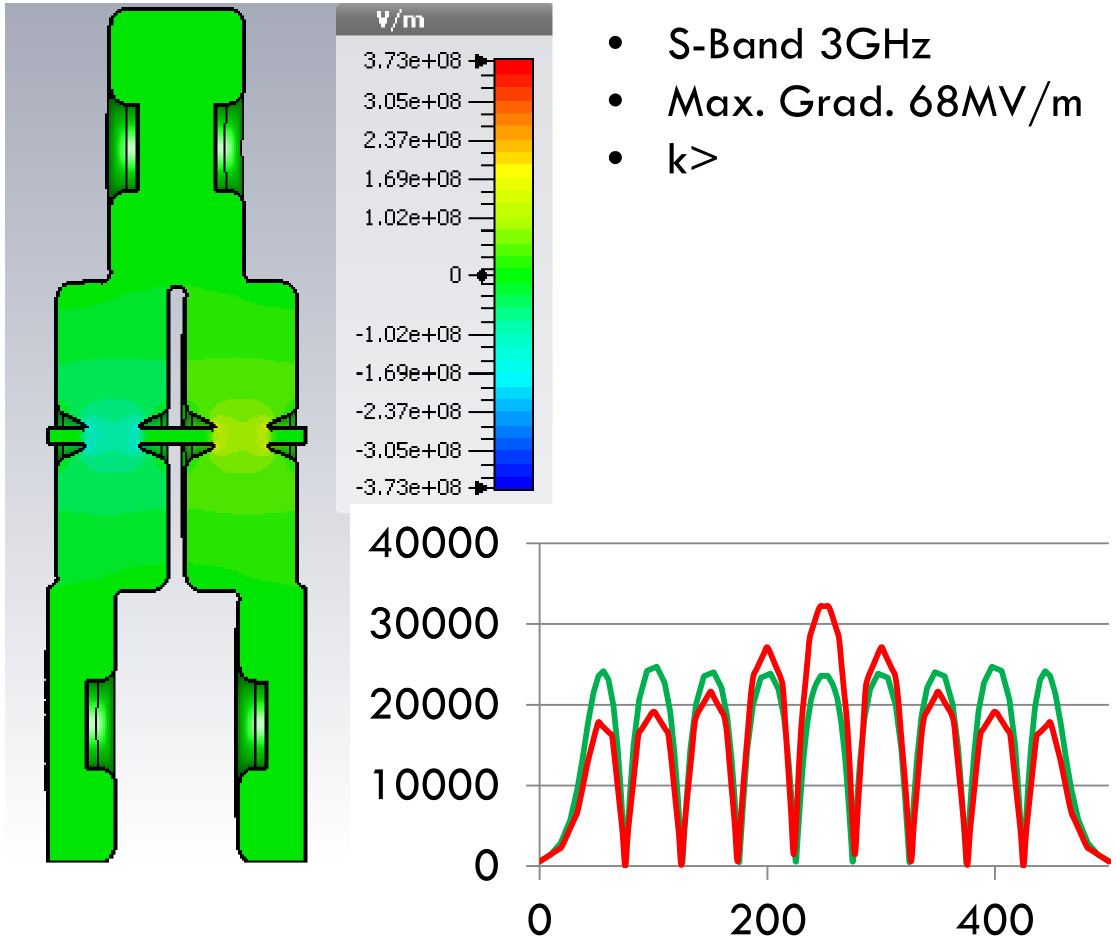
$$R = \frac{1}{2}\frac{|V|^2}{P_c}$$

SIDE COUPLED STRUCTURE



- X-Band 12GHz
- Max. Grad. 60MV/m
- Limited by Shunt Impedance
- Sc grad. limit 75MV/m
- k>12% to maintain field in end cells

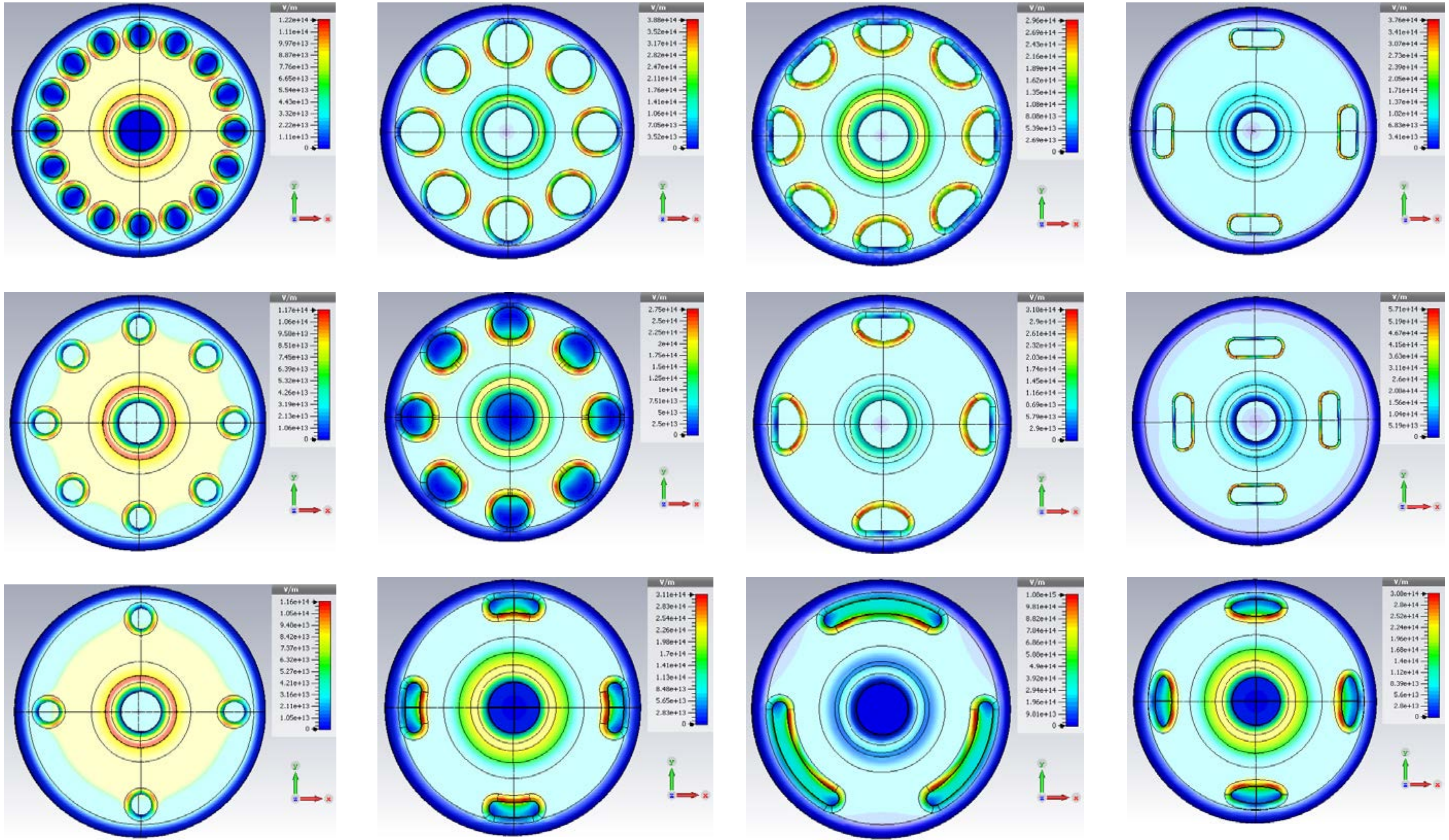


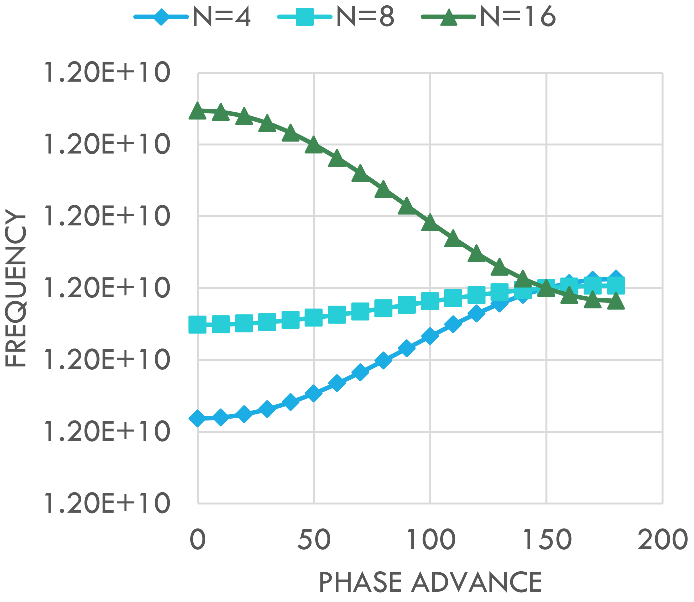


- S-Band 3GHz
- Max. Grad. 68MV/m
- k>

Modified Poynting Vector: $S_c = \mathrm{Re}\{\bar{S}\} + g_c \cdot \mathrm{Im}\{\bar{S}\},$

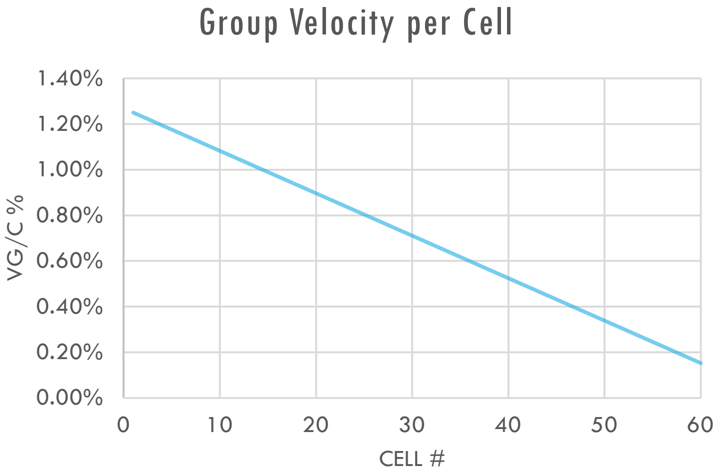
TRAVELLING WAVE STRUCTURE

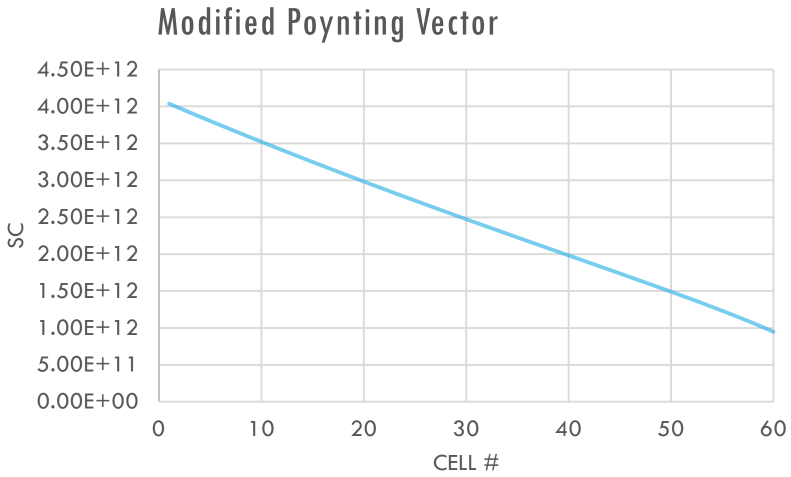




COMPLETE STRUCTURE

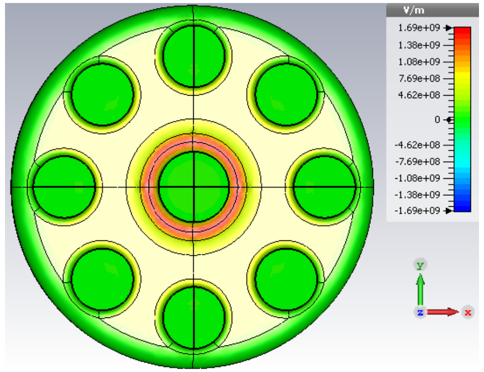
- Backwards Travelling Wave Structure with Circular slots and Phase advance of 2π/3
- Hybrid constant impedance and constant gradient structure
- Cant achieve high enough Vg for constant gradient structure
- Sc too high in first few cells for constant impedance
- Maximum Gradient 61 MV/m


Group Velocity per Cell


Modified Poynting Vector

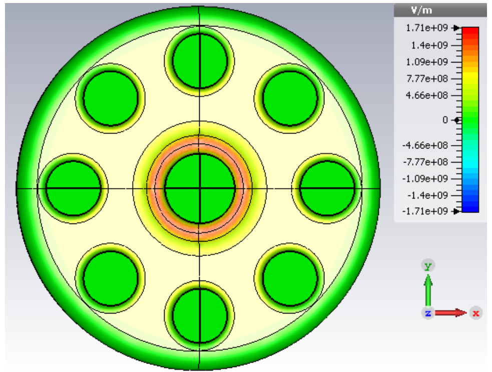
First Cell

Vg= 1.25%



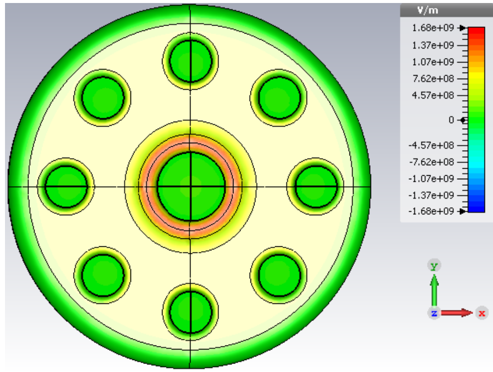
Centre Cell

Vg= 0.71%



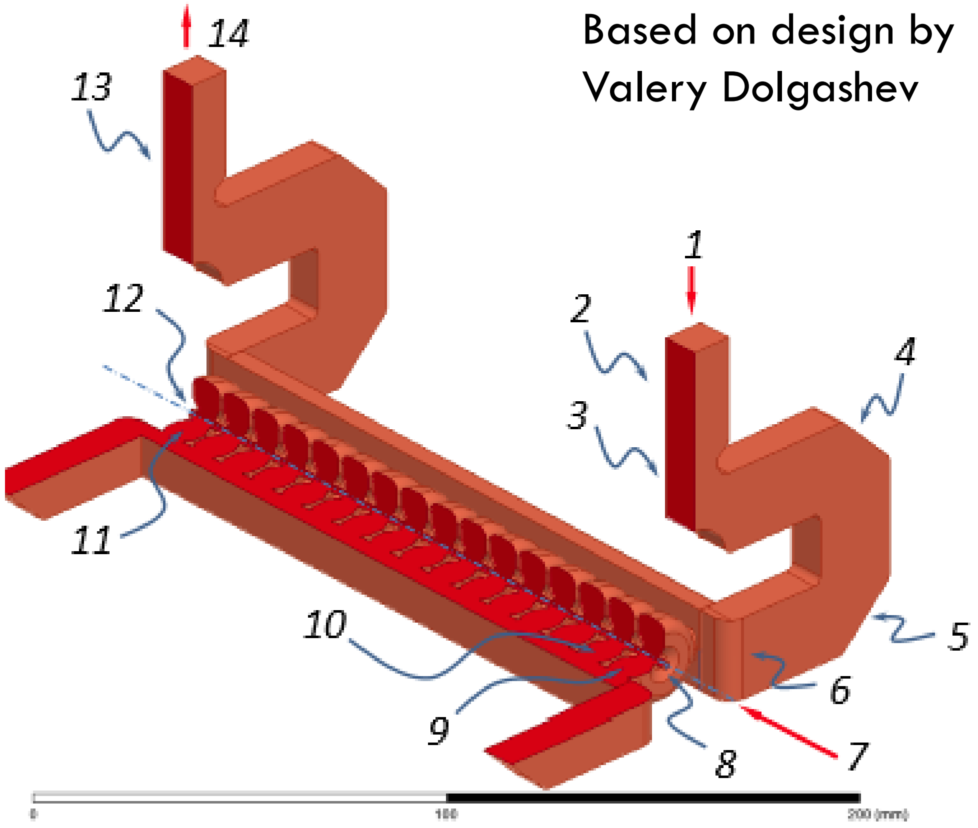
Last Cell

Vg= 0.15%



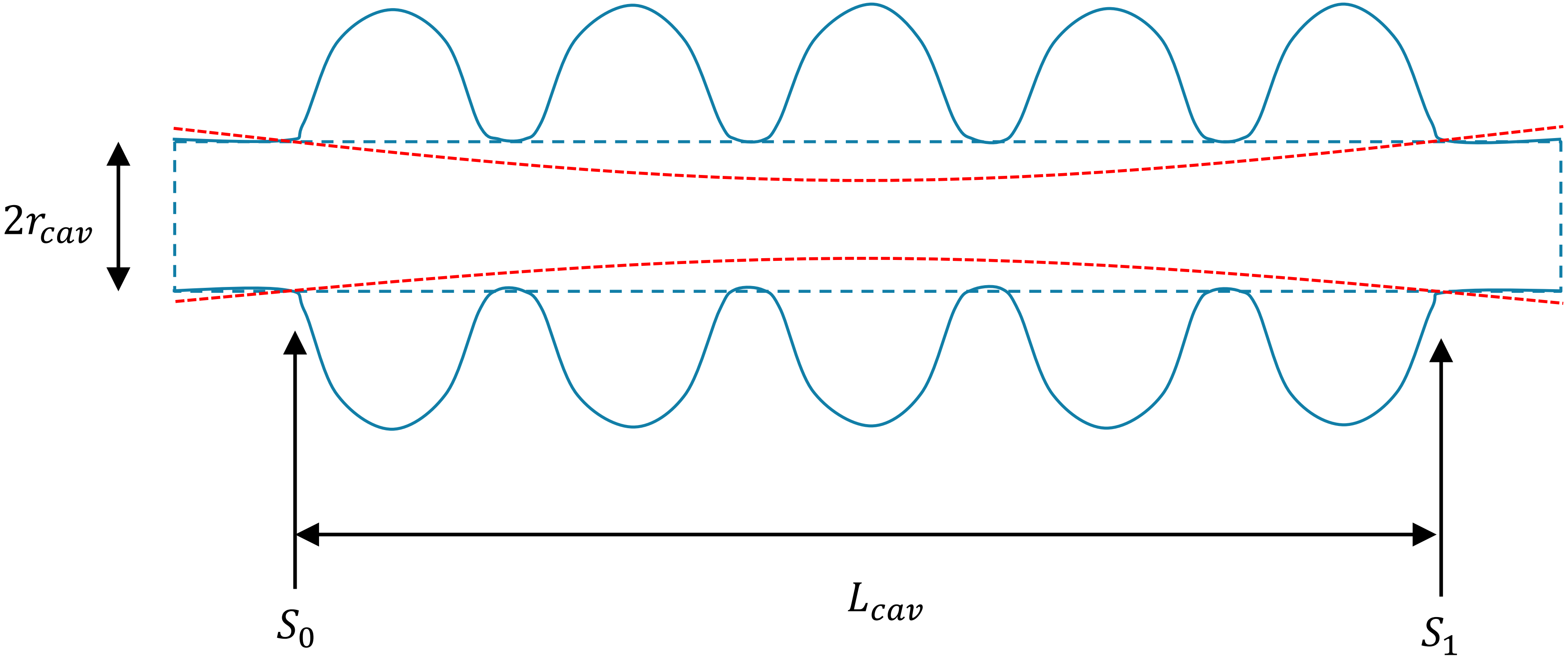
NEW DESIGN TO CONSIDER

- Further optimisation of potential structures
- Parallel coupled travelling wave structure
- Final cavity design
- Coupler design
- Manufacture prototype cavity
- Experimentally verify gradient

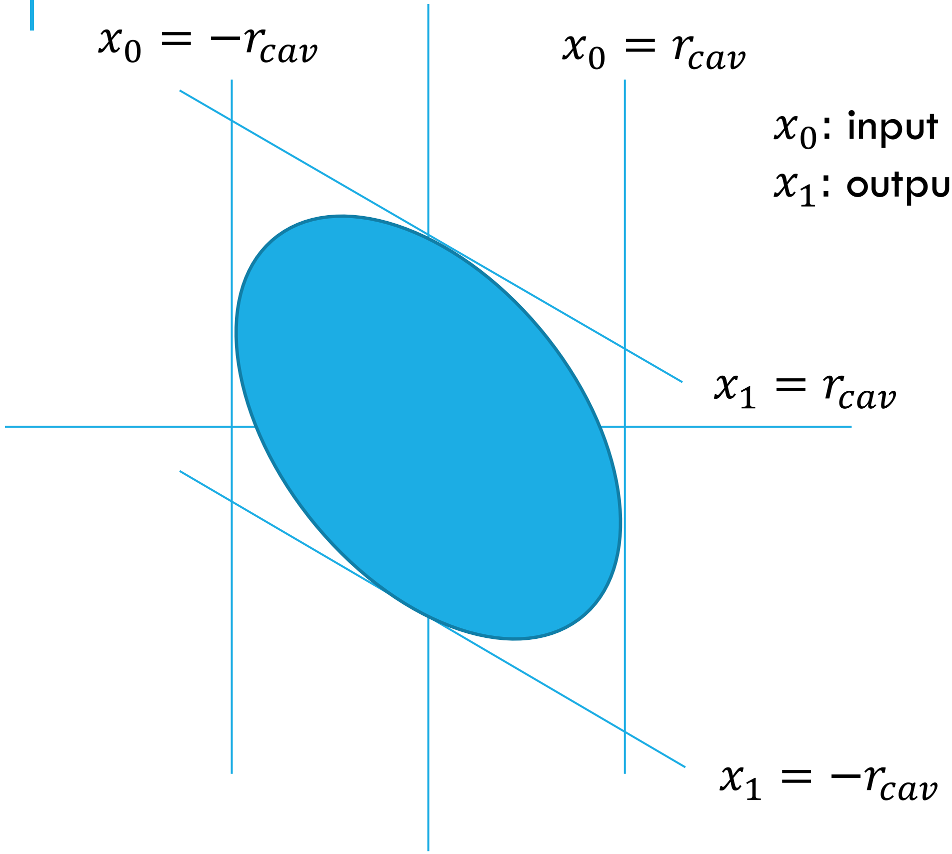


Based on design by
Valery Dolgashev

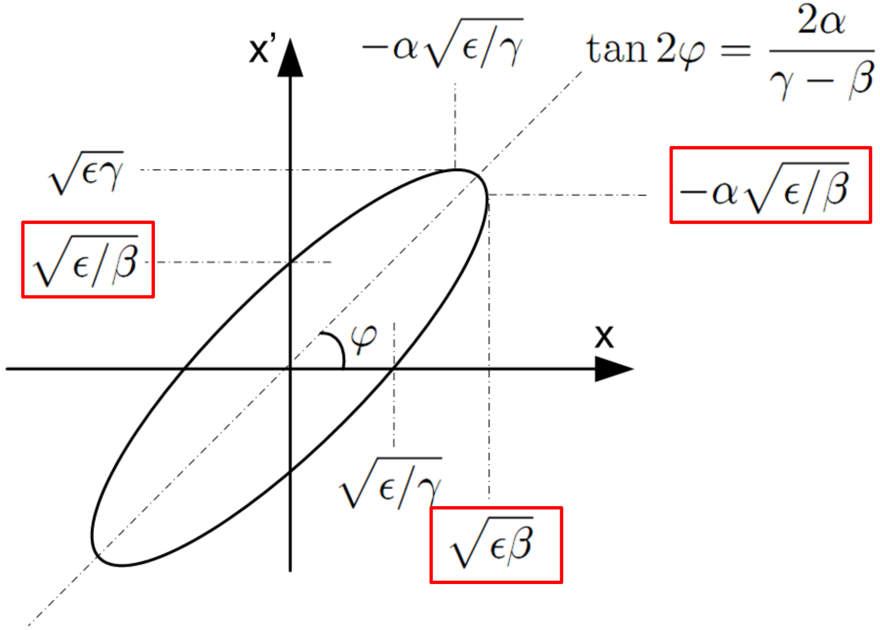
CAVITY TRANSMISSION



CAVITY TRANSMISSION



x_0: input aperture
x_1: output aperture



$$x_0 = \pm r_{cav}$$

$$x_1 = \pm r_{cav} = \sqrt{\frac{\beta_{r0}\gamma_{r0}}{\beta_{r1}\gamma_{r1}}}\left(R_{11}x_0 + R_{12}x'_0\right)$$

$$\varepsilon_{n,acceptance} = \sqrt{\beta_{r0}\gamma_{r0}}\sqrt{\beta_{r1}\gamma_{r1}}\frac{r_{cav}^2}{R_{12}}$$

CAVITY TRANSMISSION

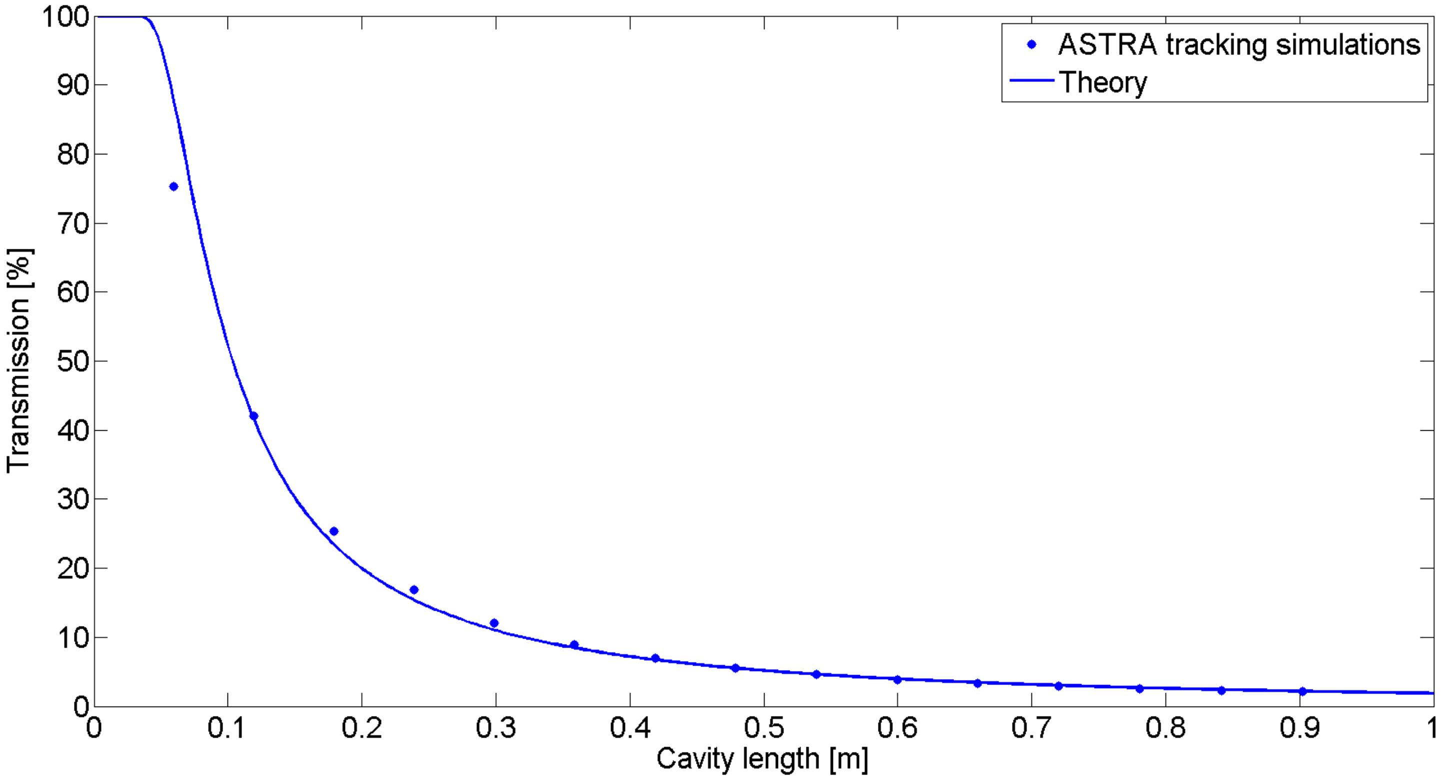
The normalised 1σ emittance of the beam from the cyclotron is:

$$\varepsilon_{n,cyclotron} \sim 5 \text{ mm mrad}$$

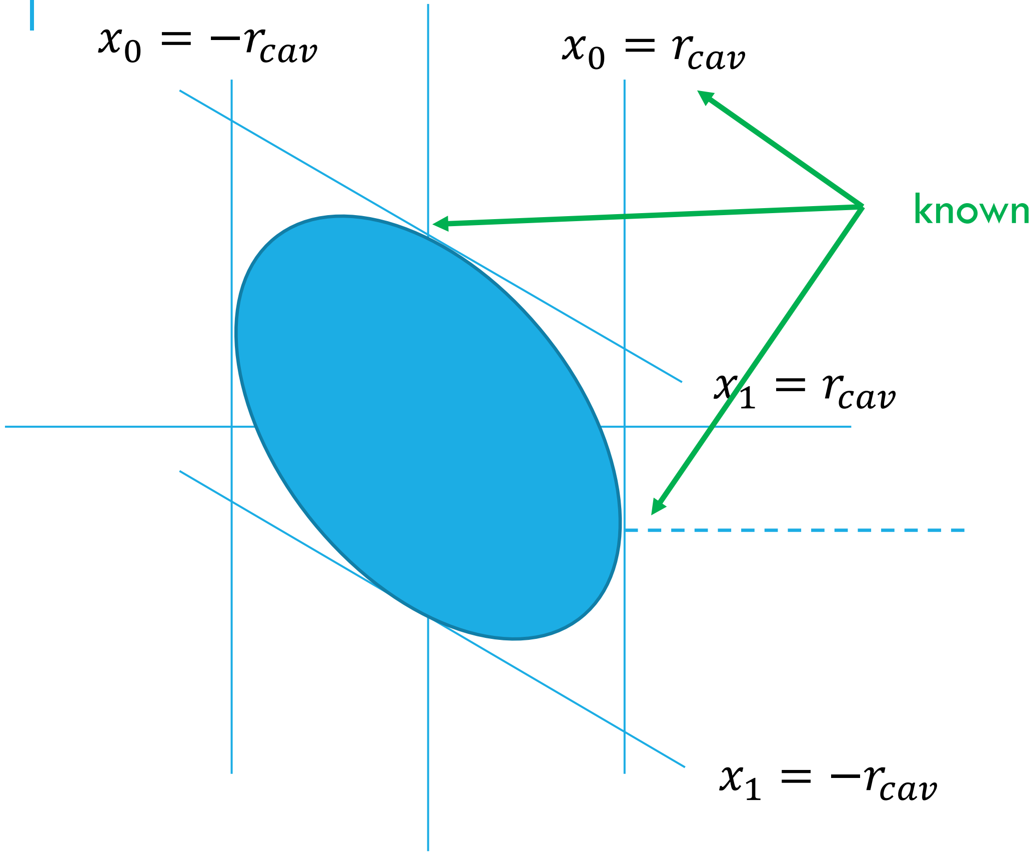
If we assume that the beam is Gaussian, then we can estimate the transverse transmission, T_{trans}, of the cavity:

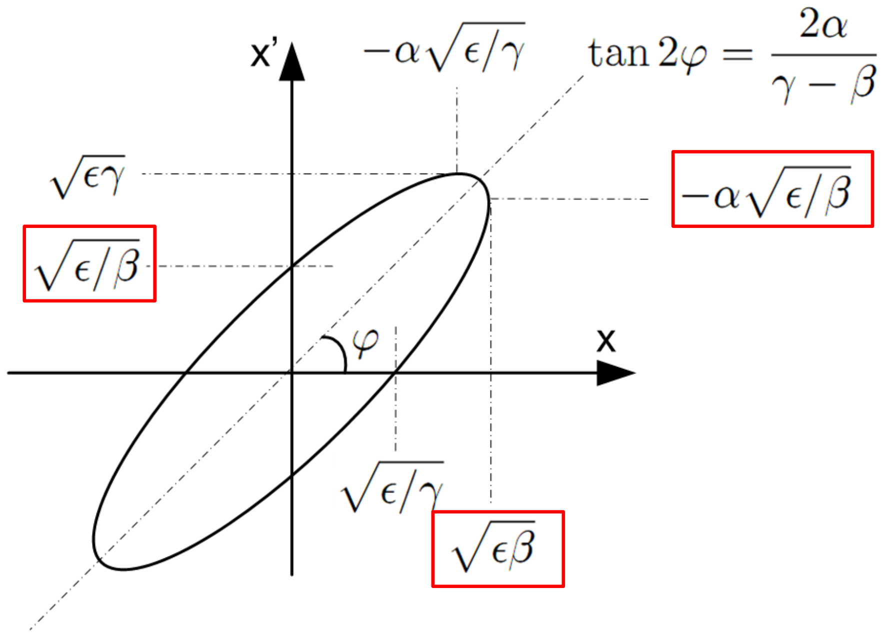
$$T_{trans} = \operatorname{erf}\left(\sqrt{\frac{\varepsilon_{n,x}}{\varepsilon_{n,y}}}\left(\frac{\varepsilon_{n,acceptance}}{\sqrt{2}\pi\varepsilon_{n,x}}\right)^{\frac{3}{2}}\right)$$

CAVITY TRANSMISSION



RECAP





$$x_0 = \pm r_{cav}$$

$$x_1 = \pm r_{cav} = \sqrt{\frac{\beta_{r0}\gamma_{r0}}{\beta_{r1}\gamma_{r1}}}(R_{11}x_0 + R_{12}x'_0)$$

$$\varepsilon_{n,acceptance} = \sqrt{\beta_{r0}\gamma_{r0}}\sqrt{\beta_{r1}\gamma_{r1}}\frac{r_{cav}^2}{R_{12}}$$

OPTIMISED BEAM PARAMETERS

Since we know the locations where the phase space ellipse touches the parallelogram, we can relate those positions to Twiss parameters:

$$\sqrt{\frac{\varepsilon}{\beta}} = \sqrt{\frac{\beta_{r0}\gamma_{r0}}{\beta_{r1}\gamma_{r1}}}\frac{r_{cav}}{R_{12}} \qquad \sqrt{\beta\varepsilon} = r_{cav} \qquad \alpha\sqrt{\frac{\varepsilon}{\beta}} = \frac{R_{11}r_{cav}}{R_{12}}$$

And we obtain the optimal beam parameters at the entrance of the cavity as:

$$\beta_0 = \sqrt{\frac{\beta_{r0}\gamma_{r0}}{\beta_{r1}\gamma_{r1}}}R_{12} \qquad \alpha_0 = \sqrt{\frac{\beta_{r0}\gamma_{r0}}{\beta_{r1}\gamma_{r1}}}R_{11}$$

$$\varepsilon_n = \sqrt{\beta_{r0}\gamma_{r0}}\sqrt{\beta_{r1}\gamma_{r1}}\frac{r_{cav}^2}{R_{12}}$$

And at the end of the cavity as:

$$\beta_1 = \sqrt{\frac{\beta_{r1}\gamma_{r1}}{\beta_{r0}\gamma_{r0}}}R_{12} \qquad \alpha_0 = -\sqrt{\frac{\beta_{r1}\gamma_{r1}}{\beta_{r0}\gamma_{r0}}}R_{11}$$

ASSUMPTIONS

Assumptions & simplifications

- Tracking simulations only performed through single cavity
- Theoretical model treats cavity as a drift length
  - Initial bunch length >> RF wavelength
    - Need to optimise transmission & beam parameters for all phases
- Longitudinal transmission neglected in simulations
  - Expected longitudinal transmission through full linac is 10-20%

⇒ Need to consider longitudinal dynamics through full linac structure

⇒ Need to optimise beam parameters for smaller range of phases

FURTHER STUDIES

- Further optimisation of potential structures
- Investigate parallel coupled travelling wave structure
- Final cavity & coupler design
- Manufacture prototype & test cavity
- Further studies on linac optics design
  - Longitudinal dynamics and transmission
  - Look at RF bunching

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Thanks for listening!

Questions?