MANCHESTER 1824

Lancaster University

The Cockcroft Institute
of Accelerator Science and Technology

The Christie
TOWARDS A FUTURE WITHOUT CANCER

CERN

PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

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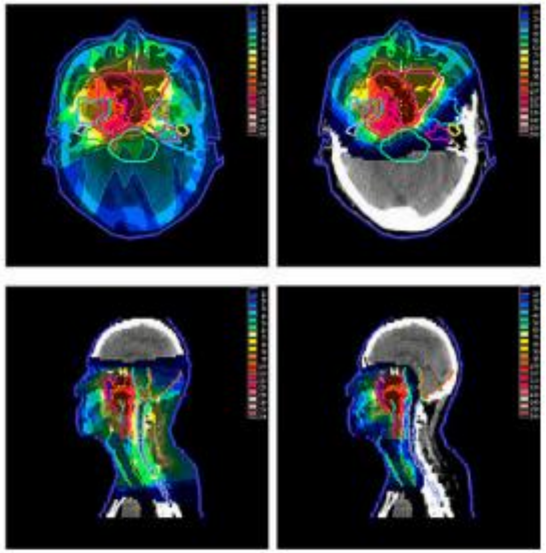
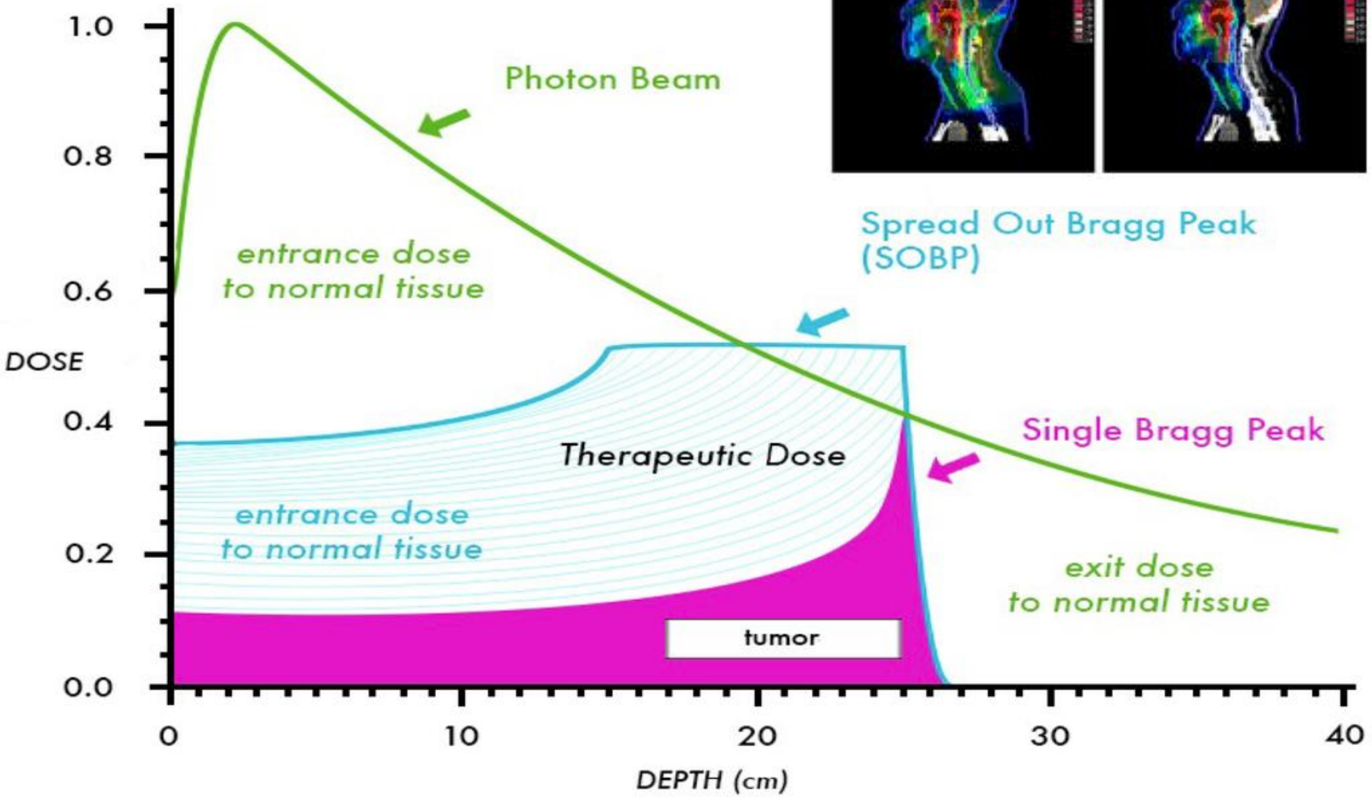
Dr Robert Apsimon

PROTON THERAPY

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



- Maximum energy is deposited within the tumour site with minimal energy deposited in healthy tissue.
- Treatment currently limited by range verification.
- Margin around tumour site is limited in treatment planning to account for uncertainties in dose delivery.

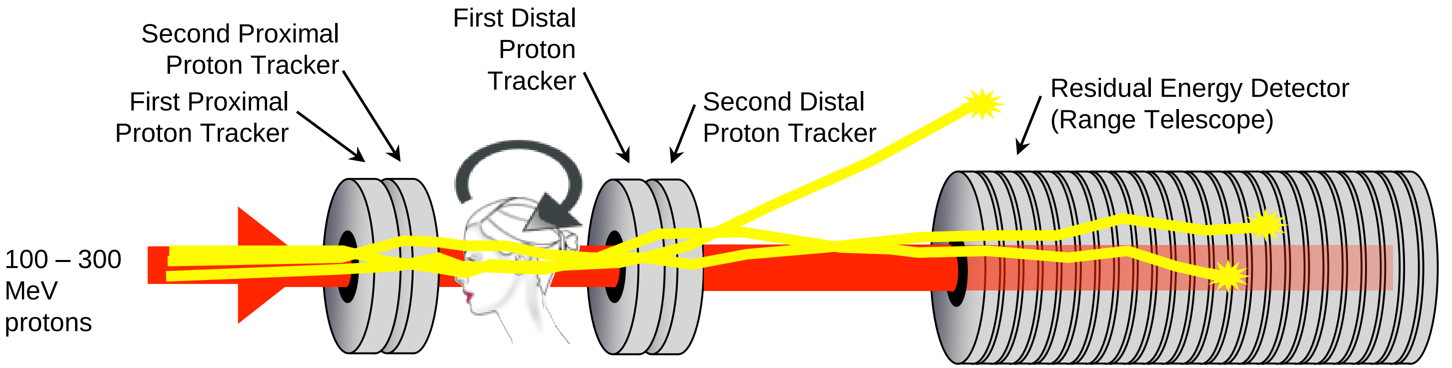


PROTON TOMOGRAPHY

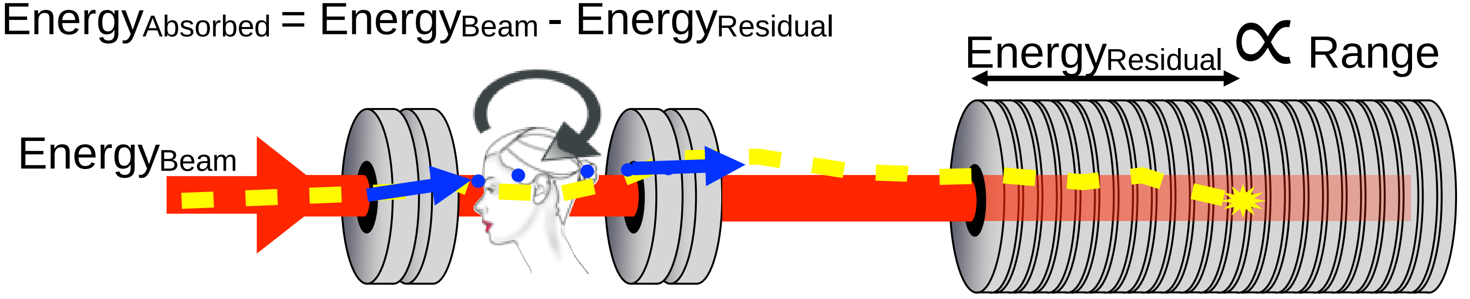
- Several modalities can aid range verification.
- CT currently used for treatment planning – conversion from Hounsfield units produces error.
- Proton imaging measures proton stopping power.
- 250 MeV sufficient to image children and heads.
- Need 350 MeV protons to image through anybody, Bragg peak must not occur inside patient.

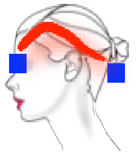
PRaVDA Technology

International Patent: WO 2015/189603



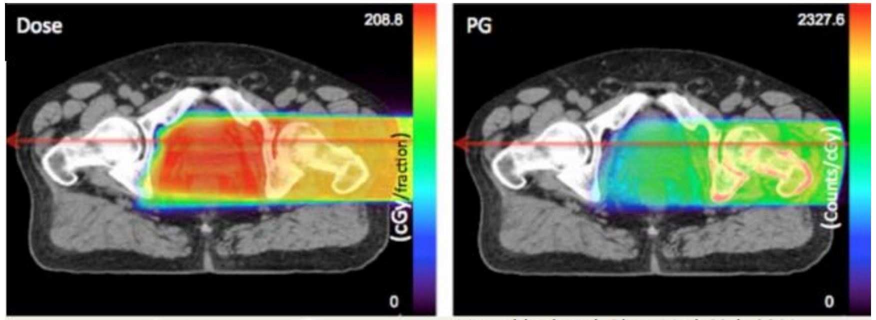
$\text{Energy}_{\text{Absorbed}} = \text{Energy}_{\text{Beam}} - \text{Energy}_{\text{Residual}}$





$\left.\begin{array}{l}\text{Entry position}\\ \text{Exit position}\\ \text{Energy}_{\text{Absorbed}}\end{array}\right\}$ Repeat millions of times!

PROTON STOPPING POWER



Moteabbed et al, *Phys. Med. Biol.*, 2011

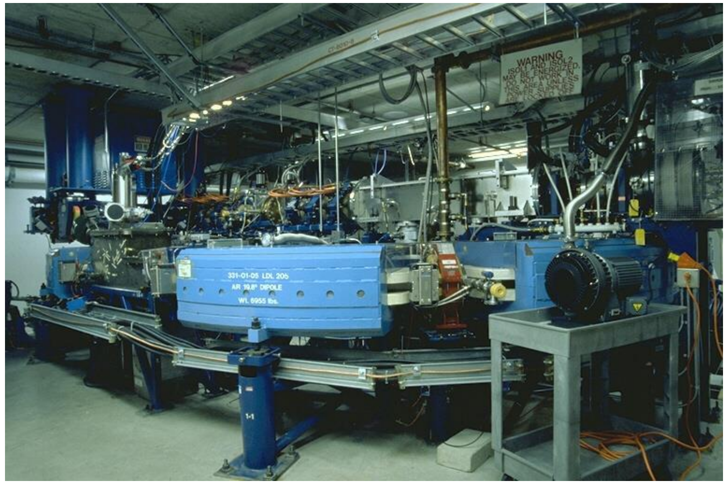
PCT

- Better accuracy than X-Ray imaging and lower dose.
- Imparts a small additional dose to the patient as opposed to prompt gamma which does not add to the therapy dose.
- Independent of treatment – can be used for treatment planning
- Large equipment cost

Prompt Gamma

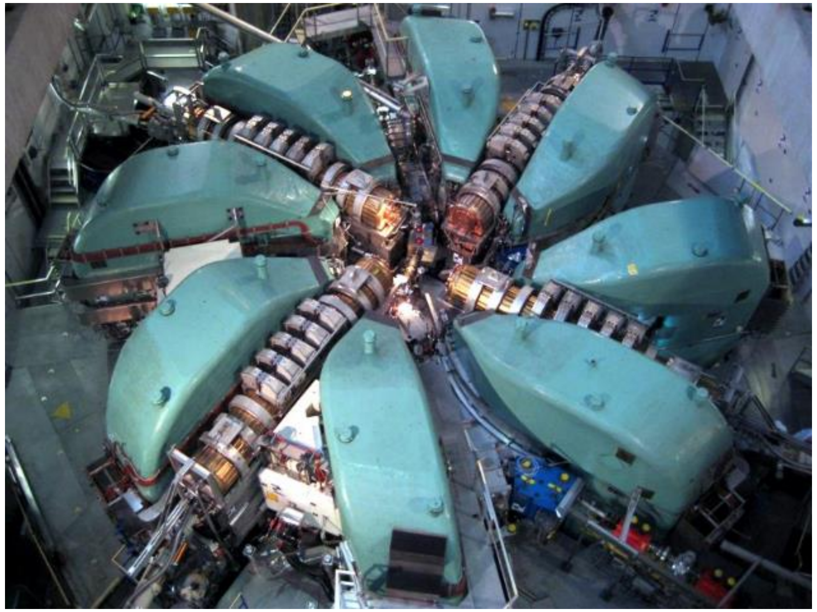
- Prompt Gamma ray emission occurs within nanoseconds of interaction.
- Each element emits characteristic gamma-rays with different energies
- i.e ‘real-time’ signal – patient must receive dose to be imaged.
- Gamma rays only emitted where proton beam interacts in the patient (i.e where dose is deposited)

PRODUCING 350MEV PROTONS



Cyclotrons

- 250 MeV - need degrader
- Small – less complex
- High dose rate possible
- PSI cyclotron 590MeV
- High cost for proton therapy centres



Synchrotrons

- Can produce 350MeV protons no degrader needed
- Large space requirement
- More complex

ASSESSING THE SUITABILITY OF A MEDICAL CYCLOTRON AS AN INJECTOR FOR AN ENERGY UPGRADE

J. A. Clarke, D. M. Dykes, C. W. Horrabin, H. L. Owen, M. W. Poole, S. L. Smith and V. P. Suller
CLRC Daresbury Laboratory, Warrington WA4 4AD, United Kingdom

A. Kacperek and B. Marsland, Douglas Cyclotron Unit, Clatterbridge Centre for Oncology, Wirral L63 4JY, United Kingdom

Abstract

The 60 MeV cyclotron at Clatterbridge operates as a UK centre for proton therapy, concentrating on treatment of eye tumours; the accelerator is a Scanditronix model MC60PF fixed energy isochronous cyclotron with a high current ion source. Although possible energy upgrades have been considered previously, interest has now been reawakened by the activities of the Italian TERA Foundation, which has proposed a compact high frequency booster linac as a potential solution to achieve the 200 MeV needed for a broader therapy programme. The paper reports progress on studies to assess if the Douglas cyclotron is suitable for a test of such a prototype booster linac. The results demonstrate that a cyclotron beam pulse of about 25 microseconds can be achieved by application of amplitude and phase modulation to its RF system. The output emittance and energy spread of the accelerator have also been measured and indicate good compatibility with the acceptance requirements of the proposed linac.

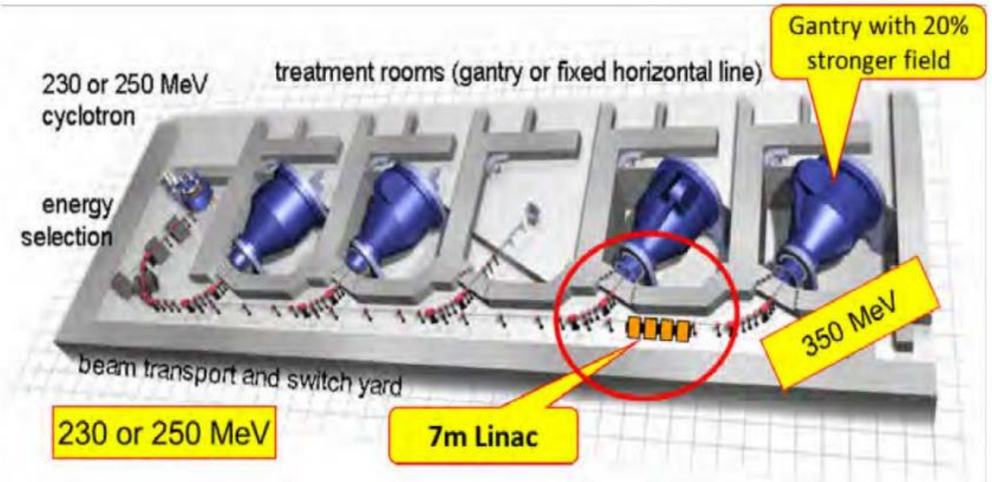
MeV; this challenge has been taken up by the Frascati team in its TOP project [4].

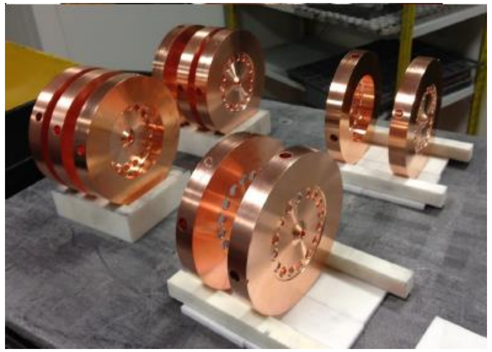
An attractive option is to exploit the same economical technology to boost the energy of existing therapy facilities, especially those in medical centres. Many are intermediate energy cyclotrons and it is necessary to assess whether their extracted proton beams can be successfully matched into the small physical aperture and restricted longitudinal phase space of a high frequency linac structure. In particular the Italian design has an acceptance of about 10π mm-mrad and 0.1 % rms energy spread [5]. Beam intensities for treatment need only be 10-20 nA average current and the linac is assumed to have a typical duty cycle of about 0.1 %, leading to an instantaneous cyclotron current of a few 10's of μA. Especially in a hospital environment it is crucial to minimise beam losses in the transfer between the two accelerators so that it will be important to develop pulsed operation of the cyclotron matching that of the linac (~10μs) as closely as possible.

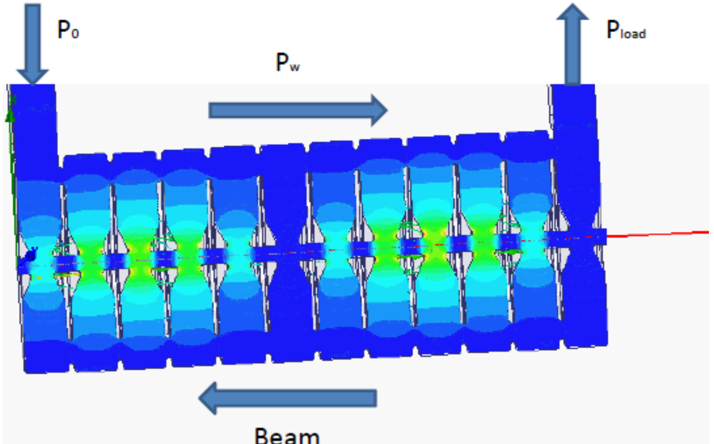
This paper reports initial studies of the suitability of

European Particle Accelerator Conference, 1998

PRODUCING 350MEV PROTONS



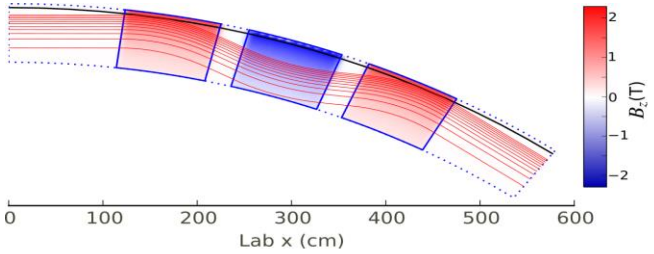




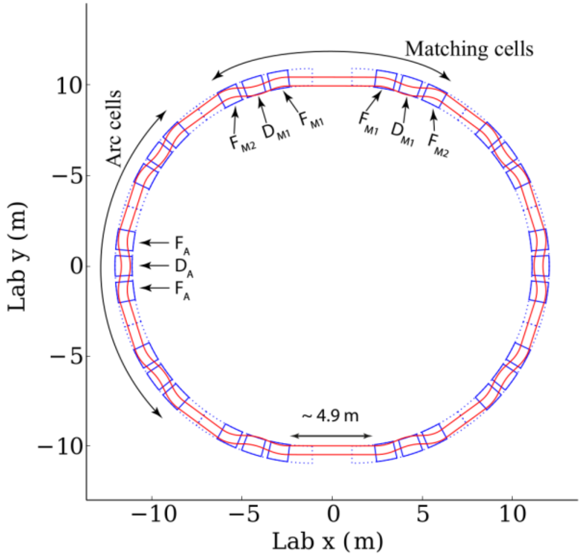
- TERA & PSI designed IMPULSE project.
  - Cyclinac
  - 10MW power source (x4)
  - 25MV/m average gradient
  - 7m Length
- TERA and CERN have developed high gradient linacs for proton therapy.
- TERA bTW achieved 50 MV/m at 3GHz.
  - Need slightly higher gradient.
  - 6.5mm aperture - Need higher transmission

PRODUCING 350MEV PROTONS

NORMA

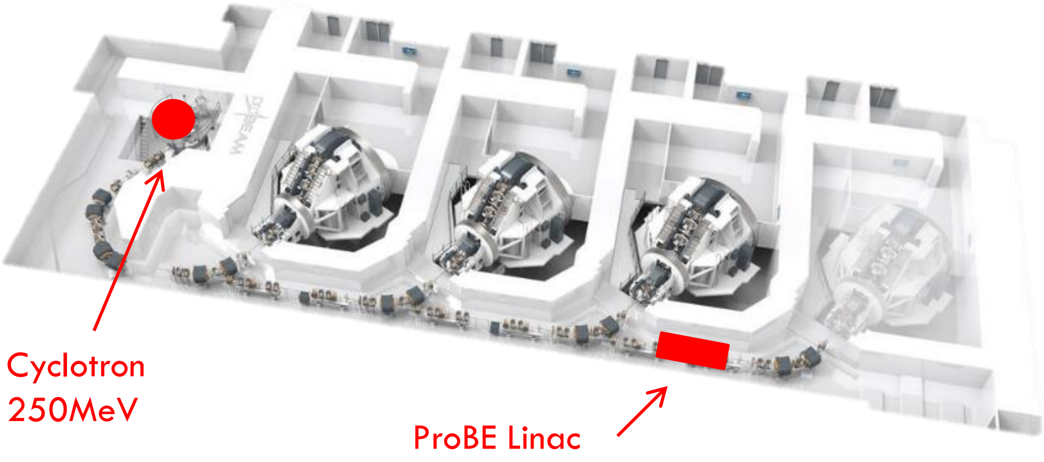


- Normal-Conducting Racetrack Medical FFAG Accelerator
- 350 MeV Protons – no degrader
- Rapid treatment
- Complex
- Large footprint – not suitable for the Christie.
- Not Yet Demonstrated

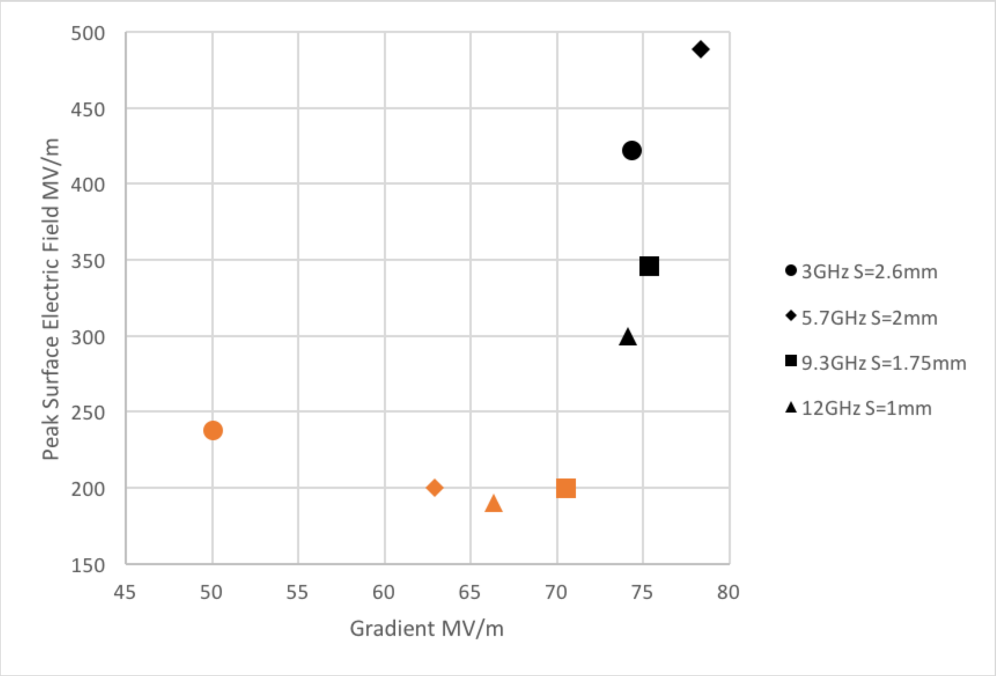


ProBE

- We propose a pulsed linac upgrade.
- 3m of available space in existing proton therapy facility.
- Cyclotron produces 250MeV protons for therapy, then ProBE linac accelerates to 350MeV for imaging.



GRADIENT LIMITED BY PEAK ELECTRIC FIELD



- Gradient limited by scaling constants found experimentally.
- Initially just optimised for Sc but this led to unreasonable electric fields
- Maximum peak surface electric field limited at 200 MV/m.
- Structures re-optimised at this limit.
- Black – Gradient limited by Sc.
- Orange – Gradient limited by Epeak
- 3.5mm Aperture diameter.

- Note this is for a single cell, coupling not included

SMALL-APERTURE HIGH-GRADIENT SCHEME

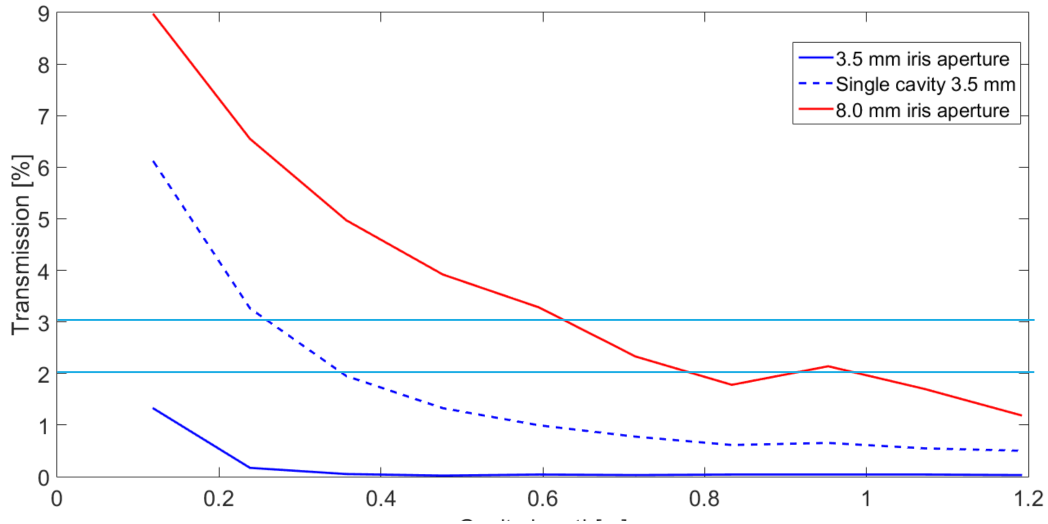
A=1.75mm	X-Band	S-Band
# cells	40	10
Coupling	12%	2%
Septum	1 mm	2.6 mm
Epeak	167 MV/m	555 MV/m
Hpeak	585 kA/m	300 MV/m
Rs/L	72.4 MΩ/m	96.8 MΩ/m
Gradient	50 MV/m	68 MV/m

- 6 x 30cm cavities = 1.8m
- 100MV/1.8m=55MV/m
- Off crest acceleration: 55/cos20=60MV/m
- +5MV/m power overhead =65MV/m required gradient.

- Coupling required between cells significantly degrades x-band shunt impedance and gradient.
- Epeak limit is 200 MV/m. peaking on the nose cone/aperture. There is no advantage to a smaller aperture at s-band, shunt impedance stays almost constant as we increase aperture. So Epeak can be optimised.
- An X-band backwards traveling-wave structure reached 58MV/m in simulation.
- Overall, it makes sense to open the aperture of the S-band structure, thus requiring less focussing magnets between structures, fitting in an extra structure, and lowering the required gradient. This then allows for optimisation lowering the peak fields.

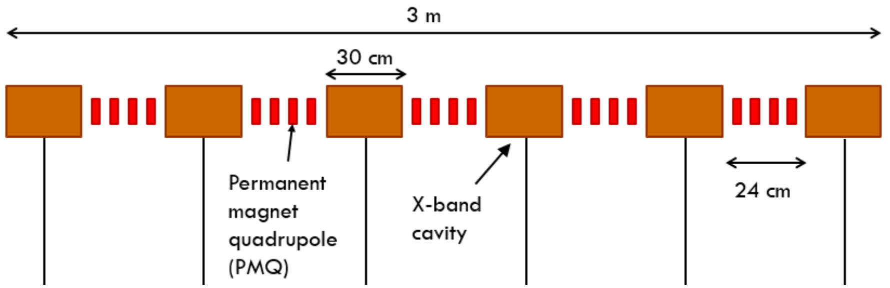
BEAM DYNAMICS

Required transmission ~ 2-3%



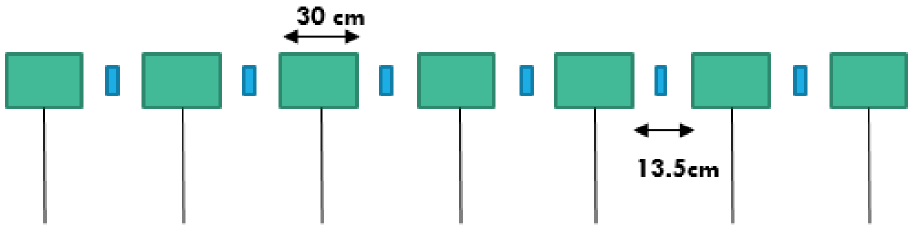
Two focusing schemes investigated:

1) Minimum aperture scheme (MA Scheme)
   a) 24 cm matching sections between cavities
   b) Very strong quadrupoles required
2) FODO lattice (minimum drift scheme)
   a) Simple design, well understood
   b) Cavity aperture 80% larger than MA Scheme



Required quadrupole strengths: ~4000 T/m with 6 mm bore radius

- Would require 17 T magnets.
- Only 1.8 m available for acceleration, required gradient is ~65 MV/m including overhead

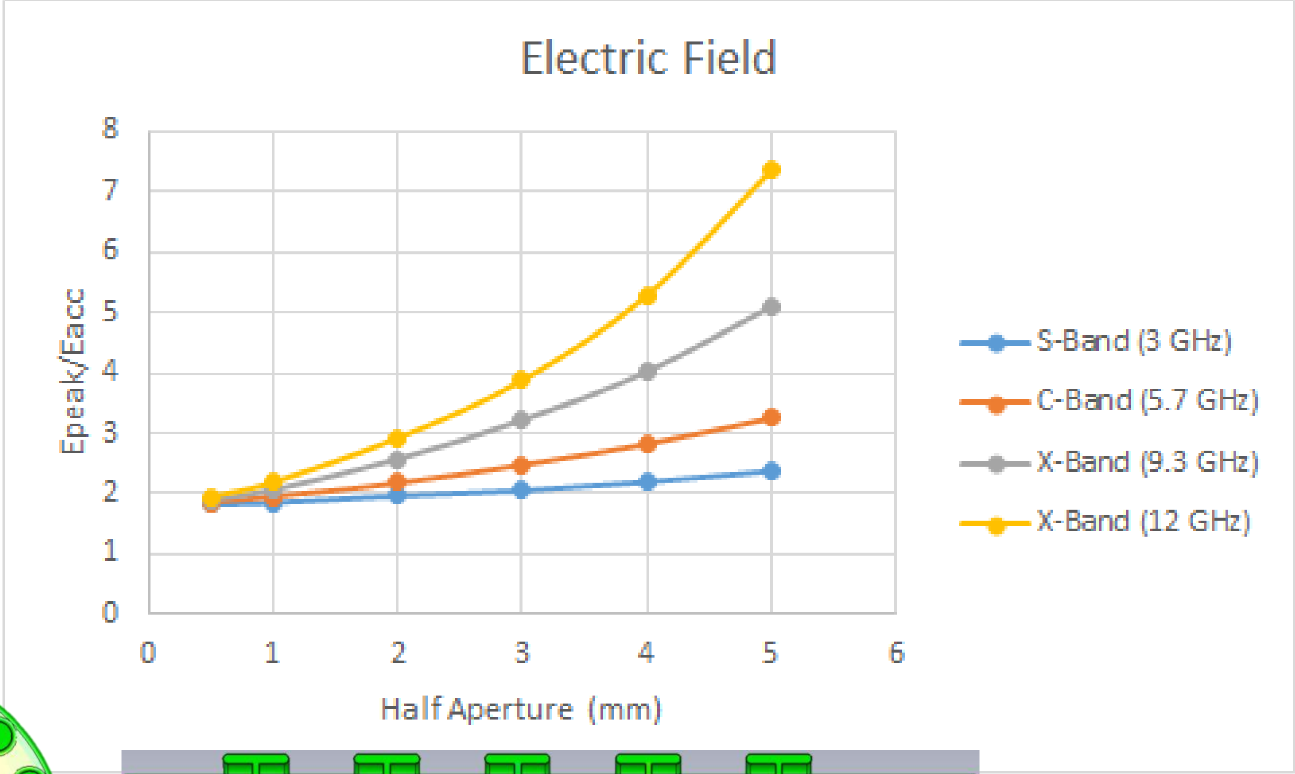


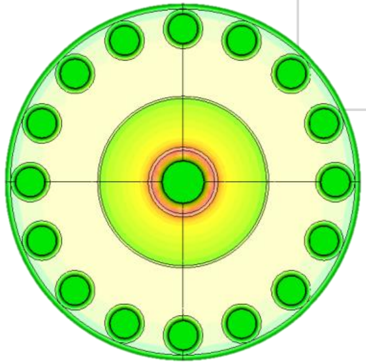
Required quadrupole strengths: 100 – 120 T/m

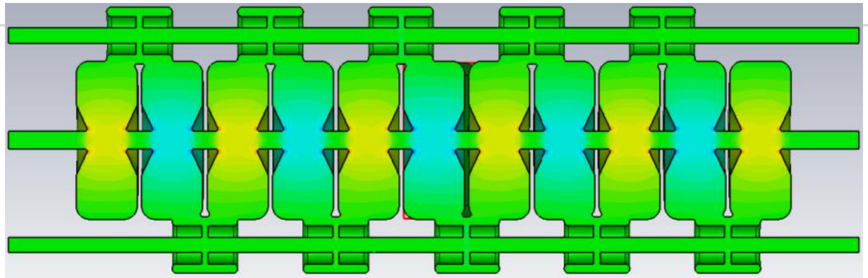
- Achievable with neodymium permanent magnets
- 2.1 m available for acceleration, required gradient is ~55 MV/m with overhead

INCREASING APERTURE SIZE

- If we increase the aperture then the peak fields go up.
- For low beta structures with large apertures peak field is a bigger issue than shunt impedance so this pushes us down to 3 GHz.
- Tried standing wave and travelling wave versions but SW is marginally better due to lower fields on the cell to cell coupling.



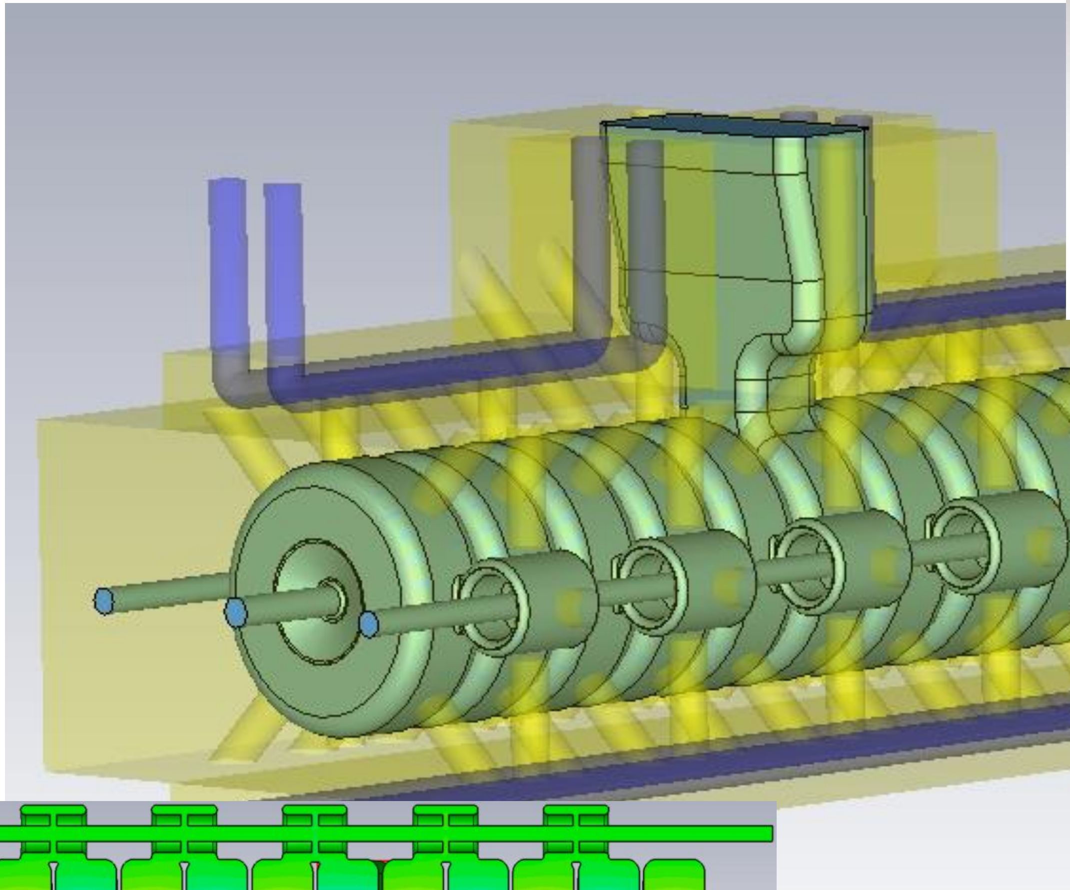


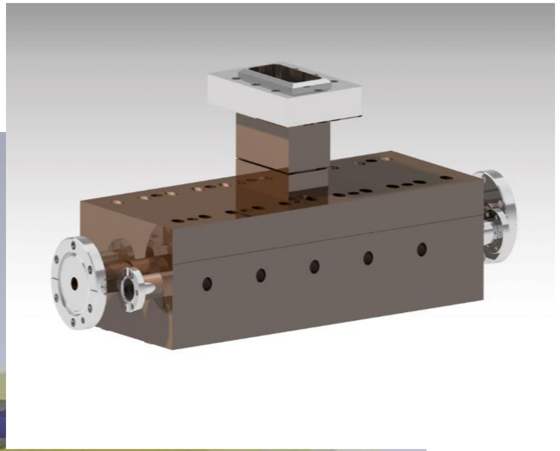


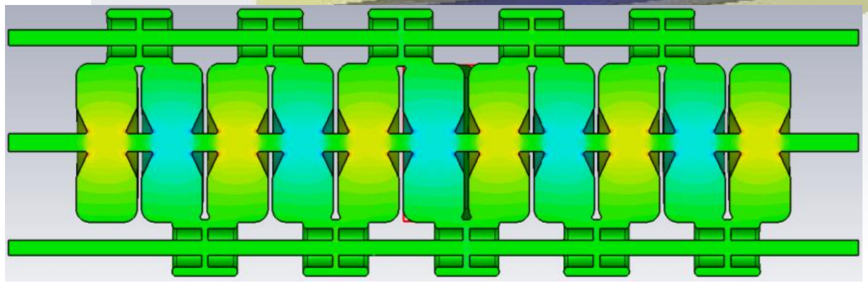
CHOSEN DESIGN – S-BAND (3 GHZ) SC-SWS

- S-band 3GHz
- Side coupled standing wave structure
- 8mm aperture
- Thin 2mm septum
- Limited by cell to cell coupling.

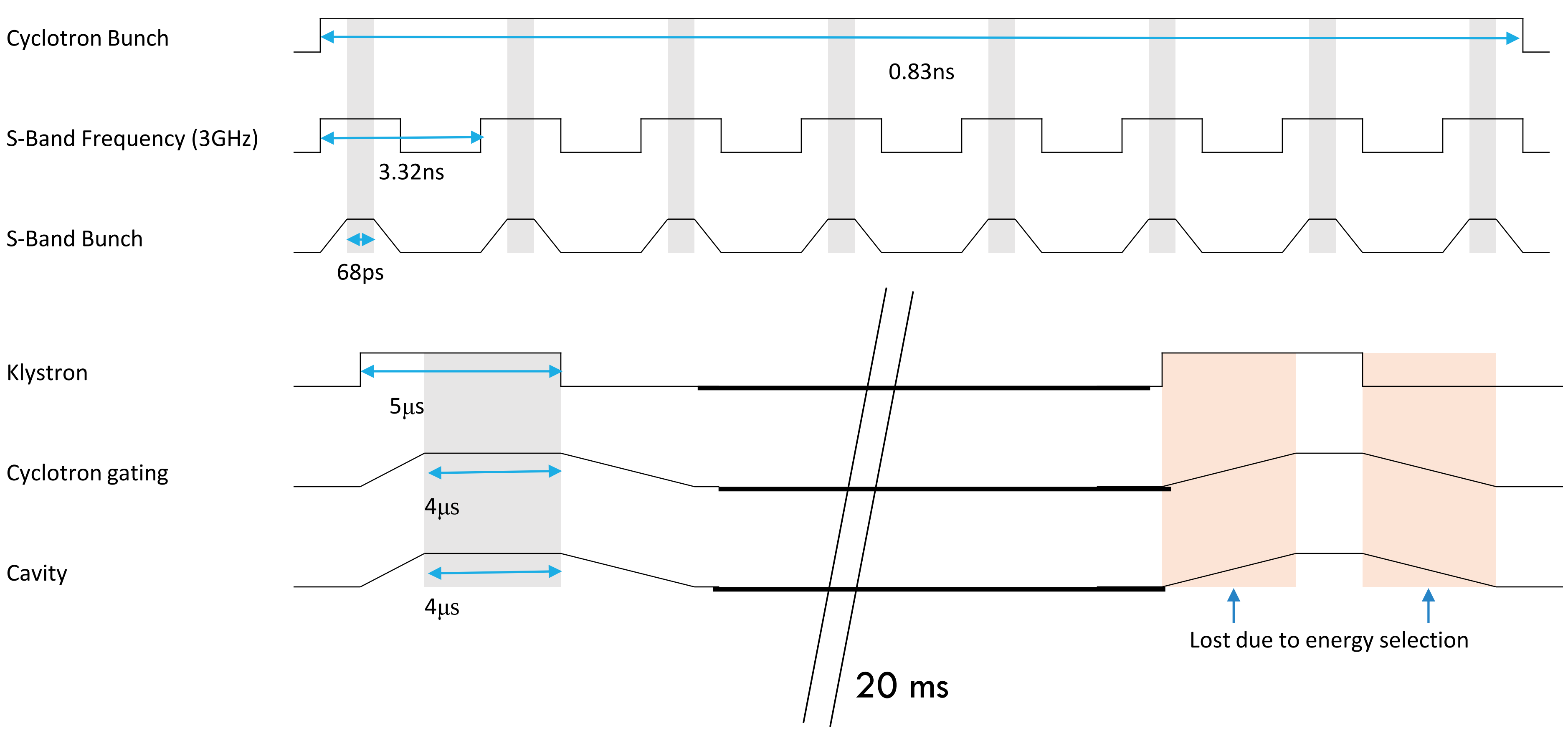
Parameter	Units	S-Band SCSWS
Phase adv.	[deg]	90
Cell Length	[mm]	29.8
Coupling Factor	[%]	2.16
Rs/L	[MΩ/m]	76
$\sqrt{Sc}$/Eacc	[$\sqrt{W}$/MV]	2.4e-2
Eacc	[MV/m]	54
Hpk	[kA/m]	254
Epk	[MV/m]	200







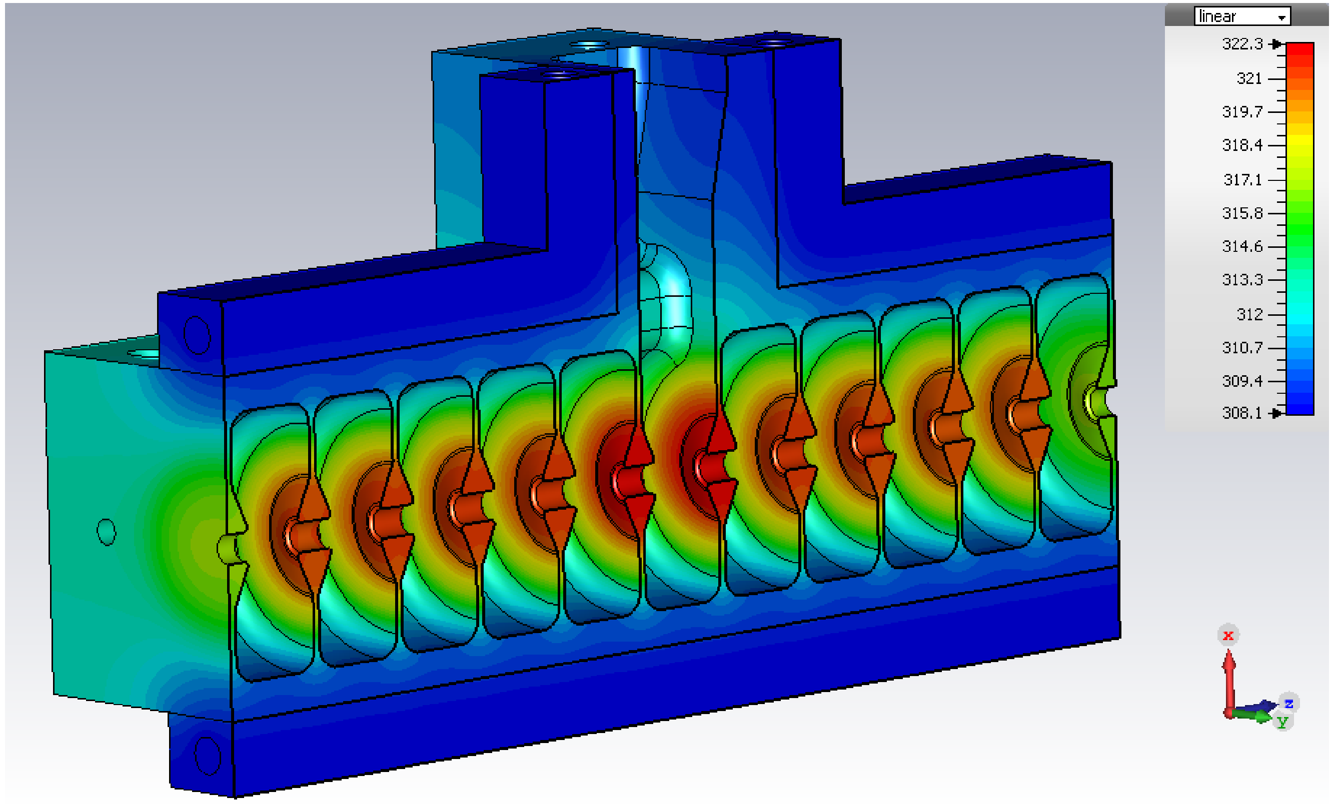
TIMING



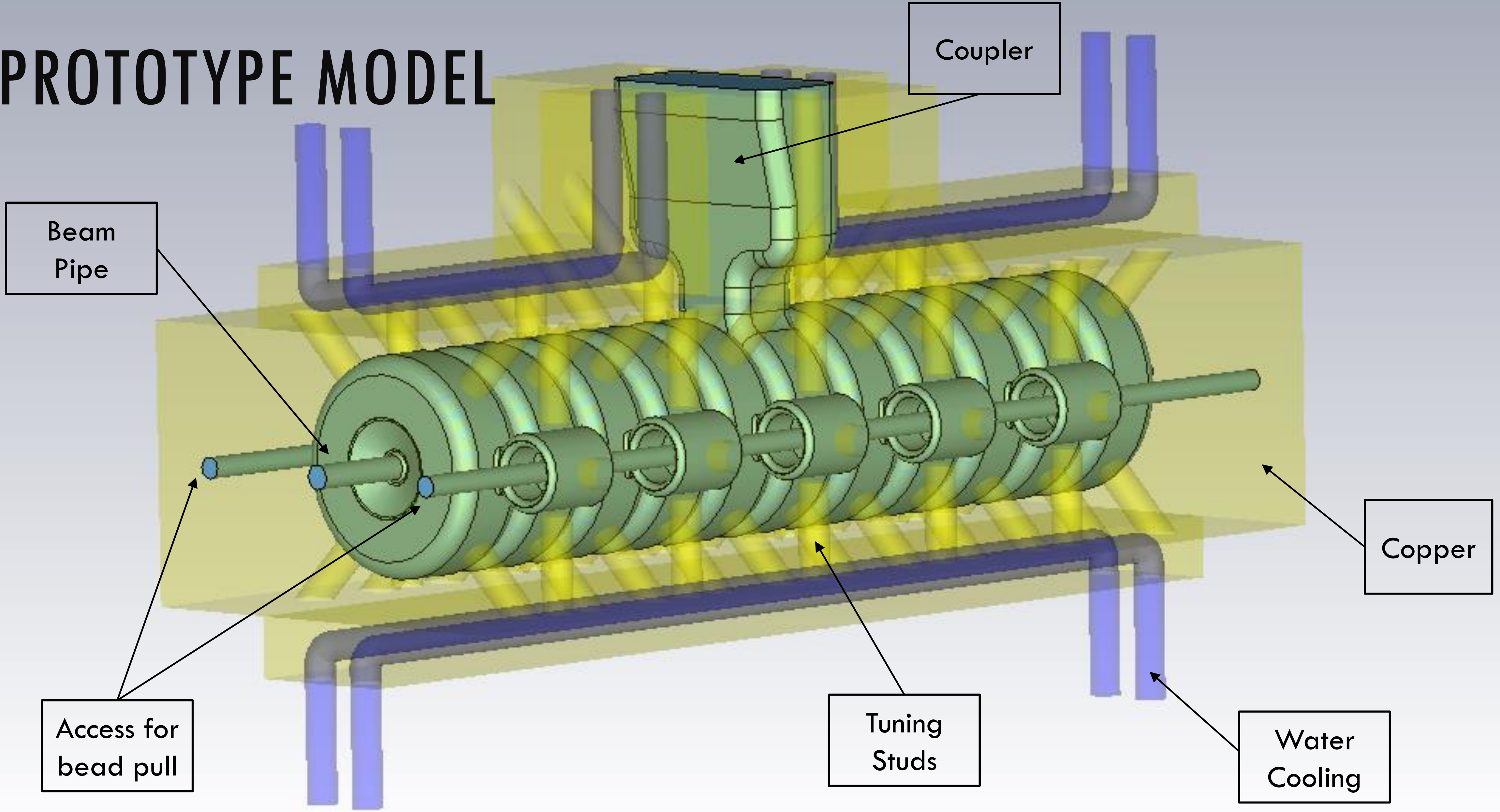
Cyclotron Bunch
0.83ns
S-Band Frequency (3GHz)
3.32ns
S-Band Bunch
68ps
Klystron
5μs
Cyclotron gating
4μs
Cavity
4μs
Lost due to energy selection
20 ms

POWER

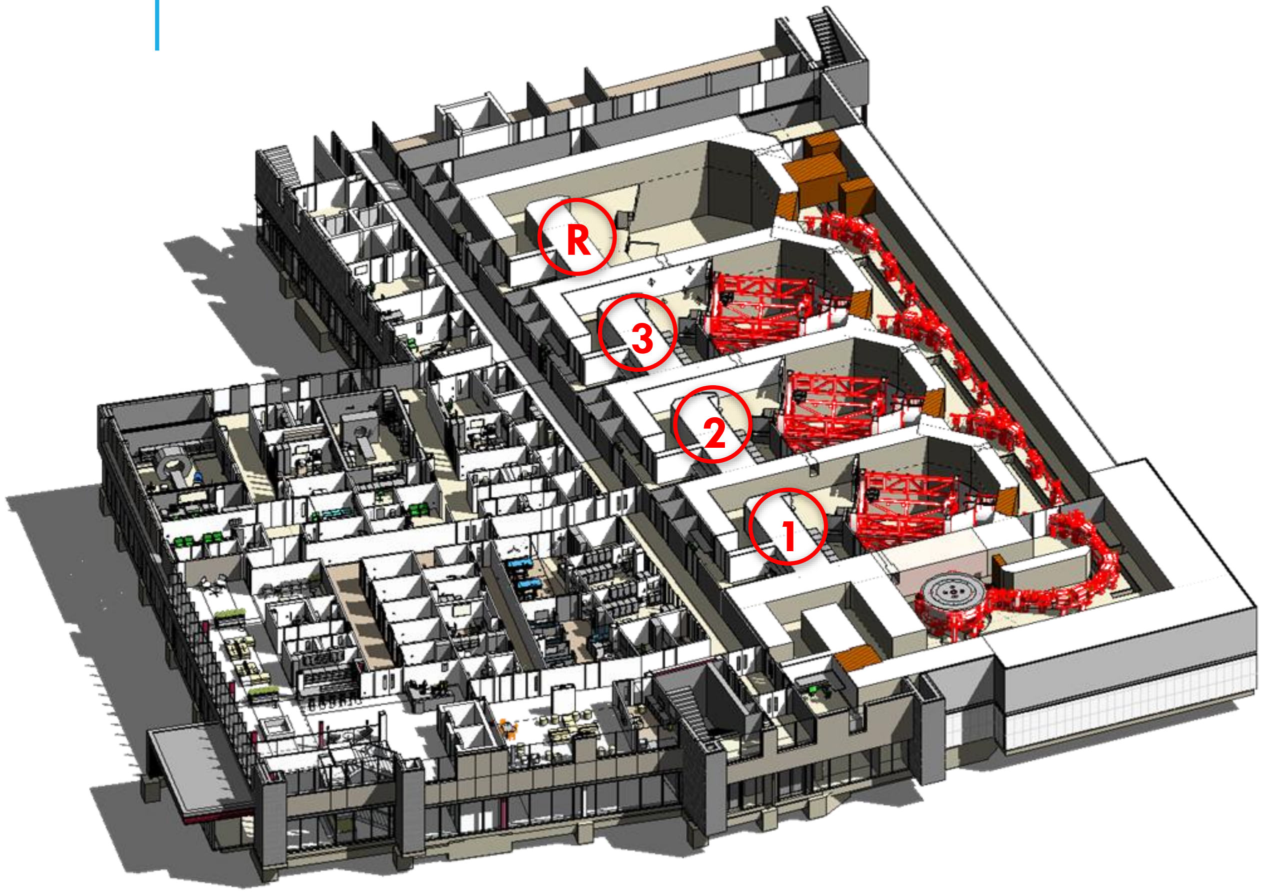
- Average power limited to around 2kW by heat transfer through thin iris.
- Temperature gradient across the structure causes operational detuning.
- Structure must stay within bandwidth of klystron (1MHz).
- 14K between cooling and iris.
- 14MW at 4.5µs long pulse.
- Rep rate 34Hz = 2kW Average power.
- Imaging current = 2.5pA.
- <2pA sufficient for imaging in 1 minute.



PROTOTYPE MODEL



PROBE



Stage 1

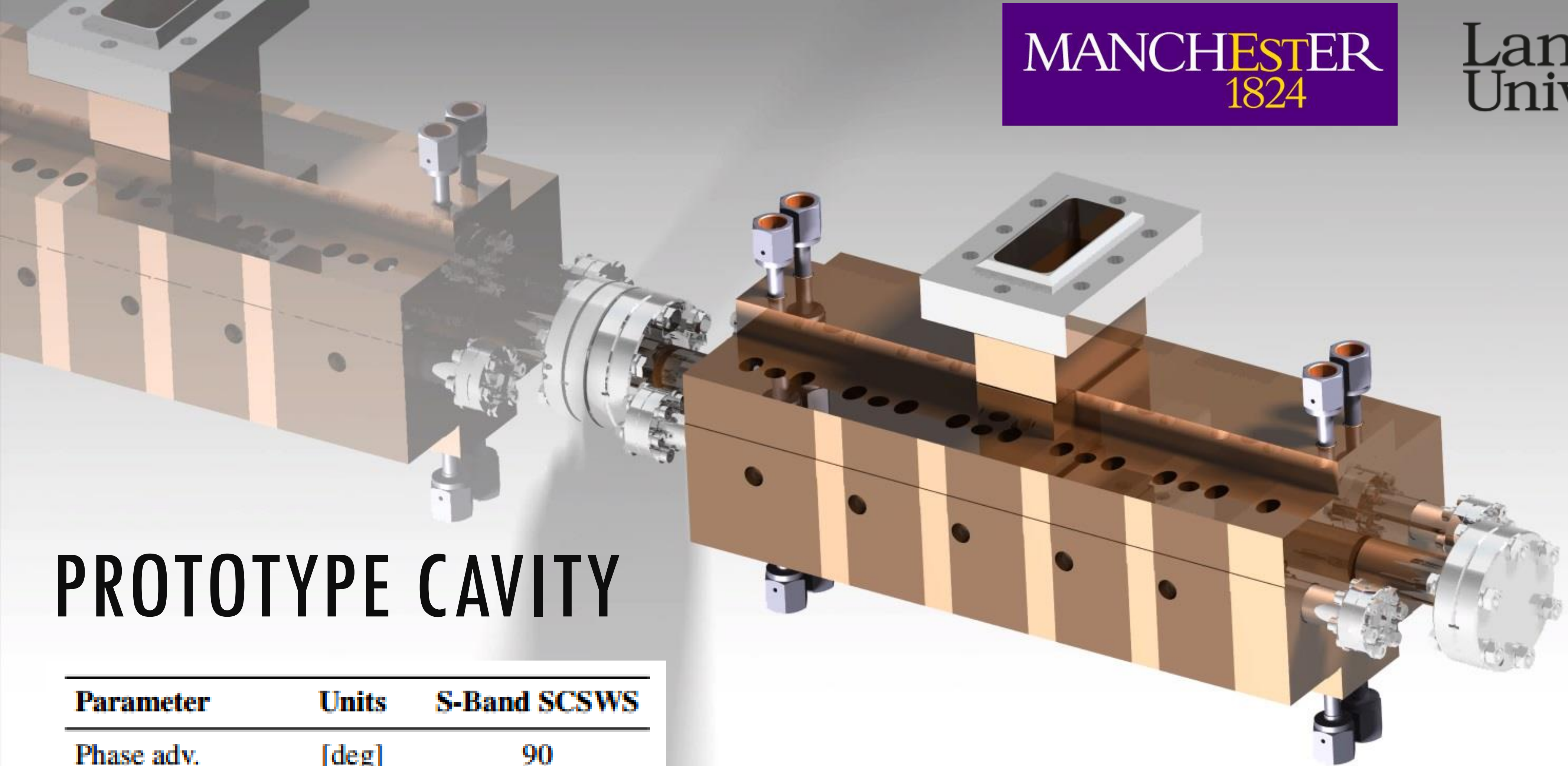
- Develop prototype linac
- S-Box
- High gradient test at CERN

Stage 2

- Research Beamline
- 4th room at Christie

Stage 3

- Linac moved back into beamline
- Superconducting Gantry



PROTOTYPE CAVITY

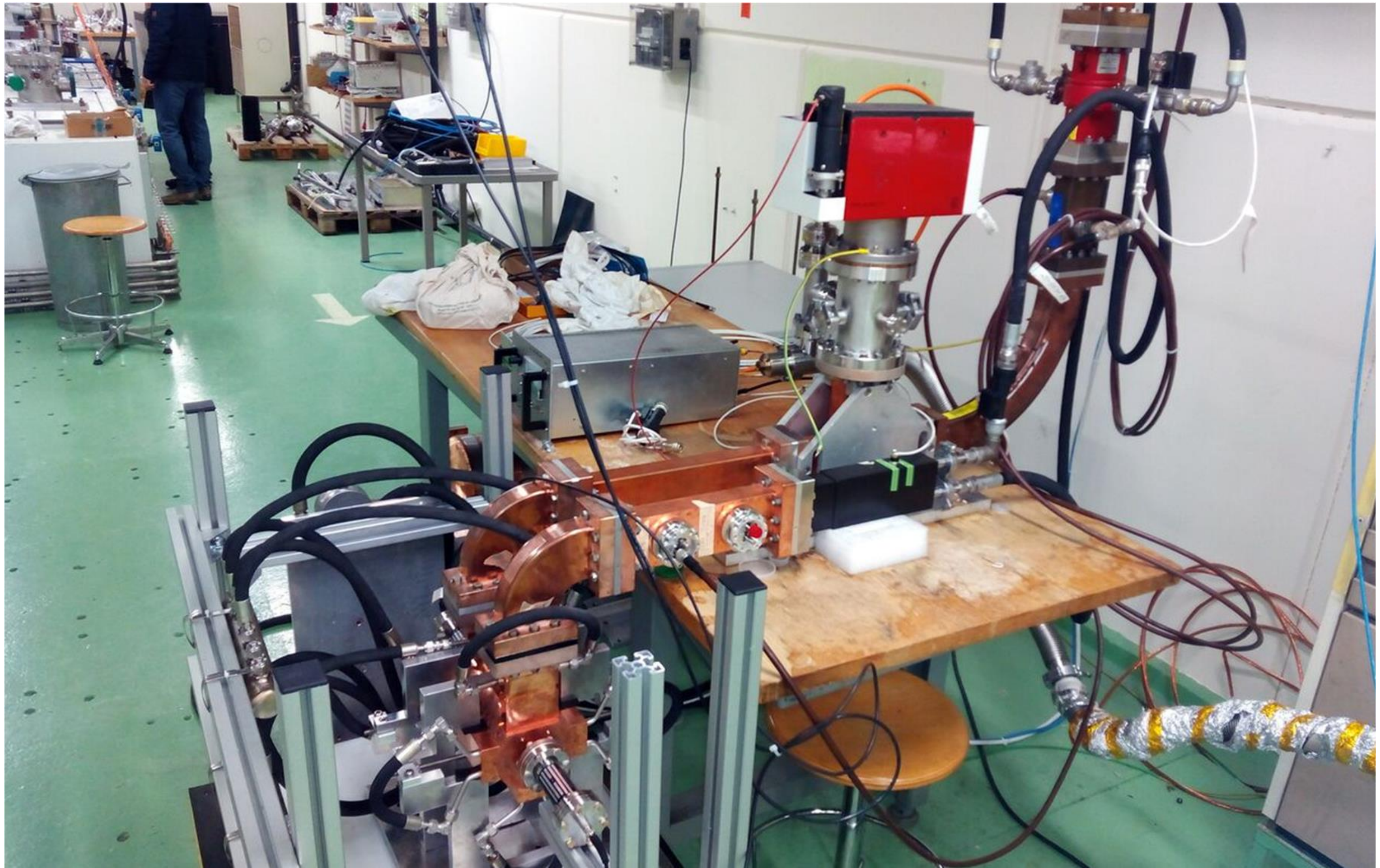
Parameter	Units	S-Band SCSWS
Phase adv.	[deg]	90
Cell Length	[mm]	29.8
Coupling Factor	[%]	2.16
Rs/L	[MΩ/m]	76
$\sqrt{Sc}$/Eacc	[$\sqrt{W}$/MV]	2.4e-2
Eacc	[MV/m]	54
Hpk	[kA/m]	254
Epk	[MV/m]	200

Disks expected in June order placed with VDL.

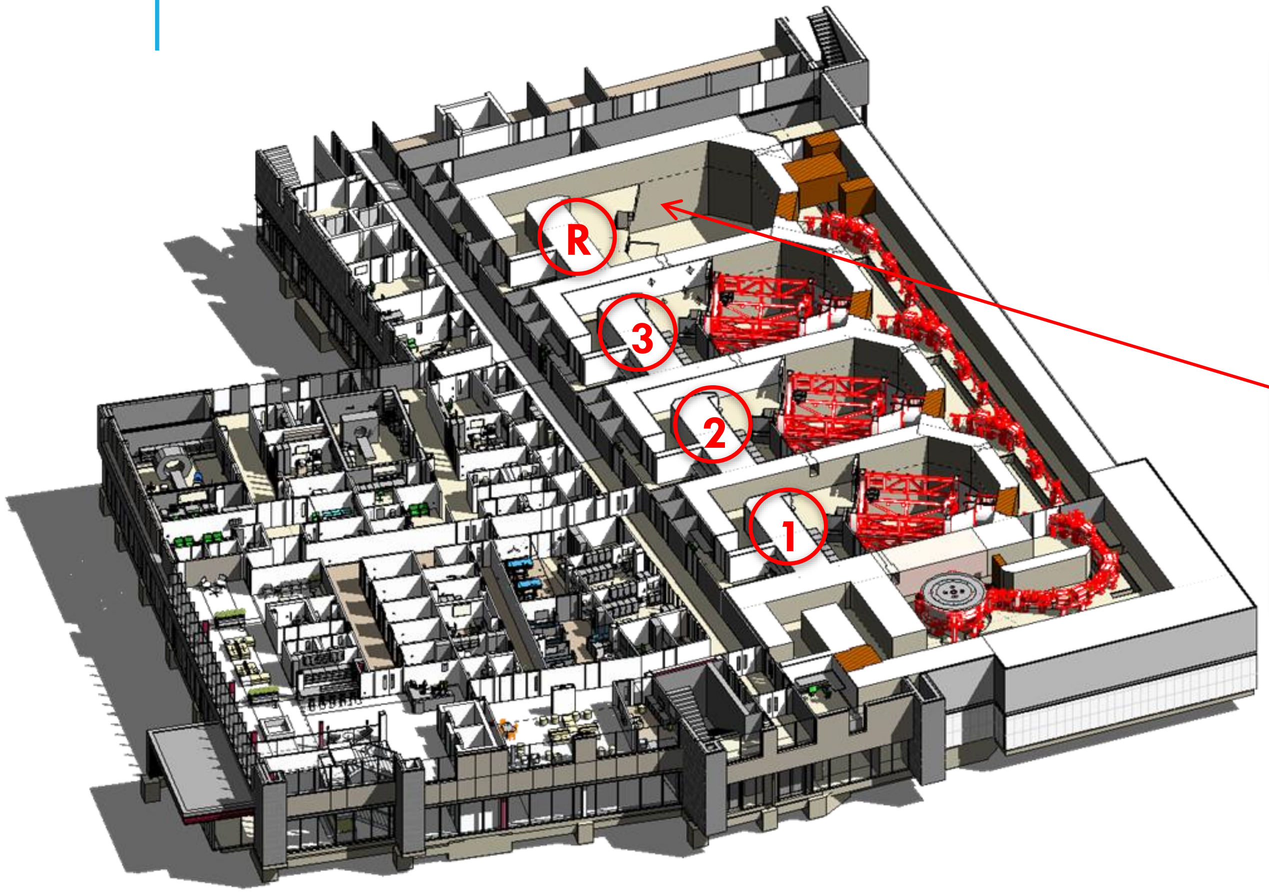
RF measurements and tuning before bonding in late summer.

TESTING

- Experimentally verify gradient of prototype cavity
- S-Box 3GHz testing facility at CERN
- Currently testing KT structure.



PROBE



Stage 1

- Develop prototype linac
- S-Box
- High gradient test at CERN

Stage 2

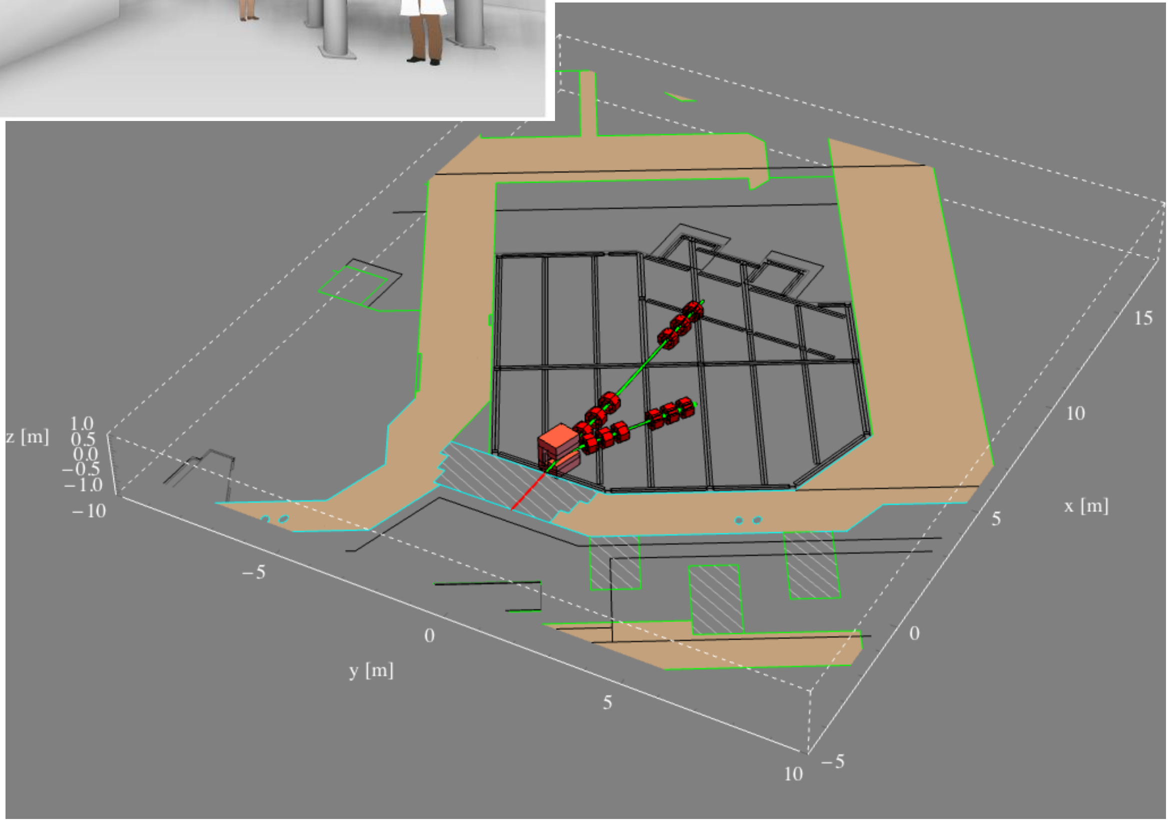
- Research Beamline
- 4^{th} room at Christie

Stage 3

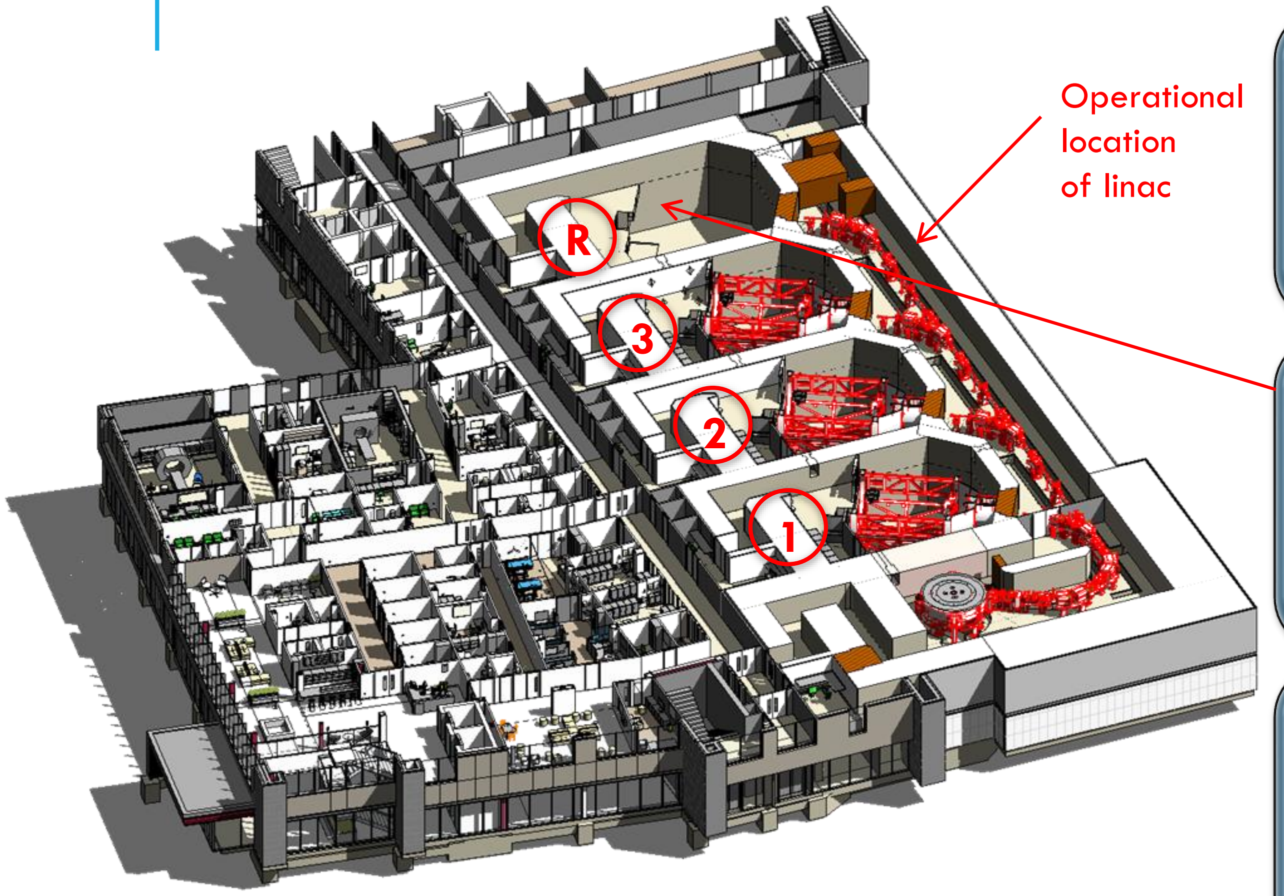
- Linac moved back into beamline
- Superconducting Gantry

RESEARCH BEAM LINE

- £4.5M funding from The Christie Charity
  - only funds room & magnets so far.
- Other charitable and research funding being sought.
- Test linac with a relevant energy beam.
- 2 cavities and spectrometer to measure the energy spectrum of the beam after acceleration.
- May need to borrow a klystron and modulator.



PROBE

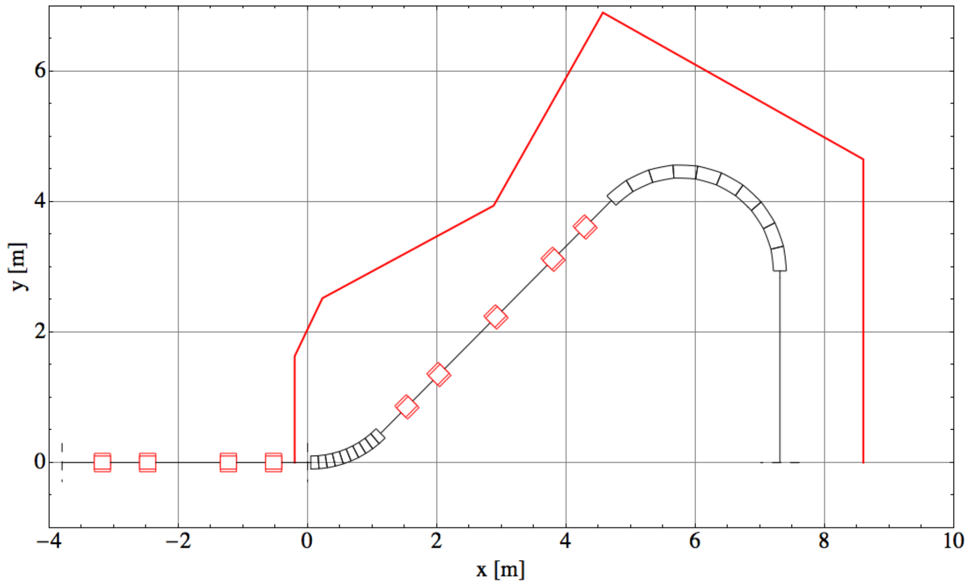


Stage 1
- Develop prototype linac
- S-Box
- High gradient test at CERN

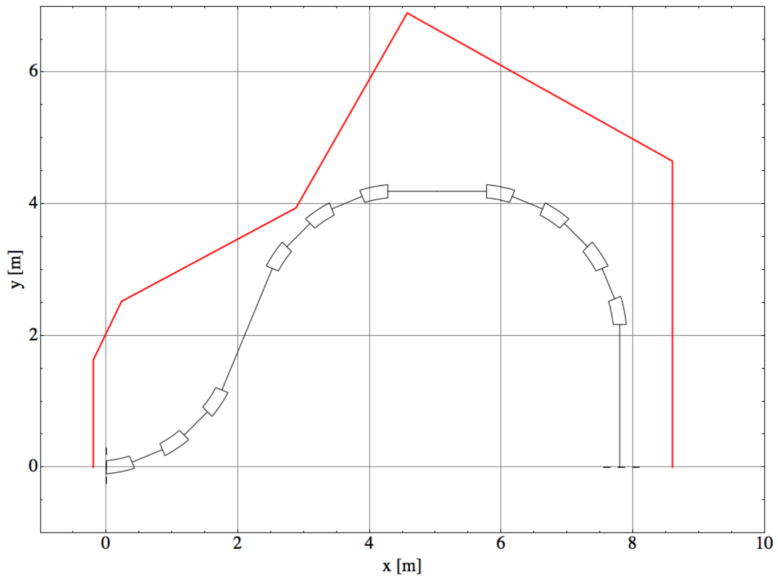
Stage 2
- Research Beamline
- 4th room at Christie

Stage 3
- Linac moved back into beamline
- Superconducting Gantry

GANTRIES AND ENERGY SELECTION



Normal conducting (c. 1.8 T)



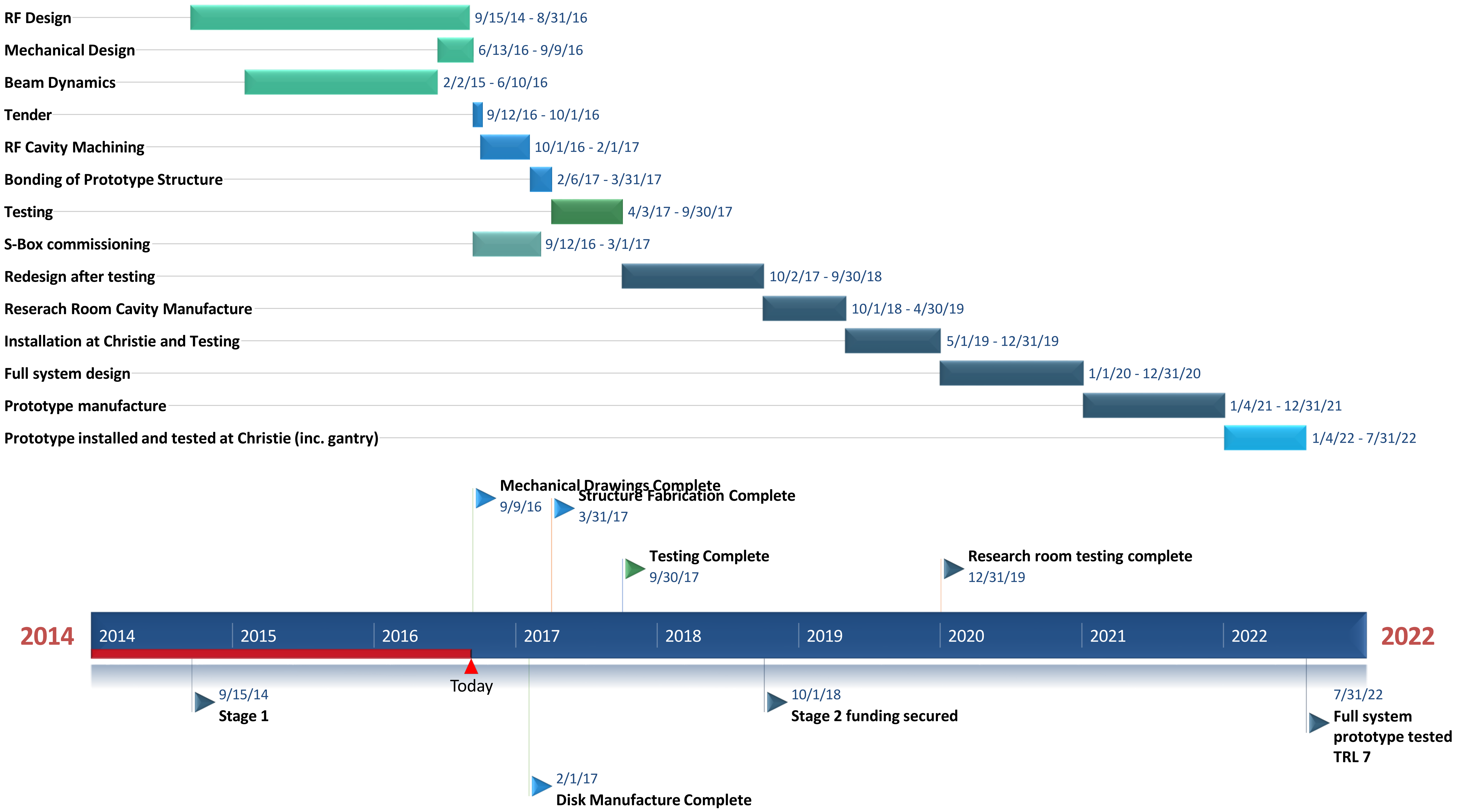
Superconducting (c. 2.8 T)

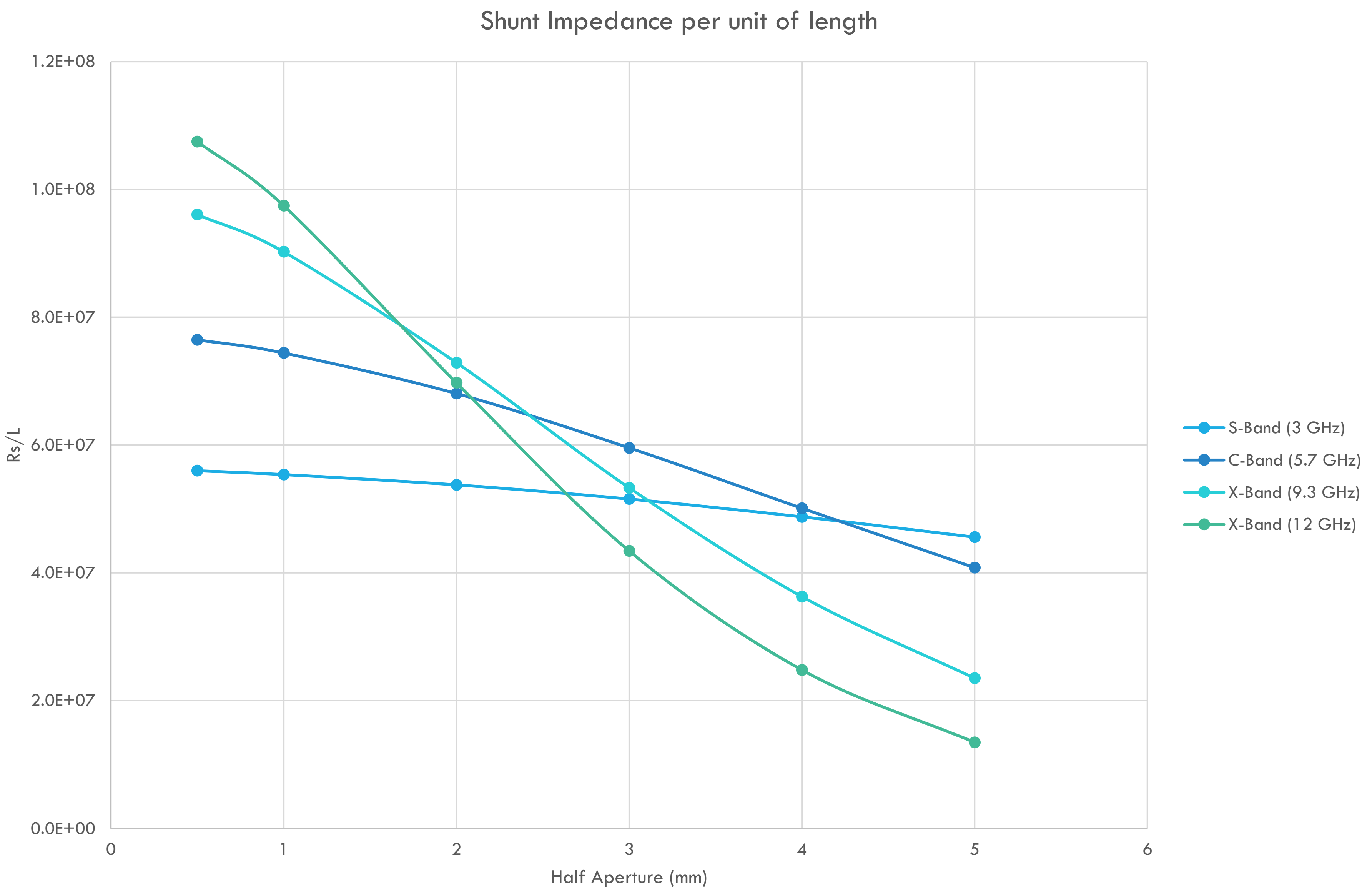
‘A compact superconducting 330 MeV proton gantry for radiotherapy and computed tomography’
In Proc. International Particle Accelerator Conference IPAC14, 2014.

- 350 MeV beam rigidity is larger – superconducting magnets.
- Booster can either go in the Beam Transport System or mount onto gantry.
- Energy selection incorporated into optics – neutrons from collimation do not reach patient.
- Gantry optics underway

Thanks for listening!

Questions?


RF Design
9/15/14 - 8/31/16
Mechanical Design
6/13/16 - 9/9/16
Beam Dynamics
2/2/15 - 6/10/16
Tender
9/12/16 - 10/1/16
RF Cavity Machining
10/1/16 - 2/1/17
Bonding of Prototype Structure
2/6/17 - 3/31/17
Testing
4/3/17 - 9/30/17
S-Box commissioning
9/12/16 - 3/1/17
Redesign after testing
10/2/17 - 9/30/18
Reserach Room Cavity Manufacture
10/1/18 - 4/30/19
Installation at Christie and Testing
5/1/19 - 12/31/19
Full system design
1/1/20 - 12/31/20
Prototype manufacture
1/4/21 - 12/31/21
Prototype installed and tested at Christie (inc. gantry)
1/4/22 - 7/31/22
Mechanical Drawings Complete
9/9/16
Structure Fabrication Complete
3/31/17
Testing Complete
9/30/17
Research room testing complete
12/31/19
2014
2014
2015
2016
2017
2018
2019
2020
2021
2022
2022
Today
9/15/14
Stage 1
10/1/18
Stage 2 funding secured
7/31/22
Full system prototype tested TRL 7
2/1/17
Disk Manufacture Complete

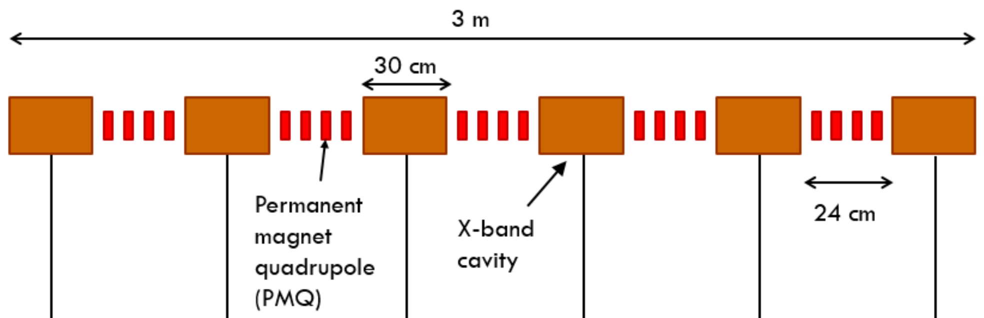

Shunt Impedance per unit of length
Rs/L
1.2E+08
1.0E+08
8.0E+07
6.0E+07
4.0E+07
2.0E+07
0.0E+00
0
1
2
3
4
5
6
Half Aperture (mm)
S-Band (3 GHz)
C-Band (5.7 GHz)
X-Band (9.3 GHz)
X-Band (12 GHz)

PROBE

Small Aperture – Ultra-high Gradient Scheme 65MV/m

- 6 x 30cm cavities = 1.8m
- 100MV/1.8m=55MV/m
- Off crest acceleration: 55/cos20=60MV/m
- +5MV/m power overheap =65MV/m

- X-Band 1.75mm Aperture (High shunt impedance)
- Standing wave ~ 50MV/m
- Travelling wave ~ 58MV/m
- S-band SW ~ 68MV/m (could increase aperture)
- Coupling necessary for X-band kills small aperture advantage.



Large Aperture – High Gradient Scheme 55MV/m

- Larger aperture requires less focussing magnets between structures.
- Smaller matching section means we can fit 7 structures in 3 metres instead of 6.
- Lower gradients can achieve the same overall acceleration.
- 7x 0.3m cavities =2.1m acceleration
- 100MV/2.1=47MV/m
- Off crest acceleration: 47/cos(20)=50MV/m
- + 5MV power overheap =55MV/m