Gantries and Beam Delivery for 350 MeV p+

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&

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EUCARD2 Workshop on SC Gantries, 19th Sept 2015

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Radiotherapy Statistics for UK

- ‘Radiotherapy Services in England 2012’, DoH
  - 130,000 treatments, most common age around 60 yrs
  - 2.5 million attendances
  - More than half of attendances are breast/prostate
- X-rays
  - 265 linacs in clinical use
  - Almost all machines IMRT-enabled, 50% IGRT (Image-Guided)
  - Each machine does >7000 ‘attendances’
  - 147 more linacs required due to increasing demand
- Protons
  - 1x Scanditronix 62 MeV, Clatterbridge, operating
  - 2x Varian ProBeam (3 rooms each), NHS, Christie Hospital and UCLH, 2018
  - 1x ProNova SC360 (2/3 rooms), University of Oxford, 2018
  - 3x IBA ProteusONE, Newport (Wales), Newcastle + ?, 2017
  - 1x AVO LIGHT, London Harley Street, 2017
- Cancer care
  - 40% curative treatments utilise radiotherapy
  - 16% cured by radiotherapy alone

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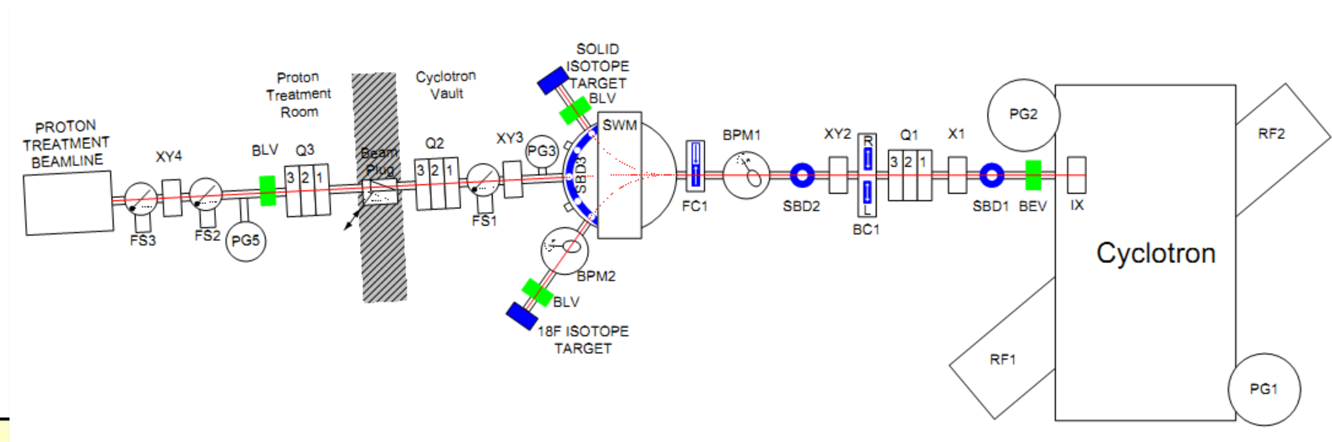
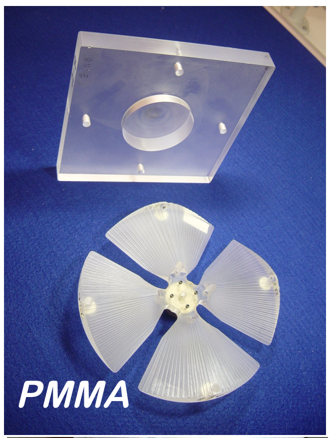
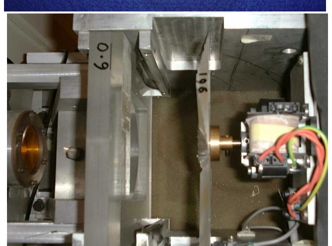
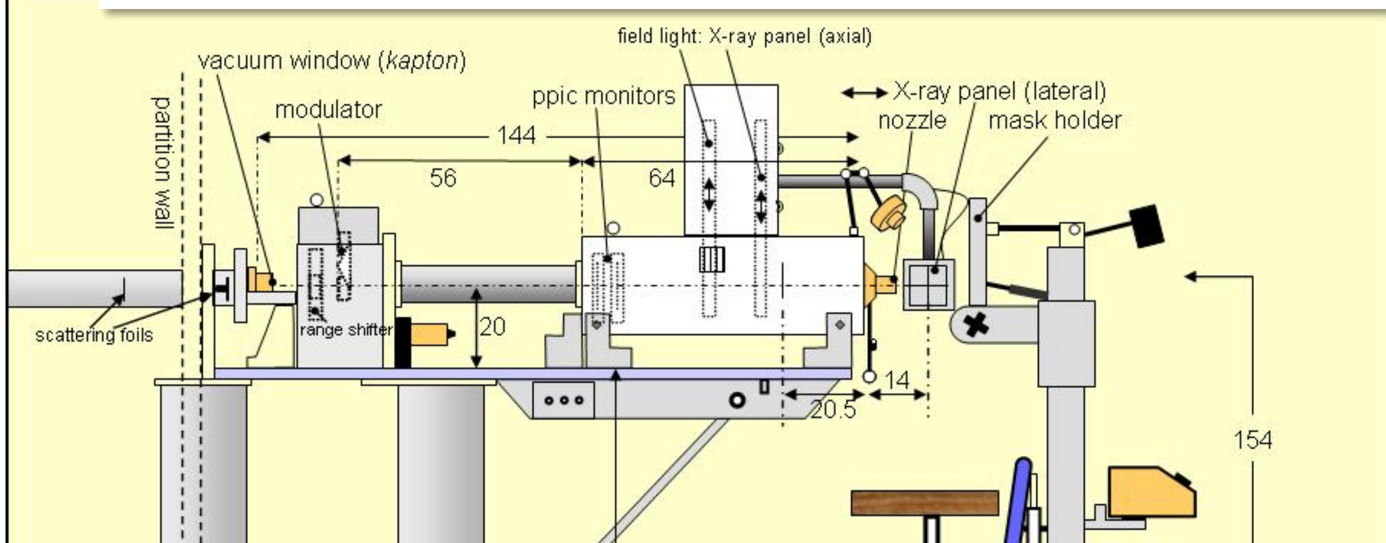
Clatterbridge

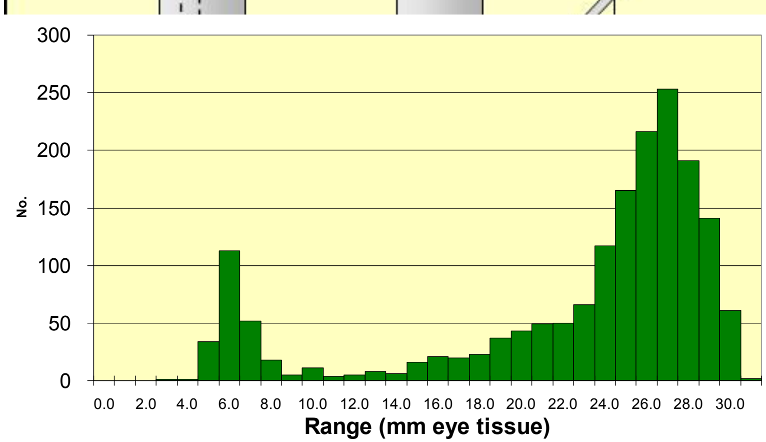
62 MeV Scanditronix Cyclotron









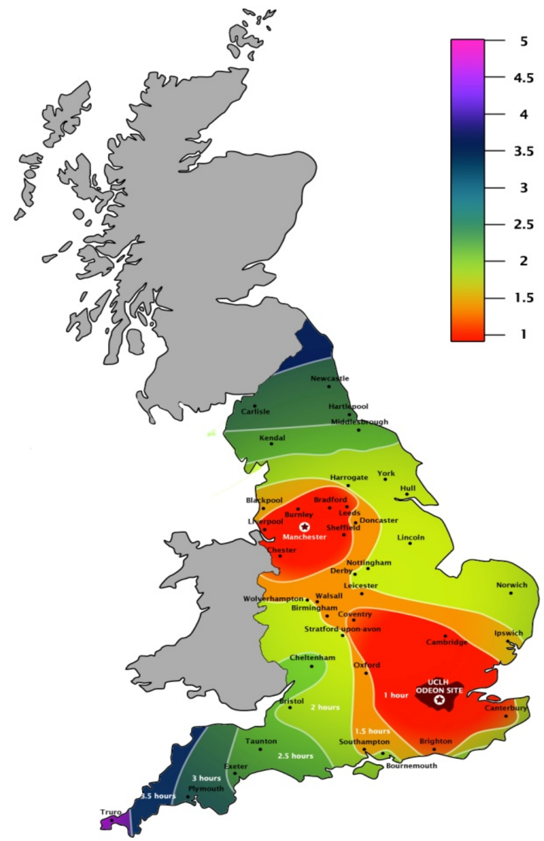


NHS Centre benefits for UK patients: Geography

- Provides UK patients with optimum 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



Why Christie Hospital?

- Largest single-site cancer centre in Europe
  - 40,000 patients a year
  - 14,000 new patients
- Dedicated oncology focus
- 16 networked linear accelerators
- Chemotherapy delivery on 15 sites
- Highly specialised surgery for complex and rare cancers
- Regional and national services including
  - Teenage and Young Adult services
  - Pseudomyxoma Peritonei

UK Clinical Pulls in Particle Therapy

- UK Clinical Pulls in Order of Priority
  - Treatment planning
  - Dose verification and background, esp. neutrons
  - Development of optimised pathways for patient treatment to optimise througput, and data handling methods and protocols;
  - Better imaging, including proton tomography
  - Diagnostics and dosimetry
  - Higher energy for tomography
  - Understanding RBE better
  - Other particles
  - More compact, cheaper sources (***)

*** - meaning e.g. laser-based etc.

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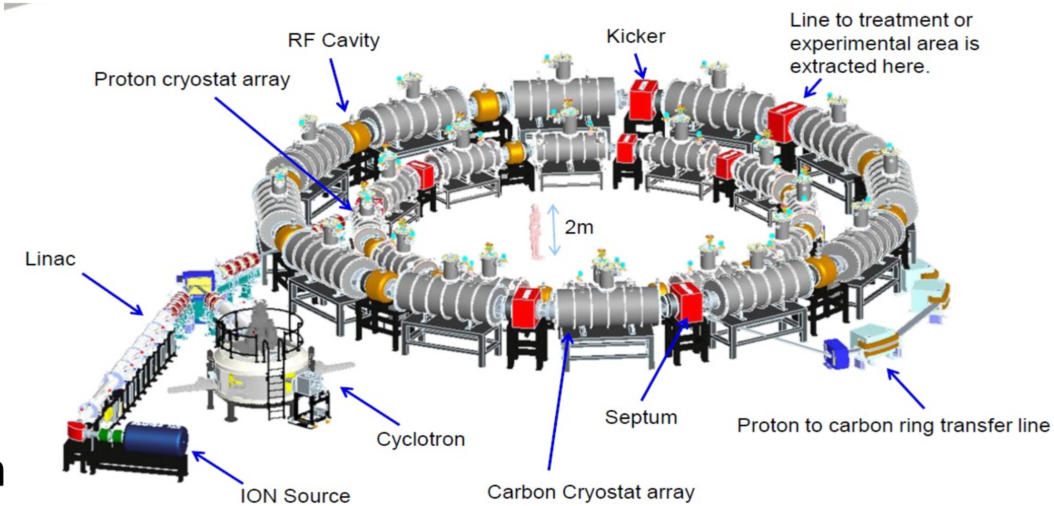
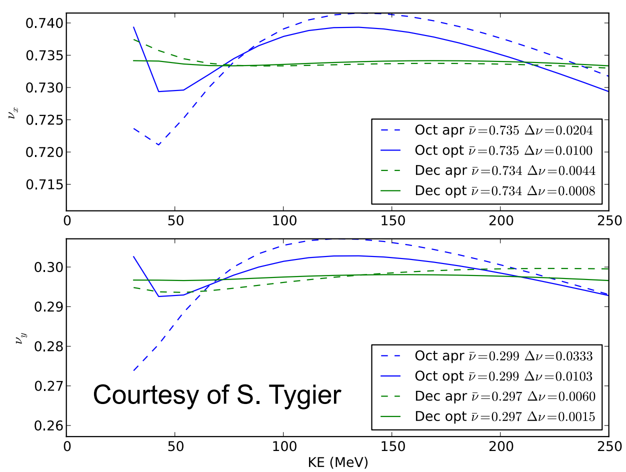
FFAGs

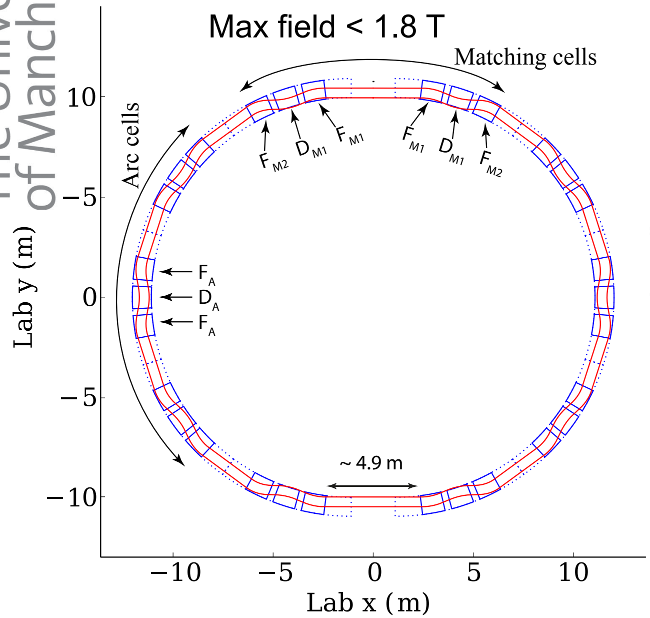
- PAMELA design study successfully completed
- Utilised semi-scaling approach
  - Tune stabilised with higher-order field components
- Next version 330 MeV protons only – proton CT

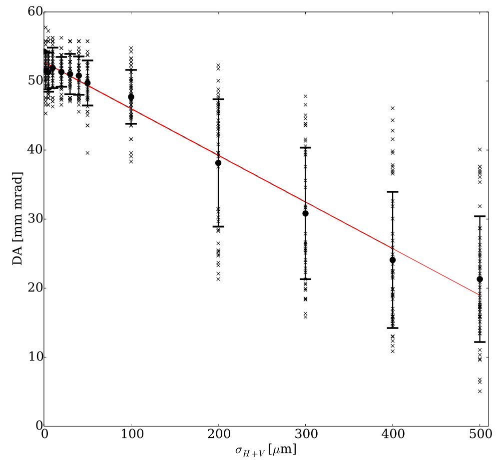


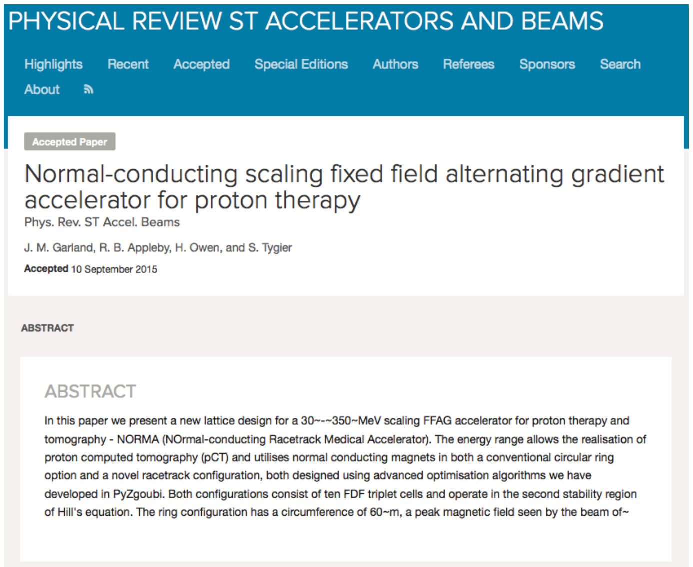
Injection	70 MeV (cyclotron)
Extraction	330 MeV
RF Cycle Rate	1 kHz
RF Frequency Sweep	10-50 MHz (approx.)
Acceleration Time	~0.4 ms
Harmonic Number	~10
Bunch Structure	Single Bunch
Bunch Charge	0.04 – 1.2 pC
Charge Stability	~10%
Average Extracted Current	~0.2 nA
Average Dose Rate	2 Gy-litre/min
Extracted Emittance	2 mm x 2mrad
Extracted Energy Spread	<0.5%
Acceleration Voltage	100-200 kV/turn



NORMA: 350 MeV NC FFAG, 1 kHz pulses + imaging



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Accepted Paper

Normal-conducting scaling fixed field alternating gradient accelerator for proton therapy

Phys. Rev. ST Accel. Beams

J. M. Garland, R. B. Appleby, H. Owen, and S. Tygier

Accepted 10 September 2015

ABSTRACT

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In this paper we present a new lattice design for a 30~-~350~MeV scaling FFAG accelerator for proton therapy and tomography - NORMA (NOrmal-conducting Racetrack Medical Accelerator). The energy range allows the realisation of proton computed tomography (pCT) and utilises normal conducting magnets in both a conventional circular ring option and a novel racetrack configuration, both designed using advanced optimisation algorithms we have developed in PyZgoubi. Both configurations consist of ten FDF triplet cells and operate in the second stability region of Hill's equation. The ring configuration has a circumference of 60~m, a peak magnetic field seen by the beam of~

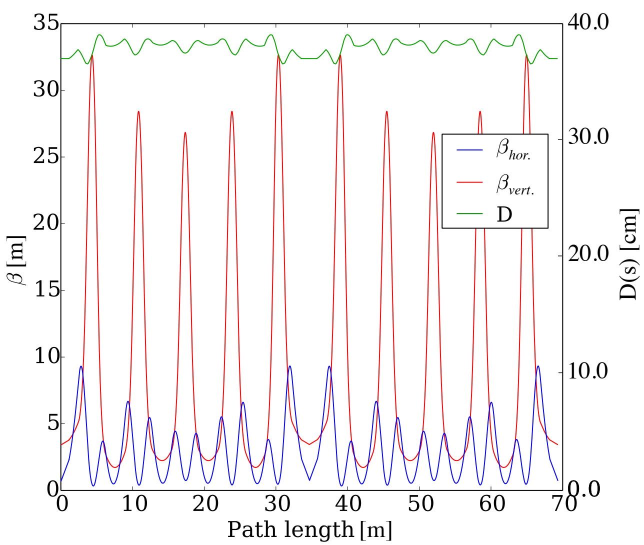
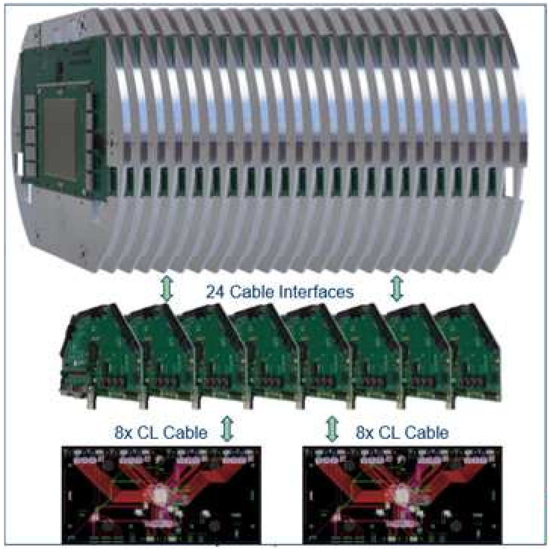


TABLE IV. The main parameters of the NORMA racetrack with $L_{RT} = 2.0$ m after initial optimisation when $f_{RT} = 1.0$, and after scaling when $f_{RT} = 0.91$.

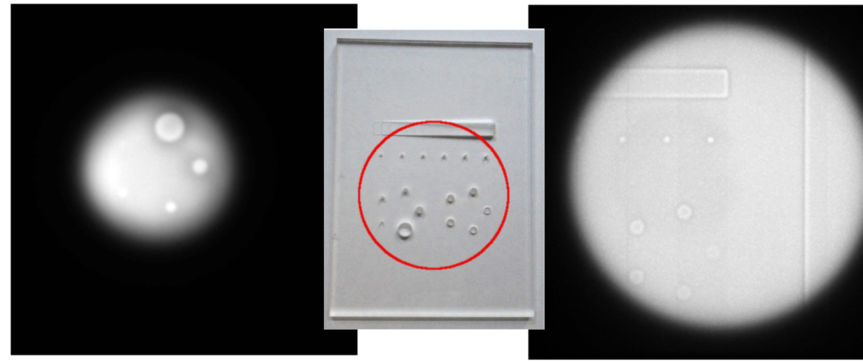
Parameter [unit]	$f_{RT} = 1.0$ **(unscaled)**	$f_{RT} = 0.91$ **(scaled)**
Average radius r_0 [m]	9.61	10.55
Circumference [m]	64.4	70.7
Av. hor. orbit excur. [m]	0.44	0.49
Average ring tune (Q_h, Q_v)	7.70, 2.66	7.71, 2.68
k	26.4	26.4
Peak F_{M1} field [T]	**1.91**	**1.74**
DA [mm mrad]	52.0	57.7
Magnet-free drift [m]	4.4	4.9

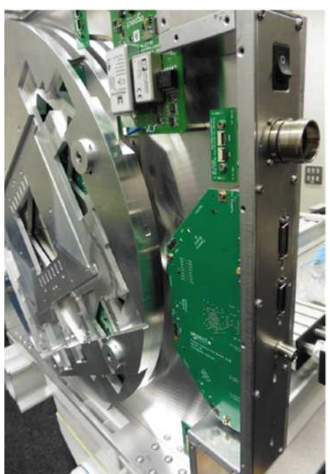
PRAVDA Si pCT Instrument

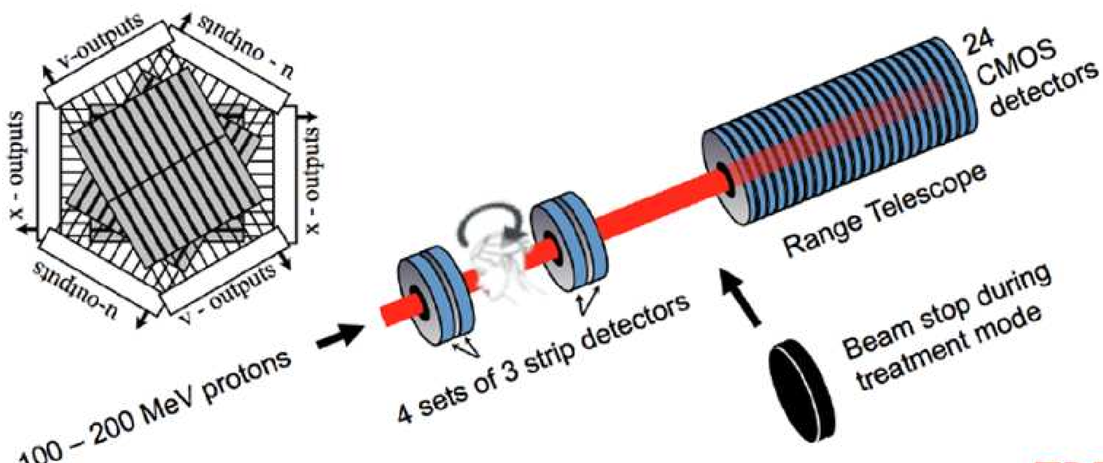


Birmingham 36 MeV, 1.5 nA 400 ms, 100 frame

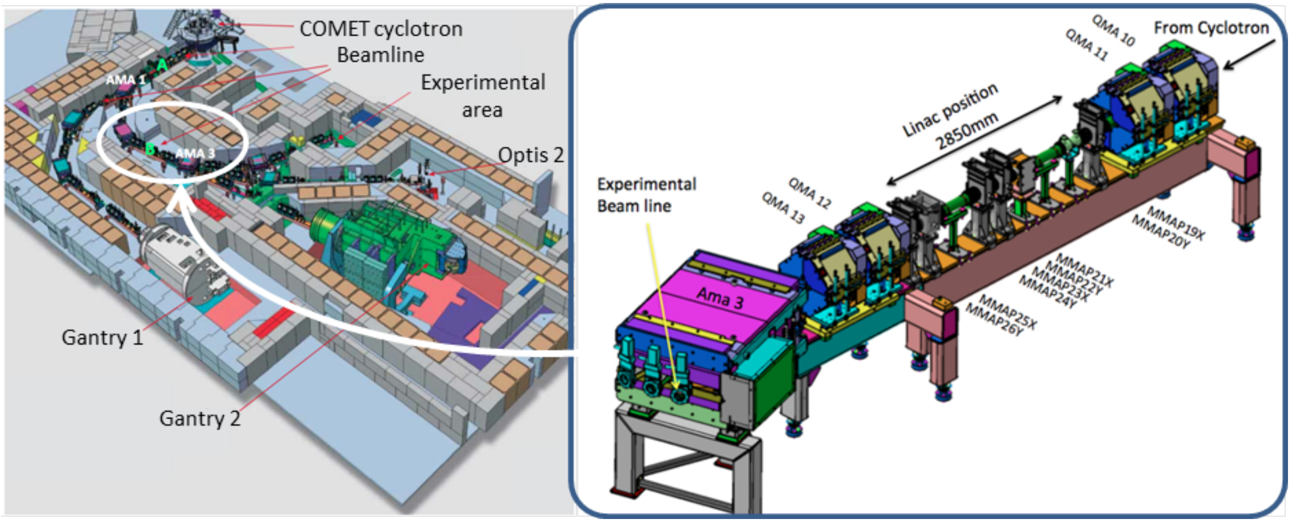
iThemba 200 MeV, 10 nA, 150 ms, 100 frame



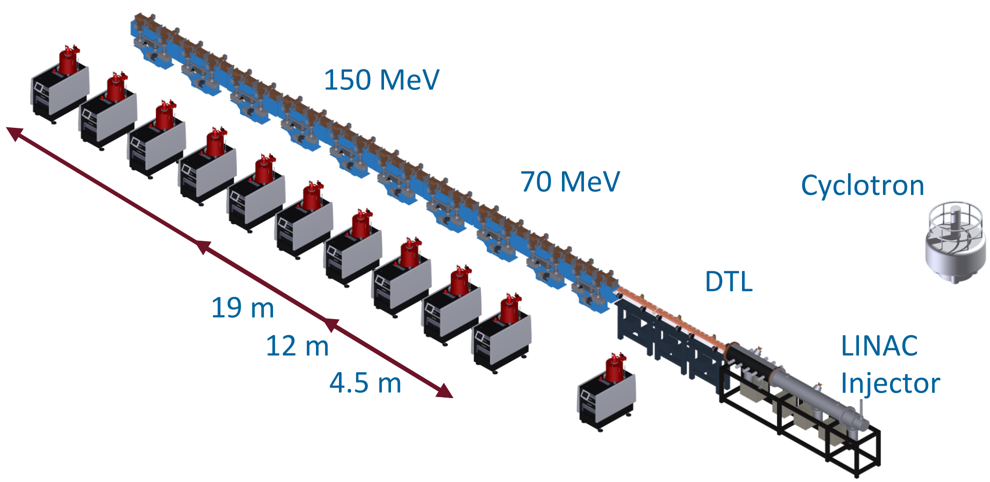




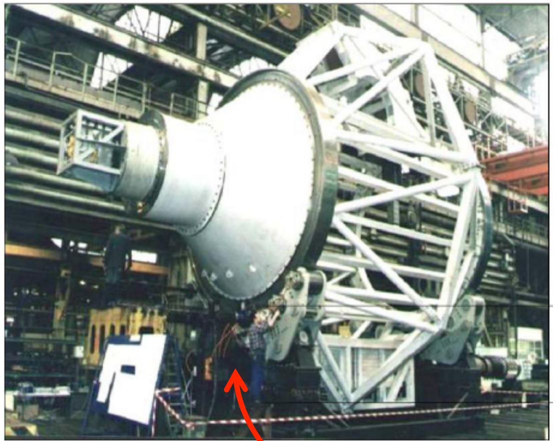
'IM-PULSE', AVO etc.



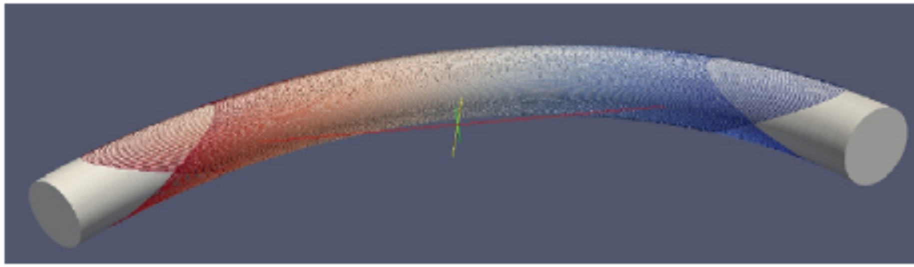
PSI IM-PULSE



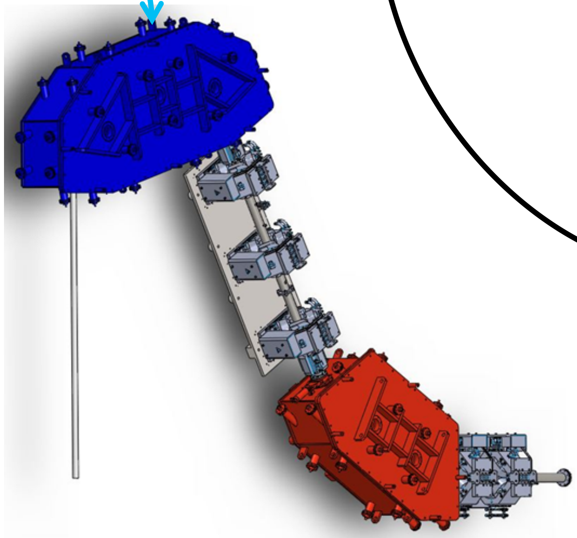
TERA/ADAM/AVO 3 GHz CCL

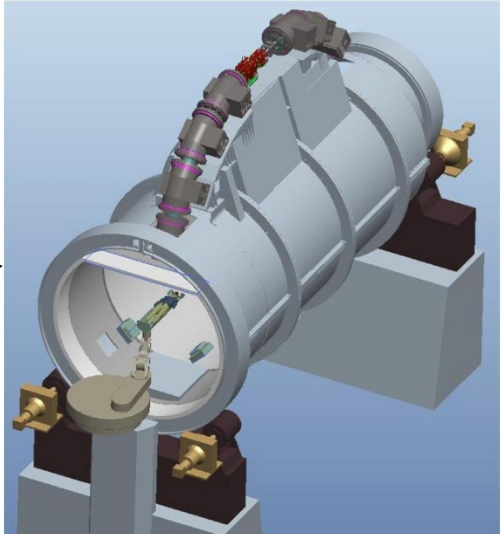


What are the technology options?



	NC	Hybrid	SC	FFAG optics
p^+	230 MeV	ProNova, PSI/LBNL	UoM	Proposed – **why not built?**
C^{6+}	HIT only	-	NIRS	Proposed

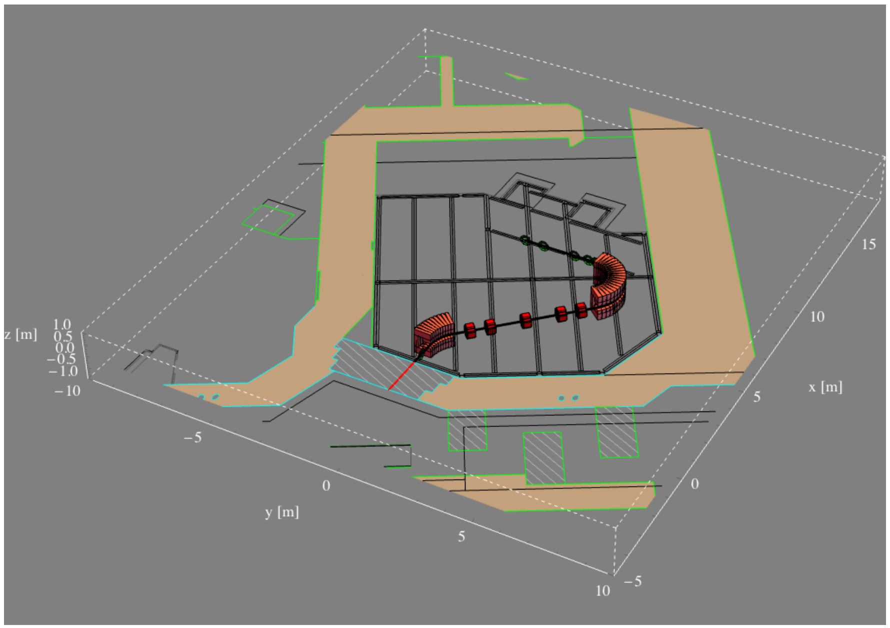




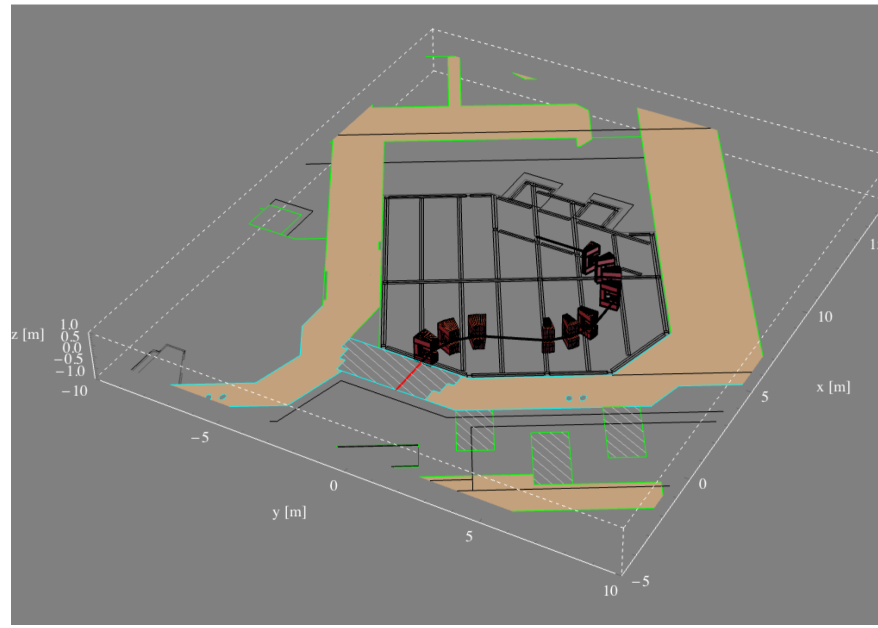
Superconducting Gantry for pCT - Options

- SC/NC – NC limit at c.1.8 T makes it not fit Room 4
  - SC magnets offer opportunity to have combined function
  - Slower ramping (0.3 T/s?), slows treatment time, but ok?
- FFAG vs 'conventional' magnets
  - FFAG has wide energy acceptance, but unproven technology
  - PM FFAG magnets may suffer from degradation, difficult to tune
  - SC FFAG magnets; at this energy may as well use fewer
  - FFAG scanning solutions not optimised
- Downstream scanning:
  - Can use single, small aperture magnet design
  - Less spot size variation during scanning, less calibration
  - Greater field size possible
  - SAD 2.0m, enough to limit additional skin dose
  - Small aperture + large distance will alleviate stray field at isocentre

Gantry Layout Comparisons



Varian (245 MeV)



pCT (330 MeV)

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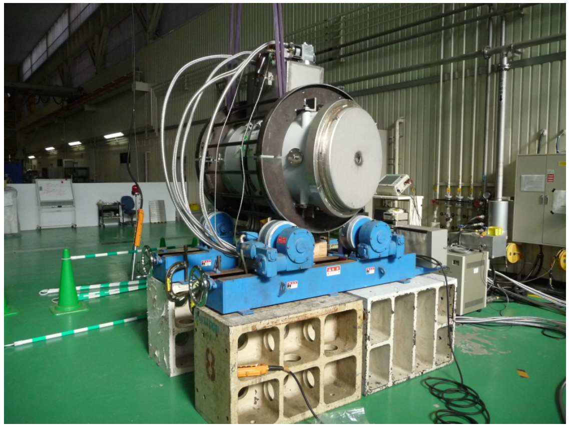
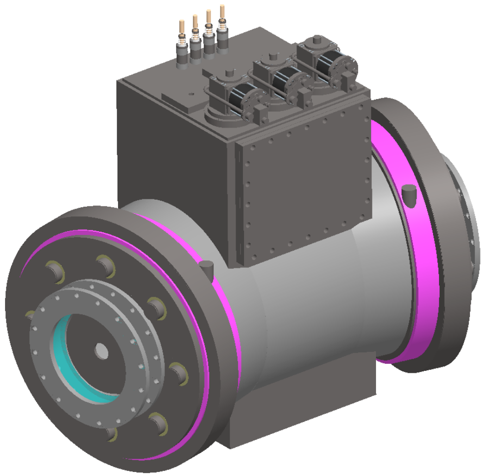
SC Gantry Magnets

- Adopt existing magnet spec from NIRS SC gantry (cryo-cooled, Toshiba)

Max Rigidity	2.84 Tm (330 MeV)
Max Field	2.88 T
Max Gradient	10 T/m
Bend Radius	1.0 m
Magnetic Length	400 mm
Bend Angle	22.5 deg
Bore Diameter	60 mm
Good Field Region	+/- 20mm
Field Quality (Dipole/Quad)	1e-4, 1e-3





All demonstrated

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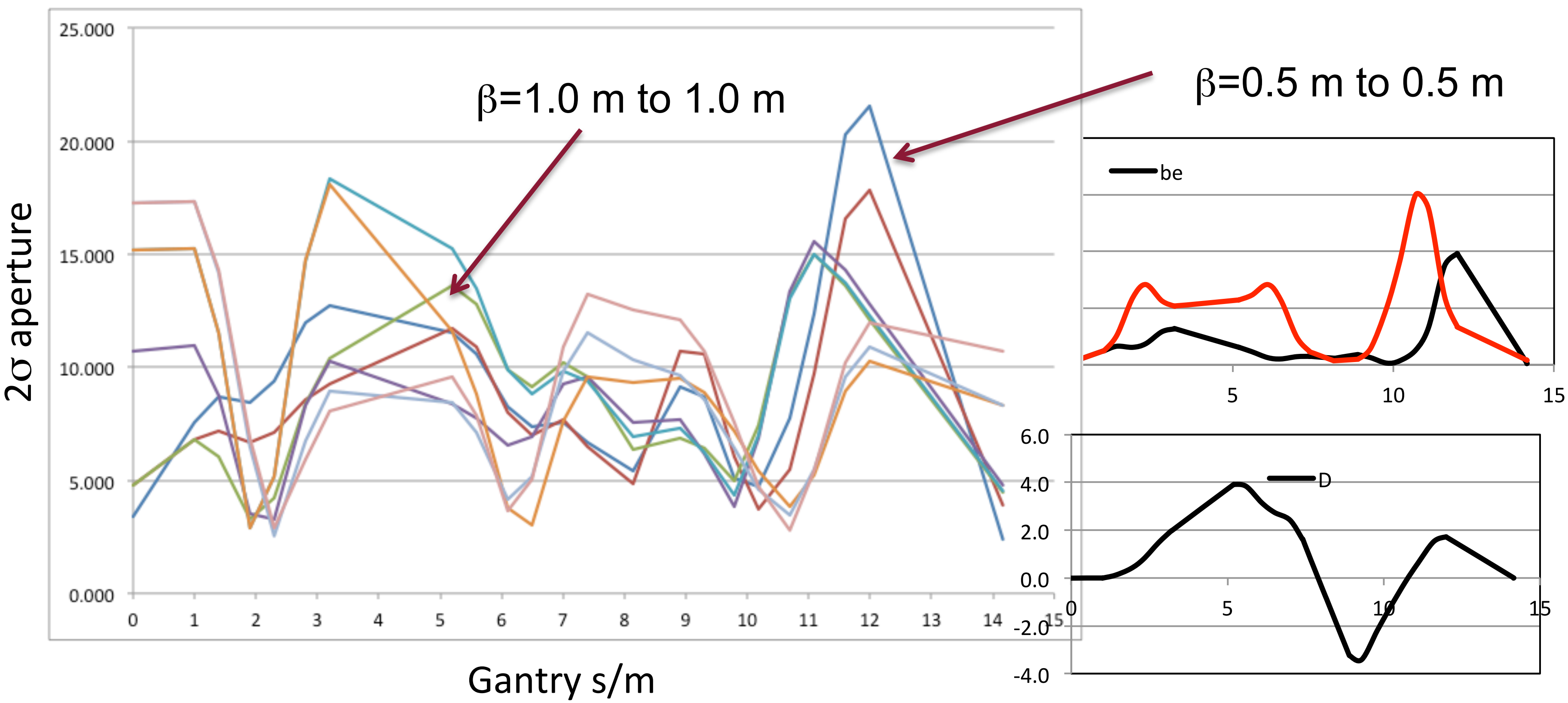
SC Gantry Optics

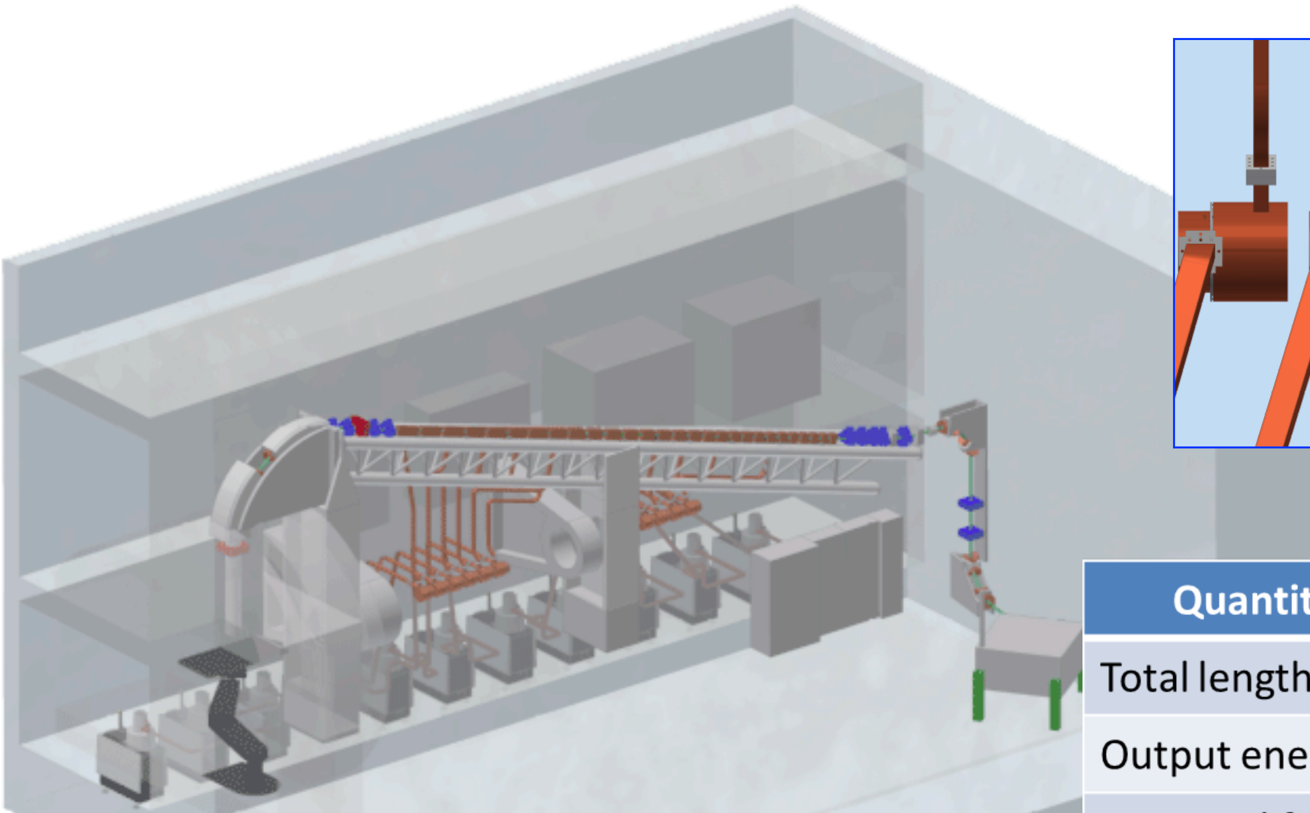
Various beam magnifications (all round beams) possible by re-matching optics

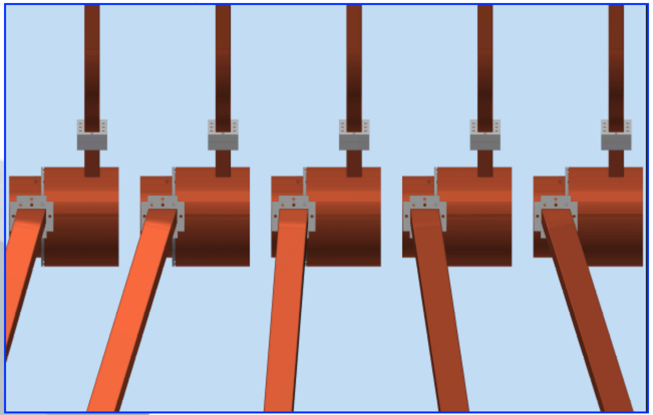
Magnet	Maximum Gradient (m^{-2})
BM1	3.11
BM2	-1.71
BM3	3.50
BM4	2.58
BM5	-2.09
BM6	2.67
BM7	3.50
BM8	0.69
BM9	1.60
BM10	1.97

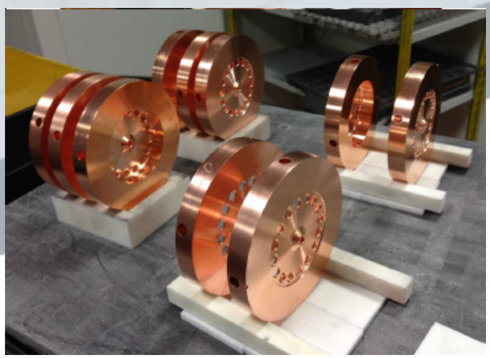
10 T/m



TULIP: Turning Linac for Proton Therapy







Quantity [unit]	Sec.1	Sec. 2
Total length [m]	3.4	7.9
Output energy [MeV]	70	230
Avg. axial field [MV/m]	22.8	29.4
Max. surf. field [MV/m]	150	170
Number of klystrons	3	8
Peak Power [MW]	22	58

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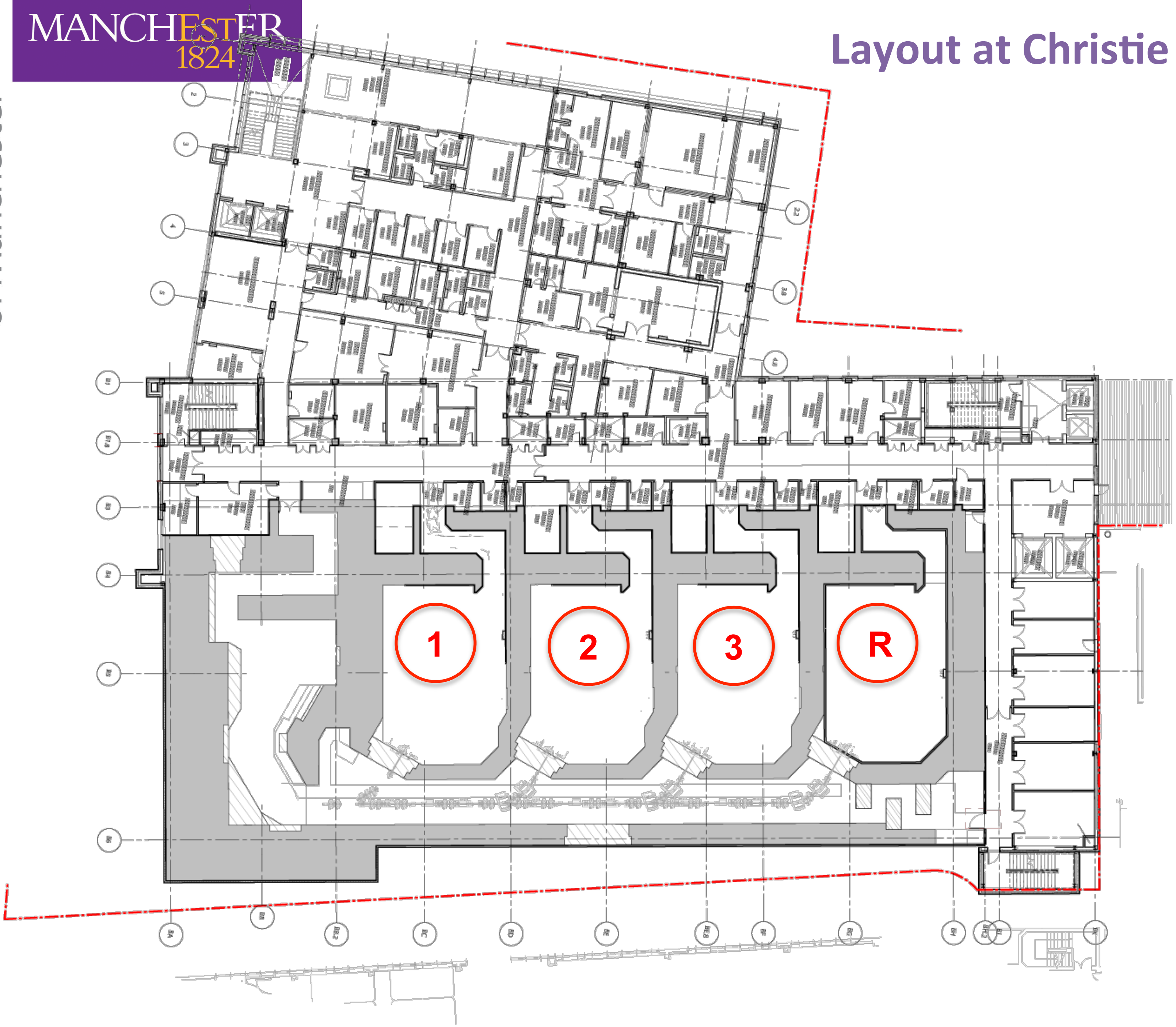
Layout at Christie



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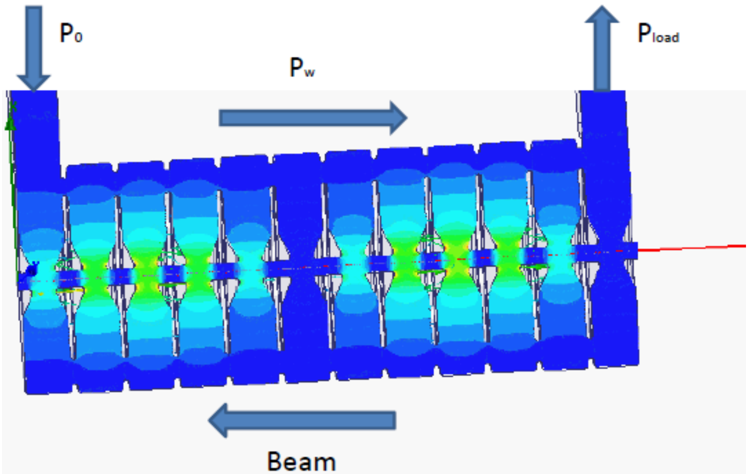
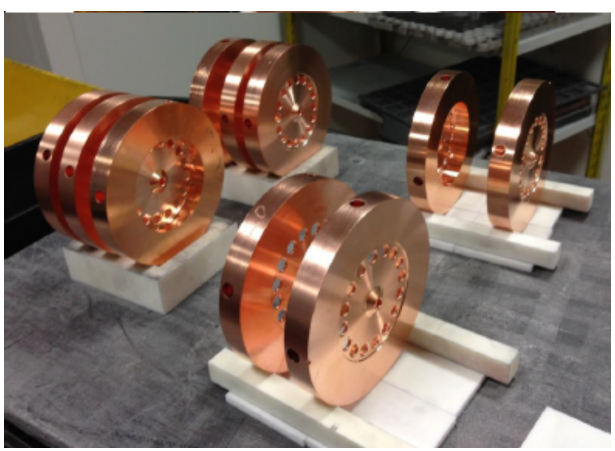
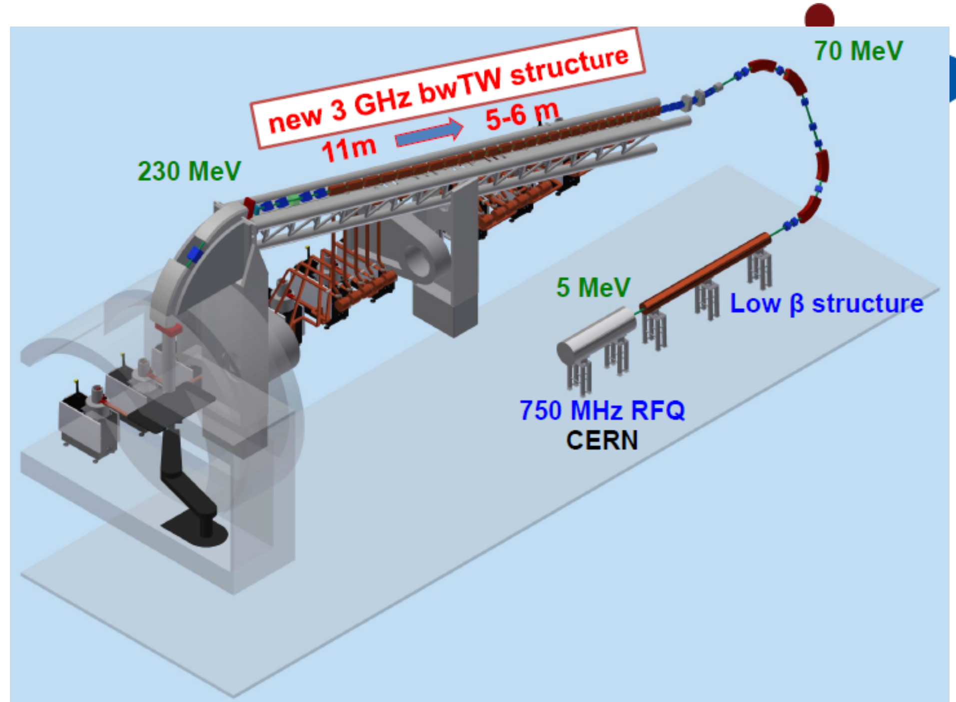
TULIP Developments

TERA 3 GHz SCL





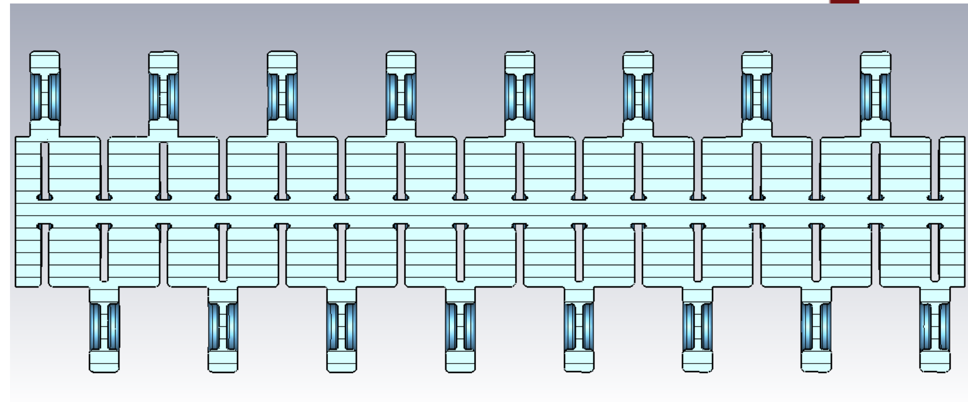


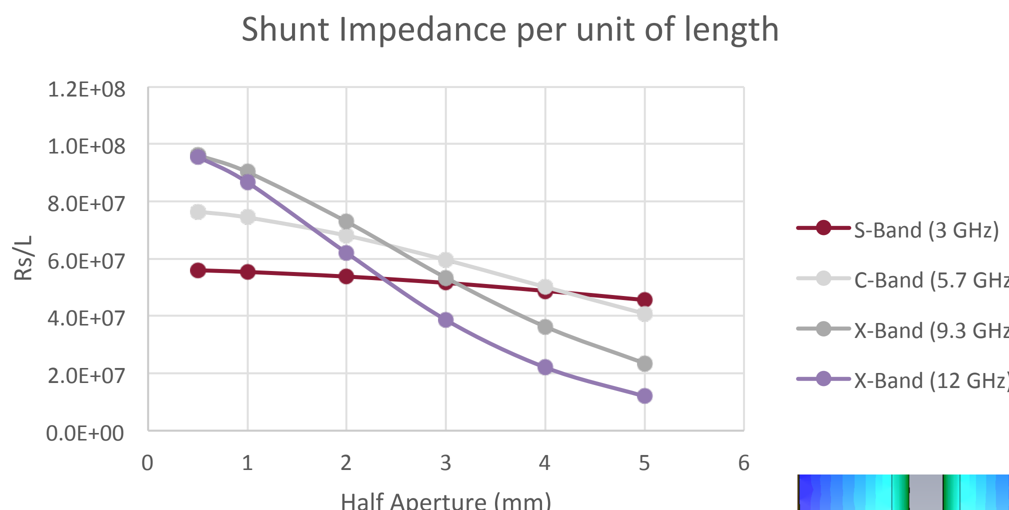
- TERA (Italy) and CERN have been working on high gradient linacs for treatment. They adopted some different design choices than us
- Optimised for cost of the linac rather than cost of the facility
- Imaging is different
- TERA need higher transmission for treatment:
    - We can have a smaller aperture
    - Therefore a higher gradient (using X band)
    - TERA achieve up to 45 MV/m (in simulation)

Structure design

- Using a higher power klystron allows a higher gradient, but this is limited by peak fields
- Need to reoptimise to maximise both limits
  - Just doing this allows a higher gradient at S-band.
- If you can use a smaller aperture then you get an even higher gradient by going to X-band.

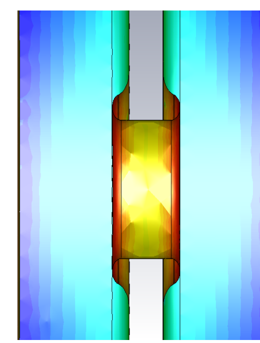
- Applications
  - pCT
  - Linac only treatment
  - High-energy treatment (lower MCS)



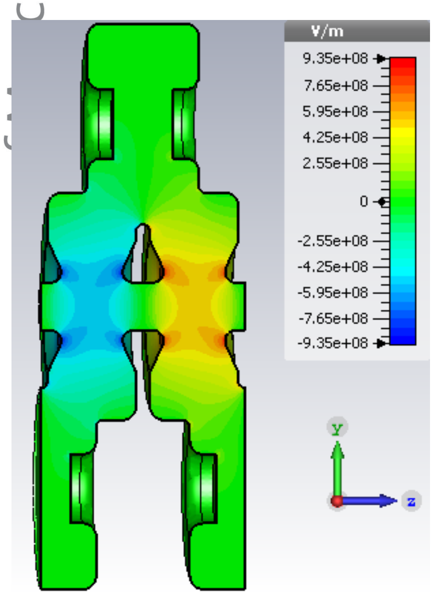


Frequency	Sc=2.4		Sc=4	
	3mm Aperture	4mm Aperture	3mm Aperture	4mm Aperture
S-Band (3GHz)	60 MV/m	59 MV/m	65 MV/m	64 MV/m
X-Band (12GHz)	67 MV/m	60 MV/m	71 MV/m	64 MV/m

Sc – modified Poynting vector

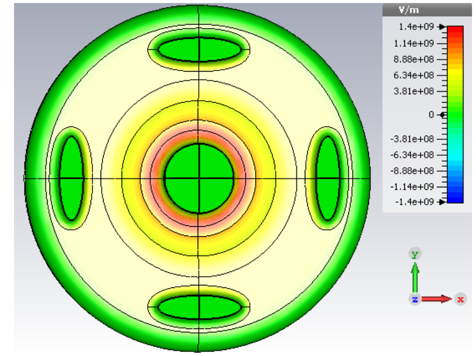


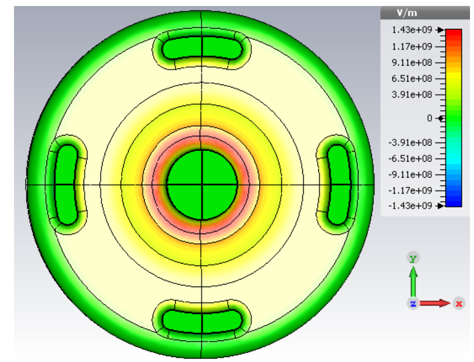
RF Cavity Designs Examined



Standing Wave Structure

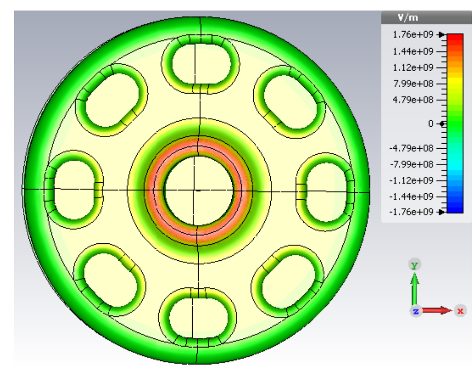
- Side Coupled Standing Wave Cavity
- Coupling Factor K=12% for 30cm structure.
- Maximum Gradient 60MV/m
- Limited by shunt impedance not Sc



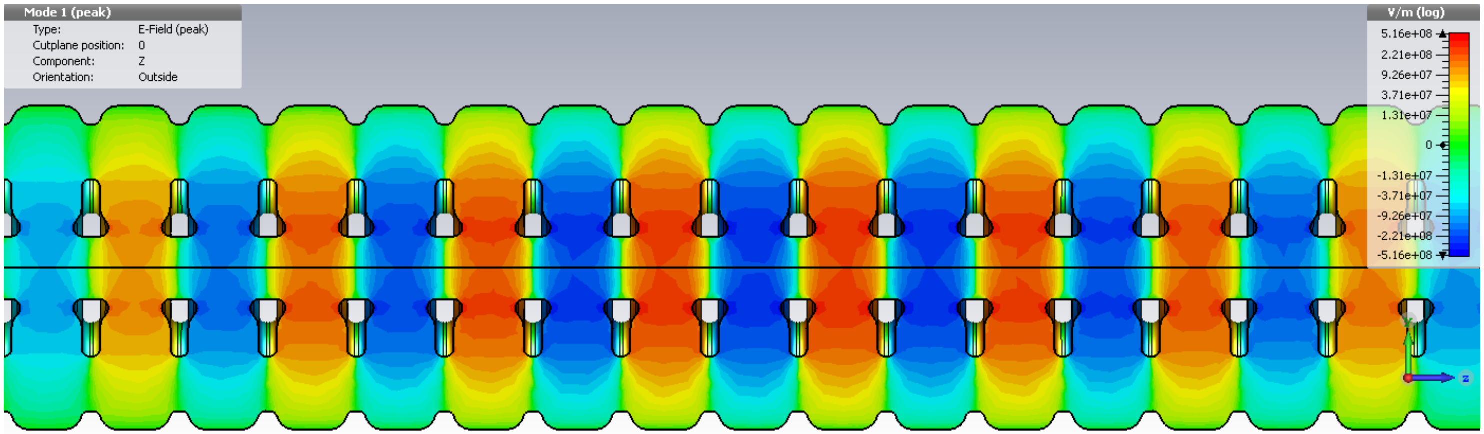


Travelling Wave Structure

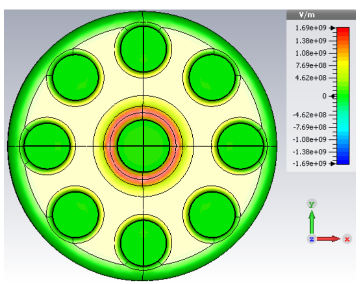
- Backwards magnetic coupling
- Phase advances: $2\pi/3$, $5\pi/6$, $7\pi/6$ were simulated
- Multiple coupling slot geometries were also simulated



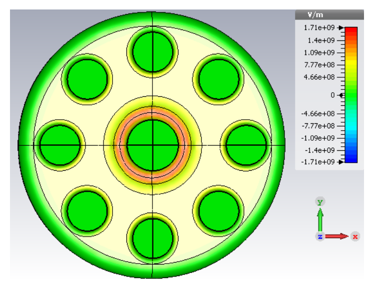
Present Design



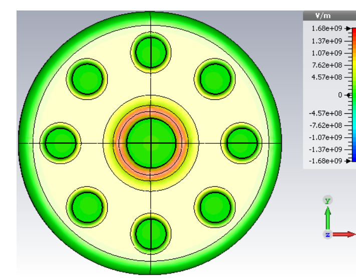
First Cell



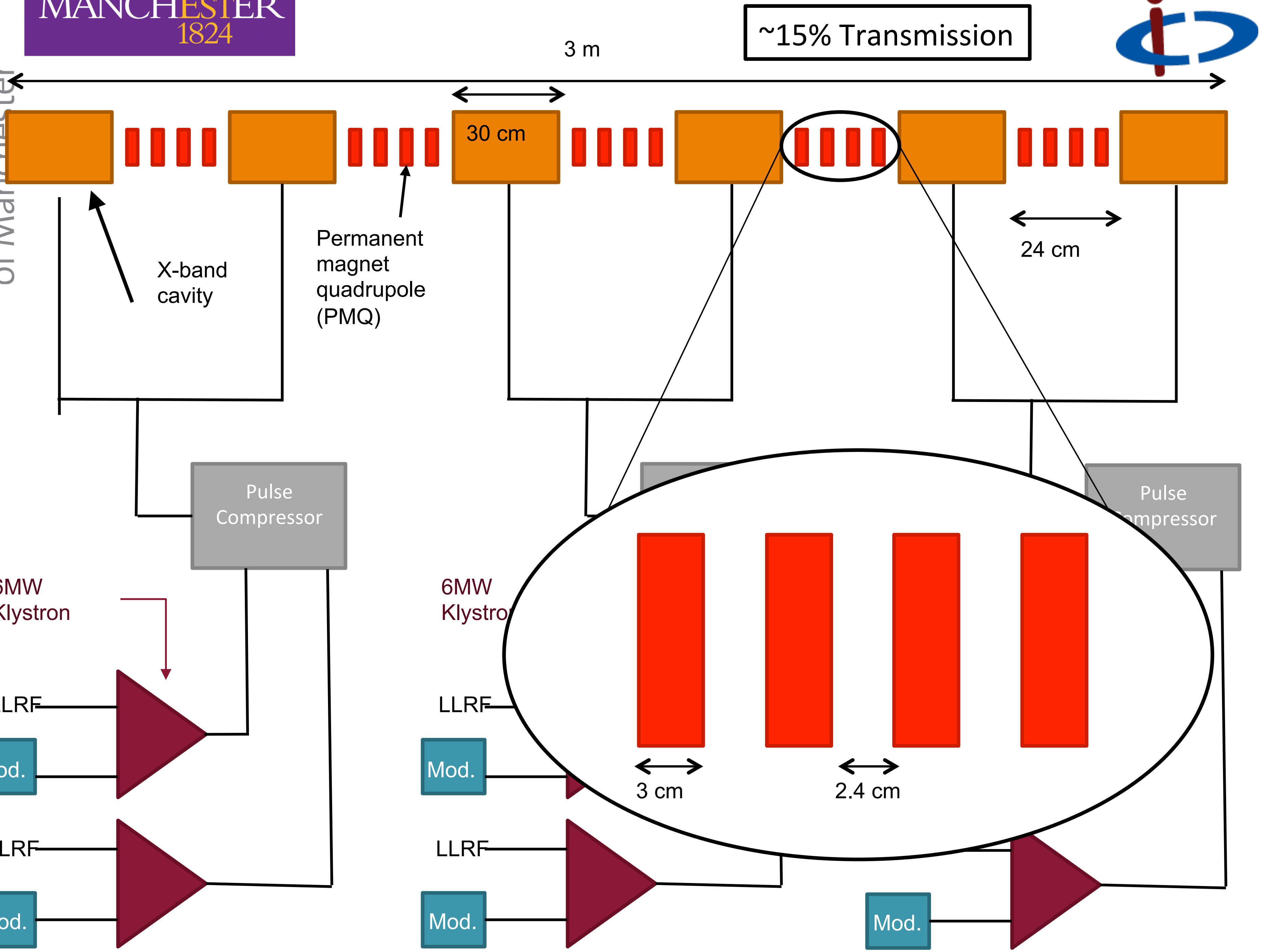
Centre Cell



Last Cell



- Backwards Travelling Wave Structure with Circular slots and Phase advance of 2π/3
- Hybrid of constant impedance and constant gradient structure
- Maximum Gradient 65 MV/m


~15% Transmission
3 m
30 cm
24 cm
X-band
cavity
Permanent
magnet
quadrupole
(PMQ)
Pulse
Compressor
6MW
Klystron
LLRF
Mod.
LLRF
Mod.
3 cm
2.4 cm

Layout at Christie

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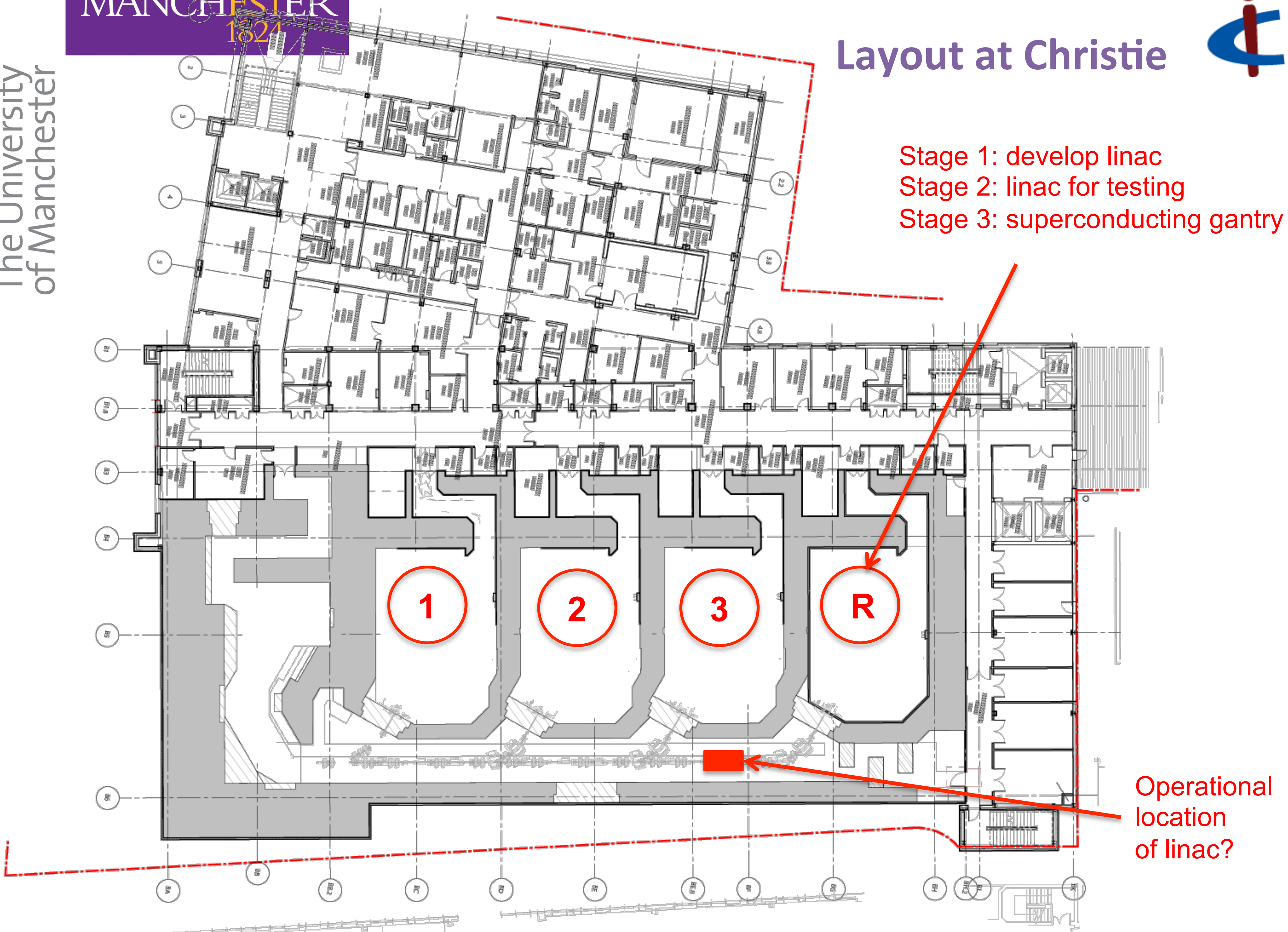
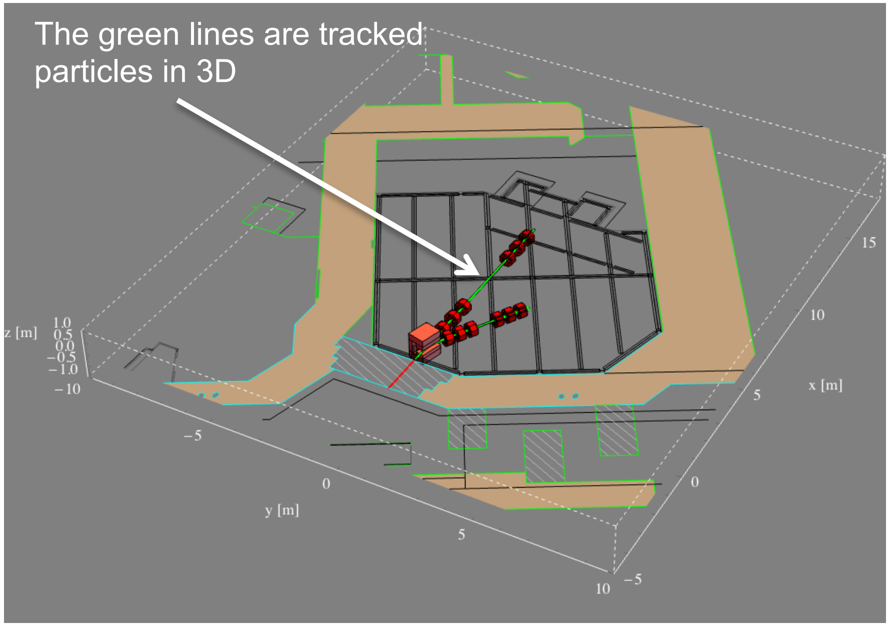
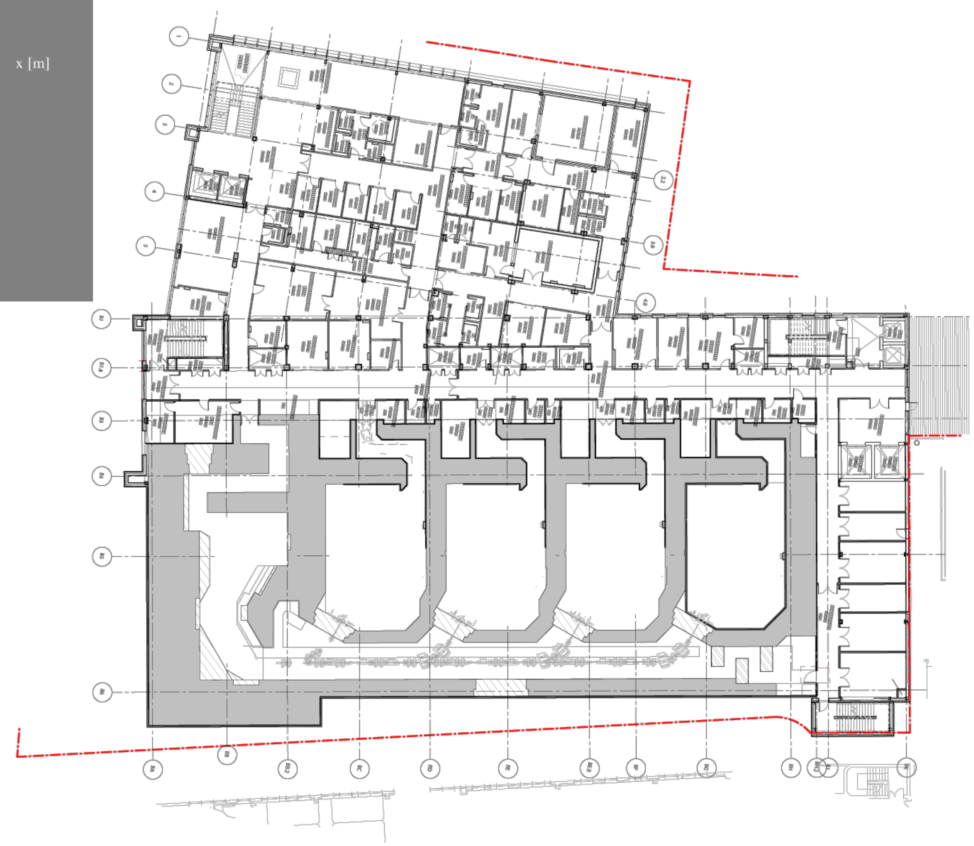


2 x CPI XL5 klystrons w/modulators

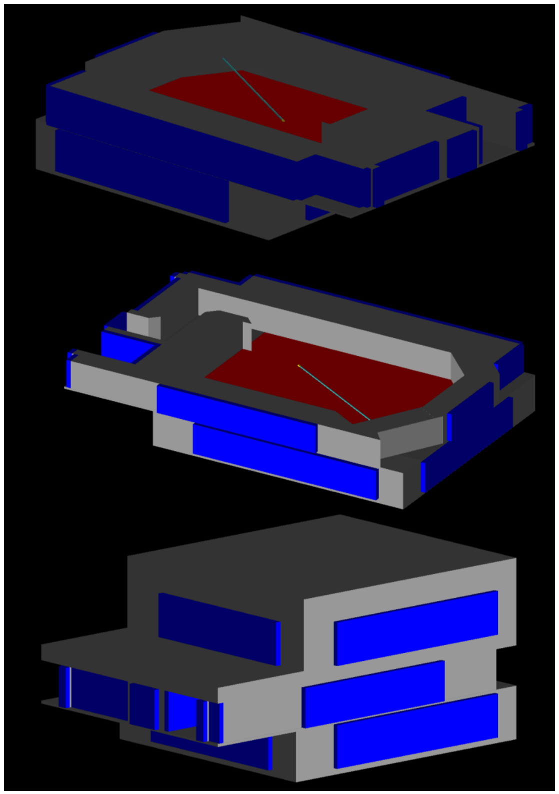
Research Beamline Optics



- 70 to 245 MeV
- Rigidity 1.23 to 2.44 Tm
- Spot size 6.5 to 3.2 mm (245 to 70 MeV)

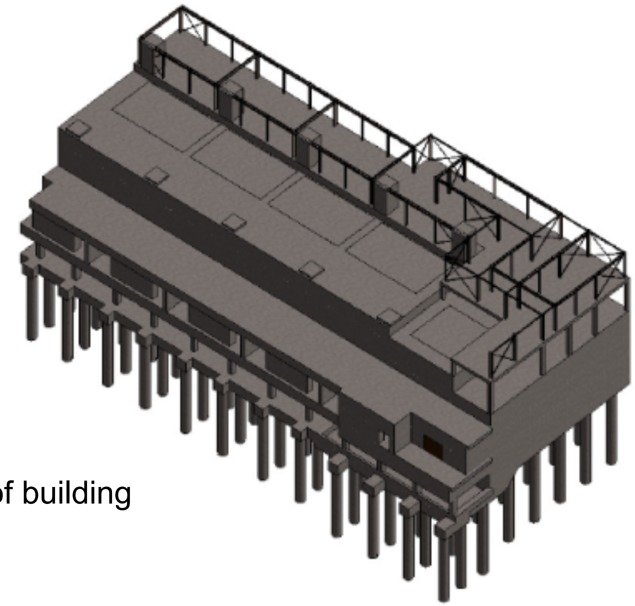


Christie Research Beamline

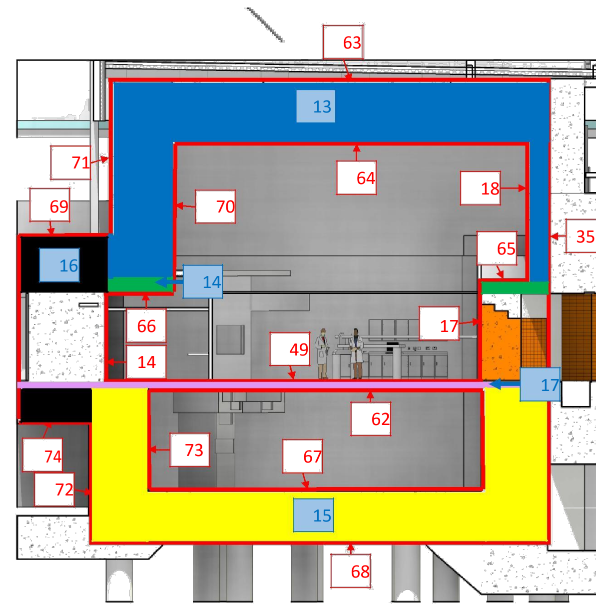


GEANT4 model of Research Beamline

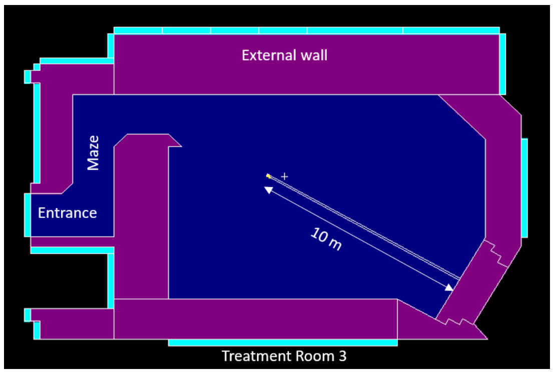
3D Geometry of building

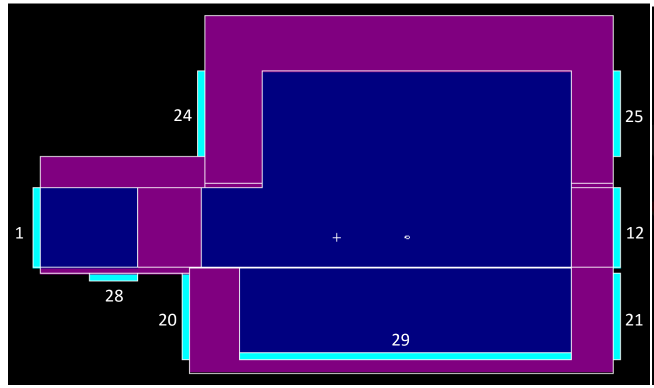


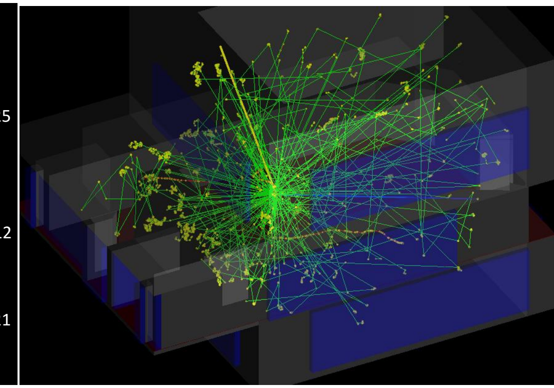
Research Beamline – Volumes and Materials



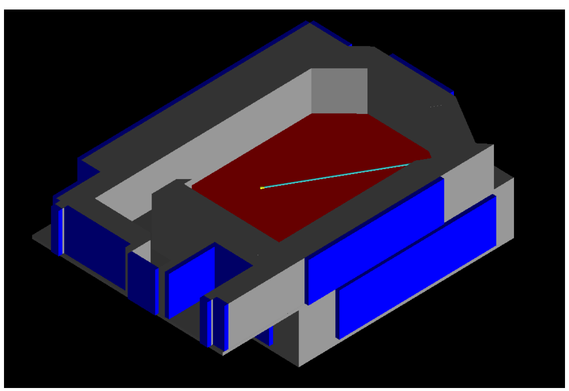
Research Beamline Shielding Calculations





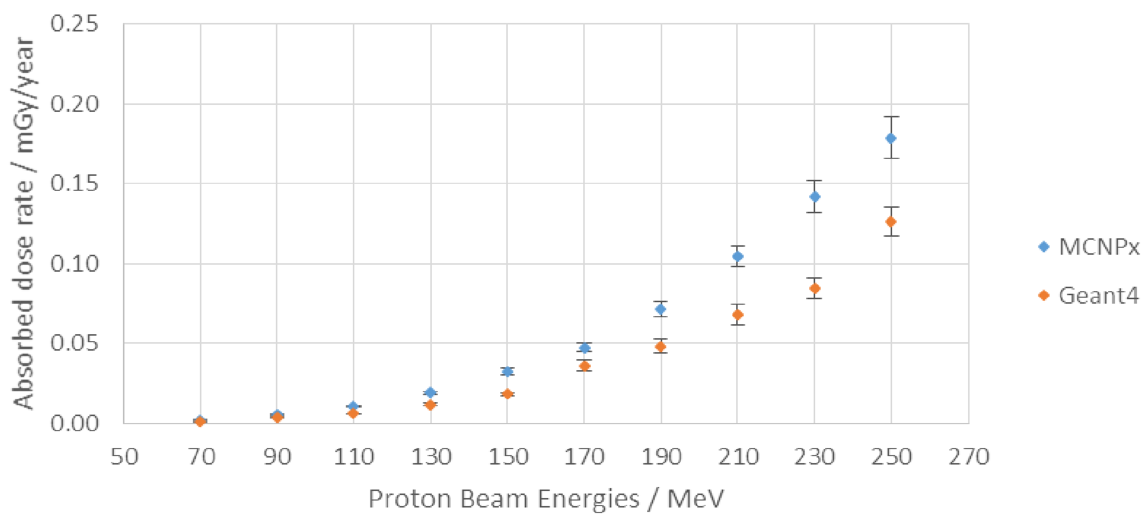


MCNPX



GEANT4

Tally 1 (Doorway dose), 520 hrs/yr @ 0.44 nA



250 MeV gives 1.36 mSv/yr

(in progress)

Next Steps

- Implementation of research beamline
- Demonstration of RF structure end 2016
- Study inclusion of booster into gantry and other options