Proton Boosting for Imaging

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Cockcroft Institute for Accelerator Science and Technology

NPL PPRIG Workshop, 1st December 2016

MANCHESTER 1824 The University of Manchester
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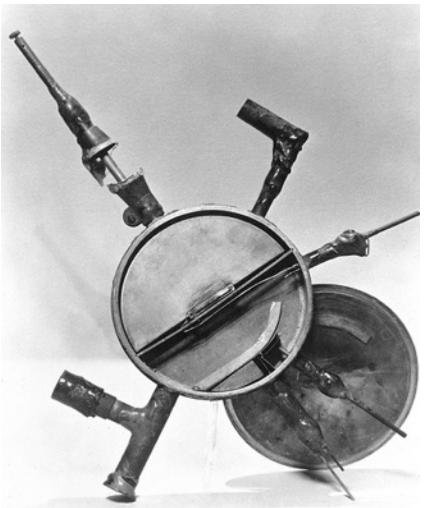
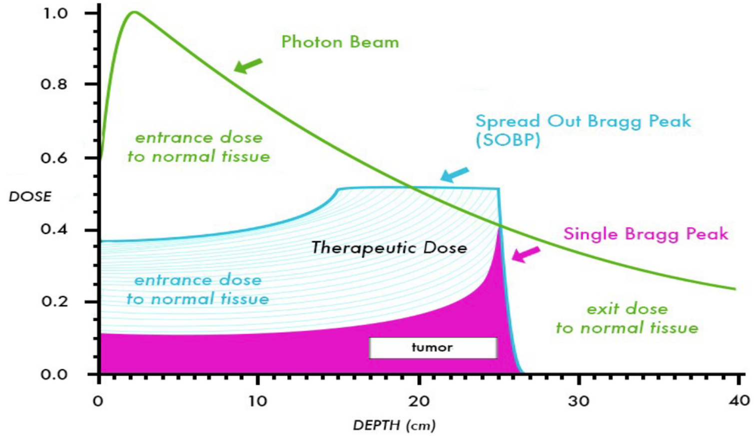
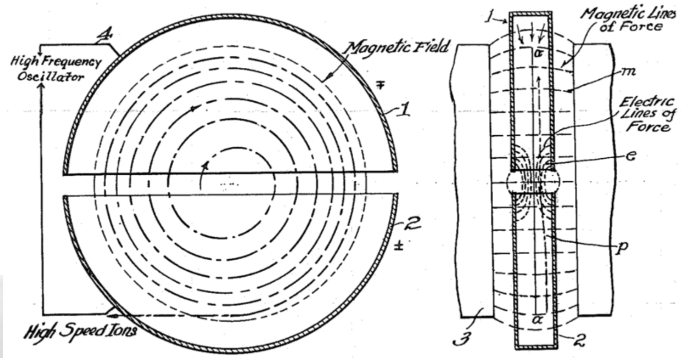
The Christie TOWARDS A FUTURE WITHOUT CANCER
CERN

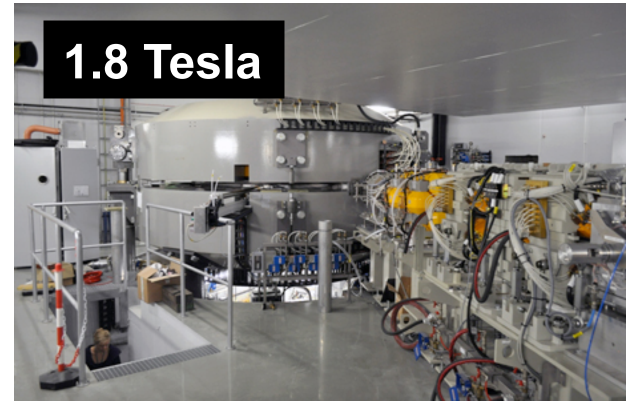
Cyclotrons!

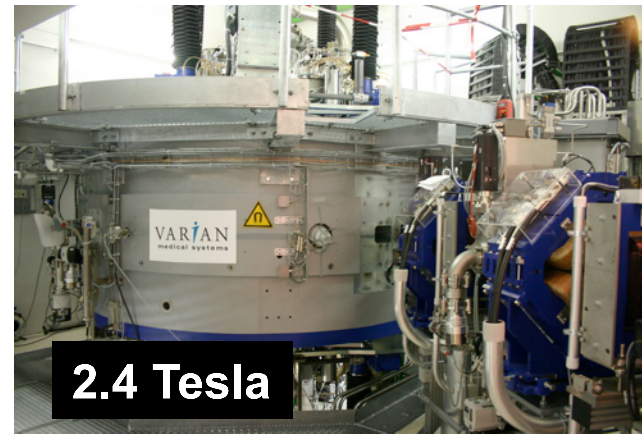




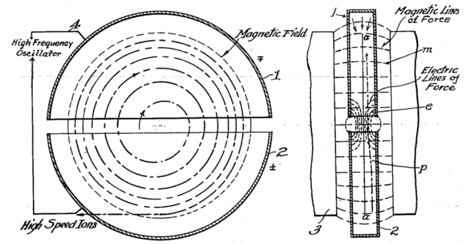


- 235 MeV:
  - Can do it with a cyclotron
  - Can treat adults with protons
- Coincidence these are at the same energy!





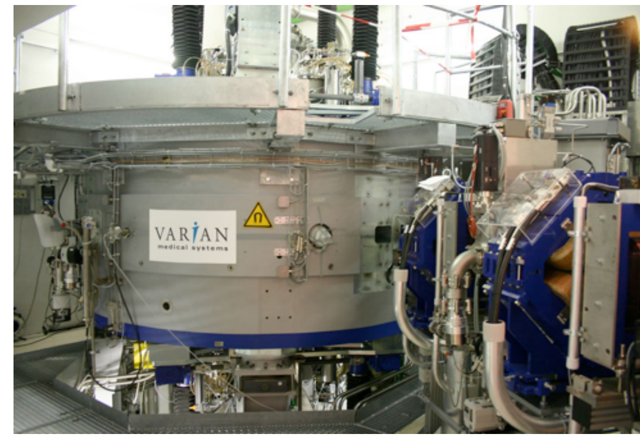
Cyclotrons



$$f = \frac{qB}{2\pi\gamma m_0} \qquad T = E_0(\gamma - 1)$$

- T = 235 MeV equiv. to γ = 1.25
- Mitigated by profiling field at outer edge, but still limited
- All deliver fixed energy, need fast degrader
- Typical currents, 1 uA (~1 nA after degrading)
- Cyclotron mass scales as $\sim 1/B^3$
- Typical bunch frequency is 30-70 MHz

1.8 T
(220 tonnes)



2.4 T
(80 tonnes)

9 T
(20 tonnes)

Advanced Oncotherapy Centre, Harley Street

- ADAM LIGHT linac
  - CERN/TERA
    3 GHz SCL

141/143 Harley Street

ADVANCED
ONCOTHERAPY

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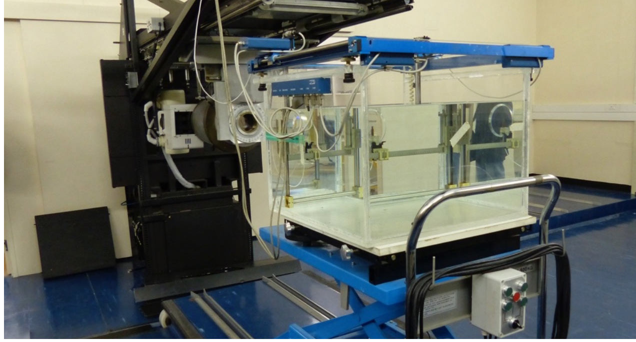
AVO Proton Therapy Centre – Harley Street

If you have enough proton energy… (i.e. >330 MeV)



International Patent: WO 2015/189603

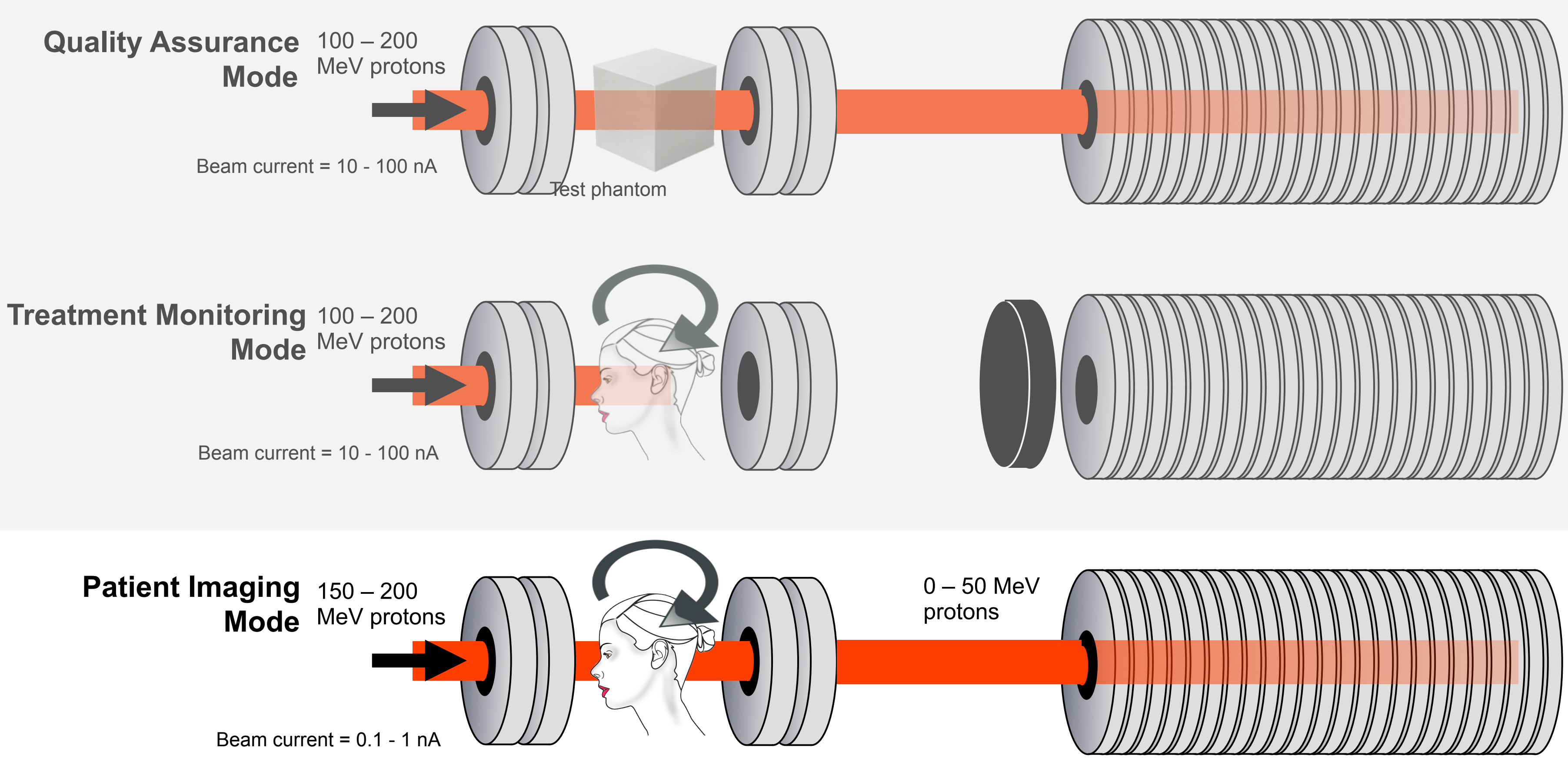


Image courtesy of PRaVDA collaboration

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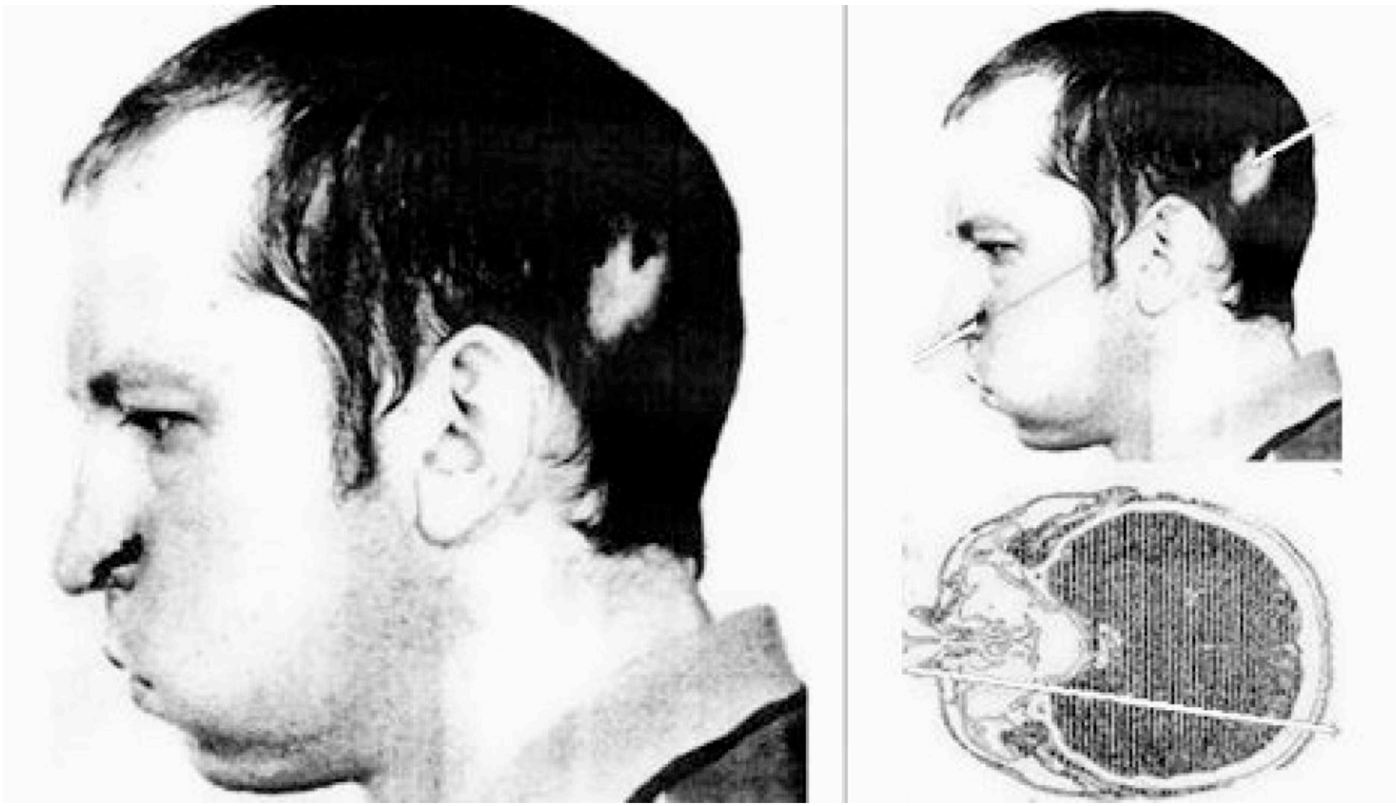
It has been done before….



Anatoli Bugorski, 76 GeV, U-70 synchrotron (IHEP Protvino), 1978

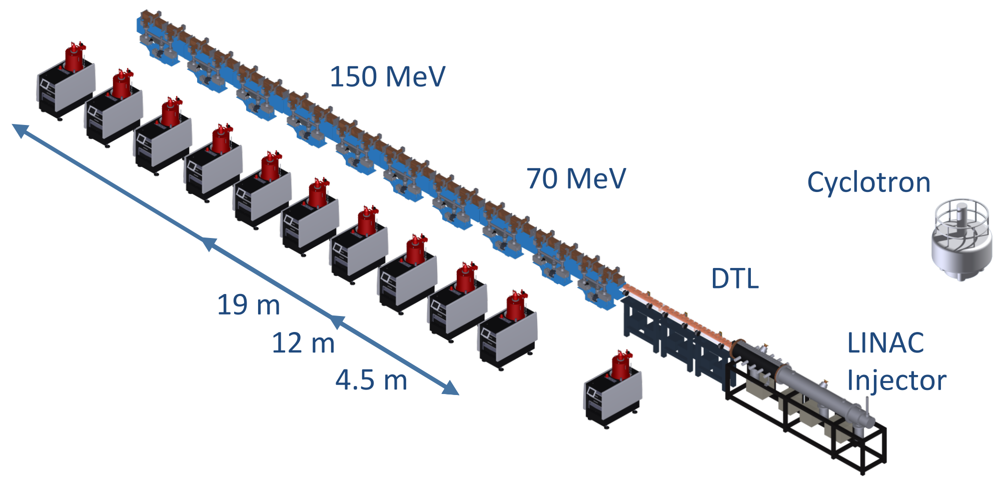
A Linac for Imaging?

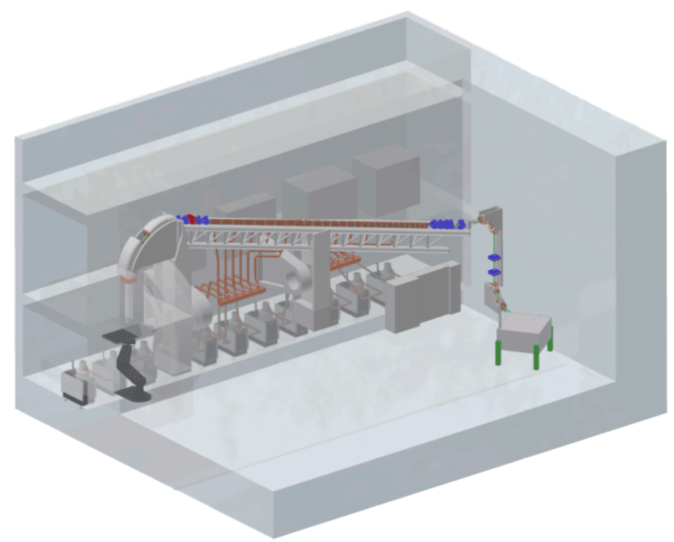
- 'A cyclinac' uses a cyclotron as injector for linac:
  - No frequency match AT ALL – 70 Mhz vs. 3 GHz
  - Overall transmission efficiency relies on pulsing/ duty cycle: < 10%
  - Idea only practical at low current; significant losses in first linac cells
  - For therapy you need ~ 1 nA, so ~ okay
  - Still much lower than cyclotron systems for therapy, where we have up to 1 uA -> 1 nA in degrader

- AVO LIGHT system uses RFQ/DTL instead
  - 'Safer' but longer
  - Lower shielding cost compensates for increased size of linac cf. cyclotron (?)

- Imaging by definition is lower dose than treatment, c. 1000x less
  - ~ 1 pA at 350 MeV
  - Radiation doesn't matter!
  - Losses irrelevant

- This is all quite different to conventional accelerator design, which usually carefully avoids losses
  - Here we just want a small unit that gets a tiny amount of current to 350 MeV





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

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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.

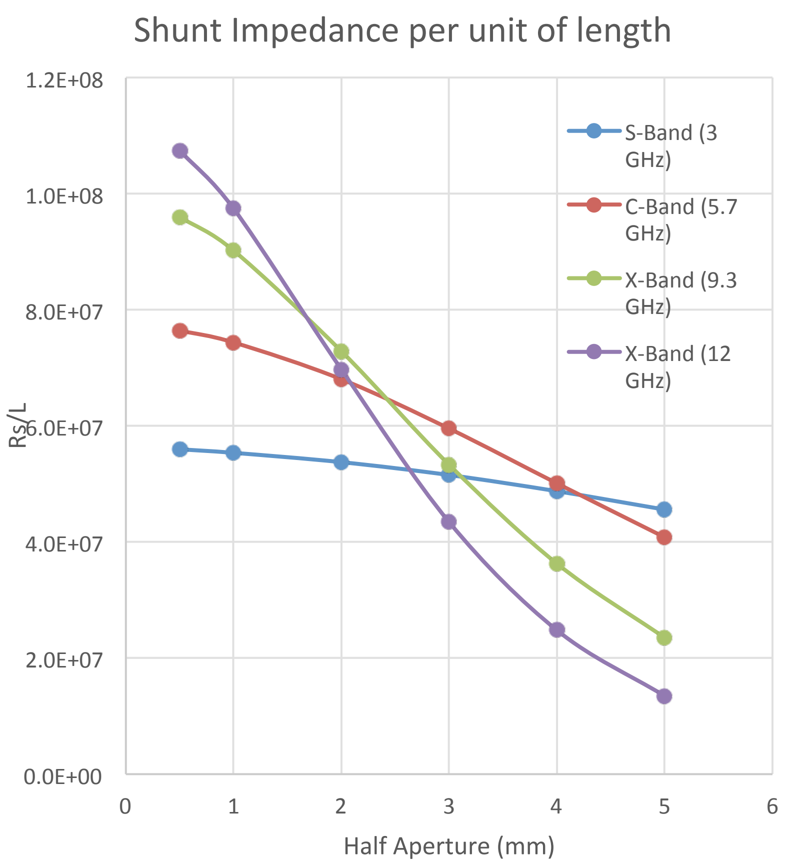
MeV; this challenge has been taken up by the Frascati team in its TOP project [4].

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!

Small-Aperture High-Gradient Scheme



- This is what led us initially to the small-aperture high-gradient scheme
- It shows single cell pillbox cavity simulation results.
- We knew that for imaging less current was required, and thus decided to squeeze the aperture down to the range of highest shunt impedance. X-band 1.75mm.
- Maximising the shunt impedance (R) of the cavity minimises the power consumption (Pc) for a fixed acceleration voltage (V).

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

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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.
- 1mm septum thickness is risky manufacturing challenge.
  s-band 4mm
- x-band 1mm (thinner septum, higher Rs)
- 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.
- The gradient in both of these cases is limited by the modified pointing vector (Sc)
- An X-band 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.

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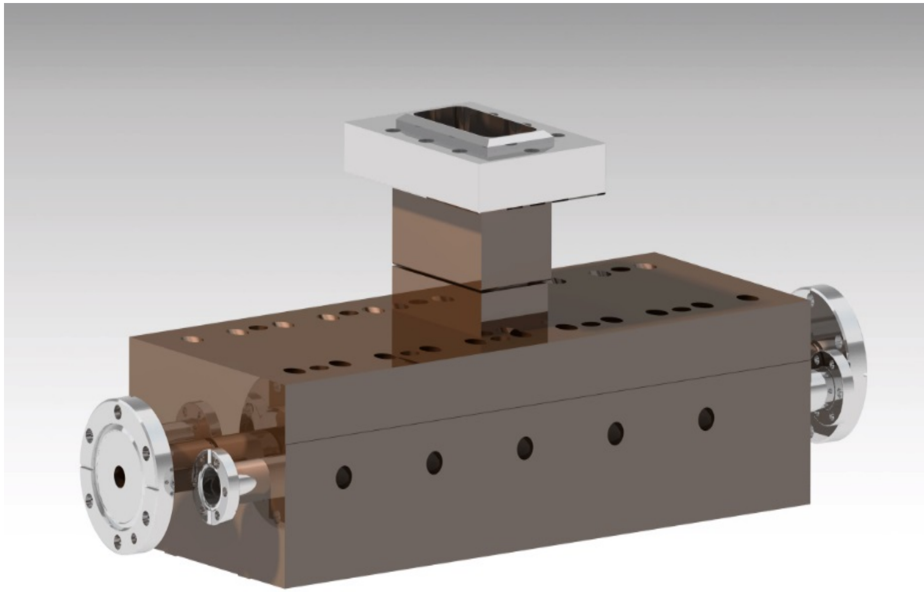
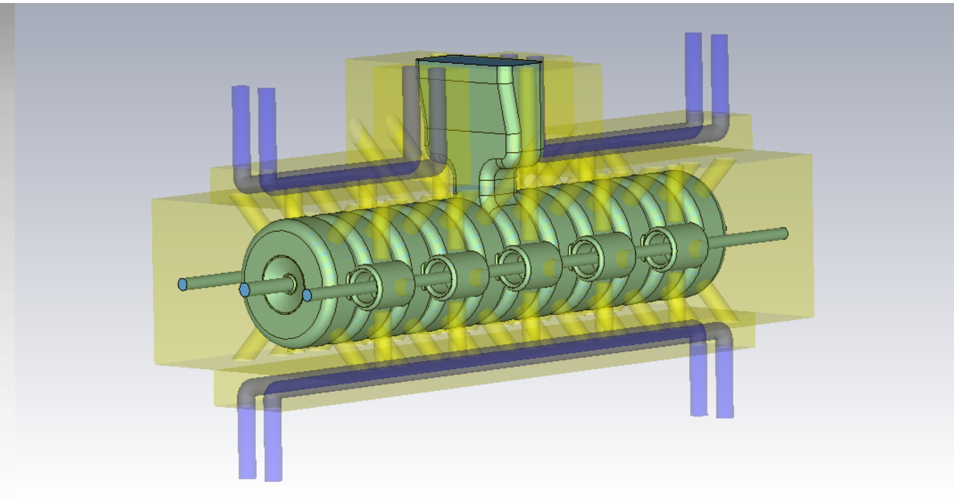
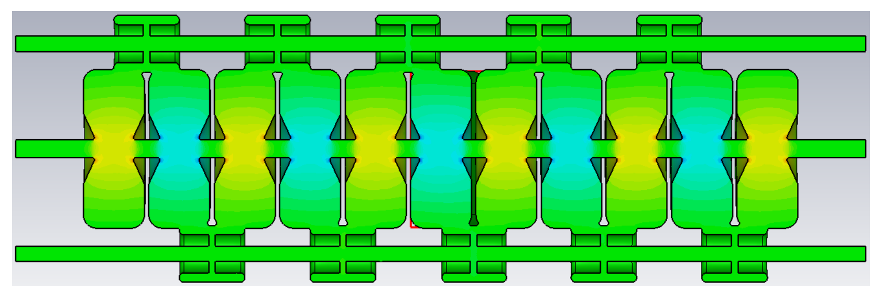
Chosen Design – S-Band (3 GHz) SC-SWS





- 54 MV/m is the gradient of the structure itself (not including focussing etc)
- 54 MV/m * 1.8m accelerating length = 97.2 MV
- 97.2/3m total structure length = 32.4 MV/m



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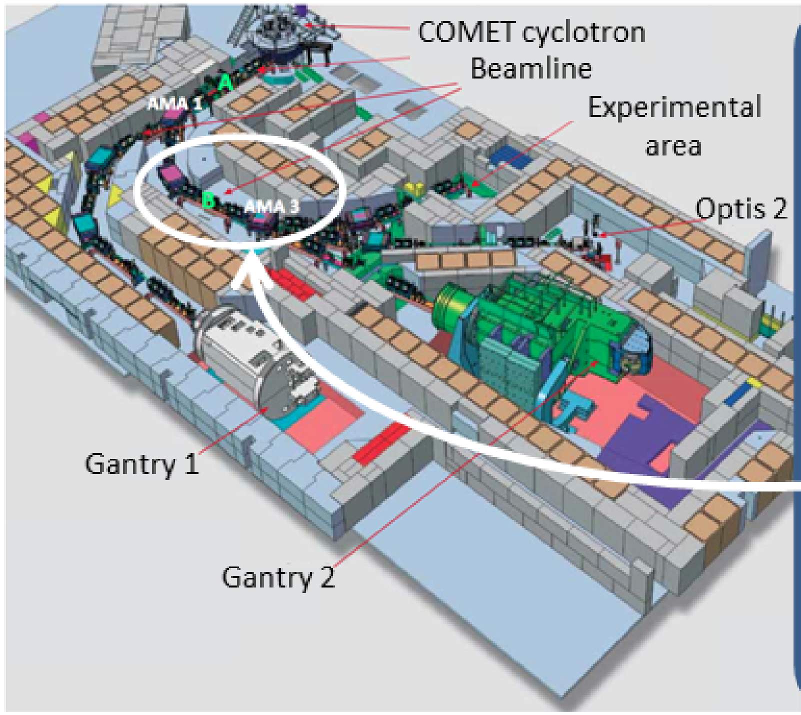
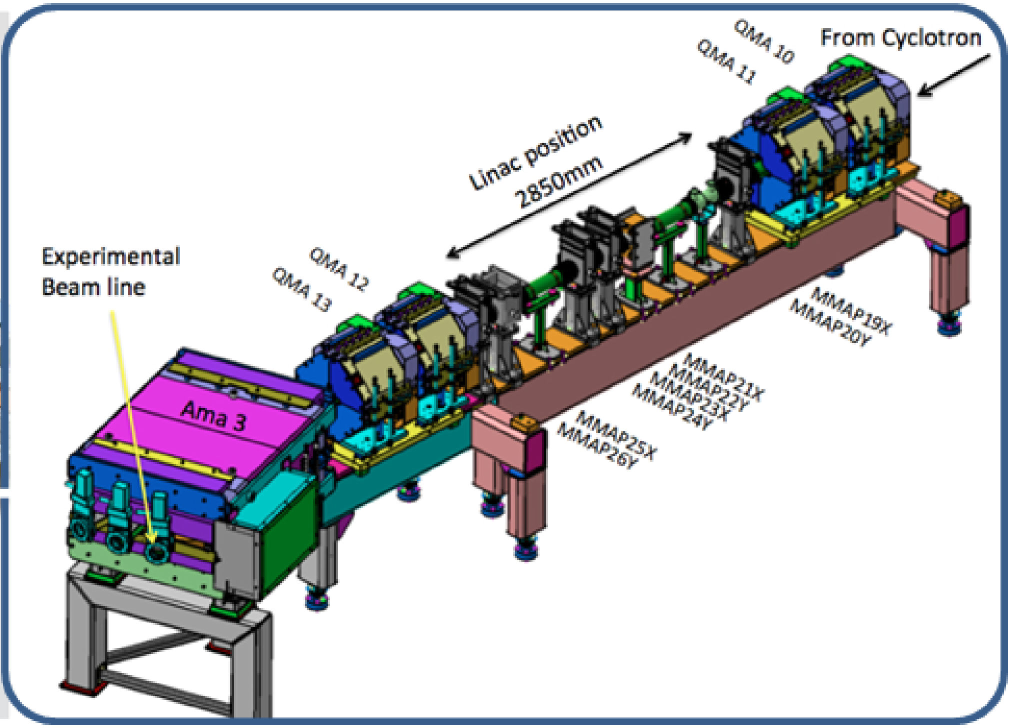
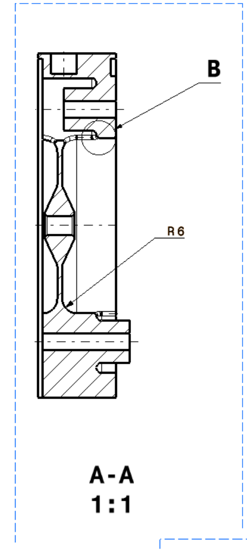
PSI IM-PULSE Proposal

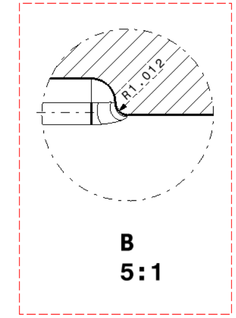


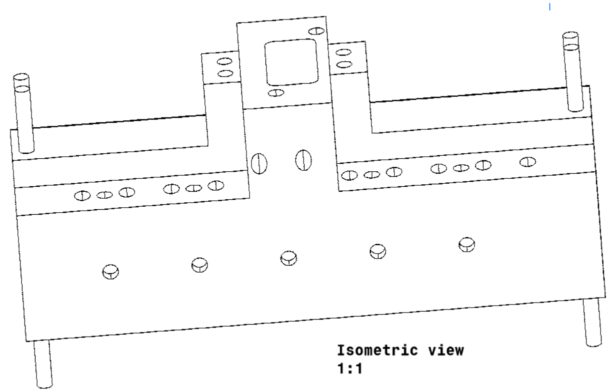


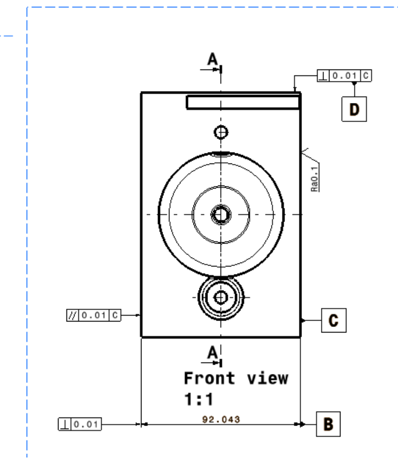
From structure to production…

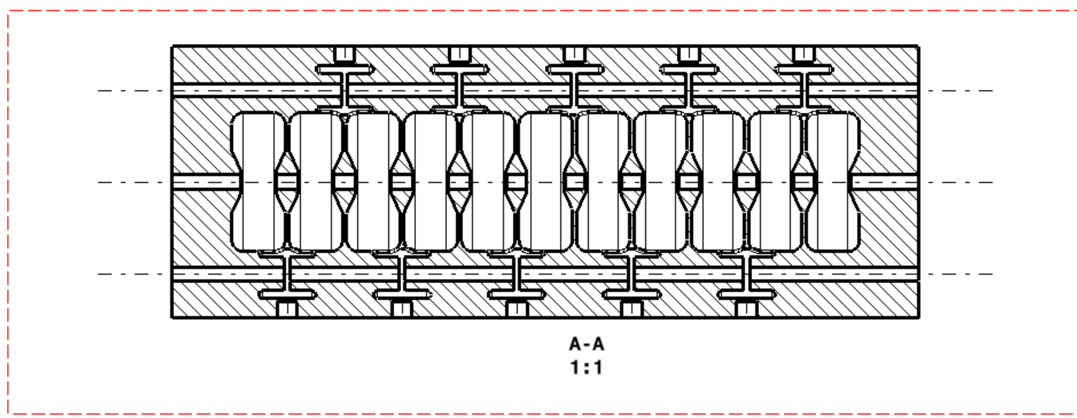
- Average power limited to around 2kW by heat transfer through thin iris.
- Temperature gradient across the structure causes operational detuning.
- Structure must stay within bandwidth of klystron (1MHz).
- 14K between cooling and iris.
- 14MW at 4.5μs long pulse.
- Rep rate 34Hz = 2kW Average power.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



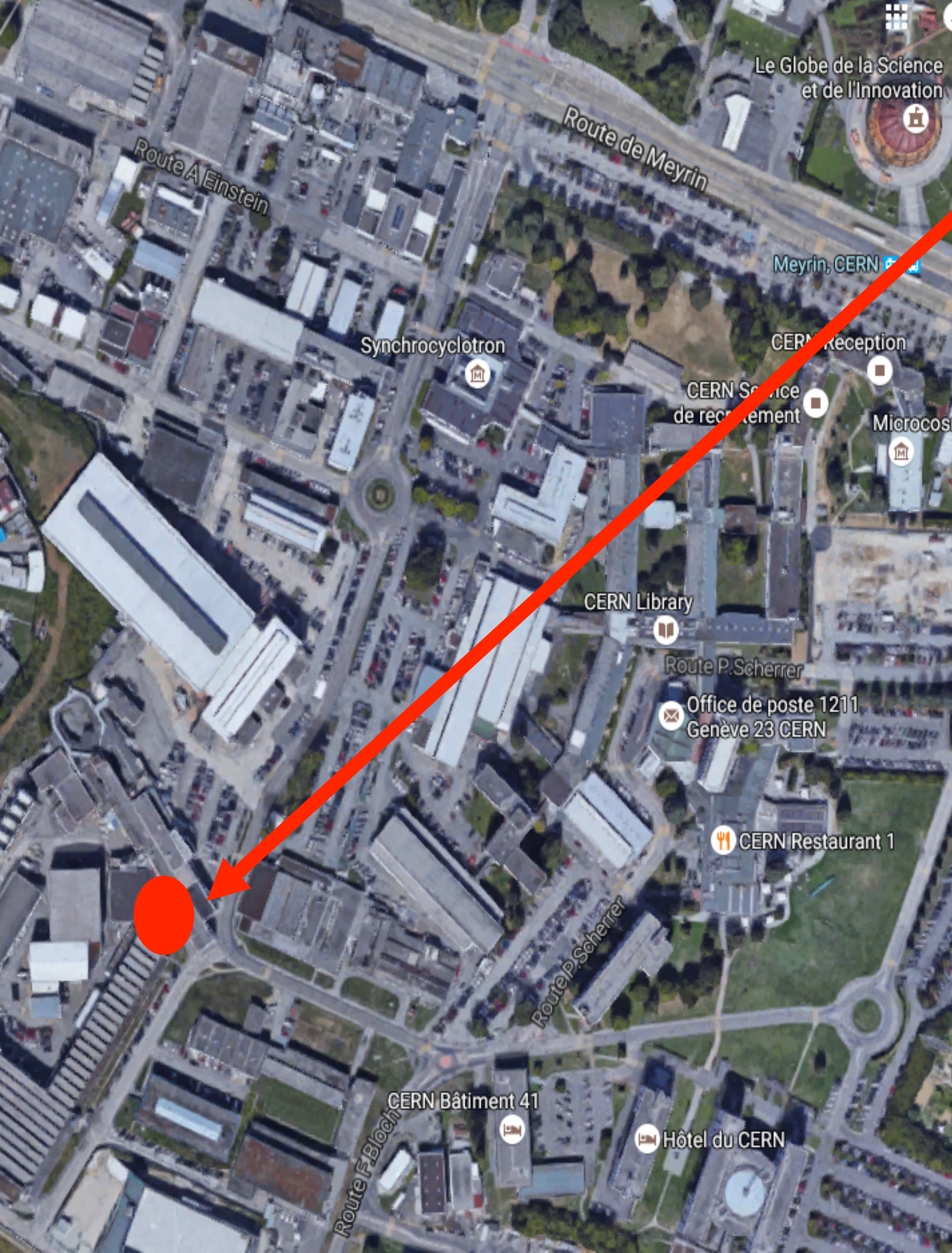








Funded by STFC Mini-IPS (2016 – 2017)



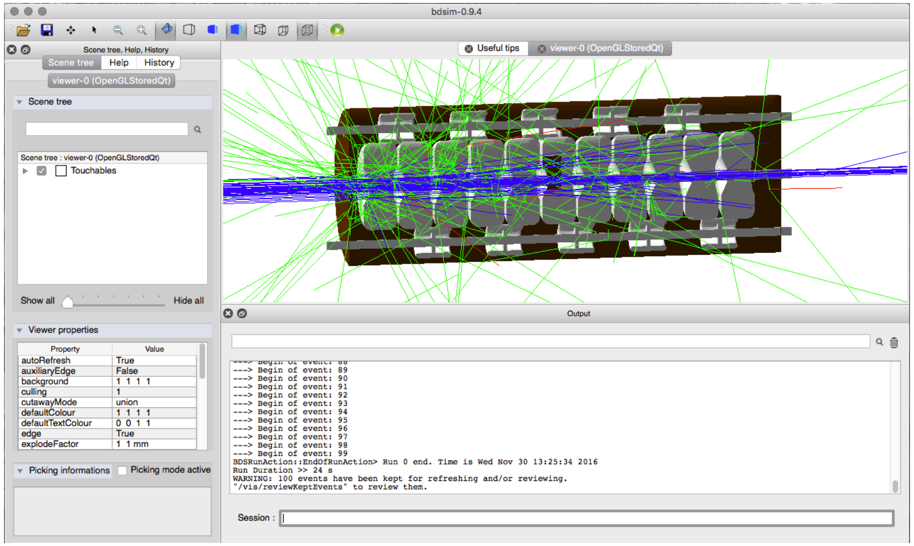
- S-Box testing facility is in building 2001 (ex CTF3).
- Currently conditioning another S-band high gradient structure (TERA) whilst our structure is built.
- All the creases will thus be ironed out for our structure tests next in line.

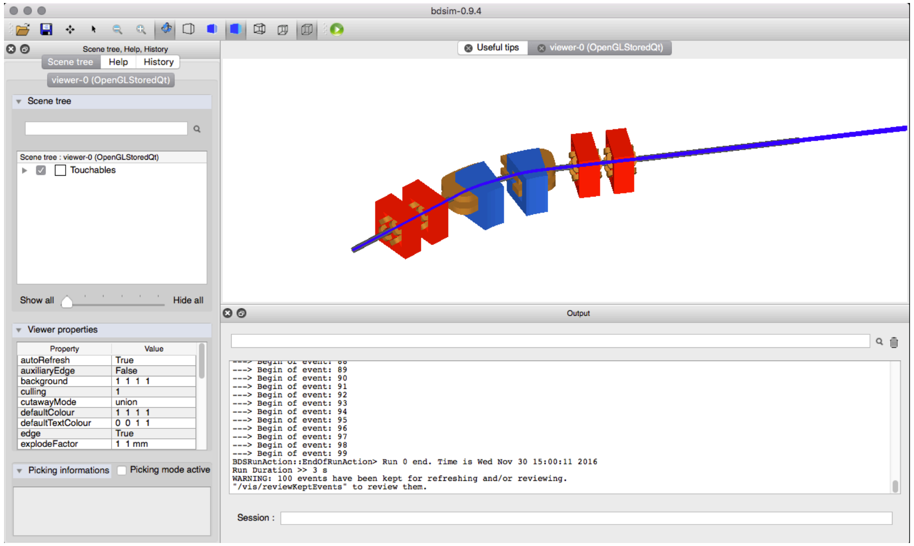
Tracking losses through the cavity (in progress!)

- Previously used a 'homebrew' tracking model plus iris radii
  - Gives approximate beam loss, but not subsequent radiation shower

- Working on a combined beam tracking/loss calculation in GEANT4
  - Uses BDSIM framework
  - We added CAD import
  - Field map import in progress
  - We added improved tracking algorithm
  - We added some parallelisation tools

  - A good general tool for proton therapy centre design, e.g. losses, shielding etc.





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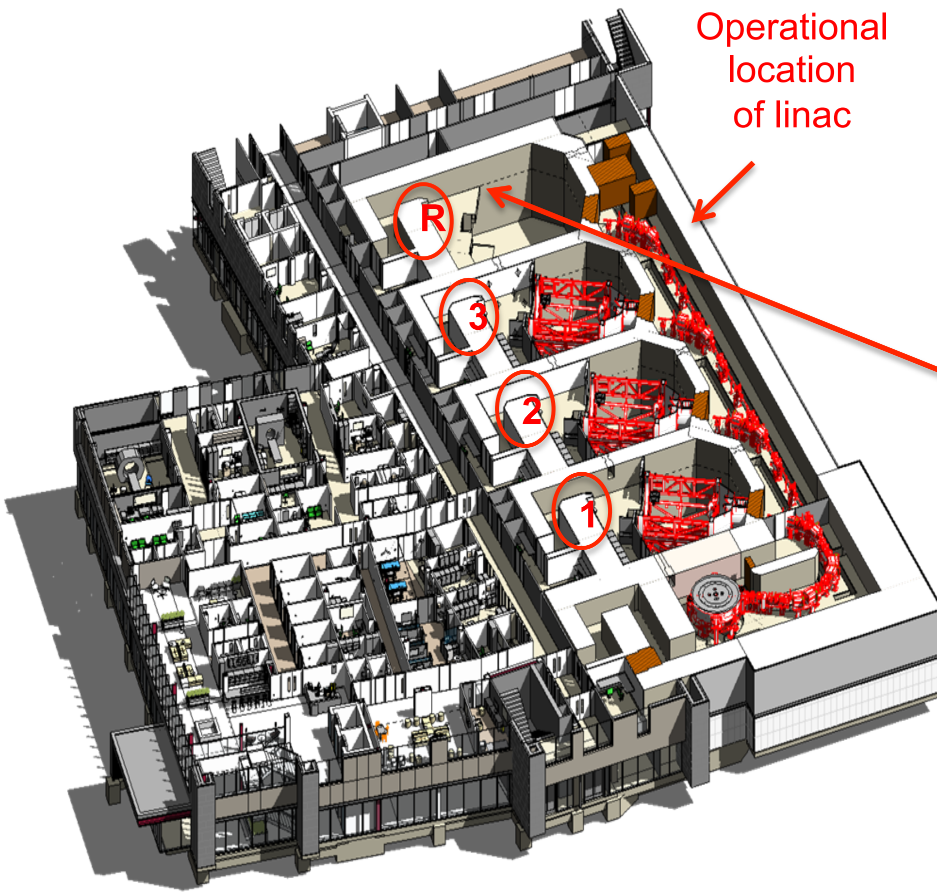
PROBE Project Stages



Stage 1

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

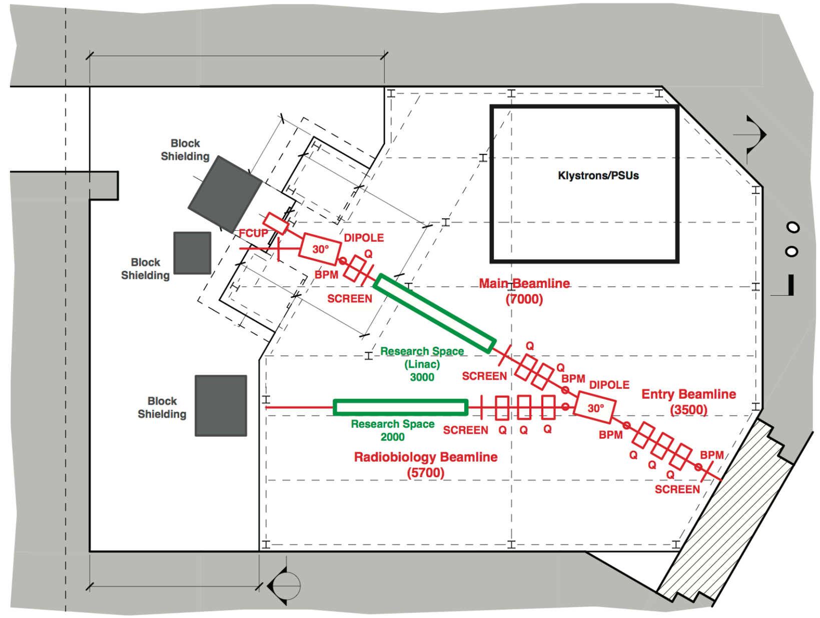
Stage 2

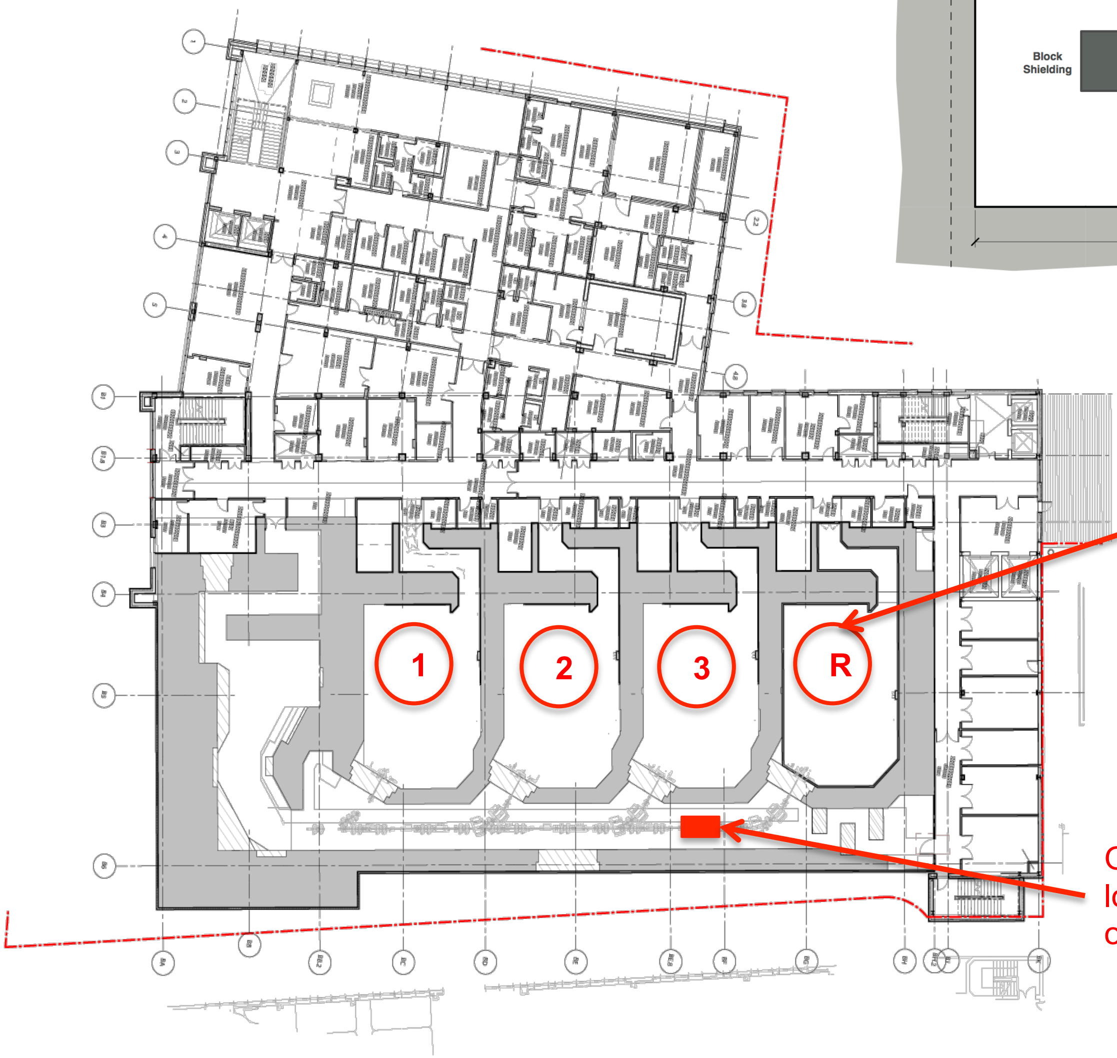
- Research Beamline
- 4th room at Christie

Stage 3

- Linac moved into beamline
- Superconducting Gantry

PROBE at Christie





Stage 1: develop linac
(PROBE project)

Stage 2: linac for testing
Stage 3: superconducting gantry

Operational
location
of linac

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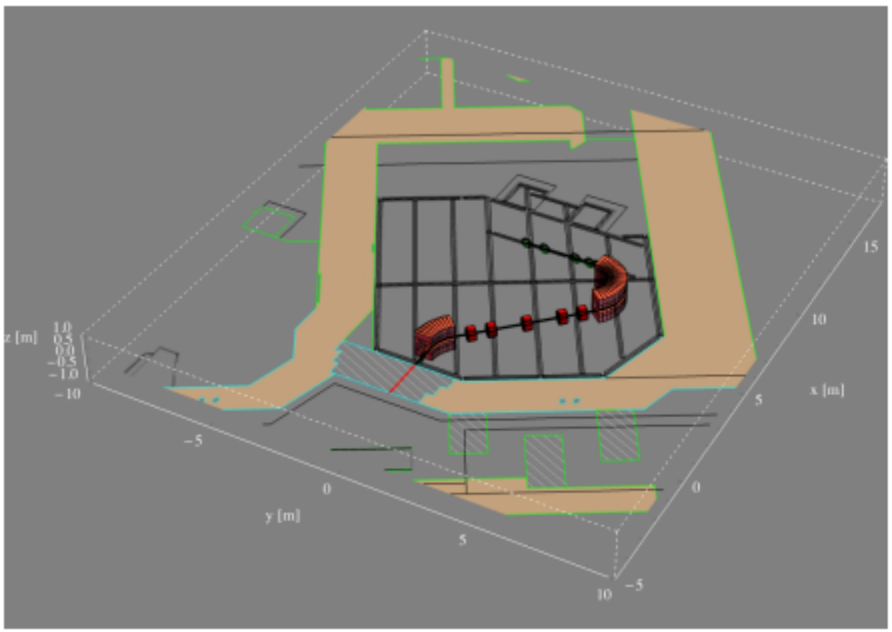
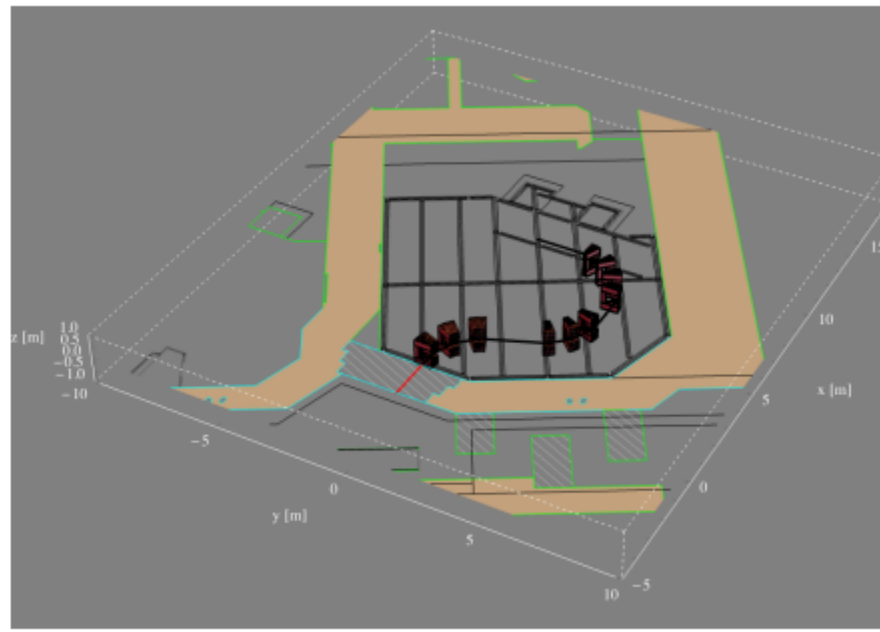
Gantry Design

- Examine SC design for 70 to 350 MeV protons;
- Incorporate booster linac if possible;
- Collaboration with PSI

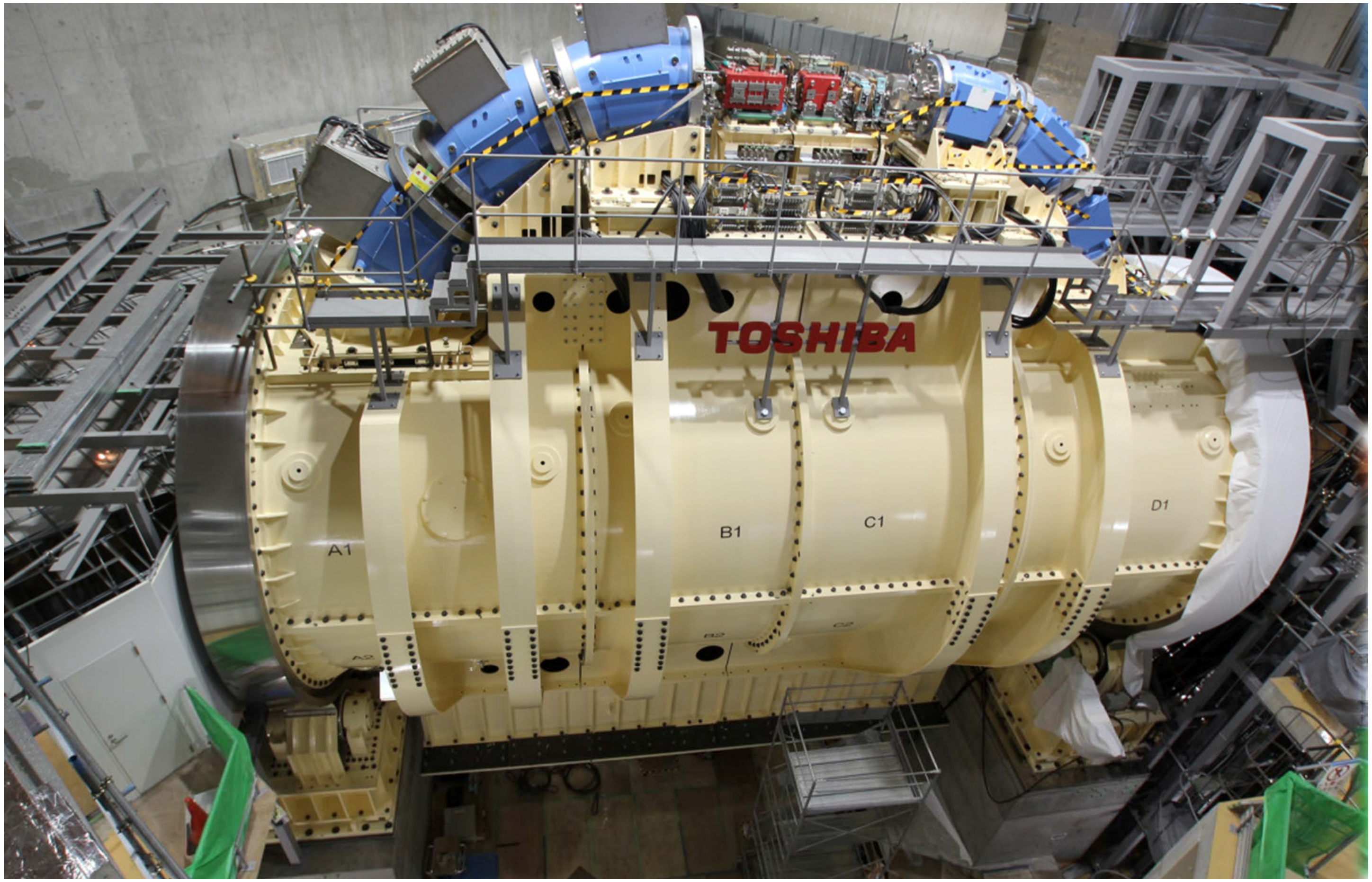


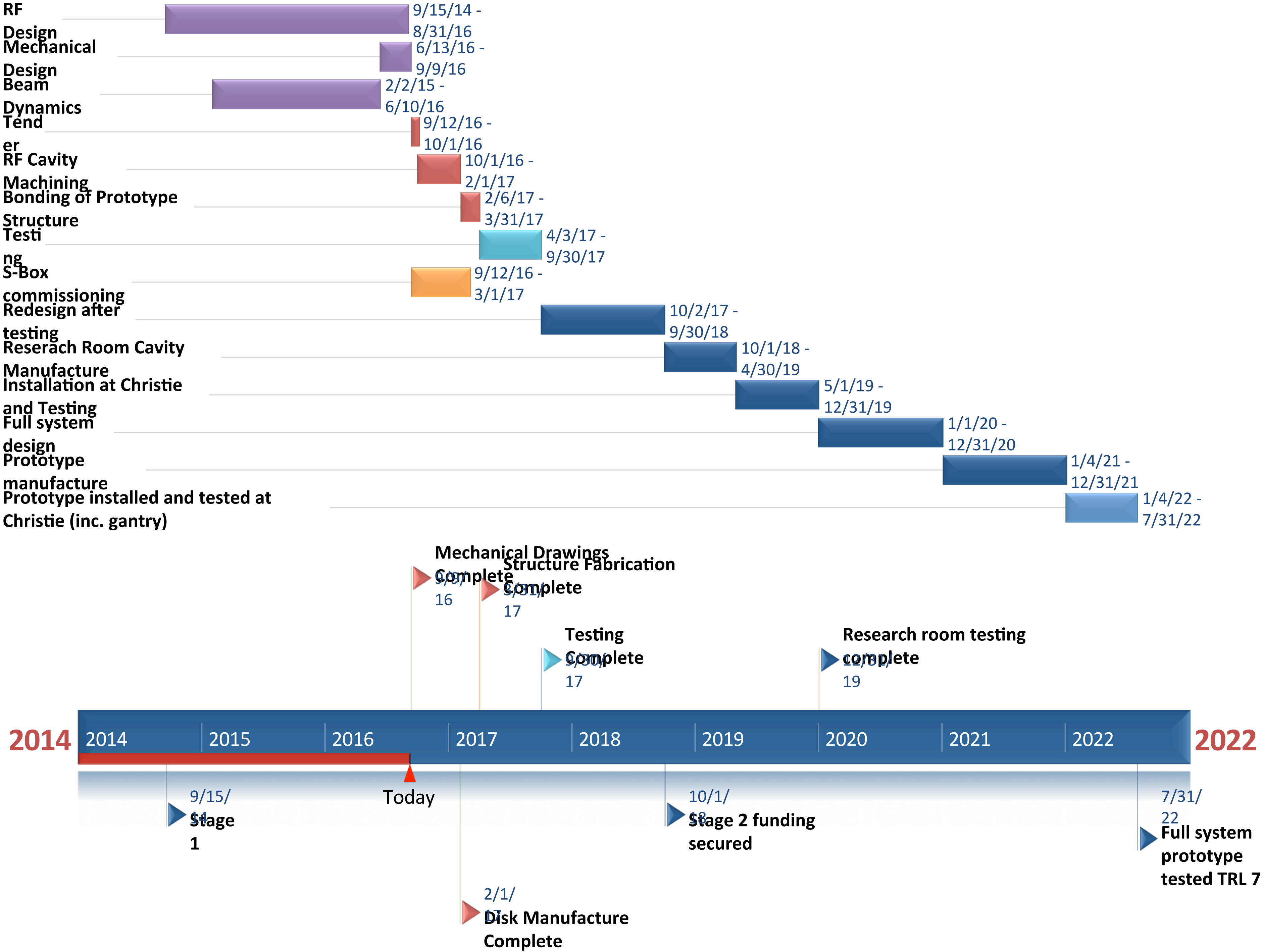


Varian (245 MeV)

pCT (330 MeV)

NIRS SC Gantry (working)

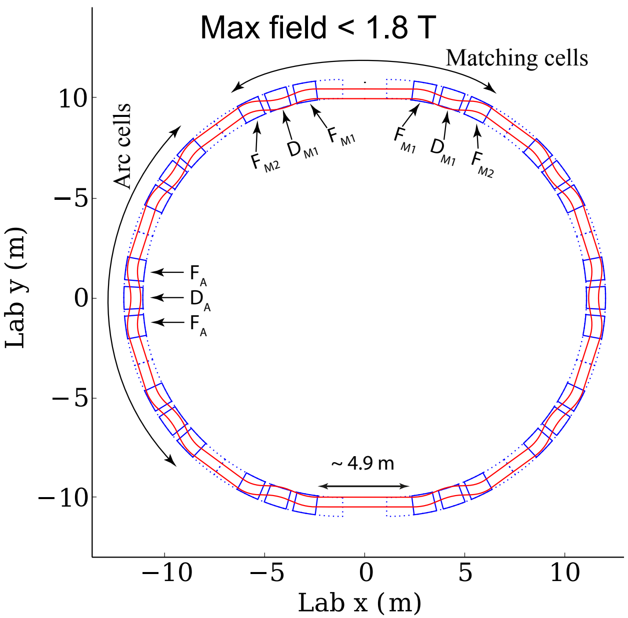


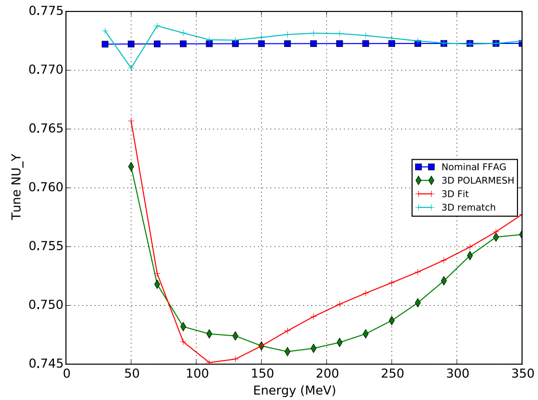


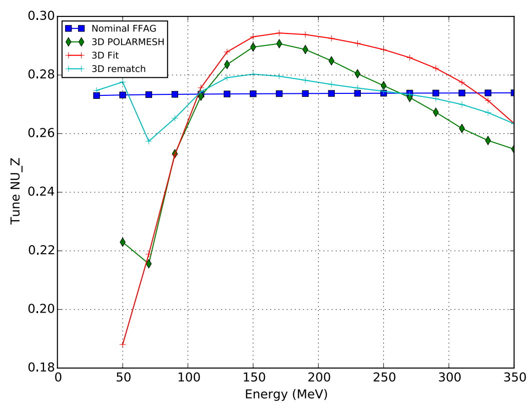
RF Design
9/15/14 - 8/31/16
Mechanical Design
6/13/16 - 9/9/16
Beam Dynamics
2/2/15 - 6/10/16
Tender
9/12/16 - 10/1/16
RF Cavity Machining
10/1/16 - 2/1/17
Bonding of Prototype Structure
2/6/17 - 3/31/17
Testing
4/3/17 - 9/30/17
S-Box commissioning
9/12/16 - 3/1/17
Redesign after testing
10/2/17 - 9/30/18
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

STFC PRD grant 2013-2015, c. £350k

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

ABSTRACT

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~

Norma Magnets

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Cockcroft Accelerator Group, The University of Manchester, UK

J. Clarke and K. Marinov
Cockcroft Institute, UK

NORMA is a design for a normal conducting race track fixed-field alternating-gradient accelerator (FFAG) for protons from 30 to 350 MeV. In this article we show the development from the nominal lattice design to a model implemented with field maps from 2D and 3D FEM magnet designs. We show that while to the fields from the 2D model are sufficient, adjustments must be made lattice to account for differences in the fringe and full 3D models. With the corrections implemented we recover the required dynamics of small tune shift and high dynamic aperture.

	Ring	Racetrack
Cell Radius (m)	9.6	10.55
Circumference (m)	60.4	70.7
Orbit excursion (cm)	43	49
Ring tune	7.72, 2.74	7.71, 2.68
Peak field (T)	1.57	1.74
DA (mm mrad)	68.0	57.7
Max drift (m)	2.4 (x10)	4.9 (x2)

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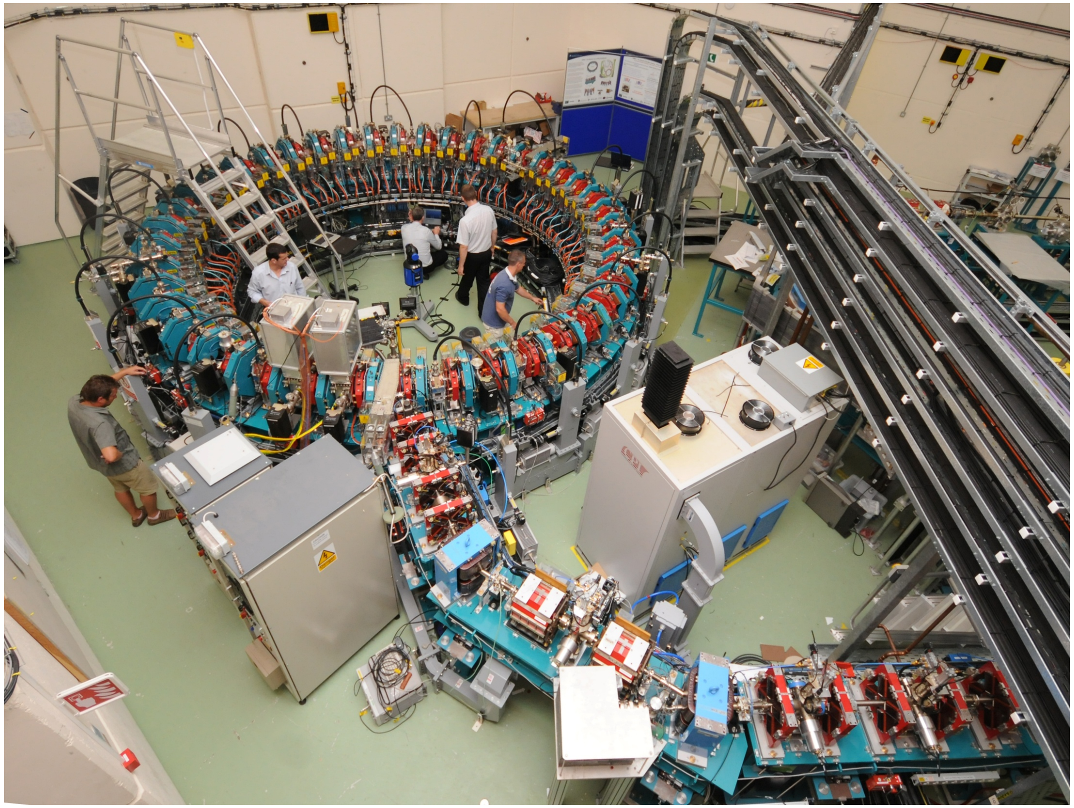
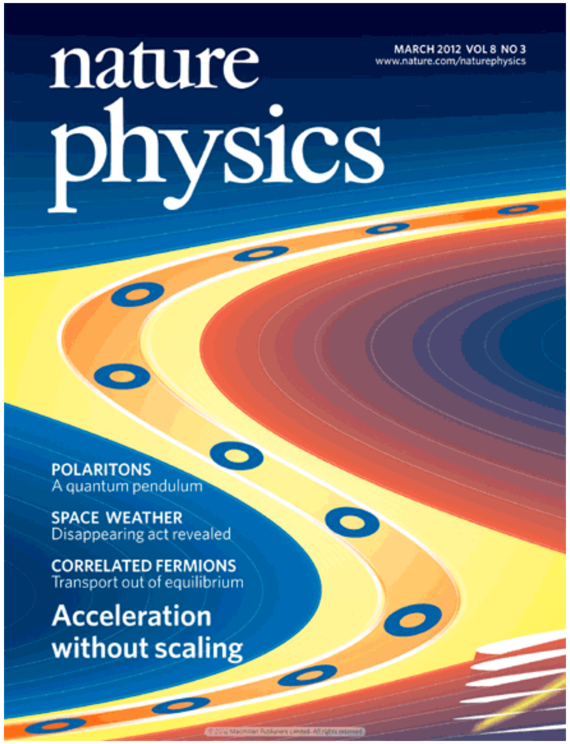
Future proton/carbon therapy - FFAGs





Basic Technology Award, £8M, 3 years
Cockcroft, John Adams, STFC, Fermilab, BNL....

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