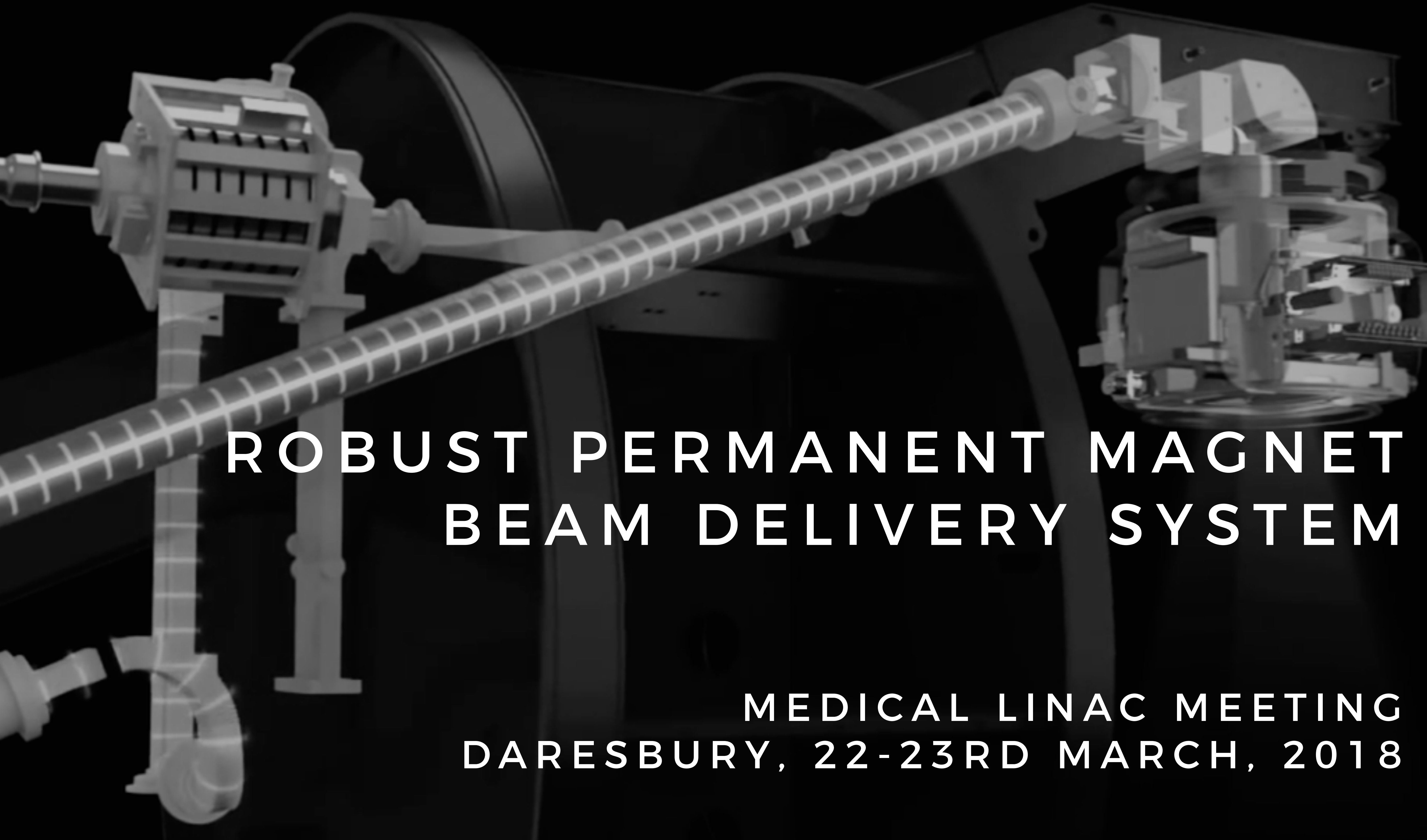


ROBUST PERMANENT MAGNET BEAM DELIVERY SYSTEM

MEDICAL LINAC MEETING
DARESBURY, 22-23RD MARCH, 2018

DR. SUZIE SHEEHY
ROYAL SOCIETY UNIVERSITY RESEARCH FELLOW
UNIVERSITY OF OXFORD

SESSION OVERVIEW

- Introduction and overview of project (Suzie Sheehy)
- Ben Shepherd (ASTeC) - Overview of permanent magnets for accelerators
- Adam Steinberg (Univ. Oxford) - Simulations of medical LINAC using ASTRA
- Paul Coe (Univ. Oxford) - Permanent magnet studies
- Discussion: Next steps on this subsystem (Suzie Sheehy & Ivan Konoplev)

THANKS TO:

- Deepa Angal-Kalinin, Ben Shepherd, Boris Militsyn, Graeme Burt, Julian McKenzie, James Jones - Cockcroft Institute and Daresbury Laboratory - for their input to this project and ASTRA input

- Frank Van den Heuvel (Oxford Oncology) for advice and tour of Oxford radiotherapy LINACs

- Prof. Paul Keall and Dr. Brendan Whelan (University of Sydney, Australia) for discussion on modelling 6MV linacs in context of MRI-Linac project

- Mr. Thomas Kron (Peter MacCallum Cancer Centre, Melbourne, Australia) for advice on medical physics & IAEA report

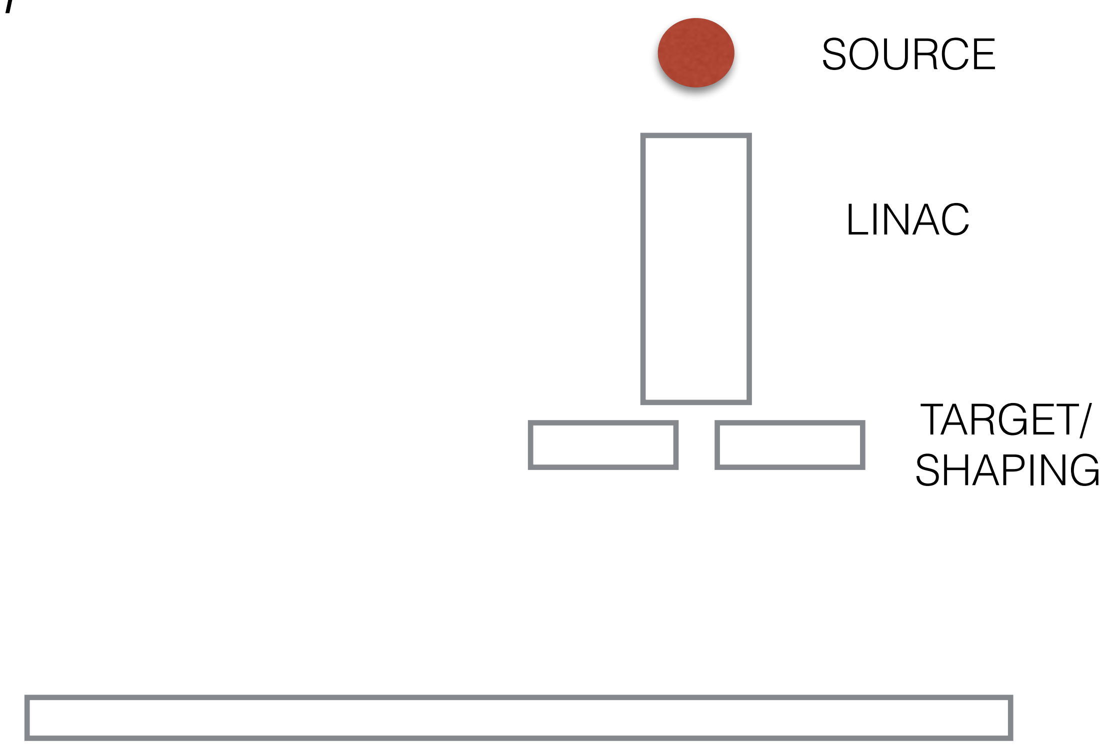
- Paul Collier and Walter Weunch (CERN) for hosting visit of Paul & Ivan.

- Julian Gascoyne (3rd year, Univ. Edinburgh) for COMSOL models of Halbach quadrupoles and quick error studies.

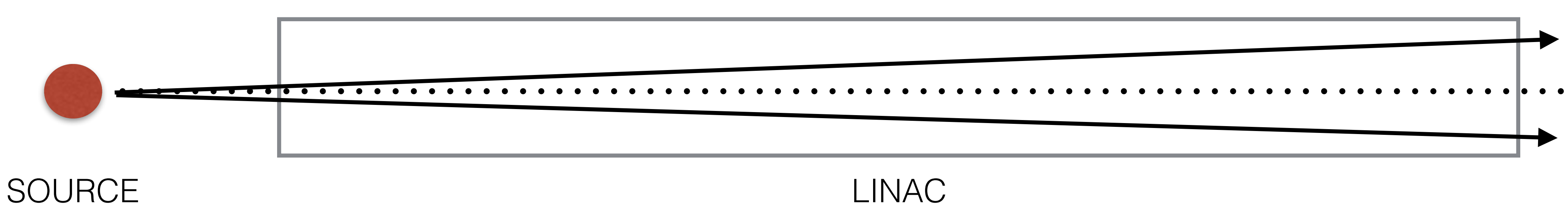
PROJECT AIM

To design and study a beam delivery system for a ***~6MeV*** *medical radiotherapy LINAC to reduce the number of required electromagnets and water cooling while providing a high quality beam to target.*

Blue = still needs defining
(iteration with rest of collaboration)



- Some low energy linacs (cf. Varian 600C) are designed assuming NO magnetic focusing, so the beam just blows up as it transmits through to the end. (Watnbersie, 1994)



PROJECT GOALS & DELIVERABLES:

1. Charged particle optics design (using open-source software if possible) of electron beam delivery system, including detailed studies of likely magnet errors arising from temperature and radiation environment.

2. Conceptual design of Halbach-style solenoid and/or quadrupole magnets with suitable magnetic field for this application.

3. Report on how this beam delivery system would be **integrated into a robust LINAC** for medical environments.

RESEARCH QUESTIONS

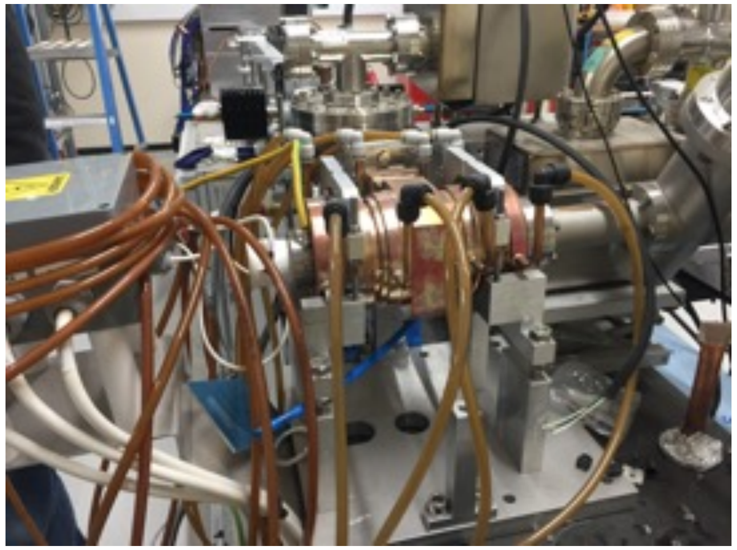
WHAT FOCUSING DOES THE ROBUST MEDICAL LINAC NEED?

"The initial emittance is determined by the electron gun but subsequent elements in the focusing and acceleration systems produce effects which substantially increase the emittance. Factors between 10 and 100 are not unusual" - pp. 29 CAS notes

- What is the emittance at the source? **(Depends on source)**
- Set up method of simulation/modelling to determine required focusing and beam quality.

Need to study beam dynamics of proposed linac structures to see losses

SEE ADAM'S TALK



4MV industrial setup at DL

ARE PERMANENT MAGNETS SUITABLE FOR THIS APPLICATION?

The electromagnets used are often *water cooled*. We should aim to remove this complexity.

Permanent magnets may offer another option (cheap, easy to maintain, no power required), but the fields are *temperature dependent* and the fields have *less flexibility* compared to electromagnets

- **SEE BEN'S TALK**

  - Need to study the error tolerances of fields in permanent magnets in potentially large temperature fluctuations.
  - **SEE PAUL'S TALK**

- Later: bring this together with beam dynamics model & study beam quality

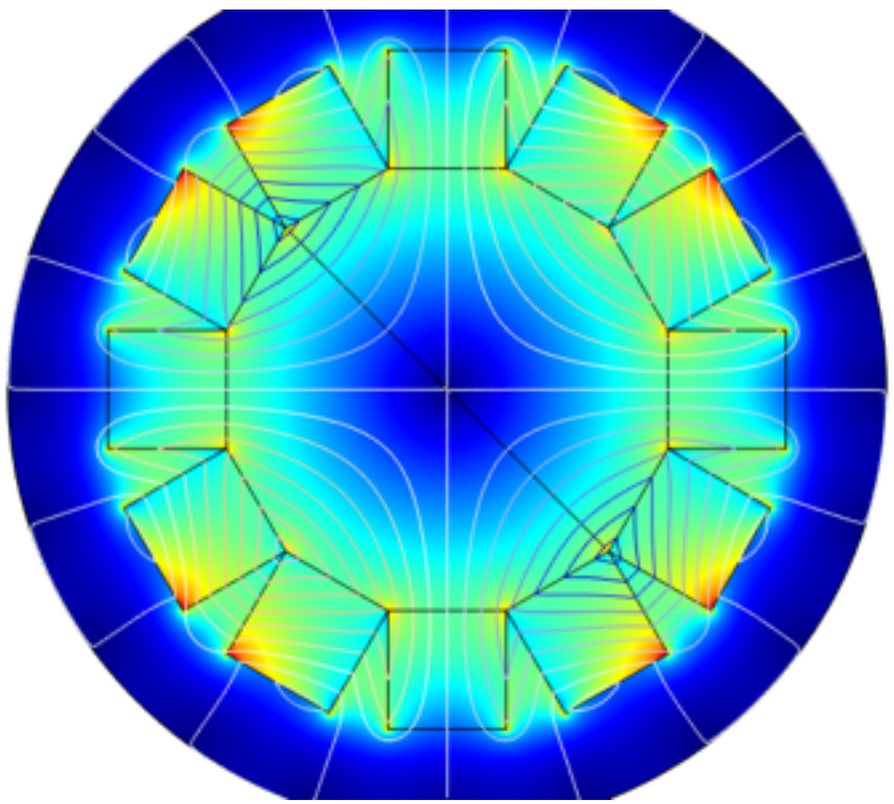
MAIN PROGRESS SINCE OCTOBER:

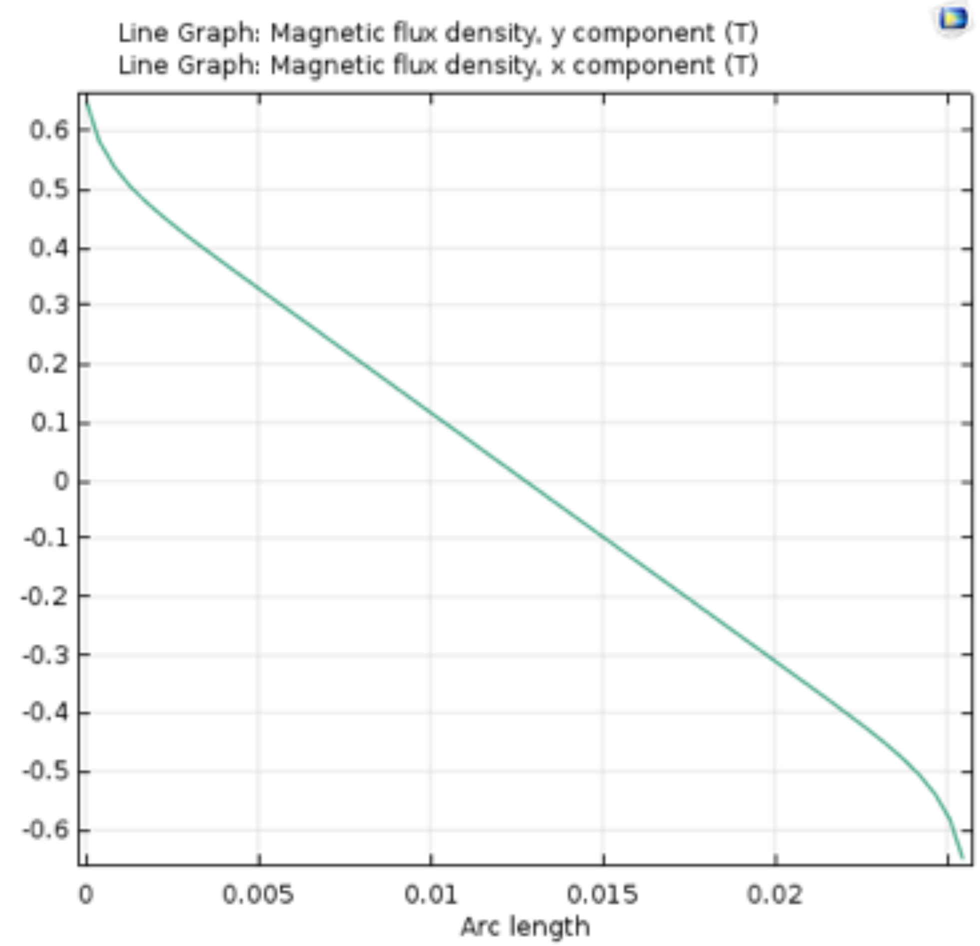
1. Building & training our team
2. Defining the problem and learning about medical LINACs
3. Setting up simulation codes
4. Comparing models and tools

WORK REMAINING:

- **Specify beam energy and likely structure with rest of collaboration**
  - feeds directly into magnet requirements!
  - Aperture of magnets driven by frequency if they go AROUND structure!
- Continue work on quadrupole magnets and extend to solenoids
- (Prototype potential magnet with Oxford Physics workshops)
- Compare beam dynamics with both options
- Write up reports on findings

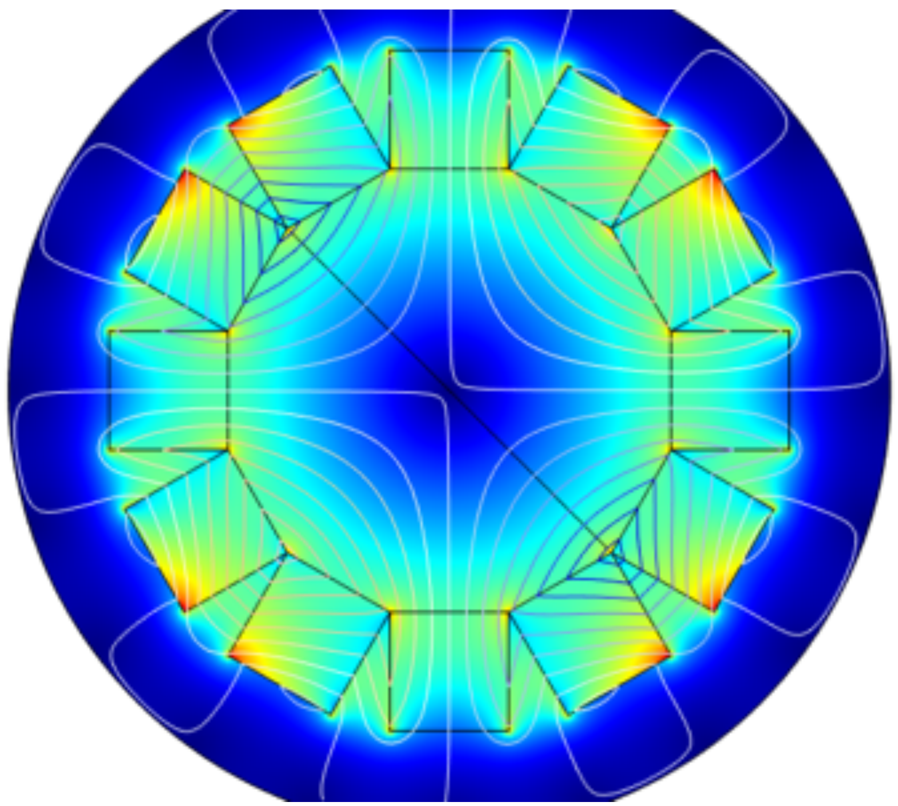
COMSOL MODEL
(J. GASCOYNE, EDINBURGH)

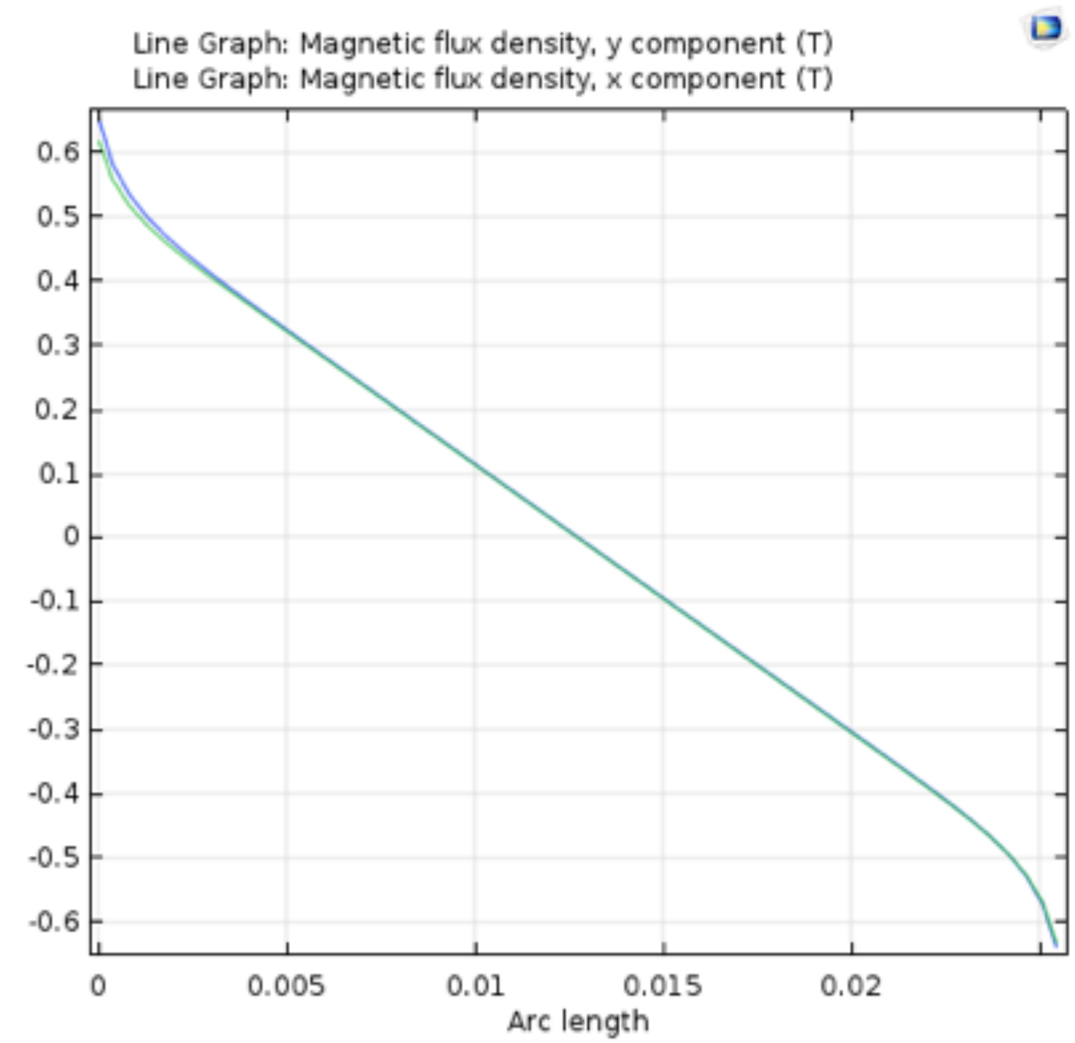




‘IDEAL’ HALBACH

COMSOL MODEL
(J. GASCOYNE)





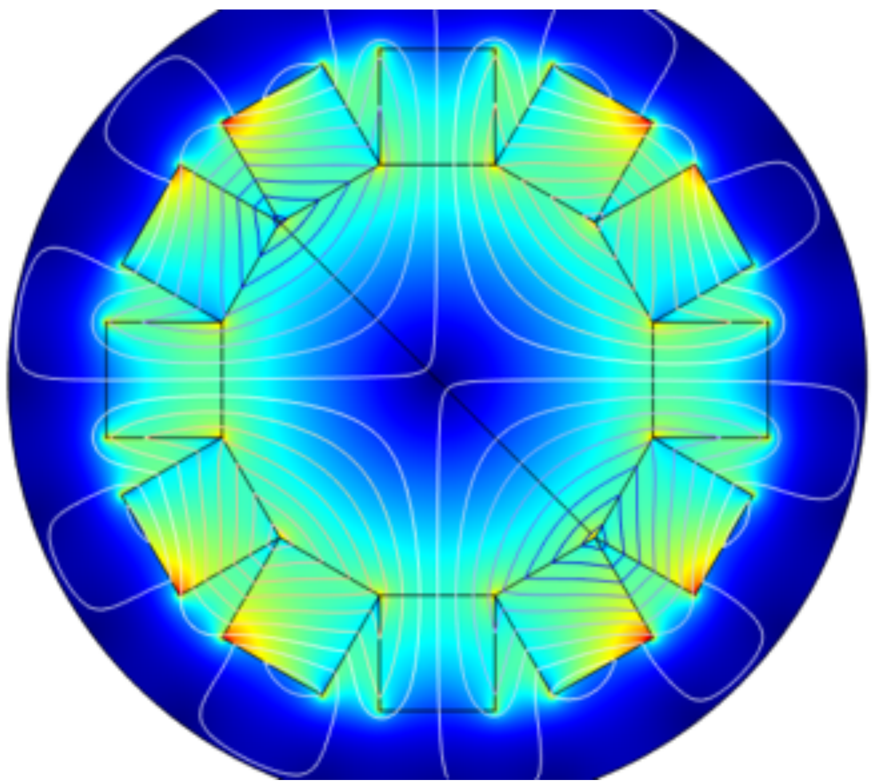
Randomly assigned field strengths

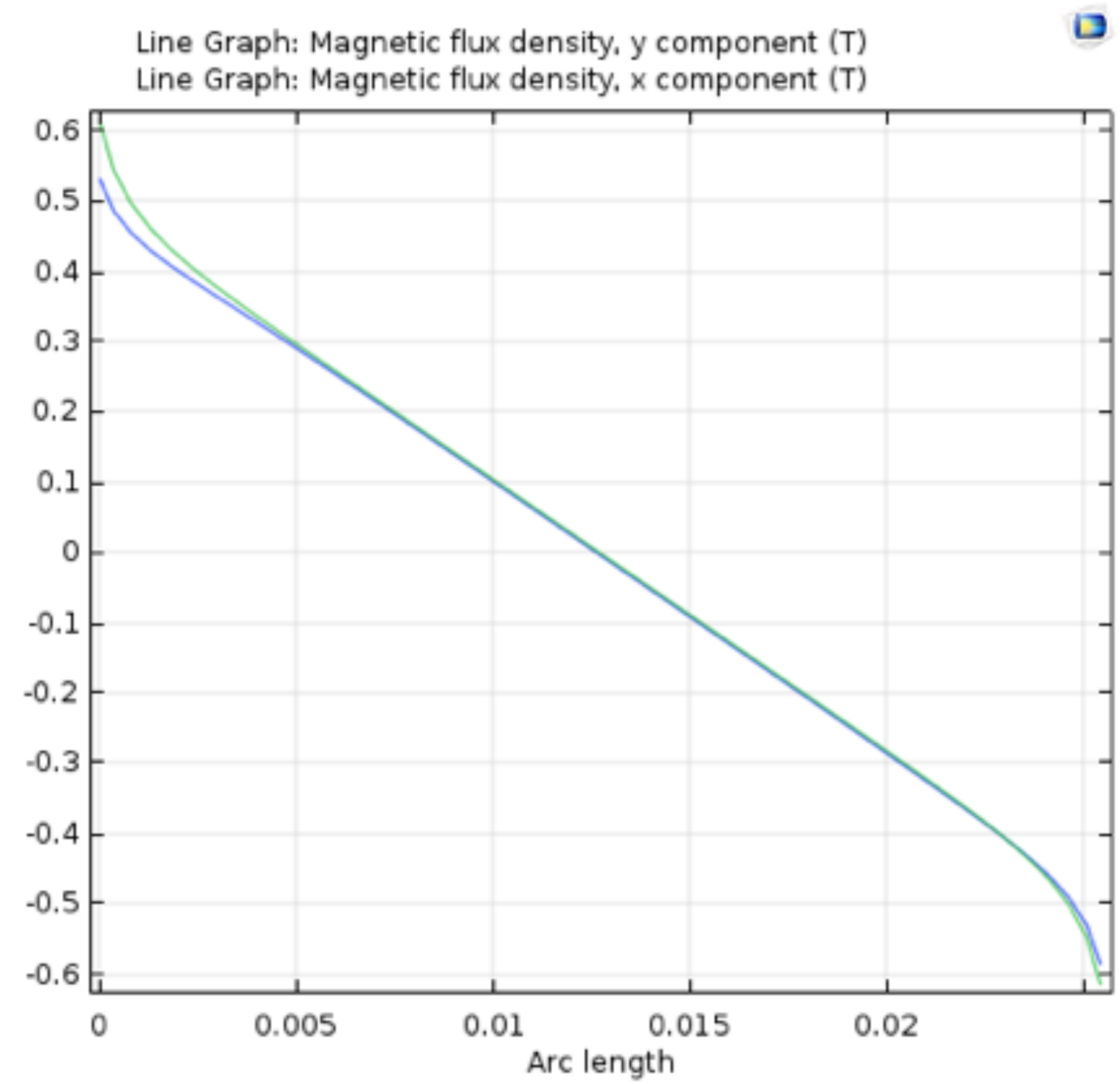
Full strength is 1.42T

These are the magnitudes of the fields of each magnet in the quad:
N magnets: 1.4T
E magnets: 1.38T
S magnets: 1.42 T
W magnets: 1.36

RANDOM ERRORS (1)

COMSOL MODEL
(J. GASCOYNE)





Full strength is 1.42T

These are the magnitudes of the fields of each magnet in the quad:
N magnets: 1.28 T
E magnets: 1.35 T
S magnets: 1.17 T
W magnets: 1.32 T

RANDOM ERRORS (2)

1. Creating the quadrupole magnet:
    a. Creating a model of a 12 magnet quadrupole
        i. These magnets are 6.73mm x 6.73mm and the internal radius (i.e., from the centre of the quad to the centre of the surface of each individual magnet) is 1.256cm
        ii. The line through the middle is simply the axis over which the plots are made
    b. Defining the magnetization vector (N, S, E, or W with magnitude 1.42 T (definition of N52 NdFeB magnet)

1. Making the colourful picture:
    a. Generating a surface plot (background colour) of the Norm(B) = sqrt(Bx^2 + By^2)
    b. Generating a contour plot (coloured lines) of the z component of the magnetic vector potential (Az)

1. Making the 1d plots of B field:
    a. The blue linear plot is the y component of the B field on the inside (By)
    b. The green linear plot is the x component of the B field on the inside (Bx)

1. Making the 1d plots of dB/dx and dB/dy:
    a. The blue line is dBy/dy
    b. The green line is dBx/dx
    c. The cyan line is dBy/dx
    d. The red line is dBx/dy

BEAM PARAMETERS

From working google doc…

Electron KE	Source ~30 keV	Exit 6 MeV
Gamma_rel = 1+T/E0	1.0587	12.742
Beta_rel = sqrt (1-gamma^-2)	0.3284	0.9969
Pc = E0*sqrt(gamma^2-1)	0.0104 (MeV)	6.49 (MeV)
Beam divergence	?	<=3 mrad
Beam diameter	1.8mm (?)	2-3 mm
Beam emittance	1.065 mm mrad (100%)	?

So if we go for a 'no-bend' solution, we still need focusing and steerers

- Usually solenoids are used, can be placed around the accelerating structure

Focusing by Solenoids

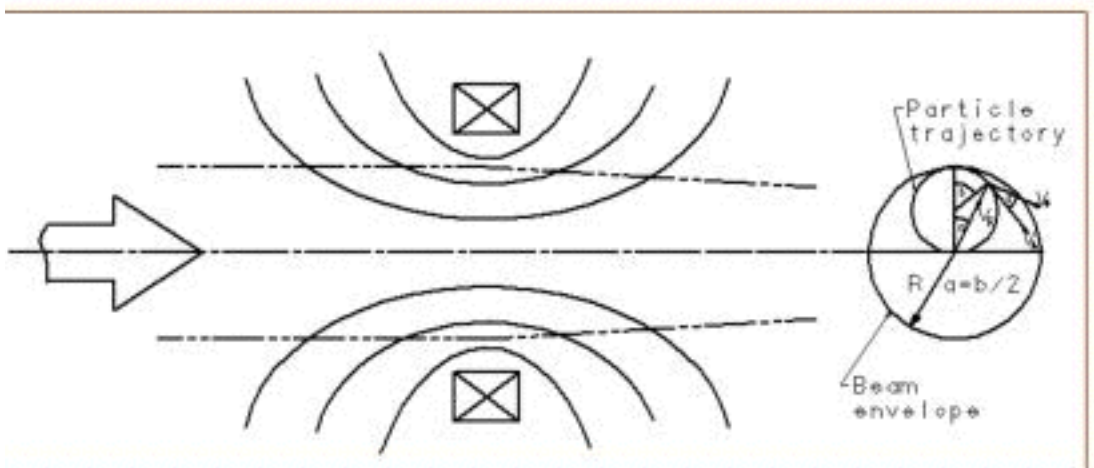
Motivation:

1. **Potentially lower rate of emittance growth**
2. **Axially symmetric focusing**
3. **Relaxed alignment requirements**

Limitation:

Low energy of protons

Only front end of RF linacs can use solenoid-based lenses



Radial component of a fringe field combined with asymmetric particle rotation (Bush theorem) provides radial component of the particle velocity; hence the focusing effect in short lenses

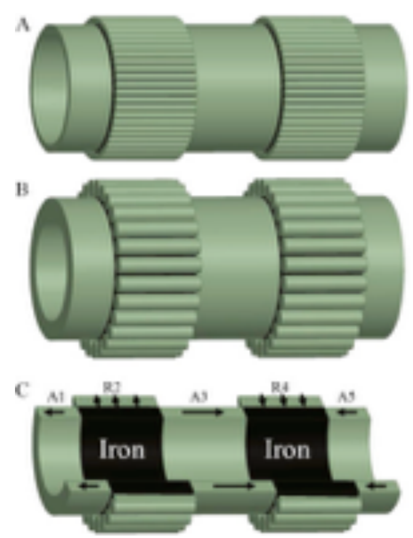
Focusing length:

$$f = R \cdot \frac{\beta c}{v_R} = 4\frac{m^2}{q^2}\beta^2 c^2 \cdot \frac{1}{B_c^2 L_{eff}} = \frac{8 \cdot \frac{m}{q} \cdot T(eV)}{B_c^2 L_{eff}}$$

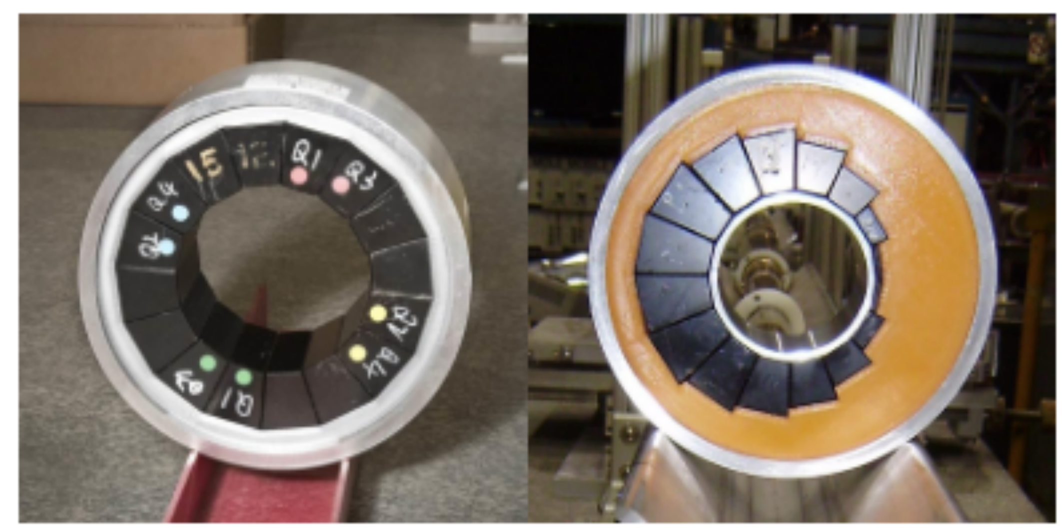
So if we go for a ‘no-bend’ solution, we still need focusing and steerers

- Could we use permanent magnet quads instead? (Need space? Temperature dependent)
- If sufficiently short linac, can just have focusing prior to the linac and transport through (e.g.) 3 GHz structure without loss. [CAS notes, pp.29]

Consider ‘Halbach’ style permanent magnets? Either quads or solenoid configuration.



http://www.sciencedirect.com/science/article/pii/S0168900217306617

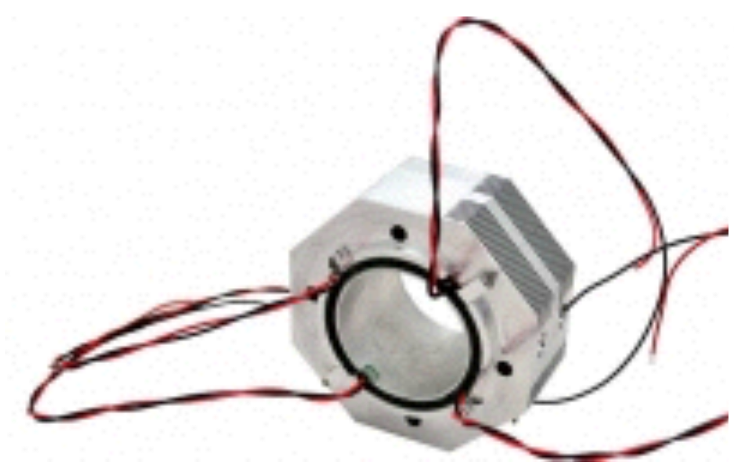


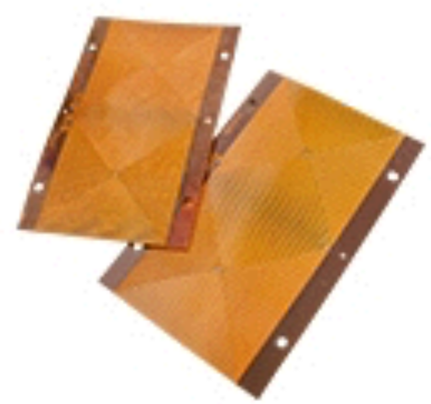
S. Brooks. BNL

See ‘Designing permanent magnet solenoids’
http://www.fieldp.com/documents/pmsolenoid.pdf

Correctors/steerers

- People have developed printed circuit steering magnets (no remnant field, good in tight spaces).
- Can also be installed on inside of PMs to provide field adjustment.





We can't do without steerers if the LINAC rotates (due to B_Earth!), but they can probably be made robust and easily replaceable. Automatic feedback can be used to make sure position is very stable.

QUESTIONS/DESIGN CYCLE…

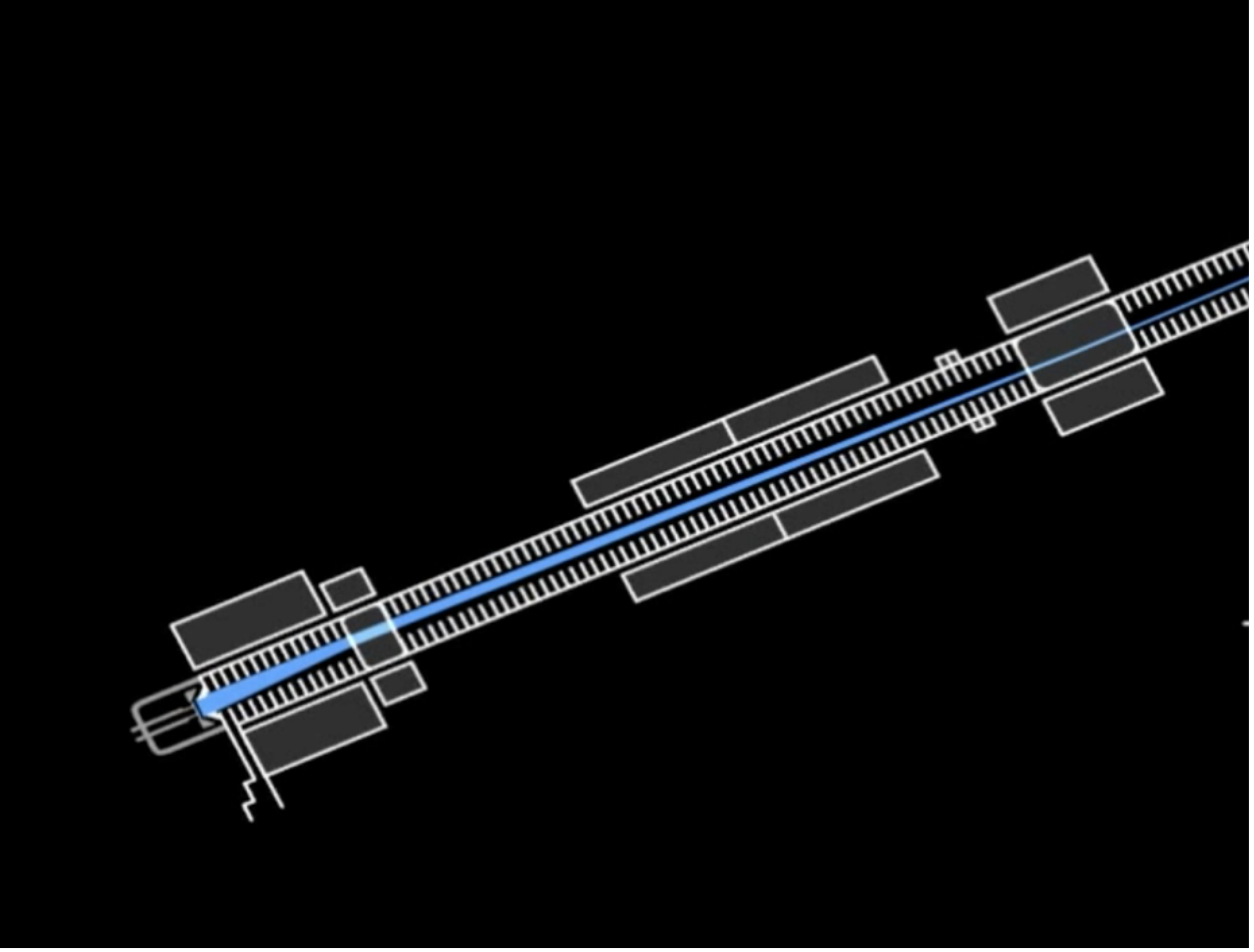
For collaboration:

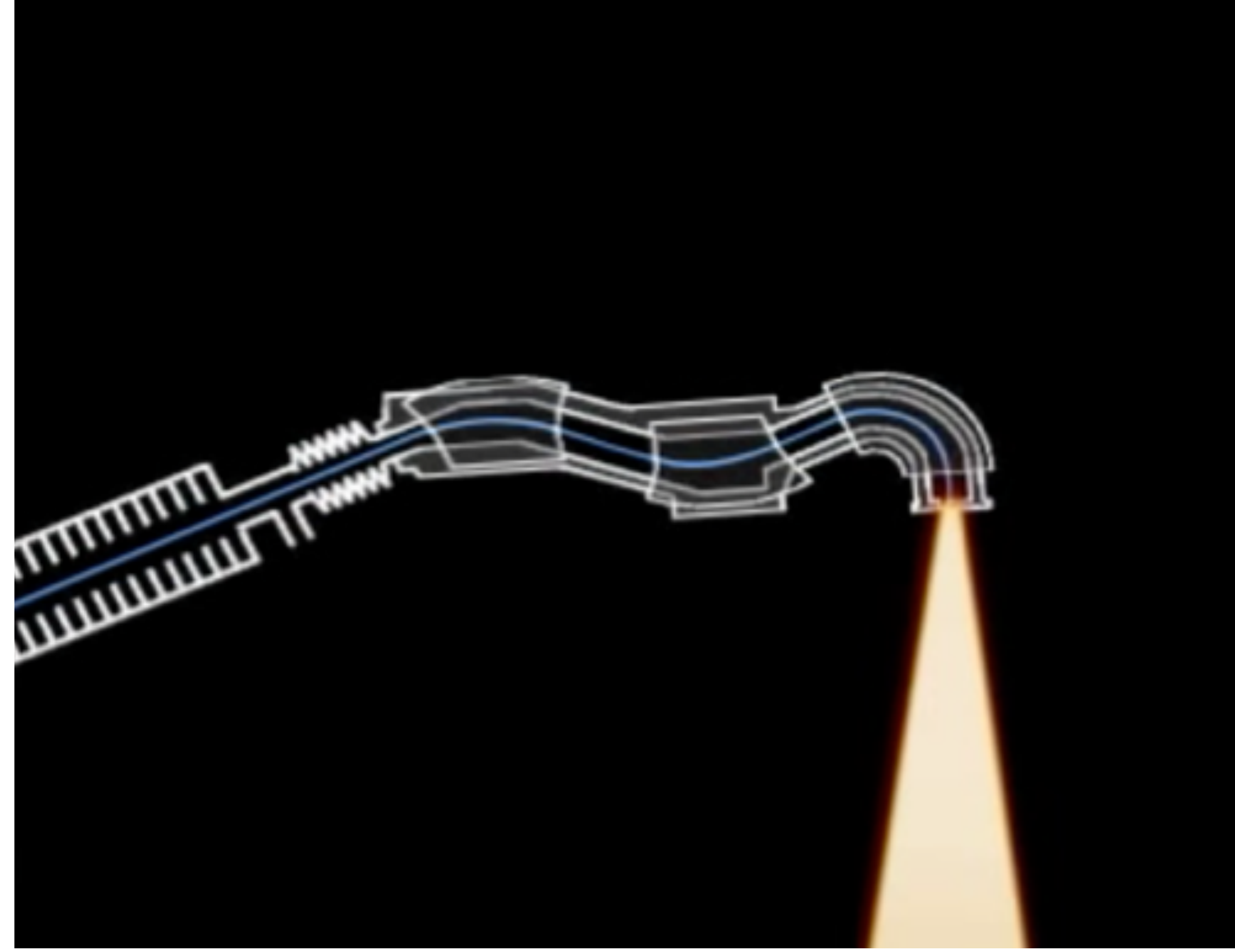
- **Define ‘MVP’ = minimum viable product**
- **Separate out requirements into MVP & LINAC 2.0**

For magnetic focusing:

- Single energy = far easier than multi energy
- Do we need an achromat/chicane anyway? How will we ensure the energy is correct otherwise?

EXTRA SLIDES





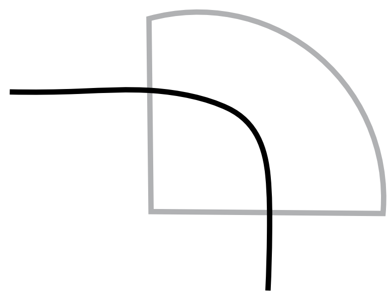
FOCUSING MAGNETS

- Keeps the beam controlled through the main linac body
- In main linac section there are also a number of steering magnets
- Should be kept fairly simple in terms of beam dynamics

BENDING MAGNETS

- Bring the beam around to the patient
- Different companies at present use different focusing systems
- Keeping the whole system compact can be achieved by thinking carefully about this part

BENDING OPTIONS

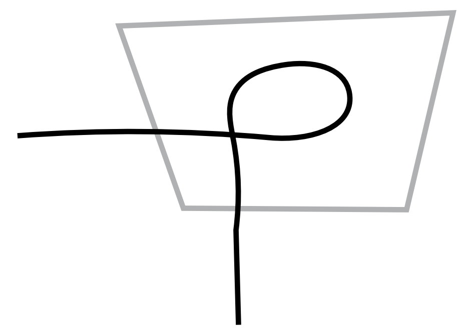


90 DEGREES

Directs beam straight round onto patient

Pros:
- compact
- simple

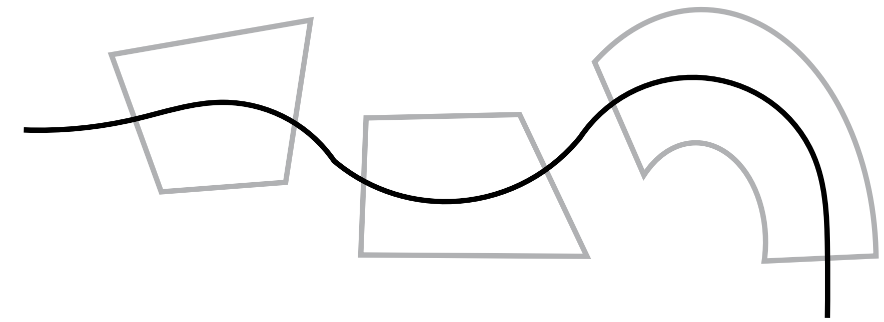
Cons:
- doesn't focus the beam to a point
- chromatic - i.e. probably not suitable in terms of beam quality



270 DEGREE ACHROMAT

Pros:
- achromat means the beam is transported to a point onto the target for all energies
- (Anecdotally, these machines don't need re-tuning as often <- ??)

Cons:
- needs a 270 degree bending magnet - which can be quite strong/large
-



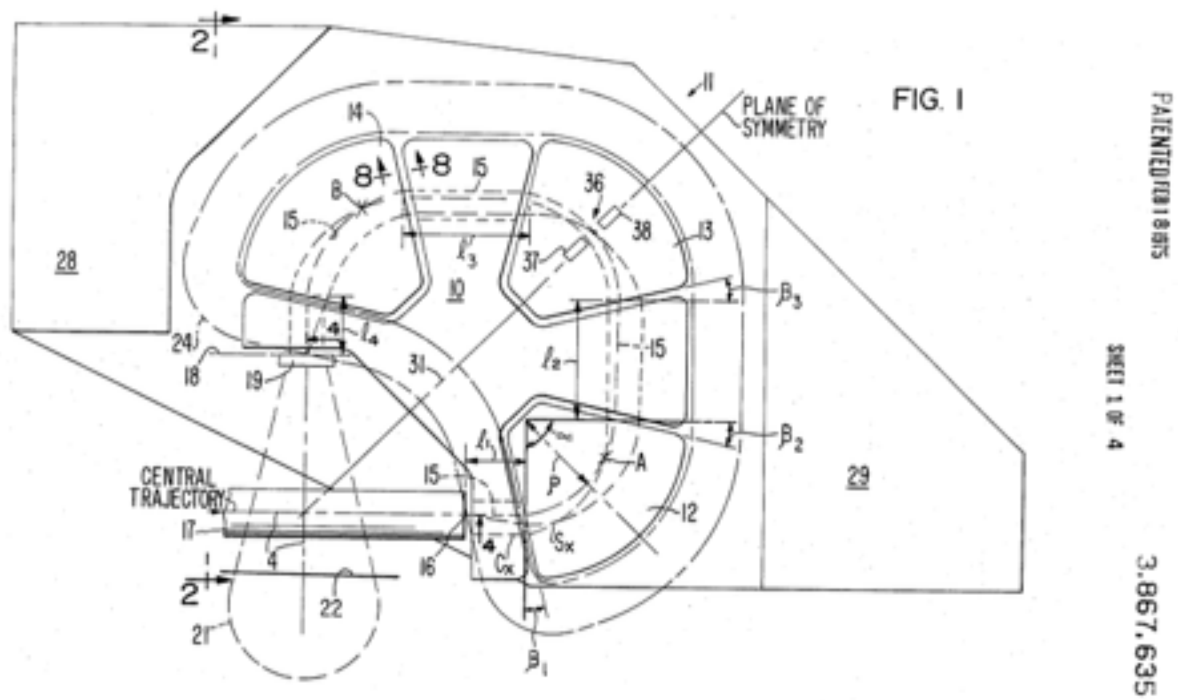
112.5 DEGREE 'SLALOM' BEND

(Used in Varian linacs)

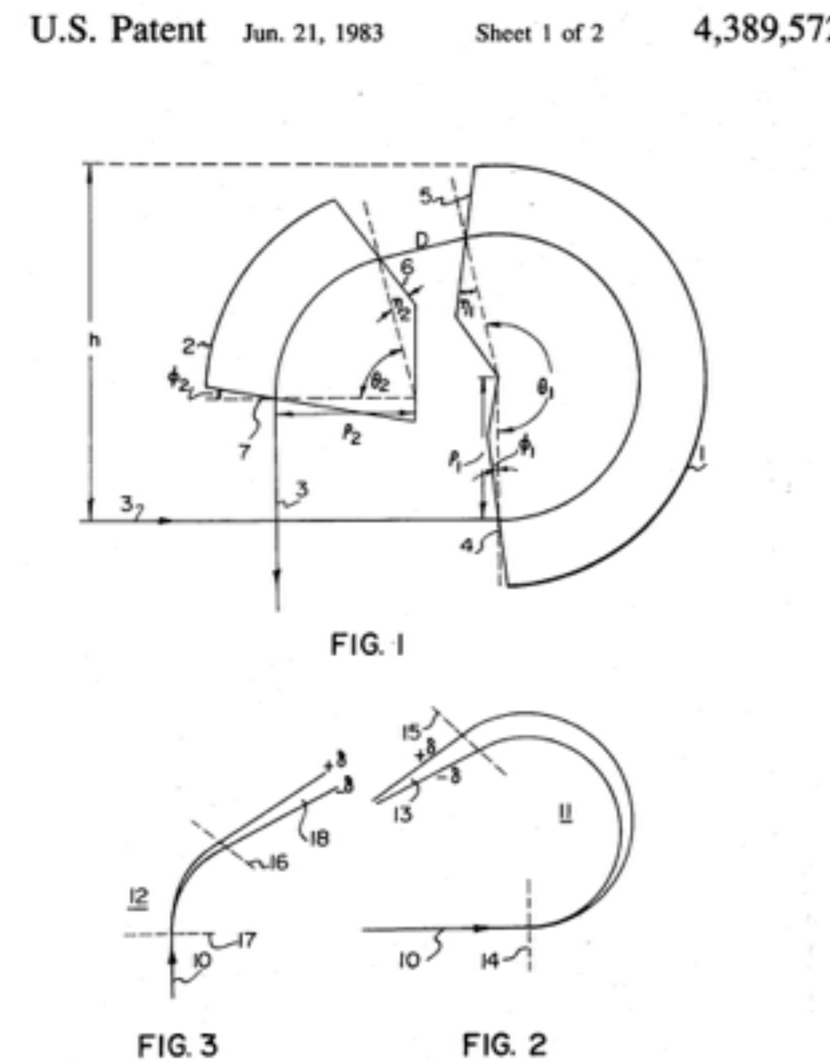
Pros:
- makes the overall treatment head lower to the isocentre
- maintains achromatic condition (I presume)

Cons:
- is larger (length-wise) than other options
- (Anecdotally, needs retuning a lot?)

Final bends…



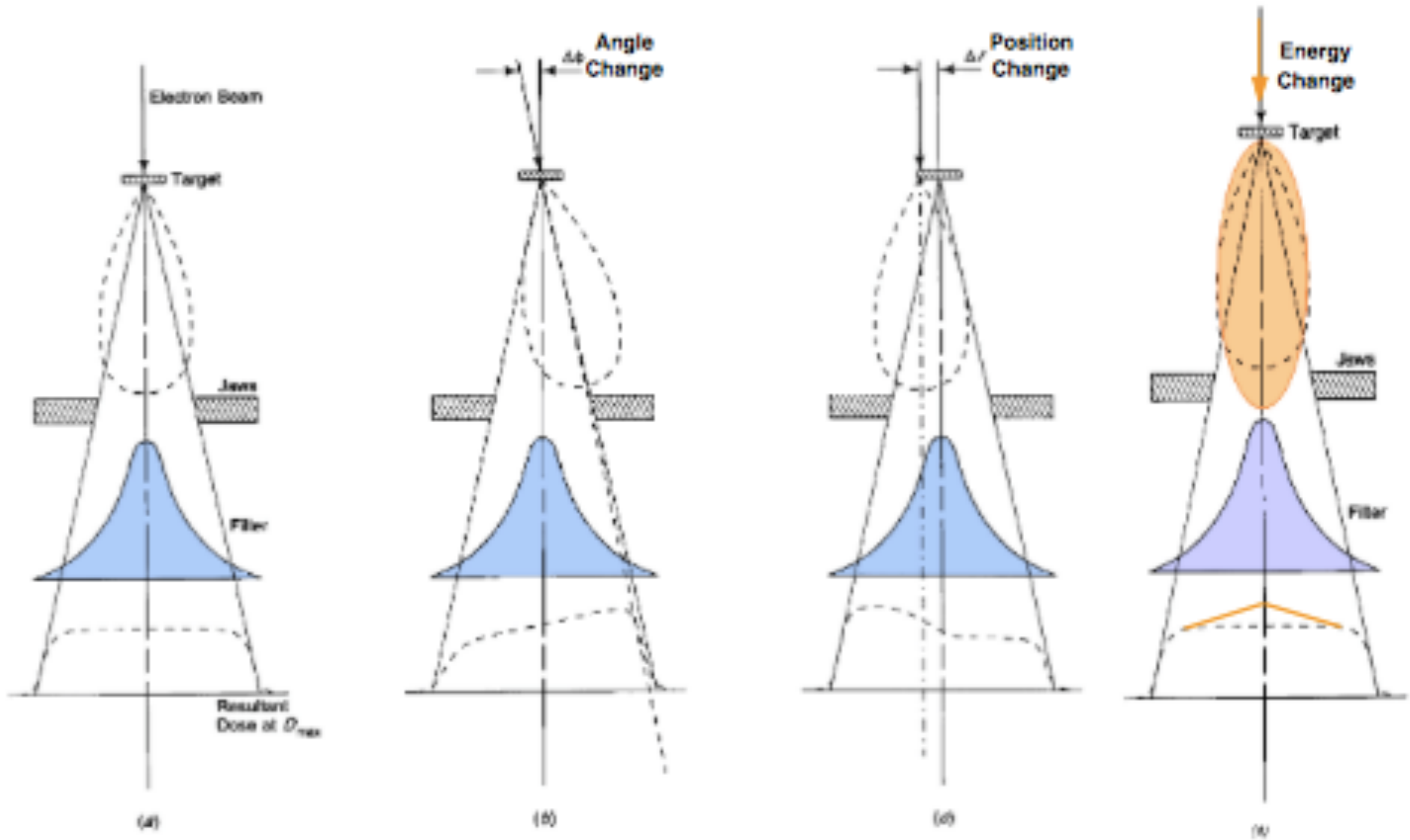
From US Patent US3867635 A, 1973

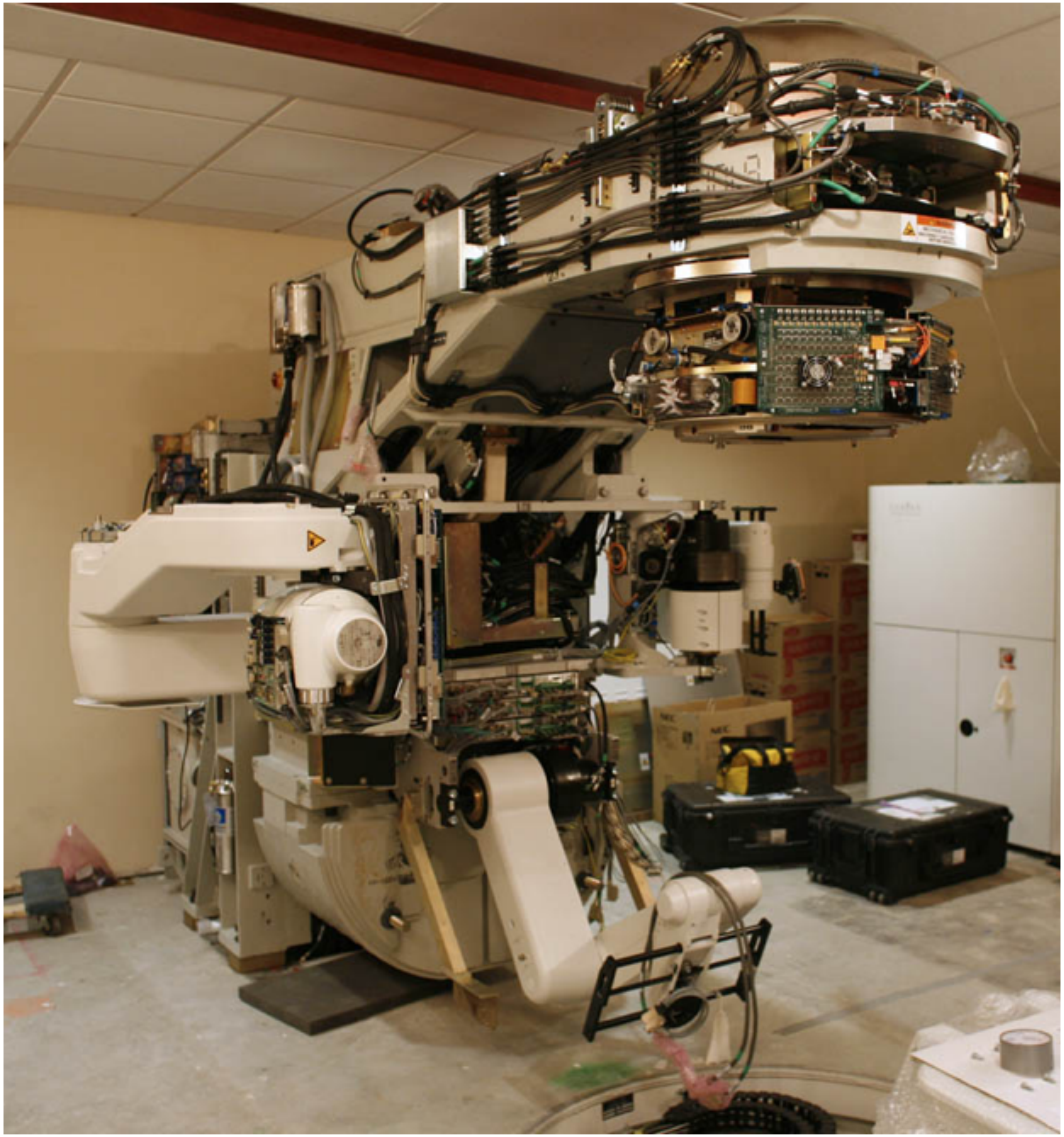


4389572 A, 1981
Lapsed

H. A .Enge invented a bend system, but in patents it's said 'system would be difficult to manufacture and requires very accurate field mapping and shimming.'
http://aip.scitation.org/doi/10.1063/1.1718372

Why does the beam have to be precise in angle & position? <— Field flatness.





REFERENCES

- LINEAR ACCELERATORS FOR RADIOTHERAPY

  2ND ED, D. GREENE AND P C WILLIAMS, MEDICAL SCIENCE SERIES, IOP PUBLISHING, 1997

- TREATMENT MACHINES FOR EXTERNAL BEAM RADIOTHERAPY

  E B PODGORSAK, http://www-naweb.iaea.org/nahu/DMRP/documents/Chapter5.pdf

- MEDICAL APPLICATIONS OF ELECTRON LINEAR ACCELERATORS

  A. WATNBERSIE AND R.A. GAHBAUER, IN PROCEEDINGS OF CERN ACCELERATOR SCHOOL ON CYCLOTRONS, LINACS AND THEIR APPLICATIONS, BELGIUM, 1994, pp.229.