PIP (Proton Isotope Producer) : a compact recirculating accelerator for medical isotopes

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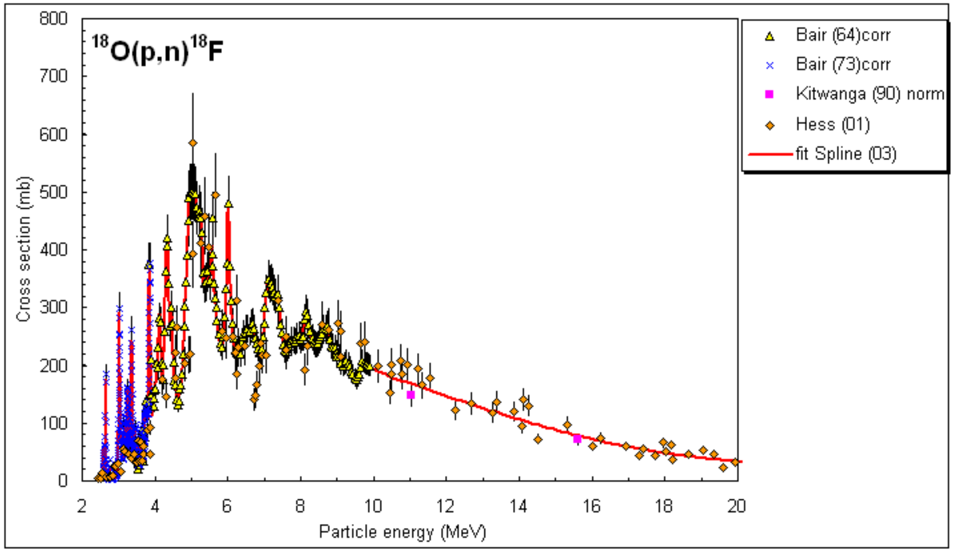
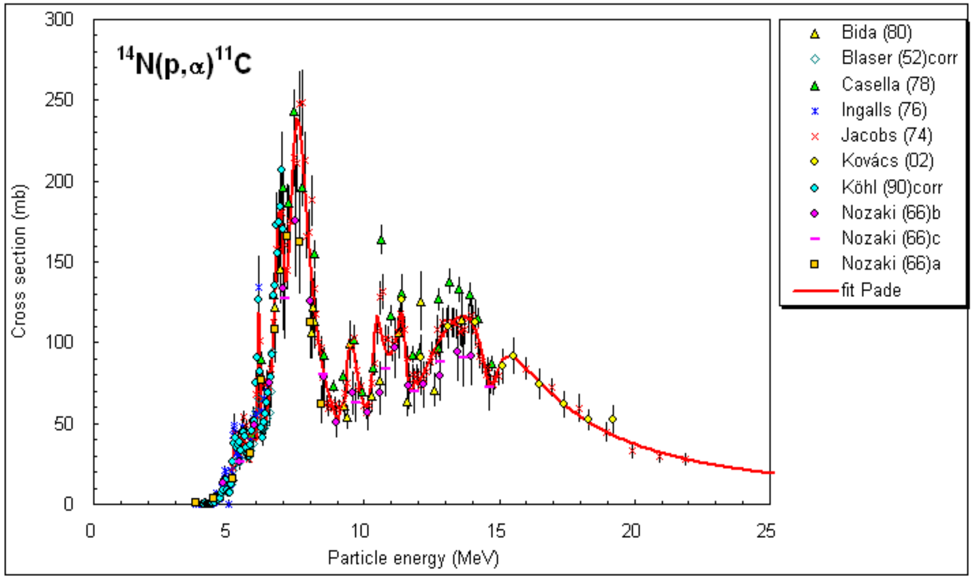
Medical isotopes - PET and SPECT

There is a high demand for making medical isotopes for imaging and treatment. Ideally isotopes can be produced locally, on demand, rather than delivered from some remote distribution centre.

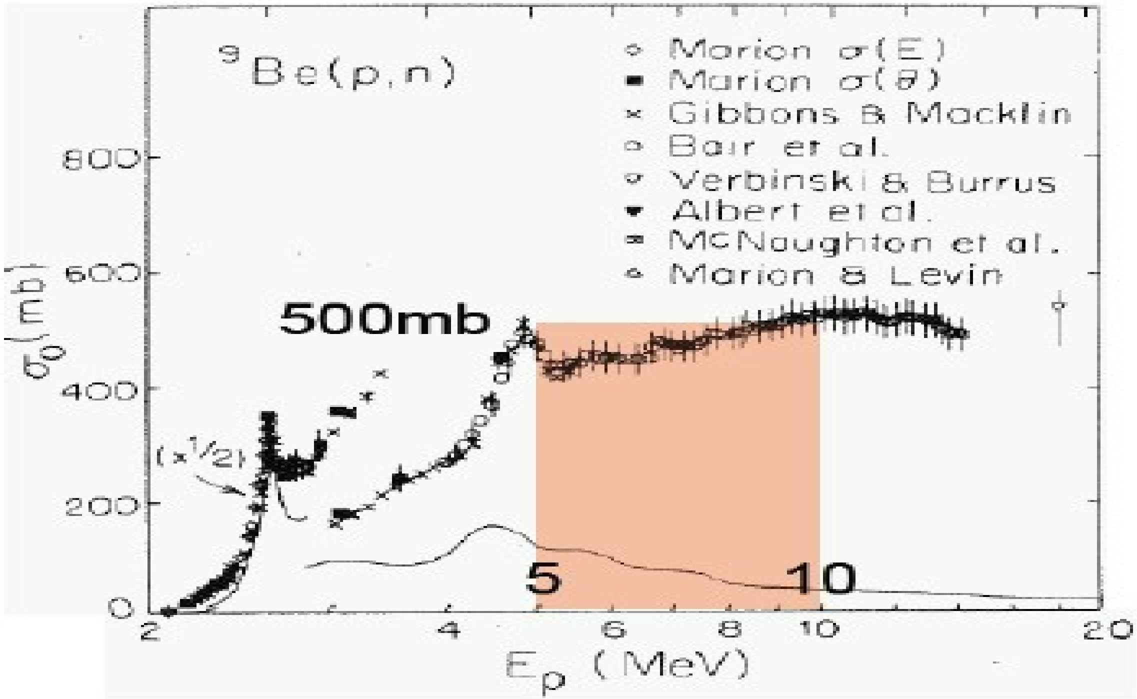




PET isotope 19F (left) and 11C. (Figures taken from the IAEA–NDS website)

Recirculation

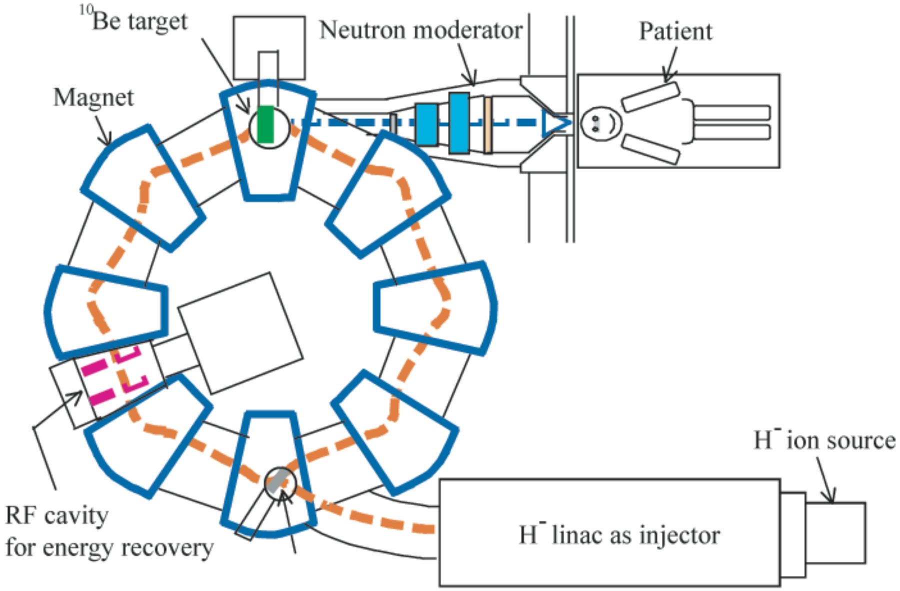
- At low (MeV) energies, proton cross sections vary strongly with energy. Particles lose energy as they travel through the target. In a thick target, dE/dx means that only a few protons have the right energy.
- Solution: Thin target & Recirculation.
  In a thin target particles that do not interact can be sent around for another try (ie replace lost energy in remaining beam by RF, try again...).



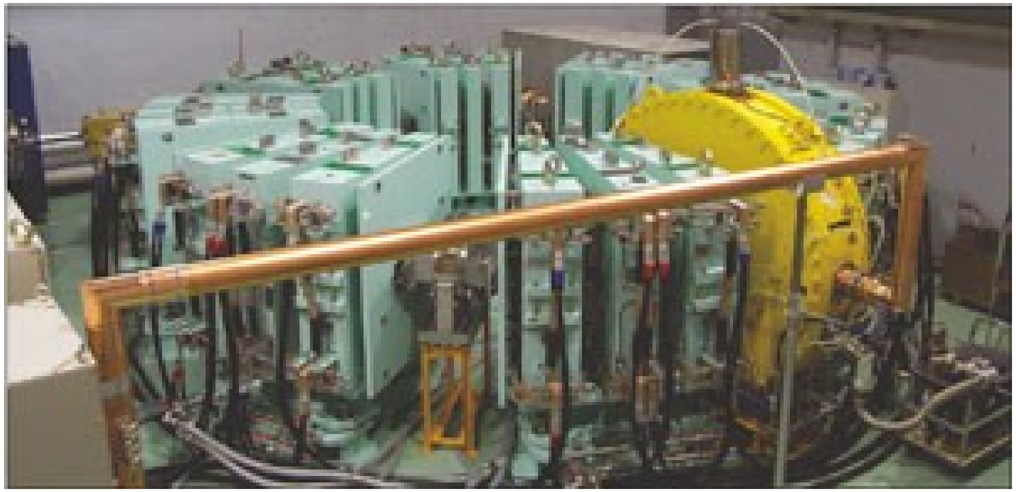
ERIT shows the way

Concept implemented at ERIT:

- **Energy/Emittance Recovery with Internal Target** at KURI Japan.
- 9 MeV protons used to make neutrons for BNCT (boron neutron capture therapy)
- ERIT is an FFAG storage ring with separate accelerator.
  ERIT is not an accelerator!
- PIP aims to combine the two using an nsFFAG accelerator.



Schematic from K. Okabe, image from Y Mori



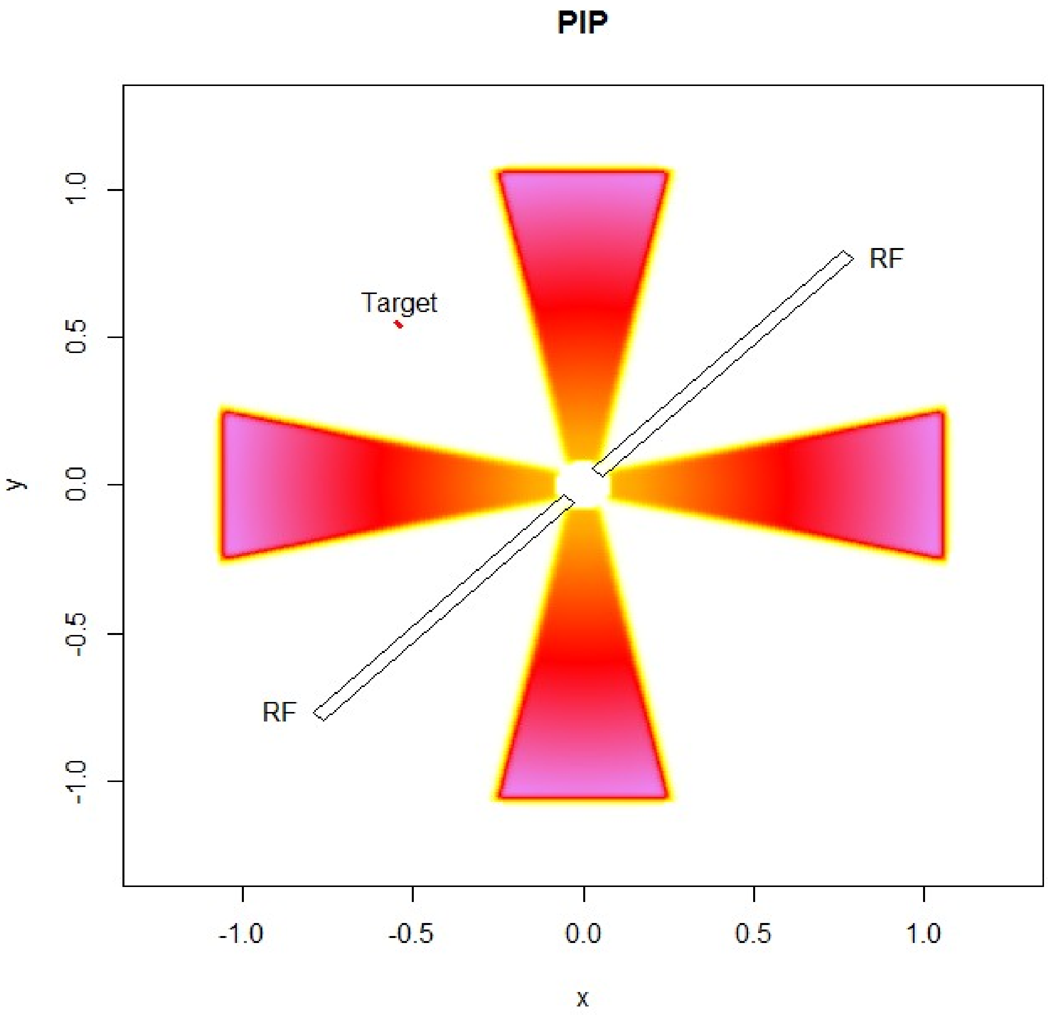
PIP-4

Basic layout

PIP is a 1m radius nsFFAG, from a 4MeV field map produced by Carol Johnstone.

- The field from 4 sector magnets increases with radius.
- RF is provided by 2 cavities.
- The Target is placed in one of the straight section. The energy of interaction can be adjusted by placing the target in different locations.

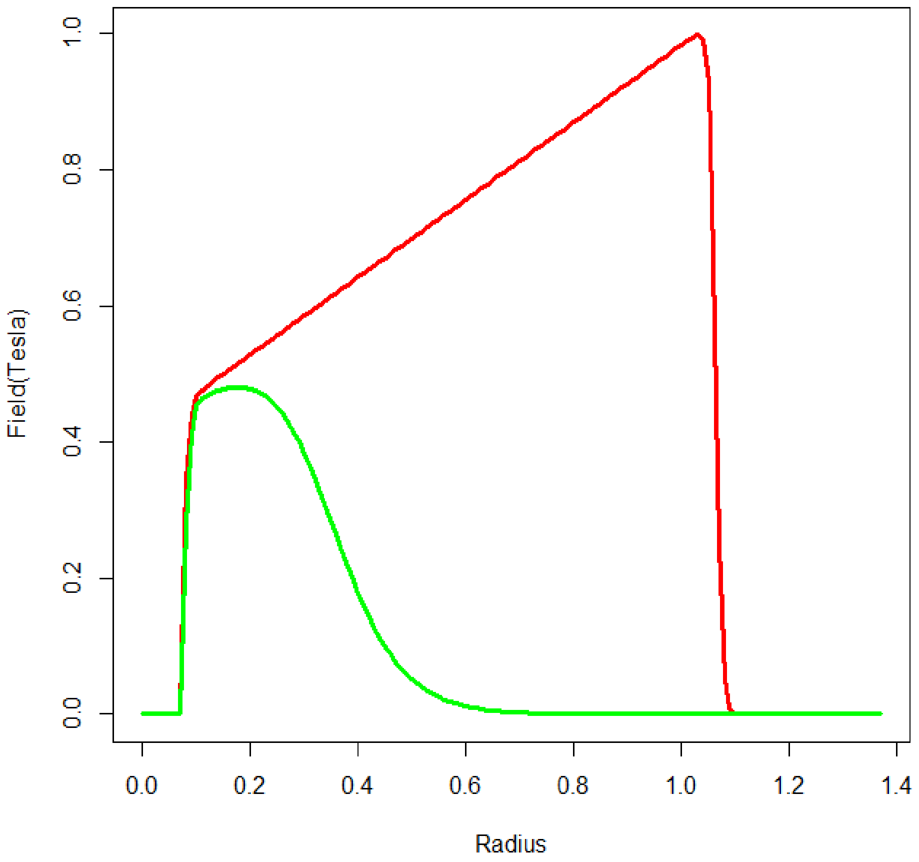
Such a machine is small enough for every hospital to have one, producing isotopes on demand.



PIP-4 is an nsFFAG

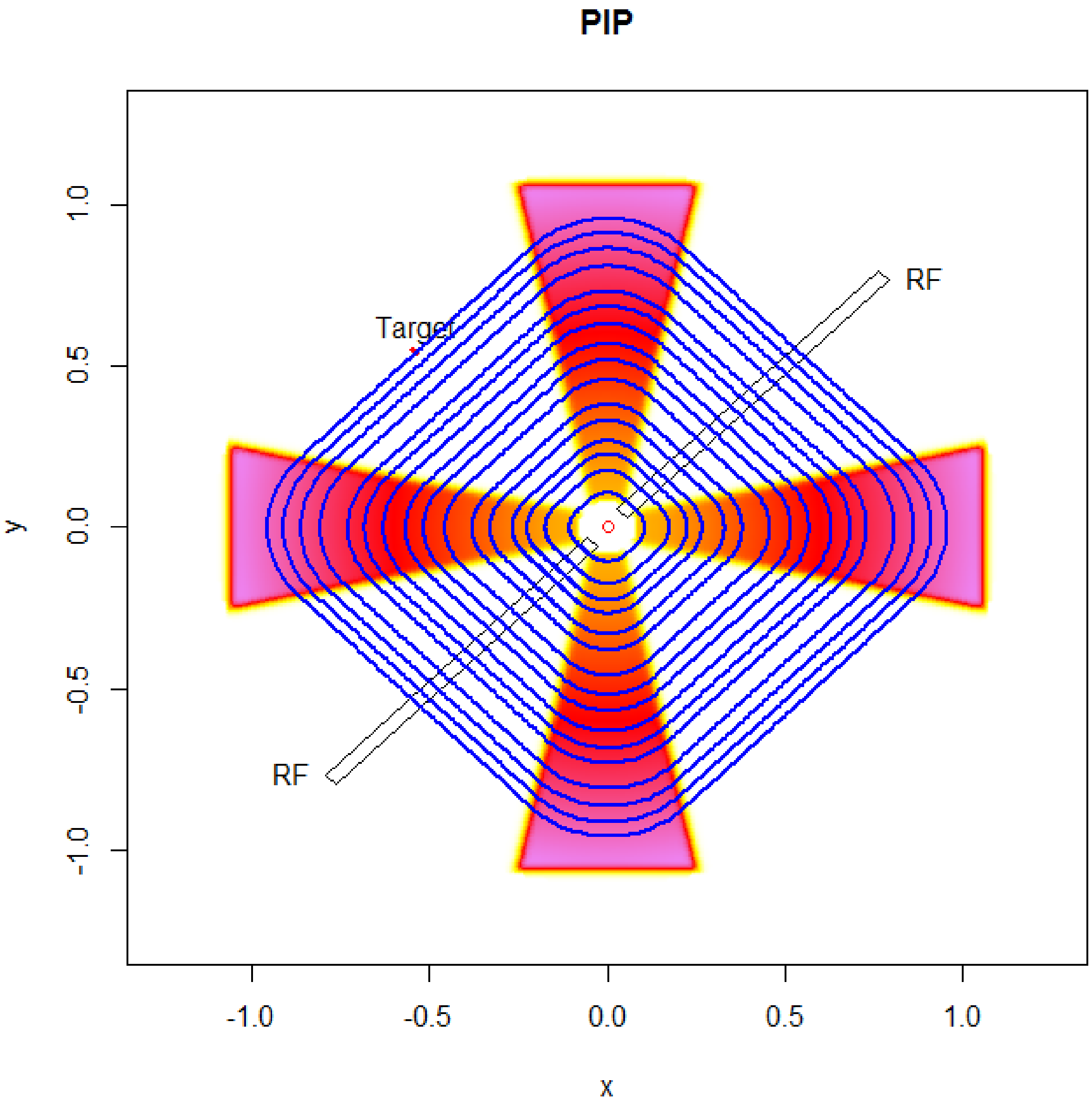
- At first sight it looks like a cyclotron but the radial field variation is enormous not just few percenent.
- The red curve (field at θ=0) shows how the magnetic field at the centre of the magnet increases from 0.5T to 1T from the inner to outer radius.
- The green curve shows the magnetic field variation along the radius at θ=30 mrad off the symmetry axis. This falls due to edge scalloping providing the alternative gradient.

- PIP is an FFAG: constant RF frequency and fixed field magnets.



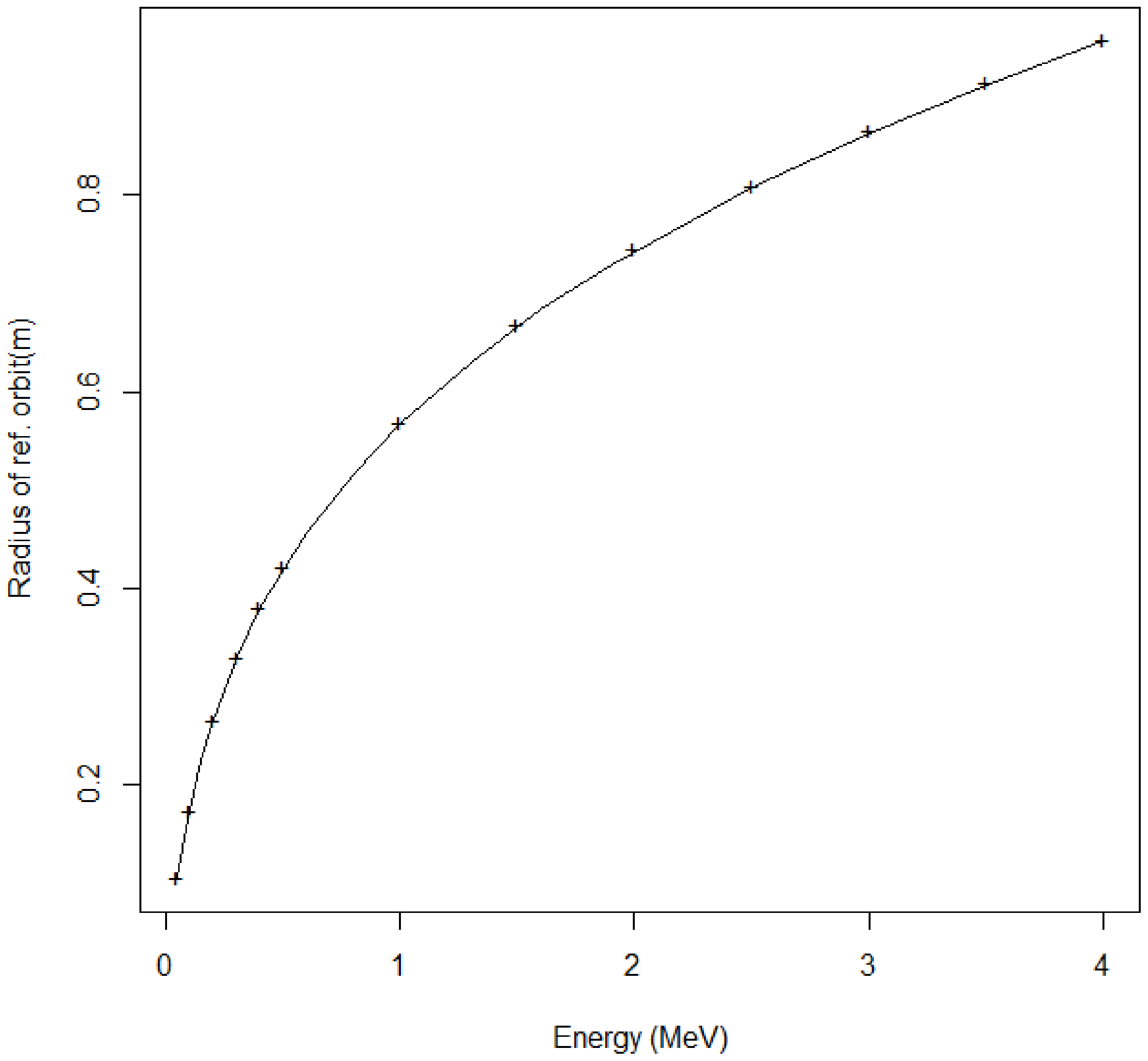
Reference orbits

Figure shows a set of different orbits and different energies, from 50 keV (innermost) to 4 MeV (outermost)



Cross-check

Orbit radii (continuous line), using the toy model accelerator by Roger Barlow, agree with results from OPAL (by S Sheehy) (crosses)

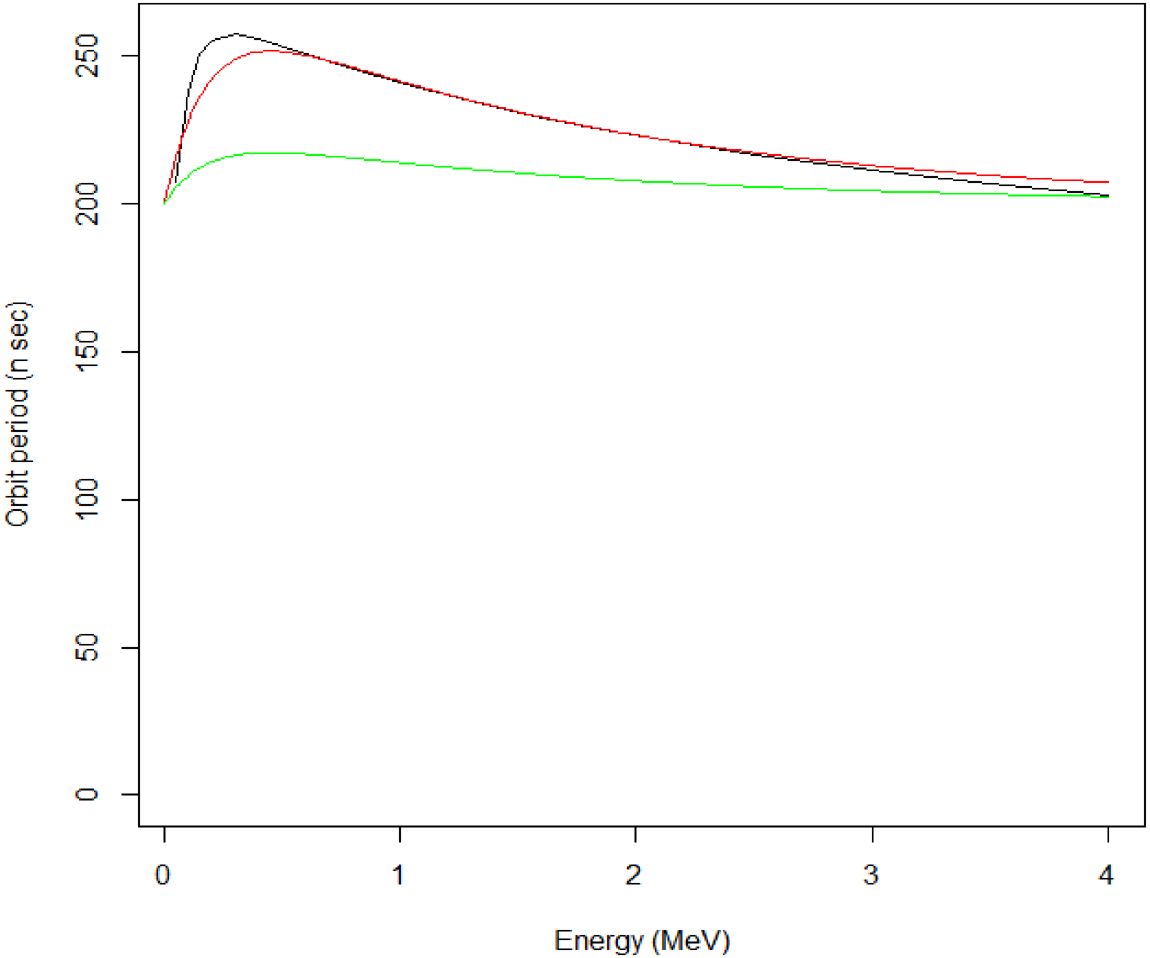


Isochronicity

From the orbits one can find the time for each orbit, and thus the isochronicity of the lattice.

Orbit period ~ 200nsec
Varies somewhat with energy (black curve)

Case study used for modelling: red and green curves

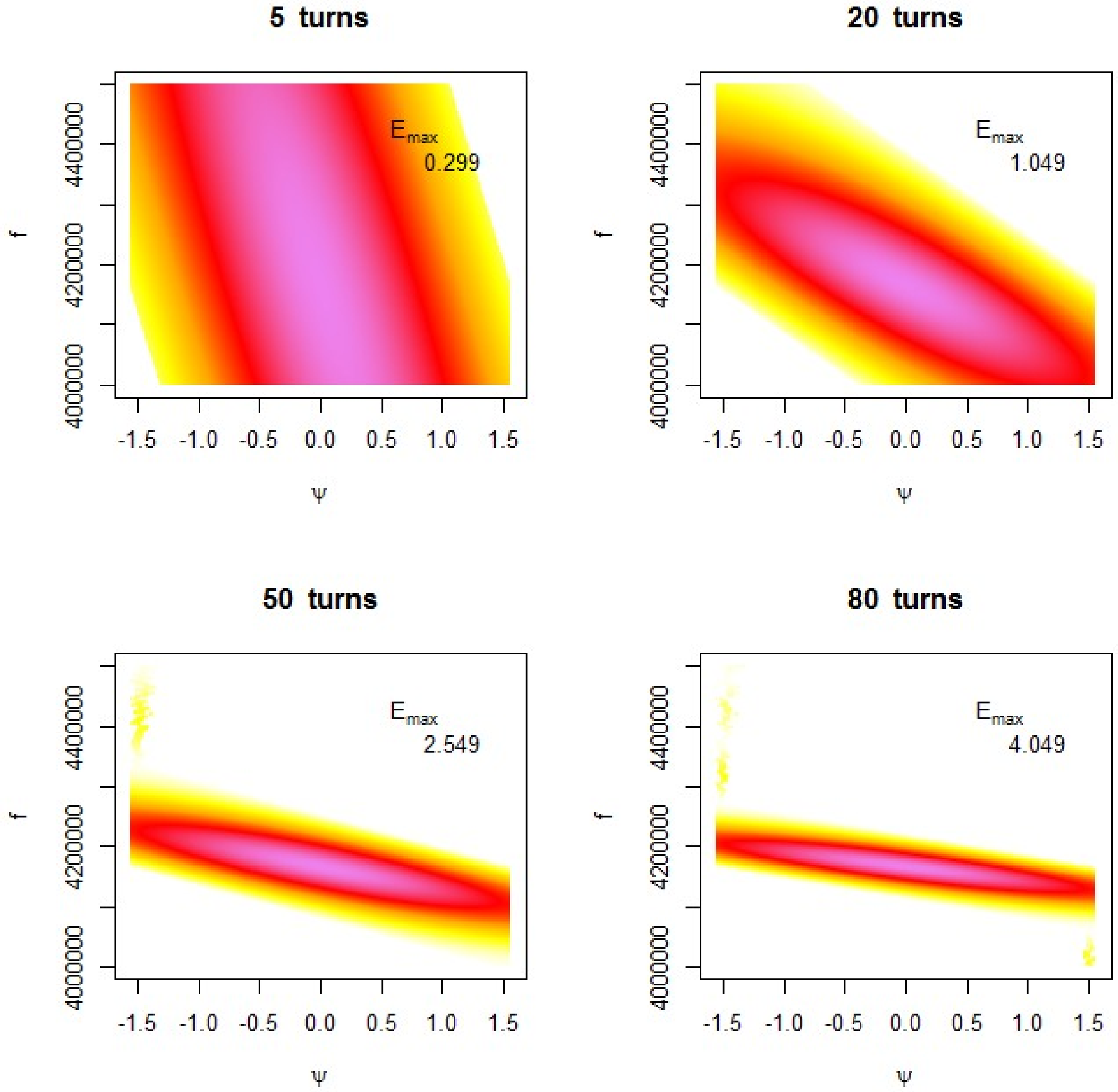


Will this work at constant frequency?!

For given lattice, energy depends on:

- Kick (MeV/turn)
- Number of turns
- RF frequency
- RF phase

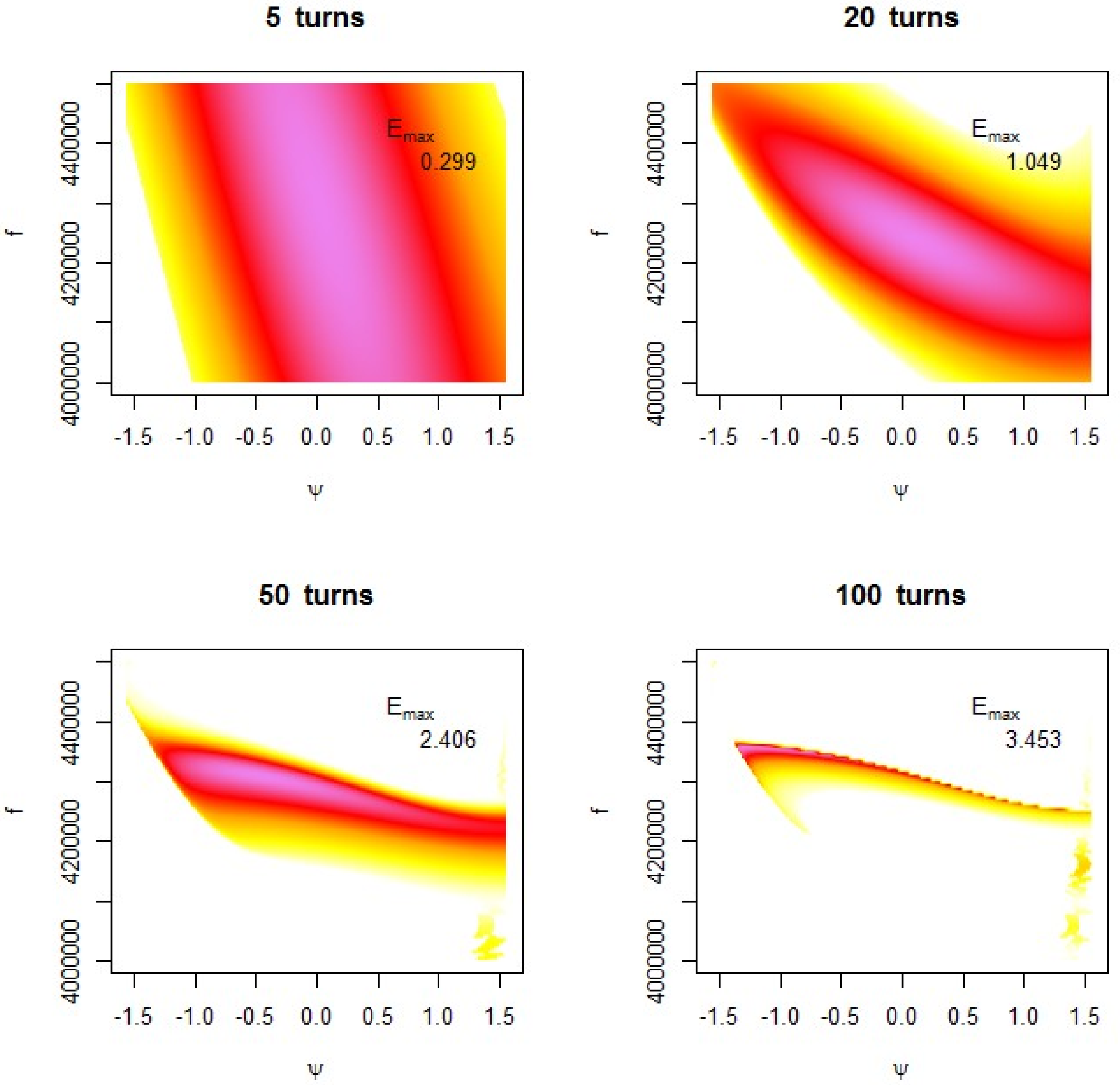
Plots show dependence on frequency and phase using simple cyclic model for 50 MeV/turn isochronous machine



Slightly isochronous

Green curve..
Same 50 MeV/turn starting energy

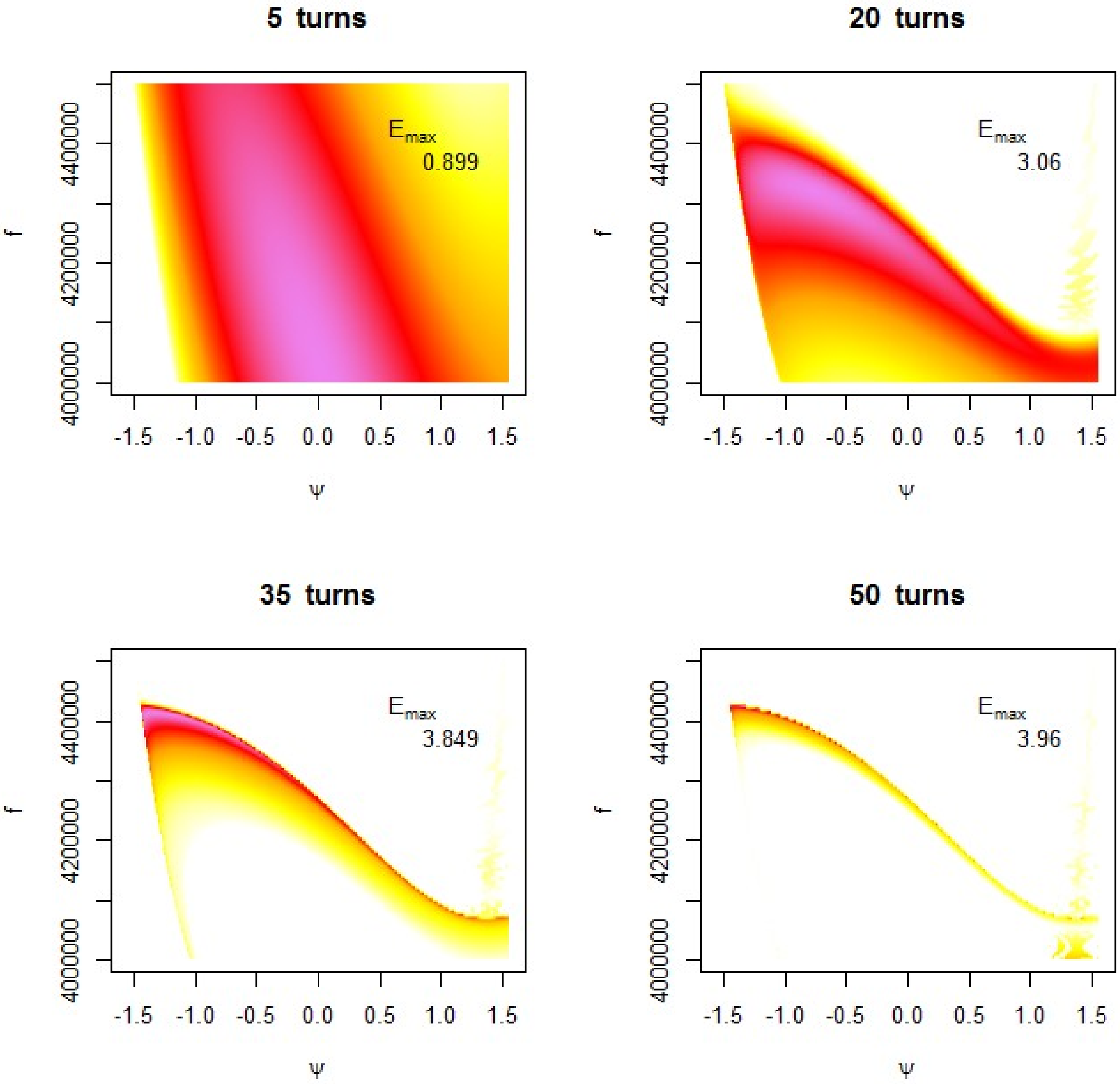
“Best region” moves left, hits the edge and particles are lost .

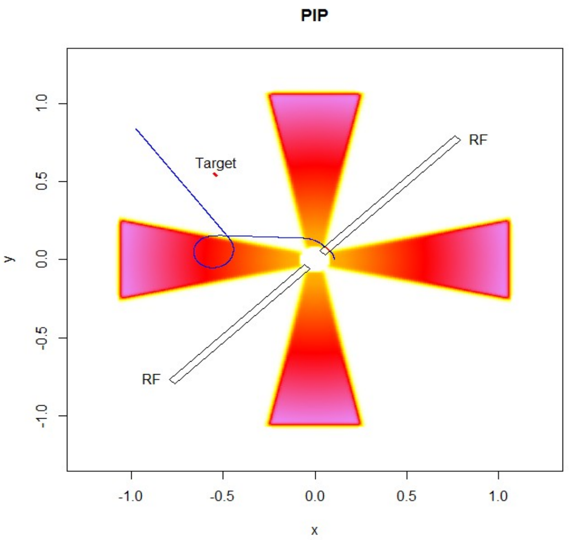


Fully isochronous

Red curve
Needs 170keV/turn
These are big kicks for the RF.

The field map needs another design iteration to improve the isochronicity.



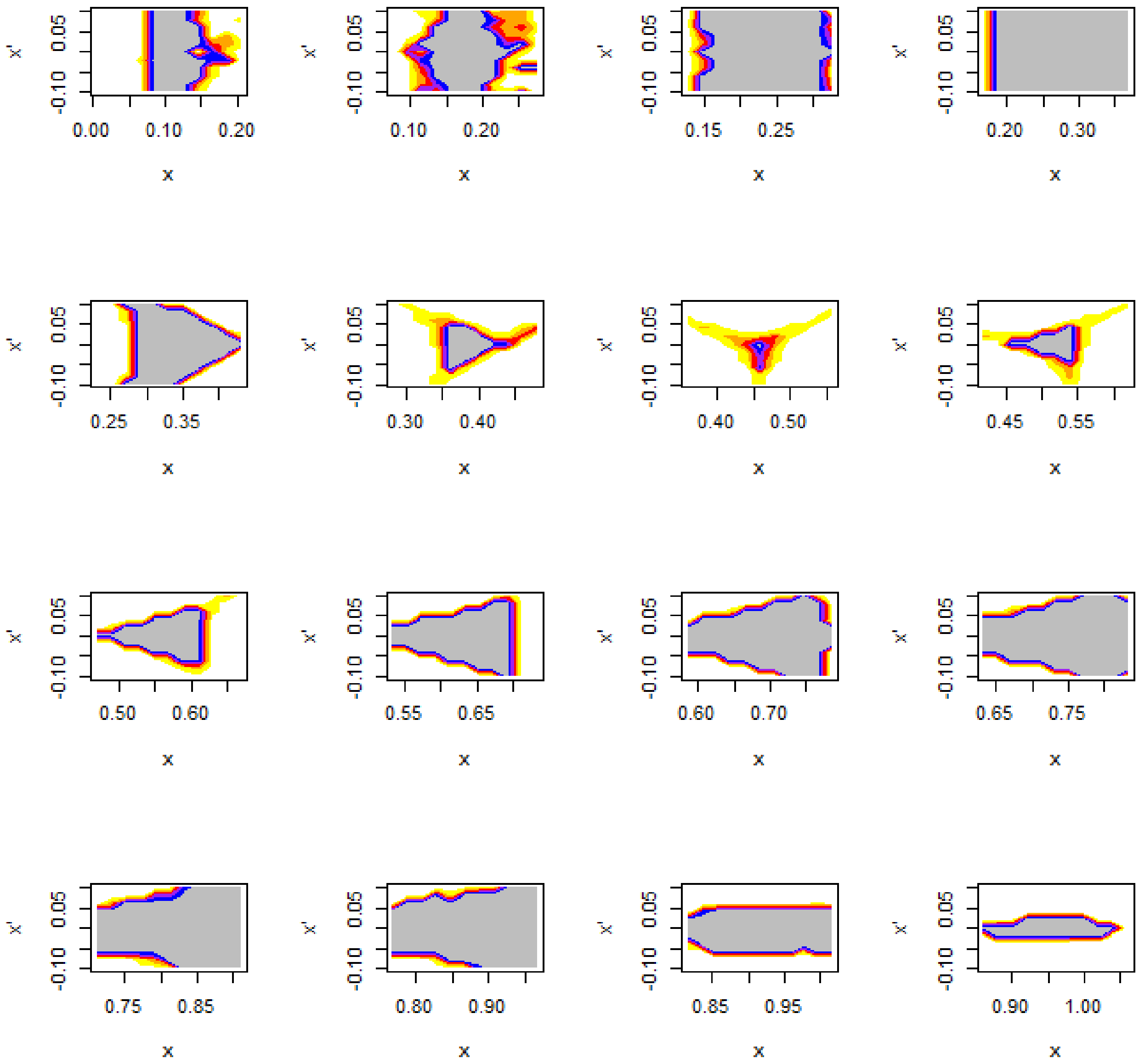


Acceptance

Survival (in turns) of particles near reference orbits for many energies – the greys areas show phase space (x,x') where particles survive for 250 turns, pretty much forever

Many features, some understood, some not quite.

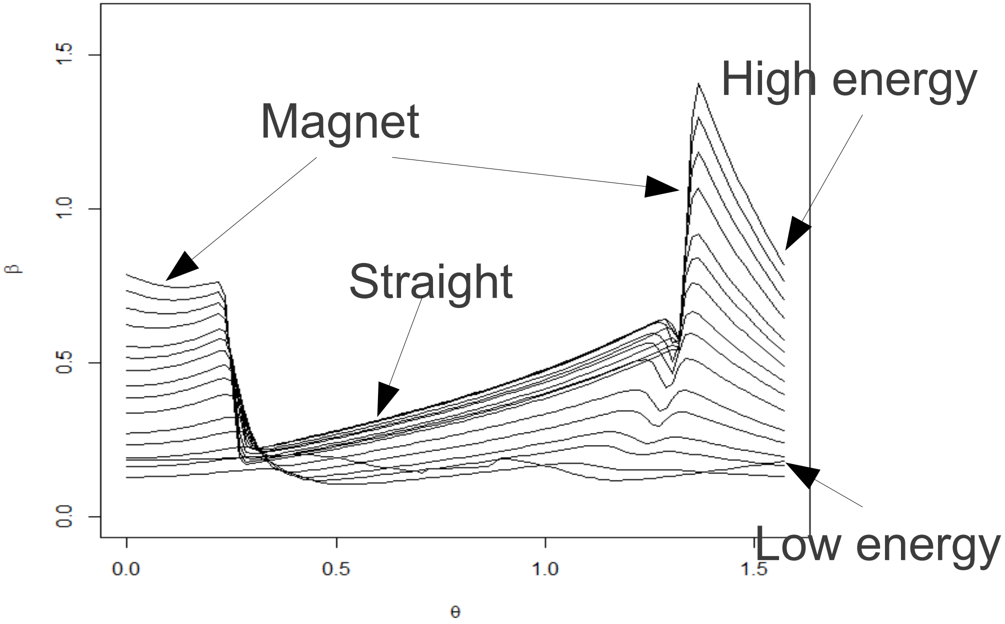
Note scales: these acceptances are enormous (20cm by 200m)

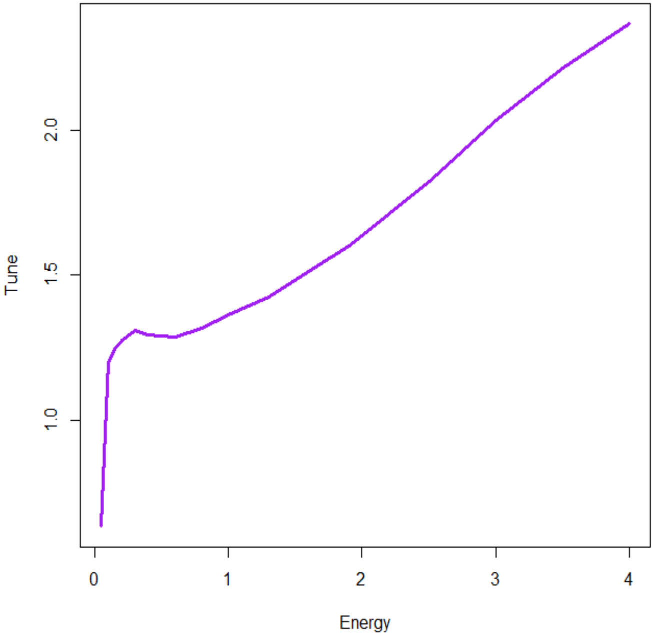


Lattice parameters

Horizontal Beta function

- found by tracking.
- large in magnets, smaller in gaps.
- increases with energy.





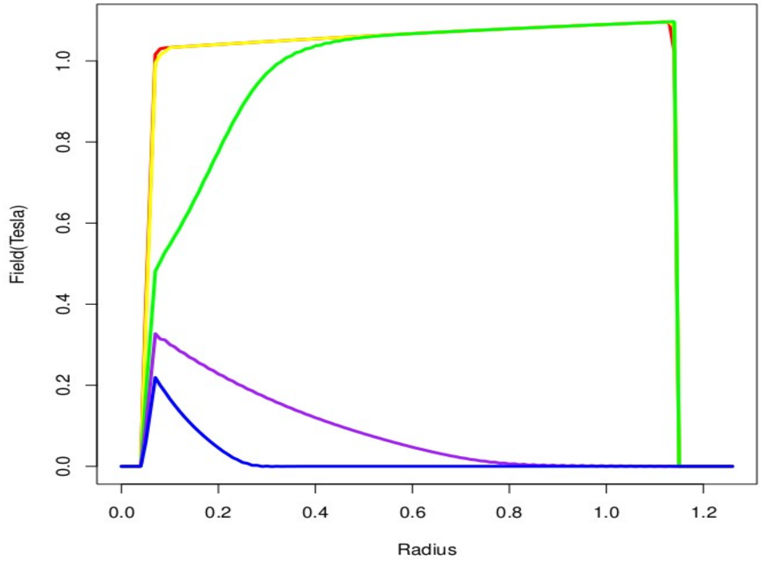
Tune varies with energy (non-scalling)! Does cross resonances.

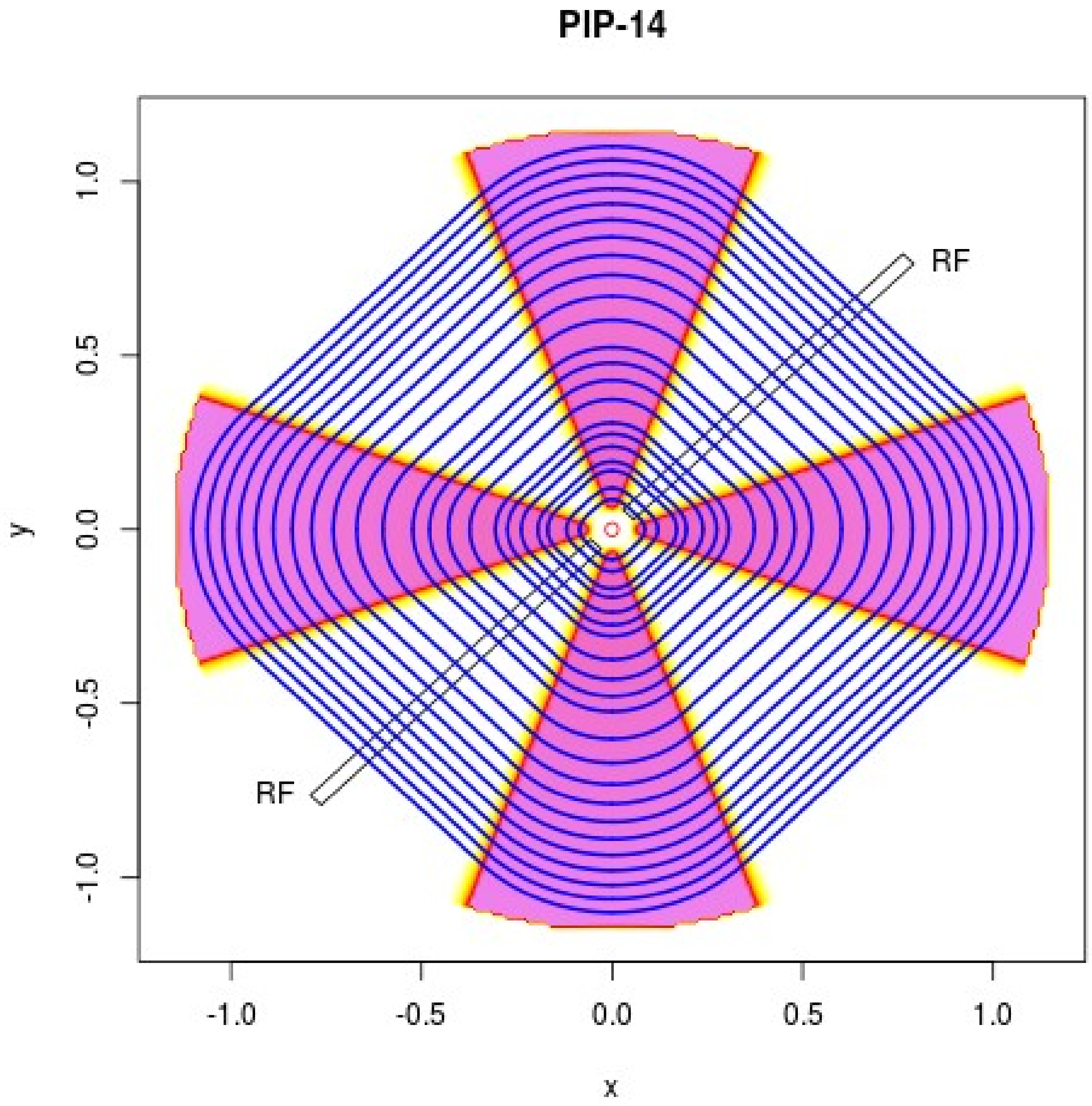
PIP-14

Reference orbits

Larger machine, 1.2m radius designed to reach proton energies of 14MeV (suitable for 99mTc).

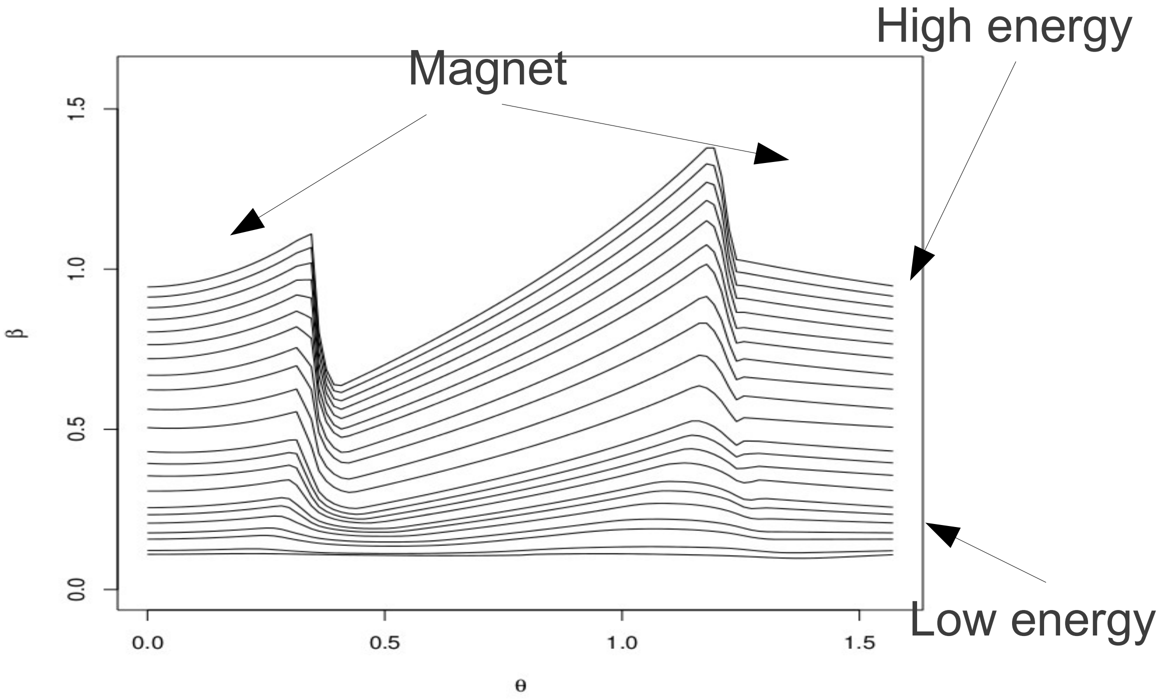
Field profile at 0, 0.1, 0.2, 0.3 and 0.4 radians.





Lattice parameters

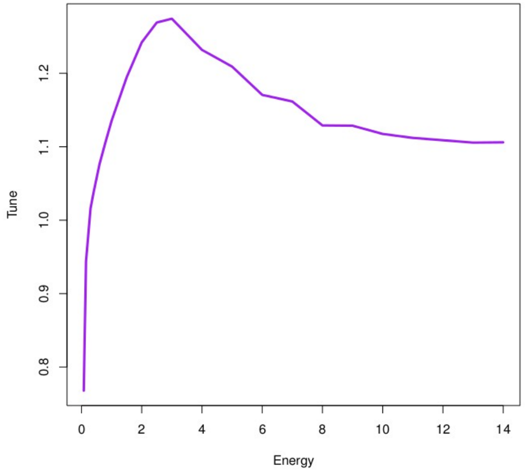
Horizontal Beta function shows the drastic effects of the sharp edges while the tune is fairly flat.



Magnet

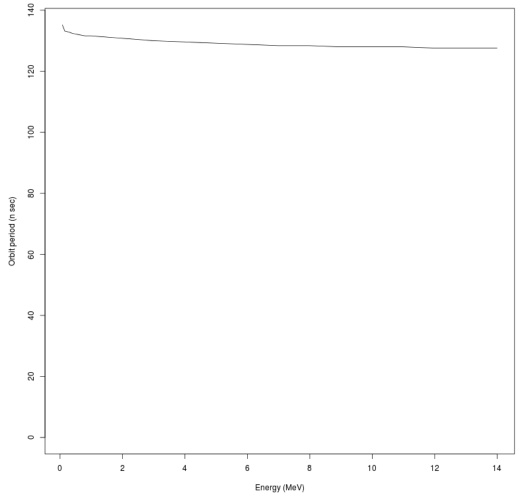
High energy

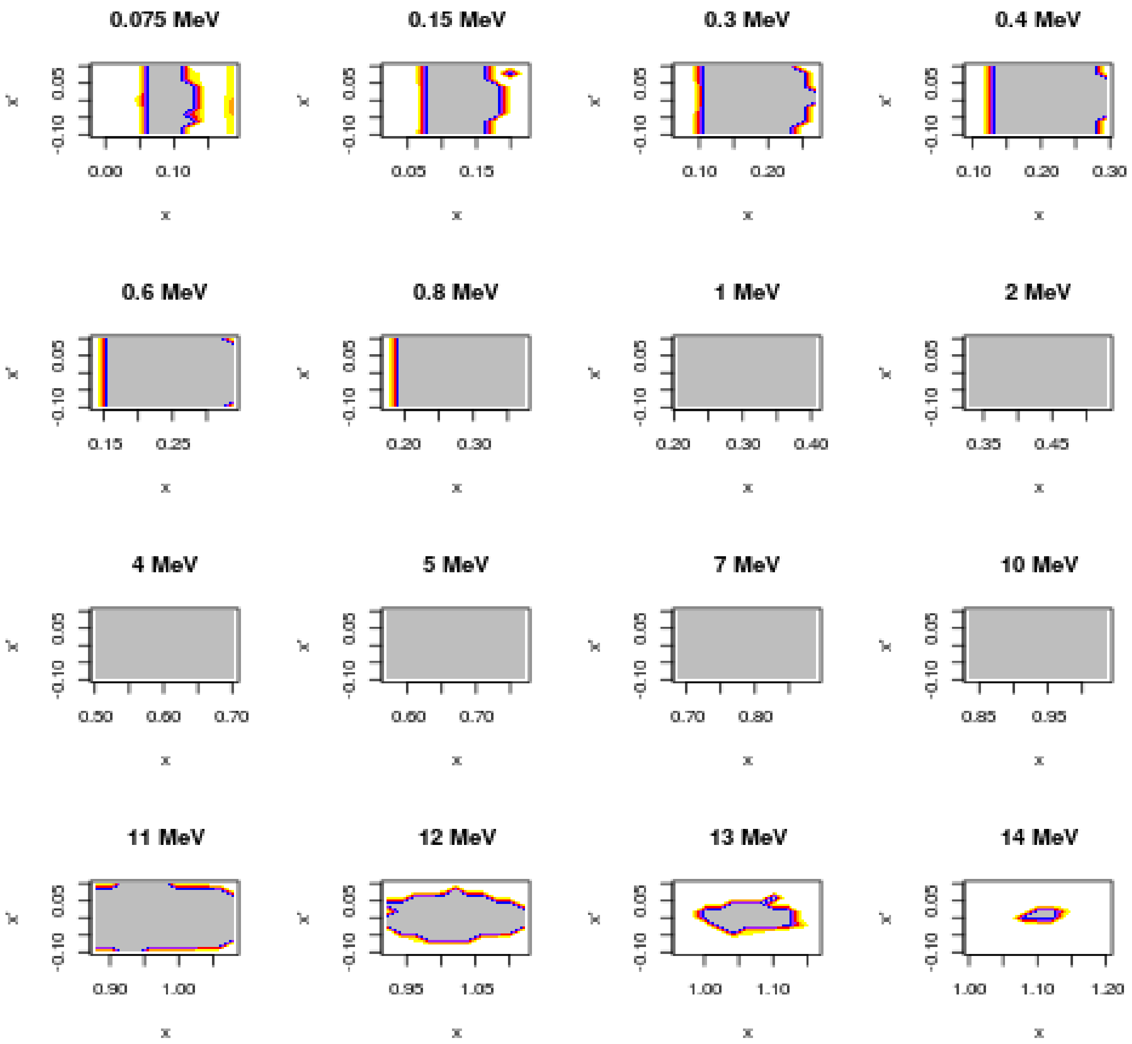
Low energy



Isochronicity and Acceptance

The isochronicity is a lot better.
The acceptance is large and shows no mid-range constriction.





Conclusion

- PIP's design is challenging but it is definitely a step forward to achieving a cost effective accelerator easier to install in a hospital and simple to operate.
- It can also produce neutrons for security scanning.
- Despite their similarities PIP-4 and PIP-14 have significant differences in behaviour. This is useful as it tells us that there is a lot of scope for optimisation.
- More studies including OPAL and COSY-infinity are under way.