PIP: A LOW ENERGY RECYCLING NON-SCALING FFAG FOR SECURITY AND MEDICINE

R.J. Barlow*, T. R. Edgecock, Huddersfield University, Huddersfield, UK
C. Johnstone, FNAL, Batavia, USA,
H. Owen, Manchester University, Manchester, UK
S. L. Sheehy, STFC/ASTeC, Rutherford Appleton Laboratory, Chilton, Didcot, UK

Abstract

PIP, the Proton Isotope Production accelerator, is a low energy (6-10 MeV) proton nsFFAG design that uses a simple 4-cell lattice. Low energy reactions involving the creation of specific nuclear states can be used for neutron production and for the manufacture of various medical isotopes. Unfortunately a beam rapidly loses energy in a target and falls below the resonant energy. A recycling ring with a thin internal target enables the particles that did not interact to be re-accelerated and used for subsequent cycles. The increase in emittance due to scattering in the target is partially countered by the re-acceleration, and accommodated by the large acceptance of the nsFFAG. The ring is essentially isochronous, the fields provide strong focussing so that losses are small, the components are simple, and it could be built at low cost with existing technology.

INTRODUCTION: THE CONCEPT

The principle of the nsFFAG has been proven by the successful operation and commissioning of the EMMA accelerator [1] at STFC Daresbury laboratory in 2011. We propose a design for a proton nsFFAG, PIP, the Proton Isotope Production accelerator. This is a low energy machine which uses the recirculation principle to boost the efficiency of production for many medical isotopes, and also of neutrons for security scanning and other purposes.

At low energies the cross sections for specific proton-nucleus interactions vary rapidly with energy, with peaks that correspond to the formation of particular resonances. (This is in contrast to the higher energy behaviour where processes such as spallation are described by random, statistical, cascade effects.) A typical example is shown in Figure 1, the cross section for ^{11}C production by protons on a nitrogen target. With a proton energy of 7.5 MeV the cross section is high, but falls rapidly at energies away from the peak.

However protons in a target lose energy from collisions with the atomic electrons, and in a thick target the energy of pN collisions is a spectrum from the nominal beam energy down to zero. Thick target production efficiencies are therefore much lower than scaled-up thin target efficiencies at the energy corresponding to the resonance peak. But thin targets are in themselves inefficient as the interaction probability is small.

This dilemma can be resolved by using a recirculating

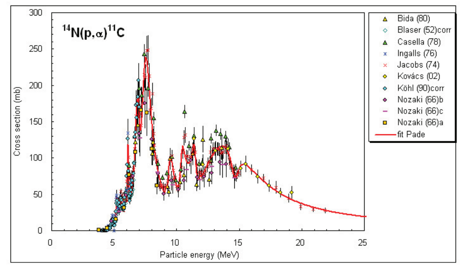

Figure 1: Cross section for ^{11}C production, from [3]

beam. Protons, at the optimum energy, pass through a thin foil. Some interact. Those that do not are circulated round the ring for a second chance, and the process is then repeated. The protons lose some energy in the target, which is made up by RF from the accelerator. They also increase their transverse emittance due to the scattering process. This is mitigated to some extent by the repeated longitudinal acceleration, as in ionisation cooling.

This principle was pioneered in the ERIT FFAG[2] at Kyoto for neutron production for Boron Neutron Cancer Therapy.

THE DESIGN

Figure 2 shows the basic design of four sector magnets(blue) and inner and outer orbits (green).

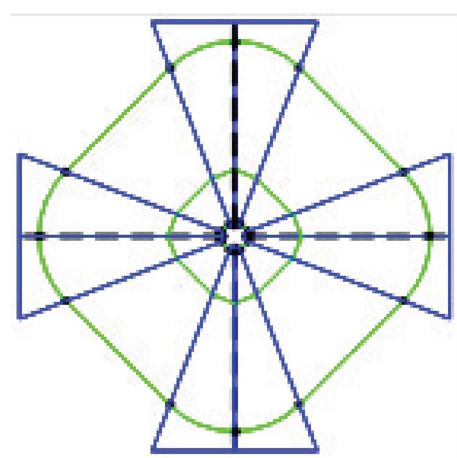

Figure 2: The PIP layout

The radius is 60 cm, making this small, though not ultra-compact. A machine of this size, plus the required shield-

* R.Barlow@hud.ac.uk

ISBN 978-3-95450-122-9

ing, would fit into a typical hospital basement room.

Machine parameters are given in Table 1.

Table 1: Baseline PIP parameters

Parameter	value
Injection Energy	50 keV
Extraction Energy	6 MeV
Max current	10 mA
RF	approx. 500 MHz
Radius	60 cm
Horizontal Aperture	40 cm
Vertical Aperture	3 cm

There are four identical normal conducting magnets. The field is of order 1 Tesla, with a field variation which can be achieved through suitable shaping of the iron pole pieces.

The wide horizontal aperture requires a relatively low RF frequency, and a high harmonic number to match the orbital frequency.

Studies have shown that the isochronicity is good, allowing CW operation. Also the betatron tunes are very stable, so resonances can be avoided.

We anticipate that currents of several mA will be achievable, thanks to the CW operation. Verification using tracking calculations with space charge are in progress.

Comparison with Cyclotrons

Whether this design is a cyclotronlike FFAG or an FFAG-like cyclotron is arguable. The field is fixed, and has a gradient, but it is not 'alternating' - it is increasing with R in all 4 magnets. Although other sector cyclotrons have increasing fields, their variation is more gentle than the gradients proposed here.

Given the availability of cyclotrons with this energy, we point out the advantages of the new design. The strong gradients, together with the edges, provide strong focussing. This reduces beam loss, which is a limiting factor in cyclotrons, so the improved focussing will enable the machine to run safely at currents a factor of ten higher than the equivalent cyclotron. Low losses also mean that the shielding required is reduced, giving a valuable reduction in the space required.

The use of separate sector magnets at these low energies, rather than a conventional single cyclotron magnet, gives the advantage of accessibility for RF and for vacuum pumps, which will enable us to achieve better vacuum, reducing beam-gas collisions and thus also contribute to lower losses.

This accessibilty also means that multiple targets can be deployed in the space, making the machine readily adaptable to different uses on a short changeover – or even simultaneously.

VARIATIONS ON THE BASE DESIGN

Higher Energies

Higher energy protons, up to several tens of MeV, could be produced by a simple scaling up of the base design. This could be done if needed for a specific application.

Energies up to hundreds of MeV can be achieved by lattices involving further magnets, including some with opposing fields to achieve alternating gradients. Various designs are under consideration.

An Extracted Beam

A version with an extracted beam is also under consideration. This would use an H^- source, and extract using a stripping foil. Again, the principle of recirculation would apply; a thin foil would remove electrons from some particles, with the remainder going round again. Any H^0 particles could be extracted on a dedicated path and stripped further in a second, thicker, foil.

Superconducting Magnets

Superconducting magnets could be used, which could make them more compact as well as requiring lower wall-plug power, but this would bring the complications of cryostats. At present we believe the disadvantages would outweigh the gains.

Permanent Magnets

Permanent magnets are being considered as a possible option. Even with permanent magnets the energy of the particles can be varied simply by moving the radial position of the extractor foil.

ISOTOPE PRODUCTION

It is helpful to consider two classes of isotopes separately: positron emitters for PET scanning, and ^{99m}Tc for SPECT perfusion.

Several positron emitters are in clinical use. Different isotopes are used for specific chemical compounds that serve a specific clinical or research purpose: ^{18}F for FDG studies is a prime example. Practical limits are imposed by the half life of the isotope. ^{18}F has a half life of 110 minutes, and can be distributed from a central production site to hospitals in the region. By contrast ^{11}C has a half life of only 20 minutes and so, despite its obvious applicability (carbon being part of any compound one could imagine having diagnostic possibilities) it is not in common use.

As a low cost and compact accelerator, PIP could be installed in every major hospital, rather than at regional centres. This would enable a wider range of isotopes to be available, and would enable clinicians to have doses generated rapidly and on demand, when the patient needed them, as opposed to waiting for a delivery.

^{99m}Tc is very widely used, currently in 50 M doses per year, and the number is rising. Although technetium is chemically unremarkable, the photon energy is well matched to typical detectors. It is produced in research reactors as the short-lived (6 hour) daughter of a longer-lived (66 hour) parent, $^{99}\mathrm{Mo}$, from which it can readily be extracted. The planned and unplanned reduction in research reactors has led to an interest in alternatives from accelerators, and many routes have been proposed [4]. Two of interest are (1) the production of $^{99m}\mathrm{Tc}$ directly, through the reaction $^{100}\mathrm{Mo}(p,2n)^{99m}\mathrm{Tc}$, which has a threshold near 10 MeV with a cross section which rises with energy till 24 MeV, and (2) the production of $^{99}\mathrm{Mo}$ from the reaction $^{100}\mathrm{Mo}(p,pn)^{99}\mathrm{Mo}$, which would retain the advantages of the long life/short life process. Yields from these (and all other accelerator-based production systems) are low compared to reactors, and proposals will require many (of order 100) accelerators to be built.

Although the baseline 8 MeV energy for PIP is not sufficient for either of these reactions, the higher energy option proposed above is ideally suited to them. The high current makes production practicable despite the low cross sections.

NEUTRON PRODUCTION

Neutron-based techniques have become standard for the non-destructive characterisation of materials in bulk, and have complementary properties to X-ray and gamma-ray analysis. There has been increasing interest in the use of neutrons for non-intrusive elemental characterisation for the detection of explosives and the detection of Special Nuclear Materials, particularly in the context of portal monitors of cargo containers at border checkpoints. There are a variety of neutron techniques including thermal/fast/pulsed-fast neutron analysis or spectroscopy, the use of associated particle production, and the radiographic and tomographic imaging methods built upon them. In many of these methods, measurement of the neutron timing is involved. This not only provides a good way of separating signal from background, it also gives a measure of the velocity of the neutron, which is important as neutrons of different velocities (i.e. energies) behave very differently in different materials. Measurement of the arrival time is straightforward, but to use it one also needs the start time of the neutron, which implies the use of a pulsed source.

Sealed-tube D-T neutron generators, although relatively inexpensive and portable, do not produce a sharp time structure. They also suffer from having relatively short operating lifetimes, low output intensities, and the use of tritium in the targets brings problems of safety and licensing for their use in public.

We propose the use of a beryllium target and the reaction $^{9}\mathrm{Be}(p,n)^{9}\mathrm{B}$ which has a reasonable cross section of 500 mb at 8 MeV. The recycling method, as opposed to a conventional thick target, would maintain the high cross section, and also give a monochromatic neutron source, due to the unique proton energy, if required for a particular technique. The small size of PIP means it could be mounted in a truck if required, for use in different checkpoints.

CONCLUSION

The PIP concept is very simple and low cost. It is the natural next nsFFAG to construct as a successor to EMMA, accelerating non-relativistic protons for which there are many applications. Funding is being sought from UK and US government research sources and also from industry.

REFERENCES

[1] S. Machida *et al.*, 'Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA' Nature Physics **8**, 243-247 (2012)

[2] T. Uesugi *et al.*, 'FFAGs for the ERIT and ADS Projects at KURRI' Proc. 11th Eur. Part. Accel. Conf. EPAC08, Genoa, Italy. TUOBM04 (2010)

[3] IAEA Medical Data Services Charged-particle cross section database for medical radioisotope production `http://www-nds.iaea.org/medical/` , accessed 5th May 2013

[4] IAEA report NF-T-5.4 'Non-HEU production technolgies for Molybdenum-99 and Technetium-999m' `http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1589_web.pdf`, (2013)

ISBN 978-3-95450-122-9