STUDIES OF HIGH INTENSITY PROTON FFAGS AT RAL

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Abstract

The paper describes studies of high intensity proton accelerators for a next-generation source of short-pulse spallation neutrons. Along with conventional designs using rapid cycling synchrotrons, the long-term nature of the project provides scope for novel accelerator designs and developing technological ideas. A range of FFAG options is under consideration for the main spallation driver. Theory and simulation in the UK are combined with experimental studies of FFAGs in Japan, and a small prototype FFAG ring is planned to go on the FETS injector at the Rutherford Appleton Laboratory (RAL) for essential R&D. The paper covers the broad scope of the programme and details the success of the study to date.

INTRODUCTION

After several years considering options to upgrade the aging ISIS spallation neutron source, there is renewed activity at RAL to explore options for a high intensity proton accelerator for next-generation neutron physics. Such a facility is being seen loosely as a successor to ISIS, which, despite its high productivity, is likely to have a limited life-span even with modest upgrades. Conventional designs using rapid cycling synchrotrons have been considered but, being long-term, the project provides opportunities for new proposals and an R&D programme based on developing technological ideas.

Existing spallation neutron sources generate a proton beam on target of up to ~1.5 MW at an energy up to about 3 GeV. The facility with the highest mean beam power is SINQ at PSI [1], with a cyclotron operating in continuous wave mode. SNS at Oak Ridge [2] is based on a pulsed H^- linac filling an accumulator ring via charge exchange injection and routinely produces 1 MW. The neutron facility at J-PARC [3] also operates at the 1 MW level though, in contrast, the accelerating structures rely on a 400 MeV H^- linac and a 3 GeV rapid cycling synchrotron (RCS). The facility with the longest history of producing world-leading science is ISIS [4] at RAL with a total beam power of 160-180 kW. Users benefit from a wide range of instruments around two different neutron production targets. In a few years, ESS will come online as a major neutron source in Europe. As ESS is a long-pulse facility (with a linac driving a proton beam straight into a spallation target), ISIS's aim is to continue to be the main provider of experimental opportunities for short-pulse neutron studies. It can either be progressively upgraded - and this has been the object of studies in the past - or a completely new facility can be designed with a view to the long-term future.

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ISIS PHASED UPGRADES

Several ideas for upgrading ISIS to the 1-5 MW level of beam power have been proposed in recent years. One is to replace the 70 MeV linac, which is the oldest part of the facility and already suffers from cavity breakdown and beam-loss, with a new linac operating at 180 MeV. Since tune shift depends on $N/\beta^2\gamma^3$, the higher energy would allow an increased number N of protons, provided practical issues such as a revised injection system can be accommodated in the ring. Another idea is to add a second RCS in series with the existing 800 MeV ring and increase the energy of the existing beam to around 3 GeV. The ring, shown in Fig. 1, would initially take the beam from ISIS by bucket-to-bucket transfer; however its design also allows for a completely new 800 MeV H^- linac to be installed at a later date, which would replace the present synchrotron. Such a system would use charge-exchange injection at 800 MeV, with phase-space painting to give a distribution that should be robust against intensity effects. Mean beam power at the target would be of the order of 2.5 MW with later upgrades to 5 MW. ISIS could continue to operate during the

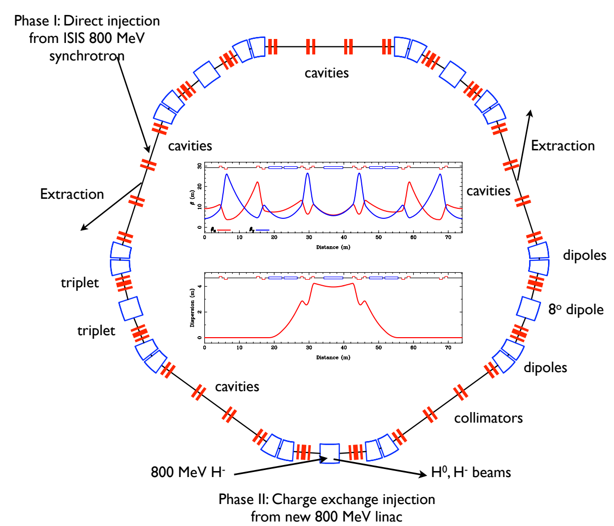

Figure 1: ISIS upgrade RCS showing lattice and optical parameters. Injection in the first phase would be directly from the present 800 MeV RCS, with a new system of H^- painting from a new linac in Phase II.

phased construction. Other options have also been considered, most notably an idea to build a second ring in the existing tunnel, but this would mean the neutron facility closing down for an extended period, so at this stage is not preferred.

A further aspect of the proton R&D programme at RAL is the development of a flexible high current H^- injector, known as FETS (Front-End Test Stand) [5]. This project has been important in covering novel ion source design, implementation of a 3-solenoid LEBT, design and construc-

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tion of a 4-vane, 4 m long, 324 MHz RFQ and application of a versatile dual fast-slow beam chopper. The H^- current is typically 60 mA with a pulse length up to 2 ms. Commissioning of the RFQ is about to start aiming for project completion in 2017, and plans for its future use are now being developed. While one application could be as a target test facility, FETS would be invaluable as an injector for a small development ring at RAL. In parallel with the design of a future multi-megawatt neutron source, a low energy ring (up to ~15 MeV, say) could provide essential guidance for the design of the main accelerating ring.

FFAG-BASED PROTON ACCELERATORS

Rapid cycling synchrotrons now provide a well-understood, reliable option for pulsed operation at the 1 MW level with a repetition rate up to about 50 Hz. But they do present challenges, and it is questionable whether conventional designs could take a very great step forward into the affordable multi-megawatt regime. There is the need for fast ramping magnets, eddy currents to be damped, and difficulties such as phasing multiharmonic rf. The H^- injection systems are highly complex, and contain controls to deal with partially stripped H^0 ions and unstripped H^- , ways to reduce stripping foil temperatures and methods of painting to create an intense beam with the correct emittances and transverse distribution. H^- linacs also suffer from intra-beam stripping, a phenomenon first identified at SNS [6].

In a forward-looking scenario we would look to eliminate at least some of these, and we believe the solution lies in fixed field alternating gradient accelerators, or FFAGs. Studies in the 1950's at MURA [7] produced a wealth of knowledge of beam dynamics in electron FFAGs. An FFAG option was proposed for the European Hadron Facility (EHF) in the 1970's, and was carried over into the 1990's study of a short pulse ESS. It was rejected in favour of a linac+accumulator ring scenario because of the cost of R&D and demands from the neutron community for a tried-and-tested - and therefore - trustworthy machine. However FFAG studies have come on in leaps and bounds with the development of technology and new materials such as magnetic alloys in Japan and initiatives in beam dynamics in the USA and the UK.

For future needs, there are several advantages in FFAGs for a spallation source. Stable dc power supplies can be used for the main magnets; fewer accelerating cavities will be required, and horizontal beam extraction will be easier. The repetition rate can be higher than synchrotrons (~ 100 Hz) and quite flexible, restricted only by the rf programme pattern. This leads to increased beam power and the ability to offer a better match to users' requirements. Neutron users do not necessarily want a high repetition rate but as an option this opens possibilities for a wider range of proton driver use: driving a sub-critical nuclear reactor, or splitting the beam so that different areas of physics can be studied using a single accelerator on a single site.

FFAGs have a large momentum acceptance. This allows particles with the injection and extraction momenta to circulate in the ring at the same time. A large horizontal aperture means that the horizontal emittance ϵ_h can be enlarged. Since the tune depression is given by

$$\Delta Q_v = -\frac{N r_p}{\pi \epsilon_v \left(1 + \sqrt{\epsilon_h/\epsilon_v}\right) \beta^2 \gamma^3} \frac{1}{B_f}, \qquad (1)$$

an emittance ratio $\epsilon_h/\epsilon_v = 10$ and a repetition rate of 100 Hz (four times J-PARC), could generate a beam power approaching 10 MW and still maintain acceptable space charge levels. The beam power could be even higher if the linac feeding the RCS operated at a higher energy.

In the absence of ramping, it is also possible to use superconducting or permanent magnets. Energy efficiency will be high; the machine is expected to be robust with high availability; and low operational costs can be achieved.

On the negative side are the non-linear magnetic fields, the perceived increased sensitivity to alignment and magnet field errors and need for a larger vertical injection acceptance. Design issues include the need for a long straight section for injection, the choice of the cell and ring tunes, the space charge field effects, and the protection against beam loss during injection, acceleration and extraction.

Parameter Requirements

For the main spallation driver, a range of FFAG structures is under consideration to meet the optical demands. The features are as far as possible carried over to a companion prototype FFAG ring to go on FETS. Possible parameters for the two scenarios are shown in Table 1. The starting points are assumptions about the injector linac current, the normalised emittance of the incoming beam (the same in both cases), the likely emittances created in the rings and the ring radii. Input energies are the FETS energy, 3 MeV, for the small ring, and 800 MeV, the ISIS top energy for the main ring. The space-charge tune depression is assumed to be $\Delta Q \sim -0.1$; then equation (1) gives the total number of protons N in the rings and the number of turns to be injected to achieve these levels. The ring designs are based around meeting these parameters.

Pumplet FFAG

The idea of pumplet[1] lattices was first developed for the muon accelerators in the neutrino factory [8] and several options followed for proton machines. The type considered in this study is the scaled pumplet whose lattice uses combined-function magnets in an Od(-)oF(+)oD(-)oF(+)od(-)O pattern. (OO) and (o) are respectively, long and short straight sections, (d,D) are horizontally defocusing fields, F is a horizontal focusing field, and (+) and (-) represent normal and reverse bending. A sample cell for the small (FETS) ring is shown in Fig. 2. It has mirror symmetry about the central D(-) magnet. Both

[1] The name comes from the Welsh 'pump', meaning five, indicating the number of magnets making up each cell.

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Table 1: Injection Requirements for the Main Spallation Source Ring and R&D Test Ring

Parameter	Main Ring	Test Ring
Kinetic energy at injection (MeV)	800	3
Linac beam current (mA)	100	1.9
Unnormalised injected emittances (π mm.mrad)	2.70	10.8
Painted horizontal emittance of ring beam (π mm.mrad)	270	270
Painted vertical emittance of ring beam (π mm.mrad)	135	135
Expected tune depression	0.065	0.065
Number of ions N ($\times 10^{11}$)	1950	2.79
Injection interval required, Ne/I (μs)	313.08	23.50
Revolution period at injection, t (μs)	1.29	1.31
Mean radius at injection energy, $\beta ct/2\pi$ (m)	52.00	4.974
Number of injected turns	241	17
Length of injection straight (m)	5.0	1.30

scaling and non-scaling designs have been considered. Orbits in the former are scaled replicas of one another with fixed beam dynamics across the energy range. The scaling property can be ensured through the use of magnet edges aligned on a common centre. Bend radii and quadrupole strengths are common to all elements. Theoretical optimisation to the desired cell tunes is carried out by varying the field gradients and the spacing of the magnet units, which in turn requires changes to the edge angles, and an iterative re-optimisation process.

The design for the FETS ring is scaling and has a circumference of 31.25 m, with 8 pumplet cells, all magnets having the same bending radius 0.91 m, as shown in Fig. 2. The energy range is 3-10 MeV and 1.3 m is provided for the injection straight. The radial orbit excursion is about 43 cm. A similar lattice is proposed for the main ring, a 26-cell pumplet structure with a 7.6 m bending radius. Each cell has a 5 m straight and a total length of 12.57 m, giving a mean ring radius of 52 m. Lattice functions for this pumplet FFAG are shown in Fig. 3. The energy range in this case is 800 MeV to 3.2 GeV. Scaling and non-scaling models have been treated but the markedly reduced vertical β-function means that for the main ring non-scaling is seen as preferable at this stage of the study.

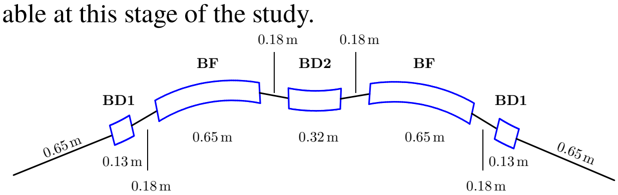

Figure 2: dFDFd pumplet cell, 0.91 m bending radius, part of an eight cell ring with mean radius 4.974 m

The alternative pumplet structure Of(+)oD(-)oF(+)oD(-)of(+)O shows larger β-functions and is ruled out at this stage of the study.

RCS lattice options

RCS pumplet-type lattices have also been examined both for the 3-10 MeV FETS ring and the larger 0.8-3.2 GeV

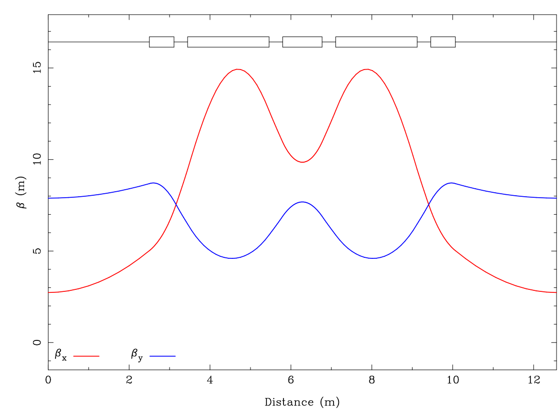

Figure 3: β-functions for the main FFAG pumplet lattice, an enlarged version of the lattice in Fig. 2; the dispersion (not shown) is non-zero throughout.

main ring. The pumplet structure is the same as for the FFAGs but the combined-function magnets all have positive bends, which allows the bending radii to be larger and the magnetic fields much reduced. The choice of a pumplet cell is found to give a wide range of betatron tunes, providing flexibility in optimising parameters for injection. There are both advantages and disadvantages in choosing between RCS and FFAG designs. Ring costs will play a role but the crucial aspect is the effectiveness of the ring injection scheme described below.

DF-spiral FFAG

A very recent idea is the DF-spiral FFAG developed by Machida [9]. This combines features of two types of scaling FFAG - radial sector and spiral - that were individually part of the MURA programme. In the radial sector FFAG, the vertical tune depends on the field flutter and there is zero spiral angle; in the spiral FFAG, the tune is adjusted by a non-zero spiral angle and the field flutter parameter is fixed at ≈ 1. Attempts to use one or other of these designs

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for a high energy, high intensity machine have resulted in either large spiral angles or very high fields in the reverse bends. The novel DF-spiral design combines normal and reverse bend magnets with finite spiral angle to create doublet focusing. The reverse bending magnet is positioned on one side of the normal bending magnet so as to enhance the edge focusing in the vertical direction. This provides a practical lattice design, with a reasonably compact size, that could provide cost effective operation, especially if superconducting technology is used. Fig. 4 shows an example of a 0.4-1.2 GeV ring with a radius of 26 m, the same size as the ISIS tunnel. There are also designs for a prototype test ring for FETS (3-27 MeV) and a larger ring with 52 m radius for a high intensity 3 GeV driver.

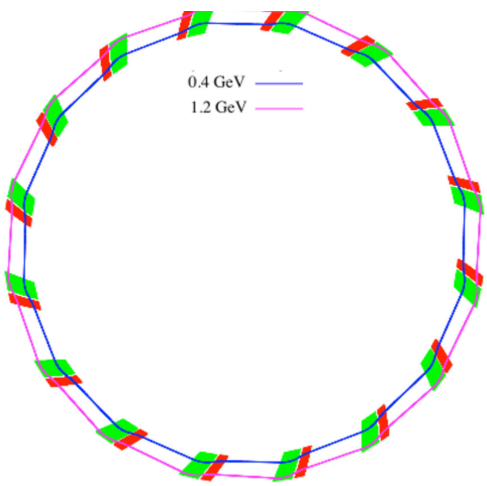

Figure 4: DF-spiral FFAG designed to fit in the ISIS tunnel.

INJECTION

Perhaps the most innovative proposal in this study is the direct use of protons in a Liouvillean injection scheme rather than charge-exchange injection using H^- ions. The use of H^- was proposed about 50 years ago and now represents standard practice in operating proton rings at high intensity. It was implemented in the Fermilab booster, for example, in 1978 [10]. However the injection system is complex because of the need to remove partially stripped and unstripped particles and there are associated issues in dealing with H^- such as foil scattering, foil lifetime and intra-beam stripping in the higher energy stages of the linac [6]. On the other hand, conventional injection into a single phase plane allows only 5-10 turns, which is clearly inadequate (see Table 1). This explains why requirements at the CERN PS-Booster are met through four stacked rings and why the machine is currently being converted to H^- to meet the demands of the next stage of LHC.

But one can in fact do much better. In the 1990's as part of the HIDIF inertial confinement fusion project [11], a two-plane Liouvillean injection scheme was proposed using a tilted electrostatic septum. Injection is then into four-dimensional x-x'-y-y' phase space and allows many more turns to be injected. The suite of codes written to optimise HIDIF has been updated and used to study Liouvillean proton injection schemes into each of the rings described above [12]. The code bases calculations on the geometric properties of linear zero-current beam dynamics, and, from nominal design values, varies tunes and ring and linac β-functions while determining a closed orbit bump programme to minimise beam loss. The model ring is then modified to meet the optimum parameters before the scheme is explored further in a non-linear tracking code with space-charge.

Two conditions are imposed in the optimisation:

$$\frac{\alpha}{\beta} = \frac{\alpha_i}{\beta_i} = -\frac{x'_o - x'_i}{x_o - x_i}, \tag{2}$$

$$\frac{\beta}{\beta_i} \leq \left(\frac{\epsilon}{\epsilon_i}\right)^{1/3}. \tag{3}$$

The subscript i refers to the injected turn; parameters without subscript are for the ring at the injection position; o identifies the closed orbit bump at this point; and ϵ is the painted emittance in the ring. Equation (2) is a 'matching' condition and ensures the incoming turn is positioned in phase space so as to minimise the emittance of the circulating beam in the ring. The second equation (3) is a condition on phase space curvatures that ensures emittances ellipses fit best together. Note that the beams do not (and should not) be 'matched' in the conventional sense that $\beta = \beta_i$ etc.

With these conditions, there are encouraging results that a zero-loss system (ignoring space-charge) could be possible with up to 350 turns for the main ISIS ring and 45-50 turns for the small R&D ring designed for FETS. We have still to explore the injection process using a detailed tracking code with a full injection bump chicane, but these figures are well within the requirements identified in Table 1.

The optimisation code contains a simple feature to account for space-charge tune depression via (1). Assuming no beam loss, N is proportional to the number of turns injected and the emittance factor is given by the painted emittances in the ring. Figure 5 (top left) gives an example of the kind of distribution created and is rectangular in real space because of the correlated painting mechanism. This is for 350 turns injection into the dFDFd pumplet FFAG and shows the septum tilted at an optimised angle of 66.4∘. Figure 5 (top right) shows the variation of the closed orbit as the circulating beam is pulled away from the septum to avoid loss and control the emittance in the ring. The displacement is achieved with four horizontal and four vertical bump magnets. Note that, according to equation (2), if α is non-zero at the injection point, it is necessary to create non-zero $x'_o - x'_i$. One would expect $x'_i = 0$ and it is a simple matter to generate both displacement x_o and angle x'_o in the closed orbit with the kickers. The two lower plots in Fig. 5 show (normalised) horizontal and vertical phase space projections (different colours identify different turns). It remains to study the effects of non-linear space-

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charge, which will fill in the phase space holes and generate emittance growth and halo, and also the effects of dispersion which, as noted above, is non-zero in the FFAG injection straights.

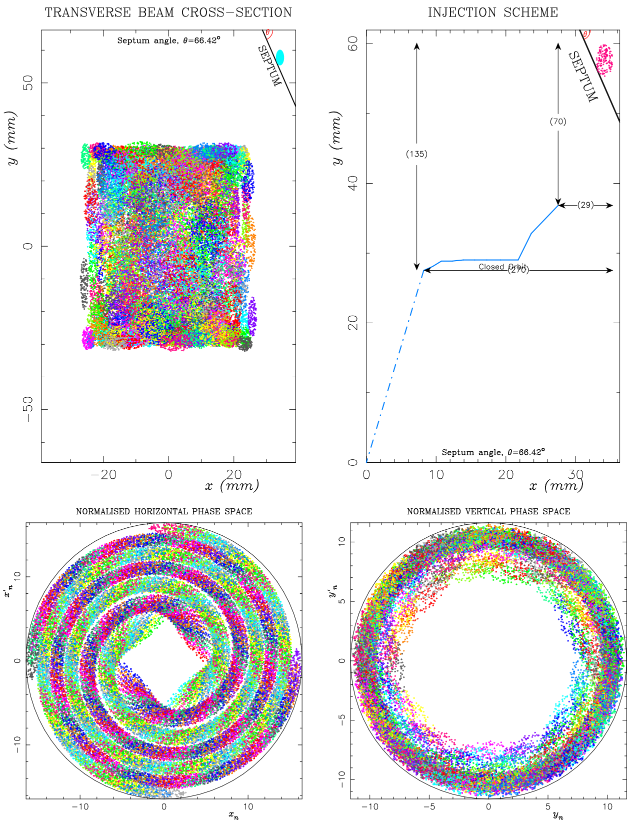

Figure 5: Simulation results for the FFAG main ring pumplet, 350 turns, in the absence of space-charge.

Extrapolating the parameters in Table 1, 350 turns at a repetition rate of 100 Hz would represent 3.6 MW of mean beam power in the ring even at the injection energy, and we might expect to increase this by a factor 4 after acceleration to the final energy. The absolute tune shift is still < 0.1. Thus, the two-plane injection system could be the way forward for future high power proton accelerators and could supersede the accepted norm of H^- charge exchange injection.

Coincidentally, the two-plane injection idea has been adopted by China's HIAF [13] for its B-ring ion accelerator, and there is now a good chance that experimental verification of the theories may be carried out.

EXPERIMENTAL PROGRAMME

Associated with the theoretical study is an experimental programme that has two aspects.

FFAGs at KURRI, Japan

With Kyoto University, we have a Memorandum of Understanding in place to share knowledge, information and training facilities related to FFAG development. This provides opportunities for regular periods of experiment and data-taking on the 150 MeV FFAG at KURRI. Unique techniques have been developed to characterise the proton beam and enhance understanding of FFAG beam dynamics. There are so few machines of this type operating anywhere in the world, and it is essential that we know how to improve and control beam quality if we are to demonstrate the feasibility of high power operation of FFAG accelerators in the future. Details are given in [14].

IBEX Paul trap at RAL

The second experimental aspect of FFAG and other high power studies in the U.K. is the design and construction of a linear Paul trap at RAL. This follows closely in the footsteps of pioneering work by Okamoto [15] at Hiroshima University, who has used the similarity between the equations of a trapped ionised plasma and the motion of a charged particle beam in a strong focusing channel to study beam dynamics in a local table-top environment. The Paul trap's flexibility, compactness and low cost make it a useful tool for the study of a wide range of accelerator physics topics. The RAL team has collaborated with Hiroshima in work that has focused on high intensity collective effects as well as a study of integer resonance crossing in the low intensity regime. A natural extension of this work is to investigate space-charge effects in intense beams in more realistic lattices to aid high power accelerator design and development.

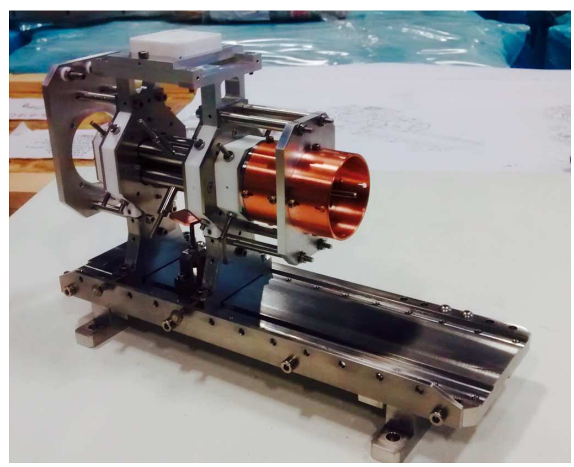

Figure 6: IBEX (Intense Beams Experiment) Paul trap at RAL.

The trap being set up at RAL (shown in Fig. 6) is a modified version of the Hiroshima design and will be used for intense beams studies [16]. Among other features, it is envisaged that it should also be able to model non-linear elements and a wider range of lattice configurations. Plans include modelling the IOTA (Integrable Optics Test Accelerator) at Fermilab [17] and contribute to the development of the MTE extraction system at the CERN-PS [18], where a combination of tune control and non-linear magnets such as octupoles is used to manipulate phase-space and control beam dynamics.

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