HIGH POWER FROM FIXED-FIELD RINGS IN THE ACCELERATOR-DRIVEN SUB-CRITICAL REACTOR APPLICATION

F. Méot, M. Haj Tahar, N. Tsoupas
Brookhaven National laboratory, Upton, NY, USA
fmeot@bnl.gov

Robert B. Appleby
The University of Manchester and the Cockcroft Institute, Manchester, UK

C. Johnstone
Fermilab, Batavia, IL, USA

S. L. Sheehy
Intense Beams Group, Rutherford Appleton Laboratory, Didcot, UK

ABSTRACT

Accelerator technologies that have been thoroughly investigated for the production of high-power proton beams include, the separated sector cyclotron and superconducting linear accelerators. Alternative approaches to high power include fast cycling synchrotron technology, with potential for ≈1 GeV beam energy, tens of Hz repetition rate, MW beam power. They also include FFAG accelerators which have potential for beam energy beyond GeV, repetition rate in the kHz range (like synchro-cyclotrons), potential for CW operation. Today’s FFAG R&D aims at demonstrating applicability in the 5-10 MW power range suitable for ADS-R application. In many instances of MW- or multi-MW-class installation and in recent design studies, linac technologies are considered the appropriate path to necessary properties or flexibility. These arguments require closer inspection when it comes to the ADS-R application, which may substantially differ, in the matter of beam properties and accelerator flexibility, from such installations as SNS, a neutrino factory and other RIB production. In particular, flexibility requirements in the ADS-R application concern essentially the beam intensity and possibly, to some extent, beam energy. Cyclotron and FFAG technologies do allow flexibility in both beam intensity and beam energy, and are attractive alternatives, within margins that still require further R&D prior to drawing conclusions and engaging on exacting R&D road maps. In this brief review, key principles will be recalled regarding these diverse fixed-field ring technologies, as well as the present status of their R&D and the performance achieved or envisioned, based on instances of existing fixed-field ring installations or on-going designs, selected for their potential to realize production of multi-MW beams in the GeV range.

1. INTRODUCTION

An accelerator driven sub-critical reactor facility is comprised of four ensembles: a sub-critical reactor, a spallation target, a high power proton driver, and nuclear data (Fig. 1). The reactor is operated in the sub-critical regime, with a neutron multiplication factor $k_{eff}$ ($= \text{number of neutrons produced/ number of neutrons absorbed}$) generally in the range [0.95-0.98] as a compromise between the accelerator power requirement and the margin from criticality. Table I shows a list of typical ADS-R parameters for several on-going projects.
I.A. Accelerator Technologies

Several accelerator technologies have been thoroughly investigated for the production of high-power proton beams. These include the separated sector cyclotrons and superconducting linear accelerators. Normal conducting proton linear accelerators are prohibited due to their operational cost. Other alternatives for high power include fast cycling synchrotron technology, with potential for ≈1 GeV, 1 MW operation (limitation is the pulsed regime, a few tens of Hz). An example is the ISIS neutron and muon source rapid-cycling synchrotron at Rutherford Lab. (UK), running since 1984, 50 Hz, 800 MeV, 200 kW beam power, a more recent development is the JPARC booster. Fixed-field alternating gradient (FFAG) accelerators can have higher repetition rate (100s of Hz, confer for instance the old Orsay Proton-therapy Center synchro-cyclotron with rotating capacitor RF system, which used to operate at 400 Hz), with potential for CW operation designs. “While promising, FFAGs have yet to demonstrate high beam power capability. With further development, FFAG technology may also demonstrate applicability in the 5-10 MW power range” [1].

I.B. Present Trends

In many cases of MW- or multi-MW-class installations and recent design studies, linac technologies are considered the appropriate path to necessary properties or flexibility. For instance:

- SNS accelerates H\(^+\) ions for injection into an accumulator ring;
- Optimum production of pions in a neutrino factory is in the 3-5 GeV range and was one of the driving applications of the Superconducting Proton Linac (SPL) project at CERN;
- The Chinese ADS-R project plans on science applications at diverse energies, including multi-GeV, in addition to ADS-Reactor R&D;
- FRIB at MSU plans on multiple particle species, multiple charge-states, in a lower 200 MeV/n, 400 kW regime.

However, these arguments should be carefully inspected when it comes to the ADS-R application. More specifically, for an ADS-R, the main beam parameter to be adjusted on the accelerator side is the current. The latter is proportional to the core thermal power and therefore provides a straightforward solution for the power control. The argument of adjusting the beam energy may be important for some applications, for instance FRIB which is better off with a linac (multiple species and charge state, a reasonable linac investment for a relatively modest amount of energy and power). However, for ADS-R, the beam energy, generally around 1 GeV, is carefully chosen in order to maximize the target multiplicity, and reduce the amount of high energy cascade neutrons that escape from the system and pose a serious shielding issue. Fig. 2 shows that the neutron yield (number of spallation neutrons normalized to the unit energy per

### TABLE I. Typical ADS-R parameters, at MYRRHA, the European Facility for Industrial Transmutation and China ADS.

| Reactor core | Thermal power (MWth) | \(k_{\text{eff}}\) | Energy (GeV) | Current (mA) | Power (MW) |
|--------------|----------------------|--------------------|--------------|--------------|------------|
| MYRRHA       | 85                   | 0.95               | 0.6          | 2.5-4        | 1.5-2.4    |
| EFIT         | Several 100          | 0.97               | 0.8          | 20           | 16         |
| C-ADS        | >1000                | 0.97               | 1.5          | 10           | 15         |
incident particle) is maximum around 1 GeV.

II. FIXED FIELD RINGS

Linacs as well as fixed-field ring methods date from the 1920s-1930s. The cyclotron was seen by its inventor as a folded linac, allowing savings on RF (still an advantage seen in the later, 1940s-1950s synchrotron methods), an argument that still holds today, with a different - much higher - energy range as an effect of the advances in linac technologies. The recent past has seen a regained interest in the development of cyclotron and FFAG methods in the ADS-R application for that very reason and for its
corollaries, such as, potential saving on construction and operation costs, use of long-proven and conservative magnet technologies, much reduced volume of accelerator equipment and footprint, and potential for improvements in reliability and redundancy. Comparing two similar-power installations for instance, the 600 MeV linac project in the MYRRHA ADS-R and the 590 MeV PSI cyclotron: the former comprises more than 100 RF cavities and associated klystron equipment, over a 140 m-long footprint; the latter accelerates the beam over two hundred turns with four RF cavities and about $\approx 40 \times 50$ m$^2$ footprint, including injectors. Methods for beam flexibility, where (and only where) it is needed in the ADS-R application, are part of current fixed-field ring R&D. Examples of this are, the use of stripping extraction in cyclotrons, or a change in global magnetic field value in FFAGs, to allow variable energy.

In what follows review key principles, and a few ADS-R drivers designs selected for their potential to realize production of multi-MW beams in the GeV range and possibly beyond. Note that this brief review is far from being exhaustive, more can be found in [2].

II.A. Principles

High beam power requires separated sectors, as seen in the PSI proton ring (Fig. 3) to allow drifts for injection and extraction systems, radio-frequency (RF) accelerating cavities, beam instrumentation, etc. Fixed frequency and high-Q RF requires isochronism, which requires $T = \frac{2\pi R}{c \beta}$ = constant, where $T$ is the revolution period independent of beam energy, $c$ the speed of light, $\beta c$ the particle velocity corresponding to the average orbit radius $R$. The property $R \beta$ is obtained by designing the field so to ensure an average value along the orbit $B_{av}(R) = B_0 \gamma(R) = B_0 \left[1 - \left(\frac{2\pi R}{c T}\right)^2\right]^{1/2}$.

This is obtained with a R-dependent radial field index $k(R) \approx \sqrt{1 + k} \approx \gamma$, $Q_z \approx \sqrt{-k + F(1 + 2 \tan^2 \xi)}$ (axial field modulation) ensure transverse stability, characterized by radial and axial wave numbers, respectively, $Q_r \approx \sqrt{1 + k} \approx \gamma$, $Q_z \approx \sqrt{-k + F(1 + 2 \tan^2 \xi)}$ (ξ is the spiral

Figure 3. The 590 MeV, 1.3 MW separated sector cyclotron at the Paul Scherrer Institue (first beam 1973), with 8 spiral magnetic sectors, 4 RF cavities in the MV range.
sector angle). These wavenumbers, $Q_x$ and $Q_z$, normally span a substantial area in the tune diagram, as shown in Fig. 4, which reveals the energy dependence and weak focusing when in particular $Q_z$ is close to or less than 1.

![Tune Diagram](image)

**Figure 4.** Typical wide span beam tune path during cyclotron acceleration.

II.B. Cranking up the PSI technology

![Cranked-up PSI Energy Amplifier](image)

**Figure 5.** Cranked-up “Energy Amplifier” PSI-type proton driver concept.

Increasing the beam energy and power for a cyclotron-based ADS-R has been investigated very early at PSI. It also happens to be the option retained in the “energy amplifier” proposal by Rubbia et al [3] which uses a 3-stage cyclotron capable of providing a 10 MW proton beam in the 1-1.2 GeV energy range (Fig. 5). A prescription for reaching the 10 MW power level using the principles addressed in the previous
section includes high acceleration rate, sufficiently large final turn separation.

II.C. Other options

Several proposals exist for ADS proton drivers based on the cyclotron technology. Some are presented and discussed below:

The Texas A&M “TAMU” concept uses an innovative approach incorporating stacked cyclotrons. The 12-sector stacked main ring is comprised of 10 superconducting (SC) cavities per stack for 20 MeV/turn. The design is based on three particular concepts, (i) a superconducting folded beam channel ensuring constant tunes, strong focusing (the beam no longer wanders in the tune diagram, in contrast to that shown in Fig. 4), (ii) flux-coupled stacked gaps, and (iii) folded, double quarter-wave, superconducting RF cavity structures. This results in four 800 MeV, 8 MW beams. Expected plug-to-power efficiency is ~50%. See Assadi et al. [4] for more.

The DAEδALUS H2+ cyclotron is the driver cyclotron of the “Decay-At-rest Experiment for δCP studies at the Laboratory for Underground Science” (DAEδALUS). It should deliver a 800 MeV, 10 mA (8 MW) proton beam, and has potential for energy in the 1-1.5 GeV range and power in 10-15 MW range as described in Calabretta et al. [5]. Major ingredients to reach these goals are, (i) acceleration of molecular H2+ (relaxes on space charge effects: they are weak for 5 mA H2+, i.e., 10 mA extracted proton beam), (ii) stripping extraction (relaxes on turn separation thus allowing high magnetic field and compactness), (iii) SC magnets in a design akin to the K2600 RIKEN cyclotron, (iv) peak magnetic field of 6 T and peak RF field of 4 MV per cavity, at the top energy.

The AIMA Revatron concept by Mandrillon et al. [6] is based on “reversed valley field”. Peak sector (respectively valley) field is 4 T (resp. -1.05 T); SC coils extend from 4.2 to 7.1 m radius; 6 RF cavities allow 12 gaps per turn and 0.15 to 0.45 MV per gap; turn separation at top energy is 15 mm. The extracted proton beam (from either proton acceleration or stripped H2+) is steered outward by the reverse field. The outcome is a single-stage, triple-injection, triple-beam, 800 MeV/u ring.

III. FFAG ACCELERATORS

The FFAG (Fixed Field Alternating Gradient) principle was devised in the mid-1950s, following the discovery of the alternating gradient in 1952. Three electron prototypes were constructed, the third one a two-way, 50 MeV ring [7]. They were called “scaling” FFAGs, by reference to the orbit shape, optics and tunes being kept the same at all energies.

III.A. KURRI-KUCA experiment

Interest in the FFAG concept was revived in the late 1990s by the potential for strong focusing, very large acceptance, fast acceleration, with the goal of applying it to a proton driver, and to the fast acceleration of short-lived, large emittance muon beams, in the Neutrino Factory. A proton prototype was built, based on a radial sector, Focusing-Defocusing-Focusing (FDF) dipole triplet cell, and then operated at KEK in December 1999 (Fig. 6-top).

A 150 MeV radial sector FFAG followed, started in 2003, and led to the KURRI KUCA installation in the mid-2000s, as a feasibility evaluation of ADS-R [8]. First coupling of the FFAG to the ADS-R core was achieved in March 2009 using a 100 MeV beam. Thorium-loaded ADS-R experiments were performed in March 2010 using the 100 MeV beam and a repetition rate of 30 Hz, <1 W beam power. Planned upgrades include variable energy in the 150-700 MeV range based on an additional 700 MeV spiral lattice
FFAG stage (see Sec. III.B) [9], allowing a neutron flux increase of a factor 30. On-going FFAG R&D experiments include H⁺ charge-exchange injection with the goal of reaching 10s of μAmp beam current.

Figure 6. Top-left: proof-of-principle 500 keV, 2.5 m diameter, proton scaling FFAG at KEK. Top-right: KURRI-KUCA ADS-Reactor experiment based on the use of an FFAG, proton driver to the left and reactor core to the right. Bottom: KURRI-KUCA 150 MeV radial sector scaling FFAG proton driver.

III.B. RACCAM

A spiral lattice proton FFAG was devised in the late 2000s (Fig. 7), in the framework of the Neutrino Factory R&D [10]. The R&D included fabrication of the scaling spiral sector magnet, first of its kind (Fig. 7). The design found application in a simultaneous multiple-beam delivery hadron-therapy facility [11]. Magnet design outcomes were exploited in the KURRI-KUCA 700 MeV upgrade, as
addressed in the previous section.

![Figure 7](image1.png)

**Figure 7.** Left: Proof-of-principle 250 MeV spiral lattice design, “RACCAM”. Right: Prototype scaling FFAG spiral sector dipole ready for field measurements.

### III.C. The concept of linear FFAG

Two concepts were introduced in the late 1990s, in the frame of the Neutrino Factory R&D [7]: (i) “linear lattice” FFAGs: lattice magnets are simple quadrupoles (Fig. 8) and (ii) “quasi-isochronous” acceleration of ultra-relativistic particles (Fig. 9), using fixed frequency RF.

![Figure 8](image2.png)

**Figure 8.** Principle quadrupole-triplet linear FFAG cell.

![Figure 9](image3.png)

**Figure 9.** Serpentine Hamiltonian path system, that allows bringing the beam from low energy (yellow path, lower left) to high energy (yellow path, upper right).
The concept was well suited for the acceleration of short-lived muons up to 20-50 GeV and later led to many developments including proton driver applications: among these developments, one can cite (i) the EMMA experiment [12] which is an “Electron Model for Many Applications” (EMMA) that was built to prove the non-scaling and serpentine acceleration concepts, in the framework of an international collaboration, (ii) the Proton driver linear FFAGs allowing to devise high power rings [7][13], (iii) isochronous optics which allows on-crest acceleration and thus CW beam delivery, a path to higher power. CW operation also gives the best plug-to-beam power efficiency. Dedicated non-linear, non-scaling lattices are currently being investigated by Johnstone and Sheehy towards the goal of CW operation.

More is on-going in FFAG R&D. Topics cover compact lattices, \( \beta < 1 \) regime, isochronous lattices and CW acceleration, reverse bend optics, serpentine acceleration, magnet and RF technology, superconducting components, and a number of potential applications.

IV. ENERGY EFFICIENCY

Energy efficiency is a vast topic in itself, however it is a paramount aspect for ADS application. The impact of the electrical power required to operate the accelerator is important to justify the competitiveness of ADS systems with fast critical reactors. Ref [14] stresses the issue: “For ADS the power required by the accelerator can represent a significant fraction of the power generated by the blanket. [...] the attractiveness of the system will be significantly hindered if it requires more power than it generates. There is a strong incentive to design ADS blankets with the highest k-effective value reasonable. However, this reduces the margins to criticality.”

![Figure 10. Corrected thermal efficiency of an ADS-like facility. The uncorrected thermal efficiency is 40% (fast reactor) while the target multiplicity assumed is 20n/p (Ep~ 1 GeV). The thick gray curve at the bottom materializes the breakeven case, where the net efficiency of the system is zero.](image-url)
As an illustrative example, Fig. 10 shows the corrected thermal efficiency of the ADS system (taking into account the power consumption of the accelerator) for various cases of accelerator efficiency (wall-plug efficiency). When the reactor is near the critical state ($k_{\text{eff}}=1$), the impact of the accelerator is no longer playing a major role: the fission reaction is self-sustaining and therefore the corrected thermal efficiency of the ADS plant does not suffer much from the low efficiency of the accelerator. However, this is generally not the case: the $k$-effective value is generally taken below 0.97 to ensure enough margin from criticality accidents (see Table I), and thus the impact of the accelerator is more and more dominant: for instance for $k_{\text{eff}}=0.95$ and $\eta_{\text{acc}} = 10 \%$, the corrected thermal efficiency is lowered from 40% to 6.5% (black dot in Fig. 10). Much R&D work is still required in order to bring the accelerator design into efficiency.

V. CONCLUSIONS

High power fixed field rings are in the development stage. Although further R&D is still required to bring these systems into maturity, such technologies, generally considered as an alternative solution to linacs, have the potential for simpler and smaller footprint installations, better beam reliability, and lower construction and operation costs.

REFERENCES

1. H. Aıt Abderrahim et al, US “ADS White paper”: Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production, 2010; http://science.energy.gov//media/hep/pdf/files/pdfs/ADSWhitePaperfinal.pdf

2. L. Calabretta and F. Méot, “Cyclotrons and FFAG Accelerators as Drivers for ADS”, Review of Accelerator Science and Technology, Vol 8 (2015) 77-97.

3. C. Rubbia et al., Conceptual design of a fast neutron operated high power energy amplifier, CERN 95-44 (1995).

4. S. Assadi et al., Strong-focussing cyclotron - high-current applications, Procs. IPAC2012 New Orleans, LO, USA.

5. L. Calabretta et al, A superconducting ring cyclotron for the DAEδALUS experiment, Procs. IPAC2012., New Orleans, LO, USA.

6. P. Mandrillon et al., Cyclotrons for ADS, ThEC’13 conference, CERN, Geneva, Oct. 2013.

7. C.Prior, Editor, Theme section: FFAG accelerators, ICFA BD Newsletter 43, pp. 14-133, Aug. 2007.

8. http://www.rri.kyoto-u.ac.jp/en/facilities/irl; http://www.rri.kyoto-u.ac.jp/en/facilities/ca

9. B. Qin and Y. Mori, Compact scaling FFAGs for medium energy applications, NIM A
10. S. Antoine et al., Principle design of a protontherapy, rapid-cycling, variable energy spiral FFAG, NIM A 602 (2009) 293–305.

11. F. Méot, A multiple-room, continuous beam delivery, hadrontherapy installation, these proceedings. http://www.sciencedirect.com/science/article/pii/S1875389215001984

12. S. Machida et al., Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMMA, Nature Physics, Jan. 2012.

13. A.G. Ruggiero et al., PAC’07, THPAS104 (2007). A.G. Ruggiero et al., Phys. Rev. ST AB, 9, 100101 (2006).

14. F. Heidet, N. Brown, M. Haj Tahar, “Accelerator–Reactor Coupling for Energy Production in Advanced Nuclear Fuel Cycles”, Reviews of Accelerator Science and Technology, Vol 8 (2015) 99-114.