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A NEW SOLUTION FOR COST EFFECTIVE, HIGH AVERAGE POWER (2 GeV, 6 MW) PROTON ACCELERATOR AND ITS R&D ACTIVITIES*

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Abstract

Due to the successful construction of a 435-ton magnet for CYCIAE-100, it has been proved that the gradient adjustment of magnetic field along radius can effectively enhance the vertical focusing during the isochronous acceleration. This key technology was applied to the general design of a 2 GeV CW proton accelerator, the energy limitation of the isochronous machine is increased from ~1 GeV to 2 GeV, by our contribution of the beam dynamics study for high energy isochronous FFAG.

This paper will introduce CIAE's engineering experience of precision magnet, beam dynamics by single particle tracking and the advantages of beam dynamics simulation based on large-scale parallel computing. The cost-effective solution for such a 2 GeV high power circular accelerator complex will be presented in detail after the brief introduction about the high power proton beam production by the CYCIAE-100.

INTRODUCTION

The 100 MeV compact cyclotron, CYCIAE-100 was approved formally to start the construction in 2011[1], and the first proton beam was extracted on July 4, 2014. In 2017, the 200 μA proton beam development was conducted, and in 2018, the production of high power beam from 20 kW to 52 kW had been delivered successfully to the beam dump, which was quantitatively predicted ten years ago [2]. After about 8 years of construction, installation, beam commissioning and operation, various proton beam intensities from 2 pA to 520 μA can be provided for users for different applications. The Fig. 1 shows the 520 μA beam with the bunching effect of about 1.6 at the high current operation. The beam was measured by the beam dump at the end of the beam line for isotope production.

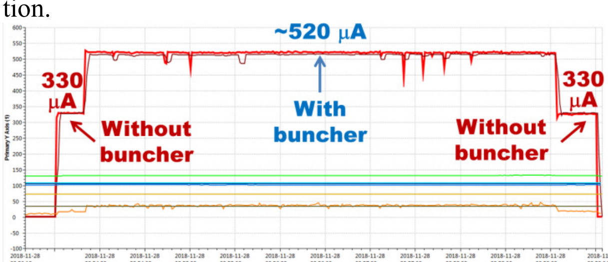

Figure 1: The 52 kW CW Proton Beam Production.

During the construction of the 435-ton large-scale precision magnet for CYCIAE-100, we noticed that the 2nd order pole profile adjustment of magnetic field gradient along radius can effectively enhance the vertical focusing from the energy of 70 MeV to 100 MeV for such a AVF cyclotron [3]. This technology is also applied to pole profiles of the F & D magnets by two 3rd order functions respectively for the general design of a 2 GeV CW proton accelerator, which is using the 800 MeV cyclotron as an injector [4].

GENERAL CONSIDERATIONS IN OVERALL DESIGN OF 2 GEV CW FFAG

There are three different types of constructed accelerators for high power proton beam production: the cyclotron, LINAC and RC synchrotron. The average power of the accelerators currently is from 0.2 MW to 1.4 MW. The proton accelerator with highest beam power under construction is the ESS's SC LINAC, with a beam power of 5 MW [5]. The FermiLab researcher reported the energy efficiency of the three operational accelerators with the highest beam power in the world [6]. The energy efficiency of the PSI cyclotron is about 3 times of the other types. In order to develop high average beam power, high power efficiency and high cost effective proton machine, the isochronous accelerator is a good technical route, if it can break through the energy limitation of 1 GeV, which is presented by Dr. Y. Ishi [7]. Based on the basic FFAG idea, the research for a new solution for cost effective, high average power, 2 GeV proton accelerator was first proposed at CIAE in 2013. Combining the engineering experiences on large radial range varying gradient magnet in CYCIAE-100 and the strong focusing in FFAG, we achieve isochronous acceleration up to 2 GeV. The overall design has been basically completed after several years of research, simulation and optimization. It is a fix frequency, CW FFAG accelerator. Its layout with 100 MeV pre-injector, 800 MeV injector and 10 FDF cell CW FFAG is shown in Fig. 2, and the main parameters in Table 1.

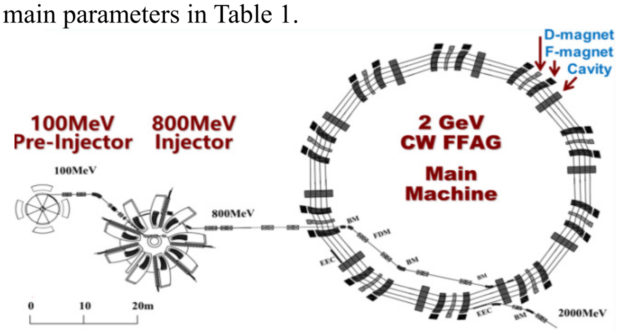

Figure 2: The layout of the circular accelerator complex.

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Table 1: The Main Parameters of 2 GeV Circular Accelerator Complex

Accelerator	100 MeV Injector	800 MeV Booster	2 GeV FFAG
Type	Separated-sector cyclotron	Spiral-sector cyclotron	CW FFAG
Overall diameter（m）	6.1	16	54
Lattice structure	FO	FO	OFoDoFO
Magnet Type	Warm	Warm	HTS
Average field(T)	0.36~0.41	0.54~0.90	F:1.5~2.7 / D:1.0~2.4
Sector number	4	9	10
Main cavity number	2	5	10
Cavity type	Double gap	Single gap	Single gap
RF Frequency(MHz)	44.4	44.4	44.4
Harmonic number	4	6	26
RF peak voltage(kV)	500	800~1000	~1200

Its basic characteristics are as follows:

- Comparing with an isochronous cyclotron, the 3rd order varying radial gradient of the magnetic field and FFAG's FDF Lattice are introduced to obtain isochronism at higher energy and bigger transverse acceptance. The two 3rd order field distributions, combining with the traditional spiral angles, angular widths and the fringe field shimming of the F & D magnets, bring more degrees of freedom to realize the isochronism and optimize the tune in the diagram.
- More than 9 m straight drift for the installation of up to 10 RF cavities to increase the energy gain per turn to 10 MeV, and for the beam injection /extraction.
- The 10 cell magnets and 10 RF cavities are arranged strictly in 10-fold symmetry to avoid driving low-order resonance.
- From the PSI's experience, the beam intensity, dominated by the space charge, is proportional to the third power of the energy gain per turn [8]. Based on that, the beam intensity is ~ 6 mA for 10 MeV energy gain per turn & big transverse acceptance of FFAG. It is conservatively estimated to be 3mA for this design.

BASIC BEAM DYNAMICS

As a nonlinear non-scaling FFAG [9], the challenge of isochronous FFAG lattice design is to maintain the isochronism up to 2 GeV and optimize the tune for resonance crossing. More challenges to design the basic beam dynamics, are from the large orbit oscillation of the FFAG machine and a large numbers of freedoms, which including the F & D magnet field and their gradient, the distance between the F and D, the straight drift section, the angular width and spiral angle of F or D magnet, etc.

A genetic-based multi-objective optimization algorithm is developed and applied to the CW FFAG optimization. The isochronous orbit and betatron tune of selected multi-energies are the goal of optimization. In order to obtain sensitive freedom variables for optimization, several methods are adopted:

- The magnetic field fitted by high-order polynomial (third order polynomial is used in this design);
- Spiral angle of F and D magnet change with radius;
- Angular width of F and D magnet increase monotonically with radius.

At the beginning of the acceleration, the isochronous condition is relaxed a little to avoid the resonance $\nu_r = 2$ crossing, just as shown in Fig. 3 and Fig. 4. In order to obtain the isochronism, the radial tune naturally grows with energy, so the tune optimization is a big challenge, as illustrated in Fig 3. The 10 MeV energy gain per turn with this 10-fold symmetry structure are helpful to cross the resonance quickly. The integrated phase shift is well controlled within ±15°, as shown in Fig 4.

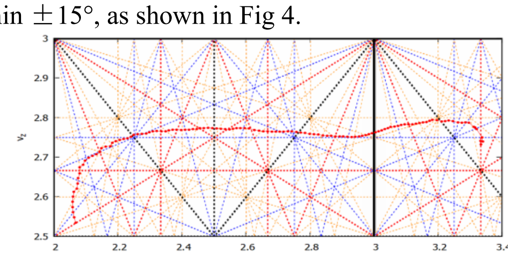

Figure 3: Tune diagram.

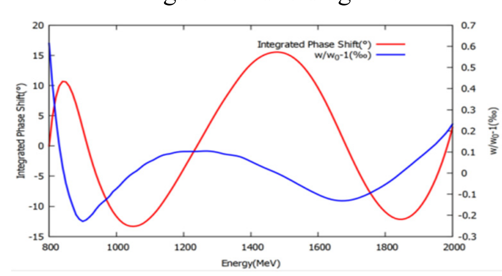

Figure 4: The isochronous behavior.

At the injection of 800 MeV proton beam into the FFAG machine, the radial acceptance is as big as 20 cm, and the vertical acceptance is also big enough, as shown in Fig 5. Although the basic beam dynamics is calculated based on the single particle, we can use:

$$i_{limit} = \Delta z \nu_Z^2 \omega_0 \varepsilon_0 \frac{\Delta\Phi}{2\pi} \frac{\Delta V}{Q_e}$$

to estimated how much ν_z shift can be caused by accelerated beams of 3 mA and 6 mA, respectively, where ε_0 is the dielectric constant, ω_0 is orbital angular frequency, Δz is

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the height of beam, ΔV is the energy gain per turn, ΔΦ is the phase width. Qe is the charge. The decrement of ν_z at 6 mA is only at 10^{-3} level. It demonstrates again that the 3 mA/6 MW is a conservative design.

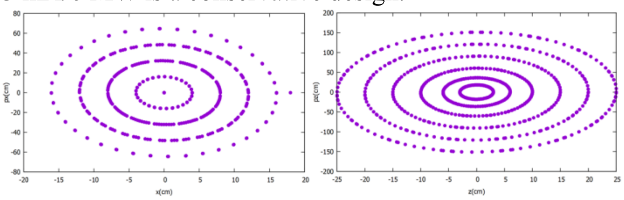

Figure 5: The radial (left) and vertical (right) phase space at 800 MeV.

RESONANCE STUDY & FUNDAMENTAL DESIGN FOR EXTRACTION

For the high power accelerator, resonance crossing is a key factor to impact the beam quality and hence increase the possibility of beam loss. The main resonances are shown in Fig. 6. These resonances are divided into two categories. One is driven by the external imperfection field, which is generally small, so only the low-order resonances need to be taken care of. The others are driven by the main field, such the average field gradient, the 10th harmonic field, etc., thus even a high order term may influence the beam quality. Among these resonances, the first order resonance $\nu_r = 3$, driven by third harmonic field B_3, is the most sensitive. Fig 7 gives the radial beam profile with and without third harmonic field near the resonance. Even a 3rd harmonic of 1 Gs leads to the beam envelop growth, which imposes strict requirements on the control of 3rd harmonic. Therefore, method to compensate the B_3 should be further investigated in this design. Also, the vertical beam profile study shows the radial and vertical coupled resonances driven by the main field have little effect on the vertical beam envelop.

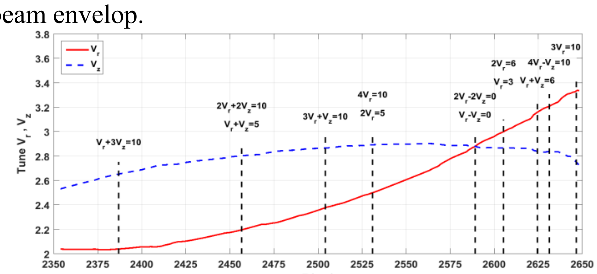

Figure 6: The tune values varying with radius and the main resonances crossed in the machine.

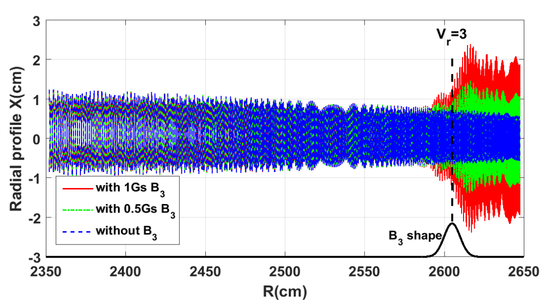

Figure 7: The radial beam profile during acceleration with and without third harmonic field near the ν_r=3 resonance.

Further, the fundamental design for the extraction is considered, mainly emphasizing on the turn separation at extraction. For a single particle, the turn separation for a cyclotron can be expressed as [10]

$$\triangle r = \triangle r_0 + \triangle x \sin(2\pi n \nu_r \theta) + x \triangle \sin(2\pi n \nu_r \theta)$$

Where $\triangle r_0$ is the separation from the energy gain, $\triangle x$ is the radial oscillation amplitude growth driven by resonance, and the third term is from the precessional motion. In the 2 GeV machine, the turn separation from 10 MeV energy gain is about 10 mm. Five more cavities are considered to be added and hence increase the turn separation to 15 mm. The radial beam profile illustrated in Fig.8 indicates the $2\nu_r$=5 resonance driven by the 5-fold symmetry of the electric field has little impact on the beam quality. In the physic design, the beam keeps stay near the $3\nu_r$=10 resonance for a long time, expecting to get larger turn separation. From Fig. 7 we know, this resonance brings little oscillation growth to the radial beam maybe due to the high order, may not helpful to increase the turn separation. The precession method is adopted for that as well. As the radial tune value is near 3.33 at extraction, with beam off centered at injection, beam can be separated significantly under the effects of precessional motion as illustrated in Fig. 9. In this simulation, 15 π.mm.mrad phase ellipse is used, corresponding to 1 cm radial oscillation amplitude at 800 MeV. 1 cm off-centered and 2 cm off-centered injection could increase the turn separation to 2 cm and 3 cm respectively, which seems to be enough for high power beam extraction. However, the beam quality with larger off-centered during acceleration should be studied further.

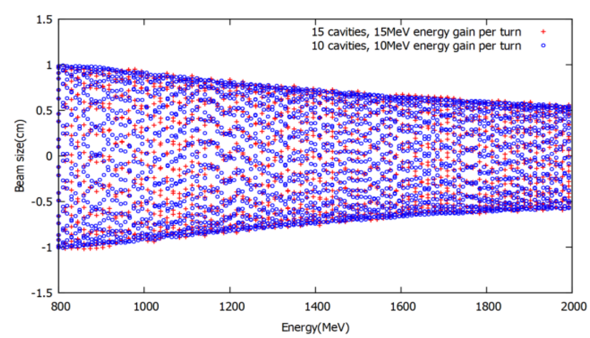

Figure 8: The radial beam profile with 10 and 15 cavities for acceleration.

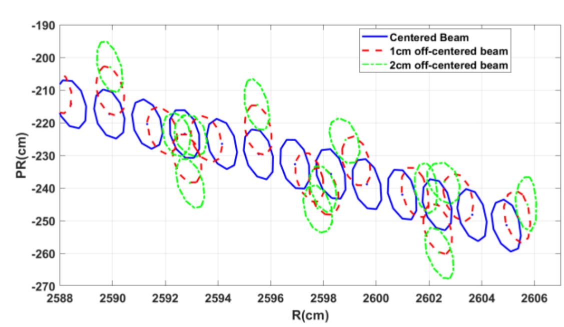

Figure 9: The radial phase space during accelerator with centered, 1 cm off-centered and 2 cm off-centered beam.

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R&D ACTIVITIES OF KEY COMPONENTS

Magnet System

Ten FDF periodic cells, each contains two bending (focusing) magnets and one reverse bending (de-focusing) magnet, form the whole 2 GeV FFAG lattice ring. Unlike the scaling FFAG scheme, where the required magnetic field is proportional to the k-th power of the orbit radius where k is the field index of the accelerator [11], the required magnetic field for the proposed 2GeV FFAG is non-parametric. The magnetic field is calculated by particle tracking during the lattice design. The variable spiral angle scheme is adopted to optimize ν_z, and the spiral angle grows from 5◦ to 30◦ with the orbit radial growth. The 3D FEM model and the magnetic field of the D-magnet and the two focusing magnets are shown in Fig10 and in Fig 11.

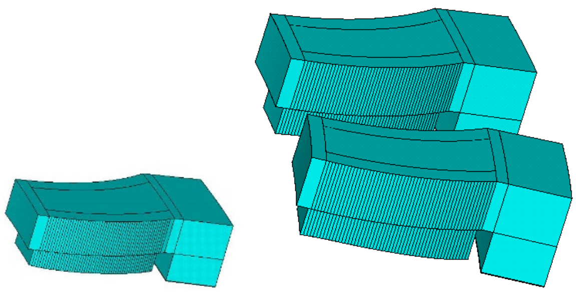

Figure 10: The 3D model of the defocusing magnet and the two focusing magnets.

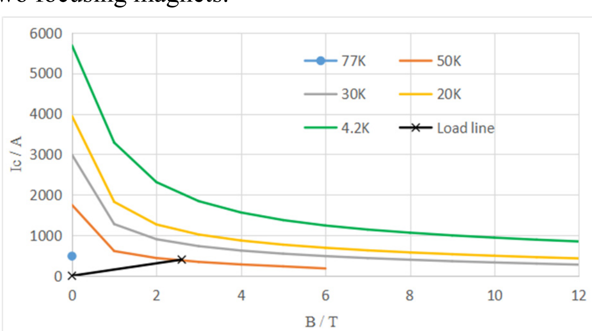

Figure 11: The load line of the HTS superconducting coil for the defocusing magnet.

Considering we have successful experiences in designing and machining of pole gap fitted with 2nd order polynomials for CYCIAE-100, and also considering the required 3rd order polynomial of magnetic field, n=3 will be used in the further magnet pole gap design.

$$g_{k(k=d,f)} = a_{k,0} + \sum_{i=1}^{n} a_{k,i}\, r^i$$

The magnetic field in the extraction radius of 2 GeV in defocusing magnet and the focusing magnet are ~-.4 T and ~2.7 T respectively. As the 2 GeV FFAG is designed to operate at high power, the 2nd generation REBCO superconducting magnet solution with both radiation resistant and thermal stable properties is preferred. The operating current of the D-magnet is 400 A @ 2.6 T, 30 K, about 50% of the Ic, as is shown in the load line drawing in Fig 11. The basic design parameters of the HTS defocusing magnet are shown in Table 2. As the SC magnet technology using 2nd generation HTS for accelerator is still under development world-wide [12, 13], an R&D project for 1/4 scale HTS D-magnet has been initiated recently to develop HTS coil winding, fixing, quench detection and protection technologies, especially for HTS coil with concave shape.

Table 2: The Parameters of the HTS D-Magnet

Item	D-magnet
Radial length of pole	3.78 m
Average azimuthal length of pole	~1.44 m
Total weight	~316 t
1/2 Pole gap distance	14~167 mm
Total Ampere turns	264000 AT
Total length of HTS wires	~14 km

RF System

The RF system includes all the hardware through which energy flows from the AC line to the RF cavities, and it is comprised of ten modules evenly spaced on the circumference of the accelerator. Fig. 12 shows one typical module of the high-power RF system schematically. The RF system will start up from the self-excitation mode and then change to the drive mode for the beam acceleration under the precise control of a fully digital Low-level RF controller.

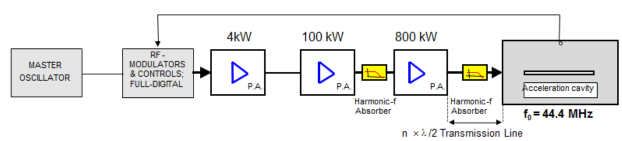

Figure 12: One typical module of the high-power RF system for the 2GeV FFAG.

Figure 13 shows the four geometries of the 44.4 MHz waveguide-type cavities for this machine, they are the: rectangular (1), omega (2), racetrack (3) and boat (4) shapes. The rectangular cavity is often used due to its simplicity for fabrication. But the research of PSI ring cyclotron indicated that the Omega cavity has a higher Q-factor [14], successfully for the ring cyclotron for 3 mA upgrade. For the 2 GeV FFAG, the peak cavity voltage averaged radially in the beam aperture is demanded to be 1.3 MV, in corresponding to a maximum value of ~1.4 MV due to the non-uniform radial distribution. By keeping some safety margin, max. 2 MV cavity voltage is determined in the design. In this situation, it is found that there are new designs so called as the racetrack and the boat cavities with even higher Q-factors.

The beam aperture of 2.8 m x 0.15 m required from beam dynamics, the RF performance of the four geometries of the 44.4 MHz waveguide-type cavity were evaluated and listed in Table 3. To keep the beam transit time factor higher than 0.95 with energy range from 800 MeV to 2 GeV, the acceleration gap is set to be 0.8 m.

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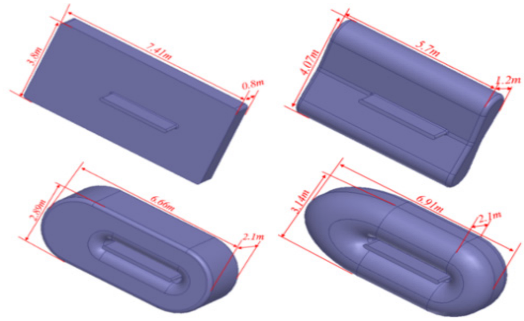

Figure 13: Four geometries of the waveguide-type cavity.

Table 3: Simulated RF Performance for the Four Geometries of the Cavity

Item	1	2	3	4
Frequency (MHz)	44.42	44.41	44.38	44.40
Operating mode	TM 110	TM 110	TM 110	TM 110
Quality factor	58497	74673	85832	92100
Shunt impedance (Max, MΩ)	5.38	10.08	19.29	20.14
Shunt impedance (Min, MΩ)	2.43	2.15	10.41	10.95
Power dissipation (kW@2MV)	743	397	207	199

Figure 14 shows the shunt impedance vs radial position relative to the beam aperture centre, the square root of the impedance is proportional to the cavity voltage amplitude in the acceleration gap. Though the boat one is the best from the simulation, the manufacture might be a little bit harder than the others, but from the on-line tuning point of view by deforming the cavity curved parts, the boat cavity is still a better choice.

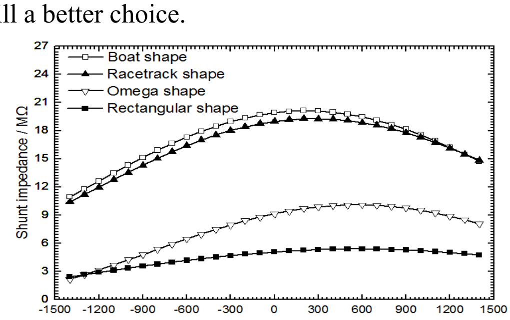

Figure 14: Relationship between the shunt impedance and the radial position relative to the aperture centre.

In order to obtain the fabrication technology of the boat cavity, and conduct the high-power RF conditioning study with the simulated beam-on scenario in the future by using the existing power source for the 230 MeV superconducting cyclotron, a 71.26 MHz scaled-down cavity prototype has been designed. Supported by the domestic industry, the discussion on the manufacture is ongoing with the potential providers.

CONCLUSION

The high power accelerator plays an important role in the internal accelerator field due to its diverse application. Based on the extensive experience of successful construction commissioning and operation of the CYCIAE-100 machine, a CW FFAG is proposed by CIAE to produce 2 GeV/6 MW beam. Beam dynamics results show a good isochronism towards 2 GeV and have a very large acceptance of the beam phase space. Resonance analysis shows the beam quality should be guaranteed when the 3rd harmonic imperfection field is compensated. The turn separation can be increased to 2~3 cm with 5 additional cavities and off-centered injection, which seems to be enough for 6 MW beam extraction. R&D Activities for key components, such as the HTS magnet and the RF system, are conducted for the 2 GeV high power circular accelerator complex.

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REFERENCES

[1] T. J. Zhang *et al.*, "Progress on construction of CYCIAE-100", in *Proc. Cyclotrons'10*, Lanzhou, China, paper TUA2CIO01, pp. 308-313.

[2] J. J. Yang, H. J. Yao, and T. J. Zhang, "Physics problem study for a 100 MeV, 500 microamp H- beam compact cyclotron", in *Proc. ICAP'09*, San Francisco, CA, USA, Aug.-Sep. 2009, paper TH2IODN04, pp. 224-228.

[3] T. J. Zhang *et al.*, "Design, construction, installation, mapping and shimming for a 416-ton compact cyclotron magnet" *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1-5. Jun. 2016, doi:10.1109/TASC.2016.2524535

[4] T. J. Zhang *et al.*, "Conceptual design of an 800 MeV high power proton driver", *Nucl. Instr. Methods Phys. Res. B*, vol. 269, no. 24, Dec. 2011 pp. 2964–2967. doi.org/10.1016/j.nimb.2011.04.053

[5] M. Eshraqi *et al.*, "The ESS LINAC", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3320-3322. doi:10.18429/JACoW-IPAC2014-THPME043

[6] V. P. Yakovlev, J. Grillenberger, M. Seidel, S.-H. Kim, and M. Yoshii, "The energy efficiency of high intensity proton driver concepts", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 4842-4847. doi:10.18429/JACoW-IPAC2017-FRXCB1

[7] Y. Ishi, "Overview of FFAG", presented at FFAG School, Kumatori, Japan, Sep. 2018. http://www.rri.kyoto-u.ac.jp/beam_physics_lab/ffag18/documents/FFA18school_Ishi.pdf

[8] M. Seidel *et al.*, "Production of a 1.3 megawatt proton beam at PSI", in *Proc. IPAC'10*, Kyoto, Japan, paper TUYRA03, pp. 1309-1313.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-FRA01

[9] C. Johnstone *et al.*, "1 GeV CW nonscaling FFAG for ADS, and magnet parameters", in *Proc. IPAC'12*, New Orleans, LA, USA, paper THPPRO63, pp. 4118-4120.

[10] W. M Schulte *et al.*, "A method to obtain single turn extraction for a large phase width in cyclotrons", *IEEE Trans. Nucl. Sci.*, vol. 26, no. 2, pp. 2392-2395, 1979. doi:10.1109/TNS.1979.4329884

[11] M. Yoshimoto *et al.*, "The magnet design study for the FFAG accelerator", *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 397-401, Aug. 2004. doi:10.1109/TASC.2004.829680

[12] H. Song *et al.*, "2G HTS coil technology development at SuperPower", *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1-6, Jun. 2013. doi:10.1109/TASC.2012.2233837

[13] G. A. Kirby *et al.*, "Accelerator-quality HTS dipole magnet demonstrator designs for the EuCARD-2 5-T 40-mm clear aperture magnet", *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1-5, Oct. 2014. doi:10.1109/TASC.2014.2361933

[14] H. Fitze *et al.*, "Development of a new high power cavity for the 590 MeV ring cyclotron at PSI", in *Proc. PAC'99,* New York, USA, 1999, paper MOP58, pp. 418-422.