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REVIEW OF HIGH POWER CYCLOTRONS AND THEIR APPLICATIONS

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Abstract

An incomplete review of existing machines and of present new projects of high power cyclotrons is here presented. Both high energy and low/medium energy cyclotrons will be described. Specific requests for different fields of applications are also discussed.

INTRODUCTION

It is from the early years of the Eighties that the cyclotron community has proposed challenging cyclotrons to produce intense beams of kaons, antiprotons, neutrinos and other particles [1, 2] or to be used to drive subcritical reactors [3]. Unfortunately, up to now the cyclotron community was not able to get funds for none of these projects intended to surpass the performances of the TRIUMF and PSI cyclotrons. The main technical problems related to the construction of these projects are here discussed. Fortunately, the creativity of our community is again alive and new projects and ideas flourished.

HIGH INTENSITY LOW-MEDIUM ENERGY CYCLOTRONS

Low energy cyclotrons (15-30 MeV) are mainly used to produce radioisotopes, producing beams with intensity in the range 0.1-1 mA. But in the latest years the 30 MeV cyclotrons have also been used to drive BNCT facilities [4], and the perspective is towards increasing of this application, whose request is a beam current increase up to 2 mA or more.

The 70 MeV cyclotrons, supplied by IBA and BEST companies, are mainly used for the production of medical radioisotopes and their declared maximum intensity is about 1 mA. The wide range of energy of extracted beams varying from 35-70 MeV with the possibility to deliver two beams simultaneously make this kind of accelerator very flexible in use and particularly suitable to be employed as driver for multipurpose facilities. The SPES facility at LNL (Italy) [5] has already carried out the commissioning of the C70 cyclotron which will provide high power beams for nuclear research and radioisotopes R&D and in next future both RISP (Daejeon, Korea) [6] and iThemba (Cape Town, South Africa) laboratories will be equipped with cyclotrons with such performances.

The above energy range and current are appropriate to produce radioisotopes but an increase in the beam current would allow to increase the production rate for the present medical isotopes and also could open the opportunity to produce radioisotopes with small production cross sections or long half-lives.

The perspective to produce the ^{68}Ge/^{68}Ga generator for imaging diagnostic, through the reactions ^{71}Ga(p,4n)^{68}Ge and ^{69}Ga(p,2n)^{68}Ge, is very appealing to replace the usual ^{99}Mo/^{99m}Tc generator. Indeed, the half-life of the ^{68}Ge parent is of about 270 days while the lifetime of ^{99}Mo is only of 66 hours. Moreover, the half-life of the ^{68}Ga is just 68 minutes versus the 6 hours of the ^{99m}Tc.

Another interesting new radioisotope is ^{225}Ac, produced through the reaction ^{226}Ra(p,2n)^{225}Ac. This is a four alpha particles emitter and it is a wonderful tool for targeted radiotherapy. To produce efficiently this radioisotope it is convenient to use a proton beam with energy higher than 50 MeV and current in excess of 3-5 mA. This trend is confirmed by the new project TR100 [7] and by the interest of PSI to develop a dedicated beam line to the radionuclide production [8].

Another viable way to produce ^{225}Ac is bombarding Thorium target with a proton beam of about 450 MeV, as recently tested at TRIUMF [9].

Bombarding ^{232}Th by a proton beam with energy higher than 50 MeV is also a way to produce ^{213}Bi, another radioisotope that decays producing four alpha, also this is very appealing for radiotherapy.

An alternative production method to produce ^{213}Bi is through the reaction α+^{232}Th as presently investigated at GANIL [10]. Bombarding ^{232}Th with alpha particles allows to produce many different alpha emitters like ^{212}Pb, ^{213}Bi, ^{225}Ra, ^{225}Ac. The energy of the alpha beam must be higher than 50 MeV. These energies and the high current for α beam are not achievable with the present commercial cyclotrons but are in the energy range of the proposed IsoDAR cyclotron [11].

THE ISODAR CYCLOTRON

The IsoDAR compact cyclotron will be able to deliver up to 5 mA of H_2^+ beam with a maximum energy of 60 MeV/amu [11]. This cyclotron was designed to drive the experiment for sterile neutrino research [12] and as first stage of the cascade cyclotrons to perform the DAEδALUS experiment [13]. This cyclotron could also be used to accelerate He beam up to 240 MeV with intensity of about 1 mA (120 kW of beam power). The possible use of the IsoDAR cyclotron to produce huge amounts of medical radioisotopes for diagnostic and therapy, using both the high intensity proton beam and the He beam, are well described in a recent paper [14].

The large pole diameter of IsoDAR and the use of 4 RF cavities allow to extract the beam with high efficiency using the electrostatic deflector. For the extraction of protons also the stripping of H_2^+ molecule can be used. The feasibility to use a stripper foil with an intensity of 1.7 mA was tested with the 72 MeV proton beam at PSI [15].

The most serious problem to accelerate the high current beam is related to injection. The relatively low velocity and

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the high intensity of the injected charged particles associated to the suppression of the effect of charge compensation makes much more effective the coulomb repulsion. As discussed in [16], the choice to accelerate H_2^+ mitigates this effect, nevertheless both the increase of particles energy and the bunching action may be suitable to get a high injection efficiency.

To achieve this goal, the design and construction of a RFQ to perform a Direct Injection Project [17] is in progress.

An alternative way to increase the injection efficiency is the use of a magnetic spiral inflector instead of the electrostatic device. This study was accomplished at LNS-INFN and it led to the optimization of a magnetic configuration based on a series of dipole Halbach rings [18] allowing to fit the ideal trajectory of the injected particles into the central region of a cyclotron, see Fig. 1. The Spiral Inflector Halbach Ring has been optimized to inject a 60 keV H_2^+ ion beam into the Isodar cyclotron [19].

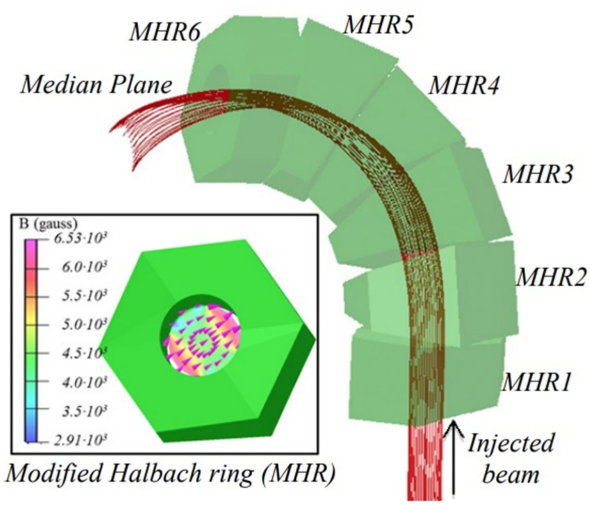

Figure 1: Layout of the six permanent magnets (MHR#) configuration to inflect the beam on the median plane of a cyclotron; into the box, magnetic field direction inside the inner region of the magic ring.

Compared to the usual electrostatic spiral inflector, the strength of the magnetic field is not adjustable during the injection operation, but the azimuth and vertical position of the magnetic inflector respect the cyclotron axis and median plane are tuneable. These two free parameters are very useful to match properly the median plane of the cyclotron and the right direction of the entering beam.

HIGH INTENSITY HIGH ENERGY CYCLOTRONS

Accelerators able to deliver proton beams with energy around 1 GeV and beam power in the range 2-10 MW are requested for experiments to investigate fundamental physics, to drive subcritical reactors for energy production, to drive new meson factories [20] and new neutron spallation sources in subcritical reactors [21]. Different approaches have been proposed and new projects are also presented at this conference [22].

The common feature of the three projects here discussed is the use of superconducting technology. The first project, studied by the INFN-LNS group [23, 24], is the two-stage cyclotron complex proposed to drive the DAEδALUS experiment to measure the CP-violation parameter δ_{CP} in the neutrino sector. The second is the single-stage superconducting cyclotron for H_2^+ proposed by P. Mandrillon [25] and the third is the stacked-cyclotron layout developed by P. McIntyre [26] at TAMU.

Superconducting Ring Cyclotron: DAEδALUS

The accelerator to drive the DAEδALUS experiment consists of two coupled cyclotrons. The first is the IsoDAR cyclotron, described in the previous section, able to accelerate H_2^+ up to 60 MeV/amu. The beam is extracted from this cyclotron by an electrostatic deflector. The second stage is a six sector Superconducting Ring Cyclotron (SRC) able to accelerate H_2^+ up to 800 MeV/amu, to be extracted by stripping [23]. Figure 2 shows the layout of this cyclotron complex. The stripper foil is placed in a region where the magnetic field stays around 0.1-0.15 T.

This low field allows to collect the removed electrons on a catcher. In Fig. 2, the trajectory of the extracted beam, crossing the central area of the cyclotron and exiting after half a turn, is shown. A small steering magnet placed in the central region is useful to drive the extracted trajectory, and to control the vertical beam envelope.

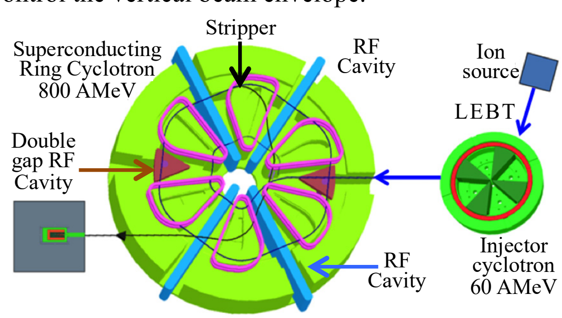

Figure 2: Layout of the two stage cyclotron complex. The SRC is equipped with four single gap RF cavities and two double gap cavities (brown). The stripper position and the extraction trajectories are also shown.

The choice to have just six sectors allows to have enough room to install RF cavities similar to those used in the PSI ring cyclotron. The use of only 4 cavities in an SRC with 6 sectors poses a problem of uncontrolled radial and vertical beam growth when the resonance $\nu_r = 2$ is crossed [27]. This problem has been solved by adding two additional double-gap RF cavities at the outer radii.

The use of a reduced number of cavities, the absence of flattop cavities, and the use of superconducting sector magnets allow to increase the conversion efficiency, from electric power grid to the 10 MW beam, up to about 60%.

The design of the superconducting sector magnet (see Fig. 3) is quite similar to the RIKEN Superconducting Ring Cyclotron. It was performed in collaboration with the Plasma Science and Fusion Center of MIT [28].

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The Beam dynamics studies along the acceleration were simulated using the OPAL code [29].

The most serious problem posed by the acceleration of H_2^+ is the dissociation of many long-lived vibrational states. The electron binding energies of these vibrational states are very low, therefore they can be dissociated by electromagnetic stripping in the high magnetic fields. These high vibrational states could be removed at the source level.

Alternatively, it is also possible to remove the most dangerous of the less-bound vibrational states introducing dangerous of the less-bound vibrational states introducing a magnetic field bump with amplitude of 0.3 T and azimuthal extension of 1°-2° on each sector of the SRC. The field bump can be produced by small permanent magnets installed at the proper azimuth on the hills. Choosing properly the azimuth of the magnetic bumps for each energy, the trajectories of the protons dissociated by electromagnetic Lorentz go to inner radii and arrive outside of the vacuum chamber where can be collected [27].

Single Stage Superconducting Cyclotron

AIMA company has proposed a single stage cyclotron able to accelerate H_2^+ [25] up to 800 MeV. Although the iron pole consists of six separated sector and the field has a symmetry six, the magnetic field is powered by one pair of superconducting coils, with very complex shape. The coil is wrapped around the outer part of the six sectors but in the inner region it is bent in the opposite direction through the valley. The two coils are symmetric vs. the median plane, but they are not parallel to the median plane.

The beam acceleration is performed by six λ/2 double-gap RF cavities. To leave room for installation of the six RF cavities, the upper and lower coils increase their distance from the median plane in the inner regions.

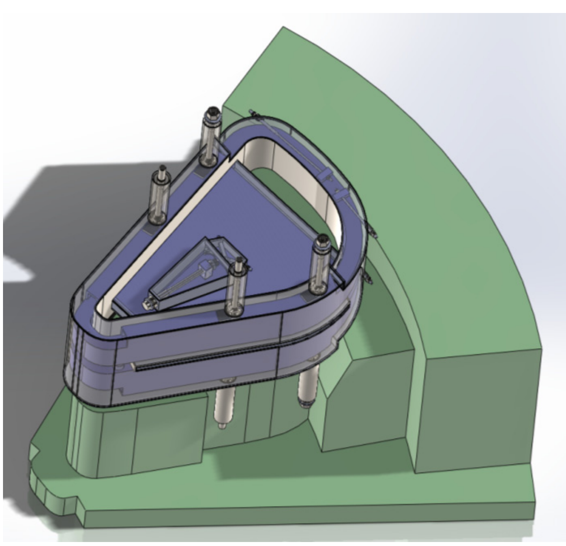

Figure 3: A sector of the SRC. The half lower part of iron, the cryostat and the tie rods, to maintain the superconducting coils in the proper position are shown.

The layout of the cyclotron is shown in Fig. 4. Beam extraction is performed by the stripper placed at the exit of the main sector, and beam trajectory is bent toward the outer radii, see Fig. 5. A key innovation of this project is the insertion in each valley of two wedges of iron , where direction of the magnetic field is reversed.

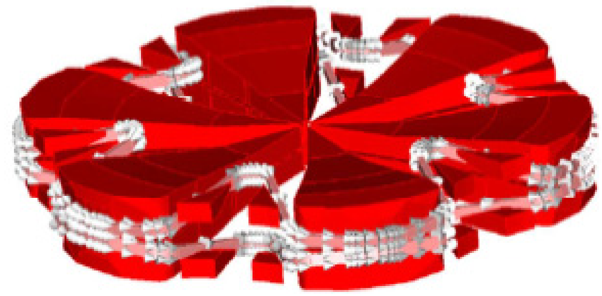

Figure 4: the magnetic circuit of the H_2^+ 800 MeV/amu single stage cyclotron.

This solution increases greatly the vertical focusing, avoids spiralling the sector edges, and allows to bend towards the outer radii the trajectory of protons extracted by stripper. This elegant extraction method could probably also be implemented in the DAEδALUS ring cyclotron.

Another innovative solution, to mitigate the space charge effects, is the use of three independent ion sources. This solution mitigates both the beam ripple and the risk of beam trips, a serious issue for the Accelerator-Driven Reactors System.

The 6 RF resonators have a special shape to fit the valley space with the coil cryostat. The RF cavities are designed to work at 36.3 MHz in harmonic 6, and the simulated quality factor Q of the cavities is 6200. The accelerating voltage rises from 150 kV to 450 kV from the inner to the outer radii. The maximum energy gains per turn at the extraction radius should be higher than 5 MeV/turn.

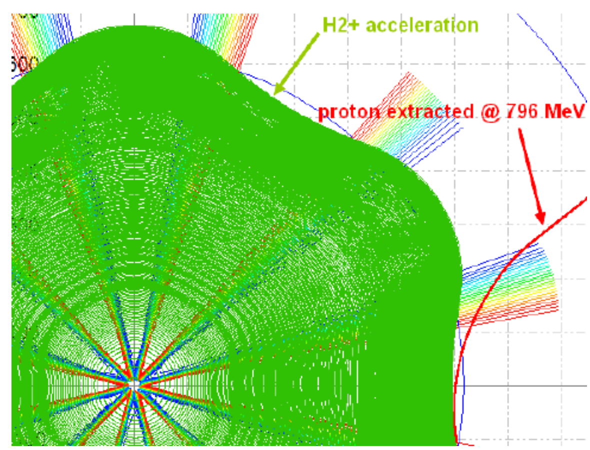

Figure 5: The trajectory of a H_2^+ reference particle along the acceleration path (green lines) and of the extracted proton (red line). The radial lines shown the electrical gradient produced by the RF cavities.

Critical issues of this project are the complexity of the superconducting coil shape and its dimensions, about 50 m long. The coil does not stay in a plane and the bending curvature of the coil is reversed at the inner radius.

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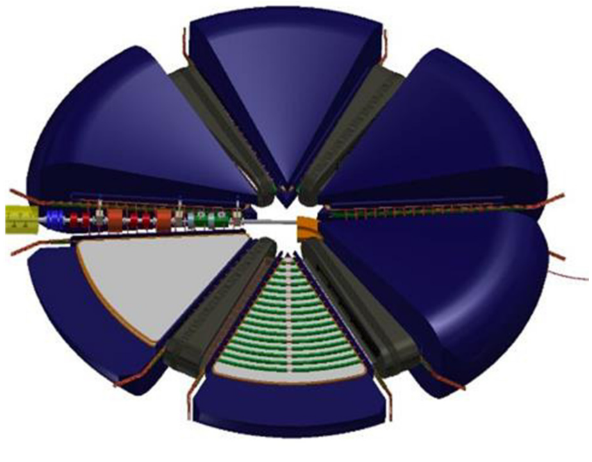

Figure 6: View of the 100 MeV SFC, showing the 16-turn spiral trajectory, the superconducting slot cavities (dark grey), and the beam transport channels (green).

A further issue is the amount of beam losses due to the interaction of the beam with residual gas: the vacuum has to be better than 8×10^{-7} Pa in order to maintain the beam losses below 150 W. The issue of the dissociation of the vibrational states contained in the H_2^+ beam has to be evaluated too. Probably, this problem could be solved inducing the electromagnetic dissociation by permanent magnets placed at proper azimuth, similar solution proposed for the DAEδALUS ring cyclotron [27].

Strong Focusing Superconducting Cyclotron

An alternative approach to achieve a 1 GeV 10 mA proton beam to drive ADS, was proposed by P. McIntyre [26] of TAMU. The proposal consists to use a two stage of acceleration performed by cyclotrons, but each stage consists of 6 stacked flux coupled isochronous cyclotron, to mitigate both the problems of space charge and cost. The TAMU group has developed new ideas both about new superconducting RF cavities and Strong Focusing Cyclotron (SFC).

In particular, the group is focused on the design of the first stage of SFC to accelerate a 100 MeV proton beam [30]. This is a separated orbit cyclotron similar to the TRITRON project [31], where the beam is forced to circulate through the transporting channel placed in the hills, see Fig. 6. According to their latest simulations this solution allows to accelerate beams with intensity up to 10-20 mA.

The SFC concept is based on the use of a local magnetic channel to focus the beam both radially and vertically. This is achieved using single layer Panofsky quadrupole with superconducting coils (MgB_2). A cable layer windings, wound as window frame, produce a dipole field used to tune the magnetic fields of each channel to match the isochronism.

An additional advantage of the SFC is the straight shape of the sectors edges. This feature simplifies greatly the insertion of the RF cavities. Since the huge turn separation implies a very high energy gain per turn, a further important contribution of the group is the design of new superconducting RF cavities [32].

Unfortunately, the acceleration of high proton beam current in the range 10-20 mA means a huge beam loading effect especially for superconducting cavities and consequently the beam instability or eventual ion source trips could produce serious problems at the RF cavities. Moreover, the tuning of the machine could be not very easy according to the previous experience of the TRITRON project.

CONCLUSION

The two frontiers of cyclotron accelerators are the beam current intensity and the high energy. According to the contribution at the present conference the goal to overcome the beam current limit of 2 mA seems to be feasible in the next years especially for the low/medium energy cyclotrons. Vice-versa, to achieve the 800 MeV needs important investments and depends also upon factors external to our community. Although the cyclotron is one of the oldest particle accelerator, it is impressive how the cyclotron community is able to propose interesting new tools [33], projects, innovations, and applications.

REFERENCES

[1] W. Joho, "ASTOR, Concept of a combined acceleration and storage ring for the production of intense pulsed or continuous beams of neutrinos, pions, muons, kaons and neutrons", in *Proc. 10th Particle Accelerator Conf. (PAC'83)*, Santa Fe, NM, USA, Mar. 1983, pp. 2083-2086.

[2] R. Laxdal, M. K. Craddock, W. Joho, G. H. Mackenzie, J. R. Richardson, and L. C. Teng, "Matching an isochronous cyclotron to a synchrotron to provide a high intensity injector", in *Proc. 10th Particle Accelerator Conf. (PAC'83)*, Santa Fe, NM, USA, Mar. 1983, pp. 2013-2016.

[3] N. Fiétier, P. Mandrillon, and C. Rubbia, "A cyclotron-based accelerator for driving the energy amplifier", in *Proc. 14th Int. Cyclotron Conf. and their Applications (Cyclotrons'95)*, Cape Town, South Africa, Oct. 1995, paper L-02, pp. 598-605.

[4] T. Mitsumoto *et al.*, "BNCT system using 30 MeV H- cyclotron", in *Proc. 19th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'10)*, Lanzhou, China, Sep. 2010, paper FRM2CCO04, pp. 430-432.

[5] Selective Production of Exotic Species (SPES), Laboratori Nazionali di Legnaro, Italy. `http://www.lnl.infn.it/_spes/`

[6] `https://www.risp.re.kr/eng/orginfo/intro_project.do`

[7] Y.-N. Rao, R. A. Baartman, Y. Bylinskii, T. Planche, and L. G. Zhang, "Conceptual design of TR100+: An innovative superconducting cyclotron for commercial isotopes production", presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper THB03.

[8] N. P. van der Meulen *et al.*, "The use of PSI's IP2 beam line towards exotic radionuclide development and its application towards proof-of-principle preclinical and clinical studies",

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-THB01

presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper TUA03.

[9] A. K. H. Robertson *et al.*, "Design of a Thorium metal target for 225Ac production at TRIUMF", *Instruments*, vol. 3, no. 1, Feb. 2019. doi:10.3390/instruments3010018

[10] A. M. Frelin-labame *et al.*, "R&D activities for the production of radioisotopes at GANIL", presented at the SPES workshop, Legnaro, Italy, Jan. 2019, unpublished.

[11] A. Adelmann *et al.*, "Cost-effective design options for IsoDAR" Oct. 2012. arXiv:1210.4454

[12] A. Bungau *et al.*, "Proposal for an electron antineutrino disappearance search using high-rate ^{8}Li production and decay", *Phys. Rev. Lett.*, vol. 109, p. 141802, Oct. 2012. doi:10.1103/PhysRevLett.109.141802

[13] L. Calabretta, M. M. Maggiore, L. A. C. Piazza, and D. Rifuggiato, "A multi MegaWatt cyclotron complex to search for CP violation in the Neutrino sector", in *Proc. 19th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'10)*, Lanzhou, China, Sep. 2010, paper TUA1CIO01, pp. 298-303.

[14] J. R. Alonso, R. Barlow, J. M. Conrad, and L. H. Waites, "Medical isotope production with the IsoDAR cyclotron", *Nat. Rev. Phys.*, vol. 1, Aug. 2019. doi:10.1038/s42254-019-0095-6

[15] R. Dölling, R. Dressler, and L. Calabretta, "A test of stripper foil lifetime in PSI's 72 MeV proton beam", in *Proc. 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'18)*, Daejeon, Korea, Jun. 2018, pp. 338-341. doi:10.18429/JACoW-HB2018-WEP2PO033

[16] L. Calabretta and D. Rifuggiato, "Superconducting cyclotrons for acceleration of H_2^+", in *Proc. 15th Int. Cyclotron Conf. and Their Applications (Cyclotrons'98)*, Caen, France, Jun. 1998, paper J-02, pp. 665-668.

[17] D. Winklehner, "Beam dynamics and preliminary design of the RFQ direct injection project", presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper WEB05.

[18] D. Campo and L. Calabretta, private communication.

[19] K. Halbach, "Design of permanent multipole magnets with oriented rare earth cobalt materials", *Nucl. Instrum. Methods*, vol. 169, no. 1, pp. 1–10, Feb. 1980. doi:/10.1016/0029-554X(80)90094-4

[20] R. Cywinski *et al.*, "Towards a dedicated high-intensity muon facility", *Physica B*, vol. 404, pp. 1024-1027, Apr. 2009. doi:10.1016/j.physb.2008.11.203

[21] V. L. Aksenov, "DNS-IV project: Present status and trends", presented at advanced ideas and experiments for DNS-IV workshop, Dubna, Russia, Dec. 2018.

[22] T. J. Zhang, "A new solution for cost effective, high average power (2 GeV, 6 MW) proton accelerator and its R&D activities", presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper FRA01.

[23] D. Campo *et al.*, "High intensity compact cyclotron for ISODAR experiment", in *Proc. 20th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'13)*, Vancouver, Canada, Sep. 2013, paper WEPPT030, pp. 384-386.

[24] D. Winklehner *et al.*, "High power cyclotrons for neutrino experiments", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 788-790. doi:10.18429/JACoW-IPAC2014-MOPRI078

[25] M. Conjat, J. Mandrillon, and P. Mandrillon, "Cyclotron drivers for accelerator driven systems", in *Proc. ThEC13 Conf.*, Geneva, Switzerland, Oct 2013. doi:10.1007/978-3-319-26542-1_37

[26] P. McIntyre, G. Kim, D. May, and A. Sattarov, "A superconducting isochronous cyclotron stack as a driver for a Thorium-cycle power reactor", in *Proc. 19th Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper WPPH062, pp. 2593-2595

[27] L. Calabretta and F. Meòt, "Cyclotrons and FFAG accelerators as drivers for ADS", *Rev. Accel. Sci. Technol.*, vol. 8, pp. 77-97, Jan 2015. doi:10.1142/S1793626815300054

[28] A. Radovinsky *et al.*, "Engineering study of sector magnet for the DAEδALUS experiment", *IEEE Trans. Appl. Supercond.*, vol. 24, p. 4500204, June 2014. doi:10.1109/TASC.2013.2281855

[29] J. J. Yang *et al.*, "High-power cyclotron beam dynamics-Space charge effects beam loss", *Nucl. Instrum. Methods Res., Sect. A*, vol. 704; pp. 84-91, 2013. doi:10.1016/j.nima.2012.12.050

[30] S. Assadi, P. M. McIntyre, A. Sattarov, and N. Pogue, "Nonlinear beam dynamics studies of the next generation strong focusing cyclotrons as compact high brightness, low emittance drivers", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 656-658. doi:10.18429/JACoW-IPAC2015-MOPMA047

[31] A. Cazan, P. Schutz, and U. Trinks, "Commissioning of the first separated orbit cyclotron triton", in *Proc. 15th Int. Cyclotron Conf. and Their Applications (Cyclotrons'98)*, Caen, France, Jun. 1998, paper C-04, pp. 323-326.

[32] J. Gerity, S. Assadi, P. M. McIntyre, and A. Sattarov, "Beam dynamics studies for a strong-focusing cyclotron", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 3522-3525. doi:10.18429/JACoW-IPAC2018-THPAK118

[33] T. Planche, "Designing cyclotrons and FFAs from their orbits", presented at the 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, paper FRB01.