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SUMMARY OF THE SNOWMASS'21 WORKSHOP ON HIGH POWER CYCLOTRONS AND FFAS

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Abstract

In this talk, we summarize the presentations and findings of the "Workshop on High Power Cyclotrons and FFAs" that we held online in September 2021. The workshop was held as part of the 2021 Snowmass Community Exercise – in which the US particle physics community came together in a year-long effort to provide suggestions for a long-term strategy for the field – and the "Accelerators for Neutrinos" subpanel thereof. Topics that were discussed during our high-power cyclotron workshop were the application of cyclotrons in particle physics, specifically neutrino physics, and as drivers for muon production. Furthermore, as these same accelerators have important applications in the fields of isotope production and possibly in energy research, we have included those topics as well. Finally, we took a look at Fixed Field Alternating Gradient accelerators (FFAs) and their potential to become high-intensity machines.

INTRODUCTION

We report the state of the field of "High-Power Cyclotrons and FFAs" (Fixed Field alternating-gradient Accelerators) as discussed by international experts during a three-day workshop of the same name [1]. The workshop was held online Sep 7 to Sep 9, 2021 with 50 registered participants, as part of the US Snowmass'2021 community exercise; specifically, the Accelerator Frontier (AF) and the subpanel Accelerators for Neutrinos (AF02). This conference proceeding is a concise summary of the workshop reports available on the ArXiv [2] and in Ref. [3].

The workshop charge was to take stock of the world inventory of high-power cyclotrons and FFAs, to asses available beam currents and beam powers, and to investigate limitations. Furthermore, to evaluate the role of cyclotrons in particle physics, directly used or as injectors to other machines. Finally, to discuss novel concepts to push the power, and provide recommendations to the particle physics and accelerator physics communities.

The program of talks is listed on the Indico website [1], and slides are available by navigating to "Timetable" then "Detailed view." References to all individual presentations are also given in the bibliography of the workshop reports.

The workshop was coarsely organized in three topical areas (one per day): 1. State-of-the-Art and Limitations; 2. Applications of high-power cyclotrons and FFAs; 3. Novel Concepts and Computation. In this manuscript, we follow the same structure.

STATE-OF-THE-ART AND LIMITATIONS

State-of-the-Art

The classical cyclotron was invented and developed for research in nuclear physics. The first major evolution of this type of accelerator was the introduction of the azimuthally varying field (AVF) cyclotron, otherwise known as the isochronous cyclotron [4]. The development of computers and superconductivity produced a further broad band of cyclotrons of different types tuned for different researches in the field of nuclear physics but also for a wide range of applications. The golden age of the cyclotron was the period from 1960 to 1990 when many cyclotron projects were studied, financed and built. Some examples are LBNL [5–7], DUBNA [8–10], GANIL [11], MSU [12, 13], iThemba Labs [14], RCNP [15], and RIKEN [16], just to remember the largest and most famous laboratories. They were often equipped with more than one cyclotron, aimed mainly at research in the field of nuclear physics and in the projects of synthesis of Super Heavy Elements [17, 18]. A special mention goes to the two large cyclotrons of PSI (Switzerland) [19] and TRIUMF (Canada) [20], laboratories which delivered the first beam in 1974 and 1975 respectively. These two machines deliver proton beams with a maximum energy of 590 MeV and 520 MeV, respectively, and were built to feed the so-called Meson Factories. Despite the fact that the initial design beam currents were only 100 µA and 50 µA, respectively, today they have significantly exceeded their initial target. In particular, the PSI machine is able to supply proton beams with currents up to 2.4 mA and probably even more in the future. A survey of the RIKEN laboratory illustrates the flexibility of cyclotrons operated in cascade, up to 4 cyclotrons including the largest superconducting cyclotron [18]. Moreover, a talk presented by Jongwon Kim (IBS, South Korea) [21, 22] describes how a new generation

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of commercial cyclotrons, the IBA Cyclone-70 [23], can be used to drive an ISOL facility. The latter aims at producing radioactive isotopes and perform experiments at the extreme limits of nuclear physics.

Comparing the three types of fixed field accelerators, we find that the average beam current from isochronous cyclotrons is typically two orders of magnitude higher than synchrocyclotrons, while FFAs (fixed field alternating gradient accelerators), despite their potential for applications beyond the GeV-level, have yet to demonstrate their capability for higher currents.

Limitations

The technical limits are mainly due to the original design of these machines. They could probably be overcome thanks to new technology and to new mechanical design options. The experiences gained along these long years of operation offer us valuable insights to apply to the problem of upgrading. It is quite evident that the amount of knowledge gained in these years allows starting new projects to achieve higher energy and higher current. The goal of 1 GeV and 10 mA for a proton beam delivered by a cyclotron seems feasible today, both using conventional technology, or also using superconducting technology to reduce the footprint of the machine (example the superconducting ring cyclotron K2500 of RIKEN). A problem that must be optimized is related to the reliability and to the maintenance of these new machine. This is a serious problem for accelerator proposed to drive sub critical reactor, so-called ADS. For cyclotrons used in the field of nuclear or particle science this is not a real limit. As pointed out in the talk by Grillenberger, technical problems like deflector failures and their replacement and the reliability of the RF cavities have to be minimized. For example, some of these problems could be mitigated using robots to replace people in the maintenance operations of the critical components like electrostatic deflectors. Of course, this implies that cyclotron components must be properly designed to allow robot maintenance. The introduction of robot or automatic maintenance will allow to operate the cyclotron also with larger amount of beam losses due to the higher accelerated current. Also, the problem to build safer RF cavities avoiding the multipactoring effect need to be optimized. Careful study of the cavity shapes and using local magnetic field to freeze the multipactoring effect could be an alternative solution to be investigated. The problem of the limit of the beam acceptance present in the compact cyclotron could be again upgraded using special ferromagnetic materials as Vanadium Permendur that allow to achieve higher magnetic field respect to the classical iron pole and then higher vertical focusing became feasible. Despite all the technical problems of cyclotrons they are up to now the only "cheaper" solution to achieve 10 MW proton beam at 1 GeV. Indeed, the FFAs while achieving energies higher than 1 GeV, have not yet a viable solution to achieve the high-power regime. Moreover, the machine protection system must be improved not only to protect the infrastructure from serious damage, but also to understand the source of the failure and to allow restarting the accelerator in a short time. Probably this goal can be accomplished using the new tool of machine learning.

The useful information collected by the operations of cyclotrons in the research centers developed worldwide have been received by commercial companies that are today able to supply high-current and reliable machine as the one bought by IBS, to drive their Rare Isotope Science Project. Commercial companies can sell cyclotrons delivering more than 700 µA of proton beam and new frontiers could be overcome soon.

The goal to achieve a proton beam with 5 mA at 800-1000 MeV using a cyclotron accelerator is realistic. However, the critical item to investigate is the best cyclotron configuration to achieve beam currents higher than 10 mA.

APPLICATIONS OF HIGH-POWER CYCLOTRONS AND FFAS

Isotope Production

Cyclotron beams [24], mainly protons, irradiate targets external to the cyclotron, reactions are characterized as A(p,X)B, where target species A is irradiated with protons, resulting in product B and emitting X particles and/or γs. Using particle beams has the advantage that B is usually a different atomic species than A, so chemical separation of the product from the target can be done yielding "carrier free" sources [25]. This allows much higher concentration of the activity in clinical use. It is usually not possible to do this with reactor-produced sources.

Medical isotopes are either "diagnostic" (for imaging of selected areas of the body) or "therapeutic" (for causing radiation damage to localized regions) [26]. A recent development has been identification of "theranostic" pairs [27], with matched isotopes of similar chemical properties, one diagnostic and one therapeutic.

Isotope production is one of the main applications of cyclotrons nowadays. Examples presented at this workshop were: RIKEN outside Tokyo, Japan, whose broadly-based research programs with beams from protons to uranium cover not only isotopes but many areas of nuclear research; TRIUMF, Canada's premier accelerator center with world-leading programs in many fields, particularly beam-based applications in nuclear physics and the life-sciences [28]; And the cyclotron center at the University of Alabama at Birmingham, a mainstream university-based facility dedicated to production and distribution of established radioisotopes, and to development of new radioisotopes and pharmaceuticals for nuclear medicine [29].

Particle Physics

The cyclotron with its capability to produce high currents of cw proton (and other ion) beams with moderate facility footprint has seen renewed interest in particle physics. Here we highlight two experiments planning to use a cyclotron driver: the highly anticipated particle physics experiments

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IsoDAR and Mu3e as presented at the workshop by J.B. Spitz [30] and F. Meier Aeschbacher [31], respectively.

If the IsoDAR design proves successful, a 60 MeV/amu compact cyclotron will accelerate 5 mA of H_2^+ ions that are stripped of the electron to form a 10 mA proton beam directly after extraction. The IsoDAR cyclotron will utilize direct axial injection using an RFQ embedded in the cyclotron yoke and a beam physics effect in space-charge dominated cyclotrons beams called *vortex motion*. IsoDAR's main goal is to provide a definitive search for sterile neutrinos, but it has many other interesting beyond-standard-model search capabilities. The main physics cases are presented in detail in Ref. [32] and recent accelerator design considerations in Refs. [33–35]. IsoDAR has preliminary approval to run at the Yemilab Center for Underground Physics, using the 2.3 kt LSC [36] as its detector.

The Mu3e experiment aims to observe the lepton flavor changing process $\mu^+ \rightarrow e^+e^-e^+$ and to exclude a branching fraction of $> 10^{-16}$ at 90 % confidence level [37]. The main backgrounds are the standard Michel decay and the radiative SM decay. The experiment requires very high rates of muons. Muons for Mu3e will be produced at PSI's *Swiss Muon Source*, which is driven by the High Intensity Proton Accelerator (HIPA) facility. Protons at HIPA are accelerated using the 590 MeV separated-sector cyclotron [19], fed by Injector II.

Other ideas to use $O(10\text{ mA})$ cyclotrons in modern particle physics experiments are: 1. @60 MeV: Cross Section Measurements with a ^{8}Li-based $\bar{\nu}_e$ flux. As discussed in Ref. [38], new facilities built with an IsoDAR target/sleeve configuration will permit measurement of the antineutrino cross sections for neutrino coherent scattering for nuclei (CEνENS); 2. @15 MeV: Neutrino flux measurements. ν_e (as versus $\bar{\nu}_e$) fluxes can be produced up to 3.75 MeV by targeting 15 MeV protons on ^{27}Al to produce ^{27}Si. This was proposed in Ref. [39] for an accelerator-based study of the vacuum-matter transition region relevant for solar neutrino experiments using a radiochemical detector located 10 m from the target; 3. Monoenergetic Photons for BSM Searches (energy to be optimized): For a future experiment, the beam energy can be chosen and the target/sleeve material selected for the purpose of producing specific monoenergetic photon peaks of interest use in searches for new physics that couples to photons, such as axion-like and Z′ particles; 4. Detector design, calibration, and testing in high-neutron-flux environments.

Accelerator-Driven Sub-critical Reactor

The Accelerator Driven Sub-critical Reactor (ADSR) is a hybrid system coupling a particle accelerator to a sub-critical reactor core: the accelerator produces the high power beam which strikes a heavy metal target, in solid or liquid state. The spallation target will thus emit neutrons among other particles in the forward direction of the beam. Such neutrons are fed into the sub-critical reactor core to induce further fission reactions. Owing to the sub-critical state of the reactor, ADSR is considered as inherently safe and shutting down the reactor can be achieved by switching off the high power beam. Two important use cases are the incineration of nuclear waste in dedicated systems with a large fraction of Minor Actinides (Np, Am, Cm,...); And Thorium-fuel cycles where producing the fissile ^{233}U from Thorium requires the intermediate ^{233}Pa ($t_{1/2}$ = 27 days).

The main challenges for the use of cyclotrons as drivers for ADSR are that 1. no existing machine currently accelerates multi-mA beams to 1 Gev energies; and 2. ADSR requires very high reliability and cannot tolerate frequent trips, which cyclotrons are prone to. Nevertheless, conceptual designs exist, e.g., the DAEδALUS [40], AIMA [41], and TAMU [42] designs.

NOVEL CONCEPTS AND COMPUTATION

Novel Concepts

We discussed novel concepts to realize high-power cyclotrons and FFAs. The main challenges are (1) increased space charge and (2) high beam losses. Space-charge leads to beam growth, tune depression, and difficulties keeping the beam focused, which leads to more beam losses and also potentially poor beam quality. The concepts discussed here covered injection, acceleration Specifically, several new ideas for spiral inflectors were presented (transverse gradient electrostatic inflectors [43], active magentic inflectors [44, 45], and cylindrically symmetric passive inflectors [46]), and a concept for embedding an RFQ directly into the cyclotron yoke for bunching and pre-acceleration [34, 35]. Another concept was to use vortex motion as a means to reduce interturn particle halo and improve extraction efficiency [35]. We also heard about concepts for self-extraction from a cyclotron [47, 48], single-stage high-energy cyclotrons [41], and multi-port injection. For FFAs the concept of vertical excursion was discussed [49, 50]. In the interest of space, we refer the reader to the given references.

Computation

In the final session of the workshop, we heard about new mathods and algorithms in computational accelerator physics. C. Rogers was talking about the use of a map approach for tracking in FFAs, P. Calvo gave an account of the Development of the simulation code OPAL and T. Planche described the TRIUMF Simulation Tools Status & Future. A thorough review of available numerical codes can also be found in the article of Smirnov [51]. The consensus was that, particularly to reproduce space-charge effects accurately and on the order of 10^{-4} in terms of relative particle loss, computationally costly particle-in-cell codes give the highest accuracy. While codes like OPAL [52] are constantly being further developed to become more efficient, include more of the pertinent physics, and run on the highest performing clusters, new technologies like machine learning (e.g., surrogate modeling) should be embraced and included.

CONCLUSION

Findings

We found that there have been several breakthroughs in the past years to further increase the available beam currents (and thus total delivered power) that make continuous wave (cw) isochronous cyclotrons the accelerator of choice for many high power applications at energies up to 1 GeV. Key innovations are: Improved injection (through RFQ direct injection, transverse gradient inflectors, and magnetic inflectors), improved acceleration (utilizing *vortex motion*, single-stage high energy designs, vertical excursion FFAs), and improved extraction (through new stripping schemes and by *self-extracting*, using built-in magnetic channels). The use of H_2^+ as accelerated ion instead of protons or H^- has also received much attention lately. Here, stripping the electron during extraction or directly after doubles the electrical beam current mitigating some of the space charge issues with high current beams in the accelerator.

There are now several projects designing new powerful cyclotrons for particle physics, medicine, and accelerator driven systems (ADS) for energy research. These are cost-effective devices with small facility footprint, thus following the mantra *better, smaller, cheaper*. Among them, the IsoDAR compact cyclotron promises a 10 mA cw proton beam at 60 MeV/amu, improving by x4 over PSI injector 2 and by x10 over commercial cyclotrons for isotope production. A design for a 2 mA superconducting cyclotron is underway at TRIUMF, further reducing the footprint. Several designs (AIMA, DAEδALUS, TAMU) are being developed for ADS and particle phyiscs (CP-violation in the neutrino sector).

Finally, we found that the field of computational (accelerator) physics has made great strides and high fidelity simulations have become a necessity to understand and design accelerators with high space charge. High performance- and exascale computing will be needed in order to accurately simulate many-particle interactions (e.g., space-charge and halo-formation), and beam-environment interactions (e.g., residual gas, wakefields). As in other fields, Machine Learning can play a big role by providing new tools to understand and predict complex behavior, and significantly reduce simulation execution time, enabling virtual particle accelerators and faster and better optimization.

Recommendations

We, the community of particle physicists, particle accelerator physicists, and funding agencies, should:

1. Recognize the important role cyclotrons are playing in Nuclear- and Particle Physics;
2. Encourage development of this type of accelerator, as an investment with high potential benefits for Particle Physics, as well as outstanding societal value;
3. Recognize and encourage the high benefit of collaboration with the cyclotron industry.
4. Recognize the opportunities the Exascale computing era will provide and adjust development of beam dynamics simulation tools accordingly.
5. Aim for a close connection of traditional beam dynamics models with (1) machine learning (surrogate models) and (2) feedback (measurements) from the accelerator, as they will pave the way to an intelligent accelerator control and on-line optimisation framework.

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