ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I3

SUMMARY OF THE WORKING GROUP C ON ACCELERATOR SYSTEMS

S. Machida, Rutherford Appleton Laboratory, Didcot, Oxfordshire, U.K.
H. Huang, Brookhaven National Laboratory, Upton, NY, USA
P. K. Saha, Japan Atomic Energy Agency, Tokai, Ibaraki, Japan

Abstract

This is the summary of all overall presentations and discussions of the working group C on accelerator systems at the 68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams, named HB2023 held at CERN during October 9-13, 2023.

INTRODUCTION

In this working group (WG), we had a total of 18 oral presentations, equally divided into half and were held in 4 parallel sessions. There were also 5 posters presented under this WG. Among 18 oral presentations, we considered a complete geographical balance by selecting 6 talks each from Asia, America and EMEA (Europe, Middle East, and Africa). The main motivation of this WG was to get full pictures and details of high-intensity accelerators worldwide to date and future developments and upgrades with new techniques and modifications by covering the following 6 categories: 1) Injection and Extraction, 2) RF systems, 3) Impedance and Instabilities, 4) New techniques and Novel ideas, 5) High-power targets and 6) Upgrades and Future Projects. We arranged joint sessions for 2) RF systems and 3) Impedance and Instabilities with WGA (Beam Dynamics in Rings) and WGE (Beam Instrumentation and Intercepting Devices). In this report, we present a summary of the key points and highlights of each presentation and some general remarks on the working group perspective.

INJECTION AND EXTRACTION

Vincent Schoefer: Mitigation of space charge effects in RHIC and its injectors

The RHIC heavy ion and spin physics program requirements provide an array of intensity and space charge related challenges to performance optimization. For polarized proton beam at the injection of AGS Booster and AGS, the space charge driven bottlenecks are mitigated by bunch lengthening with dual RF harmonics and stopband correction. The low energy Beam Energy Scan-II program in RHIC uses the Au beam below the nominal injection energy due to a combination of effects from space charge, IBS. The effects are mitigated by moving working point and optimizing the electron cooling beam current. In the future, more comprehensive simulations could be performed to identify specific drivers of intensity dependent emittance growth and beam loss.

Nicholas Evans: Self-consistent injection painting for space charge mitigation

Danilov distribution can be created by uniformly filling one transverse mode of a coupled ring. It offers an opportunity to create a beam with several properties of interest for high brightness beams. Such a distribution could be constructed using a sufficiently flexible charge exchange injection system, such as at the Spallation Neutron Source (SNS). Extensive simulations have been done to compare with the eigen painting experiment results. They have achieved the initial goal of developing a procedure for eigenpainting into a ring and are currently preparing a detailed analysis of the resulting experiments. They have identified several opportunities for improvement at SNS.

Chiara Bracco: Shaping high brightness and fixed target beams with the CERN PSB charge exchange injection

This paper first gave a brief history of CERN PS Booster (PSB) and the upgrade to 160MeV H^- charge exchange injection. With higher energy and H^- injection, the space charge effect has been greatly mitigated. The PSB commissioning started in December 2020. The paper described the steering and injection setup, injection painting setup and optimization, and stripping foil performance. The results achieved up to now meet the upgrade goals. Nonetheless, relentless endeavours persist in pushing the boundaries to assess the ultimate levels of the achievable intensity and brightness.

RF SYSTEMS

Fumihiko Tamura: RF systems of J-PARC Proton Synchrotrons for high-intensity longitudinal beam optimization and handling

The application of magnetic alloy (MA) cores to the accelerating RF cavities in high intensity proton synchrotrons for the J-PARC synchrotrons, the RCS and MR are summarized. The MA loaded cavities can generate high accelerating voltages. The wideband frequency response of the MA cavity enables the frequency sweep to follow the velocity change of protons without the tuning loop. The dual harmonic operation is indispensable for the longitudinal bunch shaping to alleviate the space charge effects in the RCS. On the other hand, since the wake voltage consists of several harmonics, which can cause coupled-bunch instabilities, the beam loading compensation must be multi-harmonic. The operation of tubes in the final stage amplifier is not trivial when accelerating very high intensity beams;

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I3

the output current is high, and the anode voltages are also multi-harmonic. The efforts against these issues in the operation of the RCS and MR for the past 10 years were summarized.

Xiao Li (Presented by Wu Bin): Development of dual harmonic RF System for CSNS-II

The upgrade of the China Spallation Neutron Source requires the development of a dual harmonic RF system for the RCS. The maximum second harmonic voltage of 100 kV is needed. To meet this requirement, a high gradient cavity is used instead of the traditional ferrite loaded cavity. Magnetic alloy (MA) loaded cavities, which can attain very high field gradients, have demonstrated their suitability for high-intensity proton synchrotrons. Over the past decade, substantial advancements have been made in the development of MA-loaded cavities at CSNS. The paper provides an overview of the RF system that incorporates the MA-loaded cavity and presents the high-power test results of the system.

Chihiro Ohmori: Magnetic alloy loaded cavities in J-PARC and CERN

The history of collaboration on the development of Magnetic Alloy (MA) cavity is summarized. MA cavities are used in several accelerators worldwide. J-PARC and CERN have been collaborating on the cavities for more than 20 years. MA loaded cavities have been used in seven synchrotrons at J-PARC and CERN. CERN employed the cavity design using a small cell structure driven by a solid-state amplifier. This became a universal design applied to many interesting applications including beam deceleration, instability damping, barrier bucket, and emittance control. J-PARC chose the direct water cooling to achieve high-field gradient for high intensity beam acceleration. This paper also contains improvements of cavity cores by magnetic annealing scheme, quality control of cores during production, the cooling methods of magnetic alloy cores: direct water cooling and indirect one using copper discs, control of cavity bandwidths from broad to narrow bands, and the methods to drive RF cavities by tube and rad-hard solid-state amplifiers.

Juan Luis Munoz: Multiharmonic buncher (MHB) for the isolde superconducting recoil separator project

The ISOLDE Superconducting Recoil Separator (ISRS) is based on a very compact particle storage ring of only 3.5 m in diameter. The injection of the HIE-ISOLDE beam into this ring requires a more compact bunch structure, so a Multi-Harmonic Buncher (MHB) device is proposed. The full design of the MHB is presented, including electromagnetic optimization of the electrode shape, optimization of the weights of each of the harmonic contributions, mechanical and thermal design of the structure. The RF generation and electronics to power up the device are given in the paper. A solution that directly generates the composed signal and is then amplified by a solid-state power amplifier is also presented in this paper.

IMPEDANCE AND INSTABILITIES

David Posthuma De Boer: Development of an impedance model for the ISIS synchrotron and predictions for the head-tail instability

ISIS has observed head-tail instability in the vertical direction soon after the start of the operation. The mode and the growth rate were, however, different from the theoretical prediction. It has been a mystery for a long time.

David challenged to understand this mystery both from the impedance and instability modelling. He first looked at the resistive wall impedance caused by the wires acting as RF shielding inside the ceramic vacuum chamber. The calculation has been done considering all the detailed geometry. A kicker magnet is a common source of a narrowband impedance. He measured the impedance and found that it made a large contribution to the observed impedance. Then, he calculated and measured a resonance type impedance caused by the RF screen wire with capacitance in the end which prevents eddy current. Although the calculation and measurement do not give a quantitative agreement yet, the resonant frequency and the impedance together with a thick wall impedance model give about the right value as measured with the beams. Finally, he calculated a head-tail mode with a newly developed Vlasov solver by himself, PyTMCI. It predicts the same mode number observed experimentally and the growth rate is very similar to the measured one. The puzzle of the head-tail instability at ISIS seems to have been solved finally although some details have to be investigated further.

Yoshihiro Shobuda: A kicker impedance reduction scheme with diode stack and resistor at the RCS in J-PARC

Kicker magnets in J-PARC RCS have a unique design to use the backward current by shortening one end of the circuit. In this way, the kicker strength can be doubled. A downside of the design is, however, that the impedance increases due to a resonant structure created by the short plates and the coaxial cables. Although instability happening at high energy can be suppressed by tune and chromaticity controls for the large emittance beams with the beam current equivalent to the 1 MW operation, a mitigation measure of the kicker impedance will be critical when they increase the beam brightness, namely a similar intensity with smaller emittance. To reduce the impedance, a matched resistor should be inserted, but that resister should not be seen by the Pulse Forming Line (PFL). Yoshihiro devised the termination resistor with a diode unit. He first discussed the idea of inserting the diode in the circuit. He then showed the results of forward and backward currents through the kicker and measured kicker impedance showing a significant reduction. That has been done with a prototype diode and resister unit.

An interesting part of his talk is the results concerning analytical, computational, and experimental measurement of the heat flow. For the high-power beam accelerator like

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I3

J-PARC RCS, the durability of the system cannot be overlooked even if the idea sounds and a prototype works. He checked analytical and computational calculations with tools like SPICE and ANSYS Fluent reproduces the reality very well.

Michela Neroni: Beam coupling impedance of the main extraction kickers in the CERN PS

According to the specification of HL-LHC, the beam intensity of the CERN PS has to be doubled keeping the transverse emittance the same. It is important to know the impedance more precisely and establish a mitigation measure. Michela focused on the longitudinal and transverse impedance issues on two main kicker magnets in the PS. Note that there was another talk on transverse impedance and instabilities in the PS given by S. Joly in WG-A.

In the longitudinal direction, kickers are the main source of the broadband impedance around GHz which excites single bunch instabilities. Kickers also have resonance type impedance at a low frequency of around 40 MHz. A detailed EM modelling reveals that the resonance comes from the stack of ferrite. A mitigation measure was discussed. In the transverse direction, quadrupolar as well as dipolar impedance was calculated. The curves in horizontal and vertical directions of dipolar and quadrupolar impedance show a broadband spectrum up to 1~2 GHz. At some frequencies, a resonant-type behaviour appears as well. It was found that transmission cables with proper terminations should be included in the simulation and measurement because a resonant-type behaviour at low frequency region, up to 50 MHz, has a big impact.

Bjorn Lindstrom: Mitigating collimation impedance and improving halo cleaning with new optics and settings strategy of the HL-LHC betatron collimation system

The increase of the beam intensity in HL-LHC imposes two critical challenges on the collimators. One is the leakage of losses from collimators. Particles with large momentum offsets are lost in the dispersion suppressor. An increased leakage directly affects the quench risk. The other is the impedance of the collimators. Reduction of beta* requires a tight collimator setting. The minimum collimator gap at the top energy becomes about 1 mm. Initially, the collimator material was replaced by a low impedance one: Mo-graphite instead of CFC for primary and Mo-coated Mo-graphite and Cu-coated graphite for secondary. Concern still remained.

A new optics design was proposed to mitigate both using Xsuite, which has large betax and betay at primary collimators, small betax at secondary collimators, increasing single-pass dispersions and small beta functions in the orthogonal plane of collimators. Beam loss at the dispersion suppressor is reduced by up to 70%. The impedance in the ~1 GHz frequency range is reduced by 45% in horizontal and 10% in vertical. This makes it possible to reduce the octupole threshold by ~52 A. Further reduction in vertical is under study. Together with simulation, measurements were done to confirm the reduction of the beam loss at the dispersion suppressor. They will measure the impedance in the future. As a result, new optics will be implemented in the HL-LHC baseline as of HLLHCV1.6 optics. Operational deployment is considered before the end of current Run 3.

NEW TECHNIQUES AND NOVEL IDEAS

Stephen Brooks: Ultra-low emittance bunches from laser cooled ion traps for intense focal points

Stephen proposes the use of Paul Trap to produce ultralow emittance bunches which provide some interesting unexplored regimes, namely 106 times smaller emittance compared with conventional bunches. Paul Trap has been used for accelerator physics study at Hiroshima Univ (S-Pod) and RAL (IBEX) but this is the first time to design Paul Trap for application using the extracted beams combined with laser Doppler cooling. Stephen proposes the acceleration of the beam further keeping its ultra-low emittance. A lot of animations were an interesting part of his talk which is available on the workshop website. There are some issues which have to be overcome: Space charge, emittance and energy spread consideration are mentioned. Optical aberrations, such as spherical aberration and chromaticity, become more significant issues with a small emittance. Experimental noise and jitter etc are other important ones.

At the moment, he is considering the following applications. He will achieve the quantum ground state, which produces, for example, entangled spin states in a beam. Ultimately, it appears capable of custom synthesis of nuclear density matter. Stephen has a start-up funding for over 2 years, and we are looking forward to the results from the experiment.

Timofey Gorlov: Laser Stripping of H^- beam

To overcome the realistic issues and practical limitations of the conventional H^- stripping by using a solid stripper foil, the basic principles of the alternate H^- stripping method by using lasers, continuous progress, and another step forward from a proof-of-principle (POP) demonstration to apply in an operational accelerator are presented. At the SNS in Oak Ridge, the injection area is 10 times hotter than the rest of the ring due to the parasitic foil hits of the circulating protons during the injection period. Starting with a POP experiment for H^- stripping of only 6 ns at the SNS, recently reached up to 10 us stripping with 90% efficiency. The method utilizes high magnetic fields for stripping electrons in the H^-, while a laser is used for exciting the deeply bound electron and is thus named as Laser Assisted Charge Exchange (LACE) injection. In this talk, basic principles of the LACE for the H^- and H0 beams as well as theoretical aspects of the electromagnetic interaction of laser with hydrogen atoms and H^- ions are discussed. To reduce the laser power down to 3 orders of magnitude as compared to POP demonstration, various manipulations of both ion and laser beams as well as a two-step sequential excitation scheme and their applications are shown. It has been suggested a higher H^- energy of around

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I3

4 GeV is favourable for a compact stripping scheme because of using only one magnet and a narrow band IR laser. The next experiment at the SNS will be carried out at 1.3 GeV for different incident angles of the laser for identifying and efficiency of each state in a sequential excitation. A different approach by using only lasers at J-PARC because of a lower H^- energy of 400 MeV is also about to start the experimental studies soon.

Valeri Lebedev: High energy cooling

Beam cooling of protons in high energy hadron colliders is one of the most challenging problems in modern accelerator physics. The subject gets more attention due to the EIC project at BNL. Considerable progress has been achieved in recent years, but a number of problems still need to be addressed, e.g. good cooling of high amplitude particles is required.

For the proton beam energy below ~250-300 GeV, the electron cooling looks like a possible technology. Presently, only ring-based cooling looks feasible for the proton energies above ~100 GeV. A solid ring design proposal was shown based on 100% coupled optics, that reduces IBS and beam space charge. With lower energy, a cooler based on an energy recovery linac looks like a possibility.

For proton energy above ~250-300 GeV, optical stochastic cooling (OSC) looks like extremely promising technology. Passive OSC was demonstrated at Fermilab IOTA in 2021. For ep-collider, it needs ~10 T undulators and an optical amplifier with a small signal delay and a large gain of 50 dB. The coherent electron cooling (CEC) development is still at its initial stage although considerable work has been done in recent years. For example, the breakthrough happened at the end of the 2000's with the transition to relativistic energies and a suggestion to use FEL as an amplifier. CEC potential and reach need to be understood better before real implementation can be considered.

Natalia Triantafyllou: Simulations and measurements of betatron off-momentum cleaning performance in the energy ramp at the LHC

LHC collimator system removes particles with large betatron and energy offsets. The most critical part is the superconducting IR7 dispersion suppressor where the cleaning inefficiency is required to be less than 10^{-4}. This talk focused on challenges for the collimation in the combined ramp and squeeze part of the LHC operation cycle where the beam energy increases and beta* decreases at the same time. The collimator requires excellent control for the emittance shrink in the ramp and the aperture shrink around collision points. Natalia uses Xsuite and Xcoll as simulation tools. Xcoll simulates particle-matter interaction with external engines: Geant4 and FLUKA and internal engines: K2 (Everest). In particular, the cleaning of off-momentum particles must be simulated with an RF frequency sweep. Xcoll demonstrated it is possible.

Studies were conducted for 2023 proton configuration during ramp and simulations and measurements are compared. She noted that loss maps cannot be compared quantitatively because beam loss monitors measure secondary particle showers outside of the magnet cryostat while simulations count protons lost in the aperture. Nevertheless, good qualitative agreement is achieved for betatron cleaning and off-momentum cleaning in the energy ramp.

HIGH POWER TARGETS

Shiro Matoba: Muon production target at J-PARC

In this talk, realistic issues for handling high-intensity target and the development prospect of the muon target at J-PARC is presented. The detailed concept of the target design, R&D of the monitoring system and target exchange procedures are given. The 1st generation fixed target made of isotropic graphite used until 2013 had 1% shrinkage due to high-intensity beam irradiation and the estimated lifetime was only 6 months at 1 MW. The 2nd generation target, which is a rotating target developed under collaboration with PSI to distribute the radiation damage over a wide area for an expected lifetime of 10 years. However, due a trouble with rotation coupling the strength of coupling was reduced and it was replaced after 5 years of operation in 2019. The real time two-dimensional temperature measurement by radiation hardness infrared camera capable of 5 Gy radiation resistance has been installed. This is very important to stop the beam immediately for any abnormal temperature rise as well as lifetime prediction by evaluating damage to the graphite and rotating shaft by image recognition. Diffusion of local heating at 1 MW beam irradiation was seen, where the measured temperature was about 1000 K and was consistent with the calculated value. A complete procedure of replacement of the target preventing tritium pollution and radiation exposure under a highly radioactive environment has also been presented.

UPGRADES AND FUTURE PROJECTS

Kazami Yamamoto: Beyond 1 MW scenario in J-PARC rapid cycling synchrotron

The Rapid Cycling Synchrotron (RCS) of J-PARC has already achieved the designed 1 MW beam power by minimizing the beam loss to an extremely low level. This allows a reliable scenario to exceed far beyond 1 MW beam power, which is also necessary to cope with present and near future upgrade paths of J-PARC. Recently, the RCS duty factor for the beam operation to the Main Ring has been increased to nearly 14% and construction of a 2nd neutron production target has also been planned. As a result, RCS is aiming for 2 MW beam power to maintain a net 1 MW beam power to the present neutron production target. A combination of the extension of injection pulse length from 0.5 to 0.7 ms and a higher peak current of 50 mA to 70 mA would double the beam power to 2 MW. The simulation results show 2 MW beam power can be achieved keeping the beam loss less than the collimator limit of 4 kW. The beam test for 1.5 MW equivalent beam power has also been demonstrated with minimum beam loss. The R&D studies for both Linac and RCS have been started. The replacement of all RF cavities of RCS with new types will be replaced by 2028, which gives more than

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-FRA2I3

50% less anode power supply current for acceleration. The beam test with triple harmonic RF operation, which gives a much higher bunching factor has been done and will be implemented in the near future.

Katsuya Yonehara: Challenging of muon acceleration for muon colliders

This talk gives an overview of the far future muon colliders project reviewed by the High Energy Physics community in the US Snowmass and P5 (Particle Physics Project Prioritization Panel) meetings. The underlying R&D challenges in the accelerator technologies for extremely high energy and high brightness muon beams and a roadmap mainly based on the accelerator complex evolution plan at Fermilab are discussed. These include numerous R&D and upgrades of the accelerator scheme at Fermilab for the high-intensity beam for the existing high-energy physics programs and with high precession The prioritization of international collaboration aspects such as, with International Muon Collider Collaboration for the accelerator scheme and the targetry and its cooling has been strongly mentioned. At present a roadmap and timeline for nearly 20 years divided into two phases, R&D and demonstration phases are considered.

WORKING GROUP PROSPECTIVES

Finally, here are some takeaway comments from conveners' rather personal views.

Hardware development of the RF cavities never stops. Further development of the magnetic alloy material continues. Single ended, instead of push-pull, operation to handle beam loading increases energy efficiency. This is a nice example that further challenge in seemingly matured technology pays off significantly. As a related subject, triple harmonic in addition to second harmonic RF waveform is the way forward.

The calculation of impedance depends on the details of an individual accelerator. However, several handy tools are now commonly available. All the talks show better understanding and reasonable mitigation measures.

Since this is a workshop on the high brightness beams, the first stage of creating the beams should not be overlooked. When it replaces the conventional ion source, the impact on the downstream of the accelerator chain must be huge. Another area where the conventional system could be replaced is the charge exchange injection system. It seems that the H^- stripping by laser is no longer a dream.

At the SNS accumulator ring, a solenoid was introduced for the coupling between two transverse planes at injection. The idea of using a linear coupling at injection was proposed a long time ago, but now it was demonstrated in a different context.