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SUMMARY OF WORKING GROUP B

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Working group B, Beam Dynamics in Linacs, featured 8 invited and 13 contributed talks over 5 sessions covering a broad range of topics relevant to linacs from operational experience to novel theoretical techniques to aid in the design and analysis of accelerators. Highlights from each session are presented below, followed by remarks from the conveners.

SESSION 1

Nicolas Chauvin, **CEA Saclay**, presented R&D activities focused on high-intensity proton and deuteron beams for the high-intensity proton injector IPHI that has been designed and developed with the primary objective of accelerating a continuous beam of 100 mA to 3 MeV [1]. This machine consists of a high-intensity ECR ion source, a low-energy beam line, a 352 MHz RFQ, and a medium-energy transport line equipped with diagnostics. The commissioning of the IPHI facility started several years ago with a proton beam operating at a low duty cycle (0.1 %) and a current of 65 mA. Since then, he showed that significant progress has been made, resulting in an accelerated beam power exceeding 30 kW. In addition, extensive measurements have been conducted to thoroughly characterize the beam accelerated by IPHI and its transport through the beam lines. he detailled end-to-end numerical model in - high space charge regime - of the IPHI accelerator and validated it against experimental data; showing that "semi-empirical" model gave an accurate description of the beam dynamics and the space charge compensation.

Austin Hoover, **ORNL**, presented simulation work showing the effects of previously observed high-dimensional correlations in phase space present at the output of the SNS RFQ on downstream beam behavior at the SNS Beam Test Facility (BTF) [2]. These correlations have been measured at the BTF, and can be reproduced in PARMTEQ simulations. The downstream evolution of the bunch appears largely independent of the presence of these correlations, as beams with the correlations artificially removed quickly converge to resemble the correlated bunches: in both an RMS sense and more general structural appearance. This work has implications for future studies examining halo formation in high-power linacs. Part of these developments are also linked to work on effect of three-dimensional quadrupole magnet model On beam Dynamics presented by **Trent E. Thompson**, **ORNL** [3].

In this session **Yuri Batygin** also discussed the feature of the **LANSCE** accelerator facility with multi-beam operation, simultaneously delivering beams to five experimental areas [4]. He showed that multi-beam operation requires compromises in beam tuning to meet beam requirements and losses throughout the accelerator. Upgrade of the facility (new 100 MeV front end), with expected significant improvement of beam quality, was also presented.

SESSION 2

Shuhui Liu, **Institute of Modern Physics, CAS** presented the design of the Chinese Accelerator Driven System (CiADS), with particular emphasis on features meant to improve availability of the machine [5]. The LEBT is designed to clean the proton beam of contaminating H_2^+ and H_3^+ prior to injection to the RFQ, and the superconducting linac begins immediately after the RFQ and MEBT at 2.1 MeV. Notably, fault recovery by online re-tuning of cavities and magnets in the vicinity of a cavity failure is built into the design, which should help the CiADS meet the strict availability requirements set on ADS. First beam at 500 MeV is expected in 2027.

Andrei Shishlo, **ORNL** gave an update on progress made in understanding SNS linac beam dynamics. Dr. Shishlo drew on a talk given by A. Aleksandrov at HB in 2010 to show how much progress has been made in understanding centroid motion, RMS size and beam loss/transmission transversely and longitudinally. Despite progress in nearly all areas, mostly using envelope-only tracking in OpenXAL, empirical tuning still drives operation. Studies with the PIC code pyORBIT show no contradiction with classical models used in accelerator design, but do not have the resolution to identify the low-loss operating point [6].

Sasan Ahmadiannamin, **STFC/RAL/ISIS**, also presented studies focused on beam physics simulation conducted on the current ISIS linac, aiming to gain a deeper understanding and analysis of various phenomena observed during routine operations and accelerator physics experimentation [7]. While **Juan E. Muller** presented beam dynamics studies and codes benchmarking activities carried out at **ESS** [8]. The aim was to Evaluate PyORBIT as a unified simulation tool for beam dynamics modeling.

SESSION 3

Jean-Michel Lagniel, **GANIL**, discussed about synchronous phases (ϕ_s) and transit time factors (T) are the key parameters for linac designs and operations [9]. He mentionned that while the couple (ϕ_s, T) is still our way of thinking the longitudinal beam dynamics, it is important to have in mind that the original "Panofsky definition" of these parameters is no longer valid in the case of high accelerating gradients in multi-gap cavities. He proposed new methods to tune cavities with respect to their buncher phase. He also presented a new definition of the synchronous phase in order

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to obtain a better understanding and a better optimization of the longitudinal beam dynamics. Finally he emphasized that the nonlinear components of the sinusoidal RF field can then excite parametric resonances, including the 4th-order resonance. He therefore suggests that parametric resonances in the longitudinal plane should not be considered as function of the the longitudinal phase advances per transverse focusing period ("σ_{l-t}") as often done. Parametric instabilities of beam eigenmodes, particle resonances -in the transverse planes only - and their mitigation were also discussed [10] by **Dong-O Jeon**, **IBS**, during the session.

Andrea Latina, **CERN**, presented RF-Track a CERN-developed particle tracking code that can simulate the generation, acceleration, and tracking of beams of any species through an entire accelerator, both in realistic field maps and conventional elements [11]. RF-Track includes a large set of single-particle and collective effects: space-charge, beam-beam, beam loading in standing and travelling wave structures, short- and long-range wakefield effects, synchrotron radiation emission, multiple Coulomb scattering in materials, and particle lifetime. Andrea's Talk was followed by **Giulia Bellodi**, **CERN**, presentation benchmarking activities between RF-Track and PATH codes [12]. She highlighted very encouraging results of the codes benchmarking with zero space charge (discrepancies < 1 % in transverse emittance values and transmission). Space charge introduces differences in the results and possible causes were identified (different space charge modelling, thin gaps vs. field maps, etc.). Next steps to improve RF-Track will be focused on RF phases optimisation, implementation of CSR (3D), intra-beam scattering and multi-bunch beams. Link to these studies and developments, **Chong Shik Park**, **Korea University**, presented studies on space charge modelling to improve and potentially decrease calculation time for space charge routines in beam dynamic codes [13].

SESSION 4

Takahiro Nishi, **RIKEN** showed recent experimental results from studies at the Superconducting Riken Linac (SRILAC) with specially designed Beam Energy Position Monitor (BEPM) to characterize the beam envelope continuously and non-destructively as a replacement for quadrupole scans with wires [14]. Initial results did not match traditional methods well, but two correction techniques presented improved results dramatically. However sensitivity for emittance remains poor. This can be improved with an occasional calibrating destructive scan. Control system upgrades are being added to record the information necessary for implementing correction schemes.

Edgar Sargsyan, **CERN**, discussed the recent developments, tests, and future plans for the Linac4 H^- ion source [15]. He explained that in the previous version of the Linac4 H^- ion source (IS03), produced an operational pulsed peak beam current of 35 mA, resulting in 27 mA after the Radio-Frequency Quadrupole (RFQ). This limited transmission was mainly due to the extracted beam emittance exceeding the acceptance of the RFQ. A new geometry of the Linac4 source extraction electrodes has been developed with the aim of decreasing the extracted beam emittance and increasing the transmission through the RFQ. The new source (IS04) has been studied and thoroughly tested at the Linac4 source test stand. At the start of the 2023 run, the IS04 was installed as operational source in the Linac4 tunnel and is being successfully used for operation with 27 mA peak current after the RFQ. As already emphasized in several talks of WGB, these studies showed the importance to have a better understanding of the beam dynamics in the low energy injector region. Indeed the beam is sensitive to mainly non-linear effects (i. e. space charge) but also other physical process which are not well know such as the source extraction (meniscus region) or residual gas interaction.

Linked to this problematic **Marco Hartmann**, **PSI**, presented realistic simulations of the TATTOOS beamline using BDSIM to get a realistic evaluation of the possible losses in the line that should transport a high power beam (60 kW) [16]. This work is carried out in the frame of IMPACT (Isotope and Muon Production with Advanced Cyclotron and Target Technology), a proposed upgrade project for the high-intensity proton accelerator facility (HIPA) at the Paul Scherrer Institute (PSI). Another detailed beam loss studies on CSNS was also presented. **Jun Peng**, **CSNS**, explained that during the beam commissioning beam losses were caused by space charge effects and collective instabilities [17]. The unexpected collective effects, the coherent oscillation of the bunches, were observed when the beam power exceeded 50 kW. Mitigation strategies (adjusting the tune tracking pattern and chromaticity with a DC sextupole) to minimize instabilities were explained and contributed to the achievement of the designed beam power: 140 kW (2020).

SESSION 5

Michele Comunian, **National Laboratories of Legnaro** presented a comparison of longitudinal emittance among several existing RFQs to illuminate the longitudinal formation process using the Toutatis code. Each RFQ is based on fundamentally different design choices: IFMiF, ESS, SPES, SPIRAL2, TRASCO. The comparison shed light on the way longitudinal bunching is achieved in a variety of designs, and how the phase space distribution develops under various strategies. Finally, an attempt was made to redesign the TRASCO RFQ using a genetic algorithm, which resulted in a 30 % decrease in RFQ power [18].

Simon Lauber, **GIS**, **HIM** presented work on the design of an "alternating phase focusing" linac. This idea from the 1950's eliminates magnetic transverse focusing in a DTL in favor of using electric field focusing provided by drift tubes. However the phases required for transverse and longitudinal focusing are not the same, but can be alternated to produce net focusing and acceleration in both planes, similar to transverse alternate gradient focusing. The idea has been used at several facilities, and is seeing a renewal of interest as mod-

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ern computing power and computer-aided fabrication make the design and construction of these machines easier. Simon demonstrated the use of modern optimization software to create a design for an APF linac that includes space charge and achieves full transmission with high quality beam [19].

Also in this session **Dong Hwan Kim**, **KAERI/KOMAC**, presented fast diagnostics method for the transverse beam emittance measurement using a solenoid magnet in intense hadron injectors [20]. Beam characterization has been studied at RFQ-based Beam Test Stand on KOMAC facility. He showed and discussed that solenoids scan may give simple and fast evaluation of low energy beam emittance even for the high-intensity proton beam by using thick-lens approximation with linear space charge. Still in these issues of beam control in high space charge regime, **Chen Xiao**, **PSI**, discussed that imposing defined spinning to a particle beam increases its stability against perturbations from space charge. He showed that cell-to-cell 4D-matching can be achieved for a coupled beam with considerable space charge forces. This has been accomplished by rms-tracking of coupled beams with KV-distribution combined with a dedicated iterative procedure of tracking and re-matching [21].

THEMES / OUTLOOK

The most striking feature of the talks throughout this session was the large number of simulation tools used to treat similar problems. Among others, we noted the use of PARMILA, Track3D, Trace3D, OPENXAL, TRAVEL, TraceWin , IBSimu, WARP, IMPACT3D, PyORBIT, PATH, RF Track, Toutatis, PARTEQM, BDSIM, MADX, SPIRAL2 generator, etc. With such a proliferation of codes, and occasional disagreements across codes e. g. [8], it seems like a community-wide calibration effort as was carried out for the HIPPI project [22] quite some time ago. It was also noticed during final restitution session that standardizing inputs data between codes is an effort that should be beneficial for the community.

There was also a great deal of emphasis on operational machines, what remains to be learned to push beam intensity and power, and how the broader lessons related to reliability and availability can be applied to new designs. In the case of both SNS, and the LANSCE facility, which have been in operation for decades, physics designs take a back seat to empirical tuning to achieve optimal operation; as well as for Linac4. This suggests plenty of opportunity to learn, but also emphasizes the need for flexible designs that can accommodate decades-long evolving missions, and empirical optimization.

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