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ACCELERATOR CHALLENGES OF PROPOSED RADIOACTIVE BEAM FACILITIES

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Abstract

Radioactive Ion Beams (RIB) have become an important tool for nuclear physics, nuclear astrophysics and atomic physics. In order to meet the worldwide demand for higher RIB intensities the proposed radioactive beam facilities ‘An International Accelerator Facility for Beams of Ions and Antiprotons’ (GSI), RIA (US) and EURISOL (EU) aim to provide primary beam power exceeding 100 kW or TW peak intensities, as in the case of the GSI proposal. The increase in primary beam power will be accompanied by advanced target and separator design as well as fast secondary beam cooling in storage rings (GSI). Following a brief review of the proposed RIB facilities, some of the main accelerator challenges specific to the different facility concepts will be outlined, e.g. control of space-charge effects (GSI) and dynamic pressure (GSI) in synchrotrons as well as multi-charge state acceleration in linacs (RIA).

1 INTRODUCTION

The opportunities offered by beams of exotic nuclei for research in the areas of nuclear structure physics and nuclear astrophysics are exciting and world-wide activity in the construction of different types of radioactive ion beam (RIB) facilities shows the strong scientific interest in the physics that can be probed with such beams. The two production methods used in RIB facilities are substantially different. One is commonly called Isotope Separation On Line (ISOL) and the other is called In Flight. In ISOL-type facilities, radioactive ions are produced essentially at rest in a thick target, that is bombarded with energetic primary particles from a driver accelerator. After diffusion out of the target and ionisation the radioactive ions can be accelerated in a post-accelerator. For the in-flight method an energetic heavy-ion beam is fragmented while passing through a thin target. After mass, charge and momentum selection in a fragment separator the selected ions can be analyzed or stored for further studies. No post-acceleration is required. As stated in a recent report (Ref. [1]) of the Nuclear Physics European Collaboration Committee (NuPECC) the two methods are regarded as entirely complementary. While the ISOL method allows good quality low energy RIBs to be produced, in-flight facilities are optimum for higher energy RIBs of short-lived nuclei. In order to move closer to the extreme limits of stability the presently available driver beam intensities have to be increased by at least an order of magnitude together with corresponding efforts in target design and instrumentation. As defined in the NuPECC report a next generation large-scale in-flight facility for Europe should provide primary beam intensities of $2 \cdot 10^{12}$/s for all elements from hydrogen to uranium with energies up to 1 GeV/u. The focus of such a next generation facility will clearly be on the energetic heavy fragment beams and uranium in-flight fission allowing very neutron-rich species to be accessed. The instrumentation should include a large acceptance fragment separator and a storage ring system allowing fast cooling and optimum storage of cooled secondary beams. The optimum driver for ’in-beam’ experiments (reaction and decay studies directly after separation) would be a superconducting linac delivering a high intensity dc beam on the target. Storage ring experiments, on the other hand, require short bunches with repetition rates of 1 Hz determined by the maximum cooling rates in a collector ring. For the next generation facility the NuPECC report recommends a synchrotron driver that can efficiently be matched to the storage ring operation and can serve in slow extraction mode the in-beam experiments. At GSI a major upgrade of the existing synchrotron based in-flight facility, presently the only one in the world that already accelerates intense uranium beams up to 1 GeV/u, towards the NuPECC recommendations is proposed [2]. The accelerator requirements for the next generation European ISOL facility, whose beams are necessary to complement the physics studied at the in-flight facilities, are presently studied in the EURISOL collaboration [3]. Supported by the recommendations of the Nuclear Science Advisory Committee (NuSAC) [4] in the US the Rare Isotope Accelerator (RIA), a combined ISOL in-flight facility is proposed. The superconducting driver linac should be capable of delivering 100 kW of beam power, and be upgradeble to 400 kW for all ions [5]. For uranium beams this would correspond to $2 \cdot 10^{13}$ ions per second. After a brief review of the two proposals (RIA and GSI) a discussion of some of the design challenges related to a heavy ion driver for a in-flight facility follows.

2 PROPOSED FACILITIES

2.1 GSI Upgrade

At GSI ‘An International Accelerator Facility for Beams of Ions and Antiprotons’ [2] is proposed that would serve radioactive beams physics as well as three other research areas (high energy nuclear collisions, antiprotons, plasma physics). The proposed heavy ion driver for RIB production (see Fig. 1) is a synchrotron complex, consisting of two separate synchrotrons (SIS 100 and SIS 200) with 100 and 200 Tm maximum magnetic bending power and with equal circumferences of about 1100 m, using the existing UNILAC/SIS18 facility as injector. For both synchrotrons,

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fast cycling superconducting magnets will be used to save investment and operation costs. Intense (up to $2 \cdot 10^{12}$ particles per second), partially stripped heavy ions will be accelerated in the 100 Tm synchrotron (up to 2.7 GeV/u for U^{28}). In the storage ring mode a fast extracted, single intense ion bunch (see also Sec. 3.4) will be delivered to a thin target coupled to a new fragment separator (Super-FRS). The short bunch length is required in order to prevent the hydrodynamical expansion of the target material during the interaction time. If the target were to expand, its density would decrease drastically and a large fraction of the projectiles would penetrate the target with considerably fewer atomic and nuclear interactions. This would not only cause a substantial loss in the optimum production rate of exotic nuclei but also would result in an increased energy spread and thus transmission losses. The principal result of hydrodynamic simulation studies is that the duration of the extracted beam bunch must be 50 ns or shorter, a condition which is also required for fast debunching and successive stochastic cooling of the separated exotic nuclei in the subsequent fragment cooler storage ring (CR). The target has to be replaced after each high-intensity 50 ns pulse. A possible technical solution could be windowless liquid lithium target, a technology which is presently under investigation worldwide. After cooling in the CR the exotic beam will be accumulated in a electron cooler storage ring (NESR). This mode enables experiments with cooled, stored energetic exotic nuclei. In the fixed target mode after acceleration in SIS 100 the second synchrotron (SIS 200) is used to slowly extract the beam to the target for in-beam experiments with high energy fragment beams and for studies with stopped isotopes.

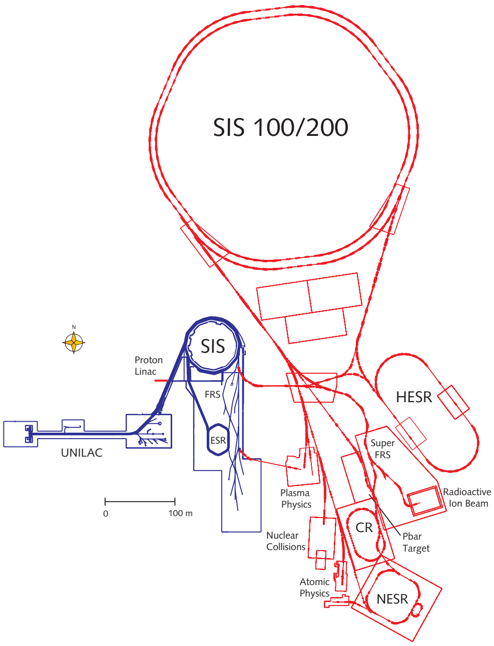

Figure 1: Schematic layout of the existing GSI facility (blue) together with the proposed upgrade (red).

2.2 *RIA*

The proposed RIA driver accelerator consists of an Electron-Cyclotron-Resonance (ECR) ion source and a short, normally conducting buncher-injector section which would feed the beam into an array of more than 400 superconducting (SC) cavities of six different types, ranging in frequency from 57.5 to 805 MHz [6]. The configuration as an array of independent-phased cavities provides the flexibility to accelerate all ions from protons to uranium with good efficiency. The array of short SC cavities also ensures large acceptances, opening the possibility of accelerated beams of multiple-charge states (see Sec. 3.2). The driver accelerator will deliver intense beams to two target areas (see Fig. 2). A thick ISOL-type target coupled to an ion source and a post-accelerator will provide isotopes from 0-12 MeV/u. A second target area will utilize a thin target coupled to a fragment separator (in-flight method) that can be operated in two modes. In one mode, after mass separation, exotic nuclei can be used directly as high energy beams for in-beam experiments. In the second mode the fast mass-separated exotic nuclei will be energy-degraded and then stopped in a gas catcher system where they are thermalized but remain singly charged and can be extracted by a combination of dc and rf fields to be further accelerated. This will provide high quality beams of short-lived isotopes or elements that are difficult to obtain from the standard ISOL target. The concept of stopping fast beams in a gas cell was demonstrated recently at ANL in a small system. A full scale prototype gas catcher system is under construction and will be tested at the full RIA energy at GSI [5]. For the post-acceleration of singly-charged radioactive ions a superconducting linac with a normal conducting injector is proposed.

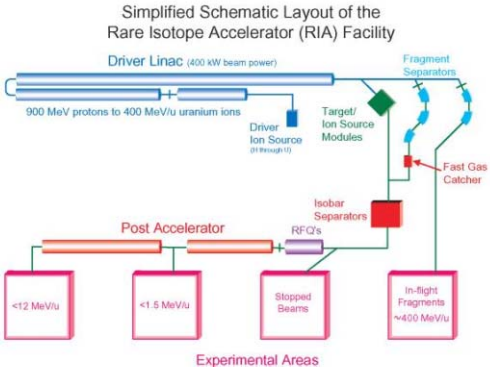

Figure 2: Schematic layout of the RIA facility.

3 ACCELERATOR DESIGN CHALLENGES

By increasing the driver output by more than an order of magnitude relative to the existing, successfully operating RIB facilities, several design challenges arise that are somewhat new to the field. In this section some important aspects concerning the design of a high intensity driver (linac or synchrotron) will be discussed. Besides the driver issues there are high power target design issues that are related to the increased driver intensity as well as instrumentation challenges (e.g. gas cell, fast cooling in storage rings) that will not be covered here.

3.1 *Loss Budget in a Heavy Ion Driver*

A major part of the design challenges in accelerator design for high intensity beams result from the low beam loss budget. The loss budget in high intensity proton drivers, e.g. for spallation neutron sources, is largely dominated by the requirement of 'hand-on maintenance': based on operational experience, hands-on maintenance (1-2 mSv/hour at 30 cm from the surface, 4 hours after shut-down) demands an average uncontrolled beam loss not exceeding about two Watts of beam power per tunnel-meter [8]. The activation induced by medium energy ($\lesssim$ 1 GeV/u) heavy ions impacting on materials like Iron can be assumed to be lower than for protons of similar velocity. Because of their large electronic stopping power per nucleon ($dE/dx \sim Z^2/A$) heavy ions deposit most of their energy in heat before nuclear reactions can become effective. Fig. 3 shows the electronic stopping power and the range of uranium ions in stainless steel calculated with the SRIM code [9]. The maximum of the electronic stopping power lies at 5.8 MeV/u (100 keV for protons). At 1 GeV/u the stopping power is reduced by a factor of seven only. The range of 1 GeV/u uranium ions in stainless steel is about 1 cm whereas the range for 1 GeV protons is about a meter.

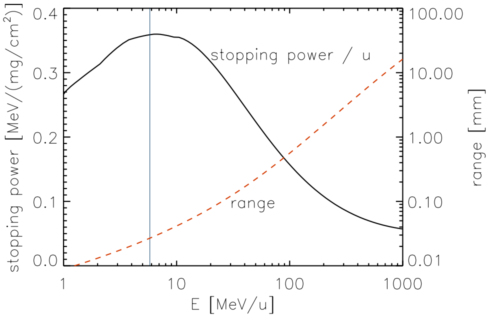

Figure 3: Stopping power per nucleon and range of uranium projectiles in stainless steel.

The influence of fragmentation on the stopping of heavy ions in matter decreases in heavier materials. Tracking simulations, including projectile fragmentation and electronic stopping of all fragments, show that the neutron yield per nucleon of 1 GeV/u Bi in Iron compared to a 1 GeV proton is reduced by more than a factor of 5 (Ref. [10]). At 400 MeV/u the difference in neutron yield is more than an order of magnitude. From these results one can estimate that the persistent activation induced by lost heavy ions is reduced by similar factors. Related GSI experiments on the activation induced by 1 GeV/u uranium beams impacting on different materials are still being analyzed. Besides activation two other beam loss induced effects must be considered in the total loss budget. Firstly, due to their large energy deposition, the impact of lost heavy ions on the vacuum chamber or on other components causes the desorption of a large number of neutrals (see Sec. 3.3). Secondly, the energy deposited by lost beam ions in or close to superconducting (SC) components can cause the magnet to quench or cause a non-reversible modification of the SC material. It is important to point out that depending on the material, each energetic ion hitting the beam pipe or other components can create a nanometric ion track consisting of extended defects and/or modified lattice structure (Ref. [11]). Concerning the quenching of SC magnets measurements at Fermilab indicated a tolerable energy deposition in the coils of about 1 mJ/g during short time intervals ($\lesssim$ 1 ms) and about 10 mW/g during dc operation (Ref. [12]). Assuming the density of copper (9 g/cm^3) and a distributed loss (1 GeV/u uranium) over a beam pipe surface (radius 1 cm) with 1 mm penetration depth (89^o grazing incidence) we arrive at 0.1 J/m for the short time limit and at 4 Watts per meter for the dc limit. The loss budget for the non-reversible degration of the SC material due to heavy ion bombardment over long times still needs to be estimated. From these very rough estimates one can easily see the importance of collimator concepts in combination with a low-loss machine design in order to reduce the beam loss in the SC sections to tolerable levels.

3.2 *Multi-Charge State Acceleration in a Linac*

For heavy ions beams such as uranium, where the present capability of ion sources is limited, and where multiple stripping is foreseen, multi-charge state acceleration can increase the output beam current. The simultaneous acceleration of five neighboring uranium charge states in the SC medium-β (10-80 MeV/u) section and three in the SC high-β (80-400 MeV/u) section is one of the key features of the proposed RIA driver linac. This becomes possible because the chosen high charge-to-mass ratio makes the synchronous phase offsets small and because of the high focusing gradients provided by the SC structures. A successful test of multi-charged (mean charge state 38^+) uranium beam acceleration was performed in the booster section of the ATLAS SC linac [13]. After stripping U^{26+} at 1.2 MeV/u all charge states where accelerated in the booster with a transmission of 94 %. The use of a multi-charged uranium beam increased the final intensity of the 6 MeV/u doubly stripped U^{51+} beam by 4 times. For the proposed RIA linac an increase in beam intensity by an order of magnitude is utilized. Here the tolerable relative beam loss (10^{-4} in the high-β section, or much less than 1 Watt per Meter) limits the charge state spread. Due to the low peak currents in cw operation space charge effects are reduced. Possible sources of emittance growth and beam loss are errors in rf fields and in the transverse focusing fields. Extensive particle simulations showed that the emittances through the whole SC linac remain well below the six-dimensional acceptance. Fig. 4 shows the simulation result for the five charge-state beam in the medium-β section (Ref. [7]).

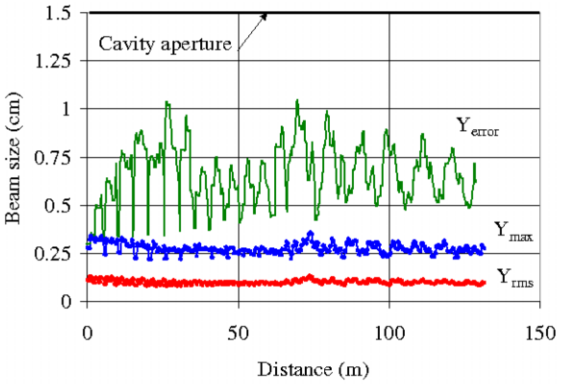

Figure 4: Five charge-state beam rms (Y_{rms}) and maximum (Y_{max}) sizes in vertical plane along the medium-β linac. Red curve is the rms beam envelope, blue curve is the beam maximum envelope. The green curve (Y_{err}) is the maximum beam size at given z due to misalignments obtained from 200 random seeds of the linac.

3.3 *Beam Lifetime and Dynamic Pressure*

Because of the limits imposed by machine cycling rates or by low injector currents synchrotron drivers for heavy ion beams require intermediate beam accumulation steps. For example the GSI scenario requires 1 s accumulation time at 100 MeV/u and for the LHC Lead ion program 3 s accumulation time in LEIR for 10^9 Pb^{54+} ions at 4.2 MeV/u are foreseen [14]. For injection at low/medium beam energies partially stripped heavy ions are prefered in order to increase the maximum number of ions in the ring for a given space charge limit. Partially stripped ions have the disadvantage of a relatively short lifetime due to electron stripping or resonant capture processes in the residual gas, causing beam loss under grazing incidence at the inner (stripping) or outer (capture) parts of the vacuum chamber. Collimation of these losses, e.g. to shield SC magnets, would require several collimators in each period. If we consider U^{28+} at 100 MeV/u the stripping cross section in collisions with Argon is of the order of 10^{-17} cm^2 (Ref. [15]). In order to achieve a lifetime of 100 s (for less than 1 % loss after 1 s) a Argon pressure below $2 \cdot 10^{-12}$ mbar during the accumulation time would be required. The experience gained at LEAR has shown that maintaining the static design pressure in the presence of a partially stripped heavy ion beam represents a major challenge to present vacuum technology. Each beam ion lost at the vacuum chamber releases a large number of neutrals (mostly CO and CO_2) from the surface. In LEAR desorption coefficients exceeding 10^4 have been measured for the impact of 4.2 MeV/u Pb^{54+} ions on stainless steel beam pipes. The resulting fast increase in the residual gas pressure ('pressure bumps') strongly reduces the beam lifetime. Similar observations were recently made in the SIS at GSI with U^{28+} beams at 11.4 MeV/u [17] and also earlier in the BNL AGS booster with low energy partially stripped Gold ions [18]. Above a threshold beam current that depends on the desorption yield, pumping speed and conductances, the amplification of pressure bumps can lead to major beam loss. An intensive experimental program at CERN came to the conclusion that various coatings and cleaning techniques cannot reduce the desorption coefficients sufficiently, but linear pumping by NEG (Non-Evaporable Getters) stripes over the whole machine can improve the dynamical pressure by more than an order of magnitude [16]. In addition beam scrubbing was pointed out as a possible low-cost cure for LEIR. Still this has to be confirmed in the real machine. Other ideas, that might be more suitable for high beam intensities, consider combined collimator/pumping ports for the localized removal of beam loss induced neutrals [19]. If for intense medium energy heavy ions in a cryogenic vacuum system with cold walls (like in the cold sections of the proposed SIS 100/200) the dynamic pressure can be reduced by the very efficient cryopumping needs to be investigated. For fully stripped heavy ions or at high beam energies, like e.g. during slow extraction, the beam loss rate due to inelastic collisions in the rest gas decreases. In this case the dynamic pressure can still be strongly affected by beam ionized residual gas components that are accelerated towards the vacuum chamber in the beam potential and by electron multipacting. The recently observed dramatic pressure bumps (up to five orders of magnitude) in RHIC (operating with fully stripped 8.6 GeV/u Gold beams) were related to the the combined effect of residual gas ions and electron multipacting [20].

3.4 *Intense Bunch Generation in a Synchrotron*

Beam fragmentation followed by fast debunching and cooling of the RIB in a storage ring requires a single, short ($\lesssim$ 50 ns) and intense (10^{12} ppp) heavy ion beam at energies $\gtrsim$ 1 GeV/u on the target. Because of the large space charge induced betatron tune shifts the generation and handling of the intense bunch (TW peak power) in a synchrotron and in the beam lines to the target represents a major challenge to high current machine design and operation. In order to minimize the dwelling time in the extreme space charge regime, the compression must be done as fast as possible. Therefore the non-adiabatic fast bunch rotation is the method of choice for the generation of intense medium energy bunches. In the proposed GSI SIS 100 synchrotron the required average field gradient for U^{28+} bunch compression is of the order of 1 kV/m. Even with the very compact magnetic alloy loaded cavity design (40 kV per gap, 50 kV/m, 0.8-1.2 MHz) presently under development at GSI (see Ref. [21]) a few percent of the ring will be occupied by rf compressor modules. During the fast (0.1 ms or 100 turns) bunch compression the incoherent space charge tune shift in SIS 100 will reach a $|\Delta Q|$ close to unity, much larger than the limiting $|\Delta Q|$ of 0.3-0.5 in conventional synchrotrons. In a bunch compression experiment with 1 GeV protons in the CERN PS for about 20 machine turns (40 μs) a $|\Delta Q|$ close to unity was already achieved [22]. The measured emittance blow-up during the compression was 30-50 %. This result shows that in an optimized machine large tune shifts can be tolerated with tolerable emittance blow-up. In order to identify the optimum machine design and working point for minimum blow-up and tolerable beam loss (e.g. much less than 1 J/m in SC magnets) self-consistent tracking simulations with 1M macro-particles are performed at GSI. Presently these simulation studies focus on the planed fast bunch compression experiments with intense uranium beams in the existing SIS [23]. In these experiments space charge parameters (final $|\Delta Q|$ close to 0.7) similar to SIS 100 will be reached. Simulations (see Fig. 5) for SIS show that during resonance crossing particles trapped in islands can be expelled from the beam core. However, all simulation particles remain well within the SIS machine apertures.

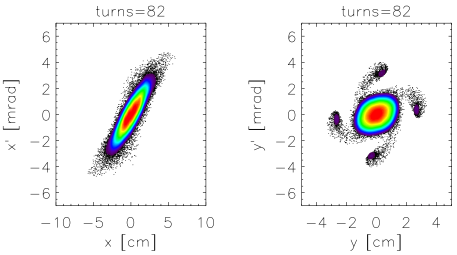

Figure 5: Simulation of fast bunch compression in SIS. Resulting particle distribution at the end of compression.

4 CONCLUSIONS

Accelerator design challenges for a next generation inflight facility arise from the tolerable relative beam loss in a heavy ion driver (RIA, GSI) together with novel multiple charge state operation (RIA), long accumulation or extraction times with intense partially stripped heavy ions (GSI) and short-term operation outside the space charge limit (GSI). The proposed RIA cw linac driver has the strong advantage of reduced space charge effects and reduced target heating relative to a pulsed driver. Nevertheless, the lower output energy, as compared to the NuPECC recommendations, must be compensated by an order of magnitude higher output intensity, that requires simultaneous acceleration of multiple charge states. Besides the simulations, operating a complex SC high energy driver within the low loss budget in this novel mode still represents a major challenge. With a synchrotron driver solution, as proposed by GSI, energies exceeding 1 GeV/u for uranium beams can be reached. For the filling of storage rings with short-lived RIBs a synchrotron driver is the optimum choice. However, accumulation, acceleration and compression into a single bunch of the required more than 10^{12} uranium ions in a chain of synchrotrons exceeds the present demonstrated capability of the existing GSI facility by more than an order of magnitude. The space charge limit requires operation with medium-charge state uranium, that has high stripping cross sections. The experience gained at LEAR and RHIC shows that strong problems with beam loss induced pressure bumps occur already at relatively low beam currents, making the control of the dynamic vacuum pressure together with a distributed collimation concept for stripping and space charge induced losses an essential point for the design of the proposed two synchrotrons.

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