DESIGN OF THE DRIVER LINAC FOR THE RARE ISOTOPE ACCELERATOR *

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Abstract

The proposed design of the Rare Isotope Accelerator (RIA) driver linac is a cw, fully superconducting, 1.4 GV linac capable of accelerating uranium ions up to 400 MeV/u and protons to 1 GeV with 400 kW beam power. An extensive research and development effort has resolved many technical issues related to the construction of the driver linac and other systems of the RIA facility. In particular, record intensities of heavy ion beams have been demonstrated with the ECR ion source VENUS at LBNL, the driver front end systems including two-charge-state Low Energy Beam Transport (LEBT) and RFQ are being tested, and a set of SC accelerating structures to cover velocity range from 0.02c to 0.7c have been developed and prototyped. Newly developed high-performance SC cavities will provide the required voltage for the driver linac using 300 cavities designed for six different geometrical betas.

INTRODUCTION

The study of the properties and reactions of short-lived isotopes is a key to our understanding of fundamental questions in nuclear physics, nuclear astrophysics and the study of fundamental interactions at low-energy. This has long been recognized by the international nuclear physics community and is reflected by the investments in that field that have been or are being made in North America, Europe, and Asia. The US nuclear physics community addressed the importance of such studies in its 2002 Long Range Plan [1] where RIA is identified as its highest priority for new construction.

RIA is a powerful combination of technologies that will enable great advancements in this science. Some of the factors contributing to the enhanced capabilities are:

- Use of a variety of production techniques for short-lived isotopes including new approaches that remove the main previous limitations of standard ISOL techniques.
- A powerful superconducting driver linac capable of accelerating any stable ion from protons to uranium and designed to allow simultaneous acceleration of multiple charge states of a given ion to attain unprecedented power for the heaviest ions.
- A very efficient post-acceleration scheme based on a superconducting linac injected by low frequency RFQs capable of accelerating singly charged radioactive ions of mass up to 240 amu from ion source energy.
- State-of-the-art experimental equipment and multiple user capability to maximize the use of the facility.

UPDATES OF THE RIA DRIVER LINAC

At the previous Workshop HB-2004 we reported the design status of the RIA driver linac [2]. The on-going R&D and prototyping [3-8] have demonstrated that the following concepts can be implemented into the linac design:

- Charge states of uranium beam from the ECR are 34+ and 35+.
- The RFQ provides higher energy beams of 250 keV/u.
- The driver linac uses two types of triple spoke cavities above 60 MeV/u.
- Superconducting half-wave and spoke-loaded cavities developed to cover the velocity range required for the RIA driver have consistently operated cw at peak surface fields of 28 MV/m.

Updating the RIA driver design using the above parameters, reduces the cost of the driver linac by reducing: a) the total number of cavities to 300, b) the cryogenic load (as a consequence of using higher-performance SC resonators), and c) the linac length.

The linac design has been optimized for the simultaneous acceleration of a two-charge-state (34+ and 35+) uranium beam in the front-end and the first section of the linac up to the first stripper, a five-charge-states beam (average charge state 76+) between the two strippers ,and a five-charge-state beam (average 89+) in the high-β section. As in the original design, the driver linac is capable of accelerating any ion from hydrogen to uranium to a final energy of 1 GeV to 400 MeV/u respectively. More detailed linac parameters are discussed in the following section.

RIA RELATED R&D

High-intensity ECR ion source

The electron cyclotron resonance (ECR) ion source for nuclear science (VENUS) project at LBNL [6] was started in 1997 with the development of the superconducting structure, cryostat, 18 GHz and 28 GHz microwave power sources. The project has been focused on the production of 200 eμA of U^{28+} to U^{30+} beams. For these intense heavy ion beams the present RIA R&D program also focuses onto the development of advanced simulation tools for the transport of intense heavy-ion beams [7] which is challenging due to the significant space-charge forces. Recently, after the installation of the 28 GHz gyrotron and waveguide system, the source was tested with bismuth beam [8]. Figure 1 shows mass-scan of bismuth beam in two regimes of VENUS: the ion source is tuned to deliver I) the highest beam intensity at optimized q/m= 0.1244 and II) the highest beam intensity at slightly higher q/m=0.139. Obviously, to save the cost of the accelerator

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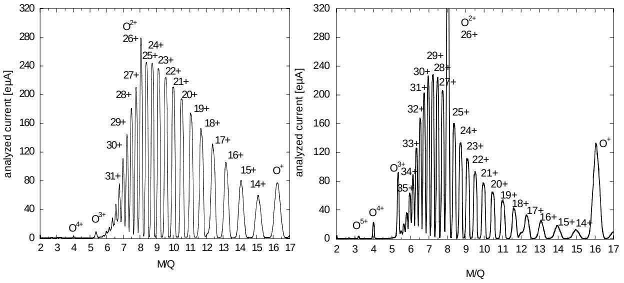

Figure 1: Mass analysis of bismuth beam produced by VENUS optimized for the maximum current (on the left) and for the higher charge state (on the right).

it is desirable to increase a q/m-ratio. The performance of VENUS with bismuth beam exceeds the RIA driver specifications. Based on this performance, we project adequate intensity for uranium beams of charge states 34 and 35+. Note, however, that such uranium beam performance has yet to be demonstrated.

Multiple charge state injector

The design goal of 400 kW uranium beam from the driver linac can be achieved employing a concept of simultaneous acceleration of several charge states. To demonstrate this concept, we are developing a prototype of the injector system for the RIA driver which includes a permanent magnet (PM) ECR ion source installed on a high voltage (HV) deck, a LEBT and one-segment of the prototype RFQ. Unlike all other ECR ion sources being operated worldwide where the HV platform voltage is applied after selecting a specified q/m, in the RIA driver injector all ion species from the ECR source are accelerated by the platform voltage and the analysis and selection of appropriate ion charge states take place in the following magnetic bending system. The HV platform has been constructed using de-commissioned 300 kV, 100 kW isolation transformer and Faraday cage available from previous accelerator projects. At present the injector system allows us to accelerate all ion species up to 100 keV total kinetic energy. The accelerating tube is followed by a 90° magnet and an emittance measurement station. The ECR source is being upgraded with an additional TWT rf amplifier operating at 14 GHz and an oven for production of heavy metal ions. The design and construction of the achromatic bending system (see Figure 2) is in progress [9].

Detailed emittance measurements of various ion species produced by the PM ECR have been made. Analysis of the measurements verifies that the ECR source forms a beam in which neighboring charge states have similar phase space distributions, This is an important property required to enable the simultaneous acceleration of two charge states as called for in the RIA driver design. Typical emittances for each charge state in a 15 eμA lead ion beam are shown in Figure 3. In parallel with the experimental work, numerical studies of beam dynamics in the ECR extraction area and LEBT are being performed using the multi-particle simulation code TRACK [10,11].

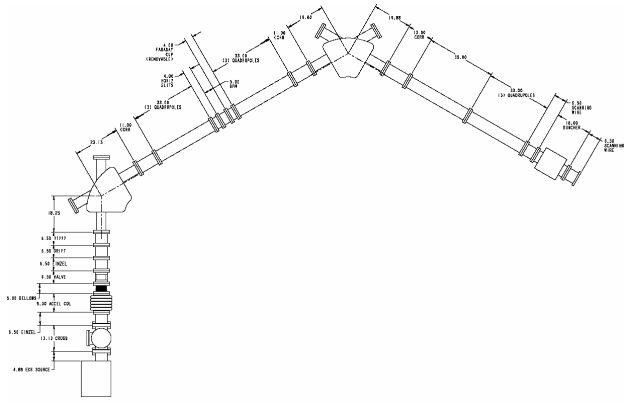

Figure 2: Schematic layout of the ECR and LEBT.

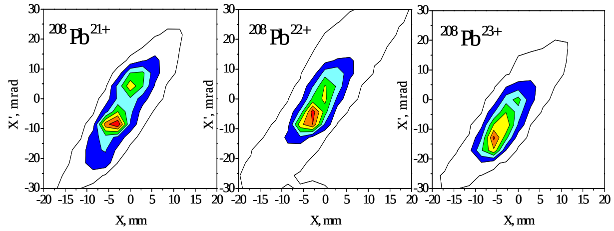

Figure 3: Horizontal emittances of the lead ion beam for three different charge states.

The two charge state heavy-ion beam will be combined downstream of the achromatic bending system, which is followed by a multi-harmonic buncher (MHB), and a 57.5 MHz RFQ.

The initial acceleration of heavy-ion beams in the driver linac will be provided by a four-meter long room temperature RFQ. The proposed accelerating structure for the CW 57.5 MHz RFQ provides high shunt-impedance, has extremely good mode separation, moderate transverse dimensions of ~49 cm, and high quality accelerating-focusing fields required for simultaneous acceleration of multiple charge state ion beams [12]. An engineering prototype of a 70-cm long segment of the high power RFQ has been developed and built. High-temperature furnace-brazed OFE-copper cavities have proven to be very reliable for acceleration of beams in CW regime, so this technology has been chosen for the RFQ prototype. The fabrication and brazing of the one-segment RFQ prototype cavity was successfully completed in 2005. Final CMM measurements after brazing show the vane tip position error to be less than 0.002″, well within design tolerance.

The cavity's unloaded quality factor was measured to be 8700 which is 93% of the value obtained from numerical simulations by the MWS and HFSS codes. The high power tests show stable cw operation of the RFQ at an inter-vane voltage 75 kV which is higher than the design voltage by 10%. The voltage is currently limited by available rf power. The voltage calibration has been performed using the X-ray cut-off method. The general view of the RFQ is shown in Figure 4.

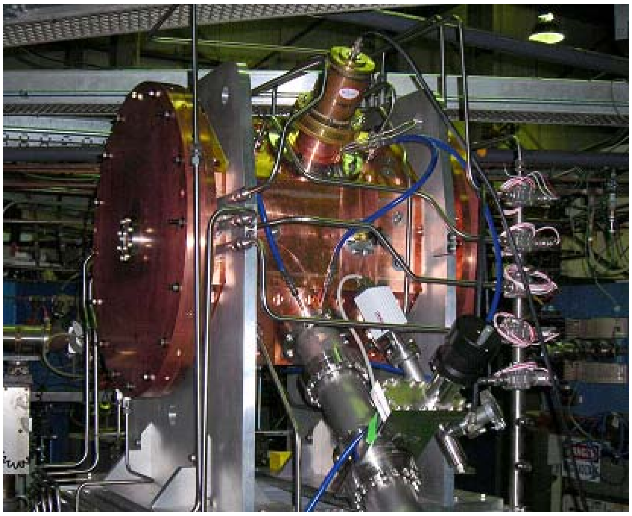

Figure 4: General view of the RFQ.

Superconducting accelerating structures

The Physics Division of ANL has an extended experience in the development and application of SCRF technology for heavy-ion beam acceleration. Owing to appreciable support from DOE and Laboratory Director, the SCRF technology has been substantially improved and four new types of SC cavities have been developed to cover the velocity range from 0.1c to 0.8c (shown in Figure 5 in multiple colors). The cavities shown in blue in Fiture 5 are similar to resonators which have been used for many years in existing SC ion linacs, such as ATLAS [13]. All types of cavities are fully developed, and ready for production.

The following main procedures have been applied for the construction of new generation high-performance SC cavities:

- Cavities are formed of 3 mm, high-purity (RRR=250) niobium sheet.
- Stainless steel is used for the helium jacket (based on ANL-developed niobium-SS braze using pure copper).
- Electropolished SC surfaces.
- Assembly by electron-beam welding.
- Light BCP after final assembly.
- Designed to employ TESLA-type high-pressure-water rinse and clean-assembly techniques.
- 600°C hydrogen degassing prior to final tests.

Prototypes for the full suite of cavities have established new performance levels for TEM-class cavities. In the most recent tests, the β_G =0.62 prototype triple-spoke cavity was operated cw,at peak surface electric fields of more than 27.5 MV/m, the nominal RIA design goal, with less than 10 watts of input power to 1.9K [14,15]. We note that in terms of voltage per cavity and refrigeration load per MV, the spoke cavities exceed the performance of elliptical cell cavities developed for this velocity range. As an example, the quality factor as a function of the accelerating field for the β_G =0.62 prototype triple-spoke cavity is shown in Figure 6.

Because of the relatively small beam-loading of the RIA driver linac, the mechanical stability and micro phonic behavior of the SC cavities are particularly critical. The mechanical properties of the prototype triple spoke cavities are excellent, and microphonic phase-noise under realistic operating conditions is sufficiently small, ~1 Hz rms, to be easily controllable [16]. Table 1 shows the basic parameters of the driver linac SC cavities.

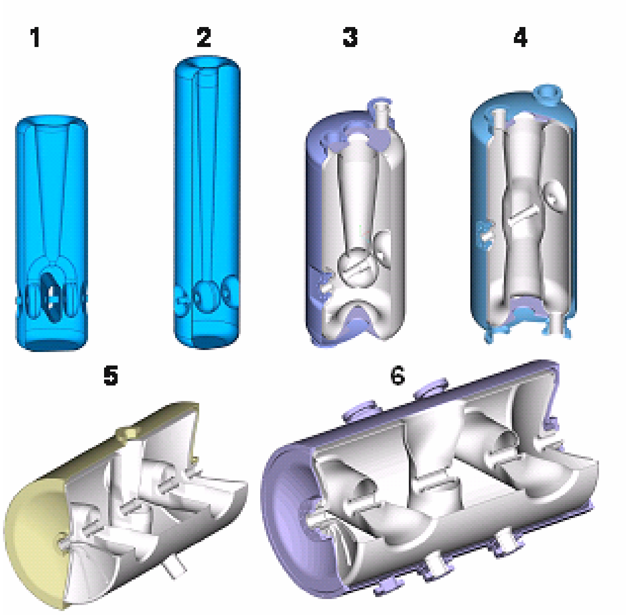

Figure 5: Six types of SC cavities developed for the RIA driver linac.

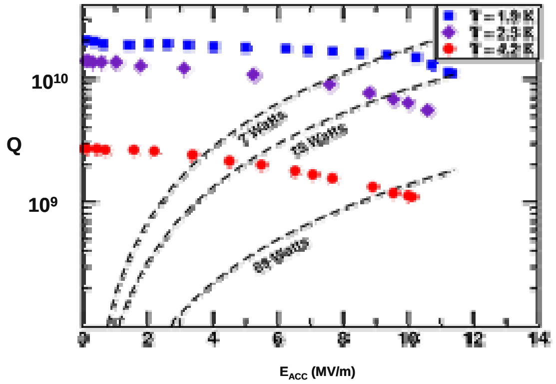

Figure 6: Cavity quality factor as a function of the accelerating field taken at three helium temperatures.

Table 1: Basic parameters of SC cavities. The numbers in the first column corresponds to the numbers in Figure 5.

	Type	f (MHz)	Beta	V (MV)	Cav #
1	FORK	57.5	0.031	1.0	3
2	QWR	57.5	0.061	1.7	21
3	QWR	115.0	0.151	2.0	40
4	HWR	172.5	0.263	2.6	72
5	TSR	345.0	0.500	6.2	64
6	TSR	345.0	0.620	7.5	100

Beam dynamics and linac optimization

Massively-parallel computer end-to-end beam simulations, including machine errors, have been performed for the new baseline design of the driver linac in order to investigate possible beam losses and determine the exact location of these losses as caused by various machine errors. The details of the simulation technique have been reported recently [10,17].

In a heavy-ion linac, major sources of particle loss are field errors and misalignments of machine elements, as discussed in [10]. For heavy ions requiring stripping, another important source of error is fluctuations in the thickness of the stripper foil or film. Errors are of two types: static and dynamic. Misalignments of accelerator elements are considered as static errors. Jitter of RF and focusing fields are examples of dynamic errors. Setting of the phase and amplitude of the accelerating cavities to a non-optimum profile when first tuning the accelerator or when restoring a tune is also a source of static errors.

In the presence of misalignments and static rf errors, multiple-charge-state beams in the driver linac require corrective steering and energy correction in order to avoid emittance growth and to minimize beam losses. To achieve effective steering and energy correction for the whole linac, the latter is divided into 10-15 short sections to each of which a steering algorithm is applied. A minimization algorithm has been developed that can correct static errors both in the four-dimensional transverse phase space and the longitudinal phase space. The correction of rf static errors is performed by measuring beam energy at the end of the sections and adjustment of accelerating field level in several cavities upstream of the virtual energy measurement device. The algorithm has been fully integrated into the code TRACK [11]. The details of the method related to the correction algorithm in transverse planes can be found in ref. [18]. In addition, we have developed automatic tuning procedure for multiple-charge-state beams [19].

The beam-based steering and energy correction algorithm is applied to every randomly generated accelerator seed to determine the steering correctors setting and adjusted cavity fields along the whole linac for the given set of the element misalignments and static rf errors. The final tracking of large number of particles occurs in the misaligned accelerator with corrective steering applied. Note that without corrective steering a major fraction of the beam would be lost. .

The eventual goal of our simulations is to establish tolerances for dynamic and static rf errors for the driver linac. These tolerances are defined by the level of uncontrolled losses in high-beta section of the linac that must be less than 1 W/m. In simulations we apply all of the errors simultaneously and study the beam dynamics and the eventual beam losses.

The thickness fluctuation of the stripping foils has been assumed to be 10% at FWHM. Misalignment errors have the same values as in ref. [10, 17] and are kept unchanged in each calculation. The accelerator was simulated using 200 sets of errors for each combination. For each set, $2{\cdot}10^5$ particles are tracked for a total of 40 million particles.

The results of these studies are summarized in Figure 7 which shows that the driver linac tolerances for static and dynamic errors of RF field amplitude have large margins compared to the practical values observed in recently built SC linacs [20]. We conclude, that the proposed design of the driver linac based on spoke resonators in the high energy section is a robust design and much less critical with respect to overall beam tuning and component failures than the other design options for this linac so far presented.

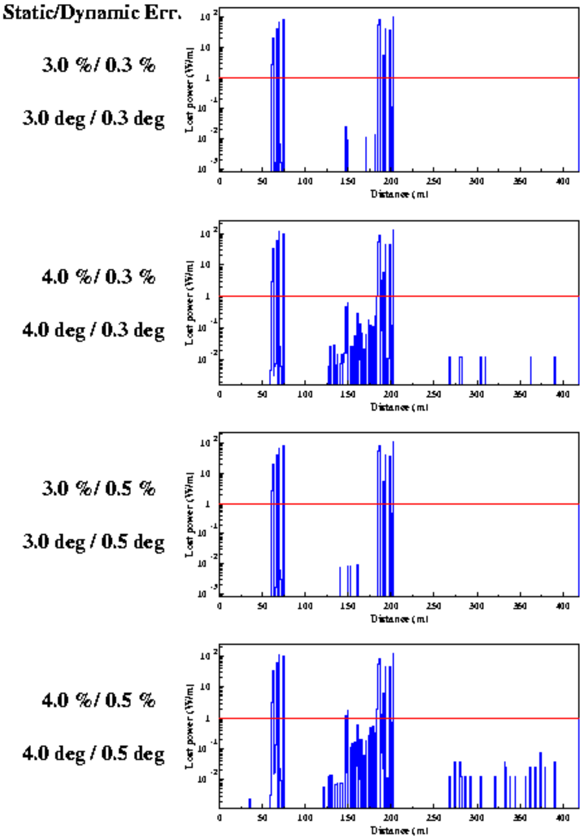

Figure 7: Beam power lost along the linac in Watts/m for different RF static and jitter error combinations. The horizontal line shows the 1 Watts/m limit to not exceed for hands-on maintenance. The first two clusters of losses on each plot correspond to the losses at the two strippers, which are controlled.

ADVANCED EXOTIC BEAM LABORATORY

Recently, it was recognized that the construction of the RIA facility should be staged due to funding reasons. We are currently looking at alternatives for staging the facility to reduce the initial cost by about a factor of two. A possibility for the first stage includes ~850 MV driver linac to deliver uranium beams at 200 MeV/u and protons at 570 MeV. Thanks to successful tests of the front end systems, 400 kW beams can be obtained with increased intensities of heavy-ion beams from the ECR and higher rf power in the linac even at the first stage of the facility.

As envisioned at ANL, the facility, named Advanced Exotic Beam Laboratory (AEBL), would consist of an 850 MV driver linac, a post-accelerator and experimental areas with upgradeable capabilities to the full-size RIA. As compared to the full-size RIA, AEBL will have the following features:

- The driver linac comprises 220 SC cavities and uses the array of developed SRF cavities. The elimination of 80 cavities in the high energy section of the RIA driver reduces the cryogenic load by a factor of two.
- For most isotopes, reaccelerated beam intensities are comparable to RIA, in the worst cases intensities are lower by 10-20%.
- The high resolution in-flight separator, large in-flight experimental area and most of the in-flight experimental equipment will be available as an upgrade option of AEBL.
- The fragment separator for the gas cell will be in the baseline of AEBL and limited in-flight experiments will be offered.
- The number of ISOL target stations reduced to two.
- Smaller astrophysics and reaccelerated beam experimental areas.
- Smaller support space for labs and offices.
- Limited multi-user capability.

Preliminary design analysis suggests that a 200 MeV/u linac should have only one stripper station. Although the one-stripper option increases the required number of SC cavities, the complex second stripper station and post-stripper magnet elements are eliminated. The basic parameters of the AEBL driver linac are shown in Table 2. The linac has been optimized for simultaneous acceleration of U^{28+} and U^{29+} in the front-end and the first section of the linac up to the stripper. However, recent progress demonstrated by the VENUS suggests that the uranium charge states may be higher, which could further reduce the required number of SC cavities.

Table 2: Basic parameters of the AEBL driver linac.

Type	f (MHz)	Beta	V (MV)	# of Cav
FORK	57.5	0.031	1.0	5
QWR	57.5	0.061	1.9	22
QWR	115.0	0.151	2.2	56
HWR	172.5	0.263	2.8	34
2SPOKE	345.0	0.400	3.7	32
3SPOKE	345.0	0.500	6.2	52
3SPOKE	345.0	0.620	7.5	20

CONCLUSION

The design of the RIA and AEBL facility is well advanced and ready for the engineering design and following construction. Meanwhile the on-going R&D and prototyping will:

- Reduce the facility construction risk by making the design more robust;
- Reduce the construction cost and improve performance by prototyping critical components;
- Extend scientific reach by improved production and collection of rare isotopes.

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