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REPORT FROM WORKING GROUP 1 — ION SOURCES AND SEPARATORS

GROUP LEADER: HERMANN WOLLNIK

Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

REPORTER: JOSE R. ALONSO

Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

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This Working Group concentrated on issues associated with ion sources and separators, summarizing both the state of the art in these areas as well as needs and requirements for first stages of the ISL post-accelerator. This report is divided into three sections: a summary of presentations made to the Working Group, a comparison of ion source technologies, and a discussion of front-end configuration issues. A concluding section summarizes key design issues novel to the ISL application, and points out areas where technology development is required.

KEY WORDS: Radioactive beams, ion sources, mass separators, ion spectrometers

1 PRESENTATIONS

1.1 G. Alton (ORNL)

Alton presented work currently underway for the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory (ORNL) (cf separate contribution in these proceedings). The central region of the ORIC cyclotron is being modified to optimize the generation, acceleration, and extraction of light ions (^{1}H, ^{2}H, ^{3}He and ^{4}He) from the machine which will be used to produce radioactive species in a thick target, close-coupled to an ISOL target/ion source located on a high-voltage platform. The platform will serve as a second injector for the 25-MV tandem accelerator. For optimum production, primary beam energies of 10 to 70 MeV will be utilized. In order to avoid excessive activation of the cyclotron and beam transport system to the target/ion source, beam intensities and beam power will be limited to $\approx$100 μA and 2 kW, respectively. Because of the low energies available from the ORIC, fusion-type reactions will dominate; therefore, the target materials must be carefully selected to optimally generate the radioactive species of interest. For example, CeS or ThS are candidate target materials for generating ^{32}Cl$^-$ and ^{33}Cl$^-$ radioactive beams (RIBs) produced in the respective reactions, ^{32}S(p,n)^{32}Cl and ^{32}S(d,n)^{33}Cl.

A CERN ISOLDE-type, high-temperature, electron-impact ionization source has been designed, fabricated, and is presently being evaluated for initial use for generation of radioactive ion beams of elements with low electron affinities. Because of the necessity of injecting negative ion beams into the 25-MV tandem for post-acceleration, positive-ion beams from this source must be converted to negative-ion beams through charge exchange. A complementary negative-surface ionization source has been designed for direct generation of negative-ion beams from elements with high electron affinities (e.g., the halogens [F, Cl, Br, I and At]); this source will be a direct replacement for the CERN ISOLDE-type electron-impact ionization source; negative ions will be formed by thermal evaporation from a low-work-function LaB_6 surface which will be maintained at 1100°C. A heat sink will be placed between the target and the ionizing surface which will be maintained at a temperature high enough to allow transmission to the ionizing surface, but low enough to condense less volatile components which otherwise would poison the LaB_6 ionizer.

In order to minimize the diffusion release times, it is desirable to heat the target to high temperatures (up to 2000°C, for example); selection of wall materials with low enthalpy values is also desirable to minimize hold-up times due to surface adsorption between the target and ionization chamber of the source. Attempts will be made to reduce the hold-up times of species during transport from the target to the ionization chamber of the source by coating all surfaces that will be exposed to the vapor with Ir. Experiments are planned which are designed to determine the effectiveness of this concept.

Ion beams will be extracted from the source at energies up to 50 keV and momentum analyzed in a split-pole, homogeneous-sector, magnetic-field isotope separator with a bending angle of 151 degrees and a bending radius of 0.56 m; the isotope separator is expected to have a nominal resolution of 800 and a maximum resolution of 2000. When positive-ion sources are used, the extraction energy is chosen to optimize charge-exchange reactions in Cs or Rb vapor following momentum analysis. After momentum analysis, all ion beams will be post-accelerated to energies up to 300 keV for injection into the 25-MV tandem accelerator.

The overall performance of the system, in terms of ionization efficiencies, beam emittances of the sources considered, and beam transport from ion source to the tandem accelerator, should be as good as or better than state of the art. The HRIBF is scheduled for first testing of ORIC and all equipment located on the high-voltage platform in April 1994; in these tests, low-intensity RIBs will be produced with proton beams in the target ion source, momentum analyzed, and post-accelerated to the 300 keV injection energy. The HRIBF is scheduled for commissioning in April 1995, at which time the experimental program will be initiated.

1.2 K-N. Leung (LBL)

Leung presented his ion source design as a possible candidate for radioactive beam production systems. The Multi-Cusp (bucket) source offers many potential advantages in this application: good ionization efficiency, wide range of operating temperatures (>1500°C if needed), good emittance and low noise, flexible geometry, good lifetime and reliability of operation. It operates over a wide range of gas pressures, can be configured for either positive or negative ion production, and can be optimized for high yield of higher charge states (2+ or 3+). Although the source has found wide acceptance in the conventional accelerator community, some questions related to specific needs of the RIB application must be answered: absolute efficiency of conversion of material from the target into a beam of the desired charge state; hold-up times in the source; specific materials and design questions relevant for operation in the high radiation fields (protection of the permanent magnets, wall-liner material, filament material or rf-electrode coating).

1.3 M. Nitschke (LBL)

Nitschke presented a concept for a wide-band separator system called BRAMA (Broad Range Atomic Mass Analyzer). (c.f. separate contribution to these proceedings.) This device would considerably improve the overall efficiency of a radioactive beams facility by making use of the diversity of reaction products generated simultaneously from spallation and fission targets. These reaction products are transported to the source and ionized with little selectivity, so the beam produced consists of many atomic and isotopic species. Typical separator systems must be tuned for transmission of a single species, most of the others are lost. The BRAMA concept, based on an Elbek-type spectrometer, would provide an extensive focal plane allowing the separation of different q/A constituents along this focal plane that could then be tapped off for specific applications. Specifically, several experimental ports could be serviced simultaneously. Feasibility studies indicate such a scheme could be employed for bombarding a radioactive target (atoms accumulated at one site of the spectrometer) with a radioactive beam (extracted and accelerated from another site). (E.g. for 10^{10} ions/sec at each channel, beam and target sizes of 1 mm^2, a target lifetime of 1000 seconds and a reaction cross section of 100 mb, the reaction rate will be 1/sec.) Another application could be the dedication of "unused" ports to constantly monitor and provide tuning information for the spectrometer. Such a concept would operate most efficiently with a "universal" (plasma) source capable of delivering the maximum number of reaction products as ions to the spectrometer entrance.

2 ION SOURCE TECHNOLOGIES

Reference was made to Kirchner's excellent review in these proceedings of the different ion sources available for radioactive beam applications. The Working Group spent considerable time analyzing the performance of several of these sources, with specific reference to beam quality produced, and matching to a high-quality separator. Resolving power for such a device contemplated for RIB research could be as high as 30,000, but to achieve this value requires very high-quality incident beams. The energy spread of the beams (characterized as the ion temperature in the source) should be below about 0.5 eV, if no additional energy-compensating stage is used, i.e. a large electrostatic sector field. The unnormalized emittance of the beam entering the spectrometer should be below 2π mm-mrad. Table 1 summarizes the consensus of opinion on the achievable performances of different source technologies.

TABLE 1: Ion Source Inter-comparisons (at 30 kV extraction potential)

Source Type	ε π mm-mrad	M amu	ΔE eV	ε_n π mm-mrad
ECR	100	40	(5–10)*q	.15
FEBIAD	<10	84	<5	≈.01
Hot Cavity Ionizer	<2	40	.4	<.01
Surface Ionizer (+)	<2	40	.2	<.01
Surface Ionizer (-)	<2	40	.2	<.01
Cusp	1	40	2–3	<.01
Laser	?	?	?	?

Notes:

All sources have respectably low emittances, though achieved ECR performance is notably inferior. Optimization of this source could improve its usefulness for RIB applications. Such improvements seem feasible since so far ECR ion source developments have focused on maximum output of highly charged ions, optimization for small energy spread has received little attention.

Performance figures are given for one set of parameters (extraction potential, mass); optimization for other masses and experimental configurations will undoubtedly yield somewhat different values.

Ion energy spreads are lowest for the cavity and surface ionizers, these would perhaps be the best sources to interface with a very-high resolution separator.

Not enough is known about laser source performance now to make a meaningful comparison with other technologies.

It should be noted that optimization of source performance for radioactive beams applications will emphasize parameters quite different from other, more conventional applications. While low emittance and energy spread are of course important, overall efficiency of ionization from neutral atom to a single charge state, very short hold-up times and ability to operate at high temperatures in a highly radioactive environment are of critical importance.

Maximizing radioactive beam current requires delivering at the high-energy end of the post-accelerator the highest possible fraction of the selected ions. Highest efficiency is obtained if all the radioactive atoms can be converted in the source into ions of a unique charge state. The best case is expected for ions of charge-state 1. The sources described elsewhere in these proceedings have in fact very high atom-to-ion conversion efficiencies for singly-charged ions. However, this leads to limited ion energies and a complex post-accelerator design because of the extreme rigidity of the ions. Cost optimization usually calls for one or two stripping stages to increase the charge state of the ion during the acceleration process. Each of these stages, if conventional stripping foils are used, is accompanied with a significant dilution of beam purity (hence to beam loss) owing to the distribution of charge states emerging from the foil. The problem is particularly pronounced for the heaviest elements: for masses greater than about 100 one should not expect more than 15%

of the beam to emerge in the most-probable charge state. Thus for such ions, each stripping station entails a loss of a factor of 7, or about a net efficiency of 2% transmission through an accelerator system with two strippers. The problem is not so severe for lighter ions with narrower distributions, but it still significantly affects the overall transmission efficiency. Several ways exist for maximizing efficiency: the use of a charge-state "enforcer" ring (cf separate contribution in these proceedings) that keeps passing the beam through the stripper on each pass through the ring, extracting from the ring only those ions in the "right" charge state; design of linac sections that can accelerate more than one charge state (experience at the SuperHILAC has shown this to be difficult because of significant phase-space dilution and emittance growth of the beam); or the use of a high-efficiency, very high-charge-state ion source. An example of the latter would be an ECR source from which ions might emerge with sufficiently high q/A ratios (q/A $\approx\geq$ 0.2) that postacceleration could be accomplished without stripping. Achieving suitable efficiency (from incoming atom to ion in a unique, and very high charge state) from such a source is an interesting problem.

3 FRONT-END CONFIGURATION ISSUES

Another difference between a RIB facility and a conventional accelerator configuration is that in the latter the ion source is normally very tightly coupled to the first stage of rf acceleration, to increase the ion velocity as quickly as possible to minimize transport and space-charge problems. However, because of the "universal" nature of the ion sources to be employed in the radioactive ion beam application, efficient isotope separators of high mass resolving power are needed to identify and isolate the specific ion species desired from the many emerging from the source for further acceleration. Such an isotope separator must feature, furthermore, an extremely low mass cross contamination between neighboring isobars and even between neighboring elements within the same isobaric chain since the production rates of such neighboring nuclei often differ by many orders of magnitude. This separation should take place prior to any rf acceleration, to optimize beam quality and separation capability. To achieve the required degree of species-purity it is anticipated that two stages of separation may be required, the first with a resolving power of about one in a thousand (adequate for isotopic analysis), and also a second, to separate elements with the same A, with a resolving power of around one in twenty-thousand, so that ions can be separated whose Q-beta/A value is larger than perhaps 5 MeV/100 amu.

The configuration of the front-end: the type of separators used (cf separate contribution in these proceedings), the ion source characteristics, experimental stations feeding directly from the separators, and the post-accelerator interface itself, presents a large number of design challenges. Some types of separators require extremely low energy spread from the source and very high stability of accelerating voltages from the source, while others are more forgiving, but have their own limitations. While this Workshop has not addressed the full range of design parameters and options, one parameter that was investigated at some depth was the question of relative high-voltage potentials between the various elements, and more specifically, arguments for holding individual stages at ground potential.

Figure 1 shows a schematic of the various elements of the front-end of a RIB facility. Arrows represent ions transported between the various elements, vertical height related to

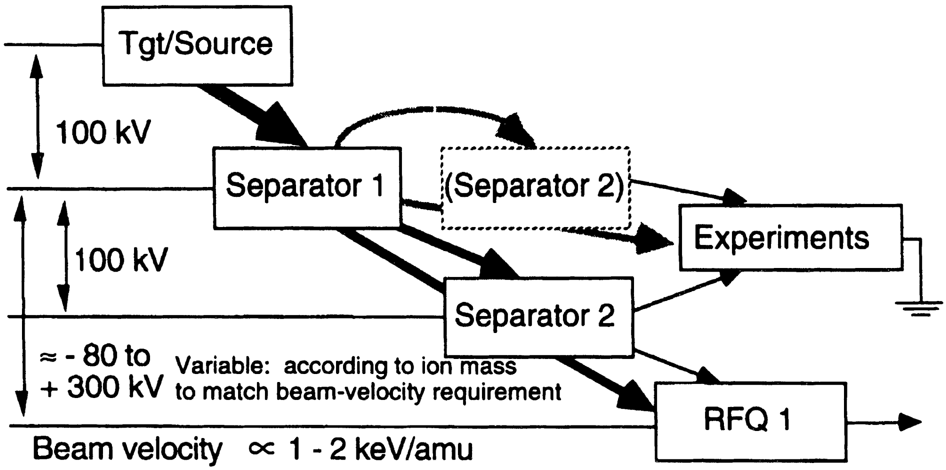

FIGURE 1: Front-end Configuration Schematic

the potential of each element. Voltages between the different stages are shown based on generally acceptable values: 100 kV is within the state-of-the-art for this type of application, and appears to be suitable for achieving good beam emittances and species purification. The schematic indicates that beams can be used with or without a second separator, and that this second separator can either be kept at the same potential as the first or ions can be further accelerated between separator stages in order to eliminate ions that were formed initially at slightly wrong energies due to charge-exchange reactions in the initial ion acceleration canal. The configuration is dependent on the specific separator types used, and the particular goals of the experimental program. The voltage between the separator(s) and the first stage of post-acceleration is determined by the particular design of the first stage of post-acceleration, shown here as an RFQ, and the ion species to be accelerated. If an rf accelerator is used, the mechanical dimensions of the accelerator require a fixed velocity profile of the ions traversing the structure. Thus the voltage between separators and the accelerator must be adjustable to bring the ions into this accelerator always with the proper input velocity. Lighter ions will have to be decelerated for proper matching.

The question of where to establish ground potential for this system of electrostatic voltages is quite complex; strong technical arguments can be made for the advantages of grounding each of the elements of the front-end. For the most part, however, good technical solutions exist for the case where each of these elements is not grounded. The only area in which general agreement was expressed was that any experiments operating off of the separators must be at ground potential. The complications to the experimenters of having to float their apparatus would be prohibitive.

Floating the target-ion-source system presents the problem of compensating for drain on the power supply from the primary beam striking the target. In addition to the anticipated ISL proton current of up to 100 μA steady state on the target (with potentially much higher peak currents), one must also consider the electron backstreaming currents or discharge currents generated when the primary beam strikes the target. For example, at ISOLDE, the PS Booster delivers about 2 amps (instantaneous current) for about 1 μsec at an 0.8 Hz repetition rate (≈ 2 μA average beam current) to the target. In this case the beam traverses a region of air at 1 atm. To prevent the high discharge currents, the target is dropped from its normal 60 kV to ground during the beam pulse, then is restored to its high-voltage setting (to a stability of 1 part in 10^5) in a few milliseconds after the beam pulse. The anticipated higher current at the ISL increases the air-activation problem for any air-path for the primary beam, rendering more attractive the option of maintaining the target in vacuum. Such an option would be important as well should it be desired to keep the target at its high-voltage operating potential throughout, as would be necessary were the primary beam to come (continuously) from a cyclotron. To maintain the operating voltage will require high-power charging and feedback systems; complex, but not outside the state-of-the-art.

The most likely component to be grounded is the separator system. This will eliminate the requirement of having high-voltage columns on all the lines to experiments taking beam directly from the separators. If the separators were to float, and the source be maintained at ground, then the ions reaching the experiments would in fact do so at zero velocity, thus creating experimental complications. In addition, providing power and suitable mechanical support systems for a high-voltage platform add significant cost and complication to the design of separator systems.

Rf accelerators are normally thought of as being at ground potential, although there is no *a priori* reason why this should be so. The RFQ community at the Workshop actually did not feel uncomfortable with the idea of floating the first RFQ to ensure proper velocity matching of the beam. Note that floating the first RFQ (to different levels for different q/A beams) will require an additional rf cavity to adjust the exit velocity from this RFQ to compensate for the velocity gain (or loss) in bringing the beam from the potential of this RFQ to ground (presumably the potential of the remaining rf accelerators).

It was noted, on the other hand, that single-gap cavities placed upstream of the first RFQ accelerator could prove very helpful. Such cavities could bunch the beam, and can in fact accomplish this at least as efficiently as the normal RFQ bunching methods, possibly yielding even smaller logitudinal phase-space distributions. With higher voltage cavities also the beam-velocity could be properly matched to the first RFQ even if this accelerator were maintained at ground potential.

The decision between these two options, whether to float the first RFQ or add single-gap cavities and maintain the first RFQ at ground potential, will depend on a detailed optimization of beam dynamics calculations and economic factors for the specificied range of performance requirements.

4 CONCLUSIONS

Several salient points emerged from the discussions of the Working Group. First, and perhaps most important, there are no technological "show-stoppers" in the current concept of the ISL. It was felt that the parameters and performance sought were within the capabilities of available technologies, as well as being appropriate for the ISL to discharge its stated mission. However, actually achieving this performance is not straightforward. It will require considerable extension in the state of the art in a number of areas. Specific areas for R&D are outlined below.

With regard to ion sources, all the source technologies discussed will deliver beam that is acceptable for all the post-accelerator concepts. However, the most stringent constraints on source requirements will come from matching to the acceptance of the separators. Specifics of maximum transverse emittance and energy spread will have to be closely coupled with the particular separator designs employed.

There are a number of aspects of the ISL that are challenging the accelerator physicist to new areas beyond the normal configuration of accelerator systems: the extremely wide range of beam parameters (q/A, intensity), the complexity of the low-velocity transport and separator systems, and the concept of having to float rf accelerator sections. These challenges should stimulate creativity in addressing new problems, none of them were viewed as insurmountable.

Specific areas where significant R&D efforts should be concentrated are: source performance (high efficiency, low hold-up time, low emittance, low energy spread, good high-charge-state performance, operation in high radiation environment, design for remote handling, decontamination issues); schemes for maintaining high voltage-stability for the target/source in the presence of intense, quite-possibly pulsed primary beam current loads; designs for high performance mass separators for low and high beam currents; as well as the placement of complex, high-power equipment on high-voltage platforms.