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ACCELERATOR ISSUES AND CHALLENGES AT THE ISOSPIN LABORATORY

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We discuss and pose questions, issues and challenges in the accelerator physics and systems aspects of an Isospin Laboratory as conceived to date.

KEY WORDS: Accelerator, isospin laboratory, radioactive beams, ions

1 INTRODUCTION

The layout of an IsoSpin Laboratory as conceived presently and its current parametric specifications are shown in Figure 1 and Table 1 respectively. The generic features of such a facility are: large dynamic range (in energy, intensity, ion species (q/A), etc.), high intensity, high duty factor, required low beam emittances, high beam purity, operation under high radiation background (e.g. 60 kRad/hour @ 1 meter from target) and almost zero tolerance for beam loss (required transmission efficiency of $\sim$100%). This last feature demands almost perfect matching of beam phase space from the ion source into the post accelerator and from the post accelerator into the high energy linac, etc. The goals of the ISL are unquestionably ambitious and challenging, leaving aside the demanding issues of targetry and radiation shielding, which were not in the scope of this workshop. Nevertheless, through dedicated R&D effort and focussed workshops in the past including the present one, reasonably feasible technical solutions seem to be emerging so that we are beginning to share an increasingly optimistic outlook on the realizability of the ISL in near future.

The major natural divisions of the post-accelerator complex are:

(a) High Energy Post-Accelerator or Secondary Beam Accelerator ($\gtrsim$ 100 keV/u).

(b) Low Energy Post-Accelerator or Secondary Beam Injector ($<$ 100 keV/u),

(c) Isobar Separator and Matching Sections, and

(d) Ion Source.

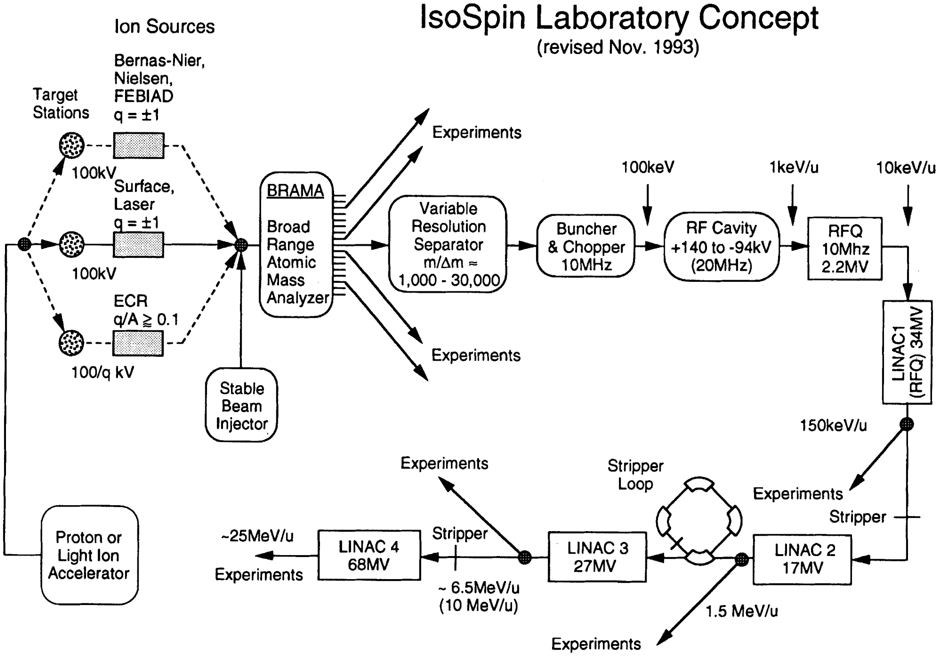

FIGURE 1: Conceptual layout of the ISL.

In what follows, we discuss these four areas and raise the issues and questions in each area that this workshop was charged to address. Many of these questions were addressed at the ORNL workshop as well.

2 HIGH ENERGY POST ACCELERATOR

This part of the accelerator complex will be defined by $E > 100$ keV/u after the first stripping section and will also be referred to as the secondary beam accelerator. This is probably the "least speculative" portion of the post-accelerator complex with many available options:

(a) Low frequency "Heavy Ion Superconducting Linac" e.g. the ATLAS type;

(b) Specially designed room temperature, normal conducting linacs; and

(c) Storage rings.

Let us discuss these options briefly in the following.

TABLE 1: IsoSpin Laboratory — Revised Specifications (Nov. 1993)

Primary Beam Accelerator:	
Particles:	p, (d, ^{3}He)
Energy:	0.5–1 GeV
Intensity:	100–200 μA (protons)
Beam structure	CW (or pulsed $\geq$ 1% D.F.)
Target:	
Matrix:	solid or liquid
Thickness:	$\sim$1 mol/cm^2
Power:	$\leq$ 40 kW
Luminosity:	$(4-8)\times 10^{38}$ s$^{-1}\cdot$cm^{-2}
RNB Accelerator:	
Energy Range:	0.2–$\sim$25 MeV/u
Intensity:	10^2-10^{11} pps
Mass Range:	1–240 u
Z range:	1–93
Beam Purity:	$<10^{-4}$ ($<10^{-5}$ nucl. astrophys.)
Macro Beam Structure:	DC (or pulsed $\geq$25% D.F.)
Micro Beam Structure:	$\sim$100 ns (for TOF)
Energy Resolution:	0.1–1 %
Emittance $\varepsilon_{x,y}$:	$\lessapprox 0.2\pi$ mm·mrad (norm.)
Emittance ε_z:	$\sim$20–50 keV ns
Transmission:	$\geq$ 90% (excl. stripper losses)

2.1 Superconducting Linac

Superconducting linacs have high shunt impedances and allow cost-effective CW operation. Previous experience with such linacs and the possibility of advanced design promise exceptional beam quality and operational flexibility from such a linac. Since losses are low, the cavity shape is not important. This allows large apertures thus guaranteeing exceptional transverse acceptance and transmission. Usually, it is also possible to gain a high degree of control of longitudinal phase space leading to beams of high quality. In general one has a broad velocity acceptance and control over the linac velocity profile.

A typical prototypical technology is exemplified by the ATLAS linac at the Argonne National Laboratory, where one accelerates ions with $q/A \lesssim 1/10$, from 35 keV/u to $\gtrsim 6$ MeV/u with a longitudinal emittance of $\varepsilon_z \sim 10 - 20\pi$ keV·nsec.

Operation of a superconducting low temperature structure in the presence of radioactive decays and activation-induced quenches are believed to be of some concern, although not in any major way.

2.2 *Normal Conducting Linac*

Various low β, low (q/A) structures (including interdigital H-type accelerating structures) have been developed for linacs with applications to radioactive beams in mind. These are very high shunt impedance structures, with CW operation and good transverse acceptance. These structures are probably optimal, cost-wise, for very low-β ions ($\lesssim$ 250 keV/u). However, the longitudinal emittance expected from these structures is rather high ($\varepsilon_z \sim 400\pi$ keV $\cdot$ nsec) and flexibility in changing output energy, effect on beam emittance, etc. need to be explored further.

2.3 *Storage Rings*

Although the option of storage rings for radioactive nuclear beams was not in the scope of the workshop, we will comment on it because of its importance.

The advantages of the storage ring scenario are: (a) large luminosities can be obtained for relatively low primary beam intensities; (b) for beam particle currents $\lesssim 10^6$/s, internal target experiments will give higher luminosities than single-pass experiments because of multiple target traversals.

The ring can also be operated at transition energy for mass measurements. However, these scenarios require installation of an internal cold-cluster gas target in the ring and utilization of particle and gamma-ray detector arrays around the target.

Yet another significant factor to be considered is the fact that large background from the beam radioactive decay products are spread over a large area lending to significant reduction of gamma background relative to achievable levels in a fixed target experiment with same luminosity.

Storage ring scenarios thus deserve serious attention.

2.4 *Outstanding Issues*

The following questions on the secondary beam accelerator need to be addressed as quantitatively as possible:

(1) Is beam quality in the longitudinal phase space (e.g. longitudinal emittance) important?

(2) If so, what is the ultimate beam quality and control required for the farthest physics reach of the facility, experimentally?

(3) A superconducting linac option presents promise in good beam quality, energy stability, variability and flexibility. Is radioactivity in a cryogenic environment a serious concern?

(4) If beam quality is of no concern, room temperature structures offer optimal systems for very low-β at a reduced cost. How much lower cost?

(5) Beam intensities swing from 10^2 to 10^{13} pps in an ISL. Tuning and beam loading are expected to be tractable due to low current, but need to be looked at in detail.

(6) What is the optimum stripping scheme and optimum stripping energy? What are the relative merits or otherwise of gas vs. foil stripping?

(7) Finally, what is the ultimate accelerator configuration for accelerating low-β, low (q/A) ions ($E \sim 100$ keV, $\beta \geq 0.0015$, $q/A \geq 0.004$) to energies of $\sim$ 10 MeV/u?

3 LOW ENERGY POST ACCELERATOR

This part of the accelerator complex will be defined by $E \lesssim 100$ keV/u and will also be referred to as the secondary beam injector. This is probably one of the "most difficult" portions of the post-accelerator complex. The difficulty is in designing an injector (RFQ, for example) that simultaneously satisfies the demands of CW operation, low input velocity, low q/A and reasonable acceptance. The beam specifications are: $(q/A) \sim 1/240$, normalized emittance of $\varepsilon_N \lesssim 1\pi$ mm-mrad and energy spread of $(\delta E/E) \sim 10^{-3}$. The possible options are: (a) room temperature RFQs; (b) superconducting RFQs and (c) cyclotrons.

3.1 Radio Frequency Quadrupoles

It is difficult to achieve large acceptance for low ion velocities and low (q/A) due to stringent RFQ focussing requirements for stability against transverse space charge, etc. The focussing coefficient, k, is proportional to $(q/A)(V/f^2)$ and hence for low (q/A), one needs low frequencies (f) and high gradients (V). For example, beams of $^{238}\text{U}^{1+}$ at 1 keV/u cannot be focussed with present technologies unless we consider frequencies as low as 10 MHz *or* so. This seems to be a major technological problem.

In the domain of normal conducting RFQs, there exist, at present, designs and operating prototypes from various laboratories in Japan, Germany, USA, etc. As an example, prototype split coaxial RFQs with (q/A) ranging from 1/30 to 1/60, duty factor of 10% and state-of-the-art CW field level at 2.2 times the Kilpatrick limit already exist and reported at this workshop by Tokuda. There have been difficulties with CW operation (heating and power level) and high gradients. However, with proper design, there seem to be no fundamental barrier in reaching close to the $(q/A) \sim 1/240$ and CW (100% duty factor) regime, as reported by A. Schempp in this workshop.

In the domain of superconducting RFQs, while it has been possible to produce high gradients in short structures, difficulties are presented in sustaining high field levels in long structures. Moreover, the requirement of large transverse acceptance favors large beam tube aperture, hence low rf frequency which implies rather large rf structures. At present, studies have been restricted to a frequency of 50 MHz and beyond. This issues of structural rigidity and associated problem of 'microphonics' for such large structures lead to difficulties in good rf phase control. Superconducting RFQs have been discussed by K. Shepard at this workshop.

In order to simplify the RFQ tasks, the following two directions need to be explored in detail:

a) To decouple the "bunching" function from the "focussing and accelerating" function, by adding a separate prebuncher injecting into an efficient RFQ (see report by J. Staples at this workshop);

(b) To accommodate multiple requirements and the large dynamic range, different front ends may be needed for different mass ranges, allowing trade-off between transverse acceptance and initial charge state.

3.2 Cyclotrons

Cyclotrons can combine the functions of mass separation and acceleration and thus could be considered as potential substitutes for the RFQs and the high-resolution spectrometer. It has been claimed that if ECR sources with high metal efficiency ($^{238}U^{30+}$) could be developed, a cyclotron with $K = 600$, with no stripping, producing 10 MeV/u U^{30+} or 50 MeV/u O^{5+} and single-turn extraction (for good beam quality) would be an attractive option. Although cyclotrons were outside the detailed scope of this workshop, they should be seriously looked into. A review is presented by D. Clark at this workshop.

3.3 Outstanding Issues

The following questions regarding RFQs need to be addressed as quantitatively as possible:

(a) What is the ultimate reach of normal conducting RFQs in "q/A" and "Duty Factor", given our present understanding of the fundamental technological limitations due to high gradient, heating, etc.?

(b) Are there foreseeable technological innovations that push these limits further? How far?

(c) Is 50 MHz the lowest achievable frequency for a practical Superconducting RFQ structure with necessary stability?

(d) What are the relative difficulties of technological solutions, if any, for normal conducting vis-a-vis superconducting RFQs?

(e) Is there a multiple front-end injector solution, at least on paper, that looks reasonable?

4 ISOBAR SEPARATOR AND MATCHING

For maximal transmission (i.e. minimal loss), phase-space matching throughout the post-accelerator is crucial. This requires sophisticated nonlinear design, possibly including space charge at lower energy for high ion currents.

'Purity' of the beam is of utmost importance as well. One has to do the very best in isobaric separation.

The following outstanding issues need to be addressed:

(a) Do we really need an isobar separator for all beams? What is the required power supply stability? What is the required beam energy spread and emittance?

(b) What are the consequences for the emittances, the necessary extraction potential and the design of the separator, should the current from the Ion Source be so high that we would require a medium-current isotope separator with full space-charge compensation?

(c) Problems of cross-contamination, high separation efficiency and high transmission simultaneously.

(d) Is multi-stage separation unavoidable?

5 ION SOURCES

Ion source characteristics (q/A, etc.) have a profound effect on the post-accelerator design. So far, ECR sources have been looked into in detail as the only contender for efficient production of highly charged ions. However, ECR sources presumably have large emittances (e.g. 400 π mm-mrad), which are clearly not acceptable. Potential alternatives e.g. laser-ion sources, etc. should be looked at.

Issues in ion sources that need to be addressed are:

(a) What are the advantages/disadvantages of starting the post-acceleration process with charge states $q > 1$ in the ion source compared to $q = 1$?

(b) What are the promising new ion sources and their developments that could become relevant for the ISL? How important are Laser Ion Sources?

(c) What is the highest practical voltage we can really use for the extraction voltage in radiation environment?

(d) List beam characteristics of standard ISOL sources (emittance, δE/E, etc.). Can one develope an universal ion source?

(e) What is the maximum current expected from the Ion Source?

(f) Importance of atom/ion storage systems e.g. Paul traps, Penning traps, the GSI (Kirchner) scheme, etc.

6 OUTLOOK

The detailed technical contributions during the workshop are reproduced in these proceedings. These together with the two working group summary reports address most of the questions raised here and point the way to future work.