SOME ASPECTS OF LINACS AS APPLIED TO THE ISL BENCHMARK FACILITY

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Introduction

This paper considers several aspects of using linacs in a radioactive beam facility in terms of the Isospin Laboratory (ISL) Benchmark Facility (BMF) plan, described in the 1991 white paper for a possible radioactive-beam laboratory [1]. The BMF is outlined schematically in Fig. 1. The intention is not to review comprehensively the application of linacs to an ISL facility, but to compare in outline form several linac options for such a facility. Particular emphasis is given to the use of superconducting rf technology for the secondary beam accelerator.

In what follows, first a possible normally-conducting light-ion linac for a primary beam accelerator is briefly outlined. Then the performance and cost of two options for a secondary beam accelerator are compared: a recent design for a normal-conducting cw linac, and an ATLAS-type superconducting linac. Finally, some of the problems which may be encountered at the entrance of a secondary beam linac are discussed.

I have included cost estimates with some reluctance and only because it is impossible to compare technical options without some discussion of costs. Although an effort has been made to indicate the sources and assumptions underlying cost estimates, please note that any costs mentioned must be considered as 'ball-park' numbers useful for only the most rudimentary planning. Even for elements of the BMF which can be modeled on existing linacs, cost comparisons between different institutions can be difficult to make. Cost estimates for elements based on untested designs or future technical development are necessarily highly speculative.

Primary Beam Linac

As has been pointed out elsewhere at this workshop [2], one option for a primary beam for ISL would be to use a 200 MV linac designed for a charge to mass ratio of 1/2. Such a linac would permit the use of a variety of fully stripped light ions (H_2^{1+},$^2H^+$,..., N) for a spallation source. The particular linac discussed would deliver 100 MeV per nucleon ions at a 2% duty factor and a pulse rate of 100 Hz, and provide 100 KW of beam power. An ion linac of this size, or larger machines providing substantially more voltage, is commercially available at a cost of roughly 10¢ per volt for the linac itself, including rf and vacuum systems, but not including the ion source or building and utility costs [3]. Such a linac could also be used as the injector for a 500 - 1000 MeV proton synchrotron for a higher energy spallation source as discussed in the BMF plan.

Another possible option for the primary beam option could be a superconducting linac. The most nearly comparable existing machine may be the CEBAF electron linac, for

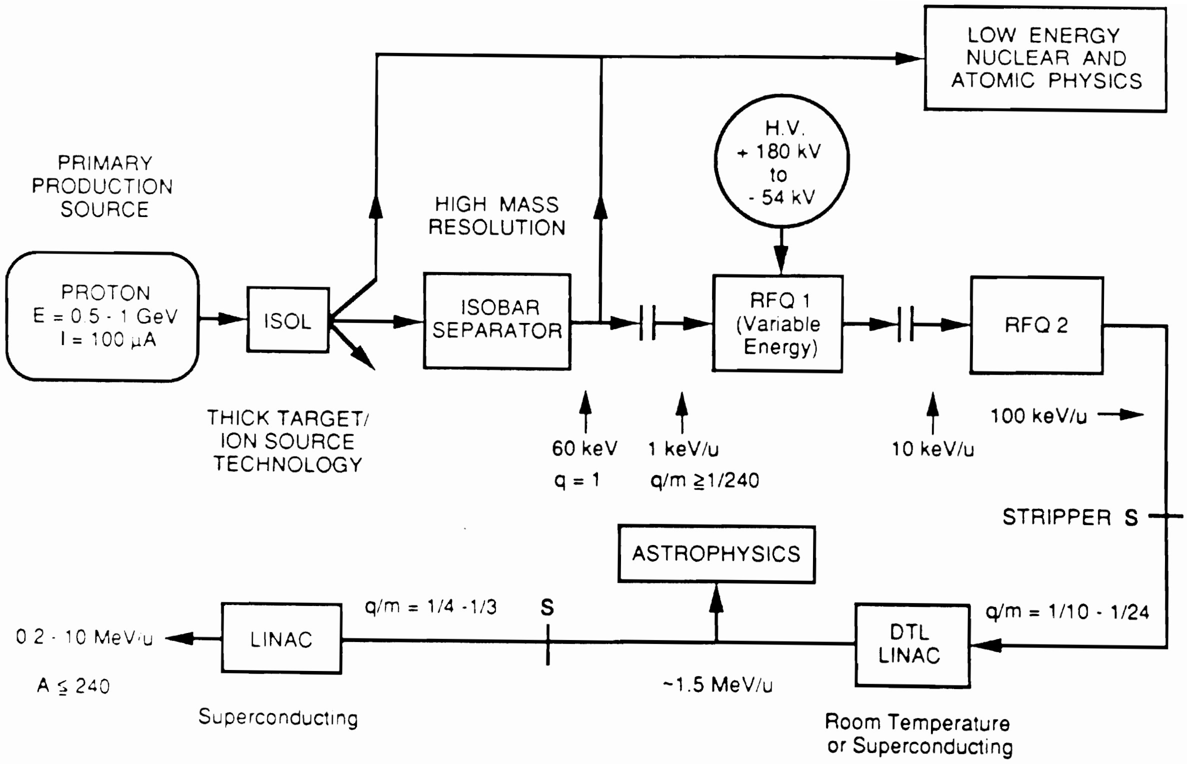

Fig. 1. Schematic diagram of the Benchmark Facility (BMF) discussed in reference [1] as a possible realization of the ISL

which current construction costs are also roughly 10¢ per volt [4], assuming an operating gradient of 5 MV/m. Although no large superconducting proton linac has yet been built, accelerating structures for the necessary velocity range have been developed and show excellent performance in single-resonator tests [5]. If CEBAF or similar facilities prove able to operate at accelerating gradients substantially in excess of 5 MV/m, then the superconducting option for a primary beam accelerator could become advantageous.

Secondary Beam Accelerator

The secondary beam accelerator defined for the benchmark facility is straightforward after the first stripping. We will refer to this portion of the machine, with energy greater than 100 keV/u, as the secondary beam linac. For the linac, several options currently exist which can more or less satisfy the specifications [1]. More difficult problems are presented by the initial section of the secondary accelerator. We will refer to this portion, where energy less than 100 keV/u, as the secondary beam injector. The difficulties with designing the injector result primarily from requiring at the same time a normalized transverse acceptance of up to 1 $\pi \cdot$mm$\cdot$mrad, charge state as low as 1/238, and a final beam energy spread $\delta E/E \leq 10^{-3}$ or better [1].

We proceed by starting with the less speculative portion of the machine and compare two options for the secondary linac: an ATLAS-type superconducting linac [6] and a recent design for a room-temperature, normally-conducting linac based on interdigital H-type accelerating structures [7].

Superconducting Linac

The high effective shunt impedance of superconducting low-velocity accelerating structures not only provides for cost-effective cw linac operation, but also enables design options which can provide exceptional beam quality and operational flexibility. Since the cavity geometry is not so strongly constrained by the need to minimize rf losses, for heavy-ion linacs the following design choices are typical:

1. Drift-tubes of large aperture provide exceptional transverse acceptance and excellent transmission.

2. Very short resonant cavities can be used, which intrinsically provide broad velocity acceptance (typically a factor of two range in velocity). By operating such short cavities in

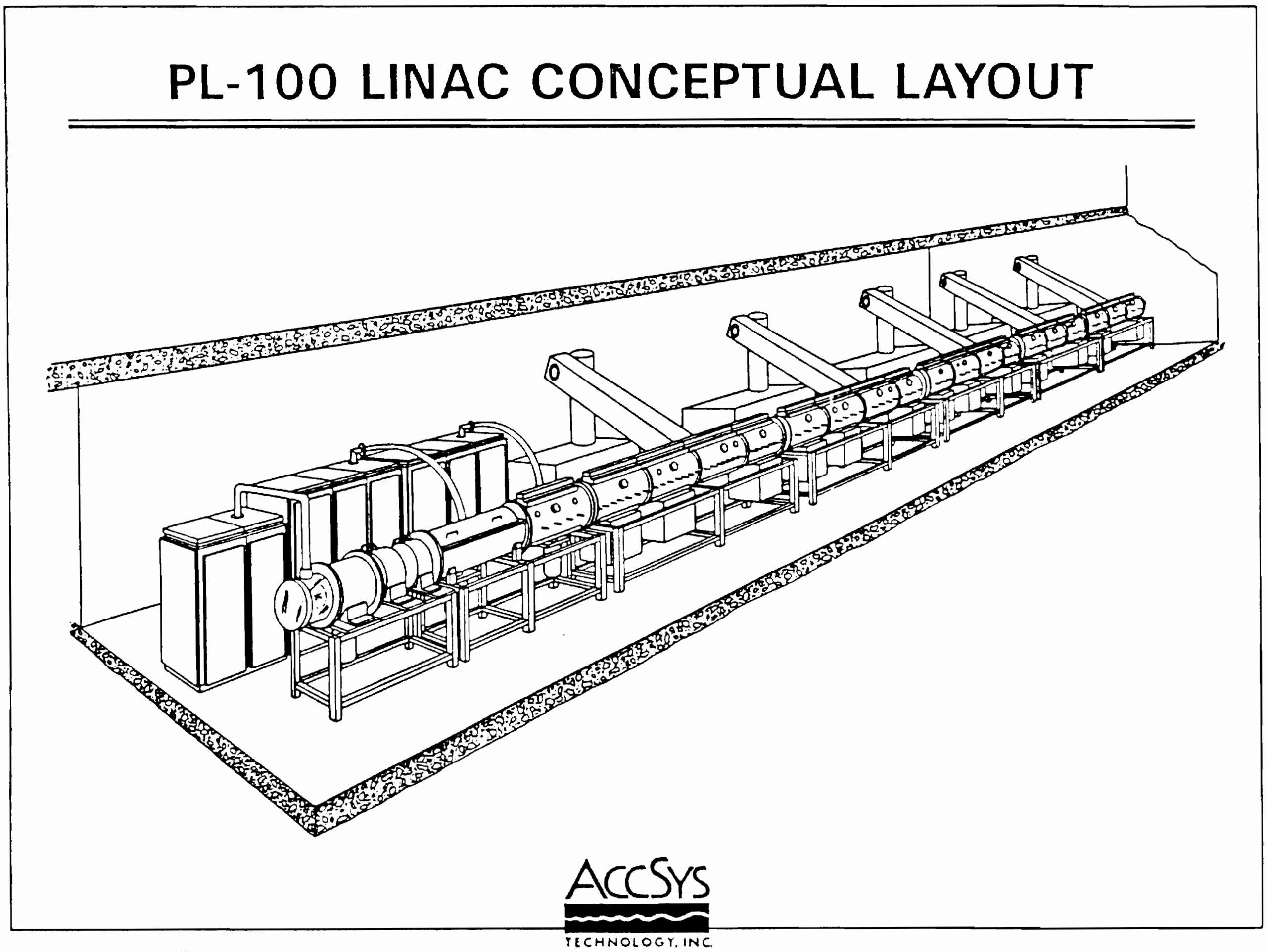

Fig. 2. Linacs suitable for a light-ion primary beam are commercially available. Shown is the layout of a 100 MV proton linac (courtesy of AccSys Inc.).

an independently phased array, one gains operational flexibility not only in being able to vary the linac velocity profile, but, more generally, in achieving a high degree of control over longitudinal phase space which, as is discussed below, has enabled heavy-ion beams of unprecedented quality.

In what follows, we take as representative of SC linacs the ATLAS accelerator which is typical of the technology and is the largest of the several superconducting heavy-ion linacs currently in operation [8]. ATLAS is presently configured to accelerate ions as heavy as uranium ($Q/A \approx 1/10$) from energies of 35 keV/u to 6 MeV/u and above: ATLAS could be used without modification as the BMF secondary beam linac from 35 keV/u on.

Normally-conducting IH-structure Linac

For a normally-conducting linac for radioactive beams, the most attractive option at this time seems to be a linac based on IH-structures [9]. The design discussed here is based on very high shunt-impedance structures recently developed specifically for radioactive beam application [7]. In particular, effort was devoted to obtaining a capability for cw operation and good transverse acceptance. The velocity ranges used in Table I below in fact correspond to the 5 different IH-structures developed by the Moscow group [7].

Comparison of Linac Parameters and Performance

Table I shows some basic parameters of the two linac designs, each evaluated at several different particle velocities. Linear accelerators being modular and extendable in fairly small increments, we normalize all parameters to the amount of linac required to produce a given amount, 1 MV, of effective accelerating potential. This enables, for example, scaling the linac design to accommodate different charge states.

Table 1A - Some parameters for the ATLAS superconducting ion linac [6, 10]. See text for details.

Velocity / c	.016	.024	.050	.086	.110
rf frequency	48.5 MHz	48.5	97	97	97
Length / MV	64 cm/MV	62	69	62	62
Power / MV *	13.5 KW/MV	9.5	11.5	7.6	7.6
Cost / MV	390 K$/MV	290	240	180	180

*Based on the ATLAS refrigeration efficiency of roughly 1 KW per watt: an up-to-date system could nearly double the efficiency, reducing the power requirement shown by nearly a factor of two.

The parameters shown are as follows:

rf frequency - operating frequency of the accelerating structure, not the bunch frequency which is usually a sub-harmonic

Length / MV - 'real estate' length of linac required to produce 1 MV of effective accelerating potential: a particle of charge Q gains energy $\delta E = Q \cdot 1$ MeV in traversing this length.

Power / MV - total 'wall-plug' electrical power required to operate the above 1 MV length of linac.

Cost / MV - equipment cost for the linac equipment only, including cryogenic refrigeration, rf, and vacuum systems, but not including any building or utility costs, or any elements preceding or following the linac proper. See further discussion below.

For the superconducting linac, the cost figures are based on construction experience with ATLAS, normalized to 1985 dollars. Costs for the IH linac designed by the Moscow group are more difficult to estimate. The cost figures shown are those given by H. Klein and R. Muller in 1985 for a similar IH linac design [11], and presumably reflects the construction experience at Munich and GSI.

Table 1B - Some parameters for normally-conducting ion linac based on IH structures [7, 11]. See text for an explanation of the cost estimates.

Velocity / c	.016	.024	.050	.086	.110
rf frequency	27 MHz	27	54	108	108
Length / MV	74 cm/MV	100	59	58	63
Power / MV	5.7 KW/MV	13.9	15.2	16.7	17.7
Cost / MV	-	210 K$/MV	210	-	-

A striking feature of the above tables is how similar in cost, length, and operating power the two very different technical options are. Performance characteristics, however, as discussed below, favor the superconducting option.

Output Beam Characteristics

Although the published requirements for the BMF specify only the energy resolution of the secondary beam, for many experiments the longitudinal emittance, or time-energy spread is a more important parameter. At ATLAS, where time-of-flight techniques have proven to be an important tool, the longitudinal emittance has been measured to be in the range 10 to 20 $\pi \cdot$keV$\cdot$nsec for a number of different beams [6]. Such beam quality will be hard to produce in a normally-conducting linac. For the IH linac designed by the Moscow group, data given in reference [7] imply substantially larger values of longitudinal emittance, perhaps as great as 400 $\pi \cdot$keV$\cdot$nsec.

For the superconducting linacs, output energy can be varied easily and continuously with no degradation of beam. In an IH-structure linac, output energy can be varied by reducing the rf level in the final structure, in general the beam emittance would in general be substantially degraded in this technique.

Secondary Beam Injector

The desired specifications for an ISL secondary beam include:

Energy resolution	0.1%
Charge / Mass down to	1/240
Emittance (normalized)	1 $\pi \cdot$mm$\cdot$mrad

Several designs have been presented for an RFQ injection section [7, 12] designed for Q/A of 1/60. A recent design also appears to provide the desired (very large) transverse acceptance [7]. CW operation, however, remains to be demonstrated for these designs, which are pushing state-of-the-art for cw field level.

Although very high rf electric field gradients have been obtained in tests of short superconducting RFQ structures [13], application of this technology to a BMF injector would not be straightforward. This is because the requirement of large transverse acceptance dictates a large beam aperture for the injector. This in turn forces the use of a low rf frequency to obtain an efficient accelerating structure. A fundamental problem with superconducting accelerating structures, particularly for heavy-ion applications, is maintaining sufficient structural rigidity to enable rf phase control in the presence of microphonic-induced phase noise [14]. At the present time, 50 MHz seems to be the lower limit of frequency for phase-controllable superconducting structures [14, 15], probably too high a frequency for a superconducting RFQ injector structure which can satisfy all the previously mentioned requirements.

Given the difficulty of producing sufficient electric field in an RFQ structure, it is surprising that all the designs presented to date include an adiabatic bunching section (producing no acceleration) that occupies as much as half the RFQ structure. Use of a separate bunching system to directly inject a more efficient RFQ might prove an attractive design choice for the following reasons:

1. Several existing systems use gridded-gap or double-drift bunching systems that can bunch more than 80% of the entrance dc beam and which have proven to be straightforward to use and cost-effective.

2. A properly designed gridded gap or double drift bunching system will produce substantially better (smaller) longitudinal emittance than an RFQ adiabatic bunching section.

3. With a separate bunching system, the bunch frequency can be chosen independently of the accelerating structure frequency or can even be varied for different beams and applications.

Conclusions

A variety of proven linac options exist for a primary beam linac, and for more than 90% of any secondary beam linac for an ISL facility. For the secondary beam, a superconducting linac presently offers the best beam quality, energy variability, and flexibility in terms both of system operation and upgrade options. Normally-conducting IH-structures at the present time probably provide lower costs at very low velocities (say below 250 keV/u).

The most problematic area is the secondary beam injector. At present, a low-frequency RFQ section seems to be the best choice and several designs for such RFQ sections have been published. However no design has even come close to meeting all the desired goals for the ISL BMF, nor is likely to in the immediate future. To facilitate machine development in this area, it would be helpful to more clearly establish requirements and tradeoffs concerning the various beam parameters. The following are suggested:

1. The ISL Design Specification should include a goal for longitudinal emittance of the secondary beam, and not just energy resolution, as is now the case. If time-of-flight techniques are to be available at ISL, then a longitudinal emittance below, say, 40 $\pi \cdot$keV$\cdot$nsec would be desirable.

2. For design of the secondary beam injector, it would be helpful if guidelines were developed for the tradeoff required between transverse acceptance and initial charge state. Possibly more than one injector section might be desirable for ISL, to handle the various and sometimes conflicting requirements.

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