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Multiple-Linac Approach for Tritium Production and Other Applications

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ABSTRACT

This report describes an approach to tritium production based on the use of multiple proton linear accelerators. Features of a single APT† Linac as proposed by the Los Alamos National Laboratory are presented and discussed. An alternative approach to the attainment of the same total proton beam power of 200 MW with several lower-performance superconducting Linacs is proposed and discussed. Although each of these accelerators are considerable extrapolations of present technology, the latter can nevertheless be built at less technical risk when compared to the single high-current APT Linac, particularly concerning the design and the performance of the low-energy front-end. The use of superconducting cavities is also proposed as a way of optimizing the accelerating gradient, the overall length, and the operational costs. The superconducting technology has already been successfully demonstrated in a number of large-size projects and should be seriously considered for the acceleration of intense low-energy beams of protons. Finally, each linear accelerator would represent an ideal source of very intense beams of protons for a variety of applications, such as: weapons and waste actinide transmutation processes, isotopes for medical application, spallation neutron sources, and the generation of intense beams of neutrinos and muons for nuclear and high-energy physics research. The research community at large has obviously an interest in providing expertise for, and in having access to, the demonstration, the construction, the operation, and the exploitation of these top-performance accelerators

The APT Linac

The Los Alamos reference design of the APT Linac for tritium production[1] is based on the use of a single accelerator device where the 200-MW design goal of proton beam power is generated by selecting an average beam current of 200 mA and a final energy of 1 GeV. The project is schematically shown in Figure 1 with proposed phases of construction[2]. The design has been optimized, to some low-order approximation, by assuming a normal-conducting rf-cavity accelerating system. Its feasibility has been evaluated and reviewed on several occasions as correct[3]. It is in particular a very clear demonstration that the accelerator technology can compete as a viable alternative to nuclear reactors for applications where the accelerator power requirements are not

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†. Accelerator-based Production of Tritium

* Work performed under the auspices of the US Department of Energy

prohibitively large. Nevertheless, the APT Linac has not yet been optimized to a higher degree, and other accelerator scenarios so far have not been considered. With the present design, the APT Linac is perceived to contain a considerable dose of technological risk. Some of the most relevant design features are described below with technical considerations.

The Linac is essentially made of two parts: the front-end, which is the most crucial for the overall beam performance, and the high-energy section, which determines the length of the accelerator, and dominates the capital and operation cost.

An average of proton beam current of 200 mA cannot be delivered by a single ion source. Thus, the reference design calls for two ion sources, each producing around 110 mA. Even this current level is too large. In a recent workshop held at Lawrence Berkeley Laboratory, positive-ion sources were reviewed by experts from several institutions in USA, Europe, and Japan. A summary table[4] was agreed upon which is reproduced herein as Table 1. A source-current value of 60 mA has been demonstrated satisfactorily with long-term stability and reproducibility. It is obvious that a lower average beam current, at the source, is more desirable as a starting design parameter, especially to guarantee reliable and reproducible operation over long periods of time.

In order to reach the design beam current of 200 mA, the APT Linac requires the duplication of the front-end with certain technical consequences caused by the combination of two beams in the following high-energy section of the accelerator. The use of an rf funnel (which works as the inverse of an rf separator) dictates the choice of 20 MeV as the energy where the two beams are merged, and thus produces the need of an intermediate low-energy Drift-Tube Linac separated by a Bridge-Coupled Drift-Tube Linac. Moreover, the same funneling principle requires the designer to operate the following Coupled-Cavity Linac at the frequency of 700 MHz, twice the frequency of the front-end section.

The larger frequency of the normal-conducting CCL, and the need for controlling the value of the cavity shunt impedance to reduce power dissipation, allow only a modest cavity aperture of 50 mm. Moreover, there is the concern that the large beam intensity will generate a considerable beam halo with the possibility of activation of the accelerator over long periods of time, which is difficult, if not impossible, to evaluate and to control in practice. It seems preferable to double the internal cavity dimension by choosing a superconducting structure operating at a lower accelerating frequency and at the same time lowering the beam current by a large factor. The lower beam current can then be achieved with a single front-end module with a greatly simplified design.

Some staging of the APT Linac, as recently proposed by the Los Alamos team, is certainly possible. But the proposal requires that, at all times, all parts of the system work simultaneously and correctly to deliver the design goal of beam power. The failure of the project, that can be tested only a long period after completion, will not provide alternatives or easy modification to other, more flexible, schemes. Furthermore, the proposed staging[2] does not really remove the major concern of the considerable technical risk, especially of the front-end. The proposed staging calls for an initial reduced energy of 500 MeV and a single front-end module. Subsequently, the energy is raised to 1000 MeV, and, finally, a second parallel front-end is added with the funnel system in place. Thus, the proposed staging does not approach the demonstration of technical performance in steps, but it merely addresses only phasing of the cost expenditure. Furthermore, the few stages of construction do not take into account tritium production, with the result of a poor production efficiency especially during the early period.

Finally, the present APT design calls for two targets for intermediate neutron spallation leading to tritium production. The design of the targets is grossly affected by unknowns due to the large amount of beam power involved and to the large size, with considerable extrapolations for the estimate of cooling, safety, and radiation hazard. Smaller-size targets, in a multiple arrangement, would be easier to design and to operate.

Comparison with Existing Facilities

The reference APT Linac design calls for a nominal 200-MW beam power. This is two orders of magnitude above demonstrated technology. Accelerator technology has the capability to progress fast, but absorbing too large a jump in performance is at certain risk. Considering the nature of the application of the project, production and stockpiling of tritium, it is crucial that the accelerator project works immediately according to specifications, reliably and practically at full-time schedule. No intense research and development program should be required to demonstrate crucial beam and accelerator performance. Yet the project, as it has been proposed, has built in a considerable technical risk which may be reduced by adopting a different scenario based on multiple lower-performance superconducting linacs.

Table 2 is a list[5] of the major intense proton sources up to few GeV. Those shown first are operating facilities among which notably is the 800-MeV LAMPF at Los Alamos, which is capable of delivering almost 1 MW of beam power (when the LAMPF is used as the injector to the Proton Storage Ring as a pulsed spallation neutron source, the available power is less than a 100 kW, owing to intensity limitations encountered during filling of the PSR). The most powerful pulsed spallation neutron source is ISIS at the Rutherford Appleton Laboratory in the UK, with an average beam power of 160 kW, whereas the AGS Booster, with acceleration to 1.5 GeV and 7.5 beam pulses per second, can provide only 30 kW. There are thus two orders of magnitude between the demonstrated performance of operating facilities and the requirements of the APT Linac. In between, there are several projects in the few-MW range which are at the moment in the proposal stage and under investigation (AUSTRON, ANL, NCNR, BNL, ESS, ANS, ETA,...). The next project under construction[6] is SINQ (Zurich, Switzerland) with a design beam power of 0.9 MW. Accelerator technology has the capability of progressing at fast rate, but it is doubtful that with the APT project we can absorb such a large jump as two orders of magnitude in a single step. One order of magnitude at a time over about a decade is more realistic, as it has been historically demonstrated.

Table 3 gives the list of operating proton linacs in USA. Table 4 is a summary of proton linacs that have been recently proposed in USA. It is noted that, with the exception of the APT Linac, none operates in continuous mode of operation, and that all make use of normal-conducting cavities.

The construction period proposed for the APT Linac is 12 years. Considering the size and the considerable jump in performance, one should expect in addition a long commissioning period before the full design parameters will be reached and satisfactorily demonstrated. Accelerator projects are known for long turn-on periods following the end of construction before they reach full capability. The length of the construction and commissioning periods is proportional to the complexity and the size of the project. Thus, tritium may be produced only after several years of preoperational testing, unless an alternative scenario is developed with the goal of reducing the turn-on and delivery period.

One of the most important requirement is the availability of the tritium plant for a large fraction of yearly time (75%). This, in turn, requires that both the accelerator and the targets have also large rates of yearly availability, probably in excess of 90%. Few particle accelerators have reached these high rates averaged over many years, and eventually only after long periods of commissioning and operation. These rates, though, may be achieved with higher confidence by taking a design with modularity and multiplicity in the performance built in from the start.

Multiple-Accelerator Approach

The following describes an alternative scenario with the same goal of $P_{total} = 200$ MW of beam power, but divided into a number of smaller accelerators of reduced requirements that can be built sooner, more conservatively, and more reliably. The major thrust is a reduction of the overall technical risk. The proposed scenario assumes that N_A accelerators are built each of beam power P_0, so that

$$N_A P_0 = P_{total} = 200 \text{ MW}.$$

For instance, a reasonable solution could be $N_A = 4$ accelerators built, simultaneously or in sequence, on the same site or at several sites, as described below, each delivering a beam power of $P_0 = 50$ MW. This power figure is an order of magnitude larger than what has been considered in present pulsed spallation neutron studies around the world. It would yield an amount of available neutrons at even larger rates than those of the Advanced Neutron Source[7] of Oak Ridge, which is based on nuclear-reactor technology. Each of these accelerators of 50-MW beam power could also constitute facilities for experimenting on energy production, nuclear transmutation for weapons and actinides waste management, medical and other isotope production, and for a variety of other applications in nuclear and neutron physics, like the generation of very intense secondary beams of neutrinos and muon mesons. According to the application, several combinations of beam parameters are possible; for instance, energy can been traded with current for the same beam power.

Linear versus Circular Accelerators

As for the 1-5 MW pulsed neutron sources at the 50-MW level of beam power, it is legitimate to question which is the most advantageous accelerator technology, among Linacs, Synchrotrons, Accumulator Rings, Cyclotrons, and Fixed-Field-Alternating-Gradient accelerators. It is difficult to conceive of an application of such large rf power in Cyclotrons or FFAG machines, and thus they should be disregarded from start, despite the fact the SINQ project is based on a Cyclotron but likely limited to only 1 MW. Synchrotrons[8] and Accumulator Rings[9] are needed if the neutron beam is to be pulsed in brief bursts of short length (microseconds) at the rate of 10-60 Hz. Moreover, there is always a need of a linear accelerator as the injector which in the case of Accumulator Rings has also to provide the full beam energy and power. The advantage of the Synchrotrons exists only if the beam energy is large, ten GeV or more, in which case conventional normal-conducting Linacs may be too expensive and less feasible. Depending on the type and nature of the application, the facility ultimately is made of a combination of linear and circular accelerators, either to boost the beam to higher energies or to provide the required time duration of the beam pulses. For the application of tritium production, if the total proton energy does not exceed a few GeV, as will be assumed in the following, a linear accelerator operating in continuous-wave mode represents the most feasible and cheapest solution, which also demands less operating power. In other applications, the linear accelerator may be the injector to a subsequent device.

General Design Considerations

Each of the smaller linear accelerators requires less average beam intensity; for instance, 50 mA at the final energy of 1 GeV, or 25 mA at 1.8 GeV and $P_0 = 45$ MW, which is closer to the present capabilities of available ion sources. Both the concern of the latent activation due to the formation of beam halo, and the constraints on the design of the front end would be significantly reduced. In particular, there is no need for beam funneling and a single-value frequency can be adopted throughout the whole accelerating device, for instance 350 MHz, which allows a larger cavity internal diameter of 100 mm, for the containment of the beam.

The use of superconducting cavities is also proposed. They indeed do represent by now a mature technology with several advantages. With a normal-conducting system, special attention need be given to the power dissipated in the walls of the cavities owing to the large wall resistivity. To reduce this power, which is dissipated also without beam acceleration, the design of the APT Linac calls for a low average accelerating gradient of about 1 MV/m and a small cavity opening of 50 mm. With superconducting cavities, it is possible to remove entirely the power dissipated in the walls of the cavity structure by raising considerably the shunt impedance, so that one has the freedom to opt for larger accelerating gradients of several MV/m which will shorten the length of the accelerating structure. Moreover, a considerable savings on the operation cost of the facility over a long period of time can be expected.

As for the application to the production of tritium with multiple linacs with superconducting cavities, an optimization of tritium production versus proton energy is in order, especially in view of the expected savings on operation cost. It has been determined[10] that the 3/8 tritium production goal can also be met with a total beam power of 180 MW at the proton energy of 1.8 GeV. As stated above, this can be accomplished with four linacs each with an average beam current of 25 mA. For reliability and redundancy, an ion source current of 30 mA is then proposed, well within present technical capabilities.

General Layout

A scenario with multiple linacs and targets is shown schematically in Figure 2. It is made of four 1.8-GeV linacs, each accelerating an average beam current of 25 mA. Each linac is followed by a straight-ahead transport for beam disposal. Each linac feeds one of two targets placed on each side of the beam dump. Beam is taken to the targets by transport lines running at the same linac elevation. The layout shown in Figure 2 is optimized so as to require only the design of a single line for transport to the target, and of a single line to the beam dump. There are a total of five target stations, which may be designed around different principles of tritium production from spallation neutrons.

Since the beam energy is higher, targets for the generation of neutrons by spallation are deeper. But, because the total beam power on a target is four times smaller, the footprint has also an area four times smaller. This simplifies the design of the beam expander, beam manipulation and target handling.

Reliability and redundancy is obvious from the inspection of Figure 2. Beam availability on targets, and, thus, of tritium production is greatly increased. Failure or maintenance of any one component will have minimum impact on the operation of the entire facility.

Furthermore, the modular approach will allow construction of various components, namely accelerators, targets and beam transport lines, in stages. Decision on the continuation of the project to the final 3/8-goal configuration (or beyond), modification, and change of siting can then proceed in sequence as experience with hands-on cost, operation, performance, and need is acquired. This will also ensure prompt delivery of tritium as required.

A Modular Linac

Beam power can be expressed as the product of beam energy E and intensity I, that is

$$P_0 = E\,I. \tag{1}$$

The two quantities, E and I, can be traded against each other, as long as P_0 remains roughly the same. Their choice depends on the expected accelerator performance and cost, and on the target yield of neutrons and therefore tritium. As an example, which is believed close to optimum, the beam power of P_0 = 45 MW requires a beam current of 25 mA and an energy of 1.8 GeV.

An example of a superconducting linac is outlined in Figure 3, which has been extrapolated from recent ESS studies[11]. It is made of three parts: the front-end, which includes the ion source and the RFQ's, the low-β section, which may be made of either normal or superconducting cavities, and the high-β section which is definitively superconducting. Major parameters are given in Table 5.

The positive-ion source sits on a platform at 50-kV potential and generates an average current of 30 mA. The beam is immediately injected into a first RFQ at 350 MHz for acceleration to about 2 MeV, and then into a second RFQ at the same frequency for acceleration to 5 MeV where β = 0.10. Depending on the magnitude of the space-charge effects and on their control in the early part of acceleration and focussing, a beam current in the range 25mA will be effectively transmitted beyond the RFQs. Beam chopping, which is needed for pulsed neutron sources, is not required for the continuous mode of operation. The beam is then injected and accelerated into the low-β section to 100 MeV, when the proton velocity is large enough (β = 0.43) for a more effective acceleration in the subsequent high-β section. Both sections operate at 350 MHz (as the RFQ's). All cavities have an internal aperture of 100 mm. With the same frequency of 350 MHz from one end to the other of the accelerator, all rf buckets are filled with 4.4 x 10^8 protons, four times less than the corresponding value of the proposed 200-MW APT Linac, and slightly less than the particle count in the LAMPF buckets.

The design described here is just a feasible example. Other configurations are certainly possible. For instance, the two RFQ's may be replaced by a single one; different intermediate energies between 70 and 150 MeV can be selected, and so on. But it is important that the design allows for conservatism to reduce technical risk and guarantee reliability and availability.

The low-β section can be made of normal-conducting or superconducting cavities. Both options are being considered by different groups[11,12]. The high-β section is superconducting as it is being explored by the ESS group[11]. In the case of normal-conducting rf system the optimal accelerating gradient is close to 1 or 2 MV/m, whereas the superconducting solution allows higher accelerating gradients, in proximity of 5 to 10 MV/m. The actual acceleration gradient will be diminished by the need for inserting space for the focussing quadrupoles, tank interconnections, pumps, etc.. This factor can be optimized to about 50%, so that a total energy gain of 1.7 GeV in the superconducting linac may require a total length of about 400 m.

Superconducting Linacs

Superconducting technology has some obvious advantages for the continuous mode of operation, which can be summarized as higher accelerating gradient and negligible dissipated power[13]. At the same time it requires a cryogenic system which bears some cost both for construction and operation. The superconducting technology has been demonstrated successfully in several facilities[14]. Capitalizing on the results at Newman Laboratory of Cornell University, the Continuous Electron Beam Accelerator Facility in Virginia accelerates electrons in two 0.5-GeV linacs, joined together by magnet arcs, at 1.5 GHz with a cavity iris of 70 mm and an effective average gradient of 5 MV/m. In Europe, superconducting cavities at 350 MHz have been added to the LEP collider, where there are also plans to replace the entire accelerating system with similar rf cavities for a total of about 1 GV. A large number of superconducting rf cavities at 500 MHz have been added in the HERA electron storage ring (Hamburg) and in the TRISTAN electron-positron collider at KEK in Japan. This technology (see Table 6) has been developed for the acceleration of electron beams which have a velocity β very close to unity, and for a continuous mode of operation. When application to acceleration of protons is proposed, the most immediate question is that one needs to demonstrate the capability of design modulation to accommodate the change of beam velocity and then the continuous mode of acceleration. Indeed protons have not yet been accelerated in superconducting linacs.

But there are several examples of superconducting low-energy linacs for the acceleration of heavy-ions[15]. A comprehensive list is given in Table 7. Most notable[16] is ALPI, shown in Figure 4. The superconducting-cavity complex is located at Legnaro (Padua, Italy), with a total of 90 MV. It was just recently brought in operation. The system is made of 80 and 160 MHz quarter-wavelength cavities, shown in Figure 5, capable of operating with ion velocities as low as $\beta = 0.05$. At the moment the cavities are made of lead-coated copper and have a modest gradient of 2-4 MV/m.

A few superconducting niobium cavities at 350 MHz have been designed and operated at

Argonne[17], some of which are shown in Figures 6 and 7, for a velocity range between $\beta = 0.1$ and 0.8. These cavities are typically made of a single cell with one or two gaps depending on their geometry and dimension. At large velocities, $\beta > 0.4$, cavities can be made of two or more cells for better acceleration and power distribution. The accelerators listed in Table 7 are examples of operating superconducting low-β linacs that, in principle, can also accelerate protons from an RFQ. They typically accelerate only modest beam intensities, and it remains to demonstrate acceleration of intense beams. The merit of a low-β superconducting linac versus a normal-conducting DTL should be explored more in detail, especially considering the beam current that ought to be accelerated.

There is another important advantage in the use of superconducting cavities. They can be individually powered and phased with respect to each other, allowing a considerable flexibility in tuning and redundancy. In the event that one cavity should fail, acceleration can still proceed by simply readjusting the phase of the neighboring cavities. Moreover, elements like quadrupole magnets for the focussing of the transverse motion, can be easily interspersed with the rf cavities at the required spacing. There is always the freedom to choose normal-conducting magnets, as done in ALPI with modules shown in Figures 4 and 8, if there should be a concern about beam activation and the need for easy maintenance and replacement, or to take advantage of superconductivity by placing all elements in the same cryogenic modules, as recently proposed[18] by ANL, and shown in Figure 9.

As noted above, with superconducting cavities the dissipated power in the cavity wall is eliminated. Contrary to the experience with electron beams, because of the considerably lower intensity per beam bunch and the longer length of the bunches, the power loss to high-order modes (HOM) is also negligible. On the other hand, there is the relative modest penalty of the power being dissipated in the refrigeration system.

For simplicity, without prejudicing on future optimization design, we shall assume next that the low-β section is a normal-conducting DTL. The following design considerations are based on this assumption.

Total Length of a Single 45-MW Linac

The total length of a single linac can be estimated as follows

$$L = L_{FE} + E_{int} / (g\, G \cos\phi)_{\text{low-}\beta} + (E_{fin} - E_{int}) / (g\, G \cos\phi)_{\text{high-}\beta} \,, \tag{2}$$

where $L_{FE} \sim 10$ m is the length of the ion source plus the RFQ's. A normal-conducting low-β section, which accelerates at the rf phase angle $\phi \sim 30^o$ to the intermediate energy $E_{int} = 100$ MeV with a gradient of $G = 1.5$ MV/m diluted by a packing factor (for focusing elements) of $g = 0.8$, is about 92 m long. Similarly, the superconducting high-β section, with a gradient $G = 10$ MV/m and a dilution factor $g = 0.5$ at the rf phase $\phi \sim 30^o$, is about 393 m long for a final energy of $E_{fin} =$ 1.8 GeV. The entire linac is thus about 494 m long.

Total rf Power Requirement for a 45-MW Linac

The total rf power is the sum of beam power, cavity-wall dissipated power, and cavity-filling power[11,19,20], namely

$$P_{rf} = P_{beam} + P_{diss} + P_{fill} \cdot \tag{3}$$

By definition $P_{beam} = 1.8\ \mathrm{GeV} \times 25\ \mathrm{mA} = 45\ \mathrm{MW}$.

The dissipated power on the cavity walls is:

$$P_{diss} = G\, \Delta E\, /\ (R/Q)\, Q_0 \cos \phi\ , \tag{4}$$

where ΔE is the energy gain, $R/Q \sim 400$-800 ohm/m the characteristic impedance, and $Q_0 \sim 5 \times 10^9$ the figure of merit in the high-β section. In the normal-conducting DTL the characteristic impedance $R/Q \sim 1000$-2000 ohm/m and the figure of merit $Q_0 \sim 1 \times 10^5$. Thus $P_{diss} = 1.1$ MW in the low-β section, and only 7 kW in the high-β section.

The power required for filling the cavities, after they have been partially emptied by the passage of beam bunches, is given by the ratio of the total cavity energy

$$U = (2 \times 10^{-4}\ \mathrm{Joules})\, \lambda^2\, G\, \Delta E\, /\cos \phi, \tag{5}$$

where $\lambda = 85.66$ cm is the rf wavelength, G is given in MV/m, and ΔE in MeV, to the filling time τ_F, which is about four times the decay time τ_D for the normal-conducting cavities, and about ten times τ_D for the superconducting cavities;

$$\tau_D = Q_0\, P_{diss}\, /\, \pi\, f\, P_{beam}\ , \tag{6}$$

where f =350 MHz. It results that $P_{fill} = 1.5$ MW for the low-β section and 4.1 MW for the high-β section.

The total rf power requirement for the operation of a single 45-MW Linac is thus $P_{rf} = 52$ MW.

Total Cryogenic Power Requirement for a 45-MW Linac

The refrigeration system absorbs the following sources of heat[19,20]: power dissipated on the cavity walls, static heat loss, and losses to cavity high-order modes (HOM), namely:

$$P_{cry} = P_{diss} + P_{sta} + P_{HOM} \cdot \tag{7}$$

It is assumed that only the high-β section is superconducting at the temperature of 4.2 ^{0}K. Moreover it is assumed that the total length of 393 m of the section is under refrigeration. It has already been determined that $P_{diss} = 7$ kW. Assuming a conservative static loss of 5 W/m, it is also derived that $P_{sta} = 2$ kW. The losses to the high-order modes can be estimated from

$$P_{HOM} = (3.3 \times 10^{-7}\ \mathrm{W/cell})\, n_{cell}\, I\, f^2 , \tag{8}$$

where the beam average current I is in mA and the rf frequency f in MHz. Cell length varies between 20 and 40 cm; there are thus about $n_{cell} = 700$ rf cells which gives $P_{HOM} = 0.7$ kW. The total required refrigeration power is thus about $P_{cry} = 9.2$ kW.

Total AC Power Requirement for a 45-MW Linac

The total requirement of AC power can be broken down as the contribution to the rf power and to the cryogenic system.

The conversion efficiency from AC to rf power is given by the following product factors: the conversion efficiency from AC to DC of about 99%, the direct klystron efficiency of about 65% and the transmission efficiency in the waveguide which here is taken to be 90%. Thus the total conversion efficiency is $\eta_{rf} = 58\ \%$.

On the other hand, the cryogenic efficiency for a 4.2 ^{0}K plant is considerably low, $\eta_{cry} = 0.4\ \%$.

We can thus estimate the total AC power requirement to operate the a single 45-MW linac:

$$P_{AC} = P_{rf} / \eta_{rf} \quad + \quad P_{cry} / \eta_{cry} \quad = \quad (92.2 \quad + \quad 2.3)\ \mathrm{MW} \quad = 94.5\ \mathrm{MW}. \tag{9}$$

Operation Cost of a Single 45-MW Linac

There are three components which determine the operation cost of a single linac: scientific and technical staffing, maintenance, and electric power cost. The latter has the largest contribution. The cost for electricity for the yearly operation can be determined as follows

$$O = (0.0665\ \$/\mathrm{kWh}) \times (365\ \mathrm{days}) \times (24\ \mathrm{hours/day}) \times \eta_{avail} \times P_{AC} \tag{10}$$

where 0.0665 \$/kWh is the assumed electricity cost in 1994 dollars. The fraction of the year for which the linac is to be available for operation is expressed by η_{avail}. With 100% of the yearly time available, $\eta_{avail} = 1$, and O = 55 M\$/year. This does not include target and tritium processing costs.

Investment Cost of a Single 45-MW Linac

The total capital cost for the construction of a single linac can be broken down in the following elements[20,21]:

• Front-End, made of the ion source and of the RFQ's	30 M\$
• Normal-Conducting 100-MeV DTL at 0.22 M\$/m all inclusive (rf cavities, focussing magnets, vacuum system, tunnel, klystron gallery, etc...)	20 M\$
• High-β Section at 0.29 M\$/m all inclusive (rf cavities, focussing magnets,	

vacuum system, tunnel, klystron gallery, etc...)	114 M$
• Klystrons at 4 M$/MW of rf power	280 M$
• Electrical Distribution at 0.14 M$/MW of AC power	15 M$
• Refrigeration Plant at 4 M$/kW of cryogenic power	40 M$

The total construction cost per linac is thus 420 million in 1994 dollars; of which about half is the cost of the klystrons. This amount does not include the cost for targets and tritium removal; and assumes no contingency and no escalation.

Comparison of the Multiple-Linac Approach with the Single APT Linac

Using the considerations made and the scaling formulas for cost and power given above, we can work out a comparison of the different phases of the Los Alamos APT Linac with the multiple-linac approach. The results are shown in Tables 8 and 9. Values are in 1994 dollars. Again the cost of targets has not been included in this analysis, and no allowance for contingency and escalation has been made. It is seen that the modular approach has three clear advantages over the phased approach of the APT Linac: the operation cost is substantially lower, the tritium production is more efficient with construction phasing, and it is clearly at less technical risk.

Before a final choice is made, it is obvious that a preliminary conceptual study is needed to determine:

1. Optimization of the modular approach.
2. Accelerator performance versus beam intensity and final energy.
3. Target performance versus beam final energy.
4. More accurate cost and power analysis.

As examples, we have considered also few other cases of linac configurations. The procedure outlined here allows flexibility with time. Once the first module has been built, it may be found more attractive and convenient to add more superconducting cavities to boost the beam to even larger energies. This allows trading of the number of linac modules with beam energy and linac length, for the same total beam power. Moreover, if at the same time ion sources should be developed far enough with even larger beam currents, it may also be found that by simply replacing the ion source and by doubling the number of rf power amplifiers, one can obtain the required performance with a single superconducting linac. All these cases are compared against each other in Table 10. The last column shows a case corresponding to a very high-current ion-source; if this should be developed, it is seen that final energy can be traded against beam intensity for a more economical solution.

In summary, the construction of a first 45-MW linac module will allow phasing based on acquired experience with beam performance. A variety of solutions will then be at hand from which one can choose to minimize cost, to improve reliability and availability, and to reduce the technical risk.

Experimental Demonstration of a High-Intensity Proton Linac

As we have seen, a single linac is made of three parts: the front-end, that is the source and the RFQs, the low-beta section, which could be normal- or super-conducting, and the high-beta section which is made of superconducting cavities. The front-end has little impact on the total cost of the accelerator (if one neglects technology development costs), but its design has crucial relevance to the beam performance, and machine availability. The nature of the project of producing tritium requires a system which can quickly and reliably be turned on with a minimum of research and development. It is thus important to develop a prototype of a few-MW low-energy conventional front-end to demonstrate continuous mode of operation at the required beam current. The demonstration could then constitute the prototype of the actual front-end of a single linac. As shown schematically in Figure 10, it requires:

1. Development of a continuous ion source at 30 mA on a 50-kV platform.
2. Development of a 2-MeV RFQ followed by a 5-MeV RFQ both at 350 MHZ.
   (As an alternative, the two RFQ's can be combined into a single device).
3. Development of a normal-conducting 20 MeV-DTL at 350 MHz.
   (As an alternative, the normal-conducting accelerator stage can be entirely eliminated).
4. Development of superconducting cavities at 350 MHz for acceleration to 40 MeV.

The cost of the experimental program[24] is close to 100 M$. A demonstration of principle can also be made with hardware available in accelerator laboratories, and would still be quite useful, even in the case the parameters do not quite match the required values, to prove acceleration of intense beams of protons in a continuous mode of operation from the low-velocity end.

A 45-MW Linac for the Advanced Spallation Neutron Source

A single proton linac which generates 45 MW of beam power, as described above for tritium production, can produce a neutron flux by spallation exceeding that of the Advanced Neutron Source[7] of Oak Ridge based on nuclear-reactor technology. The 45-MW linac represents quite a powerful proton source when it is compared to the other pulsed spallation neutron sources which are currently under investigation. At the energy of 1.8 GeV, an intensity of 1.6 x 10^{17} protons per second yields a neutron flux[22] of about 10^{16} neutrons/cm^2/s. Moreover, it is possible to generate neutron pulses of different time duration by simply pulsing the proton source. There are three conceivable modes of operation: continuous beam with 100% duty cycle, long pulses in the millisecond range, and short pulses of a few microseconds at 10 and 60 pulses per second. A layout of the Advanced Spallation Neutron Source is shown schematically in Figure 11. Because of the large beam power involved, multiple targets are required for a more efficient, safe, and reliable operation.

The full beam power can be delivered to those experiments that require continuous beam at 100% duty cycle. The target arrangement is essentially similar to the one for tritium production, but the targets are designed for other applications and to allow multiple users. By pulsing the linac at 60 Hz and at 15% duty cycle, it is also possible to provide neutron beams to those experiments that require long pulses, in the range of few milliseconds, at the same repetition rate. The average proton power available for this mode of operation is reduced to 6.75 MW, still very considerable.

This mode of operation requires adding the capability of pulsing both the superconducting linac and the ion source. The beam average intensity is lower, but the peak value remains 25 mA.

The short-pulse mode of operation, in the microsecond range, requires the inclusion of two Accumulator Rings where the proton beam is stored and compressed to the required duration, as shown in Figure 11. One ring generates beam pulses at 10 and the other at 60 Hz. There are two fundamental limitations encountered in an Accumulator Ring: first, the total number of beam turns that can be stored should not exceed the value of a thousand. This is achieved by selecting properly the circumference of the rings and thus the revolution period. Second, the space-charge limitation, customarily expressed as the depression $\Delta\nu$ of the betatron tune, should not exceed 0.2. This value is reached by allowing the beam size to increase accordingly.

To achieve a lossless multiturn injection into the rings by charge exchange, a negative-ion source feeds the linac, and the beam pulse is chopped by 60% between the two RFQ's. That generates a train of micropulses matching the rf capture in the Accumulator Rings. For the operation of one of the two rings at 60 Hz, the duty cycle of 15% is obtained by choosing a convenient circumference of the ring to allow no more than one thousand beam turns.This yields an average beam power of 4 MW. The second ring operates at 10 Hz; with the same duration of injection, the duty cycle is now only 2.5%, and the average beam power 0.67 MW.

A preliminary design of the Accumulator Rings has been made and the main parameters are given in Table 11. It is to be noticed that both rings operate well below space-charge limit. It is then possible to develop an ion source of even larger peak current. For instance an ion source of 50 mA could easily double the average beam power.

A Proton Source for the Production of Intense Muon Beams

There is recently a renewed interest for a muon collider[23], in the TeV energy range with high luminosity, for exploration of the most fundamental aspects of particle high-energy physics. This project requires a large amount of μ-mesons which are not available in nature and have thus to be produced by impinging intense beams of protons on targets at an energy of about 30 GeV. Moreover muons are unstable particles and decay fast; thus, production, collection, cooling and acceleration has to proceed in a very short time before two beams of μ^+ and μ^- are brought in collision.

The high-intensity 30-GeV proton facility is outlined in Figure 12. A 1.8-GeV proton linac, similar to the one described above for tritium production and for the Advanced Spallation Neutron Source, is the injector to a fast-cycling 8-GeV Synchrotron (the Booster in Figure 12), which operates at the repetition rate of 30 Hz. Because of the acceleration, the number of beam turns that can be injected into the Synchrotron is now limited to 300 to avoid excessive beam losses during the rf capture. The linac is thus pulsed at 30 Hz and operates with a duty cycle of 2.5%. To allow multiturn injection by charge exchange, a negative-ion source is feeding the linac. Beam chopping of 60% is also applied for matching the rf capture during injection into the fast-cycling Synchrotron. The peak current being accelerated to 1.8 GeV is 25 mA, but the average current is considerably lower. The 8-GeV Synchrotron (the Booster) has the same size and design of the Accumulator Ring described earlier, except that now the bending field is ramped to allow for acceleration.

At the end of the acceleration, a beam pulse is transferred in a Holding Ring, shown in Figure 12, held at constant field, otherwise of the same size and design of the Booster. The beam is stored circulating, waiting that a second pulse is accelerated to the same energy. Then both beam pulses are injected into a second fast-cycling Synchrotron (the Main Ring of Figure 12), which accelerates to the final energy of 30 GeV at the repetition rate of 15 Hz. The Main Ring has a circumference twice that of the Booster. At the end of the acceleration cycle, the beam is extracted from the Main Ring and used on a sequence of targets and transport channels for the production of muons. Taking the value of 0.1 for the yield of protons to a pair of muons, the facility generates about 10^{14} μ-pairs per second.

This facility can be used of course also for a variety of other applications in nuclear and high-energy physics, like neutrino physics, production of kaons and antiprotons, study of CP violation, and so on. Major parameters for the Accelerators are listed in Table 12.

Conclusions

We have explored a Modular (or Multiple) Linac approach for Tritium Production (MLTP) as opposed to the single APT Linac proposed by the Los Alamos team. Our intent has been to reduce the amount of technical risk involved in the project, considering its size and magnitude. A Multiple Linac approach, in our view, provides modularity, more flexibility, better reliability, and improved availability. For the attainment of the same goal, we have also proposed the use of superconducting cavities to eliminate, or at least to reduce, constraints such as linac length, acceleration gradient, power consumption, and difficulty of operation. Nevertheless, a 45-MW Linac still represents a considerable extrapolation, an order of magnitude above what is been investigated these days for spallation neutron sources, and considerably more above currently demonstrated technology. Thus, our proposal should be taken cautiously. Once the concept of a multiple, reduced requirement linac approach is accepted, a more realistic feasibility design needs to be done.[24]

A 45-MW linac of an energy of few GeV is also a powerful tool for basic and energy research in a variety of fields. The research community has, of course, quite some interest in the exploitation of such a facility, even and especially if it is made of only one of the four linacs, and would seek the full share of the demonstration program. In fact the know-how for developing this accelerator is currently very limited and essentially concentrated in large accelerator DOE laboratories. It seems obvious that in the case that such a project be authorized and funded, the demonstration of the required technology can and should take place in DOE laboratories. If successful, this would result in a first stage availability of the facility to the research community, and subsequently transferring of the acquired technology to industry for applications like tritium production.

Acknowledgments

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Table 1. Demonstrated Ion Source Performance CW or Positive Ions[4]

Source Type	Ion +/-	I_{peak} (mA) (protons)	Extract Voltage (kV)	Arc Pulse length (ms)	Rep rate (Hz)	Arc Duty Factor (%)	ε_{norm} (mm-mrad)	Comments
Volume PSI	+	20	60	CW	CW	100	0.3π (90%)	Modified (by PSI) Culham Filament (W) ≈33% proton yield
Volume LBL	+	60						RF ≈80% proton yield
Volume Grumman	+	44	42	CW	CW	100		RF ≈55% proton yield
Volume JAERI	+	140	100	1	100	10	0.5π (90%)	Filament 85% proton yield
Volume LANL	+	60	47	CW	CW	100		Microwave ≈200 hr longevity test 75% proton yield
Duoplasmatron LANL	+	30	35	1	120	12	0.065π (rms)	Run to 45 ma at 6% DF Directly interfaced to 750 kV column
Volume TRIUMF	-	12	25	CW	CW	100	0.3π (4 rms)	Filament (Ta) e/H ≈ 5
Volume TRIUMF	-	1.6	25	3	60	20	0.3π (4 rms)	Microwave Good lifetime

Table 2. Intense Proton Sources[5]

			Av. Current mA	Energy GeV	Power MW	Duty Cycle %
Operating:	AGS Booster	Linac/Synchr.	0.02	1.5	0.03	< 1.0
	ISIS	Linac/Synchr.	0.20	0.8	0.16	1.0
	LANSCE	Linac	1.0	0.8	0.8	7.0
Proposed:	AUSTRON	Linac/Synchr.	0.25	1.6	0.4	< 1.0
	SINQ	Cyclotron	1.5	0.6	0.9	100
	ANL	Linac/Synchr.	0.5	2.0	1.0	2.5
	NCNR	Linac/Accum.	1.25	0.8	1.0	7.2
	PSNS-BNL	Linac/Synchr.	1.35	3.6	5	2.8
	ESS	Linac/Synchr. or Accumul.	3.8 / 1.7	1.3 / 3.0	5	6.6
	ANS-Moscow	Linac/Synchr.	0.5	10.0	5	5.0
	ETA-Japan	Linac/Accum.	10	1.5	15	10
	APT	Linac	200	1.0	200	100

Table 3. Operating Proton Linacs in USA

	BNL	Fermilab	LAMPF
Source Current Voltage	50 mA 35 kV	35 mA 750 kV	30 mA 80 kV
RFQ frequency energy	201 MHz 0.75 MeV	-- --	201 MHz 2.5 MeV
DTL frequency energy	201 MHz 200 MeV	201 MHz 116 MeV	201 MHz 100 MeV
High-β frequency energy	-- --	805 MHz 400 MeV	800 MHz 800 MeV
Duty Cycle %	< 1.0	< 1.0	6.7

Table 4. Proposed Proton Linacs in USA

	SSC	PSNS-ANL	PSNS-BNL	APT
Source Current Voltage	30 mA 35 kV	33 mA 35 kV	100 mA 50 kV	2 x 110 mA 75 kV
RFQ frequency energy	428 MHz 2.5 MeV	400 MHz 2 MeV	350 MHz 2.5 MeV	350 MHz 7.0 MeV
DTL frequency energy	428 MHz 70 MeV	400 MHz 70 MeV	350 MHz 70 MeV	350-700 MHz 20-100 MeV
High-β frequency energy	1283 MHz 600 MeV	1200 MHz 400 MeV	700 MHz 600 MeV	700 MHz 1000 MeV
Duty Cycle %	< 1.0	2.5	2.8	100

Table 5. General Parameters of a Modular 45-MW Linac

	Current	Length	Frequency	Energy
Ion Source	30 mA	2 m	d.c.	50 keV
RFQ1	27 mA	3 m	350 MHz	2 MeV
RFQ2	25 mA	5 m	350 MHz	5 MeV
Low - β Section	25 mA	90 m	350 MHz	100 MeV
DTL normal-conducting. Gradient 1.5 MV/m. Packing Factor 0.8				
High - β Section	25 mA	390 m	350 MHz	1.8 GeV
Superconducting Cavities. Gradient 10 MV/m. Packing Factor 0.5.				

Accelerating rf Phase	30^o
Number of Protons per rf Bucket	4.4×10^8
Cavity Internal Diameter	10 cm

Table 6. SuperConducting RF Systems[14]

	CEBAF	HERA	LEP (*)	TRISTAN
Frequency	1,500 MHz	500 MHz	350 MHz	508 MHz
Energy	4 x 2 x 500 MeV	40 MeV/turn	1600 MeV/turn	140 MeV/m
Gradient	5 MeV/m	5 MeV/m	5 MeV/m	5 MeV/m
Inter. Diameter	75 mm	100 mm	100 mm	100 mm
Oper. Temper.	2.0 ^oK	4.2 ^oK	4.2 ^oK	4.2 ^oK
Beam Current	0.2 mA	40 mA	4 mA	14 mA
Beam Power	0.2 MW	1.6 MW	6.4 MW	2.0 MW

(*) Future Upgrade Plan

Table 7. Demonstrated Superconducting Heavy-Ion Linac Performance[15]

Laboratory	Material	Cavities	Gradient	Commissioned
Argonne / ATLAS	Nb	46	2-4 MV/m	1978
Stony Brook SUNYLAC	Pb-Cu	56	2-2.5 MV/m	1983
SACLAY / France	Nb	50	2.2 MV/m	1987
Univ. Washington	Pb-Cu	36	3 MV/m	1987
Florida State Univ.	Nb	14	2-3 MV/m	1987
JAERI / Japan	Nb	44	7 MV/m	1994
ALPI / Italy	Pb-Cu	35	2-4 MV/m	1994

Table 8. Comparison of Modular Linacs versus APT Linac

	Modular Linac	**APT**
Number of Modules	4	1
Source Current	30 mA	(2 x) 110 mA
Output Current	25 mA	(2 x) 100 mA
RFQ 1	350 MHz 2 MeV	350 MHz (2 x) 7 MeV
RFQ 2	350 MHz 5 MeV	none
DTL	350 MHz 100 MeV	350 MHz (2 x) 20 MeV
Funnel	none	yes
BCDTL	none	700 MHz 100 MeV
High - β Section	s.c. 350 MHz 1.8 GeV	n.c. 700 MHz 1.0 GeV
Permanent Magnets	possible use	no
Cavity Internal Diameter	10 cm	5 cm
Protons / Bunch (*)	0.44×10^9	1.8×10^9
Beam Halo	less relevant	very relevant
Total Length of Linac	495 m	1180 m
rf Power / Linac	52 MW	254 MW
Cryogenic Power / Linac	9 kW	none required

(*) all buckets are full

Table 9. Comparison between APT Linac and Modular Linacs

Tritium Production	3/32		3/16		3/8	
	APT-Linac	Modular	APT-Linac	Modular	APT-Linac	Modular
No. of Linacs	1	1	1	2	1	4
Beam Energy	500 MeV	1800 MeV	1000 MeV	1800 MeV	1000 MeV	1800 MeV
Beam Intensity	100 mA	1 x 25 mA	100 mA	2 x 25 mA	2 x 100 mA	4 x 25 mA
Beam Power	50 MW	1 x 45 MW	100 MW	2 x 45 MW	200 MW	4 x 45 MW
Length of Linac	580 m	495 m	1180 m	495 m	1180 m	495 m
Funnel	no	no	no	no	yes	no
rf Power	71 MW	52 MW	139 MW	104 MW	256 MW	207 MW
Cryo-Power	--	9.2 kW	--	18.4 kW	--	36.7 kW
AC-Power	123 MW	92 MW	240 MW	183 MW	443 MW	367 MW
Capital Cost	460 M$	420 M$	880 M$	840 M$	1400 M$	1680 M$
Operation Cost (*)	72 M$/y	53 M$/y	140 M$/y	107 M$/y	258 M$/y	214 M$/y
40-year Cost	3.3 B$	2.6 B$	6.5 B$	5.1 B$	11.7 B$	10.2 B$

(*) Based on 6.65 cents/kWh and 100% availability.

Table 10. Comparison of Different Linac Scenarios

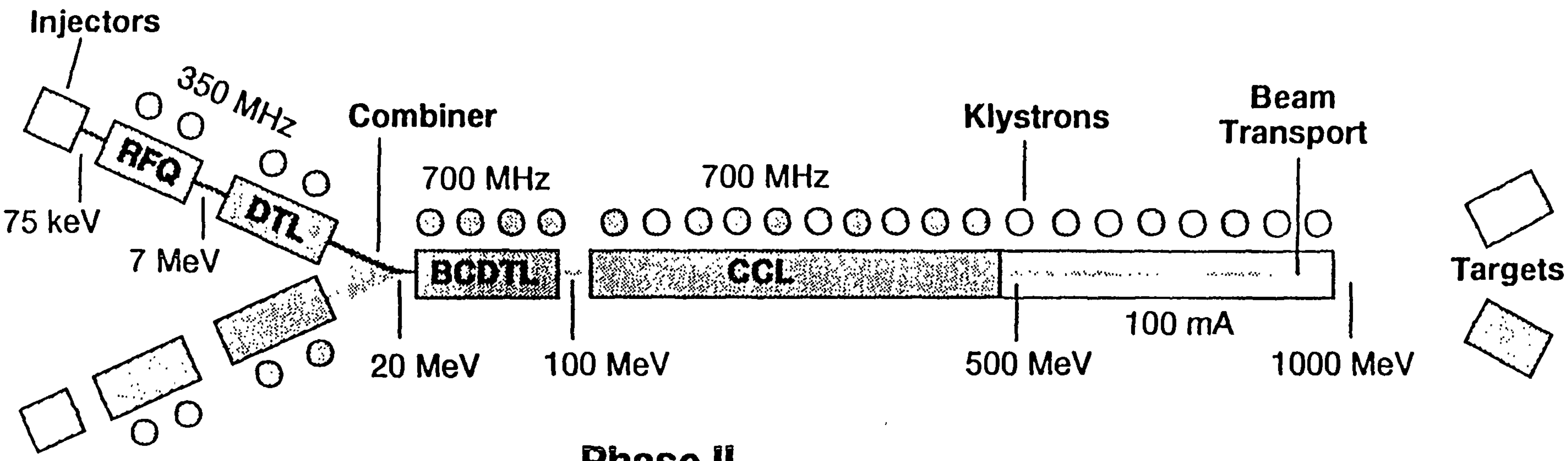
	APT	1.8 GeV Modular Linacs	3.6 GeV Modular Linacs	3.6 GeV Single Linac	2.0 GeV Single Linac
Technology	norm. conducting	superconducting	superconducting	superconducting	superconducting
Number of Linacs	1	4	2	1	1
Energy	1000 MeV	1800 MeV	3600 MeV	3600 MeV	2000 MeV
Beam Intensity	200 mA	25 mA	25 mA	50 mA	80 mA
Power	200 MW	180 MW	180 MW	180 MW	160 MW
Total Length	1182 m	494 m	910 m	910 m	540 m
rf Power	256 MW	207 MW	202 MW	201 MW	181 MW
Cryogenic Power	--	37 kW	38 kW	20 kW	12 kW
AC Power	443 MW	367 MW	359 MW	352 MW	315 MW
Capital Cost	1406 M$	1683 M$	1579 M$	1219 M$	992 M$
Operation Cost	258 M$/year	214 M$/year	209 M$/year	205 M$/year	184 M$/year
40-Year Cost	11.72 B$	10.23 B$	9.94 B$	9.43 B$	8.34 B$

Table 11. Accumulator Ring Parameters for the Advanced Spallation Neutron Source

Circumference	726.4 m
Kinetic Energy	1.8 GeV
Bending Radius	42.8 m
Bending Field	2.0 kG
Revolution Period	2.6 μs
Number of Turns Injected	970
Harmonic Number, Number of Bunches	4
Protons per Bunch	0.6×10^{14}
Bunch Area	8 eV-s
Betatron Emittance, full normalized, H & V	260 π mm mrad
Transition Energy, γ_T	18.2
rf Frequency	1.55 MHz
rf Peak Voltage	300 kV
Synchrotron Tune, Q_s	0.003
Bunch Length, rms	52 ns
Bunch Momentum Spread, rms	0.34 %
Bucket Area	26 eV-s
Bucket Height	±1.3 %
Space-ChargeTune-Shift, $\Delta\nu$	0.13
Repetition Rate	10 / 60 Hz
Duty Cycle	2.5 / 15 %
Average Beam Power	6.7 / 4.0 MW
Average Beam Current	0.375 / 2.25 mA

Table 12. Accelerator Parameters for the Advanced Proton Source

	Booster	Holding Ring	Main Ring
Circumference, m	726.4	726.4	1452.8
Repetition Rate, Hz	30	d.c.	15
Duty Cycle, in %	2.5	--	--
Kinetic Energy (GeV) @ Injection	1.8	8.0	8.0
@ Extraction	8.0	--	30.0
Bending Radius, m	42.8	42.8	85.6
Bending Field (kG) @ Injection	2.00	6.91	3.46
@ Extraction	6.91	--	12.06
max. Field Variation, T/s	46.3	d.c.	40.4
Number of Turns Injected	320	single-turn	single-turn
Harmonic Number, Number of Bunches	4	4	8
Protons per Bunch	2×10^{13}	2×10^{13}	2×10^{13}
Bunch Area, eV-s	3.0	6.0	10.0
Norm. Betatron Emittance, π mm mrad	120	120	120
Transition Energy, γ_T	18.2	18.2	36.4
rf Frequency, MHz	1.51 - 1.60	1.60	1.60 - 1.61
rf Peak Voltage, MV	1.8	0.2	5.6
rf Peak Power, MW	7.5	--	27
max Synchrotron Tune, Q_s	0.0035	0.00034	0.0011
Space-Charge Tune-Shift, $\Delta\nu$	0.17	0.025	0.042
rms Bunch Length @ Extraction, ns	10	18	5
Average Beam Power, MW	3.0	3.0	11.5
Average Beam Current, mA	0.38	0.38	0.38



Phase II
- Extend CCL to 1000 MeV
- Add RF power stations

Phase I
- 100 mA CW, 500 MeV
- Transport line from 500 MeV to targets

Phase III
- Add funneled front end
- Add RF power stations
- Increase current to 200 mA

Beam power	50 MW	100 MW	200 MW
Plant AC power	197 MW	355 MW	550 MW

Figure 1. The Los Alamos APT Linac[1] with Construction Phasing[2] shown

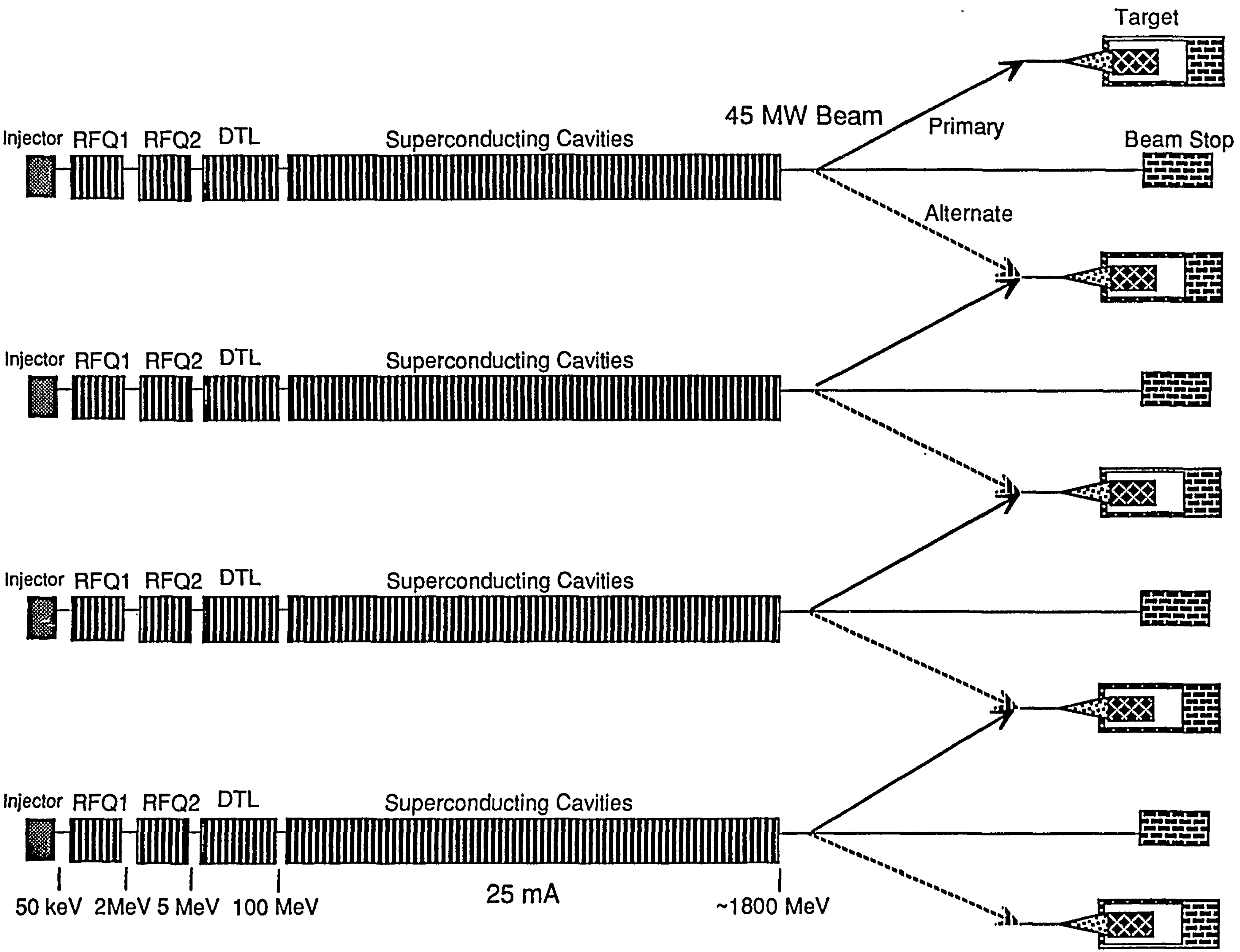


Figure 2. Multiple-Linac Approach for Tritium Production

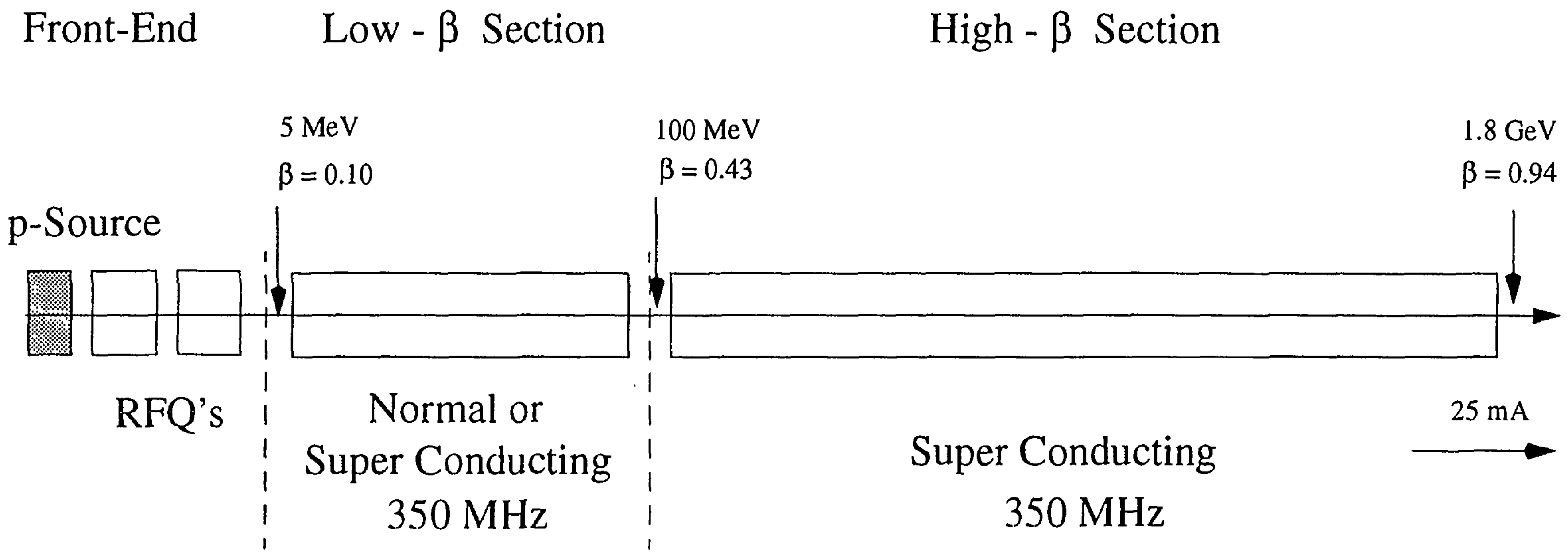
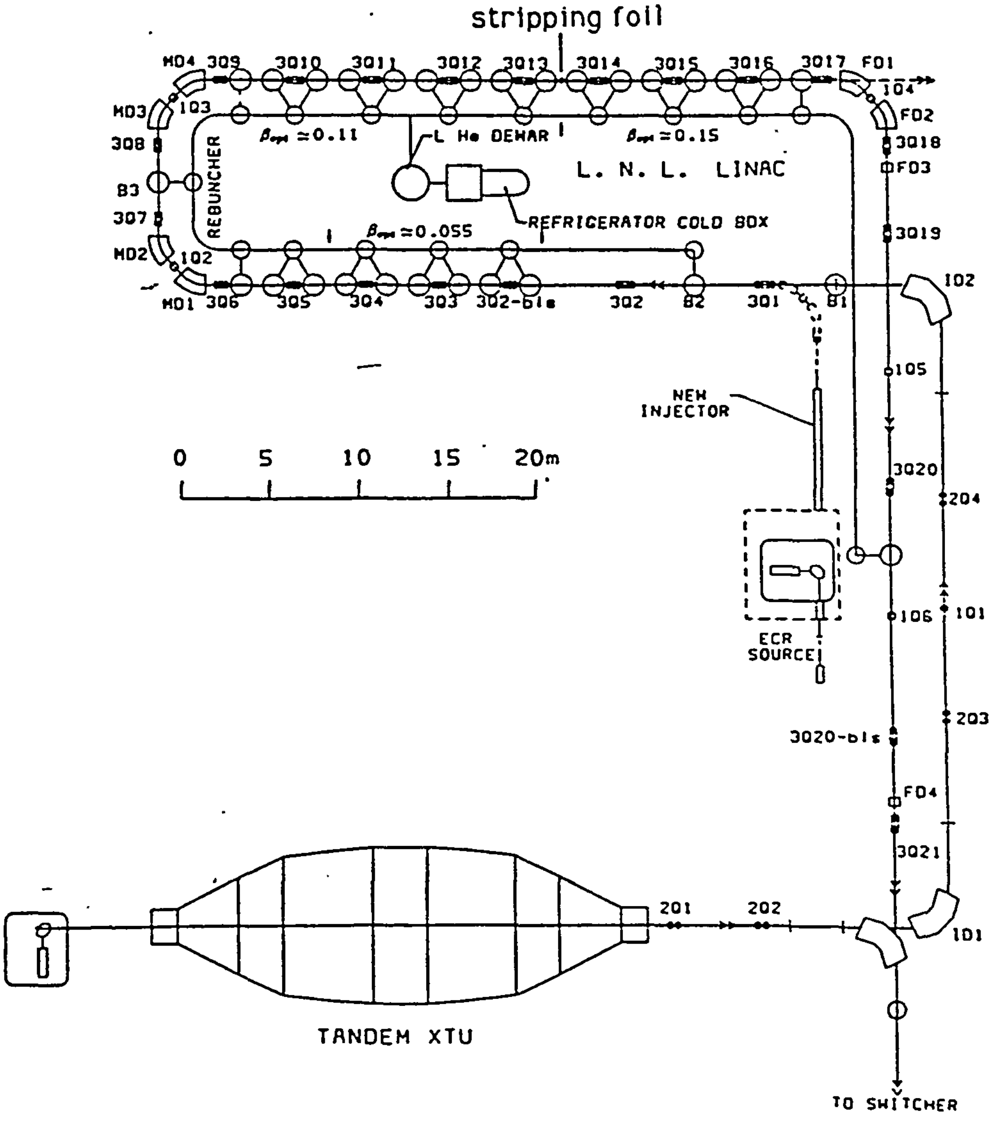


Figure 3. A Modular 45-MW Linac[11]



Acceleration to 5 - 30 MeV/u with *superconducting* low-β *cavities*

Figure 4. The ALPI superconducting accelerator at Legnaro[16] (Padua, INFN)

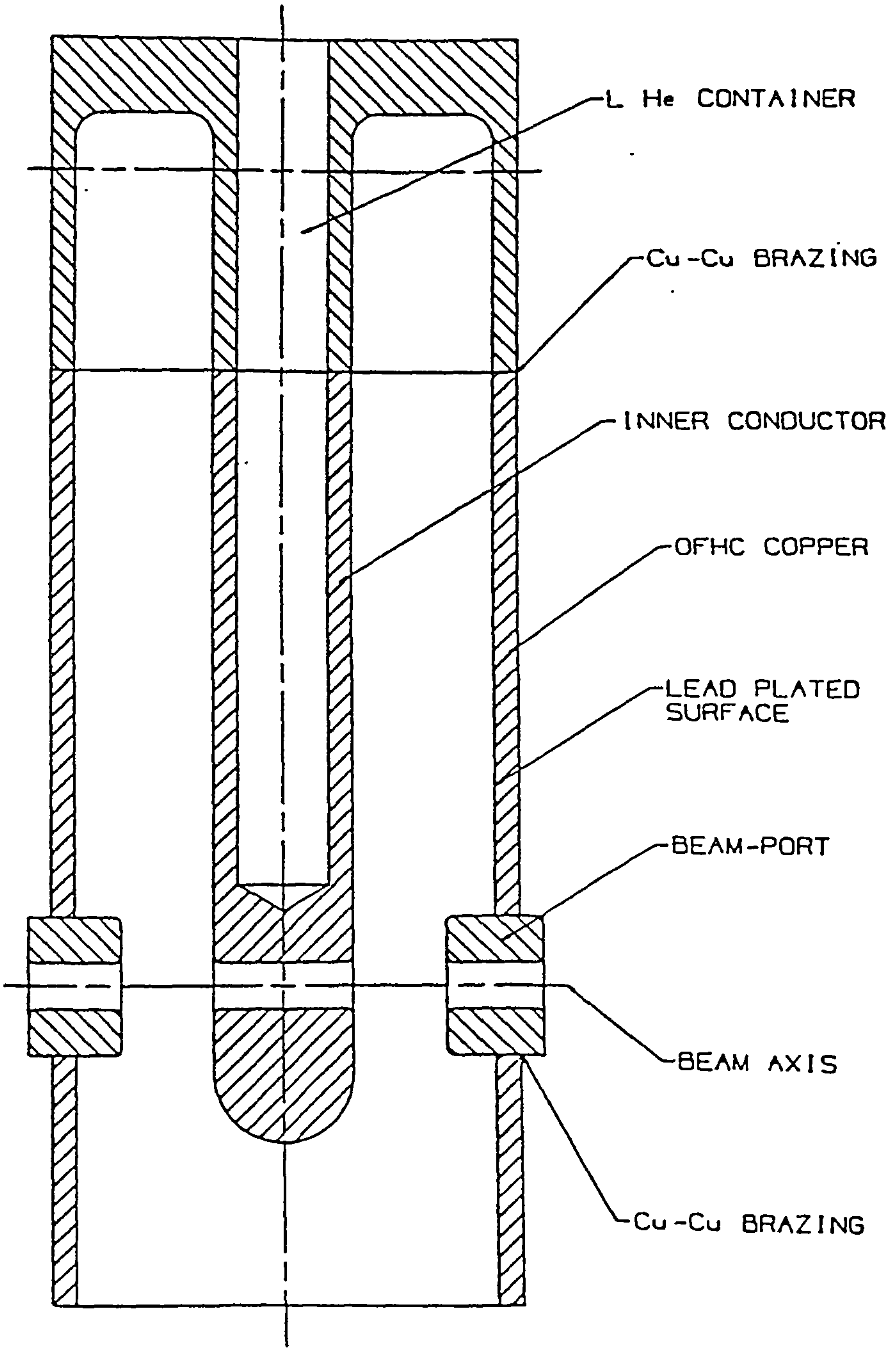
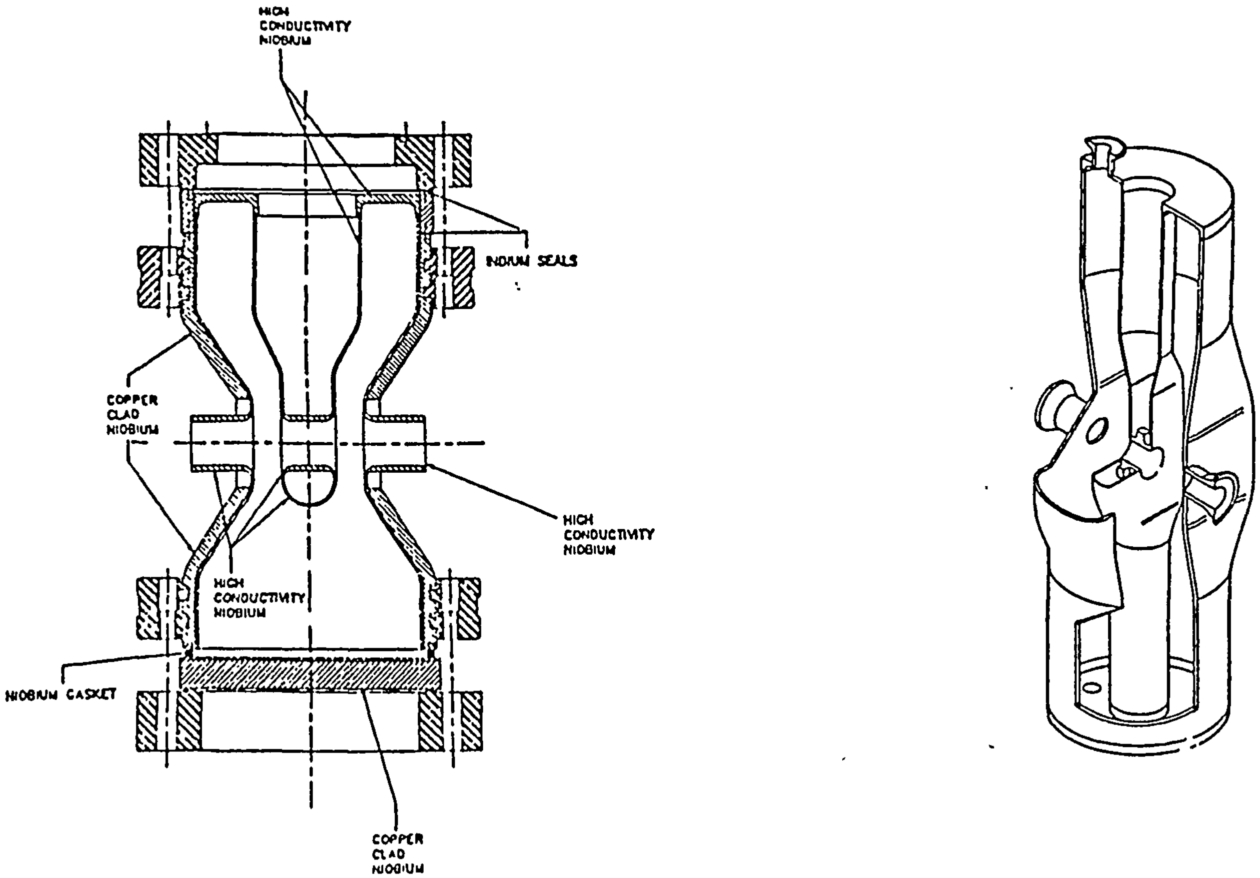


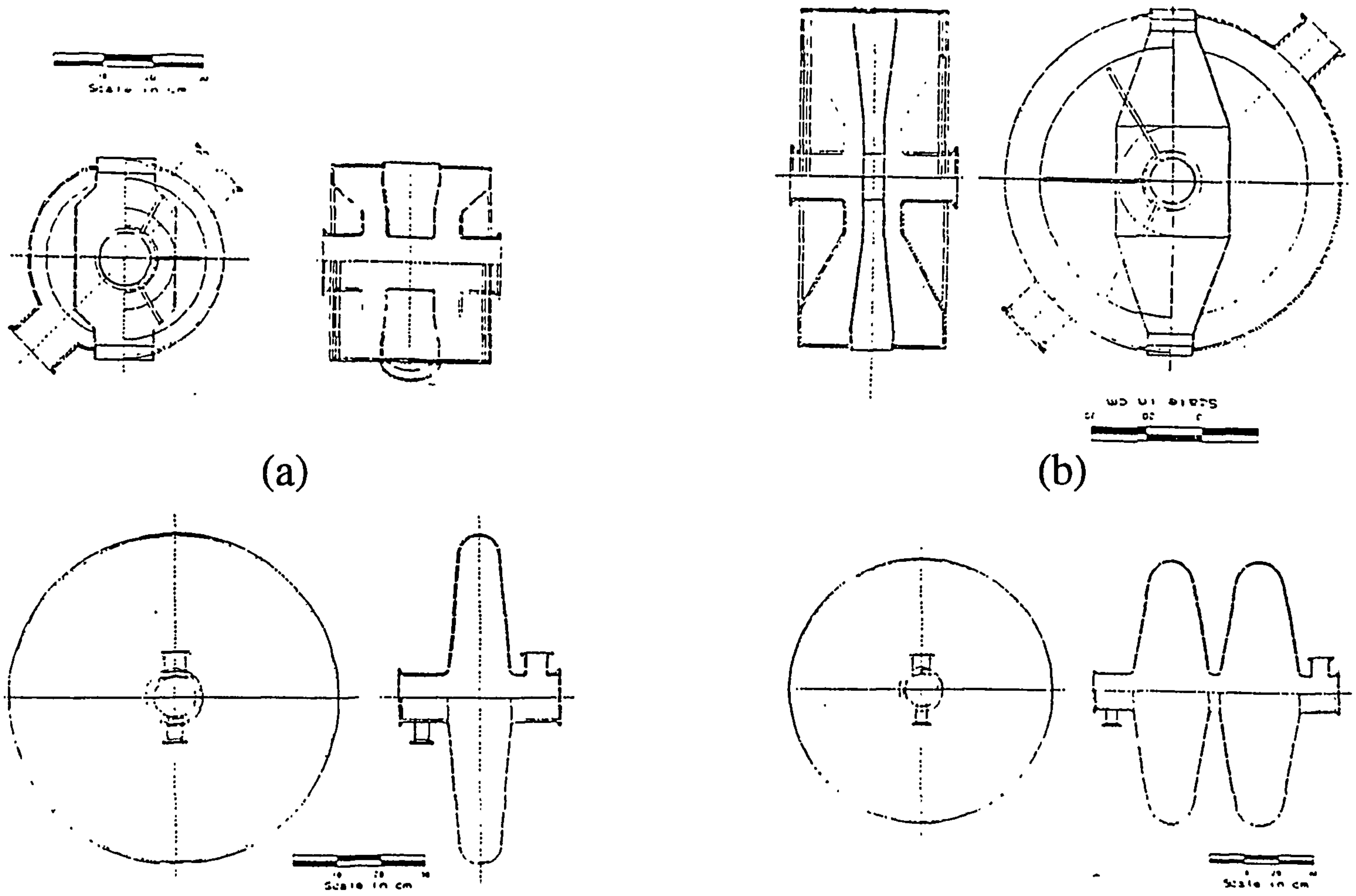
Figure 5. Quarter-Wave resonator in ALPI.[16] Lead-coated Copper Cavity. 80 and 160 MHz. Gradient 2-4 MeV/m.



(a)

(b)

Figure 6. (a) 400-MHz coaxial quarter-wave resonator[17]; $\beta = 0.15$
(b) 350-MHz coaxial half-wave resonator[17]; $\beta = 0.12$



(a) (b)

(c) (d)

Figure 7. (a) 175-MHz 2-gap spoke resonator[17]; $\beta = 0.125$
(b) 350-MHz 2-gap spoke resonator[17]; $\beta = 0.45$
(c) 350-MHz single-cell TM_{010} resonator[17]; $\beta = 0.45$
(d) 350-MHz 2-cell TM_{010} resonator[17]; $\beta = 0.8$

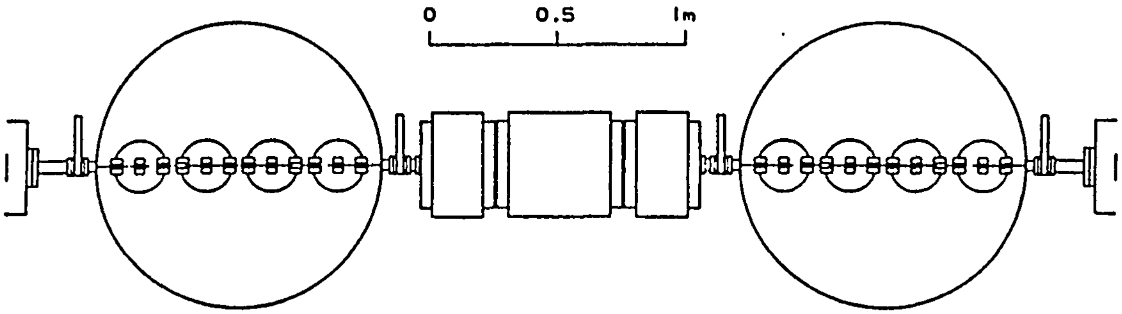


Figure 8. The Module in the ALPI Transport[16]

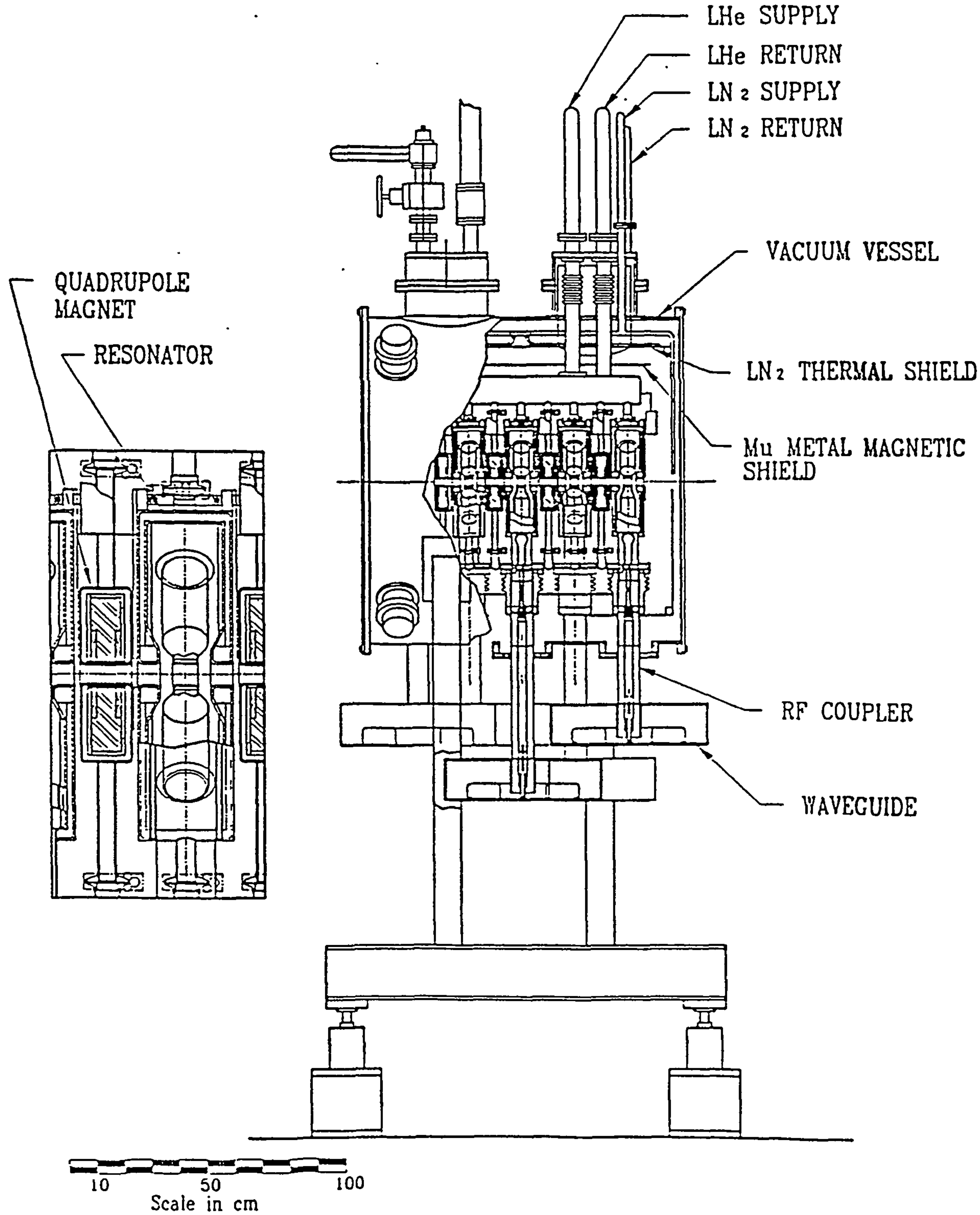


Figure 9. Conceptual drawing of a high-current superconducting linac section[18]. It comprises 5 accelerating cavities operating at 352 MHz. Focusing is provided by superconducting quadrupoles located between the cavities.

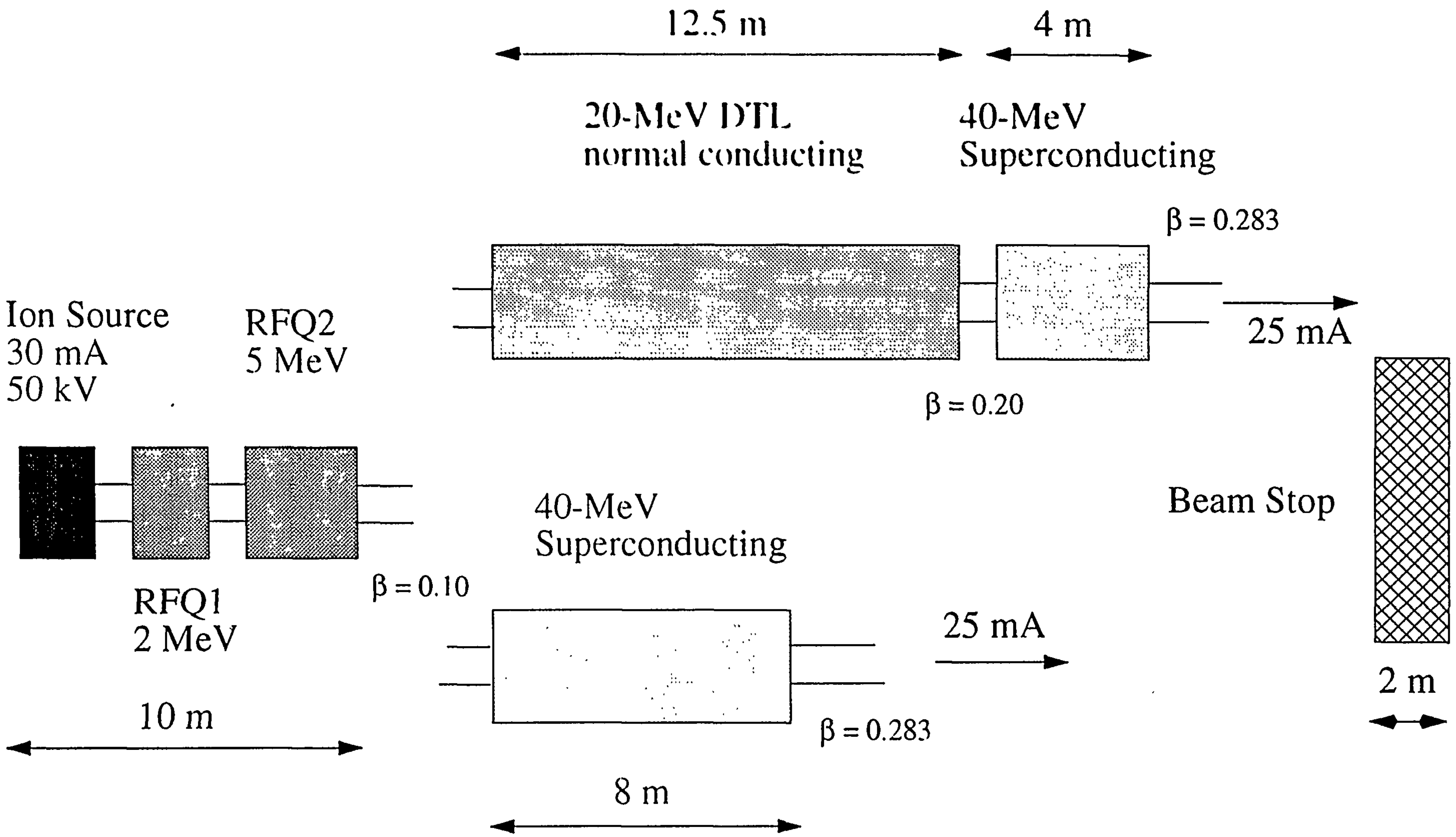


Figure 10. Experimental Set-Up to demonstrate Acceleration of Protons in Continuous Mode of Operation[24]

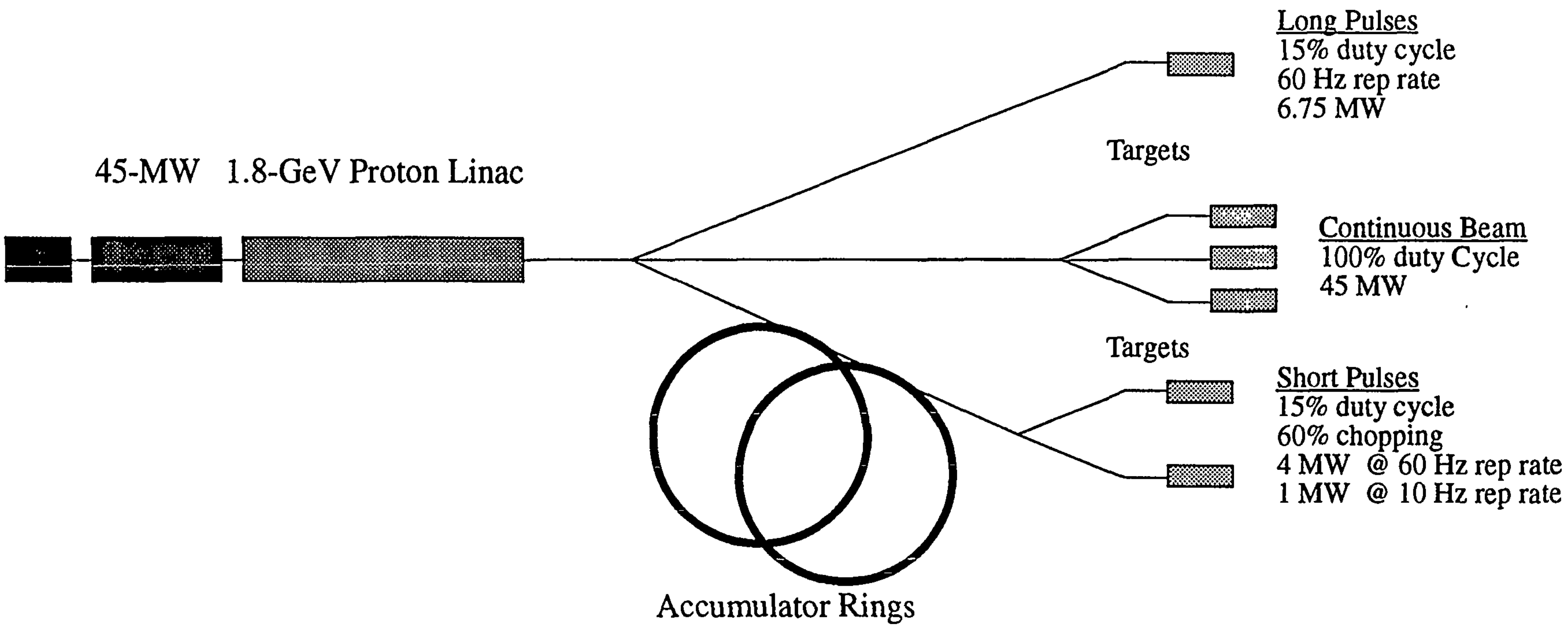


Figure 11. Layout of the Advanced Neutron Source. Neutrons are generated by spallation from a 45-MW 1.8-GeV proton Linac. Three modes of operation are possible: Continuous Beam, Long Pulses, and Short Pulses. For the latter mode the beam is compressed in one of two Accumulator Rings for 10 and 60 pulses per second.

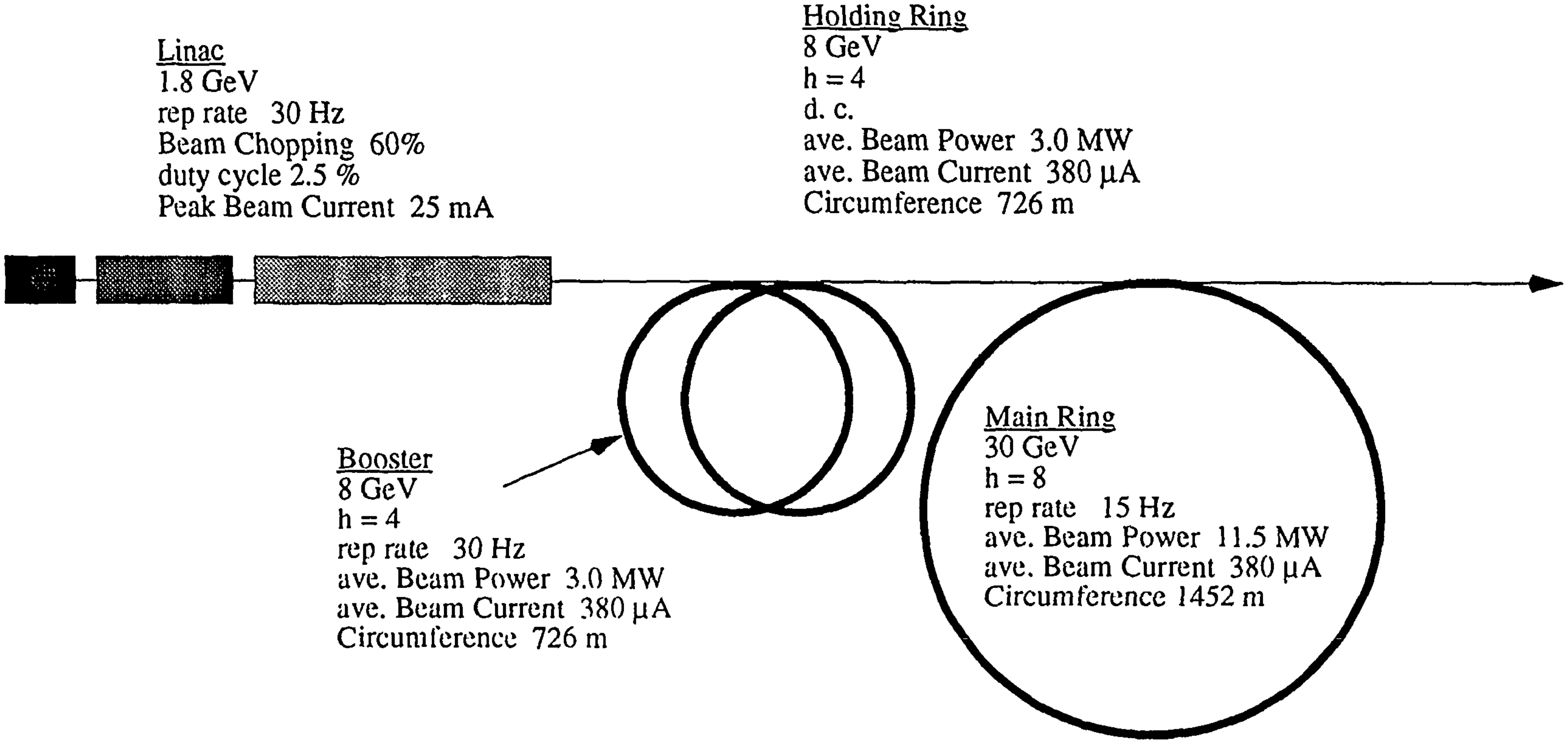


Figure 12. Layout of the Advanced Proton Source: A Facility for Nuclear and High-Energy Physics Applications, as generation of intense Beams of Muons.