CONCEPTUAL DESIGNS OF BEAM CHOPPERS FOR RFQ LINACS*

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A design study at Los Alamos of a linac/accumulator ring facility for a pulsed neutron spallation source calls for an H^- beam with a chopped structure of approximately 200-ns beam-free segments every 600 ns. The required angular impulse can easily be provided with existing pulse power technology and traveling wave structures with a transverse electric field similar to those now available [1]. The deflected beam is then restored by suitable collimation. Chopping is relatively easily done at sufficiently low energies, where the beam is easily deflected, and beam powers are not too large. However, the energy should be high enough so that the space-charge blow-up of the beam can be controlled with adequate focusing. LAMPF presently uses a traveling-wave beam chopper at 750 keV, before injection into the drift-tube linac (DTL). In the new linac designs, a radio-frequency quadrupole (RFQ) linac would typically bunch and accelerate the high intensity H^- beam from 100 keV to 7 MeV. In this paper, we present concepts for beam-chopper systems both before and after the RFQ. The beam-optics designs are presented together with numerical simulation results.

I. CHOPPING AFTER THE RFQ

In this section we describe the concept, the preliminary beam optics design, and the simulation results for the chopper after the 7-MeV RFQ. The design concept was based on a similar system proposed for the European Spallation Source [2]. In our design, we have three long drift spaces, each over one meter in length. Three drift spaces are to be occupied by the chopper (transverse deflector), a collimator, and a "restorer" (transverse deflector) as described below. The input and output of this transition section are matched to the output of the RFQ and the input to the DTL respectively. The power of the fully chopped beam bunches can be removed on a water-cooled copper or graphite/copper collimator positioned at the second drift space. To handle the high power dissipation, we propose to place the collimator at a small tilt angle with respect to the beam axis. Such placement will distribute the thermal load over the entire length of the collimator. Bunches that arrive at the chopper plates during the ~5-ns rise or fall time of the traveling wave are partially chopped and the transmitted part is nearly restored to the optic axis by an identical traveling-wave chopper called the "restorer". The restorer prevents loss of the partially chopped bunches at higher energy.

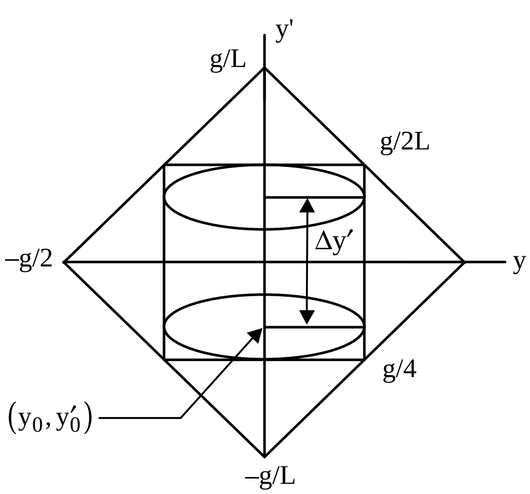

Figure 1. Phase space at the center of the chopper.

A. Concept

The y-y′ phase space at the center of the chopper plates is shown in Fig. 1. L is the length and g is the separation between the plates. Given the deflector voltage V, the emittance ε, and the separation parameter S, we calculate values of g and L that maximize use of the available phase space using equations:

$$L = 8\varepsilon S mc^2\beta^2/qV \text{ and } g = 8\varepsilon\beta\, [\, S(1+S)mc^2/qV\,]^{1/2}$$

where m is the rest mass, βc is the particle velocity and the unnormalized emittance is defined as $\varepsilon = y_0 y'_0$. We define $S = \Delta y'/2y'_0$, where $\Delta y' = 2VL/mc^2\beta^2 g$. The chopper is tilted at an angle $\Delta y'/2$ for optimal use of the rectangular phase space area. Note that S = 1 corresponds to minimum deflection required to separate deflected and undeflected ellipses. Practical limits on the voltage that can be obtained in a given rise time determine the maximum value of V. The restorer is identical in construction and operation to the deflector.

B. Design Studies

The design procedure is to choose a realistic value of V, and determine the geometry parameters using the above equations for a given value of S. If we choose V = 2.0 kV and S = 2, then for a proton beam at 7 MeV with β = 0.12 and a normalized emittance of ε_n = 1.1 mm-mrad, we obtain for the optimum case: L = 1.00 m, g = 14.8 mm, and y_0 = 3.7 mm. In this study we use L = 1.0 m, g = 12 mm, and y_0 = 3.0 mm, which is near but not exactly optimum. A layout of the section was done using the program TRACE 3-D [3], which solves for the motion of the beam envelopes, including the space-charge force for a uniform-density beam,. Figure 2 shows a TRACE 3-D plot including beam profiles for I = 38 mA. Four sets of triplets were used providing three long drift distances to accommodate the deflector, collimator, and restorer, respectively. RF cavities are also used to keep the beam bunched. The elements were adjusted to match the

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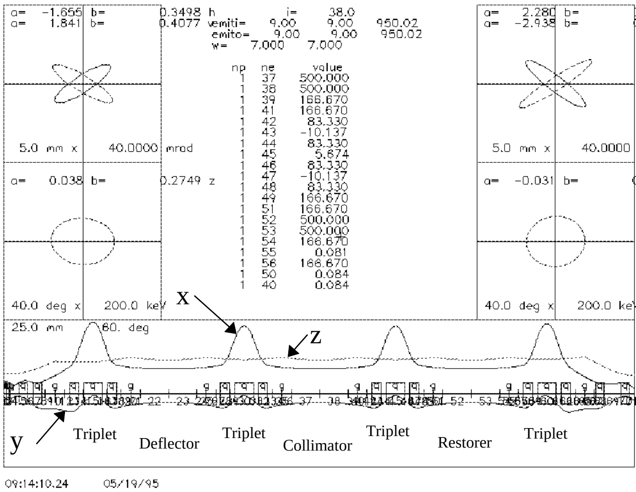

Figure 2. TRACE 3-D profile plots for I = 38 mA.

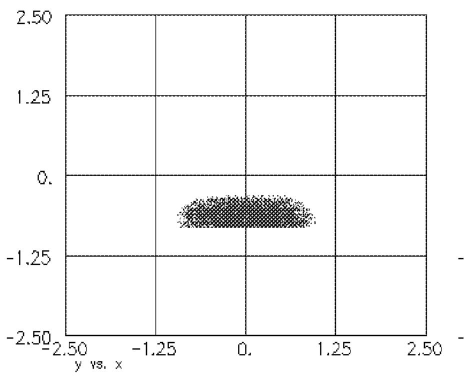

Figure 3. The x-y distribution of fully chopped bunches about one-third of the way along the collimator.

beam with the output of the RFQ and the input to the DTL. The deflection plane was chosen as the y-plane. So, the envelope size in y at the center of the chopper is kept at 3 mm, while the x dimension was not constrained. In the vertical plane we also require that from the center of the deflector to the center of the collimator $\sigma_{0y} = 270^{\circ}$, where σ_{0y} is the zero-current betatron phase advance per focusing period. This means that from the center of the deflector to the center of the restorer y'_0 is transformed to $-y'_0$. The code PARMILA, modified to incorporate the capabilities for deflection and collimation, was used to do the particle simulation studies. For simulation studies, we consider two beam bunches with different phase relationship relative to the deflecting voltage. Bunch type #1 represents the bunches which enter the chopper when the deflecting voltage has attained a maximum value of V, and bunch type #2 arrives at the chopper when the deflector voltage is ramping up or down and precisely at 0.5 V. Since the deflector is a traveling wave type, this bunch would see half the maximum deflection field throughout its journey in the chopper, while bunch type #1 would see full deflection field all along. Figure 3 shows the x-y distribution of type #1 at about one-third of the way along the collimator. Bunches of type #2 are subsequently restored (not shown) by the restorer.

II. CHOPPING BEFORE RFQ

Another option being considered for this upgrade entails the installation of a traveling wave chopper in the low energy beam transport (LEBT) line in front of the RFQ. A gas neutralized, magnetic transport system would be used. Chopping before the RFQ has the virtue that the beam-power loading from the deflected beam is easily handled on simple collimator designs and that the beam optics for chopping is relatively simple. Implementing this option will, however, be complicated by space charge effects in the LEBT, which will require a sufficiently high beam energy to preclude excitation of beam instabilities and a sufficiently short length to minimize emittance growth. The degree of beam neutralization needed and the required quiescence of the ion source will be key issues.

A. Concept

A schematic diagram showing the proposed LEBT beam line for 30-mA, 100-keV beam design is shown in Fig. 4. This design is similar to that now in operation in the LAMPF H^- high-voltage dome [4]. The ion source is operated at high voltage and the beam is extracted to ground potential and then transported by a two-solenoid-lens beam line to the RFQ. The chopper is placed between the solenoid lenses with the primary chopping aperture located at the entrance of the second solenoid lens. Two steering pairs located between the solenoids provide corrections for centroid errors at the RFQ entrance. The transport solution requires an intermediate waist at the end of the chopper, so appropriate diagnostics are required at this point. A secondary chopping aperture will be located at the entrance to the RFQ to improve rejection of the chopped beam. The filtering action of the secondary aperture and the RFQ may eliminate the need for a separate restorer element that would result in an undesirable length increase in the LEBT.

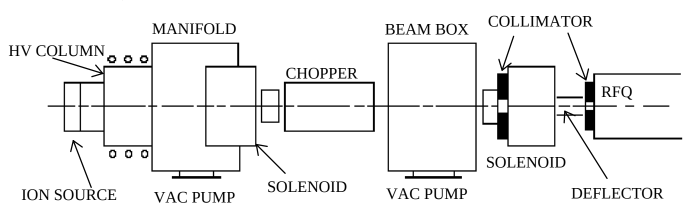

Figure 4. Schematic of the 30-mA, 100-keV H^- injector.

B. Design Studies

The beam envelopes expected were calculated using the first-order beam-envelope code TRACE 3-D [3]. In Fig. 5 we see the profiles for both the chopped and the unchopped beams at the secondary chopping apertures for the case where a 30-mrad impulse is imparted to the beam by the chopper. In the initial portion of this beam line, the extracted H^- beam will be space-charge neutralized by the effluent gas from the ion source. This gas load will be pumped at the entrance to the first focusing lens. In the chopper itself, the beam is expected to be un-neutralized when electric field is present. Previous attempts [5] to chop a low-energy beam at the Brookhaven

National Laboratory resulted in unacceptable phase-space distortions, because the neutralizing ions accumulated in the beam within the chopper. The present design entails higher beam energy and lower currents than the Brookhaven case. The electric fields produced by this chopper will be greater than the space-charge fields of the beam, thus sweeping out more of the beam-induced plasma and reducing these distortions.

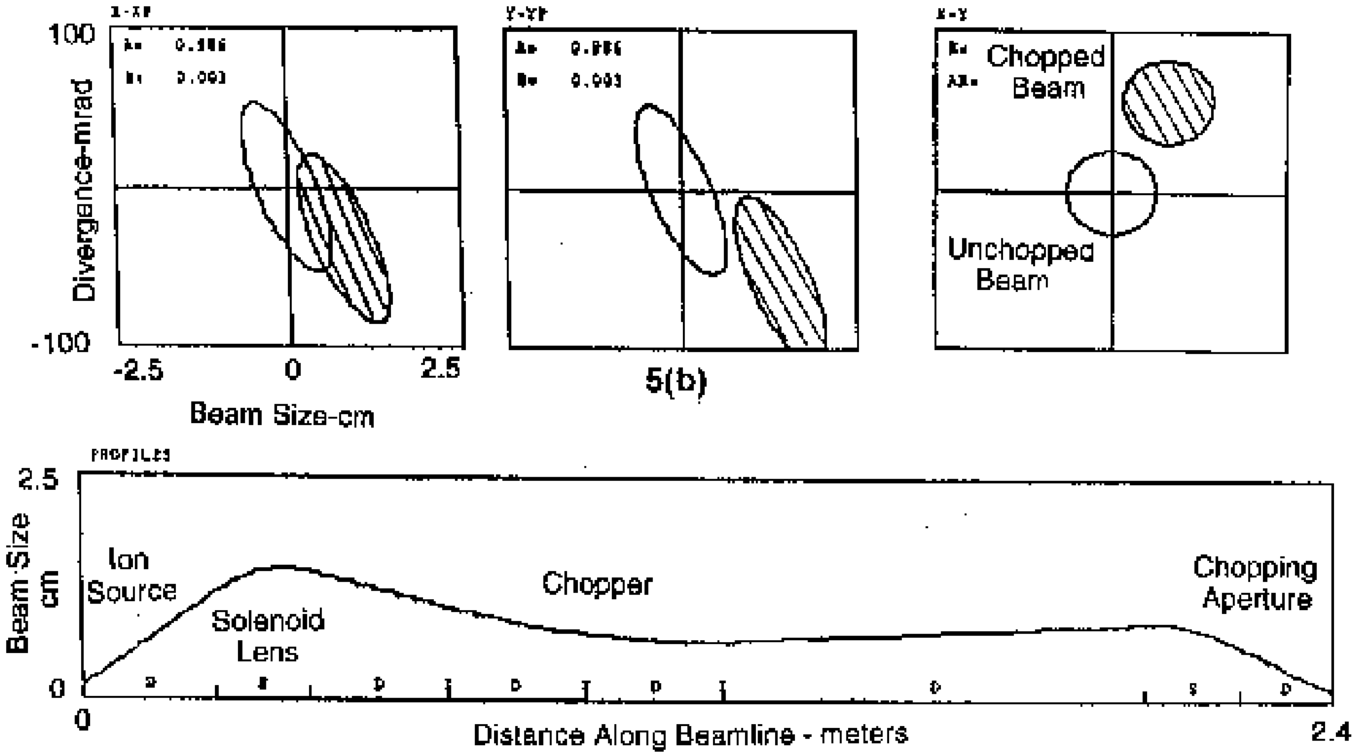

Figure 5. Beam profiles for the proposed H^- injector at the RFQ entrance (5b).

Because of unknown charge neutralization effects, the details of the proposed chopping are less certain in the final portion of this beam line. In the region between the chopping plates and the primary chopping aperture, the beam current is constant, but the chopper causes a high frequency (1.7 MHz) square-wave modulation in the beam-centroid motion. This frequency is in the range of the two-stream instability. Thus, one can expect emittance growth and, for sufficiently high beam current, excitation of this plasma instability. In the region after the chopping aperture, the beam will propagate without centroid modulation, but the beam current will now be modulated at the same 1.7-MHz frequency. The chopping period will be short compared to the neutralization time, but comparable to the decay time of the positive-ion neutralizing channel. A partially neutralized beam will be produced in this region [6]. We can, therefore, expect further emittance degradation in the transport of the chopped beam in this region. Plasma simulations using PIC codes are now being considered to clarify these issues.

III. CONCLUSIONS

The two options available for chopping the H^- beam for a pulsed neutron spallation source have been considered. The LEBT chopping option is relatively easy to implement with existing technology, but is complicated by possible excitation of beam instabilities and by emittance growth. Preliminary simulations show that a chopper system after the RFQ at 7 MeV is feasible. The beam quality is preserved and the partially chopped bunches can be restored to the optic axis, thus reducing the losses in the ring. Further work is needed to resolve the technical issues before a choice can be made between those two options.

IV. REFERENCES

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