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THE UNIVERSITY OF WASHINGTON SUPERCONDUCTING BOOSTER PROJECT

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The University of Washington Nuclear Physics Laboratory has designed a superconducting linac booster with an equivalent dc accelerating voltage of 24.35 MV, which will be injected by the existing FN tandem Van de Graaff accelerator. The design is based on the lead-plated copper quarter-wave resonator units developed by the Stony Brook/Weizmann group. The UW booster, unlike previous designs, will accelerate p, d, t, ^{3}He, and ^{4}He as well as light heavy ions ($A < 56$). Design studies of system performance give proton energies of almost 38 MeV and energies for light-heavy ions of over 15 MeV/amu, diminishing with A to about 7 MeV/amu for ^{56}Fe (assuming most probable charge). Beam dynamics studies show that debunching gives $\Delta E/E \simeq 10^{-4}$ or about 5 keV for protons, and bunching gives a time resolution on target of about 40–60 ps. The UW Booster Project has been recommended by NSAC and is to be funded in the FY'84 and FY'85 budgets of the US Department of Energy at a cost of about $8 million. Final planning and development are now in progress; construction is to begin in late 1983.

1. Overview

This paper describes the present status (as of 5/83) of the superconducting booster project at the University of Washington Nuclear Physics Laboratory (UW-NPL). The project was recommended by NSAC in 1982 and has been included in the fiscal year 1984 budget of the US Department of Energy. Final planning and development are now in progress, and construction is to begin in late 1983.

We will construct a superconducting booster linac to

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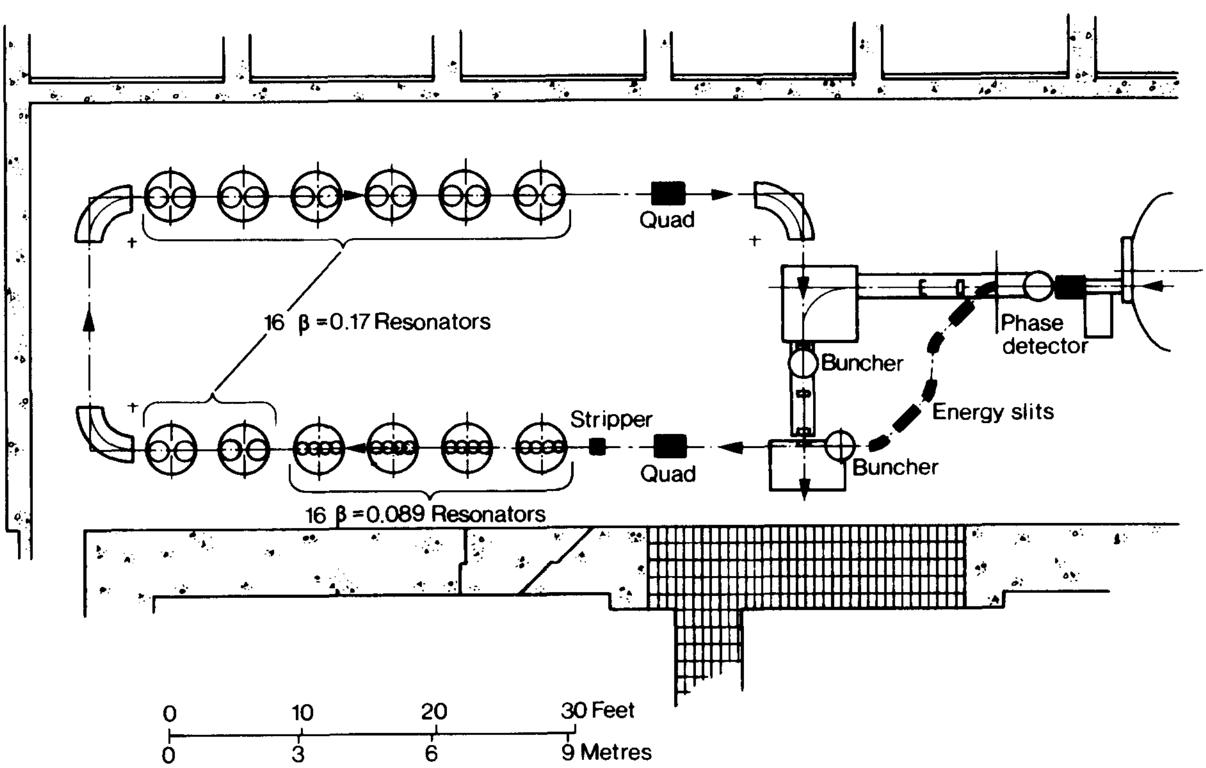

Fig. 1. Layout of UW NPL superconducting booster linac. Quadrupole doublet focusing elements (not shown) are placed between cryostats (circles) and between pair of 90° magnets at left of diagram.

be injected by our existing FN tandem Van de Graaff accelerator. The linac will use lead-plated copper quarter wave resonators (QWR) of the type recently developed by a collaboration of SUNY Stony Brook and the Weizmann Institute of Science [1]. The QWR technology offers the advantages of superior stability, ease of control and frequency stabilization, simple and relatively inexpensive construction, and good efficiency of acceleration over a broad range of ion velocities.

Fig. 1 shows the layout of the linac. The machine has been designed to fit into an existing space (Cave 3) in the accelerator vault of the UW-NPL. The layout shown has been chosen to allow sufficient drift spaces between bunchers and other accelerator elements to preserve the excellent phase space properties of the tandem beam, giving excellent time or energy resolution of the final beam for all ions.

An isochronous transport line brings the beam from the tandem to a parallel beam axis where it is bunched and focused to the second stripper at the linac entrance. The first half of the linac is located in six vertical cylindrical cryostats about 1 m in diameter, separated by 0.5 m drift spaces containing magnetic quadrupole doublet focusing elements. The first four of these cryostats contain four 150 MHz $\beta_{opt} = 0.088$ QWR units each. The last two cryostats contain two 150 MHz $\beta_{opt} = 0.176$ QWR units each. Here β_{opt} is the ratio of the velocity of the maximally accelerated ion to the velocity of light, and is a function of the geometry and operating frequency of the QWR unit used (see §2).

The linac is "folded" by a 180° isochronous transport system consisting of two 90° magnets with a quadrupole between them, the latter located at a beam waist produced by a quadrupole at the exit of the first half of the linac. This system delivers the beam to the second half of the linac which consists of six cryostats each containing two 150 MHz $\beta_{opt} = 0.176$ QWR units. The accelerated beam is brought to a waist at the center of a 90° magnet and enters the analysed beam line of the existing tandem accelerator system. It travels to a superconducting buncher where it is either debunched for good energy resolution or bunched for good time resolution (see §4). It is then transported through a switching magnet to the various beam lines of the UW-NPL facility.

The cryostats will be cooled to 4.5 K by a liquid helium distribution system supplied by a helium refrigerator with a capacity of 440 W, increasable to 510 W by using liquid N_2 precooling. The linac with all QWR units operating at 3 MV/m will have a cryogenic load of 250 W. Rough calculations based on performance of the QWR protype at high fields indicate that this load should increase to about 345 W at 3.5 MV/m and 485 W at 3.9 MV/m. Thus the refrigeration capacity will be comfortably above that required for normal operation of the linac and has the capacity to allow study of performance at accelerating fields greater than 3 MV/m.

Table 1 gives the predicted performance of the accelerator system. It is calculated under the assumptions that the FN tandem injector operates at 9 MV terminal potential, that in each of the two strippings the ion with the most probable charge state is accelerated, and that the QWR units are all operated at the stated accelerating field with a synchronous phase angle of 20°.

This introduction has given an overview of the projected accelerator system. In the following sections we will discuss aspects of the accelerator which have resulted in this design.

2. Superconducting cavity resonators

Other contributions to these Proceedings [2,3] give detailed descriptions of various types of superconducting and "warm" resonant accelerating devices, including QWR units. Therefore, we will restrict our discussion to those specific aspects of QWR units which influenced our design.

The efficiency of a given resonator in accelerating ions of various velocities is called the transit time factor $T(\beta)$. A plot of this function with β/β_{opt} is shown in fig. 2 for two gap resonators (QWR) and three gap resonators (SLR). Here β is the ion velocity. As can be seen from fig. 2, the QWR units are considerably more tolerant of ions with velocities different from β_{opt} than

Table 1
Energy performance of UW NPL superconducting booster system (all energies calculated using most probable charge state and given in MeV/amu)

Ion:	p	d	^{4}He	^{6}Li	^{12}C	^{16}O	^{28}Si	^{40}Ca	^{56}Fe
From Tandem	18.0	9.0	6.8	6.0	4.5	3.9	2.6	2.0	1.6
Linac at 3 MV/m	37.6	20.3	18.3	17.6	16.2	15.6	12.1	9.7	7.0
Linac at 3.5 MV/m	40.5	22.1	20.2	19.5	18.2	17.6	14.0	11.5	8.7

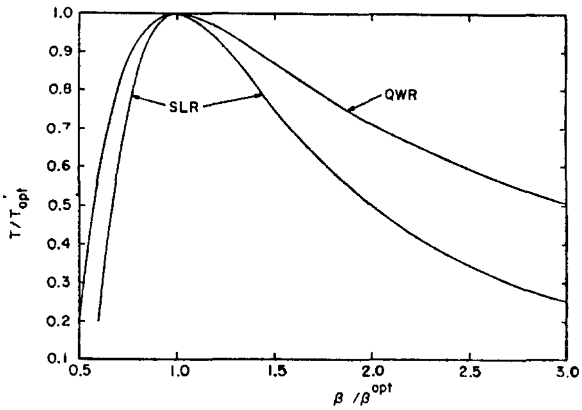

Fig. 2. Transit time factor versus velocity ratio for two types of resonant accelerator cavities. SLR is the 3-gap split loop resonator of Stony Brook type; QWR is the 2-gap quarter wave resonator of Stony Brook/Weizmann type. Both are calculated using an analytic expression [1] based on the sharp cutoff approximation.

are SLR units. Both types of resonators become quite inefficient when the ion accelerated has a velocity of about half of β_{opt}, but can accelerate ions with β several times greater than β_{opt} with reasonable efficiency.

The ions available from an FN tandem at 9 MV terminal potential range from about $\beta = 0.2$ for protons to $\beta = 0.06$ for ^{40}Ca and ^{56}Fe. The initial stages of the linac should match this spectrum of velocities and therefore should have $\beta_{opt} \approx 0.08$–0.1 to include as much of this dynamic range as possible. Thus the $\beta_{opt} = 0.088$ QWR 150 MHz units developed by the Stony Brook/Weizmann group are well suited for the first stages of the linac.

Acceleration through 16 $\beta_{opt} = 0.088$ QWR units operated at 3 MV/m will produce a spectrum of velocities ranging from $\beta = 0.22$ for protons to 0.10 for ^{40}Ca and 0.092 for ^{56}Fe. Here, resonators with $\beta_{opt} \approx 0.16$–0.18 are needed to match this dynamic range. We have designed a high-velocity portion of the linac using 16 QWR units with twice the β_{opt} of the Stony Brook/Weizmann QWR prototype or $\beta_{opt} = 0.176$, so as to achieve this matching.

These high velocity QWR units will require additional development. We have initiated this development in collaboration with Stony Brook and the Weizmann Institute. We are now constructing a $\beta_{opt} = 0.176$ prototype which will be plated and tested at Stony Brook in mid 1984. There are two ways of altering the existing $\beta_{opt} = 0.088$ design in order to double the optimum velocity: (1) by approximately doubling the diameter of the cylindrical QWR structure while keeping the height about the same and the operating frequency at 150 MHz; and (2) by reducing the height of the QWR so that the operating frequency is increased to 300 MHz. The former method was assumed in our design study and is the reason why only two of the high-β QWR units can be accomodated in a cryostat. It is preferred because it results in fewer but larger high-β QWR units in the linac (16 versus 32) for simplicity of control, and because at 150 MHz there is less distortion of the time–energy phase space of the beam.

3. Phase stability and focusing

To obtain longitudinal phase stability, the QWR units of the linac must be operated at a relative rf (or synchronous) phase ϕ which is retarded by up to 20° with respect to the phase of maximum acceleration. This produces a repeated rebunching of the accelerated beam as it passes through the linac, preserving the time structure of the beam. This longitudinal focusing of the beam brings with it radial defocusing. Since each accelerating gap can be represented as a focusing lens followed by a defocusing lens, when the electric field is *rising* as the beam bunch passes the gap (as it is when the phase is retarded) the focusing will be weaker than the defocusing, and a strong net defocusing will result.

In the design described above, the negative focal length characterising the defocusing from the resonators in a single cryostat can be of the order of a few meters. This defocusing must be compensated by a focusing system, e.g., a magnetic quadrupole doublet or solenoidal lens, or else the accelerator will have an unacceptably small transmission.

We consider it undesirable to focus with superconducting solenoids in the cryostats, as is done in the ANL ATLAS booster, because the solenoidal fields produce position-dependent spin rotations during the acceleration of polarized ions. Therefore, we have decided to place "warm" quadrupole doublets between the cryostats.

The strongest focusing is required by a triton beam in the initial stages of acceleration. For this case a negative focal length of about −4 m must be offset by a quadrupole lens with a compensating positive focal length. Calculations indicate that a close doublet with a (moderate) gradient of 20 T/m should be at least 0.21 m long to give this focusing. A nominal quadrupole doublet length of 0.25 m has been specified, with 0.50 m total separation between cryostats.

4. Beam dynamics and energy resolution

One of the design goals of the UW NPL booster is to accelerate light ions as well as light heavy ions. For the lightest ions the energy resolution is of crucial concern,

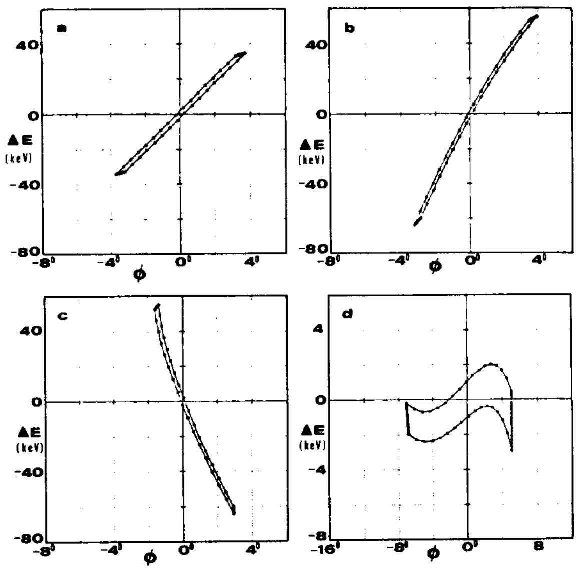

Fig. 3. Energy–phase plots calculated by program ENTIME for a proton beam at four locations in the accelerator: (a) at linac entrance; (b) before 180° bend; (c) after 180° bend; and (d) debunched on target (note change in phase and energy scales). Time scale (at 150 MHz) corresponds to 18.5 ps/degree.

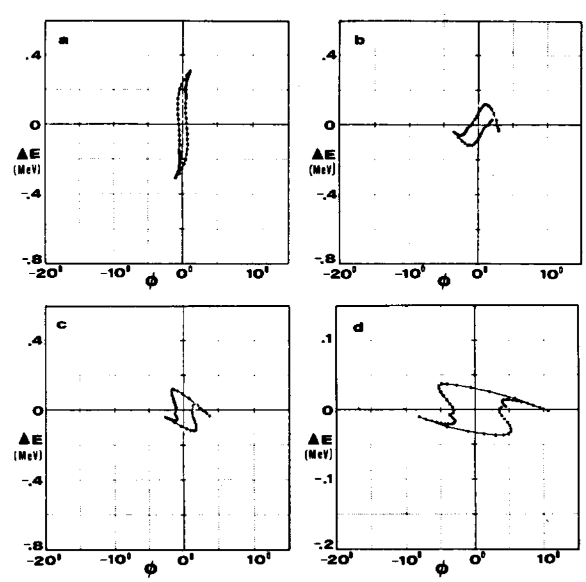

Fig. 4. Energy–phase plots calculated by program ENTIME for a ^{40}Ca (15^+) beam at four locations in the accelerator: (a) at linac entrance; (b) before 180° bend; (c) after 180° bend; and (d) debunched on target (note change in energy scale). Time scale (at 150 MHz) corresponds to 18.5 ps/degree.

particularly in a phase-stable linac in which the energy is deliberately broadened in order to preserve the time structure of the beam. Therefore, it was essential in the initial phases of the machine design that the beam dynamics of various layouts and configurations be investigated.

The interactive FORTRAN program ENTIME [4] was developed for the UW NPL's VAX 11/780 computer system. This program calculated the time–energy phase space of a "picture frame" of rays being transported through the accelerator, and displays these on any VT-52-compatible computer terminal. The interactive nature of this program permitted the rapid investigation of various configurations which lead to convergence on the present design.

Fig. 3 shows the resulting energy–phase plots of a proton beam at four different positions as it is transported through the linac and delivered to the target. At 150 MHz, 1° of phase in these plots corresponds to 18.5 ps in the time domain. Note that the initial excellent phase space from the tandem shown in fig. 3a is preserved as the beam passes through the linac. Notice also that the proton beam within the linac (figs. 3b, c) has an energy envelope width of over 100 keV, but the debunched proton beam at the target position has an energy width of of only about 4.4 keV.

Fig. 4 shows the similar transport of a ^{40}Ca beam. Here the beam within the linac is spread by about 300 keV, while the debunched ^{40}Ca beam on target has a spread of about 70 keV. If the final buncher is used to deliver a time-compressed beam to the target, the ^{40}Ca beam can be bunched to about 40 ps with an energy width of about 1 MeV.

5. Conclusion

We have presented, in broad outline, the characteristics of the booster linac which will be constructed at the UW NPL. The total cost of the project is over $9 million, and the construction will require over three years to complete and test. The staging of the project will be done so that the existing tandem can continue to operate during most of the construction period. Moreover, some of the components of the booster (e.g., the buncher system) can be tested and used with the tandem before the booster is operational.

This project, and similar ones at Florida State University, Oxford University, the Weizmann Institute of Science, and the Australian National University, represent the new second generation of booster linacs for tandem accelerators. We at the University of Washington are deeply indebted to the pioneers in this field at institutions such as the MPI Heidelberg, Argonne National Laboratory, Caltech, and SUNY Stony Brook,

who have laid the groundwork which makes our project possible.

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