DESIGN AND DEVELOPMENT OF AN 8-GEV SUPERCONDUCTING H^- LINAC*

P.N. Ostroumov#, ANL, Argonne, IL 60439, USA
G. Apollinari, G.W. Foster, R. Webber, FNAL, Batavia, IL, 60510, USA

Abstract

We discuss design of a pulsed linac based on 430 independently phased superconducting resonators for acceleration of 40 mA peak current H-minus beam up to 8-GeV. Most of the voltage gain (from ~420 MeV to 8 GeV) is provided by ILC cavities and squeezed ILC-style cavities operating at 1300 MHz. Significant cost savings are expected from the use of an rf power fan out from high-power klystrons to multiple cavities. The front end of the linac operating at 325 MHz will be based on spoke loaded cavities. A room temperature section comprised of a conventional RFQ and 16 short normal-conducting H-type resonators is proposed for the initial acceleration of an H-minus or proton beam up to 10 MeV. We have developed an accelerator lattice which satisfies the beam physics and engineering specifications.

INTRODUCTION

Recent discoveries of nonzero neutrino mass and neutrino oscillations have led to a worldwide resurgence of interest in neutrino physics. A multi-megawatt Proton Driver (PD) [1] is an essential element in the study of neutrino oscillations in any foreseeable scenario. An 8 GeV superconducting linac is being developed at FNAL as a proton driver, it will provide the intense clean beams necessary for operating the Fermilab Main Injector at 2-4 MW as well as providing independent, intense beams for a possible 8 GeV neutrino and fixed target program.

The following main concepts have been accepted for the cost-effective design of the 8-GeV linac:

- Apply rf power fan-out from high-power klystrons to multiple cavities throughout the entire linac. High-power fast phase shifters are being developed to control complex cavity fields in the 325 MHz low-energy section of the linac as well as in the high energy ILC section [2].
- Use the 1300 MHz ILC rf system [3] and directly apply SC elliptical cell cavities and klystrons originally developed for the ILC to accelerate H^- or proton beams above 1.2 GeV.
- Use squeezed ILC-style (S-ILC) cavities designed for β_G=0.81 to accelerate protons or H^- from ~420 MeV to 1.2 GeV.
- To simplify the RF system it is reasonable and cost-effective to operate the whole linac at no more than two frequencies. Several options are available for the acceleration of protons up to ~420 MeV at 325 MHz which is a sub-harmonic of the ILC frequency.

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#ostroumov@phy.anl.gov

Clearly, implementation of the proposed concepts would significantly reduce the cost of the linac in terms of dollars per volt ratio compared to that for the recently commissioned SNS linac [4].

BASIC PARAMETERS

The ultimate basic parameters of the 8 GeV H^- linac are listed in Table 1. To reduce the initial cost of the rf system there is a proposal to operate the linac with reduced beam pulse current (9 mA) at a lower repetition rate (2.5 Hz) as compared to the values listed in Table 1.

Table 1: Basic parameters of the linac.

	Parameter	**Value**
1	Particle type for the baseline mission	H^- ions
2	Beam kinetic energy	8 GeV
3	Beam current averaged over the pulse	25 mA
4	Beam peak current	40 mA
5	Pulse repetition rate	10 Hz
6	Pulse length	1 msec
7	Beam pulsed power	200 MW
8	Beam average power	2 MW
9	Wall power (estimate)	12.5 MW
10	Total length	678 m

LATTICE DESIGN

As in all recently designed and built hadron linacs, the initial acceleration and focusing will be provided by an RFQ accelerator. The required parameters of the FNAL RFQ are very similar to those at SNS [4] and J-PARC [5]. The design of the RFQ, Medium Energy Beam Transport (MEBT) and the whole PD lattice has been iterated several times to satisfy more advanced RFQ beam specifications [6]. The main function of the MEBT is to provide a space for a fast chopper and to match the beam into the following linac section. The fast chopper is required to form a gap in the beam macrostructure for the main injector extraction kicker and to remove one or two of every six 325 MHz bunches to match the beam time structure to the 52.8 MHz rf injection frequency of the main injector.

The block-diagram of the proposed linac is shown in Figure 1. The longest and most expensive part of the linac is the high-energy section where ILC cryostats can be used for the acceleration. This section of the linac has been designed to use the exact same ILC cryostats that have been developed for the future electron-positron

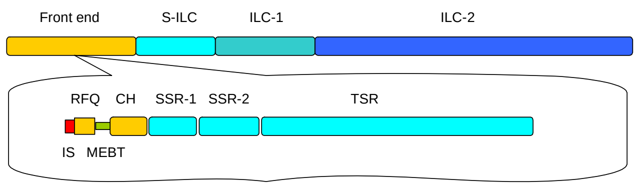

Figure 1: Block-diagram of the linac. IS is the ion source.

collider. However, in the energy range 1.2 GeV to 2.4 GeV the focusing period provided by the ILC cryostats is too long and the conditions for parametric resonance occur. Therefore, in our design we use the same ILC cryostat but replace one SC cavity in each cryostat with a focusing quadrupole, resulting in reduction of the focusing period length by a factor of two.

Successful development of spoke loaded SC cavities operating at ~345-350 MHz [7] provides a very strong basis for the application of SC structures for energies above several MeV in the front end of a multi-GeV linac. The frequency of this front end can be selected to be either the 3rd or 4th sub-harmonic of the 1300 MHz. The 4th sub-harmonic frequency option for the front end as compared to 3rd sub-harmonic option is preferable for several reasons as discussed in ref. [8].

We have analyzed the transition energy between the room temperature (RT) and SC structures and found that 10 MeV is the optimal transition energy. To boost beam energy from 2.5 MeV to 10 MeV, we propose to use short four- or five-gap cross-bar H-type (CH) cavities which have higher shunt impedance than drift tube linacs (DTL) [8].

In the energy range from 10 MeV to 120 MeV beam acceleration is provided by two types of single-spoke resonators (SSR). The geometrical betas of the SSR-1 and SSR-2 cavities have been included into the iteration procedure of the lattice design and were found to be β_G =0.22 and β_G =0.4 respectively. The energy range from 120 MeV to 420 MeV is covered by triple-spoke resonators (TSR).

In the front end, between the RFQ and TSRs, axially-symmetric focusing by SC solenoids provides strong control of beam space charge and a compact focusing lattice. In the TSR section and sections above ~420 MeV, the PD design is based on FODO structure.

Earlier studies carried out at LANL (see, for example, [9]) have established the lattice requirements necessary to avoid beam rms emittance growth through high-intensity proton linacs. SC linacs also can be designed to satisfy high-current specifications. However, such a design will be expensive due to the increased number of cavities and cryostats. A cost-effective design of SC linac will have the following properties:

- The acceleration is provided with several types of cavities designed for fixed beam velocity. For the same SC cavity voltage performance there is a significant variation of real-estate accelerating gradient as a function of the beam velocity.
- The length of the focusing period for a given type of cavity is fixed.
- There is a sharp change in the focusing period length in the transitions between the linac sections with different types of cavities.
- The cavities and focusing elements are combined into relatively long cryostats with an inevitable drift space between them. There are several focusing periods within a cryostat.

We have developed an iterative procedure for the lattice design of a SC linac which was applied to the proton driver lattice. Figure 2 shows the variation of the phase advances of transverse and longitudinal oscillations per focusing period along the linac calculated for a zero-current beam using the matrix calculation routine incorporated into the TRACK code. End-to-end beam dynamics simulations have been performed for the 45 mA beam injected into the RFQ. Figure 3 shows total and rms beam envelopes along the linac along with the cavity apertures. More detailed beam dynamics studies including all types of machine errors show that there is a moderate (~60%) rms emittance growth and there are no beam losses along the linac. The focusing fields have been selected to avoid excess H^- stripping along the linac.

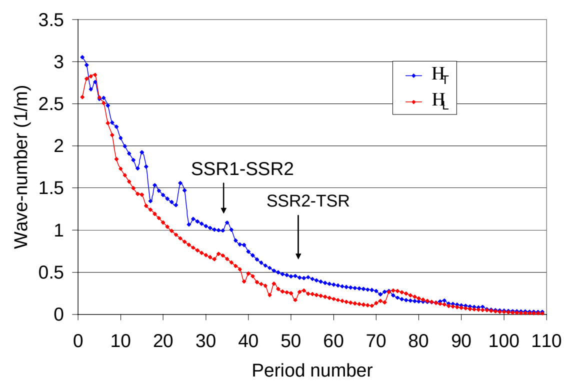

Figure 2: Wave numbers of transverse and longitudinal oscillations along the linac.

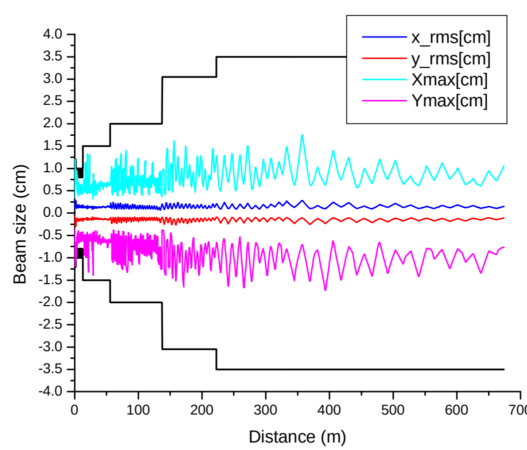

Figure 3: Transverse envelopes of 43.25 mA beam along the linac. The black solid line shows the aperture.

90-MEV FRONT END

Currently FNAL is developing a linac test facility to include the front 90-MeV of the linac: the RFQ, MEBT, chopper, RT section, and three cryomodules of single-spoke cavities of two types. A single klystron will be used to power all 58 RT and SC cavities as shown in Figure 4.

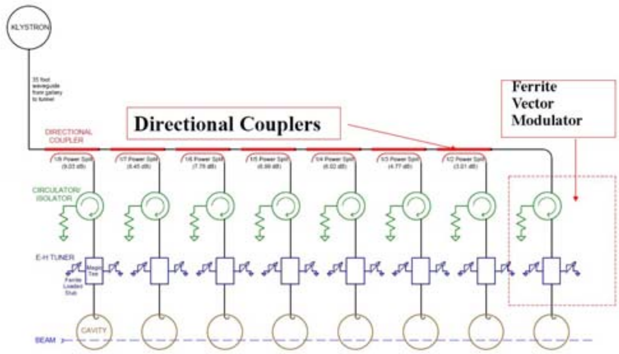

Figure 4: Schematic diagram of rf power distribution.

The main tasks of the test facility are:

- Install and commission a 2.5 MW, 325 MHz klystron system and equip and operate a 325 MHz high power RF component test facility.
- Demonstrate high power RF distribution and 4.5 millisecond pulse operation of multiple cavities from a single klystron.
- Measure axially-symmetric beam performance with RT-CH cavities and SC solenoid focusing in the RT Linac. Demonstrate transition to superconducting accelerating structures at 10 MeV.
- Demonstrate device and system performance of high power vector modulators for amplitude and phase control of multiple cavities.
- Demonstrate high-speed (nanosecond) beam chopping at 2.5 MeV.
- Install three 325 MHz SC spoke loaded resonator cryomodules and operate with beam up to 90 MeV. Demonstrate performance of the linac concept and resulting beam quality to 90 MeV.

In the RT section of the linac (see Figure 5), the CH cavities are alternated by focusing SC solenoids. The design of both the RT CH cavity (Figure 6) and SC SSR (Figure 7) has been completed and the cavities are being fabricated.

CONCLUSION

Extensive design studies of the 8-GeV proton driver show that the linac can provide high-quality beams both for the injection into the main injector and experiments.

Currently FNAL is developing and constructing the initial 90-MeV section of the linac. Particularly, prototyping of all critical linac components is being performed. The 325 MHz klystron is on-site, the RFQ, the first CH cavity and two SSRs are being procured. The engineering design of the 90-MeV linac is nearly completed.

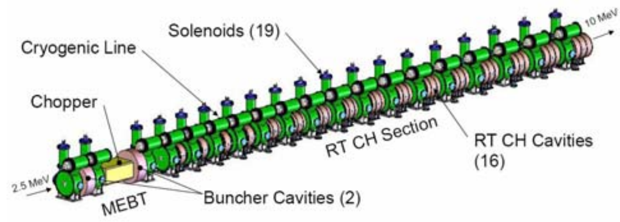

Figure 5: RT section of the linac.

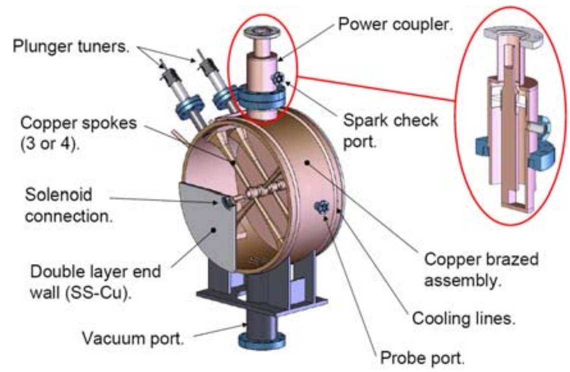

Figure 6: RT CH cavity.

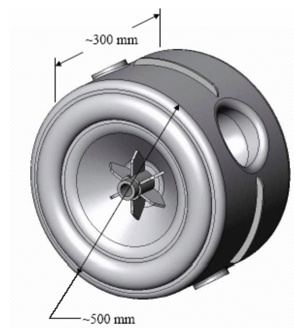

Figure 7: 325 MHz spoke loaded SC cavity, β_G =0.22.

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