OVERVIEW OF THE HIGH INTENSITY NEUTRINO SOURCE LINAC R&D PROGRAM AT FERMILAB *

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Abstract

The Fermilab High Intensity Neutrino Source (HINS) Linac R&D program is building a first-of-a-kind 60 MeV superconducting H- linac. The HINS Linac incorporates superconducting solenoids for transverse focusing, high power RF vector modulators for independent control of multiple cavities powered from a single klystron, and superconducting spoke-type accelerating cavities starting at 10 MeV. This will be the first application and demonstration of any of these technologies in a low-energy, high-intensity proton/H- linear accelerator. The HINS effort is relevant to a high intensity, superconducting H- linac that might serve the next generation of neutrino physics and muon storage ring/collider experiments. An overview of the HINS program, machine design, status, and outlook is presented.

INTRODUCTION

Fermilab has long considered options to replace its aging 8 GeV injector complex to support future accelerator-based physics programs that will demand high intensity proton beams, including neutrino physics and muon storage ring/collider experiments. A technologically advanced, enhanced performance version of the classical Fermilab Linac/Booster system is a natural concept to pursue and a great deal of effort has been invested to develop the physics and engineering details of this option [1][2]. With recent advances in superconducting (SC) RF cavity science and technology, the possibility of a full 8 GeV linac became realistic. Plans for such a machine that would leverage the best aspects of RIA, SNS, and TESLA/ILC developments were born [3] and matured [4].

By late 2005, strong interest in pursuit of the International Linear Collider (ILC) and the U. S. high energy physics community's commitment to PEP-II B-Factory and Tevatron Collider operations left little room to support construction of an 8 GeV linac. Nevertheless, it was recognized that a machine of this caliber might be a key to maintaining a strong U.S. presence in accelerator-based physics before ILC construction. This provided the basis, in the name of neutrino physics, for R&D funding to pursue the novel technical aspects of the linac and thus the Fermilab High Intensity Neutrino Source (HINS) R&D linac.

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HINS R&D SCOPE

The full scope of the HINS R&D program has included studies of various accelerator physics issues of importance to a facility expected to deliver high intensity, high energy beams for exploration of neutrino physics. With Fermilab steering the overall efforts, collaborating laboratories have also made important contributions. Argonne National Laboratory provides the major resources for the accelerator physics design and particle tracking simulations for both the HINS and the 8 GeV linacs. Argonne's experience in the design and development of SC spoke-type RF cavities [5] [6] serves as the foundation for Fermilab's entry into this technology and Argonne continues to provide resources for cavity processing in the construction phase. Lawrence Berkeley National Laboratory's participation in the HINS program has included studies of electron cloud issues, especially as related to the Fermilab Main Injector and Recycler Rings, development of linac Low Level RF system hardware and firmware, and design and fabrication of two buncher cavities for the HINS 2.5 MeV transport section. Brookhaven National Laboratory has reviewed an 8 GeV H- beam transport line design, provided consultation on H- injection and stripping, and built a prototype H- beam profile monitor based on laser neutralization to be used in the HINS Linac. The Oak Ridge Spallation Neutron Source has provided a copy of their Low Level RF system hardware modified for the HINS frequency.

This paper concentrates on the design, status and outlook for the HINS Linac.

HINS R&D LINAC OBJECTIVES

The HINS Linac R&D program will address accelerator physics and technology questions for a new concept, low-energy, high intensity, long-pulse H- SC linac. In particular, the specific goals of the program are to demonstrate:

- acceleration of beam using SC spoke-type cavity structures starting at a beam energy of 10 MeV
- use of high power RF vector modulators to control multiple RF cavities driven by a single high power klystron for acceleration of a non-relativistic beam
- control of beam halo and emittance growth with an axially symmetric optics design using solenoid focusing
- performance of a fast, 325 MHz bunch-by-bunch, beam chopper at 2.5 MeV

The plan is to achieve these goals within the context of the once-proposed Fermilab 8 GeV Superconducting Linac Proton Driver front-end design [7]. The 60 MeV HINS Linac, comprising a 50 keV H- ion source, a 2.5 MeV RFQ, a medium energy beam transport section with chopper, a 10 MeV room temperature (RT) linac with SC solenoids, two cryomodules of β = 0.2 spoke cavities and one cryomodule of β = 0.4 spoke cavities, is to be constructed and operated. The longer vision is that the HINS Linac itself might eventually become the front-end of a high energy linac. The scope of the HINS linac effort includes development of relevant accelerator design tools, RF and SC RF related technologies, components, and test facilities.

The HINS R&D program seeks to achieve these goals by the end of fiscal year 2012.

HINS LINAC

Parameters

The basic operating parameters for the HINS Linac, shown in Table 1, are consistent with those for the Proton Driver Linac to deliver 2 MW of 8 GeV beam power.

Table 1: HINS 60 MeV Linac Operating Parameters

RF Frequency	325	MHz
Particles/ Pulse	37.5*	E13
Pulse Length	3/1	msec
Average Pulse Current	~20	mA
Pulse Rep. Rate	2.5/10	Hz
Chopping ~6% @ 89KHz and 33% @ 53MHz	0-37.5	%
Bunch Current	32	mA
Bunch Intensity	6.1 98	E8 pCoul

* full un-chopped 3 msec pulse at klystron-limited 20 mA

The 325 MHz RF frequency choice is the result of a confluence of influential circumstances. It is the 4th sub-harmonic of the ILC frequency, consistent with the idea that this might be the front-end of a high energy linac based on ILC technology. It is near that of the 345 MHz spoke cavities developed at Argonne. Equally important, minor modifications to the J-PARC 324 MHz high power klystron design provide an economical path to a suitable RF power source.

The Fermilab Proton Driver design was staged for two operational phases: initially, 9 mA in a 3 msec pulse at rates up to 2.5 Hz to support 2 MW beam energy at 120 GeV from the Main Injector; then, with RF system upgrades, 27 mA in a 1 msec pulse to deliver 2 MW at 8 GeV. The HINS Linac can operate in either mode although the maximum current is expected to be klystron power limited at 20 mA. This current, however, can be available for either a 1 or 3 msec pulse length.

Chopping in 2.5 MeV transport line will demonstrate production of a beam time structure ultimately suitable for injection into the Main Injector ring. A 700 nsec chop at 89 kHz preserves an abort gap in the Main Injector with multi-turn injection. Chopping at 53 MHz ‘pre-bunches’ the beam to match the Main Injector RF frequency.

The desire to include as part of the program at least one cryomodule of β = 0.4 SC spoke cavities establishes the final energy of the HINS Linac at 60-65 MeV.

Design

The accelerator physics design philosophy of the HINS Linac, described in depth in [8], is naturally tightly coupled to the concepts and technologies the machine is intended to prove. It is punctuated by multiple independent RT accelerating cavities, SC solenoids for axially symmetric focusing, and a transition to SC spoke-type accelerating cavities at 10 MeV. Analysis of the transition energy question indicated an optimum at 10 MeV, where the energy gains per cavity can be equal in the RT and the SC sections and the beam energy is sufficiently high to allow the short drift space necessary to physically accommodate the warm–cold transition.

A 50 keV ion source provides beam to a 2.5 MeV four-vane RFQ with radial matching sections at the input and output ends that form the axially-symmetric beam. The RFQ is followed by a Medium Energy Beam Transport (MEBT) section that provides space for the beam chopper [9] while maintaining desired transverse and longitudinal beam characteristics with two RF buncher cavities and three SC solenoid magnets. The subsequent accelerating section up to 10 MeV comprises 16 RT crossbar H-type (RTCH) cavities [10] and 16 SC solenoid magnets [11]. The first four RTCH cavities are made with three spokes; the remaining 12 have four spokes. As a matter of economics, a subsequent design modification reduced the number of unique RT cavity designs required; nine unique designs fill the complement of 16 RT cavities. The solenoids, even in the RT section of the machine, will be superconducting. Field strengths of six Tesla are necessary to produce the short focal lengths required by the beam optics and for matching into the SC cavity section.

From 10 to 30 MeV, eighteen SC single-spoke cavities of a common β = 0.2 design are employed [12]. They are foreseen to be divided between two cryomodules. The cavities alternate with eighteen SC solenoids. The final 30 MeV is achieved with a single cryomodule of six solenoids and eleven SC spoke cavities of β = 0.4 design.

Extensive particle tracking simulations of the HINS and Proton Driver Linacs have been conducted using both TRACK and ASTRA codes [13] [14] [15]. This effort has proven extremely beneficial not only for the machine design, but also for the codes themselves. They have been rigorously benchmarked against each other and improvements in both features and performance have been implemented in each code.

The HINS RF power distribution and control system design is particularly demanding in light of the goal to employ a single high-power klystron to drive multiple cavities accelerating a non-relativistic beam. The physics design calls for each cavity to operate at an individual

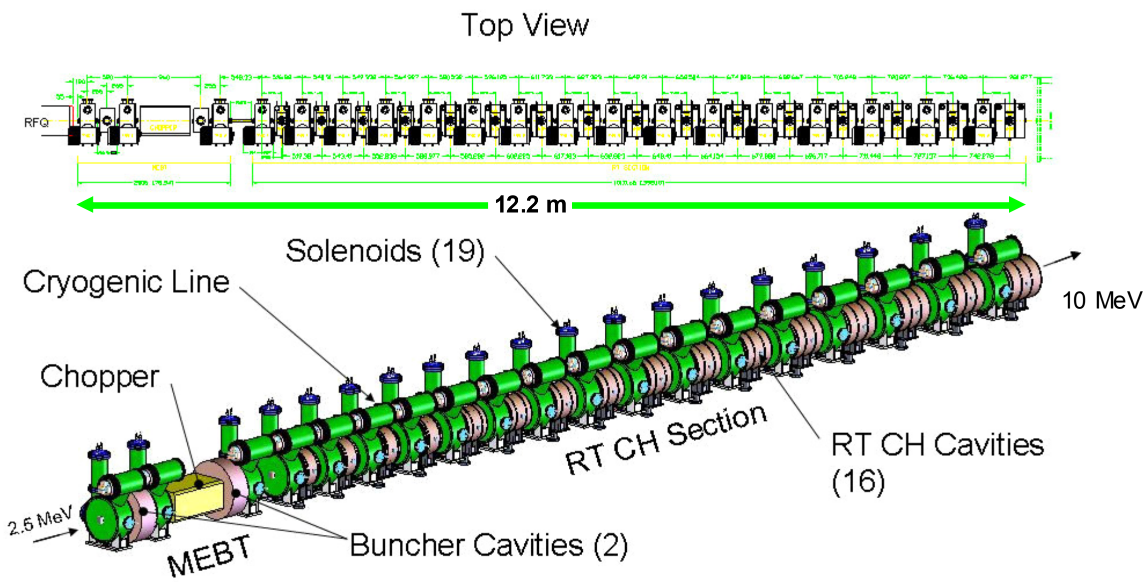

Figure 1. Layout of the first 10 MeV of the HINS linac.

gradient and synchronous phase and thus each experiences different beam loading. To meet tight amplitude and phase tolerances under these dynamic conditions, each cavity requires an individual amplitude and phase control element operating at the full power level of the cavity. This function is served by high power RF vector modulators [16]. Performance simulations of the vector modulator control under realistic RF and beam conditions are on-going. Further complicating the situation, the original HINS concept includes combining both RT and SC cavities on a single klystron. Adding a second klystron to the same modulator to separate the RT from the SC cavities remains a fall-back position.

Layout

The layout of the first 10 MeV of the HINS Linac, including the MEBT and RT section is shown in Figure 1. Conceptual drawings of the SC spoke cavity cryomodules are in Figure 2. The 60 MeV HINS linac, approximately 42 meters in length, followed by a diagnostic beam line with a spectrometer and beam absorber is being assembled in the Fermilab Meson Detector Building. In addition to the linac itself, the Meson HINS facility includes the modulator and klystron RF power system, a

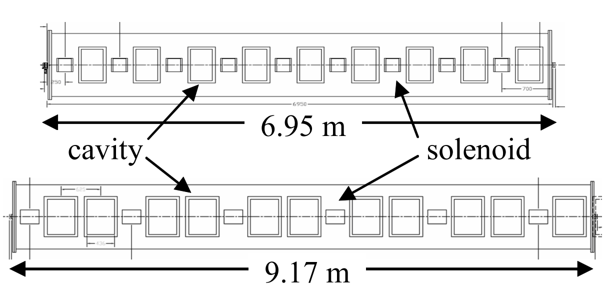

Figure 2. β=0.2 (top) and β=0.4 (bottom) SC spoke cavity cryomodule layouts.

shielded cave supporting both RT cavity testing and a cryostat for dressed SC spoke cavity testing, and an RF shielded high power RF component test area.

Status

The HINS RF power system with one 325 MHz Toshiba E3740A(Fermi) 2.5 MW klystron has been operational since April 2007 to serve vector modulator development and testing of RT cavities.

A 50 keV proton ion source is commissioned and waiting to serve the RFQ. The program will begin beam operations with protons while development of a suitable H- source is completed. H- is expected to be available in mid-2009.

The HINS RFQ [17] [18] [19], pictured in Figure 3, has been manufactured by ACCSYS Technologies, Inc. It is now undergoing final inspections at Fermilab prior to high power RF conditioning that is expected to commence in October 2008.

The two MEBT buncher cavities are being machined at LBL and are expected to be finished in early 2009.

The RTCH cavities are in fabrication. Four are

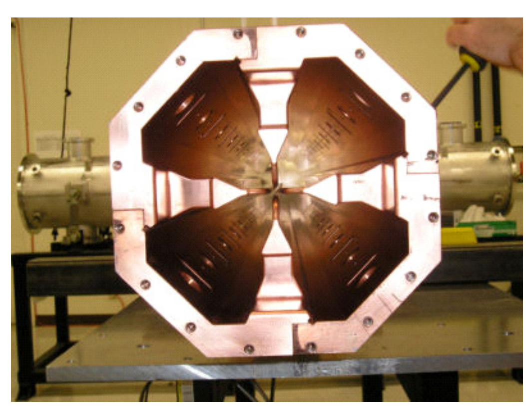

Figure 3. HINS RFQ made by ACCSYS.

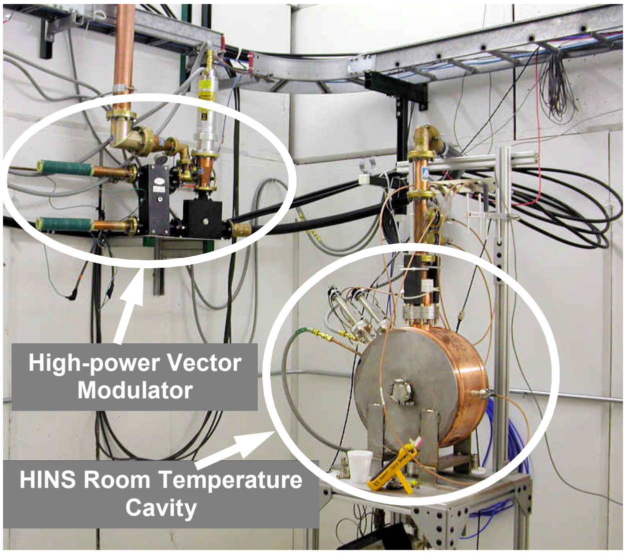

Figure 4. RT cavity coupled with prototype vector modulator on test stand.

completed; three have been successfully RF conditioned to full power [20], the fourth awaits its turn on the test stand. The remaining twelve RTCH cavities are expected to be delivered by this year's end. Figure 4 shows the first RTCH cavity coupled with a prototype vector modulator on the cavity test stand.

Prototype vector modulators for the RTCH cavities have been successfully tested [21] to 70 kW. Phase control rates in excess of 4 degrees per microsecond and an amplitude control range of 13 db have been demonstrated. One very high power vector modulator, for the RFQ, has operated successfully up to >500 kW. Problems have been experienced in obtaining the required high power performance for a companion circulator.

A prototype SC solenoid for the RT section has been successfully tested and production units are now being fabricated [22].

Two $\beta = 0.2$ SC spoke cavities have been fabricated; only one has yet been processed. The processed, bare cavity, pictured in Figure 5, has undergone several test cycles in the Fermilab SC cavity Vertical Test Stand. Results have been very encouraging despite some problems. Figure 6 shows Q vs. gradient performance for three test dates. The two curves starting at Q≈1E10 are for 2°K operation; the other two curves are for 4.4°K. Electron multipacting [23] in the cavity has been observed and overcome at various field levels (see discontinuities in Q curves). The Q slope at 2°K is steeper than expected. Obtaining reproducible results has been complicated by difficulty maintaining acceptable cavity vacuum and, in the latest test, a helium leak into the cavity that was traced to a bad RF antenna feedthrough. Nevertheless, the cavity has achieved an impressive accelerating gradient of 18 MV/m at the HINS operating temperature of 4.4°K. It has performed marginally below the target Q of 5E8 at 10 MV/m. Test results are described in detail in [24]. Further tests are planned.

Figure 5. First SC Spoke Cavity prepared for vertical test.

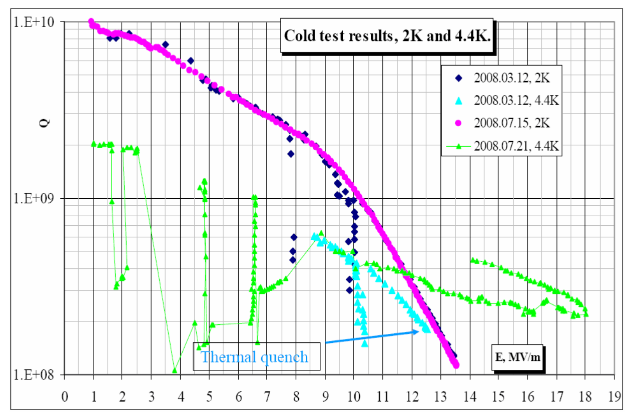

Figure 6. First SC Spoke Cavity Q vs. Gradient results.

HINS PROGRAM OUTLOOK

Following RF conditioning, the RFQ will be coupled to the proton ion source. The first 2.5 MeV beam is expected by December this year. The linac shielding cave will then be constructed, followed by staged commissioning of the MEBT and RT sections. Full 10 MeV operations are not expected before late 2009. The first beam test of SC spoke cavities is anticipated about one year later using one cryomodule of the $\beta = 0.2$ cavities.

In late 2007, the Fermilab Project X [25] [26] proposal, including an 8 GeV H- linac as a centerpiece, was announced. This followed alignment of important H- linac beam and operating parameters with those of the ILC and a realization that ILC construction is unlikely for a decade. Subsequently, in May 2008, the U.S. Particle Physics Project Prioritization Panel (P5) stated in its ten year strategic plan report [27] "The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL …" Project X is well aligned with this recommendation and Fermilab is now leading a national effort to obtain Department of Energy critical decision approval to carry out the conceptual design.

This will impact the identity of the HINS R&D program. At some stage, it will likely be absorbed into the Project X organizational structure. An evaluation of the HINS technologies, based on performance, cost and risk, will determine how and if these technologies might be incorporated into the eventual Project X Linac design. The current HINS program can positively influence this by delivering on its goals at the earliest possible date.

SUMMARY

The HINS program has ambitious goals to demonstrate the feasibility and performance of technologies never before applied to a low-energy, high intensity proton or H- linac. The program is actively designing, building, and testing accelerator components to be integrated into a novel 60 MeV superconducting H- linac. It is hoped that this might serve as the front-end to an 8 GeV linac that is a key element of the Project X proposal.

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