OVERVIEW AND STATUS UPDATE OF THE FERMILAB HINS LINAC R&D PROGRAM*

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Abstract

The Fermilab High Intensity Neutrino Source (HINS) Linac R&D program is continuing efforts to construct a first-of-a-kind superconducting H^- linac. The goal of the HINS linac is to demonstrate, for the first time, acceleration of high intensity beam with superconducting spoke cavities, control of beam halo growth by use of solenoidal focusing optics throughout, and operation of many cavities from a single high-power RF source for acceleration of non-relativistic particles. The HINS effort is relevant to any future high brightness, high intensity linac and, in particular, to the linac proposed as part of Fermilab Project X to serve the next generation of neutrino physics and future muon storage ring/collider experiments. This paper updates the technical status of the various components being developed, built, and commissioned as a part of HINS and presents the outlook for the HINS program.

INTRODUCTION

The five-year-old Fermilab HINS program is making significant progress in the development, construction, and testing of components for its first-of-a-kind 325 MHz superconducting (SC) linac. The linac, described in detail elsewhere [1,2], comprises a 50 keV ion source, a 2.5 MeV RFQ, a medium energy beam transport (MEBT) section with chopper, a 10 MeV room temperature (RT) linac with SC solenoids, and two cryomodules of $\beta = 0.2$ SC spoke-type cavities. Final beam energy for this configuration is 30 MeV. Although a third cryomodule, containing $\beta = 0.4$ spoke cavities, was eliminated from the scope of HINS early in 2009 for economic reasons, the specific programmatic goals remain unchanged. They are to demonstrate:

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

The HINS program must develop relevant accelerator design tools, warm and SC accelerator components, RF power distribution and control technologies for systems of warm and SC cavities, test facilities, and finally an integrated accelerator facility. The larger purpose of HINS, beyond simply building a technology demonstration machine, is that the HINS linac itself might eventually become the front-end of a high-energy linac like that envisioned as a part of Fermilab Project X [3].

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ION SOURCE AND RFQ

A 50 keV proton ion source and low energy beam transport line (LEBT) capable of 3-msec beam pulses at >30 mA at 5 Hz is commissioned and waiting to serve the RFQ [4]. Initial HINS beam operations will be with protons while development of a suitable H^- source is being completed. An H^- source, in an accelerating column compatible with the HINS LEBT, is assembled and 'first beam' has been established. Operational testing will continue and beam parameters will be fully characterized. This H^- source will later replace the proton source.

The RFQ, built by ACCSYS Technologies Inc. to HINS specifications [5,6], is installed in its final location [Fig.1] and RF power testing began in late 2008. The RFQ has proven able to accept full design peak power, ~450 kW without beam, for pulse lengths up to 1 msec.

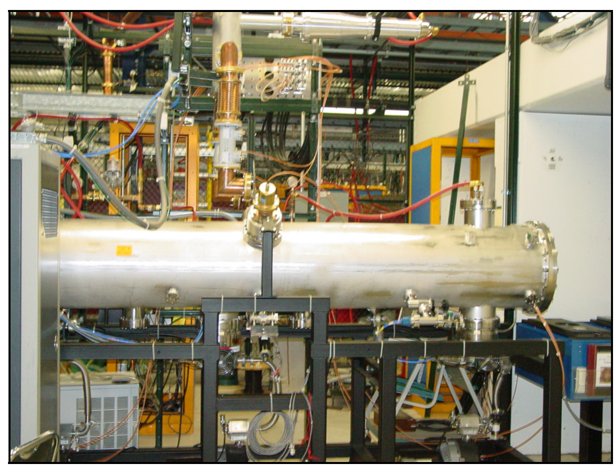

Figure 1: RFQ installation.

When the average RF power exceeds ~250 W, the RFQ exhibits anomalous behavior. By design, it should operate to nearly ten times that power. The frequency of the normal quadrupole accelerating mode is well-behaved for the first minutes of operation, but then rapidly detunes in a run-away manner. RF heating clearly drives the phenomenon; the time-to-onset of the run-away is strongly related to average RF power. A detuning of several hundred kilohertz, once established, is maintained with only a few dozen watts average RF power. Large field amplitude imbalances within the RFQ are evident in this state. The effect seems completely reversible; after twenty minutes without RF power, the RFQ returns to 'normal'.

The RFQ is built as a single, nearly ten-foot long, water-cooled copper structure. Physical distortion of the long structure due to thermal gradients might explain the problem. Investigations are continuing.

Since the RFQ appears well-behaved at low average power, beam commissioning with short pulses and low repetition rate is planned to begin in summer 2009.

2.5 MEV CHOPPER

A 325 MHz bunch-by-bunch chopper is to be located between two buncher cavities in the MEBT downstream of the RFQ. Preliminary design and testing of a slow-wave kicker structure, similar to that for LINAC4 at CERN, is finished [7] and progress has been made to develop a suitable pulsed power source. Although demonstration of chopper performance is a core HINS objective, the linac commissioning will begin without the chopper in place.

ROOM TEMPERATURE RF CAVITIES

Lawrence Berkeley Laboratory is building the two MEBT buncher cavities for HINS. These copper-plated steel cavities are now in final stages of assembly.

Crossbar-H type (RT-CH) copper cavities are employed in the 2.5-10 MeV warm linac section [8]. Fermilab has received fifteen of the sixteen required cavities from an industrial shop. Cavities #1-4 are three-spoke cavities; #5-16 are four-spoke [Fig. 2]. Five RT-CH cavities are tuned to the final frequency and have had RF power applied. Each has conditioned successfully to RF levels well above the design operating value. Initial conditioning difficulties with the first cavity were avoided for subsequent cavities by first subjecting them to a 150°C vacuum bake.

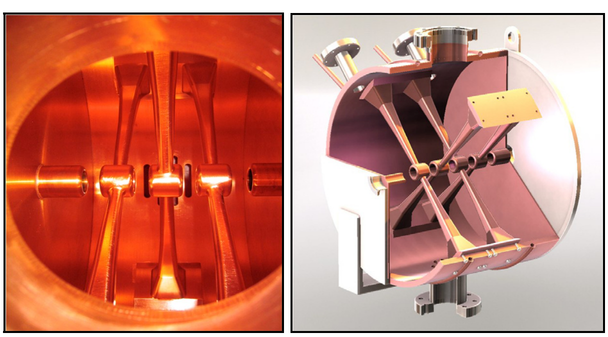

Figure 2: HINS RT-CH cavities: 3-spoke cavity photograph and 4-spoke cavity design rendering.

The RT-CH cavities are constructed with double end-walls: thick steel outer walls to withstand differential pressure forces and mechanically independent thinner copper inner walls to carry the RF currents. One cavity, apparently during vacuum pump-down, experienced a large inward deformation of both copper end-walls and an unacceptable frequency shift. The cause of the problem is attributed to an excessive rate of pump down, although the cavity had been pumped more than once previously without incident. Repair was straightforward, but the event might imply the need for specific operational procedures during the lifetime of the cavities.

SUPERCONDUCTING SOLENOIDS

The HINS lattice relies on SC solenoid magnets [9] for transverse focusing throughout the machine. Thirty-seven solenoids, about half with integral X-Y steering dipole coils, are required for the present configuration.

The nineteen in the warm linac section require individual cryostats. The magnet cold-mass production for these is nearly complete. Parts for eight cryostats are machined and assembly with the cold masses has begun. Fabrication of the remaining cryostats awaits design modifications to incorporate a beam position monitor into the bore of the warm beam tube.

The eighteen solenoids in the SC section, incorporated into the cavity cryomodules, do not require separate cryostats. These magnets, however, have stringent stray field limits due to their ultimate proximity to the SC cavities. Tight alignment tolerance requires well-characterized motion during cool-down. A prototype solenoid is ready for installation into a test cryostat prepared to facilitate these magnetic field and motion measurements.

SUPERCONDUCTING SPOKE CAVITES

The 30 MeV HINS linac requires eighteen 325 MHz $\beta = 0.2$ single-spoke resonator RF cavities [Fig.3]. Thus far, two have been fabricated [10], one by Zanon (Italy) and one by Roark Welding and Engineering (US). Two more cavities are in the early stages of fabrication for HINS by collaborators at the Inter University Accelerator Centre (IUAC) (India). These two cavities are scheduled for completion in early 2010.

The first two cavities underwent buffered chemical processing and high-pressure rinse in facilities at Argonne National Laboratory and have been tested with CW RF power in the Fermilab Vertical Test Stand (VTS).

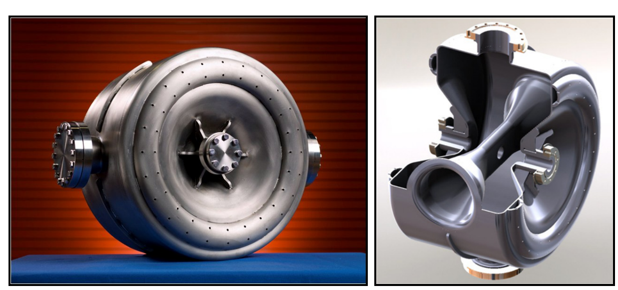

Figure 3: HINS 325 MHz $\beta = 0.2$ single-spoke resonator.

Both unjacketed cavities successfully performed in VTS to beyond the design operating point with equivalent accelerating gradients in excess of 10 MV/m at $Q_0 > 5E8$ at 4°K. VTS supports testing at 2°K as well; at this temperature, the Roark cavity achieved a record spoke cavity gradient of 33 MV/m [11]. The Zanon cavity was installed and cooled down in VTS multiple times; the Roark cavity only once. The Zanon cavity showed an unexpectedly large Q-slope in successive cool-downs suggesting Q-disease. One cycle included a seven-hour hold at ~100°K to 'invite' a show of Q-disease. Indeed, it manifested itself as an order of magnitude decrease in Q even at very low gradients. Subsequently that cavity has undergone a 600°C bake to rid the surfaces of hydrogen and is now being welded into a helium vessel in preparation for high pulsed-power tests.

A cryostat to accommodate dressed spoke cavities for full pulsed-power testing has been fabricated. Installation of the cryostat and the required cryogenic transfer lines from an existing plant is to begin in May 2009. Preliminary results from pulsed spoke cavity tests are anticipated before the end of the year.

RF CONTROL AND HIGH-POWER VECTOR MODULATORS

325 MHz power for HINS cavity and RF component testing is provided by a 2.5 MW Toshiba E3740A(Fermi) klystron. This klystron is ultimately expected to power all nineteen copper structures in the HINS warm linac section; a second E3740A will power all eighteen SC spoke cavities. The original plan to combine copper and SC cavities on one klystron now appears infeasible. Achieving control of multiple cavities with individual amplitudes, phases, and beam loading requires a high-power vector modulator per cavity and a complex low level RF (LLRF) system for precise coordination. Vector modulator development is well along and modulators that function at the required power levels with phase control rates > 4°/µsec are demonstrated [12]. Simulations of the LLRF system dynamic response with vector modulators under realistic RF and beam conditions have been made [13]. Measurements to characterize the power control element transfer functions continue.

HINS PROGRAM OUTLOOK

The HINS program looks forward to upcoming technical achievements, in particular, 2.5 MeV beam through the RFQ, installation of the SC cavity test cryostat, first results from SC spoke cavity pulsed-power tests, and demonstration of multiple cavities operating with vector modulators under LLRF system control. The prospect of beam accelerated even to 10 MeV through the warm linac is not imminent due to the timeline for designing and procuring cryogenic transfer lines and feed-cans to supply helium for the SC solenoids in that section. Plans are in the works for a temporary beam line using quadrupole focusing and only a few RT-CH cavities to advance the first demonstration of accelerated beam through vector modulator controlled cavities.

As Project X efforts proceed, the identity of the HINS program at least will be altered. An evaluation, based on performance, cost, and risk, will determine how and if the HINS technologies are incorporated into a Project X Linac design.

SUMMARY AND CONCLUSION

The Fermilab HINS program has made major progress in developing and fabricating components and systems essential to achieving its multiple, ambitious technical goals. Although realization of those goals is yet in the future, HINS remains highly relevant for the influence it can have on technology choices for any future high intensity proton or H^- linac. Success in achieving these goals at the earliest possible date is important for the science of accelerators and for positioning the HINS machine as the front-end of a Project X linac.

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