PROGRESS AT THE FREIA LABORATORY

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Abstract

The FREIA Facility for Research Instrumentation and Accelerator Development at Uppsala University, Sweden, has reached the stage where the testing of superconducting cavities for the European Spallation Source (ESS) is starting. The new helium liquefaction plant has been commissioned and now supplies a custom-made, versatile horizontal cryostat, HNOSS, with liquid helium at up to 140 l/h. The cryostat has been designed and built to house up to two accelerating cavities, or, later on, other superconducting equipment such as magnets or crab cavities. A prototype cavity for the spoke section of the ESS linac will arrive mid 2015 for high-power testing in the horizontal cryostat. Two tetrode-based commercial RF power stations will deliver 400 kW peak power each, at 352 MHz, to the cavity through an RF distribution line developed at FREIA. In addition, significant progress has been made with in-house development of solid state amplifier modules and power combiners for future use in particle accelerators. We report here on these and other ongoing activities at the FREIA laboratory.

INTRODUCTION

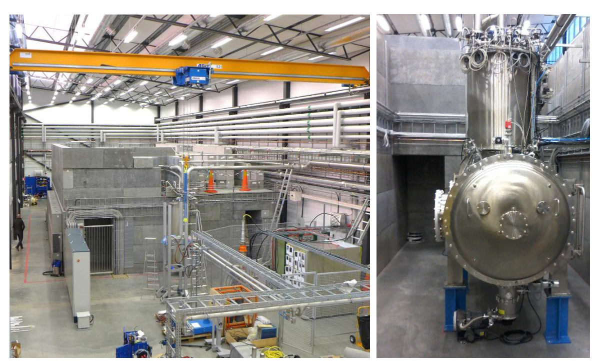
The European Spallation Source (ESS) [1] is under construction in Lund, Sweden. Once completed it will deliver spallation neutrons to a large number of experiments with users from various disciplines interested in the fundamental atomic and molecular properties of materials. As any major accelerator complex, ESS strives to keep the power consumption to a minimum, which motivated the use of a superconducting linac. This linac provides an intense 5 MW proton beam of 2 GeV energy, in 2.86 ms long pulses with 14 Hz repetition rate to the ESS target.

The first superconducting section of the linac uses double-spoke cavities designed and tested at low power at Institut de Physique Nucléaire d'Orsay (IPNO), France. FREIA is charged with designing and testing RF generation and distribution systems for ESS and to test the double-spoke cavities at nominal power. One or several prototype cavities, equipped with a input power coupler and a cold tuning system, are expected mid 2015. The high-power tests require feeding the cavity with 3.5 ms long 352 MHz RF pulses of 400 kW power. It also includes cooling the cavity to, and keeping it at, 2 K. To this end, FREIA has a high capacity helium liquefaction plant and a tailor-made horizontal cryostat, which can serve two superconducting cavities simultaneously.

In parallel with the ESS study, FREIA hosts research programs such as the development of solid-state amplifiers for accelerator applications, the design of a combined compact THz/X-ray source, and studies within the ESS neutrino super-beam project. This paper gives a status overview of the FREIA laboratory, reporting on progress in infrastructure subsystems and on its main activities.

THE FREIA LABORATORY

The FREIA laboratory was inaugurated in June 2013 and is now nearly full of state-of-the-art equipment for accelerator research and development. The view of the 1000 m^2 hall, displayed in Fig. 1(a), is dominated by three radiation bunkers built with an iron pre-loaded concrete material (magnetite) to shield people and environment from the potential X-rays emitted during operation with high-power RF. The main bunker contains the superconducting RF (SRF) equipment for the spoke cavity and cryomodule tests for ESS. A smaller bunker has been pre-assigned to tests of high-gradient, high-frequency copper accelerating structures, either for the Compact Linear Collider or for possible future free electron lasers, or medical accelerators. Another small bunker will house a neutron source for research and educational activities in applied nuclear physics.



(a) FREIA (b) HNOSS

Figure 1: The FREIA laboratory (a) and the horizontal cryostat HNOSS installed in the main bunker (b).

Helium Liquefaction Plant

The heart of the laboratory is the helium liquefaction and recovery plant. The liquefier L140 was acquired from Linde Kryotechnik AG and commissioned in March 2014.

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Since then, it regularly delivers 4.5 K helium to FREIA and to external users within and outside the university. The plant contains a cold box with a 20 K adsorber for helium purification, a 2000 l dewar for storage of liquid helium, a filling station for external users and a recovery system with a 100 m^3 gas bag and compressors. In addition, FREIA has a system for liquid nitrogen, including a 20 000 l dewar and a filling station. The standard capacity of 140 l/h of the helium liquefier, achieved with nitrogen pre-cooling, can be increased during limited periods by using the helium dewar as a buffer.

The Cryostat HNOSS

The helium liquefier and recovery system is connected to a horizontal cryostat, HNOSS [2], specifically designed and built for FREIA's various needs. HNOSS, shown in Fig. 1(b), was designed by Accelerator and Cryogenic Systems (ACS) to simultaneously house two superconducting cavities, either of the spoke type or of the TESLA-like elliptical type, or other superconducting equipment such as magnets or crab cavities. The valve box, housed in a tower on top of the main vessel, is used for cooling the 4.5 K helium to a minimum of 1.8 K. At this temperature subatmospheric pumps are employed for keeping the pressure.

HNOSS was delivered to FREIA in August 2014 and commissioned in the months following. In December 2014, a mock-up cavity was installed in HNOSS and cooling with helium at 1.8 K was achieved. Since then, the cryostat is fully operational in continuous mode and is ready to receive the first double-spoke resonator.

RF Power Generation and Distribution

Each spoke resonator requires 400 kW peak power to reach the nominal field. HNOSS can serve two cavities, and two RF stations, based on two tetrodes each, are expected to arrive at FREIA before summer 2015. Each station consists of a solid-state pre-amplifier and two tetrodes connected in parallel. They are expected to deliver 400 kW RF peak power at 352 MHz frequency in 3.5 ms long pulses at 14 Hz pulse repetition rate, in accordance with the ESS specifications [3].

Meanwhile, another three-stage tetrode RF station has been generously lent to us by CERN and has just been installed at FREIA. It includes a solid state pre-amplifier and two grid-grounded tetrodes in series and can now deliver over 40 kW pulsed or continuous-wave (CW) power for initial tests of spoke cavities.

For the high-power distribution line waveguide components are under assembly, together with two water-cooled ferrite loads and a water-cooled circulator, with power handling capability of 20 kW in CW mode and 400 kW peak power. The circulator is capable of handling full reflection for 3.5 ms. Theses components will be tested in CW mode with the CERN amplifier within the coming weeks.

Control System

All facilities installed so far in FREIA are controlled from EPICS (Experimental Physics and Industrial Control System). The basic services like the archiver, the electronic logbook and a number of operator's interface screens are in place. The main effort now is concentrated on integrating with EPICS the equipment successively coming to FREIA, building the operator's interface screens and on configuring the alarm system.

MAIN RESEARCH PROJECTS

Several accelerator projects are planned for development and test at the FREIA laboratory. Here, we report on the status of our main research activities.

SRF Testing and Development for ESS

A first experimental campaign using all available infrastructure at FREIA was performed with a single-spoke cavity, also developed at IPNO. This cavity, with optimal $\beta = 0.15$, though different from the ESS double-spoke resonator, has already been used for testing equipment, benchmarking and refining measurement techniques, and has helped us to complete the final preparations for the high-power tests of the ESS double-spoke cavities.

Using an analog self-excited loop, which is an oscillator built around the superconducting cavity under test, we measured the quality factor of this 360 MHz cavity as a function of accelerating gradient, where we use $\beta\lambda$ for the acceleration length, λ being the RF wavelength. The cavity demonstrated soft multipacting barriers, which were easily processed with an RF signal. At $T = 4$ K no thermal quench was observed while for $T = 2$ K we observed thermal quenching at an accelerating gradient of around 5 MV/m, as seen in Fig. 2.

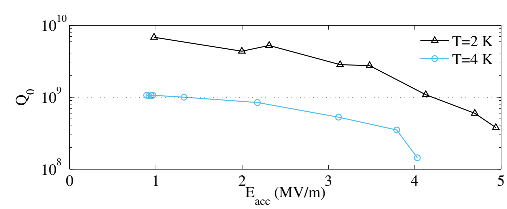

Figure 2: The quality factor Q_0 as a function of the accelerating gradient E_{acc} for single-spoke cavity operating at a pressure of 1 bar for $T = 4$ K and 31 mbar for $T = 2$ K.

Since the cavity walls are made thin for good heat transfer, the cavity is sensitive to mechanical deformation, which affects its resonance frequency. The measured deviation of the cavity frequency as a function of the vibration frequency is shown in Fig. 3. The main source of mechanical deformation at 4 K is helium bubbles and this is manifested in the spectrum as nearly uniform low-frequency noise.

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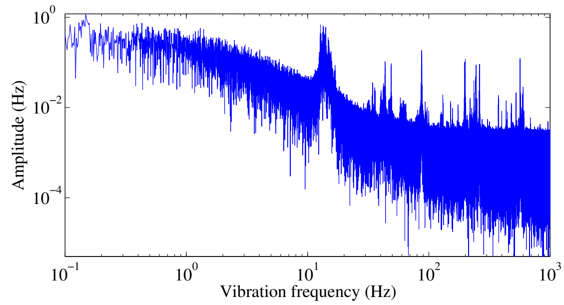

Figure 3: Fourier transform of the variation of the cavity frequency with time (microphonics spectrum) measured at $T = 4\,\mathrm{K}$, $E_{acc} = 1\,\mathrm{MV/m}$ and a pressure of 1 bar.

With these preliminary results we are ready to receive the first ESS spoke prototype. Once fully characterized, the results from FREIA will influence the final design of the spoke cavity and ancillary equipment, before tender for, and manufacturing of, the in total 26 cavities take place. In the final configuration, the cavities will be placed in pairs in cryomodules, of which a prototype will arrive for testing at FREIA late 2015. Series-testing at FREIA of cryomodules are planned for 2017-2018.

Solid-state Amplifier and Combiner Development

Solid-state based RF power stations are generating an increasing interest, due to their high efficiency, reduced maintenance, higher operability and life-time expectancy. The research and development aims at reducing manufacturing costs and overall footprint, and increasing the available power. In this context, FREIA drives an in-house development of kilowatt-level solid-state amplifier modules [4] and of the combination of these modules, towards a 10 kW amplifier demonstrator. Recently, a prototype for a compact power combiner, with a capacity of up to the megawatt level, was designed, manufactured and tested with promising results [5].

Through a collaboration with industry, we plan to develop and test a complete 352 MHz 400 kW peak solid-state based RF power station compatible with the needs for the ESS spoke linac. In this work, volume size limitation is important due to the need to install 26 RF power stations in the vicinity of the ESS linac. A prototype station is being developed by industry and is based on commercial transistor modules with 1 kW peak output power and a three-level RF power combination scheme [6]. In addition, we collaborate with various industry and research partners on similar developments at several other frequencies, (100 MHz, 750 MHz and 1300 MHz) and power levels (1kW, 10 kW and 100kW), relevant for accelerator applications.

SUCCESS: A THz/X-ray source

Terahertz (THz) radiation enables probing and controlling low-energy excitations in matter, such as molecular rotations, DNA dynamics, spin waves and Cooper pairs. In view of a growing interest in this range of the spectrum, the Swedish FEL Center and the FREIA laboratory are working on a conceptual design of a compact multicolor photon source for multidisciplinary research. We envision an outstanding source of THz radiation with a pulse duration in the femtosecond (fs) range and a MV/cm field strength complemented with a fs X-ray source for monitoring the state of excited matter. The combined fs THz/X-ray source will be based on a superconducting linear accelerator with the technology available at FREIA. The source is planned as a driver for a user facility and for testing advanced FEL schemes. See Refs. [7, 8] for details on the development.

ESSnuSB

The proton beam in the ESS linac has a world-unique intensity of 5 MW, which has motivated the study of an ESS neutrino super-beam (ESSnuSB) [9]. The neutrino beam would be produced in a dedicated target station, aiming at an underground detector located ca 500 km from the source. There, by counting the number of electron and muon neutrinos coming from the decay of either π^+ or π^-, one aims at discovering CP-violation in the leptonic sector. To be able to use the ESS linac for neutrino production it is necessary to do modifications of the existing linac, primarily doubling the duty factor from 4% to 8%. The FREIA laboratory is involved in this study, on which details can be found in Refs. [10] and [11].

CONCLUSION

The FREIA laboratory in Uppsala now has a complete cryogenic system with a helium liquefaction and recovery plant, connected to a horizontal cryostat that can host superconducting equipment during test. Liquid helium at 1.8 K was produced late 2014, final touches are given to the system for controls and data acquisition, and a distribution line for high-power RF is about to be assembled. A 40 kW amplifier for 352 MHz is installed and two 400 kW RF amplifiers are expected shortly. With this, the laboratory is ready to receive superconducting, double-spoke resonators designed for the ESS linac, for high power tests. Meanwhile, the equipment has been tested through the characterization of a single-spoke superconducting cavity. The results show that we are ready to complete the experiments that FREIA was meant for.

ACKNOWLEDGEMENTS

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