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Abstract

This report describes the test plan for the first high power RF source, ESS prototype double spoke cavity and ESS prototype cryomodule at the FREIA Laboratory.

## 1 The FREIA Laboratory

Uppsala University (UU) has established FREIA, for the development of accelerator technology [1]. The FREIA Laboratory is equipped with a superconducting radio frequency (SRF) cavity test facility centered around the HNOSS, a horizontal cryostat that can be used to test two SRF cavities simultaneously [3, 4]. It can handle a peak heat load of up to 120 W at 4 K or 90 W at 2 K operation. Two high power radio frequency (RF) amplifiers are being developed to provide the RF power for testing the SRF cavities. Their specifications are for 400 $kW_{peak}$ at 352 MHz with 3.5 ms pulses at 14 Hz repetition rate or continuous wave (CW) operation at 40 kW [5]. These are tetrode (vacuum tube) based amplifiers combined with solid-state pre-amplifiers. A full solid-state high power amplifier is developed by industry and will be tested at FREIA when available, but is not part of the project plan described in this report. The project plan that describes the build-up of the test facility, including cryostat and cryogenic system, has been reported earlier [2].

## 2 The ESS Superconducting Spoke Linac Section

The European Spallation Source (ESS) is a neutron spallation source that will create the neutrons by shooting a proton beam onto a rotating tungsten target. The proton beam, of some 62 mA, is accelerated up to 2 GeV in a linac. As shown in Figure 1, from 90 to 216 MeV it contains a section consisting of superconducting double spoke cavities. This section is

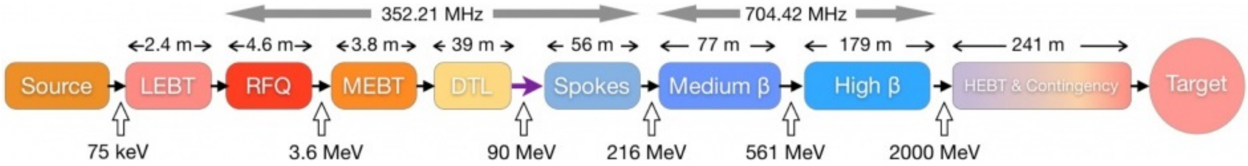


*Figure 1*: Layout of the ESS linear accelerator.

crucial for the acceleration of the proton beam up to an energy sufficiently large for efficient neutron spallation in the tungsten target. Research and development of superconducting double spoke cavities has been ongoing for many years and multiple prototype spoke cavities have been build. However, none of these have ever been operated in a real accelerator. Therefore it has been decided to perform full power tests of single cavities and complete cryomodules to verify their performance.

# 3 Project Overview

The FREIA Laboratory will test the prototype double spoke cavity and spoke cryomodule for the ESS proton linac at full RF power. The equipment is being developed at Institut de physique nucléaire d'Orsay (IPNO) which however does not have the resources to test the equipment at nominal RF power.

The project can be split in several phases:

1. test of high power RF amplifier (HPA),
2. test of bare spoke cavity,
3. test of dressed spoke cavity,
4. test of cryomodule with two spoke cavities.

Phase 3 requires the availability of one high power RF amplifier (also referred to as a RF power station, RF power source or RF transmitter) tested during phase 1. Phase 4 requires

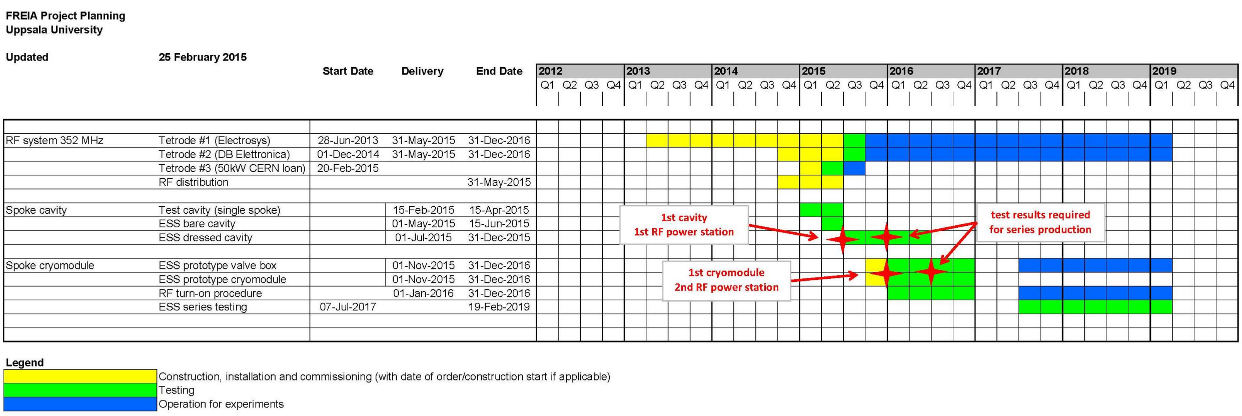


*Figure 2*: Overview of the project planning time line.

the availability of two such high power RF amplifiers. HNOSS will be used during phase 2 and 3 to house the cavity under test.

An overview of the project plan time line is given in figure 2. The first HPA, a single tetrode 50 kW amplifier on loan from CERN, will arrive mid February 2015 while two commercially build HPA system will arrive in June. At the instant of writing this report, the bare prototype spoke cavity, without fundamental power coupler (FPC) and cold tuning system (CTS), is expected to arrive during Spring 2015. It will be installed in HNOSS and tested with low power RF to verify the installation and measurement procedures at FREIA and to calibrate the measurements between IPNO and FREIA. This will prevent unexpected discrepancies during the dressed cavity test due to procedure differences. When FPC and CTS are available for mounting on the cavity, the cavity will be shipped back to IPNO. After mounting the FPC and CTS, the cavity will be once more shipped to FREIA now for test at nominal RF power. This is expected for Summer 2015. The cryomodule is scheduled for arrival end 2015.

The important dates driving the schedule are

**01-Dec-2015** test result of dressed cavity with FPC and CTS required for start ordering the series production parts

**01-Jul-2016** test results of cryomodule required for start ordering the series production parts

**Due to delays, the time available between arrival of the equipment to be tested and the delivery of results for start ordering the series production is only six months.**

In the remainder of this report we will refer to the double spoke cavities as spoke cavities, omitting the word double in its name. A single spoke cavity is thus intended to mean one (1) cavity with two (double) spokes.

# 4 Test of High Power RF Amplifier

Two high power amplifiers have been ordered from industry to be build around Thales type TH595 tetrode tubes based on a FREIA design [5, 6]. One TH595 tube has been factory tested to the required performance. Each high power amplifier will combine the output of two tetrode tubes to reach an output power up to 400 $kW_{peak}$ as required for powering one spoke cavity in the ESS linac. Figure 3 shows the internal layout of the high power RF amplifier. Each of the two parallel amplification chains consists of a solid-state driver (single transistor), then a solid-state pre-amplifier (multiple transistors) and the final vacuum tube power amplifier (single tetrode tube). Each amplifier stage, solid-state or vacuum tube, has multiple power supplies. The tetrodes require four power supplies: filament heater, screen grid, control grid and anode. One of the high power amplifier systems will have a combined anode power supply for both tetrodes while the other high power amplifier system will have separate anode power supplies for each tetrode.

After a factory test the amplifiers will be shipped to FREIA. Commissioning at FREIA will be done with a water cooled dummy load connected to the high power RF output. When operating with the cavity or a variable short (to mimic the cavity behaviour through variable reflection phase) connected, a circulator protection device will be installed at the amplifier output to prevent RF power to be reflected back into the amplifier.

The following tests are planned:

- component test, to verify the operation of the main sub-components before operation of the tetrode amplifier. At minimum verification test of the
  - controls and hardware interlocks, including crowbar and/or series-switch.
  - power supplies
  - solid-state driver and pre-amplifier
- RF test on matched dummy load, slowly increasing the pulse length and RF output power to nominal value.
- transfer curve and linearity measurement, to verify the gain and phase shift versus power. Measure
  - gain versus power
  - phase shift versus power
  - harmonics (2nd, 3rd) and noise versus power
  - efficiency versus power
- RF test with circulator on variable short, test to verify operation with variable reflection phase. Also verification of the circulator functionality. Operation of the equipment at nominal operation values while varying the reflection phase.
- soak test with matched dummy load or cavity connected, running the equipment at nominal operation values from several days to months.

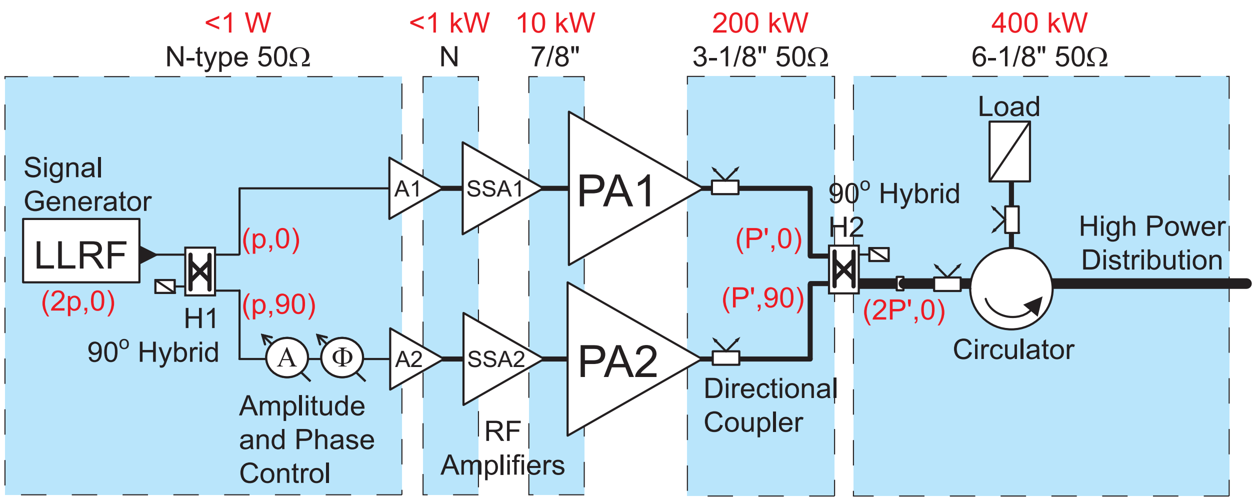


*Figure 3*: Layout of the high power RF amplifier. A1, A2 are solid-state drivers, SSA1 and SSA2 solid-state pre-amplifiers and PA1, PA2 tetrode power amplifiers.

Besides the two commercial high power RF amplifiers based on tetrode tubes, a third high power RF amplifier is being developed by industry based on high power solid-state transistors. After completion by industry and factory test, the amplifier will be lend to the FREIA Laboratory for an independent verification of the test. This amplifier will undergo the same test plan as described above.

After commissioning of the amplifiers they will be connected to a dressed spoke cavity for an integral test of the complete RF chain, see below.

# 5 Test of Bare Spoke Cavity

The spoke cavities are developed by IPNO. After assembly in industry they will undergo chemical treatment. In a clean room the cavities will then be equipped with a low power antenna for coupling the RF into the cavity volume. The cavity with low power antenna is referred to as bare cavity. They will tested in a vertical cryostat at IPN Orsay to characterize the cavity intrinsic behaviour and acceleration performance. This includes measuring its maximum achievable gradient and $Q_0$ factor, to check for field emission onset and multipacting barriers.

After test at IPN Orsay, the cavity will be transported to FREIA and installed into the HNOSS horizontal test cryostat. The bare spoke cavity will be without fundamental power coupler (FPC) and cold tuning system (CTS). The test will therefore be a repeat of the vertical cryostat test in a horizontal test cryostat environment.

Using the low power antenna for coupling the RF into the cavity it is sufficient to have a RF power source in the order of a 100 W. The high power RF amplifiers are therefore not used for this test. Instead a self-excited loop is used to lock the cavity to the resonant RF frequency, see figure 4. The amplifier creates a white noise signal which is filtered by the cavity. The cavity acts as a band-pass filter and only its resonant frequency (plus bandwidth and higher harmonics) will pass. The power attenuator and limiter prevent a run-away of

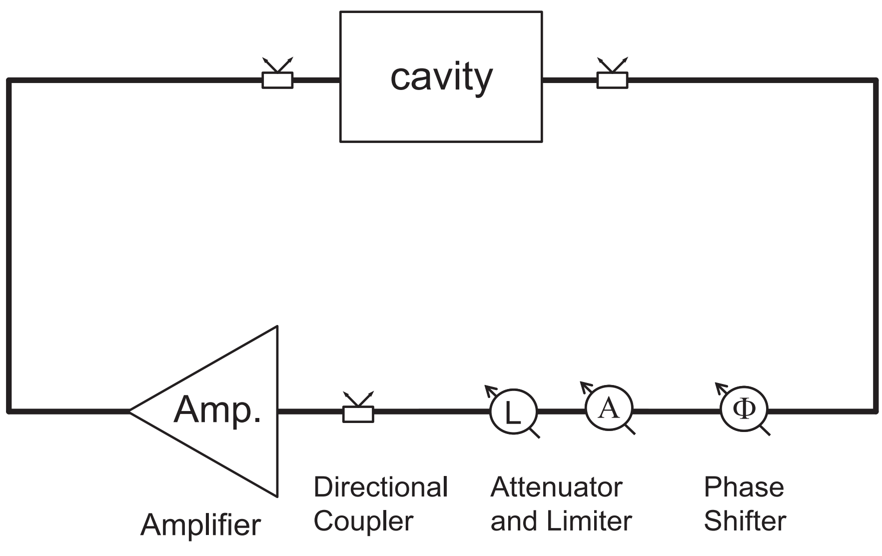


*Figure 4*: Test configuration of a bare cavity with self-excited loop.

the signal's power level. Frequency, phase and power level are monitored at the directional couplers. The LLRF uses these measurements to adjust the phase of the loop to $2\pi$ with respect to the resonance frequency.

This test has the following aims:

- verify the installation, cool down and operation procedures for the cavity in HNOSS,
- verify and develop the measurement equipment and procedures at HNOSS,
- repeat the vertical test as performed at IPNO to validate the procedures and measurements at HNOSS,
- verify cavity intrinsic ability, accelerating performance, mechanical behaviour.

Typical measurements:

- verify cavity RF behaviour on warm cavity before installation in HNOSS,
- loaded $Q$-factor, eigen and external $Q$, $Q_0 = f(E)$ curve,
- Lorentz detuning and microphonics,
- field emission onset and multipacting barriers,
- sensitivity to helium pressure fluctuations,
- achieve nominal gradient and nominal $Q_0$,
- cryogenic heat load.

Microphonics tests could be done with a phase-locked self-excited loop.

Repeating the vertical test in the HNOSS horizontal cryostat is therefore considered important as it will help to develop and verify the measurement procedures at HNOSS.

# 6 Test of Dressed Spoke Cavity

When the high power couplers are available, the bare cavity will be taken out of HNOSS and sent back to IPN Orsay. There the cavity will be equipped with the fundamental high power coupler (FPC) and cold tuning system (CTS). This will be referred to as the dressed cavity. The, now dressed, cavity will then be shipped back to FREIA and re-installed in HNOSS.

Equipped with the FPC and CTS, the cavity will be tested at full (nominal) RF power with one of the high power RF amplifiers. The object of this test thus becomes the validation of a complete chain of high power RF amplifier, high power RF distribution, FPC and spoke cavity with feedback to the LLRF system operating the CTS. Except for the power transfer to the proton beam, all elements of a superconducting spoke section chain, from RF power generation to cavity, can be validated. Figure 5 shows the layout of the cavity connected to a high power RF amplifier and low power level radio frequency and control system (LLRF).

This test has the following aims:

- verify cooling procedures, (note: power coupler might require superfluid helium cooling)
- verify cold tuning system (CTS) ability and performance,
- verify power coupler ability and performance, (note: power coupler might require re-conditioning)
- verify cavity intrinsic ability, accelerating performance, mechanical behaviour.
- verify LLRF ability and performance, develop the required software codes for Lorentz detuning and microphonics correction by using the CTS.
- verify the high power RF amplifier ability and performance in combination with the cavity and LLRF,
- achieve nominal RF pulse (note: with correction for absent beam loading).

Typical measurements:

- Loaded $Q$-factor, eigen and external $Q$, $Q_0 = f(E)$ curve,
- Lorentz detuning and microphonics,
- field emission onset and multipacting barriers,
- sensitivity to helium pressure fluctuations,
- achieve nominal gradient and nominal $Q_0$,

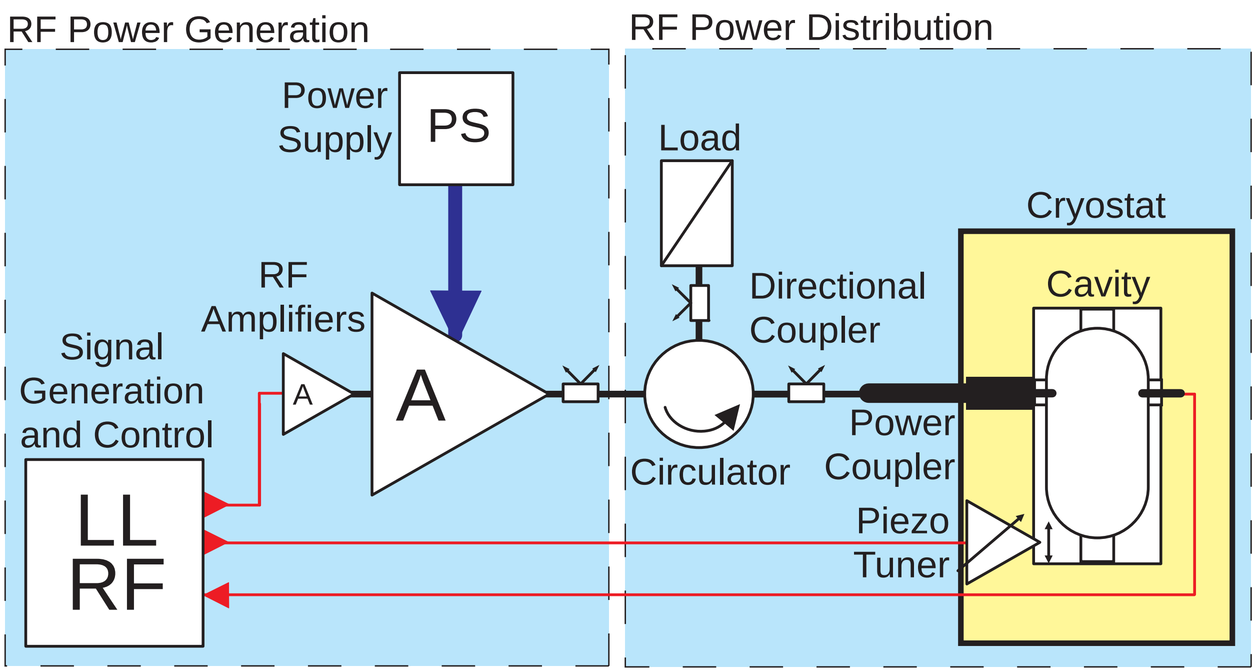


*Figure 5*: Test configuration of a high power RF amplifier and spoke cavity.

- cryogenic heat load.

A detailed list of tests is given in the appendix.

# 7 Test of Spoke Cryomodule

The next step up in the validation of the ESS spoke linac section is a cryomodule with two dressed spoke cavities. This is a prototype unit as should be installed in the ESS linac and includes all cryogenic interfaces replacing the HNOSS test cryostat. Simultaneous operation of the two cavities requires also two high power RF amplifiers. Figure 6 shows the proposed layout of the high power RF distribution. Three high power RF amplifiers can be connected to or the two cavities or two dummy loads (for test operation of the amplifier without cavity).

Difference between this test and the individual dressed cavity test in HNOSS is that each cavity in the cryomodule has its own magnetic shield integrated with the cavity. While the dressed cavity in HNOSS has no magnetic shield yet while relying instead on the HNOSS magnetic shield which is located at room temperature inside the wall of the vacuum vessel. In addition to the spoke cryomodule, also the prototype valve box shall be tested.

This test has the following aims:

- Verify valve box ability and performance. Ensure there are no flow instabilities or other issues taking into account different operation conditions. Note that the phase separator is in the valve box, thus 2K flow from valve box to cryomodule is through a

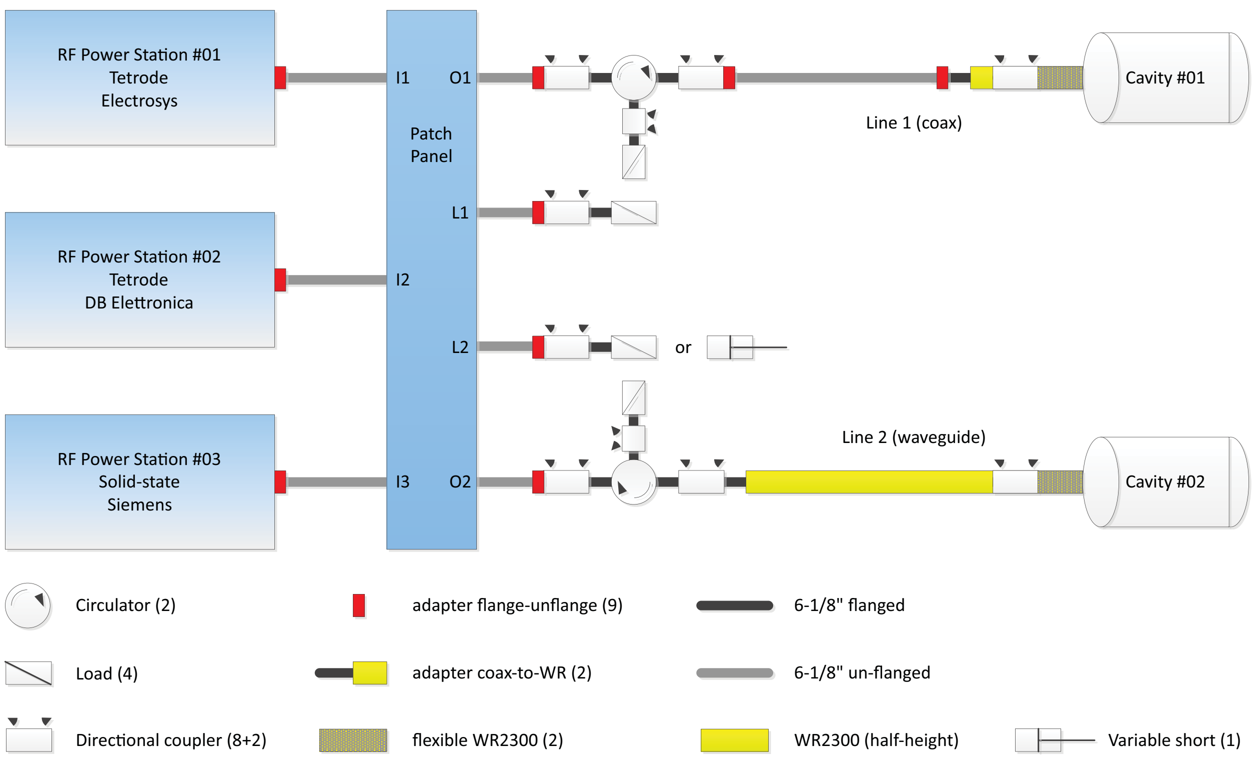


*Figure 6*: Test configuration for the cryomodule.

long transfer line. Note also that if the power couplers require cooling by supercritical helium, this has to be produced in the valve box.

- Verify ability and performance of the two individual cavities in the cryomodule, similar as the verification of the individual spoke cavity in HNOSS. This includes the FPC and CTS.
- Verify simultaneous operation of both cavities in the cryomodule in combination with the LLRF and high power RF system.
- Verify performance of the magnetic shield, verify if active cooling is required. Measure the effect on the cavity ($Q_0$) and compare with active cooling on/off when cooling below SC temperature.
- Verify ability and performance of the cryomodule including cryogenic heat load, cooling of cavity and FPC.

# 8 Summary

We have described the provisional test plan and planning for the ESS spoke cavity and high power RF amplifier. During Spring 2015 the FREIA Laboratory will do the first test of a superconducting cavity in HNOSS. The first high power RF amplifier station will also be installed and commissioned before Summer 2015. Then a busy schedule will follow to test the ESS spoke cavities and high power RF amplifier stations. Parts and pieces will be tested carefully and individually before combining all to a full slice of the accelerator consisting of two high power RF amplifiers and a spoke cryomodule. The FREIA Laboratory is prepared to receive and test these equipment.

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# Glossary

CTS . . . cold tuning system

CW . . . continuous wave

ESS . . . European Spallation Source

FPC . . . fundamental power coupler

FREIA . Facility for Research Instrumentation and Accelerator Development

HNOSS . Horizontal Nugget for Operation of Superconducting Systems

HPA . . . high power RF amplifier

IPNO . . Institut de physique nucléaire d'Orsay

linac . . . linear accelerator

LLRF . . low power level radio frequency and control system

RF . . . . radio frequency

SRF . . . superconducting radio frequency

UU . . . Uppsala University

# APPENDIX: COLD RF TESTS OF THE CAVITY

| Step | What | Why | How | By what means | Comments |
|---|---|---|---|---|---|
| 1 | Loaded Q-factor | Determines the overall cavity losses and is needed to calculate the cavity voltage. | Decay measurement | Scope | |
| 2 | Loaded Q-factor (cross-check) | | S21 measurement | VNA | |
| 3 | Eigen and external Q: Q_0 and Q_ext | Q_0 defines intrinsic cavity losses, Q_ext determines coupling of the excitation antenna to the cavity. | Reflected type measurement [1,2]. | VNA | The technique is tested on the copper cavity and matlab files for calculation of Q-factors are available. |
| 4 | Q of a pick-antenna | Q_ant determines coupling of the pick-up antenna to the cavity and defines a transmitted signal. | Reflected type measurement [1,2]. | VNA | |
| 5 | Power loss | Check the system linearity. | S21 measurement | VNA | Make sure the power loss is a linear function of input power as it must be. |
| 6 | Stored energy | For cross-check of Q_0. | Emitted power measurement [3] | VNA or scope or power meter | The power loss and stored energy is another way to calculate Q_0. |
| 7 | Shunt impedance R/Q | Along with Q_ext, it determines transformation of incident power to cavity voltage. | | | Calculated from preceding measurements. |
| 8 | Impedance of a pick-up antenna | Will be used to calculate accelerating gradient using a measured value of voltage of a transmitted signal. | Analytical calculations [4] | | Calculated analytically using the results of preceding measurements. |
| 9 | Q_0 as a function of the cavity gradient | To see at what voltage the cavity quenches. | Measure the cavity gradient and power loss | Simple signal generator, amplifier up to 1 kW, data acquisition system or VNA | Correct calibration is critical |
| 10 | Field emission onset as a function of gradient | Determine the safe accelerating gradient with no X-ray | Measure the cavity gradient and X-ray | simple signal generator, amplifier up to 1 kW, data | This measurement is done together with the previous one. |

| | | | | | |
|---|---|---|---|---|---|
| | | emission. | emission | acquisition system or VNA, X-ray detectors | |
| 11 | Multipacting barriers | May prevent from reaching the nominal gradient, so the barriers shall be determined. | Measure forward, reflected and transmitted power along with the vacuum level | generator, amplifier up to 1 kW, data acquisition system, vacuum detector | risk be trapped in the barrier that will result in cavity degradation |
| 12 | Microphonics | Defines the power overhead and caused by random variations of the cavity central frequency. | phase-locked loop (PLL) configuration [3,5,6] | LLRF in a phase-locked loop configuration | programming in LabView of the digital part |
| 13 | Measurement of the dynamic Lorentz transfer function. | This measurement shows how sensitive the cavity is to mechanical vibrations. | PLL configuration with amplitude modulation [5,7,8] | PLL LLRF plus amplitude modulation | programming in LabView |

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