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FREIA Laboratory

Facility for Research Instrumentation and Accelerator Development

System Review of the ESS Cryomodule Tests

Spoke Cryomodule Testing at the FREIA Laboratory

30 November 2017

Magnus Jobs & Roger Ruber
for the FREIA Team

Contents

Plans and schedule for the FREIA Laboratory, Uppsala University,

for acceptance testing of 13 spoke cryomodules

- Description of the FREIA Laboratory
- Control and safety systems
- Quality assurance and documentation
- Test plan
- Testing schedule

Spoiler:

Present ESS overall schedule allows 4 weeks per cryomodule test, reduced from original 18 months combined (= 6 weeks/cryomodule). No time allotted for re-test, failure or vacation (= resource squeeze).

We consider this not feasible and request a minimum 6 weeks (average).

Reminder – Some History

- **2009**: ESS-S and Uppsala start discussion on collaboration
  - development of 704 MHz RF and high power test of cavity
- **2010**: Uppsala University decides to construct the FREIA Laboratory
  - funding from KAWS, Swedish Government and Uppsala University
  - funding from ESS for ESS development work
- **2011**: Collaboration agreement ESS – Uppsala
  - development of 704 MHz RF
- **2013**: Amendment and change of direction
  - development of 352 MHz RF, tetrode and solid-state
  - test of spoke cavity package and prototype cryomodule
- **2015**: Extended collaboration for ESS construction
  - development and test of series spoke cryomodules and controls
  - test of prototype and pre-series 704 MHz RF stations
- **2017**: Modification
  - test of 704 MHz high beta elliptical cavity instead of pre-series 704 MHz RF

Spoke Cryomodule Testing at FREIA

- **Basic infrastructure available**
  - and tested during development prototype spoke RF system and high power test of spoke cavity package
- **Original time schedule** for test (and thereby training possibilities)
  - 1 year spoke cavity package
    → finally 3.5 months: 6 wks (conditioning to warmup) + 8 wks (install/remove)
  - 1 year prototype spoke cryomodule
    → now < 6 months (installation, test, removal)
  - 18 months for acceptance test of 13 series spoke cryomodules
    → now 12 months
- **Reasons for decreased testing time**
  - delays in ESS schedule but keeping with the end date (acceleration completion)
    → cut testing time to keep scheduled end date
  - now the end date has been delayed
    → but end date for testing kept on paper as the present contract with Uppsala University foresees end of financial support by ESS in February 2019

Relevant Tests Performed

- Single spoke cavity
  - antenna, low power
  - self-excited loop (SEL)
  - RF calibration procedures
- Double spoke cavity with tuner
  - antenna and cold tuner, low power
  - cryogenics: cooling, heat load
  - LLRF, SEL
  - Q_0 and gradient, microphonics
- Double spoke cavity package
  - power coupler and tuner, nominal gradient
  - Q_0 and gradient, microphonics, fill time, Lorentz force detuning
  - tuner operation
- RF Station 352 MHz (2x)
  - acceptance and functional test
    - including RF distribution components
  - soak test
  - pulsed and CW operation on cavity
- RF Station 704 MHz
  - acceptance & operation of modulator

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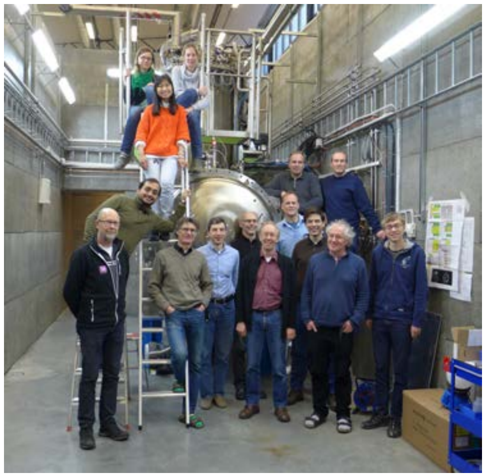
Description of the FREIA Laboratory

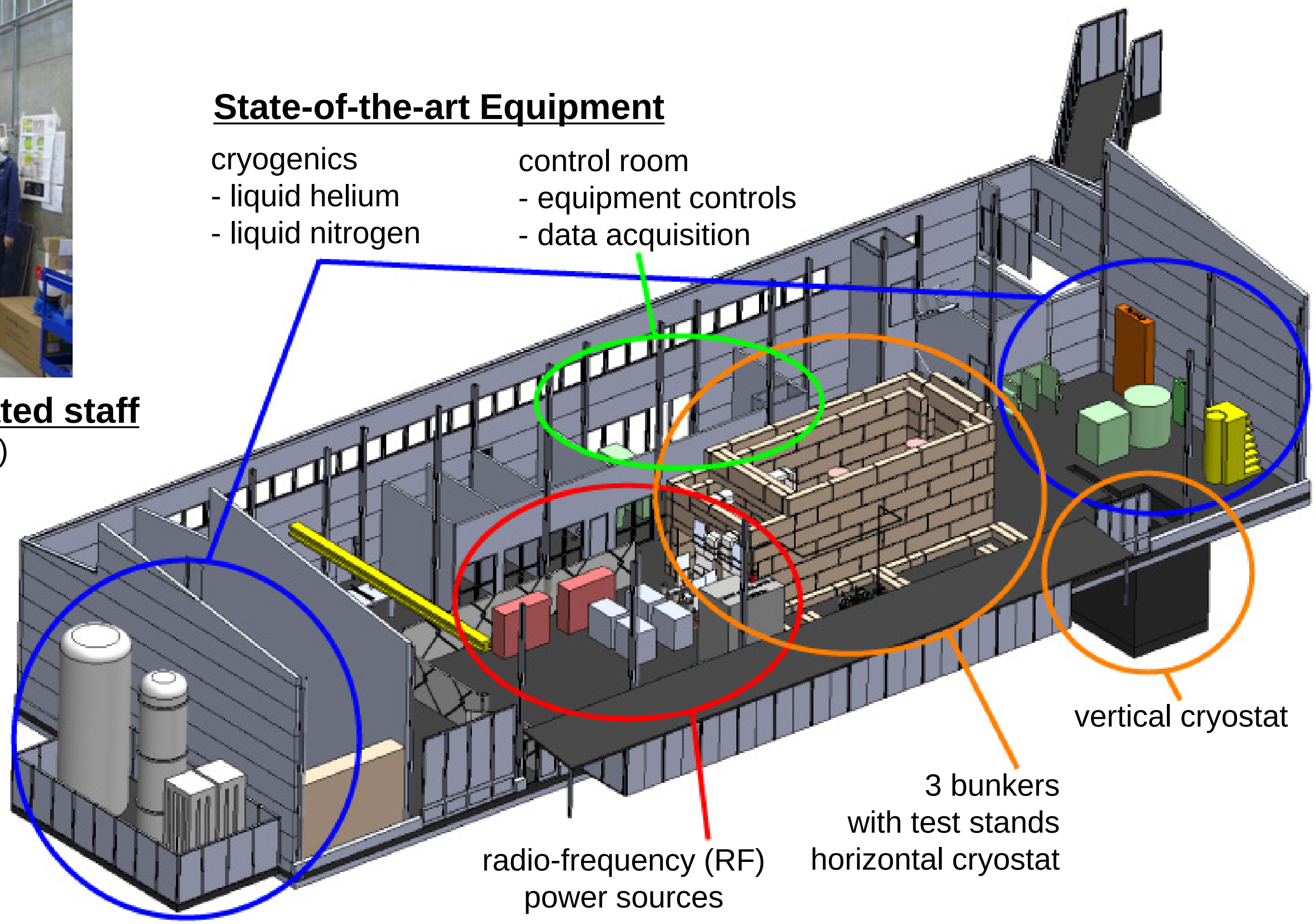
What and Whom?

Facility for Research Instrumentation and Accelerator Development



Competent and motivated staff
collaboration of physics (IFA)
and engineering (Teknikum).

Funded by KAWS, Government, Uppsala Univ.



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Cryogenics

FREIA

Helium gas recovery system

- **Helium liquefaction**
  - 150 l/h at 4.5K (LN2 pre-cooling)
  - 2000 l LHe dewar/buffer, 3+1 outlets
  - cryostats connected in closed loop
- **Gas recovery**
  - 100 m^3 gasbag
  - 3x 25 m^3/h compressor
  - 10 m^3 200 bar storage
- **2K Pumping**
  - ~3.2 g/s at 10 mbar
  - ~4.3 g/s at 15 mbar
  - 110(90)W at 2.0(1.8)K
- **Liquid nitrogen**
  - 20 m^3 LN2 tank

Sub-atmospheric pumping station

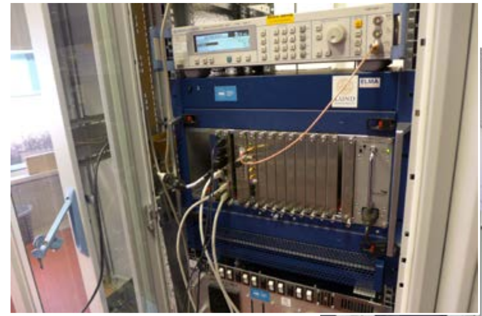
352 MHz RF Amplifiers

- **400 kW, 3.5 ms, 14-28 Hz**
  - Uppsala development
  - combined output 2 tetrodes
    - TH595
  - Itelco-Electrosys (IT)
    - in operation since August 2015
  - DB Elettronica/DB Science (IT)
    - in operation since December 2016

- **50 kW, CW**
  - on loan from CERN
    - in operation since October 2015
    - TH571b
    - 352 or 400 MHz output cavities

Low Level RF and Controls

- **Lund Univ./ESS LLRF**
  - µTCA includes timing system
  - external signal generators
- **Uppsala LLRF**
  - Nat. Instr. PXI and LabVIEW
  - digital phase control for SEL
  - extended RF measurements
- **Controls and interlock**
  - Siemens PLC, NI cRIO
  - EPICS interface with data archiver
  - connecting different sub-systems: Linde, Cryo Diffusion, Leybold ...



EPICS

Safety

- **SSM authorization**
  - as part of university license
  - for supervised operation
  - visit by SSM foreseen 18/01/2018
- **Personal dosimeter**
  - 14 pcs + spare for personnel
    - Instadose (USB interface)
    - readout once per month
  - 1 pcs hand held
    - immediate indication
- **Radiation monitoring**
  - Rotem MediSmarts
  - 1 pts inside bunker
  - 1 pts bunker entrance
  - 2 pts outside bunker

- **Oxygen deficiency monitoring**
  - 1 pts inside the bunker
  - 2 pts at cryo installation
    - dewar filling area, compressor room
- **RF leakage monitoring**
  - home build system
  - 1 pts in the RF/HV area
- **Fire and smoke alarm**
  - provided by Akademiska Hus
  - information panels installed at strategic locations
  - recent inspection by Uppsala fire brigade (10/2017)

Spares and Maintenance

- Main spare parts and maintenance contracts
  - balance between risks and costs
  - spares
    - turbines for helium liquefier too expensive, low risk
    - tetrode tubes, 2 spares, 1 already used (replacement order delayed)
  - maintenance contracts
    - compressors for helium liquefier, gas recovery
    - data backup (to university data centre)
  - framework support and procurement contracts
    - delivery liquid nitrogen and gas helium
    - installation work electricity, water, welding
    - procurement most consumables: electric, electronics, mechanics, vacuum

- Ångström mechanical workshop
    - milling, machining, welding, mechanical design

Control Systems

Control System Overview

- EPICS based,
  - the same environment as at ESS (EEE v2.0.0).
  - The goal is to keep it in sync with ESS at least to the end of the tests.
- All systems at FREIA are connected to EPICS
  - cryoplant, cooling water, LLRF, interlocks, radiation monitors, etc.
  - valve box and cryomodule needs to be integrated
    - upon arrival prototype (preparation discussions ongoing)
    - hardware will be delivered by IPNO
- Interlocks
  - slow interlocks are implemented in the PLC,
  - fast (operating the rf switch) are implemented on FPGA in CompactRIO.

Data Archiving

- Most of the process variables connected to EPICS are stored in a data archive using archive appliance.
  - The "slow" data are sampled with 60 s interval.
  - There is a possibility to save the data at every rf pulse (up to 14 Hz) using the DOD (Data On Demand) module.
  - The data is stored on local FREIA server but will be backed-up regularly using the University file backup system.
    This backup system is used now for backing up another archiver program (from Control System Studio) that is up till now used parallel to the archive appliance.

Conditioning etc

- LabVIEW programs have been used for the tests and power coupler conditioning.
  - We use so called NI Client I/O Server to gain access to all EPICS process variables.
  - The results of the measurements are saved in plain files.
  - For the acceptance tests we plan to use both LabVIEW and python/Matlab programs for automatic tests procedures.

- We plan to use as much as possible CryoModule Calibration & Measurements Configuration Management Tools proposed by Nuno Elias https://confluence.esss.lu.se/display/CRYOM/CM3T

Lund Low Level RF and Timing System

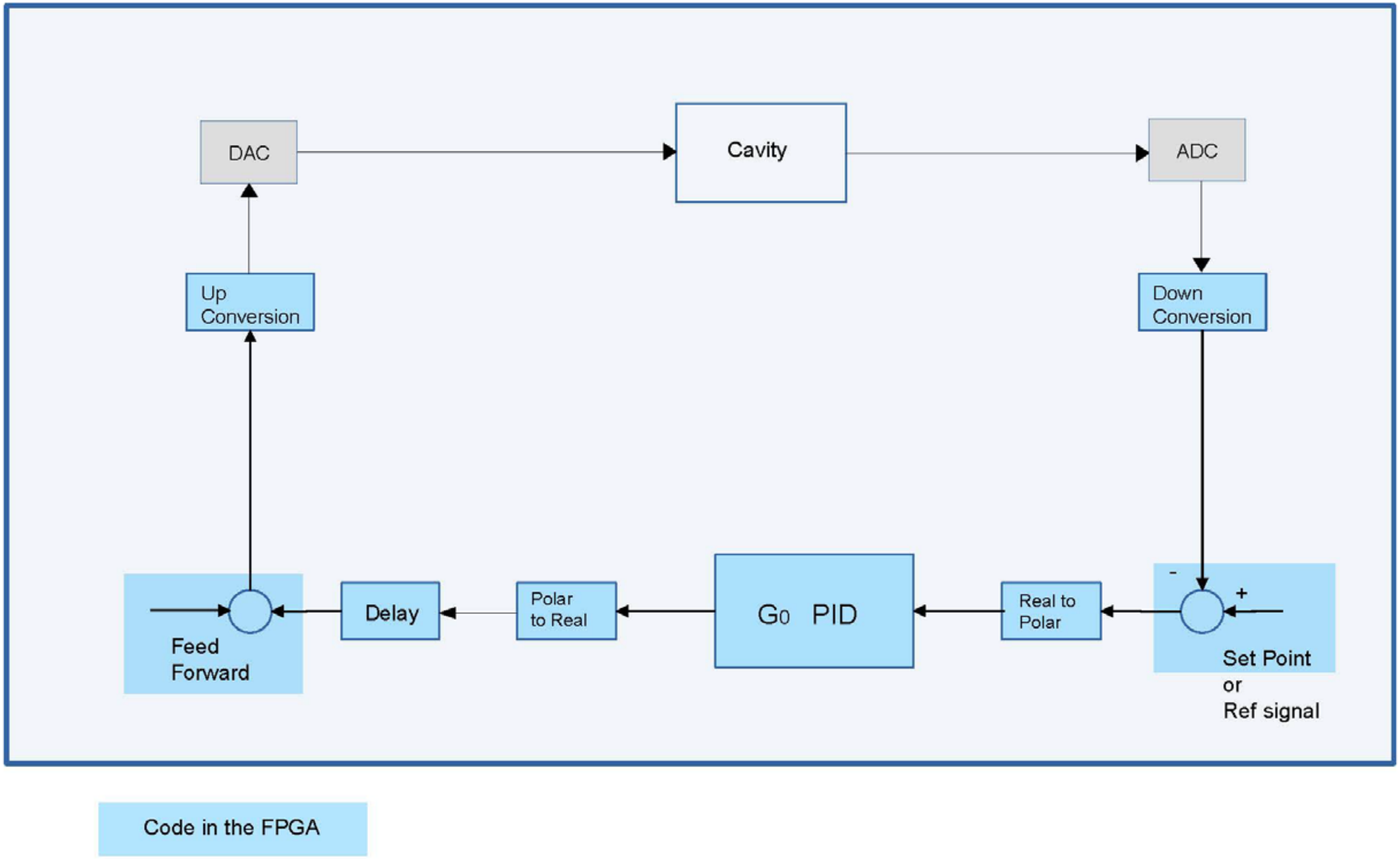
- Lund Univ. / ESS system (the "Lund" system)
  - So far mostly used in so called "special operation" mode.
    In this mode one can generate a fixed frequency rf pulse up to 14 Hz with an arbitrary shape.
  - The "normal" mode (with the feedback) has been tested
    - it's not yet clear if it will be used during the tests (depends on test program).
  - The Lund system has also been used for generation of the synchronization pulse to the RF stations.
  - The signal monitoring has been used for setting-up the interlock signals based on the forward and reflected power levels measured by the system's ADCs.
  - Saving of the DOD data (data from ADC) has been tested
    - but not routinely used during the tests of the spoke cavity.

FREIA Low Level RF System

- based on FPGA unit connected to two ADC input channels and two DAC output channels
  - ADC is sampled at 250 MSps, input bandwidth of 750 MHz.
  - DAC is sampled at 500 MSps or 1 Gsps.
  - With undersampling can operate from 10 to 750 MHz.
  - RF signal is downconverted to baseband, ie 0 Hz, with digital downconversion. No analog mixers are used. The bandwidth of the downconverted signal is either +/- 5 MHz or +/- 1 MHz, selected by user.
  - All control of the signal is done at baseband, that is amplitude feedback, phase feedback, delay, amplitude modulation etc.
- used to control the cavity with self-exited loop (SEL) measurements
- will also be used to control the cavity when running the system with a driving signal.

FREIA LLRF

Freia LLRF system



FREIA LLRF as Data Acquisition

- three FPGA's are used.
- Connected to the FPGA's are 10 ADC input channels.
  - Each ADC is sampled at 250 Msps.
  - All 10 channels are downconverted to baseband, with digital downconversion.
- At baseband, mathematical calculations can be performed in the FPGA's directly, with all the 10 channels at the same time.
  - This way data storage for post analysis will be less needed, but is still possible.
- The FPGA unit is connected to and controlled by a host computer.
  - The host computer is running LabVIEW.
  - Both the LLRF system and the data acquisition system are controlled from dedicated LabVIEW programs on the host computer.
  - These dedicated LabVIEW programs are often used as sub programs in larger LabVIEW programs, when measurements are made at FREIA.

Quality Assurance and Documentation

Quality Assurance

- Quality Assurance
  - develop installation and test procedures, and training of personnel during tests of the spoke cavity package and prototype cryomodule (upcoming)
    - note the importance of the prototype cryomodule
      - procedures for "jumper" (cryomodule to valve box) connection
      - tooling for installation RF doorknob (waveguide to power coupler connector)
      - cavity internal vacuum connections most probable not required
        - » will be transported with NEG and ion pump connected
        - » if required, procedures, tools and experience from cavity installations in HNOSS
    - will follow same procedures with same personnel during series tests
  - travellers
    - expect cryomodule to be transported with traveller documentation to register all handling and other important remarks

Non Conformities

If a deviation is found

- Document (photo, text, measures)

- Inform collaboration (ESS, IPNO)

- Wait for decision
  - – decision options
    - perform additional measurements,
    - return (repair at IPNO),
    - repair (at Uppsala or Lund),
    - make concession and accept
  - – this might impact schedule / scope / cost

Documentation

- Functional (tbd by ESS)
  - upon arrival, installation: traveller documents
    - status of instrumentation, vacuum level (ion pump current)
    - other important observations
- Acceptance criteria (tbd by ESS)
  - checks upon arrival
  - tests to be performed
- Log book
  - electronic log book used during tests
  - EPICS data archive
- Report
  - summarizing the testing and results

Relevant Publications

- Overview FREIA
  - Progress at the FREIA Laboratory,
    M. Olvegård et al., IPAC 2015, WEPMN065
  - 352 MHz Tetrode RF Stations for Superconducting Spoke
    M. Jobs et al., IPAC 2017, THPIK090

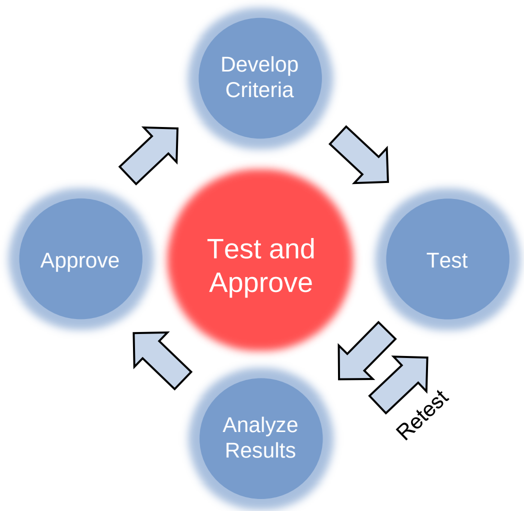
- Controls
  - The EPICS Based Control System at the FREIA Laboratory
    K. Fransson et al., IPAC 2017, TUPIK084

- Testing
  - High Power Testing of the First ESS SPOKE Cavity Package
    H. Li et al., SRF 2017, THPB035
  - ESS Spoke Cavity Conditioning at FREIA
    H. Li et al., IPAC 2017, MOPVA092

Test Plan

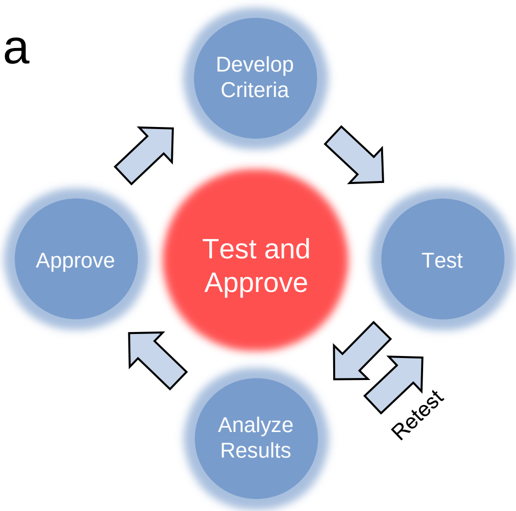
Test Plan Basics

- Arrival and inspection
  - initial checks and measurements
- Installation and connection to valve box
- Warm testing
  - conditioning of power couplers
- Cool down
- Cold testing
  - tuner functionality and range
  - conditioning of power couplers and cavity package
  - measurements
- Warm-up
- Disconnect, (wait for acceptance decision), shipment
- Write report...



Acceptance Decision

- Acceptance criteria
  – input required from ESS to define the final set of criteria



- Acceptance decision
  – FREIA informs collaboration of the test results and possible non-conformities

  – decision
    - accept,
    - repair
      – at IPNO, Lund or Uppsala.

Spoke L4 Requirements (Selection)

ID	Name	Units	Min.	Nominal	Max.
1369	Number of cavities per cryomodule	#		2	
1373	Optimal beta	v/c		0.5	
1375	Operating temperature	K		2	
1376	Accelerating voltage	MV	5.75		
1378	RF coupler power handling	kW	335		
1379	External quality factory		175’000		285’000
1381	Voltage pulse length	ms		2.86	
1382	Voltage pulse rate	Hz		14	
1383	Cavity shunt impedance	W			2.35
1384	Accelerating mode tuning range	kHz	100		
1386	Mode spacing	MHz	0.45		
1387	Higher order modes	MHz	5		
1388	Length of cryomodule vessel	m			2.9
1393	Cool down time	h			48
From: https://confluence.esss.lu.se/display/CRYOM/Interface+between+Cryomodule+and+Cavities-+Within+EMR					

Measurement Overview

Preliminary, minimum set of tests

To be adapted based on agreed acceptance criteria

Warm test	Cool down	Cold test	Warm up
✓ Cavity vacuum ✓ Mechanical checks? ✓ Cavity frequency ✓ Qext	Frequency vs. Temperature	✓ Tuner range and sensitivity ✓ Coupler and cavity conditioning ✓ Cavity frequency ✓ Loaded Q and Qext ✓ ---	Frequency vs. Temperature
✓ Coupler conditioning		✓ Q0 ✓ Dynamic heat load ✓ Nominal gradient ✓ Filling time ✓ Dynamic Lorentz force detuning ✓ Tuning range ✓ Long term stability test (4h)	

CRYO

VNA

SEL

SGD signal generator driven

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Warm Tests

- Initial inspection
  - check of cavity vacuum → connect external pump required or not
  - mechanical checks required? → dimensions?
  - instrumentation checks required?
- Measurements
  - cavity frequency and Qext (with VNA)
- RF conditioning
  - warm re-conditioning of the power couplers
    - have to agree on optimization of the conditioning algorithm to save time
    - will take at least 1 day if no major multipacting barriers
    - can do both couplers simultaneously

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Cold Tests

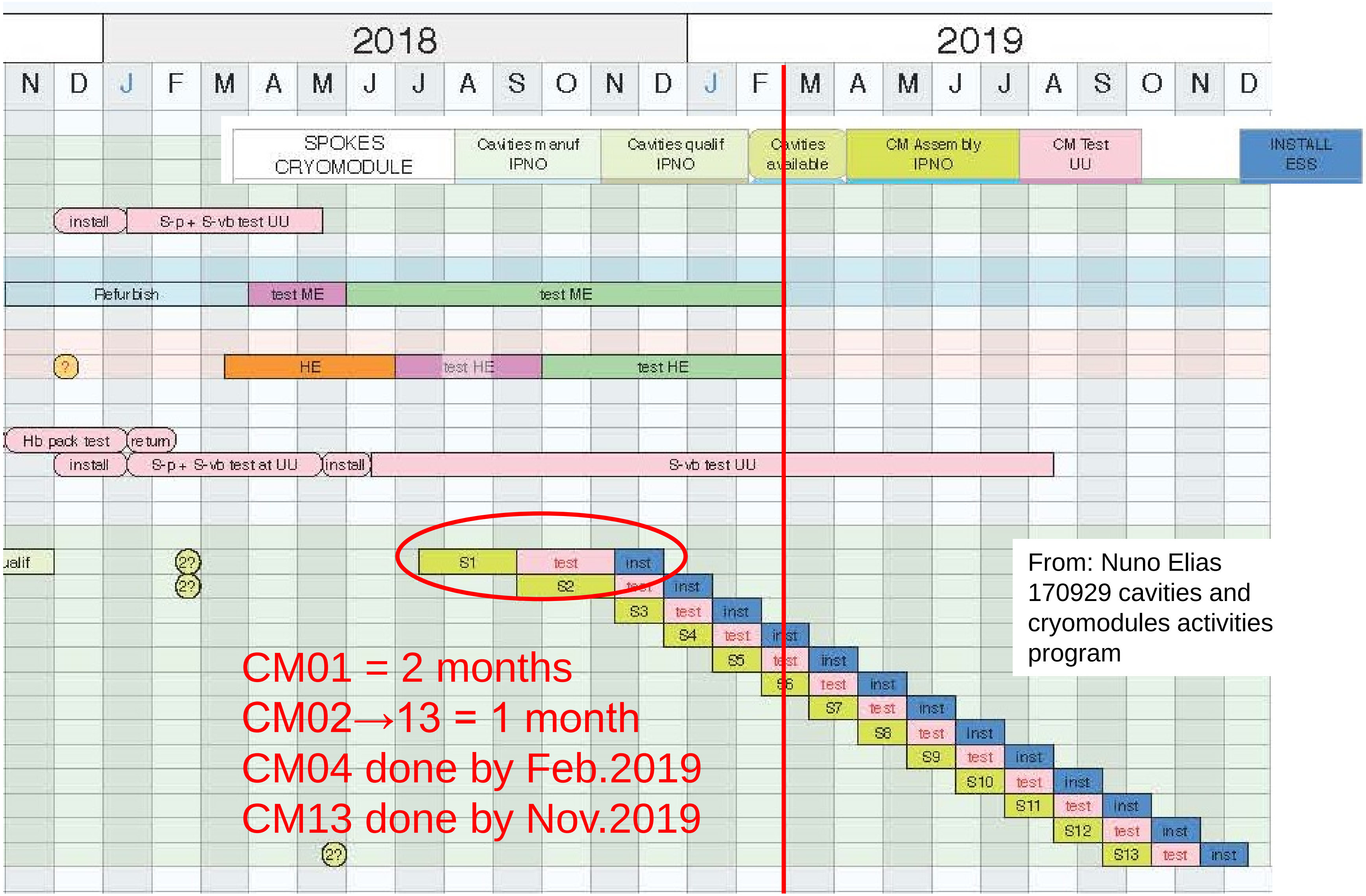
- Tuner functionality and range
  - first test, also to tune cavity frequency
- Cavity frequency and Qext
  - in combination with tuner functionality test
- RF conditioning
  - cold re-conditioning of the couple and cavity
  - both simultaneously to gain time
- Self excited loop measurements
  - Q0, dynamic thermal load, accelerating gradient, filling time
  - all measured simultaneously
- Signal generator driven measurements
  - Lorentz force detuning and tuning range
- Long term stability test
  - run for ≥4 hours

Testing Schedule

Present Schedule Overview

- Prototype cryomodule & valve box
  - arrival in January/February 2018
  - removal by August 2018
- Series cryomodule deliveries
  - CM01 in August/September 2018
  - CM02 in November 2018 (2 month after CM01), then 1 month intervals to CM13
- **Series cryomodule testing**
  - CM01 start September 2018
  - CM13 to be finished by
    - February 2019 (ESS end of support to FREIA)
    - November 2019 (present planning) = 4 weeks per cryomodule
    - February 2020 (in-time for installation) = 5.5 weeks per cryomodule
- Installation planning
  - CM01 starts November 2019 (boundary condition: CDS completion)
  - CM13 starts February 2020

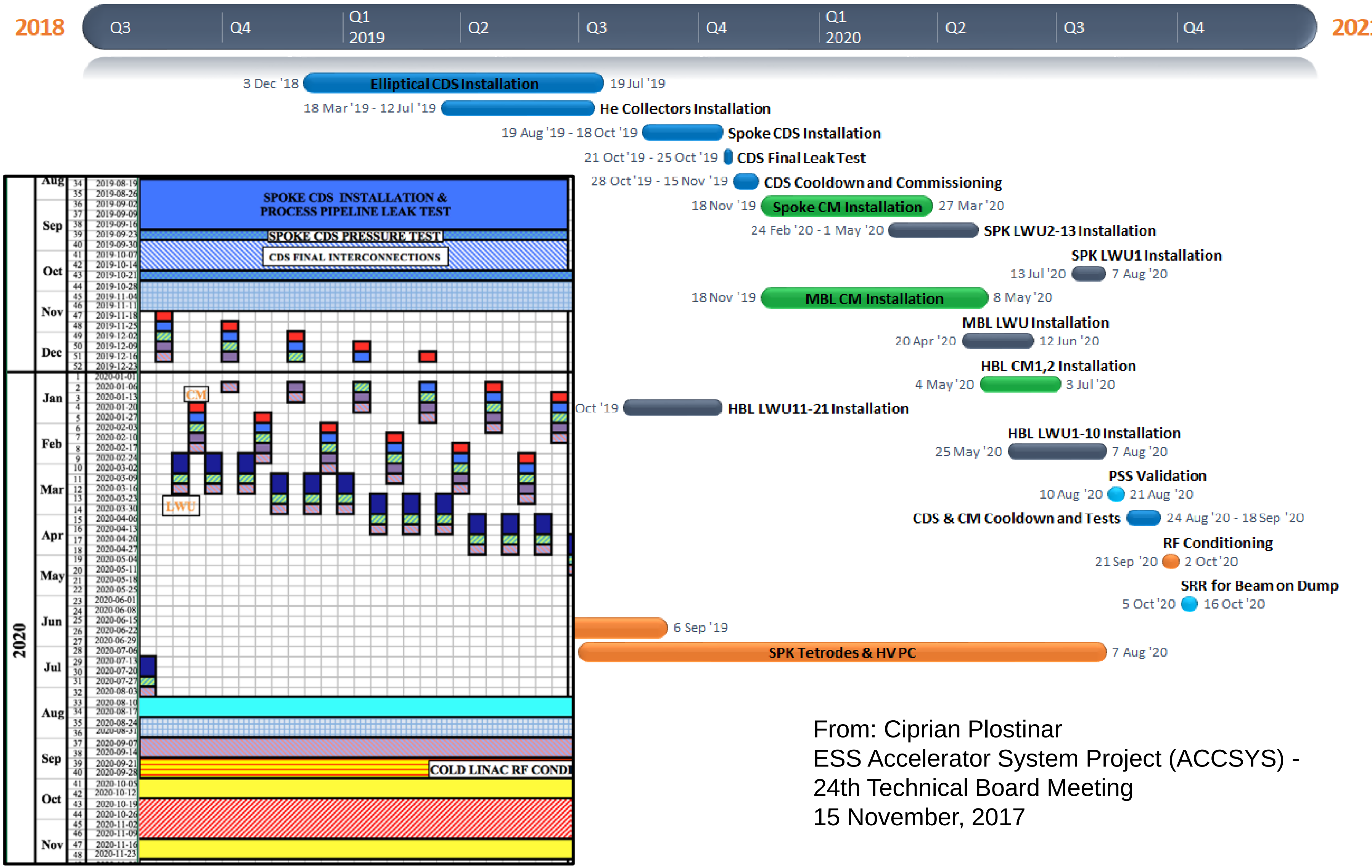
ESS Spoke Testing Schedule



CM01 = 2 months
CM02→13 = 1 month
CM04 done by Feb.2019
CM13 done by Nov.2019

From: Nuno Elias 170929 cavities and cryomodules activities program

ESS Installation Planning



From: Ciprian Plostinar
ESS Accelerator System Project (ACCSYS) - 24th Technical Board Meeting
15 November, 2017

Notes on the schedule

- Resource limitations
  - double shift work requires employing additional staff → cost increase
  - university closes for 5 weeks during summer, 2 weeks during Christmas
    - to bridge this will require additional staff → cost increase

- Prototype cryomodule test has been delayed
  - less time to perform the installation and test
  - less time to train staff and check procedures
  - will require more learning time for the first cryomodules

- Schedule optimization
  - cool down and warm-up continues automatically 24h/day
  - present SSM authorization does not allow un-attended operation when producing radiation
  - testing plan to be optimized after decision on final acceptance criteria

Testing Schedule for a Cryomodule

	time [days]	time [weeks]	in bunker [days]
Arrival, unpacking, initial inspection	2.5		
Installation, connection to valve box	5.0		5.0
Warm testing	2.0		2.0
Cool down	2.0		2.0
Cold testing	5.0		5.0
Warm-up*	4.0		4.0
Disconnect, packing, shipment	4.5		3.0
TOTAL	25.0	5.0	21.0
Spare and wasted time, 20% (DESY statistics)	5.0		4.2
GRAND TOTAL	**30.0**	**6.0**	**25.2**

Time given in 8h work days, 1 shift, holidays and vacation not included.
Details in separate document send to the committee.
*) Warm-up is shorter if during weekend

Summary and Conclusions

Conclusions

- FREIA is prepared and ready to test the spoke cryomodules
  - infrastructure, people and experience available
  - controls, data storage and reporting are prepared
- **Prototype cryomodule installation and test will be used to verify and fine tune our procedures and schedule**

- Discussions ongoing to determine acceptance criteria and thereby optimize the required test plan

- Present scheduling
  - FREIA requires 6 weeks per cryomodule,
    of which 5 weeks inside the bunker,
    decreased cold testing to absolute minimum required,
  - ESS present schedule allows only 4 weeks per cryomodule,
    however more time is available due to late start of the installation.