Status of SNS

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For the SNS Collaboration

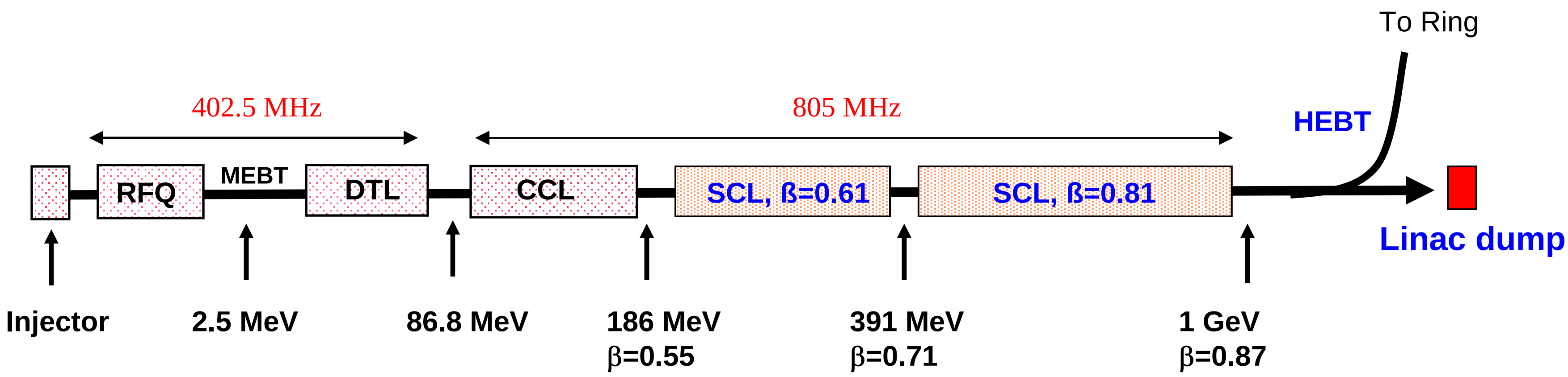
July 11, 2005

Acknowledgements

The work described is the culmination of more than five years of efforts of hundreds of people in all the partner Laboratories.
In particular it is a tribute to the successful design, construction and assembly of all the cavities and cryomodules at JLab and to the well coordinated installation and integration activities carried out by the SNS Groups interfacing the Superconducting Linac, including Vacuum, Cryogenics, Controls, Low Level RF, High Power RF, Electrical, Diagnostics, Alignment, Operations and Accelerator Physics.

The Spallation Neutron Source

SNS Linac layout

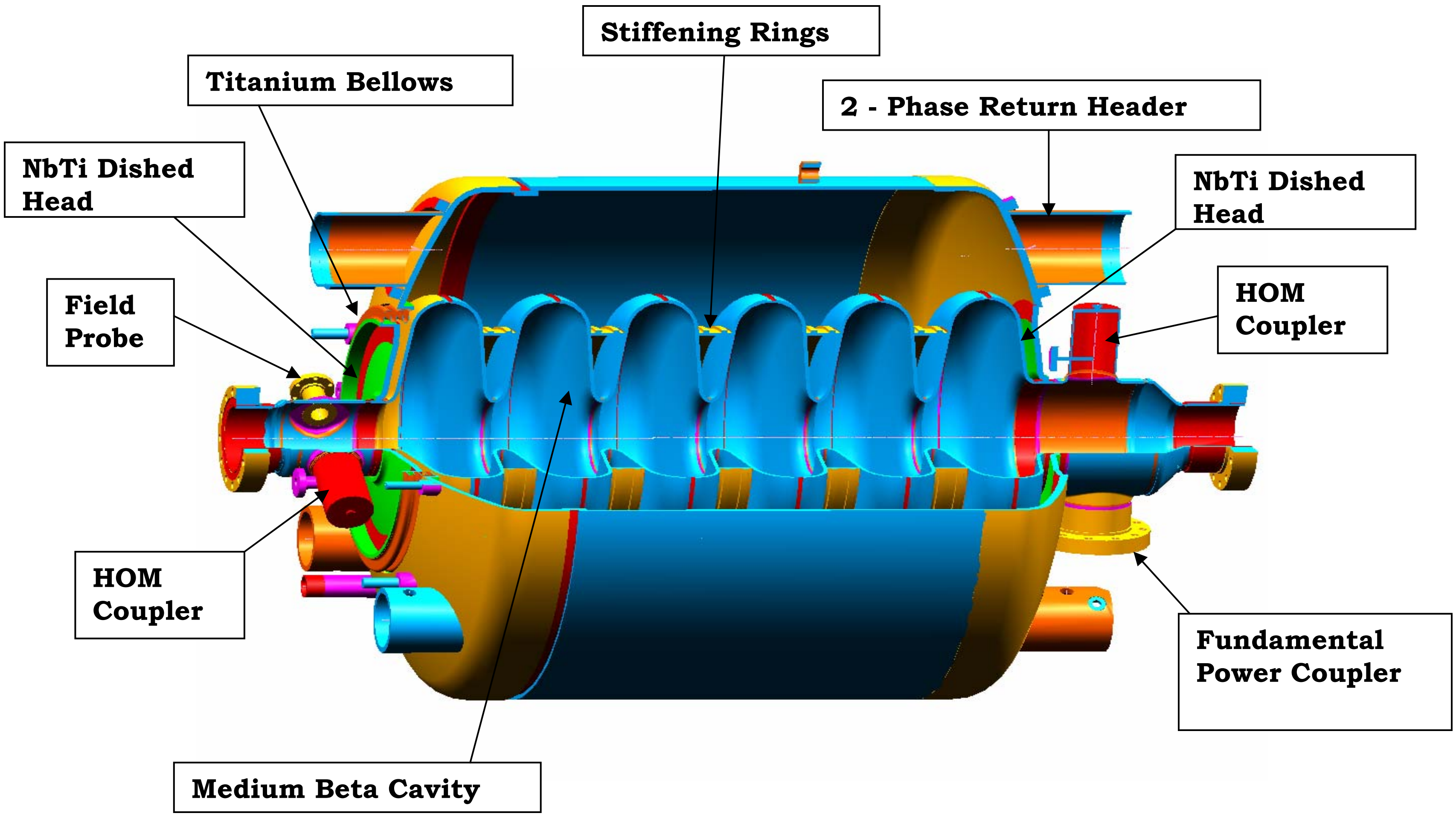


- ✓ MB (β=0.61): 11 cryomodules, 3 cavities/cryomodule – 33
- ✓ HB (β=0.81): 12 cryomodules, 4 cavities/cryomodule – 48
- ✓ Each SC cavity is driven by a klystron – 81 klystrons

Prototype Beta 0.61 and .81 Cavities

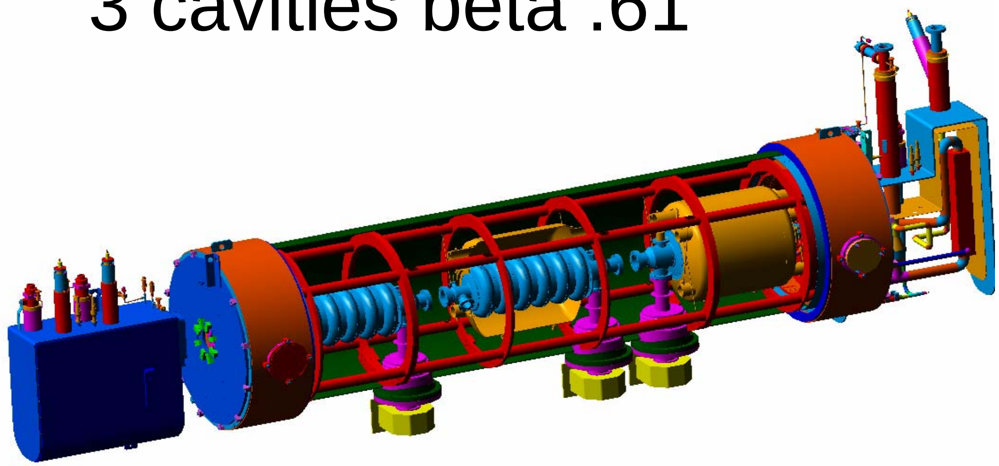
Development led by P. Kneisel with aid from colleagues all over the world

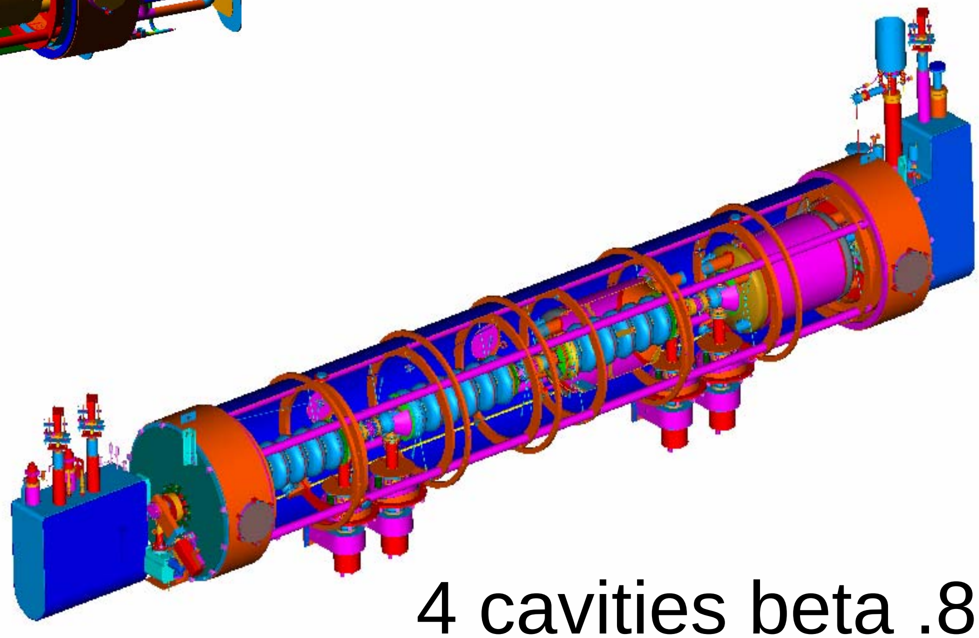
Cavity in Titanium Helium Vessel



Medium and High Beta Cryomodules

3 cavities beta .61





4 cavities beta .81

Cryomodule installation status

- 22 of 23 Cryomodules in place, cold, with all subsystems operational

Performed microphonics and seismic measurements at 4.2 K on selected cavities with JLab and MSU

4.5 K and 2.1 K Cold Boxes Commissioned

- Running since Nov '04 in different modes and with different combinations of turbines.
- Capacity at 4.2K: 2.8 kW dynamic load (limited by mass flow, could be expanded to about 7-8 kW with hardware changes)
- 7000 liter LHe Dewar is the key to stability and 4.2 K running in the Linac
- 2.1 K RF run July 1-present

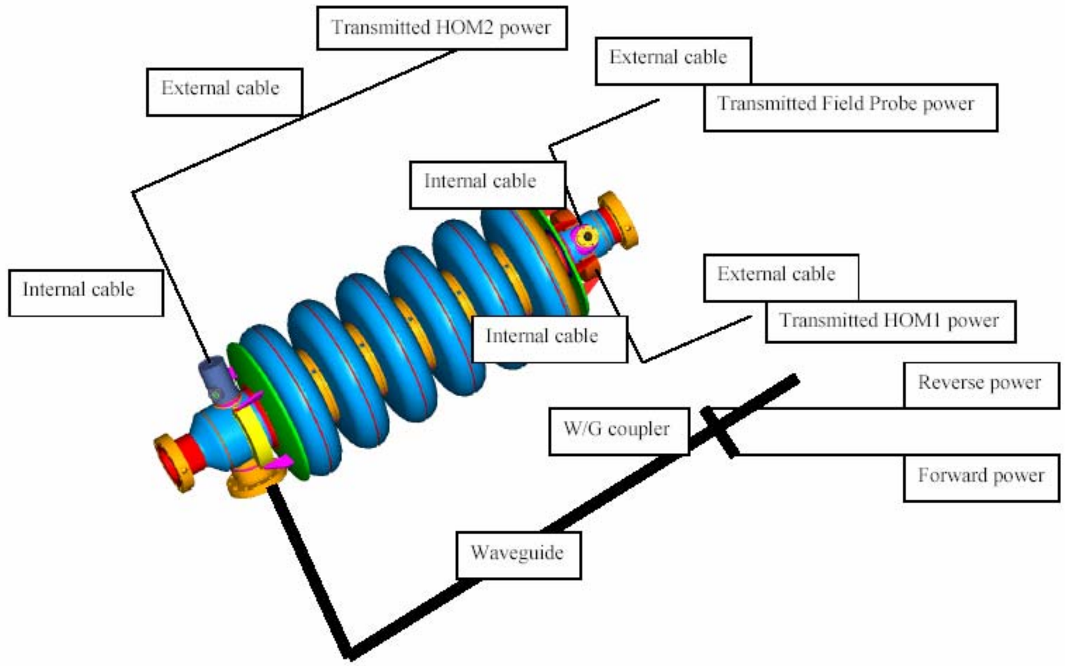
4.5 K cold box

2.1 K cold box

High Power and LLRF Status

- All SCL 81 Klystrons waveguides, circulators, loads and LLRF systems are installed.
- 77 of 81 Tubes powered into cavities.
- Integrated testing is at the system level, coordinating timing, EPICS, controls, water, LLRF and HPRF.

Available signals and calibration scheme

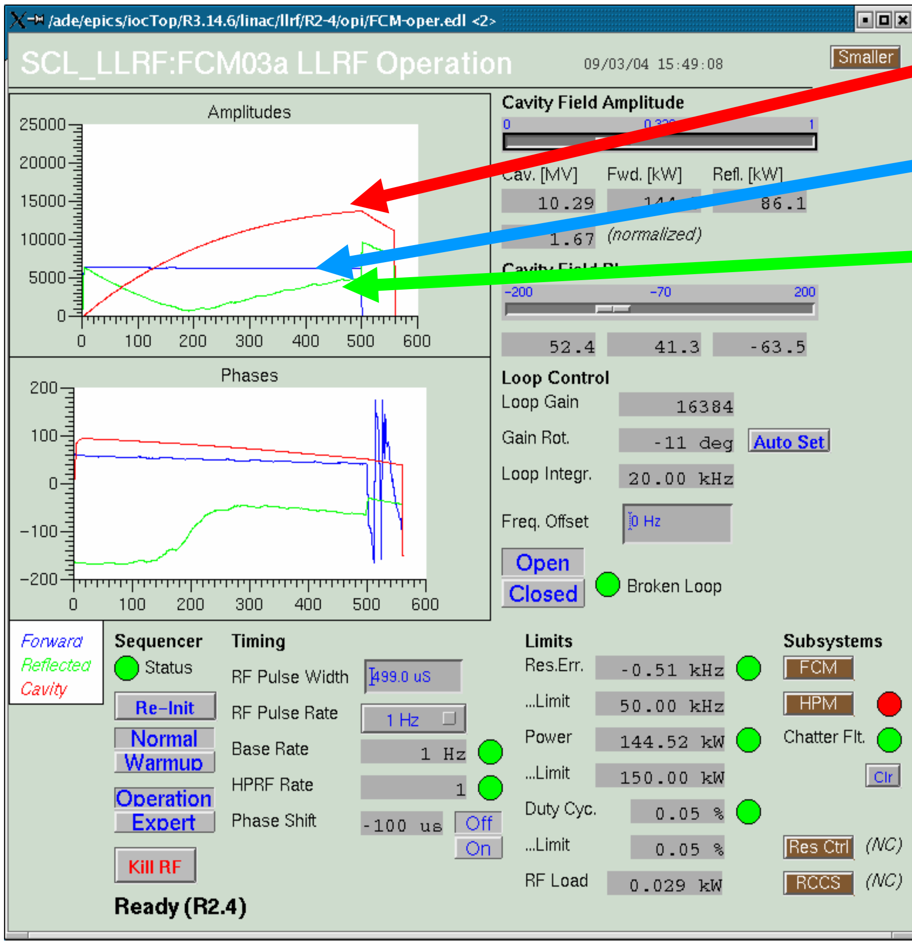


Attenuations and calibrations

Forward: W/G Coupling+ 1 way cable – 1 way W/G loss
Reverse: W/G Coupling+ 1 way cable + 1 way W/G loss
Transmitted (FP, HOM1, HOM2): 1 way internal + 1 way external cables

Field determination:
Transient, end of pulse, U(stored) for ~ 350 μsec:
1.74 MV/m SQRT(Tp x Pi x .8 [J])
Steady state : 1.32 MV/m SQRT(Pi [kW])
Ea= SQRT(600 x 4 x Pi x QL)
Ea = SQRT(600 ωU) = SQRT (600 Pt Qt)
Qt= 4 QL (Pi/Pt)

Short pulse cavity/coupler conditioning

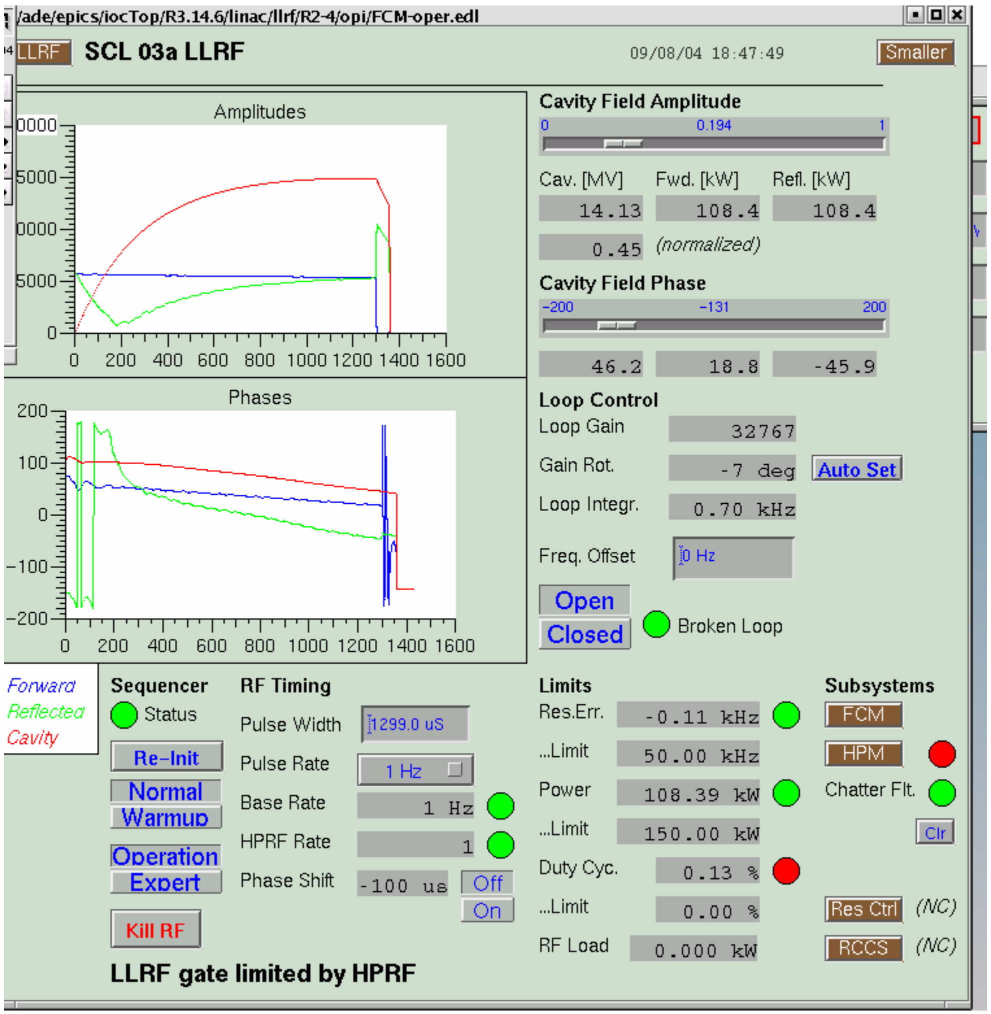


- **Transmitted**
- **Forward**
- **Reflected**

Amplitudes and phases

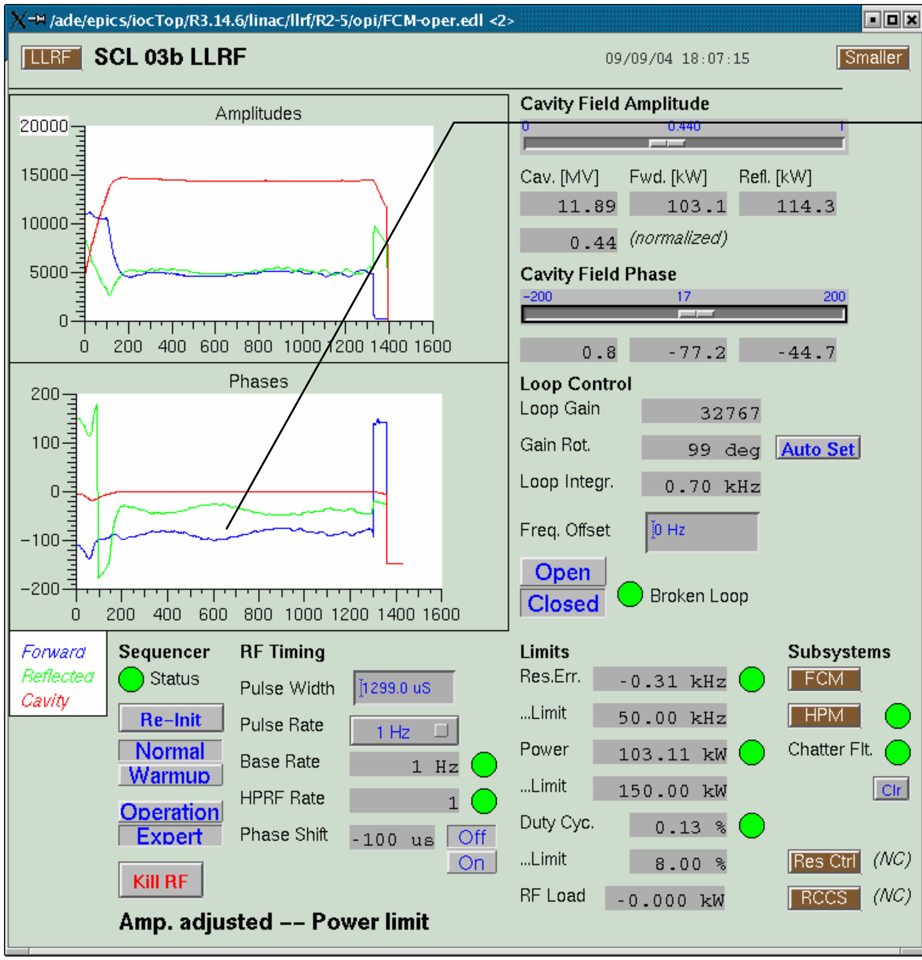
Short pulse operation allows one to process couplers beyond the multipacting levels without loading the cavity

Open loop response



- Full 1.3 msec operation leads full reflection standing wave by the end of the pulse
- Emitted traveling power four times the incident value

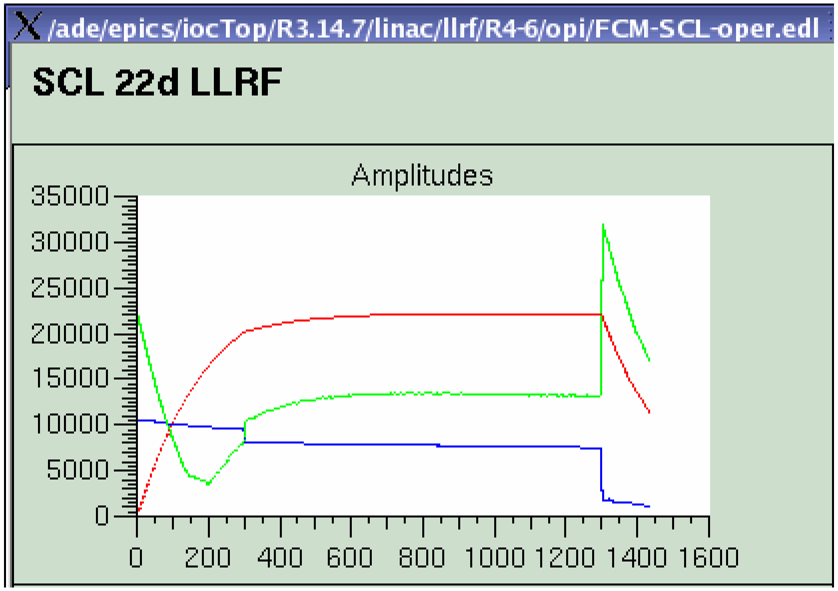
Closed loop operation



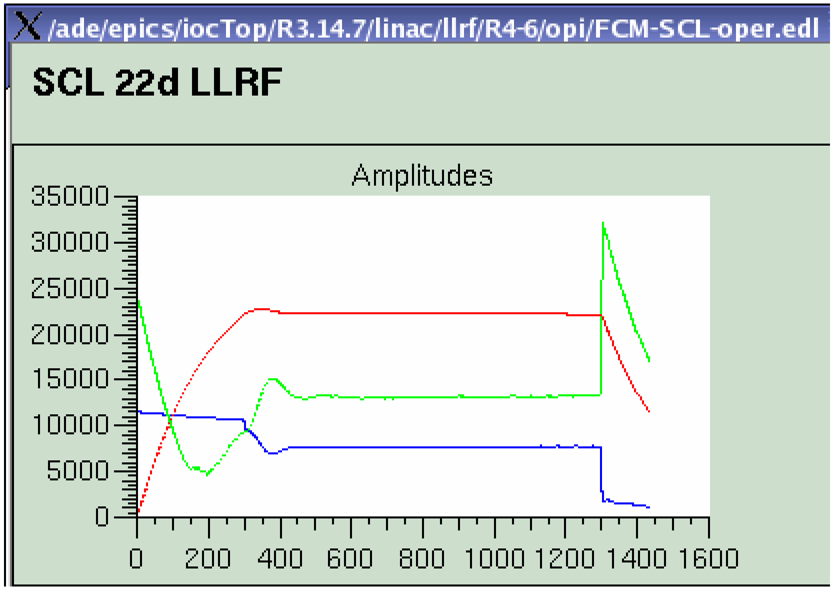
Lorentz force response at 2 kHz (~200 Hz amplitude)

Lorentz Force Detuning appears only in medium beta cavities. High beta cavities are very stable.

LLRF controls

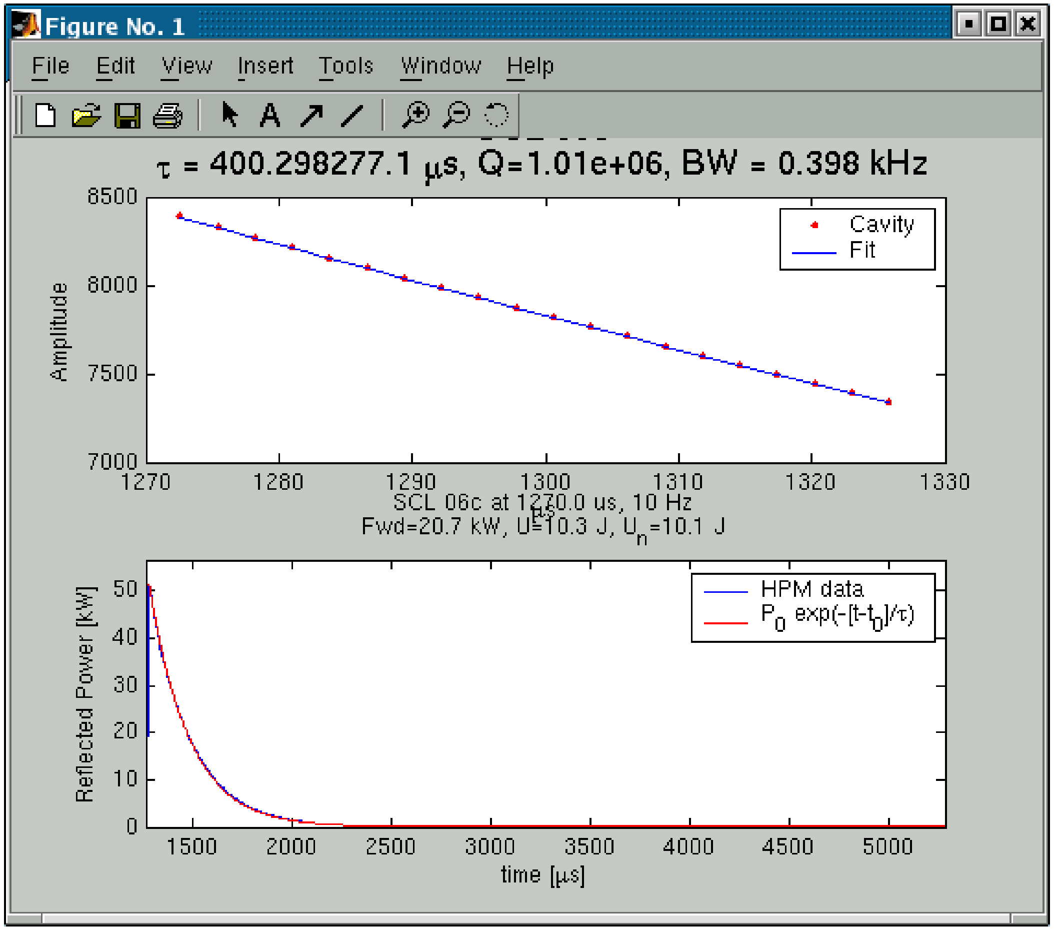


"Open loop": two step pulse



Closed loop

Stored energy and Q_L measurement



The field at the end of the pulse is determined via a measurement of the stored energy, calculated from integrating the emitted power

Cryomodule testing history since last SAR

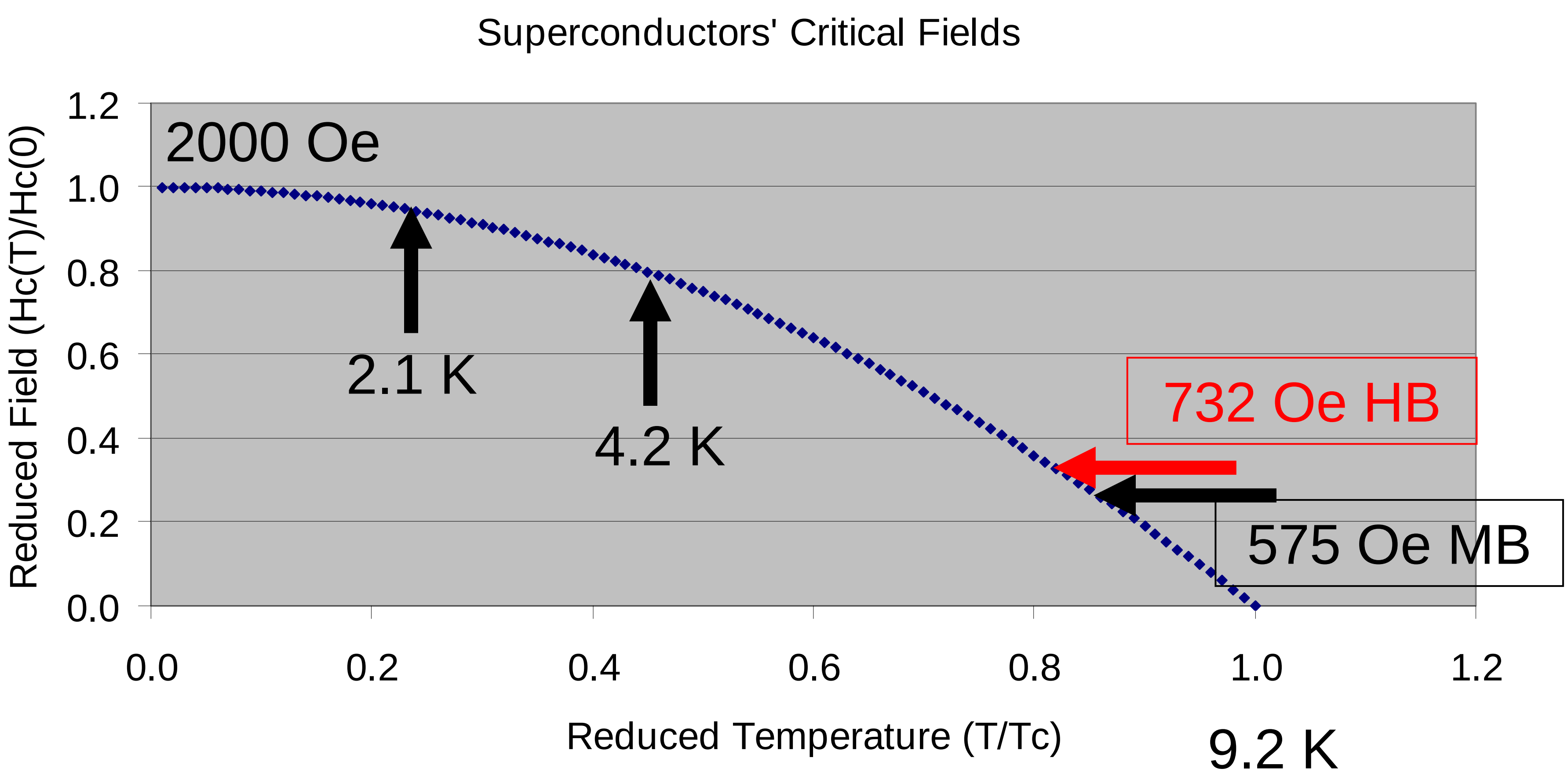
- December 18-21, 2004: When CHL operated again, we powered the cavities in MB03 again, then MB04, MB05 and MB06.
- December 28, 2004: Powered cavities MB07 (M02) without shield cooling (He leak into insulating vacuum)
- January 6 - January 10, 2005: Gate valve opening test
- January 16, 2005: Powered MB07 replacement and MB09 (never tested before)
- January 19-26, 2005: Powered CM MB10, MB08 (never tested before), MB11 and HB01 (3 cavities)
- January 27-30, 2005: Operated 10 CM simultaneously in open loop and performed preliminary tests on limiting fields and Lorentz force detuning at 4.2 K.
- March 10 – present:
  - Completed coupler conditioning, calibrations and limits on 22 CMs at 4.2 K
  - tested and operated 77 cavities in 22 cryomodules at 4.2 K
  - 76 cavities operated simultaneously (all but 7 in closed loop)
  - Operated, recalibrated and found limits for all available cavities at 2.1 K during the 4th of July weekend

4.2 K behavior: expectations

- Limiting loss mechanism at 4.2 K and 805 MHz:
  - BCS Q_o=7.3 x 10^8
- Calculated losses: 1.3 msec, 60 pps
  - Medium β: 10.1 MV/m ➔ 16.4 W per cavity (x 33 = 540 W)
  - High β: 15.6 MV/m ➔ 38.5 W per cavity (x 48 = 1848 W)
- Maximum achievable fields
  - Limited by higher average heating and marginally lower heat removal efficiency than at 2.1 K, not by critical fields
- Cryogenic system heat loads: about 3 - 3.5 kW at 4.2 K
  - Dynamic loads
    - Cavities: 2.4 kW
    - Couplers: 100 - 150 W
  - Static loads: ~ 600 W

Testing at 4.2 K: Theoretical field limits

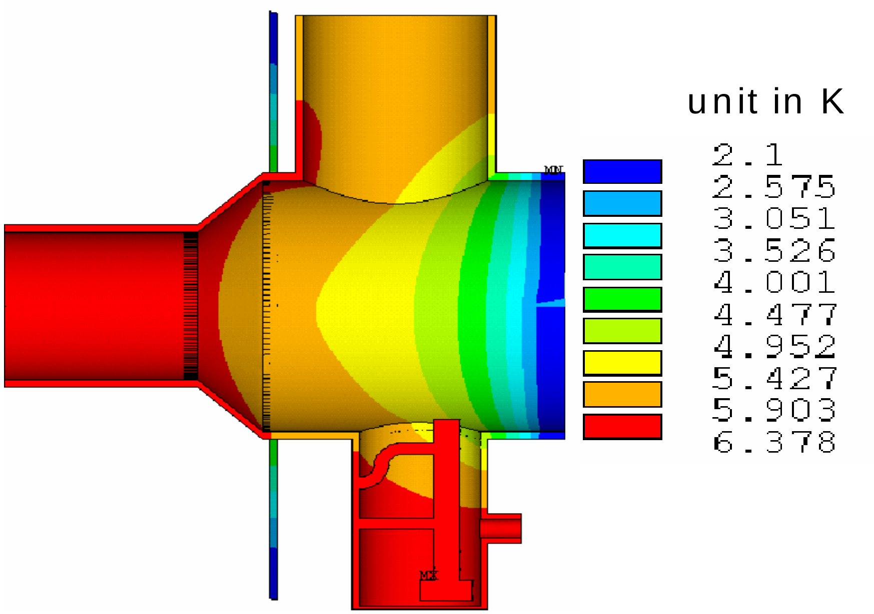
Why is it possible to do meaningful tests at 4.2 K?



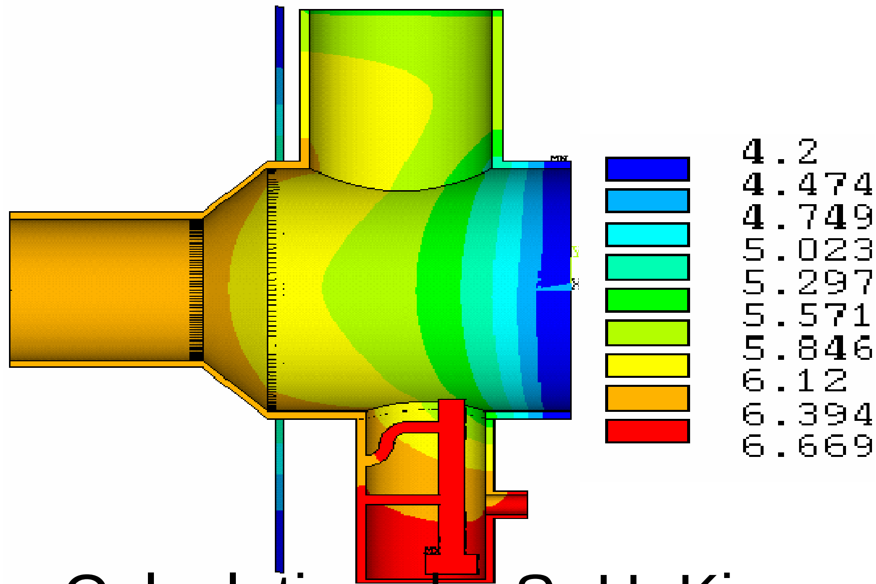
Limits and limitations

- Physical limits
  - End group quench (conduction cooling and field emission limited)
  - Strong field emission (cannot be easily corrected)
- Hardware limits
  - Coupler heating (can be adjusted externally)
  - HOM feedthrough power limits (cannot be easily replaced)
  - RF Systems protection limits (can be changed with some work)

End group temperature profiles at 2.1and 4.2 K



- 500 kW input power
- 8% duty cycle
- 5.5 K at coupler's outer conductor's flange



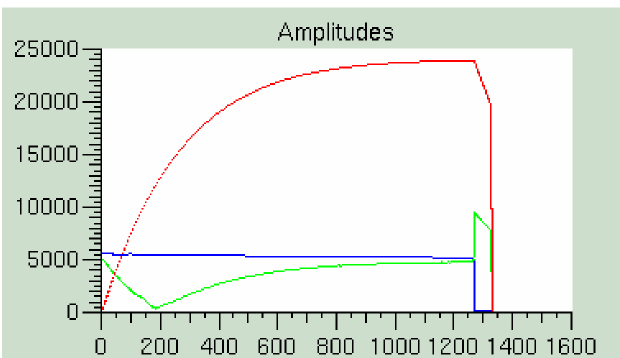
No significant difference in end groups' temperature profile in running at 4.2 K vs. 2.1 K

Does not take field emission into account

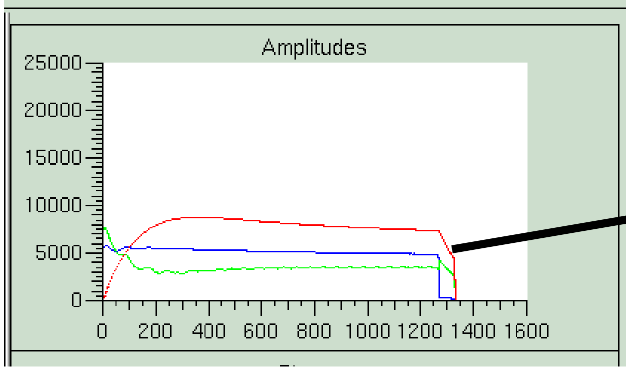
Calculations by S.-H. Kim

Limits and limitations

- Field emission-induced quench
- HOM filter detuning and power pulse (damage to feedthrough and inline attenuators)



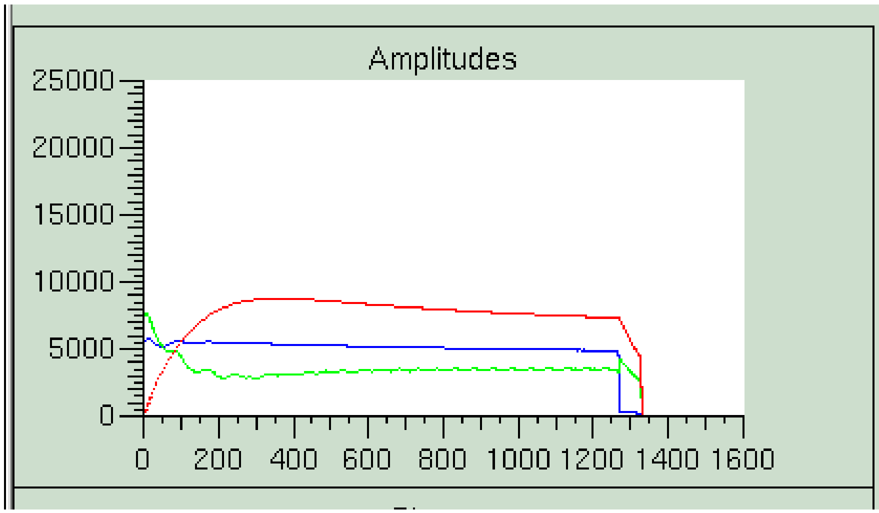
Before



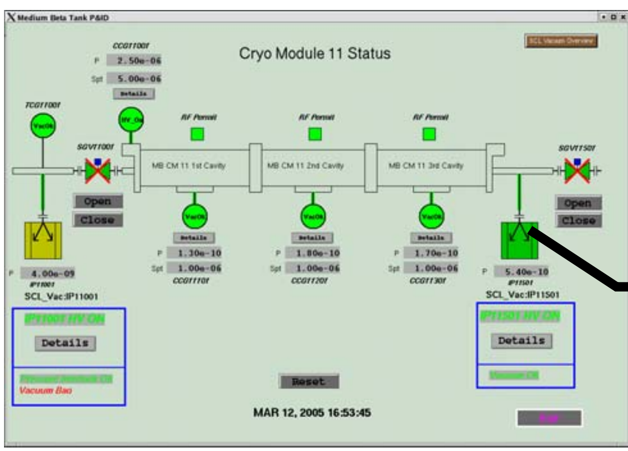
After

X-ray pulse

Quench in a superconducting SNS cavity



Reflected and Transmitted amplitudes change drastically after a quench: The coupling changes from about 1000 (Q_L~7E5, Q_o~7E8) to about 1/3 with a loaded Q of about 3E5.



- The quench is ignited by a burst of field emission hitting the cavity's end groups.
- The process is repeated several times: pulse processing.

Ion pump trips when nearest cavity quenches

Warm Section Production and Installation

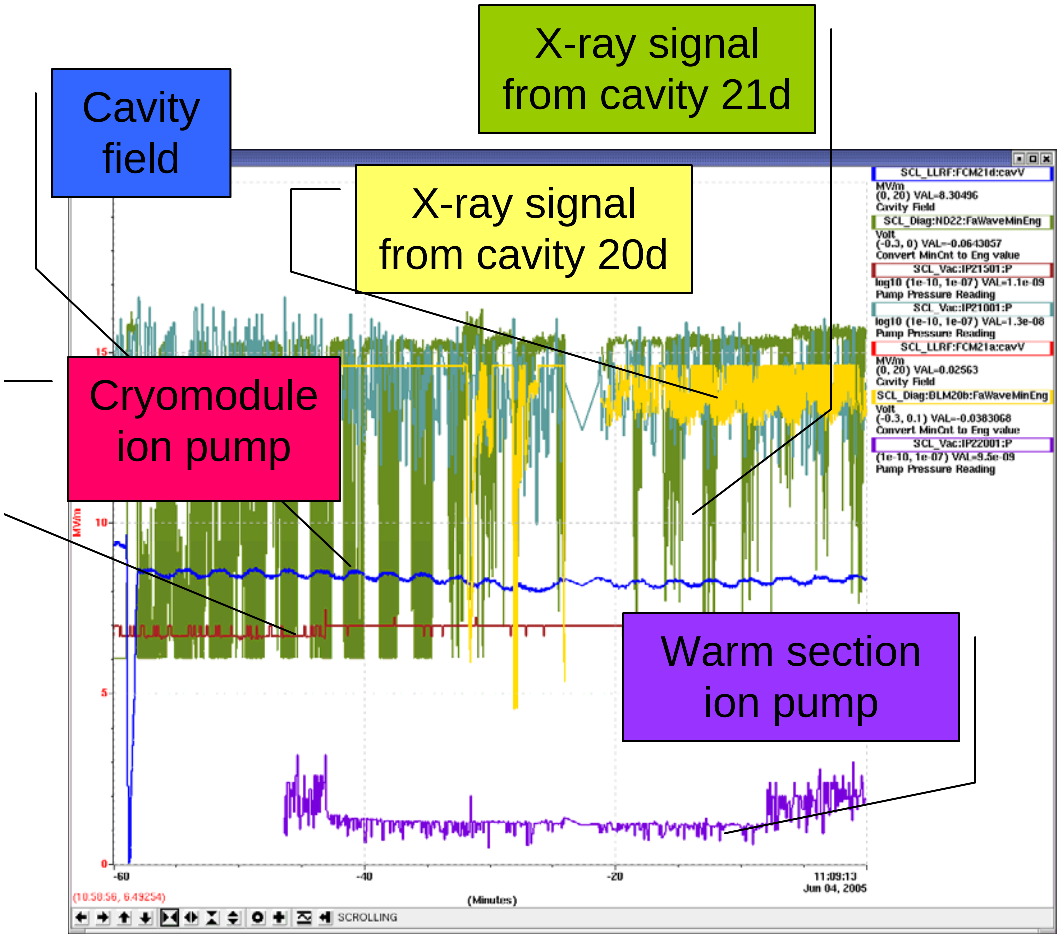
Temporary cleanroom and beam pipe cleaning facility

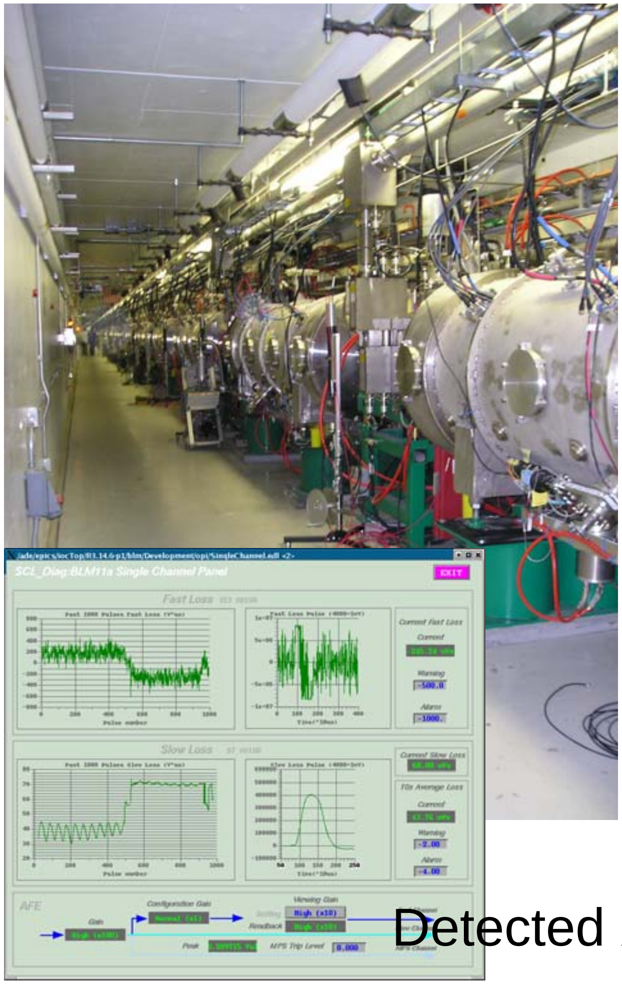
Warm section stand with beam pipe, magnets and diagnostics

Portable cleanroom for beam pipe attachments in the tunnel

Valve opening tests

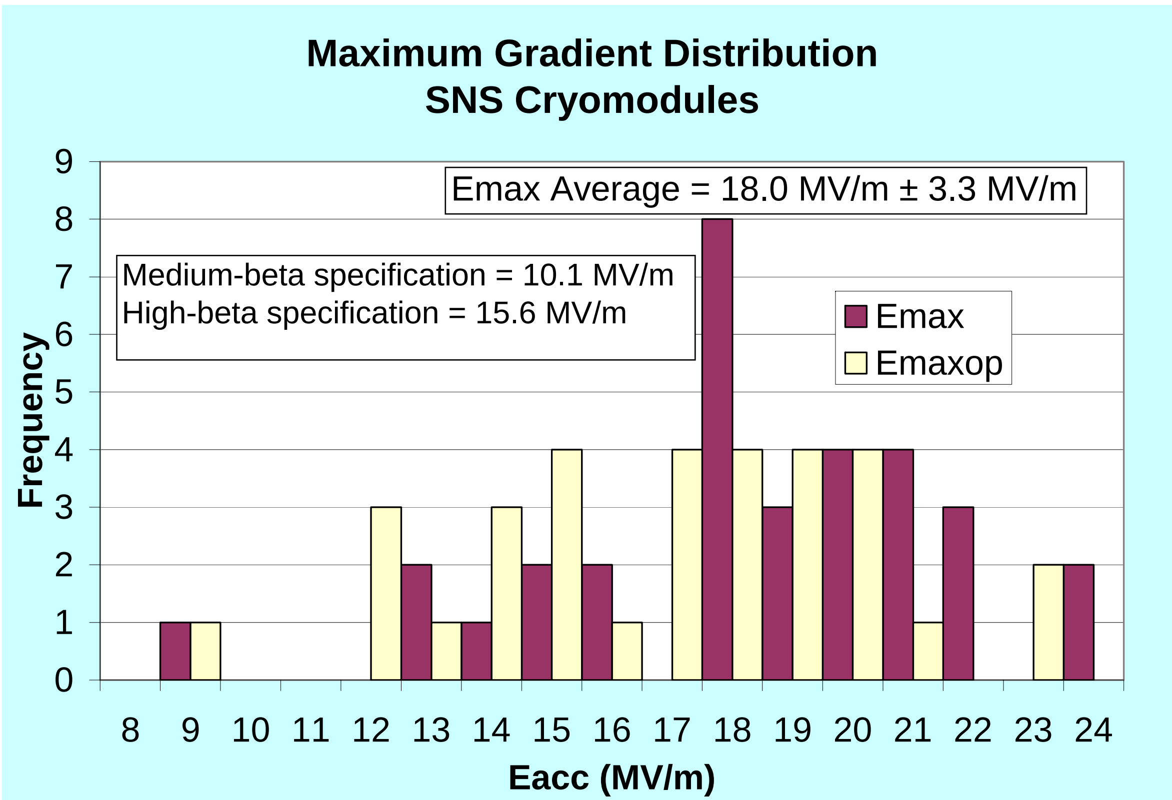
- On June 4 performed the gate valve opening test on 39 of 44 valves.
- 19 phototubes and scintillators were positioned between cryomodules





Detected X-rays

Cryomodule test results at JLab

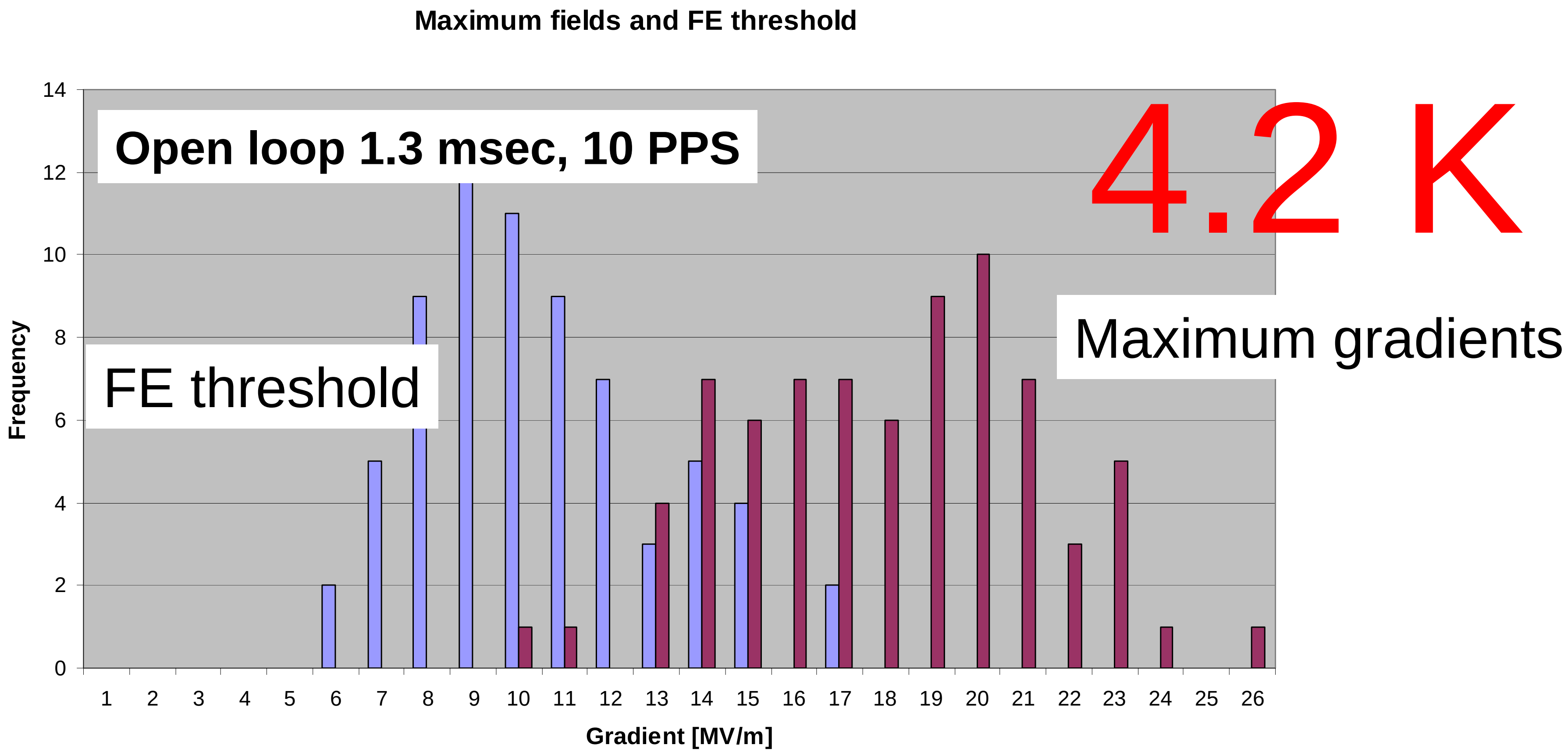


27 medium beta

8 high beta

- The measurements were performed on one cavity at a time at **2.1 K**

Gradient distributions



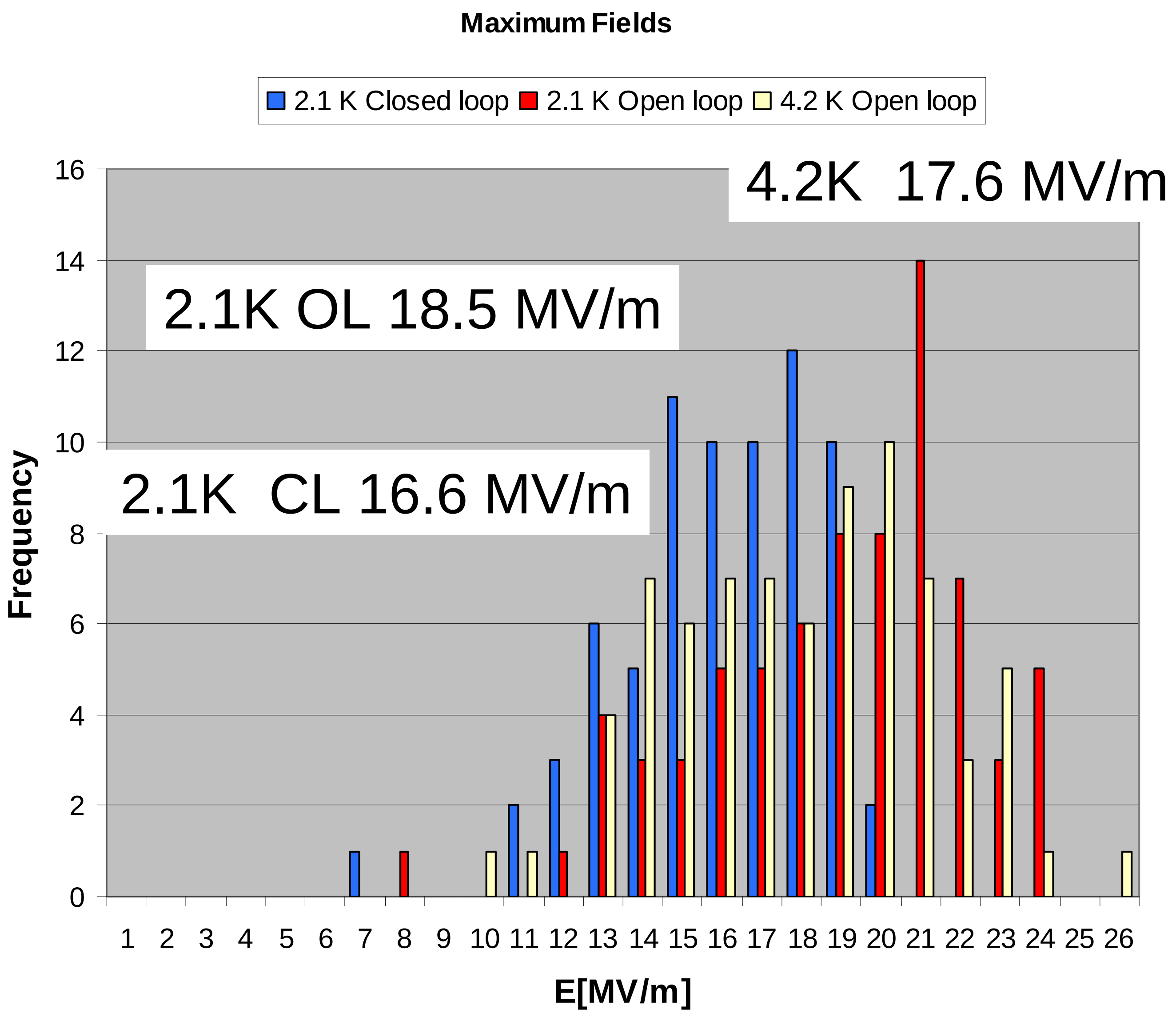
Average maximum gradient (31 MB and 44 HB): 17.6 MV/m

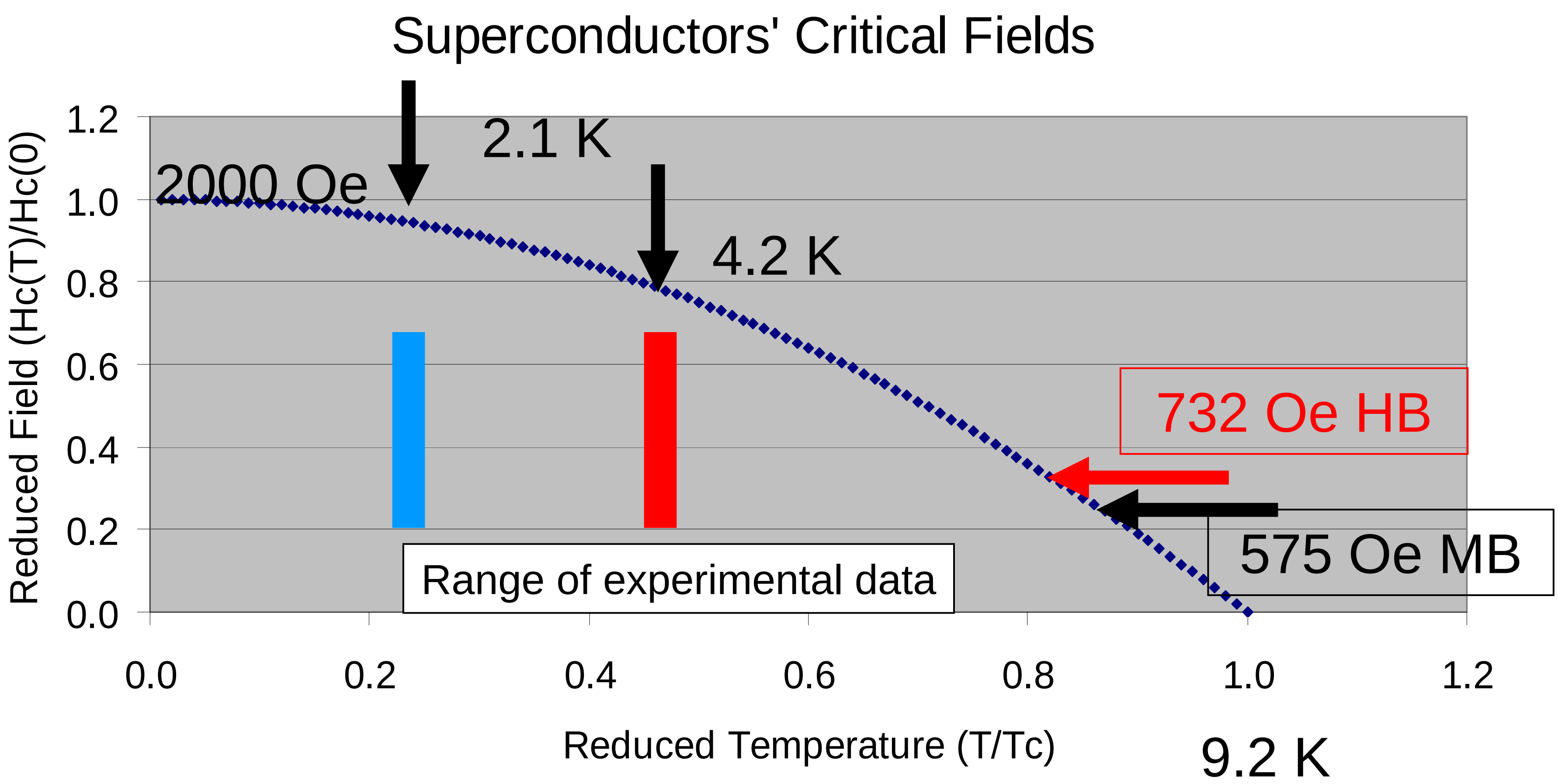
Average FE threshold: 10.0 MV

Operation at 4.2 K and 2.1 K: measured loads

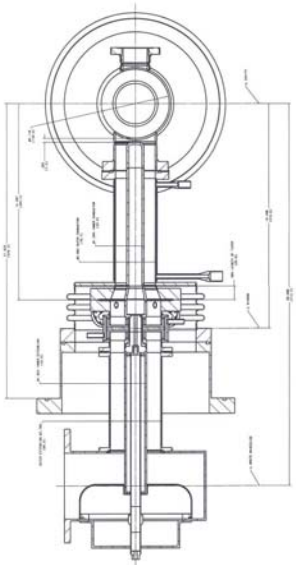
- Set up the linac with cavities near the field emission threshold, where the RF losses can be roughly estimated (about 73-75 of 77 cavities on):
  - **At 4.2 K: 200-250 W** at 10 Hz, 1.3 msec (BCS $Q_o = 7 \times 10^8$)
    - Compared to heater compensation of 250-300 W (some field emission and coupler heating)
  - **At 2.1 K: 16-25 W** at 10 Hz, 1.3 msec ($Q_o = 1.0 \times 10^{10}$)
- Measurements to determine the contribution of field emission losses are under way (temperature independent)
  - Estimates from 2.1 K operation indicate 100 W of FE at gradients 90% of maximum and at 10 pulses per second

Operation at 2.1 K vs. 4.2 K

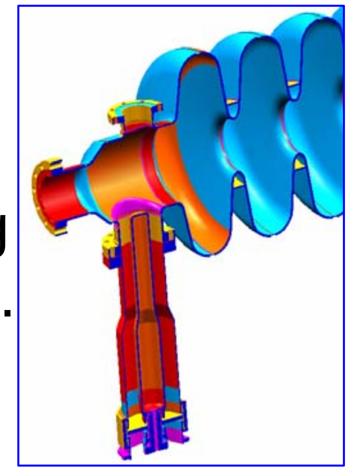


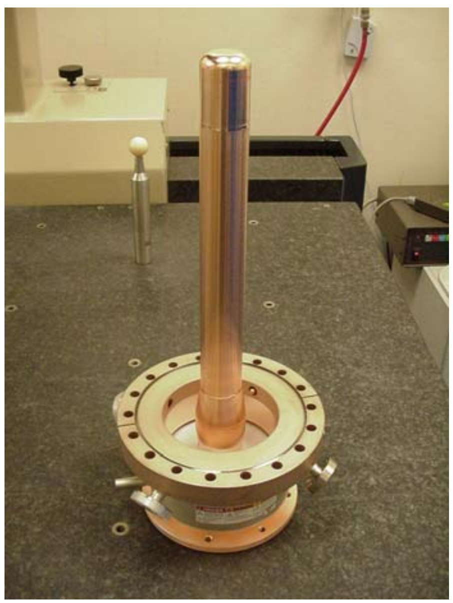

Superconductors' Critical Fields
2000 Oe
2.1 K
4.2 K
732 Oe HB
575 Oe MB
Range of experimental data
Reduced Field (Hc(T)/Hc(0))
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Reduced Temperature (T/Tc)
9.2 K

Fundamental Power Coupler Performance



All couplers have been pre-processed at JLab or SNS to nearly 1 MW peak power traveling wave and full reflection to 500 kW.





During testing of cryomodules in the SNS tunnel one coupler has transferred more than **500 kW** peak power, in full reflection and with the 2 MW traveling wave peak at the end of the RF pulse

Summary of present conditions

- 77 cavities have been tested at 4.2 K
- 76 cavities have been fully tested at 2.1 K
- Eight cryomodules have leaks in the helium circuit and are being pumped on during operation
- Four cryomodules with leaks have been repaired at SNS. Four were repaired at JLab
- One high beta cryomodule with a helium vessel leak will not be in the beamline for the initial beam commissioning
- Even without one high beta cryomodule, a final energy near 900 MeV could be achieved
- Six cavities do not reach frequency at 4.2 K (two at 2.1K)
- Two cryomodules, vented during testing at JLab due to failed HOM feedthroughs, have considerable performance degradation
- HOM power surges need to be monitored and avoided if possible
- Additional repairs will be implemented after the August beam run

Beam energy with available cavities

- Simulations have been run for a few scenarios:
  - Assume that
    - cavities can be run at 80% of the present limits at 4.2 K
    - refrigerator capacity is not a limiting factor (neither at 4.2 K nor at 2.1 K)
  - Without cavities 4a and 11b
    - **880 MeV**
  - Without previous set and 9b, 12b, and 20a (detuned)
    - **860 MeV**
  - Without previous set and 14c, 5a, 5b, and 5c (detuned)
    - **836 MeV**
  - With realistic gradients setup, **900-1000 MeV** can be reached at 4.2 K and at 2.1 K

SNS Power Upgrade Project

Primary Parameters	Baseline	Upgrade
Kinetic energy, (GeV)	1.0	1.3
Beam power on target, (MW)	1.4	3.0
Linac beam macropulse duty factor, (%)	6.0	6.0
Average macropulse, (mA)	26	42
Peak Current from front-end, (mA)	38	59
Linac average beam current, (mA)	1.6	2.3
SRF cryomodules number, (med-beta)	11	11
SRF cryomodules number, (high-beta)	12	20 (+ 1 reserve)
SRF cavities	81	113 (+ 4 reserve)
Peak surface field 0.61 cavities, (MV/m)	27.5	27.5
Peak surface field 0.81 cavities, (MV/m)	35	31
Ring injection time, (ms)/turn	1.0/1060	1.0/1100
Ring rf frequency, (MHz)	1.058	1.098
Ring bunch intensity, (10^{14})	1.6	2.4
Pulse length on target, (ns)	695	691
Maximum uncontrolled beam loss, (W/m)	1	1

SNS Power Upgrade Activities

- Power increase from 1.4 MW to 3 MW
- Obtained by increasing current and final energy
  - Requires nine additional high beta cryomodules
  - Investigating strategies for acquisition of cryomodules
  - Minimal cryomodule repair and cavity processing facility
  - Horizontal cryostat for cavity testing
    - Peripheral components qualification (HOM, FPC)
- Cryomodule improvements
  - HOM filters feedthroughs
  - Remove HOM filters ?
  - Better end group cooling
  - Higher average power FPC
  - Different process thermometers strategy
- Investigating CHL modifications to allow full 4.2 K capacity

Summary and conclusions

- Installation of the superconducting linac (cryomodules and warm sections) has proceeded at a sustained pace and is complete
- Testing of the cryomodules at 4.2 K has closely followed installation and demonstrated the operability of all the systems as soon as they were installed
- All of the SNS superconducting cavities, cryomodules, RF, Vacuum, Control systems have been tested successfully in the tunnel at 4.2 K and recently at 2.1 K.
- Most cavities meet or exceed the field specifications.
- Testing at 4.2 K has demonstrated that superconducting cavities powered in a pulse mode allow more flexible choices of operating temperatures
- Beam commissioning plans completed, based on the final tests of all the cryomodules and can be carried out at 2.1 K or at 4.2 K
- **Start beam commissioning July 25 (start at 4.2 K)**