Design, Fabrication, Commissioning and Operation of the Third RF System in NSLS-II

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Cryo

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Radio Frequency

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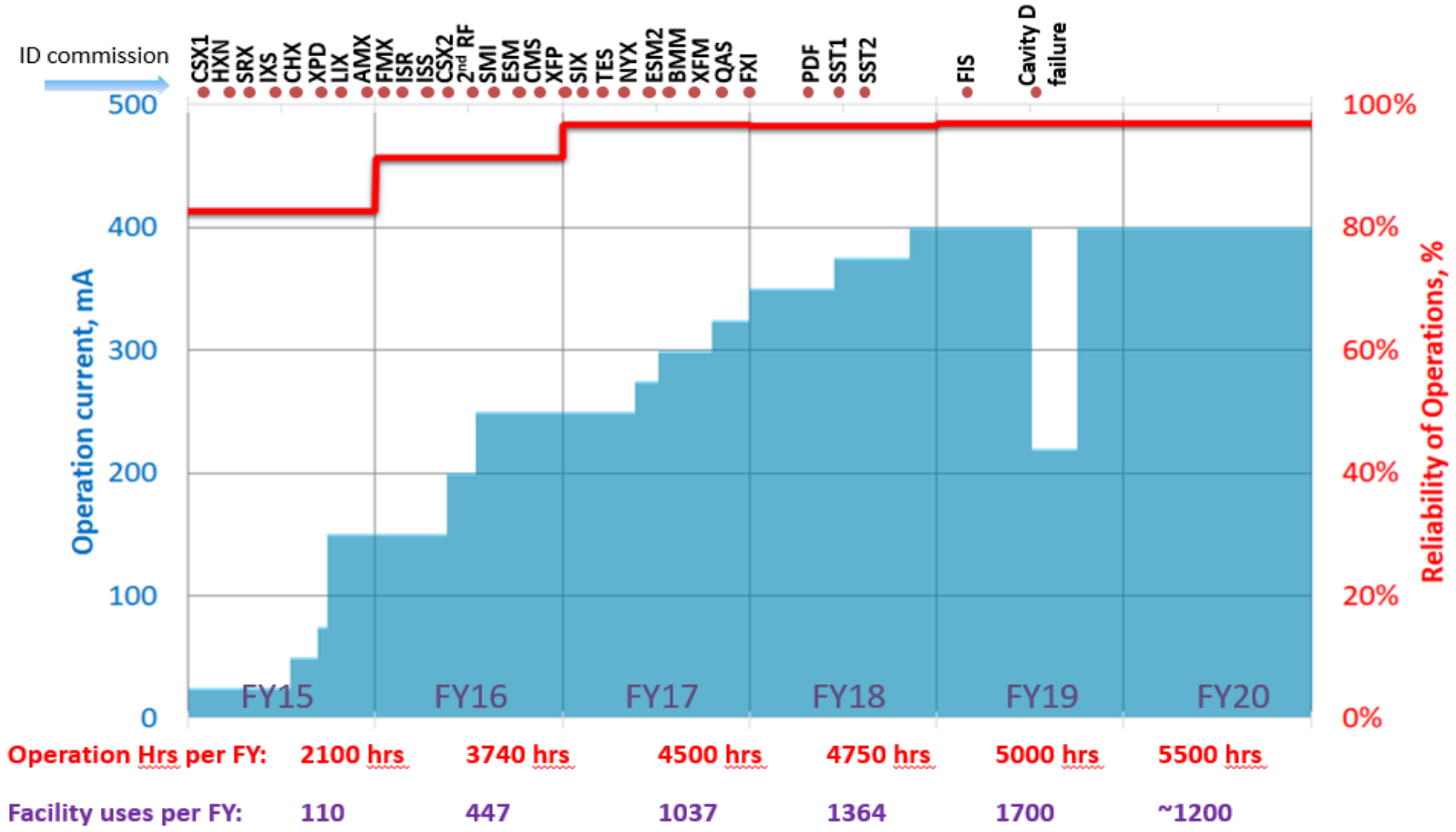
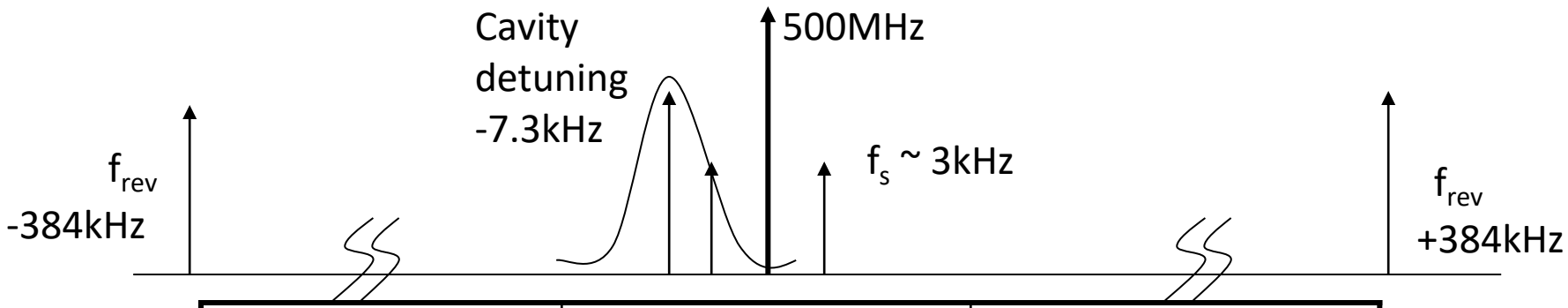
BROOKHAVEN NATIONAL LABORATORY

NSLS-II: 6 years operations



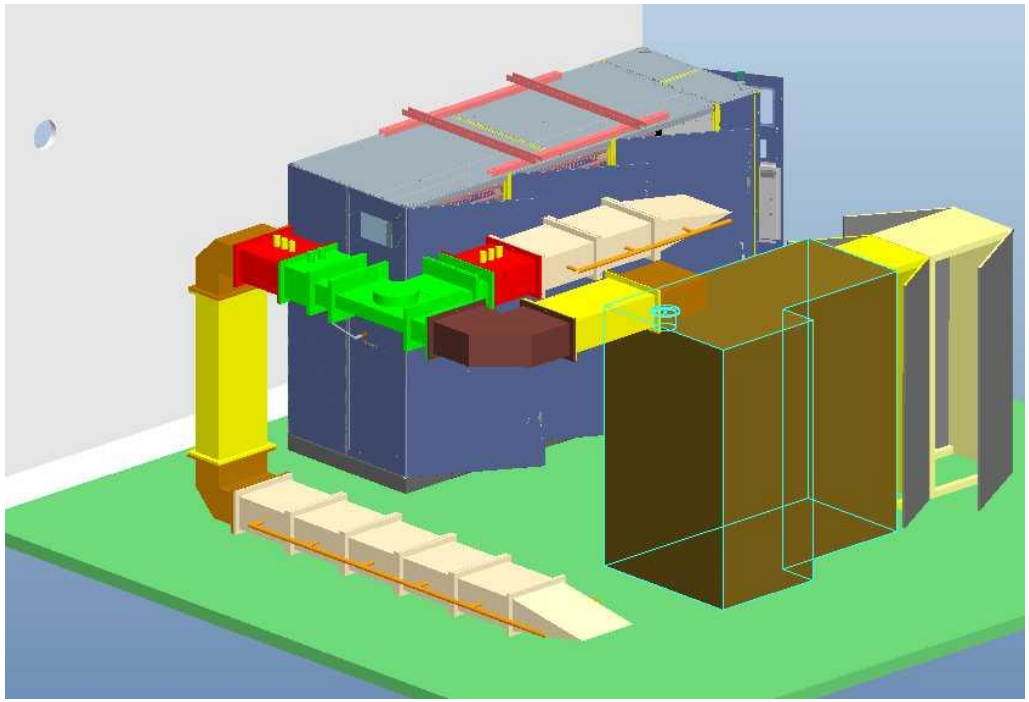
- Commissioned 29 IDs sources (10 IVUs, 6 EPUs, 6 DWs, 5 3PWs, 1 BM and 1 PU)
- High reliability has been maintained while we steadily increased beam current & IDs
- Normal operation with 2 cavities limits our performance (max 400 mA)
- Forced to decrease ops current to 220 mA due to the failure of one cavity in Apr. 2019

NSLS-II RF-Beam Parameters



	Today	Fully Built Out
Energy	3 GeV	3GeV
Beam Current	400 mA	500 mA
Energy Loss/Turn	800 keV	??1000 keV
Total V	3.6 M	4.8 MV
Synchrotron Frequency	3 kHz	4 kHz
Number of cavities	3	4
Q_L*	79000	79000
Voltage/Cavity	1200 kV	1200kV
Frequency detuning	-6.4 kHz	-8.3 kHz
* Q_L ~ 80k for minimum reflected power over all phases		

Booster RF system

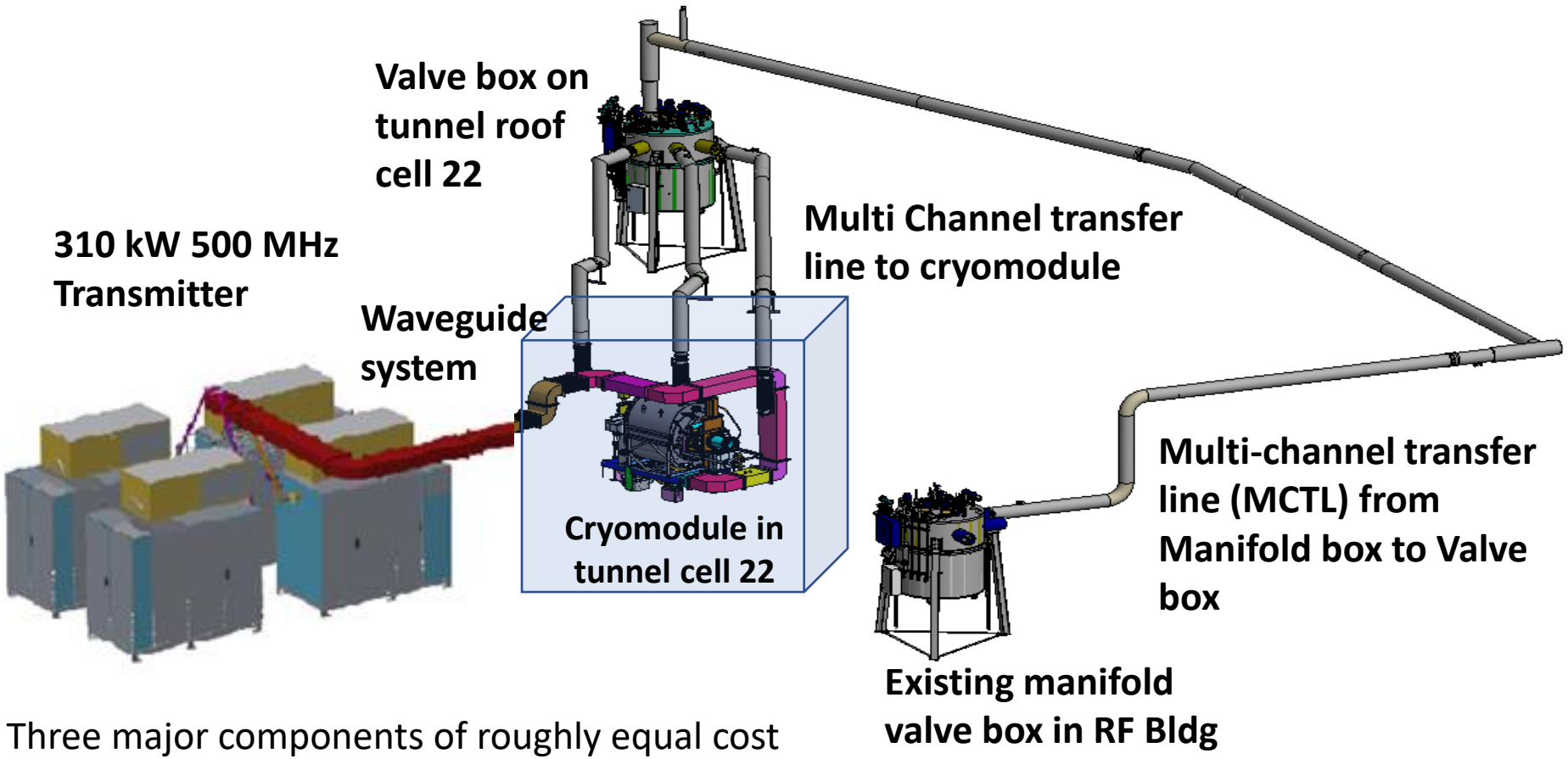


80 kW L3 4444 IOT with Thomson (Comark/Ampegon) transmitter, Ferrite Inc 120kW circulator and AFT reject load

System commissioned in 2012 with the same L3 4444 IOT still in service

Booster cycle is 1 Hz ramp from 6kW to 60 kW, average power is <30 kW- ideal conditions for IOT

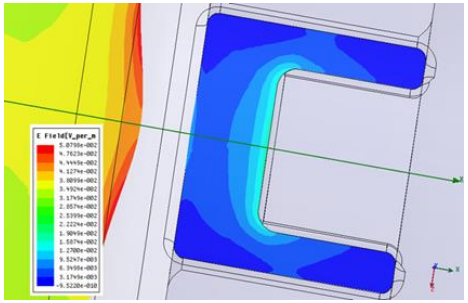
3rd RF system components



Three major components of roughly equal cost
Superconducting RF cavity/Cryomodule
310 kW Solid State Amplifier
Cryogenic system upgrade including valve box, warm and cold piping for second RF straight (3 cavities)

Storage Ring: Superconducting Cavity

- 3 (of 4) 500MHz Cornell type SRF cavities installed
- Redesigned coupling iris for Q_{ext}=79,000



400 kW coupler !!

- BNL assisted AES in assembly of first 2 cryomodules; Rebuilt first cryomodule in 2019 in-house
- RF group completed 3rd RF cryomodule in NSLS-II facilities
- Currently building a 4th cavity as spare

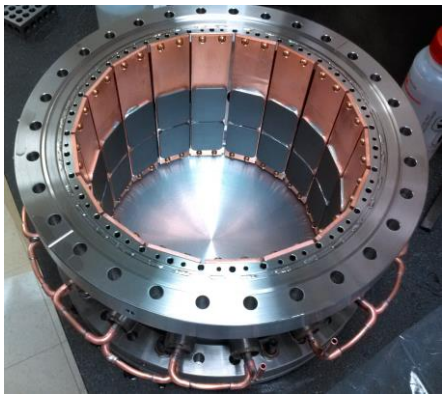
In between vertical test and HPR the indium is etched off the cavity with 70% nitric acid

This is done in a portable clean room to provide ventilation

I include this photo to prove I was doing some honest work on the 3rd RF project

Third Cryomodule in final assembly in RF lab

Cavity String Assembly



HOM built by industry

Window High Power Test Assembly
Confirms TiNi coating of window is OK

500MHz RF Window Conditioning 8/18-8/26

Description:

1. The window is specified for 500kW in TW, and 150kW in SW with full reflection. We only need 310kW in TW and 115-125kW in SW.
2. Two windows back to back on vacuum pumpout box
3. In TW mode, the window was tested up to 270kW
4. In SW mode, the sliding short was moved in 6 steps, 33mm (1.3”) per step, to scan over 90° phase up to 125kW. CW and pulsed conditioning was alternated.

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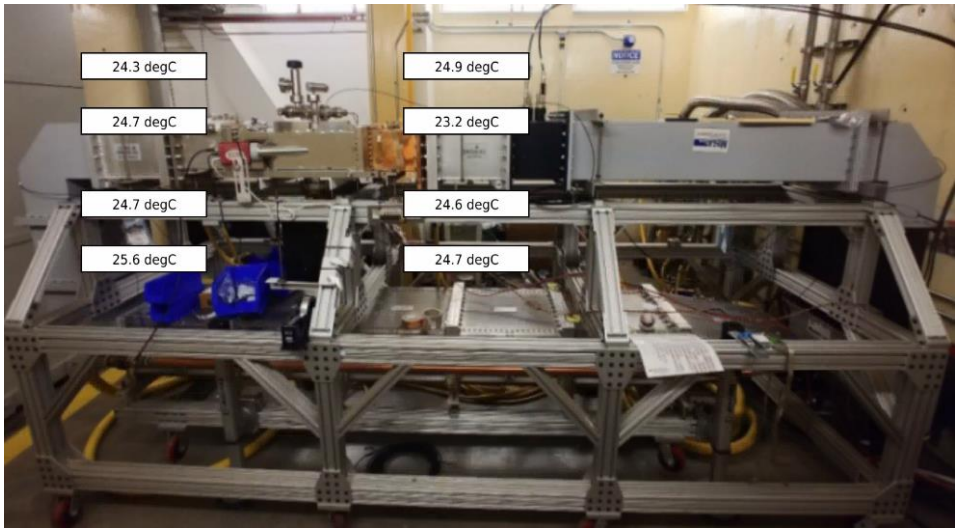
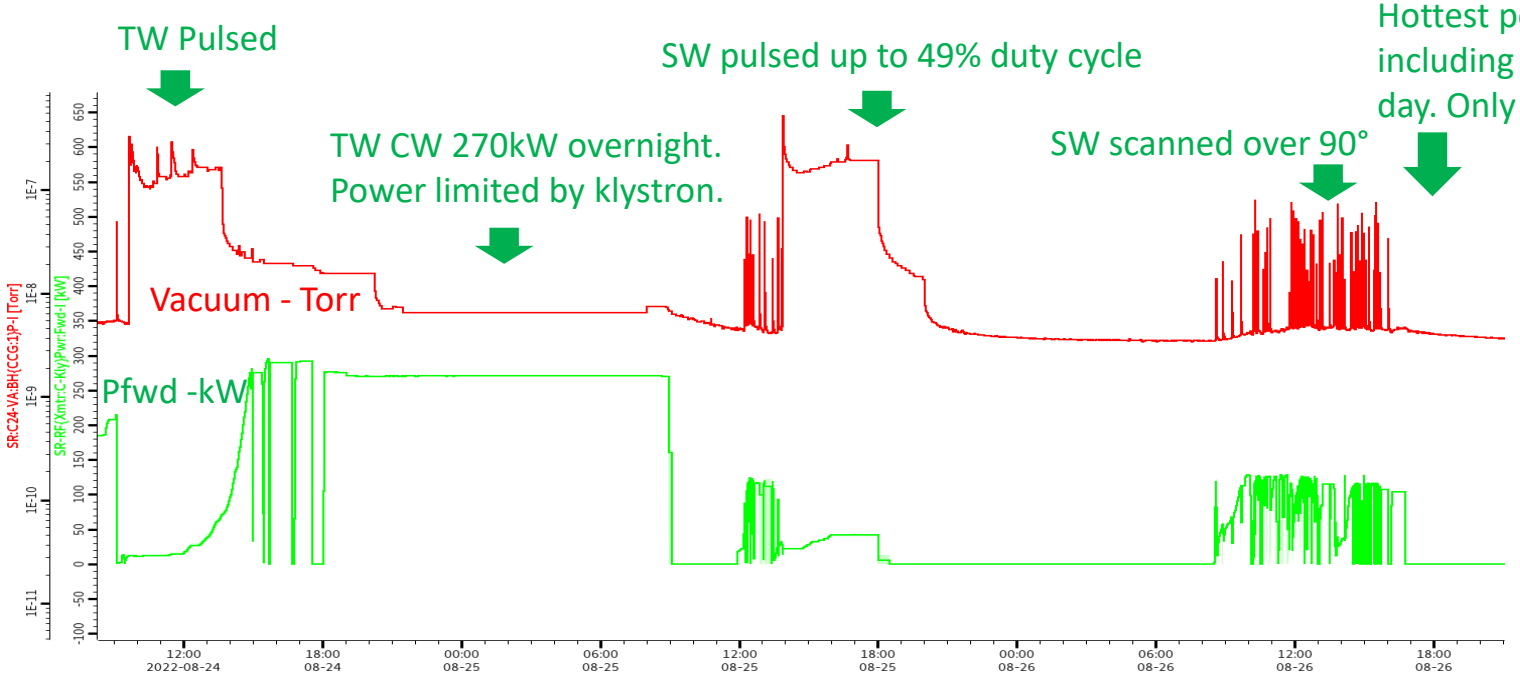
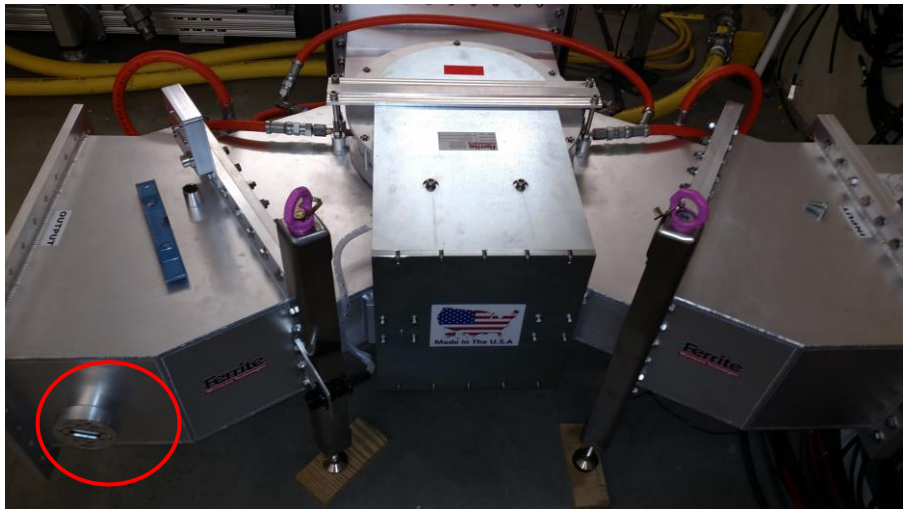




350kW 500MHz Circulator- Spare or 3rd RF system, if needed

- In 2015 the circulator delivered as part of a turn-key system did not meet specification and limited us in forward power during operations.
- Detailed tests showed the circulator performance varied out of spec at our particular reverse power phase in our cavity installation. AFT could not fix in-situ and required return to factory, which cannot be done within our 1 month shutdown periods.
- A spare/replacement was ordered from Ferrite Inc (now part of MEGA). Its control unit utilizes PLC to adjust bias current while monitoring Pfwd and Prev. It is also equipped with Daniel's arc detection system* as specified by BNL.
- When the second port is connected to a sliding short and third port to a 350kW load, the S11 of the input is below -30dB at 300kW for all phases.

* D. Valuch, CWRF



When tested at BNL, the circulator works well without needing the control box (thus no bias current).

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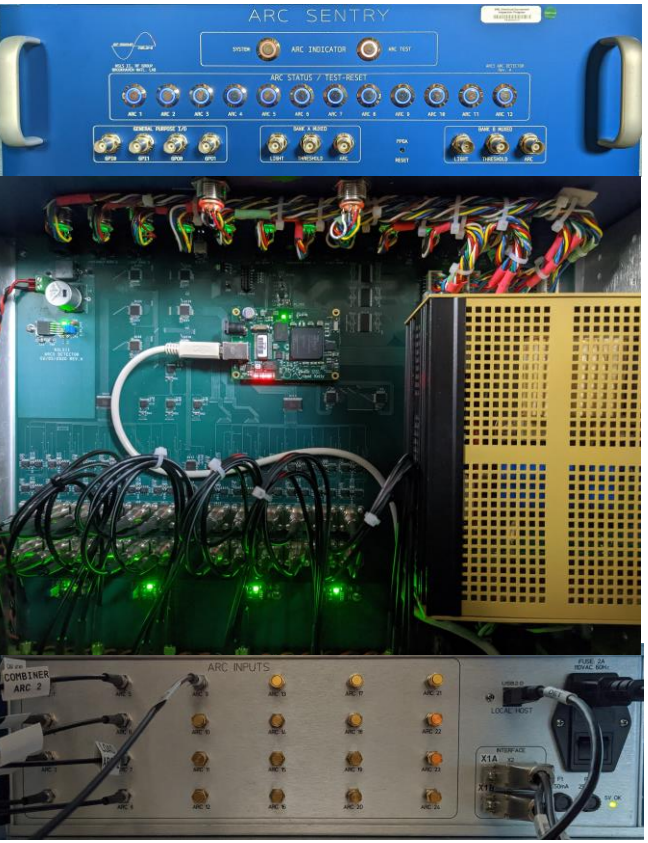
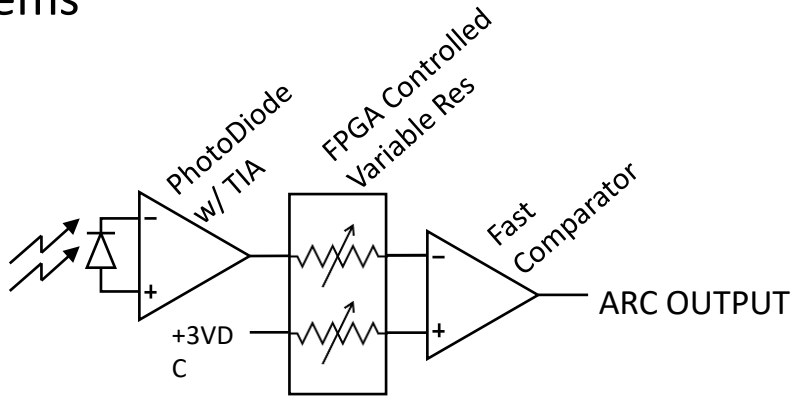
Factory used bias current for FAT, data is shown as below:

Freq (MHz)	497.68	499.68	501.68
Input reflection S11	-26.93dB	-33.93dB	-28.14dB
Isolation S12	-27.43dB	-37.87dB	-27.13dB
Insertion loss S21	-0.061dB	-0.054dB	-0.065dB
Output reflection S22	-30.53dB	-41.09dB	-27.19dB

ARC5 Arc Sentry System

Developed to take advantage of the small footprint “sma” fiber optic pickups already installed in most of our systems





Basic Principle

- 24 Arc inputs each with a comparator level that is FPGA controlled via programmable resistor and is biased ~20mV above the TIA output.
- FPGA logic filters false alarms by counting fifty successive comparator triggers at 200MHz.
- In an arc event, response time from the photodiode to the interlock output is less than 3usec.
- Maximum trigger sensitivity is around 175nW in the visible spectrum, equivalent to a tenth of home lighting.

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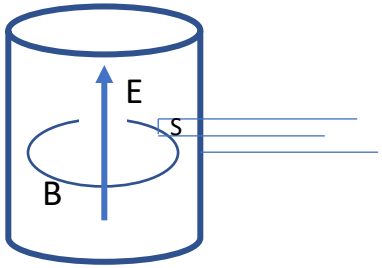
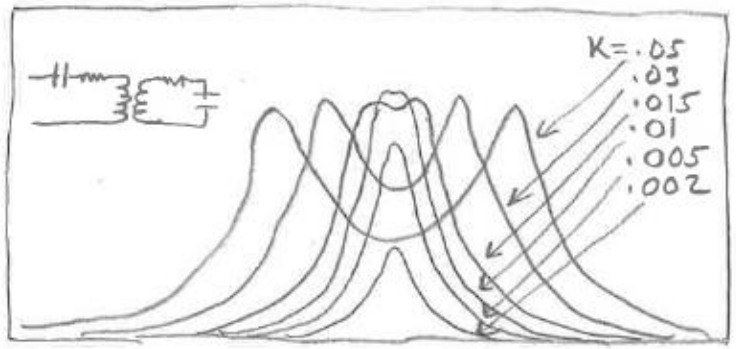
Cavity Combiner coupling to SRF cavity



We had a concern about the possibility of the two-cavity system coupling to split modes and wreak havoc



See, for example, Terman, "Fundamentals of Radio", 1938

For small perturbations: $\frac{\Delta F}{F} = \frac{\Delta U}{U}$

From Superfish, the stored energy in the SRF cavity at 1.6MV is 9 Joules, and the combiner 0.3 Joules for 1377A/m at the cavity wall

To normalize the stored energy in the cavity combiner we start with the individual module power of 640 W for nominal 80 kW output power of combiner. 640W gives 253 V in a 50 ohm line.

$$\int E \cdot dL = -\frac{d\Phi}{dt} = \oint_S \frac{dB}{dt} dS$$ where $B = B_o\, e^{j\omega t}$ and B=μH

Voltage in the loop

Integral of the time derivative of the magnetic flux in the loop area S

253V = -$\omega\mu$HS

Which gives H=142A/m where we can then normalize the combiner stored energy

$$\frac{142}{1377} \cdot 0.3 Joules = 0.003 Joules. \quad \Delta F = \frac{\Delta U}{U} = 172 \text{ kHz !}$$

Needs further investigation.

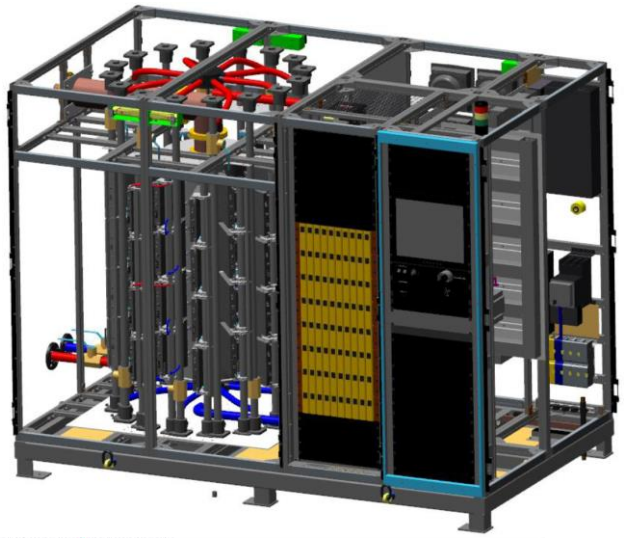
Simulation of 4-tower 3rd RF system

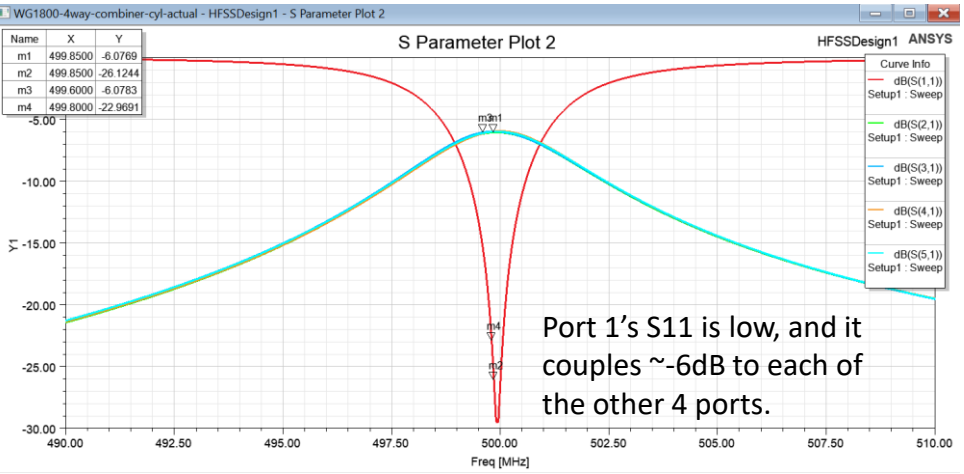
Transmitter A uses a 4-way waveguide combiner to combine output power of 4 towers. Each tower uses a 128-way cylindrical combiner to combine power of individual modules.

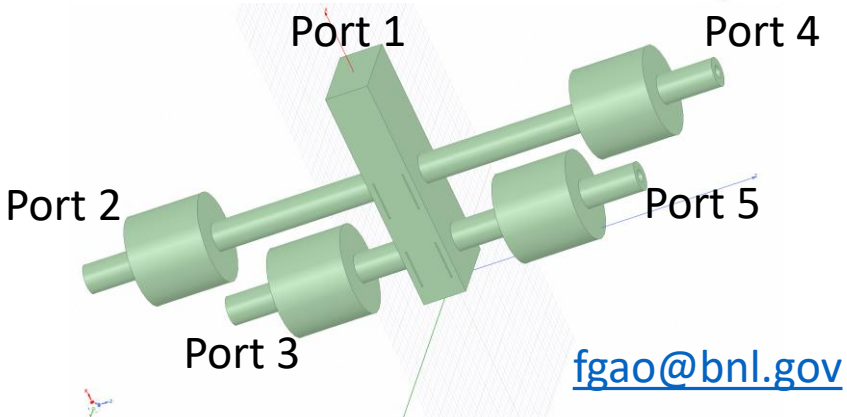
When the cavity is added, will the cavity's frequency be pulled by the cylindrical combiners? Will new adjacent harmful modes be created due to coupling?

An end-to-end simplified model has been created and analyzed. (This and next pages.)

Simple pillboxes are used to emulated the 128-combiners, whose input and output Qext are maintained. The model of the 4-way waveguide combiner is created by measuring the actual dimensions. The combo of these two sections did not create extra resonant peaks in simulation.







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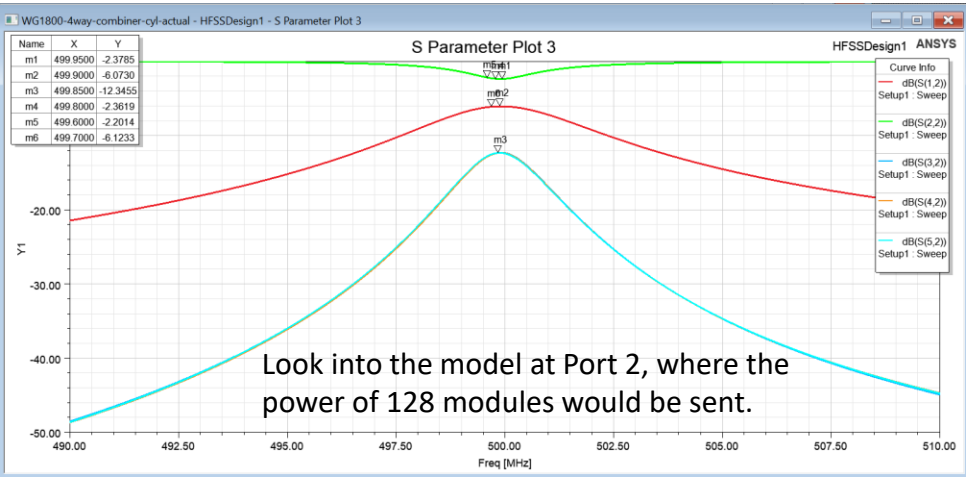
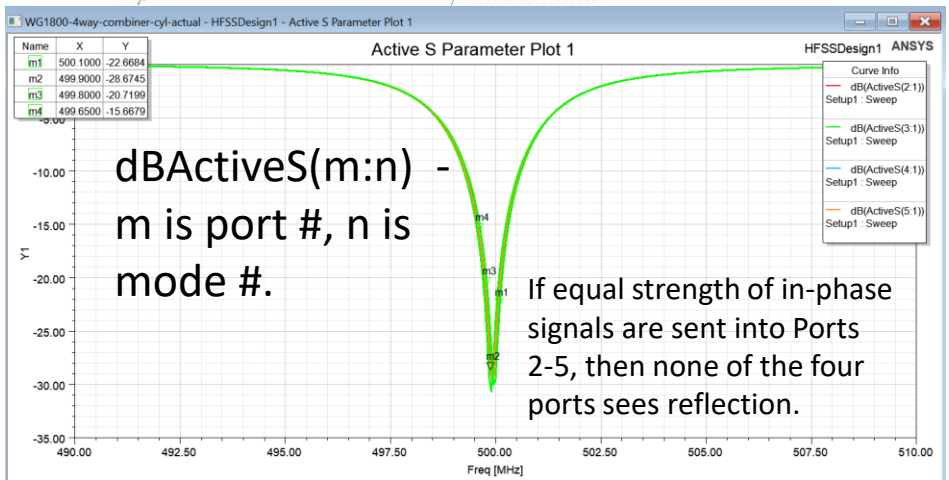
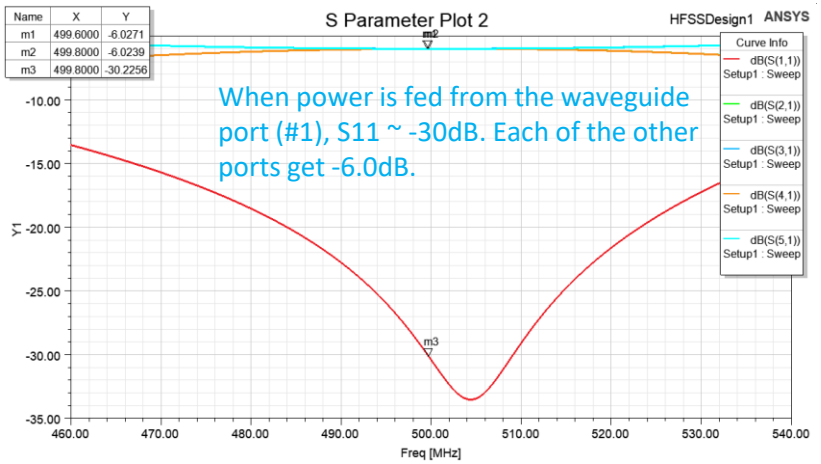
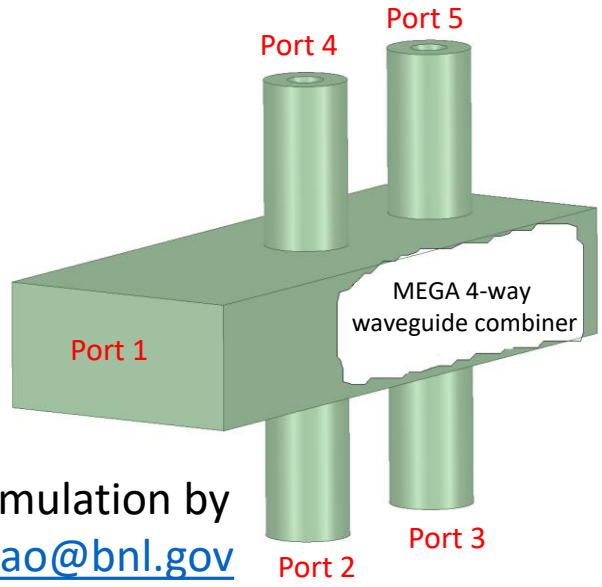




MEGA 4-way waveguide combiner:
HFSS simulation with actual dimensions (with some measurement inaccuracies).

(Note: Factory simulation yields slightly better performance, presumably because of more accurate dimensions. Not shown here.)





Simulation by
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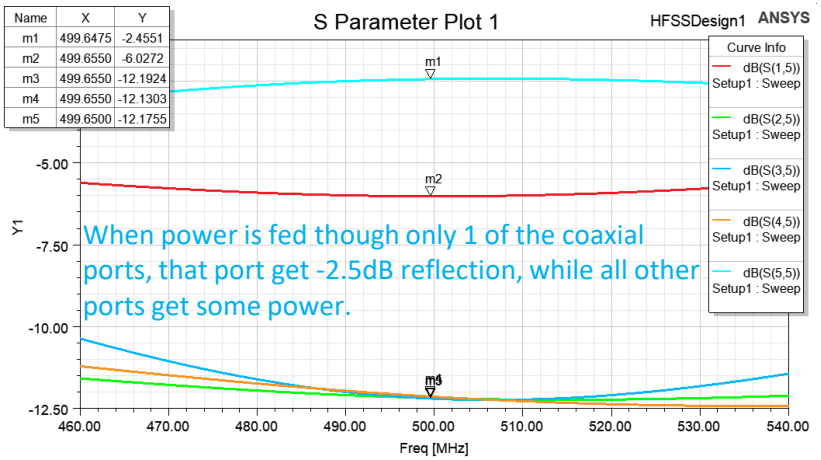

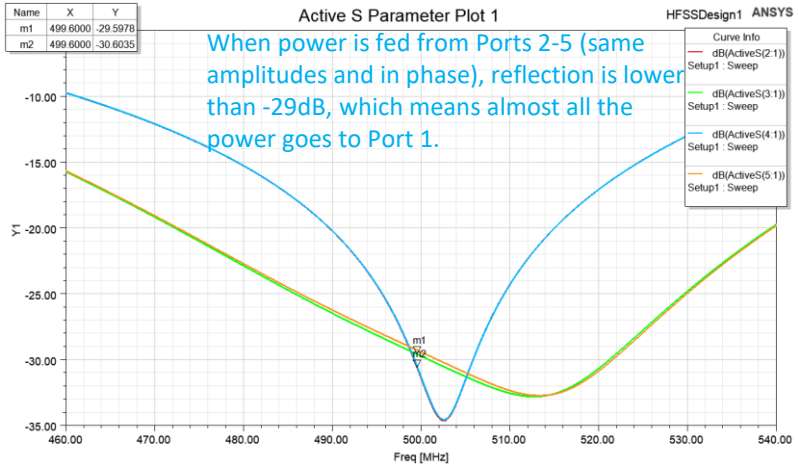

Add a beam-loaded cavity to the model

When Cavity A operates with beam, the tuner will make the cavity look like a resistive load for the transmitter, if the load angle is zero. Then the beam effect can be emulated with equivalent Q0 and QL.

Qext = 74600, Ibeam = 400mA, loss per turn 738kV, Vcav = 1.25MV each. A's Pfwd = 120kW, Prev = 21.3KW. -> eqv. beta = 2.46. -> Equivalent Q0 = 183516, QL = 53039.

The Q0 is reached by applying artificial conductivity to the cavity wall.

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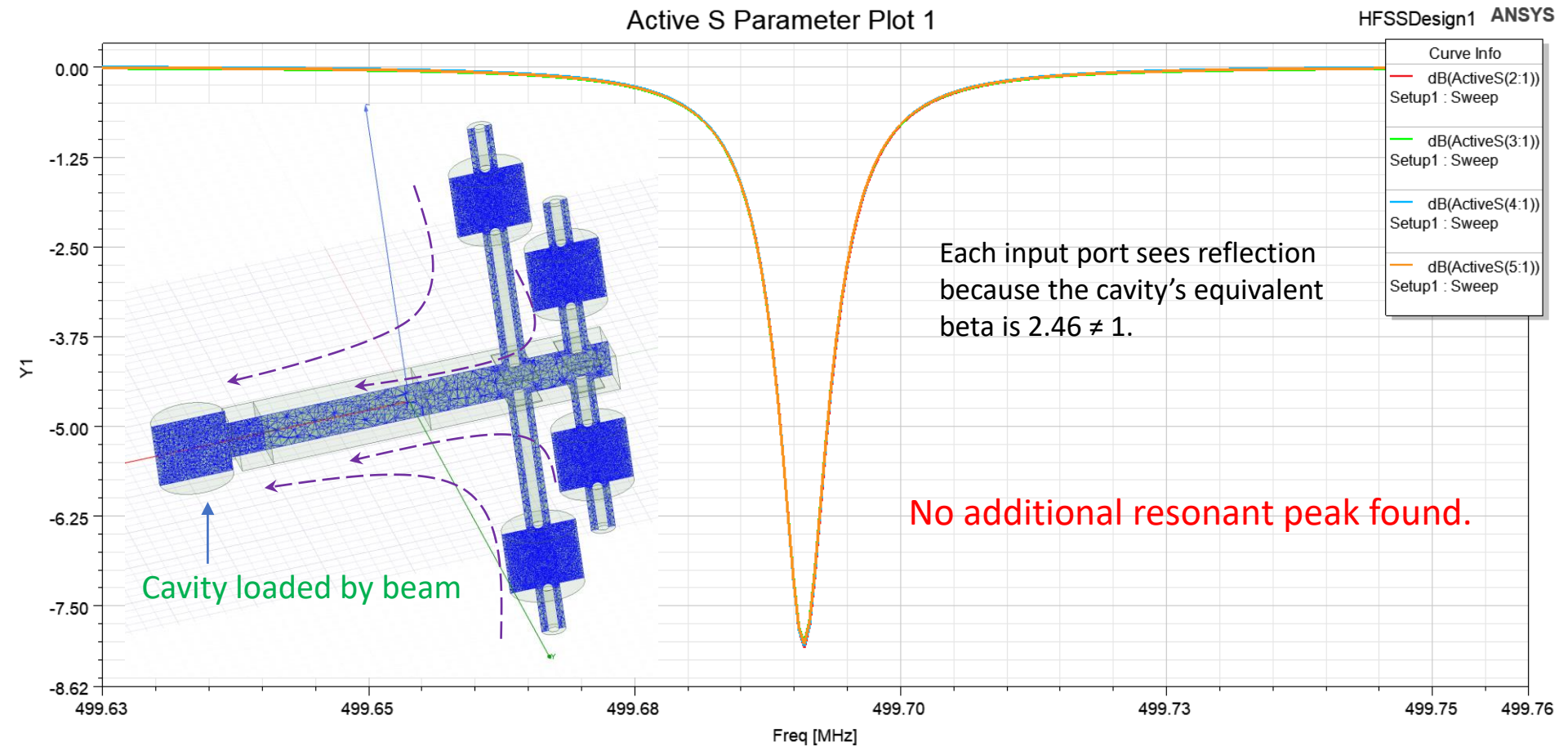
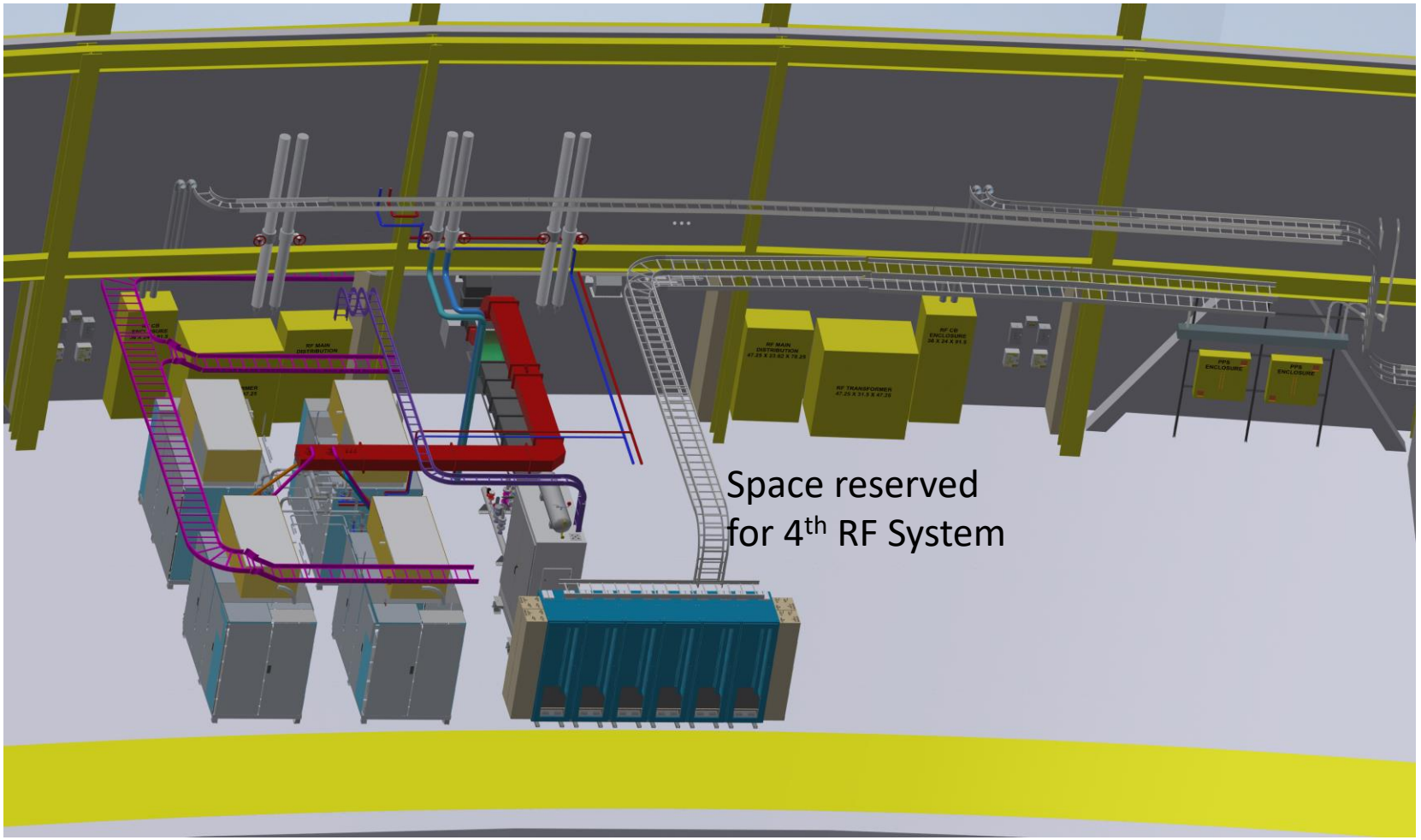


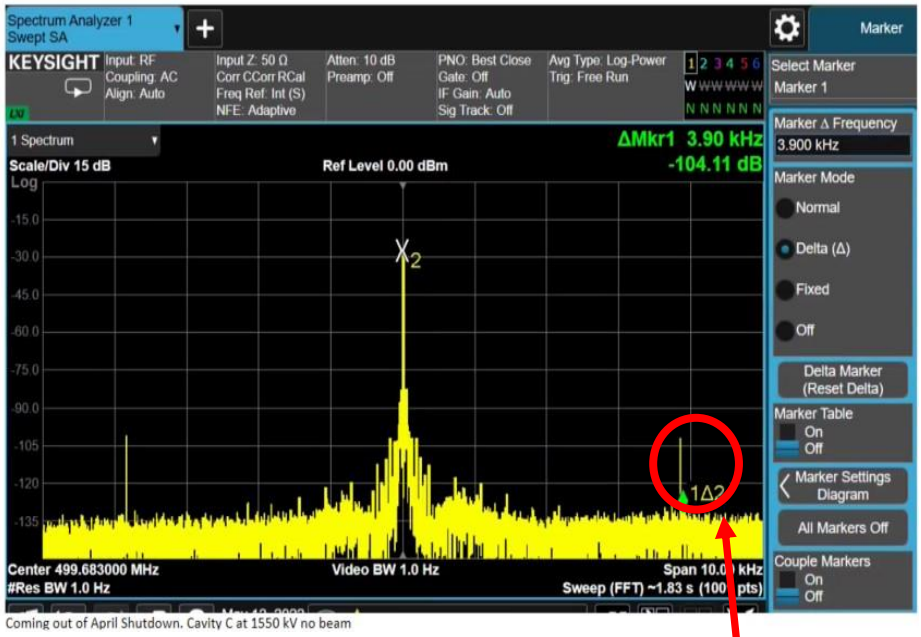
310 kW SSA installation



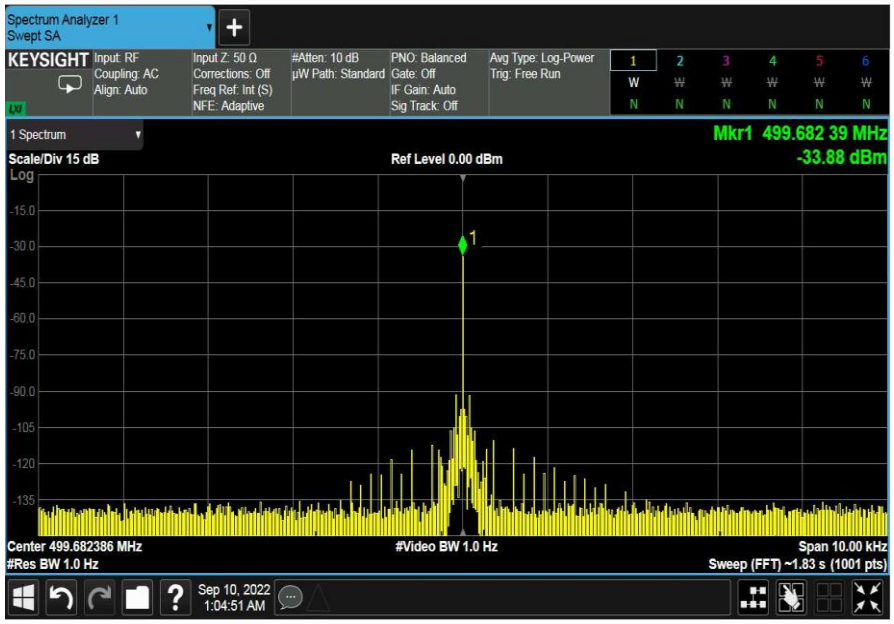
Blue racks are common for both 3rd (existing) and future 4th system and houses LLRF, Cavity vacuum, tuner controls, cryogenic instrumentation and heater power supplies

Comparing KSU /SSA Spectrums (wo / Beam)

Klystron



SSA

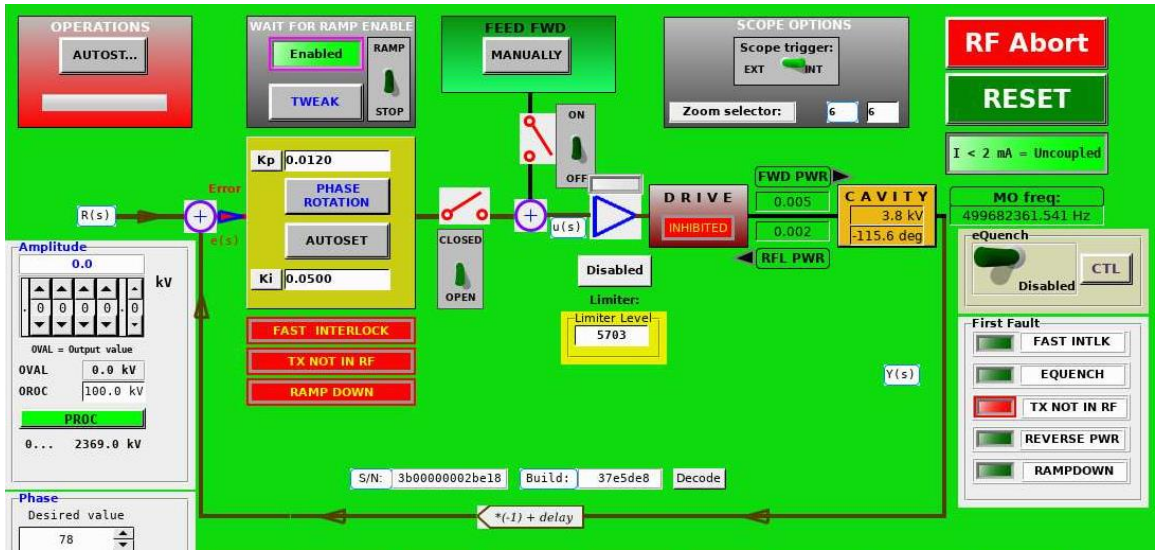


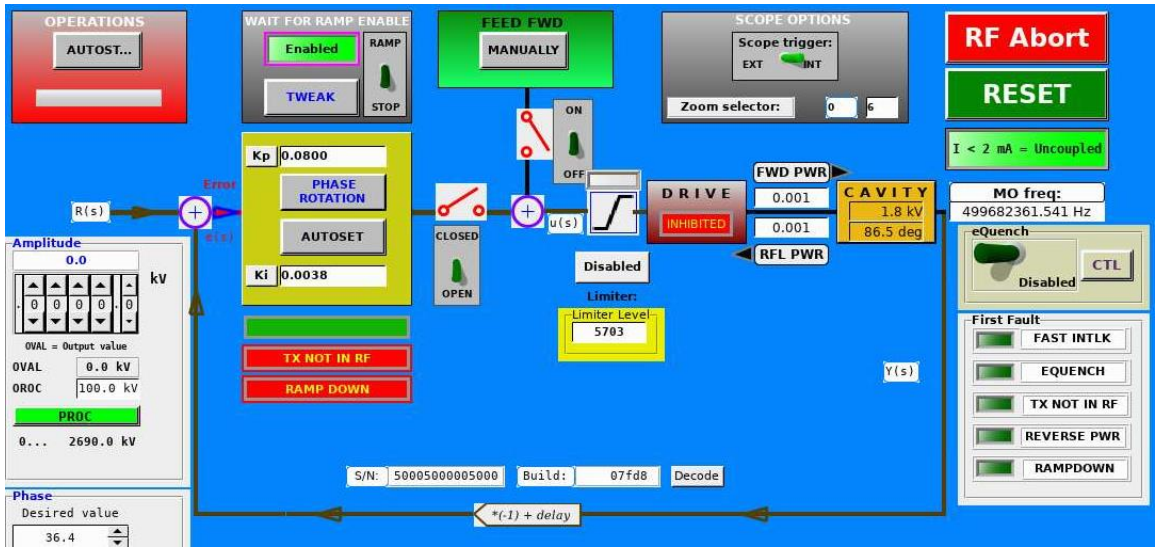
Switching Frequency line

Klystron power supply has 60 Hz Mains compensation which uses the AM characteristics of the power supply to cancel power harmonics. We can also vary the switching power supply

SSA AC power harmonics dominated by 100 W drive amplifier and can be reduced

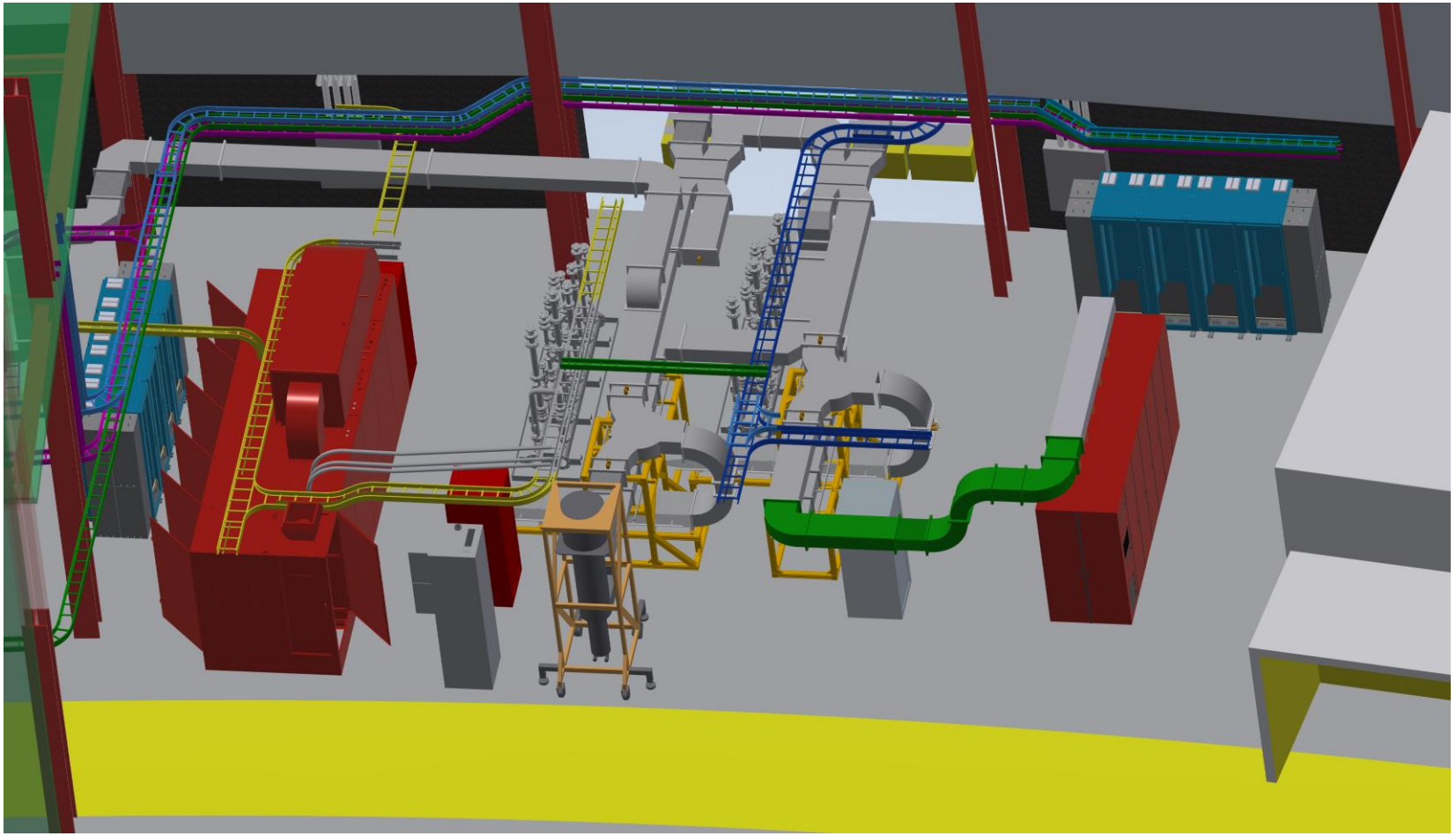
SSA supports over twice the feedback gain resulting in significant reduction in horizontal beam motion





310 kW klystron compared to 240 kW SS amplifier

The SS would extend less then an additional 1/3 of its length for 300kW



We have 5 qualified and interested vendors who requested the RFP !

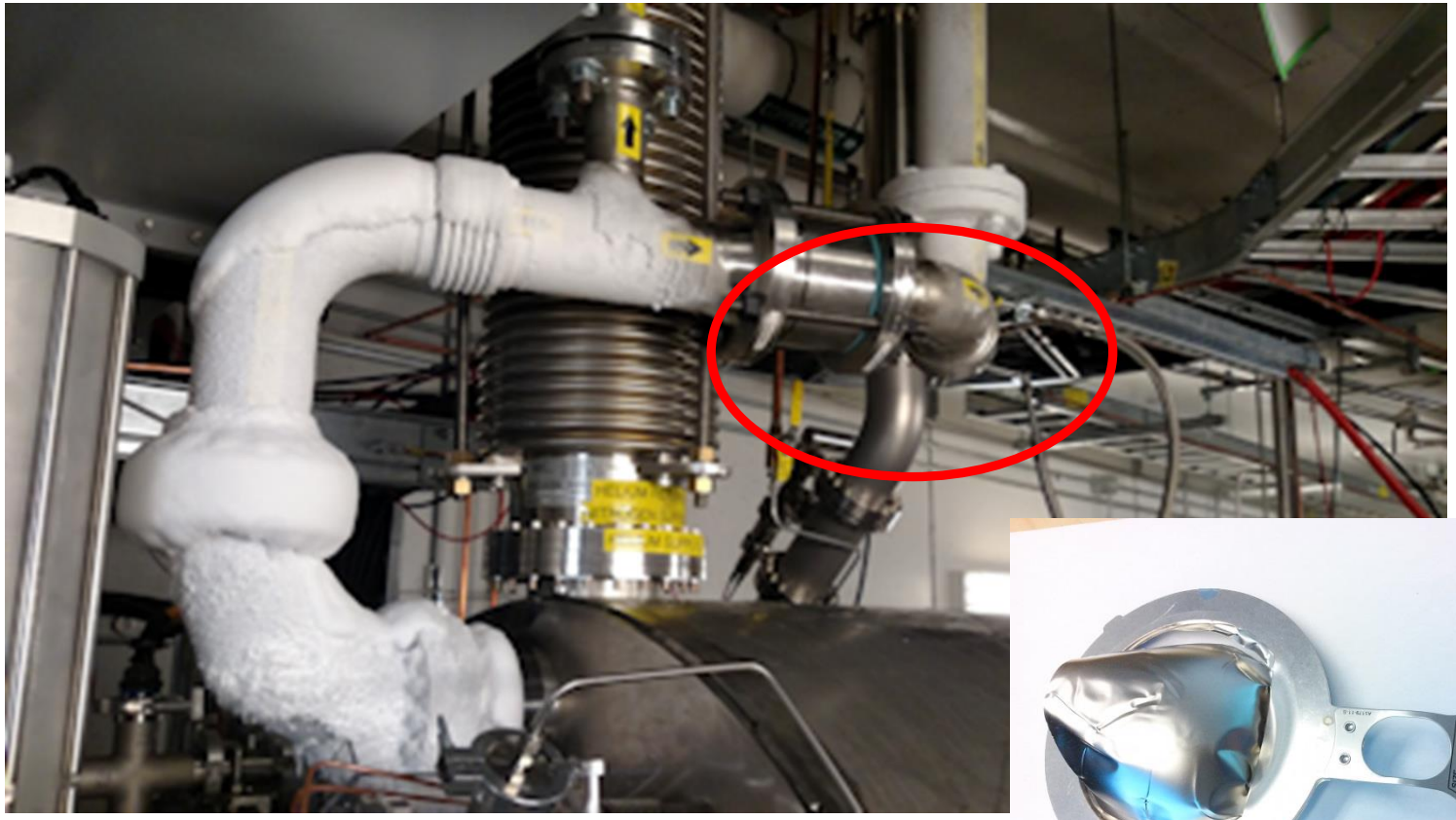
RF Look ahead to 500 mA

Assembly of 3rd RF cryomodule in RF lab

- Need 3rd RF system to meet beam power requirements
- Fourth RF system required to meet reliability through redundancy
- Harmonic cavities required for bunch lengthening to relieve beam vacuum components heating
- Enhanced feedback (MISO) on beam phase and cavity field for increased beam stability

Harmonic cavity in horizontal cold test

Burst Disk Events



We have not had any catastrophic failures in High Power RF, however we more than make up for this in Cryo Events

Summary

- The NSLS-II has been running reliably since 2014 with 2 installed SRF systems when designed for 4 plus 2 harmonic cavities
- Third RF system, required for reliability at 400mA operations and for 500mA operations with new beamlines, was installed and is 1 year in operations
- A fourth RF system in required for reliability at 500mA
- A harmonic cavity is required for low emittance operations at 500mA (to lengthen the shorter bunches) and may be required at 500mA for stability due to very high beam loading factor (we cannot raise RF voltage due to beam pipe heating from short bunches)
- These latter two projects are in our short term plans (5 years)
- Cryogenic system dominates downtime due to very long recovery times (24-48 hours). Second (redundant) cold box project is already started

Thank you