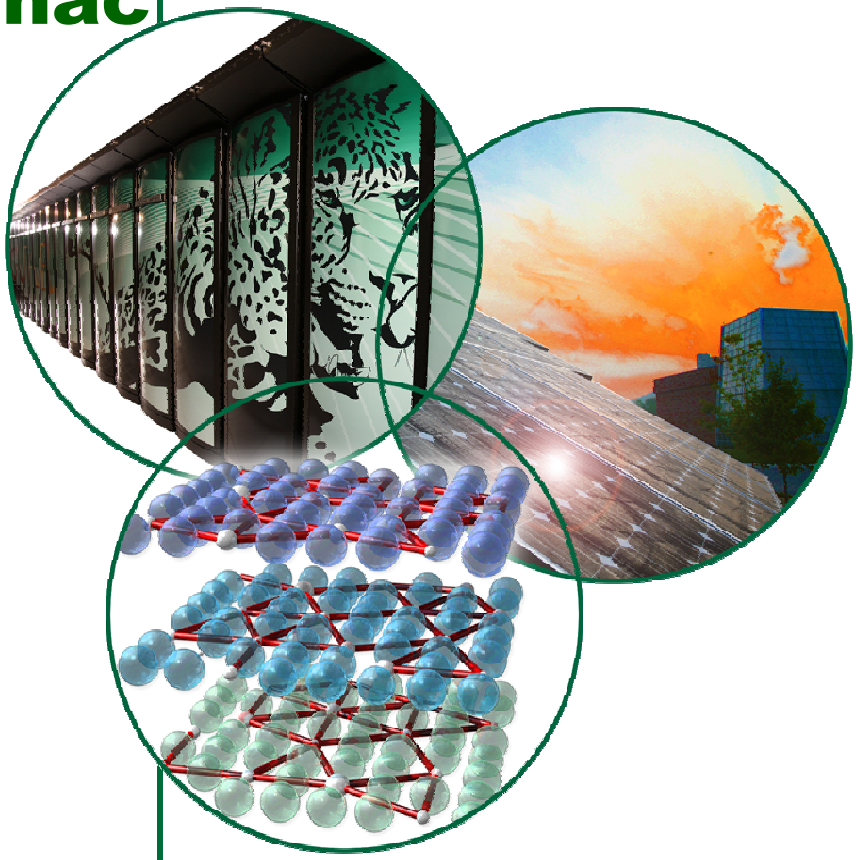
Design and Operating Experience with SNS Superconducting Linac



FNAL
September 30, 2010

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SNS/ORNL

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Machine layout

Accumulator Ring:
Compress 1 msec long pulse to 700 nsec

Front-End:
Produce
a 1-msec long,
chopped, H-beam

H- stripped to p

Linac; 1 GeV acceleration

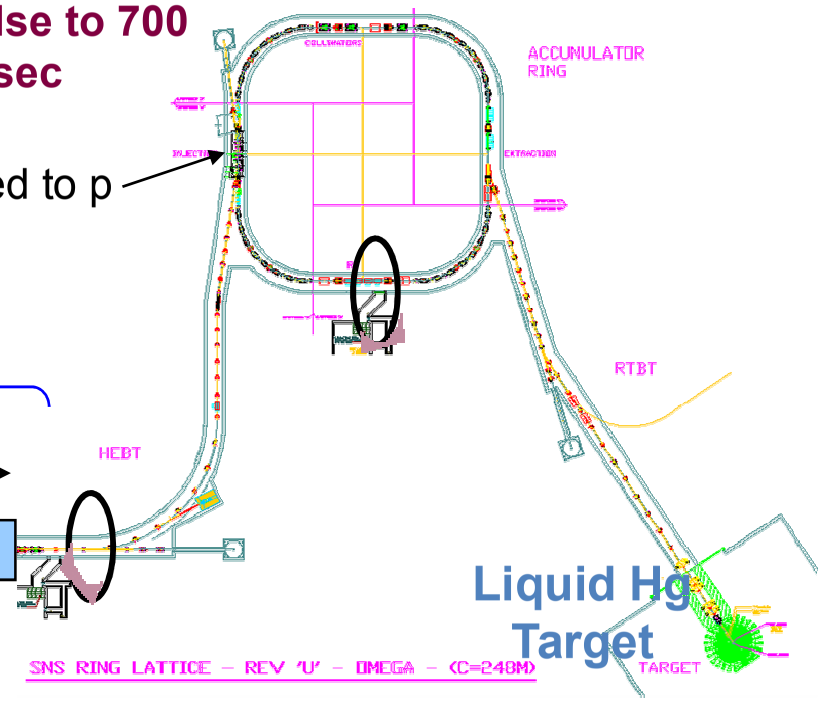
402.5 MHz

805 MHz

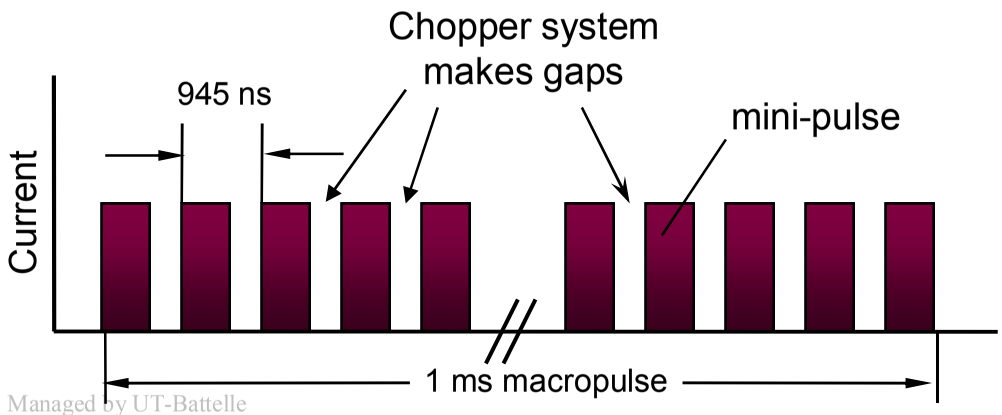
DTL | CCL | SRF, β=0.61 | SRF, β=0.81 | PUP

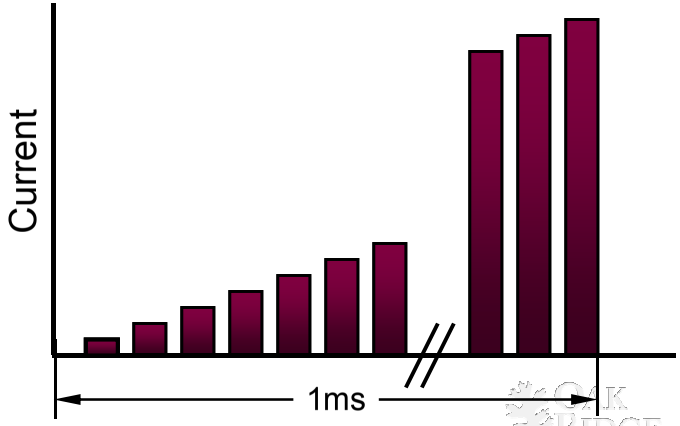
2.5 86.8 186 387 1000 MeV

259 m



Liquid Hg Target





SNS SCL History and initial design concerns

- SNS baseline change from NC to SC in 2000, relatively late in the project
- RF frequency; followed that of the NC CCL (from LANSCE)
- SRF Cavity designs were mainly driven by two constraints
  - Power coupler; maximum 350 kW (later increased to >550 kW)
  - Cavity peak surface field; 27.5 MV/m field emission concerns
    - Later increase to 35 MV/m for HB cavities by adapting EP
- With one FPC to cavity; HB cavity → 6 cell
- Long. Phase slip at low energy; MB cavity → 6 cell
- And then usual optimization process
  - TTF, peak surface field balancing, raise the resonant mechanical frequency, LFD, HOM, etc

SNS SCL Components

Cryomodule and all internal components developments

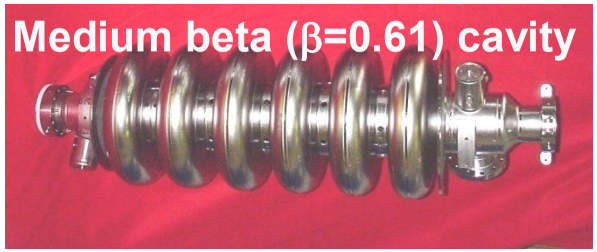
; done by JLAB including prototyping

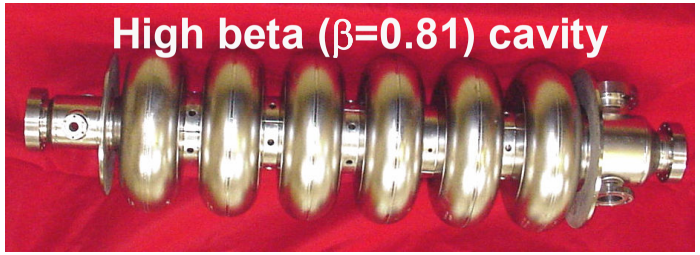
- Power coupler; scaled from KEK 508 MHz coupler
- HOM coupler; scaled from TTF HOM coupler
- Mechanical tuner; adapted from Saclay-TTF design for TESLA cavities
- Piezo tuner; incorporated into the dead leg for possible big LFD (later on)
- Cryomodule; similar construction arrangement employed in CEBAF
- Nb material RRR>250 for cells and Reactor grade Nb for Cavity end-group

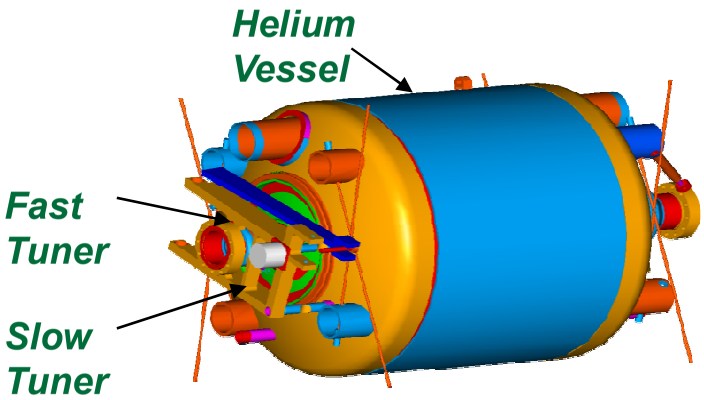
SNS Cavities and Cryomodules look;

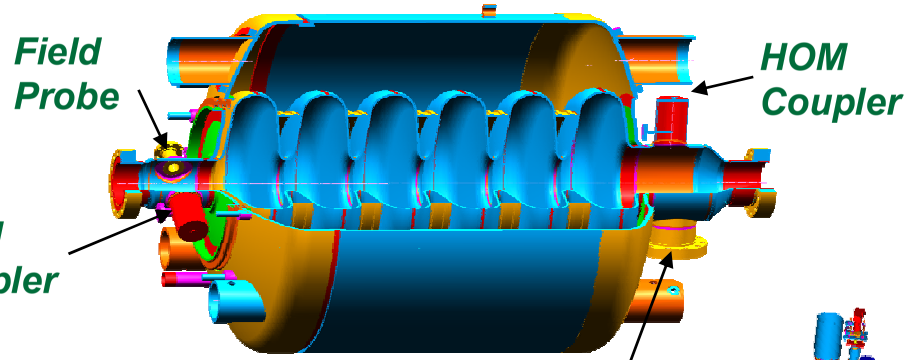
β=0.61 Specifications:
E_a=10.1 MV/m, Q_o> 5E9 at 2.1 K

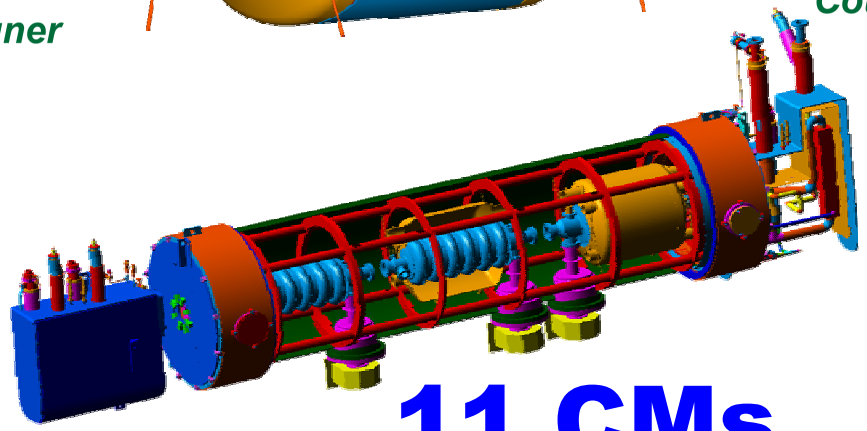
β=0.81 Specifications:
E_a=15.8 MV/m, Q_o> 5E9 at 2.1 K



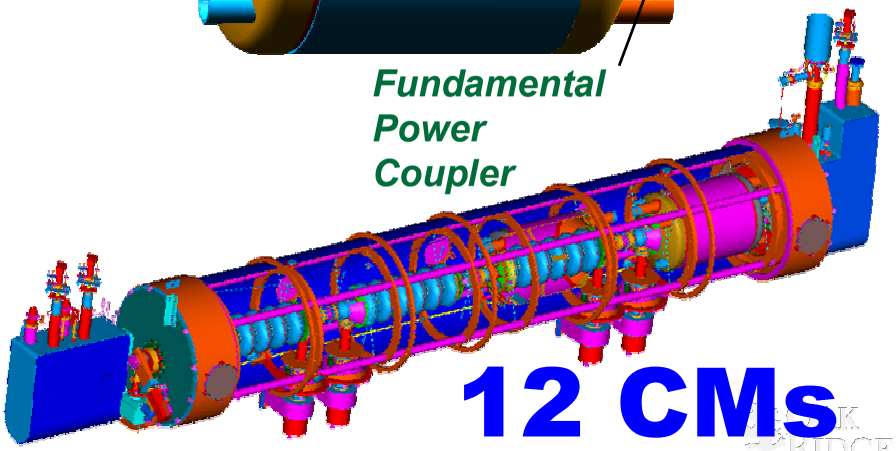








11 CMs



12 CMs

SNS SCL, Operations and Performance

- **The first high-energy SC linac for protons, and the first pulsed operational machine at a relatively high duty**
- **We have learned a lot in the last 5 years about operation of pulsed SC linacs:**
  - Operating temperature, Heating by electron loadings (cavity, FPC, beam pipes), Multipacting & Turn-on difficulties, HOM coupler issues, RF Control, Tuner issues, Beam loss, interlocks/MPS, alarms, monitoring, …
- **Current operating parameters are providing very stable and reliable SCL operation**
  - Less than one trip of the SCL per day mainly by errant beam or control noise
- **Proactive maintenance strategy (fix annoyances/problems before they limit performance)**
- **Beam energy (930 MeV) is lower than design (1000 MeV) due to high-beta cavity gradient limitations (mainly limited by field emission)**
- **No cavity performance degradation has occurred to Oct. 09**
  - Field emission very stable
  - Recently Nov. 09; Two cavity has shown performance degradation
- **Several cryomodules were successfully repaired without disassembly**
  - Multiple beam-line repairs were successfully performed

Machine Performances

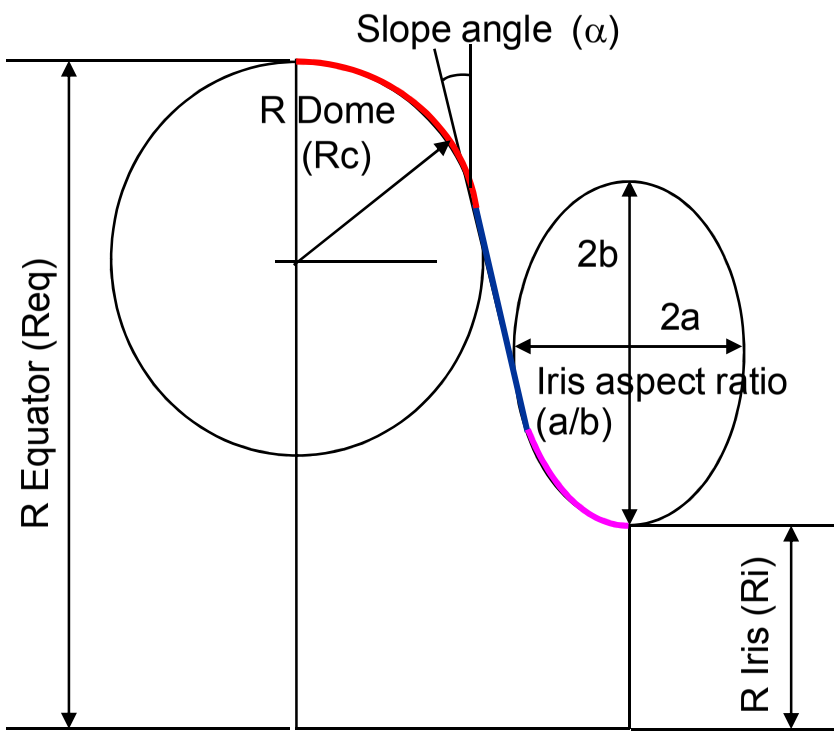
Parameters	Design	Individually achieved	Highest production beam
Beam Energy (GeV)	1.0	1.01	0.93
Peak Linac Beam current (mA)	38	42	42
Average Linac Beam Current (mA)	1.56	1.1	1.1
Beam Pulse Length (μs)	1000	1000	825
Repetition Rate (Hz)	60	60	60
Beam Power on Target (kW)	1440	1100	1100
Linac Beam Duty Factor (%)	6.0	4.8	4.8
Beam intensity on Target (protons per pulse)	1.5×10^{14}	1.55×10^{14}	1.1×10^{14}
SCL Cavities in Service	81	80	80

Cavity Specifications

Frequency	805 MHz	
N. of cells	6	
Cell-to-cell *k* [%]	>1.5	
Geom. β	0.61	0.81
E_{pk} [MV/m]	27.5	35
Lorentz K_L [Hz/(MV/m)2]	< -2 ± 1 (static)	
Q (2.1 K)	$\geq 5 \times 10^9$	

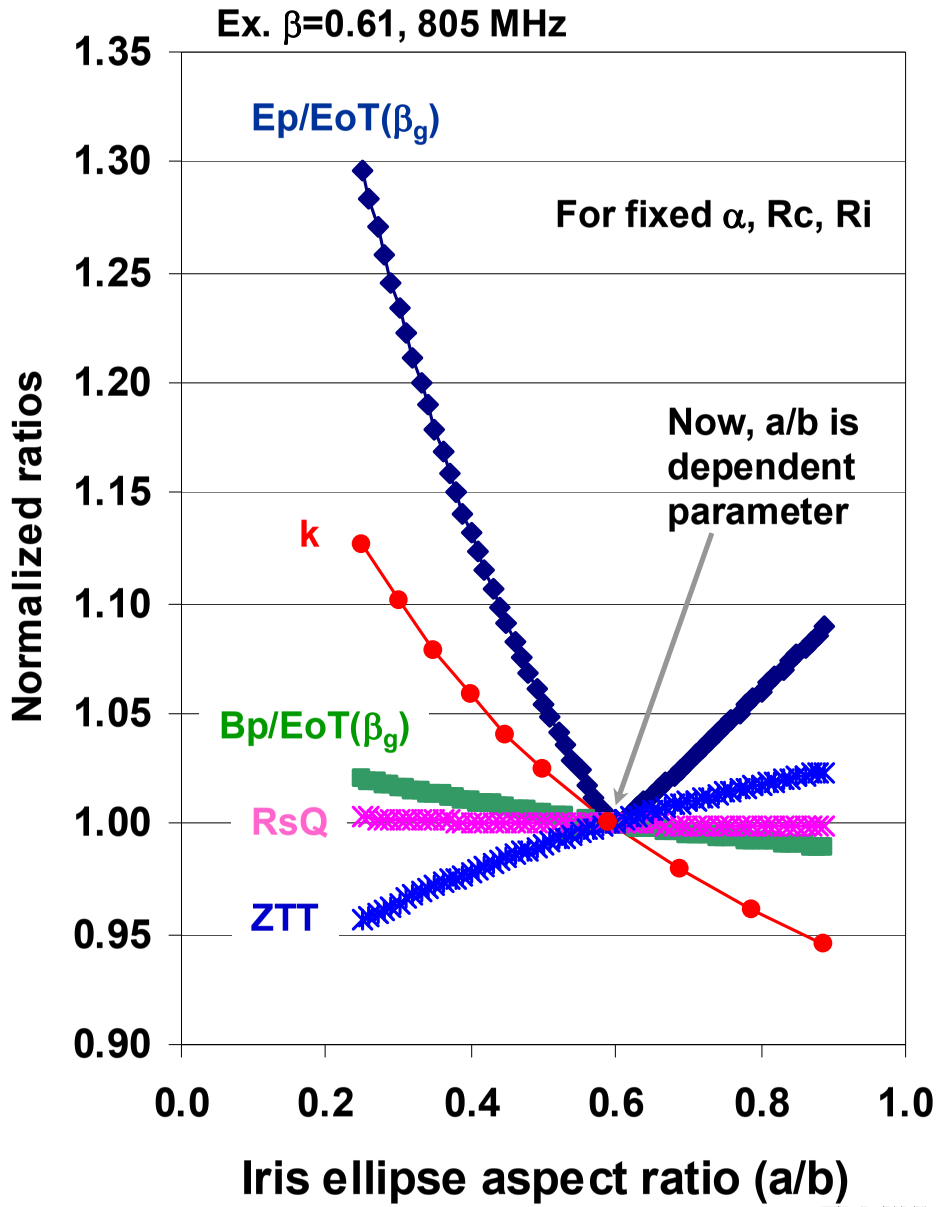
Cavity Shape Design (scan parameter space)

- **Geometry optimization;**
  Pretty well understood and straightforwa



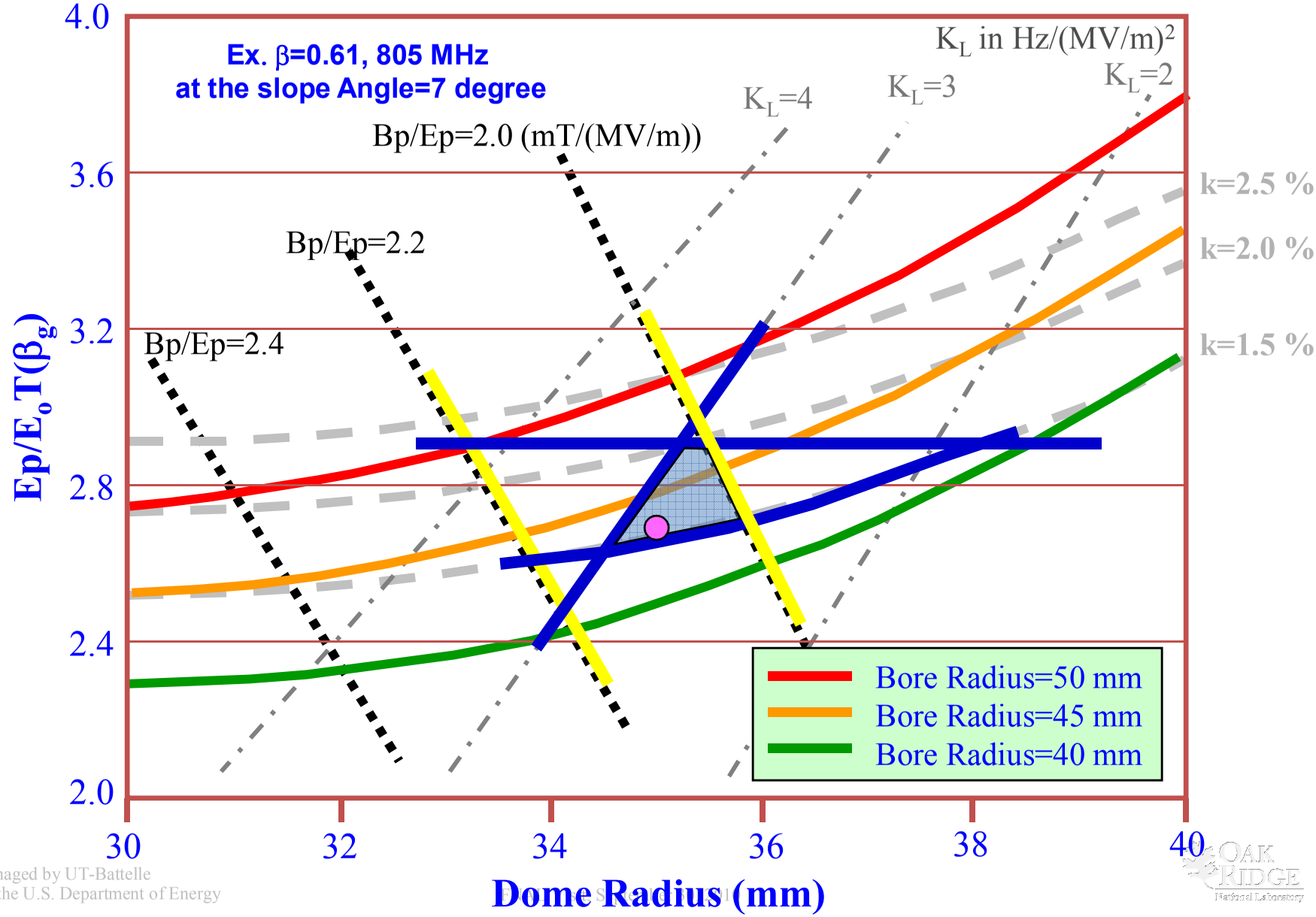
For circular dome
(Elliptical dome cases are same)

Rc, Ri, α, one of (**a/b**, a, b)
; 4 controllable parameters
Req (for tuning)

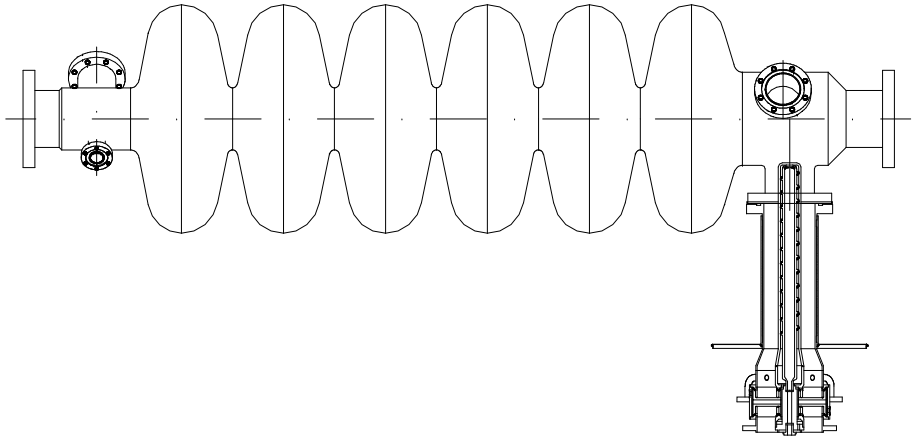


Cell Shape optimization-criteria dependent

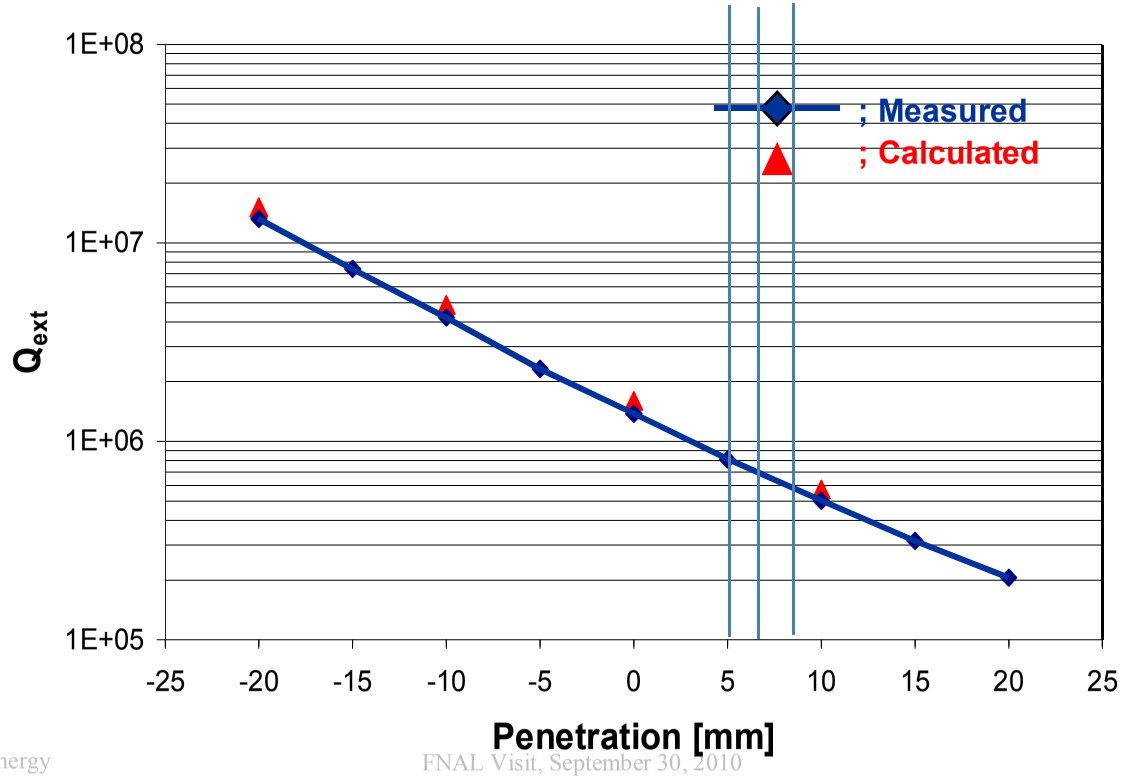
Scanning all geometry space (systematic approach)-Example



End Cell design and Qex

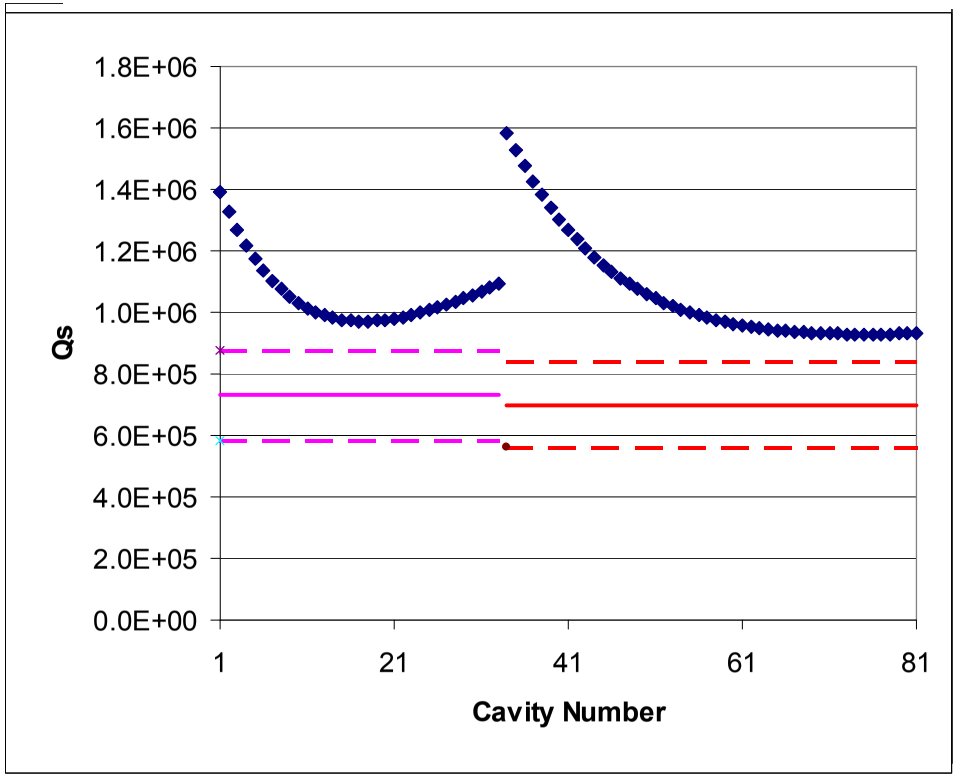


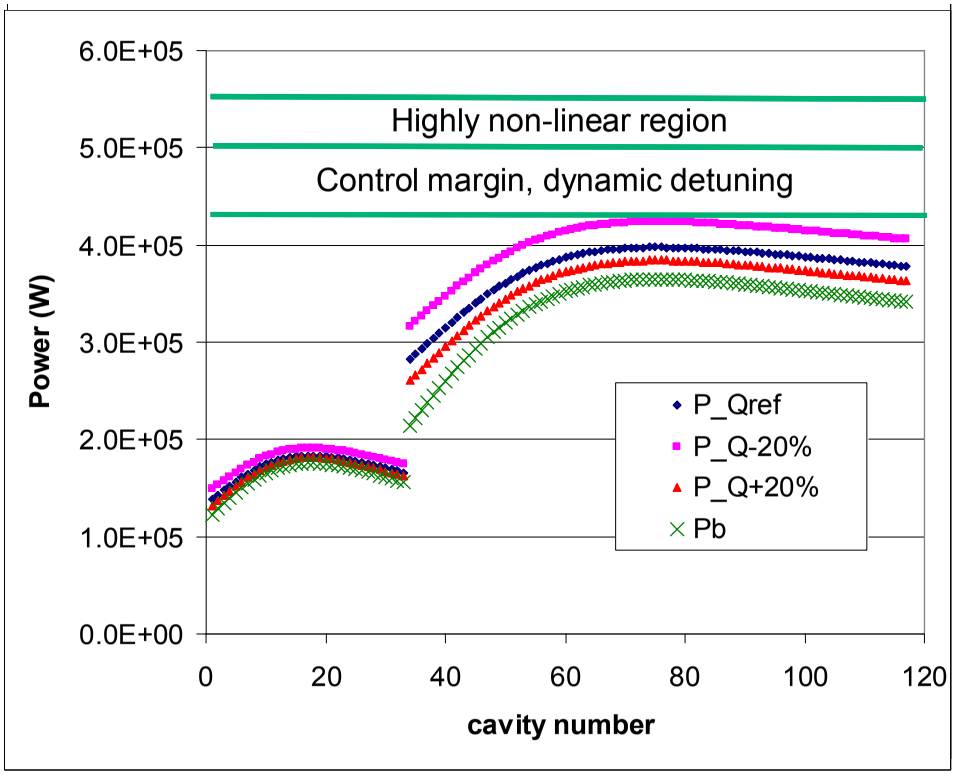
- Increase magnetic volume
- Qex estimation is quite accurate even for the high Qex system
  (Also alignment error analysis is available)



Beam, Qex, RF, margins (design)

Final SNS; 26mA, Epk=35 for high beta with 11MB CM +12 HB CM





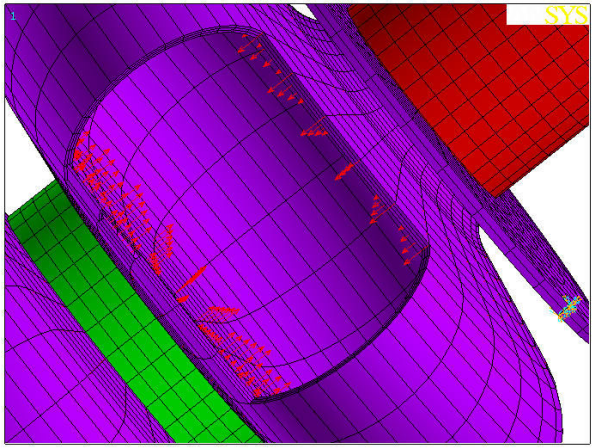
Dynamic Mechanical Behavior of Elliptical Cavities
-in design stage

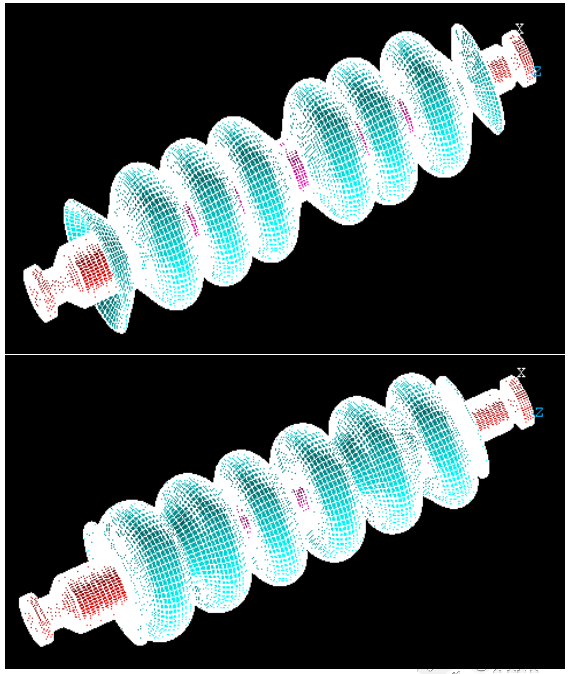
- Many groups have done
  series of analysis with FEM codes.

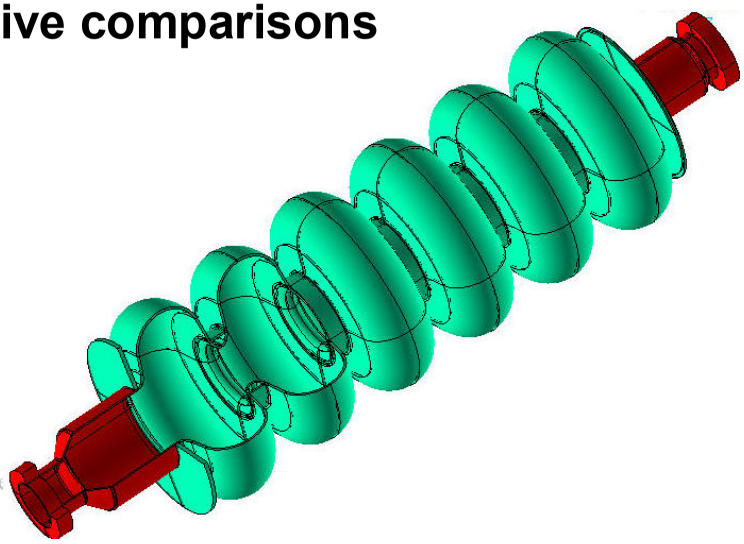
- Static properties; we can find pretty accurately

- Mode, damping, modal mass findings;
  Strongly depends on boundary condition,
  especially finding damping degree for each mode
  → very difficult

- Analysis before having experimental results
  → statistical like any other resonance issues
  → Relative comparisons

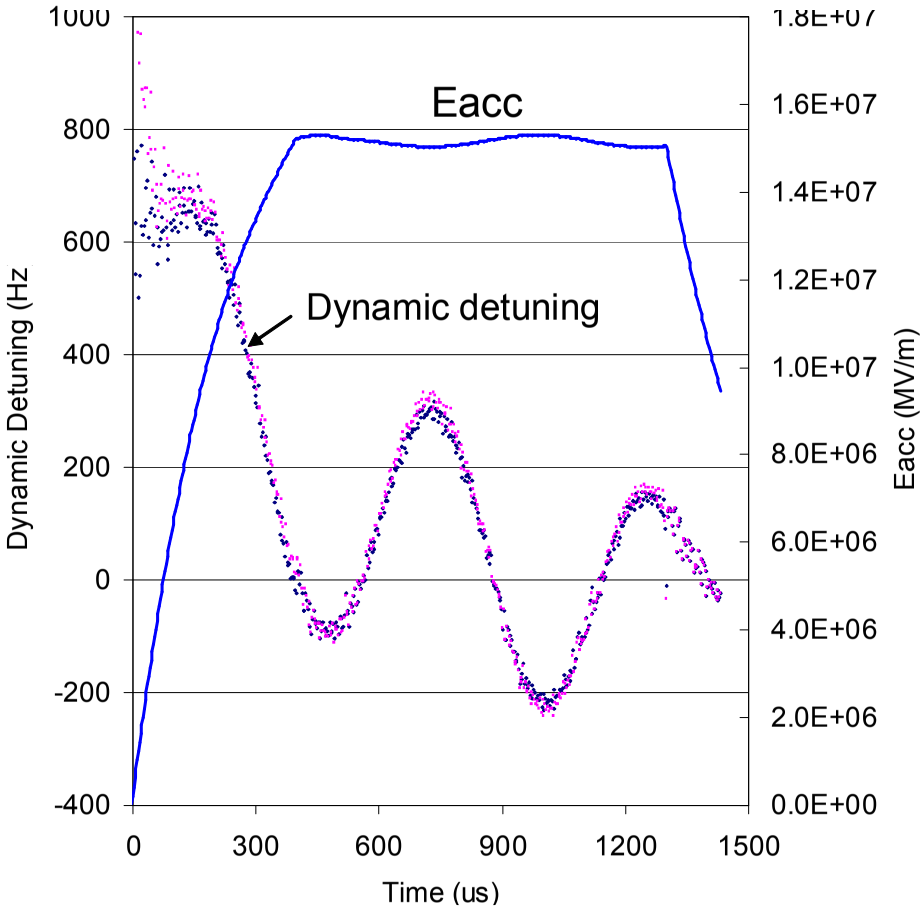




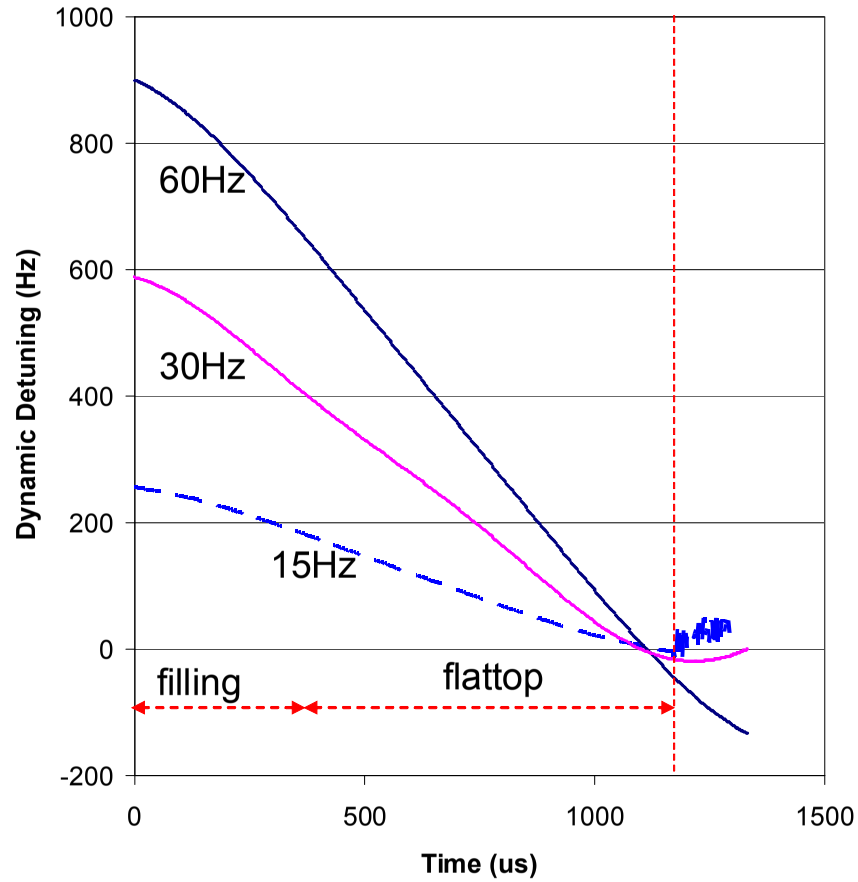


Dynamic detuning

But, a few cavities show bigger resonance phenomena as higher repetition rate

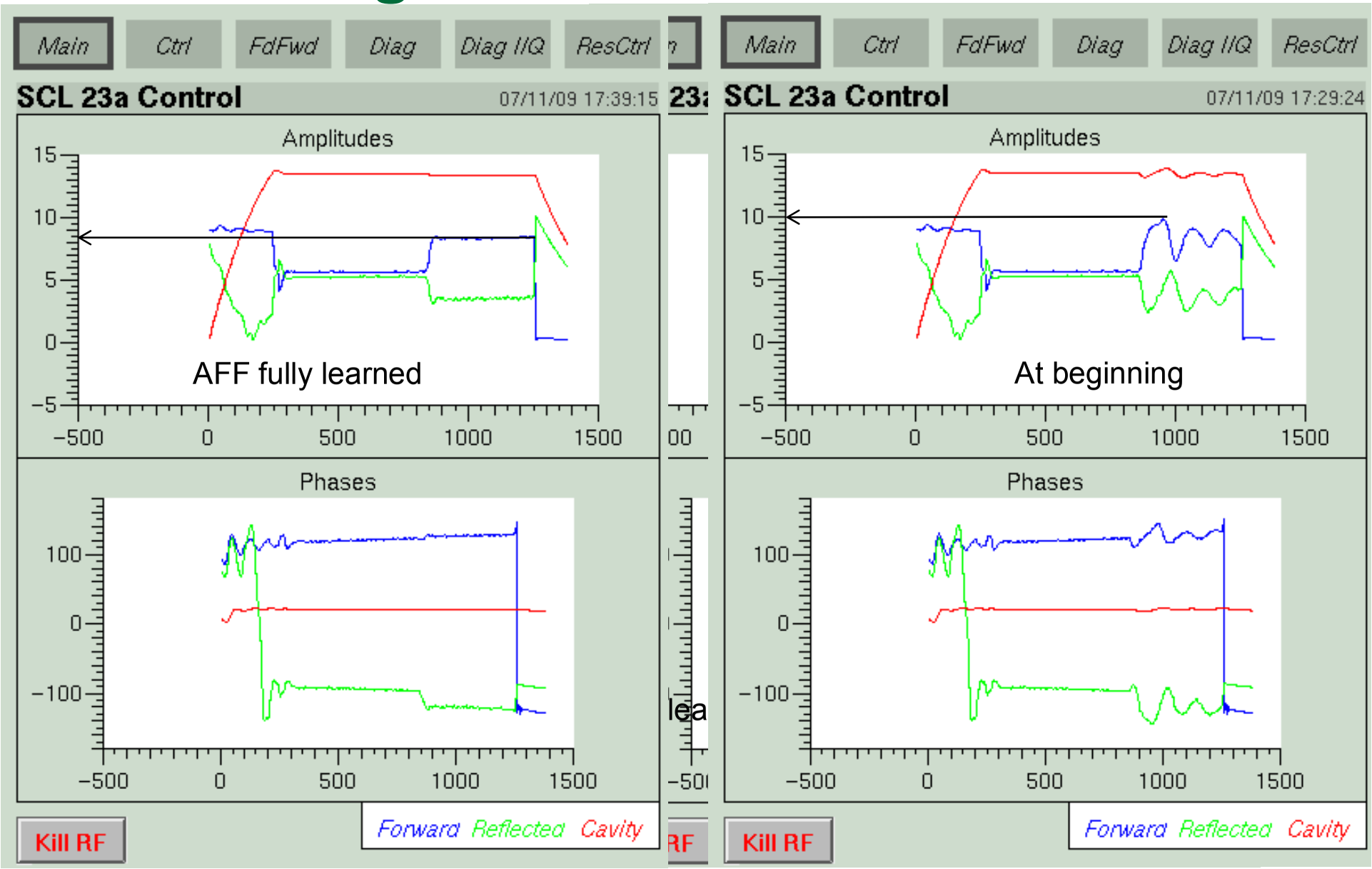


The 2 kHz components shows resonances at higher repetition rate in some of medium beta cavities



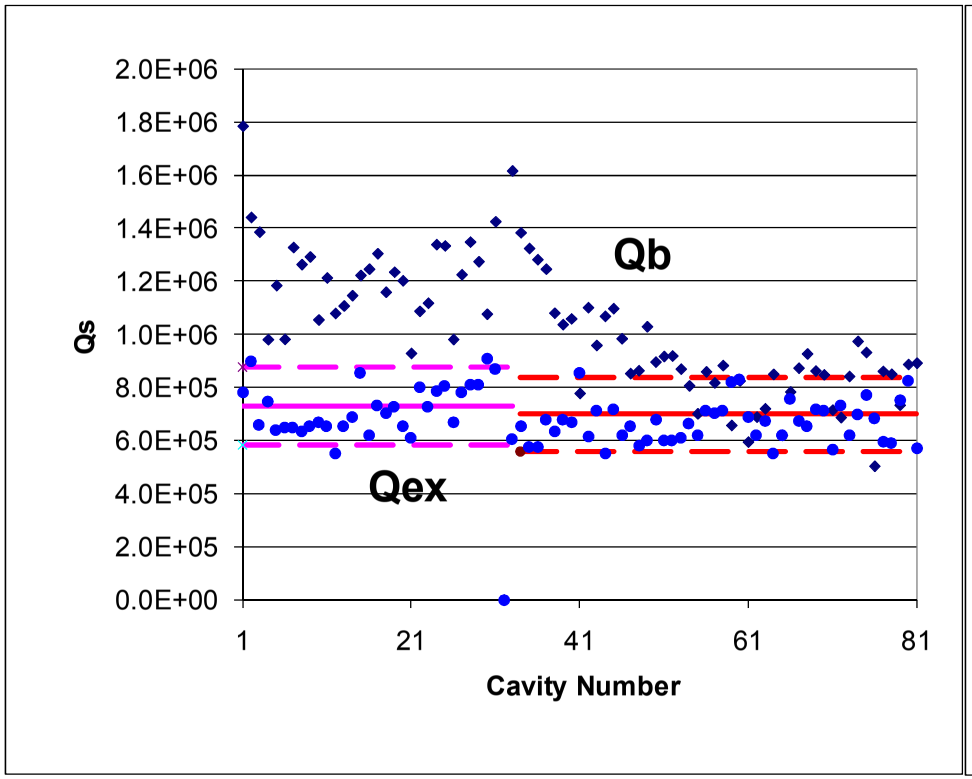
In this example the accelerating gradient is 12.7 MV/m. (high beta cavity)

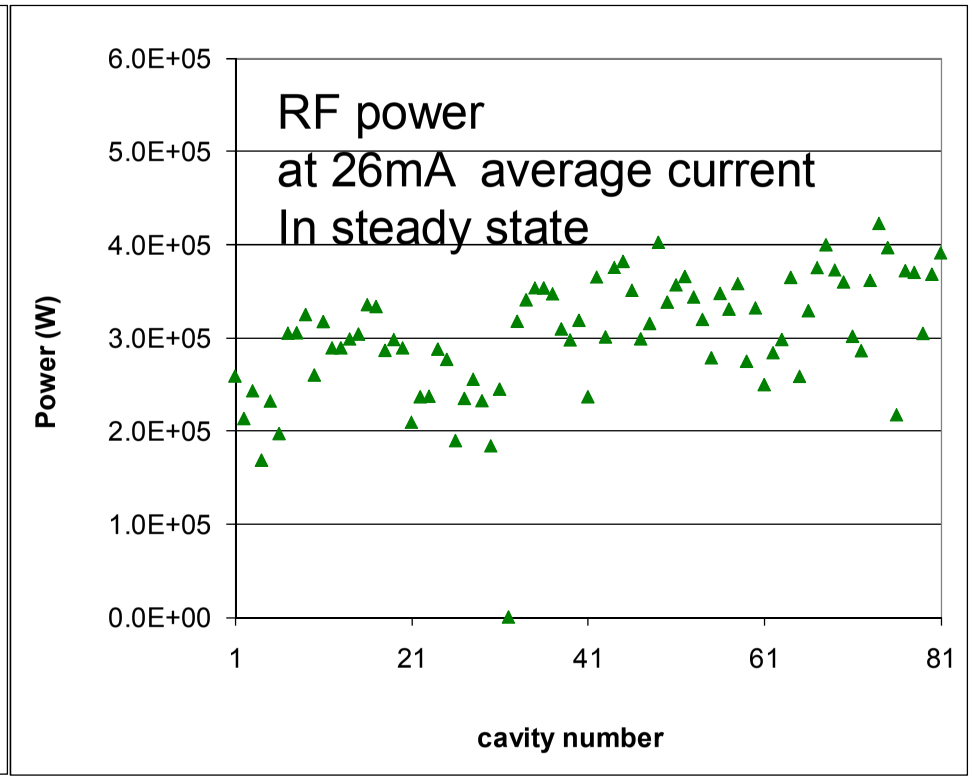
AFF learning



Some cavities need ~>25 % more RF at the beginning of AFF

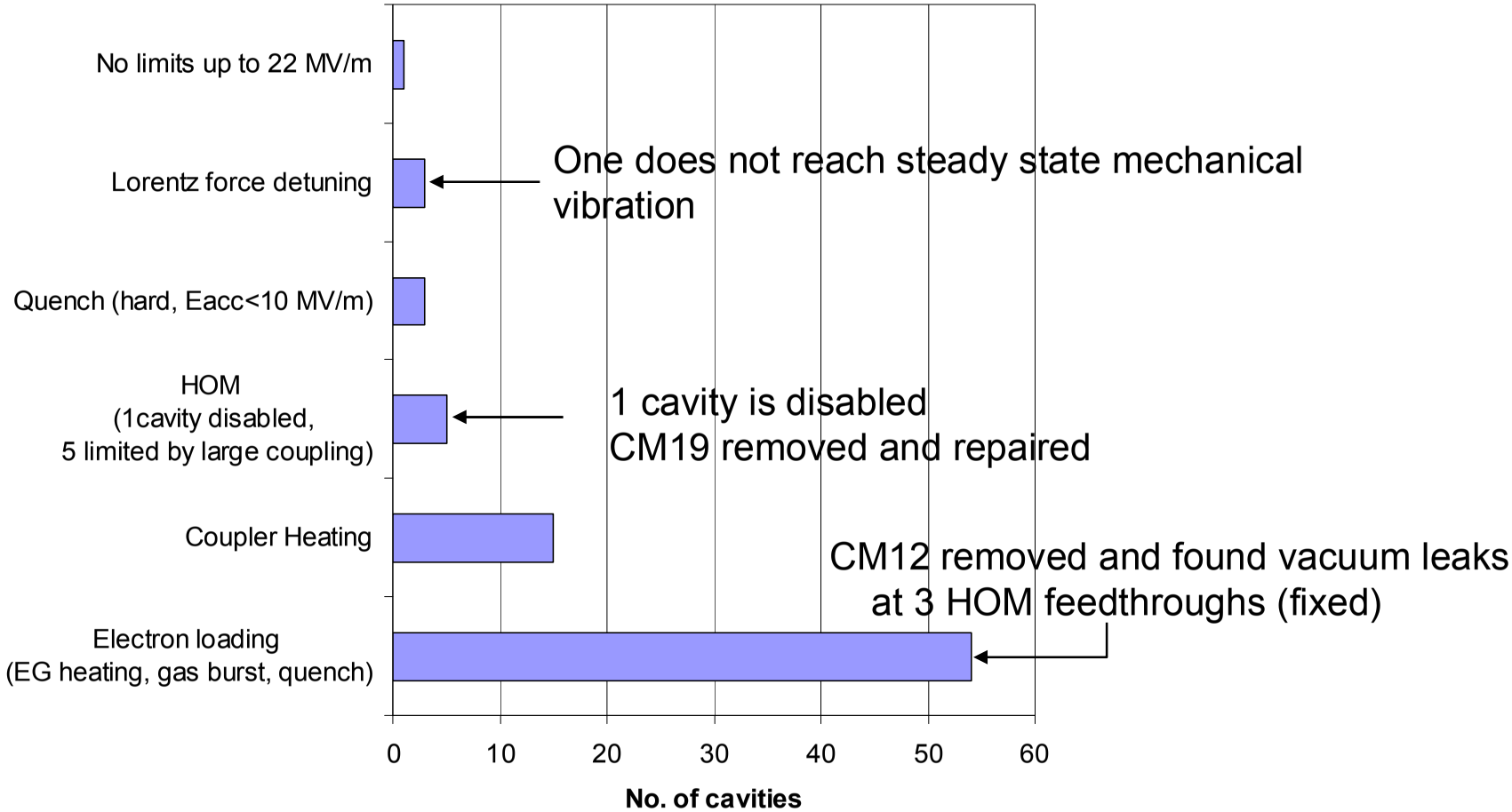
At the present operating condition





- **Overall concerns between peak field, operating gradient, inter-cell coupling, RF margin, detuning, Qex (fixed or variable), cost, and system stability**

Cavity Gradient Limiting Factors (60 Hz Operation)



-Dominated by Electron Loading (Field Emission & Multipacting)

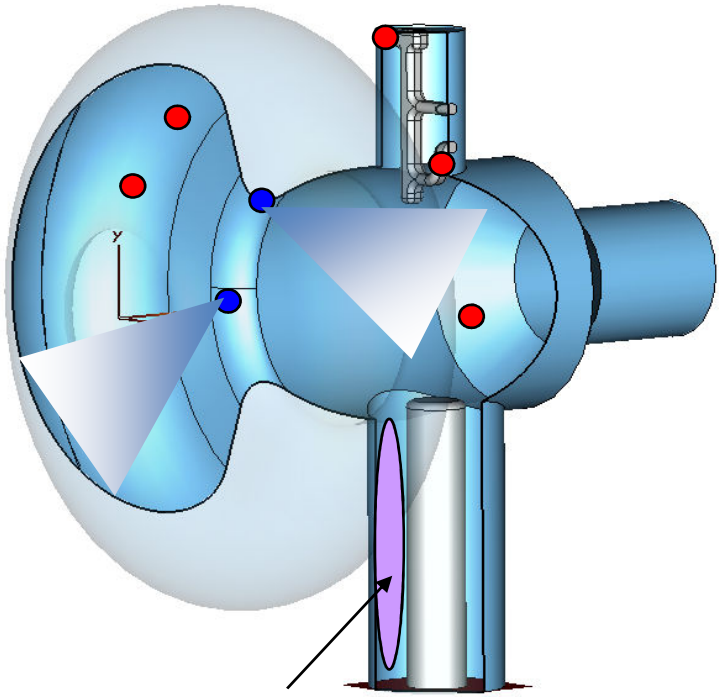
-~14 cavities are limited by coupler/end-group heating (MP), but close to the limits by radiation heating

-Operating gradients are around 85~95% of E_{lim}

Interactions between systems/cavities (collective effects)

- Cavity radiation/cold cathode gauge interaction
- Helium flow in one cavity creates "vapor lock" in another → heating of coupler's outer conductor
- Multipacting triggers radiations
- Electron activity in one cavity triggers cold cathode gauge in another
- Field emission in one cavity heat up beam pipe in another(s) depending on relative phase and amplitude
  - creates difficulty in finding proper op. gradient for all ranges of phases
  - Main limiting factor in SNS
  - Higher duty → more problematic

Electron Loading and Heating (Due to Field Emission and Multipacting)



Source of electrons

- Multipacting; secondary emission
  - resonant condition (geometry, RF field)
  - At sweeping region; many combinations are possible for MP
    - Temporally; filling, decay time
    - Spatially; tapered region
    - Non-resonant electrons → accelerated → radiation/heating
  - Mild contamination → easily processible
  - But poor surface condition → processing is very difficult in an operating cryomodule
- Field Emission due to high surface electric field

Result

End group heating/beam pipe heating + quenching/gas burst

End Group Heating & Partial quench

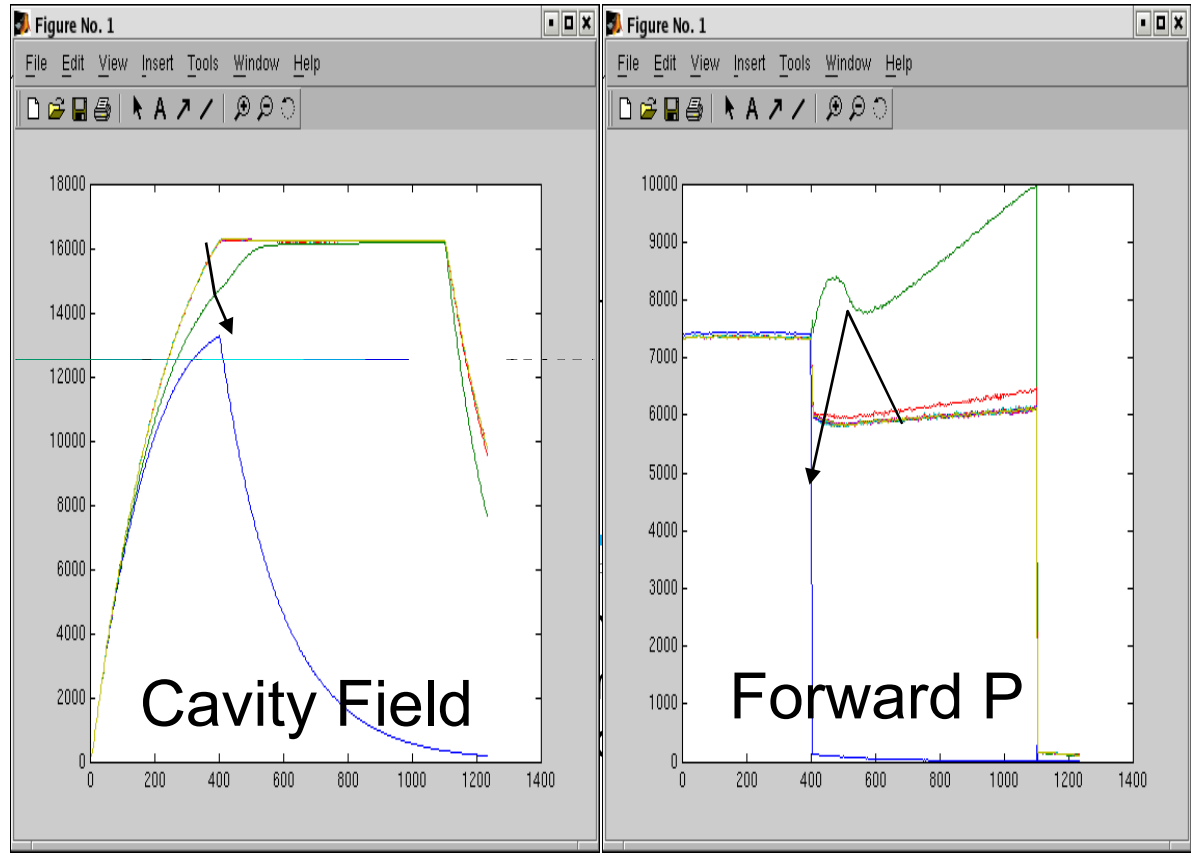
Analysis for end group stability ; >4-5 W (overall) or ~1W local can induce quench

Electron activity (Field emission, non-procesible MP)-induced end group quench:

Large temperature rise (24 K) at beam pipe.

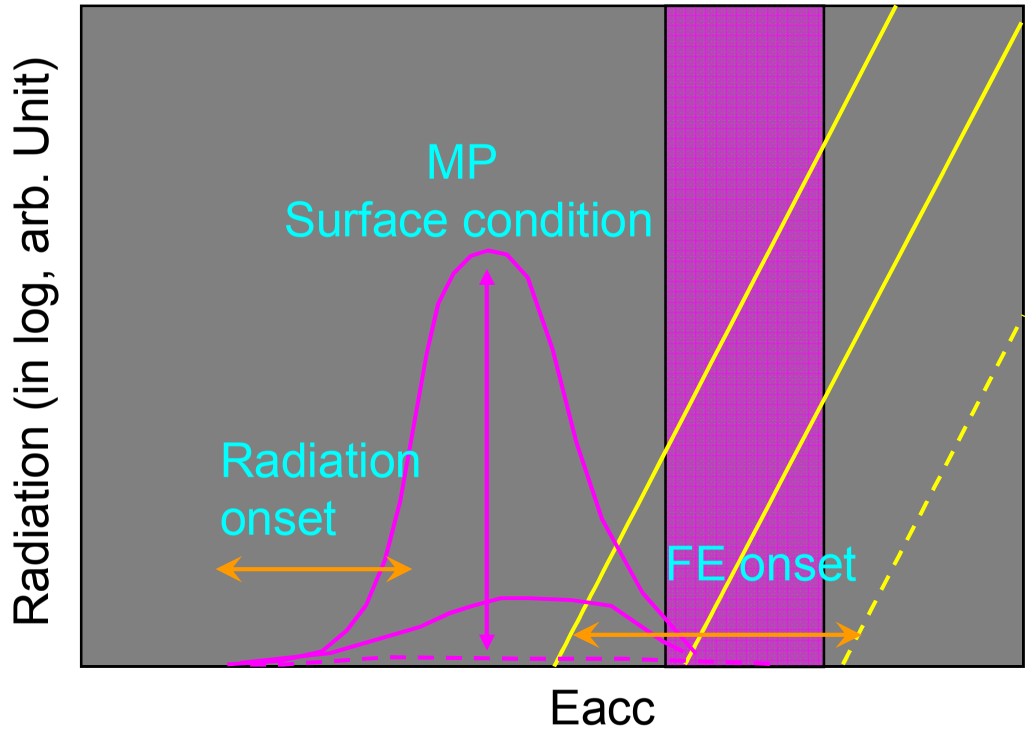
Quench leads to semi-stable intermediate state condition: Q_o~ 2-3 x 10^5

At partial Quench (Measured data)

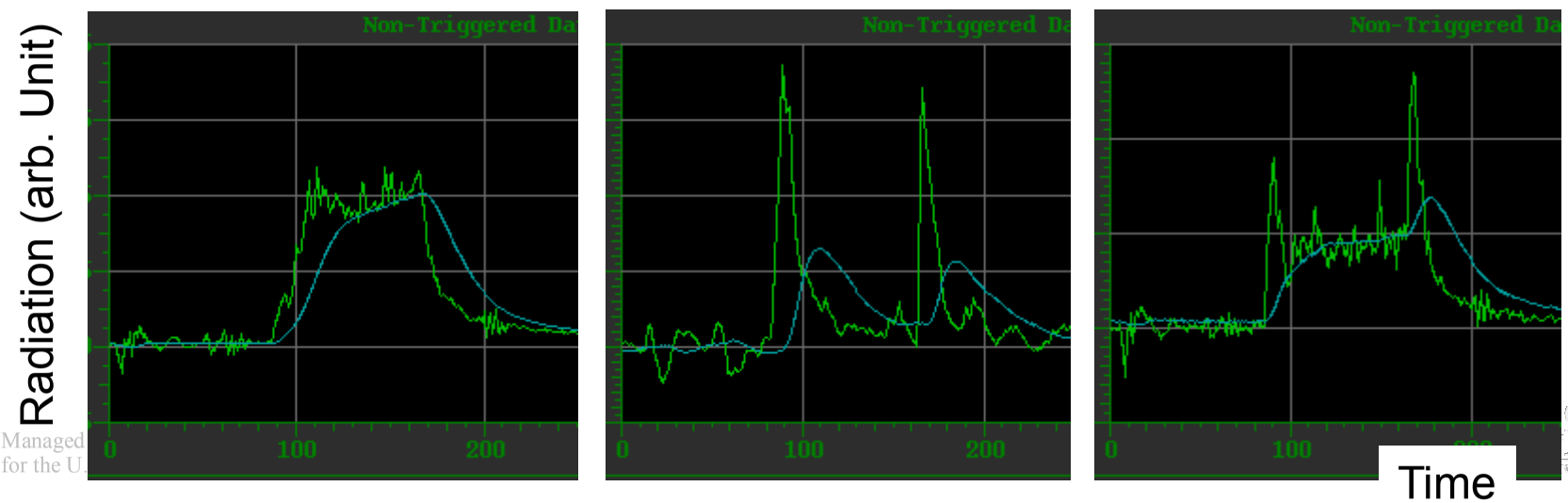


SNS Cavity Operating Regime

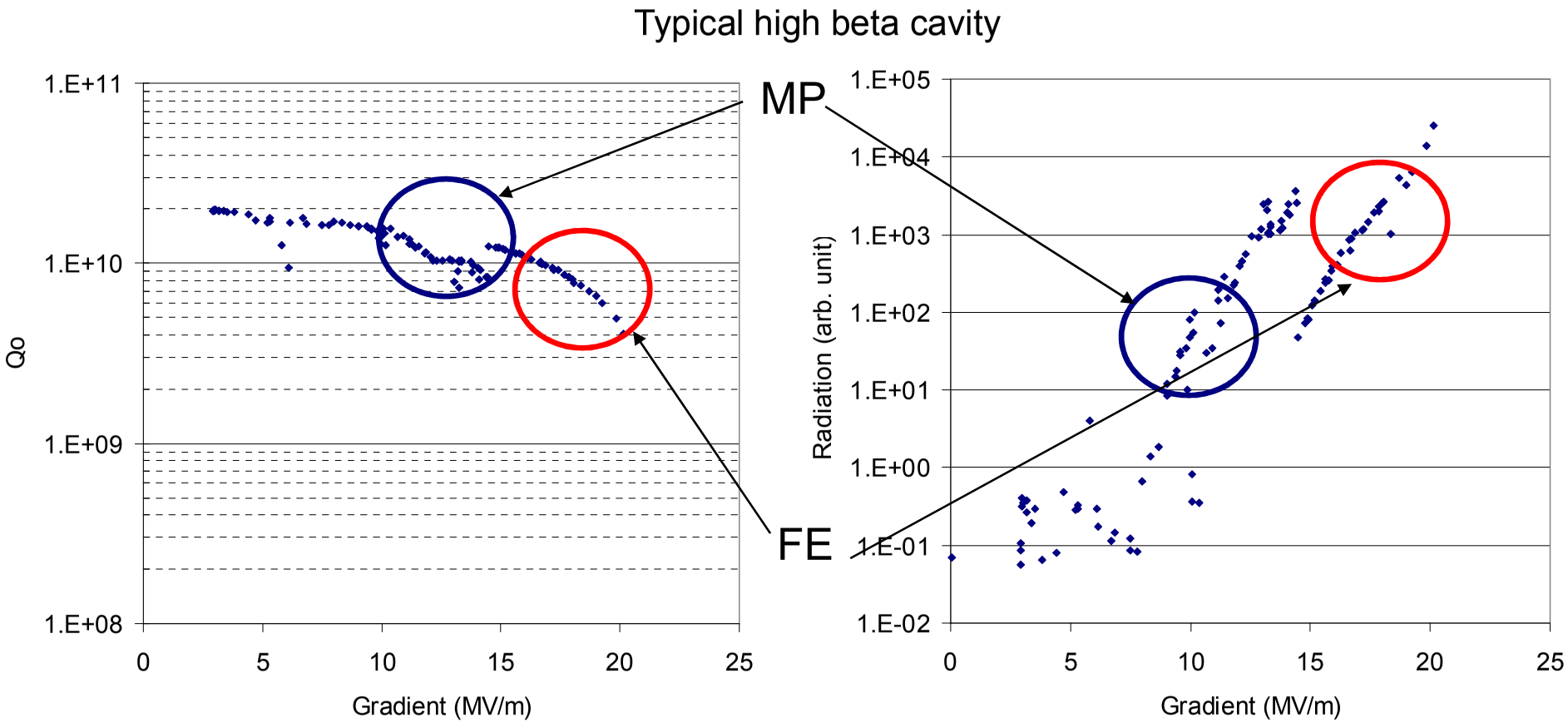
We don't have MP induced radiation at op. gradient, if any, very small.
Basically running in the field emission regime.



Measurements of Radiation during RF Pulse



Back to Cavity performances in VTA test



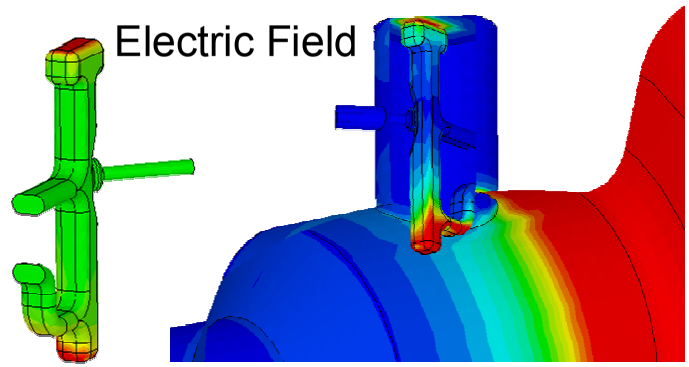
More precisely this MP indication is MP induced radiation.
We observed MP starting from 3 MV/m in both medium and high beta cavities.
In general MP can be processed and does not hurt operation that much.
A few cavities are showing a symptom of non-processible multipacting

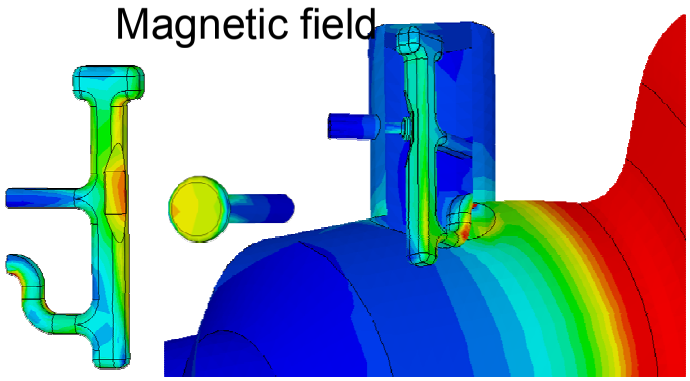
HOM; in design stage

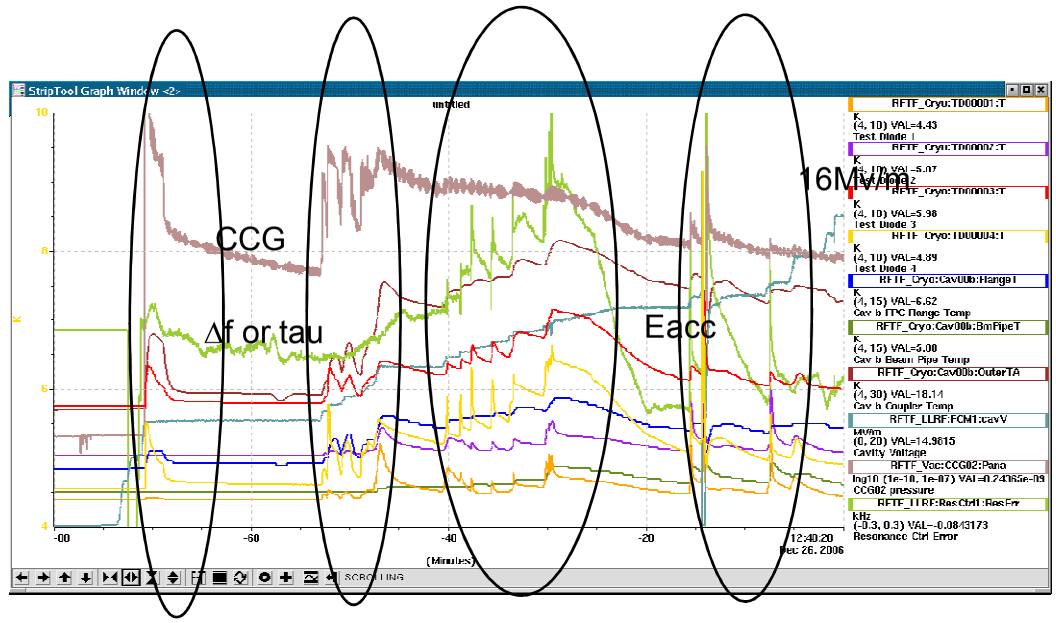
- No Beam dynamics issue
- Centroid error, f spread & location of cavities were in question
- When $Q>10^5$, 10^6, there's a concern.
  - HOM power ~ fundamental power dissipation
  - but the probability is very low even under the conservative assumptions
- Extra insurance
  - SNS is the first pulsed proton SC linac
  - Any issues were treated in a very conservative way
    - Ex. Piezo tuner; we've never used them

Problems while running RF only

Any electron activity (multipacting, burst of field emitter, etc)
→Destroy standing wave pattern (or notching characteristics)
→Large fundamental power coupling
→Feedthrough/transmission line damage (most of attenuators were blown up)
→Irreversible damages could happen statistically

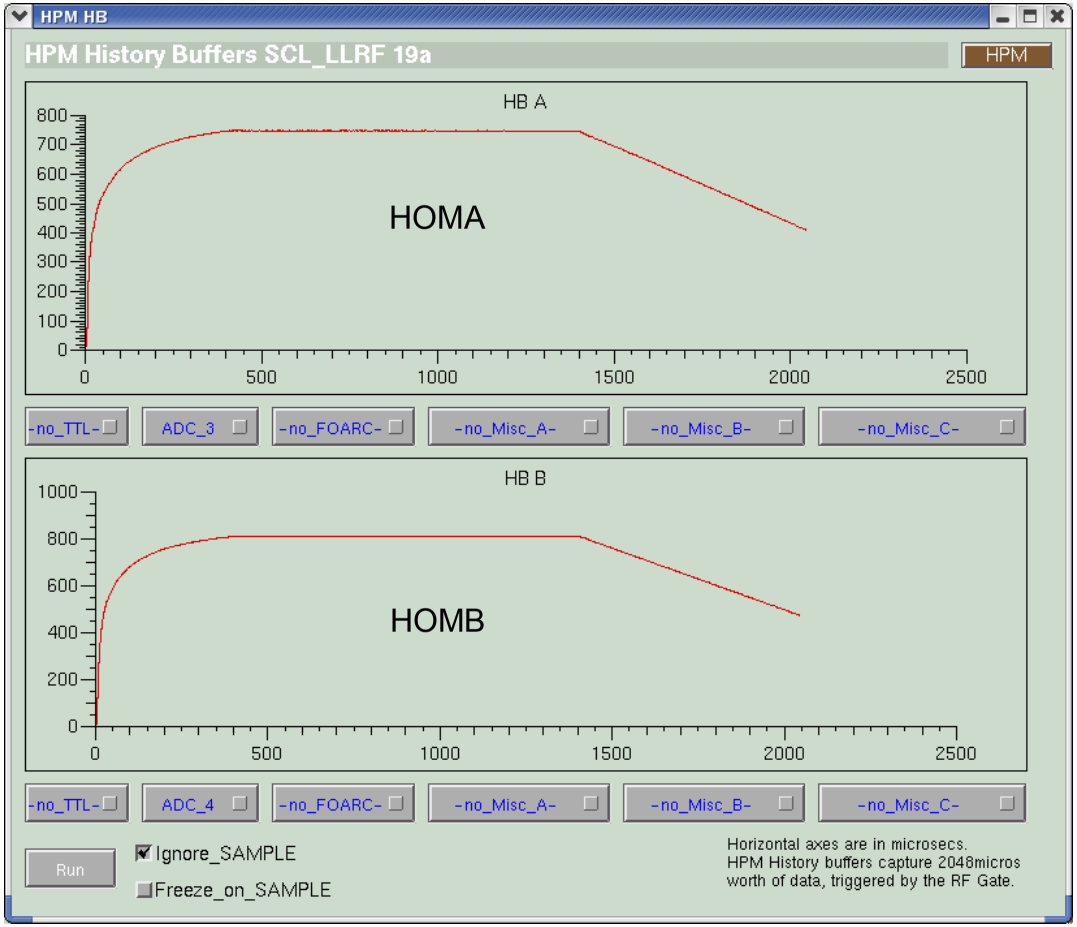






Conditioning after removing feedthrough;
Large electron activities around HOM couplers were observed ranging from ~3 MV/m up to 16 MV/m.

Fundamental mode thru HOM coupler

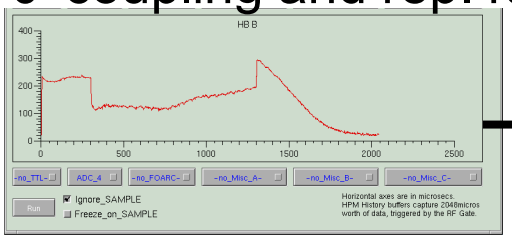


Normal waveform of fundamental mode from HOM ports (y-axis; log scale)

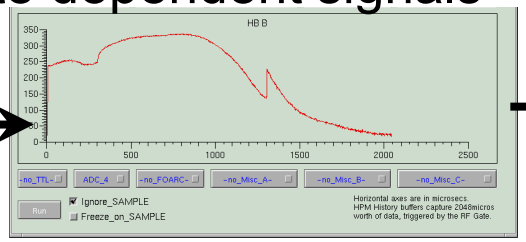
Fundamental mode coupling
High 10^{10}~ 10^{12}
; much less than a few W during pulse

Abnormal HOM coupler signals (RF only, no beam)

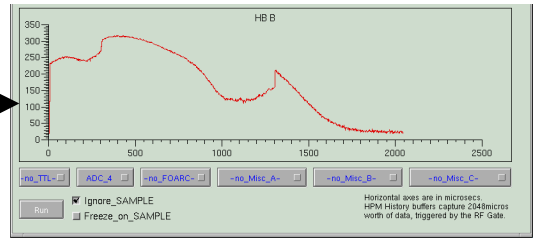
~'0' coupling and rep. rate dependent signals



1~5 Hz

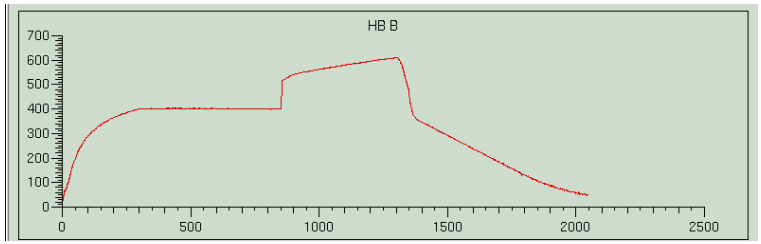


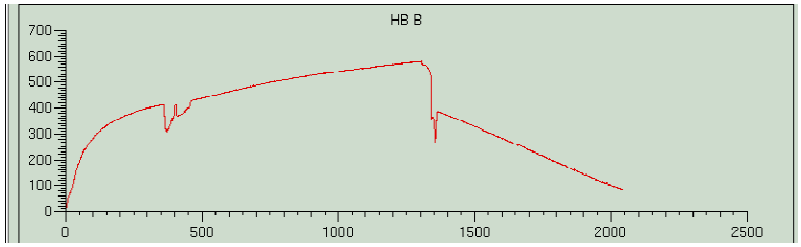
10 Hz

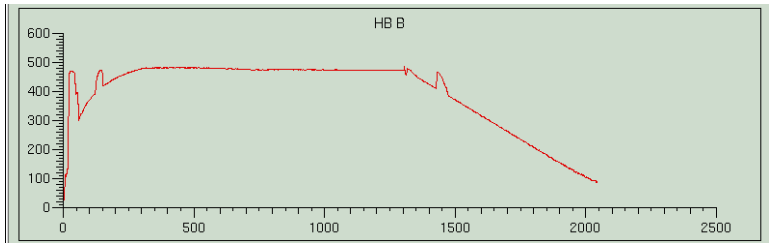


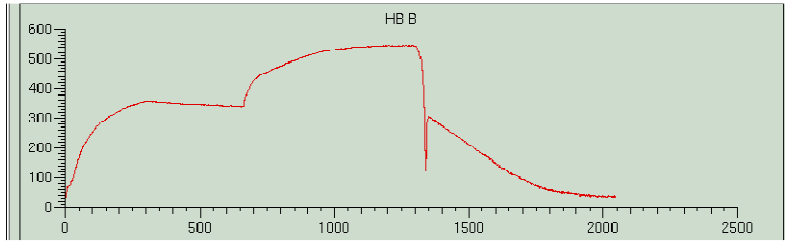
30 Hz

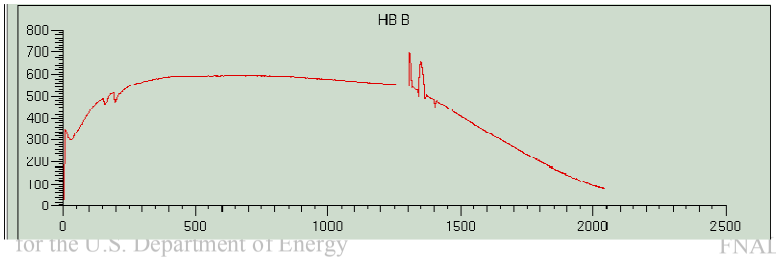
Electron activities (MP & discharge; observations under close attention)

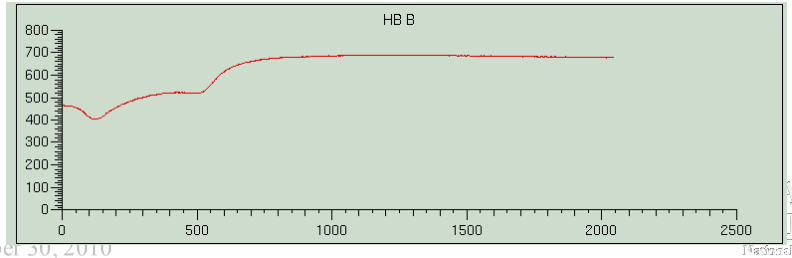




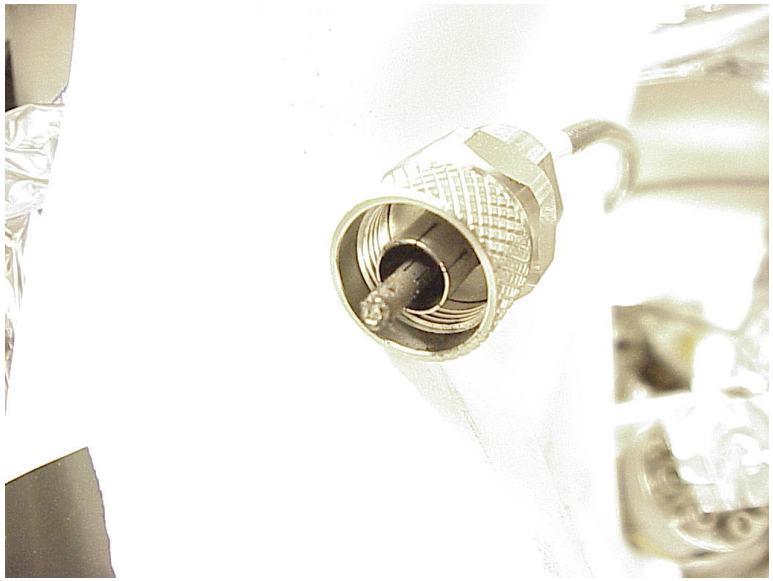






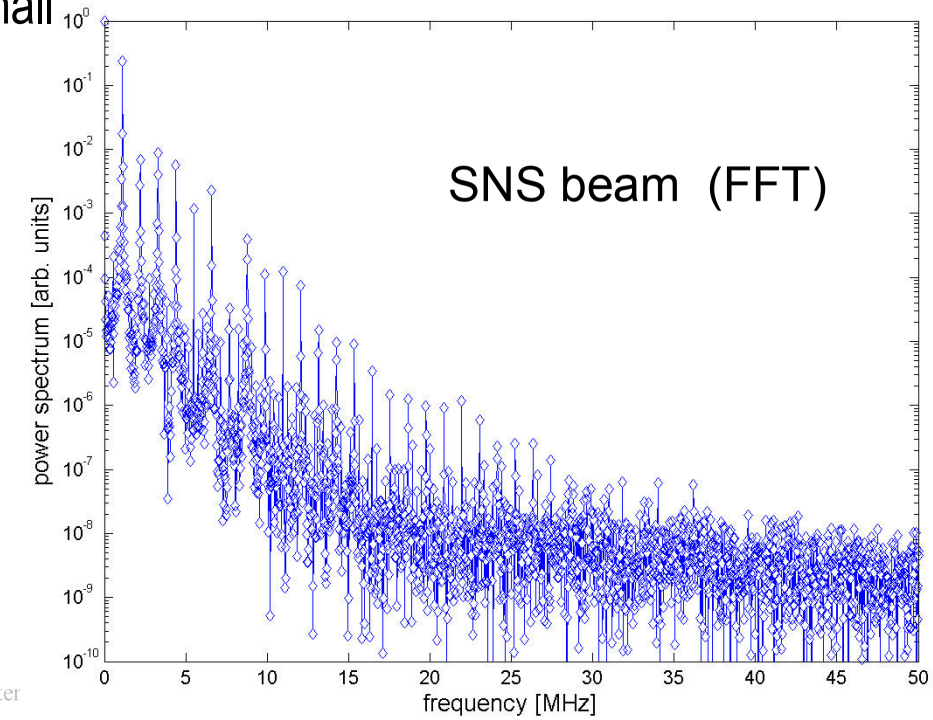


Leak, severe MP, contamination, large coupling, …



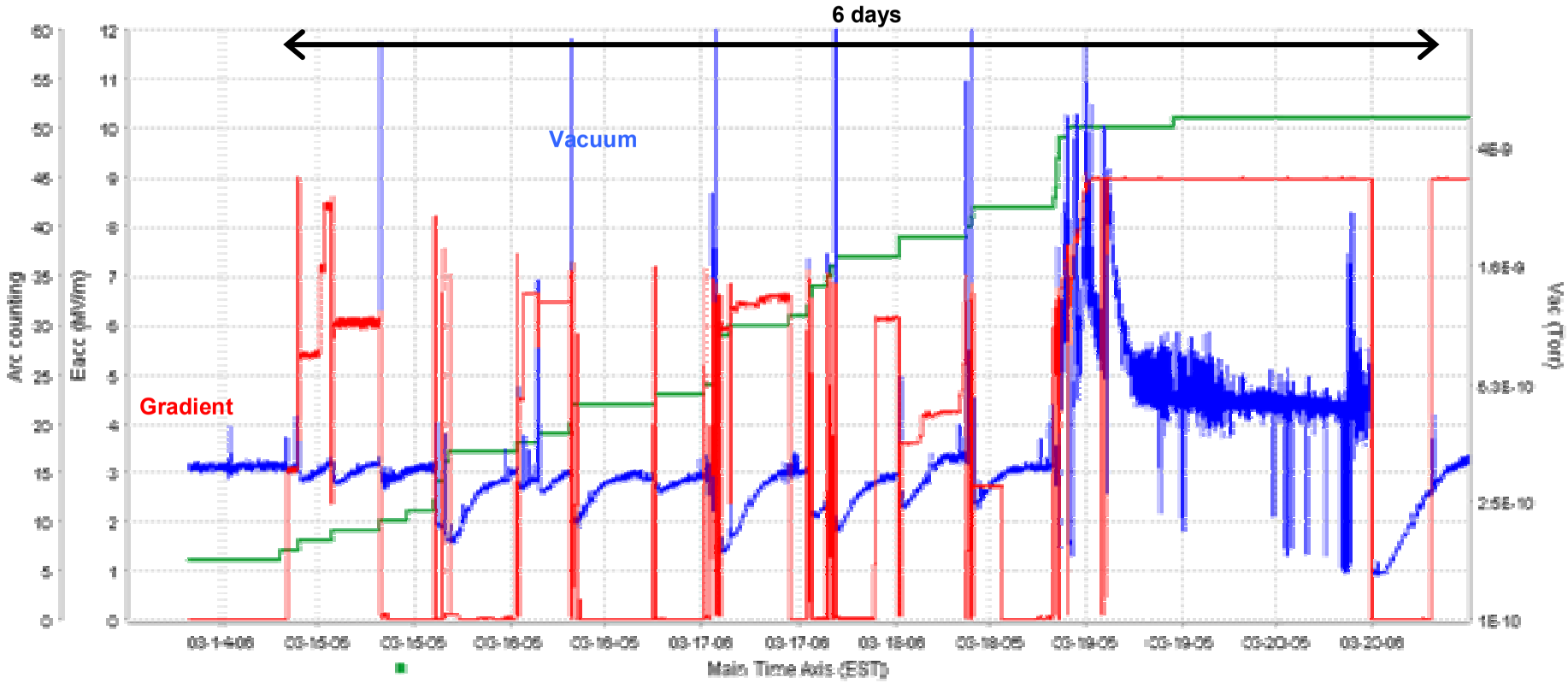
HOM in SNS

- Availability & Reliability; Most Important Issue
  - HOM couplers in SNS have been showing deterioration/failure as reported
  - Reliability & availability of SNS SRF cavities will be much higher w/o HOM coupler
- More realistic analysis with actual frequency distributions measured.
  - Probabilities for hitting dangerous beam spectral lines are much less than expected.
  - Beam amplitude fluctuation is also very small
- Future Plan
  - HOM feedthroughs will be taken out as needed
  - PUP cryomodule
    - Will not have HOM couplers



Turn-on difficulties

Vacuum Interlock



early 2006;
After a long shut-down, some cavities showed turn-on difficulties.
Gradients were lowered down or turned-off in order to reduce the down time.

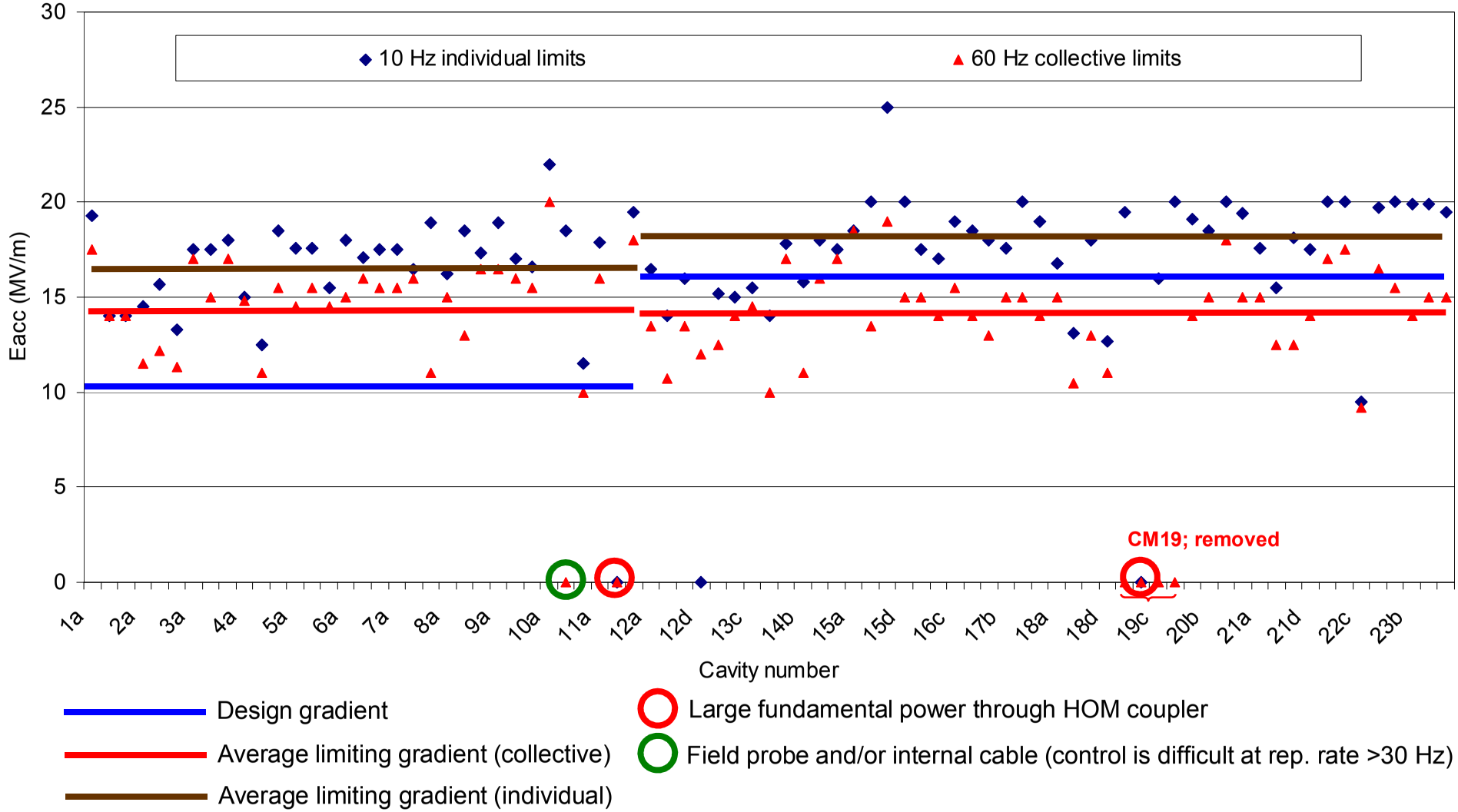
Severe contaminations in coupler surfaces or cavity surfaces ?????

Erratic behavior due to the erosions of electrode; no responses or too much

Turn-on and High power commissioning

- **First turn on must be closely watched and controlled (possible irreversible damage)**
  - Initial (the first) powering-up, pushing limits, increasing rep. rate (extreme care, close attention)
    - Aggressive MP, burst of FE → possibly damage weak components
    - Similar situation after thermal cycle (and after long shut down too) → behavior of the same cavity can be considerably different from run to run
- **Subsequent turn-ons (after long shut-down) also need close attention: behavior of the same cavity can be considerably different from run to run → gas re-distribution**
- **Cryomodules/strings must be removed and rebuilt if vented/damaged**

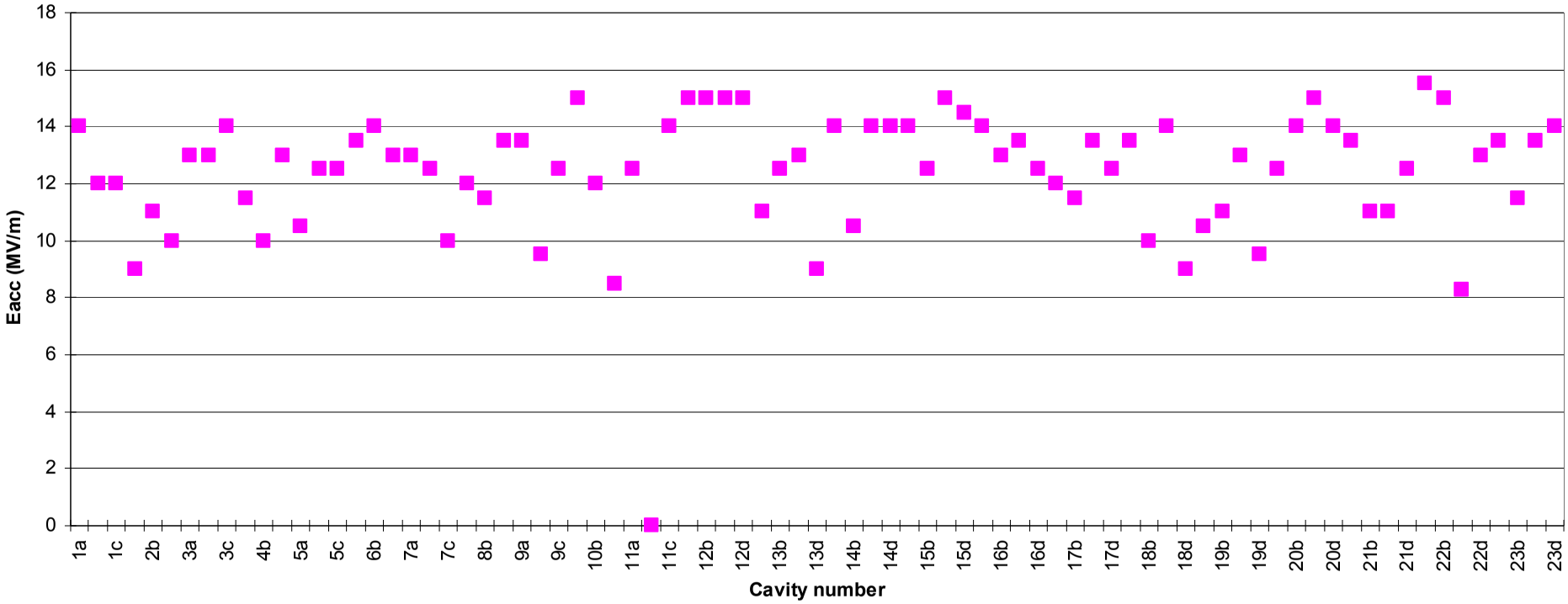
Individual limits & collective limits



- Operating gradient setting in SNS are based on the limiting gradients achieved
- Operational stability is the most important issue

Current Operating Condition

- 1105 us RF (250 us filling + 855 us flattop) at 60 Hz
  - Flattop duty; 5.1 %
- Eacc setpoints; about 85 % of collective limits in average
  - Average gradient; ~12.5 MV/m
  - 925 MeV + 10 MeV (energy reserve)
- Stable operation; < 1 trip/day (<5 min./day) mainly by errant beam, control noise



Stable Operation of SCL

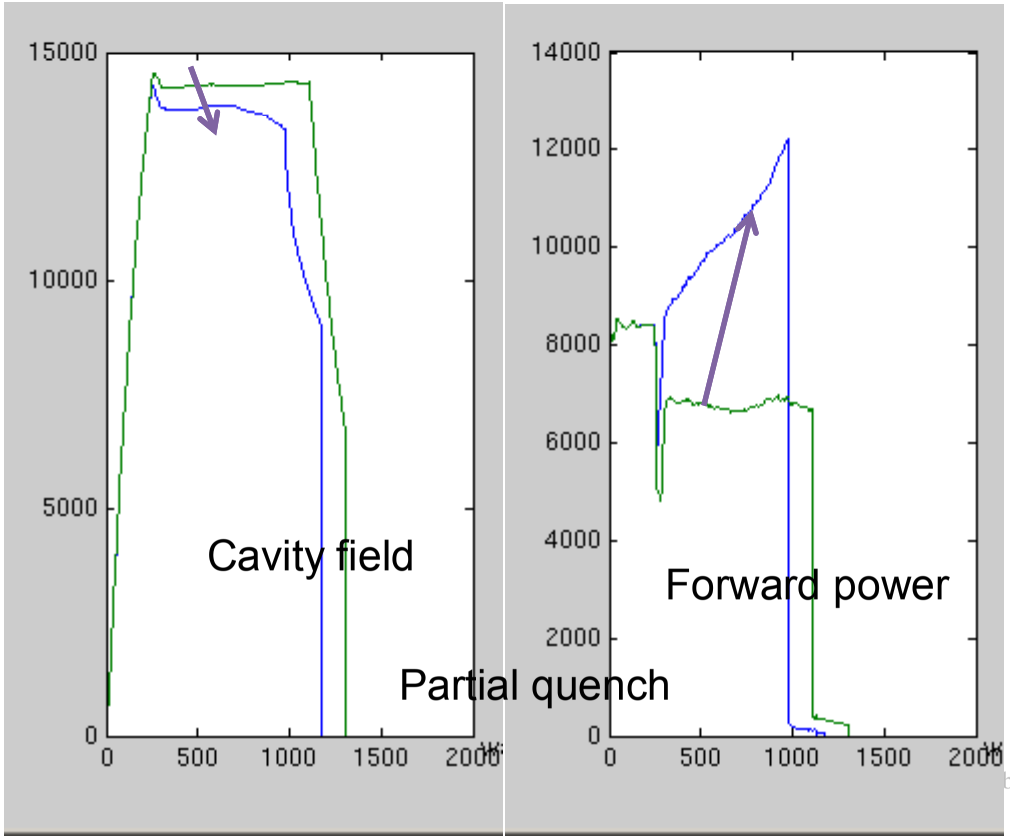
- Better understanding of:
  - underlying physical phenomena (outgassing, arcs, discharges, radiation, field emission, beam strike, dark current etc.)
  - components response (arc detectors, HOM couplers, Cold Cathode Gauges, coupler cooling, end group heating)
  - controls (LLRF logic, programming, choice of limits and stability parameters)
- Improve performances and ultimate beam power by:
  - Optimizing gradients, modulator voltages/configuration, matching of klystrons to cavities, circulator settings, available forward power for beam loading, cryomodule repair, etc.

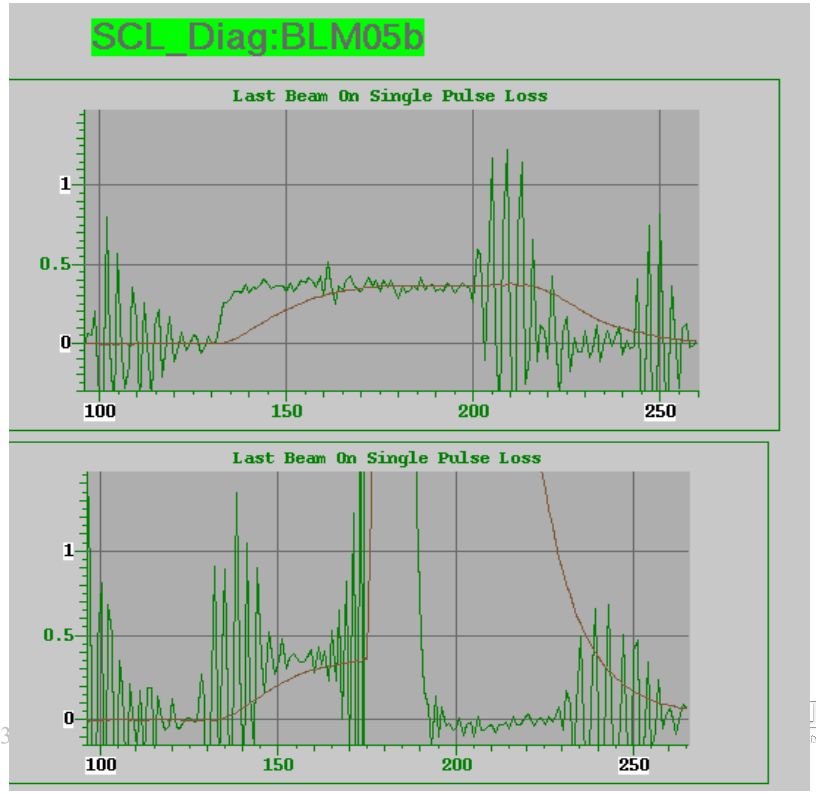
Status of components and parts

- FPC; very stable/robust
- HOM coupler; vulnerable component especially during conditioning
- Cavity
  - MP; about 25 cavities show MP, not a showstopper
  - Field emission; very stable; not changed, main limiting factor
  - Errant beam → could degrade cavity performance (had 2 events)
- Tuner; vulnerable component (both piezo and mech.)

Performance degradation by errant beam

- First time in 5-years operation + commissioning
- Limiting gradient of two cavities; 14.5 MV/m due to FE → Partial quench at 9 MV/m
- Beam between MPS trigger and beam truncation → off-energy beam → much bigger beam loss at further down-stream → gas burst → redistribution of gas/particulate → changes in performance/condition
- Random, statistical events; made HOM coupler around FPC worse

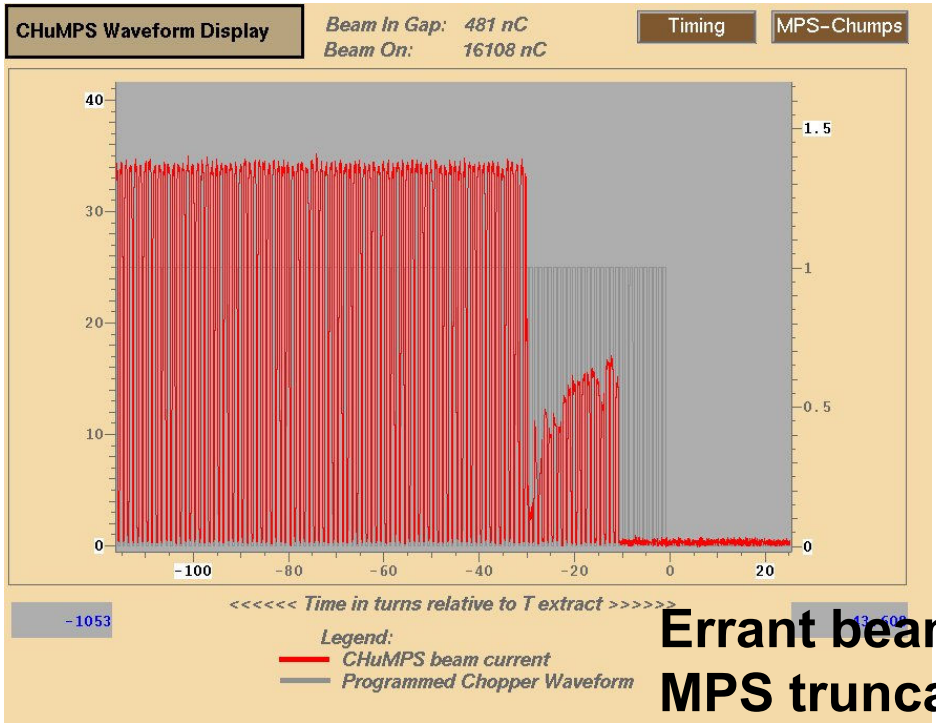


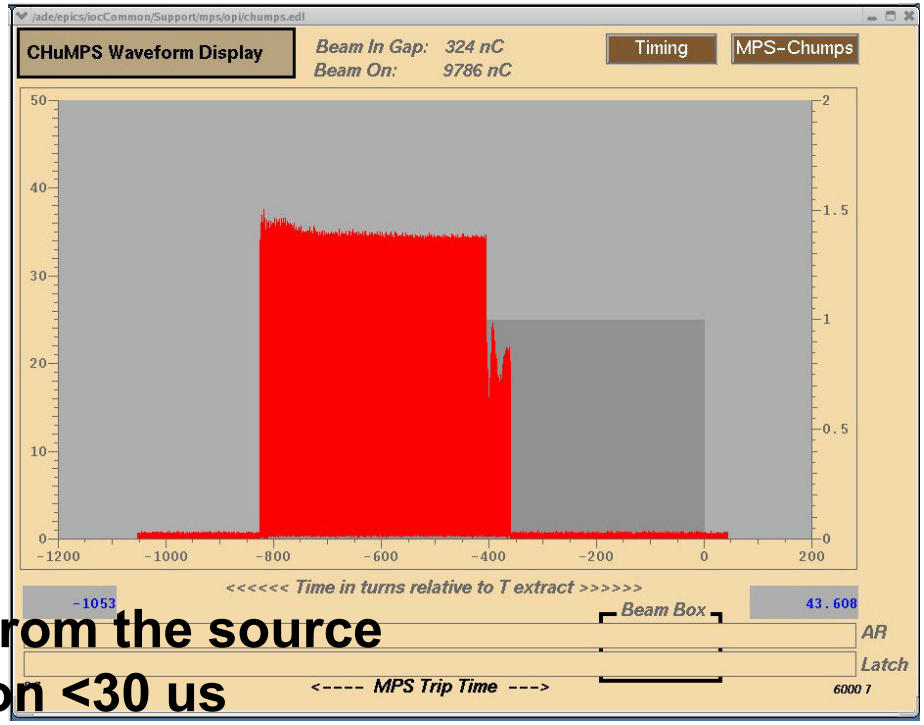


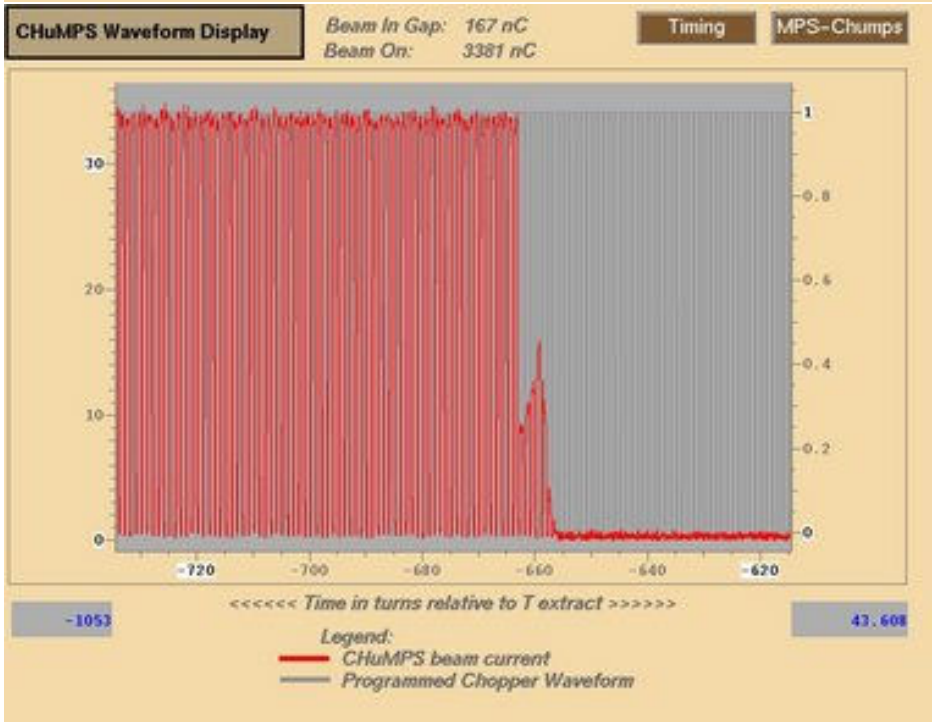
At errant beam condition; MPS

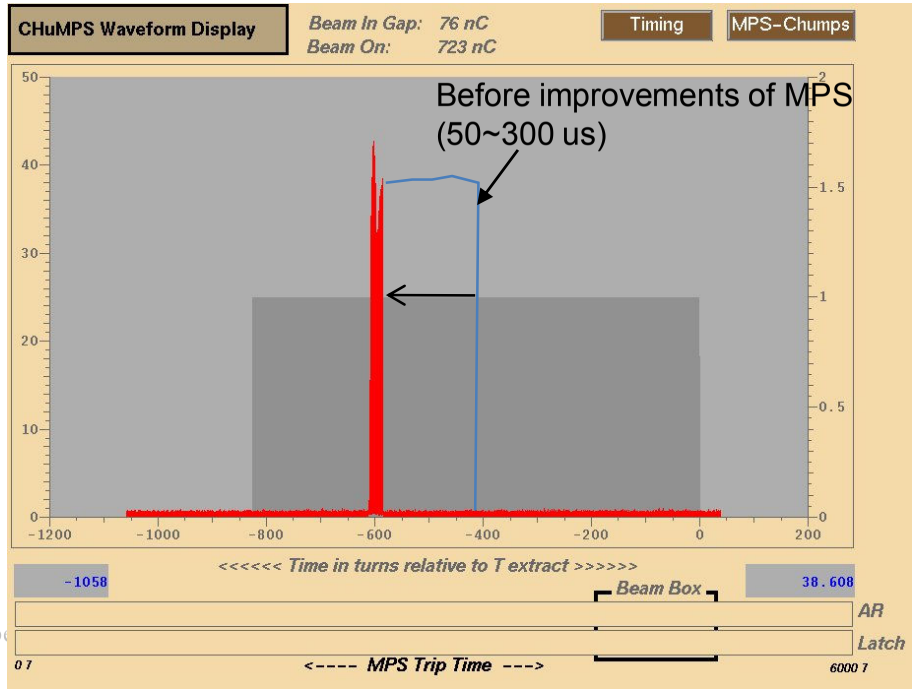
- MPS
  - If RF field regulation becomes bad, RF/beam truncation
  - If BLM signal touches the threshold, beam truncation
  - MPS; supposed to be less than 20-30 us
- Had performance degradations with 2 cavities → claimed that errant beam is too frequent and MPS delay looks long
- Measured all MPS delay in the linac; 50-300 us
  - Caps, some open collector circuit

Errant beam from the source
MPS truncation <30 us



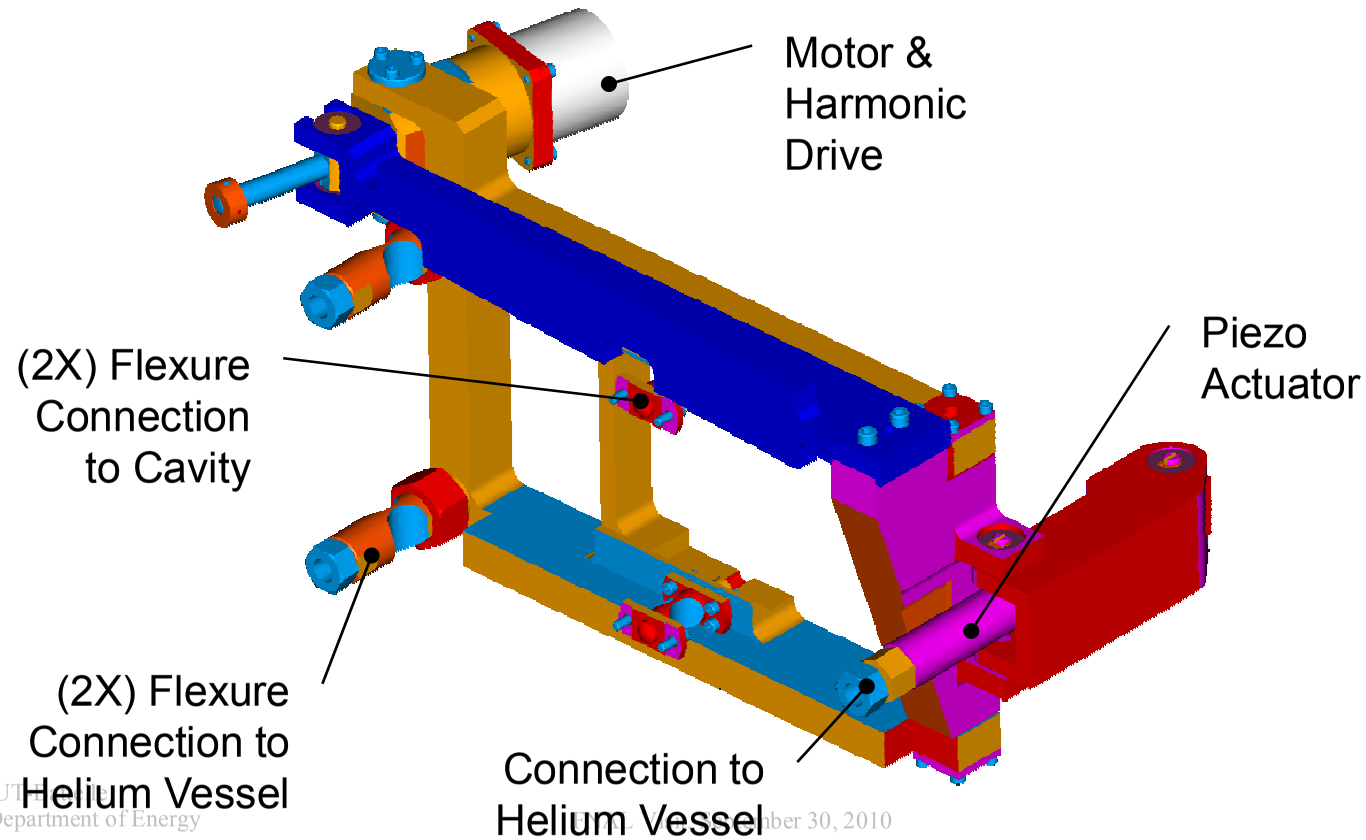




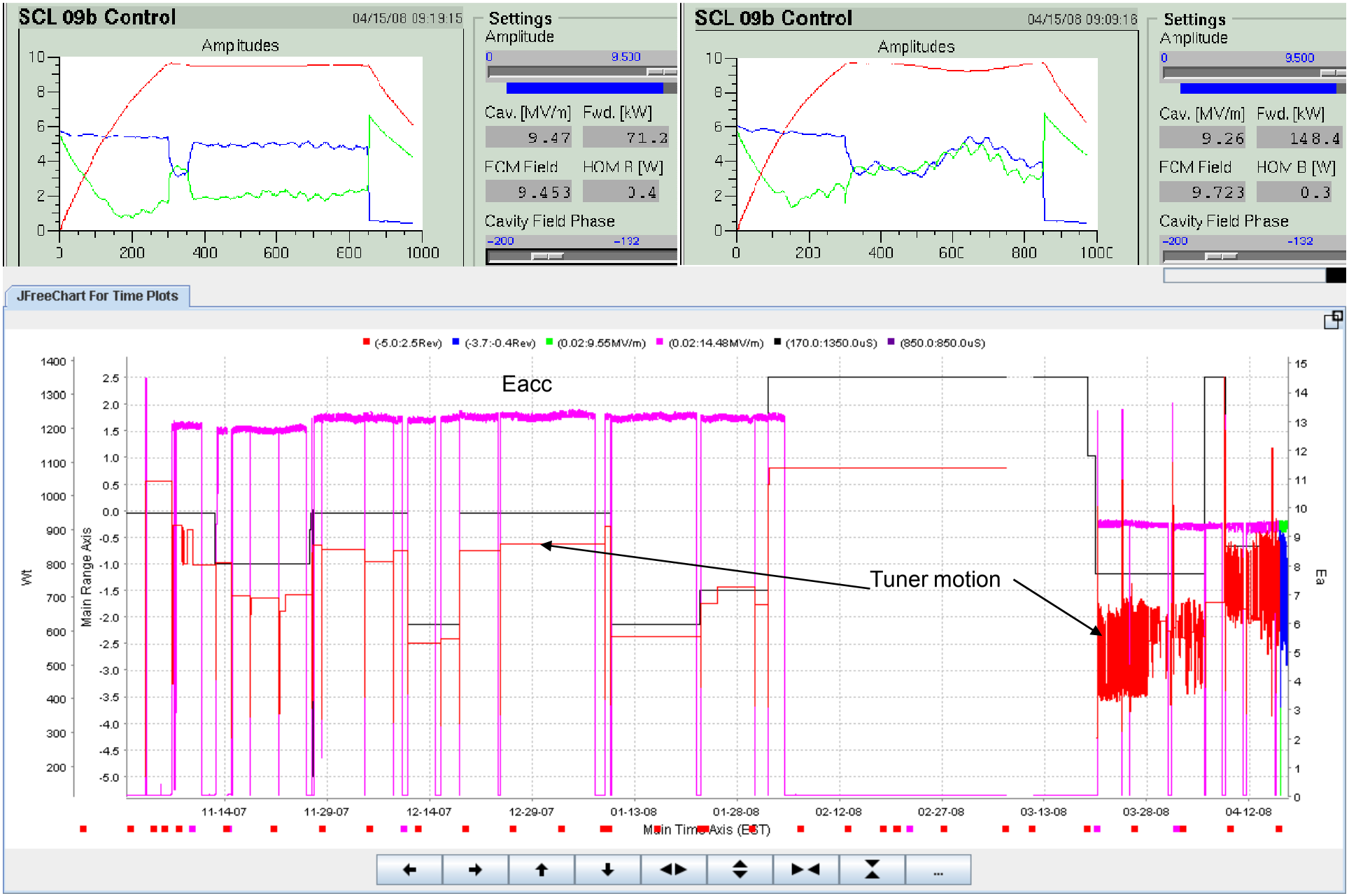


Tuner

- **Pressure incidents, 2-4-2K transition, or just short life time→ about 10 tuners are replaced.**
  - **Harmonic driver, piezo stack (and/or motor) failure**
  - **Worn out in progress, loosen connection, slips; unstable mechanical boundary; irregular detuning**



Irregular dynamic detuning (9b)



Cryogenic loads (I)

Dynamic load estimation; provide constant load condition to cryogenic system for reliable 2K operation

Static loss (20~25 W/cryomodule)→ total ~500 W

Thermal radiation from fundamental power coupler

- static; without RF
- dynamic; with RF
- estimation→ 20~50 W to 2K circuit at 1MW beam operation

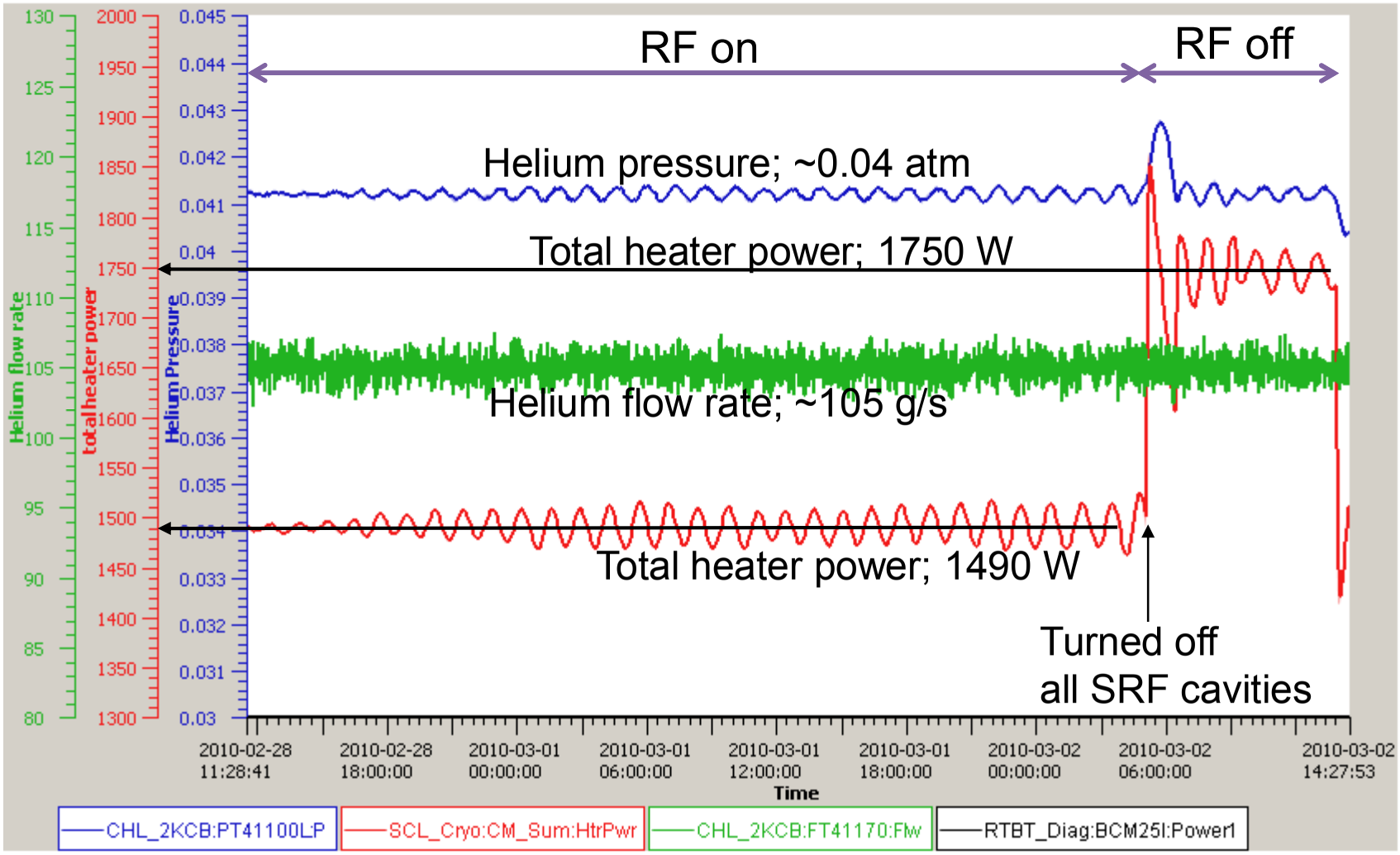
Cavity surface dynamic loss (design parameter Qo > 5e9 at 2.1 K)

- BCS resistance (~6.5 nOhm at 2.1K, 805 MHz) } Qo~1.1e10 (MB)
- residual resistance (10 nOhm) } Qo~1.3e10 (HB)
- Other heating; FE, MP, pure Q-deacy

Ex. at 6.5% duty at 60 Hz & at design gradient

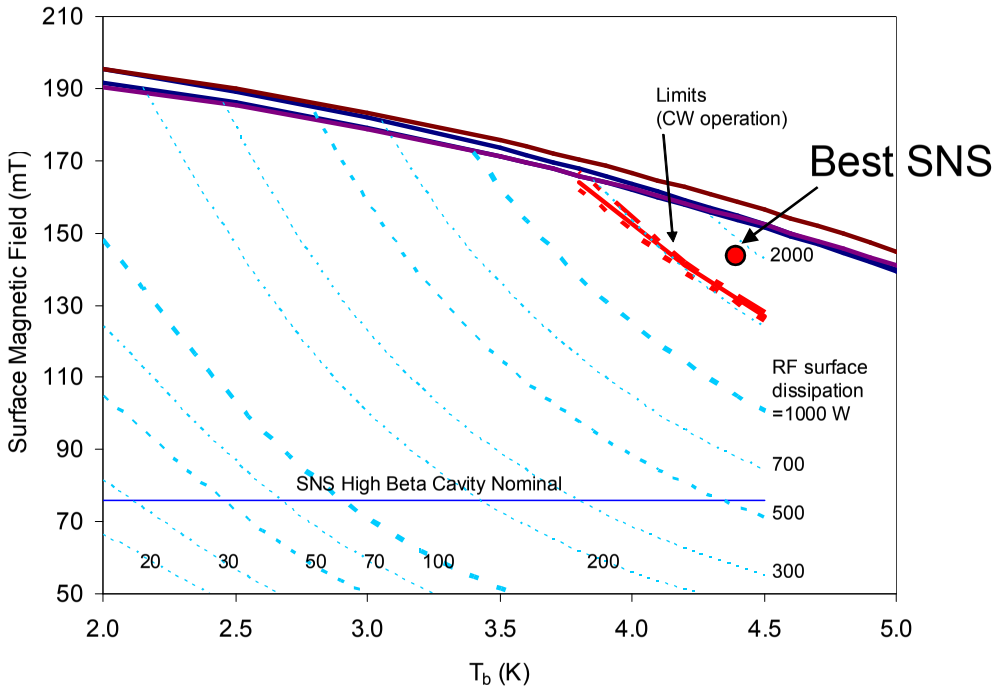
Pbcs(6.4nOhm)+Pres(10nOhm)=130 W, Pother=210 W → Qo=5e9,

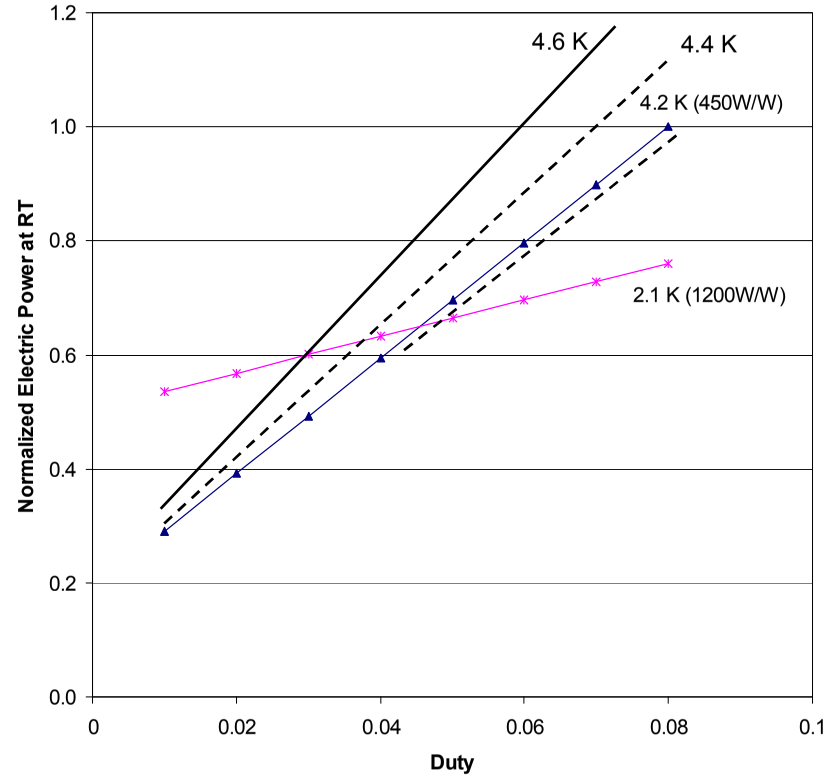
Cryogenic loads at the present operating condition



- **Overall Qo~4.5e9**

Operation temperature



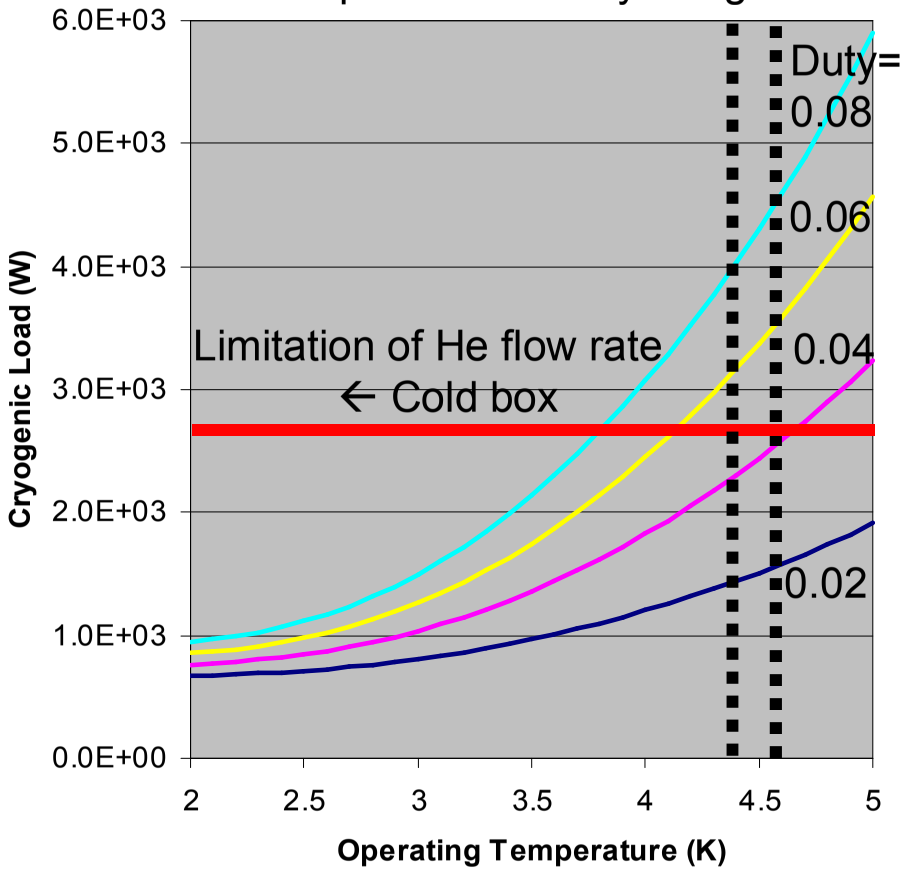


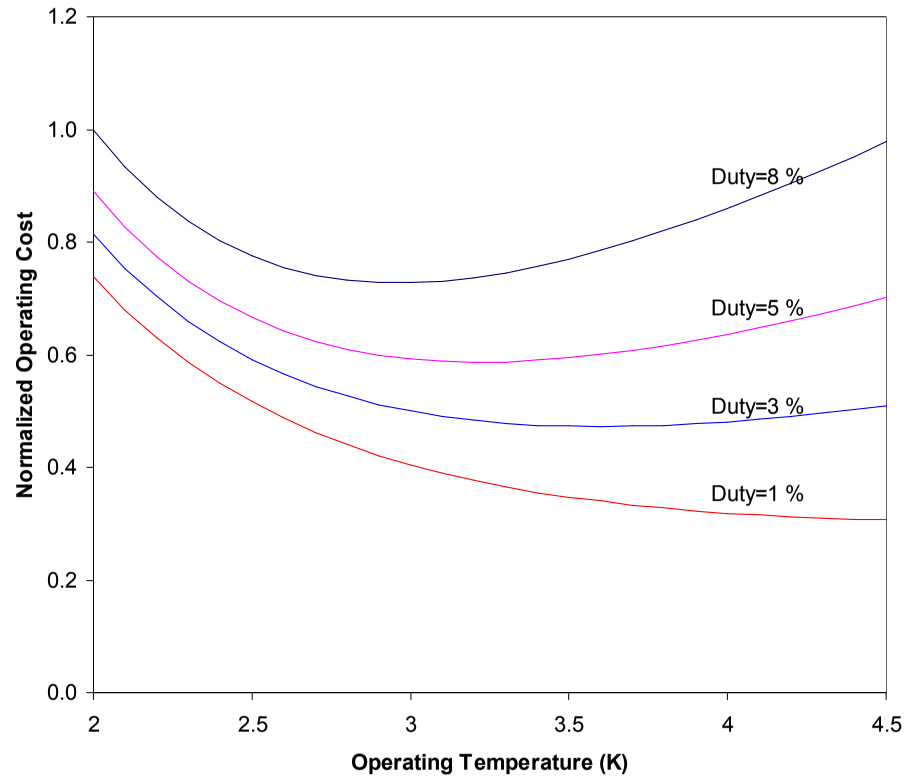
with the existing SNS cryo-plant
at the SNS SCL layout

Relatively low frequency, low field, high static loss, field emission ; 2K is not optimum

Operational efficiency

w/ existing SNS cryo-plant
~30 Hz operation → very marginal





with a cryo-plant to be designed
at the SNS SCL layout

Given the design of the cryogenic plant, the highest overall efficiency is not necessarily achieved when the nominally optimal thermodynamic conditions are reached.
Since the cryogenic plant has to run at a fixed load no matter what the actual static and dynamic loads from the cryomodules, a more efficient use of the plant would be at temperatures different from the designed ones.

SCL for the Design Goal

- 1 ms beam pulse
  - 1350 us HVCM → 1270 us RF (300us filling + 30us FB stabilization + 950us beam)
  - Shorter filling time (need more RF) 950us → 1000us
- 26-mA average current (or 38-mA midi-pulse current) at 1-GeV operation
  - Need more RF available for the design beam current

Additional HVCM/HPRF Configuration ; done

- 1-GeV energy + energy reserve (~40 MeV)
  - All cavities in the tunnel in service → 940~950 MeV (no reserve)
  - SCL HB cavity performances should be improved (+2.5~3 MV/m)

Increasing the Beam Energy

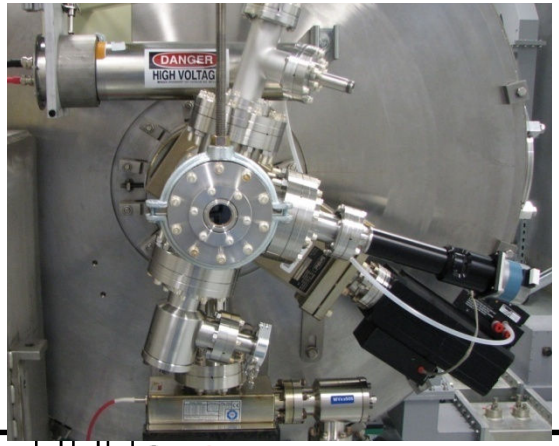
- Repaired ~12 cryomodules to regain operation of 80 out of 81 cavities
  - CM19 removed: had one inoperable cavity (excessive power through HOM); removed both HOM feedthroughs
  - CM12 removed: removed 4 HOM feedthroughs on 2 cavities
  - Tuner repairs performed on ~9 CMs
  - We have warmed up, individually, ~12 CMs in the past 4 years
  - Individual cryomodules may be warmed up and accessed due to cryogenic feed via transfer line.
- Installed an additional modulator and re-worked klystron topology in order to provide higher klystron voltage (for beam loading and faster cavity filling)
- Further increases in beam energy require increasing the installed cavity gradients to design values

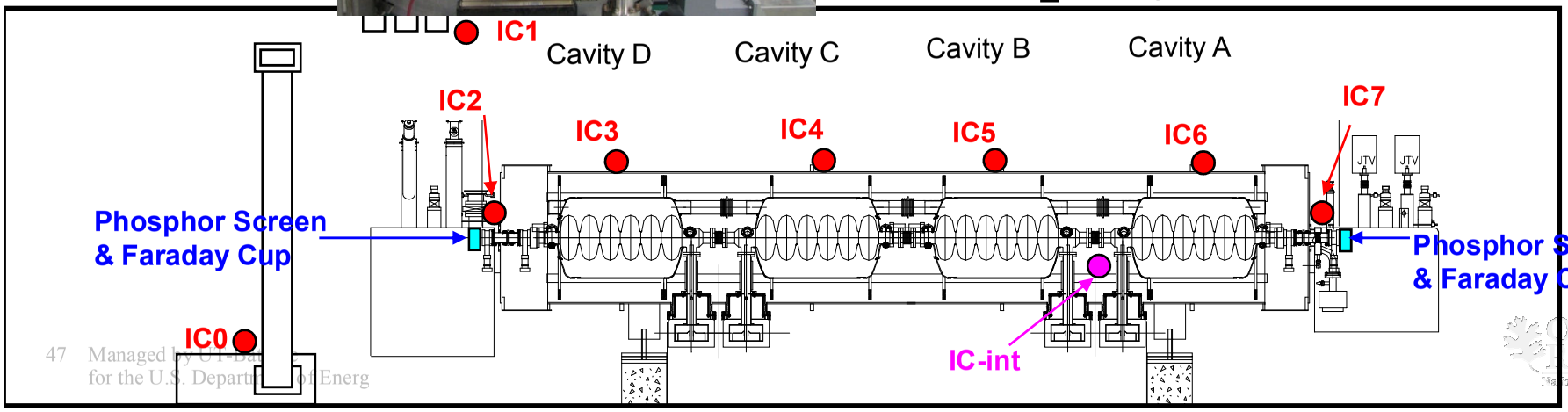
Efforts for SCL performance improvement

- Reworks; removing, disassembling, reprocessing, assembling→ not a realistic approach
- Attempted Helium processing → did not work due to heavy MP around HOM coupler
- Plasma Processing → the first attempt gives a promising result. R&D programs are on-going
- Spare cryomodule → for major repair work of weak cryomodule. Fabrication is on-going

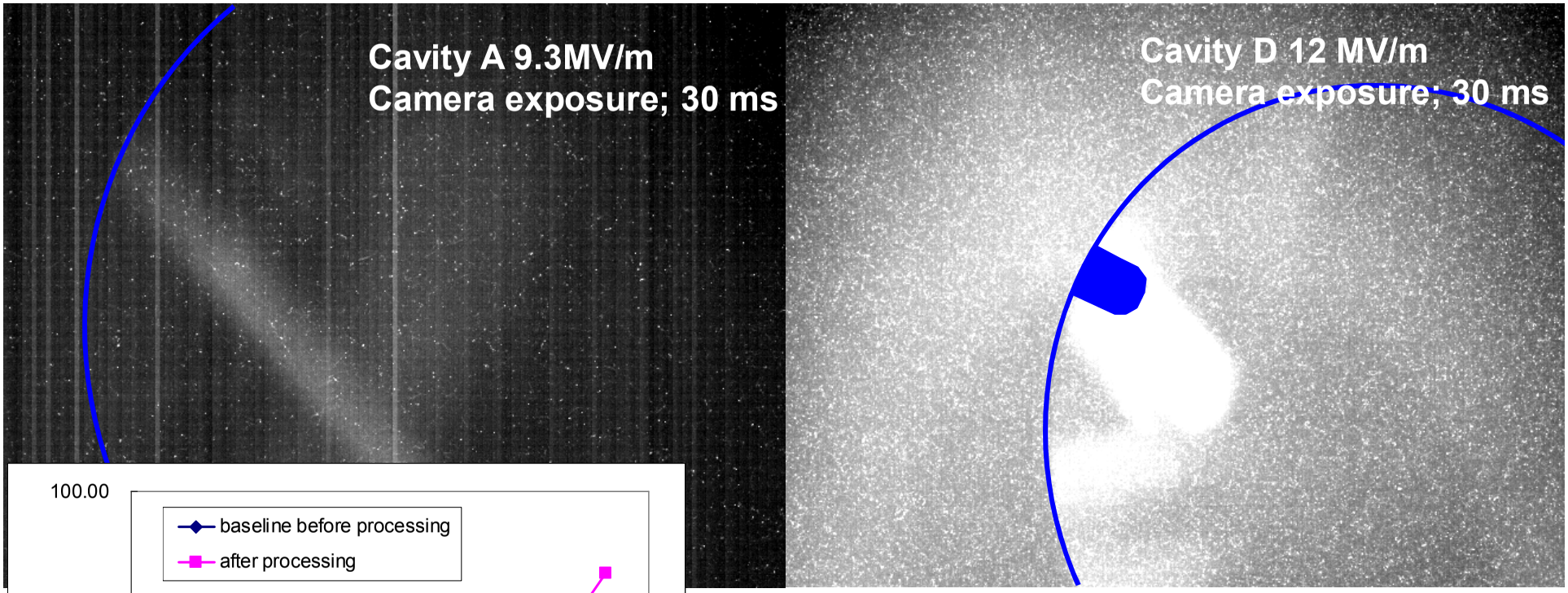
in-situ plasma processing; first attempt

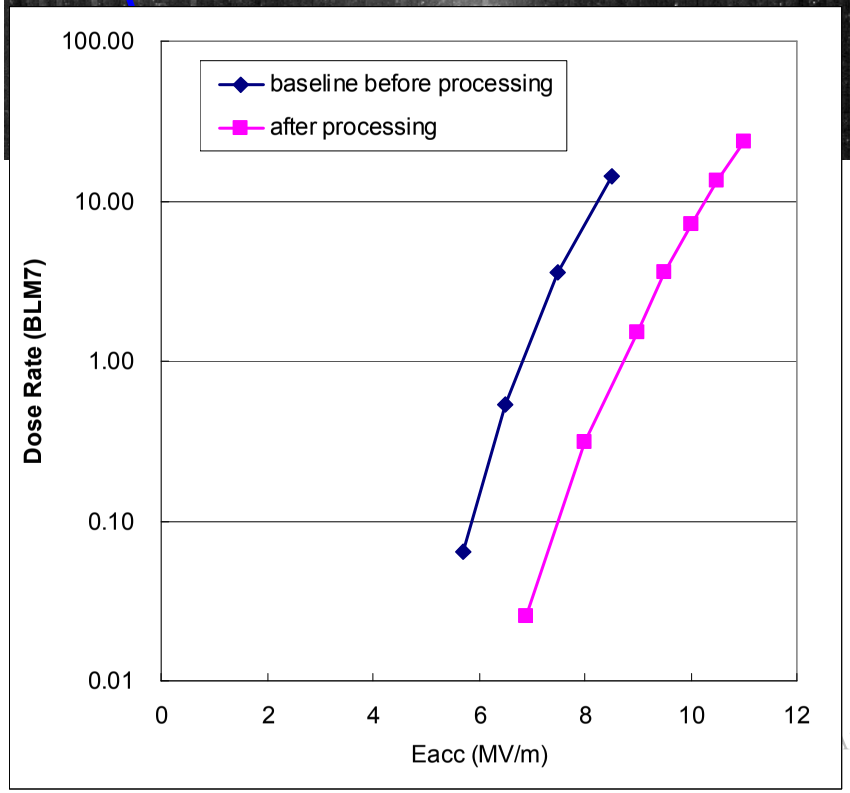
- In-situ plasma processing; First attempt with H01 showed very promising results
- Set a systematic R&D program to find optimum processing conditions
- Hardware preparations are in progress





Phosphor screen images before processing





Processed at cold and warm up
RGA analysis
All kinds of C-H-(O)-(N)

R&D for room temperature processing
Could be a post additional processing
(H2 removal, oxygen layer removal)

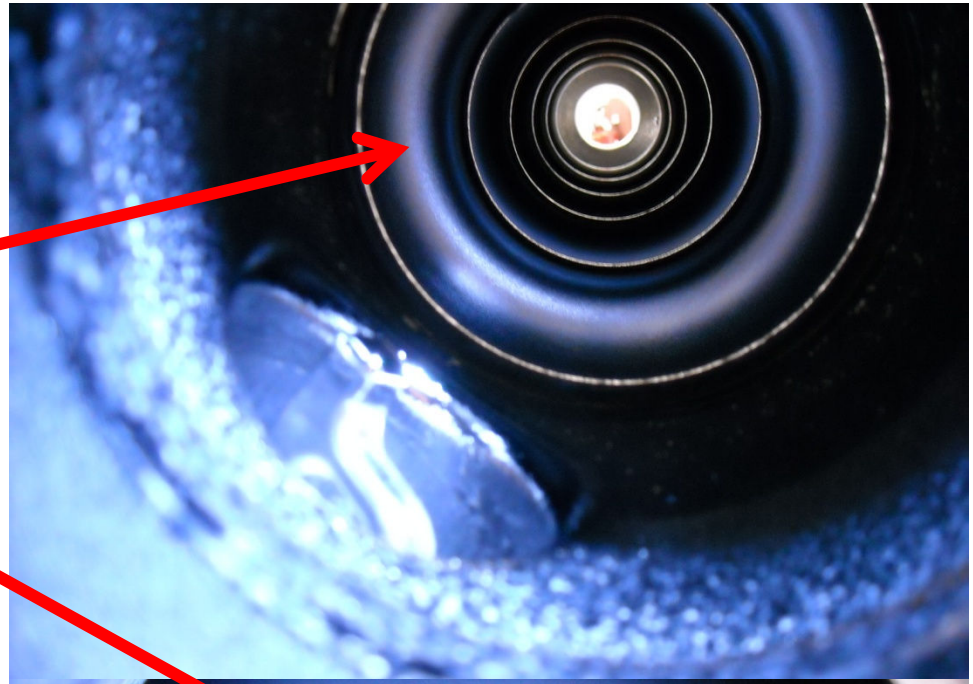
Spare cryomodule

- Revisit SNS HB cavity processing
  - Vertical test data has traditionally not been a good indicator of module performance due mainly to field emission limiting the collective gradients of all installed cavities
  - Field emission on-set point is more relevant criteria
  - What else can enhance electron activity, especially FE
- Lots of processing/testing for 4 cavities
  - Additional BCP made performance worse in many cases
  - Random variations of performance/field emission after processing cycle
  - Visual inspection tells that end group(reactor grade Nb)/first iris is very rough
  - EP seems to be the best option for the exiting SNS cavities
  - HOMless cavity achieved highest VTA results; 23MV/m

Endgroup Roughness

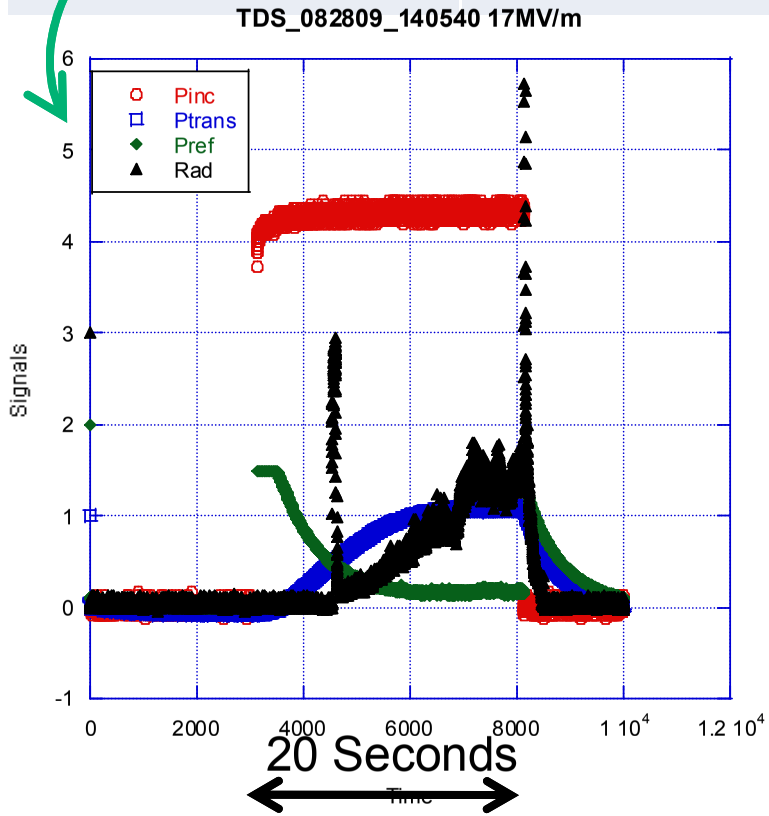
Cells have normal surface finish

Rough Surface to the First IRIS

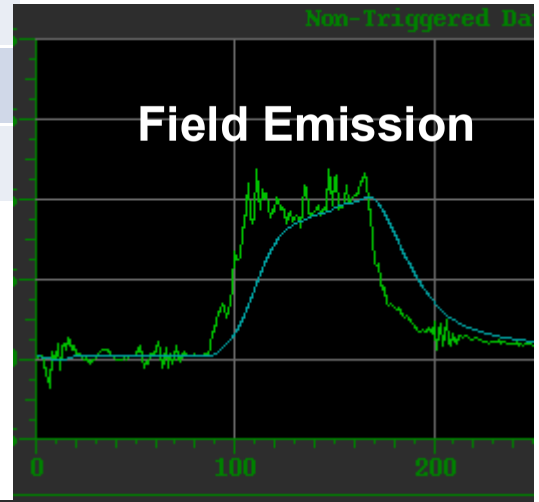


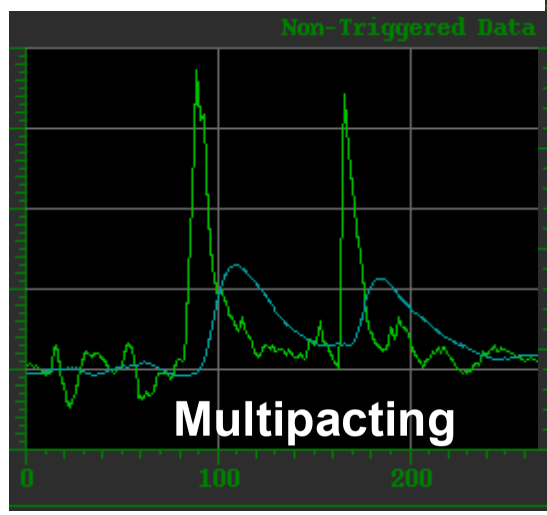
Summary of Cavity VTA Performance:

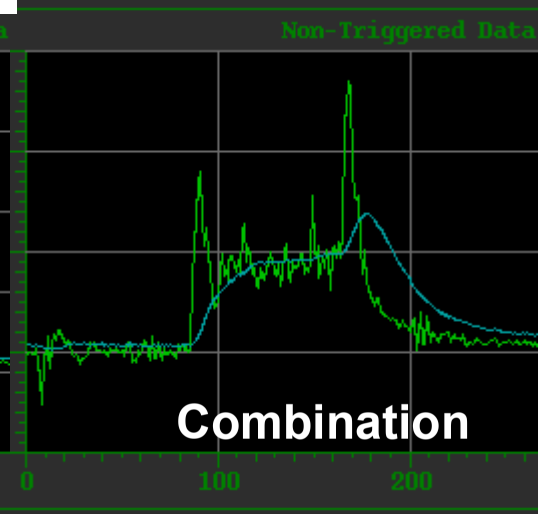
Cavity Number	Emax (MV/m)	Rad at Emax (mR/hr)
HB53	17.6	2.0
HB58	17.2	0.0
HB56	17.5	408
HB54	13.0	850



Tunnel Data RF Only

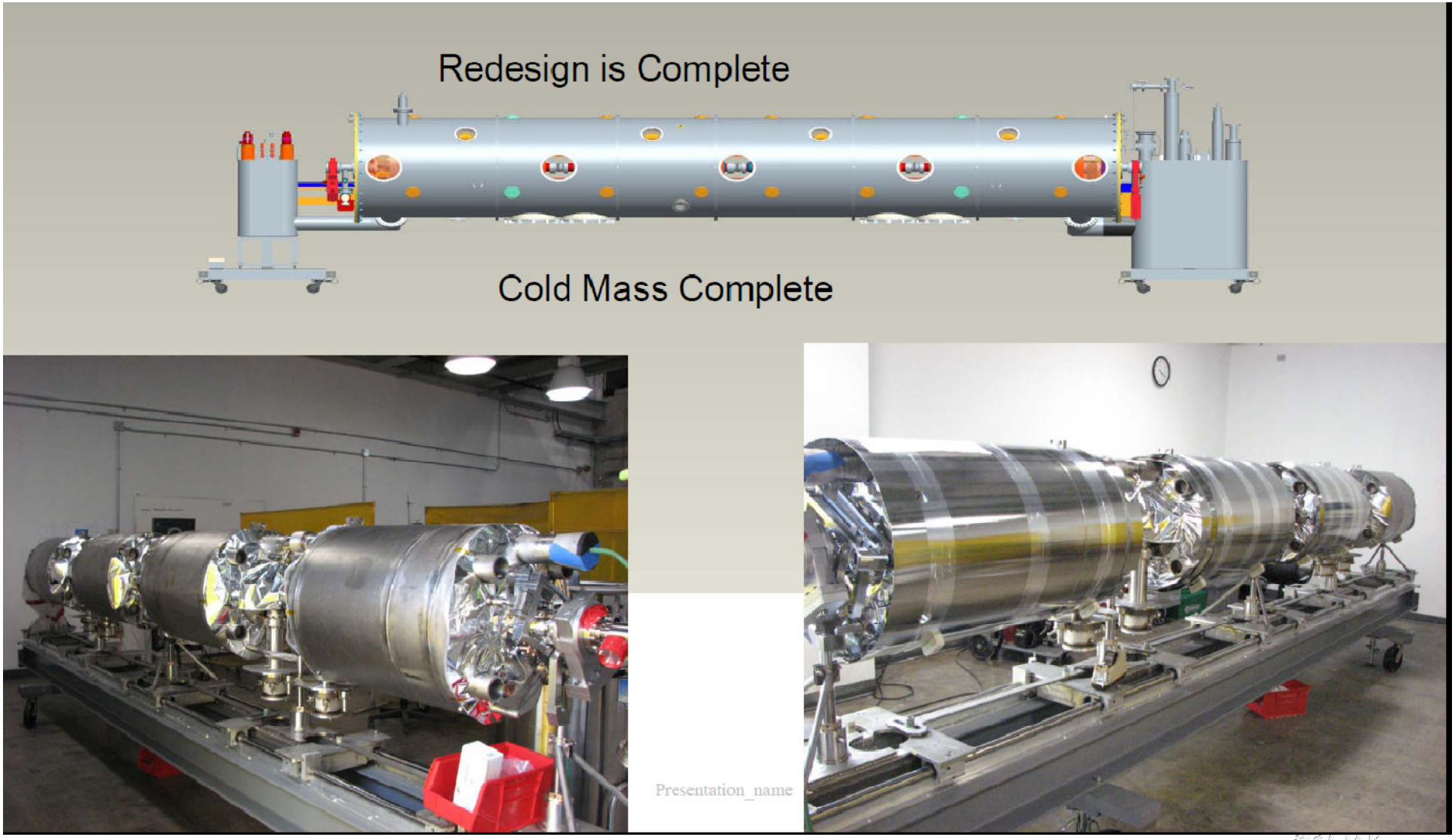






Spare Cryomodule

field emission, pressure vessel, other minor improvement (HOM, cooling, etc)



Power Upgrade Project

- Cavity
  - Field emission onset is more important
  - End group material; high RRR
- Coupler
  - Inner conductor; improve thermal conduction
- HOM coupler
  - Remove
- Pressure vessel

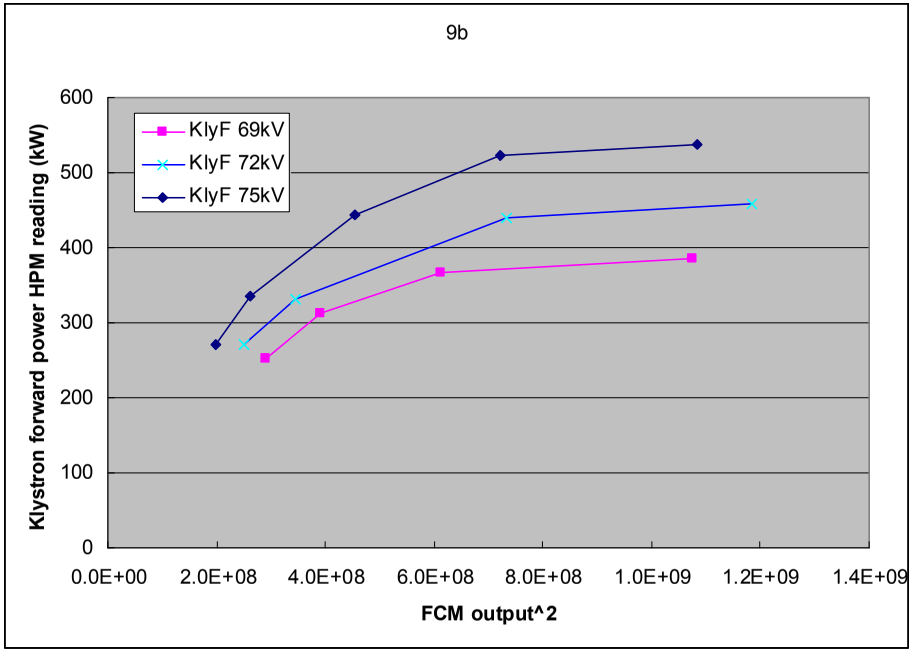
Lessons learned, experiences on design vs. real world

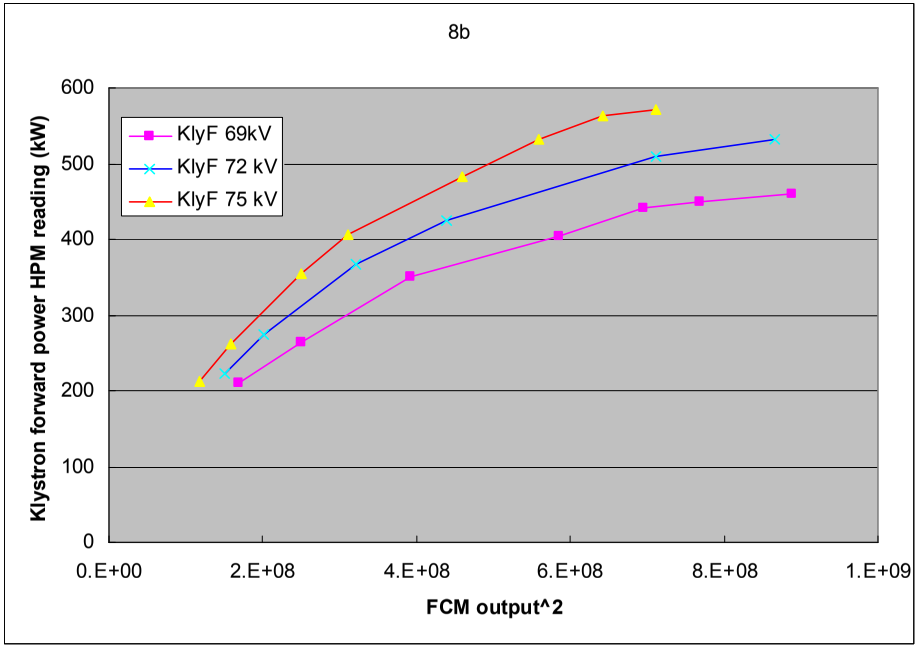
- Performances, Cost, vs. Stability/Availability
- 'Ideal' vs. 'Practically better'
- General vs. Machine specific
- Predictable vs. Unpredictable
  - Unexpected problems will arise. More complex systems lead to more troubles.
- R&D devices vs. Devices for operational machine
  - To address a specific problem→ good chance to generate other problems
  - Typically designers are not operators and vice-versa
- Simpler is always better as long as the consequence is acceptable.
- Balanced performances lead to the most efficient system.
  - Overdesign for something while overlooking something else
  - Limited by the scarcest resource; Law of the minimum
- Identify what are the practically important parameters.
- Have rooms for failures, system degradation, and unknowns.
- Establish 'reasonably' conservative physics/engineering margin and avoid designing systems using overly optimistic/pessimistic assumptions.

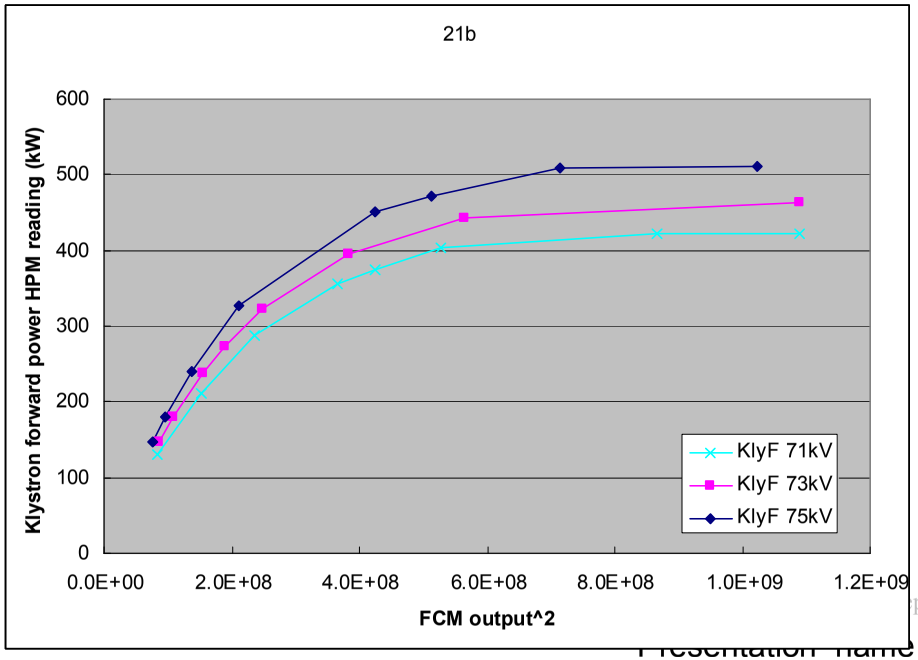
Thank you for your attention!

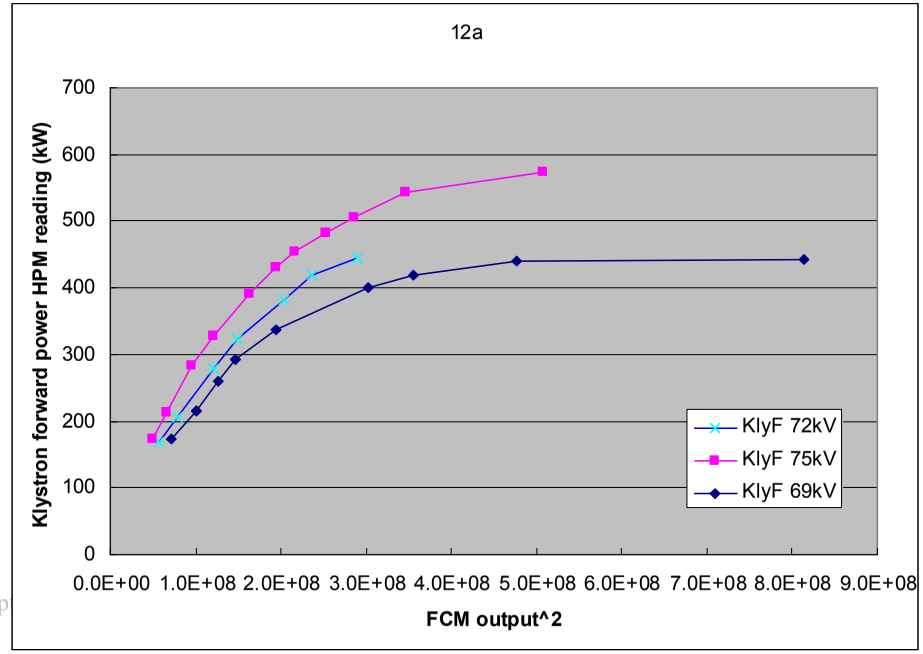
supplementary

Overall RF characteristic curves

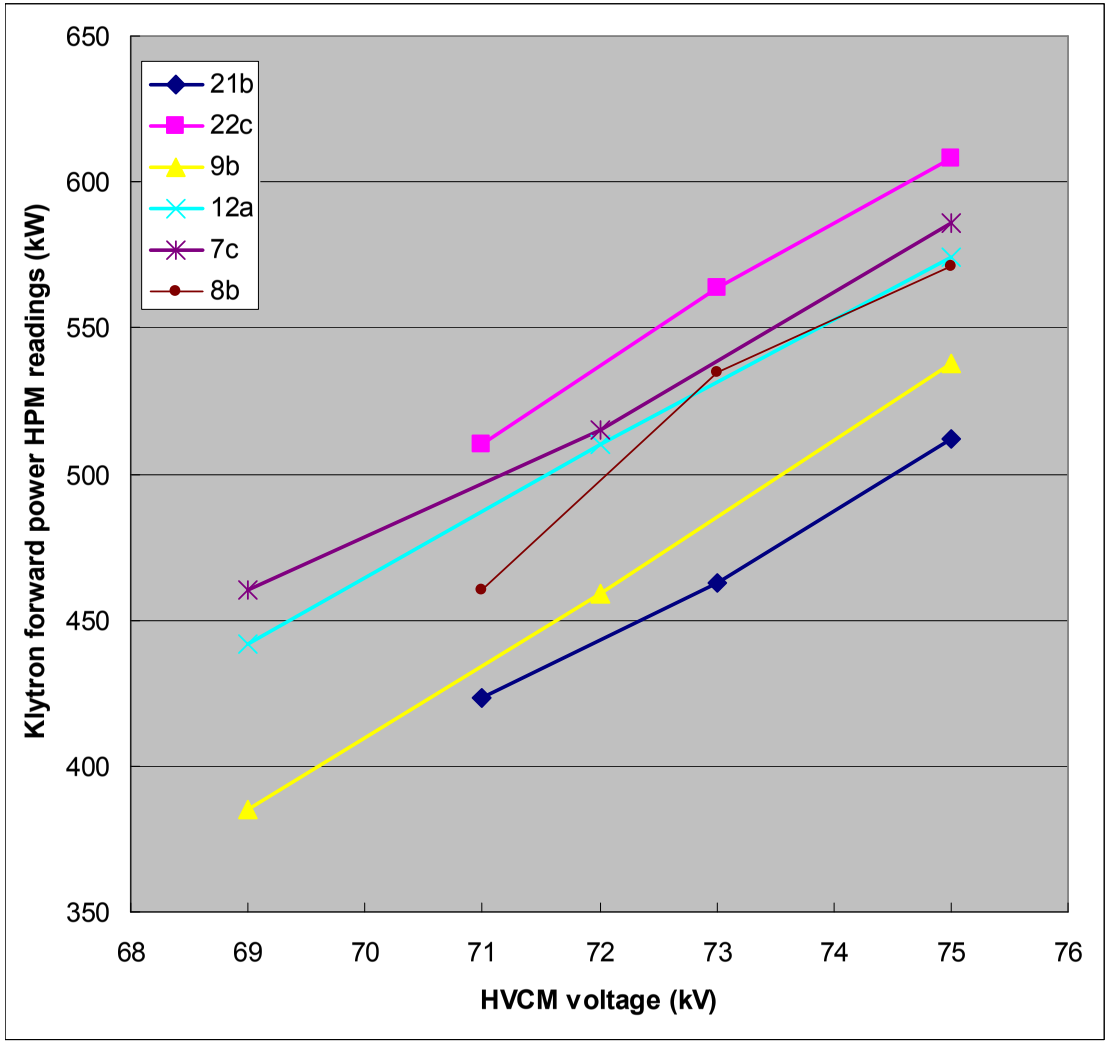






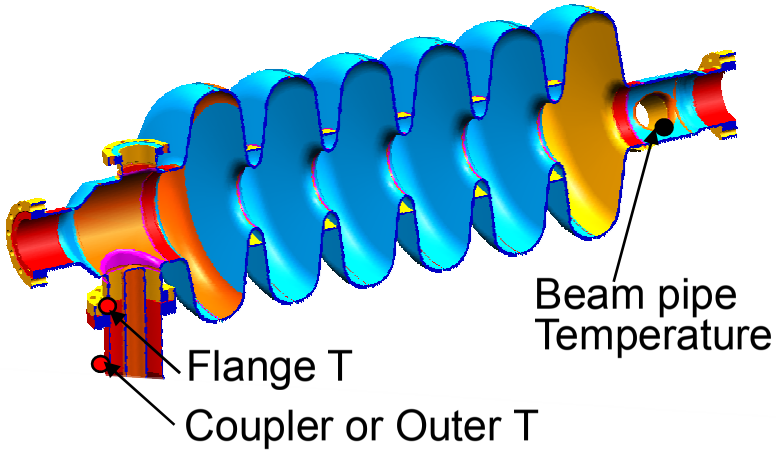


Klystron power (HPM readings) at saturation vs. HVCM voltage

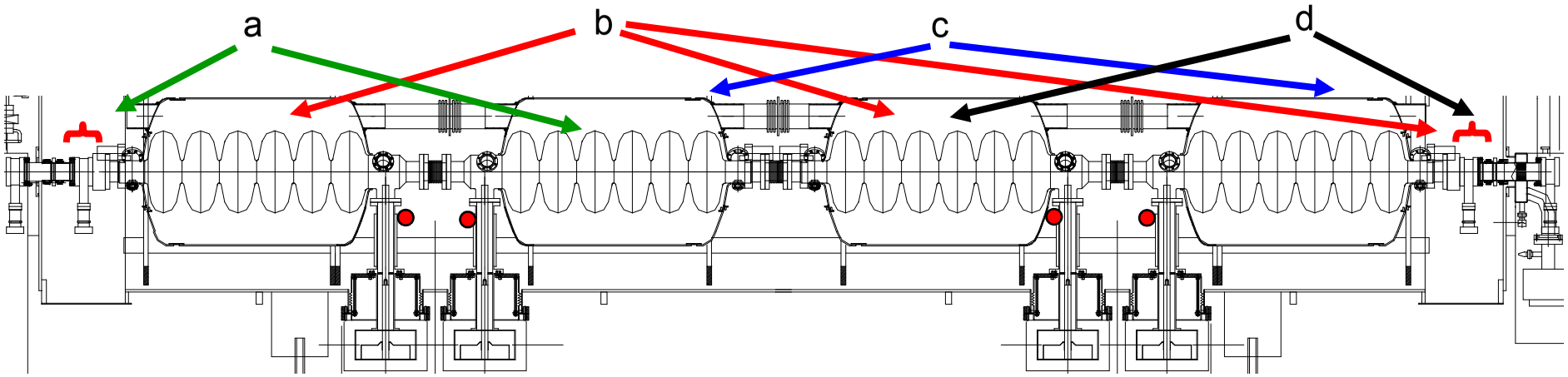


22kW~25kW of RF at saturation/kV of HVCM

Gradient Limitations from "Collective Effects"

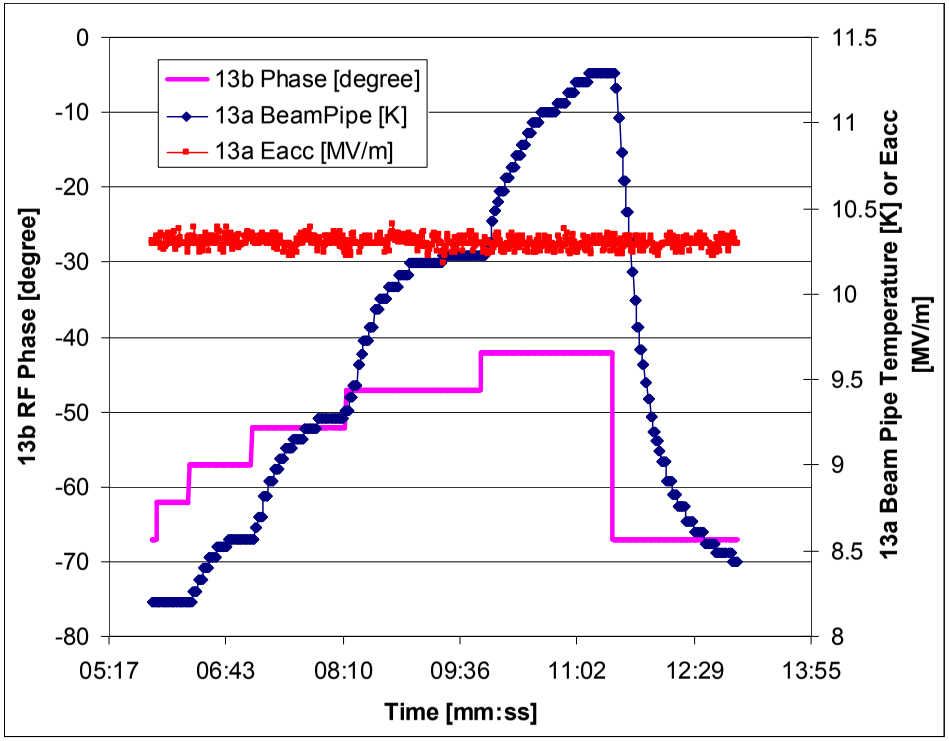


- **Electrons from Field Emission and Multipacting**
  - Steady state electron activity (and sudden bursts) affects other cavities
- **Electron impact location depends on relative phase and amplitude of adjacent cavities**
- **Leads to gas activity and heating with subsequent end-group quench and/or reaches intermediate temperature region (5-20k); H_2 evaporation and redistribution of gas which changes cavity and coupler conditions**
- **Example for CM13:** individual limits; 19.5, 15, 17, 14.5 MV/m
  collective limits; 14.5, 15, 15, 10.5 MV/m

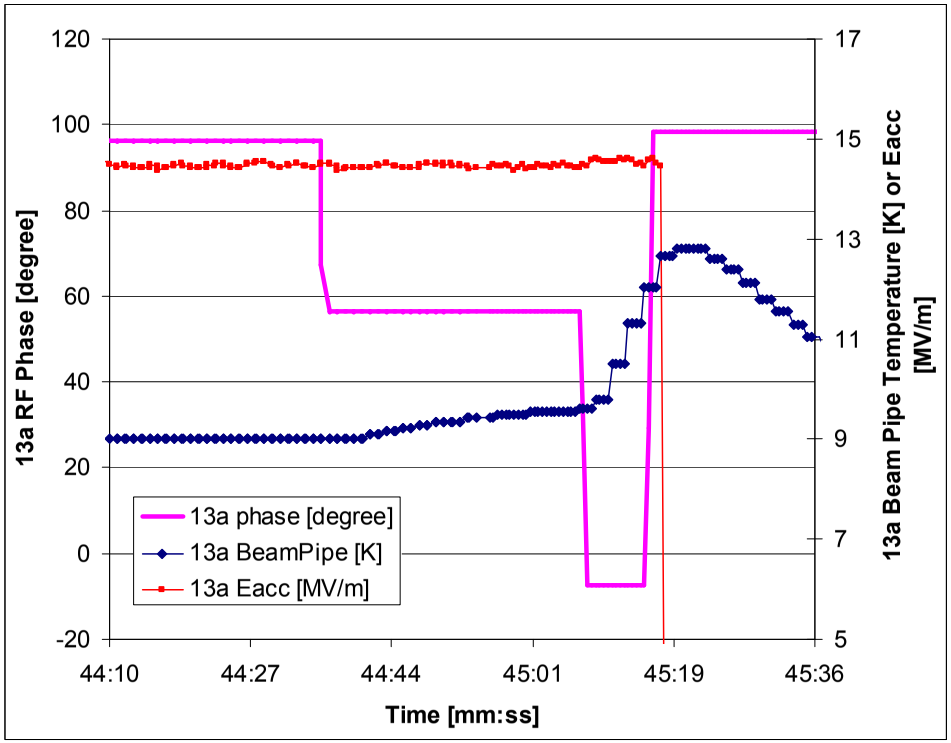


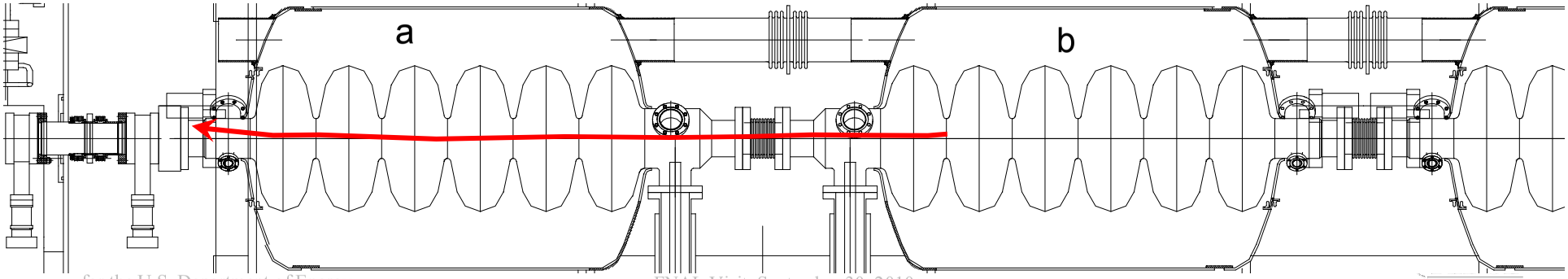
Collective effects
FE; heating vs. relative phase and amplitude

b cavity phase → a cavity beam pipe



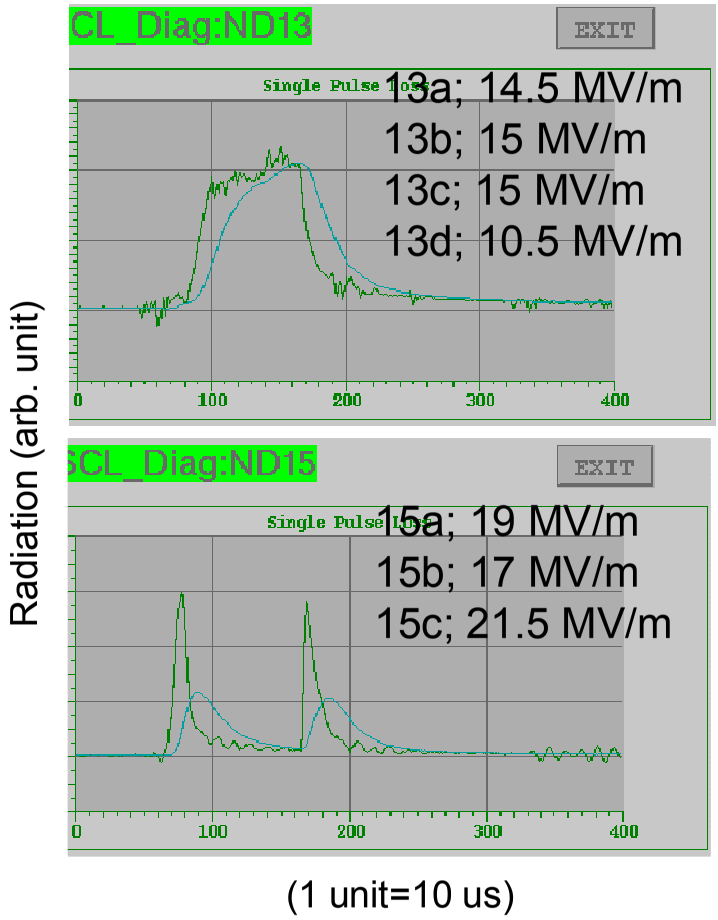
a cavity phase → a cavity beam pipe



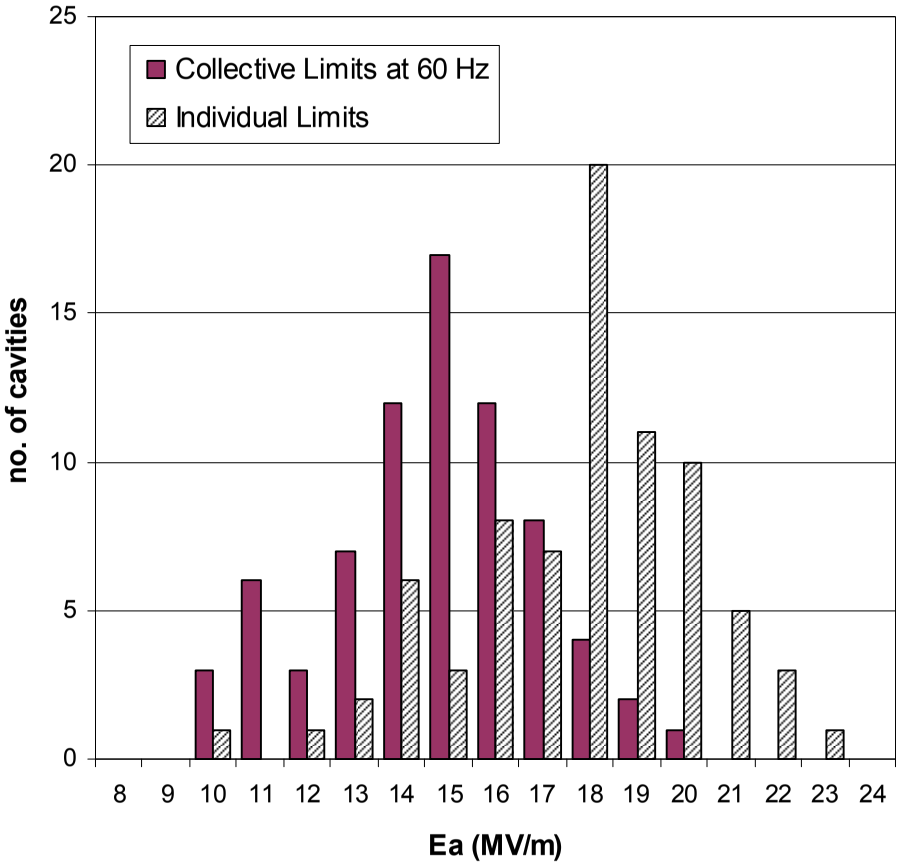


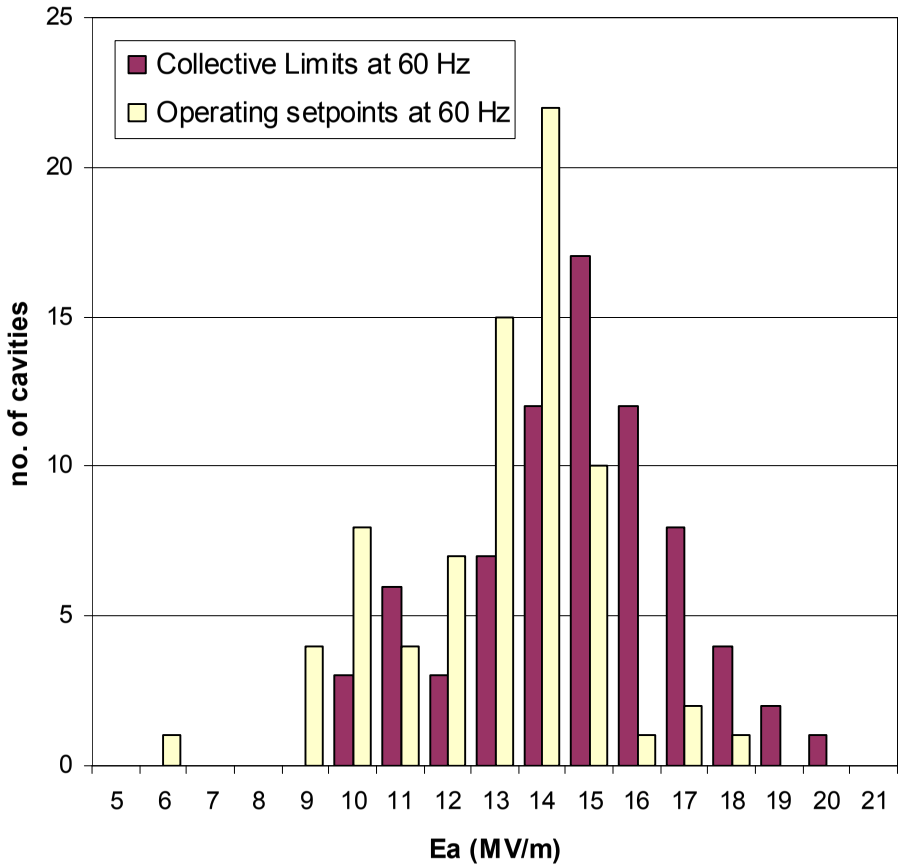
Radiation signals with RF only

Radiation Signals

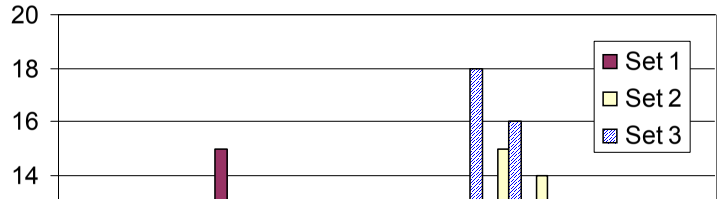


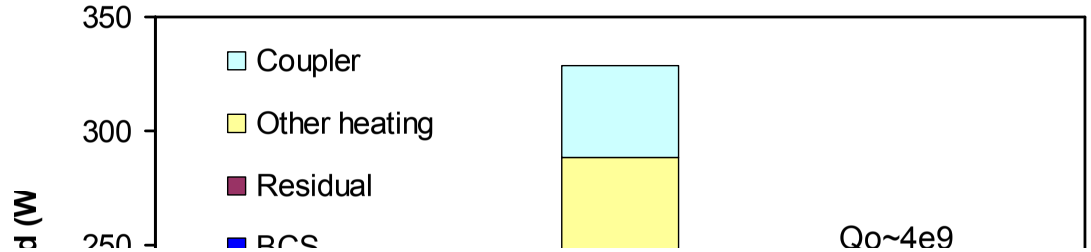
Accelerating gradients distributions

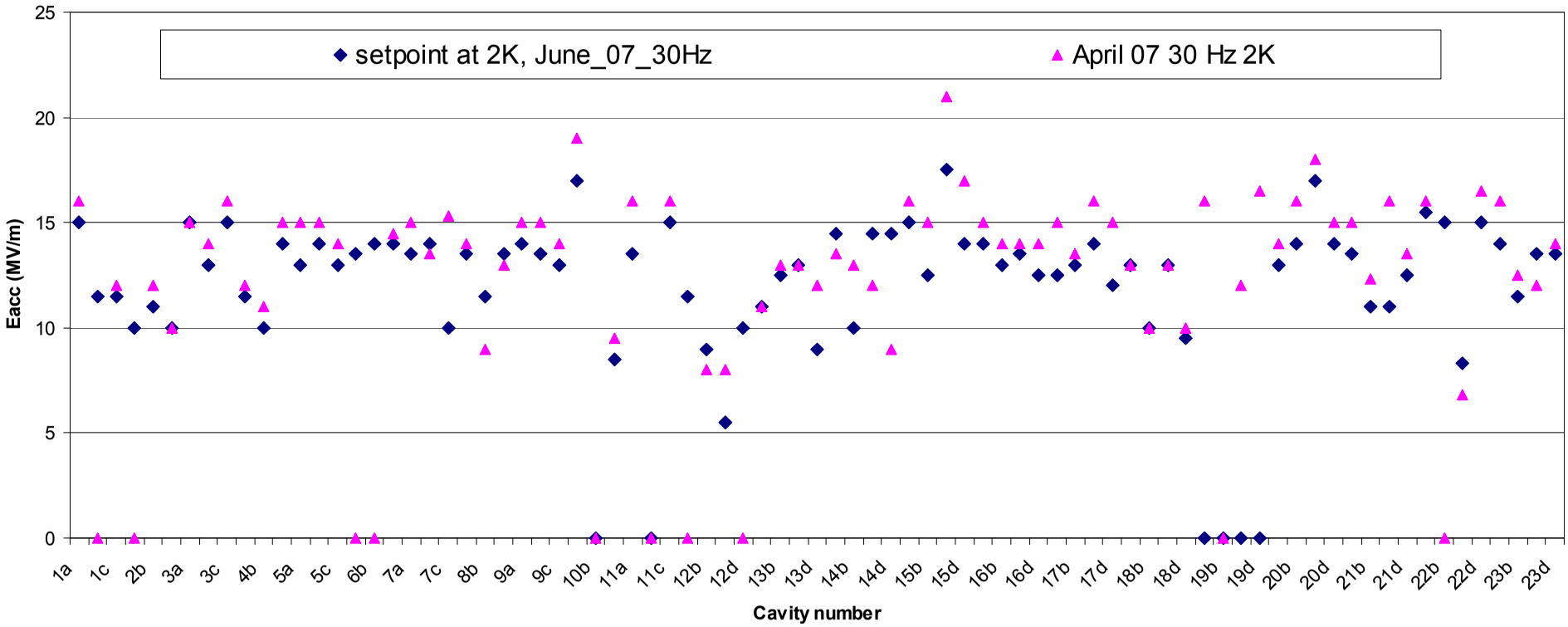




Cryogenic loads (II)





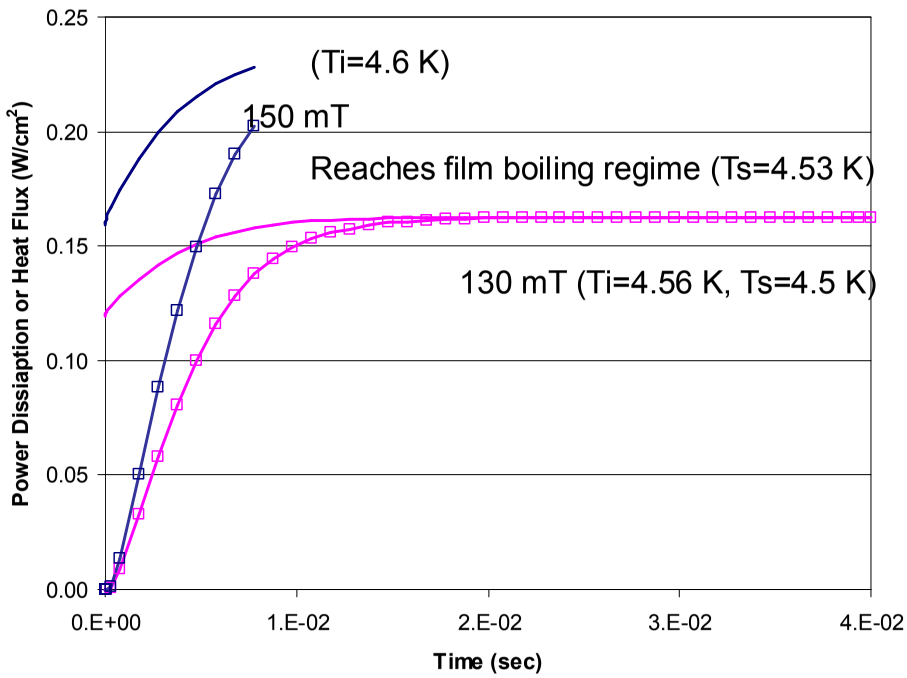


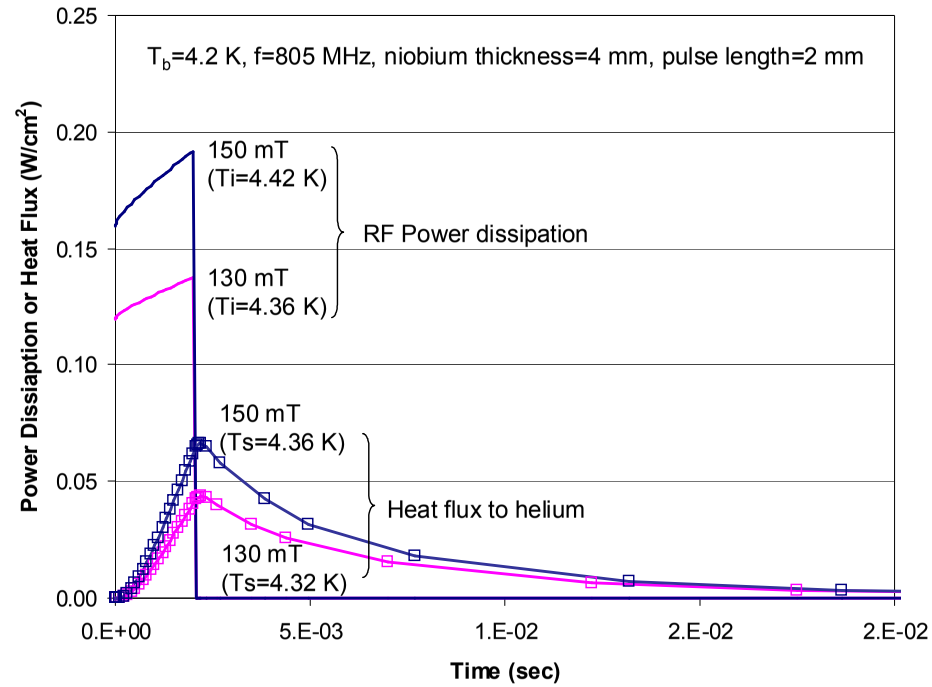
average~12.8 MV/m

Total dynamic heat loads due to different sources

CW, Pulse (BCS and cooling)

T_b=4.2 K, f=805 MHz, niobium thickness=4 mm





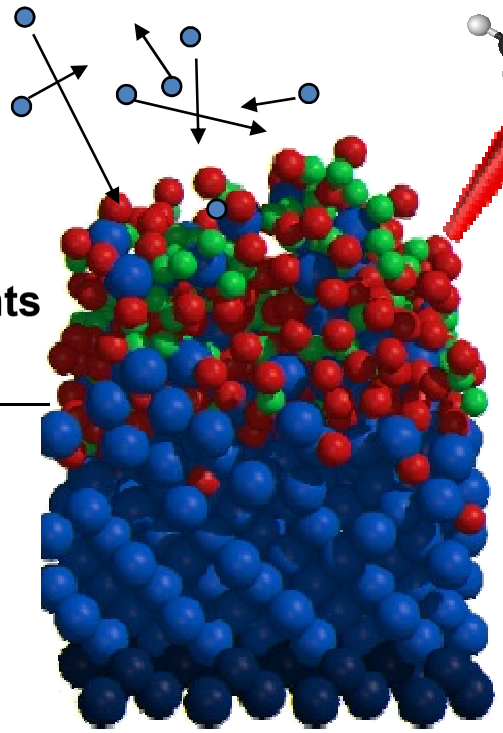
CW operation at 4.2 K, 805 MHz
→Meet film boiling regime (quench)

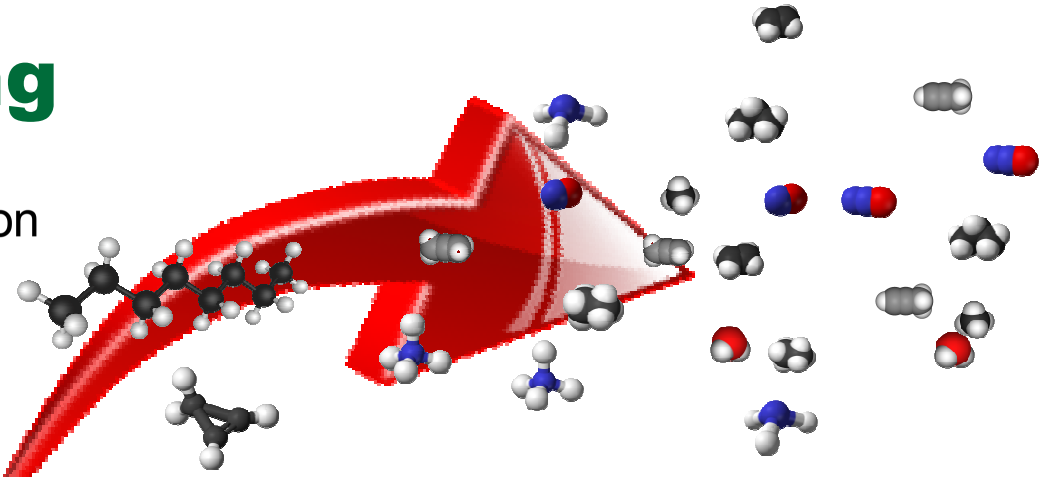
Pulsed operation at 60 Hz, 4.2 K, 805 MHz
→No limitation up to or close to the critical field
(Rs enhancement at close to critical field is not concerned)
(due to relative low operating frequency, pulsed nature)

We tested all cavities at both 2 and 4.5 K
The performances are exactly same

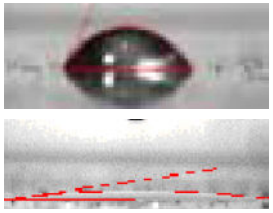
Plasma cleaning

Ion, molecule (radical), electron





wettability



before

after

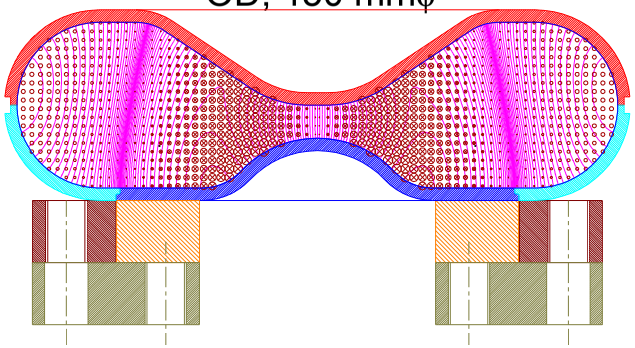
- Ablation
  - Soft
  - Etching
- Activation
- Crosslinking
- Deposition

R&D tools

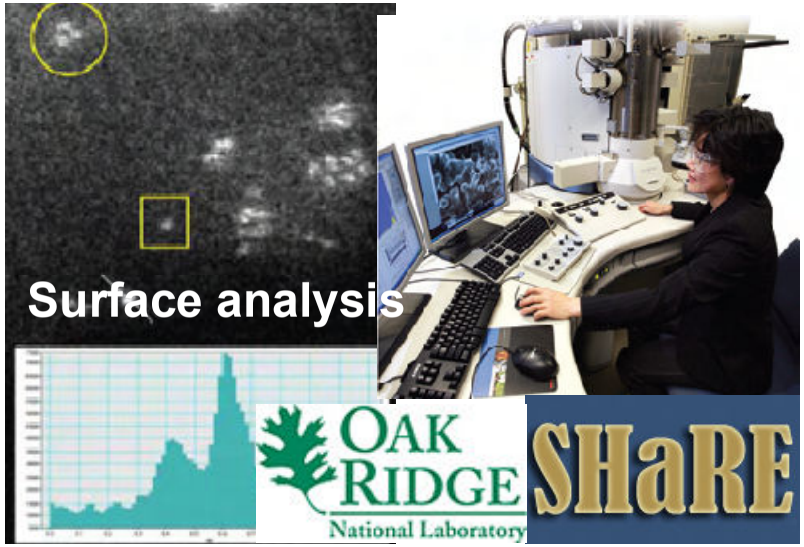
TM020 Test cavity

3.4 GHz, TM020 mode
Ep/Bp=1.12 (MV/m)/mT
Ex. Ep=50 MV/m, Bp=56 mT
P_{diss}=36 W at 4.2 K

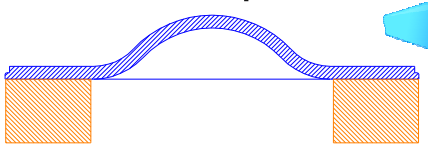
OD; 150 mmϕ



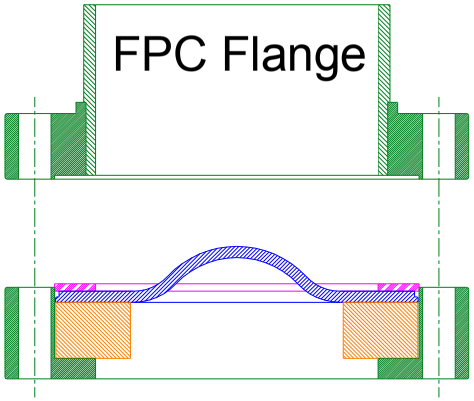
-Cold test
w/ dual mode (CW or pulse)
-Plasma processing



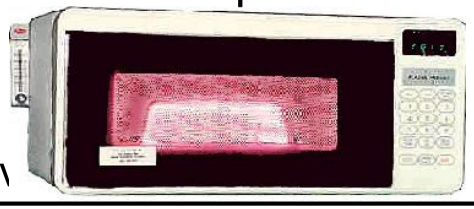
Demountable
witness plate



Witness Sample for Chemistry



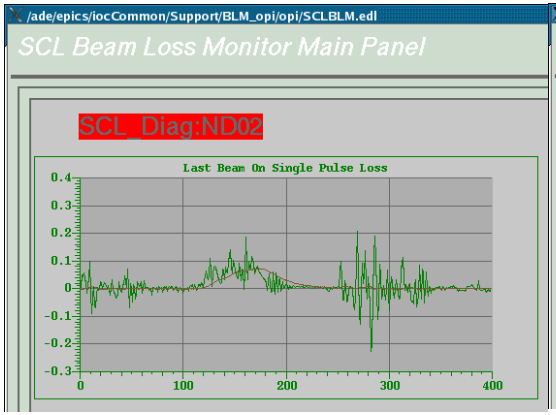
Microwave
Plasma processor



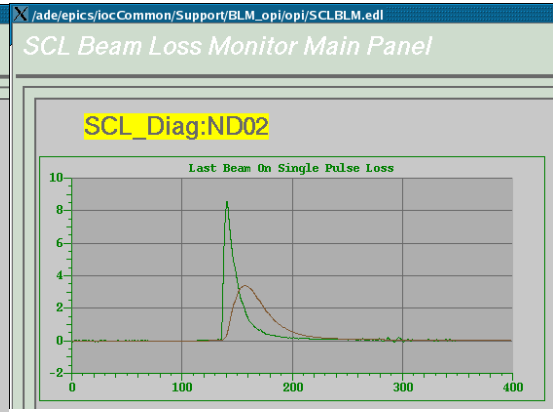
3-cell cav

Beam induced trip

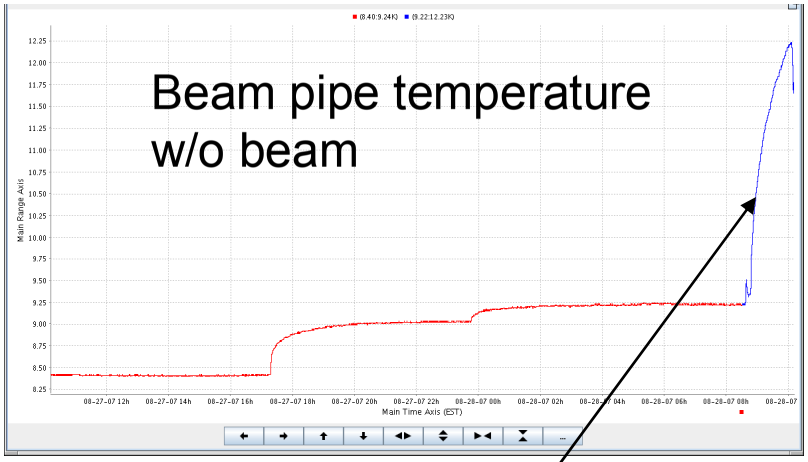
At normal beam



At errant beam



1. Errant Beam and RF truncation at upstream



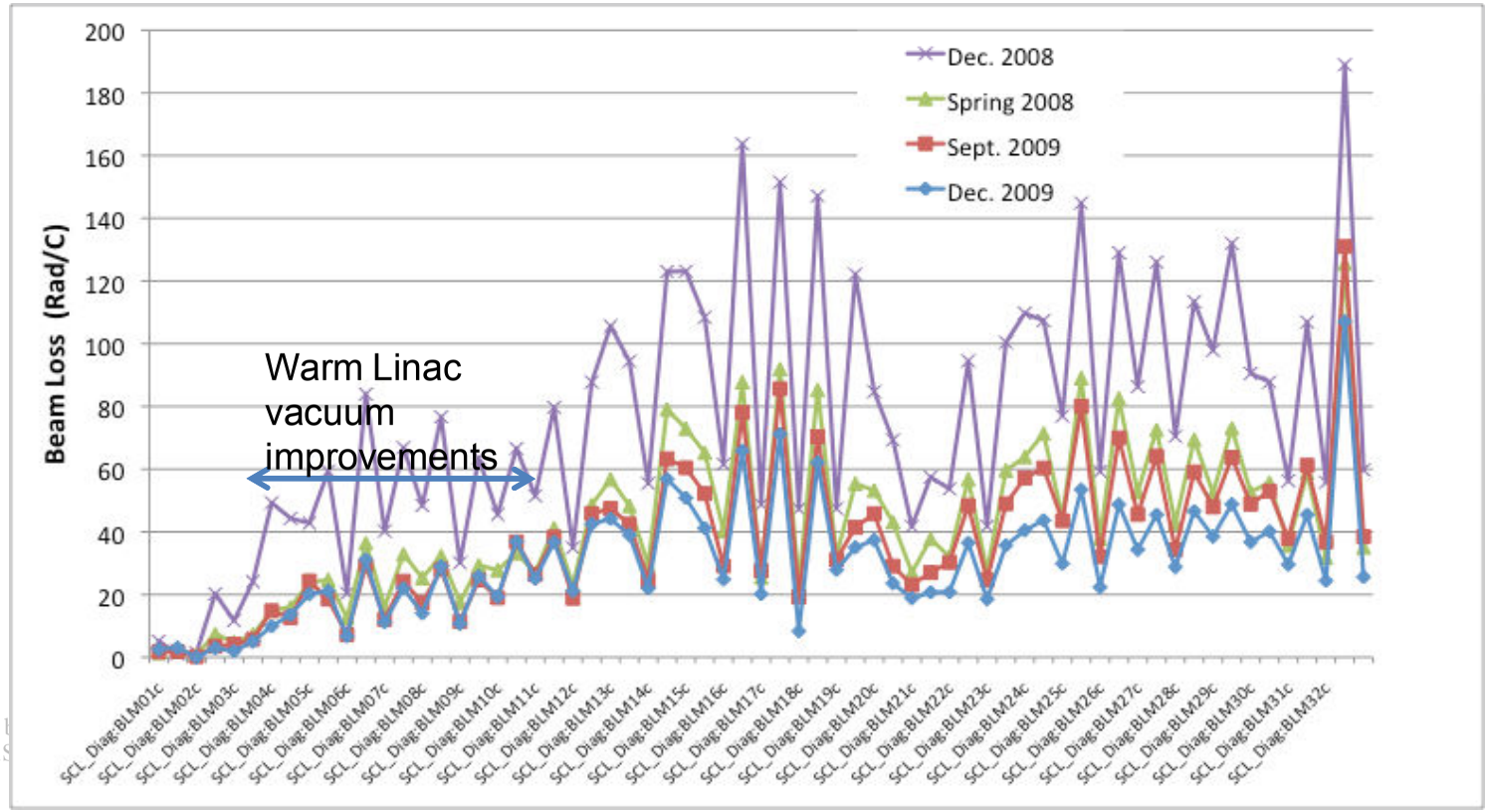
2. Dark current

SCL tuning; beam operation

- Beam Energy
  - Have operated with output energies of
    1010, 952, 930, 880, 860, 850, 550 MeV.
  - Routine operation has been near 860-930 MeV
- Tune-up:
  - It is faster to establish 81 phase/amplitude setpoints in SCL
    than for the 10 normal conducting setpoints
- Flexibility
  - One of the main benefits of a superconducting linac
    for proton beams is operational flexibility
  - We have taken advantage of the flexibility of individually powered
    superconducting cavities to "tune around" cavities
    with reduced gradients, etc.
  - Have operated with as many as 20 cavities turned off
    in initial tune-up.

Beam loss

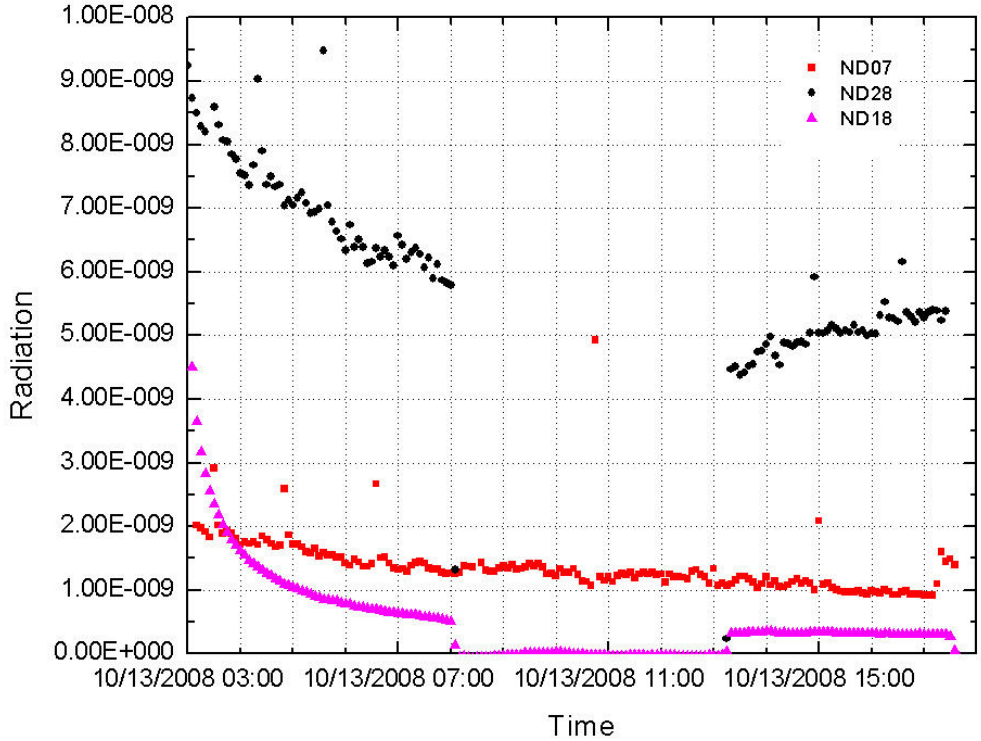
- Still not fully understood
  - Halo, Intra beam scattering, etc (multiple sources)
  - Normal production; mismatched tuning gives less beam loss
    - Operation expert's touch after initial physics tuning
    - quads ~40 % lower than design



Activation decay

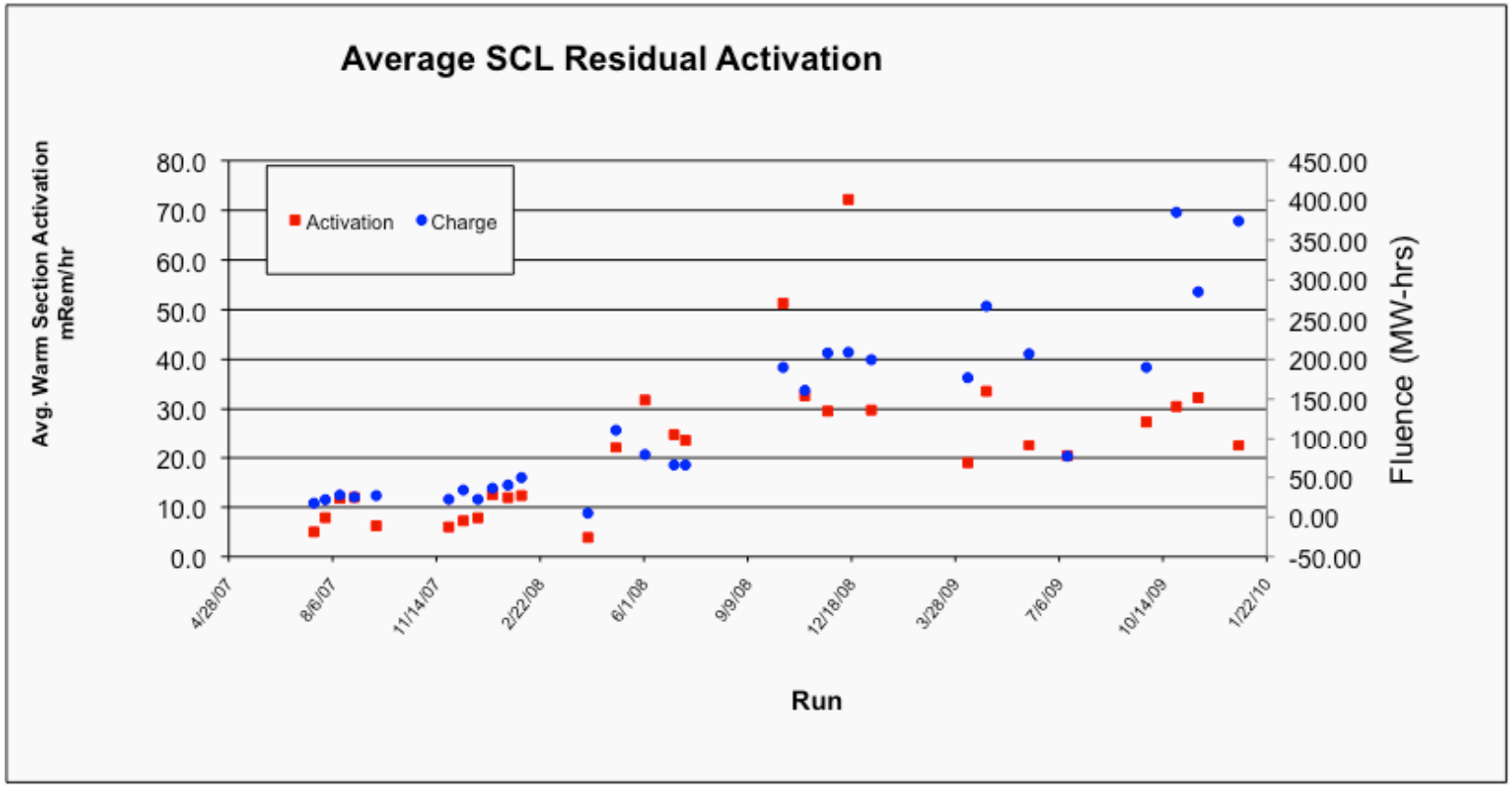
We finished 1 MW production run 6/29/10.
Residual activations in SCL
2 days after→ 25-30 mrem/hr
6 days after → 10 mrem/hr

Decay around SCL; very fast



SCL Activation History

NOT Loss limited



- Over the last year the SCL activation is not increasing, even though the accelerated charge increased
  - Reduced beam loss helps