SNS Superconducting Linac Operational Experience and Upgrade Path

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LINAC'08
Victoria, Canada

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For the SNS Team

OAK RIDGE National Laboratory

Outlines

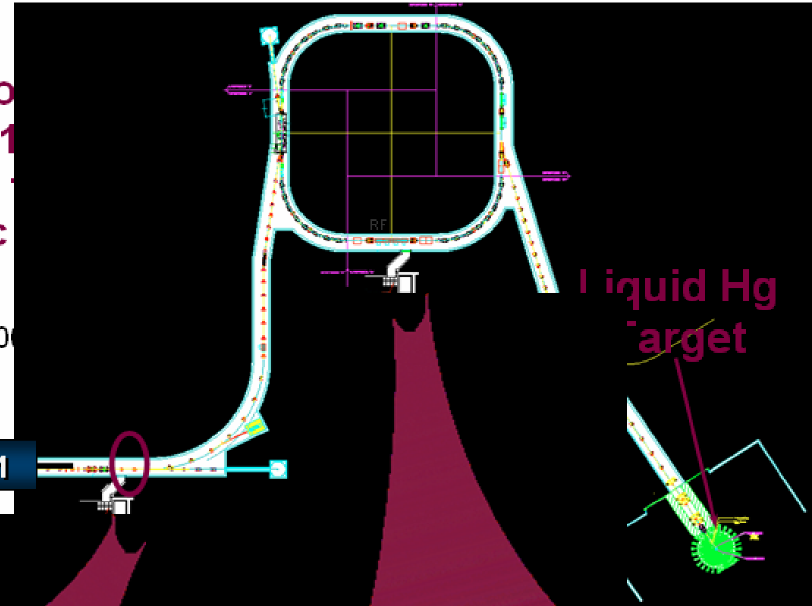
- Status
- Operational Experiences
- Power Ramp-Up
- Power Upgrade Project
- Summary

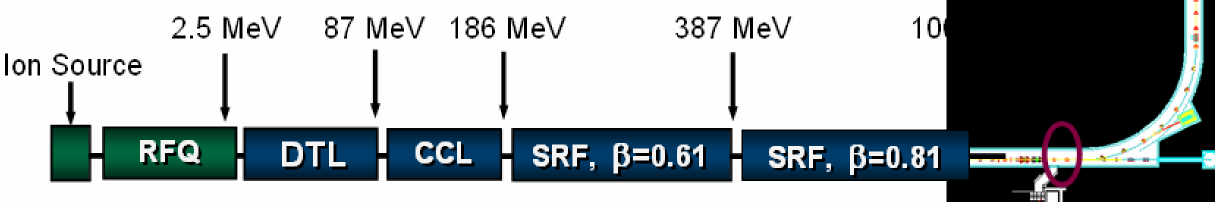
SNS Accelerator Complex

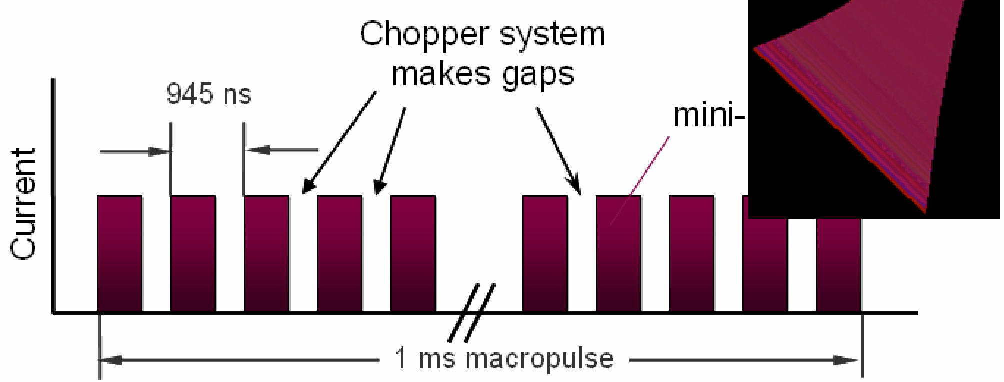
Front-End:
Produce a 1-msec long, chopped, H- beam

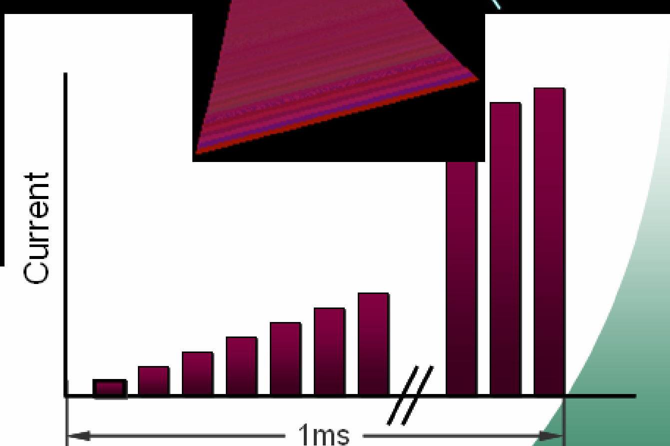
1 GeV LINAC

Accumulato
Compress 1
long pulse
nsec









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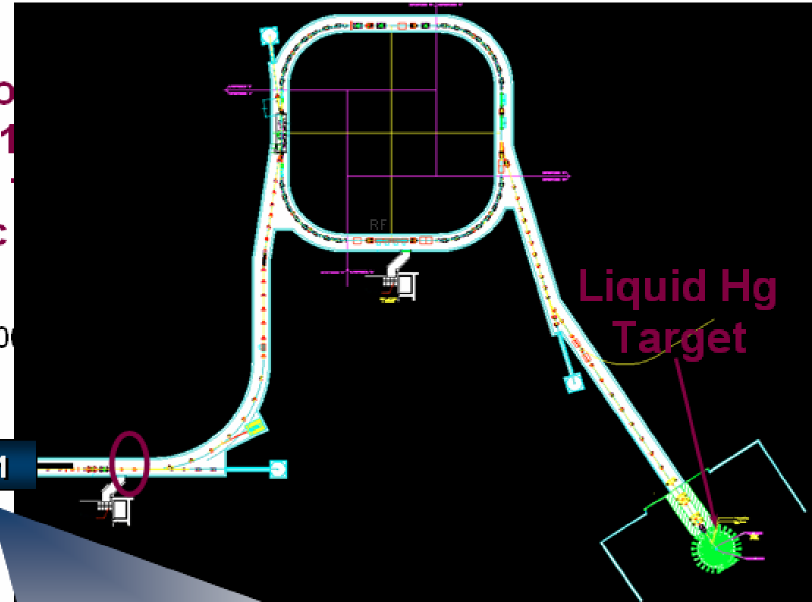
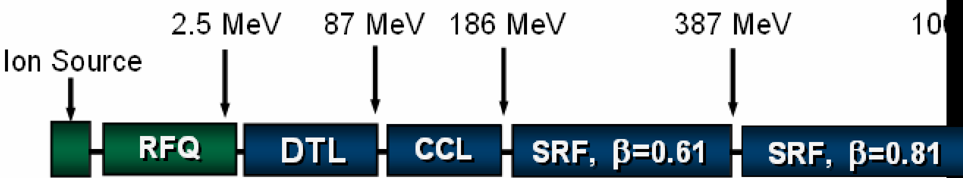
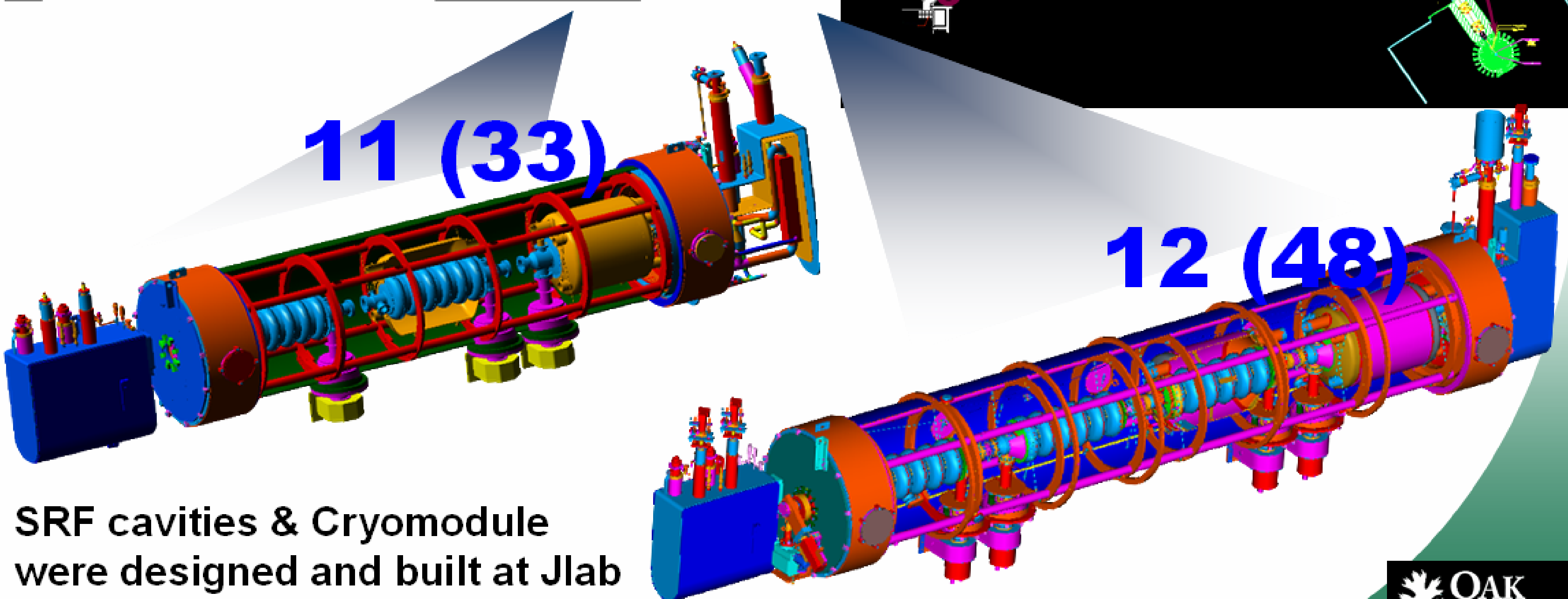






SRF cavities & Cryomodule were designed and built at Jlab

805 MHz, 1.3 ms, 7.8 % RF duty

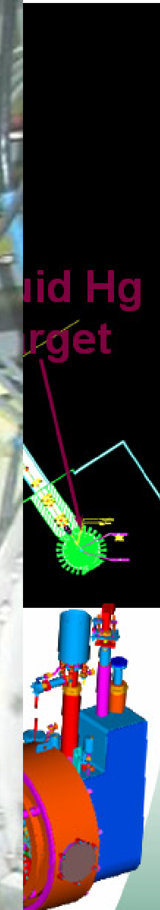
SNS

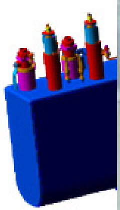
Fron

Produce
long, c
H- I

Ion Source

R





SRF
were
805 M

SNS SRF cavity

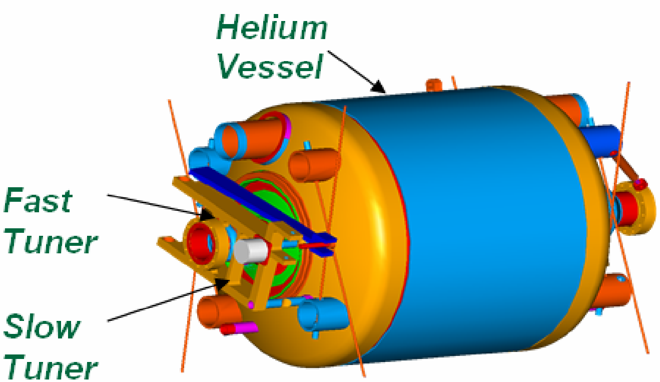
Major Specifications:

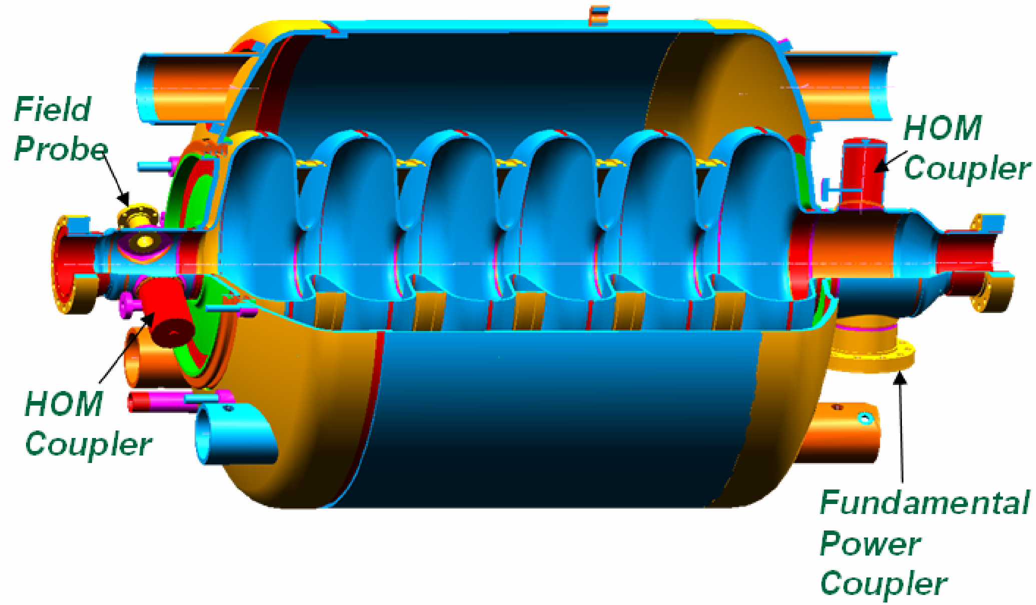
E_a=15.8 MV/m at β=0.81

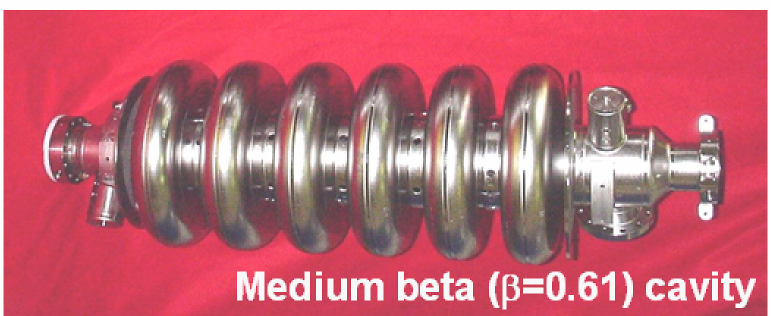
E_a=10.1 MV/m at β=0.61

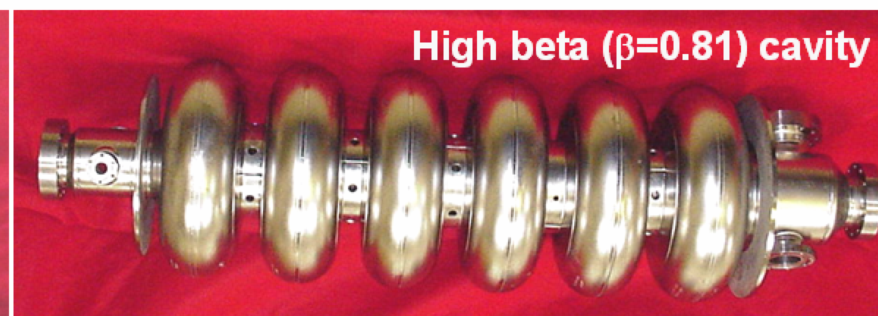
&

Q_o> 5E9 at 2.1 K









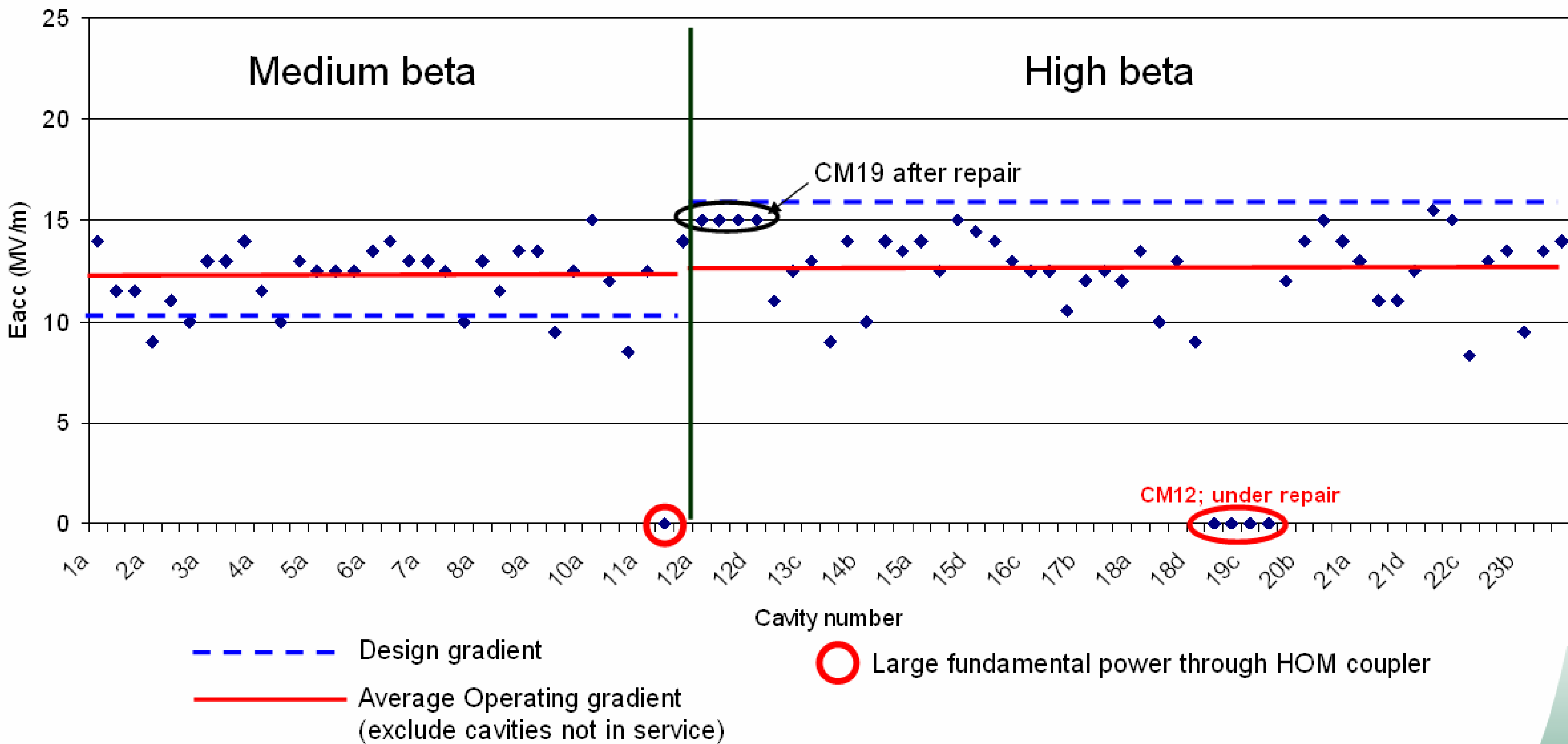
SNS SCL status

- Completed CM installation (April-June 2005)
- SCL commissioning with beam (Aug.-Sep. 2005)
- Formal production run (since Oct. 06)
- 2 K transition; 30 Hz production run (Jun./07-Sep./07)
- 60 Hz production run at 2.1 K (Since Nov./07)
- Present run; 550 kW beam on target at 60 Hz, ~900 MeV, 76 cavities in service
- **Presently SCL is one of the most reliable systems**
  - Drastically improved trip rates by better understanding of cavity/cryomodule/other systems
  - Trip rate from the cavity/cryomodule side is approaching zero

Major Parameters achieved vs. designed

Parameters	Design	Individually achieved	Highest production beam
Beam Energy (GeV)	1.0	1.01	0.9
Peak Beam current (mA)	38	40	35
Average Beam Current (mA)	26	24	18
Beam Pulse Length (μs)	1000	1000	580
Repetition Rate (Hz)	60	60	60
Beam Power on Target (kW)	1440	550	550
Linac Beam Duty Factor (%)	6	3.5	3.5
Beam intensity on Target (protons per pulse)	1.5×10^{14}	1.3×10^{14}	0.53×10^{14}
SCL Cavities in Service	81	79	76

Operating Status



- **Mainly limited by Electron loadings (mostly FE) and their affections between cavities (+ lack of RF power at high intensity beam)**
  - **Medium beta CMs are performing above spec.**
  - **High beta CMs are running 3 MV/m lower than spec.**

Operational Experiences

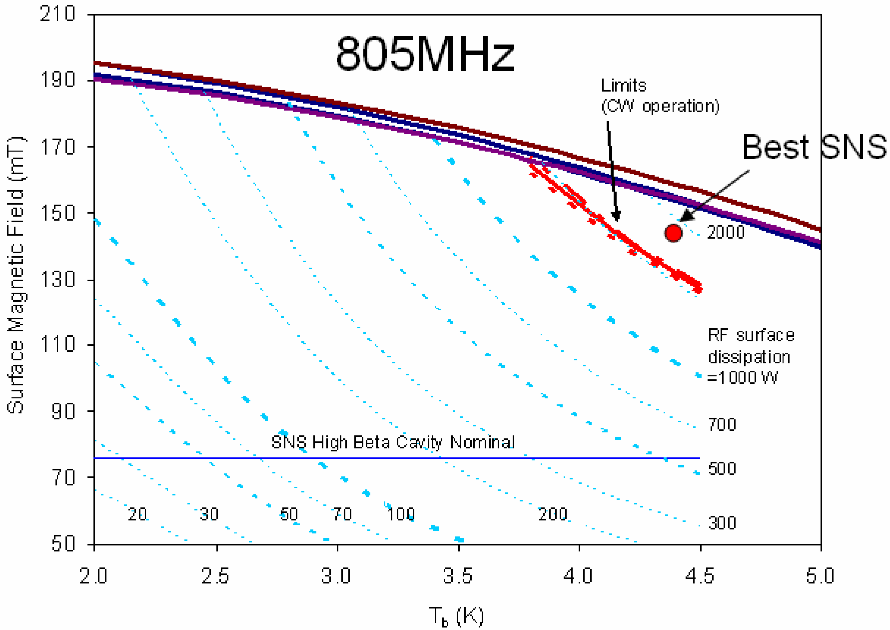
SNS SCL

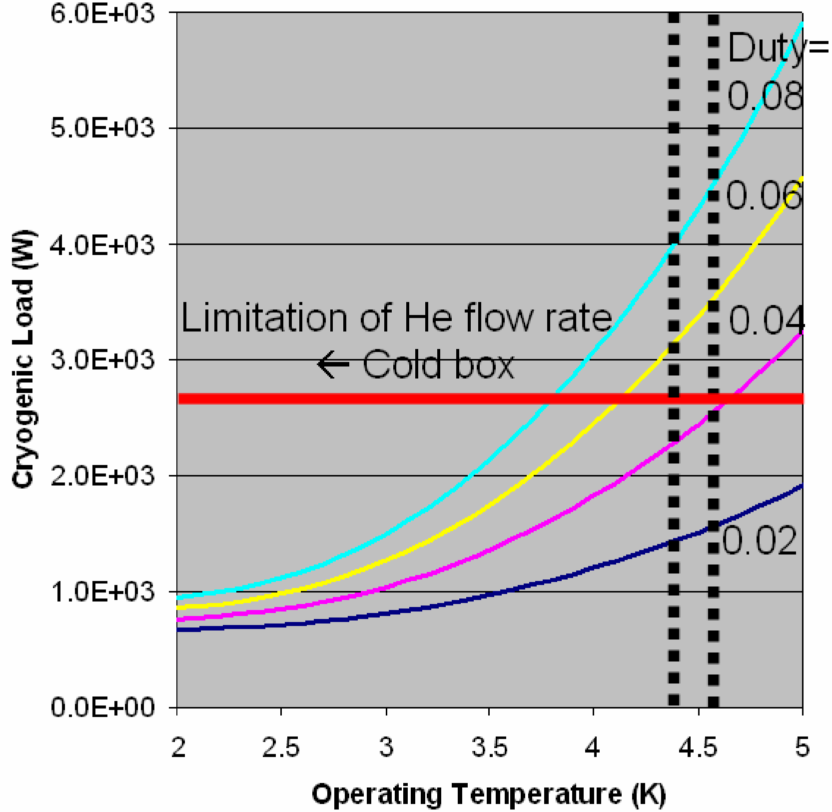
- The **first pulsed operational** machine at a relatively **high duty**
- **We have learned and are learning many aspects**
  - Operating temperature
  - Heating by electron loadings (cavity, FPC, beam pipes)
  - MP & Turn-on difficulties
  - HOM coupler issues
  - Tuner
  - Beam loss
- **Strong emphasis on a high availability as an user facility**
  - Update/upgrade/implement what we learned in a simple, reliable and robust way
  - Change system configuration as needed
  - Software upgrade for better interlocks, alarms, monitoring, llrf

Operating Temperature

Pulsed nature of the SNS operation
& relatively low operating frequency
→cavities at 4.5 K up to the critical field.
Both calculations and experiments tell
→there's no difference
in performances of the SNS SRF cavities
when the operating temperature < 4.5 K.

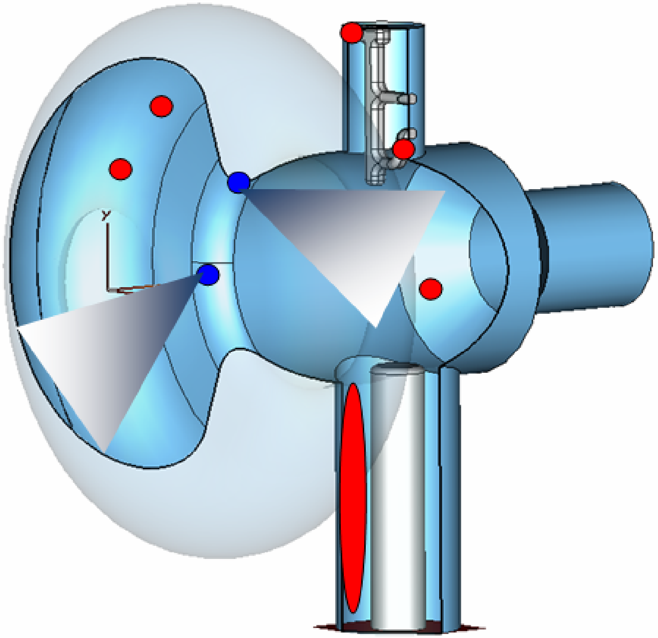
w/ existing SNS cryo-plant
~30 Hz operation → very marginal





Optimization can be done for the future machines
→ Static loss, duty, frequency, plant capital, op cost, etc.

Electron Loading and Heating



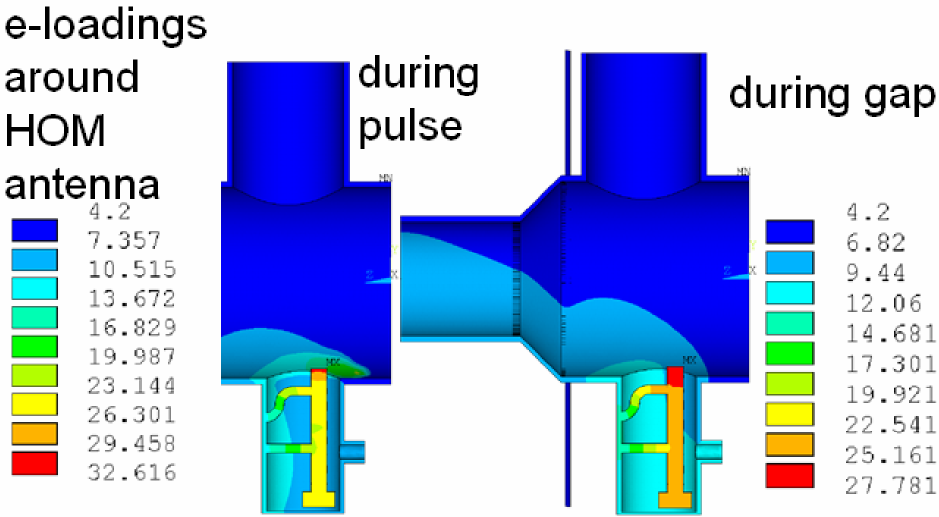
Initial VTA or CM HP tests could have a significant conditioning effects for both

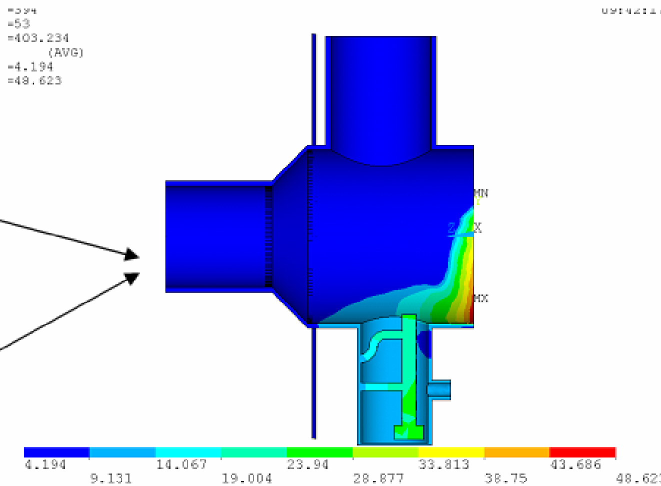
- FE; due to high surface electric field
- MP; secondary emission
  - At resonant condition (geometry, RF field)
  - At sweeping region; many combinations are possible for MP
    - Temporally; filling, decay time
    - Spatially; tapered region
    - Non-resonant electrons→ accelerated → radiation/heating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

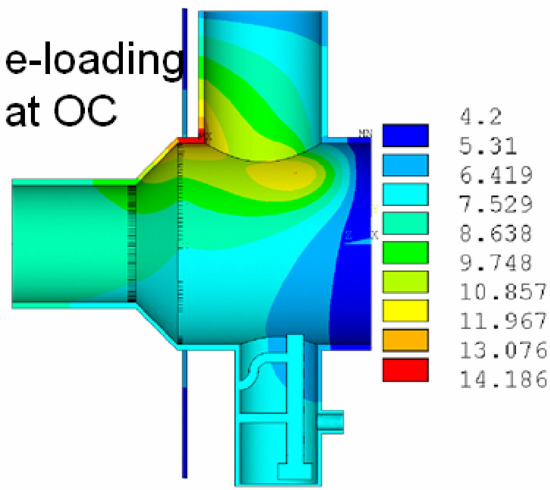
Usually ended-up

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

Quenching pattern examples in the end group







Low RRR & long path to the thermal sink

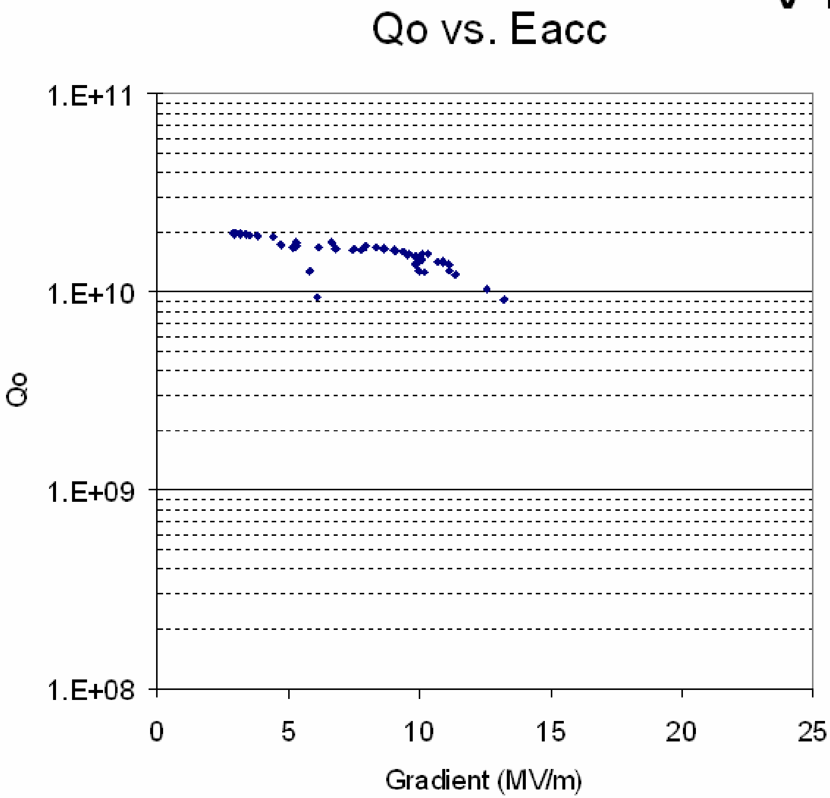
→Thermal margin is relatively small,

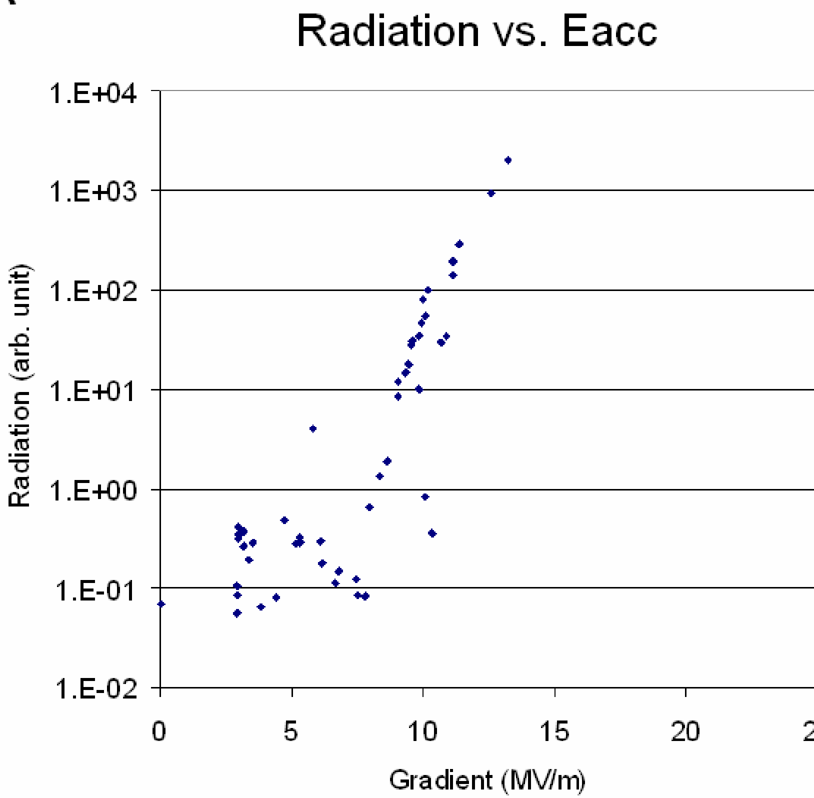
→Intermediate stage at the end-group

→Results in thermal quench/gas burst

Field Emission ?

VTA

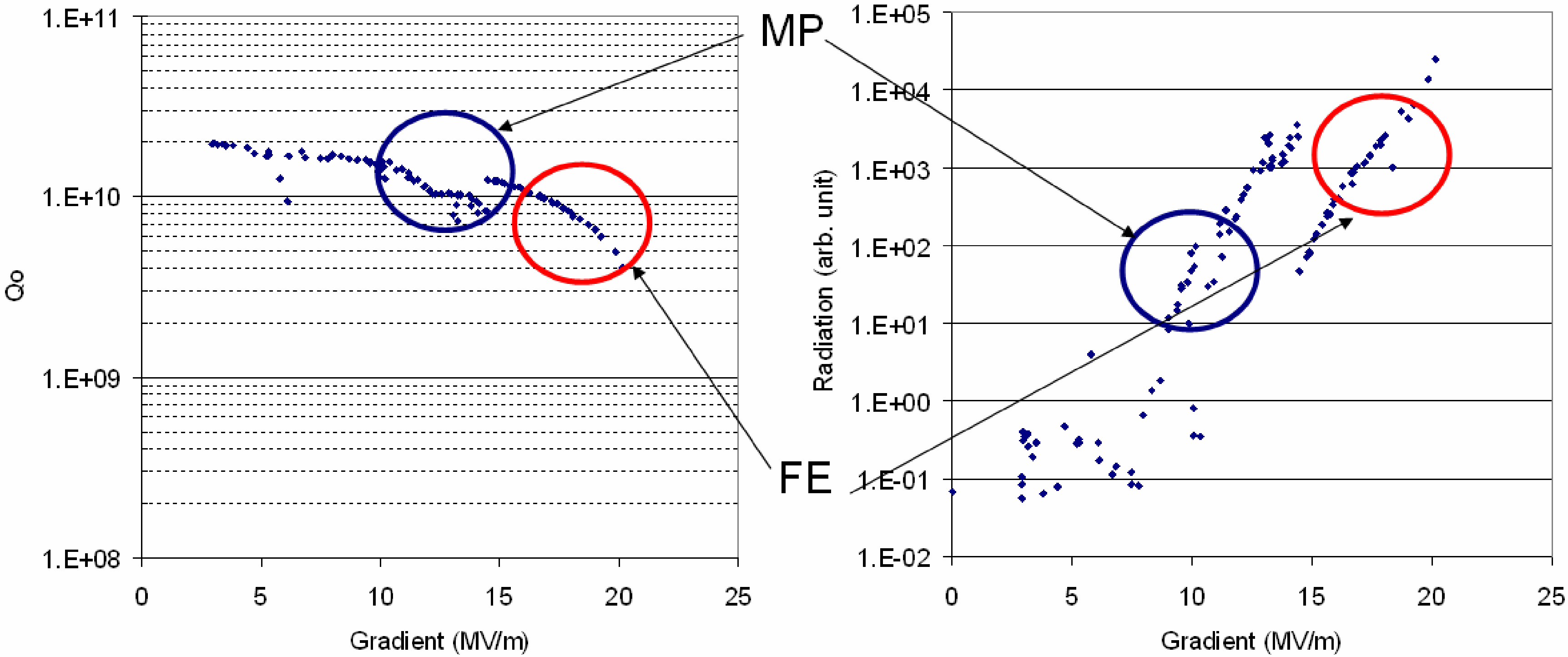




If this cavity is limited at this condition, what is the limiting factor?
Field emission?

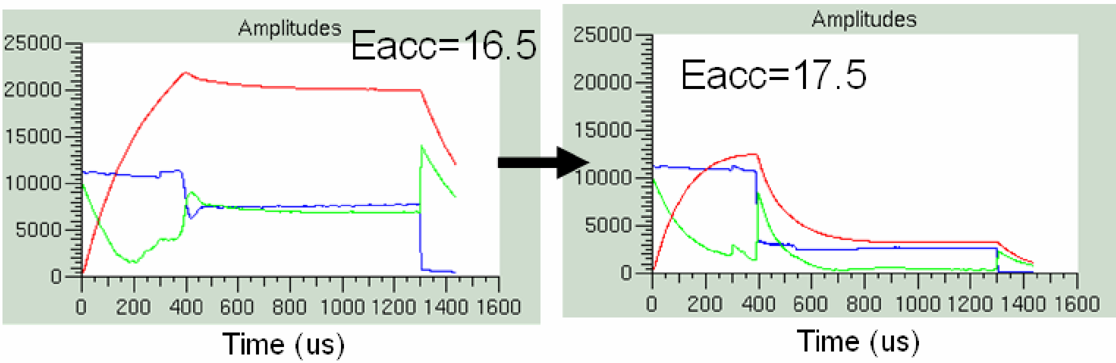
MP! And then later on Field Emission !

VTA

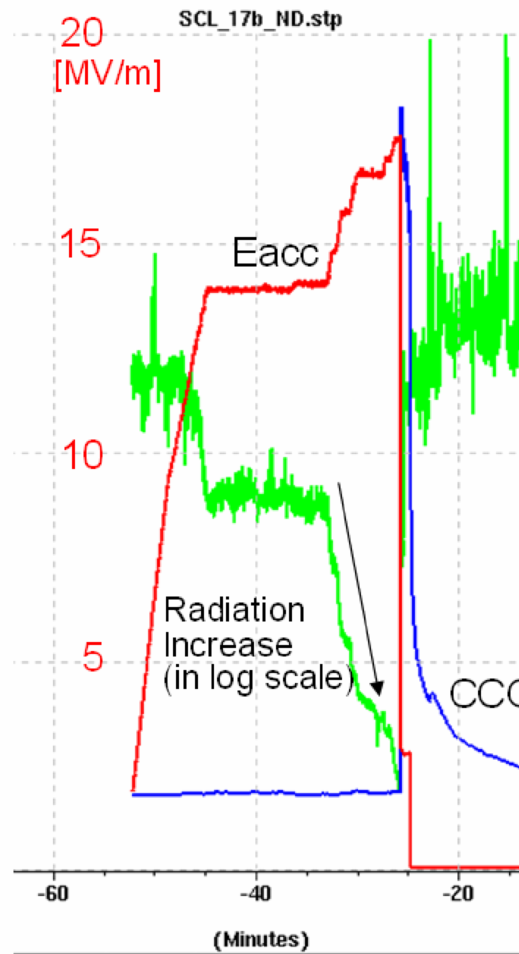


Field emission

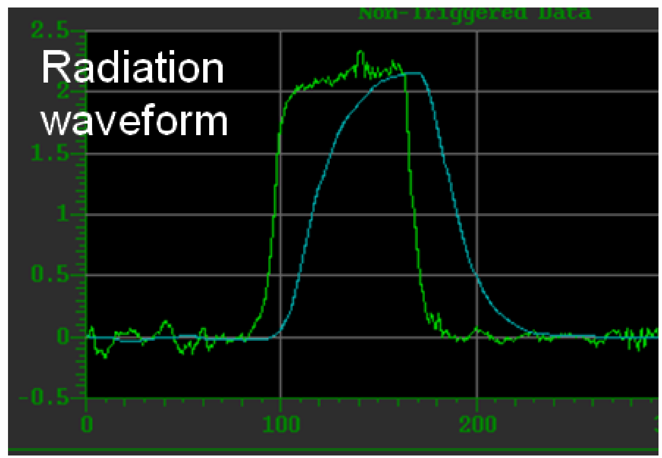
17b in open loop



Ex. 17b individual

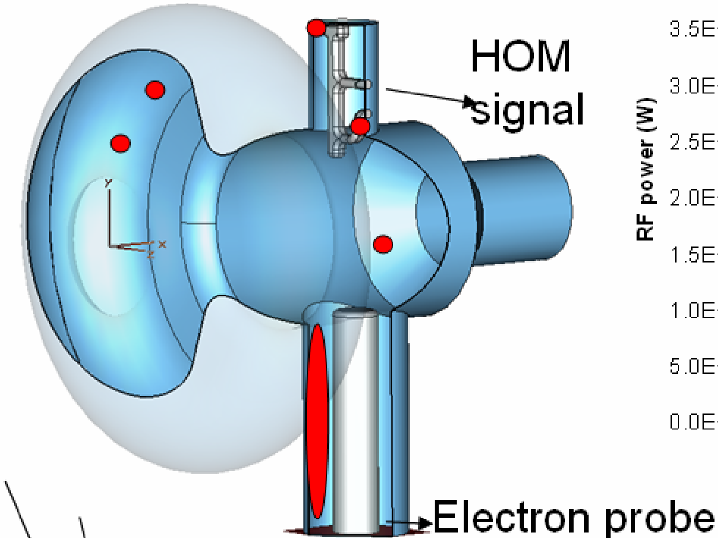


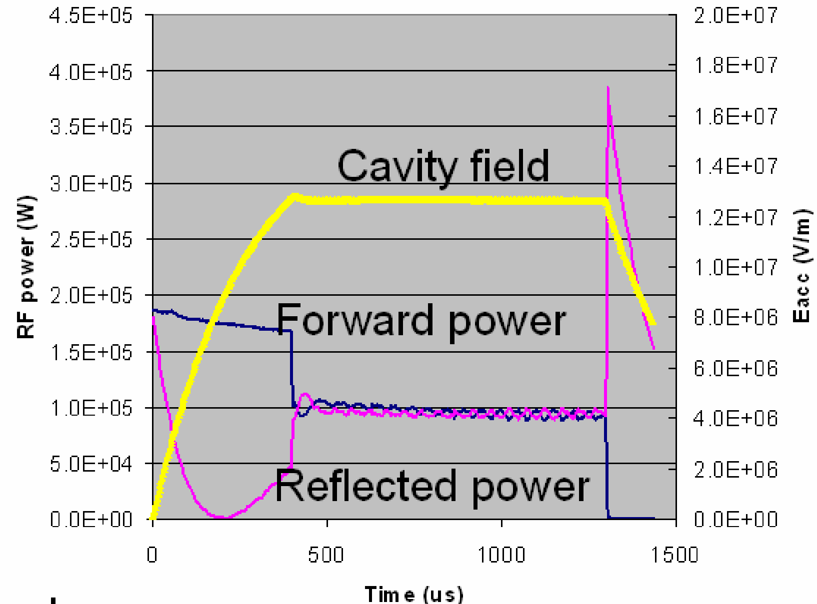
Pulsed operation
→Waveform tells us
what is happening inside

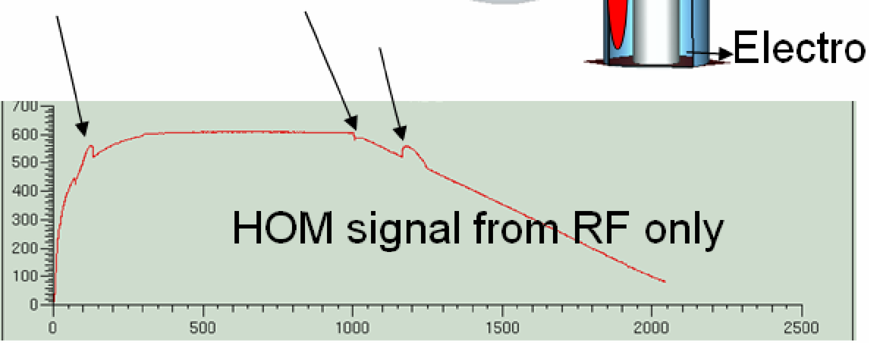


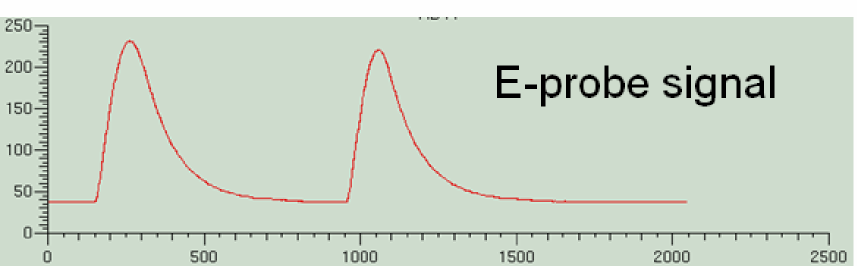
17b
Radiation at Eacc=16.5
(Elim=17.5 MV/m due to FE!)

Multipacting



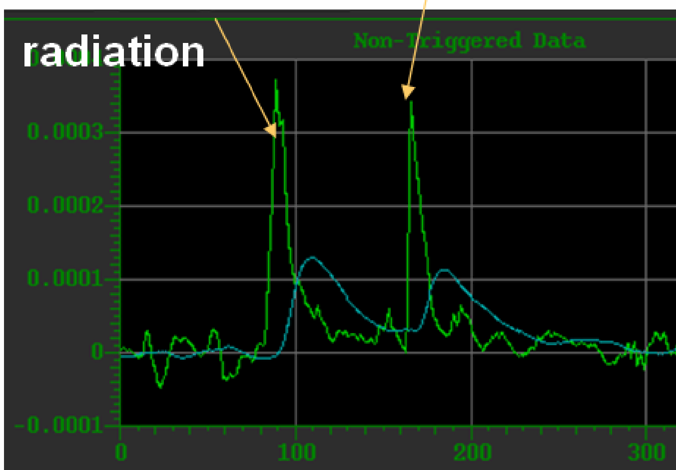






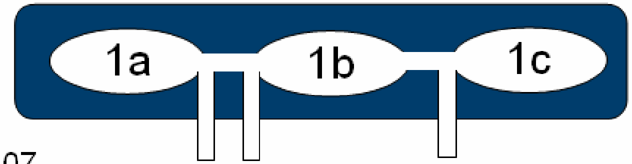
During cavity filling

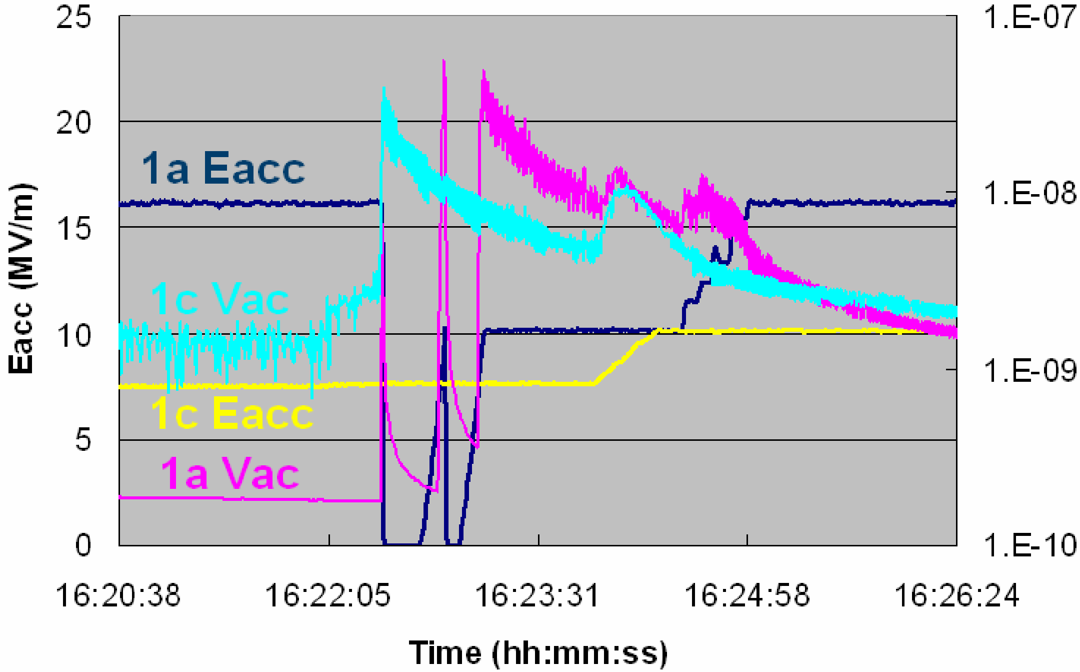
At the end of pulse or decay

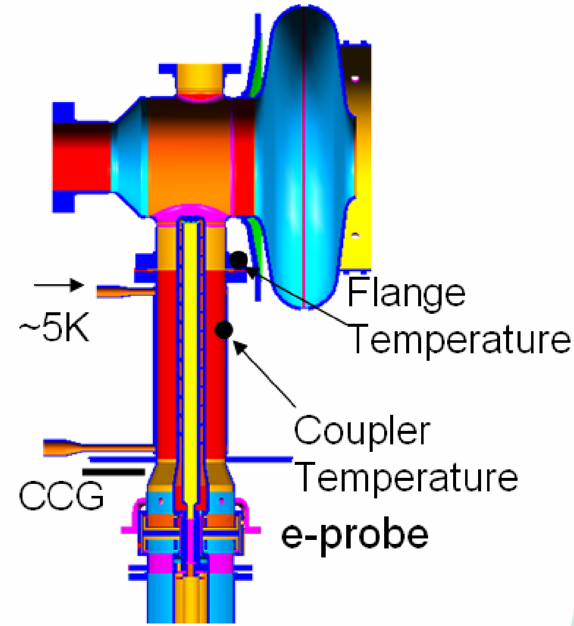


Implies that MP in one cavit
can excite the others

Turn on and MP







MP at around coupler → vacuum response, e-probe

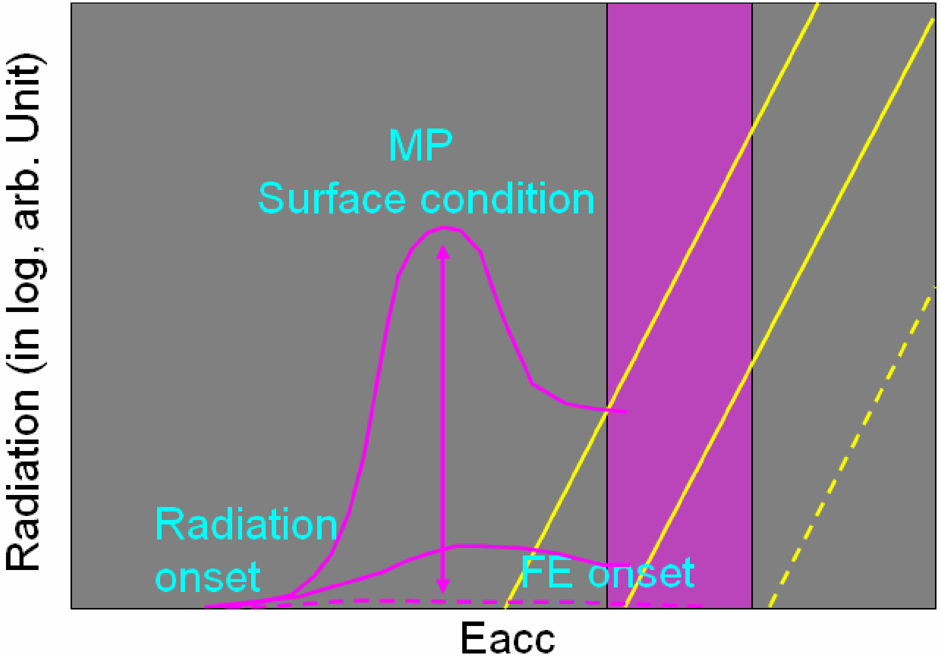
→Also electrons can travel whole cryomodule and excite MP at the neighboring cavities

Ex. Here 1a by itself does not have MP. MP excited by electrons from 1c.

Very difficult turning on cavities during the first year of operation

CCG reading; No response or too much, does not match with e-probe signal

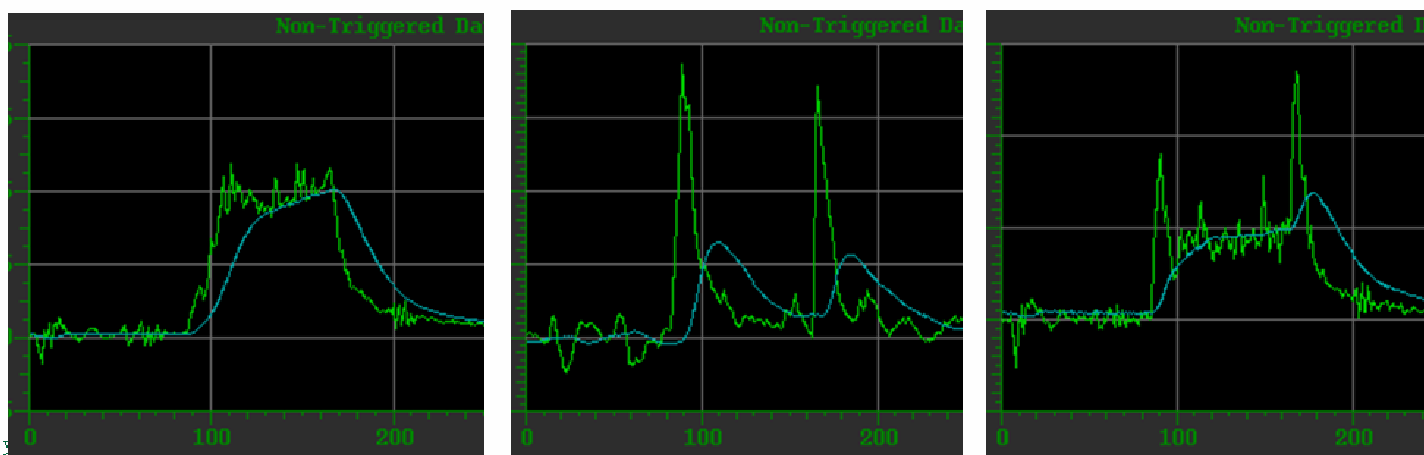
SNS cavity operating regime



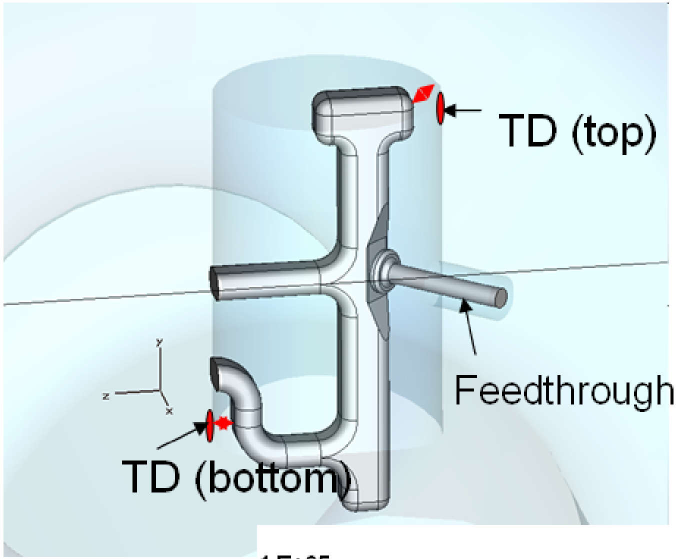
After initial commissioning and conditioning
→surface conditions are quite stable

re-distribution of gases (slow & fast)
→processible

Gradient settings in SNS SCL;
Not uniform gradients as designed
But as high as individually achievable

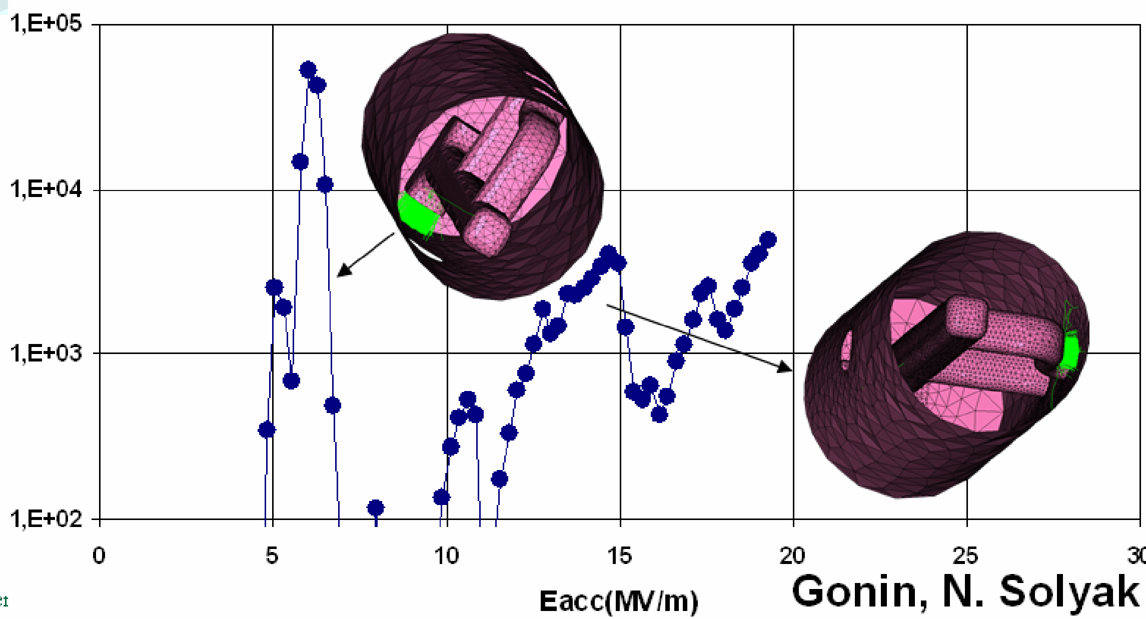


Without HOM feedthrough



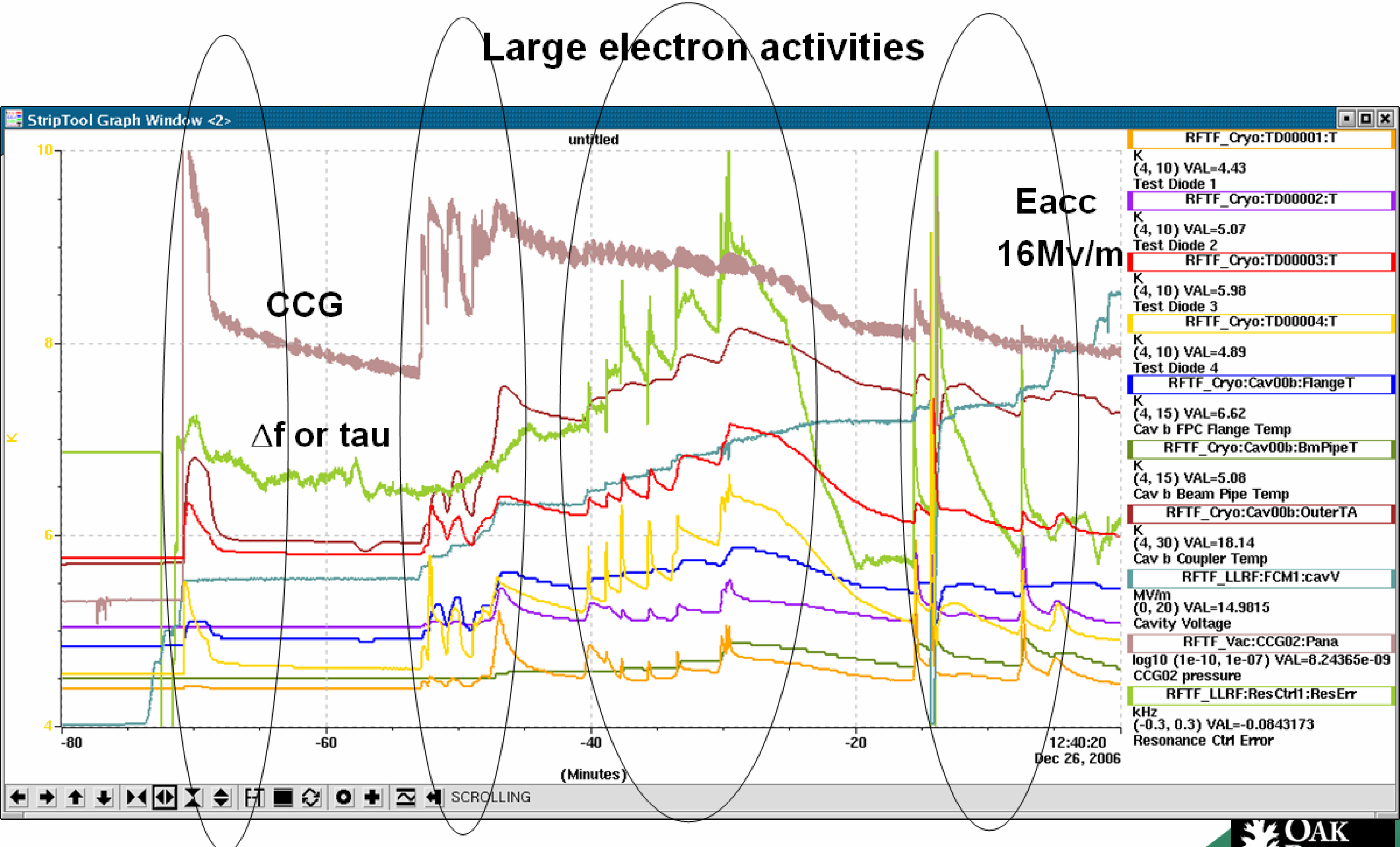
Both feedthroughs of 19b HOMA and B ; removed and blank-off
Add thermal diodes (TD)
at around multipacting regions

CM19 test at Test Cave;
All individually tested up to ~16 MV/m at 4 K, 30 Hz, 1ms, in open loop, (about the same gradient we got in the linac tunnel at 30 Hz, collectively)
→ in service in the tunnel; all at 15 MV/m (best CM)



Gonin, N. Solyak

Cavity test without HOM feedthrough



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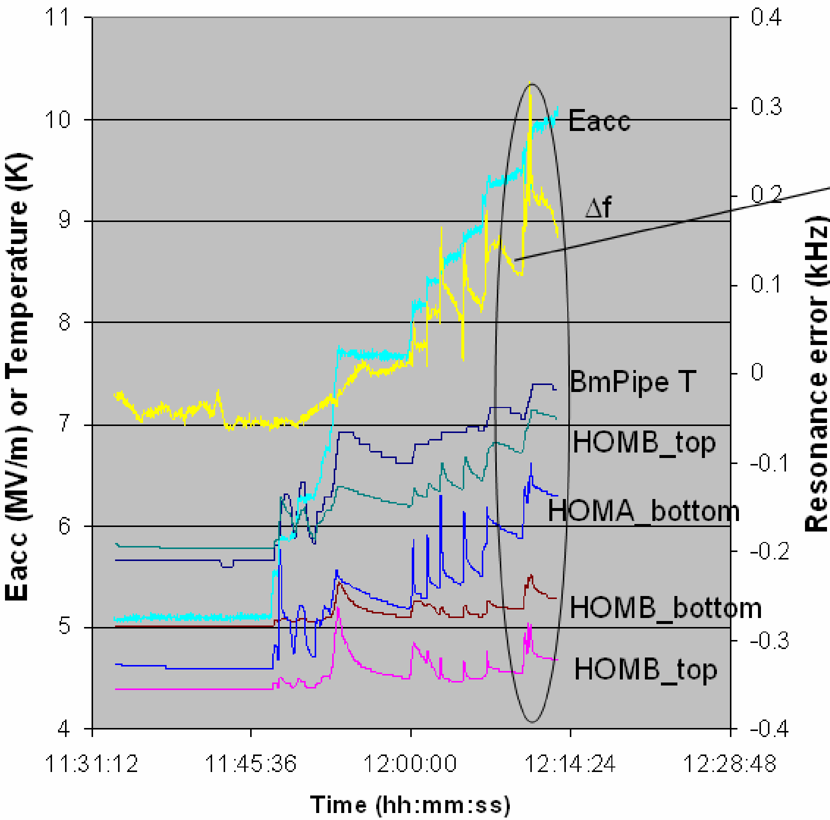
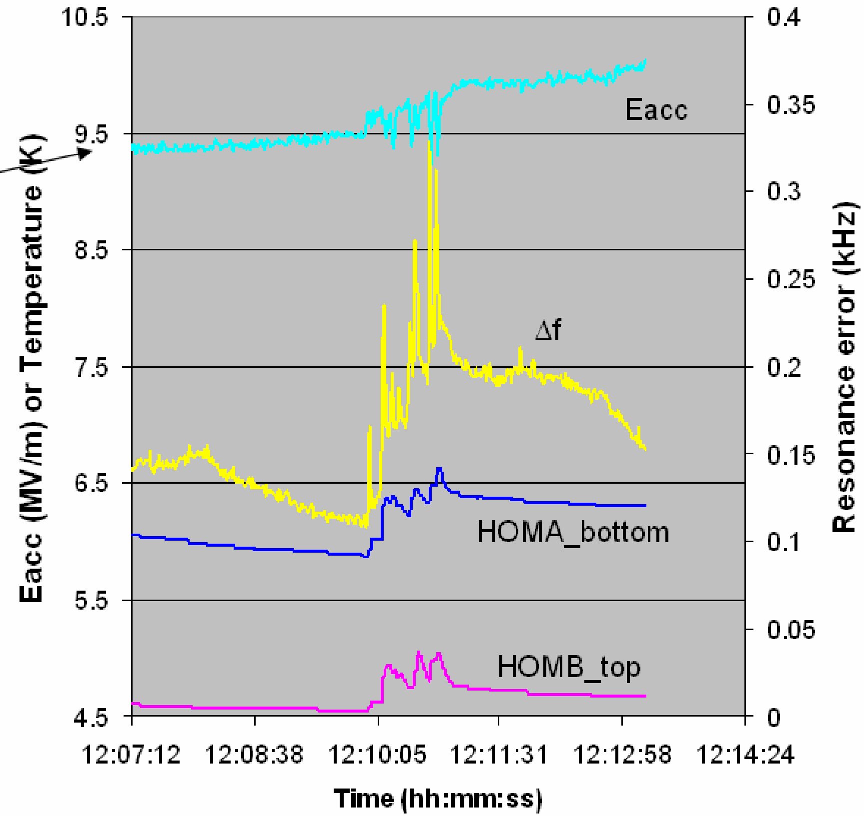
Cavity test without HOM feedthrough





HOMA bottom TD signal led all other TDs, (Coupler vacuum)

aggressive electron activity

excitation of the whole cavity

changes of bandwidth (or Qex, Δf), drops Eacc down by several %

quench (> a few kW of RF → electrons → deposit on the surfaces

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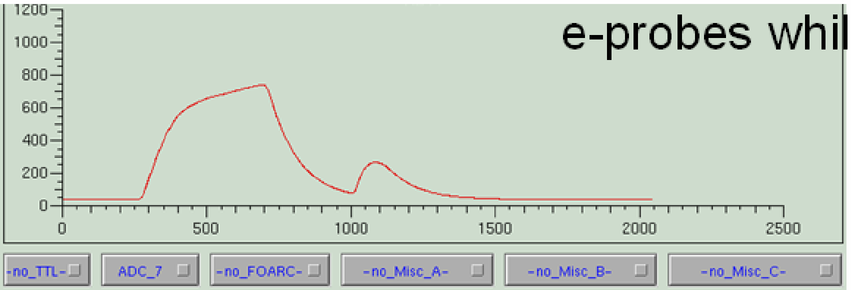
E-probe & HOM signals during CM 19 test

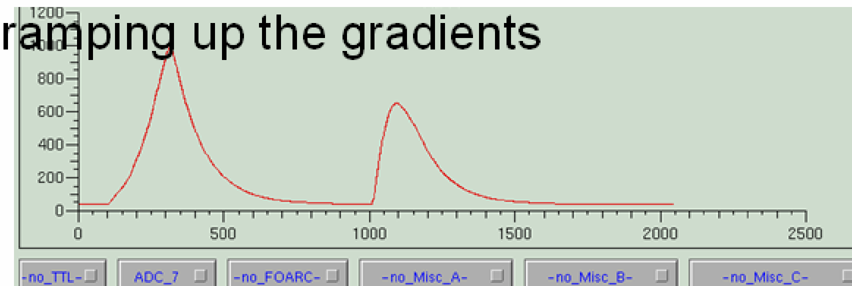
;All showed similar behavior

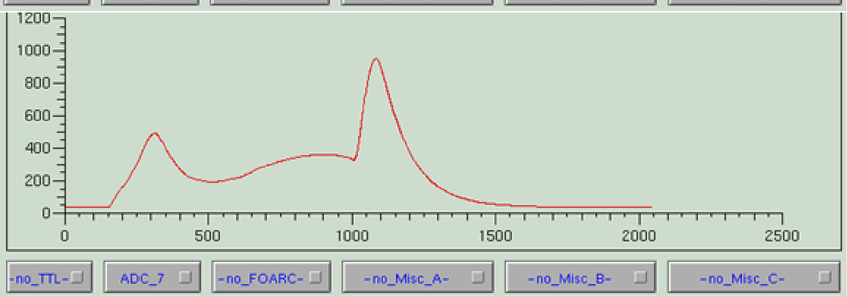
19b (no feedthrough) showed very aggressive electron activities

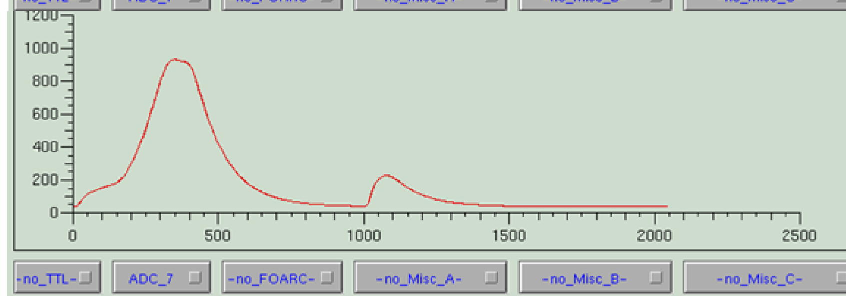
← processing was possible with no feedthrough

e-probes while ramping up the gradients

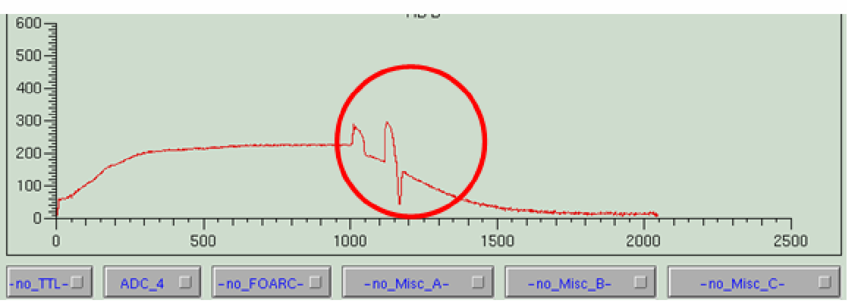


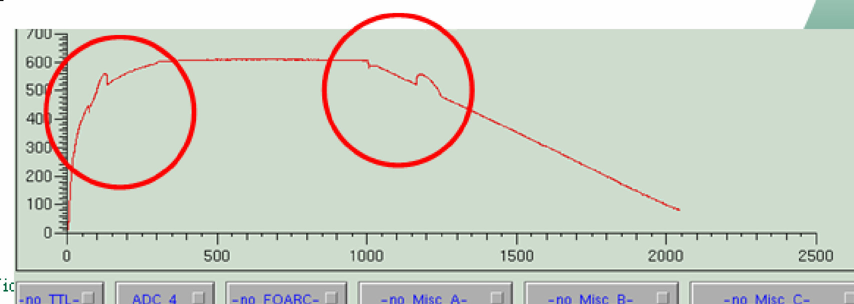




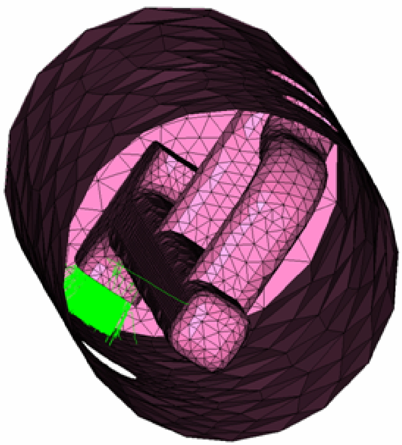


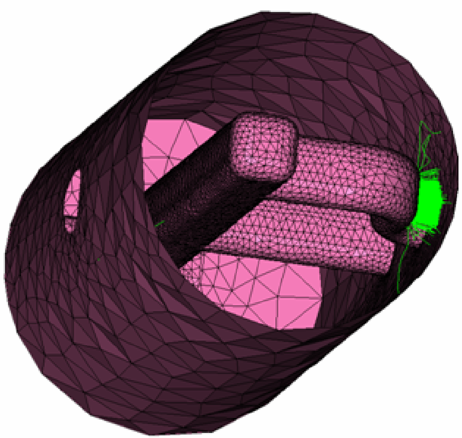
HOM

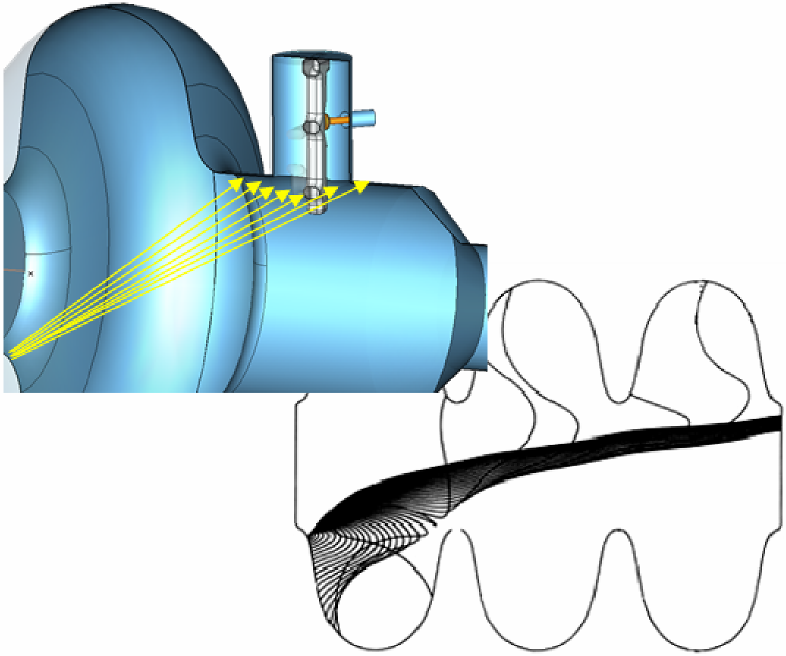


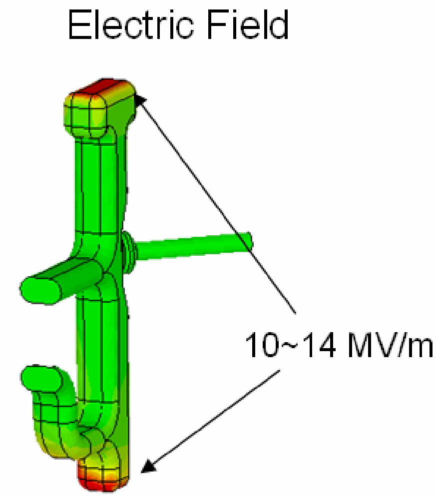


Electron activities → damage HOM coupler







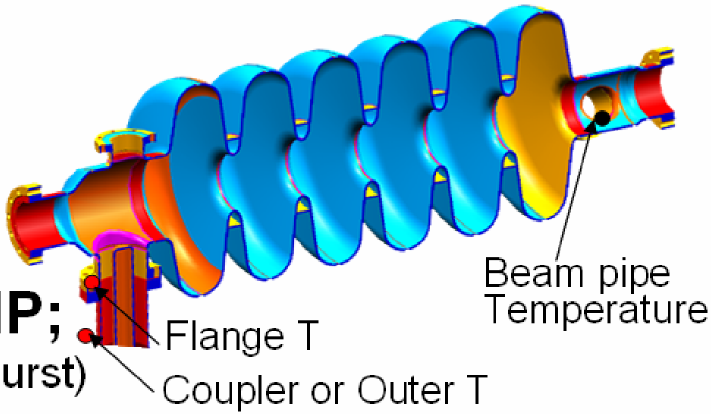


Any electron activity
→Destroy standing wave pattern
(or notching characteristics)
→Large fundamental power coupling
→Feedthrough/transmission line damage
→Irreversible

Turn-on and High power commissioning

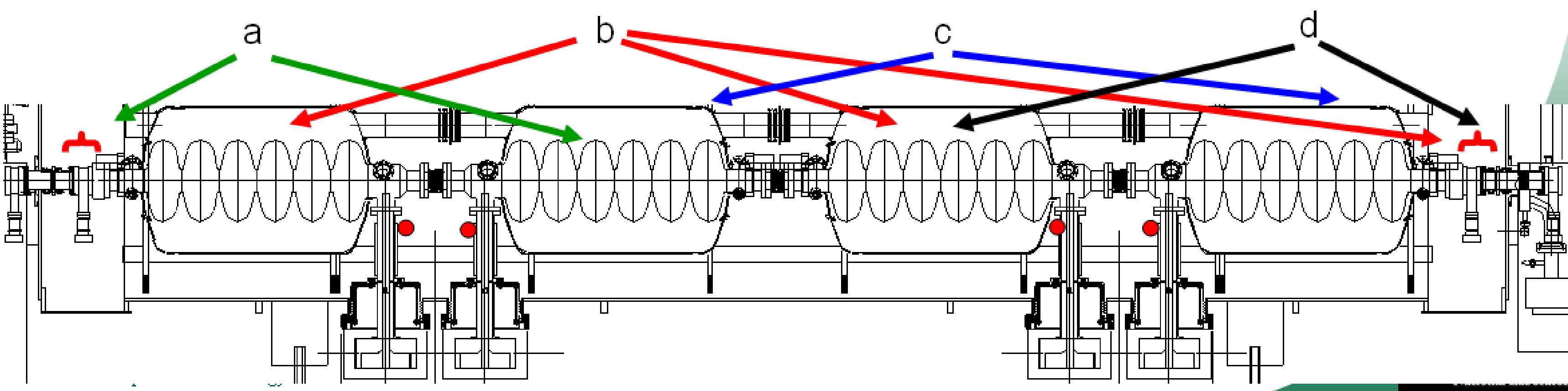
- **First turn on must be closely watched and controlled (possible irreversible damage)**
  - Initial (the first) powering-up, pushing limits, increasing rep. rate (extreme care, close attention)
    - Aggressive MP, burst of FE → possibly damage weak components
    - Similar situation after thermal 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**

Collective limits
(clear indication at higher rep. rate)

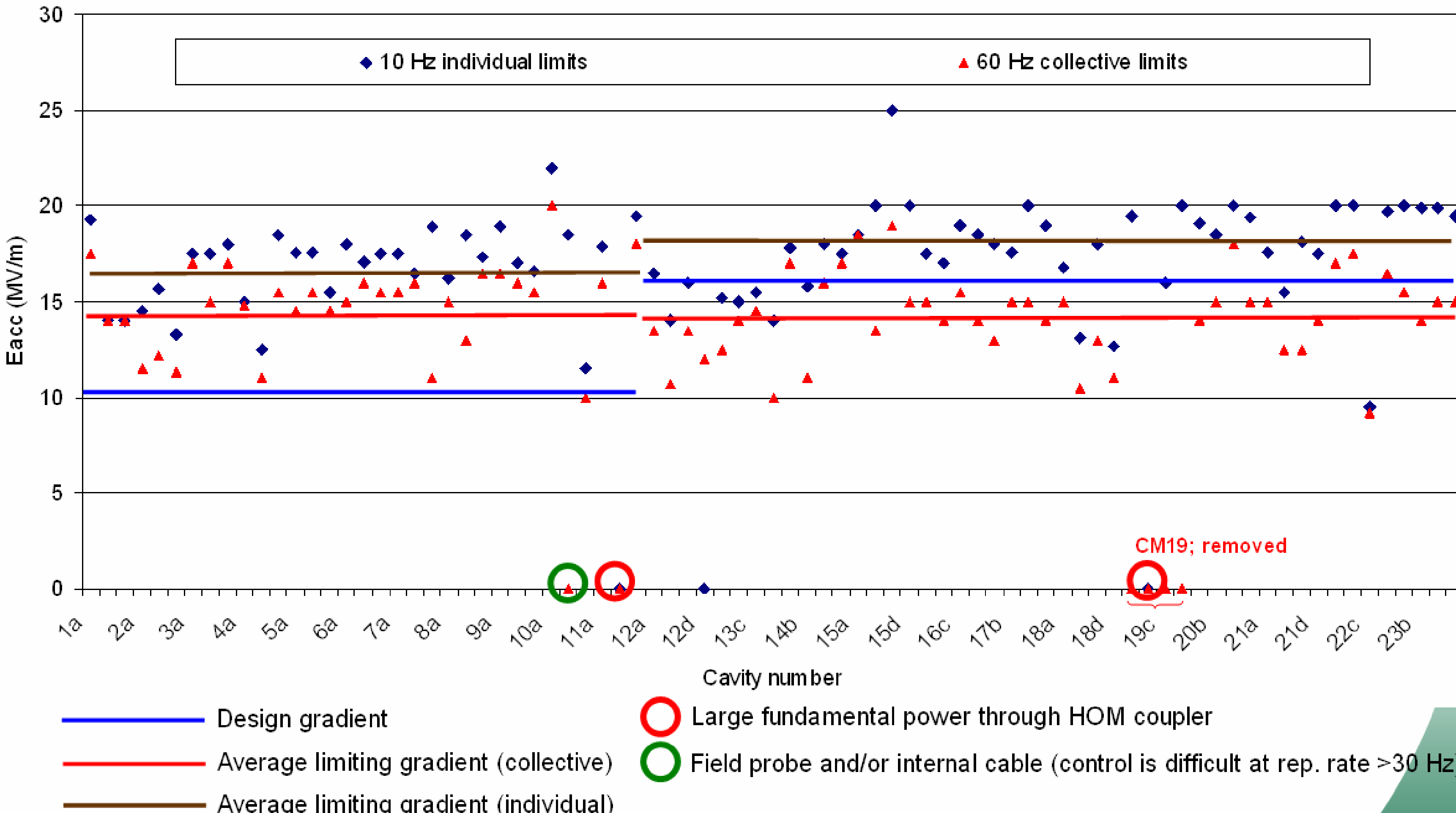


- **Electrons from Field Emission + MP;**
  - steady state electron activity (+ sudden burst)
  - affects other cavities
  - electron landing place (relative phase, amplitude)
  - leads continuous gas activity, even though all signals look quiet
  - heating starts → end group quench and/or
  - hits intermediate temperature region (5-20K); H_2 evaporation (burst of gas)
  - redistribution of gas→ changes cavity/coupler conditions

Ex. CM13 individual limits; 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits; 14.5, 15, 15, 10.5 MV/m



Individual limits and collective limits

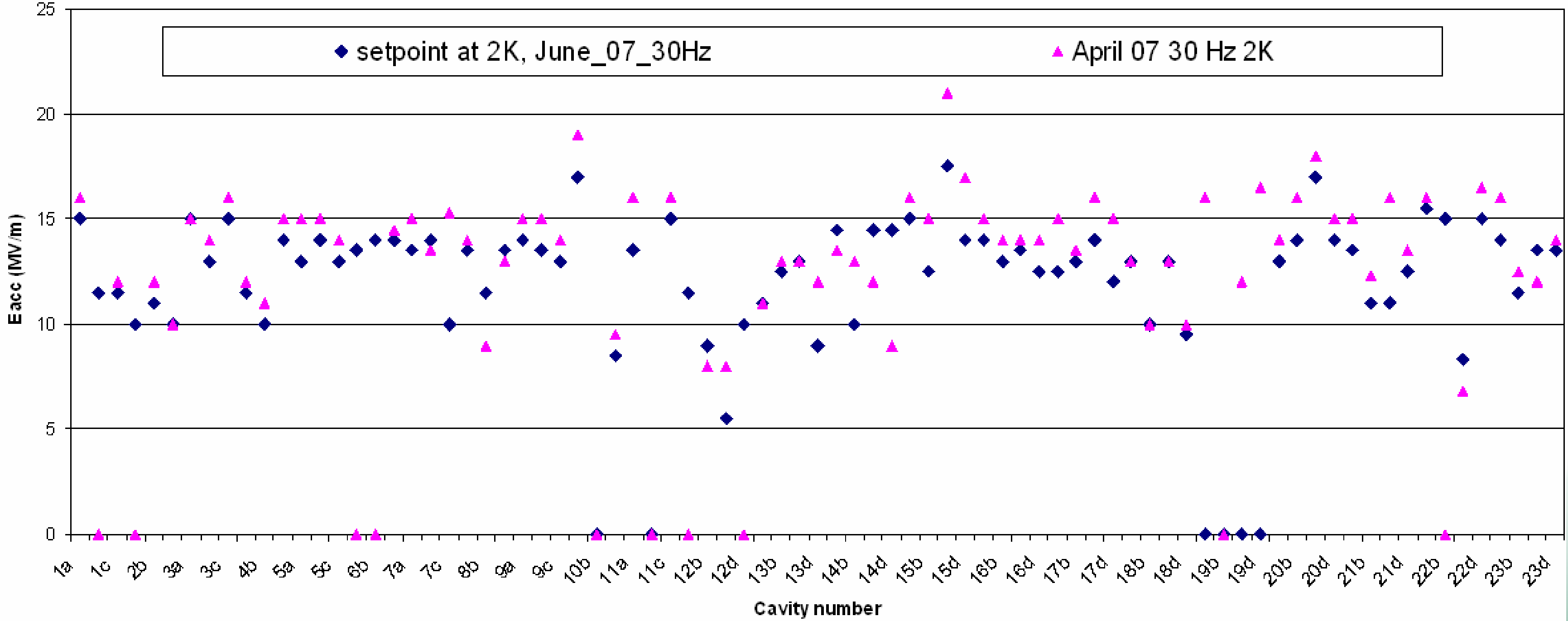


Individual; powering a cavity at a time

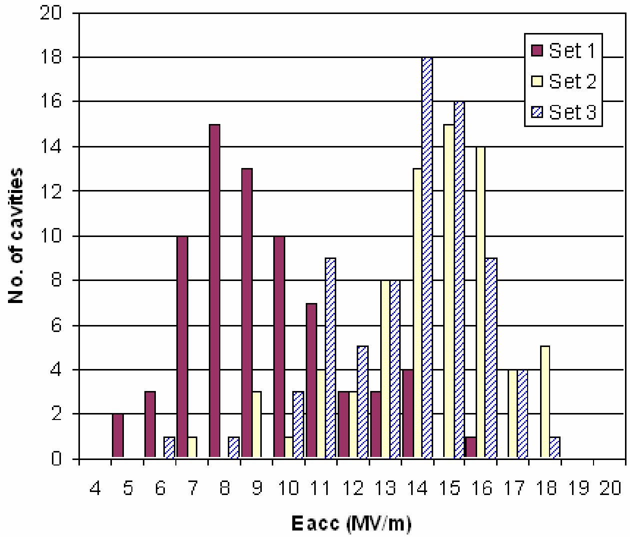
Collective; powering all cavities in a CM at the same time

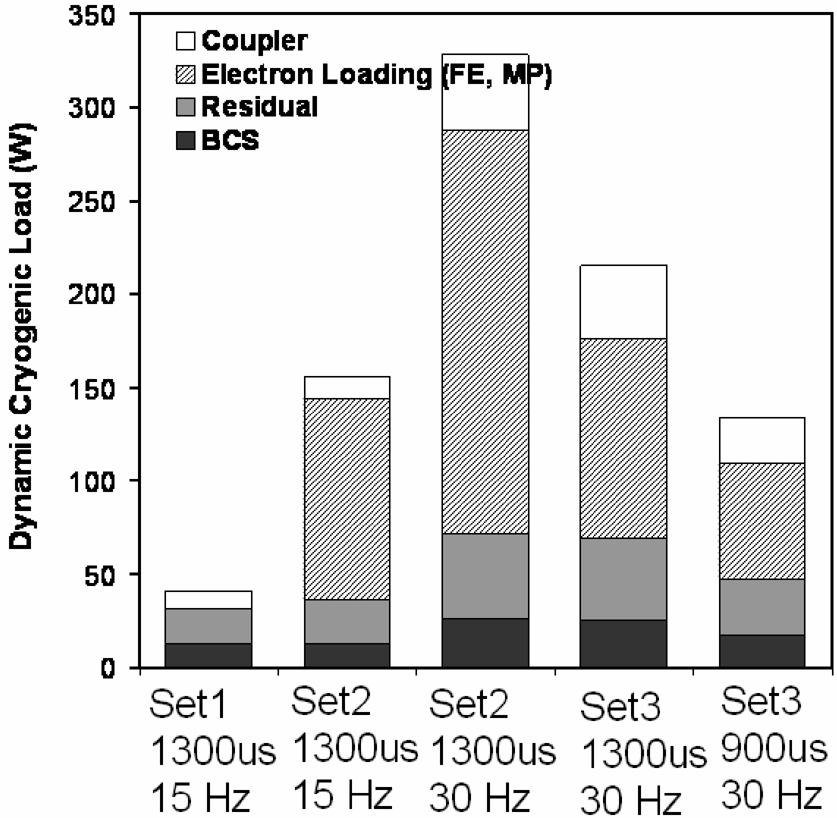
Large performance variations cavity to cavity

Electron loading (FE, MP) amount from the Cryogenic loads



Electron loading (FE, MP) amount from the Cryogenic loads



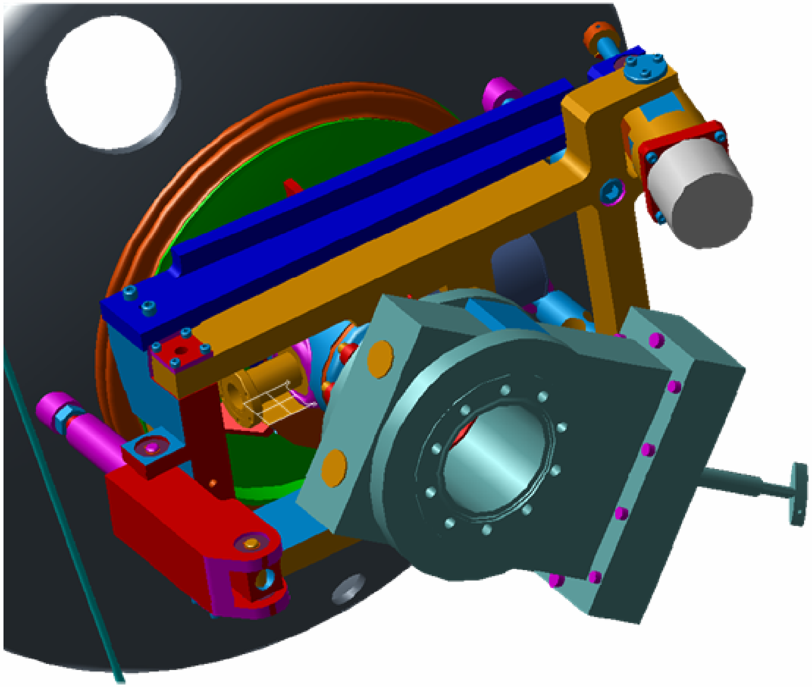


Set 1; Below radiation threshold (~9MV/m)
Set 2; 80 % of individual limits
Set 3; 88 % of collective limits
Avg(set2)-Avg(set3)~1MV/m

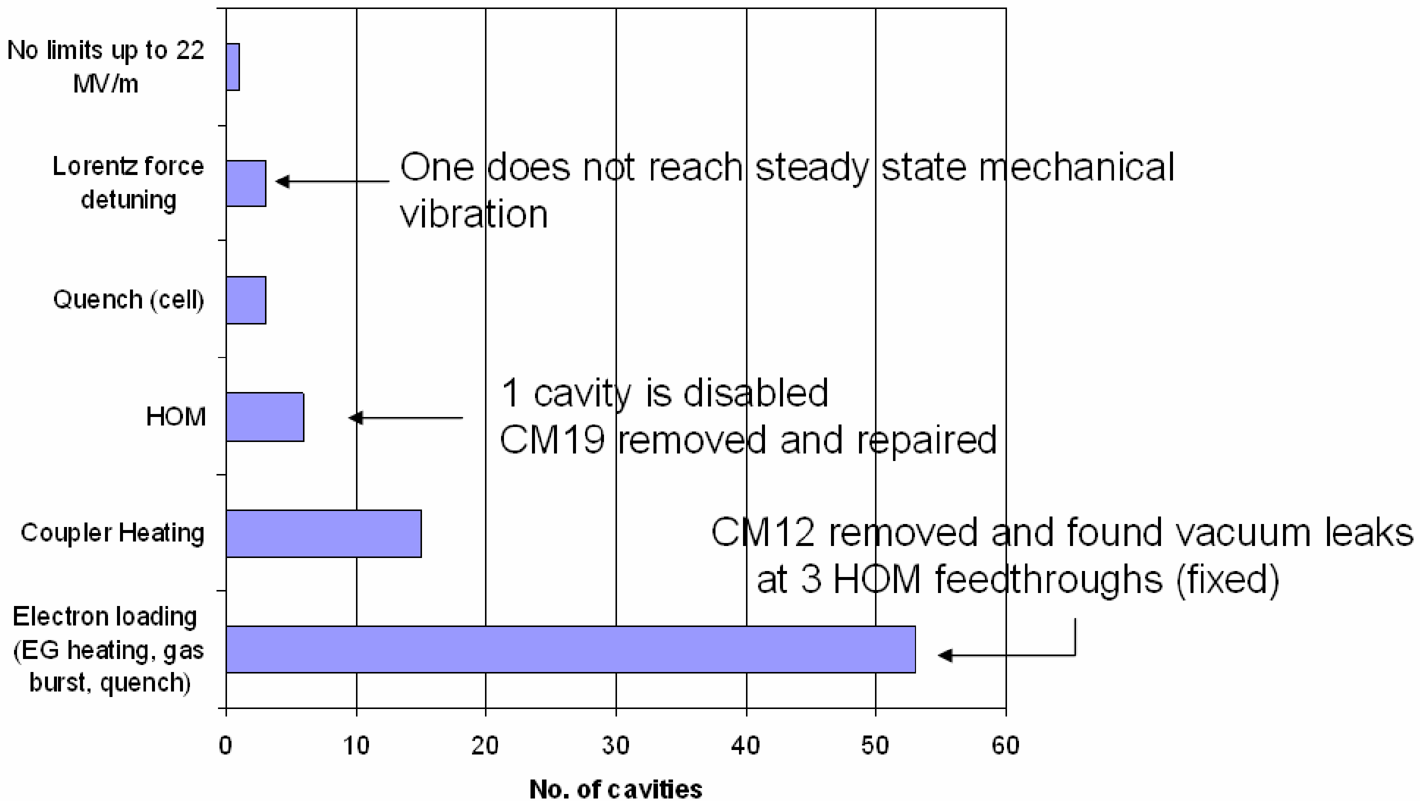
Total dynamic heat loads due to different sources

Tuner

- Slow tuner
  - Stepping Motor + Harmonic Driver
- Piezo Tuner
  - Piezo tuners installed compensate for the Lorentz detuning
  - Not yet used in operations
  - May be activated on selected cavities if necessary
  - If piezo stack fails, the cavity cannot be operated



Statistics of limiting factors (60 Hz collective)



-Performances of MB cavities are very good.

collective limits; medium~14.9 MV/m, high~14.3 MV/m

individual limits; medium~16.9 MV/m, high~17.8 MV/m (closed loop)

individual limits; medium~18.8 MV/m, high~19.1 MV/m (open loop)

-Some cavities have multiple limiting factors.

-~14 cavities are limited by coupler heating, but close to the limits by radiation heating

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

Operations constraints: improving performance since turn on

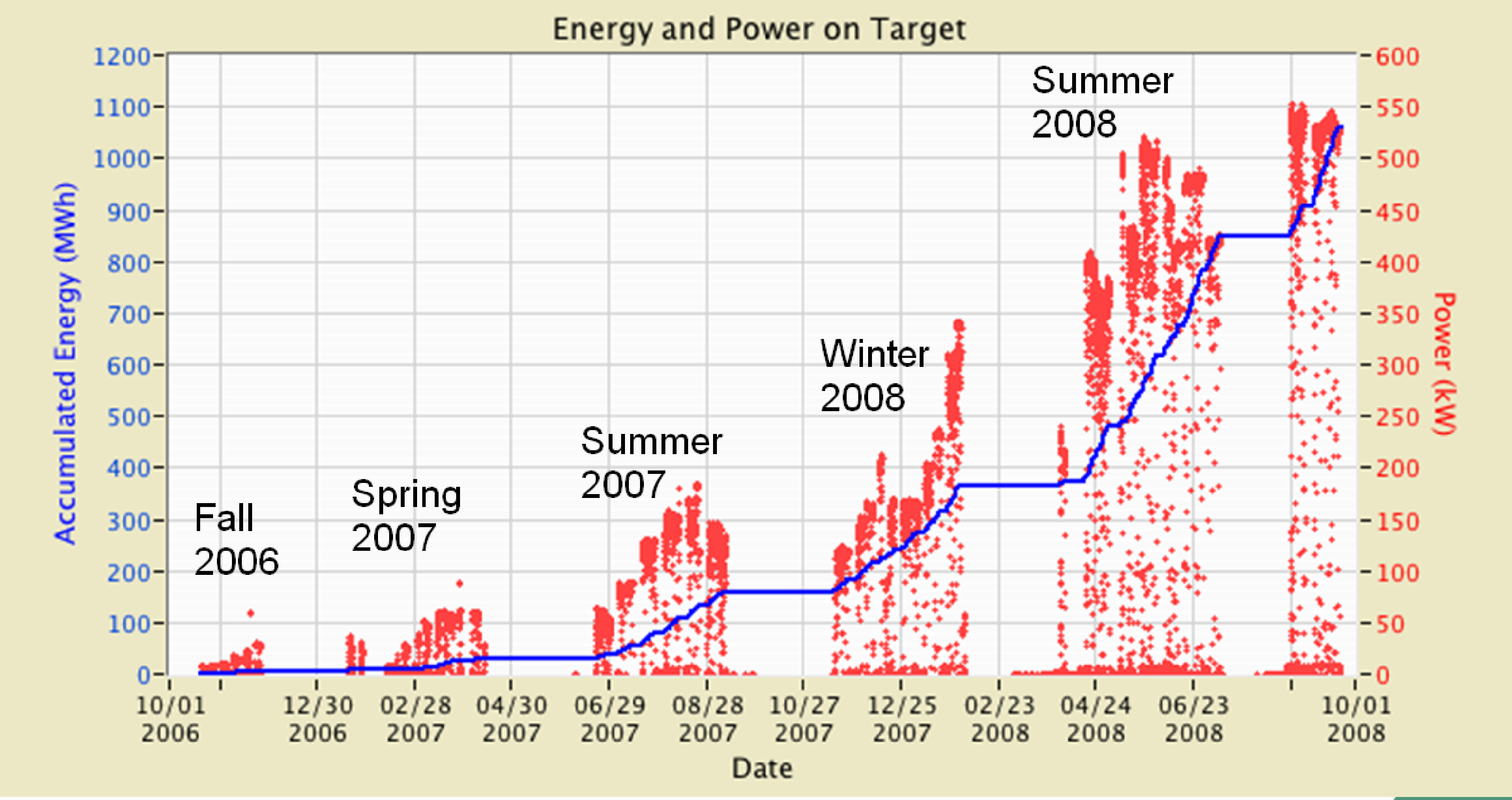
- **Drastically improved trip rates by better understanding of:**
  - underlying physical phenomena (outgassing, arcs, discharges, radiation, field emission, beam strike, dark current etc.) → 60 Hz collective limits
  - components response (arc detectors, HOM couplers, Cold Cathode Gauges, coupler cooling, end group heating) → determine what are meaningful
  - controls (LLRF logic, programming, choice of limits and stability parameters) → apply what we learned to the real control system…debugging software, 20 Hz update of LLRF control, improving interlock systems, etc
- **Continue to improve performance and ultimate beam power by:**
  - Optimizing gradients, modulator voltages, matching of klystrons to cavities, circulator settings, available forward power for beam loading etc.

Further Power Ramp-Up

Power Ramp-up Experiences

- Power ramp up over the last two years
  - 5 to 550 kW (figure out many technical/physics problems)
- Power ramp-up; identify issues/problems
  - 'Remember'; the machine power is about an order of magnitude higher than the existing ones → not only beam related but also machine/equipment related issues. Some are new technologies, the first operational attempts, etc.
  - tested machine/systems and learned limits and limiting conditions → set up the machine improvement plan (bottom-up power ramp-up plan; reaching 1MW-grade operational performance in a year from now)
  - Further power ramp-up → still challenging
- Availability is an increasing concern
  - User facility (operational machine)

Power Ramp-up for last 2 yrs
(beam experiences; WE202 J. Galambos)



Beam power ramp-up w/ high availability + reserve

- Current →38 mA peak (26 mA average)

  x

- Energy →1 GeV + reserve (3~4 %)

  x

- Pulse length →1 ms

  x

- Rep. rate →60 Hz

= 1.44 MW on target

Beam power ramp-up w/ high availability + reserve

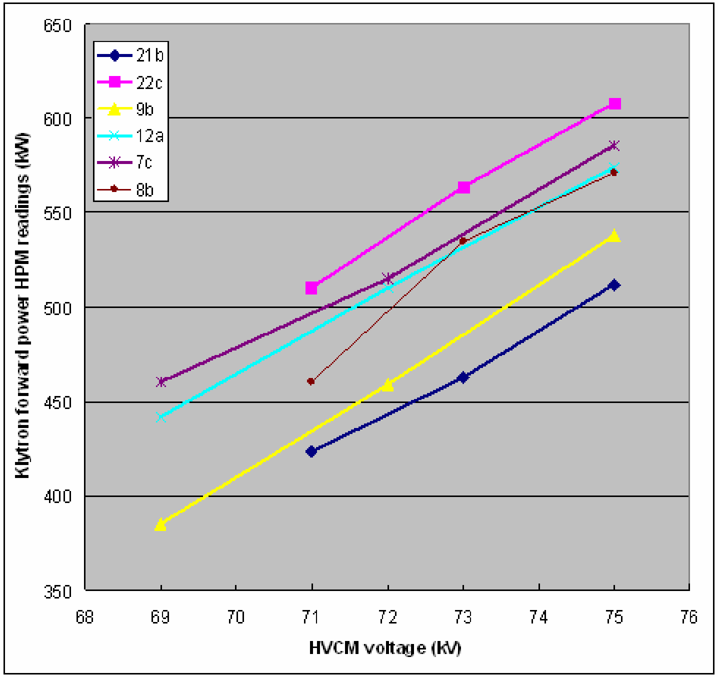
- Current → ion source, beam loading (HVCM,
  x RF), beam loss, chopper, LLRF
- Energy → SCL
  x
- Pulse length → HVCM, ion source, chopper,
  x beam loss, cavity filling time
- Rep. rate → stress for all at full duty

SCL for the Goal

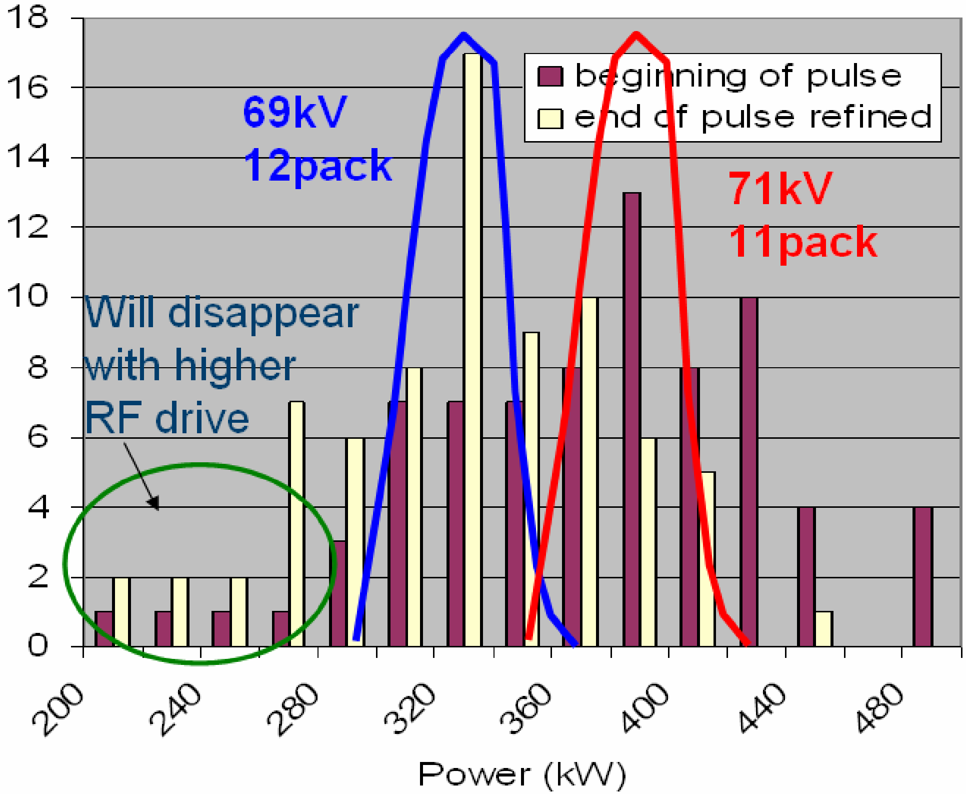
For design beam power in SCL

- 1 ms beam pulse
  - 1350 us HVCM → 1280 us RF (300us filling + 30us FB stabilization + 950us beam)
  - Shorter filling time (need more RF) 950us → 1000us
- 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)
- 26-mA average current (or 38-mA midi-pulse current) at 1-GeV operation
  - Need more RF available for the design beam current

HVCM & RF configuration for SCL cavities



~25kW of RF at saturation/kV of HVCM



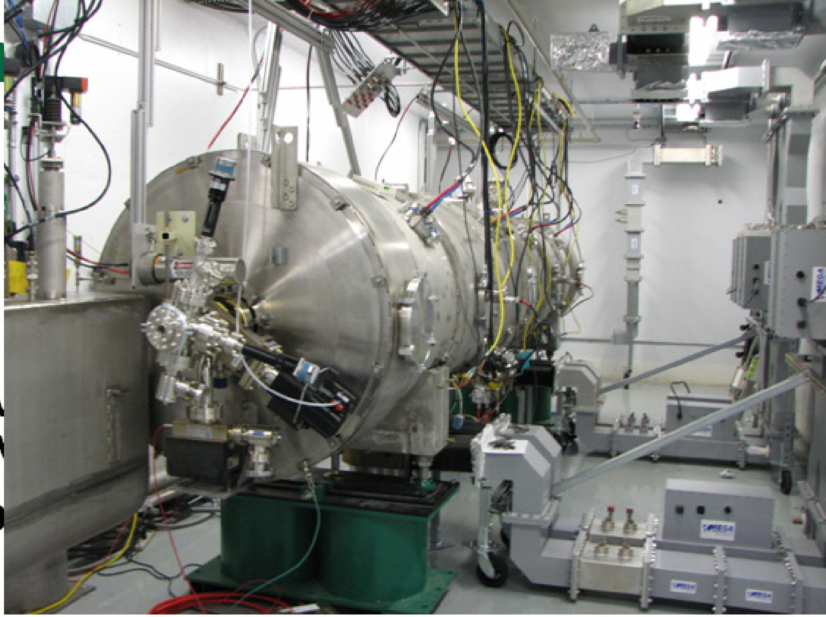
- **Add one more HVCM to get 75 kV operation w/ reliability (next year)**
  - **10 pack configuration**
  - **Enough RF power up to design beam loading**
  - **Cavity filling time can be shortened from 300 us to 250 us**

Beam Energy; repair and spare
(J. Mammosser TH103)

- 76 out of 81 are in service
- Continuous repair efforts
  - 2 CM removed. One back to service, the other is waiting for further repair and test in test cave (will back soon)
  - One cavity in the tunnel is disabled due large fundamental power through HOM coupler
- Spare cryomodules in progress (expect 1 ½ years)
- Early next year we expect 80 or 81 cavities for operation
  - Output energy; about 950 MeV
  - Surface improvements; for 1 GeV + energy reserve (high beta cavities)
    - R&D for In-situ processing; just started
    - He-processing/Plasma processing

OAK RIDGE National Laboratory

Beam Energy; repair an
(J. Mammosser TH103)



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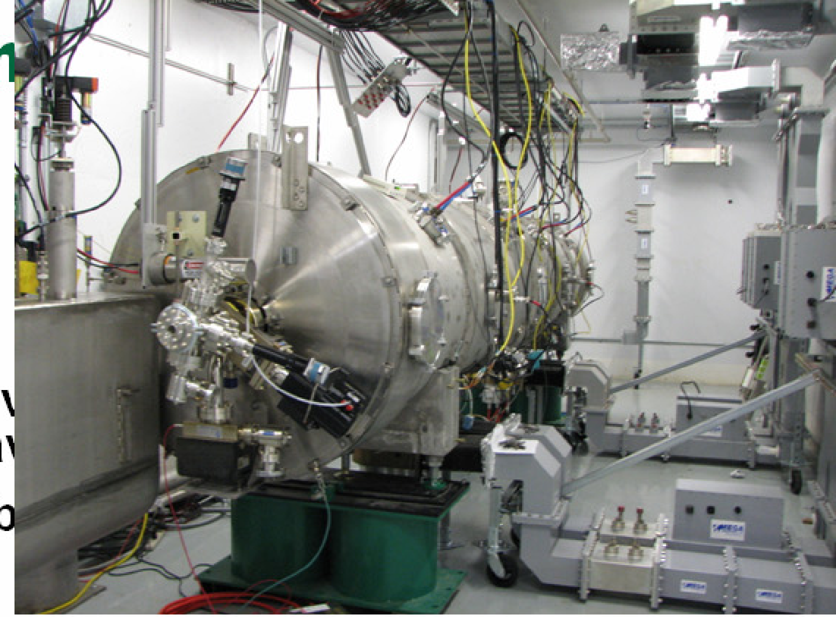

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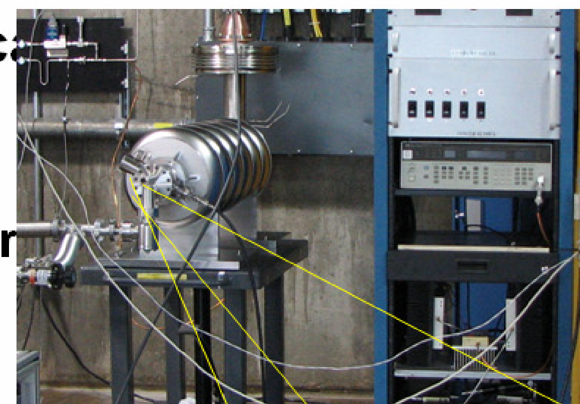
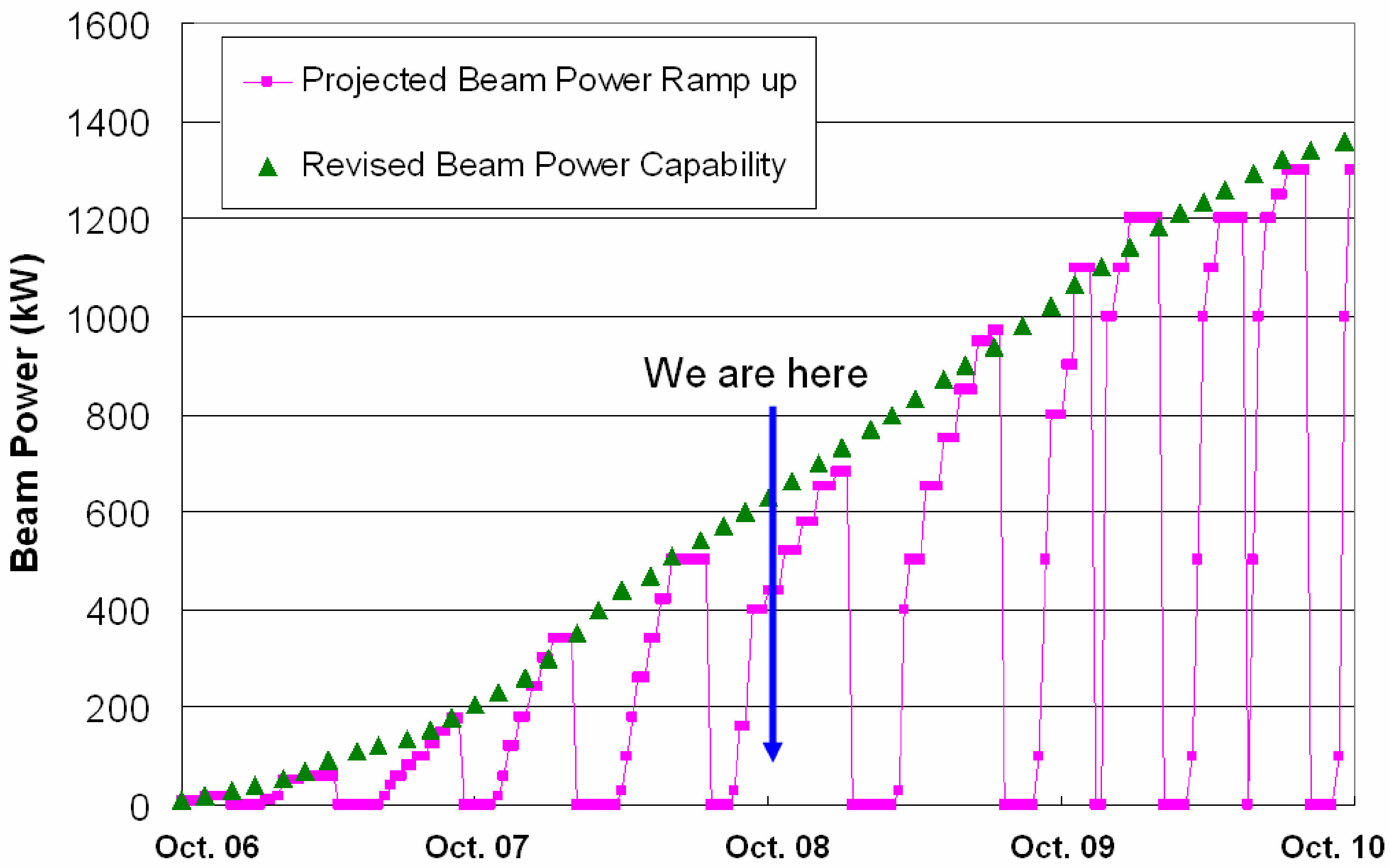


Plasma in HB cavity

Power Ramp-Up Plan



More emphasis on machine availability but still there are many challenges

Power Upgrade Project (PUP)

Power Upgrade Project (PUP)+ Accelerator Improvement Project (AIP)

Parameter	SNS Baseline	Power upgrade
Kinetic energy [MeV]	1000	1300
Beam power [MW]	1.4	3.0
Chopper beam-on duty factor [%]	68	70
Linac beam macropulse duty factor [%]	6.0	6.0
Average macropulse H- current, [mA]	26	42
Peak macropulse H- current, [mA]	38	59
Linac average beam current [mA]	1.6	2.5
SRF cryo-module number (medium-beta)	11	11
SRF cryo-module number (high-beta)	12	12+8 (+1 reserve)
SRF cavity number	33+48	33+80 (+4 reserve)
Peak surface gradient (b=0.61 cavity) [MV/m]	27.5 (+/- 2.5)	27.5 (+/- 2.5)
Peak surface gradient (b=0.81 cavity) [MV/m]	35 (+2.5/-7.5)	31
Ring injection time [ms] / turns	1.0 / 1060	1.0 / 1100
Ring rf frequency [MHz]	1.058	1.098
Ring bunch intensity [10^{14}]	1.6	2.5
Ring space-charge tune spread, DQ_{sc}	0.15	0.15
Pulse length on target [ns]	695	691

SCL Scope and Improvement for PUP

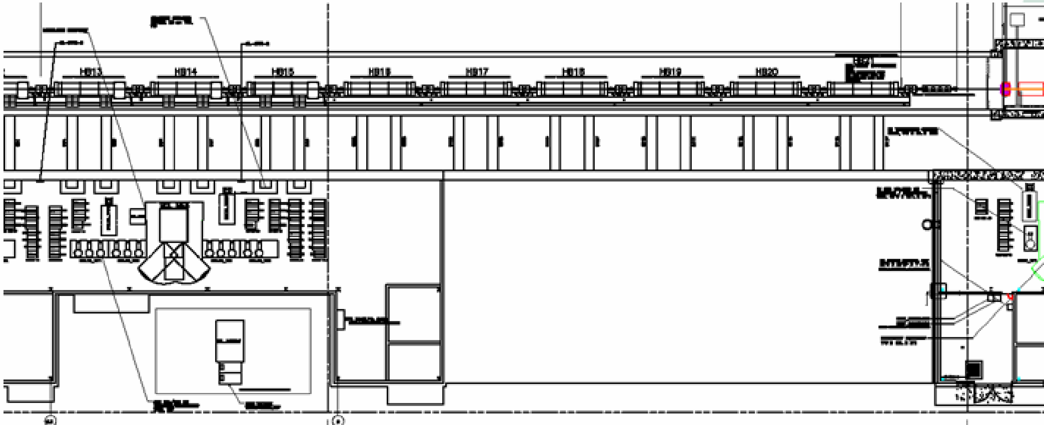
Scope

- Beam energy; 1 GeV → 1.3 GeV (PUP)
  - 9 additional high beta cryomodules (36 high beta cavities)
  - With all supporting systems (RF, HVCM, Cryogenics)
- Beam current; 26 mA → 42 mA (AIP, R&D)

Outline

- Cavity performance (better control of surface cleanness for less radiation at the operating gradients)
- Fundamental power coupler (about same or less thermal radiation at the higher average RF power)
- HOM coupler (remove feedthrough for existing cavities or remove HOM couplers for new cavities)
- Thermal improvements at the end of cryomodule (put intermediate temperature region away from the cavities)

9 additional cryomodules to fill the empty spaces at the end of the linac tunnel



Summary

- The first fully operational pulsed superconducting RF linac has been running with beam for two years, reaching full design energy
- Behavior peculiar to pulse operation is being studied, understood and the problems associated with are being corrected
  - Down time due to SRF linac is now almost nil (the most reliable among subsystems)
- Full power ramp up to 1.4 MW is being planned and facilities are being prepared to support full power operation by improving existing CMs/supporting systems and procuring spares
- Power Upgrade Project (PUP) has been initiated, waiting for CD-1 improvement

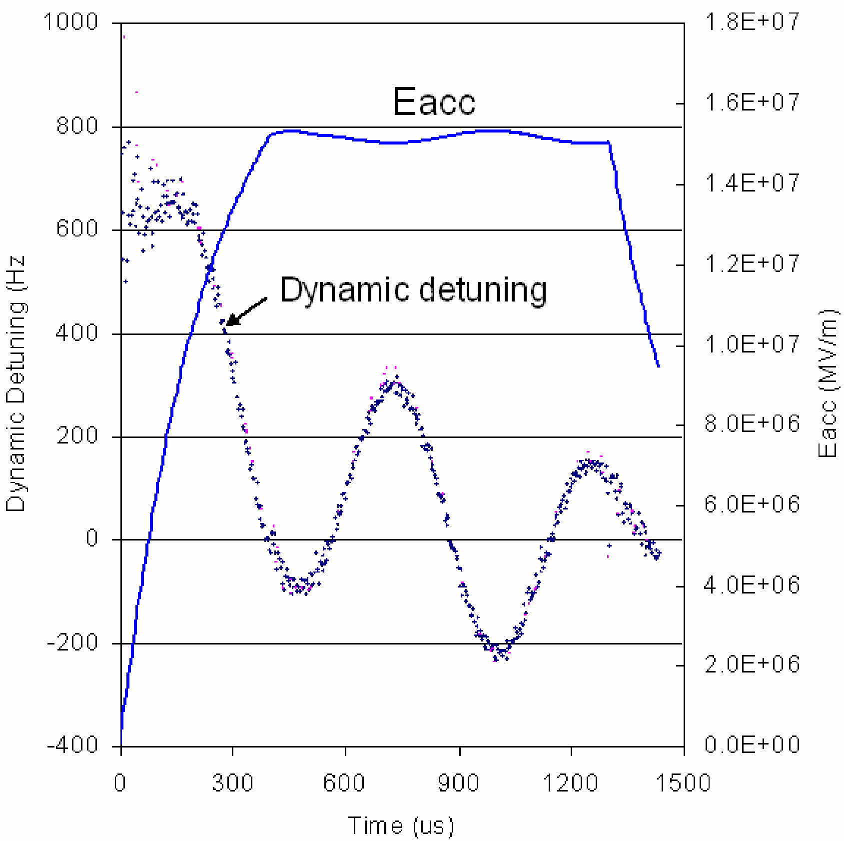
supplementary

Quenching

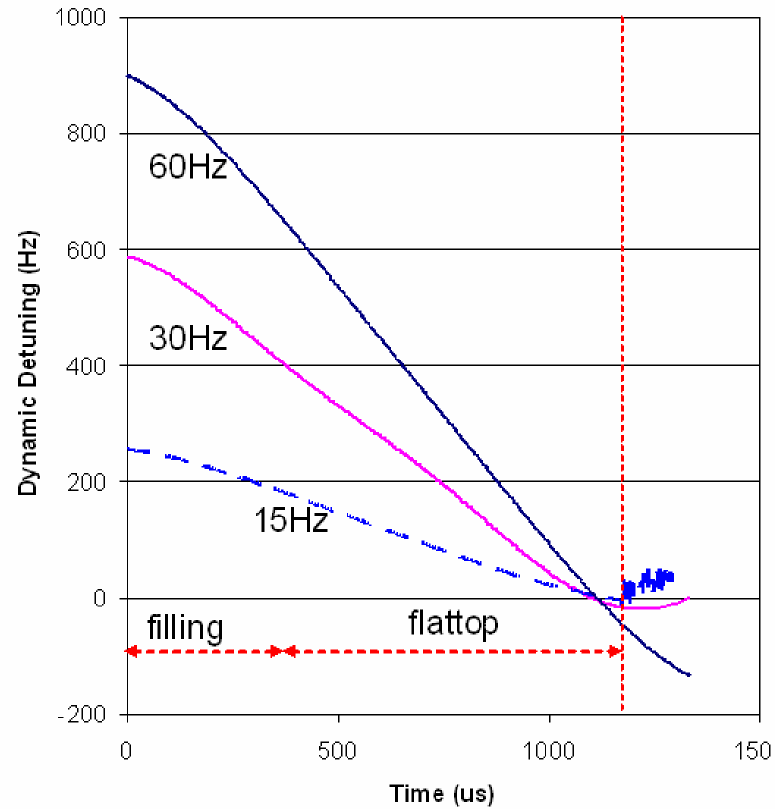
- Rs (BCS, Rres, etc. limits; intrinsic SC limits)
- Material defect (end group has more margin; low B)
  - Cell (covered with He vessel)
  - End group (indirect conduction cooled)
- External thermal load (cell region has more margin)
  - Wide range heating
  - Much smaller thermal power density
  - Thermal radiation from FPC
  - Radiation (FE, MP, cavity-coupler interaction)

Lorentz force detuning

Most cavities show dynamic detuning as expected
($K_{LFD} \rightarrow$ 3-4;medium, 1-2;high)
But, a few cavities show bigger resonance phenomena as higher repetition rate

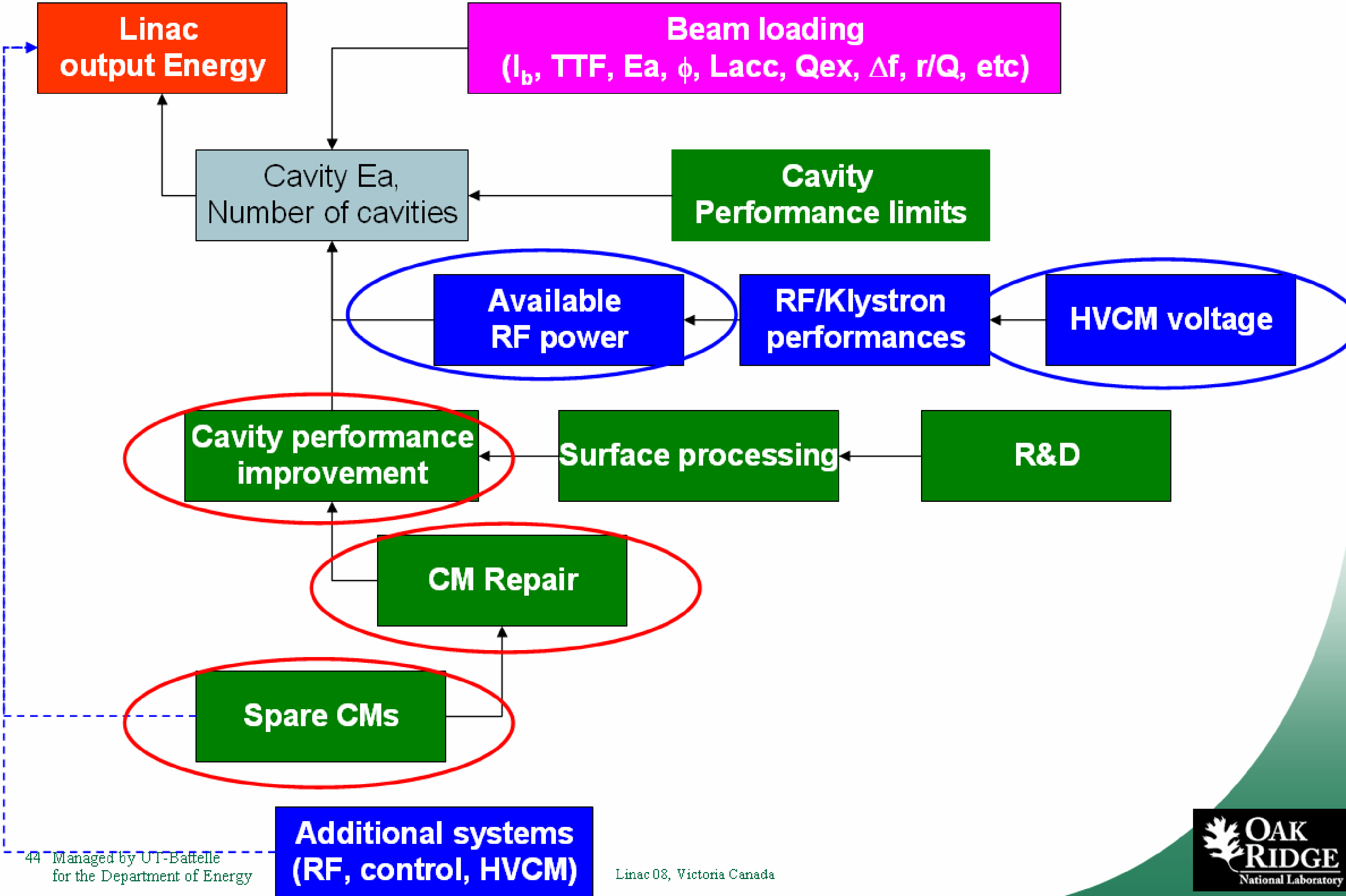


The 2 kHz components shows resonances
at higher repetition rate
in one medium beta cavities.



In this example the accelerating gradient is 12.7 MV/m.
High beta cavity

Linac Output Energy



For 1-ms beam

The max. width of HVCM; 1350us