Superconducting Linac Operations and Performance

SNS AAC Review
January 22, 2008

SANG-HO KIM

Managed by UT-Battelle
for the Department of Energy

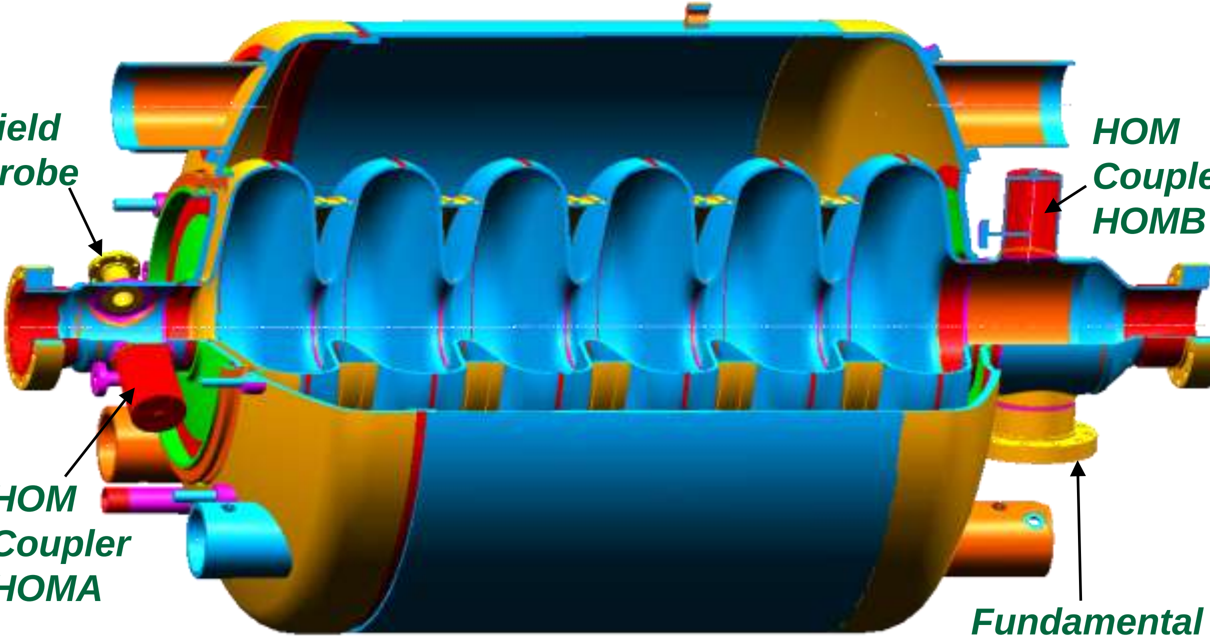
OAK RIDGE
National Laboratory

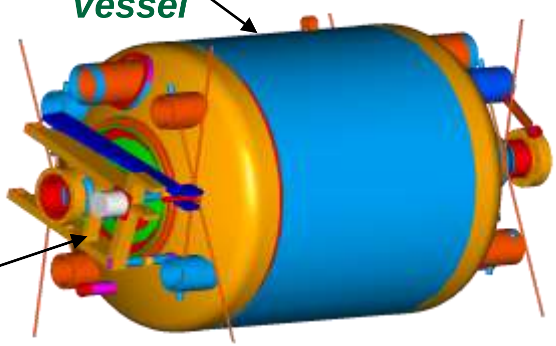
Outline

- **SCL operational status**
- **SCL performances**
  - **Limits, limiting factors and understandings**
- **High power concerns**
- **Summary**

SNS SRF cavity

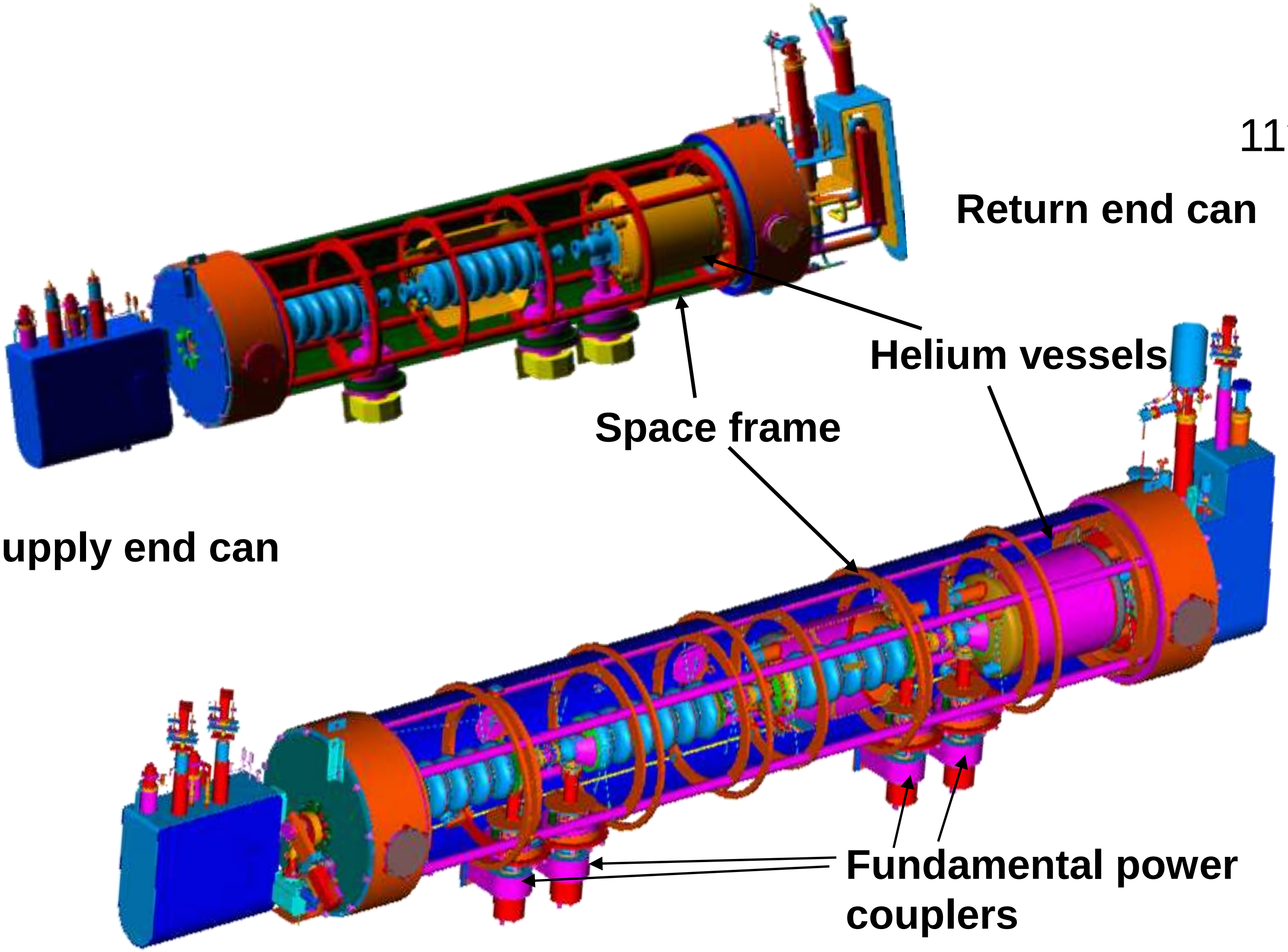
Major Specifications:
E_a=15.9 MV/m at β=0.81
E_a=10.2 MV/m at β=0.61
&
Q_o> 5E9 at 2.1 K





SNS Cryomodule

Designed to operate at 2.1 K (superfluid helium)



11*Medium beta

12*High beta

81 cavities

SCL status summary

- Completed CM installation (April-June 2005)
- SCL commissioning with beam (Aug.-Sep. 2005)
- Production run (Oct. 06-present)
- 1 GeV demo at 15 Hz, 4.4 K (79 cavities) to linac dump (Feb./07)
- 30 Hz production run in the previous operation (Jun./07-Sep./07)
- 60 Hz demo at 860 MeV, 2.1 K (75 cavities) at beam to target (Sep./07)
- Present run at 60 Hz, 850 MeV, 2.1 K (75 cavities)

Cavity/Cryomodule studies/tests

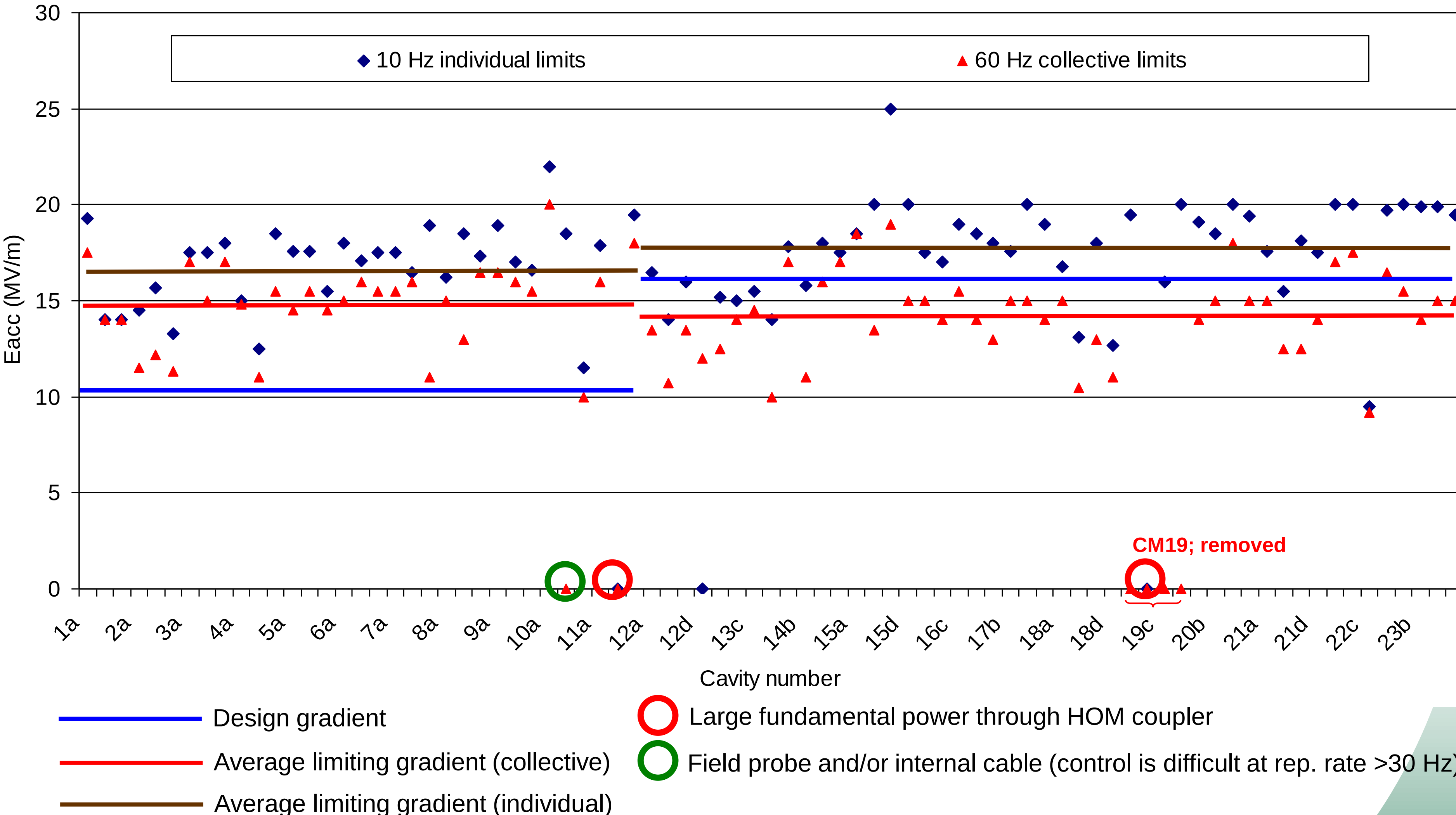
- **Initial CM tests**
  - **9 MB CMs + 2 HB CMs tested at Jlab; 35 cavities**
  - **2 MB CMs + 10 HB CMs tested at ORNL; 46 cavities**
- **Good collaboration/support between/from groups/teams**
- **Extensive studies/tests have been done (since June 06)**
  - (re-)evaluated/characterized of cavity performances at 10/15/30Hz (June 06-Nov. 06)
  - Tested Cryomodules (First test; powering all cavities in) at 60 Hz (Dec. 06-June 07)
  - Needed more attentions/understandings than expected since it is the first operational pulsed superconducting linac
  - Improved LLRF software (Feb. 07)
  - Tested CM19 in the test cave (Dec. 07)
  - Tested cavity heater compensation at 2K
  - Characterized HPRF system
  - Had better understandings of cavity physics and limiting conditions of the system in pulsed mode
  - Established balanced operating conditions including all supporting/sub systems as a whole in various operating conditions
- **New interlocks in progress; electron probe, normal sensitivity arc detector card**
- **SCL is providing more stable/reliable acceleration for Neutron Production as we learn more about the system as a whole**

Improvements in SCL operation

-Gradients setting based on 60Hz collective limits
-Fix LLRF software bugs (eliminated nuisance trips)
-New software
   20 Hz updating (much milder transition glitch)
   better diagnostics tools
   enhanced interlock features
-New quenching detection;
   detect quench/precursor of quench in 2~3 pulses

Trips during this production run (<0.1 trip/day)
No strange trips; trips when it should trip

Limiting gradients and statistics

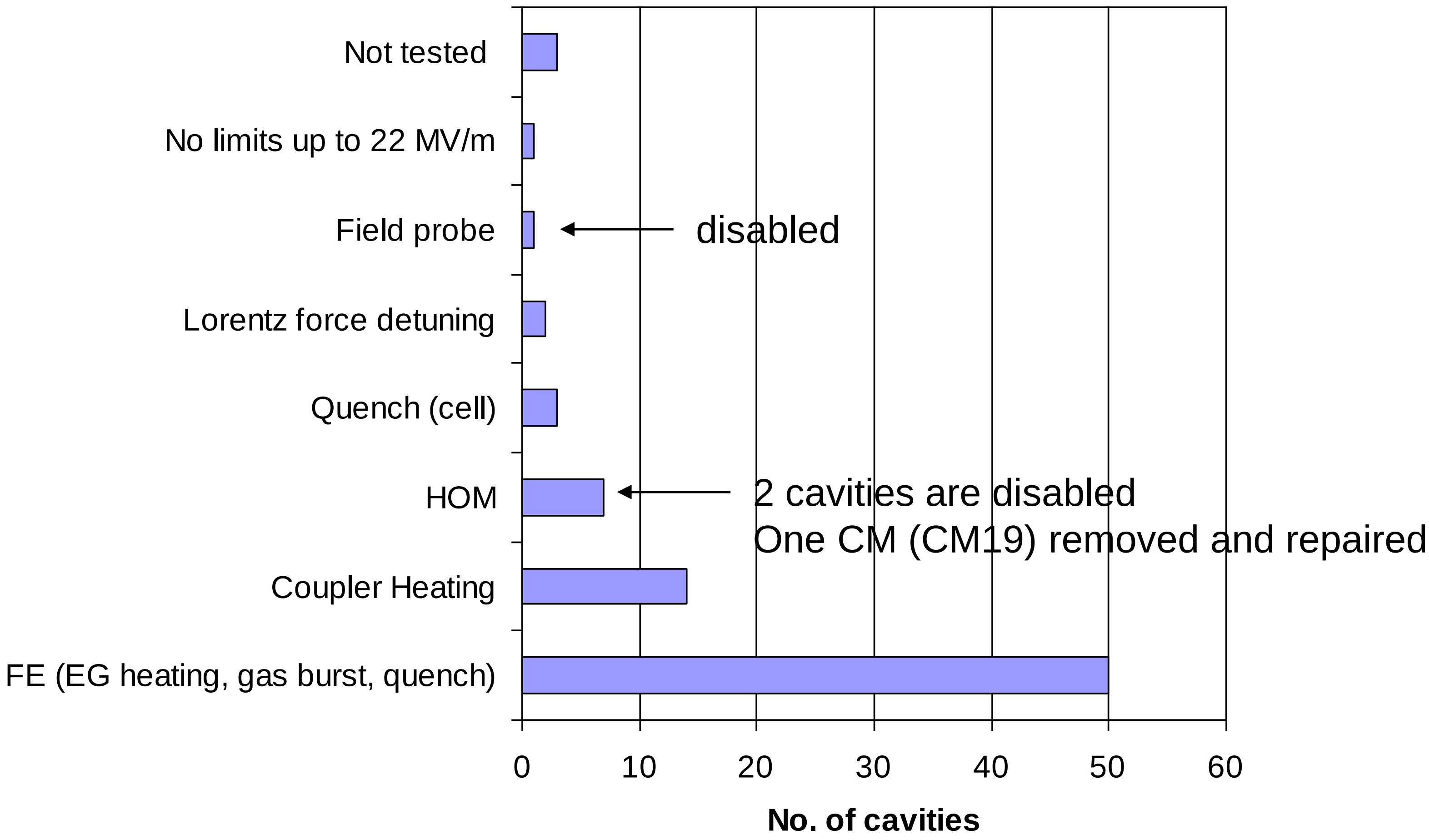


Individual test; powering a cavity at a time

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

Large performance variations cavity to cavity

Statistics of limiting factors (60 Hz collective)



-Performances of MB cavities are very good.

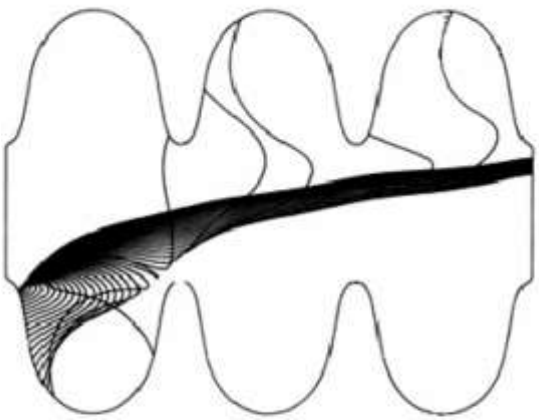
$E_{lim,avg,MB}$ ~14.9 MV/m, $E_{lim,avg,HB}$ ~14.3 MV/m

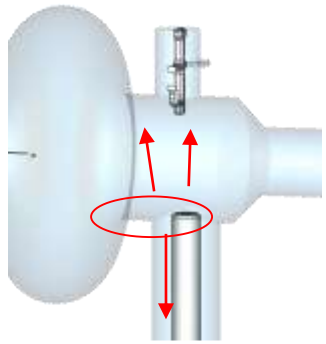
-Some cavities have multiple limiting factors.

-About 14 HB cavities are limited by coupler heating, but close to the limits by FE.

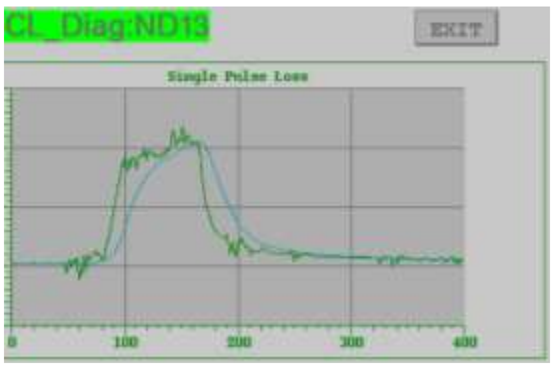
-Operating gradients are around 85~95% of E_{lim}

Radiation

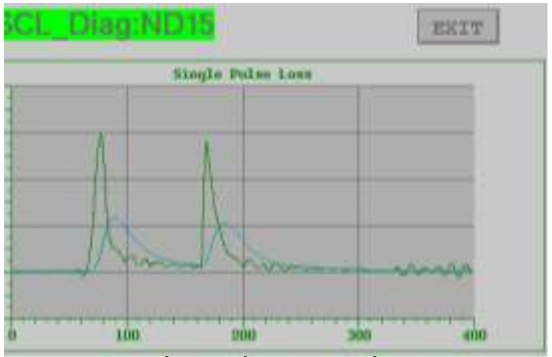




Radiation (arb. unit)



13a; 14.5 MV/m
13b; 15 MV/m
13c; 15 MV/m
13d; 10.5 MV/m

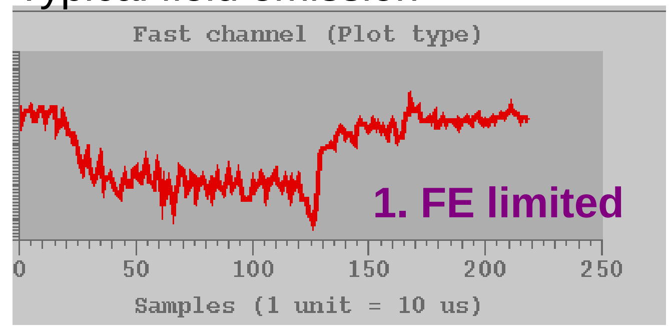


15a; 19 MV/m
15b; 17 MV/m
15c; 21.5 MV/m

(1 unit=10 us)

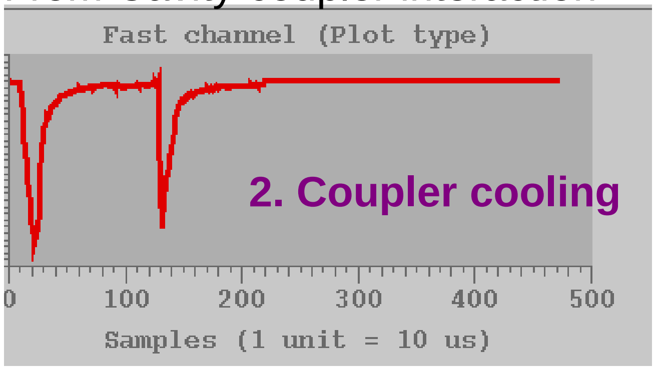
Typical field emission

Radiation (arb. unit)



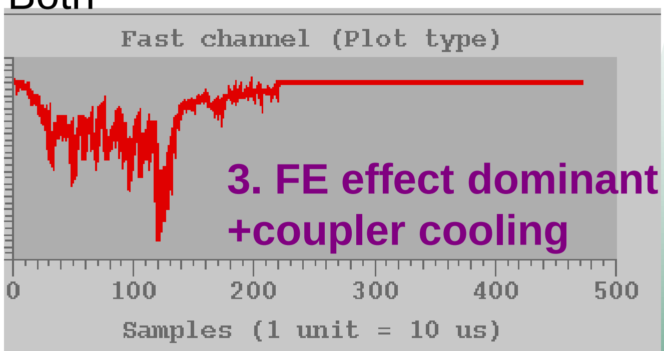
From Cavity-coupler interaction

Radiation (arb. unit)



Both

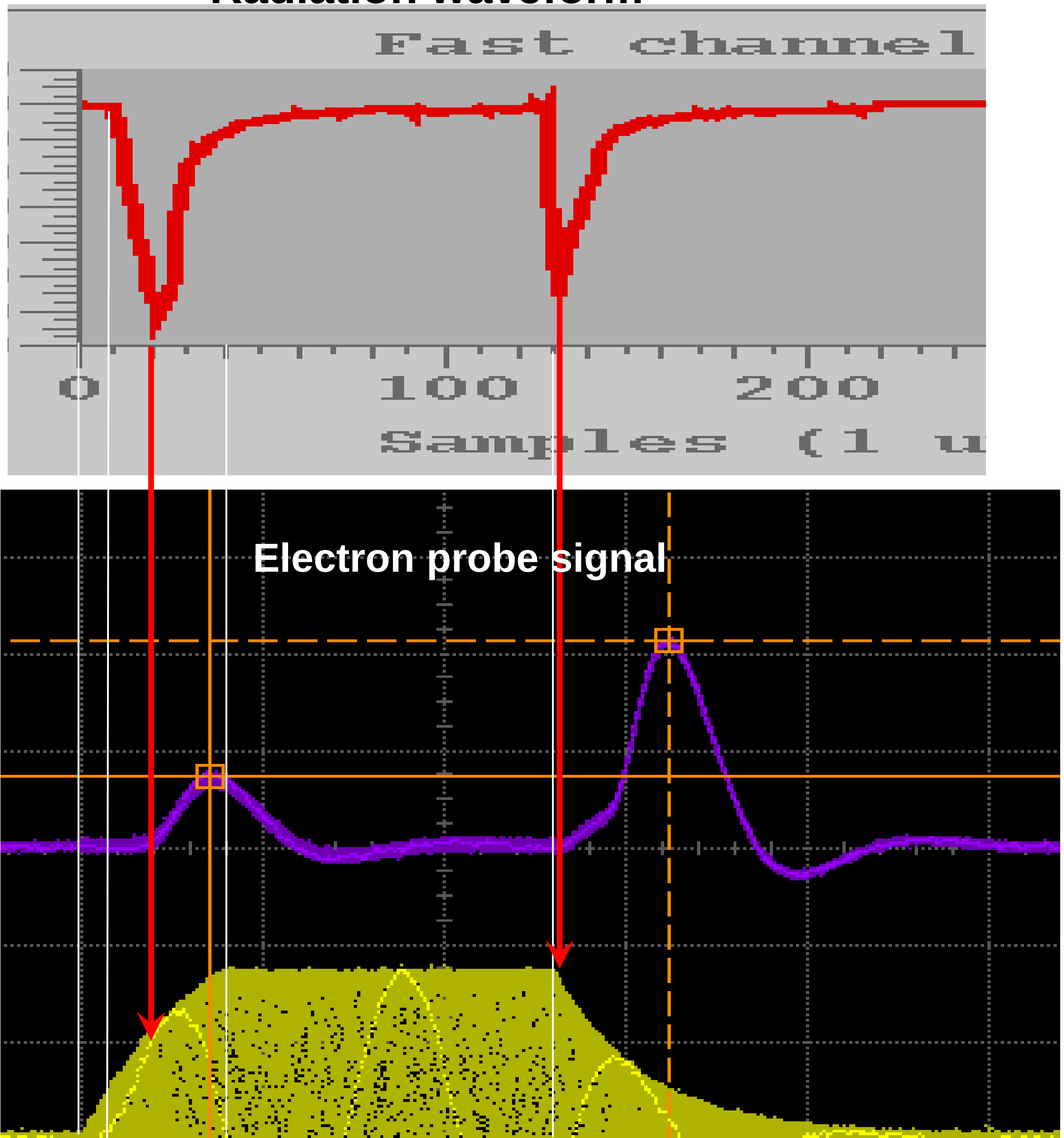
Radiation (arb. unit)

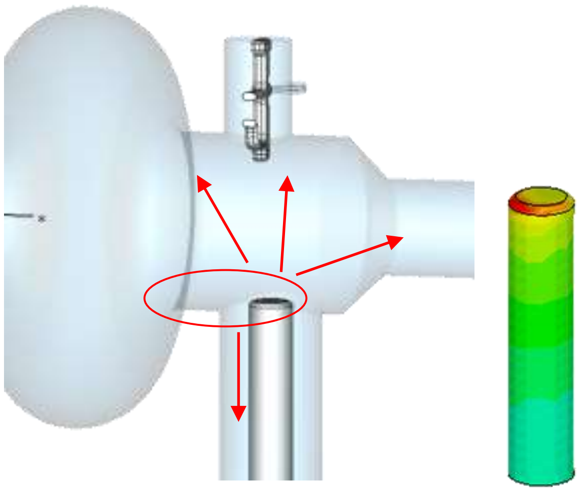


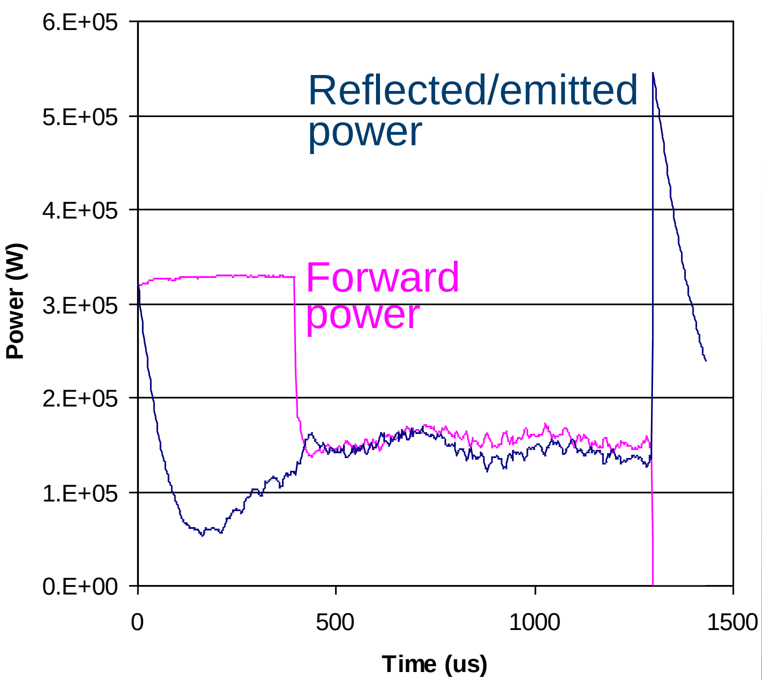
Most of cryomodules are limited by 1. and 3.

Cavity-coupler interaction

Radiation waveform







Quenching

Cell; covered with He vessel

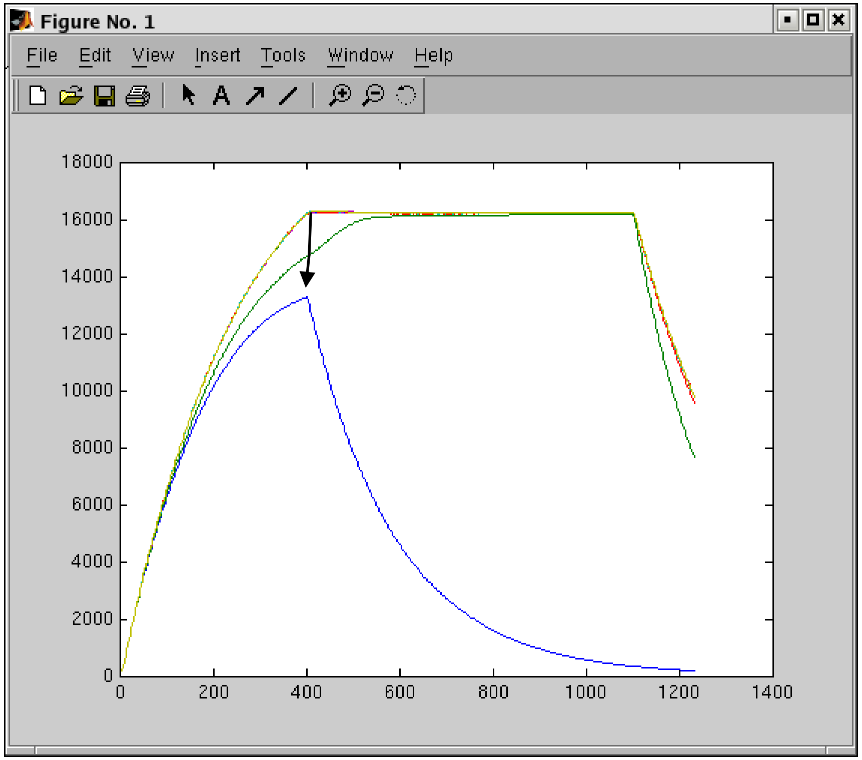
End group; indirect conduction cooled

- **Rs (BCS, Rres, etc. limits; intrinsic SC limits)**
  - **No limitation at SNS condition at T<4.5K**
- **Material defect (end group has more margin; low B)**
  - **Cell; fast thermal runaway, full quench, un-recoverable during gap**
- **External thermal load (cell region has more margin)**
  - **Thermal radiation from FPC**
  - **Steady Radiation (FE)**
  - **Wide range heating**
  - **Much smaller thermal power density**
  - **Partial quench**

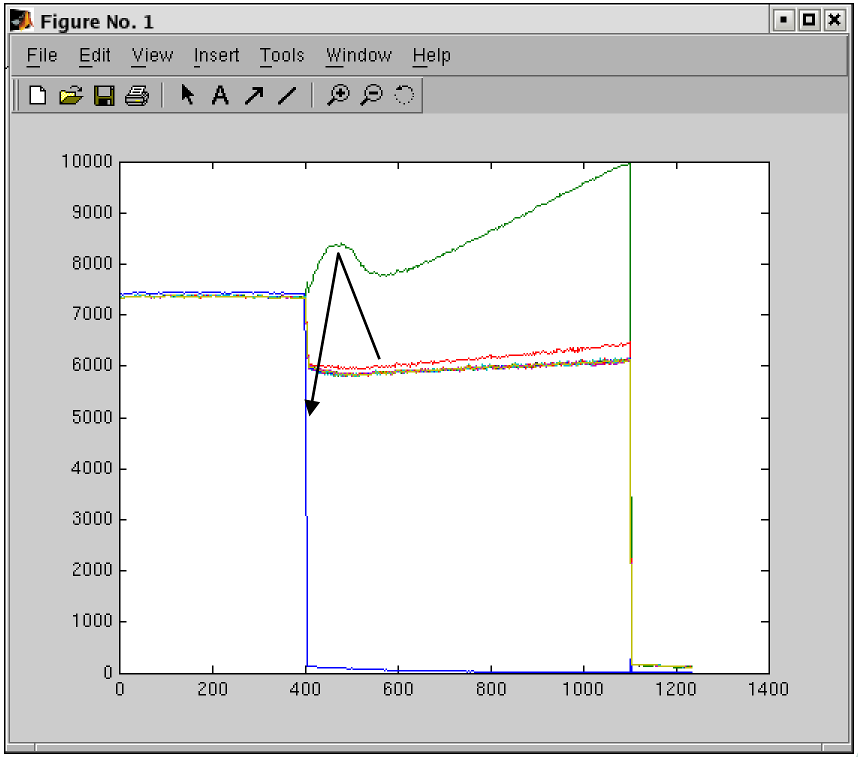
End group heating → Partial quench (I)

Usually with beam pipe heating + gas burst

Ex. 12c in closed loop (CM12 shows highest FE)



Cavity field



Forward power

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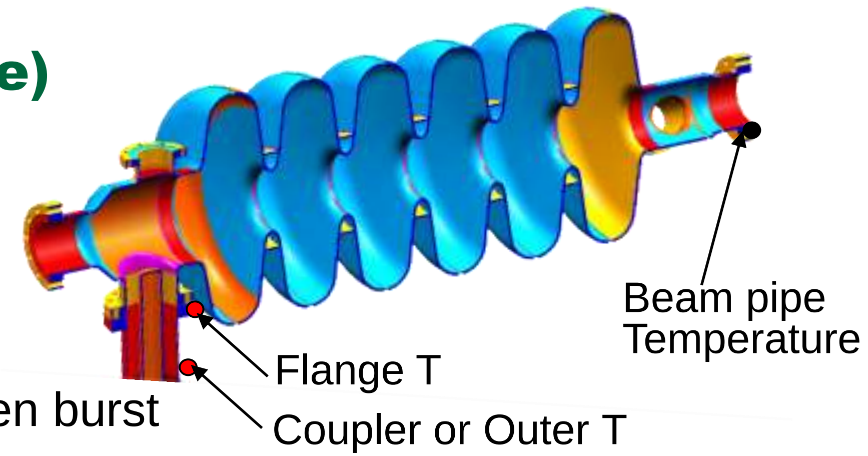
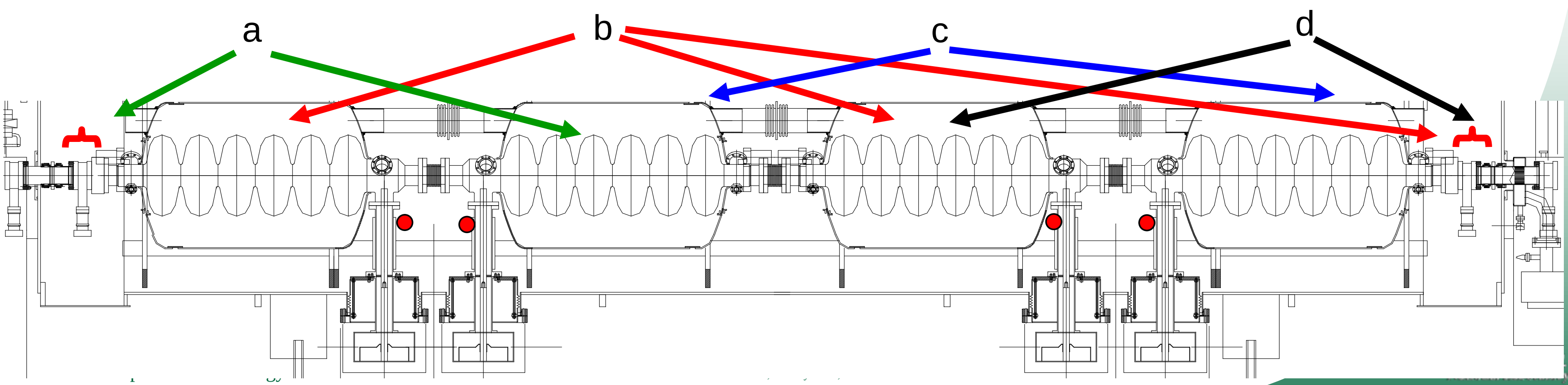
Collective limits
(clear indication at higher rep. rate)



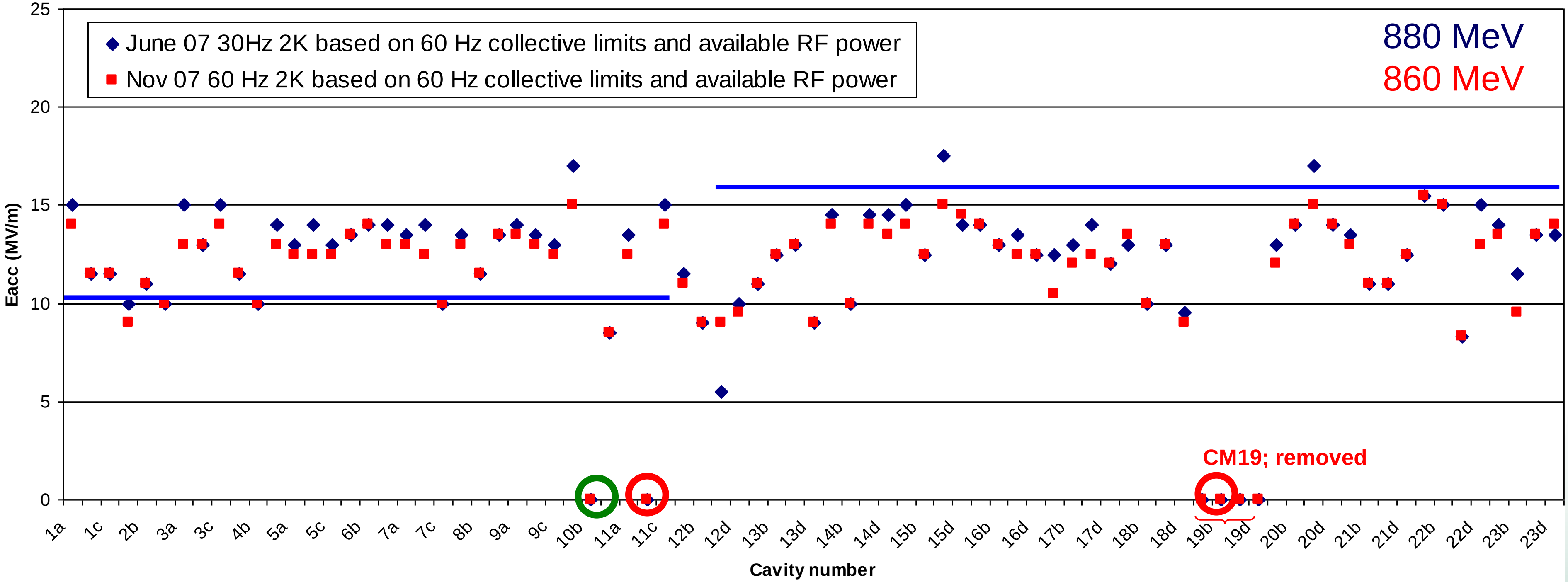
- **Field Emission;**
  - steady state electron activity + sudden burst
  - affects other cavities
  - electron landing place (relative phase, amplitude)
  - leads continuous gas activity, even though all signals look quiet
  - hits intermediate temperature region (5-20K); H_2 evaporation (burst of gas)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

CM13 individual limits; 19.5, 15, 17, 14.5
CM13 collective limits; 14.5, 15, 15, 10.5



Operating gradients at 30 Hz /60 Hz

Differences ← **higher beam acceptance, shorter filling time**, RF control stability, coupler cooling



Design gradient

Large fundamental power through HOM coupler

Field probe and/or internal cable (control is difficult at rep. rate >30 Hz)

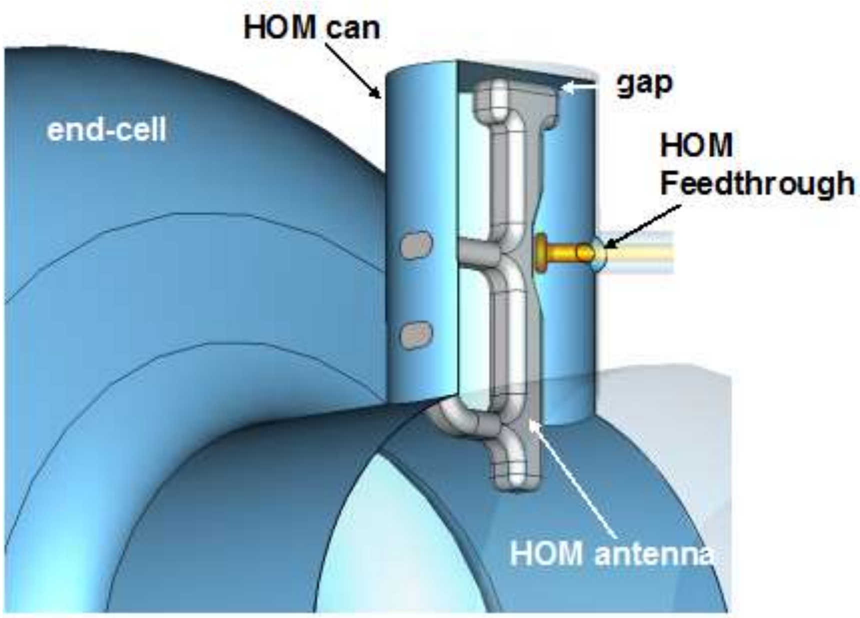
Sub-components

- Initial (the first) powering-up, pushing limits, increasing rep. rate
  - Aggressive MP, burst of FE → possibly damage weak components
  - Abnormal behaviors of HOM couplers (several) and FP (one)
  - Extreme care, close attention
  - No more significant damages are observed in the past 1.5 yrs
  - Same situation after thermal cycle (after long shut down)
- Turn on and CCGs
  - Was a problem, well understood now
- Tuner
  - Motor, harmonic driver, piezo

HOM coupler

- When Q_{hom}>10^5, there's a concern of HOM power (TM monopoles)
  - but the probability is very low
  - One (or two), if any, could have large HOM induced power
  - So far no observation
- Extra insurance
- Coaxial type notch filter scaled from TTF was chosen and installed.
- Low power tests confirmed its functionality
  - Damping; dangerous modes to have Q_{hom}◙10^4

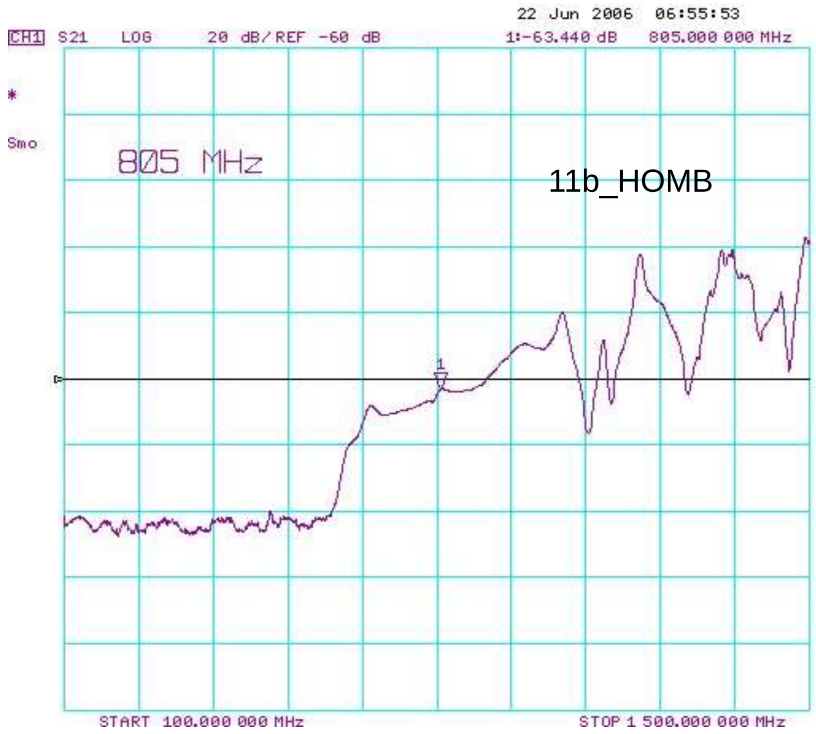
Any electron activity
→Destroy standing wave pattern
(or notching characteristics)
→Large fundamental power coupling
→Feedthrough/transmission line damage
→Irreversible



Limited by Fundamental mode in HOM coupler

- **Large fundamental mode coupling**
  - **11b; non-operable from the beginning, no notch**
  - **19b (HOM feed through removed)**
    - **TDR measurement & comparison; almost shorted**
    - **Trace of discharge**
    - **Dimension looks OK but large coupling**
    - **Recovered; back in the tunnel in Feb. 08**
  - **3 cavities; operable but limited by HOM power**
    - **Not related with damage, just worse location of notching freq.**
- **6 cavities; abnormal waveforms about '0' coupling**
  - **Seems to be a (partial) disconnection in feedthrough/cable in CM**
  - **No further deterioration, all in service**

11b HOMB



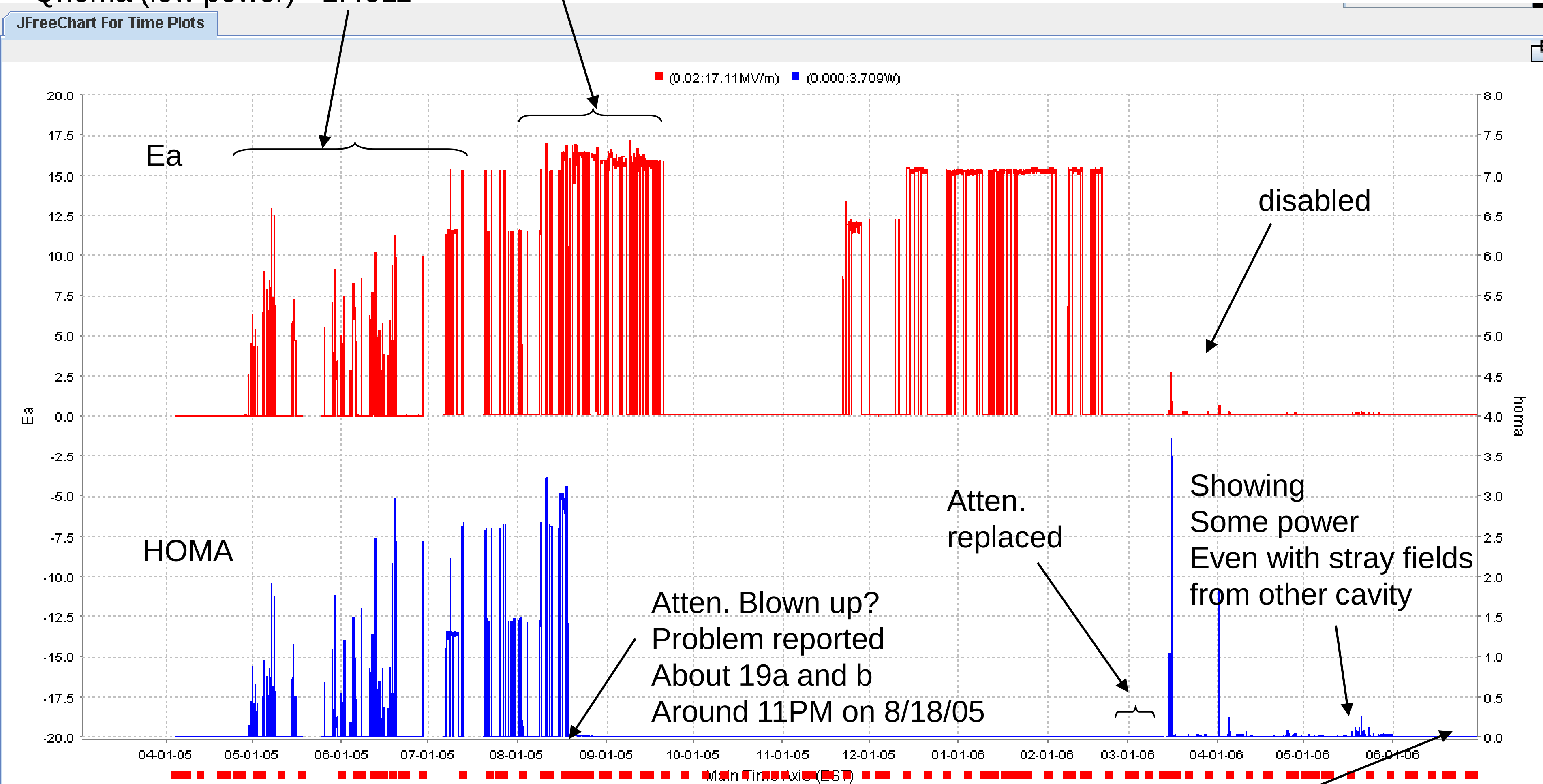
No visible notch has been identified yet since SNS

Internal damage → lost notching characteristics?

CM19 (HOMA; FP side)

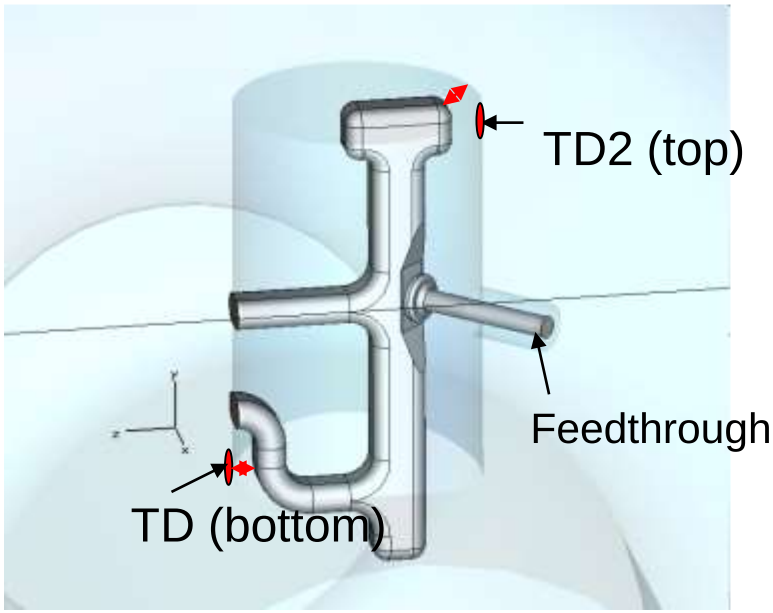
Cryomodule Commissioning at 10 Hz
19b Ea, limit~18 MV/m
; Qhoma (high power)~1.5e11
Qhoma (low power)~ 1.4e11

SCL beam commissioning



Low power measurement
At 4K in the tunnel
Qhoma~3.8e8 (+25 dB)

CM19 test in test cave

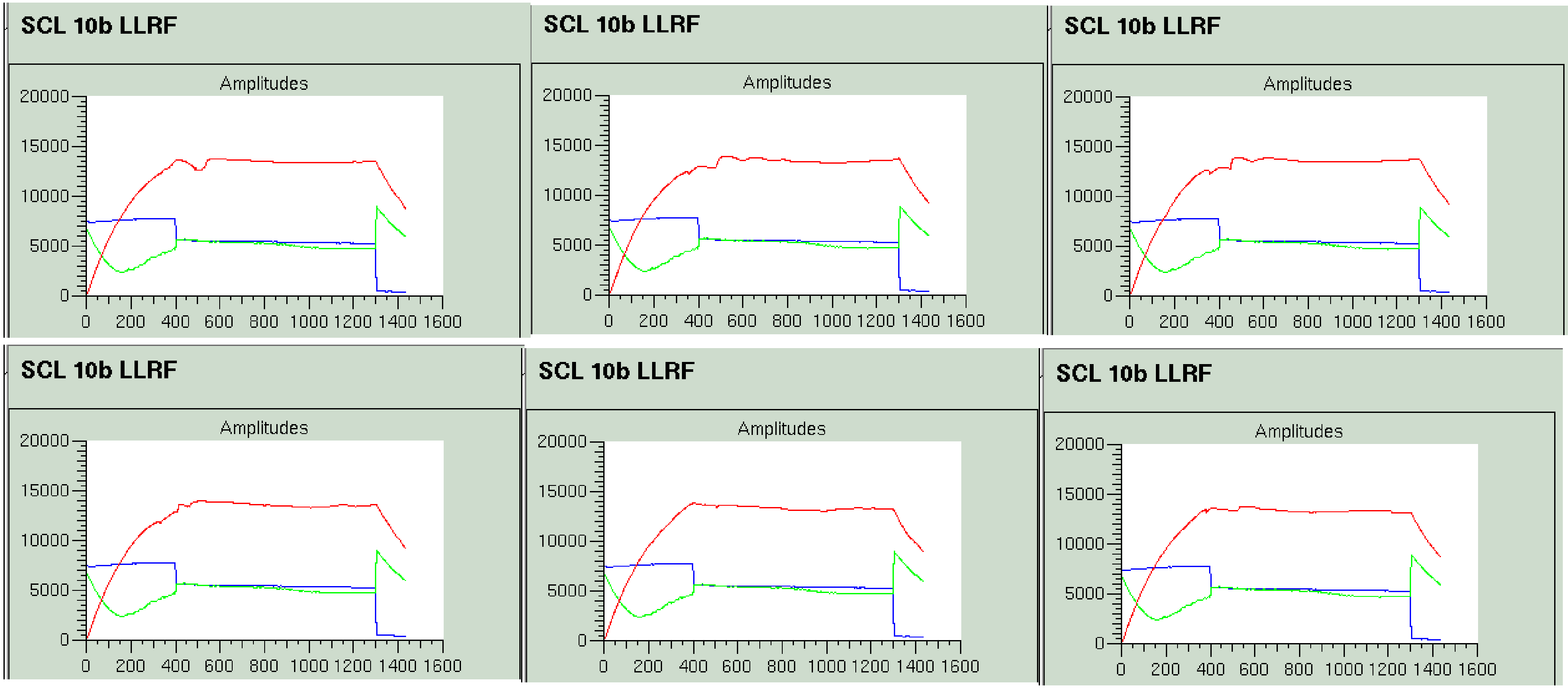


Both feedthroughs of 19b HOMA and B ; removed (details in John's talk)
Add thermal diode (TD)
at around multipacting regions

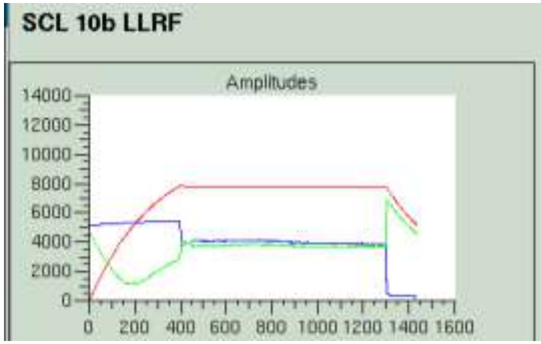
All individually tested up to 16 MV/m at 4 K, 30 Hz, 1ms, in open loop, (about the same gradient we got in the linac tunnel at 30 Hz, collectively)

-**No degradations** in cavity performances were observed after repair.
-The repair procedure was **confirmed**.
-We **gain 19b** (quick processing was possible by removing feedthroughs)
-Electron activities in the HOM coupler seem to cause many electron activities, thermal loads and vacuum.
-Large heat loads were observed while processing.
-Final check will be 60 Hz collective limit test in the tunnel.

Noisy field probe; 10b



Field Probe Signals in Open Loop at the same driving → Makes FB control very noisy
→ bad cable/FP (worse at higher rep rate; disabled at 30 Hz or higher)



Connect HOMB signal to HPM/FCM
→ Confirms internal problem

Cavity turn-on Issues and Progress

- Turn-on was extremely difficult before understanding of CCGs under pulsed operation
  - Electron activity → start of CCG response (not true)
  - CCG response → Electron activity (99 % true)
    - Cavity/coupler interactions
    - Inter-cavity interactions in a CM
  - Too much initial responses (deterioration/damage of CCG electrode)
  - Generally responses at higher repetition rate are milder (or reasonable) but not always
- Test
  - Scope monitoring of CCG waveform
  - e-probe comparisons
- Procedure for quick regulation of CCG reading
- Presently
  - Turn-on difficulties are not an issue any more
  - About 40 min. turn on + another 40 min. LLRF fine tuning (2 people)
    - Also considering 2K CHL circuit stability
  - As time goes by continuous conditioning of FPC (less e-probe signal)

Interlock for FPC window

Vacuum; very important information

CCG; specially designed electrode (razor) to read vacuum down to low 10^{-11} torr

Trip; hi (bad vacuum) & low (sleeping) limits

CCG responses at pulsed RF

-Sleeping (no responses); 3 CCGs bypassed

-Too much responses at the initial start-up

-Questions in absolute reading value

-lost of meaning as an interlock

e-probe

-reasonable responses

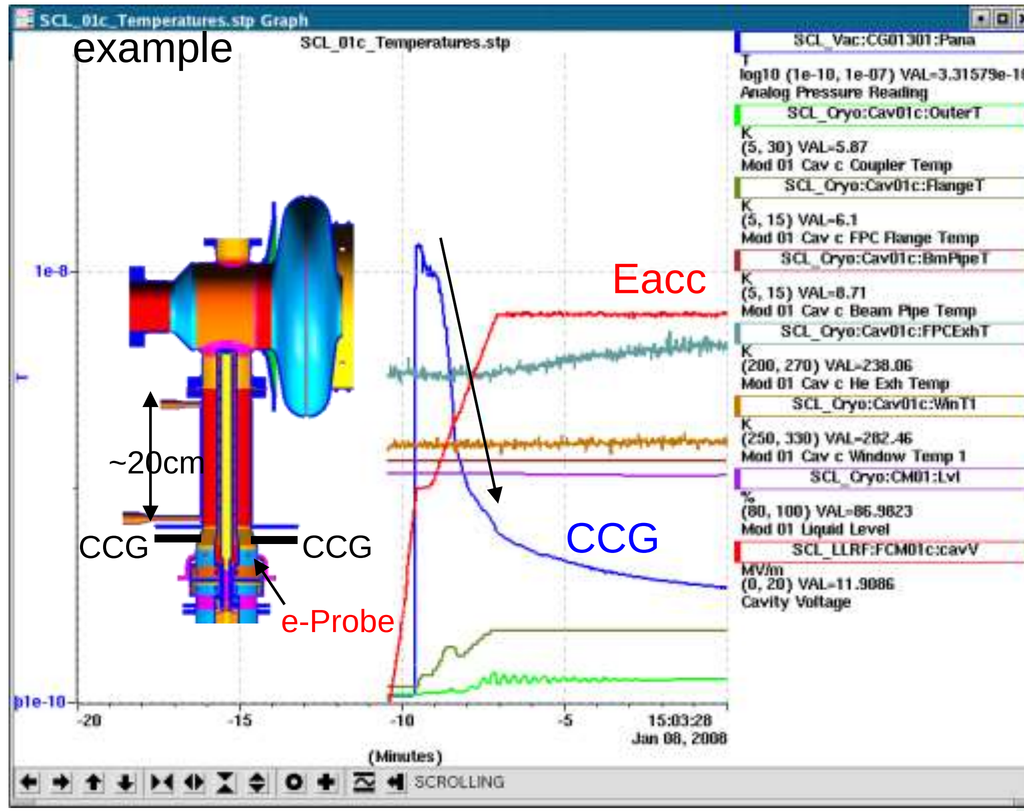
-purely passive device (no bias)

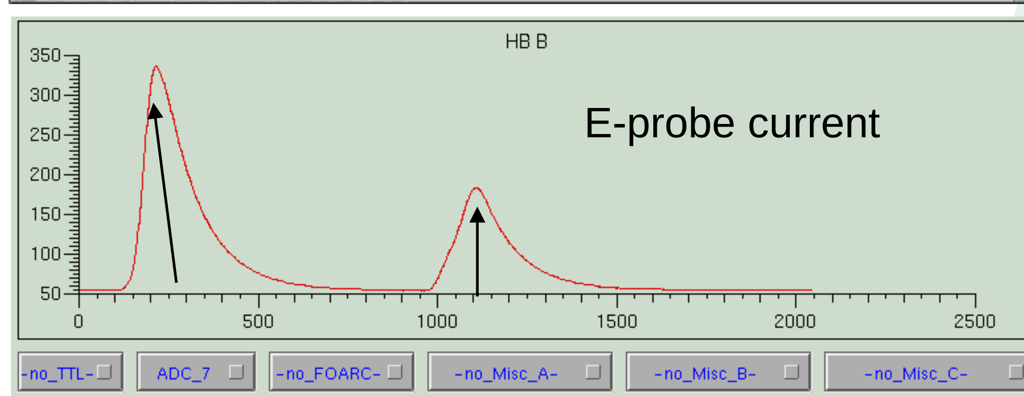
-0~40 μA at normal operation

-safe up to ~200μA

-installation is almost completed

-will be a main interlock for FPC window along with arc detector (normal sensitivity)





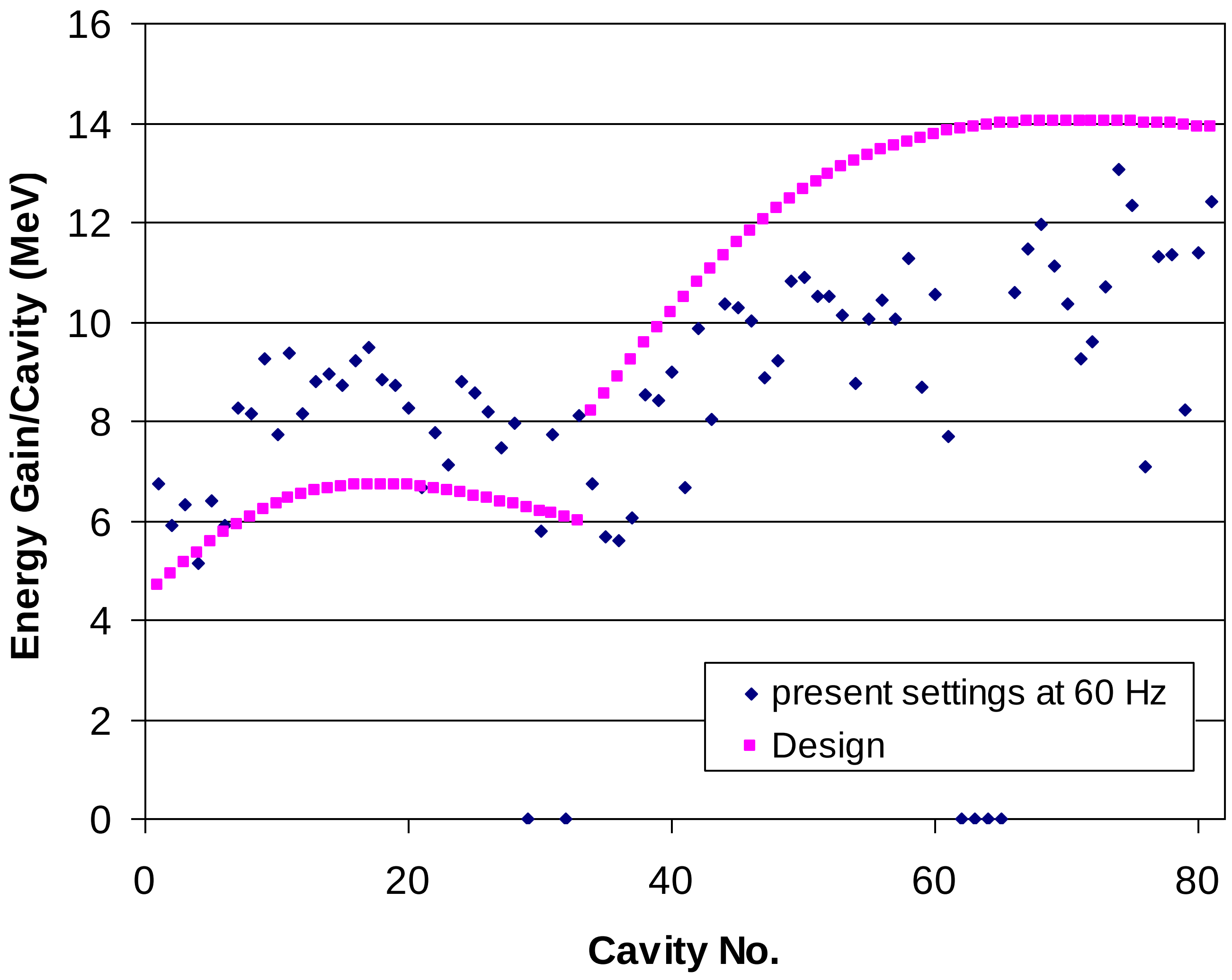
High Intensity Concerns (how high beam power can we go?)

0. Present sets & conditions; ~1MW max
   - 840 MeV + 10 MeV (reserve); ~25 MeV less for 26 mA beam
   - 880 us beam
   - 26 mA (average)
1. Full beam current (26 mA average)
   - Need more available RF power
2. Longer flattop for beam
   - Extend RF pulse into HVCM ringing region in beginning (+70us; tested)
   - Need more available RF power; shorter filling time
3. Cavity performance limitation
   - 81 cavities all in service assuming successful repair of CM12, 10b and 11b; 940 MeV + 10 MeV reserve

- For items 1 and 2; add one more HVCM
  - Presently; 4*12 pack + 3*11pack

    → available RF ~ 330 kW (12pack), ~380 kW (11 pack)

Energy Gain/Cavity



Power ramp up

A. Beam pulse width; 1 ms

- **RF pulse** (950us flattop + 300 us filling +50 us FB stabilization at 1350 us HVCM)
- w/ more available RF power → 250 filling → 1ms flattop

B. Beam current; 38 mA midi-pulse peak (26 mA average)

- **Increase available RF power**
  - **550 kW at saturation for HB**
  - **500 kW at saturation for MB**

Add one more HVCM

C. Improve SRF cavities for higher energy (1GeV + reserve); details in John's talk

- **Repair existing CMs**
  - **Fix 10b and 11 b (0.5 yr)**
  - **Repair cryomodules at SRFTF (3 CMs/yr)**
  - **Surface processing for existing HB cavities to get 2-3 MV/m higher Ea (1 yr R&D and 1.5~2 yrs application)**
- **Spare CMs (2HBs, 1MB); first spare HB in 1.5 yrs**

D. Increase Linac energy

- **Add spare CMs at the end of the linac (increase linac energy 1.0 GeV+50 MeV reserve)**
  - **Spare ; MB (1.5 yrs), HB (1 in 1.5 yrs, 2 in 3yrs)**

Summary

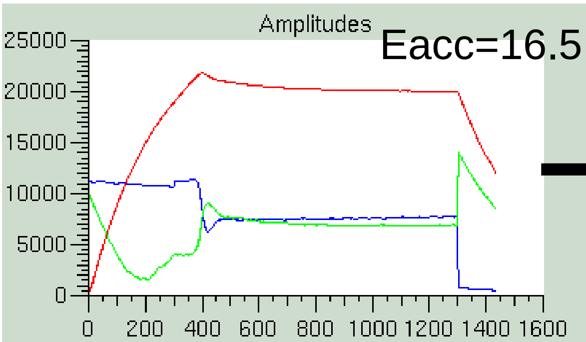
- SCL is now providing a very reliable operation for neutron production following SNS power ramp-up
- Extensive studies/tests have been successful
- We are now prepared for high intensity run

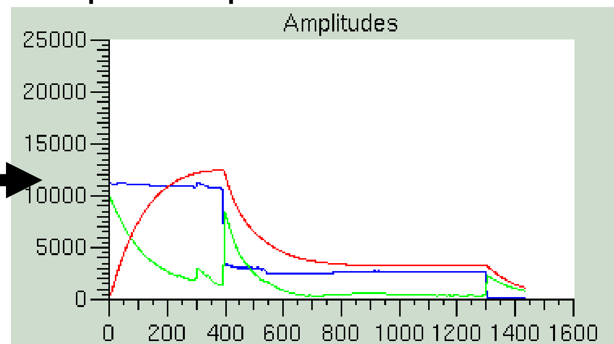
End group heating → Partial quench (II)

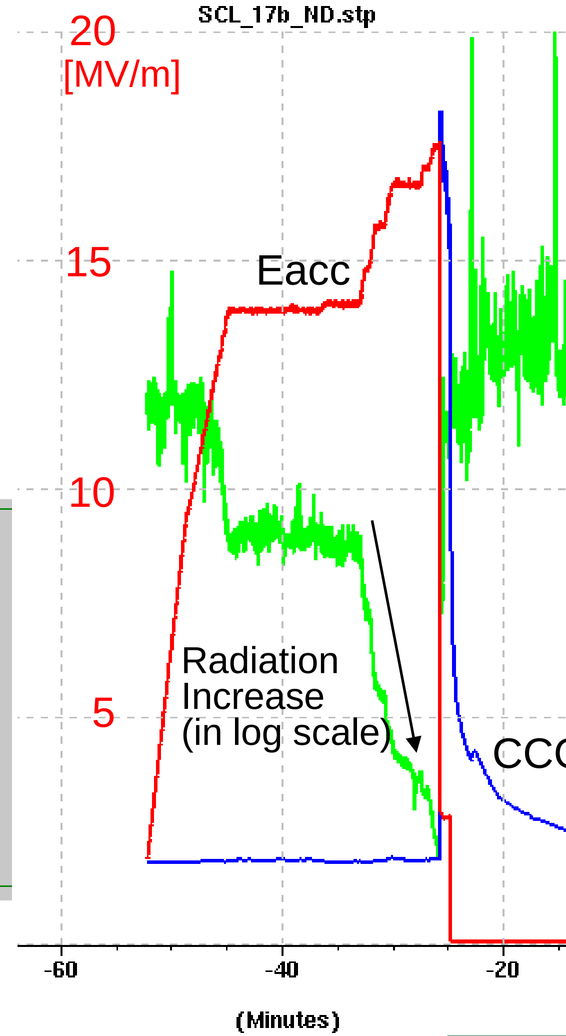
Usually with beam pipe heating + gas burst

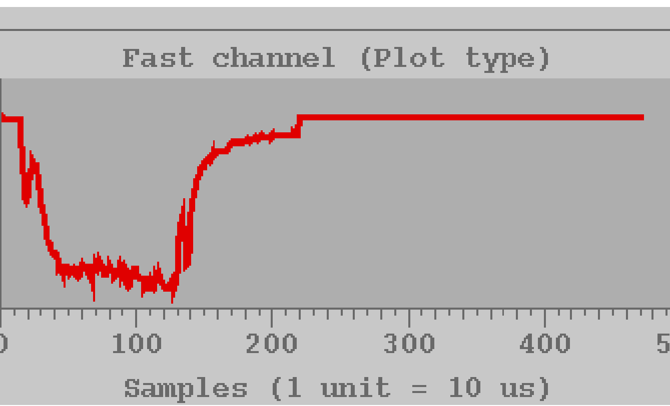
Ex. 17b individual

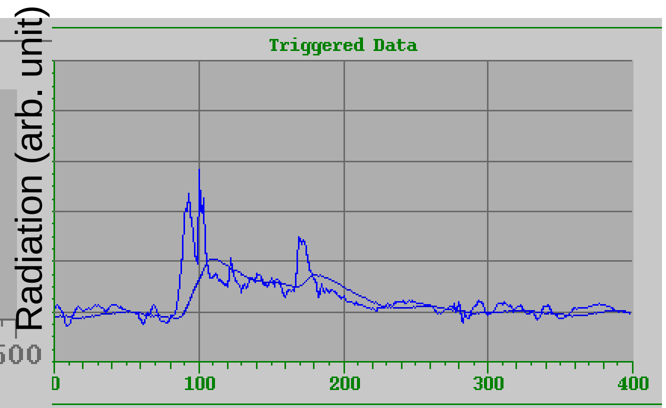
17b only in open loop









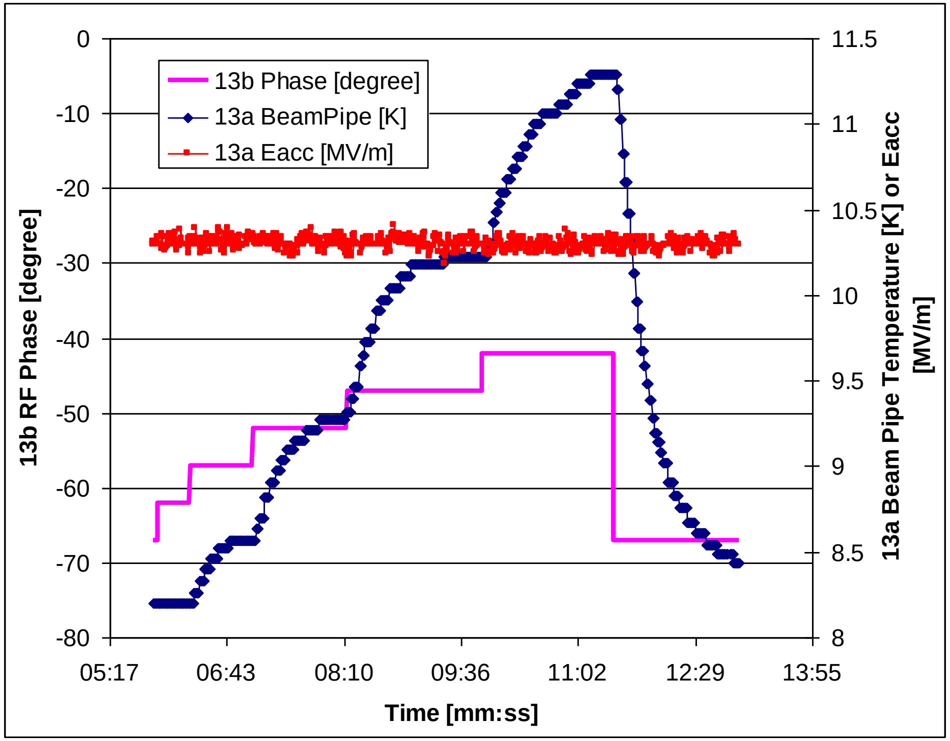


17b only
Radiation at Eacc=16.5
(Elim=17.5 MV/m)

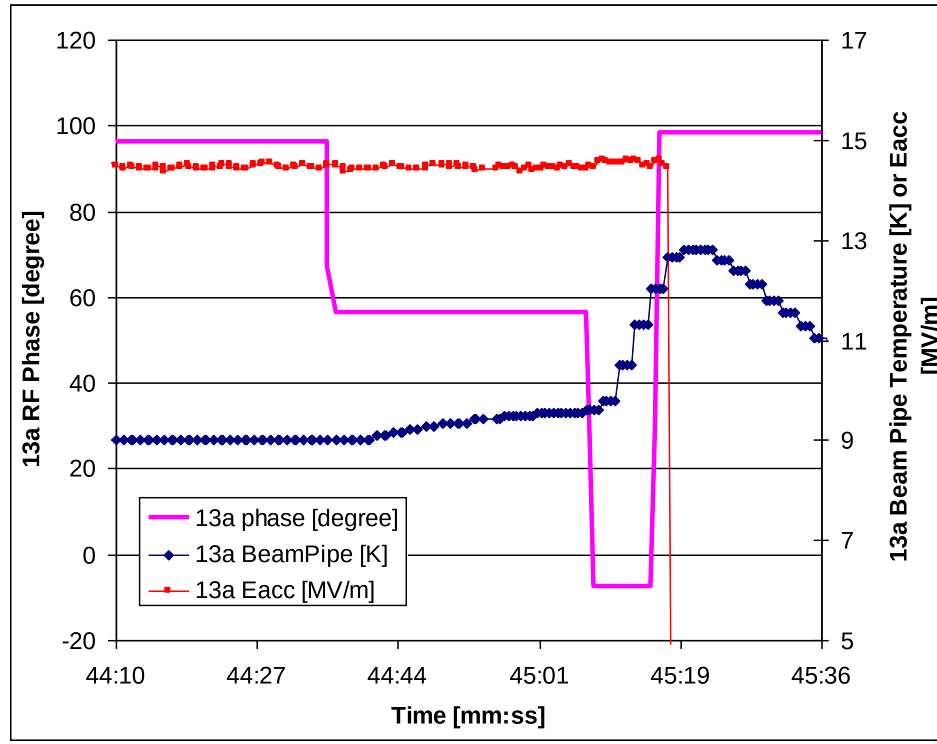
All CM17
at the present
operating setpoints (60 Hz)
10.5, 12, 12.5, 12 MV/m

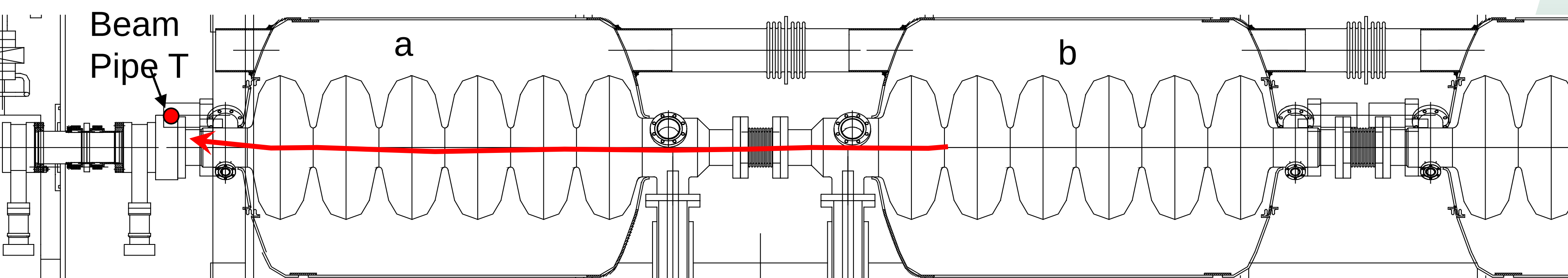
Collective limit (I)

b cavity phase → a cavity beam pipe

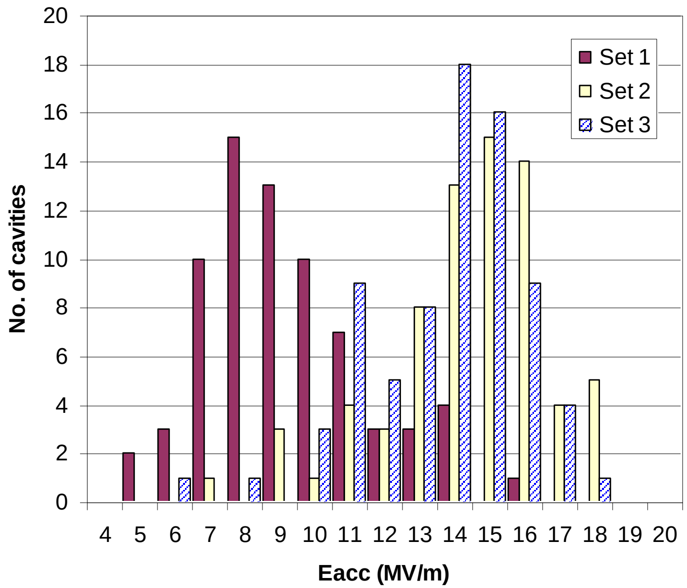


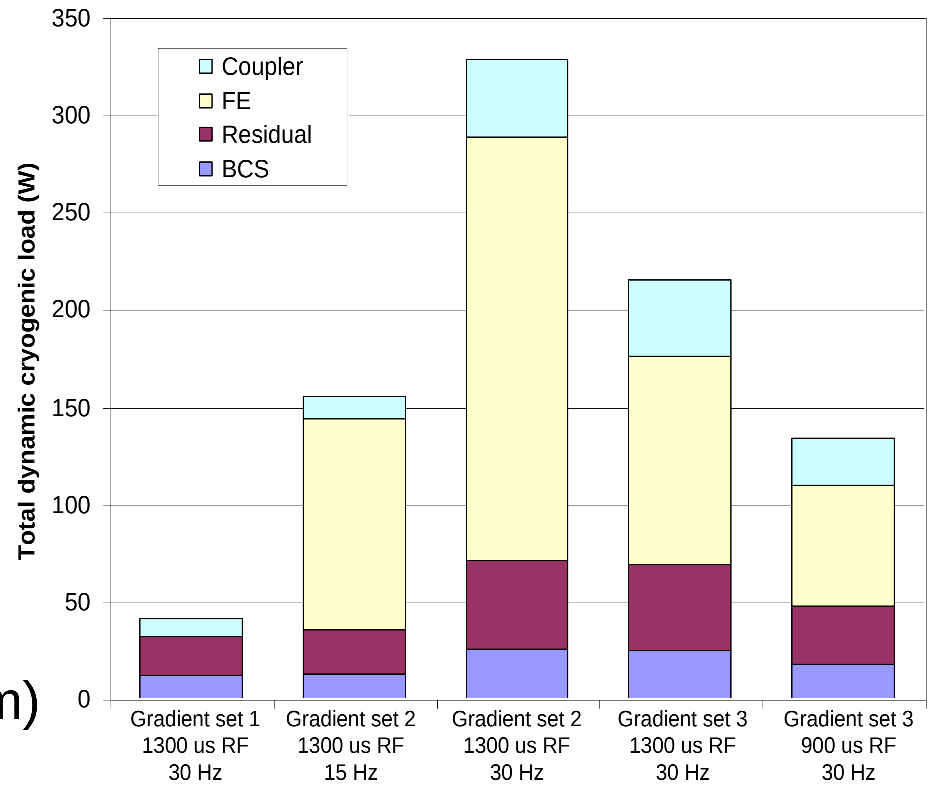
a cavity phase → a cavity beam pipe





Cryogenic loads





Set 1; Below FE threshold (~9MV/m)
Set 2; 80 % of individual limits
Set 3; 88 % of collective limits

Avg(set3)-Avg(set2)~1MV/m

Total dynamic heat loads due to different sources

Abnormal HOM coupler signals (RF only, no beam)

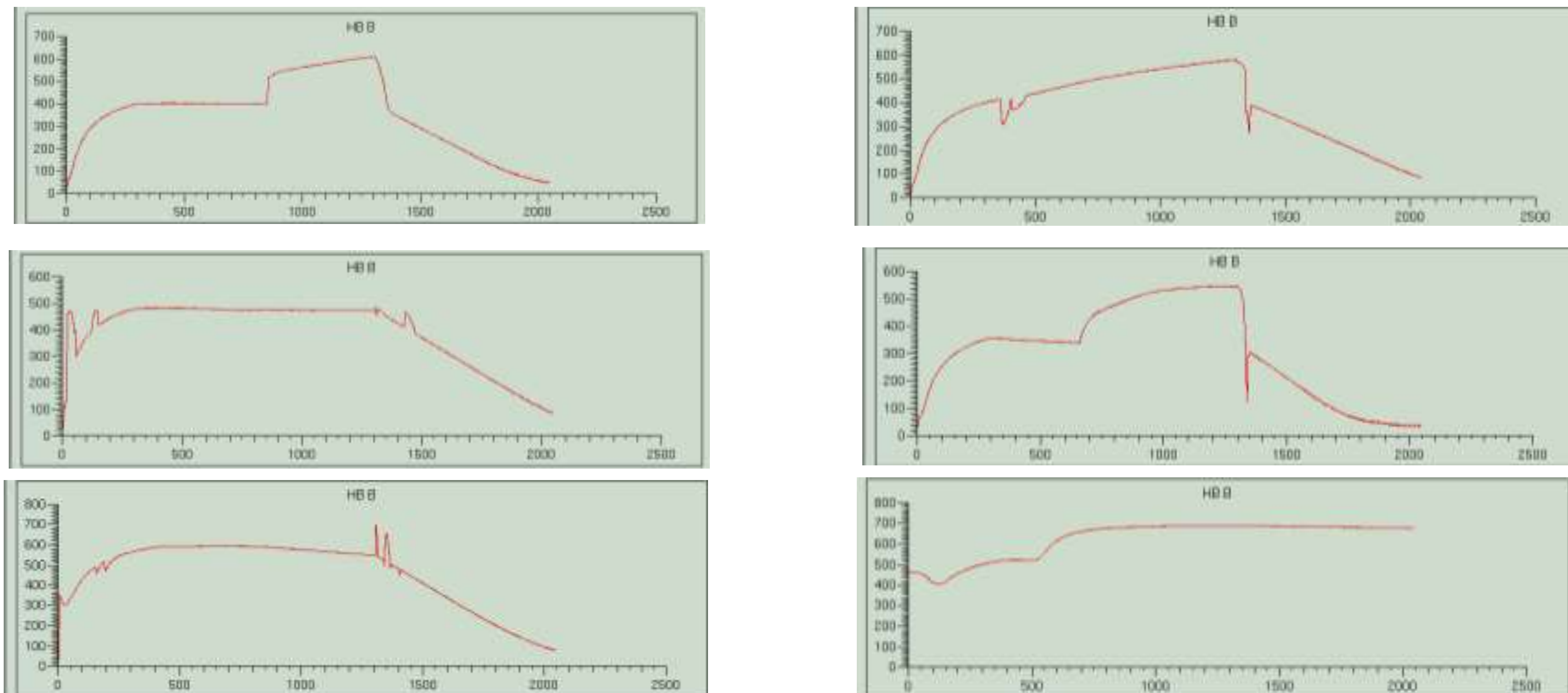
~'0' coupling and rep. rate dependent signals

1~5 Hz

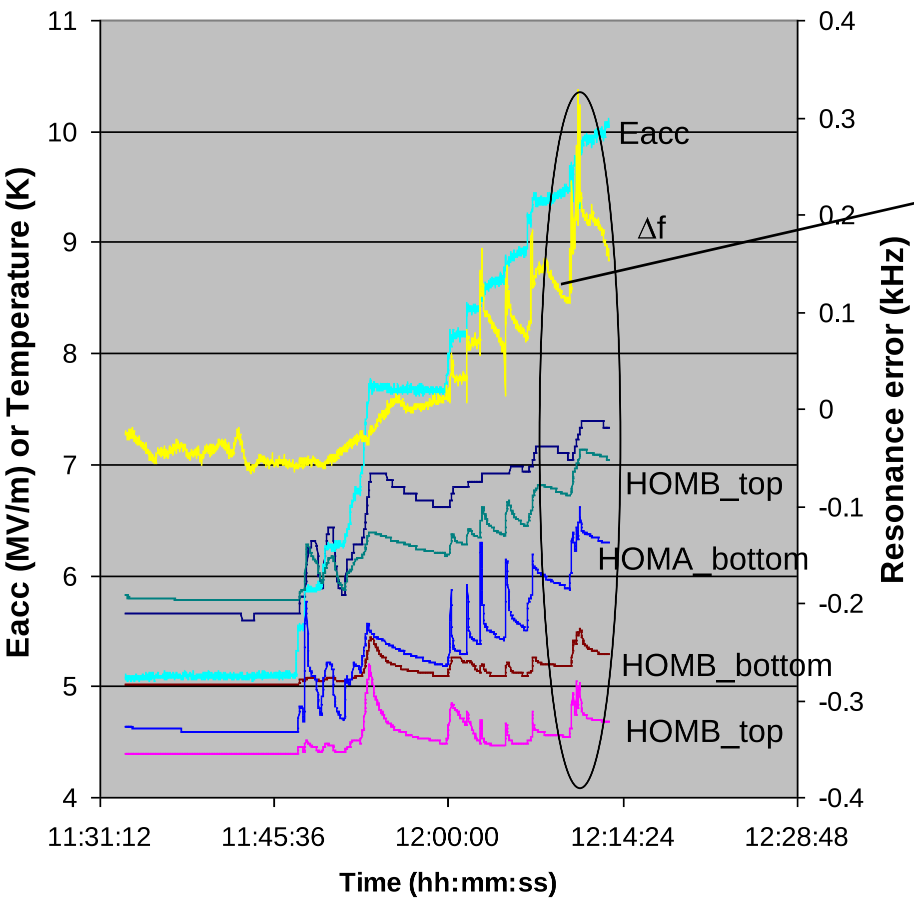
10 Hz

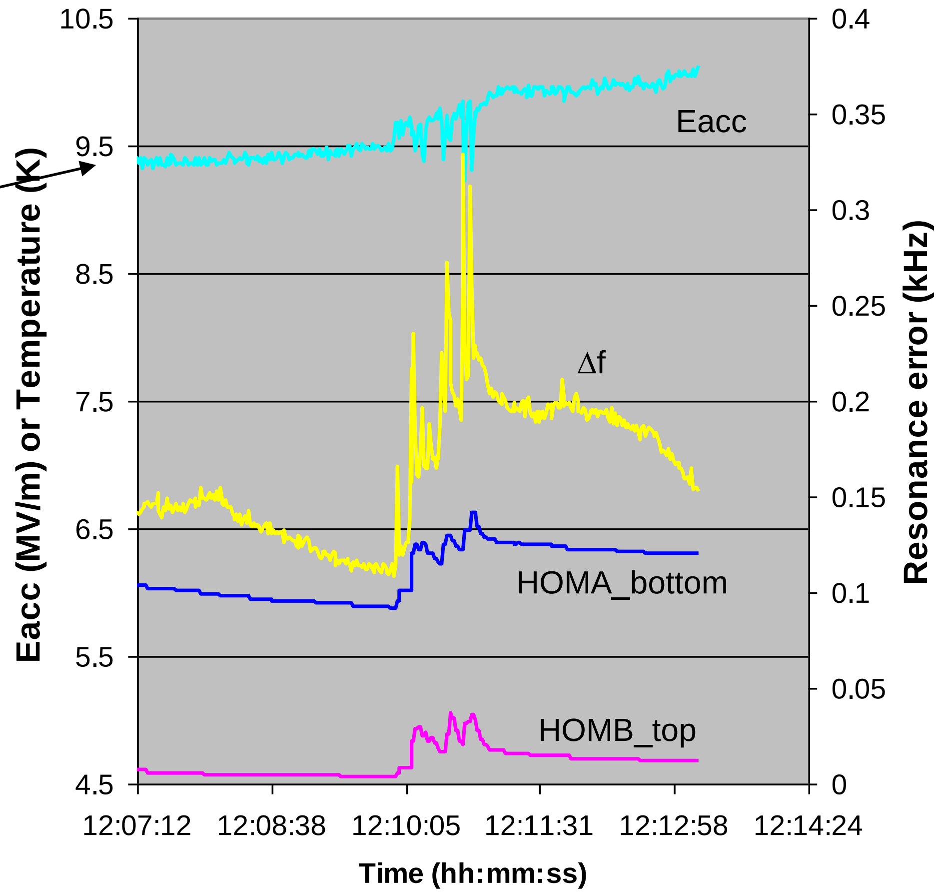
30 Hz

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



HOM coupler MP (19b)



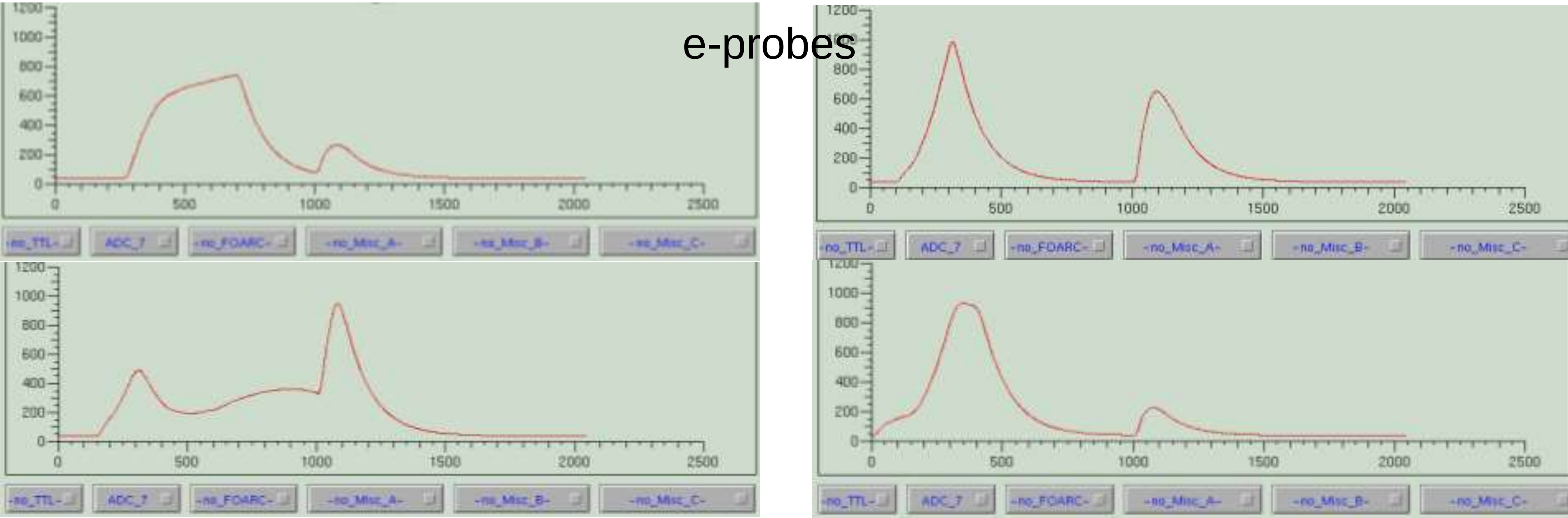


HOMA bottom TD signal led all other TDs, vacuum

- 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

Some other signals during CM 19 test

e-probes



HOM