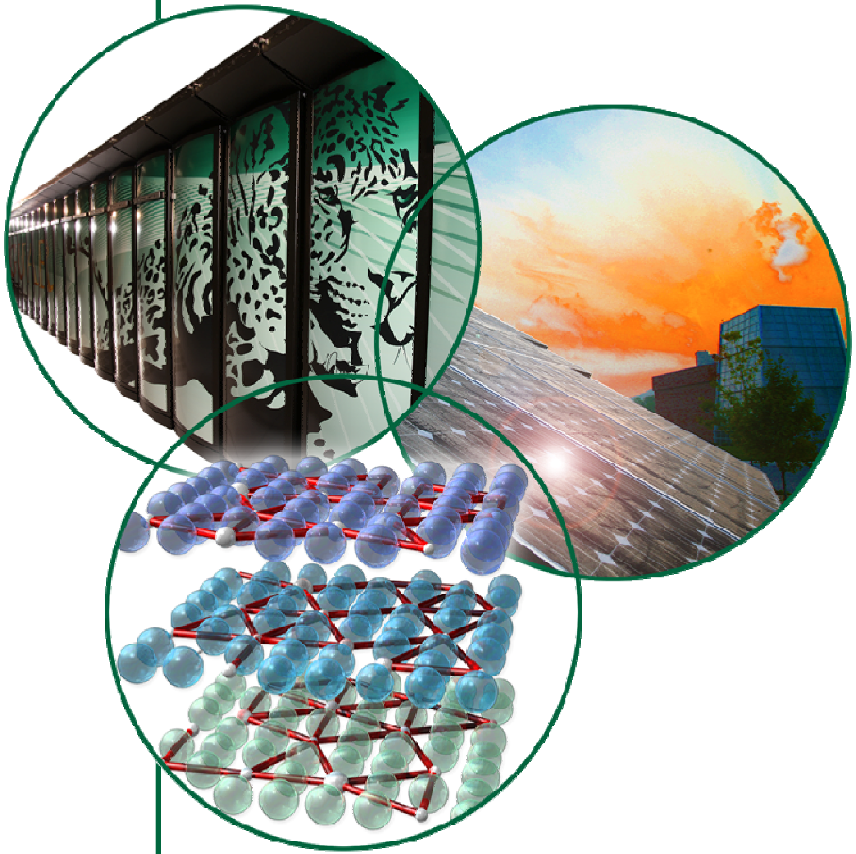
HOM Experiences at the SNS SCL



SPL HOM Workshop
CERN
June 26, 2009

Sang-ho Kim
SNS SCL Area Manager
SNS/ORNL

Outline

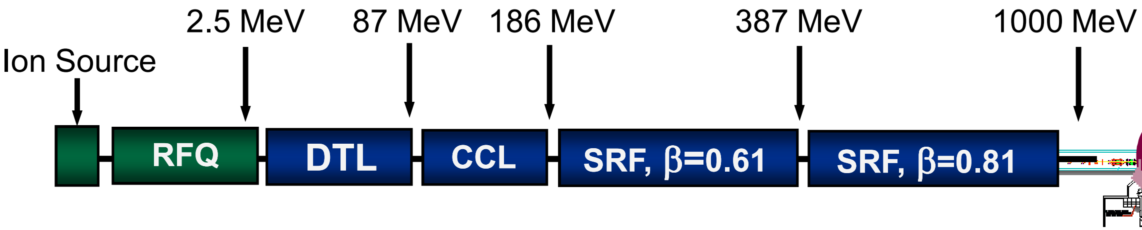
- SNS Intro
- HOM concerns in SNS SRF cavity
  - Reminder of past histories
- HOM coupler issue
- Re-evaluation
  - HOM frequency statistics
  - SNS beam
  - Beam induced signal
- Summary

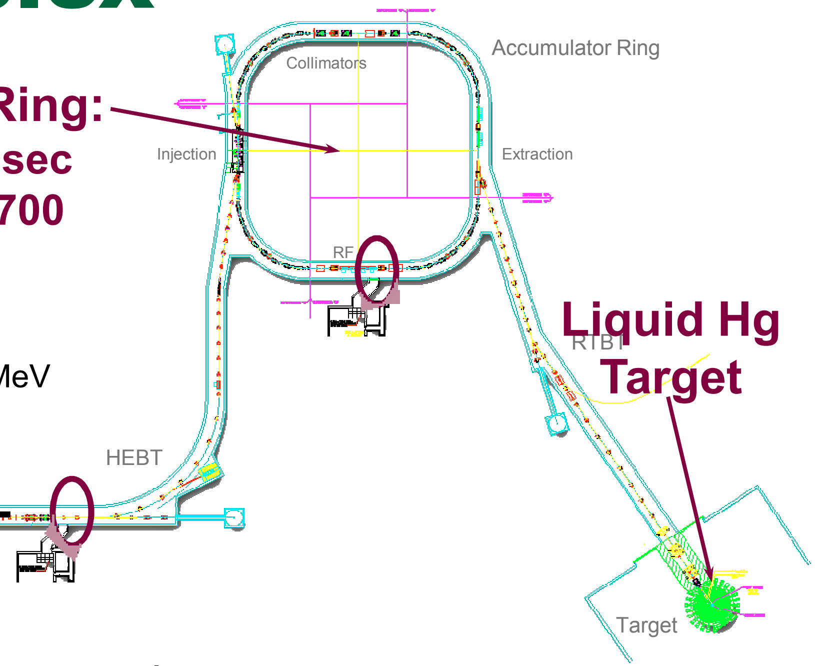
SNS Accelerator Complex

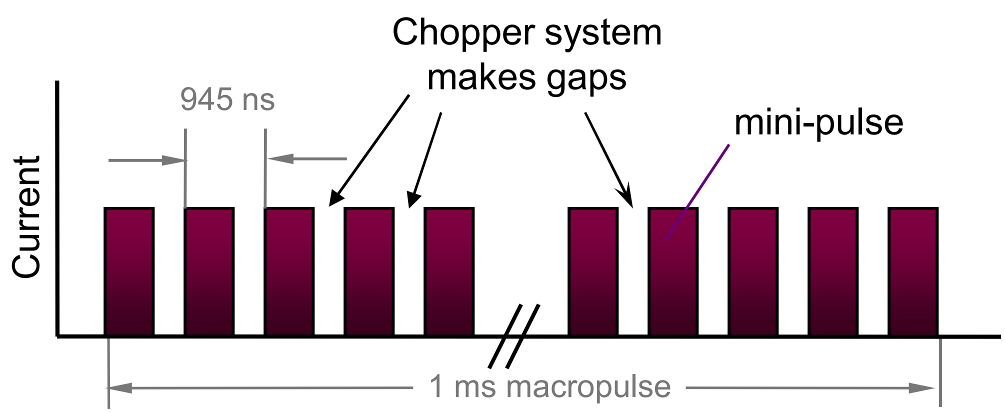
Front-End:
Produce a 1-msec long, chopped, H- beam

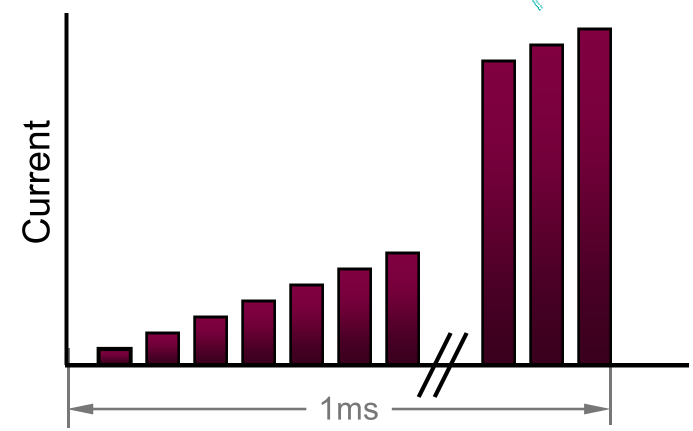
1 GeV LINAC

Accumulator Ring:
Compress 1 msec long pulse to 700 nsec









SNS SRF cavity

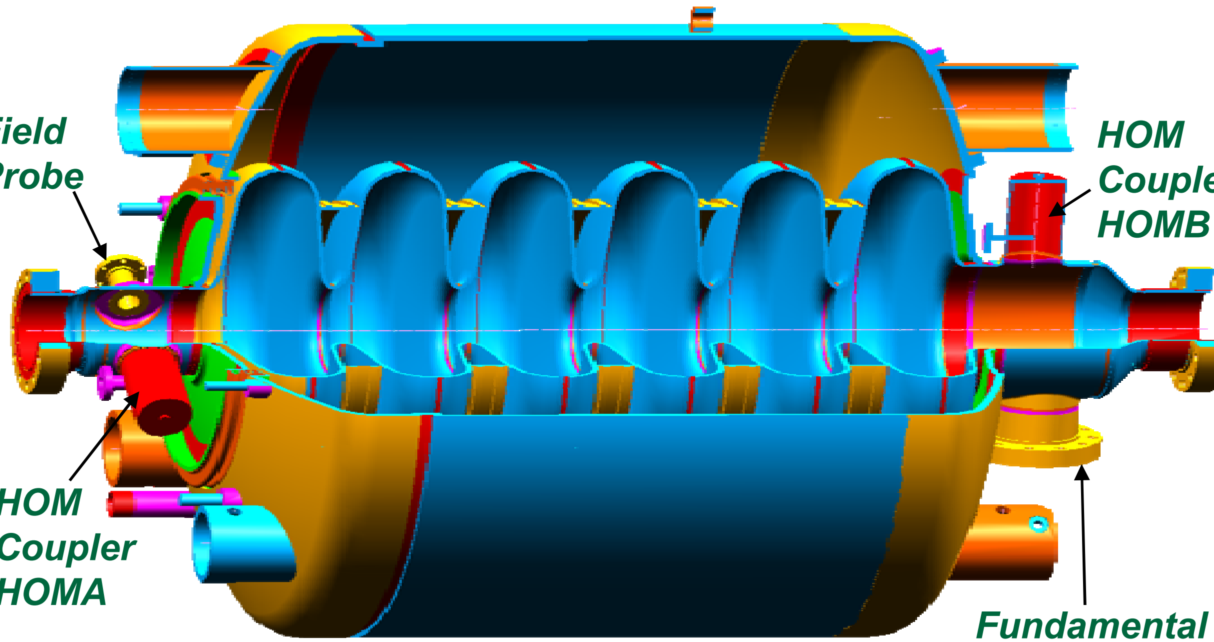
Major Specifications:

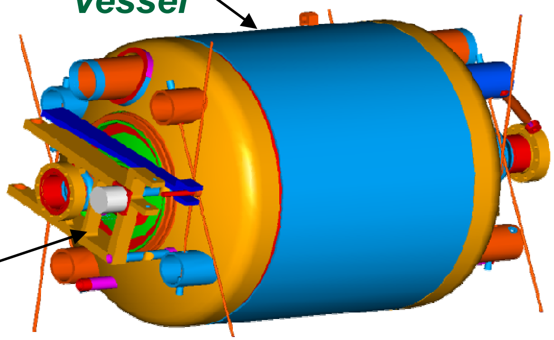
E_a=15.9 MV/m at β=0.81

E_a=10.2 MV/m at β=0.61

&

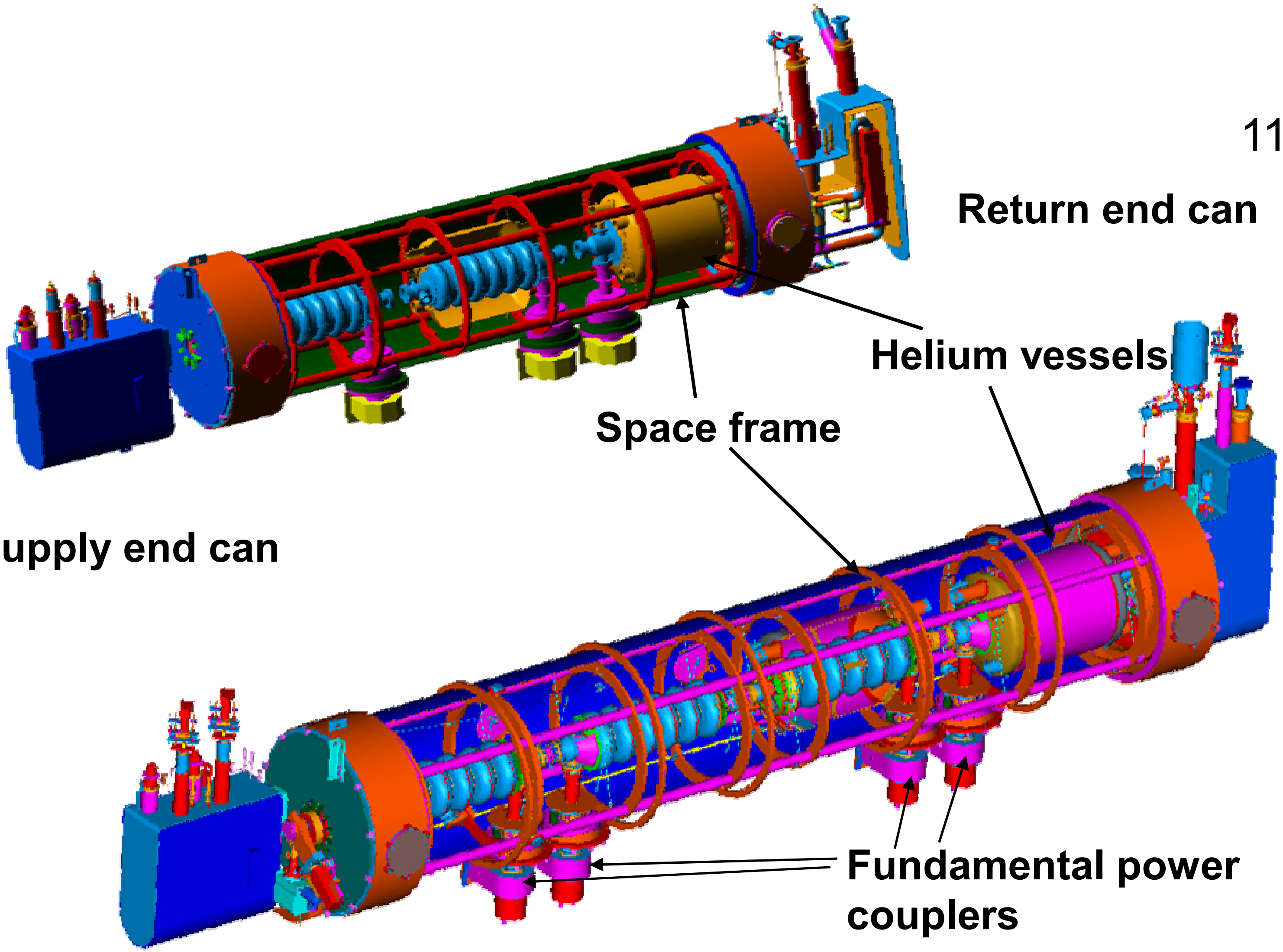
Q_o> 5E9 at 2.1 K





SNS Cryomodule

Designed to operate at 2.1 K (superfluid helium)

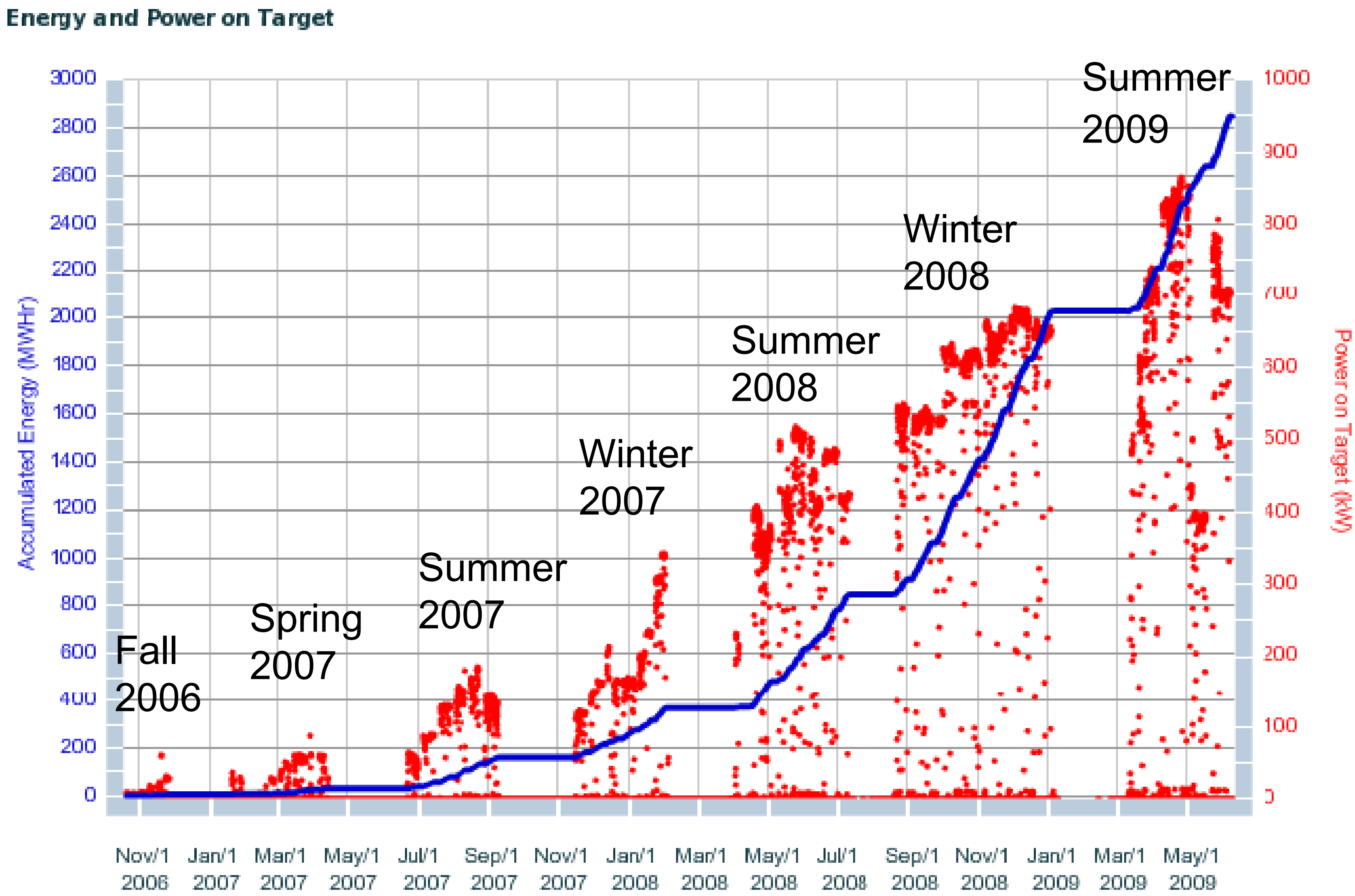


11*Medium beta

12*High beta

81 cavities

Beam power history

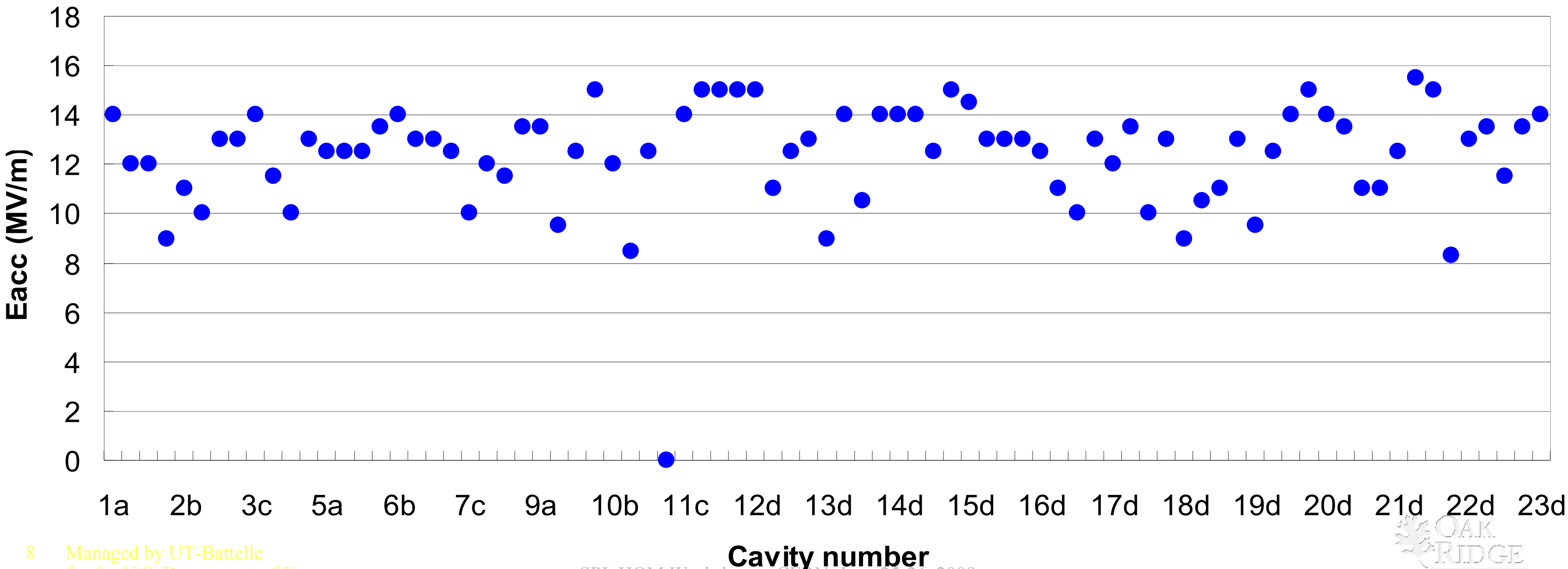


Major Parameters achieved vs. designed

Parameters	Design	Individually achieved	Highest production beam
Beam Energy (GeV)	1.0	1.01	0.93
Peak Beam current (mA)	38	40	38
Average Beam Current (mA)	26	24	24
Beam Pulse Length (μs)	1000	1000	670
Repetition Rate (Hz)	60	60	60
Beam Power on Target (kW)	1440	880	880
Linac Beam Duty Factor (%)	6.0	4.0	4.0
Beam intensity on Target (protons per pulse)	1.5×10^{14}	1.3×10^{14}	1.0×10^{14}
SCL Cavities in Service	81	80	80

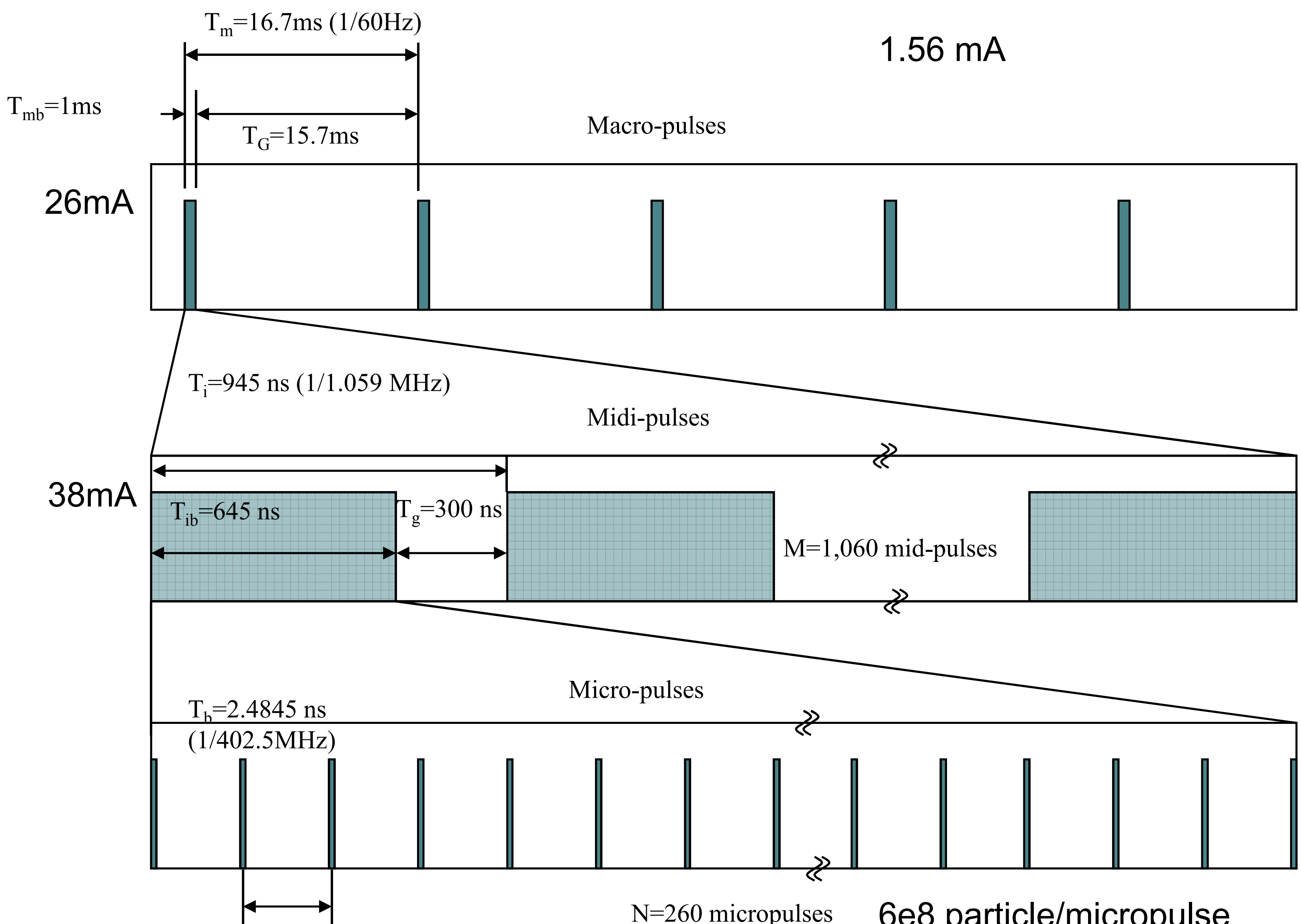
SCL status

- SCL is providing a very reliable operation for neutron production following SNS power ramp-up
  - Down time < 5 min/day (<1 trip/day)
- 930 MeV + 10 MeV (energy reserve)
- In-situ plasma processing
  - Initial attempt showed very promising results
  - R&D plan for 1 year



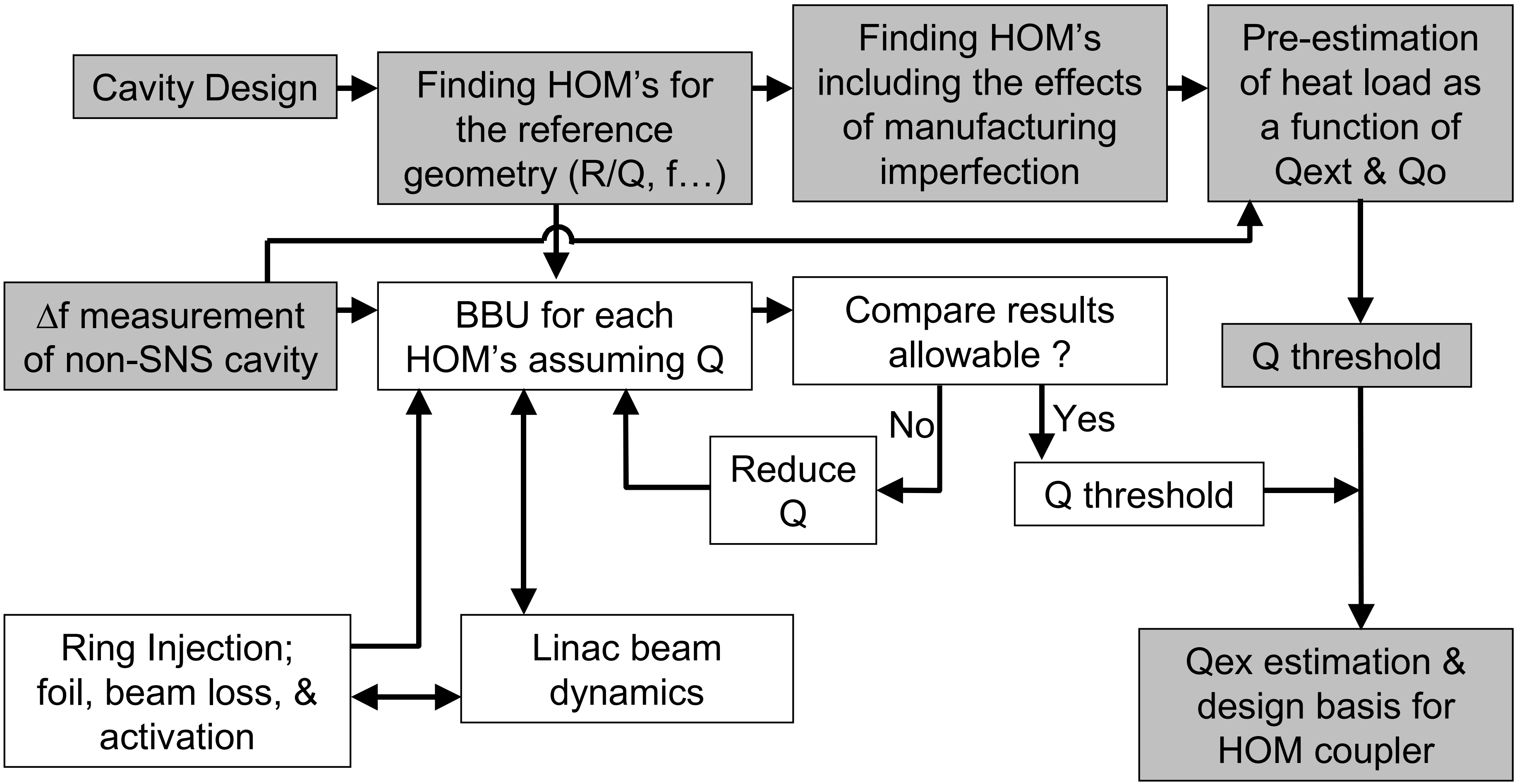
At the Design Phase

SNS Beam Time-Structure



6e8 particle/micropulse
95 pC/micropulse

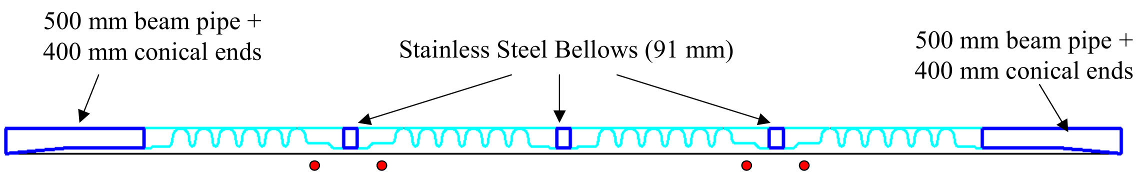
HOM analysis for SNS



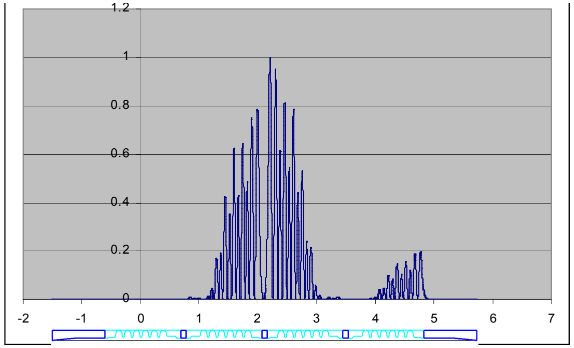
HOM findings (I)

- Monopoles, dipoles, quadrupoles, sextupoles
  - Up to cutoff frequencies of pipes (~3 GHz)
  - Single cavity, Superstructure
  - r/Q's of all modes as a function of particle velocity
- Mechanical imperfection
  - Random geometrical error based on manufacturing experiences
  - Possibility of having trapped modes

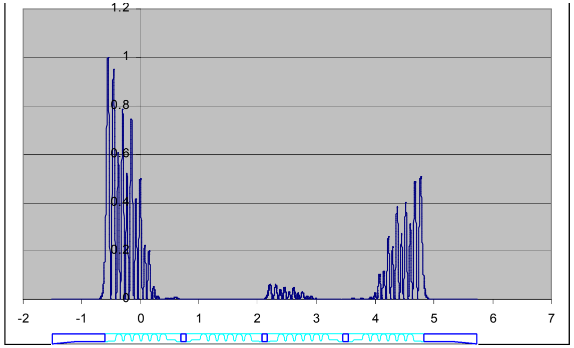
HOM findings (II)



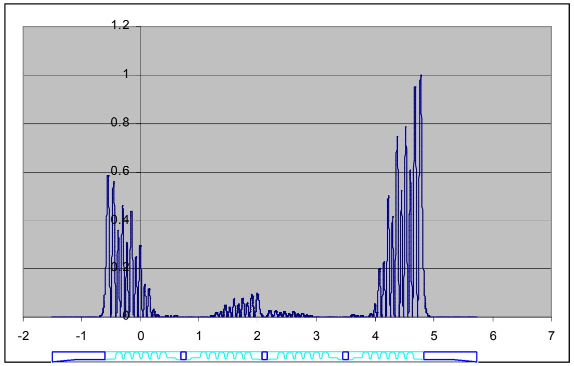
● ; FPC sides



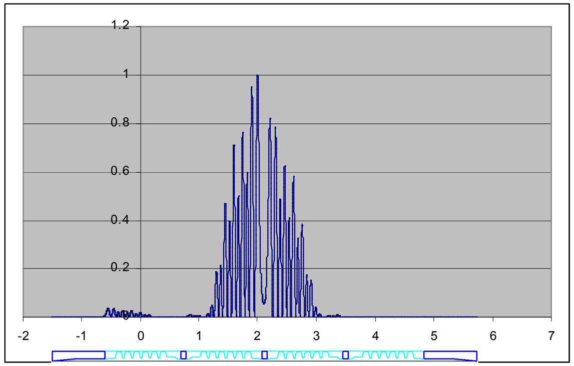
137 (35-1)



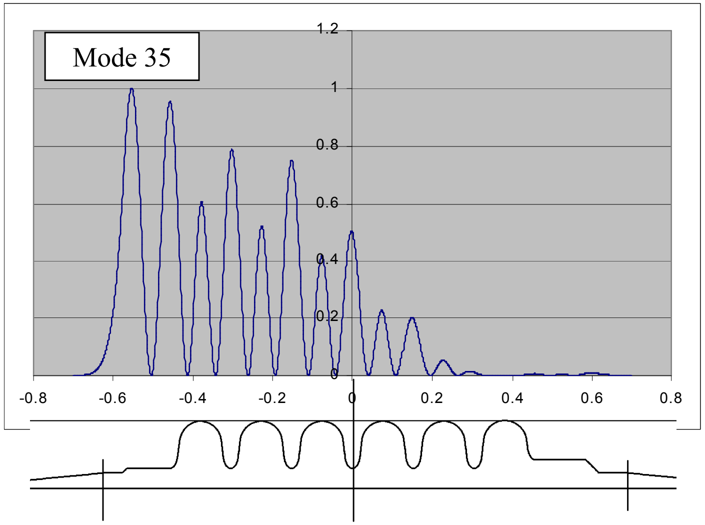
138 (35-2)



139 (35-3)

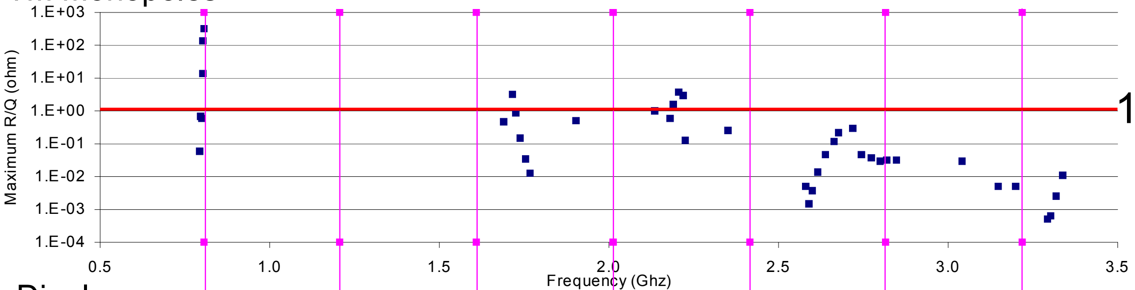


140 (35-4)

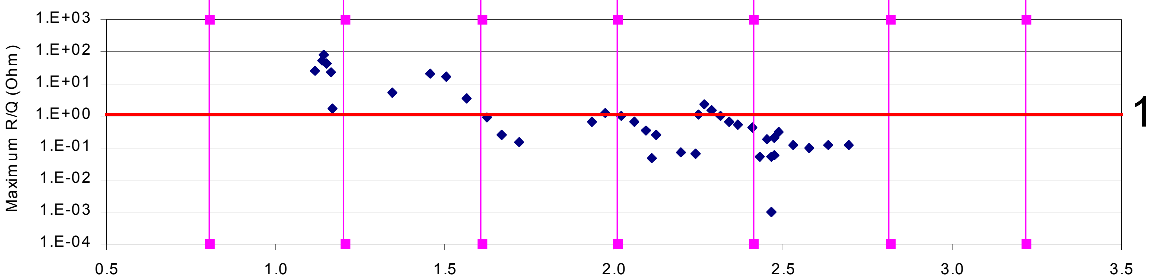


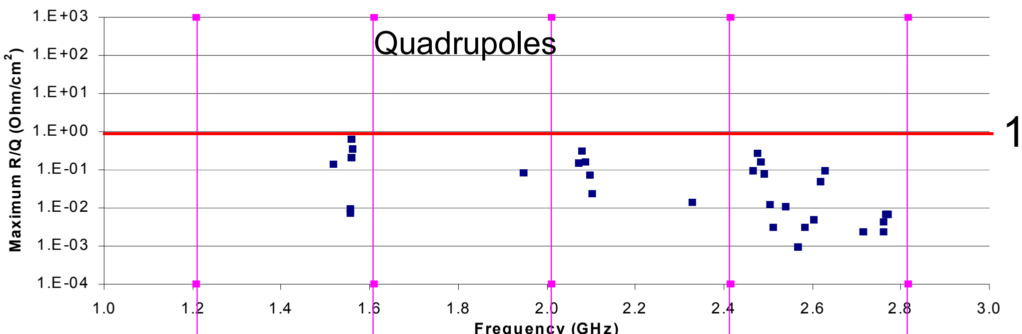
HOM findings (medium)

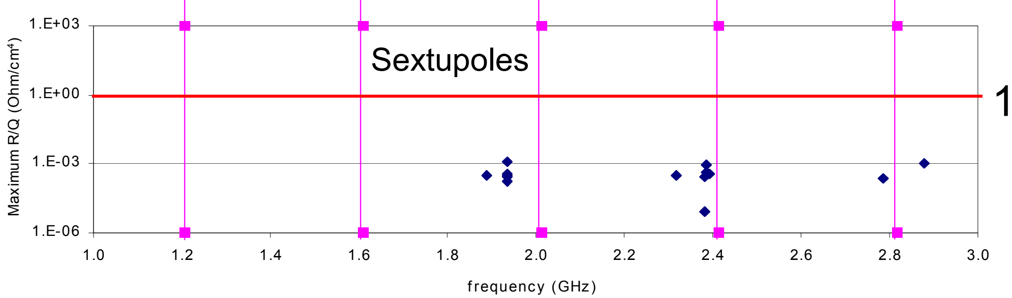
TM Monopoles

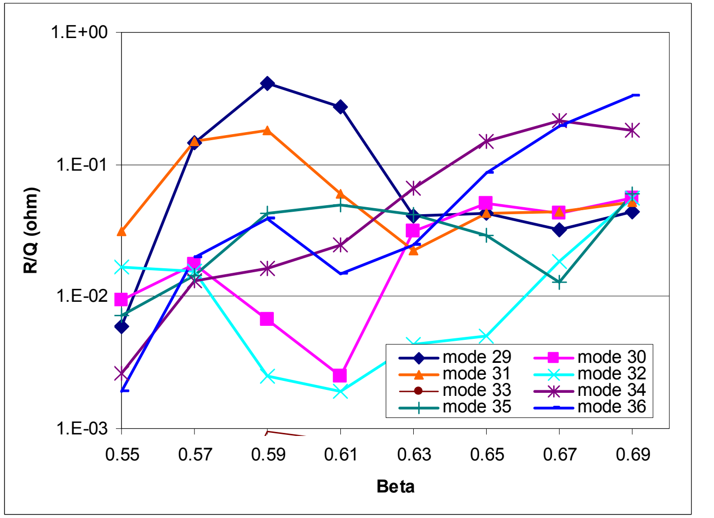


Dipoles

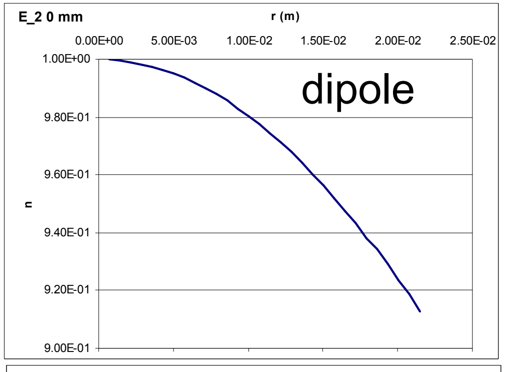


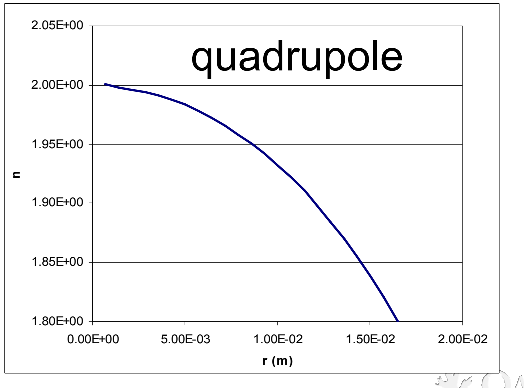






r/Q vs. β



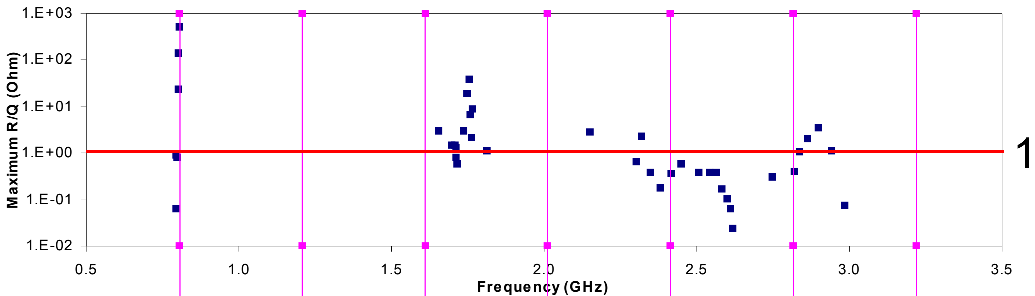


2009

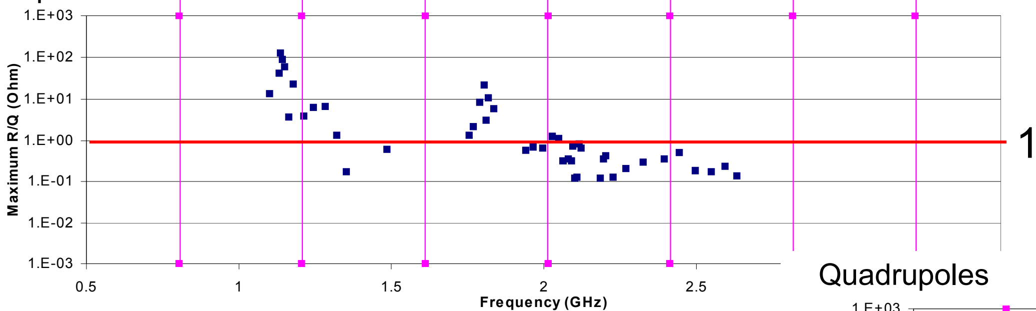
n vs. r; radial gradient of the axial electric field (Ez✪r^n)

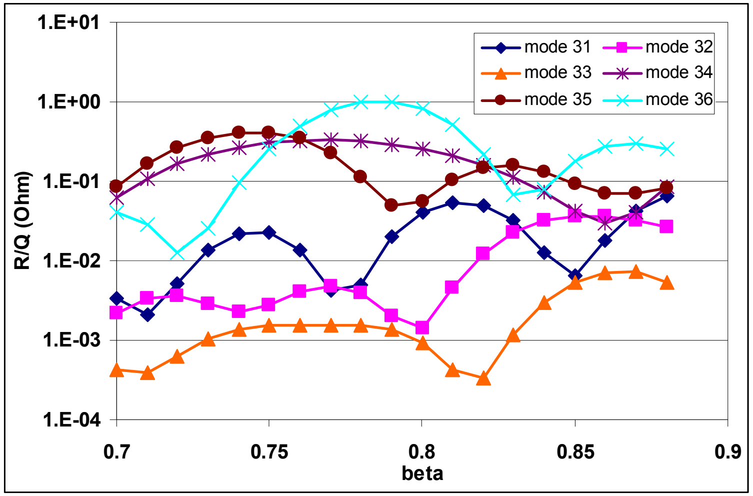
HOM findings (high)

TM Monopoles



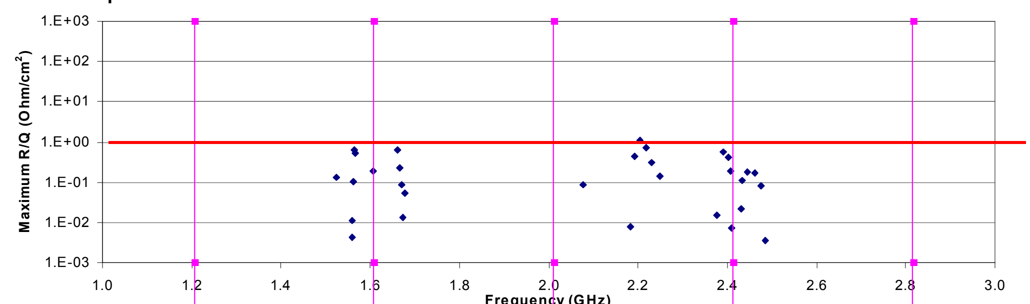
Dipoles



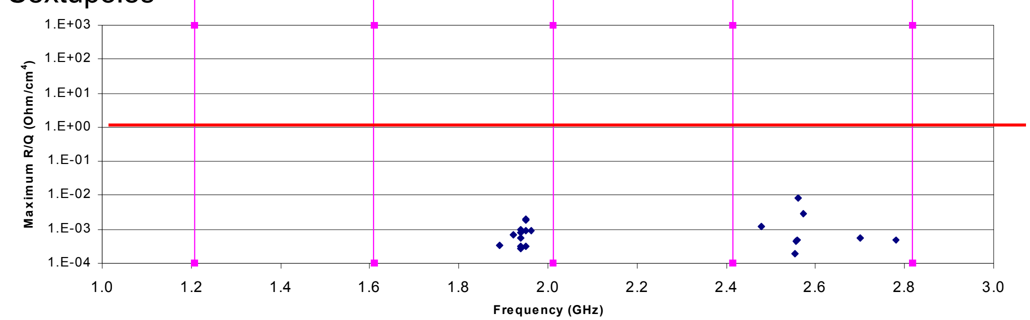


r/Q vs. β

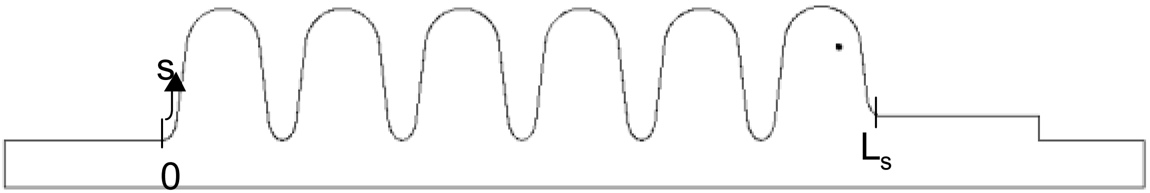
Quadrupoles



Sextupoles



Geometrical imperfection (for any possible trapped mode)

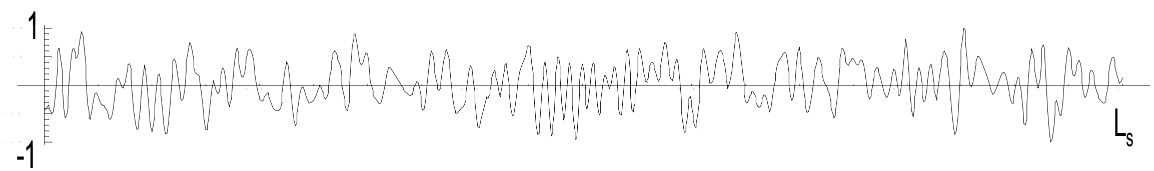


$$\text{Deviations from the reference geometry} = \sum_{i=1}^{200} (a_i \cos(i\pi s / L_s) + b_i \sin(i\pi s / L_s))$$

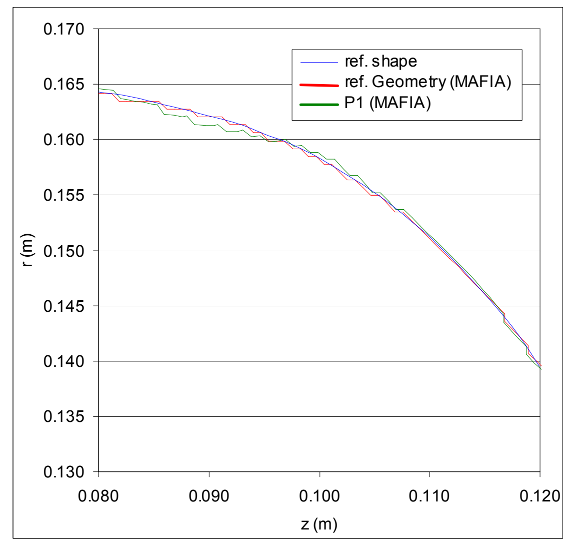
; normal to the surface

Ls; total length along the cavity surface, ~1.9 m for high beta cavity

a_i & b_i; random coefficient



An example of the random mechanical perturbation.



Trapped mode is unlikely up to quadrupole modes

Properties of HOM frequency (R. Sundelin's study at Cornell)

- HOM frequency Centroid Error between analysis & real ones
  - Fractional error; $(f_{analysis}-f_{real,avg})/f_{analysis} < 0.0038$
  - SNS used 0.8 % (for conservative analysis)
    - put frequency centroid on the highest spectral line in the range

- HOM frequency spread

$$\sigma = 0.00109 \times \left| f_n - f_0 \right|$$

f_o; fundamental frequency, f_n; HOM frequency

  - For beam dynamics 20 % of this value were used for conservative analysis

- Non-pi fundamental mode

$$\left| \frac{f_{measured} - f_{calculated}}{f_{calculated}} \cdot \frac{f_{\pi-mode}}{f_{\pi-mode} - f_{calculated}} \right| \leq 0.027,$$ 0.0675 was used for analysis

OAK RIDGE National Laboratory

Bunch Tracking (I)

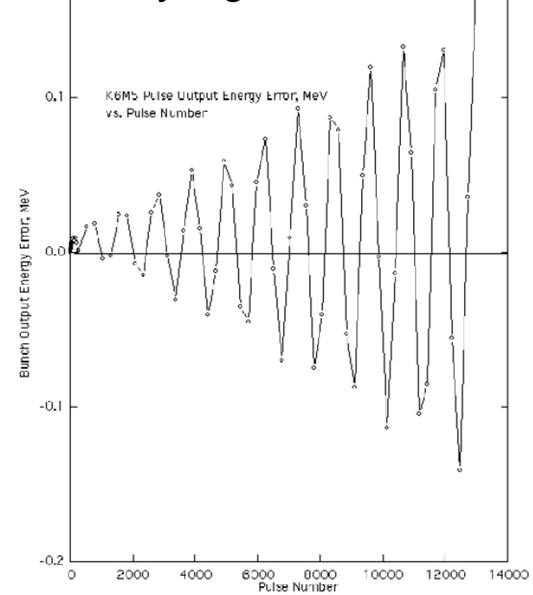
JLab; R. Sundelin, L. Merminga, G. Krafft, B. Yunn, J. Delayan
SNS; D. Jeon, J. Wei, M. Doleans, S. Kim

- **Transverse**
  - **Cumulative effects**
    - **True instability; can occur at almost any frequency**
      - **No transverse instabilities for $Q<10^8$ (20% of σ for f spread)**
    - **Error magnification; worst when an HOM frequency differs by of the order of 1 cavity bandwidth from a beam spectral lines**
      - **Error magnification~1 $\oplus$ 0.00062 (0.8 % centroid error)**

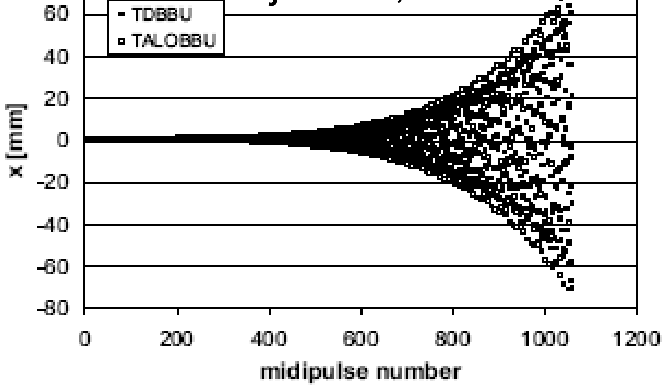
- **Longitudinal**
  - **Instability**
    - **Bunch energy error, bunch-to-bunch variation**
    - **Can occur at almost any frequency**
    - **Non-pi fundamental passband can excite oscillations**
      - **No instability & significant of energy error at $Q<10^8$**

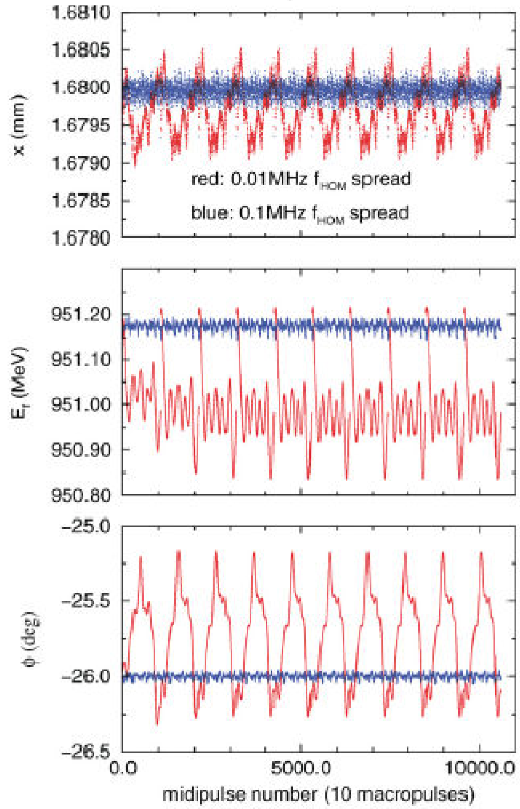
Bunch Tracking (II)

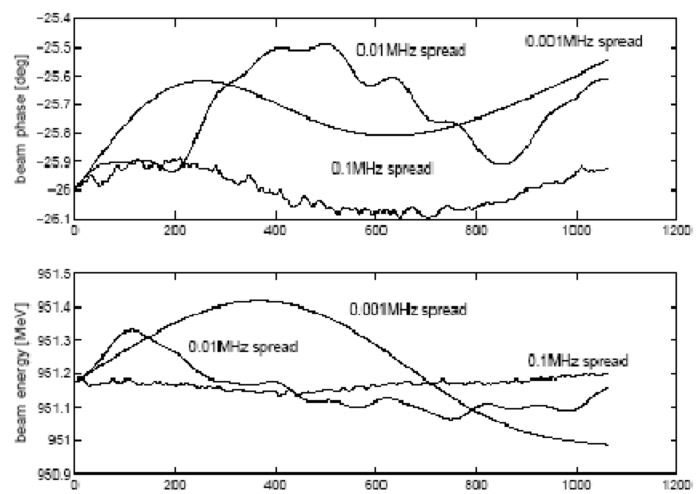
Bunch output energy error
With artificially high r/Q for 5π/6 mode



All quads are turned off for benchmarking
Beam injection; 1 mm off axis







HOM centroids; switched to the most dangerous place
Beam current; 50 mA, 1 mm off-axis injection
HOM's $Q=10^8$

HOM induced power

- Individual cavity issue
- Function of HOM f, r/Q, Q
- Same logic is applied for centroid
- Both analytic & numeric calculation
- Find the possible peak HOM induced power

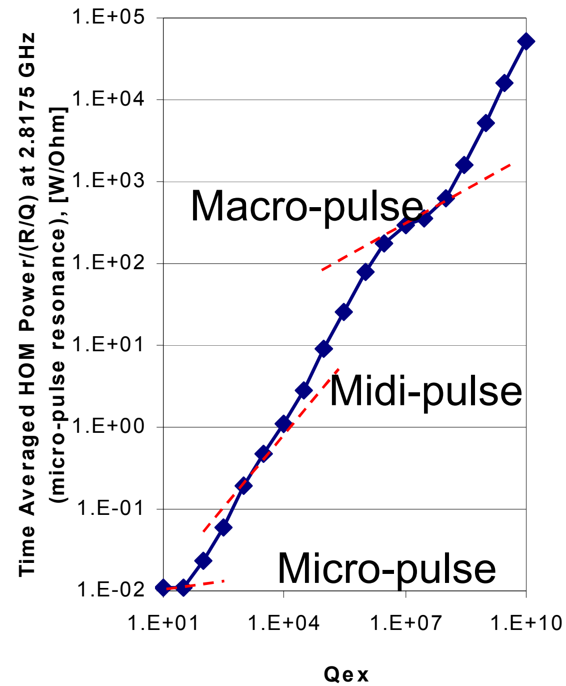
Beam induced HOM Power (I)

HOM Power

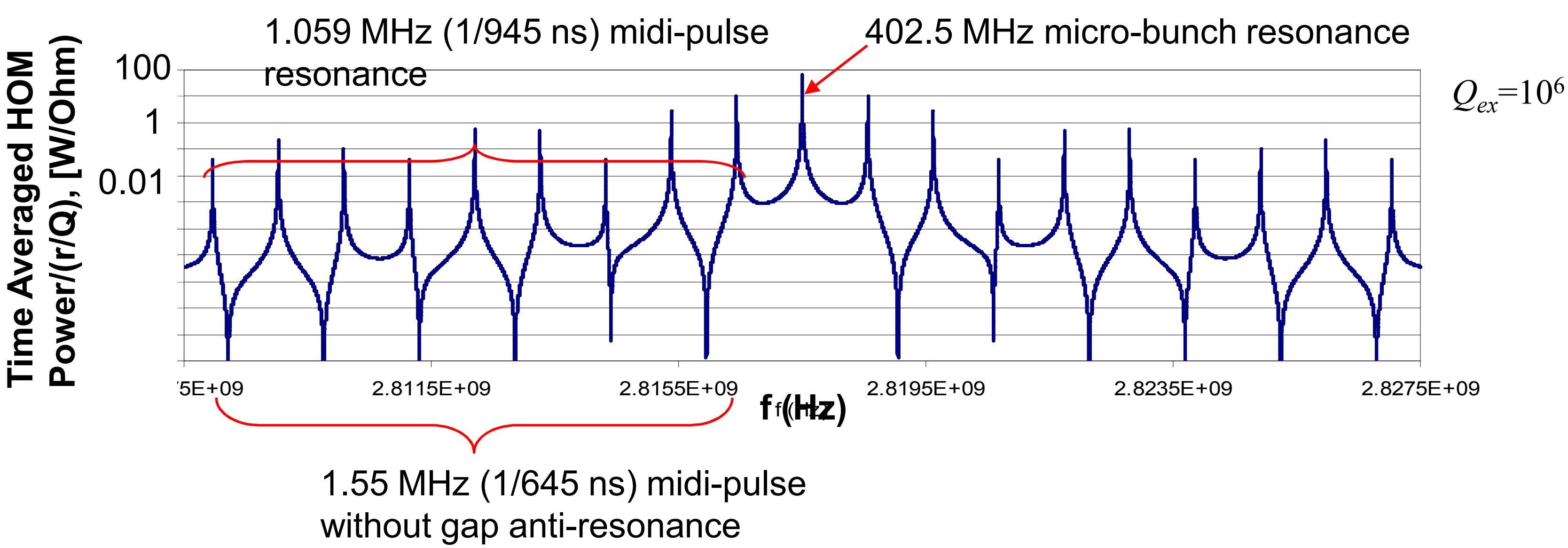
$$P(t) = \frac{V(t)^2}{\left(\frac{r}{Q}\right) Q_{ex}}$$

Time Averaged HOM Power

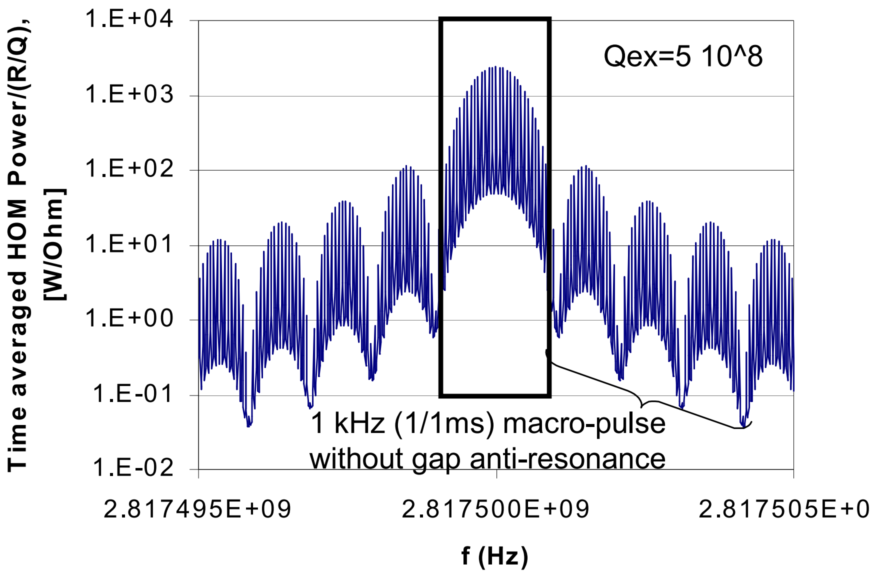
$$P_{avg} = \frac{1}{T}\int_{t1}^{t1+T} P(t)dt$$

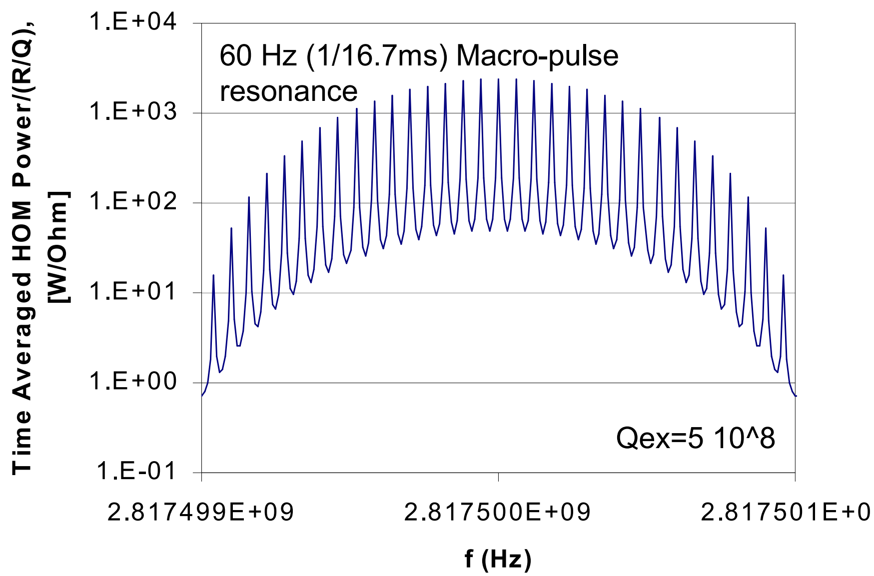


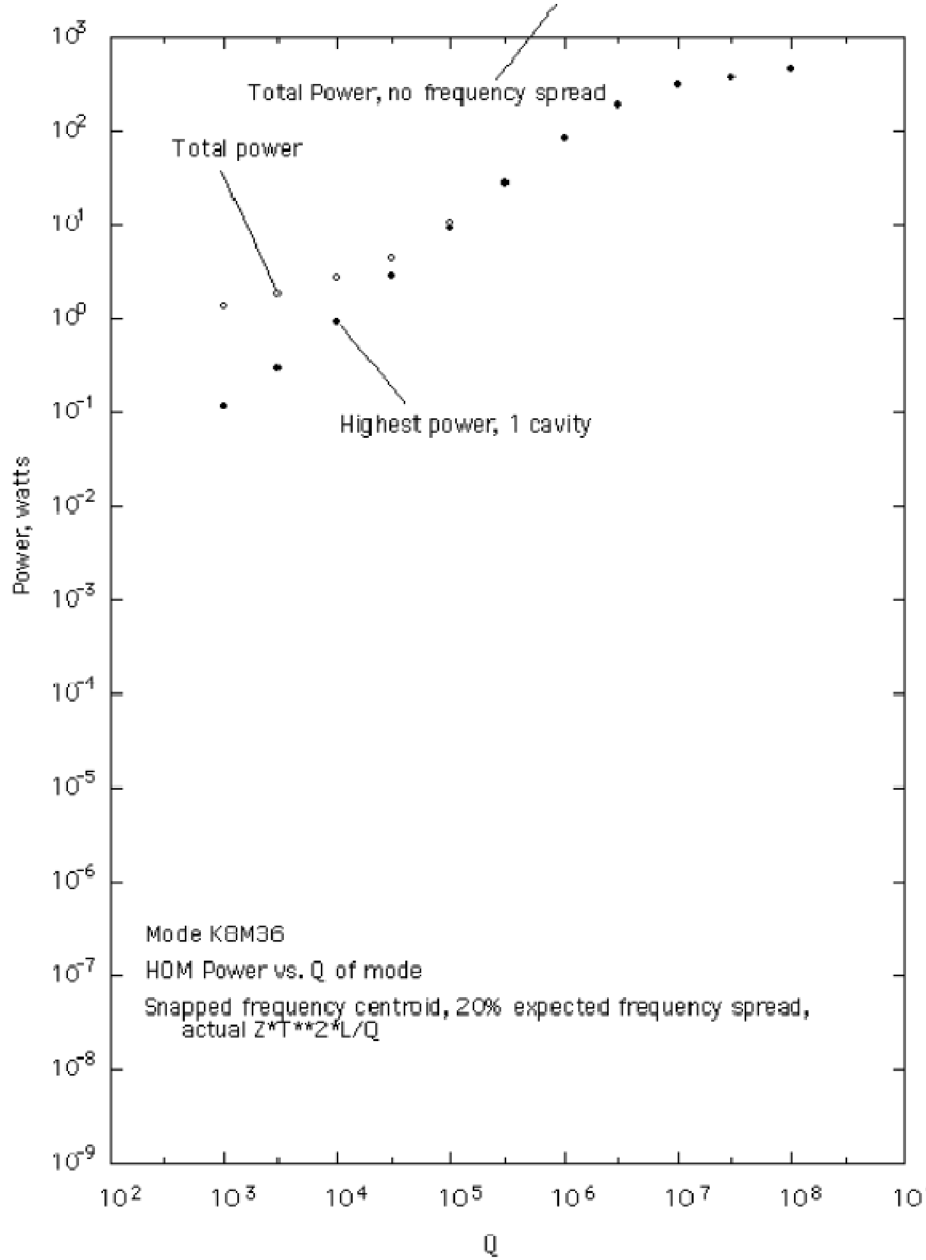
In continuous frequency domain



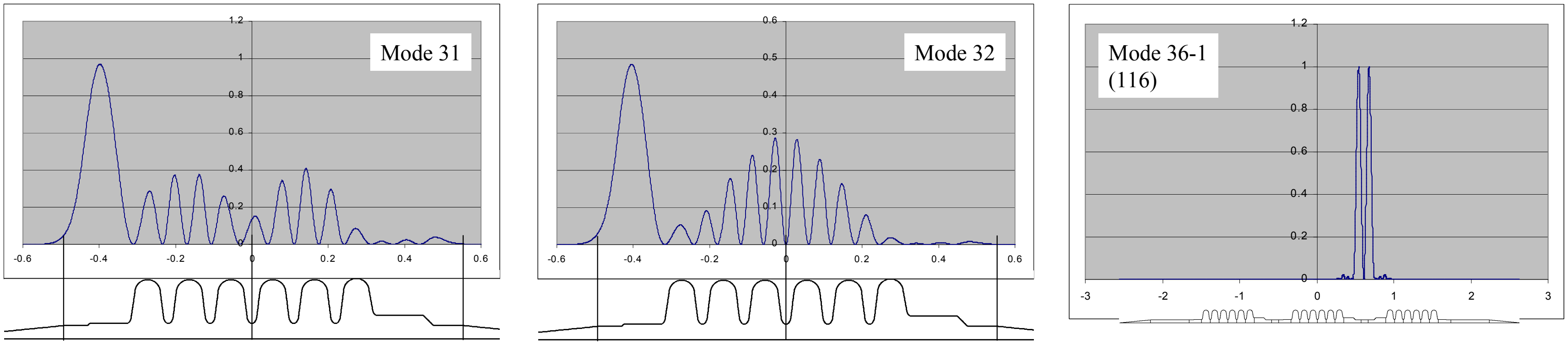
Beam induced HOM Power (II)

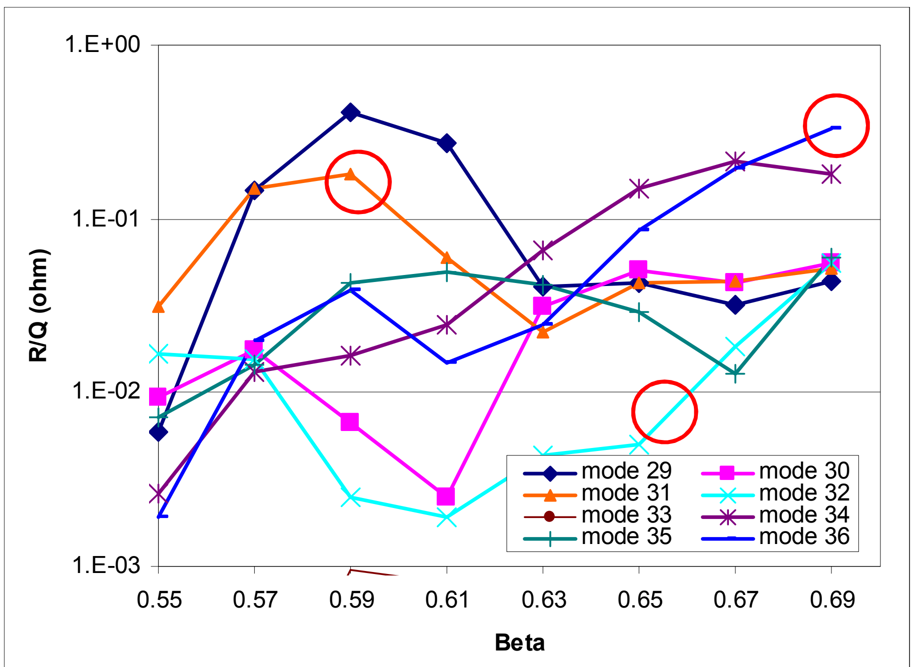






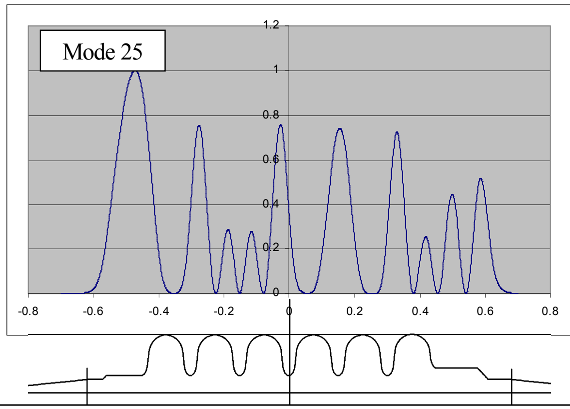
Dangerous Modes at around main spectral lines within the centroid error range (Medium beta cavity)

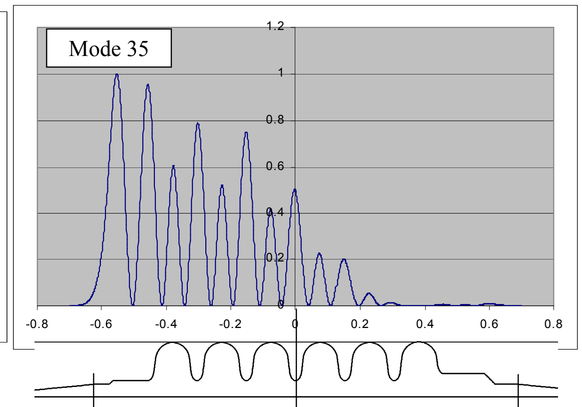


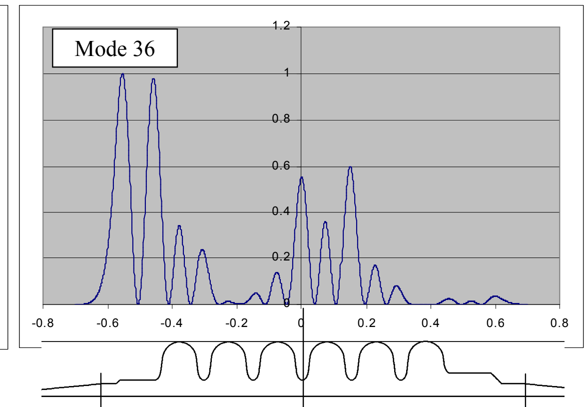


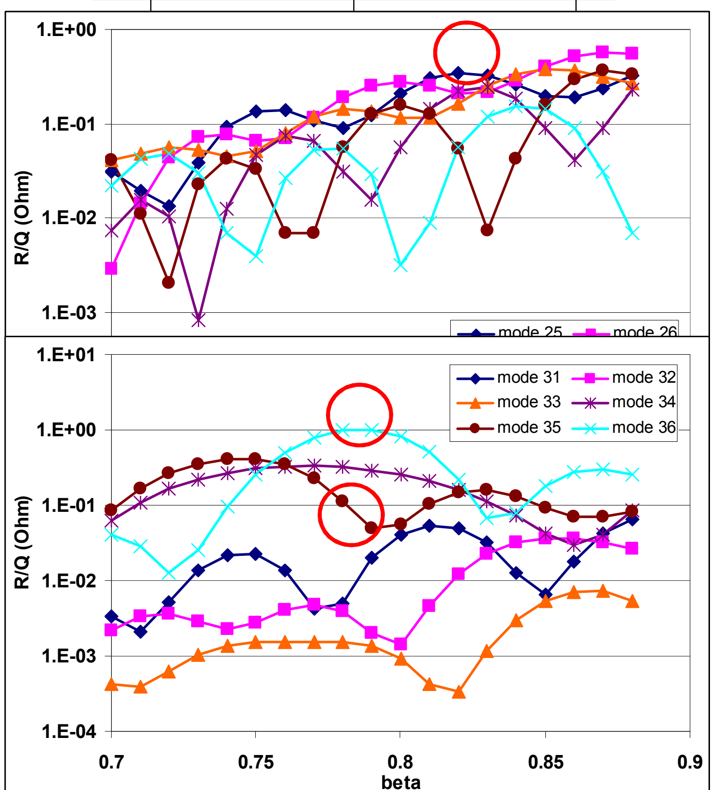
Mode	f (Hz)	Qo (due to SS Bellows)
31-1	2.800995E+09	1.5660E+07
31-2	2.800834E+09	1.6235E+07
31-3	2.800863E+09	1.5158E+07
32-1	2.820670E+09	1.9979E+07
32-2	2.820575E+09	1.8349E+07
32-3	2.820466E+09	1.9049E+07
36-1	3.230296E+09	3.5576E+04

Dangerous Modes at around main spectral lines within the Centroid Error range (High beta cavity)







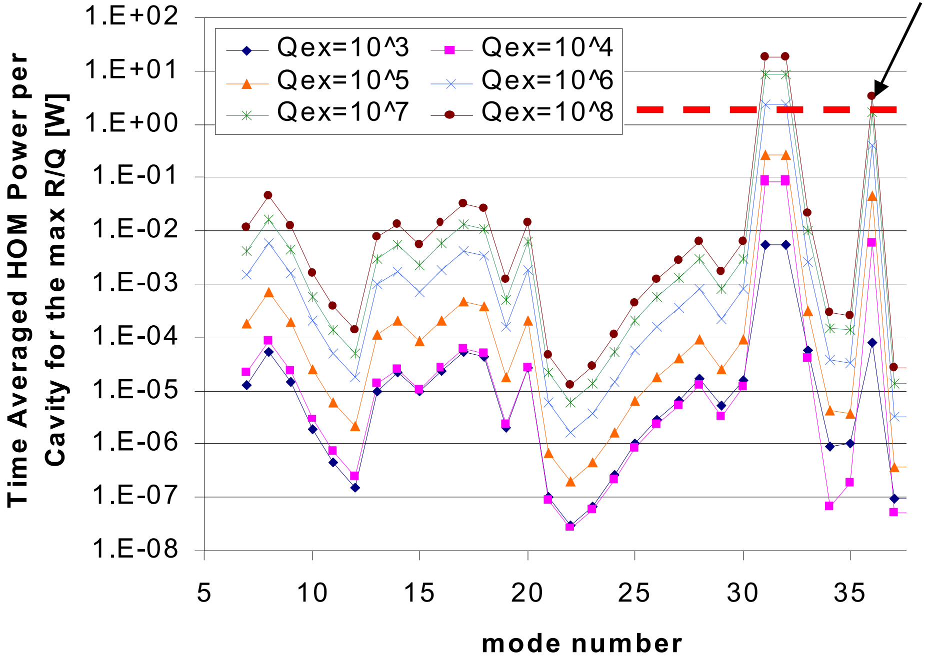


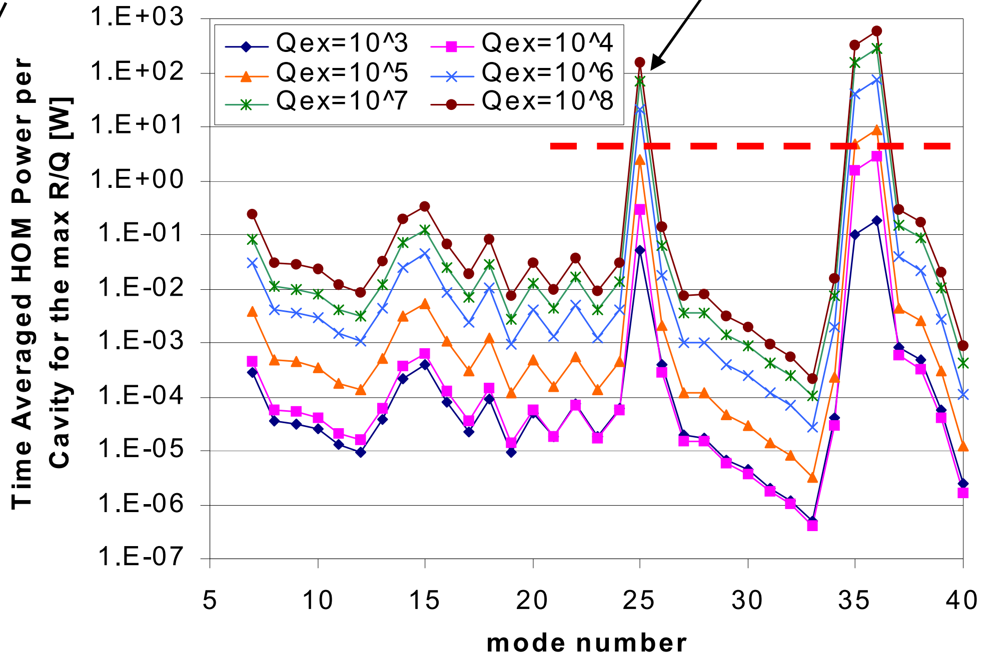
Modes	f (Hz)	Qo (due to SS Bellows)
25-1	2.41389E+09	< 2.0E+6 (FPC)
25-2	2.41406E+09	< 2.0E+6 (FPC)
25-3	2.41394E+09	< 2.0E+6 (FPC)
25-4	2.41327E+09	< 2.0E+6 (FPC)
35-1	2.81540E+09	7.942E+06
35-2	2.81576E+09	4.206E+06
35-3	2.81555E+09	4.314E+06
35-4	2.81556E+09	2.772E+06
36-1	2.83064E+09	5.508E+06
36-2	2.83046E+09	2.655E+06
36-3	2.83016E+09	2.086E+06
36-4	2.83008E+09	2.224E+06

Maximum HOM power of each mode in the Centroid Error range for Maximum r/Q

Beam pipe mode;
~ out of concern

FPC coupling;
Less concern





Damping requirement;

Medium beta cavity → 10^6
High beta cavity → 10^5

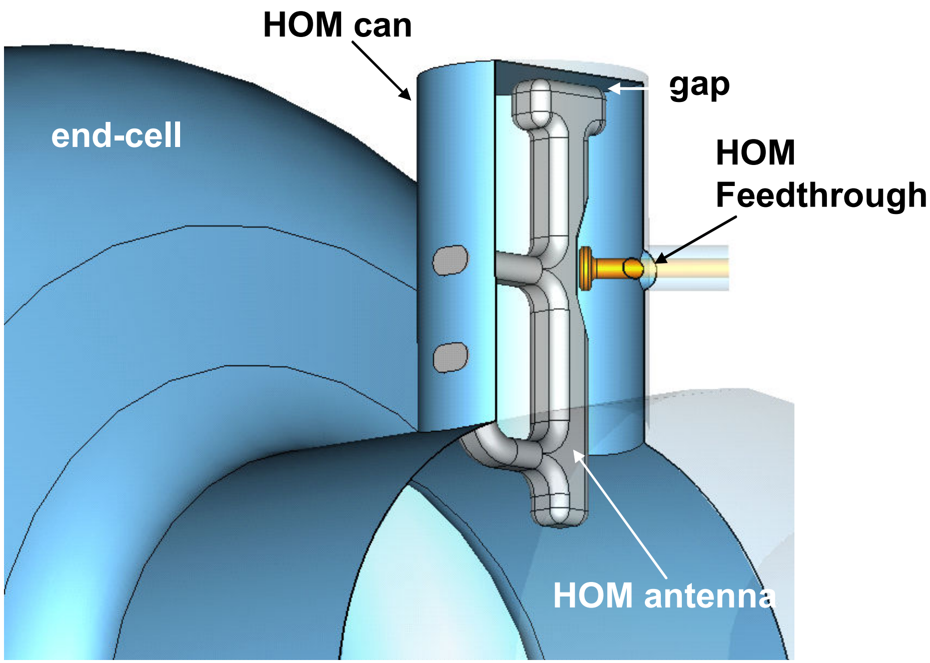
The decision for SNS HOM

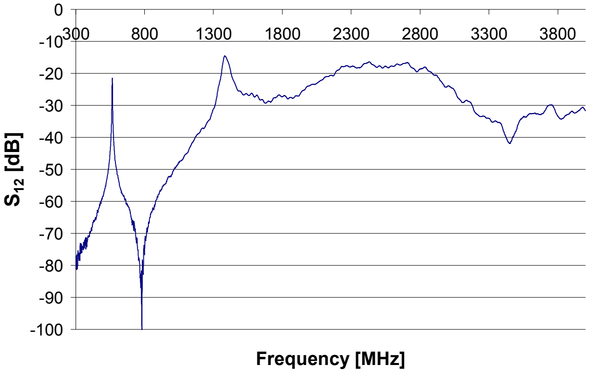
- No Beam dynamics issue
- Centroid error, f spread & location of cavities; in question
- When $Q>10^5$, 10^6, there's a concern.
  - HOM power ~ fundamental power dissipation
  - but the probability is very low even under the conservative assumptions
- Extra insurance
  - SNS is the first pulsed proton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

SNS HOM Coupler

SNS HOM Coupler

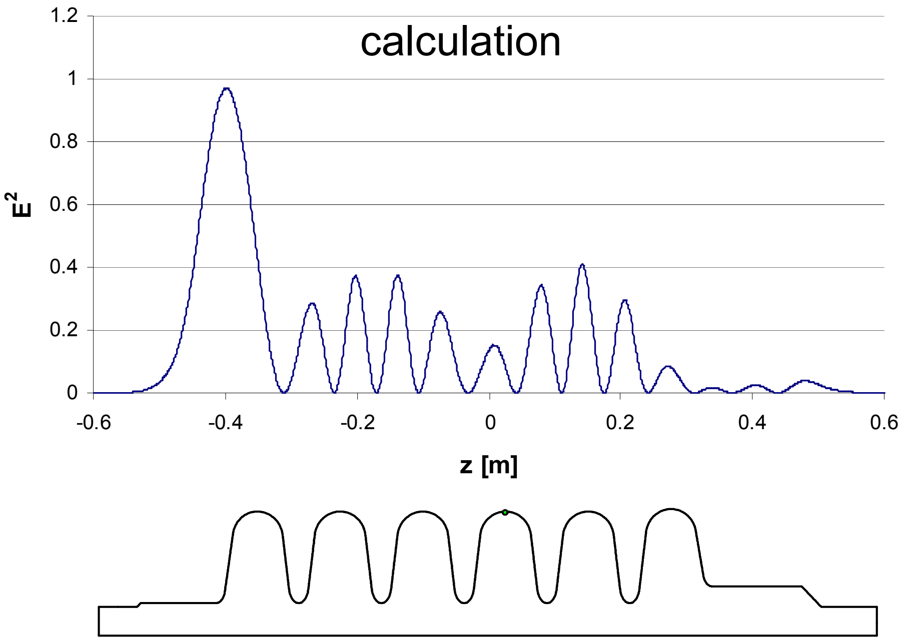
- Coaxial type notch filter scaled from TTF was chosen

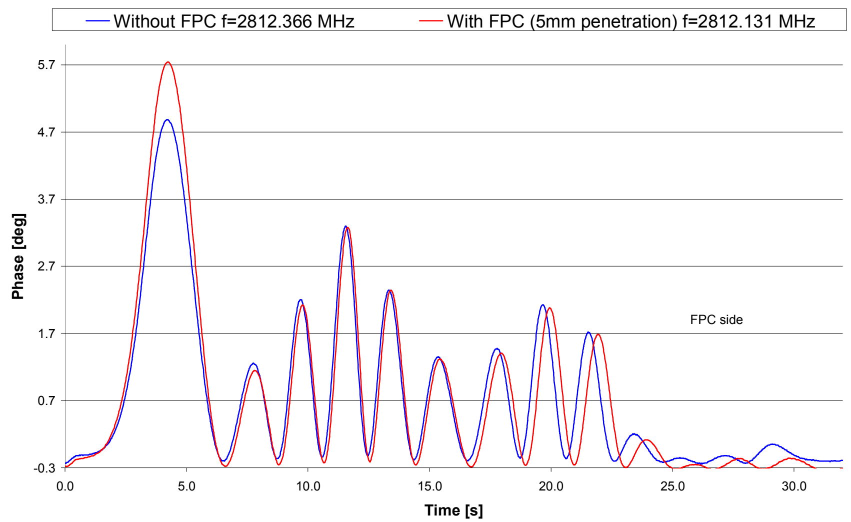




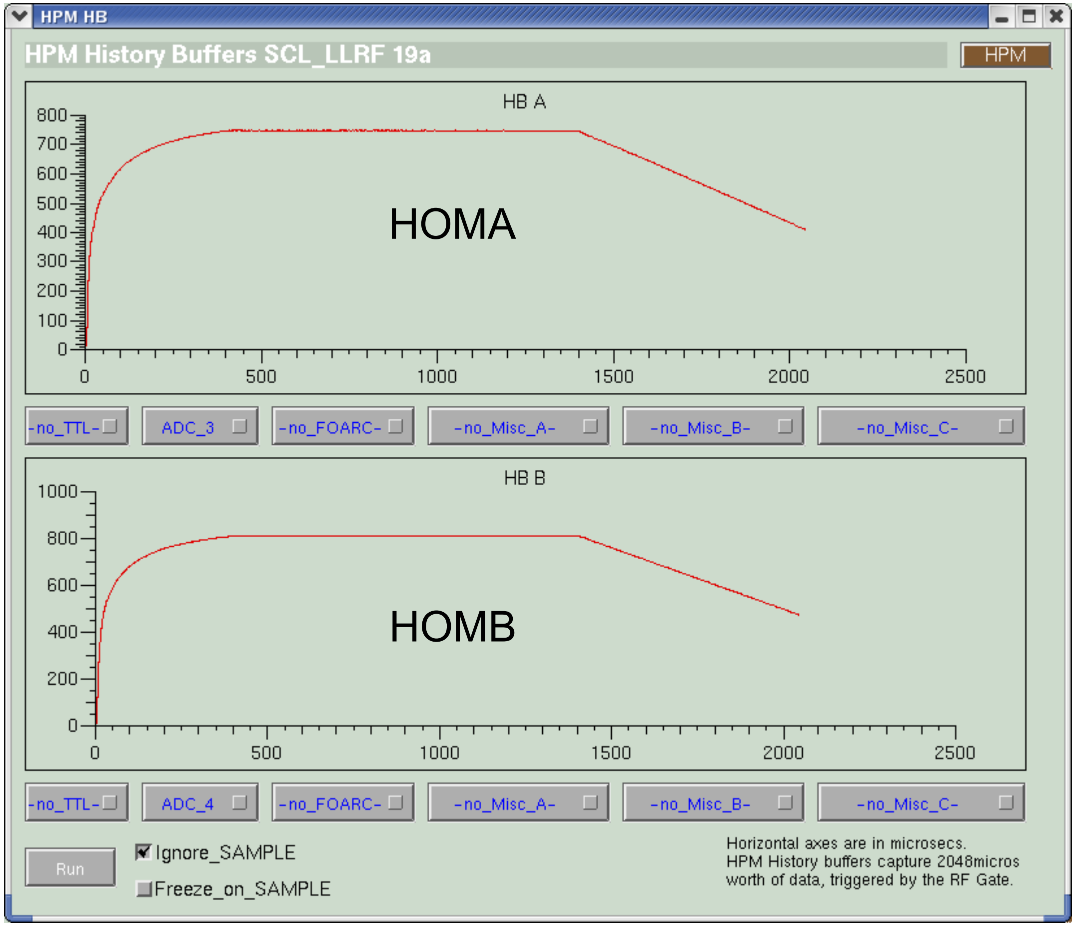
HOM coupler development

- Identification of all HOM modes; very good agreement
- Low power tests confirmed its functionality (JLab)
  - Damping; dangerous modes to have Q<~10^5





Fundamental mode thru HOM coupler



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

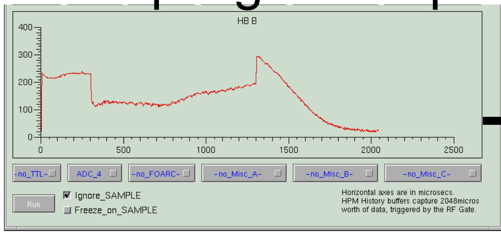
Fundamental mode coupling

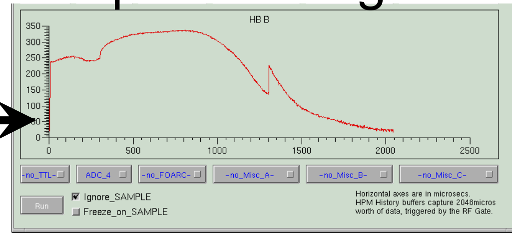
High 10^{10}~ 10^{12}

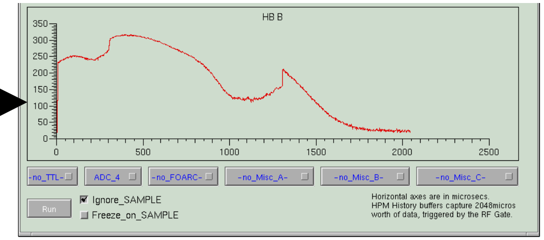
< a few W during pulse

Abnormal HOM coupler signals (RF only, no beam)

~'0' coupling and rep. rate dependent signals





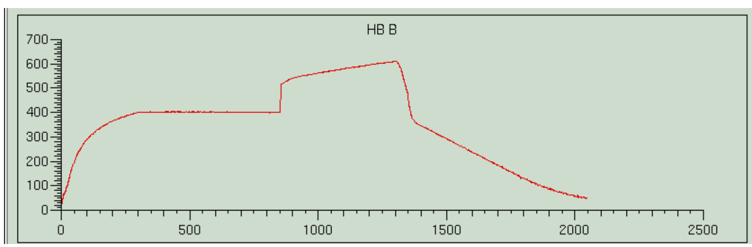


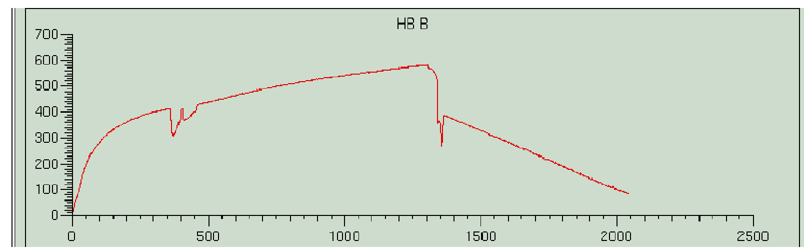
1~5 Hz

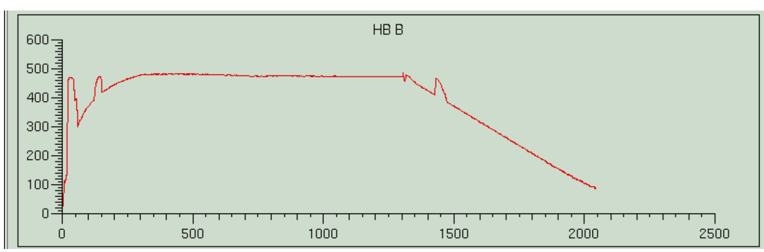
10 Hz

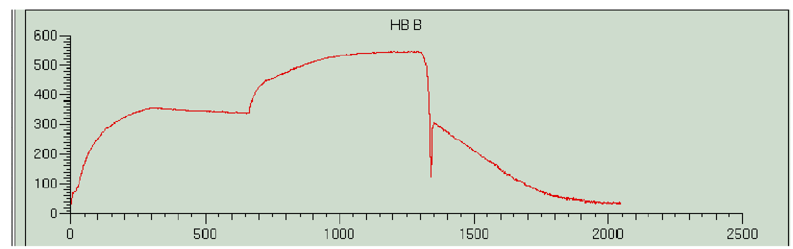
30 Hz

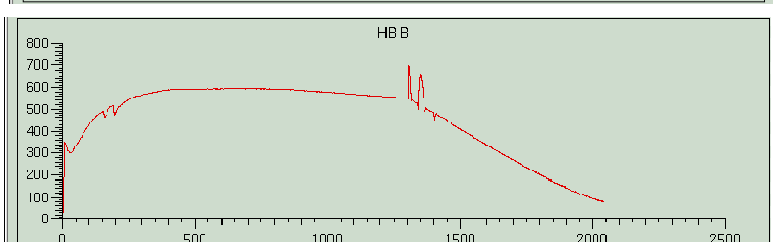
Electron activities (MP & discharge; observations under close attention)

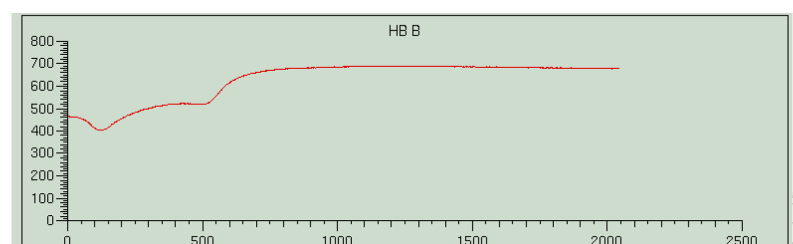








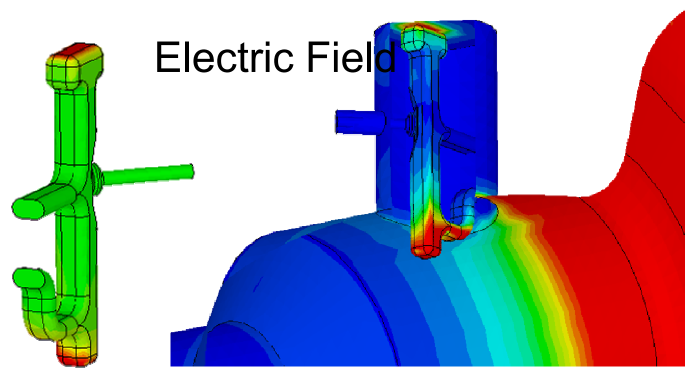


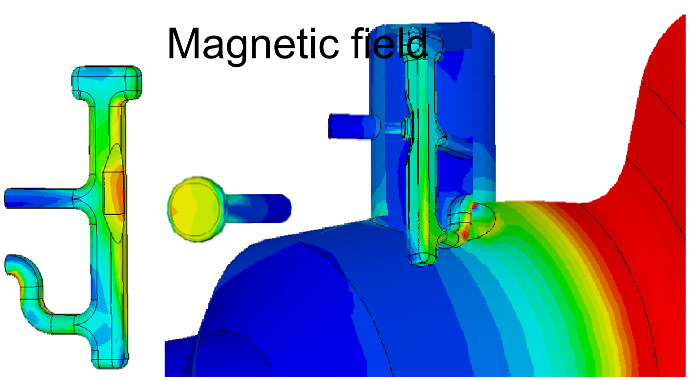


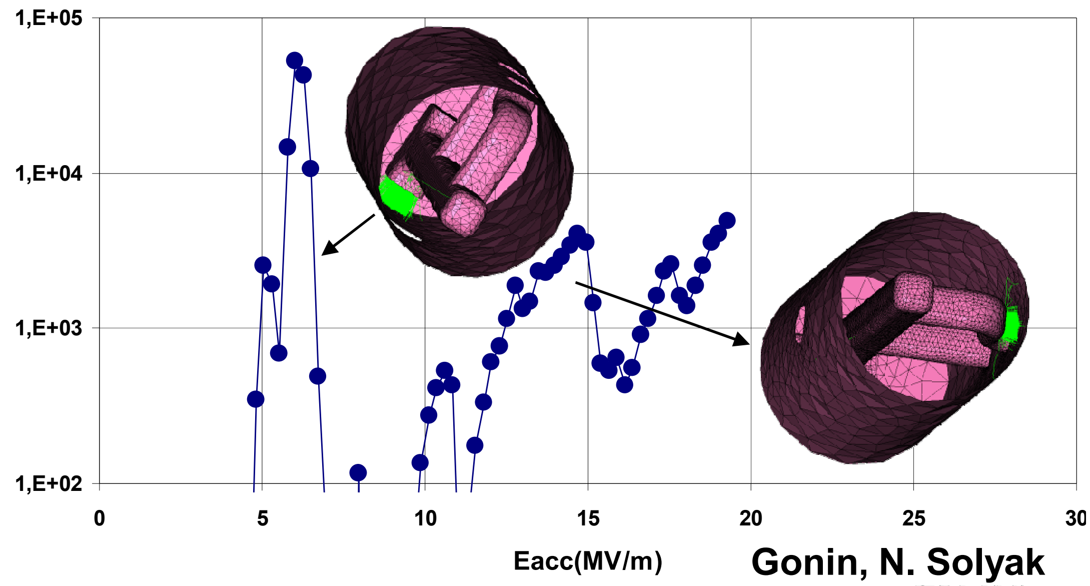
Problems (II)

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







Gonin, N. Solyak

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**

Limited by Fundamental mode in HOM coupler

- Large fundamental mode coupling
  - 11b; repaired at JLab but non-operable from the beginning, no notch
  - 19b; March 06 turned off (10 W coupling at 1 MW/m)
  - 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
  - May have leak
- beam line vacuum leak
  - CM12
    - Largest field emission
    - Feedthrough damaged?

Re-evaluation

Re-evaluation of necessities for HOM couplers

- Same arguments on BBU and instability
  - Stainless steel bellows and fundamental power coupler → $Q < 10^8$
- What is the possibility that one can have high HOM induced power?
  - HOM verifications
  - HOM statistics
  - Beam induced signal

HOM frequency measurement at 4.4 K (between HOMA & HOMB)

Frequency measurement of the dangerous modes for all cavities in the linac tunnel

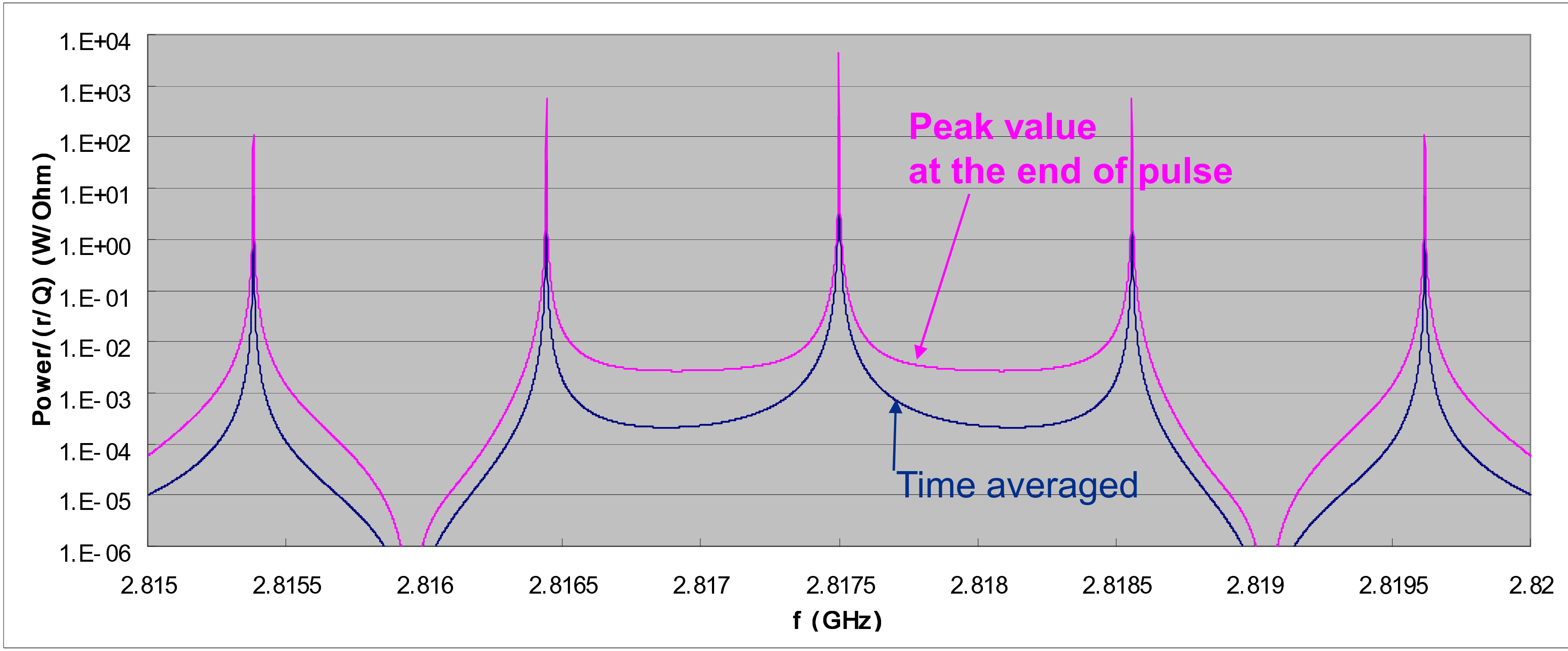
	Medium beta cavity		High beta cavity			assumption for analysis
Mode	31	32	25	35	36	
Average (GHz)	2.81197	2.83017	2.41587	2.81383	2.83018	
Sigma (MHz)	3.19626	3.33151	1.54211	2.09127	2.71721	
Analysis (GHz)	2.80100	2.82050	2.41400	2.81550	2.83030	
sigma/(fn-fo)	0.00159	0.00165	0.00096	0.00104	0.00134	0.00022
fractional centroid error	-0.00392	-0.00343	-0.00077	0.00059	0.00004	0.008

Out of concern 2.8175 GHz (mode 32, medium beta)

Out of concern 2.8175 GHz (mode 36, high beta)

In addition, to have an estimation of HOM frequency shift at 2K,
tests have been done for some high beta cavities by changing tuner position (~60 kHz)
Frequency changes → less than ~400 kHz

Zoom-in



The Q's of modes are less than about ~10^7 due to the damping on the SS bellows,

there's no macro-pulse resonance.

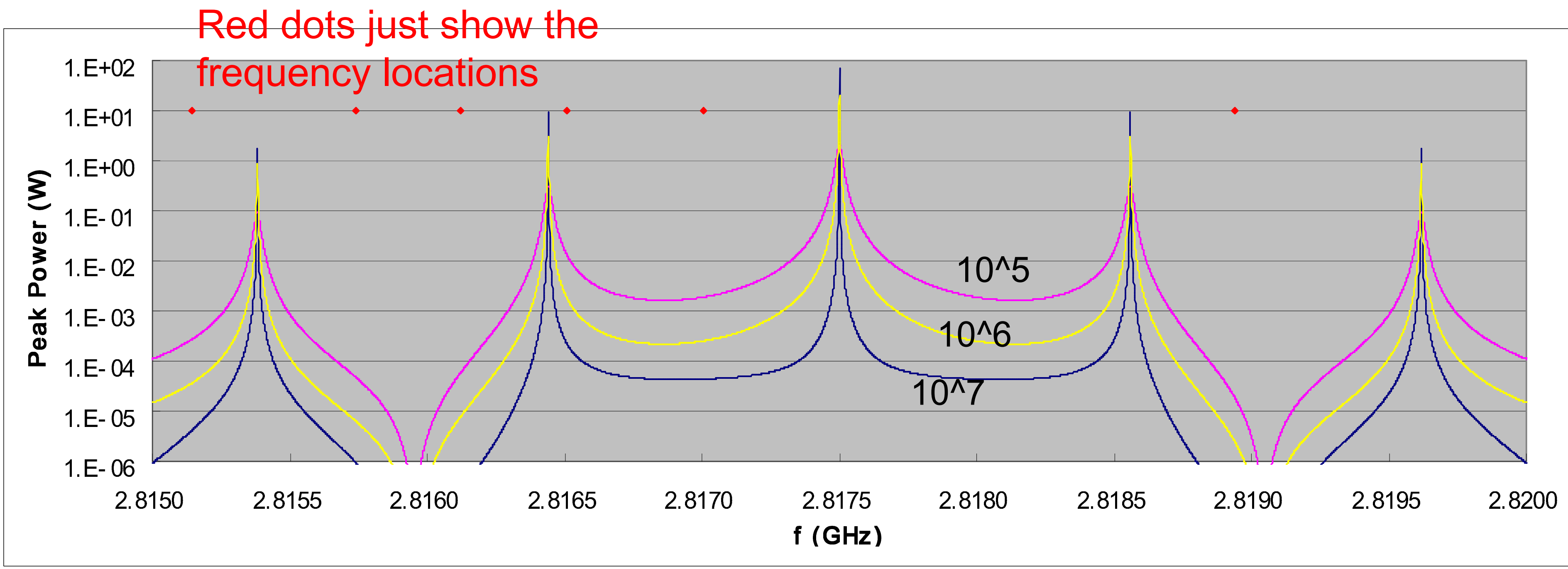
Peak value is more meaningful.

In following pages frequency distributions are plotted on the peak power spectral lines.

Beam current (38 mA peak) in the following examples

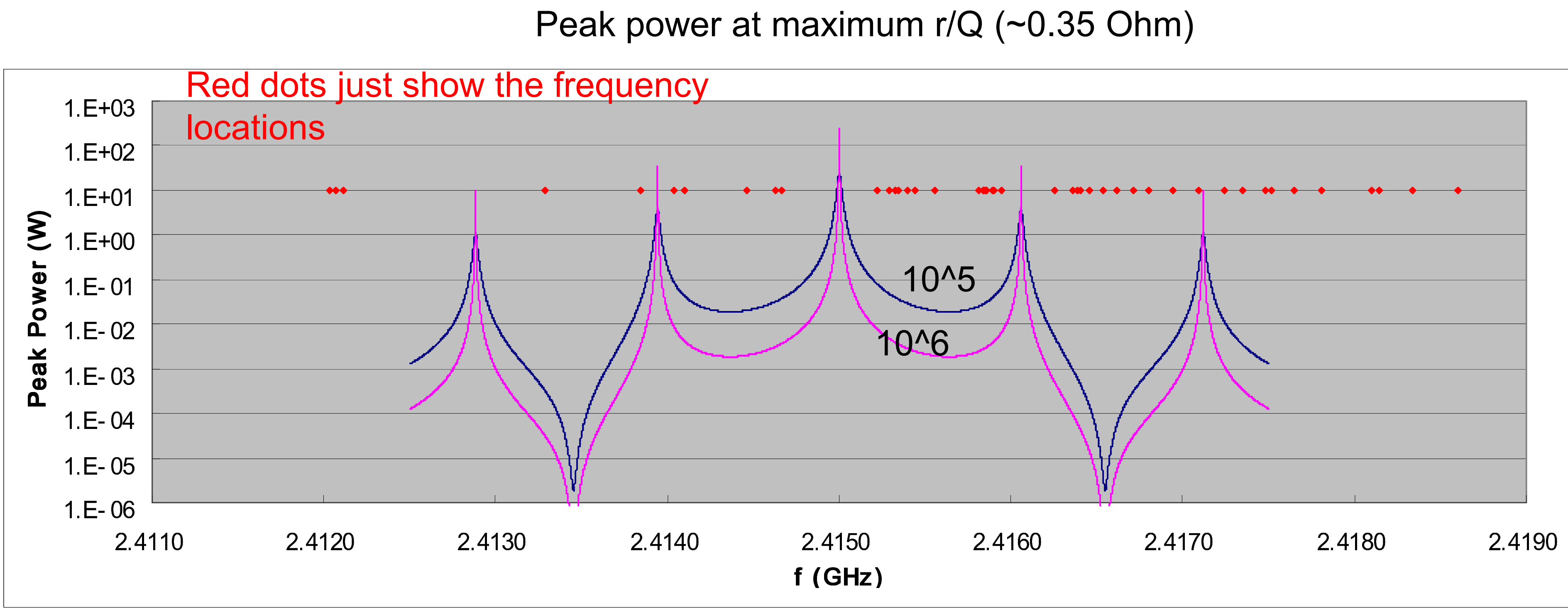
Zoom-in (Mode 31 Medium beta)

Peak power at maximum r/Q (~0.3 Ohm)



Only 5 cavities have mode 31 in +/-2.5 MHz from main spectral line (2.8175 GHz).
(Mode 25 of other 28 cavities are below 2.815 GHz)→ out of concern.
Q's <~10^7 (with HOM couplers 10^4)
Only main spectral line will be a concern.
Presently all HOM's are far away from the dangerous beam spectral line.

Zoom-in (Mode 25 High beta)

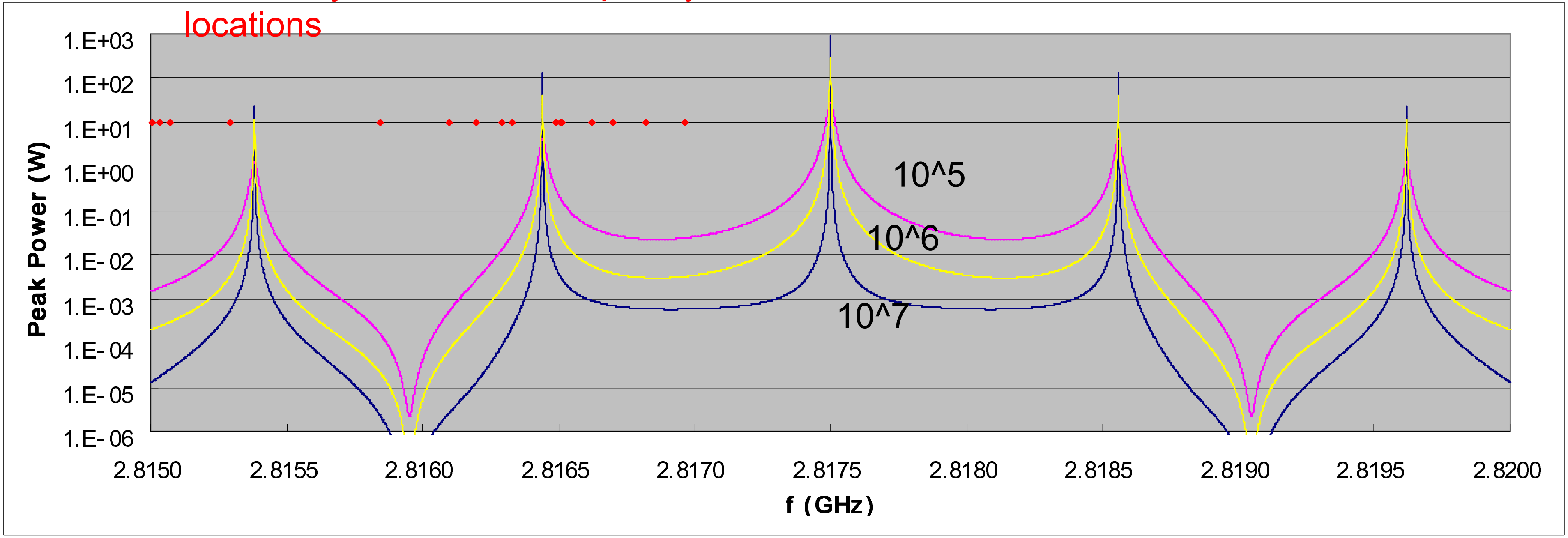


All Mode 25's are within +/-3.5 MHz from main spectral line (2.415 GHz).
FPC coupling → at most 10^5 (with HOM coupler 10^3)
The main spectral line and the neighboring ones will be a concern
Presently all HOM's are far away from the dangerous beam spectral line.

Zoom-in (Mode 35 High beta)

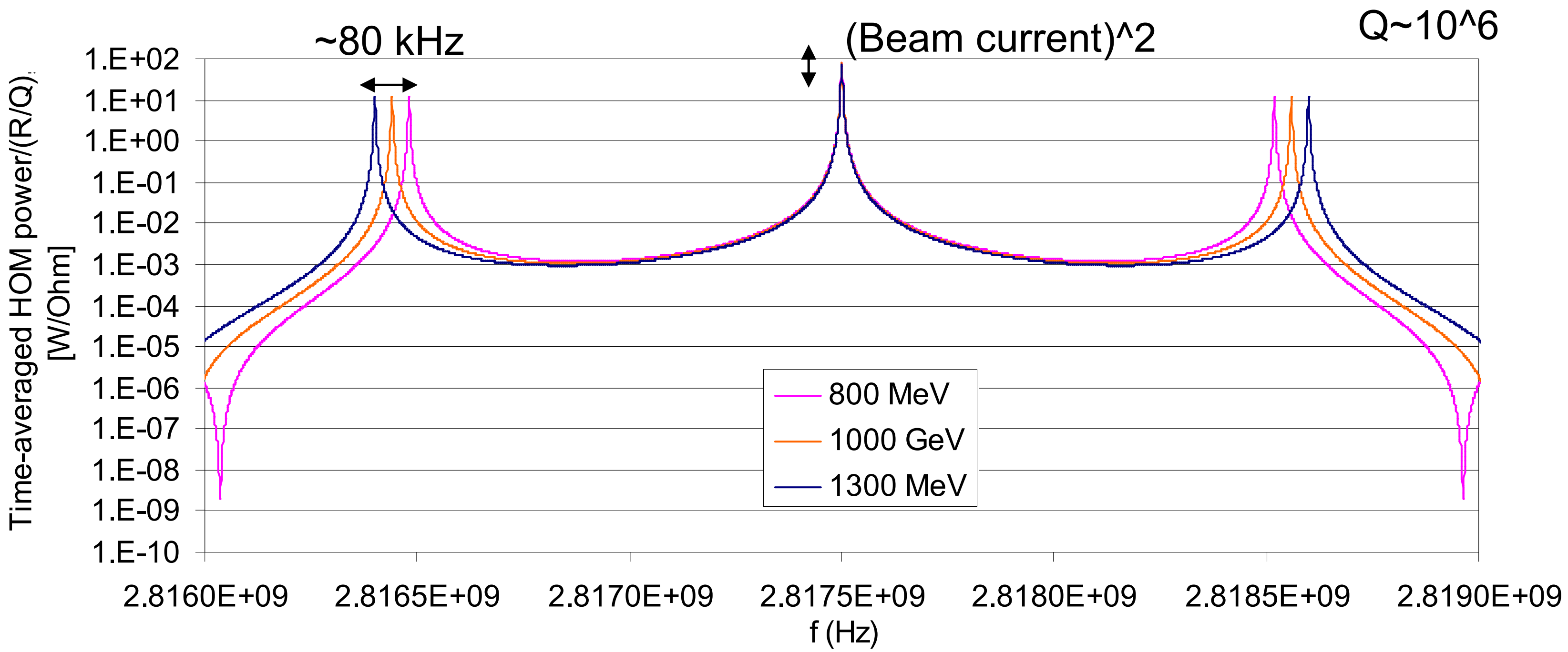
Peak power at maximum r/Q (~0.4 Ohm)

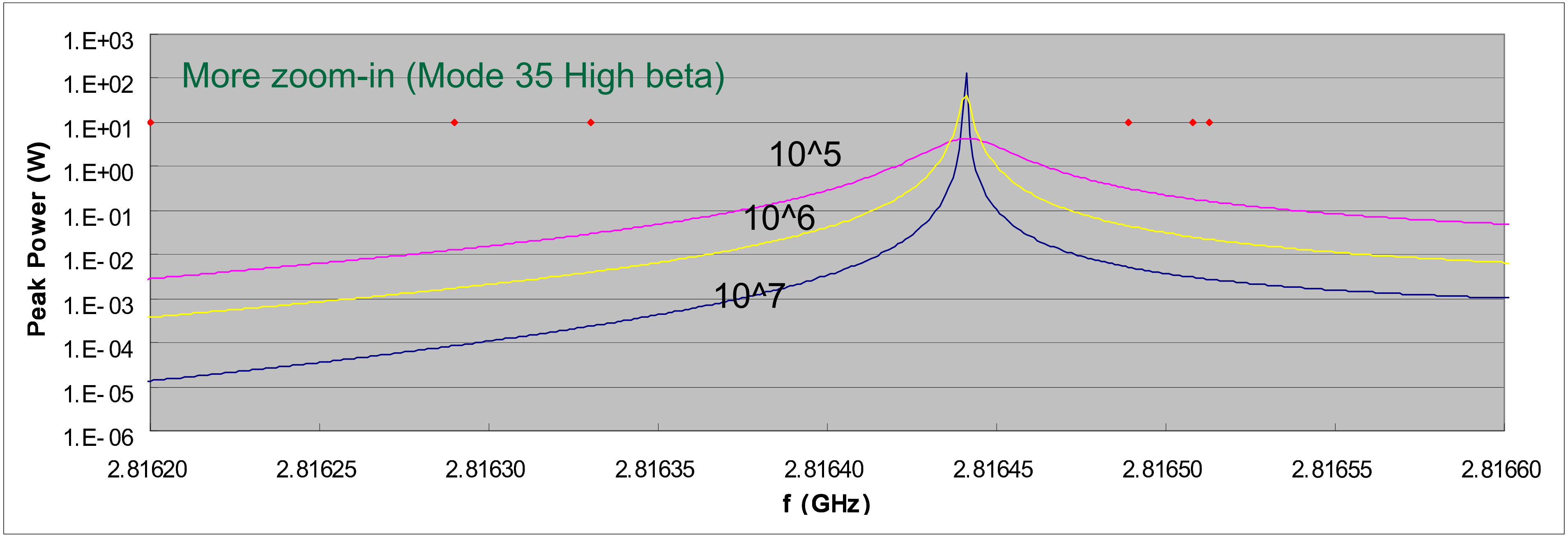
Red dots just show the frequency locations



16 cavities have mode 35 in +/-2.5 MHz from main spectral line (2.8175 GHz).
Q's <10^7 (with HOM coupler 10^4)
Only first midi-pulse sub spectral line will be a concern.
Presently all HOM's are far away from the dangerous beam spectral line.

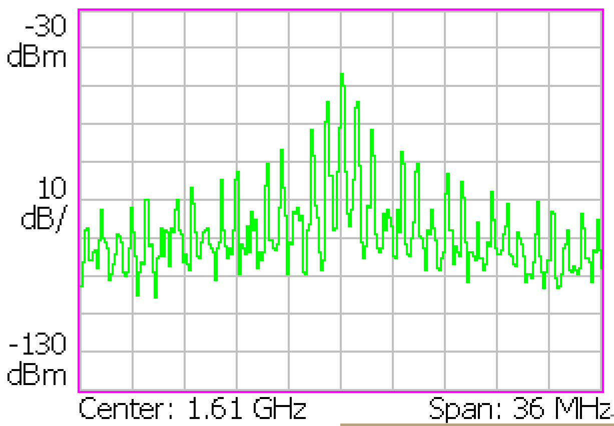
Another concerns

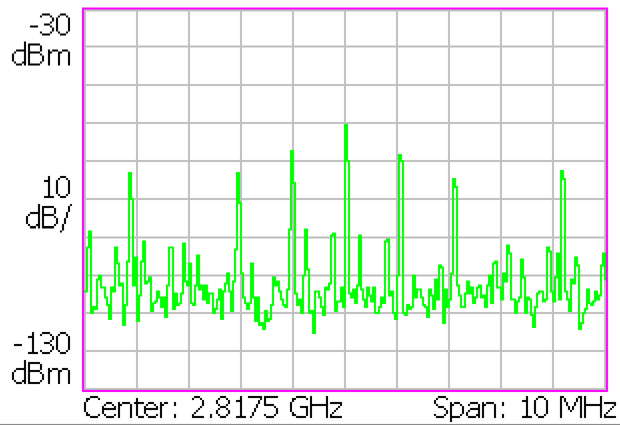


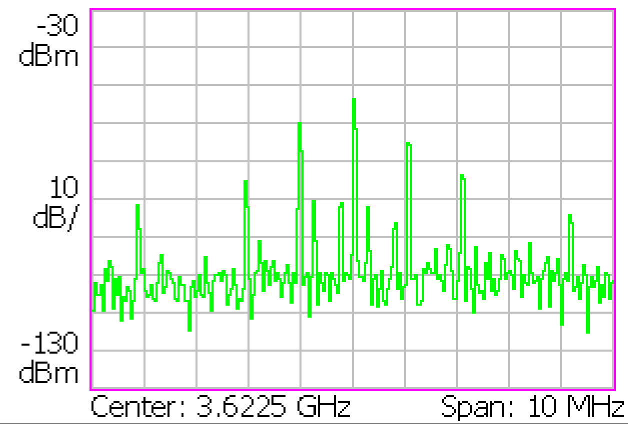


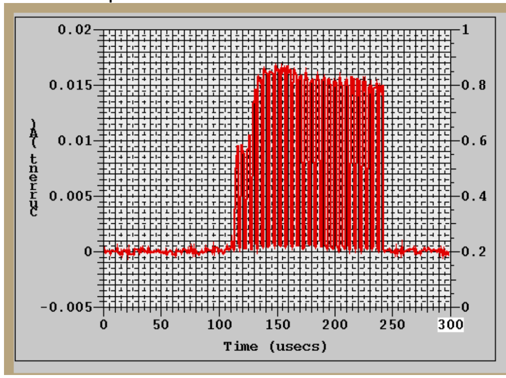
w/ Beam (no measurable HOM signals from beam was observed)

Direct wakefield, just showing beam time-structure including frequencies higher than the cut-off frequency









	MEBT BCM02	MEBT BCM11	DTL BCM200	DTL BCM248	DTL BCM400	DTL BCM428	DTL BCM600	
Current Max	26.4	29.2	44.4	44.9	33.3	37.5	35.9	mA
Current Avg	13.5	14.1	10.3	10.3	13.1	12.3	12.9	mA
Beam Length	2.4	2.5	1.8	1.9	2.4	2.4	122.9	usec

	DTL BCM622	CCL BCM102	SCL BCM00	HEBT BCM01	HEBT BCM09	LDmp BCM05	HEBT BCM20	HEBT BCM32	
Current Max	32.6	30.3	25.7	27.7	27.2	11.2	26.4	26.6	mA
Current Avg	12.7	12.9	12.8	13.1	13.0	0.0	12.9	14.2	mA
Beam Length	123.0	122.7	122.4	123.9	124.1	149.4	124.6	140.3	usec

	IDmp BCM01	Ring BCMD09	EDmp BCM02	RTBT BCM02	RTBT BCM11	RTBT BCM14	RTBT BCM25	
Current Max	0.0	1.7	0.0	1.9	1.8	2.1	1.9	mA
# of Particles	-4.2e+08	6.8e+12	-2.5e+08	6.8e+12	6.8e+12	7.0e+12	6.8e+12	
Beam Length	0.0	0.0	5.9	3.8	4.0	5.0	2.2	usec

Oak Ridge National Laboratory

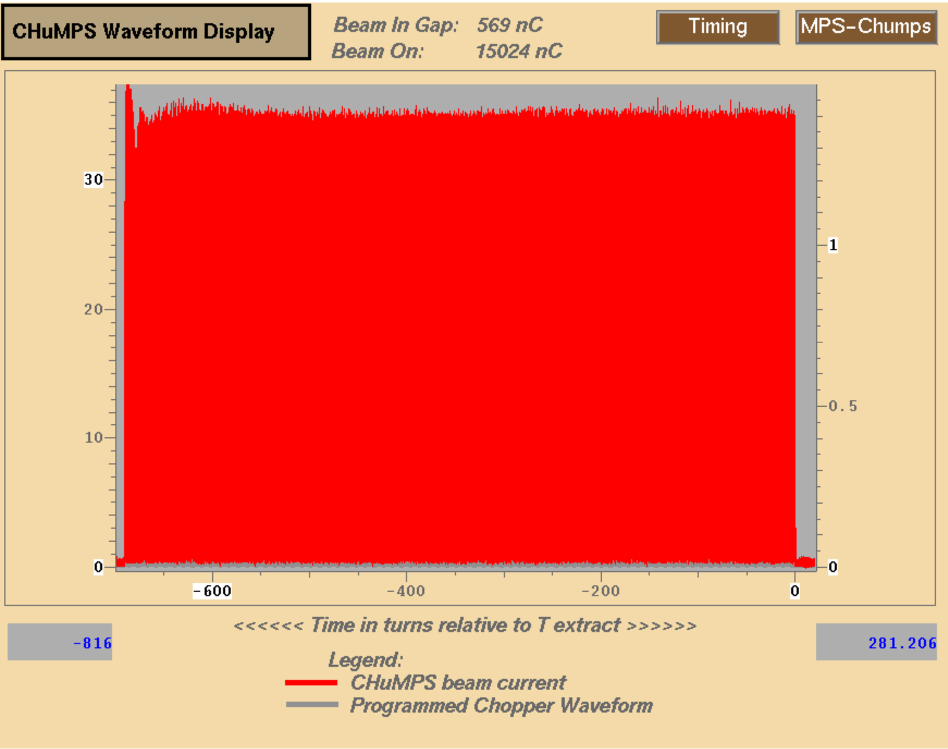
Decision in 2007

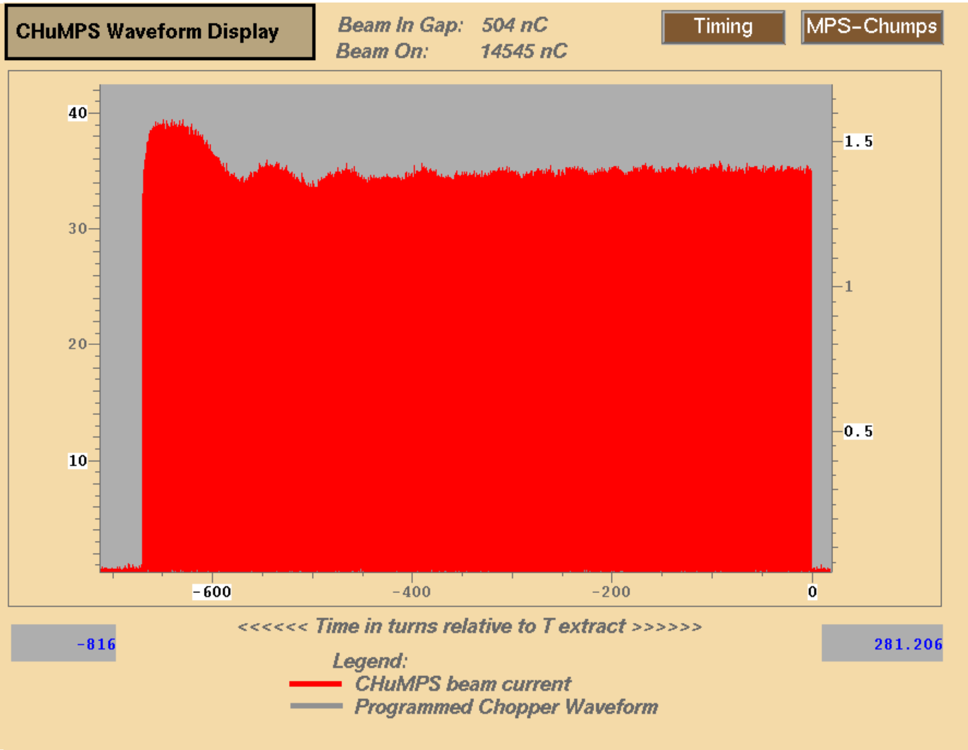
- Take out feedthrough as needed

Repair
(so far 2 CMs were taken out from the tunnel)

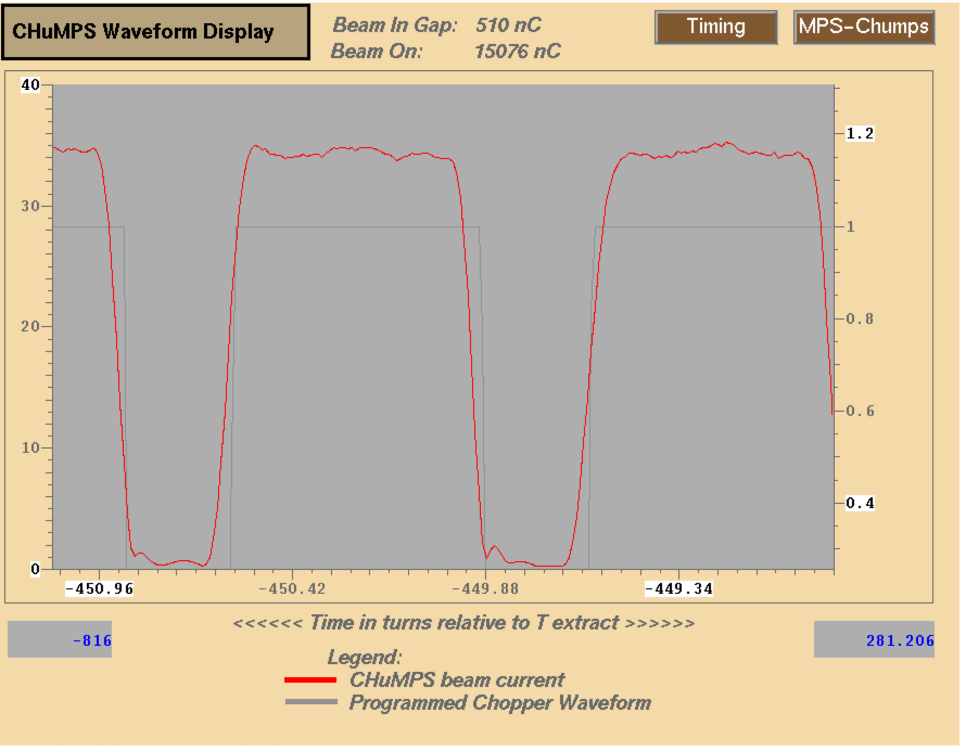
- 19b
  - TDR measurement & comparison; almost shorted
  - Trace of discharge
  - Dimension looks OK but large coupling
  - HOM feed through removed
  - Very aggressive electron activity at the HOM coupler
  - Recovered; back in the tunnel in Feb. 08
- CM12; beam line vacuum leak
  - 12a and 12d had leaks at the feedthroughs (four out of eight)
    - HOM feedthroughs are removed and back to service in Feb. 09

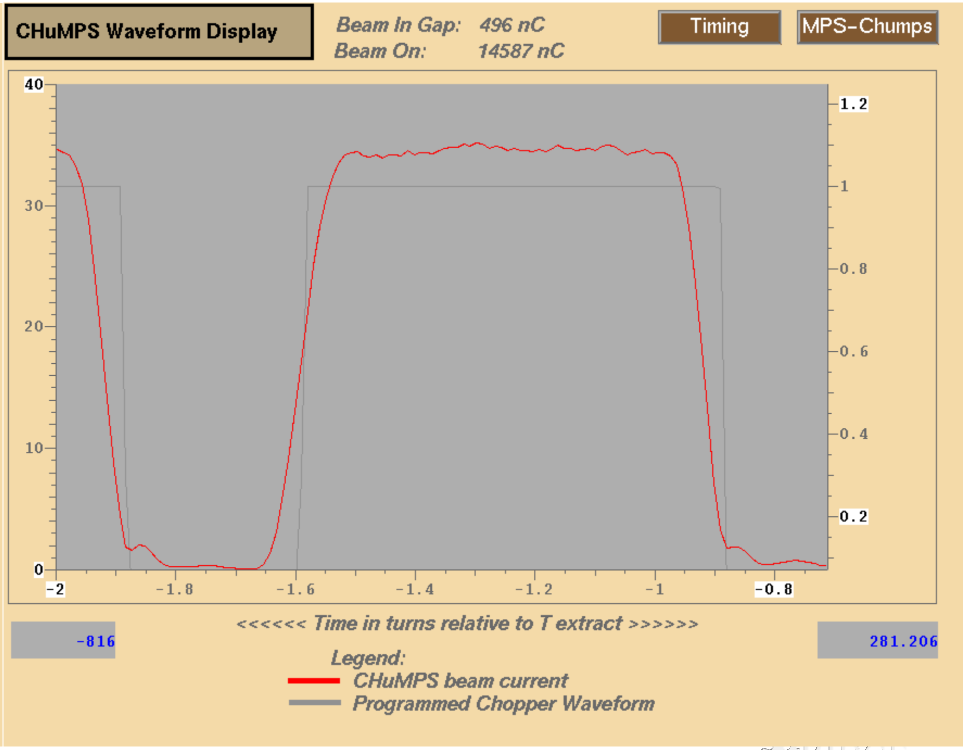
SNS beam


CHuMPS Waveform Display
Beam In Gap: 569 nC
Beam On: 15024 nC
Timing
MPS-Chumps
30
20
10
0
1
0.5
0
-600
-400
-200
0
<<<<<< Time in turns relative to T extract >>>>>>
-816
281.206
Legend:
CHuMPS beam current
Programmed Chopper Waveform

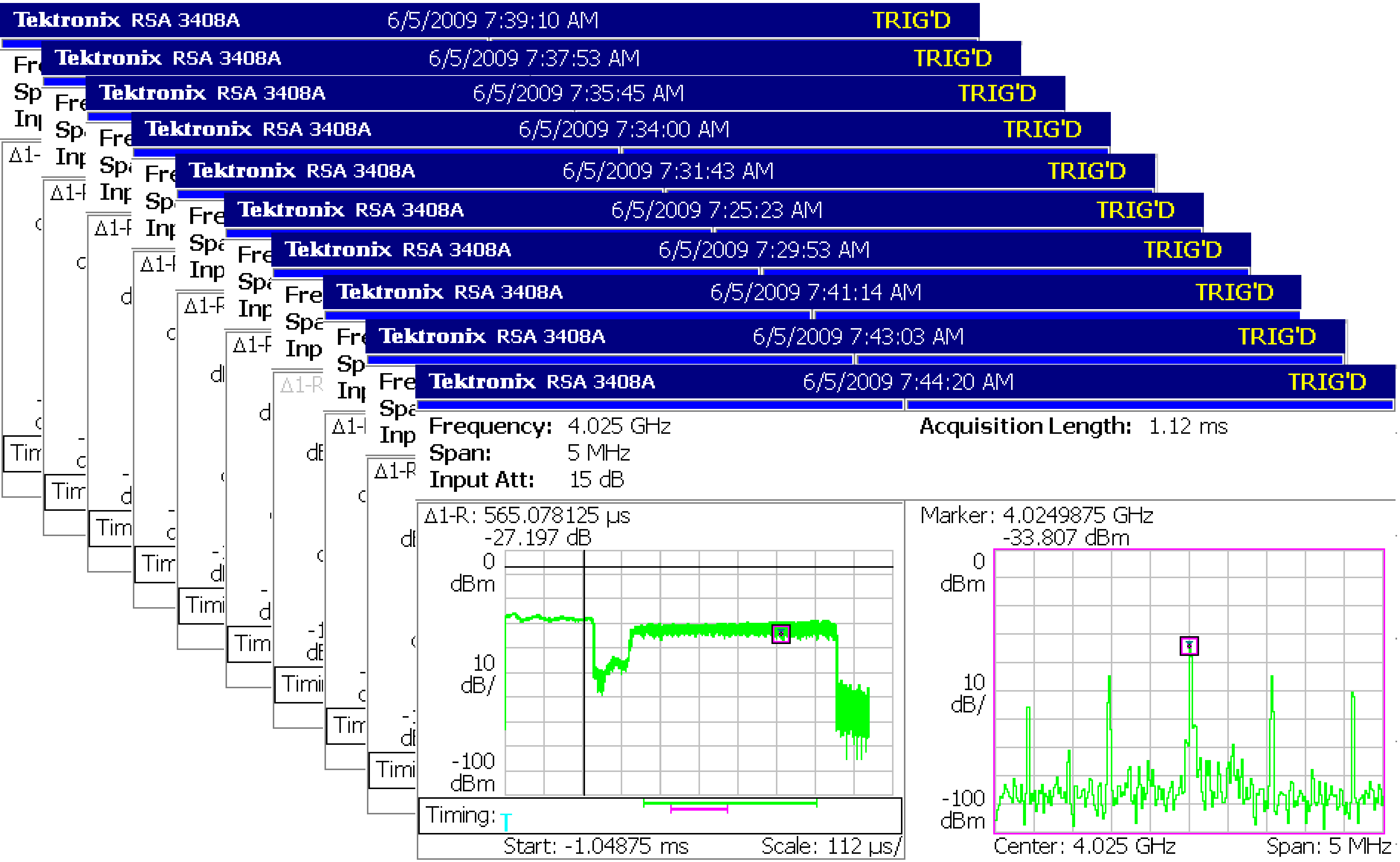

CHuMPS Waveform Display
Beam In Gap: 504 nC
Beam On: 14545 nC
Timing
MPS-Chumps
40
30
20
10
1.5
1
0.5
-600
-400
-200
0
<<<<<< Time in turns relative to T extract >>>>>>
-816
281.206
Legend:
CHuMPS beam current
Programmed Chopper Waveform

- **Bunch fluctuation**
  - **Best conservative guessing; σ~0.3 % (1% will be enough for analysis)**



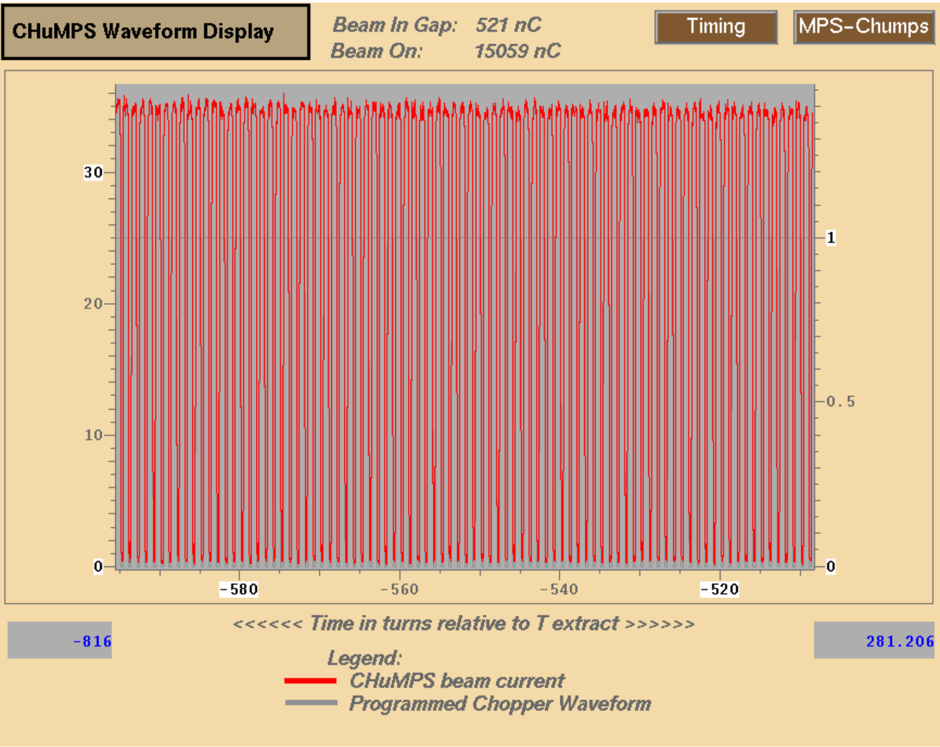


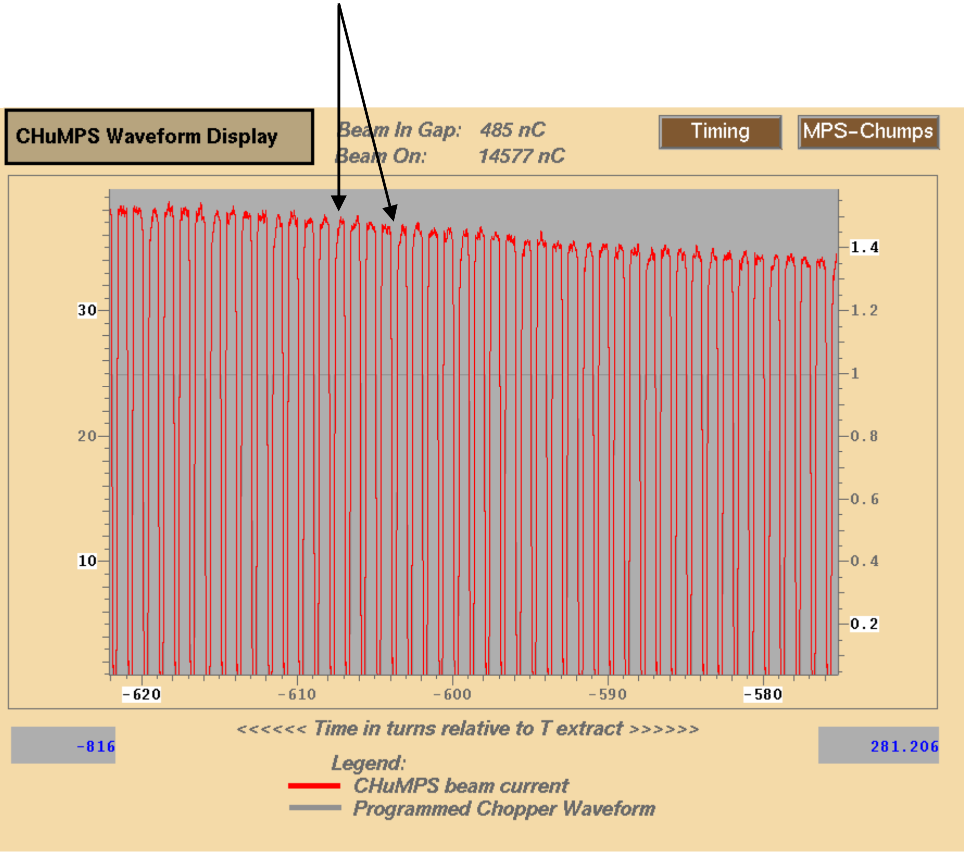
SNS beam time-structure



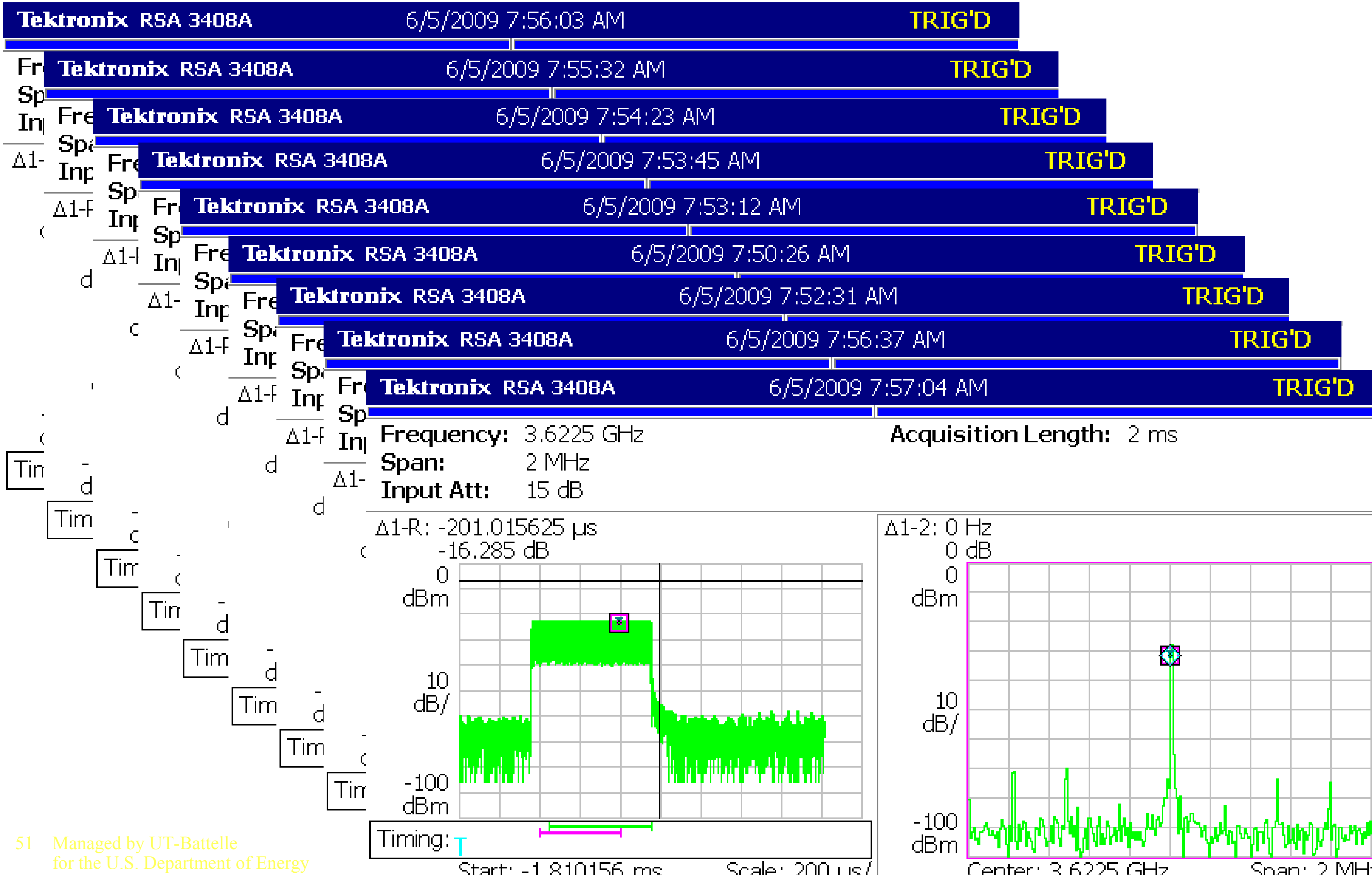
Chopper imbalance

- Every 4th midi pulse; rising is slower





40-50 dB less than main line; negligible



Beam Experiences

- Beam loss
  - Much Less than 1 W/m in average
  - Not a show stopper
- Energy jitter σ~1 MeV (from other sources)
- No dependencies on beam loss
  - Beam current
  - Pulse length
  - Pulse repetition rate
  - As tuning is getting better, less loss/C

Summary

- SNS HOM concerns & history
  - Beam breakup & instability; no issue
  - HOM power is the main reason for SNS to have HOM coupler
- 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.
- Future concerns
  - HOM feedthroughs will be taken out as needed
  - PUP cryomodule
    - At least will not have HOM feedthroughs for cavities we already have
    - Will not have HOM couplers for new cavities