LHC/MP Review
The RF system

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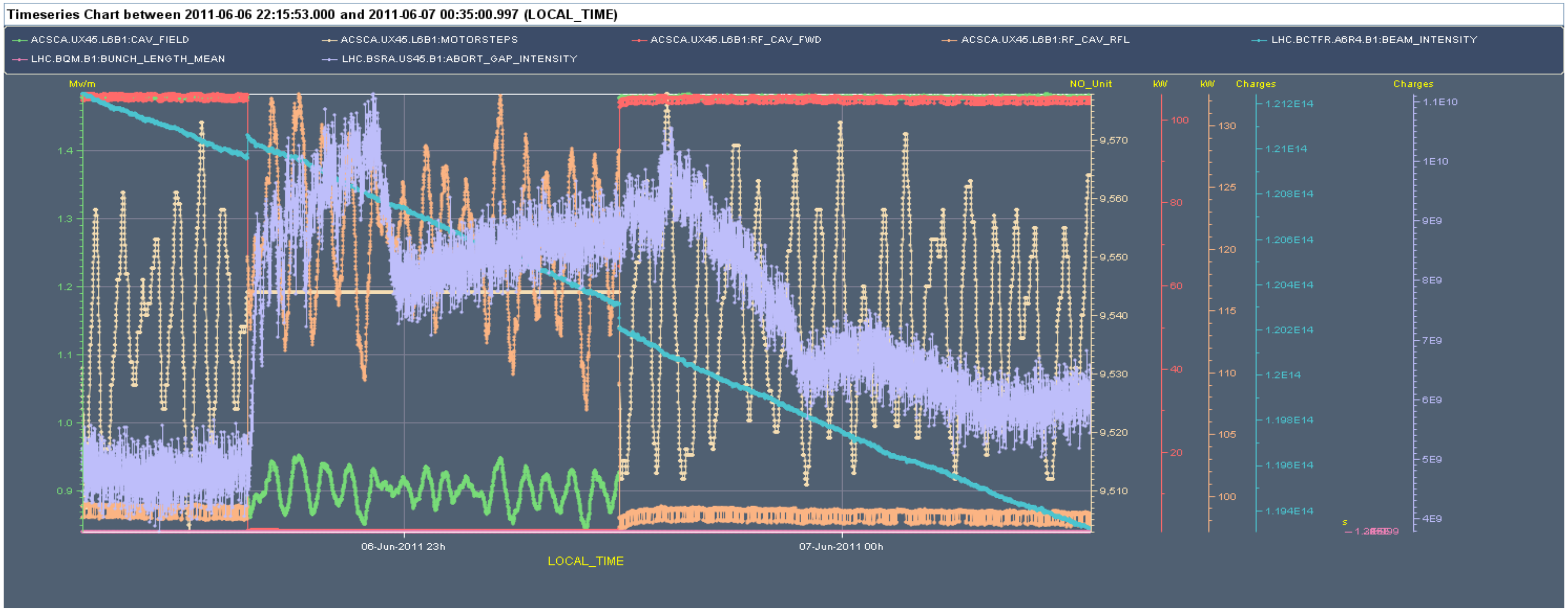
Klystron trip

When a klystron trips…

- When a klystron trips, the beam passing in the idling cavity induces a voltage. If too high, this voltage may cause an arc in the cavity
- The beam creates an E.M. wave that crosses the coupler, travels through the waveguide in the reverse direction, crosses the circulator and ends in the load. If too high this wave may break the coupler (arcing) or burn the load.
- The sudden reduction of the bucket creates particle loss (debunching). The debunched beam drifts in the machine and populates the abort gap. As it is not focused by the RF anymore, this debunched beam looses energy through synchrotron radiation and drifts to the momentum collimator.

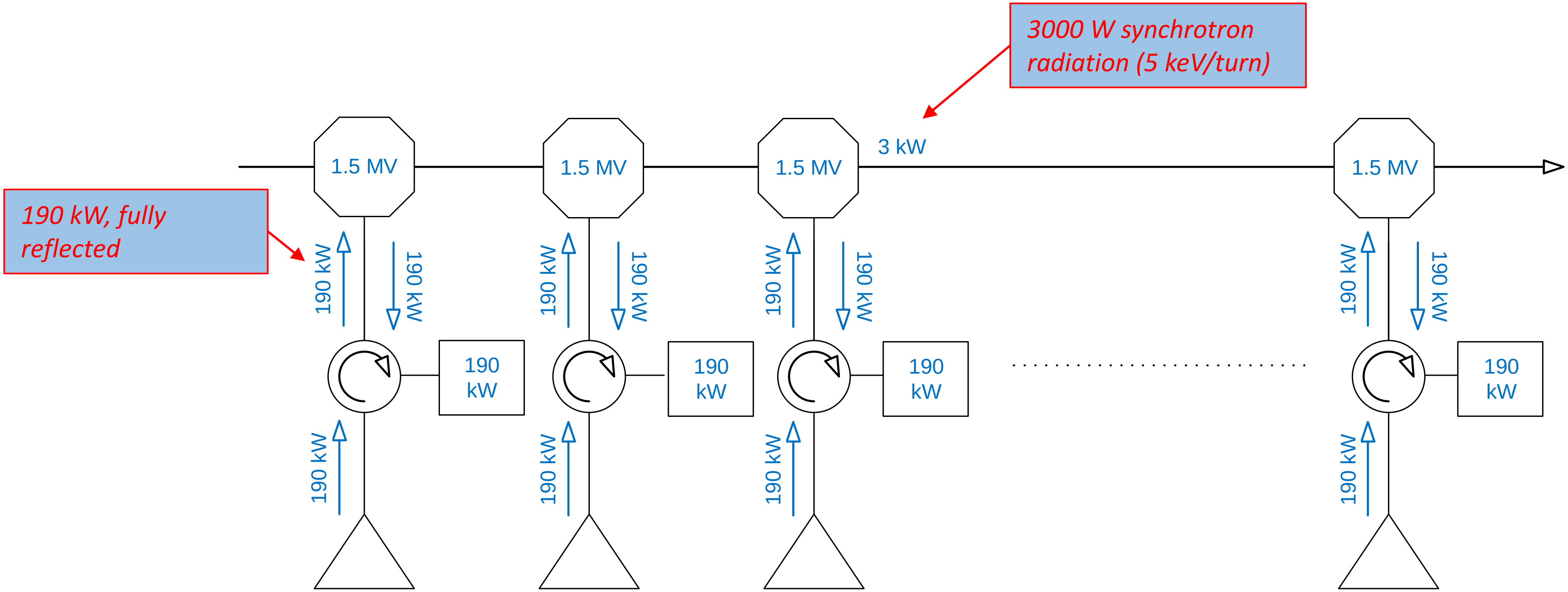
Surviving a trip: Run 1, Fill 1855, June 6th 2011



- After 6 hours in physics, 1102b, 0.22 A DC
- 0.9 MV beam induced voltage (green)
- 110-130 kW "reflected" power (orange)
- Abort gap population jumps from 5E9 to 1.1E10, then is reduced to 8E9 after 15 min (3.5 TeV). If is further reduced to 6E9, ~ 15 min after we switch the RF back ON (violet)
- No noticeable loss on BCT, only bunch length effects (blue)
- The dissipated 110-130 kW is compensated by an increase of 10 kW in all remaining 7 klystrons. The missing 50 kW comes from a reduction of the reflected power due to the non-zero stable phase

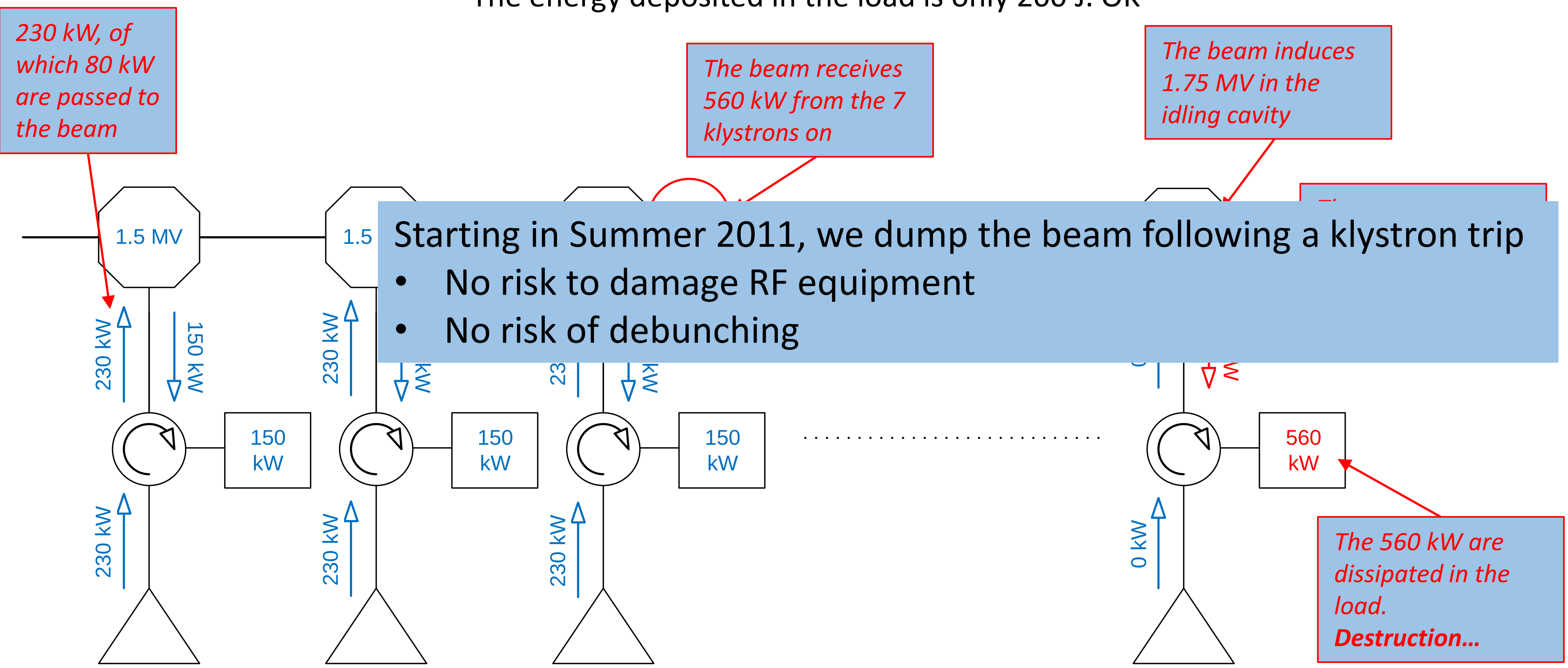
Nominal LHC conditions Run 2:

- 6.5 TeV
- 1.1E11 p/bunch
- 2808 bunches, 25 ns spacing
- 1.2 ns 4σ bunch length
- Assume CosineSquare longitudinal line density -> f_b=0.86
- 0.56 A DC, 0.96 A average RF component, 1.06 A peak RF
- 12 MV total (8 cavities), QL=60k



One klystron trip

- The beam induces 1.75 MV in the idling cavity
- The required energy come from the remaining 7 cavities
  - Stable phase goes to 174.5 degree
  - Each of the 7 klystrons gives 80 kW to the beam
- This EM energy flows out of the cavity at the 560 kW rate
- It is dissipated in the load of the circulator of the tripped klystron
- The load is rated 300 kW -> destruction…but
- We dump the beam in three turns
- The energy deposited in the load is only 200 J. OK



Starting in Summer 2011, we dump the beam following a klystron trip

- No risk to damage RF equipment
- No risk of debunching

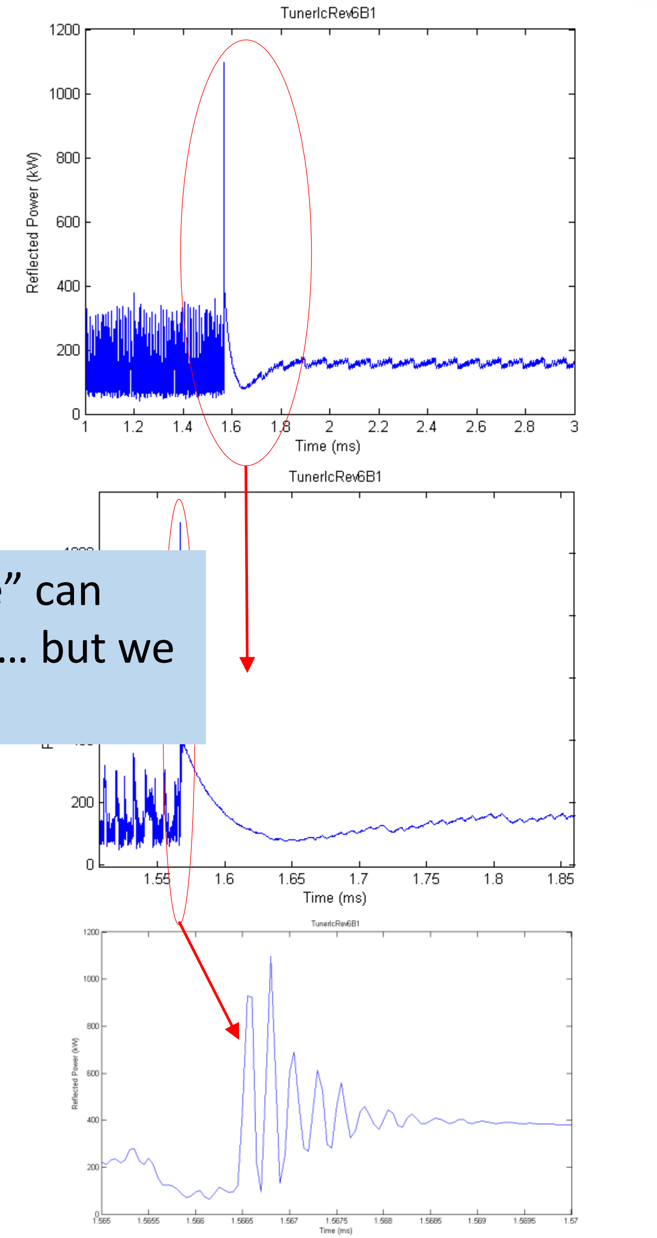
“Reflected” power transients (1102b,2011)

- We observe a very large spike peaking at 1.1 MW, followed by a decaying transient with 20-30 microsec time constant, then a slow decay to reach the steady level
  - The 20-30 microsec time-constant decay starts at 400 kW level and disappears in ~50 microsec. This power spike is the dumping of the cavity stored energy (~10 J), not a large energy. Frightening peak but it cannot damage the coupler. The measurement fits perfe
    at a t
    indep

The transients are not an issue. Only the “baseline” can damage coupler or load when increasing intensity… but we dump the beam in 3 turns

$$2\, R/Q\, Q_e$$

  - The 1.1 MW peak actually is a ~4 MHz ringing that decays in 2 microsec. It corresponds to the discharge of the klystron bunching cavity (around 405 MHz). Again frightening but very short -> 1 J ->no damage



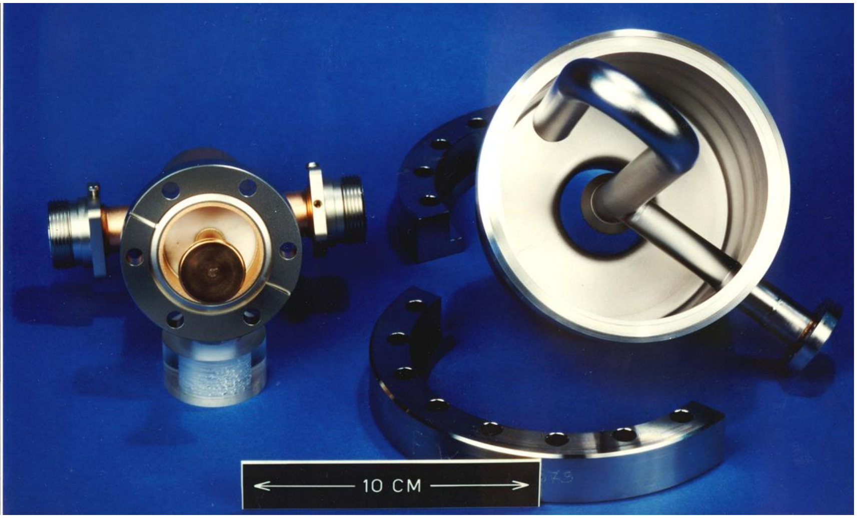
See also

Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, J. Tuckmantel, CERN-ATS-Note-2011-002 TECH

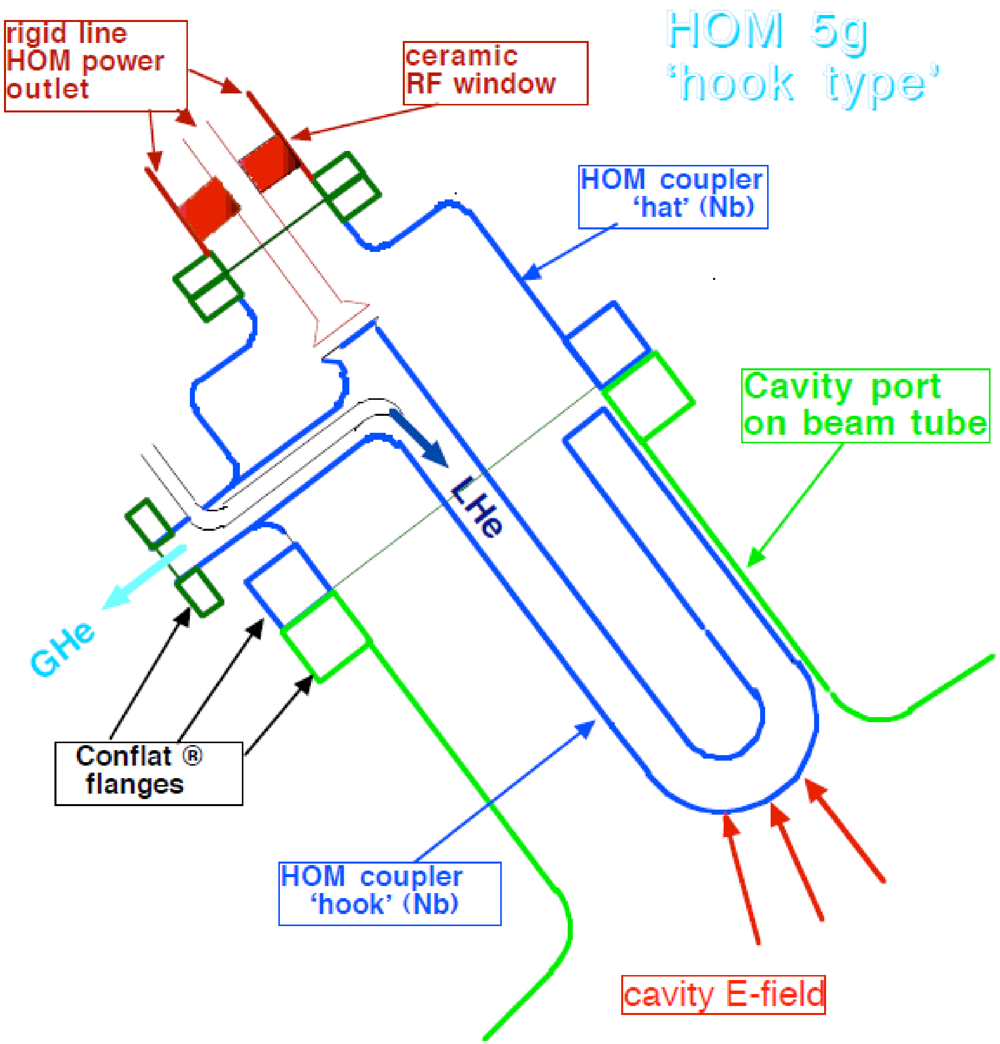
HOM Dampers

- An RF cavity is designed to optimize the accelerating mode
- But it will also resonate at other frequencies, usually above the accelerating (main) mode. These are called Higher Order Modes (HOMs)
- The klystron is narrowband and will not excite the HOMs
- The beam current has high frequency components, whose amplitude scales as the inverse bunch length-> important with short bunches
- The beam will excite the Higher-Order modes. These will induce wakefields and can cause instabilities
- The HOM fields do not couple to the main coupler that is optimized for the fundamental (400 MHz)
- Dedicated couplers must be added to "extract" the HOM energy from the cavity and dissipate it in a load outside the cryostat. These are called HOM couplers
- HOM coupler design is delicate. It must not couple to the fundamental
- The main HOMs in are at 500, 534, 779, 1184 and 1238 MHz
- Each cavity has 4 HOM couplers of two different makes: NarrowBand (NB) that couple the first two modes strongly, and WideBand (WB) for the higher frequencies

- NarrowBand HOM coupler
- Made in Nb, cooled with liquid He
- "Notch" at 400 MHz

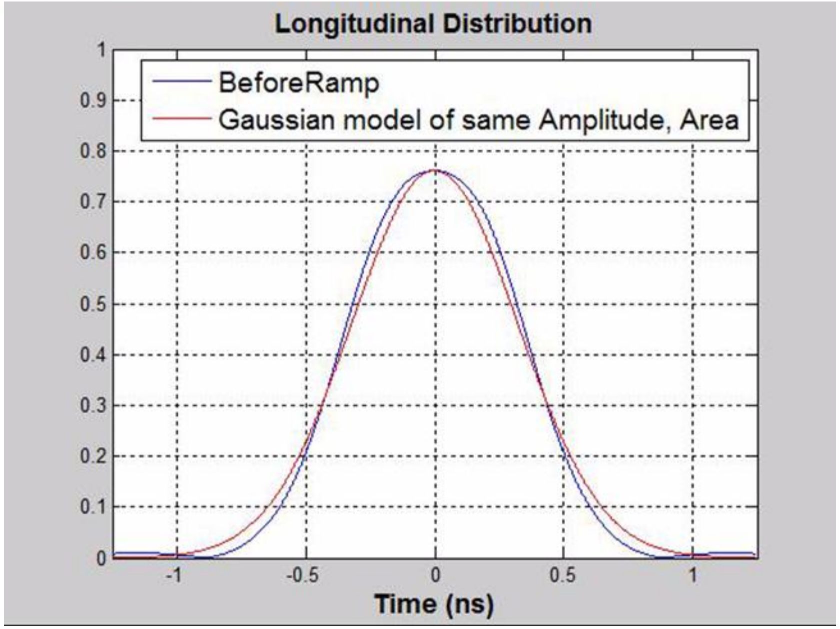


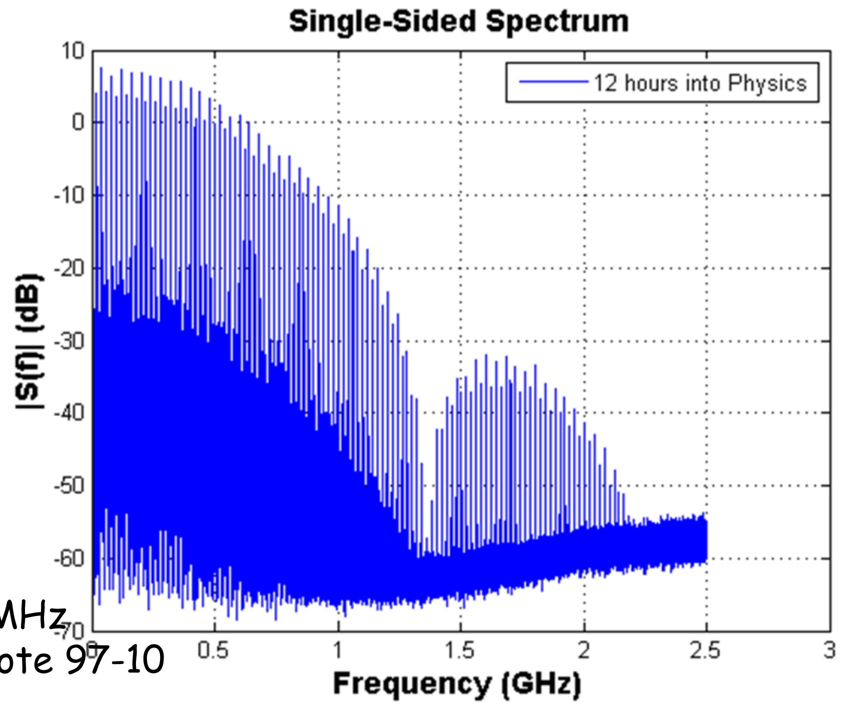
LHC WideBand coupler (left) and NarrowBand coupler



- The power "extracted" by an HOM coupler scales with the power of the beam current at the mode frequency
- We had no problem with 0.35 A DC and 50 ns spacing in 2012
- With 25 ns spacing the main spectral lines of beam current are at harmonics of 40 MHz (they were at harmonics of 20 MHz with 50 ns spacing)
- Smaller Frev sidebands caused by the gaps in beam currents (abort gap, injection kicker risetime)
- The HOM have been designed for Qe < 1000, so that
  - 0.85 A DC current
  - 40 MHz line on the HOM resonance

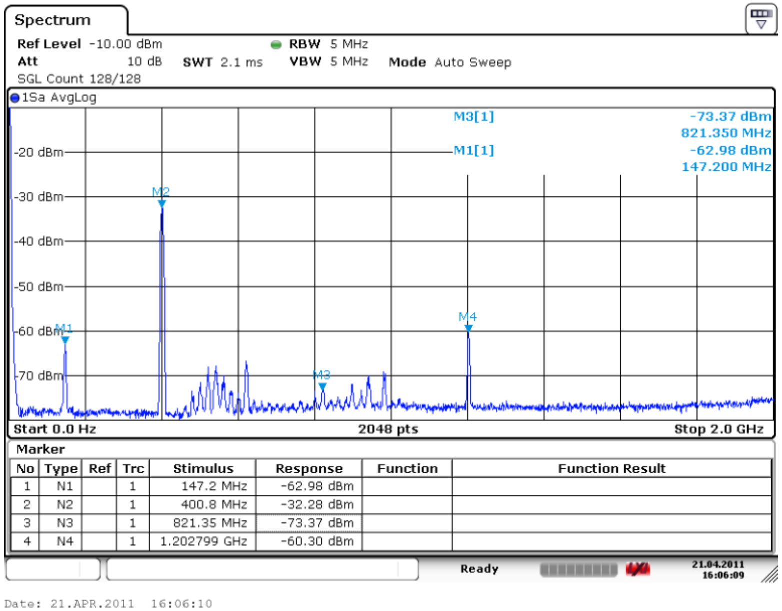
gives 1 kW power that can be dealt with by the coupler

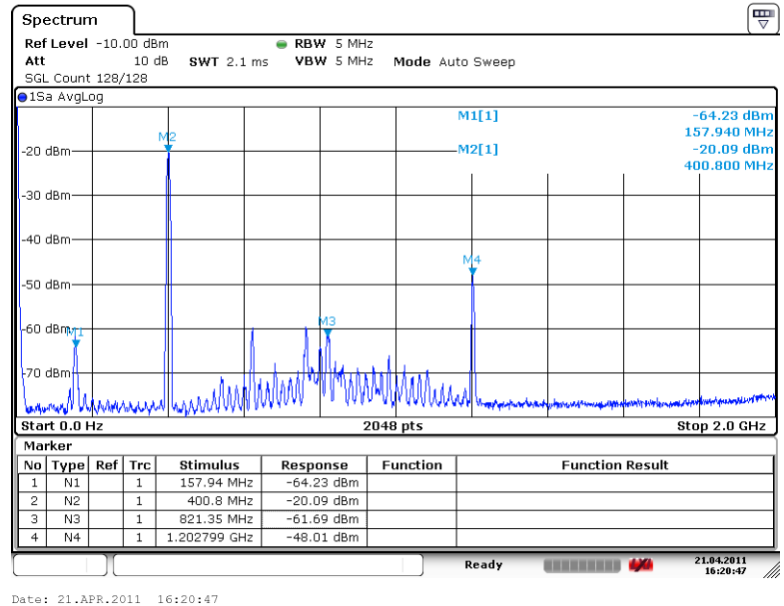




Estimation of the High-order Mode Power in the 400 MHz Superconducting Cavities of the LHC, Z.T. Zhao, SL-Note 97-10

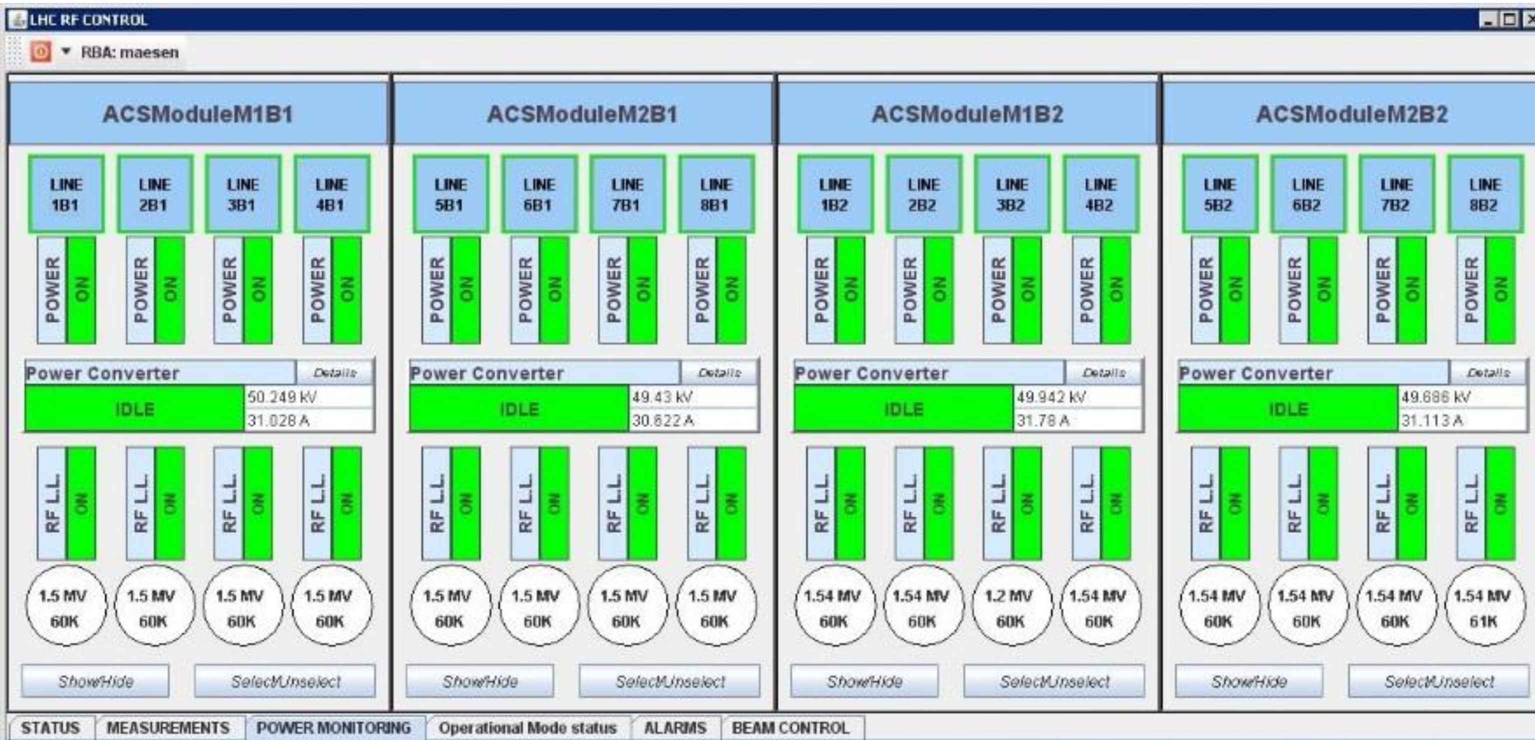
- Spectra were measured with 50 ns spacing (408b below)





Spectrum of the power extracted by NarrowBand coupler (left) and WideBand coupler

- We monitor and interlock HOM couplers temperatures and power (below 1236b)



LINE NAME	WattchI[KW]	TAMC1[K]	TAMC2[K]	TACD1[K]	TACD2[K]	LBMC1[K]	LBMC2[K]	LBCD1[K]	LBCD2[K]	NbA [W]	NbATot [W]	NbB [W]	WbA [W]	WbB [W]	WbBTot [W]
ACSLine1B1	132.78	4.31	4.27	4.19	4.34	4.37	4.23	4.46	4.46	0.04	0.08	0.52	0.43	11.07	17.13
ACSLine2B1	120.08	4.25	4.4	4.43	4.27	4.3	4.31	4.18	4.18	0.03	0.14	0.31	0.95	2.19	3.23
ACSLine3B1	115.05	4.3	4.19	4.19	4.51	4.2	4	4.31	4.31	0.03	0.14	0.02	0.87	8.12	6.37
ACSLine4B1	123.01	4.27	4.47	4.35	4.36	4.22	5.85	4.33	4.33	0.04	0.08	0.37	0.03	4.32	5.49
ACSLine5B1	131.8	4.05	4.18	4.25	4.26	4.14	4.21	4.09	4.09	0.04	0.12	0.52	16.52	0.01	4.25
ACSLine6B1	104.47	4.23	4.21	4.24	4.3	4.63	4.23	4.3	4.3	0.22	0.34	0.71	5.61	1.09	2.1
ACSLine7B1	116.46	4.21	4.64	4.31	4.3	4.15	4.12	4.24	4.24	0.09	0.23	0.45	2.48	0.26	1.03
ACSLine8B1	111.43	4.03	4.03	4.15	4.16	4	4.11	4	4	0.11	0.18	0.65	0.07	0.34	1.43
ACSLine1B2	140.23	4.07	4	4.41	4.04	4.01	4.01	4.56	4.56	0.13	0.16	0.55	1.62	0.16	1.64
ACSLine2B2	130.05	4.09	4	5.93	4	4.41	4.27	4.22	4.22	0.02	0.01	0.03	1.8	2.24	2.9
ACSLine3B2	84.08	4.17	4.03	4	4	4.31	4.13	4.31	4.31	0.03	0.14	0.42	0.04	0.57	5.72
ACSLine4B2	172.33	4.15	4	4.01	4.2	4	4	4.27	4.27	0.01	0.12	0.38	0.03	0.01	2.55
ACSLine5B2	139.31	4	4	4.1	4	4	4.03	4.06	4.06	0.03	0.12	0.5	0.99	4.18	5.12
ACSLine6B2	77.64	4	4.02	4	4.01	4.2	4	4.17	4.17	0.03	0.12	1.09	7.22	0.17	0.96
ACSLine7B2	108.99	4.08	4.09	4	5.91	4.12	4.03	4.27	4.27	0.05	0.16	0.43	4.87	0.09	0.7
ACSLine8B2	124.39	4.01	4.1	4.06	4.01	4.09	4.09	4.12	4.12	0.03	0.13	0.85	0.27	1.48	2.43

Conclusions

- Following a klystron trip, the power dissipated in the load would cause damage with nominal beam (560 kW) but the RF interlock dumps the beam in 3 turns -> OK
- The HOMs have been designed for worst-case conditions and 0.86 A DC. It is a good policy to monitor them as we increase the beam current (M1B2 is new). This is the only RF item on the ramp-up check list. We have an RF interlock on both coupler temperature and power -> OK

Thank you for your attention