Higher order mode damping considerations for the SPL cavities at CERN

W. Weingarten

Outline

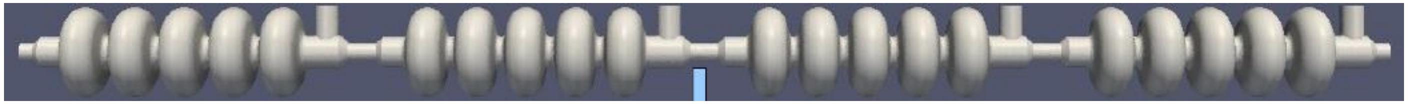
- The SPL study at CERN
- HOM damping requirements for SPL study
- Optimisation of cavity geometry related to HOM damping
- Conclusion on
  - geometry
  - damping HOMs
- Outlook

- Spare slides

  On longitudinal HOM excitation for pulsed beams

The SPL study at CERN

- International cross relations of interest with ESS, Project X, SNS, Myrrha, JPARC
- An international collaboration was established for the SPL study
  http://indico.cern.ch/categoryDisplay.py?categId=1893
- Goal: develop multi-megawatt sc proton linac cryomodule as a driver for non-LHC physics programs such as neutrino and Radioactive Ion Beam (RIB) physics.
- Deliverable: developing, in collaboration with external labs, bulk niobium 5-cell 704 MHz elliptical cavities, to be tested at 2 K, around the beginning of 2013, in a ½ length cryo-module with 4 cavities.



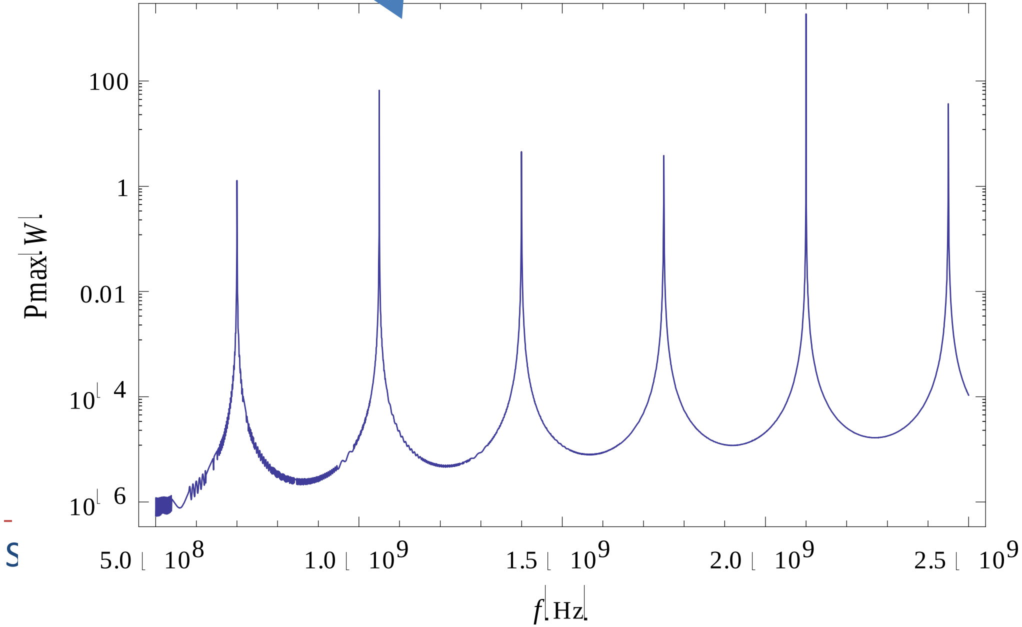
- The Superconducting Proton Linac (SPL) study is now part of CERN's Mid Term Plan.

HOM damping requirements for SPL study [1]

Beam	bunch length	1.2	mm
	bunch charge Q_b	114	pC
	average pulse current	40	mA (0.4 ms pulse length with 50 Hz repetition rate)
	energy	5	GeV
	beam power	4	MW
	no. of cavities	200	
Cavity	frequency	704.4	MHz
	number of cells	5	
	long. loss factor k @ design bunch length	4.8 @ $\sigma = 2$ mm	V/pC

HOM damping requirements for SPL study 2

HOM	single bunch HOM power spectrum		
	av. HOM power per cavity ($k \cdot Q_b \cdot I$)	22	W
	worst case HOM power per cavity (resonant excitation of mode for $Q_{ext} = 10^4$)	~ 100	W
	required damping Q_{ext} , monopole modes	10^5	
	ditto , dipole modes	10^7	

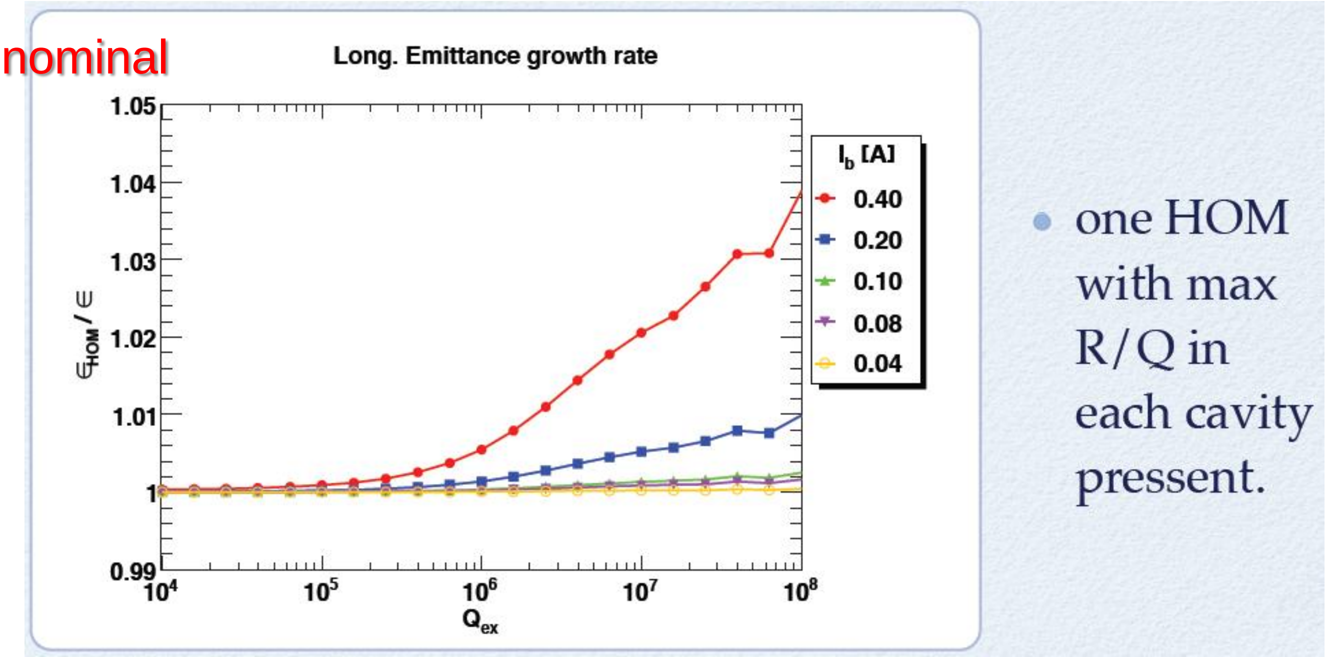


HOM damping requirements for SPL study 3

Required Q wrt beam break up for whole linac

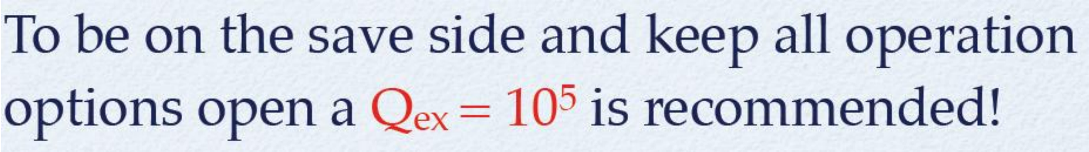
Q_{ex} limits based on beam dynamic simulations
Simulated cases: nominal, RF errors, chopped beams, fundamental pass-band modes

Example: nominal



- one HOM with max R/Q in each cavity pressent.

Overall conclusion:



To be on the save side and keep all operation options open a $Q_{ex} = 10^5$ is recommended!

Courtesy:
Marcel Schuh / CERN-BE-RF

HOM damping requirements for SPL study 4

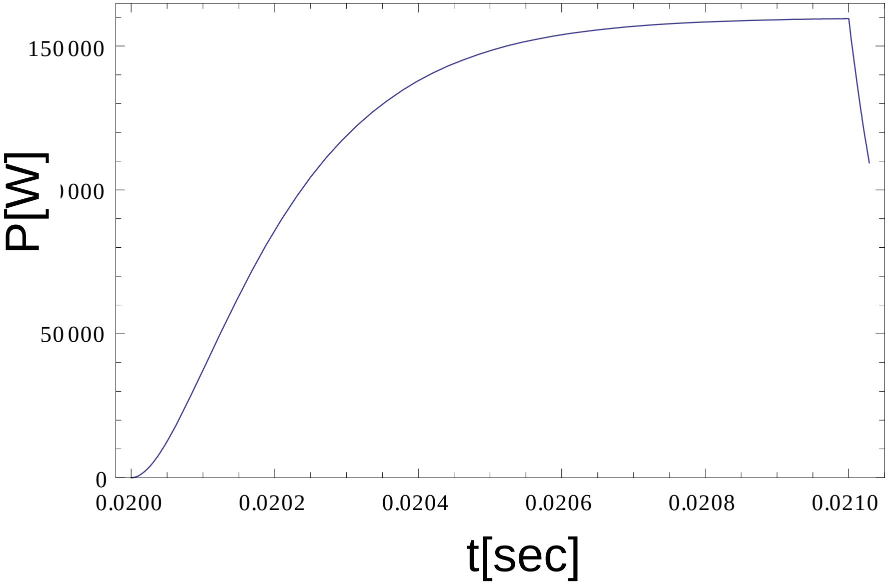
Required Q wrt power deposition per cavity

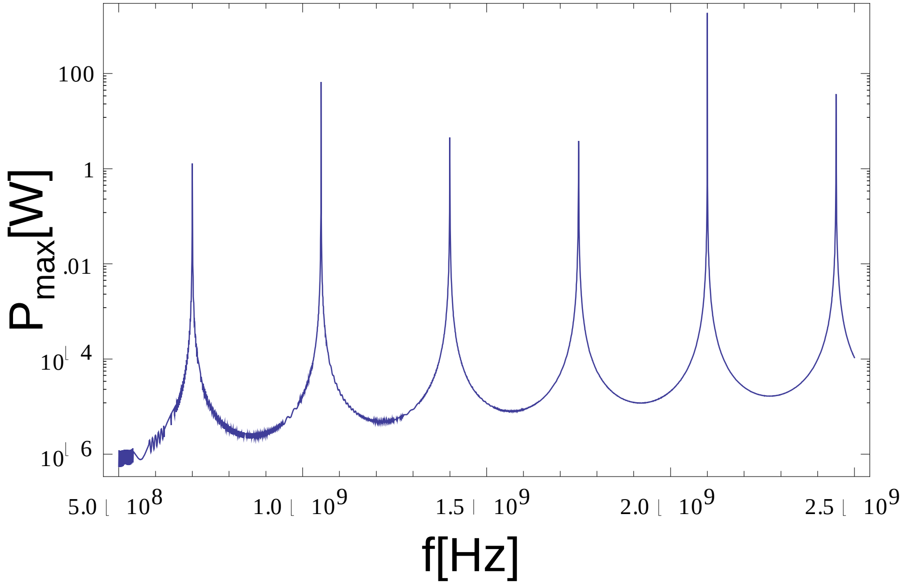
I = 40 mA; pulse length 1 ms, R/Q = 100 Ω ;

Rep. rate 50 Hz; f_{HOM} = 2.1 GHz; $Q_0 = 10^{10}$

Power built-up/decay during pulse of 1 ms

Maximum power vs. frequency showing principal Fourier components of beam





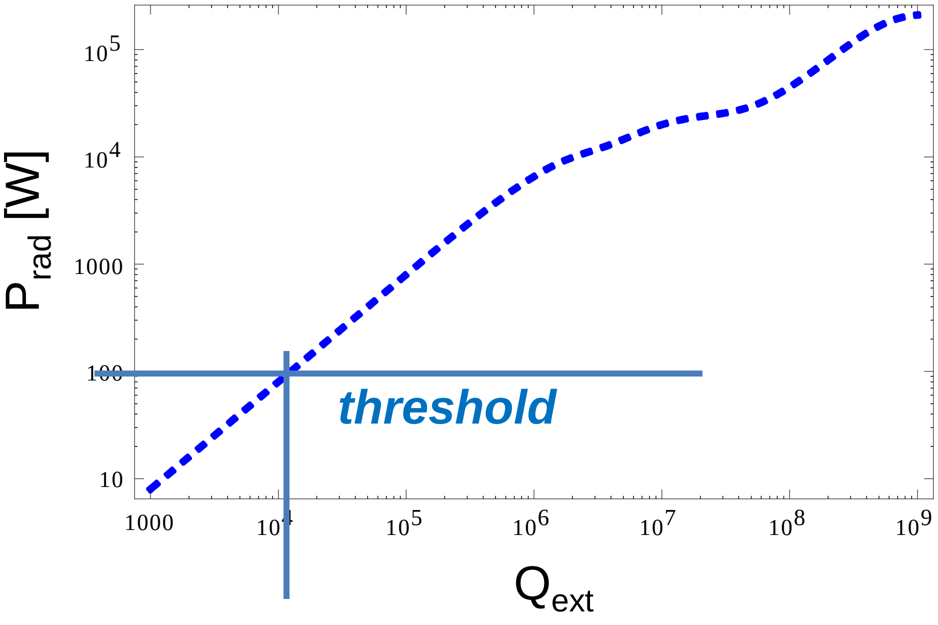
HOM damping requirements for SPL study ^{5}

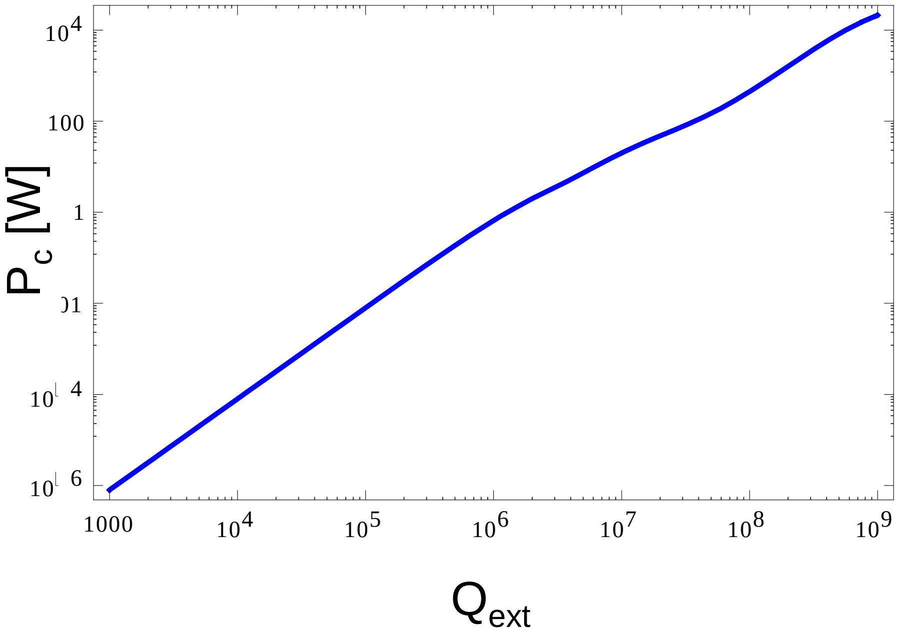
Required Q wrt power deposition per cavity

I = 40 mA; pulse length 1 ms, R/Q = 100 Ω ;

Rep. rate 50 Hz; f_{HOM} = 2.1 GHz; Q_0 = 10^{10}

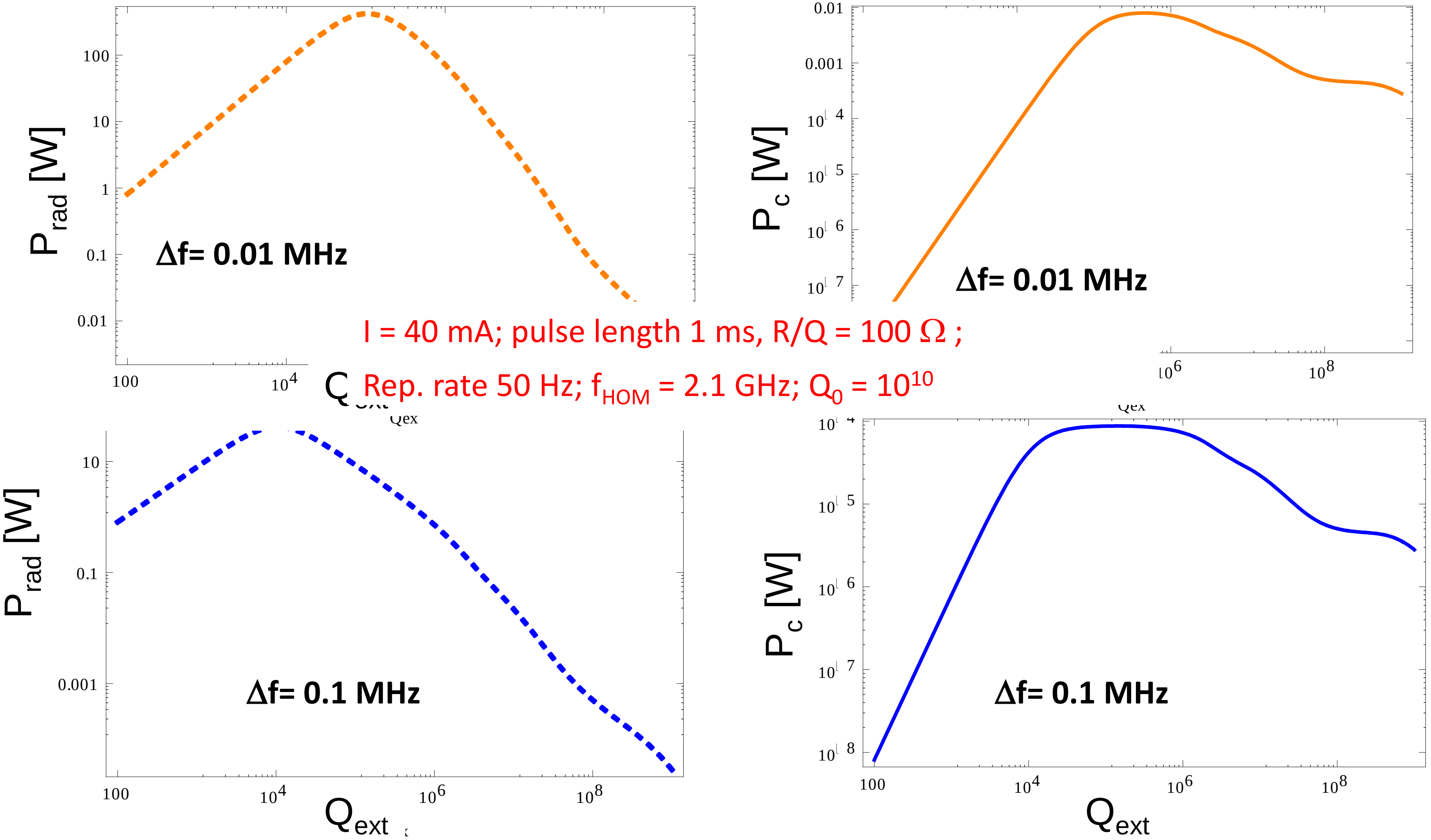
f (HOM) precisely on beam spectral line





HOM damping requirements for SPL study 6

Required Q wrt power deposition per cavity



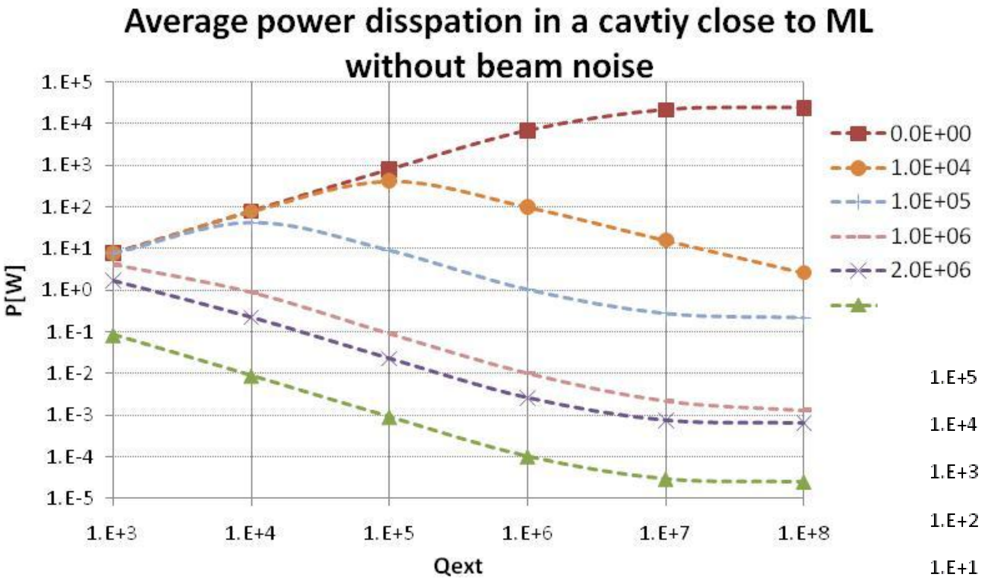
I = 40 mA; pulse length 1 ms, R/Q = 100 Ω ;

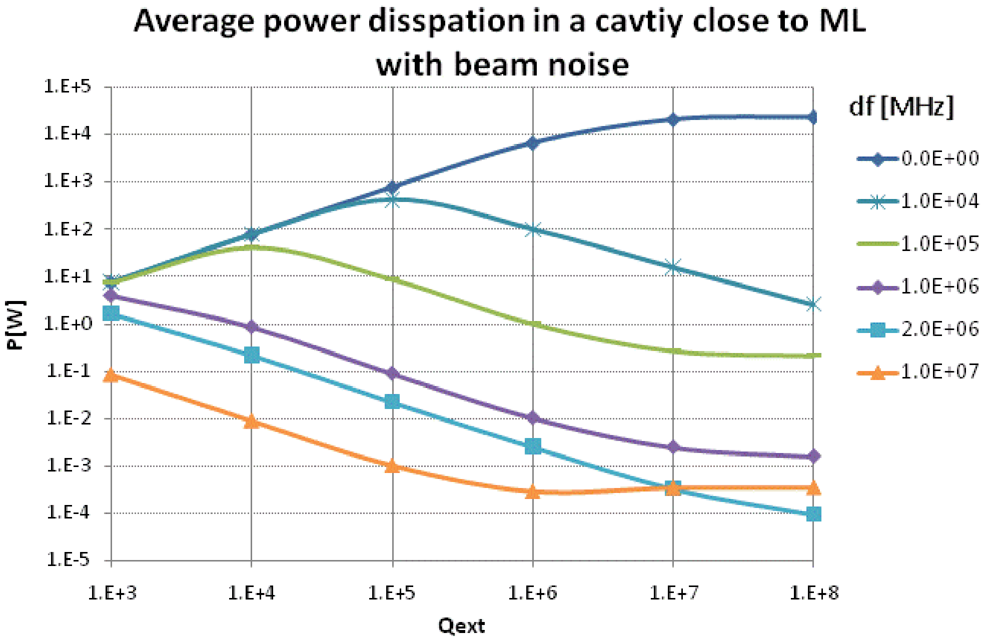
Rep. rate 50 Hz; f_{HOM} = 2.1 GHz; $Q_0 = 10^{10}$

HOM damping requirements for SPL study 7

Required Q wrt power deposition per cavity

Validation of recursive analytical calculations


Average power disspation in a cavtiy close to ML without beam noise


Average power disspation in a cavtiy close to ML with beam noise

Courtesy:
Marcel Schuh / CERN-BE-RF

HOM damping requirements for SPL study [8]

Conclusion

I = 40 mA; pulse length 1 ms, R/Q = 100 Ω ;

Rep. rate 50 Hz; f_{HOM} = 2.1 GHz; $Q_0 = 10^{10}$

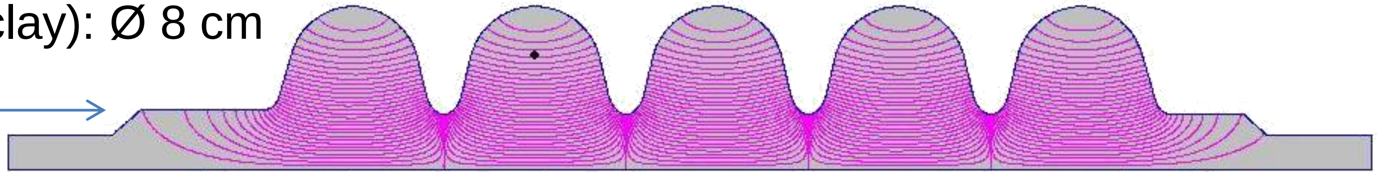
- The main beam Fourier components (n·352 MHz) contribute significantly to the HOM power, the 50 Hz Fourier component, however, only marginally; to reduce the HOM power below 100 W, the Q-value of the HOM must be $< 10^4$
- Avoiding the main beam Fourier components by the HOM frequencies within 10 kHz reduces the HOM power significantly, with a tendency to become even smaller for larger Q-values (P < 1 W @ $Q > 10^7$)

→ The HOM power could possibly be reduced by inelastic detuning or an appropriate design of the cavity (though without changing the fundamental mode frequency) with the aim to keep sufficiently off ALL HOM frequencies from the main Fourier components

Optimisation of cavity geometry related to HOM damping [1]

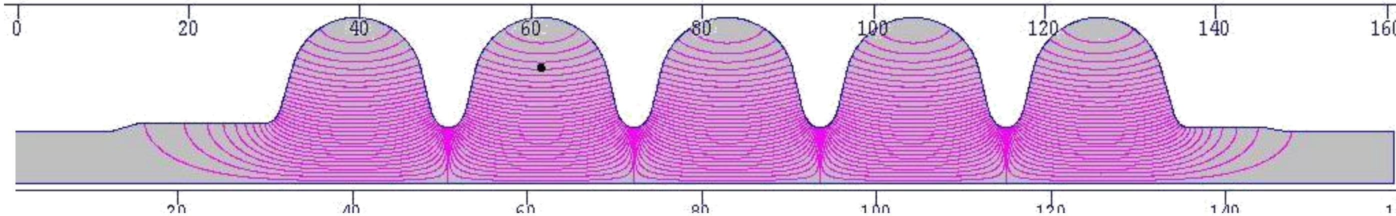
Different beam tube diameters investigated

Reference design (Saclay): Ø 8 cm

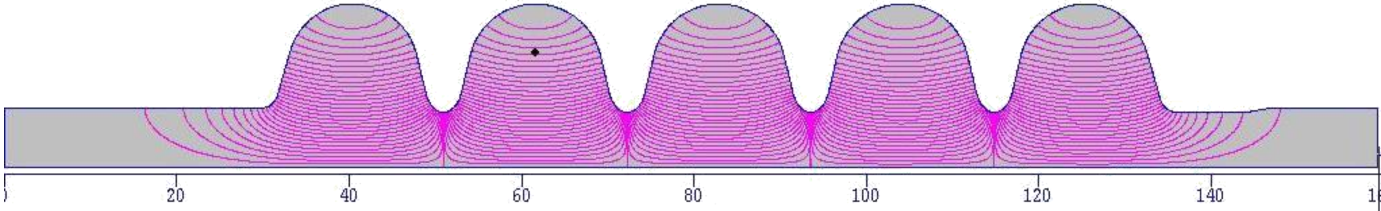


taper

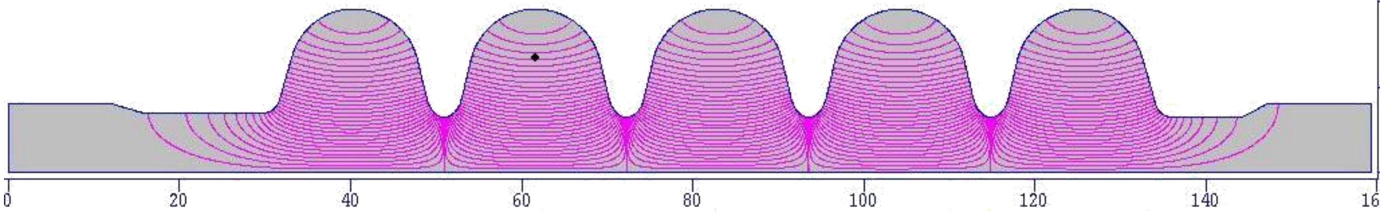
Beam tube Ø 12 cm



Beam tube Ø 14 cm

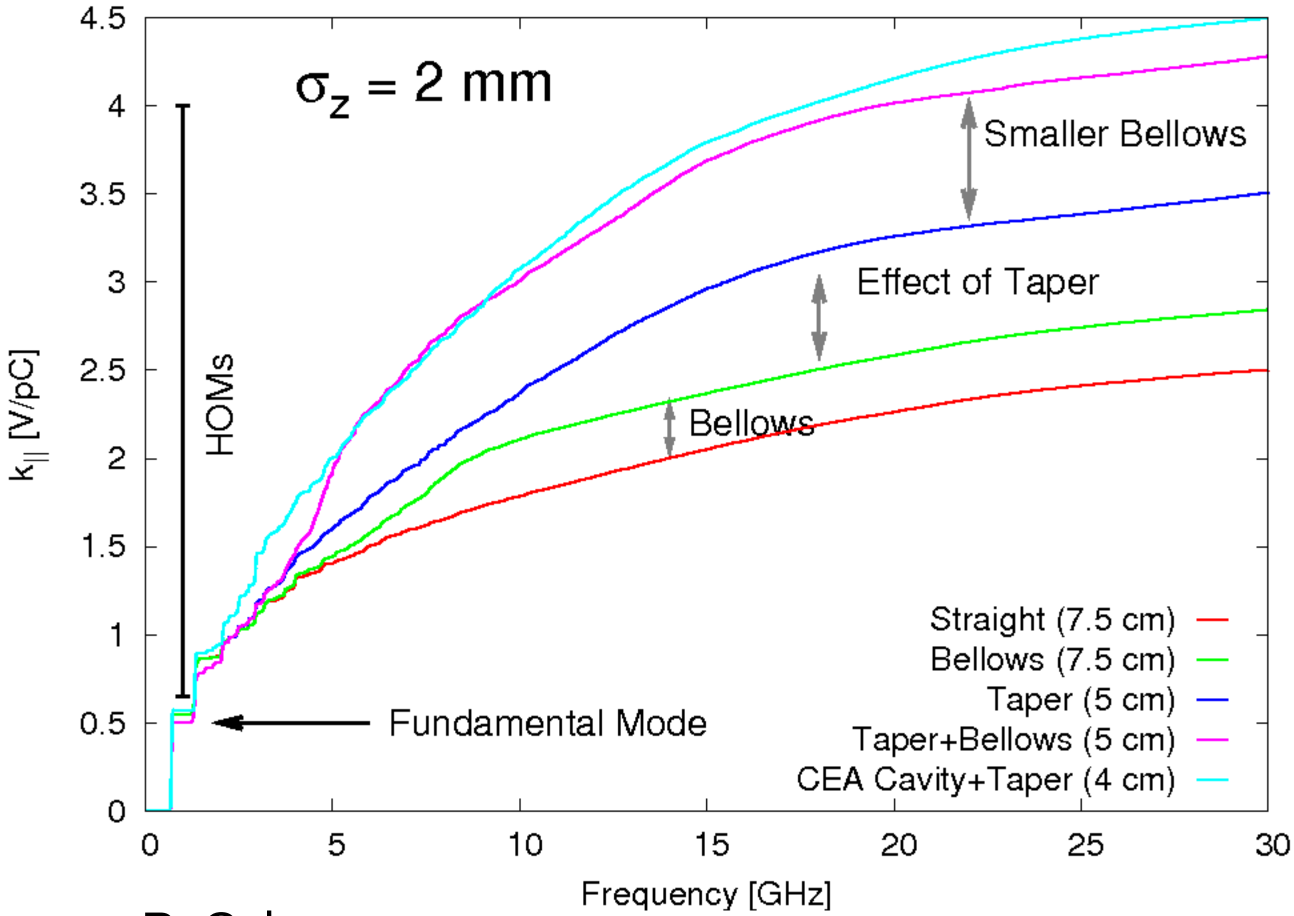


Beam tube Ø 16 cm



Optimisation of cavity geometry related to HOM damping 2

Longitudinal Loss Factors

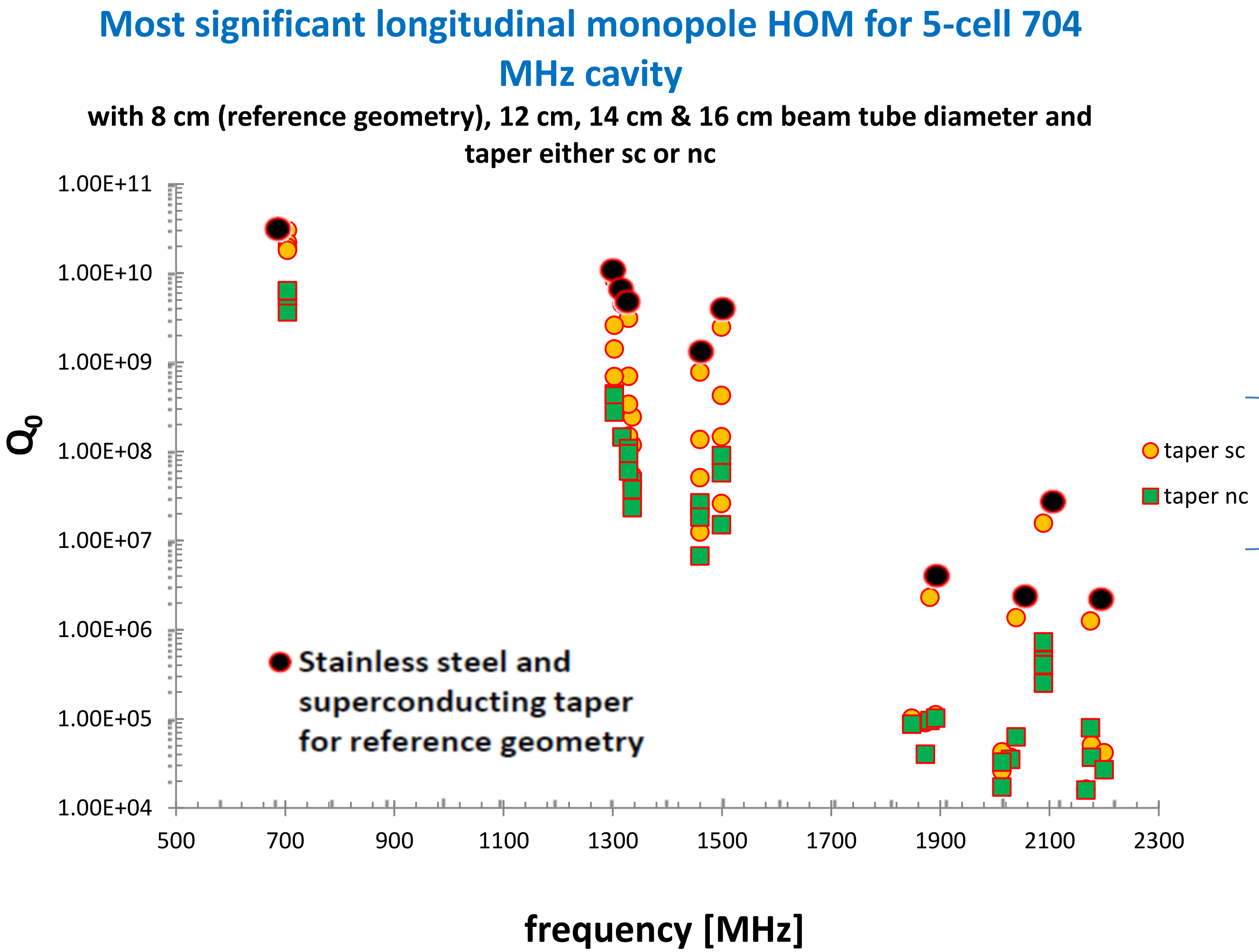


Source: R. Calaga

http://indico.cern.ch/conferenceDisplay.py?confId=80052

Optimisation of cavity geometry related to HOM damping 3

Q_L vs. f damping via normal conducting beam tube (plus normal conducting taper)



Most significant longitudinal monopole HOM for 5-cell 704 MHz cavity

with 8 cm (reference geometry), 12 cm, 14 cm & 16 cm beam tube diameter and taper either sc or nc

high Al iron

Optimisation of cavity geometry related to HOM damping 4

$Q_{HOM}/Q_{fundamental\ mode}$ vs. f damping via beam tube made of stainless steel

by Karol Krizka/University of Toronto and summer student at CERN: Technical Note, SPL cavity: Power dissipated at bellows, 9 July 2010

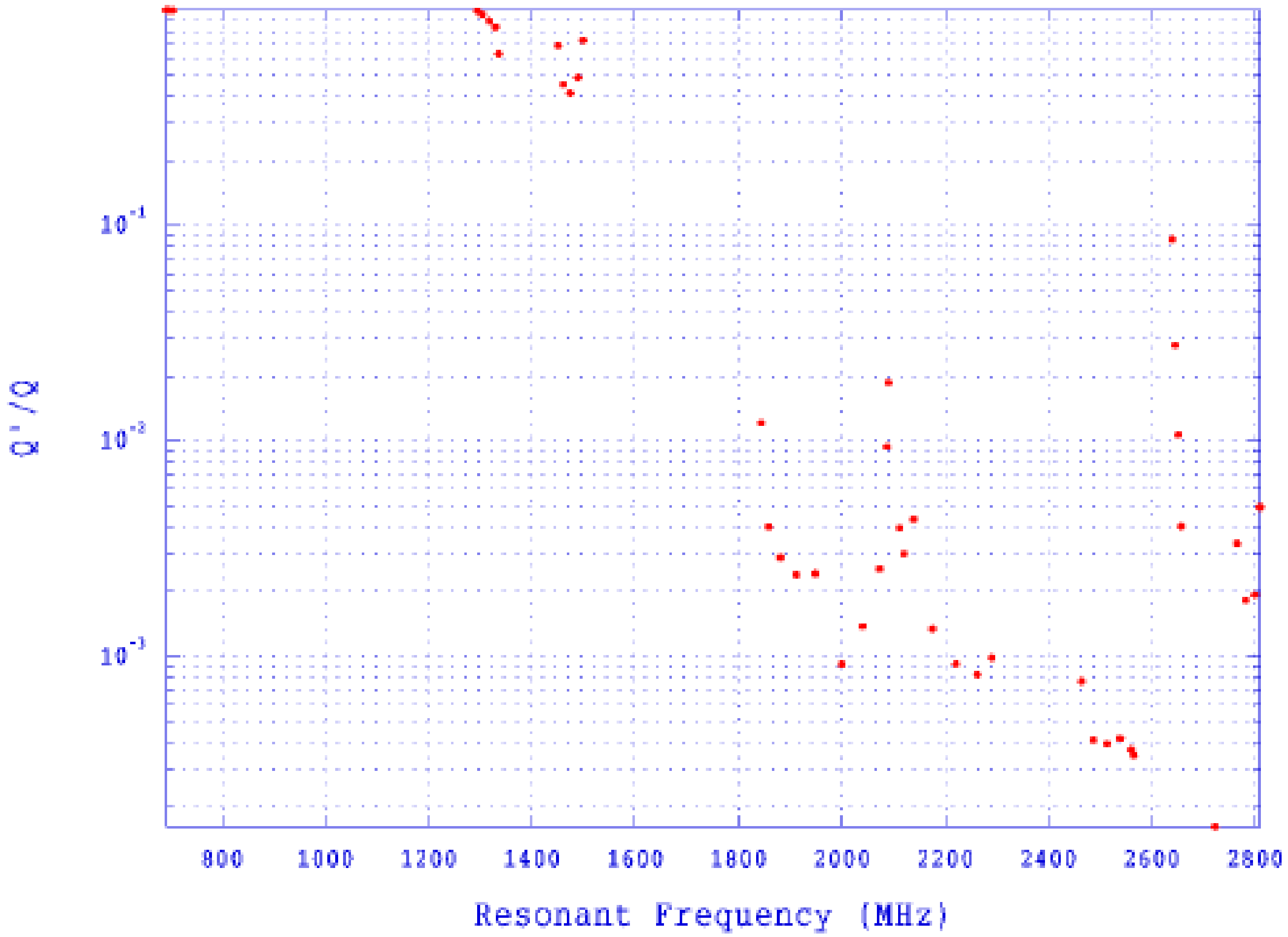
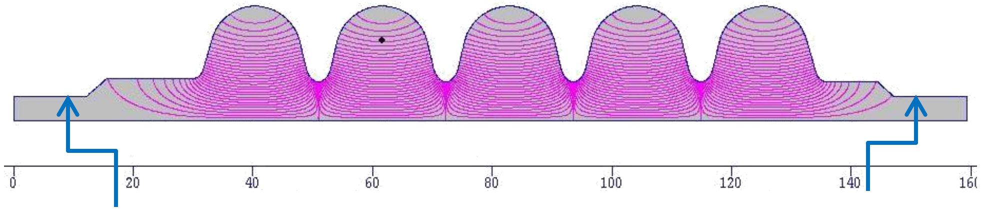


Figure 3: Change in cavity efficiencies between making the bellows superconducting and made out of stainless steel.

Optimisation of cavity geometry related to HOM damping 5

Q_L vs. f damping via two 50 Ω antennas in beam tube Ø = 3.6 cm



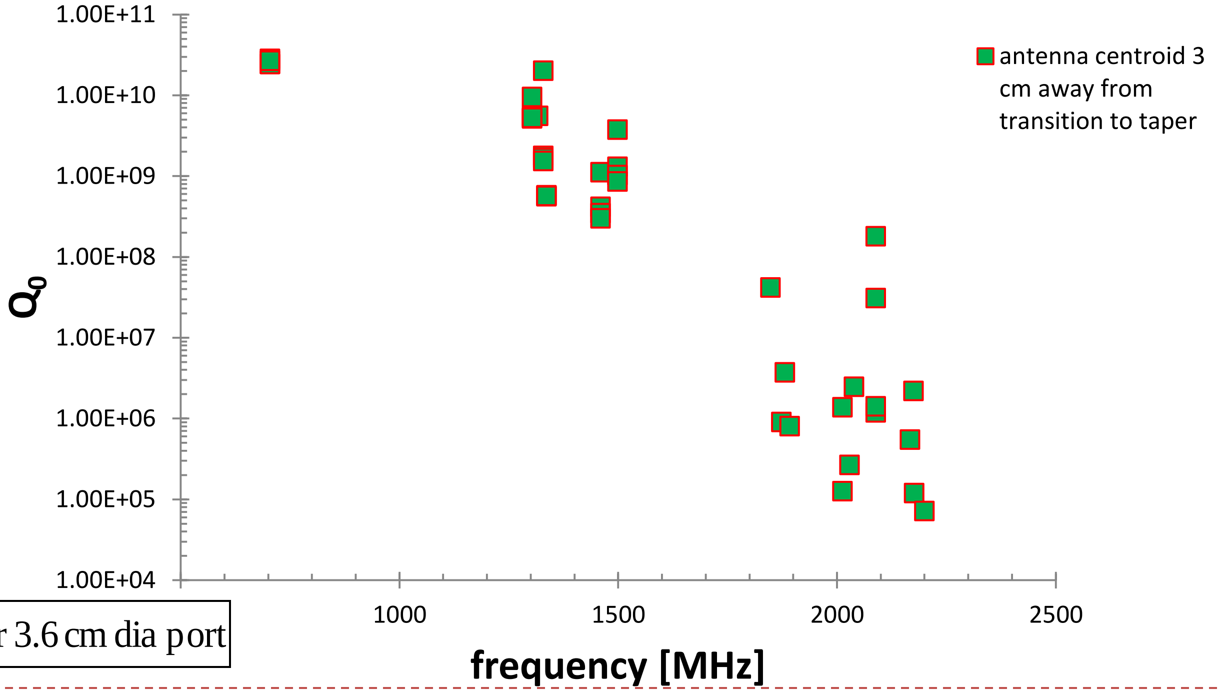
positions of HOM coupler ports

$$Q_L = Q_0 \cdot \frac{1}{1 + \frac{P_{ant}}{P_c}}$$

$$P_{ant} = \frac{1}{2} \cdot Z_0 \cdot I^2$$
$$I = j \cdot \pi r_i^2$$
$$j = \omega \varepsilon_0 E$$

5-cell 704 MHz cavity (reference geometry)

with 8 cm beam tube diameter with 2 HOM antennas

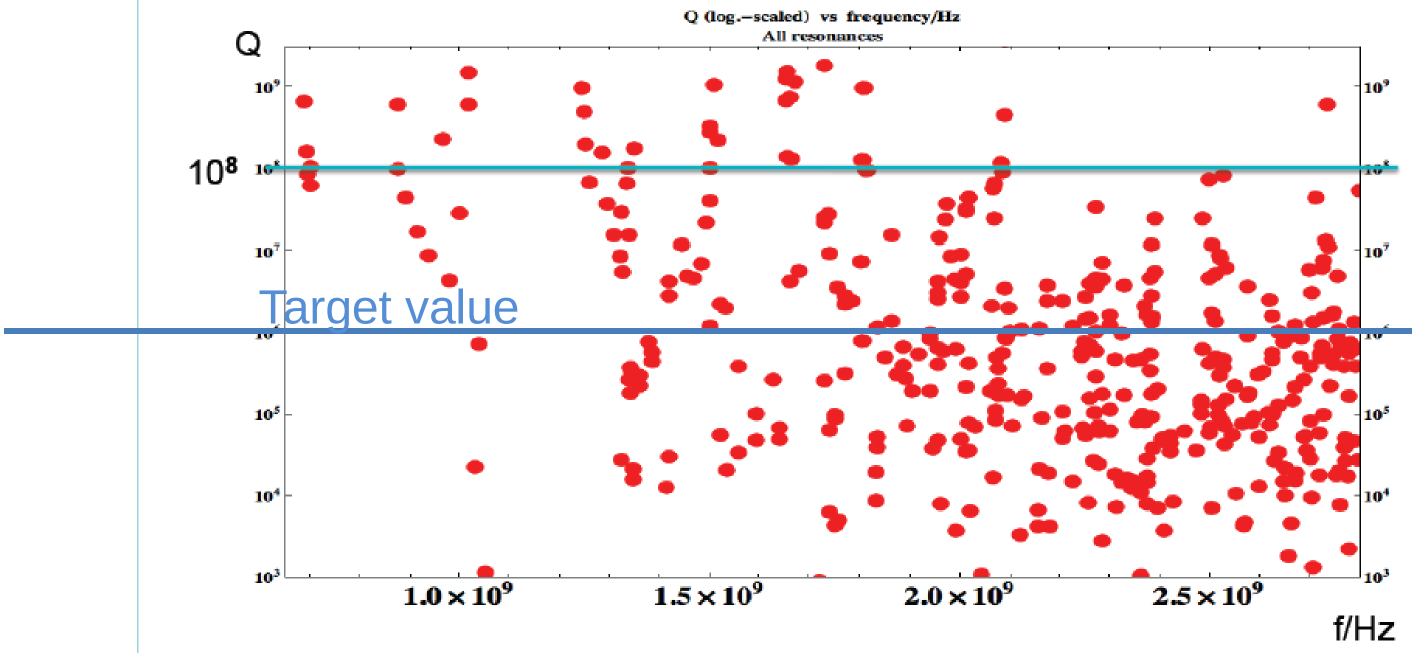


$$P_{ant}[W] = 2862 \cdot (f/GHz)^2 \cdot (E/MV/m)^2 \text{ for 3.6 cm dia port}$$

Optimisation of cavity geometry related to HOM damping ^{6}

Q_L vs. f damping via coaxial antenna

Q-value spectrum for 0 mm antenna depth:



by far to heavy loading of fundamental mode => ...

shown at 4th SPL Collaboration Meeting - jointly with ESS at LUND (Sweden)

Courtesy Hans-Walter Glock/Uni Rostock

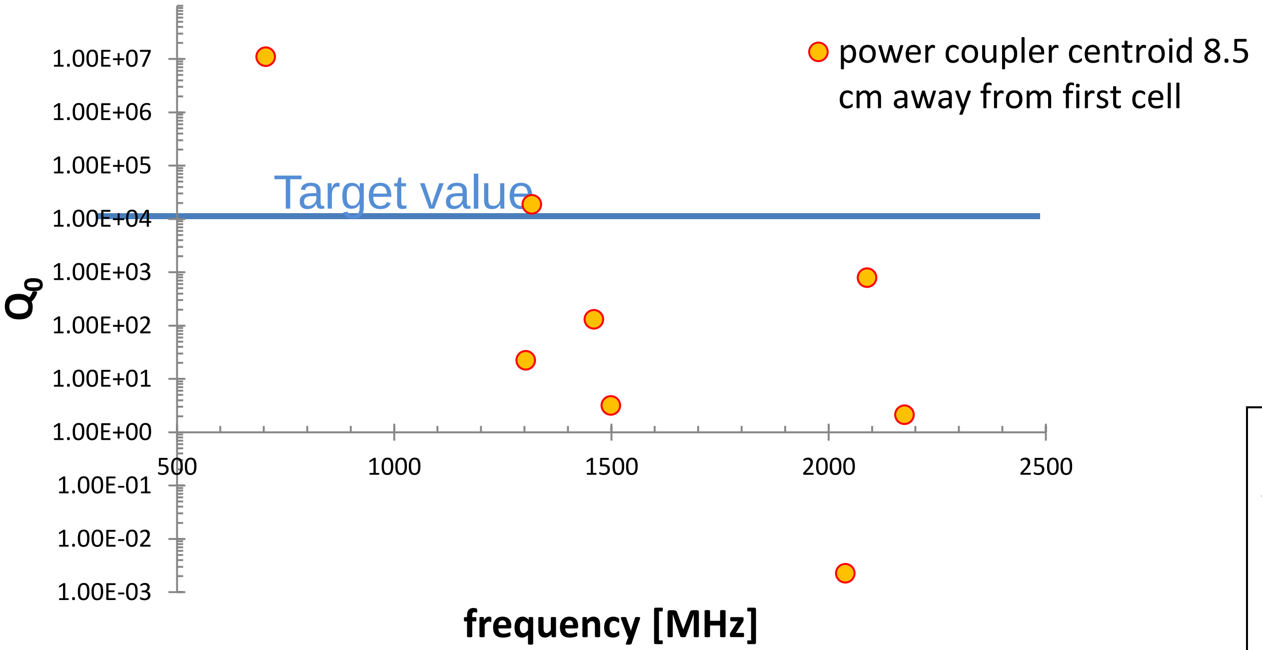
... the main message remains:

Pick-ups without fundamental mode filters will not be able both to preserve fundamental mode Q and damp all HOMs sufficiently.

Confirmed by Wolfgang Weingarten's 2D computations using beam pipe dampers.

Optimisation of cavity geometry related to HOM damping 7

Q_L vs. f damping with fundamental power coupler



for 50 Ω power coupler in beam tube Ø = 10 cm

$$\boxed{Q_L = Q_0 \cdot \frac{1}{1+\frac{P_{ant}}{P_c}}}$$

$$P_{ant} = \frac{1}{2} \cdot Z_0 \cdot I^2$$

$$I = j \cdot \pi r_i^2$$

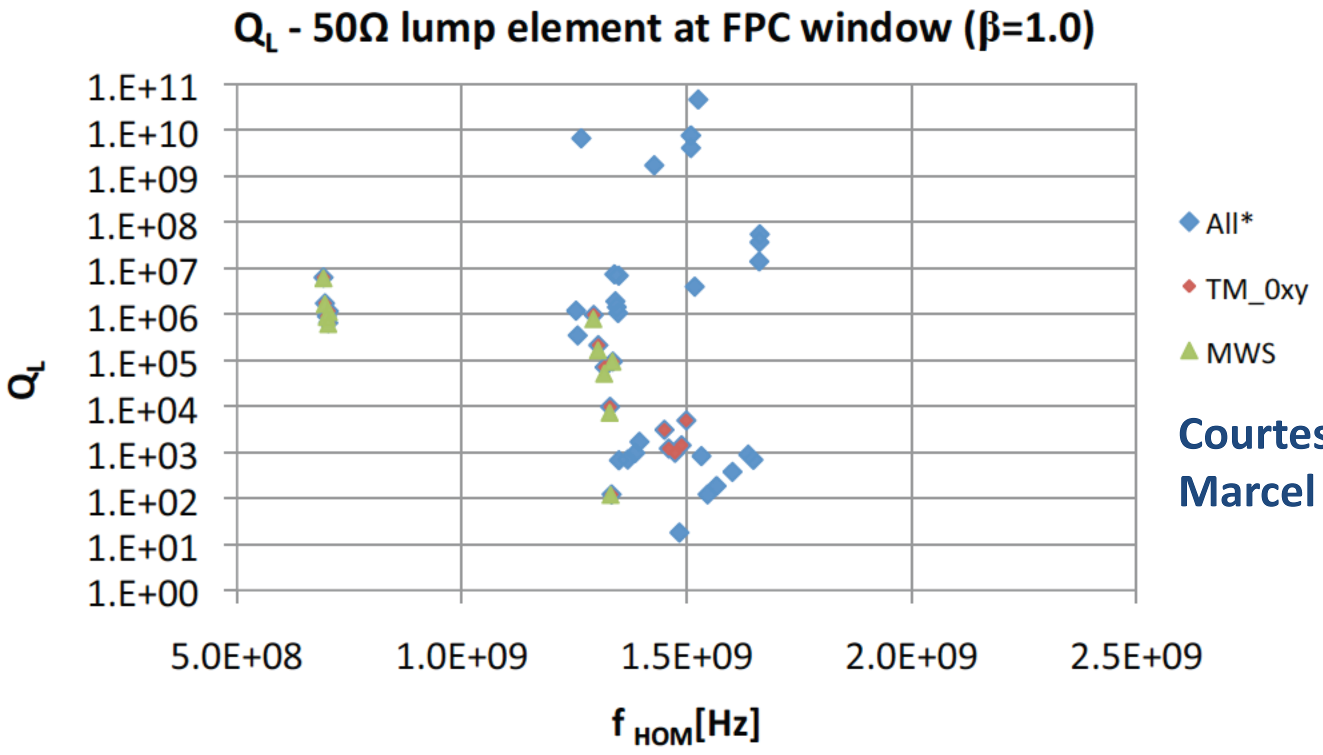
$$j = \omega \varepsilon_0 E$$

These numbers are only estimations !

Optimisation of cavity geometry related to HOM damping [8]

Q_L vs. f damping with fundamental power coupler (FPC)

- HFSS: 180° model with lump circuit element at FPC window
- MicroWave Studio: full cavity (360°) with port at FPC window
- ➡Calculate loaded Q value of system (damping)



Courtesy:
Marcel Schuh / CERN-BE-RF

Optimisation of cavity geometry related to HOM damping [9]

Heat is dissipated in ss bellows

$$P_{rad}(t)=\frac{P_{HOM}(t)}{1+\frac{Q_{ext}}{Q_0}} \qquad P_c(t)=\frac{P_{HOM}(t)}{1+\frac{Q_0}{Q_{ext}}}$$

- **Fundamental mode:** Heat dissipation in cavity @ 704 MHz, 25 MV/m, Q_0= 10^{10}: **P_c = 123 W CW => 5 … 16 W pulsed**
- Heat dissipation in SS bellows @ 704 MHz, 25 MV/m, equivalent Q_0 = $3\cdot10^{11}$:

  P_c = 4 W CW => 0.04 … 0.13 W pulsed
- **HOM:** Heat dissipation in SS bellows @ 2112 MHz, Q_0=$2.5\cdot10^7$;

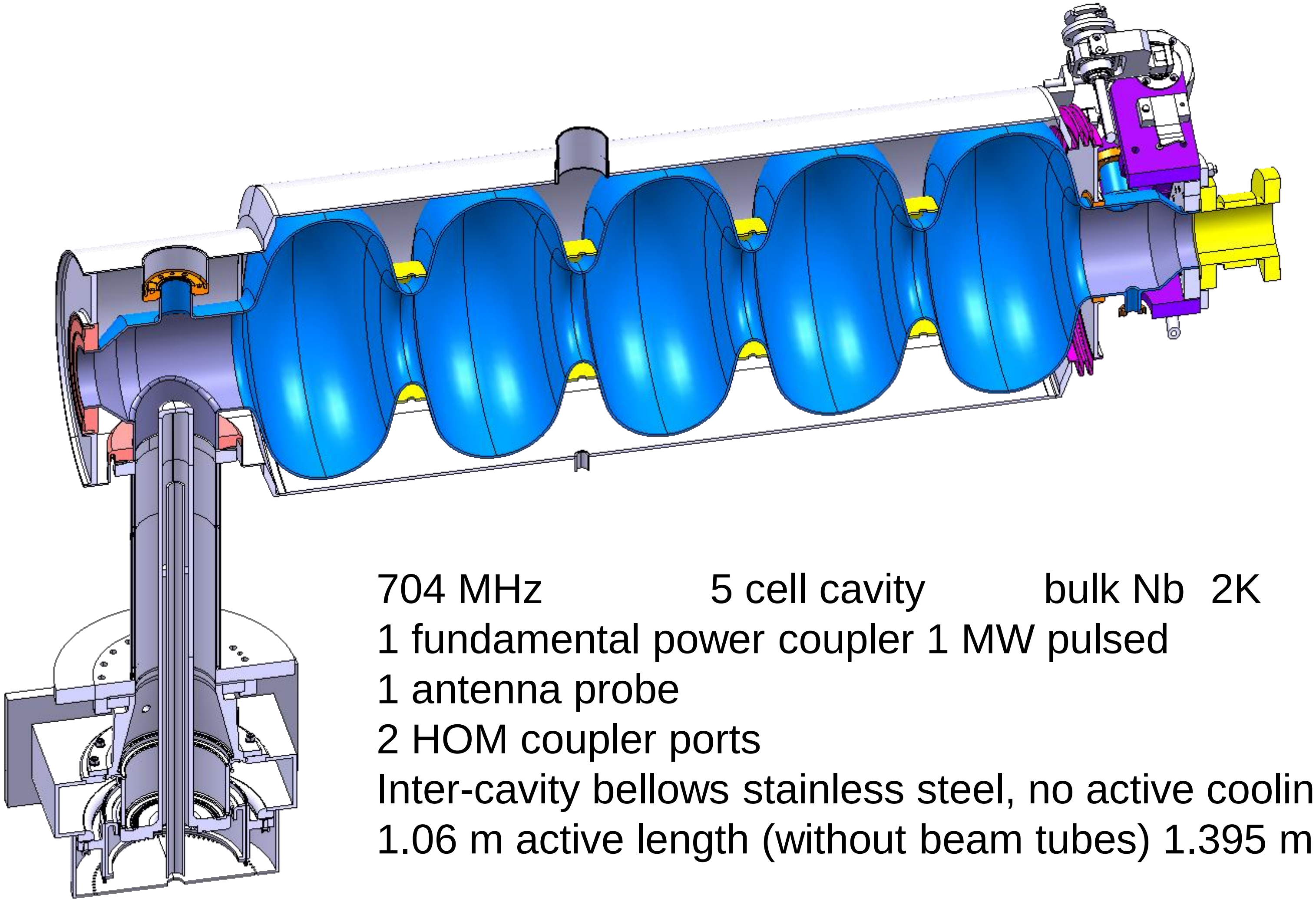
  construct HOM damper with $Q_{ext} < 10^5$ or/and

  count on damping by power coupler: $Q_{ext} < 10^4$ (**to be checked!**)

Under these assumptions the heat dissipated in the SS bellows for the HOM at 2.112 GHz is less than 3 W (worst case).

Conclusion on geometry [1]

Present cavity/tuner/coupler/He tank/beam tube layout



704 MHz 5 cell cavity bulk Nb 2K

1 fundamental power coupler 1 MW pulsed

1 antenna probe

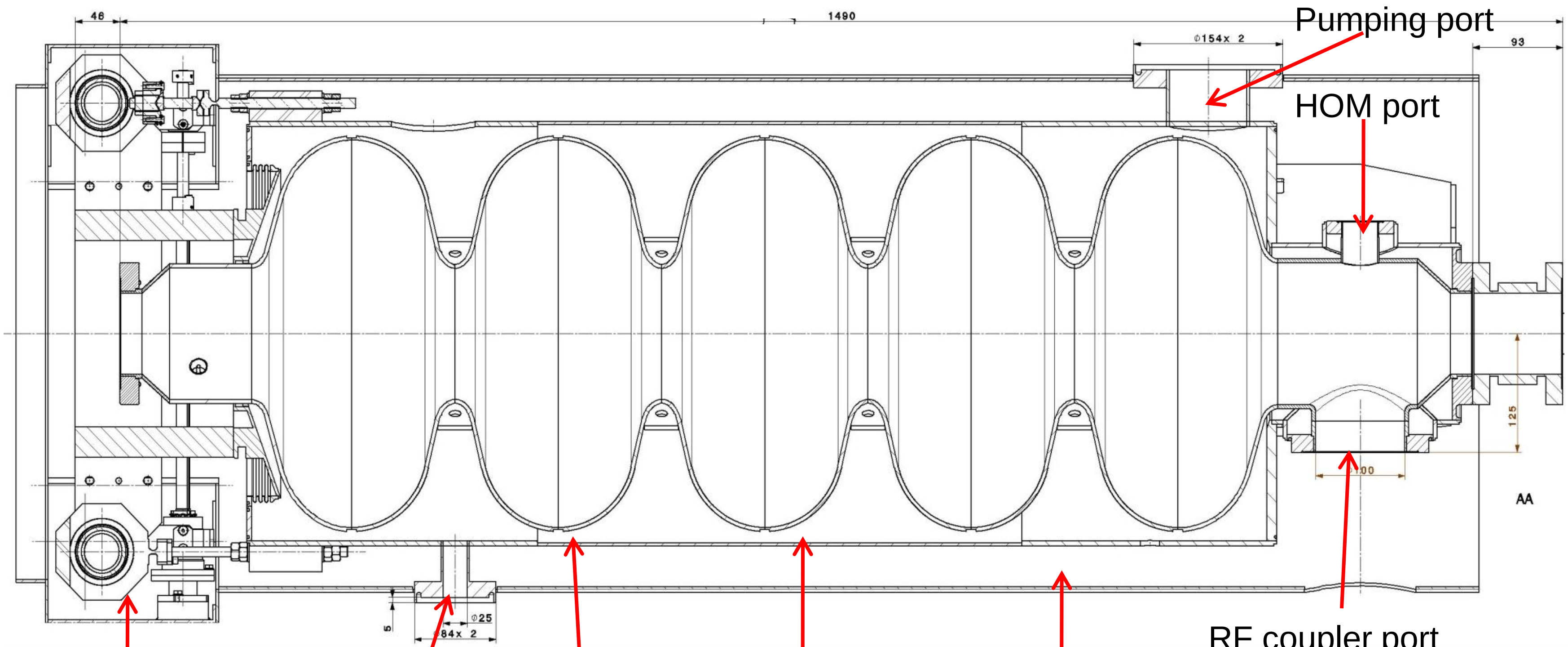
2 HOM coupler ports

Inter-cavity bellows stainless steel, no active cooling

1.06 m active length (without beam tubes) 1.395 m over all

Conclusion on geometry ^{2}

Present cavity/tuner/coupler/He tank/beam tube layout



Pumping port

HOM port

Tuner

Cool-down line port

He vessel (Ti)

Cavity (Nb)

Magnetic shielding (cryoperm™)

RF coupler port

Includes specific features for cryo-module integration (inter-cavity supports, cryogenic feeds, magnetic shielding …)

Courtesy: Th.Renaglia, V. Parma; CERN

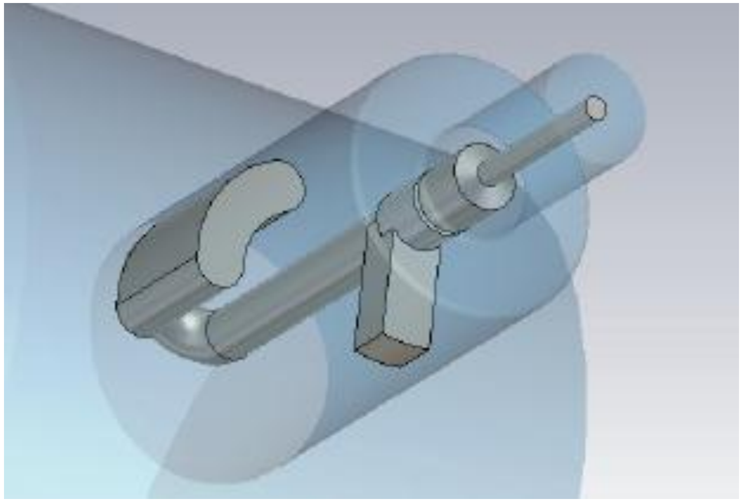
Conclusion on damping HOMs

- In the frequency range *f* = 1300 – 1500 MHz, damping of HOMs is not sufficient, neither by
  - dissipation in beam tube (largely irrespective of absorber material) or
  - 50 Ω antenna placed in beam tube
- For *f* > 1800 MHz, damping of HOMs is stronger, in particular for larger beam tube diameter than our reference design, but still insufficient for our needs ($Q < 10^4$)
- Antenna HOM absorbers are needed that are trimmed for 1300 and 1500 MHz and reject the fundamental mode
- [Corollary: There may be a chance to damp the HOMs via the fundamental power coupler (to be confirmed by simulations and measurements of the impedance of the power coupler as “seen” by the cavity)]

Outlook

- There is a first design developed at Rostock University, based on the HOM couplers for LEP and LHC


LHC HOM coupler



- The next steps are the
  - Electrical validation and the
  - Mechanical/cryogenic validation of model
  - Prototype manufacture of HOM coupler and warm RF tests on Cu cavity model

Tuning to 704 MHz OK but cooling and construction to be checked

Thank you for your attention !

Acknowledgements to my colleagues in CERN/BE-RF as well as the members of the SPL-cavity working group

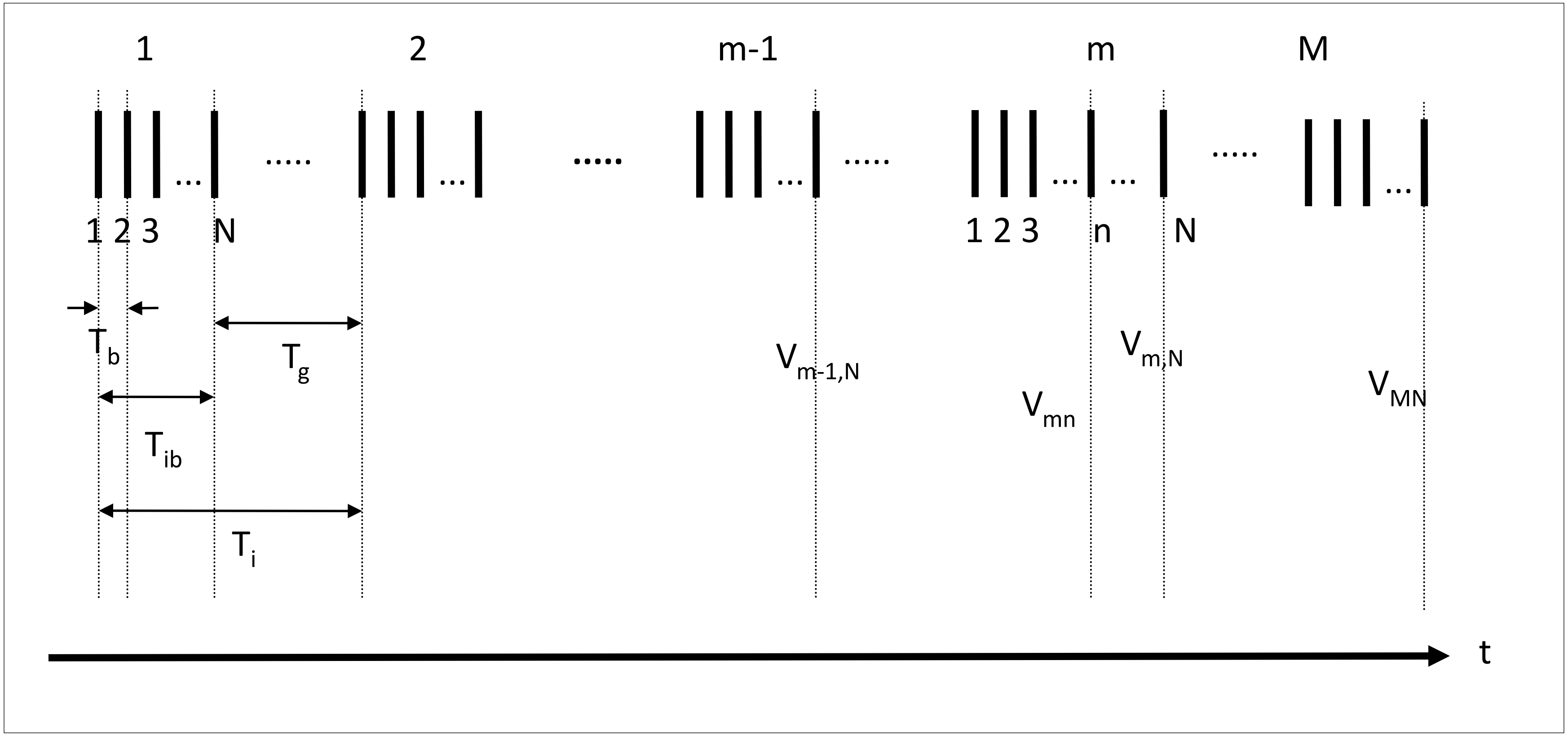
http://indico.cern.ch/categoryDisplay.py?categId=2722

Spare slides

Insertion (on recursive analytical calculations)

On longitudinal HOM excitation for pulsed beams [1]

CW beam: $V = V_q \sum_{n'=0}^{\infty} e^{-n' p T_b} = \dfrac{V_q}{1 - e^{-pT_b}}$



Insertion (on recursive analytical calculations)

On longitudinal HOM excitation for pulsed beams 2

$$m(t) = \frac{t}{T_i} + 1 \,(\text{truncated})$$

$$t^* = t - [m(t) - 1] \cdot T_i$$

$$p = 2 \cdot \pi \cdot f \cdot i + \frac{1}{T_d}$$

$$n(t) = \frac{t}{T_b} + 1 \;\; (\text{truncated}) \text{ if } t^* \leq (N\text{-}1) \cdot T_b \text{ or } = N \text{ otherwise}$$

$$T_d = \frac{Q_L}{\pi \cdot f}$$

$$T_g = T_i - T_{ib} = T_i - (N - 1) \cdot T_b$$

$$Q_L = \frac{1}{\frac{1}{Q_0} + \frac{1}{Q_{ex}}}$$

$$V_q = \pi \cdot f \cdot \frac{R}{Q} \cdot q$$

Insertion (on recursive analytical calculations)

On longitudinal HOM excitation for pulsed beams 3

$$V_{mn} = V_{m-1,N} \cdot e^{-pT_g} \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-2)pT_b} + \ldots + V_q =$$

$$= V_{m-1,N} \cdot e^{-pT_i} \cdot e^{+(N-n)pT_b} + V_q \cdot e^{-(n-1)pT_b} + V_q \cdot e^{-(n-2)pT_b} + \ldots + V_q \Rightarrow$$

$$V_{mn} = V_q \cdot \left[\frac{1-e^{-(m-1)pT_i}}{1-e^{-pT_i}} \cdot \frac{1-e^{-NpT_b}}{1-e^{-pT_b}} \cdot e^{-p[T_i-(N-n)T_b]} + \frac{1-e^{-npT_b}}{1-e^{-pT_b}} \right]$$

$$V_{mn}(t) = V_{mn} \cdot e^{-p(t-t_{mn})}; \quad t_{mn} = [m(t)-1] \cdot T_i + [n(t)-1] \cdot T_b$$

$$P_{HOM}(t) = \frac{V_{mn}(t) \cdot V_{mn}^{*}(t)}{\frac{R}{Q} \cdot Q_L} \qquad P_{rad}(t) = \frac{P_{HOM}(t)}{1+\frac{Q_{ext}}{Q_0}} \qquad P_c(t) = \frac{P_{HOM}(t)}{1+\frac{Q_0}{Q_{ext}}}$$

Source: J. Plouin et al., 3rd SPL Collaboration Meeting11-13 November, CERN

#freq	r/Q	beta_opt	Qo	Rs_nOhm
692.459406	15.495341	0.55	5.87048e+10	4.58
695.691165	40.295848	0.63	5.85048e+10	4.60
699.762722	86.977902	0.71	5.82537e+10	4.62
703.121236	173.038043	0.81	5.80475e+10	4.64
704.420268	**565.499512**	**1.00**	**5.8134e+10**	**4.65**
1293.187800	3.150182	0.66	4.06538e+10	9.75
1303.568690	7.969888	0.72	4.01921e+10	9.86
1317.445320	17.344152	0.79	3.95608e+10	10.02
1329.742220	59.154893	1.00	3.9004e+10	10.16
1335.734260	107.744313	0.98	3.8525e+10	10.23
1450.724780	0.831396	0.92	5.06898e+10	11.62
1460.366080	1.999197	0.89	5.03429e+10	11.74
1474.206000	2.839266	0.85	5.03023e+10	11.92
1488.535980	2.701775	0.80	5.09436e+10	12.10
1499.066360	2.342662	0.73	5.20134e+10	12.24
1843.272060	0.209069	0.95	3.35164e+10	17.22
1858.324840	0.596186	0.91	3.26306e+10	17.47
1881.326440	1.603429	0.98	3.28434e+10	17.84
1911.484360	1.329645	0.94	3.31308e+10	18.33
1948.248770	1.819111	1.00	3.35394e+10	18.95
2000.236410	2.451434	0.98	3.13642e+10	19.84
2039.865120	1.377179	0.78	3.70143e+10	20.53
2072.798390	3.019703	0.83	3.349e+10	21.12
2086.249930	5.689452	0.88	3.00335e+10	21.36
2089.642160	19.164504	1.00	2.90251e+10	21.42
2111.640680	**10.636820**	**1.00**	**2.94648e+10**	**21.82**
2119.767790	8.476595	1.00	2.65214e+10	21.97
2138.944200	1.075819	0.95	2.94674e+10	22.33
2175.157760	1.744804	0.91	3.24669e+10	23.00
2219.889020	4.482180	0.97	3.46431e+10	23.86
2262.192880	7.529522	1.00	3.6688e+10	24.68
2290.061390	0.330347	0.85	4.00758e+10	25.23
2464.607050	0.764947	0.95	2.5928e+10	28.82
2485.980300	1.514541	1.00	2.63647e+10	29.28
2512.576190	1.303253	0.96	2.84428e+10	29.86
2538.171130	8.505168	1.00	3.13472e+10	30.42
2559.022710	6.760250	0.99	3.40374e+10	30.88
2565.011240	2.855068	0.95	3.43392e+10	31.01
2639.339900	0.070686	0.90	2.41594e+10	32.69
2645.191100	0.071469	1.00	2.48068e+10	32.82
2650.937090	0.150348	1.00	2.47399e+10	32.96
2657.099030	0.275372	1.00	2.44513e+10	33.10
2721.471070	1.230228	0.96	2.23449e+10	34.60
2765.009700	0.249521	0.83	2.99369e+10	35.63
2781.989510	0.411752	0.87	2.61634e+10	36.04
2799.460470	0.229298	0.90	2.30615e+10	36.46
2809.660150	6.941103	1.00	2.09609e+10	36.71

Operating frequency mode (π) : f_0 = 704.4 MHz

No monopole HOM at $2f_0$

Mode at 2111.64 MHz very near $3f_0$

Cut-off frequencies for the mode TM010
Ø 80 mm : 2865 MHz
Ø 130 mm : 1763 MHz
Ø 140 mm : 1637 MHz

List of **monopole HOM** calculated with Superfish between 0 and 3000 kHz
Axisymetric calculations