Some Aspects of 704 MHz

R. Calaga, BNL, Sep 22-23, 2011

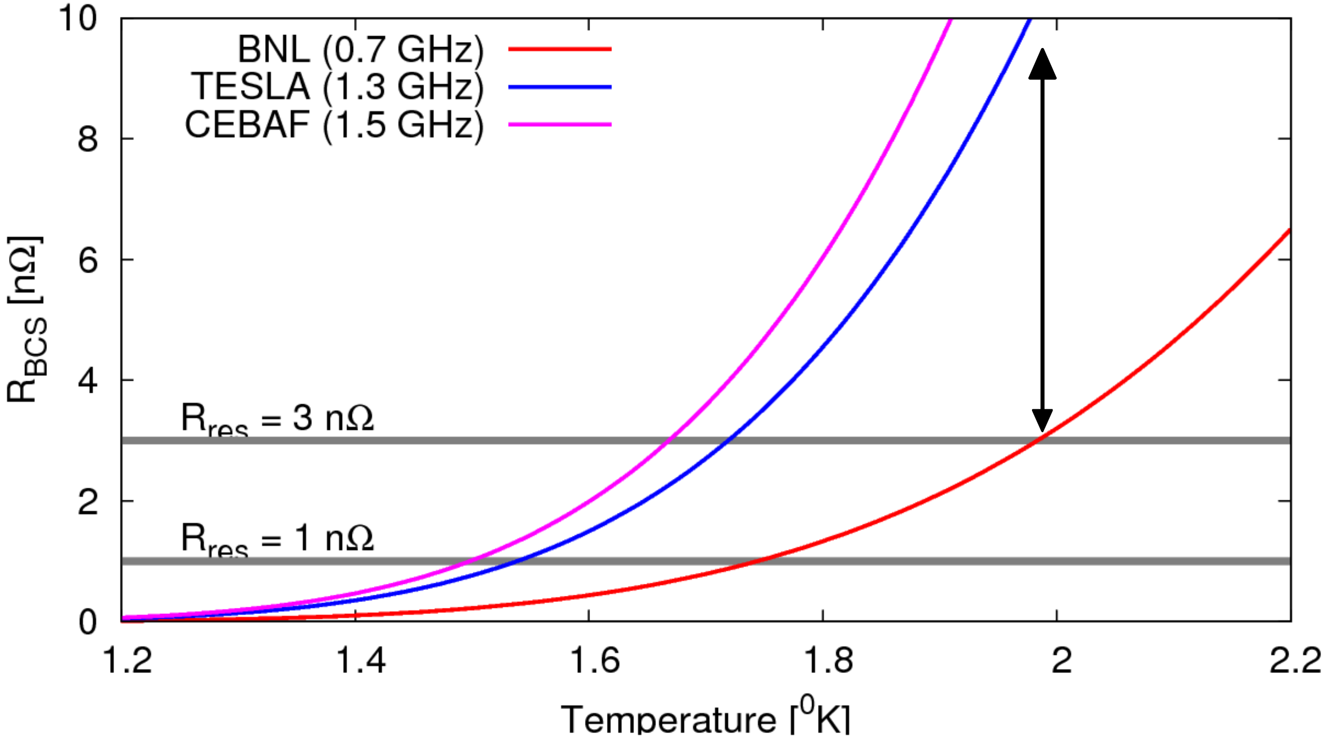
Frequency & cavity design

Higher order modes and extraction

Other relevant topics

†Note: This is a collection thoughts to stimulate discussion

Frequency Choice (0.5-1.5 GHz)



$$P_{avg} = \frac{R_s}{\frac{R}{Q} G}$$

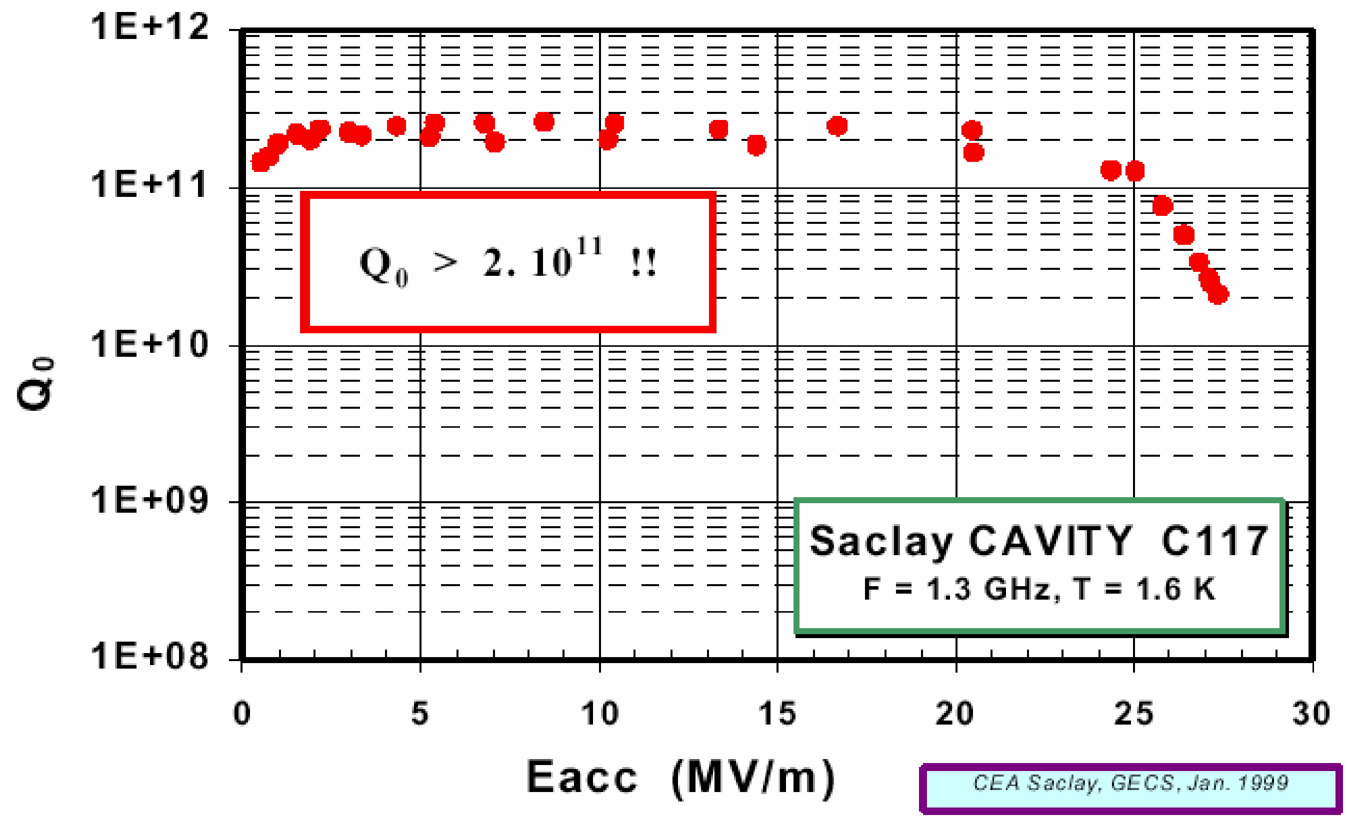
Surface resistance, R_s : $R_{BCS} + R_{residual} \rightarrow$ lower freq

$$R_{BCS} \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

Message: High Q, Medium Gradient

Saclay Cavity Example

H. Safa, SRF2001



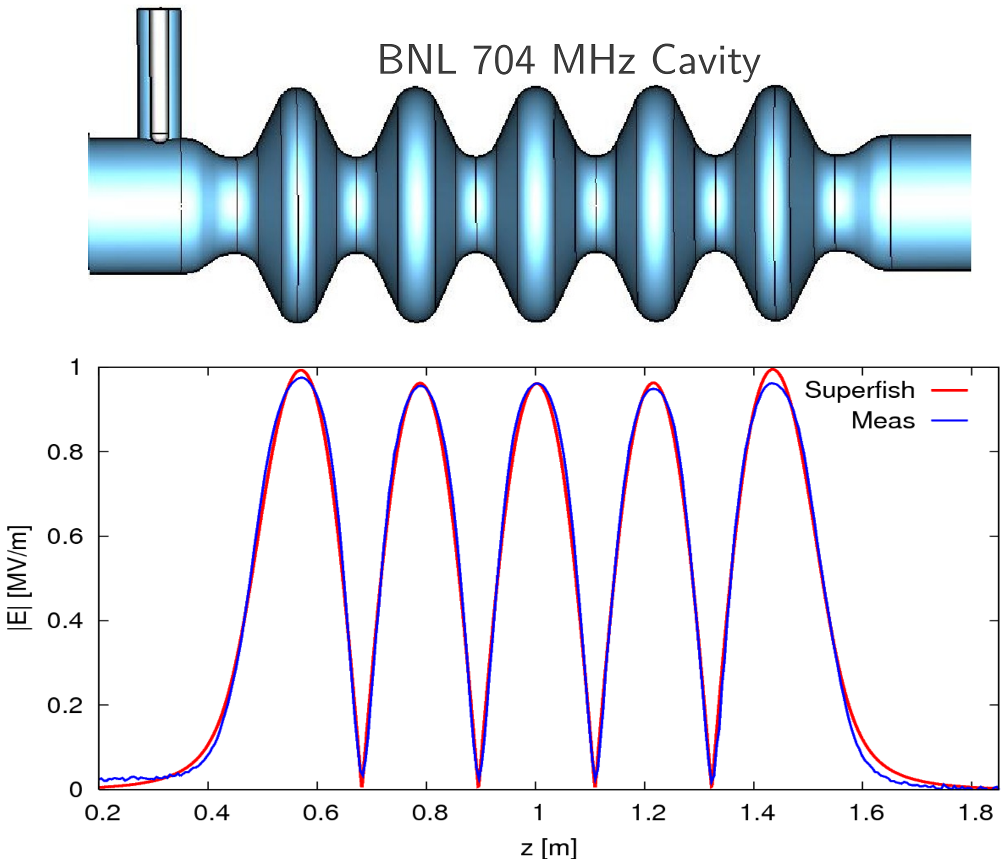
Rs ~ 0.5nΩ

High RRR + Special Chemistry

Aim $Q_0 = 1 \times 10^{11}$ at 2K (704 MHz)

Practice maybe difficult but careful preparation can pay off

Field Flatness Example



$$a = \frac{N^2}{k_{cc}}$$

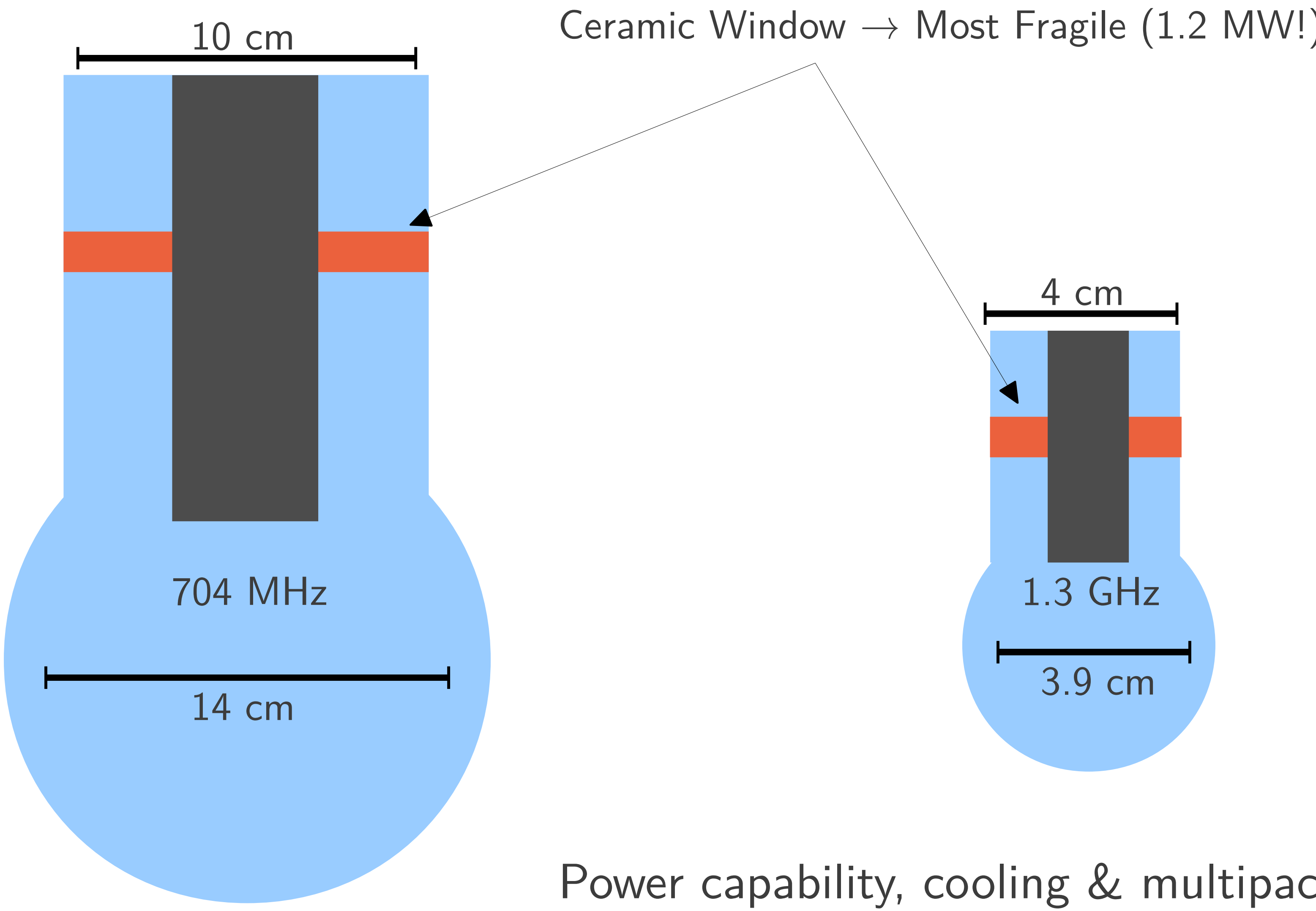
Number of cells

Cell-to-cell coupling

Field flatness to spec $\rightarrow$ Easier

Strong cell-to-cell coupling due to larger aperture

Power Coupler, No-brainer



Power capability, cooling & multipacting

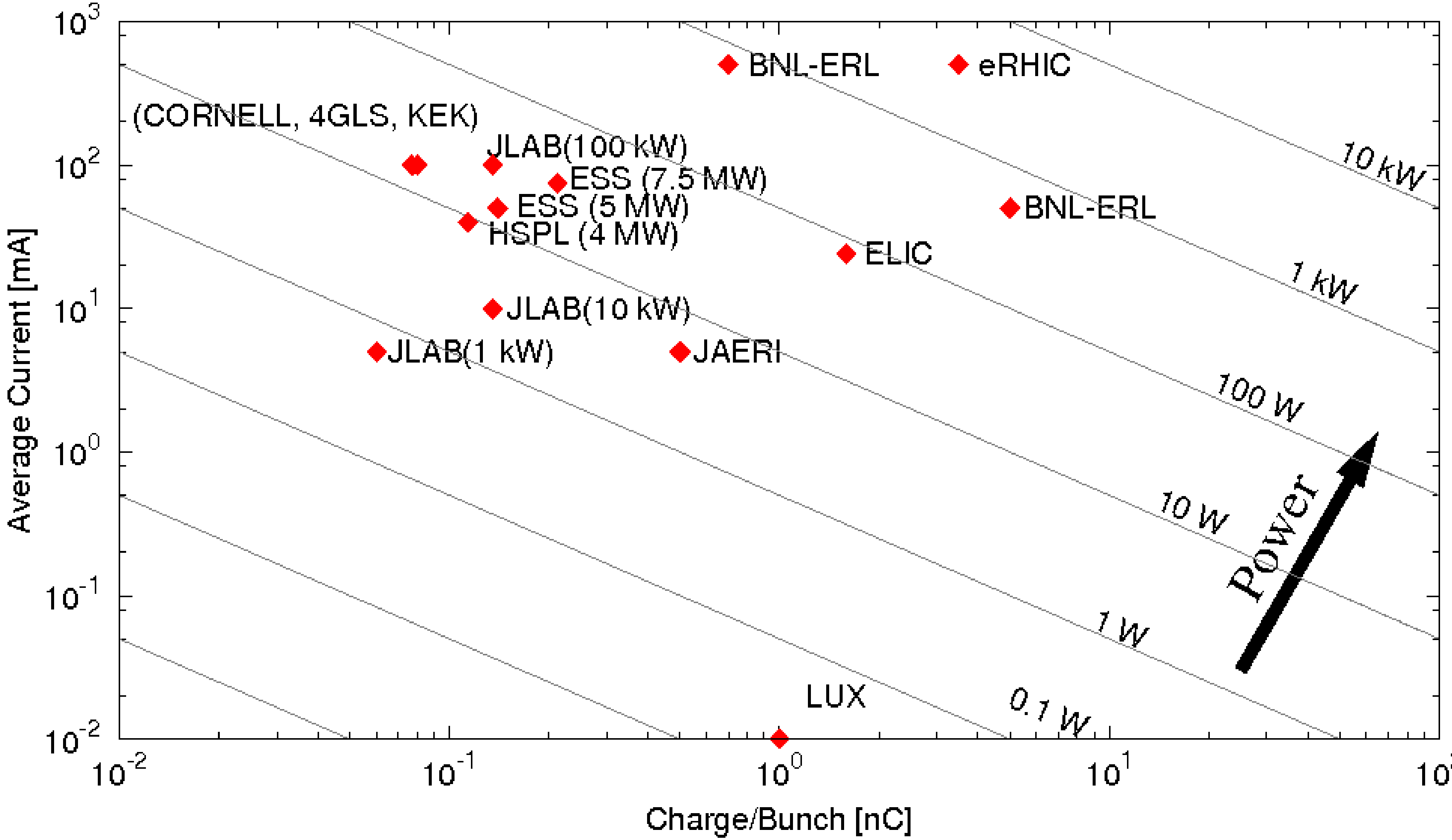
Power Coupler Operated, Pulsed

Table 2: Pulsed input couplers for superconducting cavities.

Facility	**Frequency**	**Coupler type**	**RF window**	Q_{ext}	**Max. power**	**Pulse length & rep. rate**
SNS	805 MHz	Coax fixed	Disk, coax	7×10^5	Test: 2 MW Oper: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Coax fixed	Disk, coax	5×10^5	Test: 2.2 MW 370 kW	0.6 msec, 25 Hz 3.0 msec, 25 Hz
FLASH	1300 MHz	Coax variable (FNAL)	Conical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 250 kW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH	1300 MHz	Coax variable (TTF-II)	Cylindrical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 1 MW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH / XFEL/ ILC	1300 MHz	Coax variable (TTF-III)	Cylindrical (cold and warm)	1×10^6 to 1×10^7	Test: 1.5 MW 1 MW Oper: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 Hz 1.3 msec, 10 Hz
KEK STF	1300 MHz	Coax fixed (baseline ILC cavity)	Disks, coax (cold and warm)	2×10^6	Test: 1.9 MW 1 MW	10 μsec, 5 Hz 1.5 msec, 5 Hz
KEK STF	1300 MHz	Coax fixed (low loss ILC cavity)	Disk (cold), cylindrical (warm)	2×10^6	Test: 2 MW 1 MW	1.5 msec, 3 Hz 1.5 msec, 5 Hz

Courtesy, S. Belomestnykh

HOM & Beam Power



$$P_{avg} = k_L Q_b I_a$$

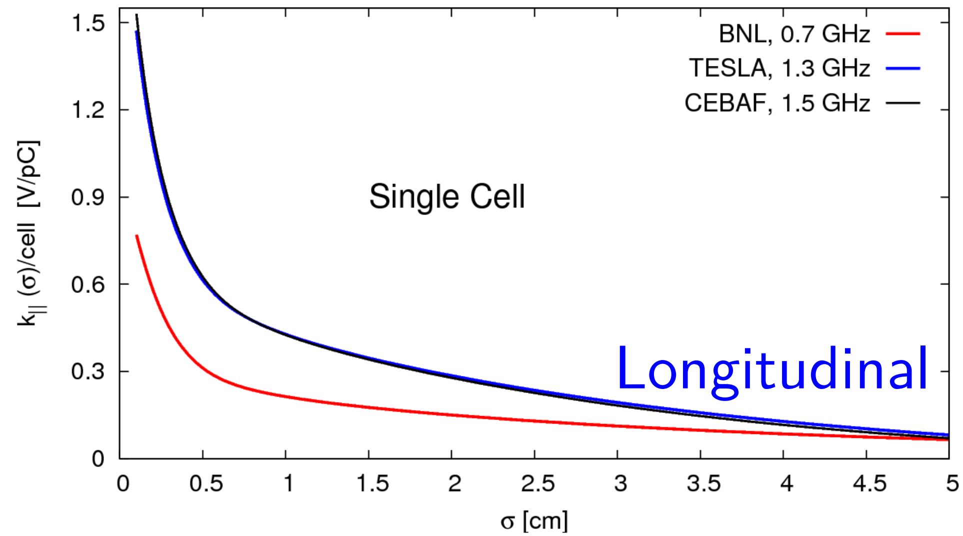
Power per 1 V/pC

Loss Factors, Single Cell

Longitudinal modes:

$$P_{ave} = (k_{loss} Q)\, I_{beam}$$

$$k_{(loss)} \propto \frac{1}{R_{(iris)}} \sqrt{(\frac{d}{\sigma_z})} \sqrt{(N_c)}$$

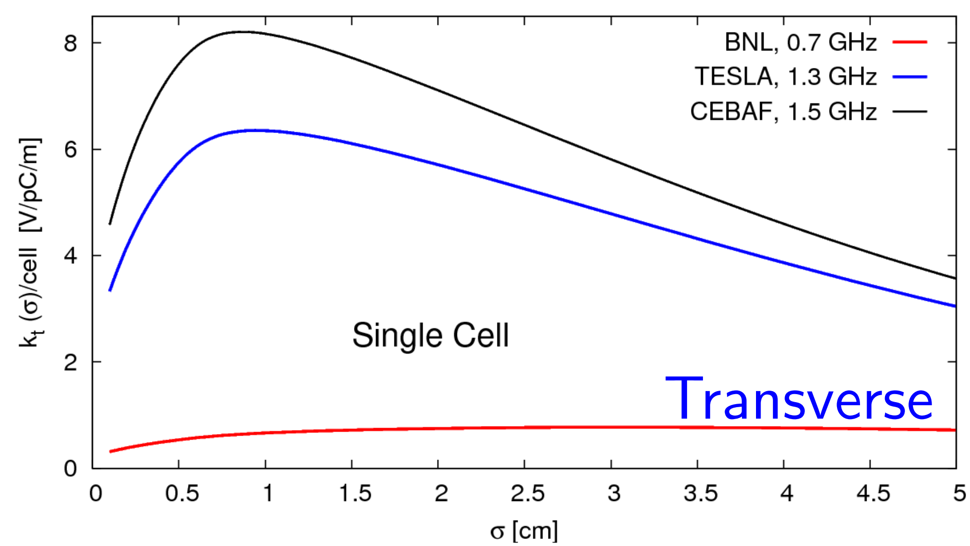


Limit, max power → 2K

Transverse modes:

$$\delta \epsilon \propto k_{trans} Q$$

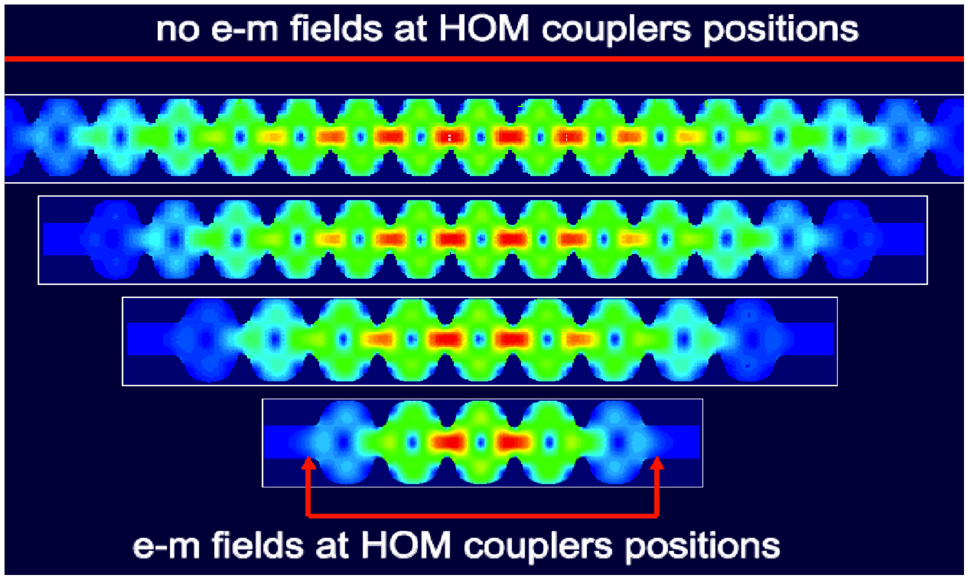
$$k_{(trans)} \propto \frac{1}{R_{iris}^3} \sqrt{d\, \sigma_z N_c}$$



Limit, max current → instabilities

N-Cells & End Cells

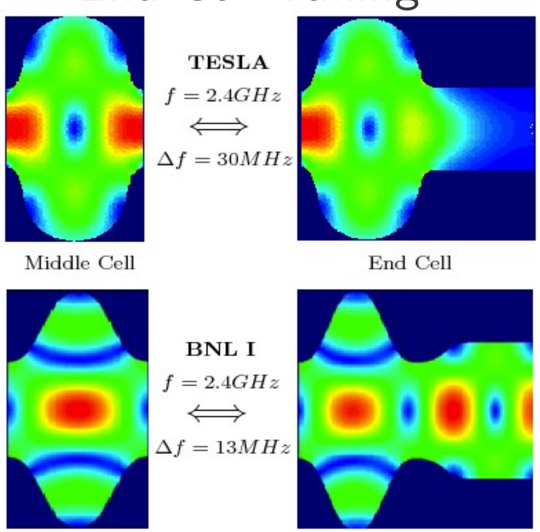
Graphic courtesy, J. Sekutowicz



HOMs: End-cells “non-resonant” or have negligible fields

TRAPPED MODE

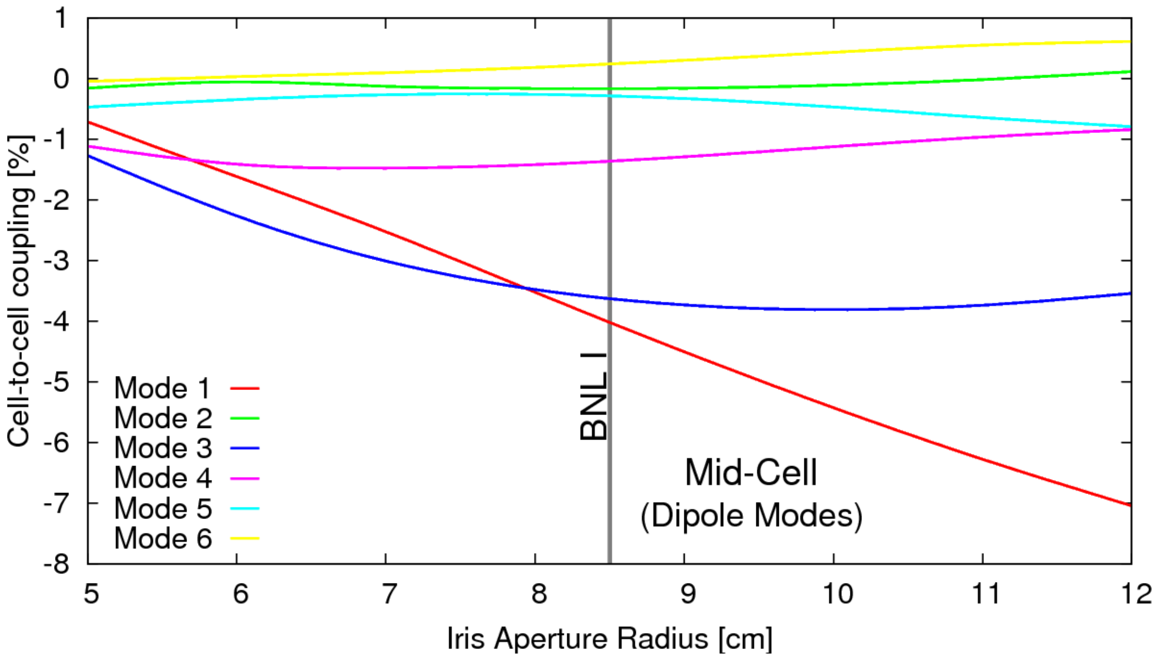
End Cell Tuning



Design Stage:

- Field enhancement as a result of freq tuning & additional entities on beam pipe
- HOM frequencies differ significantly between mid & end cells due to large variations

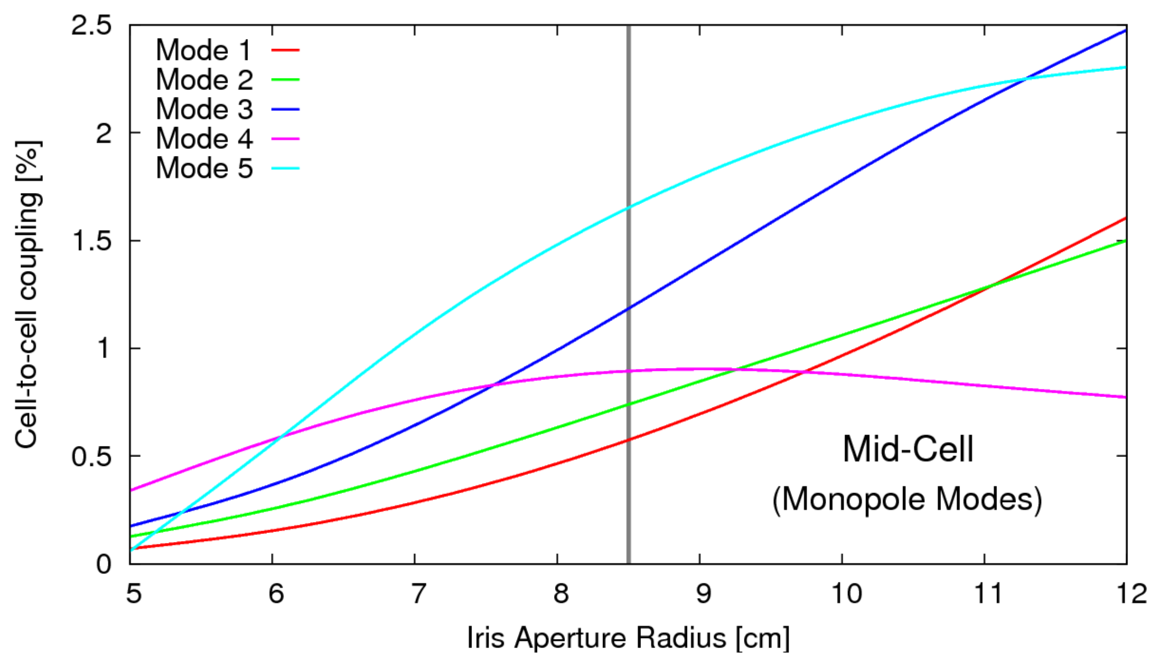
Cell-to-Cell Coupling, HOMs



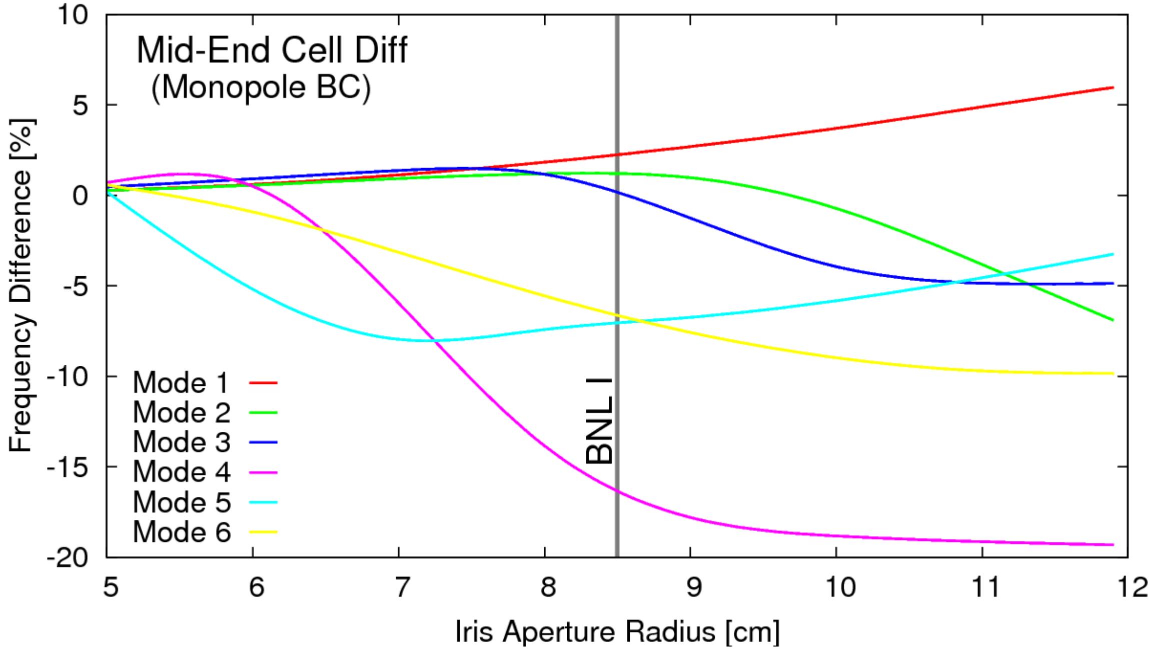
Fundamental mode ~ 4.5%

Increase aperture to increase field at the end cells for damping

Aperture > 7cm seems reasonable, but criteria complex to meet all HOMs



Frequency Difference, HOMs

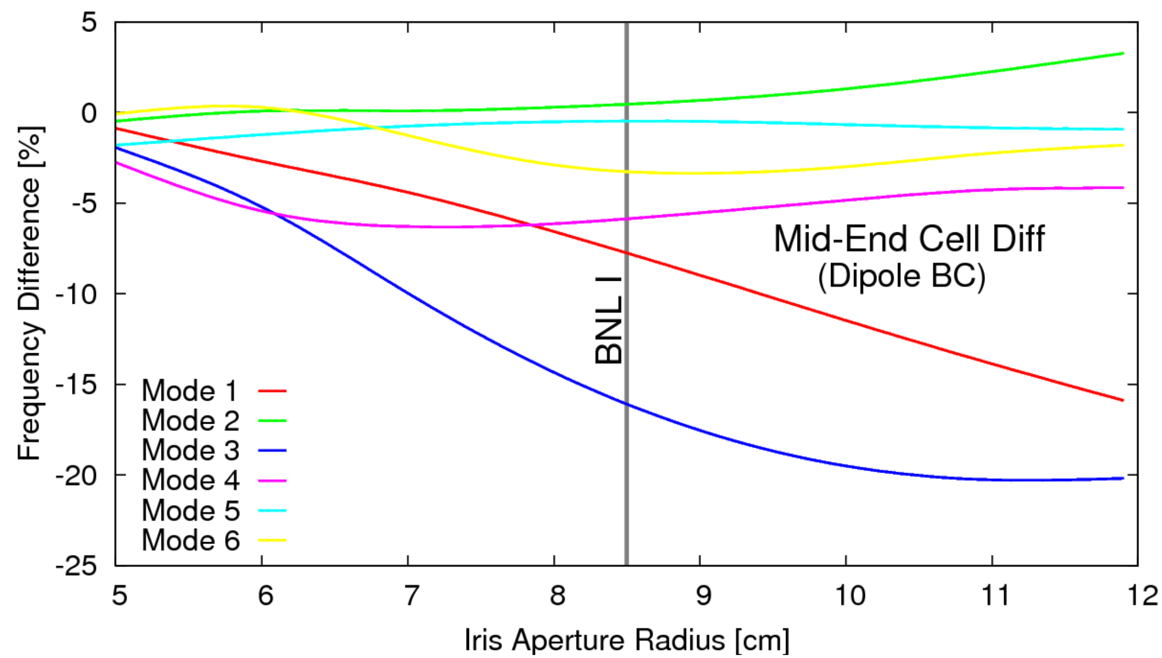


Reduce freq difference to avoid trapped modes

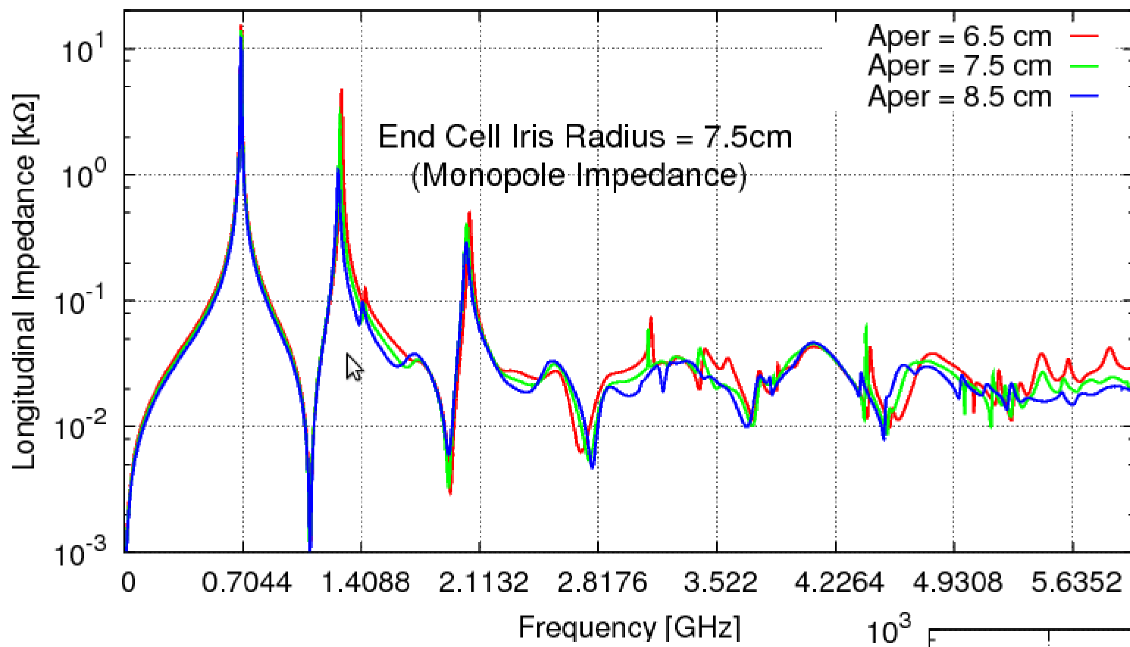
Unavoidable, but minimize

Reduce aper, but not <7 cm

1% @1GHz ~ 10 MHz

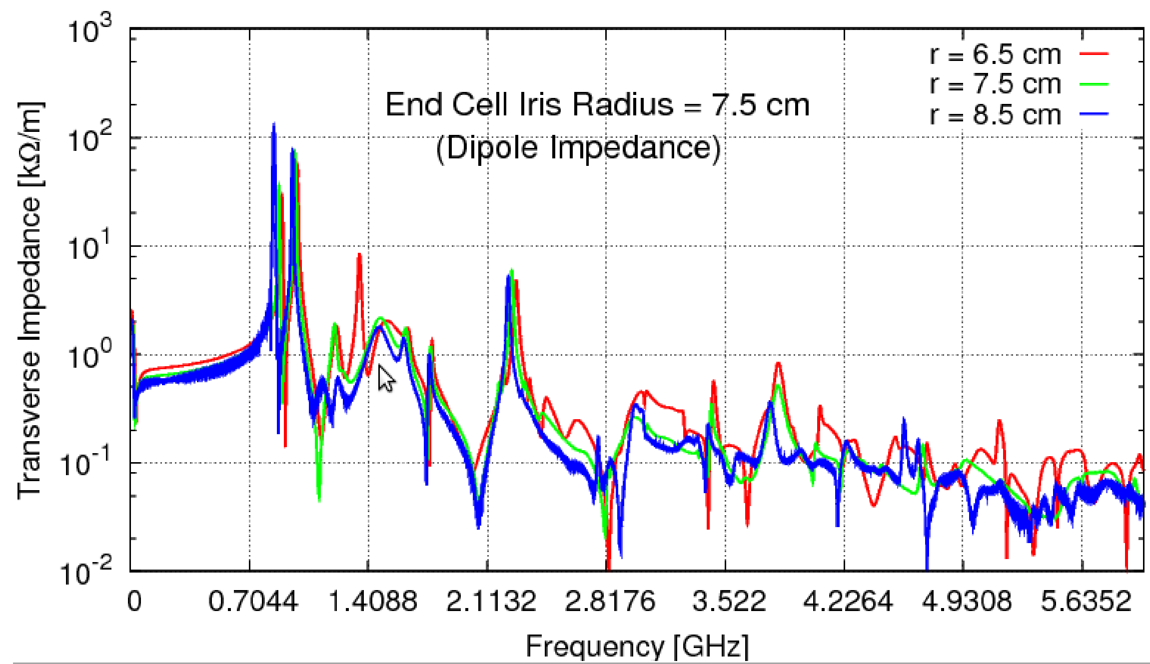


Overlap on Harmonics, HOMs



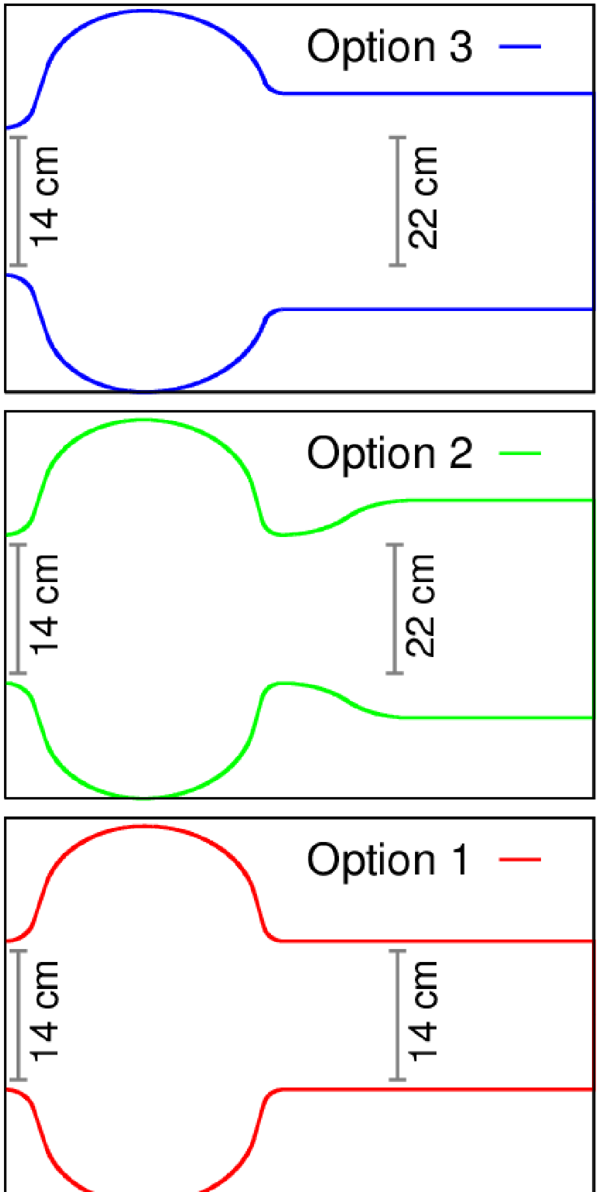
Beam structure may have many more sub-harmonics

Avoid obvious overlap with primary harmonics



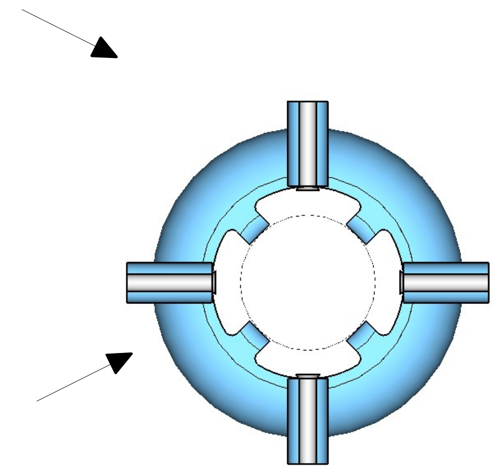
End-Cell Options

Use beam-pipe as a conduit to transmit HOMs to a load



High end-cell asymmetry

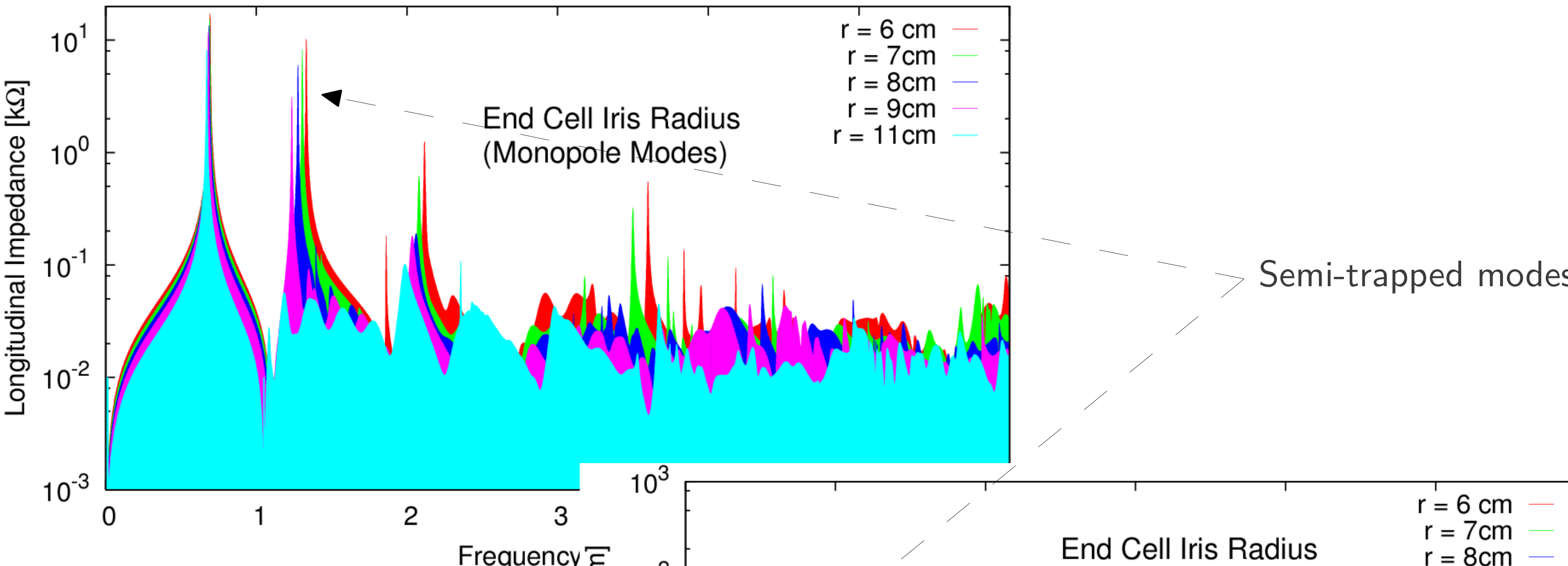
Less end-cell asymmetry

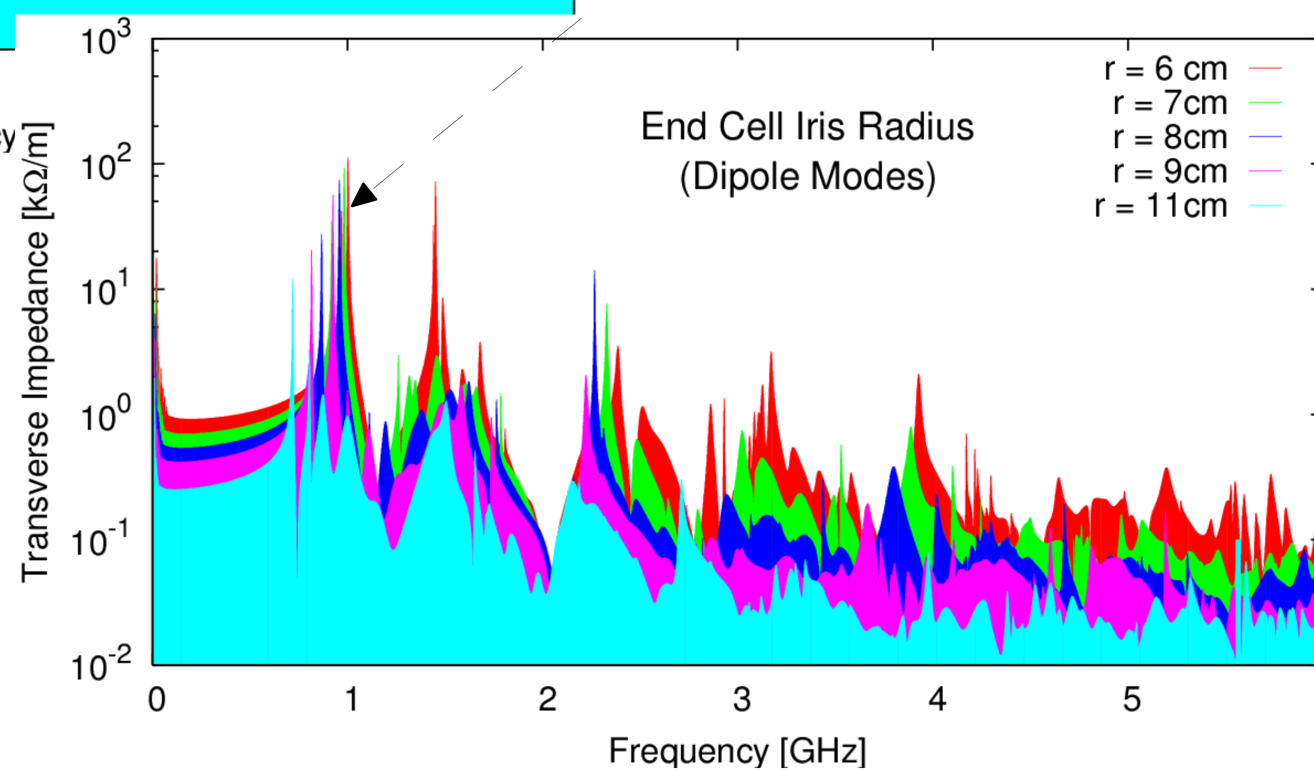


Ridged Waveguide

Notch filters maybe required (many modes are below cut-off)

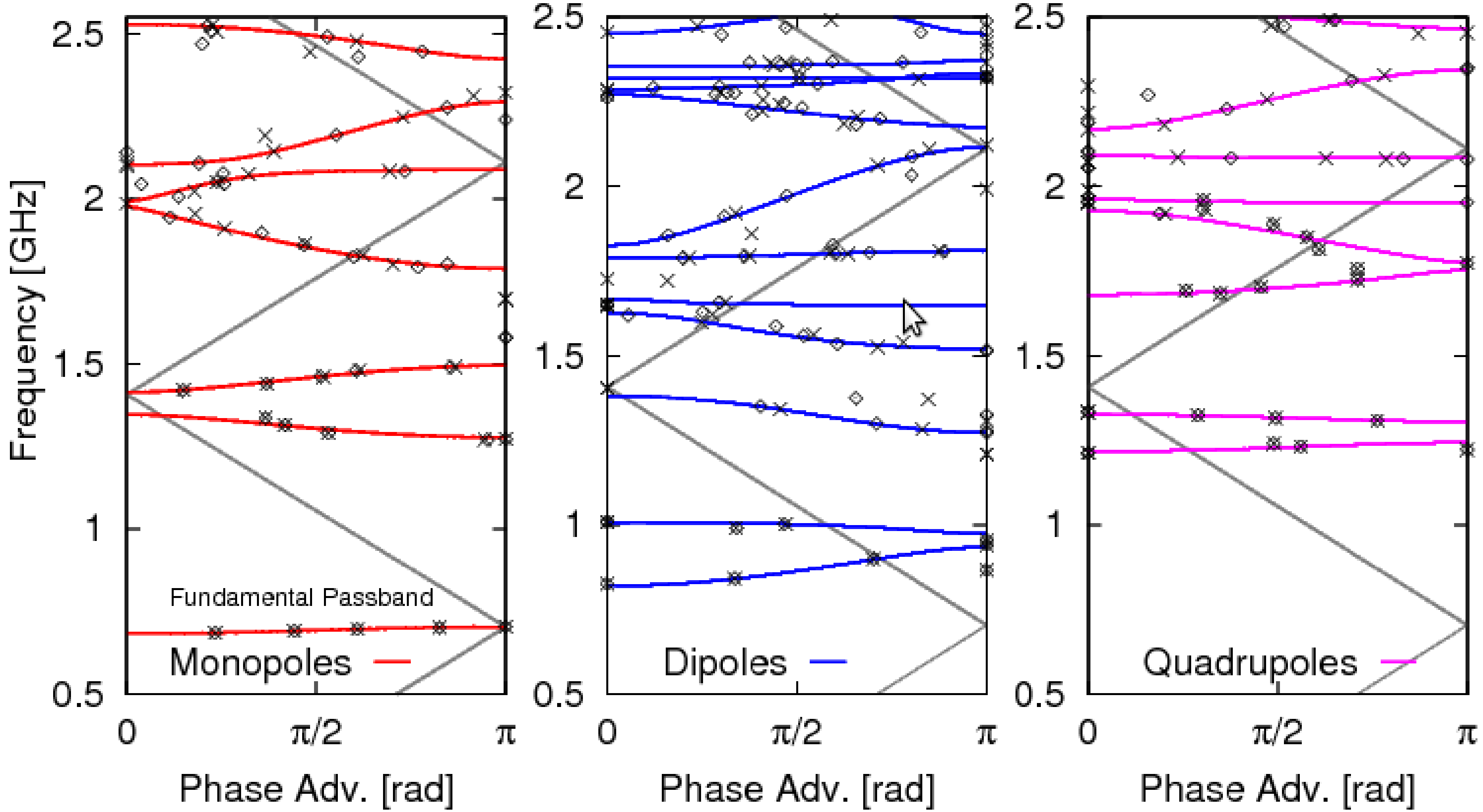
End-Cell Optimization





Always have a select few modes to damp with HOM couplers close to the cavity

Dispersion Curves



Modes with phase velocity = βc are strongly excited (also high R/Q)

Message: no magic escape route

HOM Passbands, 0.7 GHz

Monopoles

Mode	Freq [GHz]		Freq [GHz]		R/Q	$\mathcal{K}_{mid}$	$\mathcal{K}_{end}$	Δf
	E	B	E	B	[Ω]	[%]	[%]	[kHz]
1	0.683	0.704	0.694	0.704	169.7	3.0	1.4	1.1
2	1.277	1.346	1.264	1.295	105.2	5.3	2.4	1.3
3	1.415	1.496	1.438	1.486	0.2	5.6	3.3	2.3
4	1.788	1.991	1.831	1.801	23.7	10.7	1.7	4.3
5	1.978	2.088	1.992	2.027	106.3	5.4	1.7	1.4
6	2.105	2.293	2.103	2.279	3.9	8.6	8.0	0.2
7	2.425	2.616	2.349	2.542	36.8	7.6	7.9	7.6
8	2.528	2.645	2.497	2.613	3.3	4.5	4.5	3.1
9	2.710	-	2.616	2.751	24.6	-	5.0	9.4
10	2.801	-	2.736	2.946	0.9	-	7.4	6.5

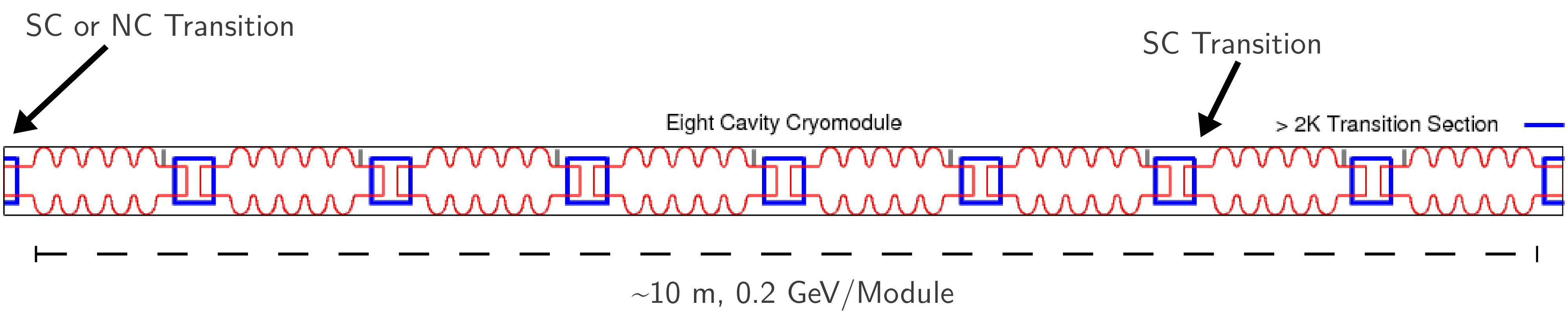
Dipoles

Mode	Freq [GHz]		Freq [GHz]		R/Q	$\mathcal{K}_{mid}$	$\mathcal{K}_{end}$	Δf
	E	B	E	B	[Ω]	[%]	[%]	[kHz]
1	0.975	0.820	0.914	0.839	4.87	17.3	8.6	6.1
2	1.008	0.935	1.011	0.969	29.8	7.5	4.2	0.3
3	1.520	1.272	1.531	1.324	19.7	17.8	14.5	1.1
4	1.649	1.382	1.642	1.497	0.4	17.6	9.2	0.7
5	1.667	1.626	1.743	1.625	2.3	2.5	7.0	7.6
6	1.788	1.809	1.804	1.806	3.0	1.2	0.1	1.6
7	2.175	1.825	2.215	2.055	0.1	17.5	7.5	4.0
8	2.284	2.115	2.256	2.237	2.2	7.7	0.9	2.8
9	2.318	2.273	2.275	2.277	2.7	2.0	0.1	4.3
10	2.334	2.320	-	-	0.04	0.6	-	-
11	2.374	2.355	2.366	2.335	0.05	0.8	1.3	0.8
12	2.452	2.450	2.455	2.364	9.0	0.1	3.8	0.3
13	2.761	2.615	2.789	2.712	17.4	5.4	2.8	2.8
14	2.863	2.830	2.860	2.859	0.07	1.2	0.04	0.3
15	2.892	2.868	2.879	2.879	0.01	0.8	0.0	1.3

Quadrupoles

Mode	Freq [GHz]		Freq [GHz]		R/Q	$\mathcal{K}_{mid}$	$\mathcal{K}_{end}$	Δf
	E	B	E	B	[Ω]	[%]	[%]	[kHz]
1	1.243	1.216	1.219	1.207	0.37	2.2	1.0	2.4
2	1.326	1.304	1.338	1.326	0.36	1.7	0.9	1.2
3	1.775	1.680	1.736	1.687	0.6	5.5	2.9	3.9
4	1.952	1.752	1.877	1.786	0.006	10.8	5.0	7.5
5	1.962	1.928	1.949	1.928	0.22	1.8	1.1	1.3
6	2.092	2.084	2.071	2.071	0.24	0.4	0.0	2.1
7	2.467	2.169	2.474	2.225	0.14	12.9	10.6	0.7
8	2.521	2.343	2.495	2.361	0.03	7.3	5.5	2.6
9	2.585	2.577	2.544	2.534	0.02	0.3	0.4	4.1
10	2.655	2.700	2.608	2.653	-	1.7	1.7	4.7
11	2.711	2.710	2.706	2.706	0.002	0.04	0.0	0.5
12	2.807	3.085	2.799	2.834	0.007	9.4	1.2	0.8

Cryomodule Boundary Conditions

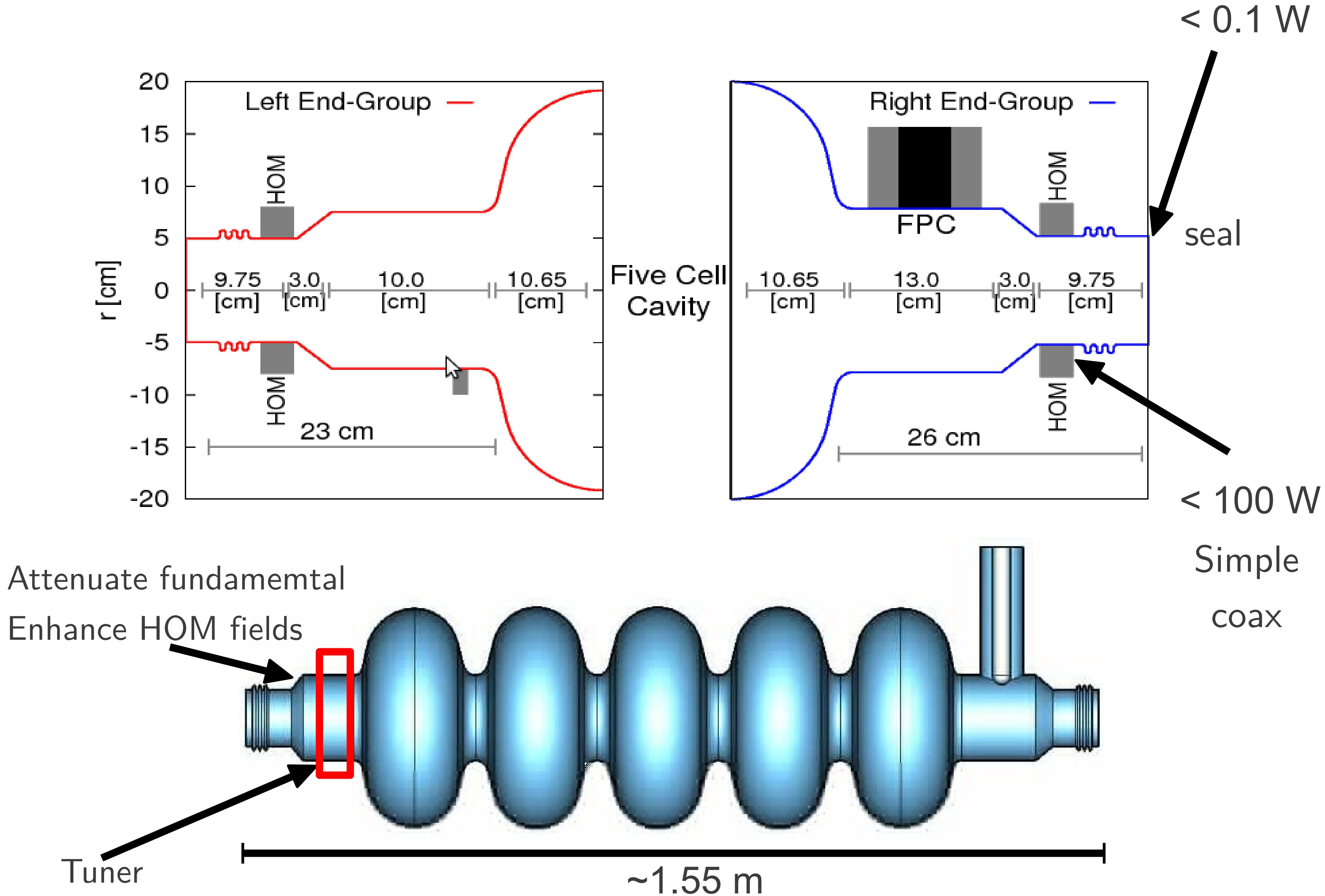


Continuous accelerating channel (4-8 Cavities/Cryomodule)

Optimum way to transition between cavities

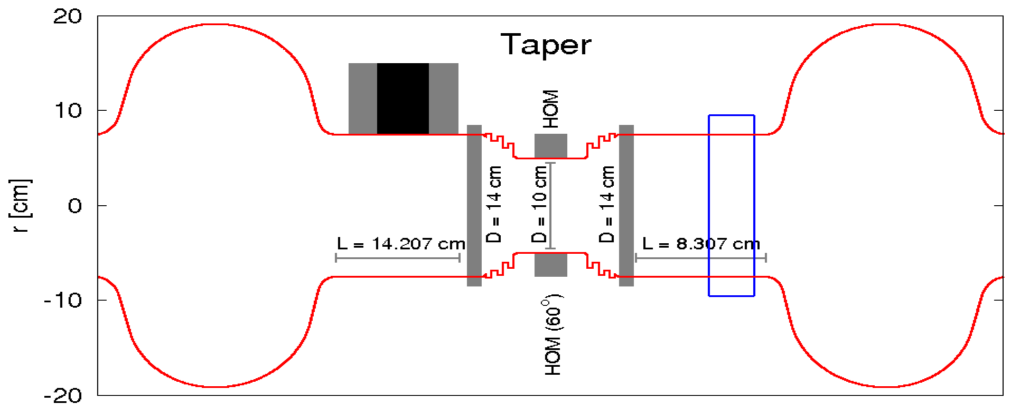
- Compact :Minimize length & SC→NC
- But reduce cross talk & HOM power to 2K

Transition Section



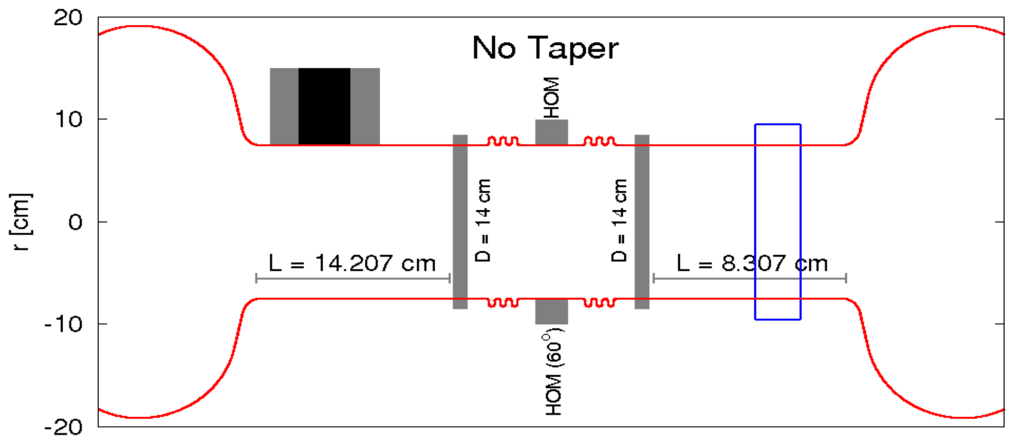
Sample Transitions

Design bellows as ¼-filters for specific dangerous HOMs ?

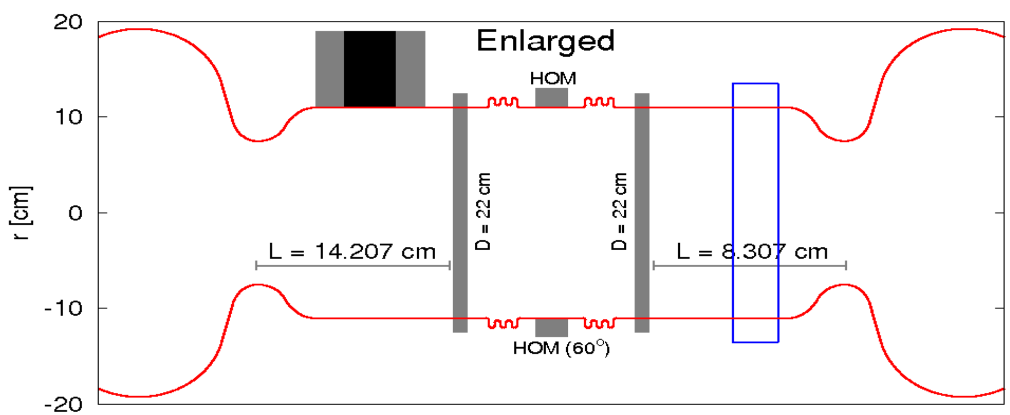


R=7.5cm → 5.0 cm: Taper

Motivation → reduce cross talk

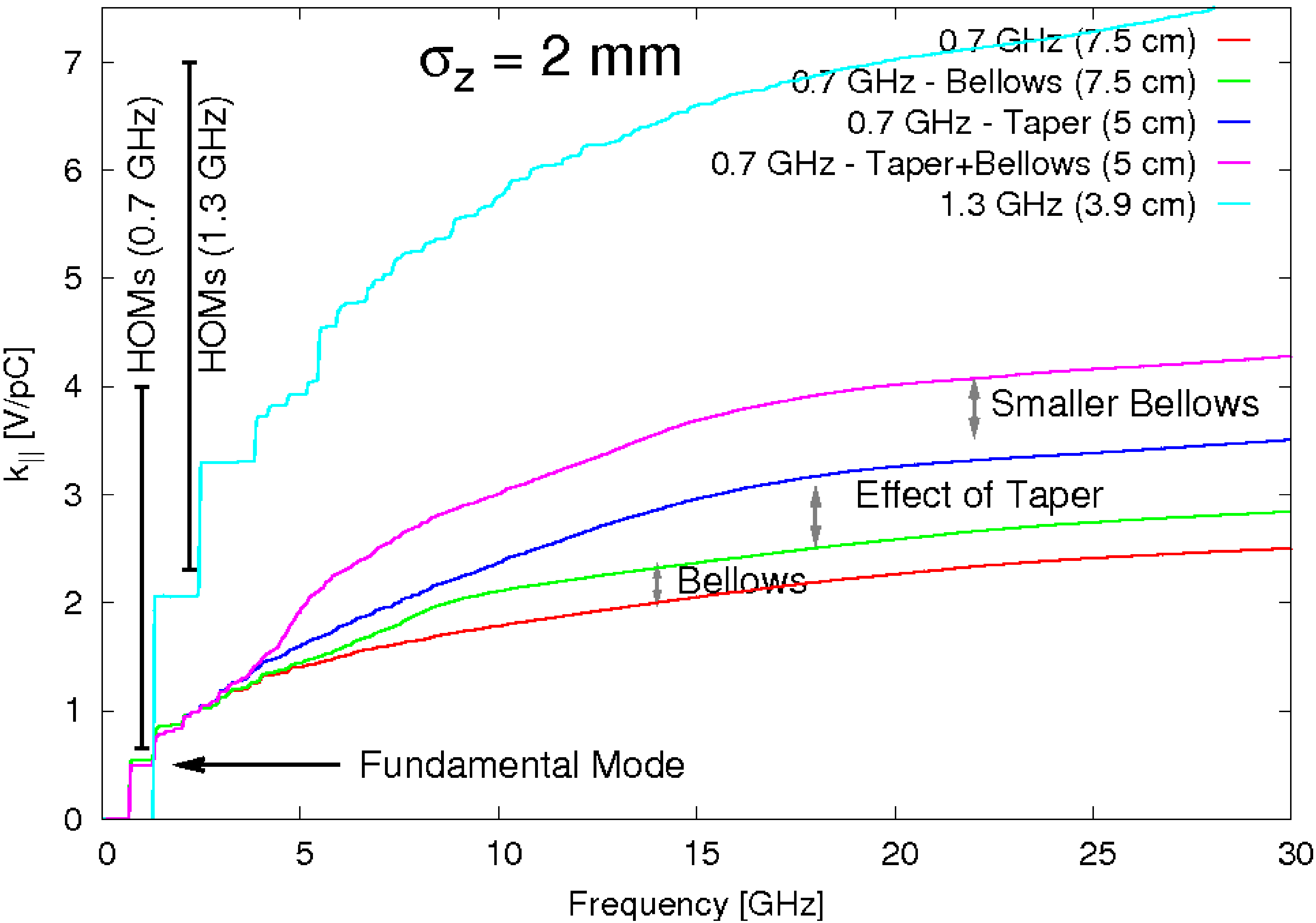


R=7.5 cm: Smooth transition



R=7.5 cm → 11 cm (eRHIC type)

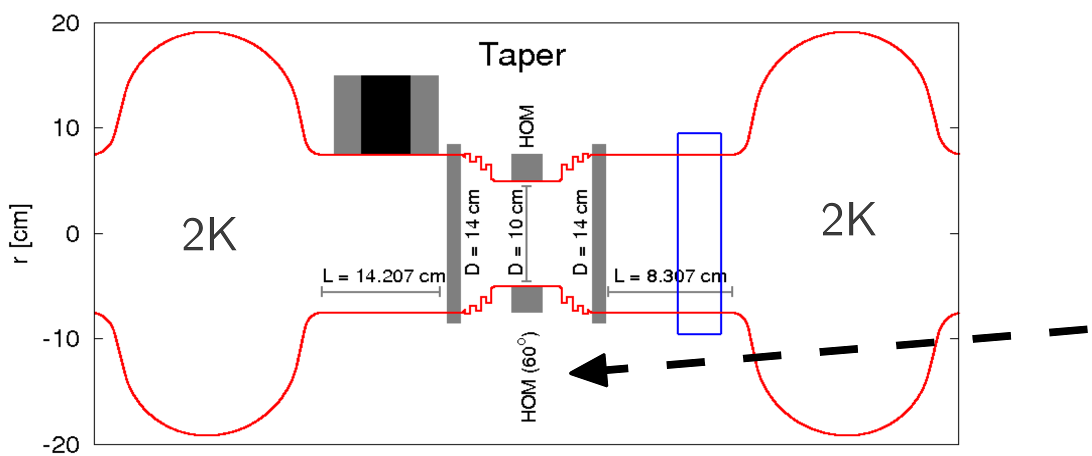
Loss Factors, Cavity



Long & Trans Loss Factors

5 MW, 50 mA

Frequency	k_L (V/pC)	k_T (V/pC/m)	HOM Power
Cavity	3.0	2.81	17.5 W
Cavity + Taper	4.03	6.47	24.5 W
Cavity +Taper+Bellows	4.6	7.44	28.7 W



28.7 W $\rightarrow$ 5.74 kW per pulse

(4.2 K $\rightarrow$ Wall plug power ~200)

Extract at higher temp with HOM couplers as shown.

Message: Avoid tapers if not needed

LINAC Impedance

Energy Spread:

$$\frac{\delta E}{E} = \frac{k_L Q_b}{E_{gain}}$$

End of LINAC: 6.5 x 10^{-3} (assuming 200 cavities, 0.7 GHz)

Emittance growth:

$$\delta p = \frac{q}{\beta c} W_T(\tau)$$

$$W(\tau) \propto \frac{Z_T}{2Q} \sin(\omega \tau) e^{-\omega \tau / 2Q}$$

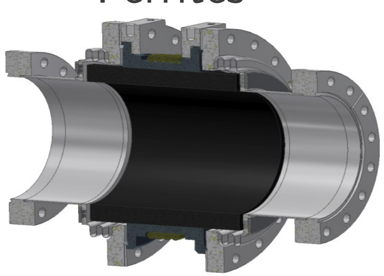
$$(\Delta \gamma \epsilon) \propto (Q_b \sigma_z W_T)^2$$

Single bunch & multi-bunch instabilities $\rightarrow$ damping threshold (M. Schuh)

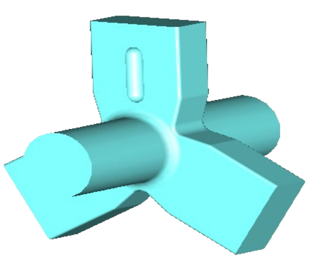
HOM Extraction

- Ferrite Absorbers
  - Broadband but dirty for SRF
- Notch Filters
  - Narrow-band and sensitive (“less robust”)
- Waveguides
  - Bulky @704 and can get expensive (fabrication + thermal losses)

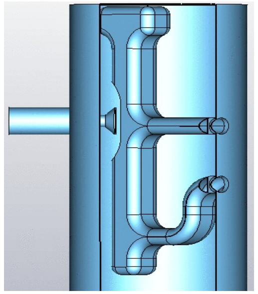
Ferrites



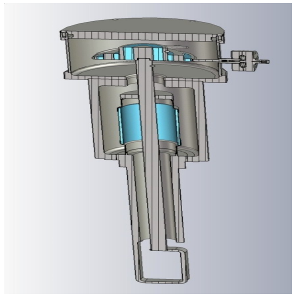
Waveguides



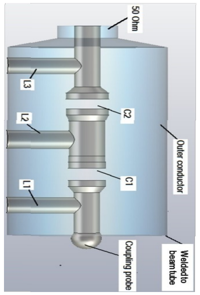
Notch filters



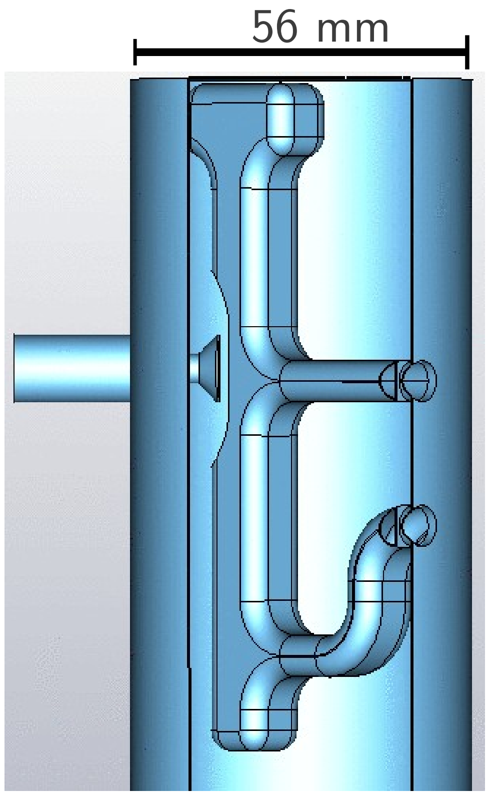
Band-Pass



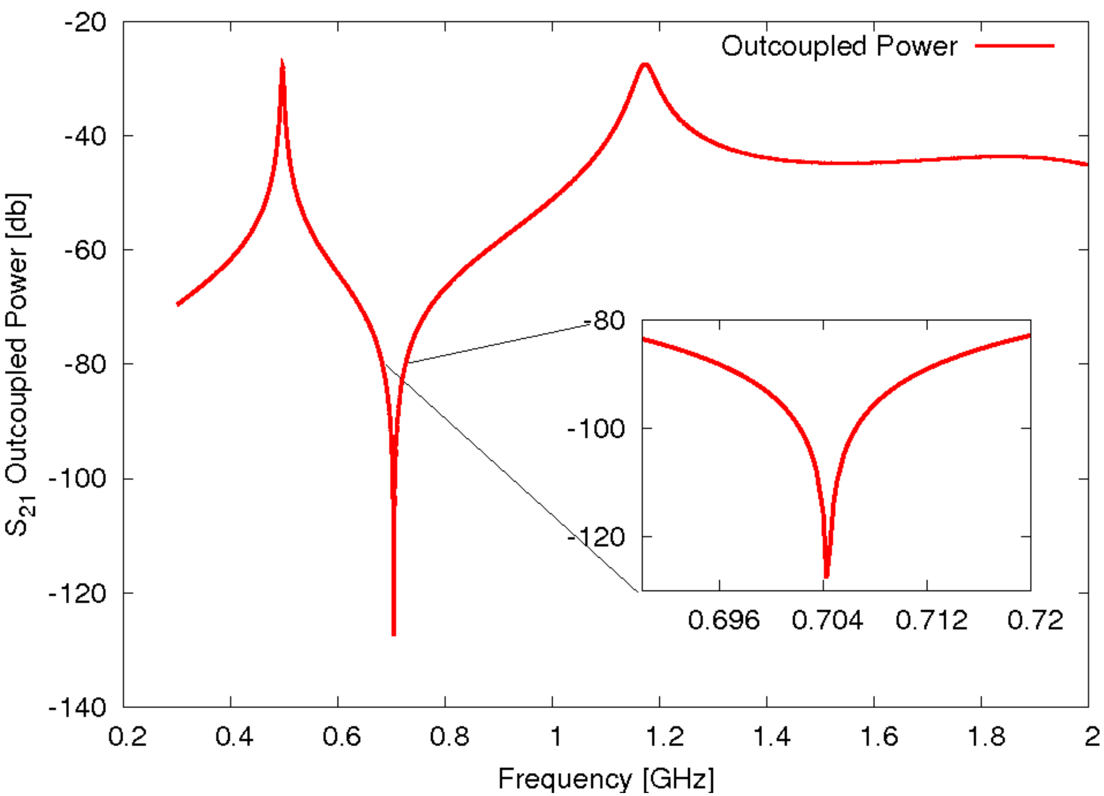
Double-Notch



ILC Type Filter @704 MHz

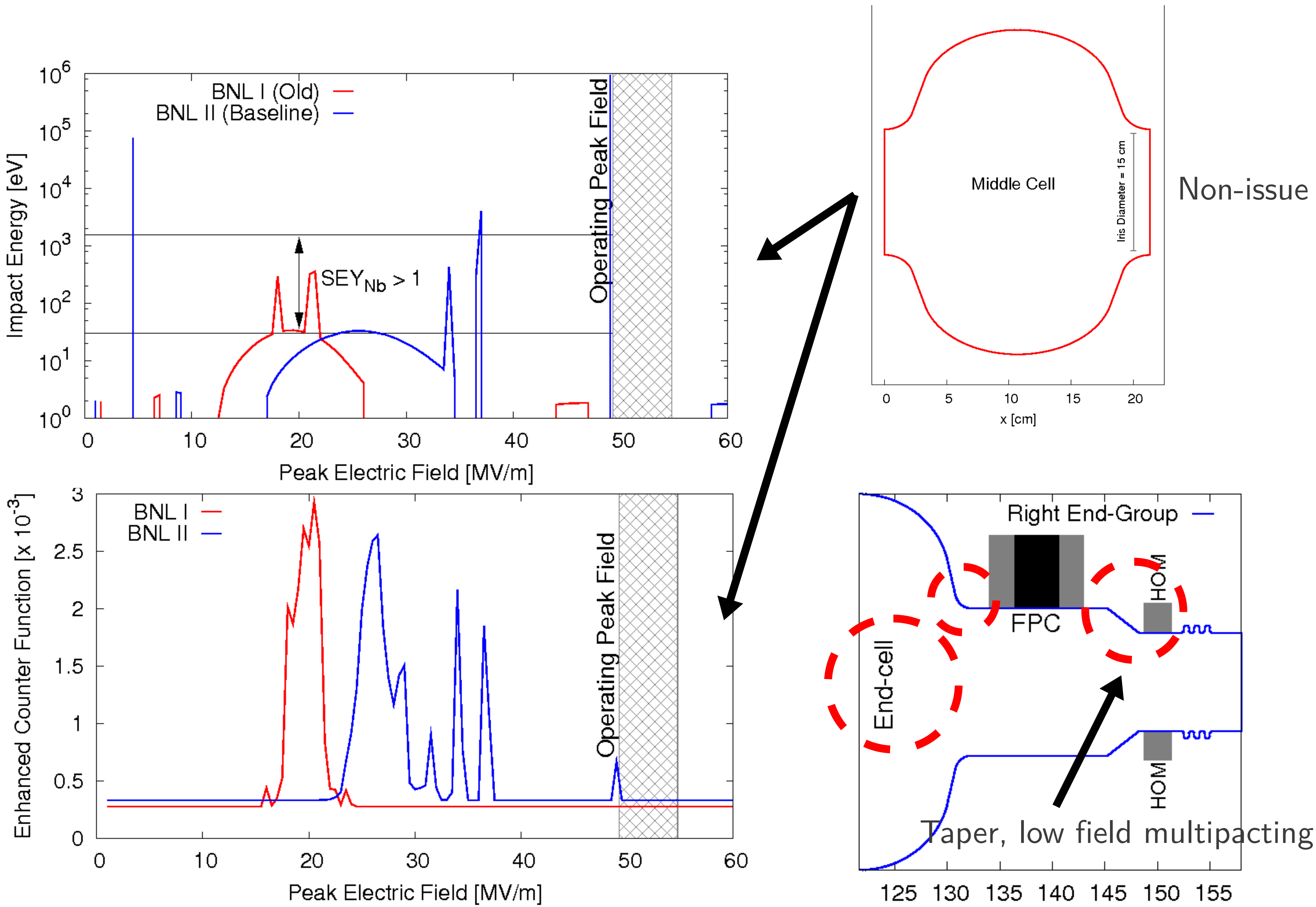


Transversely shrinked for compactness

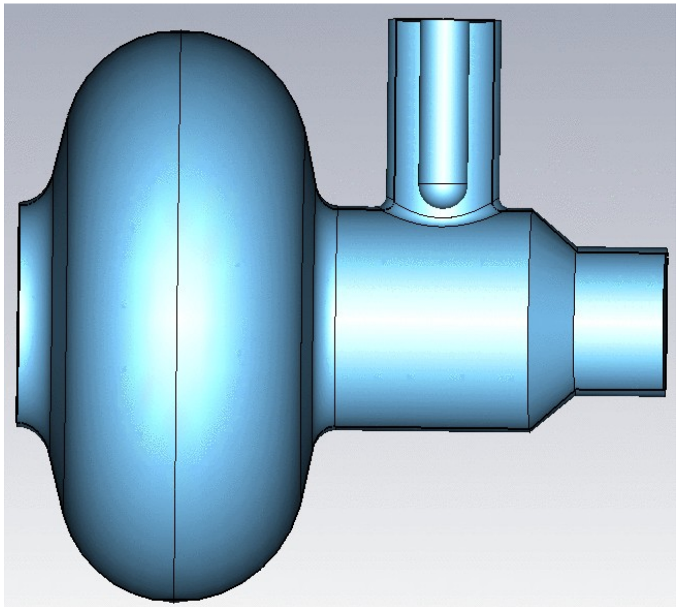


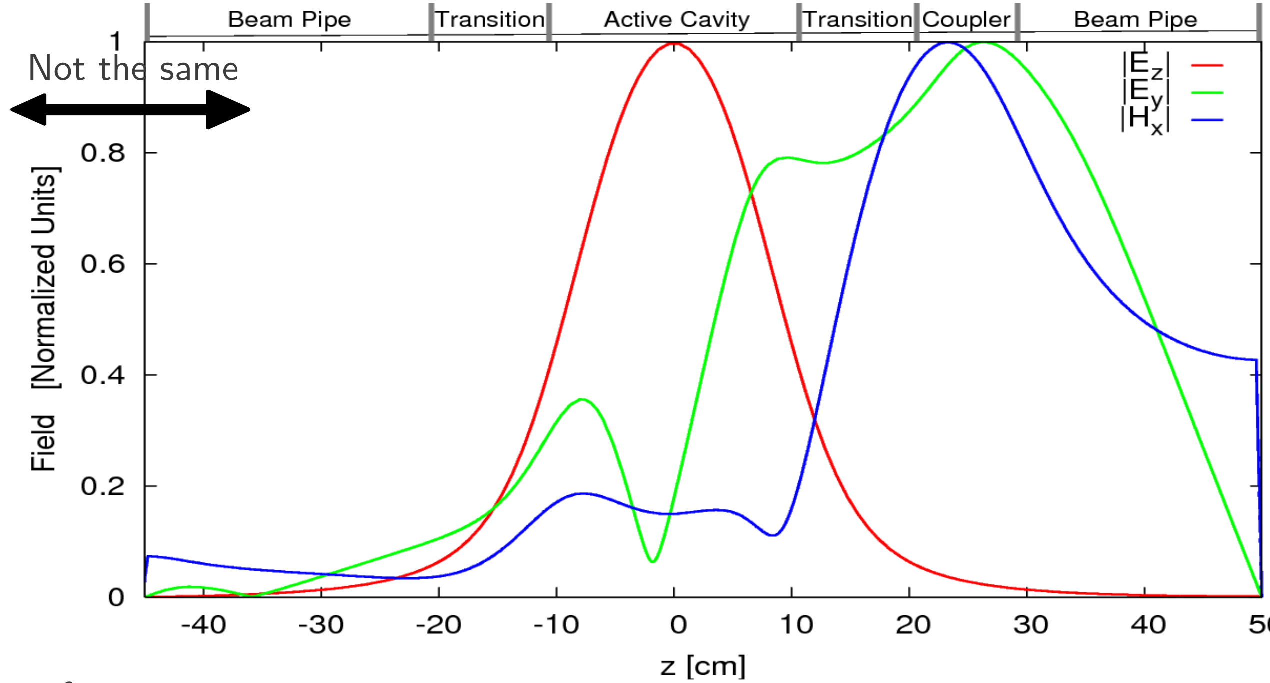
Multipacting → See R. Ainsworth

Cavity Multipacting



Coupler Kicks





Kick = $(0.72 + i0.28)$ x10^{-3}, $Q_{ext}=1\text{x}10^{6}$

- Input coupler introduces asymmetry & time dependent kick
  - Dip, quad and higher order kicks at fundamental frequency
  - Alternating coupler orientations “may” help, but $\beta \neq 1$
- These fields should be studied for orbit, emittance and halo issues
  - Dual couplers or symmetrizing stubs may alleviate this

Some Conclusions

- Frequency & cavity design
  - Medium gradient, high power & high Q
  - Larger apertures better for field flatness robust against perturbations
- Higher order modes
  - $\beta \neq 1$ HOM spectrum is more tricky, damping maybe unavoidable
  - Design of transition section vital for beam losses
  - Careful HOM couplers design & placement needed
- Additional aspects
  - End-cell region gets complicated and often the weak point
  - Higher order harmonics at fundamental freq should be studied
  - Prototype Cu models to test damping concepts