LHC CRAB CAVITY WITH REDUCED OUTER DIAMETER

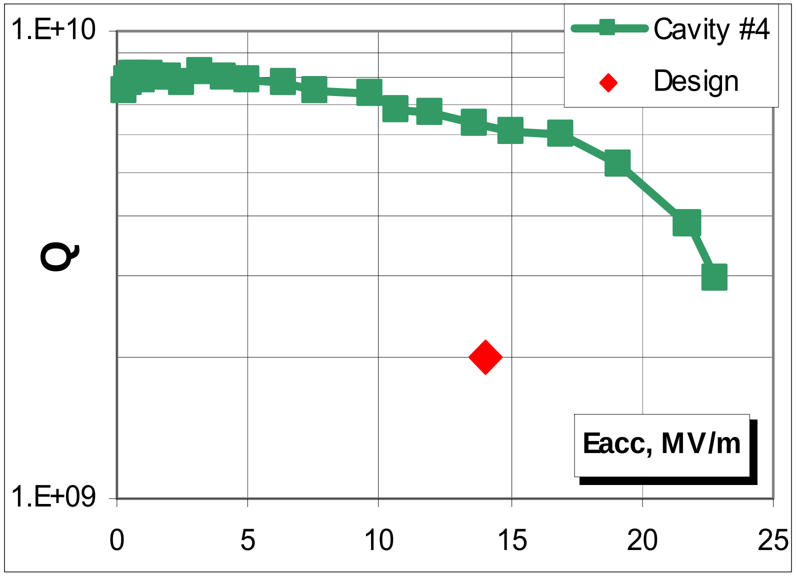
I. Gonin, N. Solyak, and V. Yakovlev
FNAL

LHC CC08 meeting, BNL, Feb. 25-26, 2008

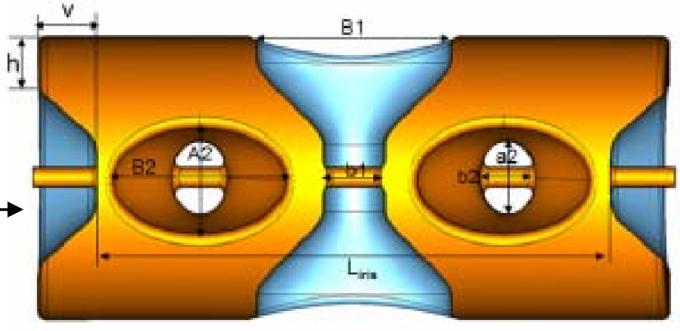
FNAL SRF infrastructure

FNAL SRF Projects:

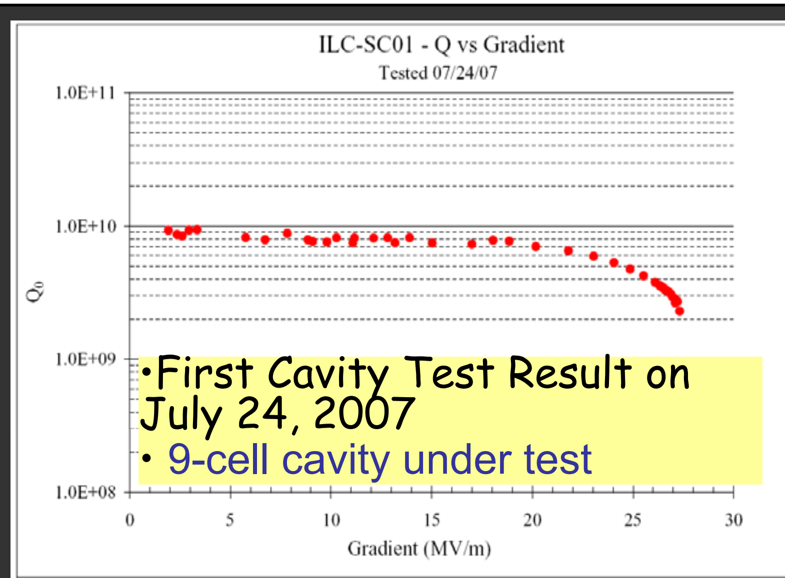
- CKM – 3.9 GHz deflecting cavity
  - -13 cells; 5MV/m (reached ~7.5 MV/m)
- 3.9 GHz accelerating cavity (3rd harm)
  - -9-cells, 8 cavities built
  - -Eacc=25MV/m; Epk=60 MV/m; Bpk~120mT
- 1.3 GHz ILC (TESLA) cavity
- 1.3 GHz beta=0.81 cavity design
  - -built, tested by MSU
- 325 MHz spoke cavity
  - -2 cavity built, under test
- Couplers, HOM couplers, tur
- Cryomodule (CM1, CM-3rd ha



Spoke 325 MHz



Cavity Vertical Test Stand



- First Cavity Test Result on July 24, 2007
- 9-cell cavity under test

- VTS-1 Upgrades:
  - Vacuum pumping
  - Variable coupler
  - Two cavity operation
  - T-mapping
- To increase capacity of the VTS
  - Add 2 more VTS pits (~200test/yr)
  - Upgrade cryogenic 125W→300W

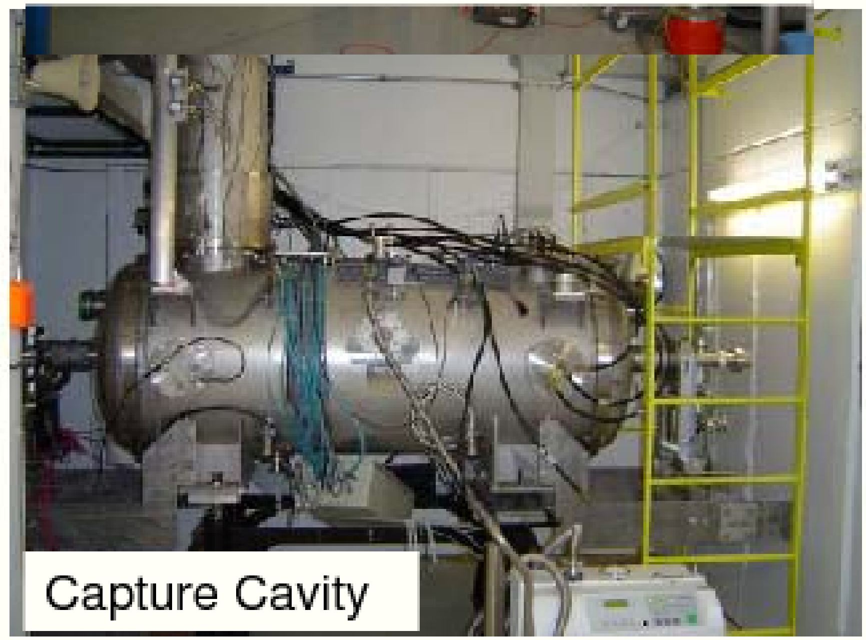
Cavity Testing Infrastructure

Fermilab

RF Power for HTS

Cryogenics for HTS ready at 2 K

Cryogenics for HTS getting ready for 2 K

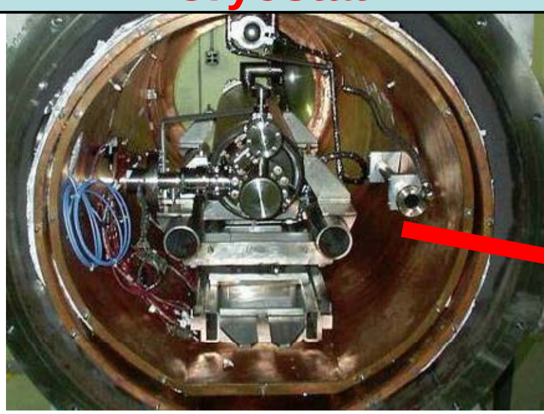


Capture Cavity

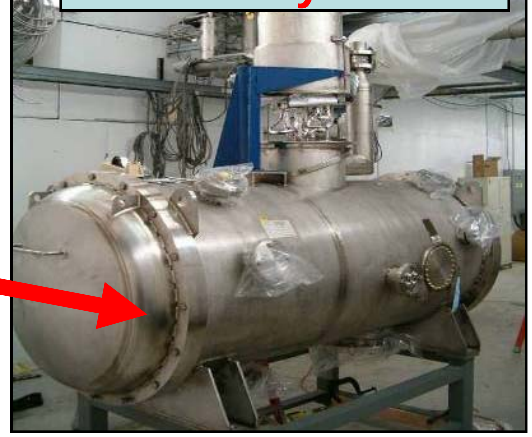
Horizontal Test System

- HTS facility is completed and commissioned
  – First test of the cavity with high pulsed RF power
  – R&D Test bed: tuners (slow), couplers, LLRF, etc
  – 1.3 GHz capture cavity
  – 3.9 GHz accelerating cavity,

1.3 GHz Cavity in HTS Cryostat

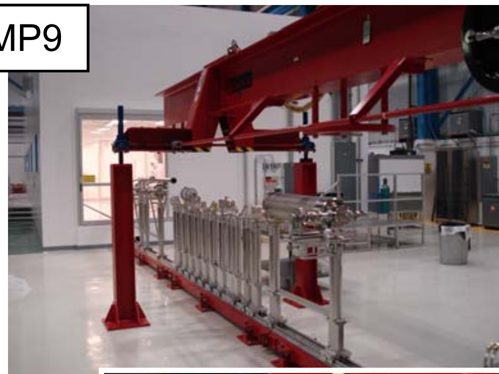


HTS Cryostat



RF Power for HTS

TD-MP9 CRYOMODULE ASSEMBLY FACILITY

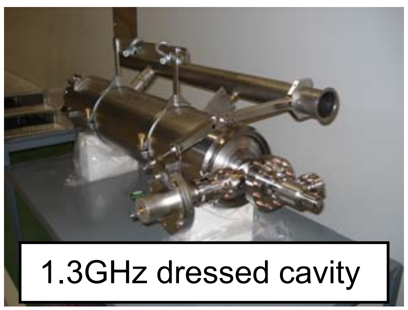



CAF-MP9

1.3GHz bare cavity hydrogen degas bake at CAF-IB4

- **Cavity string** and **Cold mass** Assembly Areas
- Fully Operational (June 2007)

Clean room technicians from FNAL & DESY working together during CM1 string assembly



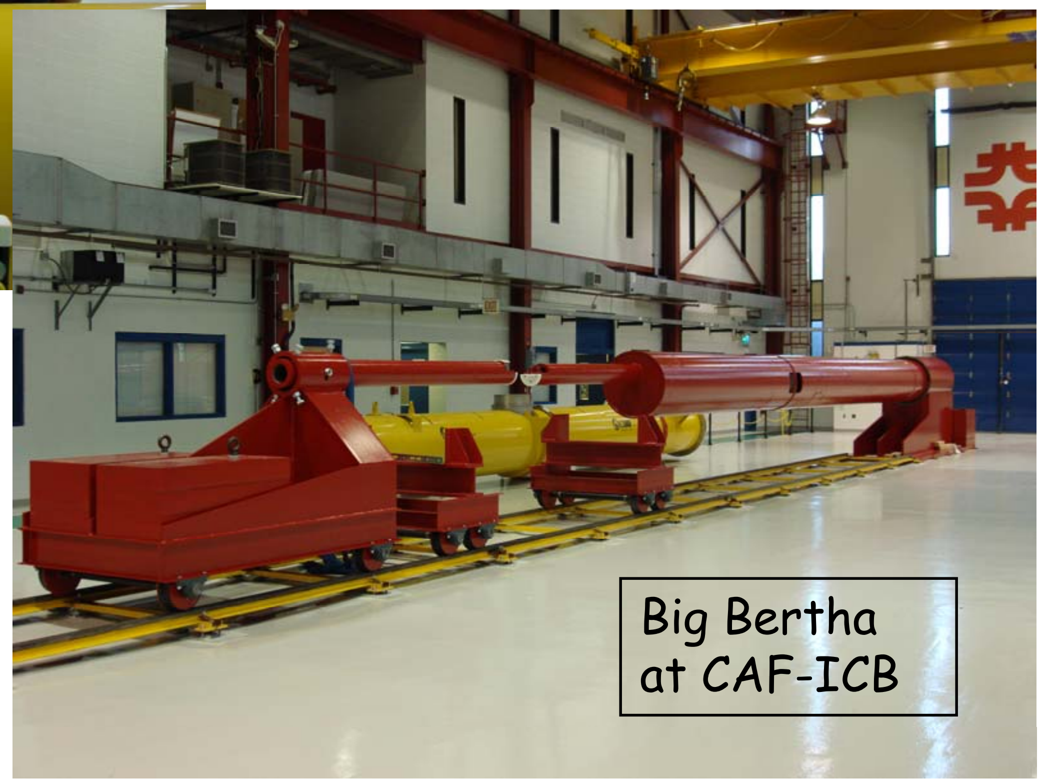
1.3GHz dressed cavity

3.9GHz Cryomodule Mockup Assembly

Cleanroom Class 10 area


Cryomodule #1 (CM1) string assembly in the cleanroom

CRYOMODULE ASSEMBLY FACILITY

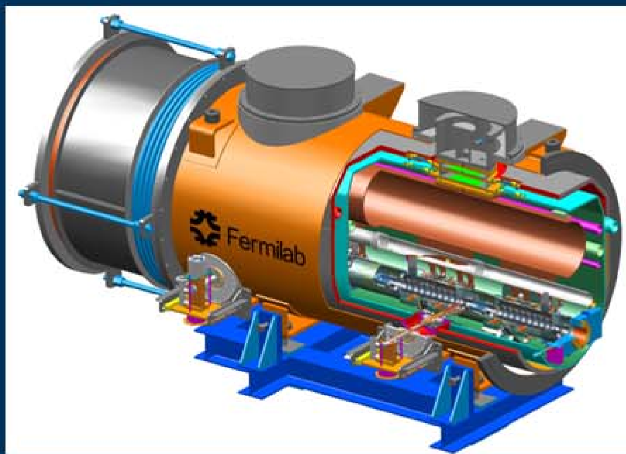


Big Bertha
at CAF-ICB

CM1 -Assembly schedule

- String Assembly: mid-Sept.
- Cold Mass Assembly: mid Oct.
- Final Assembly: Nov.
- 3rd Harm Cryomodule: Jan 2008

3rd Harmonic SRF Cryomodule



Cryomodule design completed in May 2007.

1st successful cavity test in Spring 2007!

Fabrication in process at MP9.

2008 delivery to DESY.

LHC Crab Cavity: Design Constrains

- General:
  - Frequency 800 MHz; $Q_L \sim 10^6$ (beam transverse jitter)
  - Dipole HOM: $Q_L \sim 10^2 \div 10^3$ - TCBI (Transv. Coupled Bunch Instability)
  - Monopole modes: $Q_L \sim 10^2$ - Power dissipation in load

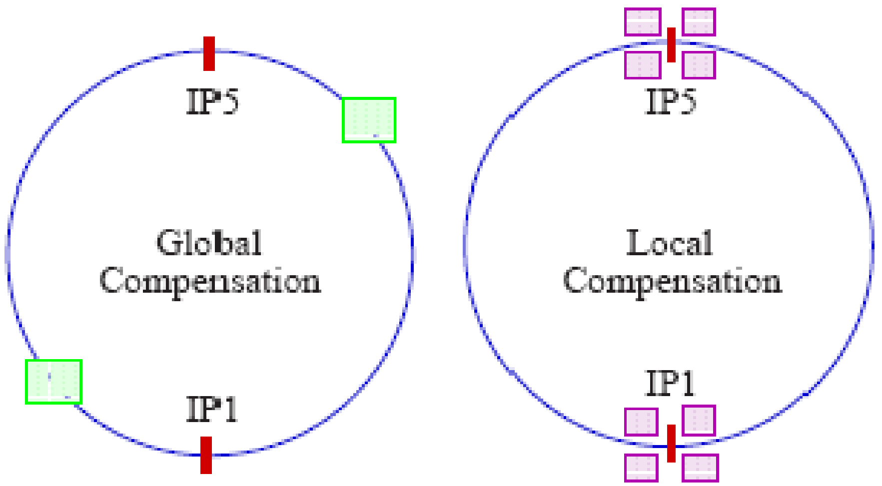


Figure 3: Schematic of global and local crab compensation at two IPs for LHC upgrade.

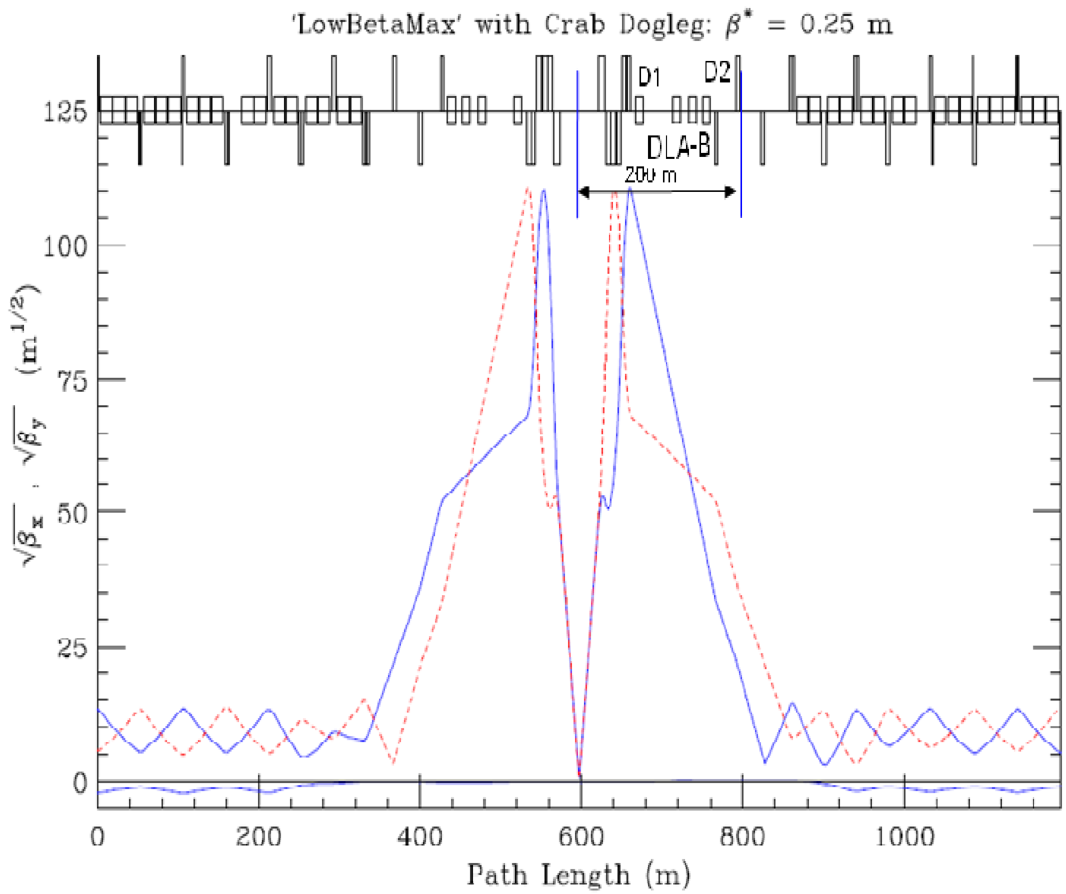
Global scheme:

Beam separation ~ 40 cm
Beta function ~ 100 m (?)
Longitudinal space ~ 5-10 m

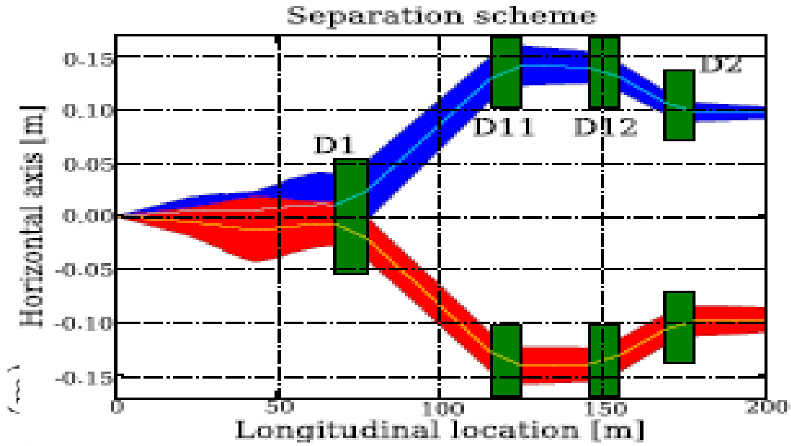
Local scheme
(preferable choice)

Beam separation ~ 30 cm
Beta function ~ 3-4 km
Longitudinal space ~10 m

Local Scheme for Crab Cavity



Optical functions of the 'LowBetaMax' Phase I upgrade option. To create the beam separation for insertion of crab cavities the baseline D1 separation magnet comprising 6 conventional magnet modules must be replaced by a single SC dipole. The remaining 3 separation dipoles in the dogleg are all superconducting.



Magnet	L (m)	B (T)	Position (m)	Separatic (mm)	βx (m)	βy (m)
D1	9.45	8.473	70.447	0	11103	4685
			79.897	32.4	9721	4552
DLA	9.45	8.473	116.229	281.6	5266	4059
			125.679	314.0	4329	3935
MID-DL			130.679	314.0	3870	3870
DLB	9.45	8.473	135.679	314.0	3437	3806
			145.129	281.6	2689	3687
D2	9.45	8.473	153.175	226.4	2125	3586
			162.625	194.0	1547	3470

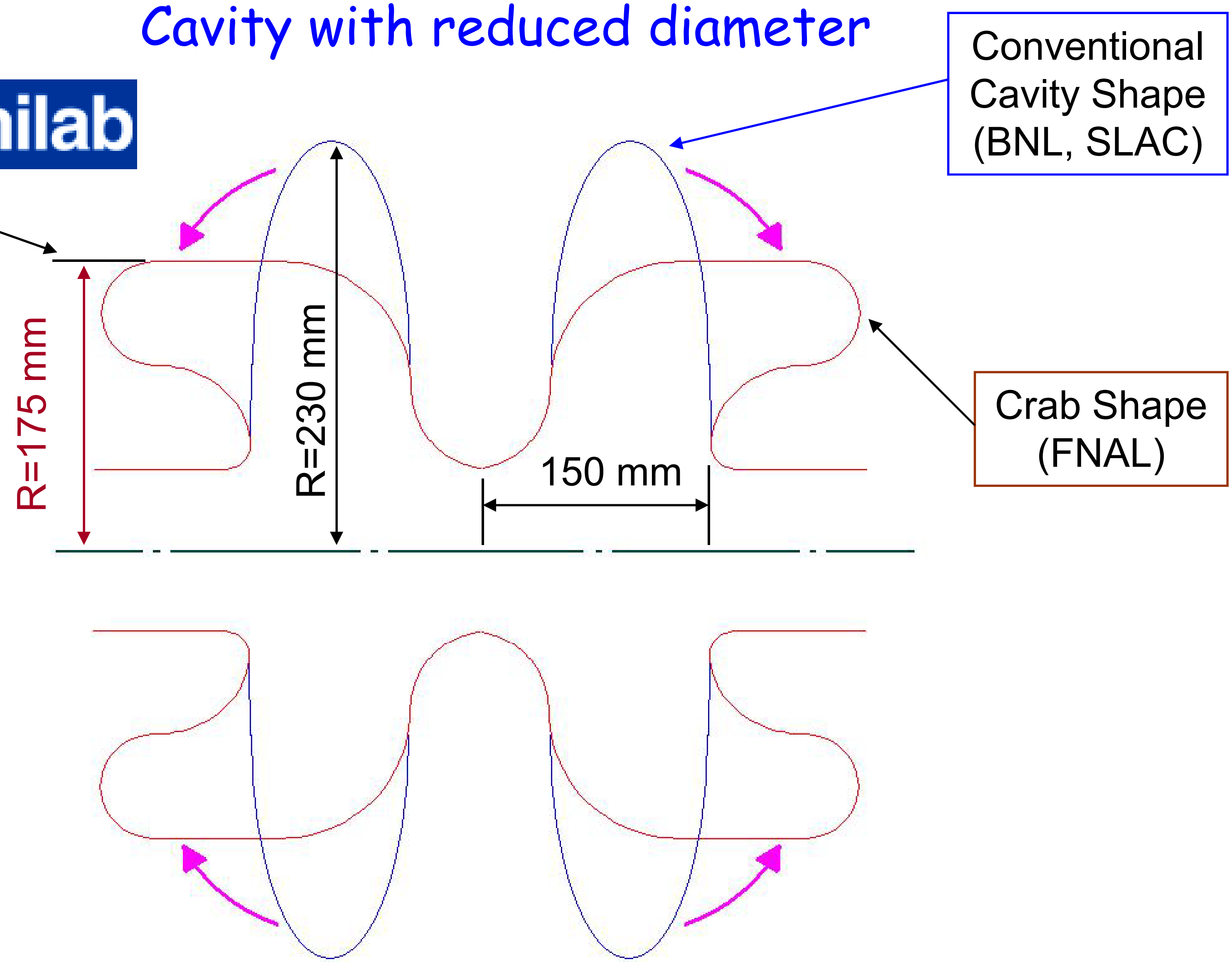
Beam separation ~30cm at 10 m

D1 - single aperture. DLA,DLB, and D2 are all double bore.

In straight section $\beta x=\beta y$.

(J.Johnstone and P.Limon (FNAL))

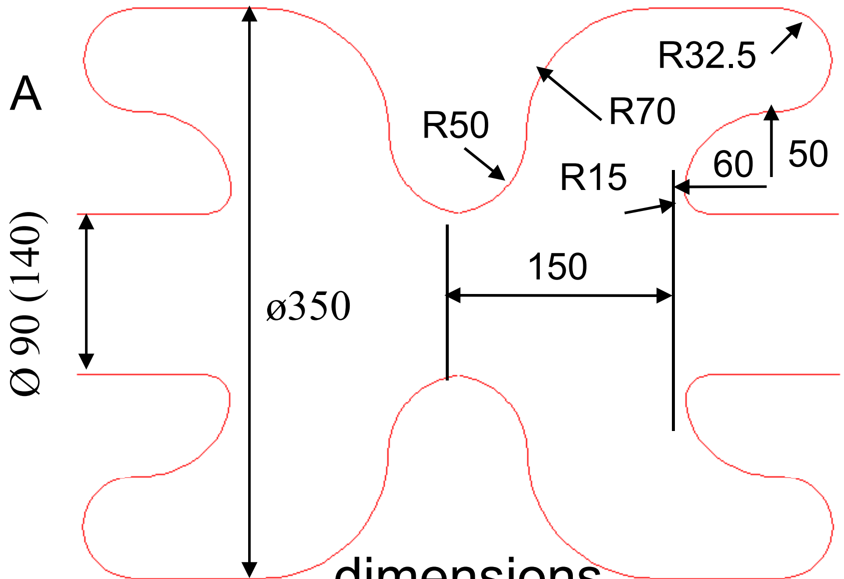
Cavity with reduced diameter



Idea of the LHC Crab cavity with reduced outer diameter to fit 30cm bunch separation. Conventional cavity (blue) vs. the cavity with reduced diameter (red)

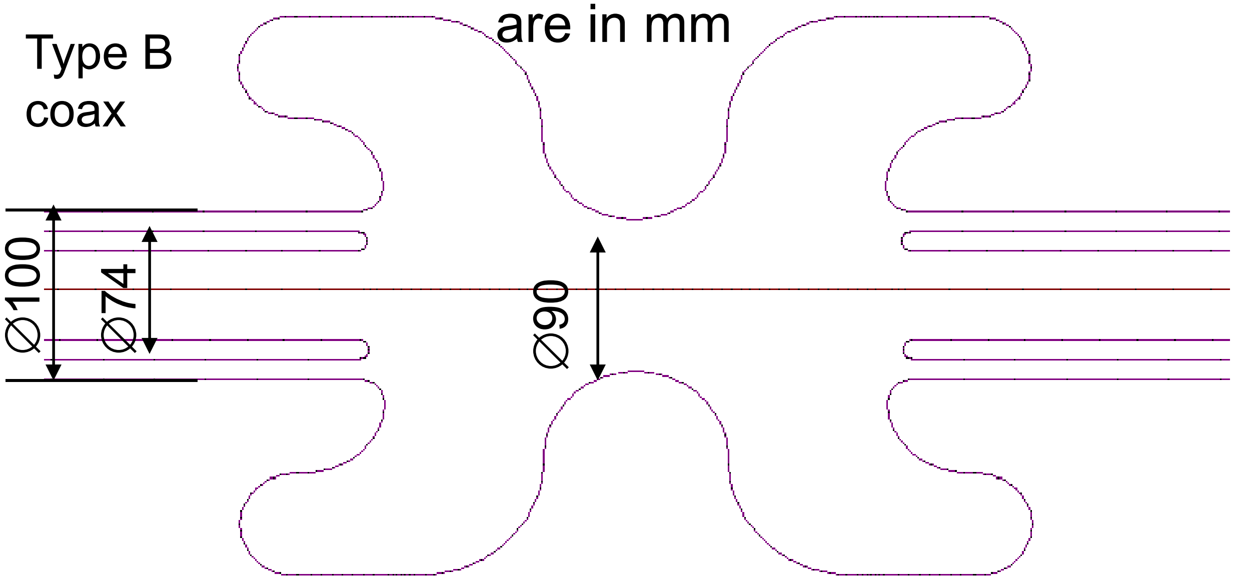
Cavity Shape

Type A



dimensions are in mm

Type B
coax



ILC-like

- Few monopole and dipole modes are trapped in cavity
- Needs LOM, HOM and SOM couples to damp all these modes

KEKB-like

Coaxial coupler

All monopole modes are propagating in coaxial line

Only working dipole mode (800 MHz) are trapped in cavity.

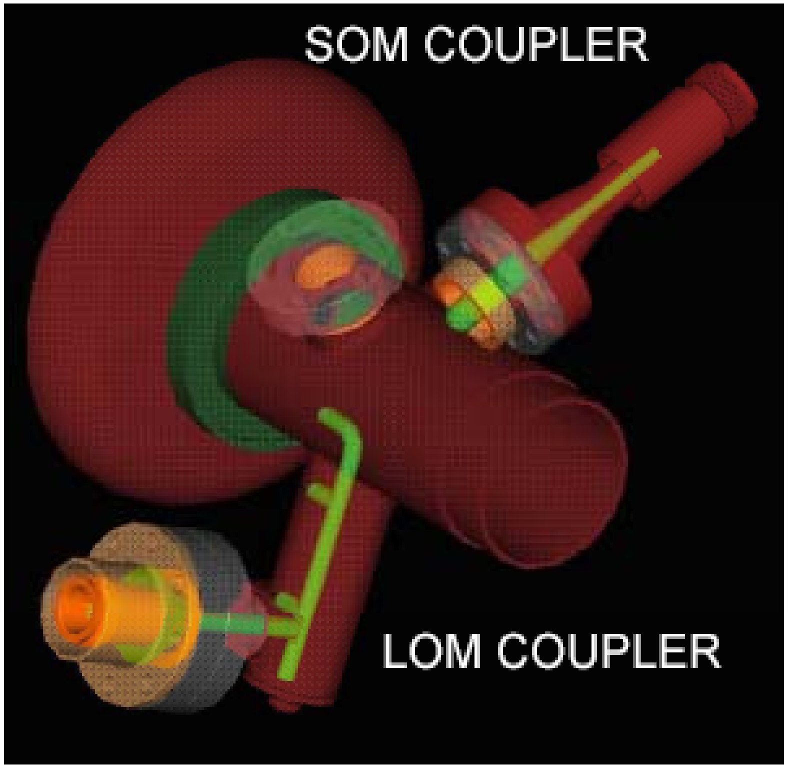
All other dipole modes are well damped. Fc>1097MHz

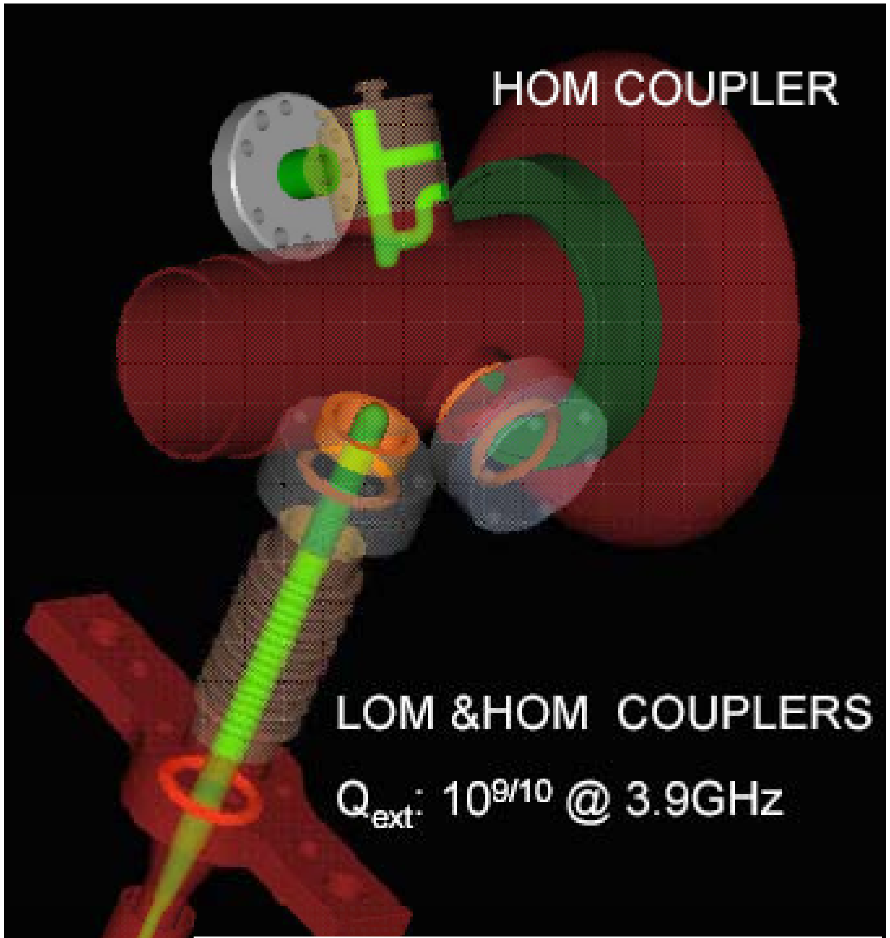
LOM, SOM, HOM COUPLERS

HOM coupler a modification of DESY design

SOM coupler will be mechanically adjusted to find the node of the TM_{110} mode

LOM at opposite end of input coupler

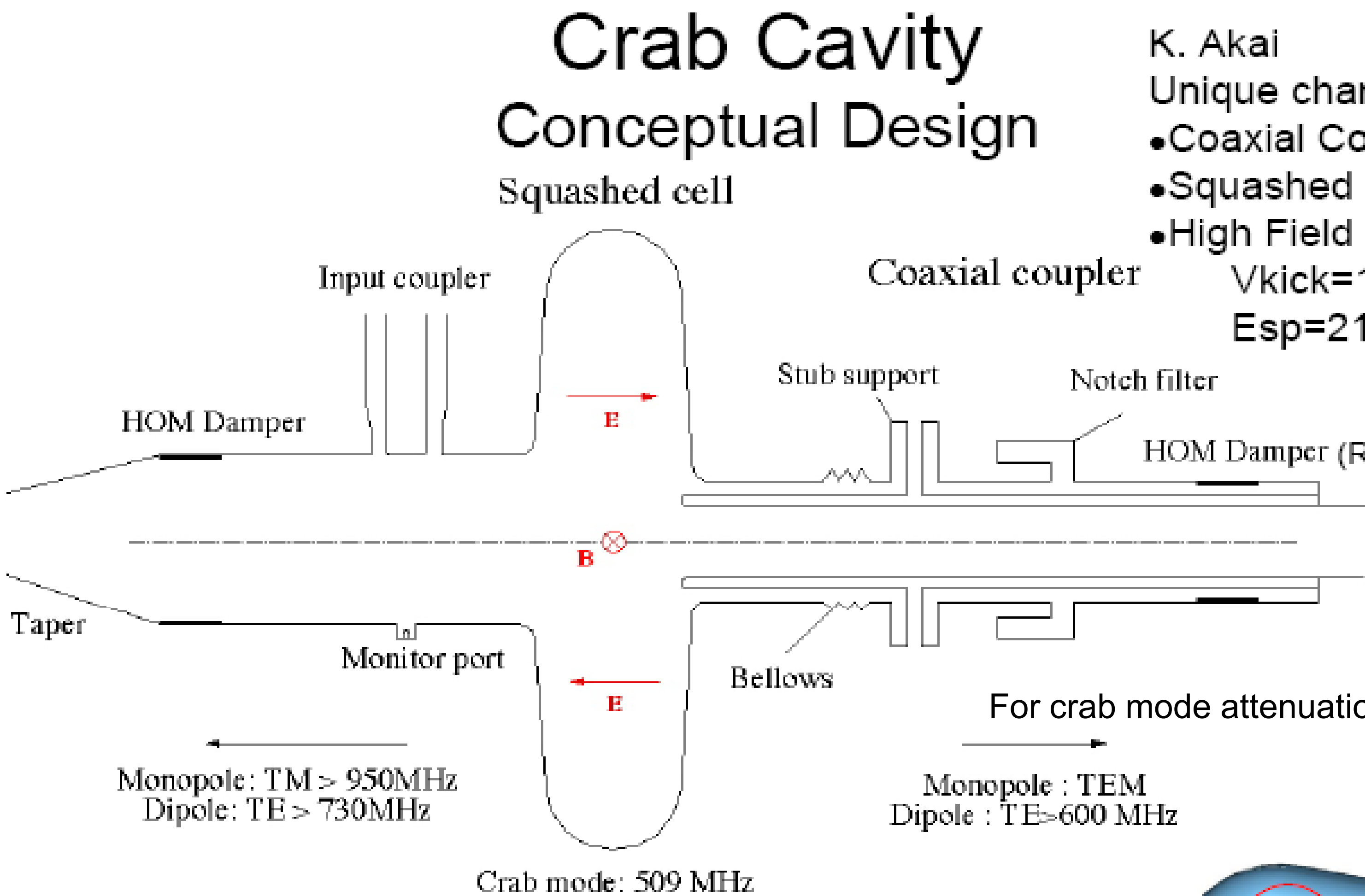




$Q \sim 10^4$ for ILC crab cavity

Can be done better for LHC

Mode damping in KEKB crab cavity



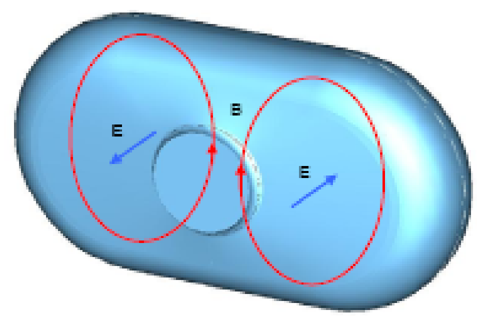
K. Akai

Unique characteristics

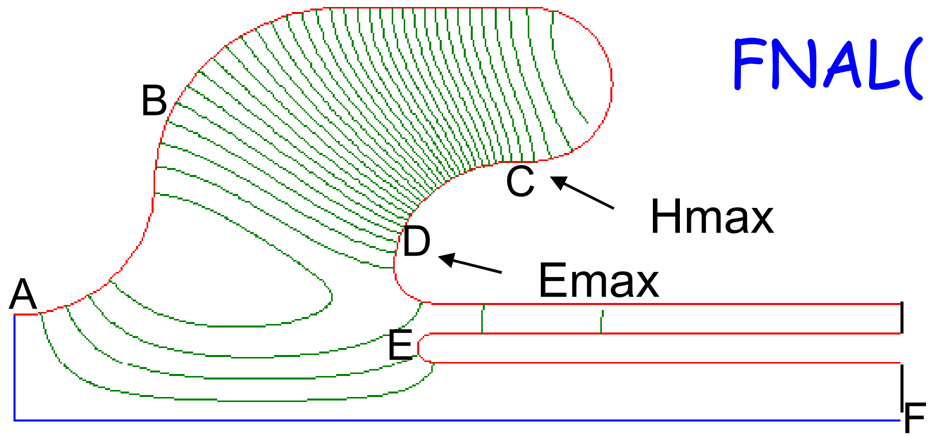
- Coaxial Coupler
- Squashed Cell
- High Field
  - Vkick=1.4 MV
  - Esp=21 MV/m

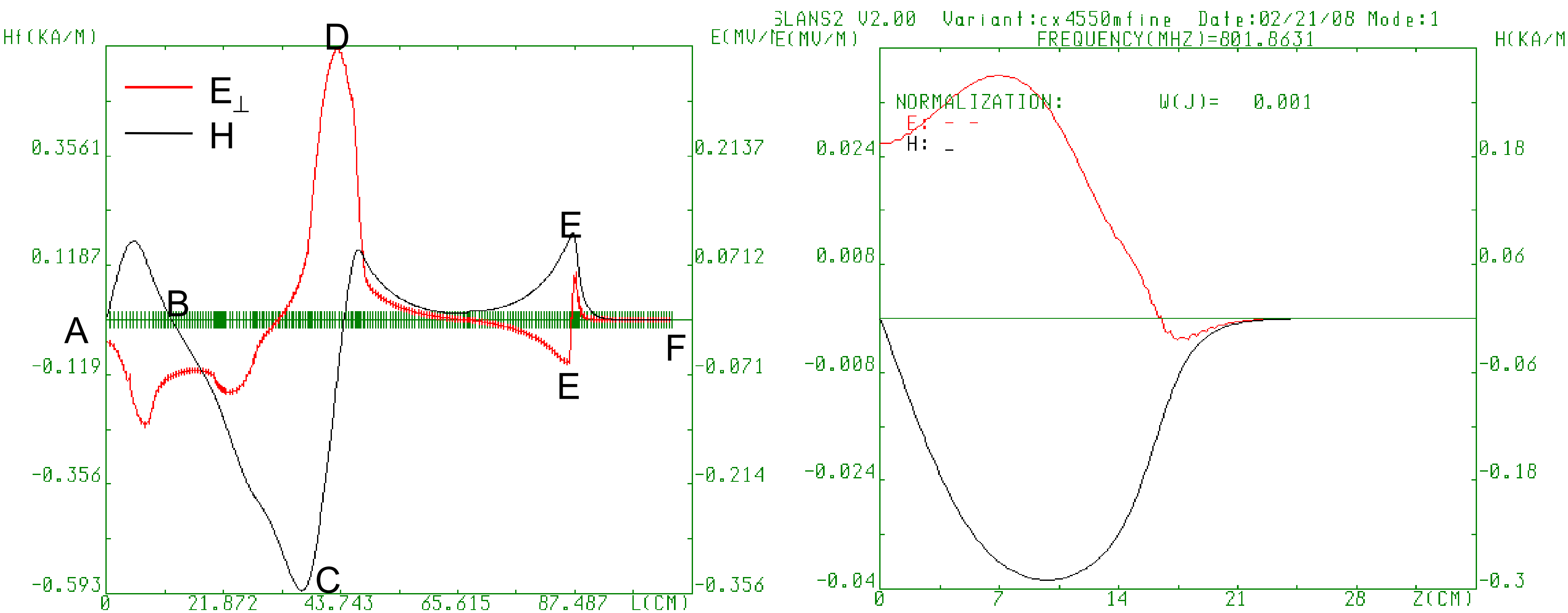
For crab mode attenuation = -60dB/m

Crab Mode: TM110-like mode (high R/Q)
Coaxial coupler: LOM damping
Squashed cell: UWP > 600 MHz
Notch filter: TEM-coupled Crab mode rejection
Stub support: support for inner conductor



FNAL(B): Half-cavity





Distribution of electric and magnetic fields along cavity surface (left) and at the axis (right).

Main parameters of the crab cavities

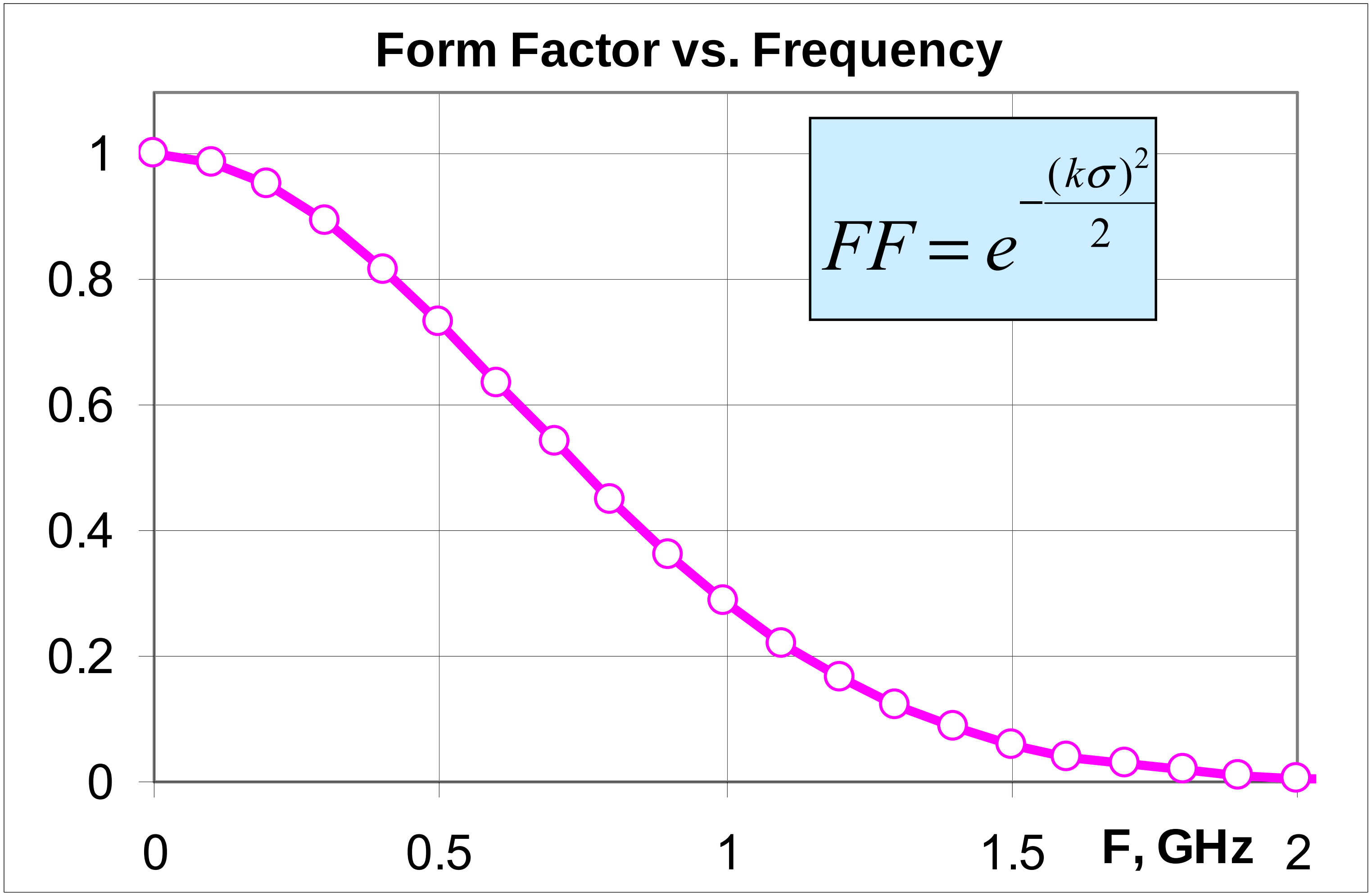
	BNL	SLAC	FNAL(A)	FNAL(B)
$V_{\perp}$, MV	5	5	5	5
B_{peak}, mT	386	189	150	152.1
$E_{peak,}$ MV/m	66.2	47.5	68.6	72.4
$r_{\perp}/Q$, Ohms**	41	56	61	58.7
Ø iris, mm	160	140	90	100x74 (coax)
Ø cavity, mm	460	460	350	350

- Crab frequency 800 MHz
- All cavities in simulations not squashed
- SLAC squashed cavity: Hs=165.5 mT; Es=49.4 MV/m

* $V_{\perp} = \Delta p_{\perp} c/e$;

**$(R_{\perp}/Q) = V_{\perp}^2/2\omega W$

(Form factor not included)



Bunch length σ = 7.55 cm

$(R/Q)_{eff}$ = FF*(R/Q)

Monopole modes in Crab Cavities

	BNL 0 - π modes		SLAC 0- π modes		FNAL(B) 0-π modes	
Beam pipe ∅ (mm)	160		140		100	
$F_{cut-off}$, MHz	1435.4		1640.4		0	
TM010: Freq, MHz	582	590	556	560	520.5	520.6
FF*(R/Q), Ω	12	6	16.5	63	20	73
TM020: Freq, MHz	1219	1256	1242	1264	1087.2	1087.8
FF*(R/Q), Ω	0.15	0.04	0.6	0.4	6.8	2.1
TM011: Freq, MHz	1384	1429	1440	1453	1675	1680
FF*(R/Q), Ω	0.06	0.6	0.08	0.7	0.02	0.3
TM030: Freq, MHz	1454	1457	1660	1661	1844.3	1843.6
FF*(R/Q), Ω	1.9	1.3	0.88	0.08	0.2	0.02

In squashed cavity (ratio=0.8)
TM010 moves up 30 MHz

Three monopole modes need to be damped in BNL, SLAC designs.

Higher frequencies (>1.5 GHz) are suppressed by form-factor

Dipole modes in Crab Cavities

	BNL 0 π modes		SLAC 0 π modes		FNAL(B) 0 π modes	
Beam pipe ∅ (mm)	160		140		Coax: 74x100	
$F_{cut\text{-}off}$ MHz	1098		1255		1097	
TM110: Freq, MHz	828	800	811	800	801.3	800
FF*(R/Q), Ω	0.36	18.6	0.08	25	0.17	26.4
TM111: Freq, MHz	980	877	1069	981	1142	1145
FF*(R/Q), Ω	1.0	0.86	0.98	0.2	0.6	0.01
TM120: Freq, MHz	1185	1164	1353	1309	1291	1286
FF*(R/Q), Ω	0.003	0.009	0.07	0.0002	1.4	1.3
Freq, MHz	1355	1293	1495	1426	1309	1302
FF*(R/Q), Ω	0.004	0.003	0.06	0.1	0.22	0.05

↑ In squashed cavity SOM (800MHz) moved up ~89 MHz

In FNAL(B) design squashing can move up frequency of other polarization (800MHz), higher than cut-off frequency in coaxial line

Damping

Monopole modes

Freq MHz	FF*(R/Q) Ohm	Q
520.6 520.7	20 73	440 420
1087.2 1087.2	2.1 6.8	330 350
1675.1 1679.6	0.3 0.02	120 115

Dipole modes

Freq MHz	FF*(R/Q) Ohm	Q
800 801.3	26.4 0.17	
1144.6 1144.9	0.01 0.6	61 60
1285.5 1291.4	1.3 1.4	509 150
1302 1309	0.05 0.22	18.8 18.4
1412.3 1434.9	0.5 0.5	28 32

Stronger damping is possible changing position of the coaxial.

Crab mode is attenuated in coaxial line -136 dB/m

Requirements for HOM damping

HOM impedances should not be worse than for the acceleration cavity (?). For LHC acceleration cavity:

- *The total power of monopole HOMs dissipated < **800 W**.*
- *Impedance of the two lowest dipole modes should not be **1.5 kΩ***
  - *Total transverse impedance is dominated by collimators*

Table 2: Estimated impedance budget for the LHC in the vertical plane.

Element	Inner radius [mm]	β/β_{av}	Z_T [kΩ/m]
Beam screen			
pumping holes	18	1.25	500
200 MHz cavities	50	3	155
400 MHz cavities	150	2.9	11
Shielded bellows	20	1.25	265
Vacuum valves	40	1.25	35
Collimators	8	4.3	2300
BPMs [6]	25	1.25	300
BI instruments	40	2.15	12
Total			3578

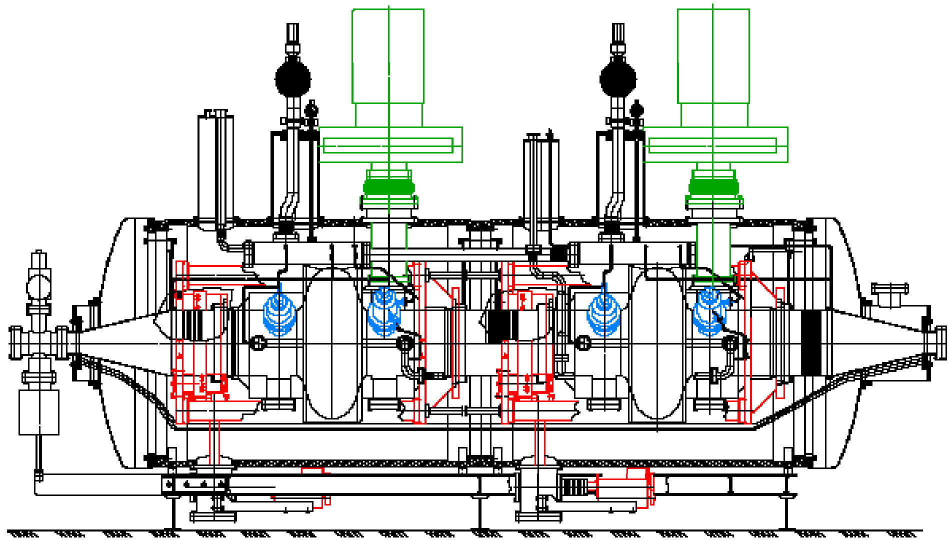
(D. Boussard, et al, "The LHC Superconducting Cavities, PAC 1999.)

For 800 MHz crab cavity if the same requirements:

Monopole modes: $FF^*(R/Q)_{max}$ ~ 70 Ohms ➔ Q ~ 30

Dipole HOMs: $FF^*(R/Q)_{max}$ ~ 1 Ohms ➔ Q ~ 100 ($\beta \sim 4km$)

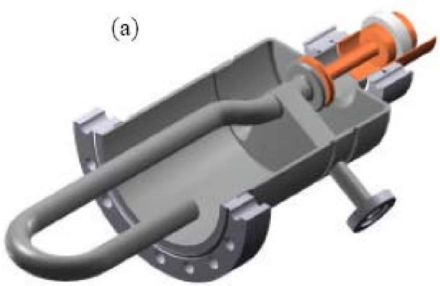
HOM damping in the LHC accelerating cavities.

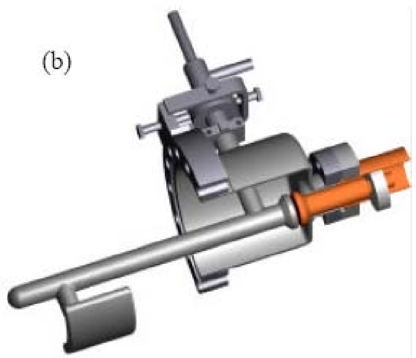


F(TM010) = 400 MHz

Beam pipe = 300mm

The cryomodule with two cavities. HOM couplers are shown in blue.



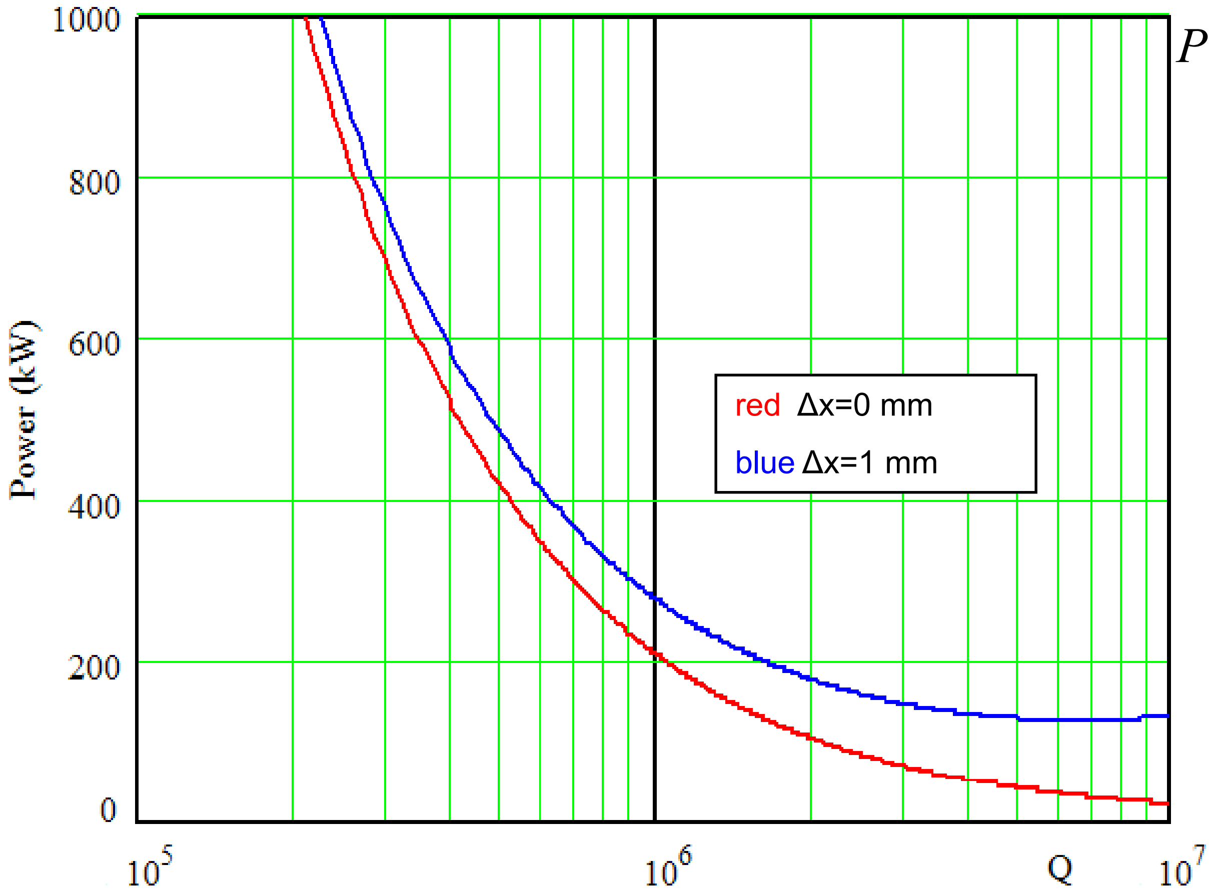


(a) Narrow band dipole mode HOM coupler;
(b) Broad band HOM coupler

Frequency (MHz)	Undamped Q	Damped Q
500 (TE_{111})	38000	137
534 (TM_{110})	40000	93
779 (TM_{011})	50000	270
1184	50000	1000
1238	50000	400

HOM damping on a single-cell cavity by one dipole mode and one broadband coupler

Power requirements. Beam jitter



$$P = \frac{(V_{\perp} + 2I_b FF \cdot (R_{\perp}/Q) \cdot Q \cdot k\Delta x)^2}{2(R_{\perp}/Q) \cdot Q}$$

$V_{\perp} = 5MV,$

$I_b = 0.84A,$

$R_{\perp}/Q^* = 60\,Ohms,$

$k = 2\pi/\lambda_{RF},$

$\lambda_{RF} = 37.5cm\,(800MHz)$

FF is form-factor,

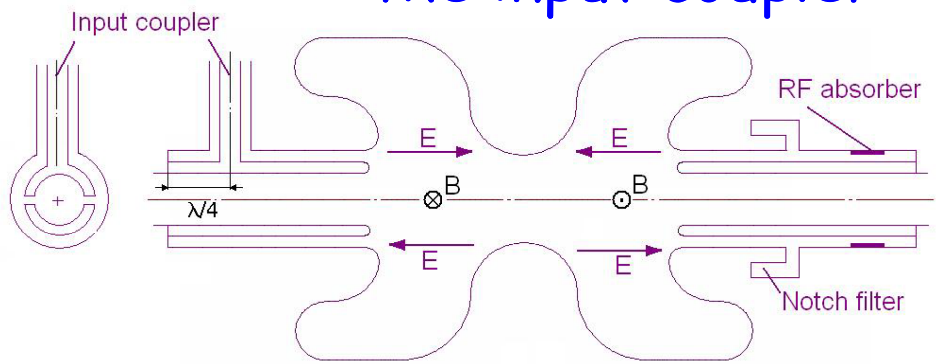
$$FF \sim e^{-\frac{(k\sigma)^2}{2}}$$

$$^* R_{\perp}/Q \equiv \frac{V_{\perp}^2}{2\omega W},$$

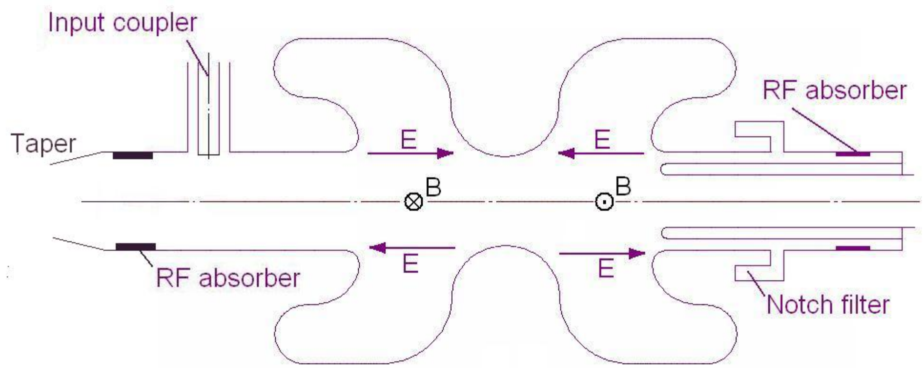
ω is cyclic frequency, W is stored energy.

Different options for the HOM damping and the input coupler

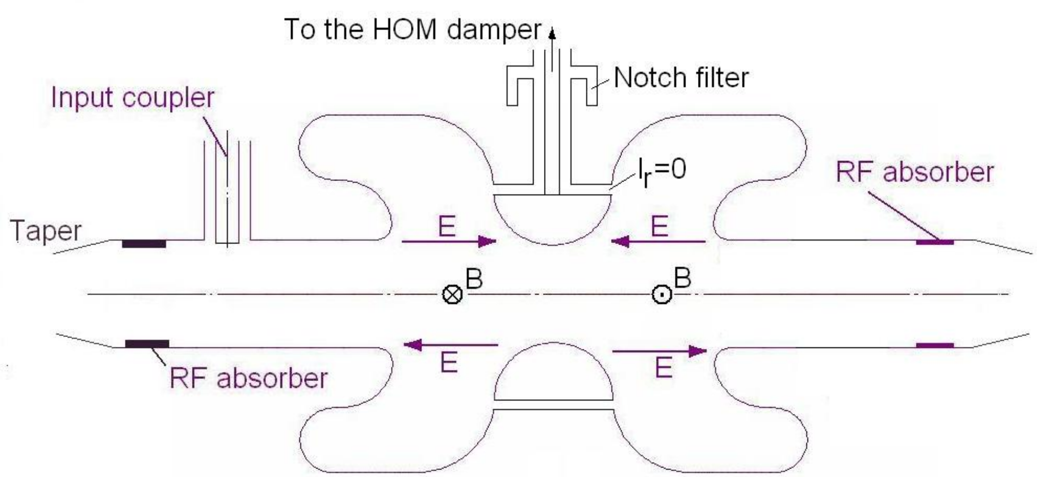
a)



b)



c)



Conclusions

- Preliminary results of R&D
  - Crab-like shape for crab cavity to reduce cavity outer diameter
  - Coaxial damping works for all modes
- Next to do:
  - Requirements (Q_{load}, beam-pipe diameter, etc.)
  - Optimize cavity shape
  - Squashed cavity design
  - Input coupler design
  - Study other options