BESSY

Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

Status of the EC Funded HOM Damped Normal Conducting Cavity

Ernst Weihreter / BESSY

for the HOM Damped Cavity Project Team

- Why HOM Damped Cavities for 3rd Generation SR Sources?
- Basic Concepts for HOM Damping and Existing Cavity Designs
- The EC Funded Normal Conducting HOM Damped Cavity Project:
  Design, Status, Essential Results
- Technical Problems and Solutions
- Conclusions

Why Do We Need HOM Damped Cavities for SR Sources?

Figure of Merrit: Photon Beam Brilliance

3rd Generation SR Sources: use undulators implemented in a low emittance lattice

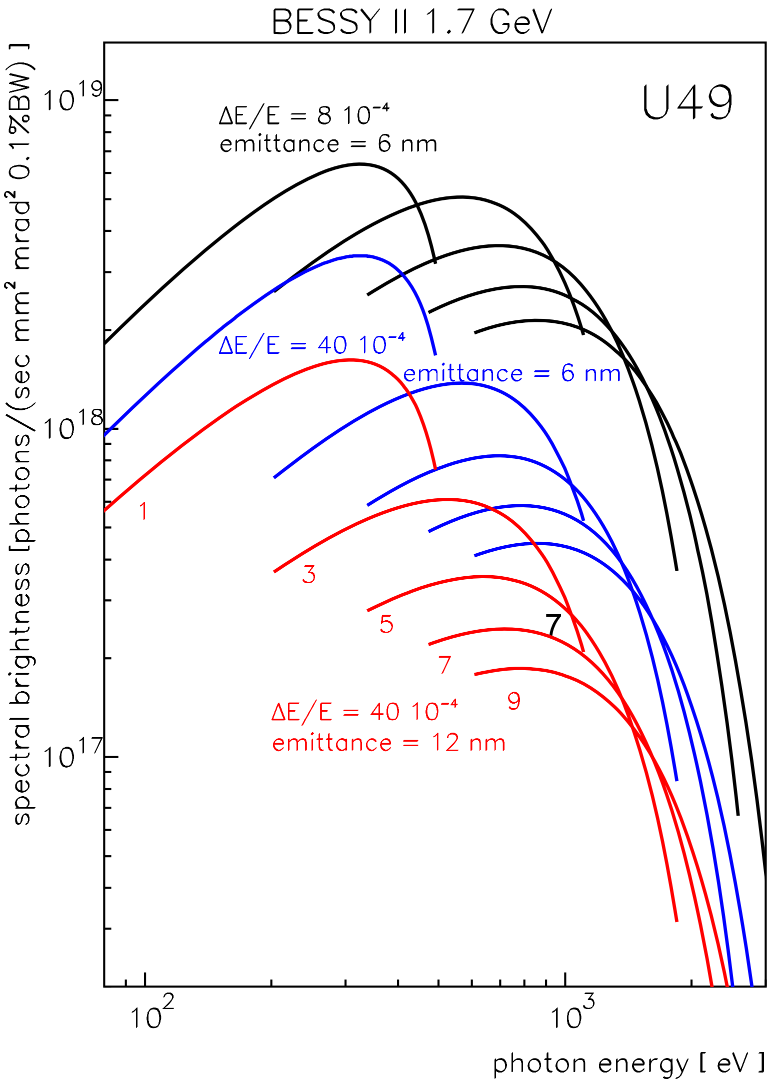
Minimize $\varepsilon \sim \gamma^2 \theta^3 \langle H \rangle$
- small θ → many lattice cells
- complex lattices → many magnets per cell

Low emittance is an expensive ingredient !

► **Avoid emittance / brilliance degradation**

Narrow band HOM impedances of the cavities excite coupled bunch oscillations if Fourier components of I_b coincide with HOMs

- Emittance increase due to transverse oscillations
- Large eff. energy spread ΔE/E due to longitudinal oscillations



Cures for Coupled Bunch Oscillations

- ♦ Detuning of the dominant HOM
  - by changing cavity temperature
  - by a second tuner

- ♦ Higher harmonic rf system for Landau damping

- ♦ Use broad band feedback systems

All these methods have their specific limitations

► **Damp all HOMs in the cavities in a broadband way by 2 - 3 orders of magnitude**

Concepts for HOM Damped Cavities

$$1/I_{threshold} \propto Z_{tot} = N_c \left(\frac{R}{Q_0} \right)_{HOM} Q_{ext}$$

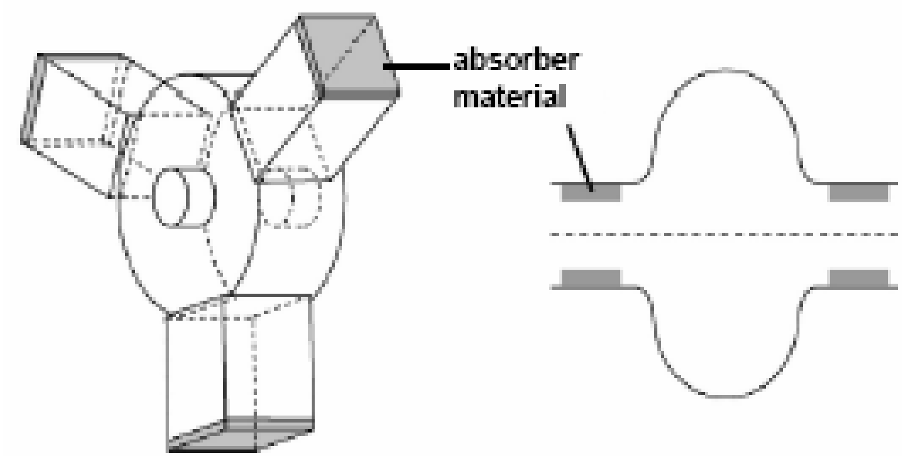
♦ Minimize number of cavities N_c

♦ Minimize $(R/Q_0)_{HOM}$

♦ Minimize Q_{ext}

Two Concepts for Broadband HOM Damping:

Waveguides **Beam Tubes**



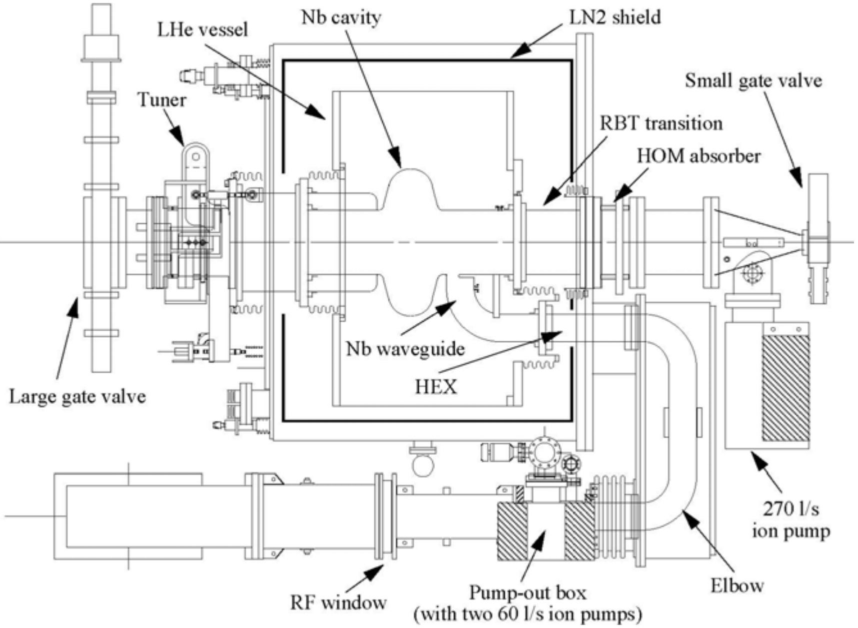
$f_{rf} < f_{cutoff} < f_{HOM}$

→ Trade off between
- effective coupling to HOMs
- Minimum coupling to fundamental mode

Superconducting Cavities

HOM Damping via Beam Tubes:

CESR-B Cavity

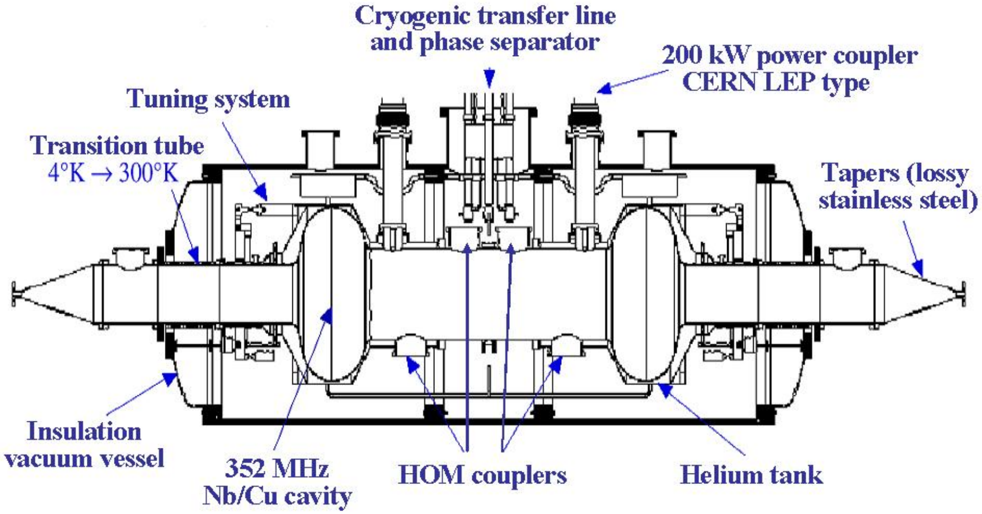


- Nb sheet material
- 2 cylindrical HOM loads
- rectangular waveguide
  input coupler, 500 kW
- cooling capacity:
  100 W at 4.2 K

Cavity used at

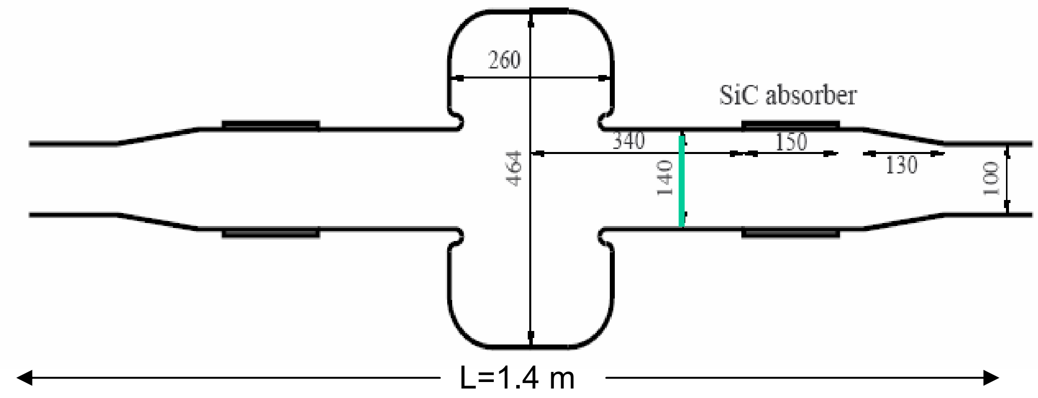
CLS/Canada
NSRRC/Taiwan
SLS/China
DIAMOND/England

SOLEIL Cavity
(Design based on LEP cavity)



- Nb sputtered on Cu
- 4 coaxial loop type HOM couplers
- 2 coaxial input couplers
  200 kW each
- cooling capacity:
  100 W at 4.5 K, 20 l/h LHe

KEK Photon-Factory Cavity

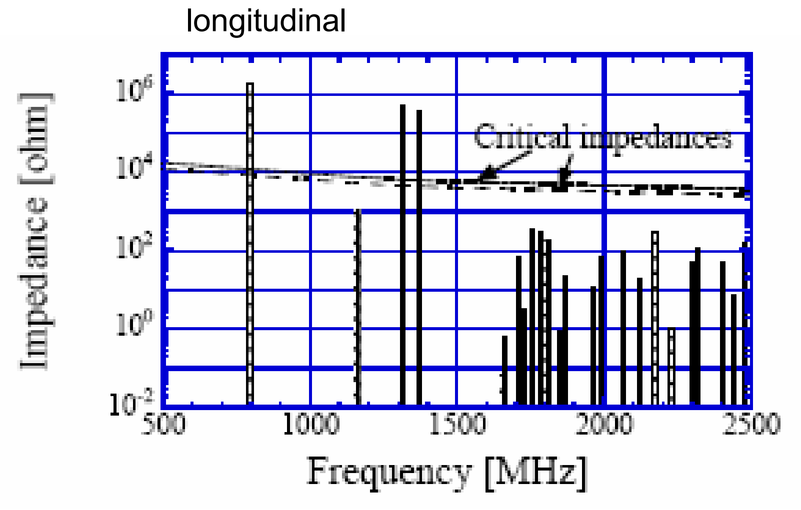


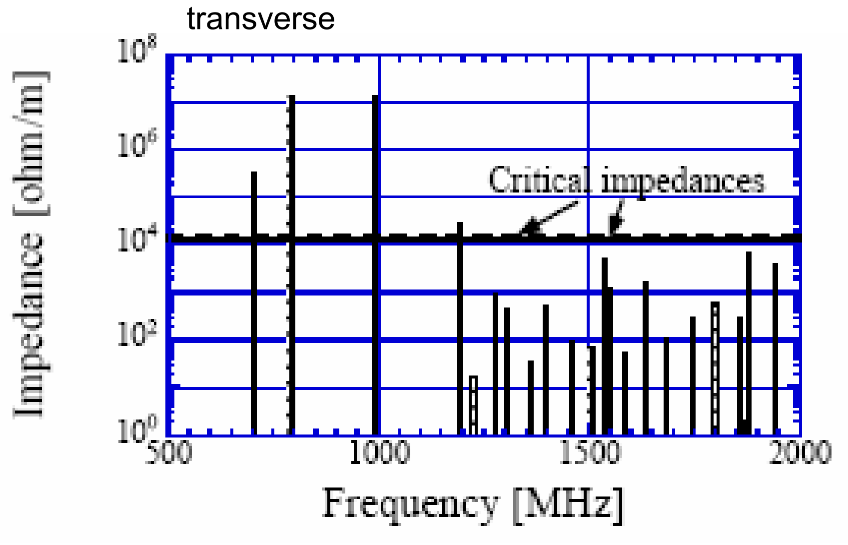
T. Koseki, Y. Kamiya, M. Izawa
Rev. Sci. Instrum. 66,1995, p.1926

f(TM010) = 500 MHz

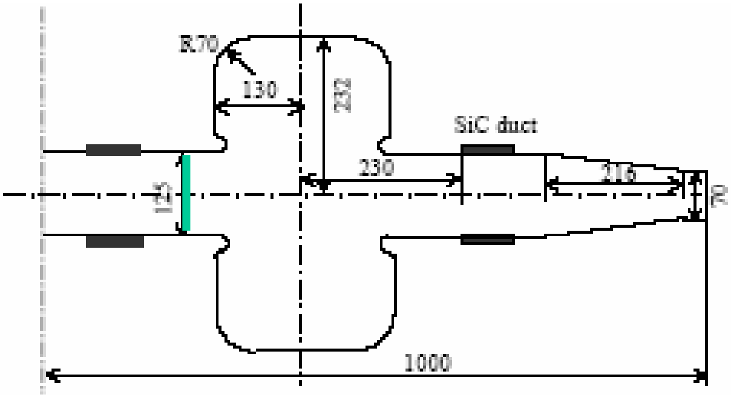
fc (TE11) = 1.26 GHz
fc (TM01) = 1.64 GHz

4 cavities in operation at KEK-PF

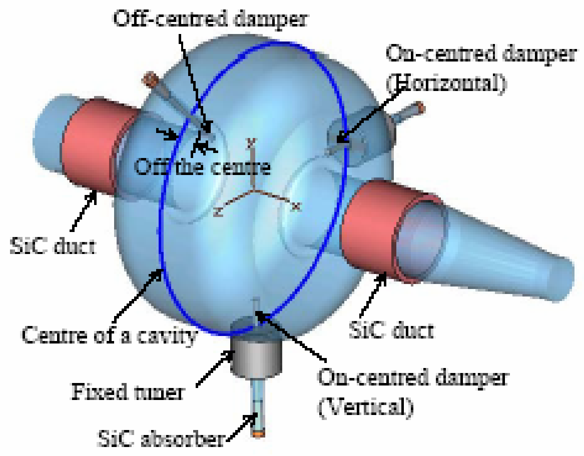




ASP / Toshiba Cavity



Improvement by addition of 3 coaxial dampers

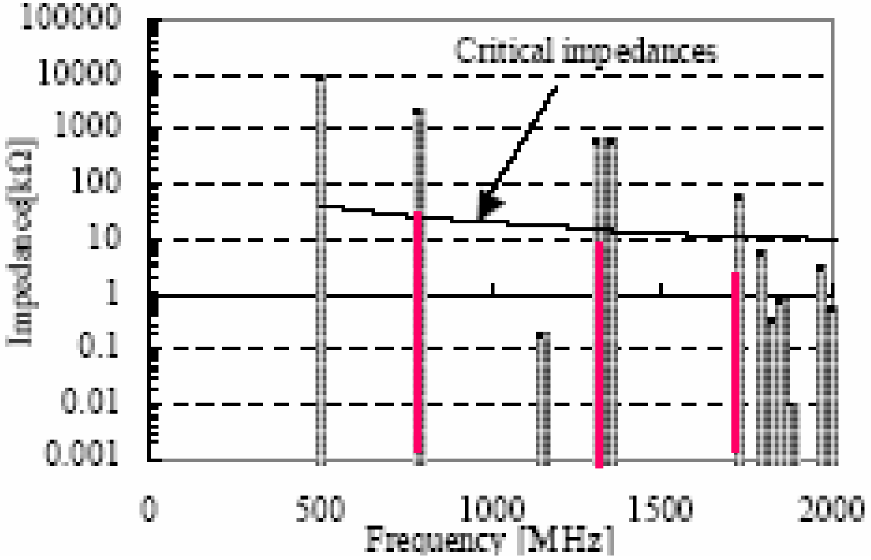


J. Watanabe et al.,
EPAC 2006 , p.1325

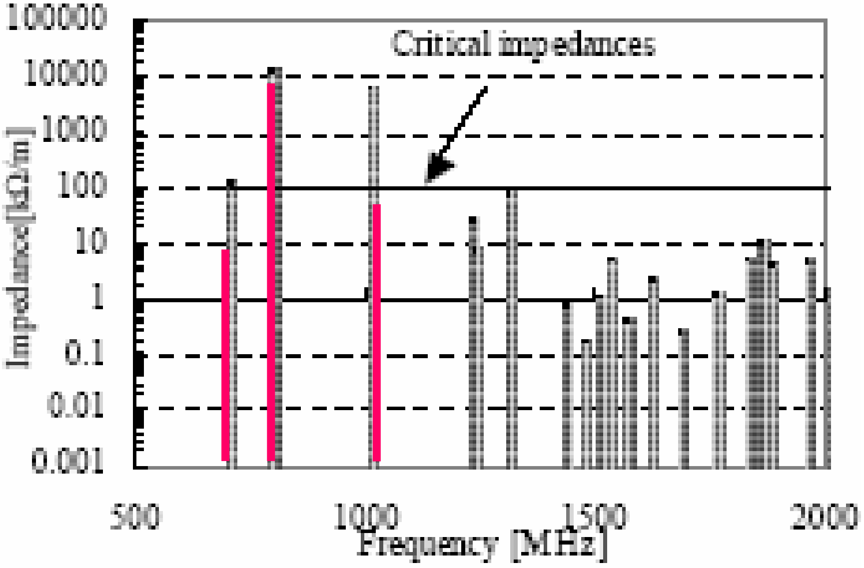
fc (TE11) = 1.41 GHz
fc (TM01) = 1.84 GHz

2 cavities in operation
at ASP / Australia

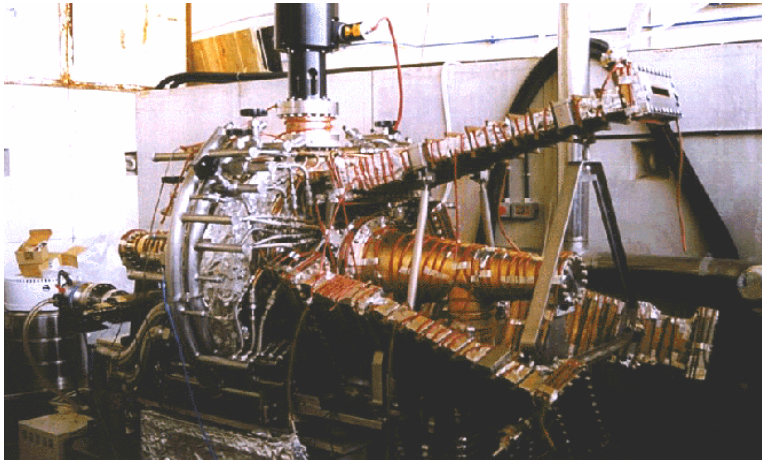
longitudinal



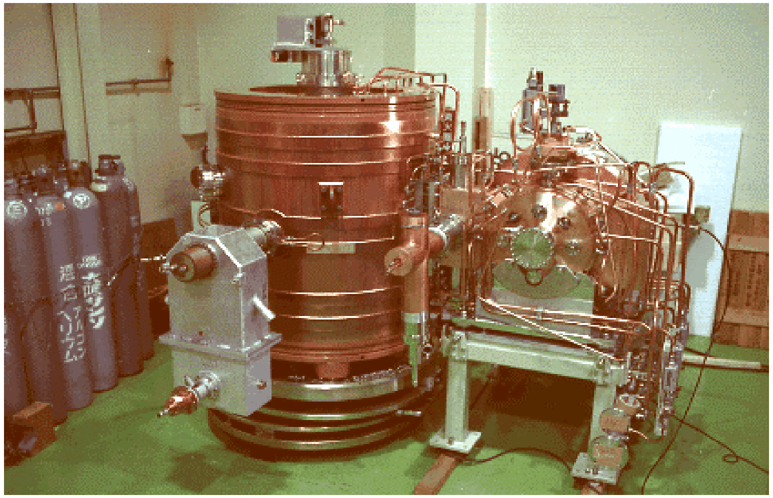
transverse



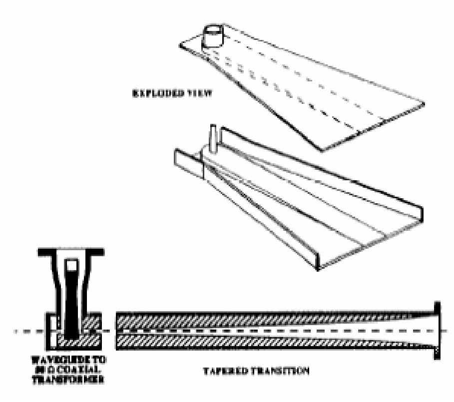
Room Temperature Cavities for Meson Factories



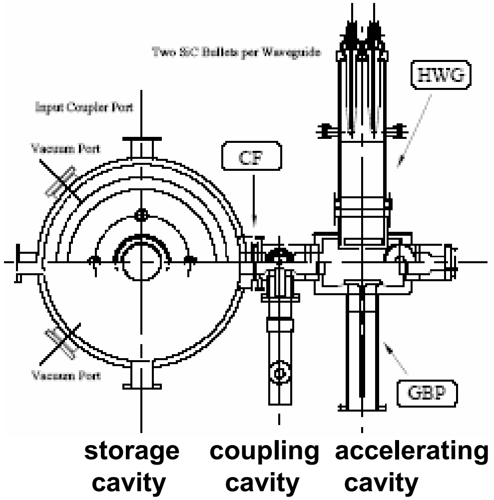
Daphne cavity, 368.2 MHz, 250 kV, 2 MΩ, L=1.9m



KEK ARES cavity, 509 MHz, 500 kV, 1.7 MΩ



4 tapered rectangular waveguides with coax transitions, rf windows, external loads

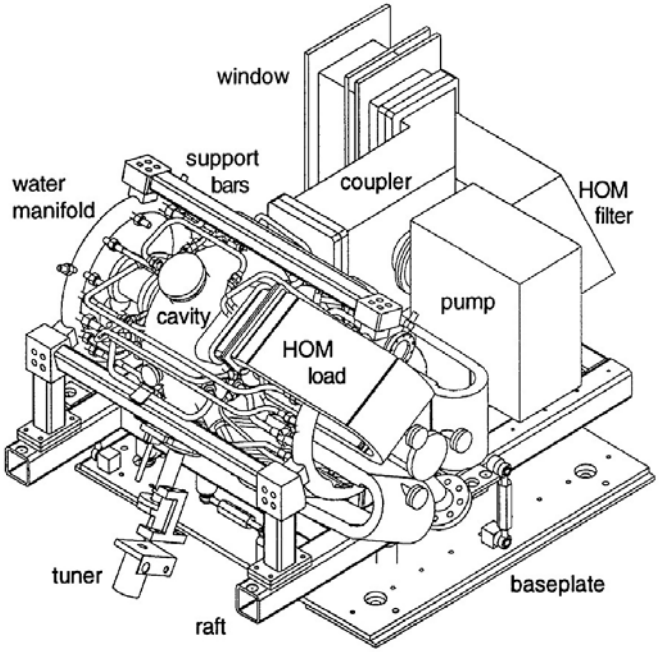


Coaxial notch filters

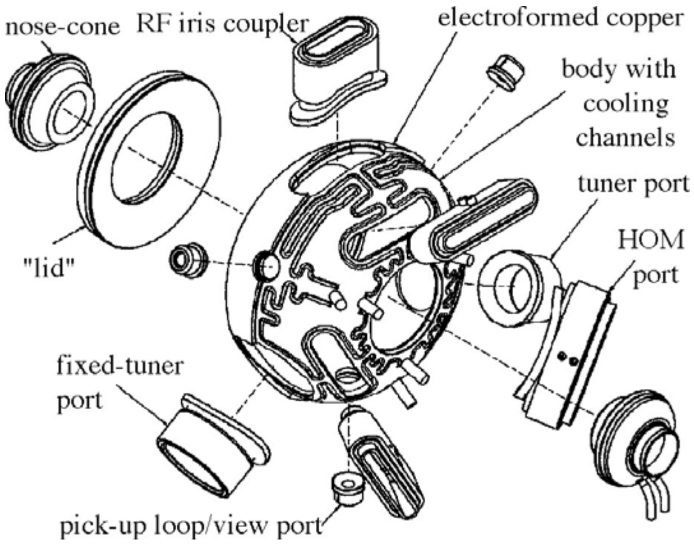
Low fundamental mode R/Q to enhance Robinson damping

Low shuntimpedance, large insertion length
→ Meson factory cavities not necessarily ideal also for SR sources

Room Temperature Cavities, cont.



PEP-II RF cavity raft assembly



f_{rf} = 476 MHz

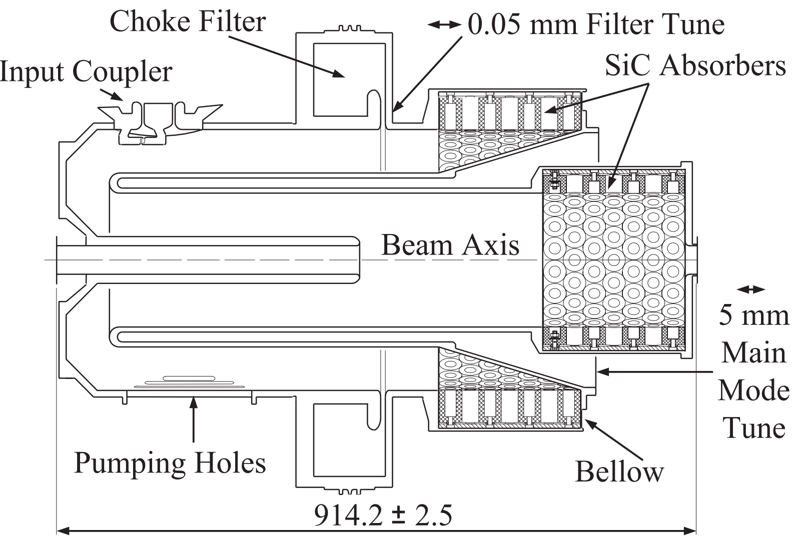
PEP II Cavity:

- **R = 3.8 MΩ, spherical shape**
- **thermal power capability of 150 kW**
- **3 rectangular HOM waveguides, AlN absorbers**
- **insertion length L = 1.5 m.**
- **circular Al_2O_3 rf window for 500 kW**
- **complex mechanical design, using e-beam welding, vacuum brazing, galvano-forming**

Cavity used for SPEAR 3

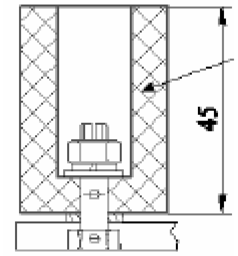
Room Temperature Cavities, cont.

Cavities developed at BINP / Novosibirsk

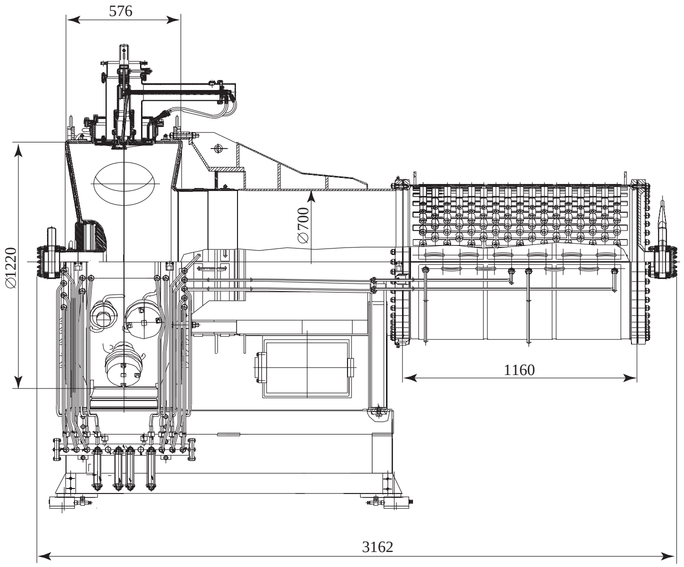


VEPP-2000 cavity

172.1 MHz, 120 kV, 0.23 MΩ



SiC absorber element



Cavity for the DUKE-FELL ring

178.5 MHz, 730 kV, 3.46 MΩ

HOM Damped Cavity Performance Parameters

Performance parameters of HOM damped storage ring cavities ($R_s = V_{cy}^2/2P_{cy}$,
L insertion length, $R_\parallel$ max. longitudinal impedance, $R_\perp$ max. transverse impedance)

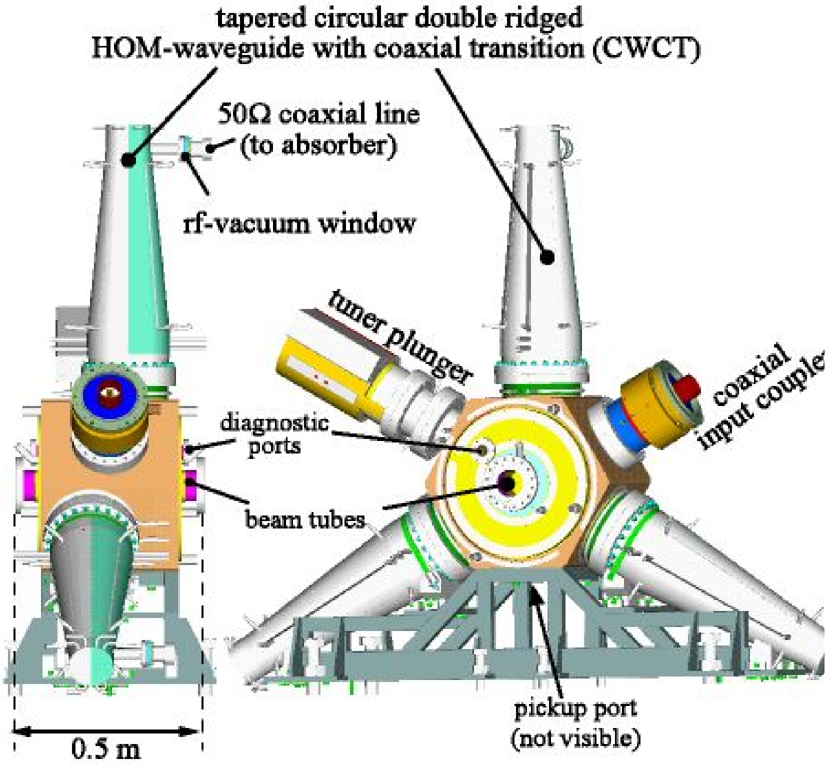
NC Cavities	f_0 MHz	V_{cy} kV	R_s MΩ	Q_0	P_{cy} kW	L m	f_{HOM} ‖ MHz	Max. R‖ kΩ	f_{HOM} ⊥ MHz	Max. R⊥ kΩ/m
PEP II	476.	850.	3.8	32400	103.	~1.5	1295.	1.83	1420.	144.
DAPHNE	368.2	250.	2.	33000	16.	1.9	863.	259.	-	-
ARES	509.	500.	1.75	118000	72.	~1.1	696.	1.35	989.	10.
VEPP2000	172.1	120.	0.23	8200	29.	0.95	246.0	0.4		<10.
DUKE-2	178.5	730	3.46	39000	77	3.16	-	-	-	-
KEK-PF	500.	785	3.45	39500	90.	1.4	791.	1000.	792.	5100.
ASP/Toshiba	500.	750	3.8	40400	75.	1.0	790.	25.	803.	8500.
BESSY	500.	735.	3.4	29600	80.	0.5	670.	11.	1072.	54.
SC Cavities		V_{cy} MV	R_s/Q Ω							
CESR	500.	2.5	44.5	-	-	2.9	2253.	0.18	715.	32.
SOLEIL	352.	2.5	45.	-	-	3.65	699.	2.1	504.	49.

BESSY HOM Damped Cavity

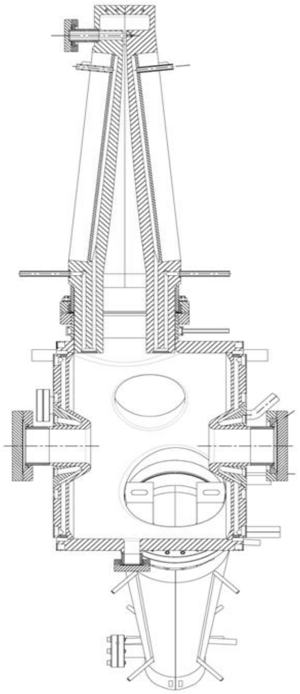
Project collaboration: - BESSY / Germany
(EC funded) - Daresbury Lab / England
- DELTA / Dortmund University, Germany
- National Tsing Hua University / Taiwan

Design Goals

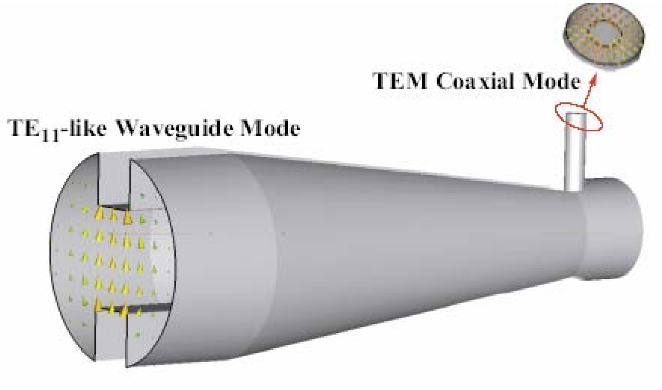
- **Frequency**
  f_{rf} = 500 MHz
- **Insertion length**
  $L < 1$ m
- **Shunt impedance**
  R ≈ 3 - 4 MΩ
- **Max. thermal power**
  P = 100 kW
- **Design to fit into**
  <u>existing</u> ring tunnels



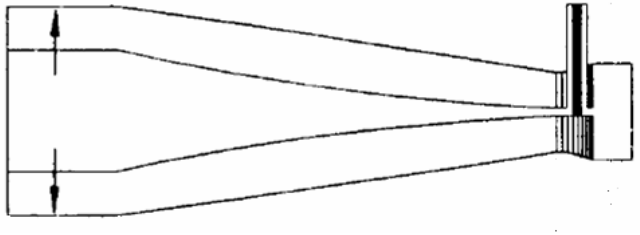
f-cutoff = 615 MHz

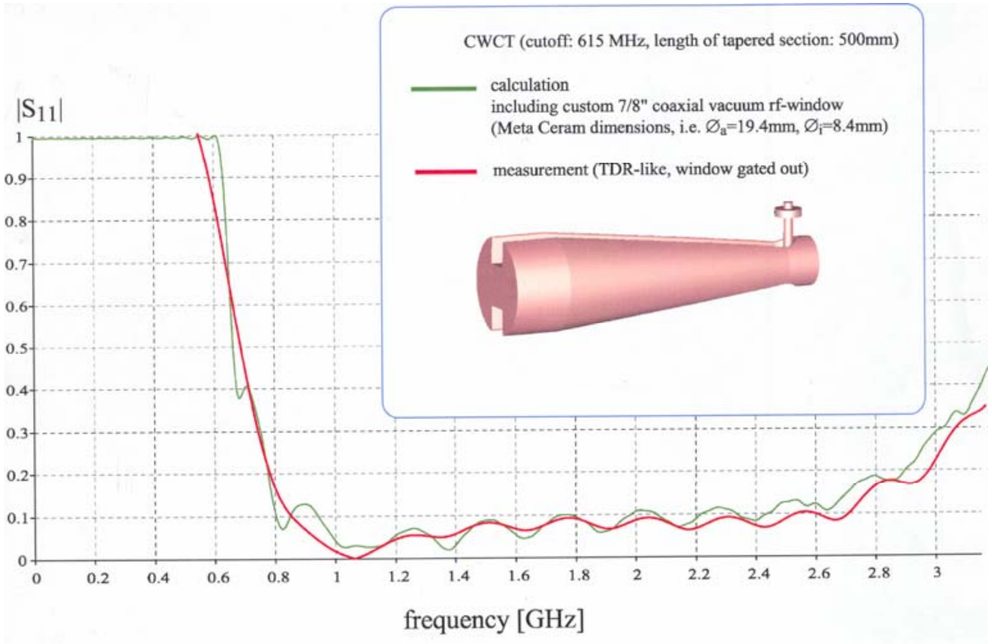


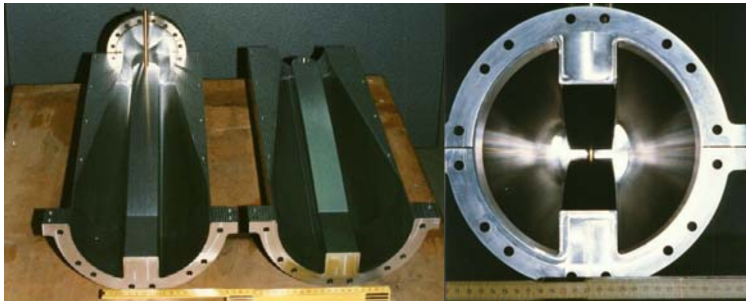
Tapered Circular WG to Coaxial Transition



Coaxial 7/8“ EIA ceramic vacuum window with commercial 50 Ohm load, 3 kW

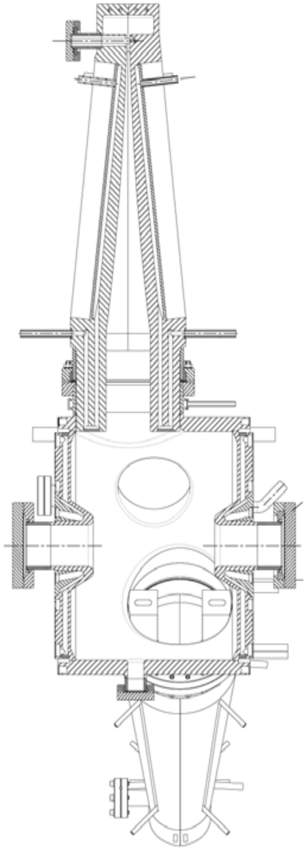




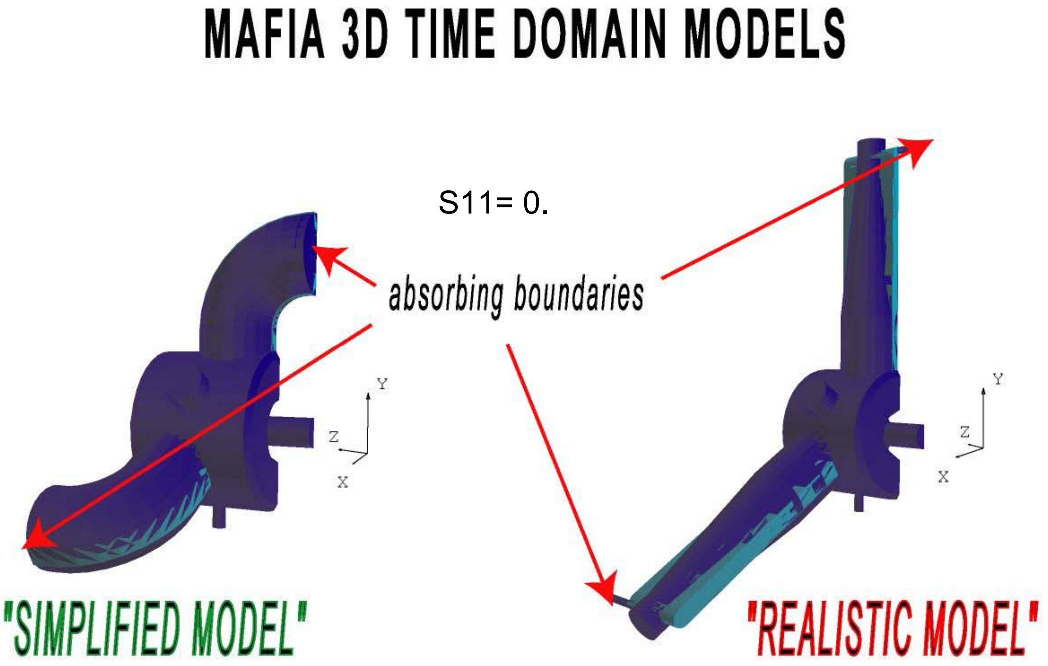


low power model

Simulation Models



Numerical optimisation:
cavity length / diameter, nose cone shape,
waveguide position and cut-off were varied
one by one



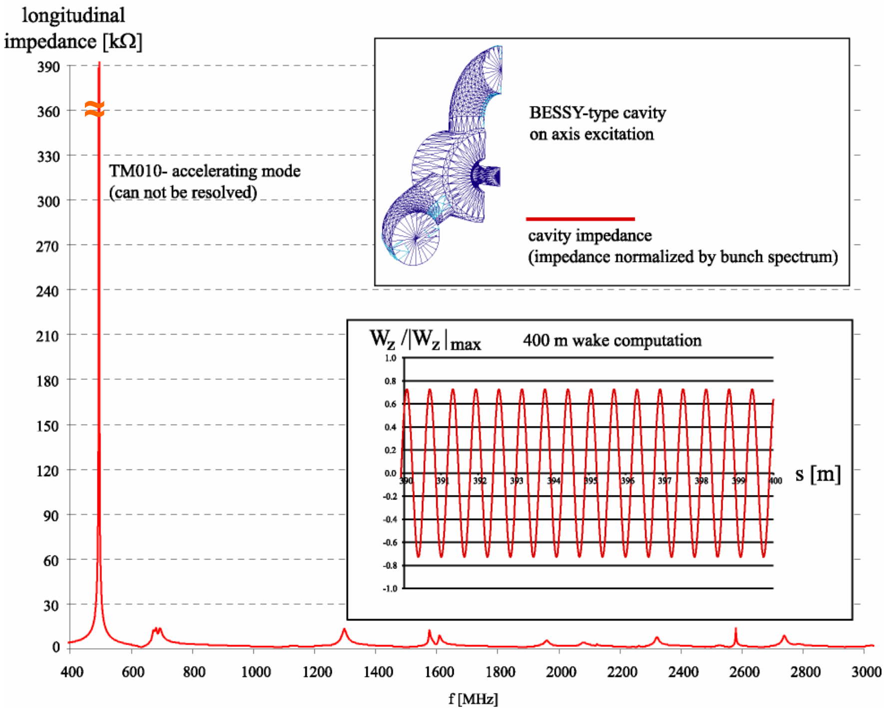
~ 10^6 mesh points
1.5 days cpu time

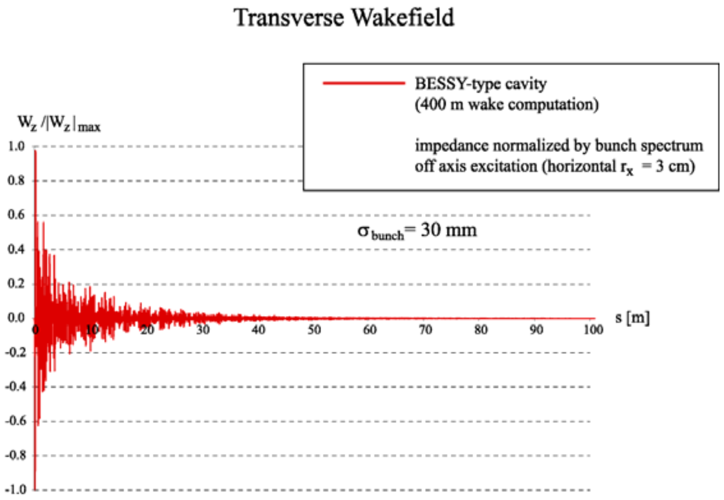
~18* 10^6 mesh points
4 weeks cpu time

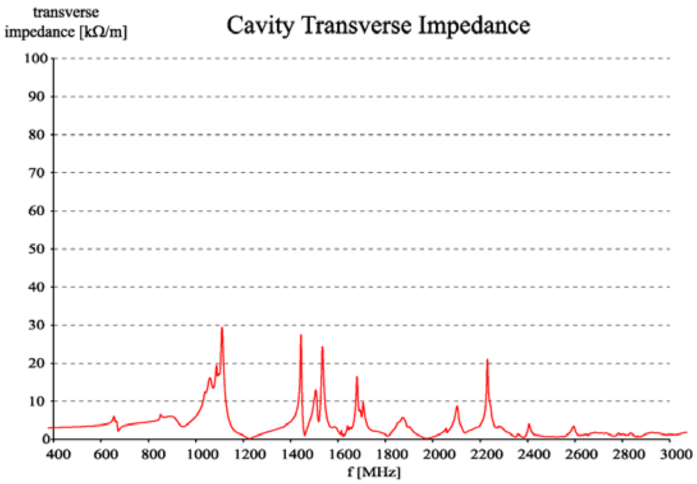
Today, with improved computer speed and software tools: ~ 1 day cpu time

Impedance Spectrum Calculations

- ♦ Evaluate wake field of a bunch in time domain
- ♦ Fourier transform of wake field
  → impedance vs frequency





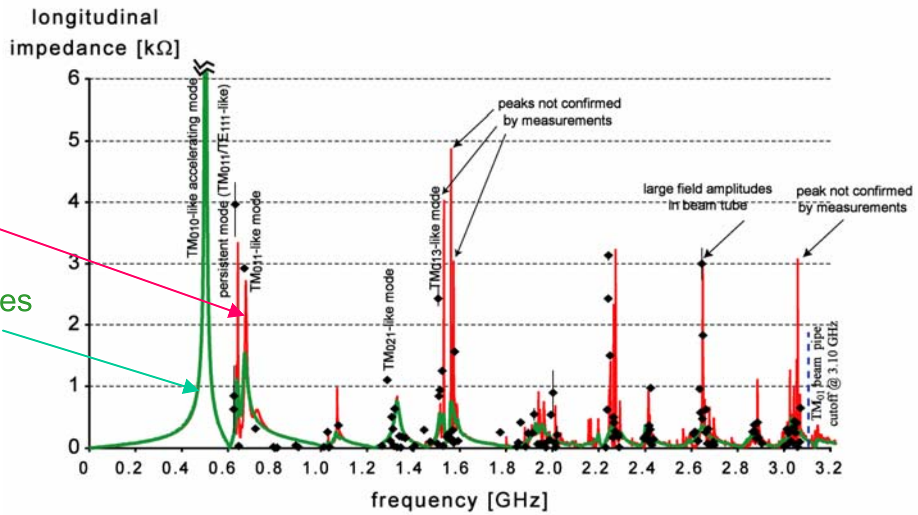


Low Power Measurements

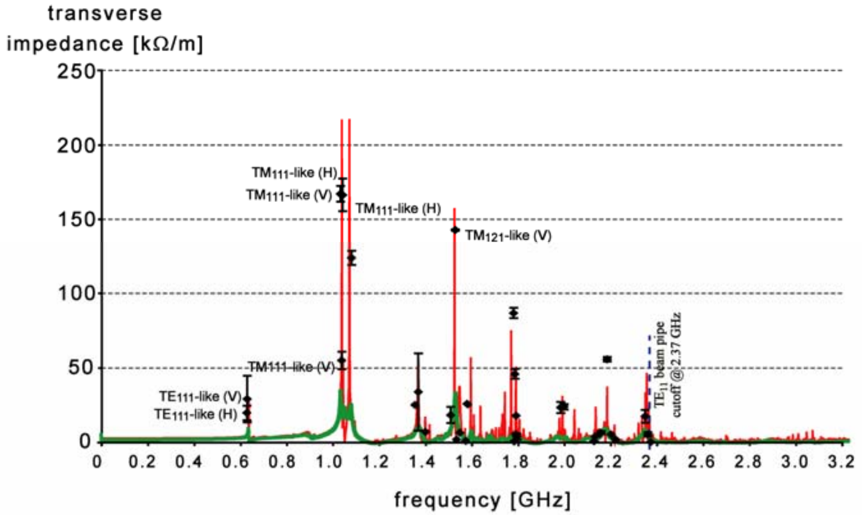
Prototype cavity:
Bead pull measurements

Tapered waveguides

Homogenious waveguides
with S11 = 0 boundary



Prototype fabricated by ZANON SpA / Italy



First Beam Tests in DELTA / Dortmund University

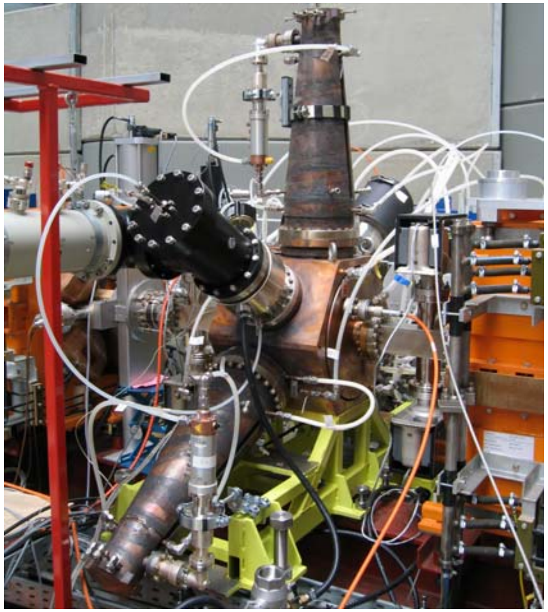
CBM beam spectra:
(longitudinal case)

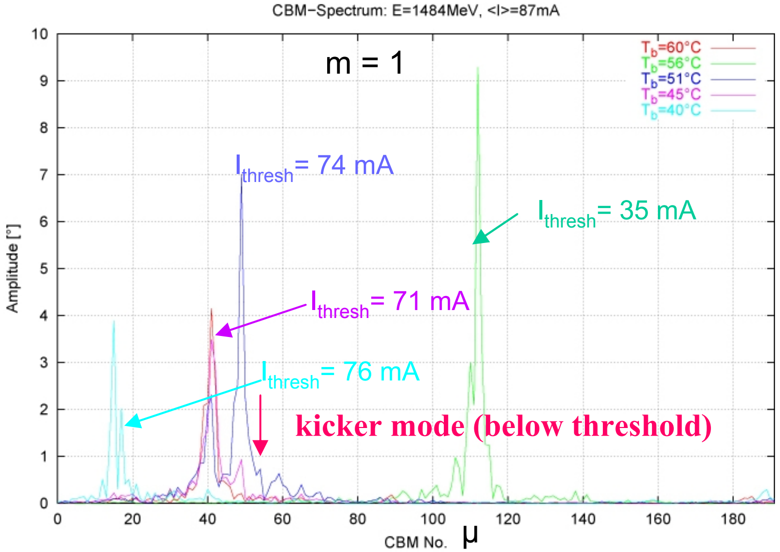
$$f_{\mu m}^{\pm} = n f_{rf} \pm (\mu f_0 + m f_s)$$

μ coupled bunch mode number

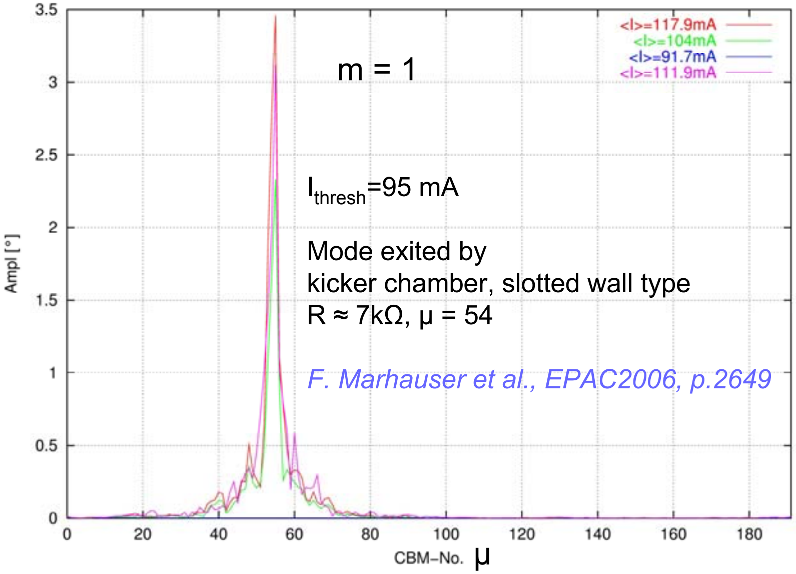
DORIS Cavity

Prototype cavity installed in the DELTA ring / Dortmund University





BESSY HOM Damped Cavity



Mode exited by
kicker chamber, slotted wall type
R ≈ 7kΩ, μ = 54

F. Marhauser et al., EPAC2006, p.2649

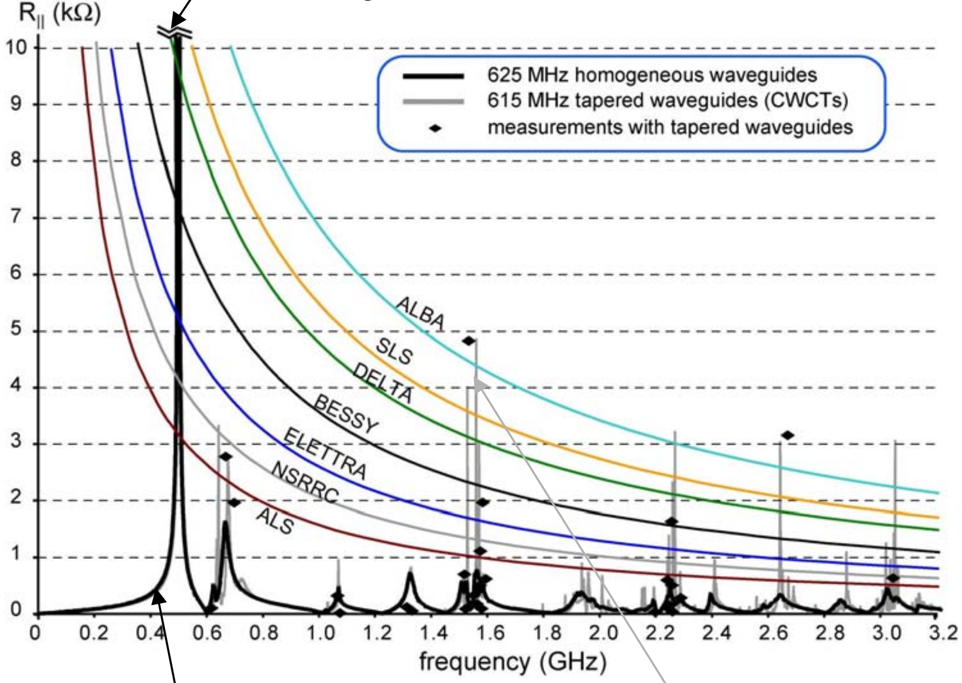
No cavity driven CBMs excited in DELTA

R. Heine et al., EPAC2006, p.2856

Impedance Spectra and Threshold Impedances

Longitudinal Impedance

$$Z_{\parallel}^{thresh}=\frac{1}{N_C}\cdot\frac{1}{f_{\parallel,HOM}}\cdot\frac{2\cdot E_0\cdot Q_s}{I_b\alpha\tau_s}$$



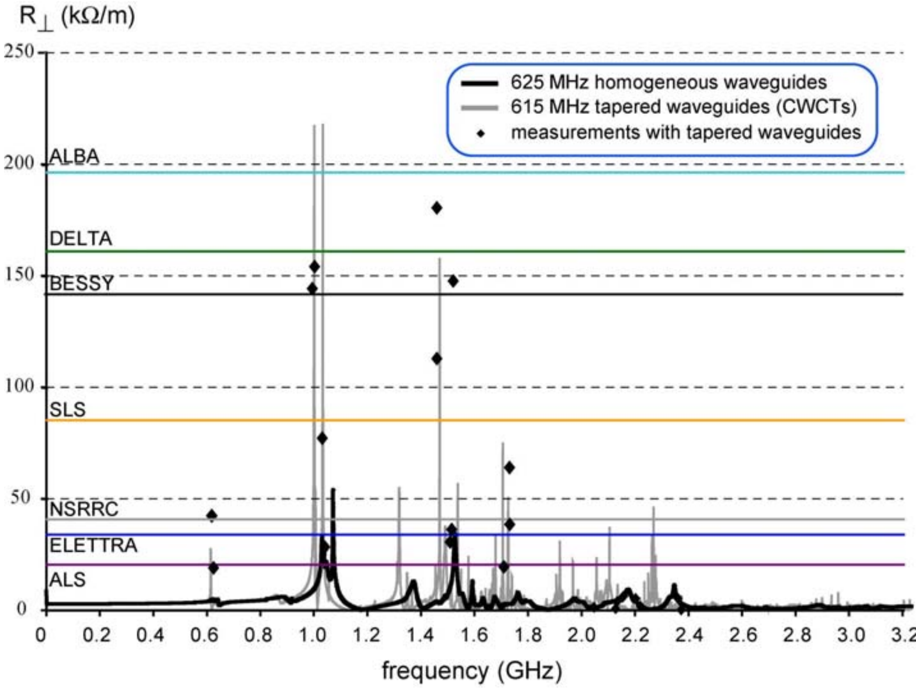
accelerating mode

homogenous waveguides

tapered waveguides

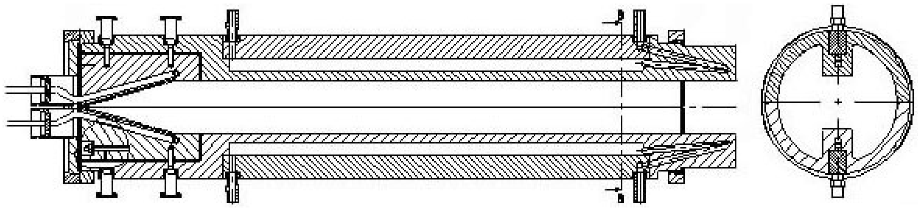
Transverse Impedance

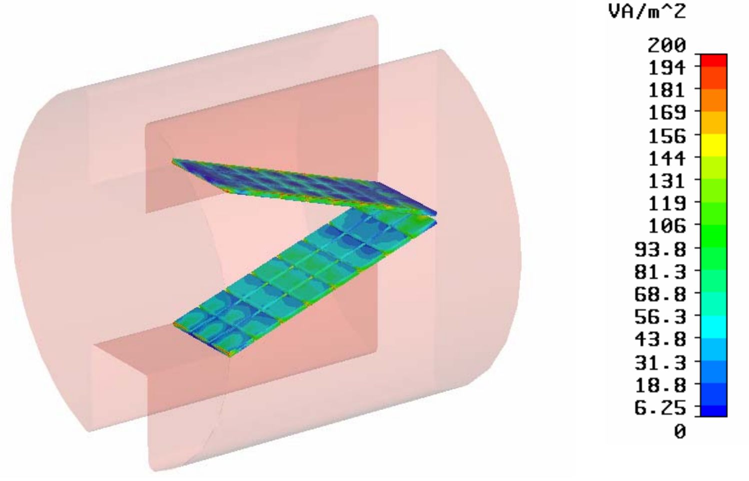
$$Z_{x,y}^{thresh}=\frac{1}{N_C}\cdot\frac{2\cdot E_0}{f_{rev}I_b\beta_{x,y}\tau_{x,y}}$$



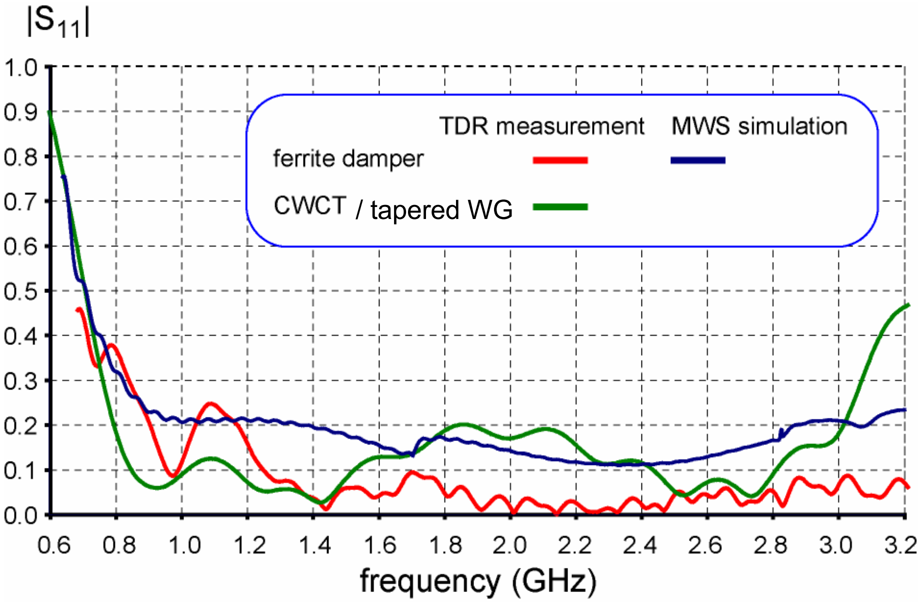
Homogenous Damping Waveguide Design

- constant cross-section
- wedge shaped ferrite absorber





Simulations and
time domain reflectometry measurement



→ **good matching, r < 20%**

Fabrication of Ferrite Absorber Elements

Callenge: Bonding of ferrite on copper

Solution adopted after tests with different technologies:

♦ Large difference in thermal expansion
→ small ferrite tiles (19.6 x 16.6 mm)

♦ NiZn ferrite tiles soldered on „soft" copper

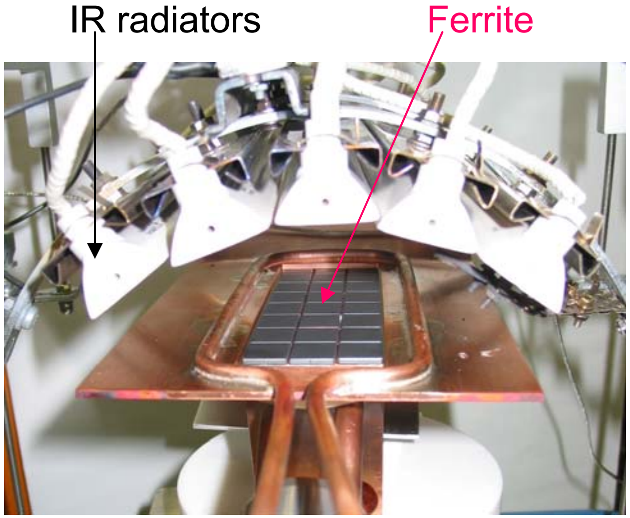
♦ Non-eutectic SnAg(0.1%) solder material,
T-melt = 295 °C

♦ Contact layer: sputtering of Ti and Cu

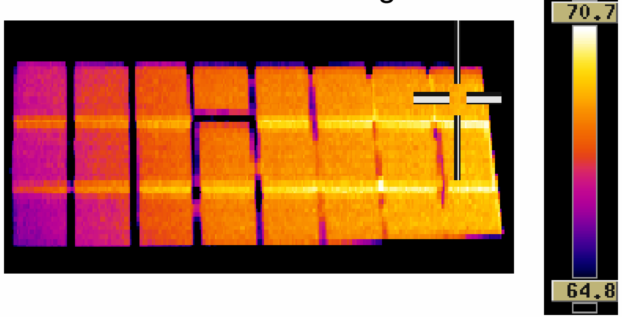
♦ Quality test of bonding process:

- Exposition with high intensity IR radiation
- Homogeniety of ferrite surface temperature checked with IR camera

IR Test: Thermal power density up to 14 W/cm^2
→ safety margin of ~ 3

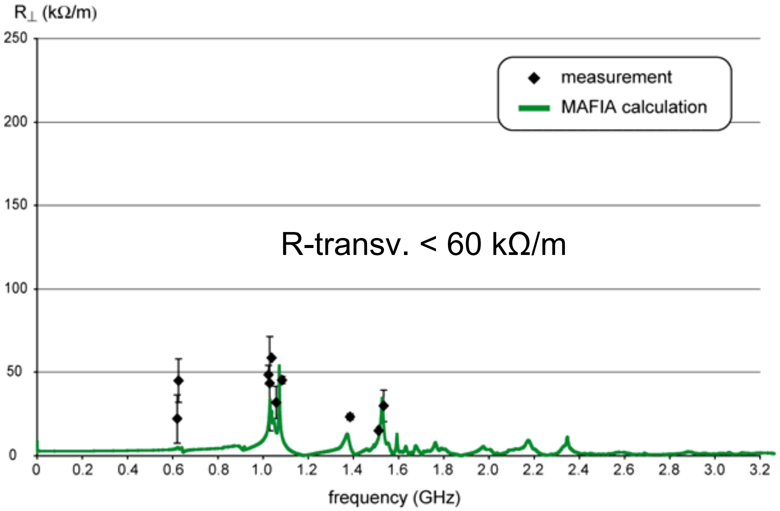


IR camera image



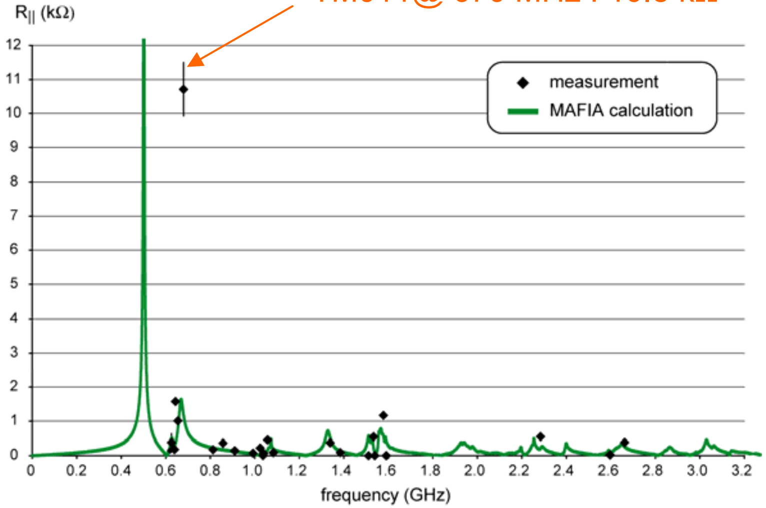
Metrology Light Source Cavity

- ♦ Cavity with homogenous ferrite loaded WG built by ACCEL (f-cutoff = 625 MHz, 30% less fundamental mode power absorbed in the ferrites)
- ♦ Bead pull measurements to verify the expected HOM impedances



R-transv. < 60 kΩ/m

TM011@ 670 MHz : 10.8 kΩ



- ♦ TM011 impedance of 10.8 kΩ not confirmed by simulations (MWS/CELLS, GdfidL/ESRF) so far
- ♦ Decision at CELLS to use the cavity for ALBA
  →Attempt to reduce TM011 impedance by a change of cut-off from 625 MHz to 615 MHz

Gap between Ridge and Cavity Wall

Measurements at CELLS with pre-series ALBA cavity (615 MHz WG cut off frequency):

♦ TM011 impedance still ~ 12 kOhm

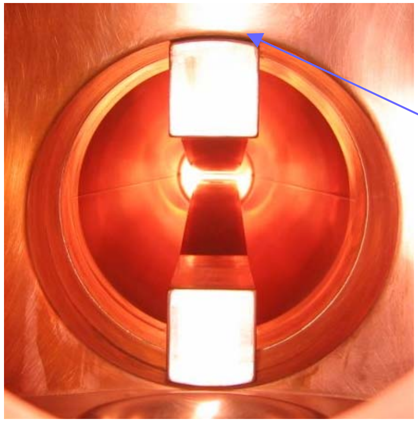
♦ Attempt to get more insight:
Closing the gaps provisionally by rf-springs reduces TM011 impedance to 5 kOhm

→ high TM011 impedance is related with the gap

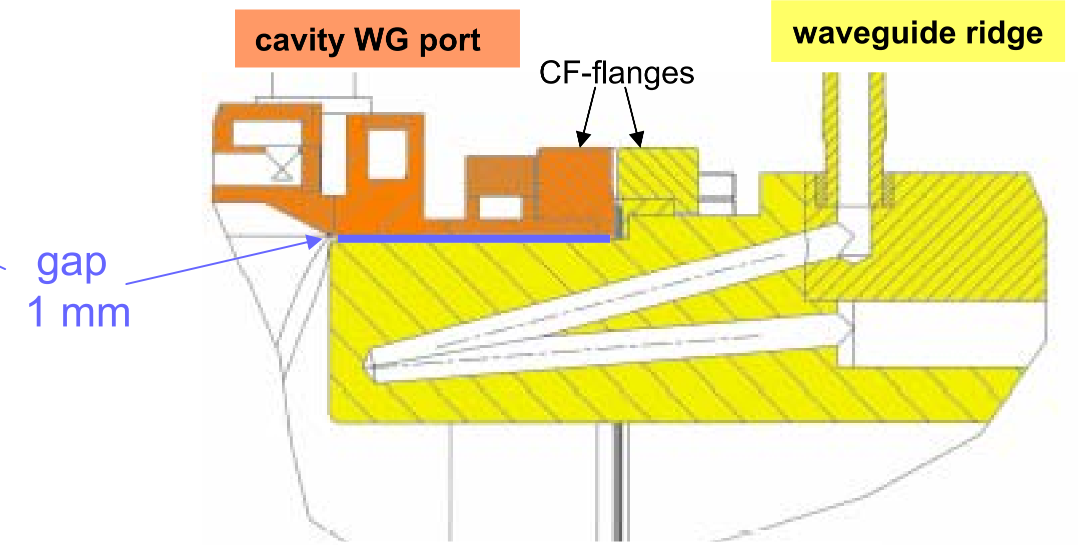
→ M. Langlois et al., this conference

♦ Gap size 1mm, comparable with minimum mesh size of numerical model

→ simulations fail to provide quantitative explanation



View along the WG axis



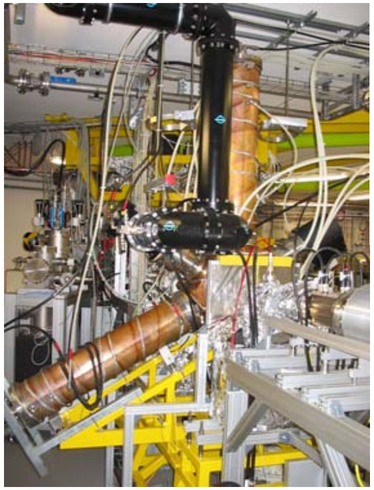
Cut through the cavity / WG flanges

Metrology Light Source Cavity Commissioning

Results of low power measurements

Resonance Frequency	499.515	MHz
Tuning Range	2	MHz
Shunt Impedance @ RT	3.4	MΩ
Max.Longitudinal HOM Impedance	10.8	kΩ
Max. Transverse HOM Impedance	60	kΩ/m
Waveguide cut-off	625	MHz
Coupling Factor for TM010 (adjustable)	0.5 - 8	

Installation in the MLS ring



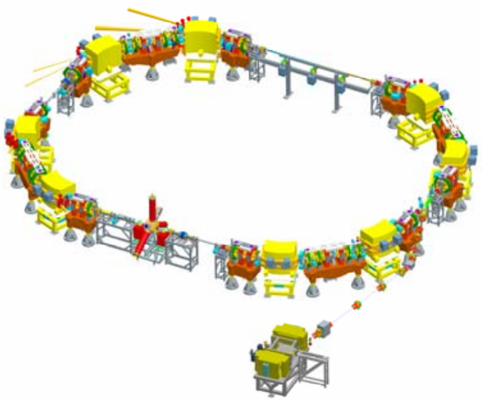
RF conditioning at high power

- After baking at 130 °C for 5 days: → base pressure $3\ 10^{-10}$ mb
- RF conditioning up to 40 kW cw in only 2 days: → good quality of inner cavity surfaces with respect to roughness and contamination
- No serious multipacting levels

Beam commissioning

- 200 mA accumulated at 100 MeV, 175 mA accelerated to 630 MeV
- Preliminary studies indicate: no cavity driven longitudinal and transverse MBO

→ *J. Feikes et al., EPAC 2008*

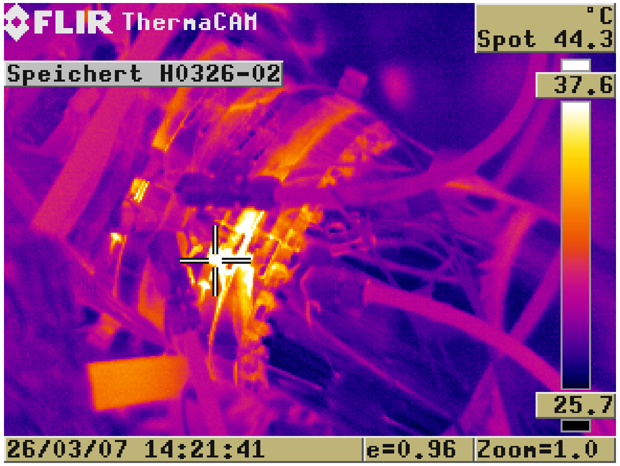


- However: Vacuum problem at 45 kW at the WG flanges related with a temperature incresase in the ridge area

→ Operation power limit so far: 40 kW

Power Limitation: Heating of Flange in the Gap Region

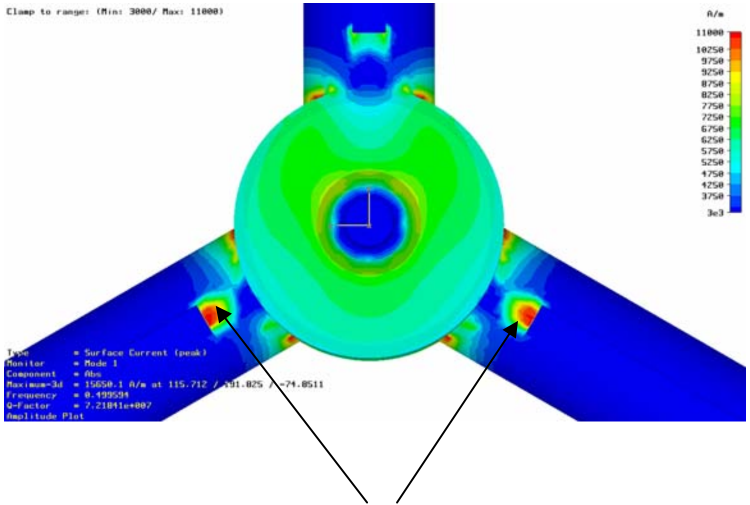
IR image of flange region



Measurement of temperature distribution on flange circumference: ΔT-max = 28°C @ 40 kW.
Max. differential axial deformation: 0.03 mm

→ CF-flange deforms due to non-homogenous temperature distribution, causing the vacuum problem

Magnetic rf field (MWS) calculation (CELLS) on inner cavity surfaces ~ sqrt (power density)

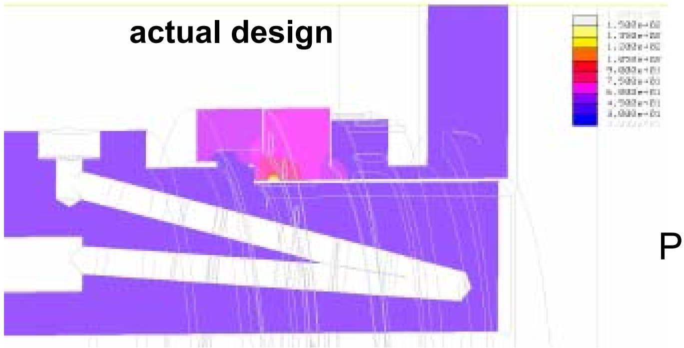


```
Type          = Surface Current (peak)
Monitor       = Mode 1
Component     = Abs
Maximum-3d    = 15650.1 A/m at 115.712 / 91.825 / -74.8511
Frequency     = 0.499594
Q-Factor      = 7.21841e+007
Amplitude Plot
```

High power density
in gap region

Gaps have not been included in the initial numerical model calculations because of mesh size limitations

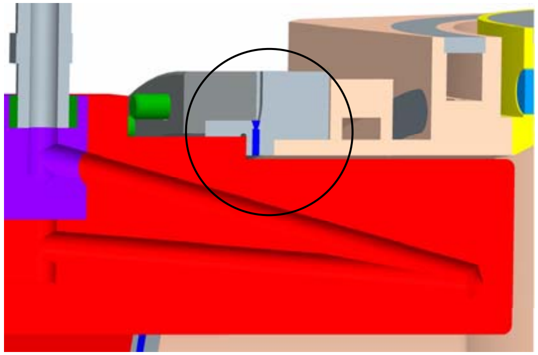
Thermal Simulations

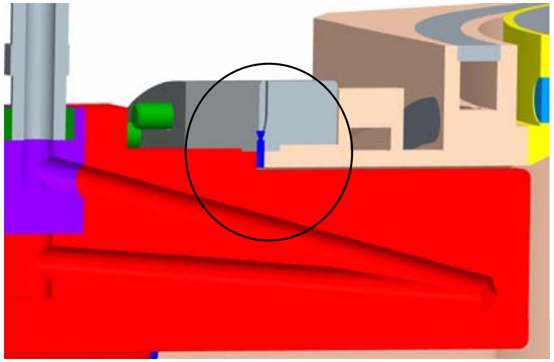


Power in gap region:
340 W

ΔT-max on cavity CF-flange: 28 °C @ 40 kW
T-max (hot spot): 160 °C

ΔT-max on cavity CF-flange: 14 °C @ 40 kW
T-max (hot spot): 62 °C



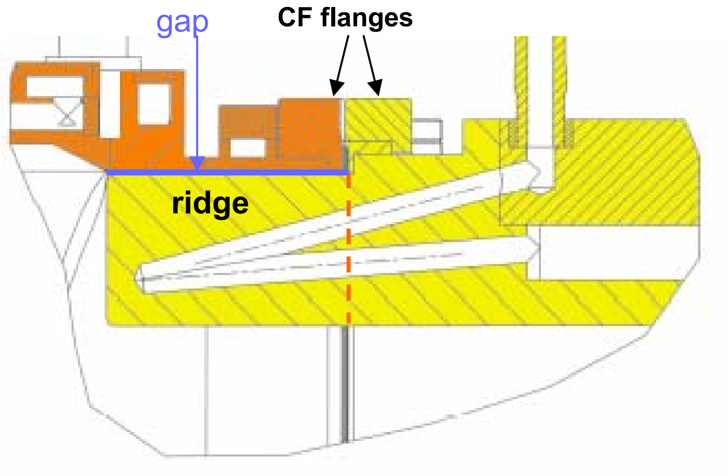


Scaling to 80 kW power: ΔT-max on cavity CF-flange: 28°C
T-max (hot spot): 95 °C

→ safe operation up to at least 80 kW rf power is expected
→ modification implemented in the series cavities for CELLS and for BESSY II, power tests at CELLS in fall 2008

Can we Avoid the Gap?

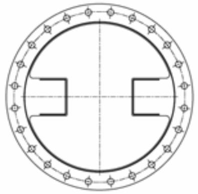
- ♦ Gap causes both problems
  - high TM011 impedance
  - local heating in gap region
- ♦ But allows simple engineering solution to connect waveguide and cavity body

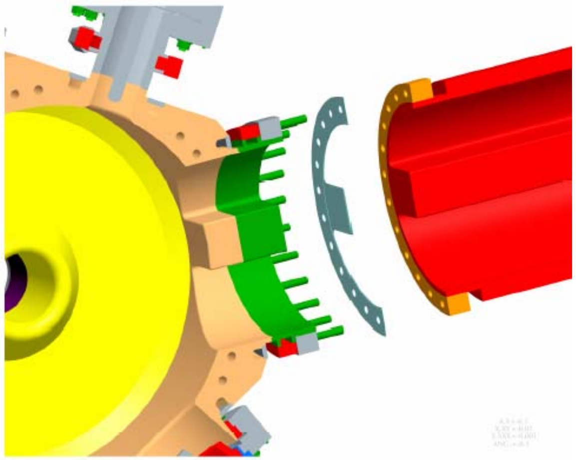


- ♦ Gap cannot be avoided by shortening the ridge → degradation of HOM damping efficiency

Concept how the gap could be avoided

- ♦ machining of the WG ridge as part of the cavity body
- ♦ special gasket following inner contour of the WG (e.g. VAT-seal technology)





- ♦ higher complexity and cost → option to extend thermal power capability beyond 80 kW

Conclusions

- HOM damped cavities are mandatory for state of the art high brilliance storage ring SR sources

- HOM impedances can conceptually be reduced down to a level where most existing synchrotron light sources can operate below threshold for multi-bunch instabilities

- The HOM damped cavity presented has demonstrated
  - max. transverse impedance < 60 kΩ/m
  - max. long. Impedance < 11 kΩ with potential for further reduction to ~ 5 kΩ
  - fundamental mode shuntimpedance ~ 3.4 MΩ
  - demonstrated operation up to 40 kW (520 kV), expected safe operation up to at least 80 kW (730 kV) after modification

- The cavity is in routine operation in the MLS ring, six cavities will start operation at CELLS / Spain in fall 2008, and four cavities will be installed in BESSY II. At ESRF work is in progress for a 352 MHz cavity based conceptually on a similar design.

- Lessons learnt: Even with the most advanced EM field codes the influence of small gaps cannot be simulated properly because of mesh size limitations. Such gaps, however, can have a strong influence on the cavity performance.

- Conceptional solution to avoid the gap: option for operation beyond the expected thermal limit above ~ 80 kW, however with higher complexity and cost.

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♦ DELTA / Dortmund University, Germany	R. Heine, T. Weis
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- NSC National Science Council / Taiwan

DELTA Beam Spectra

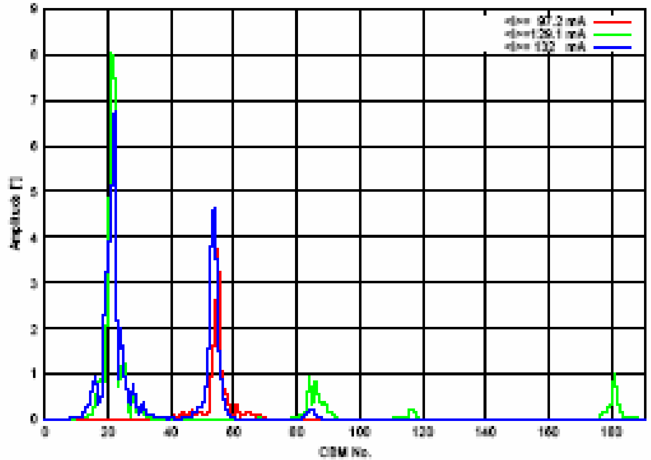


Figure 4: CBM spectra of a damped DORIS-cavity at 1.5 GeV and mean currents of 97 (red), 129 (green) and 132 mA (blue), also with this resonator CBM 21-22 and 53-55 is appearing.

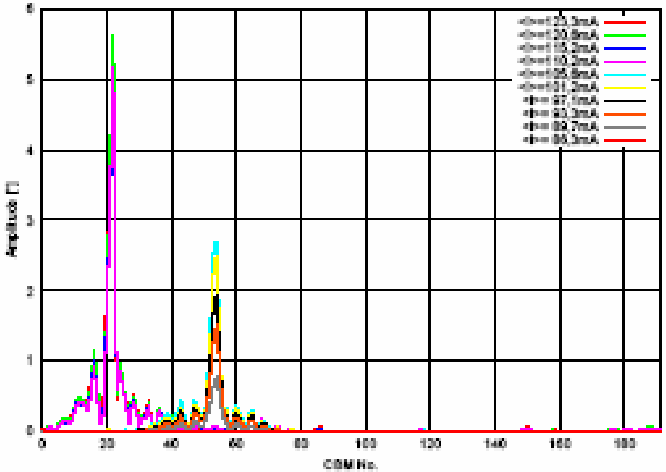


Figure 3: CBM spectra at 1.5 GeV and mean currents between 123.3 and 86.3 mA (top to bottom in legend) with the EU-cavity

$$P_{HOM} = (I_b / n_b)^2 (1/T_b) k_{//}(\sigma)$$

HOM Power Considerations

	BESSY II	ELETTRA	ALBA	ALS	SLS	ANKA	NSRRC
σ [mm]	4.8	5.4	4.6	9.	4.	9	7.5
$k_{\|\|}$ [V/pC]	0.7	0.64	0.72	0.5	0.8	0.5	0.52
E [GeV]	1.7	2.	3.	1.5	2.4	2.5	1.5
h	400	432	448	328	480	184	200
Multi-bunch							
I-beam [mA]	400	300	400	400	500	400	240
n-bunch	260	432	360	328	480	184	200
Q-bunch [nC]	1.23	0.6	1.0	0.8	1.	0.8	0.24
P-HOM [W]	530	207	360	160	400	160	60
Singel-bunch							
I-beam [mA]	30	-		2 x 20	-	-	25
Q-bunch [nC]	24	-		2 x 6.6	-	-	10
P-HOM [W]	504	-		66	-	-	66

$$P_{HOM} = Q_{bunch}{}^2 (1/T_{bunch}) k_{//}(\sigma)$$

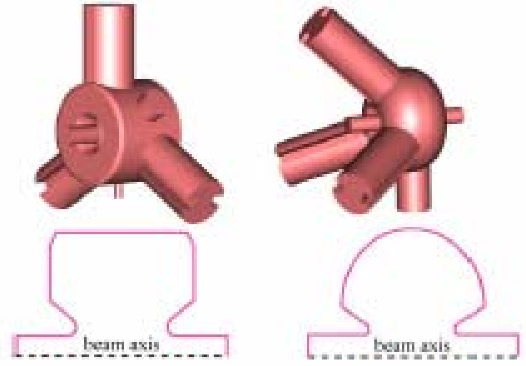
$$k_{//}(\sigma) = \sum_{n=1}^{\infty} \frac{\omega_n}{2} \left(\frac{R}{Q}\right)_n \exp(-\omega_n^2 \sigma^2)$$

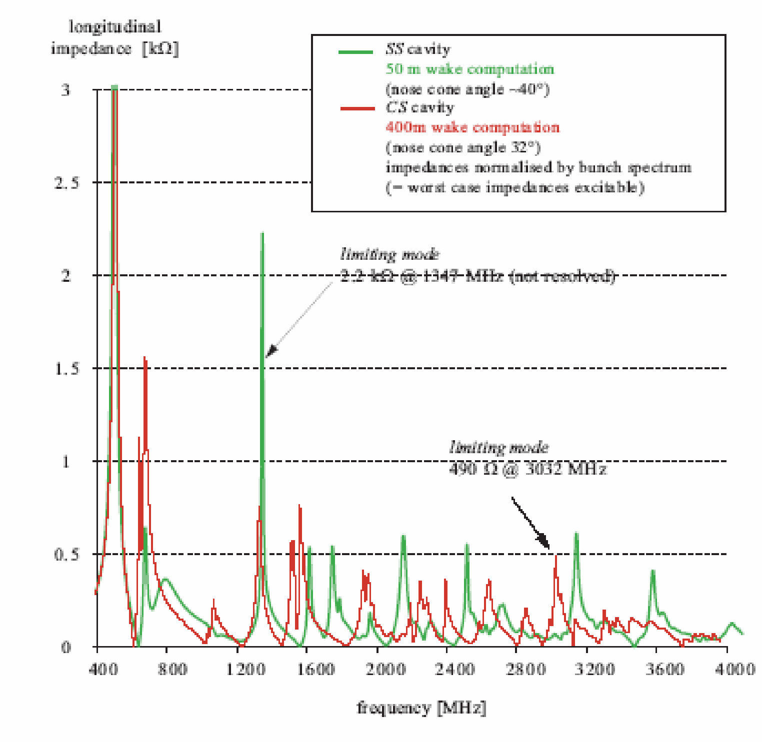
Max HOM power per cavity: P_{long} = 600 W
P_{trans} = 600 W
P_{f0} = 800 W
P_{total} = 2 kW

Test power density on ferrite: 14 W/cm^2
Total ferrite area : 480 cm^2

→ P_{max} = 6.7 kW per cavity
factor of 3 safety margin

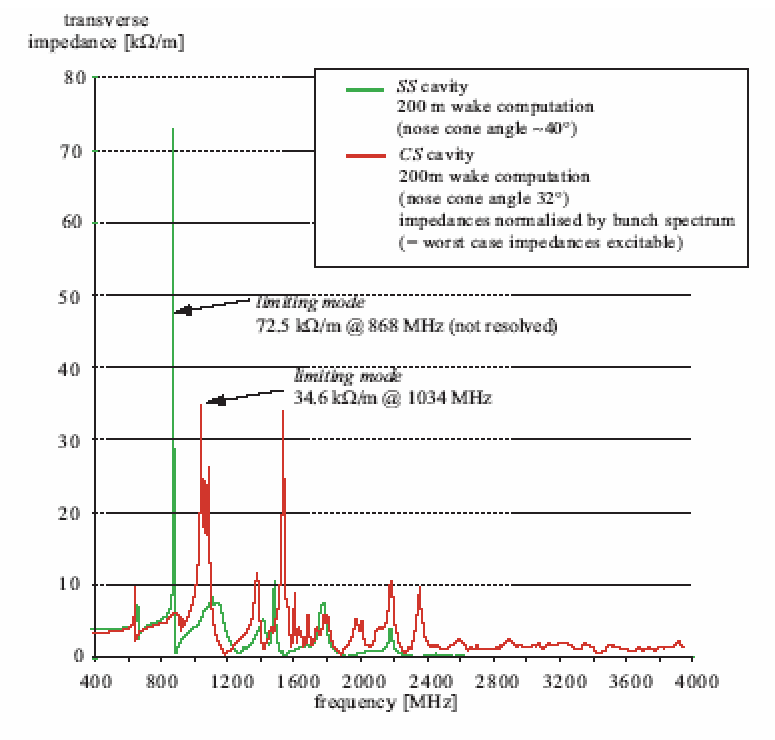
Cylindrical vs Spherical Shape





limiting mode
2.2 kΩ @ 1347 MHz (not resolved)

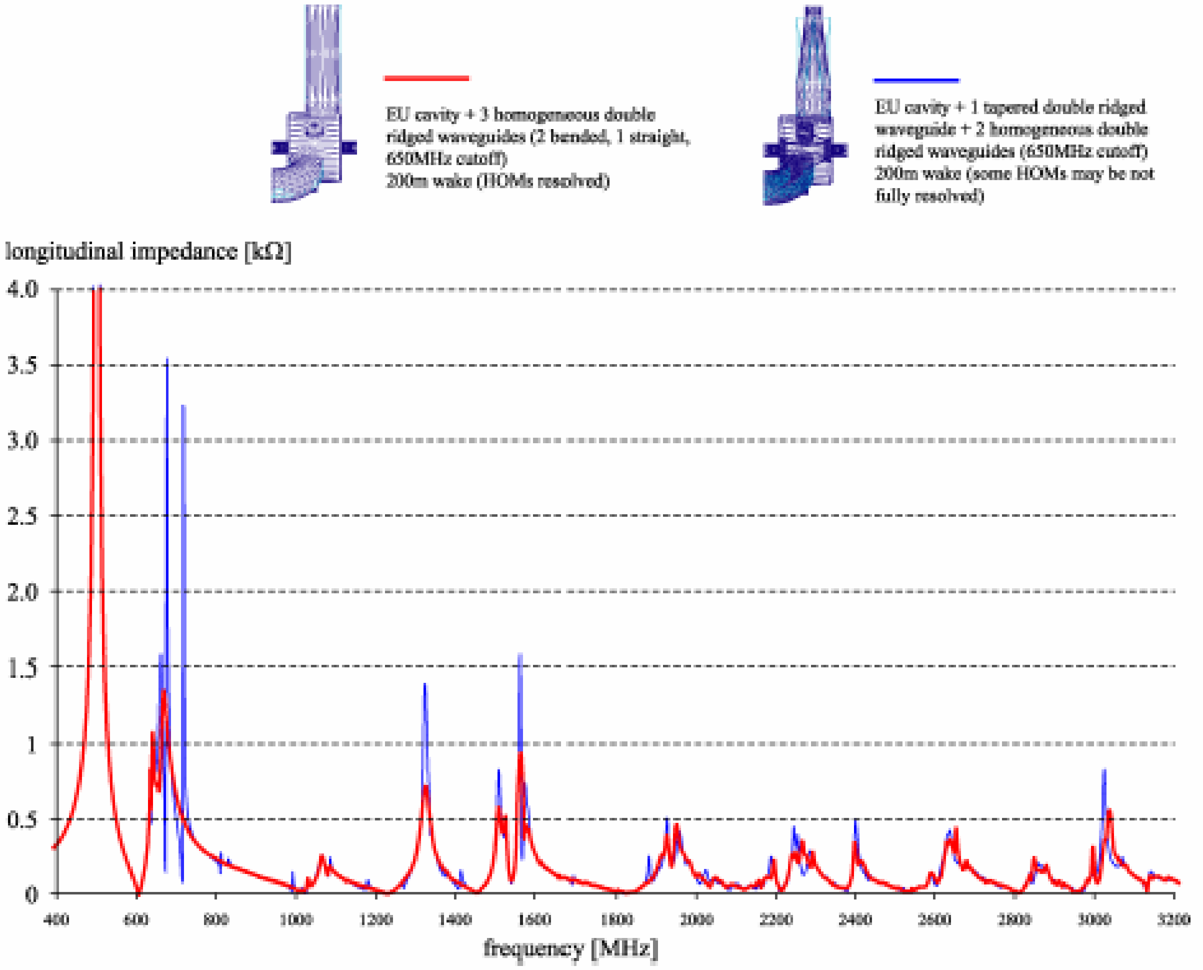
limiting mode
490 Ω @ 3032 MHz



limiting mode
72.5 kΩ/m @ 868 MHz (not resolved)

limiting mode
34.6 kΩ/m @ 1034 MHz

Tapered vs Homogenious Waveguides



EU cavity + 3 homogeneous double ridged waveguides (2 bended, 1 straight, 650MHz cutoff)
200m wake (HOMs resolved)

EU cavity + 1 tapered double ridged waveguide + 2 homogeneous double ridged waveguides (650MHz cutoff)
200m wake (some HOMs may be not fully resolved)

Fig. 2.4: Longitudinal coupling impedances of the EU cavity after replacing the upper homogenous by a tapered waveguide.