Design and Experimental Research of Harmonic Cavity for SSRF

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Background

3rd generation light source

Emittance：3～10nm.rad；

Bunch length：3～6mm；

Current：200～400mA；

→ Electron density increases

Touschek lifetime decreases

↓ Lifetime decrease → Users needs

Less radiation

← Higher harmonic cavity is one of the options

↑ Landau damping ← Damp multi-bunch instability ← Stable beam

Higher harmonic cavity's function:

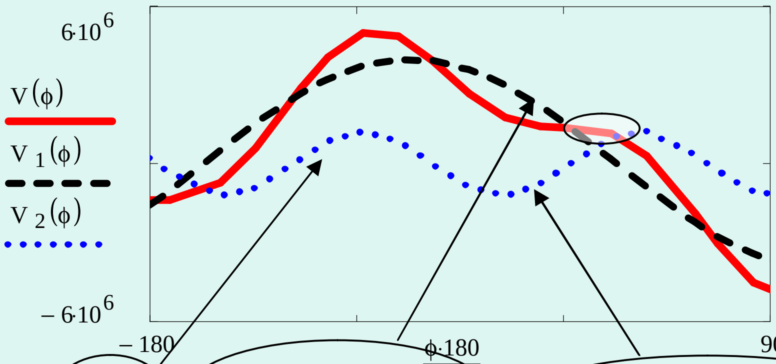
1.Increase lifetime (single bunch)

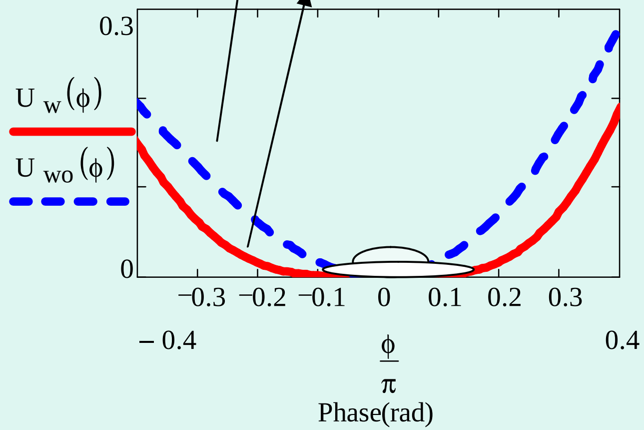
2.Damp the multi-bunch instability

Mechanism of the higher harmonic cavity

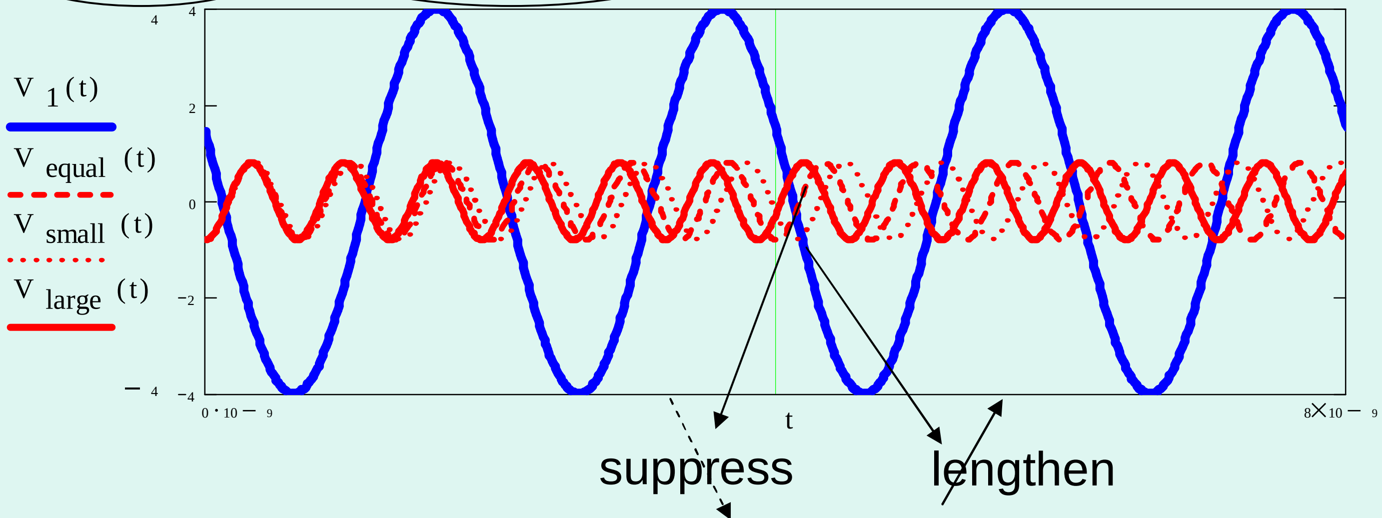
$$U_1(f) = (f - f_s)\cdot \sin f_s - \cos f_s + \cos f$$

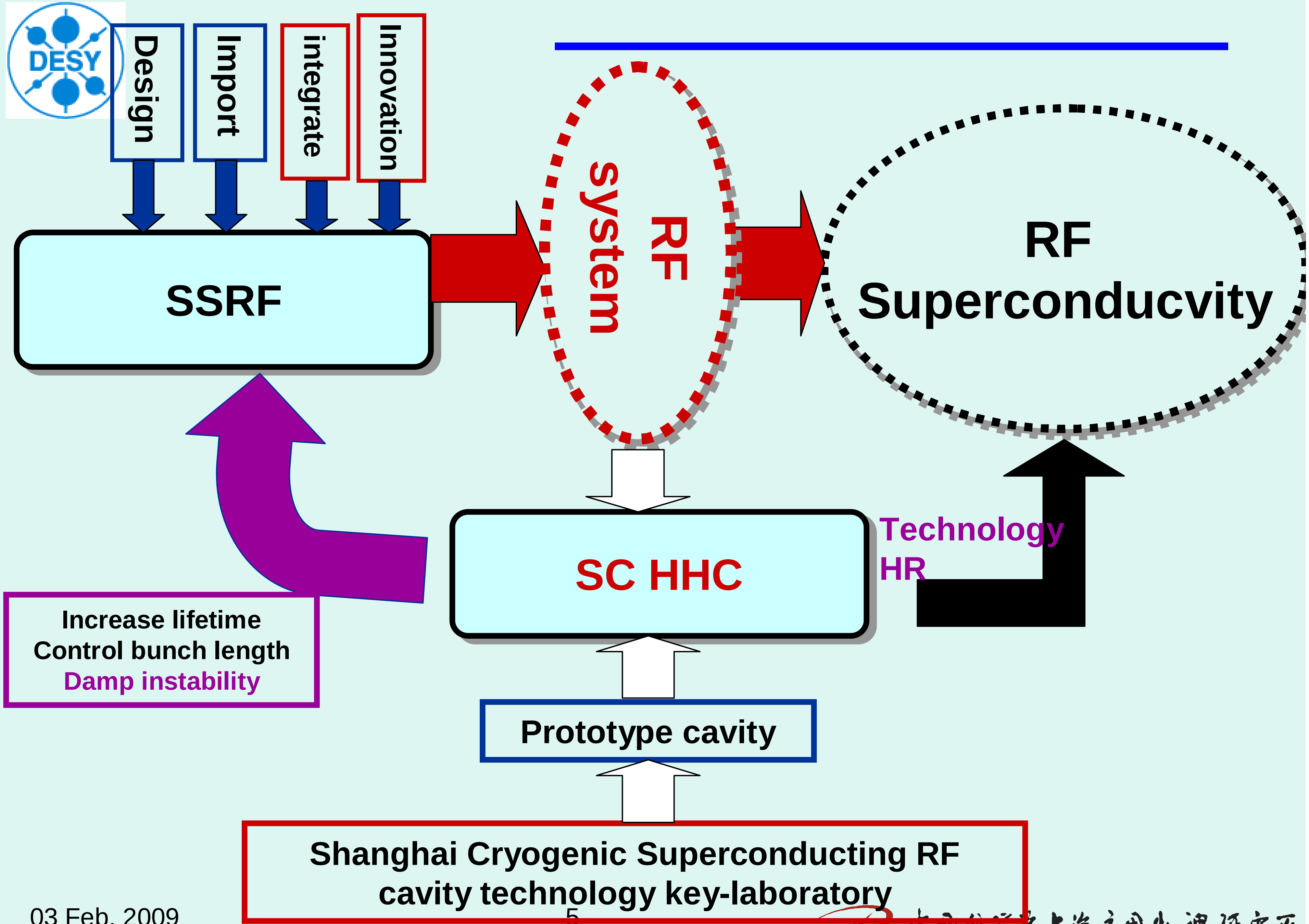
$$U(f) = \cos f - \cos f_s + \frac{k}{n}\left\{\cos\left[n\cdot(f - f_s) + f_n\right]\right\} + (f - f_s)\cdot \sin f_s + k\cdot \sin f_n$$





$$V(t) = V_c \sin(w_{RF} t + f_s) + V_{nc} \sin(n w_{RF} t + n f_n)$$




DESY
Design
Import
integrate
Innovation
SSRF
RF system
RF Superconducvity
SC HHC
Technology
HR
Increase lifetime
Control bunch length
Damp instability
Prototype cavity
Shanghai Cryogenic Superconducting RF cavity technology key-laboratory

World wide HHC

Facility	*Purpose*	*Mode*	*Status*	*Frequency (MHz)*	*N*	*Type*	*Cavity NO*	*Effect Factor*	*Energy (GeV)*
NSLS VUV Ring	L	P->A	Operation	211	4	NC	1	1.7	0.8
UV-SOR	L	Passive	Operation	270	3	NC	1	2.0	0.75
Aladdin	L	P->A	Operation	202	4	NC	1	1.7	0.8
MAX-II	L	Passive	Operation	1500	3	NC	4	1.5	1.5
Super-ACO	S	Active	Operation	500	5	NC	1	3	0.8
ALS	L	Passive	Operation	1500	3	NC	5	1.5	1.9
Bessy-II	L	Passive	Operation	1500	3	NC	4	1.5	0.9~1.9
DAFNE	L	Passive	Operation	1105	3	NC	1	1.8	0.51
SLS	L	Passive	Operation	1500	3	*SC*	2	2.2	2.4
Elettra	L	Passive	Operation	1500	3	*SC*	2	2.7	2.0
Bessy-II	L	Passive	Commissioning	1500	3	*SC*	1		0.9~1.9
PLS	L	Passive	Developing	1500	3	*SC*	2		2.5
Diamond	L	Passive	Developing	1500	3	-	-	-	3
NSLS-II	L	Passive	Developing	1500	3	*SC*	2	-	3
SSRF	L	Passive	Developing	1500	3	*SC*	3	-	3.5

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Outline

1. Cavity design

2. Cavity fabrication

3. Cavity test

4. Cavity system

1 Design

- SC/3rd/Passive
- Shape: Low loss/HOM propagate out
- Codes:
  MAFIA、SuperFISH、CLANS、 CST etc。

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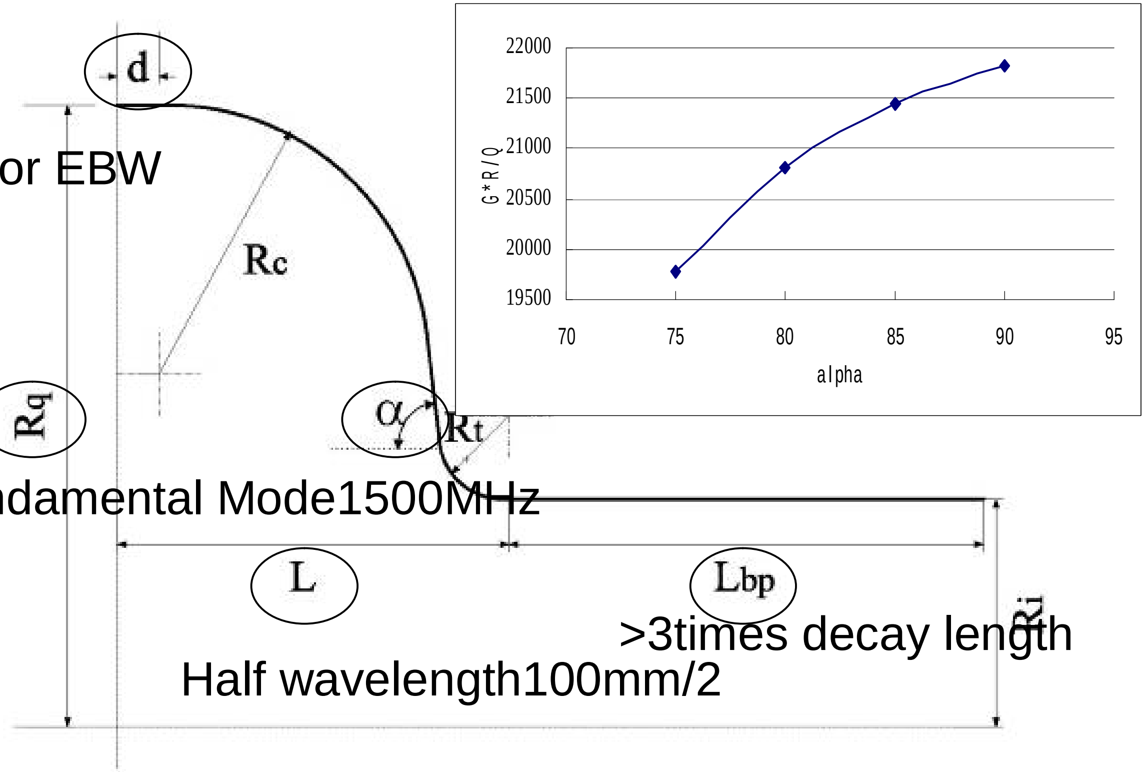
Shap

For EBW

$$P_c = \frac{1}{2} R_s \int_S |H|^2 \, ds = \frac{wU}{Q_0} = \frac{1}{Q_0} \frac{wm_0}{2} \int_V |H|^2 \, dv$$

$$Q_0 = \frac{R_{sh}}{R/Q} \qquad G = \frac{wm_0 \int_V |H|^2 \, dv}{\int_S |H|^2 \, ds} = R_s \cdot Q_0$$

$$\Rightarrow \quad P_c = \frac{V_c^2}{R_{sh}} = \frac{V_c^2}{Q_0 \cdot R/Q} = \frac{V_c^2 \cdot R_s}{G \cdot R/Q}$$



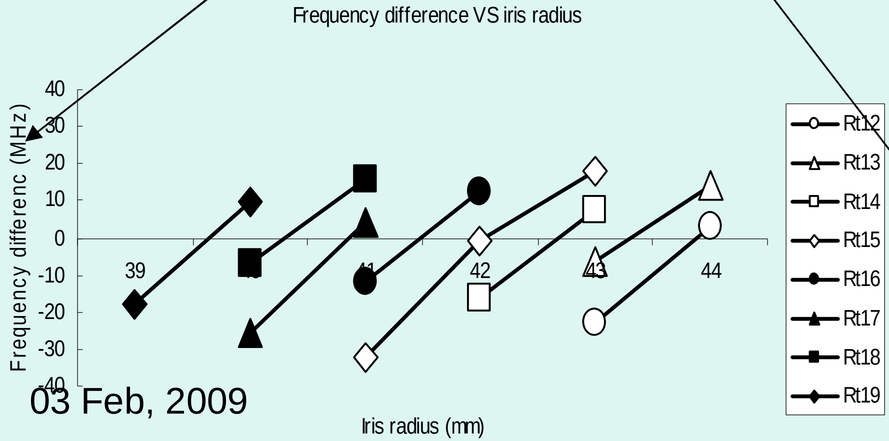
Fundamental Mode1500MHz

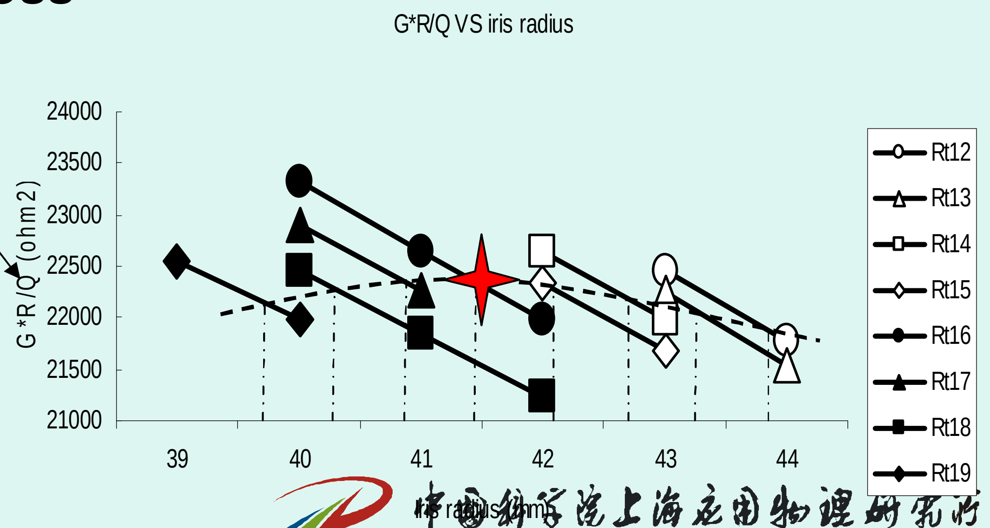
>3times decay length

Half wavelength100mm/2

1st longitudinal HOM's frequency > cutoff frequency

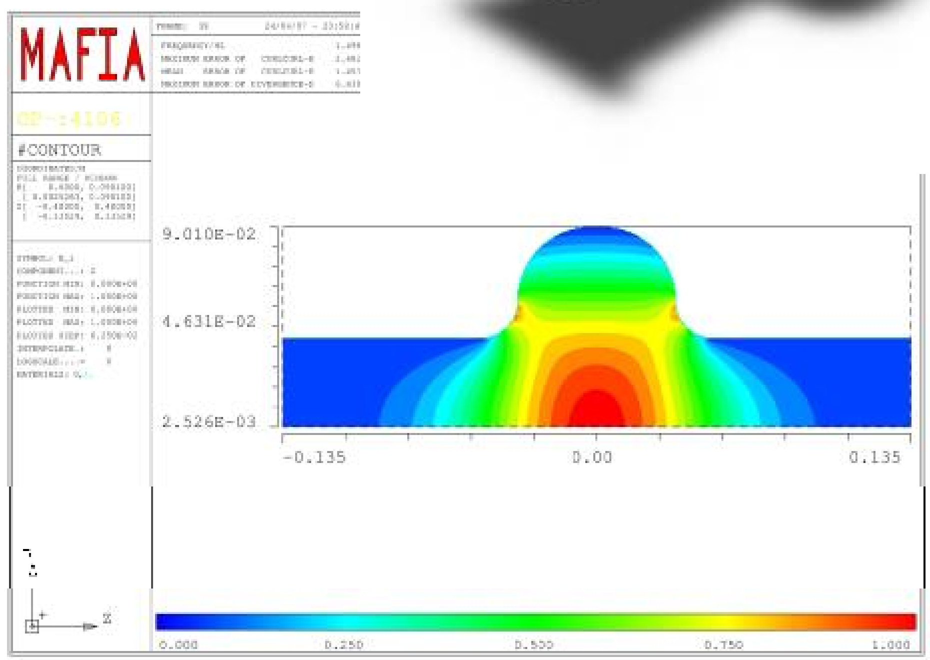
Low Loss

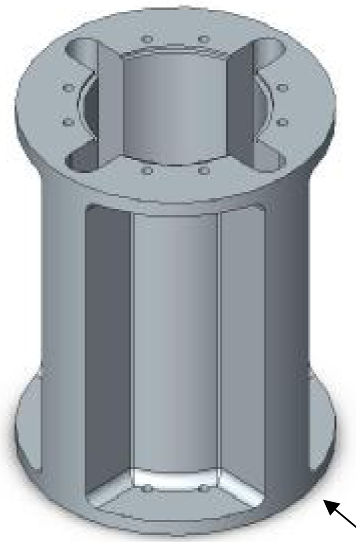


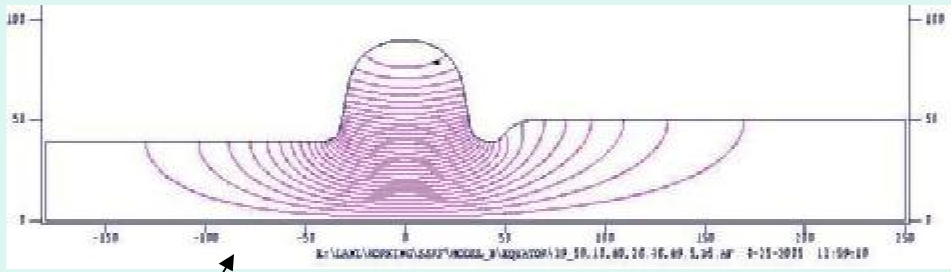


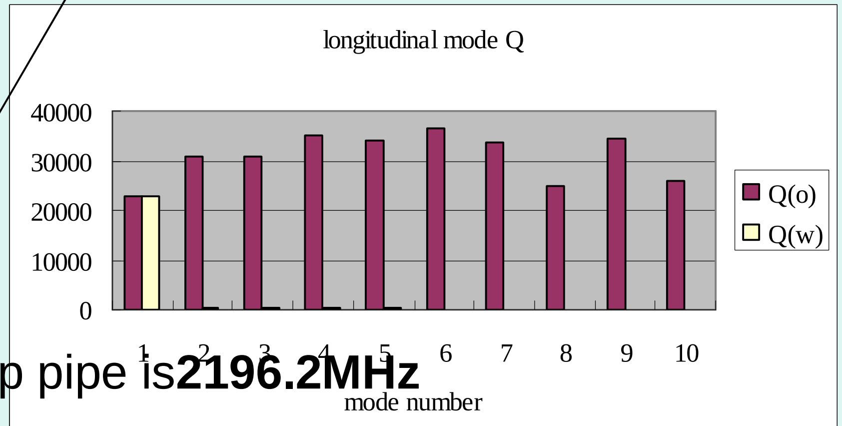
Single cell cavity shape

- freqency 1498.987MHz
- FM TM_{010}
- voltage 0.5MV
- Temp. 4.2K
- R/Q 83.0 Ω
- G*(R/Q) 22328
- Esp/Eacc 2.04

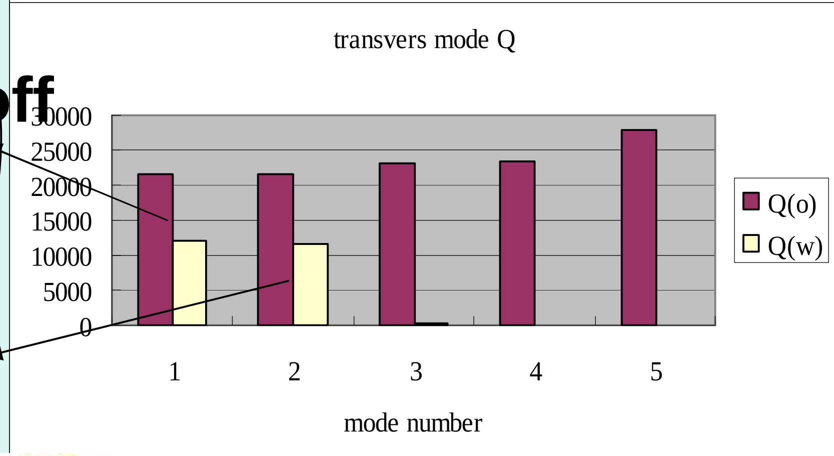


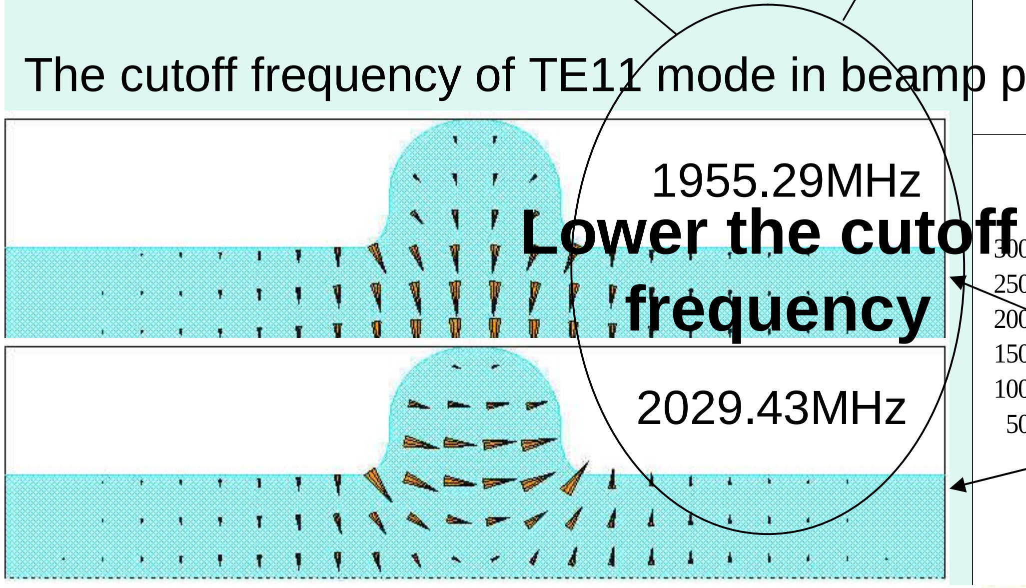


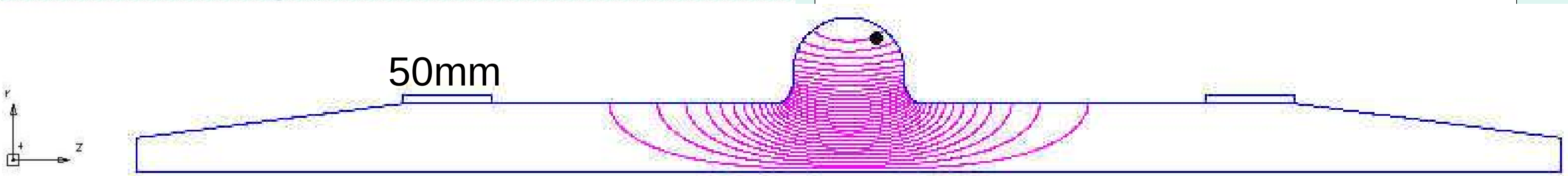




The cutoff frequency of TE11 mode in beamp pipe is **2196.2MHz**

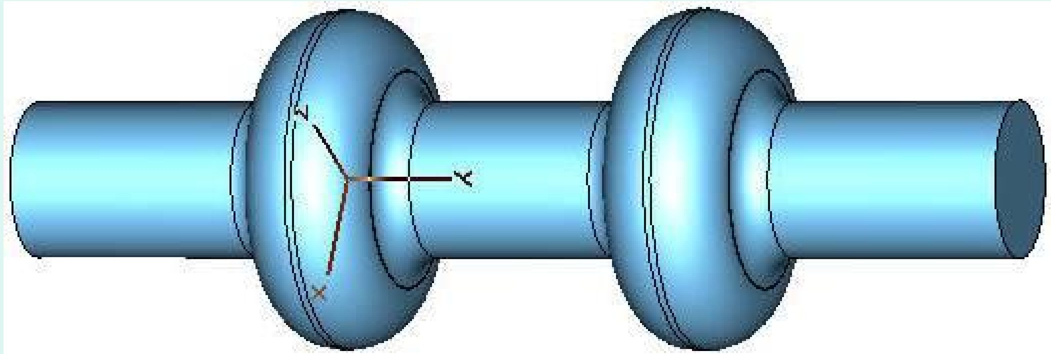


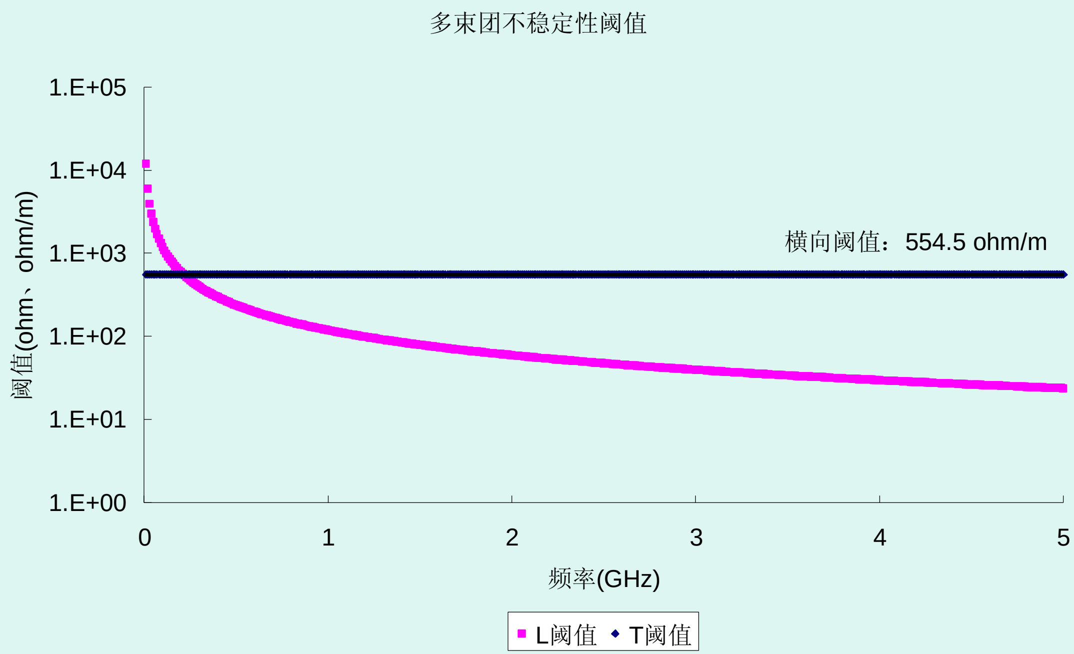




Double cell

$$P_{diss} = \frac{V_{total}^2}{R/Q \cdot Q_0 \cdot N_{cell}}$$





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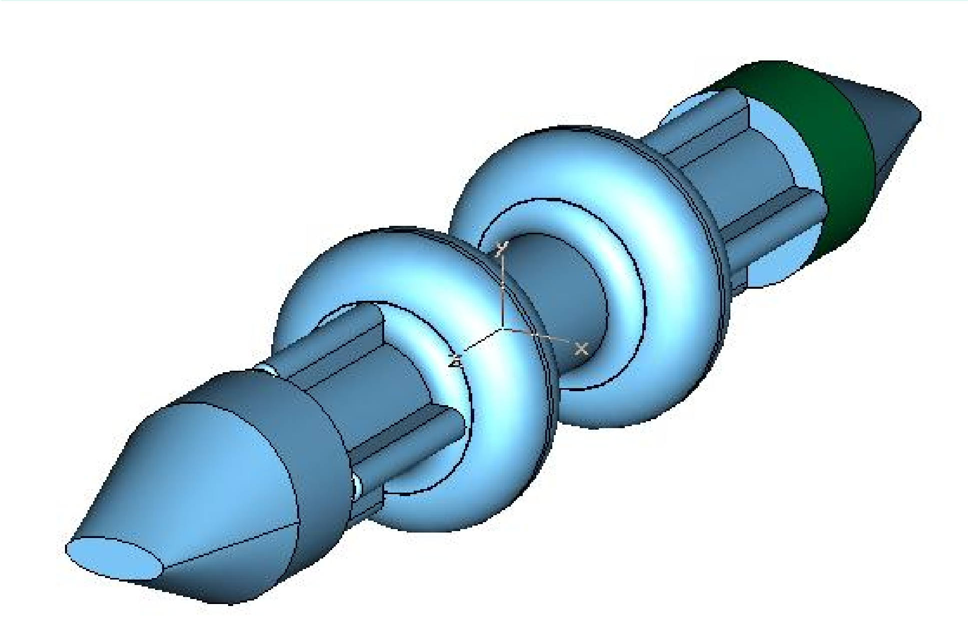
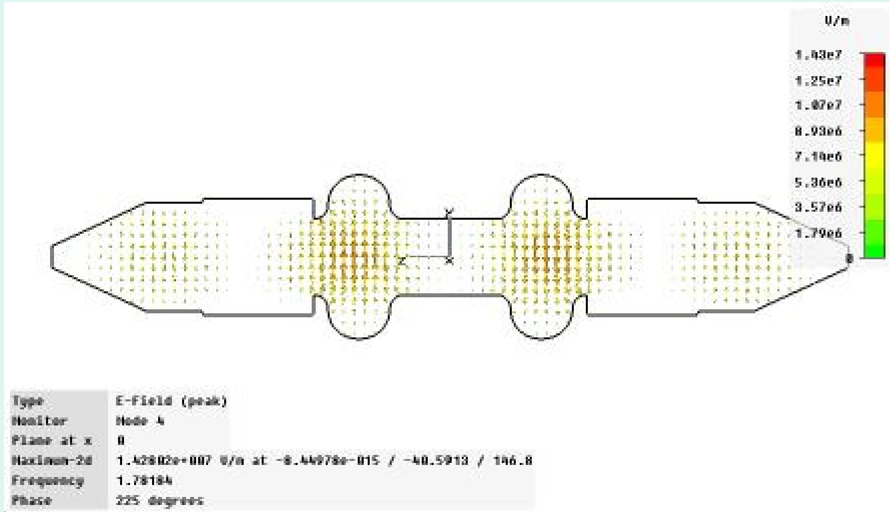
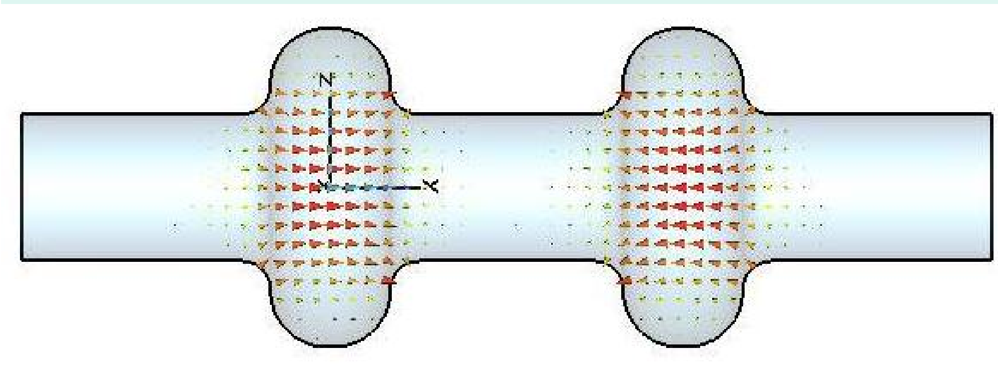
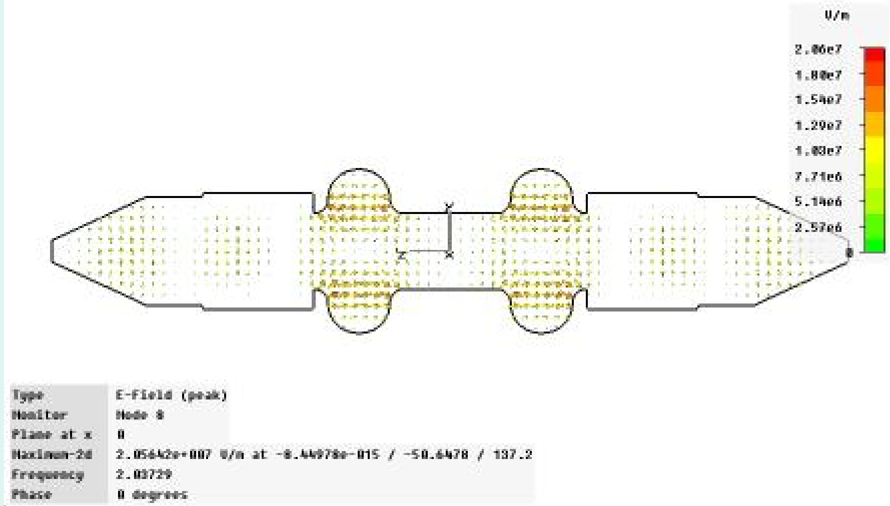
Fluted pipe

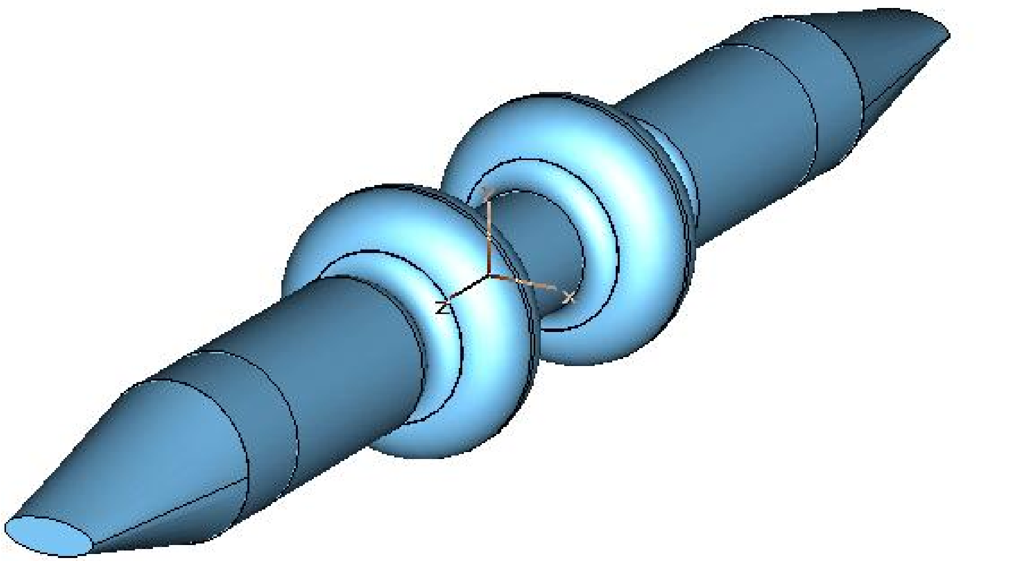


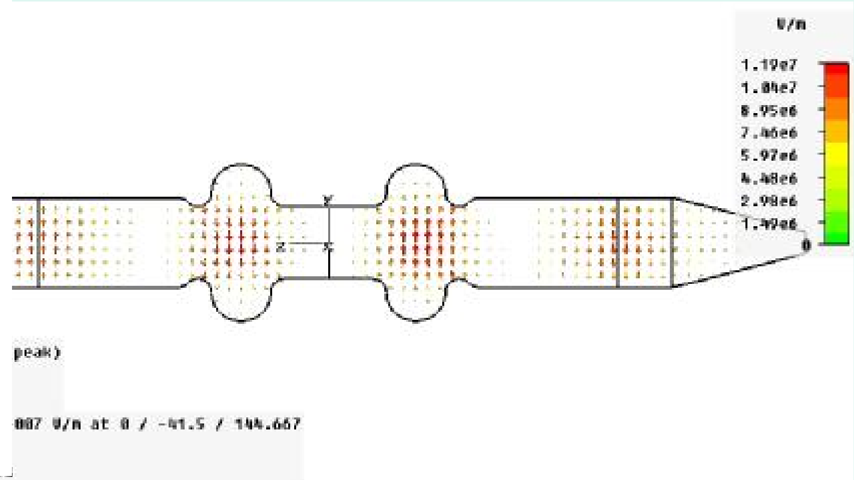

V/m
1.43e7
1.25e7
1.07e7
8.93e6
7.14e6
5.36e6
3.57e6
1.79e6
Type E-Field (peak)
Monitor Mode 4
Plane at x 0
Maximum-2d 1.42802e+007 V/m at -8.44978e-015 / -40.5913 / 146.8
Frequency 1.78184
Phase 225 degrees

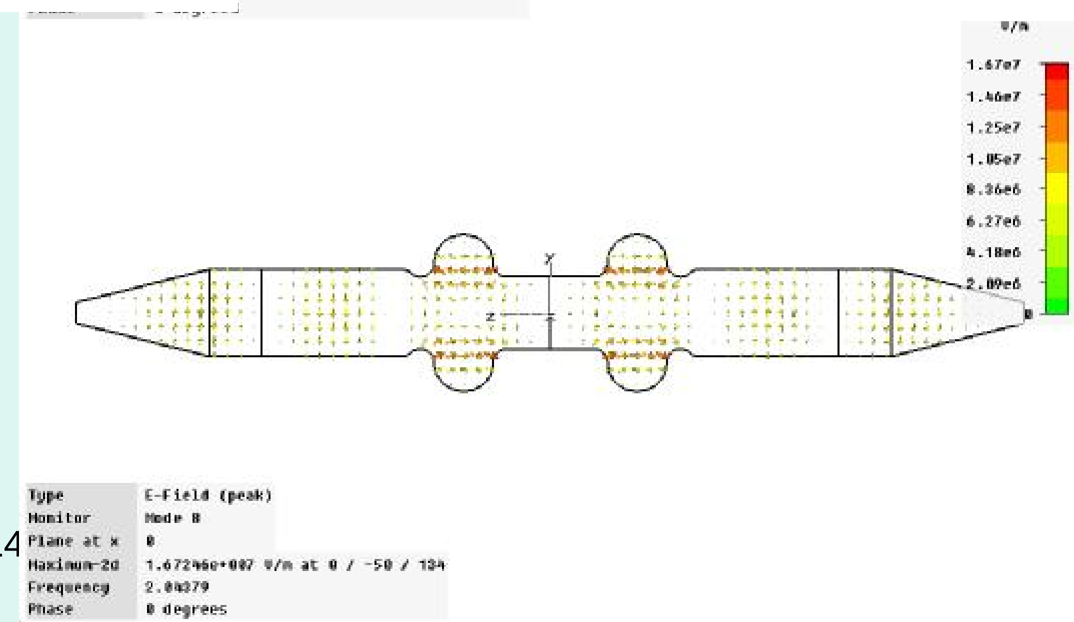



V/m
2.06e7
1.80e7
1.54e7
1.29e7
1.03e7
7.71e6
5.14e6
2.57e6
Type E-Field (peak)
Monitor Mode 8
Plane at x 0
Maximum-2d 2.05642e+007 V/m at -8.44978e-015 / -50.6478 / 137.2
Frequency 2.03729
Phase 0 degrees

Enlarged beam pipe

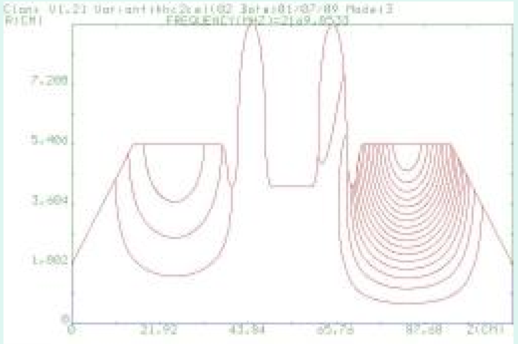


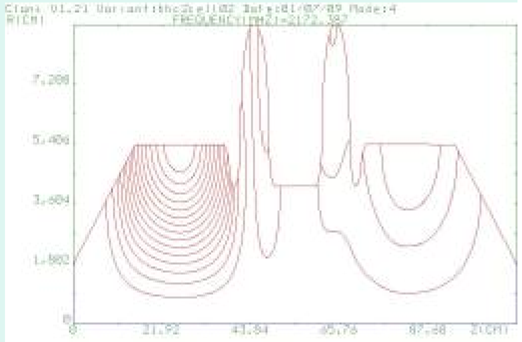


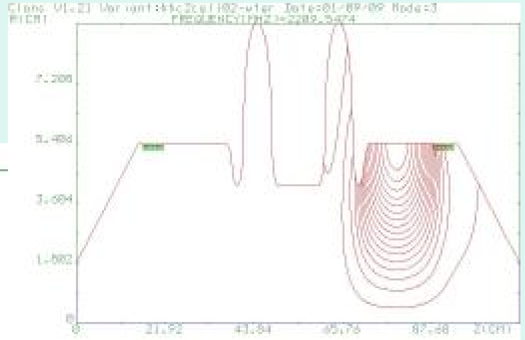


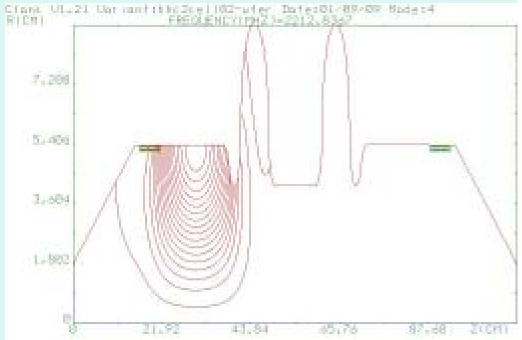
CLANS/CLANS calculation

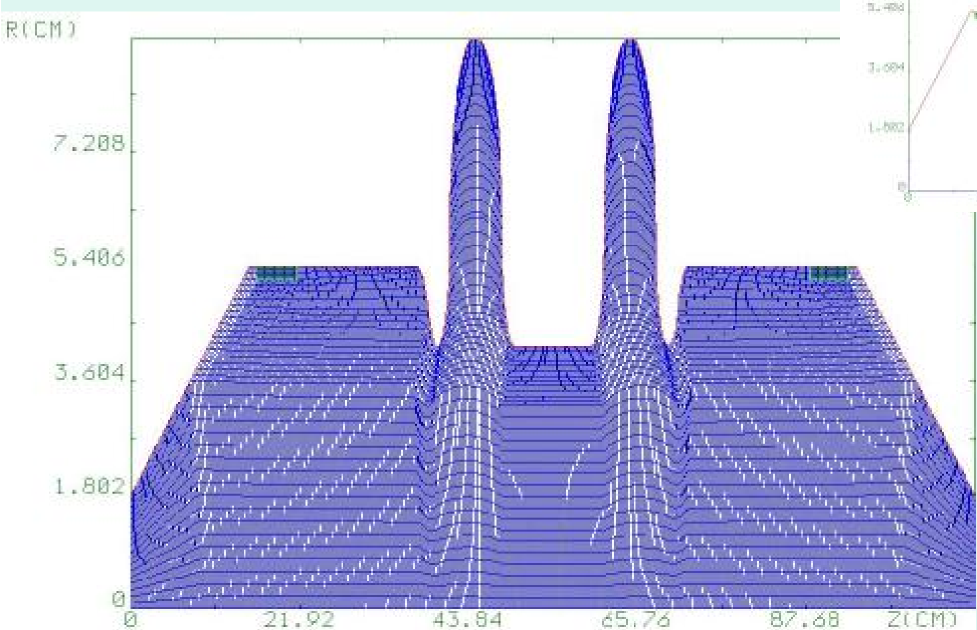
All the HOMs can propagate to the HOM damper, so that the HOM impedance can stay under the threshold.











Without ferrite				With ferrite			
Mode	Freq (MHz)	Q	Rsh(o)	Freq (MHz)	Q	Rsh(w)	Rsh
1	1699.08	13005	6.50	-	-	-	-
2	1712.91	13299	38.57	1732.16	447	7.62	482.40(kΩ/m)
3	1790.90	21363	578.94	1768.23	250	1.65	482.40(kΩ/m)
4	1834.51	18737	372.87	1838.30	253	0.43	482.40(kΩ/m)
5	1969.67	16652	106.57	2003.74	355	12.50	482.40(kΩ/m)
6	2081.38	13350	527.33	-	-	-	-
7	2169.85	37196	0.00	2209.55	57.7	0.04	53.46 kΩ
8	2172.39	37056	0.00	2212.84	56.3	0.05	53.38 kΩ
9	2313.20	37012	111.04	-	-	-	-
10	2322.27	36749	18.37	-	-	-	-

Two "double cell" solution

	SSRF double-cell	SSRF 2 double-cell	Elettra	SLS	BESSY-II
Light source	200mA, 3.5GeV, 4.5MV	200mA, 3.5GeV, 4.5MV	330mA, 2.0GeV, 2.4MV	400mA, 2.4GeV, 2.6MV	400mA, 1.9GeV, 1.5MV
HHC working freq	-	-	+64kHz	35kHz	-
Nominal voltage	1.5MV（Max 2MV）	1.6MV（Max 2MV）	0.6MV（Max 1MV）	0.8MV	0.5MV
Voltage/cell	0.75MV（Max 1MV）	0.4MV（Max 0.5MV）	300kV（Max 500kV）	0.4MV	0.5MV
material	Niobium	Niobium	Nb/Cu	Nb/Cu	niobium
gradient	7.5MV/m	5MV/m	3MV/m	4MV/m	5MV/m
Q (Vertical test)	Q_0>1E8	Q_0>1E8	Q_0>2E8（5MV/m）	Q_0>2E8（5MV/m）	7E7 (5MV/m)
Q (moduel test,4.5K)	Q_0>1E8（7.5MV/m）	Q_0>1E8（5MV/m）	Q_0>1E8（3MV/m）	Q_0>1E8（3MV/m）	5E7 (5MV/m)
R/Q（Ω）	83 × 2	83 × 4	88.4 × 2=176.8	88.4 × 2=176.8	90.8
Longitudinal HOM	$f_r \cdot R_{//}<118.1\ k\Omega \cdot GHz$	$f_r \cdot R_{//}<118.1\ k\Omega \cdot GHz$	$f_r \cdot R_{//}<7.0\ k\Omega \cdot GHz$	$f_r \cdot R_{//}<7.0\ k\Omega \cdot GHz$	-
Transverse HOM	$R_\perp<554.5\ k\Omega/m$	$R_\perp<554.5\ k\Omega/m$	$R_\perp<130\ k\Omega/m$	$R_\perp<130\ k\Omega/m$	-
Tuning range	± 500 kHz	± 500 kHz	± 500 kHz	± 500 kHz	-
Refrigeration power	150W/150W	100/150W	43W/65W	45.3W/65W	-
RF dissipation (4.5K)	135W(7.5MV/m)	77W(4MV/m）120W（5MV/m）	22W（4MV/m）	22W（4MV/m）	25W（5MV/m）
Static loss	15W	15W	5.1W	5.1W	<6W

Outline

1. Cavity design

2. Cavity fabrication

3. Cavity test

4. Cavity system

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2 Fabrication

- "punching－welding" method for niobium cavity
- Quality control（frequency/depth/shape）
- "N3＃"cavity's mechanical polishing

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（1）—punching

Circular plate → **position center** → **Make hole** → **punch**

break → **annealing** ↓ **trimming**

good → **trimming**

temperature：740±20° C
Vacuum:1E-5torr
Duration time: 24hrs

—trimming

Knife positioning → **1st cut** → **2nd cut** → **Smoothen edge** → **Length adjust** → **Half cell finish**

fabrication （3）

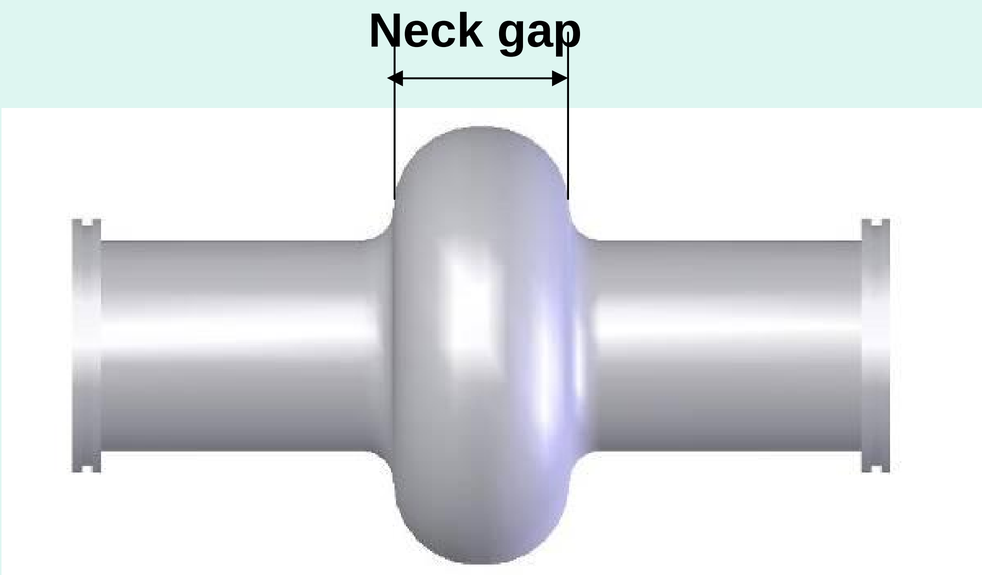
—beam pipe and end flange

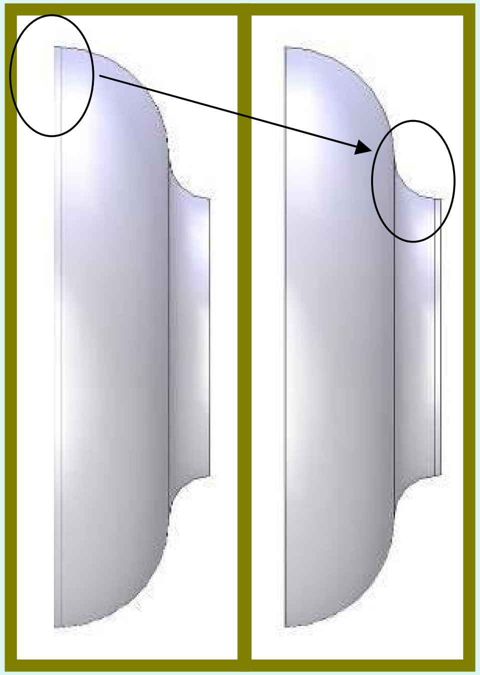
fabrication（4）－welding

Frequency measurement

	N.O.	Freq (MHz)	Error (MHz)	Error percentage (%)
1st batch	Cu 1#	1528.95	29.96	2.0
	Cu 2#	1529.14	30.15	2.0
	Nb-NX 1#	1584.37	85.38	5.7
2nd batch	Cu 3#	1502.24	3.25	0.2
	Nb-TD 1#	1498.37	-0.62	0.04
	Nb-NX 3#	1497.79	-1.2	0.08

Frequency is improved in the 2nd batch.


Neck gap



Depth measurement

Inner neck gap＝neck gap － neck depth

Results

	日C04	日C05	宁C06	宁C07	日C08	日C09	铌平均
Point 1	1.839	2.009	1.893	1.831	1.923	1.922	1.903
Point 2	2.065	2.071	1.979	1.903	1.995	1.911	1.987
Point 3	2.168	2.576	2.692	2.379	0.428	0.453	1.783
Point 4	2.716	2.796	2.801	2.761	2.761	2.873	2.785
Point 5	2.684	2.778	2.834	2.775	2.832	2.770	2.779
Point 6	2.663	2.766	2.790	2.761	2.831	2.731	2.757
Point 7	2.705	2.786	2.899	2.880	2.862	2.775	2.818
Point 8	3.104	2.934	3.543	3.347	3.376	3.399	3.284

Surface treatment

grinding

Only beginning!

开始时间	结束时间	用时	方向	抛前频率	抛后频率
14日17:00	14日17:40	40min	逆时针	1498.650 MHz	1498.350 MHz
15日8:35	16日19:55	35h20min	逆时针		
16日19:55	18日8:25	36h30min	顺时针		
测量点	抛前厚度	抛后厚度	测量点	抛前厚度	抛后厚度
AE1	3.0 mm	3.0 mm	BE1	3.0 mm	3.0 mm
AE2	3.1 mm	3.1 mm	BE2	3.0 mm	3.0 mm
AE3	3.1 mm	3.1 mm	BE3	3.1 mm	3.0 mm
AE4	3.1 mm	3.1 mm	BE4	3.0 mm	3.0 mm
AE5	3.1 mm	3.1 mm	BE5	3.0 mm	3.0 mm
AE6	3.1 mm	3.0 mm	BE6	3.0 mm	2.9 mm
AE7	3.0 mm	3.0 mm	BE7	3.0 mm	3.0 mm
AE8	3.0 mm	3.0 mm	BE8	3.0 mm	3.0 mm

Outline

1. Cavity design

2. Cavity fabrication

3. Cavity test

4. Cavity system

3 Cavity test

- Field mapping

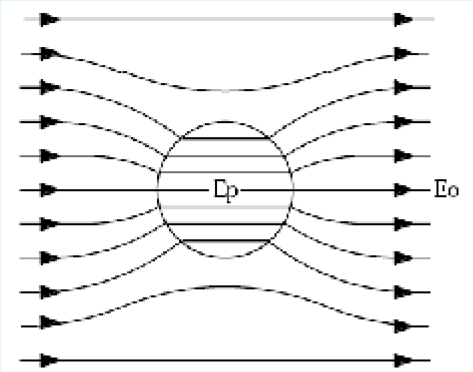
1.system establishment

2.Test the 1.5GHz copper prototype cavity

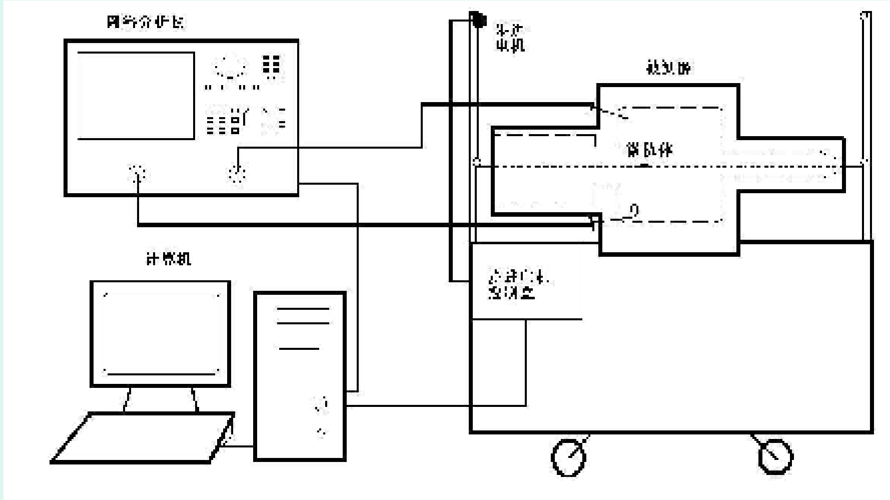
3.Test the 800MHz aluminum cavity

- Vertical test
- “Nb-NX 1＃”cavity @ KEK

Field mapping system



Field perturbation method



$$\frac{\Delta w}{w_0} \approx \frac{\int_{V_0}\left[\left(\Delta \vec{E}\cdot\vec{D}_0^{*} - \vec{E}_0^{*}\cdot\Delta\vec{D}\right)+\left(\Delta\vec{H}\cdot\vec{B}_0^{*} - \vec{H}_0^{*}\cdot\Delta\vec{B}\right)\right]dV}{\int_{V_0}\left(\vec{E}_0^{*}\cdot\vec{D}_0^{*}+\vec{H}_0^{*}\cdot\vec{B}_0^{*}\right)dV}$$

$$E = \sqrt{\frac{4W_0}{ke\Delta t\ f_0}}\cdot\Delta f$$

$$\frac{RT^2}{Q} = \frac{1}{2wp\,r^3 e_0}\,\frac{e_r+2}{e_r-1}\left[\int dz\sqrt{\frac{\Delta w(z)}{w}}(\cos kz)\right]^2$$

Software&hardware

Programming flow

Initialization — Init

Set parameters — Set

Measurement
Motor one step,
Measure once — MEAS

Field +/-
Calculate R/Q — Post M

exit — Exit

User interface

(Labview7.0)

Function realization

(dll, VISA)

interface

(PCI, USB)

Motor control

GPIB cable

Step motor

56BYG

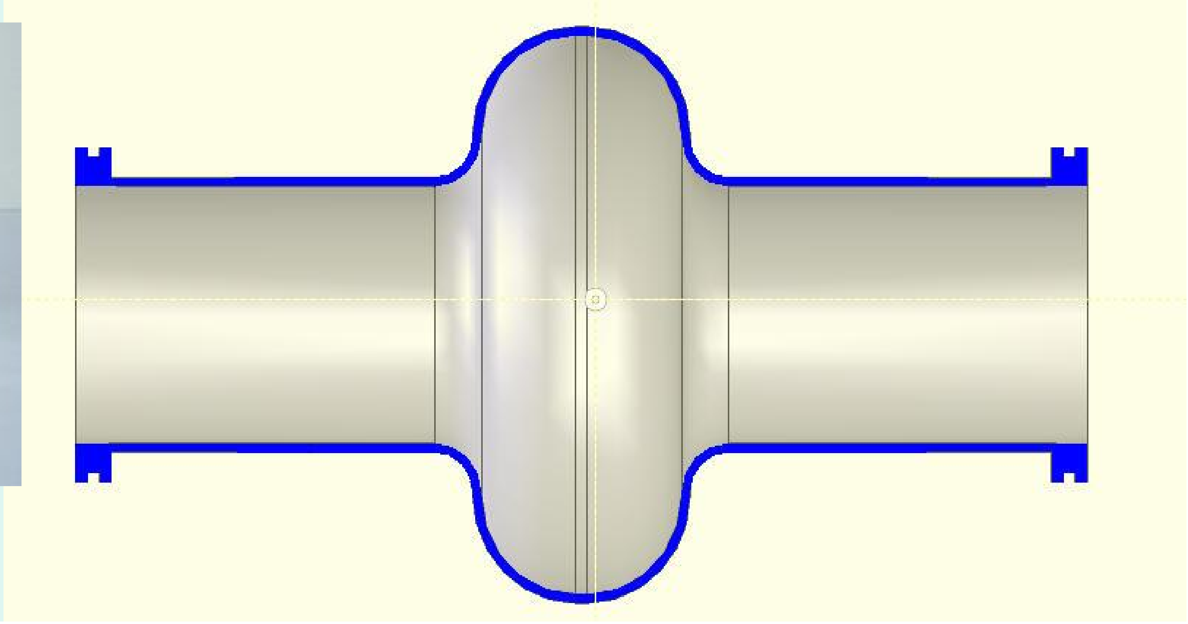
Network analyzer

E8357

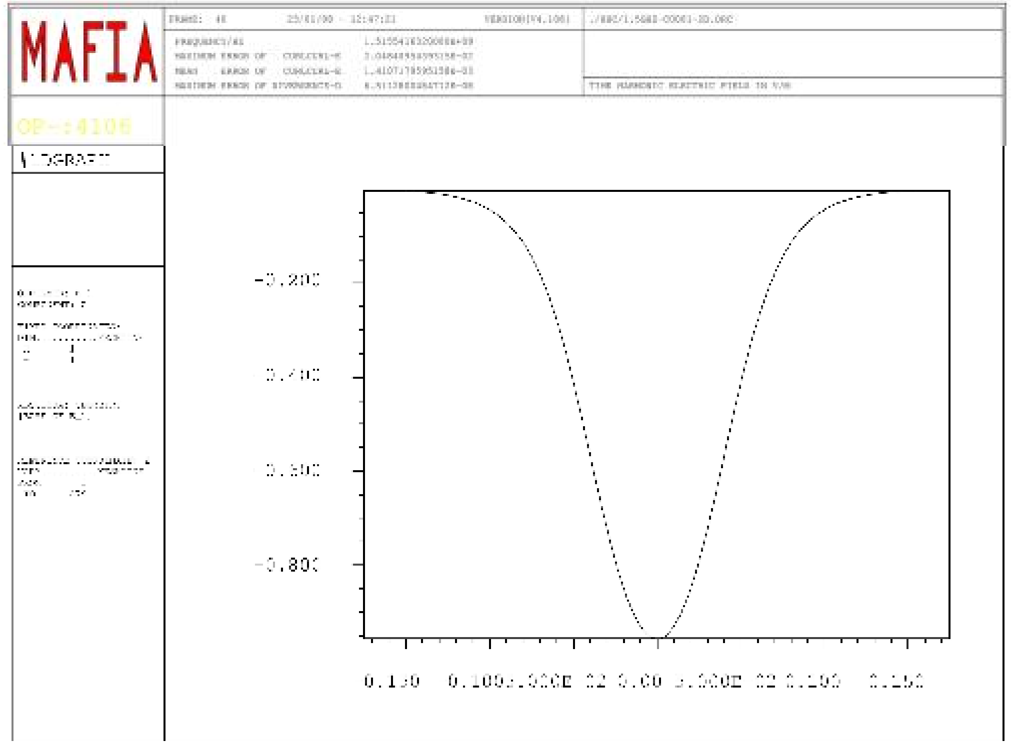
HHC prototype measurement

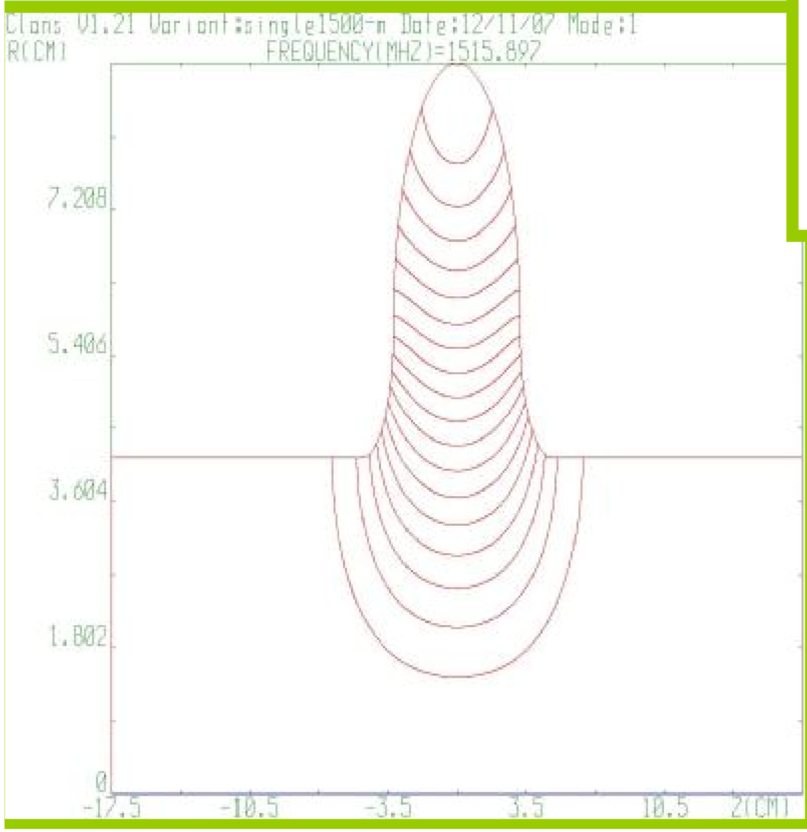
- Perturbing object

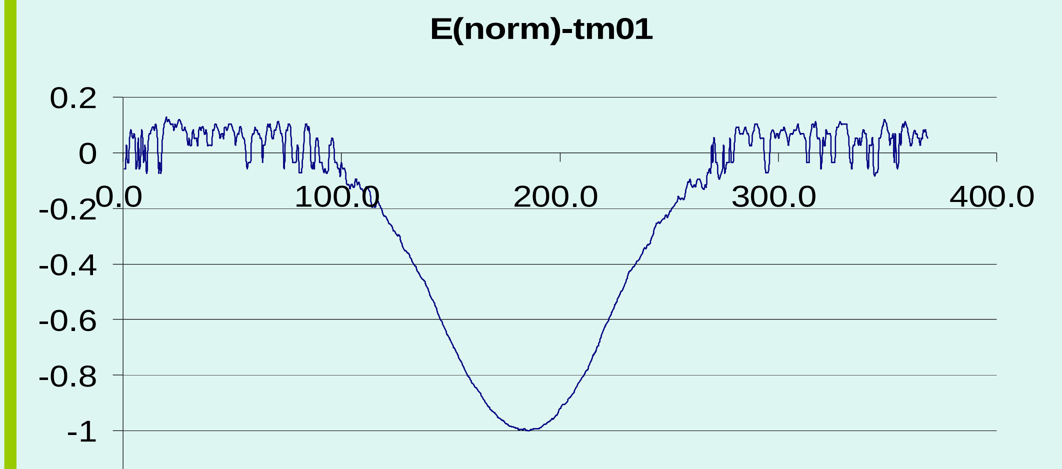
- 1500MHz copper prototype cavity



Fundamental mode







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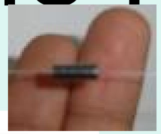
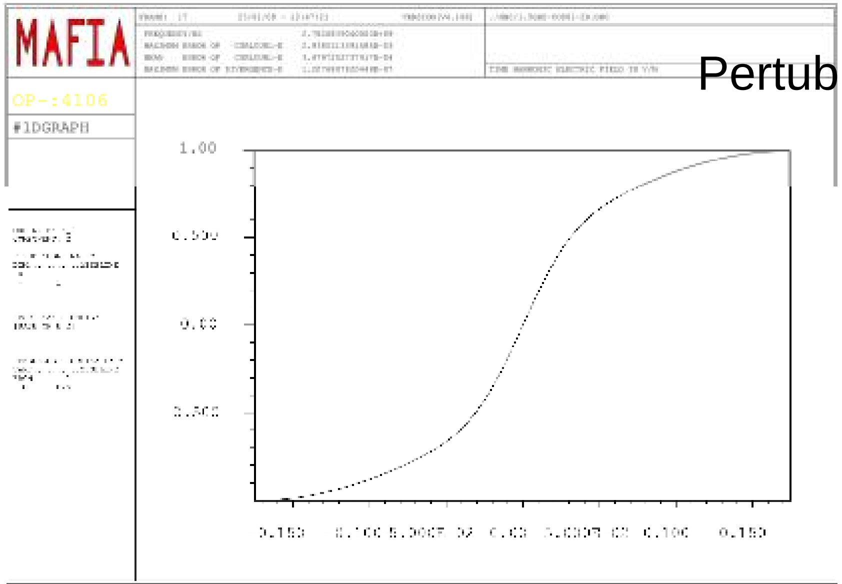
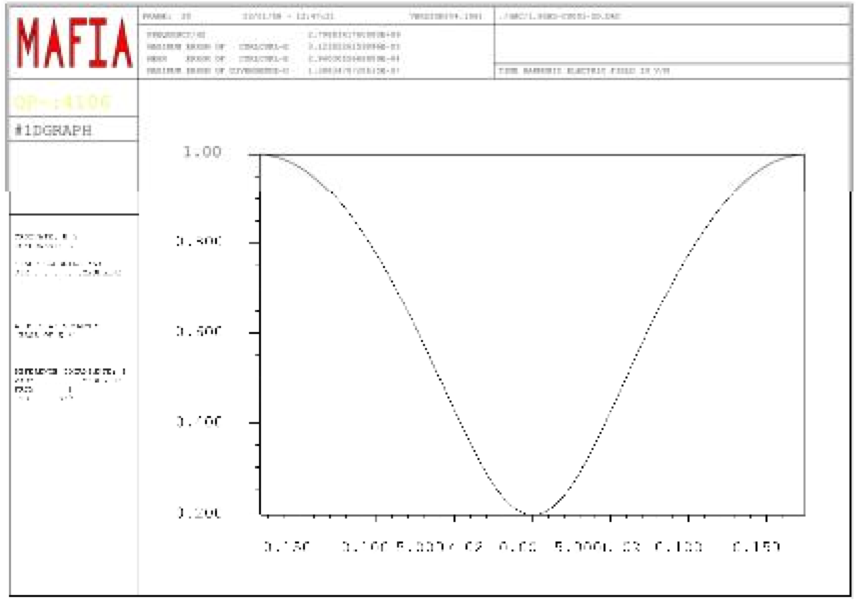
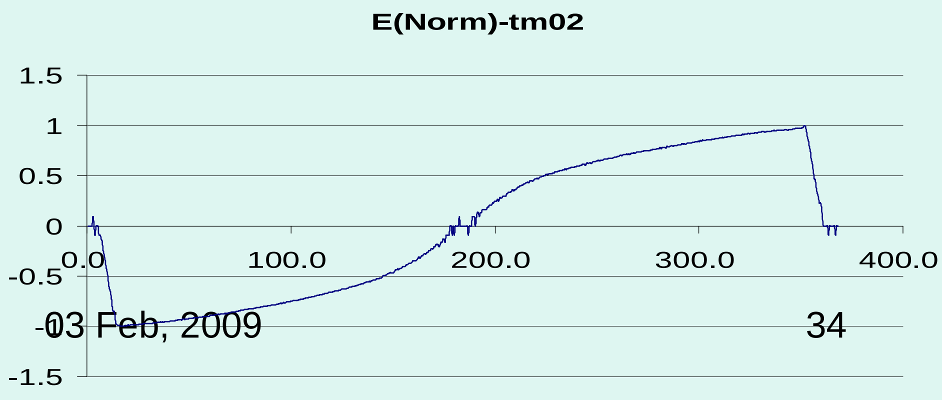
Monopole mode（1）

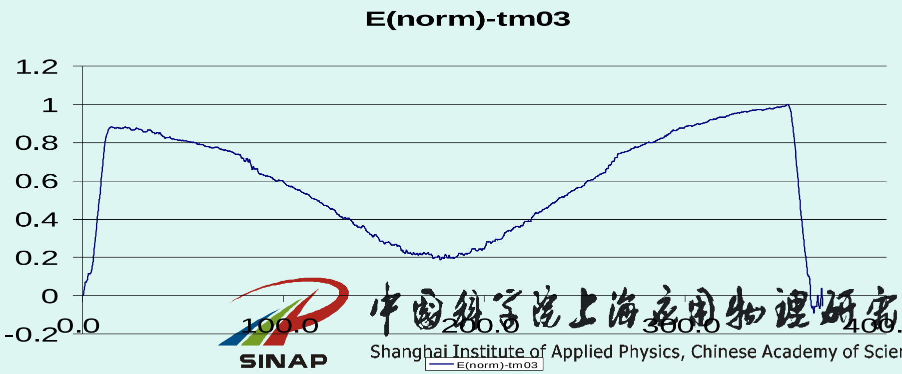


Pertubing E_z

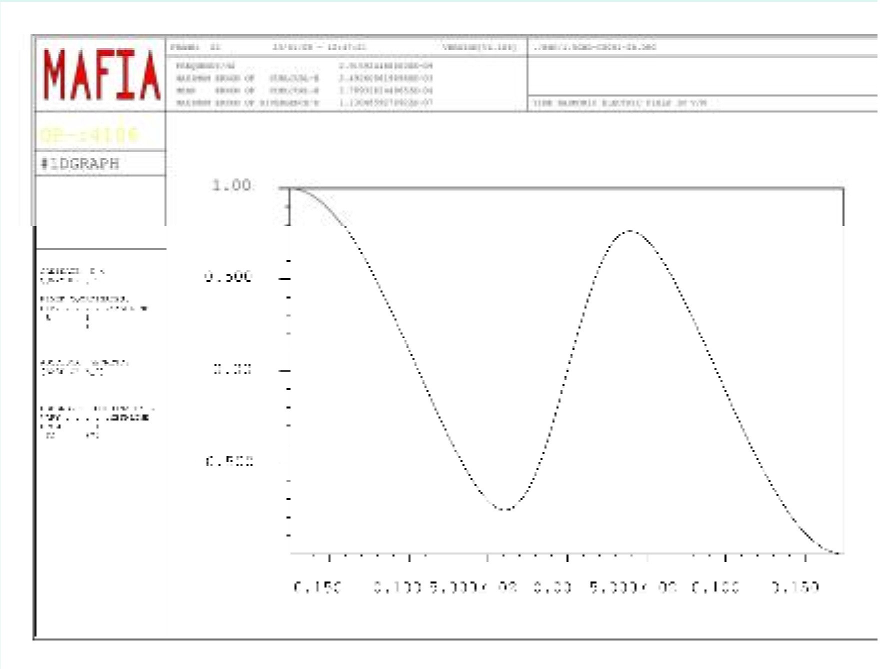


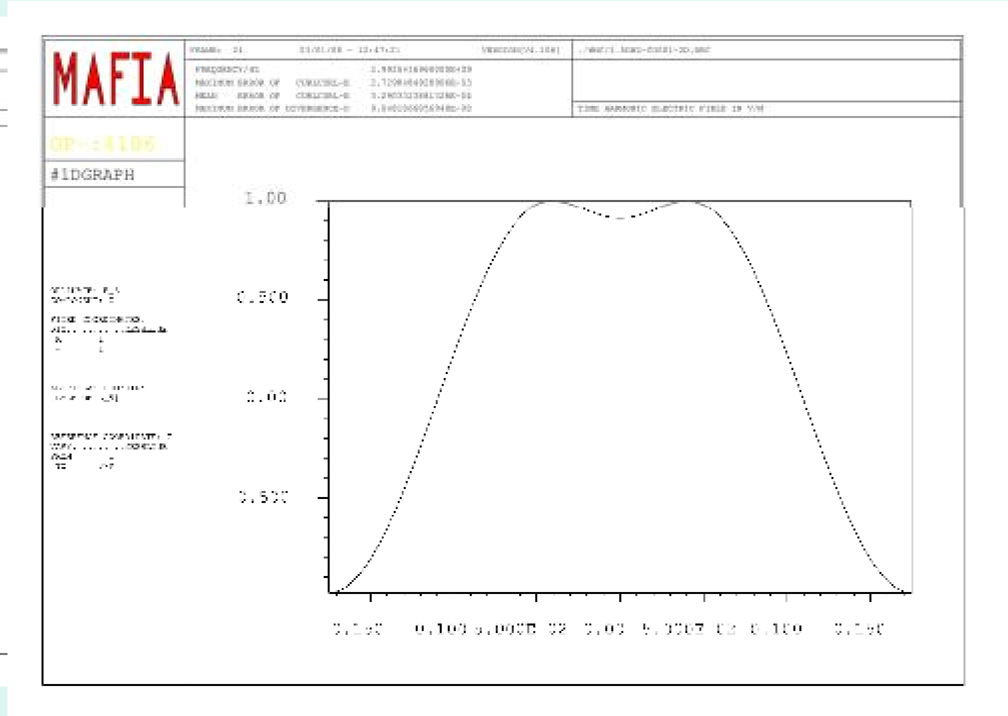


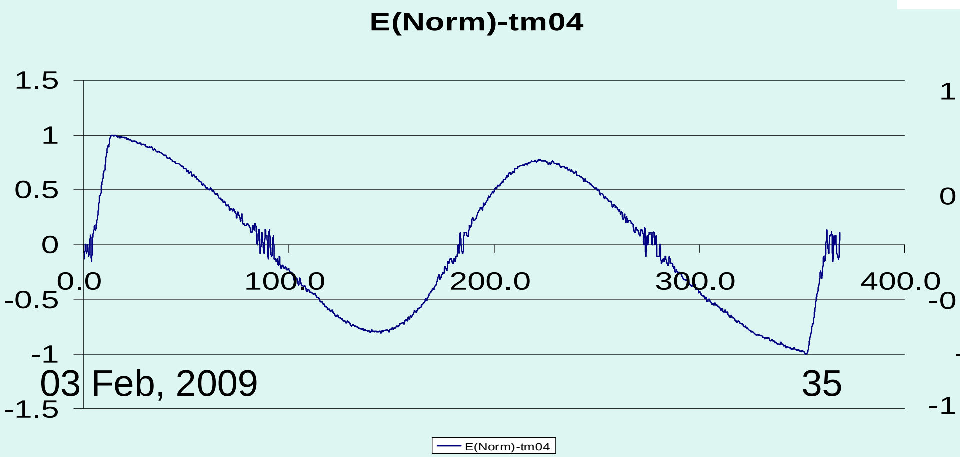


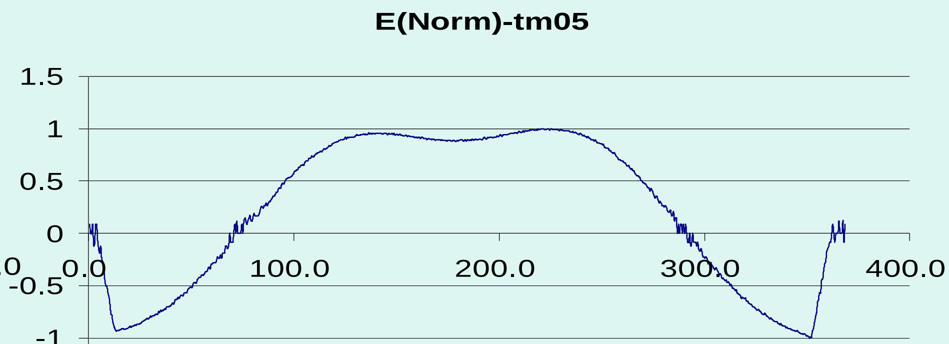


Monopole mode（2）





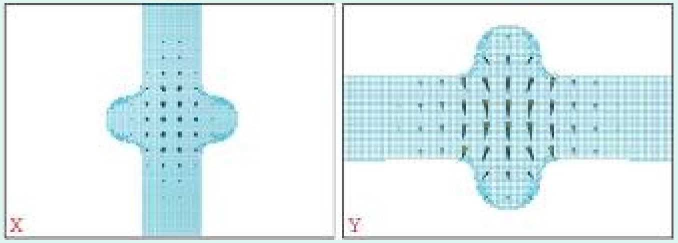




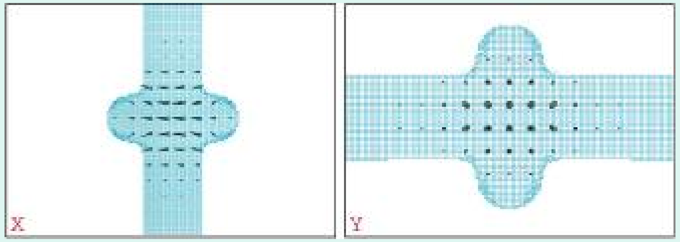
Monopole mode（3）

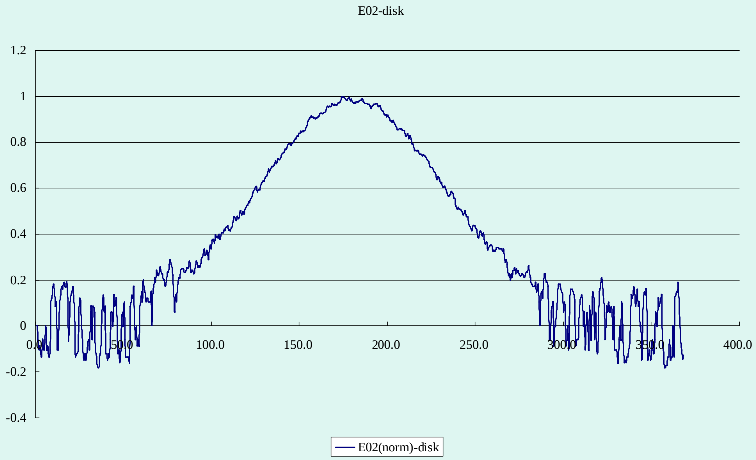
	measured		CLANS	
	Freq (GHz)	R/Q (ohm)	Freq (GHz)	R/Q (ohm)
tm001	**1.5295**	106.79	1.5159	93.32
tm002	**2.7831**	52.60	2.7927	42.78
tm003	**2.7998**	29.53	2.8045	46.38
tm004	**2.9201**	0.07	2.9260	7.41
tm005	**2.9925**	28.92	3.0010	3.06
tm006	**3.2390**	9.53	3.2720	2.07
tm007	**3.2753**	30.68	3.3648	8.08
tm008	**3.7052**	45.99	3.9621	1.56
tm009	**3.7708**	0.15	4.5622	21.72
tm010	**4.1871**	53.98	4.8895	0.78

Dipole mode（1）

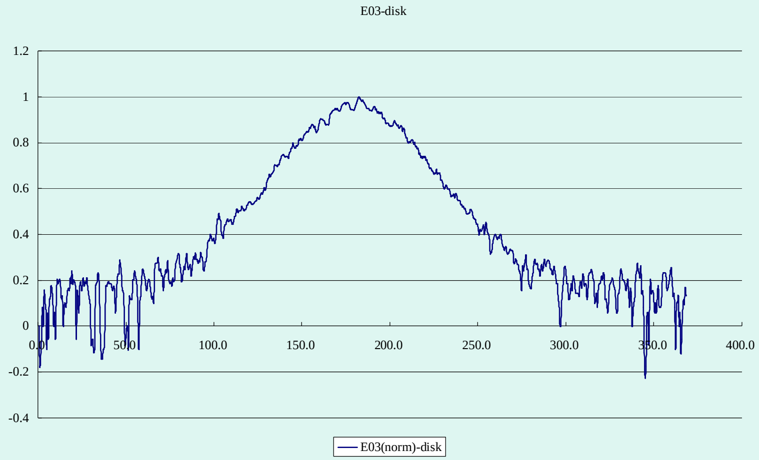


Perturbing Er



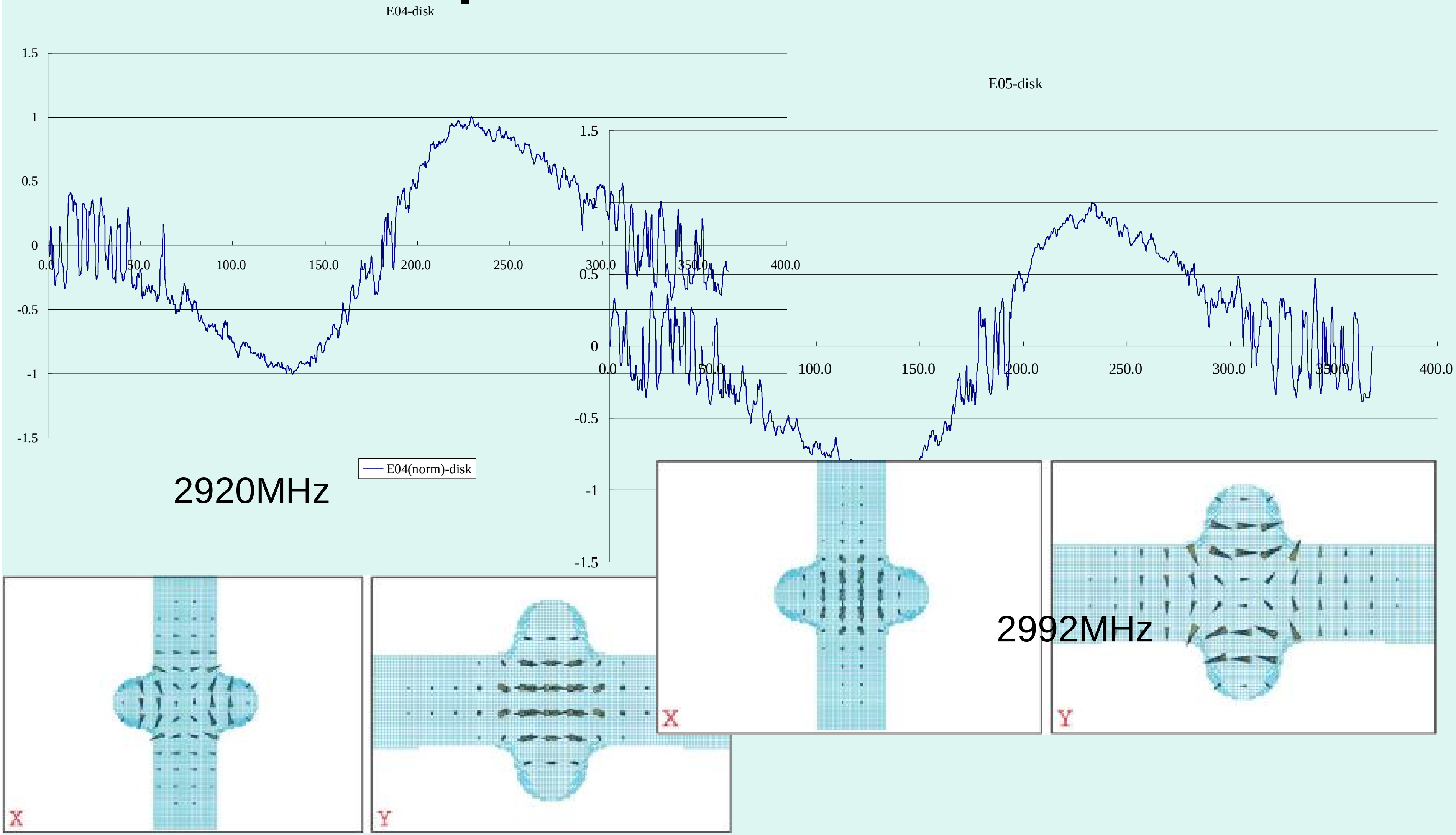


2783MHz

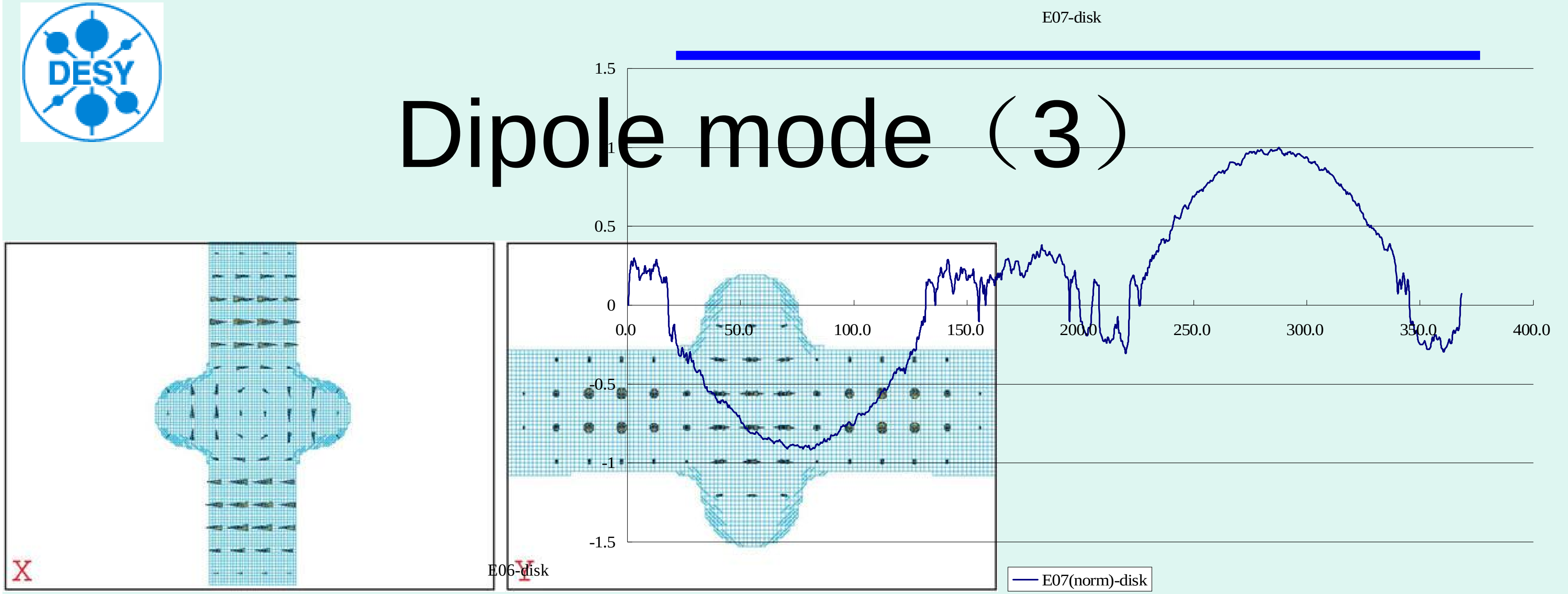


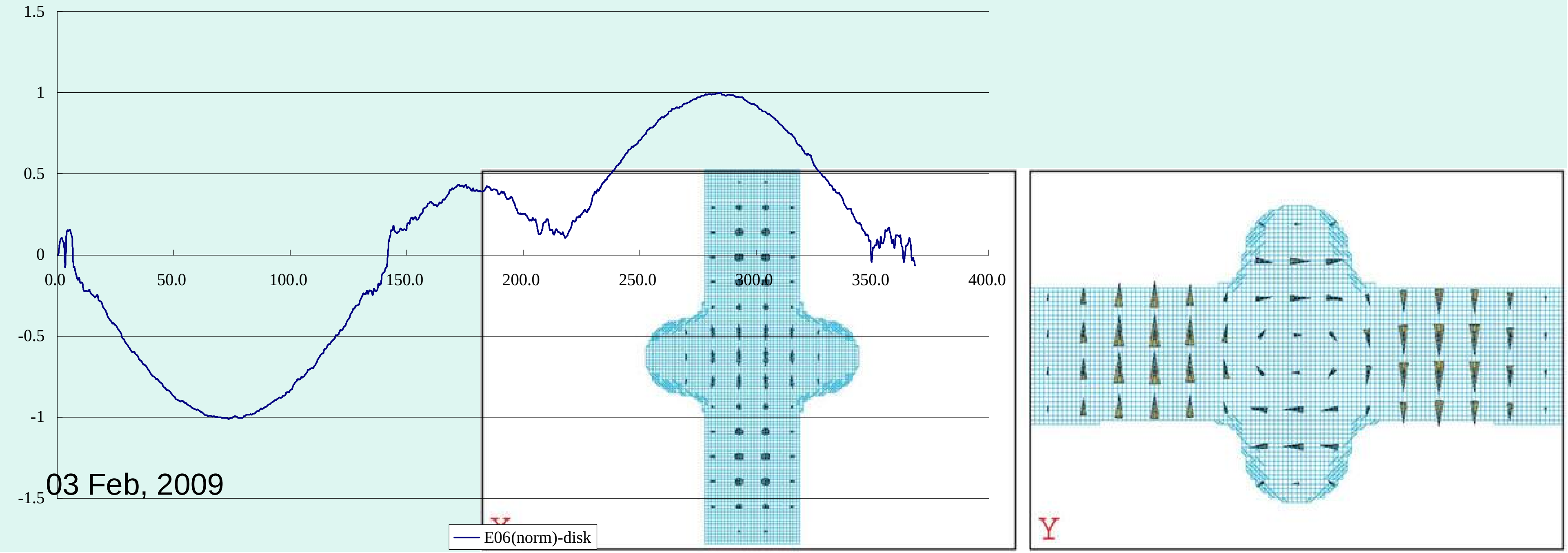
2799MHz

Dipole mode（2）



Dipole mode（3）





03 Feb, 2009

Vertical test

- Took place at STF, KEK, under supervision of Prof. Kenji Hosoyama.
- "Nb-NX 1＃" cavity, without any surface treatment.

Vertical test theory

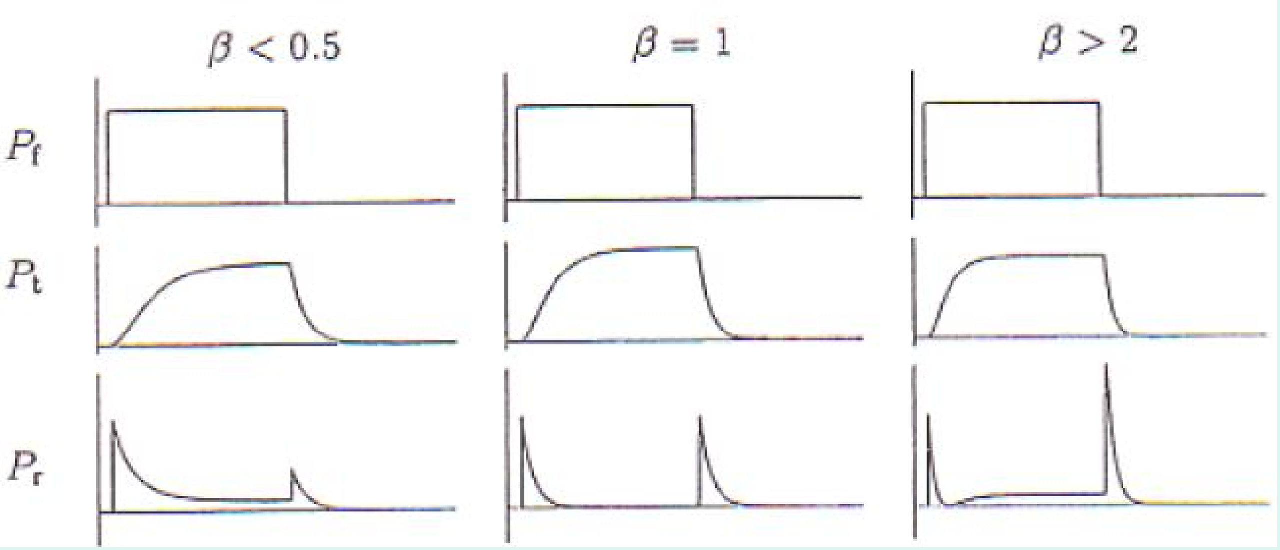
$$\frac{1}{Q_L}=\frac{1}{Q_{ext}}+\frac{1}{Q_0'}=\frac{1}{Q_{ext}}+\frac{1}{Q_0}+\frac{1}{Q_t}$$

$$U(t)=U(0)\exp\left(-\frac{t}{t_L}\right)$$

$$P_r=\frac{wU(t)}{Q_{ext}}=\frac{4b^2}{(1+b)^2}P_{in}\cdot\exp\left(-\frac{t}{t_L}\right)$$

$$Q_L=\frac{wt_{1/2}}{\ln 2}$$

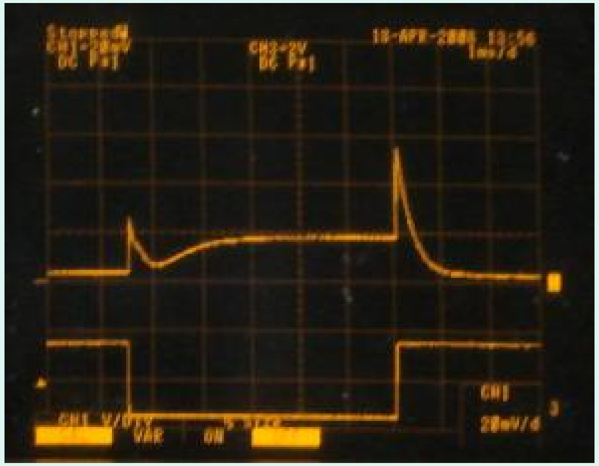
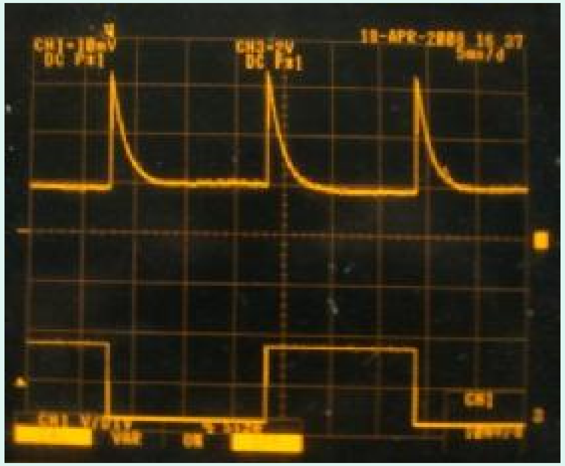
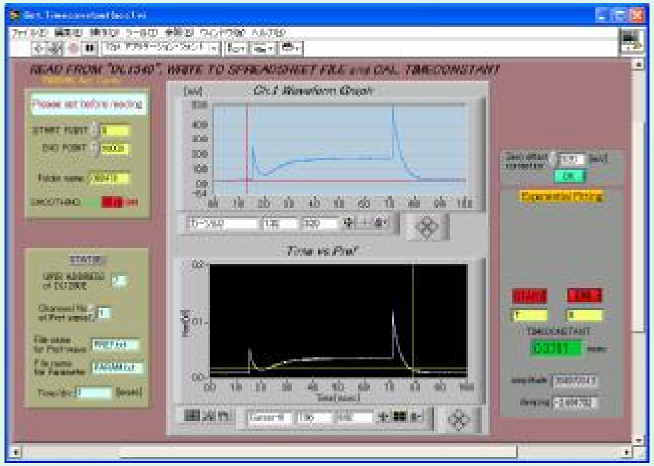
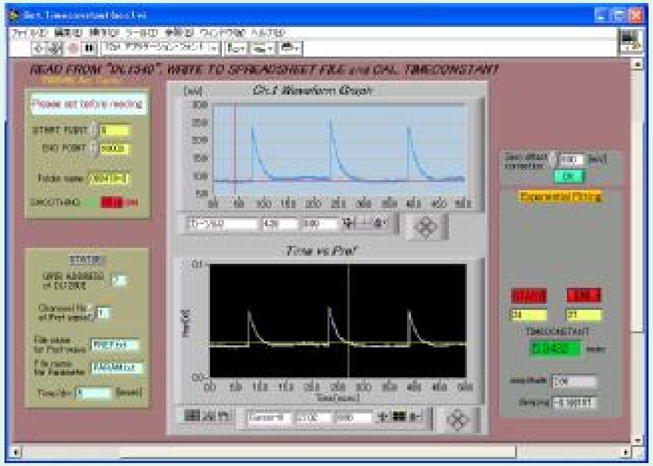
$$E_{acc}=\frac{1}{L_{eff}}\sqrt{\frac{R_s}{Q}\cdot Q_0\cdot P_{loss}}$$



Decay time

$\beta >> 1$

$\beta \sim 1$

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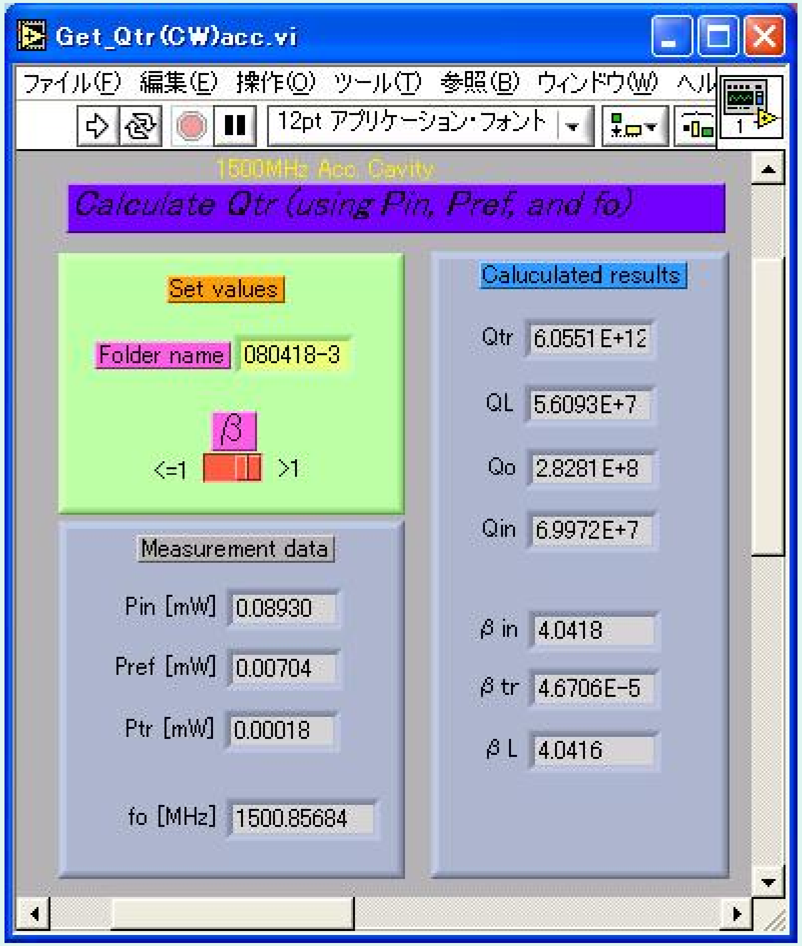
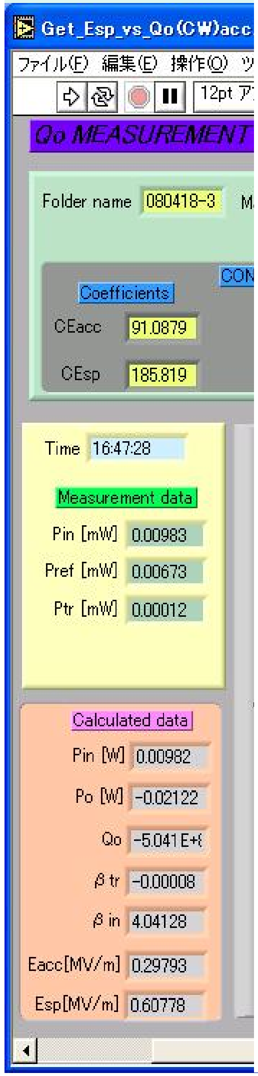
Coupling factor

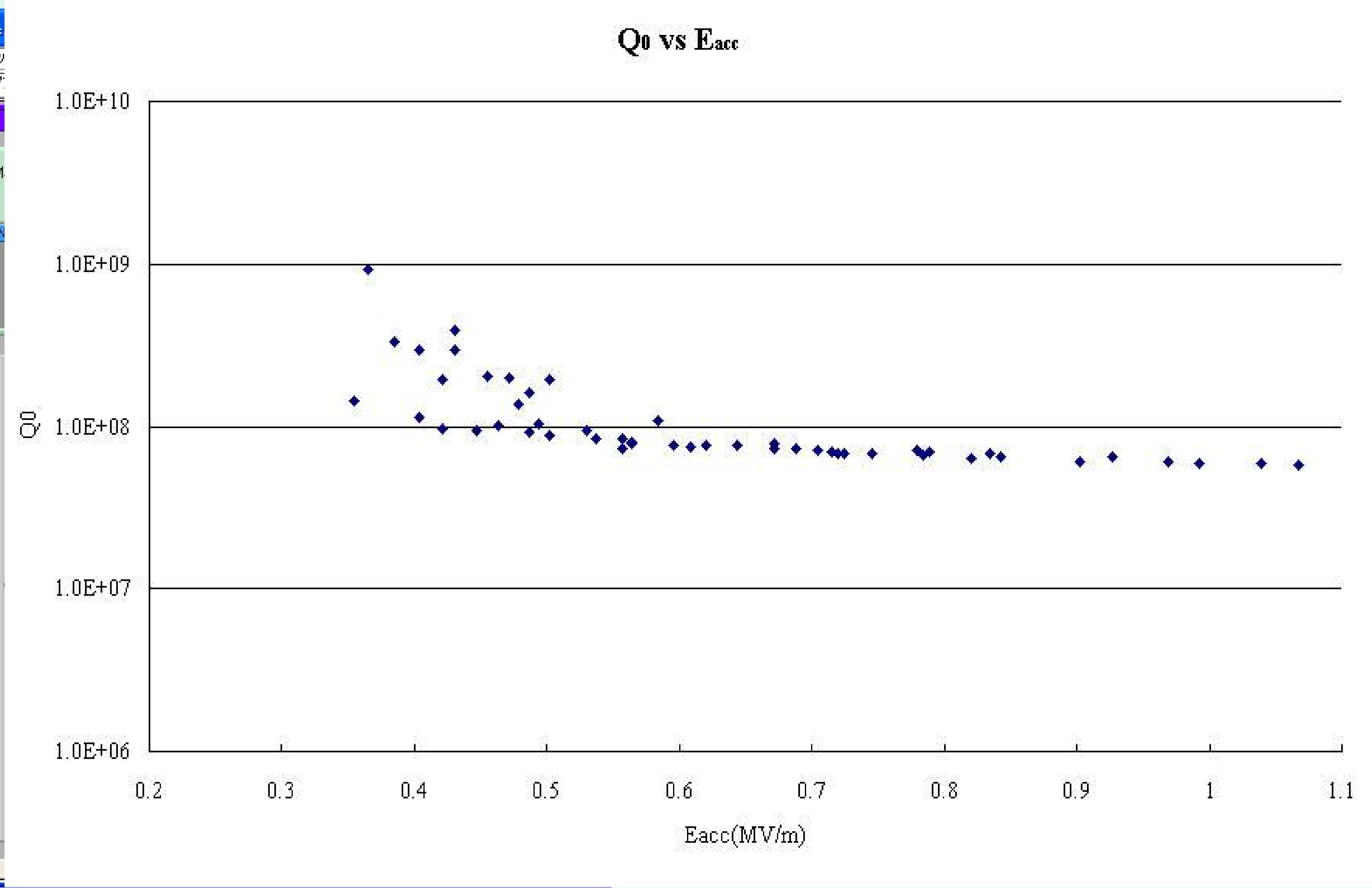
- Inner conductor was pulled out from the cavity for 12mm, to adjust the coupling factor to near 1.



- τ =5.948msec
- *f0*=1500.85681 MHz
- *QL*=6.055E+12
- *Q0*=2.8E+8
- β *in*=4.04。

Q_0~E_{acc}


Get_Esp_vs_Qo(CW)acc
ファイル(F) 編集(E) 操作(O)
12pt
Qo MEASUREMENT
Folder name 080418-3
CON
Coefficients
CEacc 91.0879
CEsp 185.819
Time 16:47:28
Measurement data
Pin [mW] 0.00983
Pref [mW] 0.00673
Ptr [mW] 0.00012
Calculated data
Pin [W] 0.00982
Po [W] -0.02122
Qo -5.041E+
β tr -0.00008
β in 4.04128
Eacc[MV/m] 0.29793
Esp[MV/m] 0.60778


Q0 vs Eacc
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
Q0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Eacc(MV/m)

Outline

1. Cavity design

2. Cavity fabrication

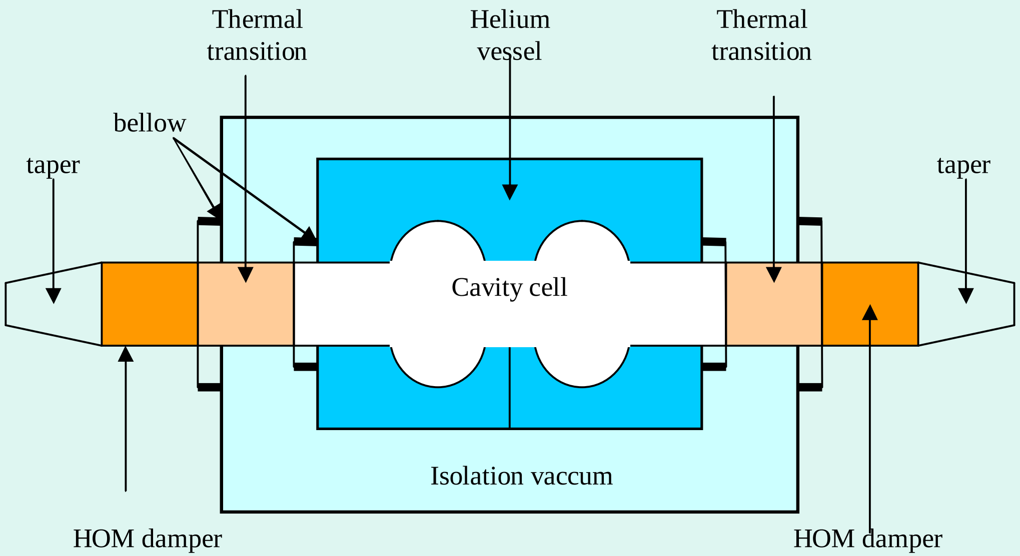
3. Cavity test

4. Cavity system

4 HHC system consideration

- Double cell
- voltage
- HOM

- Cryogenics
- Tuning system
- ……



Future

- The previous study is for the Higher Harmonic Cavity (HHC).
- SSRF phase-I project will finish in May, 2009.
- Higher harmonic cavity is part of the SSRF phase-II project, starts in this year.

You can refer to following paper:

1. MA Guangming, ZHAO Zhentang, LIU Jianfei, Design of a Higher Harmonic Cavity for the SSRF Storage Ring , Chinese Physics C, vol 32 (04): 275-279, 2008.
2. MA Guangming, ZHAO Zhentang, High Order Mode Studies of Bell-shaped Prototype Cavities, Chinese Physics C, vol 32 (12): 1012-1015, 2008.

- Thanks!
- Danke schön!
- 谢谢！