High power, high intensity superconducting proton driver linac at KEK

High Energy Accelerator Research Organization

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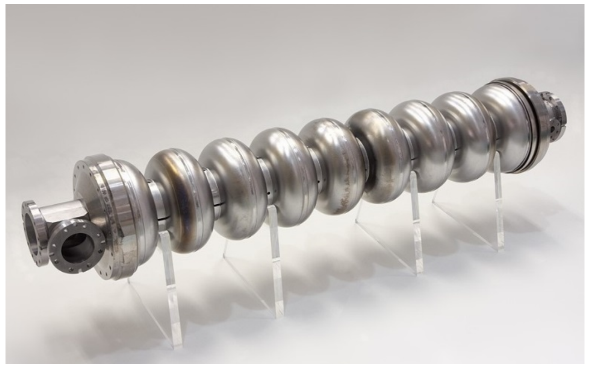
Contents

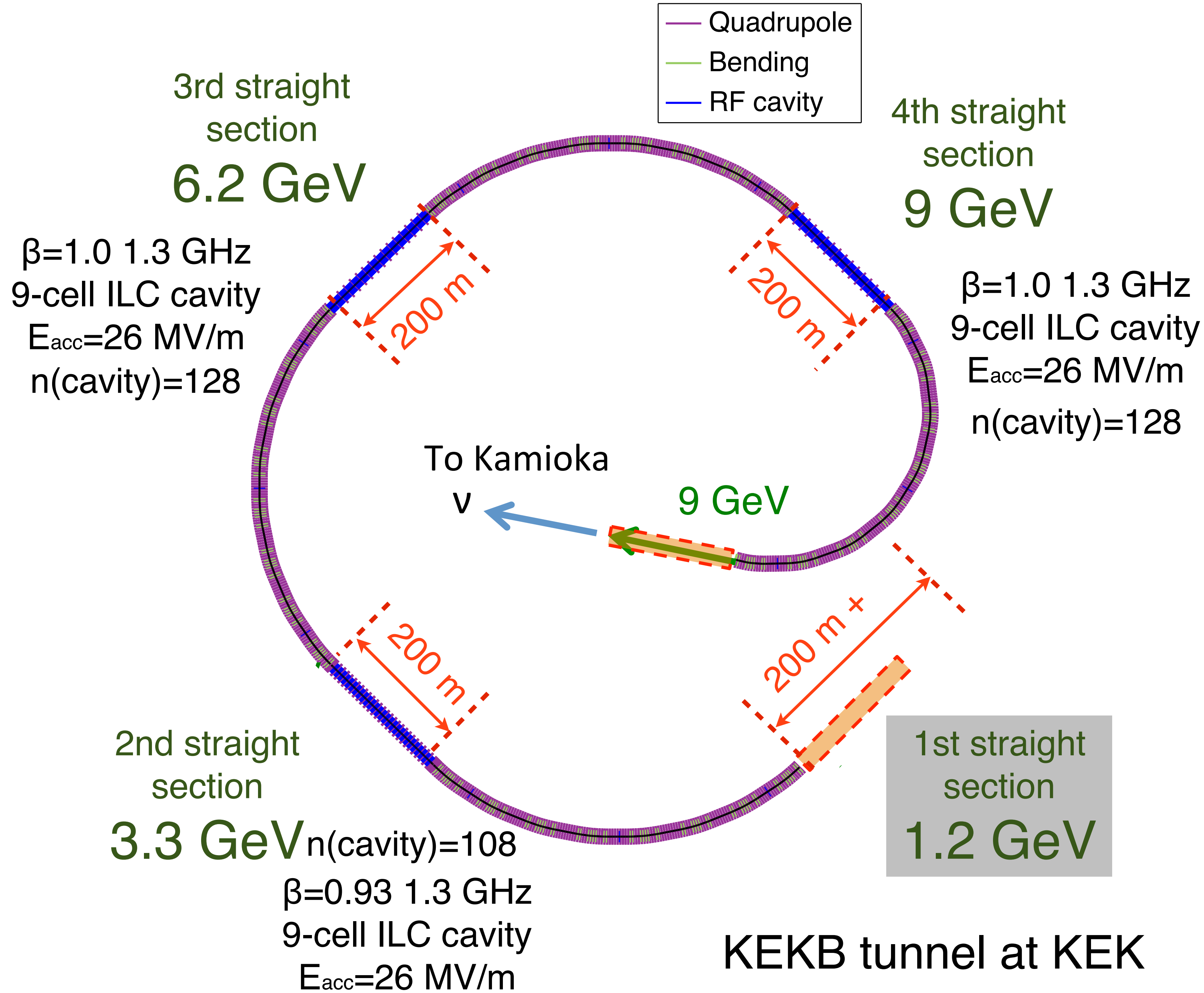
Proton driver linac overview

ILC 9-cell elliptical cavity



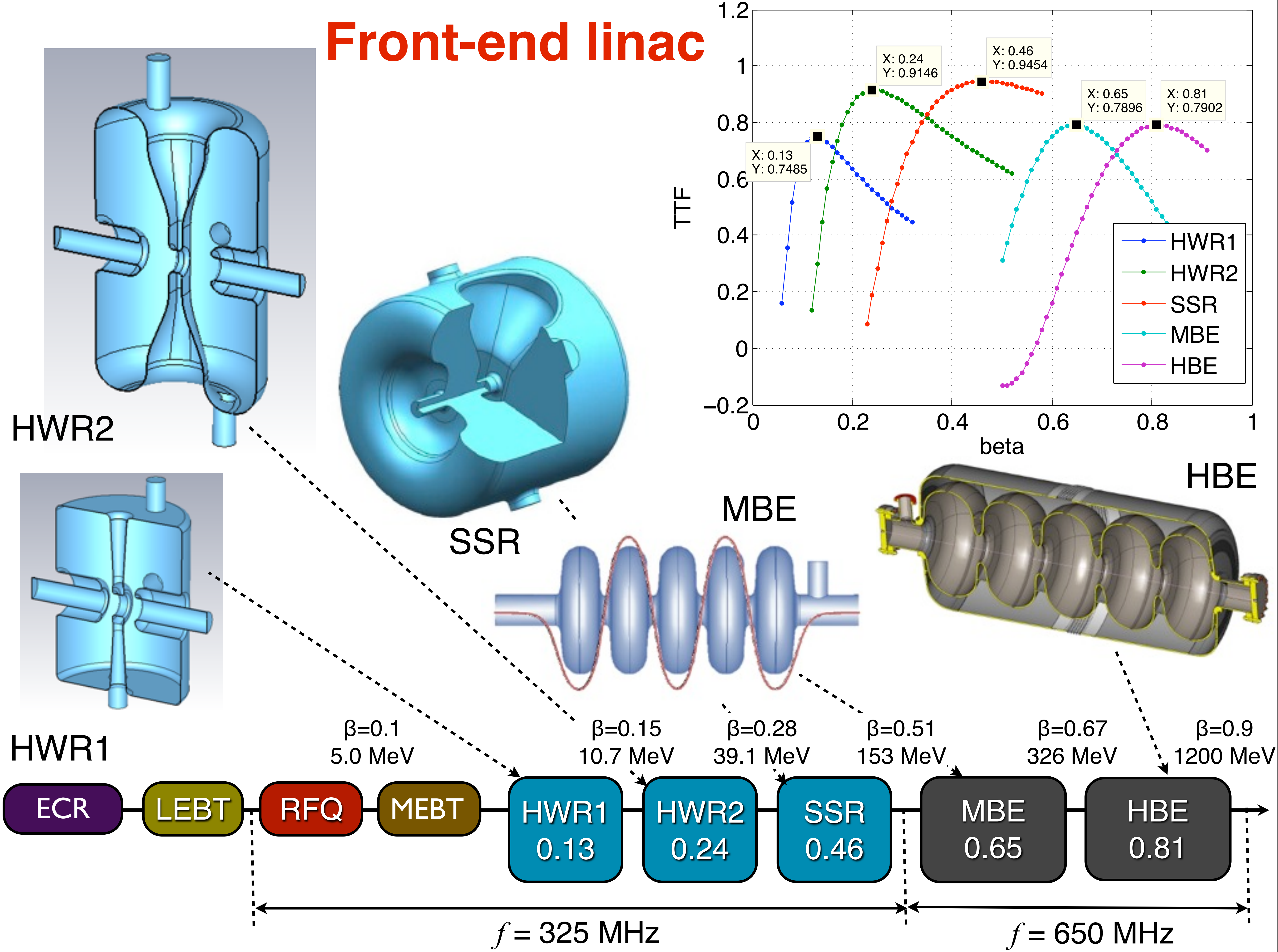
- For long-baseline neutrino oscillation physics, multi-MW proton driver linac with high intensity beam current is needed.
- For efficient acceleration, linac is operated in pulsed mode with high duty

Beam parameters	Value
Beam energy	9 GeV
(peak) Beam current	100 mA
Repetition rate	10 Hz
Pulse length	1 ms
Average beam current	1mA
Beam power	9 MW

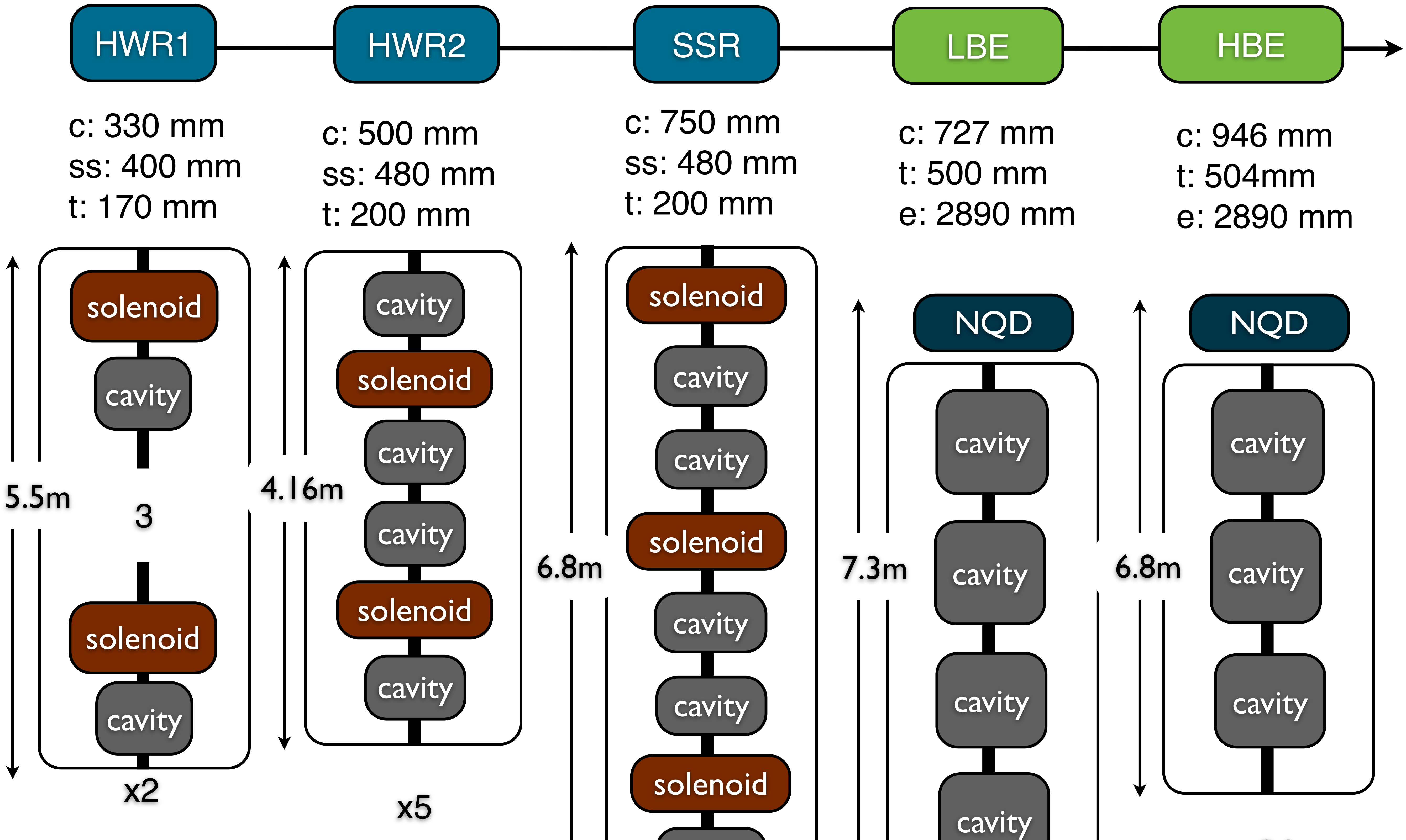


KEKB tunnel at KEK

Front-end linac



Linac structure: cryomodule



Total length: 257m

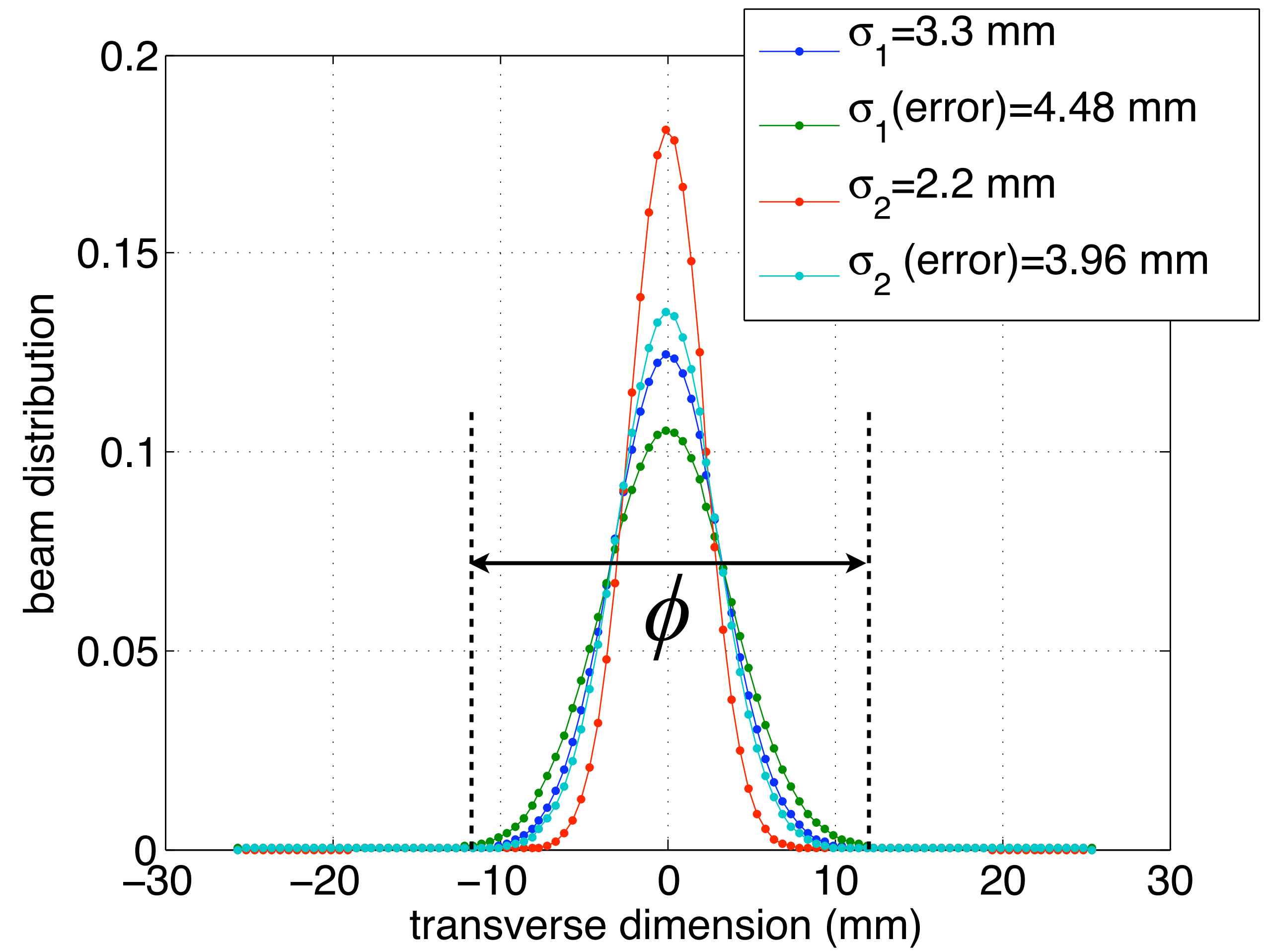
Front end component specification

cavities	HWR1	HWR2	SSR	MBE	HBE
n (cell/gap)	2	2	2	5	5
f (MHz)	325	325	325	650	650
β_{opt}	0.13	0.24	0.46	0.65	0.81
E_{in} (MeV)	0.10	0.15	0.29	0.51	0.67
E_{out} (MeV)	0.15	0.29	0.51	0.67	0.9
V_0 (MV)	0.8	2.1	5.3	10.2	15.4
synchronous phase (˚)	-30	-30	-27	-25	-25
P_{beam} (peak) (MW)	0.052	0.167	0.447	1.02	1.54
n (cavity)	10	20	30	20	72
n (cryomodule)	2	5	6	5	24

Development of two superconducting half wave resonators

- Requirements from beam dynamics

Specification	HWR1	HWR2
f (MHz)	325	325
β_{opt}	0.13	0.24
ϕ (mm)	40	40

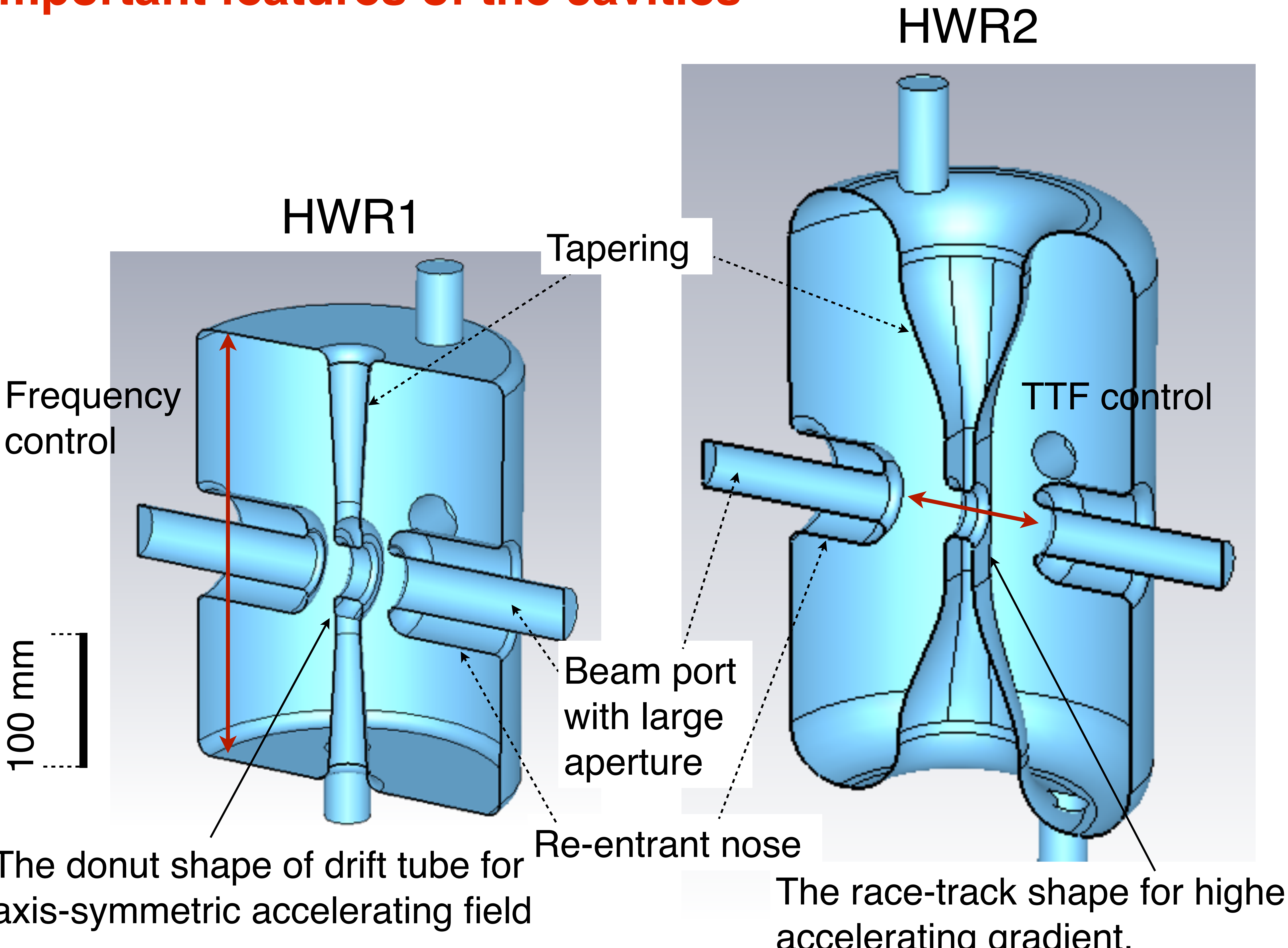


- Other considerations

must come with superconducting solenoid for tight focusing.→ axis-symmetric accelerating gradient

Specification	HWR1	HWR2
σ (mm)	3.2	2.2
P_b (W)	5.50E+04	1.40E+05
loss rate	1.80E-05	7.10E-06
aperture	±4.4σ	±4.9σ
error margin	1.4	1.8
ϕ (mm)	40	40

Important features of the cavities

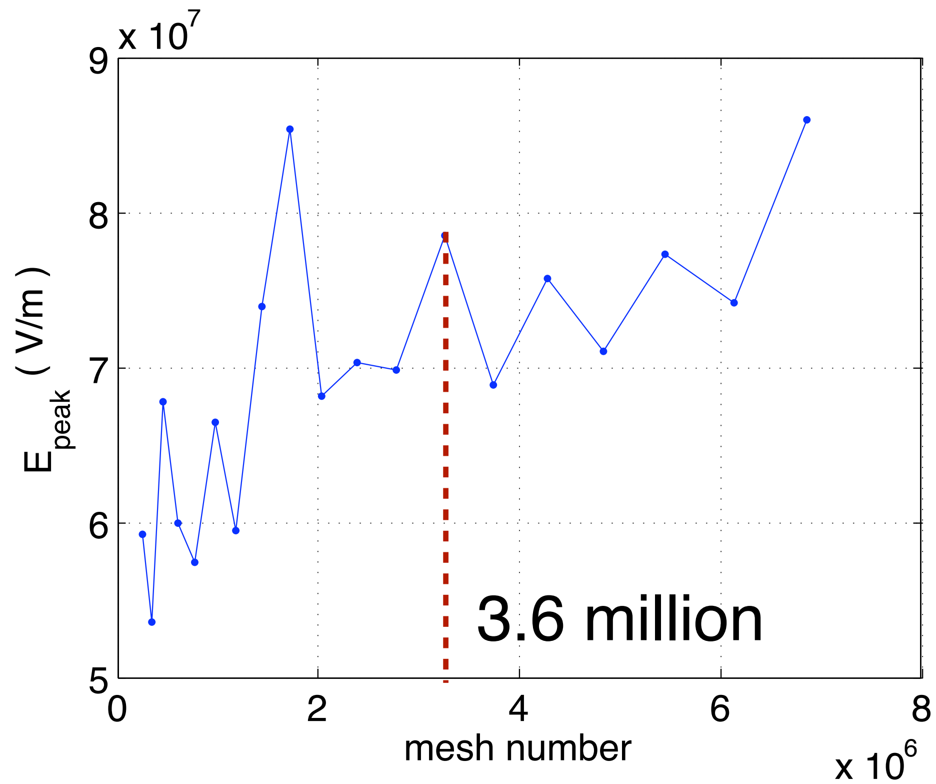


Optimization of cavity geometry

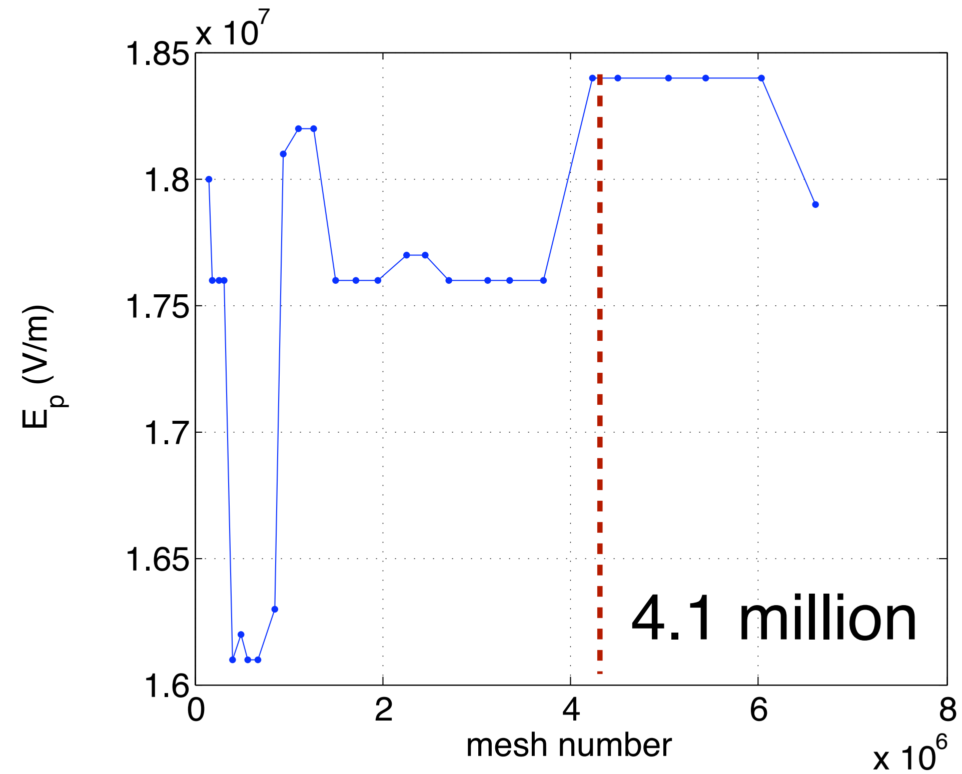
Figures of merit

f (resonant frequency)
TTF (transit time factor)
R/Q [β] (shunt impedance)
G (geometrical factor)
B_{sp} / E_{acc}
E_{sp} / E_{acc}

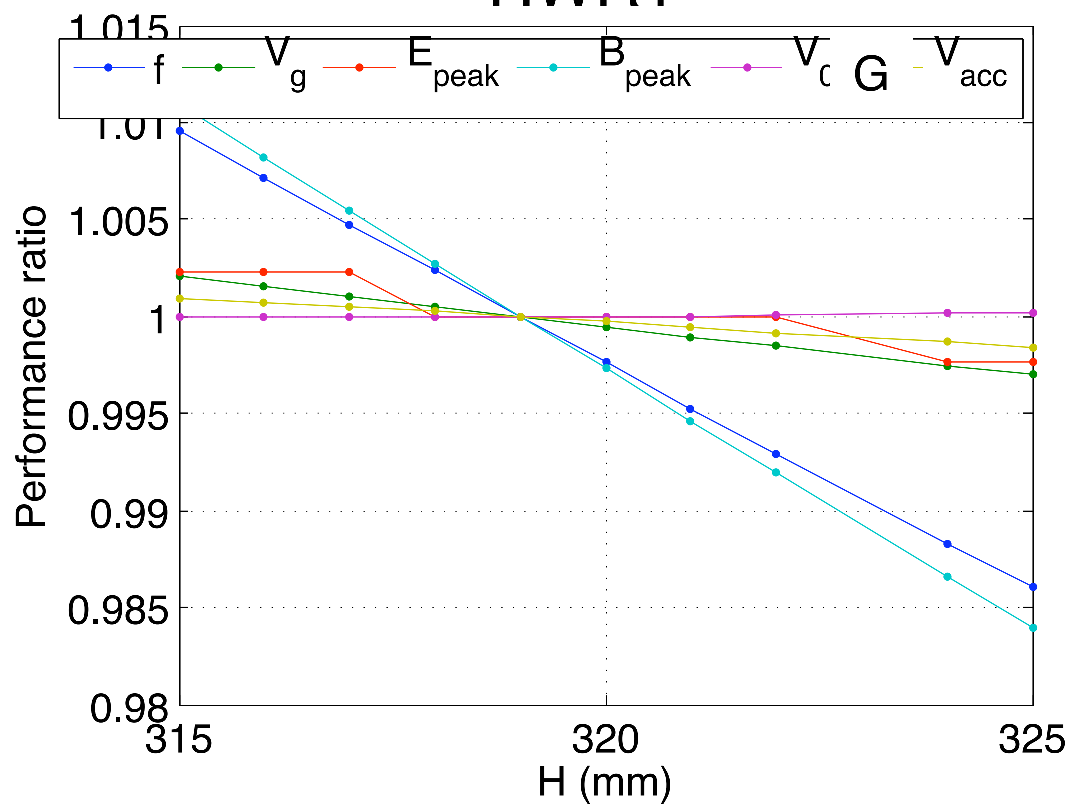
- E_p vs mesh number



HWR1

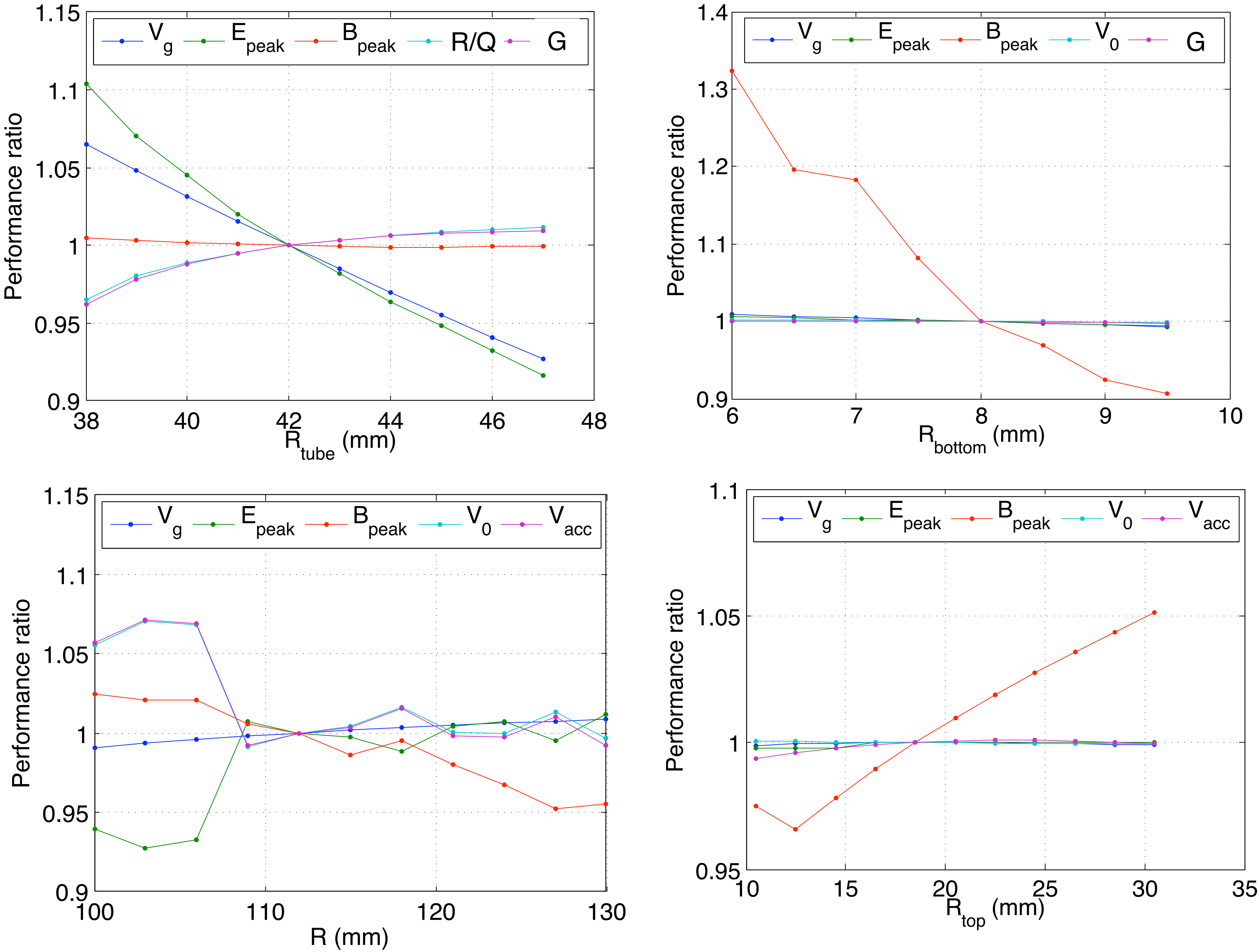


HWR2



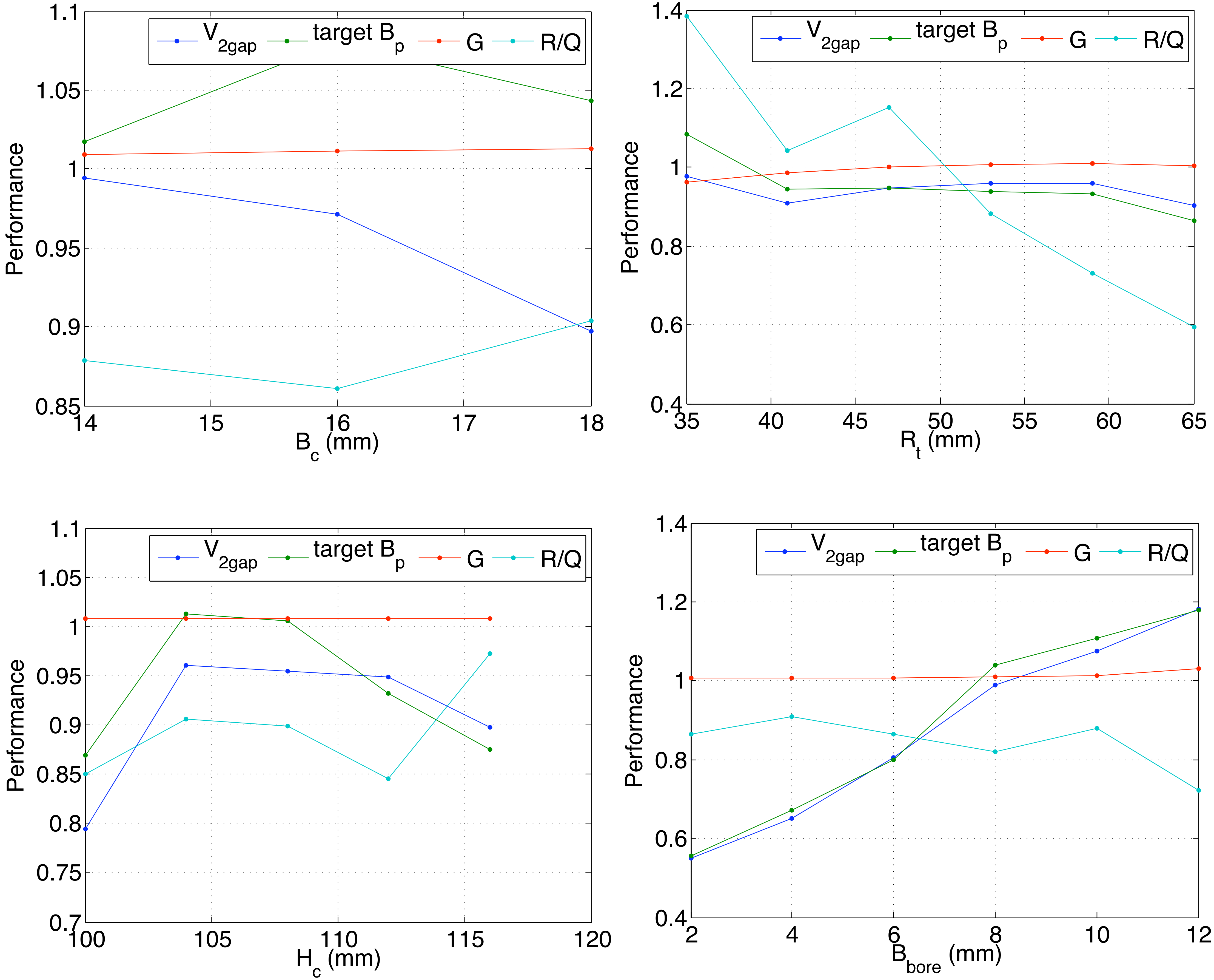
frequency was controlled by height

HWR1

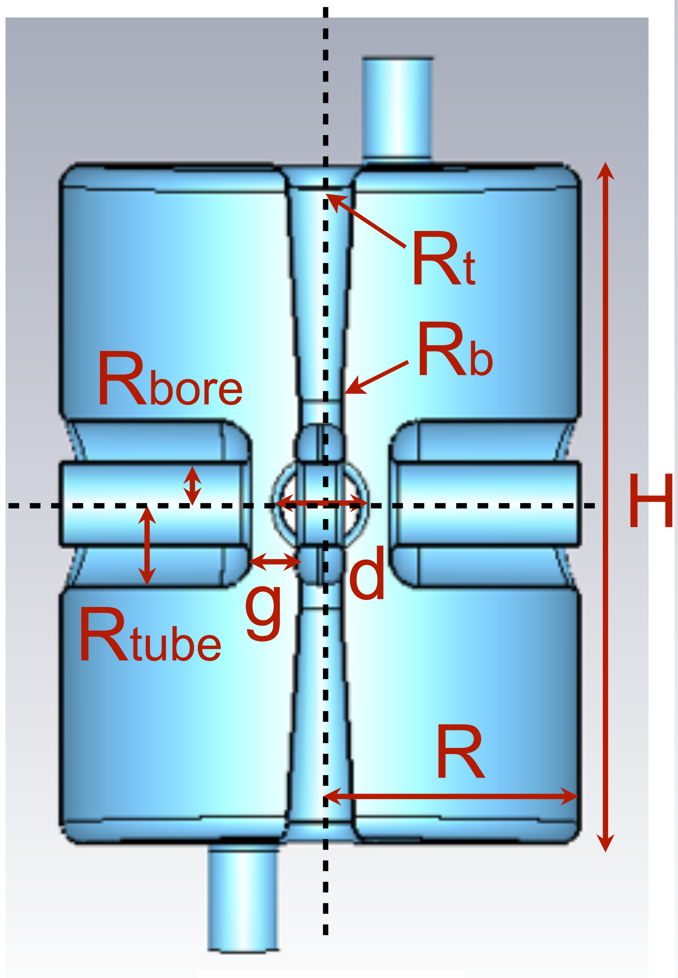


Performance ratio
V_g E_peak B_peak R/Q G
R_tube (mm)
V_g E_peak B_peak V_0 G
R_bottom (mm)
V_g E_peak B_peak V_0 V_acc
R (mm)
V_g E_peak B_peak V_0 V_acc
R_top (mm)

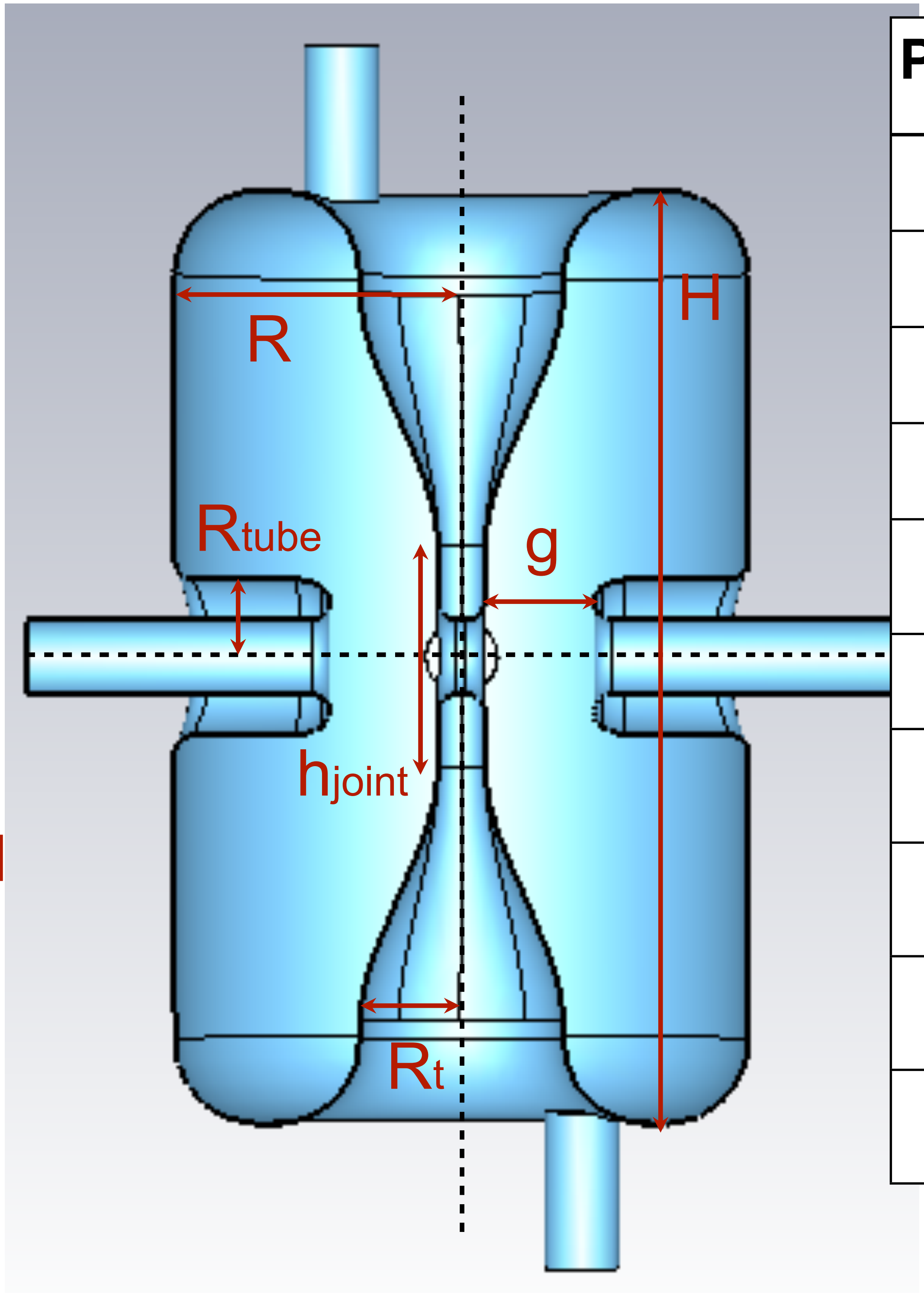
HWR2



Dimensions of the cavities



HWR1



HWR2

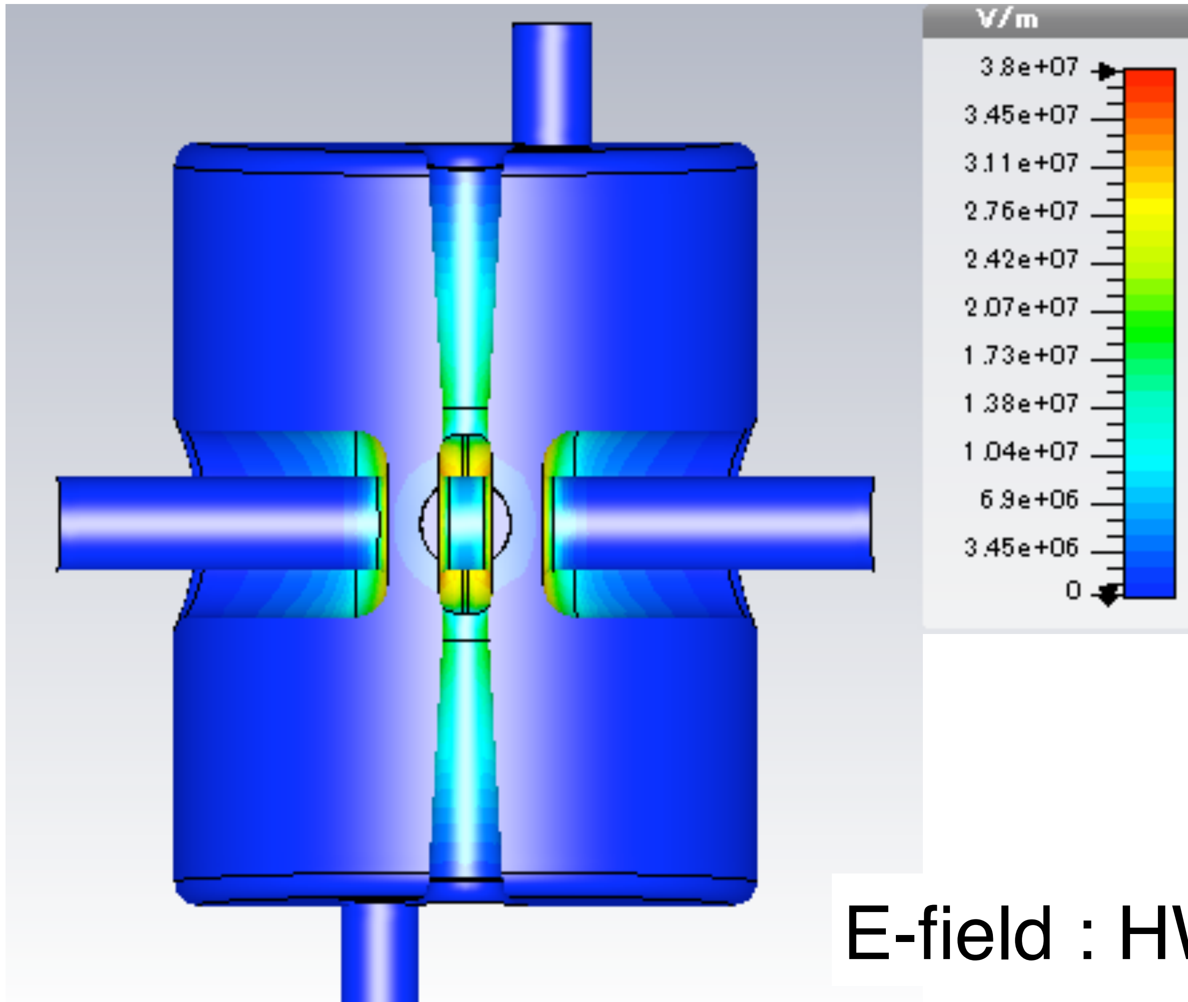
Parameters	HWR1	HWR2
H (mm)	332	503
d (mm)	45	77
g (mm)	22	52
R (mm)	125	155
R_{tube} (mm)	40	42
R_t (mm)	16	55
R_b (mm)	10	80
R_{bore} (mm)	20	20
h_{tune} (mm)	1	10
h_{joint} (mm)	10	120

RF performance of the cavities

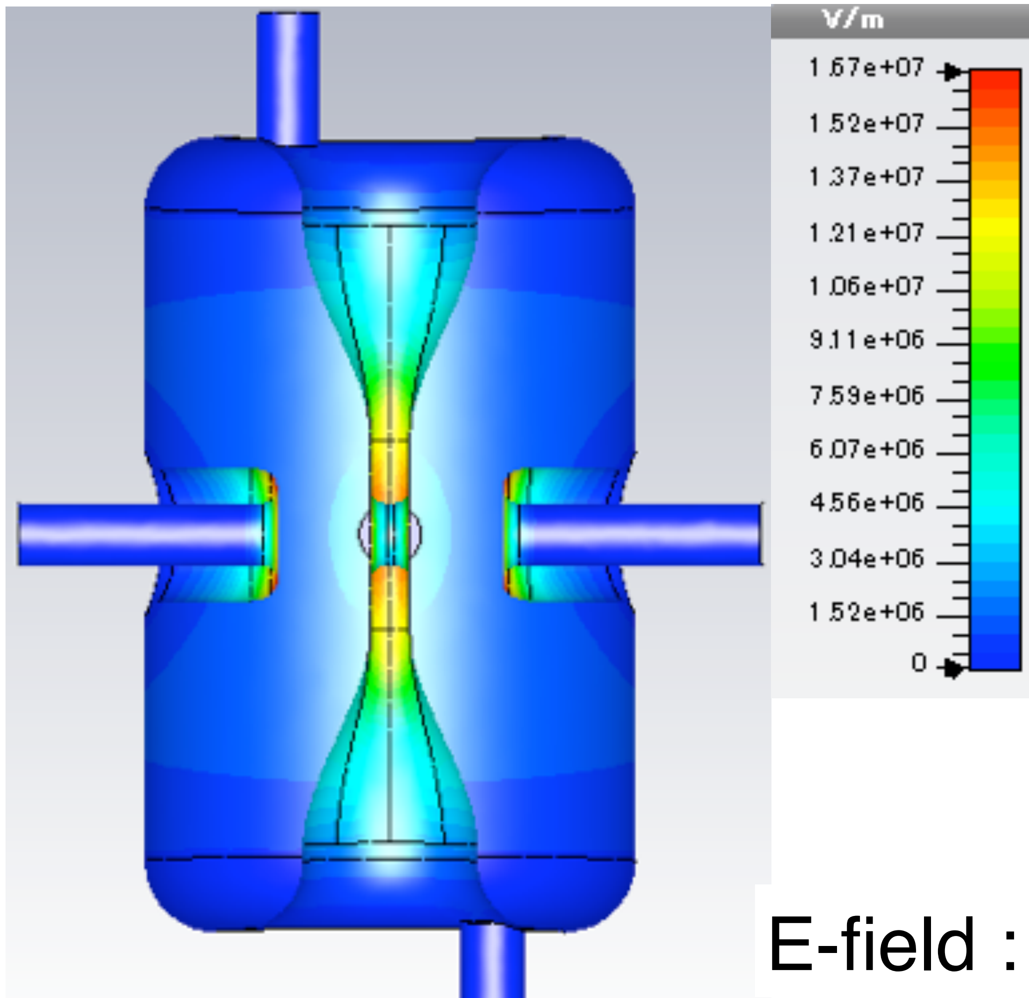
Figures of merit	HWR1	HWR2
V_0	0.86 MV	1.93 MV
TTF	0.77	0.79
V_{acc}	0.66 MV	1.52 MV
E_{acc}	5.5 MV/m	6.9 MV/m
R/Q_0	237.7 Ω	120.8 Ω
G	53.8 Ω	88.3 Ω
Q_0	1.10E+09	1.90E+09
U	0.9 J	4.4 J
P_{wall}	1.6 W	4.8 W
E_{sp}/E_{acc}	6.3	5.1
B_{sp}/E_{acc}	12.9 (mT/(MV/m))	8.3 (mT/(MV/m))
P_g	57 kW	132 kW

surface resisance for high purity Nb

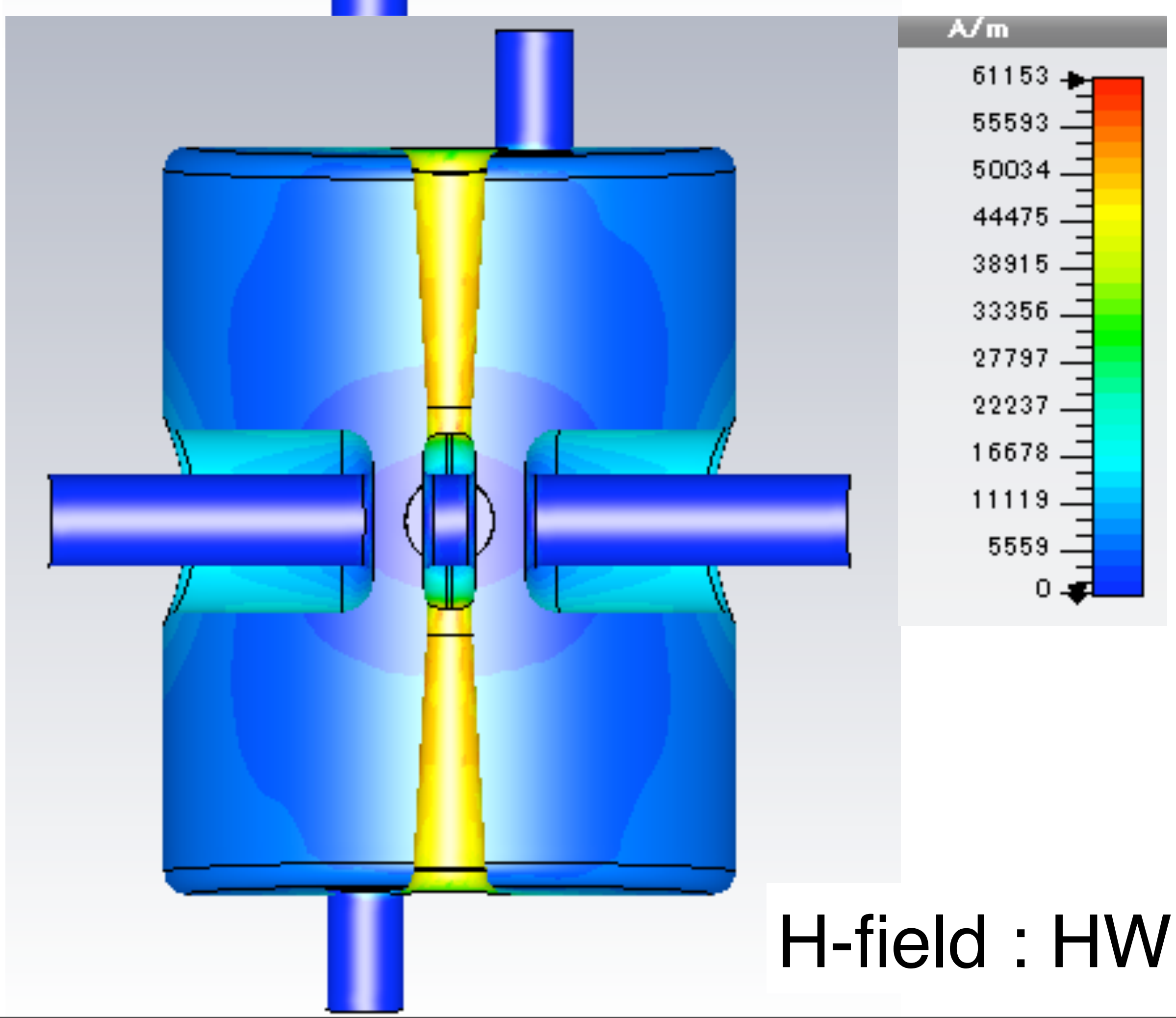
R_s (4K) = 47.4 nΩ



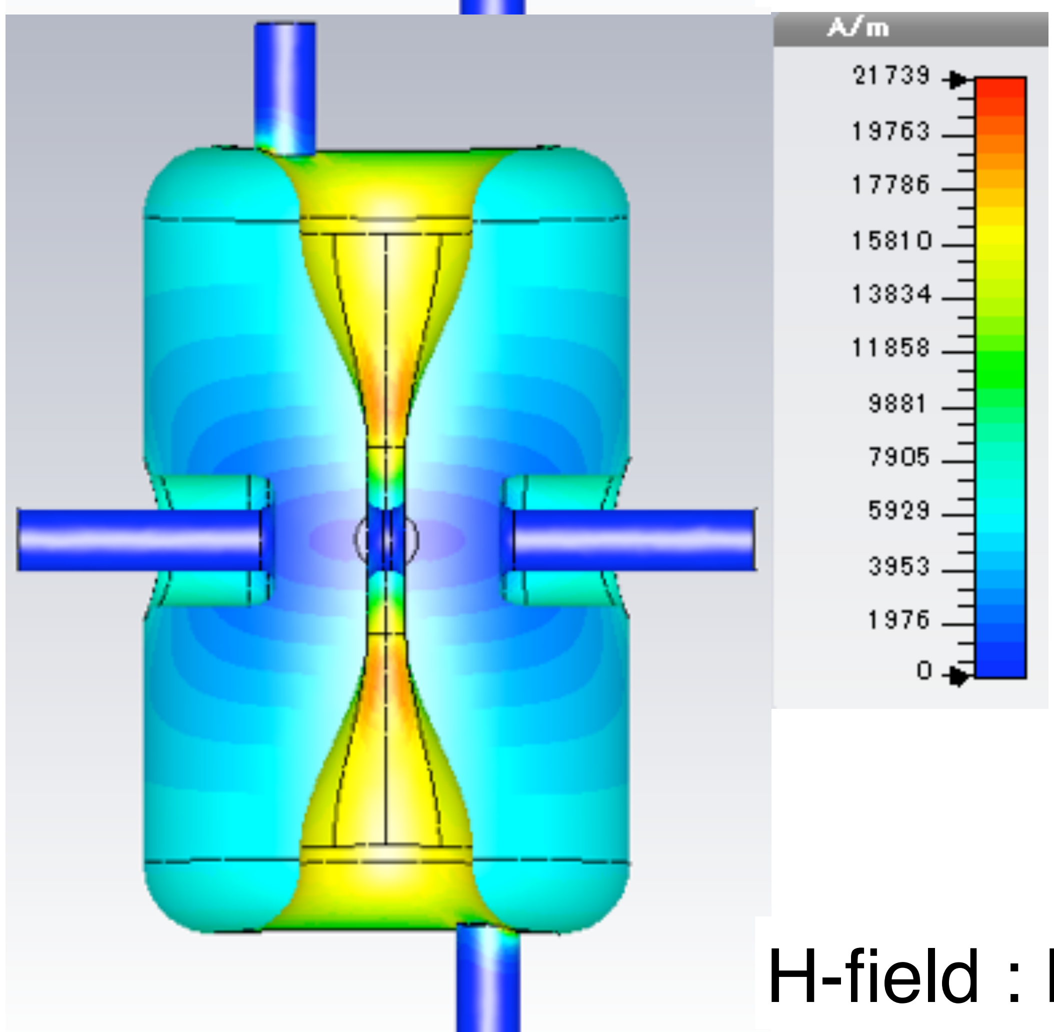
E-field : HWR1



E-field : HWR2

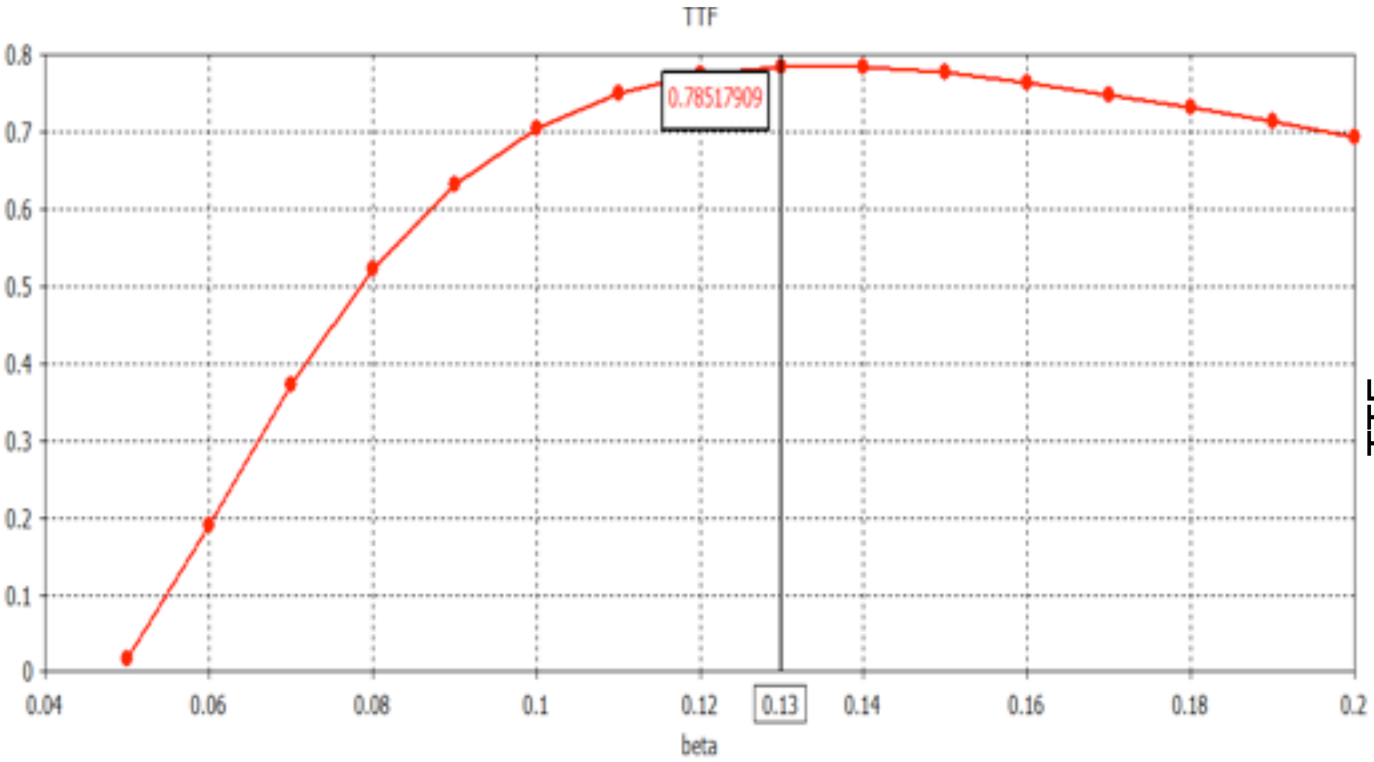


H-field : HWR1

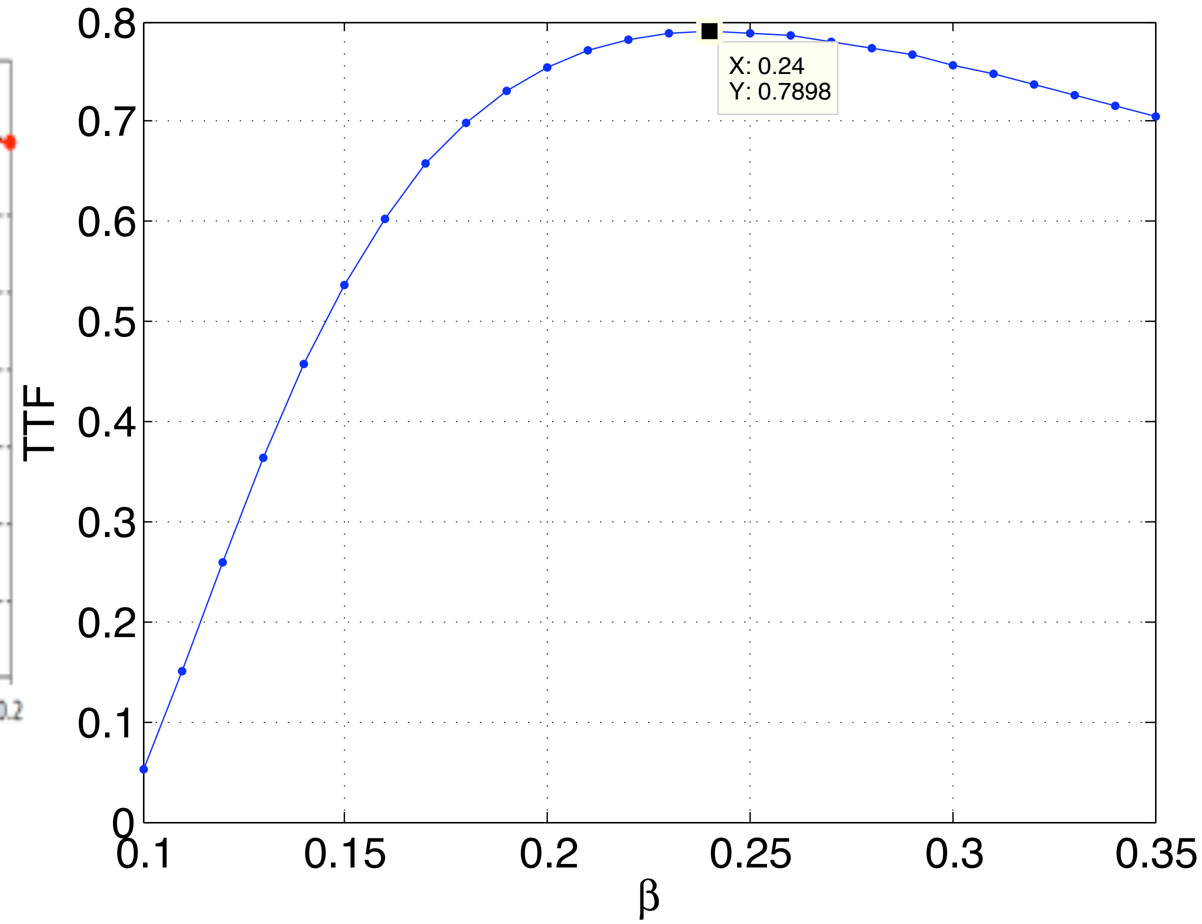


H-field : HWR2

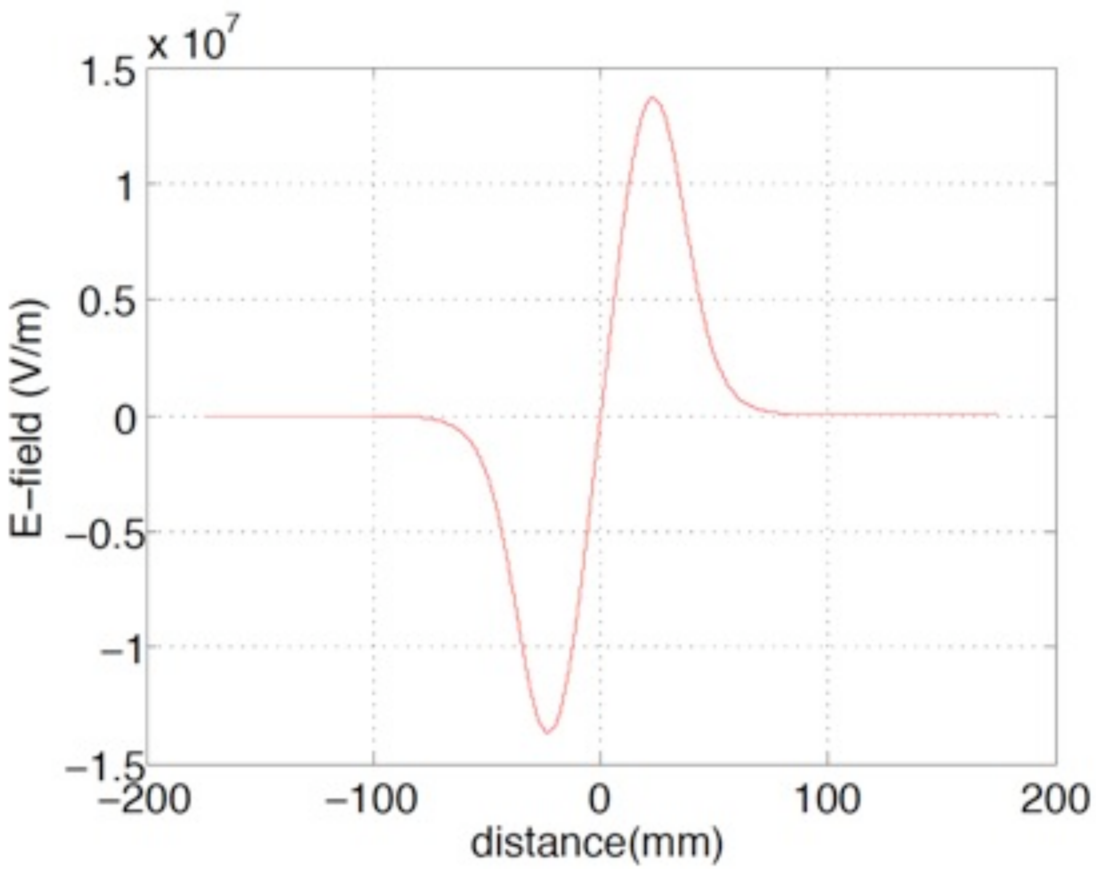
TTF: HWR1



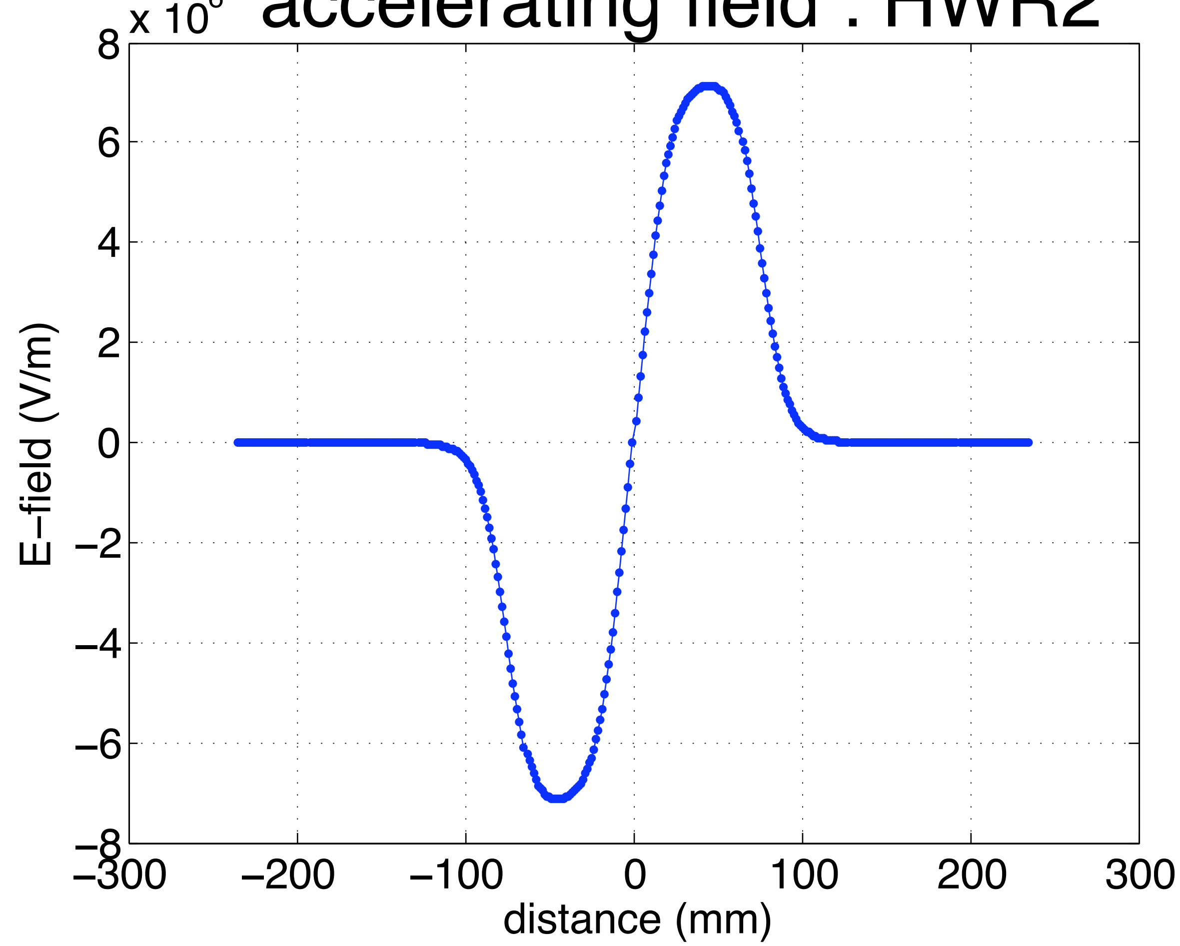
TTF: HWR2

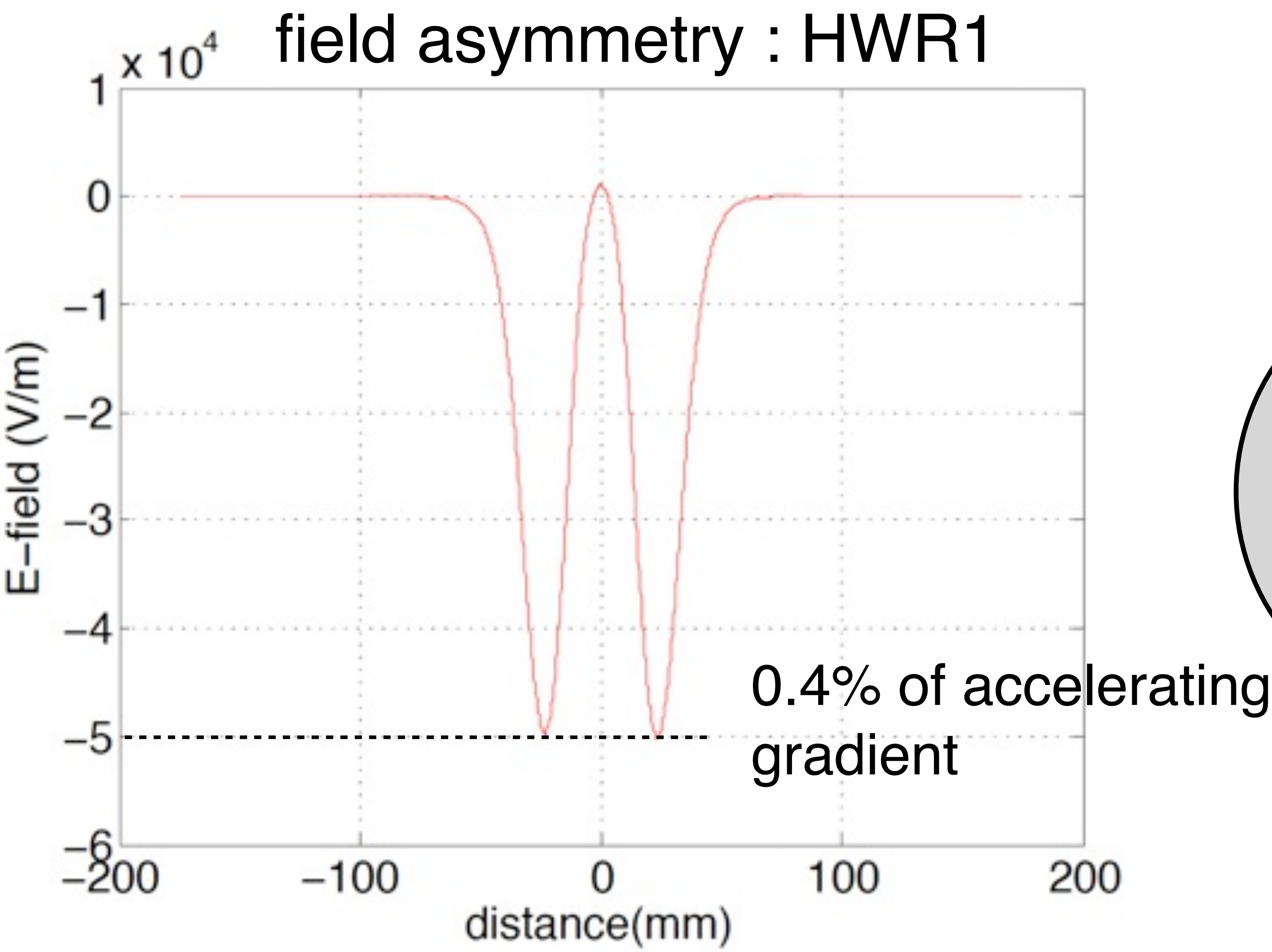


accelerating field: HWR1

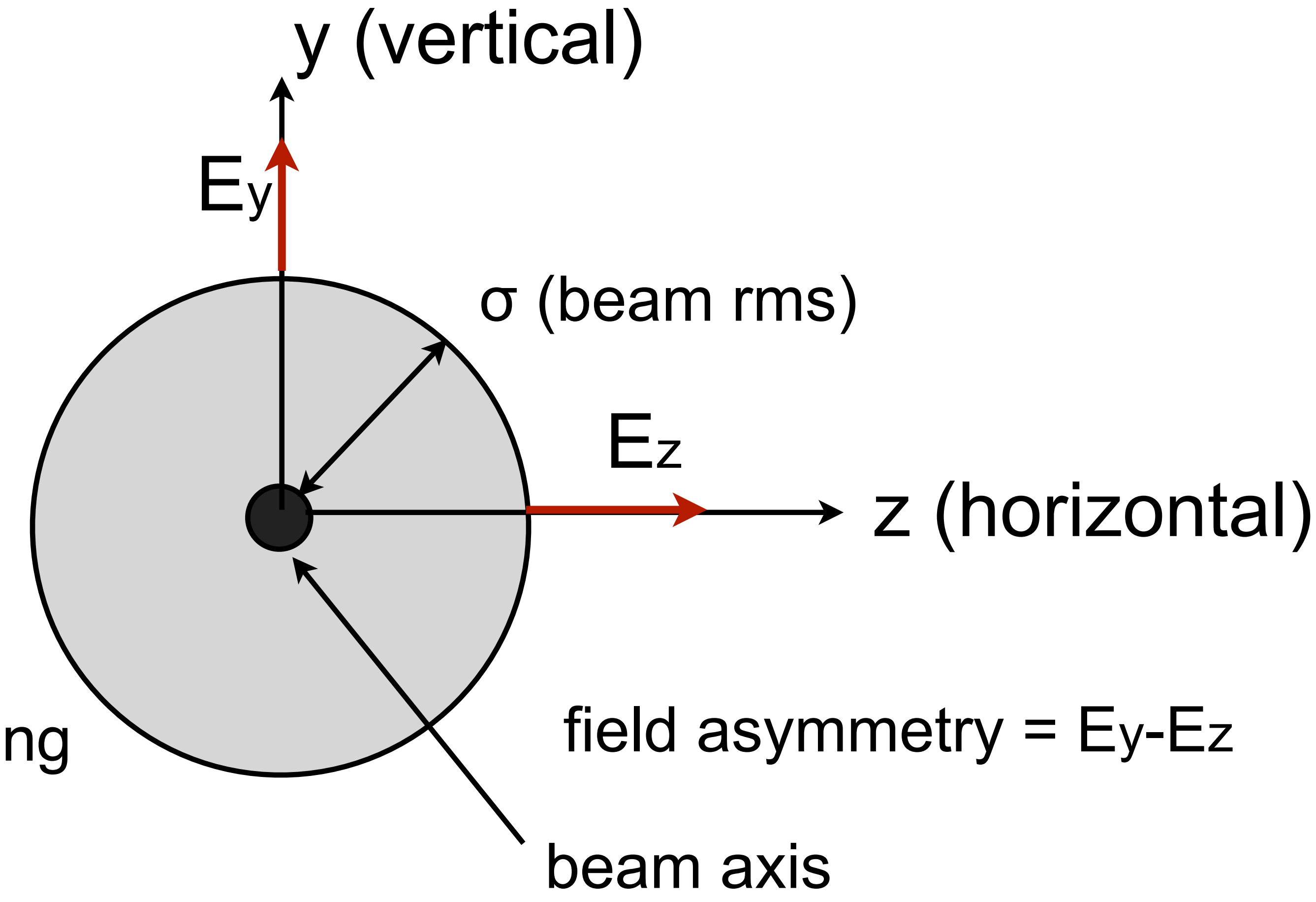


accelerating field : HWR2

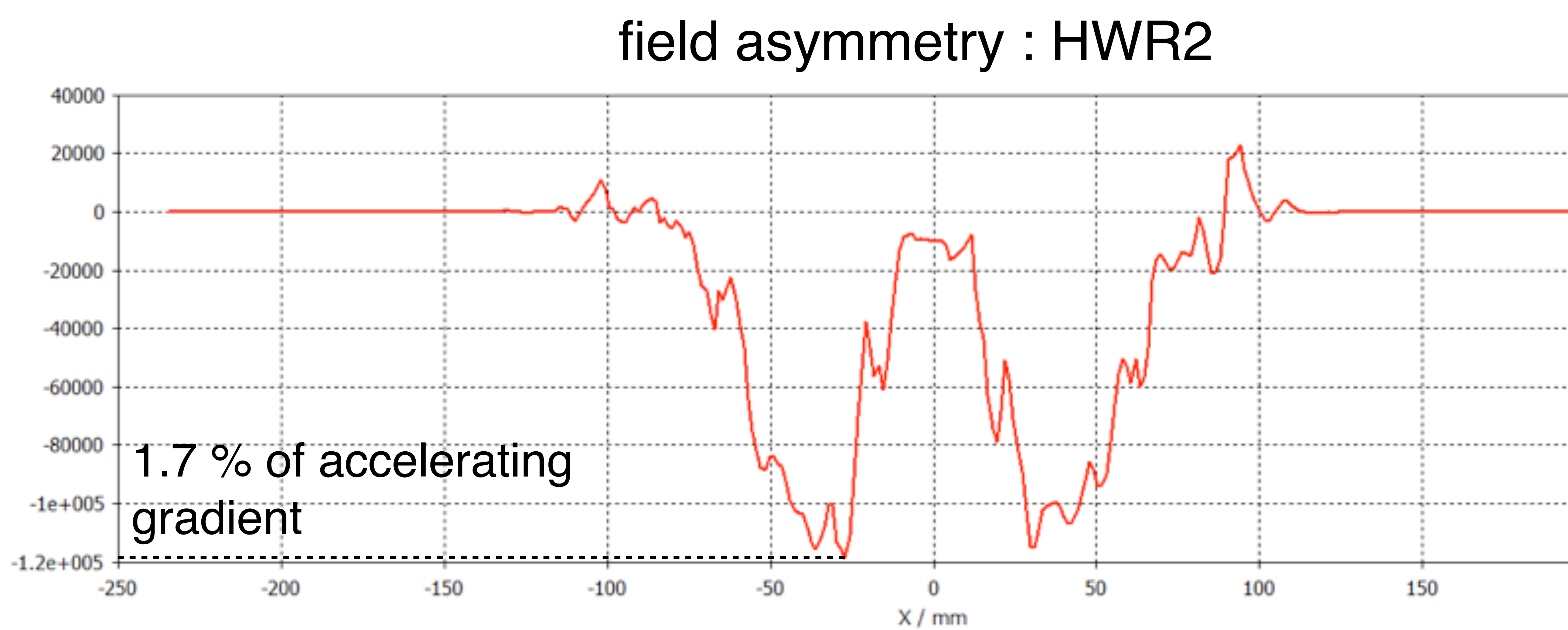




field asymmetry : HWR1
x 10^4
1
0
−1
−2
−3
−4
−5
−6
E−field (V/m)
−200
−100
0
100
200
distance(mm)
0.4% of accelerating gradient



y (vertical)
Ey
σ (beam rms)
Ez
z (horizontal)
field asymmetry = Ey-Ez
beam axis



field asymmetry : HWR2
40000
20000
0
-20000
-40000
-60000
-80000
-1e+005
-1.2e+005
1.7 % of accelerating gradient
-250
-200
-150
-100
-50
0
50
100
150
X / mm

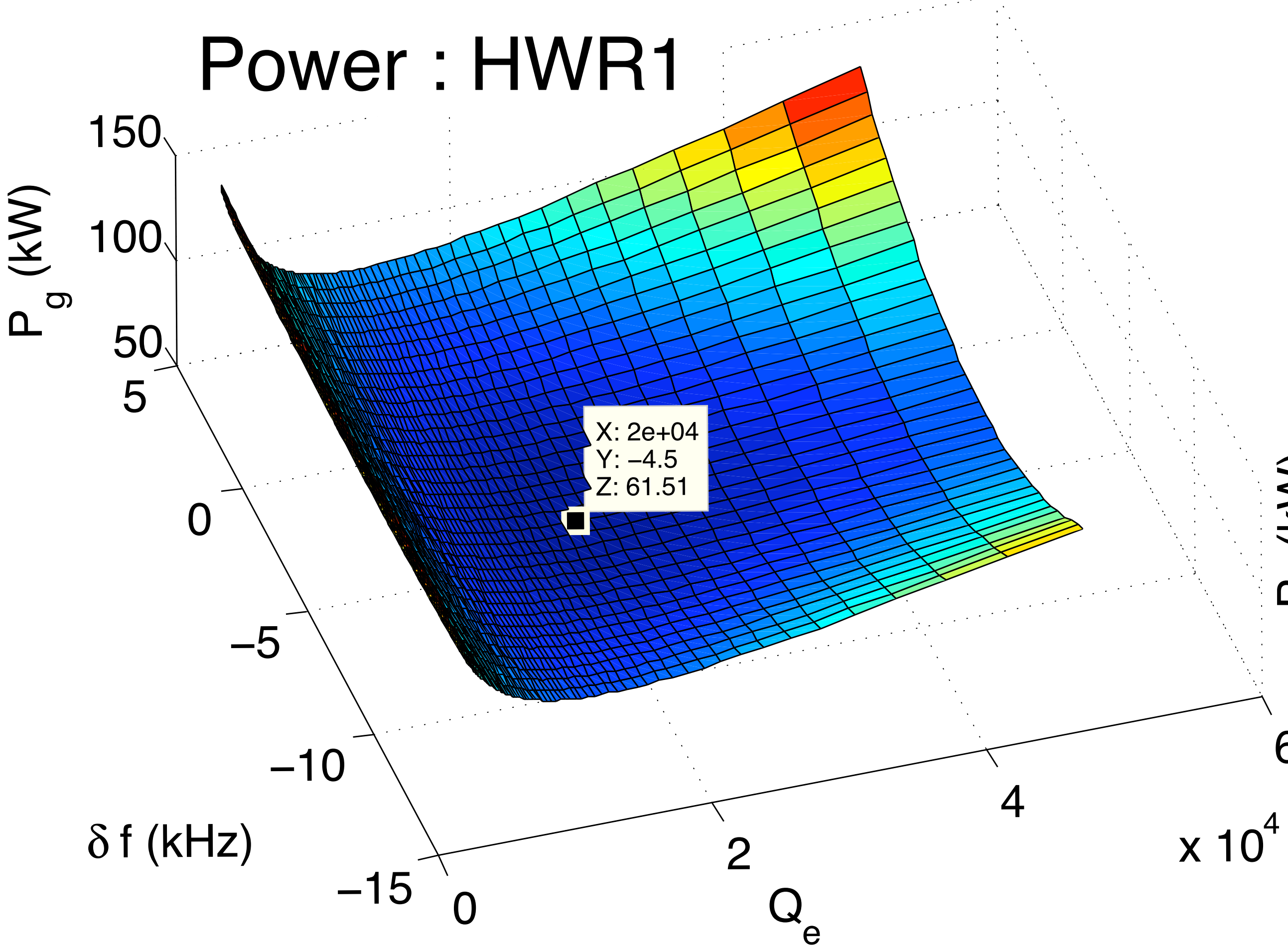
Power supply to the cavity

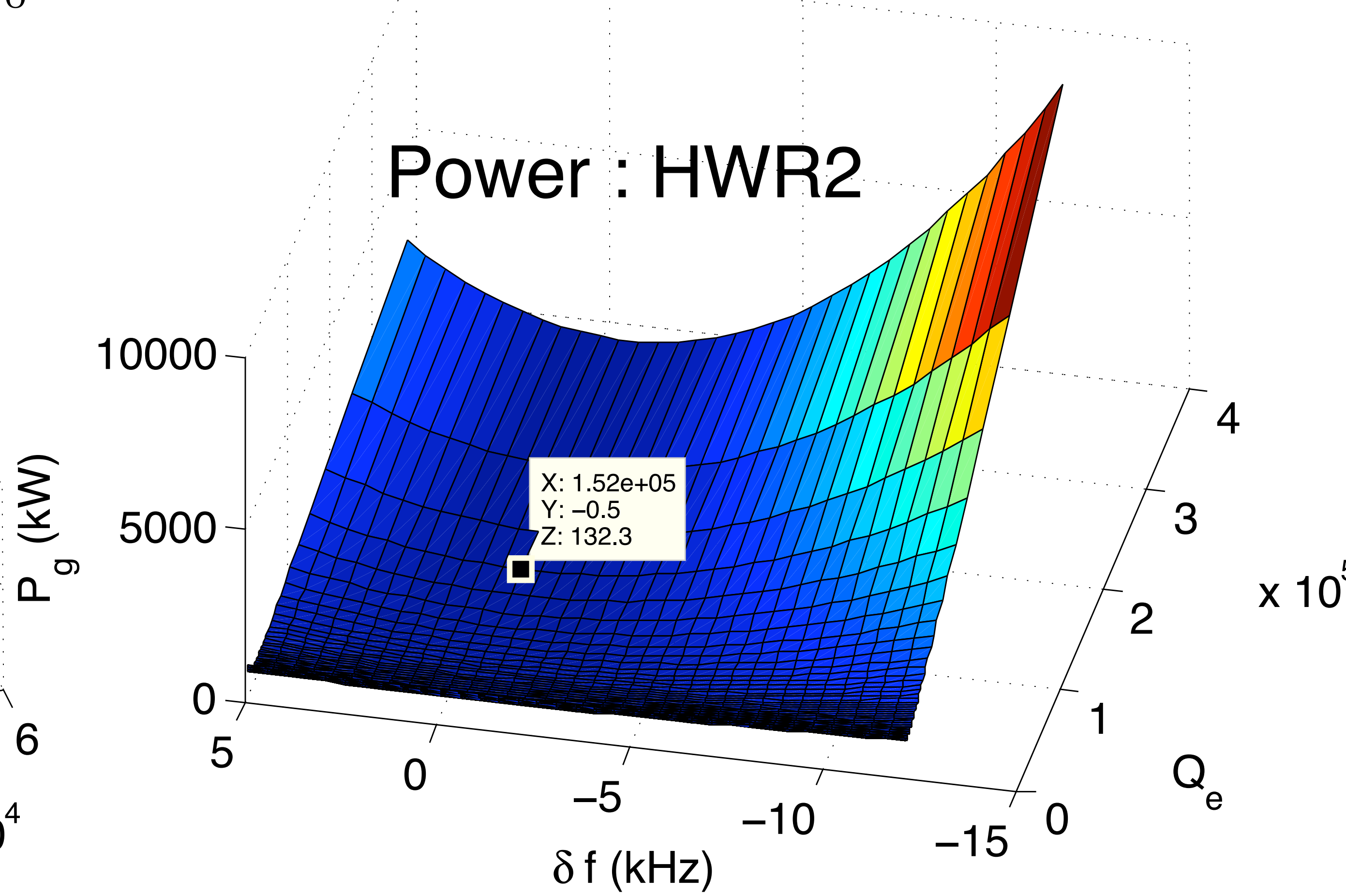
- The power supply P_g to maintain constant accelerating voltage in strong over-coupling is given as

$$P_g = \frac{V_{acc}^2}{4\frac{R}{Q_0}Q_L}\left[\left(1+\frac{R}{Q_0}Q_L\frac{I_b}{V_{acc}}\cos\phi_s\right)^2+\left(2Q_L\frac{\delta f}{f}-\frac{R}{Q_0}Q_L\frac{I_b}{V_{acc}}\sin\phi_s\right)^2\right]$$

- The matching condition

$$Q_e \approx \frac{V_{acc}}{I_b\frac{R}{Q_0}\cos\phi_s}, \quad \delta f = \frac{I_b\frac{R}{Q_0}\sin\phi_s}{2V_{acc}}f$$





- The power supply Pg without beam reduces to

$$P_g = \frac{V_{acc}^2}{4\frac{R}{Q_0}Q_L}\left[1 + Q_L^2\left(\frac{2\delta f}{f}\right)^2\right]$$

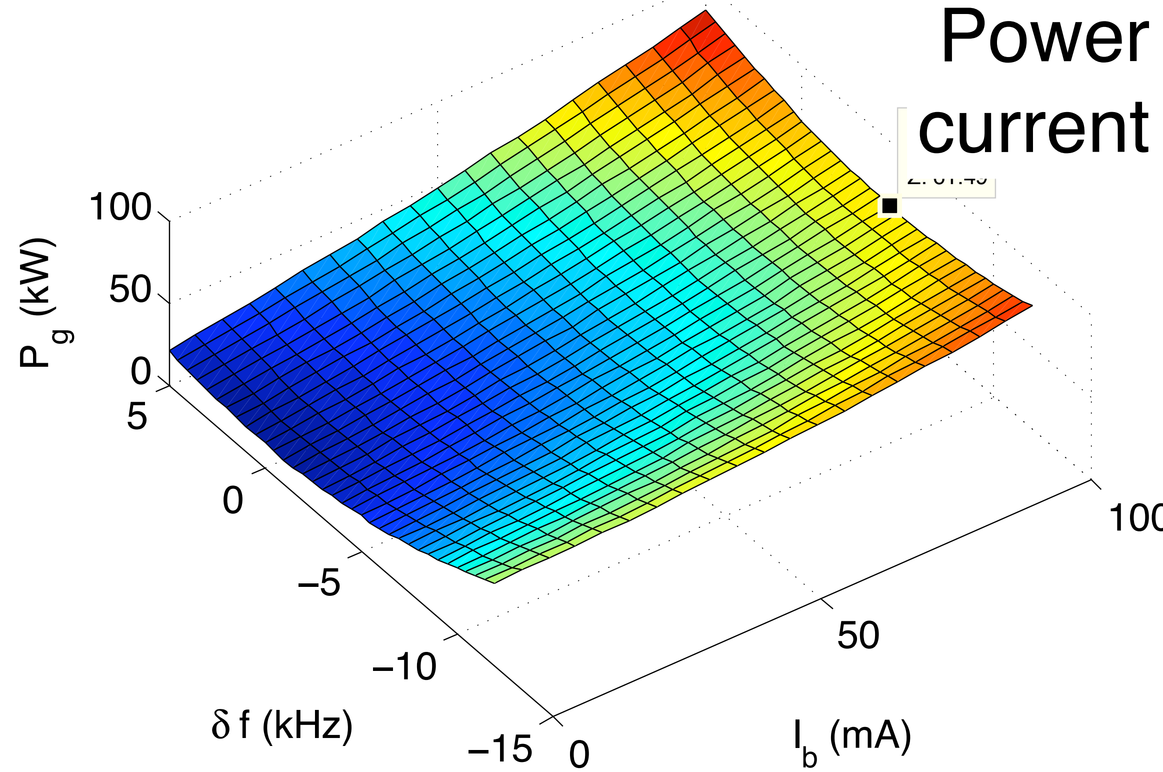
On resonance, we have for minimum power

	HWR1	HWR2
adjustable $Q_e=Q_0$	1.6 W	4.8 W
non-adjustable Q_e	44 kW	66 kW

- Beam loading parameters

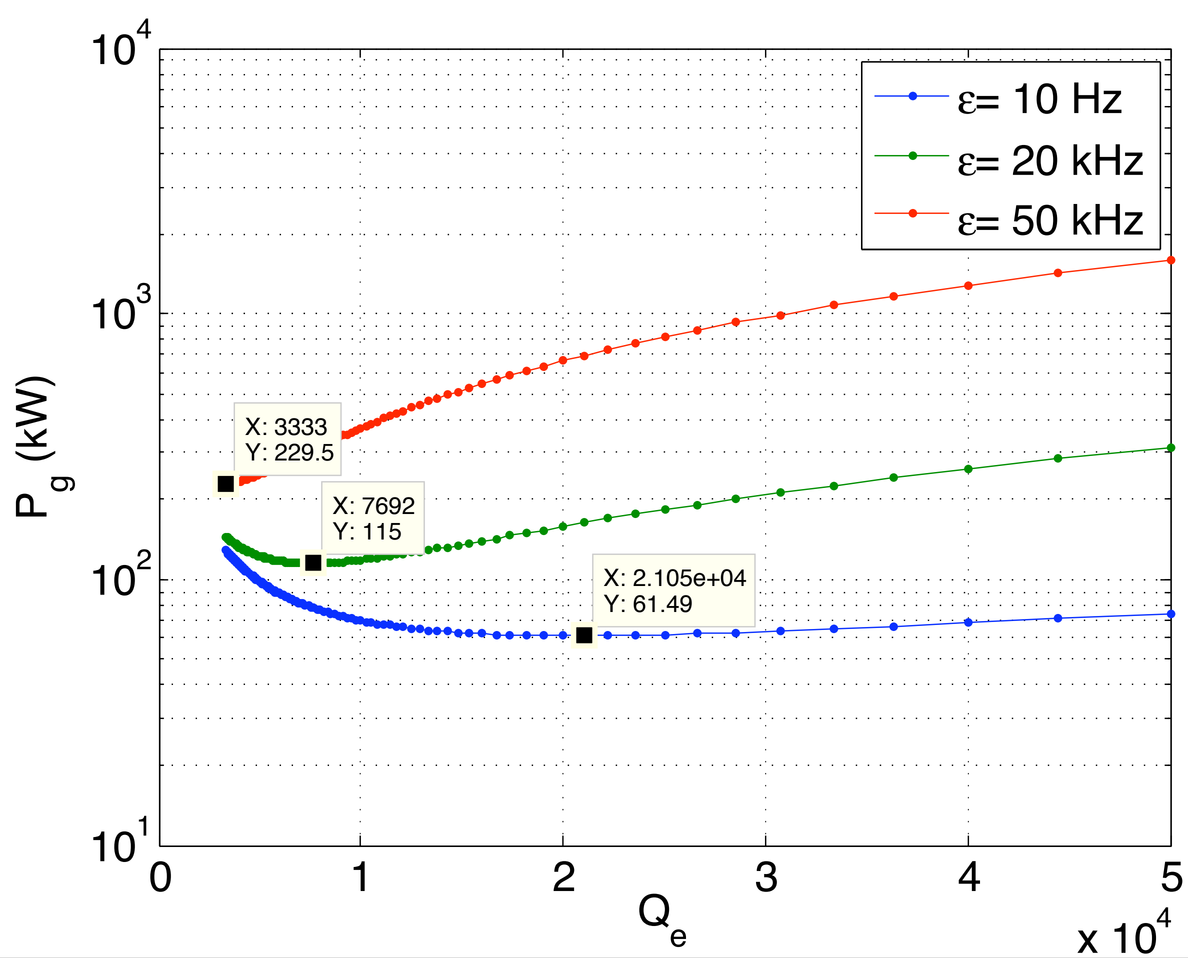
	HWR1	HWR2
I_b (mA)	100	100
ϕ_s (°)	-30	-30
Q_e	2.10E+04	1.45E+05
f_{detune} (kHz)	-4.5	-0.65
$\Delta_{\pm 3dB}$ (kHz)	15.7	2.37
P_g (kW)	62	132

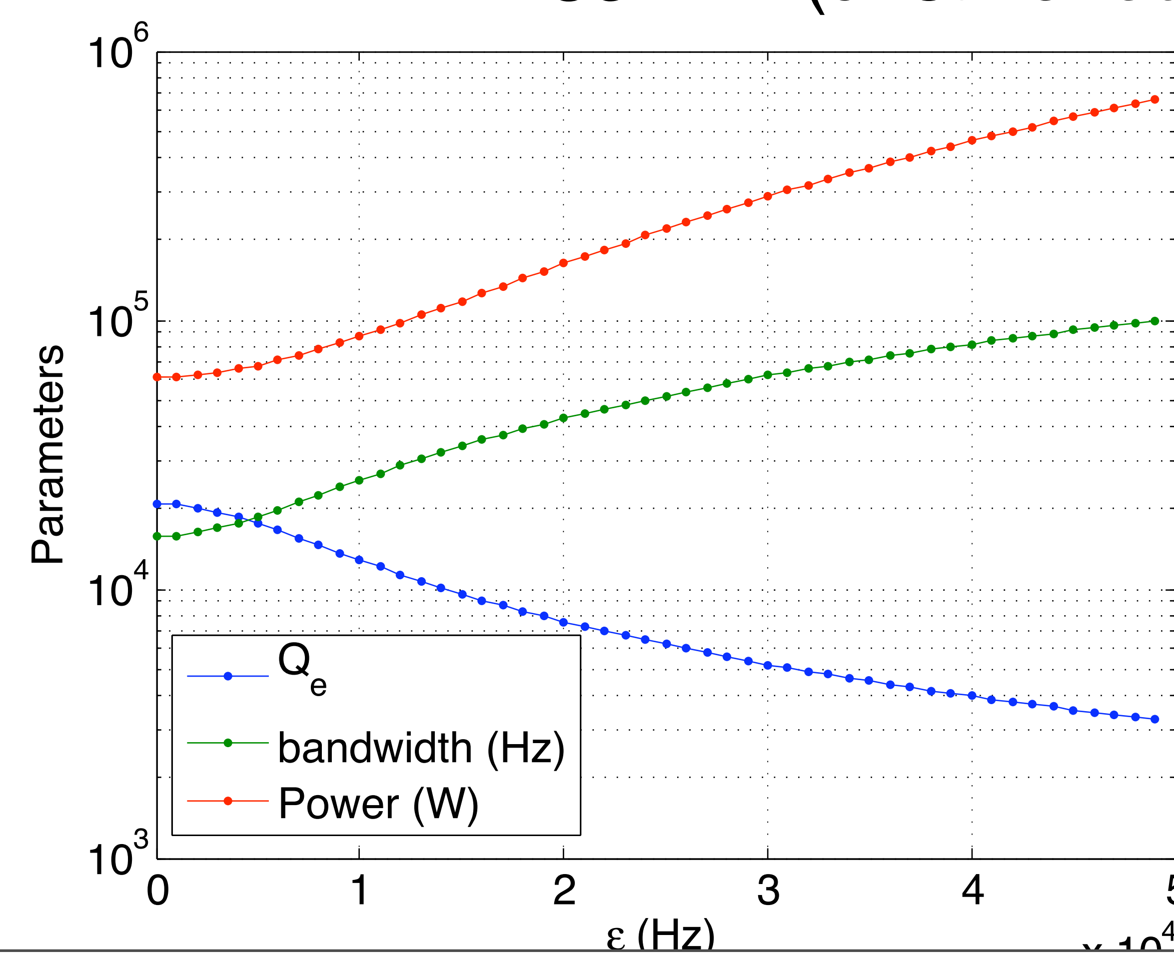
Power vs beam current : HWR2



- Power with frequency shift ε (after detuning)

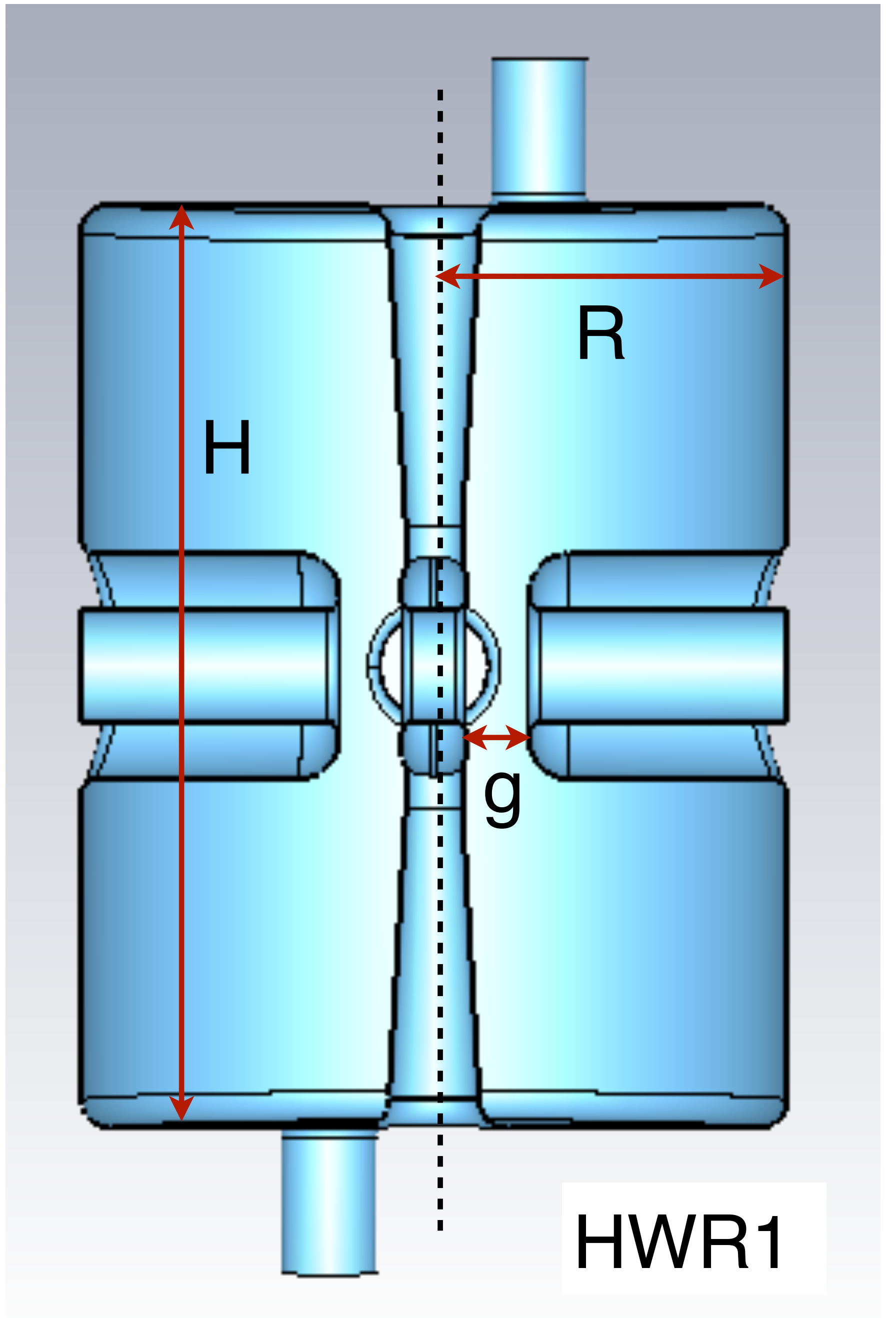
ε_{LFD}= 65~380 Hz (stiffened)
35 kHz (unstiffened)

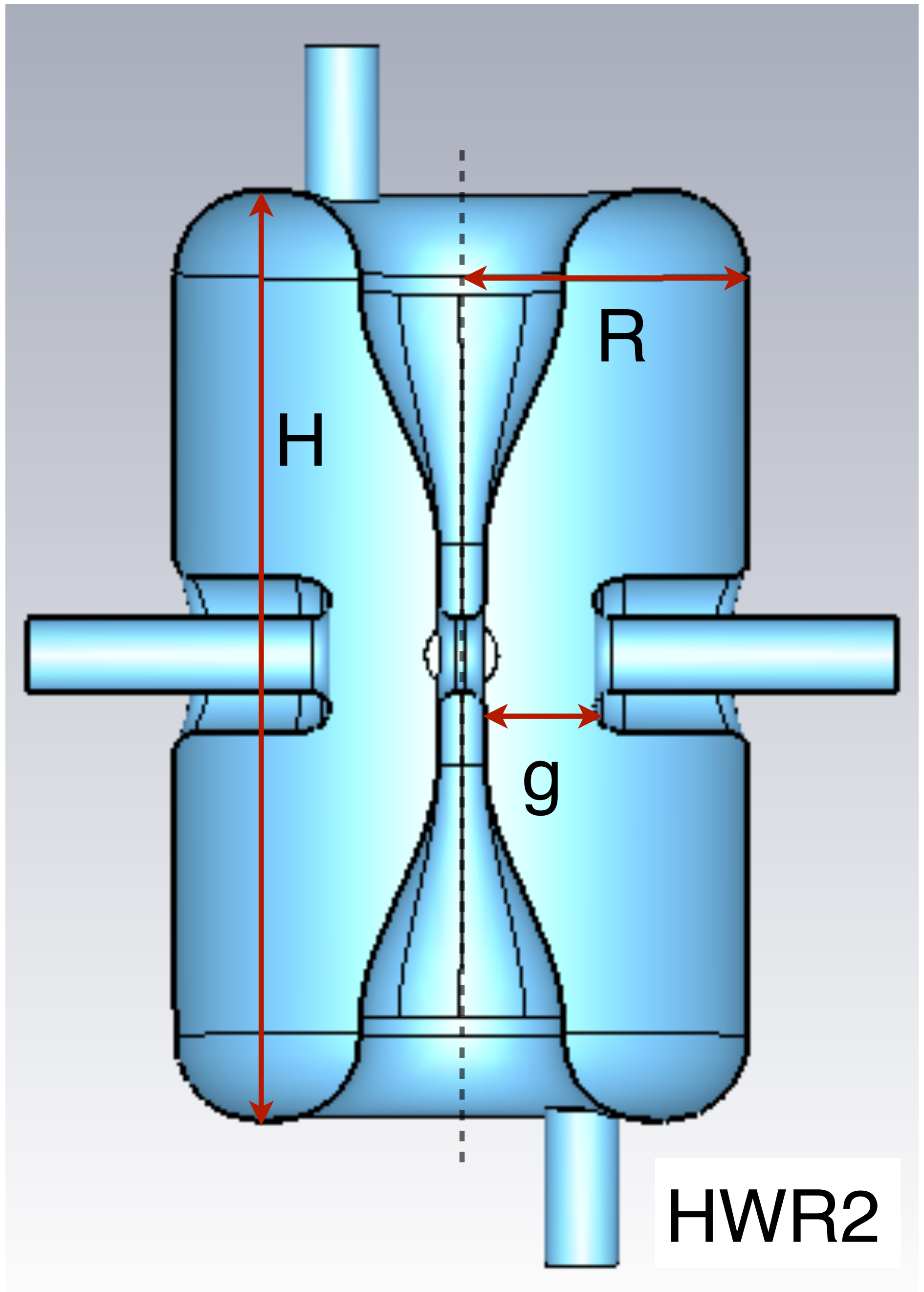




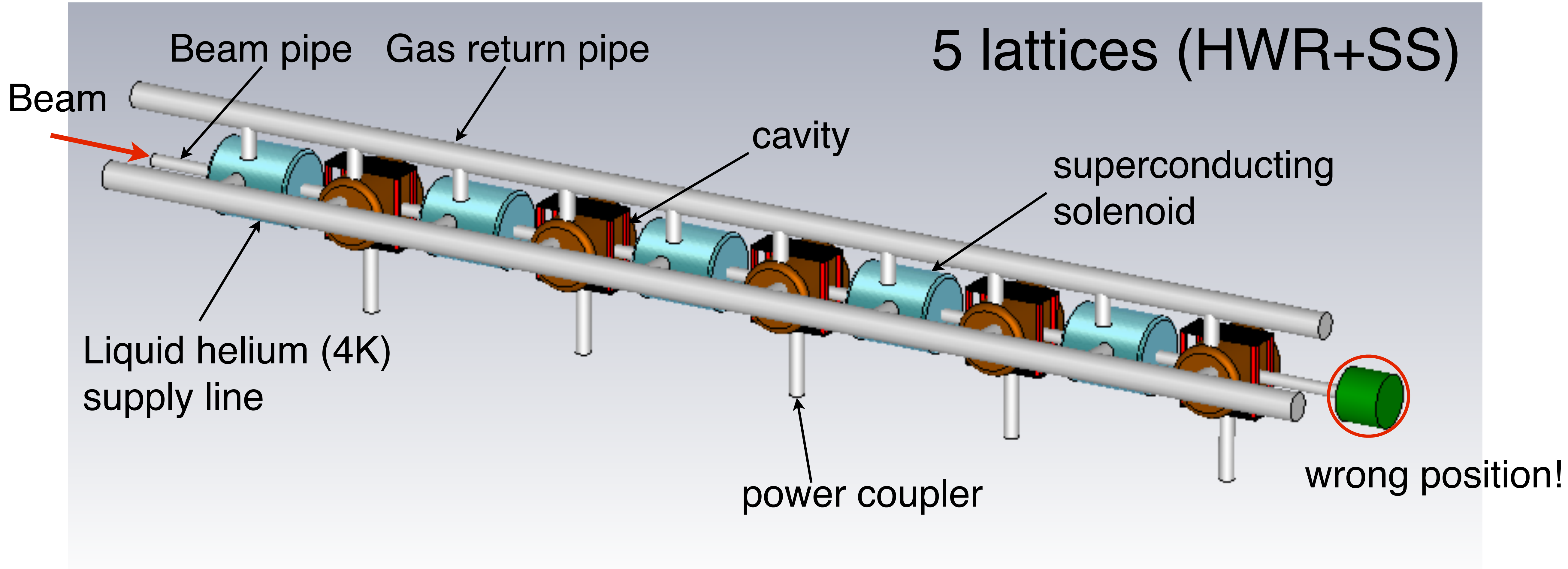
Fabrication error

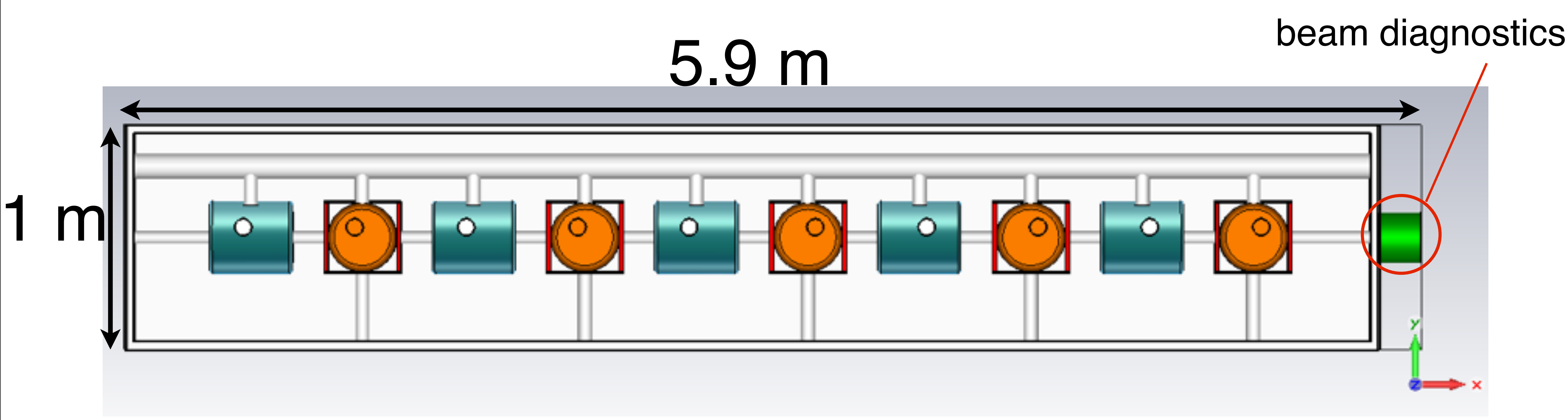
freq. shift	HWR1	HWR2
df/dH (MHz/mm)	-0.8684	-0.5972
df/dg (MHz/mm)	4.4115	1.1815
df/dR (MHz/mm)	-0.7316	-0.7992



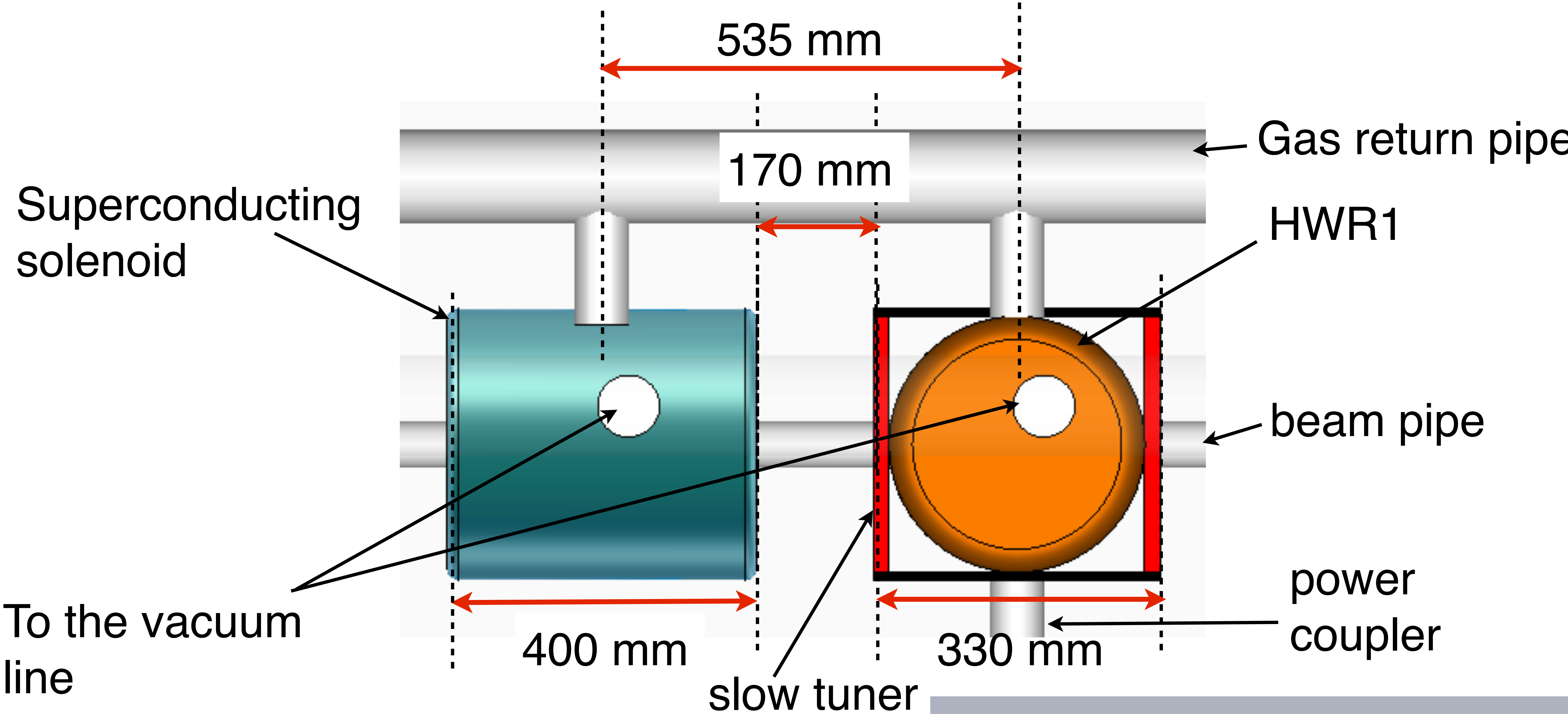


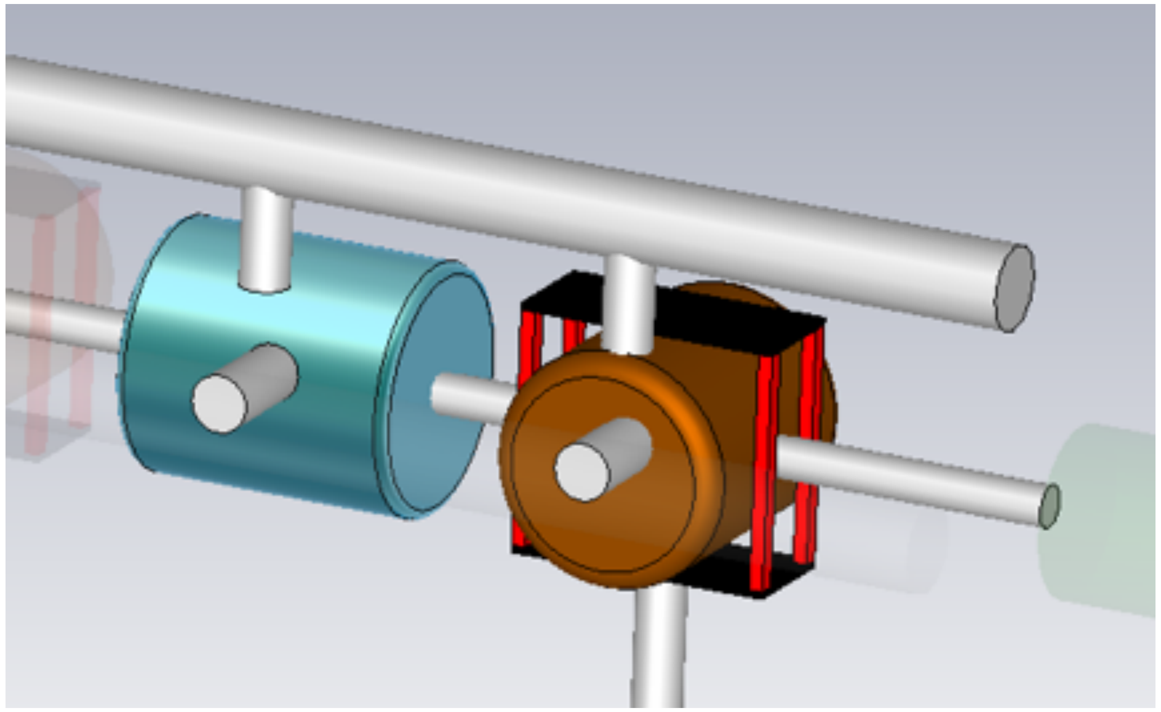
Cryomodule configuration





Lattice structure design





Perspective view

Conclusion

- Fron end design is now done with target specification of each component.

- Electromagnetic design of the two superconducting half wave resonators is complete. Their prototypes will be fabricated soon.

- Design values are close to the target values (Accelerating voltage).

- The multipaction study of the cavities are still under way.