Physics design of Superconducting RF Cavities for Indian Spallation Neutron Source

Vinit Kumar

(on behalf of Accelerator Physics design team)

RRCAT, Indore

July 18, 2017

Outline of the talk

- Multi-cell cavity basics

- Optimization of cavity geometry

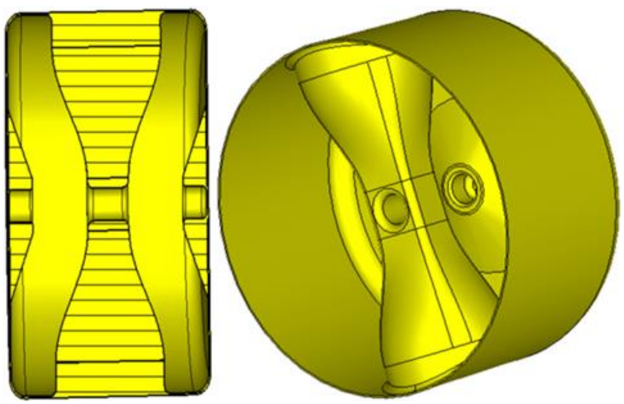
- Higher order modes

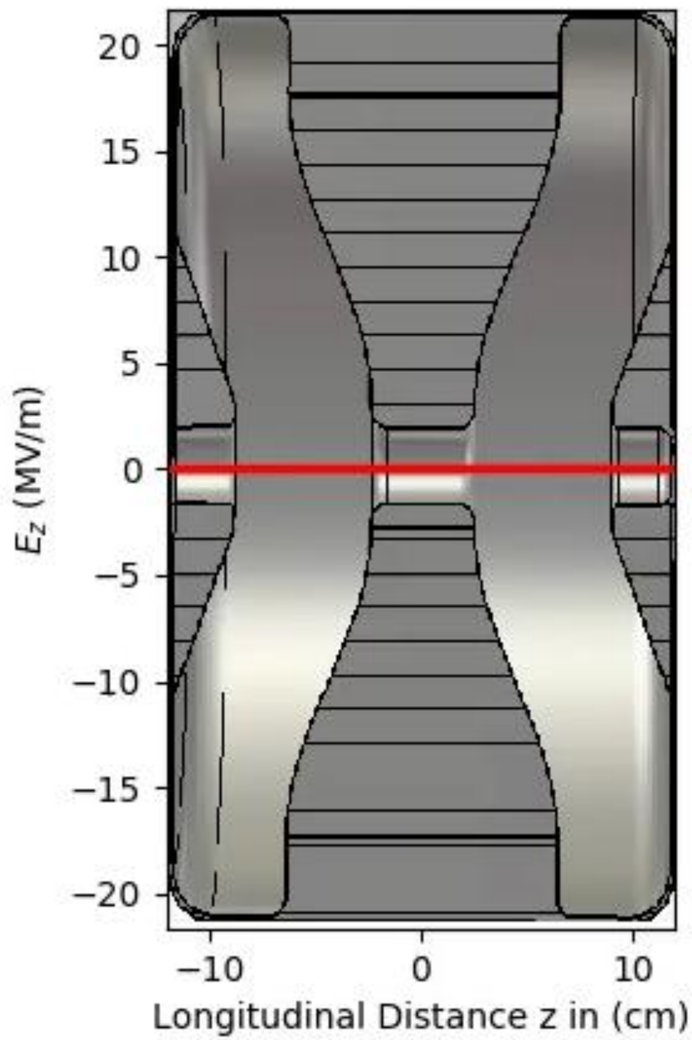
- Lorentz force detuning

- Multipacting

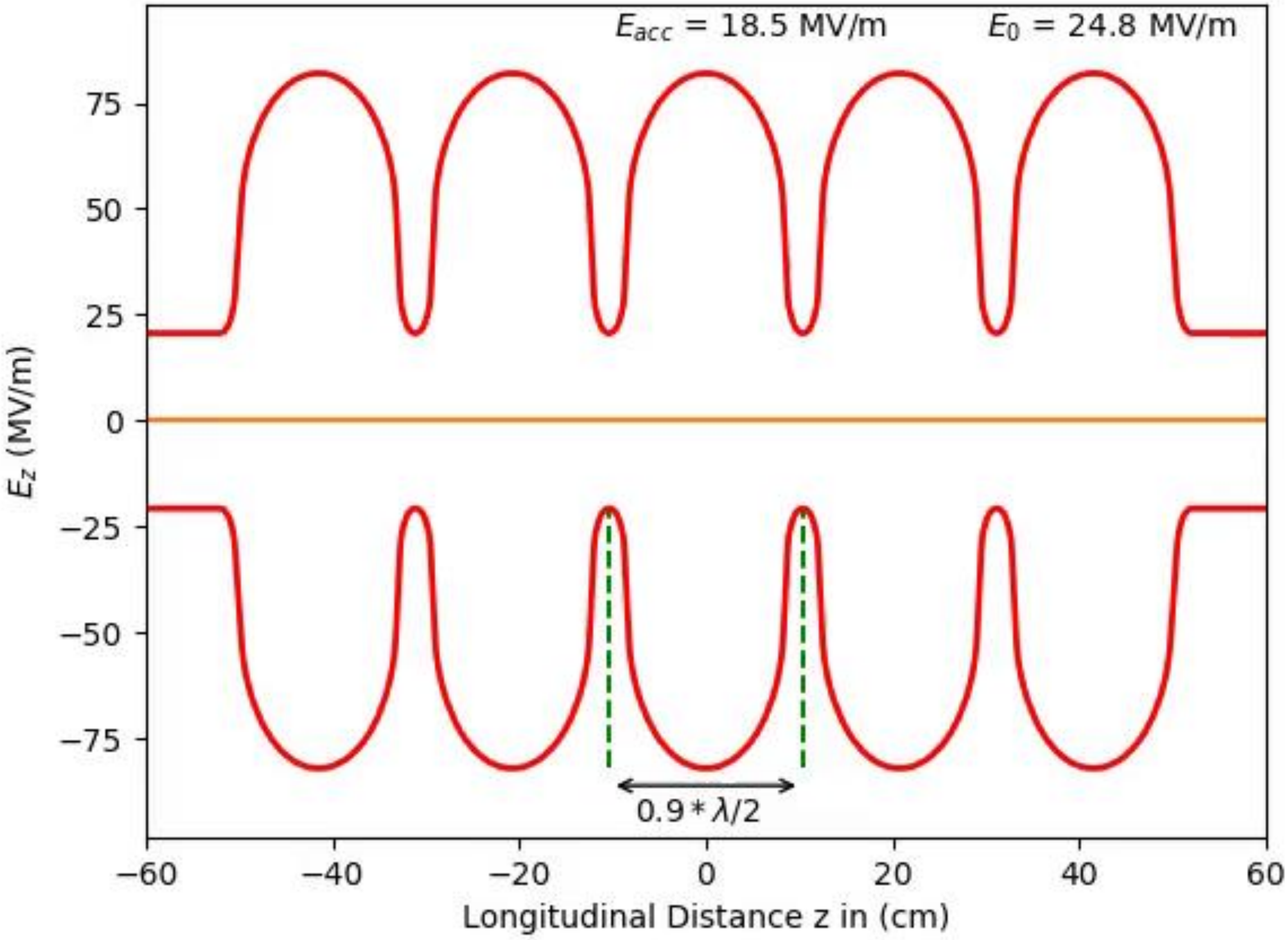
- Lattice and beam dynamics for 1 GeV ISNS linac

The pi mode (SSR)



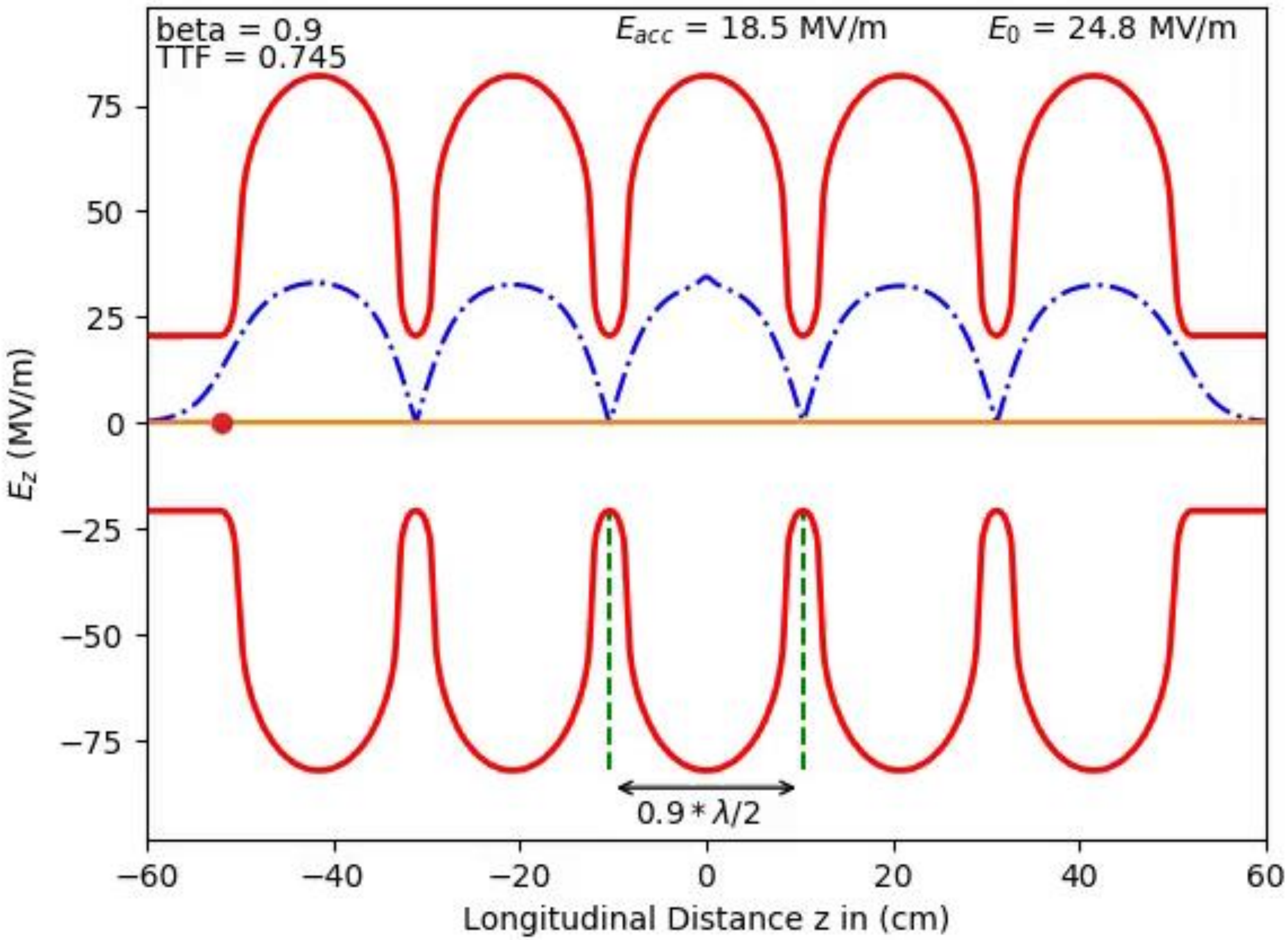


The pi mode (elliptic cavity)

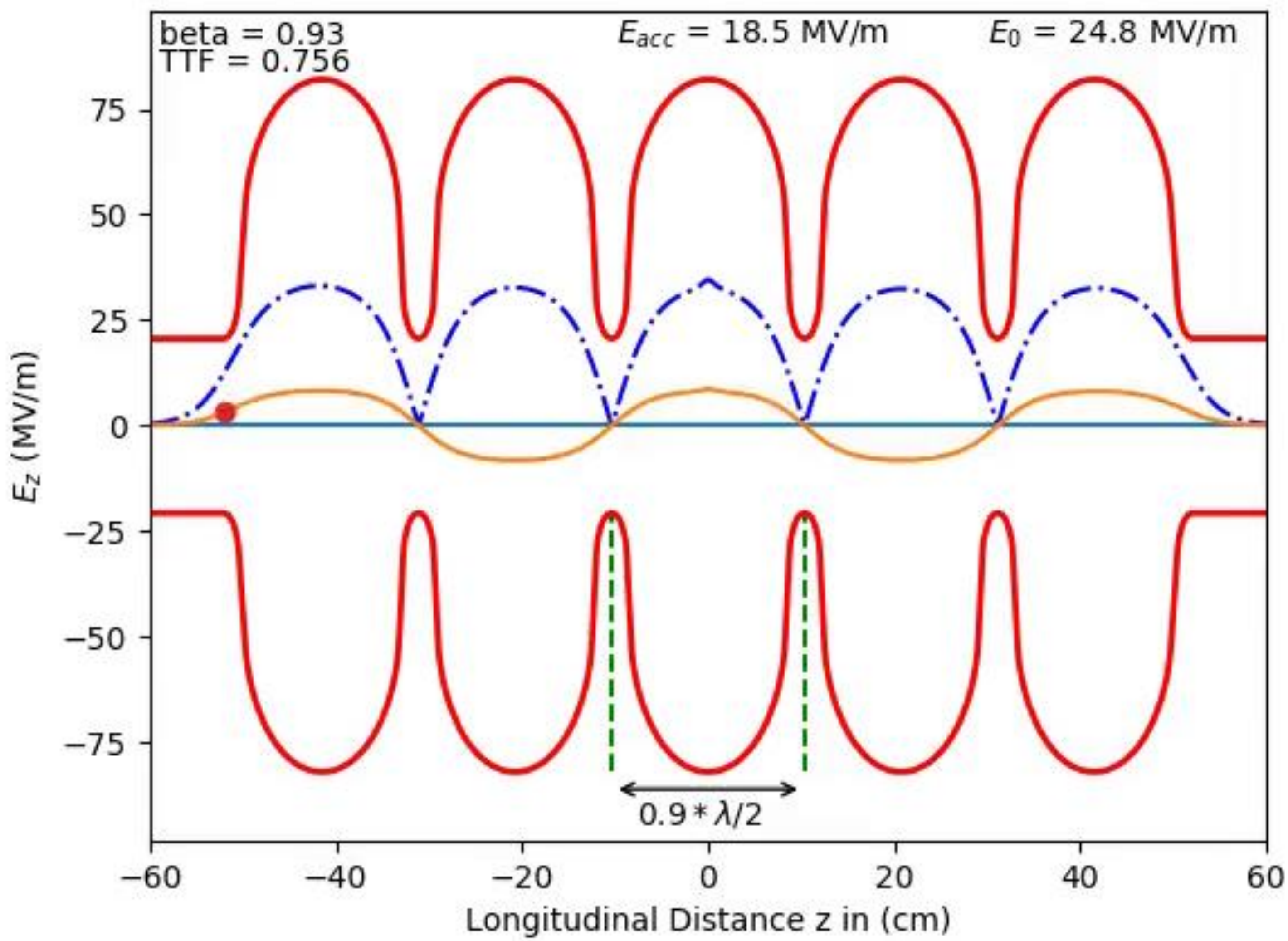


The pi mode as seen by the particle - I

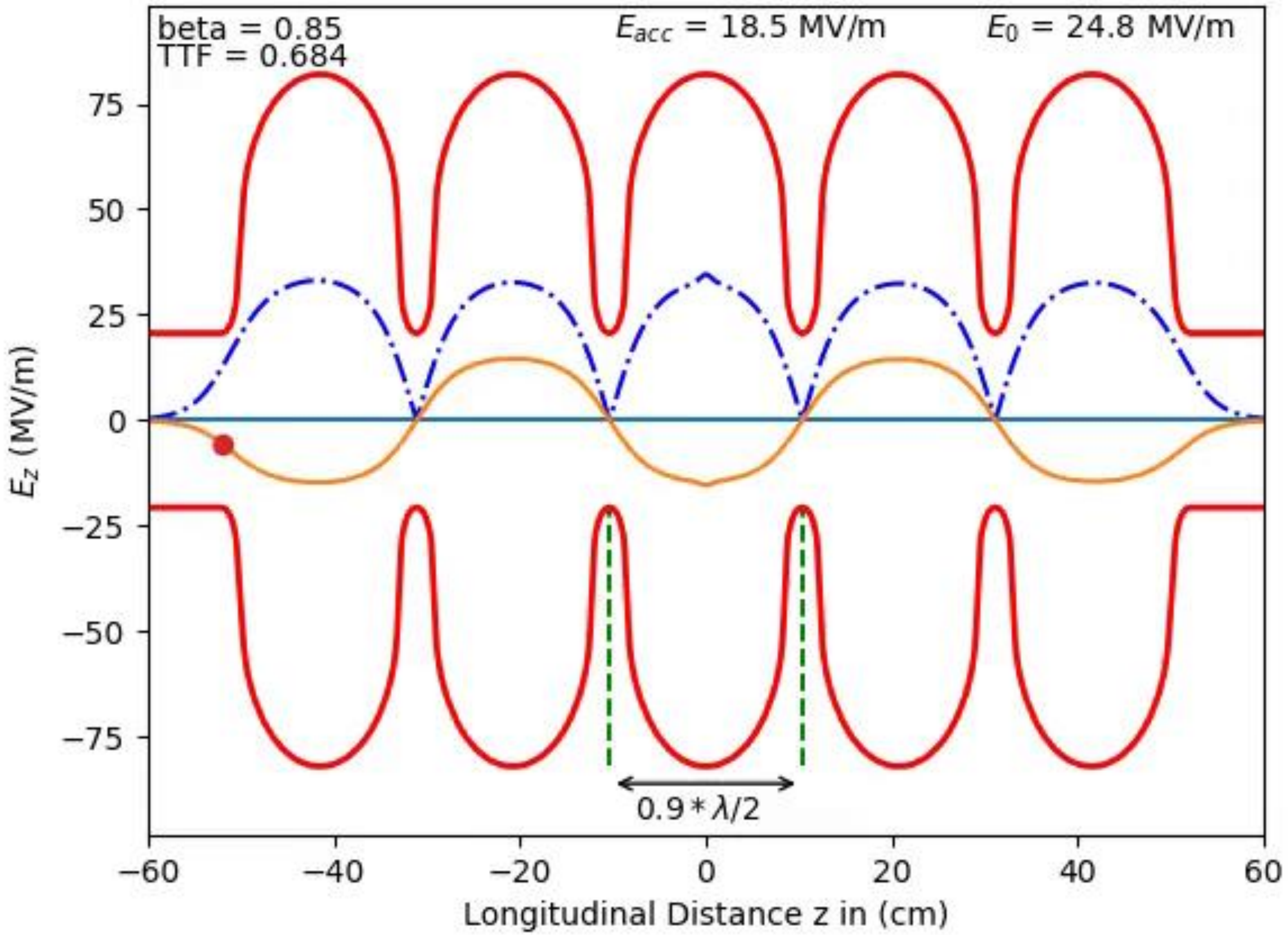
$$\Delta U = q \times E_0\, T \times L \times \mathrm{Cos}\ \phi_s$$



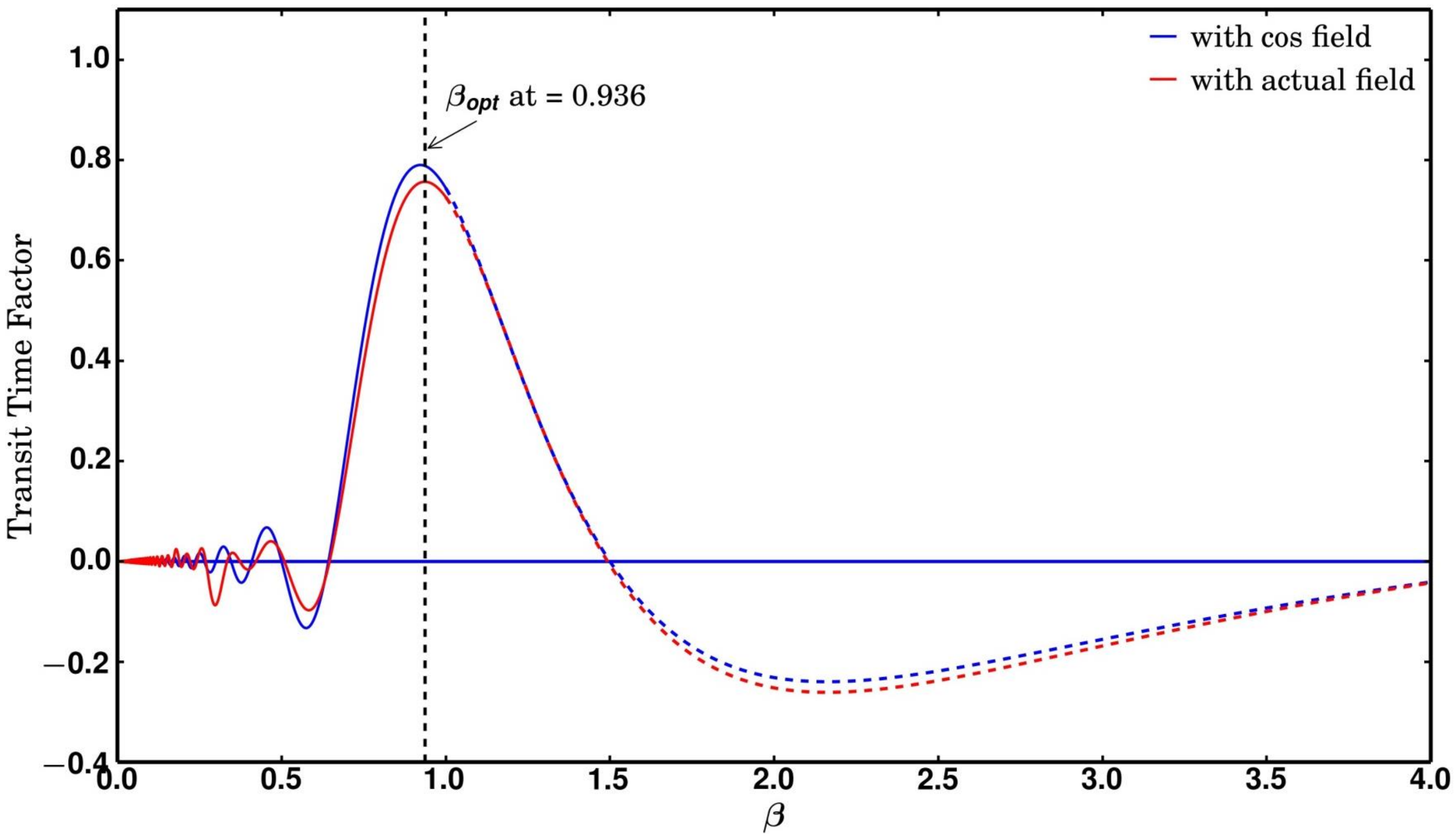
The pi mode as seen by the particle - II



The pi mode as seen by the particle - III



TTF plot: signature of the cavity



Quality factor

$$Q_0 = \frac{\omega U}{P_c}, \qquad P_c = \frac{1}{2} R_s \int H^2 ds \quad \Rightarrow \quad Q_0 R_s = \frac{2\omega U}{\int H^2 ds} = G$$

Surface resistance

Geometry factor

$$Q_0 = \frac{G}{R_s}$$

For normal conducting RF cavity:

$$R_s = \sqrt{\frac{\omega}{2\varepsilon_0 c^2 \sigma_0}}$$

R_s is not so simple for superconducting RF cavities:

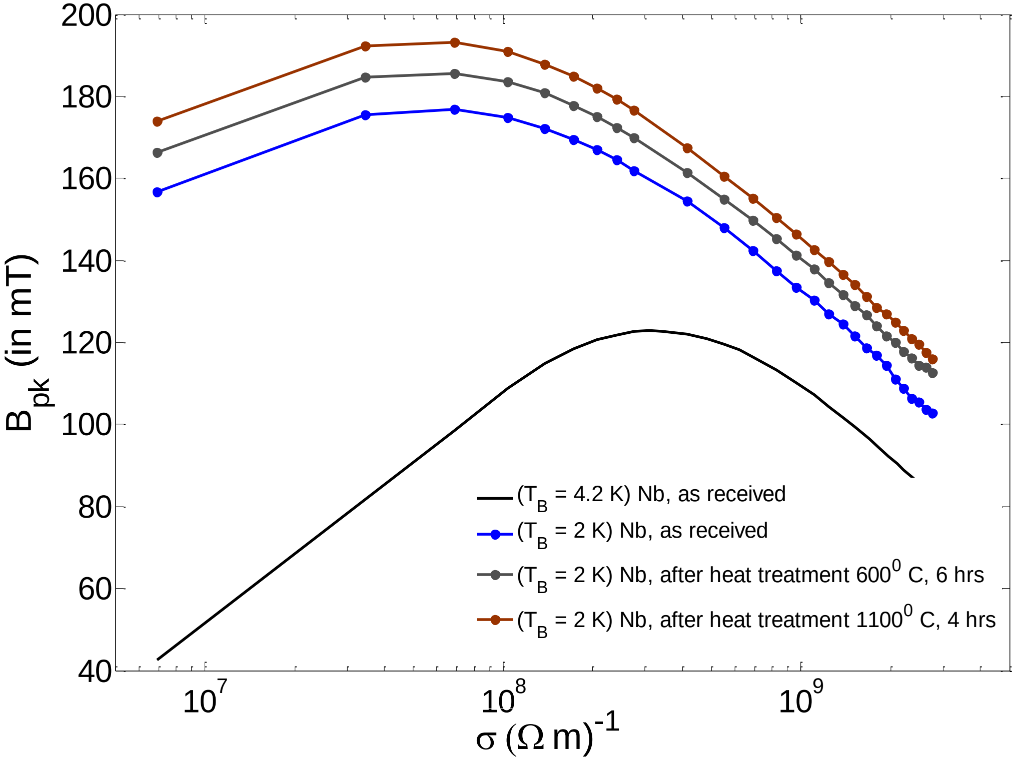
$$R_s(B_a = 0, \omega, T) = \mu_0^2 \omega^2 \sigma_{no} \lambda^3 \frac{\Delta_0}{k_B T} ln\left(\frac{\Delta_0}{\hbar\omega}\right) \exp\left(-\frac{\Delta(T)}{k_B T}\right) + R_{res}$$

Commonly used formula:

$$R_s(\omega, T) = 2 \times 10^{-4} \frac{1}{T}\left(\frac{f\ (\mathrm{GHz})}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right) + R_{res}$$

(impurity effect???)

Optimization of cavity material parameters*



$\sigma_{no} \sim 7\times10^{8}\ (\Omega\ \mathrm{m})^{-1}$

$\kappa \sim 139\ \mathrm{W\ m^{-1}\ K^{-1}}$

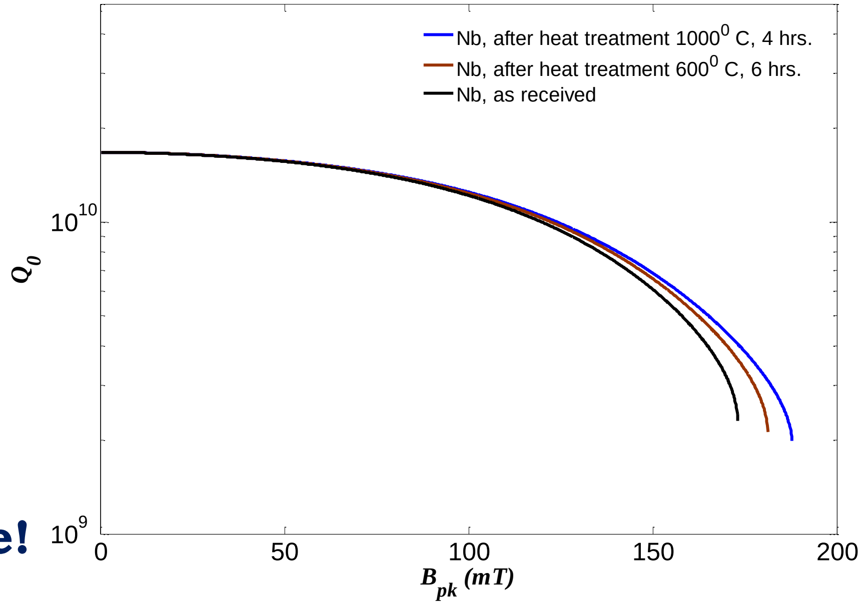
$\alpha \sim 0.005\ \mathrm{m^{2}\ s^{-1}}$

$(C_P \sim 3.4\ \mathrm{J\ Kg^{-1}\ K^{-1}})$.

$Q_0 @\ 2\mathrm{K} = 1.5 \times 10^{10}\ (\beta_g = 0.9)$

$Q_0 @\ 2\mathrm{K} = 1.1 \times 10^{9}\ (\beta_g = 0.61)$

Residual resistance taken as 10 nΩ here!

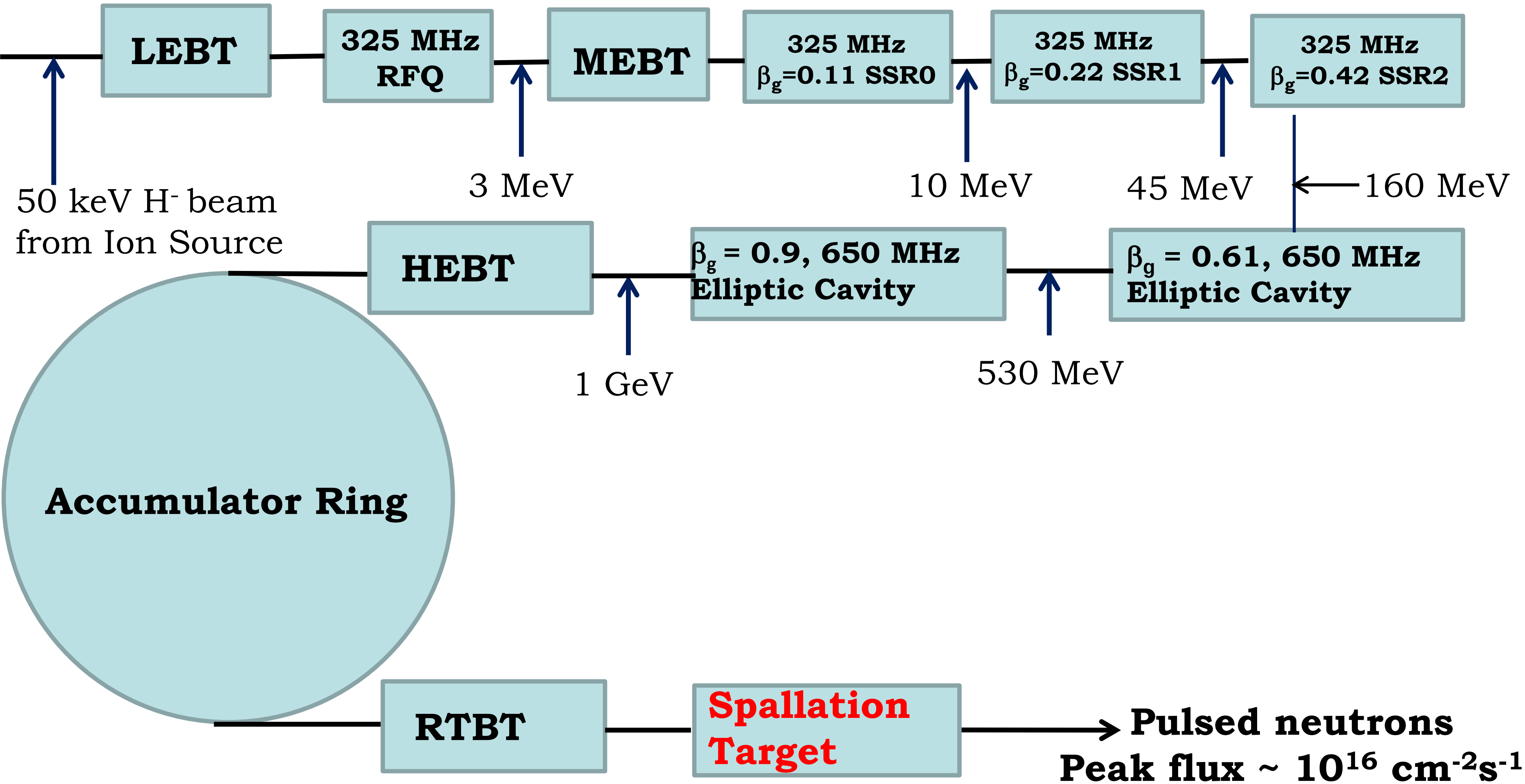


*"Influence of material parameters on the performance of niobium based superconductig RF cavities" (https://arxiv.org/abs/1703.07985)

Cavity RF parameters

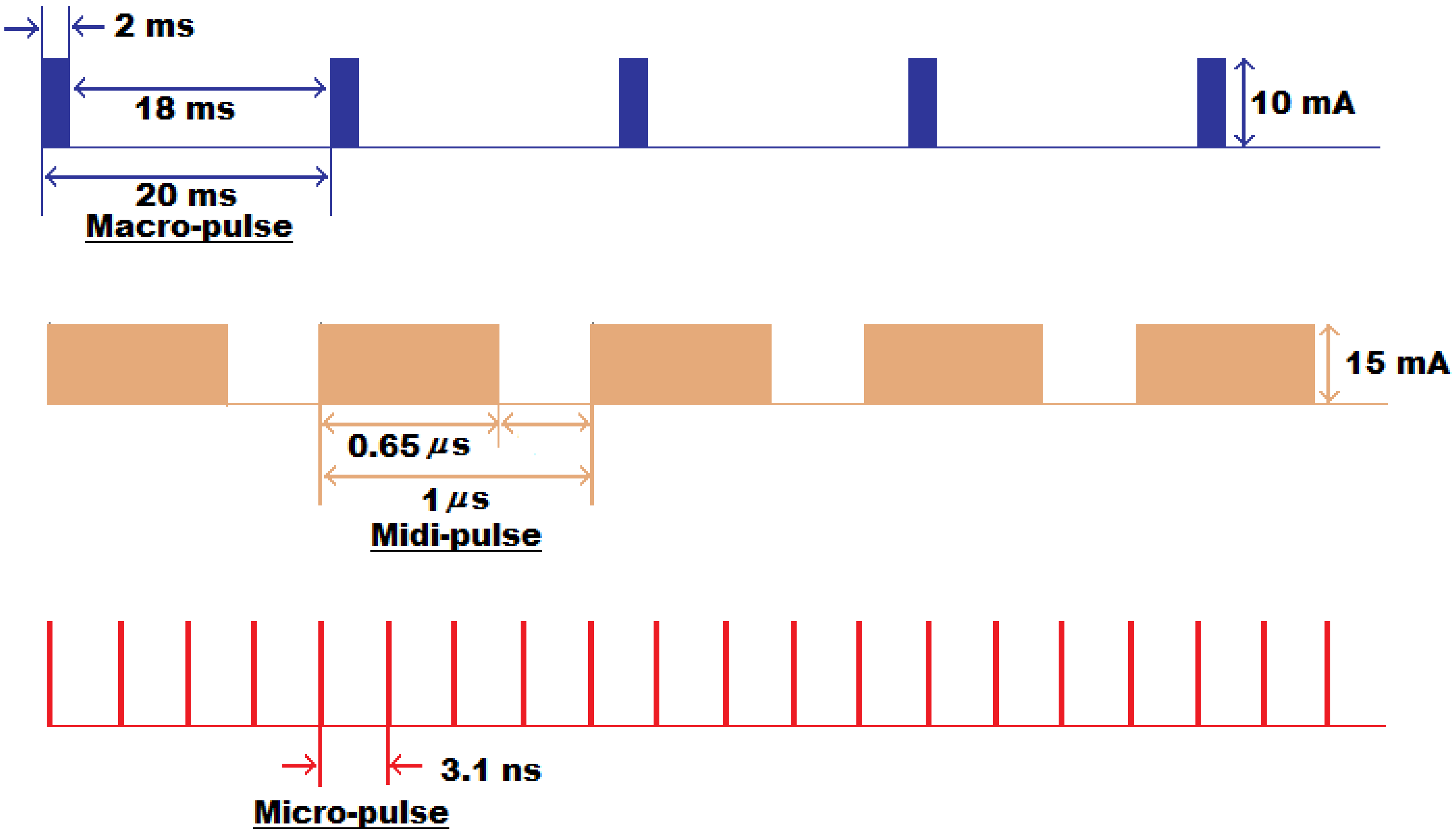
- Energy gain: $\Delta U = q \times E_0 T \times L \times \text{Cos}\,\phi_s = qV Cos\,\phi_s$
- Shunt impedance: $R = \frac{V^2}{P_C}$ (depends on cavity material and TTF)
- R by Q: $\frac{R}{Q} = \frac{V^2}{\omega U}$ (depends on cavity geometry and TTF)
- Gain in beam power: $P_b = I\ V\ \text{Cos}\,\phi_s$
- Coupling coefficient for critical coupling: $\beta = 1 + \frac{P_b}{P_c}$
- Loaded Q: $Q_L = \frac{Q_0}{1 + \beta}$
- Cavity half bandwidth: $\Delta f = \frac{f}{2Q_L}$
- Cavity fill time: $\tau_f = \frac{1}{2\pi\Delta f}$

Schematic of the accelerator for the proposed ISNS



1 GeV, 10 mA pulsed injector linac and accumulator ring

Details of the pulse structure



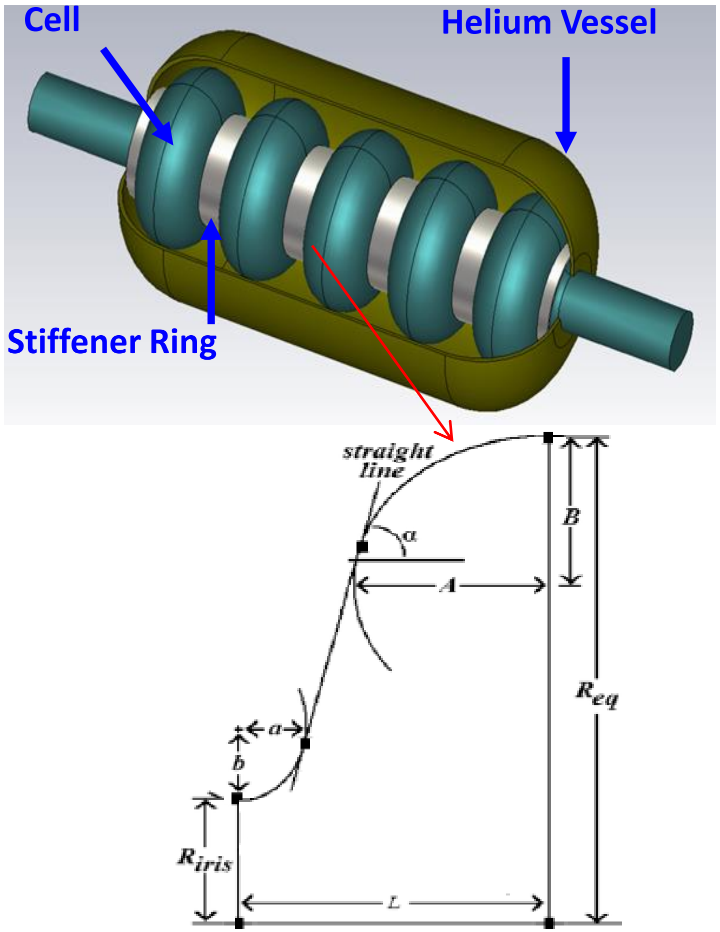
2 ms ➔ 2000 turns injection into accumulator ring.

Wish list in SCRF cavity design

- **Maximize achievable acceleration gradient**
- **Obtain good field flatness**
  (with achievable geometrical tolerances)
- **Ease of cavity processing**
- **Free from multipacting**
- **HOM effects within acceptable limits**
  (heat generation and deterioration in beam quality)
- **No beam instability issue**
  (Threshold current higher than operating beam current)
- **LFD within control**

EM Design of β_g = 0.61* and β_g = 0.9+, 5-cell, 650 MHz SCRF cavity*

Geometrical parameters optimized to minimize B_{pk}/E_a and E_{pk}/E_a, and ensure that there are no trapped HOMs and no multipacting.



Geometrical parameters

Parameter	β_g = 0.61 cavity			β_g = 0.9 cavity	
	Mid-cell	End-cell (entry)	End-cell (exit)	Mid-cell	End-cell
R_{iris} (mm)	44.00	44.00	44.00	50.00	50.00
R_{eq} (mm)	195.591	195.591	195.591	199.93	199.93
L (mm)	70.336	71.55	71.24	103.77	105.80
A (mm)	52.64	52.64	52.25	83.26	83.26
B (mm)	55.55	55.55	55.55	84.00	84.00
a (mm)	15.28	15.28	15.28	16.79	16.79
b (mm)	28.83	28.83	28.83	29.45	29.45

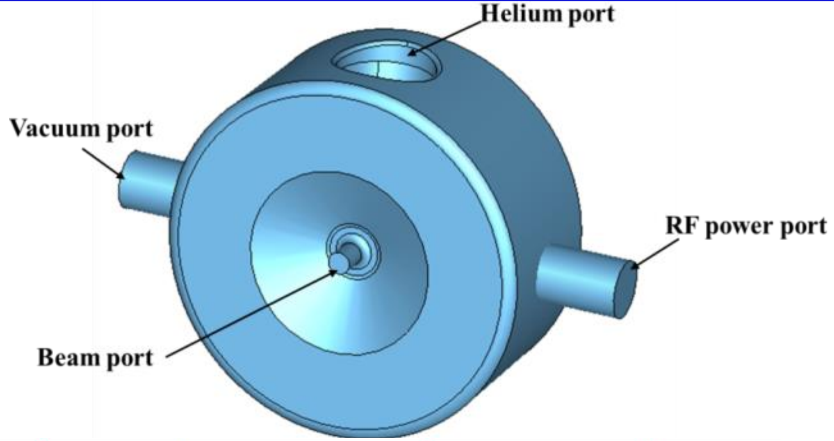
RF parameters

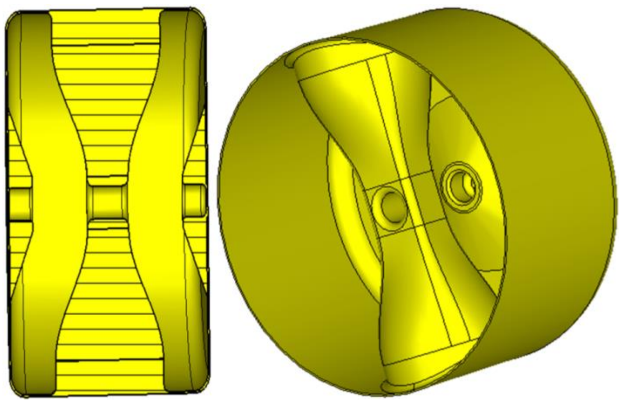
Parameter	β_g = 0.61	β_g = 0.9
E_{acc} (MV/m)	15.4	18.6
E_{pk}/E_{acc}	2.36	2.0
B_{pk}/E_{acc} [(mT/(MV/m)]	4.56	3.78
k_c	0.8%	0.75%
G(Ω)	189	257
R/Q (Ω)	328	609
Cryogenic load	16 W	20 W

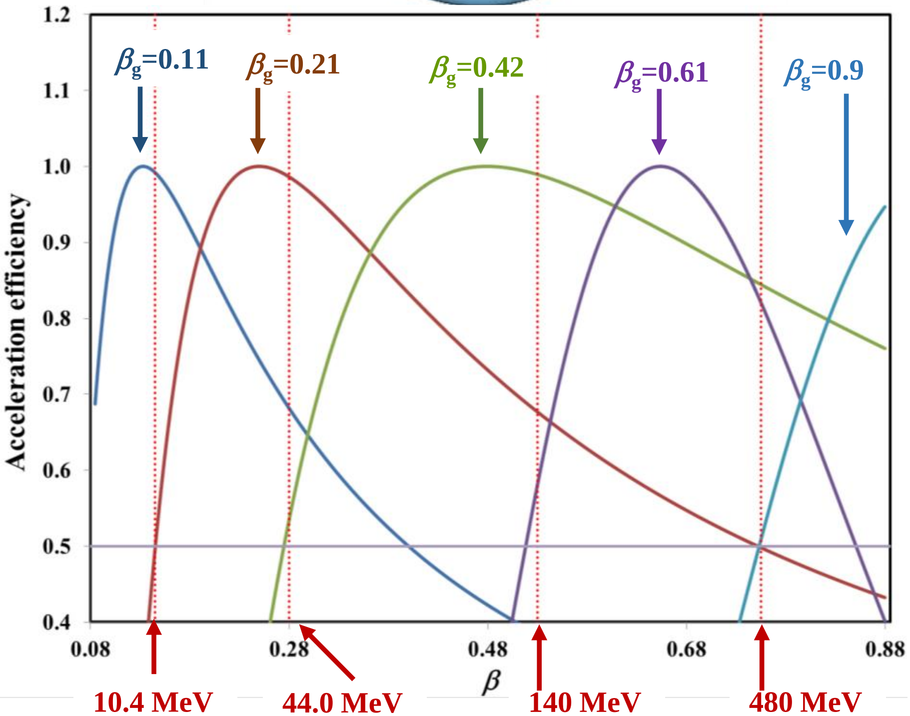
*IEEE Transactions of applied superconductivity, 23, 3500816 (2013) : +24, 3500216 (2014)

Electromagnetic Design of 325 MHz SSRs*

Geometrical optimization done to (i) minimize Ep/Eacc and Bp/Eacc, and (ii) maximize R/Q. HOM studies are done using CST-MWS. Multipacting studies done using CST-PS







Parameters	SSR0 (β_g=0.11)	SSR1 (β_g=0.22)	SSR2 (β_g=0.42)
E_p/E_{acc}	4.1	3.3	3.5
B_p/E_{acc} [mT/(MV/m)]	6.1	5.1	6.0
R/Q (ohm)	128	232	256
G (ohm)	48	80	108
$E_{acc,max}$ (MV/m)	9.8	11.8	10.0
Beam aperture dia (mm)	30.0	30.0	50.0
Cavity Radius (mm)	217.3	245.5	290.5
Cavity length (mm)	131.7	234.0	400.0
Cryogenic load	1 W	1.5 W	4.3 W

*RRCAT Internal Report No. RRCAT/2015-02(2015).

RF parameters for β_g = 0.9 cavity

- $\Delta U = q \times E_0 T \times L \times \text{Cos}\,\phi_s = 18.6 \times 1.04 = 19.3\ \text{MeV}$
- $\frac{R}{Q} = 609\ \Omega$
- $P_b = I\,V\,\text{Cos}\,\phi_s = 10\ \text{mA} \times 19.3\ \text{MeV} = 193\ \text{kW}$
- $Q_0 = 3 \times 10^{10}$
- $P_c = \frac{V^2}{(R/Q)\times Q} = \frac{\left(19.3\times10^6\right)^2}{609\times3\times10^{10}}\text{W} = 20.4\ \text{W}$
- $\beta = 1 + \frac{P_b}{P_c} = 1 + \frac{193\times10^3}{20.4} = 9462$
- $Q_L = \frac{Q_0}{1+\beta} = \frac{3\times10^{10}}{9463} = 3.2 \times 10^6$
- $\Delta f = \frac{f}{2Q_L} = \frac{650\times10^6}{2\times3.2\times10^6} = 102\ \text{Hz}$
- $\tau_f = \frac{1}{2\pi\Delta f} = 1.6\ \text{ms}$

Pulsed RF power = 193 kW × 1.25 = 250 kW
RF pulse width = 4-5 ms

Cryogenic duty factor = 16 - 22%
Dynamic Cryogenic load per cavity = 3.3 – 4.5 W

Summary of typical cavity parameters

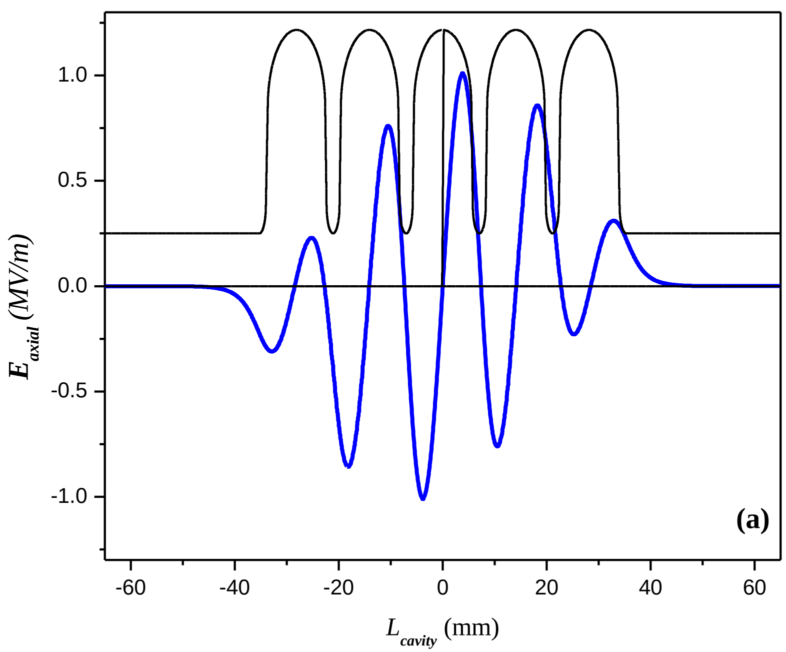
Parameters	**SSR0 (β_g=0.11)**	**SSR1 (β_g=0.22)**	**SSR2 (β_g=0.42)**	**LB (β_g=0.61)**	**HB (β_g=0.9)**
Energy gain per cavity (MeV)	0.62	1.65	3.1	10.9	19.3
Peak RF power (kW)	8	21	39	140	250
RF pulse width (ms)	2-3	2-3	2-3	4-5	4-5
Cryogenic load (W)	1	2	4.5	16	20.4
Cryogenic duty factor (%)	12	13	15	16-22	16-22

Higher Order Modes

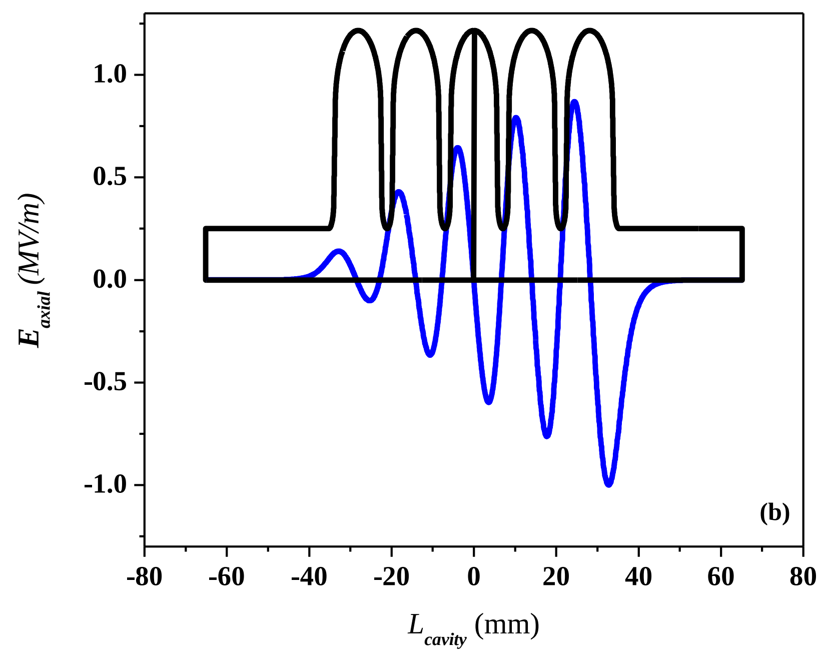
- Monopole TM modes are excited by the beam. Beyond a threshold beam current, dipole TM modes build up.

- Detrimental effects of HOM → Heat generation leading to cryogenic load ,Beam instability, which limits the maximum current that can be accelerated.

- Trapped monopole mode observed at 1653.2 MHz in $\beta_g = 0.61$ design. We tune L_e and A to achieve matching for fundamental as well as HOM. → $L_e = 71.24$ mm, $A = 52.25$ mm.



Trapped mode!



Trapped mode removed!

Higher Order Modes (Non-resonant with beam)

For non-resonant excitation of HOMs (β_g = 0.61)

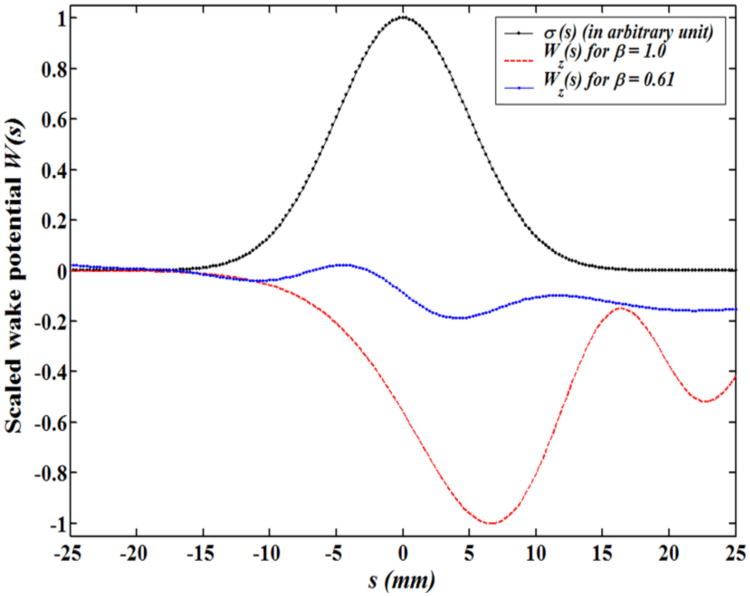
$$P = \text{micropulse rep rate} \times k_{//} \times (\text{micropulse charge})^2 \times \text{Duty factor}$$
$$= 325\ \text{MHz} \times 0.53\ \text{V/pC} \times (46\ \text{pC})^2 \times 10\%$$
$$= 36\ \text{mW}$$

Energy spread induced by HOMs

$$\delta\xi = -q\sqrt{\int ds \times \rho(s) \times W_{\|}^2(s) - k_{\|}^2}$$

$= 16\ eV$

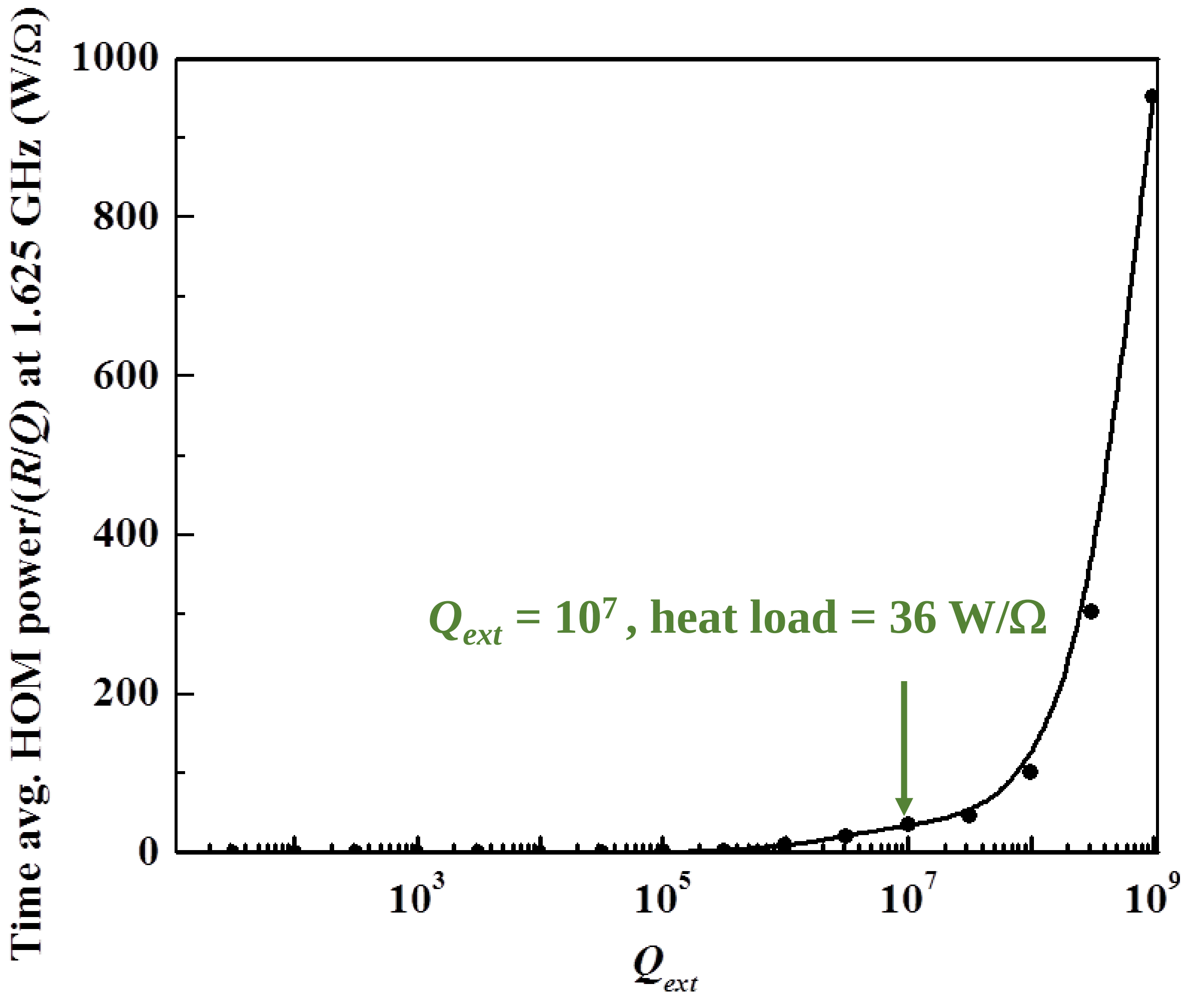
Calculated using wake field solver



Monopole HOMs affect the beam emittance also

Higher Order Modes (resonant with beam)

- Heat load calculation due to HOMs resonantly excited by the beam time structure concluded that $Q_{ext} \leq 10^7$ is required.



Regenerative Beam Break Up due to HOMs

Dipole TM modes can be excited by off-axis beam

Off-axis particles excite dipole modes → dipole mode gives transverse kick to beam

Regenerative beam break up instability (if growth rate > decay due to heat dissipation)

$$I_{th} = \frac{\pi^3 (cp_z / e) k_n}{2g(\alpha) \times (R_\perp / L_{cav}) \times L_{cav}^2}.$$

Standing wave case

No HOM coupler

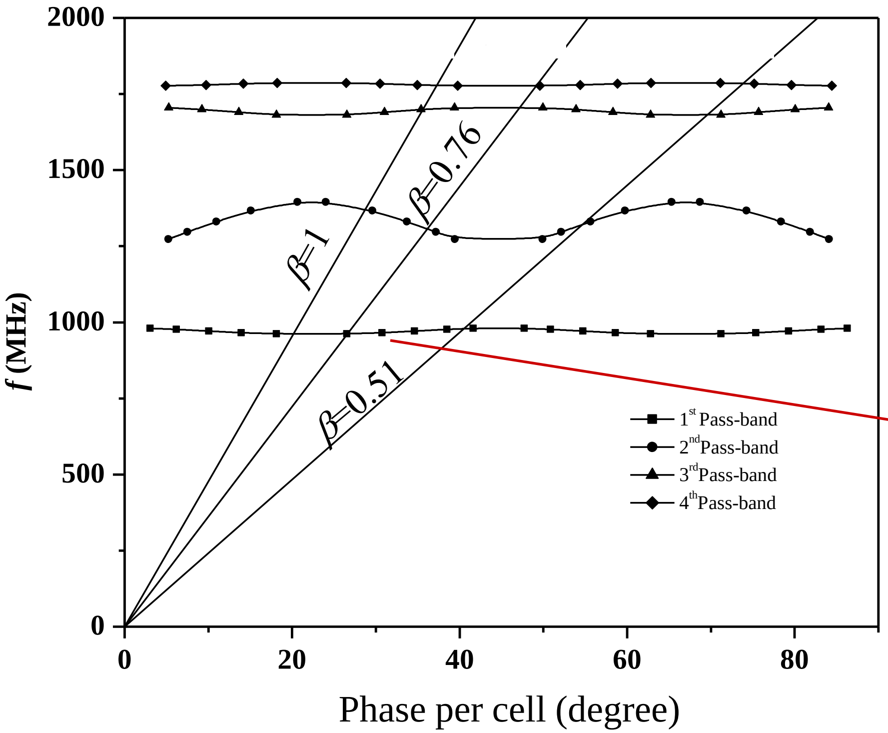
$$I_{th} = \frac{\pi^3 v_g (cp_z / e) Q}{2c \times g(\alpha) \times (R_\perp / L_{cav}) \times L_{cav}^3}.$$

Traveling wave case

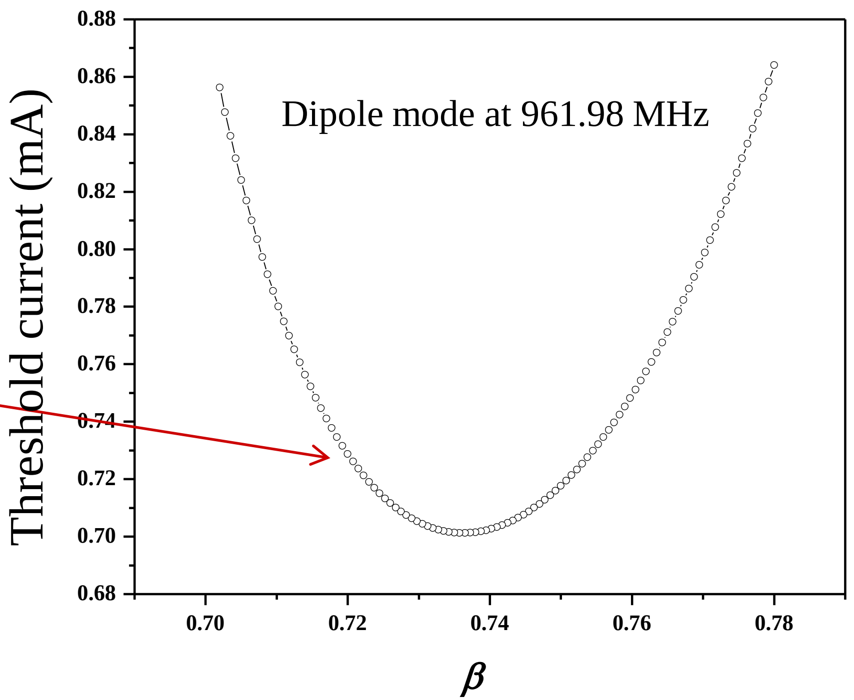
with HOM coupler

Regenerative Beam Break Up due to HOMs

Calculation of threshold current for regenerative Beam Break Up (BBU) for $\beta_g = 0.61$ case



Dispersion curve for TM dipole modes

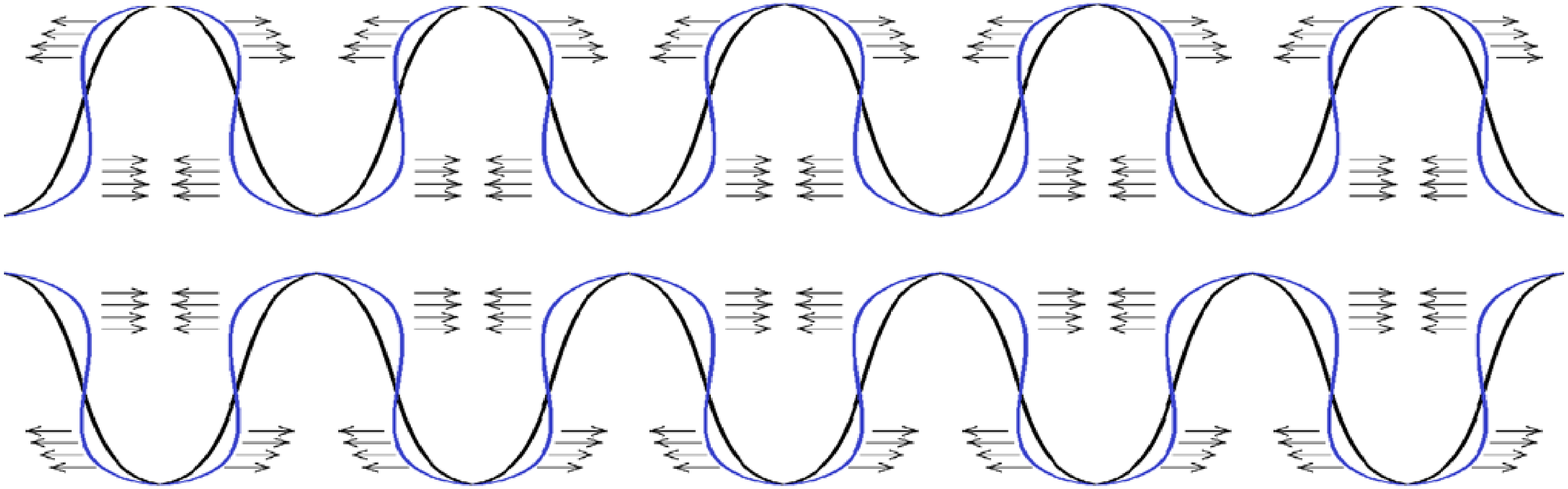


Minimum $I_{th} = 0.7$ mA

Lorentz Force Detuning

$$P = \frac{1}{4}(\varepsilon_0 E^2 - \mu_0 H^2)$$

Electric field → inward pressure
Magnetic field → outward pressure

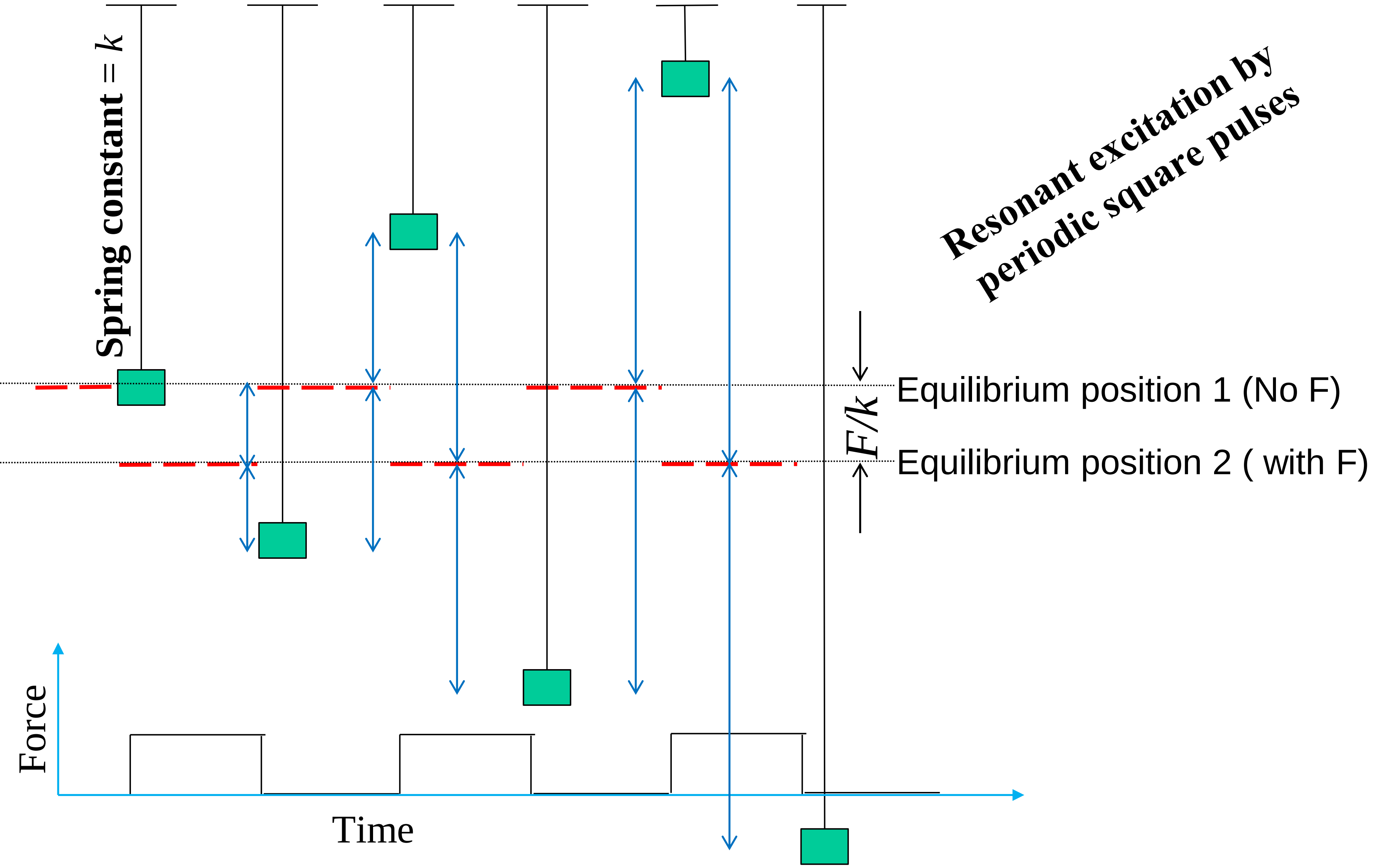


$$\Delta f = \frac{f}{Q_L} = \frac{650 \times 10^6}{3.2 \times 10^6} = 200\ \text{Hz}$$

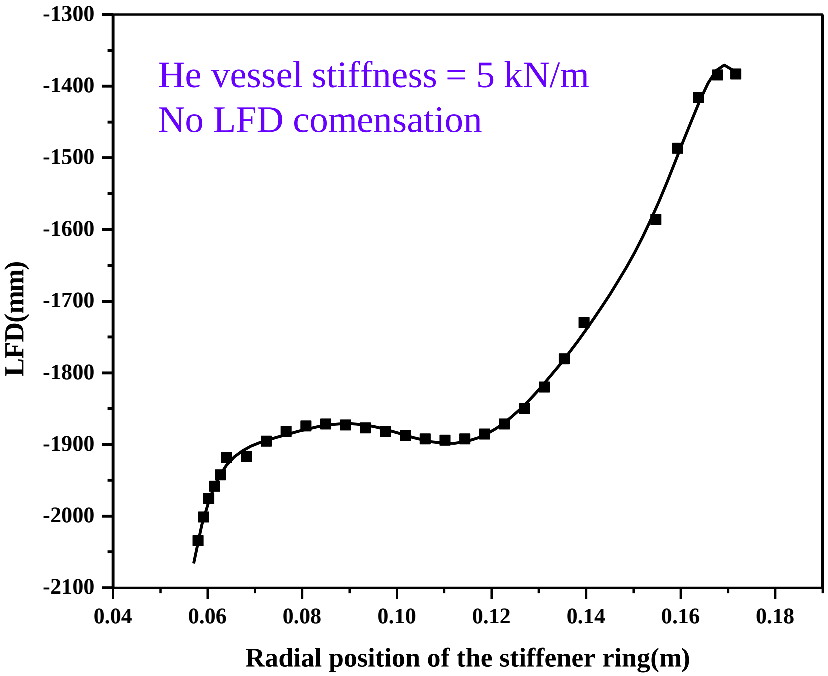
Cavity deforms and detunes
Need to compensate for that
Need to avoid resonant build up of oscillations!

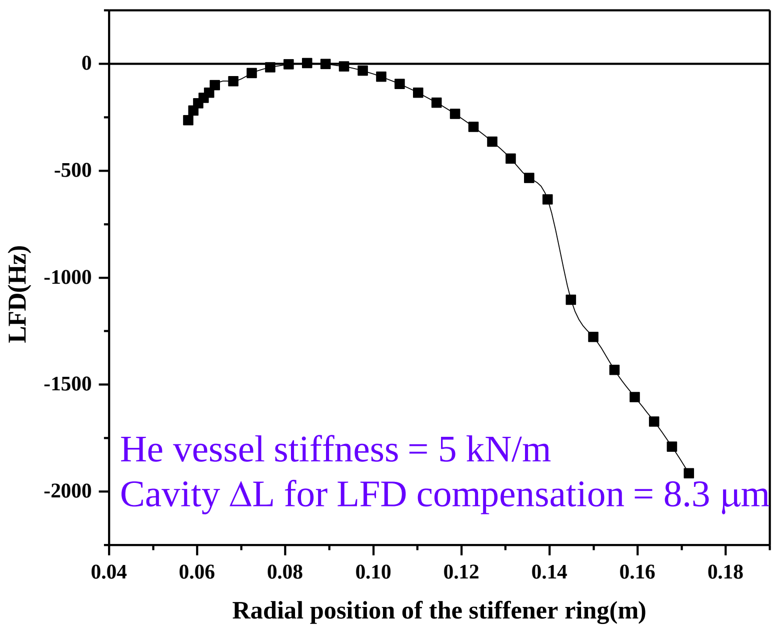
Reduce LFD by stiffening the cavity and compensate for LFD using a tuner

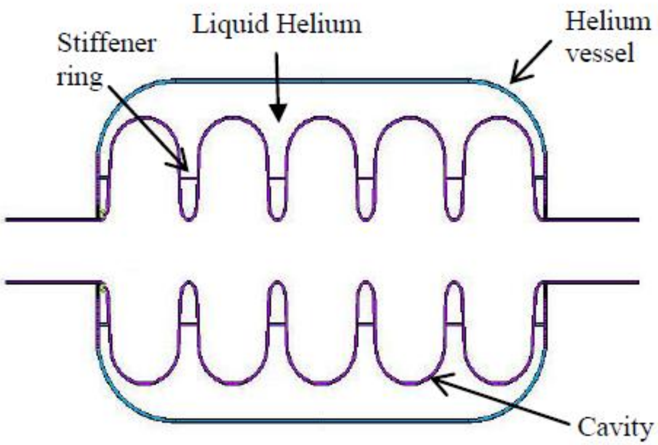
Lorentz Force Detuning



Lorentz Force Detuning

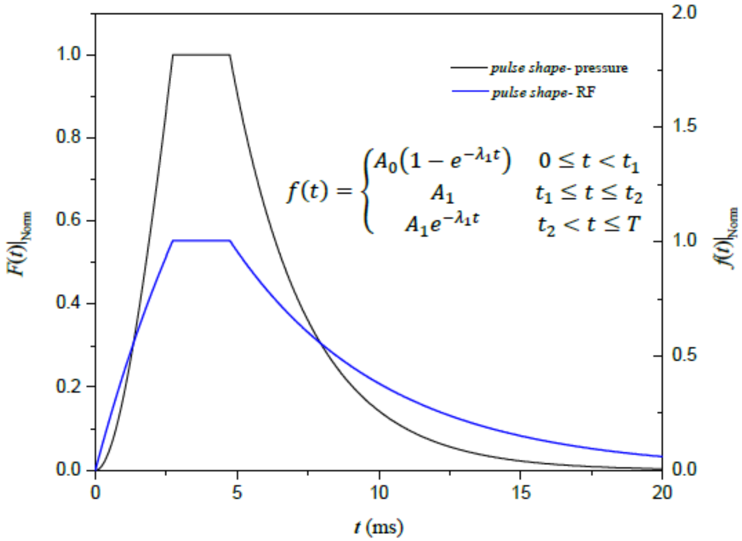


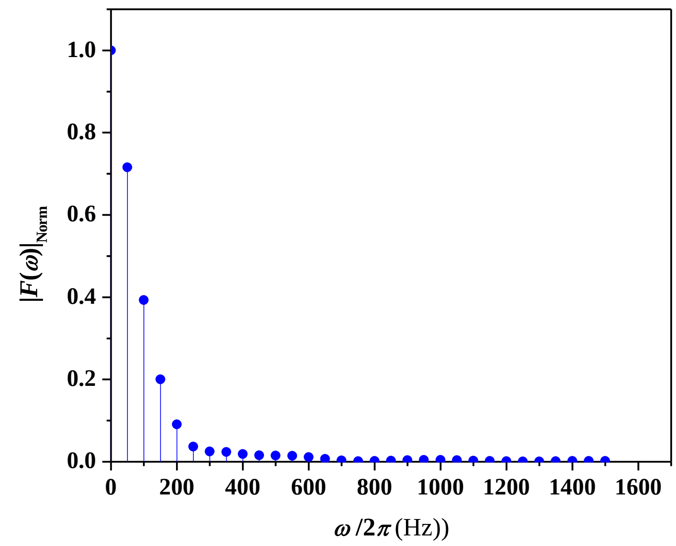


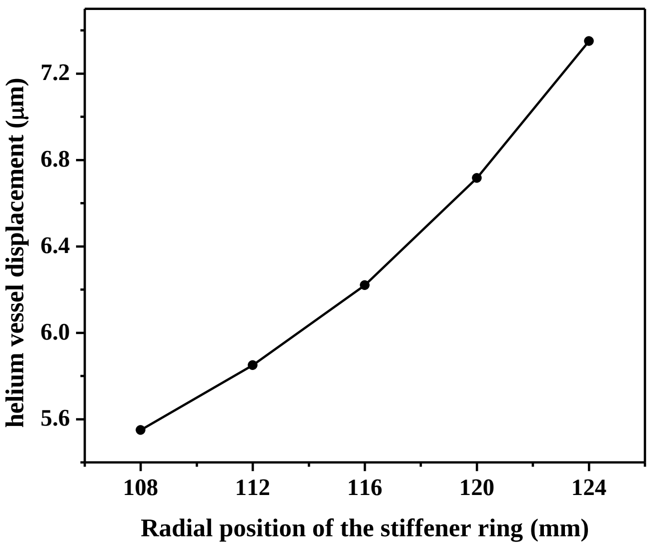


He vessel dia. = 505 mm
He vessel thickness = 5 mm
He vessel end closure tori radius = 120 mm
Stiffener ring radius = 124 mm
Cavity thickness = 4 mm
He vessel elongation for detuning = 7.35 μm

Lorentz Force Detuning







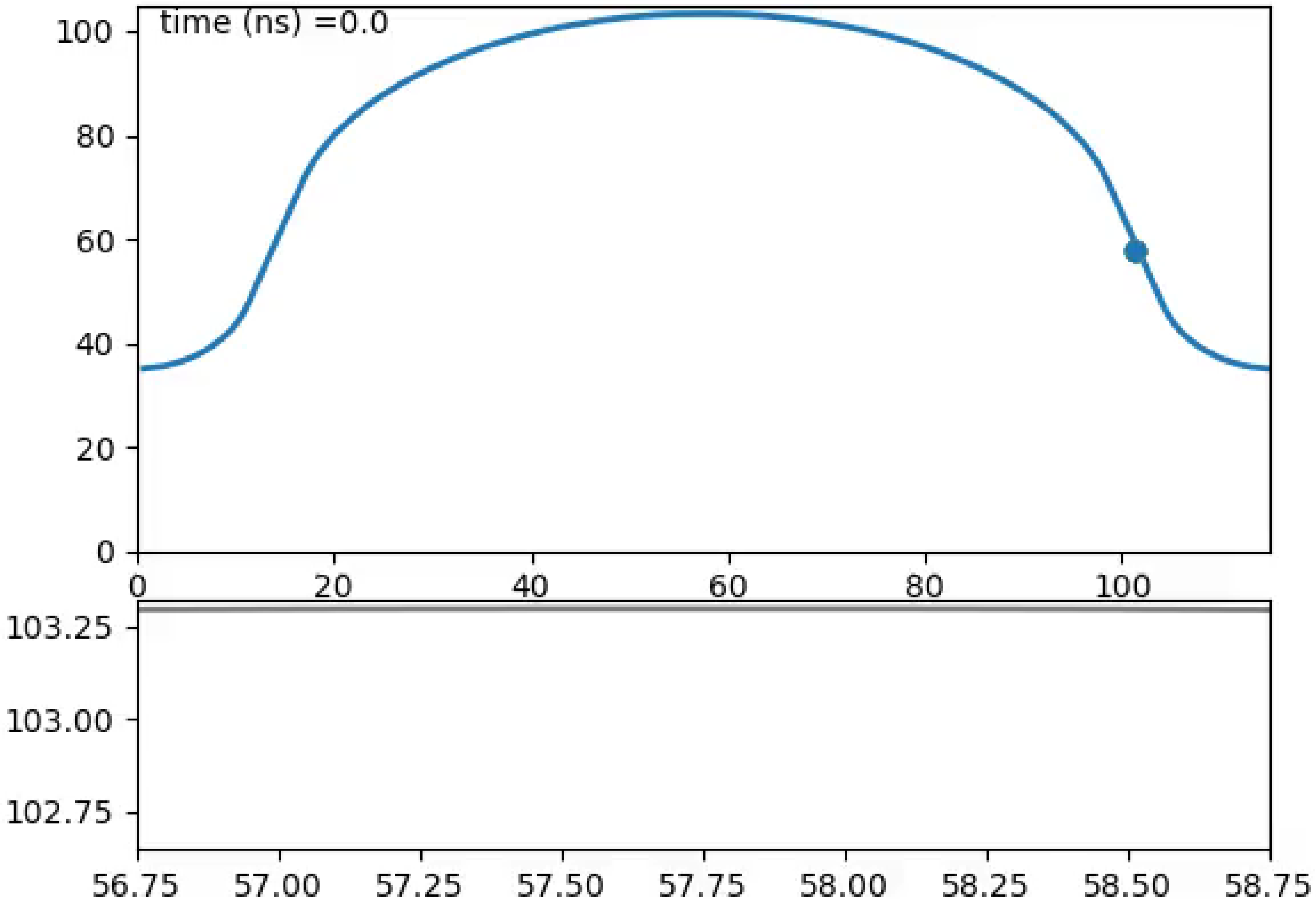
Participating structure modes:

$r_{stiffener}$(mm)	f_1(Hz)	f_2(Hz)	f_3(Hz)	f_4(Hz)	f_5(Hz)
124.00	265.07	426.48	576.19	713.59	749.42
120.00	244.87	414.74	564.03	696.97	759.72
116.00	226.00	397.09	550.89	681.37	760.72
112.00	208.76	375.45	538.55	662.98	750.70
108.00	193.18	352.27	526.39	641.40	732.29

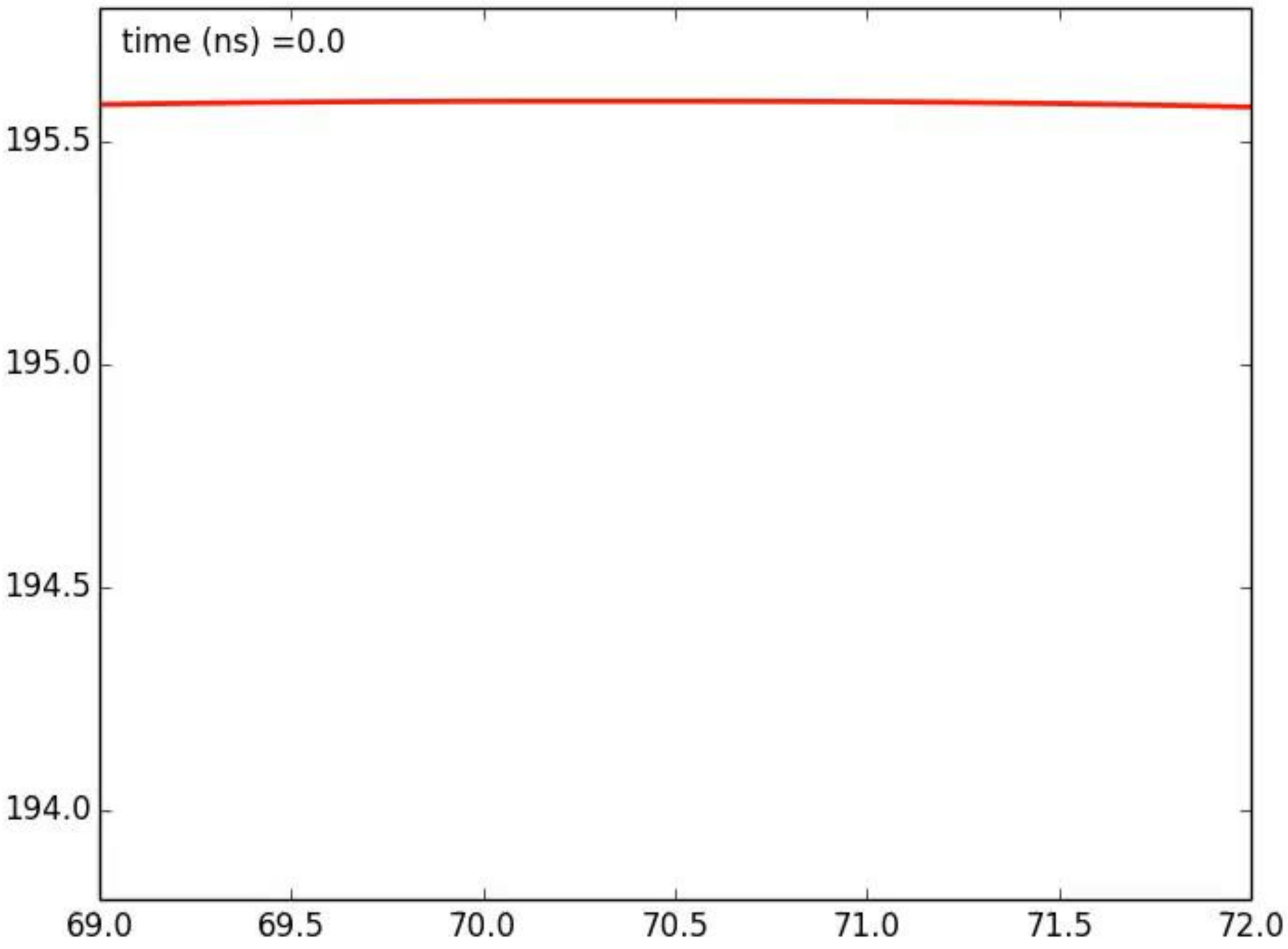
- $r_{stiffener}\uparrow \leftrightarrow f_1\uparrow$ ☺
- $r_{stiffener}\uparrow \leftrightarrow$ He vessel elongation ↑ ☹

Nucl. Instrum. and Meth. Phys. Res. A 750 69 (2014).

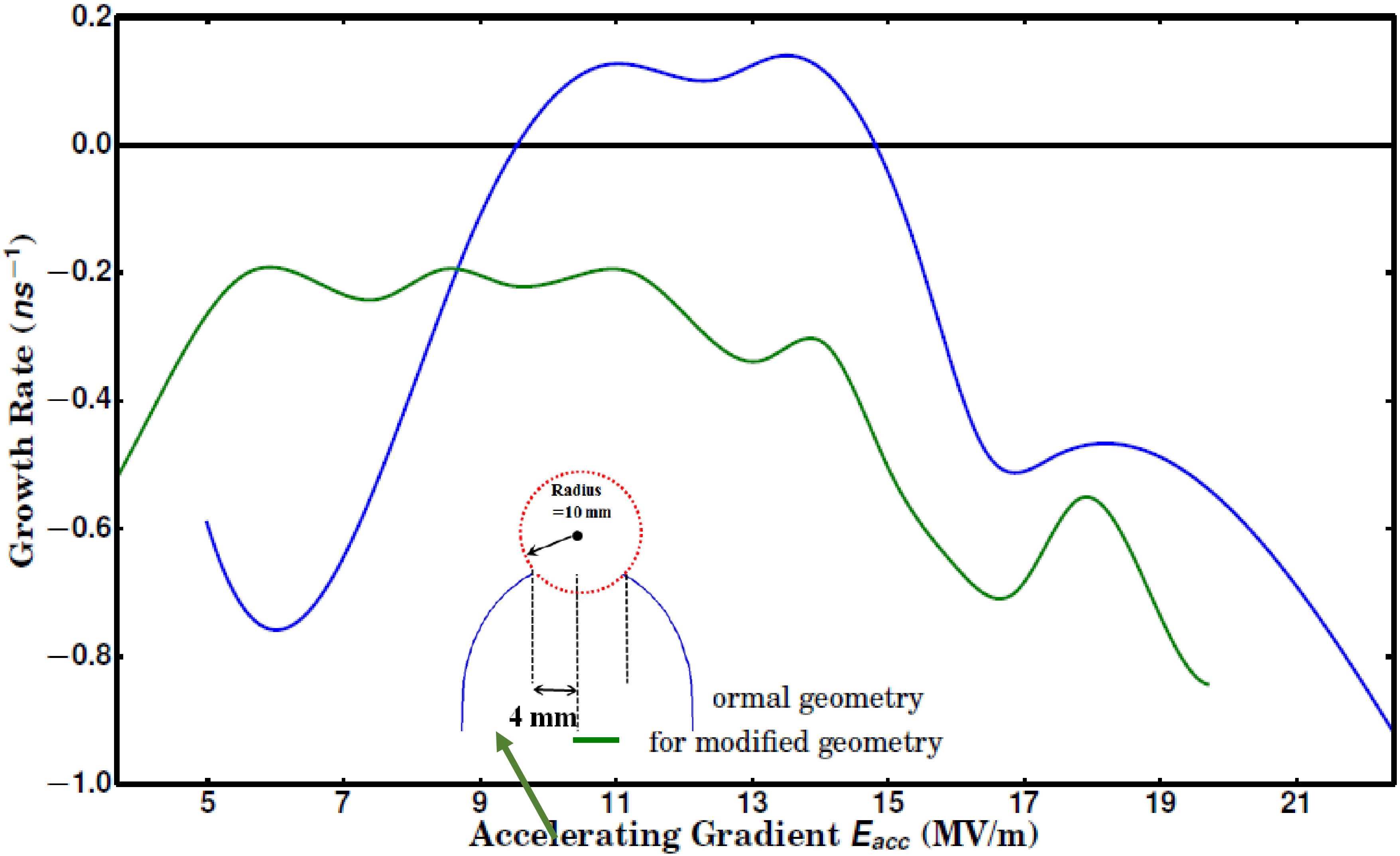
Multipacting



Multipacting

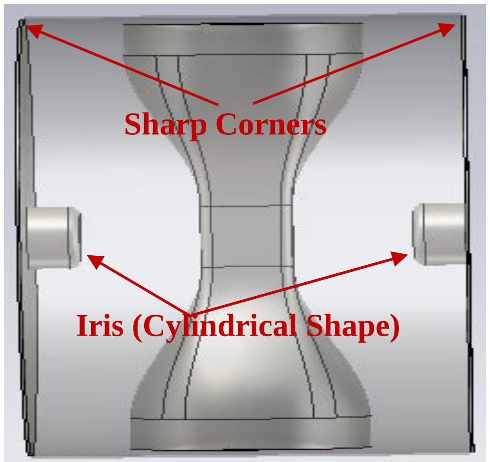


Multipacting suppression in β_g = 0.61 cavity

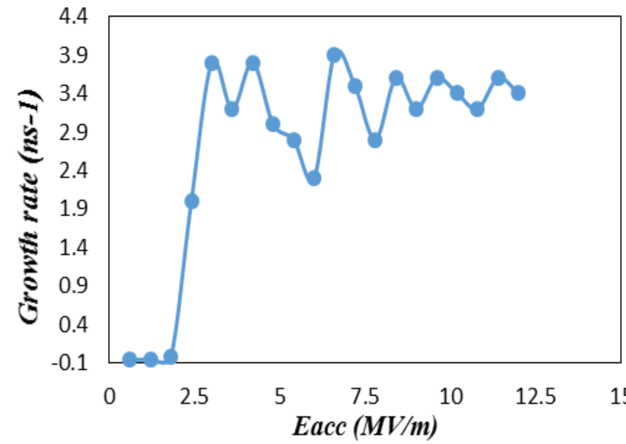


Nucl. Instrum. and Meth. Phys. Res. A 867 128 (2017).

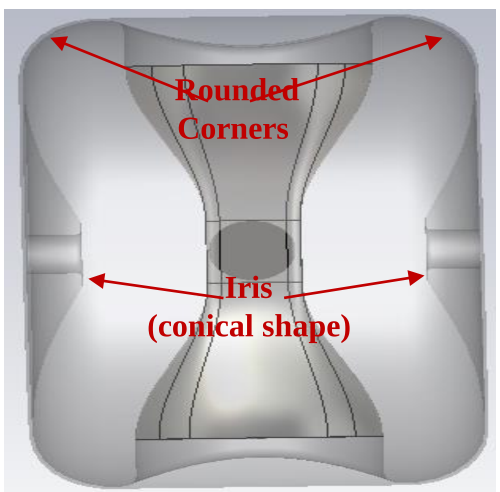
Multipacting studies in SSRs*



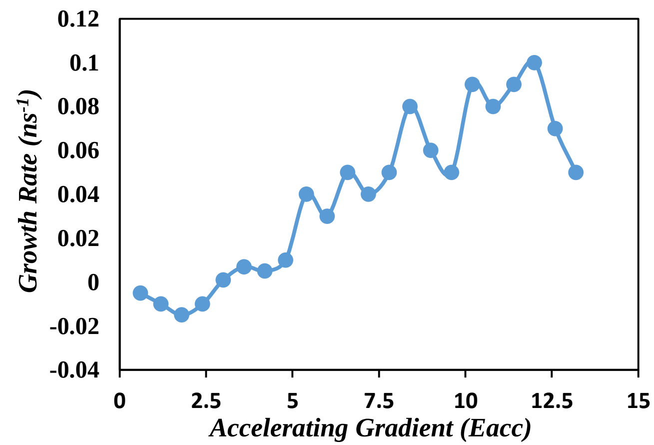
(a) *Before Refinements*



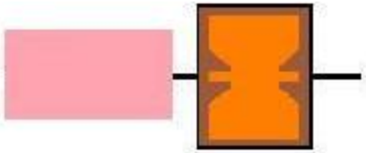
- Smoothening of all corners
- Iris shape modified from cylindrical to conical.



(b) *After Refinements*



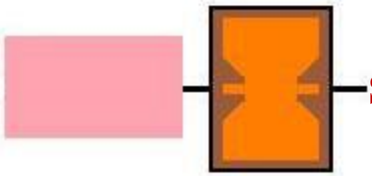
Optimized lattice configuration of 1 GeV injector linac



SSR0 → × 14 periods = 9.28 m

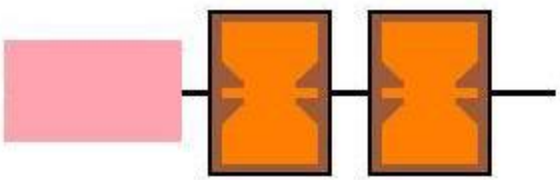
(1) 20 cm +17.5 cm + 13.77 cm + 15 cm = 66.27 cm

Section	Energy(MeV)	Cav/mag	Focusing
SSR0	3-10	14 /14	solenoid
SSR1	10- 43	20 /20	solenoid
SSR2	43-160	32 /16	solenoid
MB 650	160-527	48 /16	quad doublet
HB 650	527-1075	40 / 5	quad doublet



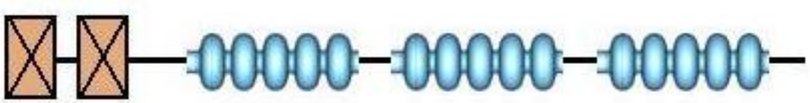
SSR1 →× 20 periods = 16.5 m

(2) 26 cm +17.5 cm + 24 cm + 15 cm = 82.5 cm



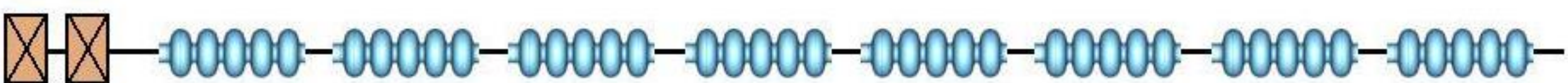
SSR2 →× 16 periods → 20.13 m

(3) 32 cm +17.4 cm + 40.08 cm + 25 cm + 40.08 cm + 15 cm = 169.56 cm



MB 650 →× 16 periods → 80.19 m

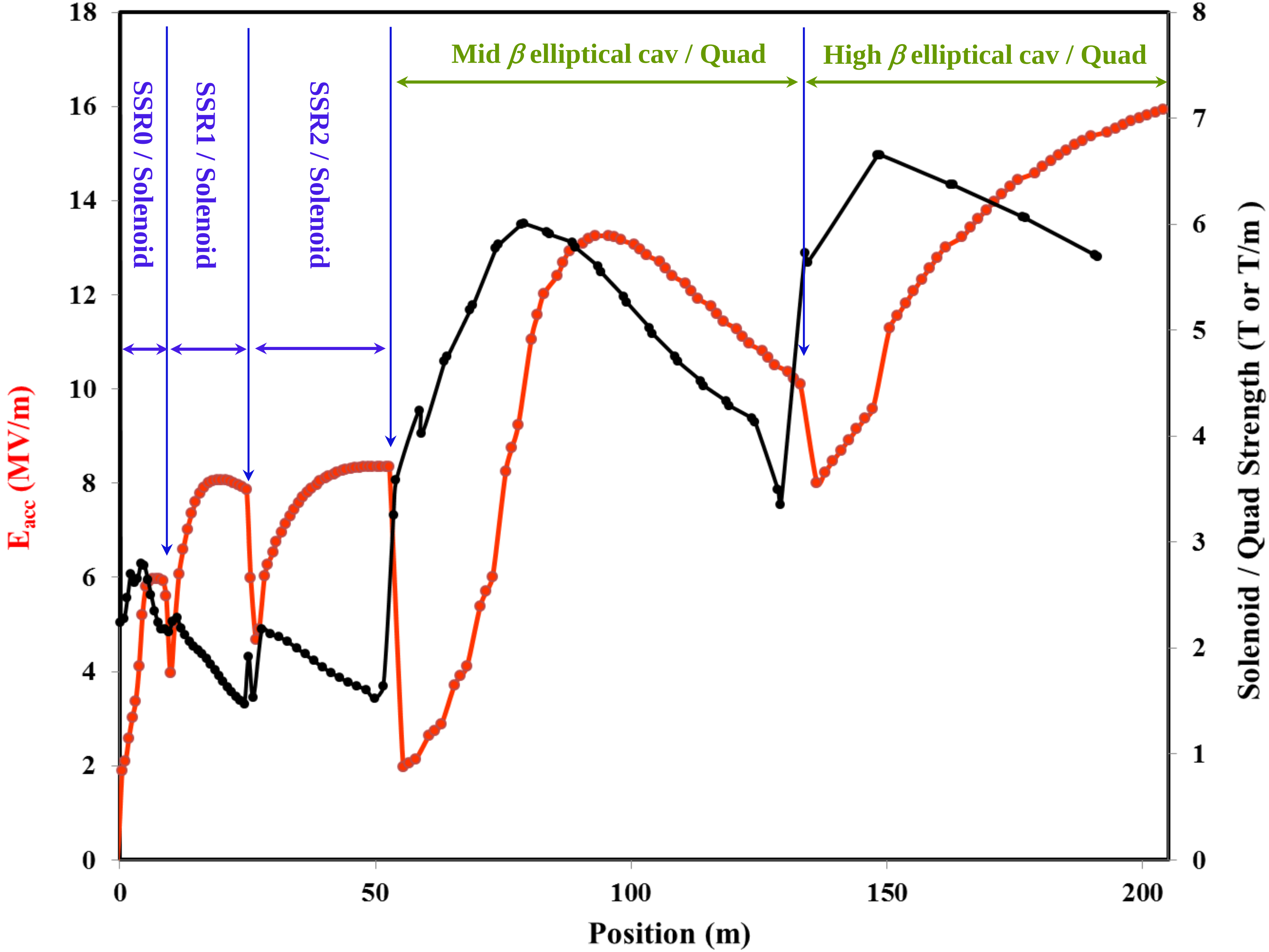
(4) (35+20+35) cm + 55.33 cm + 2 x (80.34+42.25) cm + 80.34 cm + 30.33 cm = 501.18 cm



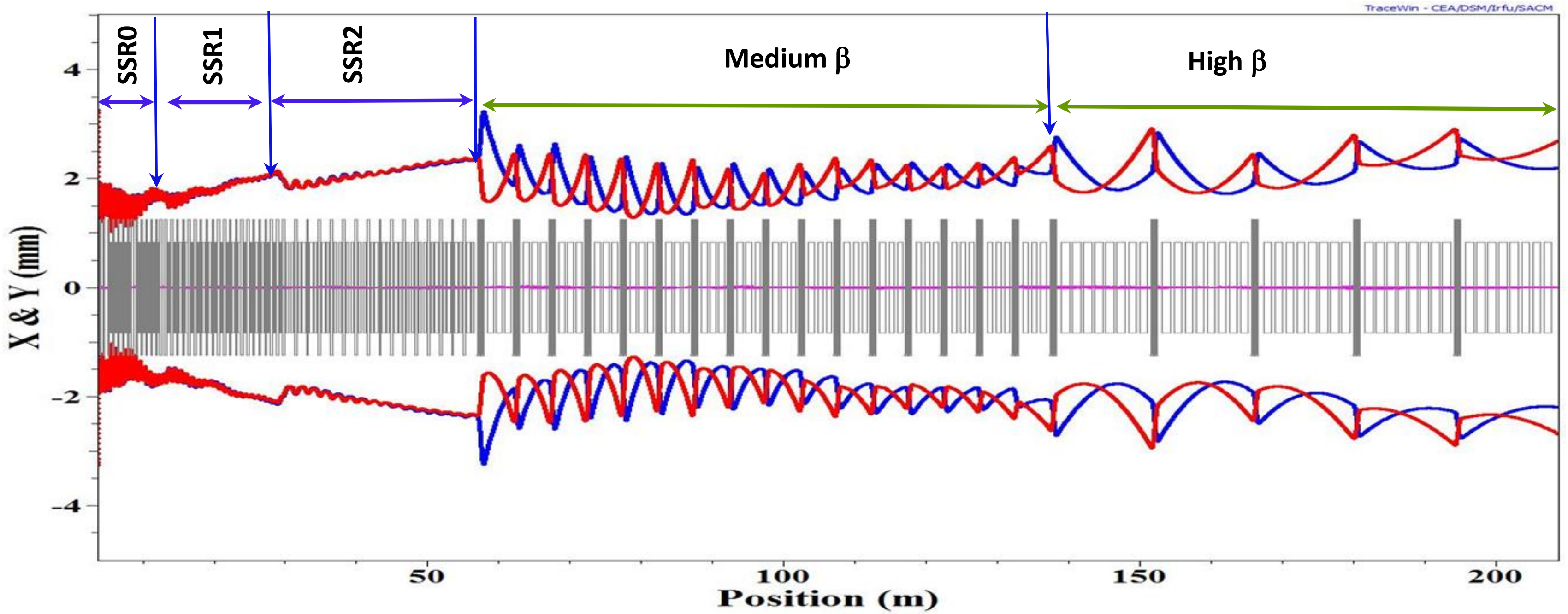
(5) (35+20+35) cm + 73.5 cm + 7 x (113.77+42. 5) cm + 113.77 cm + 48.5 cm = 1419.66 cm

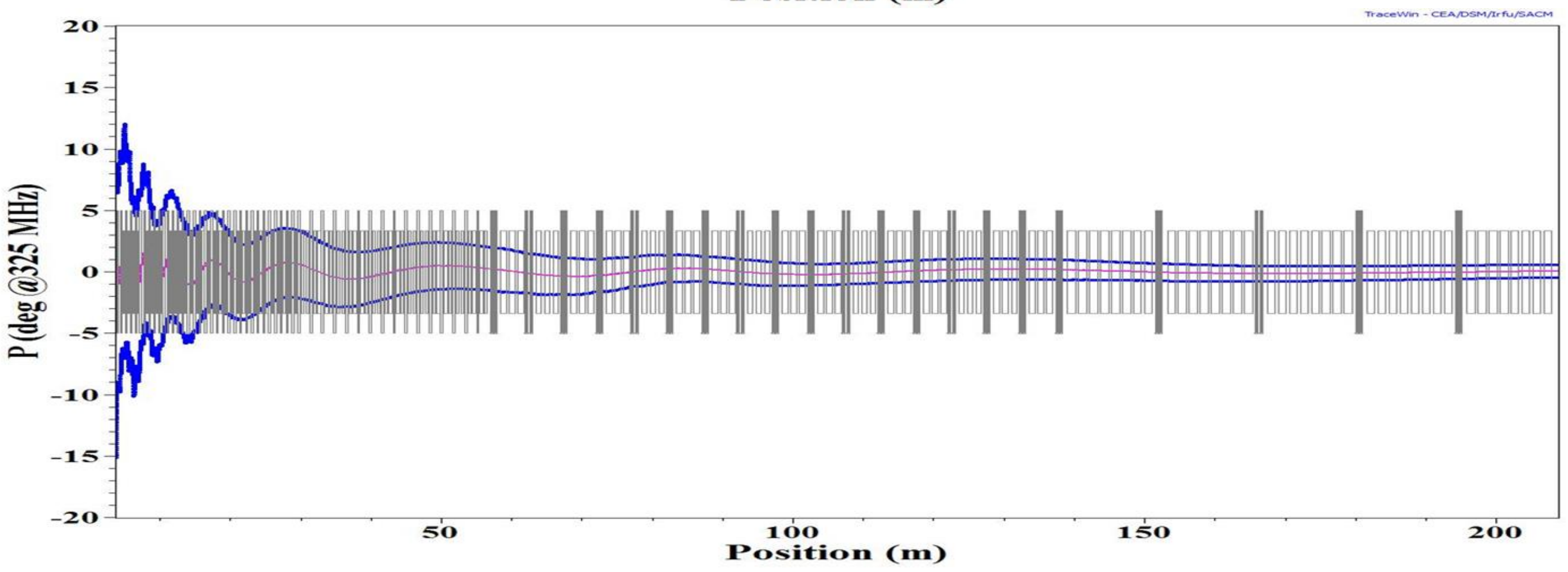
HB 650 →× 16 periods → 70.98 m

Details of lattice (cavity + focusing elements)

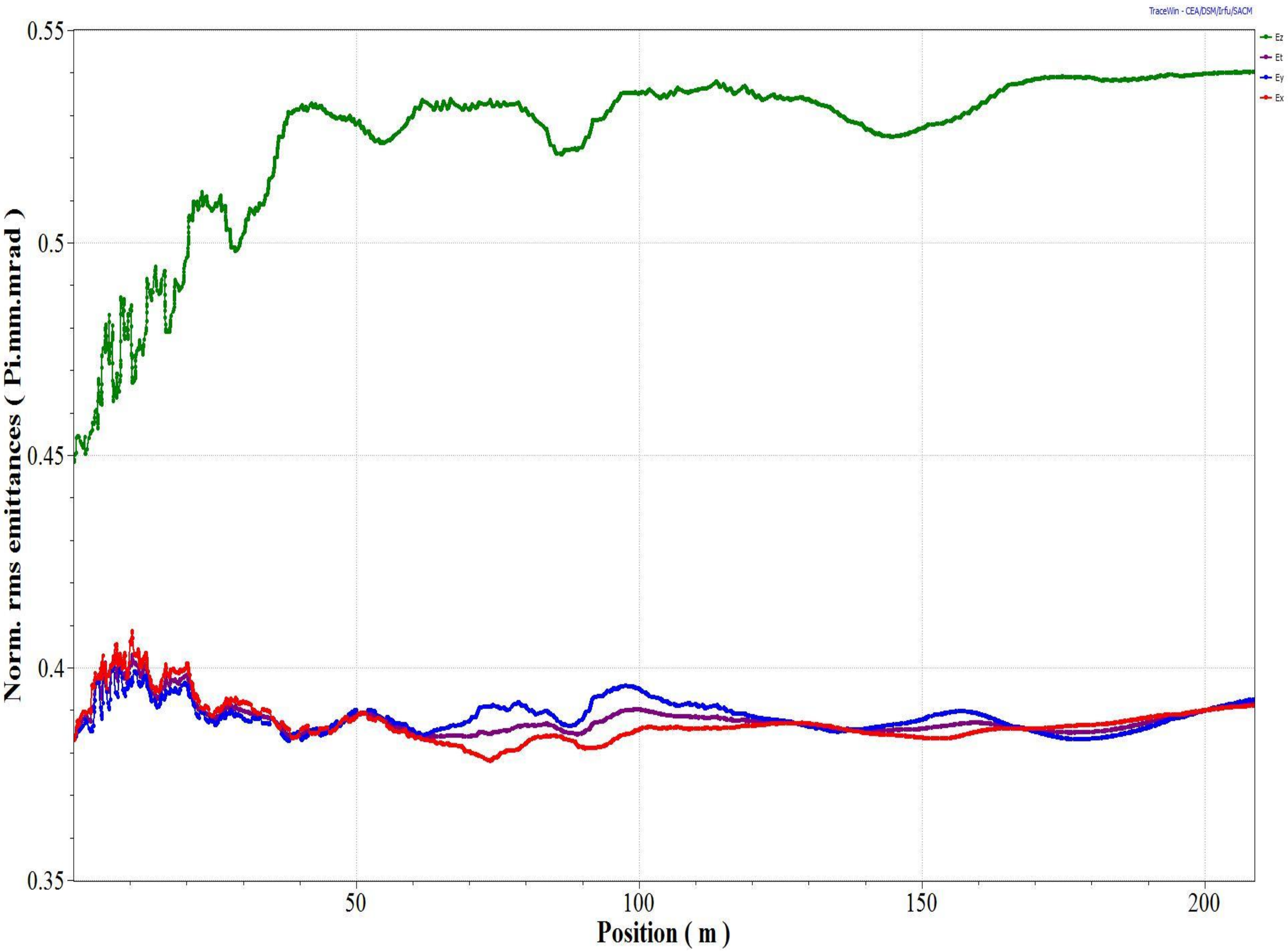


End to end beam dynamics of 1 GeV Injector Linac

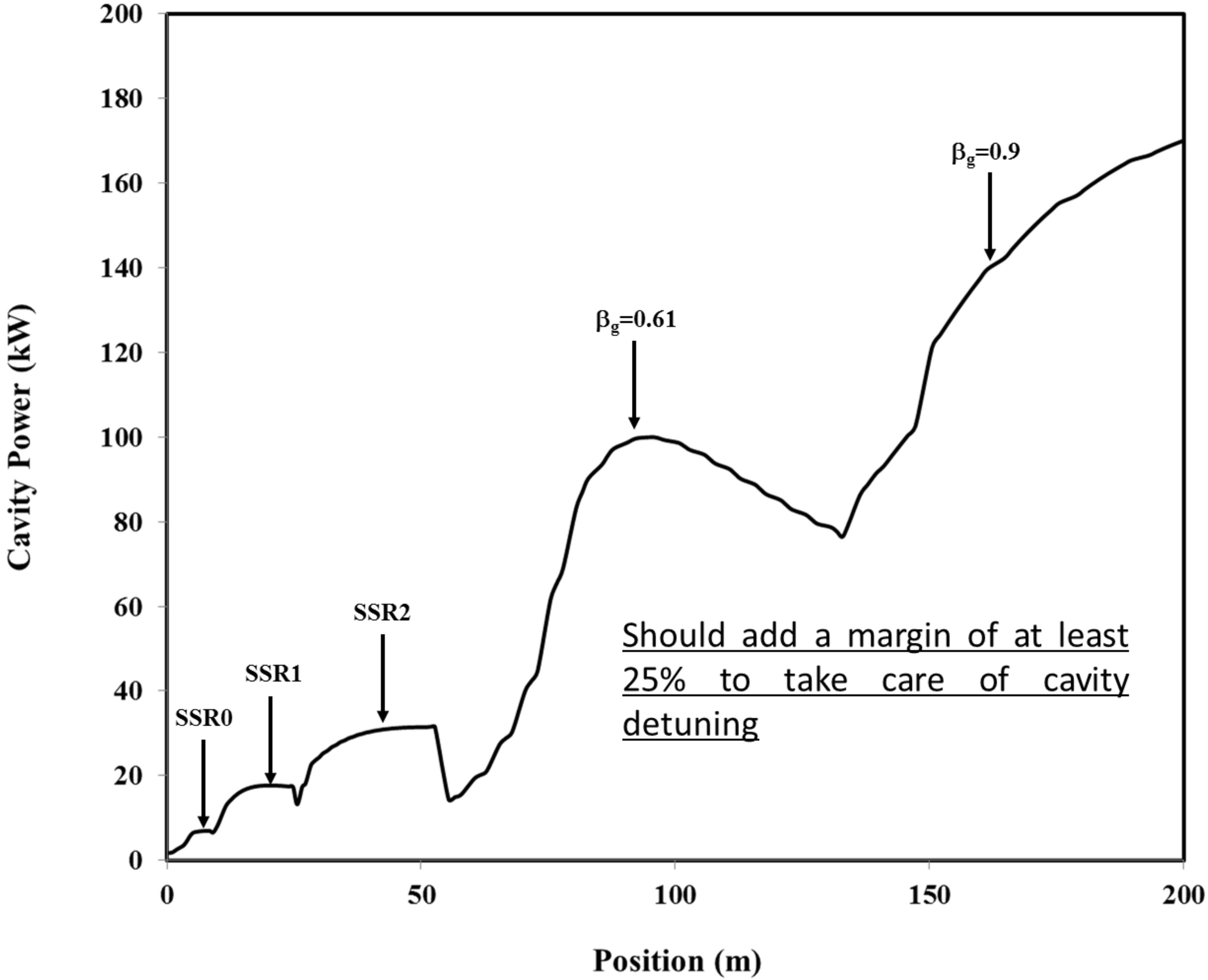




End to end beam dynamics of 1 GeV Injector Linac



RF power requirements per cavity



Summary

- We discussed the issues related to calculation of TTF and Q_0 in SCRF cavities.
- Basis for the physics design of SCRF cavity for ISNS was presented and the we discussed the status of physics design studies.
- A few sets of physics design have evolved. Further refinement in the design is in progress.


Thank You!