Design Studies of Accelerating Structures for the FCC-ee Pre-injector Complex

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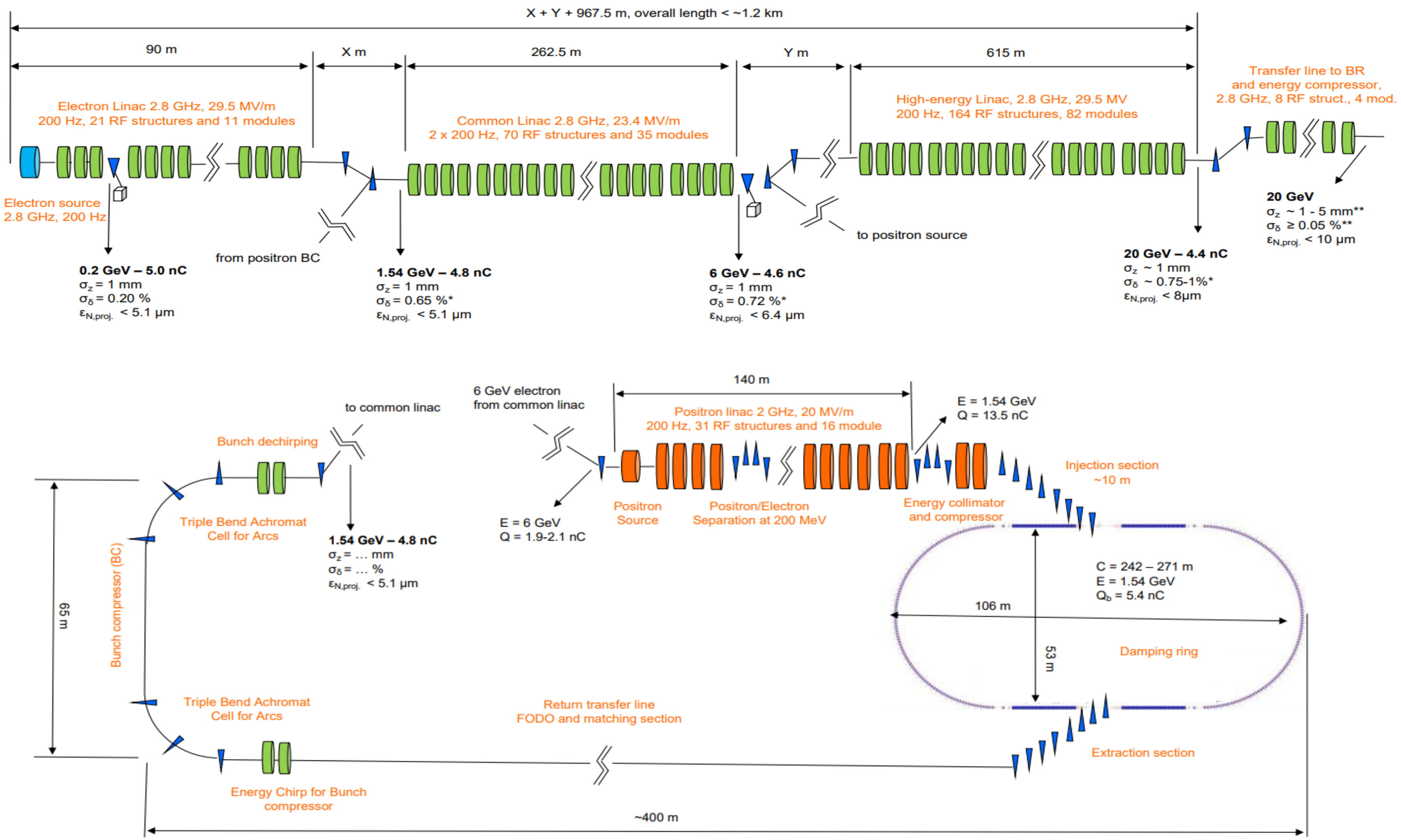
Acknowledgment: P. Wang

Introduction

FCCee injector linacs layout

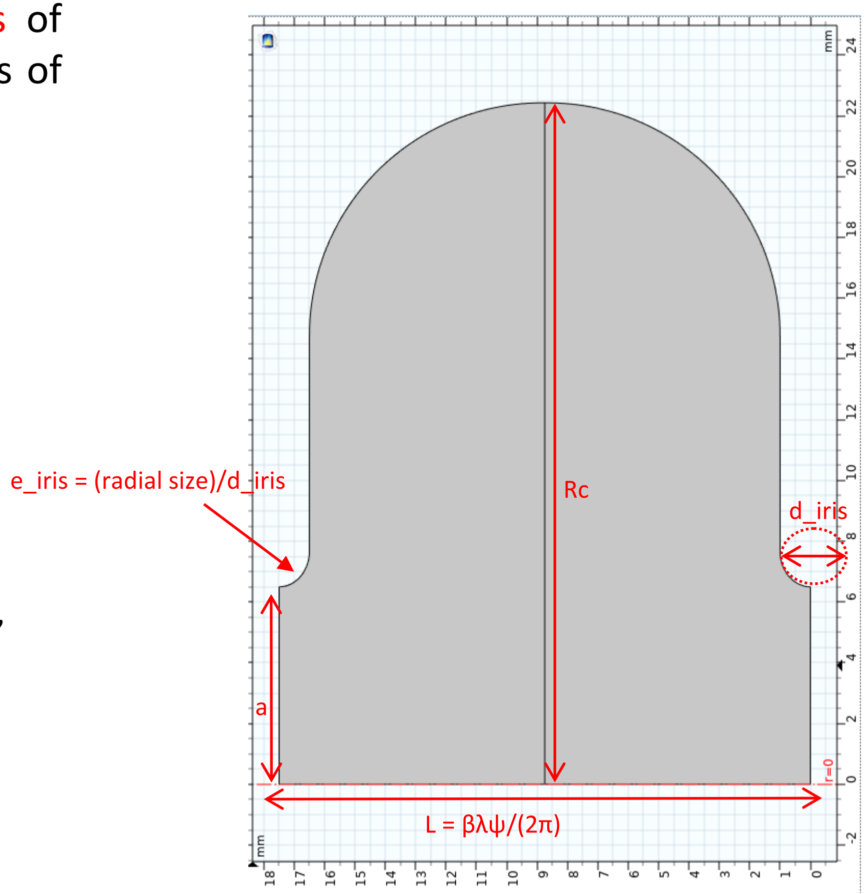


Methodology

- Initially, lookup tables were created as functions of aperture and iris thickness of convex cell geometry for the first 20 HOMs to be used to calculate RF parameters of the structure.
- This method allows us to compute many structures rapidly.

- **Motivation of the study:**
  - Increase the effective shunt impedance of the structure compared to the previous S-band structure.
  - As a result of a good compromise between beam dynamics and RF constraints, we studied accelerator structure with an average aperture of 0.12λ.

- **Structure parameters and requirements:**
  - f = 2.8 GHz, Length = 3m, Phase advance = 2π/3.
  - <a> = 0.12λ, tapered aperture, tapered iris thickness.
  - |Wx| from 17.5 to 30 ns < 0.2 V/pC/mm/m
  - Emax < 100 MV/m and Sc < 2300 mW/μm²



RF Pulse Compression and Accelerating Structure

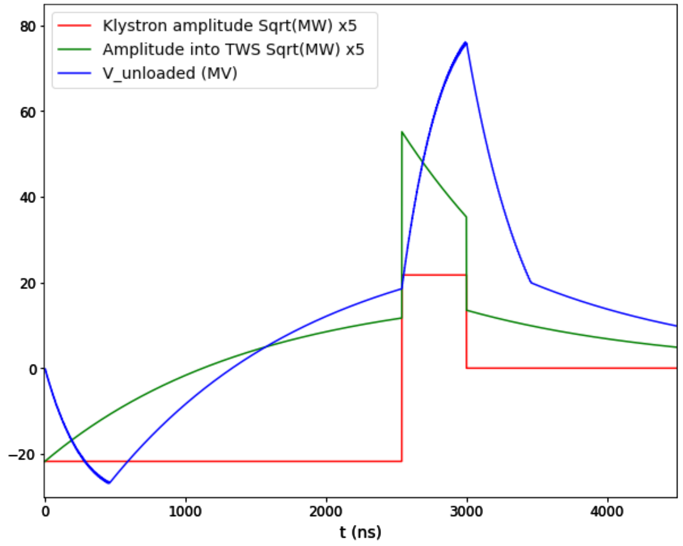
- The SLED-type RF pulse compressor has been analytically designed and realized.
- Pulse compressor increases peak pulse amplitude and reduces pulse length by charging storage cavity.
- The electric field strength within the accelerator cavities depends on the peak power of the RF signal.
- For rectangular klystron pulse, gradient at injection can also be derived analytically:

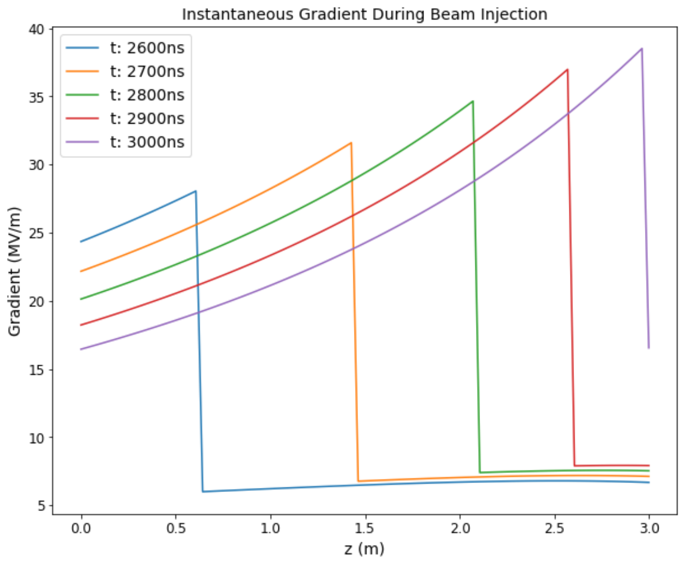
$$G(z,T_\mathrm{k}) = A_{\mathrm{k},0}\left(1-\alpha\left[1+\left(e^{-\mu T_\mathrm{k}}-2e^{-\mu T_\mathrm{f}}\right)e^{\mu\tau(z)}\right]\right)\sqrt{\omega\frac{\varrho(0)}{v_\mathrm{g}(0)}}g(z)$$

where $$g(z)=\sqrt{\frac{v_\mathrm{g}(0)\varrho(z)}{v_\mathrm{g}(z)\varrho(0)}}\exp\left[-\frac{\omega}{2}\int_0^z\frac{\mathrm{d}z'}{v_\mathrm{g}(z')Q(z')}\right]$$

$$V = \int_0^{L_s} dz' G(z,T_k)$$

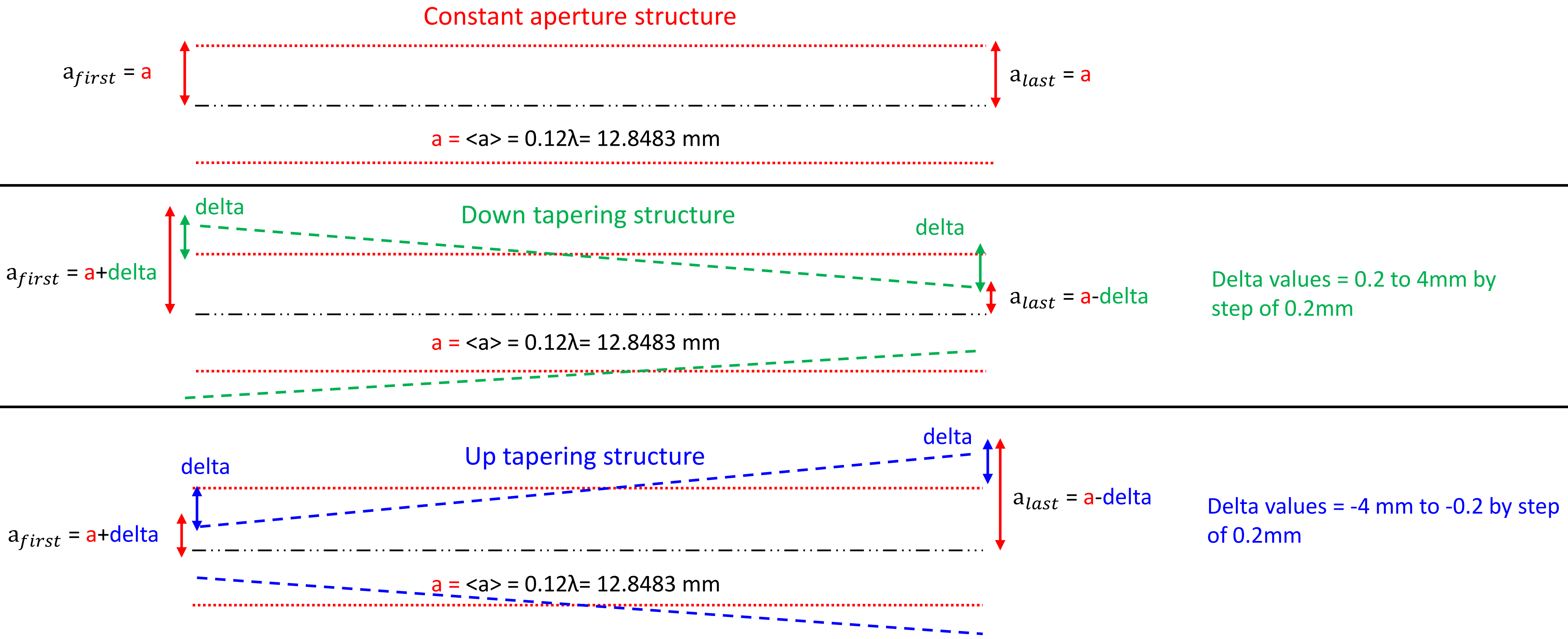
- We define an effective shunt impedance: $R_{eff} = V_{max}^2/P_{klystron}/L_{structure}$ [MΩ/m]





Parameter Sweeps

- Damping long-range wakes by HOM detuning.
- Aperture and Iris thickness sweeps to get highest effective shunt impedance which satisfies the wake condition.

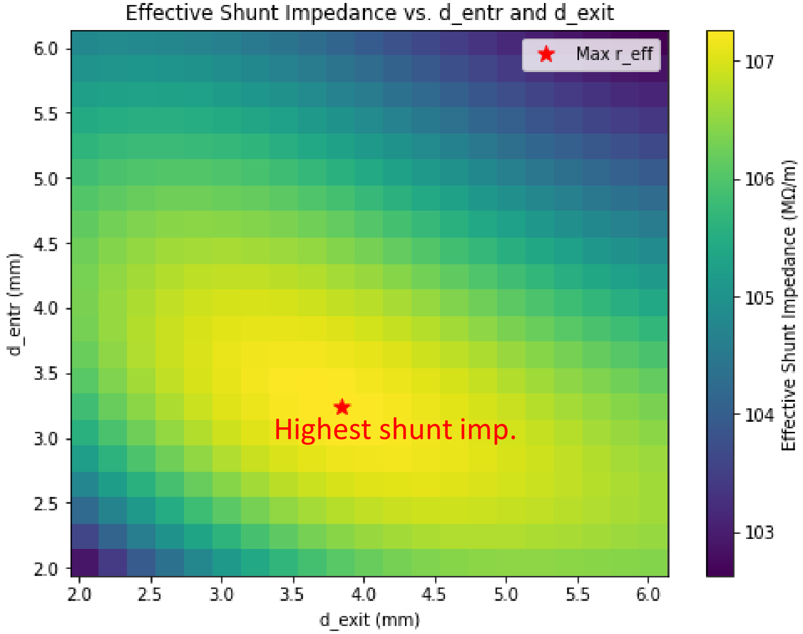


Parameter Sweeps

- For each delta we find entrance (firstlcell) and exit (last cell) iris thicknesses for the highest effective shunt impedance.
- Scanning iris thickness from 2.04 mm to 6.2 mm by step of 0.2mm (These numbers are the limits of Lookup table).
- $Q_{0,SLED}$ = 2e5, $T_{klystron}$ = 3 us, β= from 14 to 17

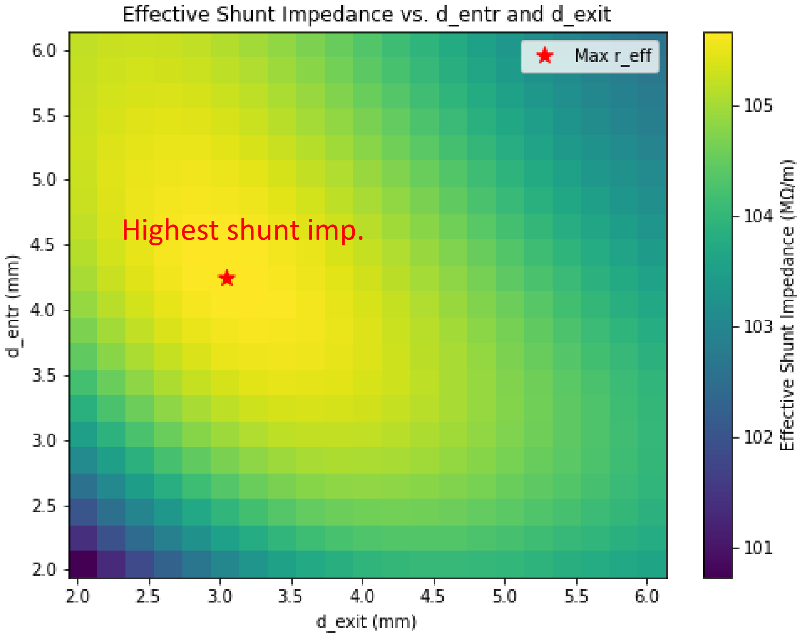
Up tapering

(Delta from -4mm to -0.2 mm)



delta= -2 mm

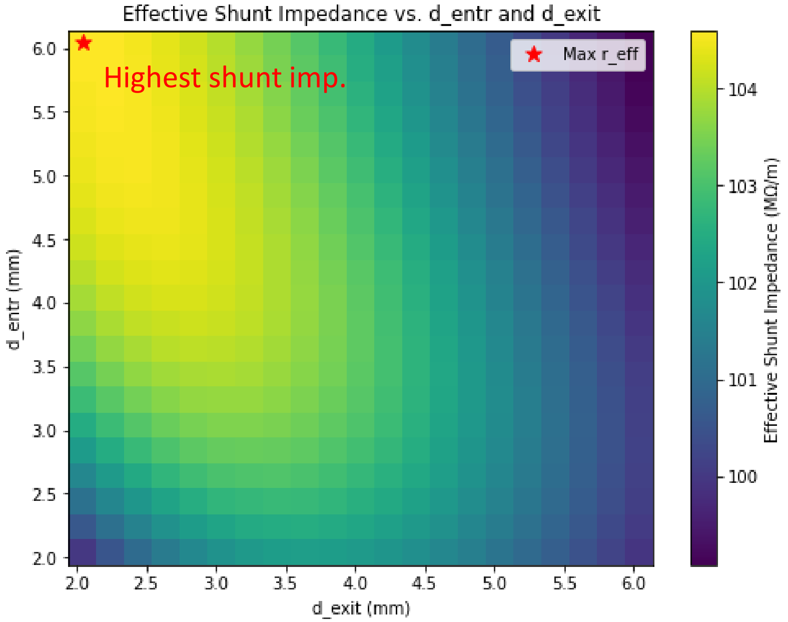
Constant aperture



delta= 0 mm

Down tapering

(Delta from 0.2 mm to 4mm)



delta= 2 mm

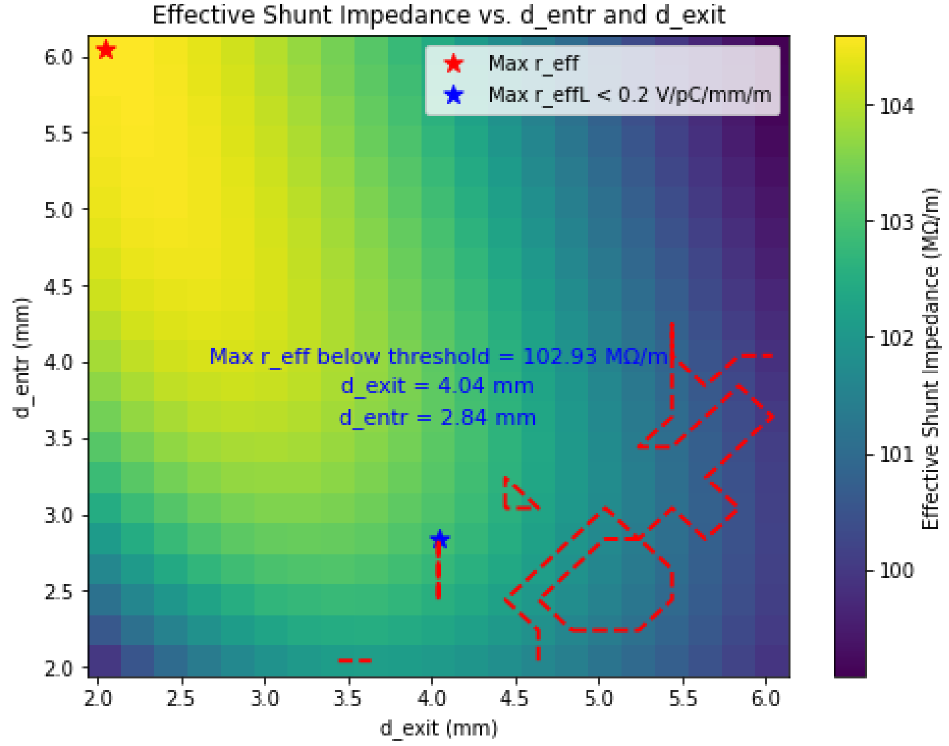
Parameter Sweeps

- Checking for Transverse wake condition: |Wx| from 17.5 to 30 ns < 0.2 V/pC/mm/m
- Long-range wake from frequency-domain parameters: R/Q, Q and ω.

$$W(s) = 2\sum_n K_n \sin\frac{2\pi\nu_n s}{c} e^{-\pi\nu_n s/(cQ_n)}$$

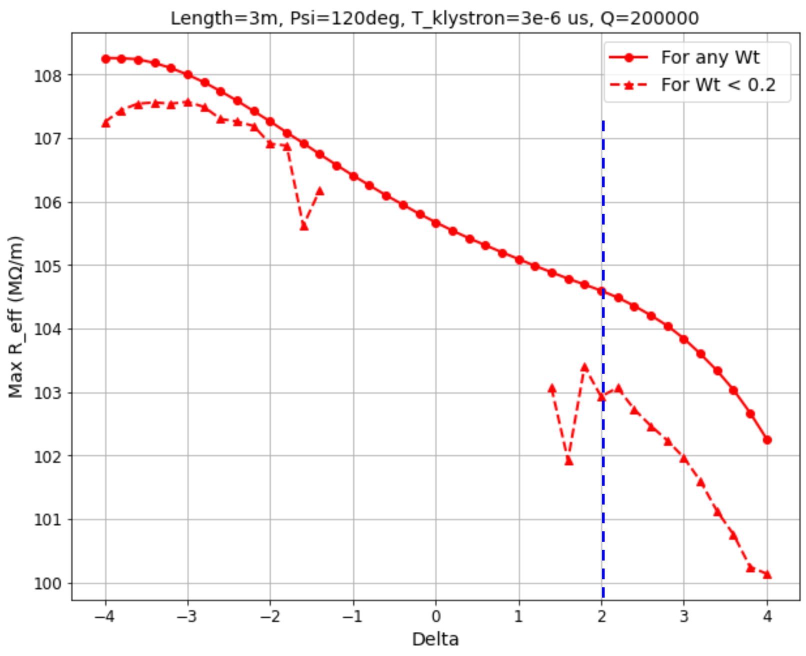
Where $K_{x,n} = \left(\frac{R'_x}{Q}\right)_n \frac{\omega_n^2}{4c} \cdot 10^{-12} \cdot 10^{-3}$ [V/pC/mm/m]

delta= 2 mm



- Highlighting the areas that satisfy the wake requirment for every delta.
- Updating maximum effective shunt impedance for < 0.2 V/pC/mm/m.
- Calculating structure parameters with the corresponding aperture and iris thickness.

Parameters Sweep Results



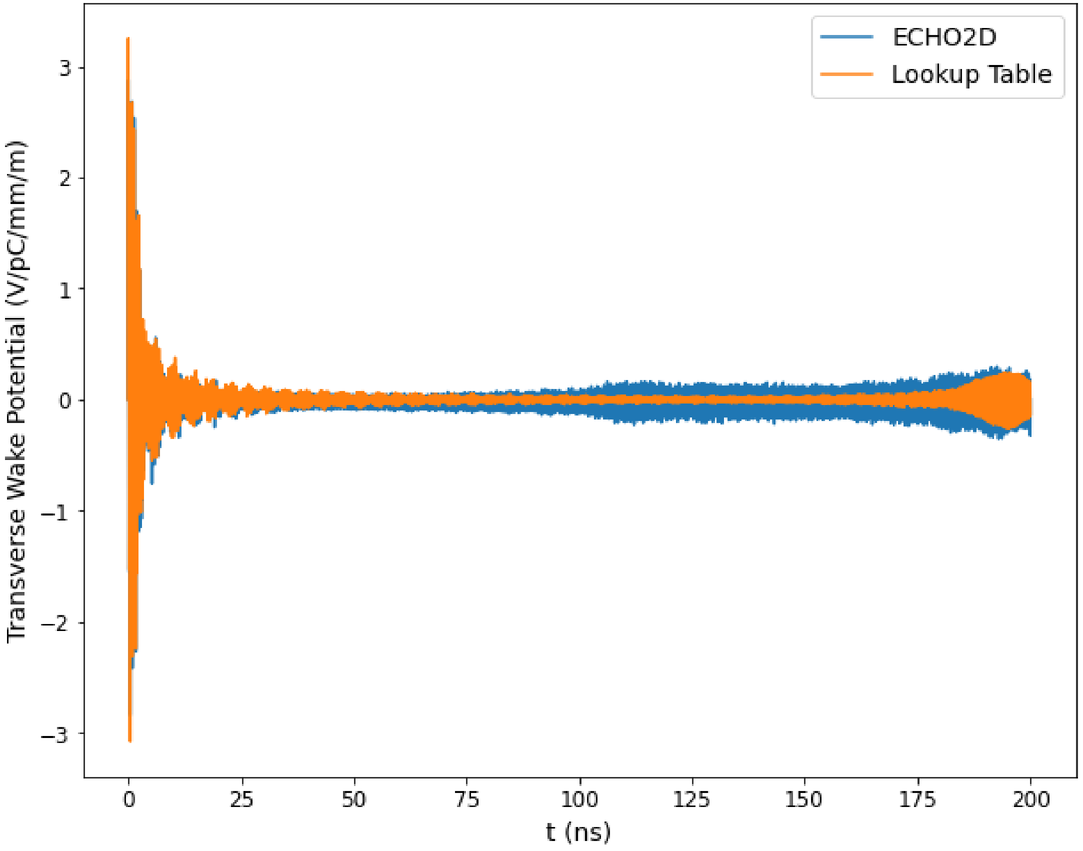
- Emax < 100 MV/m and Sc < 2300 mW/μm²
- Based on requirements delta=2mm is the best candidate.

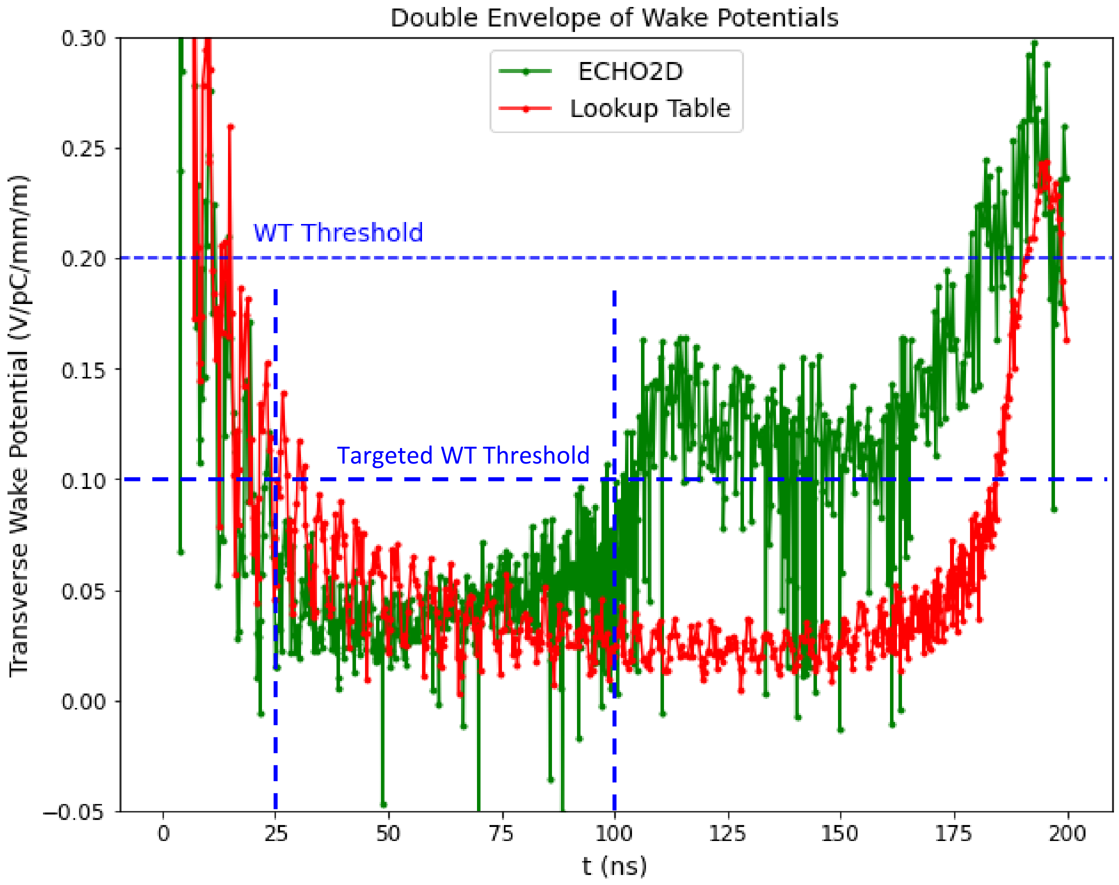
	Delta = -3 mm	Delta = -2 mm	Delta = 2 mm	Delta = 3mm
Aperture	9.85 mm → 15.85 mm	10.85 mm → 14.85 mm	14.85 mm, → 10.85 mm	15.85 mm → 9.85 mm
Iris thickness	3.44 mm → 2.84 mm	4.04 mm → 2.84 mm	2.84 mm → 4.04 mm	2.84 mm → 3.44 mm
Vg (% c)	0.97 → 4.65	1.25 → 3.87	3.87 → 1.25	4.65 → 0.97
r/Q (kOhm/m)	4.65 → 3.44	4.38 → 3.64	3.64 → 4.38	3.44 → 4.65
Q	16340 → 16685	16178 → 16642	16642 → 16178	16685 → 16340
Filling time	479 ns	462 ns	462 ns	479 ns
SLED coupling	17	17	15	15
Eff. shunt impedance	108 MΩ/m	107 MΩ/m	103 MΩ/m	102 MΩ/m
G_{avg}	25 MV/m	25 MV/m	25 MV/m	25 MV/m
E_{max} (instant.)	133 MV/m	106 MV/m	83 MV/m	102 MV/m
$S_{c,max}$ (instant.)	1226 mW/μm²	911 mW/μm²	643 mW/μm²	732 mW/μm²

Wakefield Studies

Wakefield Studies

- Wakefields are calculated both with lookup table and ECHO2D time-domain wakefield solver by I. Zagorodnov.
- Long-range wake damping by dipole mode detuning is effective by tapering both aperture and iris thickness.
- 25 ns of bunch spacing with 4 bunches.

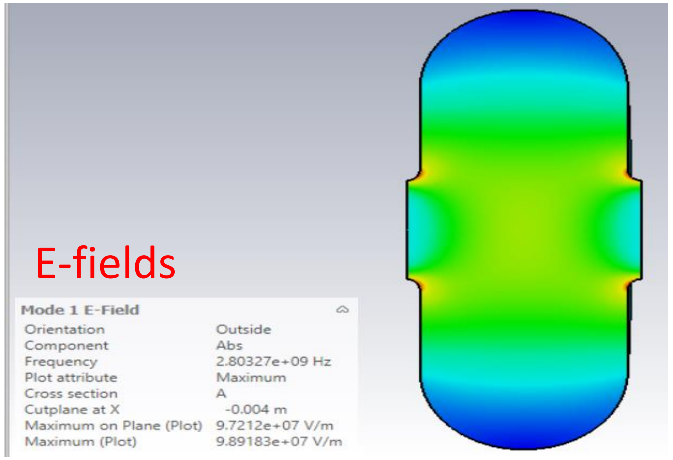


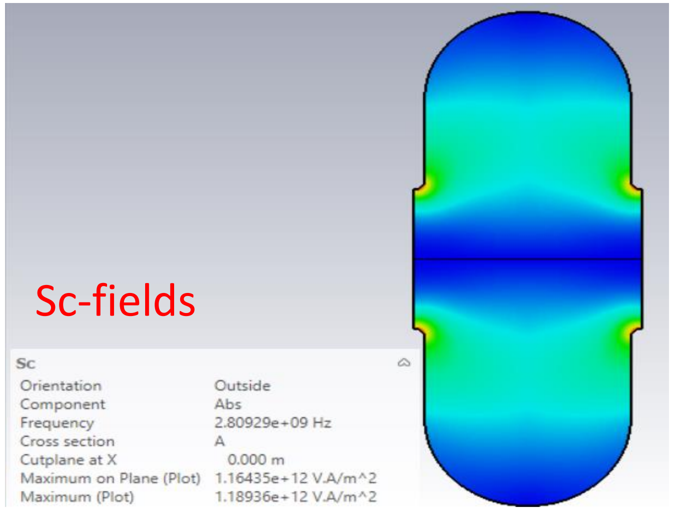


CST benchmarking

Benchmarking with CST Model

- After we decided aperture and iris thickness parameters, we benchmarked our lookup table results with the 3D model in CST for the first, middle and last cells.
- Less surface fields observed with the 3D model in CST.





	f (GHz)	Q	Rz/Q (kOhm/m)	Vg/c (%)
First Cell	2.8	16571	3.63	3.92
Middle Cell	2.8	16293	4.02	2.34
Last Cell	2.8	16039	4.38	1.25

- RF parameters are in agreement with lookup table < 2% difference.

	Esmax/G	Sc/G^2
First Cell	2.8669	9.105e-4
Middle Cell	2.4254	5.876e-4
Last Cell	2.0923	3.614e-4

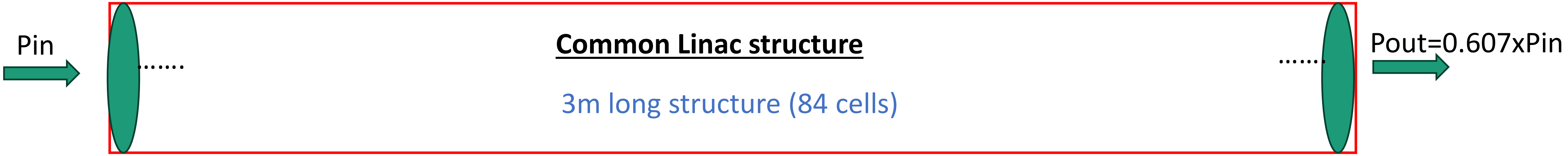
Delta = 2 mm	CST
Entr., exit aperture	14.85 mm → 10.85 mm
Iris thickness	2.84 mm → 4.04 mm
Vg (% c)	3.92 → 1.25
r/Q (kOhm/m)	3.63 → 4.38
Q	16571 → 16039
Filling time	460 ns
SLED coupling	15
Eff. shunt impedance	102 MΩ/m
G_{avg}	25 MV/m
E_{max} (instant.)	79 MV/m
$S_{c,max}$ (instant.)	638 mW/μm²

Common Linac and High Energy Linac

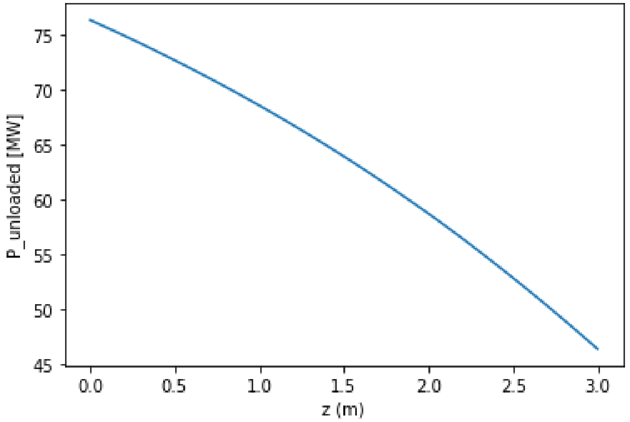
Delta = 2 mm	C-linac	HE-linac (S)
Entr., exit aperture	14.85 mm, 10.85 mm	
Iris thickness	2.84 mm → 4.04 mm	
Vg (% c)	3.92 → 1.25	
r/Q (kOhm/m)	3.63 → 4.38	
Q	16571 → 16039	
Filling time	460 ns	
SLED coupling	15	
Eff. shunt impedance	102 MΩ/m	
Repetition rate [Hz]	400	200
Klystron power per structure	18.9 MW	30 MW
Average Structure Input Power	19.8 kW	15.7 kW
G_{avg}	25.41 MV/m	32.05 MV/m
E_{max} (instant.)	81 MV/m	103 MV/m
$S_{c,max}$ (instant.)	660 mW/μm²	1056 mW/μm²

Thermo-mechanical Studies of Common Linac

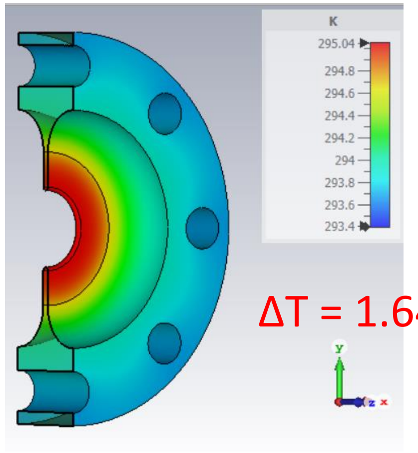
Thermal Studies



Thermal load parameters of first cell	
f_{rep} , $T_{klystron}$	400 Hz, 3 µs
$\alpha_{pulse\_compressor}$	0.87
Pin (Klystron power per structure)	18.9 MW
<Pin> (Avg. structure input power)	**19.8 kW**
U_{first_cell}	**6.005e-5 J**
P_{loss} (Avg. wall losses first cell)	**64.41 W**



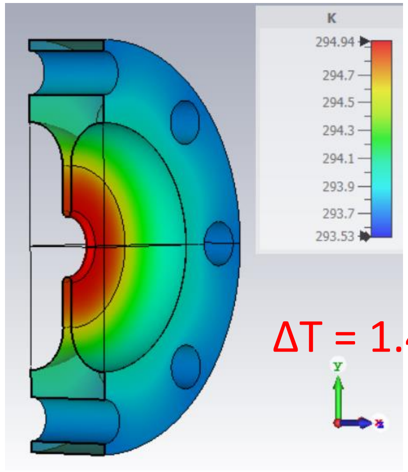
Thermal load parameters of last cell	
$\alpha_{struture}$	0.607
<Pin_last> (Avg. Last cell input power)	**12.03 kW**
U_{last_cell}	**5.6e-5 J**
P_{loss} (Avg. wall losses last cell)	**61.43 W**



ΔT = 1.64 °C increase

- $< P_{in} > = P_{in} . f_{rep} . T_{klystron} . \alpha_{pulse\ compressor}$
- $< P_{in\ last} > = < P_{in} > . \alpha_{structure}$
- $U = < P > . L_c / V_g$
- $P_{loss} = U . \omega / Q$

Cooling channel diameter	16 mm
Convection to water channel	4 kW/m²/K

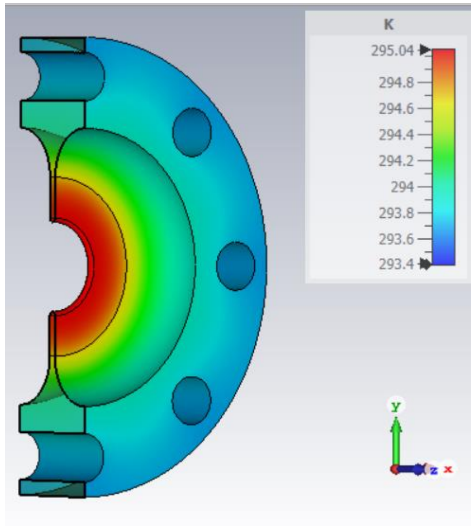


ΔT = 1.41 °C increase

Thermal Studies

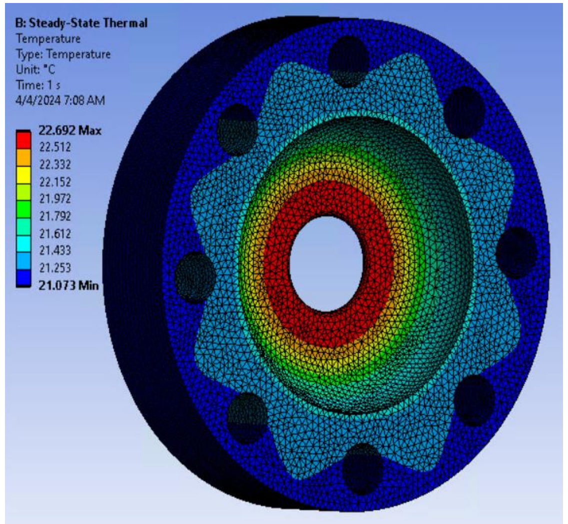
- Additionally, we also benchmarked our CST thermal simulation results for the first cell with ANSYS Thermal solver.

CST



$\Delta T = 1.64\ ^{\circ}C$

ANSYS

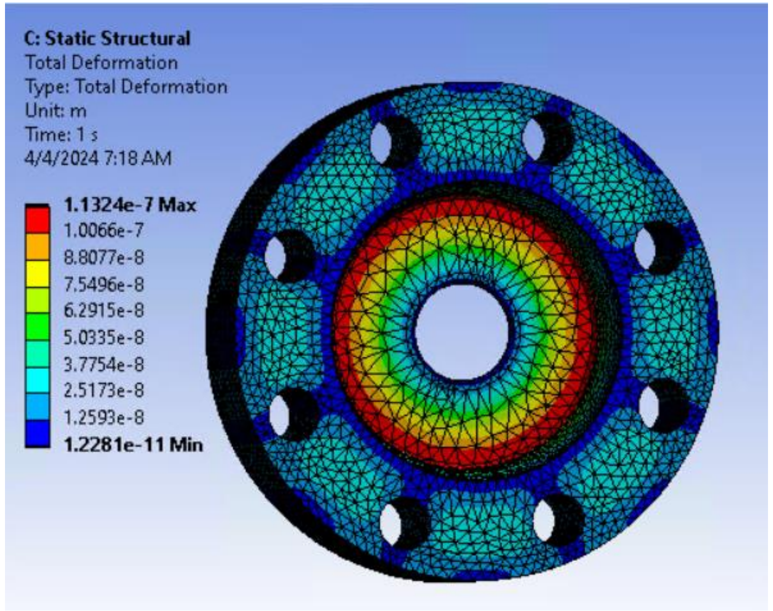


$\Delta T = 1.62\ ^{\circ}C$

0.02 ˚C differences observed.

Mechanical Studies

- Based on thermal studies we simulated total deformation on the first cell with mechanical solver of ANSYS.

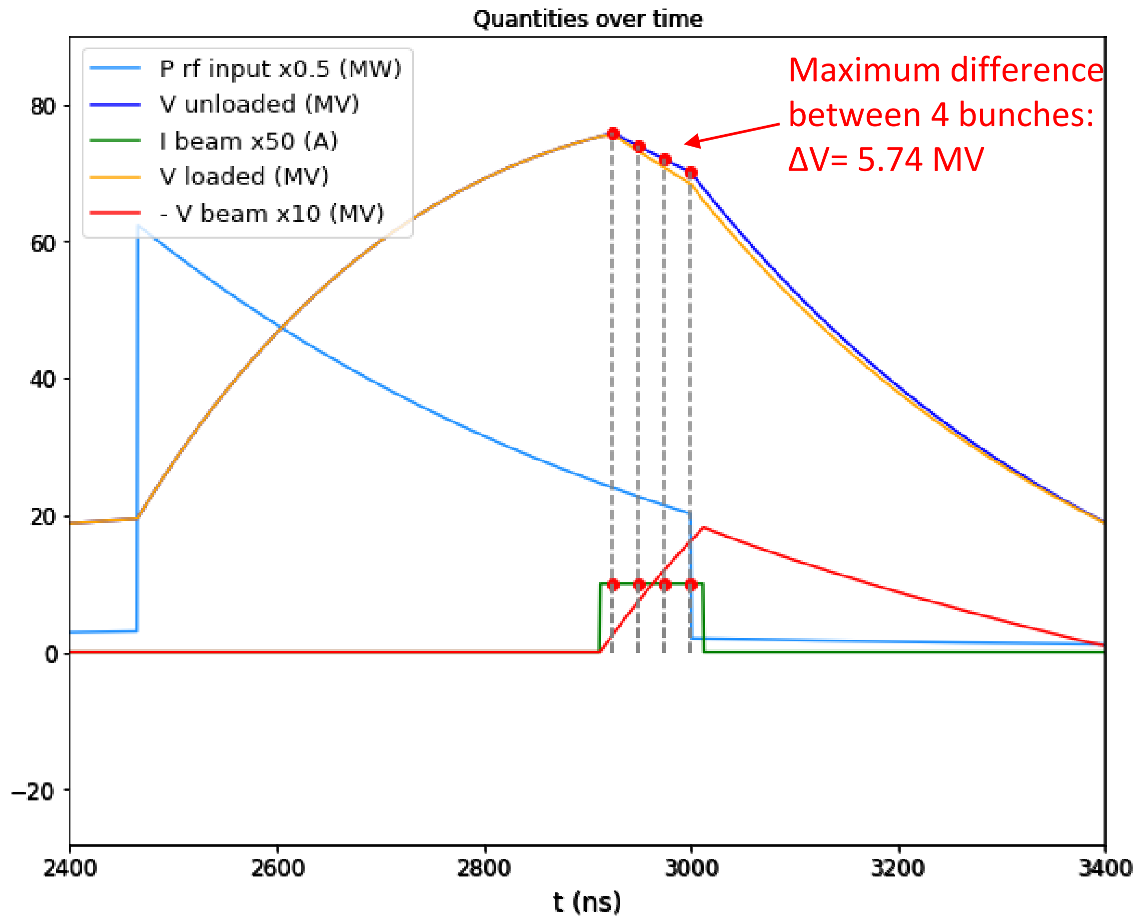


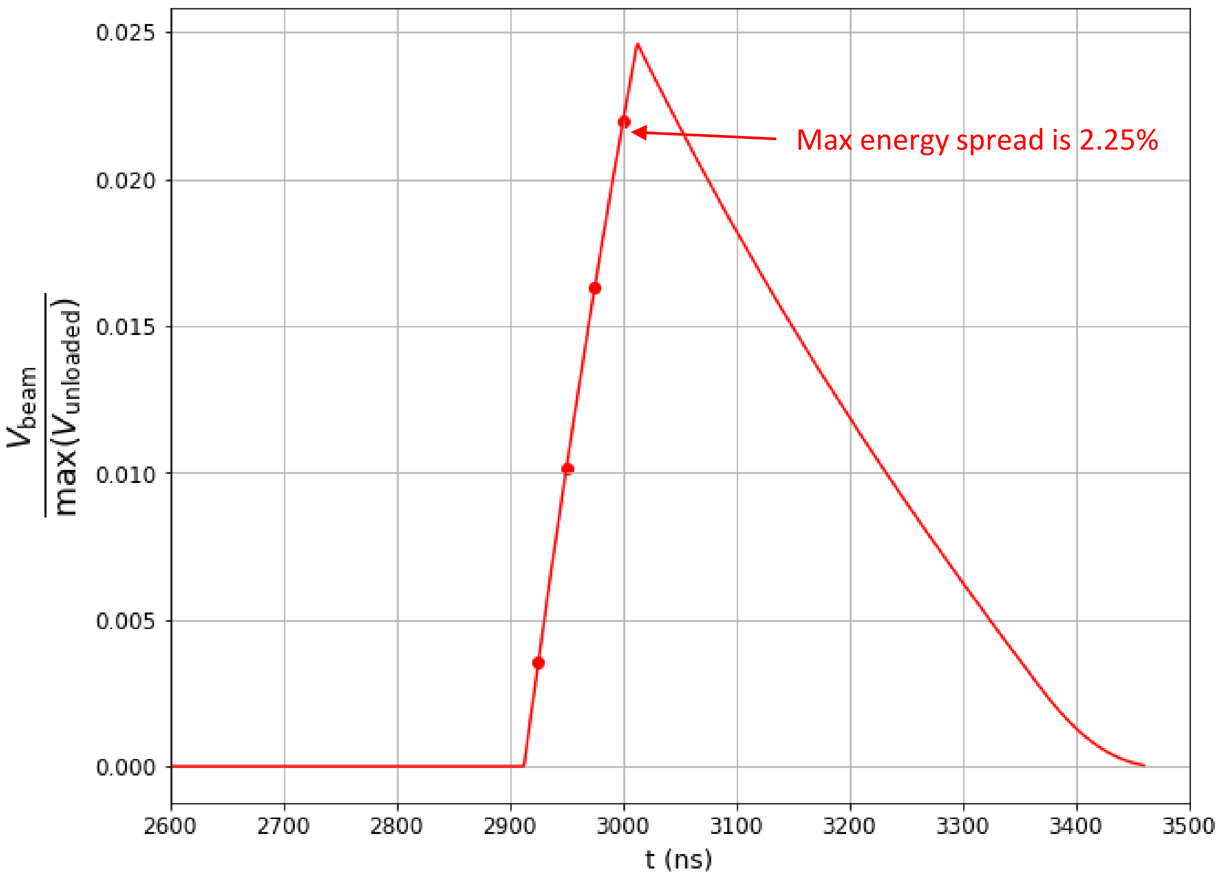
Max deformation ≈ 0.1 μm which is negligible

Beam-loading effect

Beam-loading effect

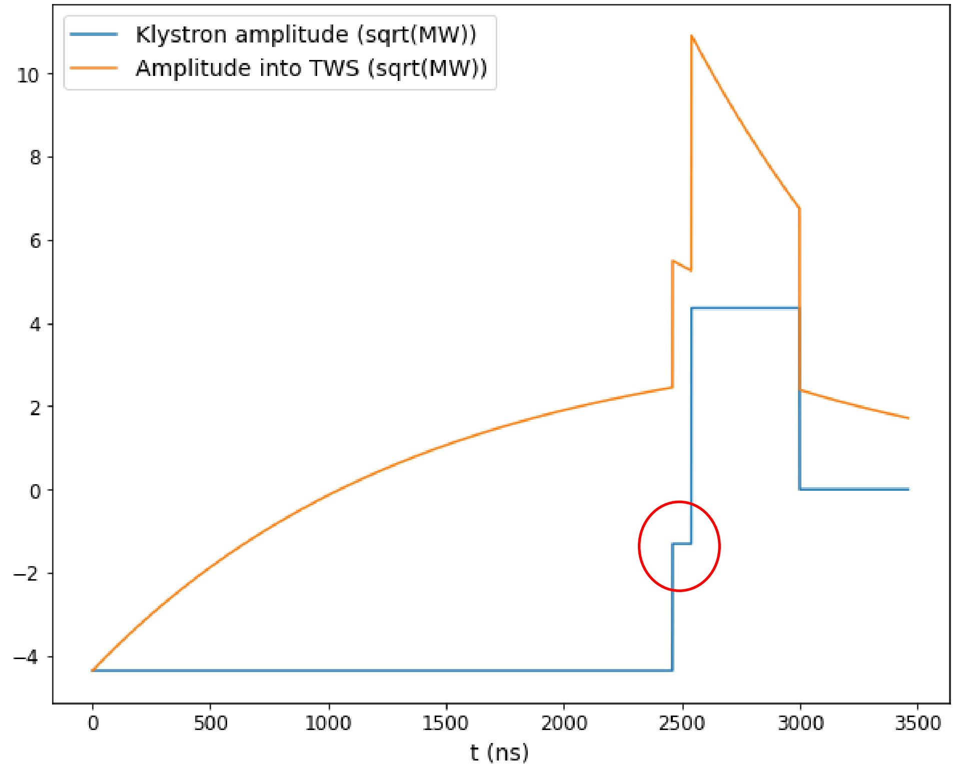
- **Parameters for the structure:**
- f = 2.8 GHz, Length = 3m, Phase advance = 2π/3, <a> = 0.12λ, $Q_{0,SLED}$ = 2e5, $T_{klystron}$ = 3 us, $G_{avg} = 25.4$ MV/m.
- 4 bunches with Q_{bunch} = 5 nC, $T_{bunch\_seperation}$ = 25 ns, I_{beam} = 0.2 A.

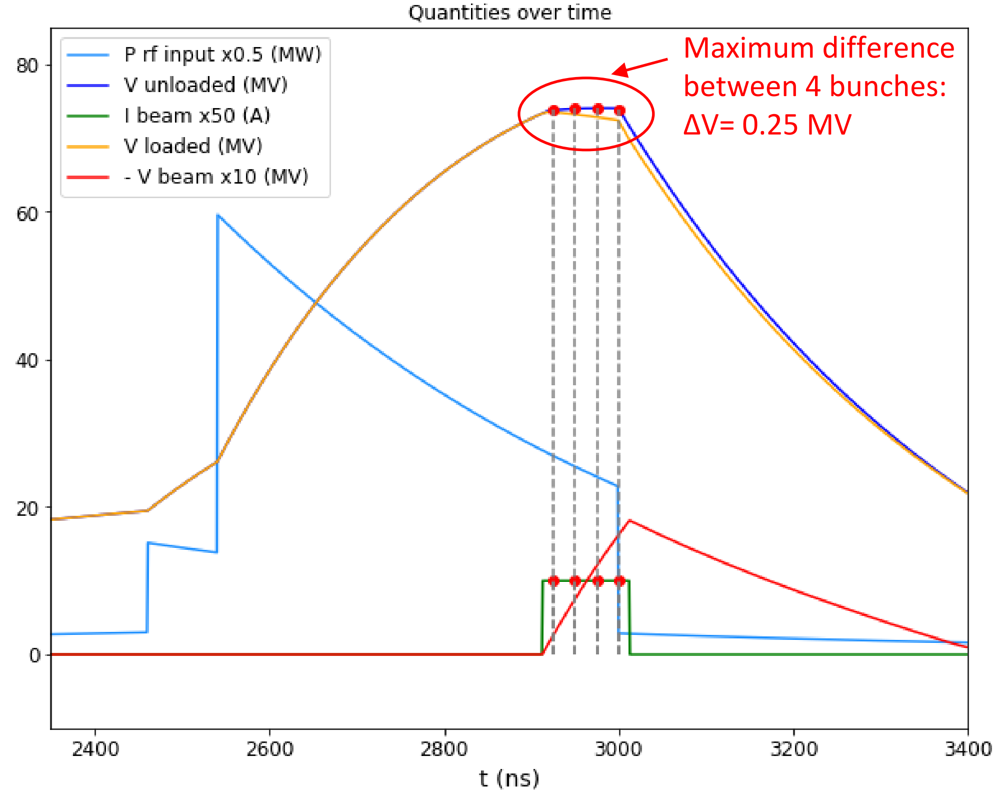




Minimization of bunch-to-bunch energy spread

- By modulating the input pulse shape of the klystron, we can optimize the energy spread between the bunches.





- After modifying the input pulse shape of the klystron, the maximum unloaded voltage difference between four bunches lowered to 0.25 MV, which was 5.74 MV when we applied standard square pulse shape.

Conclusion

- **Design and Optimization :**
  - Conducted design studies of accelerating structures for the <a> = 0.12λ.
  - Optimized aperture size and iris thickness to determine optimal configurations for highest shunt impedance and minimal long-range wakefield impact.

- **RF Pulse Compression Design**:
  - Designed and implemented a SLED-type RF pulse compressor to enhance RF performance.

- **Benchmarking:**
  - Benchmarked design parameters using CST's eigenmode solver, ensuring accuracy of lookup table predictions.

- **Beam-Loading and Energy Spread Reduction for 4 bunches of 5nC:**
  - Studied the effect of beam-loading.
  - Minimized bunch-to-bunch energy spread (from 5.74 MV to 0.25 MV) by optimizing klystron input pulse shape.

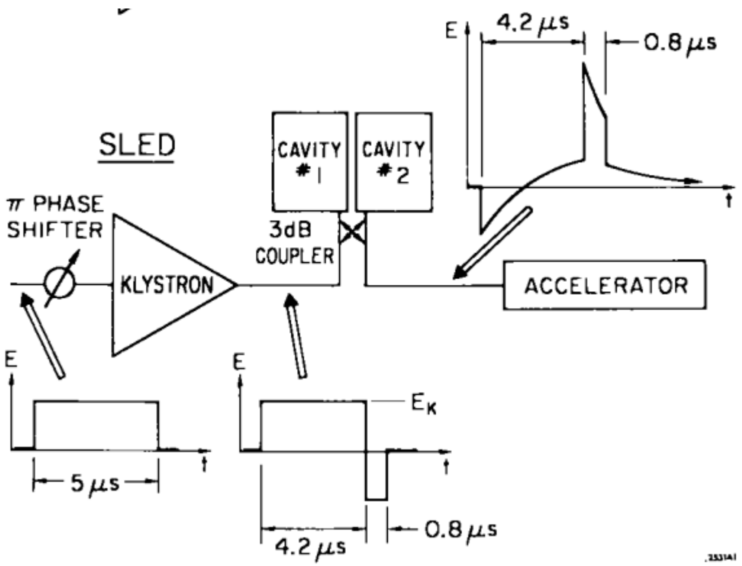
- **Thermal and Mechanical Robustness for the Common Linac operating at $G_{avg} = 25.4$ MV/m and $f_{rep} = 400$ Hz :**
  - Conducted thermal and mechanical studies to ensure structural integrity and performance stability.
  - Thermal studies are done with CST's Thermal solver.
  - Also benchmarked thermal simulations with thermal solver of ANSYS.
  - Negligible deformation (0.1 μm) observed.

Thanks for your attention!

Spare Slides

SLED-type RF pulse compressor

Farkas et al., A method of doubling SLAC's energy, Proc. HEACC 1974



- Increase peak pulse amplitude and reduce pulse length by charging storage cavity
- Output pulse A_L given by $$A_\ell(t) = A_\mathrm{k}(t) - \frac{\omega\beta}{Q_0} e^{-t/\tau} \int_0^t e^{t'/\tau} A_\mathrm{k}(t')\mathrm{d}t'$$

  where A_K: klystron pulse, β, Q_0, τ: coupling, Q-factor, filling time of storage cavity.

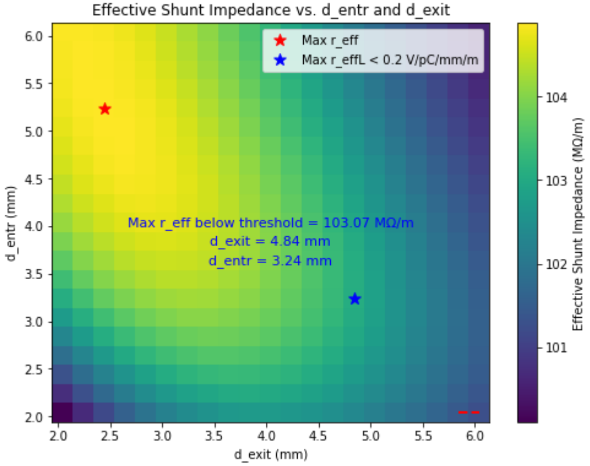
$$\tau = \frac{2Q_\ell}{\omega} = \frac{2Q_0}{\omega(1+\beta)}$$

DOWN TAPERING

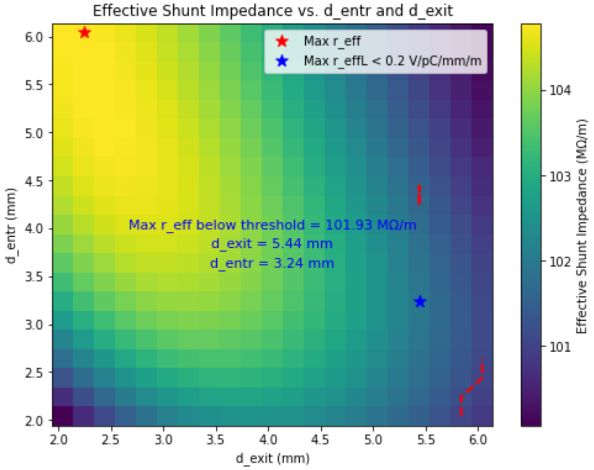
@2.8 GHz, 0.12λ = 12.8483 mm

a_entr = 12.8483 + delta, a_exit = 12.8483 – delta, where delta = -4 to 4 mm by step of 0.2mm

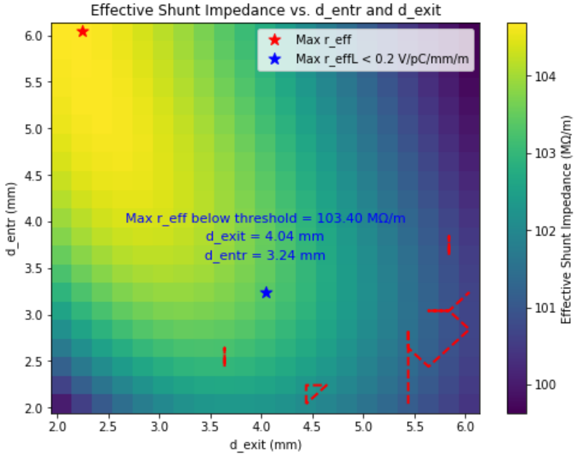
delta=1.4 mm
a_entr = 14.2483, a_ext=11.4483



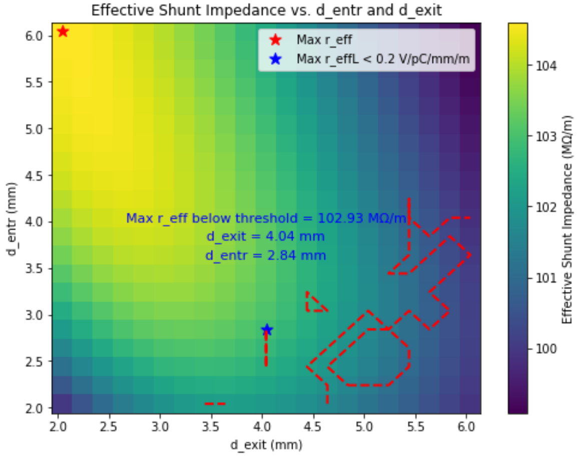
delta=1.6mm
a_entr = 14.4483, a_ext=11.2483



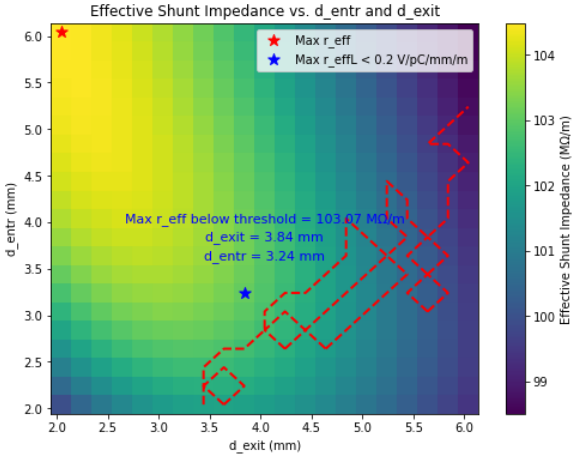
delta=1.8mm
a_entr = 14.6483, a_ext=11.0483



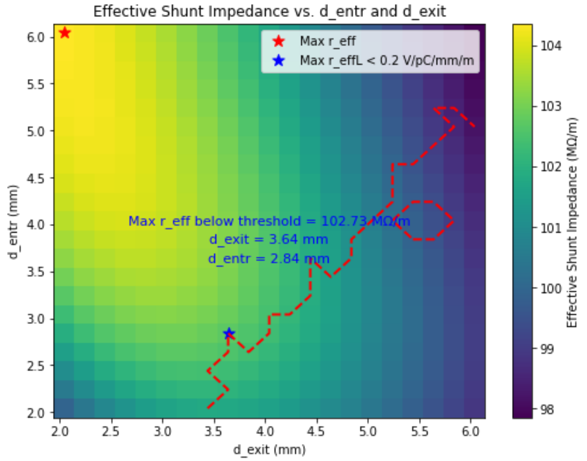
delta=2mm
a_entr = 14.8483, a_ext=10.8483



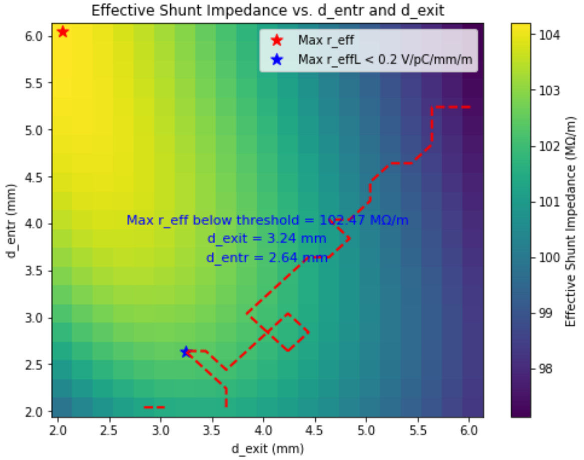
delta=2.2 mm
a_entr = 15.0483, a_ext=10.6483



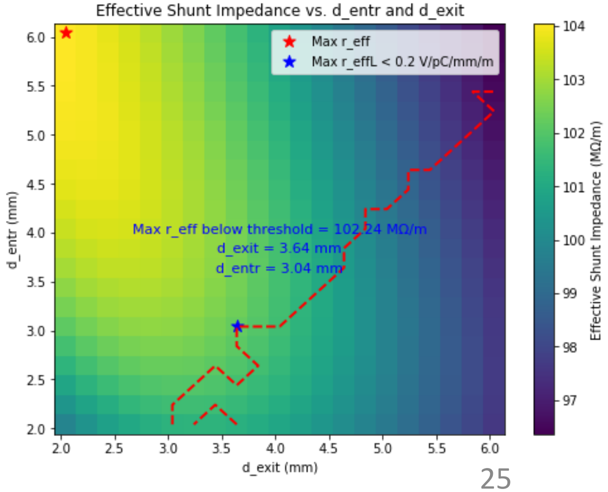
delta=2.4 mm
a_entr = 15.2483, a_ext=10.4483



delta=2.6 mm
a_entr = 15.4483, a_ext=10.2483



delta=2.8 mm
a_entr = 15.6483, a_ext=10.0483

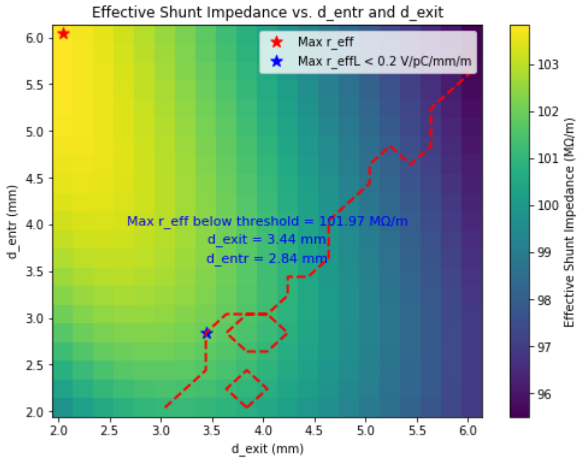


DOWN TAPERING

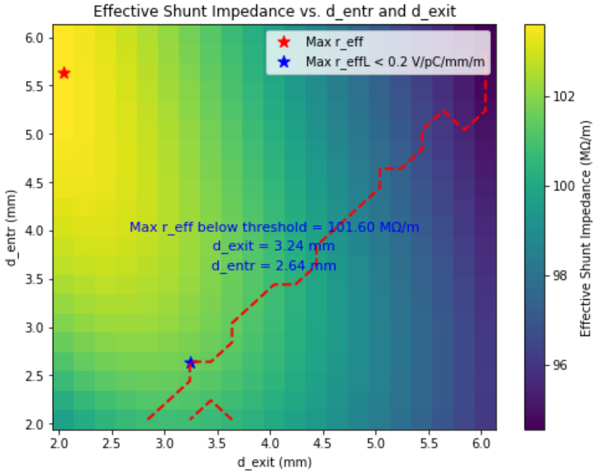
@2.8 GHz, 0.12λ = 12.8483 mm

a_entr = 12.8483 + delta, a_exit = 12.8483 – delta, where delta = -4 to 4 mm by step of 0.2mm

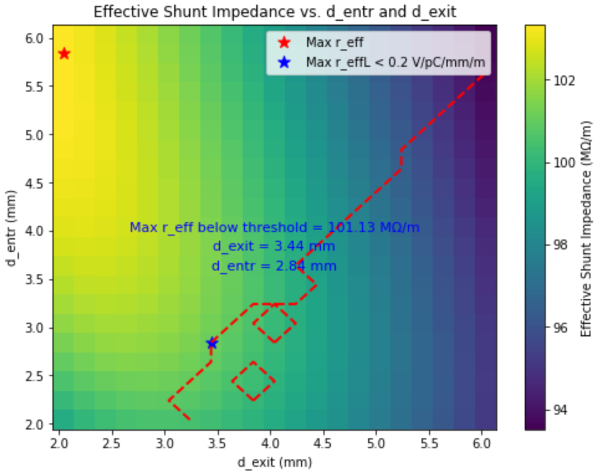
delta=3 mm
a_entr = 15.8483, a_ext=9.8483



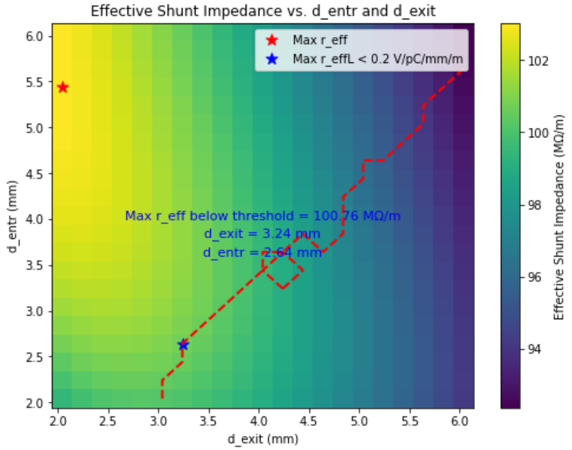
delta=3.2 mm
a_entr = 16.0483, a_ext=9.6483



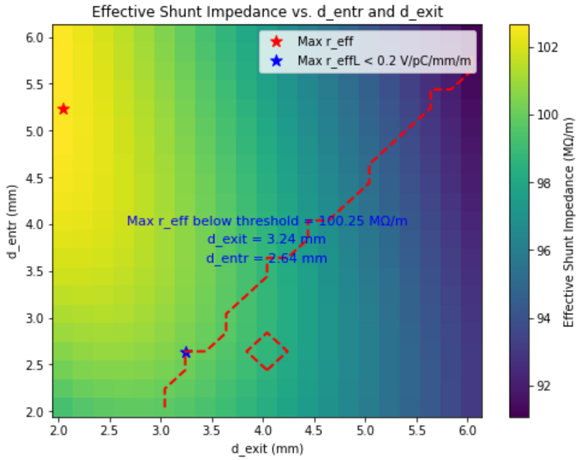
delta=3.4 mm
a_entr = 16.2483, a_ext=9.4483



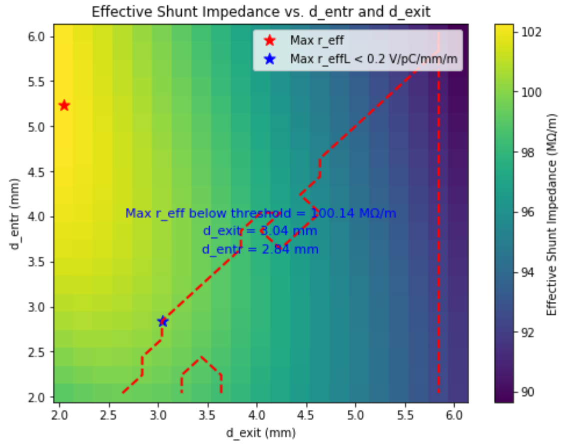
delta=3.6 mm
a_entr = 16.4483, a_ext=9.2483



delta=3.8 mm
a_entr = 16.6483, a_ext=9.0483



delta=4 mm
a_entr = 16.8483, a_ext=8.8483



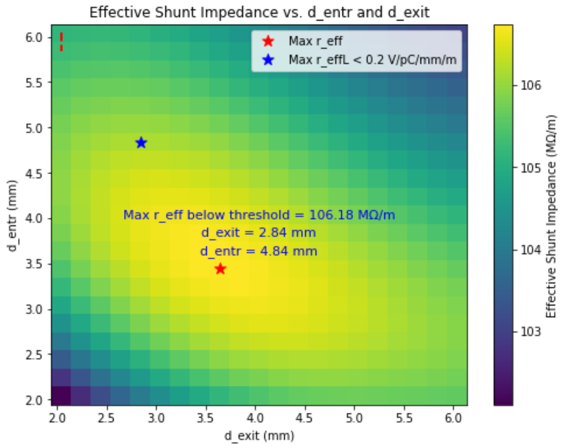
UP TAPERING

@2.8 GHz, 0.12λ = 12.8483 mm

a_entr = 12.8483 + delta, a_exit = 12.8483 – delta, where delta = -4 to 4 mm by step of 0.2mm

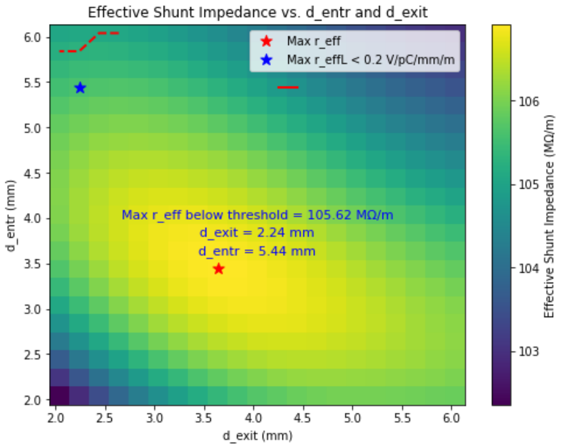
delta= -1.4 mm

a_entr = 11.4483, a_ext= 14.2483



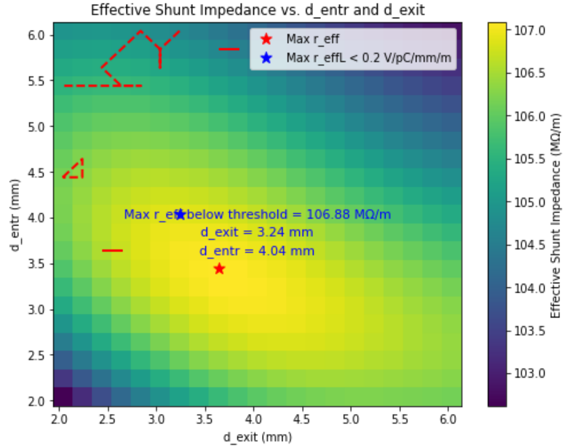
delta= -1.6 mm

a_entr = 11.2483, a_ext= 14.4483



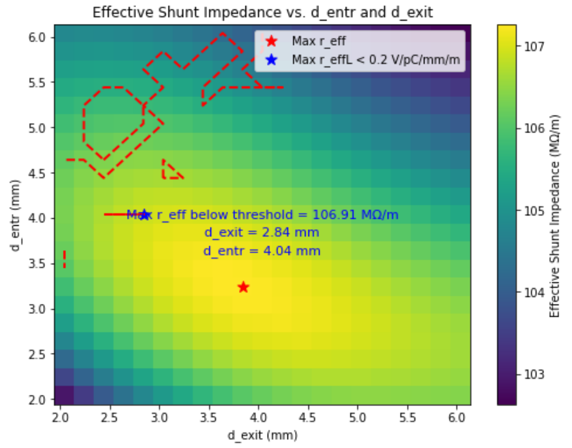
delta= -1.8mm

a_entr = 11.0483, a_ext= 14.6483



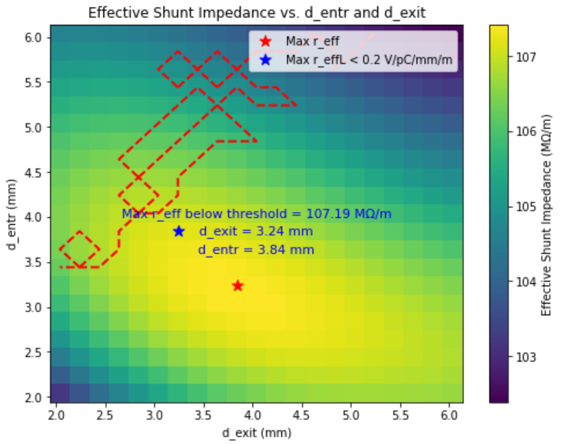
delta= -2mm

a_entr = 10.8483, a_ext= 14.8483



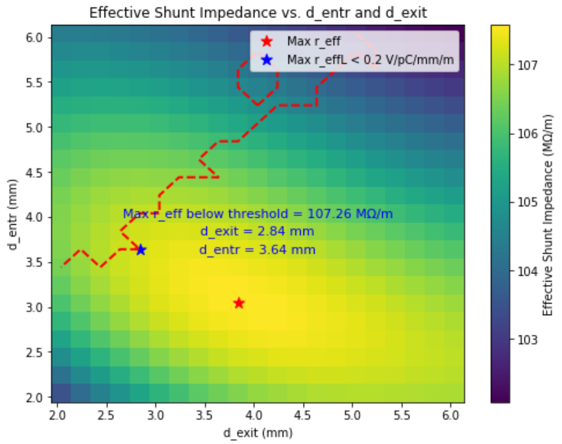
delta= -2.2 mm

a_entr = 10.6483, a_ext= 15.0483



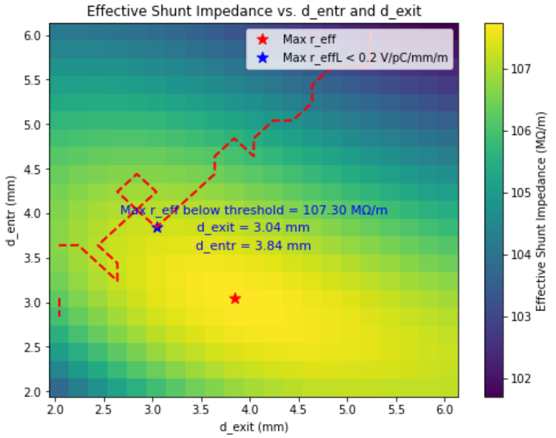
delta= -2.4 mm

a_entr = 10.4483, a_ext= 15.2483



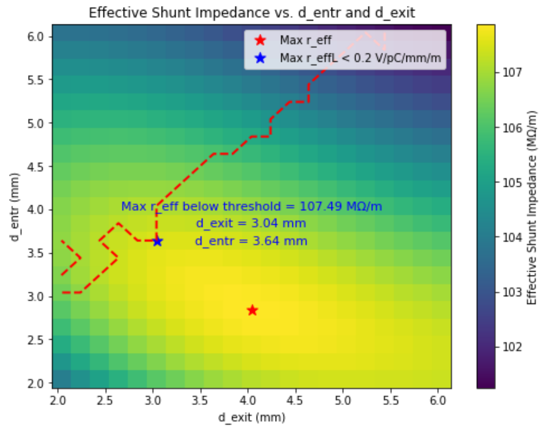
delta= -2.6 mm

a_entr = 10.2483, a_ext= 15.4483



delta= -2.8 mm

a_entr = 10.0483, a_ext= 15.6483

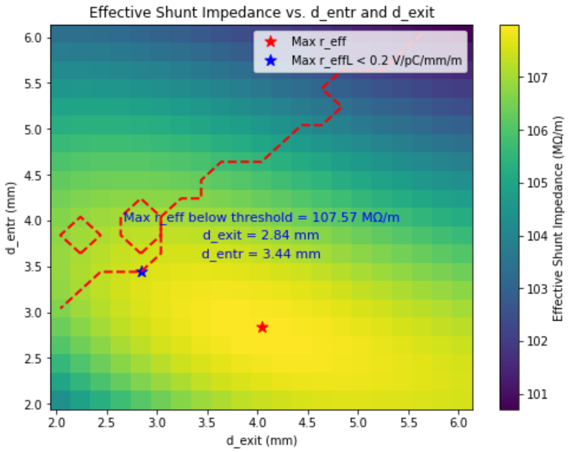


UP TAPERING

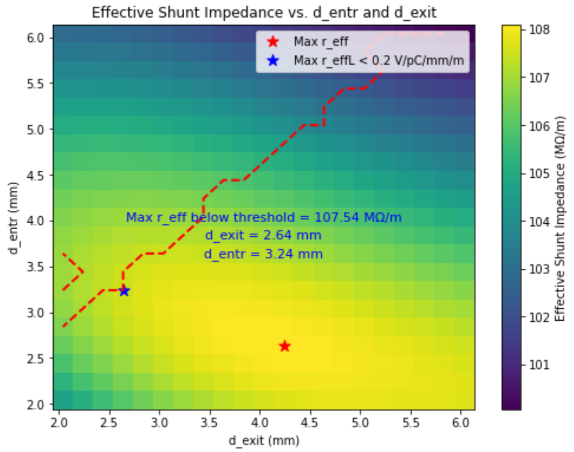
@2.8 GHz, 0.12λ = 12.8483 mm

a_entr = 12.8483 + delta, a_exit = 12.8483 – delta, where delta = -4 to 4 mm by step of 0.2mm

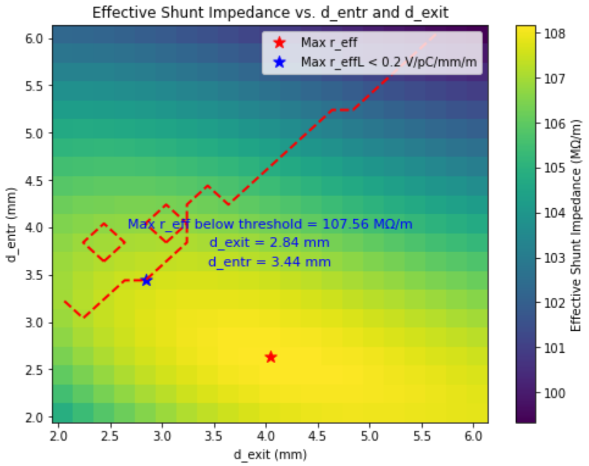
delta= -3 mm
a_entr = 9.8483, a_ext= 15.8483



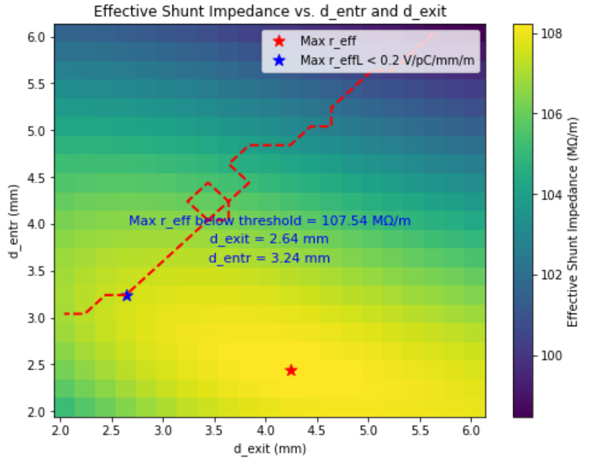
delta= -3.2 mm
a_entr = 9.6483, a_ext= 16.0483



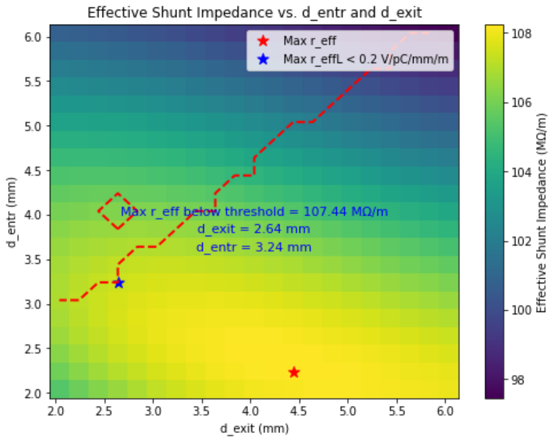
delta= -3.4 mm
a_entr = 9.4483, a_ext= 16.2483



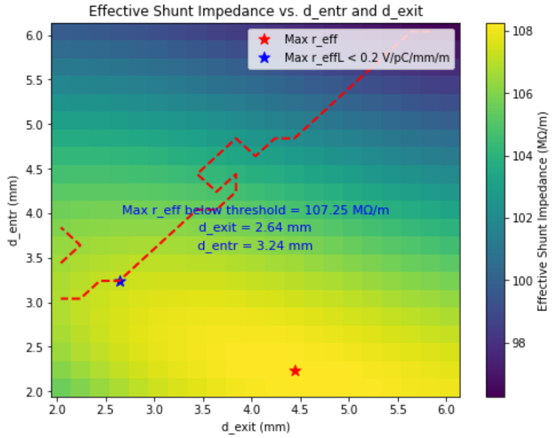
delta= -3.6 mm
a_entr = 9.2483, a_ext= 16.4483



delta= -3.8 mm
a_entr = 9.0483, a_ext= 16.6483



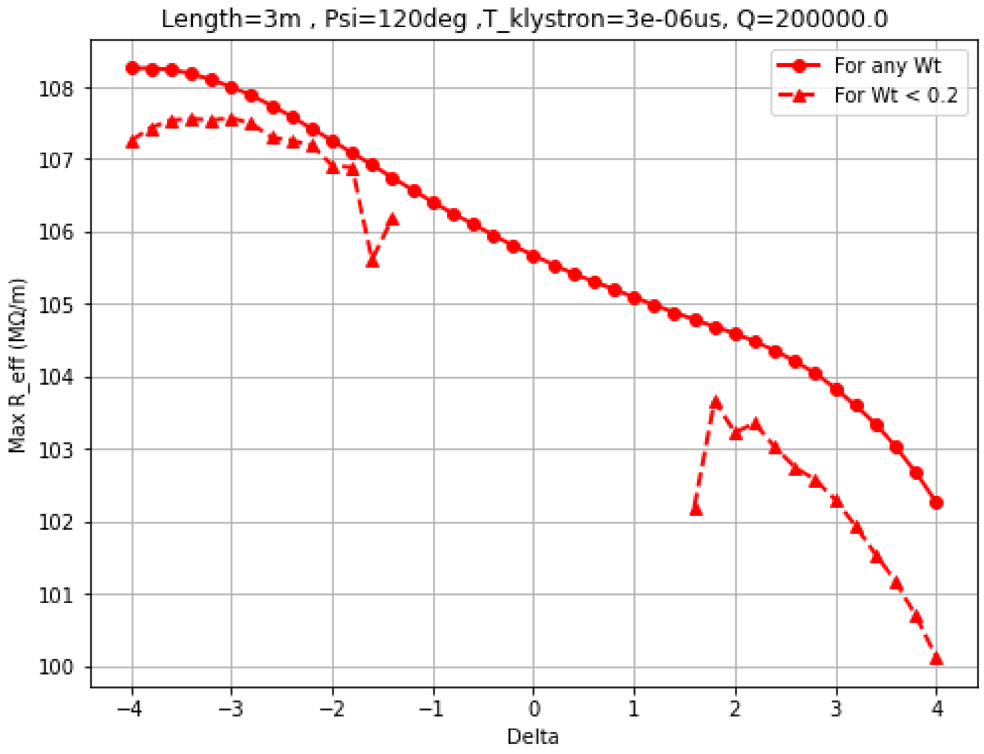
delta= -4 mm
a_entr = 8.8483, a_ext= 16.8483

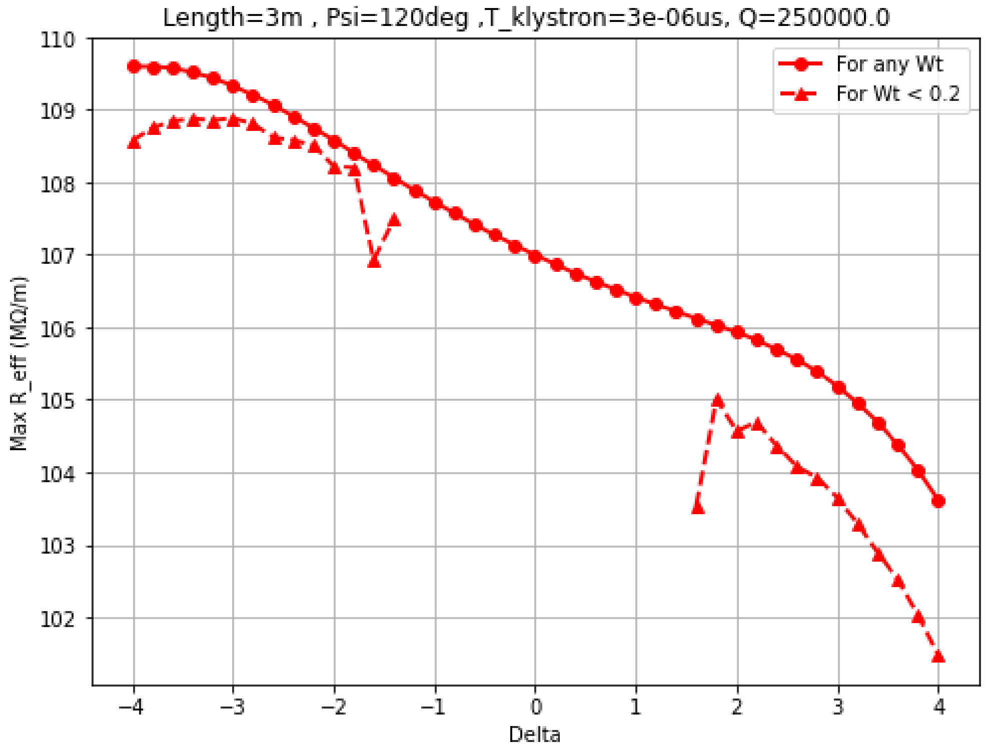


Other parameter scans

- Different $Q_{0,SLED}$, $T_{klystron}$, Length of the structure, Phase advance scanned .

$Q_{0,SLED}$ from 2e5 to 2.5e5.



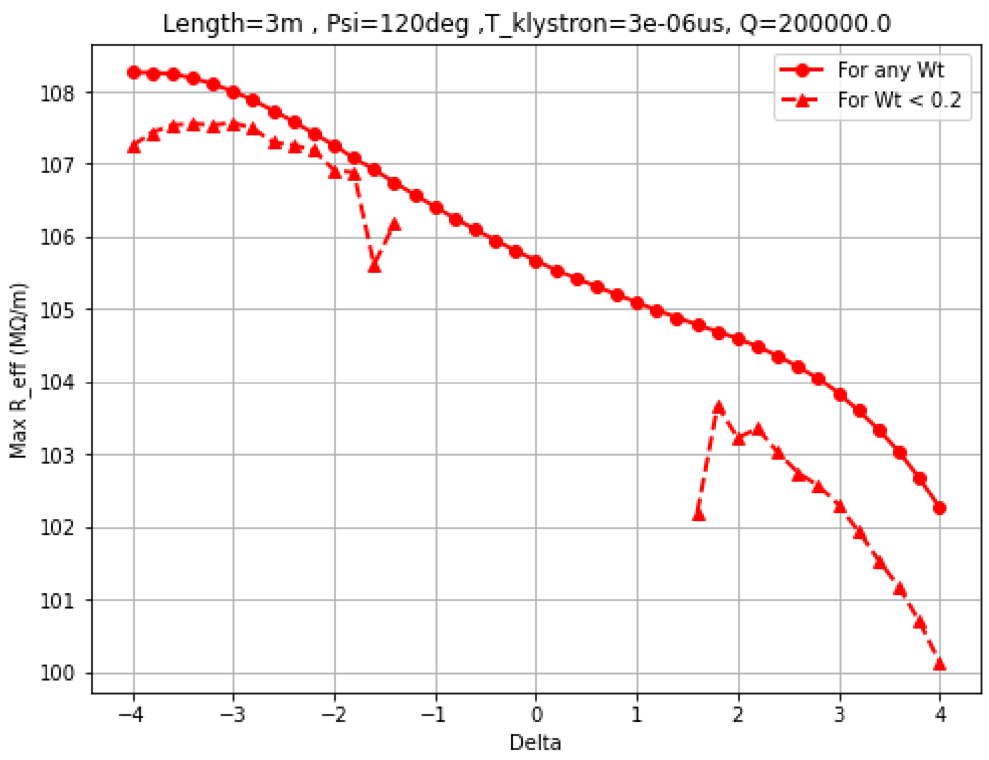


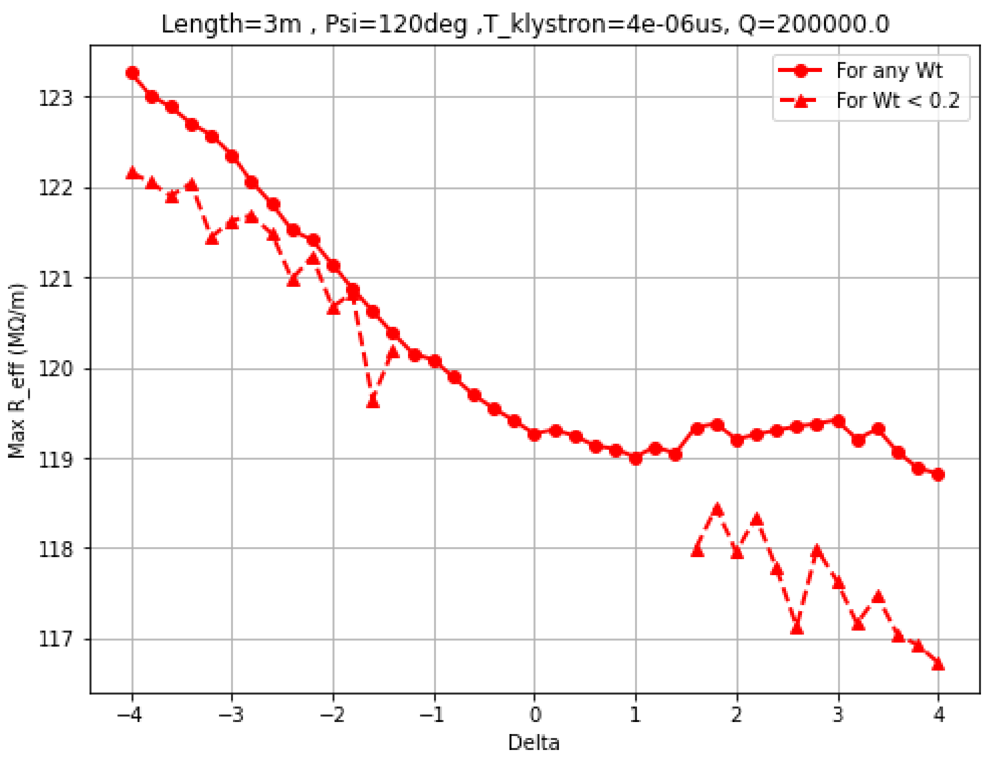
≈ 1% of increase

Other parameter scans

- Different $Q_{0,SLED}$, $T_{klystron}$, Length of the structure, Phase advance scanned .

$T_{klystron}$ from 3 us to 4 us.



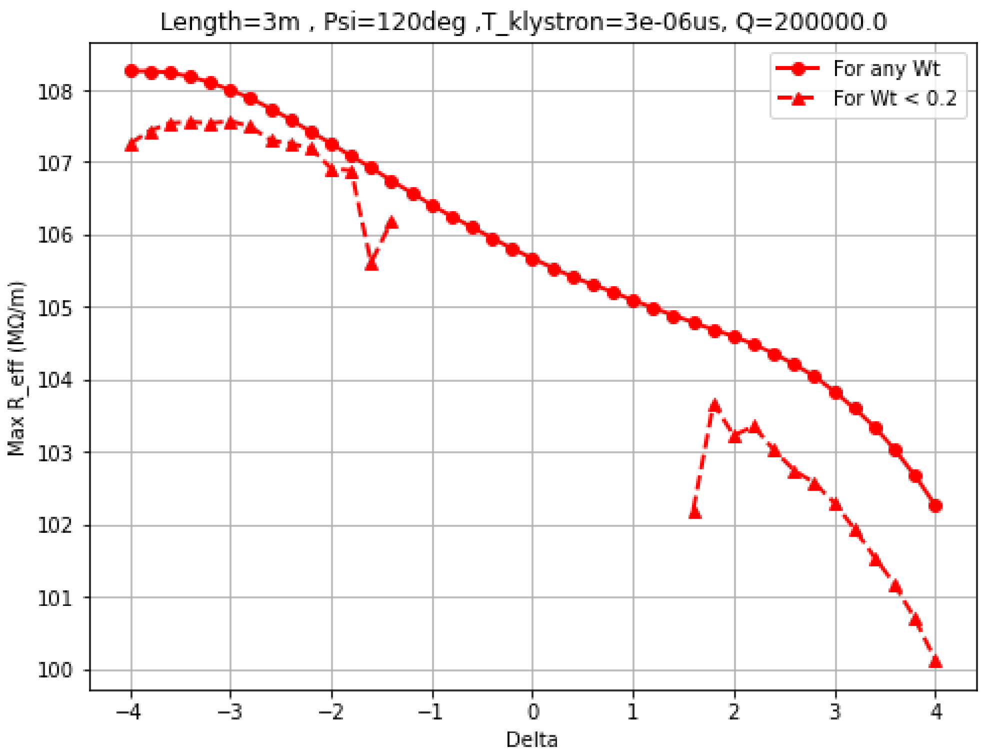


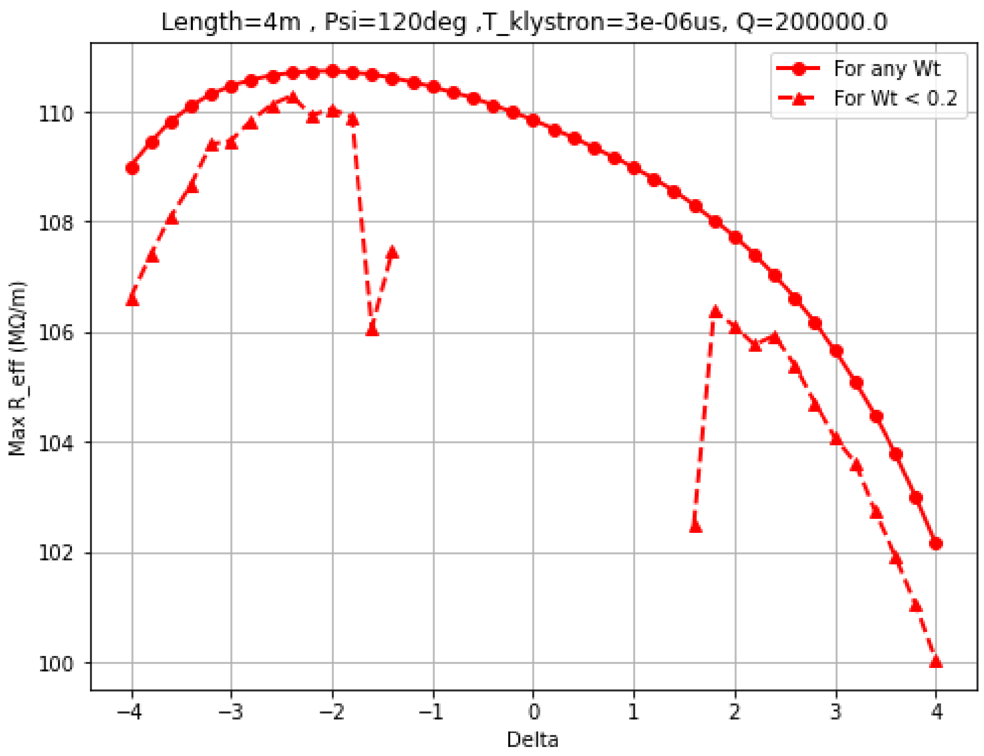
≈ 14% of increase

Other parameter scans

- Different $Q_{0,SLED}$, $T_{klystron}$, Length of the structure, Phase advance scanned .

Length of the structure from 3 m to 4 m.

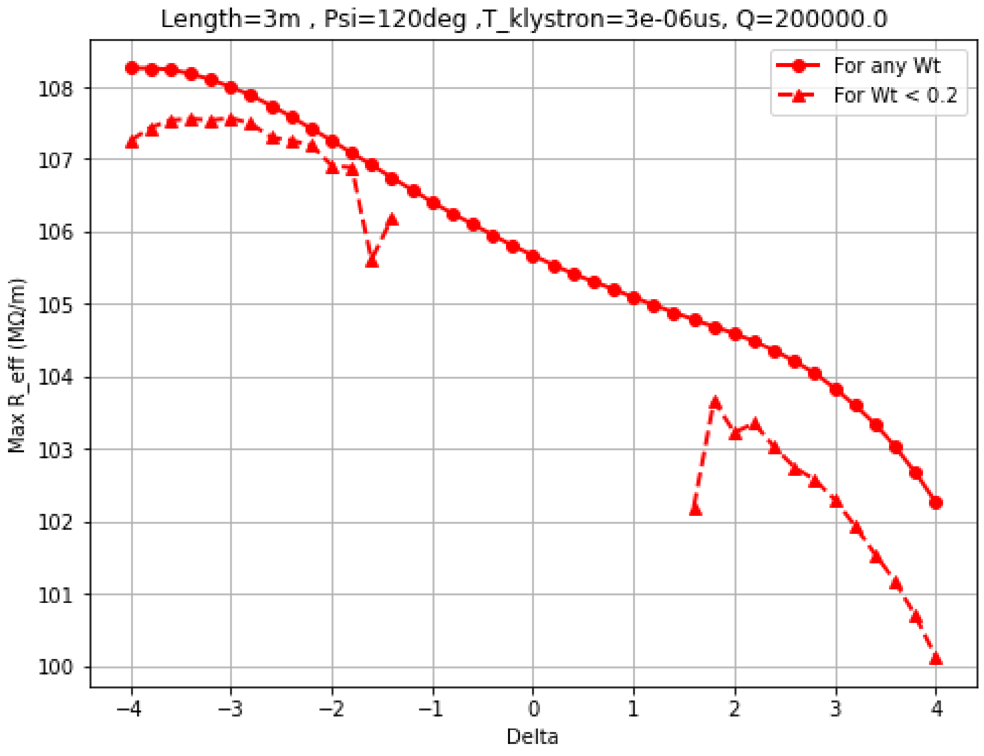


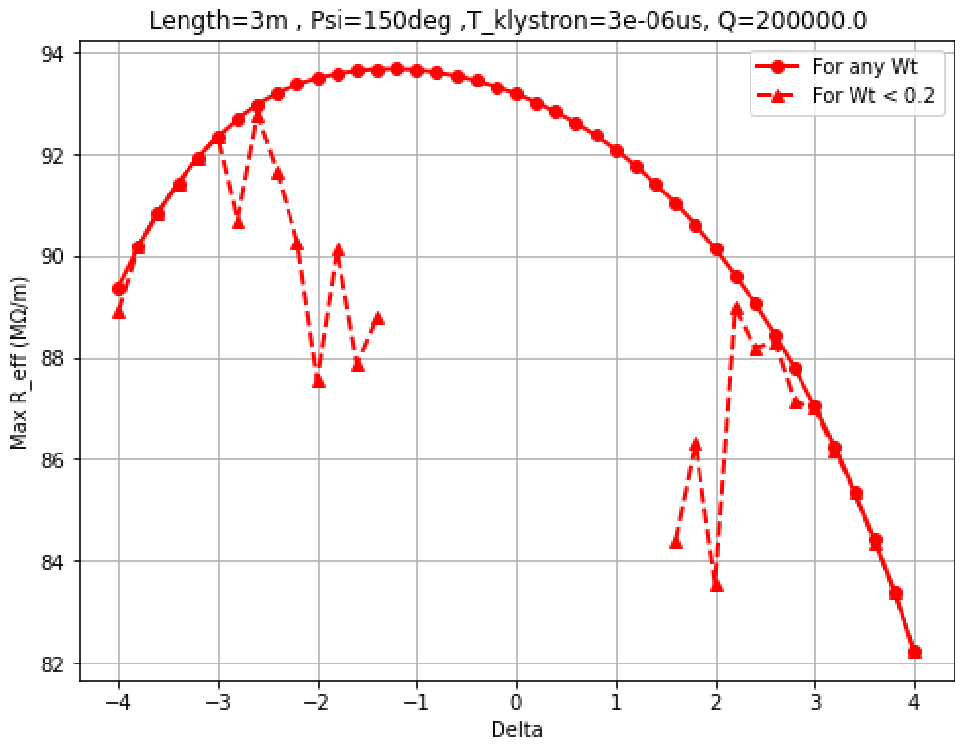


Other parameter scans

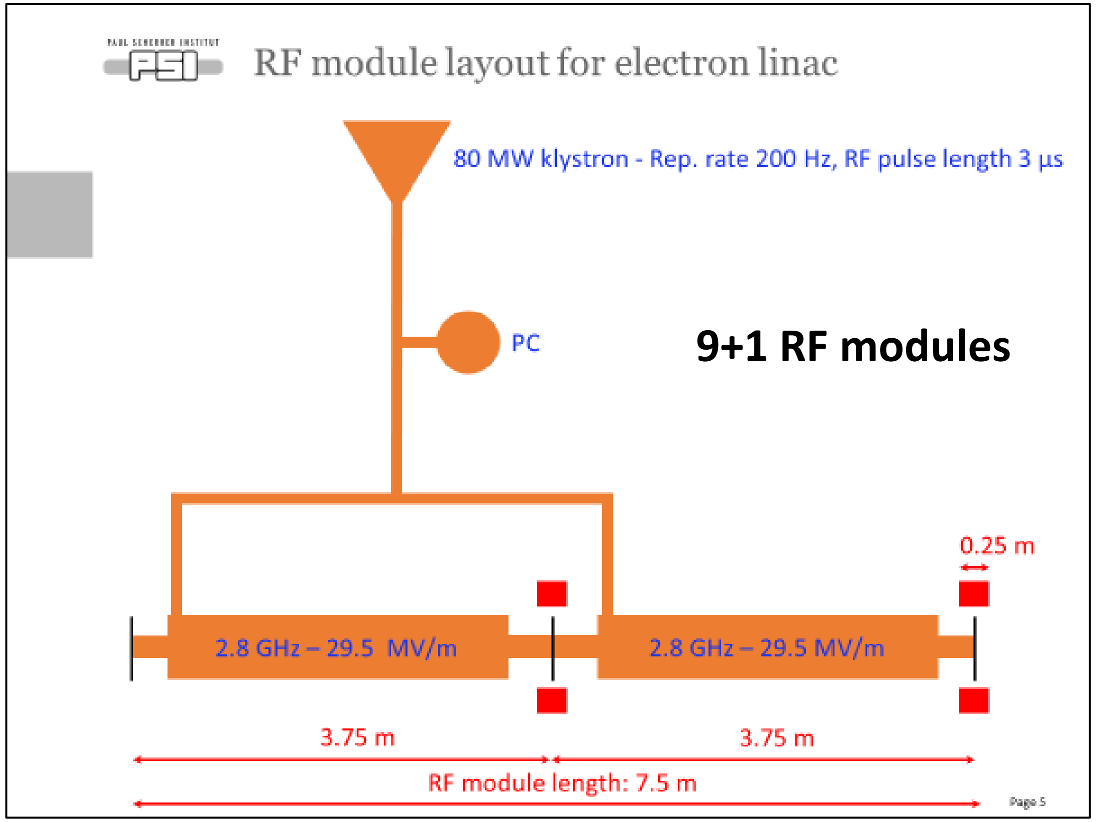
- Different $Q_{0,SLED}$, $T_{klystron}$, Length of the structure, Phase advance scanned .

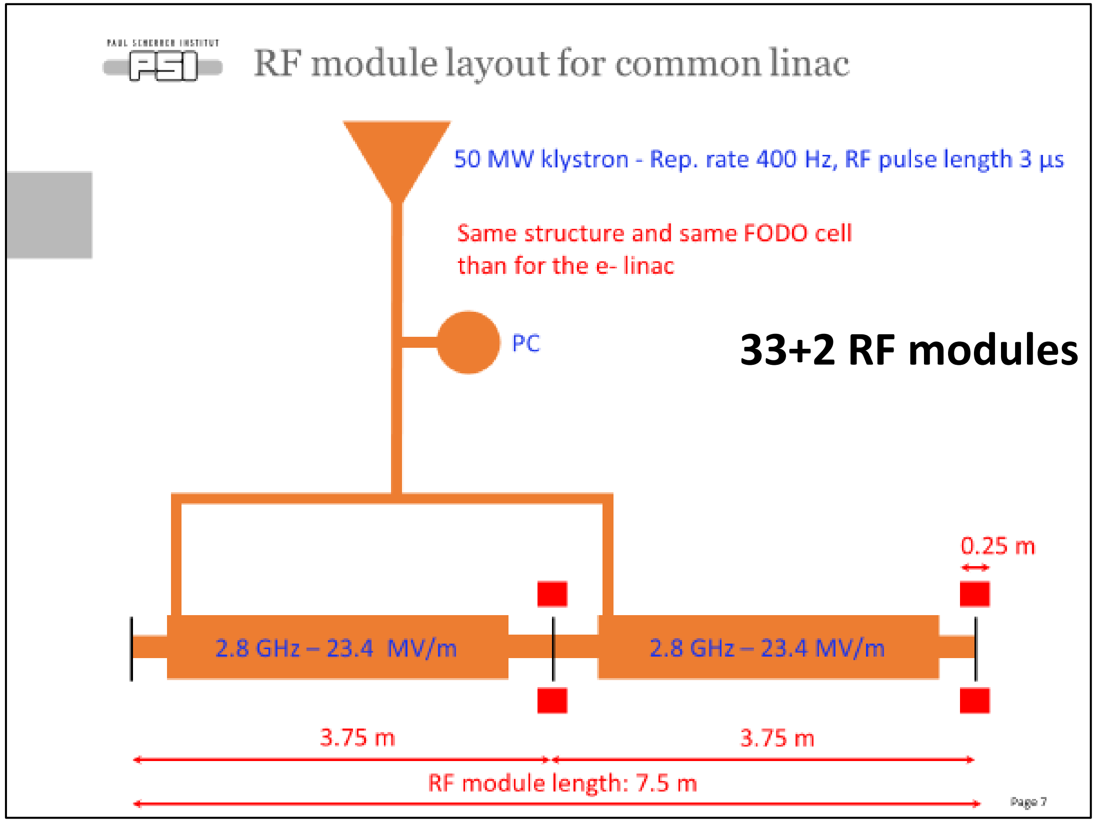
Phase advance from 2π/3 to 5π/6.

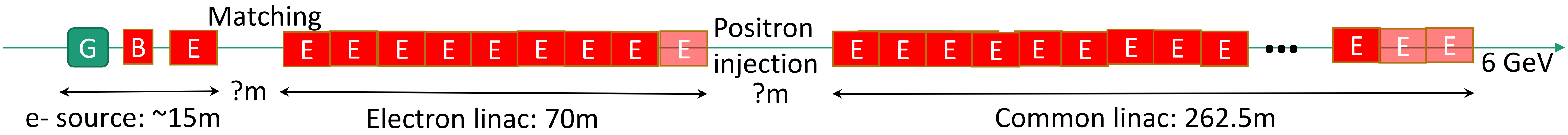




Layout of electron and common linacs







RF module summary table for all linacs

	p-linac	e-linac	c-linac	HE-linac (S)	HE-linac (C)	
Frequency [GHz]	2	2.8	2.8	2.8	5.6	
Accelerating structure	F3	a/λ=0.15	a/λ=0.15	a/λ=0.15	a/λ=0.19	
Repetition rate [Hz]	200	200	400	200	200	
Aperture radius [mm]	30	16.1	16.1	16.1	10.2	
Length [m]	3	3	3	3	3	
Filling time [ns]	447	486	486	486	334	
SLED coupling	17	15	15	15	10	
Klystron RF pulse length [µs]	5	3	3	3	3	
Average gradient [MV/m]	**20**	**29.5**	**23.4**	**29.5**	**28.8**	
Energy gain per structure [MeV]	60	88.5	70.2	88.5	86.4	
Klystron power per structure [MW]	31	30	18.9	30	18.2	
Klystron output power specification [MW]	80	80	50	80	50	Inc. WG loss and 90% margin
Number of structures per klystron	2	2	2	2	2	
Number of structures total	1 + 30	1+20	70	164	172	Same for quads, corrs. and BPMs
Number of modules total	1 + 15	1+10	35	82	86	
Total length of all modules [m]	140	90	262.5	615	645	