Thermionic & RF Gun Simulations for the CLIC DB Injector

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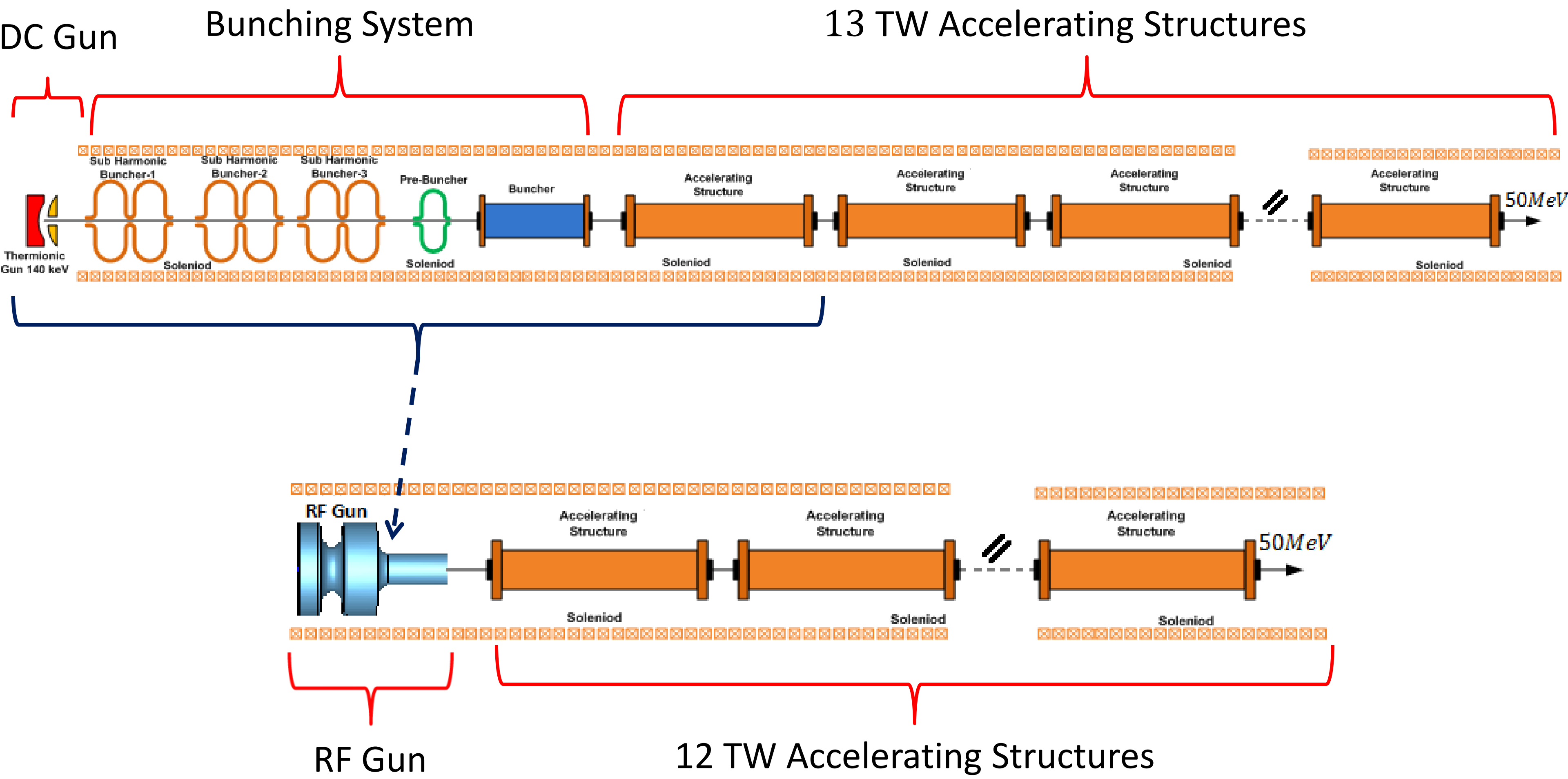
Contents

1.1. CLIC DB Injector Layout (2 Options)



1.2. Beam Dynamics Studies (Emittance Growth)

Wangler's formula: $$\frac{d\epsilon_n{}^2}{dz} = -\frac{ecR^2}{2Imc^2\sqrt{\gamma^2-1}}\frac{d}{dz}\Delta U$$

RMS beam radius

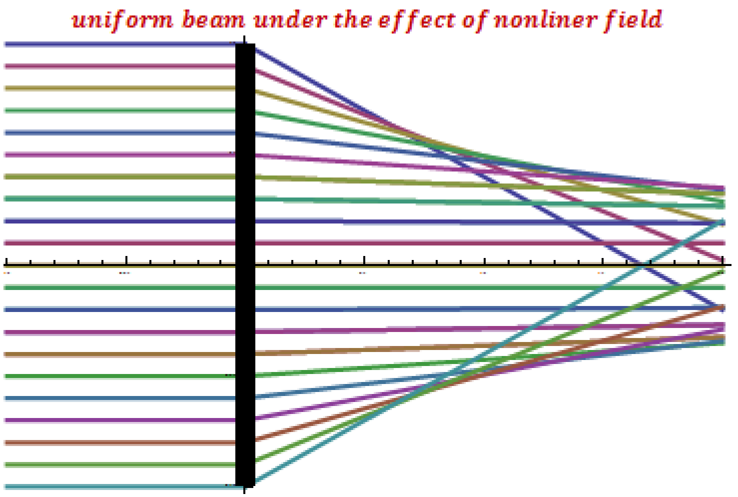
Gamma Energy

Potential Energy difference

Between the beam and its equivalent uniform beam

Any non-uniformity in the beam distribution will result in the emittance growth *specially in nonrelativistic beams and beams with bigger RMS radiuses*

$$\varepsilon_n = \sqrt{\langle x^2\rangle\langle\gamma\beta x'^2\rangle - \langle x\gamma\beta x'\rangle^2}$$



Nonlinear fields *change the beam uniformity and cause to emittance growth*

1.2. Beam Dynamics Studies (Designing Strategies)

Wangler's formula: $\frac{d{\epsilon_n}^2}{dz} = -\frac{\pi\varepsilon_0 e c R^2}{2Imc^2\sqrt{\gamma^2-1}}\frac{d}{dz}\Delta U$

Strategies for designing a low emittance electron gun

1) *Design the gun with as much as possible linear electromagnetic fields*

2) *Minimize the action of remaining nonlinearities with faster acceleration and smaller beam size*

2.1. Thermionic Gun Design (Potential Expansion)

According to the Maxwell equations for axisymmetric electrostatic fields we can write:

$$V(r,z) = \left(1 + \sum_{n=1}^{\infty} \frac{(-1)^n \left(\frac{r}{2}\right)^{2n}}{(n!)^2} \frac{d^{2n}}{dz^{2n}}\right) V(z)$$

$$E_z(r,z) = -\left(1 + \sum_{n=0}^{\infty} \frac{(-1)^n \left(\frac{r}{2}\right)^{2n}}{(n!)^2} \frac{d^{2n}}{dz^{2n}}\right) V'(z)$$

$$E_r(r,z) = \frac{r}{2} \times \left(1 + \sum_{n=1}^{\infty} \frac{(-1)^n \left(\frac{r}{2}\right)^{2n}}{n!\,(n+1)!} \frac{d^{2n}}{dz^{2n}}\right) V''(z)$$

If we can somehow find the potential function on symmetric axis z then we can easily find the electrostatic potential every where and so the electrode shapes

If we want to have a linear electrostatic field we should have a parabola shape for potential function on symmetric axis

2.1. Thermionic Gun Design (Envelope Equation)

Envelope equation:

$$R'' + \left(\frac{\gamma \times \gamma'}{\gamma^2 - 1}\right) \times R' + \left(\frac{\gamma \times \gamma''}{2(\gamma^2 - 1)}\right) \times R = \frac{qI}{4\pi\epsilon_0 cmc^2(\gamma^2 - 1)^{3/2} R} + \frac{4{\varepsilon_n}^2}{R^3(\gamma^2 - 1)}$$

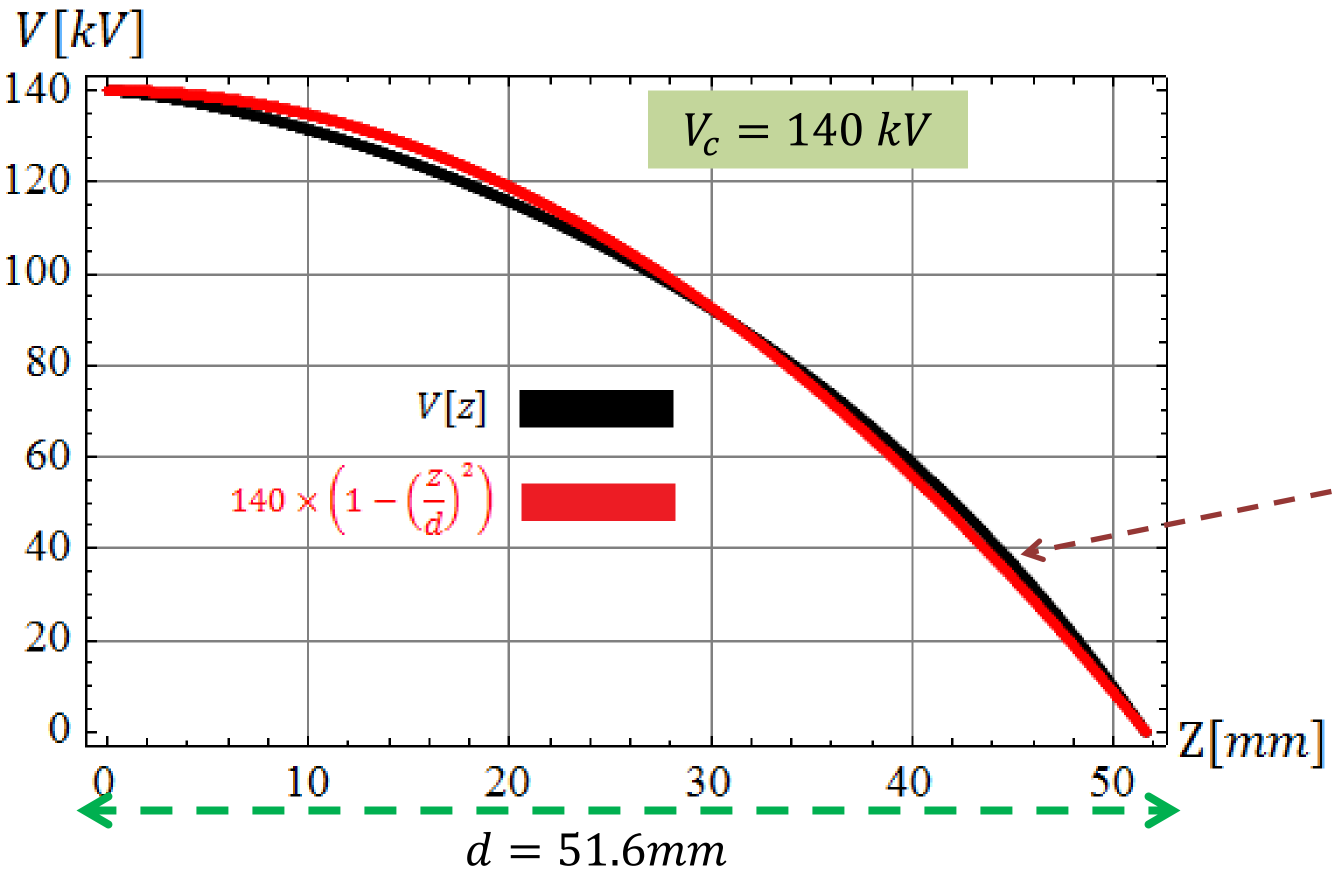
+

$$\gamma(z) = 1 + \frac{q}{mc^2}[V_{cathode} - V(z)]$$

$$V'' + \frac{2R'}{R}V' = -\frac{2mc^2}{q\gamma}\left\{\frac{4\sqrt{\gamma^2 - 1}{\varepsilon_n}^2}{R^4} + \frac{qI}{4\pi\epsilon_0 cmc^2 R^2\sqrt{\gamma^2 - 1}} - \frac{R''}{R}(\gamma^2 - 1)\right\}$$

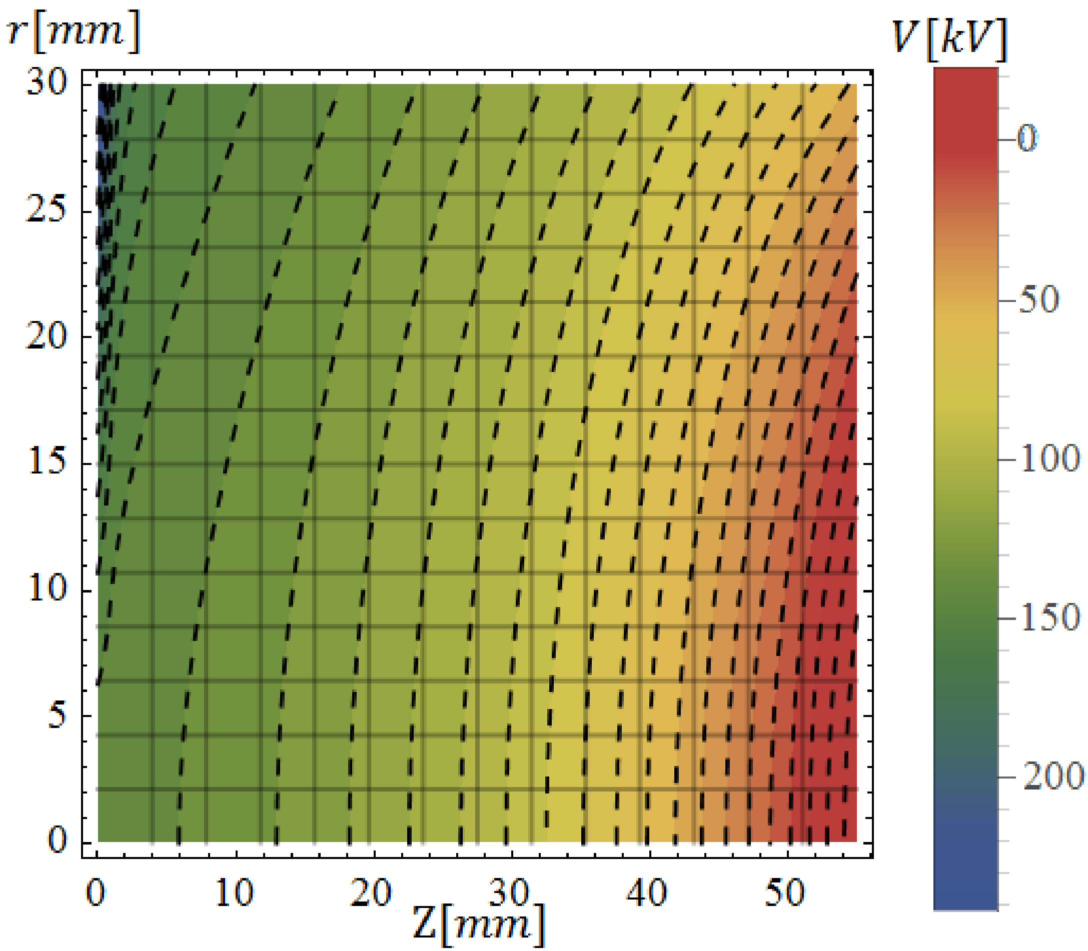
2.1. Thermionic Gun Design (Potential Equation)

$$V'' + \frac{2R'}{R}V' = -\frac{2mc^2}{q\gamma}\left\{\frac{4\sqrt{\gamma^2-1}\,\varepsilon_n{}^2}{R^4} + \frac{qI}{4\pi\epsilon_0 cmc^2R^2\sqrt{\gamma^2-1}} - \frac{R''}{R}(\gamma^2-1)\right\}$$



Very close to a parabola and so linear fields

2.1. Thermionic Gun Design (Equipotential Surfaces)

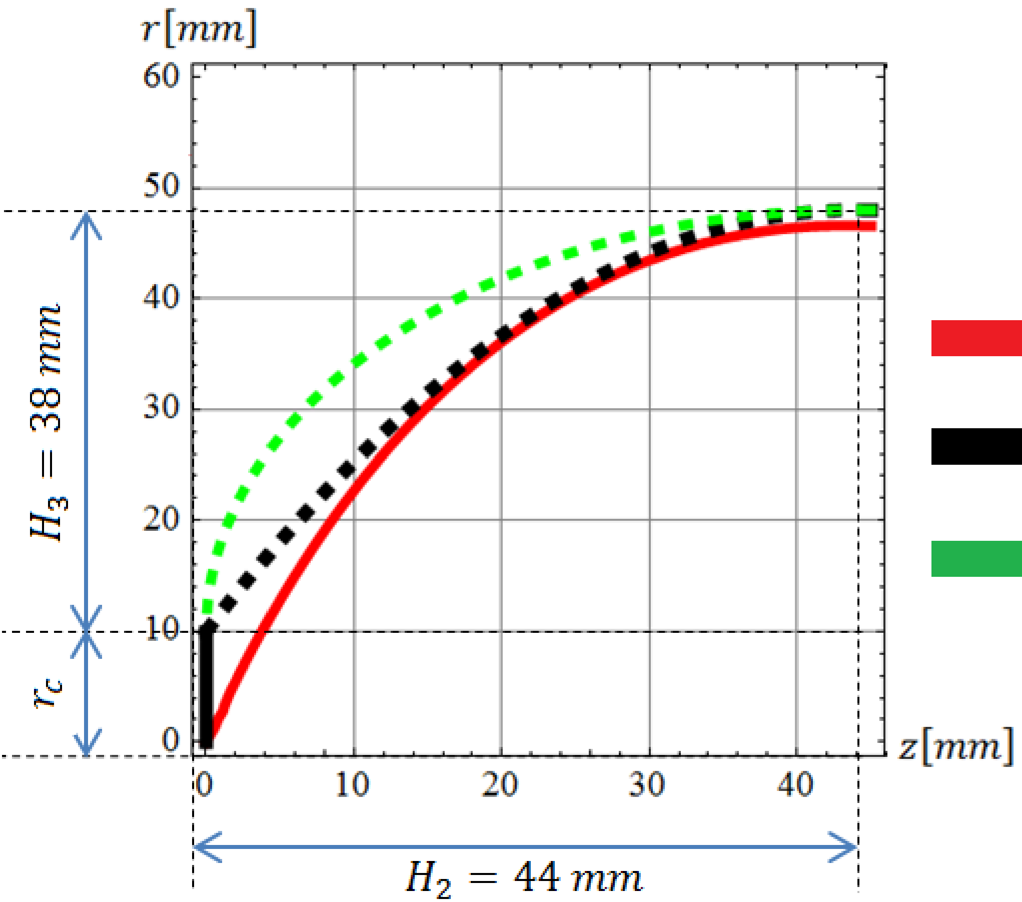


$$V(r,z) = \left(1 + \sum_{n=1}^{\infty} \frac{(-1)^n \left(\frac{r}{2}\right)^{2n}}{(n!)^2} \frac{d^{2n}}{dz^{2n}}\right) V(z)$$

$V(r,z) = 0\,kV$ ⟶ *Anode*

$V(r,z) = 140kV$ ⟶ *Cathode*

2.1. Thermionic Gun Design (Cathode Shape)



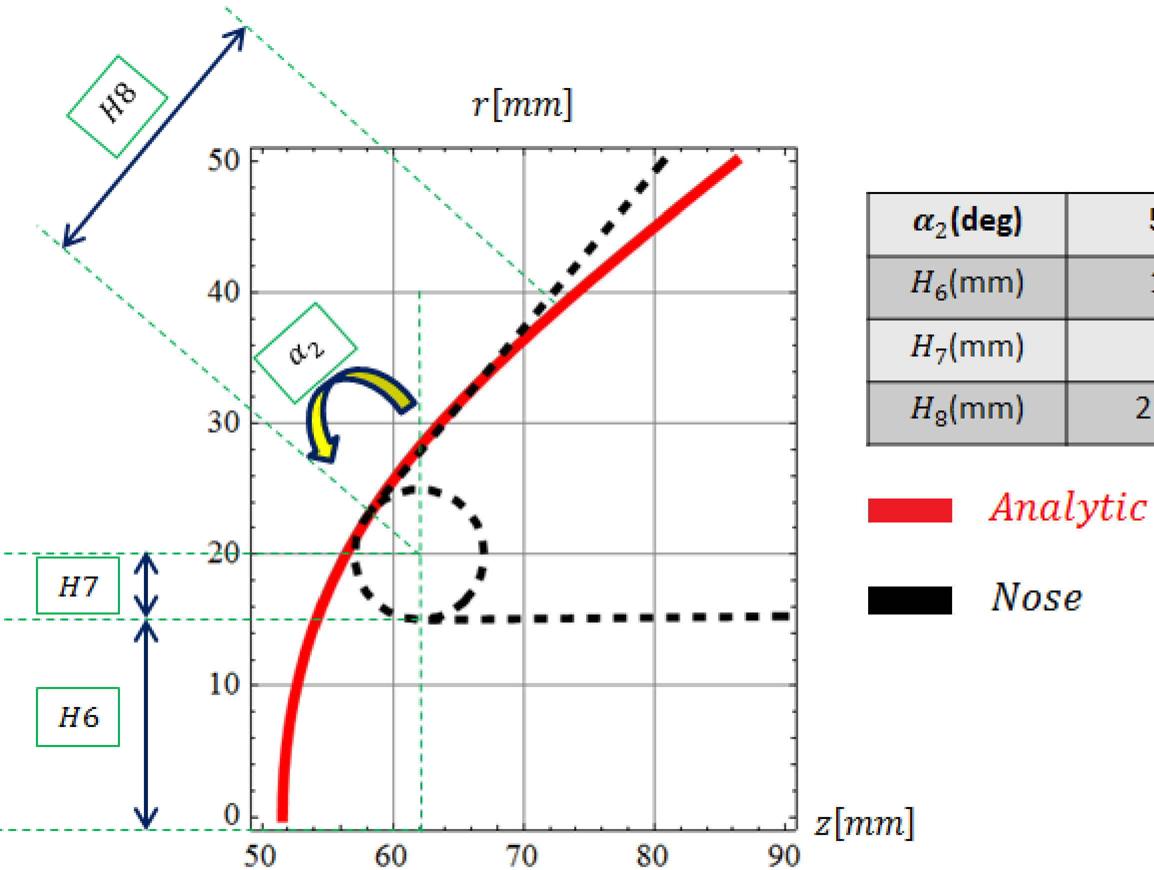
Analytic

$r - r_c = H_3 \times \left[1 - \left(1 - \left(\frac{z}{H_2}\right)^2\right)\right]$

$\left(\frac{r - r_c}{H_3}\right)^2 + \left(1 - \left(\frac{z}{H_2}\right)^2\right) = 1$

A parabola could be a good approximation for the cathode shape

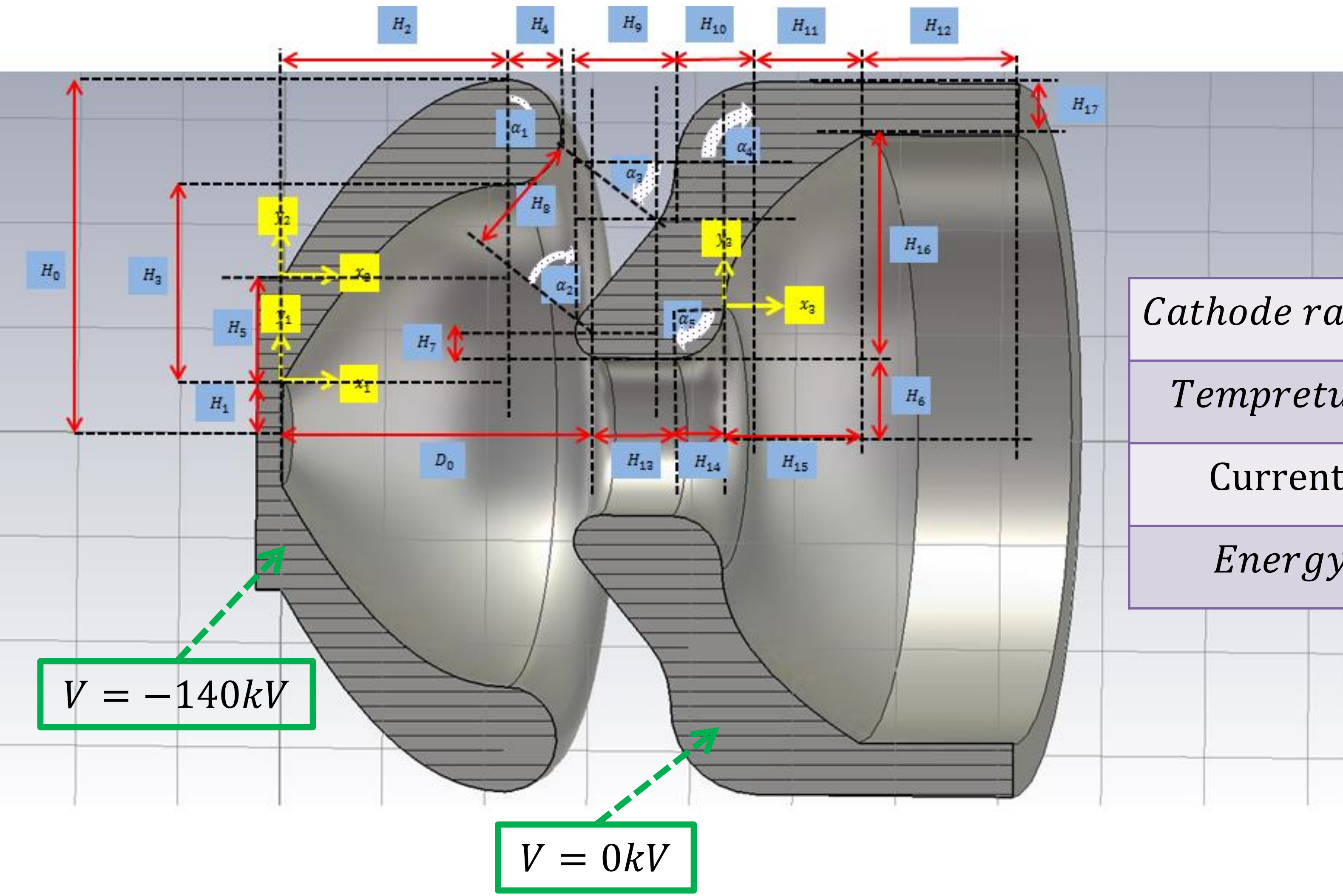
2.1. Thermionic Gun Design (Anode Shape)



α_2(deg)	50
H_6(mm)	15
H_7(mm)	5
H_8(mm)	21.5

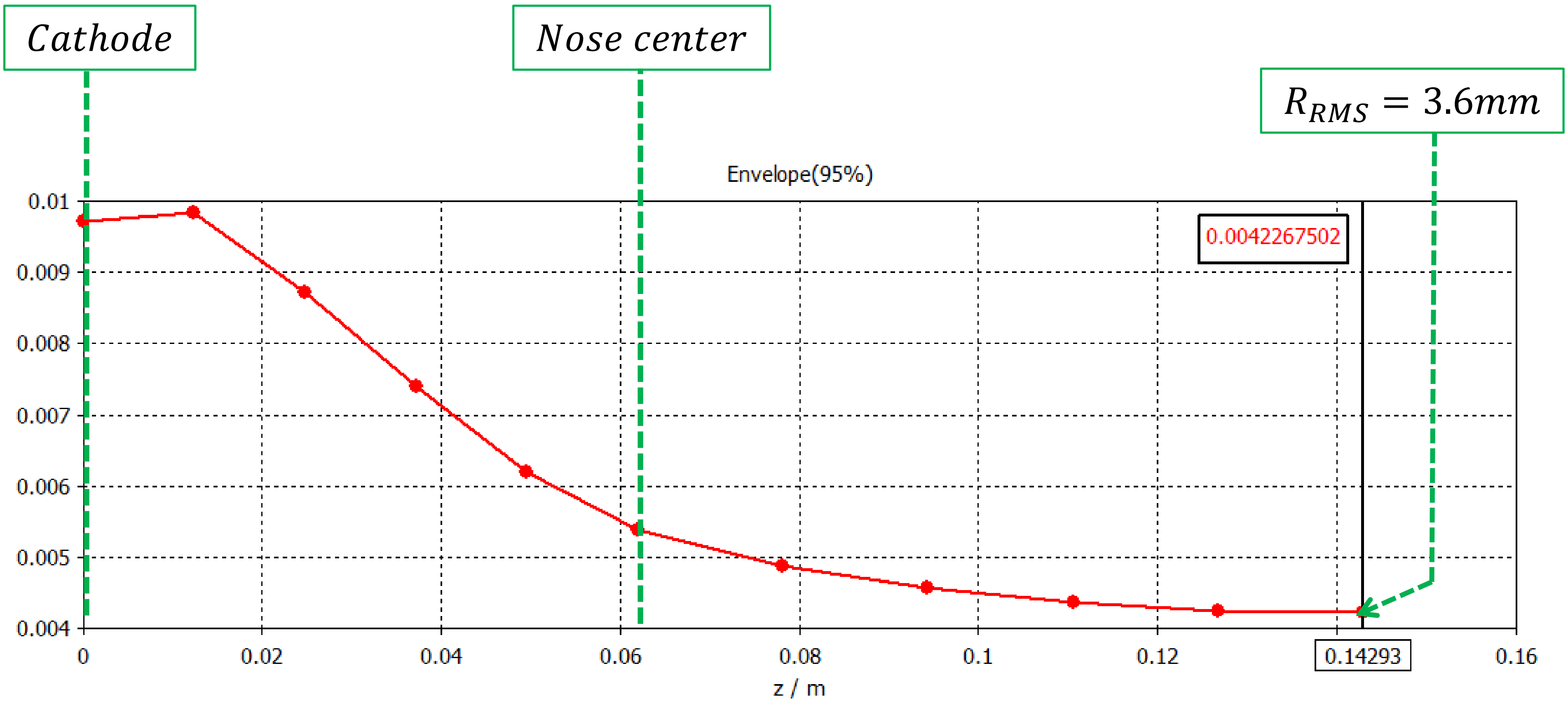
A nose could be a good approximation for the anode shape

2.1. Thermionic Gun Design (DC Gun Geometry)

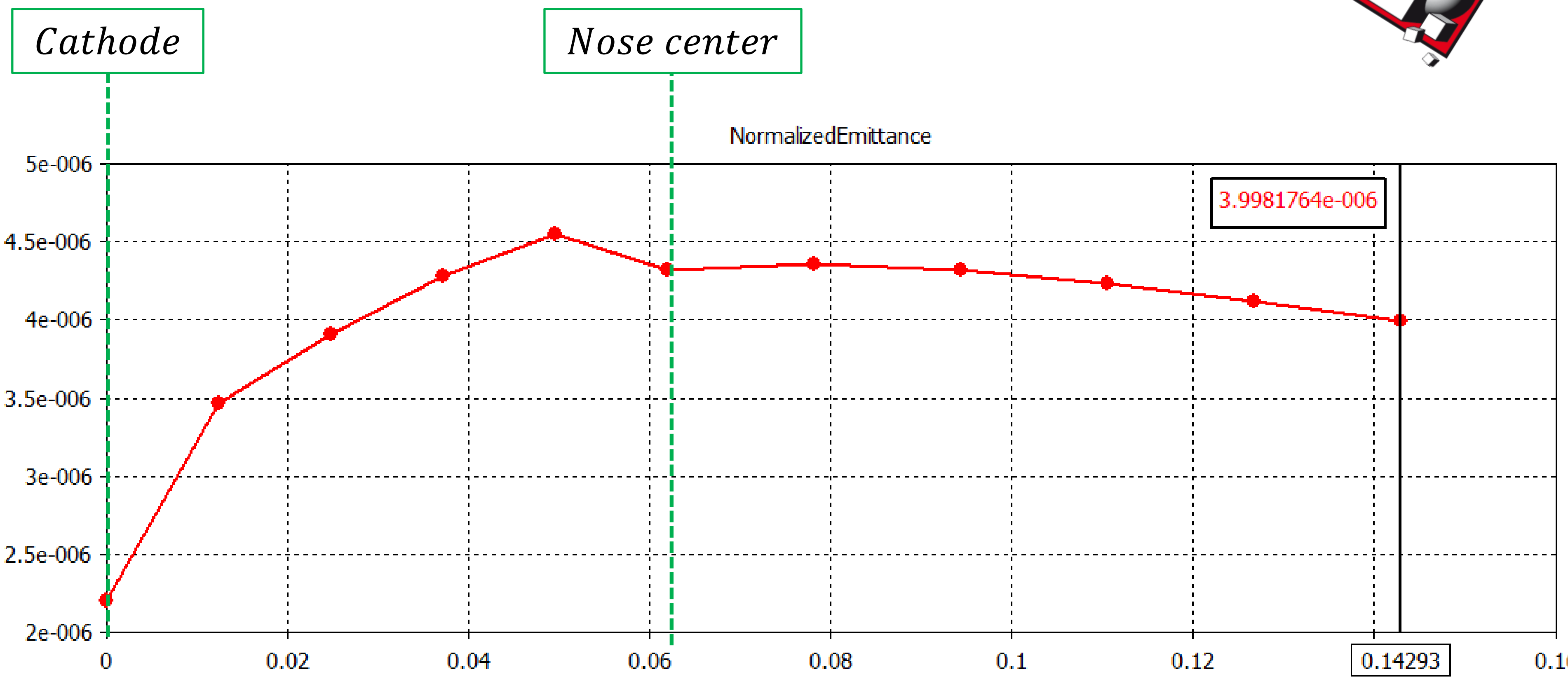


Cathode radus	10mm
Tempreture	≈ 1500k
Current	5A
Energy	140keV

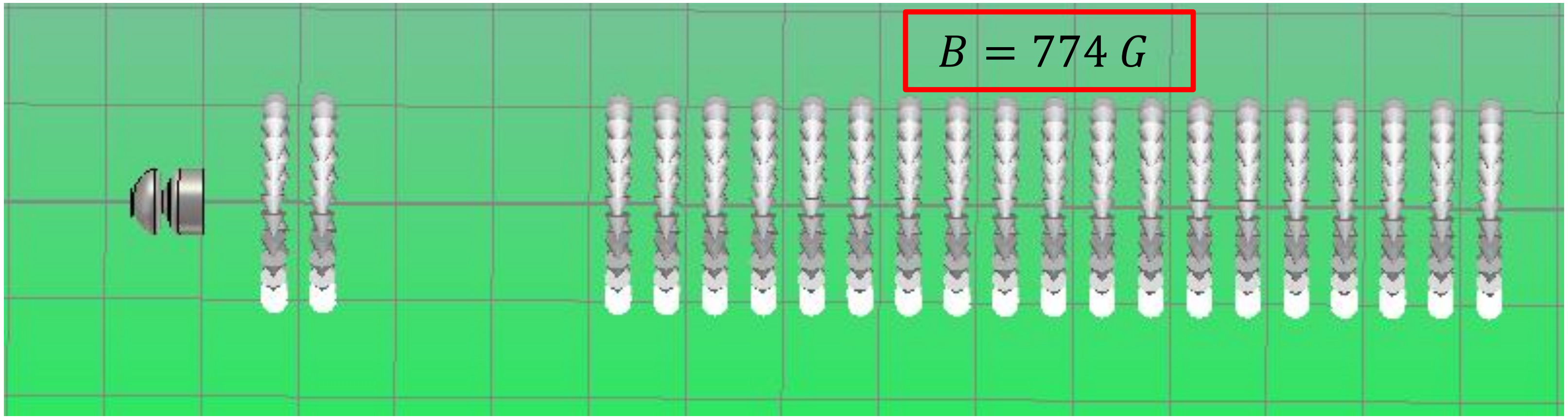
2.2. Thermionic Gun Simulations (Beam Envelope)

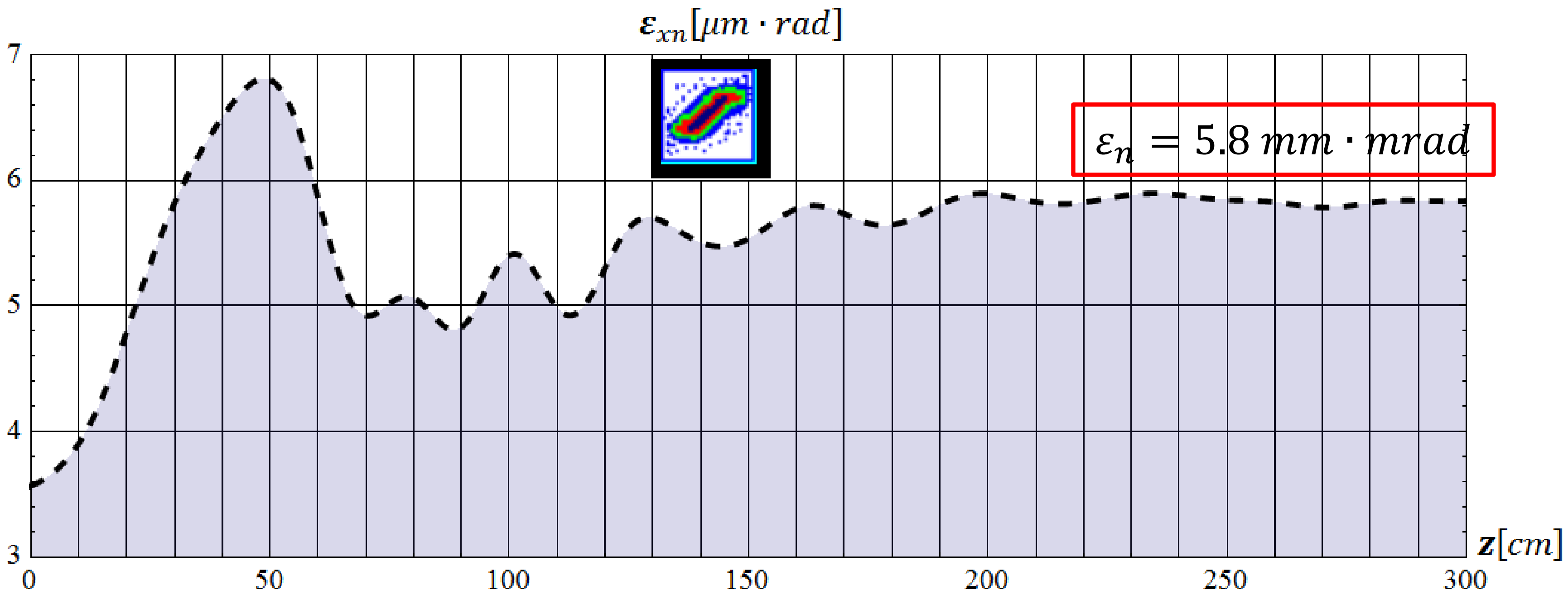


2.2. Thermionic Gun Simulations (Normalized Emittance)

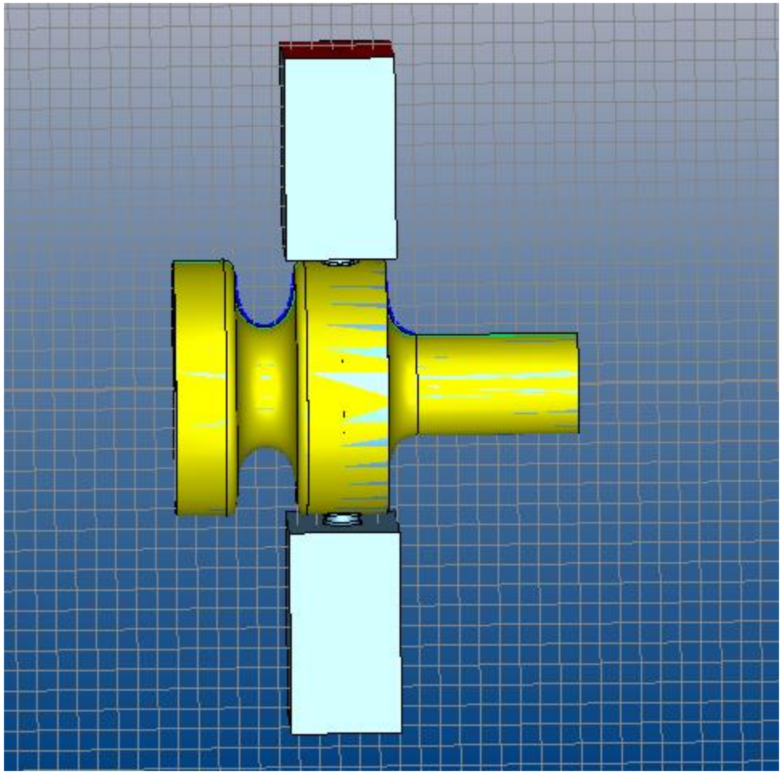


2.2. Thermionic Gun Simulations (Solenoid Channel)



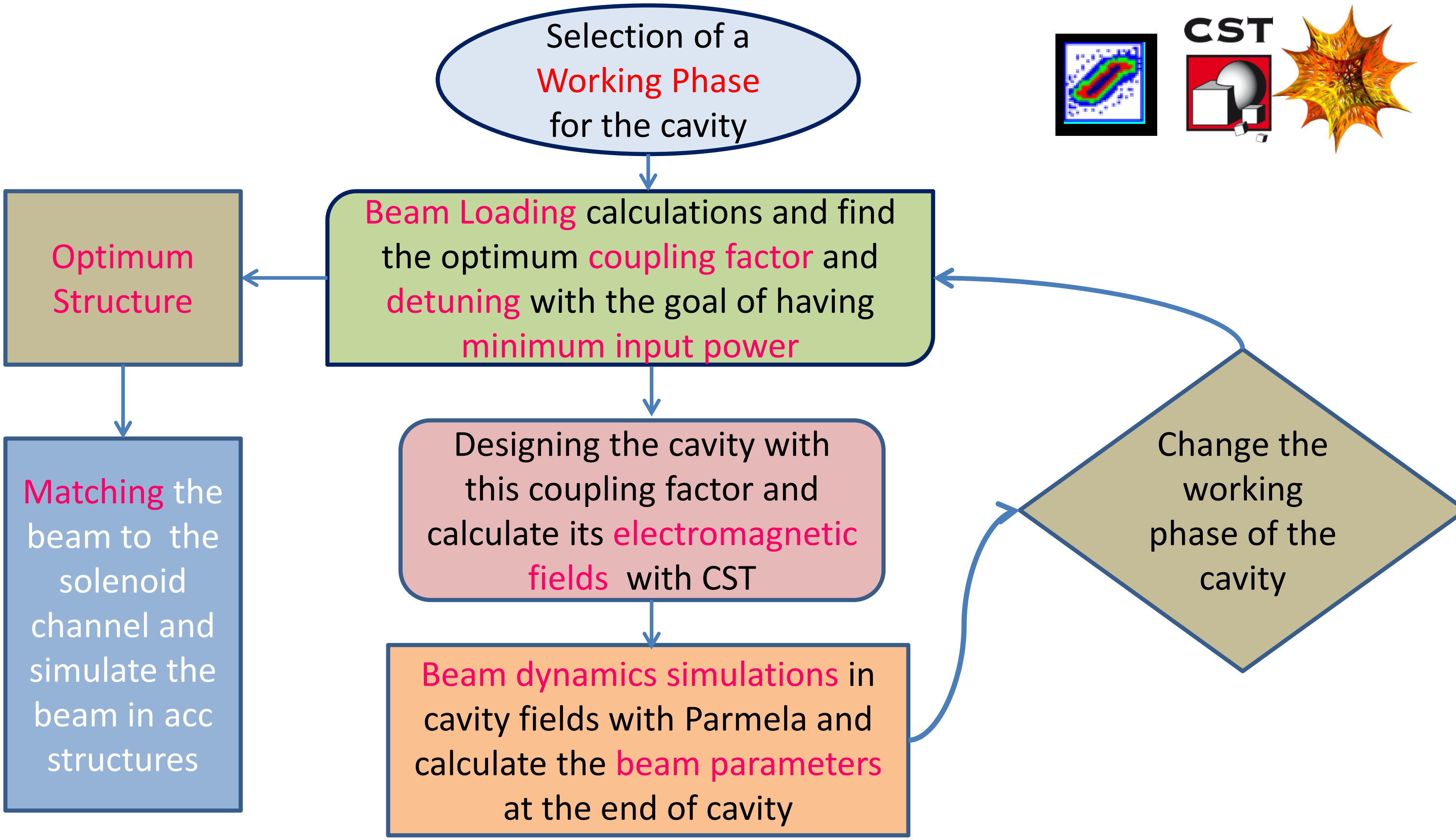


2.1. RF Gun Design (Specifications)

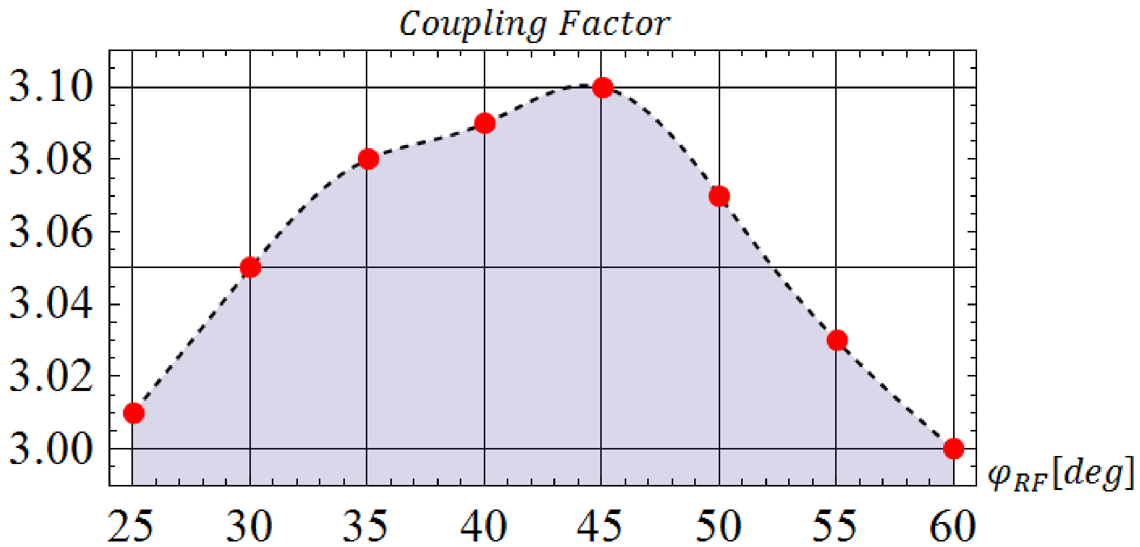


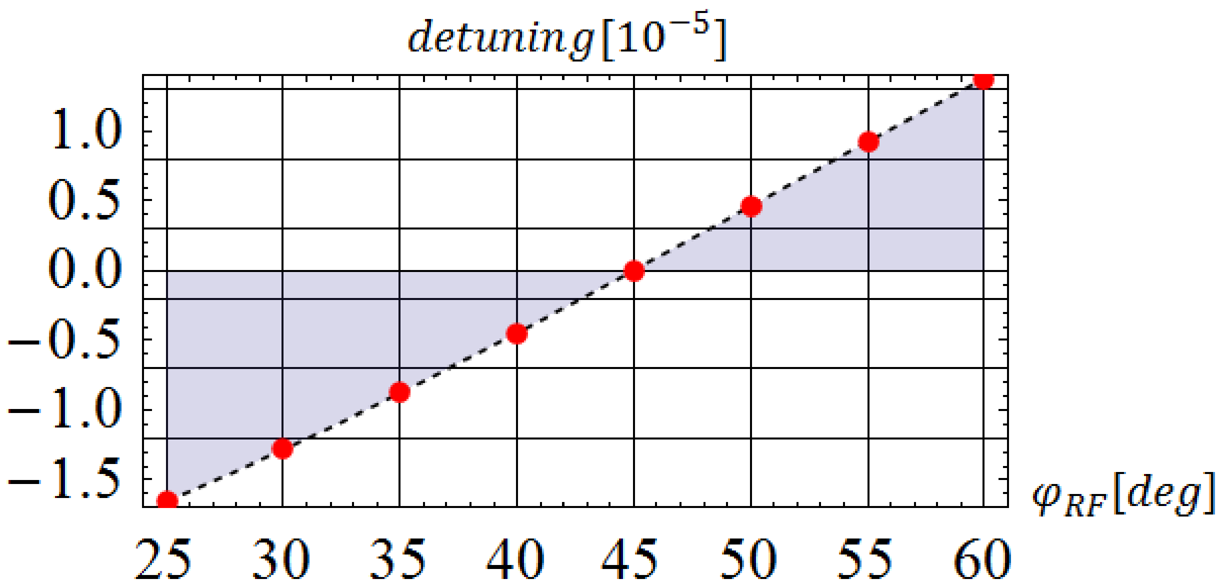
Parameter	*Value*
Number of Cell	1.6
Frequency [*GHz*]	1,2,3
RMS Bunch Length [*PS*]	10
Charge per Bunch [*nC*]	8.4
Bunch Frequency [*GHz*]	0.5
Current [*A*]	4.2
Palse Repetation Rate [*Hz*]	50
Input Power [*MW*]	*up to* 40
Palse Length [*μS*]	140

2.1. RF Gun Designing (Designing &Optimization Algorithm)

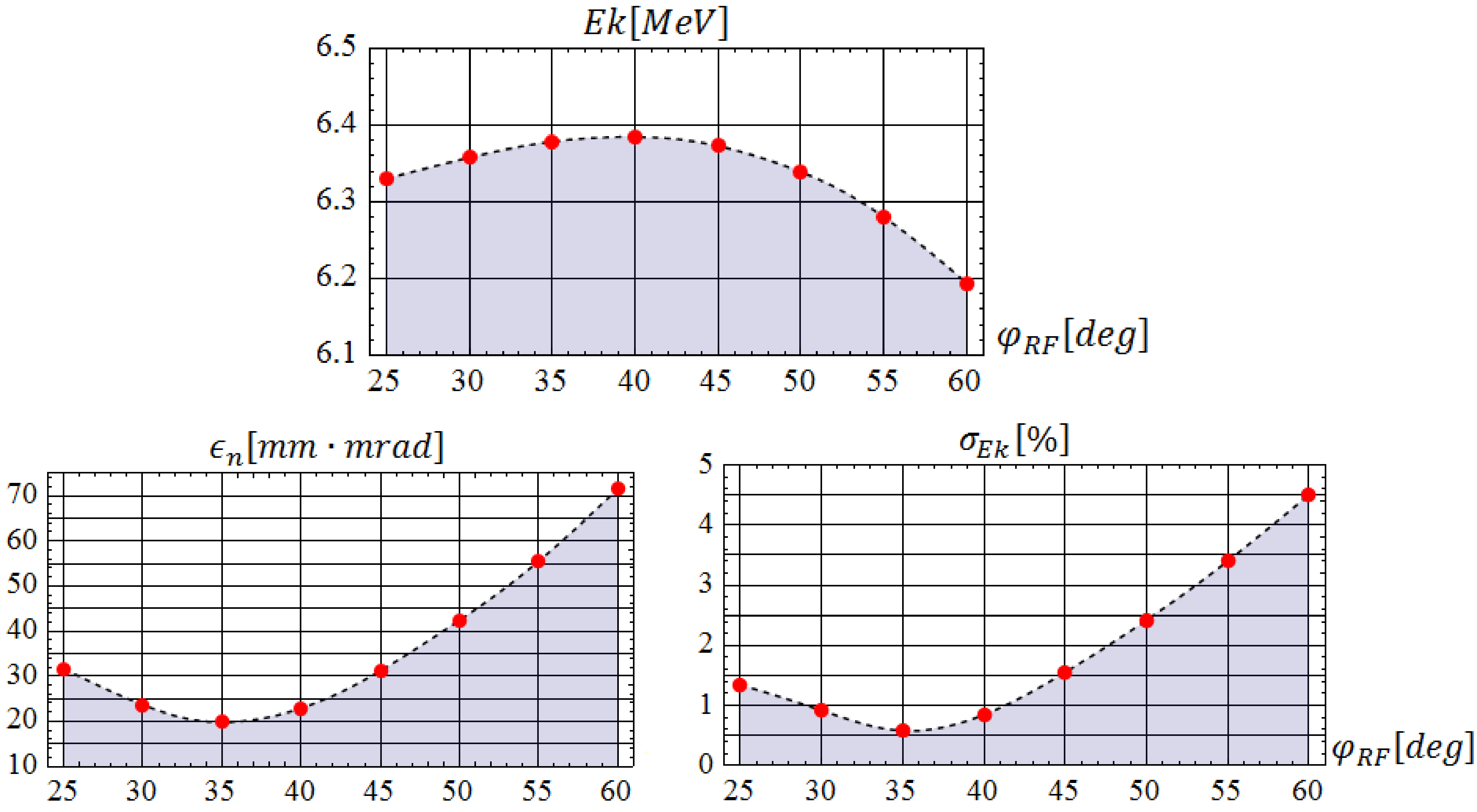


2.1. RF Gun Design (Beam Loading Optimization)

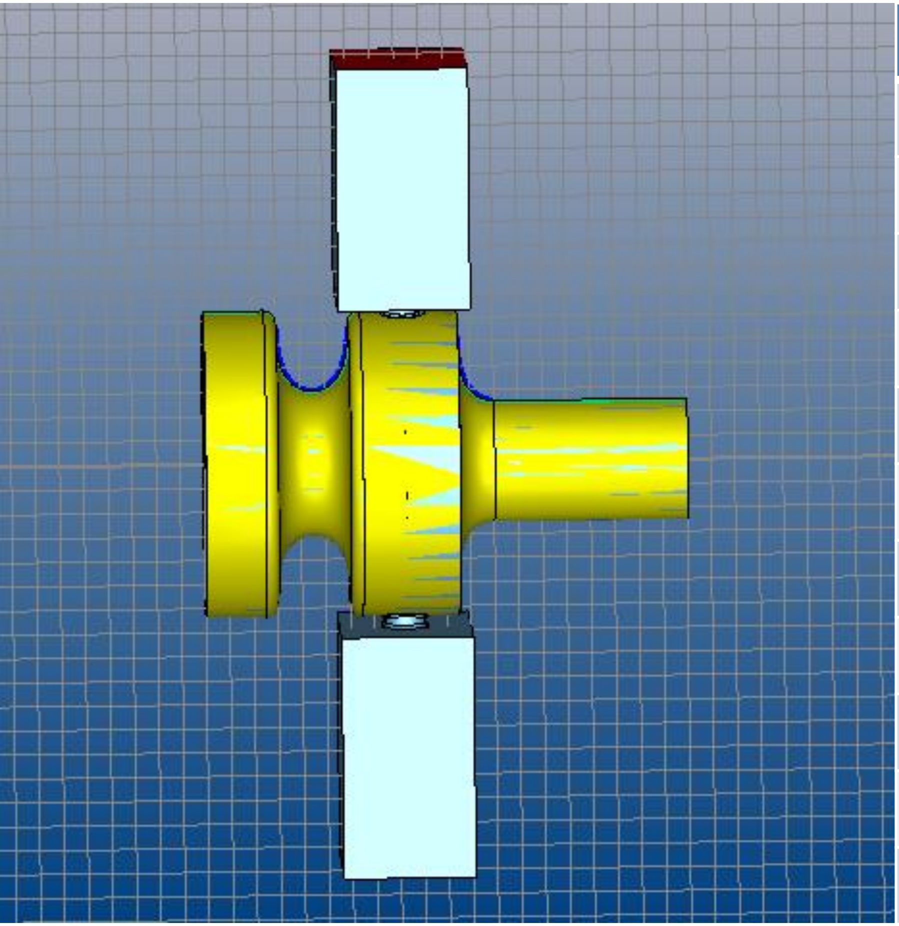




2.1. RF Gun Design (RF Phase Optimization)

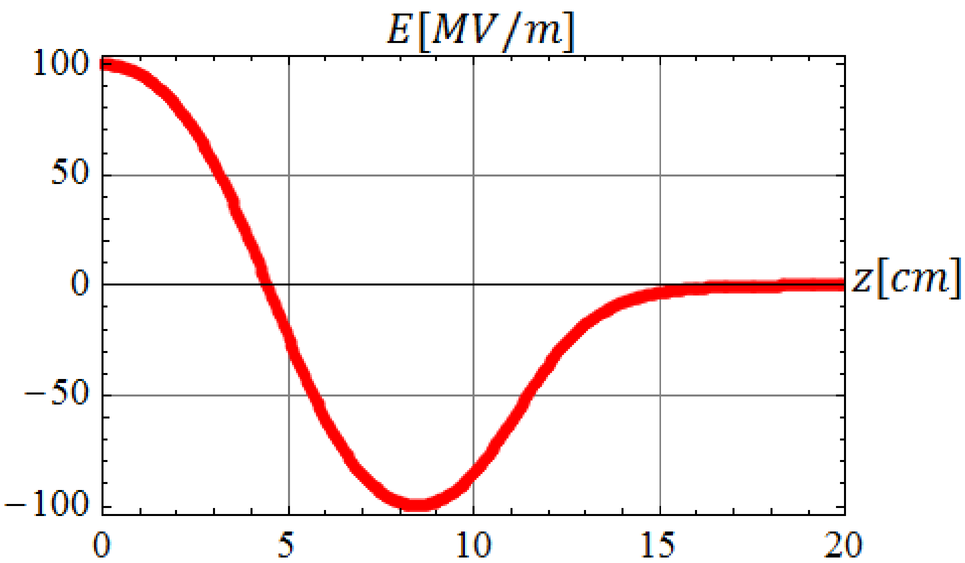


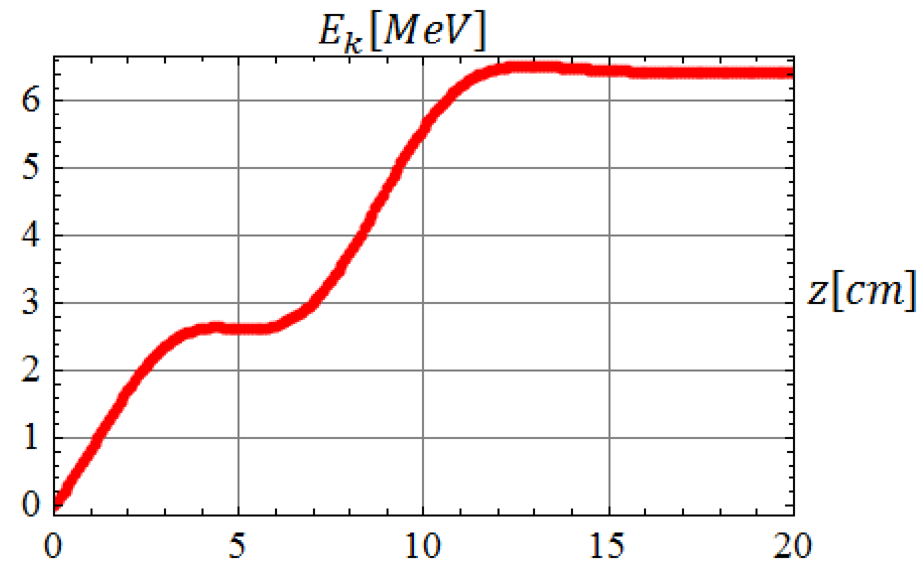
2.1. RF Gun Design (Specifications of Optimum Structure)

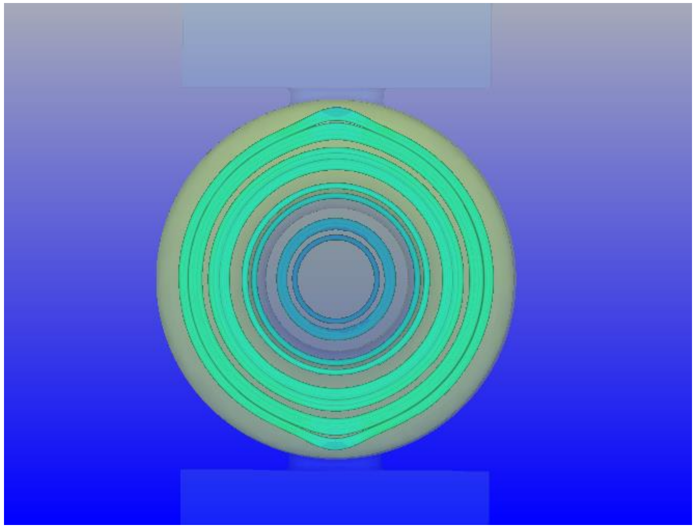


Parameter	Value
Number of Cell	1.6
π mode Frequency [GHz]	2
Frequency Difference [MHz]	46
Coupling Factor	3.08
Quality Factor	17263
Band Width [kHz]	237
Filling Time [μS]	0.672
Shunt Impedance [$M\Omega$]	3.165
Max Electric Field [MV/m]	99.83
RF Phase[deg]	35
RF Power [MW]	Up to 40

2.1. RF Gun Design (Cavity Fields)

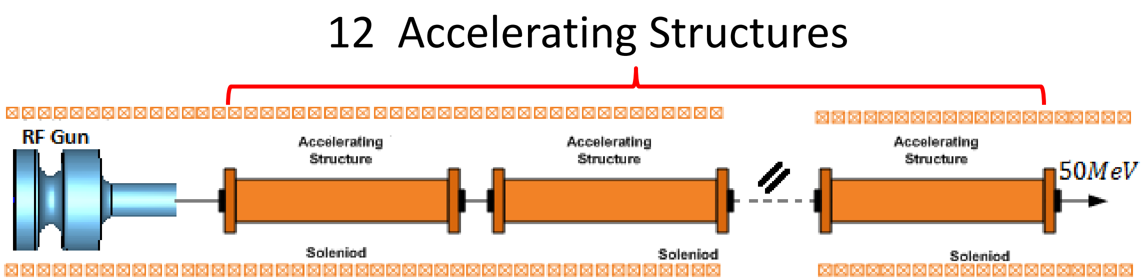






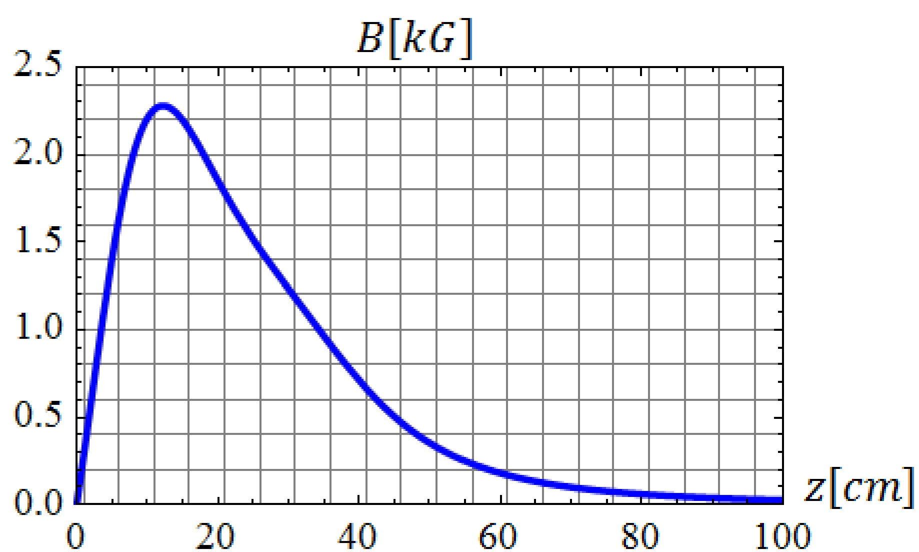
Parameter	*Value*
$k_x[1/m]$	29.3
$k_y[1/m]$	27.3

2.1. RF Gun Design (Focusing Channel)

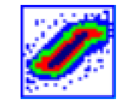


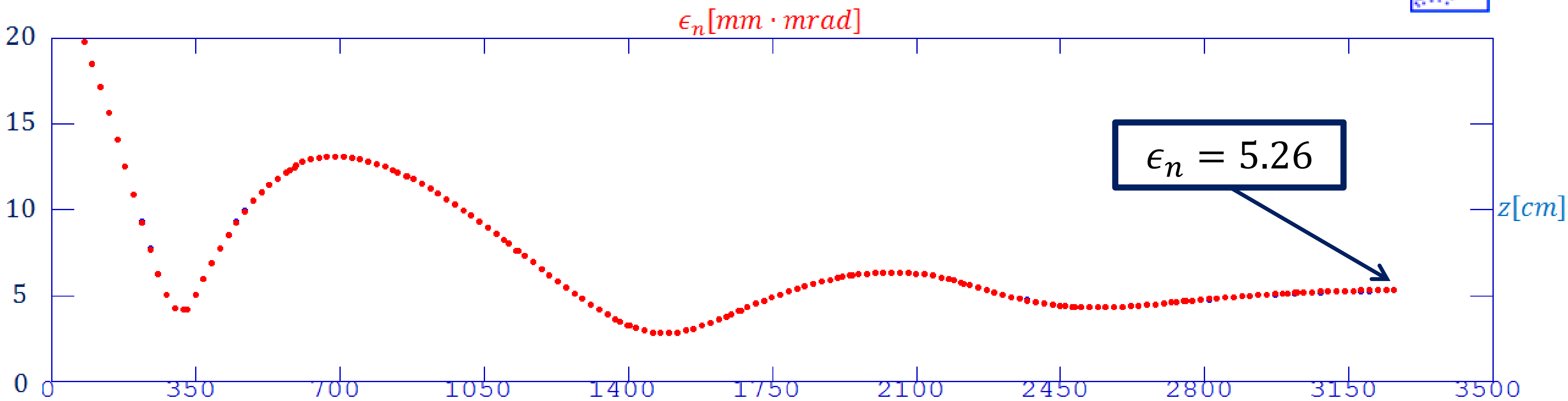
Parameter	*Value*
Cell per Acc	24
Acc Length [m]	2.4
Acc Voltage [MV]	3.8

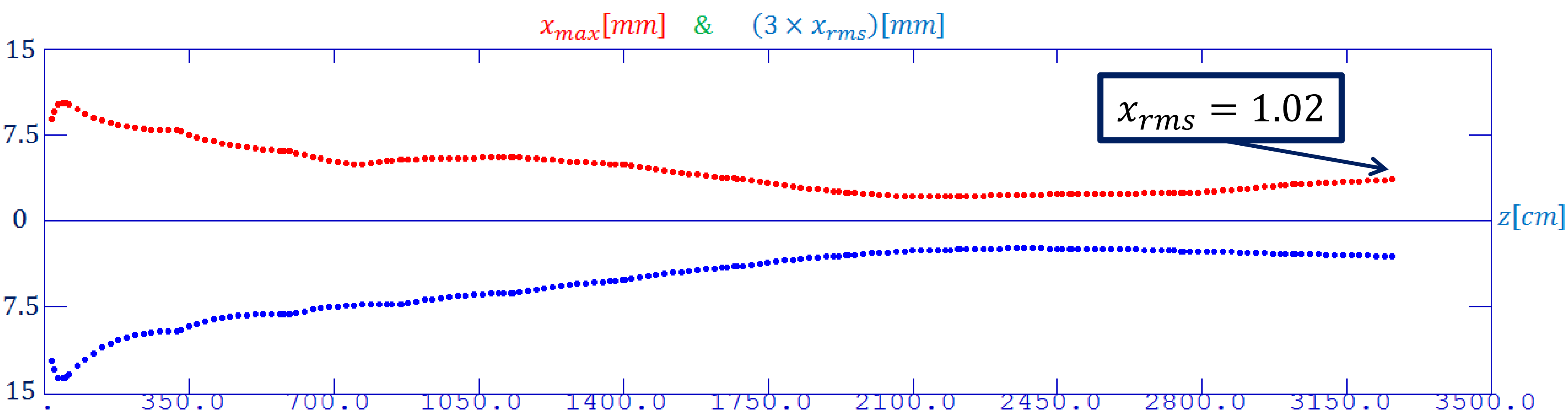
Envelope Equation ⇒



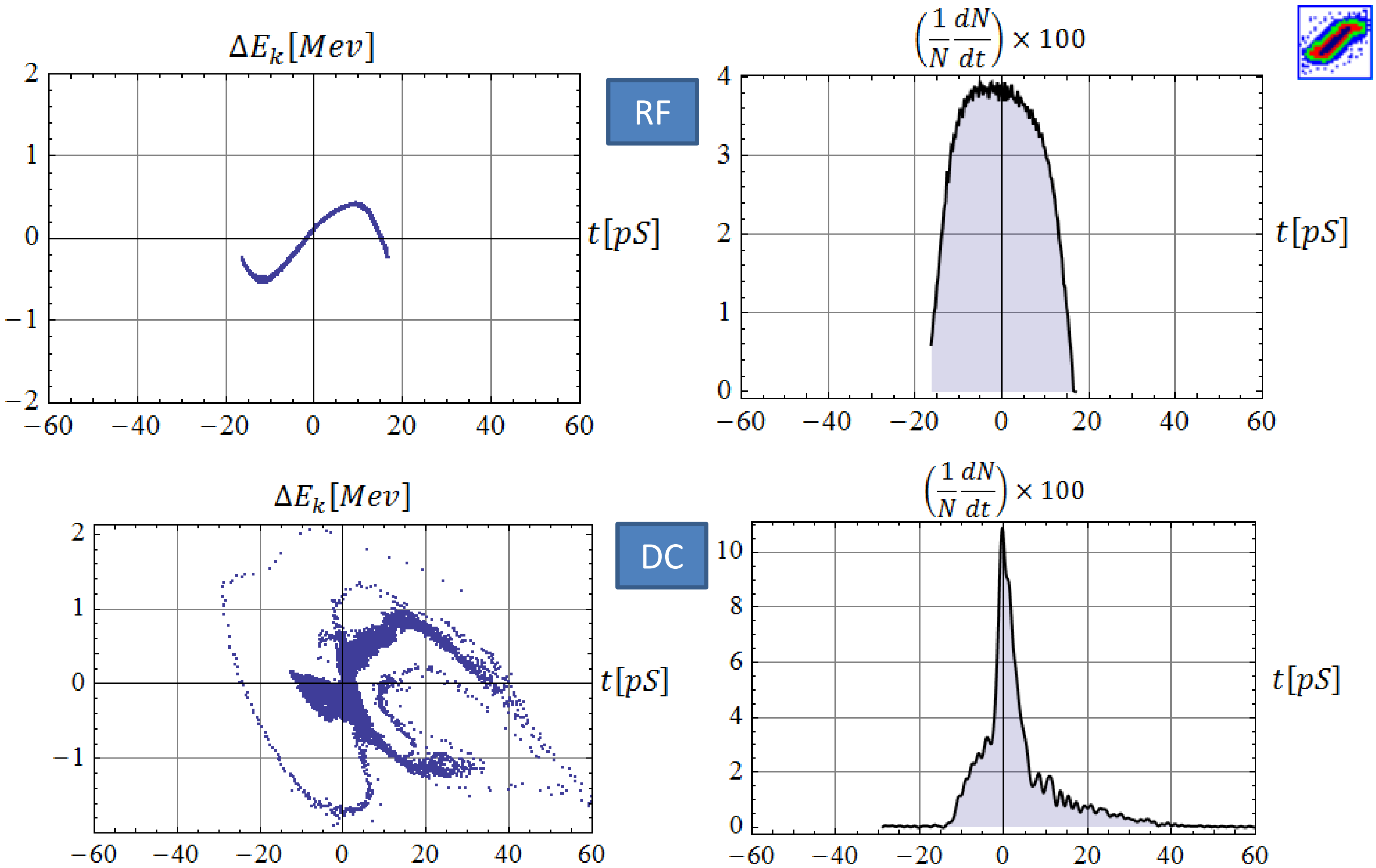
2.2. RF Gun Simulations (Emittance & Envelope)



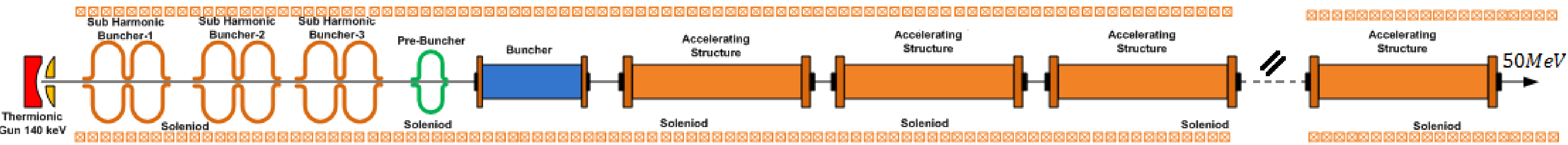


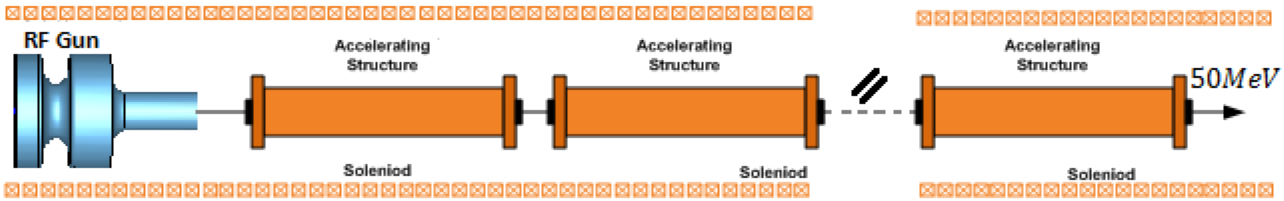


2.3. RF Gun Simulations (Longitudinal Parameters)



2.3. Comparison





characteristic	***DC***	***RF***
Normalized Emittance [*mm · mrad*]	35	5
Energy Spread	1%	0.75%
Satellite population	2.1%	0
Bunching System	*Yes*	*No*
Longitudinal Distribution		*Very Uniform*
Longitudinal Phase Space		*Very Clean & Symmetric*

Work in Progress

Thanks for Attention