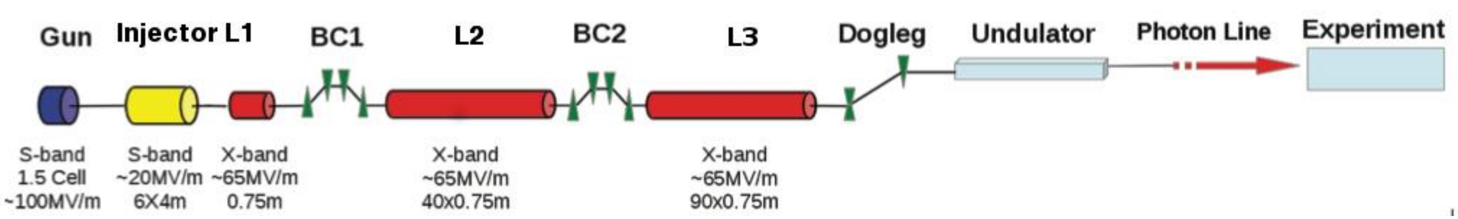
RF design of an X-band accelerating structure for the CompactLight Project

(on the base of the work done for theEuPRAXIA@SPARC_LAB project)

XLS Performance

Presented by G. D'Auria at Compact Light kick-off meeting on Jan. 25 2018

Parameter	Value	Unit
Minimum Wavelength	0.1	nm
Photons per pulse	$>10^{12}$	
Pulse bandwidth	<<0.1	%
Repetition rate	100 to 1000	Hz
Pulse duration	<1 to 50	fs
Undulator Period	10	mm
K value	1.13	
Electron Energy	4.6	GeV
Bunch Charge	<250	pC
Normalised Emittance	<0.5	mrad



Preliminary Parameters and Layout of XLS hard X-ray FEL facility

Beyond the state-of-the-art

Presented by G. D'Auria at Compact Light kick-off meeting on Jan. 25 2018

European XFEL (Germany)	24 MV/m	Superconducting L-band
Swiss FEL (Switzerland)	28 MV/m	Normal-conducting C-band
SACLA (Japan)	35 MV/m	Normal-conducting C-band

Examles of Linac gradients of current X-ray free electron

Parameter	Value
Length L	0.75m
Phase advance per cell φ	120°
First iris aperture a1/λ	0.15
Last iris aperture a2/λ	0.1
First iris thickness d1	0.9mm
Last iris thickness d2	1.7mm
Fill time τ	150ns
Operational gradient G	65MV/m
Input power Pin	41.8MW

Preliminary parameters of an optimized RF structure (x-band)

	unit	XLS X-band	SwissFEL C-band
Structures per RF unit		10	4
Klystrons per RF unit		2	1
Structure length	m	0.75	1.98
Allowed gradient	MV/m	80+	
Operating gradient	MV/m	65	27.5
Energy gain per RF unit	MV	488	203
Klystron nominal power	MW	50	50
Power in operation	MW	45	40
Klystron pulse length	μs	1.5	3
RF energy/pulse/GeV	J	277	591

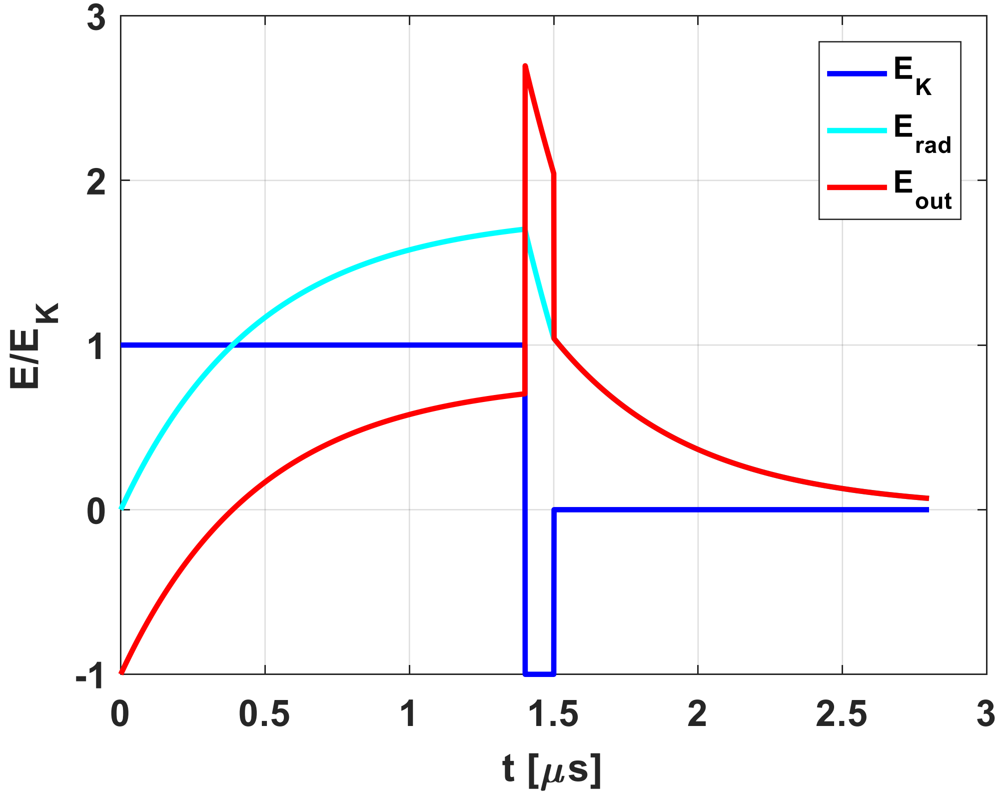
Preliminary parameters for the X-band RF unit, compared with the C-band SwissFEL technology.

Our task in WP4 is to draw the final version of these tables. We need inputs from WP2, 5 and 6 to proceed. We will use the same approach as for the design of the X-band accelerating structure for EUPRAXIA@SPARC_Lab

RF design of the linac for the EuPRAXIA@SPARC_LAB project

SLED TYPICAL PULSE SHAPE

Example: compressed pulse of 100 ns and Q_e of 20000



RF system parameters	
Frequency [GHz]	11.9942
t_k [μs]	1.5
Q_0 of SLED	180000

Effective shunt impedance of Acc. Structure + Pulse Compressor

Time - dependent accelerating gradient : $E_{acc}(z,t') = G(z,t') = G_0[t' - \tau(z)]g(z)$ [2];

Signal time delay : $\tau(z) = \int_0^z \frac{dz'}{v_g(z')}$; Filling time : $t_f = \tau(L_s)$; $t' = t - t_1$;

$$G_0(t') = G(z=0,t') = \sqrt{\frac{\omega}{v_g(0)} \frac{R(0)}{Q(0)} P_{in\_s}(t')} = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_{in\_s}(t')} = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_K(t=0)} \frac{E_{out}}{E_K}(t) \quad [2]$$

with R shunt impedance per unit lenght and Q quality factor

Attenuation per unit lenght : $\alpha(z) = \frac{1}{2}\left[\frac{1}{v_g}\frac{dv_g}{dz} - \frac{1}{R/Q}\frac{d(R/Q)}{dz} + \frac{\omega}{v_g Q}\right]$ [2]

$$g(z) = e^{-\int_0^z \alpha(z')dz'} = \sqrt{\frac{v_g(0)}{v_g(z)}} \sqrt{\frac{R(z)}{Q(z)} \frac{Q(0)}{R(0)}} e^{-\frac{1}{2}\int_0^z \frac{\omega}{v_g(z')Q(z')}dz'} \quad [2]$$

$Hyp: \frac{R}{Q}$ constant along z $\Rightarrow g(z) = \sqrt{\frac{v_{g0}}{v_g(z)}} e^{-\frac{1}{2}\frac{\omega}{Q}\int_0^z \frac{dz'}{v_g(z')}} = \sqrt{\frac{v_{g0}}{v_g(z)}} e^{-\frac{1}{2}\frac{\omega}{Q}\tau(z)}$

Section attenuation : $\tau_s = \int_0^{L_s} \alpha(z)dz$

Accelerating Voltage : $V_a = \int_0^{L_s} dz' G(z', t' = t_f = t_2 - t_1)$;

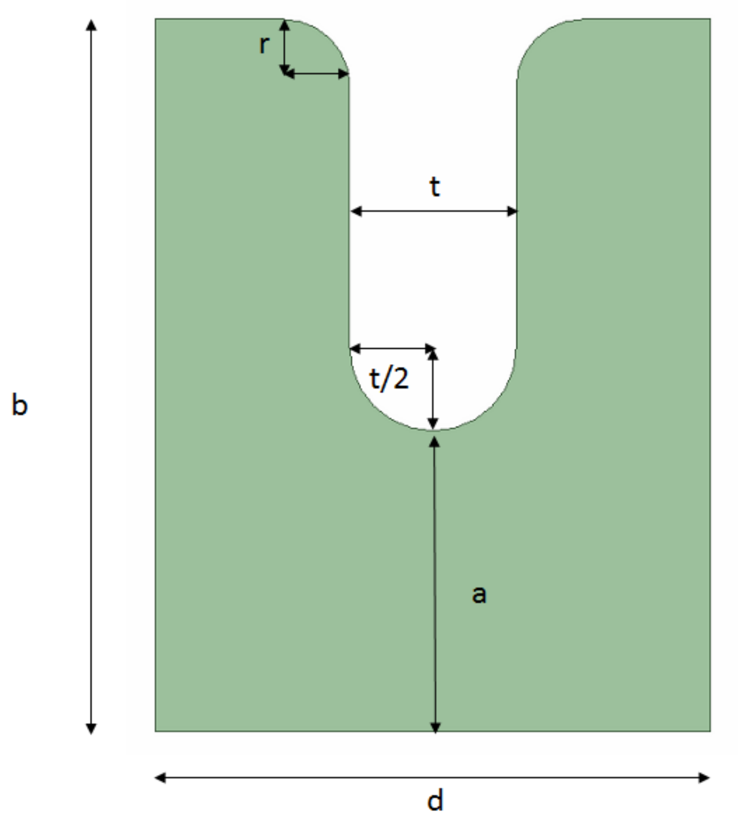
Effective shunt impedance : $R_s = \frac{V_a^2}{P_K(t=0)L_s} [\Omega / m]$ [3];

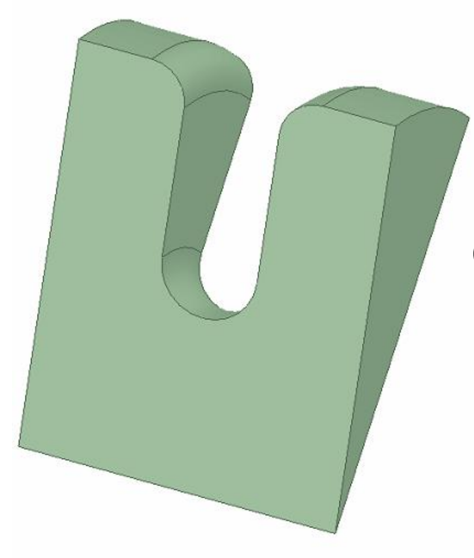
Total Power : $P_{tot} = \frac{V_{tot}\langle G \rangle}{R_s}$

[2] A. Lunin, V. Yakovlev, A. Grudiev, PRST-AB 14, 052001, (2011)

[3] R. B. Neal, Journal of Applied Physics, V.29, pp. 1019-1024, (1958)

Single cell parameters





Cell portion for HFSS simulations

A scan of the iris radius **from 2 mm to 5 mm** a has been performed with HFSS in order to obtain the single cell parameters (**R, v_g/c, Q, Sc_{max}/E^2_{acc}**) as a function of the iris radius. Also the related polynomial fits have been derived.

freq	11,9942 GHz
a	2 mm ÷ 5 mm
b	9.828 mm ÷ 10.917 mm
d	8.332 mm (2π/3 mode) $\Delta\phi = k_z^* d = \frac{\omega}{c} d$
r	1 mm
t	2.5 mm

Single cell formulas

$$V_z = \left| \int_0^D E_z \cdot e^{j\omega_{RF}\frac{z}{c}} dz \right|$$ single cell accelerating voltage $[V]$:

$$E_{acc} = \frac{V_z}{D}$$ average accelerating field in the cell $[\frac{V}{m}]$

$$P_{in} = \int_{Section} \frac{1}{2} \mathrm{Re}\left(\vec{E} \times \vec{H}^*\right) \cdot \hat{z} dS$$ average input power (flux power) $[W]$

$$P_{diss} = \frac{1}{2} R_s \int_{\substack{cavity\\wall}} \left|H_{\tan}\right|^2 dS$$ average dissipated power in the cell $[W]$

$$R_s = \sqrt{\frac{\pi f_{RF}\mu_0}{\sigma}} = \frac{1}{\sigma\delta}$$ surface resistance $[\Omega]$

$$\delta = \frac{1}{\sqrt{\pi f_{RF}\mu_0\sigma}}$$ skin depth $[\mathrm{m}]$

$$p_{diss} = \frac{P_{diss}}{D}$$ average dissipated power per unit length $[\frac{W}{m}]$

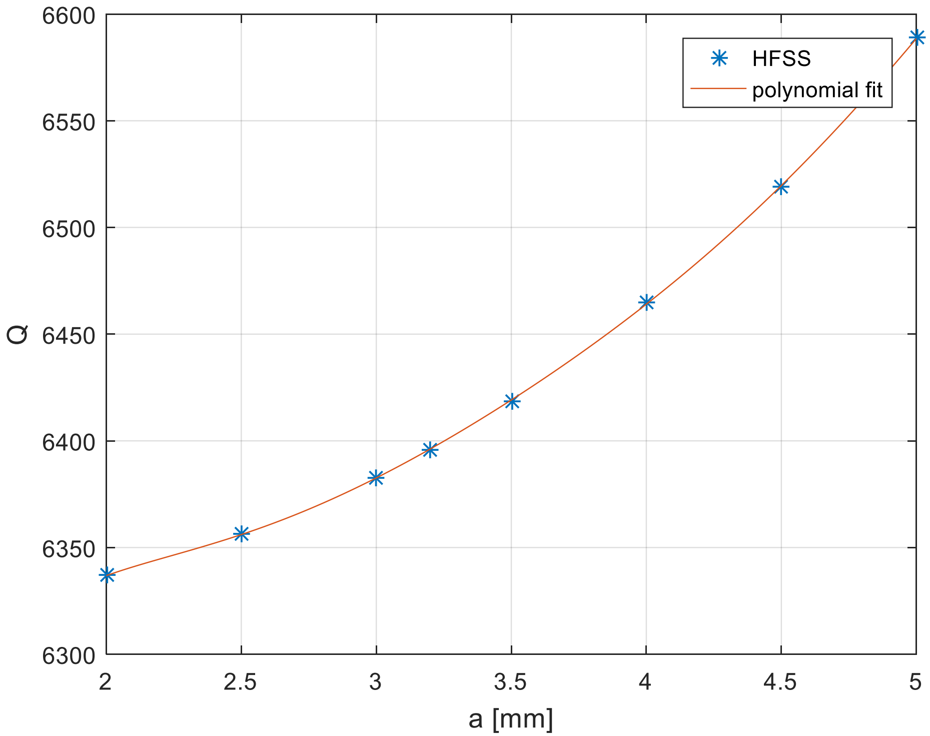
$$W = \int_{\substack{cavity\\volume}} \left(\frac{1}{4}\varepsilon\left|E\right|^2 + \frac{1}{4}\mu\left|H\right|^2\right) dV$$ stored energy in the cell $[J]$

$$w = \frac{W}{D}$$ average stored energy per unit length $[\frac{J}{m}]$

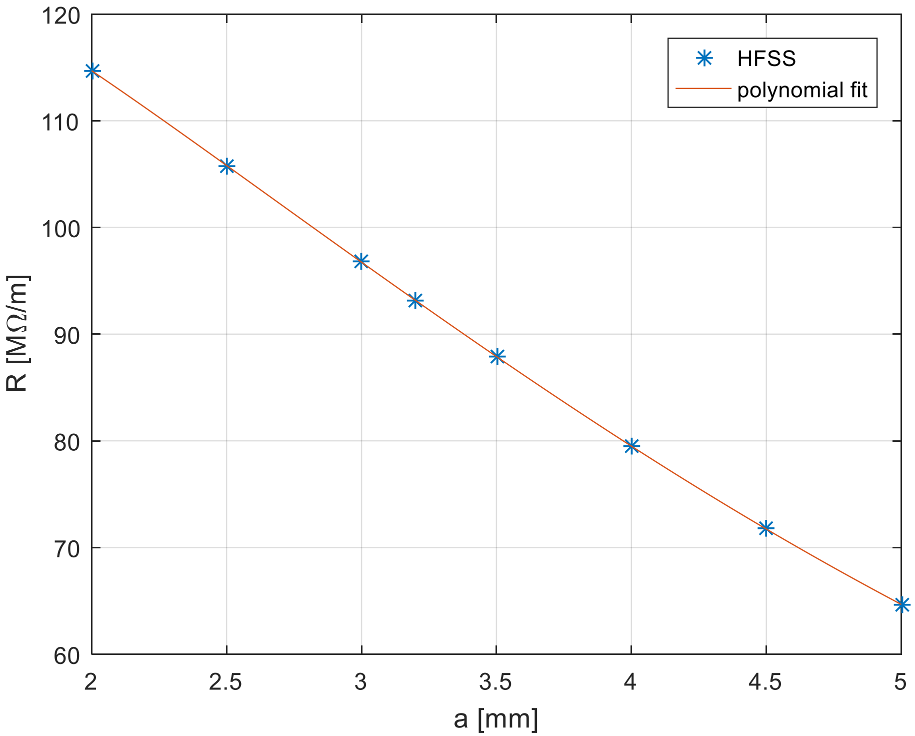
$$Q = \omega_{RF} \frac{w}{p_{diss}}$$ quality factor [arb. units]

Single cell parameters

Quality factor



Shunt impedance per unit length

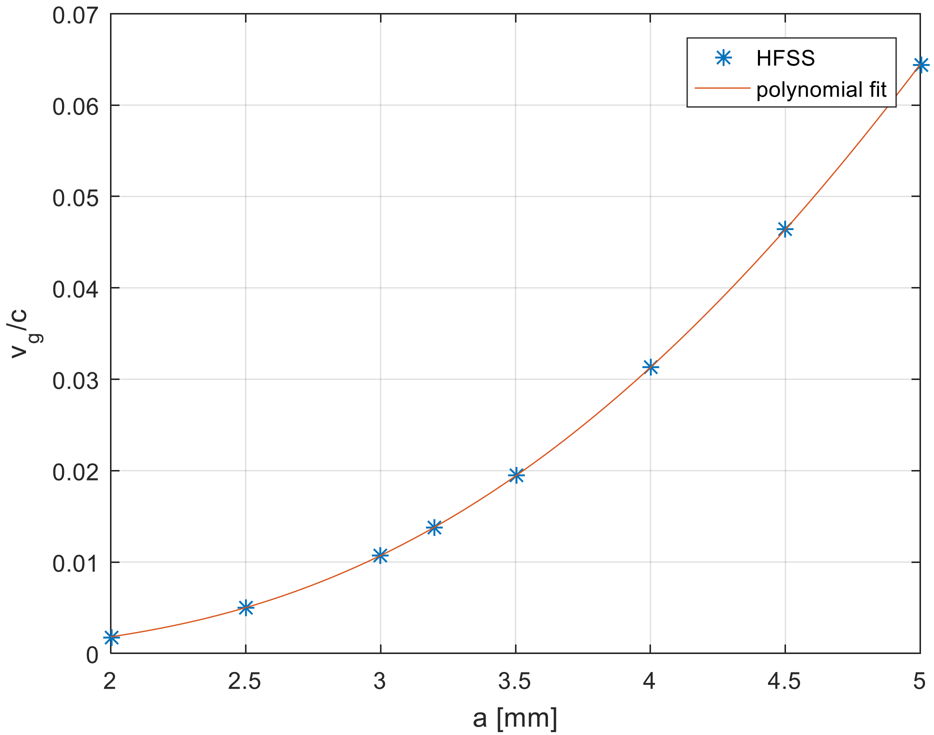


Reference formula

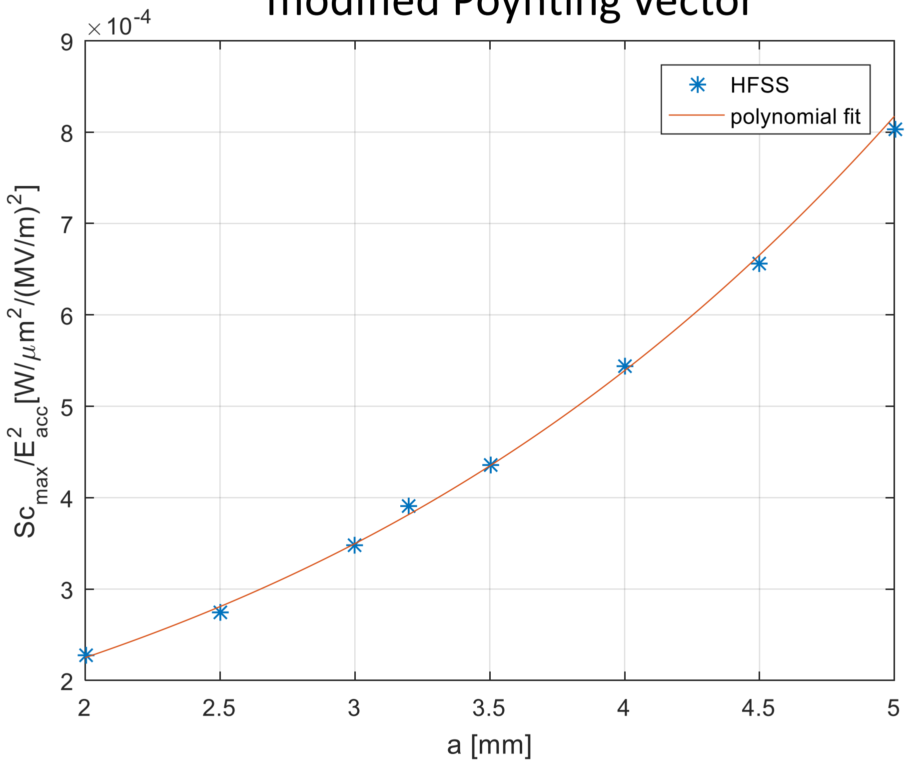
$$R = \frac{E_{acc}^2}{p_{diss}} \quad \left[\frac{\Omega}{m}\right]$$

Single cell parameters

Group velocity



Maximum value of normalized modified Poynting vector



Reference formula

$$v_g = \frac{P_{in}}{w} \qquad \left[\frac{\mathrm{m}}{s}\right]$$

Reference formula

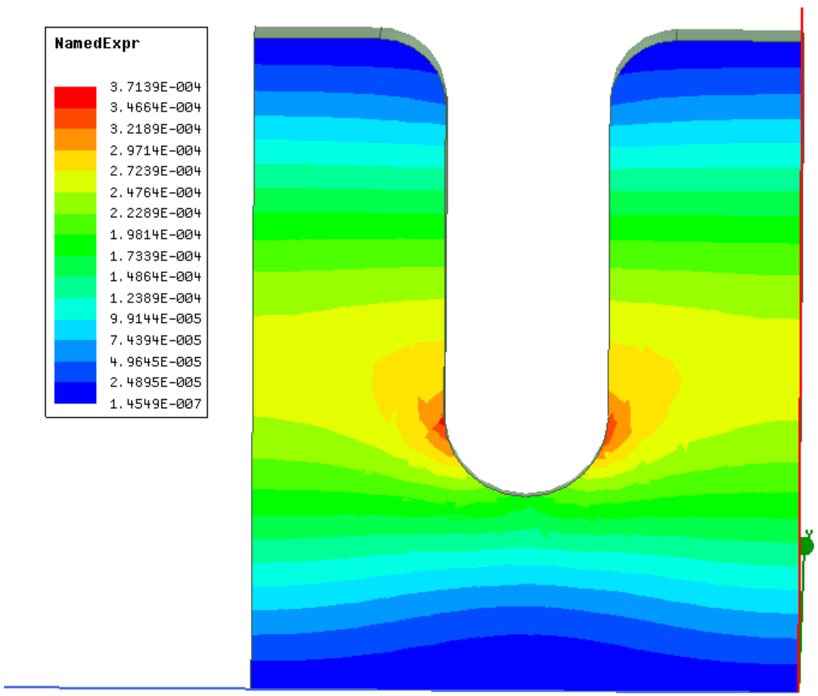
$$S_c = \mathrm{Re}\{\bar{S}\} + g_c\,\mathrm{Im}\{\bar{S}\}$$

$$g_c = \frac{1}{6} \qquad [4]$$

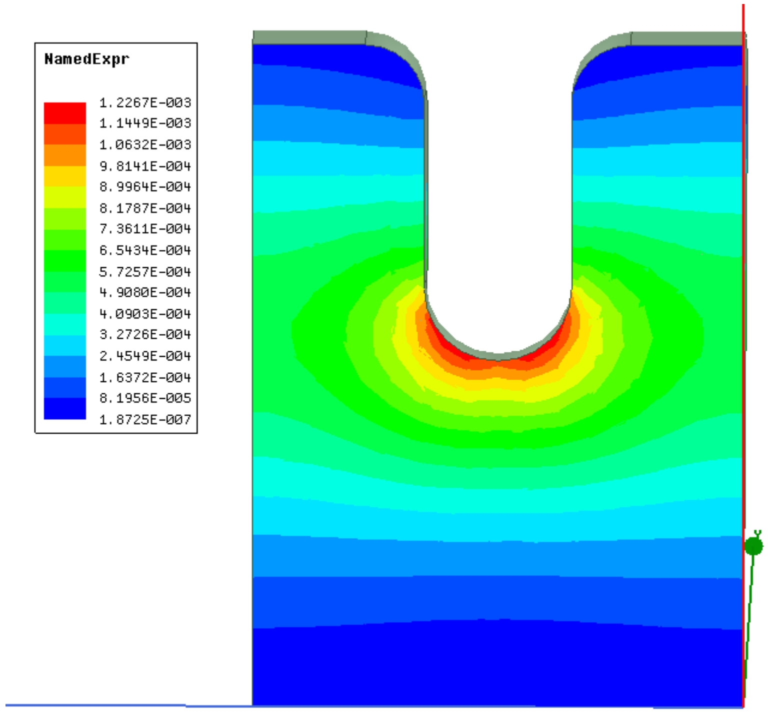
[4] A. Grudiev, S. Calatroni, and W. Wuensch, New local field quantity describing the high gradient limit of accelerating structures, PhysRevSTAB.12.102001 (2009)

Single cell parameters

Maximum value of normalized modified Poynting vector



a=3 mm



a=6 mm

Single cell parameters for EUPRAXIA@SPARC_LAB project

We do need the corresponding specification for the Compact Light project to proceed with the TW section design and optimization

WP2, WP5 -> q_b, σ_z

WP6 -> beam dynamics

The **average iris radius <a>** has been fixed equal to **3.2 mm,** according to the beam dynamics calculations and single bunch beam break up limits.

Single cell parameters (a=3.2 mm)	
b [mm]	10.139
R [MΩ/m]	93
v_g/c [%]	1.382
Q	6396
Sc_{max}/E^2_{acc} [A/V]	$3.9x10^{-4}$

Analytical study:

-Constant impedance w pulse compression
-"Constant gradient" w pulse compression

Constant Impedance (CI) AS formulas

$$v_g(z) = v_{g0}; \quad \tau(z) = \int_0^z \frac{dz'}{v_g(z')} = \frac{z}{v_{g0}}$$

$$t' = t - t_1; \quad \tau_s = \alpha L_s = \frac{\omega}{2 v_{g0} Q} L_s; \quad t_f = \tau(L_s) = \frac{L_s}{v_{g0}} = \frac{2Q\tau_s}{\omega} \quad [5];$$

$$g(z) = \sqrt{\frac{v_{g0}}{v_g(z)} e^{-\frac{1}{2}\frac{\omega}{Q}\tau(z)}} = e^{-\tau_s \frac{z}{L_s}}, \quad G_0(t') = \sqrt{2\tau_s \frac{R}{L_s} P_K(t=0)} \frac{E_{out}}{E_K}(t')$$

$$G(z,t') = \sqrt{2\tau_s \frac{R}{L_s} P_K(t=0)} \frac{E_{out}}{E_K}(t' - \tau(z)) e^{-\tau_s \frac{z}{L}}$$

[5] T. P. Wangler, RF Linear Accelerators, John Wiley & Sons, 2008

Constant Impedance (CI) AS – With pulse compression

$$\frac{E_{out}}{E_K}(t')=\gamma\, e^{-\frac{t'\omega}{2Q_L}}-(\alpha-1); \quad G(z,t')=\sqrt{2\tau_s\frac{R}{L_s}P_K(t=0)}\left(\gamma\, e^{-\left(t'-\frac{z}{v_g}\right)\frac{\omega}{2Q_L}}-(\alpha-1)\right)e^{-\tau_s\frac{z}{L_s}}=G_0\left(\gamma\, e^{-\left(t'-\frac{z}{v_g}\right)\frac{\omega}{2Q_L}}-(\alpha-1)\right)e^{-\tau_s\frac{z}{L_s}}$$

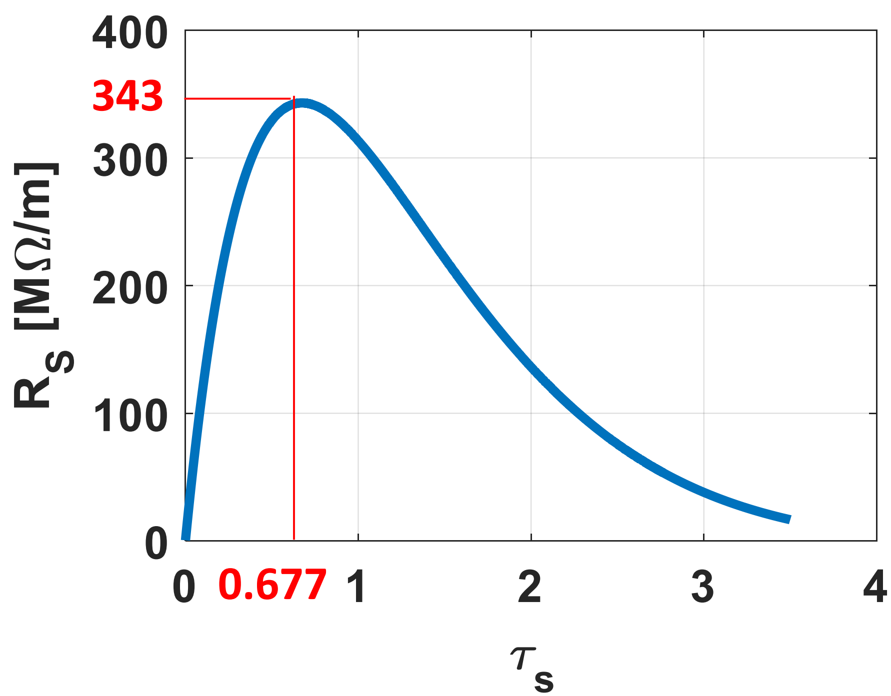
$$V_a=\int_0^{L_s}dz'G(z',t'=t_f=t_2-t_1)=\sqrt{P_K(t=0)RL_s}\sqrt{\frac{2}{\tau_s}}\left[\gamma\left(\frac{1}{\frac{Q}{Q_L}-1}\right)\left(e^{-\tau_s}-e^{-\frac{Q}{Q_L}\tau_s}\right)+(\alpha-1)\left(e^{-\tau_s}-1\right)\right]=\sqrt{P_K(t=0)RL_s}\sqrt{\frac{R_s}{R}} \quad [6]$$

$$\frac{R_s}{R}=\frac{V_a^2}{P_K(t=0)RL_s}=\left\{\sqrt{\frac{2}{\tau_s}}\left[\gamma\left(\frac{1}{\frac{Q}{Q_L}-1}\right)\left(e^{-\tau_s}-e^{-\frac{Q}{Q_L}\tau_s}\right)+(\alpha-1)\left(e^{-\tau_s}-1\right)\right]\right\}^2$$

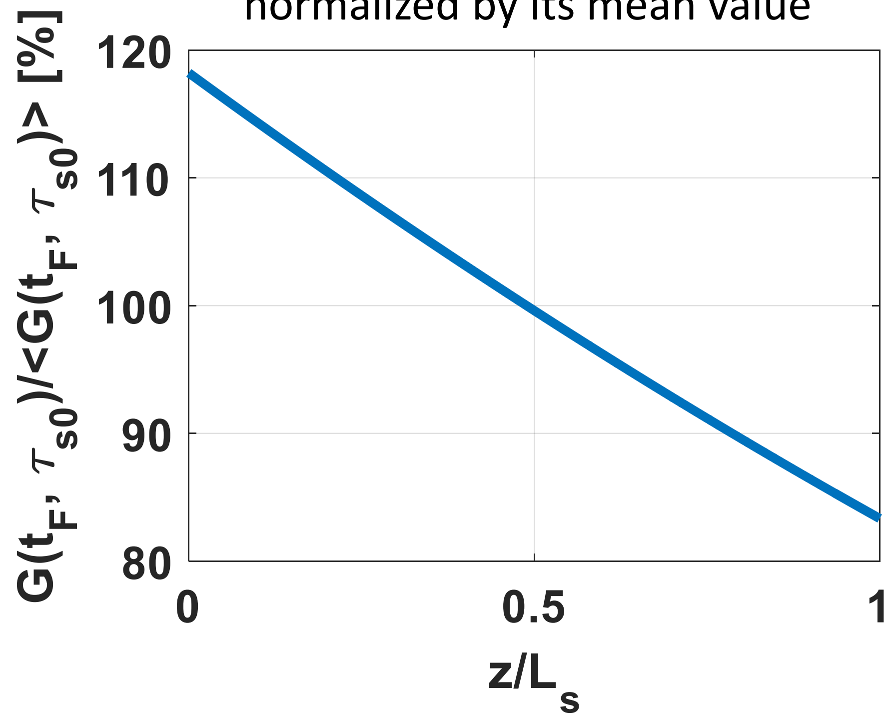
$$\frac{G\left(\frac{z}{L_s},t_F,\tau_{s0}\right)}{\left\langle G\left(\frac{z}{L_s},t_F,\tau_{s0}\right)\right\rangle}=L_s\frac{\left(\gamma\, e^{-\left(1-\frac{z}{L_s}\right)\frac{Q}{Q_L}\tau_{s0}}-(\alpha-1)\right)e^{-\tau_{s0}\frac{z}{L_s}}}{\int_0^{L_s}\left(\gamma\, e^{-\left(1-\frac{z}{L_s}\right)\frac{Q}{Q_L}\tau_{s0}}-(\alpha-1)\right)e^{-\tau_{s0}\frac{z}{L_s}}dz}$$

[6] J. Le Duff, High-field electron linacs, CERN 95-06, (1995)

Constant Impedance (CI) AS – With pulse compression



Gradient after 1 filling time normalized by its mean value



Reference formula

$$R_s = 2\tau_s R\left[\frac{\left(1-\frac{2Q_l}{Q_e}\right)}{\tau_s}\left(1-e^{-\tau_s}\right)+\frac{\left(\frac{2Q_l}{Q_e}\left[2-e^{-(\tau_k-\tau_p)}\right]\right)}{\tau_s\left(1-\frac{Q}{Q_l}\right)}\left(e^{-\tau_s\frac{Q}{Q_l}}-e^{-\tau_s}\right)\right]^2$$

Reference formula

$$G(z,t'=t_f)=\sqrt{\frac{\omega}{v_g}\frac{R}{Q}P_{in}e^{-\tau_s/L_s z}}\;\cdot$$

$$\cdot\left\{1+\frac{2Q_l}{Q_e}\left[\exp\left(-\frac{\omega(L_s-z)}{2v_gQ_l}\right)\left[2-\exp\left(-\frac{\omega t_0}{2Q_l}\right)\right]-1\right]\right\}$$

Effective Shunt impedance in Const Gradient (CG) AS

Beware! *It assumes constant R/Q values along the structure (inaccurate approximation)*

$$v_g(z) = \frac{\omega L_s}{Q} \frac{\left[1-\left(1-e^{-2\tau_s}\right)\frac{z}{L_s}\right]}{\left(1-e^{-2\tau_s}\right)}; \quad \tau(z) = \int_0^z \frac{dz'}{v_g(z')} = -\frac{Q}{\omega}\ln\left[1-\left(1-e^{-2\tau_s}\right)\frac{z}{L_s}\right] \quad [5]$$

$$\tau_s = \int_0^L \alpha(z)dz; \quad t_f = \tau(L_s) = \frac{2Q\tau_s}{\omega} \quad [5];$$

$$g(z) = 1, \quad G_0(t') = \sqrt{\frac{R}{L_s} P_K(t=0)\left(1-e^{-2\tau_s}\right)} \frac{E_{out}}{E_K}(t') \quad [5]$$

$$G(z,t') = \sqrt{\frac{R}{L_s} P_K(t=0)\left(1-e^{-2\tau_s}\right)} \frac{E_{out}}{E_K}(t'-\tau(z)) = G_0 \frac{E_{out}}{E_K}(t'-\tau(z))$$

[5] T. P. Wangler, RF Linear Accelerators, John Wiley & Sons, 2008

Constant Gradient (CG) AS – With pulse compression

$$\frac{E_{out}}{E_K}(t')=\gamma\, e^{-\frac{t'\omega}{2Q_L}}-(\alpha-1);$$

$$G(z,t')=\sqrt{\frac{R}{L_s}P_K(t=0)\left(1-e^{-2\tau_s}\right)}\left\{\gamma\, e^{-\frac{t'\omega}{2Q_L}}\left[1-\left(1-e^{-2\tau}\right)\frac{z}{L_s}\right]^{-\frac{Q}{2Q_L}}-(\alpha-1)\right\}=G_0\left\{\gamma\, e^{-\frac{t'\omega}{2Q_L}}\left[1-\left(1-e^{-2\tau_s}\right)\frac{z}{L_s}\right]^{-\frac{Q}{2Q_L}}-(\alpha-1)\right\}$$

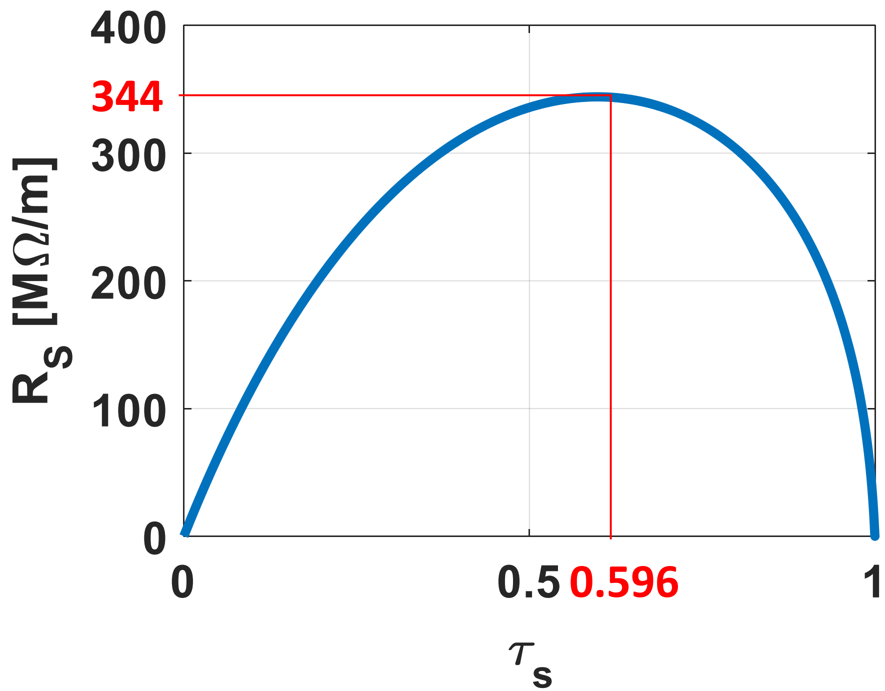
$$V_a=\int_0^{L_s}dz'G(z',t'=t_f=t_2-t_1)=\sqrt{P_K(t=0)RL_s\left(1-e^{-2\tau_s}\right)}\left\{\gamma\, e^{-\frac{Q}{Q_L}\tau_s}\left[\frac{1-\left(e^{-2\tau_s}\right)^{\left(1-\frac{Q}{2Q_L}\right)}}{\left(1-\frac{Q}{2Q_L}\right)\left(1-e^{-2\tau_s}\right)}\right]-(\alpha-1)\right\}=\sqrt{P_K(t=0)RL_s}\sqrt{\frac{R_s}{R}}\quad [1]$$

$$\frac{R_s}{R}=\frac{V_a^2}{P_K(t=0)RL_s}=\left(1-e^{-2\tau_s}\right)\left\{\gamma\, e^{-\frac{Q}{Q_L}\tau_s}\left[\frac{1-\left(e^{-2\tau_s}\right)^{\left(1-\frac{Q}{2Q_L}\right)}}{\left(1-\frac{Q}{2Q_L}\right)\left(1-e^{-2\tau_s}\right)}\right]-(\alpha-1)\right\}^2$$

$$\frac{G\left(\frac{z}{L_s},t_F,\tau_{s0}\right)}{\left\langle G\left(\frac{z}{L_s},t_F,\tau_{s0}\right)\right\rangle}=L_s\frac{\gamma\, e^{-\frac{Q}{Q_L}\tau_{s0}}\left[1-\left(1-e^{-2\tau_{s0}}\right)\frac{z}{L_s}\right]^{-\frac{Q}{2Q_L}}-(\alpha-1)}{\int_0^{L_s}\left\{\gamma\, e^{-\frac{Q}{Q_L}\tau_{s0}}\left[1-\left(1-e^{-2\tau_{s0}}\right)\frac{z}{L_s}\right]^{-\frac{Q}{2Q_L}}-(\alpha-1)\right\}dz}$$

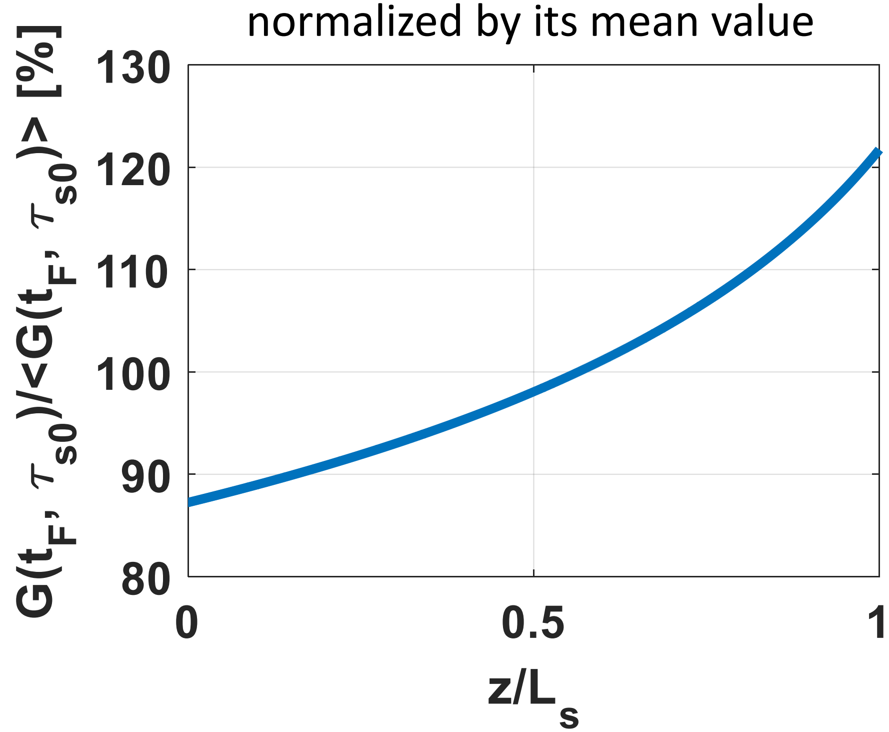
[1] Z . D. Farkas et al. SLED. A METHOD OF DOUBLING SLAC's ENERGY, Proc. 9th Int. Conf. on High Energy Accelerators, Stanford, 1974, (SLAC, Stanford, 1974).

Constant Gradient (CG) AS – With pulse compression



Reference formula

Gradient after 1 filling time
normalized by its mean value



Reference formula

$$R_s = R\frac{2\tau_s}{1+\tau_s}\left\{1-\frac{2Q_l}{Q_e}+\frac{2Q_l}{Q_e}\left[2-\exp\left(-\frac{\omega t_k}{2Q_l}\right)\cdot\left(\frac{1+\tau_s}{1-\tau_s}\right)^{Q/2Q_l}\right]\cdot \frac{1-\tau_s}{2\tau_s}\frac{1}{1-Q/2Q_l}\left[\left(\frac{1+\tau_s}{1-\tau_s}\right)^{1-Q/2Q_l}-1\right]\right\}^2$$

$$G(z,t'=t_f)=\sqrt{\frac{2\tau_s/L_s R}{1+\tau_s}P_{in}}\cdot\left\{1+\frac{2Q_l}{Q_e}\left[\left(\frac{1+\tau_s-\tau_s/L_s z}{1-\tau_s}\right)^{-\frac{Q}{2Q_l}}\left[2-\exp\left(-\frac{\omega t_0}{2Q_l}\right)\right]-1\right]\right\}$$

Analytical study results

Fixed the quality factor **Q** of the cells it is possible to calculate the **effective shunt impedance R_s** as a function of the **section attenuation τ_s**. The choice of τ_s fixes the **filling time of the structure t_f** and hence the **compressed pulse length after the SLED t_p**. The value of the **external quality factor Q_e** of the SLED has been chosen in order to maximize R_s. If we consider the optimum τ_s value (**τ_{s0}**) it is possible to calculate the **accelerating gradient profile after one filling time $G(z,t'=t_f)$**. Once calculated the optimum τ_s it is possible to calculate the **main LINAC parameters: structure length L_s, number of structures N_s, t_p, total required RF power P_{RF}, maximum value of modified Poynting vector Sc_{max}**.

CIAS parameters	
R_S [MΩ/m]	343
L_s [m]	0.474
t_f [ns]	114

CGAS parameters	
R_S [MΩ/m]	344
L_s [m]	0.432
t_f [ns]	118

Numerical study for the linac optimization

Using the theoretical formulas (constant impedance and constant gradient) we are able to find the optimal length of the structure (and the value Qe of the SLED) in order to maximize the Rs.

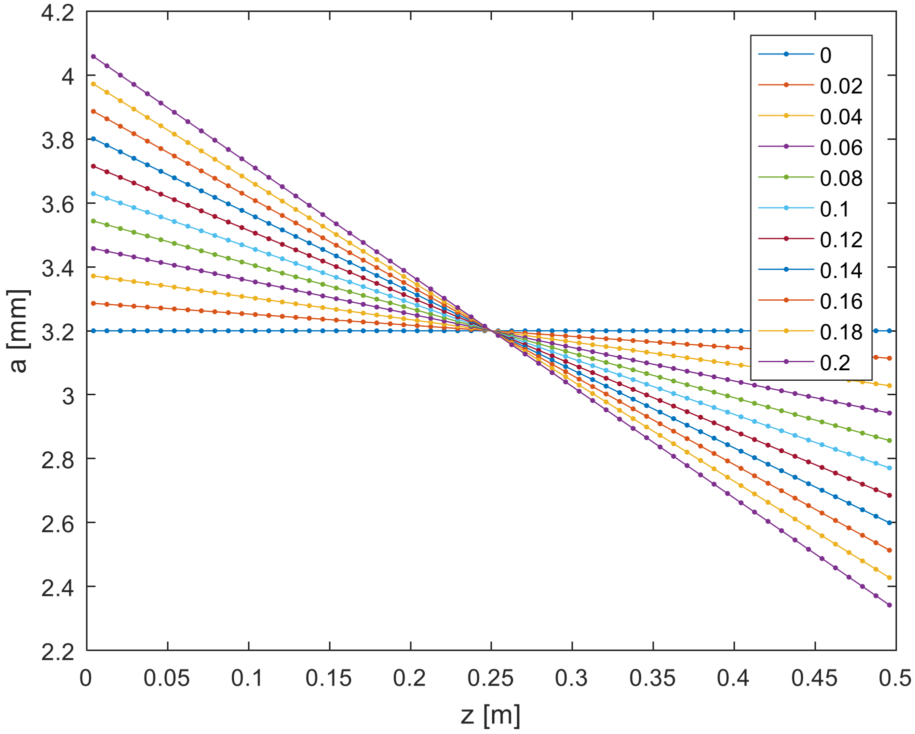
But the constant gradient formulas are not exact, there is the approximation of constant R/Q along the structure.

Considering this fact and the fact that we have a **constraint in terms of active length**, we thought a different approach: fixing several lengths of the structure we want investigate several angles of iris tapering (linear tapering for the moment) using non-approximated formulas [2] and find the optimal tapering.

To do this we used the polynomial fits of the single cell parameters calculated with HFSS.

Ls=0.5m (60 cells), Ns=32

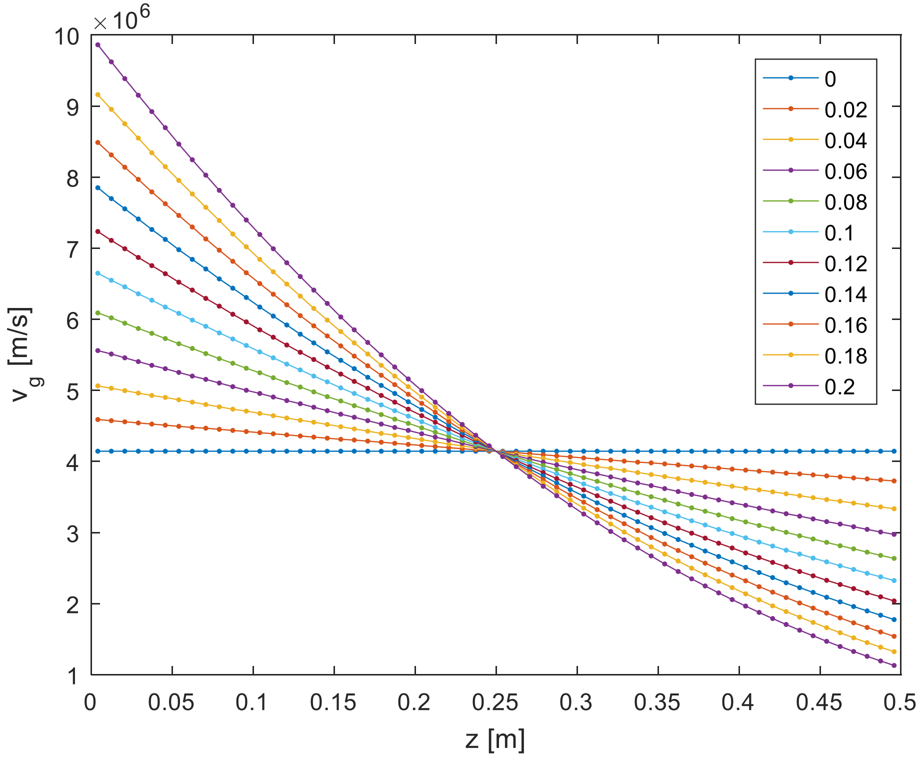
Slope from 0° to 0.2° (step 0.02°)

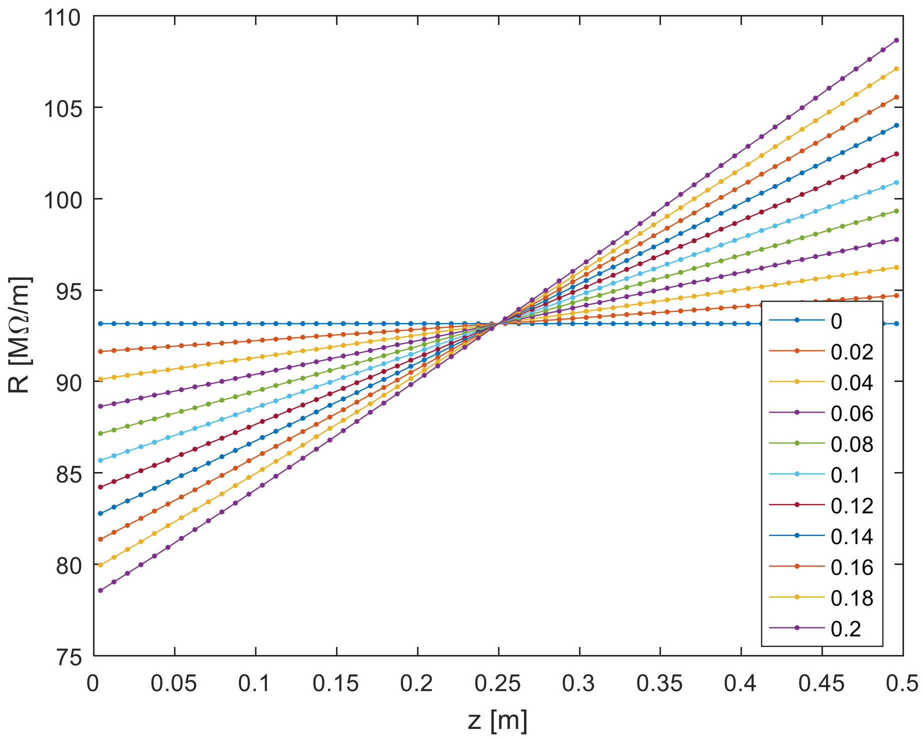


With an active length of 16 m we can have 32 structures of 0.5 m

Fixing the length of the structure (60 cells for example) and the slope of the tapering (from 0° to 0.2° for the moment, <a>=3.2 mm) it is possible to find the iris radius of each cell (every · is a cell) and then the related values of vg, R, Q, normalized modified Poynting vector using the polynomial fits.

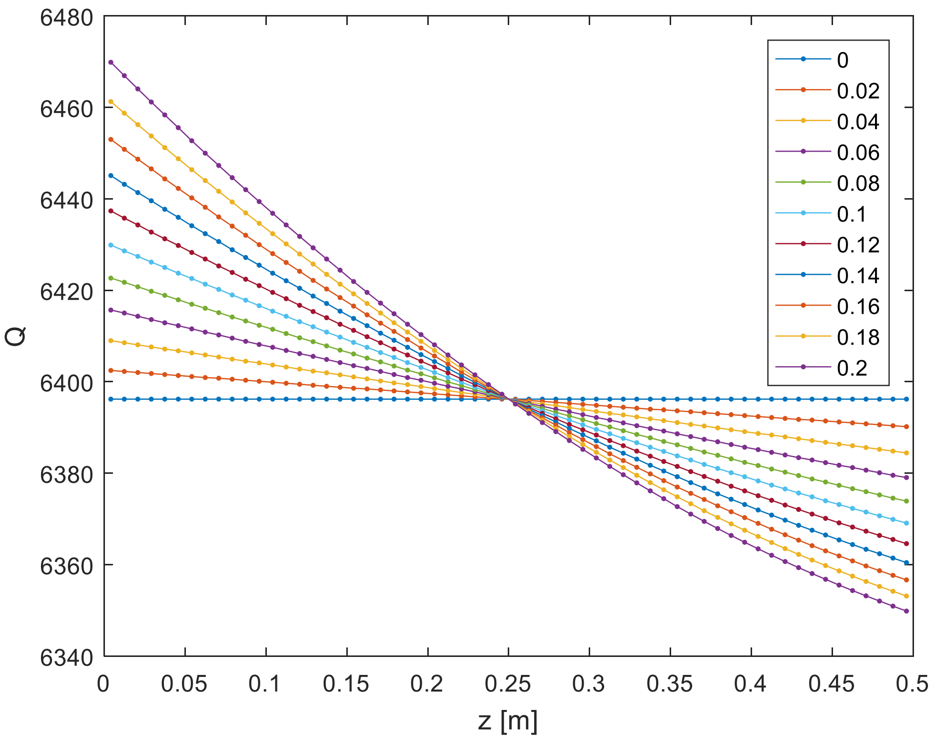
Ls=0.5m (60 cells), Ns=32

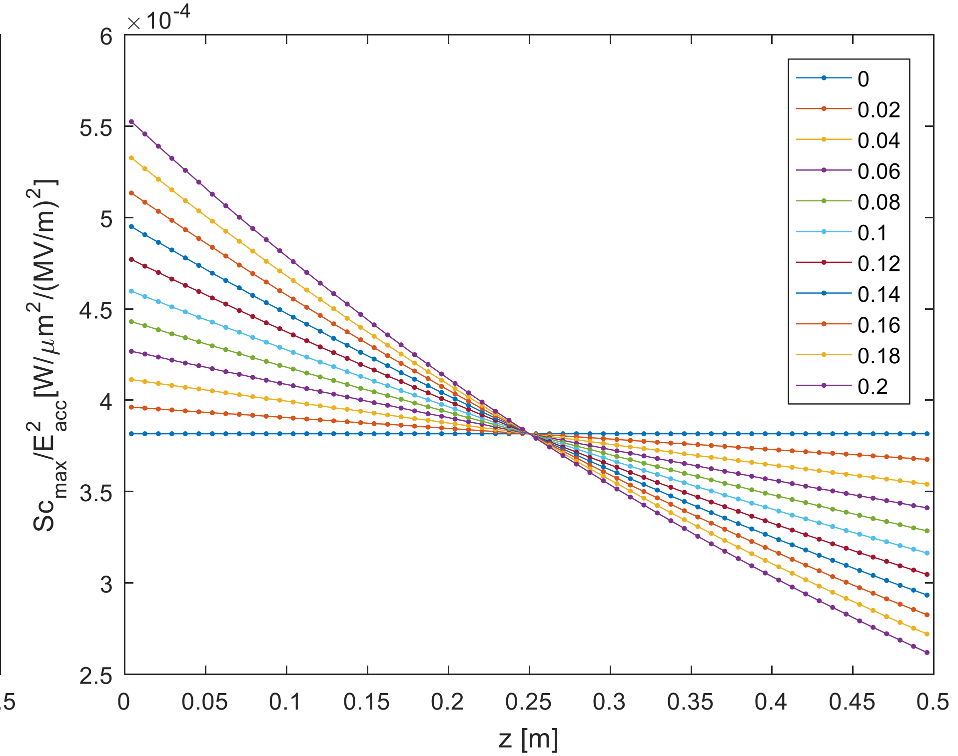




With a linear tapering there is a non-linear behavior of the group velocity along z.

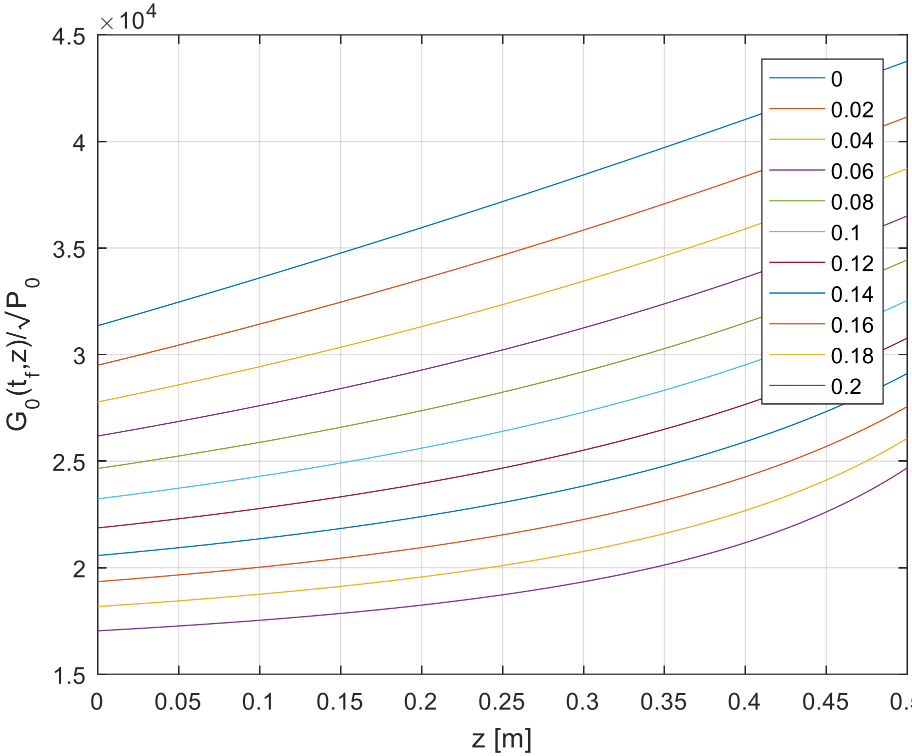
Ls=0.5m (60 cells), Ns=32

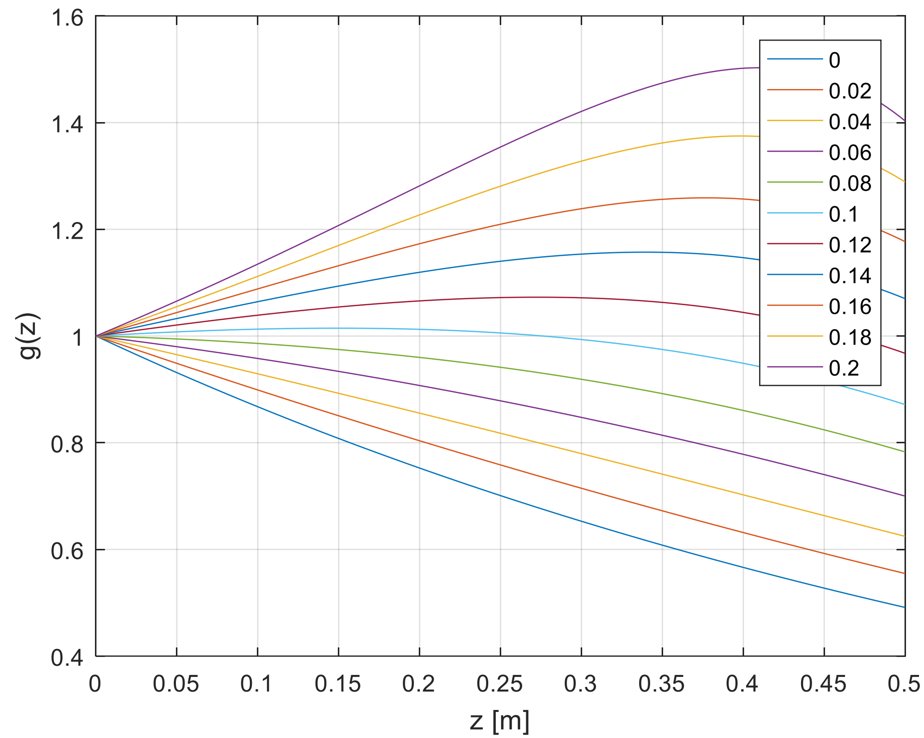




Since now we have the parameters of every cell it is possible to apply the general formulas in order to find the optimal slope for every fixed length (finding for each slope the optimal value of Qe for the SLED).

Ls=0.5m (60 cells), Ns=32, Q0=180000





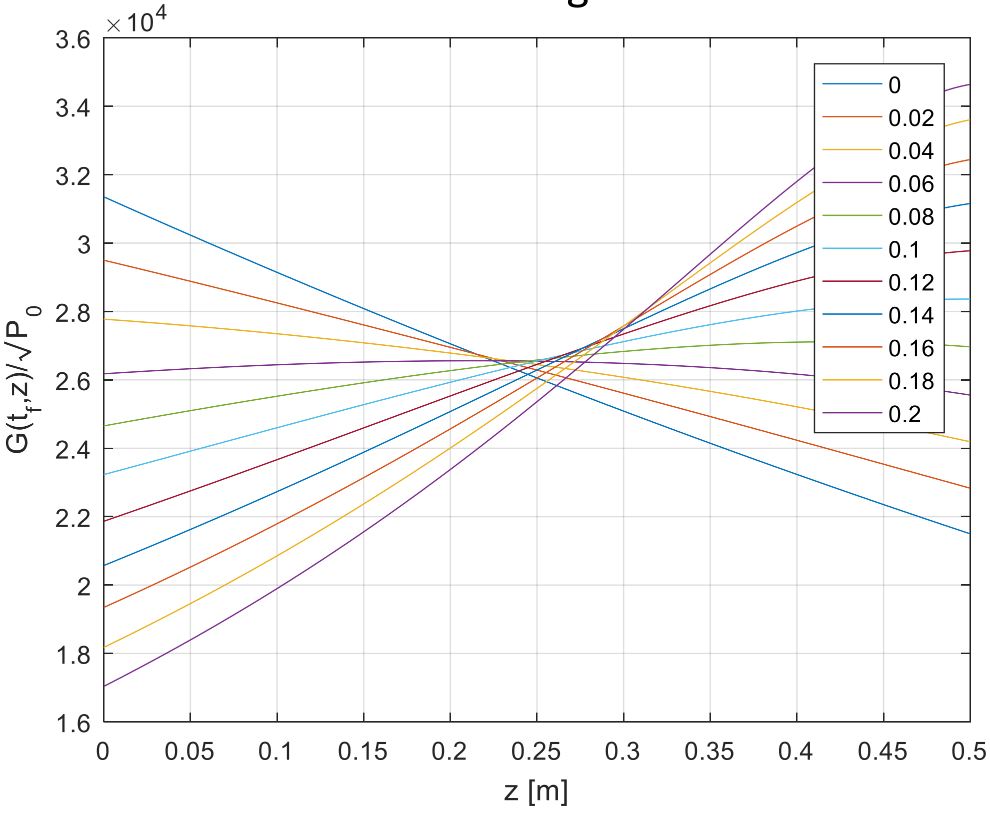
$$G_0[t_f - \tau(z)] = \sqrt{\frac{\omega}{v_g(0)} \frac{R(0)}{Q(0)} P_0} \, \frac{E_{out}}{E_K}(t_f - \tau(z))$$

$$g(z) = e^{-\int_0^z \alpha(z')dz'} = \sqrt{\frac{v_g(0)}{v_g(z)}} \sqrt{\frac{R(z)}{Q(z)} \frac{Q(0)}{R(0)}} e^{-\frac{1}{2}\int_0^z \frac{\omega}{v_g(z')Q(z')}dz'}$$

$$\alpha(z) = \frac{1}{2}\left[\frac{1}{v_g}\frac{dv_g}{dz} - \frac{1}{R/Q}\frac{d(R/Q)}{dz} + \frac{\omega}{v_g Q}\right]$$

Ls=0.5m (60 cells), Ns=32, Q0=180000

Normalized gradient vs z
after 1 filling time

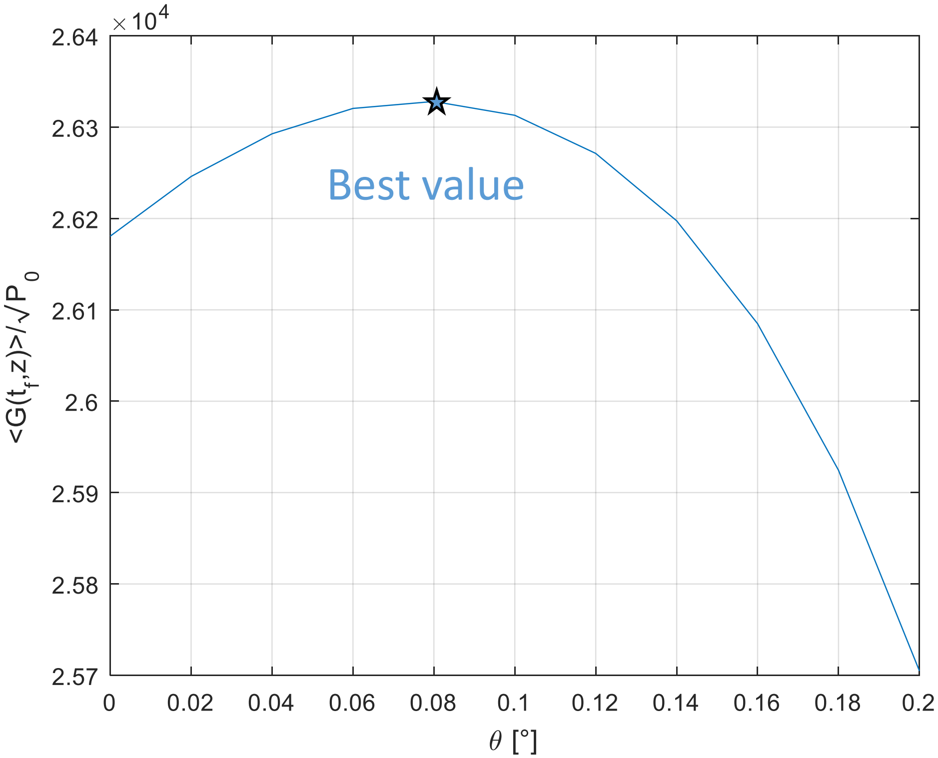


It is possible to observe that for each slope we obtain different profiles of the gradient.

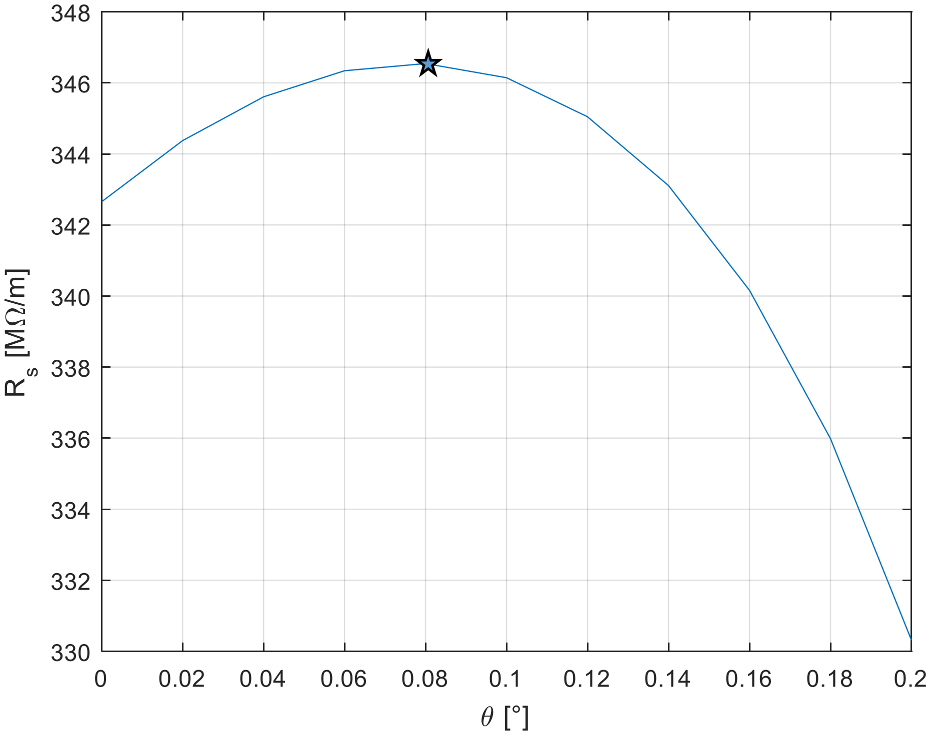
$$G(z,t_f) = G_0[t_f - \tau(z)]g(z) = \sqrt{\frac{\omega}{v_g(0)}\frac{R(0)}{Q(0)}P_0}\,\frac{E_{out}}{E_K}(t_f - \tau(z))\sqrt{\frac{v_g(0)}{v_g(z)}}\sqrt{\frac{R(z)}{Q(z)}\frac{Q(0)}{R(0)}}\,e^{-\frac{1}{2}\int_0^z \frac{\omega}{v_g(z')Q(z')}dz'}$$

Ls=0.5m (60 cells), Ns=32, Q0=180000

Average normalized gradient



Effective shunt impedance

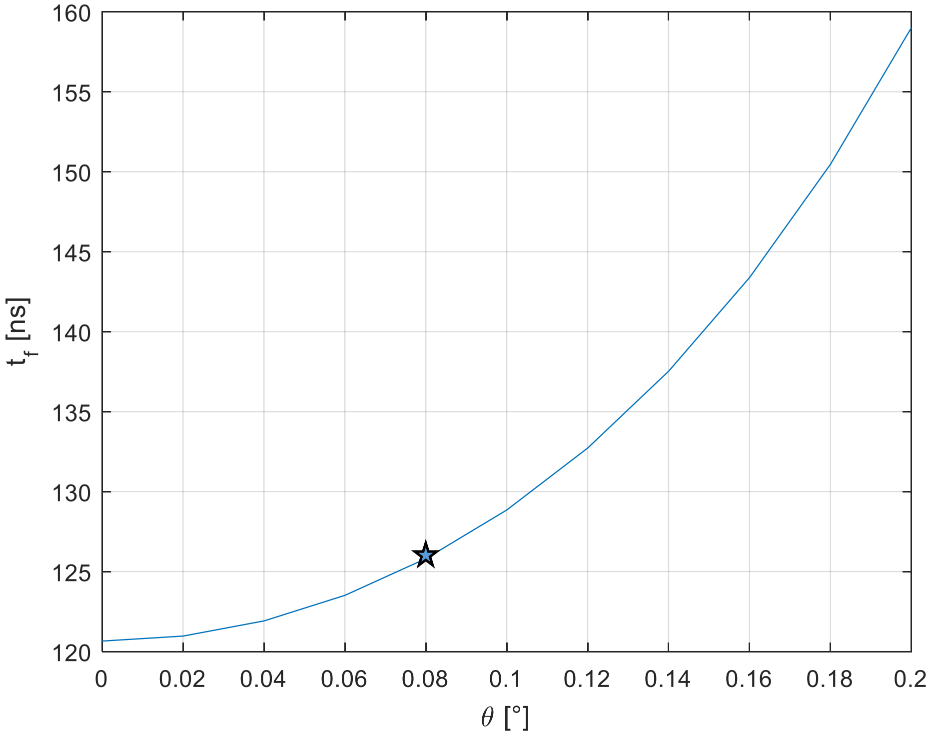


$$R_s = \frac{V_a^2}{P_0 L_s} \qquad V_a = \int_0^{L_s} dz' G(z', t' = t_f)$$

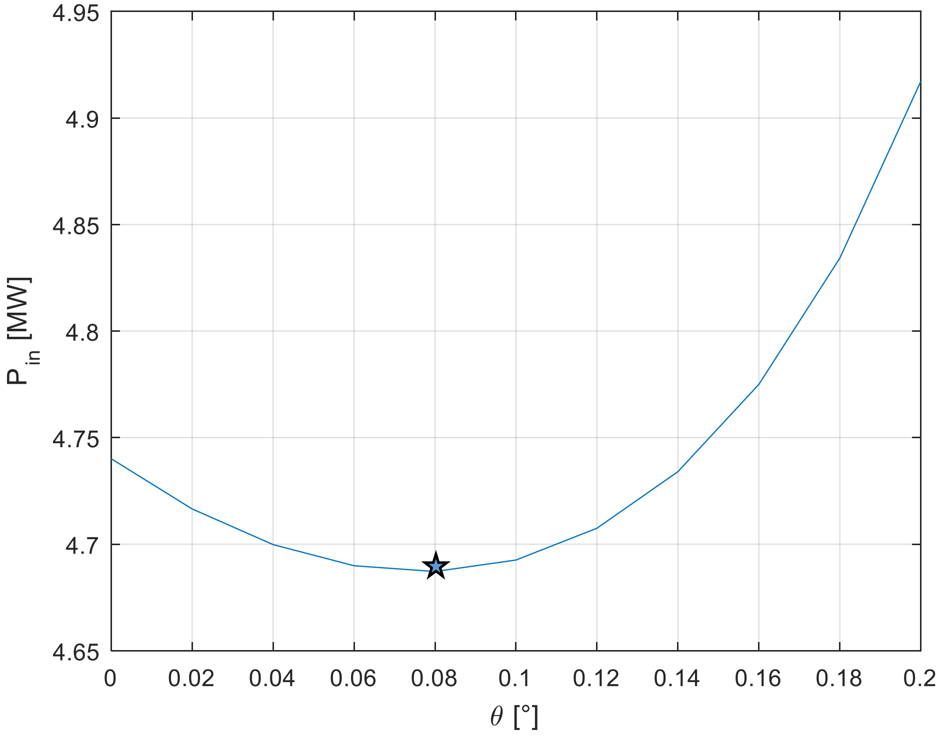
Considering the average (normalized to the input power) gradient or the effective shunt impedance we find that the optimal slope is 0.8° (corresponding to an iris radius variation from 3.5 mm to 2.9 mm).

Ls=0.5m (60 cells), Ns=32, Q0=180000

Filling time



Input power for each structure
(in order to obtain 57 MV/m)



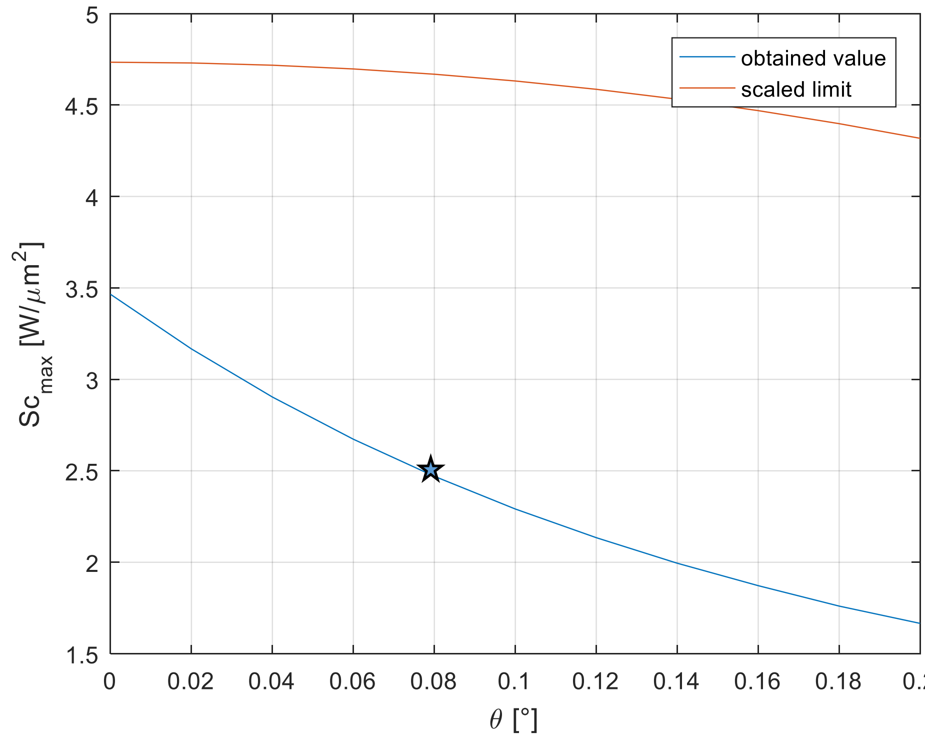
$$\tau(L_s) = \int_0^{L_s} \frac{dz'}{v_g(z')}$$

Ls=0.5m (60 cells), Ns=32, Q0=180000, <G>=57 MV/m

Modified Poynting vector (calculated at the first cell)

The modified Poynting vector should not exceed 4 W/um^2 in order to have BDR below 1x10^{-6} bpp/m at pulse length of 200 ns

For each slope we are below the scaled limit (for an average gradient of 57 MV/m)

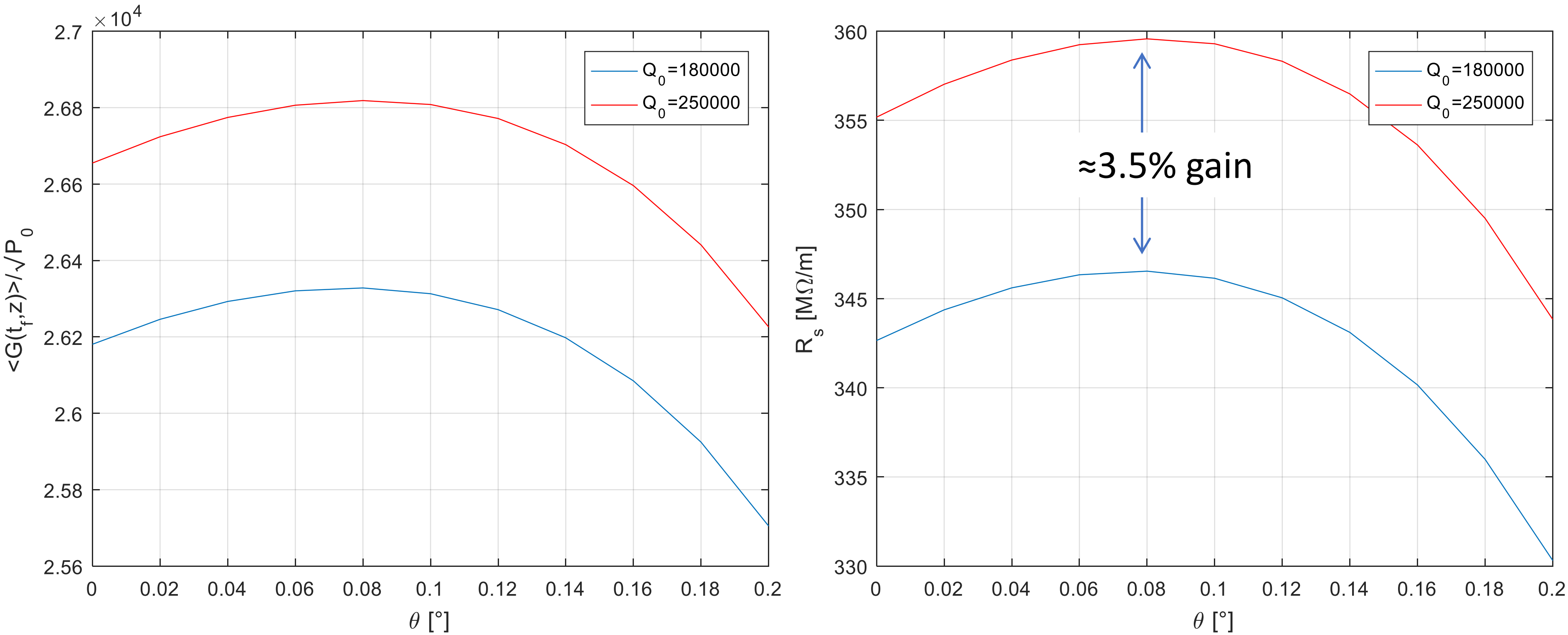


With this formula we take into account the fact that for every slope the filling time is slightly different

$$Sc_{scaled} = 4\, W/\mu m^2 \frac{(200\, ns)^{1/3}}{t_p^{1/3}} \quad [4]$$

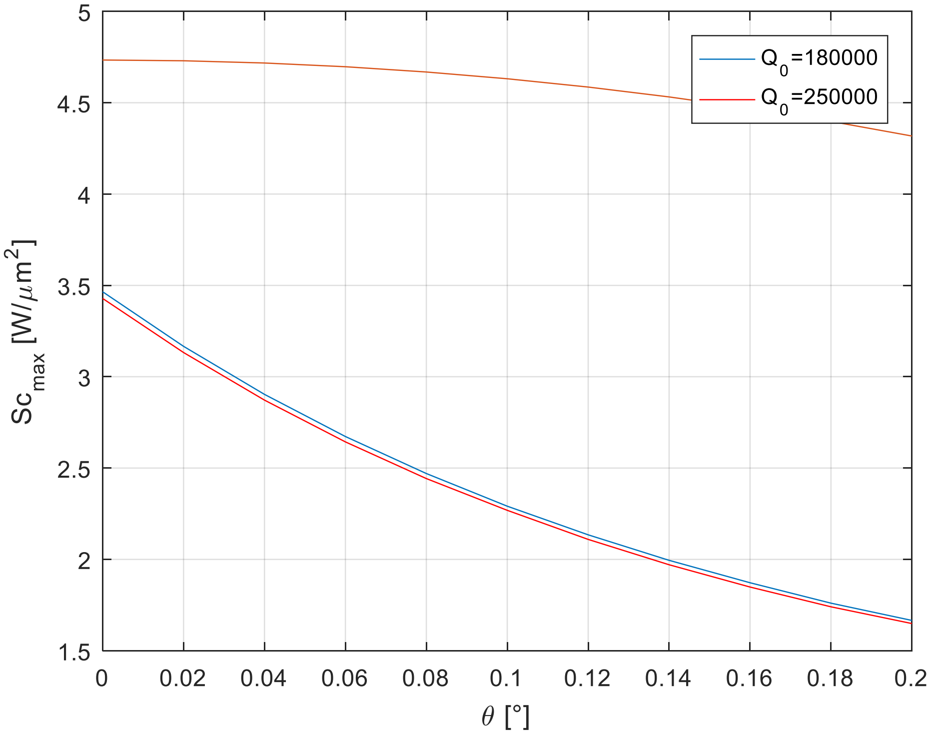
[4] A. Grudiev, S. Calatroni, and W. Wuensch, New local field quantity describing the high gradient limit of accelerating structures, PhysRevSTAB.12.102001 (2009)

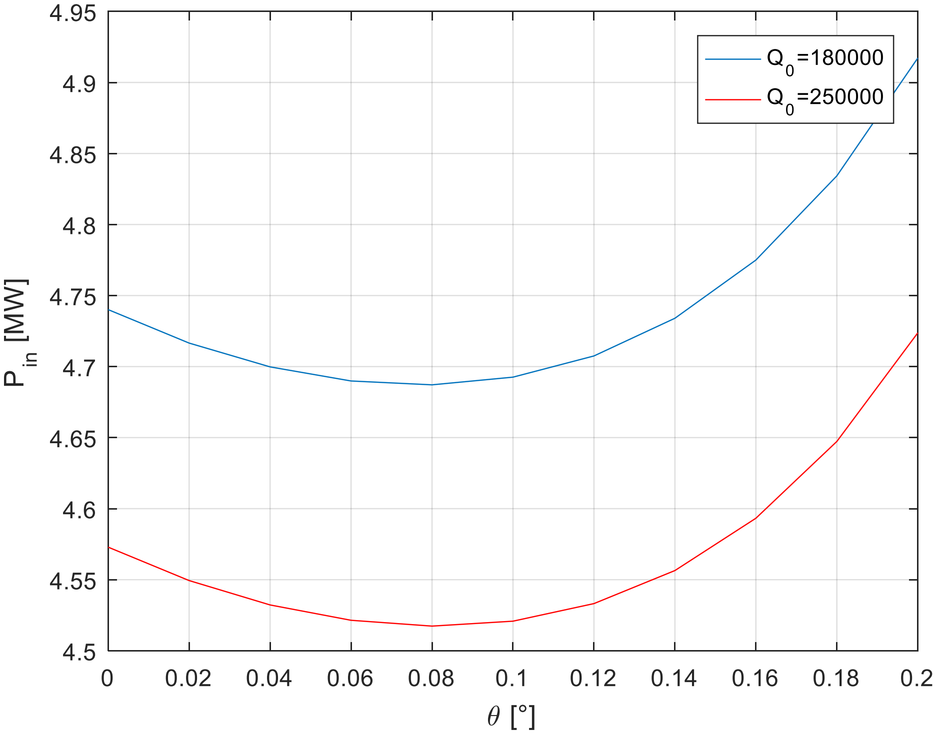
Ls=0.5m (60 cells), Ns=32, Q0=250000



We can repeat the same exercise with a Q0 of 250000 (barrel open cavity - **BOC solution**) and compute the gain in terms of average gradient (or Rs).

Ls=0.5m (60 cells), Ns=32, Q0=250000

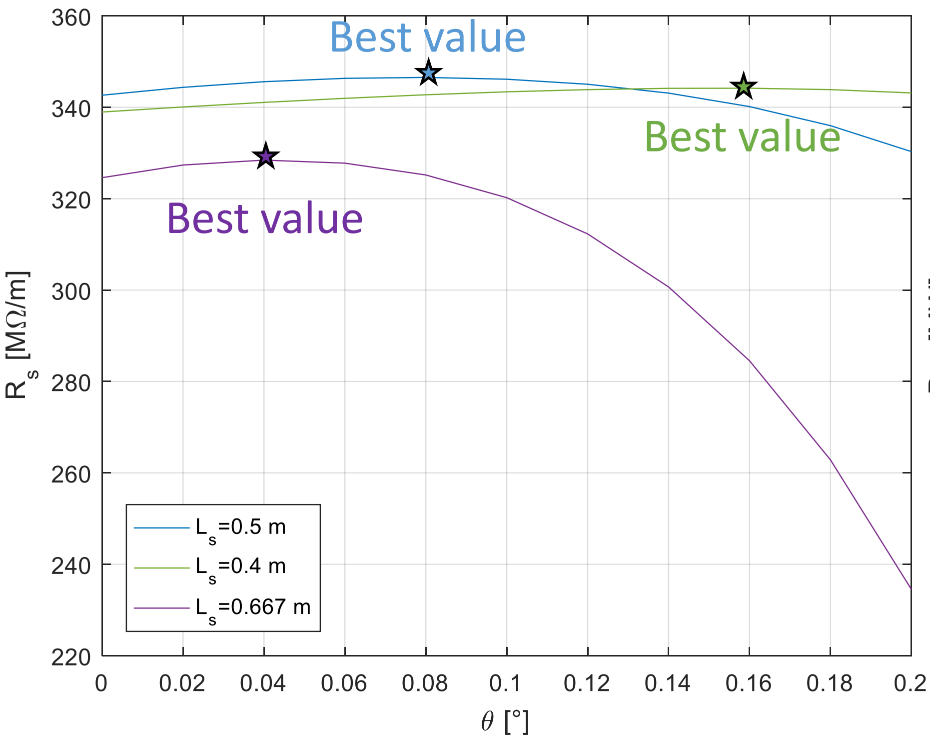


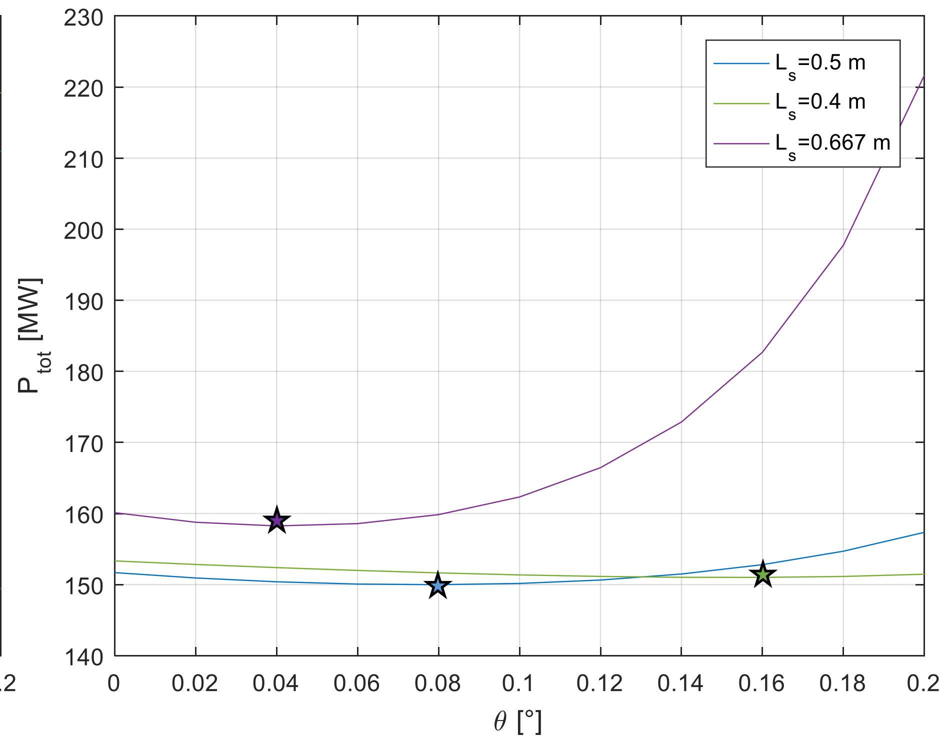


Other structure lengths

We can repeat the calculation considering other structure lengths: **0.4 m** (48 cells, 40 structures) and **0.667 m** (80 cells, 24 structures) for example. I fixed a **Q0 of 180000**.

Other structure lengths

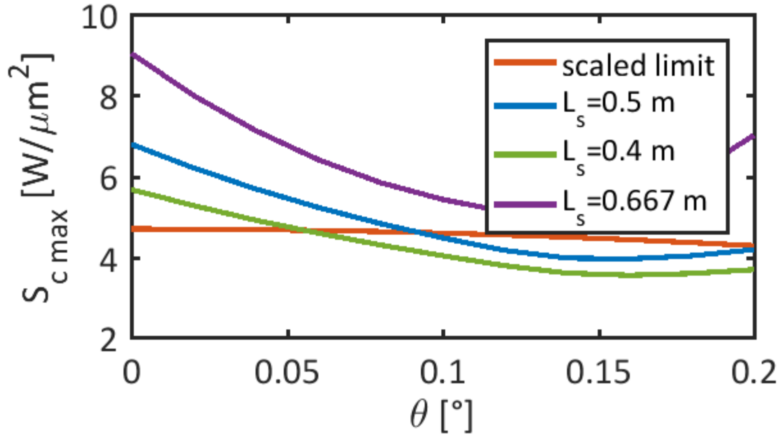




From this two plots we obtain that the best solutions are: 0.8° for 0.5 m (2.851mm<a<3.549mm) and 0.16° for 0.4 m (2.642mm<a<3.758mm). The longest option seems not so good as the other two.

Other structure lengths

80 MV/m



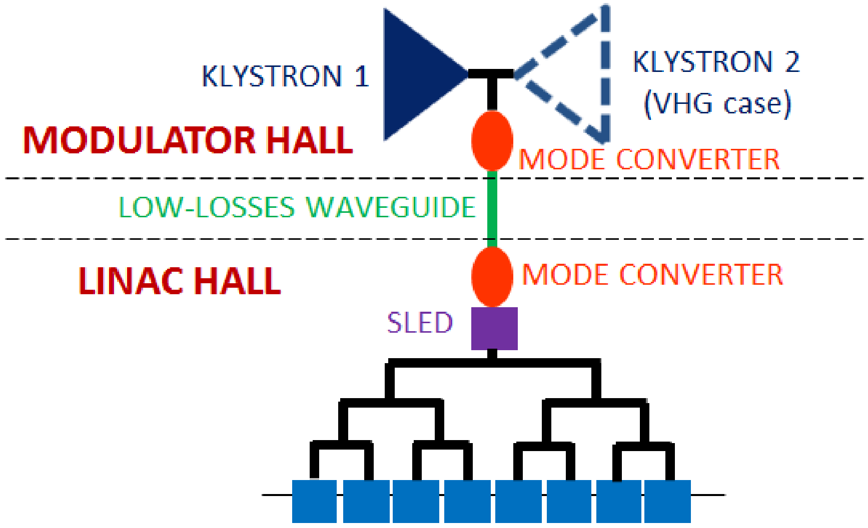
Considering the best solutions for 0.5m and 0.667m cases, the modified Poynting vector is above the scaled limit in the 80 MV/m scenario, anyway it is possible to move towards harder tapering in order to stay below. The 0.5 m solution with an angle of slope of 0.1° has been chosen.

Results and RF layout

LINAC parameters		
<a> [mm]	3.2	
a first-last cell [mm]	3.636 – 2.764	
L_s [m]	0.5	
No. of cells N_c	60	
L_t [m]	16	
No. of structures N_s	32	
Q_e	21800	
v_g/c [%]	2.2 – 0.78	
t_p [ns]	129	
R_S [MΩ/m]	346	
Available RF power / klystron	50 MW (@ klystron output coupler) 40 MW (@ section input couplers)	
	HG option	VHG option
<G> [MV/m]	57	80
W_{gain} [MeV]	912	1280
P_{RF} [MW]	150	296
No. of klystrons N_k	4	8

The TW X-band accelerating sections optimized for the EuPRAXIA@SPARC_LAB application are **0.5 m** long and show an effective shunt impedance per unit length value of **346 MΩ/m** including the peak power gain provided by the pulse compressor. Commercially available X-band klystrons provide up to **50 MW** peak power in **1.5 µs** long pulses. **RF losses** in the waveguide distribution system reduce the klystron available power to the accelerating sections by **≈ 20%**, so that a single tube can actually deliver **≈ 40 MW** and power 8 TW structures in parallel up to the required gradient. The **basic RF module** of the EuPRAXIA@SPARC_LAB X-band LINAC can be conveniently composed by a group of **8 TW sections** assembled on a single girder and powered by a **one (for HG) or two (for VHG) klystrons** by means of one pulse compressor system and a waveguide network splitting and transporting the RF power to the input couplers of the sections.

Results and RF layout



RF MODULE FOR EUPRAXIA@SPARCLAB

- 8 TW sections (60 cells – 50 cm active length each)
- 4 m active length, ≈5 m actual length
- 57 MV/m gradient with 1 klystron + pulse compressor
- 80 MV/m gradient with 2 klystrons + pulse compressor (VHG option)

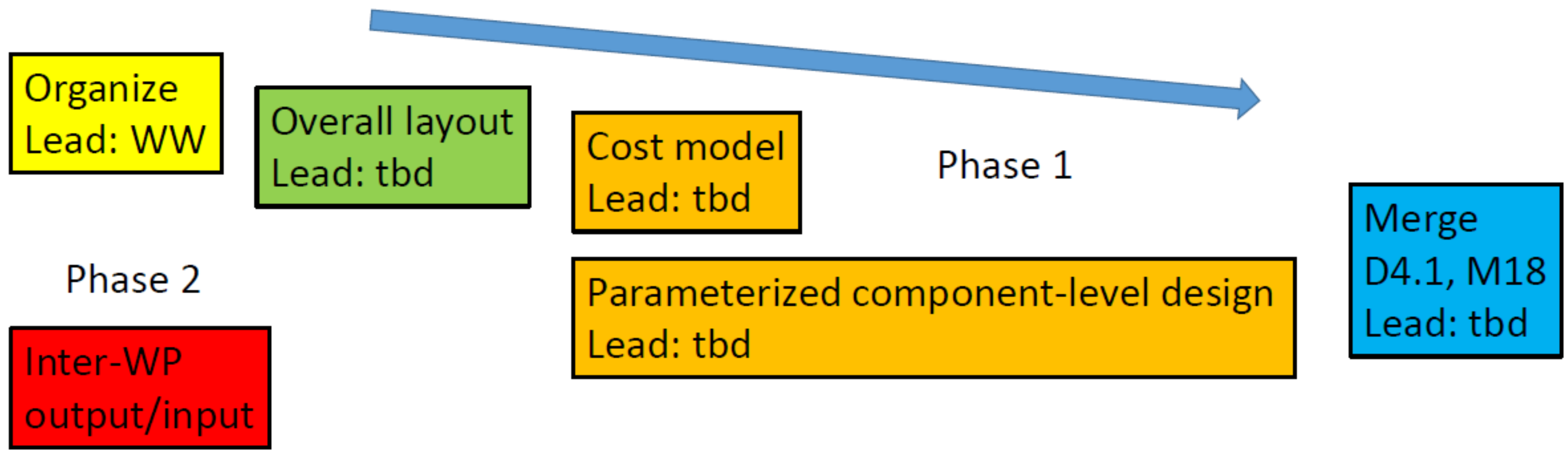
Compact Light Accelerating Structure Design Workflow

- Define an average iris value
- Find the highest effective shunt impedance structure by scanning the total length, iris tapering and pulse compressor characteristics
- Chose a reference value of the accelerating field
- Verify the max modified Poynting vector values @ nominal gradient
- Design power distribution networks on the base of existing klystrons. Propose a limited number of alternatives.
- Elaborate a cost model to compare different configurations providing different (but still well beyond the present state of the art) operational accelerating gradients.
- Finalize the electromagnetic (input and output couplers) and mechanical design of the structures
- Design a realistic RF module

Iterations among these various steps will be very likely needed, as a consequence of discussions and data exchange with others WPs.

Compact

Tasks, workflow and responsibilities



	Technical area						Activity			
	Modulator	Power source	Waveguide network	Accelerating structures	Module	LLRF/control/ diagnostics	rf design/ optimization	Mechanical design	Layout/ integration	Costing/ industrialization
CERN		■	■	■	■		■	■	■	■
CNRS-LAL				■			■			
INFN Frascati			■	■			■		■	
Institute of Accelerator Technology, Ankara				■			■			
SINAP	■		■	■			■	■	■	
Sincrotrone Trieste										
University of Helsinki/HIP					■			■	■	■
University of Melbourne/ANSTO			■			■	■			
University of Strathclyde		■					■			
Uppsala University	■									■
VDL			■	■	■			■	■	■

INFN-LNF contribution to WP4 (towards D4.1, M18)

≈ 6 months FTE (to be more precisely defined)

Persons involved:

A. Gallo / D. Alesini (supervision)

M. Diomede (RF design: calculations and simulations)

F. Cardelli / L. Piersanti (support to RF design)

B. Buonomo / M . Bellaveglia (support and discussion)