RF design of high gradient accelerating structures for high brightness electron linacs

Accelerator Division: Young researchers presentations

27/03/2018

Marco Diomede

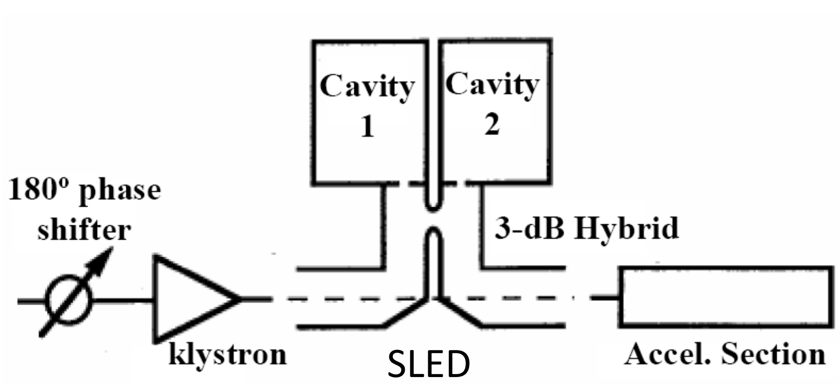
Outline

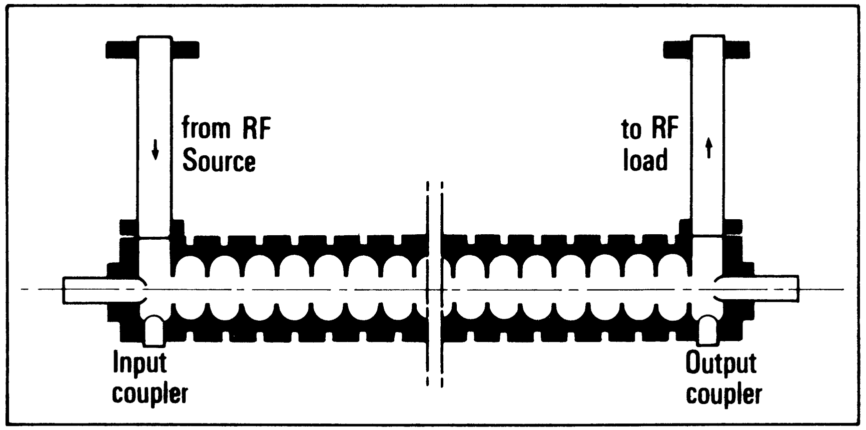
- Introduction
  - Traveling wave accelerating structures
  - Pulse compressor: SLED
  - Design parameters
  - Breakdown
- Context
  - The EuPRAXIA@SPARC_LAB project
- Activity and overall progress
  - Single cell design
  - X-band booster optimization
  - Coupler study
  - Mechanical drawings
- Work in progress

Outline

- Introduction
    - Traveling wave accelerating structures
    - Pulse compressor: SLED
    - Design parameters
    - Breakdown
- Context
    - The EuPRAXIA@SPARC_LAB project
- Activity and overall progress
    - Single cell design
    - X-band booster optimization
    - Coupler study
    - Mechanical drawings
- Work in progress

Traveling wave accelerating structures



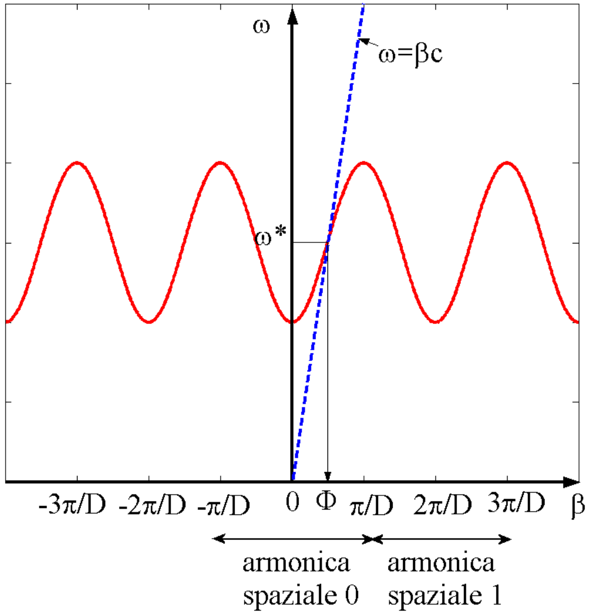


Propagation constant

$$\beta = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_t^2} \Rightarrow v_{ph} = \frac{c}{\sqrt{1-\left(\frac{k_t c}{\omega}\right)^2}} > c$$

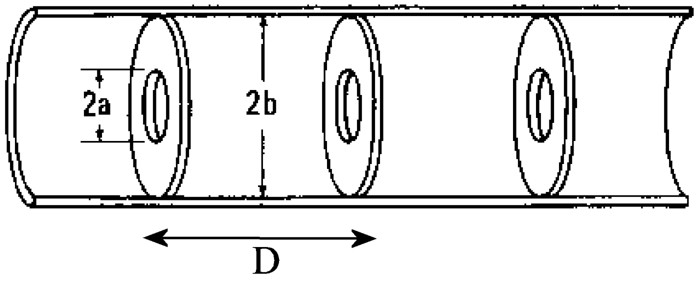
dipendente dalla geometria della guida e dal modo considerato

Phase velocity



Phase advance

$$\Phi = \beta D = \frac{\omega}{v_{ph}} D = \frac{\omega}{c} D$$

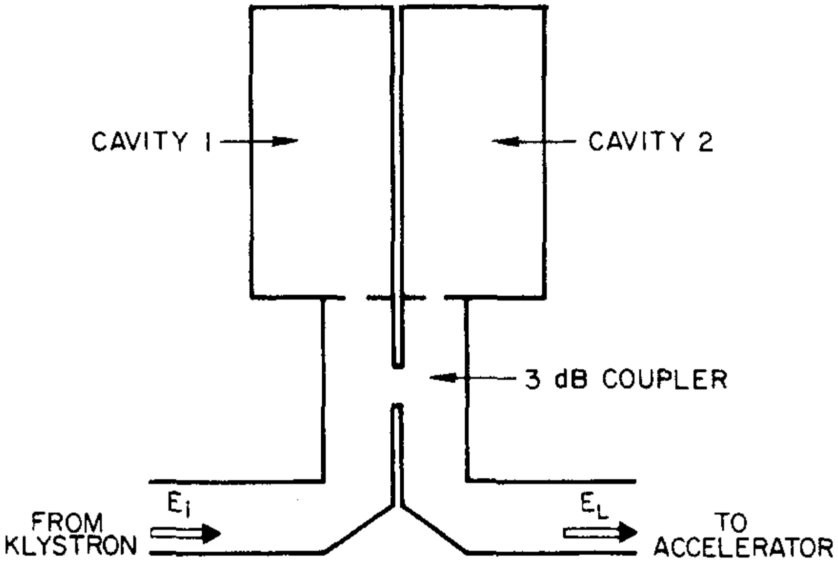


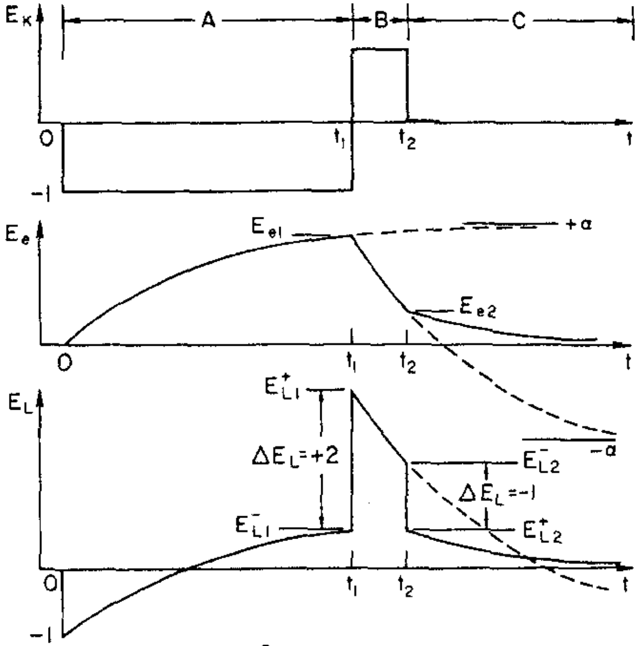
A TWAS is basically a **circular waveguide loaded by irises** in order to slow down the wave phase velocity.
The spacing D between the irises determines the **phase advance per cell**.

Courtesy of A. Gallo and D. Alesini

Pulse compressor: SLED

A pulse compressor is a component that allows to increase the peak power at the section input by reducing the pulse length. This is obtained by combing the power reflected by 2 high-Q cavities.





$$\frac{E_{out}}{E_K}(t) = -\alpha e^{-\frac{t\omega}{2Q_L}} + (\alpha-1), \quad 0<t<t_1$$

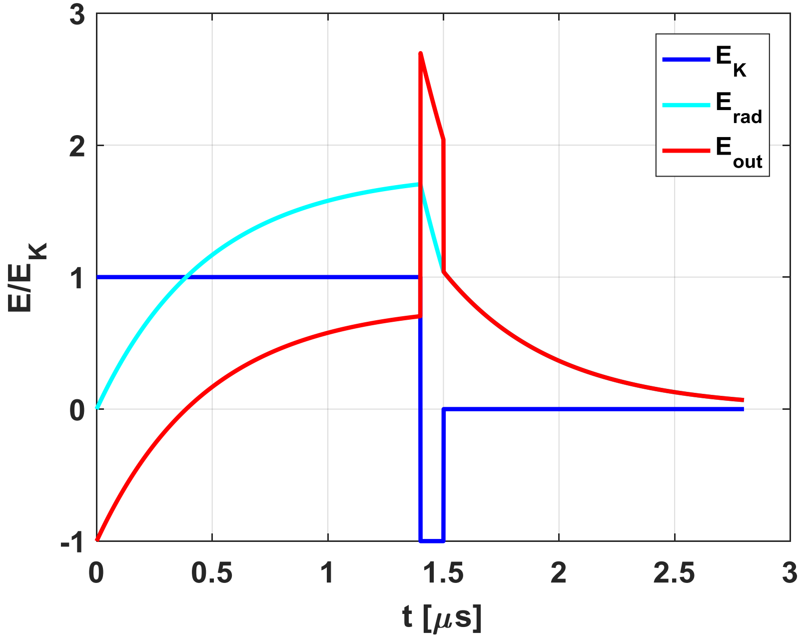
$$\frac{E_{out}}{E_K}(t) = \gamma e^{-\frac{(t-t_1)\omega}{2Q_L}} - (\alpha-1), \quad t_1<t<t_2$$

$$\frac{E_{out}}{E_K}(t) = \left[\gamma e^{-\frac{(t_2-t_1)\omega}{2Q_L}} - \alpha\right] e^{-\frac{(t-t_2)\omega}{2Q_L}}, \quad t>t_2$$

$$\alpha = \frac{2\beta}{1+\beta} = 2\frac{Q_l}{Q_e}, \quad \beta = \frac{Q_0}{Q_e}$$

$$Q_L = \frac{Q_0}{1+\beta}, \quad \gamma = \alpha\left(2-e^{-\frac{t_1\omega}{2Q_L}}\right) = 2\frac{Q_l}{Q_e}\left(2-e^{-\frac{t_1\omega}{2Q_L}}\right)$$

$$P_{out\_SLED}(t) = P_K(t=0)\left(\frac{E_{out}}{E_K}(t)\right)^2$$



Example: compressed pulse of 100 ns with a Q_e of 20000

Z. Farkas, et al. , SLED: A method of doubling SLAC's energy, Proc. Of 9th Int. Conf. On High Energy Accelerators, 1974, p. 576.

Design parameters

Cell parameters:

$$Q = \omega_{RF} \frac{w}{p_{diss}}$$

Quality factor

It measures the merit of a cell as a resonator

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

Shunt impedance per unit length

It defines the efficiency of the cell

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

Group velocity

It is the velocity at which RF energy flows

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

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

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

with R shunt impedance per unit lenght and Q quality factor

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

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

$Hyp: \frac{R}{Q}$ 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: $\boxed{R_s = \frac{V_a^2}{P_K(t=0)L_s} [\Omega/m]}$

It defines the efficiency of the structure

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

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

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

Breakdown

The major obstacle to high gradient is **RF breakdown**. It is a phenomenon that abruptly changes transmission and reflection RF power directed towards the structure. A local field quantity which predicts the high gradient performance of an accelerating structure is the **modified Poynting vector S_c**:

$$S_c = \mathrm{Re}\{\bar{S}\} + g_c \,\mathrm{Im}\{\bar{S}\} \left[\frac{W}{m^2}\right], \text{with } g_c = \frac{1}{6}$$

The dependence of the modified Poynting vector on RF pulse length t_p at a fixed breakdown rate (BDR) ha well established **scaling law** observed in many experiments:

$$\frac{S_c^{15} t_p^5}{BDR} = const$$

The **BDR** is defined as the probability of having a breakdown and it is typically measured in breakdown per pulse for 1 m long structure. As design guideline for a new RF structure, S_c should not exceeds **4 MW/mm^2** if the structure is supposed to operate at a breakdown rate smaller than **10^{-6} bpp/m** and a pulse length of **200 ns**.

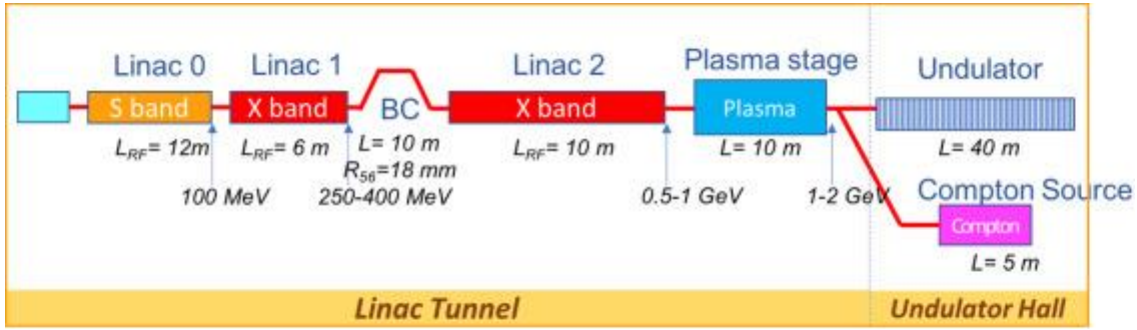
A. Grudiev, S. Calatroni, and W. Wuensch, PhysRevSTAB.12.102001 (2009)
K. Sjobak, E. Adli, A. Grudiev, MOPP028, Proc. of LINAC2014 (2014)

Outline

- Introduction
  - Traveling wave accelerating structures
  - Pulse compressor: SLED
  - Design parameters
  - Breakdown
- Context
  - The EuPRAXIA@SPARC_LAB project
- Activity and overall progress
  - Single cell design
  - X-band booster optimization
  - Coupler study
  - Mechanical drawings
- Work in progress

The EuPRAXIA@SPARC_LAB project

New multi-disciplinary user-facility, equipped with a **soft X-ray Free Electron Laser (FEL)** driven by a **~1 GeV** high brightness linac based on **plasma accelerator modules**. This design study is performed in synergy with the **EuPRAXIA** design study.



2 cases:

- w plasma acceleration
- w/o plasma acceleration

L1 and L2 linac parameter list				
L_t [m]	16			
	PWFA	LWFA	Full RF	Ultimate
W_0 [MeV]	102	98	171	171
W_L [MeV]	582	550	1052	1450
<G> [MV/m]	20(L1)-36(L2)	20(L1)-36(L2)	57	80

RF parameters	
f [GHz]	11.9942
t_k [μs]	1.5
Q_0 SLED	180000

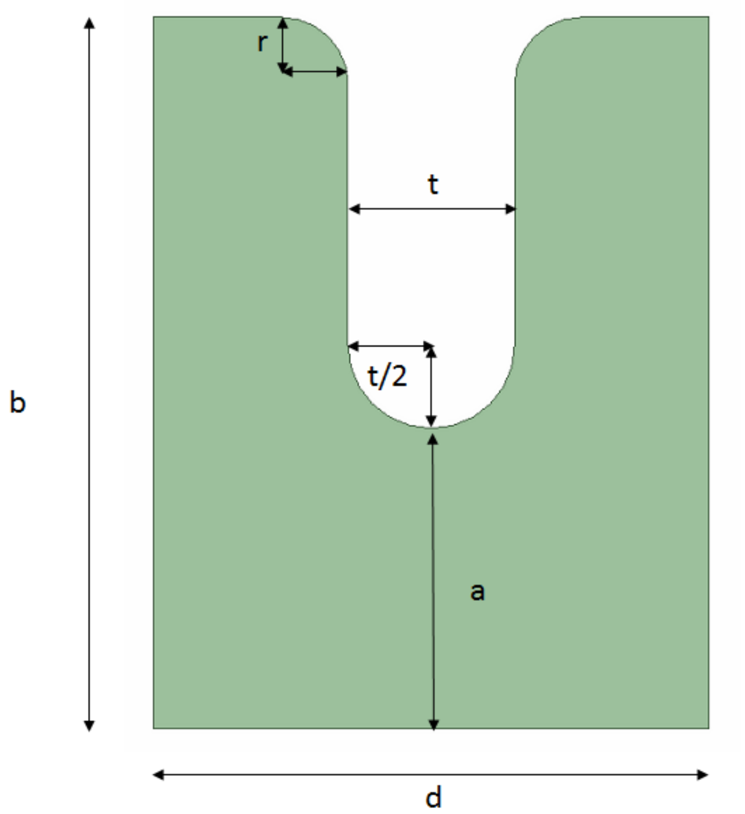
Ultimate: Full RF with double power (a factor of $\sqrt{2}$ in terms of gradient)

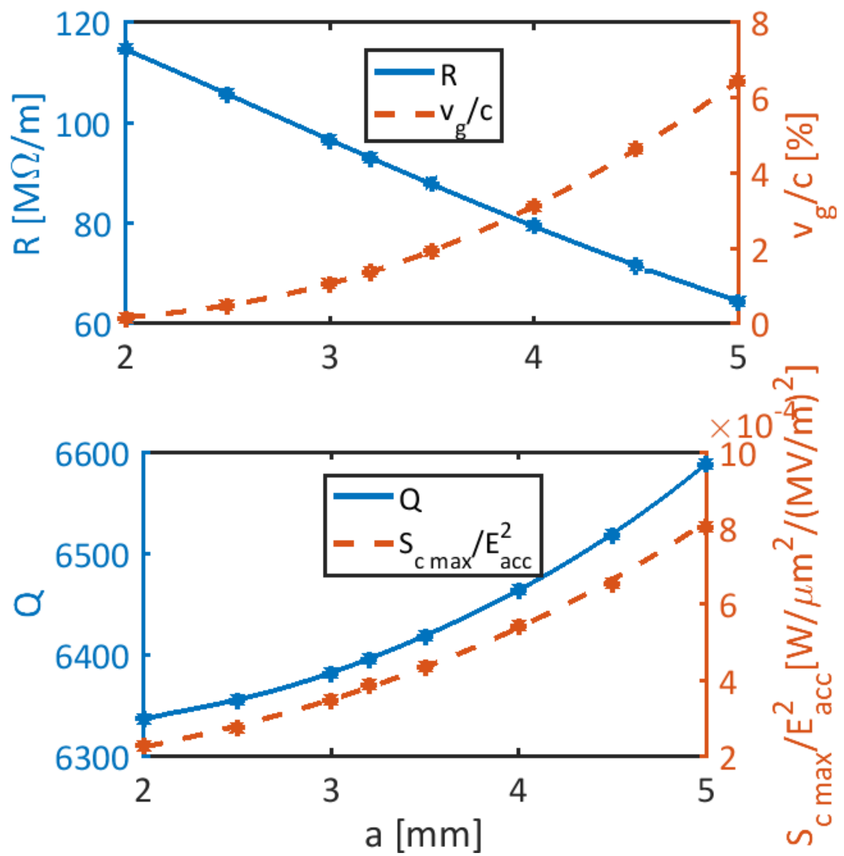
M. Ferrario et al., EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF, proceedings of EAAC2017.

Outline

- Introduction
    - Traveling wave accelerating structures
    - Pulse compressor: SLED
    - Design parameters
    - Breakdown
- Context
    - The EuPRAXIA@SPARC_LAB project
- Activity and overall progress
    - Single cell design
    - X-band booster optimization
    - Coupler study
    - Mechanical drawings
- Work in progress

Single cell design





Single cell parameters (a=3.2 mm)	
a [mm]	3.2
b [mm]	10.139
d [mm]	8.332
r [mm]	1
t [mm]	2.5
R [MΩ/m]	93
v_g/c [%]	1.382
Q	6396
$S_{c\,max}/E^2_{acc}$ [A/V]	$3.9\cdot10^{-4}$

A scan of the iris radius a **from 2 mm to 5 mm** 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.

According to beam dynamics calculations and single bunch beam break up limits, an **average iris radius <a>=3.2 mm** has been taken into account for the optimization.

C. Vaccarezza et al., EuPRAXIA@SPARC_LAB: Beam Dynamics studies for the X-band Linac, proceedings of EAAC2017.

X-band booster design: analytical optimization

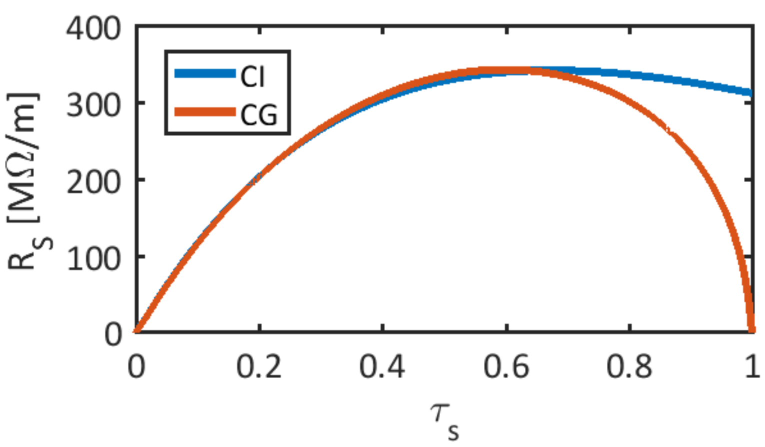
Two kinds of **analytical solution** it is possible to find in literature: **Constant Impedance (CI)** and **Constant Gradient (CG)** structure. CI: $v_g(z)$=const, CG: $g(z)$=const.

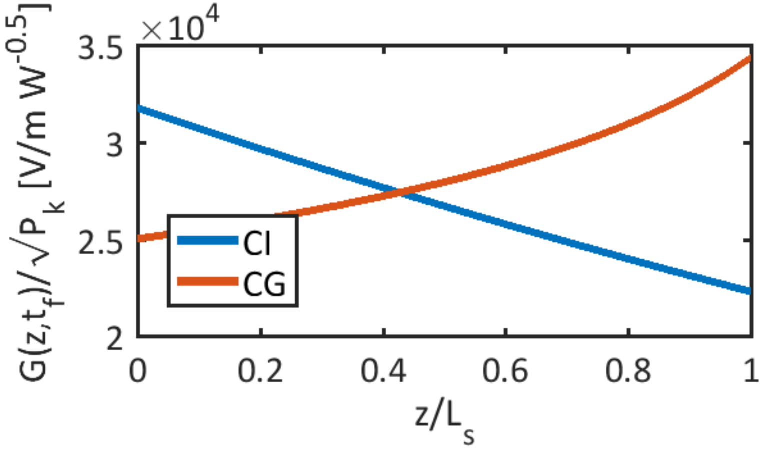
$$R_s = 2\tau_s R\left[\frac{\left(1-\frac{2Q_l}{Q_e}\right)}{\tau_s}\left(1-e^{-\tau_s}\right)+\frac{\left(\frac{2Q_l}{Q_e}\left[2-e^{-(\tau_k-\tau_p)}\right]\right)}{\tau_s\left(1-\frac{Q}{Q_l}\right)}\left(e^{-\tau_s\frac{Q}{Q_l}}-e^{-\tau_s}\right)\right]^2$$

CI

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

CG





Optimal structure parameters		
	CI	CG
R_S [MΩ/m]	343	344
L_s [m]	0.474	0.432
t_p [ns]	114	118
Q_e of SLED	20030	21170

The **CG solution** is approximated because of the assumption of constant R/Q along the structure. On the other hand, in the **CI case**, one exceeds the maximum value of S_c that allows to have a BDR lower than 10^{-6} bpp/m (Ultimate case).

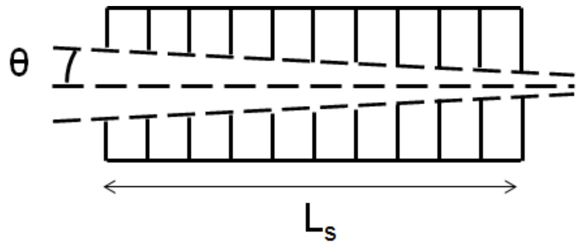
For these reasons, also a **numerical study** has been performed.

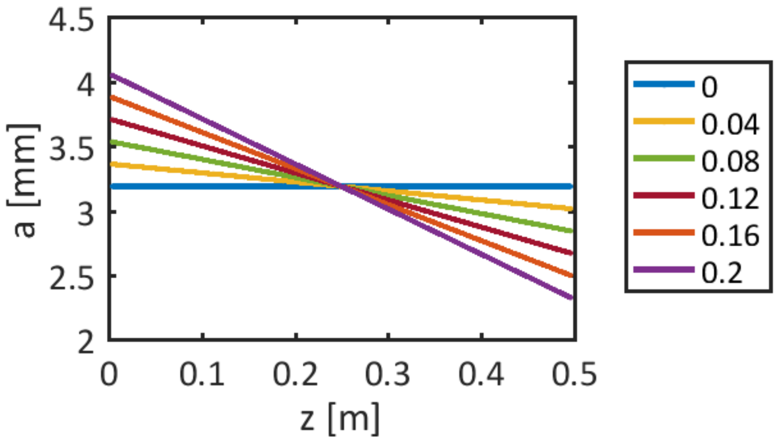
J. Le Duff, High-field electron linacs, CERN Yellow report CERN-95-06, 1995.

Z. Farkas, et al. , SLED: A method of doubling SLAC's energy, Proc. Of 9th Int. Conf. On High Energy Accelerators, 1974, p. 576.

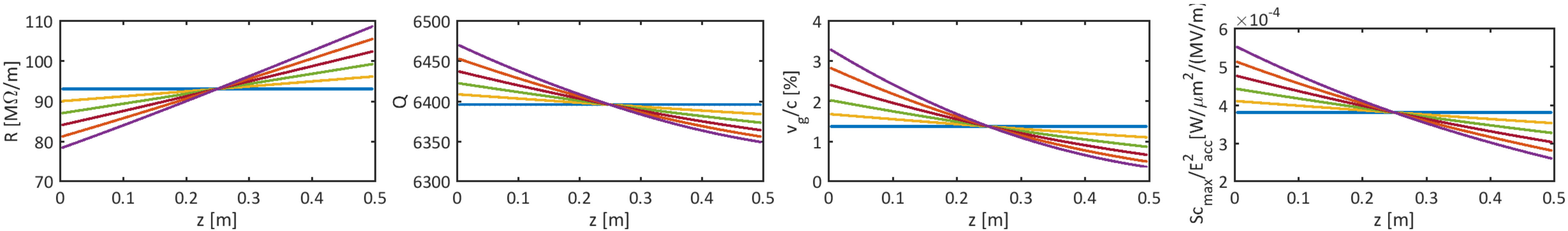
X-band booster design: numerical optimization

A **linear tapering** of the irises, defined by the modulation angle θ, has been considered.

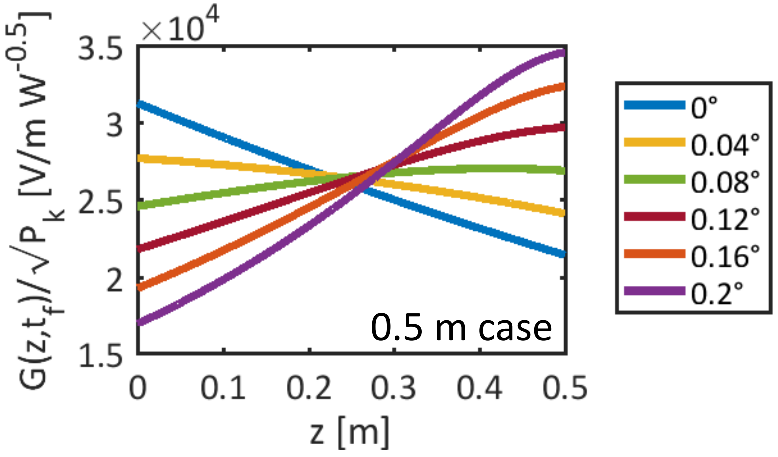


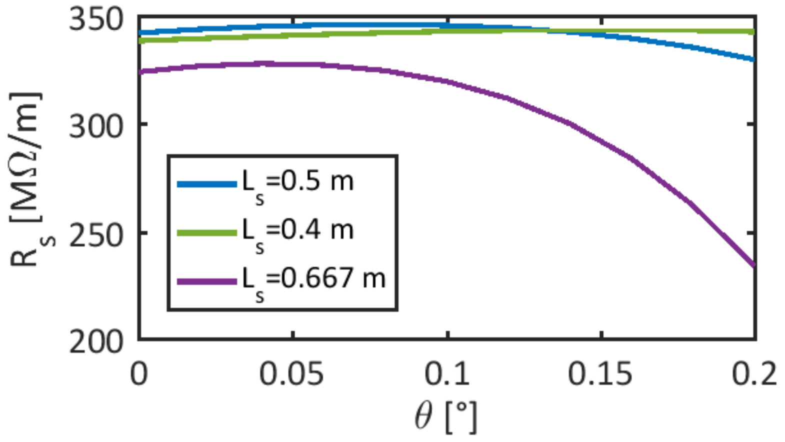


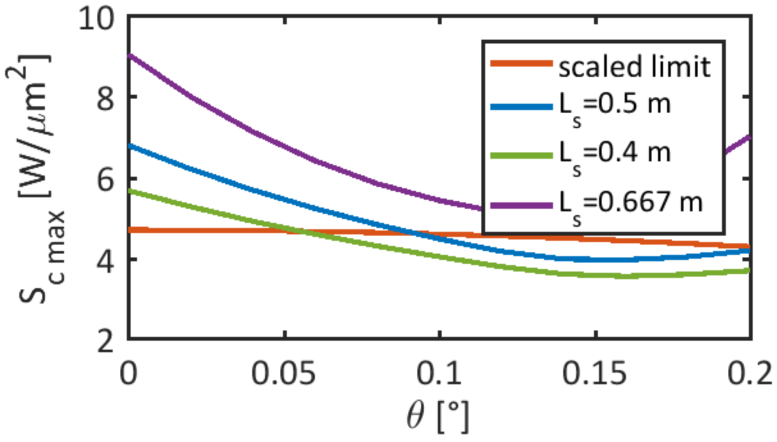
Once defined the values of θ and L_s (No. of cells per structure) it is possible to obtain the value of the **single cell parameters along the structure** using the polynomial fits.



X-band booster design: numerical optimization







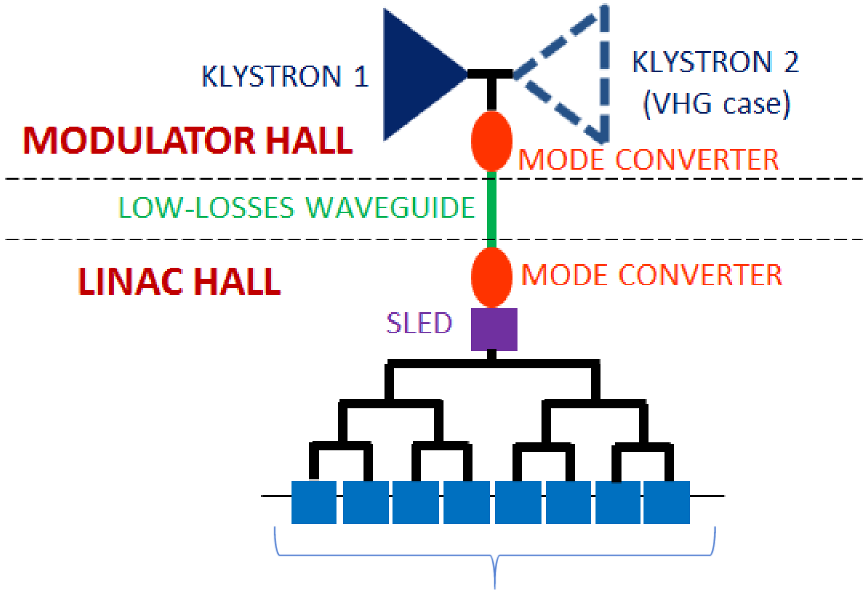
The **gradient profile** along the structure for different θ (0°-0.2°) and L_s (0.4 m: 40 structures, 0.5 m: 32 structures, 0.667 m: 24 structures) has been calculated. From the gradient profiles the **effective shunt impedance per unit length** and the **peak value of the modified Poynting vector** have been calculated.

The 0.4 m and 0.5 m long structures have the same efficiency. The 0.4 m solution has a better value of S_c but requires a higher number of structures per unit length. The **0.5 m case with θ = 0.1°** has been chosen as the **design baseline** for the X-band linac.

The same calculations have been performed to study a **C-band** and an **X-band cryogenic booster**.

X-band booster design: results & basic layout

X-band booster parameters		
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 [%]	2.23 – 0.77	
t_p [ns]	129	
R_S [MΩ/m]	346	
WG attenuation	≈ 20%	
	Full RF	Ultimate
<G> [MV/m]	57	80
W_{gain} [MeV]	912	1280
P_{RF} [MW]	150	296
No. of klystrons N_k	4	8



8 structures per module

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 **one or two 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.

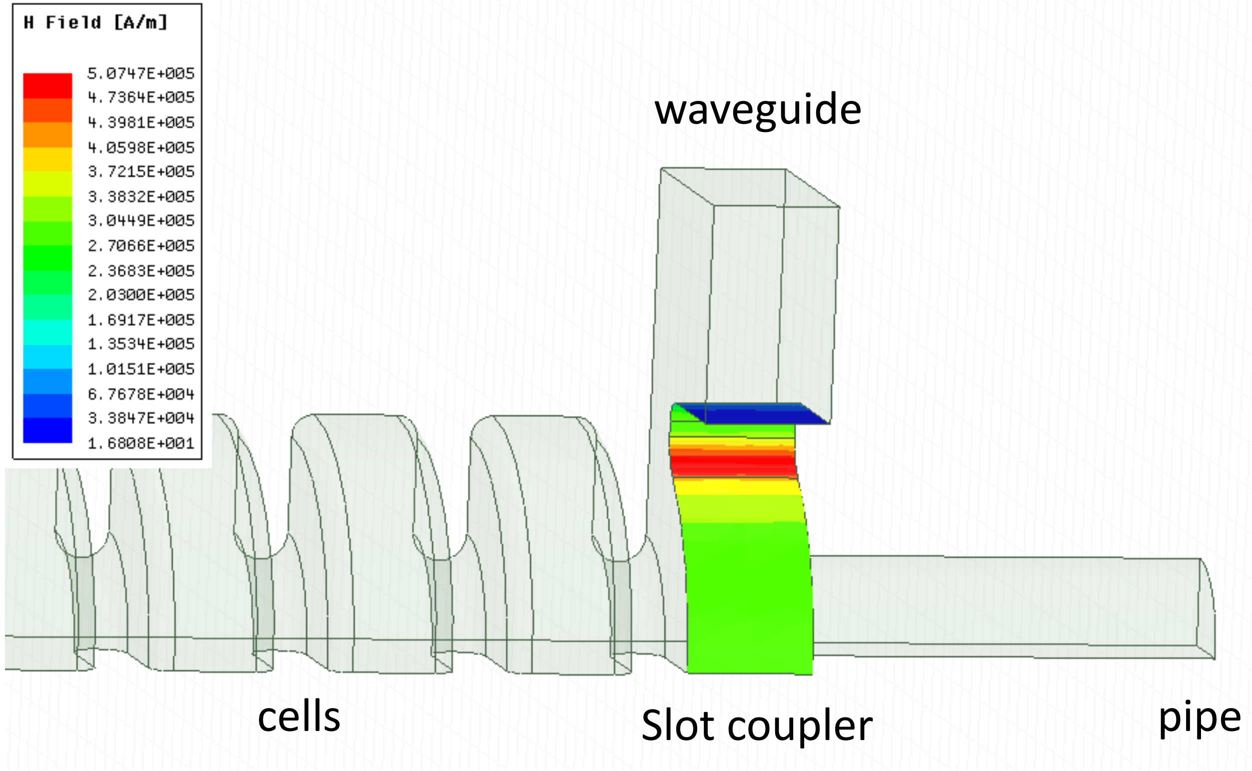
M. Diomede et al., Preliminary RF design of an X-band linac for the EuPRAXIA@SPARC_LAB project, proceedings of EAAC2017.

Coupler study

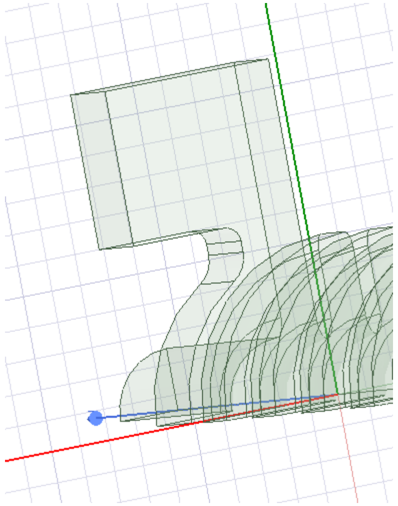
For couplers, an important parameter is the **pulsed heating**. It is defined as (for copper):

$$\Delta T[°C] = 127\left|H_{\parallel}[MA/m]\right|^2 \sqrt{f_{RF}[GHz]}\sqrt{t_p\ [\mu s]}$$

As a general experimental rule, if the pulsed heating is **below 50 °C** damage to the couplers is practically avoided.



Peak input power (80 MV/m)	65.34 MW
H_surf_max	5.0747e5 A/m
Pulsed heating	40.682°C



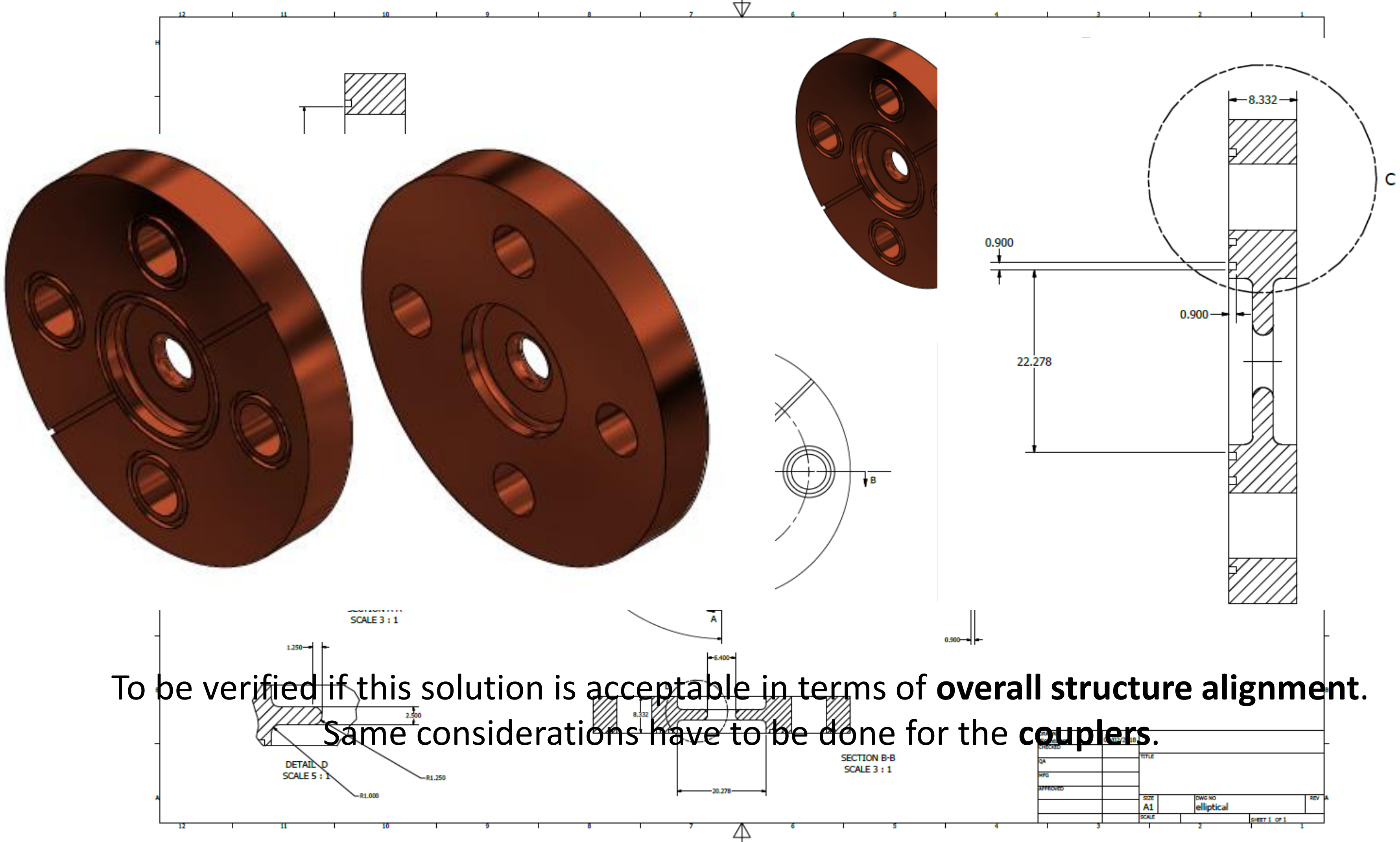
R_mc	9.73 mm
W_mc	8.224 mm
r1	1 mm
r2	2 mm

The e.m. simulation shows that is possible to adopt a **slot coupler** solution. Also a **waveguide coupler** study is foreseen.

Mechanical drawings

A crucial aspect is the **mechanical feasibility** of the e.m. design.

Preliminary ideas: simple cell design, no tuning.



To be verified if this solution is acceptable in terms of **overall structure alignment**.

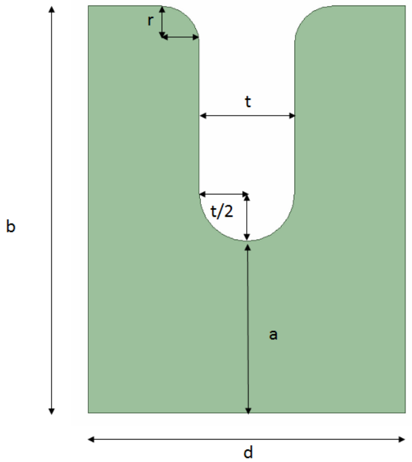
Same considerations have to be done for the **couplers**.

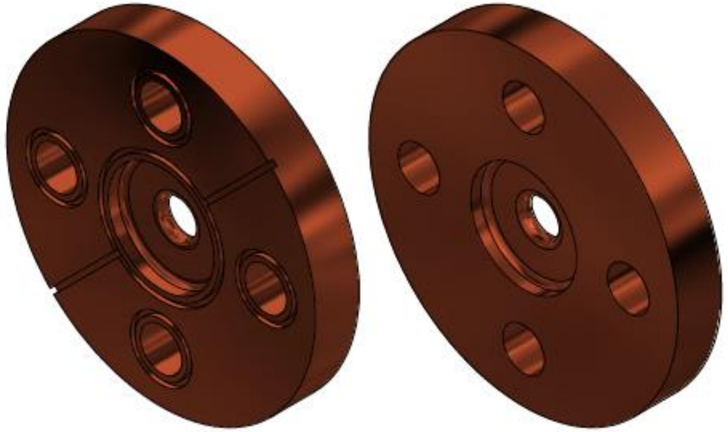
Outline

- Introduction
    - Traveling wave accelerating structures
    - Pulse compressor: SLED
    - Design parameters
    - Breakdown
- Context
    - The EuPRAXIA@SPARC_LAB project
- Activity and overall progress
    - Single cell design
    - X-band booster optimization
    - Coupler study
    - Mechanical drawings
- Work in progress

Work in progress

- Single cell optimization: shunt impedance and modified Poynting vector → structure optimization
- Sensitivity study of the cells: resonance frequency and phase advance → mechanical tolerances
- Final design of input and output couplers
- Evaluation of the total waveguide attenuation → total required RF power
- RF tests on a 3 cells prototype: check frequency and phase advance
- Mechanical drawings: brazing and tuning considerations
- Study about BPMs integrated into the accelerating structures
- …





The XLS-CompactLight project

The key objective of the CompactLight Design Study is to demonstrate, through a **conceptual design**, the feasibility of an **innovative, compact and cost effective FEL facility suited for user demands** identified in the science case.

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**

The goal is to design a **Hard X-ray Facility** using the very latest **concepts** for:

- High brightness electron photoinjectors.
- Very high gradient accelerating structures.
- Novel short period undulators.

Tasks in WG3 (Gun and Injector) and WG4 (RF systems): preliminary design and optimization of a C-band and X-band SLED + accelerating sections system .

That’s all folks!