Preliminary RF design of an X-Band LINAC for the EuPRAXIA@SPARC_LAB project

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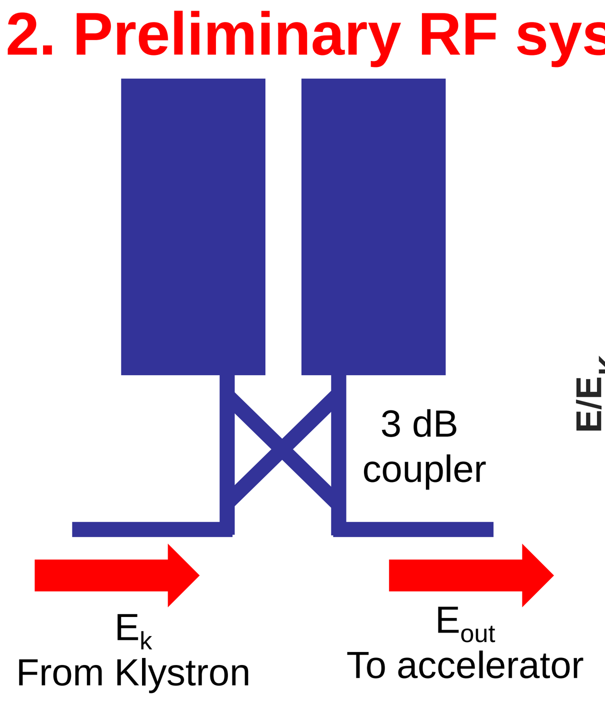
Abstract

In the framework of the upgrade of the SPARC_LAB facility at INFN-LNF, named EuPRAXIA@SPARC_LAB, a high gradient LINAC has been foreseen. One of the most suitable options is to realize it in X-Band. A preliminary design study of the accelerating structures and power distribution system has been performed. It is based on 0.5 m long travelling wave (TW) accelerating structures operating on the 2π/3 mode and fed by klystrons and pulse compressor systems. The main parameters of the structures and LINAC are presented with the basic RF LINAC layout.

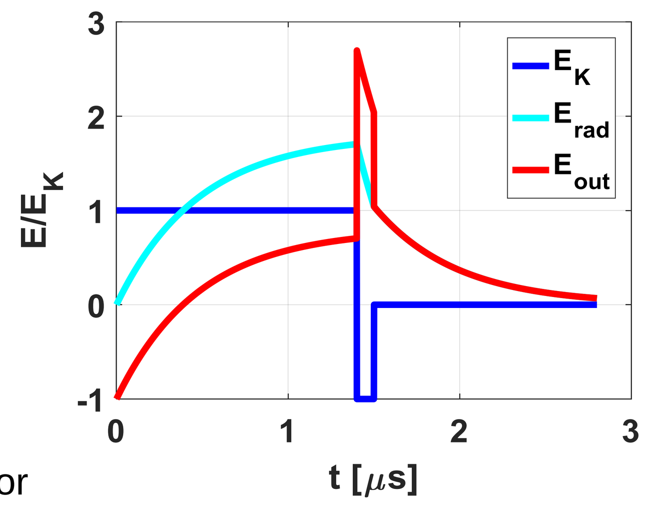
1. EuPRAXIA@SPARC_LAB

In the framework of research and development of novel acceleration schemes and technology, the upgrade of the SPARC_LAB facility at INFN-LNF is foreseen, based on a high gradient LINAC. High brightness electron bunches are fundamental for the successful development of plasma-based accelerators, for instance, whereas external injection schemes are considered, i.e. particle beam driven and laser driven plasma wakefield accelerators (PWFA and LWFA, respectively). Indeed, the ultimate beam brightness and its stability and reproducibility are strongly influenced by the RF-generated electron beam. To take profit of the compactness of these novel acceleration techniques, one of the most suitable options is to realize the LINAC in X-Band. In this scenario the SPARC_LAB upgrade, named as **EuPRAXIA@SPARC_LAB**, might be one of the possible candidates to host EuPRAXIA. EuPRAXIA, "European Plasma Research Accelerator with eXcellence In Applications", is a design study in the framework of Horizon 2020, funded to bring together for the first time novel acceleration schemes, based for instance on plasmas, modern lasers, the latest correction/feedback technologies and large-scale user areas (INFRADEV-1-2014). Such a research infrastructure would achieve the required quantum leap in accelerator technology towards more compact and more cost-effective accelerators, opening new horizons for applications and research.

2. Preliminary RF system parameters



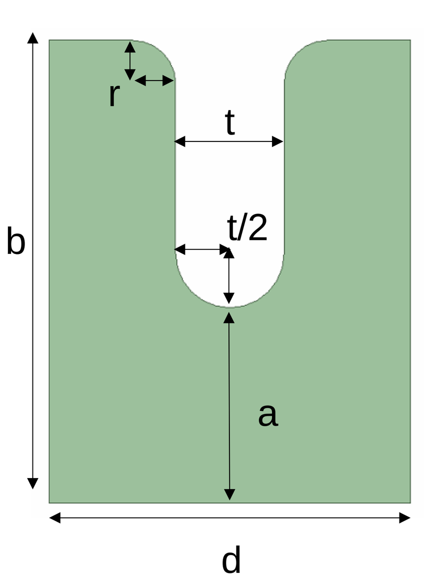
Example: compressed pulse of 100 ns and Q_e of 20000



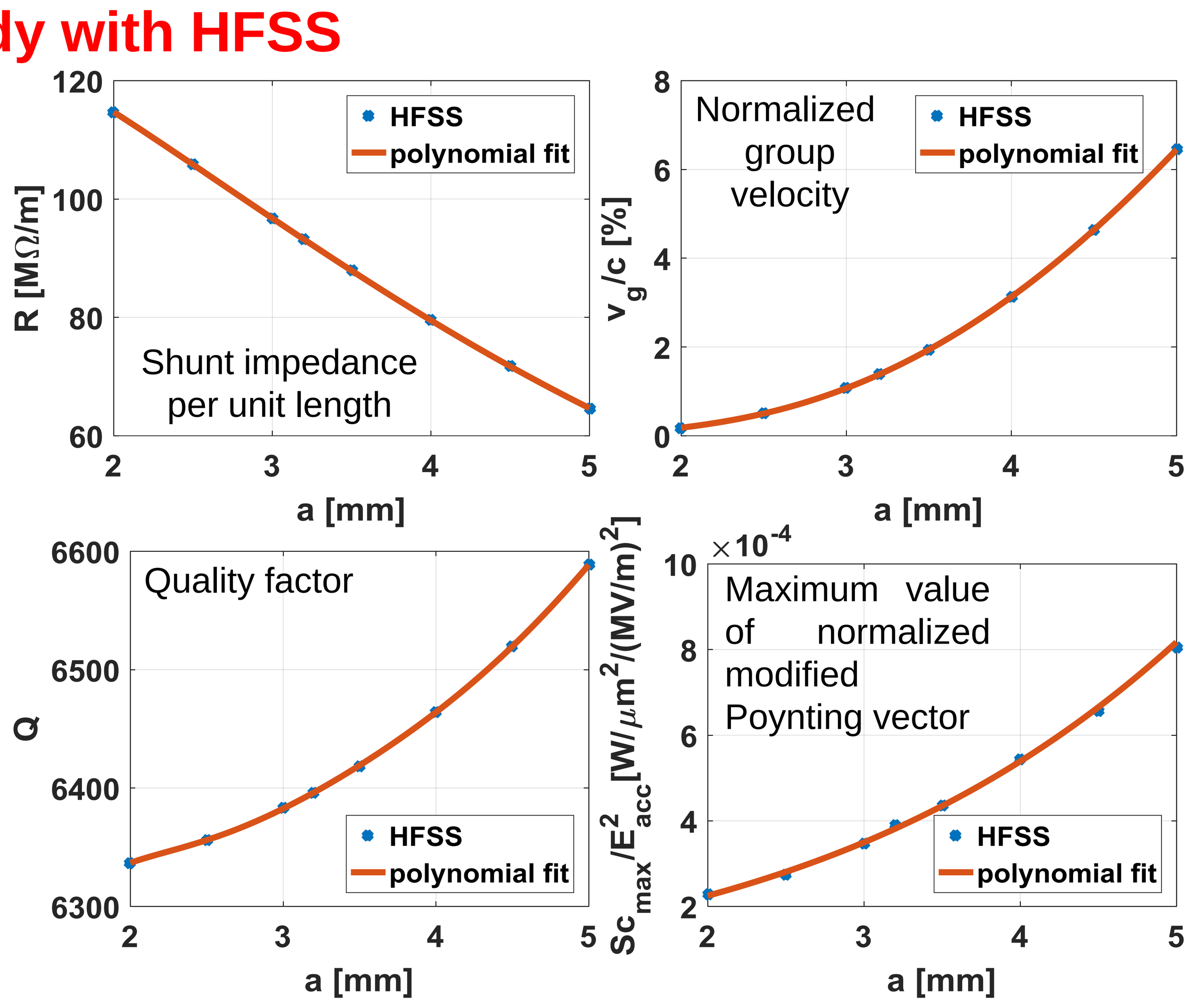
RF system parameters	
Frequency [GHz]	11.9942
t_k [μs]	1.5
Q_0 of SLED	180000

The RF LINAC layout is based on **klystrons with SLED** that feed several **TW accelerating structures** operating on the **2π/3 mode** at a frequency of **11.9942 GHz**.

3. Single cell study with HFSS



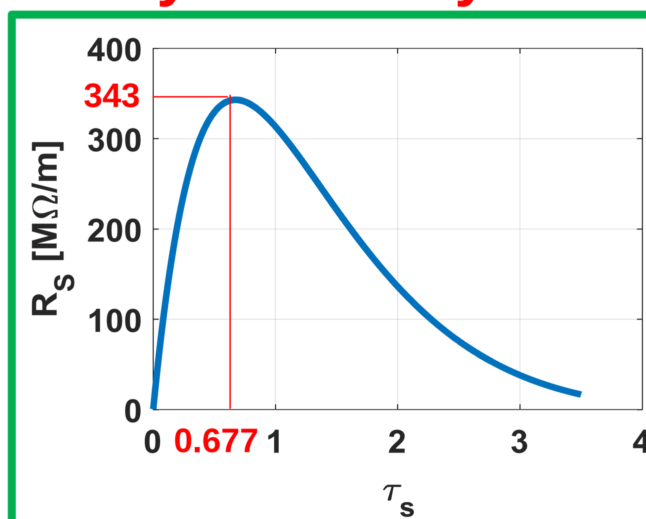
Geometrical parameters	
a [mm]	2 ÷ 5
b [mm]	9.828 ÷ 10.917
d [mm]	8.332 (2π/3 mode)
r [mm]	1
t [mm]	2.5



The single cell parameters (**R**, v_g/c, **Q**, Sc_{max}/E^2_{acc}) have been calculated with **HFSS** as a function of the **iris radius**. Also the related polynomial fits have been derived.
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.

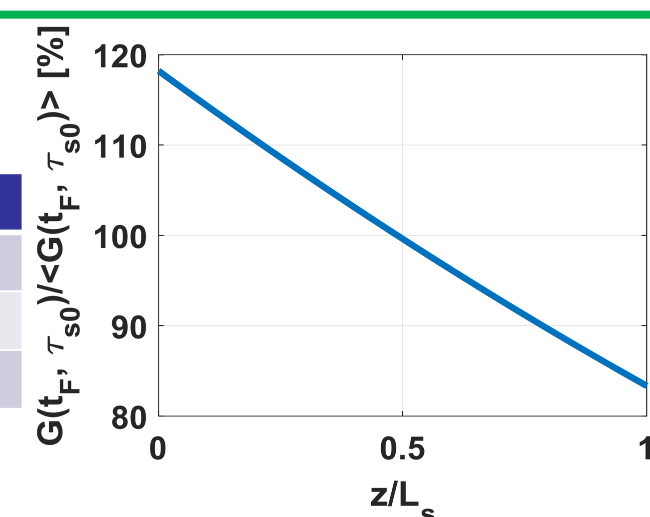
Single cell parameters (a=3.2 mm)	
b [mm]	10.139
R [MΩ/m]	93
v_g/c [%]	1.382
Q	6396
Sc_{max}/E^2_{acc} [A/V]	3.9x10⁻⁴

4. Analytical study



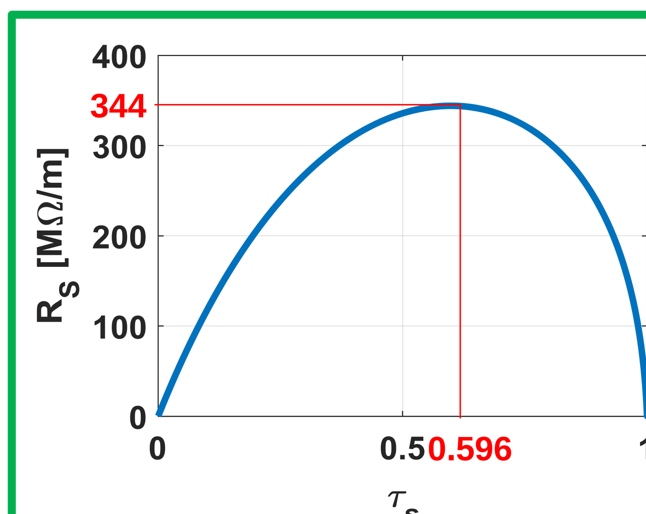
CI (Constant Impedance)

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



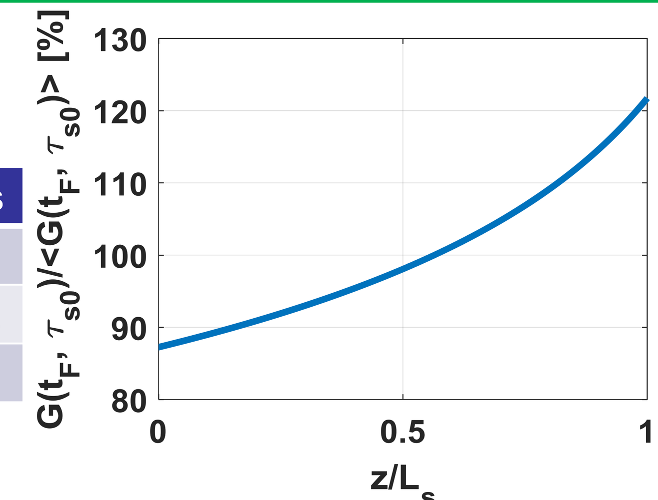
$$R_s = 2\tau_s R\left[\frac{\left(1-\frac{2Q_l}{Q_e}\right)}{\tau_s}\left(1-e^{-\tau_s}\right)+\frac{\left(\frac{2Q_l}{Q_e}\left[2-e^{-(\tau_k-\tau_p)}\right]\right)}{\tau_s\left(1-\frac{Q}{Q_l}\right)}\left(e^{-\tau_s\frac{Q}{Q_l}}-e^{-\tau_s}\right)\right]^2$$

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



CG (Constant Gradient)

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

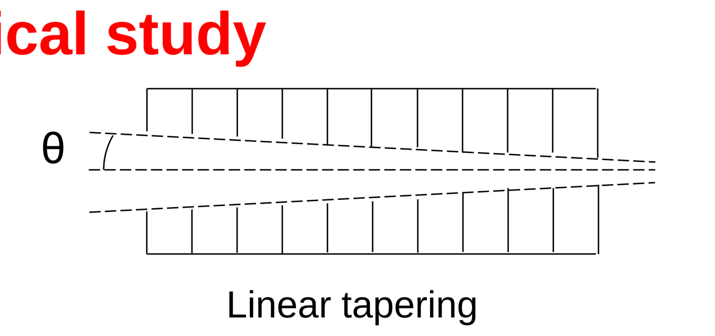


$$R_s = R\frac{2\tau_s}{1+\tau_s}\left\{1-\frac{2Q_l}{Q_e}+\frac{2Q_l}{Q_e}\left[2-\exp\left(-\frac{\omega t_k}{2Q_l}\right)\cdot\left(\frac{1+\tau_s}{1-\tau_s}\right)^{Q/2Q_l}\right]\cdot\frac{1-\tau_s}{2\tau_s}\frac{1}{1-Q/2Q_l}\left[\left(\frac{1+\tau_s}{1-\tau_s}\right)^{1-Q/2Q_l}-1\right]\right\}^2$$

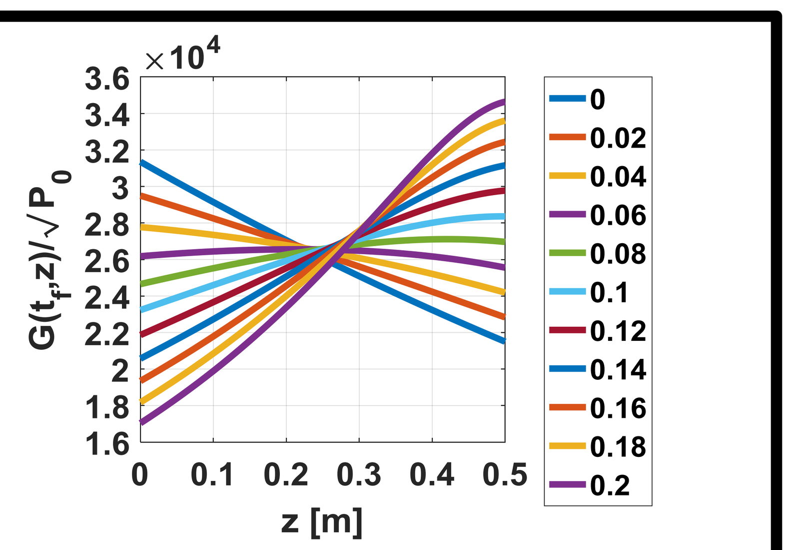
$$G(z,t'=t_f)=\sqrt{\frac{\frac{\omega}{v_gQ}R}{1+\tau_s}P_{in}}\cdot\left\{1+\frac{2Q_l}{Q_e}\left[\left(\frac{1+\tau_s-\frac{\omega}{v_gQ}z}{1-\tau_s}\right)^{-\frac{Q}{2Q_l}}\left[2-\exp\left(-\frac{\omega t_0}{2Q_l}\right)\right]-1\right]\right\}$$

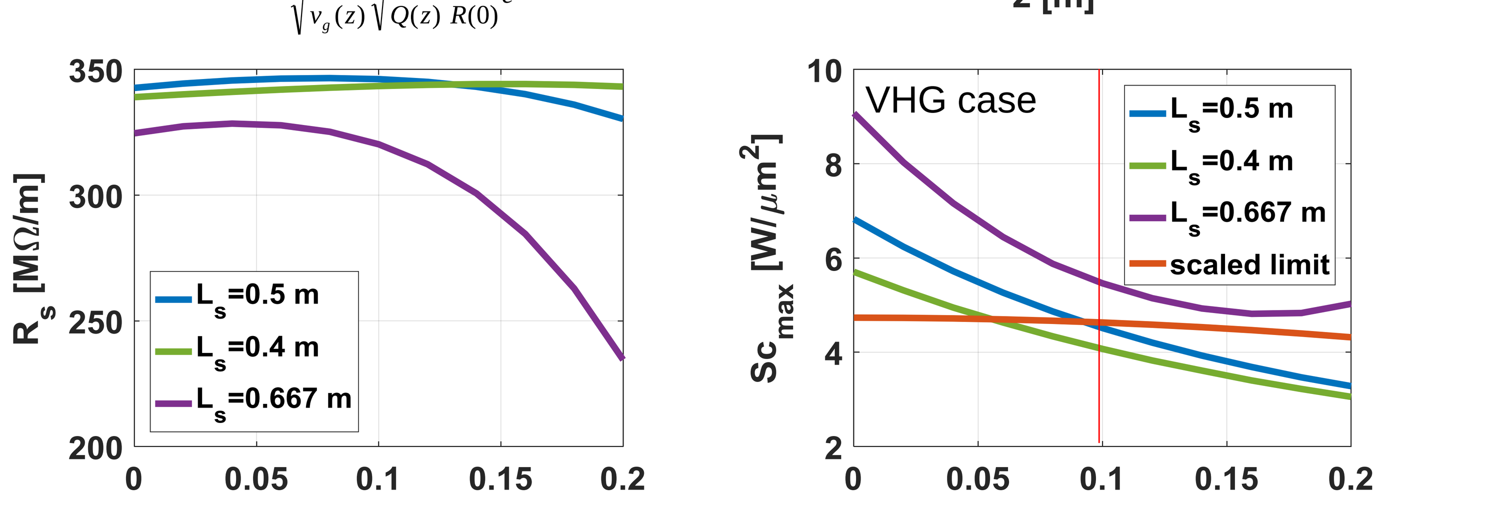
Fixed the quality factor **Q** of the cells it is possible to calculate the **effective shunt impedance R_s** as a function of the **section attenuation τ_s**. The choice of τ_s fixes the **filling time of the structure t_f** and hence the **compressed pulse length after the SLED t_p**. The value of 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}.**

5. Numerical study



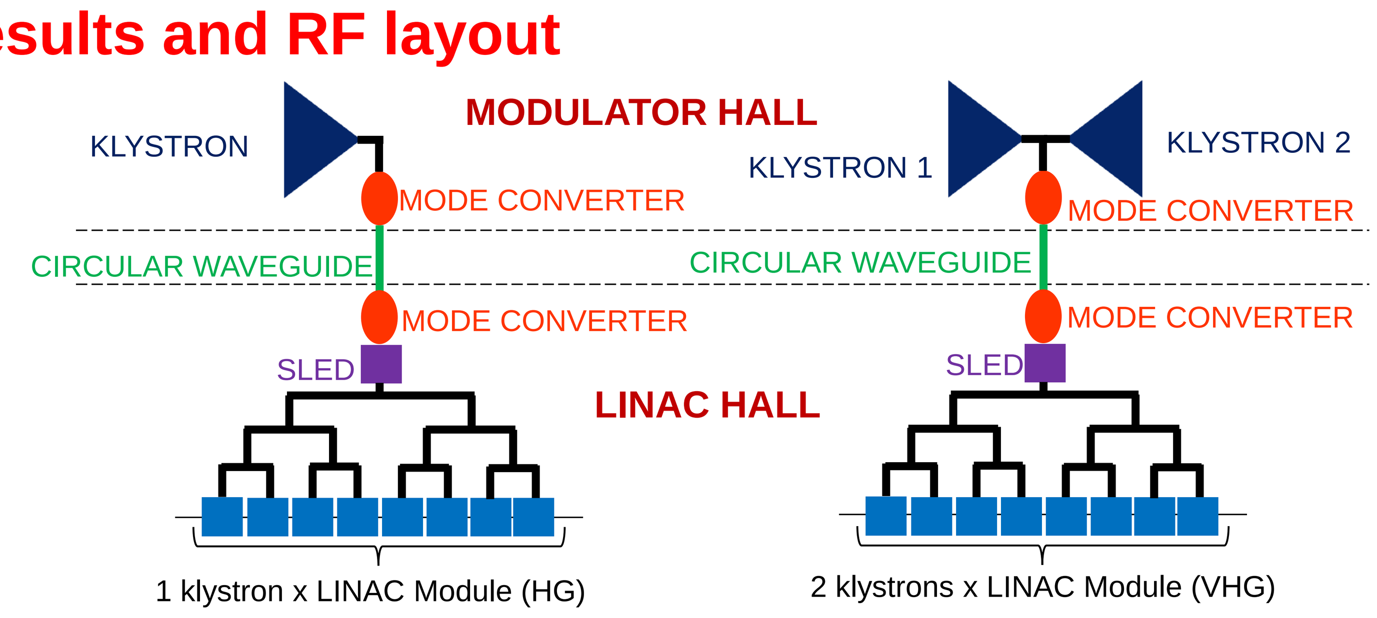
$$G(z,t)=G_0[t-\tau(z)]g(z)=\sqrt{\frac{\omega}{v_g(0)}\frac{R(0)}{Q(0)}P_K(t=0)}\,\frac{E_{out}}{E_K}\left(t-\int_0^z\frac{dz'}{v_g(z')}\right)\cdot\sqrt{\frac{v_g(0)}{v_g(z)}}\sqrt{\frac{R(z)}{Q(z)}\frac{Q(0)}{R(0)}}\,e^{-\frac{1}{2}\int_0^z\frac{\omega}{v_g(z')Q(z')}dz'}$$





The **preliminary LINAC layout** foresees an S-Band Gun, S-Band TW structures and an X-Band booster with a bunch compressor. The **active length L_t** of the X-Band LINAC is **16 m**. Two average accelerating gradient options are foreseen: **high gradient (HG) with 57 MV/m** and a **very high gradient (VHG) with 80 MV/m**, corresponding to double the power of the HG case.
Also a **numerical study** has been performed. Fixing the slope of the linear tapering and the structure length, it is possible to apply the general formulas in order to obtain the **effective shunt impedance, the normalized gradient profile after one filling time and the modified Poynting vector**. It has been performed a **scan from 0 to 0.2°** for **three structure lengths**: **0.4 m (40 structures), 0.5 m (32 structures) and 0.667 m (24 structures).** In terms of R_s the 0.4 m and 0.5 m solutions have the same efficiency (choosing the proper angle), while in terms of S_c the 0.4 m solution is better. The **0.5 m solution with an angle of slope of 0.1°** has been chosen.

6. Results and RF layout



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.

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

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