Layout and optimization of the linac rf system

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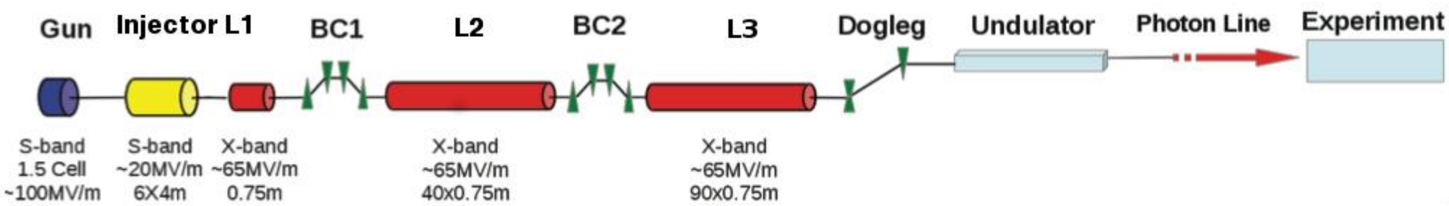
and with the contribution of N. Catalan Lasheras, A. Grudiev, W. Wuensch (CERN)

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

Examples of Linac gradients of current X-ray free electron laser facilities

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*

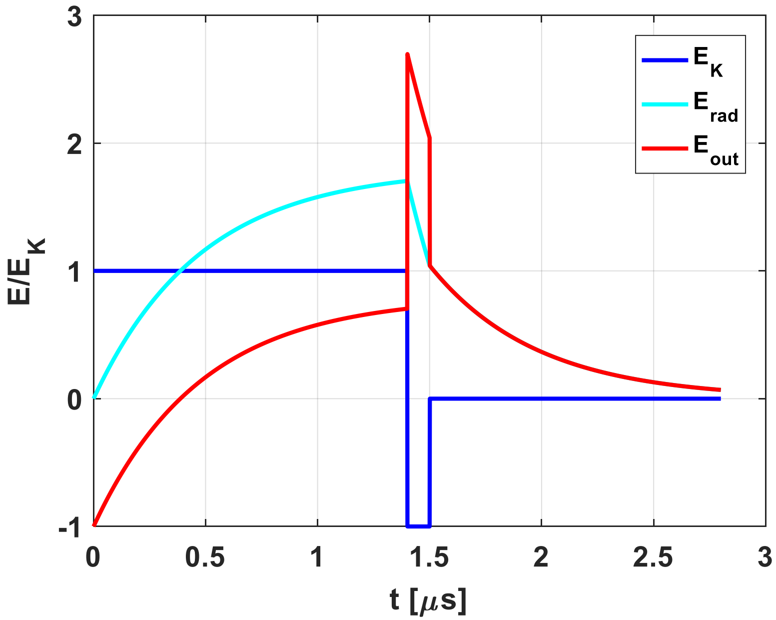
STRUCTURE DESIGN WORKFLOW

- Baseline accelerating gradient: **≈ 65 MV/m**
- RF system and pulse compressor characteristics
- Average iris radius: **3.5 mm**
- Electromagnetic parametric study of the TW cell
- Effective shunt impedance optimization by a 2D numerical scan of the total length and the iris tapering
- Check of expected Breakdown rate (modified Poynting vector values @ nominal gradient)
- Design a realistic RF module including power distribution network
- Finalize the electromagnetic design (input and output couplers)

Iterations among these various steps are typically required.

PULSE COMPRESSOR SYSTEM

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



SLED: $\langle E_{gain}\rangle = 2.35$ ---> $\langle P_{gain}\rangle = 5.5$

$$E_{gain} = f(\omega, t_k, t_p, Q_0, Q_e)$$

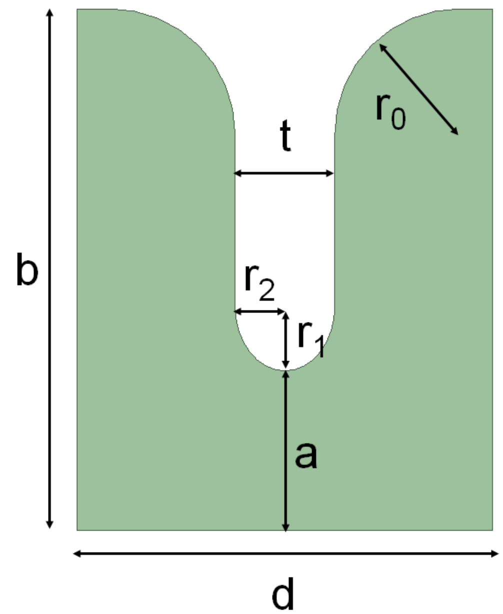
X-band CPI klystron

RF system parameters	
f [GHz]	11.9942
t_k [μs]	1.5
Peak power [MW]	50
Q_0 of SLED	180000

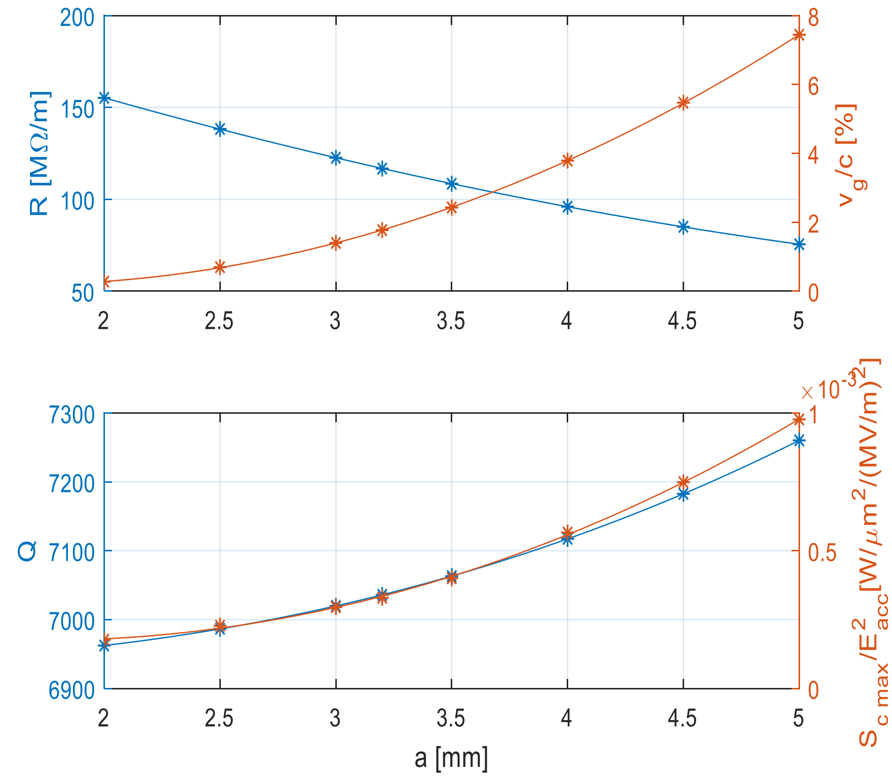
The optimum external quality factor Q_e and the pulse length t_p can be computed by our **numerical tool**

The pulse compressor $\mathbf{Q_0}$ and the klystron pulse length $\mathbf{t_k}$ are **input** data for the calculation (the larger the better for both).
Optimal external quality factor $\mathbf{Q_e}$ and RF pulse length $\mathbf{t_p}$ values are **outcomes** of the optimization process.

SINGLE CELL PARAMETRIZATION



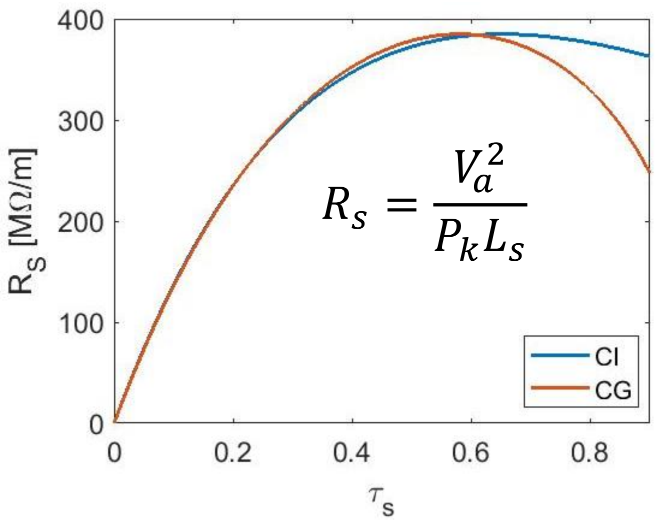
a [mm]	2 ÷ 5
b [mm]	10.155 ÷ 11.215
d [mm]	8.332 (2π/3 mode)
r_0 [mm]	2.5
t [mm]	2
r_1/r_2	1.3 (Min Sc max for a=3.2 mm)



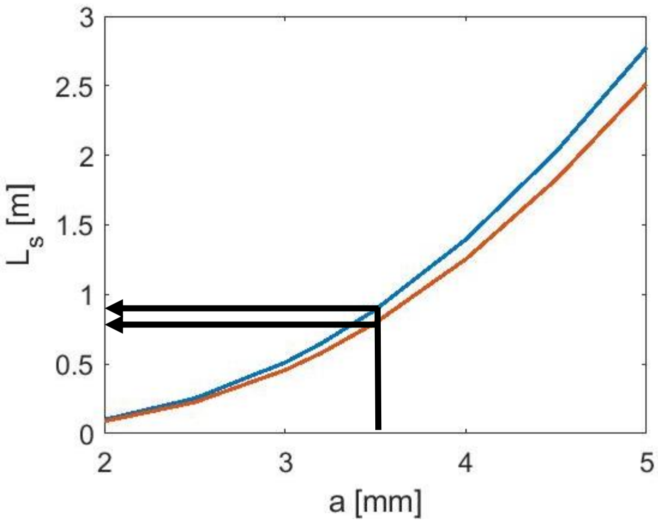
A scan of the iris radius a **from 2 mm to 5 mm** has been performed with **HFSS** in order to obtain the single cell parameters (**R, v_g/c, Q, Sc_{max}/E^2_{acc}**) as a function of the iris radius. Moreover, the iris has been shaped (tapered) with an elliptical shape to minimize Sc_{max}/E^2_{acc}.

STRUCTURE ANALYTICAL OPTIMIZATION

Assuming constant values for Q, R/Q, we calculated the structure attenuation constant (τ_S) that maximizes the **effective shunt impedance** (CI and CG cases). This allows to calculate the **structure length** (for a given iris aperture).



Calculations started by A. Grudiev



$$\tau_s = \int_0^L \alpha(z)dz$$

$$\alpha(z) = f(\omega, R/Q, v_g, Q)$$

<a>=3.5 mm

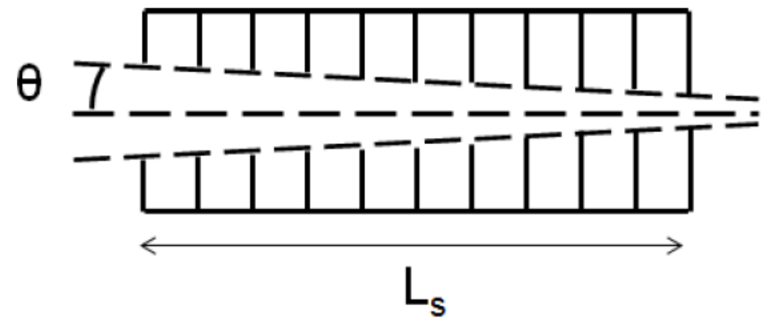
L_{opt_CI}=0.9 m (107 cells)

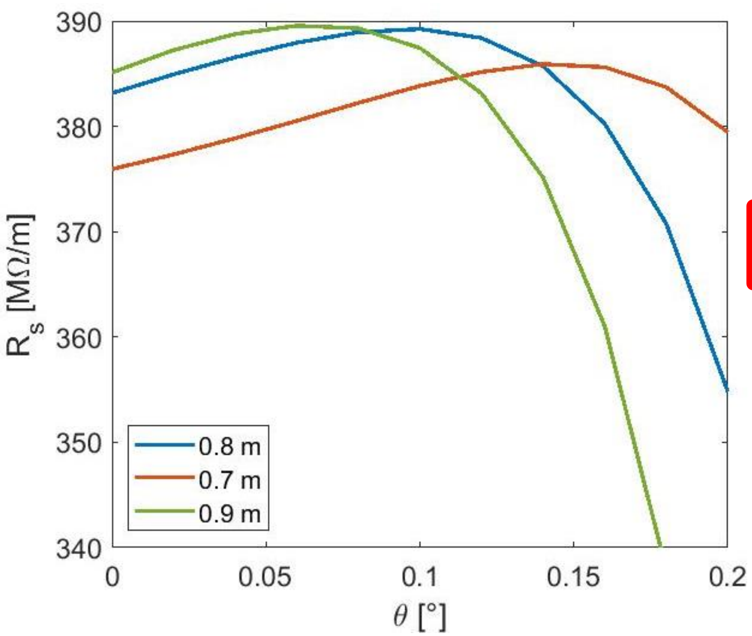
L_{opt_CG}=0.8 m (96 cells)

STRUCTURE NUMERICAL OPTIMIZATION

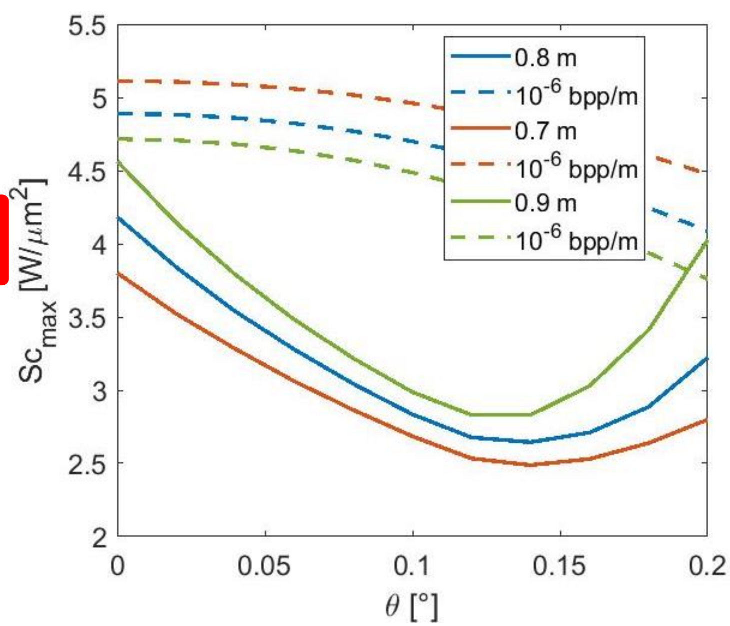
R/Q variation with iris aperture is not negligible and CG concept does not apply for not-flat RF pulses (SLED).

For this reason we have implemented a **numerical tool** able to calculate the main **structure parameters** (effective shunt impedance, modified Poynting vector, field profile) **with an arbitrary cell-by-cell iris modulation along the structure**. We have considered linear iris tapered structures.





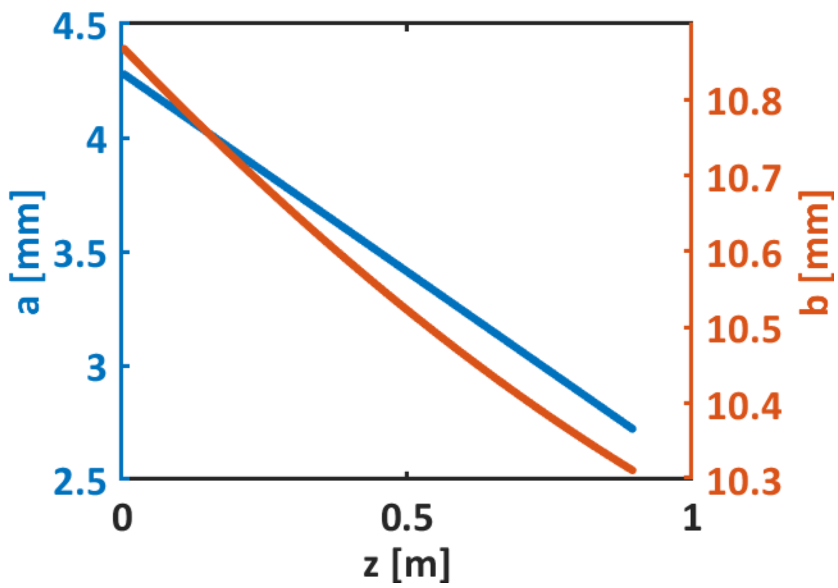
<a>=3.5 mm



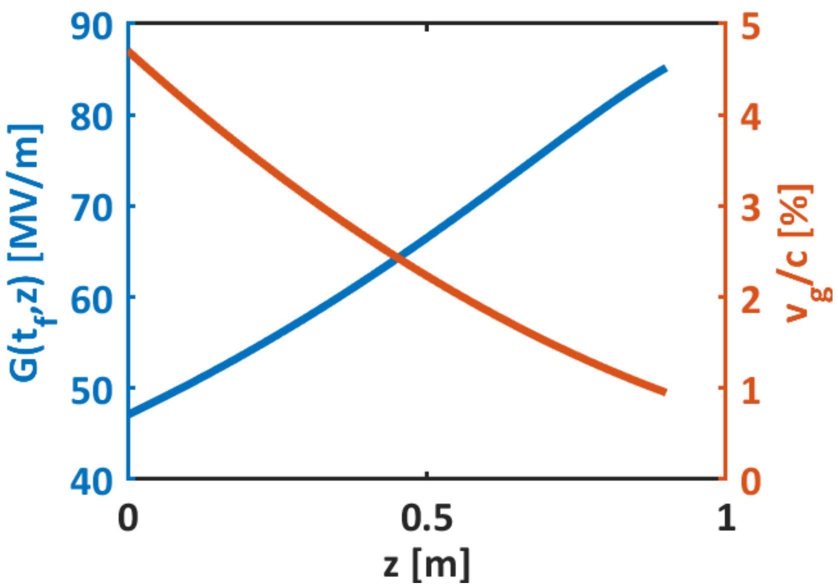
STRUCTURE NUMERICAL OPTIMIZATION

For a better power distribution we opted for the **0.9 m** solution, with a tapering angle of **0.1 deg** as a good compromise between RF efficiency and breakdown rate probability.

Iris and outer radius tapering

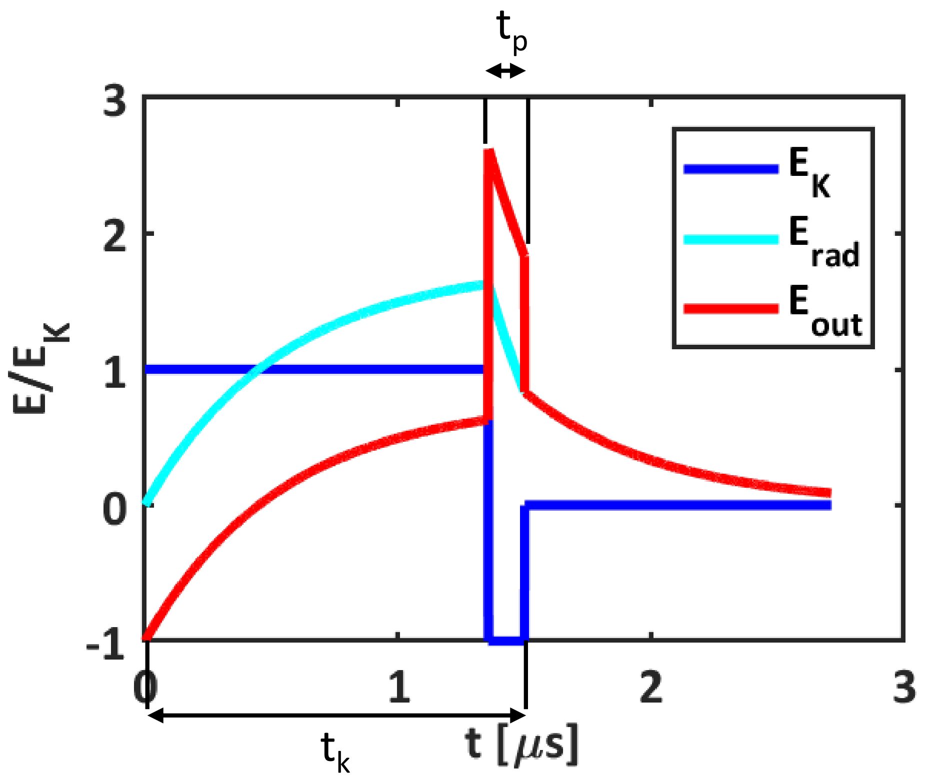


Gradient and group velocity profile



RF PULSE

The **outputs** of the optimization procedure are the **pulse length t_p** and the **external quality factor Q_e of the SLED**.



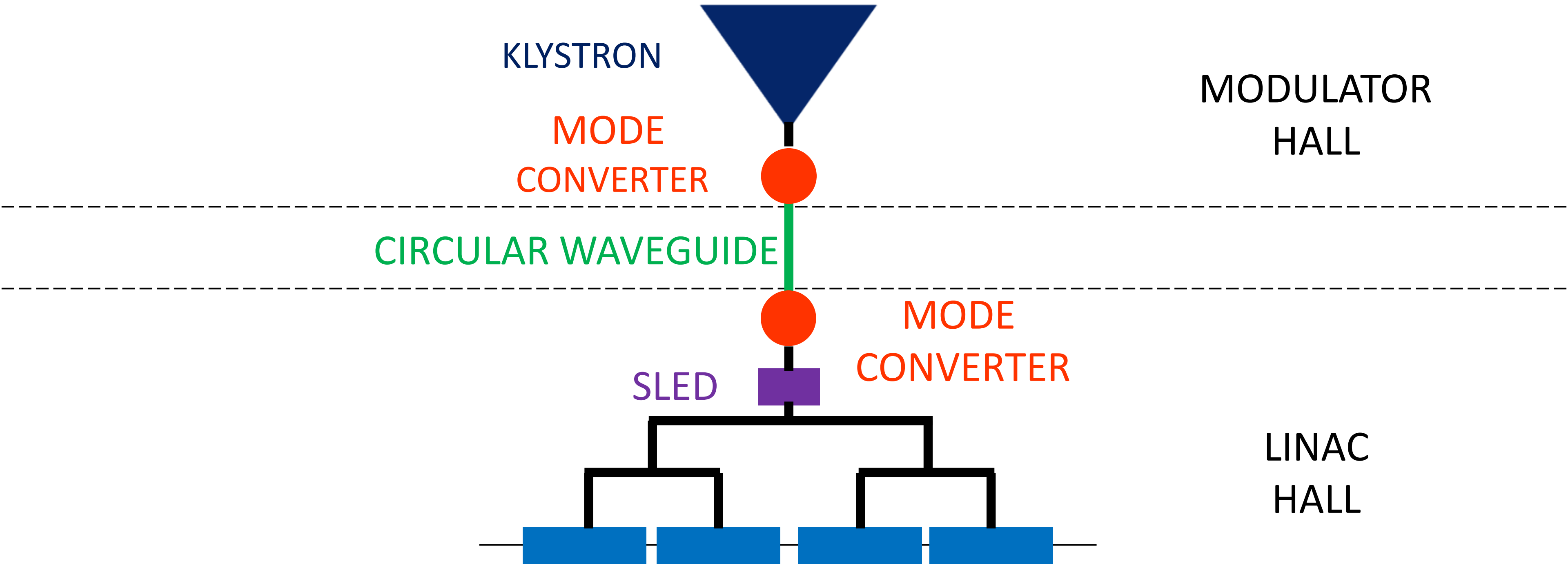
$\langle E_{gain} \rangle$= 2.23 ---> $\langle P_{gain} \rangle$= 4.96

Optimal SLED pulse

Pulse length t_p [ns]	144
External SLED Q-factor Q_E	23000

RF MODULE

The preliminary **RF module** is made up of **4 TW structures** fed by **1 klystron** with **1 SLED**.



LINAC OPTIMIZATION

X-band linac main parameters	
Freq. [GHz]	11.9942
RF pulse [µs]	1.5
Average gradient <G> [MV/m]	65 MV/m
Linac Energy gain E_{gain} [GeV]	4.5
Linac active length L_{act} [m]	70
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23000
No. of cells	107
Structure length L_s [m]	0.9
Iris radius a [mm]	4.3-2.7
Group velocity v_g [%]	4.7-1
Effective shunt Imp. R_s [MΩ/m]	387
Filling time t_f [ns]	144
Klystron power per structure P_{k_s} [MW] (w/o attenuation)	10
Structures per module N_m (kly. power per module P_{k_m} [MW])	4 (40)
Total number of structures N_{tot}	≈80
Total number of klystrons N_k	≈20

COUPLER MAIN PARAMETERS

For couplers, an important parameter is the **RF pulsed heating**. It is a process by which a metal is heated from magnetic fields on its surface due to high-power pulsed RF. The **temperature rise** 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.

Coupling slots introduce a **distortion in the field distribution** and **multi-pole components** of the field can appear and affect the beam dynamics.

The multi-pole field components in the coupler are completely dominated by the **magnetic field asymmetry**. Odd components can be avoided with a symmetric feeding.

First order development of the **azimuthal magnetic field** near the beam axis:

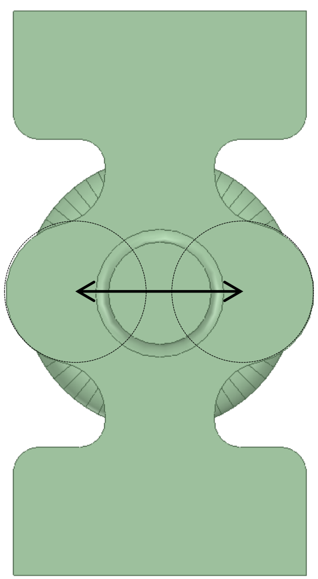
$$B_\phi(r,\phi,z) \cong A_0(z)r + \sum_{n=1}^{\infty} A_n(z)\cos(n\phi)\, r^{n-1}$$

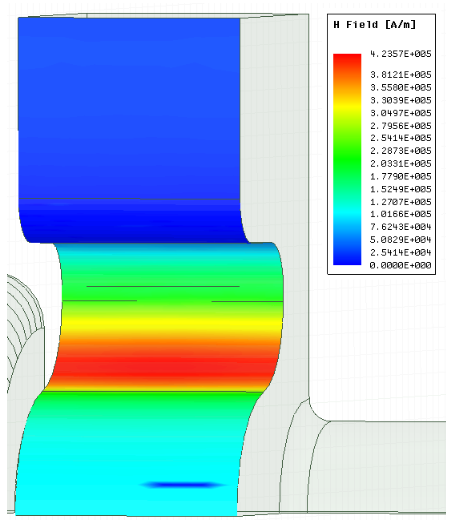
The **quadrupolar component** is the component associated to the term with n=2 and the gradient of the quadrupole component is exactly the term $\mathbf{A_2}$.

COUPLERS DESIGN

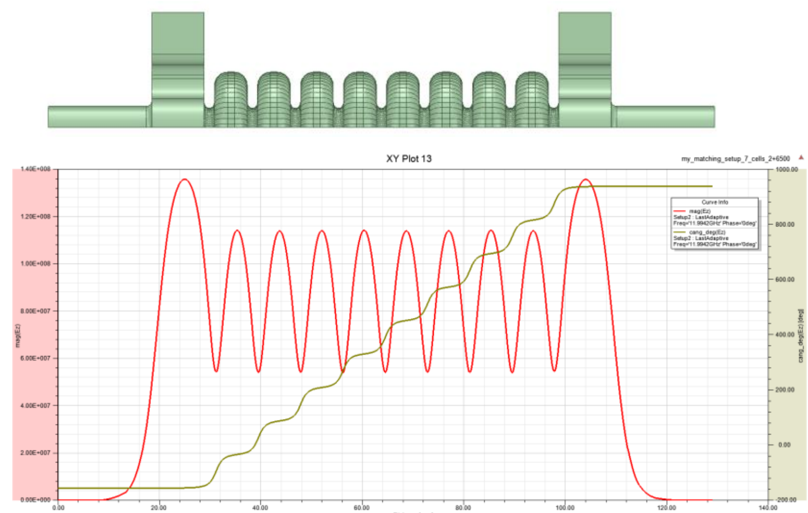
As first case, we have considered a **z-type coupler** because of its compactness with respect to the waveguide and mode launcher ones. **Racetrack geometry** has been implemented in order to compensate the residual quadrupole field components. Dipole field components are avoided with the **symmetric feeding**.

The calculated **pulsed heating** on the **input coupler** is **<22 °C** , the obtained **reflection coefficient** is **<−30 dB**.



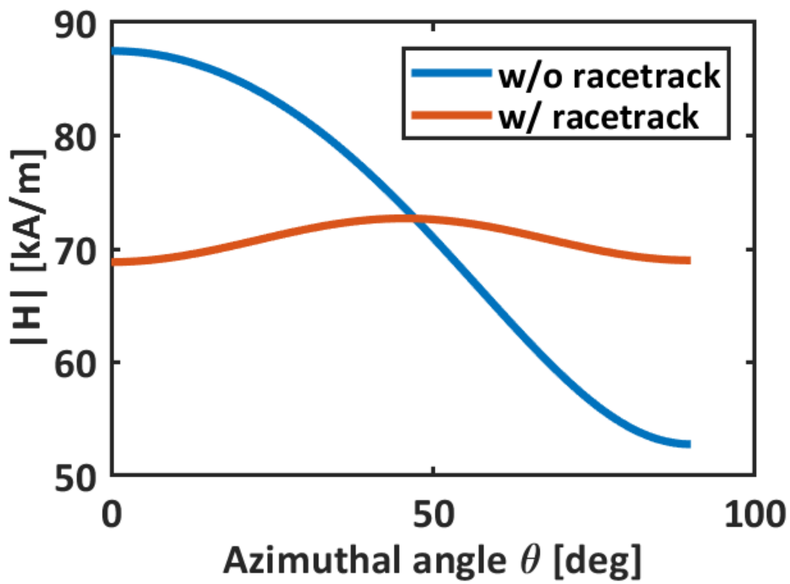


7 cells model



COUPLERS DESIGN

2 mm from the center of the input coupler



w/o racetrack

A_2/A_0=24%

w/ racetrack

A_2/A_0=0.1%

The racetrack geometry doesn't affect the **octupolar component**.

Same results have been obtained for the **output coupler**.

NEXT STEPS

- Go through the iteration process with different or updated starting conditions
- Finalize the electromagnetic design (input and output waveguide couplers)
- Design the RF module: waveguide network, converters, RF windows… (input for Task 5: Integration)
- Simulate the entire structure (feasibility to be checked)
- …