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Compact

X-band RF electron gun injector design

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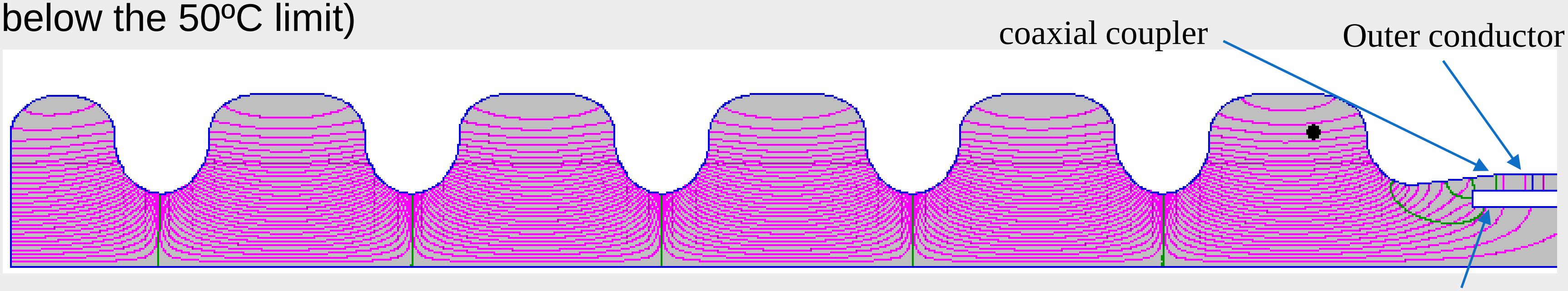
Summary

Main characteristics of the X-band RF photoinjector:

- It consists of a 5.6 cell structure operating in Standing Wave (SW) with the π-mode
- Fed by a coaxial coupler (preserves the rotational symmetry of the gun)
- RF design made with SUPERFISH (2D software, allows to obtain the cavity modes)
- Design has taken into consideration the presence of neighbor modes (circuital model + SUPERFISH)
- Cavity irises with elliptical shape to reduce the superficial electric field (to prevent RF breakdown)
- Study of the RF breakdown risk at the gun surfaces has been carried out (breakdown rate for different RF pulse parameters and electric field cathode values are estimated)
- Multipactor analysis performed at the coaxial coupler (multipactor discharges can be suppressed with a solenoid)
- RF pulse heating thermal analysis of the gun surfaces (for the operating point, temperature increase is below the 50ºC limit)

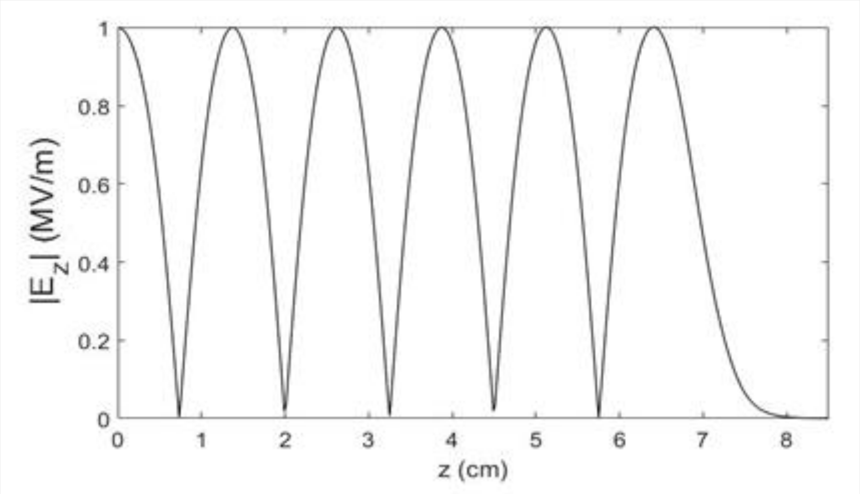


Scheme of a 5.6 cell RF gun with a coaxial coupler

Summary

Main performance parameters of the photoinjector prototype:

Parameter	
E_z flatness at peaks	>99 %
Resonant frequency, f_π	$11.994\ GHz$
Cathode electric field	200 MV/m
RF pulse length	400 ns
Mode separation, Δf	27.1 MHz
Coupling factor, β	1.027
Filling time, t_F	111.4 ns
$max(E_{surf})$ for 1 MV/m at cathode	0.988 MV/m
BDR (for 400 ns pulse length)	$5.59 \times 10^{-6}\ bpp/m$
RF pulse heating (for 400 ns pulse length), max(ΔT)	31°C
Required magnetic field to suppress multipactor	360 mT



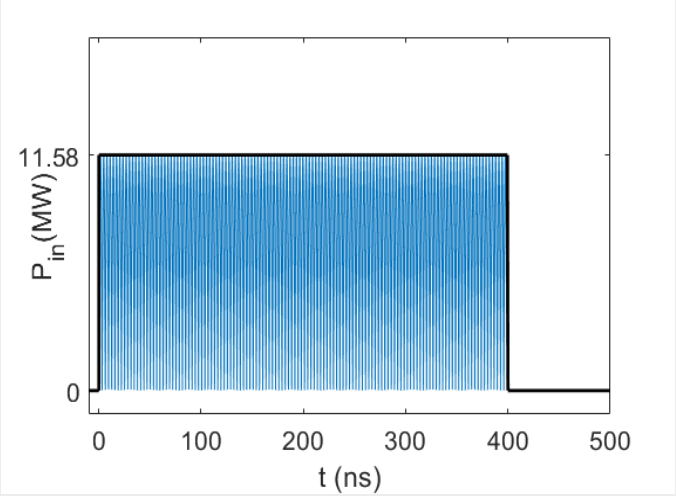
RF axial electric field along the gun axis

RF power system

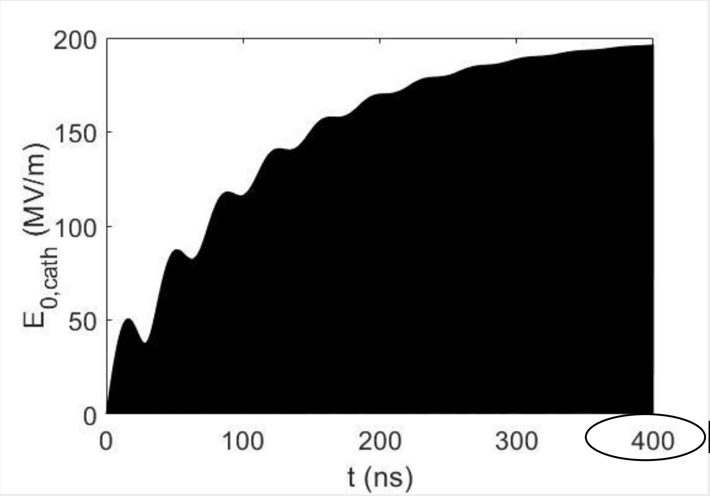
- The RF gun is intended to operate with a $E_{0,cath}$ = 200 MV/m, which requires to feed the coaxial coupler with a peak power of:

$$P_{in} = \frac{(1+\beta)^2 E_{0,cath}^2}{8\beta\alpha^2} \qquad \alpha = 41567.69\, Vm^{-1}W^{-0,5} \quad \beta = 1.027\ (coupling\ factor) \qquad \alpha = \frac{E_{0,cath,Pdiss}}{\sqrt{2P_{diss}}} \qquad \boxed{P_{in} = 11.58\ MW}$$

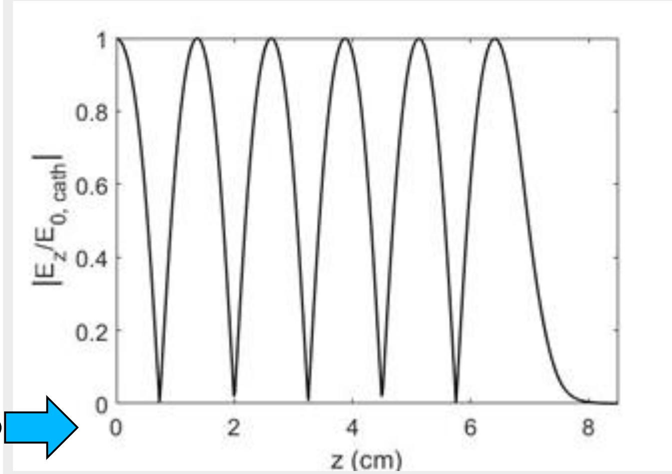
- The RF pulse active length was expected to be T_p =400 ns, being T_p>> τ = 111.4 ns, thus ensuring the operation at the stationary state after the filling transient:



RF input power provided by the generator



RF electric field at cathode during the cavity filling



RF axial electric field along the gun axis at 400 ns

- In the previous plots it has been considered the presence of both the operating π-mode plus the first neighbor mode (other neighbor mode contributions are negligible)

RF power system

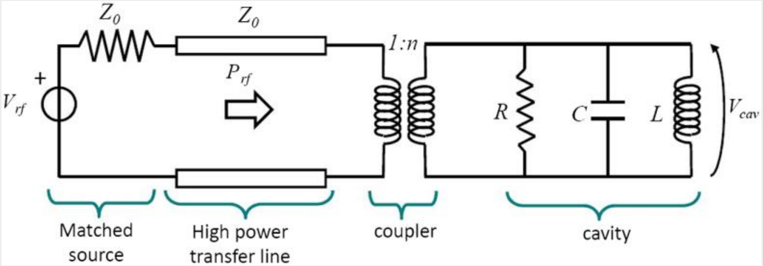
- Since the RF gun operates in the standing wave (SW) configuration, there will be a significant amount of reflected power towards the RF source during the filling transient.

- The reflected power can be calculated using a circuital model to describe the system (RF source + coupler + gun cavity)

$$\frac{P_{ref}}{P_{in}} = \left|\frac{V_-}{V_+}\right|^2 = \left\{\frac{2\beta}{\beta+1}\left(1-e^{-\frac{t}{\tau}}\right)-1\right\}^2$$

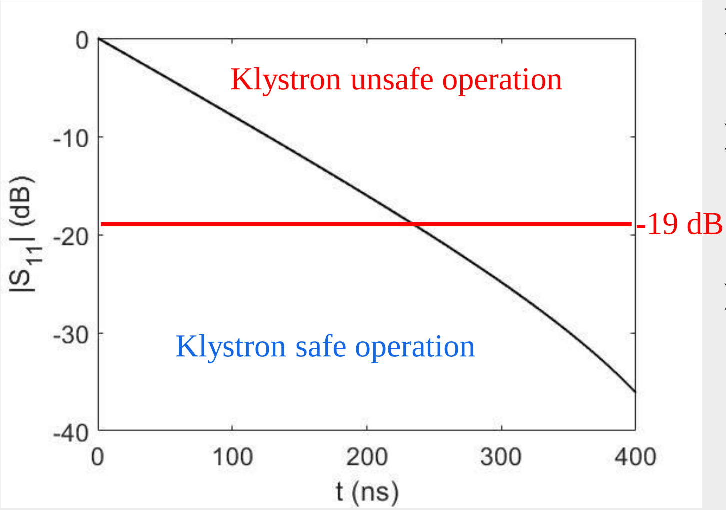
$$|S_{11}|\,(dB) = 20\log_{10}\left|\frac{V_-}{V_+}\right|$$

P_{ref} is the reflected power
P_{in} is the generator input power
V_+ is the incident generator voltage
V_- is the reflected voltage
τ is the filling time of the gun



Equivalent circuit describing the RF generator, coupler and gun cavity (extracted from ref. 1)

Note that for t = 0, always $P_{ref} = P_{in}$, regardless the β value

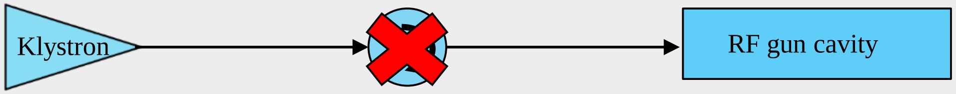


S_{11} parameter for the transient in the RF gun

- The reflected power from the RF gun can damage the klystron amplifier if the $|S_{11}| > -19$ dB

- In the photoinjector case this is a major concern since there will be a long time lapse (more than 200 ns) during which the klystrons operates unsafely

- For other RF frequency bands (L, S and C) the commonly employed solution is the use of a circulator to protect the klystron. However, there are no circulators available for X-band operation



[1] D. Alesini et al., “Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun”, Physical Review Accelerators and Beams. 21, 112001 (2018)

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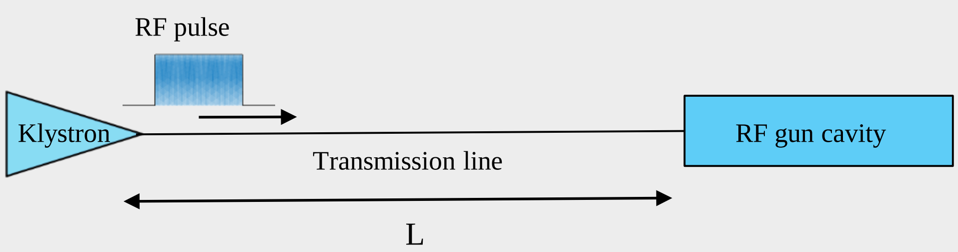
RF power system

- The damage in the klystron only occurs if the reflected power reaches the klystron while it is emitting RF power

- Hence, the klystron is naturally protected if the reflected power starts to arrive when RF pulse has finished and the klystron is switched off. This conditions relates the maximum RF pulse length for a certain electromagnetic path between the klystron and the photoinjector:



$$T_{p,max} = \frac{2L}{v_g}$$

$$v_g = \frac{d\omega}{d\beta_g}$$

For T_p = 400 ns → L = 50.24 m

$$v_g = \frac{\beta_g c^2}{\omega} \qquad \beta_g = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

$$v_g = 0.84c$$

v_g is the group velocity
β_g is the propagation factor

ω is the RF angular frequency
a is the width of the rectangular waveguide

- For our design (T_p = 400 ns), the required length is too large (L= 50.24 m), since taking into account the attenuation[1] of the typical copper WR-90 rectangular waveguide (α_{at} =0.11 dB/m), this will result in a total attenuation of 5.52 dB (≈ 72% of input power is lost before reaching the RF gun)

- In order to reduce losses the circuit length has to be diminished, and hence:

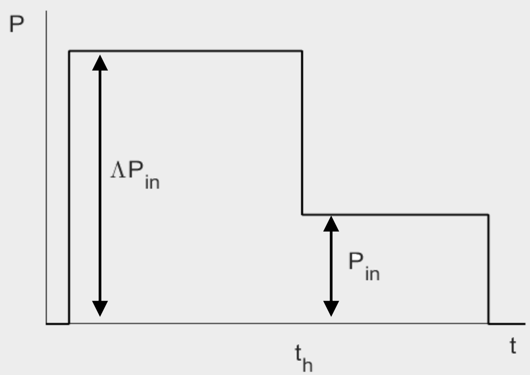
    - The pulse length has to be shortened to fulfill the klystron protection requirement

    - The RF peak power value has to be increased in order to achieve the required electric field at cathode at a shorter time

[1] Waveguide Specification guide, A.T. Wall Company, available at: http://www.alpharep.de

RF power system

- The following RF input power pulse shape is chosen to fill the RF gun cavity in a shorter time, trying to reduce the transient effects with a step in the RF power amplitude[1]:

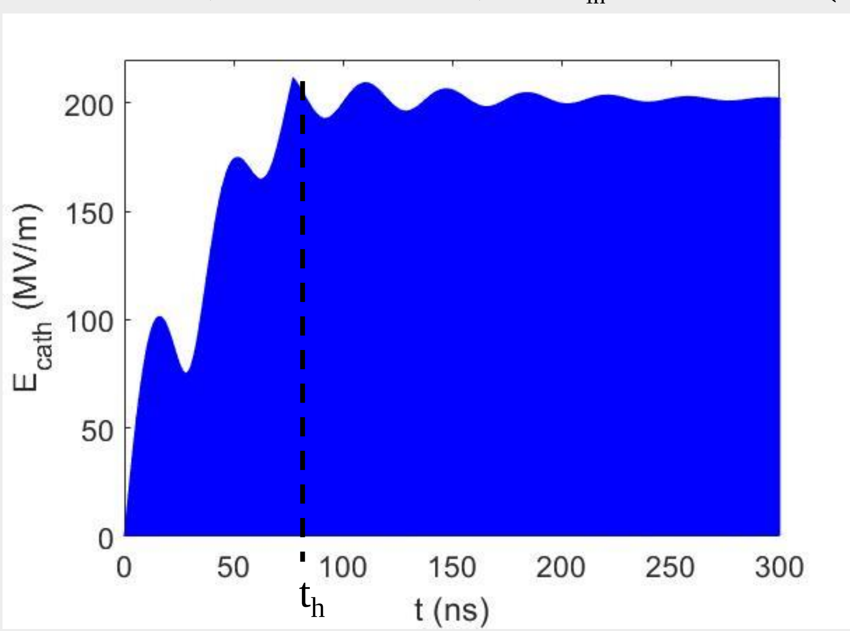


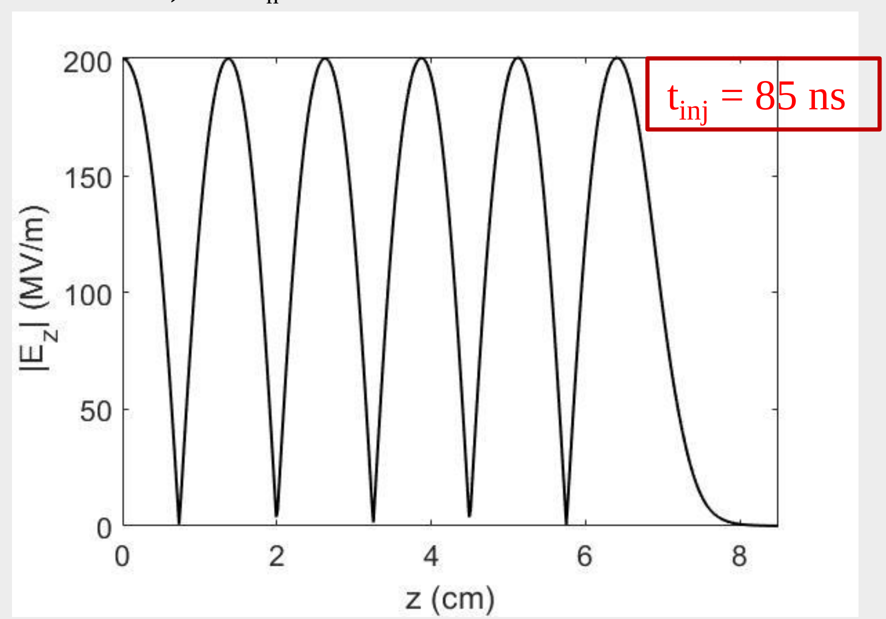
$$V_{acc} = \sqrt{P_{in}R}\,\frac{2\sqrt{2\beta}}{1+\beta}\begin{cases} \sqrt{\Lambda}\left(1-e^{-t/\tau}\right) & 0 < t < t_h \\ 1+\left[\sqrt{\Lambda}\left(1-e^{-t_h/\tau}\right)-1\right]e^{-\frac{t-t_h}{\tau}} & t > t_h \end{cases}$$

V_{acc} is the gun cavity accelerating voltage
R is the circuit model resistance
P_{in} is the input power required to achieve the operating cathode electric field at the steady state

Note that if $\Lambda = \dfrac{1}{\left(1-e^{-t_h/\tau}\right)^2} \longrightarrow V_{acc} = \sqrt{P_{in}R}\,\dfrac{2\sqrt{2\beta}}{1+\beta} \quad t > t_h$

- For our case, we choose $\Lambda = 4$, so $\Lambda P_{in} = 46.32$ MW ($P_{in} = 11.58$ MW) and $t_h = 77.2$ ns





[1] D. Alesini et al., "Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun", Physical Review Accelerators and Beams. 21, 112001 (2018)

RF power system

- The optimum injection time for the electron beam fixes the pulse duration, and hence determines the circuit length to protect the klystron:

$$\boxed{T_p = t_{inj} = 85\ ns} \longrightarrow L = \frac{v_g T_p}{2} \qquad \boxed{L = 10.67\ m}$$

- Assuming that the extra length of the circuit is achieved by the addition of WR-90 rectangular waveguide sections (α_{at} =0.11 dB/m) between the klystron and the RF gun, it is required to compensate the power losses to ensure that the RF gun is feed with the required power (ΛP_{in} = 46.32 MW)

$$\alpha_{at} = \frac{10}{L}\log_{10}\left(\frac{P(z_1)}{P(z_2)}\right)$$

For our case, the power losses are 1.173 dB

$$P(z_2) = \Lambda P_{in} = 46.32\ MW \longrightarrow \boxed{P_{klystron} = P(z_1) = 60.7\ MW}$$

- We propose a RF power system layout similar to that existing in the Xbox 3 at CERN[1], which is composed of:
  - Four combined Toshiba E37113 klystrons
  - SLED pulse compressors

Toshiba E37113 klystron parameters

Parameter	Value
RF peak power	6 MW
Pulse length	5 µs
Max repetition rate	400 Hz

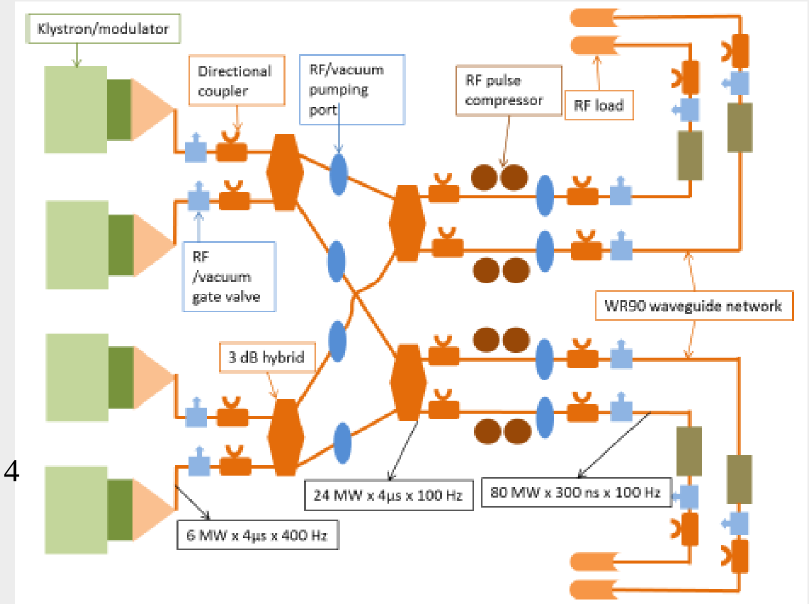
Each klystron can provide 6 MW with 4-5µs

↓ combining the four klystrons

Combined pulse with 24 MW and 4-5µs

↓ pulse compression with factor between 3 and 4

Output pulse with 70-80 MW and 300 ns, and a max repetition rate of 400 Hz

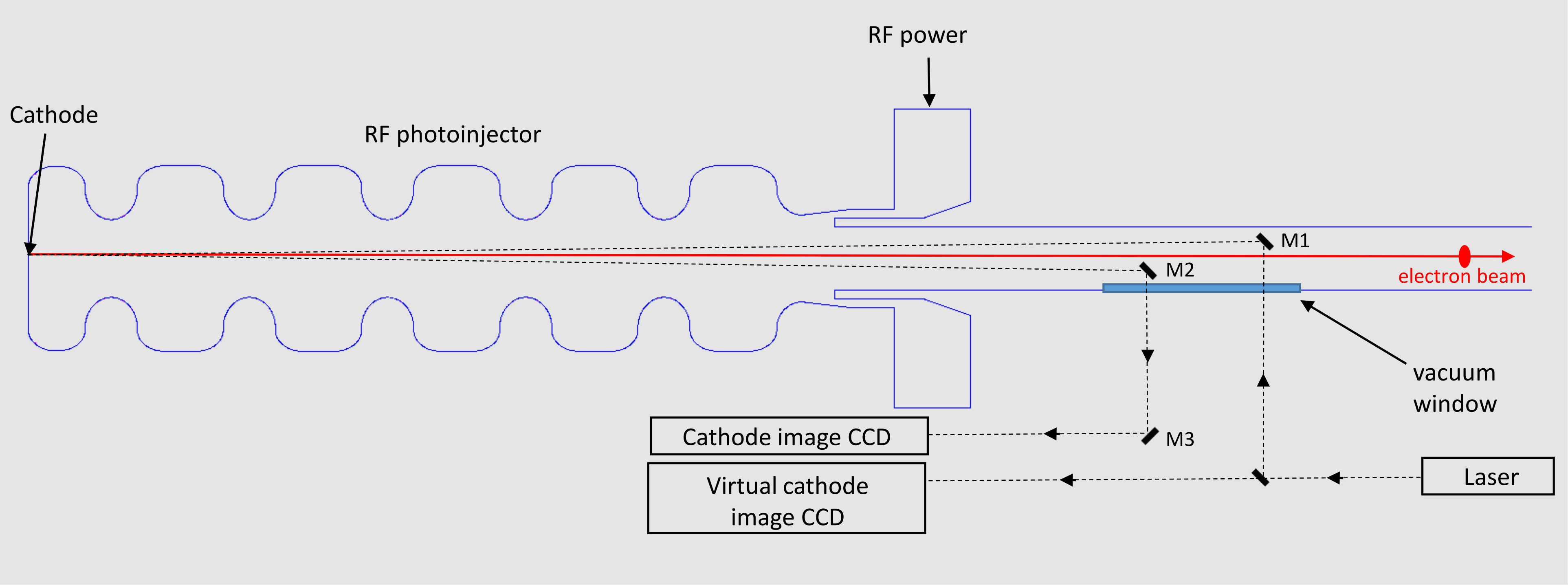


Scheme of the CERN Xbox3

[1] B. J. Woolley, "High Power X band RF Test Stand Development and High Power Testing of the CLIC Crab Cavity", PhD Thesis, 2015

Laser injection

The following scheme is proposed in order to inject the laser beam in the RF photoinjector[1]

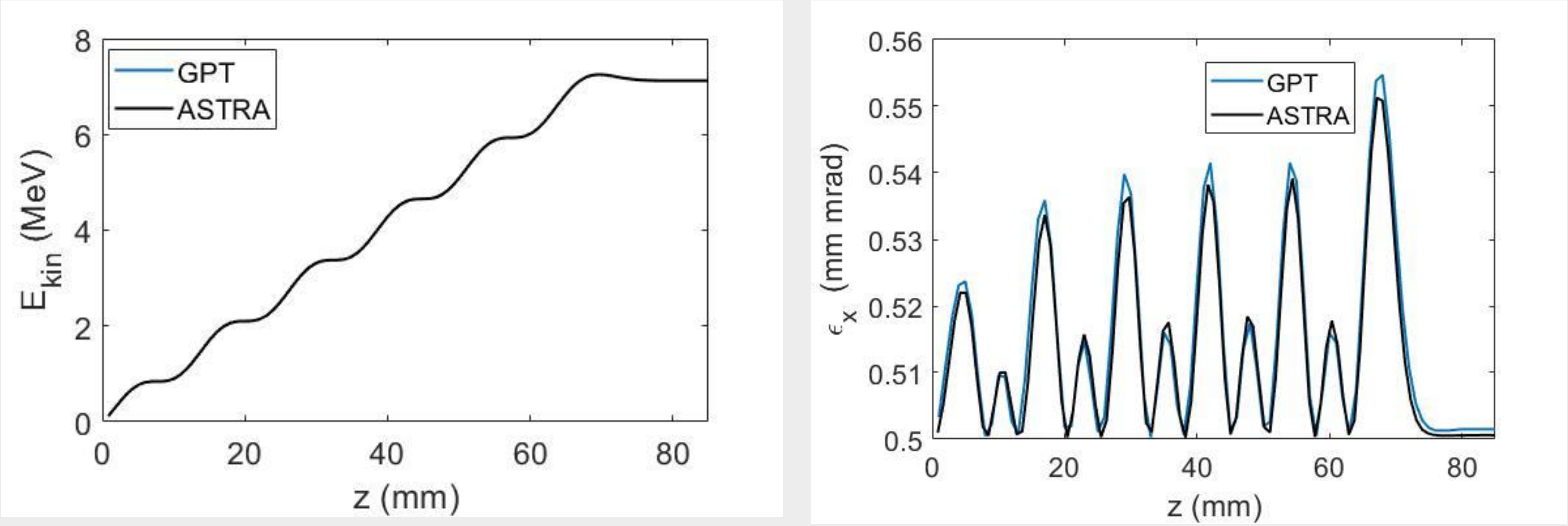


- The laser beam is inserted in the gun cavity by means of a vacuum window and a set of mirrors
- The current scheme allows to monitor the input laser beam (virtual cathode image CCD) and the cathode image

[1] X. Stragier, "Towards external injection in laser wakefield acceleration", PhD Thesis, Eindhoven University of Technology, 2011.

Future work

- The last point remaining in the RF gun analysis are the beam dynamics simulations (which includes the solenoid design for beam emittance compensation and multipactor suppression)
- During the last months, we have spent some time learning to use the *General Particle Tracer*[1] (GPT) software and the ASTRA[2] code in order to study the beam performance in the photoinjector
- Currently, we are focused on the design of the beam emittance solenoid. To do this, we are doing a bibliographic research about this topic, besides we are learning to use the software POISSON[3] for the solenoid design



Some preliminary plots obtained with GPT and ASTRA

[1] http://www.pulsar.nl/gpt/ [2] http://www.desy.de/~mpyflo/ [3] https://laacg.lanl.gov/laacg/services/download_sf.phtml

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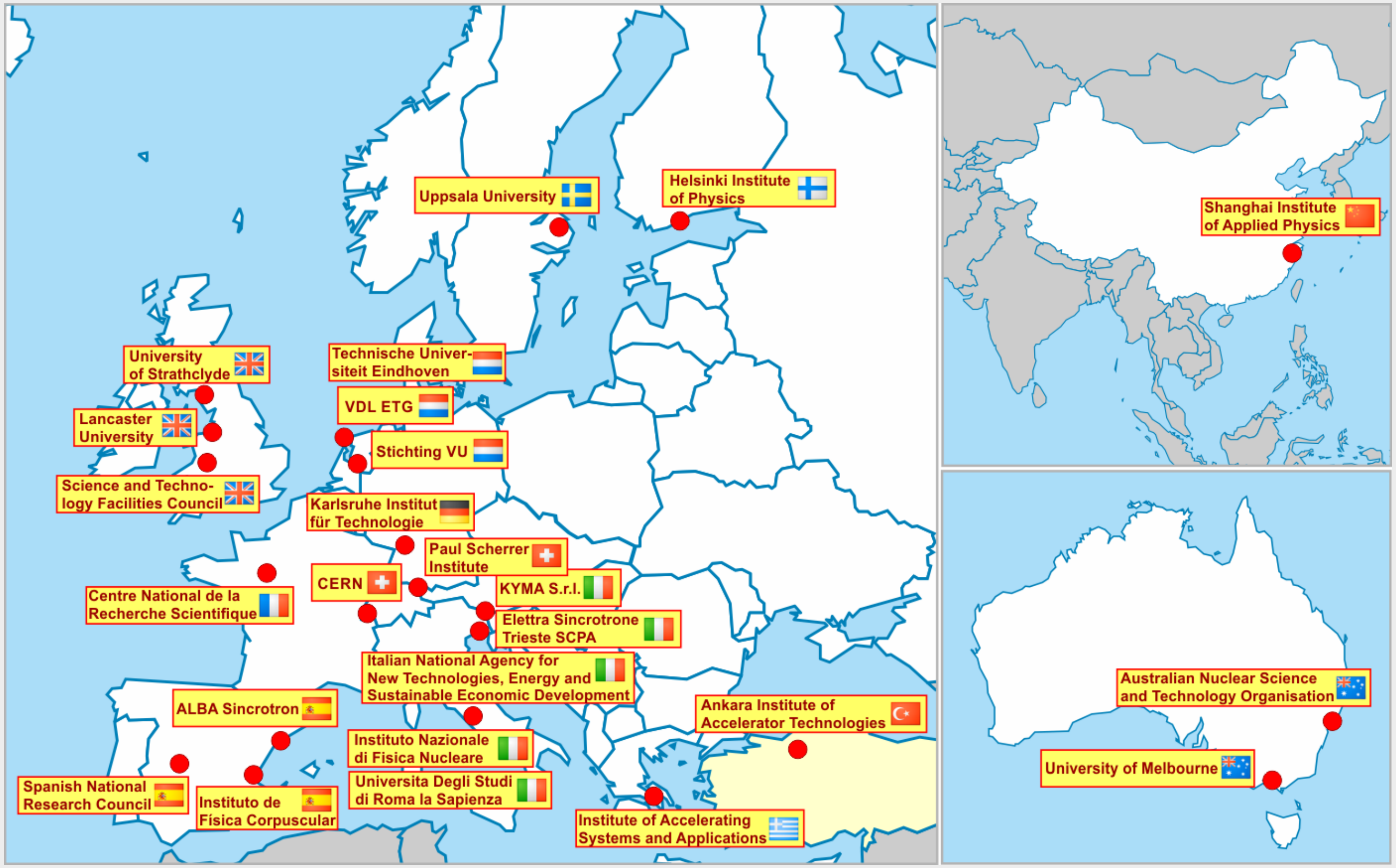

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