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START-TO-END BEAM DYNAMICS SIMULATIONS FOR PRAE

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Abstract

The PRAE project (Platform for Research and Applications with Electrons) aims at creating a multidisciplinary R&D facility in the Orsay campus gathering various scientific communities involved in radiobiology, subatomic physics, instrumentation and particle accelerators around an electron accelerator delivering a high-performance beam with energy up to 70 MeV and later 140 MeV, in order to perform a series of unique measurements and future challenging R&D. In this paper we report the first start-to-end simulations from the RF gun, going through the linac and finally to the different experimental platforms. The beam dynamics simulations have been performed using a concatenation of codes. In particular for the linac the RF-Track code recently developed at CERN will be used and benchmarked. The different working points have been analysed in order to minimise the transverse emittance and the beam energy spread including space charge effects at low electron energies.

INTRODUCTION

The PRAE accelerator consists of a RF gun, a High-Gradient (HG) accelerating section and two beam lines with the corresponding experimental setups: the subatomic physics ProRad and the radiobiology research sharing the direct line and the instrumentation platform in the deviated line, as shown in Figure 1. The performances of the PRAE accelerator are summarized in Table 1 [1].

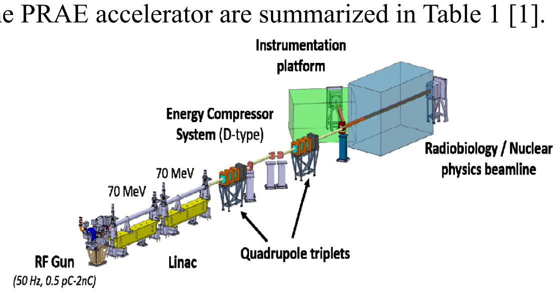

Figure 1: Schematic view of PRAE accelerator (140 MeV) with experimental platforms.

The RF Gun

A photo-injector has been chosen as electron source since a low-emittance beam is required. The photo-injector consists of a normal conducting RF gun, a drive-laser and two focusing solenoids. To obtain high-charge per bunch, a metallic magnesium photocathode will be used.

The S-band (3GHz) RF gun is made of 2.5 copper cells, magnetically coupled to a waveguide. To get 1 nC with an emittance lower than 5 mm mrad, an accelerating field of 80 MV/m is required, which means a RF power of 5 MW in a 3 μs pulse. The electron beam energy at the exit of the gun will be of the order of 5 MeV. The RF gun characteristics are listed in Table 2.

Table 1: PRAE Accelerator Performances

Energy	70 – 140 [MeV]
Charge (variable)	0.00005 – 2 [nC]
Normalized emittance	3-10 [mm mrad]
RF frequency	3.0 [GHz]
Repetition rate	50 [Hz]
Bunch length, rms	< 10 [psec]
Energy spread, rms	< 0.2 %
Bunches per pulse	1

A new design based on the beam photo-injector (PBPI) of CLIC Test Facility (CTF3) at CERN [2] but with an optimized solenoids configuration which was originally developed for ThomX [3] as shown in Figure 2, has been adopted for PRAE. More details about the optimization will be described in the following section.

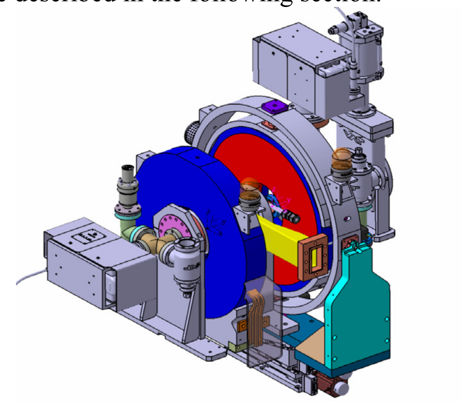

Figure 2: PRAE RF gun 3D design with new solenoids configuration.

The HG Linac Section

The HG acceleration section will be a 3.47 m long S-band, in order to make the machine more compact. The accelerating section will be located after the RF gun as shown in Figure 1. The HG accelerating structure will be a travelling wave (TW), quasi-constant gradient section and will operate at 3 GHz (30°C in vacuum) in the 2π/3 mode. The choice of a single cell shape derives from an optimization aiming to maximize RF efficiency and minimize surface fields and modified Poynting vector at very

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HG. Such gradients can be achieved using shape optimized elliptical irises, quasi-symmetrical type coupler, and specialized fabrication procedures developed for HG structures. A detailed description is found in [4].

Table 2: RF Gun Characteristics

Charge per bunch	1 [nC]
Q/Rs	14400/49 [MOhm/m]
Length	0.125 [m]
Energy gain	~5 [MeV]
Peak accelerating field	80 [MV/m]
RF input power	5 [MW]
Laser wavelength	266 [nm]
Laser pulse energy	100 [µm]
Laser pulse duration	2 [ps]

The RF design consists of 97-cells (95 regular cells + 2 coupling cells) as shown in Figure 3. The calculations have been carried out with HFSS and CST [5, 6].

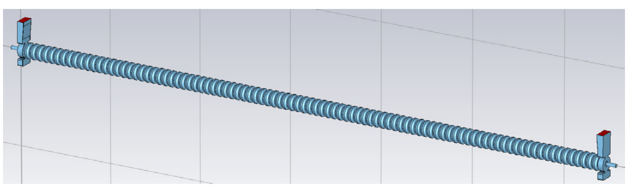

Figure 3: 3D design with CST for PRAE HG accelerating structure.

RF GUN OPTIMIZATION

Since a low emittance beam is required is crucial to mitigate the emittance growth in the RF gun. Different parameters could be optimized as the laser characteristics and the solenoid configuration.

A first study of the laser spot size in function of emittance and particles losses has been performed. Figure 4 shows the scan over the different laser spot sizes over normalized emittance and particle losses percentage, a decrease in the laser spot size gives an increase of particle losses due to electron emission saturation (space charge limit). A total bunch charge of 1nC and 2 ps laser pulse duration are found as the optimal one, with rms $\sigma_{x,y}$ = 0.5 mm and 0.85 mm mrad normalized transverse emittance, supposing a Gaussian distribution. The particle loss is kept to an acceptable value of 5%.

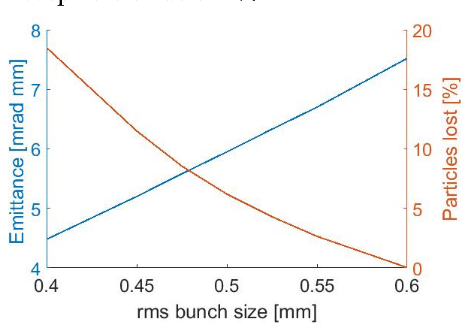

Figure 4: Normalized transverse emittance and particle losses in function of the laser spot size, calculated with ASTRA.

The second optimization concerns the solenoid configuration. The magnetic field generated on the photocathode is maximum close to the photocathode and has a waste at the exit of the RF gun. Changing the distance between the two solenoids could optimize the slope of the magnetic field profile, see Figure 5.

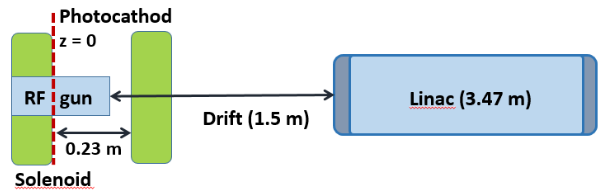

Figure 5: Schematic drawing of the PRAE injector.

Due to mechanical constraints, we have a limited range of 23 cm. The distance is corresponding to the exit face of the bucking solenoid and the middle of the focusing solenoid. The magnetic field of both bucking and focusing solenoids has been calculated by the 3D OPERA [7] solver and the beam dynamics simulation have been done using the code ASTRA [8]. The results for 0 and 23 cm distances are shown in Table 3 for comparison. The solenoid magnetic field giving a minimum emittance is 0.254 T.

Table 3: Beam Performances for 0 and 23 cm Distance Between the Two Solenoids of the RF gun Calculated with ASTRA

D_{coils} [m]	0	0.23
E [MeV]	5.3	5.3
ΔE/E [%]	0.32	0.43
$\varepsilon_{x,y}$,[mrad mm]	5.97	5.85
$\sigma_{x,y}$, [mm]	2.89	0.71

TW ACCELERATING STRUCTURE

The next beam dynamic calculation along acceleration structure are performed using two programs: ASTRA and RF-Track [8, 9].

ASTRA

One RF period has been considered, corresponding to a length of 100 mm. A total of 97 cells have been tracked in a simplified model without input and output couplers, substituted by drifts, with space charge effects. The acceleration gradient is 26 MV/m, and the required RF power is about of about 30 MW. The transverse emittance and the β-function along the injector line are plotted in Figure 6. A minimum emittance of 4 mm mrad is obtained at the end of the TW structure (z = 5 m), while the β-function is increasing along the accelerating structure. The total energy gain is around 65 MeV.

After setting the main parameters, a phase adjustment process in order to minimize the emittance has been made

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has been made. The optimal phase dierence between the laser and the RF field at the cathode and the Rf-gun and the accelerating structure are: -13.5° and -3° respectively. The characteristics of the beam at the end of the structure are summarized in Table 4.

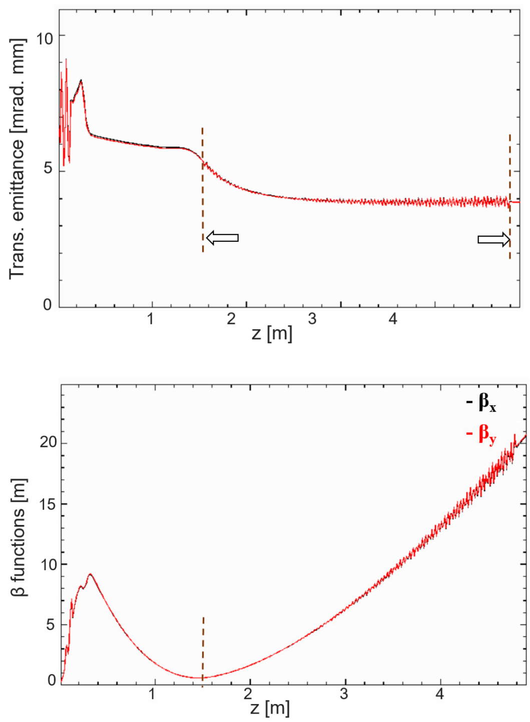

Figure 6: Normalized transverse emittance (top) and β-function (bottom) versus distance, calculated with ASTRA. The arrows indicate the beginning/end of the accelerating structure.

Table 4: Beam Performances at the Exit of Linac Calculated by ASTRA

E [MeV]	67
ΔE/E %	0.22
$\varepsilon_{x,y}$ [mm mrad]	3.89
$\sigma_{x,y}$ [mm]	0.78
Particle loses [%]	5%

RF-track

The particle distribution simulated by ASTRA for the RF gun has been tracked along the accelerating structure using a new code developed at CERN, RF-track. This new tracking code has been developed for the optimization of low-energy linacs in presence of space-charge effects. Furthermore, RF-Track gives possibility to transport bunched beams through conventional elements and field maps of oscillating electromagnetic fields. The 3D electromagnetic field profile of the accelerating section has been defined via HFSS and CST [9, 10].

In our case we have used the full 97-cell structure calculated by CST. The first results for the phase space and main parameters at the end of the linac are shown in Figure 7 and Table 5. The results are obtained after a complete scan of the phases between the RF gun and the linac in order to optimize maximum energy gain and emittance. The best results corresponds to 250°. The dependence of energy on phase is shown in Figure 8.

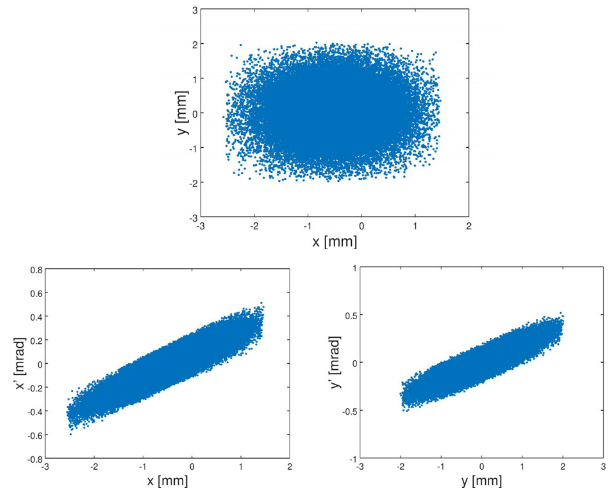

Figure 7: Beam profiles (top) and transverse phase space (bottom) at the end of accelerating section calculated with RF-Track.

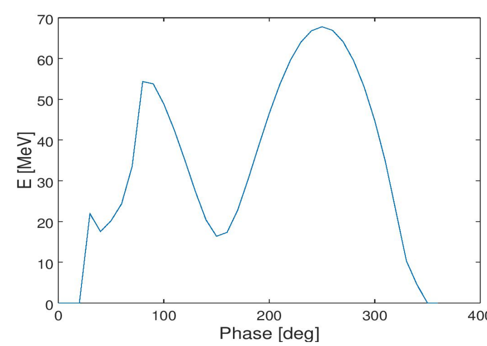

Figure 8: Energy dependence on the phases between the RF gun and the linac.

Table 5: Beam Performances at the Exit of Linac Calculated with RF-Track

E [MeV]	67
$\varepsilon_{x,y}$ [mrad mm]	5.32
$\alpha_{x,y}$ [mm]	-2.15 / -1.9
$\beta_{x,y}$ [m]	10.33/10.96

CONCLUSIONS

Realistic beam dynamic simulations have been performed for the PRAE injector (RF gun + linac) using a concatenation of codes (ASTRA + RF-Track). Results of the new RF-Track code are very promising and simulations are on going to optimize the system performances as well as the program.

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