DESIGN OF A LOW EMITTANCE HIGH CURENT PHOTOCATHODE RF GUN FOR THE IPM LINEAR ACCELERATOR

M. Dayyani Kelisani, H. Shaker, School of Particles and Accelerators, Institue for Research in Fundamental Sciences, Tehran, Iran

Abstract

The IPM accelerator project is developing a 10-50 MeV linear accelerator to use as a terahertz source or an IR FEL. The design specifications require a laser driven photocathode located in one end of a high gradient RF cavity operated at 3 GHz frequency and a solenoid channel for the beam transport. In this work, we report on the RF design of a special photocathode RF gun and its associated focusing channel for the emittance compensation process along the whole injector.

INTRODUCTION

The IPM LINAC project requires a photo-injector which can provide a high current and high quality electron beam. Figure 1 shows the general layout of the IPM LINAC.

In the injector the electron bunches will be generated in a single shot RF gun from a Laser driven pulsed photocathode operated at 10 Hz repetition rate. The cathode is located in one end of a high gradient RF cavity which is fed by a 6 MW klystron at 2998 MHz frequency and 10 Hz repetition rate. The electron bunches that are produced from a 1 mm laser spot on the cathode have 0.1-1 nc charge and 5ps bunch length. After generation they are accelerated instantaneously by the high gradient RF fields and at the end of the RF gun the energy of the electrons arrive to about 5 MeV. The further acceleration up to 50 MeV is provided through five identical 1 m long traveling wave accelerating structures at 3 GHz frequency located downstream of the RF gun. Also for the beam transport the whole injector is located in a long solenoid channel. Our goal is to design the required RF gun and its associated focusing channel to provide a beam with high quality and low emittance within the injector. The two critical issues which have to be considered in the design are high gradient RF field excitation and emittance compensation process [1]. For the first problem one special RF structure with very symmetric fields is presented which can excite up to 74 MV/m on-axis fields for the available RF power. Such RF fields not only accelerate fastly the bunches but also minimize the action of unavoidable nonlinearities and preserve the emittance. On the negative side, high gradient operation leads to RF emittance growth due to non-conservative nature of the RF fields which should be compensated later. Around the whole LINAC an appropriate solenoid channel is designed to manipulate the bunch phase space and notably compensate the bunch emittance. In the next section we start with RF design of the required RF gun where we explain the general structure of the designed RF cavity and simulation results with CST [2] microwave solver for the important RF quantities. In the third section we describe the design of the focusing channel which is necessary for the beam transport and also the emittance compensation process. By using the Astra [3] code we track the beam along the whole injector to get information about the beam envelope, emittance and energy spread.

RF DESIGN

To design the required RF gun there are three important points that should be considered in the course of designing. First, to have a fast acceleration, the structure should be started by a half cell cavity to have maximum field gradient on the cathode surface. Second, for better synchronization between the particles and fields, the cavity should be operated a little off-crest to have a situation in which the first emitted electrons from the cathode will receive lower forces than the latter ones. Third, for an efficient acceleration, the distances between subsequent cells should be so that the electrons will receive the maximum field gradient at the center of subsequent cells. It can be shown that all these requirements can be met easily by a 2.5 cell standing wave cavity operated at π mode which is shown in Fig. 2. This structure is composed of a 2.5 cell RF cavity (cell length $= 50\,mm$) and is fed by a WR284 standard rectangular wave guide (length $= 34.036\,mm$, width $= 72.136\,mm$) $3\,mm$ above the cavity and a 50mm shorted

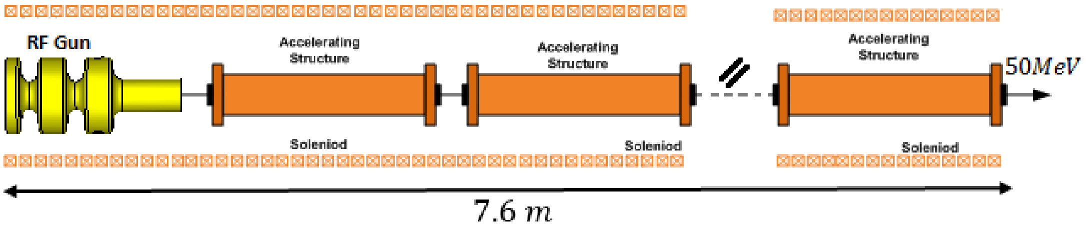

Figure 1: IPM LINAC layout with a total length of 7.6 m consists of a photocathode RF gun, five same travelling wave accelerating structures and a long solenoidal which covers the whole injector.

waveguide which is inserted symmetrically with respect to the wave guide (to compensate the asymmetry inside the cavity).

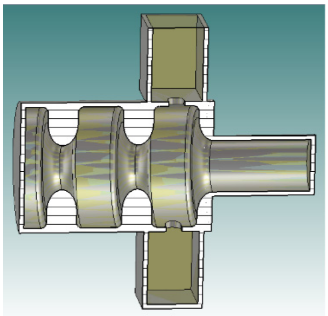

Figure 2: CST model for the IPM RF gun.

For this structure the Figure 3 shows the CST simulation result for electric field profile on the beam axis. As it can be seen the excited electric field in the cavity has exactly π phase advance per cell with the maximum value of 74 MV/m.

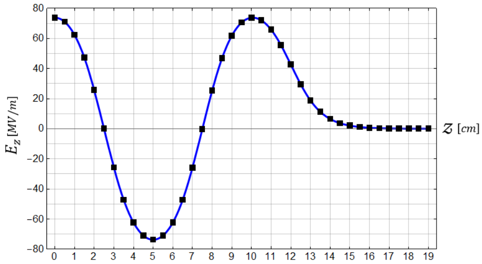

Figure 3: On axis field profile in the IPM RF gun cavity.

Since the structure will be operated at 10 Hz bunch repetition frequency, then the induced field by the beam in cavity can be ignored and there is no need for beam loading compensation [4]. In such a situation to excite the fields in the cavity with maximum gradient we should design the cavity with the coupling factor equal to 1 (critical coupling) without any detuning. Figure 4 shows the CST simulation results of the power accepted by the structure for 1 W input power versus frequency. The diagram implies that the structure is tuned exactly on the desired frequency (2998 MHz) with a coupling factor very close to 1 (1.03).

For the structure all the important RF quantities are also listed on Table 1. The parameters ν_r, Q_u, β_c, τ_f, R_{sh} and TT imply for resonant frequency, unloaded quality factor, coupling factor, filling time, shunt impedance and transit time factor, respectively.

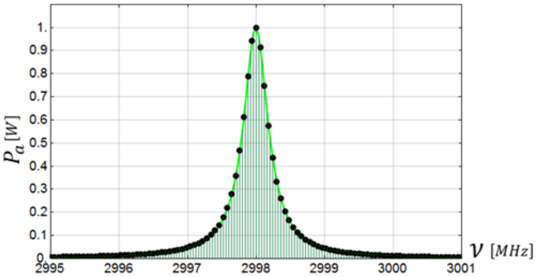

Figure 4: CST simulation results for the power accepted by the IPM RF gun for 1 W input power.

Table 1: CST Simulation Results for the Cavity Quantities

Quantity	*Value*
$\nu_r[MHz]$	2998
Q_u	13974
β_c	1.03
$\tau_f(\mu s)$	0.74
$R_{sh}(M\Omega)$	3.86
TT	0.73

At the end of the RF gun depending on the phase of the excited RF field within the cavity, the electron bunches arrive to few MeV kinetic energy. Further acceleration up to $50\,MeV$ is provided using five subsequent same traveling wave accelerating structure at $2998\,MHz$. The accelerators are constant gradient structures which have $1\,m$ length, $10\,MV/m$ gradient and separated from each other by 30 cm. Figure 5 shows the average kinetic energy of the electrons along the injector.

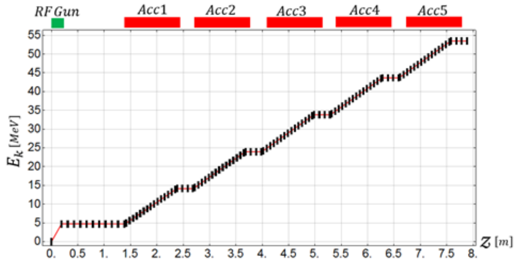

Figure 5: Average kinetic energy of the electrons along the injector.

BEAM DYNAMICS DESIGN

To transport the beam after the electron gun we need to make use of a focusing channel otherwise the electrons will be diverged due to the repulsive space charge forces [5] and the beam gets lost. The focusing channel is in fact a series of several circular magnetic coils which can produce a longitudinal magnetic field along the beam axis. Such a focusing channel can be designed in such a way that to fix the beam RMS radius on a constant value along the whole injector. The focusing channel has two different parts: a matching cell and a solenoid. In the matching cell the currents and positions of the coils should be calculated so that the derivatives of the beam envelope vanish at the beginning of the solenoid and in the meantime reduces the beam RMS radius from its initial value at the end of the RF gun to our required fixed value (say 0.5 mm) within the solenoid. Assuming these conditions are satisfied and the strength of the magnetic field in the solenoid is adjusted appropriately, the beam reaches a thermal equilibrium with 0.5 mm constant RMS radius within the solenoid. Figure 6 shows the distribution of our designed magnetic field profile within the injector. The average magnetic field strength is about 817 G.

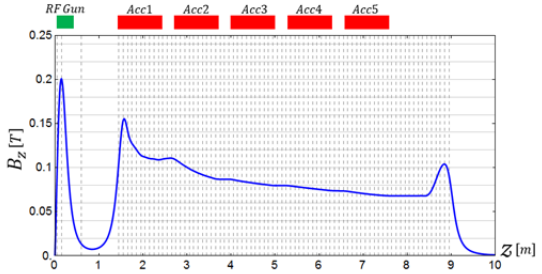

Figure 6: magnetic field profile of the focusing channel along the beam axis.

With the designed focusing channel we can appropriately control the space charge forces and fix the beam RMS radius on our desired constant value i.e. 0.5 mm. Figure 7 shows the Astra simulation results for variations of the beam RMS radius along the injector.

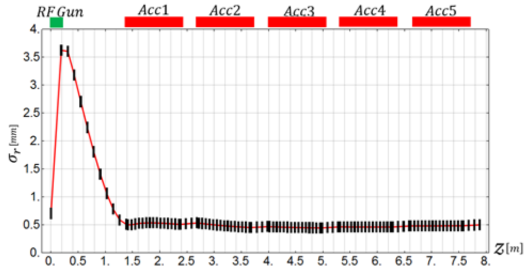

Figure 7: Astra simulation result for variation of the RMS beam radius along the injector.

Astra simulations also shows that with the designed focusing channel the initial emittance growth steams from non-conservative RF forces in the RF gun will be well compensated. Figure 8 shows the results of simulations for the variations of the normalized beam emittance within the designed focusing channel. As it can be seen at the end of the injector the beam emittance arrives to a very small constant value of 2 $mm.mrad$.

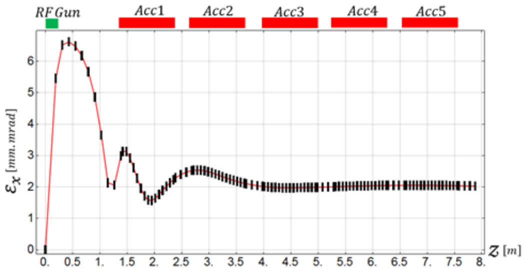

Figure 8: Astra simulation result for variations of the normalized beam emittance within the focusing channel.

Figure 9 also shows the simulation results for variations of the beam energy spread along the injector. At the end of the injector due to the merit of the design the bunch energy spread arrives to a very small value of only 0.2 %.

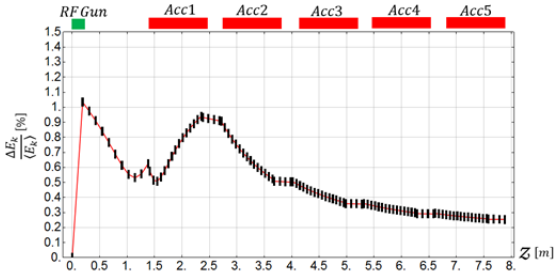

Figure 9: Astra simulation result for variations of the beam energy spread along the injector.

CONCLUSION

A photocathode RF gun and its associated focusing channel are designed for the IPM photo-injector. The design is based on the RF and beam dynamics studies with the goal of having an RF structure with a high gradient RF field and a focusing channel which can provide a high quality beam with very small emittance and energy spread. In the part of RF design a 2.5 cell high gradient RF cavity is designed which can produce 74 MV/m RF field with 6 MW input power. In the beam dynamics course an appropriate focusing channel has been designed which can well transport the beam along the whole injector and compensate the beam emittance growth. At the end of the designed injector the beam arrives to 2 $mm.mrad$ and 0.2 % for the beam emittance and energy spread, respectively.

REFERENCES

[1] L. Serafini and J. B. Rosenzweig, Phys. Rev. E 55, 7565 (1997).
[2] CST Studio Suite 2014, Computer Simulation Technology.
[3] K.Floetmann, ASTRA, http://www.desy.de/~mpyflo/Astra_dokumentation/
[4] M. Dayyani Kelisania et al, Nucl. Instr. and Meth. in Phys. Res. A 828 (2016), 132-144.
[5] M. Reiser, "*Theory and Design of Charged Particle Beams*", 2nd Edition, Wiley-VCH Verlag GMBH, (2008).