BEAM DYNAMICS SIMULATION OF W-BAND PHOTOINJECTOR

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Abstract

We present a beam dynamics simulation study on W-Band photocathode RF gun which is capable of generating and accelerating 300pC electron bunch. The design system is made up of 91.392GHz photocathode RF gun and 91.392GHz traveling wave linac cells. Based on the numerical simulation using SUPERFISH and PARMELA and the conventional RF linac scaling law, the design will produce 300pC at 1.74MeV with bunch length 0.72ps and normalized transverse emittance 0.55mm mrad. We study the beam dynamics in high frequency and high gradient; due to the high gradient, the ponderomotive effect plays an important role in beam dynamics; we found the ponderomotive effect still exist with only the fundamental space harmonics (synchrotron mode)due to the coupling of the transverse and longitudinal motion.

1. Introduction

Recently, high gradient, high frequency accelerators of mm-scale are of interest in advanced accelerator research now[1]. Research on short wavelength, high gradient, RF driven acceleration has concentrated on 90GHz which is in the range of W-Band (75GHz-110GHz), it involves the understanding of millimeter wave source, high power operation of millimeter wave, beam dynamics in high frequency and high gradient, and technologies for fabrication and measurement of millimeter accelerator.

The scaling of RF accelerator with respect to RF frequency f is as follow
Shunt impedance $r \sim f^{1/2}$,
Accelerating gradient $G \sim f$,
Peak power required per meter $\sim f^{1/2}$.
In this paper, we use the above scaling law and codes (SUPERFISH, PARMELA) to design the W-Band photoinjector, and study the beam dynamics in high frequency and high gradient.

2. Design of W-band photoinjector

The design system is made up of photocathode RF cavity, emittance compensation drift section, and 60 $2\pi/3$ travelling wave cells. We use the conventional RF linac scaling law to scale down the BNL S-Band photocathode RF cavity[2,3] and S-Band SLAC $2\pi/3$ traveling wave cells. The RF cavity length is 0.46cm, the drift length 2.3cm and the linac section length 6.55cm, the drift length is decided in order to get good match between the photoinjector and linac cells.

Table 1 and Table 2 give the structure parameters of the RF cavity and linac cell are calculated using SUPERFISH, the shunt impedance and quality factor agree with the scaling law well.

Table 1 The gun cavity design parameters

Inner radius of the cell(mm)	1.3
Radius of the iris(mm)	0.39
Width of the iris(mm)	0.689
Length of the cavity(mm)	4.69
π mode frequency(GHz)	91.392
Shunt impedance(MΩ/m)	269.67
Quality factor	2806

Table 2 The linac cell design parameters

Inner radius of the cell(mm)	1.303
Radius of the iris(mm)	0.409
Width of the iris(mm)	0.182
Length of the cavity(mm)	1.092
$2\pi/3$ mode frequency(GHz)	91.392
Shunt impedance(MΩ/m)	284.5
Quality factor	2435

3. Simulation of W-band linac

We use PARMELA to study the beam dynamics of our system, the RF cavity works in π mode, while the linac cells work in $2\pi/3$ mode. Table 3 gives the typical parameters of the photoinjector

Table 3 photoinjector parameters

solenoid peak field[T]	5.8
gradient[GV/m]	1
charge[pC]	300
bunch length[ps]	0.72
emittance[mm mrad]	0.55
energy[MeV]	1.74
energy spread	7.2%

Because of the high frequency (small structure), it is difficult to get high charge bunch, the maximum bunch charge we get in the simulation is 300pC, above this value, the beam break up fast with the space charge effect. Fig.1 shows the r.m.s. emittance relation with bunch charge under the condition B=5.8T, and the average RF cavity gradient=1GV/m. The single bunch charge in W-band linac is constrained by the beam break up. Zimmermann[6] has estimated the longitudinal and transverse wake fields in a W-Band (91GHz) accelerating structure. The transverse wake field is almost completely determined by the structure geometry (iris radius). For a 60pC charge, and $a/\lambda \geq 0.18$, the transverse beam break up is negligible.

In order to get low emittance bunch, we use POISSON to design the emittance compensation solenoid whose peak field is as high as 5.8T. We have simulated the emittance dependance on the solenoid field shown in Fig.2 under the condition Q=300pC, average gradient=1GV/m.

In our case, the peak electric field in the half and the full cell of the RF cavity is not the same, the electric field amplitude has effect on RF focusing and defocusing which play a role in the emittance evolution of the beam. Fig.3 shows the beam r.m.s emittance evolution with the photoinjector longitudinal position .

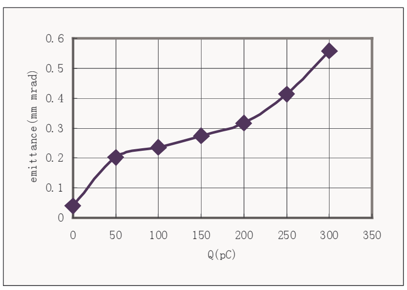

Fig.1 The r.m.s emittance dependance on the bunch charge

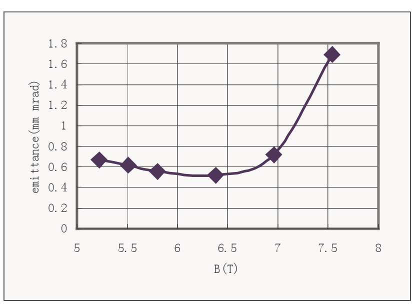

Fig.2 The r.m.s emittance dependance on the peak magnetic field

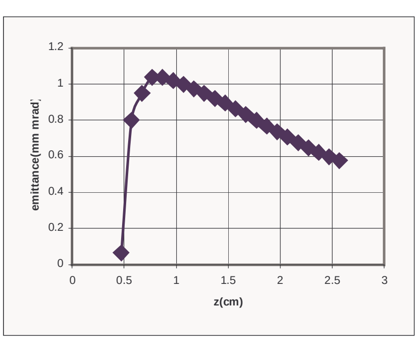

Fig.3 The r.m.s emittance evolution with the longitudinal distance

Up to now, there are few works on the beam dynamics in high frequency and high gradient case. Due to high electric field, the RF focusing and defocusing will become more important. We use 60 linac cells operated at the gradient 1GeV/m to study the beam dynamics in W-band, the cells operated at the fundamental $2\pi/3$ mode. In the simulation, SUPERFISH is used to calculate the RF field coefficients, the high space harmonics were not included. We observe the beam envelope osillation, the periodical time of this kind of oscillation approximately like the square of the electric field amplitude approximately, and is almost independent of the bunch charge. Hence, we can conclude that there exists the transverse ponderomotive effect of the fundamental mode. According to the rf ponderomotive focusing theory developed by Hartman and Rosenzweig[4,5], the accelerating field in a traveling wave structure with spatial periodicity over a length d , can be specified by the following Floquet form:

$$E_Z = E_0 \sum_{n=-\infty}^{\infty} b_n \exp(i(\omega t - \beta_n z)),$$

where $\beta_0 = \beta_0 + (2\pi n / d)$, the constant $\beta_0 d = \psi$ is the phase shift per period. For relativistic electron $\beta_0 = \omega / c = k$, and b_0 is the unity in this normalization. Setting $\omega t = \beta_0 z$ for the maximal acceleration , we can get the ponderomotive tranverse focusing force:

$$\overline{F_r} = -r \frac{(2eE_0)^2}{\gamma m_e c^2} \sum_{n=-\infty}^{\infty} |b_n|^2, n \neq 0.$$

there will be no such effect if only fundamental travelling mode available ($n = 0)$. When the coupling of the longitudinal and transverse motion is considered, i.e. $\omega t = \beta_0 z + \psi_0(z),$ if only the fundamental traveling mode is available, the accelerating field is

$$E_z = E_0 \exp(i\psi_0).$$

Then the ponderomotive transverse focusing force is

$$\overline{F_r} = -r \frac{e^2 E_0^2}{\gamma m \omega^2} < (\frac{d\psi_0}{dz})^2 \exp(i2\psi_0) >,$$

where $<\cdots>= \frac{1}{d}\int_0^d \cdots dz,$ there still exists the pondermotive effect for the case of fundamental travelling mode.

4. Disscussion

The simulation result shows that the photoinjector can produce 300pC electron bunch. In order to maintain such high bunch charge, the beam current density should be in the order of MA/cm^2. Due to this high beam current density, Palmer adopted multicell structure to give an setup of W-band photoinjector[7], the nominal bunch charge is 30pC in their result. However, recent experiment reports MA/cm^2 beam current density in 1GeV/m electric field gradient[8] which is an exciting result to support our simulation result.

The conventional RF linac scaling law works well in W-Band. The ponderomotive effect becomes obvious due to the high gradient. There will exist the ponderomotive effect in the case of fundamental travelling mode due to the coupling of the longitudinal and transverse motion.

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