EXPERIMENTAL OPTIMIZATION OF TTF2 RF PHOTOINJECTOR FOR EMITTANCE DAMPING

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Abstract

In this paper, we describe our experimental optimization experiences of TESLA Test Facility Phase 2 (TTF2) RF photoinjector to get a strong emittance damping along RF photoinjector, and we also present our first experimental demonstration of Ferrario's new working point or invariant envelope in booster linac with Gaussian laser beam.

INTRODUCTION

At a low energy region of RF photoinjector, by accelerating electron beams quickly, we can reduce an initial strong plasma oscillation in the transverse plane, which is induced by space charge force [1], [2]. However the remain plasma oscillation due to space charge force still induces distortions or coupling in longitudinal and transverse phase spaces, and perturbation in the transverse phase space beam distribution. In this case, under the linear external focusings such as solenoid focusing and the ponderomotive RF focusing in the standing wave linac, each longitudinal slice within a single bunch is controlled by different beam dynamics in the transverse phase space [1], [2]. After the focusing channel, each slice is slightly tilted or rotated with a different angle in the transverse phase space because each slice has different current or space charge field [1], [2]. By accelerating and focusing quasilaminar electron beams properly, space charge forces can be reduced, and emittance oscillation due to the plasma effects can be adiabatically damped [1], [2]. Therefore a minimum projected transverse emittance at the end of RF photoinjector is obtained by aligning all longitudinal slices to have a common angle in the transverse phase space, where each slice is controlled by a common beam dynamics in the transverse phase space. This particular solution of envelope equation which gives a transverse emittance compensation along RF photoinjector as well as a minimum transverse emittance at the booster exit is called by Ferrario's new working point or invariant envelope in the booster [1], [2]. However, up to 2005, no laboratory experimentally demonstrates this emittance damping in the booster linac. During TTF2 commissioning, for the first time, we could experimentally demonstrate Ferrario's new working point or strong emittance damping in booster with Gaussian gun driving laser beam. In this paper, we describe our experimental experiences of TTF2 RF photoinjector to get a strong emittance damping along RF photoinjector.

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TTF2 RF PHOTOINJECTOR

Layout of TTF2 RF photoinjector is shown in Fig. 1, and its normal parameters during emittance measurements without bunch length compression are summarized in Table 1. Here all emittances are projected normalized rms transverse emittances estimated from ASTRA and ELEGANT simulations. TTF2 injector consists of four main parts; RF gun, booster linac (ACC1), first bunch compressor (BC2), and three 1.9 m long FODO cells with four OTR screens and four wire scanners to measure transverse emittance [3]-[5]. In additionally, there are eleven horizontal and vertical steerers along TTF2 RF photoinjector to correct mis-steered beam orbit. RF gun part consists of a 1.5 cell copper cavity which accelerates electron beams to about 4.7 MeV, a Cesium Telluride (Cs_2Te) cathode whose quantum efficiency is higher than about 1%, a bucking solenoid to remove emittance growth due to the residual magnetic field on cathode surface, and a main solenoid to compensate emittance growth due to defocusing space charge force, two YAG screens (2GUN and 3GUN) to measure beam size, and a spectrometer dipole (IDUMP) and a YAG screen to measure beam energy and energy spread at gun region [1], [3]. Booster linac part consists of eight 1.3 GHz TESLA superconducting cavities with nine cells, where the first four cavities have a lower gradient and the last four cavities have a higher gradient to control strength of ponderomotive RF focusing in booster [1]. The first bunch compressor part consists of a chicane with four 0.5 m long rectangular dipoles, a thin quadrupole triplet at the upstream of the chicane, which can keep zero α and low β Twiss parameters at the fourth dipole in the chicane to reduce projected emittance growth due to coherent synchrotron radiation (CSR) [4], [6]. Three FODO cells part with four OTR screens (4DBC2, 6DBC2, 8DBC2, and 10DBC2) and four wire scanners consists of five quadrupoles to match Twiss parameters between BC2 and three FODO cells, seven quadrupoles to make three FODO cells with 45 degree betatron phase advance, four OTR screens and four wire scanners to measure beam size and shape periodically, and three quadrupoles to match Twiss parameters between three FODO cells and the second TESLA module (ACC2) [1], [5], [7].

EMITTANCE DAMPING IN BOOSTER

When we designed our photoinjector, we considered many emittance degradation sources in advance to get about 1 μm projected transverse emittance at the end of injector, and we reflected them in fabrication time [1], [3],

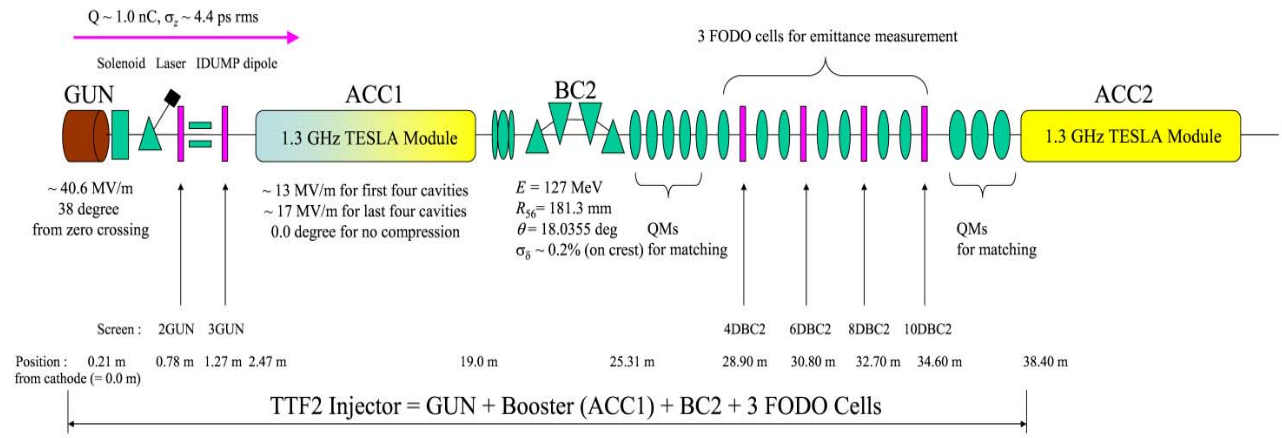

Figure 1: Layout of TTF2 RF photoinjector.

Table 1: Parameters of TTF2 injector without compression.

Parameter	Unit	Value
RF frequency of gun and TESLA module	GHz	1.3
number of gun cell	cell	1.5
measured rms laser pulse length	ps	~ 4.4
peak current at the end of injector	A	~ 65
single bunch charge Q	nC	~ 1.0
transverse thermal emittance	μm	~ 0.64
net gun RF power	MW	~ 3.03
maximum gradient on cathode	MV/m	~ 40.62
gun RF phase from zero crossing	deg	~ 38
maximum main solenoid magnetic field	T	0.1632
beam energy at gun exit	MeV	~ 4.7
low / high accelerating gradient in ACC1	MV/m	$\sim 13/17$
ACC1 phase from on crest	deg	0
beam energy at the end of injector	MeV	~ 127
measured rms lasersize at virtual cathode	mm	~ 0.75
measured rms beamsize at 2GUN screen	mm	~ 4.30
measured rms beamsize at 3GUN screen	mm	~ 3.00
simulated rms beamsize at ACC1 exit	μm	~ 500
measured rms beamsize at screens in FODO	mm	~ 140
simulated rms beamsize at screens in FODO	μm	~ 140
simulated trans. emittance at 3GUN (100%)	μm	~ 5.00
simulated trans. emittance at FODO (90%)	μm	~ 1.05
simulated trans. emittance at FODO (100%)	μm	~ 2.00

[7]. However, during the beginning days of TTF2 injector commissioning, our measured projected normalized rms transverse emittance at the end of injector was around 5 μm with 100% whole beam intensity even though all machine parameters were close to design ones and we performed scanning of those parameters. Therefore we had to remove all other sources which degraded transverse emittance along RF photoinjector. First of all, we aligned a big misalignment in a beamline between the main solenoid and booster. Its horizontal and vertical misalignments were about 0.9 mm and 0.5 mm, respectively [7]. Secondly, we reduced misalignment of laser beam on cathode and misalignment of the main solenoid by a beam based alignment technique [8]. Thirdly, we reduced orbit offset and kicking due to the higher order mode (HOM) in the booster by optimizing gun steerers while monitoring amplitude of HOM signal [9]. Fourthly, we measured residual dispersion and RF steering effect due to booster by monitoring beam positions on four screens in FODO cells while changing gradient of booster. Those residual dispersion and RF steering effect were minimized by re-optimizing gun steerers [7], [10]. Fifthly, we slightly re-optimized gun steerers to reduce vertical beam chopping due to 12 mm aperture of IDUMP dipole [7]. Sixthly, we optimized steerers between booster and BC2 to reduce transverse wakefield due to 8 mm aperture of BC2 vacuum chamber [7]. Seventhly, we tried to improve profile, uniformity of gun driving laser, and adjusted laser spot size on cathode by adjusting aperture of an iris in laser transport beamline, which helps in controlling thermal emittance and reduced nonlinear space charge force around beam edge [3], [7]. Transverse profile of our gun driving laser was clipped Gaussian because the iris chopped edge of laser beam, and longitudinal profile was normal Gaussian shape with about 4.4 ps long rms pulse length [3]. Eighthly, we reduced overestimation in measured emittance by keeping a good optics matching in three FODO cells [1], [5], [7].

After removing all other sources which degraded transverse emittance along photoinjector, we performed rescannings of machine parameters while measuring emittance. Since we should keep a local emittance maximum and a minimum beam size or laminar beam waist at the entrance of booster to obtain invariant envelope and continuous emittance damping in booster linac, with fine steps, we carefully scanned strengths of the main solenoid, gun phase, and gun gradient which may change ponderomotive RF focusing [1], [2], [7]. After those fine scannings, to get a low level frozen emittance at the booster exit, we also carefully scanned booster gradient which is determined by the rms beam size, peak current, beam energy at the booster entrance [1], [2], [7]. By continuously repeating fine scannings of gun gradient, gun phase, main solenoid, and booster gradient while measuring emittance, we could get optimized injector parameters as summarized in Table 1, which produced one of the best emittances on February 23rd, 2005. Detail things on emittance measurements are described in reference [5]. To confirm beam size and emittance damping along our RF photoinjector, on April 7th, 2005, we measured electron beam size along injector and emittance at three FODO cells as shown in Fig. 2 and reference [7], where we can clearly see that beam size is damped along injector. Specially, four beam images at the downstream of BC2 have almost same size and shape, which indicates a good optics matching in three FODO cells. From beam images on four screens in the FODO cells, we could measure transverse emittance on April 7th, 2005, which was about 2.3 μm for 100% beam intensity and about 1.4 μm for 90% core beam intensity as shown in reference [7]. Since profile of gun driving laser was not its best one on April 7th, 2005, measured emittance was slightly larger than its best one. However, on February 23rd, 2005, by optimizing gun gradient and gun phase, main solenoid, and booster gradient carefully and by removing all other sources which degraded transverse emittance, we could get one of our best emittances as shown in Fig. 3 and reference [7]. Its measured emittance at three FODO cells was about 1.9 μm for 100% beam intensity and about 1.1 μm for 90% core beam intensity which is almost close to slice emittance. According to our invariant-envelope-based simulation results as summarized in Table 1 and as shown in reference [7], our optimized emittance at 3GUN screen is about 5 μm for 100% beam intensity, its emittance at three FODO cells is about 2.0 μm for 100% intensity and 1.05 μm for 90% beam intensity, and beam size on four screens in the FODO cells is about 140 μm for 100% beam intensity. Note that those simulation results are almost perfectly agreed with our measured ones on February 23rd, 2005.

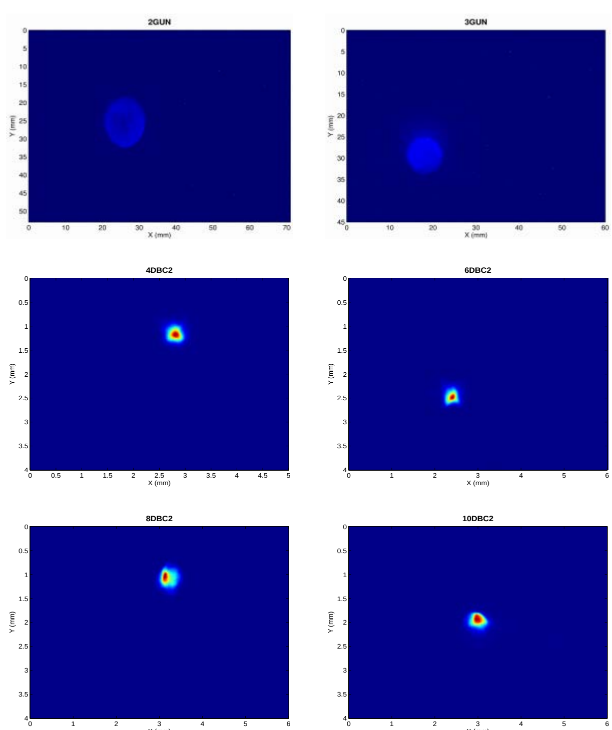

Figure 2: Measured electron beam images at 2GUN (top right), 3GUN (top left), 4DBC (middle left), 6DBC2 (middle right), 8DBC2 (bottom left), and 10DBC2 (bottom right) screens on April 7th, 2005.

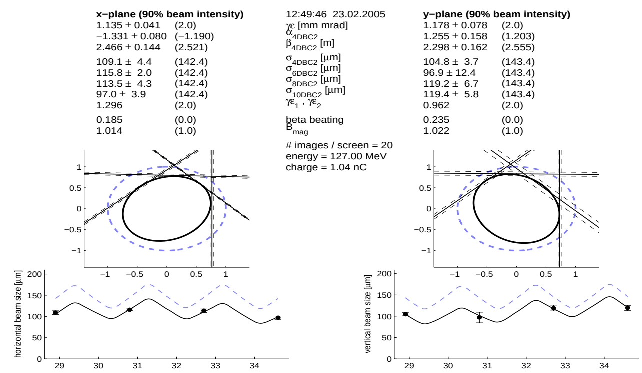

Figure 3: Measured transverse emittance with 90% core intensity on February 23rd, 2005.

SUMMARY

After removing all emittance degradation sources, our measured projected normalized transverse rms emittance was about 1.1 μm with 90% core beam intensity and about 1.9 μm with 100% beam intensity for a single bunch charge of about 1 nC and peak current of about 65 A. Since our measured beam size and emittance are well agreed with our simulation results which were optimized by using Ferrario's new working point, it is certain that for the first time, we experimentally demonstrated strong emittance damping in booster and Ferrario's new working point or invariant envelope in the booster linac with Gaussian laser beam profile. Authors sincerely thank all members of the FLASH team for their great contributions in injector optimization.

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