EMITTANCE MEASUREMENT OF ELECTRON BEAM OF RF GUN WITH PLASMA FERROELECTRIC CATHODE

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An RF gun with a plasma ferroelectric cathode can generate intense electron beams with peak current in a bunch up to 10^2 A. The space charge forces of the beam increase errors of the beam emittance measurement using a ‘quadrupole’ technique. The errors of the measurements and the implementation of the ‘pepper-pot’ technique are referred in the paper. Studied is the beam emittance generated by a single-cell S-band RF gun with the plasma ferroelectric cathode. The beam pulse current is 6 A (current in a bunch is 60 A) with pulse duration 40…90 ns and particle energy ≅ 500 keV.

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1. INTRODUCTION

An RF gun is a source of electron beam that is guided and shaped by the RF electric field of high strength (~10^7 V/m) [1,2]. The RF gun can be the source of a nanosecond pulse beam with the maximum charge in a bunch > 10^2 nC [3]. One of the ways the charge can be achieved is the application of the cathodes that are featured both by the high emission current density (≥ 10^2 A/cm^2) and by the ability to provide the duration of a beam current pulse of few tens nanoseconds. The experimental operation of the plasma ferroelectric cathode in the RF gun [4] has resulted in the generation of an electron beam with pulse current pulse 4…9 A, with the current pulse duration 40…90 ns and particle energy ≅ 500 keV [5]. Within the RF power pulse duration >10^{-6} s, the RF gun with the ferroelectric cathode operates in the storage energy mode and generates the intense electron beam.

Considerable impact of the space charge forces on the spatial particle movement in an intense beam gives rise to errors in intense beam emittance measurements using the conventional ‘profile scan’ technique. The beam emittance will be defined highly accurate if measurement technique used has minimum errors. In the paper considered are the estimations of the errors risen from the emittance measurement of the beam generated by the RF gun with the plasma ferroelectric cathode. The ‘pepper-pot’ technique minimises the effect of the space charge forces on the measurement results. This technique has been implemented into emittance measurements of the beam studied. The results of the measurements are also summarized in.

2. BEAM INTENSITY ESTIMATION

The intensity rate of the researched beam has been pre-estimated from results of analysis of the beam envelope equation for the one of transverse direction with space charge forces taken into account [6]:

$$\sigma''_x = \frac{\varepsilon_n^2}{\gamma^2 \cdot \sigma_x^3} + \frac{4 \cdot I}{\gamma^3 \cdot I_0 \left(\sigma_x + \sigma_y \right)}, \tag{1}$$

where I is the beam pulse current, A, I_0 – the Alfen current, A (17 kA), γ – the Lorenz factor, ε_n – the normalized emittance, mm·mrad, σ_x, σ_y – the beam transverse sizes, mm. The ratio of the second term in the right-hand side of the Eq. (1) to the first term is a coefficient K defining the dominant rate of space charge forces in a beam. In an axisymetric beam assumption ($\sigma_x = \sigma_y \equiv \sigma_o$):

$$K = \frac{2 \cdot I \cdot \sigma_0^2}{I_0 \cdot \gamma \cdot \varepsilon_n^2}. \tag{2}$$

A beam is treated as an intensive one with domination of the space charge forces, if $K > 1$. The substitution of numerical values (I=60 A, γ=1.7, σ_0=10 mm, ε_n=180 mm·mrad) into the Eq.(2) results in $K \approx 10$. This value defines the beam generated by the RF gun with the plasma ferroelectric cathode as an intense space charge dominated beam. In this case, the space charge forces affect the electron dynamics dominantly and substantially affect the results of beam parameters measurement.

3. PROFILE SCAN TECHNIQUE TEST

The space charge forces effect on the experimental beam emittance measurement has been pre-checked using a wide-usable in accelerator technology technique of the beam emittance measurement by the definition of a σ – matrix of a beam passing transport element with a priory defined transfer matrix R [7]. In the experiment [5] the beam was generated in the single-cavity RF gun with the plasma ferroelectric cathode which emitting surface is ≅ 1 mm^2. The beam pulse current and particle energy is 4.5 A and 500 keV, respectively. For the beam emittance measurement, there was used an axial lens with maximum axial magnetic field 2 kOe installed at the gun exit. According to the technique, the beam emittance is derived as $\varepsilon = \sqrt{\det \sigma'}$, where σ' is the beam matrix at the end of interval ‘lens-drift’. The initial beam matrix σ^0 is derived by the equation $\sigma' = R\sigma^0 R^T$. The element σ'_{11} is a beam profile that applying axial lens is derived as $\sigma'_{11} = 1 - L/f$, where L is the drift length, $1/f = \pi a B_0^2 / 8(B\rho)^2$ is the focal length of the lens, a is the lens aperture, $B\rho$ is the magnetic rigidity, B_0 is the maximum axial field of the length. The beam profile has been measured for three different values of magnetic field by the system of actuator-driven slits with 0.2 mm slit width. The drift length was 230 mm. The measured normalized beam emittance in horizontal plane is ε_x=109 mm·mrad.

The space charge forces effect on the measurement result has been estimated using computer simulation of the measurement procedure. An electron beam with corresponding pulse current was simulated with PARMELA code [8]. Twiss parameters of the beam α, β, γ were the input data for the program TRACE3D [9], which computes beam particle trajectories in a defined transport channel using the matrix instrumentation with the space charge forces both taken and not taken into account. The normalized beam emittance computed with the space charge forces taken into account is ε_x=117 mm·mrad that corresponds to the measured value with relative error 1%. The value of the normalized emittance computed without space charge forces is ε_x=27 mm·mrad that is approximately four times smaller than the value computed with the space charge forces taken into account. Therefore, the emittance measurement of the researched beam using the outlined above technique is featured by a high (> 100%) relative error.

4. 'PEPPER-POT' MEASUREMENTS

The beam emittance of the RF gun with the plasma ferroelectric cathode has been measured using the 'pepper-pot' technique. The main idea of the technique is the collimation of a beam into beamlets with the space charge forces effect neglected. This permits elimination of the space charge forces effect from the error estimation of the measuring procedure that makes the high accuracy measurement of intense beams with K~10^2 to be possible [10]. Particle density distribution and total beam emittance is deduced from the measured angular divergence and particle density distribution in the beamlets according to the corresponding analytical relations [6].

The beam in a transport channel is collimated by the plate P (Fig.1) with apertures that are disposed with the definite step d across the probable beam cross-section. The detecting plane M is disposed on the distance L from the plate P. Each beamlet width in the detecting plane is the direct measure of the width of the transverse momentum distribution in the collimating plane. The total beam emittance is deduced directly from the beam intensity distribution under the approximation of the Gauss beam particle distribution [11].

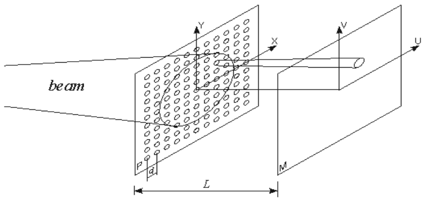

Fig.1. «Pepper-pot» layout

For the experimental emittance measurement all elements of the two-plate system has been calculated in the definite order according to the technique requirements [6]. Initial data for the calculation have been accepted from the following beam parameters: pulse current is 4.5 A, normalized emittance is 200 mm·mrad and particle energy is 500 keV.

The collimating plate P is made of tantalum of 0.2 mm thickness. The plate material and its thickness are defined by the length of the total beam absorption in material. The length is approximated by the relation [6]:

$$L_s = \frac{W}{dW/dx} \approx \frac{W(MeV)}{1.5(MeV\cdot cm^{-2}\cdot g^{-1})\cdot\rho\,(g\cdot cm^{-3})}, \quad (3)$$

where W is the beam particle energy, ρ is the material density. Twenty-five apertures of 0.5 mm diameter are disposed in crossing of horizontal and vertical lines and grouped in five per line. The lines are distributed from the origin axial lines uniformly across the plate P with the step of 2 mm. The distance between the plate P and the plane M is 50 mm. For the calculated parameters of the measuring system, the ratio K in a single beamlet is $5\cdot 10^{-4}$ that fits the condition $K<<1$ of the space charge forces neglecting in a beam.

The particle density distribution in each beamlet is defined from the total beam current distribution that has been measured within the detecting plane using the actuator-driven slit and Faraday cup. Distribution of the total beam current measured in transverse direction X includes four beamlet current distributions (Fig.2). The point X=0 mm corresponds to an axial symmetry of the beam pipe.

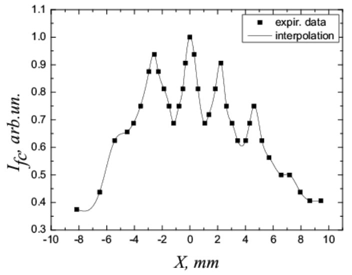

Fig.2. Intensity distribution of the total beam passed through the collimated plate

The fifth distribution that should be in the left-hand side was not detected. It is most evidently that the amount of particles is too small to be detected or the particle divergence is too large to be resolved. Each distribution can be approximated by a Gaussian function [11] that permits derivation of the angular divergence in each beamlet. Beam trace space constructed from the beamlet intensity profile is illustrated in Fig.3.

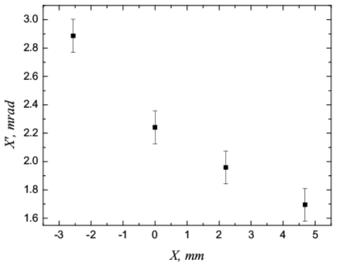

Fig.3. Beam trace space

Each point represents the position of the beamlet in the trace space and the error bars indicate the most probable thermal spread of the beamlets. RMS emittance is derived from the second moments of the trace space distributions as following:

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}\,.$$

It is easy to derive Twiss parameters of the total beam from this equation that permits definition the matrix coefficients for each beamlet. The matrix coefficients conversion into rectangular frame coordinates resolves ellipse envelope for each beamlet and the total beam. A contour plot (Fig.4) is the representation of the resolved ellipse envelopes. According to the resolved phase space of the total beam (Fig.4, the largest ellipse) the measured normalized beam emittance is 40 mm·mrad for 50% of particles passed through the collimating plate.

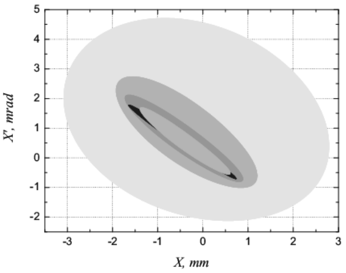

Fig.4. Phase space approximated ellipses for the measured beam intensity distributions

CONCLUSION

Because of too large errors (up to 300%), the profile-scan technique cannot be used for the emittance measurements of the beam generated by the RF gun with the plasma ferroelectric cathode. The emittance measurement has an essentially lower error in case of using the 'pepper-pot' technique. Corresponding measuring system has been designed and applied to the emittance measurements of beam with current in a bunch 60 A and electron energy 500 keV. The measured normalized beam emittance is 40 mm·mrad.

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ИЗМЕРЕНИЕ ЭМИТТАНСА ЭЛЕКТРОННОГО ПУЧКА В ВЧ-ПУШКЕ С ПЛАЗМЕННЫМ ФЕРРОЭЛЕКТРИЧЕСКИМ КАТОДОМ

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ВЧ-пушка с плазменным ферроэлектрическим катодом может генерировать интенсивные электронные пучки с током в сгустке до 10^2 А. Силы пространственного заряда такого пучка увеличивают погрешности измерения эмиттанса с использованием квадруполей. В работе рассмотрены погрешности измерений и реализован 'pepper-pot'-метод измерения эмиттанса. Был исследован эмиттанс пучка, генерируемого однорезонаторной ВЧ-пушкой S-диапазона с плазменным ферроэлектрическим катодом. Импульсный ток пучка составляет 6 А (ток в сгустке до 60 А) при длительности импульса 40…90 нс и энергии электронов ≅ 500 кэВ.

ВИМІР ЕМІТАНСУ ЕЛЕКТРОННОГО ПУЧКА У ВЧ-ГАРМАТІ З ПЛАЗМОВИМ ФЕРОЕЛЕКТРИЧНИМ КАТОДОМ

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ВЧ-гармата з плазмовим фероелектричним катодом може генерувати інтенсивні електронні пучки зі струмом у згустку до 10^2 А. Сили просторового заряду такого пучка завищують погрішності вимірювання емітансу з використанням квадруполів. В роботі розглянуті погрішності вимірювань та реалізований ‘pepper-pot’-метод вимірювання емітансу. Було досліджено емітанс пучка, що генерується однорезонаторною ВЧ-гарматою S-діапазону з плазмовим фероелектричним катодом. Імпульсний струм пучка дорівнює 6 А (струм в згустку до 60 А) при тривалості імпульсу 40…90 нс та енергії електронів ≅ 500 кеВ.