Particle Accelerators, 1990, Vol. 31, pp. 89–95
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Beam Guiding in the Ion Focused Regime at the KEK FEL Test Stand

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Abstract In a test stand of the X-band microwave free-electron laser at KEK, an 1.6 kA electron beam of 700keV was successfully transported in the laser assisted ion focused regime(IFR) without any external magnetic field through a 2.2m long ion channel. Preliminary beam transport in a FEL wiggler in the IFR has been also realized.

INTRODUCTION

A high current electron beam of 2-3kA at 10-20MeV is required for driving a multi-stage FEL in a two beam accelerator employing a free-electron laser(TBA/FEL).[1] Long distance propagation of multi-kiloampere electron beams is one of the most important key issues since the strong beam break-up instability(BBU) may prevent beams from traversing over long distance. Although a large rf bucket in the FEL causes a large energy spread of the driving beam, phase mix damping can not be expected for the BBU[2] and the resistive wall instability[3]. Beam transport in the IFR seems to be a most promising method to avoid BBU, since the nonlinearity in ion focusing introduces a spread in betatron tune and causes strong phase mix damping for the BBU and also for the resistive wall instability. In fact, 7kA electron beams have been guided through the 95m induction linac without any external magnetic field[4]. In addition, beam transport in the IFR may require no extra magnets for phase space matching between a FEL wiggler and a reacceleration unit, and will bring about no serious problems on the FEL performance in the microwave regime[5].

In the KEK FEL test stand[6], an experimental investigation of the IFR beam guiding in a microwave FEL is planned. A preliminary experiment of the IFR beam transport has been performed at the KEK FEL test stand, and an about 1.4 kA electron beam from the 700keV induction gun was monitored to traverse through a 2.2m long plasma channel produced by a KrF excimer laser without any external magnetic field. In this test stand a preliminary IFR beam transport through the 2m long FEL wiggler which is placed behind the 2.2m IFR test chamber has been also demonstrated.

BRIEF REVIEW OF ION CHANNEL GUIDING

A general view of the IFR may be given as follows. Before firing of an electron beam, a laser beam is introduced through a experimental chamber which is filled with a gas such as DEA(diethlaniline) with large photo-ionization cross section. A small fraction of gas is ionized; consequently a column of positively charged ions and free electrons is left along the laser path. Strong electric fields of a coming electron beam expel light plasma electrons leaving only massive ions. Space charge forces of positively charged ions will focus and guide the remainder of electron beam through the ion channel. In order to avoid undesirable instabilities such as the two-stream instability associated with over dense ionization, a condition of $Ni < N_b/\gamma^2$ (N_i; ion density, N_b; beam electron density, γ ; beam energy) should be satisfied. For this purpose laser parameters are appropriately adjusted, following a relation[7]

$$N_i = \frac{\alpha I_L^2 \delta t\, N_o}{h\nu} \qquad (1)$$

where N_o is the gas molecule density, α is two photon ionization coefficient for used gas, I_L is the laser power density, δt is half laser pulse length and $h\nu$ is a single laser photon energy.

Beam head erosion and an equilibrium state are our main concern in the present situation of a short propagation distance and a short pulse length which are particular in our device. Essential aspects of the erosion mechanism can be evaluated by solving a coupled system of beam envelope equation and simplified eruption equation for plasma electrons,

$$\frac{d^2 r_b}{ds^2} + 2f_n\left(\frac{I_b}{I_A}\right)\frac{1}{\beta^3\gamma\, a^2}\left(1-\frac{a^2}{16r_e^2}\right) r_b - \frac{2I_b}{I_A(\beta\gamma)^3}\frac{1}{r_b} = \frac{\varepsilon_n^2}{(\beta\gamma)^2}\frac{1}{r_b^3} \tag{2a}$$

$$\left(r_b \leq a\,,\ r_b(0) = 0\,,\ \dot{r}_b(0) = 0\right)$$

$$\frac{d^2 r_e}{dt^2} = -2c^2\left(\frac{I_b}{I_A}\right)\frac{r_e}{a^2}\left[f_n\left(1-\frac{a^2}{16r_e^2}\right)-\frac{a^2}{r_b^2}\right] \tag{2b}$$

$$\left(r_e(0) = {}^{a}\!/_{4}\,,\ \dot{r}_e(0) = 0\right)$$

where uniform distributions of beam electrons and plasma electron are assumed, a is a plasma channel radius, f_n is neutralization factor, I_b and I_A are beam current and Alven current, respectively, β and γ are relativistic parameters of an electron beam. Eq.(2b) gives a characteristic expansion time

$$\tau = \left(\frac{a}{c}\right)\sqrt{\frac{I_A}{2I_b}} \tag{3}$$

for the current case where a is a few centimeter and I_b is order of kiloamperes, this is less than 1nsec. Thus convective erosion of the beam head will be not significant in the present case.

Meanwhile, an equilibrium state of beam envelope is straightforwardly derived from Eq.(2a) In the limit of $r_e \to \infty$, Eq.(2a) becomes

$$2\left(\frac{I_b}{I_A}\right)\left[\frac{f_n\ r_b}{\beta^3\gamma a^2} - \frac{1}{(\beta\gamma)^3}\frac{1}{r_b}\right] = \frac{\varepsilon_n^2}{(\beta\gamma)^2}\frac{1}{r_b^3} \tag{4}$$

Algebraic calculation gives an equilibrium radius in the form

$$r_b^2 = \frac{a^2}{2\gamma^2 f_n}\left(1 + \sqrt{1 + \frac{2\,\varepsilon_n^2 f_n \gamma^3}{a^2\left({}^{I_b}\!/_{I_A}\right)}}\,\right) \cong \frac{a^2}{\gamma^2 f_n}\left(1 + \frac{1}{2\pi^2}\frac{f_n\gamma^3 I_A}{a^2 B_n}\right) \tag{5}$$

where Bn is the beam brightness. From this expression, the parameter dependence of the equilibrium radius is quite clear.

BEAM EMITTANCE

A beam injector, which consists of 4 induction cells and a field emission cathode [8]where a 50mm diameter velvet, is used as a emitter. An 800kV electric potential is imposed on the cathode by energizing each induction cell with a 200 kV and about 100nsec pulse from the magnetic pulse compressor. In order to investigate beam quality which is essential for the FEL performance, a beam emittance was measured using a multi-hole plate as shown in Fig.1.[9] A stainless steal mesh with a transmission of 64% as an anode is placed about 50mm downstream of the cathode and a 2kA electron beam passed through the anode. In the present operation, a peak cathode voltage was 700kV. The beam impinges on an array of 64 pinhole aperture with 1mm diameters in a 1mm thick Al disk placed just behind the anode. Each hole is separated by a distance of 5mm in a 8×8 square pattern. Transmitted

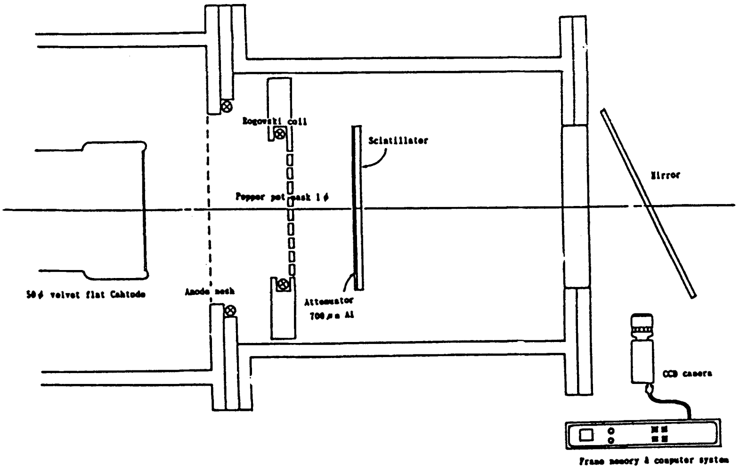


Fig.1 The set-up for emittance measurement

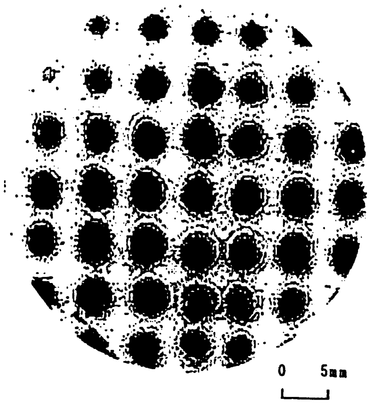
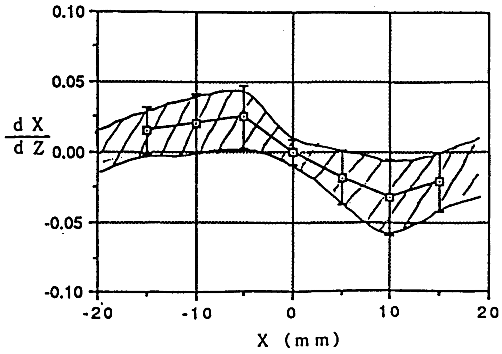


Fig.2 photograph of a recorded pepper pot image

Brigthness 5.0 kA/cm^2·rad^2



Normalized emittance --- 0.41 cm·rad

Beam size --- 40mm ϕ

Beam current --- 840 A

Fig.3 phase space contour plot

beamlets traverse a field free region of 50mm in length and then strike a target which is made of an Al plate attenuater of 0.7mm and a plastic scintillator. Beamlet images on a scintillator are viewed with a CCD camera and displayed on the VIDEO monitor as shown in Fig.3. In Fig.3 is shown the angular spread distribution reconstructed from the beamlet images ,i.e., phase space contour plots. For a beam size of 40mm diameter, we obtained a normalized beam emittance of ε_n=0.41cmrad and beam current of I_b=840A; consequently this yields the brightness of $B_n = I_b/\pi^2\varepsilon_n^2 = 5.0\text{kA/cm}^2\text{rad}^2$.

IFR SET-UP

Fig.4 shows the experimental set-up for the IFR experiment. A commercial KrF laser (Lambda Physik EMG150MSC) is chosen for its high brightness (500mJ, 27nsec). The laser beam is introduced into the experimental chamber from the window at the chamber end. A diameter of the laser beam can be varied by an external telescope from 5mm to 50mm. Diethlaniline(DEA) is used as working gas. An automatic leak controller and differential pumping allow to keep a pressure of 5×10^{-5} to 5×10^{-3} Torr of DEA in the chamber. The DEA pressure profile was constant within ±30%. The chamber has a variable beam slit at 20cm behind the anode and a total available propagation length of 2.2m. The beam diagnostics are done with 8 current monitors(Rogowski coils), 5 position monitors and 5 nylon string profile monitors [10].

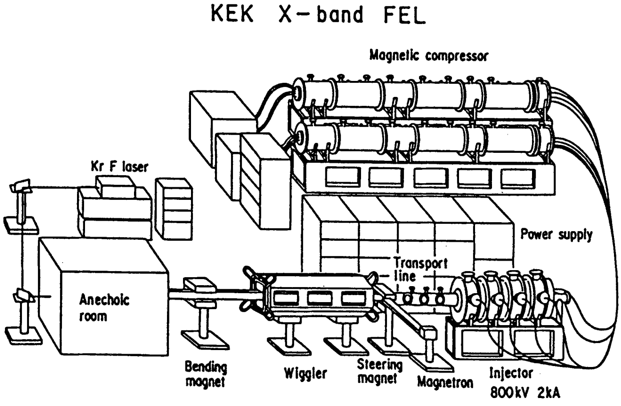


Fig.4 IFR set-up

EXPERIMENTAL RESULT

To confirm beam transport in the IFR, following four cases were tested:

(1) DEA wasn't filled in the chamber. (A base pressure is 4.2×10^{-5}Torr.)

and Laser beam wasn't introduced through the chamber.

(2) DEA wasn't filled in the chamber. (A base pressure is 4.2×10^{-5}Torr.)

LASER OFF

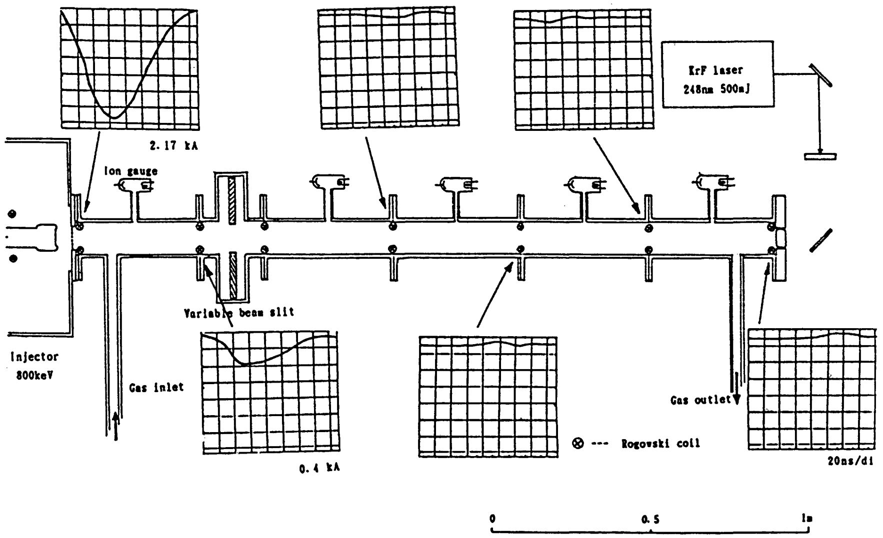


Fig.5(a) case(3) laser off , DEA pressure 4.0×10^{-4}

LASER ON

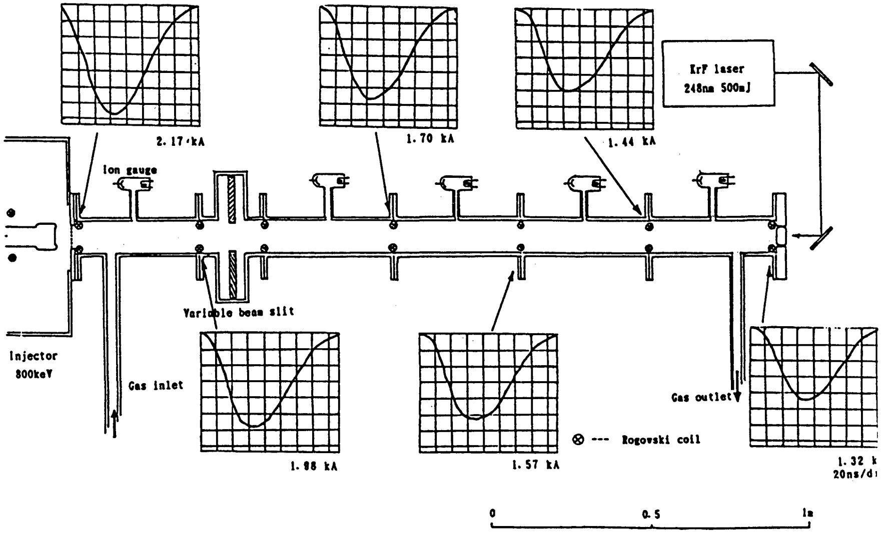


Fig.5(b) case(4) laser on , DEA pressure 4.0×10^{-4}

and Laser beam was introduced through the chamber. (Laser beam power is 100mJ, laser beam size is 30mmϕ)

(3) DEA was filled in the chamber. (DEA gas pressure is 4.0×10^{-4}Torr.)
and Laser beam wasn't introduced through the chamber.

(4) DEA was filled in the chamber. (DEA gas pressure is 4.0×10^{-4}Torr.)
and Laser beam was introduced through a chamber. (Laser beam power is 100mJ, laser beam size is 30mmϕ)

Any difference are not found among first three cases and the current profile of the case (3) is shown in Fig.5(a). The beam current just after the anode is 2.7kA and it is only 300A at 22cm after anode. No signal of the beam current was detected even at 42cm after anode. Result of the case(4) is shown in Fig.5(b). Obviously one can find successful transportation of an 1.6 kA beam through the 2.2m ion channel. From the above laser parameter, the neutralization factor was estimated about 0.27.

DISCUSSION

We have confirmed transportation of the high current beam through the ion channel. The betatron wavelength wasn't directly measured in the experiment. Even the estimated betatron wavelength of 3.8m seems to be large for discussion on an equilibrium state in the IFR. Betatron wavelength λ_β should be enough larger than a wiggler period for desirable FEL performance. However, to study in detail physics of the ion channel guiding, that is an equilibrium state, the hose instability, and the two-stream instability, λ_β should be varied in a wide range. A systematic study of these issues will remain as coming works.

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