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X-Band Free Electron Laser Experiment in the Ion Channel Guiding Regime

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Abstract

Recent experimental results are reported for an induction-driven X-band FEL, with ion channel guiding inside the wiggler. Power in excess of 20MW at 9.4GHz, has been observed with a beam energy of 800keV and a current of 500-700A. Maximum gain is 22dB/m, with no saturation after 15 wiggler periods. A self-amplified spontaneous power of 4kW was also measured. Data for the detuning curve, field evolution and current transmission are presented and discussed. The expected performance at 1.6MeV is also discussed.

Introduction

To realize a TeV-class electron-positron linear collider with a reasonable length and cost, the FEL two beam accelerator (TBA) has been proposed as a power source[1]. To assess the feasibility of such a TBA, we proposed an X-band FEL test-stand[2,3], and subsequently modified the design to include ion channel guiding throughout the beamline[4]. The study of such an ion-focussed FEL is motivated by the need for stable transport of a multi-kiloampere beam over large distances in a TBA. In particular ion channel guiding has been proposed to suppress beam breakup caused by the deflecting mode in the TBA induction gaps[5].

At the test stand, the first ion channel transport studies commenced in July, 1989[6,7]. Preliminary FEL experiments commenced in August, with only modest success[8]. Since then, we have extended the wiggler from 12 to 15 periods and shortened the beam line from the injector to the wiggler. Recent measurements reveal a vast improvement in FEL performance.

In this test stand the microwave FEL at 9.4GHz is driven by a 80nsec induction beam with current in excess of 700A, and a voltage of 800kV---too low a voltage at present for the multi-stage FEL configuration which is an essential part of the TBA concept. The purpose of the test stand is to provide experience with high-current beam generation and ion-focused (IFR) transport in the FEL. For TBA studies, we are planning to increase beam energy by extending the induction linac; extension to 1.6MeV is the next step.

Experimental Set-Up

The FEL test stand consists of an injector, a wiggler, the microwave system and the laser guiding system (Fig.1). Further detail is illustrated in Fig.2.

Injector

The beam is drawn from a 50mm diameter velvet cathode of the "laser-based foil-less" type[9], with an anode-cathode gap of 40 mm. The injector consists of 4 induction cells, and each cell produces about 200kV with 80nsec pulse duration, for a beam voltage of 800kV. The induction cells are driven by two magnetic pulse compressors[10]. Output pulse power of each compressor is 3.2GW. One compressor is driven by a GTO switch, with timing jitter less than 2 ns. The other compressor is driven by an air gap switch, with timing jitter of almost 20nsec. (This air gap switch is slated to be replaced with a GTO, since such a large timing jitter is unacceptable for reliable FEL performance.)

The beam current after the injector is typically 2.7kA. The normalized beam emittance of 0.41cm rad was obtained by means of multi-hole plate. At a distance of 40cm from the anode, the

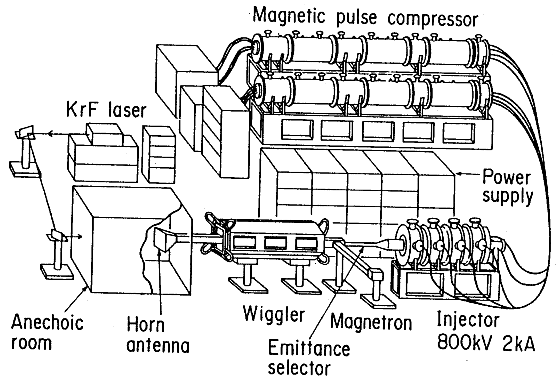

Fig.1 The layout of the KEK FEL test stand.

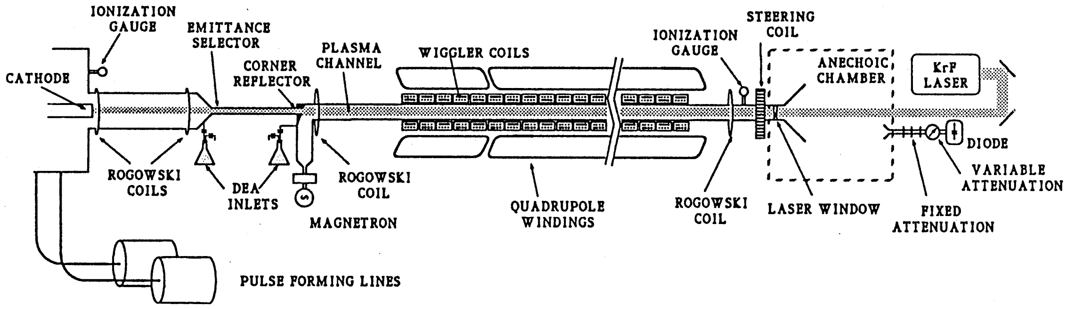

Fig.2 Details of the beamline set-up.

beam enters an emittance selector, consisting of a 60cm length tubing with 20mm diameter and tapered entrance. From the emittance selector the beam enters the FEL interaction region, consisting of 5.5cm x11 cm stainless steel waveguide. Beam current is monitored by three Rogowski coils as indicated in Fig. 2. Typical current passed by the emittance selector is 0.5-0.7kA, depending on the laser fluence and Diethylaniline (DEA) gas pressure at the injector. Just after the wiggler, the beam is dumped on the waveguide wall with a steering coil.

Wiggler

The wiggler is the planar, reversed coil type with 15 periods and a 16cm wiggler period length. The magnetic field is produced by exciting solenoid coils and by eddy current in copper plate placed on the vertical walls of the stainless steel waveguide[11]. The fifteen power supplies are wired so that the first two half periods may be adjusted for orbit matching. The repetition rate of the power supplies is 0.1Hz. Two air core quadrupole magnets provide additional orbit matching at the entrance, and focussing in the wiggle plane.

Microwave system

The microwave source is a pulsed magnetron operating at 9.4GHz. The microwave signal is converted from the TE_{10} mode to TE_{01} via a tapered waveguide, and fed into the beamline (5.5cm x 11cm waveguide) with a corner reflector. The corner has a beam passing aperture covered with thin wire mesh. The microwave power in the oversized rectangular waveguide is amplified and passed through a laser window and a horn into an anechoic chamber. The laser window is transparent to both the KrF laser and the microwave. The receiving horn is placed 1.8m from the transmitting horn at an angle of 3° from the forward direction, so as not to interfere with laser guiding. The signal is attenuated and detected by a crystal diode, calibrated via thermistor and powermeter. A second horn, mounted on a turntable is used to study the horizontal and vertical components of the mode profile in the horizontal plane.

IFR beam transport

DEA gas is fed into the beamline from two flasks as indicated in Fig.2. The gas pressure is monitored by two ionization gauges of the Bayard-Alpert type, placed at the injector and the wiggler exit. A Lambda-Physik KrF laser operating at 248nm with 18nsec pulse length is used to ionize the DEA by a two-photon resonant process[12]. Laser pulse energy is measured by joulemeter and typically is 50-100mJ, with a shot-to-shot jitter of 1mJ. The laser diameter is 2.5cm. In practice, gas pressure and laser fluence are critical in tuning beam transport. The experiments are performed under the nitrogen-equivalent pressure of 0.3mTorr at the wiggler exit. The resulting current transmission through the wiggler is depicted as a function of wiggler field strength in Fig.3. By tuning gas pressure and magnetic field, we can achieve up to 90% current transmission over a useful range of wiggler field.

FEL Amplification

To date the maximum power achieved is 25MW, with an input RF power of 18kW. For this shot the beam energy was about 760keV and the current passed through the wiggler was 520A. The rf pulse is depicted in Fig. 4, together with the beam current. The full width of the amplified microwave signal was 40-50nsec.

In Fig. 5, the measured detuning curve is depicted. The scatter in the figure is due to beam voltage variation produced by the timing jitter of the air-gap switch. These data correspond to a timing difference of less than 10nsec. Maximum gain occurs at 620 gauss, or 87% of the resonant field. The height and location of the peak can be understood from Raman FEL theory. The gain observed at low wiggler field can be attributed to the "head" and "tail" of the beam voltage profile. The evolution curve is shown in Fig. 6 and corresponds to an exponential gain of 20.8dB/m, with no saturation. The maximum gain obtained so far is 22dB/m and saturation has not been observed.

We have also observed exponential gain of the self-amplified spontaneous emission (SASE). The maximum power was 15kW, and the average was 4kW.

Although the dominant mode for the FEL amplification is TE_{01} mode, theoretically one expects a non-negligible coupling to the

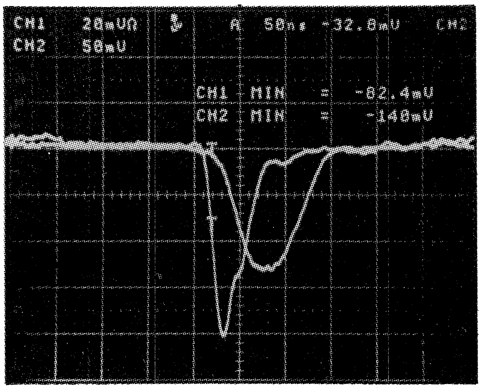

Fig.4 Oscilloscope trace of the amplified microwave signal, and the beam current (broad trace). (The beam is delayed by 50 nsec due to the difference in the cable lengths.)

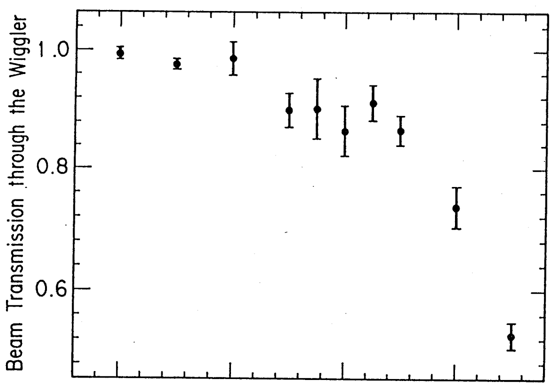

Fig.3 Beam transmission ratio versus peak wiggler field.

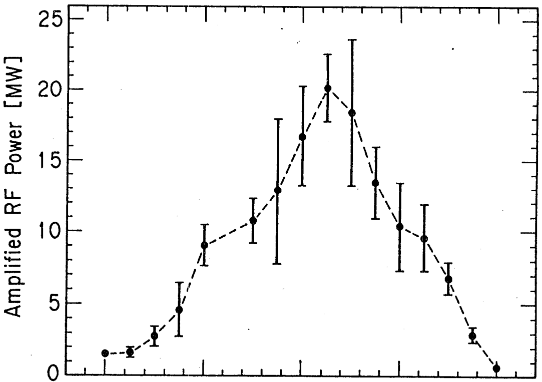

Fig.5 Microwave power versus peak wiggler field.

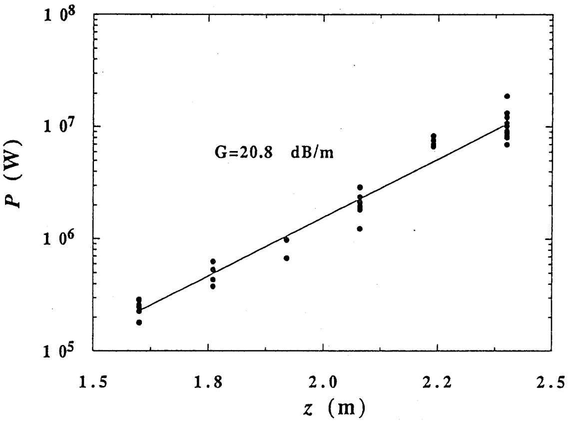

Fig.6 The evolution of the microwave power through the wigggler corresponds to an exponential gain of 20.8dB/m.

TE_{11} mode or TE_{21} mode. We have begun preliminary studies of the mode profile in the horizontal plane of the anechoic chamber. Indeed, interference is evident in the measured field profile. However, at present the mode content appears to vary from shot to shot and we are continuing to study possible explanations, including mode conversion in the laser plasma.

The frequency was measured by using bandpass filters. At 600 gauss, 63 % of the amplified power lies within a bandwidth of 9.320-9.460 GHz, while 72% of the magnetron lies within this bandwidth. The component in the Ku-band is less than one percent.

Discussion

We have demonstrated beam transport and microwave amplification in an ion-focussed free-electron laser. Detailed theoretical studies of the detuning curve are in progress and have thus far shown that low energy and space-charge corrections, as well as multi-mode effects are important. To analyze the experimental data, we developed a one-dimensional FEL dispersion relation without high-γ approximation following essentially the treatment of Orzechowski *et al.*13), while including space-charge using a harmonic model. The best fit to the data is shown in Fig.7 corresponding to a ±2.1% detuning spread and a 2.0cm beam radius. The peak gain and corresponding wiggler field B_W in the measured detuning curve agree well, underscoring the importance of space-charge. In order to confirm this simple fit, current experimental efforts are focused on reaching saturation which is expected in the 50MW range.

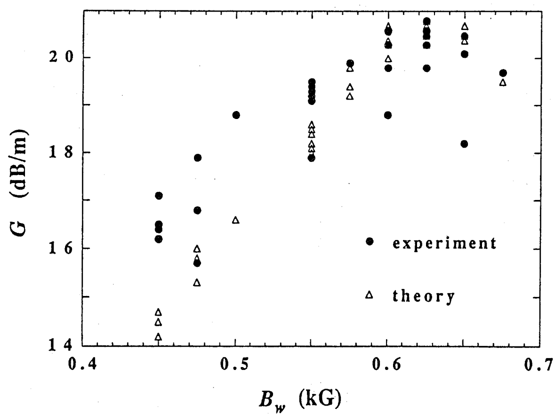

Fig.7 Experimental detuning data and theoretical best-fit with the low-γ 1-D warm Ramman dispersion relation. Scattere is due to variation in beam current.

Due to the complexity of the nonlinear ion-focussing problem, an understanding of the current loss at high wiggler field is best approached numerically. To this end we have developed a 3-dimensional FEL simulation incorporating realistic beam transport effects and detailed "benchmarking" of the code is in progress to confirm the equilibrium spot-size and current loss characteristics.

Since more than several MeV will be desirable to the TBA, the beam energy will be increased year by year by extending the induction linac. The extension program to 1.6MeV will be completed in next spring and much higher gain and power are expected since gain degradation by space charge will be less severe. As shown in Fig.8, the theoretical calculation at this energy with ±1% energy spread, and a spot-size of 1.85cm predict gain of 31dB/m (an improvement of 10dB/m), and saturation before the 12th wiggler period at 130MW (for 30kW input). With tapering more than 250MW could be achieved. At the same time, one expects that that at higher energy a large current could be transported due to the reduction in transverse space-charge effects. For 1.5kA, gain of 39dB/m could be expected with saturation at 370MW. With tapering more than 700MW could be achieved.

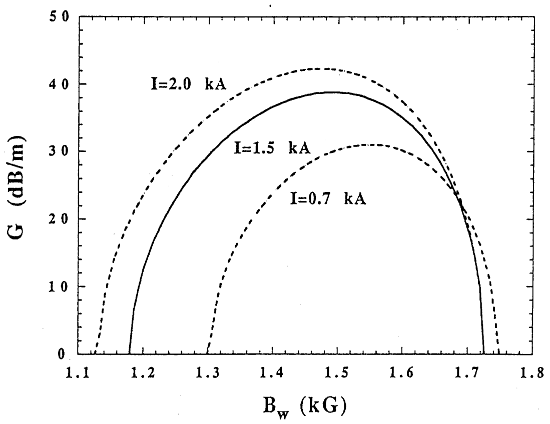

Fig.8 Expected gain at 1.6MeV.

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