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Ion-Channel Guided X-band Free-Electron Laser Amplifier

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Abstract. All aspects of the ion-channel guided x-band free-electron laser amplifier which has been developed at KEK are described in detail. Amplification experiments(1,3) were performed at two different beam energy of 0.8MeV and 1.5MeV. At 9.4GHz, a peak power of 25MW with a gain of 18dB/m and 100MW with a gain of 21dB/m have been demonstrated in each experiment. In the 1.5MeV experiment, saturation in the evolution curve has been achieved and a frequency *spread* of 0.9% was observed. The amplified microwave was separated from the driving beam line and extracted without break-down.

INTRODUCTION

A microwave FEL has been regarded as a possible candidate of power sources for future linear colliders(3) since the successful demonstration at LLNL(4). Although the Livermore/LBL 34.6GHz experiment really triggered extensive theoretical studies on a multi-stage microwave FEL(μ -FEL) in the so-called two-beam scheme at KEK and LBL/LLNL/MIT, most of experimental issues for multi-staging such as reorbiting of driving beams, efficient power extraction, or reacceleration have been left unsolved. Particularly, subsequent beam transport is crucial in the multi-stage regime. Ion channel guiding(ICG) in the regime was proposed(5), expecting

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Landau damping of beam break-up instability(BBU) and resistive-wall instability which are counter attacks for such long distance transport(6). ICG technique was employed in the FEL amplification experiments after successful demonstration of the proceeding beam-transport experiment(7). Other crucial problems are seed power injection into the beam line and amplified-power extraction from it with sufficient efficiency. In fact a large magnitude of the seed power has been theoretically proved to mitigate output-phase's sensitivity to injection errors in driving beam current or accelerating voltage(8). Recently we have developed miter-bend *over-sized* input and output couplers with efficiency of nearly 90% in TE₀₁ mode which can minimize reflection and mode conversion. This microwave coupler was employed in the 1.5MeV experiment.

Other attractive applications of the μ -FEL such as a planetary radar(9), thunder-bolt control by atmosphere ionization(10), or power transfer in space(9) have become to be discussed on the various occasions(11). These applications shall utilize its figure of merits of extremely high peak power, very short wave-length, relatively small frequency-spread, and pure mode, which have not been simultaneously satisfied in conventional microwave sources. Most of applications are operated in a single-stage regime. Such a single-stage μ -FEL may be driven by high current but low energy beams, guiding of which is not so easy in practice. Ion-channel guiding will serve as a powerful guiding technique in μ -FELs for those purposes.

In our "proof of principle" experiments, the present IXFEL which integrates ICG, conventional planar wiggler, and RF handling system with efficient μ -couplers has demonstrated its capability.

FIGURE 1a. Set-up of 0.8MeV FEL experiment.

FIGURE 1b Set-up of 1.5MeV FEL experiment

EXPERIMENTAL SET-UP

The experimental set-ups of 0.8MeV and 1.5MeV are depicted in Fig. 1a and Fig. 1b, respectively.

Injector & Driving Beam

The electron beam was generated in the induction linac energized by two magnetic pulse compressors (MPCs). Details of the injector are described in references (12). In the 0.8MeV experiments, the induction linac composed of four induction cells was used. A velvet cloth cathode and stainless steel mesh were used as a cathode material and anode. A beam current of 2.7kA was extracted.

In early experiments, initial pulses introduced to the MPCs were triggered by switching air-pressurized spark gaps, compressed, and stepped up in the subsequent stage of the MPC. The timing of the spark gaps was controlled by the air pressure with the two MPC timing jitter of 10 - 20nsec and it lead to an ambiguity in the electron beam energy. This timing jitter was, however, largely improved by replacing the spark gaps with the gate turn-off thyrister (GTO)(13). In the 0.8MeV experiment, one of the two MPCs was driven by GTO pulser and the other by spark gaps. In the 1.5MeV experiment, more four induction cells were added. All induction cells were energized by two GTO-driven MPCs, so very stable electron beam was generated in a foil-less diode with a carbonized felt cathode as seen in

Fig.2. An electron beam of 1.3kA was usually extracted to enter into the emittance selector region described later.

FIGURE 2 Diode Configuration in the 1.5MeV Experiment

Beam energy measurement was not done by using an analyzer magnet with a slit because such a narrow slit interrupts ion-channel guiding. The maximum beam energy was known with a set of well calibrated CuSO_4 voltage-divider mounted in each of induction modules. An actual energy spread at the same pulse-timing has been unknown for the same reason.

Oversized RF Components

In the 0.8MeV experiment, a pulsed magnetron (JRC 2J55) was used as a microwave source. A peak power was nominally 50kW and its typical pulse duration was 1.5 μs . The input power was introduced into the interaction region of over-sized rectangular waveguide (WRJ-2) through a tapered mode-converter (from TE_{10} to TE_{01}) and a corner bend with a hole of 20mm diameter for electron beam passage. About one-third of the 50kW input power was transmitted into the interaction region as a seed power. This transmission efficiency was in agreement with the MAFIA simulation(14). The output signal was radiated from a large horn antenna into a anechoic room through a quartz window for a KrF laser beam. A small fraction of the radiated power was detected with a fundamental x-band waveguide which is placed in the opposite side of the anechoic room enough far from the large horn to obtain a far-field pattern of the emittance fields. The detected

signal was attenuated down to milliwatt level and monitored with a crystal diode. All of used attenuators were periodically checked for reproducibility.

In the 1.5MeV experiments, to increase the seed power, a pulsed magnetron(EEV Model M5188), capable of nominally generating an output power of 91kW was adopted. In addition, a miter-bend coupler which was designed so as to minimize reflection and mode-conversion was used. This input coupler(Fig.3) has a passing small 20mm ϕ aperture for electron beams. The amplified microwave through the 3m-long rectangular waveguide (RW) is coupled out from the driving-beam line with the other miter-bend(Fig.3) connected with the *over-sized* ceramic RF-window and the laser window of 20mm ϕ . Mode-conversion in *over-sized* RF components was measured in the full lineup as well as component-by-component by the phase interference method where a far-field pattern of the transmitted reference signal from a Gunn-oscillator is monitored as a function of the straight-RW length being varied over a wavelength of beatwave between the dominant TE₀₁ mode and possible higher mode such as TE₀₃. Both of the input and output coupler demonstrated the transmission efficiency of 85% in TE₀₁ mode, giving a net seed-power of 77kW, which is consistent with the MAFIA simulation(14)¹.

FIGURE 3. Input coupler and output coupler.

¹ For the input/output coupler, power fraction is 92% in TE₀₁, 1% in TE₀₂, 1.8% in TE₀₃, 2.7% in summation of other modes, 2.5% in reflection.

Ion-Channel

Diethylaniline(DEA, $C_6H_5-N-(C_2H_5)_2$) gas which has a large photo-ionization cross-section for uv laser is fed into the beam line from three reservoir flasks. An ionized molecule ($A=149$) is heavy and unlikely to move during an electron beam pulse of 50nsec. It is unnecessary to worry about instabilities such as two-stream instability. The gas pressure is monitored by four Shultz and BA gauges calibrated to a Baratron capacitance manometer. Uniformity of the pressure through the beam-line was maintained by valve control of reservoir flasks. An KrF excimer laser($\lambda=248nm$) with 18nsec pulse length is used to ionize the DEA by the two-photon resonant process(Fig.4).

FIGURE 4. Two resonant ionization process.

Laser pulse energy is measured by a joulemeter and typically is 90mJ/25mm ϕ in the 0.8MeV experiment. In the 1.5MeV experiments, however, laser optics were modified and the pulse power density was improved to 140mJ/20mm ϕ , with shot-to-shot jitters of 5mJ. Laser intensity through the beam-line was almost constant

with slight degradation in nominal operation pressure. Plasma density in operation was not directly measured; however, it was extrapolated from two independent informations(15): (A) a magnitude of ion-channel relaxation of the relativistic Langmuir-Child limited diode current which straightforwardly reflects ion density in the diode region, that is, $i_{\max} = IA\gamma/2\pi d^2 + e n_i c$ (see Fig.5) where IA is Alfvén current and n_i is the ion density, (B) a critical ion-density at which beam's envelope hits the waveguide wall 2.5m downstream from the emittance selector, that is,

$$L(2.5m) = \int_0^{b/2} \frac{dy}{\sqrt{-2V(y)}} \propto \sqrt{\frac{\gamma}{n_i}} \text{ where } V(y) \text{ is the ion-channel trapping potential (See$$

Fig.6). They lead to a nominal ion-density of $2 \times 10^{10} \text{ cm}^{-3}$.

FIGURE 5. Diode current vs. pressure

FIGURE 6. Transmitted current through 2.5m waveguide, a difference between I and I* in the high pressure region is within a measurement error of the calibration constant of used Rogowskii coils.

Emittance Selector

A driving electron beam generated in the induction gun was transmitted through the ion channel and injected into the interaction region. In the 0.8MeV experiment, a beam current of 800A was obtained after the emittance selector of 0.6m-long, out of 2.7kA beam current at the entrance. A 600A electron beam of the 1.3kA traversed through the 1m-long emittance selector in the 1.5MeV experiment. The emittance selector is simply a combination of ion channel and narrow aluminum pipe of 20mm ϕ in diameter. The principle of ion-channel guided emittance selector is rather simple; An

acceptance of the emittance selector is given by the formula, $r\sqrt{\frac{2I}{\gamma I_A}(f - \frac{1}{\gamma^2})}$ where r

is the pipe radius, f is the neutralization factor, I is the beam current. For 1.5MeV electron beam, the emittance selector has an acceptance of about 0.06 cmrad for a nominally fixed gas pressure and laser intensity. In the maximum amplification regime mentioned later, a beam current of 450A was monitored at the wiggler end.

Wiggler

Each unit of the air-core planar wiggler magnet is independently energized with a pulse power-supply and the eddy-current assisted field-uniformity(16) is provided with thick copper bars inserted in both sides of the wiggler gap. The field profile in the horizontal direction is shown in Fig.6; the field strength at the waveguide boundary edge is only small by 1.5% than in the central position. In addition to ICG, a set of air-core quadrupole magnets was excited for further focusing in the horizontal direction. In order to minimize a coherent betatron amplitude in the wiggler, a steering magnet locating slightly upstream was slightly excited. Basic parameters of the IXFEL are listed in Table1.

TABLE 1. IXFEL operating parameters

Wiggler		
Period[cm]	16	
Length[m]	2.4	
Number of periods	15	
Peak magnetic fields[kG]	0-1.6	
Electron beam		
Kinetic energy[MeV]	0.8	1.5
Current(in/out)[A]	700/500	650/450
Unnormalized acceptance[cmrad]		0.06-0.04
Microwaves		
Frequency[GHz]	9.4	
Waveguide size(axb)[cm]	11x5.5	
Input seed-power[kW]	15	77
Design mode	TE ₀₁	
Ion channel		
Laser wave-length[nm]	248	248
Laser intensity[mJ/20mm ϕ]	90	140
Ion density[10 ¹⁰ cm ⁻³]		2

FIGURE 7. Cross-section of the wiggler magnet and the measured field distribution.

AMPLIFICATION EXPERIMENTS

(A) 0.8MeV Experiment

Detuning

Dependence of the amplified power on the wiggler magnetic field was measured. In Fig.8, measured amplified power was shown as a function of wiggler magnetic field. Since the timing between two MPCs was unstable as mentioned before, only shots with fairly small jitter (less than 10nsec) were selected to produce this result. The data points always correspond to the maximum power in pulse obtained at each wiggler field. However, it is noted that a beam-pulse portion with the maximum energy of 0.8MeV doesn't necessarily yield this maximum amplified power, as seen more clearly in the 1.5MeV experiment. Around the wiggler magnetic field of 0.54kG, a maximum amplified power of 25MW was obtained. Beam transmission efficiency was about 75% around the peak and notably decreased at higher wiggler fields.

FIGURE 8 Detuning curve : Gain vs. wiggler field

Evolution

Spatial evolution of the power was observed at the fixed wiggler field where the maximum amplification was obtained. Its procedure is quite simple; the wiggler units were turned off one by one from the most downstream. The result is shown in Fig.9. As easily seen in the figure, the amplified power evolves exponentially with the normalized wiggler length and the evolution curve shows no saturation even at the most downstream. We can read the gain of 18dB/m from the slope of the power evolution. In order to understand this experimental results, three-dimensional simulations and theoretical analysis based on the dispersion relation were done. The simulation code takes account of ion channel focusing, quadrupole focusing, and self space-charge effects. Space charge effects were evaluated assuming an averaged charge density in a uniform beam cross-section. Since an exact beam size and beam emittance at the wiggler entrance which are always required in the 3D-simulations were unknown, these parameters were obtained from beam transport simulations in the upper stream which were separately performed. A magnitude of the evolution which was experimentally obtained is lower by about a factor of two than that of theoretical calculations. A sizable part of this discrepancy can be attributed to reflection and mode-conversion of the amplified microwaves in the laser window as mentioned earlier.

The amplification gain is also calculated using the dispersion relation. The electron beam density required in the dispersion relation was obtained, providing the averaged beam size which was evaluated in the 3D beam-transport simulation. Since the simulation takes accounts of ion channel focusing as mentioned above, effects of ion channel guiding are included in the dispersion relation.

Detuning curves which are calculated from the dispersion relation and directly given by FEL simulations are also shown in the Fig.8. There is apparently a discrepancy between experimental results and others in the lower wiggler-field region than $B_w=0.54\text{kG}$, where beam-loss should be not significant. This may be explained by a speculation that a lower energy portion in pulse contributes to the maximum power.

FIGURE 9 Evolution: Amplified power vs. normalized wiggler length

(B) 1.5MeV Experiment

Resonant Structure in Signal

Typical examples of the amplified signal for two different wiggler fields (1.21kG and 0.93kG) are shown in Fig.10. Resonant structure in the pulse duration clearly indicates the existence of resonant beam energy. Two resonant portions in time merges at the central position in pulse beyond $B_w=1.2\text{kG}$ which corresponds to the peak energy position.

Frequency Spectrum

Frequency spectrum of the amplified signal was measured by a low-Q transmission-type frequency counter. The filling time of the counter cavity, $2Q/w$,

is about 4 nsec which is much shorter than the pulse duration of 10-15nsec. Fig.11 represents the frequency spectrums of the injected magnetron and amplified signals at $B_w=1.21\text{kG}$. The frequency *spread* of $\Delta f/f=0.9\%$ within 3 dB of the peak power is found for the amplified signal, while that of the injected magnetron signal is $\Delta f/f=0.6\%$ which is set by a finite Q-value of the frequency counter, that is, 120. The actual frequency *spread* of the magnetron obtained by a spectral analyzer is less than 0.1% in FWHM[17]. Another notable result of frequency measurements was a shift in the frequency spectrum for the resonant portion which corresponds to FEL interaction of lower-energy beams in a lower wiggler field just mentioned above. We observe that in a case of $B_w=.93\text{kG}$ the spectrum is downshifted from the magnetron frequency by $\sim 60\text{MHz}$, as seen in Fig.11. Reasonable explanation for the shift has not been found yet.

FIGURE 10. Amplified signals at $B_w=0.93\text{kG}$ (solid) and 1.21kG (broken) with beam voltage(bottom) profiles in time.

FIGURE 11. Frequency spectrum of the amplified signal at $B_w=1.21\text{kG}$ (solid) and at $B_w=0.93\text{kG}$ (long dash), magnetron signal(short dash), by a spectral analyzer(short dash).

Detuning

Dependence of the gain on the wiggler field was measured at the wiggler position just before saturation which will be mentioned later. In Fig.12, a magnitude of the amplified power is shown as a function of the wiggler field. Indicated data here were taken at the same pulse timing that gives the peak power for $B_w=1.2-1.25\text{ kG}$. Within 3 dB of the peak power, the fractional magnetic field "bandwidth", $\Delta B_w/B_w$, is about 8.1%. Beam transmission efficiency gradually degraded beyond

$B_w=1.2\text{kGauss}$. Therefore, the detuning curve should be somewhat different from the case without beam loss. This speculation seems to be consistent with some estimation from the theoretical detuning curves shown in the same figure where a lower beam current certainly gives much small gain in the region of higher wiggler field. Assuming possible transmission beam currents ($I=450,200\text{A}$) and energy-spread of 1.5%, these detuning curves are derived from a cubic dispersion relation taking account of geometrical coupling² with TE01 mode, vertical betatron motion and quadratic wiggler field variation in the vertical direction which depend on a spatial size in the RW effectively occupied by beams. A beam size of $2r_b=4\text{cm}$ which is obtained by numerical tracking with the realistic magnetic fields was assumed in calculation(15).

² The geometrical coupling coefficient for TEMn mode is defined by

$$\langle \mathbf{j} \cdot \mathbf{E} \rangle \propto \langle \langle \langle \langle \frac{dx}{dz} [\cos(\frac{m\pi}{a}x_i) \cos(\frac{n\pi}{b}y_i)] \cos(k_s z - \omega_s t + \phi_s) \rangle_w \rangle_{VB} \rangle_{TD} \rangle_{LD} = \kappa_{mn} \langle \frac{\cos \psi}{\gamma} \rangle_{LD}$$

$$\text{for TE01} \quad \kappa_{01} \approx 1 - \left(\frac{\pi}{4}\right)^2 \left(\frac{r_b}{b}\right)^2,$$

$$\text{for TE21} \quad \kappa_{21} \approx \frac{4}{\pi r_b^2} J_0^2\left(\frac{2\pi x_w}{a}\right) \int_0^{r_b} \int_0^{\pi/2} J_0\left(\frac{\pi r \sin \theta}{b}\right) J_0\left(\frac{2\pi r \cos \theta}{a}\right) r dr d\theta$$

where $\langle \rangle_w$ $\langle \rangle_{VB}$ $\langle \rangle_{TD}$ $\langle \rangle_{LD}$ denote averaging over one wiggler period, one vertical betatron period, transverse particle distribution, and longitudinal distribution, respectively. Here the correlation in the 3-dimensional direction is neglected for simplicity. Meanwhile, the longitudinal velocity of an individual particle is written by

$$\frac{1}{(v_z)_i} \approx \frac{1}{c} \left\{ 1 - \frac{1 + a^2 \left[1 + \frac{3}{2} k_w^2 \psi_i^2(0) \right]}{\gamma_i^2 - 1} \right\}^{-1/2},$$

averaged over one wiggler and vertical betatron period.

FIGURE 12. Experimental detuning curve and theoretical calculations for $I=450A$ (long dash) and $200A$ (short dash).

Evolution

Evolution curve was obtained by simply turning on the wiggler unit in order. Evolutions for RW-length covering a beatwave length between TE₀₁ and TE₀₃ are depicted in Fig.13. The evolution curve adjusted by the phase interference method which places roughly in the middle of scattered points indicates the exponential gain of 21 dB/m. Apparently, TE₀₁ mode dominates the received power. A small fraction of the received power originates from TE₀₃ mode converted in the output coupler including the RF-window but the TE₂₁ mode which is a possible one evolving through the interaction region rarely contributes to the received fraction of

the amplified power in our forward receiving system. The experimentally obtained size of the gain is in good agreement with theoretical estimation mentioned in the previous paragraph.

FIGURE 13. Evolution for different RW-length and the adjusted TE01 mode evolution.

Higher Mode Evolution

For amplified power measurement for TE₂₁ mode, the receiver horn was positioned at $\theta=20^\circ$ less than the ideal location of $\theta=\lambda/b\approx 33^\circ$ (18) because of a finite-size of the anechoic room. The signal level was not distinguished in the hide of the dominant mode. Theoretical calculation(15) based on the cubic dispersion

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demonstrated. In the 1.5MeV experiment employing miter-bend μ -couplers, effective saturation was achieved. The experimental results were well explained by theoretical considerations; particularly, they complementally manifested an important aspect of the geometrical coupling between TE₀₁, TE₂₁ modes and a driving beam largely expanding in the RW. The IXFEL has demonstrated the viability of the ICG for future interesting applications beyond two proceeding ICG experiments(20). Seed power injection and amplified-power extraction required in realistic applications of the μ -FEL were realized with high efficiency.

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Erratum:

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relation tells us that the gain for the pure TE₂₁ mode is quite small, that is, less than a few dB/m in the wiggler field region of current interest because of the lower resonant field and small geometrical coupling due to an effectively expanded beam size, assuming an uniform particle distribution within the diameter of $2r_b=4\text{cm}$. A power fraction in TE₂₁ mode should be negligible in the total output-power .

DISCUSSION

In both experiments of 0.8MeV and 1.5MeV, effects of the ion channel density on FEL amplification have not been systematically studied; nonetheless, the gain was notably reduced, accompanied with further beam-loss, in a higher pressure region than the nominally operating pressure(0.8mTorr). This indicates that beam transport through the wiggler region takes a trivial but practical role in FEL amplification; the amplitude of the coherent betatron motion in the FEL interaction region as well as phase-space matching depends on the upper magnetic field environment where a beam having been guided through the continuous ion-channel alone sees different guiding fields(tapered input wiggler field + rising Q-field + ion-channel). An experimental fact that beam-loss is notable in the higher wiggler field region strongly suggests expanding of the beam size. This is consistent with that of our preliminary numerical FEL simulations(15). Such diffusion of a driving-beam in the physical space seems to suppress evolution of TE₂₁ mode as numerically demonstrated by Freund et al. (19). Since the driving frequency of the magnetron as a master oscillator was unable to be varied, the frequency "bandwidth" of the IXFEL was not explored. Differentiating the FEL resonance equation with respect to Bw, however, we find that the fractional frequency bandwidth, $\Delta f/f$, is equal to about $1.43(\Delta B_w/B_w)$, or 11.2%.

Although both experiments have not been done under the same conditions as discussed, the basic FEL performance such as evolution behaves in a similar manner. In this sense, there seems to be no essential differences in FEL physics itself between 0.8MeV and 1.5MeV experiments.

SUMMARY

By integrating ion-channel guiding, ion-channel guided emittance selection, the eddy-current assisted wiggler, and the reasonable μ -FEL amplification was