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

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Experiments on the Ion-Channel Guided X-band Free-Electron Laser Amplifier (IXFEL) generated peak microwave power exceeding 100MW at 9.4GHz with a *gain* of 21 dB/m. 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.

A microwave FEL has been regarded as a possible candidate of power sources for future linear colliders[1] since the successful demonstration at LLNL[2]. While the Livermore 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, other attractive applications of the μ-FEL such as a planetary radar[3], thunder-bolt control by atmosphere ionization[4], or power transfer in space[3] have become to be discussed on various occasions. Subsequent beam transport is crucial in the multi-stage regime. Ion channel guiding(ICG) in the regime was proposed[5], expecting 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 weakly relativistic X-band FEL(800keV)[7] which was our preliminary set-up. 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 *over-sized* input and output couplers with efficiency of nearly 90% in TE01 mode which can minimize reflection and mode conversion. The present IXFEL integrates the ICG, conventional planar wiggler and RF handling system with efficient μ-couplers.

As schematically shown in Fig.1, an input signal from a pulsed magnetron(EEV M5188) is fed into the *over-sized* rectangular waveguide (RW, WRJ-2, 5.5cmx11cm) with a miter-bend with a small hole of 20mmϕ in diameter. The amplified microwave is coupled out from the driving-beam line with the other miter-bend. A fraction of μ-waves eventually emitted into the anechoic room with a horn-antenna is received with a basic-size open-RW placed in the well-aligned forward direction. The radiation signal is attenuated down to the milliwatt level and monitored by a crystal diode. The used attenuators were periodically checked for reproducibility. Mode-conversion in *over-sized* RF components was measured by the phase interference method[9] 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 a transmission efficiency of 85% in TE01 mode, giving a net seed-power of 77kW, which is consistent with the MAFIA simulation[10]. A pressure of Diethylaniline(DEA) gas filling the beam-line is monitored by four Shultz and BA gauges calibrated to a Baratron capacitance manometer. An KrF excimer laser(18nsec pulse length, λ=248nm, 140mJ/20mmϕ with shot-to-shot jitters of 5mJ.) is used to ionize the DEA by the two-photon resonant process. An ion-density of 2×10^{10} cm^{-3} in typical operation was extrapolated from two independent informations[9]: a magnitude of ion-channel relaxation in the relativistic Langmuir-Child limited beam current which straightforwardly reflects the ion-density and a critical ion-density at which beam's envelope hits the waveguide's wall 2.5m downstream from the emittance selector. Details of the induction gun energized with two magnetic switches were given elsewhere[11]. A good emittance region of 650A was diged out of an arriving 1.3kA e-beam with this emittance selector which is simply a combination of ion channel and narrow 1m-long aluminum pipe of 20mmϕ in diameter. The emittance selector has an acceptance of .06-.04 cmrad[12] for a fixed gas pressure and laser intensity. In the maximum amplification regime mentioned later, a beam current of 450A was monitored at the wiggler end. Each unit of the air-core planar wiggler magnet(λ_W=16cm and 15 periods) is independently energized with a pulse power-supply and the wiggler's field-uniformity (ΔBw/Bw=1.5% at the RW's horizontal edge)[13] is provided with thick copper bars inserted in both sides of the wiggler gap, eddy currents on which protects flux-leakage in the horizontal direction.

Typical examples of the amplified signal for two different wiggler fields (1.21kG and .93kG) are shown in Fig.2. 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 Bw=1.2kG which corresponds to the peak energy position.

_F_requency _s_pectrum(FS) of the amplified signal was measured by a low-Q transmission-type frequency counter, the filling time (2Q/ω) of which is about 4 nsec to be much shorter than the pulse duration of 10-15nsec. Fig.3 represents the FS of the seed and amplified signals at Bw=1.21kG. The frequency *spread* s of Δf/f=0.6% and 0.9% in FWHM were found, respectively. The former was set by a finite Q-value of the frequency counter, that is, 120, because that of the seed pulse obtained by a spectral analyzer is less than 0.1% in FWHM. Another notable result of frequency measurements was a shift in the FS for the resonant portion which corresponds to FEL interaction of lower-energy beams in a lower wiggler field just mentioned above; in a case of Bw=.93kG the FS is downshifted by ~60MHz, as seen in Fig.3. Reasonable explanation for frequency-broadning and the shift has not been found yet.

Dependence of the gain on wiggler field was measured at the position just before saturation which will be mentioned later. In Fig.4, 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 Bw=1.2-1.25 kG. A fractional magnetic field "bandwidth", ΔBw/Bw, in FWHM is about 8.1%. Beam transmission efficiency gradually degraded beyond Bw=1.2kGauss. Therefore, the detuning curve should be somewhat different from an ideal 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=450,200A) and an energy-spread of 1.5%, these detuning curves are derived from a cubic dispersion relation taking account of space-charge effects, geometrical coupling 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[9].

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.5. 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. The experimentally obtained size of the gain is in good agreement with theoretical estimation mentioned in the previous paragraph. For power measurements of possibly evolving TE21 mode, the receiver horn was positioned at $\theta=20^0$ less than the ideal location of $\theta=\lambda/b \approx 33^0$ because of a finite-size of the anechoic room. The signal level was not discriminated from that of the dominant mode.

Theoretical calculation based on the cubic dispersion relation[9] also tells us that the gain for the pure TE21 mode is quite small.

A systematic study on effects of the ion channel on FEL amplification was not easy. Since there should be no change in the refraction index in the under-dense regime($n_i<n_b$) of our interest, the FEL condition depends on the ion-density only through a change in betatron-frequency. We observed that the gain was largely reduced, accompanied with significant beam-loss, in lower and higher pressure regions than the nominally operating pressure. This indicates that beam transport through the wiggler region takes a trivial but practical role in FEL amplification.

By integrating ion-channel guiding, ion-channel guided emittance selection, the eddy-current assisted wiggler, and efficient miter RF-bends, the reasonable μ-FEL amplification was achieved with effective saturation in a reliable manner. The IXFEL has demonstrated the viability of the ICG for future interesting applications beyond two proceeding ICG experiments[14].

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Figure Captions

Fig.1 Schematic view of the IXFEL.

Fig.2 Amplified signals at Bw=0.93kG(solid) and 1.21kG(dash), Beam voltage profile in time(lower trace).

Fig.3 Frequency spectrum of the amplified signal at Bw=1.21kG(solid) and at Bw =0.93kG(long dash), magnetron signal(short dash), by a spectral analyzer(shortest dash).

Fig.4 Experimental detuning curve and theoretical calculations for I=450A (long dash) and 200A(short dash).

Fig.5 Evolution for different RW-lengths and the adjusted TE01 evolution curve.

Fig. 1

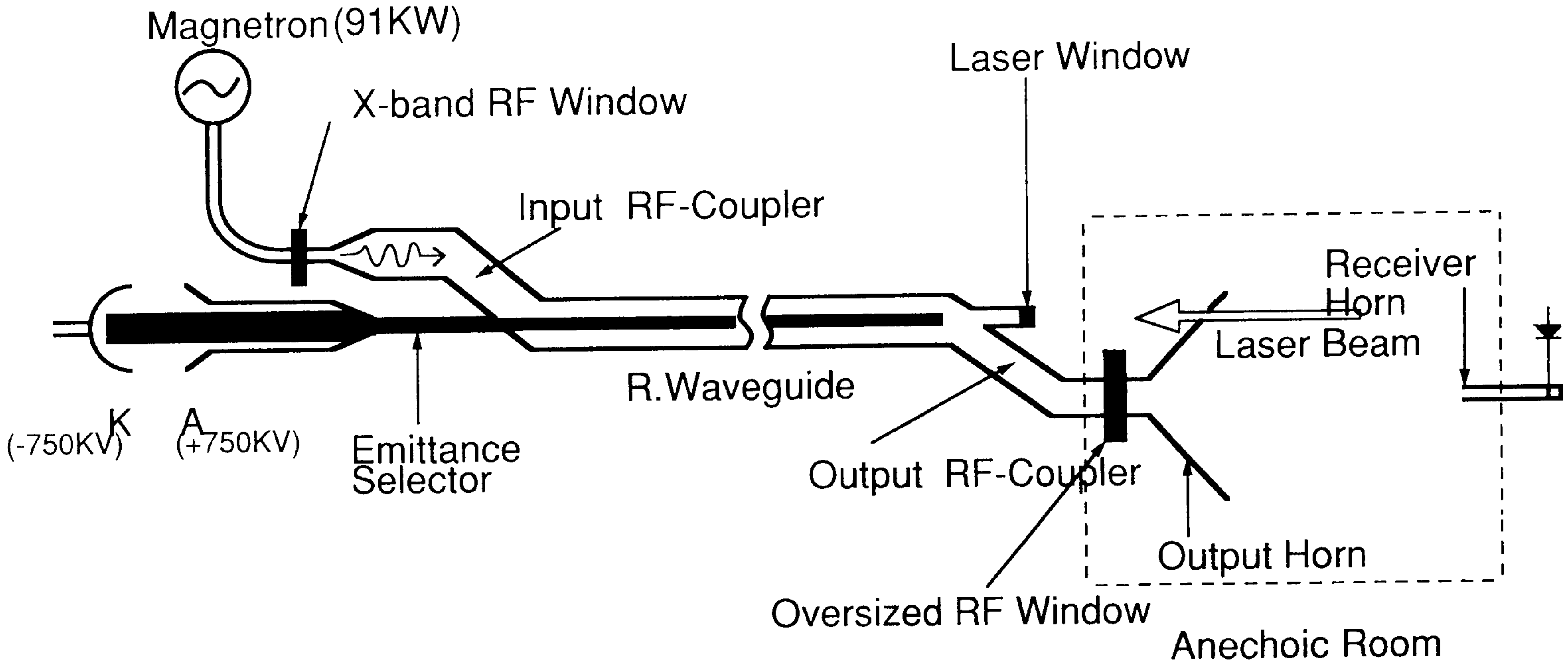

Magnetron(91KW)
X-band RF Window
Input RF-Coupler
Laser Window
Receiver Horn
Laser Beam
K (-750KV)
A (+750KV)
Emittance Selector
R.Waveguide
Output RF-Coupler
Output Horn
Oversized RF Window
Anechoic Room

Fig. 2

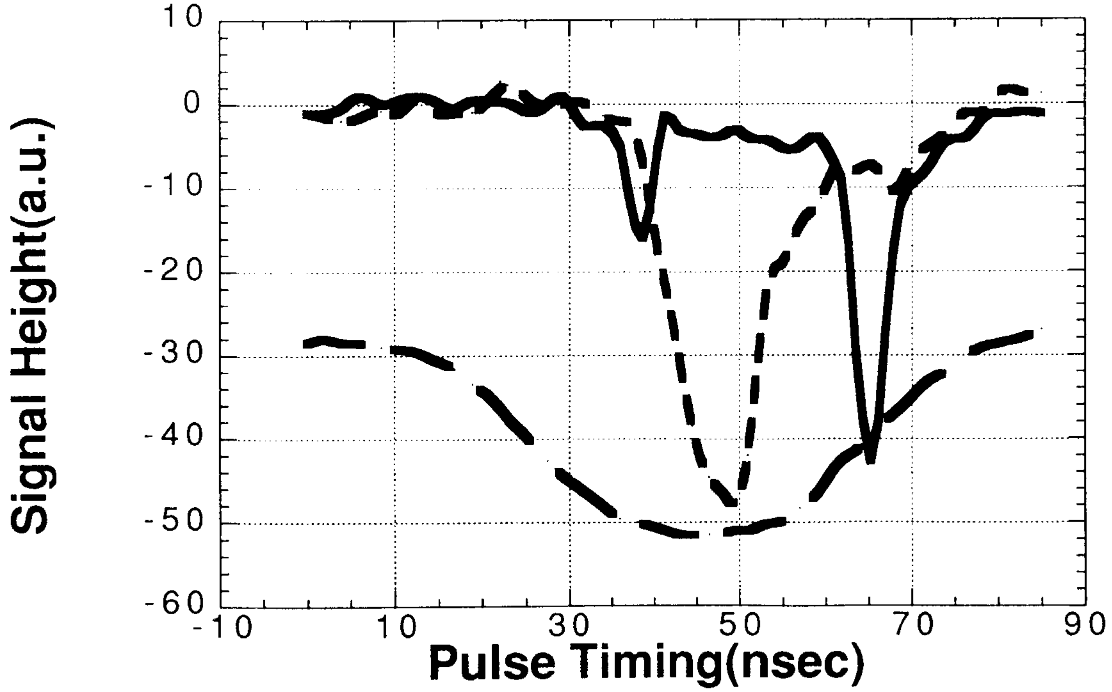

10
0
-10
-20
-30
-40
-50
-60
Signal Height(a.u.)
-10
10
30
50
70
90
Pulse Timing(nsec)

Fig. 3

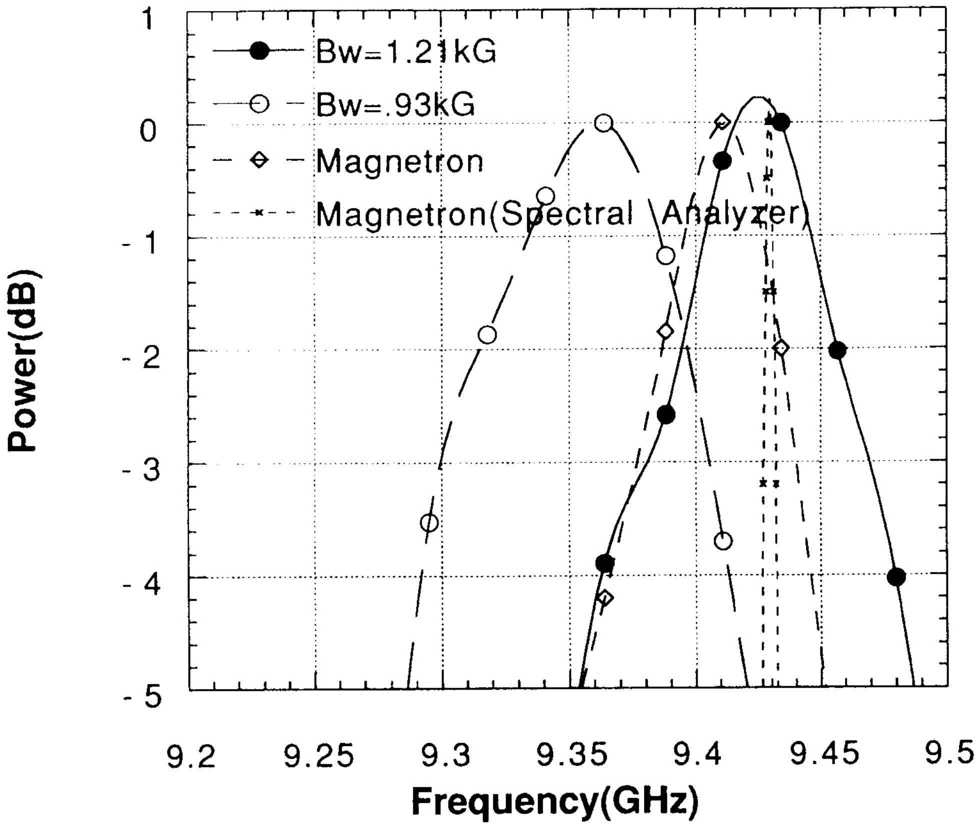
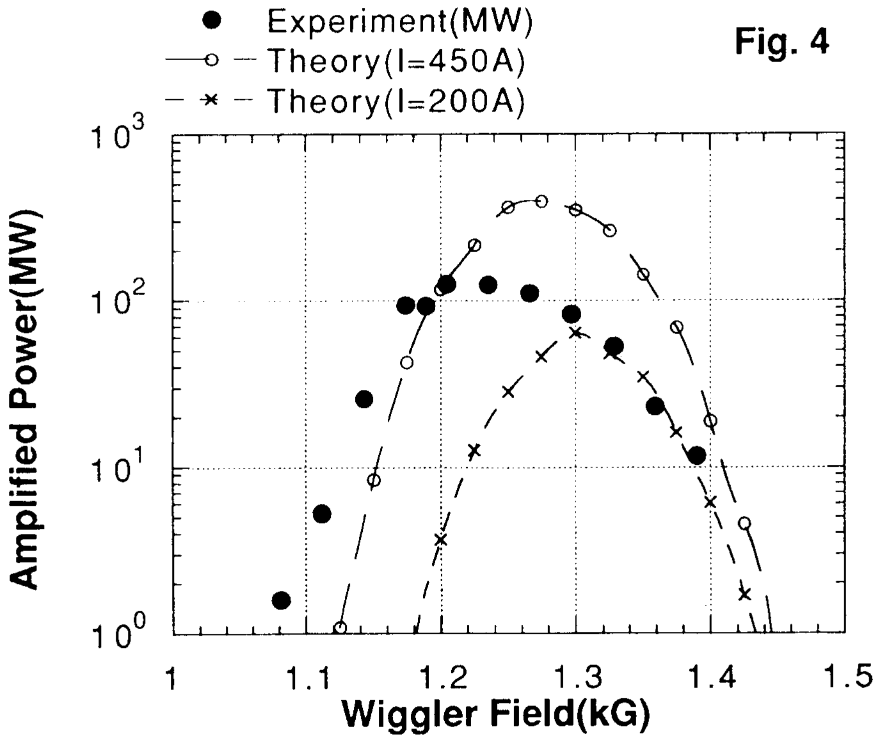
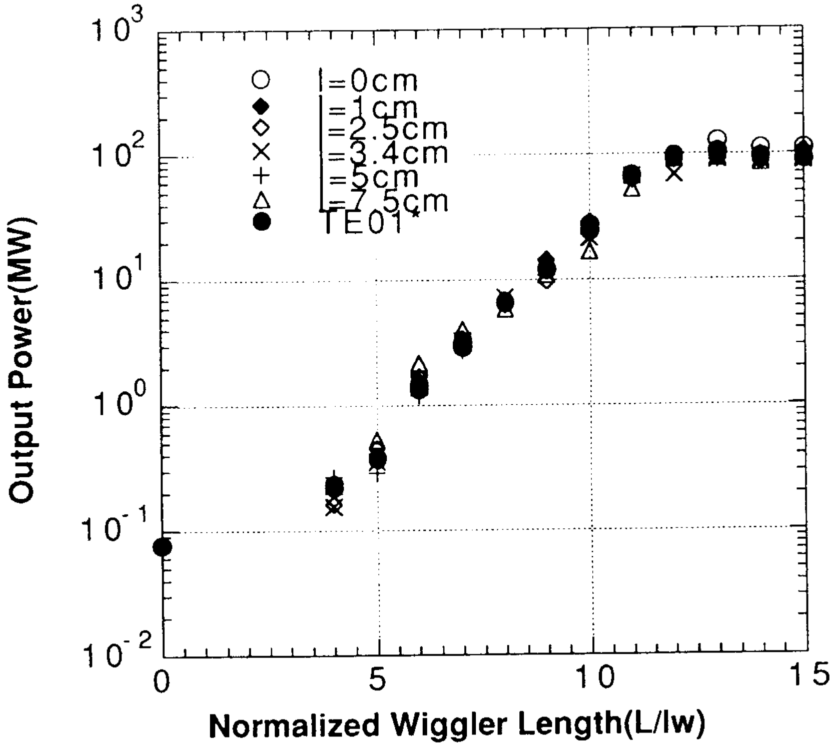

Bw=1.21kG
Bw=.93kG
Magnetron
Magnetron(Spectral Analyzer)
Power(dB)
1
0
-1
-2
-3
-4
-5
9.2
9.25
9.3
9.35
9.4
9.45
9.5
Frequency(GHz)

Fig. 4



● Experiment(MW)
—o— Theory(I=450A)
– ✕ – Theory(I=200A)
Amplified Power(MW)
10^3
10^2
10^1
10^0
1
1.1
1.2
1.3
1.4
1.5
Wiggler Field(kG)

Fig. 5


○ l=0cm
◆ l=1cm
◇ l=2.5cm
× l=3.4cm
+ l=5cm
△ l=7.5cm
● TE01*
Output Power(MW)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
5
10
15
Normalized Wiggler Length(L/lw)