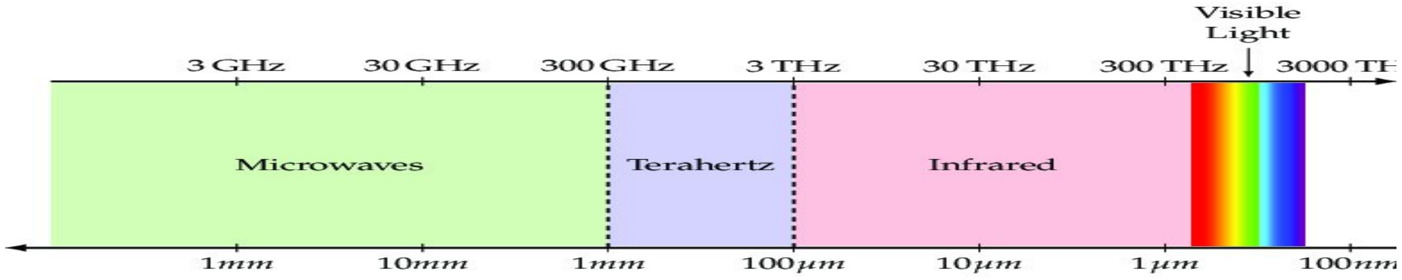

Optical klystron for IR/THz radiation

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HZDR

Overview

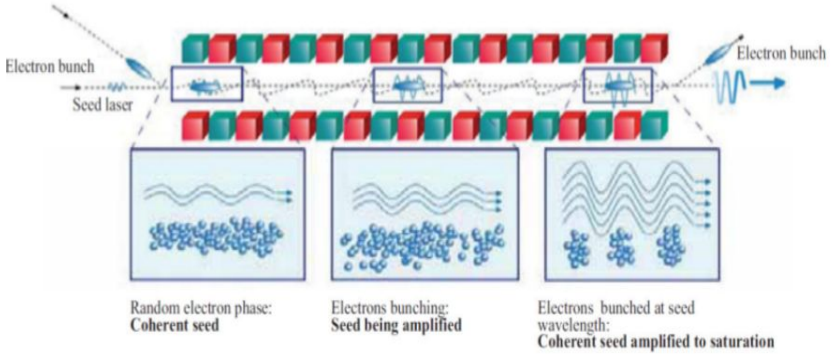
- ❑ FEL concept and THz problem
- ❑ Optical Klystron and its Principle
- ❑ Simulation results
- ❑ Alternative Strategies for Mitigating Slippage Effects
- ❑ Conclusion and Outlook

FEL concept and THz problem

The concepts of **coupling**, **synchronism** and **bunching** are the underlying principles of the FEL operation.

Interaction With Radiation

The energy exchange between the electron and the radiation



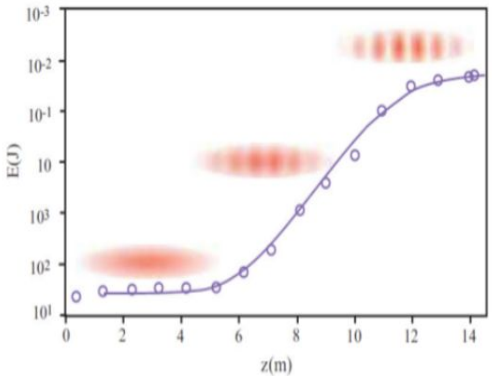
$$\dot{\gamma} = \frac{eE_0K^*}{\sqrt{2}mc\gamma}\sin[(k+k_w)(\beta_z ct+z_0)-\omega t],$$

$$\frac{d\psi}{dt} = (k+k_w)\beta_z c-\omega$$

The Phase between the electron and radiation wave only varies very slowly with time and remains virtually constant.

$$\frac{d\gamma}{dt} = \frac{eE_0K^*}{\sqrt{2}mc\gamma}\sin[(k+k_w)z_0].$$

$$b(k,\zeta) = \frac{1}{N}\sum_{j=1}^{N}\exp(ikz_j(\zeta)),$$



THz FELs , seeded and SASE FEL

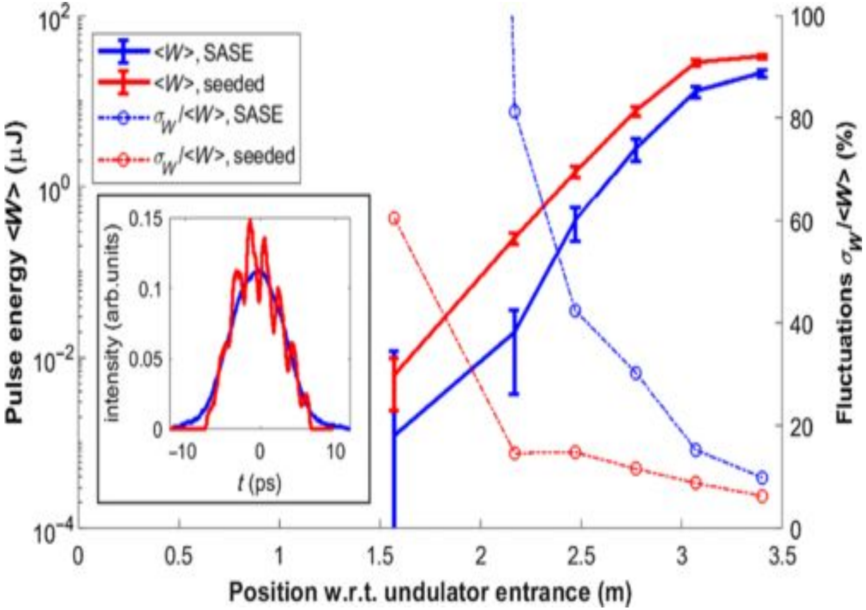
FEL is one of the best options for radiation generation in this frequency range, but **slippage effects require the use of relatively long** and low-current electron bunches to drive the terahertz FEL, limiting amplification gain and output peak power.

Challenges:

Temporal and transverse overlap

(Slippage and diffraction)

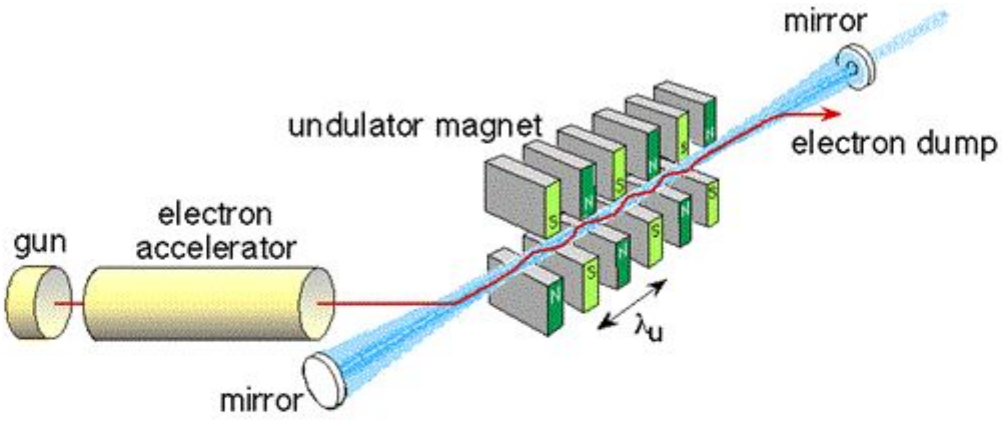
Rayleigh length is short $z_R = \frac{\pi w_0^2}{\lambda}$



First high peak and average power single-pass THz free-electron laser in operation

Mikhail Krasilnikov*, Zakaria Aboulbanine†, Gowri Adhikari‡, Namra Aftab, Aida Asoyan§, Prach Boonpornprasert, Hakob Davtyan§, Georgi Georgiev, James Good *et al.*

Oscillator FEL



$$P_1 = P_s$$
$$P_n = R(1+G)P_{n-1} + P_s \quad \text{for } n \geq 2,$$

$$P_n = \frac{[R(1+G)]^n - 1}{R(1+G) - 1} P_s \,.$$

Challenges:

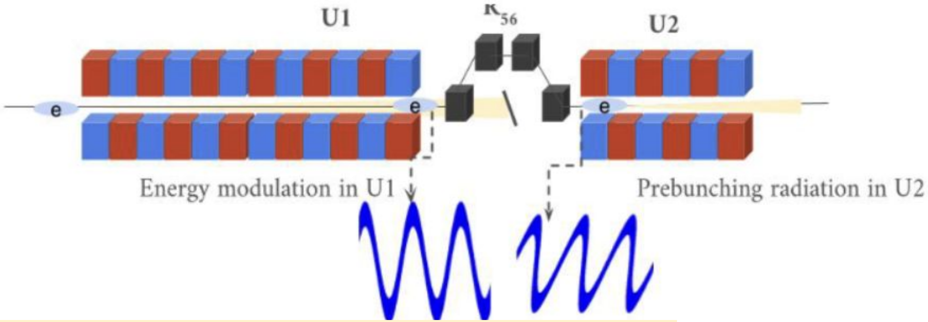
Low gain, Low energy, long pulse,

Cavity tuning, Mode Competition & Spectral Purity, …

Broad gain spectrum: THz oscillators often lase on multiple longitudinal modes, making stable single-frequency operation challenging.
Cavity dispersion: Managing cavity length and slippage is tricky because radiation slippage per undulator pass can be comparable to the pulse duration.

FELBE@ELBE has been showing very good performance for over 21 years, U. Lehnert, M. J. Klopf

Optical Klystron



RF klystron: velocity modulation → drift → bunching → output cavity.
Optical klystron: energy modulation (1st undulator) → dispersion → bunching → radiation amplification (2nd undulator).

Seeded OK

SASE OK

Oscillator based OK

For THz range SASE-OK is good choice

In this regime, the **magnetic undulator field imprints a longitudinally correlated energy modulation across the bunch,** and the **accumulated slippage tends to align the modulation phase of head and tail sections despite the noise start.** In other words, a long modulator can partially synchronize the phase of the induced energy modulation across a THz-scale bunch.

$$S \simeq N_u \lambda_r.$$

$$L_b \sim S \iff N_u \sim \frac{L_b}{\lambda_r},$$

Optical Klystron

Principle OK:

1- Energy modulation in first Undulator

Seeded

$$\Delta\gamma(r) = \sqrt{\frac{P_L}{P_0}}\frac{K_u L_u}{\gamma\sigma_r}\left[J_0\left(\frac{K_u^2}{4+2K_u^2}\right) - J_1\left(\frac{K_u^2}{4+2K_u^2}\right)\right] \times \exp\left(-\frac{r^2}{4\sigma_r^2}\right),$$

SASE

$$\Delta\gamma_{\rm rms}(L_1) \approx \rho\gamma\,\frac{\sqrt{3}}{\sqrt{N_\lambda}}\exp\left(\frac{L_1}{2L_g}\right).$$

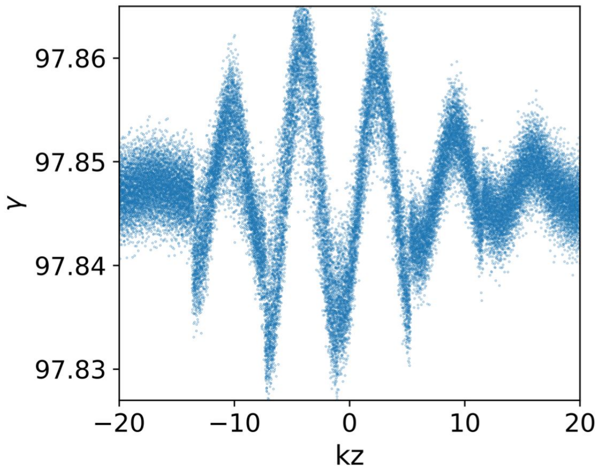
$$L_g^{(1D)} = \frac{\lambda_u}{4\pi\sqrt{3}\,\rho},$$

Optical Klystron

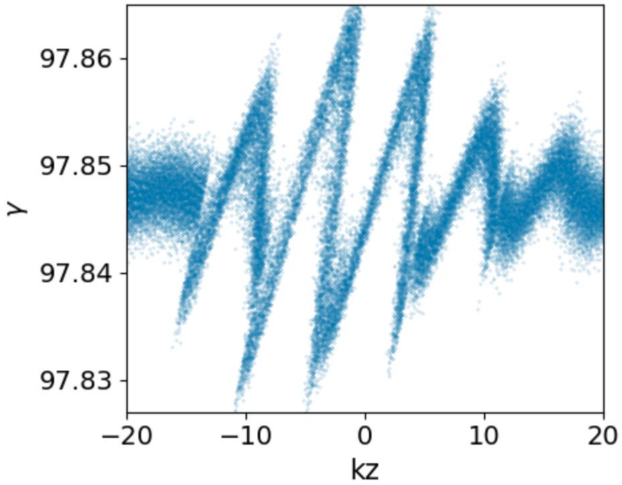
Principle OK:

2- Density modulation by Chicane

$$b \simeq J_1\left(k_r R_{56}\frac{\Delta E}{E_0}\right)\exp\left[-\tfrac{1}{2}(k_r R_{56}\sigma_\delta)^2\right].$$



R56=2 mm



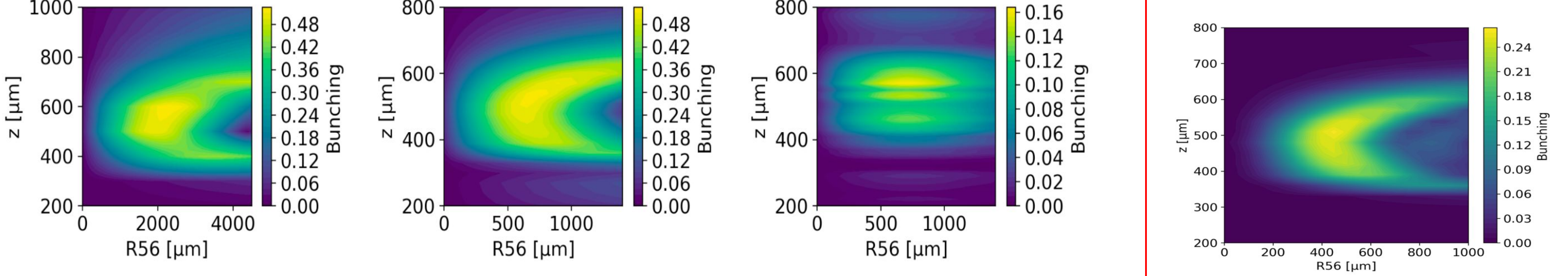
Simulation results

Beam energy E_0	50 MeV
Bunch charge Q	1 nC
RMS bunch length σ_z mu m	120
Peak current I_p	1 KA
Norm. emittance $\varepsilon_{n,x/y}$	10 mm mrad
RMS rel. energy spread σ_δ	0.002
Repetition rate f_{rep}	1 MHz]
Target wavelength λ_r	10 - 100 μm
U1&U2 Undulator type	planar
U1&U2 Undulator period λ_u	100 mm
U1&U2 Undulator parameter K	0.97–4.4
Magnetic gap g	40-100 mm
U1 length L_{u1}	4 m
U2 length L_{u2}	2 m
Chicane compaction R_{56}	0–1cm
Beta functions $\beta_{x/y}$	8/0.3 m
Aperture (vacuum)	35 mm

$$b(k,\zeta) = \frac{1}{N}\sum_{j=1}^{N} \exp(ikz_j(\zeta)),$$

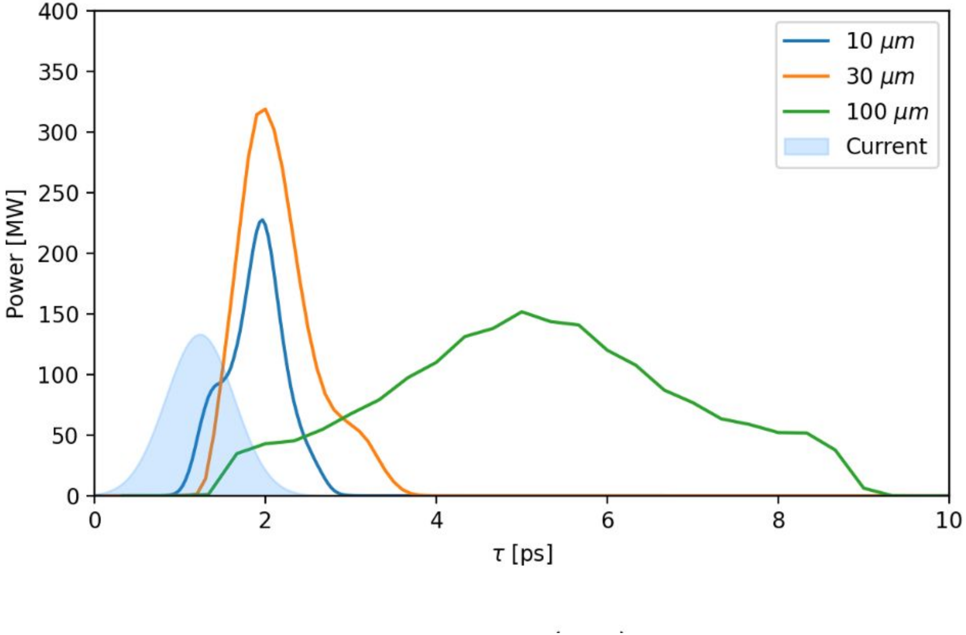
Scan of R56 for λr = 100 μm (left), 30 μm (middle), and 10 μm (right).

3rd Harmonic of 30 micron

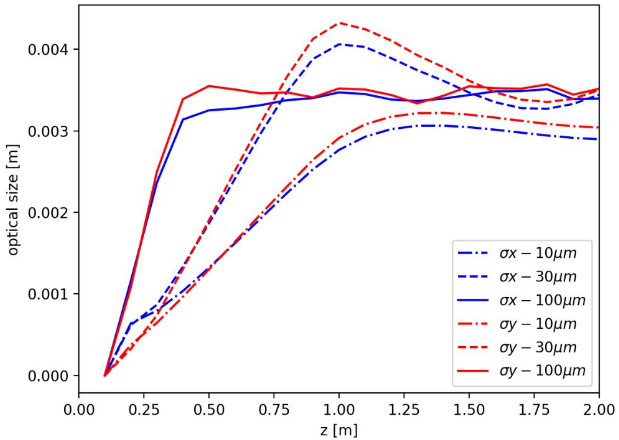


Simulation results

Collective effects are ignored!



Simulated FEL output power after the second undulator (U2) for radiation wavelengths of 10 µm, 30 µm, and 100 µm. The blue shaded area represents the electron beam current profile. The effect of slippage is evident in the temporal structure of the FEL pulses, with longer wavelengths exhibiting broader pulse durations due to stronger slippage.

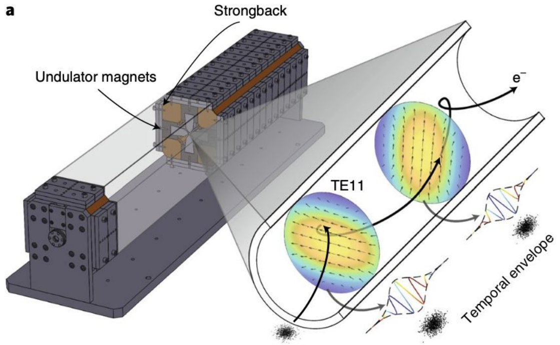


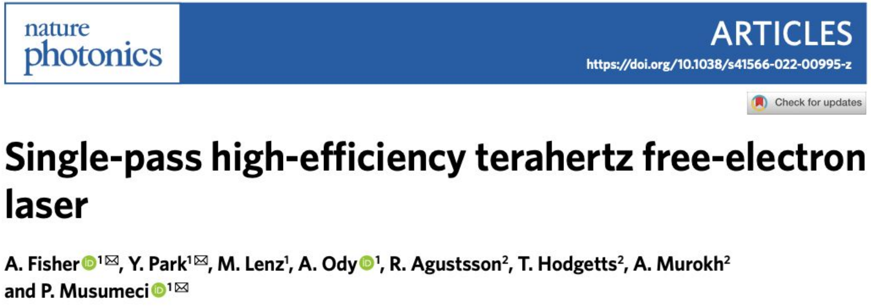
Alternative Strategies for Mitigating Slippage Effects

Waveguide-assisted propagation

The use of parallel-plate or corrugated waveguides can significantly extend the Rayleigh length of THz radiation, thereby reducing diffraction and helping to maintain overlap between the electron beam and the optical field.

A waveguided undulator section or transport line suppresses the effective slippage by confining the radiation mode and enhancing its on-axis field strength.





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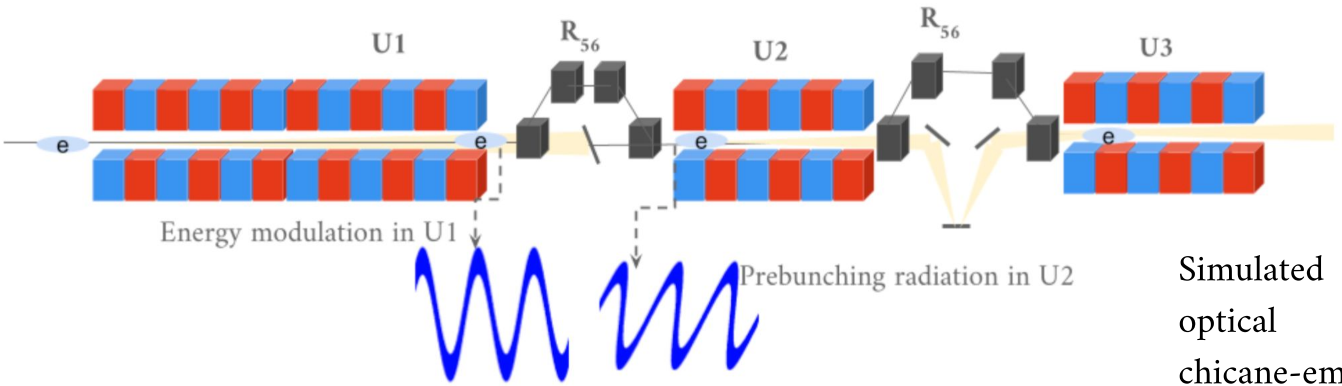
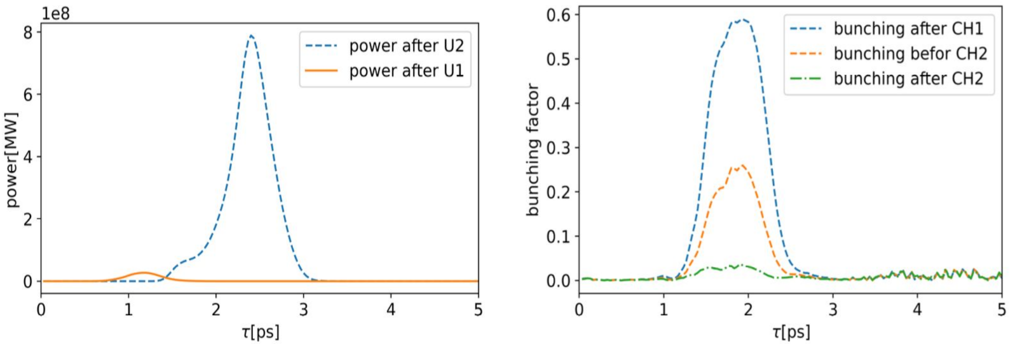
Single-pass high-efficiency terahertz free-electron laser

A. Fisher[1], Y. Park[1], M. Lenz[1], A. Ody[1], R. Agustsson[2], T. Hodgetts[2], A. Murokh[2] and P. Musumeci[1]

Alternative Strategies for Mitigating Slippage Effects





Simulated performance of the staged optical klystron with chicane-embedded optical delay. Left: FEL output power after U1 and U2. Right: bunching factor evolution at different positions: after first chicane (CH1), before second chicane (CH2), and after CH2. A moderate R56 in the first chicane limits energy extraction in U2 but preserves beam quality, enabling strong amplification in U3.

Conclusion and Outlook

The OK approach can be a promising option for THz FELs and may represent the most suitable configuration for single-pass operation. However, the challenge of slippage remains significant. Simulations indicate that the pulse power can be amplified up to a few megawatts, and further amplification of the radiation may be achieved through additional optimization strategies.

Thanks for your attention

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