TECHNOLOGIES TOWARD A 100-KW FREE-ELECTRON LASER*

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Abstract

The challenges of a 100-kW free-electron laser (FEL) are not insurmountable but nevertheless require technological solutions beyond the incremental refinements of mature technologies. Efforts are underway to develop technologies that will enable a new level of FEL performance, e.g. 100-kW average power or greater. These technologies include high-gain amplifiers driven by high-brightness electron beams, high-average-current electron injectors, spoke resonator cavities for energy recovery linac, beam-break-up (BBU) suppression, and new concepts of high-efficiency tapered wigglers. Some recent progress in developing these technologies will be reviewed in this paper.

100-KW FEL CHALLENGES

The FEL, with electrons travelling near the speed of light as the gain medium, is known for its scalability to high average power. Recent experiments at the Jefferson Lab have shown that FEL can achieve up to 10 kW [1]. Scaling the FEL power to above 100 kW introduces several new challenges. For instance, with 1% typical extraction efficiency, the electron beam power needed for a 100-kW FEL is 10 MW, necessitating both high beam energy, which increases the FEL size, and high average current, which increases the BBU risks. Also, at high average power, thermal distortion in the resonator optics becomes the limiting factor for the oscillator FEL. For an amplifier FEL, optical damage in the first mirror that intercepts the FEL beam may occur due to the small divergence of the amplifier FEL beam.

ENABLING TECHNOLOGIES

The solutions to the 100-kW FEL challenges lie with the advanced electron beam technologies that are being developed for the x-ray FEL and energy recovery linac (ERL). These technologies are: 1) the high-gain amplifier FEL, 2) the high-average-current electron injectors, 3) superconducting radio-frequency (SRF) resonators for high-BBU linac, 4) high-efficiency tapered wigglers, and 5) novel BBU suppression techniques.

High-gain Amplifiers

High-gain amplifiers differ from low-gain oscillator FEL in a very important way: they don't have high-Q mirrors that can distort under high thermal loads. In a high-gain FEL, the FEL power grows exponentially along the wiggler length with a characteristic power gain length that scales linearly with beam energy, inversely with peak current to the one-third power and electron beam radius to the two-third power. The wiggler must be long enough for the FEL power to saturate and have two-plane focusing to keep the electron beam's radius small through the wiggler. Optical guiding, an effect in which diffraction of the FEL beam is balanced by the FEL interaction in the wiggler, also keeps the FEL beam radius small and approximately constant, except when FEL saturation sets in.

Large single-pass gains have been demonstrated with self-amplified spontaneous emission (SASE) FEL [2]. Due to their relatively low saturated power, SASE will not be used for the 100-kW FEL. Instead, a seeded high-gain amplifier will be employed. To achieve high peak saturated power, the gain of the amplifier must be limited to between 10^3 and 10^4. Thus the seed laser's average power must be between 10 and 100 W.

Table 1: Representative parameters for the 100-kW FEL

Parameter	Symbol	Value
Beam energy	E_b	80.8 MeV
Average current	I_{ave}	35 mA
Bunch charge	Q	1 nC
Bunch length	τ	1 ps
Peak current	I_{peak}	1 kA
rms Emittance	ε_n	10 mm-mrad
Energy spread	$\Delta\gamma/\gamma$	0.25%
Wiggler period	λ_w	2.18 cm
Wiggler parameter	K_{rms}	1.187
FEL wavelength	λ	1.05 μ
FEL Efficiency	η_{FEL}	4.5%
FEL peak power	P_{peak}	3.5 GW
FEL average power	P_{ave}	125 kW

A concept that combines the large single-pass gains with low-power optical feedback, dubbed the Regenerative Amplifier FEL, to restart the amplification process so that the FEL saturates in a few passes has been demonstrated at LANL. Although this is a low-duty-factor device, the Regenerative Amplifier FEL has achieved up to 1.9 mJ per micropulse at a micropulse repetition rate of 108 MHz. This translates into 200 kW power over the microsecond-long pulse trains [3] and proves the physics of high-gain amplifiers over the microsecond timescale. The keys to achieving this level of performance are the high bunch charge, 1 nC or above, and high peak current (>200 A) at low emittance (~10 mm-mrad). It is important to generate the high-bunch-charge, low-emittance beam, compress it in a buncher and transport the high-current

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beam around bends without significant emittance growth.

A problem with FEL amplifiers is the low-divergence, high-power FEL beam that can damage any optical elements that intercept the FEL beam before it expands to a sufficiently large radius. One possible solution to this problem is to mismatch the electron beam at the wiggler entrance in such a way that the electron beam undergoes scalloping motion and comes to a focus near the wiggler exit. With optical guiding, the focused electron beam causes the FEL beam to "pinch" near the exit of the wiggler (Fig. 2). The resulting increase in the divergence angle allows the FEL beam to spread out quickly after it exits the wiggler, thereby minimizing the risk of optical damage. We show through simulations that with a scalloped electron beam, the divergence of the FEL beam can be increased by a factor of two [4]. This means for the same distance between the wiggler and the optics, the optical intensity can be reduced by a factor of four. Alternatively, the distance between the wiggler and the optics can be halved. This is important for applications in which the FEL length must be kept to a minimum.

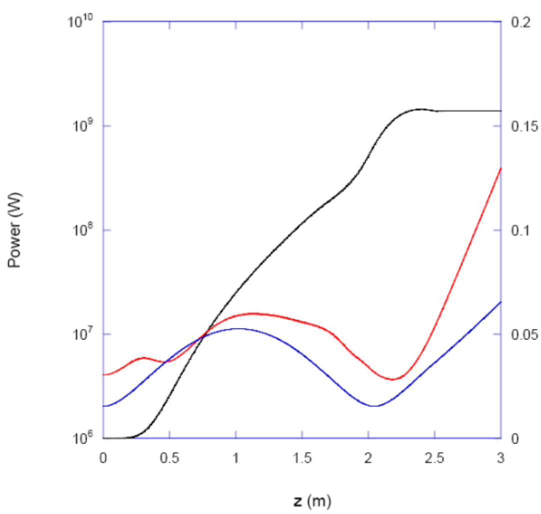

Figure 1: Plot of peak power on log scale (black), FEL beam radius (red) and electron beam radius (blue) versus wiggler length in a scalloped electron beam FEL.

High-average-current Injectors

Three candidates for the high-average-current injectors are being developed [5]. They are the DC gun-SRF booster combination, the SRF gun and the normal-conducting radio-frequency (NCRF) gun. The DC gun has been the workhorse of the Jefferson Lab FEL. It has achieved 10-mA average current. With the new SRF booster cavities from Advanced Energy System (AES), their goal is to demonstrate 100-mA average current. The SRF gun is being developed at both Brookhaven, in collaboration with AES, and Forchsungszentrum Rossendorf. The Rossendorf SRF gun is designed to achieve 1-mA average current. The goal of the BNL/AES gun is 0.5-A average current.

NCRF guns have been used as the front end of many FEL, albeit at low duty factors and thus low average current. The highest average current ever achieved from the NCRF gun was from the Boeing 433-MHz injector which delivered 130 mA at 25% duty factor [6]. LANL and AES are collaborating on a new NCRF injector that will operate at 100% duty. The new NCRF gun is a 700-MHz, 2.5-cell, π-mode, copper on Glidcop cavity designed with thermal and vacuum management (Fig. 2). At 7 MV/m, the new NCRF gun can deliver 3-nC bunch charge with a normalized rms emittance of 6 mm-mrad. The NCRF gun is designed to achieve 100 mA or higher.

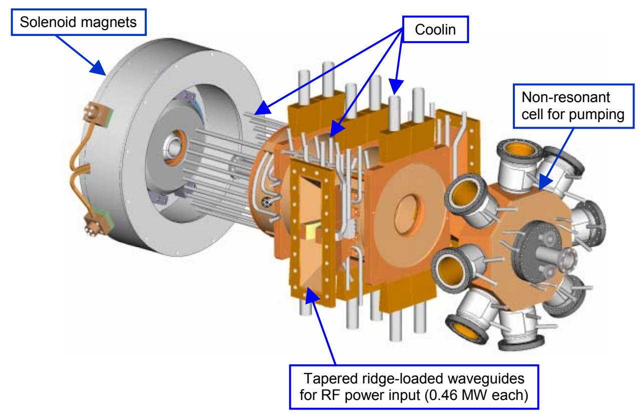

Fig. 2. LANL/AES NCRF high-average-current gun.

Spoke Resonators

A relatively new design of superconducting RF cavities called the spoke resonators offer a number of advantages: mechanical rigidity to resist vibrations, small transverse dimension, strong cell-to-cell coupling and the potential for high BBU limits. At the same diameter, the spoke resonator's operating frequency is about one-half that of elliptical cavities. This means that a 350-MHz spoke cavity has the same diameter as a 700-MHz elliptical cavity but can operate at 4.5 K. The fundamental and HOM power couplers can be mounted on the side of the cavity. Thus, unlike elliptical cavities whose power couplers are mounted on the beam pipes, spoke cavities can afford to have many HOM couplers, i.e. good HOM damping, without reducing its real-estate gradient. This translates into a potentially high BBU limit for spoke cavities.

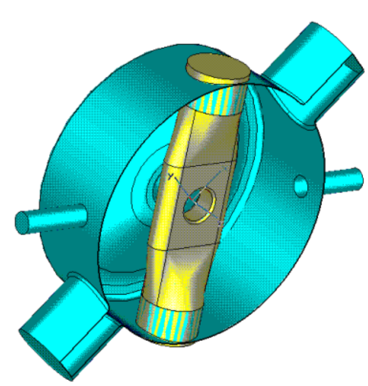

Fig. 3. The LANL single-spoke cavity at 350 MHz. The fundamental and HOM couplers are mounted on the side.

Before spoke cavities can be seriously considered, a β=1 spoke resonator must be designed. Spoke resonators with β=0.6 has been designed and there are no foreseeable reasons why a β=1 spoke resonator won't work. The challenge is in getting the accelerator gradients without exceeding the critical peak magnetic field or electric field. Using today's values, a representative design can achieve an accelerator gradient of about 10 MV/m. With packaging, a reasonable real-estate gradient for the spoke cavities is about 7 MV/m.

Another issue that needs to be studied is wakefields induced by the high-bunch-charge beams traversing the small apertures of the spoke cavities. Since room-temperature L-band cavities with about the same apertures have been tested with nC bunch charge, we don't expect significant wakefields will result from the use of the spoke cavities. However, measurements of wakefields in a spoke cavity are being planned.

Stair-step Tapered Wiggler

A new concept of a tapered wiggler called the stair-step wiggler has the potential of delivering the same extraction efficiency as, but not the complexity of, a conventional linearly tapered wiggler. The stair-step tapered wiggler consists of several uniform wiggler segments with decreasing wiggler periods (or decreasing K_{rms}). Compared to continuously tapered wiggler, the stair-step taper is easier to fabricate and optimize. Large gains can be realized in the uniform wiggler segments, leading to high extraction efficiencies and partial optical guiding. With the same wiggler field taper (Fig. 4), the FEL peak power produced by the stair-step tapered wiggler is slightly better than that of the linearly tapered wiggler (Fig. 5). At an extraction efficiency of 4.5%, the energy spread of the exit electron beam is 13%, within the energy acceptance of a well-designed 180° bend to transport the spent beam through the ERL.

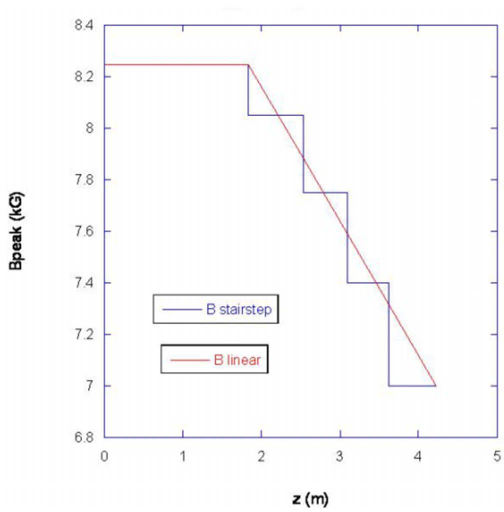

Fig. 4. Magnetic field profiles of both stair-step (blue) and linearly (red) tapered wigglers.

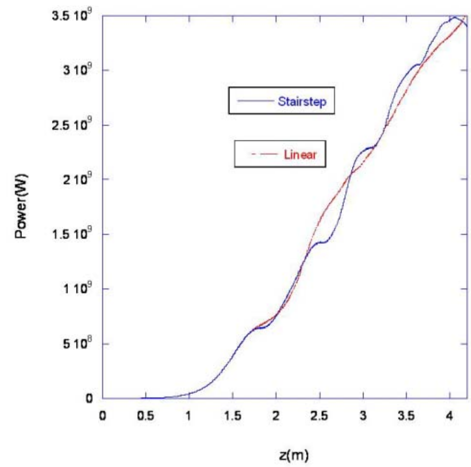

Fig. 5. FEL peak power versus distance for both the stair-step (blue) and linearly (red) tapered wigglers.

Beam-break-up Suppression

A very innovative way to significantly increase the multi-pass, multi-beam BBU limit in an ERL is by modifying the recirculation transfer matrix using skewed quadrupole magnets. This modification could be either a rotation or a reflection in such a way that BBU cannot develop or develops at a much higher current. This novel approach has quadrupled the measured BBU limit at the Jefferson Lab FEL [7]. With refinements, it is conceivable that much higher BBU limits can be achieved.

CONCLUSION

A number of advanced beam technologies are being developed for both the x-ray FEL and ERL. It is expected that these technologies will also be applicable for scaling the FEL to 100-kW average power levels.

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