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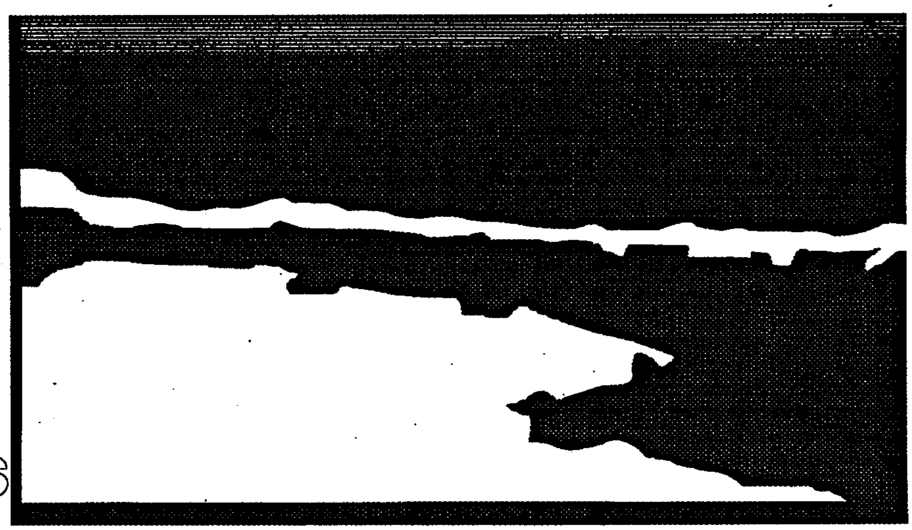

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Synchronously Injected Amplifiers, A Novel Approach to High-Average-Power FEL*

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Abstract

Two new FEL ideas based on synchronously injected amplifiers are described. Both of these rely on the synchronous injection of the optical signal into a high-gain, high-efficiency tapered wiggler. The first concept, called Regenerative Amplifier FEL (RAFEL), uses an optical feedback loop to provide a coherent signal at the wiggler entrance so that the optical power can reach saturation rapidly. The second idea requires the use of a uniform wiggler in the feedback loop to generate light that can be synchronously injected back into the first wiggler. The compact Advanced FEL is being modified to implement the RAFEL concept. We describe future operation of the Advanced FEL at high average current and discuss the possibility of generating 1 kW average power .

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1. Introduction

Free-electron lasers (FEL) have been touted as broadly tunable, high-power devices with average power scaleable to the megawatt level. Yet, thus far the highest average power generated continuously by an FEL is only slightly more than 10 watts [1]. The low average power is caused by a typically poor extraction efficiency and by deleterious effects on the resonator mirrors such as optical damage and thermally induced distortion. Tapering the wiggler to improve extraction efficiency has met with some success [2, 3] but due to losses in the optical resonator, the true efficiency of FEL remains low, typically less than 1% for infrared wavelengths. To obtain a higher average power, one must operate the FEL in the high gain, high efficiency regime without the use of an optical resonator. A number of mirrorless FEL schemes such as self-amplified spontaneous emission (SASE) [4] and electron outcoupling [5] have been proposed as new approaches to short-wavelength or high-average-power FELs. In this paper, we present two new approaches of FEL based on the idea of synchronous injection of the optical pulses into a high-gain, high-efficiency wiggler. We also describe the experimental implementation of one of these concepts on the existing Advanced FEL at Los Alamos. We show the possibility of generating 1 kW average power from a compact FEL.

2. Synchronously Injected Amplifiers

Synchronously Injected Amplifiers (SIAM) relies on the reinjection of the optical pulses into a high-gain, high-efficiency wiggler through the use of a small amount of optical feedback. Due to the micropulse structure of the electron beam, the optical feedback must be timed appropriately so that the optical pulses overlap with the electron bunches. The idea differs from the oscillator in a fundamental way: the optical feedback does not have to be an eigenmode of the resonator. Rather, its main purpose is to seed the wiggler with sufficiently high power such that the amplification process does not start from noise, as in the case of SASE, but from a coherent input signal. Due to the large single-pass gain, the optical intensity at the wiggler exit is orders of magnitude above the input and the optical mode strongly depends on the electron beam.

The simplest way to provide a small optical feedback is to employ mirrors to return a fraction of the optical power generated in the wiggler from the previous pass to seed the subsequent passes (Fig. 1). As it is similar to conventional laser regenerative amplifiers, we called this approach Regenerative Amplifier FEL (RAFEL). The second method involves using a high-efficiency tapered wiggler as both a radiator and an optical klystron (Figure 2). In the small signal regime, the wiggler modulates the electron beam energy, causing the beam to bunch after a drift. The bunched beam is then directed through an achromatic bend into a second wiggler where it radiates optical power coherently. The radiated power is returned to the first wiggler where it induces more energy modulation in the next electron pulse. This process goes on for a few passes until the optical power in the feedback loop is sufficiently high to cause the tapered wiggler to radiate a high-power optical beam. Note that the radiation from the first wiggler always exits the system and is not fed into the second wiggler as in the case of the conventional optical klystron FEL.

3. Experimental implementation of RAFEL

The compact Advanced FEL (AFEL) currently uses a low-energy electron beam and a 1 cm period wiggler to produce coherent infrared in the 4–6 μm region [6]. For the high-average-power RAFEL demonstration, the wiggler period will be changed to 2 cm to produce light at 16 microns. In addition, a number of hardware modifications and upgrades will be implemented on the AFEL facility. The new beam line arrangement for the 1 kW demonstration of RAFEL is shown in Fig. 3. The most important change to the beam line is the straight beam path from the accelerator through a 2 meter long wiggler bracketed by two annular mirrors. This feature facilitates operating the machine at different beam energies without significantly changing the matching conditions. The electron beam generated by the photoinjector/linac is focused by two quadrupole doublets through a small hole in the first annular mirror. The beam is matched into a 2 meter long permanent magnet wiggler that provides two-plane focusing. Due to the large single-pass gain, the optical beam generated inside the wiggler remains guided by the electron beam. In the small-signal regime, the light exiting the wiggler diffracts into a donut beam at the second annular mirror. This donut beam is fed back to the entrance of the wiggler by an optical feedback loop. At saturation, most of the optical power resides on axis and the optical beam exits through the large hole in the second annular mirror. The electron beam also goes through the second annular mirror, turns around in a 120° bend followed by a -30° bend before terminating in the beam dump (Fig. 3).

In addition to the beam lime modifications, the following upgrades to the AFEL facility are in progress:

3.1 High-average-current electron beam:

The electron beam needed for the 1-kW demonstration of RAFEL is a train of 17 MeV, 300 A micropulses (6 nC in nominally 20 ps pulses) at 108.3 MHz (1/12th of the 1300 MHz rf).

This micropulse frequency is being provided for by a modelocked Nd:YLF laser driving a cesium telluride photocathode. The macropulse repetition rate of 60 Hz will be achieved by switching from the lamp-pumped amplifiers to diode-array-pumped amplifiers designed to operate at a high duty cycle. The micropulse and macropulse structures of the electron beam are shown in Fig. 4. Coincidentally, both the micropulse and macropulse duty factors are about 0.2%. With a micropulse peak current of 300 A, we will have an average current during the macropulse of ~0.6 A and a true average current of ~1.2 mA. The average power of the 17 MeV electron beam is thus 20 kW. Details of the electron beam physics and beam line design are described elsewhere [7].

3.2 High-average-power rf station:

The new rf system for the Advanced FEL produces an output greater than 20 MW peak for 30 microsecond pulses at a repetition rate up to 60 Hz. The average power of this 1300 MHz klystron-based transmitter is up to 50 kW in bursts. The Thomson-CSF TH-2104U klystron now in the system was acquired from Boeing Aerospace Company. The system was designed to have a compact size, high power output and fully automated operation. The modulator is a thyratron-switched, transformer-coupled unit of conventional layout, though the use of high power density switching power supplies allows the overall system to be extremely compact for its rating. The phase and amplitude of the output rf are stabilized by a sophisticated analog-digital control system.

3.3 High-gain, high-efficiency wiggler:

The high-gain, high-efficiency wiggler is a 2 meter long, segmented (1 meter uniform and 1 meter tapered) plane-polarized wiggler with 2 cm periods. Each period consists of four samarium-cobalt permanent magnets in a modified Hallbach configuration. A rectangular notch is cut on the pole face of each magnet to provide nearly equal two-plane focusing via the sextupole component of the wiggler field. The second 1 meter segment has a 30% taper in field by opening up the wiggler gap. Details of the wiggler design are described elsewhere [8].

3.4 Optical feedback loop:

The optical feedback loop is designed to provide a small amount of optical power to the wiggler entrance so that the amplification process restarts from a coherent optical signal. The optical feedback loop consists of four mirrors— two flat annular mirrors and two paraboloids—

forming a rectangular ring (Fig. 5). The separation between the two annular mirrors is 239.2 cm. The separation between the annular mirrors and the paraboloids is 37.5 cm. Thus, the optical feedback loop reinjects the optical pulses after a delay of 18.46 ns, twice the micropulse separation of 9.23 ns. The radii of curvature of the two paraboloids are 75 cm for the upstream paraboloid and 120 cm for the downstream one. These values were chosen so as to collimate the donut-shaped beam between the paraboloids and to reimage the optical beam to the wiggler entrance. The first annular mirror has a 5 mm diameter hole to maintain greater than 99.5% electron beam transport through the mirror. The hole in the second annular mirror is chosen to be 14 mm in diameter.

The above design is dictated by simulations which show that, in the small-signal regime, the optical beam takes on a donut shape with most of the power located outside a 7 mm radius at the second annular mirror. As the optical power reaches saturation, the optical beam evolves into a lorentzian shape with most of the optical power residing on axis. Thus, in the large-signal regime, the majority of the power exits through the hole in the second annular mirror. Due to this mode evolution, the optical feedback loop provides a variable outcoupling that changes from negligible outcoupling (nearly 100% feedback) in the small-signal regime to greater than 97% outcoupling in the saturated regime. This variable outcoupling offers three advantages. First, the optical power on the second annular mirror remains low at all time, thereby minimizing the risk of optical damage. Second, almost all of the saturated power exits the FEL as useful output. Third, the variable outcoupling allows the optical power to build up rapidly to saturation, resulting in a high-power beam from almost all micropulses. Unlike conventional oscillators, the RAFEL efficiency is nearly the same as the extraction efficiency.

4. Expected Results and Discussion

The expected performance of the RAFEL approach has been evaluated with the three-dimensional FEL code FELEX. The results are discussed in details in a separate paper [9]. The two notable features are the evolution of the optical beam from a donut shape to a lorentzian shape as the optical power reaches saturation, and the rapid saturation of the optical power within a few passes (less than five). The optical mode evolution is reminiscent of the transformation from the cold-cavity mode to warm-cavity mode in a hole-coupled FEL resonator [10]. In the RAFEL case, the optical beam is always a warm-cavity mode, but a similar transformation can take place if the wiggler undergoes changes in its gain-guiding property. In the small-signal regime, the tapered section of the wiggler does not provide sufficiently high gain. Consequently, the optical beam diffracts strongly upon entering the tapered section and evolves into a donut beam at the output annular mirror. In the large-signal regime, the optical field is sufficiently high to turn on the tapered section of the wiggler, leading to a higher gain in the tapered section and resulting in an on-axis lorentzian beam that does not diffract significantly after it exits the wiggler.

FELEX simulations predict a quasi-steady-state optical power after the fifth pass of approximately 550 MW, corresponding to an efficiency of ~10%. Even with slippage effect (5.5 ps out of 18 ps), the optical energy in each micropulse is still about 6.9 millijoules. Taking into account the micropulse and macropulse structure, ~1.8×10^5 micropulses per second, we arrive at an average power of ~1.2 kW.

5. Conclusions

We present two new approaches to high-average-power FEL based on synchronous injection of the optical power into a high-gain, high-efficiency wiggler. The implementation of one of these approaches, the regenerative amplifier FEL, on the existing Advanced FEL is described. This approach appears capable of reaching 1 kW of true average power from a compact, low-energy FEL. These implementations are in progress and the results will be described in the near future.

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Figure Captions

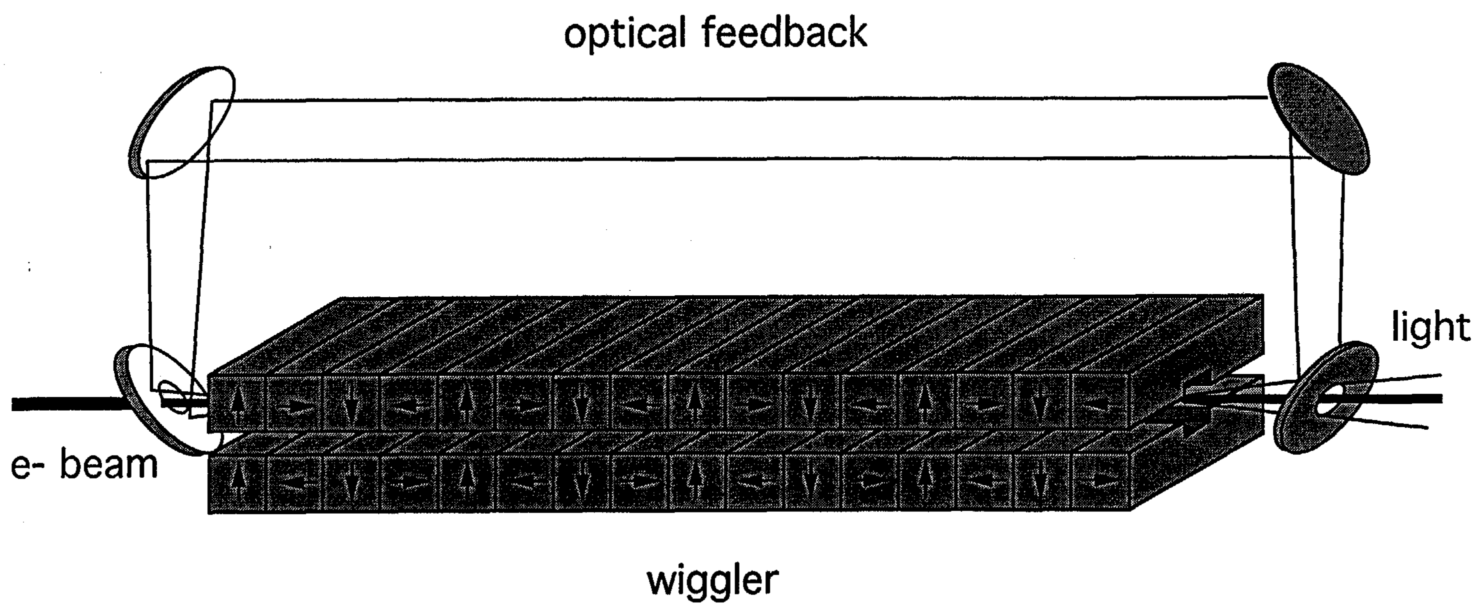
Fig. 1 Regenerative Amplified FEL (RAFEL) concept.

Fig. 2 Radiator-Optical Klystron (ROK) concept.

Fig. 3 Schematic of the Advanced FEL modified for the RAFEL demonstration.

Fig. 4 The temporal format of the high-average-current electron beam needed for RAFEL implementation.

Fig. 5 Optical feedback loop for RAFEL.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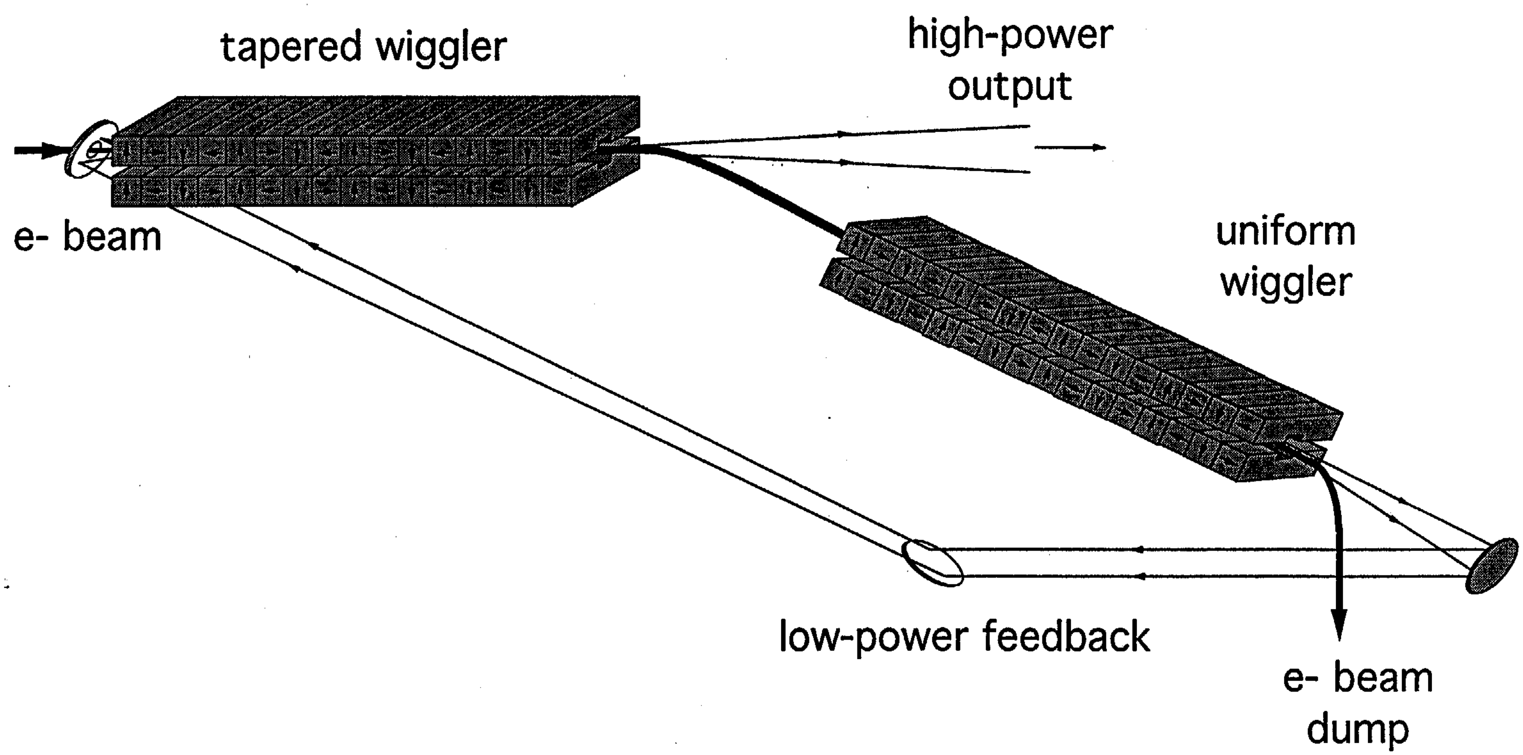
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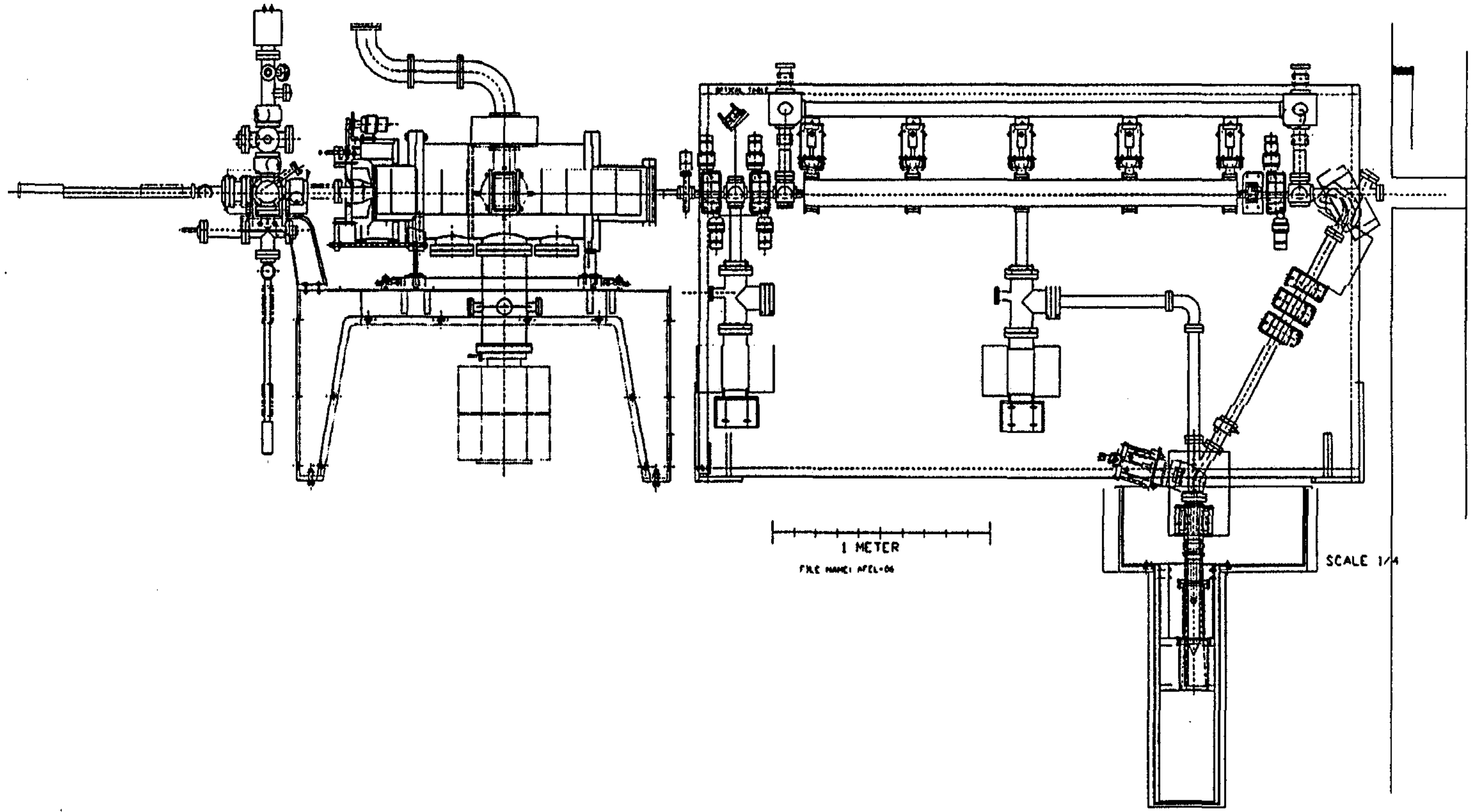

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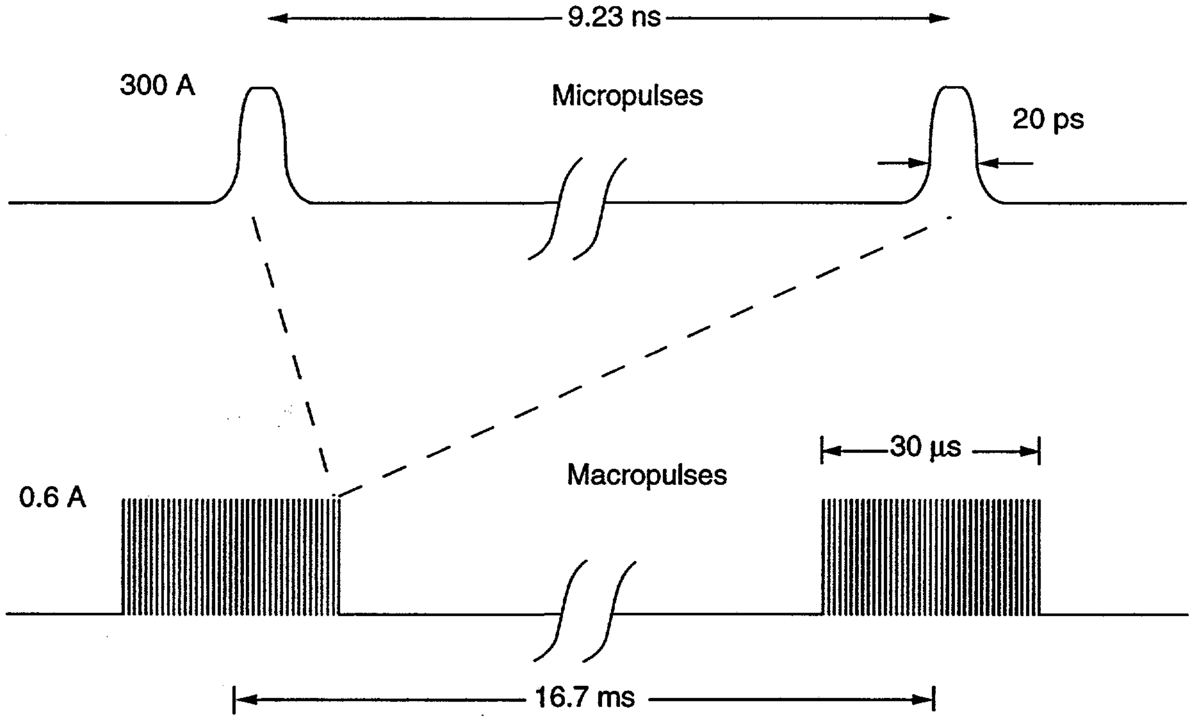
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Micropulses
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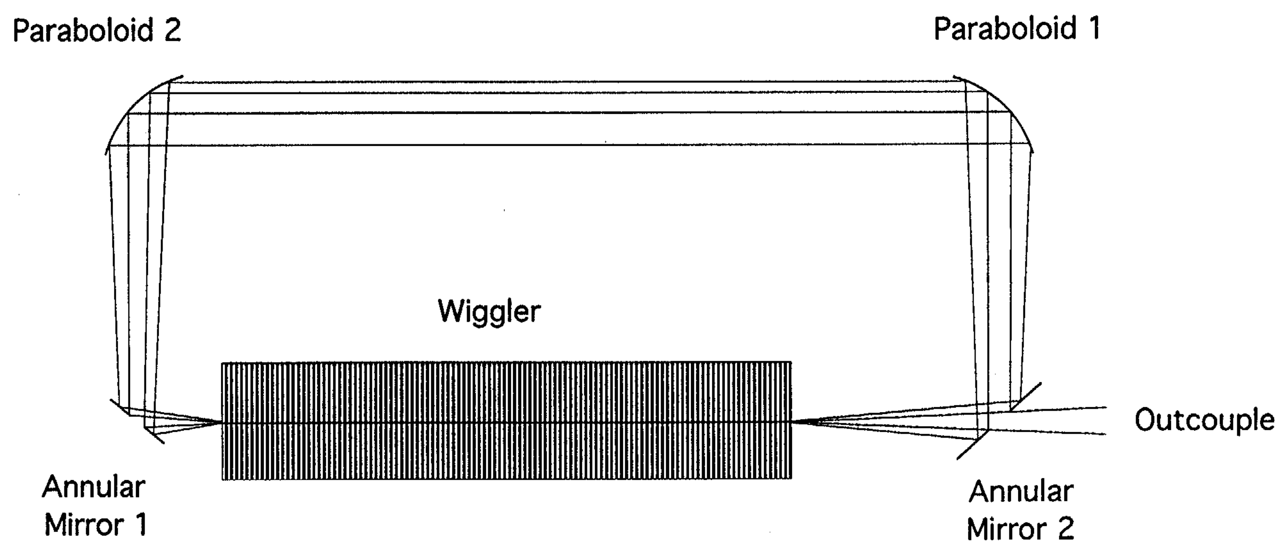
30 µs
0.6 A
Macropulses
16.7 ms


Paraboloid 2
Paraboloid 1
Wiggler
Outcouple
Annular
Mirror 1
Annular
Mirror 2