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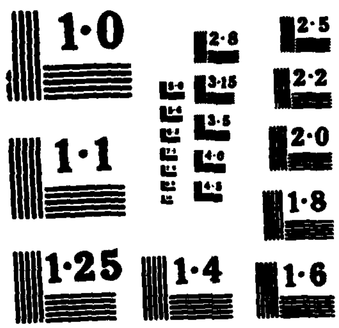

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Proposal for FEL Experiments Driven by the National Bureau of Standards' CW Microtron

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Free Electron Laser

We propose FEL experiments driven by the race-track microtron (RTM), which is under development at the National Bureau of Standards (NBS). The design of ~~NBS~~ RTM has many exceptional properties: i) normalized transverse emittance of 10 mm mrad, comparable to a storage ring, ii) axial emittance < 30 keV-degree, much superior to r.f. linacs, iii) electron energy tunable from 20 to approximately 200 MeV, iv) CW operation, v) energy stability, vi) compactness, and vii) high power-conversion efficiency.

We propose accelerator up-grades to increase the peak current and to recover a significant part of the electron beam energy. It seems possible to obtain peak current of I_p = 5-10A, for electron pulse length of $\ell_{eb} > \sim 1.2$ mm.

We have made conservative estimates based on I_p = 1.0 A in estimating the performance of the FELs to be used with the RTM. Low gain calculations indicate that the FEL can oscillate at the fundamental wavelength ranging from 0.15 μm to 100 μm. Furthermore, we will outline experiments to generate harmonic in the XUV.

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PROPOSAL FOR FEL EXPERIMENTS DRIVEN BY THE NATIONAL BUREAU OF STANDARDS' CW MICROTRON

I. The NBS Racetrack Microtron

The RTM has not previously received serious consideration as an electron beam source for an FEL, because it is deficient in peak current compared to electron linacs which operate in the same energy region. However, the RTM is superior in terms of energy spread, and competitive with, if not actually superior to, the linac in most other beam properties. The RTM is comparable to a storage ring in terms of beam emittance and energy spread, but there is no restriction on insertion length or "stay clear" aperture. The beam energy can be varied continuously over a wide range without significant loss of performance. In addition, microtrons are compact and energy-efficient. We propose an accelerator upgrade to increase the peak current of the NBS RTM. With this upgrade, the RTM is a suitable driver for an FEL. The RTM now under construction at NBS is shown schematically in Fig. 1. It is described in detail in Ref. 1. The design values are shown in Table I.

A major objective of our proposed research is to obtain the highest possible peak current from the RTM. As presently designed, the RTM peak current will be $I_p = 0.14$ A with a micropulse length of $\ell_{eb} = 0.5$ mm (an r.f. phase spread of 1.4°). A laser-driven photocathode, with a pulse length of 30 ps and a peak current of 10 A, would produce RTM output beam with $I_p = 7.2$ A, $\ell_{eb} = 1.2$ mm (3° phase spread). The limiting factor in increasing the beam current is the beam breakup phenomenon (BBU). This potential problem will require detailed study. We are in an excellent position to study and control BBU because of the strong focusing provided on the return paths of the NBS RTM. In the interim, we are using a projected value of $I_p = 1.0$ A in estimating the performance of FELs to be used with the RTM. While this will require a significant upgrading of the injector system, we believe it is a conservative estimate of what we will be able to achieve.

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The design goal for the normalized transverse emittance of the RTM beam is $\varepsilon_n = 10 \times 10^{-4}$ radians-centimeters.* This implies a design value of normalized brightness $B_n = 5.7 \times 10^4\ A/cm^2$ at $I_p = 0.14$. If the emittance could be preserved while increasing the peak current to 7.2 A, the normalized brightness would be an impressive $3 \times 10^6\ A/cm^2$.

The energy spread of an RTM is much better than that of an electron linac because the acceleration process in an RTM exhibits synchrotron-like phase focusing. Our design calculations indicate a longitudinal emittance $\varepsilon_z \leq 20$ keV degrees. On any return path, the corresponding energy spread (for a matched beam) is 57 keV full-width. That is, $\delta\gamma/\gamma = 3 \times 10^{-4}$ for a beam energy of 185 MeV, which is an order of magnitude better than any existing linac in this energy range.

In the design of the NBS RTM, achieving a high electrical efficiency was not a major goal. Nevertheless, the efficiency for converting r.f. power to beam power is expected to be 22%, a value which is competitive with existing high energy linacs. A significant amount of r.f. power can be saved by reducing the accelerating gradient by 20%. (The maximum energy would be 148 MeV.) It would then require only 190 kW to provide the accelerating fields. With the same available total power and distribution losses, the beam power can be increased to 220 kW (45% efficiency).

It is possible, in principle, to recover a significant part of the electron beam energy by the methods indicated schematically in Fig. 2. After passing through the wiggler, the beam is passed through a bending system (not shown in the figure) which imposes an energy-dependent transit time on the path to the reaccelerator, such that after passing through the reaccelerator, the average beam energy is restored to the value before the wiggler, and the energy spread is compressed to match the energy acceptance of the microtron. The reconditioned beam is reinjected into the microtron, along the path it would have followed

* Our definition of emittance is that $\pi\varepsilon$ is in the area of the smallest ellipse in x, x' transverse phase space which encloses all of the particles in the beam. Normalized emittance is given by $\varepsilon_n = \beta\gamma\varepsilon$, where β and γ are the velocity and energy of the beam in natural units ($m_o = c = 1$). Thus, our definition of brightness is identical to that of Lawson (Ref. 2). $B = I_p/\pi^2\varepsilon^2$, for a beam of constant current density within the bounding phase of ellipse. The normalized brightness is $B_n = B/(\beta\gamma)^2 = I_p/\pi^2\varepsilon_n^2$.

if it had not been extracted from the RTM, but at a different (by $\sim 180°$) phase relative to the r.f. In passing through the accelerating section, the reinjected beam loses the same amount of energy as an accelerated beam would gain. The beam is thus decelerated and ultimately removed from the RTM and dumped. If the beam had made N passes through the RTM while being accelerated, it would be removed after $N-1$ decelerating passes. For $N = 15$, this would imply a recovery of 93% of the beam energy. Considering the necessity to power the reaccelerator and to deal with an increase of beam emittance in the wiggler, it is more realistic to set a goal of 70% energy recovery. Then the power in the beam entering the wiggler could be as high as 730 kW for an average current of 5 mA at 148 MeV. With a projected peak accelerated current of 7.2 A in 3° of r.f. phase, the injecter system would operate at the 12th subharmonic of the r.f. fundamental at this power level. Under these conditions, an FEL output power in the range of 20 kW average and 30 MW peak at $\lambda = 0.5\ \mu$m should be possible. This would be the first continuous beam visible laser capable of testing mirrors and other optical components at high peak and average power levels.

II. FEL Experiments

We propose FEL experiments for (i) FELs with uniform wigglers for a radiation wavelength ranging from $0.15\ \mu\text{m} \leq \lambda \leq 100\ \mu\text{m}$, (ii) efficiency enhancement with spatially and temporally varying wigglers, and (iii) coherent harmonic generation in the UV spectrum.

The parameters that are used for the following examples assume that the peak current can be increased to 1 A, and the pulse length increased to 6° of r.f. phase ($\ell_{eb} = 2.4$ mm). We will further assume that the normalized emittance will be 20 mm-mrad and the longitudinal energy spread will be 70 keV (to be compared to design value of 10 mm-mrad and 57 keV).

Based on preliminary calculations, the FEL would oscillate with a uniform wiggler for almost three orders of magnitude in wavelength. The formula for the amplitude gain G in the low gain regime, can be written as

$$G = \frac{\pi^2}{4\sigma_R}\frac{\nu}{\gamma^5\lambda}L_w^3(1+K^2)K^2,$$

where λ is the radiation wavelength, and $\sigma_R = \pi w_o^2$ is the cross-sectional area of the radiation , w_o is the waist of the Gaussian radiation beam, $\nu = I_p(A)/1.7 \times 10^4$ is the Budker parameter, $K = (|e|B_w/m_oc^2k_w)_{RMS}$ is the wiggler parameter, B_w is the magnetic field amplitude in the wiggler and k_w is the wavenumber of the wiggler. The equation for the gain includes the filling factor $F = \sigma_b/\sigma_R$, where σ_b is the area of the electron beam.

The FEL performance at four output wavelengths is summarized in Table II. All the wigglers can be built with present technology. The FEL oscillator will lase when $G > (1 - R)$, where $2G$ is approximately the power gain and R is the mirror reflectivity. If necessary, the gain can be increased by designing the wiggler in the optical klystron configuration.

The causes that prevent the FEL from oscillating on the NBS RTM at wavelengths much shorter than 0.15 μm are a combination of poor mirror reflectivities, low beam current, low electron beam energy, and a limited interaction length. The limit on the gain for the long wavelength end is the requirement $N\lambda > \ell_{eb}$, where $N\lambda$ is the pulse slippage distance, N is the number of wiggler periods and λ is the radiation wavelength. Both the electron energy spread and the emittance are well within the limiting conditions for all the examples.

The efficiency of the FEL can be enhanced[3] by tapering the wiggler period or amplitude, or by applying a DC electric field. Tapering the wiggler amplitude is the most convenient. A tapered wiggler reduces the small signal gain in the start-up phase of the FEL, and could possibly prevent the laser from oscillating. The CW operation of the NBS RTM can overcome this difficulty in two ways. When the gain is larger than the losses, the CW feature of the RTM always allows the FEL to reach a steady state. If the small signal gain becomes less than the losses as a result of the taper of the wiggler, one can initially keep the wiggler uniform to obtain the gain needed for start-up, and then taper the wiggler after the laser starts oscillating. The temporal application of efficiency enhancement is presently unique to the NBS RTM.

We also propose experiments of coherent harmonic generation to obtain very significant amounts of power in the XUV region. One possible method is to optimize the design of the FEL for maximum harmonic output. A second method is to use a transverse optical klystron[4] whose laser source is an FEL (of very high peak power) driven by the RTM electron beam. To do this, the micropulses in the electron beam would be divided between two channels, one for the FEL and one for the TOK, by an r.f. beam splitter. If an equal split were chosen, each beam would have a micropulse frequency of 100 Mhz (24th r.f. subharmonic). Even without energy recovery, each electron beam could be in the range of 100 kW average, 300 MW peak power. This is a subject for research, since at present we do not know if the approach is feasible. In either method, the FEL would be continuously tuneable, the harmonic radiation would also be continuously tuneable. For an FEL fundamental wavelength of 0.3 μm, substantial amounts of radiation might be obtainable down to wavelengths of order 20 nm.

III. Summary

With the exception of the beam current, the NBS RTM has many beam properties superior to or competitive with linacs as a driver for the FEL. Preliminary calculations indicate that after an upgrade to increase the beam current, the FEL would oscillate over the wavelength regime of $0.15\ \mu m \leq \lambda \leq 100\ \mu m$. The radiation pulses would be CW, and would have high peak powers. In addition, coherent spontaneous harmonics could be produced in the UV spectrum regime. Furthermore, the efficiency can be improved by tapering the wiggler and by converting the power of the spent beam to r.f. power.

Acknowledgment

This work is supported by ONR.

References

1. P. H. Debenham et al., IEEE Trans. on Nucl. Sci. NS-30, 1391 (1983).
2. J. D. Lawson, The Physics of Charged-Particle Beams, Clarenden Press, Oxford (1977).
3. P. Sprangle, C.-M. Tang and W. M. Manheimer, Phys. Rev. A21, 302 (1980).
4. R. R. Freeman and B. M. Kincaid, "Production of Coherent XUV and Soft X Rays Using a Transverse Optical Klystron," in Laser Techniques in the Extreme Ultraviolet, ed. S. E. Harris and T. B. Lucatorto, American Institute of Physics, New York (1984).

TABLE I. NBS CW RTM Design Parameters

Injection energy	5 MeV
Energy gain per pass	12 MeV
Number of passes	15
Maximum energy	185 MeV
Maximum average current	550 μA
Macroscopic duty factor	100%
r.f. frequency	2380 MHz
r.f. wavelength, λ	12.596 cm
Increase in orbit circumference per pass	2λ
End magnet field	1.0 Tesla
Gradient in accelerating section	1.5 MV/m
Transverse tunes, ν_x and ν_y	Variable, 0 to 0.25
Longitudinal tune, ν_z	0.25
Normalized emittance, ε_n	< 10 mm-mrad
Longitudinal emittance, ε_z	< 30 keV-degrees
Power source	One 500 kW klystron

TABLE II. FEL Examples

Parameters	$\lambda = 100\ \mu m$	$\lambda = 10\ \mu m$	$\lambda = 1\ \mu m$	$\lambda = 0.15\ \mu m$
Wiggler period, λ_w(cm)	20	4	2.4	2.4
Wiggler amplitude, B_w(kG) (Linearly polarized)	1	3.8	6.3	6.3
γ	55	77	155	400
Rayleigh length, z_o(m)	waveguide	2.5	3.5	3.5
Spot size, w_o(cm)	0.4	0.28	0.11	0.04
Wiggler length, L_w(m)	5	6	8	8
Single pass amplitude gain, G (%)	3	16	47	19
Mirror loss, (1-R) (%) (or equivalent loss)	1.5	1	< 1	< 5

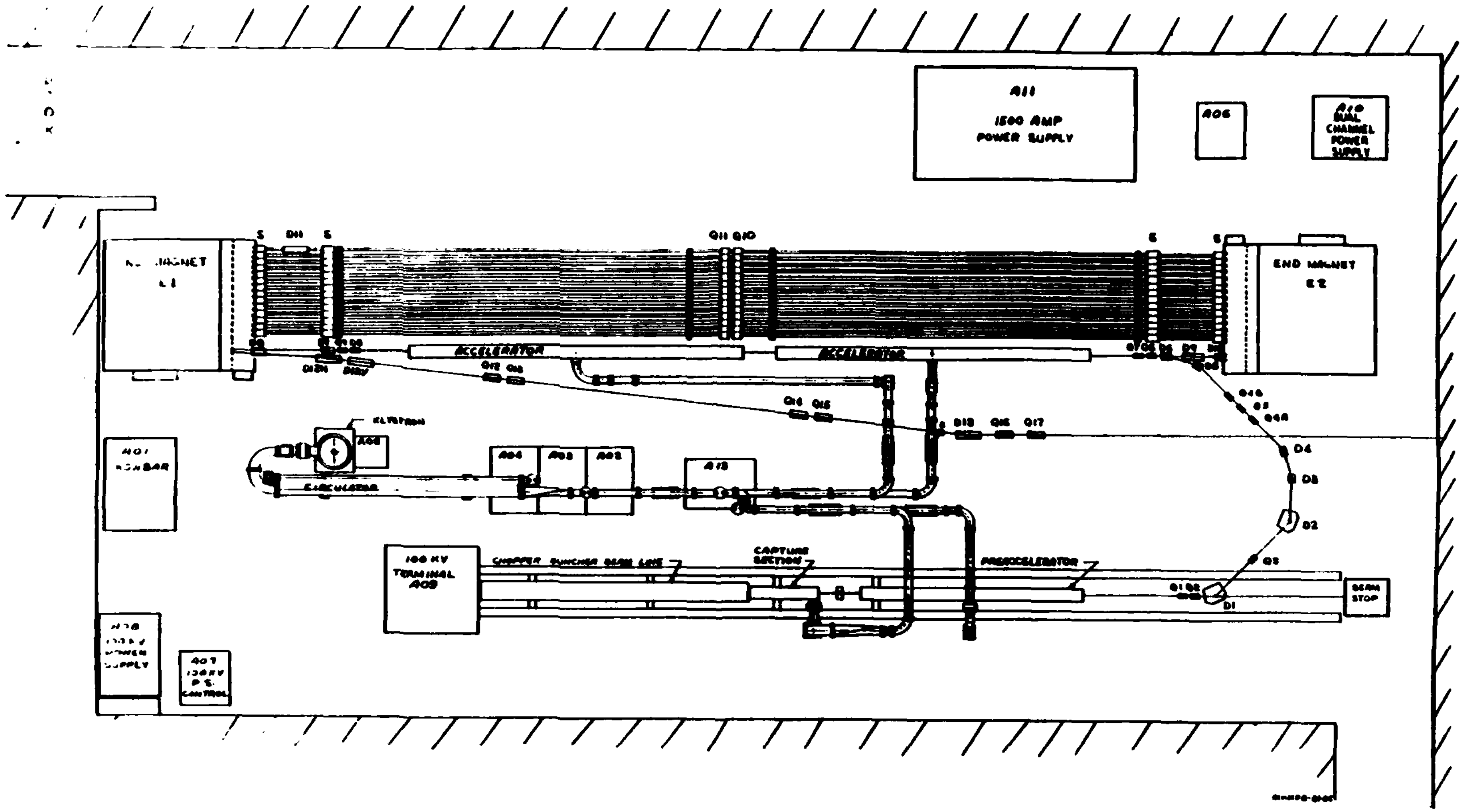

Fig. 1 The schematic of the NBS race-track microtron.

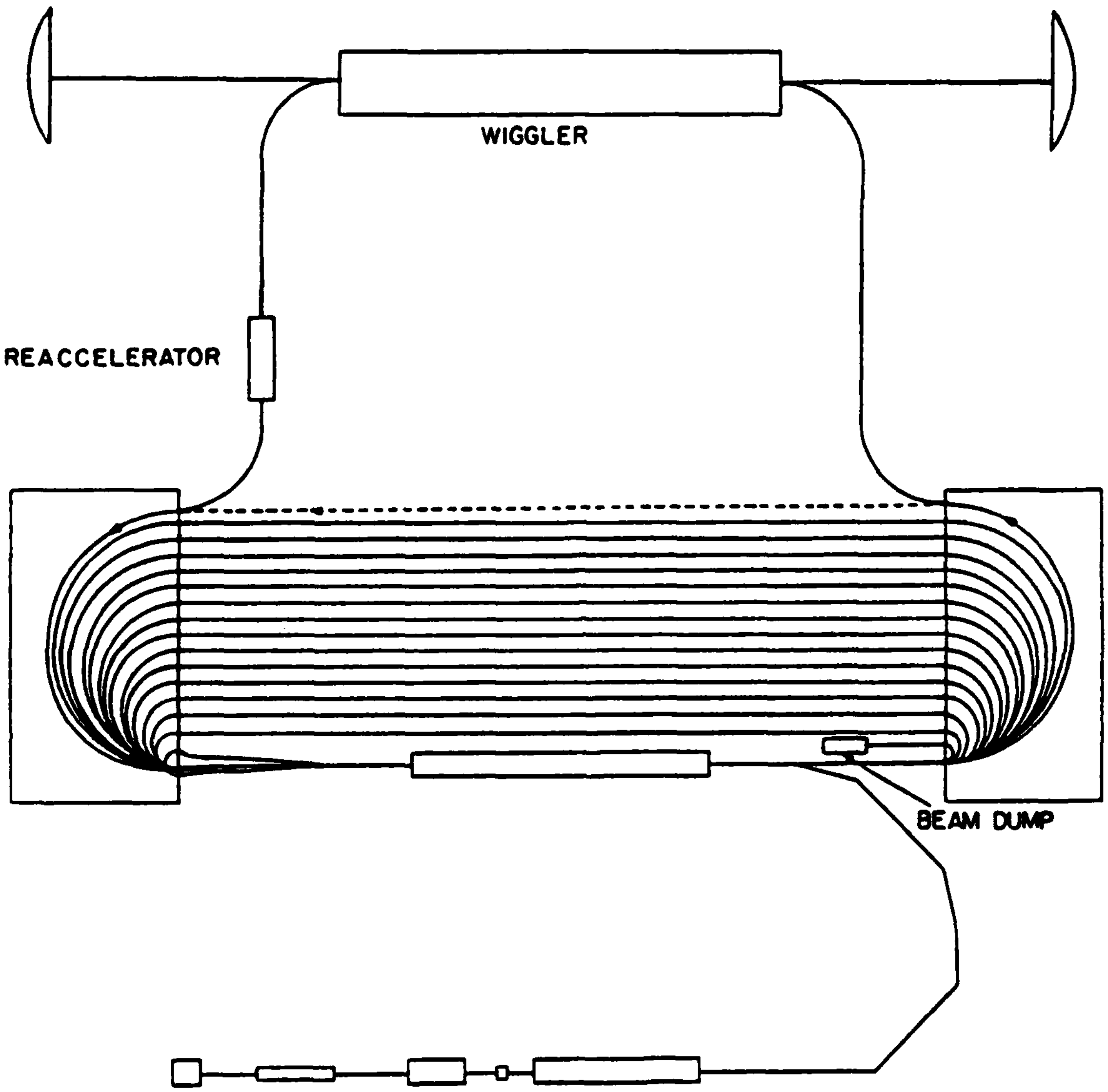

Fig. 2 The schematic of the proposed FEL and the electron beam energy recovery on the NBS race-track microtron.

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