A COMPACT ENERGY RECOVERED FEL FOR BIOMEDICAL AND MATERIAL SCIENCE APPLICATIONS*

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Introduction

In this paper we describe how, with present day technology, it is possible to build a modest size infrared-to-visible free electron laser (FEL) machine that offers tremendous flexibility in operating parameters, while producing a time average output laser power of 1 kw. Different FEL applications have different requirements, both in terms of wavelength and pulse durations. The machine outlined below would have an operating wavelength range of 0.5 microns to 10 microns. The output radiation is in the form of a continuous train of micropulses 40 ns apart, with pulse widths ranging from 2 ps (corresponding to a peak pulse power of 20 MW) to 200 ps. The size of such a machine would be about 10 meters long: larger than the average room, but not by much.

It is our belief that such a machine offers significant advantages over present facilities and may be very attractive to the growing community of FEL users.

The accelerator for this machine is a superconducting RF linac. A number of features have been included in the design (such as recirculation, energy recovery, dual-cell accelerating structures and harmonic acceleration) in order to get the most performance out of a small system. This design has been strongly influenced by our experience with the Superconducting Accelerator (SCA) at Stanford, on which we have been conducting FEL experiments for several years in collaboration with TRW.

In this paper we discuss the salient features of the accelerator and the design choices that have been made. This is followed by a discussion of the FEL wiggler and the operation of the system over its parameter space.

Accelerator

Figure 1 shows the proposed design. A 4 MeV 2.5 mA electron beam is fed into the accelerator. The beam makes two accelerating passes through the superconducting linac reaching up to 50 MeV. This beam goes through the wiggler and generates FEL radiation. The 'used' beam is sent twice more through the accelerator at a decelerating phase in order to recover its energy, and is eventually dumped at 4 MeV. The relevant parameters for the electron beam, the accelerator, the wiggler, and the FEL radiation are all collected in Table 1. It should be stressed that all the elements of the design are feasible today; the design numbers have already been attained or are considered readily attainable.

The heart of the accelerator is a superconducting RF linac running at 500 MHz. The primary advantage of a superconducting linac is efficient high-gradient operation. Other advantages are CW operation and very good beam quality, both of which are important to the FEL. The 500 MHz accelerator frequency is lower than most present day linacs, and offers both engi-

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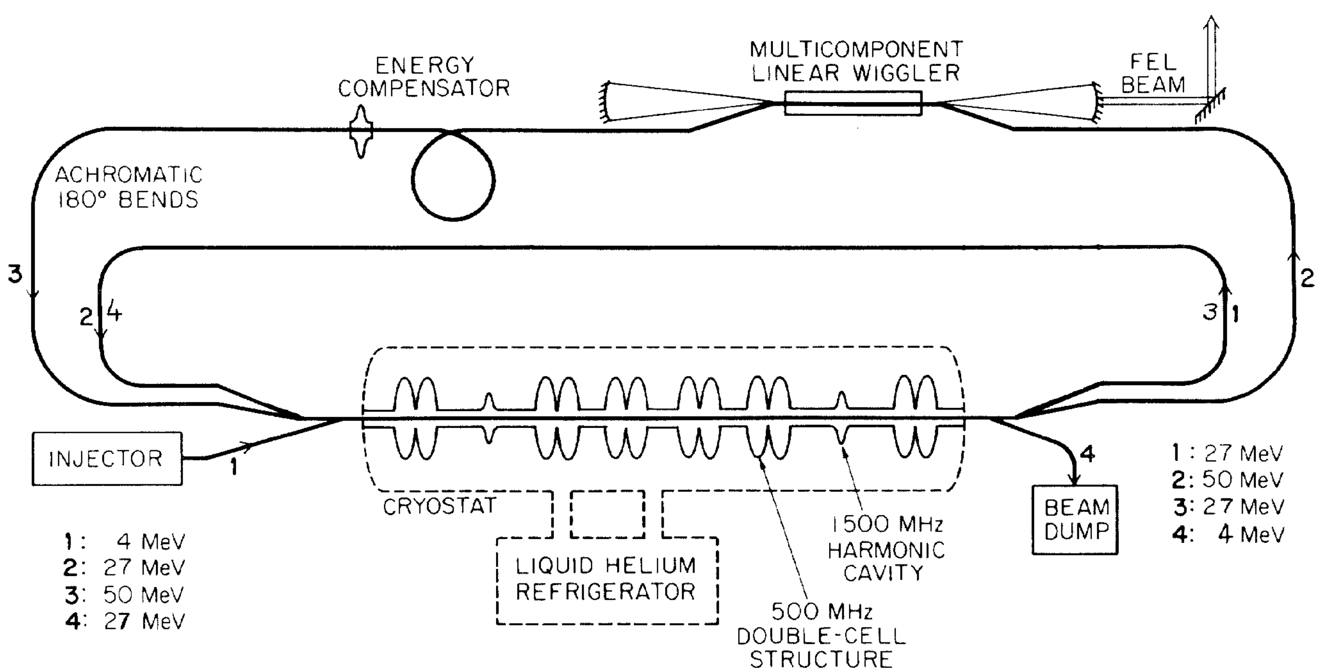

Figure 1. **COMPACT FLEXIBLE FEL**

neering and physics advantages. First, RF power is substantially cheaper at lower frequency. Second, 500 MHz superconducting cavities run well at 4.2 K, unlike higher frequency cavities which attain maximum Q at lower temperatures. This makes the refrigeration problem easier. Third, at low frequencies the beam micropulse may be elongated, thus reducing the space charge forces and emittance growth. The emittance growth due to space charge is particularly severe at low energies: at higher energies one may still bunch the beam in order to reduce the micropulse length and increase the peak current. (Superconducting 500 MHz cavities have been successfully developed at CERN and are a proven technology.[1]) The accelerator consists of six dual-cell RF structures operating at 7.1 MV/m plus two single-cell harmonic cavities (1500 MHz). The harmonic cavities are used to cancel the second derivative of the voltage gain, $\partial^2 V/\partial\phi^2$ where ϕ is the RF phase; this increases the usable phase extent to $\cong 36^\circ$, or 200 ps.[2] Harmonic cavities are very useful in the injector design as well; however injector design issues have been discussed elsewhere[2] and are not treated here.

The refrigeration power required for the accelerator is estimated to be 140W at 4.2 K. It should be pointed out that if operation is less than 24 hours a day, liquid Helium can be accumulated during 'off' time and depleted during 'on' time, thus permitting operation with a considerably smaller refrigerator.

Several linacs employ recirculation: Stanford-SCA, MIT-Bates, Illinois, MAMI at Mainz, and now CEBAF. Recirculation has been incorporated into our proposal in order to reduce physical size and refrigeration requirements. Recirculation also permits bunching of the beam at high energy, by putting a momentum spread on the micropulse and using achromatic but non-isochronous bending optics to compress the beam.[3] This was successfully demonstrated recently on the SCA where a pulse length of 3.1 ps was instrumental in the successful operation of a 0.5 micron FEL.[4] In addition to recirculation for energy gain, two further recirculation passes have been incorporated for energy recovery. Use of energy recovery reduces the RF power required in the accelerator from 115 kW to perhaps 5 kW, which is less than the injector would require. Further, this is a power level at which solid-state sources are quite attractive. Energy recovery also offers the substantial advantage of reducing the energy of the dumped beam from 50 MeV to around 4 MeV, which is below the threshold for neutron production. This greatly reduces the radiation hazard, an important consideration for installation at a user site. Preliminary demonstrations of energy recovery have been made at Los Alamos[5] and on the SCA.[3] Further experiments are planned to demonstrate (1) the stability and control of a high power beam with a small amount of control power, and (2) the ability to handle a degraded beam coming out of the FEL wiggler. This beam has a 1-2% energy spread. One could go to some effort and design the energy recovery recirculation loops with this much acceptance. Alternatively one might convert the energy spread into a temporal spread by means of a non-isochronous ring followed by a suitably phased RF cavity, as shown in Fig. 1 (the energy compensator).

Table 1. Accelerator and FEL Parameters

ELECTRON BEAM			
Energy		20 MeV to 50 MeV	
Average Current		$\leq$ 2.5 mA	
Normalized Emittance		10π mm-mrad	
Micropulse			
	Charge per Bunch	$\leq$ 0.1 nC	
	Duration	2 ps to 200 ps	
	Rep Rate	40 ns	
ACCELERATOR			
Type		Superconducting RF Linac	
Energy Gain		$\leq$ 23 MeV each pass	
Stored RF Energy		40 J	
RF Power Dissipation		140 W	
Cavities		Dual-Cell	Harmonic
	Frequency	500 MHz	1500 MHz
	Length	60 cm	20 cm
	Gradient	7.1 MV/m	6.4 MV/m
	Energy Gain	4.3 MeV	-1.3 MeV
	Q	1×10^9	1×10^9
	R/Q	450 Ω	250 Ω
WIGGLER			
Period		L	2.0 cm
Normalized Vector Potential		a	0.70 rms
Number of Periods		N	50 or 100
Optical Cavity Q			> 100
FEL BEAM			
		Fundamental	3rd Harmonic
Wavelength		10 - 1.5 μ	3.3 - 0.5 μ
Average Power		$\leq$ 1 kW	$\leq$ 300 W
Micropulse Length		2 - 200 ps	2 - 200 ps
Output Peak Power		20 - 0.2 MW	6 - 0.03 MW

The most serious problem with recirculation, whether for energy recovery or acceleration, is the regenerative beam breakup instability. Here a transverse mode deflects a low energy beam in such a way that the recirculated beam amplifies the transverse mode. The use of dual-cell structures serves to reduce this problem. By separating the accelerating structures into several short lengths and putting couplers with loads on the beam pipe adjacent to each cell, both the spatial extent and the Q of the transverse modes can be greatly reduced, compared to conventional long multi-cell structures. Thus the threshold current for the instability is increased. A second approach to the problem, not shown in Fig. 1, is the use of a beam rotator[6] to rotate the recirculated beams by 90° with respect to the first pass beams, eliminating coupling between the recirculated beams and any transverse mode. We believe that 10 mA average current through the accelerator is readily attainable.

The electron pulse structure is largely dictated by the needs of the FEL. The electron beam is pulsed on every 20 RF periods, in order to obtain higher peak currents for given accelerator power. This rep rate corresponds to an optical cavity length of 6 m, a reasonable value. The micropulse duration is flexible and can be varied from 2 ps using bunching to 200 ps using harmonic acceleration (see Figure 2). The micropulse train can be gated as desired to form a macropulse. A lower limit on the macropulse length is given by the rise time of the FEL, which is expected to be of the order of 10 μs.

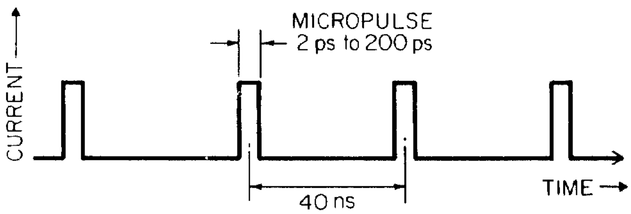

Figure 2.

FEL

The wiggler in this proposal is a permanent magnet linear wiggler with period 2 cm and normalized vector potential $a_w = 0.7$ rms. It is a modular design that could be configured with either 50 or 100 periods, and adjustable taper, allowing for some degrees of freedom in trading off small-signal gain for efficiency and output power. Electron beam energies from 20 to 50 MeV yield FEL radiation from 10 μ to 1.5 μ. Third harmonic FEL operation would permit lasing down to 0.5 μ. Different sets of mirrors are required in order to span the wavelength range.

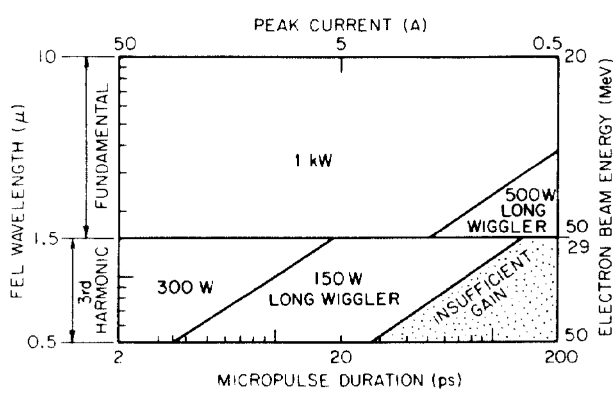

Figure 3. **FEL PARAMETER SPACE**

Parameter Space

The parameter space for operation of our device is principally characterized by FEL wavelength (or beam energy) and pulse duration (or peak power). There are other adjustable parameters: one can reduce the FEL efficiency or impose a macropulse structure, but these are relatively uninteresting. The wavelength chosen depends directly on the user's application. Regarding pulse duration, some experiments demand high peak power or very short pulse length; here the ability to go to short pulses is important. For other applications low peak power (optical fiber transmission) or narrow linewidth may be desirable; these are two important reasons to be able to go to relatively long pulses.

It should be stressed that while our system does have considerable flexibility, there are some limitations. Not all combinations of parameters are attainable. First, long pulses mean low peak current, which may be below the threshold for oscillation at short wavelength. For some wavelengths, long pulse operation may require a long wiggler with lower efficiency, and for even shorter wavelengths long pulse operation may be impossible. Second, long pulse high effiency FEL operation (at long wavelengths of course) means that the electron beam emerging from the wiggler has both large energy spread and large phase extent; in this case the energy compensator discussed above is ineffective. Third, FEL operation at the third harmonic is expected to have lower efficiency than at the fundamental, resulting in time average laser power of a few hundred watts rather than a kilowatt. Fourth, a slippage problem exists at long wavelength and short pulse length. 10 micron 2ps operation is marginally attainable. These limitations on the parameter space are shown in Figure 3.

Conclusion

We have sought to convince the community that there is a tremendous untapped potential in the FEL machines that can be built with present-day technology, and that a flexible and compact machine such as we have outlined above is worthy of a full-fledged design study.

References

[1] C. Benvenuti, et al., Proc. 2nd Workshop on RF Superconductivity, p. 25, Geneva (Nov. 1984).

[2] T. I. Smith, Proc. 1986 Linac Conference, p. 421, SLAC-303 (1986).

[3] T. I. Smith, et al., Proc. 1986 International FEL Conference, Glasgow, to be published.

[4] J. Edighoffer, et al., at this conference.

[5] D. Feldman, et al., Proc. 1986 International FEL Conference, Glasgow, to be published.

[6] R. E. Rand and T. I. Smith, Particle Accelerators 11, 1 (1980); also R. E. Rand, Recirculating Electron Accelerators, p. 177, Harwood Publishers (London) 1984.