HIGH CURRENT RF ACCELERATOR FOR FEL APPLICATIONS

D. Price, G. Frazier, R. Miller,* and R. Genuario**
Physics International Company
2700 Merced Street,
San Leandro, CA 94577

*Stanford Linear Accelerator Center, Stanford University, CA
**Brobeck Corporation, Berkeley, CA 94710

Sponsored by SDIO-DEW through the Office of Naval Research Code 126 on contract N00014-88-C-0267.

Introduction

The feasibility of basing free electron lasers in space depends upon reducing the size and weight of all system components to manageable levels. Two of the largest and most complex subsystems in any FEL concept are the accelerator and wiggler. Improvements in these two subsystems can provide a very high payoff.

Only two types of accelerators hold promise for high power FELs: the induction linac[1] and the rf accelerator.[2] Both types can produce the high quality (i.e., high brightness and monoenergetic), high voltage (of order 100 to 200 MeV) electron beams needed to drive the FEL wigglers.

Of these two, the induction linac concepts suffer size disadvantages because they are designed with relatively low accelerating field, "real estate" gradients and often use very heavy magnetic materials in acceleration cavities. Their advantage over most rf accelerator concepts is that they produce higher currents. These higher currents (of order a few kiloamps) can simplify the FEL wiggler subsystem by allowing it to operate as a single pass amplifier. At the lower currents typical of existing rf accelerator concepts, the wiggler must be configured as a master oscillator that requires a large and complex ring resonator and either grazing incidence optics or gas lenses.

If an rf accelerator can produce currents similar to an induction linac (i.e., 1 to 2 kA) while retaining the high brightness characteristic of rf devices, then the best features of both accelerator types can be combined. The high current rf linac (HCRF) concept proposed here has such advantages. The principal advantage is reduced system weight and volume. Another advantage is that cryogenics are not required. All other space-based rf concepts being considered today use superconducting technology to achieve high real estate gradients. We will show in this paper that the HCRF concept promises to achieve an average gradient of order 20 MV/m using standard conductors and low Q cavities. Therefore, relatively "low technology," robust construction techniques can be used for the accelerator. Risk is reduced accordingly.

The HCRF design is described in the next section. Initial analysis of two critical issues, accelerator efficiency and beam quality, are treated in the sections following. The concept uses high peak power (approximately 10 GW) microwaves to drive low Q rf cavities. The beam loading fraction will be near 95%. This permits some sacrifice of the shunt impedance, allowing the apertures to be large so that the beam is relatively immune to wake-field disturbances. The cavities are designed to selectively damp modes that lead to transverse beam-break up (BBU) instabilities in the accelerator. The high power microwaves (HPM) will be generated in external devices such as phase stable klystron amplifiers driven by relativistic electron beams (REBs). A parallel, lower voltage (approximately 1 MeV) accelerator will produce the REBs to drive the HPM devices. The HCRF accelerator will produce a 200 MeV FEL quality electron beam with 1500 2 kA, 50 ps micropulses contained in 50 A (average current), 3 μs macropulses that are repeated every 300 μs (PRF = 3.3 kHz). Average electron beam power into the wiggler will be 100 MW and overall duty factor is 2.5×10^{-4}.

HCRF Linac Concept: Motivation and Design Parameters

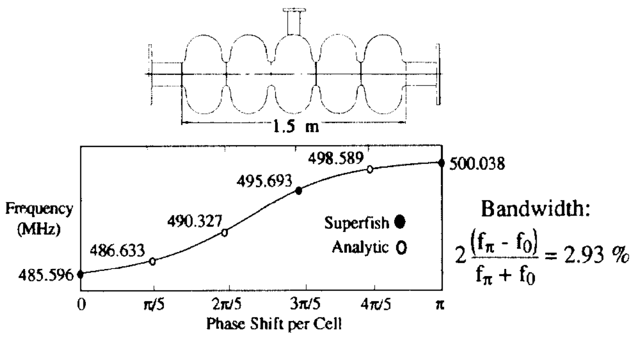
Most space-based free electron laser concepts employ superconducting rf accelerators driving wigglers that are configured as master oscillators. Superconducting rf accelerators have higher real estate gradients than their conventional room temperature counterparts but are limited to rather low average currents in the macropulse because of transverse beam instabilities.

The transverse instabilities are proportional to the loaded Q for the transverse modes. In general, the higher the Q for the fundamental mode, the higher the Q will be for the transverse modes, and the more difficult the problem of suppressing transverse instabilities. The peak micropulse current in high Q superconducting rf accelerators is limited by single bunch wake-field effects. The longitudinal, axisymmetric wake-field causes energy spread and loss, and the transverse dipole fields degrade emittance, and threaten beam propagation through the accelerator. Wake-field effects are a strong function of the fundamental driving frequency and depend superlinearly on the inverse of the aperture size. Wake-field effects limit the micropulse current to a few hundred amps in standard designs with a fundamental driving frequency of 500 MHz. Beam breakup instabilities limit the average current during the macropulse to a few amperes.

Lawrence Livermore National Laboratories and NRL have developed a theory and experiment for alternate wiggler configurations that are designed to operate as high gain single pass amplifiers.[3] These configurations require high peak currents in the micropulse. Currents on the order of 2 kA are optimal to achieve high extraction efficiency and suitable guidance control of the optical pulse within the FEL wiggler. In the past, only induction accelerators were thought capable of generating the high peak micropulse currents required for the high gain single pass wiggler. However, induction accelerators have very low real estate gradients (on the order of less than 1 MV/m), and are relatively heavy and large. The challenge is to achieve high peak micropulse currents with a compact (high accelerating field gradient), room temperature, rf accelerator design that avoids longitudinal energy spread and emittance degradation during acceleration, and that efficiently converts rf to electron beam energy.

The HCRF accelerator concept promises to answer this challenge by using high peak power pulsed rf sources to drive a standing wave rf structure. The HCRF operates at room temperature and employs low Q cavities. Transverse instabilities are suppressed with damping probes and a segmented cavity design to spoil the Q for dangerous modes. Large apertures are possible since the high beam loading makes the accelerator relatively insensitive to shunt impedance. Hence, wake-field effects are reduced sufficiently at a fundamental driving frequency of 500 MHz to make acceleration of 2 kA or more current in the micropulse without emittance degradation or energy spread likely.

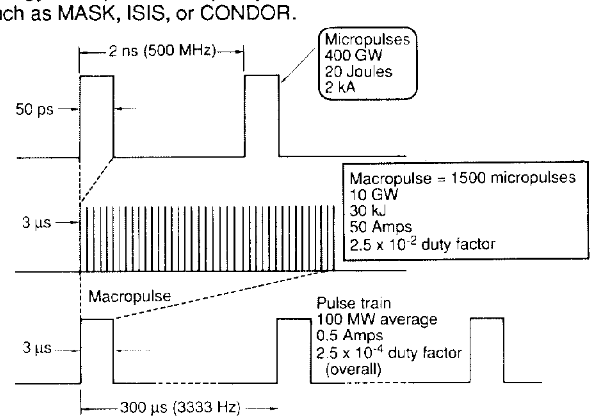
The 5-cell, 500 MHz, center fed, HCRF accelerating section (Fig. 1) is a modification of a CERN SC design. The principal modifications are the center cell coupling and an increase of the aperture radius to 10 cm. Initial SUPERFISH analysis shows that the bandwidth of this structure is 2.93%, yielding suitable separation between the longitudinal normal modes (Fig. 1). The radius of the beam tube separating individual sections will be less than 10 cm to provide space for strong focusing quadrupoles and to cut-off the backward travelling wave associated with regenerative beam breakup.



1. A single 5-cell, 500 MHz, HCRF accelerating section and SUPERFISH calculation of π-mode frequency and bandwidth.

The injector design for the present HCRF concept is based upon recent work on high brightness, high current electron guns at Los Alamos National Laboratories[5] and Thermo Electron Corporation. Basically, a low power laser is used to irradiate a suitable photocathode (CsK_2Sb) that can provide more than 800 A/cm^2 of emitted current density. The beam is emitted in an rf accelerating cavity which has peak surface fields of 58 MV/m. The low power laser is Q-switched and mode-locked to the rf accelerating power train; it can also serve as the seed laser for the wiggler for some geometries.

The injector produces a 50 ps micropulse that contains a charge of 10^{-7} C in an area of ~ 1 cm^2. (The current state-of-the-art is ~ 10^{-8} in 22 ps[3], however, the physical limit with an on-axis accelerating gradient of E_g = 20 MV/m and a beam radius of r_b = 1.4 cm is: $(\varepsilon_0 E_g)\pi r_b^2 = 10^{-7}$ C.) A micropulse is generated at every rf period. Using 500 MHz rf frequency and filling every rf bucket gives the train of micropulses shown in Fig. 2, repeating every 2 ns for the 3 µs duration of the macropulse. The rf energy that the beam extracts from the injector accelerating cavity is not a large fraction of the stored energy. Output beam quality must be estimated with design codes such as MASK, ISIS, or CONDOR.



2. 200 MeV Electron Beam pulse format for HCRF.

The accelerating cavities provide the final energy amplification. The endpoint energy is 200 MeV and the peak current in each 50 ps micropulse is 2 kA. To obtain the desired average electron beam power, the macropulse is repeated at the required frequency. For 100 MW average power in the electron beam and a 200 MeV endpoint energy, one needs an average current of 0.5 amp. This is achieved by repeating the micropulse train with the characteristics of Fig. 2 at a repetition rate of 3.3 kHz. A summary of these parameters is given in Table 1.

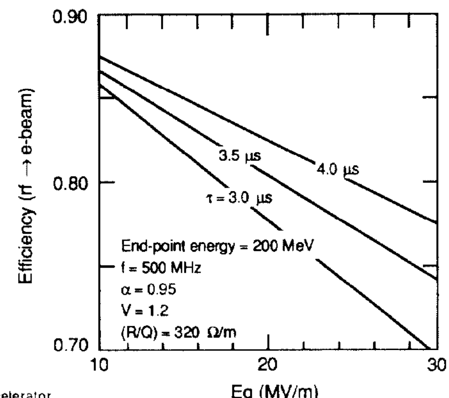
TABLE 1: Summary of Fundamental Beam Parameters: Average electron beam power, 100 MW

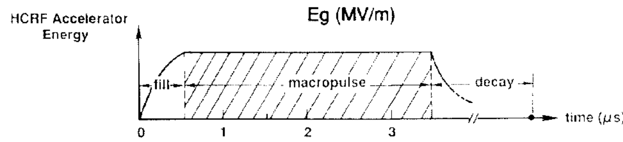
- Voltage = 200 MeV
- Peak Micropulse Current = 2 kA
- Average Current in Macropulse = 50 A
- Input RF Frequency = 500 MHz
- Repetition Rate = 3.3 kHz (3 µs macropulse duration)
- Duty Factor = 2.5 x 10^{-4}

The high power microwave source that powers the accelerator cavities furnishes rf energy at a rate sufficient to maintain a 10 GW average beam power for the full 3 µs macropulse. For 90 to 95% beam loading, a single source or group of phase locked devices supplying approximately 11 to 12 GW with a pulsewidth of 3.5 µs coupled into a low-loss waveguide network, can power such a beam. At an accelerator gradient of 20 MV/m, the rf source ensemble must provide approximately 1 GW per meter of accelerator length. We are currently investigating a high efficiency concept based on a series configuration of klystrons with beam reacceleration between each stage.

Accelerator Efficiency

In order to sustain high gradients and to efficiently convert rf to beam kinetic energy to provide this power while keeping the wall losses in the room temperature HCRF cavity structure manageable, the beam loading (i.e., the fraction of stored rf energy taken out by the beam) must be > 90%. Results of an initial point design analysis are given in Fig. 3.





Channels	RF Energy (kJ)	
Output e-beam	30	eff = $\frac{30}{30 + 4 + 1.5 + 1.0}$ = 82%
Stored	4	
Wall Load	1.5	
Fill time mismatch	1.0	

Accelerator Parameters

Beam power during macropulse = 10^{10}W
(Avg. beam power 100 MW for 100 seconds)

Input Parameters:		
Gradient	E_g = 20 MV/m	
Frequency	f = 500 MHz	
Pulse length	τ_0 = 3.5 µs	
Accel. length	L = 10 m	
Output Parameters:		SUPERFISH Output:
VSWR (beam on)	VSWR = 1.2	
Beam loading fraction	α = 0.95	
Shunt impedance	R/Q = 320 Ω/m*	R/Q = 296 Ω/m
Stored RF energy	U = 3.98 kJ	3.87 kJ
Minimum intrinsic Q	Q_0 = 2.375 (10^4)	3.8 (10^4) (Al)
Beam Q	Q_b = 1.25 (10^3)	
CW wall losses	$\langle P \rangle_{wall}$ = 526 kW/m	

*Longitudinal shunt impedance scaled from CEBAF design [H. A. Grunder, et al., "The Continuous Electron Beam Accelerator Facility," IEEE Particle Accelerator Conference, Washington, DC, p. 13 (1987)] $(R/Q)_{CEBAF}$ = 960, 1497 MHz.

3. Point design parameters and parametric dependence of efficiency on gradient and rf pulse duration.

The efficiency is the product of: 1) the beam loading fraction, 2) the ratio of the duration of the accelerating phase (total rf pulse duration minus the fill time) to the total rf pulse duration, and 3) the transmitted to incident rf power ratio. With this definition the efficiency scales directly with both the beam loading and the rf pulse duration. The optimal VSWR is 1.2. Values of efficiency greater than 90% appear feasible. With an assumed shunt impedance of R/Q = 320 Ω/m, and a beam loading fraction of 95%, the intrinsic Q value is 23750. Subsequent iterations of this point design will tend toward slightly increased beam loading and rf pulse duration and slightly decreased accelerating gradients in order to reduce the CW wall losses to demonstrated levels (in an 800 MHz accelerator[6]) near 100 kW/m.

Beam Quality and Stability

The intrinsic energy spread of the 50 ps micropulse in the 2 ns period rf is $\Delta\gamma/\gamma \approx 0.3\%$. Energy variation due to wake-field interactions with the fundamental and all higher order modes should be < 2%. This spreading can be effectively suppressed (so that $\Delta\gamma/\gamma < 0.5\%$) by moving the micropulse phase ahead of the rf by ~ 6°.

Efficient FEL operation constrains the energy variation, $\Delta E/E$, from micropulse to micropulse to be < 2%. The demonstrated laser photocathode time jitter and beam current stability already meets this constraint. The issue of realizing a high power microwave source with phase and amplitude stability better than 1% is open.

Initial estimates of the immunity of the HCRF linac design to several varieties of the beam breakup instability are promising. Beam propagation through the structure is not threatened. Strong quadrupole focusing may be required to keep the output beam emittance consistent with FEL requirements.

Regenerative beam breakup is an oscillation due to the interaction of the beam with a backward travelling transverse mode. For a standing wave structure, the critical current (for a continuous beam) above which this instability can be expected is:

$$I_R = \frac{0.25\,\lambda^2 E_g}{Q_\perp L}$$

For the parameters: E_g = 20 MV/m, L = 10 m, γ = 0.6 m and $Q_\perp$ = 100, I_R = 180 A. For a beam pulse of finite length, the starting current is increased by a factor near 2. If the beam tube is too small to allow propagation of the backward wave then the oscillation will be confined to a single acceleration section. In any case, the critical current should be well above the 50 A HCRF macropulse current.

The mechanism for cumulative beam breakup is quite different. In a multi-section pulsed accelerator each section provides a small increase in the amplitude of the beam displacement. The current, I_c, expected to generate about 15 e-fold growths over the accelerator length is I_c = 50 A. This current threshold is just equal to the design macropulse current. Strong focusing can increase this critical current by a factor of two or more.

Summary

The HCRF linac is a fundamentally new accelerator concept for driving space-based FELs. The potential technical advantages of the HCRF linac approach to powering free electron lasers are:

1. Compactness and ruggedness,
2. No cryogenics necessary, and
3. Simpler allowed wiggler configuration.

To achieve these advantages, high power, rf sources capable of delivering 1 GW/m must be available. Promising concepts such as relativistic klystrons are under development now.

The two principal technical milestones for the accelerator to provide this capability will be the successful matching of the high power microwave sources to the standing wave structure, and demonstration of an effective HOM suppression scheme.

Acknowledgements

The authors wish to thank Dr. Vern Smiley, Dr. Robert Behringer, and Lt. Col. Ed Pogue for their help and encouragement in developing the HCRF concept. Helpful guidance on FEL physics and calculations by Dr. William Colson and Dr. Robert Kares is appreciated.

References

[1] R. J. Briggs, D. L. Birx, D.S. Prono, D. Prosnitz, and L. L. Reginato, "Induction Linac-Based FELs," Proceedings of the 1987 IEEE Particle Accelerator Conference, Vol. 1, p. 178, Washington, DC, March 16-19-1987.

[2] S. Penner, "RF Linac Based Free Electron Lasers," Proceedings of the 1987 IEEE Particle Accelerator Conference, Vol. 1, p. 183, Washington, DC, March 16-19, 1987.
B. E. Newnam, R. W. Warren, R. L. Sheffield, J. C. Goldstein, and C. A. Brau, Nucl. Instr. & Methods in Phys. Res. A237, 187 (1985).
J. M. Slater, J. L. Adamski, D. C. Quimby, T. L. Churchill, L. Y. Nelson, and R. E. Center, IEEE Journal of Quantum Electronics QE-19, 374 (1983).

[3] P. Sprangle, Cha-Mei Tang, and W. M. Manheimer, "Nonlinear Theory of Free-Electron Lasers and Efficiency Enhancement," Phys Rev. A, Vol. 21, No. 1, January 1980.

[4] P. Bernard, et al., IEEE Trans. Nucl. Sci., Vol. NS-30, No. 4, August 1983.

[5] R. L. Sheffield, et al., "RF Photoelectron Gun Experimental Performance," 1988 Linear Accelerator Conference, Williamsburg, VA, October 3-7, 1988.

[6] J. McKeown, et al., "High Power, On-Axis Coupled Linac Structure," Proceedings of the 1981 Linear Accelerator Conference, Santa Fe, New Mexico, October 19-23, 1987.