CONCEPTUAL DESIGN OF A HIGH CURRENT INJECTOR FOR THE NIST-NRL FREE ELECTRON LASER

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Abstract

The NIST-LANL Racetrack Microtron (RTM) is to be used as a driver for a cw Free-Electron Laser. To achieve the peak currents of 2-4 A required for lasing, 15-ps, 120-keV electron pulses at 66.111 MHz with 7-14 pC per pulse will be accelerated to 5 MeV by the existing injector linac for injection into the RTM. The conceptual design of a high current injection system to produce this beam using a pulsed electron gun and sub-harmonic chopping and bunching is described, and the results of PARMELA calculations are presented.

Introduction

The 185-MeV cw Racetrack Microtron (RTM) at NIST, originally intended for nuclear physics research, is being modified to become a driver for a cw Free Electron Laser. It also must still provide low emittance electron beams for a variety of other accelerator physics related experiments, such as channeling and transition radiation, micro-undulators and dosimetry. The principal modification of the RTM consists of changing the 5-MeV injector to provide the diverse beams needed for these new experimental usages.

The present 5 MeV cw injector[1] consists of a 100-keV, 5-mA dc electron gun, followed by fundamental-frequency RF choppers and a buncher. This produces 15-ps, 23-mA electron pulses which are accelerated by two accelerating sections to provide ≈ 3.5-ps, 0.35-pC (.1 A) electron pulses at 2380 MHz (accelerator frequency). The transverse and longitudinal emittance of this electron beam are 0.7 μm (normalized) and 5 keV-degrees respectively, for 95 % of the current. This beam is well suited for some of the intended applications of the RTM, but the peak current, ≈0.1 A, is not high enough to initiate lasing in the FEL. For optimum performance, 2-4 A peak current is needed. Because the RTM is cw, we cannot simply increase the current injected, as this would increase the total average power in the electron beam from the present maximum of 100-150 kW, which is fixed by the amount of RF power available. The solution is to reduce the cw repetition rate of the injected beam while raising the current, keeping the average power in the electron beam fixed. The repetition rate has to be an integral sub-multiple of the accelerating frequency and a multiple of the frequency defined by the round trip optical transit time of the FEL cavity. For the 9.076 m long FEL cavity being built at NIST, this frequency is 16.528 MHz. The repetition rate to take advantage of the maximum available average RF power would be 66.111 MHz, which is 1/36 of the accelerating frequency and 4 times the optical cavity frequency. The goal of the new injector is to provide 5-MeV cw electron beams at these frequencies, 66.111 and 16.528 MHz, at a design emittance of 5 μm (normalized), transverse and 20 keV-degrees, longitudinal. The new injector also must supply cw electron beams similar to the ones provided by the existing injector, and low repetition rate (≈10-10000 Hz) beams for tune-up modes.

To produce such a wide variety of beams, we considered several different types of sources. Laser driven photocathode[2] sources were investigated, but were found to lack the flexibility to provide the many different repetition rates we required. Also, they have not demonstrated sufficient lifetimes and high enough average beam currents to be of practical use for our application. The other types of sources considered use conventional thermionic cathodes and RF chopping and bunching to produce the desired electron beams. Injectors using a variety of combinations of sub-harmonic RF bunching and chopping were modeled and optimized using the computer program PARMELA. The design of the new injector is to use existing injector components where possible to save cost and time.

PARMELA Calculations

The program PARMELA allowed the modeling of the new injector to minimize the space charge effects of the higher current. The starting point was our existing injector. Modifications investigated were different chopped beam lengths, buncher frequency changes and lens strengths. The design requirement of a longitudinal emittance of 20 keV-degrees proved to be the most difficult problem. The PARMELA calculations indicated that this could be best met by using a short pulse (70 ps) from the chopper and only a modest amount of bunching. Using a longer pulse from the chopper with greater bunching introduced unacceptable longitudinal emittance growth due to non-linear space charge effects. The longitudinal charge distribution in the chopped pulse was also found to be important in minimizing emittance growth. Best results were achieved by using a parabolic longitudinal charge distribution.

To meet our design longitudinal and transverse emittance goals, several changes were made in the electron optics. Some were quite simple, such as scaling beam sizes with current and varying lens strengths appropriately. Considerable reduction in emittance growth is achieved by raising the gun voltage from 100 kV to 120 kV. This presented problems, as the existing first accelerator section is a 1.2-MeV gain, tapered-β design, intended for 100 keV injection. However, by reducing the voltage gradient slightly (5%), and changing the beam entrance phase, this problem could be completely compensated. It was also discovered that because of space charge induced longitudinal spreading of the chopped 70-ps beam, an on-frequency buncher did not have sufficient linearity to bunch the beam without increasing the longitudinal emittance. This was solved by changing to a half-frequency buncher. The new buncher is to be operated at significantly higher voltage levels than the existing buncher, as longitudinal space charge effects tend to de-bunch the beam. Also, the higher bunching voltage compensates for the change in accelerator phase mentioned above, which produces less bunching by the first accelerator tank.

Figure 1 shows the PARMELA longitudinal and transverse beam sizes through the injector for 14-pC pulses. Table 1 lists the PARMELA-predicted emittances for the various beams.

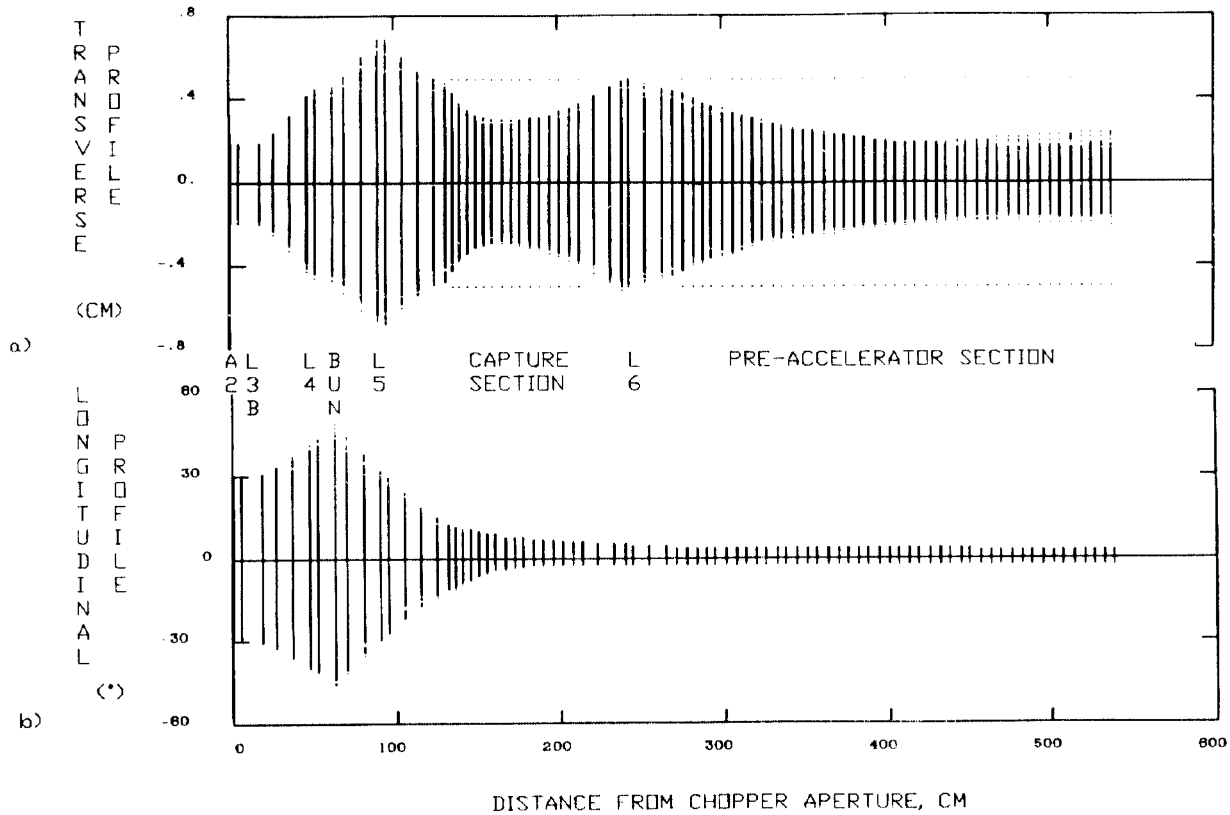


Figure 1. Plots from PARMELA calculations showing (a) transverse beam profile in cm. and (b) longitudinal beam profile in degrees of fundamental frequency, 2380 MHz, for a 14 pC electron pulse as a function of position along the injector beam line from the chopper aperture.

Table 1. Longitudinal and Transverse Emittances for 90 % of beam particles from PARMELA for New Injector.

Charge per Pulse, pC	Transverse Emittance, (Normalized) μm	Longitudinal Emittance, keV-degrees
0.35	1.8	4.7
7	4.4	14
14	5.0	22

New Injector Description

A schematic drawing of the proposed new injector is shown in figure 2. The major differences between the new injector and the existing injector are in the gun, the chopping scheme, and in the buncher. The two accelerating sections remain unchanged, although they are to be operated at slightly different power levels and phases than previously. Most lenses are also the same, and are to be near their original locations. The new injector is to work as follows: A 2-3 ns, 300-mA electron pulse is produced by the gun at 66.111 or 16.528 MHz by the use of a modulating anode or grid. These pulses are chopped to 70 ps by a sub-harmonic chopping system. As in the existing injector, the chopping system is followed by a buncher to compress the beam to 15 ps for injection into the injection linac. The system also has the ability to produce high repetition rate cw electron beams (at 1190 or 2380 MHz) similar to the existing injector.

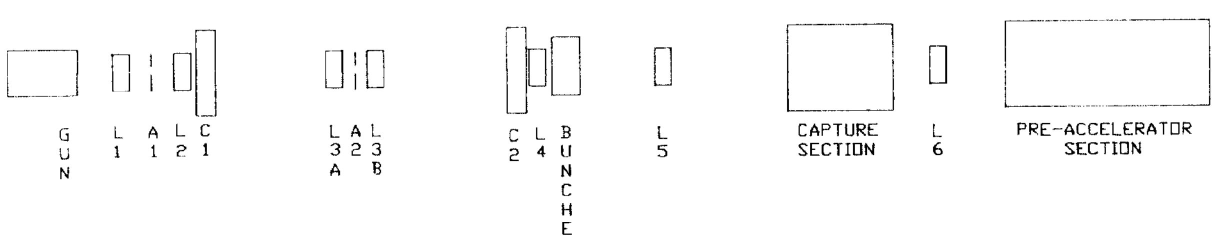


Figure 2. Schematic Representation of proposed injector (not to scale).

Electron Gun

The design emittance is to be less than 1.8 μm normalized at 120 keV with a maximum current output of 300 mA. Pulse synchronism for the 120 kV gun will be provided via optical links from a ground-potential solid-state laser-transmitter. The pulsing system will also have to accommodate low frequency pulsing for tune-up modes, and allow low current (<20 mA) operation for high frequency cw beams. A short pulse is desirable, as it simplifies the chopper system design. Short pulse guns with pulses less than 1 ns have been produced in the past[3], but not at these repetition rates. Provisions will be made to install our existing electron gun in place of the new gun should applications arise that require even lower emittance.

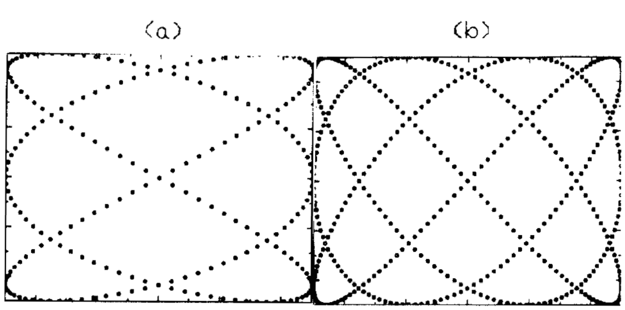
RF Chopping and Bunching System

The final design of the chopping system is dependent on the pulse length from the gun. If a 2-ns pulse is achievable, an RF deflecting cavity with 1/2 (X) and 1/3 (Y) of the fundamental frequency will be used to generate the lissajous figure shown in figure 3a at the chopper aperture location. This figure has a period of 2.5 ns. The lissajous figure shown in figure 3b will be used if the pulse from the gun is as long as 5 ns. This figure is generated by a 1/4 (X) and 1/3 (Y) deflecting cavity. In either case, a centrally located chopper aperture 8 mm in diameter (twice the beam diameter at this point) will subtend 40 degrees of primary-frequency phase. This will serve to approximate the parabolic longitudinal charge distribution used for the PARMELA calculations. A comparison of a parabolic and the actual longitudinal charge distribution is shown in figure 4. The chopped, RF deflected beam then has its deflection cancelled by a second RF deflecting cavity identical to the first cavity. This chopping scheme is similar to that used successfully in the present injector, and in the case of the 1/2 by 1/3 RF deflector is identical to the one used by the University of Illinois[4]. The higher frequency deflection cavities are smaller, and the amount of deflection needed is less, so these cavities are more desirable than the lower frequency cavities. The shorter gun pulse used with the higher frequency cavities also reduces the total power dissipated on the aperture plate. In either case, the beam is next bunched by a half-frequency buncher, and accelerated by the injection linac.

To produce high repetition rate cw electron beams similar to those produced by the existing injector, the 1/3 frequency deflector is turned off and a 5 ma dc beam from the gun will oscillate back and forth in a straight line over the chopper aperture at either 1/2 or 1/4 the fundamental frequency, crossing the aperture twice per oscillation. This yields either 2380 or 1190 MHz chopped electron beam pulses. The RF chopper amplitude is adjusted to yield 70 ps pulses.

In the case of the 2380 MHz beam (produced by the 1/2 by 1/3 chopping scheme), an on-frequency buncher will be added to bunch the beam to 15 ps. For the 1/4 by 1/3 chopping scheme, the 1/2 frequency buncher will be used.

The control circuits for the new RF components will be similar to existing controls. The timing accuracy of these circuits is sufficient for the new system. The timing accuracy needed for the gun pulser is about ± 200 ps, as the chopper selects only a small part of the gun pulse.



Figures 3a and 3b. Lissajous figures generated by sub-harmonic choppers at chopper aperture location. Figure 3a is generated by 1/2 (X) by 1/3 (Y) fundamental frequency chopper, and figure 3b by 1/4 (X) by 1/3 (Y) chopper. In both figures each point represents 10 degrees at the fundamental frequency.

Conclusion

A conceptual design of an injector has been presented that will produce the desired electron beams for FEL and other planned usage of the RTM. The new injector uses conventional, proven technology similar to that used in the present injector, which has operated successfully.

Acknowledgment

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References

[1] M.A. Wilson et al, "Performance of the 5 MeV Injector for the NBS-Los Alamos Racetrack Microtron", in Proceedings of the IEEE 1987 Particle Accelerator Conference, 1987, pp. 322-324.

[2] R.L. Sheffield, "RF Photoelectron Gun Experimental Performance" to be published in Proceedings of the 1988 Linac Conference, 1988.

[3] R.F. Koontz, "One Nanosecond Electron Gun Systems", IEEE Trans. Nucl. Sci., vol. NS-26, pp. 4129-4130, June 1979.

[4] Nuclear Physics Research with a 450 MeV Cascade Microtron, Proposal by the Physics Department of the University of Illinois, Champaign, Illinois, March 1986, pp. IV 13-20.

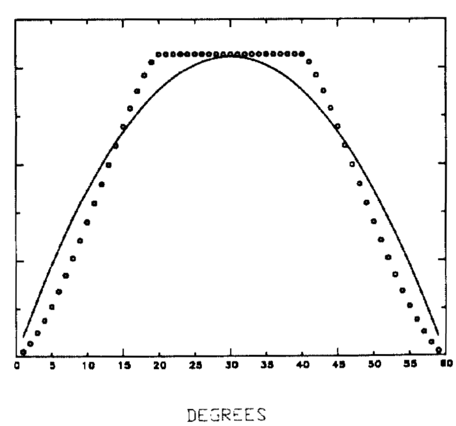

Figure 4. A comparison of the longitudinal charge distribution used in the PARMELA calculations (solid line) and a longitudinal charge distribution produced by a uniform circular beam of diameter D, being chopped by a aperture of diameter 2D (open circles). Both distributions contain the same total charge.