CONCEPTUAL DESIGN OF A BRIGHT ELECTRON INJECTOR BASED ON A LASER-DRIVEN PHOTOCATHODE RF ELECTRON GUN*

S. Chattopadhyay, Y.J. Chen (LLNL), D. Hopkins, K.J. Kim, A. Kung (UCB), R. Miller (SLAC), A. Sessler, T. Young

Lawrence Berkeley Laboratory, University of California, Berkeley CA 94720

Abstract

Conceptual design of a bright electron injector for the 1 GeV high gradient test experiment, envisaged by the LLNL-SLAC-LBL collaboration on the Relativistic Klystron is presented. The design utilizes a high-brightness laser-driven RF photocathode electron gun, similar to the pioneering LANL early studies in concept (different parametrically however), together with achromatic magnetic bunching and transport systems and diagnostics. The design is performed with attention to possible use in an FEL as well. A simple but realistic analytic model including longitudinal and transverse space-charge and RF effects and extensive computer simulation form the basis of the parametric choice for the source. These parameters are used as guides for the design of the pico-second laser system and magnetic bunching section.

Introduction

A preliminary physics design of a bright electron injector based on a laser-driven photocathode RF gun has just been completed at LBL. This work was performed as part of the LLNL-SLAC-LBL collaboration on the Relativistic Klystron. One of the immediate goals of this collaboration is to demonstrate the feasibility of an ultra-compact linear RF accelerator providing "bright" electron beams of 1 GeV in energy and not exceeding 5 meters in length. This is the so-called "1 GeV Test Experiment." This goal is motivated by various interests: (a) high energy physics (linear colliders), (b) compact linear coherent light sources (FELs), (c) propagation of intense bright beams, (d) coherent x-ray holography, etc. The principal components of the experiment would be: (1) an efficient power source (peak power > 500 MW) such as the "relativistic klystron," feeding (2) a high-gradient accelerating structure, injected by (3) a bright electron source. We are concerned with the last component in this report.

The injector beam requirements for the 1 GeV Test Experiment are special, specific to the particular use of induction linacs at LLNL and the chosen frequency of the high-gradient linac. The basic requirement is to provide a 300-600 Amp peak current, low-emittance electron beam within 15 degrees of RF phase in a high-gradient 11.4 GHz linac. There should be at least a few pulses (5-10) in the useful time of 20 nanoseconds or so left after filling the high-gradient structure with microwave power generated with ETA-II pulses (typically 40 nanoseconds long). The required pulse-train characteristics is depicted in Fig. 1.

A comparison of different electron guns, existing or planned is shown in Table I.

Our beam dynamics studies described in the next section indicate that for square bunches, both a 2 ps half-width bunch and a 6 ps half-width bunch with the normalized transverse emittance of roughly 8-15 mm-mrad with 1 nC charge/bunch can be generated by guns with (1) f = 1269 MHz, E_0 = 30 MV/m; (2) f = 1269 MHz, E_0 = 60 MV/m; and (3) f = 2856 MHz, E_0 = 60 MV/m. Here f is the rf frequency, and E_0 the peak accelerating field. Our preliminary physics design has focussed on a (2 + 1/2) cell 1.269 GHz RF cavity with E_0 = 30 MV/m, a 6 ps laser system compatible with cesium-antimonide photocathode surface with a high quantum yield of 1% and a magnetic compression scheme.

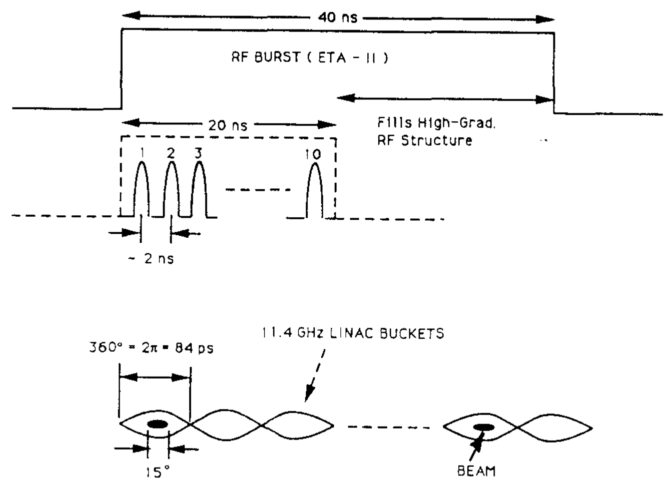

Fig. 1 Required Pulse Train Characteristics for 1-GeV Text Expt.

Table I - Comparison of Different Guns

	Emittance (m-rad) [Normalized $\gamma \sigma_x \sigma_x'$]	Charge (nC)	Bunch Length (psec)
1 GeV experiment (12 GHz)	3 x 10^{-5}	1-2	3.5
SLAC Gun	1.5 x 10^{-4}	12	2500
SLAC Gun after buncher	2-3 x 10^{-4}	12	15
SLAC Gun after mag. compressor	2-3 x 10^{-4}	12	5
LANL RF Gun	0.5-1 x 10^{-5}	5-10	60-70 (now 15)
BNL RF Gun (planned)	3-6 x 10^{-6}	1	3-5
Stanford Microwave	1-10 x 10^{-6}	< 0.1	4

Beam Dynamics

The evolution of the electron beam phase-space distribution in a laser-driven RF gun has been studied by taking into account both the time-variation of the RF field and space-charge effects. A simple analytical model has been developed that provides simple formulae for the transverse and longitudinal emittances at the exit of the gun and agrees reasonably well with the simulation code PARMELA. This is reported elsewhere in these proceedings[1]. In summary, the rf and space-charge contributions to the transverse emittance are given by:

* This work was supported by the Office of Energy Research, Office of Basic Energy Sciences, Department of Energy under Contract No. DE-AC03-76SF00098 and W-7405-ENG-48.

$$\epsilon_x^{rf} = \frac{\alpha k}{\sqrt{2}}\, \sigma_x^2\, (k\sigma_z)^2$$

$$\epsilon_x^{sc} = \frac{1}{2\alpha k} \cdot \frac{\pi}{2} \cdot \frac{1}{\sin\phi_o} \cdot \frac{I}{I_A}\, \mu_x(A)$$

where $\alpha k = eE_o/2mc^2$ is the normalized maximum electric field gradient, σ_x and σ_z are transverse size and length of the electron beam at the cathode, I_A the Alfvén current, I the peak current in the beam, ϕ_o the phase of the laser pulse with respect to the RF pulse as it hits the cathode and $\mu_x(A)$ is a space-charge form factor depending on the beam aspect ratio, A. The sum total emittance of the beam is expected to be given by:

$$\sqrt{\left(\epsilon_x^{sc}\right)^2 + \left(\epsilon_x^{rf}\right)^2} \le \epsilon_x \le \left(\epsilon_x^{sc} + \epsilon_x^{rf}\right)$$

The RF photocathode gun parameters for various scenarios that will satisfy our 1-GeV injector requirments have been obtained by extensive PARMELA simulations[2] and analysis as above. These are listed in Table II. In the following we describe the RF, laser system and magnetic compression design for the case outlined by the second column in Table-II.

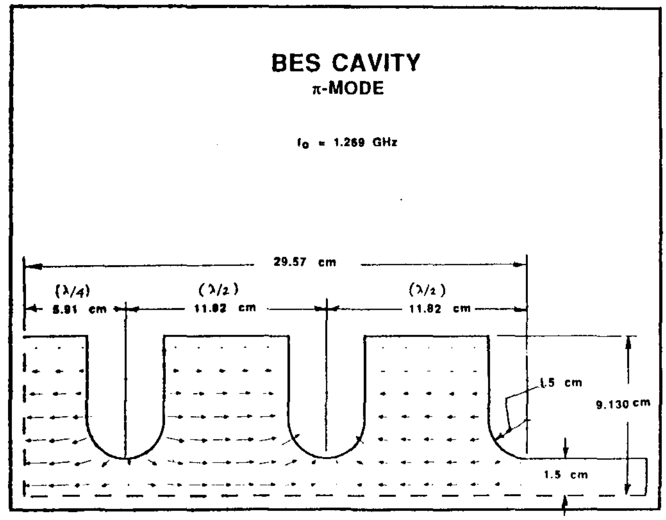

Fig. 2 Electric field distribution in BES cavity.

Table II - Rf Photocathode Gun Parameters

	case 1		case 2		case3	
rf frequency (MHz)	1269		1269		2856	
field on cathode (MV/m)	30		60		60	
optimal injection phase ϕ_o	58°		70°		47°	
laser spot radius* (mm)	3	3	3	3	3	3
laser pulse half width* (ps)	2	6	2	6	2	6
charge per bunch (nC)	1	1	1	1	1	1
peak current (Amp)	133	82	212	118	212	106
emitting r.m.s. ϵ_x (mm-mrad)	0.56	0.56	0.56	0.56	0.56	0.56
normalized ϵ_x at the exit (mm-mrad)	17.43	12.60	13.39	8.30	14.30	9.64
$\delta\epsilon_x/\epsilon_x$ due to 1 ps jitter (%)	20	4.4	20	8.5	11	0.5
beam energy (MeV)	5.0	5.0	10.0	10.0	4.1	4.1
energy jitter (x10^{-4})	4	2	2	2	4	8
energy spread $\Delta\gamma/\gamma$ (%)	0.7	0.6	0.3	0.2	0.5	0.3
exit beam angular divergence x' (mrad)	8.8	8.3	6.0	5.3	13.4	12.1
exit r.m.s. bunch radius (mm)	4.1	3.7	3.0	2.8	3.2	3.0
exit r.m.s. bunch length (mm)	0.8	1.3	0.5	0.9	0.5	1.0

*for a uniform cylindrical laser pulse

RF, Magnetic Compression & Laser Systems

A feasible RF design would involve a 1.269 GHz RF cavity, containing 2 + 1/2 cells, driven in the π-mode configuration externally by a klystron. When driven through the first half-cell, the electric-field configuration would look like as shown in Fig. 2[3] below.

The early design[3] has achieved a ratio of peak to cathode surface maximum electric field of 1.12. A shunt impedance of 13 MΩ/m (ZT^2) is obtained without attempts to optimize it. The maximum field on cathode is 60 MV/m with average fields of 30 MV/m. The exit beam energy would be about 5 MeV. Frequency, amplitude and phase stability, synchronization and beam loading compensation has been looked at and found entirely feasible to implement.

The exiting bunch from the gun would have an rms length of 6 ps and .6% energy spread. The incoherent energy spread is about a quarter of the full coherent energy spread (correlated energy tilt of the bunch) and so one can expect a magnetic bunch compression by a factor of four at best. A possible magnetic compression scheme, providing a path length dispersion $[\partial\ell/\partial(\Delta p/p)]$ of about 2mm/% and achromatic to all orders in principle is shown in Fig. 3. A beam

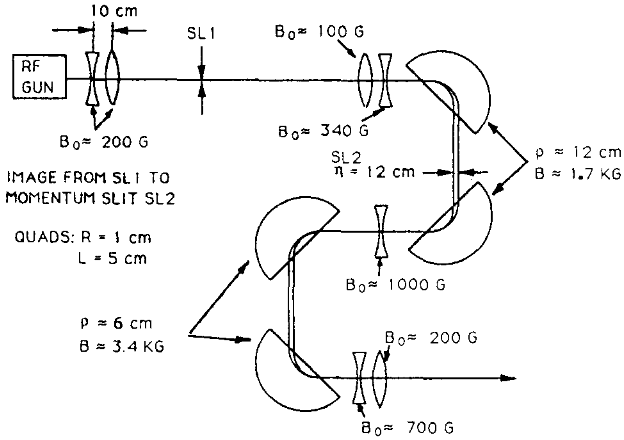

Fig. 3 BES Magnetic Bunch Compressor

with input geometic emittance ($\sigma_x\ \sigma_x'$) of 1 mm-mrad, will go out of the magnetic transport with an output geometric emittance of about 1.5 mm-mrad. It is absolutely essential for achromaticity to avoid optical elements in between the two bending magnets in each 180° bend section.

Another alternative scheme using sector bends and sextupoles and a scheme based on alpha magnets are yet to be explored in detail.

A laser system has been designed[4] starting from a 0.5 μJ/pulse 532 nm Nd-YaG Laser, yielding 2 nC of electron charge per bunch for a Cs_3Sb photocathode surface with a quantum yield of 10^{-2}. The pulses are 15 psec FWHM, preferably square, externally synchronized to the RF driver, with a repetition rate of 423 MHz over a 20 nsec macropulse, repeated at 1-5 Mz with an absolute timing jitter less than a pico-second. The spot size is about 6 mm in diameter. The laser is designed to be diffraction-limited with plane wavefront good for at least 10 m, implying a confocal parameter of $b \simeq 100$ m and a waist spot size of $\omega_0 = 4$ mm @ 1 μm wavelength. The details of the laser design will be reported else where. But it is basically a Nd-YaG CW mode-locked oscillator, followed by a Fiber-grating pulse compressor, regenerative amplifier/pulse selector, frequency doubling by second harmonic generation, pulse multiplexer using multiple mirrors and additional beam optics. The block diagram of the laser system is shown schematically in Fig. 4.

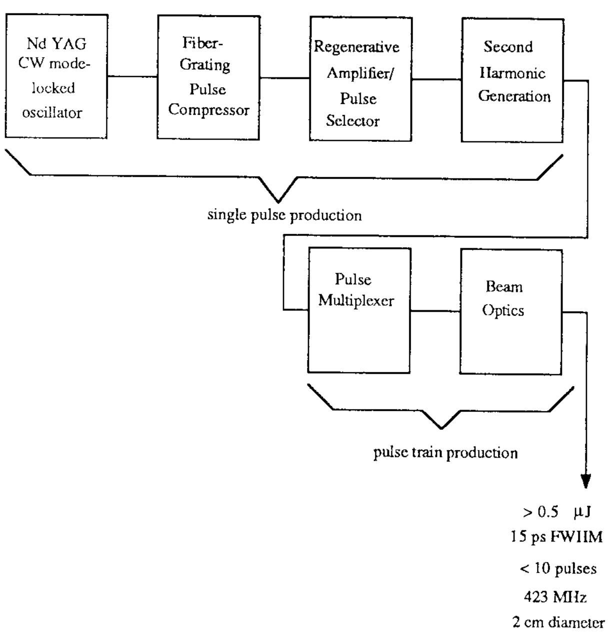

Fig. 4 Block Diagram of Laser Source

Details of the laser system is quite complicated and requires a separate presentation. We show instead a sample layout of the Bright Electron Source, including all its components and associated shielding in Fig. 5. A rough look at cost and schedule indicate that such a facility would take about 2 years to build at an approximate total cost of 5 M$ with 11 Full Time Equivalent of man effort spread over the 2 years.

Conclusion

The basic goals of this preliminary design study have been: (a) understanding the scaling of different parameters for optimization via simple Analytic models and simple computer simulations; (b) independent reexamination of the required laser system and its feasibility; (c) feasibility of the required Magnetic Compression Scheme; (d) survey of photocathodes and the associated surface chemistry; (e) scope and survey of the mechanical, RF and other engineering and hardware issues and (f) broad physics design and feasibility of a Bright Electron Source that satisfies the beam requirements of the 1 GeV Test Experiment. Not addressed in this study are issues regarding detailed optimization, detailed engineering design, extensive parameter search to find the extremes (e.g., long pulse capability (~ 10 μs), higher peak currents (~ 1 kA), lower emittance, etc.), details of the effect of beam distribution e.g., CORE vs. TAILS, detailed photodcathode studies, etc. These will be the subject of the next round of investigations on the Bright Electron Source.

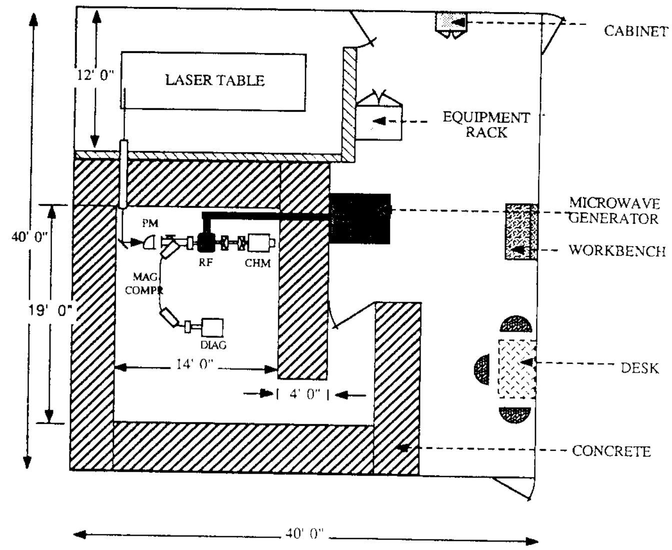

Fig. 5 Sample BES Layout

Acknowledgment

The authors are indebted to Dr. K. McDonald of Princeton Univ. for providing his modified version of the code PARMELA, to Dr. C. Kim of LBL for initial debugging of PARMELA and to Dr. R. Sheffield of LANL for critical discussions at various stages of this work.

References

1. Kwang-Je Kim and Yu-Jiuan Chen, "RF and Space-charge Induced Emittances In Laser-driven RF Guns," these proceedings.

2. Yu-Jiuan Chen, "Simulations of High-Brightness RF Photocathode Guns for LLNL-SLAC-LBL 1 GeV Test Experiment," LBL internal notes BES-11, ESG Tech. Note-86.

3. D.B. Hopkins, "URMEL Studies of Cavity Structure-Interim Report ," LBL internal notes BES 4, ESG Tech Note-74.

4. A.T. Young and A.H. Kung, "Picosecond Laser System," LBL internal note BES-12 and ESG Tech. Note-87.