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Report of the Working Group on Far Field Accelerators

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13. ABSTRACT (*Maximum 200 words*)

This report describes the accomplishments of the Working Group on Far Field Accelerators. In addition to hearing presentations of current research, the group produced designs for "100 MeV" demonstration accelerators, "1 GeV" conceptual accelerators and a small electron beam source. Two of the "100 MeV" designs, an Inverse Free Electron Laser (IFEL) and an Inverse Cerenkov Accelerator (ICA), use the $C0_2$ laser and the 50 MeV linac at the Advanced Test Facility (ATF) at Brookhaven National Laboratory (BNL), requiring only modest changes in the current experimental setups. By upgrading the laser, an ICA design demonstrated 1 GeV acceleration in a gas cell about 50 cm in length. For high average power accelerators, examples based on the IFEL concept were also produced utilizing accelerators driven by high average power FELs. The Working Group also designed a small electron beam source based on the inverse electron cyclotron resonance concept. Accelerators based on the IFEL and ICA may be the first to achieve "100 MeV" and "1 GeV" energy gain demonstration with high accelerating gradients.

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ABSTRACT

This report describes the accomplishments of the Working Group on Far Field Accelerators. In addition to hearing presentations of current research, the group produced designs for "100 MeV" demonstration accelerators, "1 GeV" conceptual accelerators and a small electron beam source. Two of the "100 MeV" designs, an Inverse Free Electron Laser (IFEL) and an Inverse Čerenkov Accelerator (ICA), use the CO_2 laser and the 50 MeV linac at the Advanced Test Facility (ATF) at Brookhaven National Laboratory (BNL), requiring only modest changes in the current experimental setups. By upgrading the laser, an ICA design demonstrated 1 GeV acceleration in a gas cell about 50 cm in length. For high average power accelerators, examples based on the IFEL concept were also produced utilizing accelerators driven by high average power FELs. The Working Group also designed a small electron beam source based on the inverse electron cyclotron resonance concept. Accelerators based on the IFEL and ICA may be the first to achieve "100 MeV" and "1 GeV" energy gain demonstration with high accelerating gradients.

I. INTRODUCTION

Far field laser accelerating schemes utilize electromagnetic fields to accelerate electrons at a distance far from boundaries compared to the radiation wavelength. Two such schemes, which may be the first to achieve a 100 MeV or more energy gain with a high accelerating gradient, are the IFEL and ICA.

The Far Field Working Sessions heard reports on research by the participating members. Most papers described projects utilizing IFELs and ICAs. Some new concepts were presented, including vacuum acceleration without undulators, inverse-Bremsstrahlung electron acceleration and 1 MeV storage ring damped by lasers. Highlights from many of these papers will be outlined below in their appropriate sections.

Members of the Working Group were: W. Barletta, C. Brau, C. Chen, A. S. Fisher, J. R. Fontana, J. C. Gallardo, M. Hussein, W. D. Kimura, T. Marshall, C. Pellegrini, I. Pogorelsky, S. K. Ride, J. Sandweiss, G. Shvets, P. Sprangle, A. van Steenbergen, L. C. Steinhauer, D. Sutter, C. M. Tang, G. Travish and A. A. Varfolomeev

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The working group also spent half of its time designing electron accelerators outlined by D. Sutter of DOE: i) "100 MeV" demonstration, ii) "1 GeV" baseline design and iii) small source for use as injector in existing laser accelerator experiments. The guidelines are: i) to provide a first pass parameter set, ii) to identify major research and development issues and iii) to obtain a rough cost estimate. The working group produced three "100 MeV" demonstration accelerator designs, two "1 GeV" baseline accelerator designs and a small electron beam source design. Since IFEL and ICA experiments on the ATF accelerator are close to demonstrating acceleration, modifications of those experiments to obtain 100 MeV energy gain can be accomplished with a modest budget in a short time.

II. INVERSE ČERENKOV ACCELERATOR

When laser light propagates at an angle with respect to an electron beam, as shown in Fig. 1, there is a component of the electric field in the axial direction. In order to utilize this component of the electric field to accelerate electrons in the axial direction to large energies with little phase slippage, it is necessary to slow the phase velocity of the laser beam to that of the electron velocity by changing the index of refraction, n. This can be accomplished by the introduction of a gas. The phase matching condition is

$$\theta_c = \cos^{-1}(1/n\beta),$$

where $\beta = v/c$, v is the velocity of the electron and θ_c is the Čerenkov angle.

The ICA concept has been demonstrated at Stanford.[1] STI Optronics reported on their ICA experiment[2] at the ATF with an improved laser configuration, which uses a radially polarized annular CO_2 laser beam formed through an axicon. For 100 GW peak laser power and a nominal H_2 gas pressure of 1.7 atm, the energy gain for electrons is predicted to be 38 MeV in 20 cm. STI also addressed the issues of multistaging and electron beam trapping,[3] which are important for large final acceleration energies. This analysis was helpful in assessing the multistaging issue in the working group designs.

A "100 MeV" demonstration experiment based on the ICA concept can be achieved by lengthening the gas cell of the STI experiment and using the existing CO_2 laser and accelerator at the ATF, shown in Fig. 2. Due to the change in β, the ICA requires two acceleration stages, each at the appropriate Čerenkov angle and each roughly 75 cm long. The accelerating gradient is approximately 67 MeV/m for a 50 GW CO_2 laser. The accelerated electrons will have a distribution of energies similar to the existing ICA experiment. More efficient acceleration of the electron bunch is possible using a prebuncher before the ICA cell. This "100 MeV" demonstration experiment can be achieved with low cost and within a short period of time.

A "1 GeV" baseline experiment based on the ICA concept, shown in Fig. 3, has an accelerating gradient of 2 GeV/m. This high gradient is possible with a 1 TW glass laser of wavelength 1 μm. The improvement in the acceleration gradient is due to the shorter wavelength and higher power. Gas breakdown is probably not a problem, even at this high power, because the peak laser power in the axicon configuration is distributed over a large area in a ring around the electron beam. Three acceleration stages are required, each at the appropriate Čerenkov angle, to adjust for the energy gain of the electron beam.

To achieve a few percent energy spread for the accelerated electron beam, a prebuncher has to be installed before the 3-stage ICA. The prebuncher can be a short ICA section (approximately 20 cm length) utilizing a 1 GW glass laser.

III. INVERSE FREE ELECTRON LASER

The field of a laser beam combined with a periodic magnetic field forms a ponderomotive traveling potential. When the phase velocity of the ponderomotive wave, v_{ph}, is matched to the axial electron beam velocity in the wiggler, v_z, electrons can be trapped and accelerated by varying the period and/or amplitude of the magnetic field, i.e.,

$$v_{ph} = \frac{\omega}{k + k_w} = v_z,$$

where ω is the frequency of the laser, $k = \omega/c$ is the wavenumber of the laser, $k_w = 2\pi/\ell_w$ is the wavenumber of the static magnetic field, $v_z/c = \sqrt{1 - 1/\gamma_z^2}$, $\gamma_z^2 = \gamma^2/(1 + a_w^2)$, γ is the relativistic mass factor before entering the magnetic field, $a_w = (eB_w/m_o c^2 k_w)|_{rms}$ is the normalized vector potential of the static magnetic field, ℓ_w is the wavelength of the magnetic field and B_w is the magnitude of the magnetic field. The concept of the IFEL has been experimentally demonstrated[4] and experiments using improved configurations were presented in the working session.

Experimental results of the IFEL auto-accelerator at Columbia University[4] were reported by T. C. Marshall. This is a compact IFEL accelerator, where the radiation source is provided by an FEL. The same electron beam that generated the FEL enters a second wiggler that satisfies the IFEL acceleration condition. The results are in good agreement with simulation. In addition, Columbia proposed an IFEL Beat-Wave Accelerator,[5] in which the IFEL mechanism is used to bunch a dense but low-energy electron beam, and then uses the electric field generated between the bunches to accelerate another higher-energy electron beam.

Brookhaven National Laboratory gave a series of presentations on the development of IFEL experiments at the ATF.[6] The acceleration of electrons is accomplished by decreasing the wavenumber, k_w, of the wiggler. The period of the wiggler is 2.86 cm at the entrance and is increased to 4.32 cm at the exit.

The wiggler is 0.47 m long, with a peak magnetic field of 1.25 T. Computer calculations of a 200 GW CO_2 laser propagating in a low loss dielectric-coated waveguide yield acceleration of electrons to a final energy of 87.95 MeV for electrons injected into the wiggler at an energy of 48.9 MeV.

A B-factory design was presented by C. Pellegrini[7] based on the concept of an FEL driven IFEL. The generation of an FEL was necessary to provide a high average power laser source. Finally, A. A. Varfolomeev[8] presented analytical and numerical calculations on optical guiding effects in an IFEL.

The working group's designs of IFELs are extensions of the presentations. Two different approaches were used utilizing 1) the conventional laser and accelerator at ATF and 2) high average power IFEL accelerators driven by FELs.

A simple modification of BNL's IFEL experiment, lengthening the wiggler to 2 m, can lead to a "100 MeV" demonstration experiment, as shown in Fig. 4. The wiggler is divided into four parts for ease of construction. The parameters of the IFEL with four wiggler sections are listed in Table I. Similar to the "100 MeV" ICA demonstration, the "100 MeV" IFEL demonstration can be accomplished with a modest budget and in a short time.

An extension of the "100 MeV" design to "1 GeV" utilizing conventional lasers was not prepared in detail during the working session, due to time limitations. A guess at the configuration calls for 14 sections of wigglers with a total wiggler length of 8.4 m. The length of the accelerator would be about 10 m. The required laser power would vary with wavelength: i) $\lambda_L = 100\ \mu m$, $P_L = 0.4$ TW, ii) $\lambda_L = 10.2\ \mu m$, $P_L = 1.7$ TW and iii) $\lambda_L = 1\ \mu m$, $P_L = 7$ TW, where λ_L is the laser wavelength and P_L is the laser power required to achieve the acceleration within the designed wiggler length. Due to the large laser power needed, a drive laser would have to be developed. This supports the concept of an FEL as a laser driver of an IFEL.

Working towards a high average power, high gradient accelerator, the UCLA group, headed by C. Pellegrini, proposed to develop IFELs driven by FELs rather than conventional lasers. These examples are similar to the B-factory design.

The parameters and schematic of the "100 MeV" IFEL are shown on the bottom half of Fig. 5. A 15 MeV gun with peak current of 100 A and 10 ps rms pulse length is injected into the undulator. The undulator length is 2 m with a uniform 16 cm period. The peak of the magnetic field increases from 337 G at the entrance to 7.6 kG at the exit. Since the wavelength of the injection laser is preferred to be long, the injected laser wavelength is picked to be 200 μm, and the required laser power is 40 GW. The propagation of the 200 μm laser beam in a 4 mm × 4 mm waveguide will reduce the slippage between the electron pulse and the laser pulse.

Currently, no conventional laser can produce the required power at 200 μm. An FEL is ideal for this purpose. Various conceptual FEL design configurations are possible to achieve the required power, provided the electron beam quality is good. The parameters for an FEL are shown in the top half of Fig. 5.

One example of a "1 GeV" setup, shown in Fig. 6, is achieved by connecting a series of modules similar to the one shown in Fig. 5. The period and amplitude of the magnetic field must be changed to match the accelerated beam energy. The input laser power is increased to 120 GW. The injected electron beam, 100 MeV at 300 A peak, is required to have a pulse length of 3.3 ps rms and an emittance of 3×10^{-6} m.

The FEL driven IFEL conceptual designs still have many issues to be addressed. The energy transfer between the laser beam and the electrons must be optimized. The beam quality requirement and the development of electron beams for the FEL and the injector are important. When $N\lambda \gtrsim \ell_b$, slippage control between the electron pulse and the laser pulse is important in the FEL as well as the IFEL. Here, N is the number of wiggler periods, λ is the wavelength of the laser and ℓ_b is the length of the laser pulse.

The electron beam and the high power FEL necessary to drive the IFEL are conceptually feasible, but require considerable development. The goal of high average accelerated beam power further requires the development of high repetition rate FELs and their drive accelerators.

IV. SMALL ACCELERATOR

An analysis of the scaling laws for the cyclotron resonance laser accelerator (CRLA)[9-12] was presented by C. Chen. The configuration is shown in Fig. 7. The resonance condition is

$$\gamma \left(1 - \frac{\beta_z}{\beta_{ph}}\right) \omega - \Omega_c = 0,$$

where $\Omega_c = eB_z/m_o c$, $\beta_{ph} = \omega/ck_z$. To overcome the dispersion of the laser field, the magnetic field has to be tapered. This mechanism is very simple and applicable to a small electron source.

Utilizing existing microwave and electron beam sources available in many major laboratories, this concept can produce a small electron beam, which may be used, for example, as an injector into other laser accelerators.

Two examples were constructed, based on a 33 GHz, 50 MW rf source in a 200 cm long 3 cm radius waveguide. The electron pulse duration is assumed to be 10 ps.

(i) Electrons can be accelerated from $\gamma = 1.5$ to $\gamma = 8.5$ by tapering the magnetic field from 7 kG to 14 kG. The peak current is 20-200 A with a total number of electrons of 1.2×10^9 -12×10^9.

(ii) Electrons can be accelerated from $\gamma = 3.0$ to $\gamma = 40$ by tapering the magnetic field from 2 kG to 4 kG. The number of electrons accelerated is 1×10^9-2×10^9 corresponding to a peak current of 16A-32 A. The laser energy is depleted by only 0.6%.

The beam would be extracted by magnetic cusp.

V. OTHER FAR FIELD ACCELERATION CONCEPTS

1. Vacuum Acceleration with Laser Field Only

Acceleration of electrons by a laser in free space without additional fields is possible with the appropriate configuration if the interaction length is finite. STI presented calculations based on the axicon configuration[13] originally suggested by D. Sutter. Electrons can be accelerated in a vacuum if the phase slippage between electrons and the light wave can be controlled. STI proposed minimizing the phase slippage by using the short interaction lengths provided by the axicon. High energies are attainable through multistaging.

Another configuration, presented by A. A. Varfolomeev,[14] consists of periodically spaced cavities. The optimal angle between the direction of electron propagation and the resonator axis must be small. Thus, resonator mirrors require holes for the electrons to enter and exit the resonator. Calculations indicated that a stable laser resonator mode is possible with holes, and far field laser driven accelerators without an undulator magnet are possible.

2. Nonlinear Amplification of Inverse-Bremsstrahlung Electron Acceleration (NAIBEA)

Acceleration of electrons with a laser and a small perpendicular static electric field[15] or magnetic field[16] was presented. Calculations of nonlinear equations show acceleration of the resonant electron $\sim$ 150 MeV/m. However, many important issues have not yet been addressed, such as: the trapping efficiency, energy spread and emittance of the trapped beam.

3. Other Presentations

There were a few presentations that did not directly address high gradient acceleration with far fields. Nevertheless, the topics were somewhat related. They were: i) design of 1 MeV storage ring damped by lasers[17] ii) high brilliance, femtosecond x-ray source with FEL assist,[18] iii) SNōELF: a high current injector for CLIC[19] and iv) frequency upshifting in the FELs [20]

VI. SUMMARY

The "100 MeV" demonstrations based on the ICA and IFELs utilizing the accelerator and the CO_2 laser at the ATF require only modest changes of current experimental setups. Thus, the time required for the demonstration would be short and costs would be low.

FEL driven IFELs may be necessary for "1 GeV" illustration experiment, both for single pulse or high repetition rate. There are many physics and design issues yet to be addressed.

The "1 GeV" baseline experiment based on the ICA concept and utilizing the ATF accelerator may be the top candidate for achieving high gradient acceleration ($\sim$ 2 GeV/m) using the laser acceleration concept. The proposed laser power has been reported.[21] Thus, the laser does not require long research development time and the cost would be moderate.

Acknowledgements

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Table I: Preliminary Parameters for A "100 MeV" IFEL Accelerator

Electron Beam	Modules			
	I	II	III	IV
Injection energy [MeV]	49	78	104	127
Exit energy [MeV]	78	104	127	149
Mean accel. gradient [MeV/m]	58	52	46	44
Number of electrons	10^9			
Energy Spread		$\lesssim$ few %		
Normalized emittance [m rad]			$\simeq 2 \times 10^{-5}$	
Wiggler				
Module length [m]	0.5	0.5	0.5	0.5
Period λ_w [cm]	2.86-4.00	4.00-4.85	4.85-5.54	5.54-6.16
Field on axis (constant B_w) [T]	1.25			
Gap [mm]	4			

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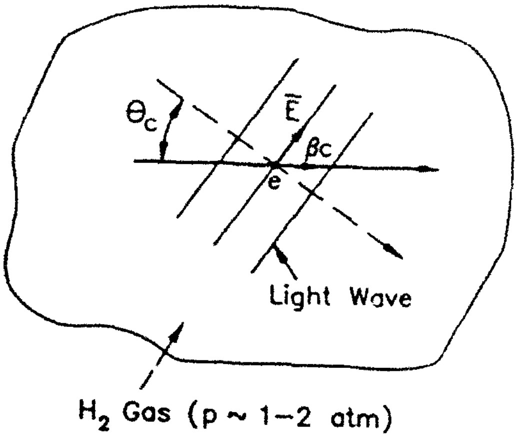

Fig. 1. Schematic illustrating the principle of the ICA concept.

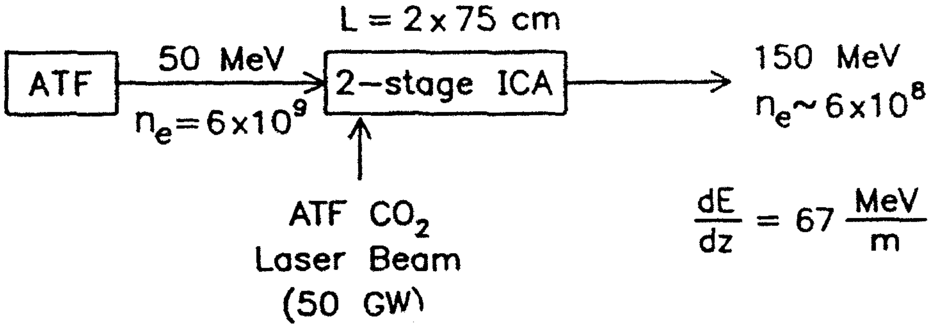

Fig. 2. Schematic of the "100 MeV" demonstration accelerator based on the ICA concept utilizing the CO_2 laser and accelerator at the ATF.

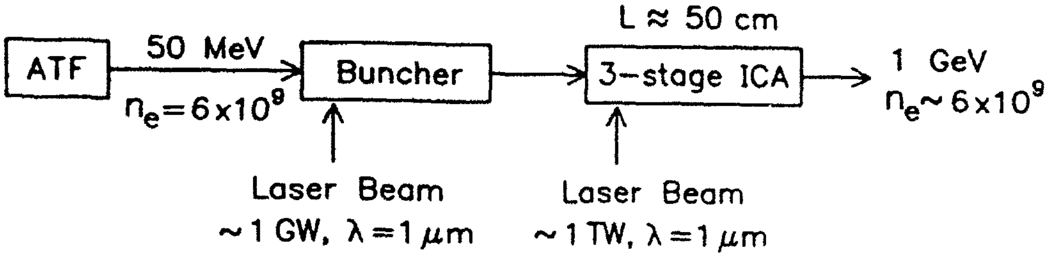

Fig. 3. Schematic of the "1 GeV" accelerator based on the ICA concept utilizing a solid state laser and the accelerator at the ATF.

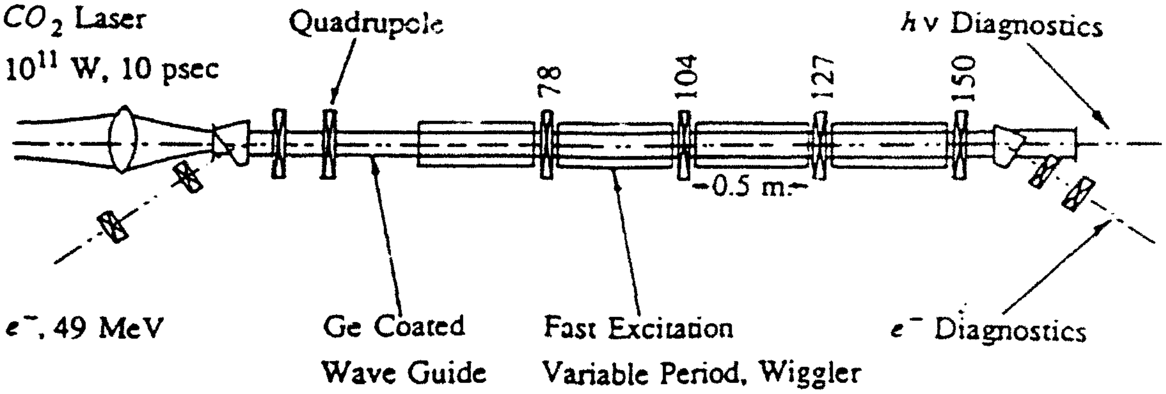

Fig. 4. Schematic of the "100 MeV" demonstration accelerator based on the IFEL concept utilizing the CO_2 laser and accelerator at ATF.

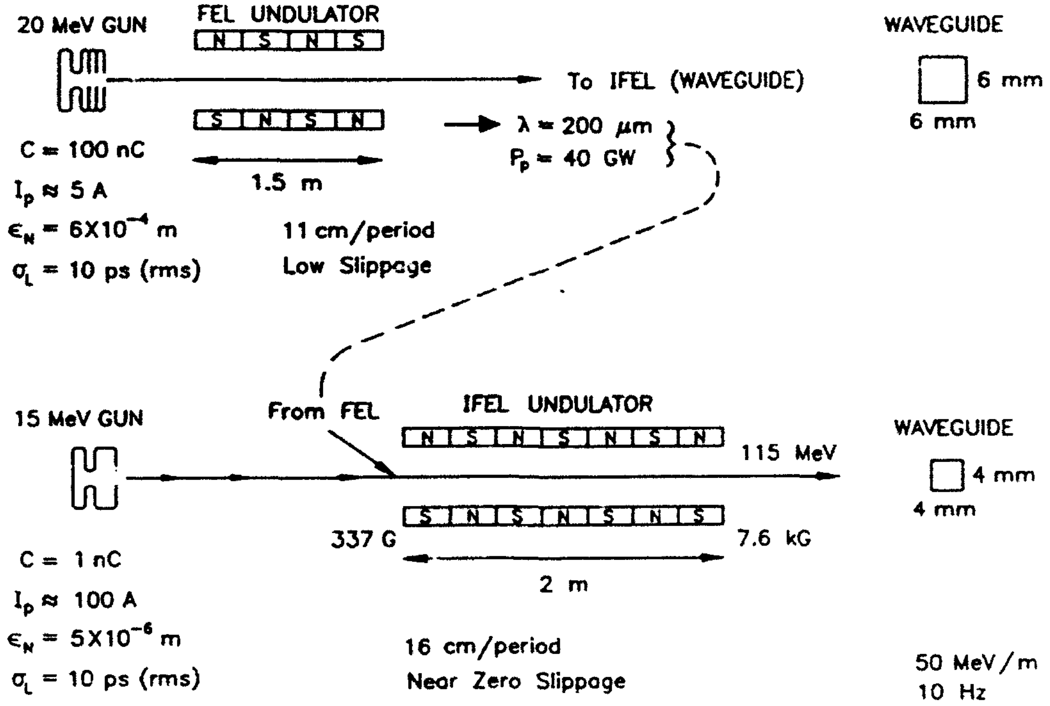

Fig. 5. Schematic of the "100 MeV" demonstration IFEL driven by FEL.

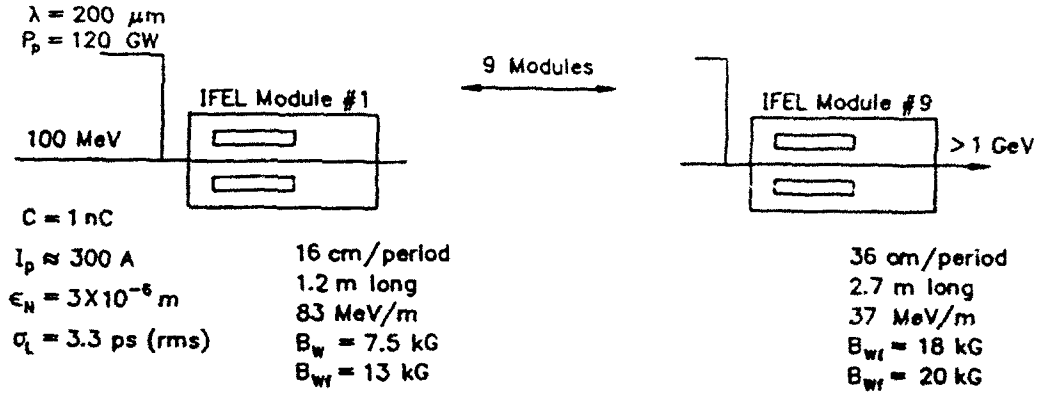

Fig. 6. Schematic of the "1 GeV" IFEL driven by FEL.

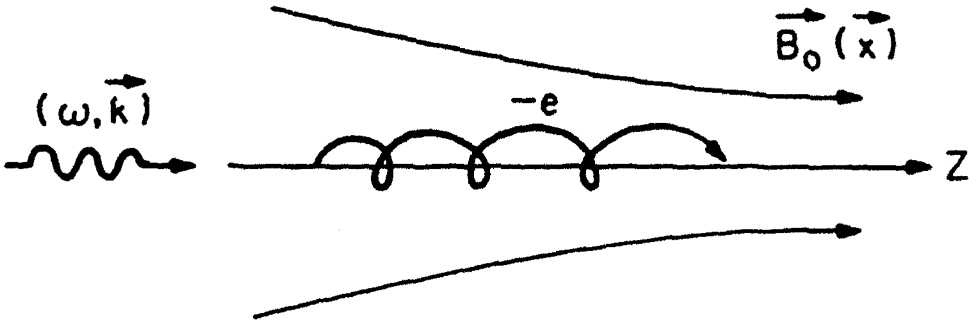

Fig. 7. Schematic of the CRLA concept.