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A High Power CW Electron Beam for FEL Devices

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ABSTRACT

The problems relevant to an accelerator of electrostatic type for a FIR-FEL and a Two-Stage FEL are investigated.

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1-INTRODUCTION

The possibility of producing hundreds of kW tunable and CW radiation in the millimiter-FIR region (Far Infrared Radiation) of the e.m. spectrum is getting increasing attention for the varied scientific and technological applications. A powerful and tunable FIR source would be, indeed, very helpful in condensed matter and molecular system to study the majority of the singular and collective excitations in molecules (1,2). Preliminary experiments, exploiting tunable FIR radiation have been done in Biomedical research (3) and condensed matter (4).

The toroidal plasma heating at the cyclotron frequency is a further important issue of application. In fact, in the new generation of high-field Tokamaks a very high power (MW) 1-0.5mm source could be a good candidate to solve the problem of plasma heating (5,6).

A further interesting application is the use of this generator as a power supply of a high gradient linac (7,8).

The oscillator capable of both high power and wide tuning range (from millimetre to FIR region) is the Free Electron Laser (FEL).

The gyratron, the other high power short-wavelength oscillator, may provide hundreds of kW around 150 GHz but with no frequency tuning (9,10).

For a millimiter-Fir high power FEL the major problem is the electron beam (eb) source. It is required, indeed, a good quality electron beam, a current of about ten Amperes and an energy of a couple of Mev. The requirement of a CW laser demands a continuous eb (11) and, therefore, the electrostatic accelerator is the suitable candidate. The further requirement of high optical power demands high eb power (as well as reasonable extraction efficiency). So far eb power about 200 kW has been achieved with electrostatic accelerators (12). However, larger power can be obtained using the beam-recovery system (13).

In this paper we analyze electrostatic accelerators suitable for CW millimiter-Fir high power FEL operation. We also briefly discuss the laser performances with main emphasis to the efficiency and power output.

2- THE ACCELERATOR

As already stressed the accelerator capable to provide CW, or at least long pulsed, operation is of electrostatic type. Furthermore, among the electrostatic accelerators we need the one that can supply very high power to the high voltage terminal.

To fix the ideas, we say that we need an eb of 20 MW power (i.e. 2

Mev energy-10 A current). Since it is not possible to get such a large power without beam recovery, we must evaluate the efficiency of the recovery system, which is in turn a function of the laser efficiency (i.e. eb power-optical power conversion). This evaluation amounts to the extra power to be supplied by the high voltage generator to the high voltage terminal to compensate the overall losses.

The conversion and the recovery efficiencies are correlated: the higher is the conversion (which in turn leads to higher energy spread) the poorer is the recovery efficiency. To give an example, in the UCSB-FEL experiment the recovery efficiency was 0.994 (14) with the laser off and 0.95 with the laser on (15,16), being the energy spread $\Delta\gamma/\gamma$ induced by the FEL interaction 0.3% . Just to fix numbers, we assume that the total power losses (including laser conversion ad eb recovery), amounts to 2%. Thus with our numbers a fresh power of 400 kW has to be added to the circulating electron beam, that is a current of 0.2 A has to be supplied to a 2 Mev terminal.

We analyze now the electrostatic accelerators to understand their capability to accomplish our requirements of both high eb power and recovery.

The Van De Graaf is in principle unable to provide so large charging current. The rotating pelletron [12] (fig.1) carrying the charges to the high voltage terminal has an upper limit to its mechanical speed (about 15 m/sec). Owing to this limit the current results to be typically 1 mA .

The Cockroft-Walton accelerator (fig.2) with its cascade of generators (voltage multipliers) (12) has the theoretical (and practical) possibility to reach the required high current and high voltage. The point is that this generator (as all those discussed below) operates on electrodynamic principles, unlike the mechanical principle of the Van De Graaf accelerator, thus the limit in the power is imposed by the maximum current allowed by the circuit elements (in particular the rectifiers).

The Dynamitron is again a cascade accelerator of voltage multipliers [17,18] but, unlike the Cockroft-Walton, the capacitors of the several stages are in parallel (fig.3). This means that its operational frequency is typically 100 kHz (one order of magnitude higher than the Cockcroft-Walton frequency) and the capacitances' value is much less. This accelerator seems to preserve the main advantages of the Van De Graaf in compactness and stability of voltage (thanks to the high frequency operation of the system) and of the Cockcroft-Walton machine in its high

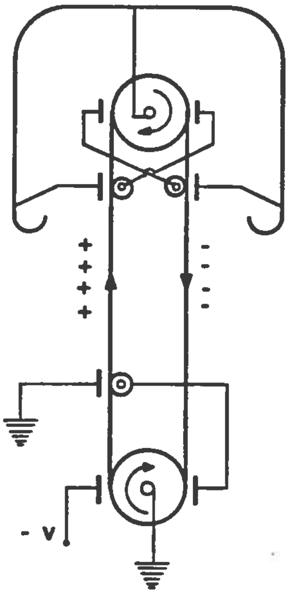

Fig. 1 - Schematic of pelletron charing system of Van de Graaf Accelerator.

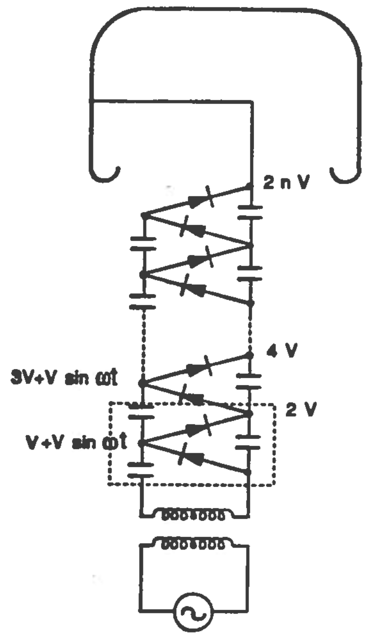

Fig. 2 - Diagram of a Cockcroft-Walton generator. The section inside the dashed line is the voltage doubler stage.

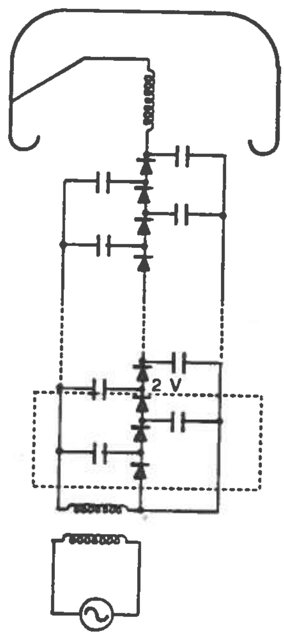

Fig. 3 - Electric scheme of the parallel coupled voltage multiplier circuit-The Dynamitron;the section enclosed inside the dashed line is the voltage double stage.

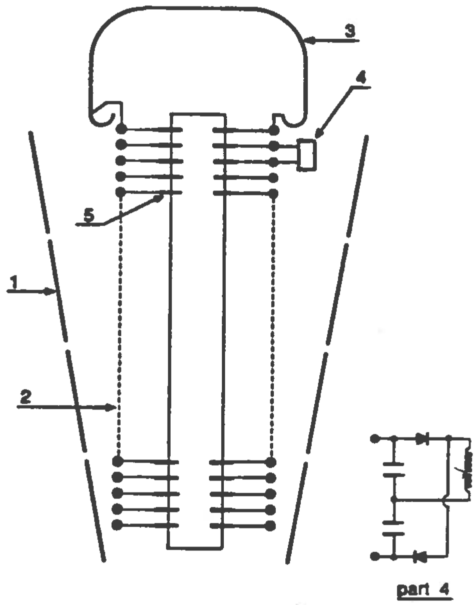

Fig. 4 - Transformer generator scheme. 1-Primary, 2-Secondary, 3-High voltage terminal, 4-Schematic of rectifier circuit applied to any couple of coils (or group of coils), 5-Accelerating tube with the corona rings voltage dividers connected to the secondary.

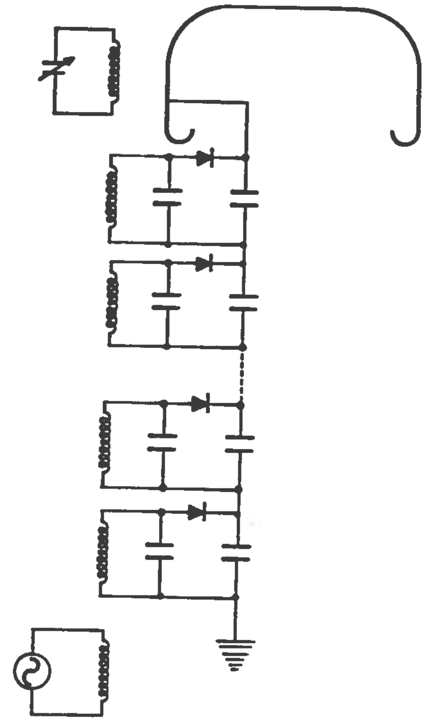

Fig. 5 - Schematic of a Transformer Line Generator.

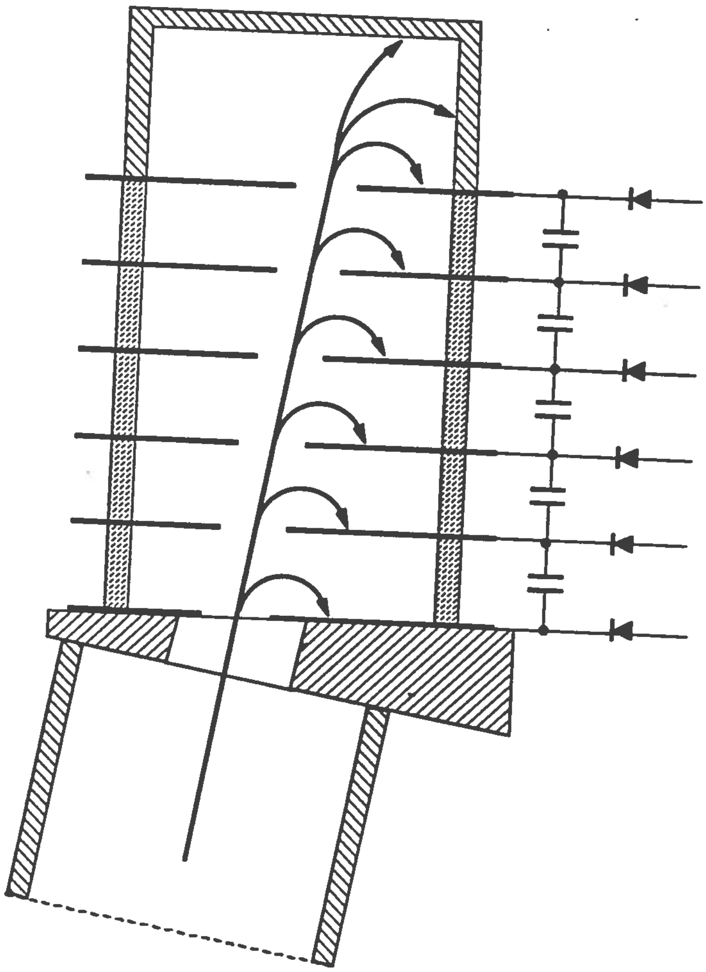

Fig. 6 - Conceptual design of the collector. The voltage at the plates decreases monotonically. The electron beam is titled and enters through small holes to avoid the back return of secondary electrons.

power rating while avoiding the high energy storage of the latter.

The Transformer accelerator [19] (fig.4) is for sure capable to deliver the power we are talking about. In its version built at the Institute of Nuclear Physic in Novosibirsk it has already reached a voltage of 2 Mev and a current higher than 50 mA with enough low ripple at the voltage terminal [20].

In the Transmission Line generator [21,22] the ac power propagates along a column of LC cells, column that behaves like a band-pass delay line (fig.5). The outputs of each stage, rectified, are connected in series.

In these four types of accelerators the energy goes from the low voltage section to the high one via the transferring of an electromagnetic wave through an inductive coupling (Transformer) or a capacitive coupling (Cockcroft-Walton) or an electromagnetic coupling (Transmission Line). With the up-to date technology it is possible to obtain more than 100 mA at a voltage terminal of 2 Mev.

A viable possibility to increase the generator power is by the use of a parallel of many rectifiers and/or using a parallel two high voltage stacks.

The crucial point to get a continuos-high power radiation generator is to have a very high recovery efficiency, 97-99% , also with a return beam having a large energy spread, >0.5%. The accelerators having a stack of stages at increasing voltage (that is all of the cited accelerators except for the Van De Graaf) are suited to accomplish that requirement. In fact, the final portion of the decelerating column (or, at need, all the decelerating column) can be arranged as a multistage collector.

The principle of a multistage collector is to spatially disperse the electrons with different energies and to collect each separated stream of electrons inside a stage (a kind of Faraday Cup) at zero energy (fig.6). In order to have a 100% recovery efficiency the array of collectors should have a continuous voltage distribution and, in addition, the energy dispersion should be very efficient. Practically, the voltage distribution is discrete with a typical step of 2-5 kV and the resolving power of the electrostatic dispersive element obtained tilting the axis of the decelerating column with respect to the electron beam line is of the same order. The effort is to reduce the step to the minimum, to design the collecting stage in such a way that the electrons can enter but not exit (like in a black-body) and, finally, to use a good absorbing material (i.e. a material that favours the entrance of the electrons into its bulk with no secondary emission). It is worth remarking that a Faraday cup collector when used to recover a quasi-monochromatic eb has shown an efficiency equal or better than 99,9% [20].

We want to observe that, in order to avoid any additional energy spread due to transport channel elements (lenses and bending magnets) and to space charge force (which is effective at our current and energy), an accelerator with a guiding solenoidal magnetic field along all the eb path has to be used. Moreover, since the eb spot size, with our eb figures, doubles in one meter in free space, that full immersion scheme could be obliged by the wiggler design. The radius r of an eb at a distance z from its waist of radius a is (23)

(1) $$r(z) = (a/2)(1+\sqrt{1+2Ke\ (z/a)^2})$$

where the perveance Ke is given by

$$Ke = (2/\gamma^3)\ I/I_A$$

Here, I is the current, I_A is the Alfven current (I_A = 17 kA), and we have taken $\beta = v/c = 1$.

The principle of operation of an accelerator with a stack of stages is that some stages are supplied (or at least partially supplied) by the return eb, the others are supplied by the current coming from the power supply. For concreteness, working , for instance, with a Transformer Accelerator this will mean that the coil relevant to the stage supplied by the return eb will not have to feed the capacitors of its own section, but it will convey its energy (coming from the primary) to the next stage.

Anyway, since the interaction of the eb with the FEL spreads out the energy of the eb in a more or less a uniform way (11), it is not possible to collect all the energy of the return eb because of the discreteness of the voltage at the plates.

A proper way to look at the problem is the study of the energy distribution of the eb after the interaction with the FEL and to match the collector plates' voltage distribution to the eb energy distribution.

An important remark on CW laser is that the high voltage terminal is held finely constant by the exact balance between the output and the input power. Therefore, the laser output will be constant in power and frequency. This is figured out from the experiment of ref.16 where the frequency shift together with the power variation have been found related to the terminal voltage dropping (24).

3- A POSSIBLE FEL LAYOUT

The FEL we want to design should have both enough gain to overcome easily the cavity losses and enough efficiency to spill out from the eb around 100 kW.

Assuming a current of 8 A and 2 Mev energy, with a wiggler periods number N = 70 and FEL parameter K = 0.12 the electron beam-optical beam conversion results in about 0.7% and the gain about 20% (see for example the gain formula in ref. 25). This means that the output power should be around 100 kW and recovery efficiency has to be better than 98%. Here we have assumed a fresh power of 400 kW coming from the generator. If the recovery is better we may increase the output power and/or decrease the generator power.

In order to reach the FIR region the wiggler period has to be about 1.5 cm. With the chosen value of K, the magnet field will be around 1.2 kG. The gap distance, thus, ends up to around 1.5 cm and eb diameter, in turn, to 3 mm.

It is worth deserving few lines on the second-stage operation.

The quasi-monochromatic and high power optical beam together with the good eb figures obtainable with these accelerators indicate that the system may be suitable for a second-stage operation (13,26,27,28).

The gain of the FEL with the wave-wiggler provided by the first-stage is given by (26)

$$g \sim 3.7\ 10^{-14}\ N^2 \lambda_p^2\ [\mathrm{cm}]/\gamma^3 \alpha\ P\ f(\sigma_\varepsilon, \varepsilon) \qquad (2)$$

where N and λ_p are the periods number and wavelength of the wave-wiggler respectively, α is the eb "brightness" parameter, P is the pump field power and f is the function that gives the gain dependence on the eb emittance ε and energy spread σ_ε , see refs. 25 and 26.The wavelength is $\lambda = \lambda_p/4\gamma^2$.

It is reasonable to assume for the electron beam an energy spread $\sigma_\varepsilon = 10^{-4}$ and a normalized emittance $\varepsilon_n = 10^{-5}$ mrad (the two transverse emittances $\varepsilon_x, \varepsilon_y$ are taken equal) and a brightness $\alpha = 10^6$. Since the first stage FEL operates in single mode, the frequency bandwidth of the radiation can be assumed $\Delta\omega \sim 10$ MHz; the coherence length of the optical beam results in some meters, which leads to a value of 10^3-10^4 for N in some meters interaction length if the wavelength is λ =0.5-0.1 mm.

The value of the function f in (2) is reasonably around 0.2. Putting the numbers inside the gain formula and assuming a pump wavelength of 0.3 mm we get for the gain

(3) $$g \sim 10^6 \ P \ [MW].$$

If we require a gain >10% we need an optical beam power inside the cavity of 100 kW.

The output power of the up-frequency converted optical beam, roughly estimated with the formula (26)

(4) $$P \sim 10^5 \lambda_p^2 \ [cm]/N$$

is around a Kilowatt.

CONCLUSIONS

A high power CW FEL covering all the FIR-IR e.m. spectrum seems feasible using an electrodynamic accelerator of 2 Mev energy with electron beam recovery.

The last section (or, at need, a portion) of the decelerating column is arranged in a multistage collector fashion.

In the hypothesis of doubling the power of the present-day high voltage generators, that is assuming a power of 400 kW for the voltage generator, and recovery efficiency of 98%, a 100 kW FIR radiation generator can be built. With the up-conversion (second-stage) FEL it is possible to get around 1 kW in the IR region.

The high recovery efficiency is made possible by using a good collector design and, possibly, by using the full-immersion electron beam transport.

Since the quoted efficiency of these accelerators is around 80% (starting from the main) the overall efficiency of this radiation generator should reach interesting values. If a recovery efficiency of 99% could be possible the overall efficiency ought to be around 50%.

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