FELTRON, a microwave source for High Gradient TeV Collider.

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Abstract

FELTRON is a microwave source designed to power the high gradient structure of the TeV Collider. Its features are: 20 GHz, 200 MW, 6 parallel 50 ns long rf beams, a repetition rate greater than 1 kHz and an overall efficiency higher than 60%. A Cockcroft-Walton accelerator drives a multibeam Free Electron Laser.

1 - INTRODUCTION

FELTRON is a new pulsed rf-source of 200 MW-20 GHz, 6 rf- outputs aimed to power 6 meters of 100 MV/m High Gradient Structure of the TeV Collider [1]. It is a multibeam FEL driven by an electrostatic accelerator of the Cockcroft-Walton type, but of novel design [2], see fig.1. The source characteristics match the LINAC requirements of power, frequency, repetition rate, pulse length and number of rf-beams [3].The LINAC must be fed at each meter because of losses. The FEL is designed with 3 channels of 400 MW, each of them is split into 2 outputs. In a previous paper [3] one of the authors has shown that the FEL efficiency can be as high as 70%. This means that the electron beam power, $P_{eb} = V * I$, must be 600 MW. The characteristics of the rf and electron beams are listed in table 1.

TABLE 1
RF &Electron beam characteristics

rf beam			electron beam		
Frequency	20	GHz	eb power	600	MW
Power/m	200	MW	eb numbers	3-5	
Rep Rate	1-2	kHz	current	120	A
Pulse Length/m	50	ns	voltage	5	MV

2- THE NOVEL DESIGN COCKCROFT-WALTON

The accelerator can be thought of as a current compressor: a low current continuous beam is converted into a high current pulsed one, see fig. 2. The low current continuous beam is provided by the Cockcroft-Walton High Voltage Generator shown in fig. 1. The two stacks of concentrated capacitors of the classical design, are substituted by the concentric semi-elepsoid (or something like) volume-air-capacitors, whose plates separation is such as to sustain 300 kV. The generator is discussed in ref [2], here we report only that the "onion" design has the important advantage of shielding the high

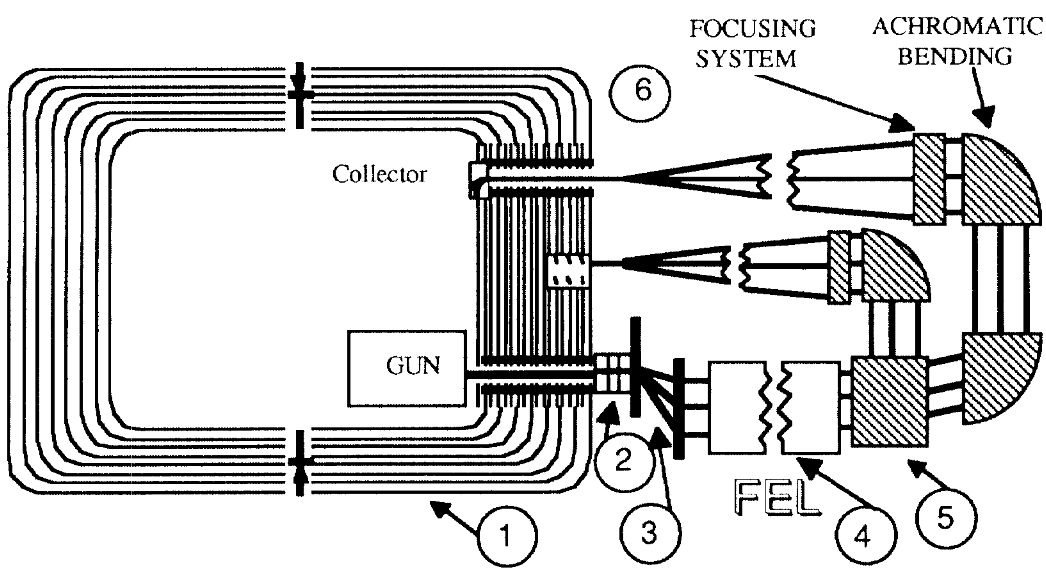

Figure 1. General overview of FELTRON machine. The electron beam is provided by the "onion" Cockcroft-Walton accelerator (1); the 60 kV ramp induction linac (2) shapes the energy of the electron beam; the electron beam is spatially separated into n = 3 pieces by the dispersive system (3); the FEL (4) provides the three 400 MW rf beams; the dispersive system (5) separates the slow and the fast electron beams; a system (6) conveys the three fast beams into the decelerating column for recovery.

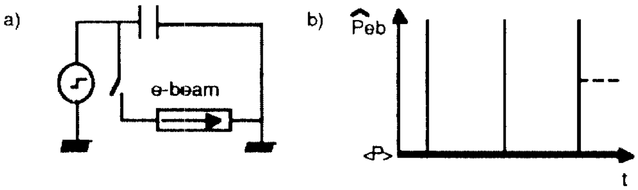

Figure 2. Principle scheme of FELTRON as power compressor: a) the low current generator charges the high voltage capacitor, which, through a pulsed switch, provides the high current; b) the average power <P> is 3 orders of magnitude less than the peak power.

voltage terminal (and parts inside it) from ground. Hence, the flashover risk is greatly reduced. This idea of enclosing the energy in the center of the machine and, furthermore, to hide it to grounds by successive shielding has been successfully implemented in the Vivitron machine [4]. The onion design is especially important with very high voltage. Although FELTRON needs moderately high voltage, the machine is stressed by pulsed operation.
The output voltage V_0 depends on the the number of multiplier stages N and also on the ratio of the capacitance of the column capacitors C and the shunt capacitance C_p

$$V_0 = \sqrt{\frac{C}{C_P}}\, V \tanh\left(2N\sqrt{\frac{C_P}{C}}\right) \qquad (1)$$

In our design the higher the capacitance C, the larger the volume of the machine. A tradeoff between the values of N and C must be chosen. The generator characteristics are listed in table 2.

Table 2
The Cockroft-Walton characteristics

capacitance value	1.5 nF	average current	20	mA
shunt capacitance	~ 1 pF	voltage	5	MW
oscillator voltage	170 kV	average power	100	kW
number stages	20	pulse length	150	ns
frequency	0.5 MHz	peak current	120	A
ripple	1%	discharge drop	200	kV

The value of the capacity leads to a length L > 6 m for the tank. The field strength at 10 lb/inch^2 of SF_6 has been assumed 200 kV/cm. The compact geometry of the two half onions does not affect, with a very good approximation, the shunt capacitance C_p because the field lines leaving a plate end at the two neighboring plates, being the in front plates comparatively too far.
The ripple of the Cockcroft-Walton is of no importance in our project because: a) the pulse length is enough shorter than the frequency period, b) the voltage drop due to the high voltage terminal discharge during the operation is much more relevant. During the discharge the two columns behave substantially as a unique capacitor. The relative voltage variation of the terminal during the pulse discharge results in

$$\frac{\Delta V}{V_0} = \frac{1}{2}\frac{\Delta W}{W_0} \approx 10\% \qquad (2)$$

where $W_0 = (1/2)\, C^* V_0^2$ is the energy stored, C^* is the resultant capacity and $\Delta W = P * t = V * I * t$ is the energy variation of the terminal during the discharge. We have assumed a high voltage terminal capacitance of 100 pF.
The driving oscillator is composed of low voltage oscillator and a resonant LC. The output voltage results in $V_{LC} = 1.27$ V_i Q. Being $V_i \approx 500$ Volts and Q ≈300 (with load, without load it can be estimated around 1500) we can get an output voltage greater than 150 kV. The power can be as high as 60 kW. A parallel of 2 drivers are required.
In order to obtain a set of parallel electron beams, each 50 ns long, a small sawtooth induction linac of 60 kV and 50 ns period is added at the exit of the accelerating column (see figs. 1 and 3). The superposition of the sawtooth voltage to the decaying voltage generates an electron beam with a stepwise energy shape. Two adjacent peaces have an energy difference of 1%. A dispersive system separates them spatially exploiting that energy difference.
The electron gun is of a Field Emission Controlled type [5], so to gate it only during the positive cycle of the sawtooth generator. The usual 2 FAO11060 NEC column is provided with focusing lenses for containing the 120 A beam, see fig.4.

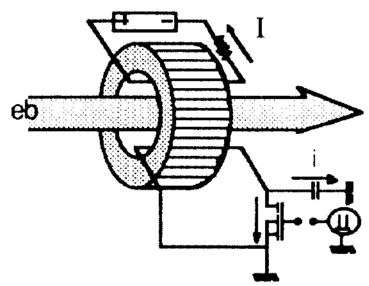

Figure 3. Sketch of the ramp sawtooth induction Linac

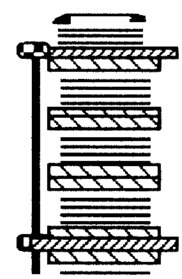

Figure 4. Accelerating column with magnetic lenses with local power supplies.

The recovery of the spent electron beam (eb) has been studied. The eb after the FEL interaction results in an 80% part with a final energy of about 1 MeV and a second 20% part with the initial energy. The two beams are separated and then conveyed into two different decelerating columns and finally collected.The onion design is tailored to the recovery (see fig.1), because the voltage distributed plates are tailored to collect an energy distributed eb.

3- THE FEL.

The FEL Amplifier operates in the high gain+tapered regime. In fact the Pierce parameter ρ [6] is greater than 0.01, that is

$$\rho = 0.00839\, \frac{a_0^{2/3}\, \lambda_0^{2/3}}{\gamma_r} \left(\frac{I}{ah/2}\right)^{1/3} > 0.01 \qquad (3)$$

where a_0 is the wiggler parameter, λ_0 is the wiggler wavelength, γ_r is the beam energy resonance, I is the beam current, a and h are the waveguide dimensions. The efficiency of an FEL operating in the high gain+tapered regime is roughly given by

$$\eta \approx b\, \frac{\gamma_i - \langle\gamma_f\rangle}{\gamma_i - 1} \qquad (4)$$

where b is the bunching coefficient, γ_i is the initial value of the Lorentz factor and $\langle\gamma_f\rangle$ is final value of the bunched part of the electron beam. The bunching is around 80%, γ_f can be around 2 with our eb energy and wiggler design. We recall that the final value of γ is very near to $\gamma_{||}$, the longitudinal Lorentz factor, because the FEL interaction requires that the electron beam travels at the same velocity of the ponderomotive potential. The energy associated with the perpendicular part of the motion is extracted from the eb and transformed into em energy. The tapering is a mean to transfer the transverse energy of the eb into the longitudinal one, so to keep constant $\gamma_{||}$ while the eb is decelerating. The design of the system has been done in such a way to have a large fraction of the eb energy in the transverse part (large transverse velocity $\beta_{\perp}$). The FEL parameters are listed in table. 3.

Table 3
FEL parameters

Energy [MeV]	5.25	Wigg. period [cm]	$\lambda_0 = 10$
Current [A]	120	Gap [cm]	3
Energy Spread	≤ 0.5 %	Peak Field [kG]	$B_0 = 7.5$
Emittance [m rad]	$\varepsilon_n < 10^{-3}$	FEL parameter	$a_0 = 5$
Eb radius [mm]	4	Frequency [GHz]	20
$\gamma_{||}$	2.2	Polarization	planar
Pierce parameter	$\rho \sim 3$ %	Mode	TE_{01}
Wigg. length [m]	9	SSG	$G_0 = 11$
Wigg. type	Hybrid	Waveguide (cm^2)	$a{\cdot}h = 3{*}3$

The FEL has been simulated with a 1-D code based on the set of equations used by the Livermore group [7]. In fig. 5 the diagram shows that the output rf power is 420 MW.

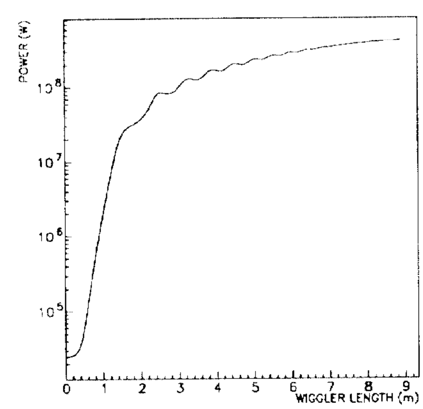

Figure 5. rf power down the wiggler .

The multibeam FEL is obtained separating a unique eb into several pieces. Each electron beam travels inside its own waveguide. The FEL is composed of a unique wiggler with a set of parallel waveguides attached one another as in fig. 6.
The ponderomotive force would have been completely counteracted by the space charge force without the effect of the waveguide wall. This effect has been accounted for in the motion equations multiplying the space charge force by a reducing factor obtained solving the Maxwell equations with the boundary conditions [8].

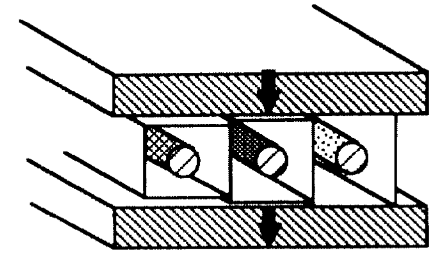

Figure 6. Schematic of the three beams FEL with a unique wiggler. The three waveguide heights are different in order to match the requirement of the synchronism condition with different γ.

The FEL efficiency is further increased by recovering the spent eb. It is by definition

$$\eta_{FEL} = \frac{P_{RF}}{P_{eb} - P_{recovery}} = \frac{1}{1 + P_{loss} / P_{RF}} \quad (5)$$

The energy spread of the fast and slow eb after the FEL interaction are $\Delta\gamma/\gamma = \rho$, that is $\Delta E \approx 200$ KeV. Assuming that the eb is collected at 200 KeV, $P_{loss} \approx 25$ MW (at the peak). From eq. 5, the efficiency results in 95%. Since the accelerator efficiency can be estimated 80%, the overall efficiency would be about 75%.

4- CONCLUSIONS

FELTRON ought to be a viable rf-source for powering a 20 GHz LINAC operating at an accelerating field of 100 MV/m. The onion Cockcroft-Walton Generator has a design to operate in a pulsed mode and with a stair-shape energy electron beam.
A 3 beams FEL has a hybrid wiggler, 20 cm wide, with a set of 3 parallel rectangular waveguide. Each FEL channel should deliver 400 MW rf power with an extraction efficiency of 70%. That power is then split into two parts. The overall efficiency can reach a value of 75% recovering the spent electron beam.

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