A HIGH POWER CW MM-THZ WAVE SOURCE BASED ON ELECTROSTATIC ACCELERATOR FEL

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Abstract

Lots of applications with mm wave need very high power (from tens of kW to MW), such as surface processing of metals and ceramics, heating magnetically confined plasma in thermonuclear fusion reactors, isotope separation and so on. Recently developed gyrotrons can provide up to 1 MW CW mm-wave source, however there are a number of limitations, needs of supper conducting magnet, cathode lifetime degradation because of very high current, almost approaching the upper limit of their power and frequency capabilities, and so on. It is thought that the electrostatic accelerator FEL (EA-FEL) will be a promising high power IR-mm source, because of its high average power generation, high-energy conversion efficiency and high spectral purity. The property of an EA as a high quality electron beam source for a FEL is crucial for attaining high brightness spontaneous emission radiation. The unique features of EA-FELs make them naturally fitting for a variety of applications in the present and in the near future. And few high power mm-IR EA FEL facilities have been successfully built around world. Here an EA of 3 MeV with beam current of 2 A is studied for a high average power (kWs) mm-THz source.

INTRODUCTION

While most FEL facilities are produced with ulta-short (~ps) electron beam pulse with normal conductor rf linac, they are not able (extremely hard) to operate in CW mode because of huge amount of rf power consume, and very challenge of cooling. The EA-FEL naturally fits for CW or quasi-CW operation with an electron beam retrieval scheme, which high average power and very high efficiency could be achieved. There are some EA-FEL IR-mm sources, which are operating very well, such as University of California Santa Barbara (UCSB) 6 MeV Pelletron accelerator [1], Israeli EA –FEL based on 6 MeV EN-Tandem van de Graff accelerator [2], and KAERI MMW FEL at 430 keV [3].

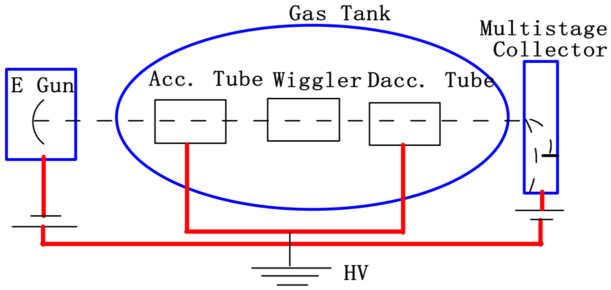

Figure 1: Conceptual design of a 3MV EA-FEL with electron beam retrieval.

A conceptual design of a compact low energy (up to 3 MeV), high current (up to 2A) EA-FEL is proposed as an efficiency high average power source in mm-THz wavelength. The scheme for such an EA-FEL based on straight accelerator is shown in Fig.1.

APPROACH/METHODS

Beam Energy

With undulator period of 1 cm and parameter K of .5, EA-FEL radiation wavelength is shown in Figure 2 at different beam energy. Therefore, with beam energy at 1.5 MeV is enough for Thz radiation, however it is difficult to transfer such high current and low energy beam, hard to extend to short wavelength radiation and ultra high beam recovery efficiency needed for quasi-cw operation. Therefore, a 3 MeV beam is suggested, which will result some margin for short wavelength radiation and help to achieve small beam size at the entrance of undulator. For different energy, Figure 3 shows the typical size of EA [4]. With 3 MeV design, the total length of the facility will be around 10 meters, which is still compact.

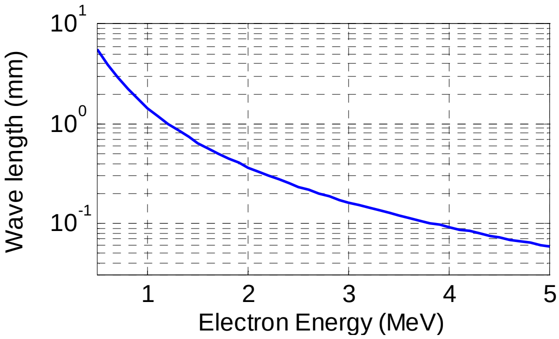

Figure 2: FEL radiation wavelength with 1 cm magnetic period and K = 0.5.

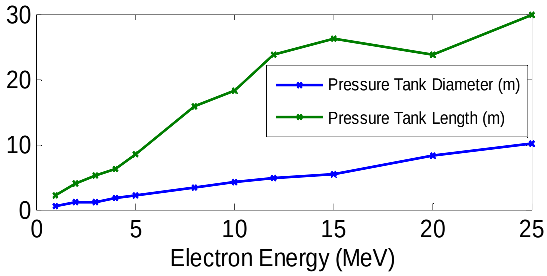

Figure 3: EA pressure tank size at different energy, where for these with energy below 5 MeV are built at horizontal orientation and others are vertical.

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Beam Recovery Efficiency

EAs can generator very high quality beam with very low beam energy spread (~10^{-5}). However, in their normal configuration, the beam current of EA is very low (typically 100s μA), which is too low to drive FEL. Since the current is limited by charging system, it will not help to operate with a high current electron gun. The beam current recirculation scheme makes the EA possible to transport a high beam current to drive FEL [5]. For a FEL oscillator starting from noise to reach gain saturation, 1) the high current beam pulse should sustain long enough (few μs), and 2) during this period of time, the beam energy change should be smaller than the requirement for beam energy spread for FEL ($1/2N_u$). With the two condition, the beam recovery efficiency is required as

$$\eta \geq 1 - \frac{\gamma m_e}{2N_u T_b} \frac{C}{I_b}$$

where γm_e is beam energy is Volt, N_u undulator periods, C terminal capacitance, T_b minimum beam pulse width, and I_b beam current. With a typical design for beam energy of 3Mev and current of 2A, T_b = 5 us, C = 100 pf, Nu = 100, the minimum efficiency is 0.73. Currently, the UCSB FEL has achieved beam recovery efficiency of 0.997 and beam energy spread of 10^{-5}. And Figure 4 shows achievable beam pulse length with different undulator period.

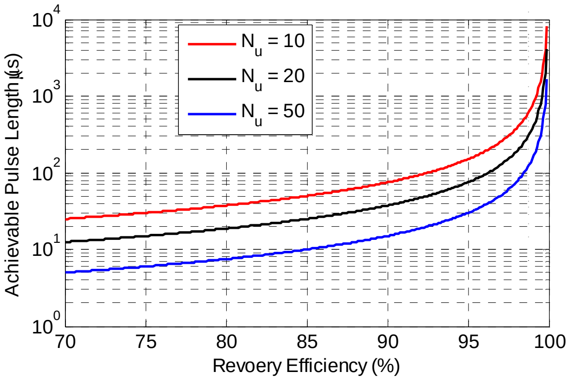

Figure 4: Achievable beam pulse length with Table.1 parameter at different undulator periods.

E-Gun

Since emittance is not sensitive for this application, a high current gun is desirable. And a DC HV gun is usually used. For R&D a field emission array (FEA) DC gun could also be considered, which can afford comparable low emittance beam with photo gun. The currently limitation for FEA gun is low current (100s mA).

THz FEL Parameter Design

Table 1 lists the baseline design for a quasi-cw (> 1ms) THz (1.84) EA - FEL radiation. Figure 5 shows the gain length dependence on beam energy spread. It indicates that the FEL radiation performance is quite stable as the energy spread is at the order of 10^{-4}, which is moderator for an EA. And the gain length varies with beam size is shown in Figure 6. Clearly, we have a tight tolerance on beam size for this design.

Table 1: Basic design parameters of accelerator and FEL at 1.84 THz radiation

Section	**Parameter**	**Symbol**	**Value**	**Unit**
Accelerator	Gun HV	V_g	100	kV
	Maximum Gun Current	I_g	3	A
	Beam Energy	E_b	3	MeV
	Beam Current	I_b	2	A
	Beam Pulse Width	T_b	> 1	ms
	Recovery Efficiency	η	> 99.6	-
	Beam Radius at undulator	r_b σ_x	1.22 0.41	mm
	Emittance	ε	10	um
	Energy Spread	δ_E	10^{-5}	-
	Maximum Charging Current	I_{ch}	200	uA
	Terminal Capacitance	C	200	pf
Undulator	Period	λ_u	1	Cm
	Parameter	K	0.5	-
	Magnetic Field	B	0.54	Tesla
	Numbers	N_u	20	-
Resonator	length	L	0.5	m
FEL	Wavelength	λ	163	um
	Gain Length	L_G	0.5	m
	Rayleigh Length	R	0.1	m
	Pierce Parameter	ρ	0.00418	-
	Saturated Power	P_s	25.1	kW

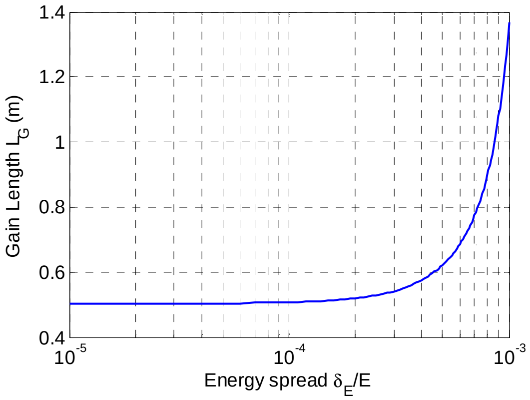

Figure 5: Gain length dependence on beam energy spread.

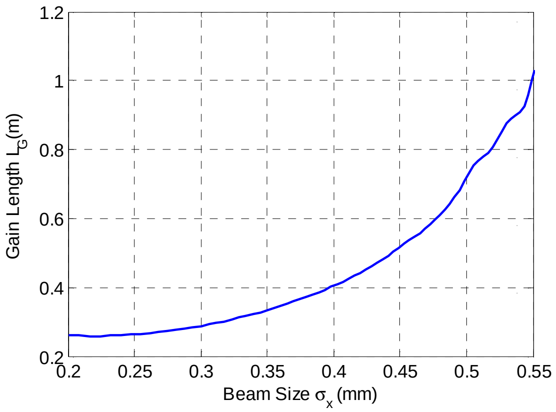

Figure 6: Gain length dependence on beam size.

MMW FEL Parameter Design

Table 2 lists the baseline design for a quasi-cw (> 1ms) MMW (1 mm) EA - FEL radiation. And the performances of the EA FEL varying with beam quality are showing in Figure 7~9.

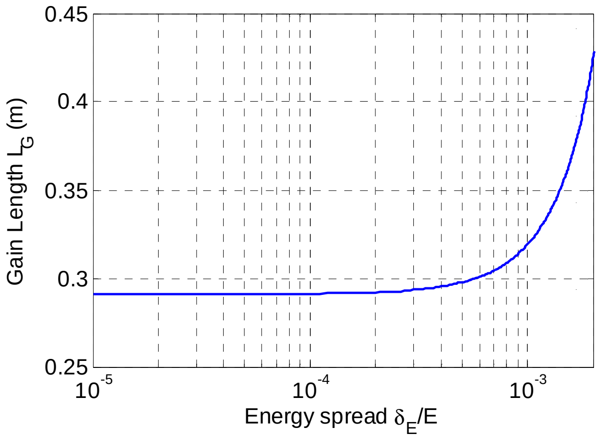

Figure 7: Gain length dependence on beam energy spread.

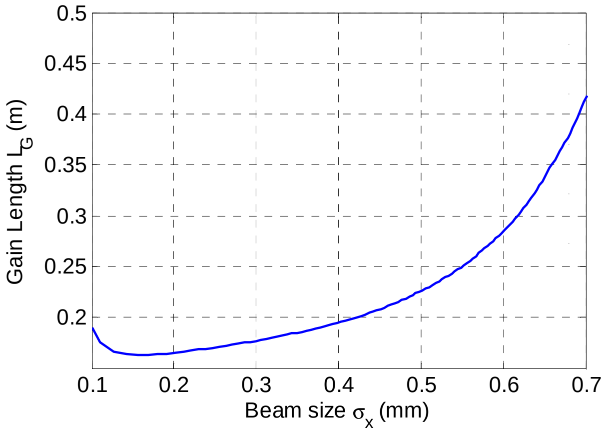

Figure 8: Gain length dependence on beam size.

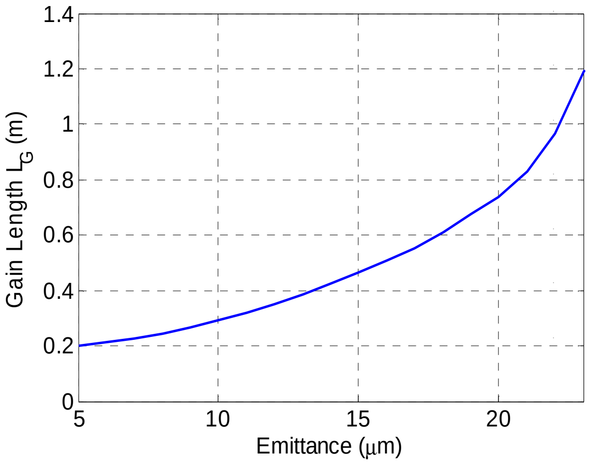

Figure 9: Gain length dependence on beam normalized emittance.

Table 2: Basic design parameters of accelerator and FEL at 300 GHz radiation

Section	Parameter	Symbol	Value	Unit
Accelerator	Gun HV	V_g	100	kV
	Maximum Gun Current	I_g	3	A
	Beam Energy	E_b	2	MeV
	Beam Current	I_b	2	A
	Beam Pulse Width	T_b	> 1	ms
	Recovery Efficiency	η	> 99.8	-
	Beam Radius at undulator	r_b σ_x	1.8 0.6	mm
	Emittance	ε	10	um
	Energy Spread	δ_E	10^{-4}	-
	Maximum Charging Current	I_{ch}	200	uA
	Terminal Capacitance	C	200	pf
Undulator	Period	λ_u	2	cm
	Parameter Magnetic Field	K B	1.03 0.55	- Tesla
	Numbers	N_u	20	-
Resonator	length	L	0.5	m
	Dimensions	axb	15x15	mm^2
FEL	Wavelength	λ	1	mm
	Gain Length	L_G	0.29	m
	Rayleigh Length	R	0.014	m
	Pierce Parameter	ρ	0.0125	-
	Saturated Power	P_s	50	kW

Challenge

1) Beam Recovery Efficiency

For long pulse (~ ms) operation, an ultra high recovery efficiency (>99%) is needed. This requires very good beam transportation system and carefully design of multi-stage collector. Since UCSB EA-FEL has achieved 99.7% recovery efficiency, the high efficiency is possible for the proposal.

2) Energy Stability with Long Pulse

The EA could produce very high quality beam (~ 10^{-5} energy spread) in normal operation. For the proposed scheme with electron beam recovery, the transient effect on beam energy stability should be carefully studied, especially with long pulse operation.

3) Design of Oscillator

The design of the oscillator for such a FEL is a very difficult part, because of diffraction in such a long wavelength range.

Possible Applications

Table 3 lists some possible applications with such a high average power EA-FEL facility [6].

Table 3: Applications of high power mm-THz FELs

Application	Wavelength	Average Power
Material Biological Research	30 ~1000 um	0.1 ~ 1000 W
Material Processing	10 ~ 1000 um	> 5 kW
Photochemical, isotope separation	16 ~ 200 um	100 kW
Lidar remote sensing	IR	1 ~ 100 kW
Tokmak Electron Cyclotron Resonance Heating	0.5 ~ 1 mm	1 ~ 20 MW, fast tunability

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