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Conceptual Design of an Stockholm-Uppsala THz FEL Oscillator:

report I of the series of reports by the Swedish FEL Center

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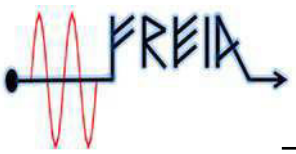

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May 17, 2013

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CONCEPTUAL DESIGN OF AN STOCKHOLM-UPPSALA THZ FEL OSCILLATOR: report I of a series of reports by the Swedish FEL Center

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Abstract

The Stockholm-Uppsala FEL center is currently studying the user interest in terahertz radiation in the Mälaren region and considering the possibility of building a TeraHertz free-electron laser (THz FEL) in the FREIA laboratory. In this memo we discuss the conceptual design of a THz FEL and a superconducting linear accelerator to drive it. The required resources are estimated.

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1 Introduction

At present the word "TeraHertz" is very popular and maybe even speculative. To get some insight into research activities associated with the THz light we refer to the scientific publications of the American Physical Society (APS). Fig. 1.1 shows the number of the APS publications related to the THz research as a function of year. As we can see, we are now in the period of exponential grows and the interest to the THz radiation is currently exploding. The number of publications

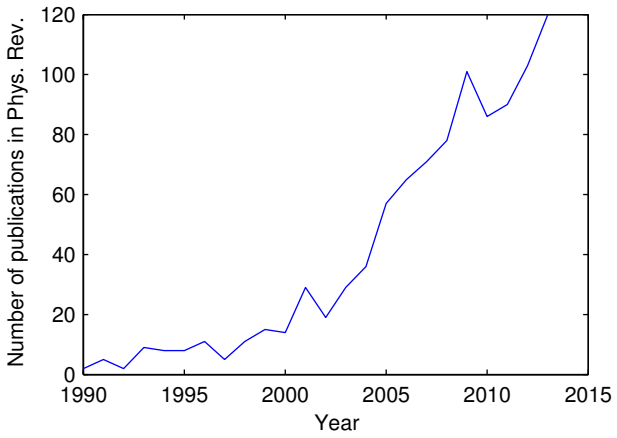


Figure 1.1: The number of papers related to THz radiation and published in the APS journals versus time [1].

in different APS journals are:

- Phys. Rev. Lett. (234)
- Phys. Rev. A (51)
- Phys. Rev. B (548)
- Phys. Rev. E (43)
- Phys. Rev. X (2)
- Phys. Rev. ST Accel. Beams (19)
- Rev. Mod. Phys. (2)
- Phys. Rev. Focus (3)

Interesting to note that most of the papers appeared in Phys. Rev. B and focus of this journal on solid-state physics. Just an example, the most cited papers deal with

- high-Tc superconductors, terahertz responses of intrinsic Josephson Junctions in high-T_C superconductors;
- semiconductor superlattices;

- metamaterials and left-handed media;
- time-resolved terahertz spectroscopy;
- terahertz Spin Precession in semiconductor quantum wells;
- ultrafast charge carrier dynamics in graphite using time-resolved terahertz spectroscopy.

The growing applications of THz radiation in a variety of different fields are demanding versatile sources that combine high-power and excellent output performances. However, in the THz region traditional microwave source like backward wave oscillators, orotrons, vircators and klinotrons suffer from simple physical scaling problems, metallic wall losses and the need for higher static magnetic and electric fields, as well as higher electron current densities as the frequency is increased. The mentioned devices have already achieved saturation in their development so that a lot of efforts were put towards the development of novel sources of THz radiation. Nowadays, free electron lasers (FELs) are capable of generation high-power tunable radiation in wavelength ranges from microwaves to the X-ray range. In particular, the THz range of the electromagnetic spectrum can be covered by the FEL and the THz FEL light beam shows good performances in pulse energy stability, polarization, spectrum, and spatial distribution. The key parameters of operating FELs are presented in Fig. 1.2, where λ is the wavelength, σ_z is the bunch duration, E is the beam energy, I is the beam current, N is the number of undulator periods, K and λ_0 is the undulator parameter and period, respectively. The operating FELs produce fully coherent radiation and the wavelength is continuously tuned, the pulse length can be very short, and the peak power is of MW level. Certainly, availability of a THz source with unique features like an FEL will give rise to novel THz experiments and applications and stimulate further progress in the THz light based research.

Location (Name)	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	
Frascati (FEL-CAT)	760	15–20	1.8	5	16	2.5	0.75	RF, O
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA, O
Novosibirsk (RTM)	120–230	70	12	10	2x33	12	0.71	ERL, O
KAERI (THz FEL)	100–1200	20	4.5–6.7	0.5	80	2.5	1.0–1.6	MA, O
Osaka (ISIR, SASE)	70–220	20–30	11	1000	32	6	1.5	RF, S
Himeji (LEENA)	65–75	10	5.4	10	50	1.6	0.5	RF, O
UCSB (FIR FEL)	60	25000	6	2	150	2	0.1	EA, O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF, O
Osake (ISIR)	32–150	20–30	13–19	50	32	6	1.5	RF, O
Osaka (FELI4)	18–40	10	33	40	30	8	1.3–1.7	RF, O
Dresden U100-FELBE)	18–280	1–25	18–34	15	38	10	0.5–2.7	RF, O, K
Nieuwegein (FELIX)	3–250	1	50	50	38	6.5	1.8	RF, O
Orsay (CLIO)	3–150	10	8–50	100	38	5	1.4	RF, O

RF–radio-frequency linear accelerator; ERL–energy recovery linear accelerator; MA–microtron accelerator; EA–electrostatic accelerator; O–FEL oscillator; K–FEL klystron.

Figure 1.2: Overview of the operating FELs, adopted from [2].

The user requirements are of the highest priority and they should underlie the FEL and linear accelerator (linac) design. In this memo we aim at working out a flexible design of an RF linac to enable FEL to operate in different regimes and, thus, to be attractive to users with different research background. However, in practice we are limited by some boundary conditions like time, budget, space available at the FREIA hall, experience and manpower. The latter is especially crucial and we cannot launch a large R&D program on the main components like a gun or a cavity. Even the power coupler for the cavity is a very tricky device and as we can see from experience with the LEP coupler at CERN or the TESLA coupler at DESY such an R&D takes several years. Then, it is natural for a small facility to buy off-the-shelf components or components that require small modifications. Learning the physics of the main components and assembling them will give experience that can be used later for building a large-scale advanced linac. However, even if we buy off-the-shelf components our facility must be a prototype for an advanced full-scale future linac. Building a sustainable superconducting (SC) facility is an important way of developments in the area of SC linac and currently many labs are working on energy recovery linacs (ERL). Maybe we should consider the possibility of designing a flexible linac layout that can be later modified to include the energy recovery as an option.

ERL is a source for FELs operating as oscillators with feedback provided by mirrors. For example, KEK has a project [7] to construct a 3-GeV ERL-based light source with an X-ray FEL oscillator (XFEL-O). In order to demonstrate excellent ERL performances toward the 3-GeV ERL project, the compact ERL project is on going. The Japanese collaboration team is making efforts for R&D on key components such as high-current superconducting cavities and high-brightness electron gun. The lattice and optics design of the 3-GeV ERL has been recently started.

2 Time structure of electron beams at different FEL facilities

FEL configurations are very similar at different FEL facilities and the difference in FEL outputs is mainly determined by the properties of an electron beam. Let us consider in detail the characteristics of linacs but first we will define some terms that maybe confusing:

- micropulse repetition rate is a rate of individual electron bunches (typically MHz or GHz);
- macropulse repetition rate is a rate at which the linac generates trains of electron bunch (typically 10-100 Hz);
- accelerating frequency is a frequency of the main linac;
- beam means macropulse, *i.e.*, a train of bunches.

Depending on the design, RF linacs generate two principally different trains of electron bunches. If an RF signal used for acceleration is applied to the grid of a thermionic gun, then the repetition rate of electron bunches is equal to the fundamental frequency of accelerating field. This is the case for the FLARE linac, see Fig. 2.1. In such linac electron bunches are much shorter than the acceleration wavelength so that the buncher can effectively compress electrons at the fundamental accelerating frequency because the accelerating electric field is quite uniform along bunches. At FLARE the repetition rate is 3 GHz and the bunch duration after bunching is only a few ps. This

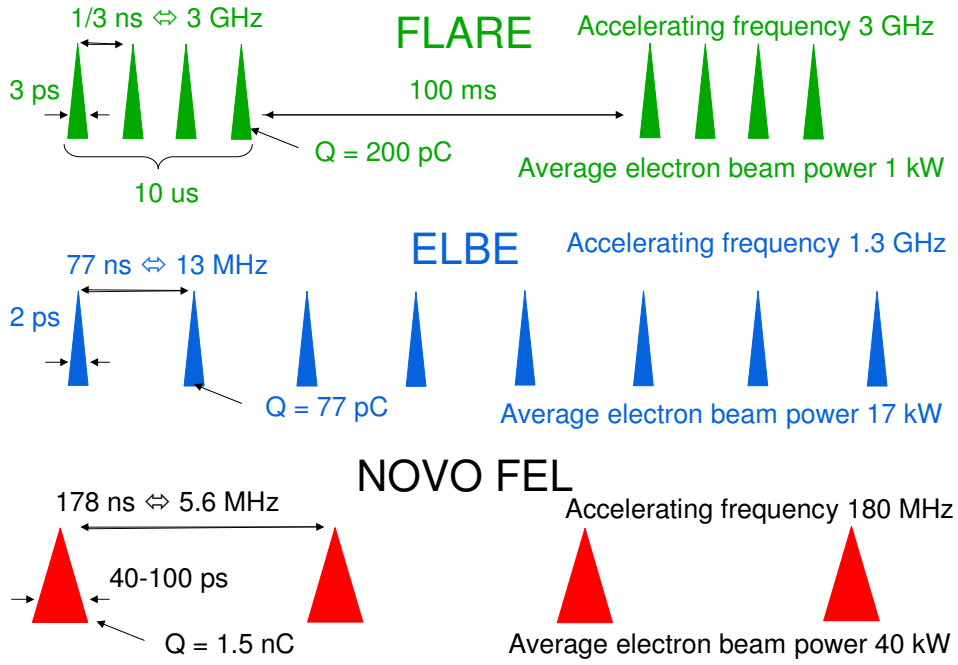


Figure 2.1: The time structure of the train of electron bunches at different FEL facilities.

high repetition rate means high macropulse current of 0.6 A for bunch charges of 0.2 nC so that the macropulse duration (duration of the train of electron bunches) is limited because of the beam break-up instability caused by wakefields. The maximum macropulse duration cannot exceed a few tens of μs and at FLARE it is 10 μs.

In order to accelerate the beam to an energy of 10-15 MeV with a 3 GHz repetition rate and a 0.3 nC bunch charge, the RF power transferred to the beam has to be around 10 MW. This high peak RF power is another factor that limits the macropulse duration. Typically, klystrons can deliver such high power only during tens of μs or even less, see the overview of klystrons 2.2. At the same time, the repetition rate is usually limited to 100 Hz. This means that the FLARE linac cannot operate at a duty factor of more than 0.1%. In fact, the same effect of beam break-up instability that limits the maximum average current in linac also limits the maximum average current in a klystron. High-power CW RF sources are available only at frequencies approximately below 500 MHz. Thus, the regime of a continuous train of electron bunches cannot be realized in a compact normal conducting RF linac.

At ELBE an RF signal of a relatively low frequency of 13 MHz is applied to the gun's grid and electron bunches of around 0.5 ns are generated. The pulsed electron beam delivered by the gun has an energy of 250 keV and a bunch charge of 77 pC corresponds to an average beam current of 1 mA. The repetition frequency turns out to be the 100^{th} subharmonic of the operating frequency of the 1.3 GHz accelerator. Since the bunches generated by the gun are long a subharmonic cavity is needed for bunching. The wavelength of an accelerating field of the subharmonic buncher has to be much longer than the bunch duration so that at ELBE the buncher is operated at 260 MHz (one fifth of the working frequency) and at the Novosibirsk FEL (NovoFEL) at 180 MHz (wavelength

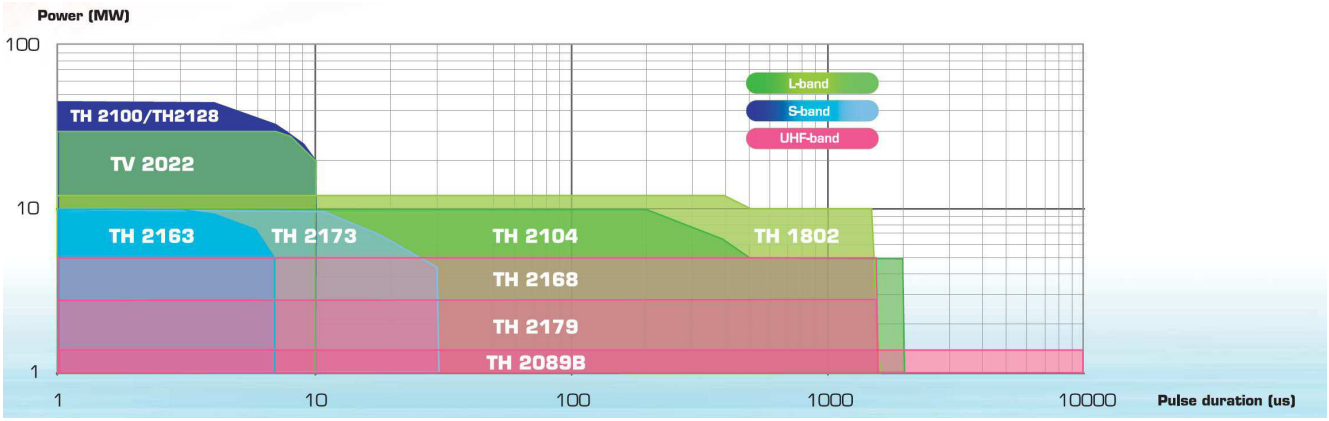


Figure 2.2: Klystrons produced by THALES (Toshiba and CPI klystrons have similar characteristics).

is 1.66 m). The ratio of the buncher wavelength to the bunch length is 7.7 for ELBE and 5.5 for NovoFEL.

In order to reach higher bunch charge one should increase the peak cathode current and/or increase an initial bunch length. The first way is limited by the space charge fields in the gun and low-energy part of linac whereas the second one is limited by the buncher wavelength.

3 Choice of beam structure: long or short pulses?

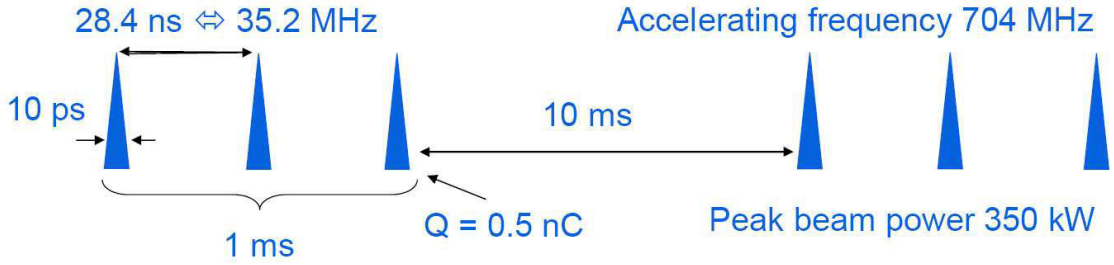
The main differences between FLARE and ELBE are the repetition rate of electron bunches and the duty factor so that different types of experiments can be performed with these machines. The regime with a high duty factor is of interest for experiments that demand sweep over frequency and/or intensity to study resonant and nonlinear effects. Another application of a high duty factor machine is the scanning of samples with large area that may take a lot of time with a low repetition rate machine. As an example of the experiment that is time demanding one can mention the scanning of near field optical images of oesophageal cancer using the InfraRed ALICE FEL in UK [6]. This research is based on collaboration between the Cockcroft Institute, the Royal Liverpool and Broadgreen University Hospitals NHS Trust and the Institute of Translational Medicine. The aim of the collaboration is to develop a diagnostic test by imaging tissue obtained by endoscopy from patients with a precursor condition called Barrett's oesophagus. Recall that ALICE is an infrared FEL based on a SC CW linac operating with a repetition rate of 81.25 MHz. It took one hour to scan a sample with 50 μm by 50 μm area. The images were taken at single wavelengths of 8.05 and 7.3 μm in the infrared corresponding to features in the IR spectrum of DNA and glycoproteins, respectively. In general, a high duty factor linac is more universal tool since it can be run in a pulsed mode and even with a repetition rate of the fundamental accelerating frequency. To this end one can install the second thermionic gun operating with a high repetition rate.

Some applications like studying the resonant response of biocells to THz radiation requires as high peak power as possible and as short pulses as possible. To meet these requirements we

propose to generate 20 MeV electron macropulses of 1 ms duration with a bunch charge of 0.5 nC at a repetition rate of 35.2 MHz and a duty factor of 10%, see Fig. 3.1. This corresponds to a macropulse current of 17.6 mA and a beam power of 350 kW. For such high duty factor and current the SC technology is a natural choice. The beam structure is a working proposition and a starting point to demonstrate potential users what we can offer. The FEL will produce radiation micropulses of tens of ps with an energy of tens of μJ and a peak power on MW level. The FEL regime of high frequency resolution $\Delta\omega/\omega \sim 10^{-5}$ is under study.

4 Choice of the fundamental frequency

Nowadays, a wide variety of SC cavities covering the frequency range from tens of MHz to a few GHz is available and the decision as to the fundamental accelerating frequency and gradient is nontrivial. Often, such choices are made based on existing designs, which with reasonable modifications can be used in a new linac. However, the fallacy of using existing designs is that they frequently result in a machine with sub-optimal beam physics parameters [4]. Thus, our design will be based on general physical arguments rather than on a specific existing design. One of the most important parameters of a SC cavity is the fundamental frequency because its choice affects the accelerating gradient (length of linac), the quality factor (electricity bill), the cavity type and size (fabrication cost), an RF source (one of the major cost component) and the beam quality. There are distinct arguments for the choice of a high or low frequency of the fundamental



LINAC:

Beam energy: 10-20 MeV

Energy spread: 0.3%

Emittance: 30 mm*mrad

Beam current: 17.6 mA

Duty factor: 10%

Repetition rate: 100 Hz

FEL output:

Frequency: 0.3-6 THz (50-1000 um)

Micropulse energy: ~10-20 uJ

Micropulse length: 50-100 ps

Bandwidth: ~1% (10^{-9} ?)

Resonator length: 4.26 m

Peak power: > MW

Figure 3.1: The proposed electron beam structure of a linac for a THz FEL. The FEL will produce radiation micropulses of tens of ps with an energy of tens of μJ per micropulse and a peak power on MW level.

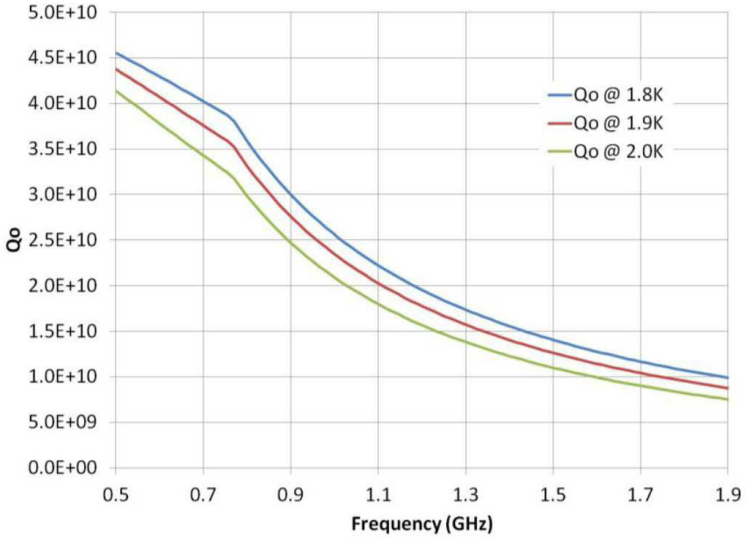


Figure 4.1: The quality factor Q_0 of a bare cavity as a function of frequency and temperature at 16 MV/m (adopted from [4]). The curves are based on the statistical data from the Jefferson Lab. All frequencies are scaled from CEBAF C100 cavity.

accelerating mode.

Arguments in favour of high frequency are:

- The surface area of the cavity decreases with increasing frequency. An analysis of the maximum surface fields measured shows that higher fields can be reached with smaller surfaces. This is explained by a statistical model of defects and an empirical model of breakdown field strength (NC linac).

- The threshold of captured field emitted current, *i.e.*, the onset of dark current scales linearly with frequency.

The shunt impedance per length increases linearly with frequency but the quality factor Q_0 of a bare cavity decreases with frequency as $1/f^2$, see Fig. 4.1. This means that cryogenic loss depends weakly on frequency in the frequency range from 0.5 GHz to 2 GHz.

Arguments in favour of low frequency are:

- Wakefields are strongly influenced by the iris diameter. The longitudinal and the transverse wavenumbers scale inverse with the third and fourth power of the cavity iris diameter, respectively. Therefore, emittance growth is strongly reduced at lower frequency.

- The SC surface resistance scales with f^{-2} so that the quality factor is higher at lower frequency, see Fig. 4.1.

- availability of high-efficient semiconductor RF sources.

One should stress on importance of wakefields since they determine the emittance growth and the beam break-up instability (BBU), which limits the maximum beam current accelerated in a

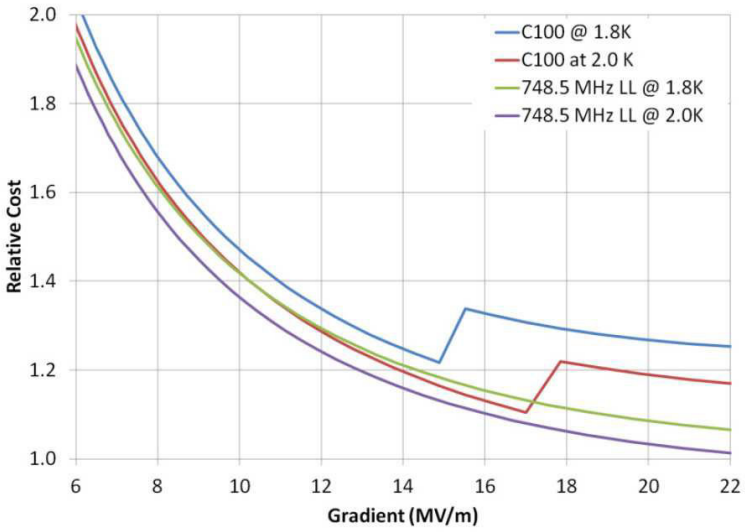


Figure 4.2: The quality factor Q_0 of a bare cavity as a function of frequency and temperature at 16 MV/m (adopted from [4]). The curves are based on the statistical data from the Jefferson Lab. All frequencies are scaled from CEBAF C100 cavity.

cavity. For example, the decrease of the TESLA cavity aperture from 70 mm to 60 mm raises the longitudinal beam-excited wakefields by 18 % and transverse wakefields by 65 %. Higher transverse wakes demand more stringent cavity alignment in order to preserve beam emittance in a linac. Note that BBU limits the beam current in Energy Recovery Linacs (ERL) and since ampere-class ERL is of interest for many applications BNL launched the development of a new SC cavity able to accelerate the beam with a current of 0.5 A. This development program resulted in a new 704 MHz elliptical cavity with extremely low wakefield and high accelerating gradient of 20 MV/m.

Apart from the technical characteristics, the linac must be cost-efficient even if it is a small machine. Below, we will present some results about the linac economics adopted from [4]. The results were obtained for a 2 GeV linac with taking into account the costs of construction plus ten years of operation including cryogenic and RF consumption. As we can expect the relative cost decreases as the accelerating gradient increases as it is shown in Fig. 4.2 but the relative cost turns out to be almost independent on frequency in some frequency regions as depicted in Fig. 4.3. Steep jumps of the curves for some parameters are related to the discrete number of cavities, cryomudules and warm-to-cold transitions. A weak dependence on frequency is an interesting result and together with technical characteristics this makes the arguments for lower frequency more relevant.

In summary, the arguments for lower frequency are more relevant since much lower wakefields allows for much higher beam currents and smaller emittance degradation.

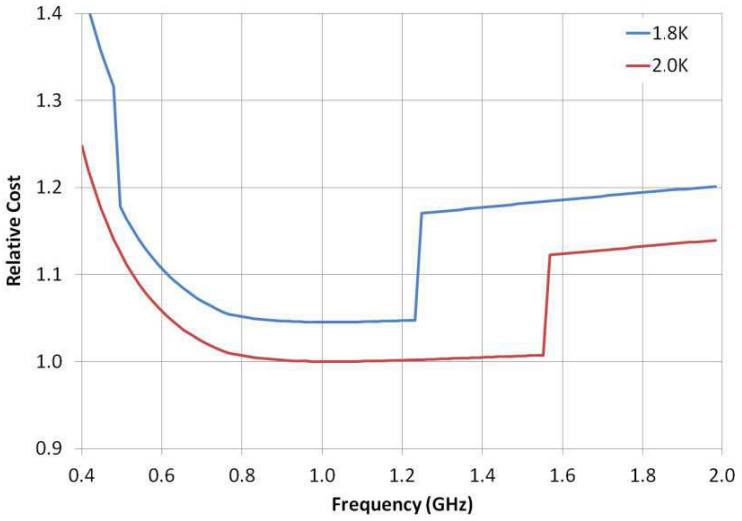


Figure 4.3: Relative cost of a 2 GeV linac plus 10 years of operation.

5 General linac layout

The 5-cell 704 elliptical cavity is a promising candidate for the main accelerating cavity. This cavity is a heart of the Brookhaven ERL and a similar design is chosen for SPL at CERN and ESS. Note that an elliptical cavity operating at 748.5 MHz is proposed for ERL at the Jefferson Lab, 650 MHz cavity at J-PARC and 805 MHz cavity at SNS. Currently four cavities for SPL are under fabrication by the company Research Instruments and the cavities for ESS are in design phase. The BNL cavity is already measured, so it is useful to consider its main characteristics:

- 5 cell SRF cavity, 17 cm iris, 24 cm beampipe;
- 703.75 MHz, 20 MV/m $Q_0 = 10^{10}$;
- No trapped HOMs;
- Cavity is inherently stiff, so no additional stiffeners are needed;
- Coaxial power coupler for power delivery;
- Ferrite Dampers for HOMs;
- 5 K heat intercept on beampipe;
- Mechanical Tuner with 100 kHz tuning range, piezo; provides 9 kHz fast tuning.

During testing of the BNL cavity in CW mode a gradient of 13 MV/m was well repeatable and stable with no radiation observed. The 22 MV/m gradient is demonstrated in quasi-CW mode operation (3-4 seconds). CW higher gradient operation is limited by the temperature rising of thermo-transition near the power coupler and the tuner. In the BNL ERL the cavity will be operated in CW mode with gradient of 18 MV/m. At CERN the nominal accelerating gradient of

Gun	Buncher	Pre-accelerator	accelerator
• 35.2 MHz	• 352 MHz single spoke cavity	• 1-cell 704 MHz	5-cell 704 MHz elliptical cavity
• 17.6 MHz	• warm 176 MHz buncher	• 352 MHz single spoke cavity	

Figure 5.1: Possible choice of accelerating cavities.

25 MV/m is planned and 18 MV/m at ESS. Note that the maximum gradient reached in TESLA cavities is more than 35 MV/m but the nominal gradient is 23.8 MV/m so that there is no much difference between BNL and TESLA cavities in terms of nominal gradient. Recall that higher gradient means higher heat load and the maximum achievable gradient may be not optimum choice from the viewpoint of running cost.

The choice of the main accelerating cavity affects the choice of other components like a pre-accelerator and a buncher. The possible components for the linac are summarized in Table 5.1. Further studies are needed to work out a flexible linac design with a high quality of electron bunches. Preliminary parameters of the gun and accelerating cavities are summarized in Table 1. The FEL layout and required space are schematically shown in Fig. 5.2.

High repetition rate thermionic cathode based guns have traditionally been used in long wavelength FELs like FELIX, FELBE, NovoFEL and FLARE and successfully operate at high repetition rate in CW mode. They are simple in operation, do not require extra high vacuum conditions, the cathodes are very robust and have long operational lifetime. Recall that the ELBE FEL injector delivers 1 mA average current through 77 pC bunches at a repetition rate of 13 MHz. For a THz FEL such beam quality is good enough and the peak current is sufficient. Thus, we can use a thermionic triode gun like a gun in an Inductive Output Tube. It consists of a cathode, an anode and a grid. There is a DC voltage between the cathode and anode, the grid is biased. An RF signal of 35.2 MHz is applied to the grid and there is current through the gun during only a small faction of the RF period when the grid voltage exceeds some threshold. Hence, the repetition rate of bunches is 35.2 MHz. In addition, we will also trigger the DC grid voltage with 100 Hz, this will determine the repetition rate of macropulses.

Table 1*: Technical characteristics of the main linac components.*

thermionic gun	buncher	pre-accelerator	main accelerator
500 pC	NC	SC	SC
500 ps	176 MHz	1-cell 704 MHz elliptical	5-cell 704 MHz elliptical
35.2 MHz	standing wave	25 MV/m	18 MV/m
30 mm·mrad	$Q_0 = 10^5$	35 kW	315 kW
250 keV		1.8 K	1.8 K
10 % energy spread		$Q_0 = 10^{10}$	$Q_0 = 10^{10}$

The buncher frequency depends on the initial bunch length. For many applications we need as high bunch charge as possible. The high bunch charge can be achieved in different ways by increasing the cathode current (typically operated at almost maximum) or the cathode area or the bunch duration. The cathode current is limited by emission properties of material and around 3-4 A/cm^2, the maximum cathode area is limited by emittance, so we have to generate relatively long bunches of around 0.5 ns, *i.e.*, around 8 cm bunch length. The bunching is realized by introducing velocity modulation that converts into density modulation as the bunch propagates. In order to have good bunching, the wavelength of the field that is used for velocity modulation should be around 10 times longer than the bunch length, i.e. around 80 cm. This approximately corresponds to a frequency of 352 MHz. So, the buncher frequency should be maximum 352 MHz. At ELBE buncher is 260 MHz and 180 MHz at Novosibirsk FEL. An option of 352 MHz buncher should be investigated but certainly it is safer to have 178 MHz buncher.

The purpose of the pre-accelerator is two-fold: further compress bunches by accelerating them off-crest and bring the beam velocity close to the speed of light so that the beam can be efficiently accelerated in a high-β cavity. Recall that accelerating structures designed in such a way that the phase velocity of the accelerating field is close to the velocity of electrons in a beam so that the energy of the accelerating RF wave can be effectively transferred into the kinetic energy of the beam. A simple visualization is a surfer riding on-crest of an ocean wave and getting the kinetic

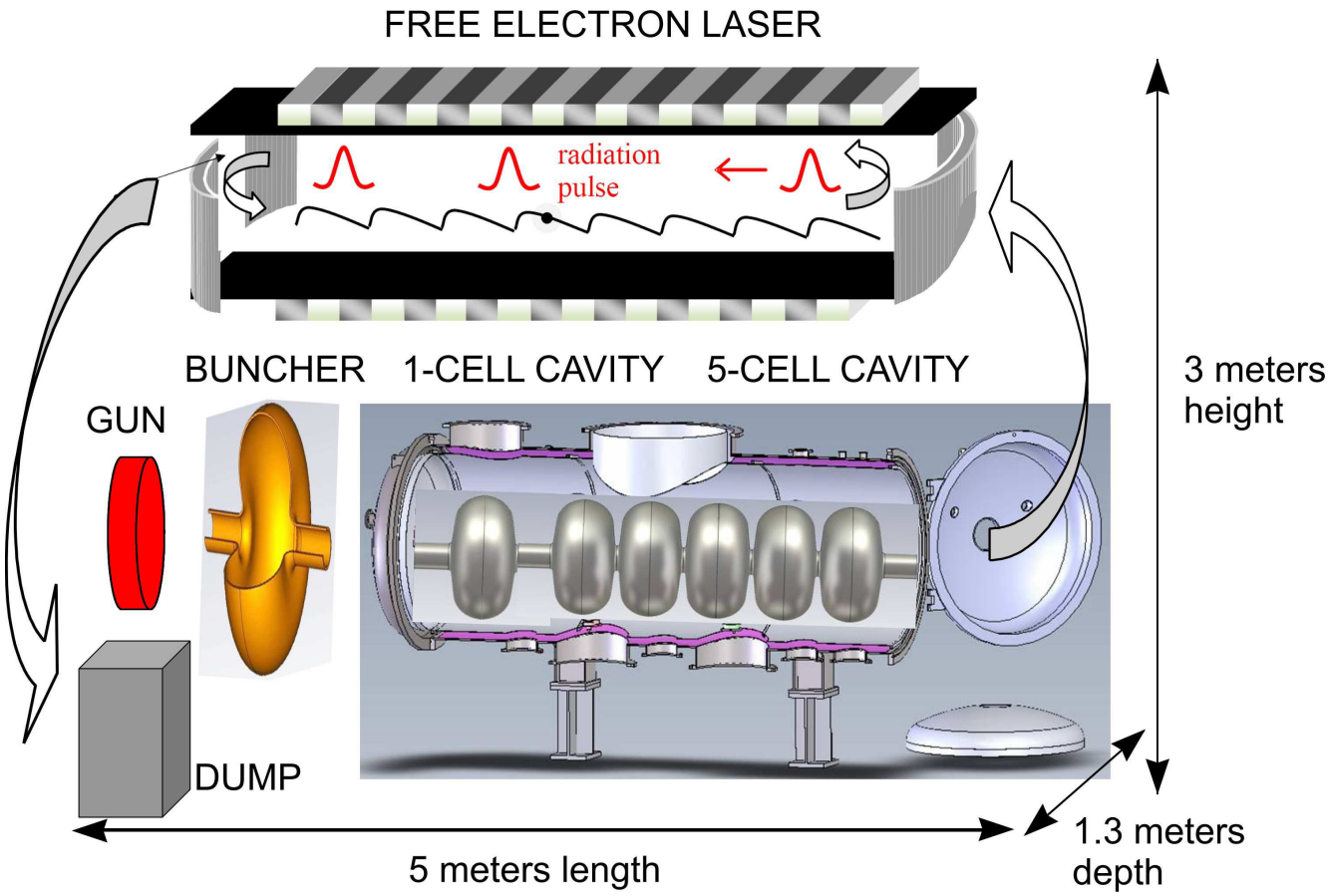


Figure 5.2: Schematic layout of a THz FEL.

energy from the wave. However, if the surfer rides not on-crest or has an initial velocity different from the velocity of the wave it will not be picked up by the wave. For the accelerating beam the situation of different velocities or acceleration off-crest means that the energy of the accelerating RF field will not be transferred completely to the beam. So, in a low energy part of the linac we need cavities with different phase velocities so that the phase velocity of the accelerating field of a cavity is close to the beam velocity.

6 FEL physics and design

Traditionally, IR and far-IR FELs are designed to operate as oscillators, *i.e.,* they are equipped with resonators confined by two mirrors: one of those is highly reflective and another one is either translucent or contains outcoupling aperture. We note that in some literature the FEL oscillator is defined as an FEL, which start lasing from spontaneous emission and, as an example, according to this terminology, the SASE X-ray FEL should be considered as an oscillator. Throughout this text by oscillators we mean multi-pass devices, in which light is bounced by mirrors, while by amplifiers we mean single-pass devices. Examples of IR and far-IR oscillators are FELIX, ELBE FELs, FLARE and Novo-FEL. There are also a few THz FEL amplifiers, *e.g.,* superradiant short-pulse THz ELBE facility and some proof-of-principle studies are also available for seeded-THz FEL amplifiers [8].

Most of the existing THz facilities employ "warm" RF LINACs, which can only operate at a low duty-cycle of less than 1 %. The super-conducting technology enables significant enhancement of the linac duty cycle up to 100 % and a THz FEL driven by a SC RF linac will generate much more powerful light compared to "warm" THz FELs. Nowadays, only a few SC THz FELs exist worldwide and the exponentially growing THz research community will benefit tremendously through the use of the extremely powerful THz source. The envisioned applications of such a source are high-repetition rate pump-probe experiments and investigation of reactions with very small quantum yield. Let us consider four possible THz FEL configurations and discuss in more details their compatibility with the SCT. The following configurations are considered: 1) seeded THz FEL amplifier; 2) SASE THz FEL; 3) short-pulse super-radiant THz facility; and 4) multi-pass oscillator.

Seeded THz FEL. In such devices a seed pulse is amplified upon a single pass through an undulator. A powerful seed source is proposed to be the CO_2 laser, output of which is non-linearly mixed on a crystal providing a THz seed signal. The main two advantages of this scheme are *a)* very high THz FEL power can be achieved; the initial seed power of 1 kW can be amplified to MW; and *b)* compactness of the FEL; it was demonstrated that few meters long undulator was sufficient to achieve signal saturation [8]. The main disadvantage, which makes it less interesting to us, is that it is not compatible with the regime of high repetition rate, since the seed laser will ultimately define the repetition rate of the THz pulses rather than a SC RF linac.

SASE THz FEL. In such a THz FEL scheme, the electron bunch at the beginning of an undulator emits spontaneous emission, which can be expected to be partly coherent, and then it is amplified by the same electron bunch saturating at the undulator end. This scheme can be interesting to us as it is readily compatible with the high repetition rate of electron bunches and long macropulses generated by the SC RF linac. An obvious disadvantage is a relatively long undulator required for the SASE which might not fit to the FREIA hall. However, few additional

points need to be taken into account. In the case when the SASE is driven by electron bunches longer than a resonant wavelength, an FEL output pulse consist of spikes which are only partly coherent and, furthermore, it could be a jitter in generated photon energies. These obstacles can be overcome by compressing electron bunches down to a length comparable to a wavelength. On the other hand, electron bunch compression will induce additional energy spread, which will result in drop of an FEL gain and saturation power.

Short-pulse super-radiant THz facility. Such facility is now available at ELBE. The term super-radiance means that all emitters emit light in phase and the generated power scales as a squared number of emitters. The superradiance is achieved at FELs when electron bunches become shorter than a wavelength. The advantage of this FEL scheme, which is also relevant to seeded and SASE THz FELs, is that no strict limitations are imposed on the electron bunch repetition rate. The main disadvantage is that for super-radiance very short electron bunches are required, which are compressed by a chicane. This, on the other hand, induces additional energy spread and super-radiance can occur only at small distances inside an undulator. As an example, the super-radiant THz ELBE facility contains thee undulator with 8 periods, which is significantly shorter than a saturation length and limits the energy of THz pulses down to 100 μJ.

Multi-pass FEL oscillator. The oscillator mode is the most common for IR FELs. The advantages of this mode are: *a)* compactness; as oscillators are equipped with resonators confined by mirrors, undulators are compact and a high output THz power is achieved via multiple passes of an optical pulse through an undulator such that at each oscillator pass the light pulse interacts with a "fresh" electron bunch. The cavity length, L, relates to the repetition rate of electron bunches, F, as $c/2L = F$. From the formula it follows that with higher repetition rates more compact cavities can be employed. The RF linac rate of 35 MHz corresponds to the cavity length of 4.26 m; *b)* relaxed requirements for a quality of electron bunches; the quality of electron bunches determines the FEL gain and in oscillators a reduced gain, *e.g.,* due to the emmittance, energy spread *etc.* can be compensated by multi-pass scheme. Furthermore, ultra-short electron bunches, *i.e.,* shorter than a resonant wavelength that, for instance are required to drive super-radiant THz facility, can hamper the optical energy build-up in an oscillator cavity. The reason is that with ultra-short electron bunches the additional gain mechanism, known as the stimulated super-radiance, will become available and can compete destructively with the conventional FEL stimulated amplification mechanism; *c)* the oscillators are suitable for SC linacs enabling one, *e.g.,* to generate powerful quasi-cw light. In contrast to the abovementioned schemes, the FEL oscillators require a stable repetition rate of electron bunches with almost zero jitter.

We conclude that the most attractive scheme for our envisioned SC THz FEL is an oscillator configuration.

6.1 Preliminary THz light characteristics

Historically the THz spectral range lacked light sources and it is often called in the literature as "THz gap". Nowadays, the interest to the THz region grows very rapidly and development of a powerful and versatile THz light source at this moment of time, when we are still on the crest of growing THz community (Fig. 1.1), is the most appropriate. An envisioned THz FEL spectral range covered is 100 μm to 1 mm, because *a)* it is often requested by users and *b)* in this spectral region other types of available light sources cannot compete with the FELs for tunability, peak and average power.

Table 2: *Preliminary THz light characteristics.*

Electrons energy	10-20 MeV
Electron bunch duration	5-10 ps
Optical wavelength range	50−1000 μm
THz pulses repetition rate	35.2 MHz
FEL cavity length	4.26 m
Undulator K parameter	1-4
Undulator period length	9 cm
Number of undulator periods	30
Single THz pulse duration	5-100 ps
Single THz pulse energy	10−20 μJ
Peak THz power	order of MW
Average THz power	350-700 W

The FEL light parameters can accurately be predicted based on numerical calculations and we have at our disposal the multi-frequency multi-mode FEL code developed by Vitali Z. during his PostDoctoral project devoted to the development of FLARE, which is well suitable for simulating the THz FEL dynamics. Some preliminary parameters can roughly be estimated without performing time-demanding calculations. With a 30 periods undulator we can expect a maximum FEL efficiency at saturation to be 1-3 %, which implies for the 10-20 MeV electron energies and for 10 % cavity outcoupled energy an optical pulse energy to be around 10-20 μJ with an average power of 350-700 W. The gain should be sufficiently high to achieve saturation within a few μs. Very preliminary THz light characteristics are summarized in Table 2. Note that the values quoted in Table 2 present higher limits for THz energy and power since losses were not taken into consideration.

6.2 Operational principle of the short-pulse FEL

The slippage parameter is defined as

$$\mu = \frac{N_u \lambda_r}{\sigma_z}, \tag{6.1}$$

where N_u is the number of undulator periods, λ_r is the FEL light resonant wavelength, and σ_z is the length of the electron bunch. When an FEL operates at a slippage parameter larger than 1, the short-pulse effects play an essential role in the FEL operation. Short-pulse effects literally mean that at any place inside the undulator an electron bunch interacts only with a fraction of a THz pulse. In short-pulse FELs, the maximum gain and maximum efficiency are achieved at different cavity length. The highest efficiency occurs at completely synchronized cavity which, on the other hand, is characterized by a very small FEL gain, a phenomenon known as "lethargy". This behavior provides a tool to vary a length of produced THz pulses. At higher efficiencies, which occur at small cavity detunings, a larger amount of cavity longitudinal modes is excited and, as a result, shorter THz pulses are generated. For instance, as it was demonstrated at FELIX, with such an approach 6 optical cycles pulses were obtained [9].

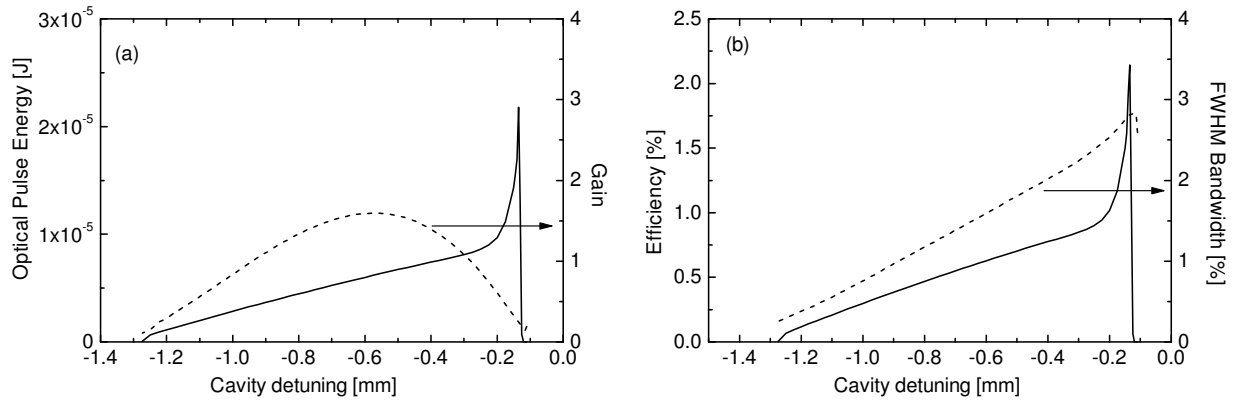


Figure 6.1: Numerically obtained data for FLARE at the resonant wavelength of 100 μs. a) The detuning curve (solid line) and linear-signal FEL gain (dashed line). b) The FEL efficiency at saturation (solid line) and FMHM bandwidth of THz pulses (dashed line).

6.3 FEL waveguide dynamics

Due to the significant diffraction of THz light even at short distances, the THz FELs are usually equipped with waveguides. Because of the waveguide dispersion an FEL can simultaneously fulfill resonant conditions at two different frequencies such that a lower frequency resonant wave propagates with a group velocity slower than electrons and it is opposite for a higher frequency resonant wave. Usually the higher frequency wave is amplified while another one is suppressed to avoid two branches competitions. On the other hand, as it was recently demonstrated by Zhaunerchyk *et al.*, the selective amplification of the lower-frequency branch can be obtained via stimulated super-radiance [10]. By varying waveguide geometry, *e.g.*, a distance between waveguide walls, which in its turn will affect the resonant conditions, it is possible to achieve a grazing point at which two resonances will emerge into one. The obtained single pulse will propagate with a group velocity close to electrons speed, *i.e.*, THz light will be generated with zero slippage resulting in short THz pulses [11].

6.4 Pulsed and cw-mode

The envisioned THz FEL will operate in a pulsed mode generating a continuous train of 10-100 ps short light pulses and the pulsed mode is an intrinsic feature of FELs driven by RF LINACs. An operation in a cw-mode producing a continuous light with nearly constant in time intensity will be of great benefit as it will open up new directions of research. The prominent application of the cw THz FEL is an extremely high-resolution spectroscopy. The cw-mode of pulsed IR FEL was demonstrated with FELIX [13]. The main idea behind this principle is to phase-lock a train of THz pulses, which literally means, to make them identical and to eliminate any jitter in optical pulse time periods. The inter-pulse phase-locking (coherence) can occur spontaneously or it can be induced by introducing additional intra-cavity (see, *e.g.*, ref. [12]).

6.5 Enhancement of the FEL efficiency

The efficiency of the oscillators is usually around a few percent which means that only a few percent of electron bunch energy can be transferred to the light energy and, in this respect, the FEL is a low-efficient device. The efficiency can be enhanced in different ways. One way is to implement two planar undulators instead of one located perpendicular to each other. Such a combined undulator resembles a helical one and it will generate circularly polarized light. Another way is to introduce longitudinal magnetic field into an undulator [14], [15]. An additional axial magnetic field also allows one to generate the second frequency and excite modes with different polarizations. The proper mode selection can be achieved by means of frequency and mode selective Bragg mirrors [16].

7 Conclusion

THz radiation is an important research tool in solid-state and molecular physics, superconductivity and biophysics. The number of publications on research using THz radiation is increasing exponentially and the area of applications is expanding. We propose a versatile THz source based on free-electron laser with a superconducting linac that can not only meet today users requirements but also provide THz radiation with novel unique features.

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