8 Free Electron Lasers

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The accelerators at MAX-lab give new opportunities reagarding Free Electron Lasers (FELs). The linac can run both as a driver for an IR-FEL (infra red) at 25-75 MeV and for a UV-FEL (ultraviolet) at 200-500 MeV. The new storage ring has capabilites to supply beam to a storage ring FEL.

8.1 IR-FEL

The IR-FEL will need an electron beam meeting a number of critera which will allow fruitful operation:

Desired parameter	**Influences**
Peak current	Gain
Charge	Output power
Bunch length	Slippage
Emittance	Gain
Energy spread	Gain

From the viewpoint of the Gun and accelerator some of these parameters are interchangeable (like peak current and bunch length).

Table 8-1. Summary table. Not including output power considerations.

	Injector design	5 um	75 um
Peak current	30 A	30 A	<30 A
Bunchlength	1 - 10 ps	> 0.3 mm (1 ps)	> 2.25 mm(7.5 ps)
Charge	0.25 nC	> 0.08 nC *)	(0.17 nC at 10 A)
Emittance	30 mm mR	< 50 mm mR	
Energy spread	0.2 %	< 0.3 %	
Pulse length	2 us **)	~10 us ***)	

*) The charge is given by the need for peak current and bunchlength. If a longer bunchlength is used, the charge has to increase.
**) The value at the existing system. It can fairly easy be elongated.
***) The pulse length is dependent of the peak current, energy spread and emittance. With the given performance saturation is reached earlier than 10 us at 5 um.

8.1.1 Electron beam charge

The charge in the electron beam defines not only the gain, but also the maximum output powers from the system. A set of combinations has been simulated showing the characteristics of the problem.

Table 8-2. Bunchlength, peak current and charge (assuming gaussian longitudinal charge distribution).

Case	***Bunch length (sigma) (mm / ps)***	***Peak current (A)***	***Charge (nC)***	***Max wavelength (um) due to slippage***
0	2 / 6.7	30	0.5	22
1	1 / 3.3	30	0.25	11
2	1 / 3.3	20	0.17	11
3	0.5 / 1.7	30	0.13	5.5
4	2 / 6.7	20	0.34	22
5	2 / 6.7	10	0.17	22
x	0.66 / 2.2	30	0.17	(no simul.)
y	0.3 / 1	30	0.08	(no simul.)

The gain is mainly dependent of the peak current, thus case 0, 1, 3 and x will give approximately the same gain (all with 30 A peak current). At 5 um the cases with less peak current will not give sufficient gain.

At 20 um the situation is very much improved. All cases have gain enough, but some will have problems reaching saturation before 5 us. The various charges are directly shown in the maximum saturating energy.

The saturating energy is dependent of the charge in the bunch. To make the laser operate it is more important to reach shorter bunches than a high charge. On the other hand to extract a high power the charge is of higher importance.

8.1.2 Slippage

The slippage is given by the number of periods time the radiation wavelength. This distance should be smaller than the bunch length.

Table 8-3. Slipage for two different undulators at different wavelengths.

Number of U periods	*Wavelength (um)*	*Slippage (mm)*
60	5	0.3 / 1.0
60	10	0.6 / 2.0
60	20	1.2 / 4.0
60	50	3.0 / 10
30	50	1.5 / 5
30	75	2.25 / 7.5

The slippage gives a minimum bunchlength of 1.0 ps at 5 um. At the other edge we need to operate up to above 7.5 ps at 75 um. (50 um can be reached in both undulators, reducing the bunch length size).

8.1.3 Energy spread

At 5um very little is gained by reducing the energy spread from (σ_E/E) 0.2 % to 0.1 %. On the other hand if the energy spread increases to 0.5 % a significant reduction in gain results, and a further increase will give an almost impossible situation.

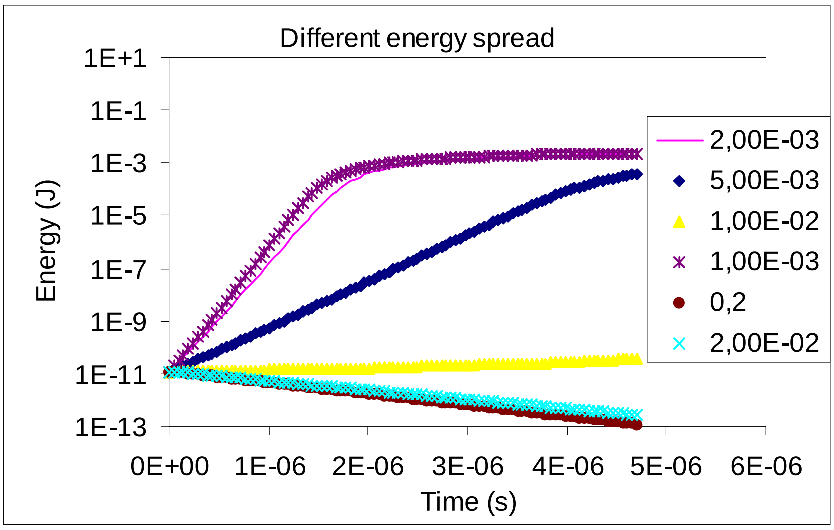

Fig. 8-1. Intracavity energy at different energyspreads

8.1.4 Emittance

The sensitivity to emittance in the actual range is not very large. A reduction of the emittance below (ε_{norm}) 30 mm mRad will not give an increase in performance, while an increase has to be up to 100 mm mRad before a significant reduction in gain is observed.

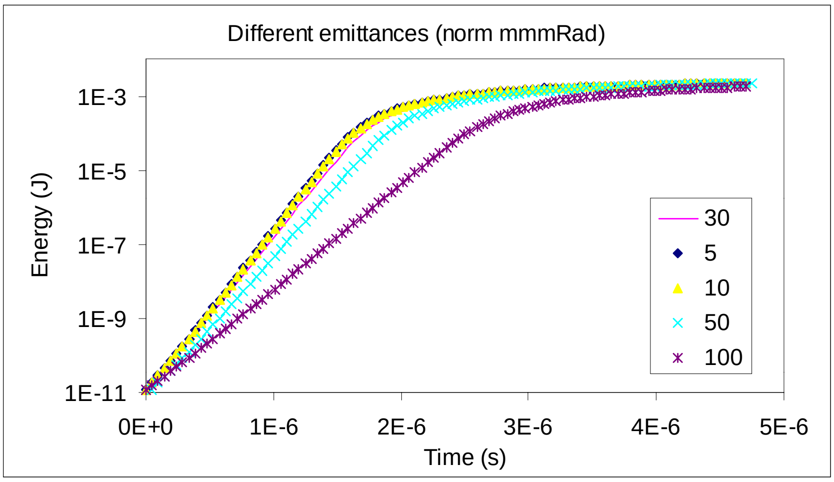

Fig. 8-2.Intracavity energy at different emittances

8.2 VUV-FEL at the recirculated LINAC

Two years ago there were discussions regarding a 500 MeV linear accelerator as injector for MAX II. The idea was abandoned by several reasons. Included in these discussions were the concept of using the source as a driver for a SASE (Self Amplified Stimulated Emission) FEL in the VUV region (225 - 25 nm or 6 - 50 eV).

With the new ideas of a recirculating linac using an RF gun it is tempting to see how such a systems compares to the desires presented then (Table 8-4).

Table 8-4. Specifications for the VUV SASE FEL [xxi]

Electron energy	175 - 500 MeV
Peak current	400 A *)
Energy spread	0.07 % HWHM
Normalised emittance	10 mm mRad
Electron micropulse length	> 1 ps **)

*) Corrected to 400 A in the errata to [xxi].
**) The value on electron pulse length is mainly dominated
by slippage, and the system can tolerate shorter micropulses than 1 ps.

The accelerator system performes in a way that:

1. Energy spread is mainly given by the micropulse length while passing the linac.
2. The micropulse length is given by the gun and the compressor.
3. The emittance is mainly given by the gun, space charge and the compressor.
4. The peak current is given by the charge from the gun and compression.

8.2.1 Energy spread

A HWHM energy spread of 0.07% translates into a FWHM of 3 deg in phase of a 3 GHz cycle => Δl= 2.8 ps. Thus by keeping the micropulse below 2.8 ps will ensure the energy spread. (By a perfect phasing in the linac the double pulse length could in principle be accepted).

8.2.2 Peak current and bunch length

A conservative maximum value for the bunch charge of a thermionic rf-gun can be assumed to be Q = 0.2 nC [xxii,xxiii].

$$Q = \frac{1}{2}\hat{I}\Delta l$$

To reach $\hat{I}$=400 A means Δl= 1ps.
Simulations at lower charge (0.03 nC) has shown a length of 0.83 ps FWHM, though with a very non Gaussian shape.

The linac is relatively unsensitive to the peak current and only "sees" the average current. The linac can stand up to 250 mA average current and can accelerate 100 ns macro pulses. Each microbunch of 0.2 nC will give 2 mA average current over 100 ns, which allows for 125 filled buckets out of 300. In practice one will probably operate with just 1 or 2 buckets filled due to beamloading giving a change in energy between microbunches and thus a change in photon energy.

8.2.3 Emittance

In simulations the normalised emittance is around 15 πmm mRad. Such a value would make operation below 50 nm very difficult.

8.2.4 Summary

The performance of the recirculated linac with a thermionic rf-gun is close to the desires of the SASE VUV-FEL, though some values are still unreliable.

Table 8-5. Recirculated linac performance

Electron energy	25 - 500 MeV	
Normalised emittance	15 π mm mRad (hor)	at 0.03 nC/bunch
Energy spread	0.27 % FWHM 0.012 % FWHM	after compressor, 0.03 nC after linac at dl=0.83 ps
Micropulse length	0.83 ps FWHM	very non Gaussian shape, at 0.03 nC/bunch

The gun performance at higher micropulse charges, causing space charge problems, has to be investigated and a careful review of the buncher has to be made. It is also necessary to address weather a second buncher has to be introduced. In the present linac design there is suitable space at 250 MeV, or lower if the final energy is below 500 MeV.

A better way to solve the problem is to introduce a photo RF-gun where the actual production process of electrons can be tailored to suit the overall accelerator system. More electrons with a smaller emittance can be produced.

8.3 Storage ring FEL

See Design report part B.