EUROFEL-Report-2007-DS2-046

EUROPEAN FEL Design Study

Deliverable N°:	D 2.5
Deliverable Title:	Effects of CSR/LSC and comparison with simulation results at FERMI
Task:	DS-2
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Contract N°:	011935

Project funded by the European Community
under the "Structuring the European Research Area" Specific Programme
Research Infrastructures action

FORMATION OF ELECTRON BUNCHES FOR HARMONIC CASCADE X-RAY FREE ELECTRON LASERS

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Work partially supported by the EU Commission in the sixth framework programme, contract no 011935 EURO-FEL-DS2.

Introduction

The operation of x-ray free electron lasers (FELs) relies on extremely high quality electron beams. The main phenomena affecting electron bunches include space charge effects, wake-fields and coherent synchrotron radiation (CSR). Nonlinearity of the waveform of the accelerating field in the linac and nonlinear time-of-flight characteristics of bunch compressors also play an important role [1,2]. More demanding for the electron beam quality are FELs that are designed to generate temporally coherent x-rays, as for example FERMI@elettra. These FELs, called high-gain harmonic generation FELs or simply harmonic cascade FELs (HC FELs) [2-5], employ a laser to seed the radiation at a lower harmonic of the output FEL radiation. Very often several FEL cascades are used to obtain the radiation at the x-ray wavelength. In these cases the radiation produced in one cascade by one group of electrons proceeds ahead and interacts with other electrons from the same electron bunch in the next cascade. Thus, relatively long electron bunches are needed to accommodate this technique. The overall goal for a design of the electron beam delivery system responsible for the formation of the electron bunches for HC FEL is to obtain a so-called flat-flat distribution, i.e., flat in the peak current and flat in the energy, which means that there are no peak current and energy modulations of electrons along the electron bunch.

Reverse tracking

The basic premise is that the output bunch configuration is largely pre-determined by the input bunch configuration and, thus, it is possible to find a unique electron density distribution at the beginning of the linac that produces a flat-flat distribution at the end of linac. Finding this distribution can be relatively easy. One just needs to reverse the problem, i.e. start at the end of the linac and move backwards towards the beginning of the linac. In ref. [1-2] it is well justified the concept of reverse tracking in accelerating sections and in bunch compressor, assuming relativistic electron beams long enough to ignore

CSR effects on the energy electron distribution.
Starting with the desirable flat-flat distribution (energy and current) at the end of the linac and tracking it backward, the nearly linear ramped peak current shown in Fig. 1 is obtained at the start of the accelerator.

This result can be understood if one uses the wake function for an accelerating section consisting of an array of cells [8] and convolute it with the linear ramped peak current distribution shown with the red line in Fig. 2a. Producing the linear ramped peak current distribution at the beginning of the linac is a challenging task addressed in [9]. The main idea is to use the photocathode laser and to shape the intensity of its pulse such as to produce the electron density distribution at the cathode that will eventually evolve due to the space charge forces into the linear ramped peak current distribution at the end of the injector (assumed to be at approximately 100 MeV). Simulations show the best distribution has a characteristic quadratic ramp in the electron density.

Bifurcation in phase space and peak current spikes

The peak current spikes at the edges of the compressed electron bunches are largely due to the compressor's second order time-of-flight parameter T_{566} and the cubic chirp in the electron energy distribution ($\mu = d^3E/dt^3$) . Controlling μ is likely the only way to control the bifurcation for a given R_{56} since T_{566} is often bound to $T_{566} \approx -3/2R_{56}$ if sextupoles are not used in the bunch compressor.
It should be pointed out that by using a cubic energy chirp as a knob, one can obtain either flat-flat distributions or distributions without spikes rather routinely, but not both features at the same time. However, one can effectively employ the peak current distribution in the gun to provide the needed μ using the wakefields. In the case of strong wakefields this method has been found to be much more effective than a correction using high harmonic cavity [10].
The electrons sitting at the edges of the electron bunch often deviate in energy from the energy of most other electrons. This feature can be explored in a complementary procedure for the removal of the spikes in the peak current if the electron distribution in the phase space has a characteristic s-type shape. Then, it is possible to dissolve clusters of electrons at the edges of the electron bunch by sending the electron beam through the lattice with a properly adjusted time-of-flight parameter R_{56}. Typically a ''dog-leg'' type lattice is used to connect the end of the linac to a chain of FEL's undulators and the necessary adjustments in R_{56} can be easily done there. The particle tracking code ELEGANT [11] was used in order to obtain the electron distribution in the longitudinal phase space and a histogram of the electron peak current at the entrance of the FEL, thus verifying the validity of all the techniques described here. These calculations were performed for FERMI@Elettra linac [12] using a ramped peak current distribution at the entrance of the linac shown with the black line in Fig. 2a. The result of these calculations is shown in Fig. 3. We note that these calculations included CSR effects in the bunch compressors,

but predictably its impact is not much visible on a large time scale.

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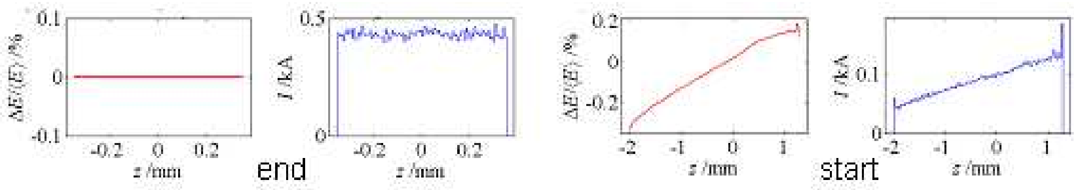

Figure 1. Reverse tracking beginning with flat-flat distribution at the end of the accelerator (end) and moving towards beginning of the accelerator (start). Results obtained by LiTrack [7].

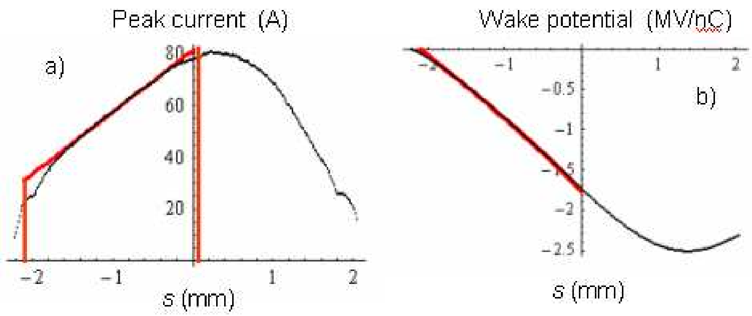

Figure 2. Density distribution with a linear ramped peak current (a) and a correspondent wake potential (b). The red line shows a desirable ideal distribution and its associated wake potential. The black line shows the realistic density distribution obtained in the studies of the photo-injector using the laser pulse with a quadratic ramp in the intensity (a), and the wake potential that corresponds to that distribution (b).

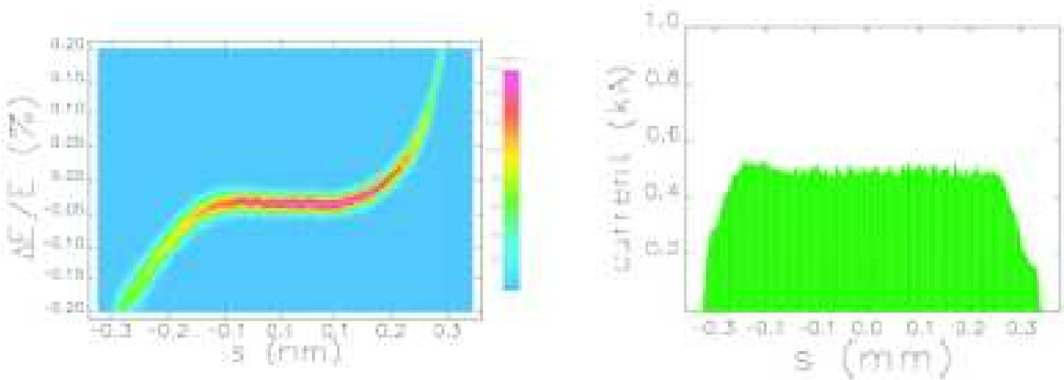

Figure 3. The electron density distribution in the longitudinal phase space (left plot) and a histogram of the peak current (right plot) at the entrance of the FEL undulators calculated for the FERMI@Elettra linac.