

AUTOMATION OF THE WAVELENGTH CHANGE FOR THE FERMI FREE ELECTRON LASER*

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Abstract

FERMI is a user facility based on a seeded Free Electron Laser (FEL). A unique feature of FERMI in this new class of light sources is the tunability of the emitted photon beam both in terms of wavelength and polarization. Tuning is obtained by choosing the appropriate gap and phasing of the undulators in the chain and by opportunely setting the seed laser wavelength. A series of adjustments are then necessary in order to keep constant the machine parameters and optimize the radiation characteristics. We have developed a software application, named SuperGap, which does all the calculations and coordinates the operations required to set the desired wavelength and polarization. SuperGap allows operators to perform this procedure in seconds. The speed and accuracy of the wavelength change have been largely exploited during user dedicated shifts to perform various types of scans in the experimental stations. The paper describes the algorithms and numerical techniques used by SuperGap and its architecture based on the TANGO control system.

INTRODUCTION

FERMI is a FEL based fourth generation light source operated by Elettra - Sincrotrone Trieste S.C.p.A., as a user facility. It produces stable, high brilliance, coherent, narrow bandwidth photons in the VUV soft X-rays wavelength regions, with variable wavelength and polarization [1]. Two FEL lines cover the foreseen range. FEL-1, based on a High Gain Harmonic Generation (HGFG) single stage source seeded by an external UV tunable laser (230 - 260 nm), covers the range from 100 to 20 nm [2]. In order to get down to 4 nm, still starting from the external UV seed laser, a double stage HGFG cascade is adopted for FEL-2. The FEL-1 line consists of a planar undulator ("modulator") and six APPLE-II type undulators ("radiators"). The FEL-2 line consists of a first stage of one modulator and two radiators followed by a second stage of one modulator and 6 radiators. The two FEL chains are fed by electrons produced by a laser driven photocathode gun and accelerated to 1.2 or 1.5 GeV energy by a normal conducting 3 GHz linac. Recent reports on the status and progress of FERMI can be found in [3] and [4].

A unique characteristics of FERMI is the possibility to rapidly change the polarization and wavelength of the FEL radiation. The speed and ease of polarization and wavelength change is extremely important for all the experiments exploiting the FERMI radiation. We have developed a software tool, named SuperGap to perform this rou-

tine operation in a simple and effective way by means of a graphical use interface.

OVERVIEW OF OPERATION

The HGFG FEL mechanism of FEL-1 requires that the "modulator" (an undulator) of the FEL beamline be tuned to emit synchrotron radiation at the same wavelength of seed laser. The seed laser beam and the electron beam travel on the same trajectory in the centre of the undulators. The "radiators" (undulators) are tuned to emit their radiation at a wavelength that is an integer harmonic of the seed wavelength. In between each couple of "radiators" there is a magnetic device known as phase shifter which introduces a small delay in the electron trajectory in order to compensate the delay introduced by the undulators and keep electron and photons in phase. The setting of each magnetic shifter is determined by the operating conditions of the upstream and downstream undulators (see Fig. 1). In order to tune the FEL to a certain wavelength we must calculate the gap and phase of the undulators and the gap of the phase shifters and the wavelength of seed laser. These parameters are calculated starting from three independent variables: electron beam energy, desired FEL wavelength, desired polarization. The available polarizations are : linear vertical, linear horizontal, right circular, left circular.

SUPERGAP ARCHITECTURE

We have designed SuperGap following a classical layered object-oriented architecture (see Fig. 2). All the SuperGap objects are implemented as TANGO devices [5] and are fully integrated in the control system of FERMI [6].

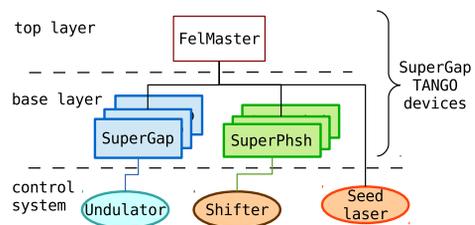


Figure 2: SuperGap architecture.

The base layer consists of TANGO devices in charge of controlling the undulators and phase shifters. The top layer consists of a TANGO device in charge of coordinating and integrating all the devices under a common interface. All these layers have been designed so that all the calculations, logic, etc. are delegated to the lowest possible layer. Beside

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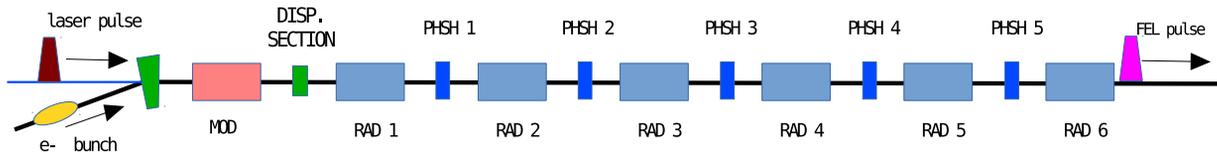


Figure 1: Schematic of FEL 1.

these specifically written devices, SuperGap exploits other already existing TANGO devices for carrying out some of the tasks required for tuning the FEL.

COORDINATION, HARMONIC AND SEED WAVELENGTH SELECTION

When the user selects the desired FEL wavelength L_{FEL} , the coordination layer, named FelMaster, calculates the required wavelength L_{seed} of the seed laser and the harmonic number H to be used by the radiators. The relationship between these quantities is written in Eq. 1:

$$L_{seed} = H * L_{FEL} \quad (1)$$

H must be an integer number, while the seed wavelength must be in the range of the tunable seed laser [7]. There can be multiple valid values for H , in that case we choose the H that maximizes the seed wavelength. The electron beam energy, another important parameter, is acquired directly from the machine or manually inserted by the operator. Once the values of beam energy, harmonic number, polarization and seed wavelength have been determined, FelMaster sends them to the base layer devices. These devices transform the requested parameters into predicted mechanical settings (e.g. gap, phase) which are displayed and evaluated by the operator. If the prediction is acceptable, the operator acknowledges the FelMaster, which instructs all the lower level devices to move to the calculated position, and sets the tunable seed laser to the new wavelength. The FelMaster TANGO device is implemented in Python.

Seed Laser Control

The seed laser wavelength control is carried out by means of a set of TANGO devices which integrate the seed laser, the optical spectrum analyzer and other diagnostics. The spectrum analyzer is used improve the precision and repeatability of the seed wavelength by means of feedback algorithm which is fired at each wavelength change. The feedback loop runs until the desired wavelength is reached or the number of iterations exceeds a certain threshold.

The trajectory (i.e. pointing) of the seed laser is stabilized by a real-time shot-by-shot feedback system implemented in software. The seed laser position is sensed by a CCD camera. The trajectory is steered by means of piezo-controlled tip/tilt mirrors.

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The performance of these system is of critical importance for guaranteeing stable and repeatable FEL operations.

Fixed Wavelength Seed Operation

During some experiments a non tunable seed laser is used [7] [8], which offers a higher seed intensity. This condition is know as third harmonic operations. In this case the operator can only choose the harmonic number H in order to tune the FEL. The FelMaster device performs the same operations already explained with the exception of seed laser wavelength setting.

UNDULATOR CONTROL

Undulators are controlled by a dedicated TANGO device, known as SuperGap. Its main task is to calculate the required mechanical settings to obtain the desired radiation from the electron beam. SuperGap is implemented in Python. SuperGap manages also some auxiliary operations such as setting “parking position”, maximum gap, etc.

All the calculations performed by SuperGap start from tabulated values obtained from measurements performed on each different undulator [9]. From the point of view of SuperGap the undulator is a system with two degrees of freedom: gap and phase (mechanical tapering is not yet used). The calibration tables contains the values of several magnetic and radiation parameters of the undulator, mapped on a two-dimensional grid of discrete (gap,phase) values (for example see Fig. 3).

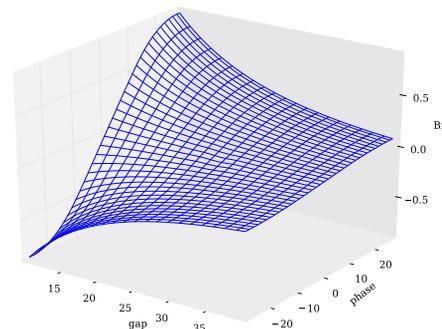


Figure 3: Example of tabulated horizontal magnetic field.

The parameters used by SuperGap are the vertical (B_y) and horizontal (B_x) magnetic field components, the photon wavelength at the nominal electron energy of 1.2 GeV, the electron/photon phase shift at the nominal electron energy.

The requested polarization is obtained by imposing certain relationships on the B_x and B_y components: $B_x - B_y = 0$ for left circular, $B_x + B_y = 0$ for right circular, $B_x = 0$ for linear horizontal, $B_y = 0$ for linear vertical. The two linear cases are very simple, implying by definition, respectively, phase=0 and phase=maximum. The circular cases require some calculations to obtain the correct gap/phase relationship. SuperGap proceed as follows. An auxiliary calibration table is calculated, for example $B_x - B_y$. The auxiliary calibration is used for finding, for each tabulated gap value, the phase at which $B_x - B_y$ is zero.

For each gap value of the original calibration the auxiliary table is evaluated for all the phase values, the resulting $B_x - B_y$ values are used to build an interpolating function using the UnivariateSpline algorithm of the python.scipy [10] package. We then use the interpolated curve to find the phase value giving $B_x - B_y = 0$ using the roots() algorithm [10], thus obtaining the tabulated values of the (gap,phase) couples for the desired polarization (See Fig. 4). The (gap,phase) couples are finally used to evaluate the normalized wavelength and build the wavelength/gap curve for the given polarization. The normalized wavelength is evaluated by means of the RectBivariateSpline function [10], a 2D interpolating function, built on the wavelength calibration table. The process is repeated for the other circular polarization working with $B_x + B_y$.

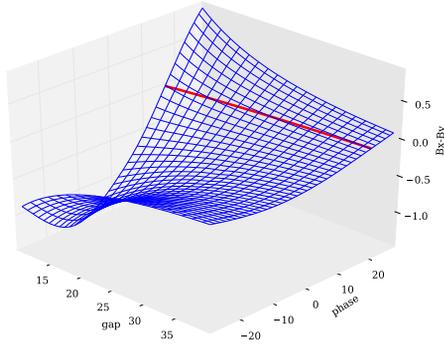


Figure 4: Gap/phase curve for left circular polarization

These new tables are then used to calculate four interpolating functions, one for each polarization, for estimating the nominal photon wavelength as function of the undulator gap. (See Fig. 5).

$$L = f(\text{gap}) \quad (2)$$

All these curves are calculated once during the initialization stage of the TANGO device.

When a new photon wavelength is needed, SuperGap uses the interpolating curve of the wanted polarization to estimate the needed gap. This happens in two stages. First

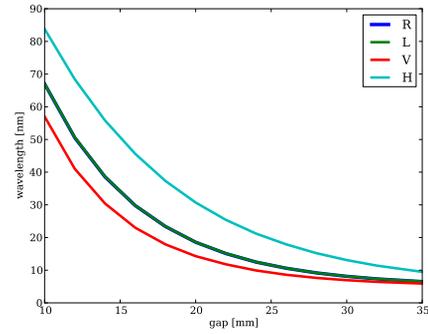


Figure 5: Wavelength/gap curves for the four polarizations: R and L curves are almost identical.

the requested wavelength $L_{undulator}$ is scaled to the nominal wavelength $L_{nominal}$ depending on the effective electron energy E according to (3), where E_0 is the reference energy (1.2 GeV) at which all the undulator parameters have been calculated.

$$L_{undulator} = L_{nominal} \left(\frac{E_0}{E} \right)^2 \quad (3)$$

Then the requested gap is calculated by numerically finding the value that gives $L_{nominal}$ on (2), which is equivalent to finding the root of the base function minus the wanted value. The algorithms used for solving are the Brent method [10] as first choice, and Newton-Raphson in case the first does not converge.

Another important parameter estimated by SuperGap is the phase delay of the electron with respect to a photon emitted by the undulator. Its value is a function of the gap and phase setting and is available in the form of a calibration table; in this case too a RectBivariateSpline interpolating function is built on the calibration data and is used to estimate the phase delay.

SuperGap gives the possibility to modify the setting of each individual undulator by adding an offset to the electron energy used for the calculations and/or adding an arbitrary offset to the calculated gap. These offsets are used to perform some fine tuning of the FEL performance.

PHASE SHIFTER CONTROL

A phase shifter [11] is a small magnetic component used to compensate the shift of the electron bunch relatively to the emitted photon due to the path lengthening of the electron trajectory induced by the undulator. The phase shifter induces a further controlled delay to the electron bunch so that the total shift is an integer number of wavelengths of the FEL photons. FERMI phase shifters are permanent magnet type, the shift is varied by changing the mechanical gap between the two magnet arrays.

The shift for an electron at 1.2 GeV has been calculated relatively to a 100 nm wavelength for a certain set of different gaps and stored in a calibration table.

Phase shifters are controlled by a dedicated TANGO device, known as SuperPhsh. SuperPhsh has been developed in C++. It uses the phase shifter calibration table to calculate the electron shift at its current energy in relation to the FEL wavelength. The nominal shift is estimated by using a spline curve to interpolate the points of the calibration. The nominal shift is then scaled to the preset one by using the current FEL wavelength and electron energy. SuperPhsh main task is to calculate the gap required to compensate a given electron shift. The shift induced by the radiators is read from the the upstream and downstream radiators SuperGap TANGO devices and averaged. SuperPhsh calculates the additional shift needed to bring the total shift to an integer number of wavelengths. The additional shift is then scaled to the standard conditions of the calibration (1.2 GeV, 100nm) and used to solve for the required gap on the calibration interpolation curve using the “regula falsi” algorithm [12]. The interpolating spline and related algorithms are implemented in a custom C++ class.

GRAPHICAL USER INTERFACE

All the main parameters used by the FelMaster, SuperGap and SuperPhsh tango devices are controlled by means of a Graphical User Interface (GUI) (see Fig. 6).

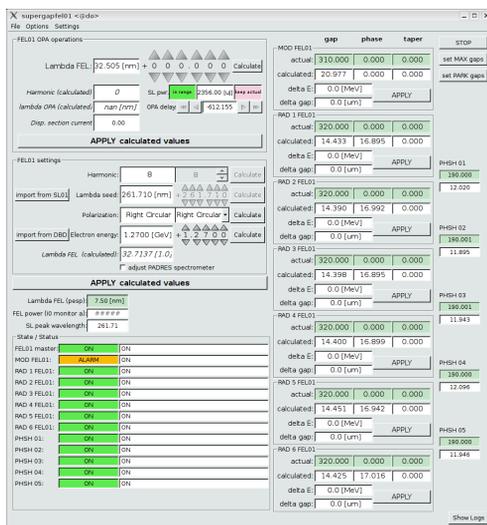


Figure 6: SuperGap Graphical User Interface.

The GUI has been developed in C++ with the QTango library [13]. In addition to the main FEL parameters the GUI displays and allows to change other machine parameters which are used for doing small empirical optimizations of the FEL.

FUTURE DEVELOPMENTS

The possibility to tune some of the radiators to a non-integer harmonic is being implemented. It will be used for “turning off” some of the radiators while performing measurements and optimizations. The present method of turning off a radiator is to open it to a very large gap, which

is quite time consuming and perturbs the propagation of the electron beam.

CONCLUSIONS

SuperGap has been effectively used during many machine study and user dedicated shifts. It has proved to be robust, reliable and very easy to use. Concerning the speed of wavelength/polarization changes, they are practically limited by the speed of the mechanical actuators of the undulators and phase shifters, while the calculation overhead of SuperGap is negligible.

ACKNOWLEDGEMENTS

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