Optimizing the Laser Pulse Shape

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Abstract

Photo Injector Test Facility at DESY Zeuthen (PITZ) is a major challenge in optimizing a high brightness electron beams for future Free Electron Lasers and linear colliders. The goal is to produce intense sources of electrons with very small transverse and reasonably small longitudinal emittance, which meets the requirements for the XFEL project. Decreasing of emittance is main task, which is closely connected to the optimizing the longitudinal shape of UV photocathode laser pulse to the flat top form. This process includes distinguishing the main parameters of the laser flat-top shape, like: full width half of maximum, rise/ fall times and modulation, as well as their dependence on the set parameters of the laser pulse shaper: temperatures and rotation angles of two crystals. The pulse shape parameters together with emittance values retrieved from ASTRA simulations will be used to create a Goal Function, which will contain behaviour of emittance on large scales and will help us to develop an algorithm, which can optimize laser pulse shape and minimize recent emittance value meeting the experiment demands.

1 Introduction

1.1 What is Free Electron Laser?

A free electron laser, or FEL, generates tuneable, coherent, high power radiation, currently ranging in wavelength from millimetres to the visible. While an FEL laser beam shares the same optical properties as conventional lasers such as coherent radiation, the operation of an FEL is quite different. Unlike gas or diode lasers which rely on bound atomic or molecular states, FEL uses the relativistic electron beams as the lasing medium, hence the term free-electron. Free electron lasers can be used to generate terahertz radiation.

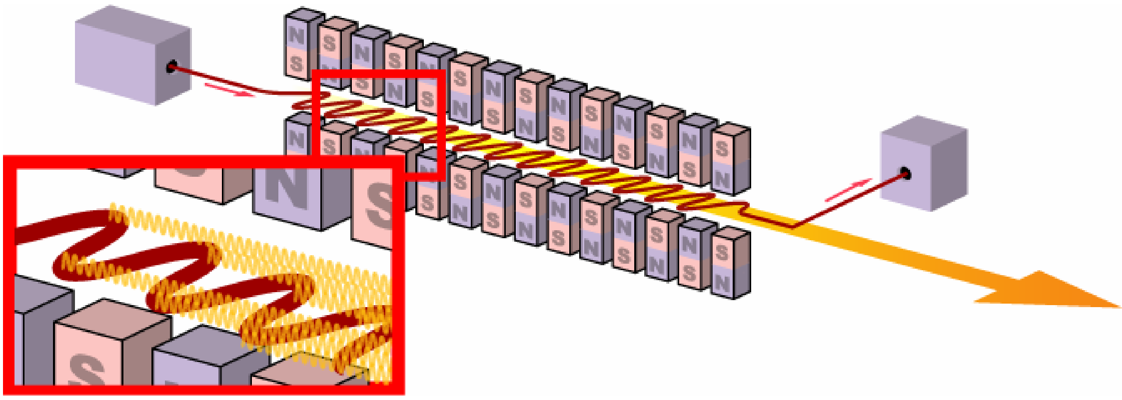

Figure 1: *X-ray free electronic laser scheme of operation*

To create an FEL, a beam of electrons is accelerated to relativistic speeds. The beam passes through a periodic, transverse magnetic field. This field is produced by arranging magnets with alternating poles along the beam path. This array of magnets is sometimes called a undulator because it forces the electrons in the beam to assume a sinusoidal path. The acceleration of the electrons along this path results in the release of a photon (bremsstrahlung or synchrotron radiation, but not in the most common sense of either term).

Relatively viewed, in the rest frame of the electron, the magnetic field can be treated as if it were a virtual photon. The collision of the electron with this virtual photon creates an actual photon (Compton scattering). Mirrors capture the released photons to generate resonant gain. Adjusting either the beam energy (speed/energy of the electrons) or the field strength tunes the wavelength easily and rapidly over a wide range. Since the photons emitted are related to the electron beam and magnetic field strength, an FEL can be tuned, i.e. the frequency or colour can be controlled.

Today, a free electron laser requires the use of an electron accelerator with its associated shielding, as accelerated electrons are a radiation hazard. These accelerators are typically powered by klystrons, which require a high voltage supply. Usually, the electron beam must be maintained in a vacuum which requires the use of numerous pumps along the beam path. Free electron lasers can achieve very high peak powers. Their tuning ability makes them highly desirable in several disciplines, including medical diagnosis and non-destructive testing.

In a klystron an electron beam is accelerated by a 200 kV DC electric field. An electromagnetic wave interacts with it modulating velocity. In a drift tube this velocity distribution is converted to a density modulation. In a second interaction region energy can be converted from the electron beam to the EM-wave or vice versa depending on the relative phase with which both are fed in. If energy is converted to the EM-wave, this device is called a klystron; otherwise it is a linear electron accelerator (LINAC).

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1.2 XFEL Project

In February 2003, the German Federal Ministry of Education and Research gave the green light for the X-ray laser based on the Free Electron Laser concept - XFEL. The project is to be further developed with European partners. After a construction period lasting about six and a half years, the commissioning of the facility could start in 2013. An international research team, the TESLA collaboration, developed and tried out the facility's pioneering technology at a test facility in Hamburg. The free-electron X-ray laser will make it possible to do leading-edge research in Europe and will guarantee a major role for Germany as a location for research and industry.

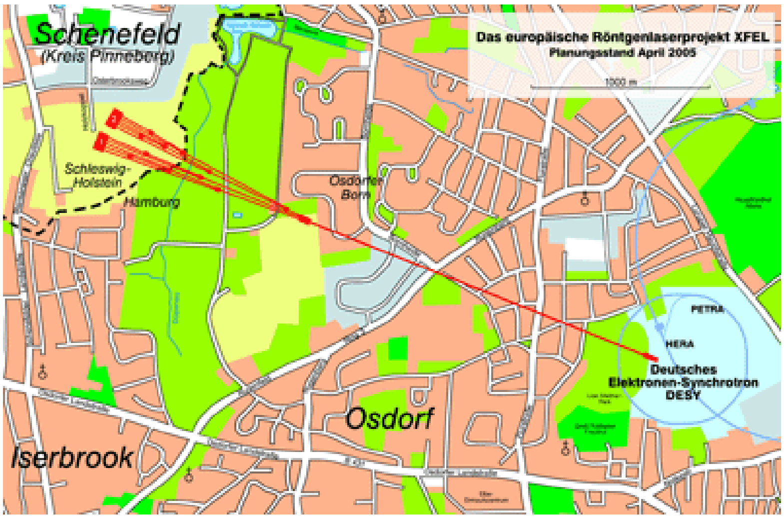

Figure 2: *XFEL future location – tunnel begins in DESY Hamburg and ends in town of Schenefeld*

The purpose of the facility is to generate *extremely brilliant* (peak brilliance ~ 10^{33} photons/s/mm^2/mrad^2/0.1%BW), *ultra-short* (~ 100 fs) pulses of *spatially coherent* x-rays with wavelengths down to 0.1 nm, and to exploit them for revolutionary scientific experiments in a variety of disciplines spanning physics, chemistry, materials science and biology. The design contains a baseline facility and provisions to facilitate future extensions and improvements, in preparation of further progress in the relevant technologies. The basic process adopted to generate the x-ray pulses is SASE (Self-Amplified Spontaneous Emission), whereby electron bunches are generated in a high-brightness gun, brought to high energy (up to 20 GeV) through a superconducting linear accelerator, and conveyed to long (up to ~200 m) undulators where the x-rays are generated. Five photon beamlines deliver the x-ray pulses to ten experimental stations, where state-of-the-art equipment is available for the experiments.

From this new user facility, novel results of fundamental importance can be expected in materials physics, plasma physics, planet science and astrophysics, chemistry, structural biology and biochemistry, with significant possible impact on technologies such as nuclear fusion, catalysis, combustion (and their environmental aspects), as well as on biomedical and pharmaceutical technologies. Thanks to its superconducting accelerator technology, in spite of competing American and Japanese projects, the European X-ray Free-Electron Laser Facility will allow Europe to keep its leadership in basic and applied science with accelerator-based light sources, a leadership it acquired in the early 90's with the construction and operation of the European Synchrotron Radiation Facility (ESRF) in Grenoble.

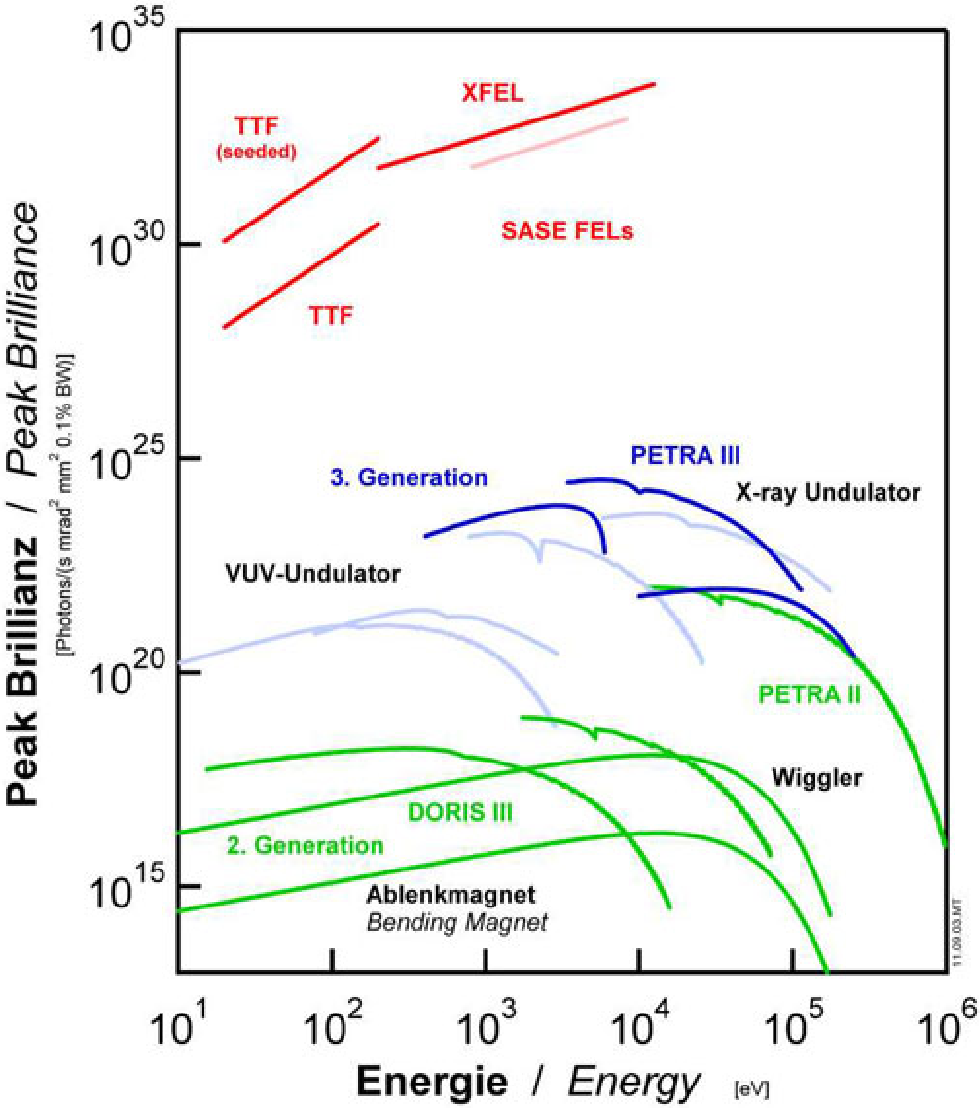

Figure 3: *This comparison of the peak brilliance of synchrotron radiation sources with free-electron lasers shows the great leap in brilliance offered by the FELs.*

2 Photo Injector Test stand in Zeuthen

2.1 What is PITZ?

PITZ (The **P**hoto **I**njector **T**est Facility at DESY **Z**euthen) is a test facility at DESY Zeuthen for research and development on the laser driven electron sources. The main challenge is to produce an intensive electron beam with a very small transverse emittance and rather small longitudinal emittance. The operation includes a continuous conditioning, characterization of the gun, test of new components and optimization. The TESLA Test Facility (TTF) working as VUV-FEL at DESY Hamburg is already running with a gun characterized at PITZ, but to fulfil the high requirements for the European X-ray free-electron-laser (XFEL) an extension of the PITZ facility and its research program is necessary.

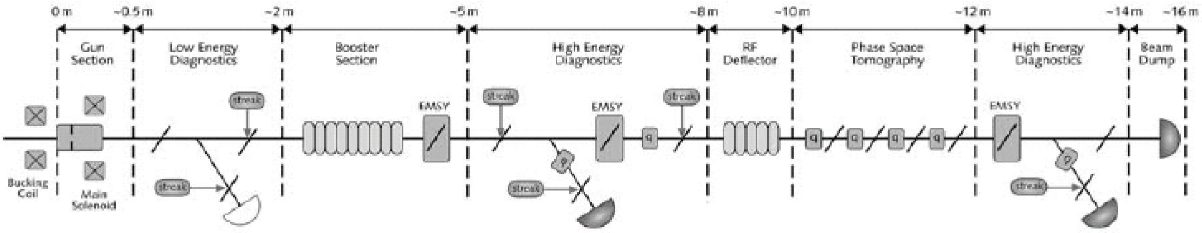

Figure 4: *Schematic view of PITZ*

2.3 Contributions of the existing devices

The first component setting the stage for successful FEL operation is a low-emittance electron source of FLASH (former TTF, VUV-FEL). For that purpose a dedicated photoinjector has been developed, commissioned and characterized at the Photoinjector Test PITZ at DESY-Zeuthen. Having shown satisfactory performance, the gun was moved and installed into TTF, thus considerably saving commissioning time at TTF.

Commissioning of the entire beam line, some 30 m long, from the photoinjector through the first bunch compression at approximately 125 MeV was the first, major commissioning milestone. The beam dynamics of the dense electron bunch is heavily affected by space charge forces up to (at least) 100 MeV, thus representing a serious challenge for the commissioning procedure.

The most important result of injector commissioning was the proof that the injector beam line works as theoretically predicted. For measurement of the beam emittance (see Fig 5), a periodic FODO channel was inserted, permitting a reliable and reproducible determination of beam emittance by four OTR screens, thus eliminating the need of a quadrupole scan.

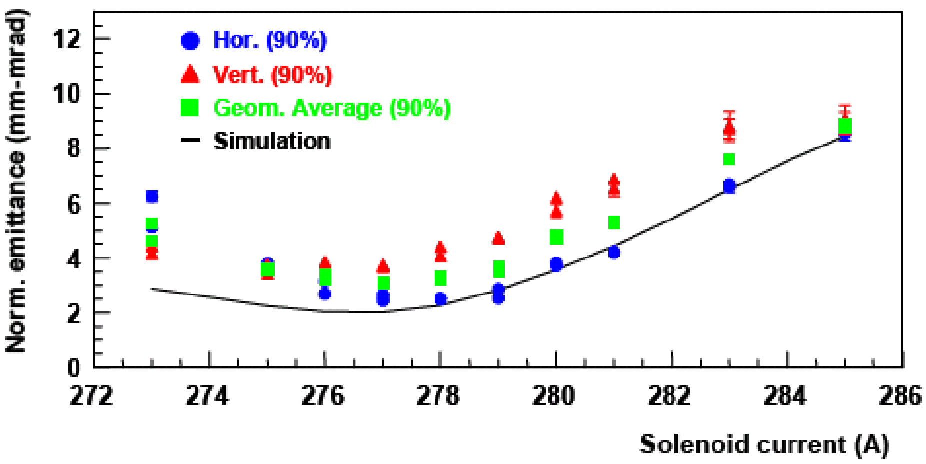

Figure 5: *Measurement of beam emittance at 125 MeV, 1 nC bunch charge as a function of the solenoid current at the RF gun. Emittance values quoted contain 90 % of the bunch charge.*

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Measurements at the PITZ gun test facility indicate that the kinetic energy of the photoemitted electrons is larger than previously assumed leading to a larger initial emittance. This can be largely compensated by reducing the initial spot size and re-optimizing the focusing parameters into the accelerating module. Figure 6 shows the final projected emittance of the electron beam after re-optimization for different initial kinetic energies. The simulation shows, that final emittance for XFEL photoinjector stays below the design value of 1 mrad mm for kinetic energies below 1 eV.

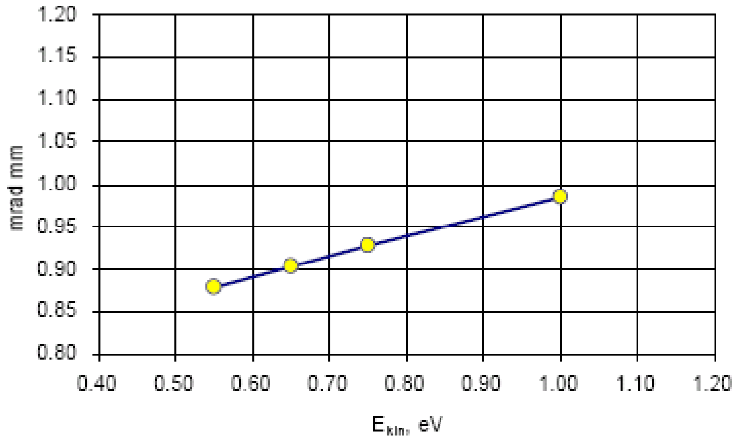

Figure 6: *Final normalized transverse emittance as function of the initial kinetic energy of the photo emitted electrons. A significant increase of the emittance can be avoided by reducing the initial spot size and re-optimizing the matching conditions into the accelerator module.*

2.4 Experimental Status and Future Developments

Transverse core emittance measurements at the photo injector test stand PITZ and at the VUV-FEL yield values of 1.4 mrad mm and below. The measurements at PITZ are performed directly behind the RF gun cavity at beam energy of about 4.5 MeV. The photocathode laser beam is shaped transversely (uniform, circular distribution on the cathode) and longitudinally (flat top, 20 ps length, 5-7 ps rise/fall time). At the VUV-FEL (FLASH) the optimal longitudinal laser pulse form is not available yet, but the acceleration in the first module improves the emittance compensation mechanism, so that similar emittance values are achieved. Measurements at the VUV-FEL are performed at ~125 MeV beam energy and the photocathode laser beam has a longitudinally Gaussian shape of 4.4 ps rms width. The measurement results of the beam emittance and other beam parameters obtained at PITZ and the VUV-FEL are in good agreement with simulation results and the beam dynamics in the gun and the injector are well understood.

While the measured core emittance values reach already the design slice emittance values for the XFEL at the entrance of the undulator, the design value for the injector is specified tighter, in order to operate with a sufficient safety margin. To realize the required improvement of the performance the gradient in the gun cavity has to be increased from the present 42 - 45 MV/m to 60 MV/m, additionally the rise/fall time of the trapezoidal laser pulse should be decreased to 2 ps or below. The development efforts at the test stand PITZ will hence focus on these topics in the upcoming years. Other developments concentrate on further improvements of the high duty cycle operation, general stability issues, reduction of dark current and further investigations of the thermal emittance of photocathodes.

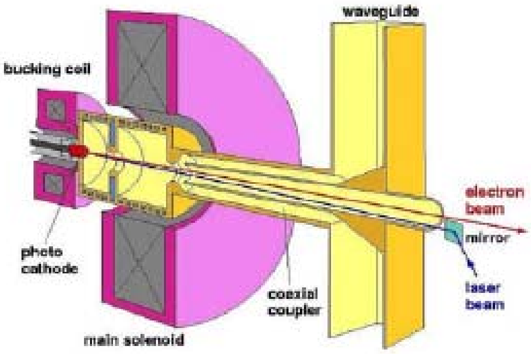

Figure 7: *Schematic view of normal conducting RF gun of PITZ*

2.5 Photocathode Laser

Development of the laser system is mostly considered at PITZ, where interesting ideas, especially the generation of flat-top laser pulses are studied. In the present configuration, the laser is based on a diode pumped pulse train oscillator (PTO). The oscillator is synchronized with the master RF. The pulse train generated by the PTO is longer and has a shorter intra-pulse distance than the required electron bunch train structure (27 MHz at the VUV-FEL).

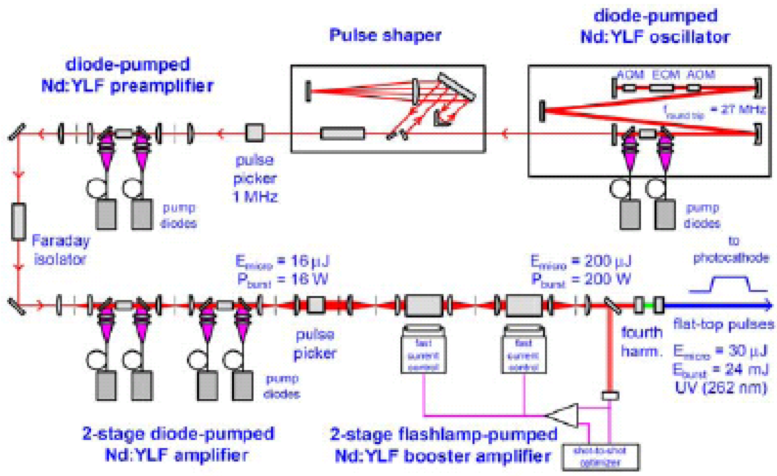

Figure 8: *Schematic view of normal conducting RF gun of PITZ*

A Pockels cell based pulse picker picks out the required pulse train which is then amplified by a chain of diode-pumped amplifiers. The pulse picker not only gives flexibility in choosing the pulse train structure, it also serves as a fast switch-off mechanism for the machine protection system. Since the preferred photocathode material Cs_2Te requires radiation in the UV, the infrared light of the laser is quadrupled in frequency by non-linear crystals to 262 nm. The good quantum efficiency of the photocathode (in the order of a few percent) translates into required laser pulse energy of a few μJ per pulse for a charge of 1 nC. The formation of synchronized picosecond pulses in the PTO is accomplished by an active mode-locking scheme. The laser pulse shaper includes a grating for FT of the Gaussian pulse is changed with the PTO filter with tuneable apparatus function. The filter properties can be controlled by two temperatures T1 and T2, also two rotational angles α1 and α2. The key part is an electro-optic phase modulator driven by the 1.3 GHz frequency of the accelerator. It provides a phase stability of the laser

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pulse in respect to the master RF of less than 0.1 deg or 200 fs (rms). This has been confirmed by measurements of the electron beam arrival time after acceleration at the VUV-FEL. The shot-to-shot stability in energy of the laser pulses and thus the electron bunch charge is 2 % (rms) for single pulses and 1% (rms) averaged over a pulse train. The generation of flat-top laser pulses both in the transverse and longitudinal plane is being successfully tested at PITZ. Operation of such a system is foreseen at the FLASH (VUV-FEL) in the near future.

2.6 Streak Camera

The function of streak camera is the measurement of the light pulse intensity in dependence on the time and the horizontal distribution in space. Figure 9 shows its schematic setup. The light enters through a small horizontal slit and following entrance optics into the streak camera. The entrance optics projects the photon distribution at the slit plane onto a photo cathode, which transforms the light into electrons. These electrons are accelerated in the direction of micro-channel plate by passing by the streak tube, where a high frequent electrical field of 108 MHz is applied, so that electrons are deflected in vertical direction. Depending on the moment of arrival at the streak tube the electrons are differently deflected. The vertical direction displays the temporal distribution of the photon package. The time distribution of the RF field is produced by the master-generator; this has the advantage that deflecting field in the streak camera is synchronized with the production of electron packages in the gun. Therefore successive photon packages are displayed on the same point in the vertical axis and can be superimposed. The micro-channel plate can multiply the number of electrons, which hit afterwards a phosphor screen. The light produced by this screen is recorded by a CCD-camera.

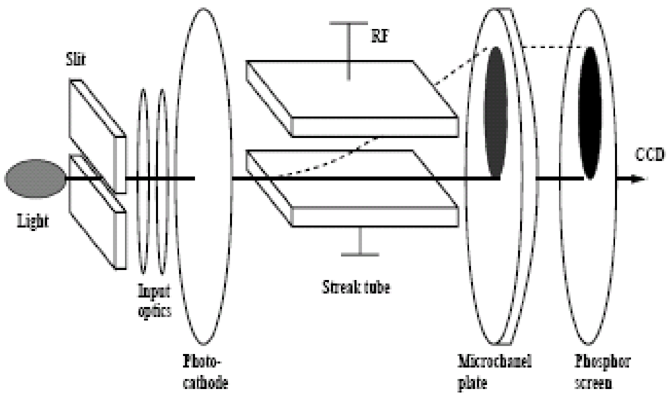

Figure 9: *Schematic set-up of the streak camera and signal producing*

3 Overview of the completed work

3.1 Motivations of research

The laser system is one of the key elements for normal functioning of the Photo Injector, which is critical for the FEL type lasers. Having the laser pulse flat top shape is also very important for reducing the emittance and successful operation. Unfortunately, getting the flat top shape is very difficult, because of the nonlinearity of optical systems, which is the cause of the most flat top shape defects.

These defects can not be avoided, so there is only a way to minimize their value and optimize the laser pulse shape. For this, we have four set parameters for the laser output signal – these are:

temperatures of the two crystals and their rotating angles. Though, the problem still is that there is no clear dependence between the final shape and given set parameters.

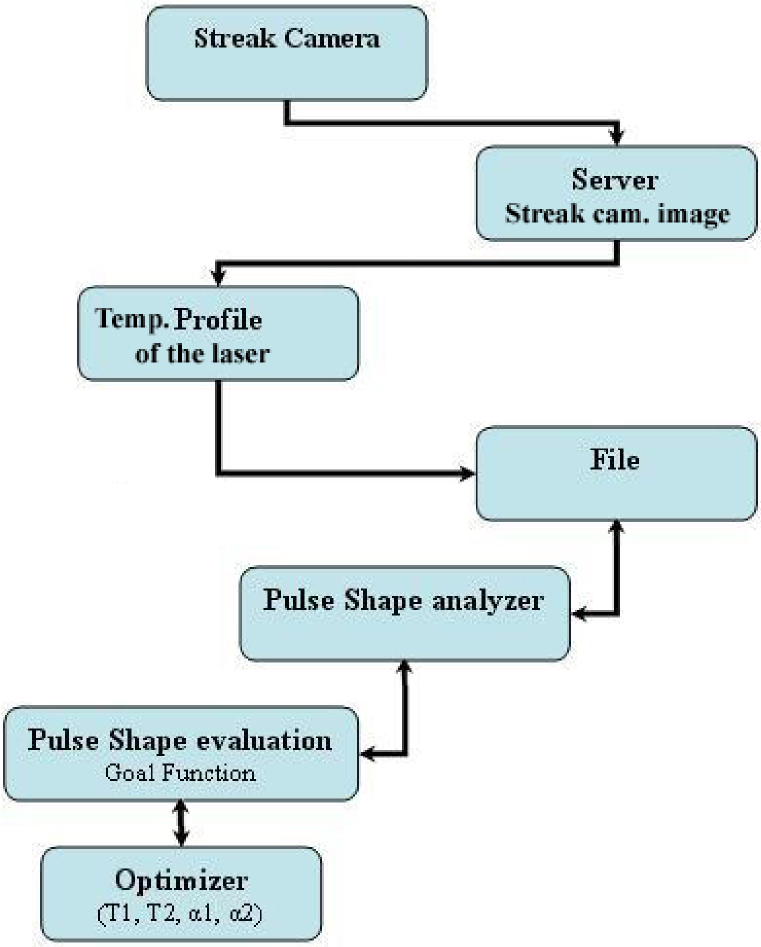

Figure 10: *Scheme of the pulse shape optimization tool*

In that case, we have developed a set of tools, which helps us to analyze the laser pulse shape behaviour due to the set parameter values. As far as, there is no obvious dependence, the block of multi-analysis chain should be constructed, which can be observed in detail on the Figure 10.

For gaining the best flat top shape available all these steps have to be processed in above described manner. Thus after completing the algorithm, laser properties have better solutions.

3.2 Streak camera profile readout

The laser pulse intensity CCD image obtained from streak camera, which can be seen on the Figure 11, is obtained as a continuous motion stream, where observer can easily see its fluctuation and instability over the certain time period. The motion stream is scanned and stored as a numerical array in separate file with csv extension by a custom tool [private communications with S.Weisse], which is updated every 2 seconds. This means we are obtaining a new picture every 2 seconds in a separate file.

The weakness of this method is that the most of the laser pulse shape transform data is lost due to the slow readout and only few pictures from there are analyzed. But as far as the further analyzing mechanisms are slower, this shortcoming should be acceptable.

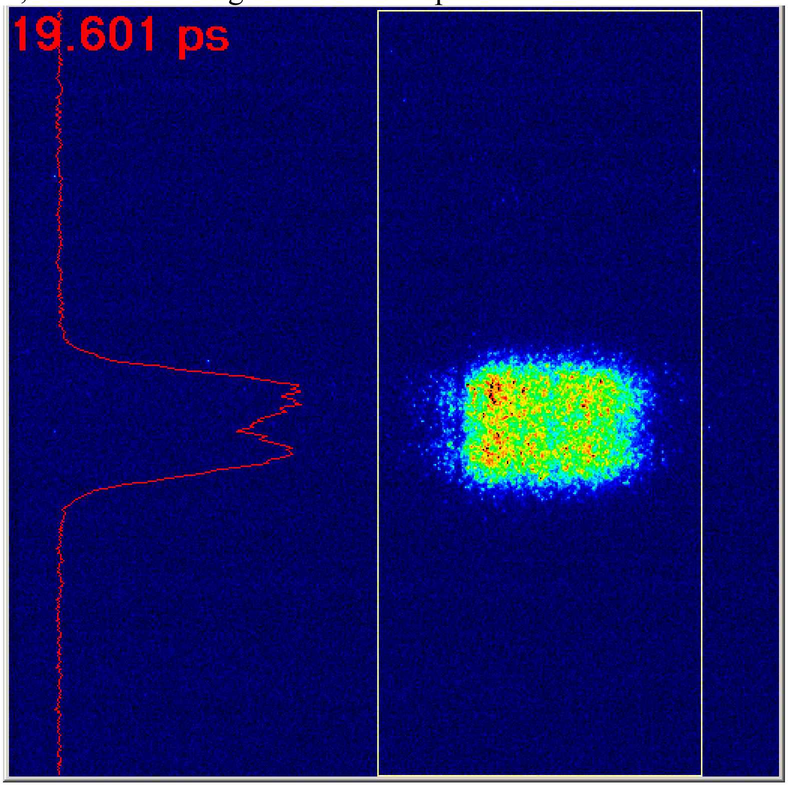

Figure 11: *Laser pulse shape CCD image obtained form Streak Camera*

3.3. Laser pulse shape analyzing program

As one can see from the Figure 11, the laser pulse shape profile is a little bit distorted and hard to analyze. Observer barely can retrieve the parameters of such shape (as Full Width Half of Maximum, rise & fall times, modulation) without having the proper tool, which can fit the desired flat top shape to the measured signal.

For that occasion, we already had the custom Matlab scripts called *fitFT.m* and *TempProfFitGet.m* [private communications with M.Krasilnikov], which reads the numerical array from the above mentioned csv file and fits an asymmetric trapezoidal shape to the saved laser pulse shape, returning the four parameters: FWHM, rise/fall times in ps and modulation in %.

The scripts fit the shape through the minimization of the area difference below measured shape and fitting curve, which can easily understood from the source code of the script. Process runs through the number of iterations (about 100) and finally converges into the trapezoidal shape. Though, the method is highly reliable, multiple evaluations of the fit program, makes our target process slower. Depending on these issues, we tried to modify the initial fitting script.

The previous script used to form a rectangular shape, as the starting fitting curve for the measured pulse shape. The modification idea was to do the additional calculations and change the rectangular shape into a trapezoidal using the deliberated results in the middle of the program itself, named *FlatTopHead.m*. Modification was done and it improved the speed of the fit program, reducing the number of iterations during the fit by 30%, which makes the target minimization algorithm 30% faster.

Though, such kind of approach caused additional problems: in case of the highly asymmetric laser pulse shape, the trapezoidal fitting was inefficient and in most events caused illegal results. This bug was fixed during the test operations of the minimization algorithm in the PITZ Control Centre by adding some additional conditions to the flat top fitting script.

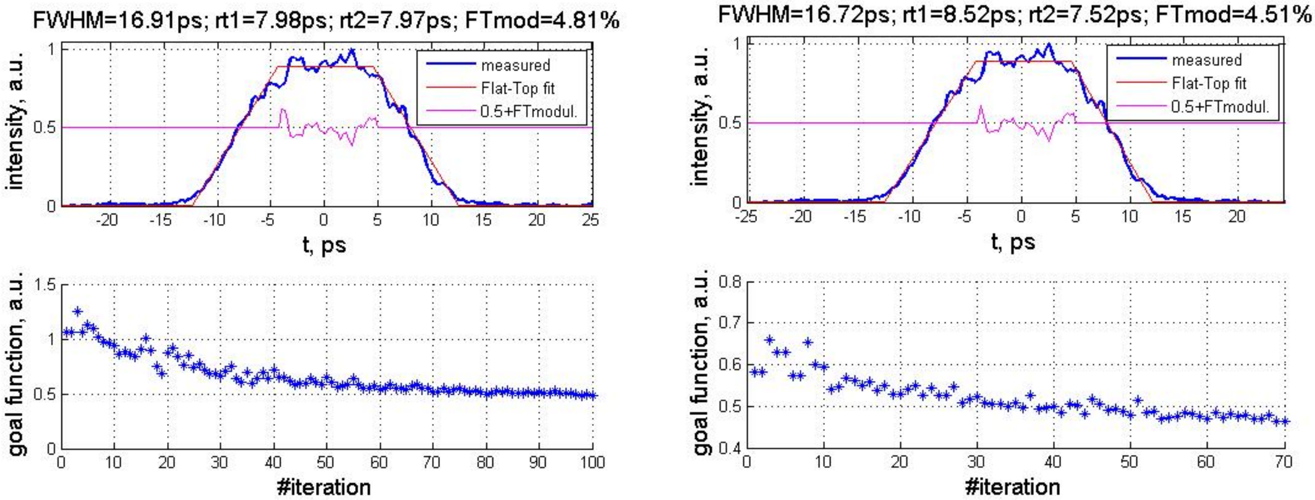

Figure 12: *On this figure you can compare the old (left) and new (right) fitting scripts*

On Figure 12 one can easily see the difference between the old and modified flat top shape fitting scripts: old (on the left) converges to the solution after 100 iterations and new (on the right side) after 70. This makes operation much faster and in several cases fitting seems to be more reliable. Blue line on the upper plots stands for the actual readout of the numerical array from the csv file; pink line along the actual shape is the fitting curve, parameters of the fit are displayed in top line; and the strikethrough red line corresponds to the modulation.

3.4 ASTRA simulations and construction of Goal Function

We described the process of getting the laser pulse shape intensity profile and retrieving the pulse parameters from it. After this process, we should evaluate our form and decide whether it is good or not – change or keep it in order to elaborate figure of merit.

Retrieved parameters serve as an input for the Goal Function defined before, from numerous simulations, made by program ASTRA (A Space charge Tracking Algorithm), which projects the tracks of input particles and take their space charge into account, in our case, we used 10000 particle simulations for different types of modulations. We used the script, which modifies the input file for ASTRA (cathgen.ini) and writes a sinusoidal shape for with different amplitudes, without harming the injection process, in a precise manner, which does not spoil tracking process.

Furthermore, retrieved values from ASTRA simulations you can see on one of the contour plots, horizontal axis correspond to a FWHM and vartical axis to the Rise/Fall time. Color fill describes the value of simulations. On the left you can see normalized transverse emittance, which is coupled with the normalized longitudinal emittance along the line FWHM=20ps. Both of the emittances are normalized in the point FWHM=20ps and rise/fall times=2ps; which is needed for coupling these values.

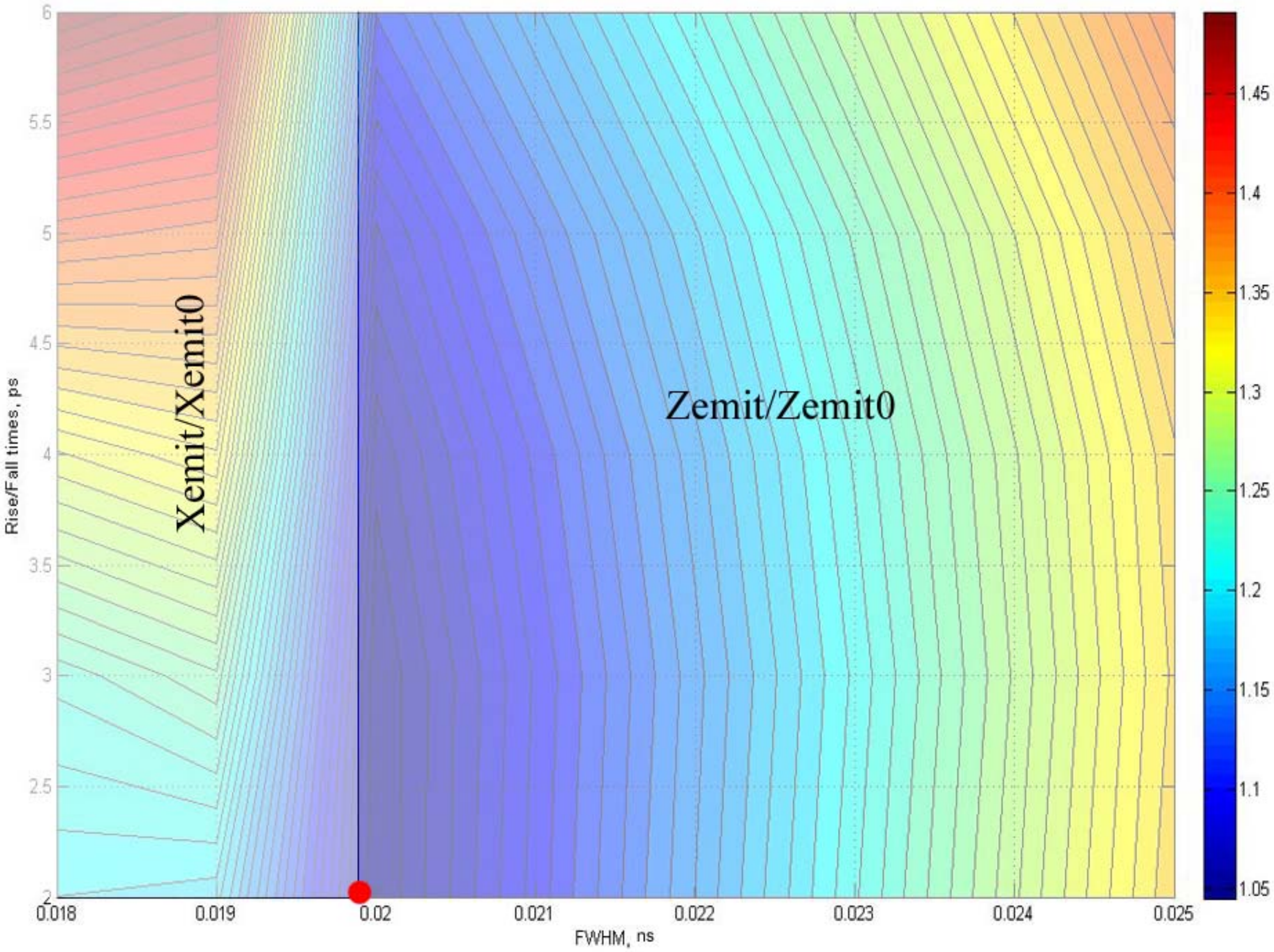

Figure 13: *The figure shows the contour plot gained from ASTRA simulations, modulation is equal to the 25%*

Coupling of different values is done for getting the exact behavior of the Goal Function, because for small FWHM and rt/ft the longitudinal emittance is small, but transverse emittance is quite high, for large parameters transverse emittance decreases, but we have reasonable increase for the longitudinal component. Thus we have to find a solution, where both of the emittances would be small enough to meet experimental demands.

Later the results from simulations were processed and interpolated leading to the final Goal Function. We can admit, that a clear dependence on the flat top fit parameters was defined, which has quadratic behavior for the most part of the parameters.

On Figure 14 one can observe the result of two value coupling in a point, where it is clearer. As far as both emittances are normalized in point FWHM=20, they have same value of 1; which makes adjustment of coupling easier. We have to admit, that this plot is constructed along the line rise/fall times equal 2ps.

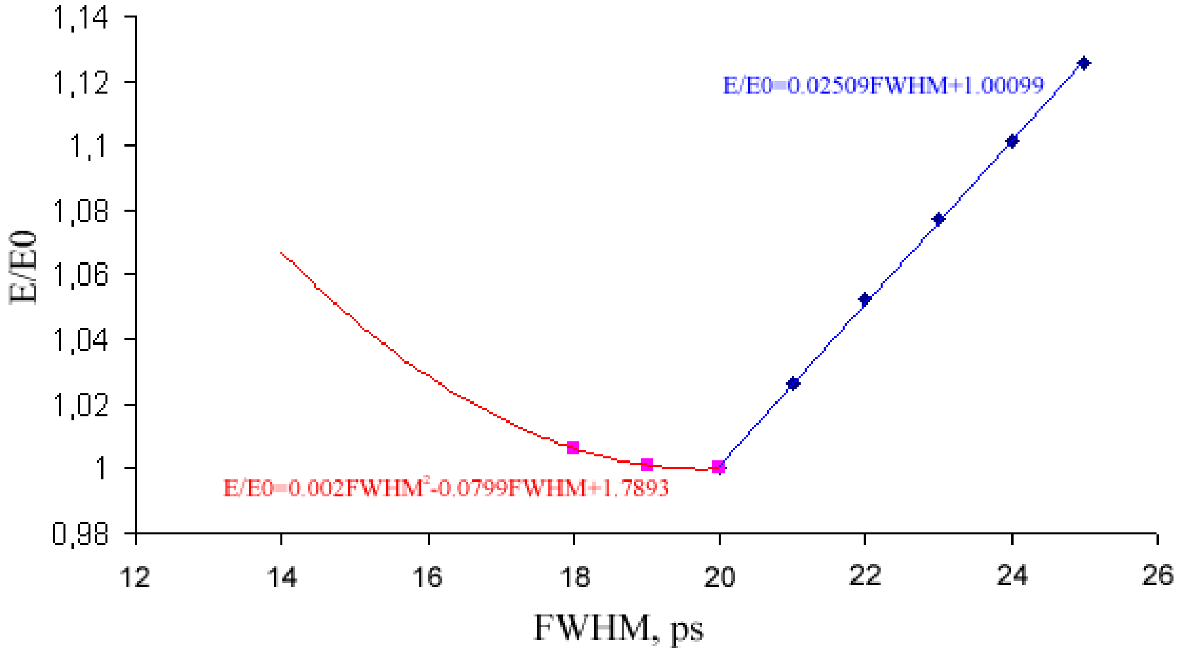

Figure 14: *The figure shows the contour plot gained from ASTRA simulations, modulation is equal to the 25%*

After the construction of the simple fits, assembling the final Goal Function is not so difficult, by multiplying the consistent parts with together. It seems to be easy, but in practice we had to increase some weights of different parameters for excluding the separate very exotic cases, where Goal Function still tend to be low.

Constructed Goal Function value is given by a Matlab script *goalfunction.m*, which does simple numerical calculations according to the curve fit, like described above and gives one final number, as a criterion.

3.5 Optimization procedure

After defining the Goal Function, we constructed another script, which uses FTfit and Goal Function as nested functions, and simply connects the laser intensity pulse shape and its fit parameters to actual set values (two temperatures and rotation angles), which are connected to the hardware and are remotely controlled.

We had to design a custom functions for Matlab script, which can set these values and read actual rate back. This milestone is vital for working of our algorithm, though if we wouldn't be able to change these parameters, we would get no results at all. The special libraries were compiled for accessing the DOOCS mechanism, which remotely controls the PITZ, for Matlab script, which is called *semit.m* [private communications with B.Petrosyan].

We also had to define penalty function concerning the hardware set parameters (two temperatures and rotation angles), because they have some limited region, where they can change. Setting values outside that region is usually blocked and script is stuck.

In practice we also have small difference between the set values and actual readback, which is also confusing a little, but it can be ignored, because there are multiple small fluctuations even during the measurement of one point. This concerns mostly the temperatures, which keep fluctuating for most periods of measurements; that are why we have to accept small difference between the set and actual readout of temperatures while optimizing the laser pulse shape.

After the defining the function, we can do the actual 4 dimensional minimization procedures, using the Matlab *fminsearch* function, which represents the Nelder-Mead multi-dimensional optimization algorithm. It constructs a simplex figure around the starting point, which consists of 5 points and evaluates function in every one of them. The simplex changes during the minimization procedure and “shrinks” in size, converging to the local minimum around the starting point.

This algorithm uses the default step for input parameters, which does not change. So, we normalized the values of the set parameters, where you can vary the initial step size without changing the minimization script.

On the Figure 15, one can see the history of set parameter change during the optimization mechanism. Though, oscillations in the beginning are quite big, near the end they become smaller, which is the clear sign of optimization process converging to the local minimum. On the left plot you see the temperature change history, and on the right one can observe same history for rotation angles.

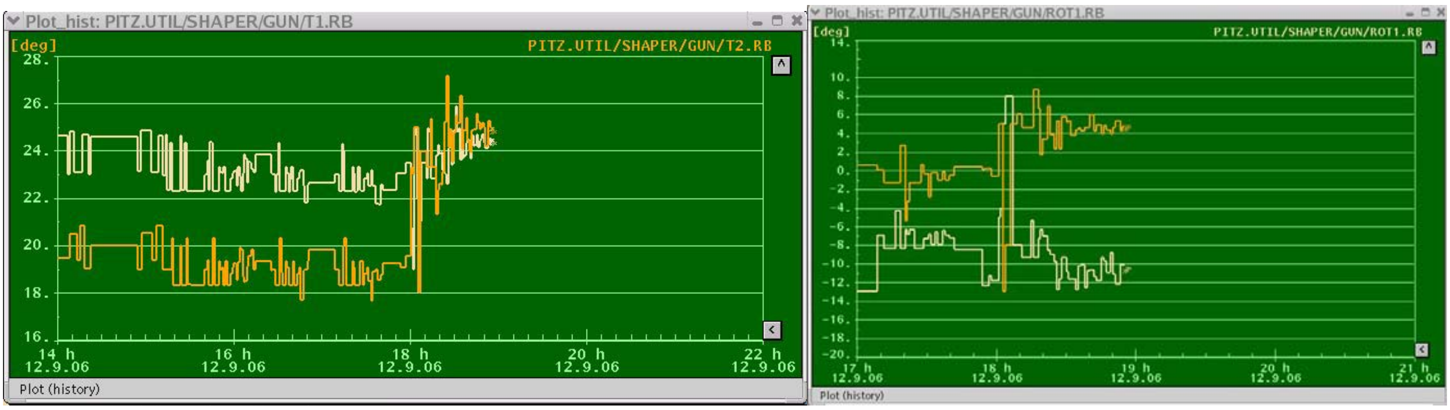

Figure 15: *The history for the set parameters changing during the minimization procedure*

On the figure 16, one can see the intermediate results obtained from the first test of the minimization algorithm. These pictures represent local minima, obtained from different starting points. First case is quite exotic, as well as the FWHM and rise/fall times are small, but modulation is quite high. Second picture describes more mare case, where FWHM is short and we have reasonably big rise/fall times, although modulation is quite small. This kind of tests will help in the future development of the optimization algorithm, because it seems to be obvious, that in practice, some weights for the flat top fit parameters, which we received from simulations, need to be slightly raised.

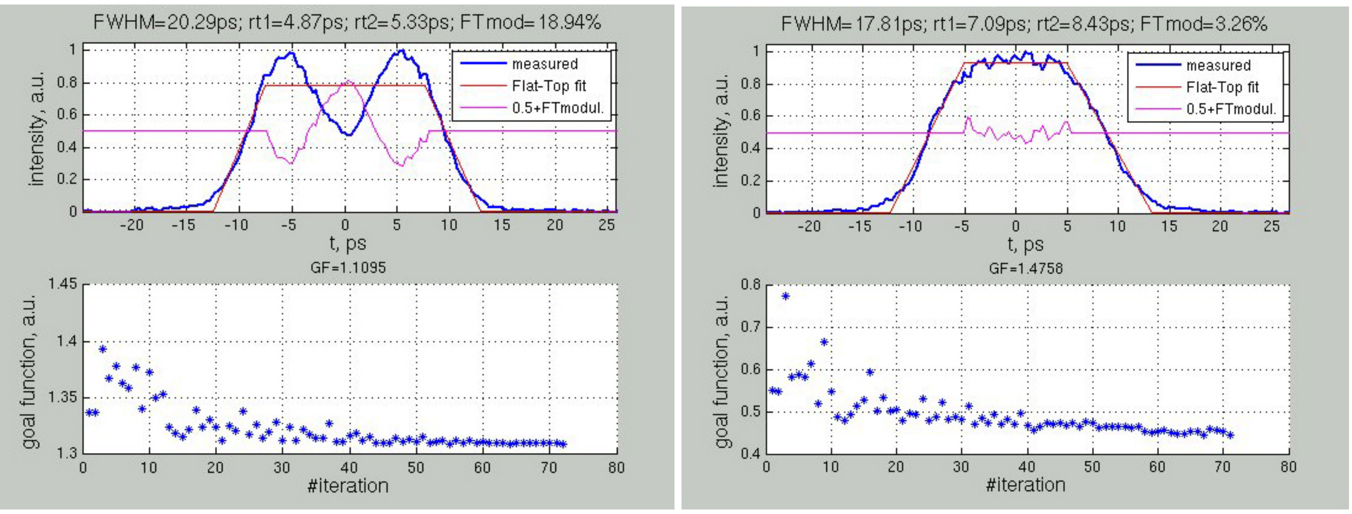

Figure 16: *The local minima obtained from optimization procedures with different start points*

4 Conclusions

4.1 Results

The first result was the combining all the existing separate tools for laser shape analysis into one tool, which represents the multi-process, but one can admit, that calculations are quite fast and they are giving one final result, which is very important.

Second improvement stands for the flat top shape fitting script modification, which in practice makes it 30% faster, providing an optimization process also more flexible and easy.

The never existed criterion of the laser pulse shape analysis has been developed in the way of Goal Function, giving an opportunity to compare different laser pulse shapes in a unique manner. Though it may not be perfect solution, but it will serve for the beginning and its improvement is not so hard afterwards. For example, one just can vary the weights of flat top fit shape parameters in Goal Function.

The minimization algorithm has been developed on the basis of the above mentioned Goal Function value and still in the testing regime, which will take some period of time. Afterwards some conclusions could be made and new ideas for modification appear.

During the first tests it has been found that the Goal Function has rather satisfying structure numerous local minima. The suggested algorithm converges to a solution, which is very often related to the initial simplex (laser pulse shape parameter settings).

4.2 Outlook

Although, the minimization algorithm has been developed, it still needs much time for testing and approval, even it seems to be very reasonable. First test show, that Goal Function, as well as emittance, dependence on the set parameters are not clear. The points do not arrange in fine structure, but are scattered around some area.

There is an idea to combine Monte-Carlo techniques and/or Gelfand global minimum search algorithm with the Nelder-Mead minimization procedure to obtain better results and get some idea, how to distinguish the global minimum from so rough structure.

One can also perform readout acceleration during the streak camera phase to get the flat top shape intermediate changing parameters, which easily can be used in the new type of algorithm to distinguish the signal evolution strategy before constructing simplex form – so called generic algorithms, which will “shrink” simplex size much faster and more efficiently.

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