BEAM BASED MONITORING OF THE RF PHOTO GUN STABILITY AT PITZ

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Abstract

The stability of the photo injector is a key issue for the successful operation of linac based free electron lasers. Several types of jitter can impact the stability of a laser driven RF gun. Fluctuations of the RF launch phase and the cathode laser energy have significant influence on the performance of a high brightness electron source. Bunch charge measurements are used to monitor the stability of the RF gun phase and the cathode laser energy. A basic measurement is the so called phase scan: the accelerated charge downstream of the gun is measured as a function of the launch phase, the relative phase of the laser pulses with respect to the RF. We describe a method which provides simultaneous information on RMS jitters from phase scans at different cathode laser energies. Fluctuations of the RF gun phase together with cathode laser energy jitter have been measured at the Photo Injector test facility at DESY in Zeuthen (PITZ). Obtained results will be presented in comparison with direct independent measurements of corresponding instability factors. Dedicated beam dynamics simulations have been done in order to optimize the method performance.

INTRODUCTION

The stability of the phase in the RF photo gun is one of the most important specifications for the linac based FELs. The requirements on the RF phase stability are derived from the desired electron beam parameters such as bunch-to-bunch and pulse-to-pulse energy spread, the bunch compression in the injector, and the arrival-time of the beam at the undulators.

The RF systems in the injector of the XFEL require tight control of the RF field in the gun. The RF launch phase stability is expected to be in the order of 0.1 deg for the phase [1]. The shot-to-shot stability in energy of the cathode laser pulses is expected to be 2% (RMS) for single pulses and 1% (RMS) averaged over a pulse train [1]. This determines the stability of the bunch charge, which could be slightly better than the cathode laser one due to space charge related effects.

The photo injector test facility at DESY in Zeuthen (PITZ) develops electron sources for FELs like FLASH and the European XFEL at DESY in Hamburg. The stability of the electron source is one of the central issues of the research program at PITZ. This paper presents a method for precise monitoring of the gun stability, including RF phase and the cathode laser energy.

PHOTO INJECTOR IN ZEUTHEN

The PITZ photo injector consists of an L-band RF gun supplied with a cathode load-lock system and solenoids for space charge compensation. The cathode laser system is able to generate trains of electron pulses including temporal and transverse laser beam shaping. Further on the electron beam line contains a booster cavity and a big variety of beam diagnostics systems for the characterization of the electron beam at different energies.

The RF gun cavity is a 1½-cell normal conducting copper cavity, operated at a resonance frequency of 1.3 GHz with a peak power of up to ~7 MW. The RF power to the gun is supplied by a 10 MW multibeam klystron through two equal output ports. In front of the gun the RF pulses from both waveguides are combined using a custom T-shape combiner. No field pickups are available for the current gun cavity design. Before 2010 the control of the RF feed to the gun was realized via two directional couplers installed before the T-combiner. Cross-talking of both directional couplers under not well-known resonance conditions of the gun cavity made the control of the RF field in the gun practically impossible. So, no routine feed back was available and only the feed forward had been used. After the facility upgrade in spring 2010 a 10 MW in-vacuum directional coupler has been installed after the T-combiner. Measurements of the combined RF pulses should provide a possibility for better control on the field in the gun closing a feedback loop for the amplitude and phase stabilization.

The PITZ photo cathode laser system is developed by the Max-Born Institute (MBI, Berlin) and is capable to generate trains of flat-top pulses with up to 800 micropulses with 1 MHz frequency at 10 Hz repetition rate. An individual micropulse with a typical duration of ~20 ps (FWHM) and very short rise and fall time (~2 ps) has a wavelength of 257 nm, the pulse energy provides the possibility to emit high charge electron bunches (up to several nC) from Cs_2Te cathodes.

The master oscillator (MO) is one of the major components of the timing system at PITZ. Its fundamental frequency of 9.027775 MHz is used for timing and diagnostics and to generate harmonics for the synchronization of the low-level RF (144th harmonics – 1.3 GHz) and the photo cathode laser system (3rd , 6th and 144th harmonics – 27, 54 MHz and 1.3 GHz correspondingly).

A detailed description of the diagnostics available at PITZ can be found in [2, 3]. Most related to the subject of this work are bunch charge measurements, monitoring of the RF phase and amplitude in the gun and the laser pulse energy diagnostics. The bunch charge at PITZ can be measured using Faraday Cups (FCs) and Integrating

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Current Transformers (ICTs) [4]. Whereas the FC being a ground-insulated copper absorber intercepts the whole electron beam, an ICT monitors the bunch charge without interception. The 70-ns output signals from ICTs give the charge with a precision of ~30 pC [2] and are more suitable to measure the bunch charge in the range from 100 pC to several nC. Faraday cups can measure much lower charges down to several pC with a precision of ~ 2 pC [2].

Recently more reliable RF measurements became available at PITZ. They are based on signals of forward and reflected waves obtained from antennas of the 10 MW in-vacuum directional coupler. The vector sum phase can be used to estimate the phase jitter in the RF gun.

To monitor the cathode laser pulse energy an industrial energy meter is integrated in the cathode laser diagnostics system before the laser beam enters the vacuum beam line. The laser pulse energy fluctuations within the pulse train and shot-to-shot jitter is monitored by a photomultiplier tube (PMT).

PHASE SCAN

The RF gun phase scan for a given laser energy – measurement of the accelerated charge downstream of the gun as a function of the cathode laser launch phase – is one of the basic measurements to characterize emission properties of an RF photo gun. A phase scan measured at PITZ is shown in Fig.1. This measurement has been performed using the first FC (~0.8 m from the cathode). RF peak power in the gun is plotted at the right axis in Fig.1a, its mean value is ~1.09 MW. The main solenoid current of 210 A has been applied to focus beams with high energy at the FC location.

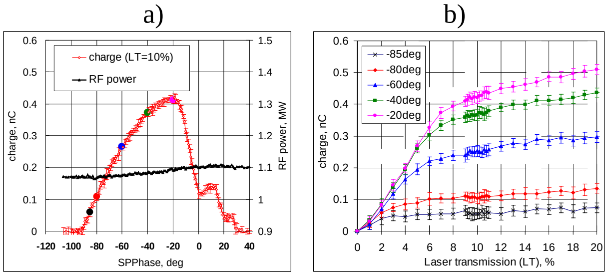
a)
b)

Figure 1: a) Measured phase scan for a bunch charge. The set point RF phase (SPPhase) is used for the horizontal axis. It has an arbitrary (but fixed) offset to the mathematical phase of the gun cavity resonator. b) Bunch charge measured for selected RF phases as a function of the cathode laser pulse energy (laser transmission - LT).

The shape of the phase scan is impacted from many parameters of the gun. The space charge density at the cathode due to the laser temporal and transverse profiles at the given laser pulse energy determines the charge dependence in the phase range from the field zero-crossing to the phase of the maximum beam energy gain from the gun (-90 deg to -40 deg in Fig.1a) [2]. A Schottky-like effect – a charge production enhancement due to the presence of a high electric field at the cathode – contributes in an additional slope in the phase scan for the phases corresponding higher RF field during the photo emission (-40 deg to -20 deg in Fig.1a) [5].

The control of the cathode laser pulse energy is realized at PITZ by means of a polarizer based attenuator. By its rotation the laser transmission (LT) can be tuned in order to adjust the energy of the laser pulse hitting the photo cathode. The laser transmission scans for selected RF phases are shown in Fig.1b. Initial (linear) parts of these curves are typically used for the quantum efficiency (QE) determination, their further (nonlinear) behaviour is strongly influenced by the space charge effects during emission.

PHASE SCAN FOR GUN STABILITY MEASUREMENTS

Fig.2a shows a simulated phase scan. Standard PITZ gun conditions have been applied: electric field of 60 MV/m at the cathode, a flat-top cathode laser temporal profile with 20 ps FWHM and 2 ps rise and fall time, ~0.4 mm RMS laser spot size. These and all other fixed parameters were taken from a simulation setup optimized to minimize the beam emittance in the PITZ photo injector. Additionally a Schottky constant of 0.005 nC/(MV/m) has been used in these ASTRA simulations [6]. A 2D phase scan – simulated accelerated charge as a function of the RF phase and the laser pulse energy – is shown in Fig.2b. The value $qe \cdot E$ used for one of horizontal axis can be treated as a charge which could be extracted from the cathode if no space charge or Schottky-like effects would be applied. Zero RF phase on these plots refers to the gun phase with maximum mean energy gain (the beam energy is plotted at the right axis in Fig.2a).

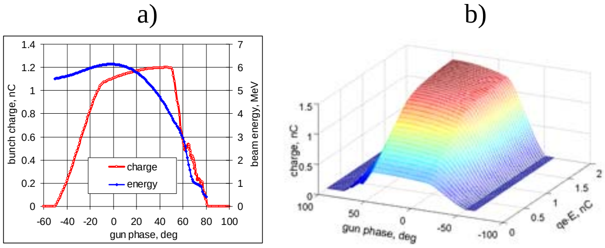
a)
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Figure 2: a) Simulated phase scan: bunch charge (left axis) and mean beam kinetic energy (right axis). b) 2D scan – bunch charge vs. the RF gun phase and the cathode laser pulse energy E, factor qe is related to the QE of the cathode.

The dependence of the bunch charge on the gun phase and the laser energy can be used to determine gun phase and laser energy jitters. The main assumption of the method is an independence of the jitters of the RF launch phase and the cathode laser pulse energy, so the distribution function of the RF launch phase ϕ and the laser energy E can be presented by a 2D Gaussian distribution:

$$P_2(\phi,E)=\frac{1}{2\pi\sigma_\phi\sigma_E}\exp\left(-\frac{\Delta\phi^2}{2\sigma_\phi^2}-\frac{\Delta E^2}{2\sigma_E^2}\right), \qquad (1)$$

where $\Delta\phi=\phi-\phi_0$ and $\Delta E=E-E_0$ are RF phase and laser energy centred around the point of interest, σ_ϕ and σ_E are the RMS jitters of the phase and laser energy respectively. In order to find the probability distribution $P_1(Q)$ of the bunch charge one can integrate (1) along the curve of equal charge:

$$G(\phi,E)=\mathrm{Q}\,, \qquad (2)$$

where $G(\phi,E)$ is a 2D charge phase scan (e.g. Fig.2b). Equation (2) determines for a given (fixed) charge Q a flat curve. Assuming a parameterization of this curve:

$$\begin{aligned}\phi &= F_\phi(Q,\xi)\\ E &= F_E(Q,\xi)\end{aligned}\,, \qquad (3)$$

where ξ is a scalar parameter, the charge probability distribution can be found from:

$$P_1(Q)=\int P_2\left(F_\phi(Q,\xi),F_E(Q,\xi)\right)\cdot\sqrt{\left(\frac{\partial F_\phi}{\partial\xi}\right)^2+\left(\frac{\partial F_E}{\partial\xi}\right)^2}\,d\xi \qquad (4)$$

A rough estimation of the dependence (2) is the Taylor expansion up to linear terms:

$$Q=\left.\frac{\partial Q(\phi,E)}{\partial\phi}\right|_{(0)}\Delta\phi+\left.\frac{\partial Q(\phi,E)}{\partial E}\right|_{(0)}\Delta E\,, \qquad (5)$$

where partial derivatives are taken in the point of interest $(0)\equiv(\phi_0,E_0)$. Using equation (5) in the integration of (4) yields Gaussian distribution function for the charge fluctuations with RMS width:

$$\sigma_Q=\sqrt{\left(\left.\frac{\partial Q(\phi,E)}{\partial\phi}\right|_{(0)}\right)^2\sigma_\phi^2+\left(\left.\frac{\partial Q(\phi,E)}{\partial E}\right|_{(0)}\right)^2\sigma_E^2}\,. \qquad (6)$$

The formula (6) can be used to estimate the jitters of the RF phase and the laser energy by measuring the charge jitter for various RF phases and different levels of the cathode laser pulse energy. In principle, two measured points (ϕ_{01},E_{01}) and (ϕ_{02},E_{02}) are sufficient to resolve the linear system:

$$\begin{pmatrix}\left(\left.\frac{\partial Q}{\partial\phi}\right|_{01}\right)^2 & \left(\left.\frac{\partial Q}{\partial E}\right|_{01}\right)^2\\ \left(\left.\frac{\partial Q}{\partial\phi}\right|_{02}\right)^2 & \left(\left.\frac{\partial Q}{\partial E}\right|_{02}\right)^2\end{pmatrix}\times\begin{pmatrix}\sigma_\phi^2\\ \sigma_E^2\end{pmatrix}=\begin{pmatrix}\sigma_{Q1}^2\\ \sigma_{Q2}^2\end{pmatrix} \qquad (7)$$

in order to obtain (σ_ϕ,σ_E). Practically the matrix in (7) can be ill-conditioned or/and determined with a rather large discrepancy. More reliability can be achieved by taking into consideration also nonlinear behaviour of the function $G(\phi,E)$. This could be realized by producing a charge histogram (Fig. 3b) using a folding of the 2D Gaussian probability distribution (1) with the mapping function $G(\phi,E)$ (Fig.3a). A fitting of the obtained charge histogram to the measured one should result in the RMS jitter values (σ_ϕ,σ_E).

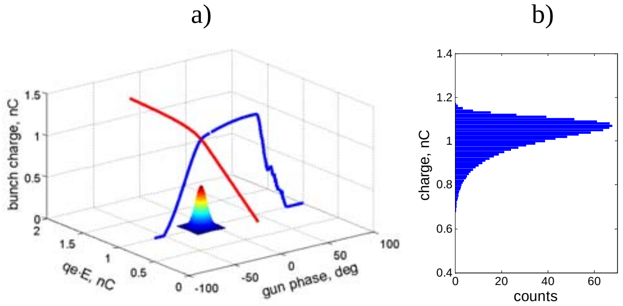
a) b)

Figure 3: Simulated procedure of the gun phase monitoring: a) folding of the 2D Gaussian distribution with charge dependence on RF phase and laser pulse energy; b) charge histogram obtained from the folding.

Fig. 3 shows the simulations of the gun jitters for the gun phase -10 deg. To illustrate the method to measure the phase and the laser energy jitter 5 deg RMS phase jitter and 5% RMS laser pulse energy jitter were applied. The envelope of the charge histogram for these conditions, obtained by mapping the Gaussian probability function with a nonlinear surface $Q=G(\phi,E)$ is shown in Fig.4 with a blue curve.

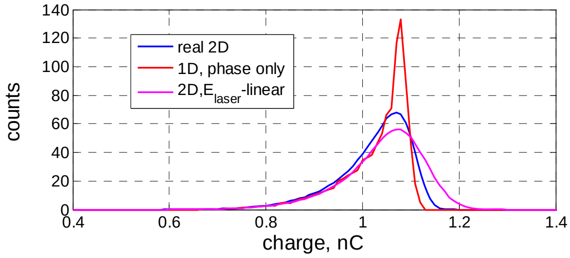

Figure 4: Simulated charge histogram, reconstructed using different approaches.

The red curve in Fig.4 depicts the charge histogram reconstruction if only phase jitter is applied (a similar approach has been described e.g. in [7]). It's clearly seen that the exclusion of the laser energy jitter from the reconstruction procedure results in significant underestimation of the charge jitter and therefore overestimation of the phase jitter if compared to measurements. The magenta curve corresponds to the 2D linear approach (see Eq. (5)). This approach overestimates the charge jitter and therefore underestimates the phase and the laser energy jitter if compared to measurements.

Indeed, the nonlinearity of the charge dependency (especially on the laser pulse energy) leads to the damping of the charge fluctuations.

The general approach is simultaneous simulations of the measured charge histograms at various gun phases by minimizing the functional:

$$\Phi(\sigma_\phi,\sigma_E)=\sum_n w_n\cdot\int\left|QH_n^{meas}-QH_n^{sim}\right|dq \qquad (7)$$

Here $QH_n^{meas}(q)$ and $QH_n^{sim}(q)$ are measured and simulated histograms for a set of chosen phases $\{\phi_n\}$. This approach is illustrated by Fig. 5, where five representative simulated charge histograms are shown.

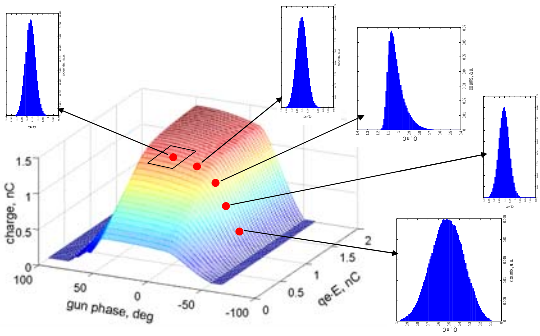

Figure 5: Charge histograms obtained for marked points in the 2D phase scan. Assumed phase and laser pulse energy jitters are 5 deg and 5% respectively.

To optimize the choice of the phases $\{\phi_n\}$ the linear approach (5) can be used. Simulated contributions to the charge fluctuations from the phase and laser energy jitters are shown in Fig.6. Whereas the gun phase of -10 deg corresponds to equal contributions from the phase and laser energy jitter to charge fluctuations, the charge fluctuations at the phase of -30 deg are fully dominated by the RF phase jitter.

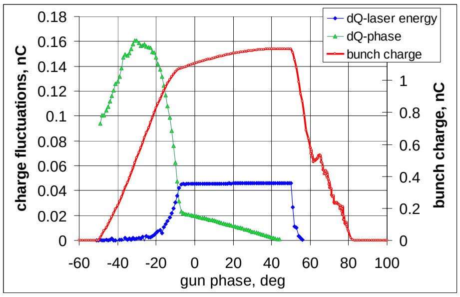

Figure 6: Simulated linear contributions to charge fluctuations from phase and laser pulse energy jitters $(\sigma_\phi = 5\,\mathrm{deg}, \sigma_E = 5\%)$. The total charge is plotted at the right axis.

EXPERIMENTAL TESTS

A new gun cavity is under conditioning now at PITZ. The full expected RF power (of ~7 MW) is not yet achieved, therefore some preliminary stability monitoring tests have been performed at reduced peak power in the gun (~0.85 MW). The gun temperature has been tuned in order to keep the gun cavity strictly at resonance. The basic phase scan is shown in the centre plot at Fig.7. Estimated contributions from RF phase and laser pulse energy jitter are shown in the centre plot as well.

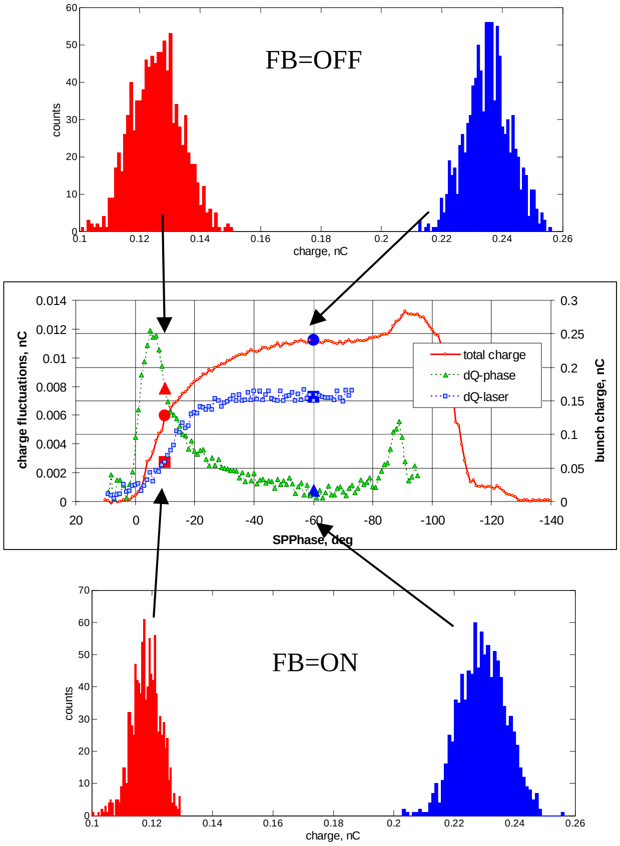

Figure 7. Experimental tests of the method for the opened (FB=OFF) and for the closed feed back loop (FB=ON) of the LLRF system applied to the gun.

An upper plot of charge histograms for various phases at Fig.7 have been measured with opened loop of the LLRF feed back, corresponding histograms with closed feed back loop are shown in the bottom plot.

The above mentioned procedure applied to these sets of measured data resulted in the laser energy jitter of ~11%. Closing the LLRF feed back loop reduced the RF phase RMS jitter from 0.82 deg to 0.32 deg. It should be noticed that all these preliminary measurements have been done at a reduced RF power in the gun, so the klystron was rather far from the saturation. Cross check measurements of the phase fluctuations have been done using a vector sum of signals from the 10 MW in-vacuum directional coupler and resulted in 0.43 deg and 0.16 deg phase jitter for the cases with and without feed back respectively.

The phase scan shown in Fig.1 has been used to test the general approach (7). Charge histograms have been fitted at four phases (SPPhase=-80; -60; -40; -20 deg). Corresponding histograms with fit curves are shown in upper plot of Fig.8. The phase scan and contributions to the charge fluctuations from the phase and laser pulse jitter are shown in bottom plot in Fig.8. The applied method yielded an RMS jitter of 1.77 deg for the RF phase and 12.5 % for the laser pulse energy. No feed back has been applied for these measurements. It should be also mentioned that these measurements have been done using short Gaussian laser pulses with ~2ps FWHM, which is significantly shorter the nominal value (20 ps). This can partially explain rather high laser energy jitter, PMT measurements of the laser pulse energy on the laser table are in good agreement with the RMS value obtained from electron beam charge measurements.

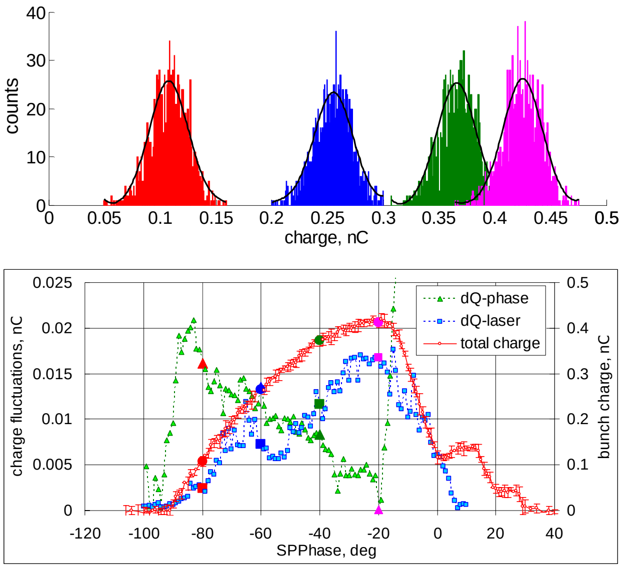

Figure 8. Results of the general approach to the gun phase and laser pulse energy jitter monitoring. The measurements have been performed at ~ 1.09 MW in the gun cavity with opened feed back loop.

SYSTEMATIC LIMITATIONS ON RESOLUTION OF THE METHOD

There are several sources of systematic limitations of the proposed method. The bunch charge measurements using FC or ICT with a scope readout is usually disturbed by the noise of the scope base line and by the jitter of the background due to the dark current fluctuations. A method to reduce the signal dependence on the dark current intensity can be based on a dark current envelope fitting corresponding to the actual peak power in the gun. This has to be tested in future when the nominal power level in the gun (7MW) will be achieved. A dependence of the extracted charge on the RF gradient in the gun is not included in the above described method. However for some conditions when the electric field at the cathode plays a significant role in the emission process the RF field jitter (e.g. due to the resonance temperature fluctuations) could contribute in the bunch charge jitter as well. This can also include the klystron nonlinearity – namely the dependency of the output RF power on the set point RF phase, which can be a substantial effect by the operation of the klystron close to saturation. If RF gradient in the gun is well controlled by the LLRF system these effects are assumed to be rather small.

Another factor limiting the method performance is the laser timing synchronization to the MO, which are intrinsically included in the measured phase jitter. Using measurements from the directional coupler it should be possible to estimate this jitter as well.

SUMMARY AND OUTLOOK

The presented technique to monitor the RF gun launch phase and the cathode laser pulse energy has been tested at the Photo injector test facility at DESY in Zeuthen (PITZ). It is rather robust and based on the electron beam charge measurements for various gun launch phases and different levels of cathode laser pulse energy. The preliminary results obtained for various machine conditions have been compared to the direct measurements. The systematic limitations and source of discrepancies of the method have been discussed.

In the nearest future extensive gun stability studies are foreseen at PITZ. More detailed phase jitter measurements have to be performed for different resonance conditions of the gun cavity at significantly higher levels of the peak RF power. Cross check of the laser pulse energy jitter obtained using presented method with direct measurements of energy meter and PMT in the PITZ tunnel should be available soon.

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