

Fast High Voltage Signals Generator for Low Emittance Electron Gun

Martin Paraliev¹

Abstract – The construction of X-ray Free Electron Lasers (XFEL) requires high brightness, low emittance, monoenergetic, relativistic electron beams. In order to achieve those parameters and to reduce scale of needed accelerator facilities, alternative electron sources should be designed. This article is to describe the progress of the 500kV pulser dedicated to provide HV signals for cold (field) emission based cathodes test bed.

Keywords – High Voltage, Low emittance, 500kV Pulse Generator, High gradient electron acceleration, Tesla coil.

I. INTRODUCTION

To reduce size and cost of XFELs better quality electron sources are needed, capable of producing high brightness, low emittance, monoenergetic electron beams and to preserve those parameters during acceleration. Low Emittance electron Gun (LEG) project at Paul Scherrer Institut (Switzerland) is dedicated to the studies of an alternative low emittance electron sources based on cold (field) electron emission and high gradient acceleration [1]. In order to achieve the needed surface electric field for cold emission, and the necessary acceleration gradient to prevent space charge-driven beam emittance degradation, high voltage (HV) should be applied across anode-cathode gap. To decrease the probability of a vacuum breakdown the HV pulse should be short. The current task is to design and to construct a HV pulse generator to test and to optimize cold emission based electron sources. The next step is, based on this design, to develop a LEG injector for a XFEL.

The behavior of the field emitted current from vacuum-conductor interface is described by Fowler-Nordheim equation (1), [2], [3] and [4]:

$$J(E, \phi) = A \frac{e^{B\phi^{-1/2}}}{\phi} E^2 e^{C\phi^{3/2}/E} \quad (1)$$

where J is emitted current density in A/m^2 , A , B and C are constants ($A = 1.4 \times 10^{-6}$, $B = 9.85$, $C = -6.53 \times 10^9$), E is electric field in V/m (including the field enhancement factor) and ϕ is work function of emitting material in eV. Relative sensitivity of the field emission process $\frac{\Delta J}{J}$ in function of the relative

change of electric field $\frac{\Delta E}{E}$ is given by equation (2). The shot-to-shot voltage stability is set by the requirement emitted current variation to be less than 10%. For the targeted current ($\sim 5A$) emitted by ZrC ($\phi_{ZrC} \approx 3.5eV$) single tip (emitting area $\approx 0.5\mu m^2$) the surface electric field (including the field enhancement factor) should be in the range of 7GV/m and the relative voltage shot-to-shot stability should be better than 1%.

$$\frac{\Delta J}{J} = \frac{dJ}{dE} \frac{E}{J} \frac{\Delta E}{E} \quad (2)$$

The electric gradient, for the first phase of the project, was set to 125MV/m (500kV across 4mm anode-cathode gap). A direct connection to the ground potential will be beneficial because it will allow future development including adding a fast gating impulse and testing of multi layer cathode array structures with additional DC focusing.

This HV pulse generator is to be used for testing of different field emitting (FE) structures (single emitting tips, FE arrays, laser-assisted FE cathodes). In addition, operating experience will be used for a design of a higher voltage (1MV) pulse generator for a future XFEL low emittance electron injector facility.

Table 1. Advantages and disadvantages of considered pulsed technologies capable of producing fast HV pulses

Technologies	HV	Stability and load	Short/Single pulse	Scalability	Variable output	Unipolar pulse	Long life	Direct contact	Low cost
Spark gaps	++	--	++	++	--	++	--	no	++
Semiconductor switches	--	++	-	-	++	++	++	no	-
Magnetic voltage adder	++	++	--	-	++	+	++	yes	--
Resonant circuit	+	+	--	++	++	--	++	yes	+
Coupled resonators ($k=0.6$)	++	+	+	++	++	-	++	yes	-
Transm. line based U adders	+	-	++	+	++	+	++	no	+
Nonlinear transmission lines	-	-	++	--	--	++	++	yes	--
Nonlinear magnetic transf.	++	+	+	--	--	-	++	yes	--

Different pulsed power technologies were considered for the HV pulse generation [5], [6]. Table 1. gives an overview of their advantages and disadvantages.

Critically coupled air-core resonant transformer was chosen to give the best engineering compromise for the particular application.

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II. RESONANT AIR-CORE TRANSFORMER

A. Critical coupling

In the particular design a rather unusual resonant configuration is used, where the resonant amplitude is built in one cycle only. To achieve this, primary and the secondary resonant circuits are tuned to the same frequencies and the coupling K between them is set to 0.6 (critical coupling). In this condition the transformer resonance is split in two spectral lines, with frequency of one twice the frequency of the other. The voltage of the secondary side (as well as in the primary) is a superposition of fundamental and second harmonic with zero phase difference between them.

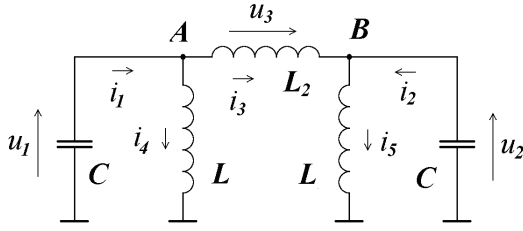


Fig.1. Equivalent circuit of an ideal air-core resonant transformer

The equivalent circuit shown on Fig. 1 is used to study analytically the behavior of the air-core resonant transformer. After referencing the secondary to the primary side the differential equation system (3) was derived. It describes analytically the behavior of the ideal transformer.

$$\begin{cases} \ddot{u}_1 + k_1 u_1 - k_2 u_2 = 0 \\ \ddot{u}_2 + k_1 u_2 - k_2 u_1 = 0 \end{cases} \quad (3)$$

where

$$L_2 = L \frac{1-K^2}{K} \quad (4)$$

$$k_1 = \frac{1}{LC(1-K^2)}, \quad k_2 = \frac{K}{LC(1-K^2)} \quad (5)$$

The solution of the differential system is given below [8]:

$$u_1 = \frac{U}{2} [\cos(\omega_1 t) + \cos(\omega_2 t)] \quad (6)$$

$$u_2 = \frac{U}{2} [\cos(\omega_1 t) - \cos(\omega_2 t)] \quad (7)$$

where

$$\omega_1 = \sqrt{\frac{1}{LC(1+K)}} \quad (8)$$

$$\omega_2 = \sqrt{\frac{1}{LC(1-K)}} \quad (9)$$

and ω_1 and ω_2 are the two resonant lines of the air-core transformer. The critical coupling factor K was analytically calculated for this ideal case using the condition $2\omega_1 = \omega_2$ [7]. The normalized voltage u_1 in the primary side and u_2 in the secondary one are shown on fig.2.

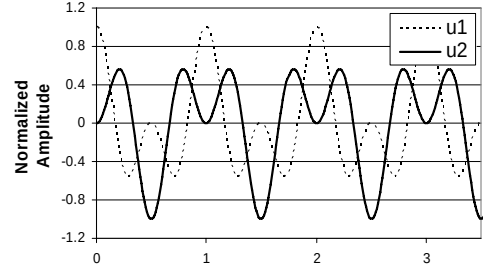


Fig. 2. Primary (u_1) and secondary (u_2) voltage signals of an ideal critically coupled ($K = 0.6$) resonant transformer

The lossy case was simulated (using pSpice®) to find the optimal values for coupling factor and tuning of a real transformer structure [7].

B. Transformer geometry

In order to achieve the necessary coupling without a magnetic core, the transformer geometry was studied. Scaled models and numerical simulations were employed to determine the optimum coil layout. Simulated and measured results from the reference layouts were in a good agreement. A single-turn primary around flat spiral secondary gave the best coupling for given transformer dimensions and coils' conductor cross-sections. An interesting observation was that the coupling factor does not depend much on the conductor's cross-section perimeter, but rather than the conductor's cross-section perimeter. In general, the larger conductor cross-section perimeter gives better coupling.

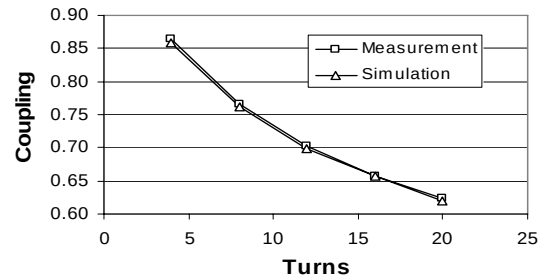


Fig. 3. Measured and simulated coupling factors of reference layouts as a function of secondary number of turns

C. Commutation

In order to keep the transformer pulse response fast the length of its secondary winding was kept as short as possible.

This adversely affects the transformer step-up ratio and requires higher primary voltage. The type of the switching element in the primary side was determined by the operating voltage, speed and life time requirements. There are basically two switch types suitable: thyratrons and spark gaps. In spite of their low cost, the spark gap technology was not used because of short life-time and jitter.

Two air-cooled thyatron switches are used to energize the resonant step-up transformer. They are connected in parallel to decrease the stray inductance. The thyratrons switch the charged primary capacitor to the primary transformer winding. A hollow anode thyatron (CX1725A) was chosen in order to tolerate reverse current. The thyratrons are placed in two electrically sealed aluminum boxes to screen the electromagnetic noise generated during commutation.

D. Construction

To ensure HV performance of the transformer, it is operated inside a pressurized tank with sulfur hexafluoride (SF_6) gas. The secondary coil is fixed in a grove machined on an insulating plastic base. Concentric undulations are machined on the back side of the transformer base to prevent surface discharges. The single-turn primary is 80mm copper strip wound around the secondary coil.

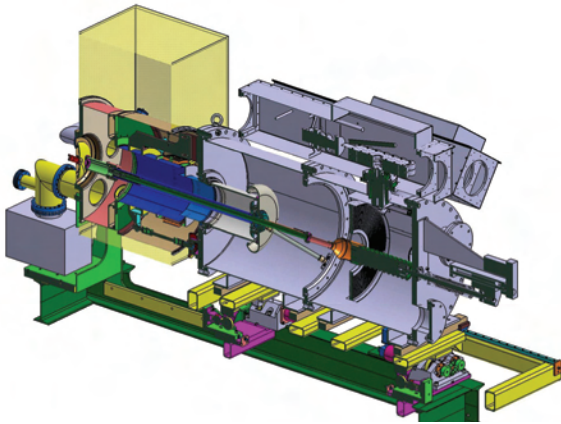


Fig. 4. Cross section of the HV pulse generator.

a – thyatron, b – capacitor bank, c – feedthrough, d – HV transformer, e – pressure tank, f – vacuum feedthrough, g – middle stalk, h – vacuum chamber with anode and cathode

The primary capacitor is split in two capacitor banks, one in each thyatron box, and it is connected to the primary coil through low inductance gas-tight feedthrough. The secondary HV pulse is conducted by the middle stalk and through a large ceramic feedthrough is applied to the vacuum chamber. A removable cathode electrode is attached to the other end of the stalk. The anode-cathode separation is adjustable (0..30mm). The entire pressure tank is sitting on a precision 5-axes positioning system in order to control the location of the cathode with respect to the anode and the rest of the accelerating structures. Fig. 4. shows a cross section of the pulse generator 3D CAD model.

E. Electrical modelling

A detailed electrical model was made to study the HV pulse generator behavior. Numerical PC based simulator (pSpice®) was used to model the output waveforms and to define the optimum tuning of the resonant transformer.

F. Measured results

The first tests proved the capability of the pulser to deliver an HV pulse to the anode-cathode system. The designed pulse amplitude of -500kV (250ns FWHM) was reached successfully with 20% voltage margin. Fig. 5. shows a very good agreement of the measured and the simulated waveforms.

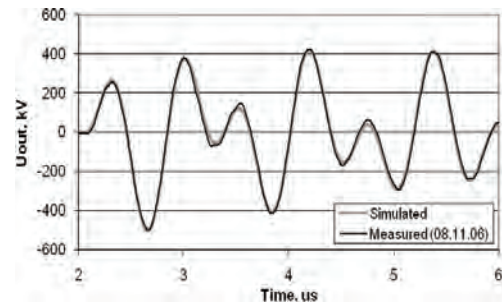


Fig. 5. Simulated and measured output waveforms

Due to mechanical modifications the secondary inductance was higher than the designed value. This shifted the tuning range of the transformer and made the tuning for critical coupling impossible.

To decrease the shot-to-shot variations due to pulsed charging supply voltage fluctuation an active amplitude stabilization system was built. The stability measurements of hundred consequent pulses (Fig. 6.) showed a reduction of shot-to-shot fluctuation from about 1.4% (stabilization off) to less than 0.4% (stabilization on).

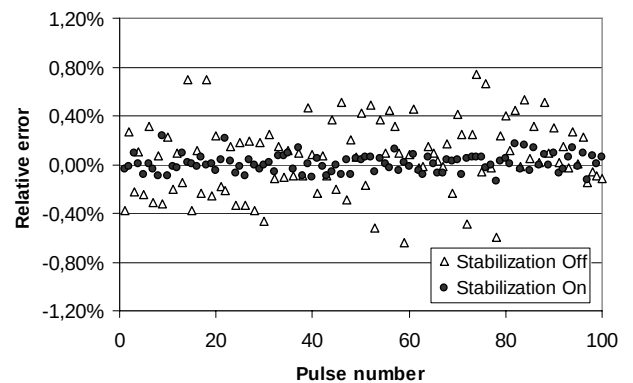


Fig. 6. Shot-to-shot stability measurement with and without active stabilization

G. Radiation safety

Due to HV potentials in the vacuum tank any parasitically emitted electrons are accelerated to high energies and their impact on the vacuum chamber will generate a shower of secondary electrons and high energy photons, including X-rays. In order to ensure the radiation safety for personnel, the HV pulse generator is situated in a bunker with 1m thick concrete walls. A built-in safety interlock system blocks the HV if there are people in the bunker.

The control electronics is placed in two 19" racks – one next to the pulser and the other in the control area. Fig. 7. shows the present position of the HV pulse generator in the bunker.

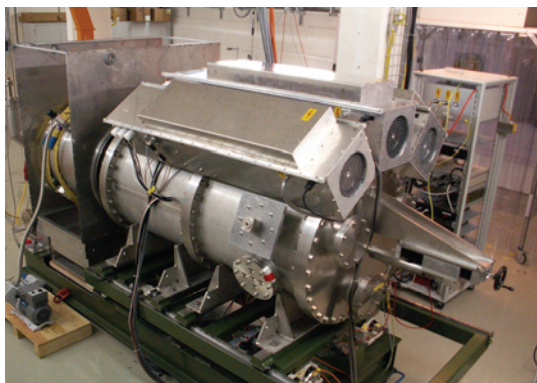


Fig. 7. The HV pulse generator and the control electronics rack in the concrete bunker

III. CURRENT TASKS

The HV transformer is being modified to decrease the secondary inductance. This will make the tuning for critical coupling possible and the positive peaks before and after the main pulse will be with the same amplitude.

There is an ongoing task to add a “tail biter” to cut-off the following oscillations. The electric simulations showed that it is possible to take the energy out of the system after the first cycle. Unlike common resonant systems, in critically coupled one the energy is fully exchanged between the resonators within one cycle. When the primary capacitor has maximum voltage, the currents in the inductors and the voltage over the secondary capacitance are zero. At this moment the entire energy of the system is in the primary side. With an additional switch to discharge quickly the capacitors, the energy is removed and the oscillations stop. A motorized spark gap is being built into the third aluminum box to prove the concept.

Measuring the output voltage of the pulse generator is not a trivial task. The standard RC dividers suitable for this voltage amplitude are large and with limited bandwidth. A capacitive divider is used to measure the HV pulse. It is used to monitor the output from the control area. An optical HV measurement system is being designed to give a second independent measurement of the output pulse. This serves to increase the reliability of the system in case of slow degradation or failure of the voltage monitor.

IV. SUMMARY

An extensive study was done to choose the most suitable technology for generating short HV pulses for cold emission cathode test bed. A critically coupled air-core transformer was chosen to give the best engineering compromise for this particular application. The behavior of coupled resonators was studied analytically and by simulations. The tuning and coupling of the transformer were parametrically optimized. Using scaled physical models and simulations, magnetic coupling of different transformer layouts were examined. The measured results of reference models were in a good agreement with the simulations. Based on these studies, a fast HV pulse generator was successfully designed and constructed. The tests confirmed that it is capable of reaching the designed pulse voltage amplitude of -500kV with pulse length of 250ns (FWHM). The stability studies showed shot-to-shot peak voltage fluctuations within 0.4%. This was utilized by employing an active voltage stabilization subsystem. A detailed equivalent circuit of the pulse generator was created in order to further optimize its performance. The measured output waveforms were in a very good agreement with the numerically generated ones. There is an ongoing task to prepare the pulse generator for the high gradient tests and, as well, to define the possible ways to upgrade the pulser towards 1MV goal.

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