# PULSED POWER TECHNIQUES FOR THE LOW EMITTANCE GUN (LEG)

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*For the Low Emittance Gun (LEG) project, a Field Emitter Array (FEA) cathode is used in a vacuum diode configuration to provide an electron beam. The required charge density and emittance of the electron beam call for an accelerating field in the range 500 – 1000 MV/m. This field brings the electrons to relativistic velocities within a few picoseconds. Several technologies exist for generating such high fields. The present task is to apply these to this new extreme situation: the accelerating gap is a few millimetres, the potential between anode and cathode is 1-2 MV; the pulse rise time is in nanoseconds; surface defects, dust and surface contaminants must be absent down to atomic scale; and the mechanical tolerances are in the sub-micrometer range.*

## INTRODUCTION

World-wide, several groups are studying the generation of low emittance (<1 πμm-rad), high current (> 1 kA), short (<100 fs) electron bunches for use in X-ray Free Electron Lasers (XFELs). Most groups rely on the extremely short laser pulses from Ti-Sa lasers, using chirped amplifiers and frequency tripling to give intense (>1 TW/cm$^2$) pulses in the 100 fs-1 ps range; when these pulses are projected onto a metal cathode, the short intense electron bunch which is emitted can have the same time structure as the applied laser pulse. The disadvantage of this scheme is that large charge emission requires that the applied light is considerably more energetic than the work function, resulting in transverse momentum in the 350 meV range (in comparison, thermal momentum of electrons freely emitted at room temperature is around 25 meV). Thus the beam emittance is limited to around 1 πμm-rad. A good overview of this approach is given in [1].

One group, at the Spring8 accelerator in Japan, are concentrating on using thermionic emission at 1500°K from a single crystal cathode, accepting a higher thermal momentum but without a laser to give photoemission.

At PSI, we are concentrating on using Field Emitting Arrays (FEAs) to give large electron emission over a larger area, but at room temperature.

## EMITTANCE DEFINITION

An ideal electron beam should have zero emittance, that is it should be able to be focussed down to a single point. This is true when the electron transverse velocity is exactly proportional to the distance from the beam axis. This could be a perfectly diverging beam from a single point at low current density (for example, an electron gun for an electron microscope), or a perfectly parallel beam which results from using broad anode-cathode plates at low current density.

In Fig. 1, the emittance is the area on a trace space (or phase space) plot near to an FEA cathode. With $x_{rms}$ as the transverse displacement and $x_{rms}'$ as the transverse divergence, the emittance can be defined in modern units by:

$$\varepsilon_x = x_{rms} x'_{rms}$$

For example, by inspection of the plot in Fig. 1, the rms displacement is about 0.5 mm and the rms angle is about 50 μrad. The emittance value given in modern literature is likely to be the simple product, that is 19 πnm-rad, where "π" is used to indicate this convention. (in older literature, the area of this plot would be given, a value that is four times larger, or 76 nm-rad).

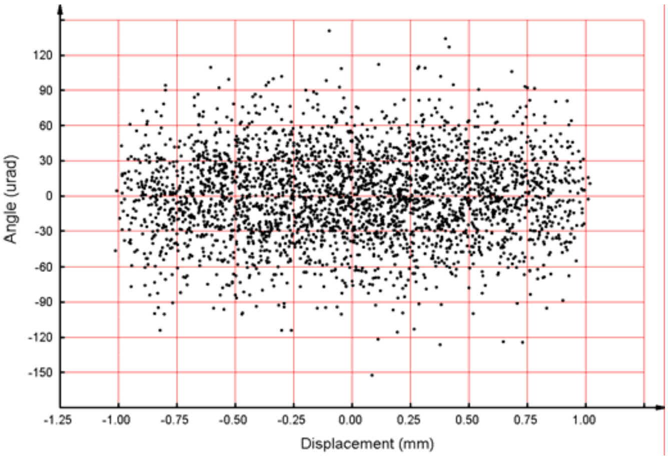

**Fig. 1**: Transverse trace space plot for a 1 mm radius cathode, transverse velocity given by 300°K thermal excitation, after 2 MV acceleration.

For field emitted electrons, the average transverse velocity is 54 km/s, with a Maxwell distribution. The divergence angle is the ratio of the transverse velocity to the longitudinal velocity (usually the speed of light), scaled by relativistic factor βγ.

A divergence angle of ±50 μrad is very severe; without further acceleration, it corresponds to sending each electron from the cathode FEA into a defined 2 mm diameter target set at 20 m distance. The mechanical tolerances, vibration, etc should remain in the sub - micrometer range, so that the mean electron path angle, shot to shot, is also stable to ±50 μrad. These tolerances should be maintained even though the cathode is replaceable. A related problem is the effect of parasitic electron emission near to the FEA. Even a few amperes flowing from a surface defect will generate a strong local magnetic field, giving uncontrolled emittance degradation.

## RELATIVISTIC EFFECTS

During extreme acceleration across the gap, the electrons are taken quickly to a speed near to that of light. For each electron, time is slowing with respect to the laboratory frame of reference by the factor $\gamma$. In addition, the longitudinal separation between electrons in the rest frame of reference moving with the electrons is also increasing by the factor $\gamma$. Thus the increase of $\gamma$ by the initial acceleration should be sufficient to permit a short drift space with negligible emittance degradation before further acceleration in, for example, an RF Linac.

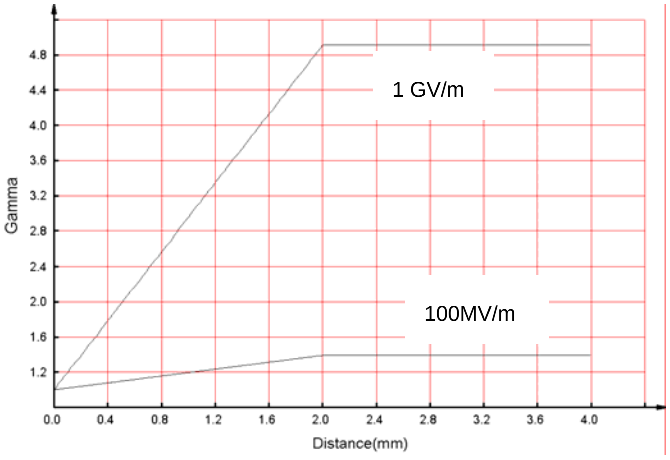

**Fig. 2**: Gamma across 2 mm gap, followed by 2 mm drift.

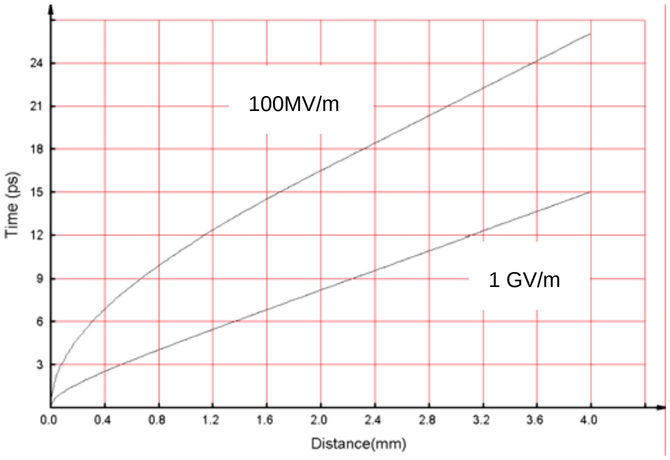

**Fig. 3**: Electron travel time across 2 mm gap, followed by 2 mm drift.

Referring to Fig. 3, at 1 GV/m, the slope is almost linear, so almost the entire path is travelled at the speed of light giving the minimum time for transverse forces to act. However there is a negative consequence of the short transit time: parasitic, or unwanted, electron emission occurs from surface defects in the same time frame, and the energies are so high that uncontrolled ion, electron and x-ray emission will cross the gap many times, even within 100 ps, giving uncontrolled breakdown. Thus there is little chance of using fast pulse technology to prevent breakdown.

## CHARGE DENSITY

When a high charge density is present in an accelerating gap, the effective field strength is reduced for some of the electrons; when taken to the limit, this gives the Child Law which can be approximated by:

$$j_e = \left[\frac{2\varepsilon_o m_e c^3}{q_e d^2}\right]\left[\left(1-\frac{q_e V}{m_e c^2}\right)^{1/2} - 0.8471\right]^2$$

This equation is plotted in Fig. 4. Using this indicates that a current of 500 A is reasonable with the conditions of 2 MV, 2 mm gap and 1 mm radius cathode. This current over the relatively large area of the cathode gives a charge density of only 1 C/m$^3$. With the software STARBURST, this low charge density gives transverse space charge velocities which are small in comparsion to the thermal velocities. Once the electrons are relativistic, radial focusing can be used to reduce the radius to around 35 $\mu$m; this gives charge densities above 1 kC/m$^3$ (in the laboratory frame of reference) which is more typical for use in XFELs.

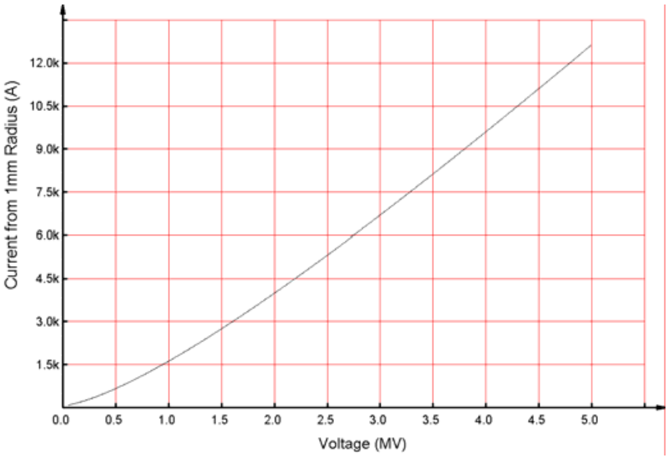

**Fig.4**: Static relativistic saturation current (Child Law) for 1 mm radius cathode and 2 mm gap.

## PULSE POWER TECHNOLOGY

Different pulse power technologies are summarised in Fig. 5. The dotted curves are not pulse devices as such, but rather oscillating fields from RF cavities and lasers - in a sense, each cycle can be viewed as a pulse. Resonant cavities are an easy way to get high voltages. The cavity is driven with megawatt powers at the same frequency as its natural resonance. It may require several microseconds of driving the cavity, but finally oscillating gradients above 100 MV/m may be achieved. However, in this basic form, an oscillating field is not suitable for an FEA cathode because; with polarity inversion, the FEA is bombarded with ions and electrons for hundreds of alternate half-cycles; the slow resonance growth increases the probability of breakdown from thermal processes; and high Q resonance implies high impedance so the peak voltage is strongly dependant on the energy loss from parasitic emission.

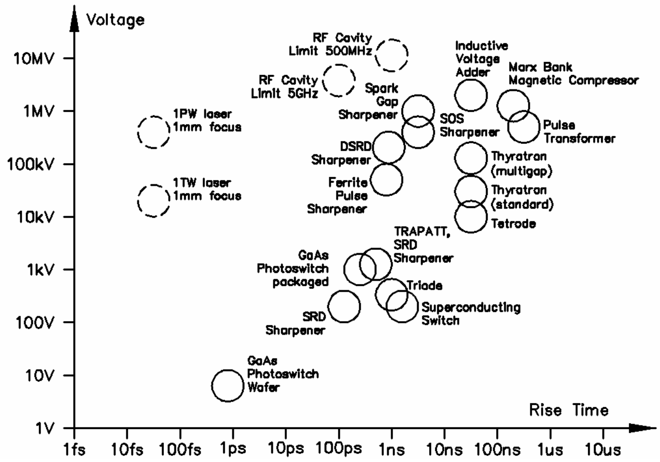

**Fig. 5**: Overview of pulse power technology

The breakdown of a gap with extreme fields has been studied extensively, but results are critically dependant upon the absence of surface defects and adsorbants. As a first approximation, there are fast electron / ion / radiation processes (picoseconds) and slower processes involving the formation of a plasma (in nanoseconds). Thus there is a belief that a fast pulse, in the nanosecond range, should permit higher accelerating fields. Indeed, colleagues at Eindhoven and Brookhaven have used spark-gap technology to achieve gradients of 1 GV/m over a gap of 1-2 mm. One problem with this approach is that the laser-triggered spark gaps have shot-to-shot jitter in the range of 1 ns(rms) and amplitude jitter in the range of a few percent. For FEA cathodes, small variations in field give large variations in charge. Even worse, the laser-triggered spark gaps are operated at extreme power density, giving erosion and a lifetime of thousands of shots only before disassembly is needed. The LEG project needs stable operation at 10-1000 Hz over a period of weeks.

In Fig. 5, the spark gap and several other devices are shown as "sharpeners". This means that these devices can switch a high voltage rapidly, but they depend on another device to generate the high voltage.

The choice is made to use only semiconductor technology for switching, to guarantee the voltage stability from one week to the next. The cathodes are operated in ultra high vacuum; when new cathode surfaces are introduced from atmospheric conditions, a bake-out and conditioning procedure lasting one week may be necessary. Thus the long term stability requirement comes because different cathode surfaces needed to be compared with exactly the same gradient.

In Fig. 5, the "Inductive Voltage Adder" is attractive because high voltages can be generated by summing the outputs from many identical semiconductor modules; disadvantages include high cost and mechanical complexity. "Magnetic compressor" technology is also attractive because the main requirement is simple magnetic cores, and this is commonly used to drive pulse sharpeners; disadvantages include timing jitter and drift. "Pulse transformer" technology is well known for driving klystron modulators, but is relatively slow. However, all these three technologies use magnetic cores, and our measurements have confirmed that commercially available cores have poor performance / cost for rise times below 100 ns.

## MAGNETIC COMPRESSOR

When magnetic cores are driven with a high current pulse, the core presents a high inductance for a while, but once the magnetic material is saturated, the inductance drops rapidly. The sudden decrease in inductance can be used to increase the rate of change of voltage in a circuit. When combined with a capacitor as a resonating element, a compression of pulse length of about ten is possible with one magnetic core. Connecting several stages in series can convert, for example, a 10 kV / 10 kA / 10 μs pulse into a 1 MV / 5 kA / 100 ns pulse with 50 % energy efficiency. Fig. 6-7 show such technology can be optimised for excellent performance for fixed load and voltage conditions.

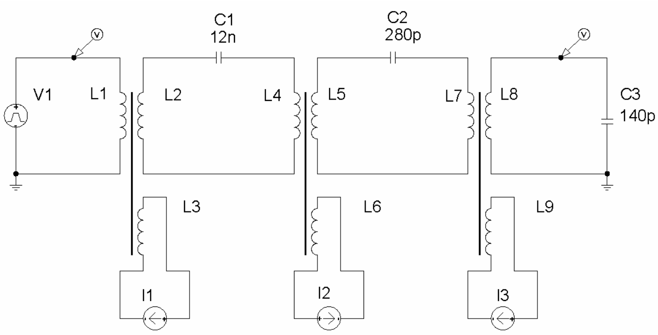

**Fig. 6**: Magnetic pulse compressor circuit.

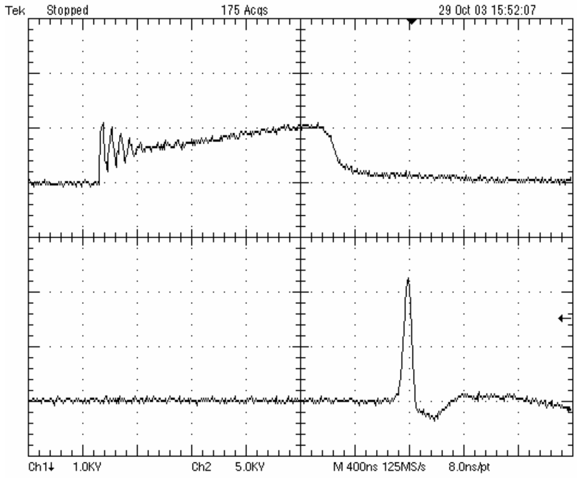

**Fig. 7**: Measured result – 1 kV / 1.7 μs input pulse is compressed to a 12 kV / 50 ns output pulse.

## EXAMPLE OF PULSER

Several pulser designs are under evaluation. The sketch in Fig. 8, together with its electrical circuit in Fig. 9 [4], are a simple example of the present development. The 500 kV pulse, generated by some magnetic compression circuit (not shown), is applied to an SOS pulse sharpening diode through the pulse voltage connection. These diodes are first biased into forward conduction, then reverse biased. After a few nanoseconds, these diodes cut off rapidly, giving a 400 kV pulse with fast rise time to the cathode stalk. The simulation results are shown in Fig. 10. When the stalk is modelled as a lumped inductance, a reasonable 400 kV / 5 ns pulse is given. However, when the stalk is more correctly modelled as a transmission line with a propagation time of 2 ns, the pulse is badly distorted. This illustrates that pulsers giving a pulse length of a few nanoseconds must also provide 5-20 kA for driving low transmission line impedances.

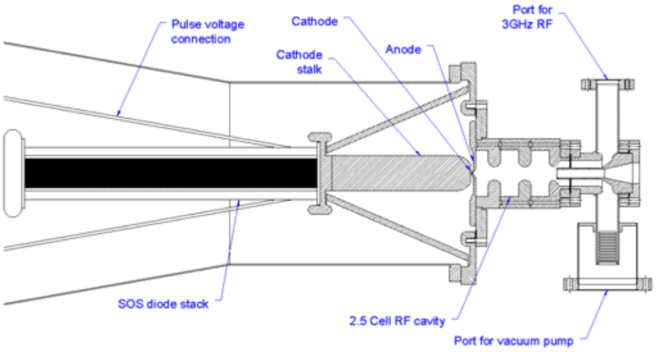

**Fig. 8**: Example fast pulser mechanical layout.

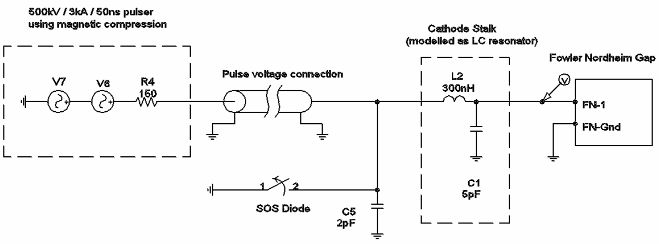

**Fig. 9**: Example fast pulser equivalent electrical circuit.

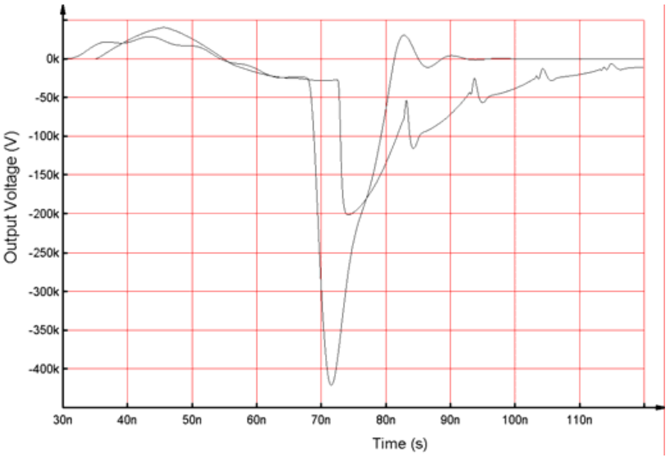

**Fig. 10**: Example fast pulser simulated response, showing the difference between lumped element and transmission line modelling.

## CONCLUSIONS

While the idea of providing a stable extreme accelerating gradient is simple, the practical requirements have given serious technical challenges for decades. Several solutions are under investigation, generally with rise times longer than 50 ns; while shorter rise times may help to reduce the probability for breakdown, the transit time of the gap is so short that this does not seem likely. A voltage of 2 MV, a cathode radius of 1 mm and a current of 500 A seem a reasonable compromise.

Provision of a DC voltage to the cathode is also interesting because, without the large pulse currents to obscure measurements, it is possible to resolve microampere emission currents from the FEA.

The mechanical and vacuum design of the cathode chamber have extreme requirements for positioning to sub-micrometer accuracy and the absence of surface defects down to atomic scale [2-3]; this is in contradiction with the requirement that the cathode assembly should be exchangeable quickly.

The emitted electron bunch would be several nanoseconds long, or maybe 100 ps if gating circuits can be added to the FEA. This bunch then has to be further compressed during the acceleration to GeV energies. This shortening is necessary to maintain the high charge density needed for lasing in an XFEL. The standard technique to shorten bunches requires that the electron bunch passes through several stages of magnetic chicanes, once the bunch has been accelerated higher energies. However, these magnetic chicanes may degrade the emittance [5].

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