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APPLICATION OF A REDUCED PHASE VELOCITY HIGH BRIGHTNESS PHOTOGUN FOR MeV ULTRAFAST ELECTRON DIFFRACTION

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Abstract

MeV ultrafast electron diffraction has become a new frontier for the study of molecular dynamics. With the temporal resolution of MeV-UED being limited, in part, by the electron bunch length at the target, electron sources used for this technique are becoming ever more intricate in the push for shorter bunches length. However, moving to these complex setups makes them less feasible in a small-scale setting, such as universities, where keV-UED setups are becoming increasingly popular. In this paper, we use a multicell reduced phase velocity RF photogun without any additional bunch compressor to generate ultra-short electron bunches whose lengths rival that of the most intricate magnetic or ballistic compression schemes. Two separate RF designs for such devices are presented based on two competing technologies. When combined with state-of-the-art synchronization systems and lasers, these RF photoguns will be demonstrated to cross the so-called '50-fs time-resolution barrier' and push towards the <10 femtosecond regime.

INTRODUCTION

MeV ultrafast electron diffraction (UED) is a rapidly developing technique opening up a new frontier to the investigation of molecular dynamics on the sub-picosecond scale [1, 2]. The electron sources for MeV-UED have so far relied on using electron sources developed for FELs whose designs are optimised for high charge applications. To continue to push the boundaries in the MeV-UED technique, it is important to push pulse lengths to the femtosecond scale. Achieving femtosecond scale bunch downstream of an electron sources is feasible through the use of compression schemes. However, these compressors add complexity and cost to the beamline, as well as increase the footprint of the machine. In this work, we investigate a new design for a multi-cell RF photogun that gives strong longitudinal compression, using a reduce phase velocity, in order to generate femtosecond-scale electron bunches from a stand-alone device.

GENERATING FEMTOSECOND BUNCHES FROM AN RF GUN

Understanding how to generate femtosecond bunches from an RF gun means understanding the beam dynamics mechanisms within an RF photogun. Particularly important is to note how the reduced phase velocity affects commonly discussed mechanisms.

Capture Condition with Reduced Phase Velocity

Capture in accelerating structures is a well-known concept that has been widely reported [3, 4]. In the case of a reduce phase velocity section or device, such as the cathode cell of an rf photogun or a reduced-length cell, such equations must be generalised for a variable phase velocity. This generalised equation has been reported in Ref. [5] and is written as:

$$E_a \geq \frac{\pi}{\lambda_g}\frac{m_e c^2}{e\beta_{ph}}\left(\frac{1-\beta_0\beta_{ph}}{\sqrt{1-\beta_0^2}} - \sqrt{1-\beta_{ph}^2}\right) \qquad (1)$$

where e and m_e are the charge and mass of the electron, respectively, c is the speed of light, λ_g is the wavelength of the RF in the accelerating structure, and β_{ph} and β_0 are the phase and particle velocity, respectively. From this we find that by reducing the phase velocity, one reduces the threshold gradient for capture. With the beam successfully captured, we can then look into its acceleration to the MeV-scale and how one can also achieve significant longitudinal compression for the generation of MeV femtosecond bunches.

Acceleration and Longitudinal Compression with Reduced Phase Velocity

When describing the acceleration and compression of a bunch within an RF structure, we can describe it in terms of the electric fields seen within the structure. Like the capture, we must also generalise for the case where $\beta_{ph} \neq \beta_0$. This can be written as [3]:

$$E_z(z) = |\mathbf{E}(z)|\cos\left[\int_0^z\left(\frac{\omega}{c\beta_0(z)} - \frac{\omega}{c\beta_{ph}(z)}\right)dz + \phi_0\right], \qquad (2)$$

where $|E(z)|$ is the electric field magnitude, ω is the RF frequency and ϕ_0 is the initial phase. For an RF photogun, one desires to inject when the phase is close to the crest as this maximises the brightness that can be generated on the cathode. However, for longitudinal compression one requires that the bunch is close to the zero crossing. Achieving each of these in a single device means having $\beta_{ph} < \beta_0$. In the following RF photoguns, we aim to reduce the phase velocity to generate, accelerate and compress electron bunches all within a single device.

Number of Cells vs Phase Velocity

As we rely on phase slippage between on-crest and the zero crossing which occurs at a finite rate, one can investi-

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gate how many cells and what reduction in phase velocity is required for appropriate longitudinal compression to generate the ultrashort bunches a few metres downstream of the photogun. Numerical simulations were ran in General Particle Tracer (GPT) [6] using a 75 fC bunch on a cathode with the bunch properties used at SLAC MeVUED facility [2]. The RF photoguns' cells' fieldmaps were generated using an electromagnetic model in CST [7] to produce a single cell and then concatenated to produce a multicell device. The cathode cell was assumed to be a half-cell in length. Figure 1 displays the bunch length at the longitudinal compression point for an RF photogun of varying number of accelerating cells and cell length (equivalent to phase velocity). We find that a combination of 10-12 cells and a phase velocity reduced of $0.94c$ leads to a significant longitudinal compression between 1-3 metres downstream with a bunch length of the order of 10 fs. With this concept of the phase velocity and optimal number of cells, one could now proceed with an RF design.

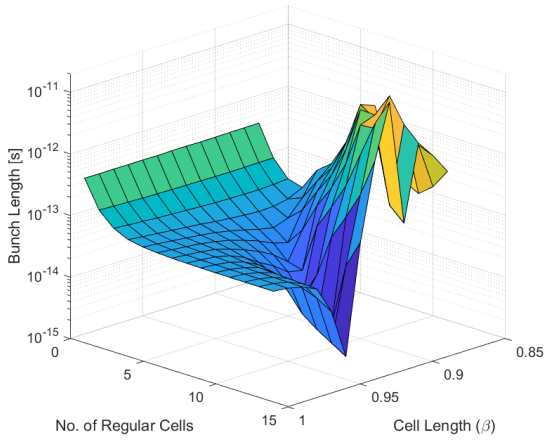


Figure 1: Scan of number of cells and cell length to find optimal values for strong longitudinal compression.

RF DESIGN OF REDUCED PHASE VELOCITY PHOTOGUNS

To understand how to design an RF photogun within these properties, we must first look at the concept of phase velocity. In a standing-wave (SW) RF photogun, there exist discrete modes. These narrow-band modes mean that reducing the phase velocity is restricted to shortening the length of the accelerating cells. This technique is of course very well-known in the accelerator community and has widespread use. For travelling-wave (TW) system, employing the cell length reduction is also an option. However, the broadband nature of TW systems means that one can, more continuously, adjust the phase advance per cell through a difference in the driver and resonant RF frequencies. This means that tuning the phase velocity is as simple as changing the driver frequency or, equivalently, changing the operational temperature. With these techniques in mind, Fig. 2 demonstrates the RF design

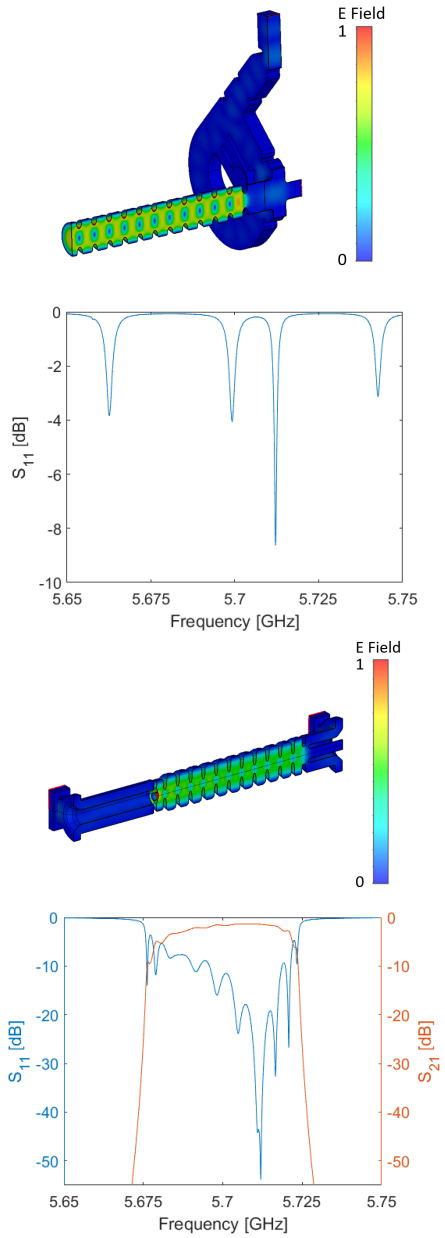


Figure 2: RF Design and S-parameters of two proposed RF photoguns with a reduced phase velocity.

and scattering parameters of two separate multi-cell, reduced phase velocity rf photoguns. The first is a SW RF photogun based on a design realised under the IFAST programme [8]. A notable feature of the SW gun is its many cell design consisting of 11.5 cells. To increase mode separation, the iris size was increased leading to a minimum mode separation of 12 MHz. Furthermore, to reduce the phase velocity, all of the cells' lengths were reduced by 6%. The power is fed into the gun through a four-port coupler, originally design for the SW gun mentioned above.

The second design is a TW gun designed also as part of the IFAST programme and extensively report on in Ref. [9]. Here we find the RF design is the same. However, the struc-

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ture is run 10 °C above the nominal temperature and the RF driver runs 3 MHz above the nominal 5.712 GHz. These factors combined reduce the phase velocity also by 6%. The RF parameters of both guns are listed in Table 1.

Table 1: RF parameters of the reduced phase velocity SW and TW RF photoguns.

Parameter	TW Gun	SW Gun	Units
Mode Frequency	**5.711**	5.712	GHz
RF Driver Frequency	**5.715**	5.712	GHz
No. of Accelerating Cells	11.5	11.5	
Cell Length	17.495	**16.445**	mm
Structure Active Length	250	250	mm
Mode Phase Advance	>120	180	°
Peak Power	10	15	MW
Cathode Field	80	80	MV/m

BEAMLINE SIMULATIONS AND TEMPORAL RESOLUTION

To determine the performance of the new designs, beam dynamics simulations were performed for a simple beamline. The beamline consists of the multi-cell rf photogun (here we have chosen the TW gun), the gun's solenoid, another solenoid downstream to focus onto the interaction point and a collimator (Fig. 3). Three cases have been simulated: Case 1 is for a 100 fC charge case; Case 2 uses the same initial cathode parameters but with a collimator to reduce the beam down to 10 fC; and Case 3 is for a 20 fC cathode charge collimated down to 10 fC. Figure 4 demonstrates bunch length and the bunch size along the three cases with the interaction points illustrated by a point. One can see in the three cases that the bunch length achieved is below 30 fs, even at 100 fC. A full summary of the bunch parameters on the cathode, and at the interaction point, is given in Table 2. With the known RF amplitude and jitter from the C-band systems of SwissFEL [10, 11], we can simulate the arrival time jitter caused by the RF system. We find that the arrival time jitter approximately 17 fs and 6 fs, if we assume the median and best performance of the SwissFEL RF modules, respectively. Taking Case 2, summing in quadrature the electron bunch length, the 35 fs (FWHM) pump laser pulse length and arrival time jitter, and assuming the velocity mismatch at 5 MeV is negligible, we find that the temporal resolution of the system is 25 fs.

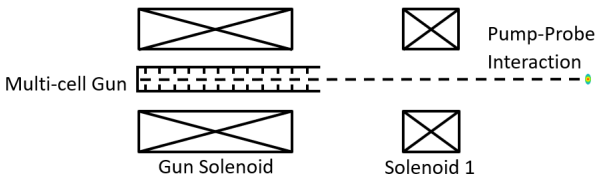


Figure 3: Beamline layout consisting of the multicell rf photogun with its solenoid, along with two solenoids downstream to focus the beam onto the sample.

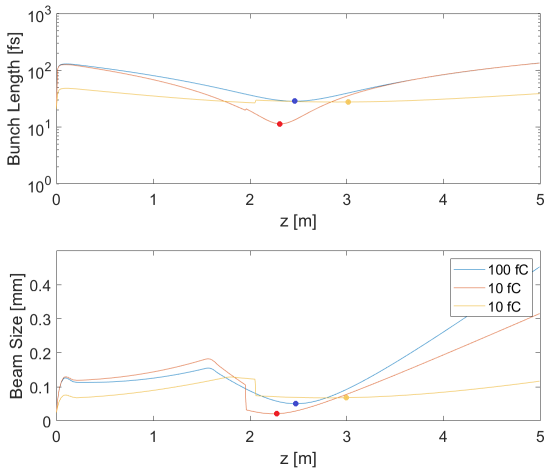


Figure 4: Beam dynamics for the three cases.

Table 2: Summary of the bunch properties at cathode and the interaction point. Common values are 80 MV/m on the cathode, a 25 µm laser pulse radius on the cathode with 50 fs (FWHM) UV pulse length with an intrinsic emittance of 0.5 mm·mrad/mm.

Parameter	Case 1	Case 2	Case 3
Cathode Bunch Charge [fC]	100	100	20
Location of IP [m]	2.44	2.3	3
Charge at IP [fC]	100	10	10
Energy [MeV]	5.04	4.87	5.25
Relative Energy Spread [%]	0.026	0.127	0.012
Bunch size (RMS) [µm]	50	21	68
Bunch length (RMS) [fs]	28	11	27
Emittance (RMS) [nm·mrad]	20	7	9
Divergence (RMS) [µrad]	37	30	12

CONCLUSIONS

An MeV-UED beamline based on a multi-cell rf photogun with a reduced phase velocity has been proposed. Two separate RF designs have been demonstrated each that can be used as a stand-alone device in an MeV-UED beamline. The first RF design is a standing-wave rf photogun that features reduced length cells to reduce the phase velocity while the second RF design uses the broadband nature of travelling-wave devices to vary the phase velocity. Using a combination of a reduced phase velocity and high cathode fields, these stand-alone devices can produce 10 fC electron bunches with a bunch length of 11 femtoseconds and normalised emittance of 7 nm·rad. Finally, when driven with a SwissFEL style RF system and femtosecond laser system, the temporal resolution is just 25 fs.

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