DESIGN OF ULTRAFAST HIGH-BRIGHTNESS ELECTRON SOURCE*

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Abstract

Generation and preservation of ultrafast, high-brightness electron beams is one of the major challenges in accelerator R&D. Space charge forces play a fundamental role in emittance dilution and bunch lengthening for all high brightness beams. In order to generate and preserve the ultrafast high-brightness electron beam, transverse and longitudinal space charge effects have to be considered. Several approaches to achieving ultra-short bunches have been explored, such as velocity bunching and magnetic compression. However, each option suffers drawbacks in achieving a compact ultrafast high-brightness source. We present an alternative scheme that uses radial bunch compression in an X-band photocathode radio frequency electron gun. By compensating the path length difference with a curved cathode and using an extremely high acceleration gradient (~230 MV/m, peak), we numerically demonstrate the potential for achieving a near order of magnitude increase in beam brightness over existing electron guns.

INTRODUCTION

In the generation of ultrafast, high-brightness electron beams, space-charge forces play a fundamental role in emittance dilution and bunch lengthening within the gun and subsequent emittance compensation drift. In order to generate and preserve the beam brightness, transverse and longitudinal space charge effects have to be precisely managed. Several different approaches have been reported and are being actively pursued within the worldwide accelerator community. These include various velocity bunching and magnetic compression techniques. However, each option suffers drawbacks that must be overcome in order to deliver a compact and economic ultrafast, high-brightness source.

In recent years, due to a better understanding and improved control of the propagation dynamics in the non-relativistic electron guns used to date for ultrafast electron diffraction (UED) experiments, sub-picosecond level temporal resolution has been achieved. These approaches succeeded by firstly, placing the sample in close proximity to the electron source in order to minimize the propagation distance and, secondly, by decreasing the number of particles in the beam to avoid excessive bunch lengthening due to space-charge forces. Single electrons with very high repetition rates are used to obtain the diffraction pattern with resolution limited by the temporal jitter of the laser pulses used to generate the electrons [1].

*This work was supported by the U.S. Department of Energy, under Contract No. DE-SC0006210
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In order to develop an improved ultrafast source, we have proposed a scheme that compensates for path length differences by using a curved cathode [2] to introduce radial compression that compensates for geometric bunch lengthening effects when coupled with extremely high acceleration gradient (~230 MV/m from an 11.4 GHz RF gun [3]) that minimizes the impact of space-charge forces. The axial symmetry of our selected geometry also eliminates contributions to transverse emittance from non-axisymmetric modes [3, 4]. We show that combining these two effects is feasible and does indeed deliver a more compact, economic, ultrafast high-brightness electron beam for various applications such as UED.

CAVITY DESIGN

The physics design of an X-band RF gun cavity with a curved cathode and a coaxial RF coupling scheme, embedded in an emittance compensating magnetic field has been optimized. Various curved and flat cathode geometric models were designed using SUPERFISH. We varied the radius of curvature to optimize the beam dynamics output. The resultant SUPERFISH output field files were translated into input files for the TStep beam dynamics code [5]. Figure 1 shows a cavity cross-section with field lines from SUPERFISH. The PITZ gun-style coaxial coupler dimensions [4] were chosen to prevent the transmission of the lowest high-order TE01 mode through the coaxial waveguide.

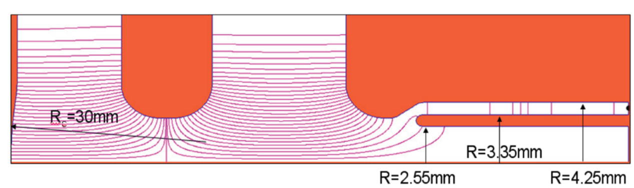

Figure 1: SUPERFISH model of the 1.6 cell, X-band, π-mode, RF gun cavity. The cathode radius of curvature is 3 cm and the coaxial coupling at the gun exit is evident.

The longitudinal electric field profiles on axis for flat and curved cathodes that illustrate the differences in the near cathode region are shown in Figure 2(a). The difference derives from the field modification caused by the curvature. Off-axis, the cathode region has radial focusing, as shown in Figure 2(b), and this focusing can deliver a smaller radial output beam at the gun output than can be achieved with a flat cathode. This 20% effect is illustrated in Figure 3 where "Cathode A" is curved and "Cathode C" is flat. In a cavity with a flat cathode, the beam is initially affected by a defocusing force in the first half cell before the beam is respectively focused and defocused at the entry and exit of the second cell around the 1 and 2 cm points from the cathode.

ISBN 978-3-95450-115-1

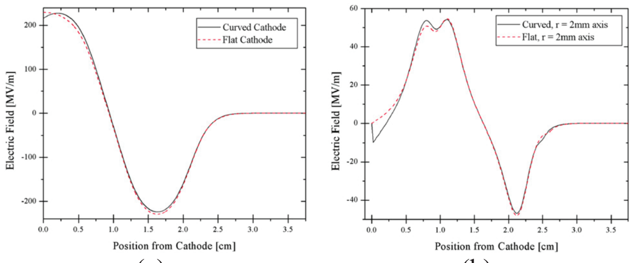

Figure 2: (a) Longitudinal electric field profile on axis and (b) radial electric field profile at r = 2 mm. The curved cathode A (black lines) field peaks slightly ahead of the surface and the electron bunch is initiated in a radial focusing region. Red dots are the flat cathode C.

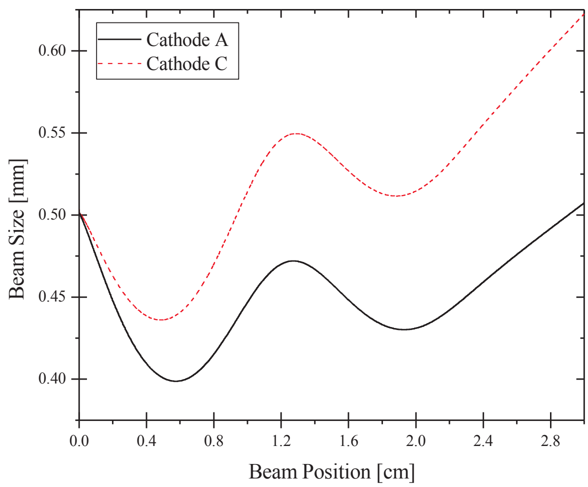

Figure 3: Transverse bunch size evolution in the gun showing a smaller curved cathode A beam.

BEAM DYNAMICS CALCULATION

Figure 4 is a schematic of our concept for a UED experimental beam line [2] showing an RF gun, two solenoid coils and the laser system. We will use copper as the photocathode material and thus need to deliver a normally-incident, UV beam from the target pump laser to the cathode, that is suitable-timed with respect to the target interaction.

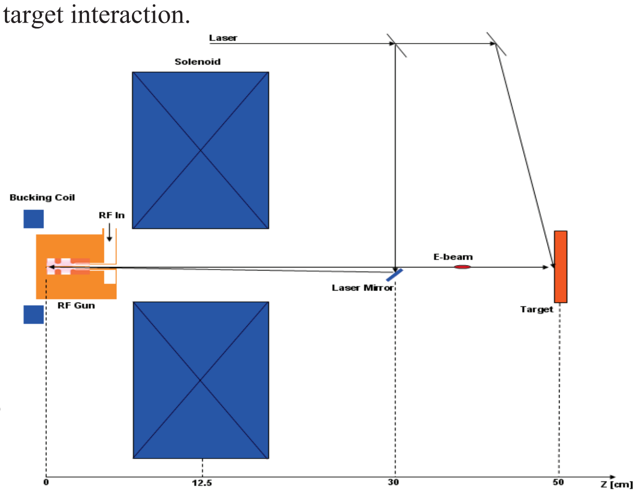

Figure 4: Schematic diagram of a proposed femtosecond electron diffraction experimental setup.

The beam dynamics analysis addressed several aspects of the gun design. Firstly, we anticipated that the higher accelerating field in the X-band cavity would reduce the longitudinal and transverse emittance growth produced by space charge forces, thereby contributing to the satisfaction of our goal of an ultrafast high-brightness electron bunch. Secondly, by utilizing a curved cathode, we expected that the focusing field near the cathode surface would lead to improved integrated transverse beam focusing and improved beam brightness. Finally, we believed that the curved cathode would compensate for the bunch lengthening induced by path length variation across the cathode due to the combined effect of the focusing elements and the RF in the cavity.

Various simulations were performed using TStep [5], an evolved version of PARMELA, to investigate the effect of the bunch charge on the bunch length and beam brightness. Figure 5 shows a comparison of the bunch length at the nominal target position as a function of bunch charge and cathode geometry. In this figure, Cathode C is the flat cathode used for comparison. Cathode A has a radius of curvature of 30mm and no laser pulse shaping. Cathode B has a radius of curvature of 40 mm and adds laser pulse shaping so that the outer radius of the drive laser is 14 femtoseconds ahead of the center of the pulse when reaching the cathode. Although both these effects can lead to similar behavior, Figure 5 shows that combining both delivers the optimum performance with cathode B. The peak accelerating field of the gun was maintained at 230 MV/m which delivers a 2.7 MeV beam. The peak solenoidal magnetic field was 2.1 kG and the initial laser pulse width was 25 femtoseconds.

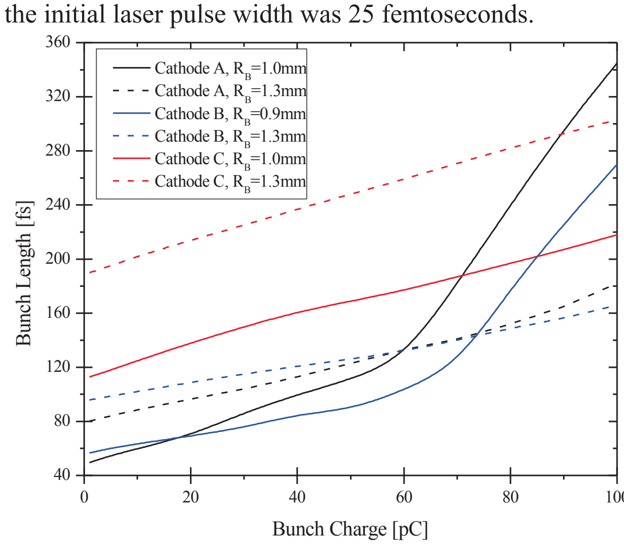

Figure 5: Comparison of bunch length at the nominal target as a function of bunch charge for the three cathodes A, B and C, and different drive laser spot sizes.

Figure 5 shows that cathode C is not competitive with curved cathodes at lower charge, and though the bunch length grows more slowly with charge, it is always surpassed, even at 100pC, by the other cathode configurations with a 1.3 mm laser spot. Cathode A with a 1.0 mm laser spot delivers less than 100 femtosecond electron bunches up to 50 pC bunch charge. Above 50 pC, the bunch length quickly increases. With a 1.3 mm laser spot, the lower charge bunch length performance is not so good, but the ~180 femtoseconds at 100 pC is significantly improved and much better than Cathode C. Cathode B delivers an 89 femtosecond bunch with a 0.9 mm laser spot at 50 pC but blows up rapidly above this charge level. At 100 pC and 1.3 mm laser spot, Cathode B delivers the best result of a 166 femtosecond bunch showing that the combination of wavefront manipulation and geometry provides the best ultrafast bunch length performance, but as shown in Table 1 which summarizes the beam dynamics results, not the brightest transverse beam. Here, cathodes A and B at 50 pC are five times brighter than the 100 pC cases because the lower charge beam is brighter due to the shorter bunch length and lower emittance. Our preference is to select the lower charge case for UED experiments and utilize higher repetition rate for the pump and probe beams to deliver the desired time resolution.

Table 1: Beam dynamics simulation results at the nominal z = 50 cm target location.

Parameter	Unit	Value by Cathode Type				
		A	B	C	A	B
Peak Accelerating Gradient	[MV/m]	230	230	230	230	230
Beam Energy	[MeV]	2.7	2.7	2.7	2.7	2.7
Bunch Charge	[pC]	50	50	50	100	100
Bunch Length	[femtosec]	99	89	169	182	166
Beam Current	[A]	506	562	296	550	602
Energy Spread	[keV]	14.8	13	11.7	26.2	21.2
Target Beam Size	[mm]	1.36	1.54	1.64	1.72	1.92
Transverse rms Emittance	[mm-mrad]	0.69	0.67	1.16	1.94	1.69
Brightness	[10^{14} A/m^2]	10.6	12.6	2.2	1.5	2.1

Figure 6 shows the evolution of the bunch length from the cathode to the target highlighting that there is little to choose at 50 pC between curved cathodes A and B, while the flat cathode C is not competitive. The advantage of the initial compression of cathodes A and B is clear. The earlier electron birth off-axis for a curved cathode leads to bunch compression due to path length differences before space charge forces drive bunch lengthening in the drift region. With a curved cathode X-band gun, the natural initial smaller size of the transverse electron bunch and very high accelerating field quickly raises the electron energy and largely locks in both the transverse and longitudinal emittance.

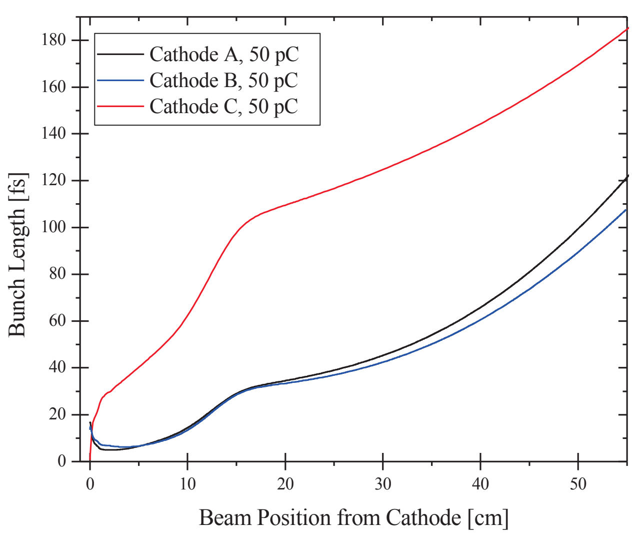

Figure 6: Comparison of bunch length evolution for cathodes A, B and C with 50pC bunches.

SUMMARY

We have successfully developed a concept for achieving ultrafast, high-brightness electron beams and optimized the performance. Geometric compensation from a 30 mm curved cathode and the extremely high acceleration gradient (~230 MV/m) of an X-band gun is used to control the lengthening of the electron bunch. Coaxial coupling minimizes contributions to transverse emittance growth from non-axisymmetric modes. Elsewhere, we have developed an engineering concept for the gun that is robust and suitable for near term fabrication. Using beam dynamics simulations, we have demonstrated that such a gun could generate a less than 100 femtosecond, 50 pC, 2.7 MeV electron bunch that at 10.6×10^{14} A/m^2 is between five and ten times brighter than the brightest S-band photocathode guns. The transverse normalized rms emittance is ~ 0.7 mm-mrad and the longitudinal emittance is better than 1.5 keV-psec, for a peak current is 0.5 kA. We have also shown that high-brightness operation up to 100 pC is possible and that the use of drive laser wavefront modification can deliver even higher performance.

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ISBN 978-3-95450-115-1