SIMULATION STUDY OF DARK CURRENT IN THE THOMSON SCATTERING X-RAY SOURCE *

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Abstract

This paper focuses on the study of beam dynamics of the dark current, including the dark current generation and transmission in the photocathode injector. For the longitudinal compression of the nominal beam in the Thomson scattering X-ray source, we add a velocity bunching cavity behind the RF gun. We analyse the influence of the bunching cavity on the transmission efficiency of the dark current. At last, some methods to reduce the dark current are discussed.

INTRODUCTION

Photocathode injectors are important electron source in Thomson scattering components. In order to obtain the electron bunch with lower emittance and higher brightness, accelerating gradient in RF guns becomes increasingly higher, which produces non negligible dark current under the effect of field emission. Our photocathode RF gun, in which the maximum electric field exceeds 100MV/m, is operated at high acceleration gradient. Dark current is mainly produced in the RF gun, accelerated to high energy level by the linacs along the beamline and then activates the components and produces background radiation because of bremsstrahlung, then influences the application of the light source. In our Thomson scattering X-ray source, trying to avoid this situation is pretty necessary. For the longitudinal compression of the nominal beam in the Thomson scattering X-ray source, we add a velocity bunching cavity behind the RF gun. The bunching cavity will have an obvious influence on the transmission efficiency of the dark current. This is a new phenomenon that we are interested in.

GENERATION OF THE DARK CURRENT

Dark current is produced under the effect of field emission, which can be described by Fowler-Nordheim equation:

$$I_{FN} = 1.54\times10^{-6}\times10^{4.52\phi^{-0.5}}\frac{A_e\beta^2E^2}{\phi}\exp\left(-\frac{6.53\times10^9\phi^{1.5}}{\beta E}\right) \quad (1)$$

where A_e is the effective emitting area in m^2. β is the field enhancement factor(dimensionless) that depends on the material and the roughness of the surface. ϕ is the work function of the material in eV. E is the electric field on the surface in V/m.

In our simulation, we take ϕ=4.65eV for copper, use the measurement results of β from PSI(β =84)[1]. In fact, the deviation of β has little impact on the simulation results.

We calculated the 3D electric field on the surface of the photocathode RF gun using CST, then drew the simplified profile of the gun and its corresponding surface electric field, as showed in Fig. 1.

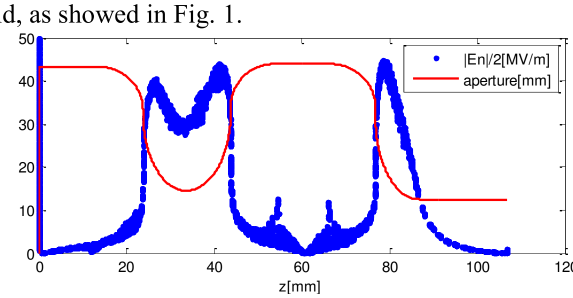

Figure 1: Simplified gun geometry and the corresponding surface electric field.

Due to the asymmetry of the gun, the surface electric field has slight dispersion at some longitudinal positions. We ignored this dispersion and established a 1D model. We drew a curve s along the gun aperture and revealed the relation between the surface electric field E and the position s.

Considering the time dependence of the dark current emission, we multiply the electric field with a sine function. Furthermore, we can obtain the probability density distribution of electron emission with the position s and the time t in a RF period using the Eq. (1). Then we use two-dimensional Monte Carlo sampling to get the position s and the time t of the macro particles. The distribution of the longitudinal position z and the time t is shown in Fig. 2.

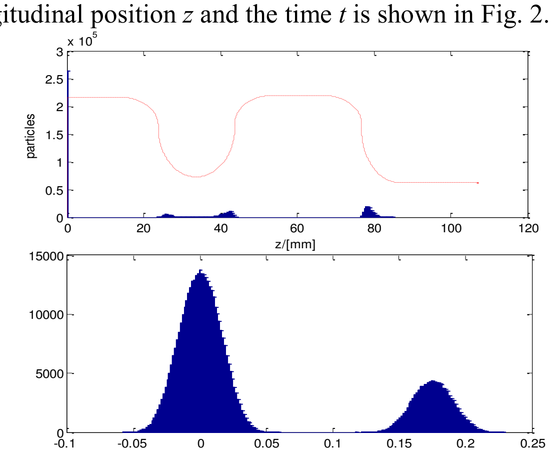

Figure 2: The distribution of the longitudinal position (upper plot) and time in a RF period (bottom plot) for emitted macro particles.

*Work supported by the National Natural Science Foundation of China (Grant No. 11127507 and 11375097)
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ISBN 978-3-95450-171-7

DARK CURRENT TRANSPORT

Transport in the RF Gun

We imported the generated macro particles into ASTRA[2]. In our simulations, we ignored the space charge effect and the secondary electron yield, the approximations of which are acceptable for the dark current[1][3]. In order to precisely describe the off-axis field that the particles experienced, we used a 3D field map in the RF gun.

Our simulations show that a large fraction of particles are lost on the aperture and the cathode because of the energy mismatch and the geometric restriction of the gun. At the position of 0.2m downstream the gun, only 10.8% of the particles pass through. And 97.6% of this part of particles come from the cathode, while only a very small fraction comes from the irises. In Fig. 3 the locations of the particle losses on the aperture are especially indicated.

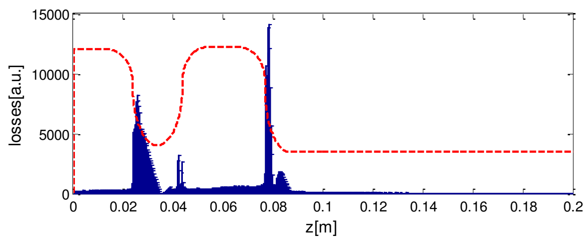

Figure 3: The locations of the losses on the aperture.

Impact of the Velocity Bunching Cavity

For the longitudinal compression of the nominal beam in the Thomson scattering X-ray source, we add a velocity bunching cavity between the RF gun and the first accelerating tube. The dark current passes through the bunching cavity with low energy and the transport trajectories are influenced greatly.

The phase of the bunching cavity is expressed in the sinusoidal form, 90°is the peak acceleration phase, the nominal beam is injected at 0°. The momentum-phase plot of the dark current is indicated in Fig. 4.

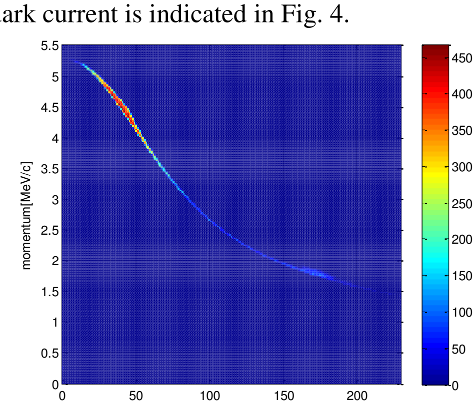

Figure 4: The momentum at the entrance of the bunching cavity and the acceleration phase for the cavity.

The dark current occupies the total phase width of 0°~180°, the main part of which is at the acceleration phase of 25°~60° and then accelerated to higher energy level. As shown in Fig. 5, in the bunching case, dark current has higher energy before the first accelerating tube. It is helpful for the dark current with higher energy to resist the over-focused effect of the solenoids, reduce the divergence and transport further along the beamline. Higher energy makes the dark current enter the following accelerating tubes with 10 degrees phase advance and get a more ideal acceleration.

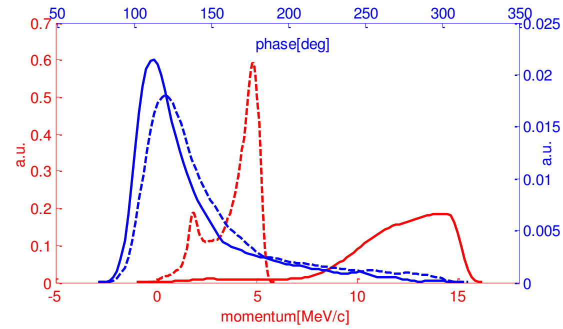

Figure 5: The momentum distribution after the bunching cavity (red line) and the acceleration phase for the first accelerating tube (blue line). Solid line in the bunching case and dotted line in the case without bunching.

On the other hand, the dark current is transversely focused during the transmission in the bunching cavity. In Fig. 6 the transverse distribution density map of the macro particles at the position behind the bunching cavity (1.3m) is shown, and as a comparison, the density map without bunching is plotted too.

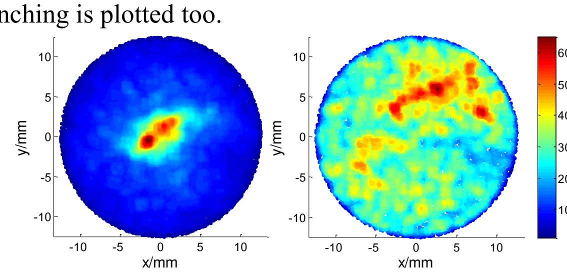

Figure 6: The transverse distribution of the macro particles at 1.3m in the bunching case (left plot) and without bunching case (right plot).

As shown in Fig. 7, in the bunching case, start from the entrance of the bunching cavity (0.8m), the beam size of the dark current is reduced, which indicates the trajectories of the dark current changed from divergence into convergence, and correspondingly, the losses in the bunching cavity is significantly reduced.

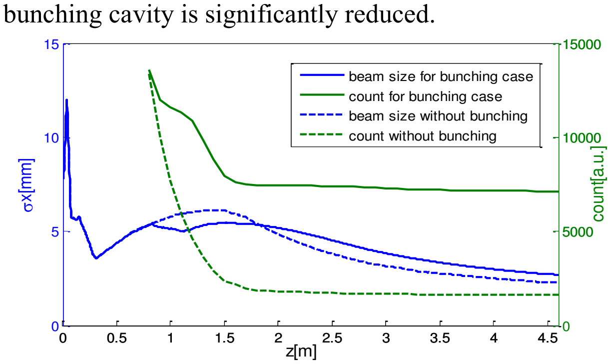

Figure 7: Beam size of the dark current (blue line) and the number of particles (green line). Solid line in the bunching case and dotted line in the case without bunching.

ISBN 978-3-95450-171-7

Above all, we draw a conclusion that the bunching cavity is conducive to the transport of the dark current. In Fig. 8 the changes of particles along the total beamline is shown and the number of particles with the bunching cavity is 4 times than that without bunching.

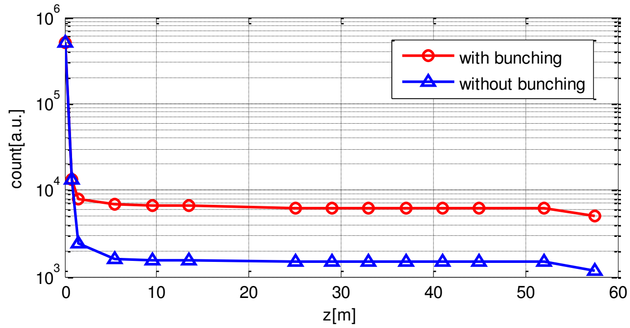

Figure 8: Number of particles along the total beamline.

REDUCTION OF THE DARK CURRENT

Given the significant increase of the dark current in the bunching case, we need to look for effective methods to decrease the flux of the dark current. One direct way is to install a cylindrical collimator at an appropriate position in the beamline.

In Fig. 9 the beam size of the nominal beam and the dark current is indicated and we decide to install the collimator at 1.3m between the bunching cavity and the first accelerating tube, where the beam size of the dark current is maximum and the beam size of the nominal beam is small.

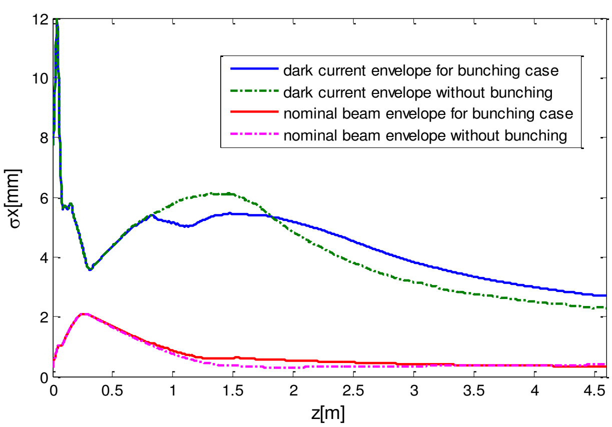

Figure 9: The beam size of the nominal beam and the dark current.

As shown in Fig. 10, most of the dark current can be reduced by the collimator with a relatively small diameter. Unfortunately, because of the focusing effect of the bunching cavity in the bunching case(shown in Fig. 6), it's not good enough for the collimator to reduce the dark current compared with the situation without bunching, so some other methods are expected to reduce the dark current additionally.

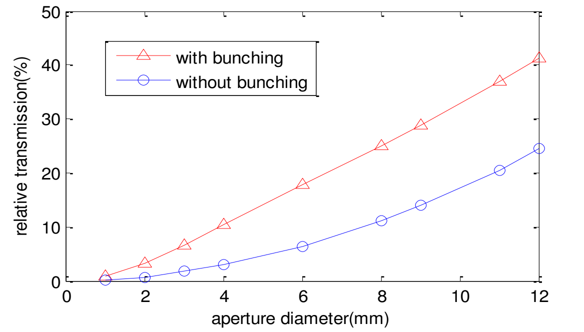

Figure 10: Transmission of the dark current renormalized to the transmission without the collimator.

Chicane is another commonly used method to reduce the dark current[4]. According to our preliminary calculations, if the chicane is placed at 19m with an appropriate strength, combined with the collimator, more than 90% of the dark current can be scraped off by the scraper installed in the middle of the chicane, the remaining part of which have the energy close to the nominal beam's and have a small energy spread, thus can pass through the whole beamline without losses.

But for our initial design, a bunching cavity is enough to satisfy the requirement of the longitudinal compression for the nominal beam, chicane isn't part of the design so other methods to reduce the dark current without chicane are still demanded.

CONCLUSION

In the Thomson scattering X-ray source, dark current produced in the RF gun leads to components activation and background radiation. For the longitudinal compression of the nominal beam, we add a velocity bunching cavity behind the RF gun. Our study shows that the bunching cavity is conducive to the transport of the dark current. From the longitudinal perspective, most of the particles are at the acceleration phase and accelerated to higher energy level. From the transverse perspective, dark current is transversely focused during the transmission in the bunching cavity. A collimator is used to reduce the dark current, but the effect is not good enough. Dark current suppression chicane is ideal but for our initial design, chicane isn't part of the design so other methods to reduce the dark current without chicane are still demanded.

REFERENCES

[1] S. Bettoni et al., TUPSO03, Proc. FEL2013, http://jacow.org/.
[2] Klaus Floettmann, A Space Charge Tracking Algorithm (ASTRA), http://www.desy.de/~mpyflo/
[3] Han J H et al., Phys. Rev. ST Accel. Beams **8**, 033501 (2005).
[4] H. Schlarb, WEPLE039, Proc. EPAC2002, http://jacow.org/.

ISBN 978-3-95450-171-7