

# COHERENT WIGGLER RADIATION OF PICOSECOND CW ELECTRON BEAM PRODUCED BY DC-SRF PHOTOINJECTOR

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## Abstract

The DC-SRF photoinjector at Peking University is capable of providing CW electron beam with the energy of 3 – 5 MeV. The beam has high repetition rate, picosecond bunch length and high quality, which can be used to produce high repetition rate THz wave by wiggler radiation. Through off-crest acceleration, electron beam from the injector may be bunched, which will lead to coherent enhancement of the radiation power. With current setup of the DC-SRF injector and a 10-period wiggler, THz radiation power of 10s mW to a few watts can be achieved within the wavelength range of 200  $\mu\text{m}$  to 500  $\mu\text{m}$ . In this work, we will present the calculation results about THz radiation produced by the electron beam from DC-SRF photoinjector. The preparation for the experiments will be also described.

## INTRODUCTION

DC-SRF photoinjector[1], a combination of DC Pierce gun and 3.5-cell, 1.3 GHz TESLA-type superconducting cavity, is designed to generate high-quality CW electron beam with the energy of 3 – 5 MeV, an repetition rate of 81.25 MHz, an average current of mA and a bunch length of a few picoseconds.

Through off-crest acceleration, electron beam from the injector may be bunched, which can be used to produce high repetition rate THz wave through coherent wiggler radiation. Calculations indicate that with current setup of the DC-SRF injector and a 10-period wiggler, THz radiation power of 10s mW to a few watts can be achieved within the wavelength range of 200  $\mu\text{m}$  to 500  $\mu\text{m}$ .

After several cycles of beam loading tests, update to auxiliary system has been performed for stable operation of DC-SRF injector. The beam line that delivers the electron beam to wiggler has been fabricated and is under installation. A 10-period wiggler will be installed later and experiments on THz radiation have been scheduled.

## COHERENT WIGGLER RADIATION

Relativistic electron beam traveling through a wiggler will emit spontaneous radiation into a central cone with the opening angle of  $1/\gamma\sqrt{N_w}$ [2, 3]. With planar wiggler, linearly polarized radiation will be produced, whose total power  $P_t$  is [4]

$$P_t = \frac{2N_w\pi e^2\gamma^2 a_w^2}{3\epsilon_0\lambda_w} \cdot \frac{I_e}{e}, \quad (1)$$

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where  $\gamma$  is the relativistic energy factor,  $I_e$  is the electron beam current,  $\lambda_w$  is the wiggler period,  $N_w$  is the number of wiggler periods,  $a_w = eB_{rms}\lambda_w/2\pi mc$  is the dimensionless wiggler parameter for a given wiggler field  $B_{rms}$ , and  $e$  and  $m$  are the charge and mass of an electron and  $c$  is the speed of light. The total radiation power can also be calculated with

$$P_t[W] = \frac{14.52E_e^2[GeV]I_e[A]N_w a_w^2}{\lambda_w[cm]} \quad (2)$$

where  $E_e$  is the energy of electron beam.

The wiggler radiation has an FWHM bandwidth of  $0.9/N_w$  and a central wavelength of  $\lambda = \lambda_w(1 + a_w^2)/2\gamma^2$ . By tuning the electron beam energy and/or the wiggler field (thus  $a_w$ ), the central wavelength can be changed continuously.

When bunched electrons traverses the wiggler, coherent superposition of their radiation field will give rise to the wiggler radiation power greatly. In this paper the enhanced wiggler radiation of bunched electrons is called coherent wiggler radiation, while the ratio of power increase due to coherent superposition is named as coherence enhancement factor, which can be calculated with

$$F_{ce} = \frac{1}{N} \left| \sum_{j=1}^N e^{kz_j} \right|^2, \quad (3)$$

where  $N$  is the number of electrons in a bunch, and  $k$  is the wave number of radiation.

For electron bunch which has a longitudinal Gaussian distribution, the coherence enhancement factor can be calculated with

$$F_{ce} = 1 + (N - 1)e^{(-\frac{2\pi}{\lambda}\sigma_z)^2}, \quad (4)$$

where  $\lambda$  is the radiation wavelength. This formula is consistent with those used to calculate coherent wiggler radiation power of Gaussian beam in most literature. However with perfect Gaussian distribution, the electrons should be distributed in an infinite region, which is different to the real case. What's more, for off-crest acceleration, the typical longitudinal distribution of bunched electrons can not be assumed to be Gaussian any more. Therefore, real distribution of the electrons has to be taken into account and numerical method should be used to calculate coherence enhancement factor.

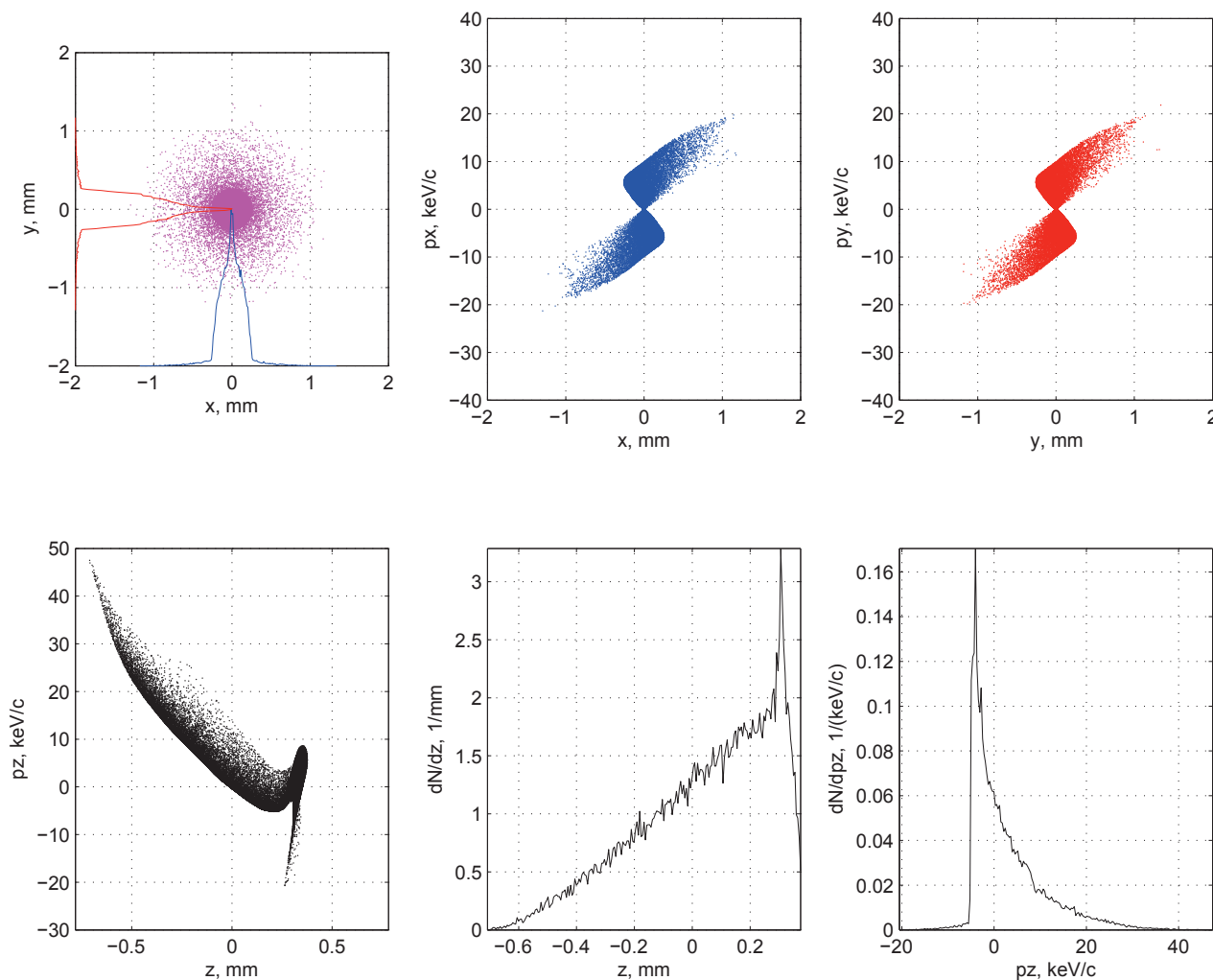


Figure 1: Distribution of electron beam at wiggler entrance, i.e., 4.43 m downstream the photocathode. RF field phase is supposed to be  $160^\circ$  for off-crest acceleration, which is  $34^\circ$  away from the optimized operation phase.

### OFF-CREST OPERATION OF DC-SRF PHOTOINJECTOR

Astra[5] is used to track the electron beam in the DC-SRF photoinjector. According to practical condition, we suppose that

- Voltage of the DC gap is 50 kV;
- Gradient of the 3.5-cell cavity is 10 MV/m;
- Transverse distribution of the drive laser is Gaussian and cut at  $3\sigma$ ;
- RMS beam size of the drive laser is 1 mm;
- Longitudinal distribution of the drive laser is Gaussian and cut at  $3\sigma$ ;
- FWHM pulse length of the drive laser is 10 ps;

Due to the limitation of input RF power at the moment, the average beam current is supposed to be around 1 mA, which is a compromise with the operating gradient of the 3.5-cell cavity. Accordingly, the bunch charge is 12 pC.

The optimized RF field phase of 3.5-cell cavity is  $194^\circ$  for best beam quality. However the bunch length would be

about 4 ps (rms) and when traversing a 10-period wiggler, the incoherent THz radiation power produced by the beam is in  $\mu W$ s. To produce THz radiation with considerable power, the electron beam has to be bunched for coherent enhancement of the radiation power by 5 – 7 orders.

With off-crest acceleration and appropriate drifting, the electron beam from DC-SRF injector can be bunched while sacrificing some energy and quality. As a trade-off between bunch length and beam quality, the RF field phase of 3.5-cell cavity is set to be  $160^\circ$ , which is  $34^\circ$  away from the optimized operation phase. Two solenoids are applied to constrain the beam envelop along the beam line and match the beam into wiggler. Distribution of electron beam at the wiggler entrance is plotted in Fig. 1. Distortion in both transverse and longitudinal phase space can be observed due to effects of off-crest acceleration and space charge force. Simulations also show that the longitudinal space charge force tends to cancel out the bunching effects, especially when the beam is strongly focused in transverse direction.

## THZ RADIATION POWER ESTIMATION

The coherence enhancement factor for the off-crest accelerated beam, whose distribution is plotted in Fig. 1, is calculated and plotted as red solid curve in Fig. 2. As shown in the figure, coherence enhancement of 4–6 orders can be achieved in the radiation wavelength range from 100  $\mu\text{m}$  to 1  $\text{mm}$ , which is much higher than that for a longitudinal Gaussian beam with same RMS bunch length and charge (plotted as blue dashed curve). It indicates that in this case the off-crest accelerated beam has advantage in producing coherent radiation in THz region.

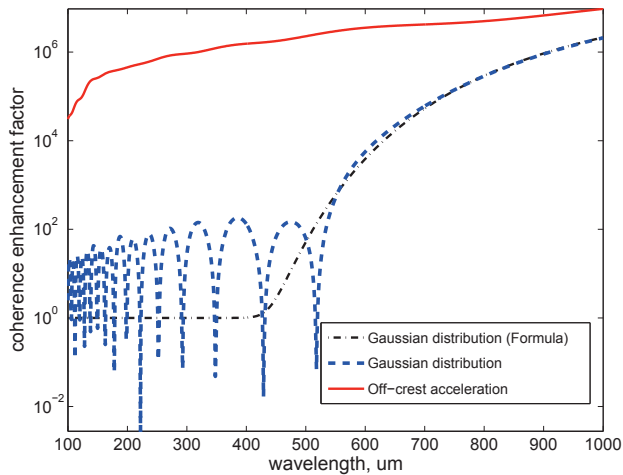


Figure 2: Coherence enhancement factor vs wavelength for off-crest accelerated beam from DC-SRF photoinjector (the red solid line) and Gaussian beam with the same RMS bunch length (the blue dashed curve). Coherence enhancement factor calculated with analytical formula for Gaussian beam is also plotted (the black dash-dot curve).

THz radiation power is estimated with Eq. (2) and Eq. (3). The calculation is performed with two wigglers. One is the existing 10-period wiggler with the period length of 2.7  $\text{cm}$ , which was fabricated by IHEP, Beijing. The other is a newly-designed, 10-period wiggler with the period length of 3.0  $\text{cm}$ . The calculation results are shown in Fig. 3, which indicates that THz radiation with a power of 10  $\text{s mW}$  to about 1  $\text{W}$  may be obtained by using the existing wiggler; while THz radiation power of 100  $\text{s mW}$  to about 3.9  $\text{W}$  within the wavelength range of 230  $\mu\text{m}$  to 510  $\mu\text{m}$  may be achieved with the newly-designed wiggler.

## CURRENT STATUS

Several cycles of beam loading experiments had been performed since 2011. After that, update and commissioning of the auxiliary systems of DC-SRF injector, including cryogenic system, RF power amplifier, control system, LLRF, diagnostic system, etc, have been carried out and are coming to an end at present. An FT-IR spectrometer, Bruker VERTEX 80v, which covers the wavelength range of 1.25  $\mu\text{m}$  to 1  $\text{mm}$ , is also in position and the commis-

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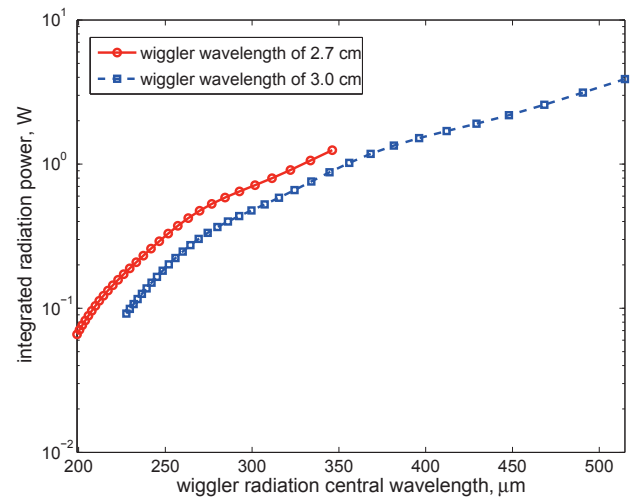


Figure 3: Power of THz radiation produced by off-crest accelerated beam from DC-SRF injector. The calculation is performed with two wigglers: one is the existing 10-period wiggler with the period length of 2.7  $\text{cm}$  (red solid curve with circle marker); the other is a newly-designed, 10-period wiggler with the period length of 3  $\text{cm}$  (blue dashed curve with square marker).

sioning has been accomplished.

The beam line that transfers the beam to wiggler has been fabricated and is under installation; especially, new solenoids, quadrupoles, correctors and high-precision power supplies for magnets have been applied. Beam loading experiments will be carried out firstly for stable operation of DC-SRF injector in the coming cycle, while the 10-period wiggler is planned to be installed afterwards for THz radiation tests.

## CONCLUSION

The electron beam provided by DC-SRF photoinjector will be used to produce THz radiation. With off-crest acceleration, the electron beam can be bunched for coherent enhancement of radiation power. With current setup of DC-SRF injector and a 10-period wiggler, THz radiation power of 10  $\text{s mW}$  to a few watts can be achieved in the wavelength range of 200  $\mu\text{m}$  to 500  $\mu\text{m}$ .

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