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DIAGNOSTICS OF ELBE SRF GUN - STATUS AND FUTURE DESIGN

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Abstract

Since 2015, Mg photocathodes have been applied for the ELBE SRF gun. In 2016, user experiments with a bunch charge of 100 pC and beam transport experiments with 200 pC have been performed. Beams diagnose methods are presented in this article, mainly including measurements of transverse emittance and bunch length. Measurements and corresponding simulations show that the operation parameters of the SRF gun significantly affects the beam quality. A gun lab has been proposed to run as an analog optimizer aiming to explore the potentials of the SRF gun. With the experience of former beam diagnostics, the design of a diagnostics beamline for the future gun lab is described. The purpose is to rebuild phase space projections, either transversely or longitudinally, in a short time scale of several seconds to support analog optimizations for multiple operation parameters.

INTRODUCTION

The concept of SRF (Superconducting Radio Frequency) gun was first proposed in 1988 at the University of Wuppertal [1] and realized in 2002 at HZDR (Helmholtz Zentrum Dresden Rossendorf) [2]. To achieve CW beams with good quality and high bunch charge has always been motivating SRF gun projects. However, the development of SRF guns is still challenged by the processing of cavities, the performance of photocathodes and their lifetime, as well as the risk of cavity contamination [3]. In spite of these challenges, since 2015 an SRF gun has been operating with a magnesium cathode and a 4 MeV, 100 kHz electron beam with the bunch charge up to 200 pC was available in 2016.

As proof of principle, a 100 pC beam was applied in ELBE (superconducting Electron Linac for beams with high Brilliance and low Emittance) for neutron time-of-flight experiments and generation of THz radiation. The beam with the maximum bunch charge of 200 pC was transported in the main beamline of ELBE with negligible beam loss. The energy, energy spread, beam profile and transverse emittance of the beam were measured in a dedicated diagnostics after the SRF gun. The bunch length and slice emittance were measured with the ELBE accelerator modules.

In addition to the design of gun cavity, several operation parameters dominate the beam quality. In general, the phase difference between the RF and the driving laser determines the orientation in the longitudinal phase space; The distance from the cathode surface to the entrance of cavity sets up a trade-off between bunch length and transverse emittance; The transverse size of the laser could be optimized for balancing thermal emittance and space-charge-induced emittance; Moreover, a longer laser pulse reduces the space charge effect but introduces longitudinal nonlinearity to the electron bunch. The working point of all these parameters should be optimized according to a specific requirement.

A new gun lab has been proposed to support the research and development of SRF guns. It will be separated from the ELBE accelerators and therefore offer more experimental time for the gun. The gun lab will consist of an SRF gun and a diagnostics beamline. The beam diagnostics include energy measurement and distribution measurement in both transverse and longitudinal phase spaces. Among them the phase space diagnostics are required to be fast (in 10 seconds) so that gun parameters can be analog and automatically optimized. Longitudinal phase space diagnostics will be probably realized by a transverse deflecting cavity which is possible of single bunch measurement. For transverse phase space diagnostics, different setups based on one dimensional scanning are discussed in the following sections.

CURRENT DIAGNOSTICS BEAMLINE

A diagnostics beamline is connected directly behind the SRF gun at ELBE. Its setup is shown in Figure 1. A Faraday cup is installed to measure the total current. After that three quadrupoles focus the beam for further transport, followed by Screen-station 2 and 3 for beam observation and slit-scan emittance measurement. A 180° horizontal dipole (C-bend) is installed following Screen-station 3 for energy and energy spread measurement, which images the input beam reversely. The distance from its entrance to Screen-station 4 is the same as the distance from its exit to Screen-station 5, as shown in Figure 1. Therefore, projections of a monoenergetic beam on both screens should be the same.

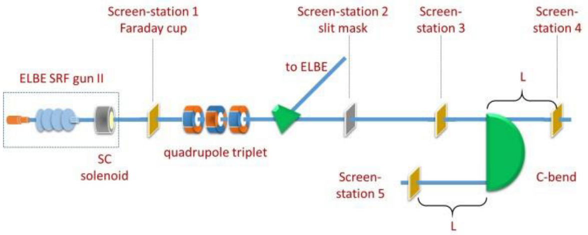

Figure 1: The diagnostics beamline of ELBE SRF gun.

The principle of distribution measurement in transverse phase space is shown in Figure 2. A slit mask is installed at the position of Screen-station 2. It is vertically moveable with a horizontal slit, which has the dimension of 10 mm × 0.1 mm. Screen 3 is located 77 cm after the slit mask to record the sampled beamlet, with the screen installed at 45° to the beam. The scanning step is usually set to 0.1 mm, which is the width of the slit, and thus the entire beam is sampled. The exposure time of the camera should be adjusted to avoid saturation on a normally used YAG (Yttrium Aluminium Garnet) screen for every beamlet. In case of single pulse saturation at high energy

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and high bunch charge, an OTR (Optical Transition Radiation) screen is also installed as a backup.

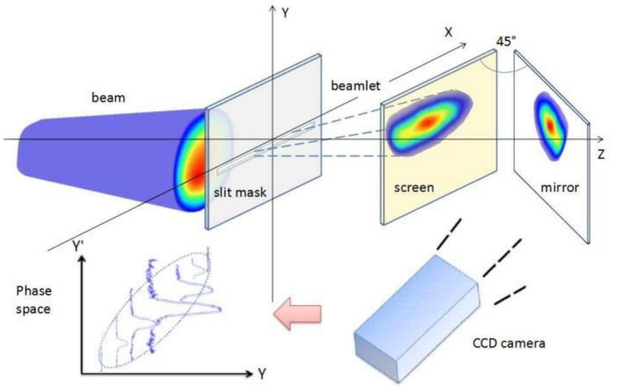

Figure 2: The setup of the slit-scan based distribution measurement in transverse phase space.

It is also necessary to observe the beam in advance at the same position of the slit mask to make sure the entire beam can be sampled by the slit. Therefore, a YAG screens and an OTR screen are installed in Screen-station 2. A calibration screen with coordinates is installed in Screen-station 3 to calibrate beamlet images. The setup of Screen-station 2 and 3 is shown in Figure 3.

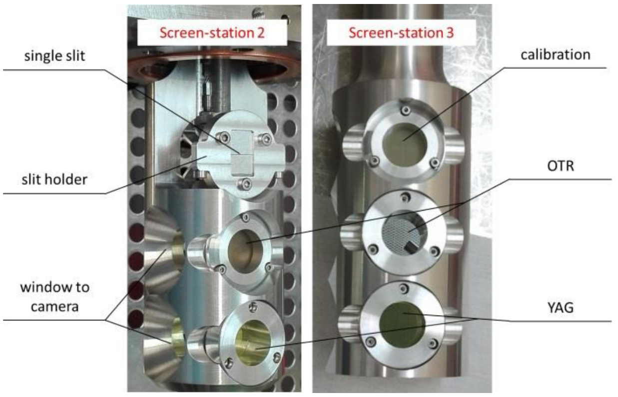

Figure 3: The structure of Screen-station 2 and 3.

The measured transverse phase space distribution can be used further to calculate the rms transverse emittance, with an error less than 15% [4]. The measurement time is over 10 mins, mainly due to the radiation limitation on the slit mask which limits the frequency of macro pulses, and the beam instability which requires more than one image at one position.

CURRENT BUNCH LENGTH AND SLICE EMITTANCE MEASUREMENT

The current diagnostics beamline of ELBE SRF gun is not capable of time resolved measurement. ELBE Linacs have been applied to support it. One of the cavities is used to accelerate the electron bunch at the zero-phase (zero energy gain), which is supposed to quasi-linearly chirp the bunch. In this way the temporal distribution of the bunch is transferred to energy distribution, which can be further transferred to transverse coordinate distribution by a dipole. The longitudinal distribution and bunch length can be calculated from the image of the bunch behind the dipole. This measurement works only if the energy chirp of the bunch before entering the cavity is much smaller than that from the cavity. The setup of this bunch length measurement is indicated in Figure 4.

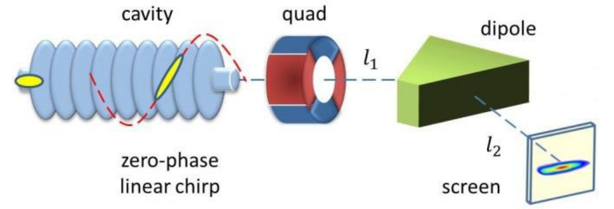

Figure 4: Indication of bunch length and slice emittance measurement at ELBE.

The quadrupole in Figure 4 is used for slice emittance measurement. On the screen, the temporal slices of the bunch have been resolved. The vertical size of each slice is slightly or not affected by the dipole. By scanning the quadrupole and measuring the vertical size of each slice, the emittance of each slice can be calculated applying the well-known method of “quadrupole scan emittance measurement” [5]. The application at ELBE and examples of measurements can be found in Reference [6]. In this measurement, the transverse size-variation of slices due to the quadrupole limits the resolution of slices.

Both the above bunch length and slice emittance measurements are not performed directly to the SRF gun, but assuming that the temporal structure of the bunch maintains from the gun exit to the linac cavity. This is not true for high bunch charges. In this case, complex front to end simulations [4] are necessary to evaluate the measurement. Direct time resolved diagnostics of the SRF gun is highly demanded for optimizing operation parameters.

BEAM DIANOSTICS DESIGN FOR THE NEW GUN LAB

A gun lab has been planned to be built up, separated from the ELBE accelerator, focusing on optimizing the gun itself. Improvements of the gun cavity and photocathode are not included in this article, instead, the design of a dedicated diagnostics beamline will be presented in the following.

The new diagnostics beamline should be able to provide energy measurement and phase space measurements. All measurements are preferred to have a short time scale in ten seconds, resulting in 10^5 parameter combinations are possible to be measured in one-day operation. From the past experiences, the energy measurement will be realized with the same method using a C-bend as shown in Figure 1. When the beam energy changes according to any operation parameter, the current of the dipole should be automatically fed back from the movement of the beam projection on the screen behind the dipole. 10 s is quite relaxed for this procedure.

The transverse emittance measurement using the current slit-scan method takes 10 mins which is significantly longer than the desired 10 s. As described, two reasons are dominating the measurement time: beam loss limitation and beam instability. The current macro pulse for beam diagnostics has the minimum duration of 5 ms, realized by a mechanical shutter of the driving laser. Shorter macro pulse will not maintain the same quality of the CW beam for now. For the future new gun lab, better shutters will be applied and the macro pulse length will be mainly limited by the beam loading which is around 0.5 s. A minimum duration of 1 ps is realistic. In this case a frequency of 10 Hz for the macro pulse is possible, and 100 positions of the beam (typical diameter 10 mm) can be measured in 10 s, which is adequate for measuring its emittance.

This measurement time of ten seconds will be enlarged if several images have to be taken at a same position. However, for the purpose of scanning parameter spaces to find the working point, beam instability could be tolerated and a fast processing of measured data is enough to fit the trend of emittance in the parameter space. More accurate measurements can be done around the working point candidate from the fitted trend.

Till now, every measurement parameter has been assumed ideal and the measurement time is right at the limit of 10 s. In the new gun lab the beam loss on the sampling slit could be more tolerable, for example, to apply water cooling slit mask. That means the frequency of the Macro pulse might be one magnitude higher, to 100 Hz, requiring the movement speed of the water cooled slit mask to be more than 10 mm (20 mm considering acceleration/deceleration) per second. The stability of this movement speed in vacuum can be challenging.

Another approach, which will cancel the challenge from scanning the slit, is to scan the beam instead, as already realized in Connell University [7]. A pair of steering magnets are installed in front of the slit mask with opposite fields. The beam through the magnet pair has a horizontal kick and keeps the distribution in transverse phase space. By scanning the beam position, the slit can also sample the beam completely, which is equivalent of scanning the slit. The advantage of this method is the faster scanning speed and the absence of mechanical movement. However, proper design and commissioning of the magnet pair to keep the beam quality undisturbed will also take more effort.

In the emittance measurement described in Reference [7], after the sampled beamlet, there is another group of magnet pair and slit to scan the beamlet. Particles are separated both by position and angle. A Faraday cup is installed to measure the sub-beamlet, which corresponds to the signal on each pixel line if a camera is used. The advantage of the Faraday cup is its higher dynamic range compared to a camera, which will be more universal to scan multiple operation parameters without adjusting the system. With two times of beam scanning, the realized measurement time is 10 s [7]. All three possible setups of transverse emittance measurement are shown in Figure 5. The comparison of these three setups is summarized in Table 1. The term of "drift space" in the table means a distance in the order of 1 m to resolve the distribution by either position or angle. Such a distance is necessary between the 2 steering magnets and between the slit and screen.

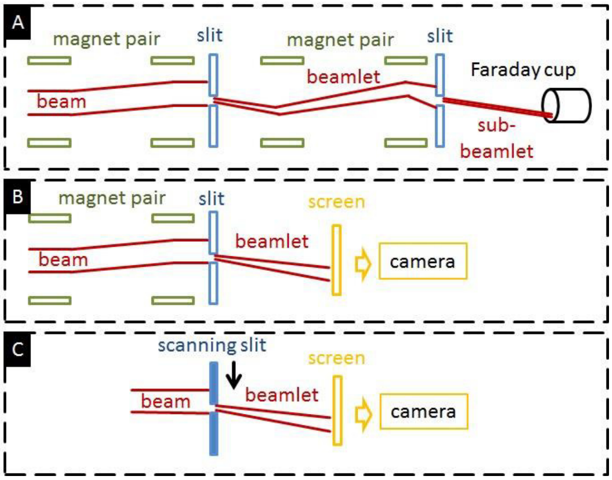

Figure 5: Three possible setups of emittance measurement for the future gun lab.

Table 1: Summary of Different EmittanceMeasurements

setup	A	B	C
magnet pair	2	1	0
slit	2	1	1, movable
Farady cup	1	0	0
screen & camera	0	1	1
measure-ment time	10 s	1 s	1 to10 s
drift space	~ 2 * 1 m	~ 2 * 1 m	~ 1 m
dynamic range	10^5 to 10^6	10^3	10^3

For diagnostics in the longitudinal phase space, single-bunch-based measurement with a deflecting cavity is preferred [8]. The desired measurement time of 10 s is very relaxed even for averaging with multiple bunches. The longitudinal distribution of an electron beam will be deflected to a transverse direction, e.g. vertical, where the bunch length could be calculated simply using a transverse screen.

If a horizontal bending magnet is applied afterwards, the energy distribution could also be resolved and the longitudinal phase space will be directly projected on a transverse screen after the magnet. The dimension of the system and the parameters of the deflecting cavity should be closely designed, while in this article only simple estimations are made. In general, a measurement range of 50 ps within the ±30° of the deflecting RF field requires the cavity frequency around 3 GHz; A deflected beam with an vertical angle of 15 mrad is desired, indicating that the distance from the exit of deflecting cavity to the screen should be less than 1.6 meters if a 2 inch diameter screen is applied. In between, a 180° bending magnet should be included. From the measurement of the longitudinal phase space, energy spread, bunch length and the uncorrelated energy spread could be calculated, which can be used to evaluate the multiple parameter scanning. Similarly, only rough and systematic results are required to reveal the trend. More accurate measurements can be made around the fitted peak point of the trend.

CONCLUSION

The current beam diagnostics of the SRF gun at ELBE provides vigorous experiences for the design of a new gun lab, aiming to optimize multiple operation parameters in a short time scale, e.g., 24 hours. A measurement time of 10 s is set to be a design target. Energy and the longitudinal phase space measurements are expected to be faster than 10 s for each point, however, transverse emittance measurement is challenging. Three different setups are compared which are all possible to provide a measurement time within 10 seconds. The same setup as the current measurement using a movable slit and a camera is still preferred to better utilize the accumulated experience. More calculations will be followed up to determine details of the diagnostics beamline for the gun lab.

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