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PHOTOINJECTOR BEAM HALO FORMATION DUE TO A SECONDARY PICOSECOND TIME-DELAYED LASER PULSE

V. Mușat*[1,2], P.N. Burrows[2], S. Doebert[1], E. Granados[1], A. Latina[1]
[1] CERN, Geneva, Switzerland
[2] JAI, University of Oxford, Oxford, UK

Abstract

Beam halo formation is a significant challenge for high-intensity accelerators, as it can lead to performance degradation and radiation safety risks. This study investigates the formation and mitigation of beam halos caused by a picosecond time-delayed laser pulse, which generates a secondary electron bunch in the same RF bucket as the main bunch. The energy difference between the two bunches creates a defocusing effect, leading to the halo generation. Experimental validation of RF-Track simulations was conducted at the AWAKE Run 2c test injector (ARTI). The research outlines methods for identifying, analyzing, and mitigating laser-driven beam halo formation, contributing to more effective control of beam halos in accelerator operations.

INTRODUCTION

High-intensity machines are inevitably affected by the formation of beam halos. The beam halo is defined as a region with low particle density surrounding a beam core. Due to the large span of the halo, it can interact with the beam pipe walls, leading to beam loss and vacuum degradation. The mechanisms of halo formation depend on the type of accelerator: linear, circular or ERL [1]. Whatever the mechanism, the sources of beam halos need to be well understood in order to prevent halo formation, minimise beam loss and ultimately improve machine performance.

This paper studies a potential source of halo formation in photoinjector guns. Halos at the gun level are typically attributed to space charge forces due to a high-intensity beam. Here, we consider a formation mechanism based on a secondary laser pulse delayed by a few picoseconds, which would create a secondary electron bunch in the same RF bucket. The delayed electron bunch would be poorly focused by the focusing magnet system and evolve into a halo. Mitigation strategies are addressed. The experimental results were taken at the AWAKE Run2 Test Injector (ARTI), and RF-Track was used to model the electron gun and verify the measured data [2, 3].

ACCELERATOR BASELINE

A schematic of the operating gun set-up is shown in Fig. 1 [2]. Brazing-free technology was used to fabricate the S-band electron gun [4]. To generate small emittance bunches under a moderate vacuum level, the photogun was equipped with a copper cathode. A PHAROS laser producing a 2 mJ infrared pulse at 1 kHz repetition rate, was used to create the bunches. The nominal extracted bunch charge is 400 pC, and the nominal gun gradient is 106.7 MV/m, corresponding to a beam energy of 6 MeV and a relative energy spread of 2 ‰.

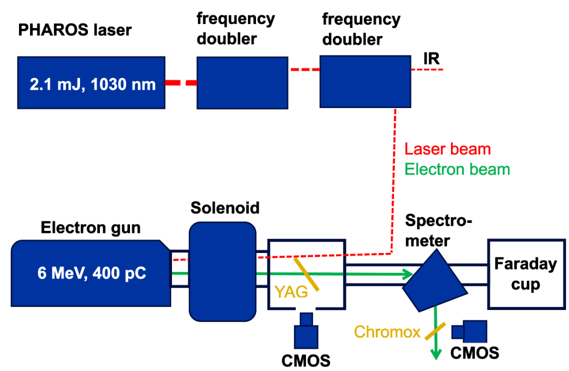

Figure 1: Schematic diagram of the AWAKE Run2 Test Injector.

A solenoid focuses the electron bunch. The beam can be visualised using a YAG screen and CMOS camera placed 0.57 m from the cathode. For the spectrometer, at 0.92 m from the cathode, an imaging system consisting of a Chromox screen and CMOS camera is used to measure the beam energy, RF phase, and energy spread of the electrons deflected by the 90° dipole bend. A Faraday cup is located downstream of the main line for bunch charge measurements.

MEASUREMENT OF THE BEAM HALO

The beam halo was observed using an Optical Transition Radiation (OTR) screen, consisting of a silicon wafer with a 100 nm-thick aluminium coating. When the electron beam was tightly focused by the solenoid, a low-density region of electrons was redistributed around the focused beam. This description is consistent with a beam halo. A typical beam profile is shown in Fig. 2. The horizontal and vertical beam distributions were determined by projecting the 2D profile onto the orthogonal planes crossing the peak in beam intensity. The fit of the beam core was obtained with a Gaussian function, where the amplitude was fixed to match the peak of the distribution. For the beam halo, only the tails of the distribution were used to fit the Gaussian function. Both fits were derived using the least squares method.

Beam-Core Percentage

The horizontal distributions can be used to estimate the percentage of electrons occupying the halo. To achieve this,

* vlad.musat@cern.ch

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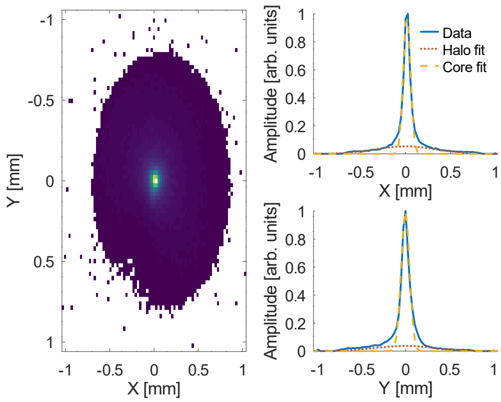

Figure 2: The measured profile of the electron beam, optimised for the smallest spot size. Gaussian fits of the beam core and halo are shown in the horizontal and vertical distributions.

a Gaussian function was used to fit the beam core and halo horizontal and vertical distributions. By summing up the amplitudes of the halo and core fits and comparing them with respect to the amplitude of the data, the halo was found to account for 25.6% of the bunch charge, while the beam core corresponded to 74.4%.

MECHANISM OF HALO GENERATION

The initial observation of the focused beam profile revealed an unexpected large-amplitude halo distribution, which was not present in the RF-track simulations, even after taking into account the strong space charge effect and the misalignment of lattice elements. The observation of two bunches with different energies was further analysed as a possible cause.

This led to the elaboration of a new halo formation mechanism: a secondary ps-delayed laser pulse that produced an additional electron bunch in the same RF bucket. The delayed bunch experiences a different RF phase, resulting in a higher beam energy, followed by a chromatic variation in focusing in the solenoid. Due to the non-negligible intensity of the secondary laser pulse and the high quantum efficiency of the copper cathode, the generated halo bunch acquired a significant bunch charge.

The secondary laser pulse can be created from multiple reflections in an optical element, as shown in Fig. 3. In order for the halo bunch to be generated in the same RF bucket, a delay of no more than a few picoseconds should be expected. This corresponds to a thin optical element with a few millimetres thickness. At ARTI, this element was identified as the thin film polariser that attenuates the laser.

Methods for Classifying the Halo Mechanism

There are several methods to show that the beam halo is caused by a secondary laser pulse. Given the difference in energy between the halo and core bunches, the two would be displaced in a dipole spectrometer. Additionally, by tuning the focusing strength, a regime would exist where the beam core is tightly focused, while the halo is visibly defocused. An RF phase scan of the electron gun can then be used to determine the difference in RF phase between the two bunches. This, in turn, would lead to the calculation of the difference in time between the two laser pulses and, therefore, the necessary thickness of the optical element. Once the optical element causing the multiple reflections is identified, it can be removed from the beamline (or replaced with a different thickness alternative), which would prevent the halo formation.

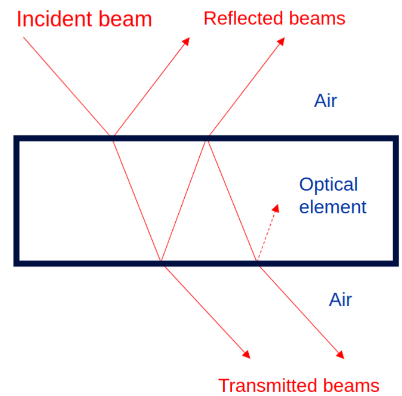

Figure 3: Schematic showing the generation of secondary time-delayed laser pulses through multiple reflection.

The UV laser pulse, which was used to generate the core bunch, had a FWHM pulse length of 770 fs and an RMS spot size of $241 \times 308\ \mu m^2$. The total pulse energy of the two pulses was measured to be 15 µJ. Using the percentages derived from the Gaussian fits of the beam distribution, the primary pulse would have 11.16 µJ, while the secondary pulse, 3.84 µJ [5].

BEAM HALO OBSERVED FROM THE DIPOLE SPECTROMETER

For the beam halo measurement, an RF phase of $-17°$ with respect to crest was used. As shown in Fig. 4, the horizontal beam profile from the spectrometer camera presents two peaks, indicating the existence of a secondary bunch. The two beam peaks were each fitted to a Gaussian function.

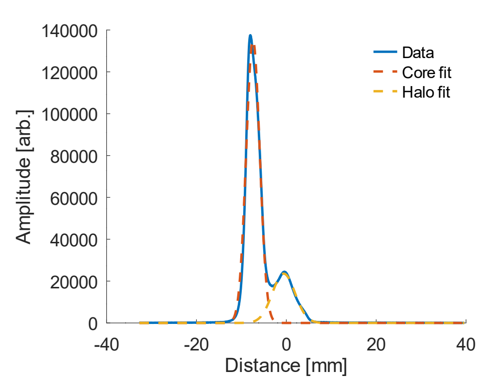

Figure 4: Gaussian fits of the beam core and halo from the horizontal distribution, measured using the dipole spectrometer.

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The integral of each fit was computed, resulting in a 77.4% share of the bunch population to one peak, and 22.6% to the other. These values correspond to the previously measured percentage of the halo and core distributions from Fig. 2.

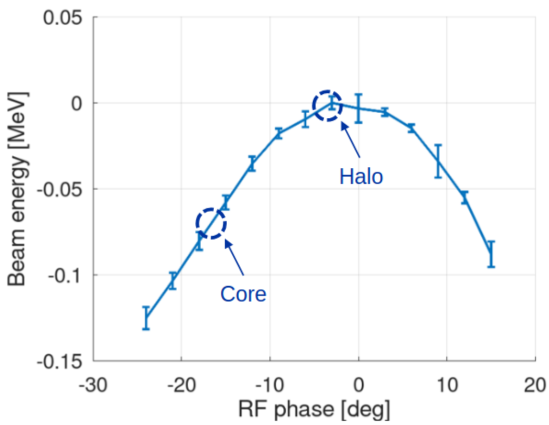


Figure 5: Normalised experimental RF phase scan indicating the difference in energy between the halo bunch and core bunch.

A difference in energy between the two peaks of 70 keV was measured with the spectrometer which, according to a measured RF phase scan from Fig. 5, corresponds to a difference in phase of 13.2 ± 0.1°. The ARTI gun frequency is 3 GHz, which translates into a 0.9259 ps/deg conversion factor. Given the phase difference between the two bunches, it was found that the two laser pulses would be separated in time by 12.2 ± 0.9 ps, or 2.43 ± 0.30 mm in fused silica. This corresponds to the 3 mm thickness of the thin film polariser thought to be generating the secondary bunches.

RF-TRACK RECONSTRUCTION OF THE MEASURED BEAM PROFILE

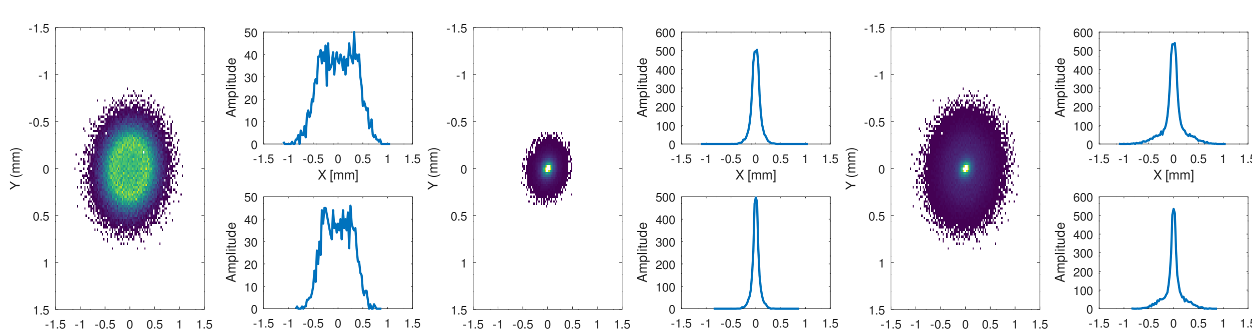
Knowing the bunch population and the difference in energy between the the beam core and halo, the beam profile from Fig. 2 could be reproduced in RF-Track. The bunches were generated in RF-Track using Gaussian transverse and longitudinal profiles, corresponding to the measured UV pulse properties at the cathode. The initial beam conditions are summarised in Table 1. Using the measured solenoid strength from ARTI and the energy difference calculated from the phase scan, both the core and halo bunches were then tracked under space charge effects to the screen position. The simulated beam profiles are displayed in Fig. 6. The addition of the two resulting beam profile amplitudes matches very well the distribution of the experimental profile.

Table 1: Initial Beam Conditions Used as RF-Track Input

Parameter	**Unit**	**Value**
RF phase (Core/Halo)	deg	–17 / –4
RF gradient	MV/m	112.5
Solenoid field	T	0.321
Laser RMS spot (X/Y)	µm	212 / 269
Laser RMS pulse length	fs	327
Bunch charge	pC	400

CONCLUSION

A mechanism to explain the formation of beam halo in photoinjectors was presented. Under multiple reflections, secondary laser pulses can be generated in the laser beamline transport. Given the temporal offset of a few picoseconds between the two pulses, the secondary pulse can create an additional electron bunch in the same RF bucket that subsequently evolves into a halo. By removing the specific optical element, or replacing it with a thicker alternative, the creation of the halo bunch can be avoided. The core and halo bunches can be characterised using a dipole spectrometer. This can determine the percentage of the bunch population occupying the beam core and halo and, by measuring the energy difference between the two bunches, can be used to determine the time offset between the two laser pulses. RF-Track simulations were shown to accurately reconstruct the measured beam profile. The methodology described in this paper can be used to characterise and mitigate a potentially common source of beam halo formation in photoinjector facilities.



(a) (b) (c)

Figure 6: Beam profiles generated with RF-Track, showing the halo (a), core (b), and reconstructed beam profile (c).

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