E31x collaboration

Plasma formation via electron-beam driver ionization at SLAC FACET-II

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Abstract

Electron-driven plasma wakefield accelerators offer an advantageous environment for realizing advanced ionization-injection schemes, such as "Trojan Horse" plasma photocathodes [1]. Plasma photocathodes utilize a synchronized laser pulse to release electrons from a dopant species directly inside the wake structure. In comparison to laser drivers, the substantially lower peak electric field of electron drivers facilitates the retention of a dopant species that can, in turn, be accessed for injection already with comparatively low-power laser pulses. Plasma photocathodes therefore promise to generate ultra-cold electron beams with emittances on the order of ~10 nm-rad.

The "E310: Trojan Horse-II" experiment at the Facility for Advanced Accelerator Experimental Tests II (FACET-II) at SLAC National Accelerator Laboratory utilizes a 10 GeV electron driver and employs a gas mixture of hydrogen and helium. The hydrogen component can either be pre-ionized by a dedicated laser pulse or self-ionized by the FACET drive beam, however, ideally without compromising the helium dopant reservoir for selective ionization injection.

We present results from first systematic ionization tests in the context of the E310 experiment and discuss the employed experimental methods.

Introduction

At relativistic energies electron beams posses a unipolar electric field that reaches field strength on the order of 10s GV/m. This field strength can tunnel-ionize neutral atoms, producing a *self-ionized* plasma. The unipolar field pushes the self-ionized electrons off its propagation axis creating a region of lower electron density trailing the relativistic electron beam. In this region strong electric fields arise, known as *wakefields*. *Plasma wakefield acceleration* (PWFA) exploits these fields to accelerate electrons.

For plasma photocathode experiments it is crucial to mitigate the electron beam self-ionization of a so-called high ionization threshold (HIT) medium. The HIT medium provides a reservoir of neutral atoms to be ionized by solely an injector laser directly inside the wakefield.

Furthermore, to create a stable wakefield and mitigate effects such as head-erosion a *pre-ionized* plasma is of essence for plasma photocathode injection.

Experimental Set-Up in S20 at FACET-II

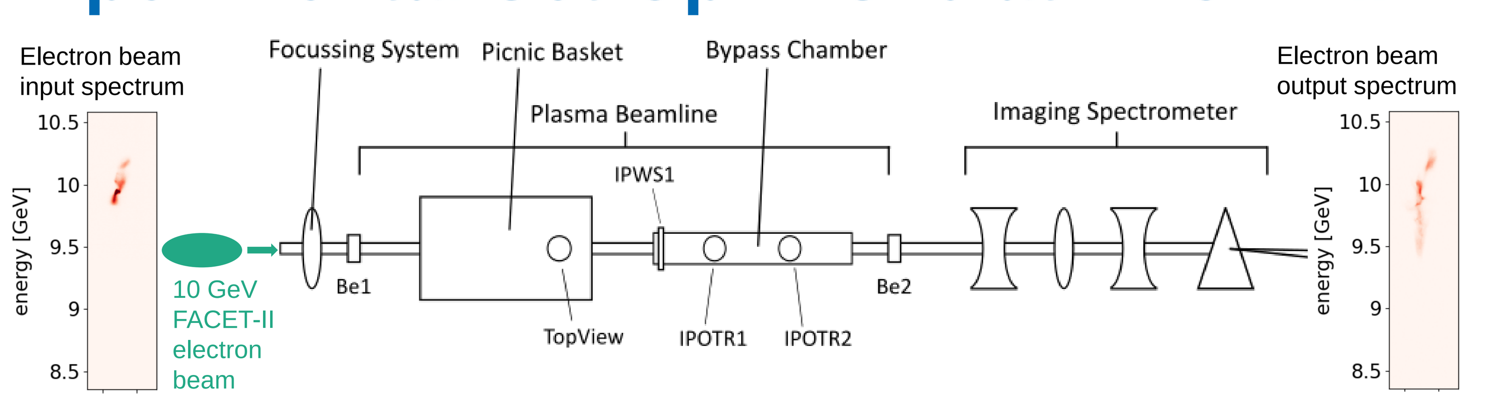
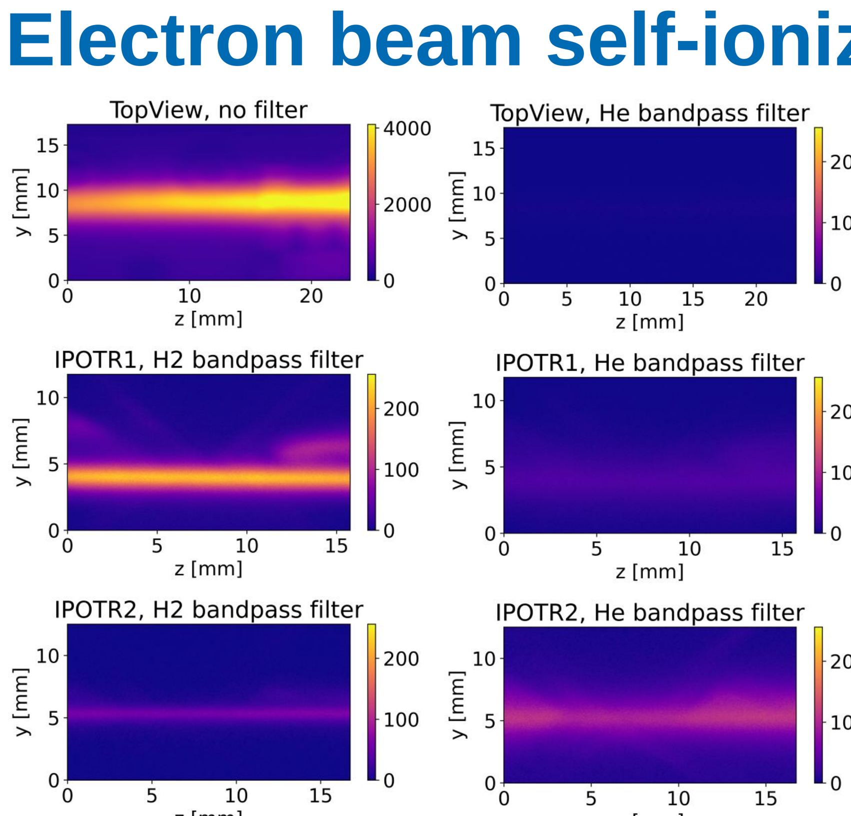


Figure 1: Schematic of the 14m long experimental area. Inserts show recorded data.

- Plasma Beamline can be filled with gas, we used: Pure He and a 50/50 *mixture* of H_2/He
- The plasma afterglow is imaged at *TopView*, *IPOTR1* and *IPOTR2*
  - Bandpass filter to look at strong He (587.6 nm) or H_2 (656.3 nm) transition lines were used
- The electron beam is imaged by the *Imaging Spectrometer* onto a spectrometer screen

Electron beam self-ionized plasma



- Figure 3 shows the plasma afterglow observed at the three observation positions
  - The electron beam is propagating in the H_2/He mixture, focused to IPWS1
- The distance between TopView and IPOTR2 is about 1.4 m
  - Showing strong ionization capabilities of the beam
- Notably, He is ionized mostly downstream of the focus position
  - This observation is also visible in Figure 5

Figure 2: Images of an electron beam self-ionized plasma. A shot with H_2/(He) bandpass filter on the left/(right).

Self-ionized wakefields

- The main goal is to investigate FACET-II driver electron beam self-ionization capabilities
- spectra of about 420 shots are presented in Figure 3 in the mixture (left) and pure He (right)

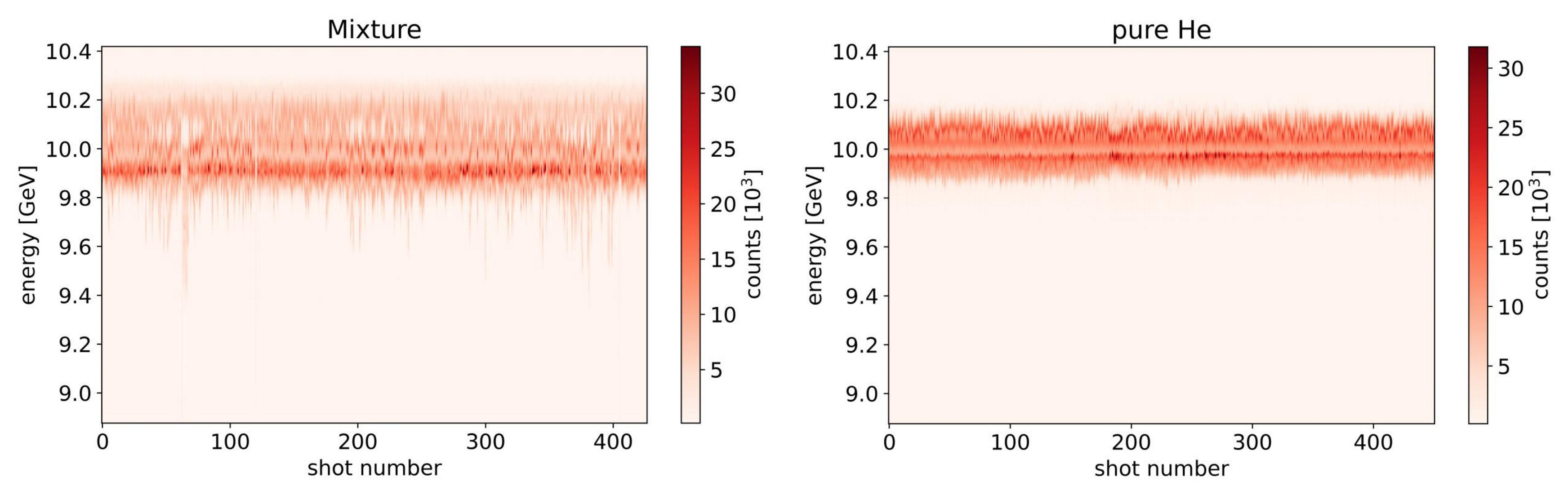


Figure 3: Waterfall energy spectra of the electron beam after interacting with the mixture (left) and pure He (right).

- Interestingly, we found signature of plasma lensing in the self-ionized H_2 plasma [4]
- The afterglow filtered in the range of the strong He transition line show strong linear correlations to the decelerated charge below 9.80 GeV (cf. Figure 4)
  - Pearson correlation coefficients: TopView: 0.77, IPOTR1: 0.92 and IPOTR2: 0.88

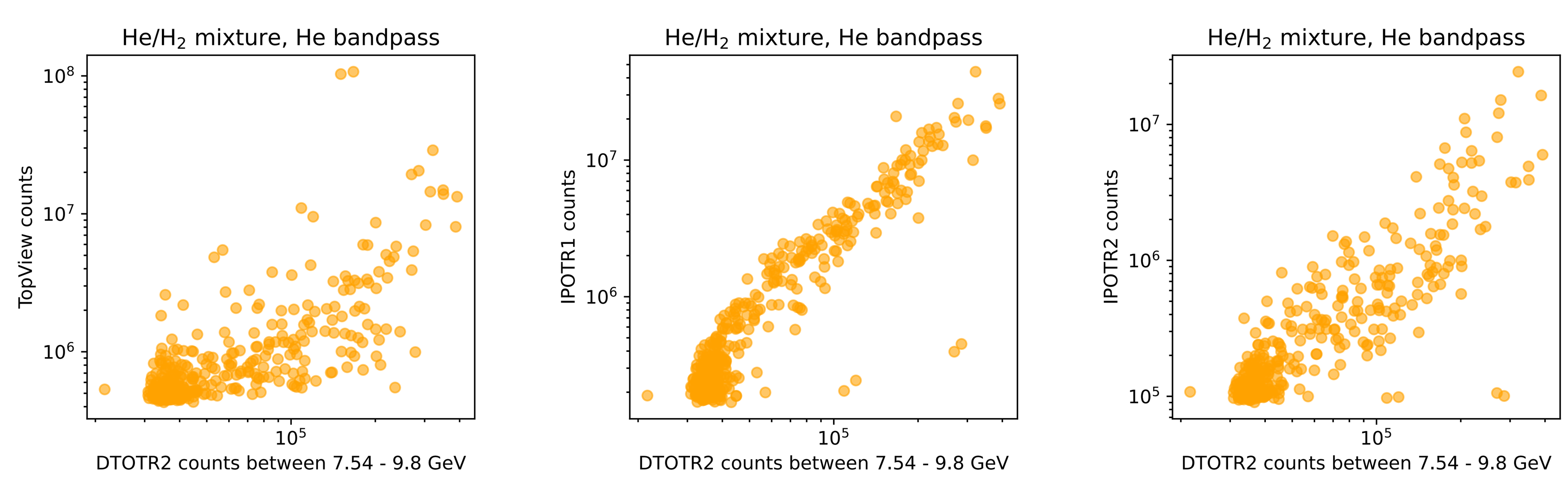


Figure 4: Correlations of the plasma afterglow in the mixture on TopView (left), IPOTR1 (center) and IPORT2 (right) with the decelerated charge detected on the DTOTR2 spectrometer screen.

Laser pre-ionized wakefields

- If the electron beam hits a pre-ionized plasma, the plasma is heated and emits more afterglow [5]
- A scan of the ionization laser delay reveals the relative timing of the laser and the electron beam (cf. Figure 5)
- Regardless of the laser delay, decelerated charge is detected (cf. Figure 6)
- Accelerated charge observed in the pre-ionized regime
  - A likely source is driver bunch charge that slips into the accelerating phase of the wakefield

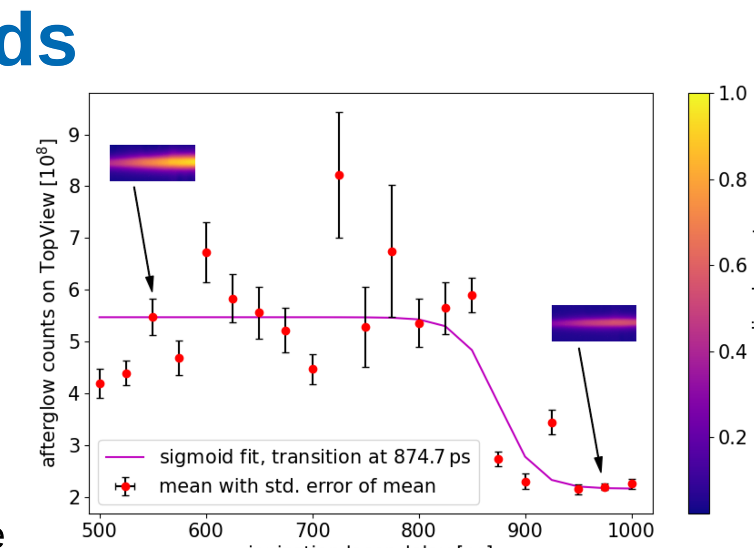


Figure 5: Afterglow signal on TopView during an ionization laser delay scan.

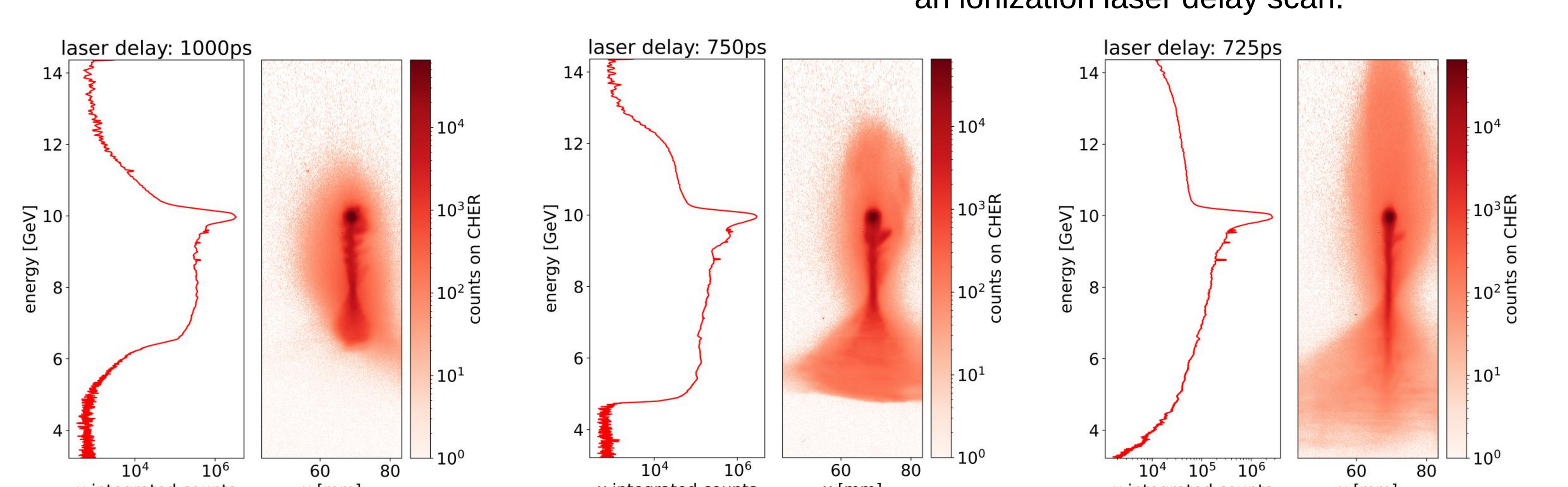


Figure 6: Example spectra showing purely decelerated charge (left) and additionally accelerated charge (center and right). The blue graphs on the left show the integrated signal along the spatial axis respectively.

Conclusion and Outlook

This experiment has shown that the electron beam at FACET-II is capable of ionizing H_2. Due to plasma lensing in the H_2 the beams electric field becomes strong enough to ionize He. Clear signatures of driven wakefields are found in the self-ionized plasma. The experimental results collected in this campaign strongly indicate that the requirements for plasma photocathode injection with the SLAC FACET-II driver bunch are satisfied. By tailoring the bunch parameters self-ionization of He shall be mitigated and use He as a pure HIT medium in future experiments.

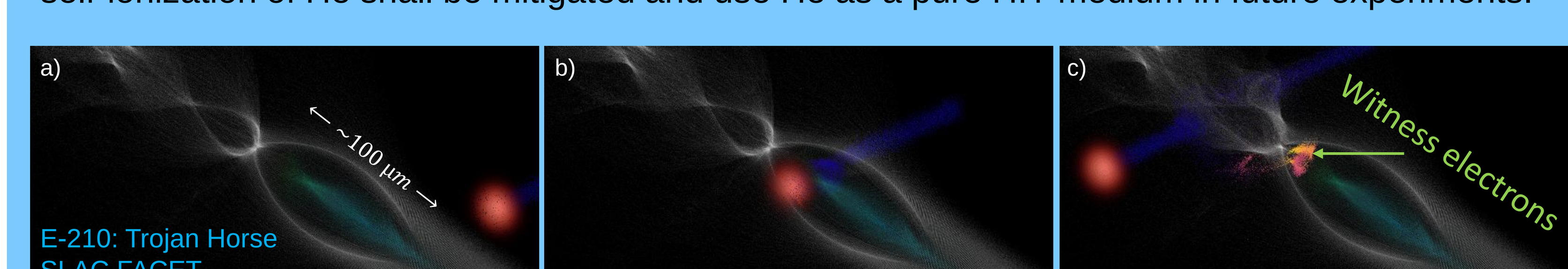


Figure 7: Visualization of the 90° Trojan Horse injection. [1]

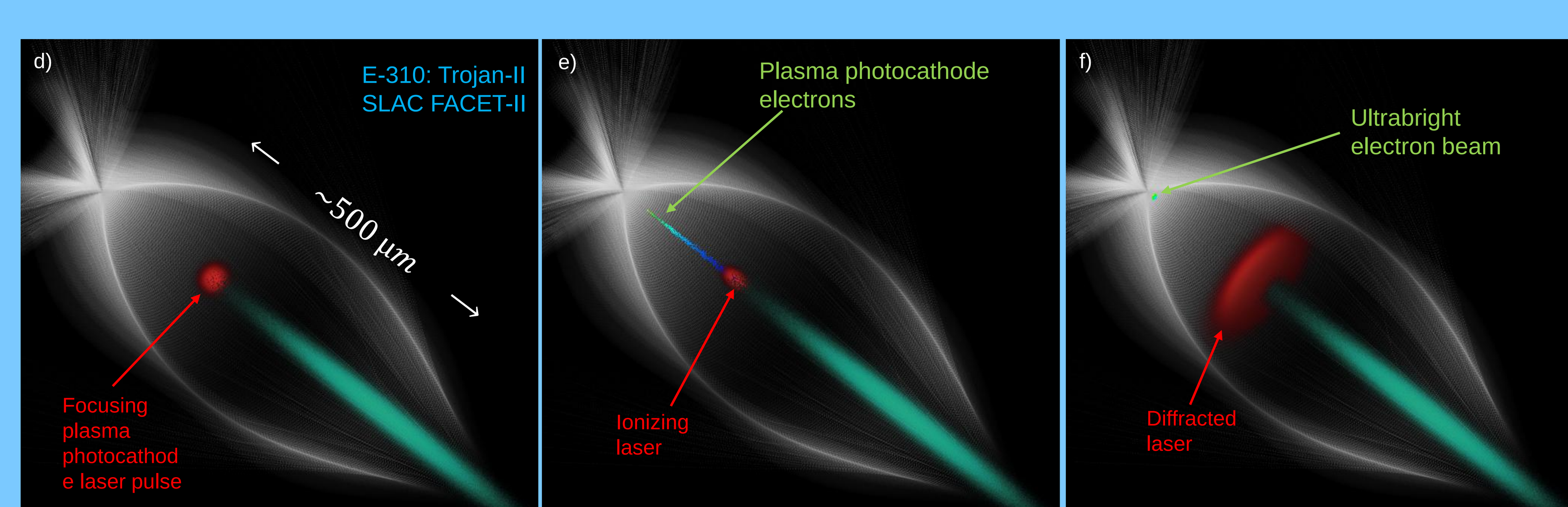


Figure 8: Visualization of collinear Trojan Horse injection. [1]

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