

High energy electrons from interaction with a 10 mm gas-jet at FLAME

G. M. Grittani^{a,b,c}, M. P. Anania^d, G. Gatti^d, D. Giulietti^{a,b,c}, M. Kando^e, M. Krus^f, L. Labate^{a,b}, T. Levato^{f,g}, Y. Oishi^{b,h}, F. Rossiⁱ and L. A. Gizzi^{a,b}

^aILIL, INO-CNR, Via Moruzzi,1 56124 Pisa, Italy;

^bINFN, Sez. Pisa, Largo B. Pontecorvo, 3 - 56127 Pisa, Italy

^cDipartimento di Fisica E. Fermi, Università di Pisa, Italy

^dLaboratori Nazionali di Frascati, INFN, Via E. Fermi, Frascati, Italy

^eJapan Atomic Energy Agency (JAEA) Kyoto, Japan

^fFyzikální ústav AV ČR v.v.i., Praha, Czech Republic

^gU. Tor Vergata, Roma, Italy

^hCRIEPI, Kanagawa, Japan

ⁱUniversità di Bologna e Sez. INFN, Bologna, Italy

ABSTRACT

In this paper we discuss the spectra of the electrons produced in the laser-plasma acceleration experiment at FLAME. Here a <30 fs laser pulse is focused via an f/10 parabola in a focal spot of $10\ \mu\text{m}$ diameter into a 1.2 mm by 10 mm rectangular Helium gas-jets at a backing pressure ranging from 5 to 15 bar. The intensity achieved exceeds $10^{19}\ \text{Wcm}^{-2}$. In our experiment the laser is set to propagate in the gas-jet along the longitudinal axis to use the 10 mm gas-jet length and to evaluate the role of density gradients. The propagation of the laser pulse in the gas is monitored by means of a Thomson scattering optical imaging. Accelerated electrons are set to propagate for 47,5 cm before being detected by a scintillating screen to evaluate bunch divergence and pointing. Alternatively, electrons are set to propagate in the field of a magnetic dipole before reaching the scintillating screen in order to evaluate their energy spectrum. Our experimental data show highly collimated bunches (<1 mrad) with a relatively stable pointing direction (<10 mrad). Typical bunch electron energy ranges between 50 and 200 MeV with occasional exceptional events of higher energy up to 1GeV.

1. INTRODUCTION

Nowadays the production of ultra-relativistic electron beams via Laser Wakefield Acceleration has attracted much attention by the scientific community because it can be a possible technology for the next generation radiation sources. In the upcoming γ -resist experiment¹ at the FLAME laser in the Laboratori Nazionali di Frascati facility, we are exploring the production of γ -radiation using electrons produced by LWA. The production of stable electron beams at FLAME has been investigated in a recent experiment in view of the use for a radiation source. Some important parameters of the bunch have to be monitored, including the energy spread, defined as the FWHM over the peak energy of the bunch spectrum, the divergence of the beam and its pointing stability, the beam charge and the beam emittance.

2. EXPERIMENTAL SETUP

The experiment was carried with the 220 TW FLAME laser at the Laboratori Nazionali di Frascati. This system uses 11 YAG pump lasers and 3 titanium-sapphire crystals to produce linearly polarized pulses with a central wavelength of $\lambda_0=0.805\ \mu\text{m}$, pulse duration of $\tau_L \leq 30$ fs and maximum energy of 7 J. The laser is then transported to a radiation shielded target chamber and focused via an f/10 off-axis parabolic mirror in a $15\ \mu\text{m}$ diameter spot on a gas jet exiting a 10 mm by 1.2 mm rectangular nozzle. The gas-jet pressure is regulated by a

Further author information: (Send correspondence to G. M. Grittani)
G. M. Grittani: E-mail: gritta89@hotmail.com, Telephone: +39 333 451 6473

Target chamber – legenda of diagnostics

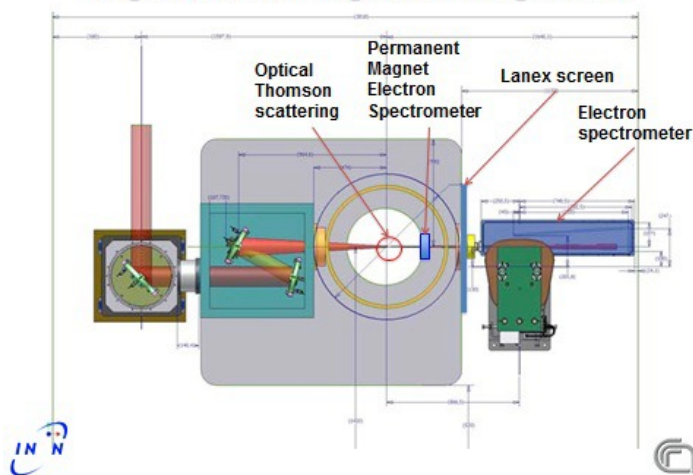


Figure 1: Description of the FLAME Target Chamber. The lanex is set perpendicular to the laser propagation axis and distance between the gas jet and the lanex screen is 47.5 cm

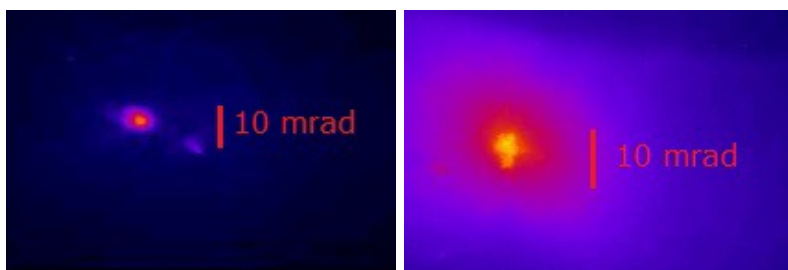


Figure 2: Left: Image of the scintillating LANEX screen at 47 cm downstream the interaction point showing a bunch transverse size of approximately 0.5 mm and a corresponding divergence of 1 mrad. Right: Integrated image of the electron bunch over 10 laser shots showing a pointing stability of approximately 10 mrad.

valve and in our experiment we used helium with backing pressures ranging from 5 to 15 bars. The high intensity of the laser in the gas jet ($I=5.2 \cdot 10^{19} \text{ W/cm}^2$) led to the the production of a bunch of electrons accelerated along the laser propagating direction. We investigated the properties of these electrons using a lanex screen perpendicular to the propagation axis at 47.5 cm from the nozzle. This screen emits green light in function of the energy deposited on it by the incident electrons, so by measuring the size of the light spot created by the electrons we can measure the divergence of our beam and its pointing stability. We also used a 5 cm long magnetic dipole of nominal field intensity of 1 T along the propagation estimate the bunch energy spectrum. All the images have been recorded using a commercial camera which was positioned outside the propagation axis in order to avoid damage.

3. EXPERIMENTAL RESULTS

The divergence and the pointing stability of our electron bunches have been measured at three different backing pressures: 5, 8 and 15 bars. After the optimization of our laser system, we found few-mrad divergence at all the different pressures, obtaining best-1 mrad divergence at 8 bars (fig.2) in roughly half of the shots.

Also while running with the magnet it was possible to monitor the divergence looking at the non dispersive e-axis of the magnet. After the evaluation of the divergence, we focused our attention on the evaluation of the pointing stability, which plays a fundamental role in the electron spectrum retrieval. So we took 200 shots at each of the 3 backing pressures mentioned above, obtaining best stability with 5 and 8 bars.

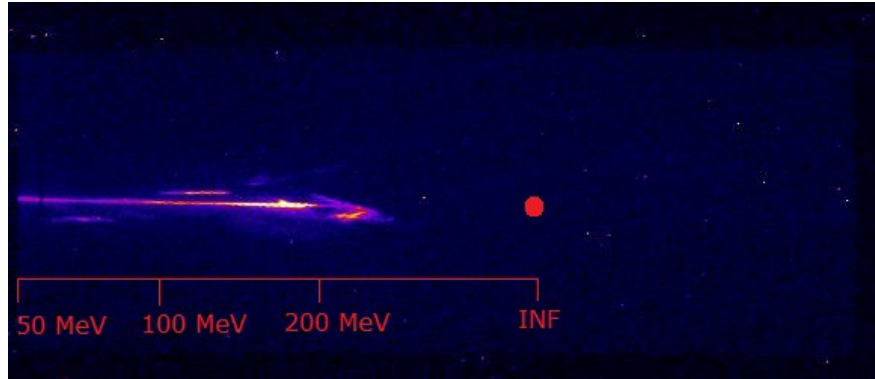


Figure 3: Image of the LANEX scintillating screen with a typical dispersed electron bunch accelerated from 8 bar helium gas jet. The right dot indicates the average pointing position.

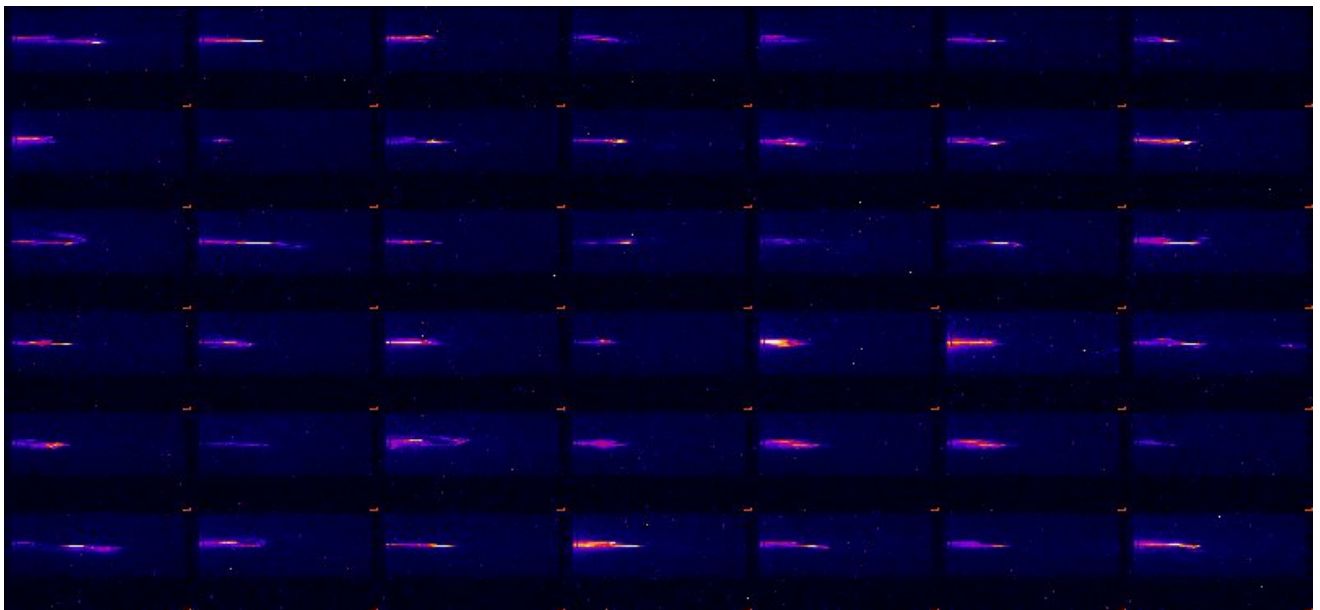


Figure 4: 42 consecutive shots at a helium backing pressures of 15 bars. The dispersion axis is the same of Fig.3. We observe stable production of electron bunches ranged between 50 and 200 MeV with some occasional traces of high energy (>500 MeV) electrons.

Once evaluated the average pointing direction, we set it as the axis of the magnetic spectrometer (infinite energy) and we could retrieve the electron bunch spectra by the evaluation of the dispersion. Fig.3 shows one of our typical spectra, showing a broadband and almost flat spectrum ranged between 50 and 200 MeV with an higher energy trace around 250-300 MeV.

We obtained similar-spectral-shape and electron energies both at 8 and 15 bars, but we have observed a more stable production of similar bunches at 15 bars. In Fig.4, we report 42 consecutive shots taken at 15 bars backing pressure, showing stable bunch divergence and energies, with also some occasional high energy (>500 MeV) traces.

In a recent paper, Banerjee et al.² have showed their results obtained in an interaction regime similar to ours (we had $I=2\cdot 10^{19}$ W/cm² and $3\div 12\cdot 10^{18}$ e/cm³ gas densities, they had $I=1.77\cdot 10^{19}$ W/cm² and $6\div 9.6\cdot 10^{18}$ e/cm³ gas densities), but using different slits: they used two different circular slits of respectively 3 mm and 4 mm diameter. Furthermore their laser had the adaptive optic installed, so they had much better wavefronts respect

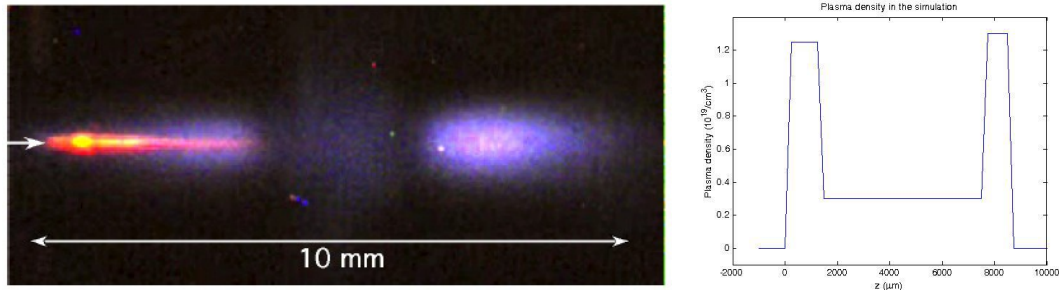


Figure 5: Left: Image of the Thomson emission from propagation of the laser pulse in a helium gas-jet at 8 bar valve pressure. The laser propagates from left to right. Also visible in the image is the plasma self-emission. Right: Plasma density profile used in the 3D PIC simulations. To retrieve the plasma density we have used the results of R. Taki³

to us. A comparison of our results shows that while we had similar beam divergence (few mrad), they had much better pointing stability (nearly an order of magnitude better) and also they had twice our electron bunch energies. We think that this is due to their better laser wavefront.

4. PRELIMINARY DISCUSSION

This general behavior was quite reproducible from shot to shot. The quite large energy spread compared to the spectrum expected by the optimized bubble regime is not surprising here due to the relatively lower laser intensity compared to the intensity required for the bubble regime. This scenario is being investigated via numerical simulations and alternative acceleration regimes are being taken into account also in view of recent results obtained recently in similar experimental conditions.² In fact we are currently performing 3D PIC simulations with the code AlaDyn at CINECA to investigate which acceleration regime of our experiment in a realistic density profile. Relying on the results of R. Taki³ we have extrapolated the density profile showed in Fig.5. Although 3D PIC simulations of our experiment are still ongoing, we have obtained some preliminary results showing that during propagation along the first density ramp the laser focuses and reaches the first density plateau in favorable conditions for bubble self-injection. The bubble is then likely to become unstable and supposedly breaks during the descent ramp. Furthermore, as we can see in the Thomson emission image in fig.5, the laser propagates well collimated for approximately 4 mm. At this stage we anticipate possible contribution of self-focusing effects to the observed behavior of the laser pulse. In fact, according to the well known expression for the critical power for relativistic self-focusing, $P_{cr} = 17 \left(\frac{\omega}{\omega_p}\right)^2$ GW and taking into account the estimated maximum electron density given above, we find that the critical power in our experimental conditions ranges from 3 TW for the highest density case to approximately 50 TW of the lowest density case. Therefore we expect the interaction in the higher density case to be affected by self-focusing that could set the conditions for a moderate channeling of the laser pulse, thus effectively extending the propagation length. Detailed numerical simulation will be necessary for a confirmation of this result. In contrast, no evidence of collimated laser propagation occurs in the remaining 6 mm, where we expect, the accelerated electron bunch to propagate preserving good properties until it reaches the LANEX screen.

5. CONCLUSIONS

In our interaction regime we achieved stable electron beam production with mrad divergence and 10 mrad pointing stability for helium gas jets at three different backing pressures: 5, 8 and 15 bars. We obtained the lowest beam divergence with 8 bars and the best pointing stability with 5 bars. We have seen also a more stable production of similar electron bunches in the case of 15 bars. The energy spectra of the electron beams are almost flat and ranged between 50 and 200 MeV, with occasional high energy traces of more than 500 MeV and occasionally up to 1 GeV.

ACKNOWLEDGMENTS

We thank the staff of the LNF Accelerator and Technical Divisions for the support during the the SITE operations at LNF. "SITE" and " γ -RESIST" are funded by INFN through the CN5. The work was carried out in collaboration with the High Field Photonics Unit at INO-CNR (MD.P03.034) and was partially funded by CNR through the ELI-Italy project.

REFERENCES

- [1] L. A. Gizzi, M. P. Anania, G. Gatti, D. Giulietti, G. Grittani, M. Kando, M. Krus, L. Labate, T. Levato, Y. Oishi, and F. Rossi, *Acceleration with Self-Injection for an All-Optical Radiation Source at LNF*, Phys. Rev. Lett., 43, 4, 267, 1979.
- [2] S. Banerjee, S. Y. Kalmykov, N. D. Powers, G. Golovin, V. Ramanathan, N. J. Cunningham, K. J. Brown, S. Chen, I. Ghebregziabher, B. A. Shadwick, D. P. Umstadter, B. M. Cowan, D. L. Bruhwiler, A. Beck, and E. Lefebvre, *Stable, tunable, quasimonoenergetic electron beams produced in a laser wakefield near the threshold for self-injection*, Phys. Rev. STAB, 16, 031302, 2013.
- [3] R. Taki, *Gas density measurements at JAEA*, Internal report, 2007.