Beam dynamics in THz dielectric-loaded waveguides for the AXSIS project

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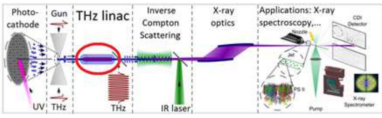
1. Introduction



AXSIS schematic layout: AXSIS (Attosecond X-ray Science: Imaging and Spectroscopy) aims at obtaining 1 pC and 15 MeV sub-fs electron bunches to produce attosecond X-ray photon pulses via Inverse Compton Scattering with an infrared laser.

* Particle acceleration currently requires large infrastructures due to the low frequencies (a few GHz) and relatively low field amplitudes (a few tens of MV/m) used in conventional accelerating structures. **One of the schemes currently studied to reduce the footprint of particle accelerators is to use dielectric-loaded waveguides (THz linac) driven by laser-generated multi-cycle THz pulses**, in which the frequencies (100 GHz up to 10 THz) and field amplitudes (100 MV/m to a few GV/m) are expected to be much higher than in conventional accelerating structures. This is one of the goal of the AXSIS project [1].

* The purpose of our study is to investigate with ASTRA simulations the evolution of the bunch properties with several properties of the THz linac: Phase velocity of the accelerating field and injection phase of the electron bunch into the THz linac; Frequency and amplitude of the accelerating field into the THz linac.

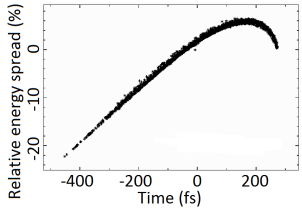
2. The ASTRA model of the THz linac

* TM_{01} mode in the THz linac: Pulse travelling with group velocity v_g, phase velocity v_{ph} and having a finite number N of wavelengths λ → Interaction length $L = (N\lambda)/(1-v_g/c)$.

* ASTRA model: Superimposition of two identical standing waves phase-shifted by 90°. Phase velocity adjusted by changing the wavelengths of the standing waves. Time profile of the THz pulse given by the one of the input standing waves (flat-top in our case). Length of the accelerating section sets to L. Frequency spectrum of the THz pulse not taken into account (only central frequency) → No pulse distortion due to group velocity dispersion.

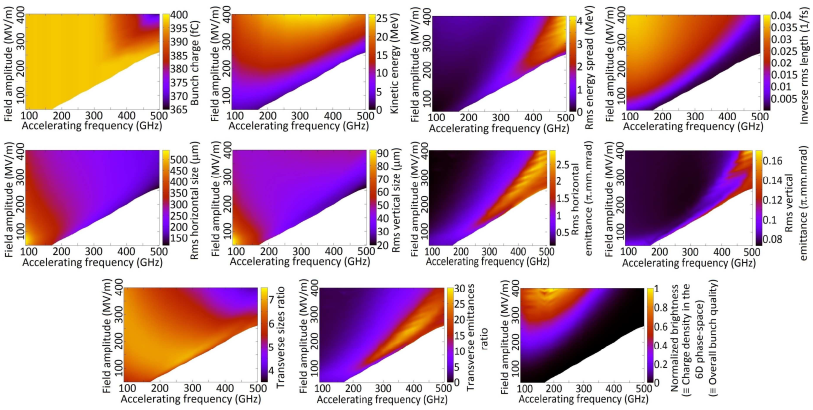
Bunch property	Input value
Charge	0.4 pC
Mean kinetic energy	1.48 MeV
Rms energy spread	82.9 keV
Rms length	43.5 µm (≡ 150.1 fs)
Rms horizontal size	28.9 µm
Rms vertical size	18.8 µm
Rms horizontal emittance	0.102 π.mm.mrad
Rms vertical emittance	0.083 π.mm.mrad

Bunch properties at the entrance of the THz linac



Bunch longitudinal phase-space at the entrance of the THz linac

3. Influence of the frequency and amplitude of the accelerating field



Bunch properties at the exit of the THz linac simulated by ASTRA. $v_{ph}=c$; $v_g=0.62c$; L=6.4 cm. Injection phase optimizing the bunch length. White zone: The bunch performs more than one complete phase oscillation during its path in the linac.

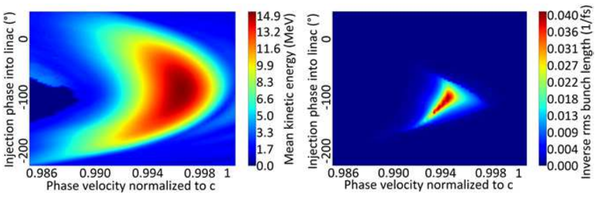
* Bunch longitudinal properties (length and energy spread) and transverse emittance are optimized at low operating frequencies (< 300 GHz). Higher frequencies require high field amplitudes to obtain acceptable bunch properties, as it is summarized by the plot of the bunch brightness, but this comes with particle losses due to smaller linac radius and stronger transverse fields.

* This is due to two facts: The phase slippage, strongly limiting the achievable bunch properties in the THz linac, is intrisically reduced at lower frequencies; The fraction of the accelerating field wavelength covered by the bunch, which is significant, is also intrinsically reduced at lower frequencies → Less induced energy spread and longitudinal phase-space curvature.

* The asymmetries of the bunch transverse size and emittance, initially present, are minimized in different conditions (respectively high and low frequencies) and only a combination of high frequency and amplitude could be a compromise, with all the drawbacks aforementioned.

* Tapered linac [2] is currently investigated to solve the difficulty.

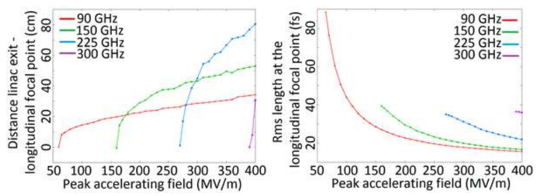
4. Influence of the injection phase and phase velocity



Bunch kinetic energy and inverse rms length as a function of the injection phase and phase velocity. L=10 cm; N=42; 300 GHz; 150 MV/m

* High sensitivity to the phase velocity and therefore to the mechanical precision (2 µm variation in the dielectric thickness → v_{ph} varies from c to 0.99c) → Challenging.
* Less sensible to injection phase → Margins for possible instabilities.

5. Capability of ballistic bunching



Longitudinal focal distance and rms bunch length at the longitudinal focal point. $v_{ph}=c$; $v_g=0.62c$; L=6.4cm.

* Ballistic bunching needed for adding transverse focusing after the linac and having, several tens of cm away, common longitudinal and transverse focal points. Possible only with low frequencies (< 300 GHz).

6. Conclusions & Prospects

- **Proper energy gain, control of the longitudinal focal distance and margins for instabilities of the injection phase have been demonstrated for THz-driven dielectric-loaded waveguides in our simulations**. A challenging high sensitivity to the phase velocity (therefore to the mechanical precision of THz linac production) is also revealed.
- The simulated bunch length (≈15 fs rms) is still far from the AXSIS goal (≤1 fs rms). The reason is the already strong curvature of the longitudinal phase-space at the entrance of the THz linac, due to the high frequency (300 GHz) of the gun considered in AXSIS [3] → Studies to use more classical guns (DC-gun and Sband RF-gun) as sources are ongoing.

Acknowledgements

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement n. 609920.

*** References:**

[1] F. X. Kärtner *et al.*, *Nucl. Instr. Meth. A*, vol 829, pp. 24-29, 2016.
[2] F. Lemery *et al.*, *IPAC'17*, paper WEPAB123.
[3] A. Fallahi *et al.*, PRAB, vol 19, p. 081302, 2016.