EUROPEAN NETWORK FOR NOVEL ACCELERATORS
EuroNNAc4
NPACT supported by EU via I-FAST

Contribution ID: **49** Type: **Poster (student)**

Early dynamics of the self-modulation instability growth rate

Tuesday, 20 September 2022 19:20 (1 hour)

The self-modulation instability (SMI) is instrumental for single-stage plasma wakefield accelerator concepts with long, high-energy drive bunches such as the AWAKE experiment. It provides a self-consistent mechanism to reach high-amplitude wakefields despite the driver's length, which would otherwise not excite the plasma resonantly.
In recent demonstrations of acceleration with a self-modulated proton driver, the use of a linear plasma density gradient has been a key factor in maximising the energy gain [1]. It is known that a density gradient effectively delays or hastens the growth of the SMI, though this effect has been discussed in the context of asymptotic models that assume small gradients [2], or of the saturation phase of the SMI [3].
We present a new framework for understanding the onset of the SMI, and show that its growth rate varies according to the frequency of the seed (a beam radius perturbation), which can be tuned by varying the plasma density. This may have implications for the control of the SMI's growth and the associated acceleration process.
[1] AWAKE Collaboration, Nature **561**, 363-367 (2018)
[2] C. B. Schroeder, *et al.*, Phys. Plasmas **19**, 010703 (2012)
[3] F. Braunmüller, *et. al.* (AWAKE Collaboration), Phys. Rev. Lett. **125**, 264801 (2020)

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Session Classification: Poster Session