Self-consistent simulations of positron creation and acceleration in a plasma channel

B. Martinez*, M.Vranic

GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, University of Lisbon, Portugal

*bertrand.martinez@tecnico.ulisboa.pt

Self-consistent creation and acceleration of positrons in a Particle-In-Cell simulation

Current schemes for positron acceleration[1-5]

They provide an energy boost of 5-10 GeVs to positrons exiting a conventional accelerator
Previous simulations were typically initialised with test positrons or idealised beams

Our scheme for positron acceleration[6] includes

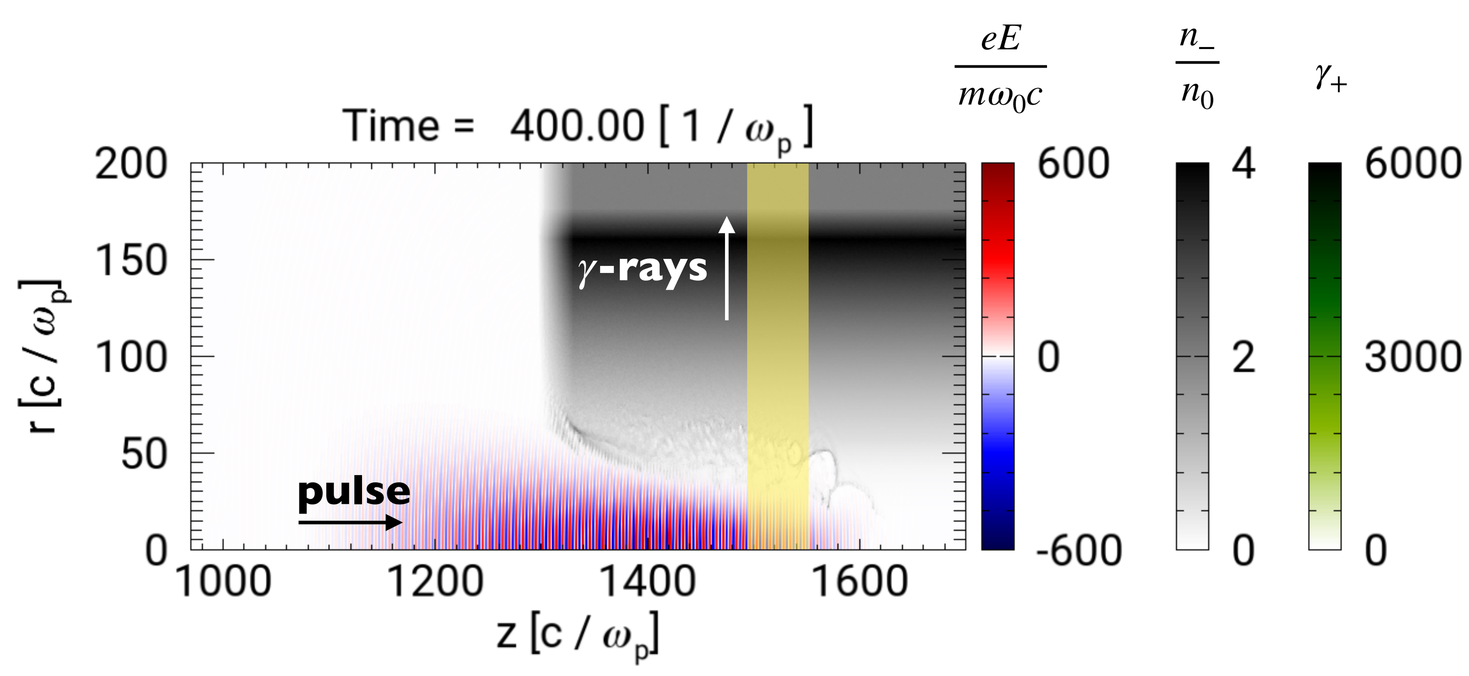
A self-consistent positron initialisation via the Breit-Wheeler process
An acceleration of positrons via Direct Laser Acceleration up to $\sim 4\,\mathrm{GeV}$

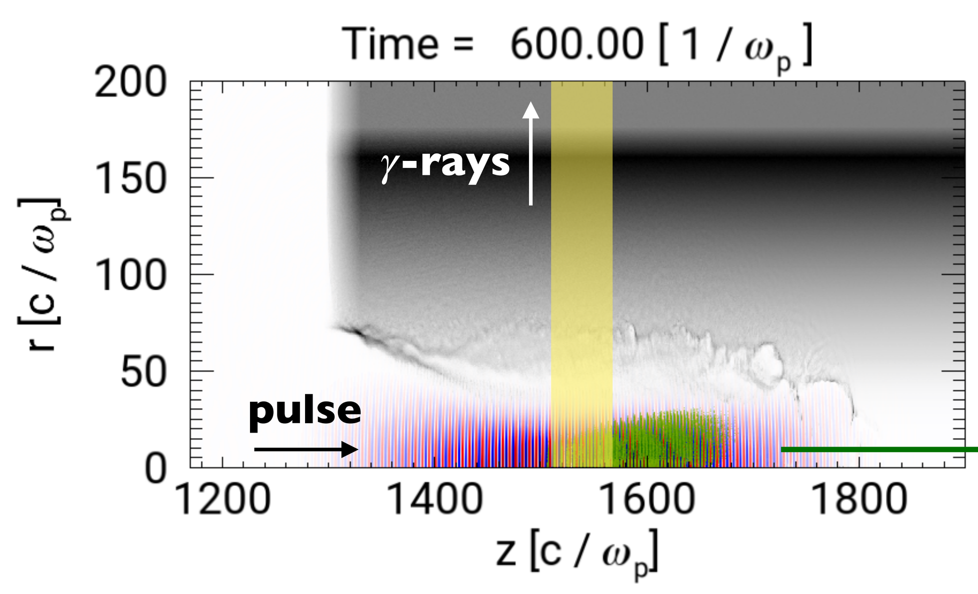
Steps of the Scheme

- An intense laser pulse ($I \gtrsim 10^{23}\,\mathrm{W/cm^2}$) propagates in a pre-formed plasma channel
- At the laser focus, a photon beam ($\simeq 700\,\mathrm{MeV}$) at normal incidence is used to create positrons via the Breit-Wheeler process
- Some positrons are deflected in the laser propagation direction by its strong electromagnetic radiation
- These positrons can gain energy via Direct Laser Acceleration

Methods

Particle-In-Cell simulation with OSIRIS
Quasi-3D geometry with hard photon emission (NLIC) and pair production (Breit-Wheeler)





Self injection of positrons in the plasma channel

[1] S. Corde et al, Nature, 524 442-445 (2015)
[2] J. Vieira et al, Physical Review Letters, 112 215001 (2014)
[3] N. Jain et al, Physical Review Letters, 115 195001 (2015)
[4] C. Lindstrom et al, Physical Review Letters, 120 124802 (2018)
[5] A. Doche et al, Scientific Reports 7 14180 (2017)
[6] M. Vranic et al, Scientific Reports 8 4702 (2018)

Estimates for the number of positrons created[7,8]

Problem a γ-ray travelling in a plane wave with an angle θ : $\vec{k}_0 \cdot \vec{k}_\gamma = |k_0||k_\gamma|\cos\theta$

Estimate of $P_+(t)$, the probability of decay

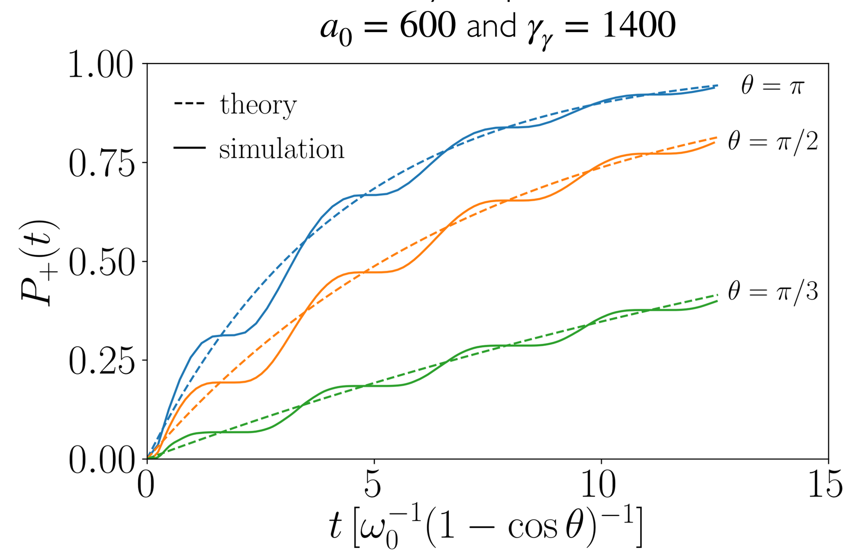
One has $P_+(t) = 1 - \exp(-Rt)$

where $Rt = \dfrac{1}{2\omega_0}\displaystyle\int_0^\pi \frac{dN_\pm}{dt}\left[\chi_\gamma(\phi)\right] d\phi$

and $\chi_\gamma(\phi) = 2\gamma_\gamma (a_0/a_s)\sin(2\phi)$

Generalisation to a finite focal spot[8]
Using a distribution $dN/da_{0,\mathrm{eff}}$

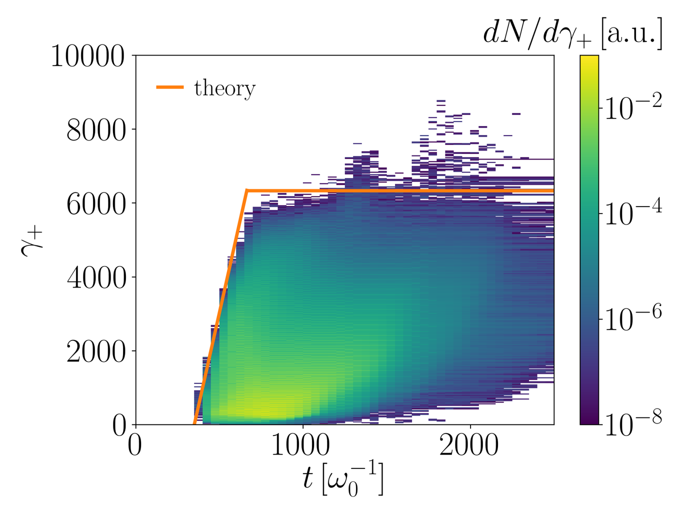
Probability of pair emission
$a_0 = 600$ and $\gamma_\gamma = 1400$



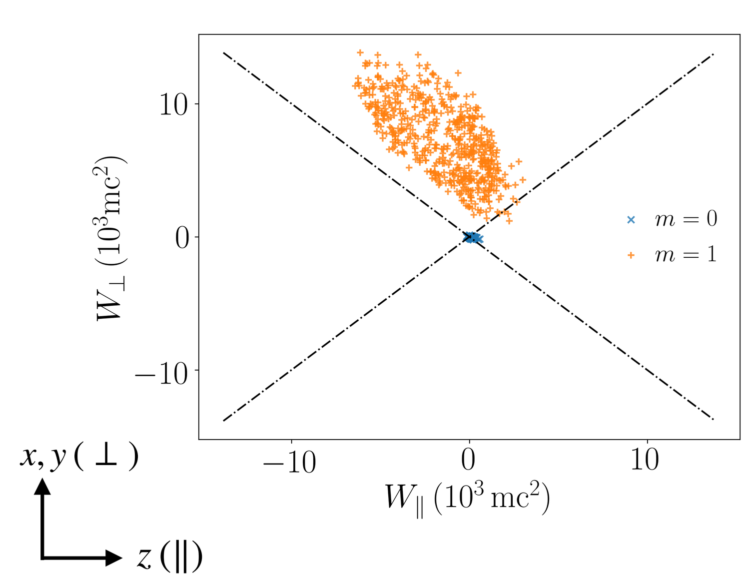
[7] T. Blackburn et al, Physical Review A, 96 022128 (2017)
[8] Ó. Amaro et al, arXiv:2106.01877 (2021)

Direct Laser acceleration of positrons

Maximum energy gain is consistent with DLA acceleration predictions[9]



Work performed by the different field components → DLA

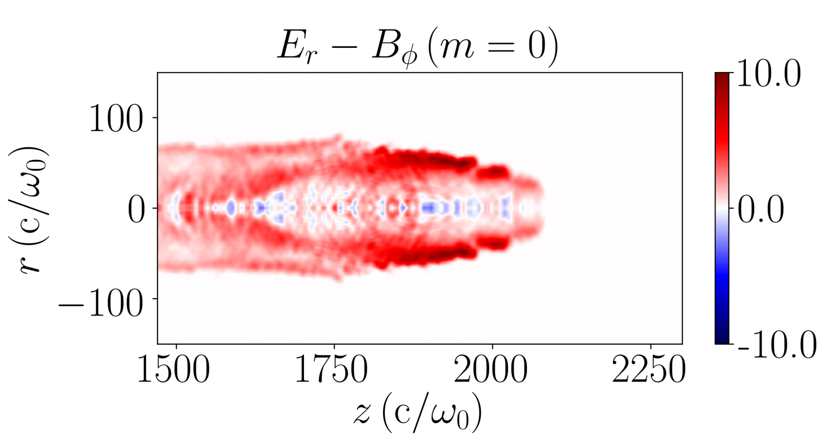


[9] M Jirka et al 2020 New J. Phys. 22 083058

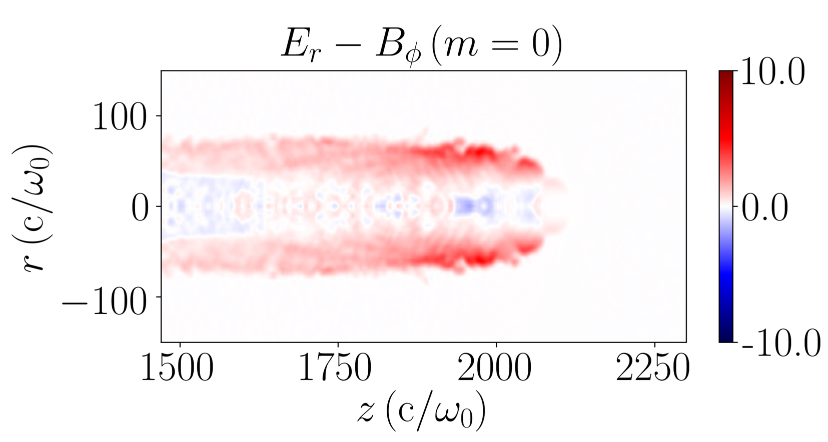
Focusing fields for positrons are achieved by adjusting the plasma channel

Defocusing fields have a large amplitude, but this can be decreased by tuning the plasma channel properties

Channel radius $R_{ch} = 13\,\mu m$



Channel radius $R_{ch} = 26\,\mu m$

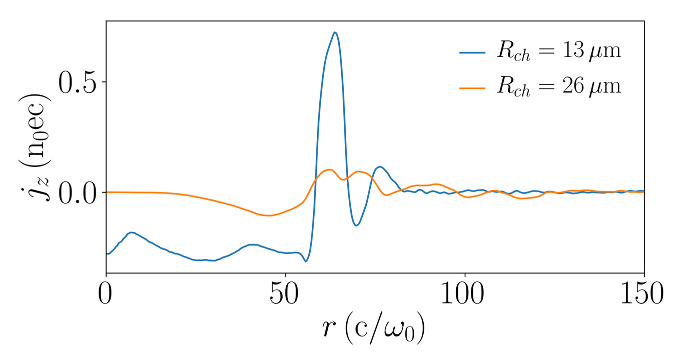


As the channel radius increases, one observes
A decrease of the defocusing fields at the walls of the channel (red colour)
Locally focusing fields at the channel centre (blue colour)

General Guidelines

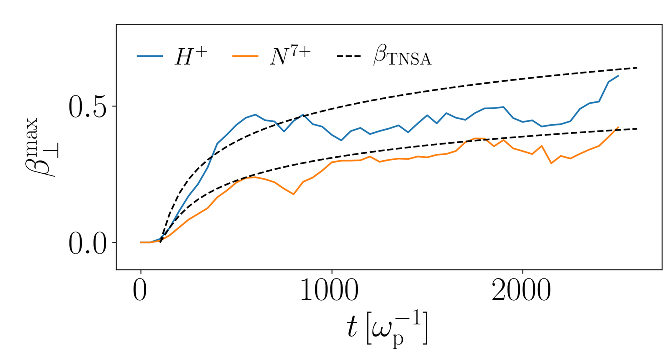
- Avoid a strong return current at the channel's walls
- Avoid ion injection and acceleration at the channel centre

Line-out of the total current j_z



The return current along the walls of the channel induces a defocusing force on positrons

Radial ion acceleration time scale



Ions with a large Z^*/A ratio are loaded at the channel centre and repel e^+

Conclusions & Future work

It is possible to create positrons within a plasma channel
The positrons are in good conditions to be trapped and experience DLA
Defocusing fields can be mitigated by adapting the plasma channel

Obtained positron beam : $\sim 10^4$ positrons with a $\sim 3\,\mathrm{GeV}$ maximum energy

Emittance $\epsilon_{\mathrm{rms}} = 0.5\,\mathrm{mm\,.\,mrad}$ and normalised emittance $\epsilon_{\mathrm{n,rms}} = 1000\,\mathrm{mm\,.\,mrad}$

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