GeV-scale accelerators driven by plasma-modulated pulses from kilohertz lasers

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John Adams Institute & Department of Physics, University of Oxford, UK.

In memory of Oscar Jakobsson
1993-2022

* Now at BELLA Center at Lawrence Berkeley National Laboratory.

Outline

- Modify the way LPA is driven in order to use rapidly evolving, high average power lasers, such as thin-disk (**1J@1ps@kHz achived**), fibre or diode lasers. The Multi-pulse Laser-Wakefield Accelerators (MP-LWFA) concept.

- Guiding trains of laser pulses and plasma wake excitation by trains of laser pulses.
  ► **See next talk by Aimee Ross and talk by James Cowley on Thursday.**

- **P**lasma-**Mo**dulated **P**lasma **A**ccelerator (**P-MoPA**) ► PRL **127**, 184801 (2021) .

- **k**Hz **P**lasma **A**ccelerator **C**ollaboration (**kPAC**).

- Thin-disk lasers to drive GeV@kHz P-MoPA are available.

John Adams Institute for Accelerator Science

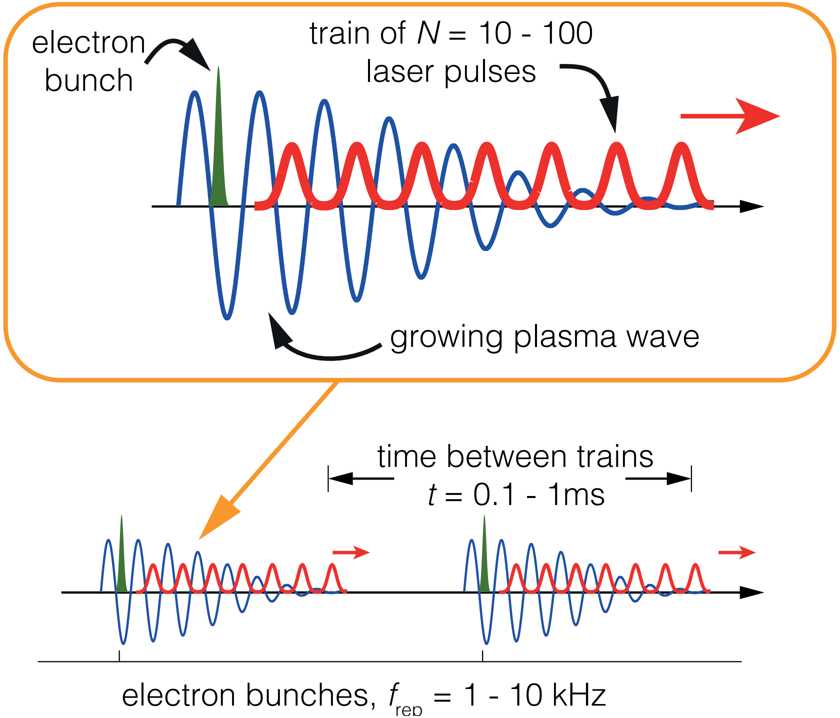
MP-LWFA

▶ **Modify the way LPA is driven.**
The MP-LWFA concept:

- A train of laser pulses (red) -or a long, modulated pulse - will resonantly excite a growing plasma wave (blue) if the pulses (modulations) are spaced by the plasma period.

- **Convert a long laser pulse to a train of short laser pulses** (AWAKE: convert a long proton bunch to a train of short proton bunches) and drive a plasma wake to accelerate electrons (AWAKE: 2 GeV achieved already)

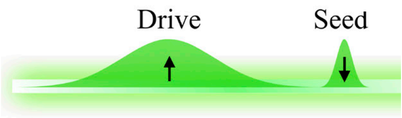
P-MoPA ▶ PRL **127**, 184801 (2021).



▶ J. Phys. B **47**, 1-14 (2014), PRL **119**, 044802-6 (2017)

P-MoPA

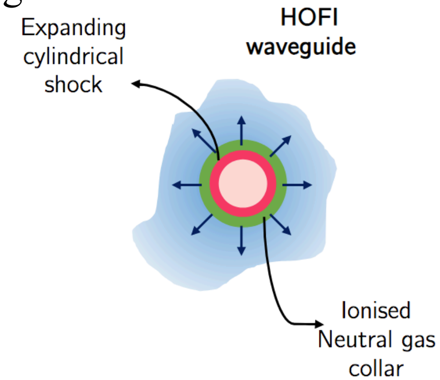
- Long (~ps), Joule-level drive pulse
- Short (<100 fs), 10s mJ seed pulse

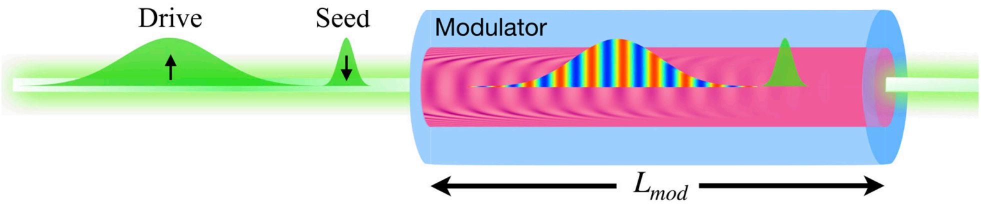


P-MoPA

- Long (~ps), Joule-level drive pulse
- Short (<100 fs), 10s mJ seed pulse
- $\delta n/n_0 \sim 1\%$

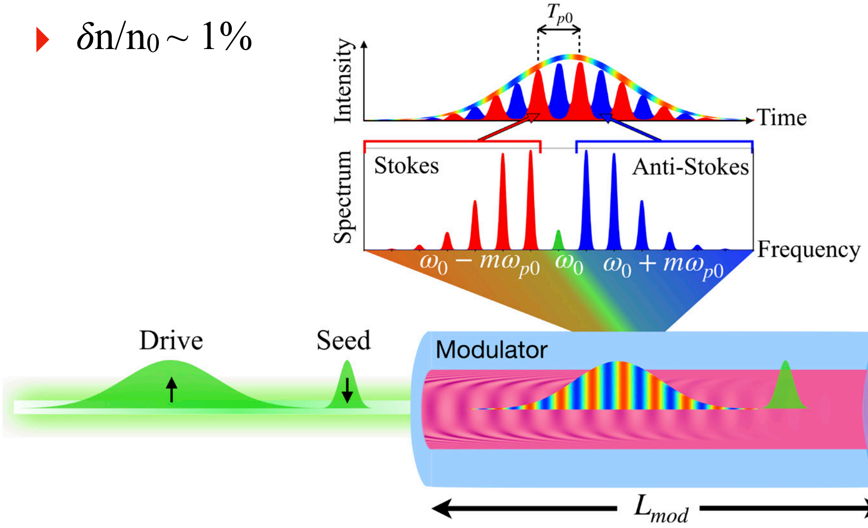
- Plasma waveguide

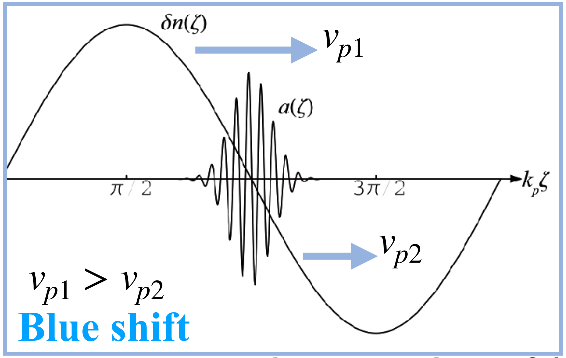




P-MoPA

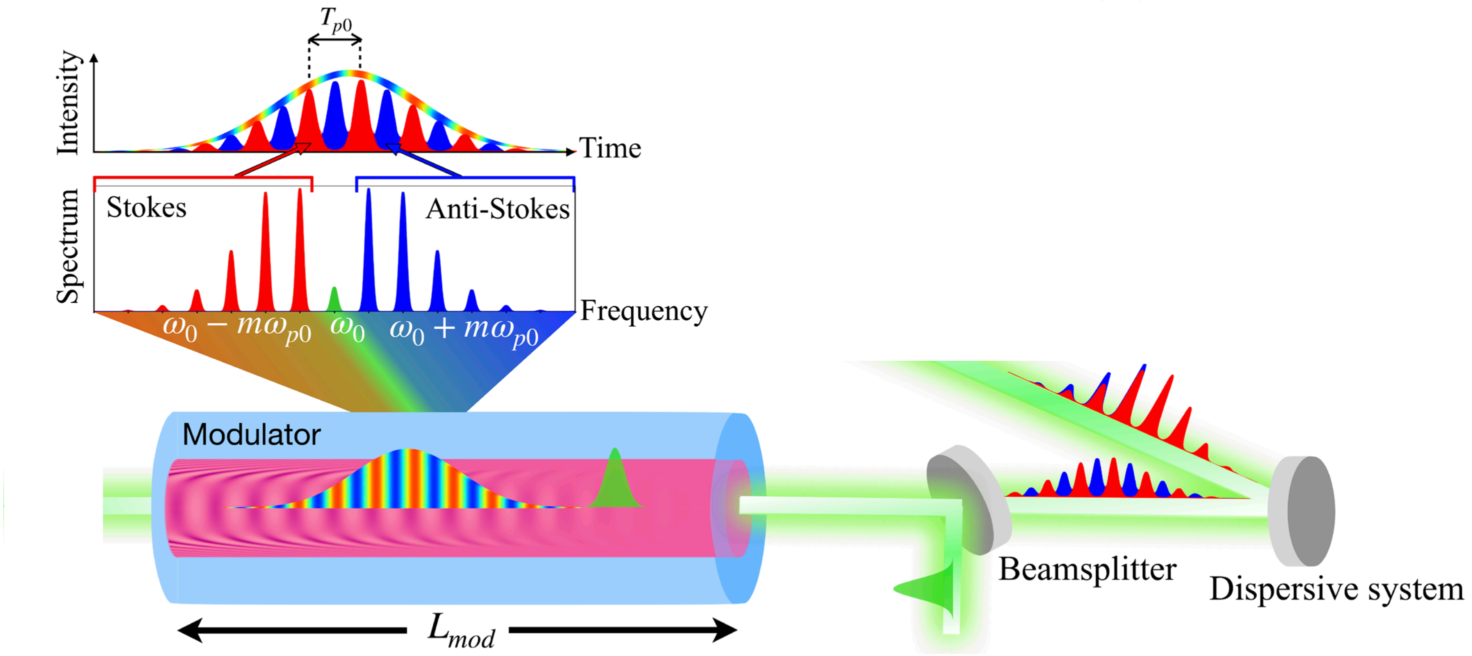
- Long (~ps), Joule-level drive pulse
- Short (<100 fs), 10s mJ seed pulse
- $\delta n/n_0 \sim 1\%$
- Plasma waveguide
- Photon acceleration





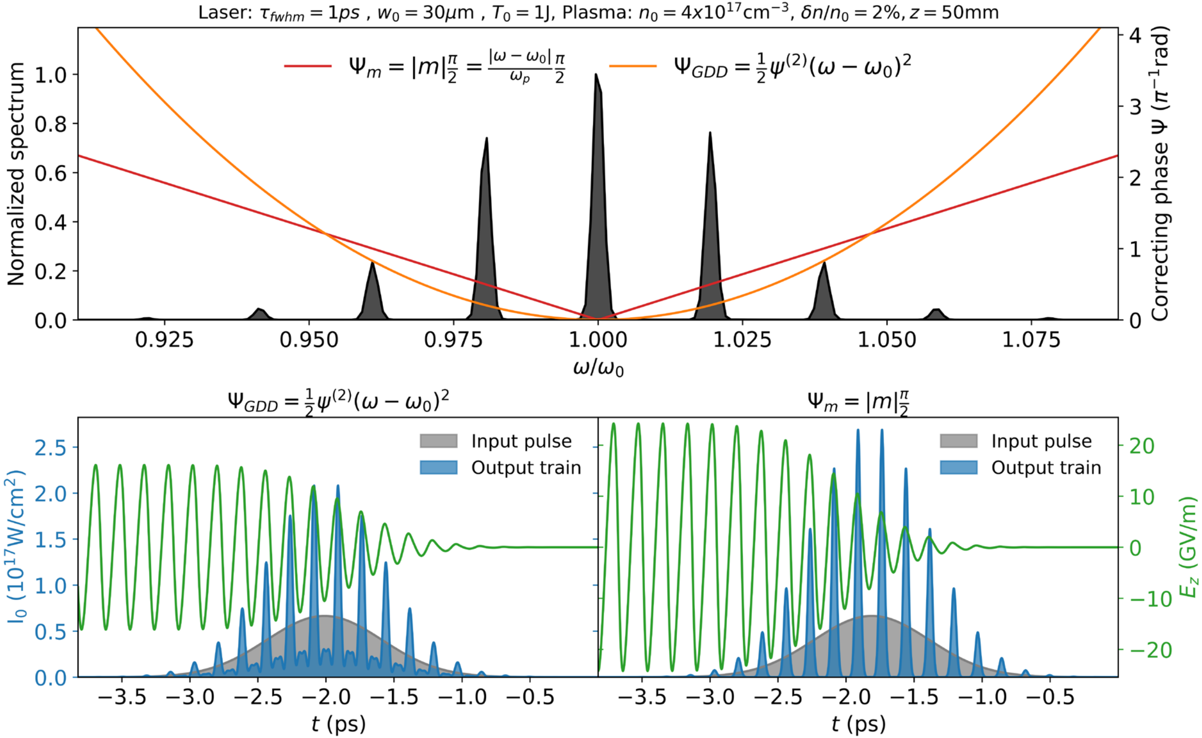
- Rev. Mod. Phys. **81**, 1229 (2009)

P-MoPA



T_{p0}
Intensity
Time
Spectrum
Stokes
Anti-Stokes
Frequency
$\omega_0 - m\omega_{p0}$
ω_0
$\omega_0 + m\omega_{p0}$
Modulator
L_{mod}
Beamsplitter
Dispersive system

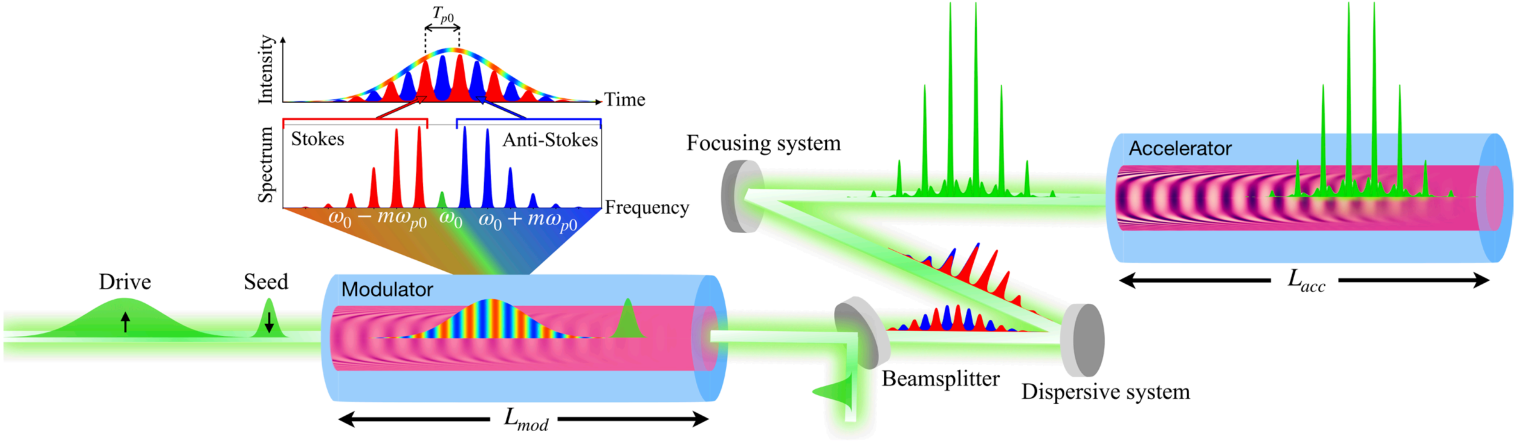
P-MoPA



Laser: $\tau_{fwhm} = 1ps$, $w_0 = 30\mu$m , $T_0 = 1$J, Plasma: $n_0 = 4x10^{17}$cm^{-3}, $\delta n/n_0 = 2\%, z = 50$mm
$\Psi_m = |m|\frac{\pi}{2} = \frac{|\omega - \omega_0|}{\omega_p}\frac{\pi}{2}$
$\Psi_{GDD} = \frac{1}{2}\psi^{(2)}(\omega - \omega_0)^2$
Normalized spectrum
Correcting phase Ψ (π^{-1}rad)
ω/ω_0
$\Psi_{GDD} = \frac{1}{2}\psi^{(2)}(\omega - \omega_0)^2$
$\Psi_m = |m|\frac{\pi}{2}$
Input pulse
Output train
I_0 (10^{17}W/cm^2)
E_z (GV/m)
t (ps)

P-MoPA

- Full scheme: Spectral-to-temporal modulation of a ps-duration pulse using low-energy seed pulse.



Parameters

- Driver:
  - λ_0 = 1.03 μm,
  - 600 mJ, FWHM 1 ps, w_0 = 30 μm, bi-Gaussian envelope.
- Seed:
  - λ_0 = 1.03 μm,
  - 50 mJ, FWHM 40 fs, w_0 = 30 μm, bi-Gaussian envelope
  - 1.7 ps in front of the driver.
- Plasma:
  - electron-proton plasma; electron density on axis = 2.5×10^{17} cm^{-3}, λ_p = 66 μm, T_p = 220 fs,
  - plasma channel α = 10, w_M = 30 μm.

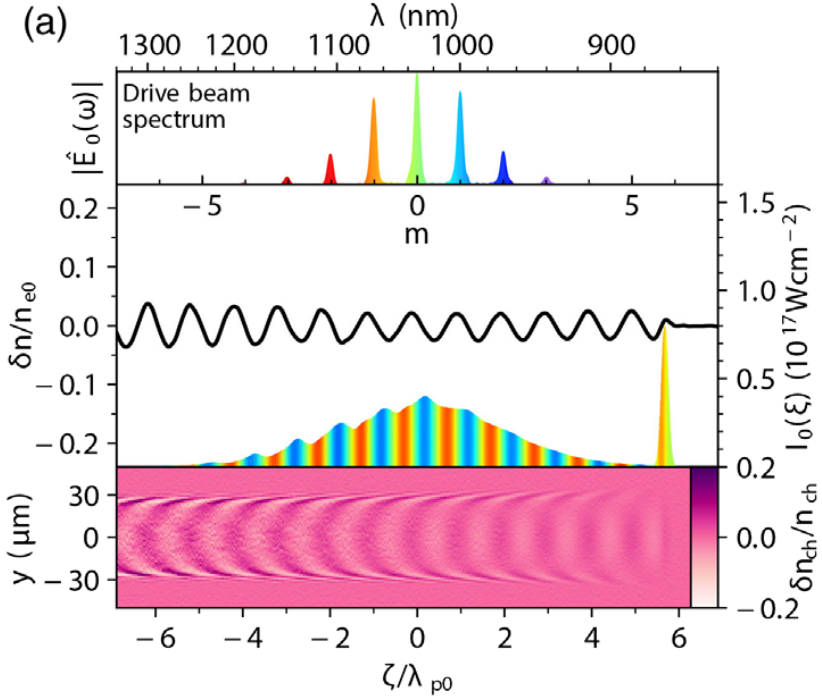
Parameters called PRL parameters

$$n_e(\rho) = n_e(0) + \frac{1}{\pi r_e W_M^2}\left[\frac{\rho}{W_M}\right]^{\alpha}$$

- PIC code EPOCH 2D v 4.17.10 on ARCHER and ARCHER2

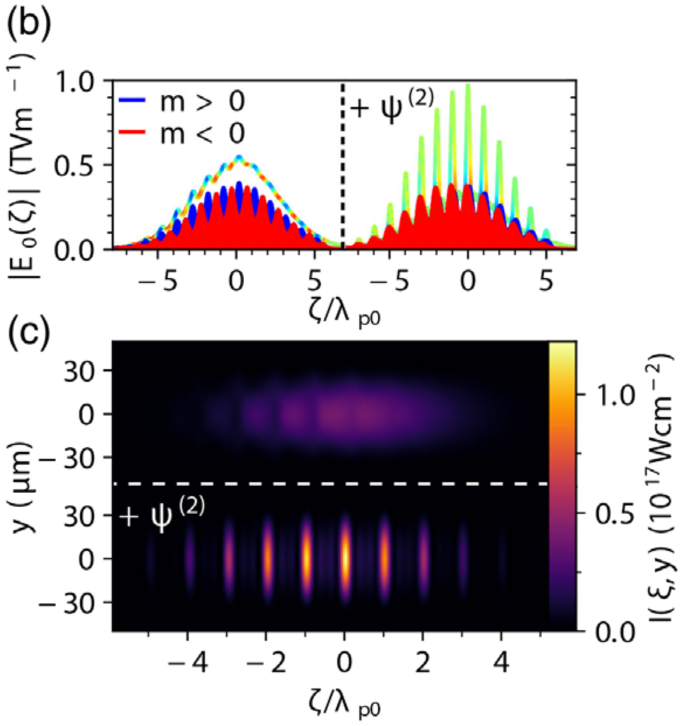
PIC; the modulator

- After 12 cm propagation in the modulator.



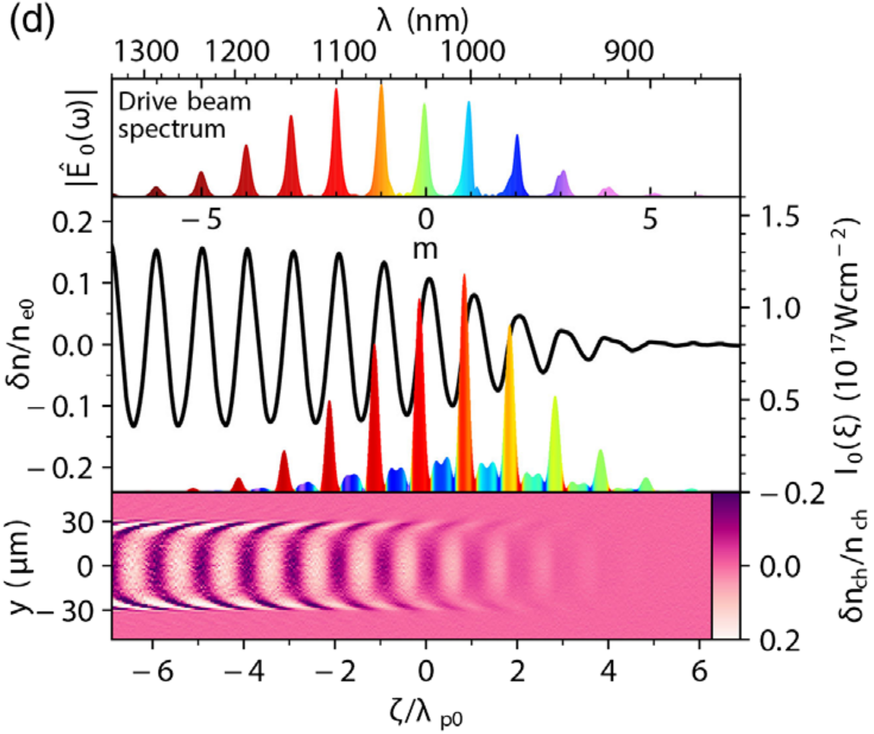
PIC; the modulator

- After 12 cm propagation in the modulator.



PIC; the accelerator

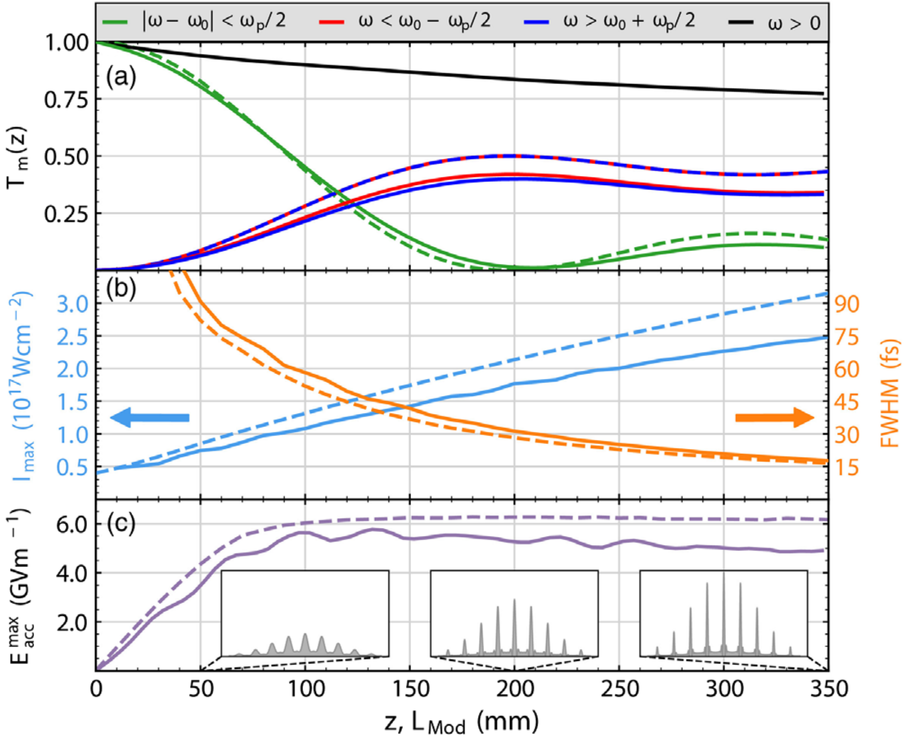
- After 5 cm acceleration.



PIC in comparison with analytic calculations

- $T_m(z)$; the relative transmitted energies of the drive pulse and of its components.

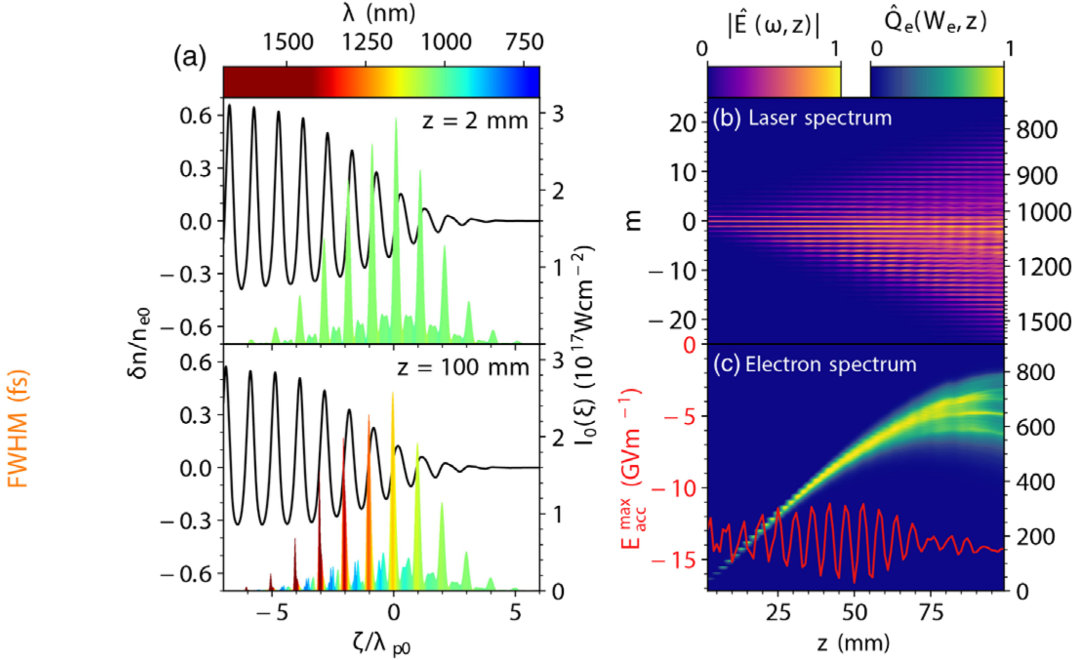
- Dashed lines: 1D analytic model
Solid lines: PIC.



PIC; higher energy accelerator

- Three parametrs have been changed:
  - w_M= 50 μm in the modulator.

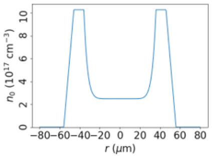
Keeping a_0 fixed:
- Driver 1.7 J.
- Seed 140 mJ.

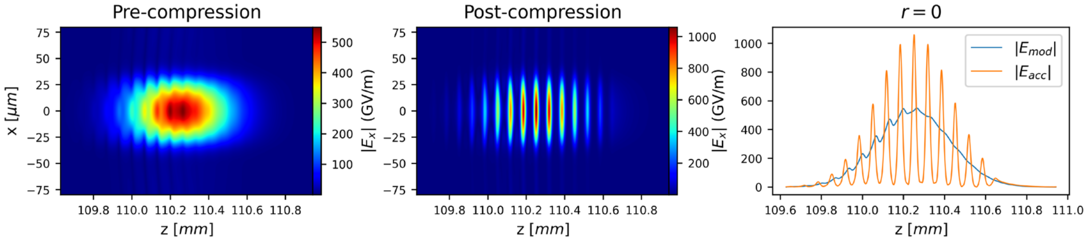


- 1 pC electron bunch inserted "by hand": 35 MeV, 5 fs RMS duration and 4 μm transverse width.

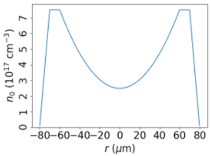
Different channel profiles

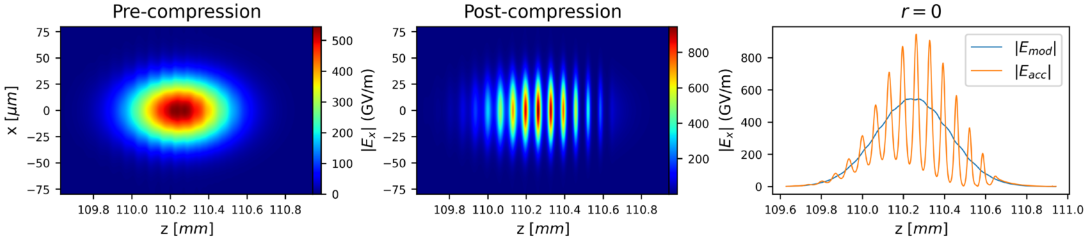
Square, w_M= 30 µm ►



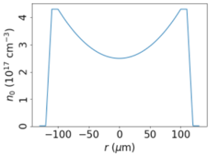


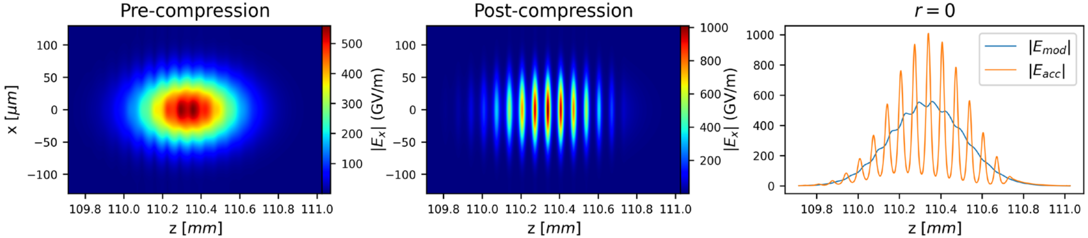
Parabolic, w_M= 30 µm ►





Parabolic, w_M= 50 µm ►





WarpX 2D

Roman Walczak
University of Oxford

Plasma Phys **2**, 2196 (1990)

Modulator limit

PRL parameters except:

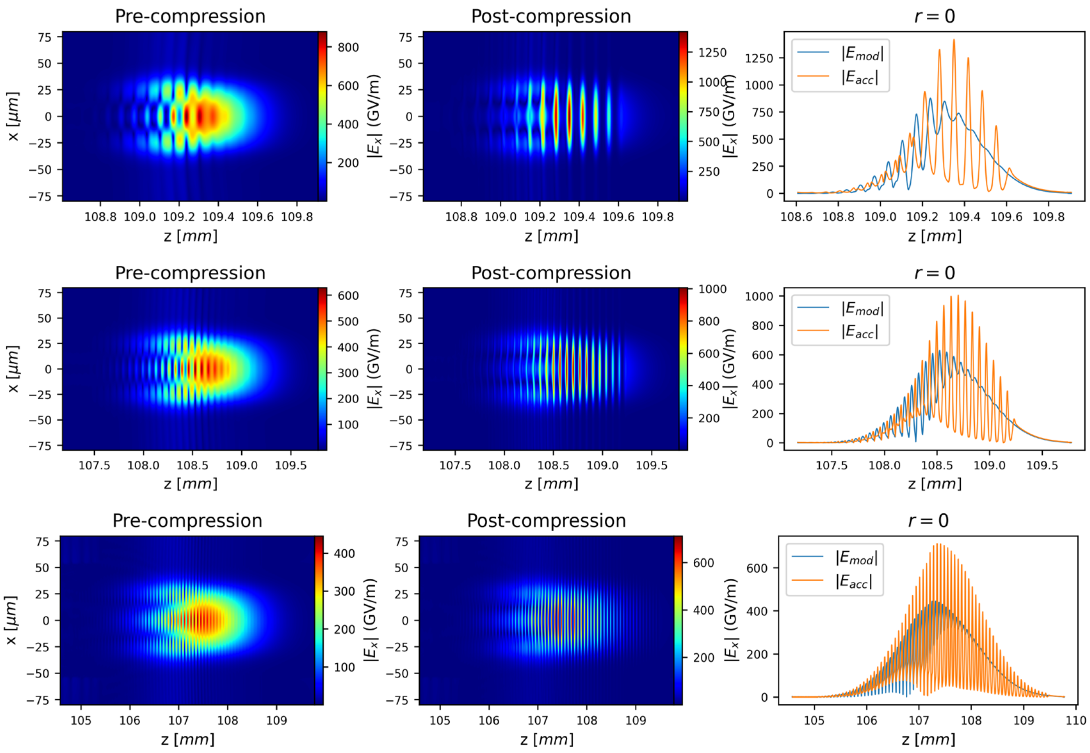
1.2 J, 1 ps

1.2 J, 2 ps

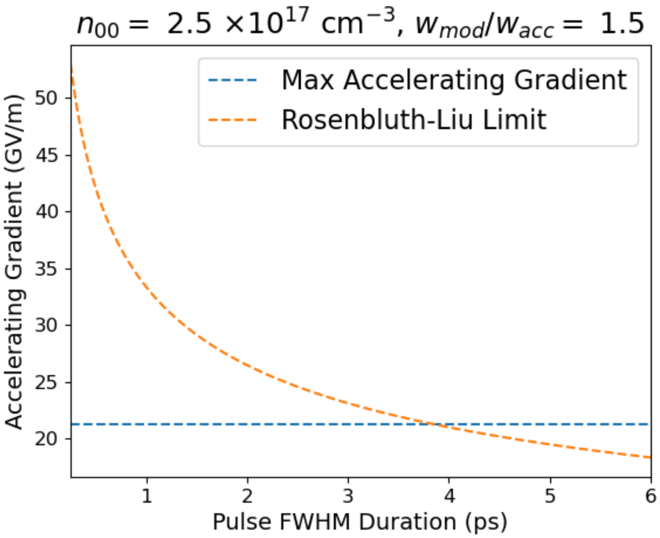
WarpX 2D

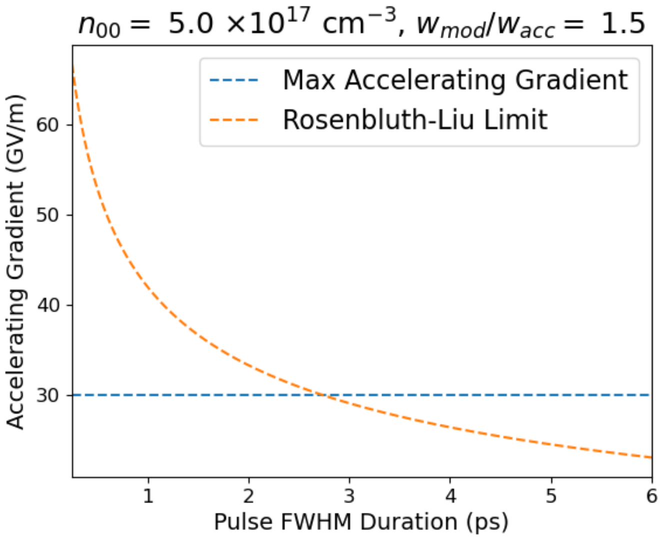
1.2 J, 4 ps

Horizontal scale is changing!



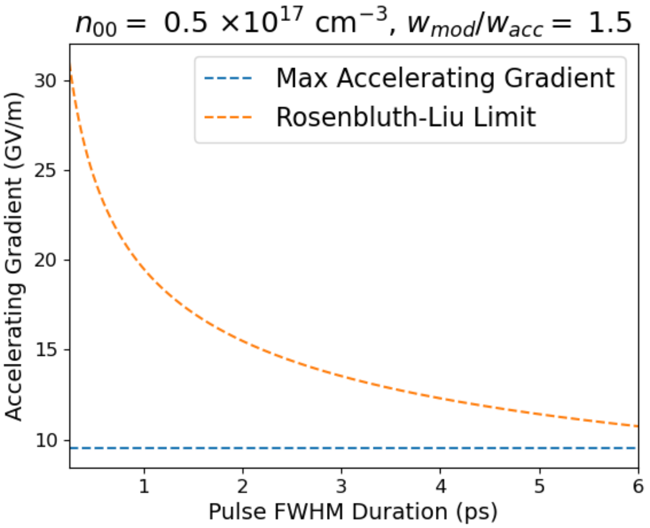
P-MoPA constraints

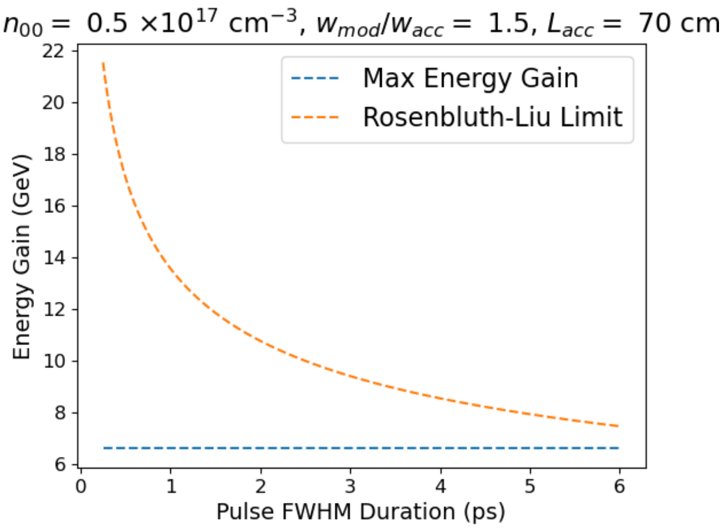




- **Extra focusing in the accelerator $w_{mod}/w_{acc} = 1.5$**

P-MoPA constraints





- **Extra focusing in the accelerator $w_{mod}/w_{acc} = 1.5$**

Electron injection

► Optical internal electron injection

- 2PII scheme ► Phys. Rev. Lett. **73**, 155004, (2013)
- ReMPI scheme ► Phys. Rev. Accel. Beams **22**, 111302, (2019)
- Transverse HOFI channel ► plasma density gradient, CALA scheme,
  ► arXiv:2206.00507v1 [physics.acc-ph]

► External electron injection: RF plus THz-driven compression

- Sub-10 fs electron bunch duration and sub-10 fs synchronization with high intensity laser pulse, >10 pC charge,
  ► Nature Phot, **14**, 755-759 (2020)
  ► Phys. Rev. Lett, **124**, 054801 and 054802 (2020)

▶ **k**Hz **P**lasma **A**ccelerator **C**ollaboration (**kPAC**)
CLF, LMU, TRUMPF and Oxford
To study P-MoPA physics at CALA, get funding to develop GeV@kHz accelerator.

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

TRUMPF

TRUMPF Scientific Lasers

UKRI Science and Technology Facilities Council

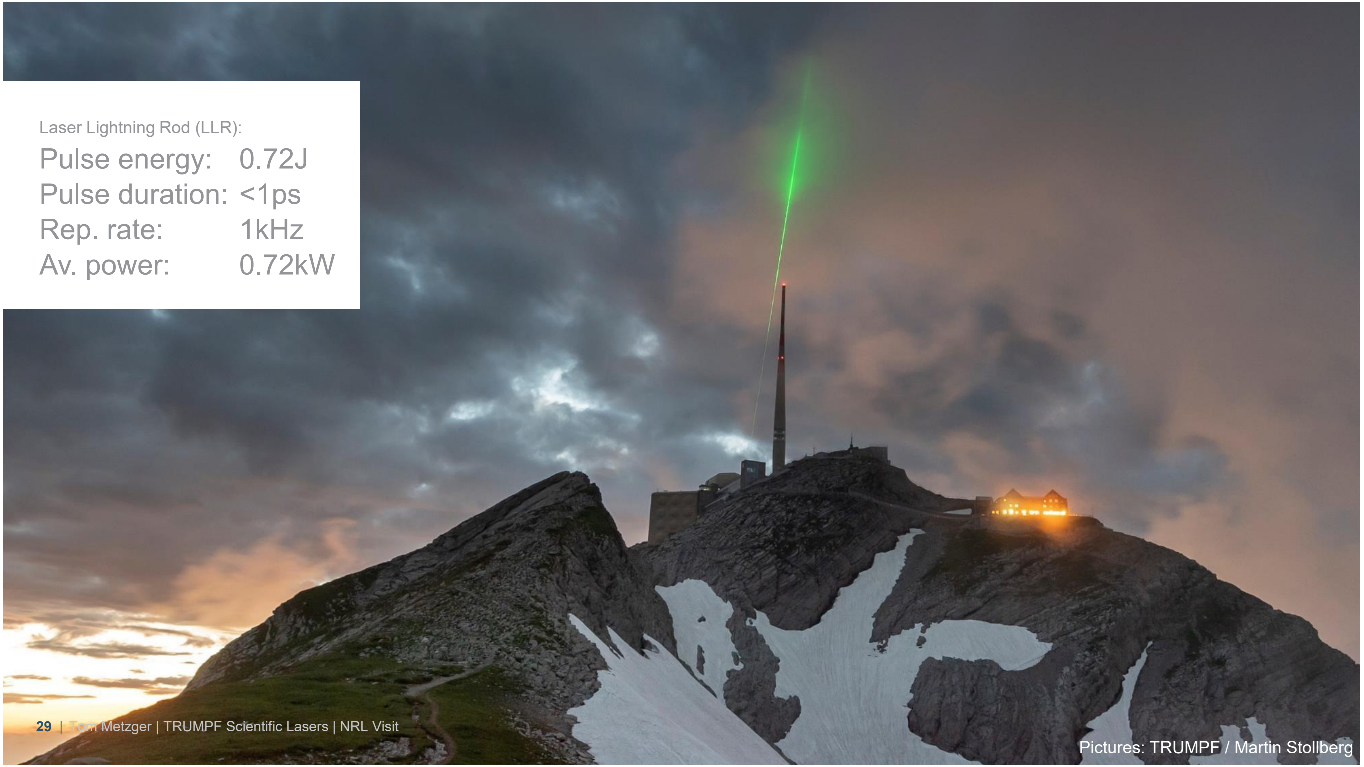
CLF central laser facility

UNIVERSITY OF OXFORD

TRUMPF Scientific Lasers

Laser Lightning Rod (LLR):

Pulse energy:	0.72J
Pulse duration:	<1ps
Rep. rate:	1kHz
Av. power:	0.72kW



Pictures: TRUMPF / Martin Stollberg

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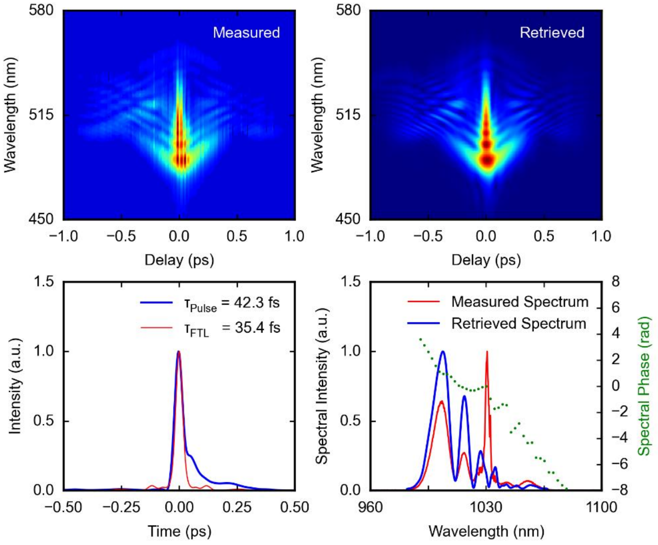
TRUMPF Scientific Lasers

Nonlinear Compression of a Dira 1000-5

Status June 2022: 180mJ @ <45fs



36 Tom Metzger | TRUMPF Scientific Lasers | NRL Visit

The most powerful nonlinear compression in the world:

150mJ; <40fs
5kHz; 750W
3.3TW peak power

See also

- CSU: 1.1 J, 4.5 ps, 1 kHz, cryogenic temp. Opt. Lett. **45**, 6615-6618 (2020).

and

- Developments of coherent combina-tion of fibre lasers

TRUMPF

Summary

GeV@kHz

Ready to go

Roman Walczak
University of Oxford

Acknowledgements

- STFC UK: Grants No. ST/P00 2048/1 and No. ST/V001655/1.
- EPSRC UK: Grants No. EP/V006797/1 and No. EP/R513295/1.
- AFOSR: Grant No. FA9550-18-1-7005.
- EU Horizon 2020 Grant No. 653782.
- The plasma HEC Consortium (EPSRC Grant No. EP/R0291/1 and UKRI funding (ARCHER2 Pioneer Projects).
- Computing ressources were provided by ARCHER and ARCHER2 (ARCHER2 PR17125) UK supercomputers as well as STFC SCARF cluster.
- EU Horizon 2020 Grant No. 101004730.

iFAST

EUROPEAN NETWORK FOR NOVEL ACCELERATORS

EuroNNAc4

NPACT supported by EU via I-FAST