# Controlled, High-repetition rate Plasma Accelerators

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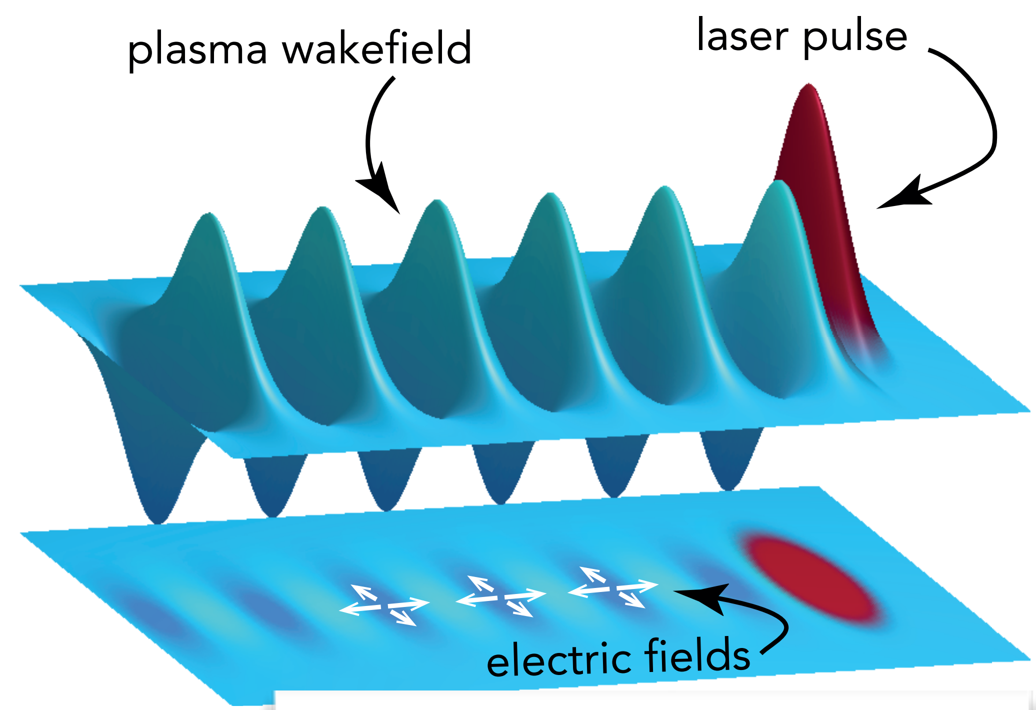
*Friedrich-Schiller-Universität, Jena, Germany*

# Long-term vision

**Laser-plasma accelerators have already produced:**

- ✓ GeV-scale electron beams
- ✓ fs-duration bunches
- ✓ High peak current

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Pulse duration ~ 50 fs
Rep. rate (frep): < 10 Hz
Wall-plug efficiency < 0.1 %

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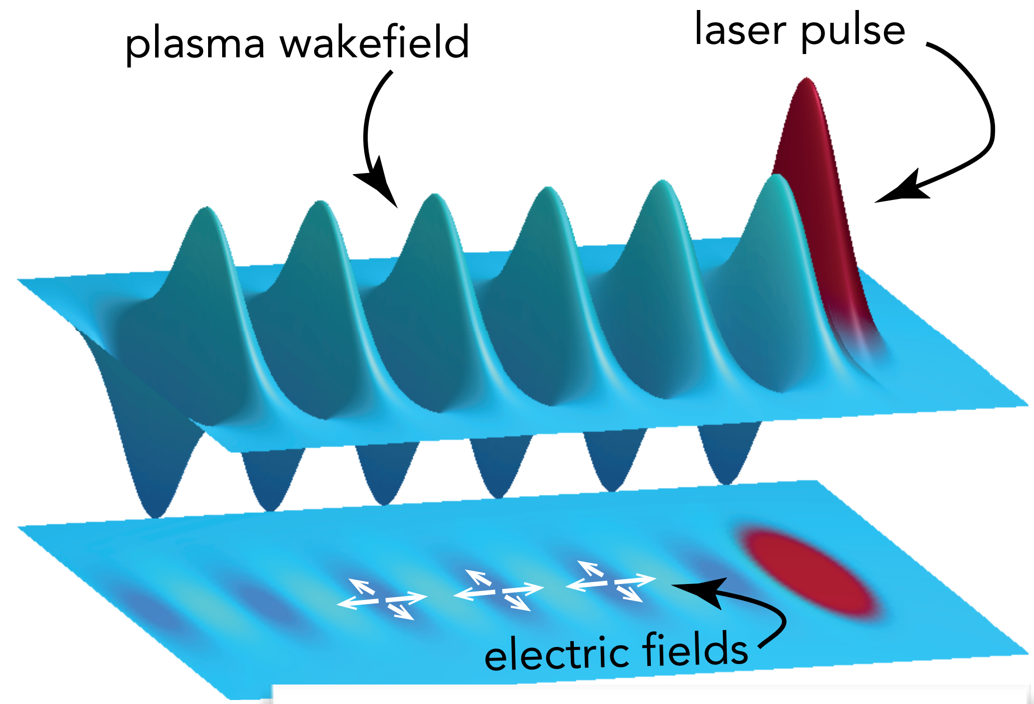


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**Future laser-plasma accelerators will need:**

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- Reduced energy spread
- Reduced emittance
- Reduced shot-to-shot jitter

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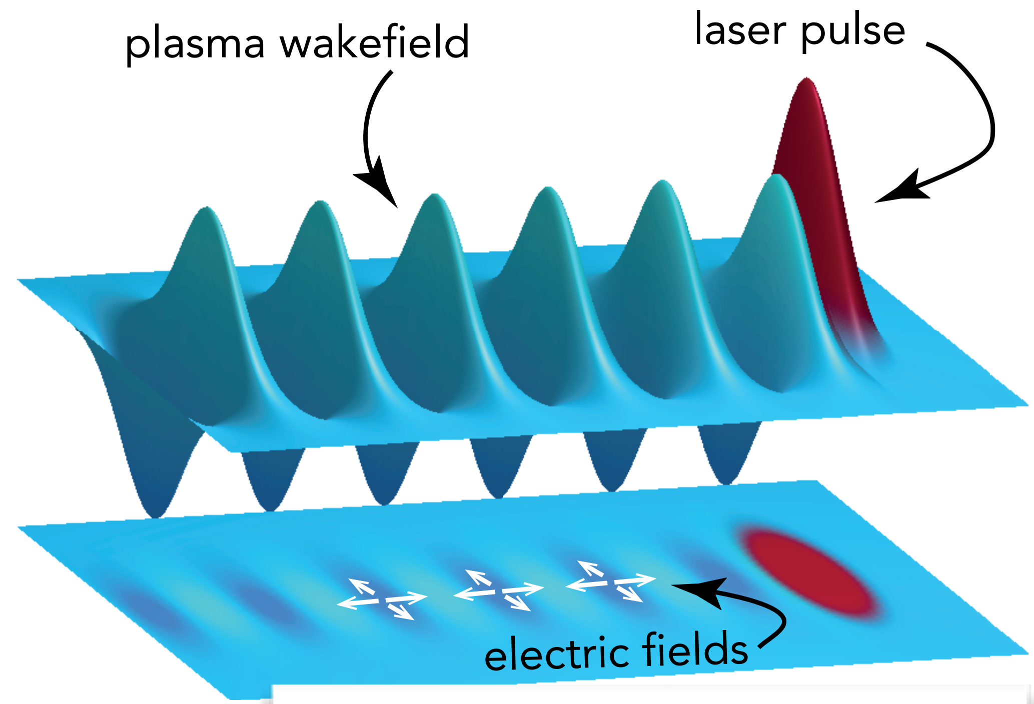


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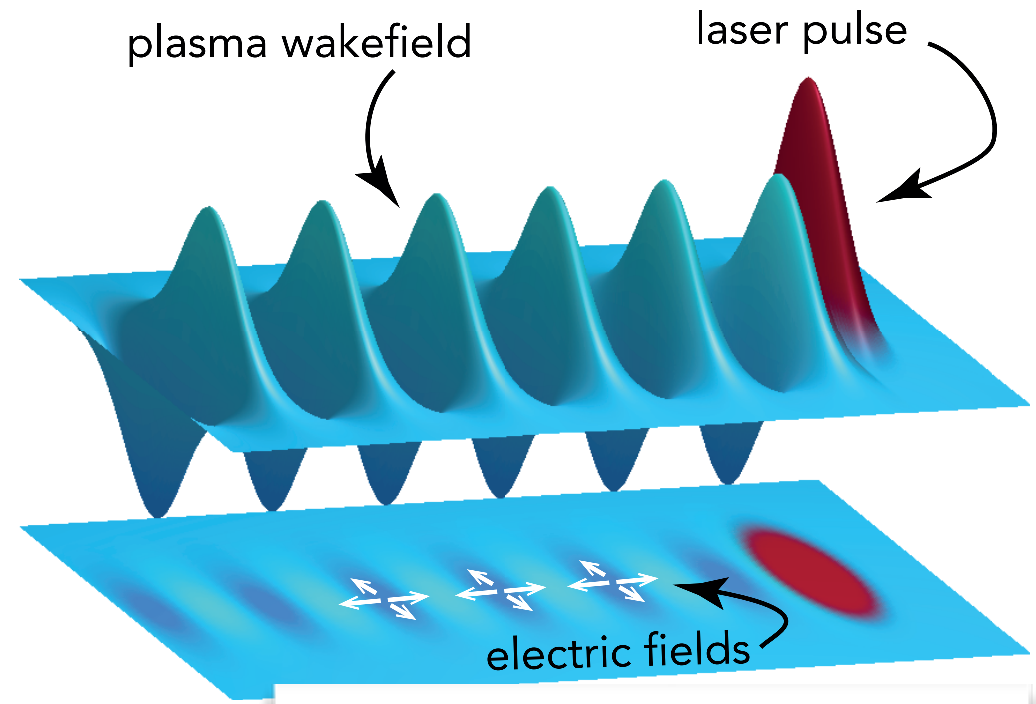


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**New laser drivers**

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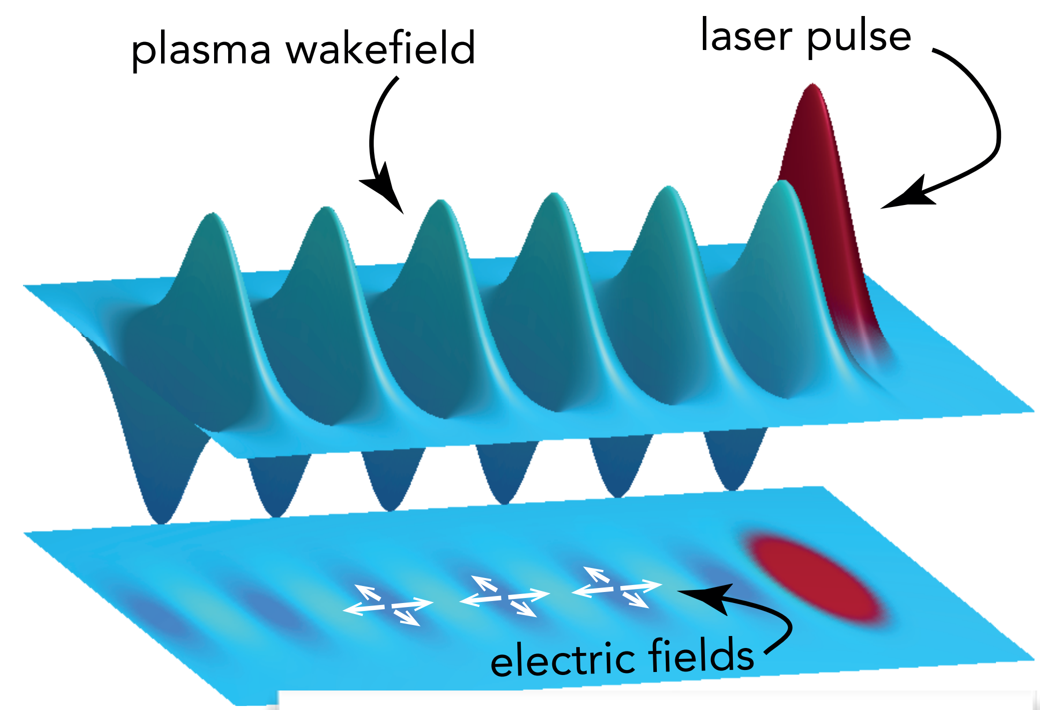


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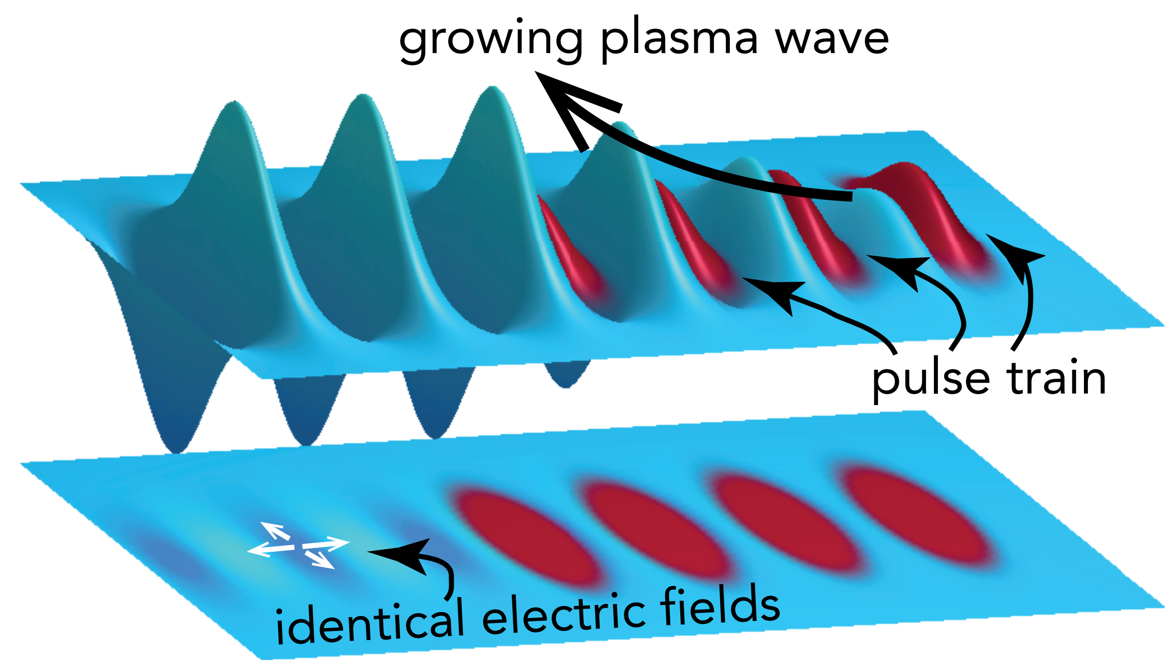
- Our approach is to develop accelerators based on **controlled injection** into **quasi-linear** wakefields driven by **multi-pulse laser pulses**


UNIVERSITY OF OXFORD

# Multi-pulse LWFA (MP-LWFA)

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- MP-LWFA: Use a train of many pulses separated by plasma period to resonantly excite wakefield
  - Can tune pulse separation to avoid saturation (unlike simple beat-wave scheme)
  - Pulses in train do not need to be coherent
- This is not an original idea!
  - K. Nakajima *PRA* **45** 1149 (1992)
  - Dalla & Lontano *PRE* **49** R1819 (1994)
  - D. A. Johnson *et al. Phy. Scr.* **52** 77 (1994)
  - Umstadter *et al. PRL* **72** 1224 (1994)
- Wake excitation by multiple (5-8) particle bunches has been demonstrated
  - Kallos *et al.*, *Proc. EPAC* p. 1912 (2008)

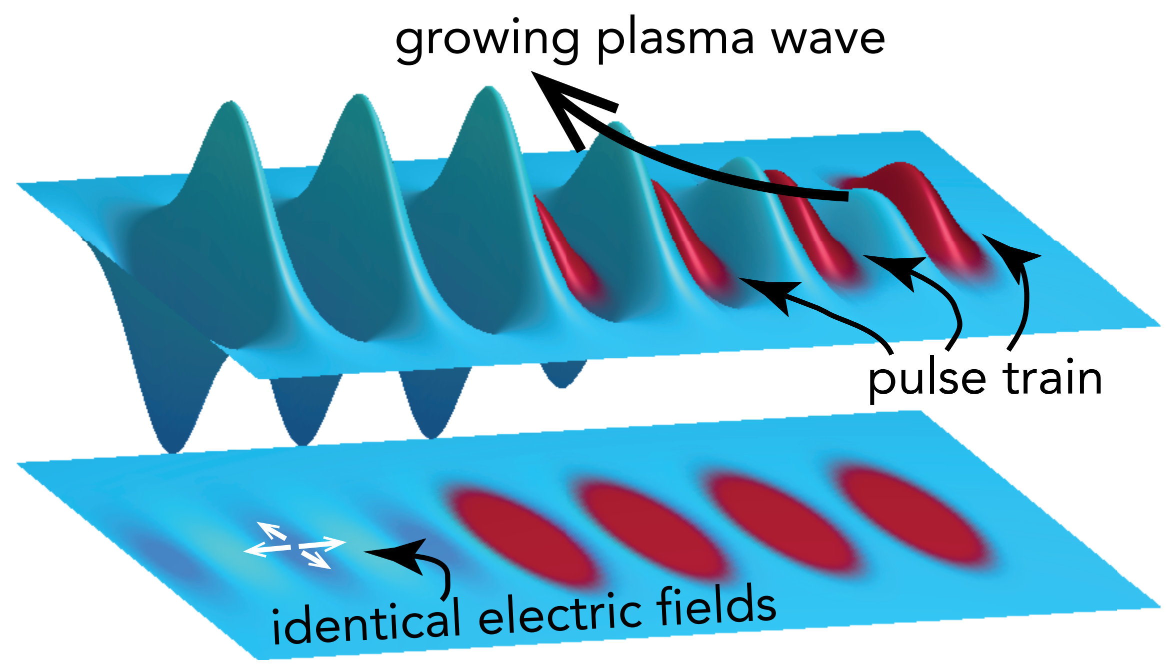



Multi-pulse LWFA
Only 4 laser pulses shown. In reality would use 10 - 100!

# MP-LWFA: Advantages

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- Move energy storage from laser material to the plasma
- Reduce energy per laser pulse from joules to 10s mJ
  - Allows new, efficient laser technologies (thin-disk, fibre lasers, OPCPA)
- Peak intensity on optics reduced by *N*
  - Could reduce optical damage
  - Or, allow smaller diameter, shorter focal length optics
- Additional control over wake excitation
  - Vary spacing, energy, wavelength of pulses in train
- Natural architecture for “energy recovery”

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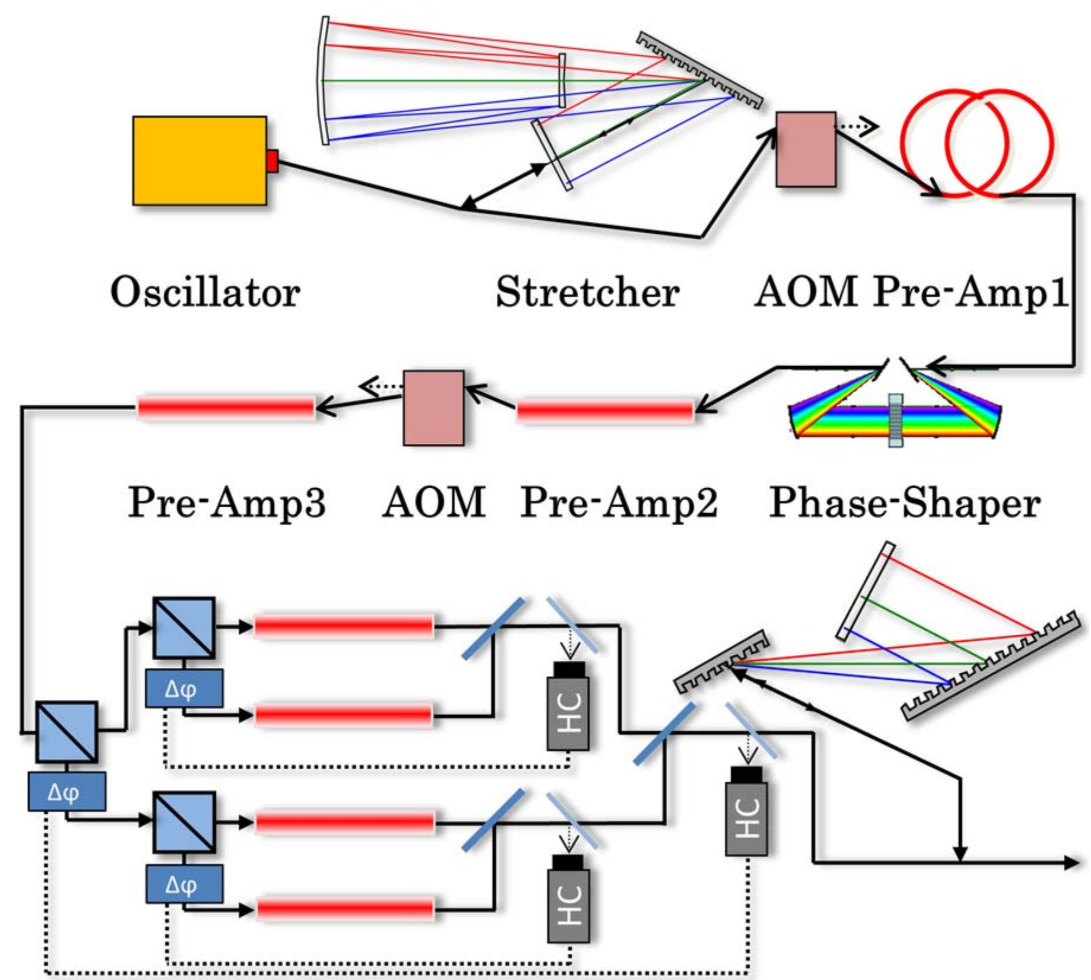
# Driving lasers for MP-LWFA

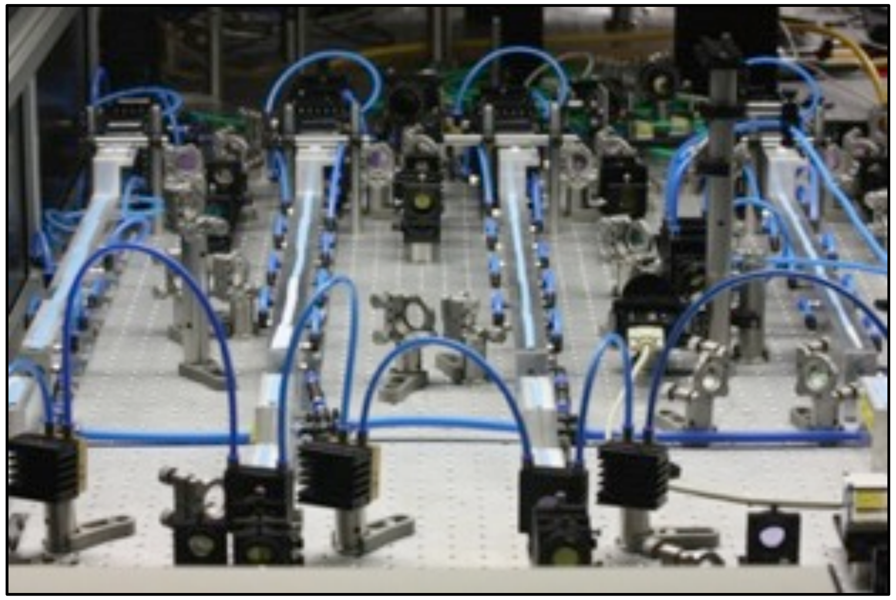
A. Klenke *et al. Opt. Lett.* **39** 6875 (2014)

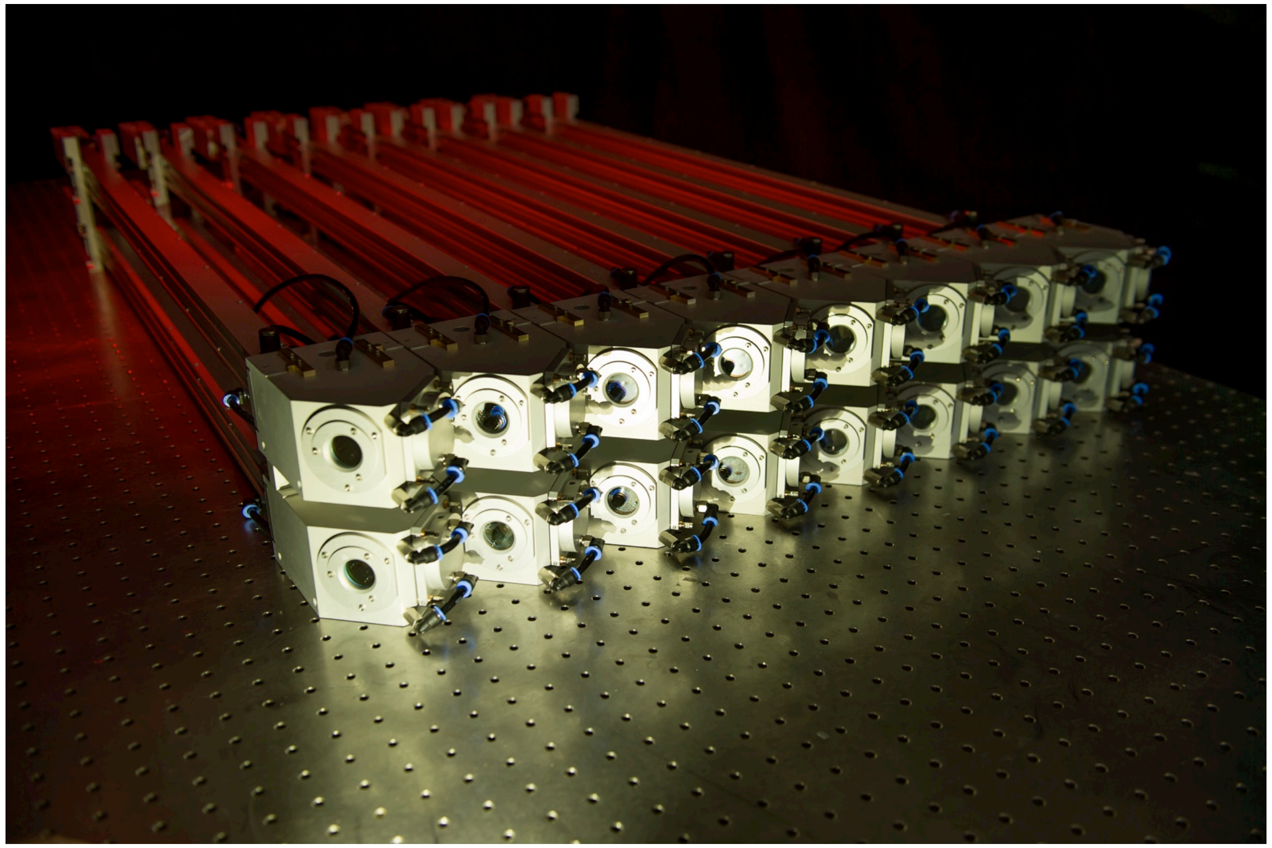
- Fibre lasers can deliver kW mean powers at wall-plug efficiencies > 20%
- Fibre lasers can now also generate short pulses at very high $f_{rep}$
  - 5.7 mJ, 200fs pulses generated at $f_{rep}$ = 40 kHz
  - > 200 W average power



# Coherent Addition of Ultrashort Pulses

## 4-channel fiber CPA system -> upgrade to 16-channel FCPA





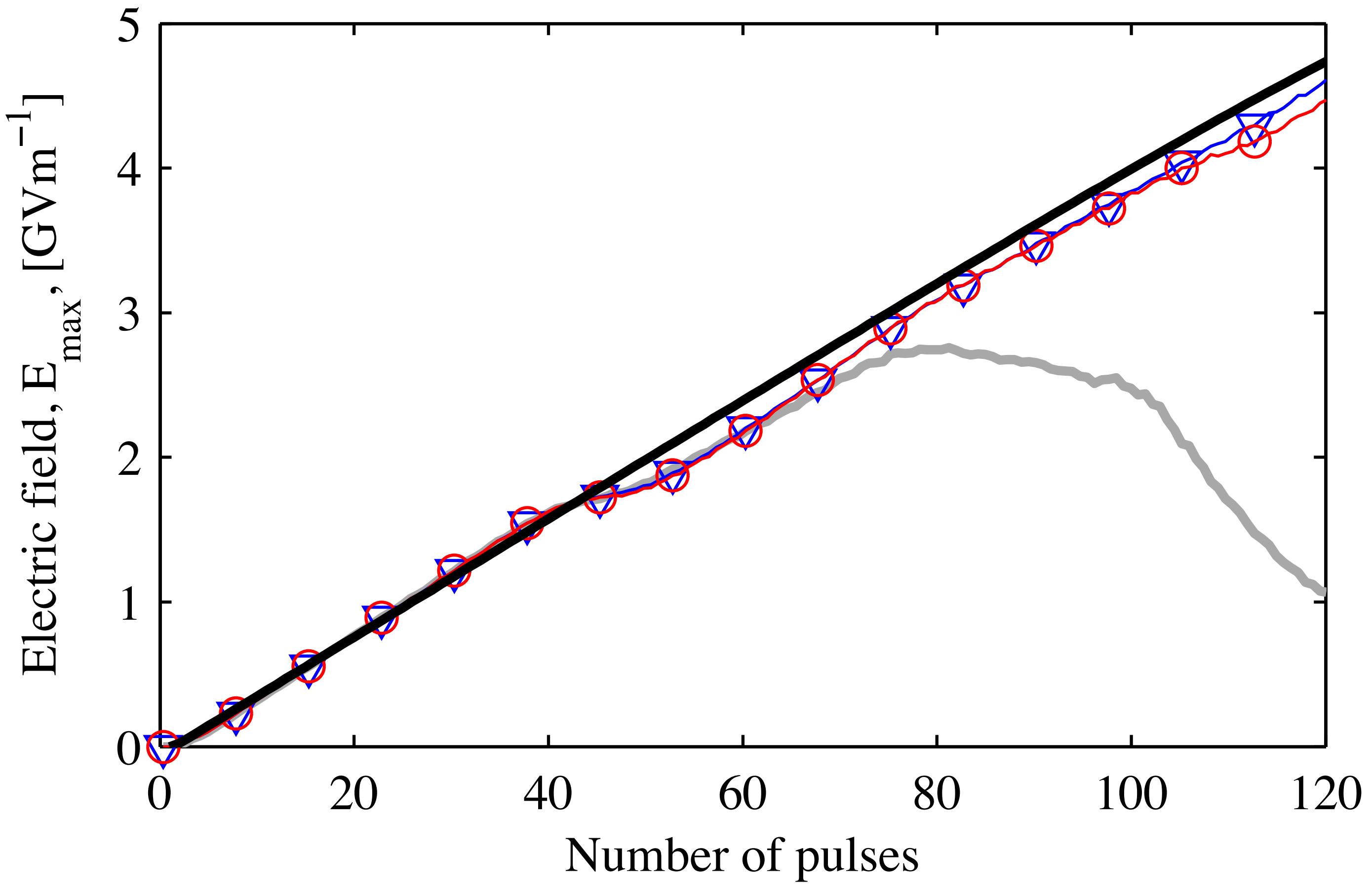
- **up to 5.7 mJ** pulse energy
- **200 fs** pulse duration
- **22 GW** peak power[1]
- **>500W** average power[2]
- **90%** combining efficiency
- **$M^2 < 1.2$**

**Targeted performace:**
**>20mJ pulse energy and >2kW average power**

[1] A. Klenke et al. “22 GW peak-power fiber chirped-pulse-amplification system,” Opt. Lett. **39**, 6875–6878 (2014).
[2] A. Klenke et al. “530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse [...],” Opt. Lett. **38**, 2283-2285 (2013)

# MP-LWFA

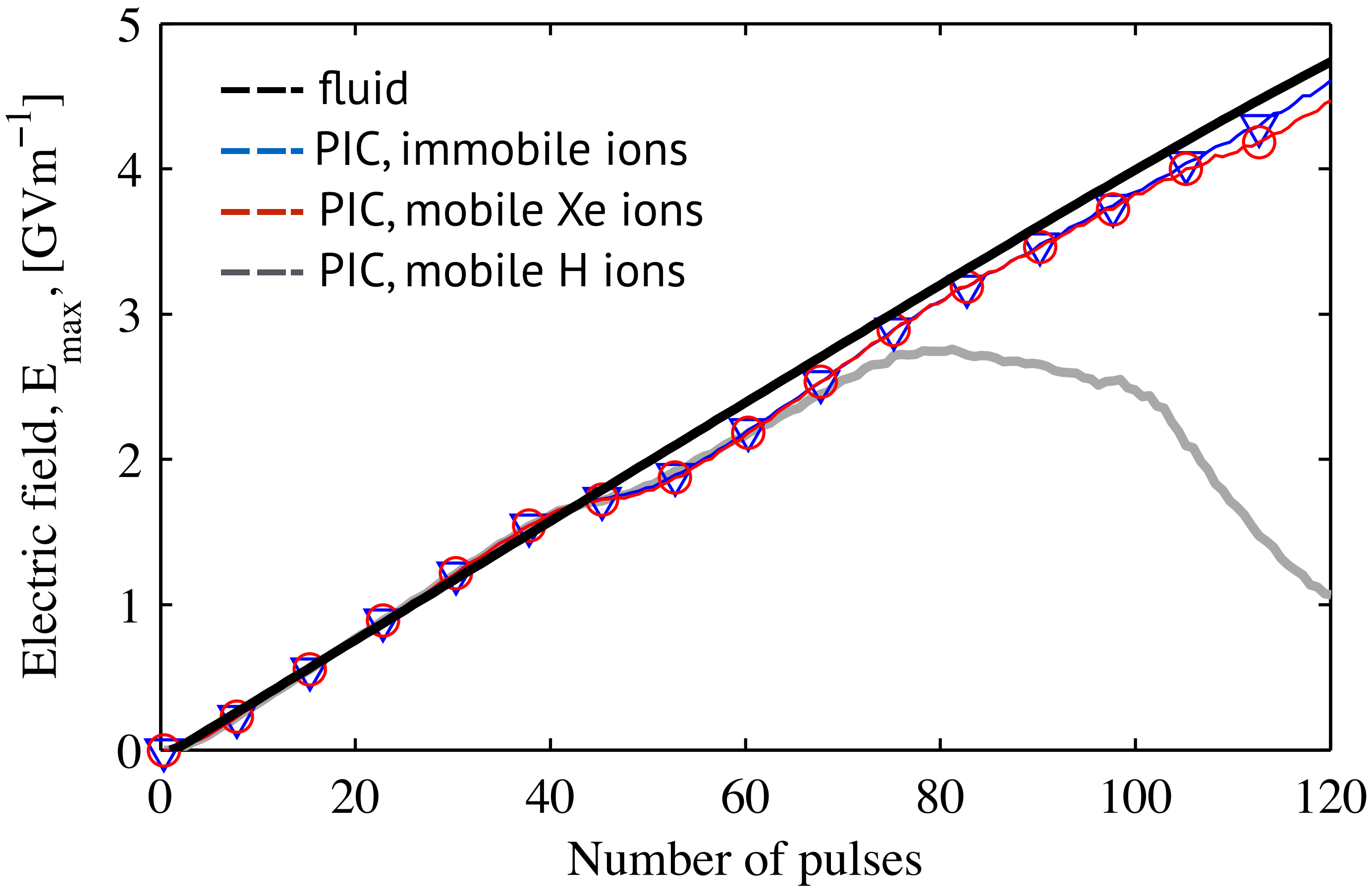
S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)



# MP-LWFA

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- Fluid and PIC simulations show gradients of 4.7 GV/m for train of 100 pulses
- For $L_{acc} = L_d/2 = 260$ mm, energy gain is 0.75 GeV
- Pulse trains of up to ~ 100 pulses can be used before ion motion damps plasma wave




**Laser-plasma parameters**
E = 10 mJ / pulse
τ = 100fs
w0 = 40 μm
a0 = 0.05
ne = 1.75 × $10^{17}$ cm-3

# MP-LWFA-driven radiation sources

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- Model radiation sources assuming
  - $E$ = 0.75 GeV, $Q$ = 50 pC, $\tau$ = 5 fs, $\Delta E / E$ = 1%, $\varepsilon_n$ = 0.1 $\pi$ μm
  - For betatron assume $w_0$ = 30 μm, $r_\beta$ = 10 μm

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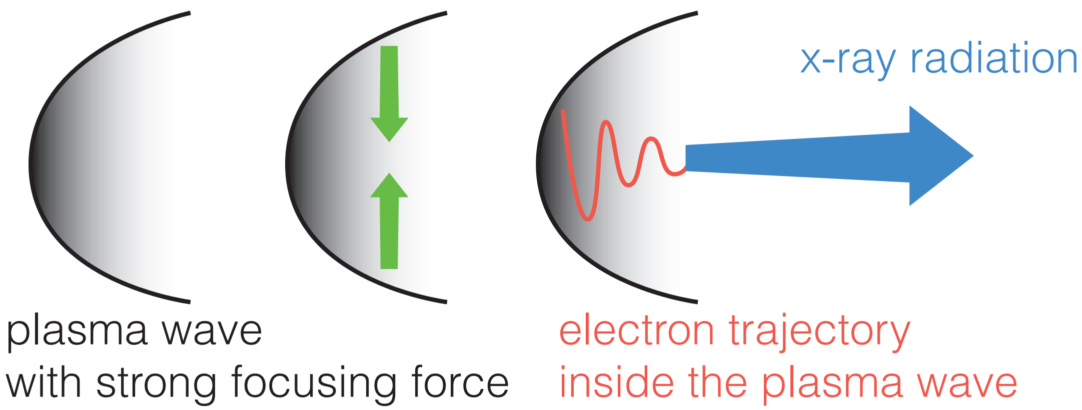
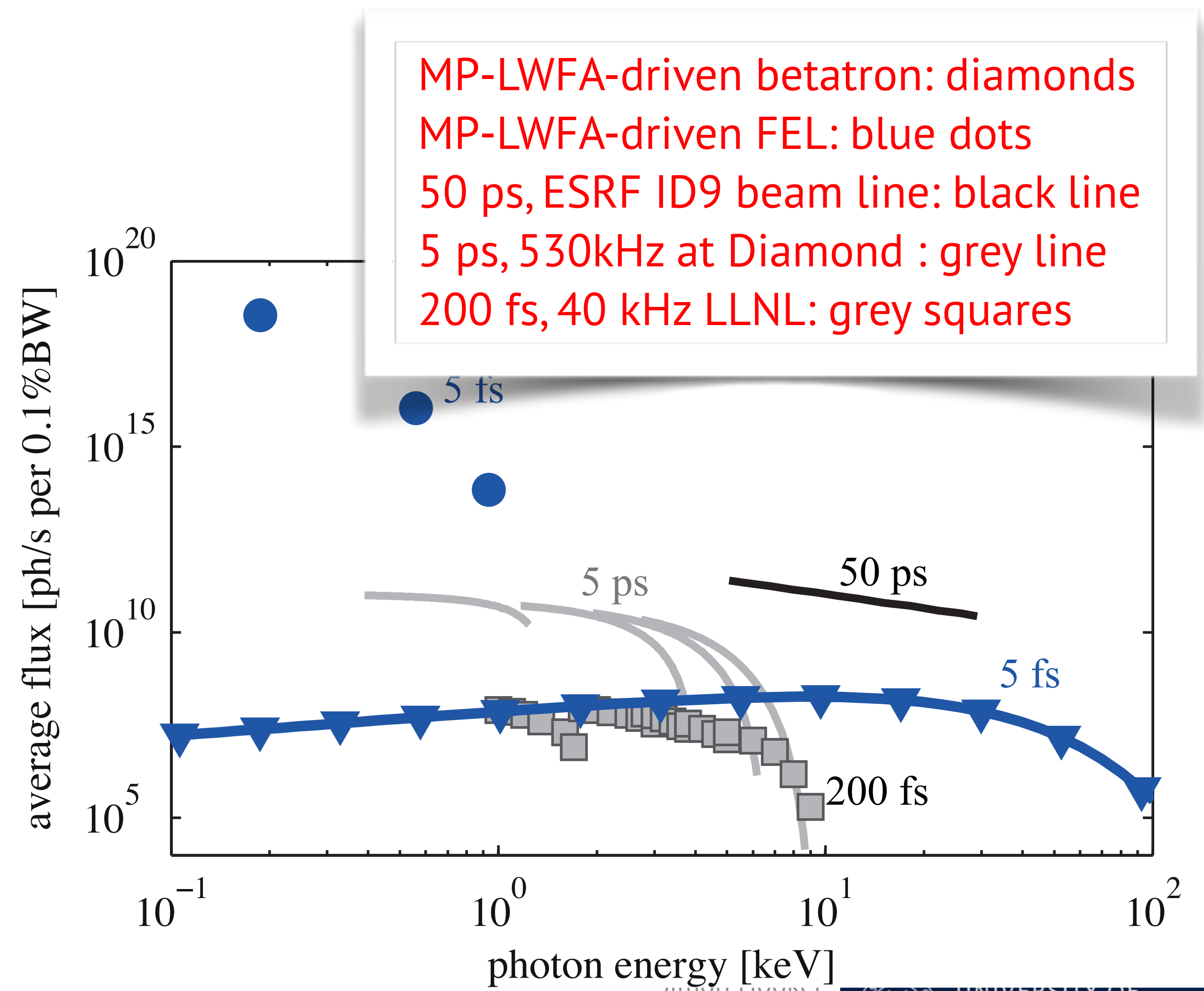
- Betatron radiation
  - Average photon flux @ 10keV is ≈ 2 × $10^8$ photons $s^{-1}$, per 0.1% BW
  - Greater than existing short-pulse 3rd gen sources (but 100 x better resolution)



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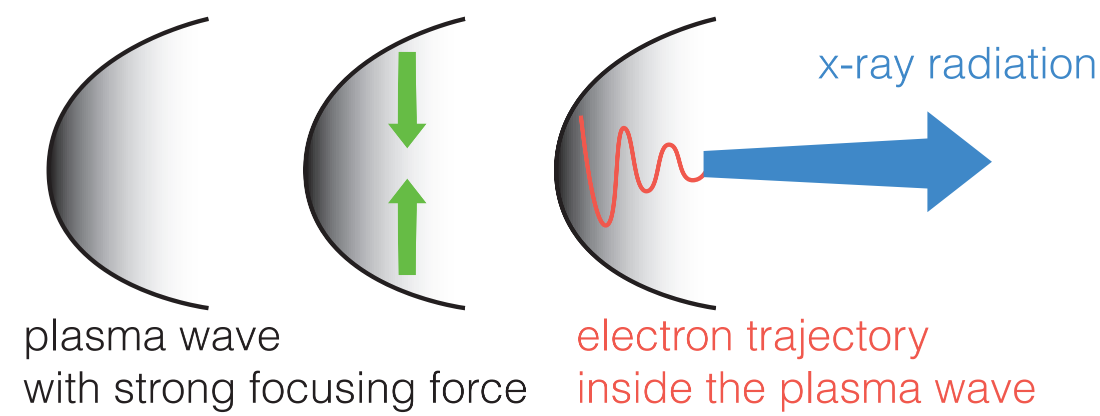
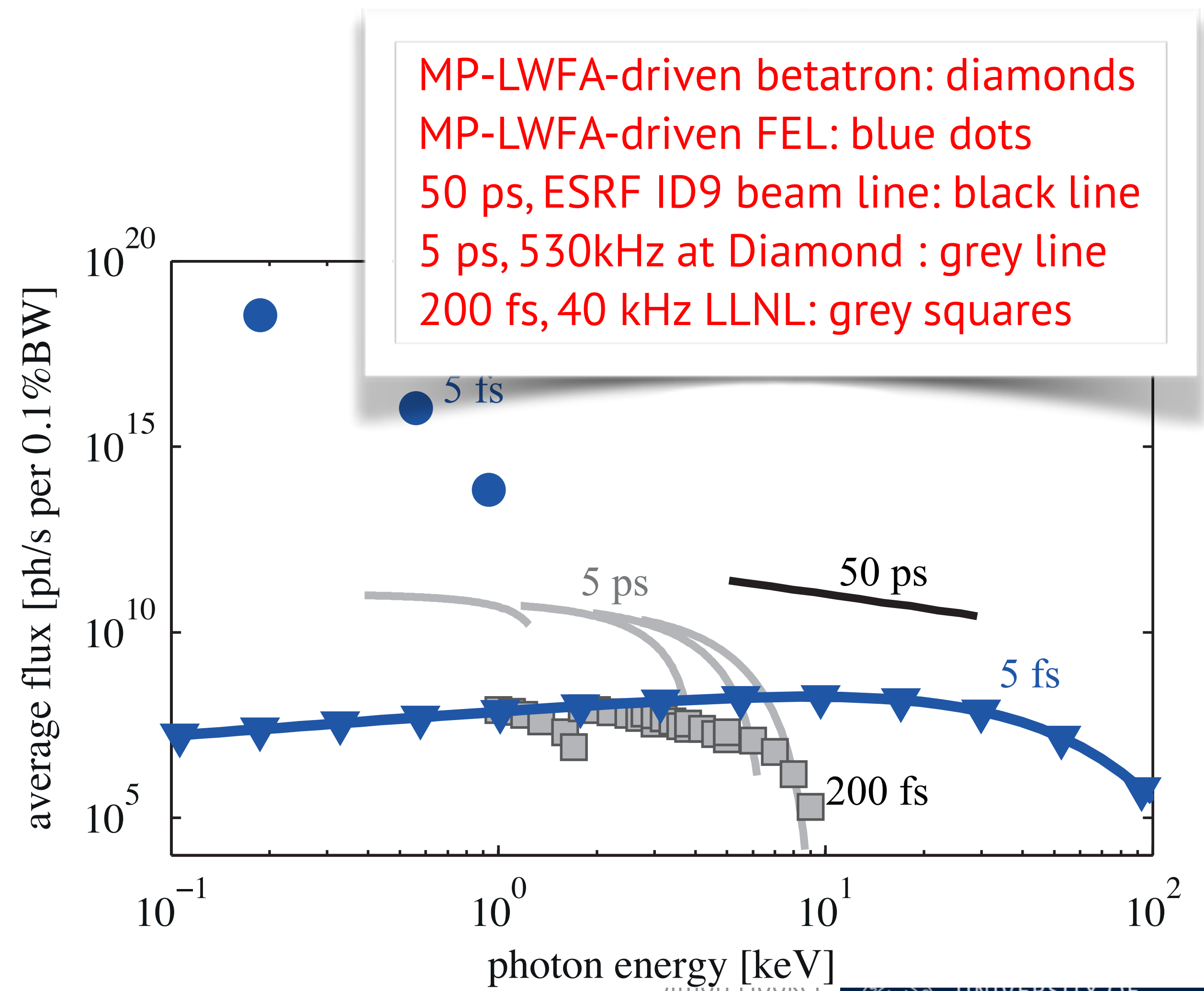
  - Average photon flux @ 10keV is ≈ 2 × $10^8$ photons $s^{-1}$, per 0.1% BW
  - Greater than existing short-pulse 3rd gen sources (but 100 x better resolution)
- FELs
  - Simulations show SASE saturation reached in soft X-ray range ($\lambda_{FEL}$ = 6.9 nm) in 4 m TGU
  - Peak FEL power similar to km-scale FELs but much higher repetition rate than non-superconducting machine



# Update on current activities

# Research programme

## Research programme

- Physics of MP-LWFAs.
  - Ion motion
  - Plasma or pulse train errors & non-uniformities
  - Laser hosing
  - Laser depletion
- Controlled injection in quasi-linear regime
  - Two-pulse ionization injection (2PII)
  - Colliding pulses
  - Density ramps

Roman Walczak's talk: WG1, Mon 19:10

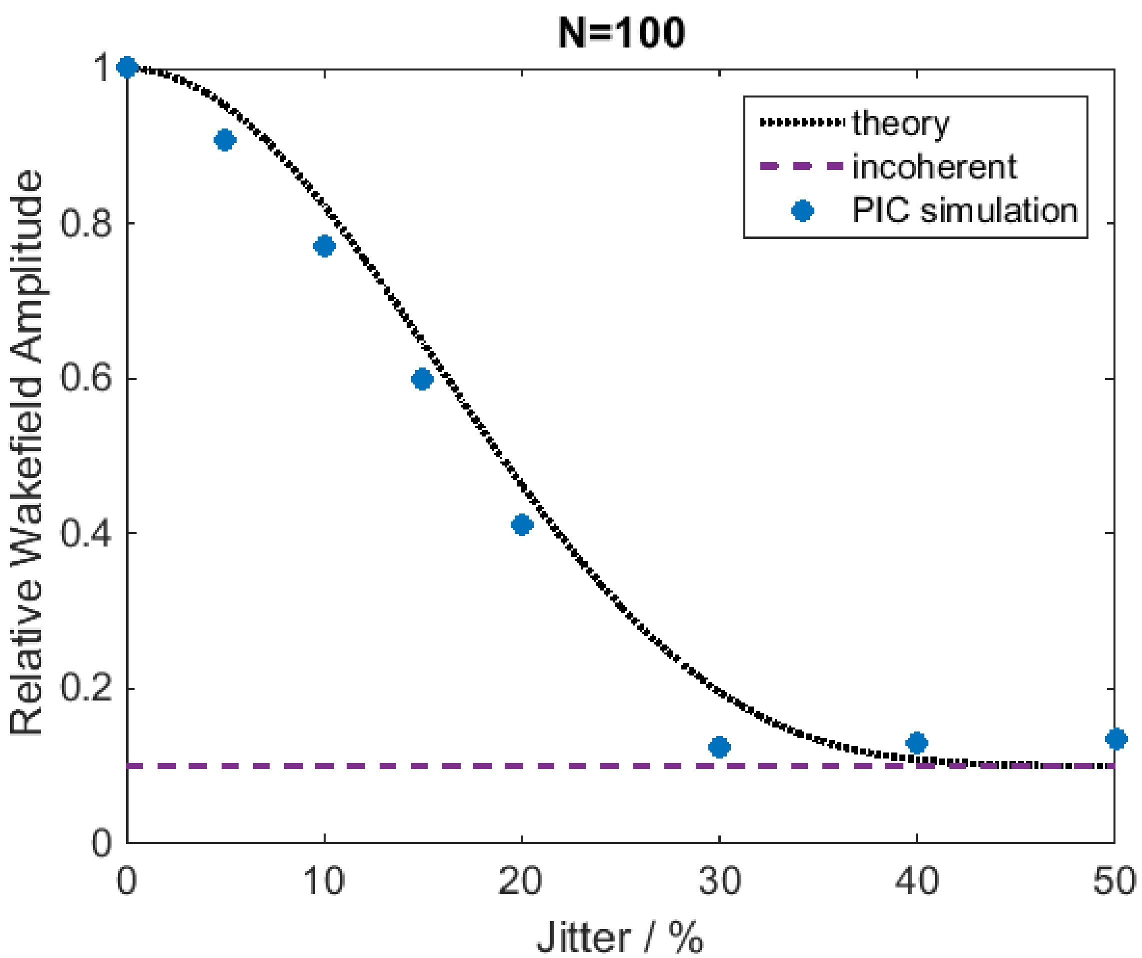
- Development of fibre laser systems for MP-LWFA
- Development of kHz, low-density waveguides
  - Hollow capillary waveguides
  - Low density plasma channels
- Applications of MP-LWFAs
  - X-ray phase contrast imaing for medical applications

This work is supported in part by:

- STFC
- AOFSR (grant no. FA8655-13-1-2141)
- Helmholtz Association (grant no. VH-VI-503)

# Effects of “errors” in plasma / pulse train

## Random errors




- Relative error < 10%

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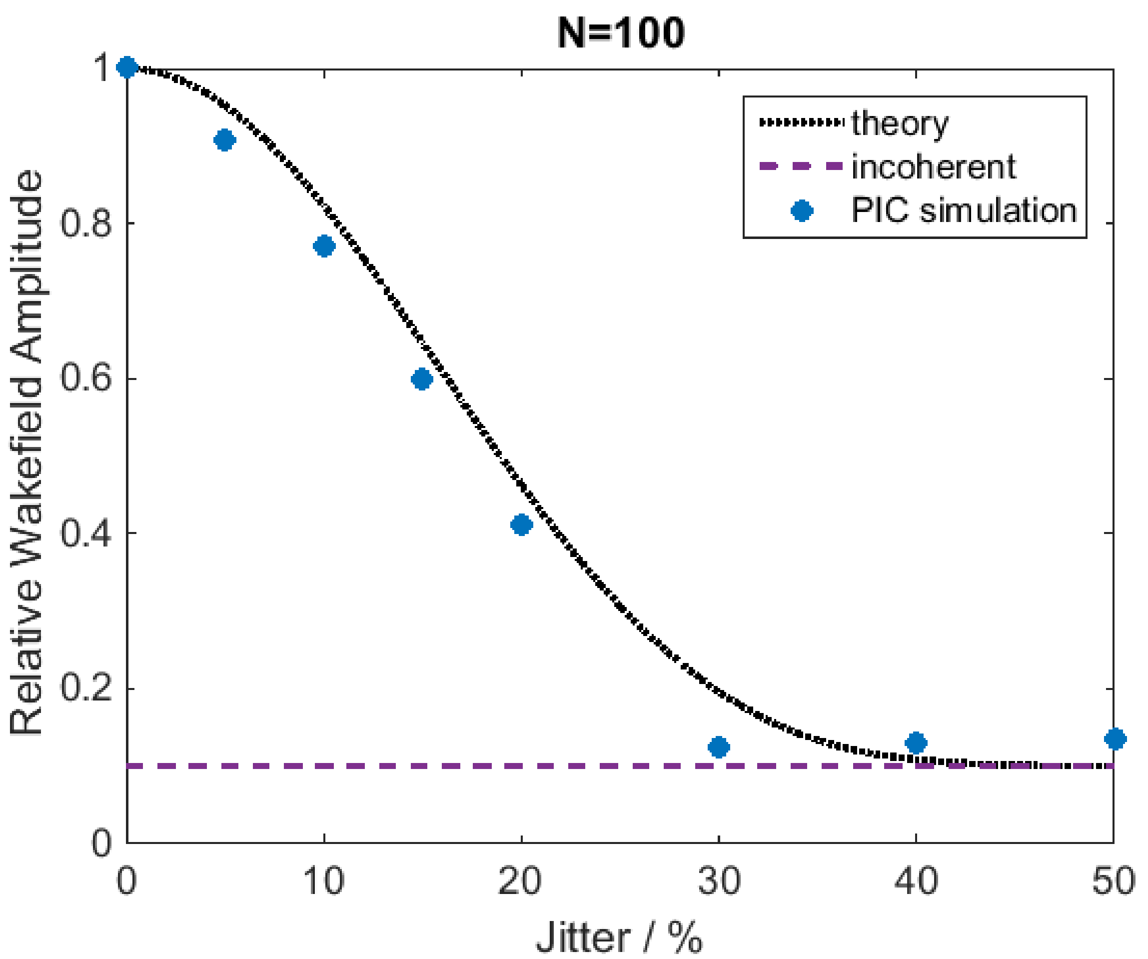


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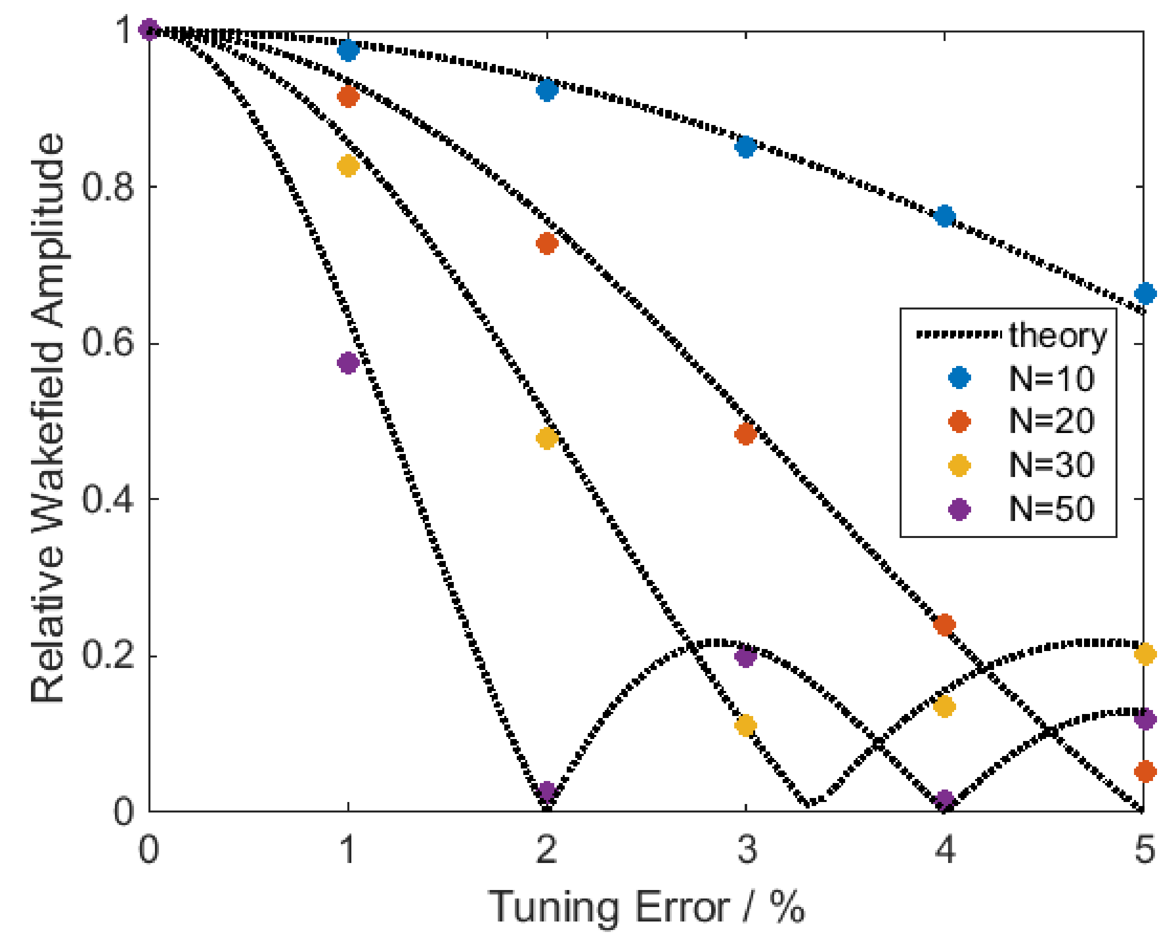
## Systematic errors




- Relative error < 1/*N*

See Chris Arran’s talk
WG6: Th 18:40

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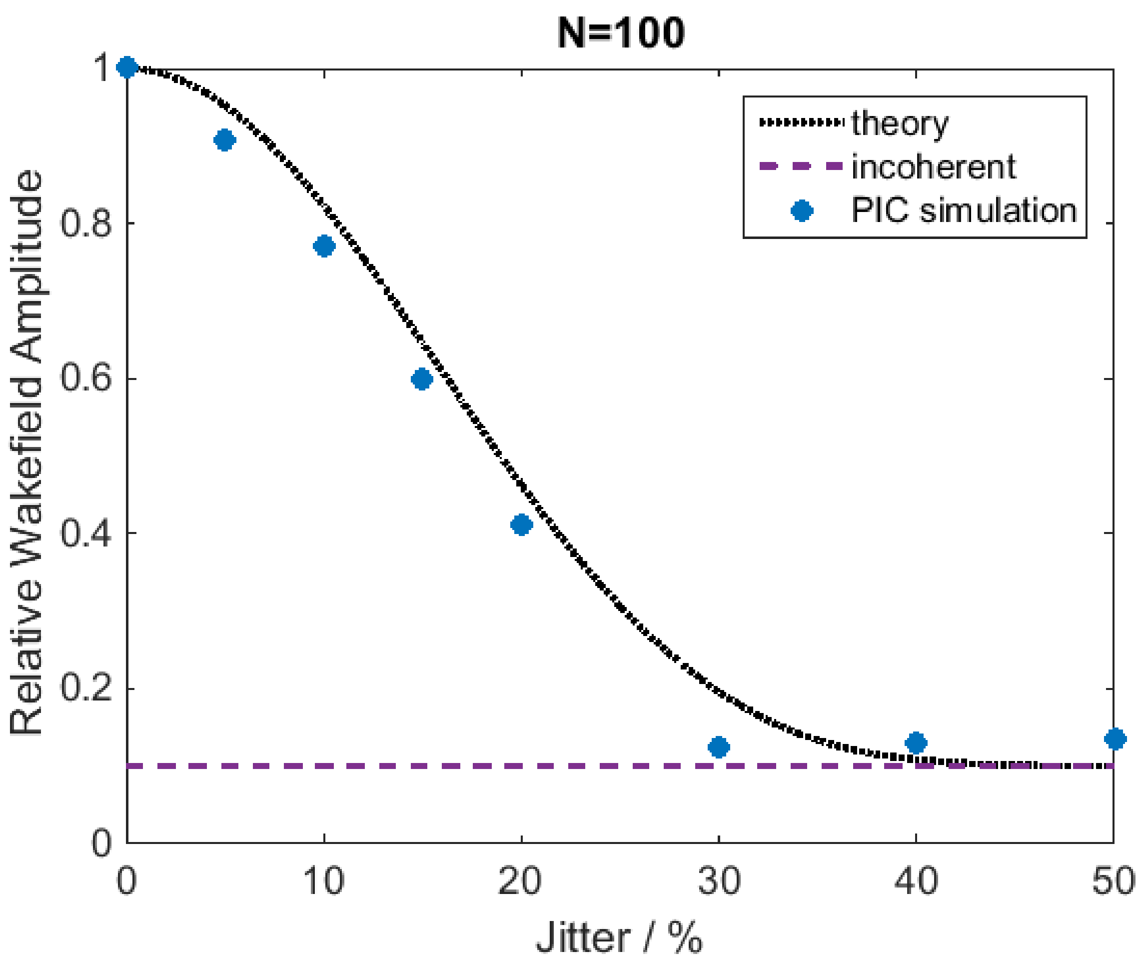
John Adams Institute for Accelerator Science

## Random errors

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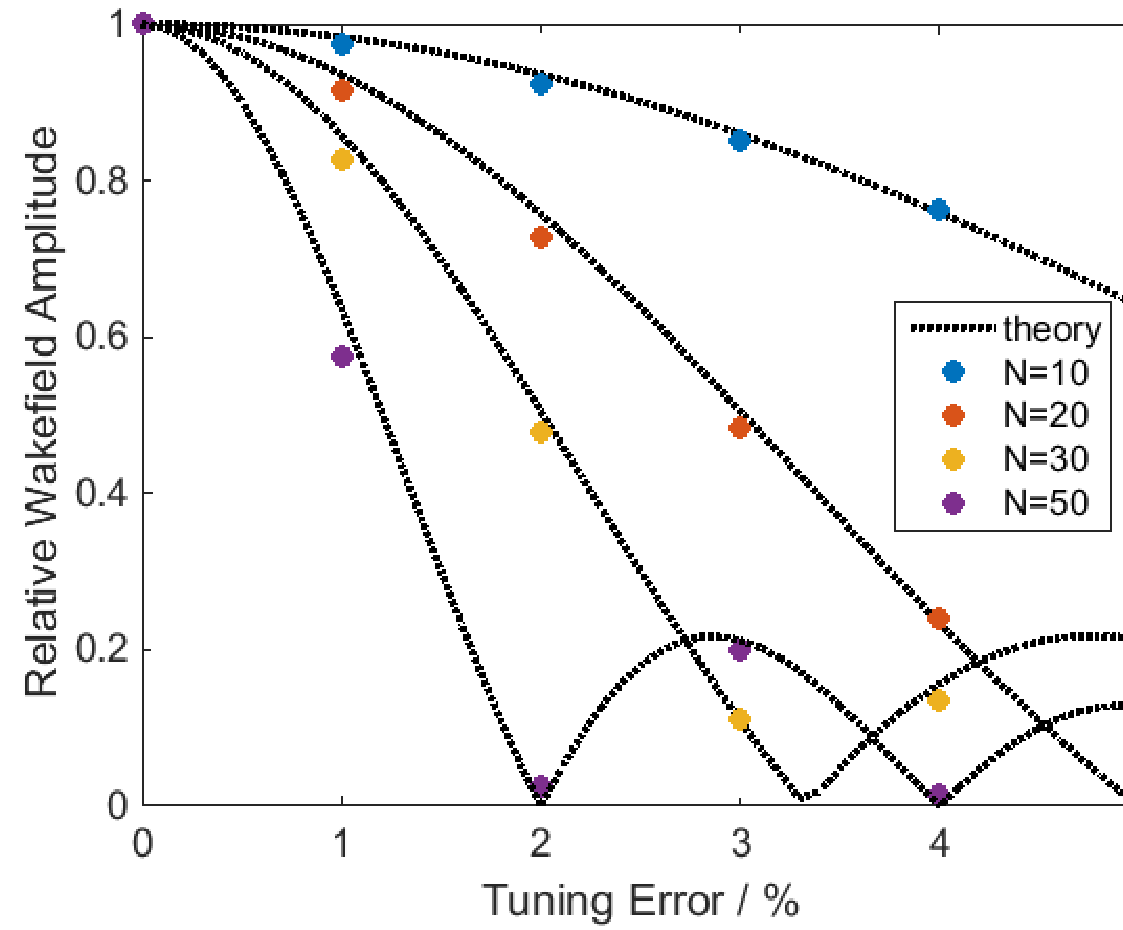


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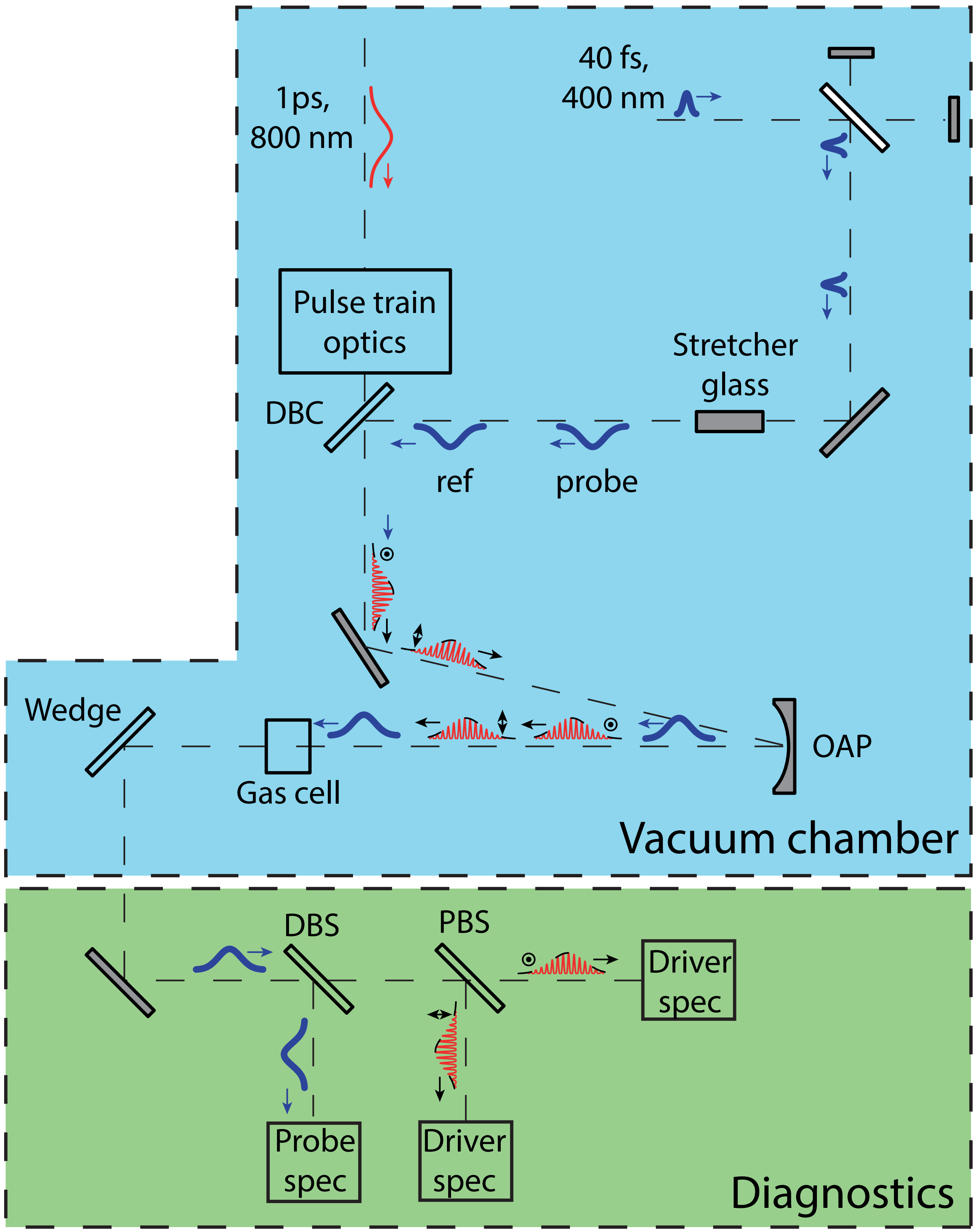
WG6: Th 18:40

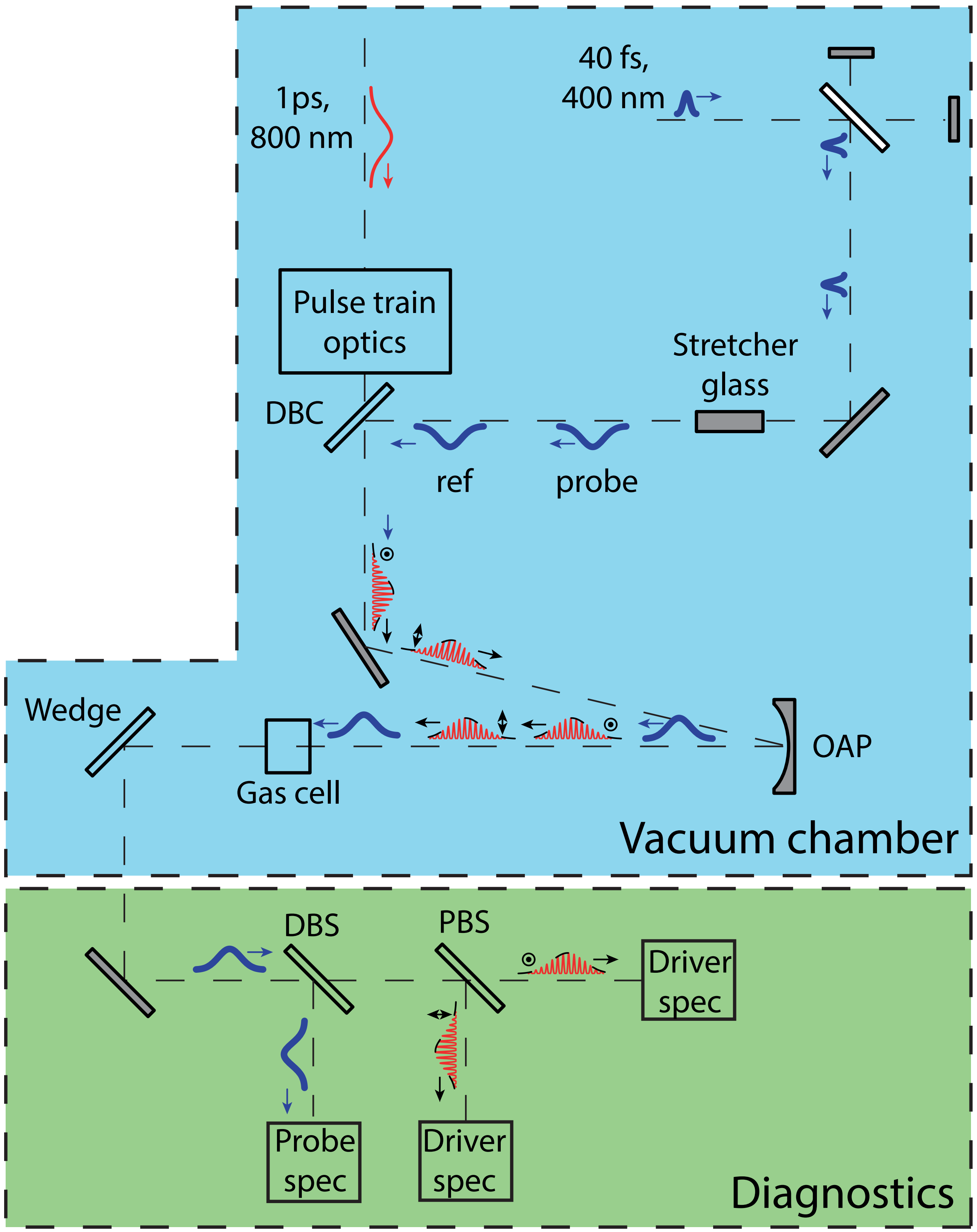
- Conclude that errors are no show-stopper
- Exploitation of **auto-resonance** could provide additional robustness

# Proof-of-principle demonstration




- Expts to demonstrate MP-LWFA underway using Astra TA2 laser at RAL
- Objectives:
  - Proof-of-principle demonstration
  - Study ion motion
  - Demonstrate coherent addition of wakes from two pulse trains
  - Demonstrate “energy recovery”

# Proof-of-principle demonstration



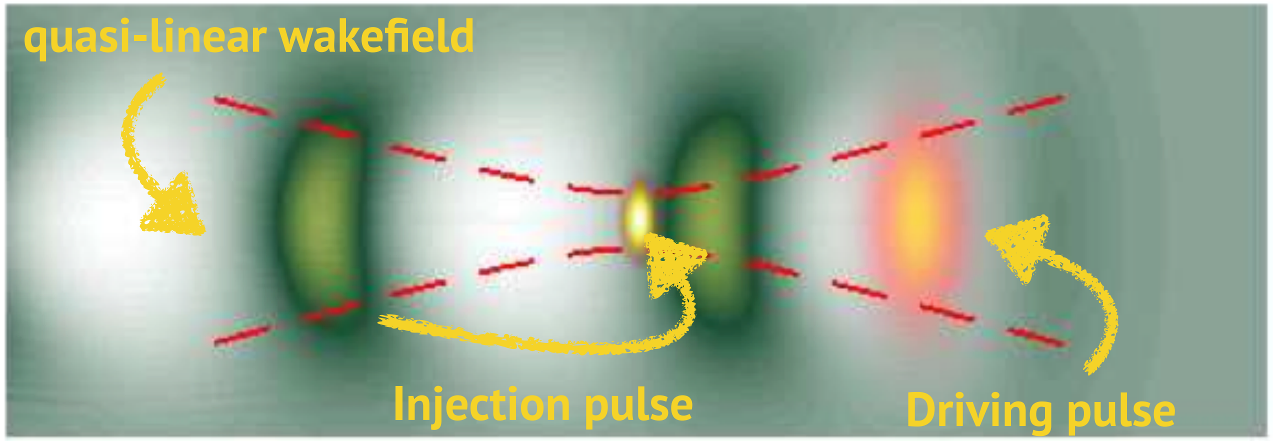

- Single 500 mJ, 40 fs Ti:sapphire pulses converted into train of 10 - 50 pulses
- Pulse train focused into 1 - 4 mm long gas cell by f/20 OAP
- Wakefield measured by:
  - Frequency-domain holography
  - Spectroscopy ("photon acceleration") of drive and probe pulses

See James Cowley's talk: WG1, Tues 16:10

# Two-pulse ionization injection (2PII)

T. Rowlands-Rees *et al Phys Rev Lett* **100** 105005 (2008)
C. McGuffey *et al Phys Rev Lett* **104** 025004 (2010)
C.E. Clayton *et al Phys Rev Lett* **105** 105003 (2010)
M. Chen *et al Phys Plasmas* **19** 033101 (2012)

- Ionization of dopant species by driving pulse can introduce additional electrons to wakefield
- Offers potential for controlling electron injection
- BUT!
  - Only electrons ionized near peak of pulse are trapped, but most ionization on leading edge of pulse
  - Injection is not localized
- 2PII scheme
  - Low $a_0$ driving matched to waveguide
  - High $a_0$, small $w_0$ injection pulse gives localized ionization injection



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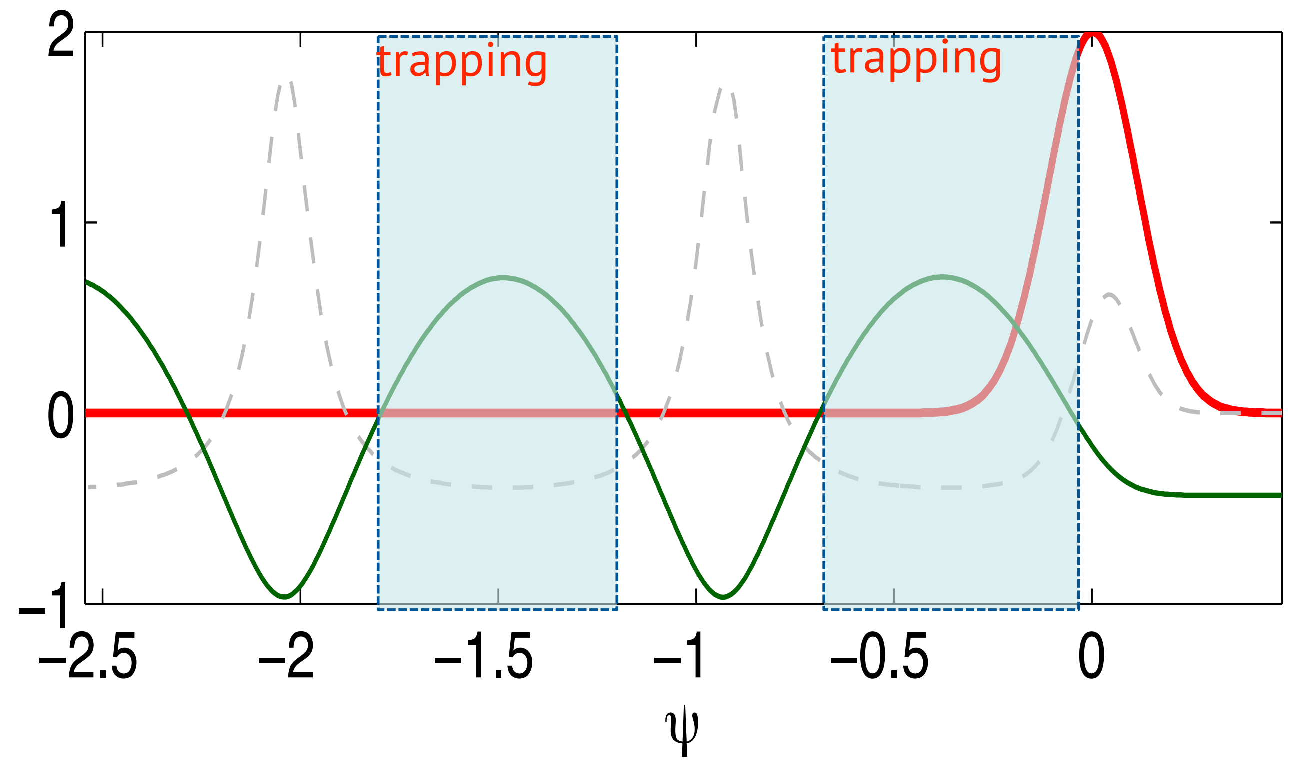
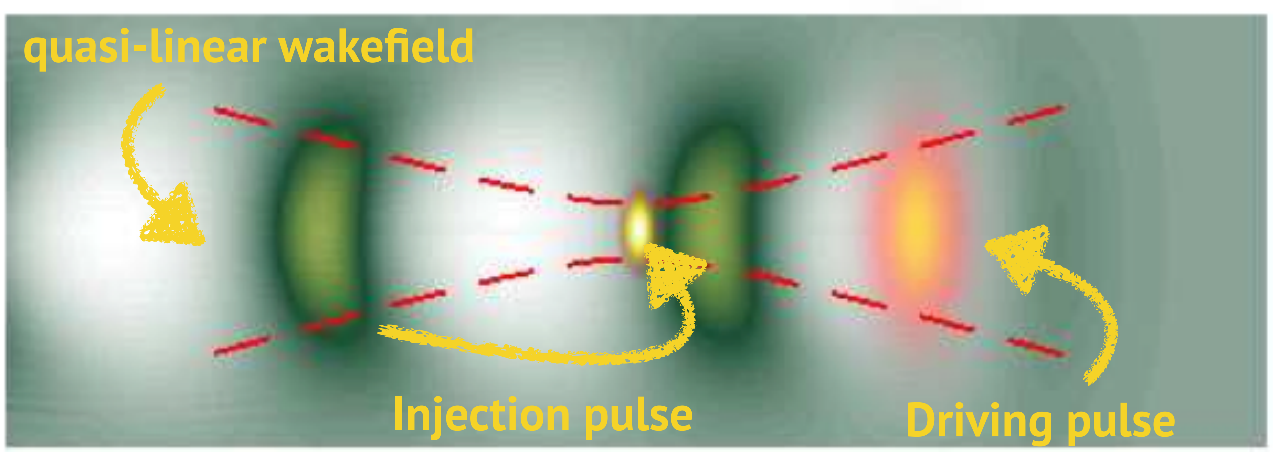


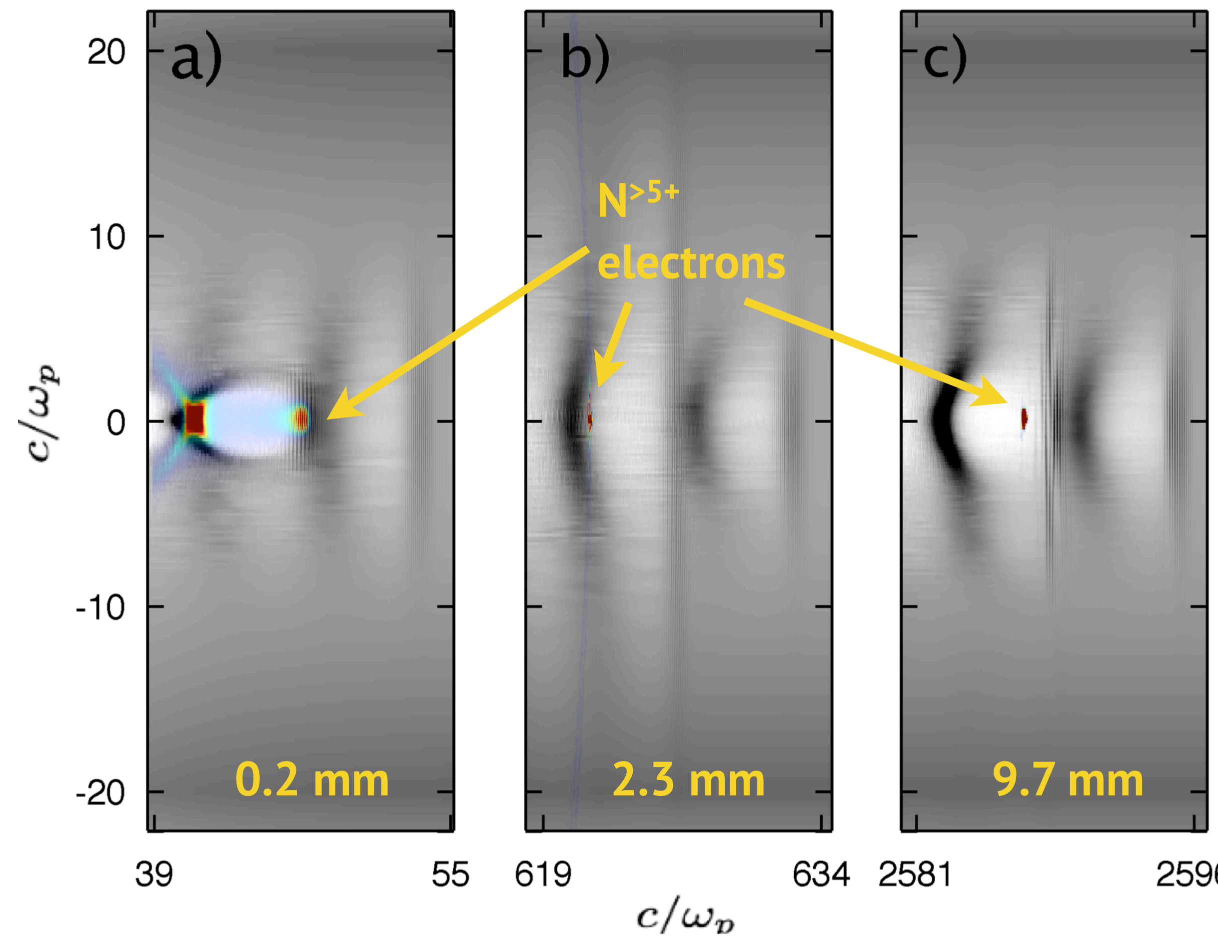
# Controlled injection

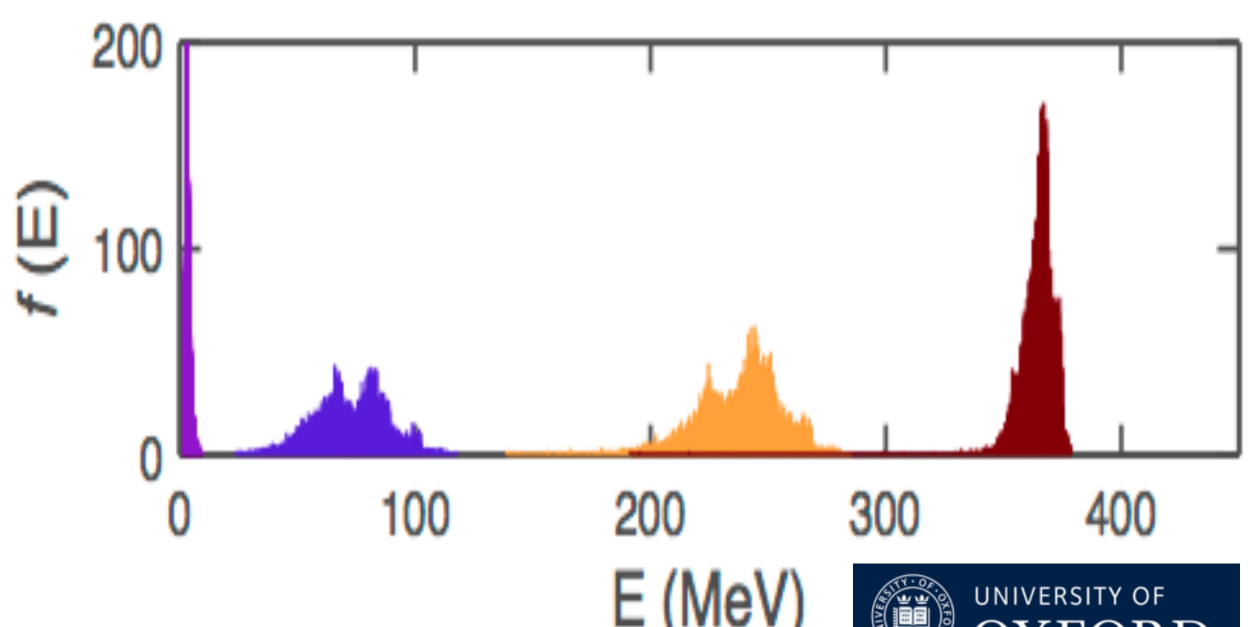
N. Bourgeois *et al Phys Rev Lett* **111** 155004 (2013)

| | |
|---|---|
| Driving pulse: | a0 = 1, w0 = 30 μm |
| Injection pulse: | a0 = 2, w0 = 8 μm |
| Density: | $2 \times 10^{18}$ cm-3 |
| Dopant: | 5% N atoms |

OSIRIS simulations show

- Only electrons from N atoms trapped
- Injection localized to 200 μm region
- Non-optimized simulations show controlled injection and acceleration to:
  - *E* = 370 MeV
  - Δ*E* / *E* = 2% (RMS)
  - Normalized emittance $\varepsilon_n$ = 2 μm
- Plan to extend to MP-LWFA regime
- Will explore addition of SSTF to further localize injection regime



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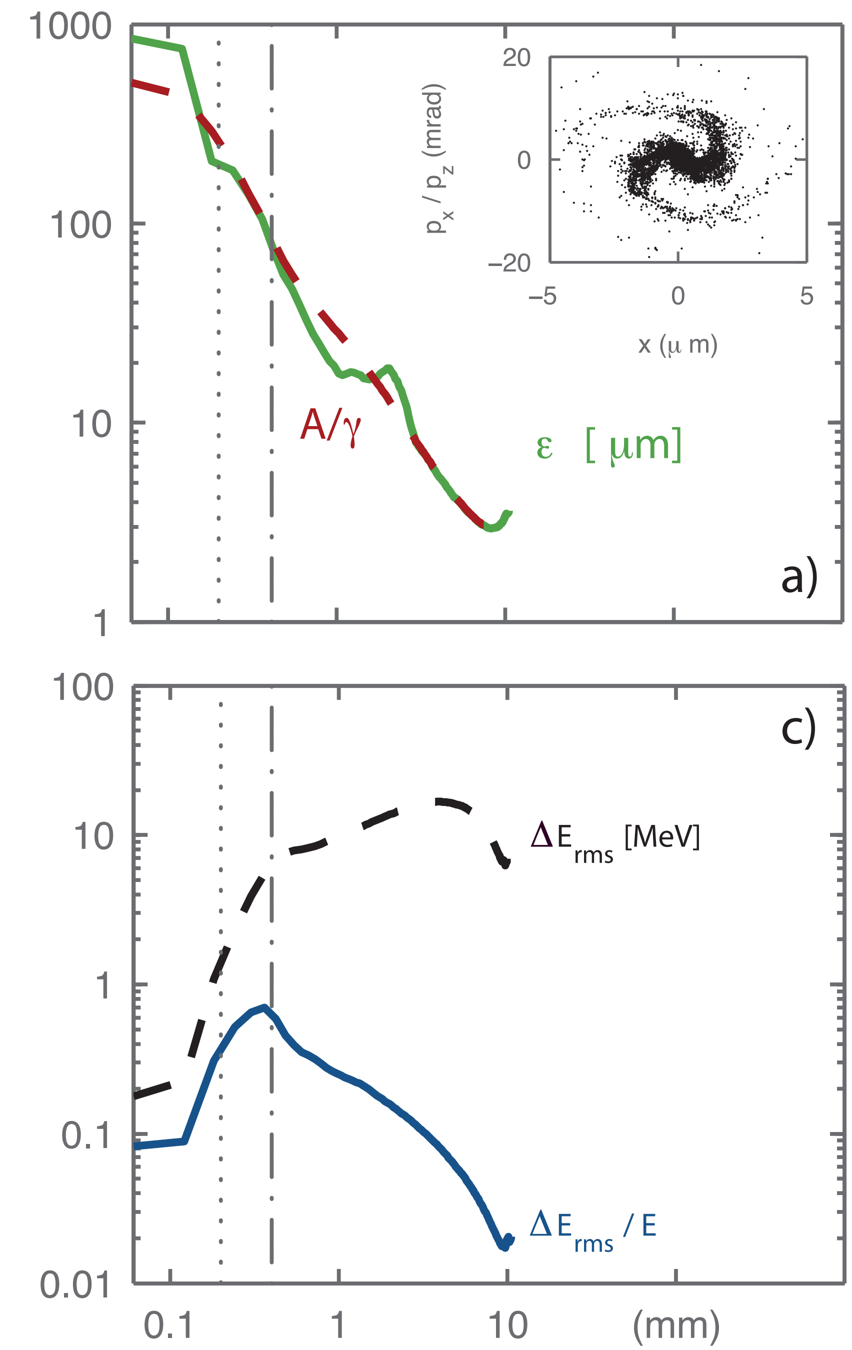
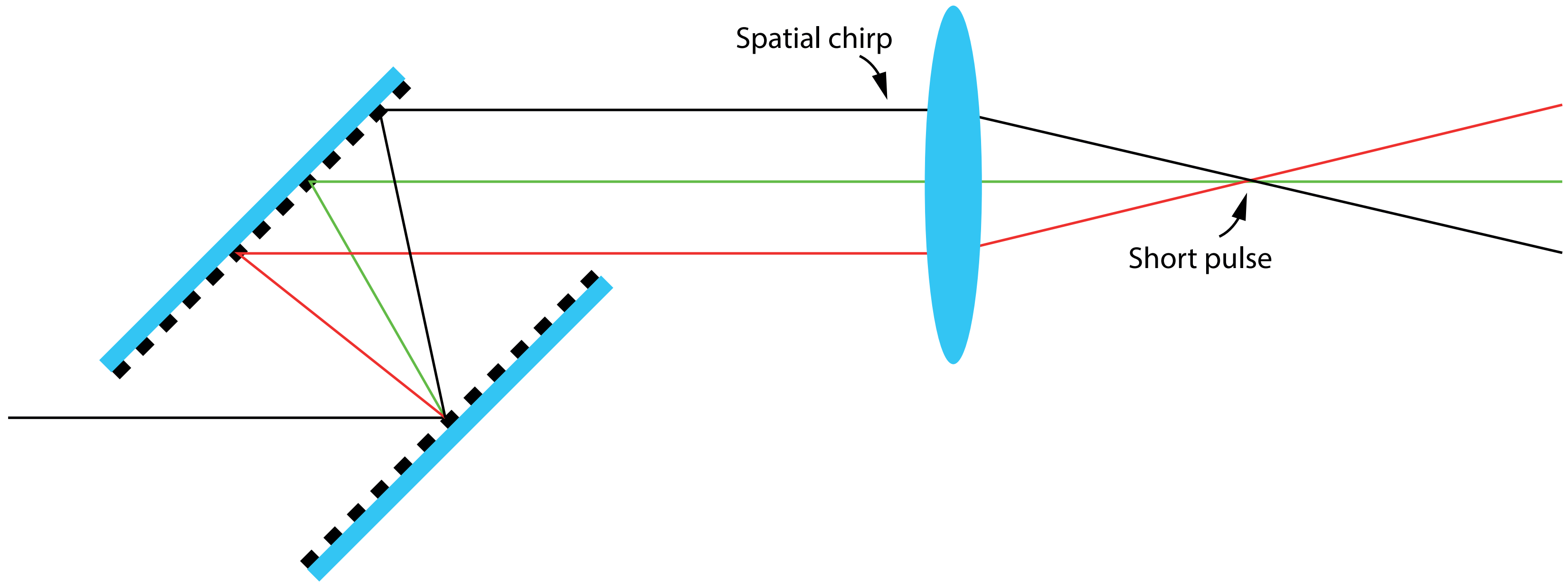


# 2PII with SSTF




- SSTF: focus beam with spatial chirp
- Short pulse only generated close to waist
- Decreases effective Rayleigh range
  - In practice **factor 10 decrease in $Z_R$ possible**
- Could further localize injection & reduce energy spread and emittance

# Summary

- MP-LWFA could provide an architecture for controlled, high repetition rate plasma accelerators
- Initial simulations suggest GeV-scale energies could be generated at kHz rep. rates
- Ideal for driving X-ray sources with very high mean and peak photon flux
- No show-stoppers identified yet!
- Initial proof-of-principle demonstration under way