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Feedback control of the spatio-temporal properties of high-intensity laser pulses to optimize x-ray and 100 MeV electron generation

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Newton Fund

European Network EuroNNAc for Novel Accelerators

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Outline

- Compact 100 MeV LWFA with 10 TW Gemini TA2

- Operation of LWFA at 5 Hz

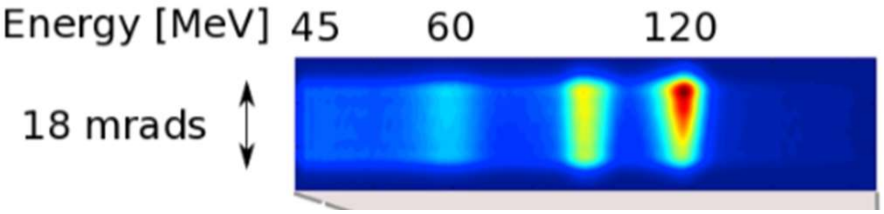
- Feedback optimisation of laser-matter interactions

- Optimisation of x-ray yields and electron beams from cluster targets

Gemini TA2 experimental area

- Laser ~ 450mJ in 40 fs, *f*/17, ~10^{18} Wcm^{-2}
- Maximum rep-rate 5 Hz

Recent LWFA experiments in Gemini TA2



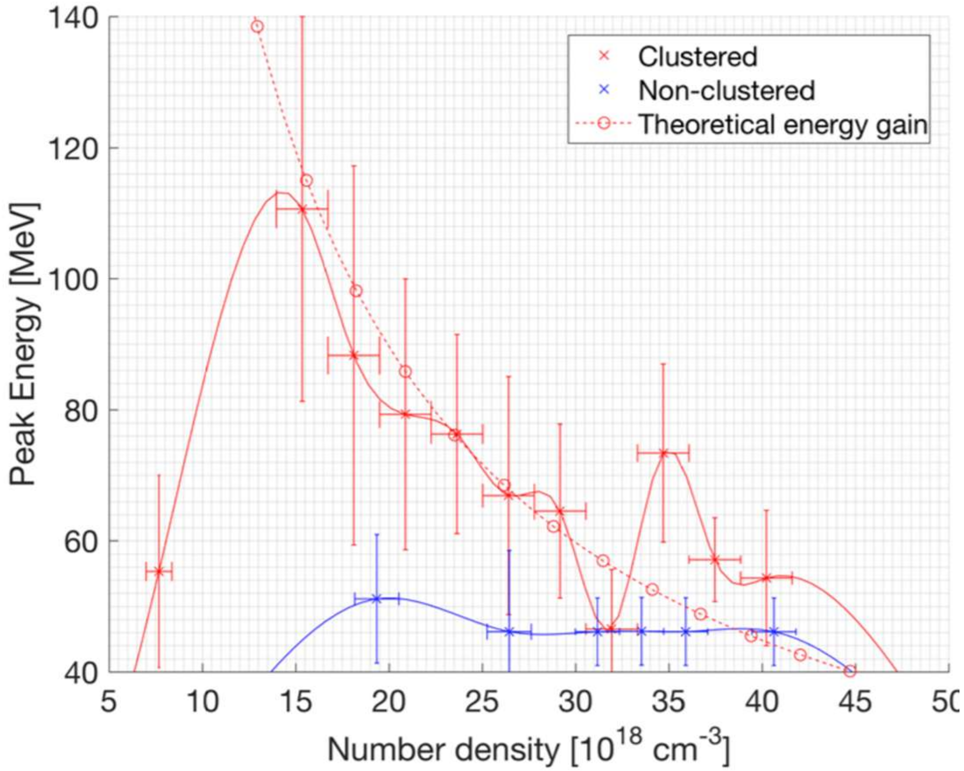
Distinct differences between cluster and helium interaction:
Higher $Z \rightarrow$ Higher charge

Locally solid ρ but average gas ρ
$\rightarrow$ Inner and outer ionisation
$\rightarrow$ Collisional and collisionless heating

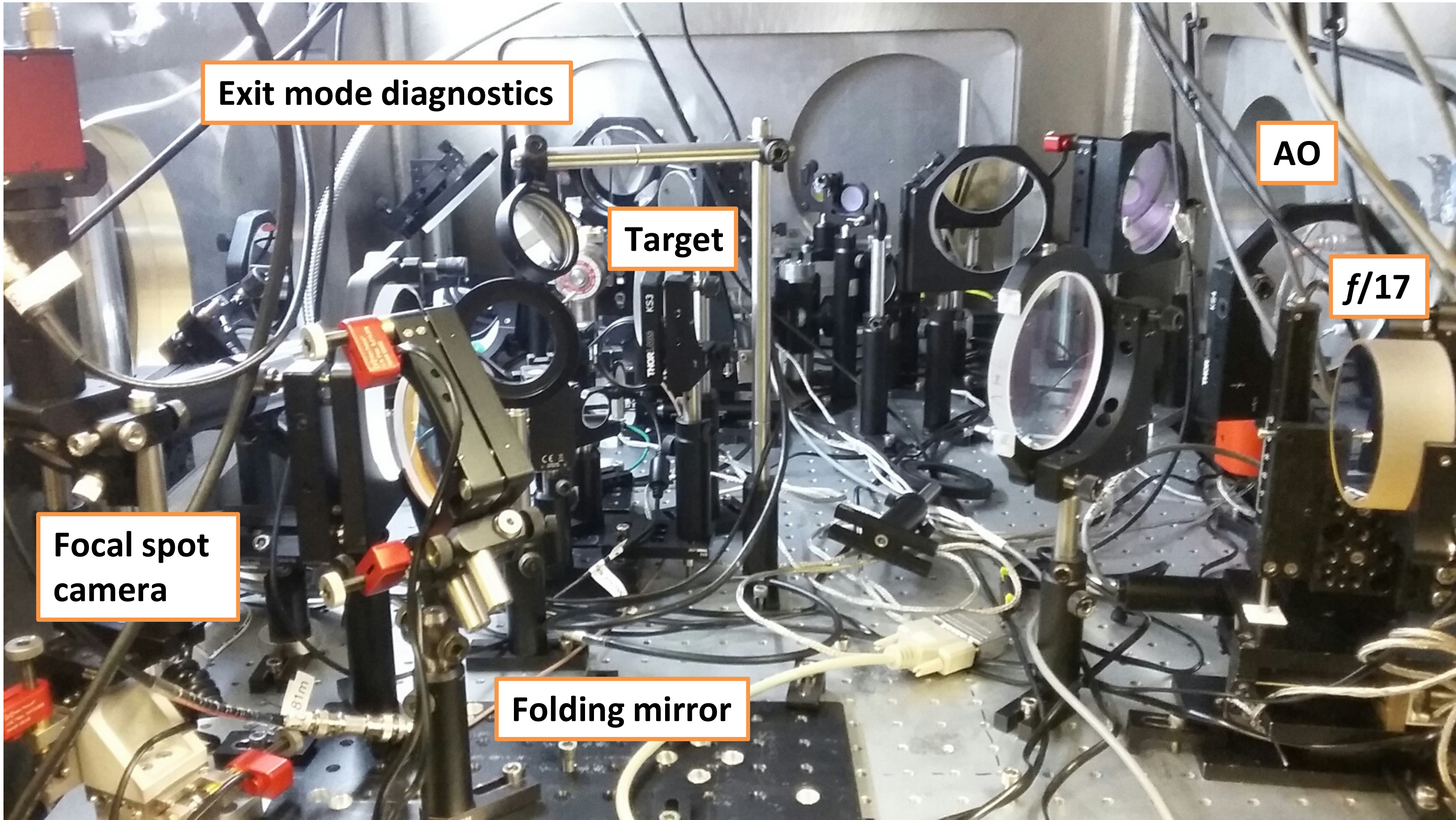
Complicated interaction
$\rightarrow$ Very sensitive to pulse shape
$\rightarrow$ High electron temperature (keV)

See talk by Savio Rosario

Methane cluster target
>100 MeV electrons in 2 x 2 x 2 m^3 space



Target chamber arrangement for TA2 *f*/17 gas target interaction



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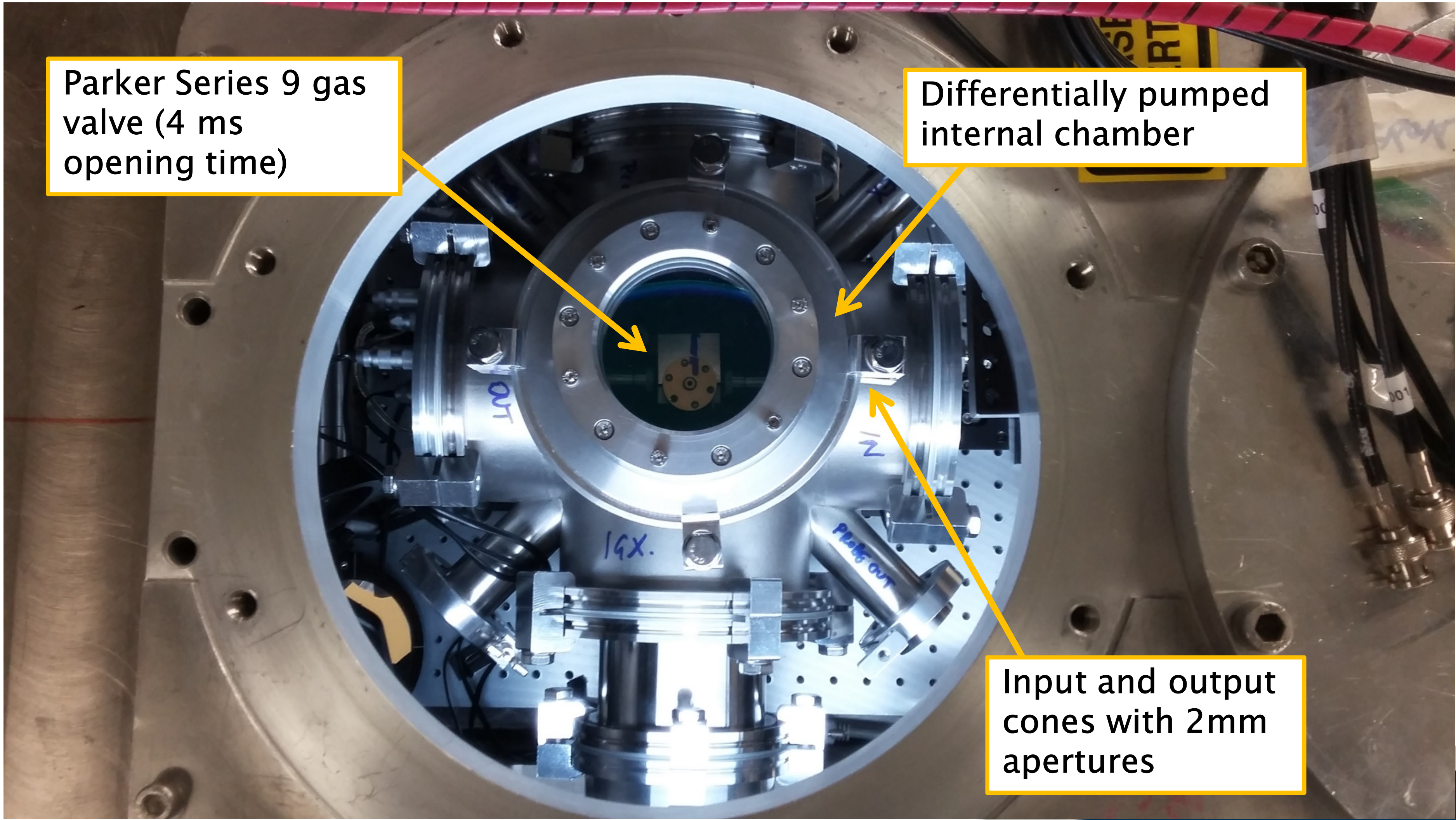
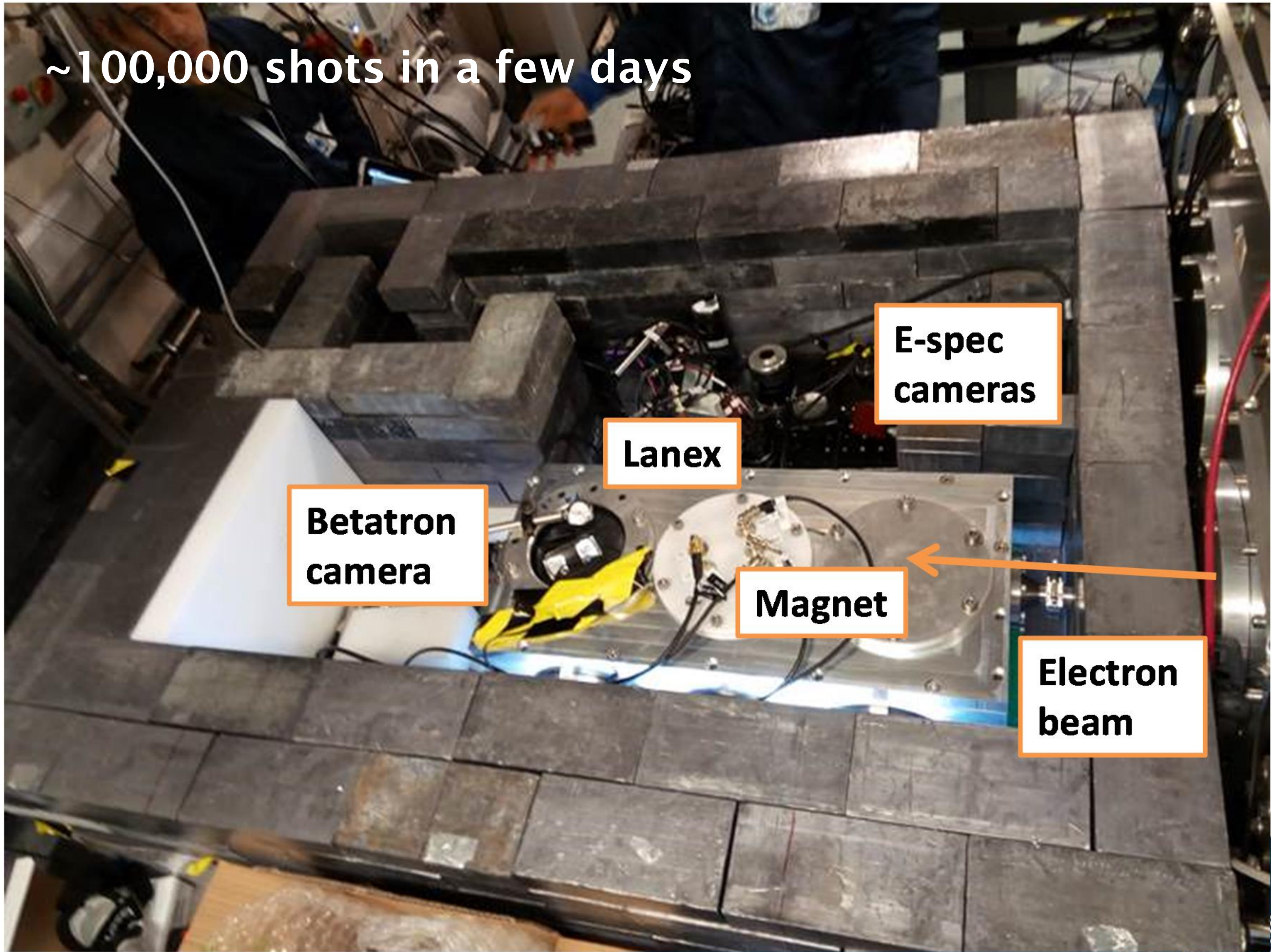
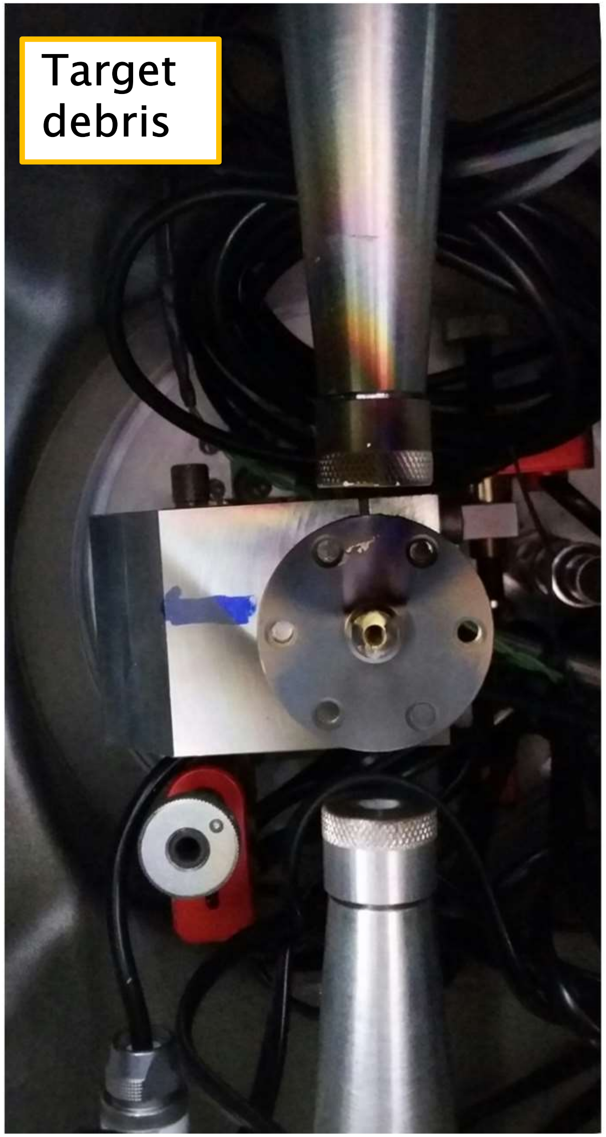
Gas jet housed inside internal chamber for operation at high repetition rate

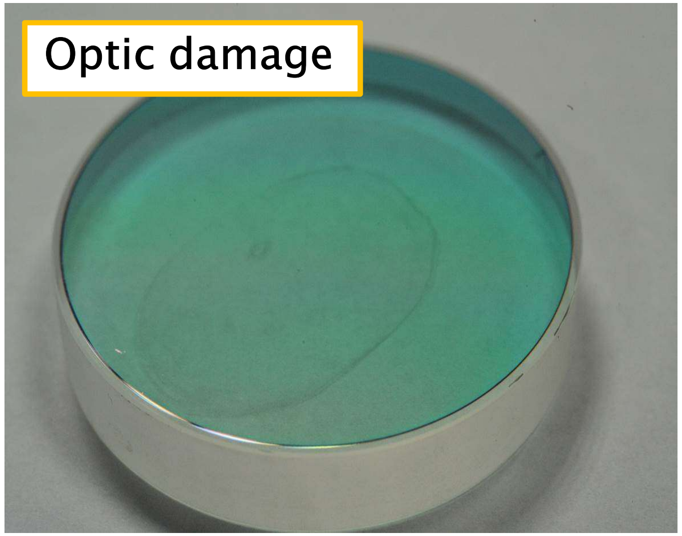


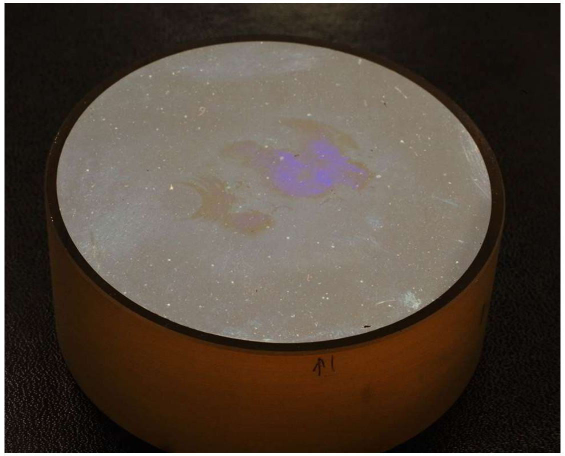
Biggest problem for increased repetition rate is e-beam radiation shielding



Challenges operating at high rep-rate

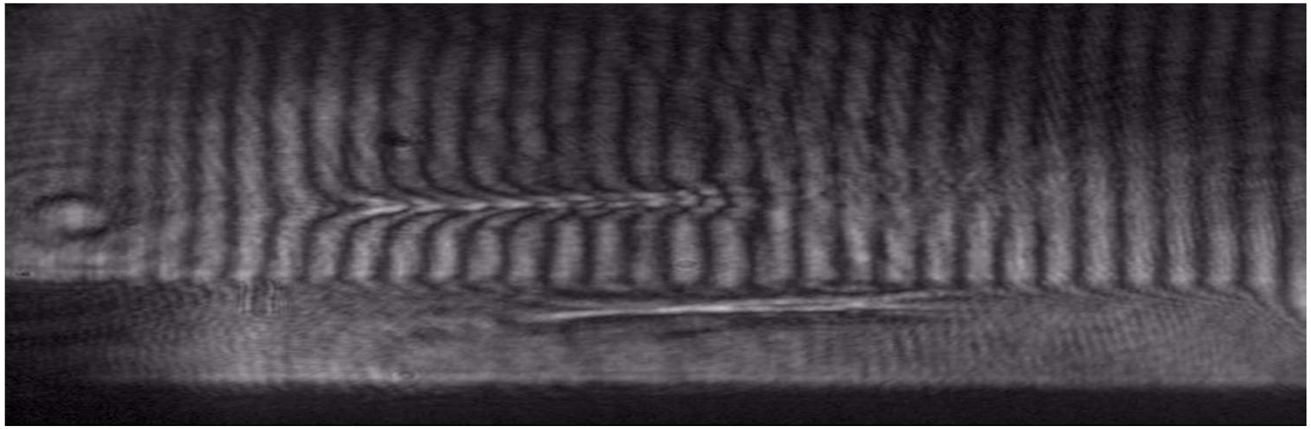




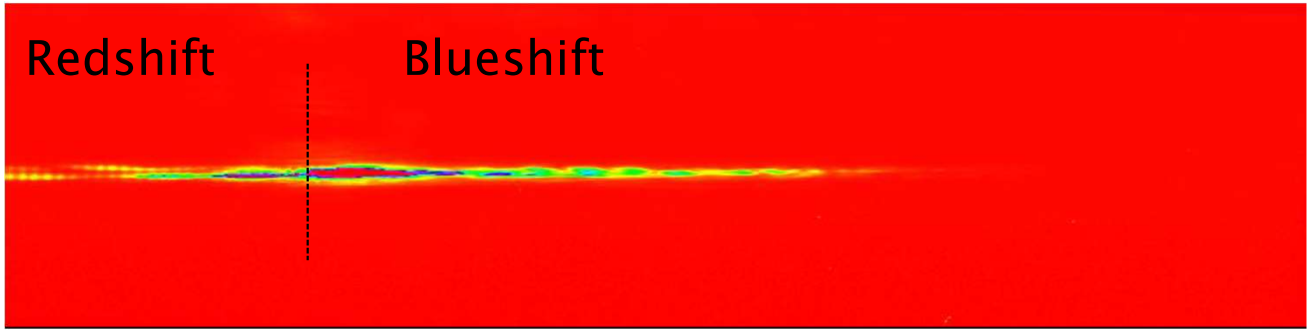


100 MeV LWFA running at 5 Hz

Electron spectrometer

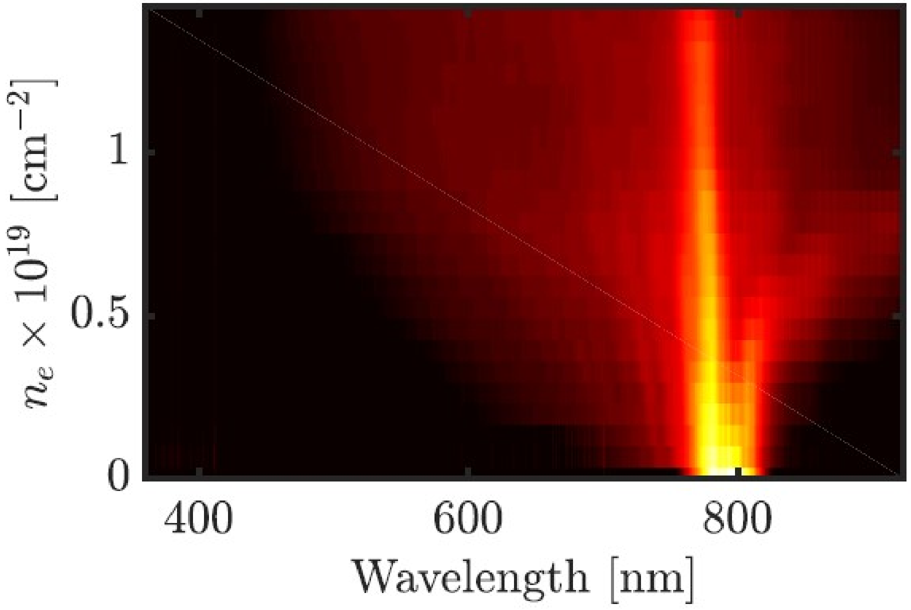


Interferometer



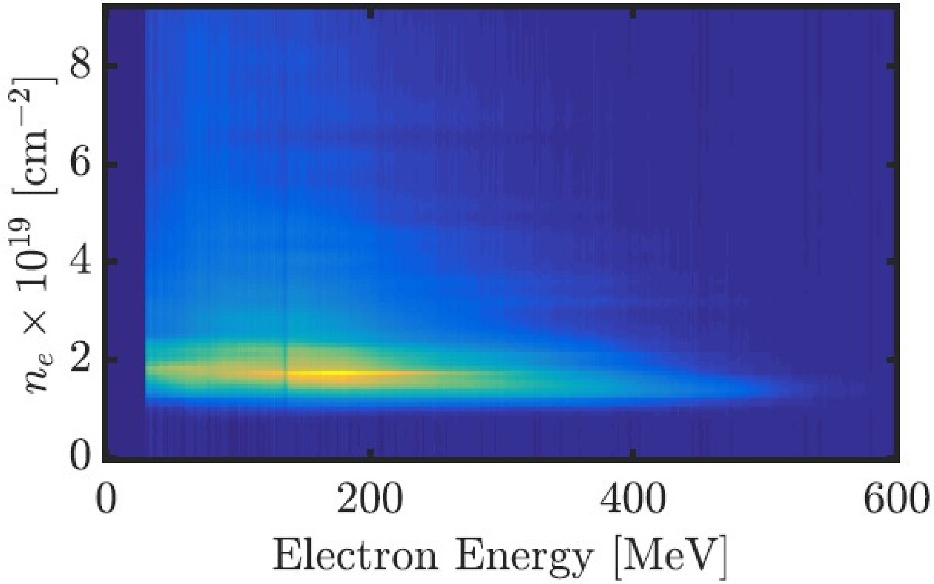
Exit mode spectrometer

High rep-rate allows a fine resolution scan of parameter space



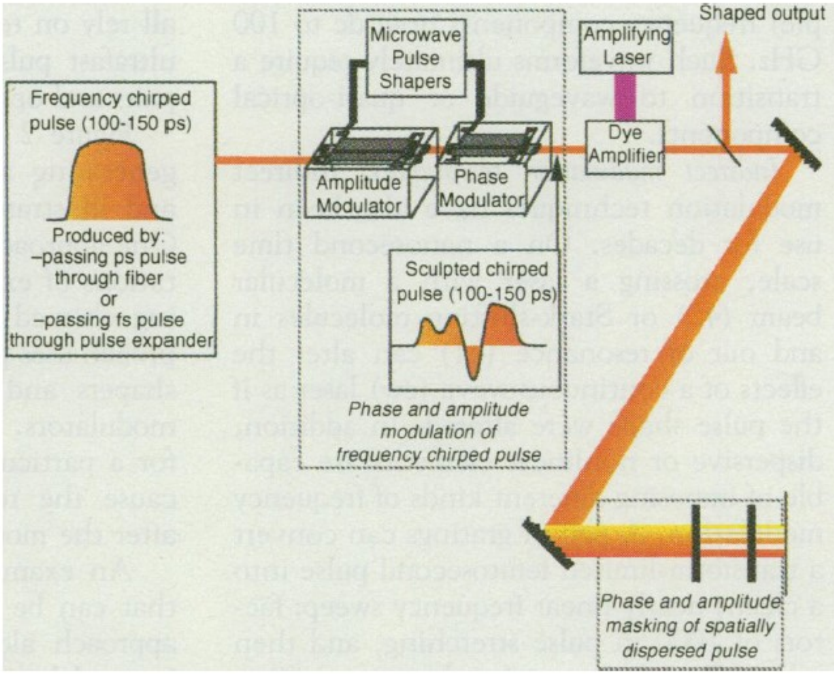
Laser spectrum post-plasma as a function of electron density

Electron spectrum as function of electron density



- Each row of data is 50-shot average
- Features that may be missed with coarser scan

High repetition rate means we can apply active feedback techniques



Coherent Control of Quantum Dynamics: The Dream Is Alive

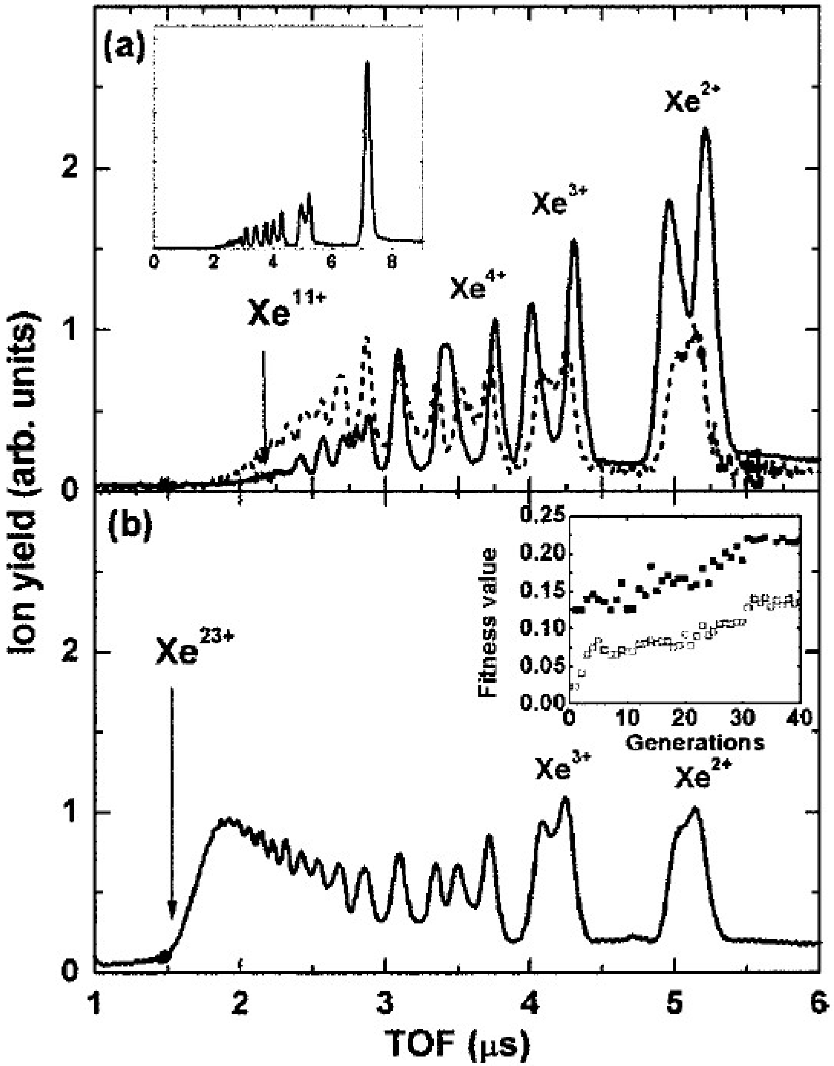
Warren S. Warren, Herschel Rabitz, Mohammed Dahleh

Current experimental and theoretical progress toward the goal of controlling quantum dynamics is summarized. Two key developments have now revitalized the field. First, appropriate ultrafast laser pulse shaping capabilities have only recently become practical. Second, the introduction of engineering control concepts has put the required theoretical framework on a rigorous foundation. Extrapolations to determine what is realistically possible are presented.

SCIENCE • VOL. 259 • 12 MARCH 1993

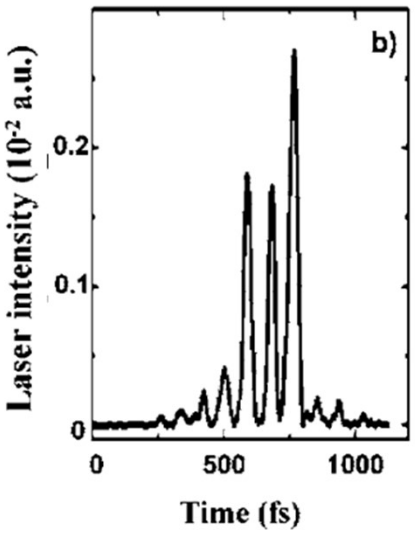
- “Fitness function” based on desired outcome defined
- Feedback loop shapes the pulse to improve output each generation
- Commonly used on kHz (few mJ energy) lasers
- Unexpected outcomes can happen

Temporal control of pulse shape through SLM or Dazzler



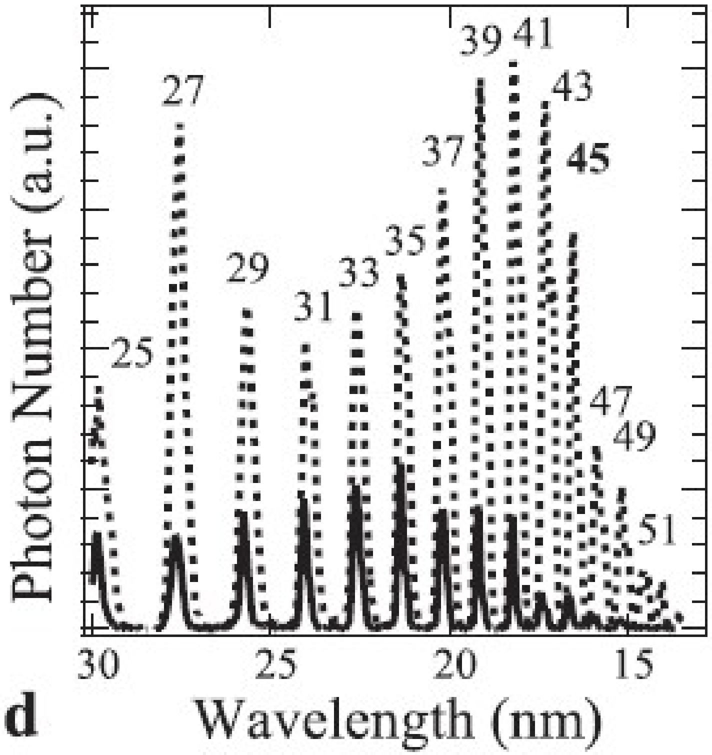
Example: optimising ionisation of clusters

Zamith *et al*, PRA **70**, 011201(R) (2004)
Martchenko *et al*, PRA **72**, 053202 (2005)



Pulse shape optimised for cluster ionisation

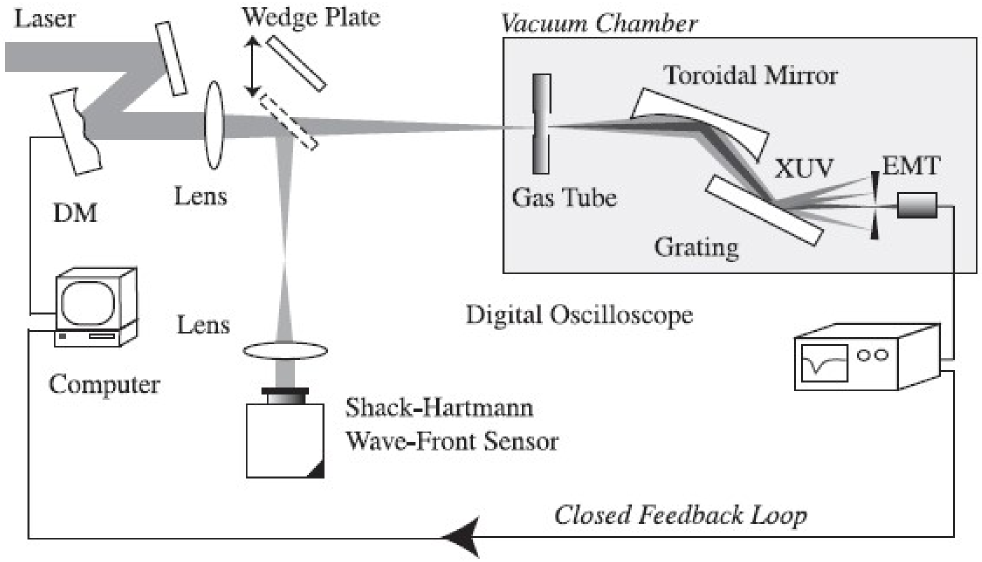
Spatial control of focal spot with a deformable mirror



Harmonic yield increased through wavefront shaping

Example: optimising HHG yield

Yoshitomi *et al*, App. Phys. B **78**, 275 (2004)



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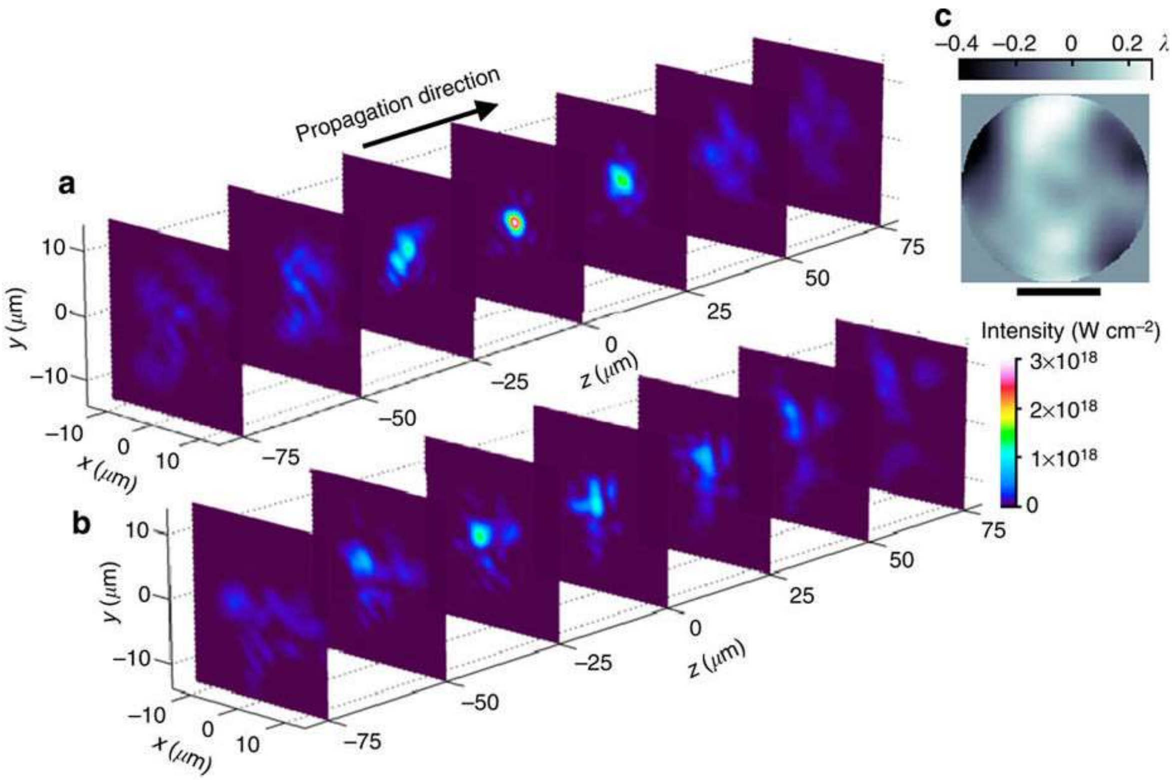
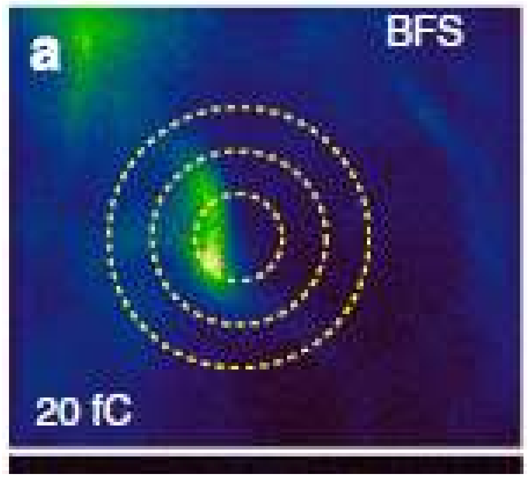
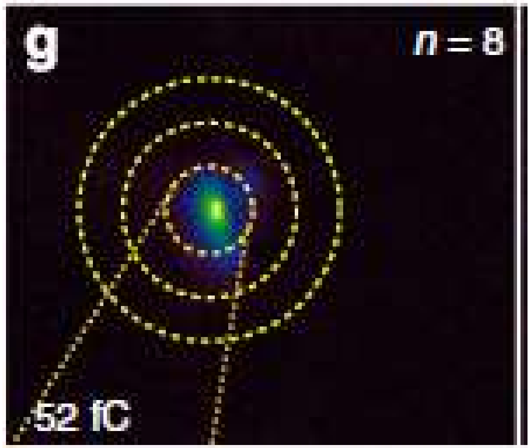
Optimisation of electron beams with spatial feedback with CUOS λ^3 laser



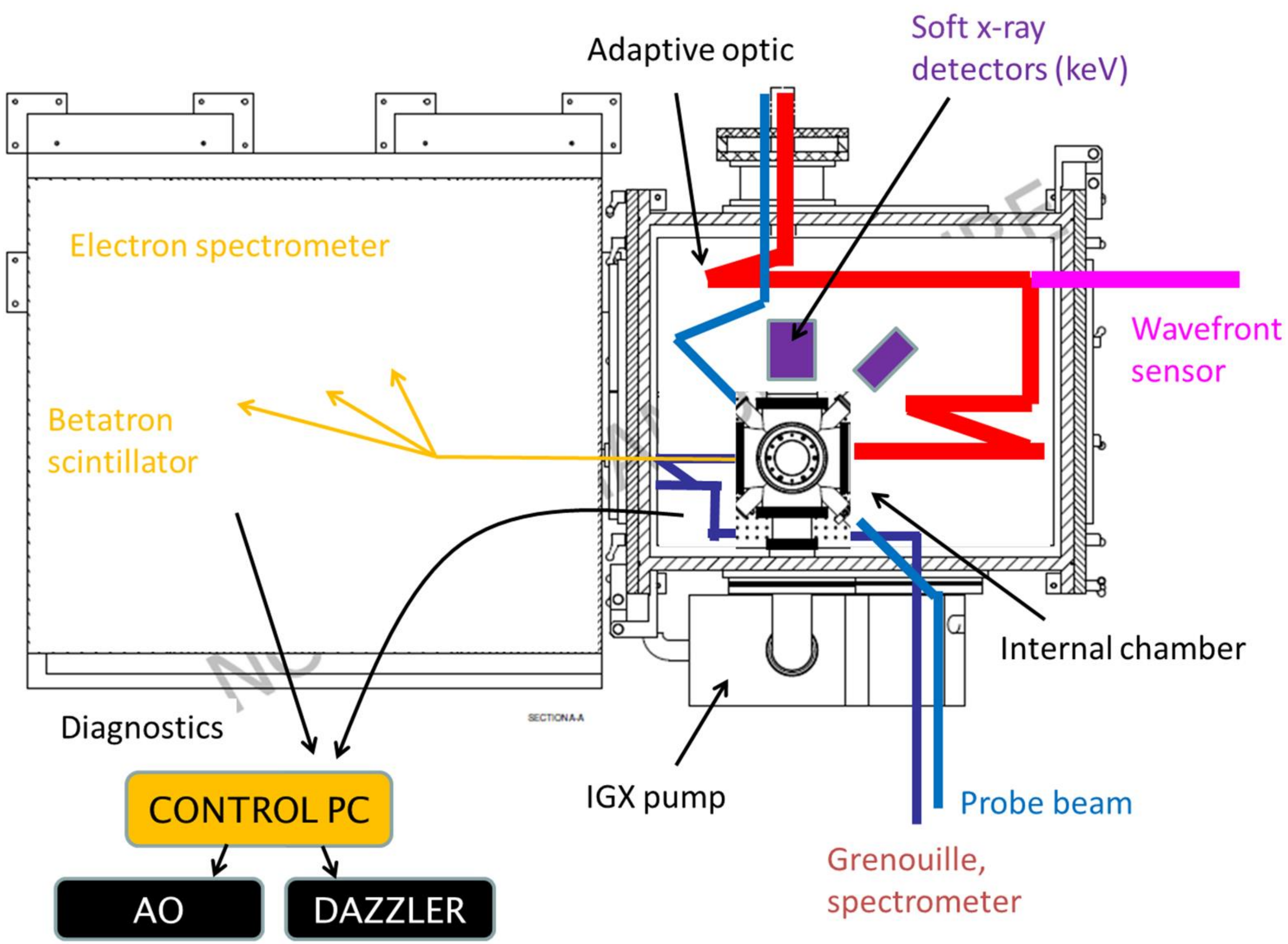




Non-ideal focus gave **higher charge** and **better divergence**.

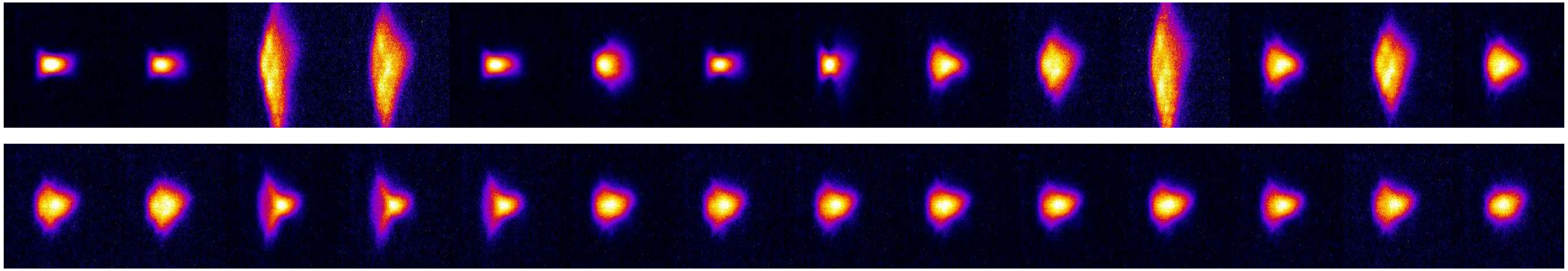
Z. H. He *et al*, Nat. Comm 2015

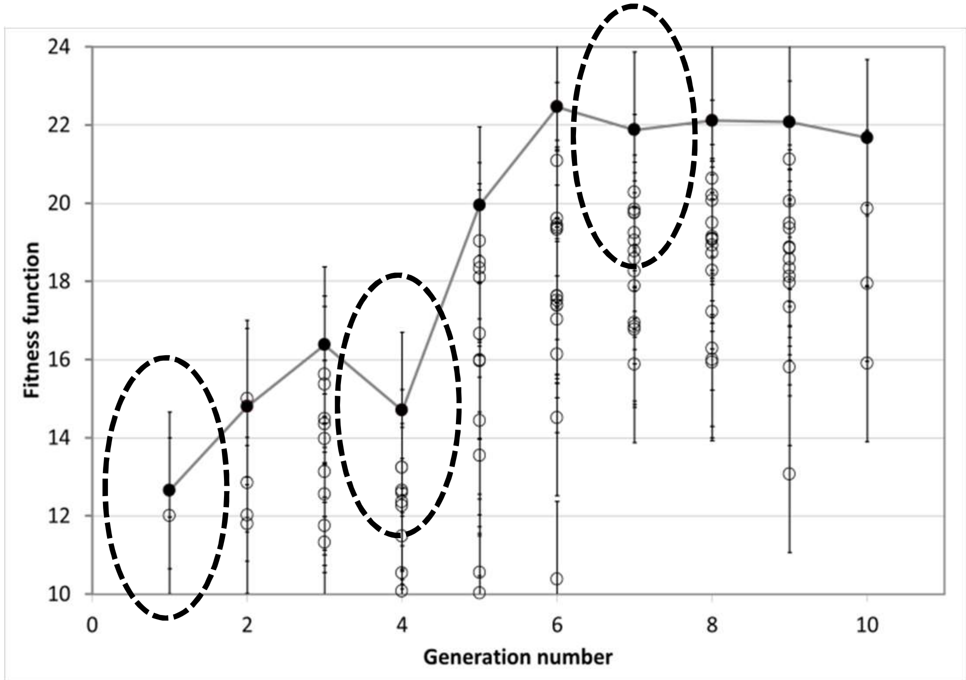
TA2 has much higher laser energy than previous optimisation experiments



- LWFA and x-ray diagnostics
- Spatial and temporal control

Optimisation of soft x-ray emission from argon clusters





Generation 1

- Start with best pulse compression
- Apply random Dazzler settings

Generation 4

- Laser defocus problem

Generation 7

- Reaches optimum
- Poor performers have been rejected

Soft x-ray emission measured at 90° with PIN diodes

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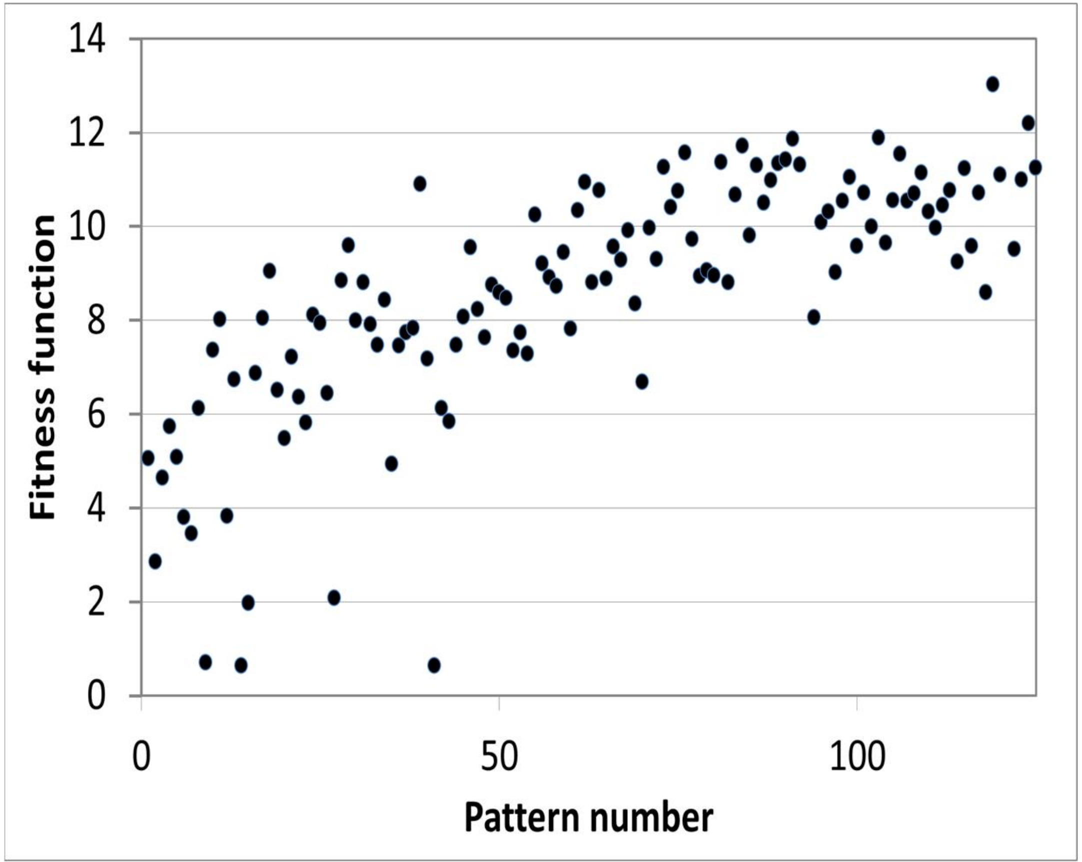
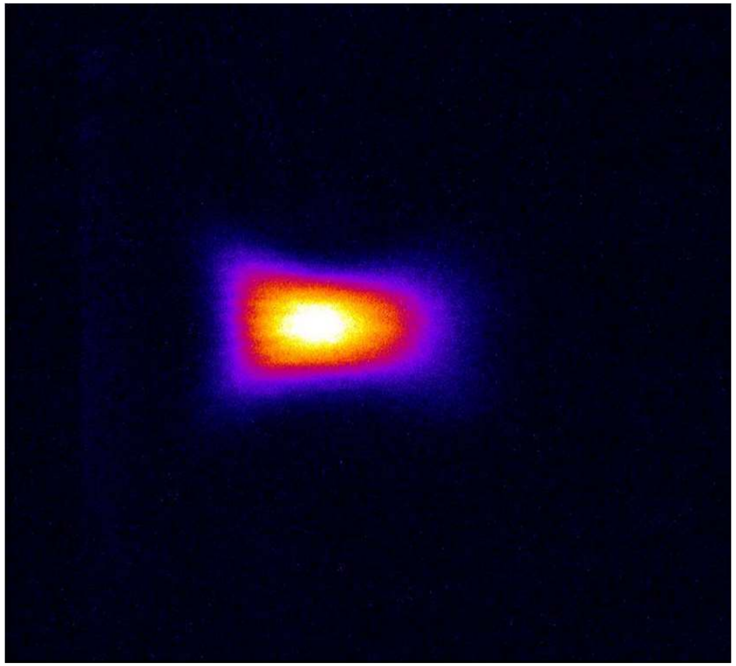
Optimisation of LWFA performance

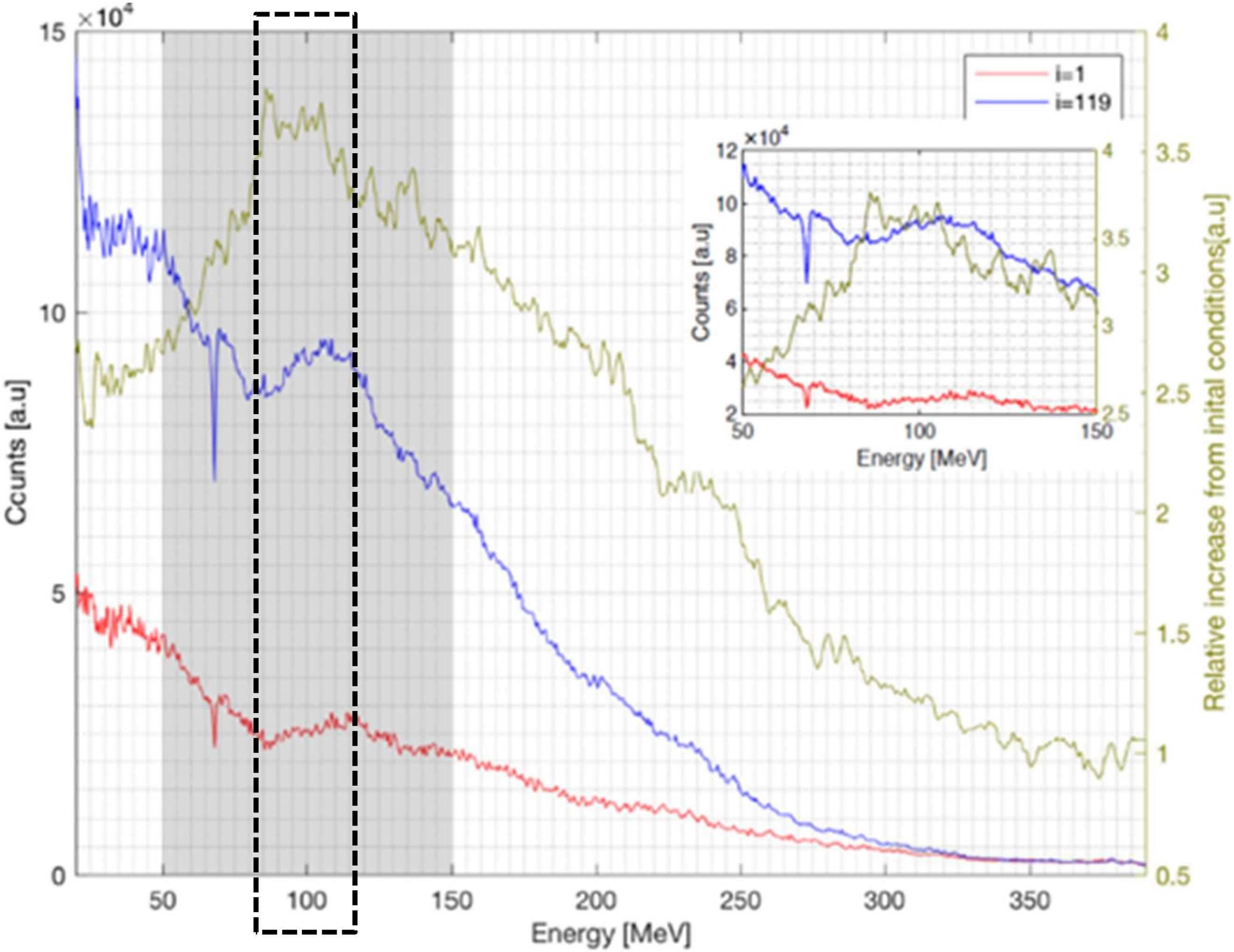




Grenouille signal of top performers

- Fitness function defined to maximise the signal in an energy "bucket" 90 – 110 MeV

Increased beam charge in specified region was achieved



Fitness function optimised signal in this region

- Overall increase in beam charge
- Greatest increase in the targeted region (x3)
- More stable beams should be easily adaptable

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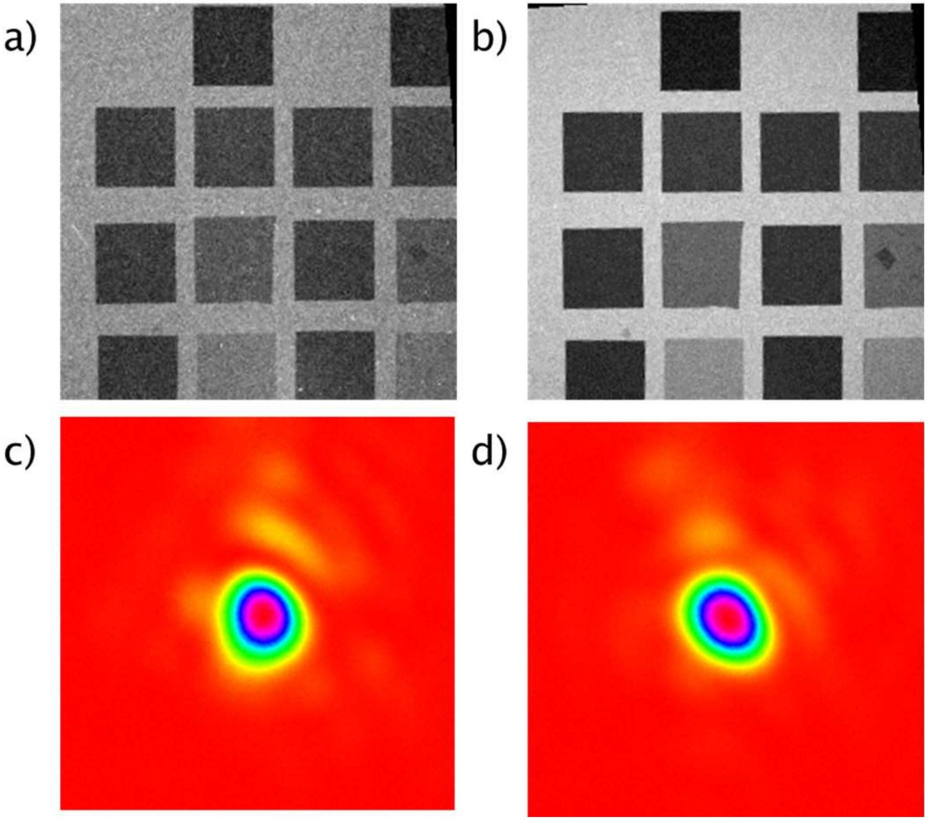
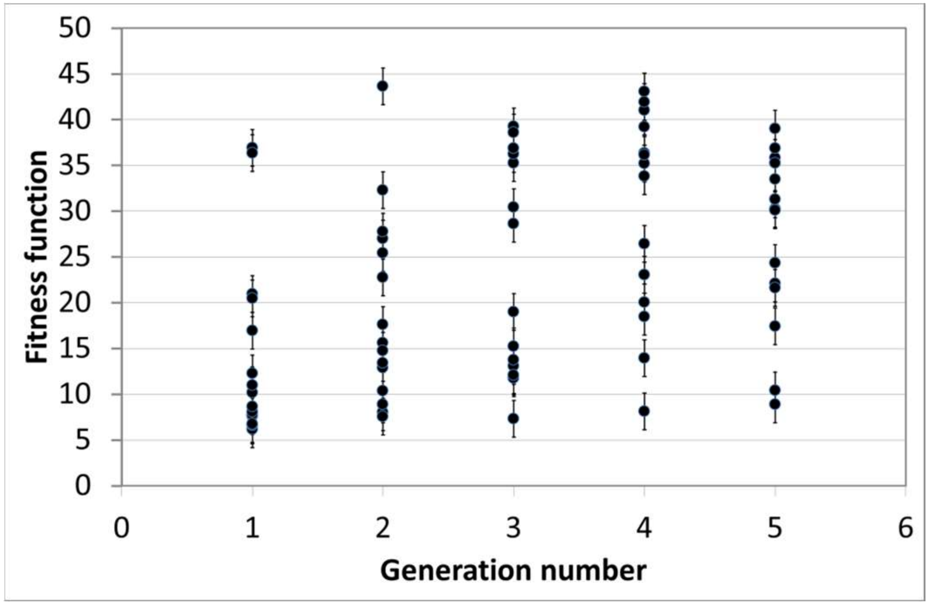
Improving betatron by adapting the spatial profile with deformable mirror

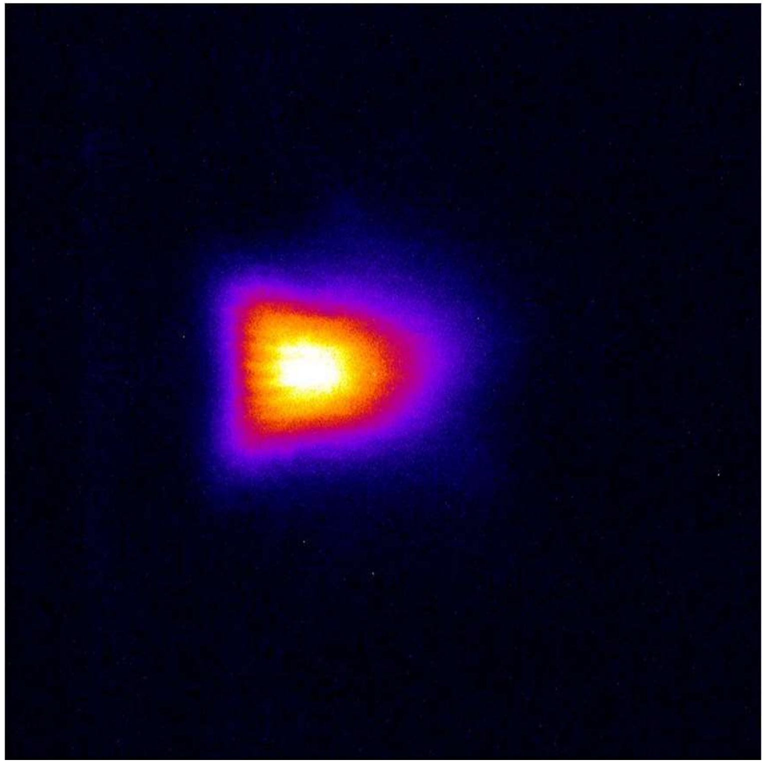




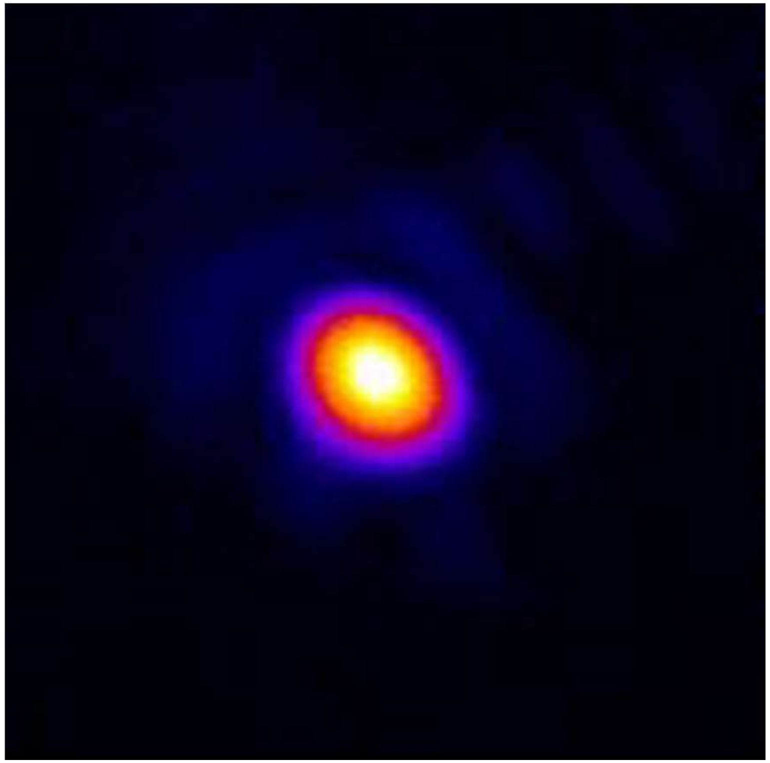
Betatron signal through filter pack and focal spot measurements

- Optimisation did not work at all
- But can use the large parameter scan to determine the best pattern

Poor focal spot stability may explain inability to optimise



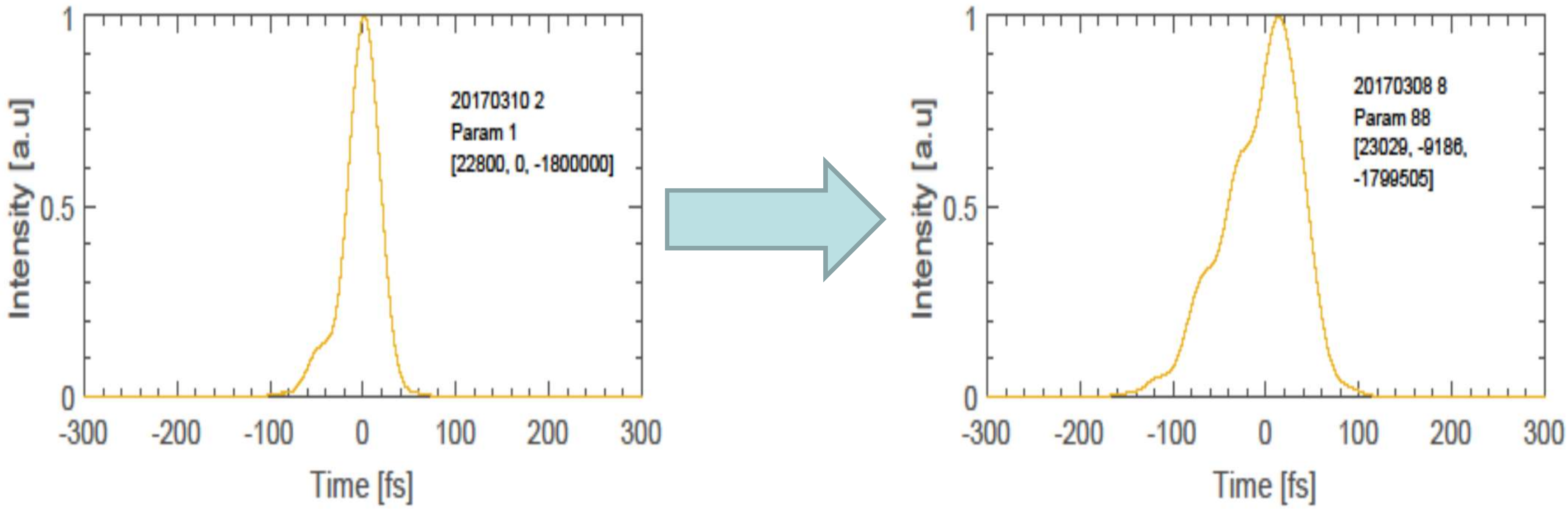
Grenouille signal



Focal spot

- Temporal pulse shape is more stable

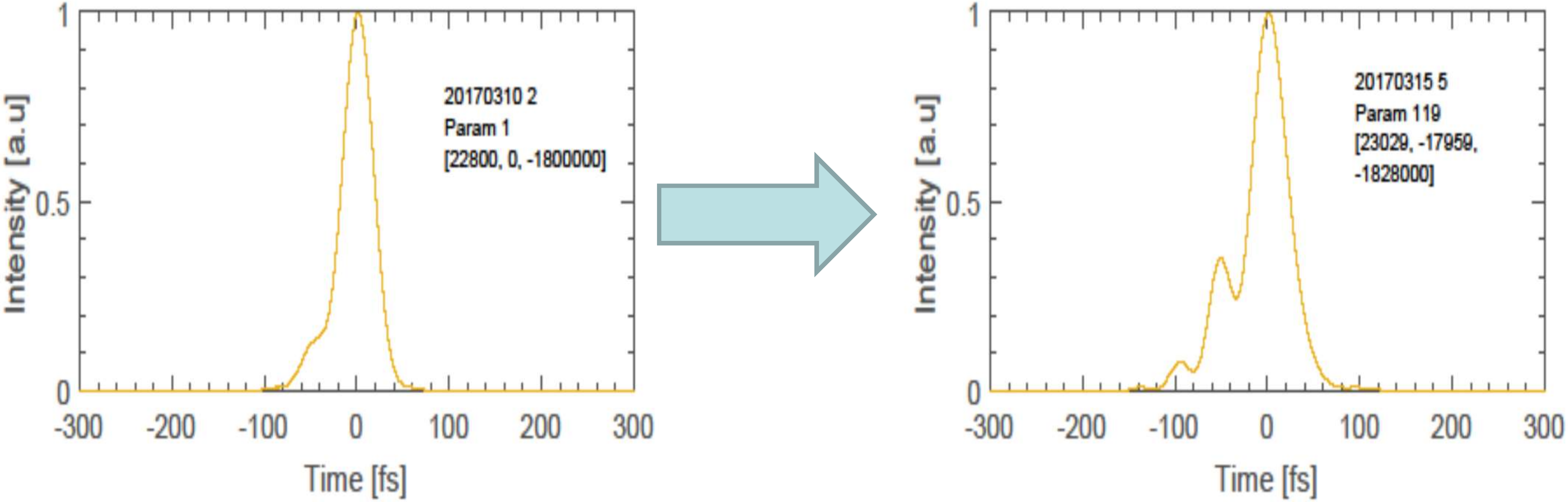
Optimisation of argon x-rays through more efficient electron heating



Pulse shapes measured with SPIDER

- Added third and fourth order to shape the rising edge
- Critically important for optimising electron extraction and heating

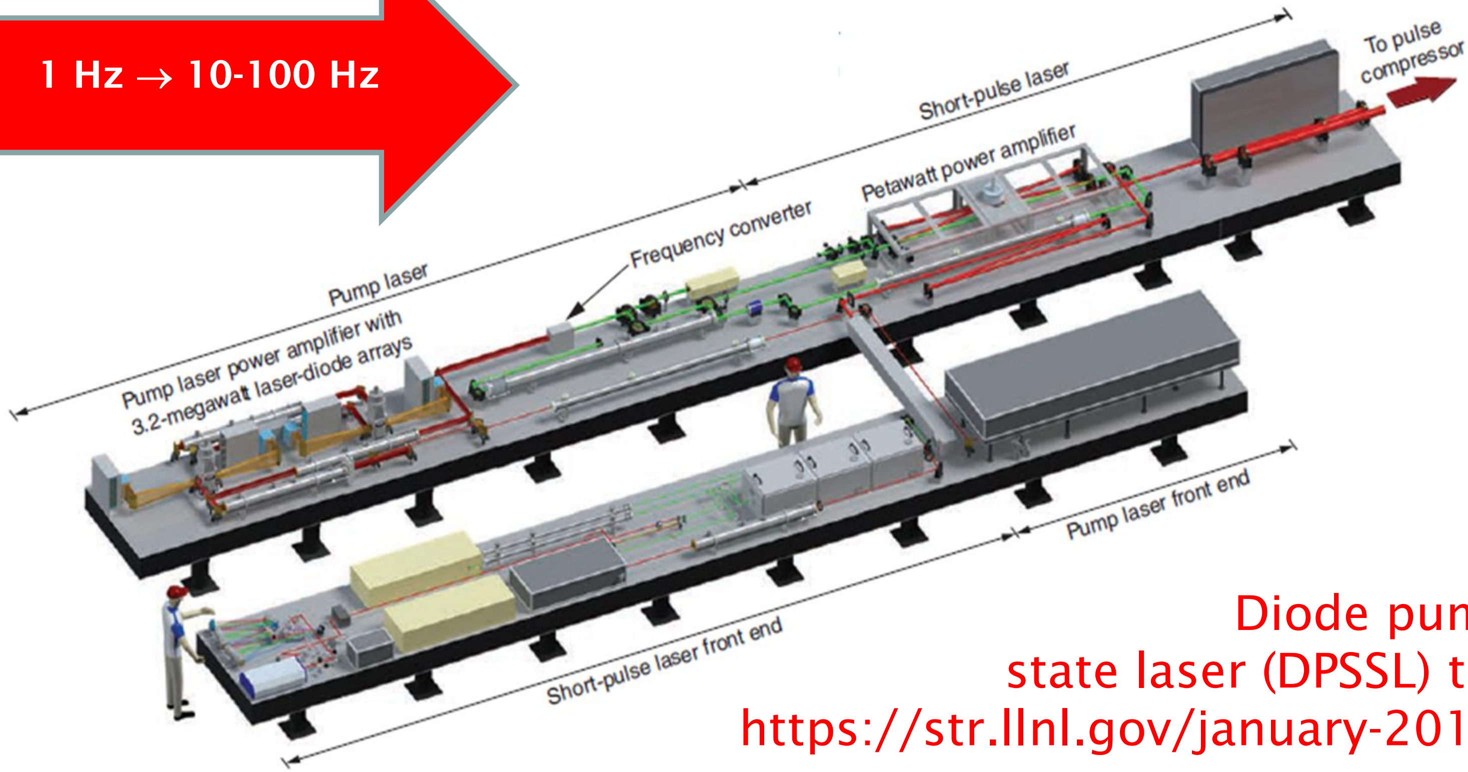
Triple pulse structure formed in LWFA optimisation



- Pulse 1 initiates cluster expansion, Pulse 2 extracts and heats electrons, Pulse 3 drives accelerator
- Higher extraction fraction → **higher charge**
- How does this pulse shape affect the build up of the plasma wave?
- How does electron heating affect the injection?

Petawatt lasers at 10 – 100 Hz

1 Hz → 10-100 Hz



Diode pumped solid
state laser (DPSSL) technology
https://str.llnl.gov/january-2014/haefner

- Diode pumped technology making higher repetition rates achievable
- Facilities envisaged dedicated to secondary source application
  → ELI, EuPRAXIA, Gemini upgrade
- Feedback techniques provide a powerful tool

to optimise beam performance

Summary

- Feedback routines can be used to optimise any parameter

- Control of both spatial and temporal profile of the focus

- There are many more algorithm options
  $\rightarrow$ Different input parameters
  $\rightarrow$ More sophisticated fitness function

- Importance to 10 Hz PW e.g. ELI Beamlines