High Repetition-Rate Laser Wakefield Acceleration

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On behalf of Prof. Alec Thomas and Karl Krushelnick
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MICHIGAN ENGINEERING

THE GÉRARD MOUROU CENTER FOR ULTRAFAST OPTICAL SCIENCE

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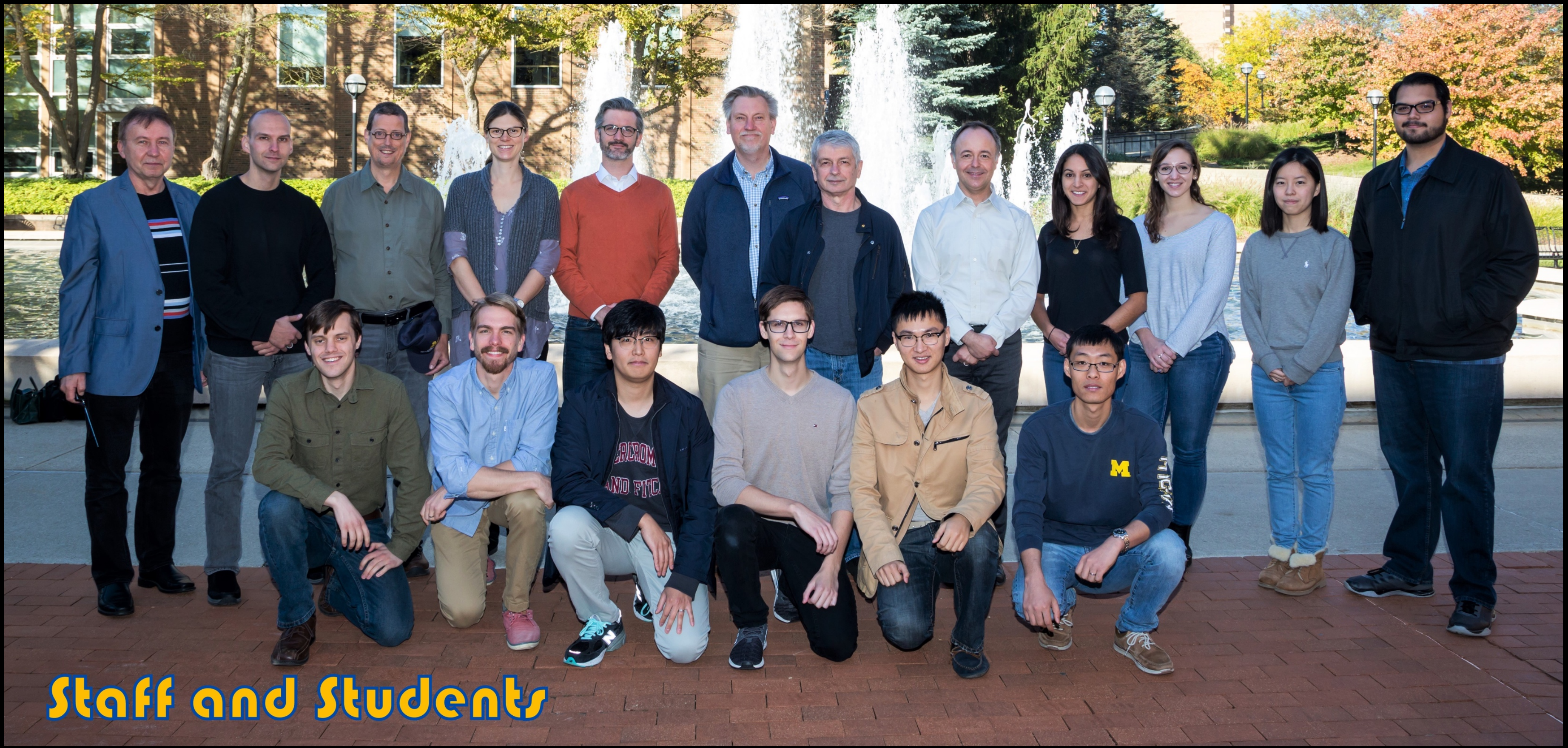
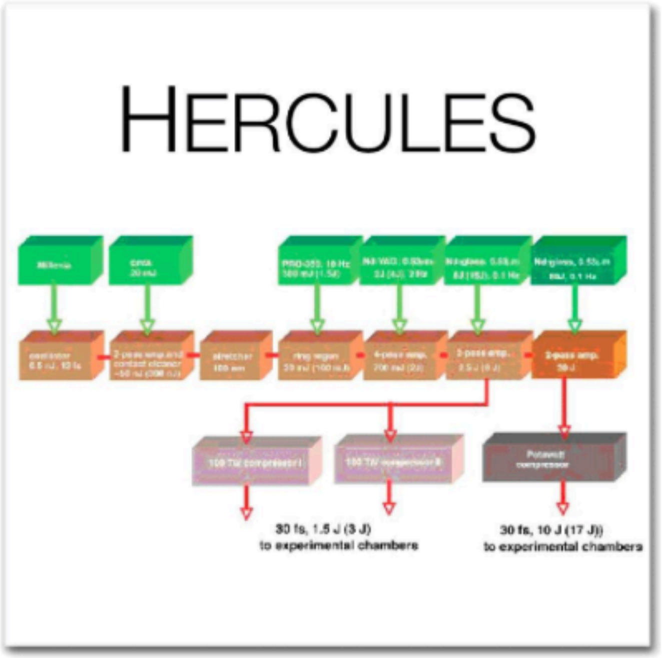
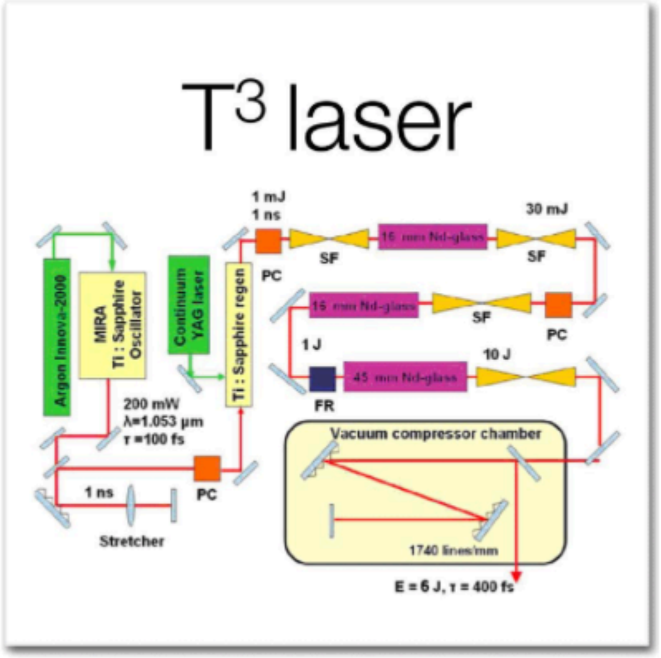
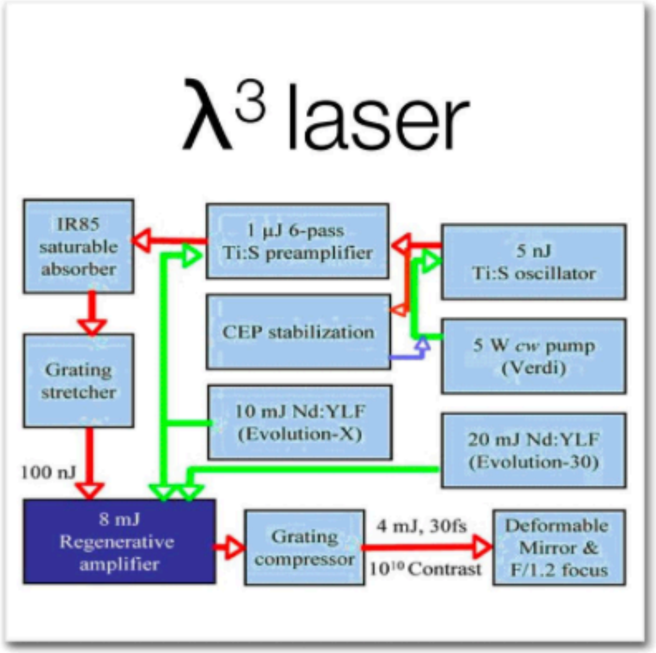


High Field Science group







300TW, 9J, 30fs

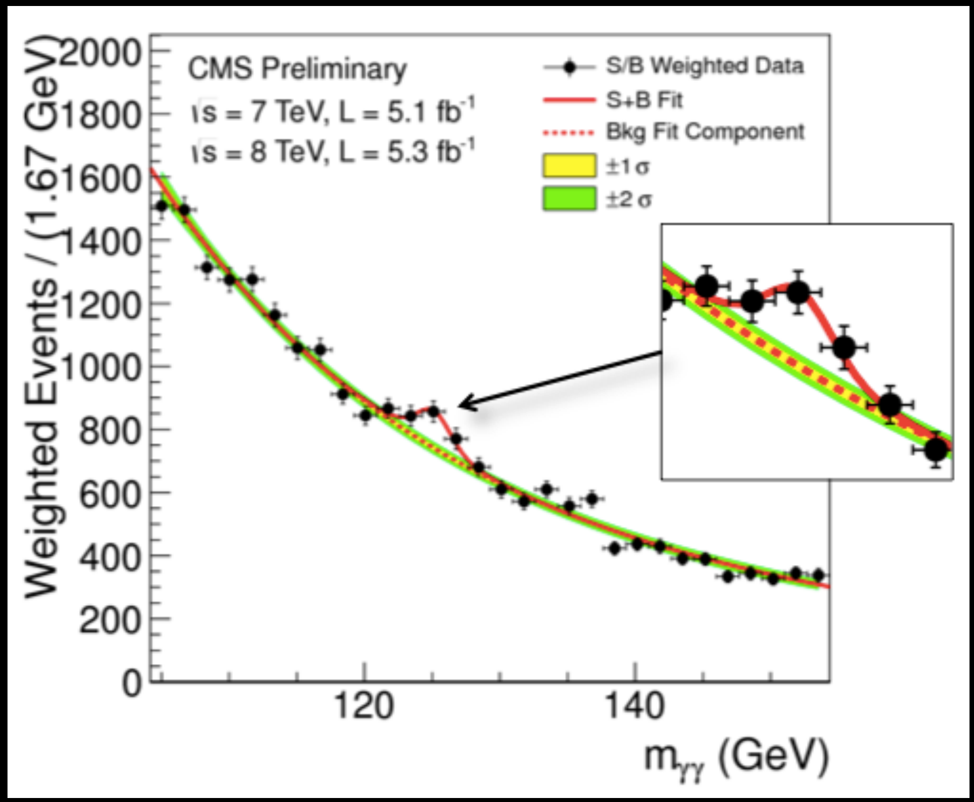
20TW, 8J, 400fs

500Hz, 20mJ, 30fs

Motivation: Why is high repetition rate important?

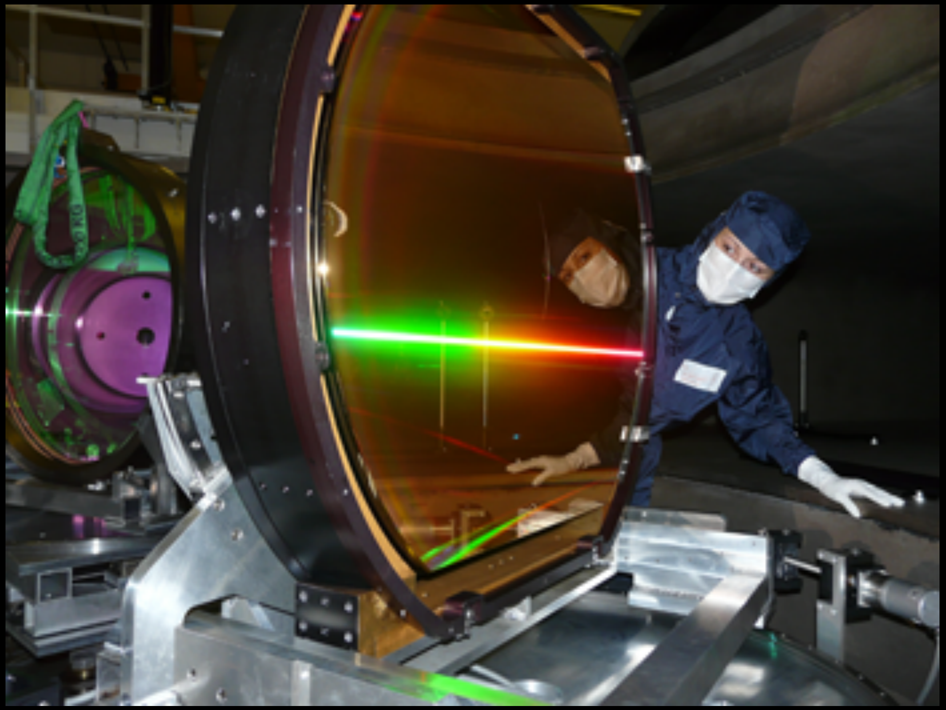
- Collecting **statistically significant data** and improving S/N for **sensitive measurements**

- Allows the use of **machine learning** to seek regions of parameter space with desirable properties and predict outcomes



Not only due to applications
It's about science!

What limits repetition rate in plasma experiments?

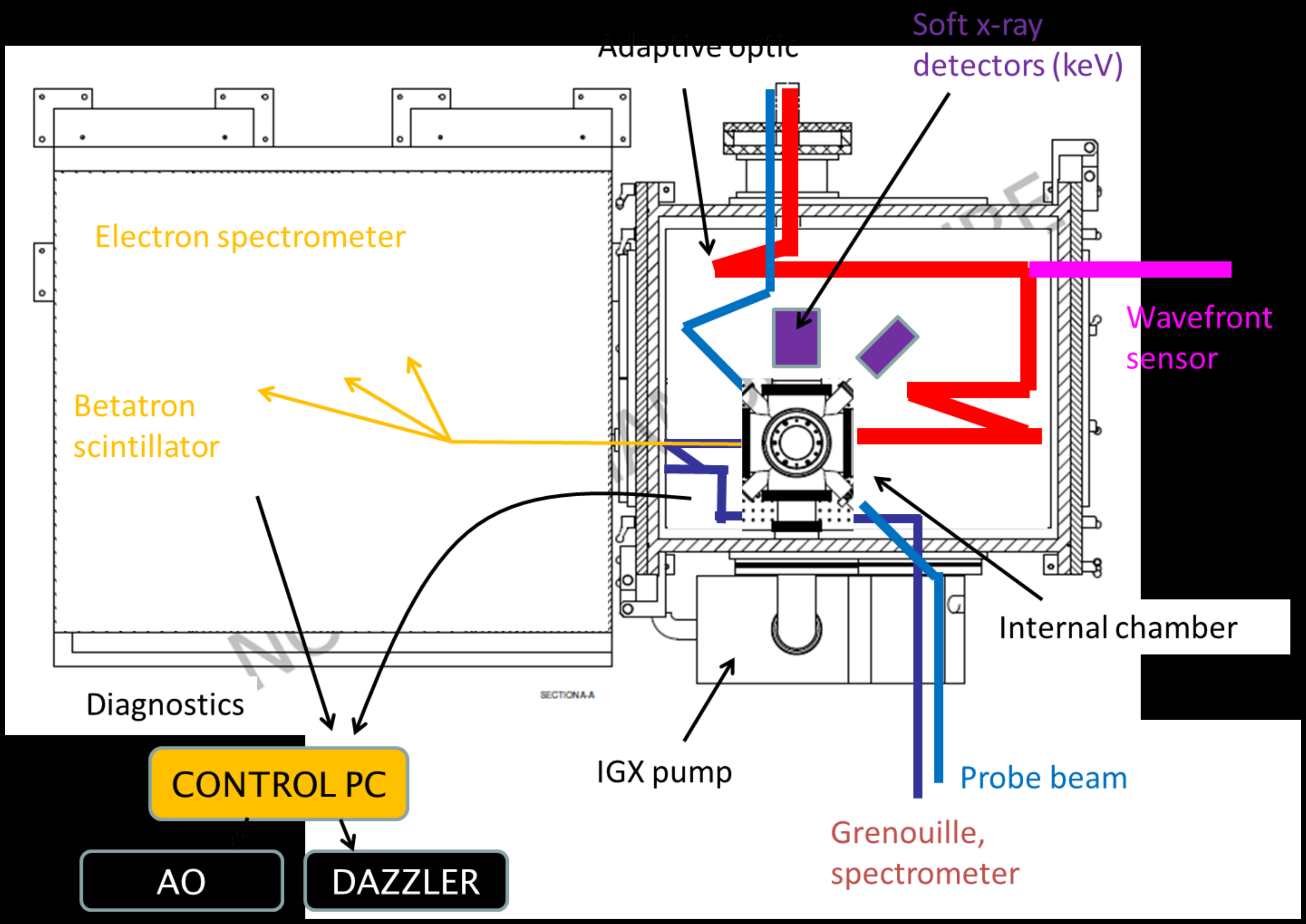


- repetition rate of the laser driver
- replenishing the target/vacuum
- compatible diagnostics

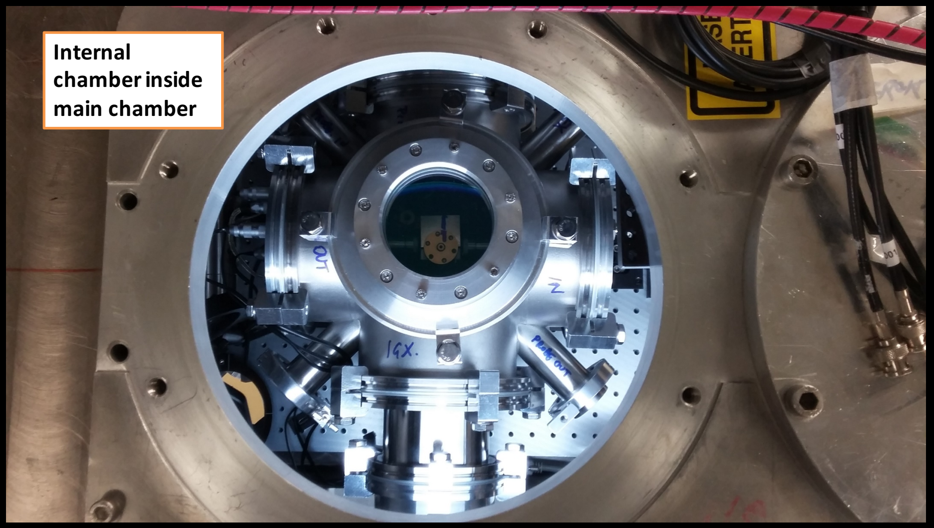
Can we run at high rep-rate with multi TW-PW class laser systems?

Previous work: Proof of principle LWFA at 5 Hz

Collaboration CLF (Dan Symes: PI) / Lancaster U. / Michigan / Imperial College/ TIFR India / DESY



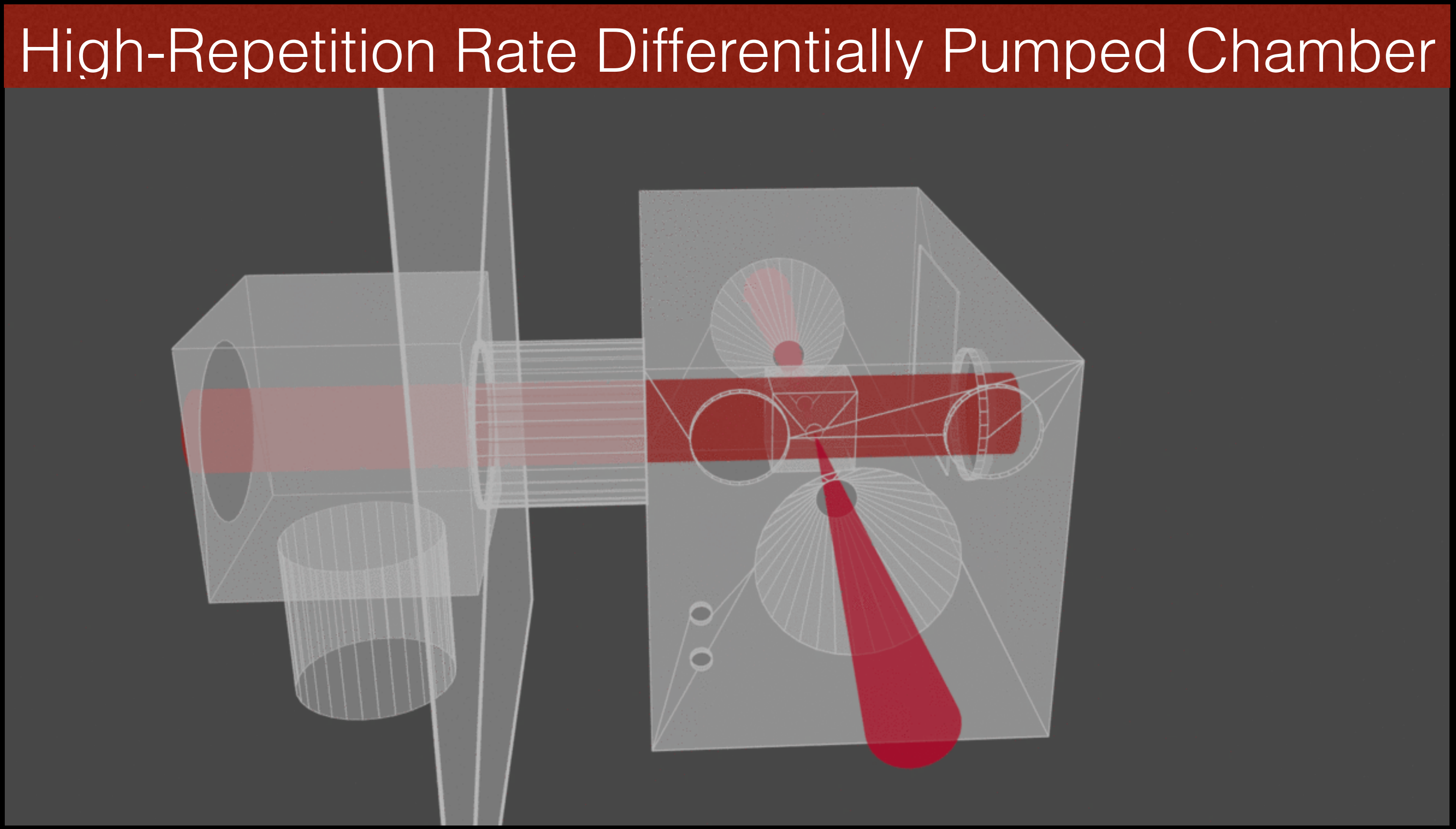
Methane gas jet in differentially pumped internal chamber



Experiment on Gemini TA2 laser, RAL
Recently upgraded to 5 Hz
10 TW power
45 fs duration

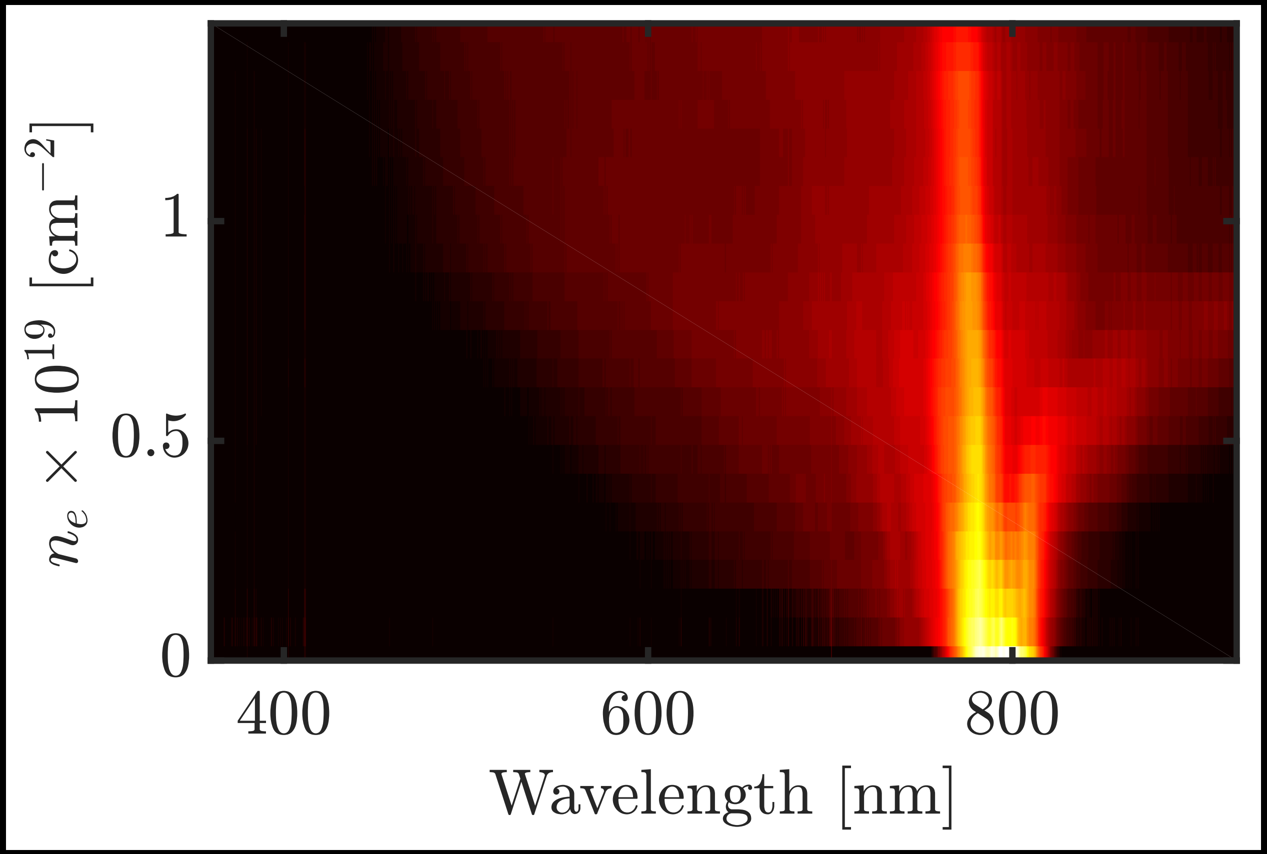
Differential Pump: Vacuum Chamber-Within-Chamber, makes high rep-rate achievable

Differentially pump, which allows high-pressure gasses to be sustained in inner-vacuum chamber without damaging primary-vacuum chamber



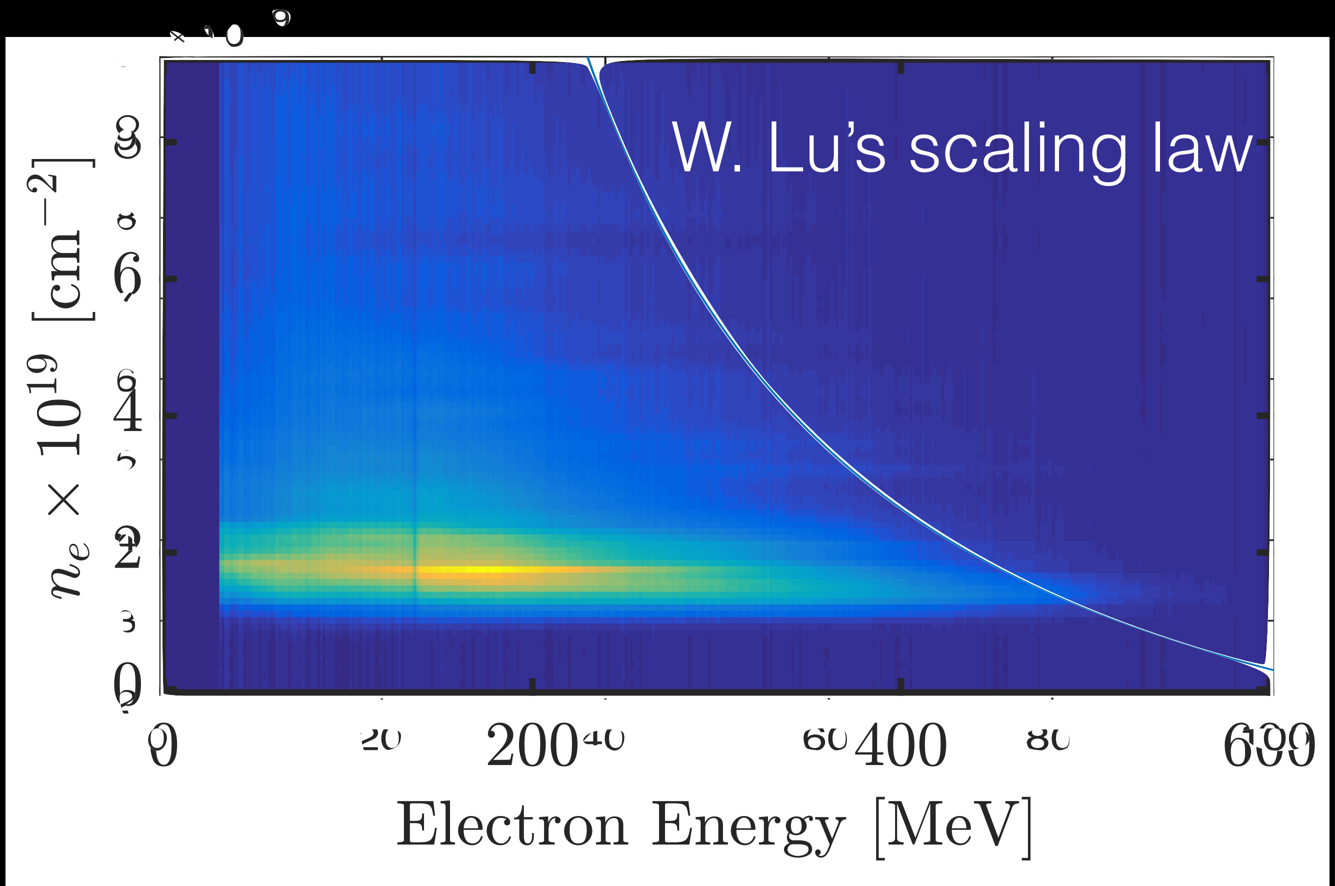
Differential Pumping Setup and Current Experimental Application at Gemini Target Area II, Rutherford Appleton Laboratory (-Collaboration Imperial, Michigan, York, RAL)

The high repetition rate allows fine resolution of parameter space



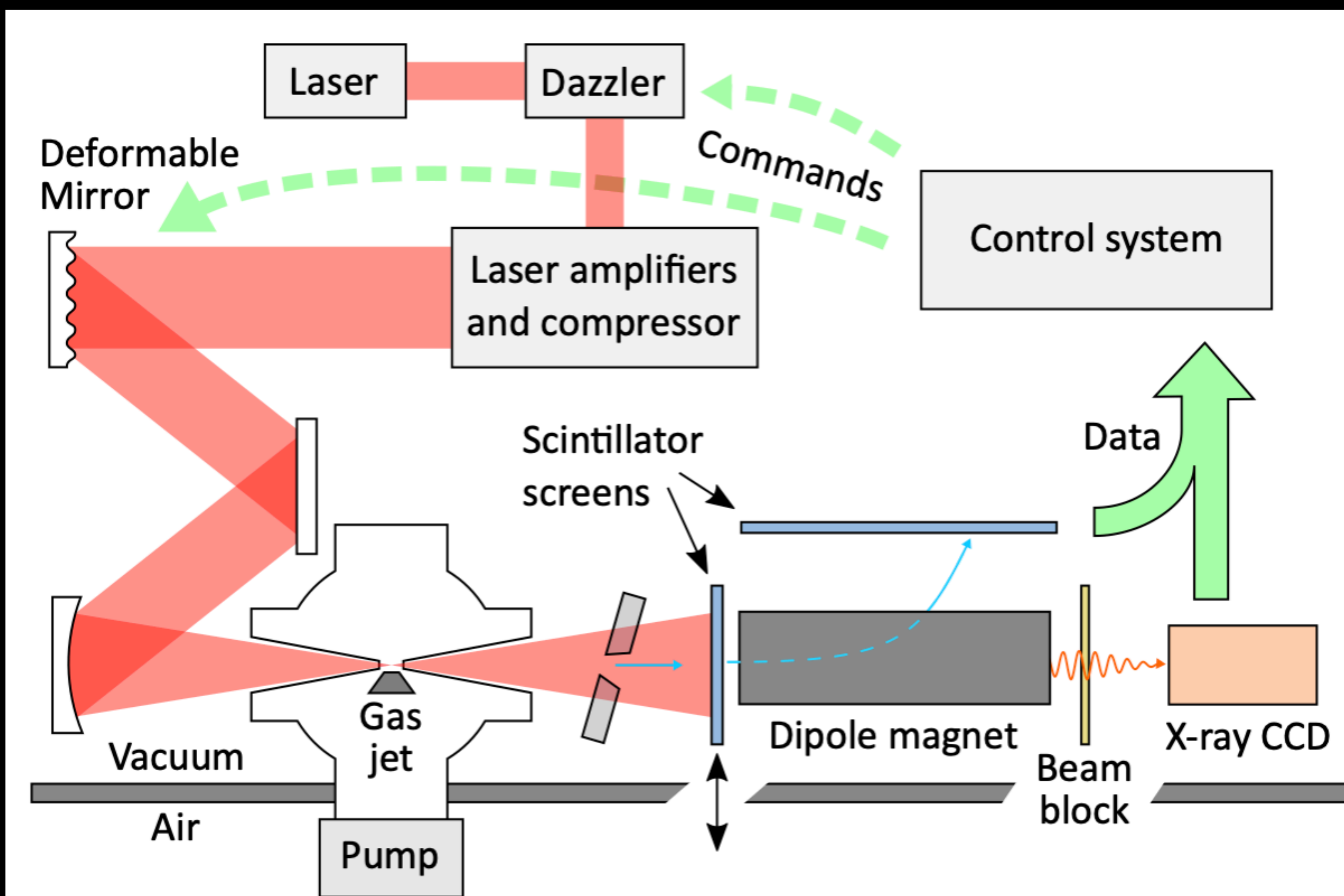
- Laser spectrum post plasma as function of density

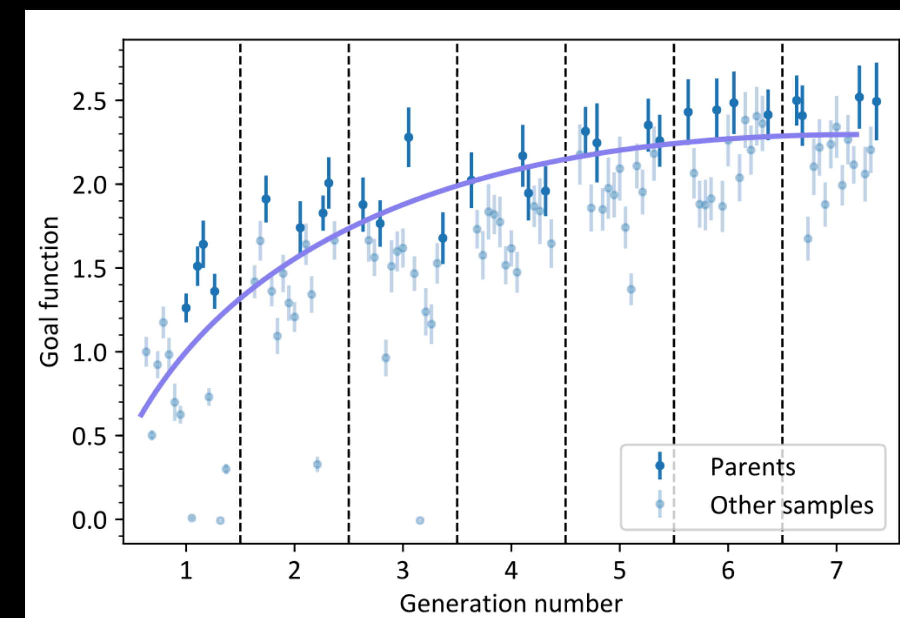
Each row is average over 50 shots



- Accelerated electron spectrum as function of density

High rep rate allows active feedback optimization techniques





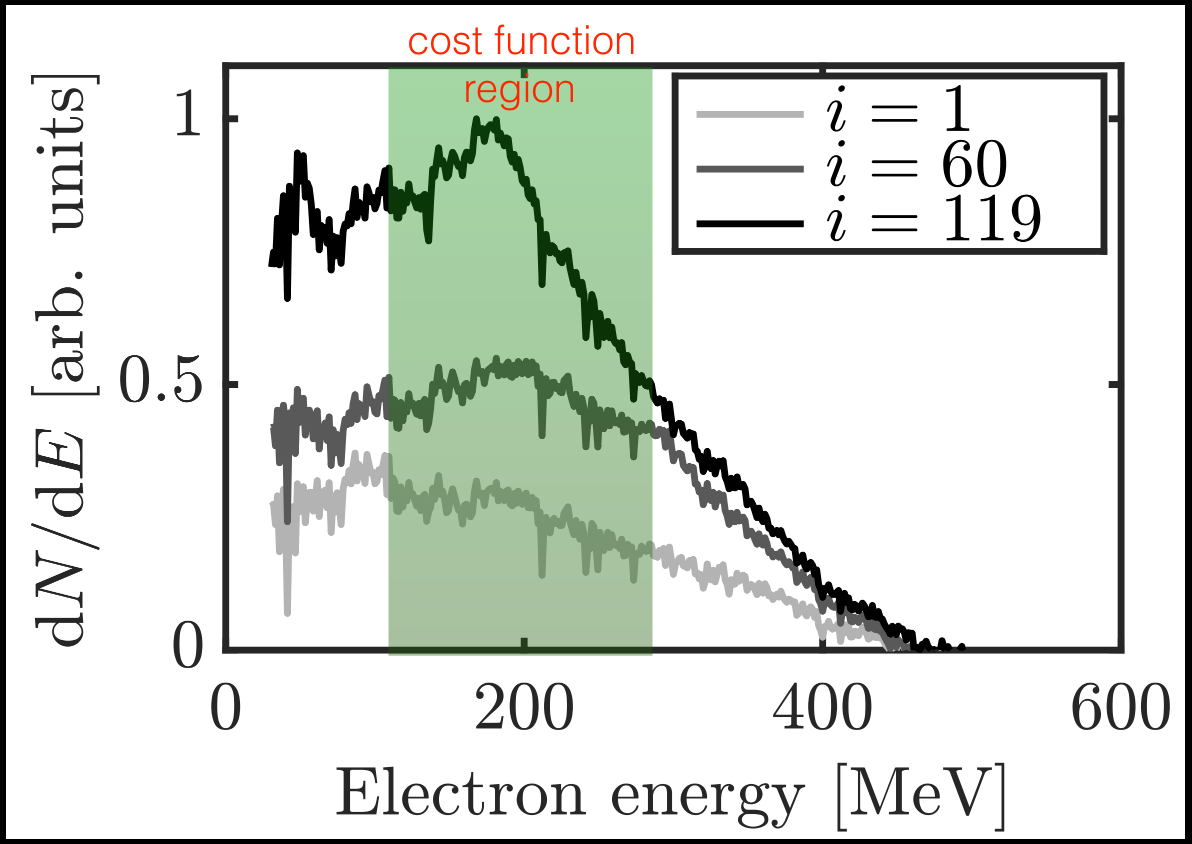
Active feedback optimization techniques

Goal function	Charge		X-rays	
Algorithm	GA	NM	GA	NM
Improvement	**130%**	95%	70%	**100%**
Evaluations	45	**25**	75	**40**

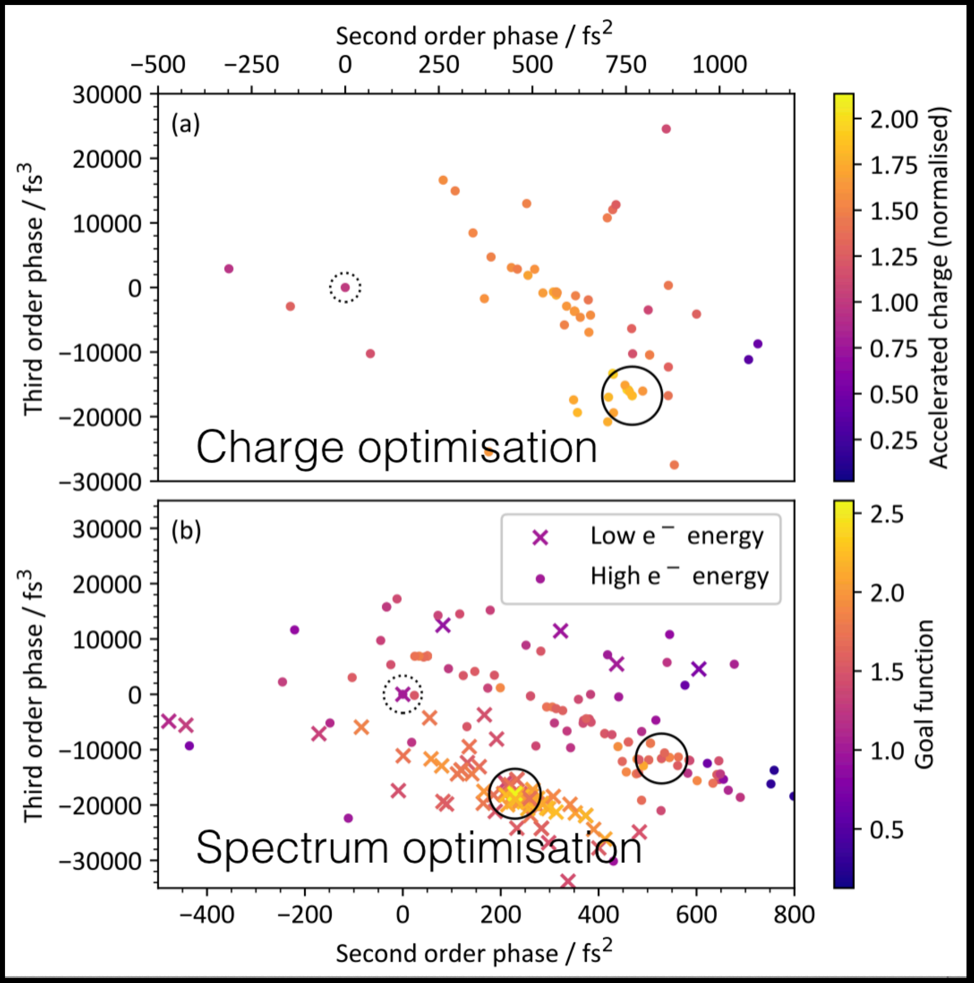
S. J. D. Dann et al., *Laser wakefield acceleration with active feedback at 5 Hz,* PRAB 22, 041303 (2019)

Active feedback optimization of electron spectrum

- Use dazzler to adaptively control pulse spectral phase and maximize signal in cost function region



Dazzler phase



S. J. D. Dann et al., *Laser wakefield acceleration with active feedback at 5 Hz,* PRAB 22, 041303 (2019)

Current Experiment: High Repetition-Rate Tomography

- Optimized high-repetition rate, bright X-ray beams will be used to produce in-situ images of a reaction of ‘quasicrystal’ aluminum alloys subjected to heat, tracking its active progress to an equilibrium state.

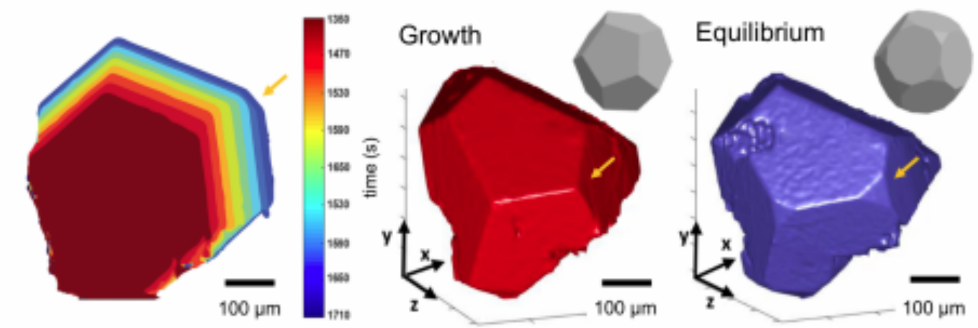
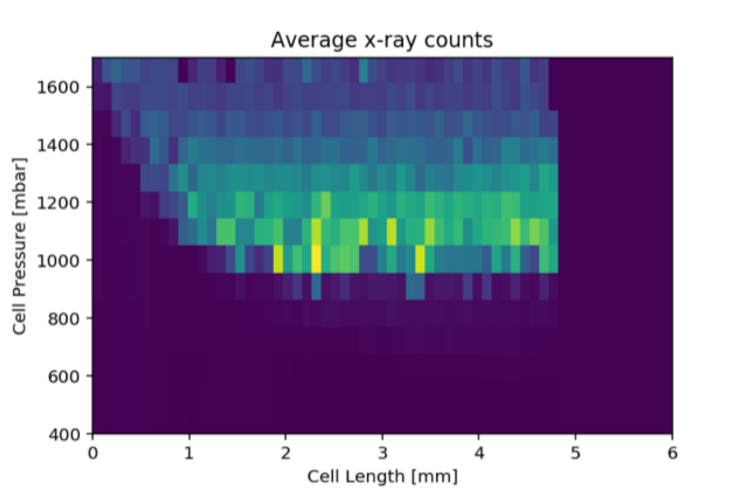
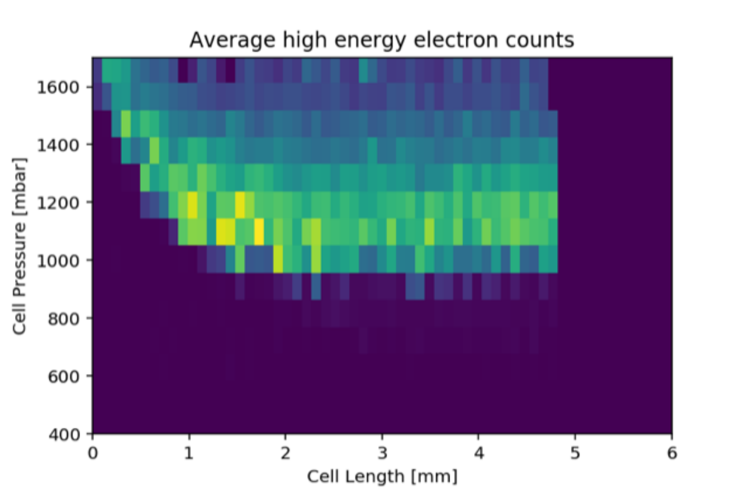


Figure [N. Senabulya, I. Han, X. Xiao, A.J. Shahani, Scripta Mater. 146, 218 (2018)] (left) Two-dimensional isochrones of a solid Al-Pd-Mn icosahedral during solidification, where color indicates the passage of time. 3D renderings of the QC at an early stage of growth (middle) and at a later stage (right). Note the change in structure between the two stages (inset).

- Successful **2D-parameter space scans** have taken place to optimize electron output and x-ray output from the LWFA targets in these experiments, as can be preliminarily seen in results below from one set of laser shot runs at 5 Hz.





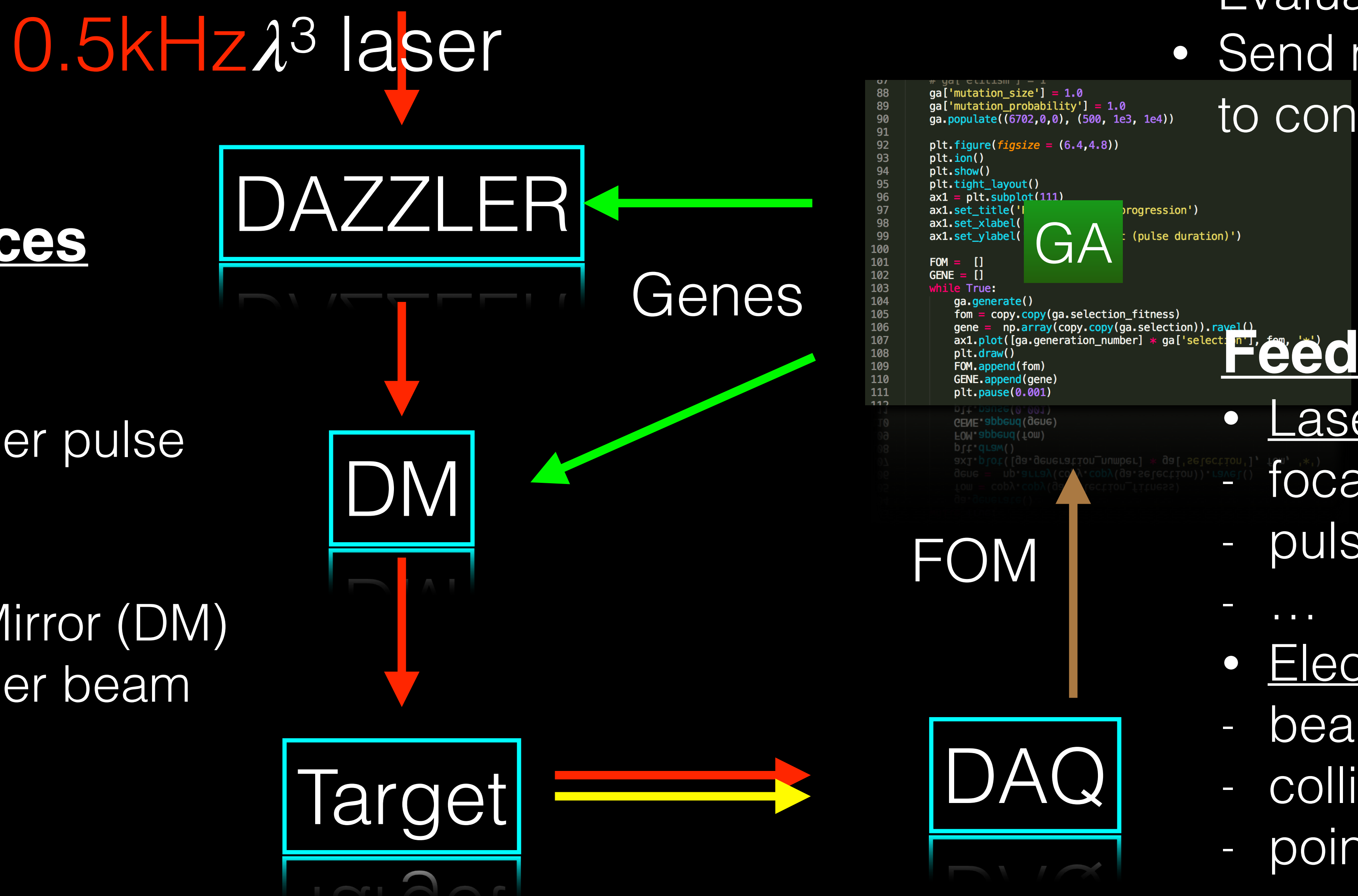
kHz LWFA at Lambda3 platform with adaptive control

Genetic algorithm
- Evaluate feedback
- Send new commands to control devices

Control devices

- DAZZLER
  - to control laser pulse shape

- Deformable Mirror (DM)
  - to control laser beam profile



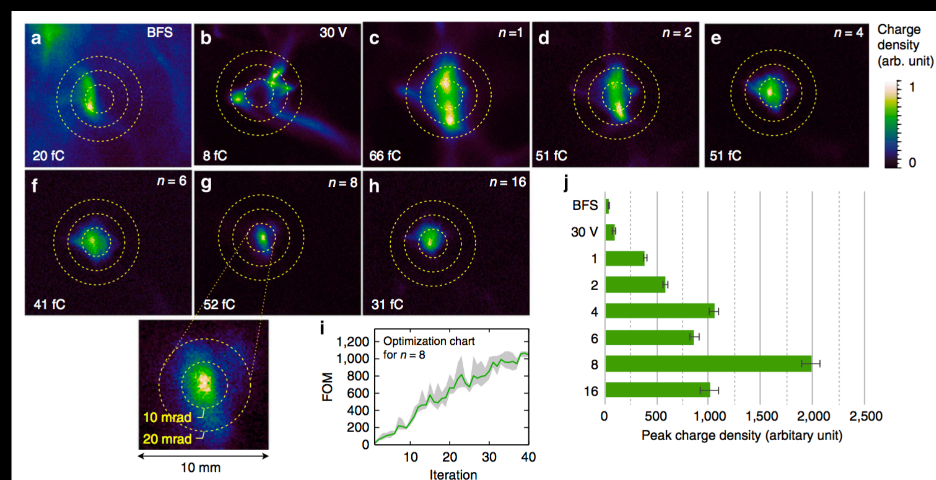
Continuous gas flow through fused silica capillary

Feedback
- Laser beam:
  - focal spot,
  - pulse shape
  - …
- Electron beam:
  - beam charge,
  - collimation,
  - pointing,
  - spectrum
  - …

Optimization of electron beam quality with **DM** via GA

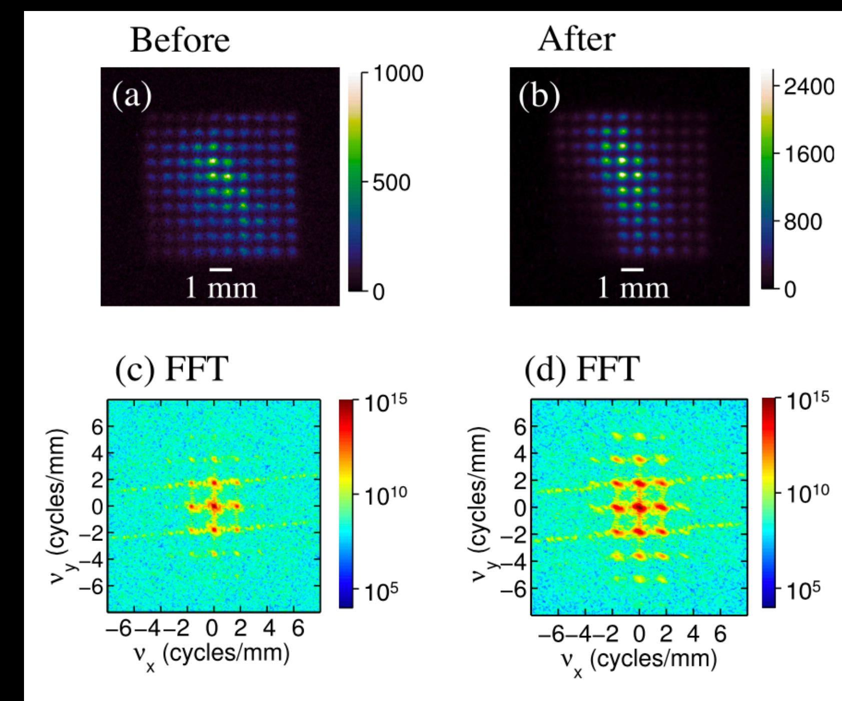
1. Beam profile
- Beam charge
- Collimation
- Pointing

$$\mathrm{FOM} = \sum_{\substack{(i,j)\\ \mathbf{r_{ij}} \neq \mathbf{r}_0}} \frac{I_{ij}}{\left|\mathbf{r_{ij}} - \mathbf{r}_0\right|^n}$$



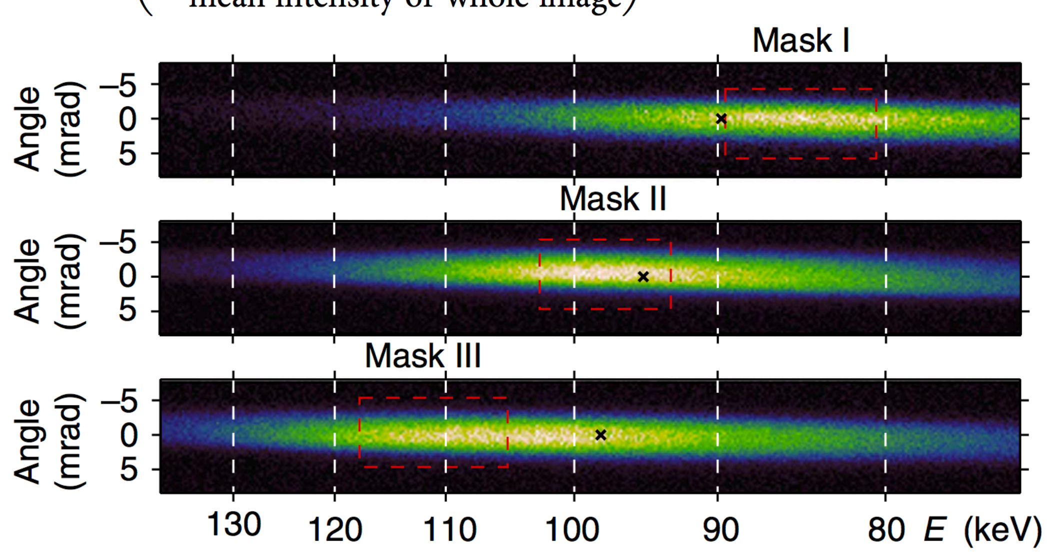
Beam intensity increased
2 orders of magnitude

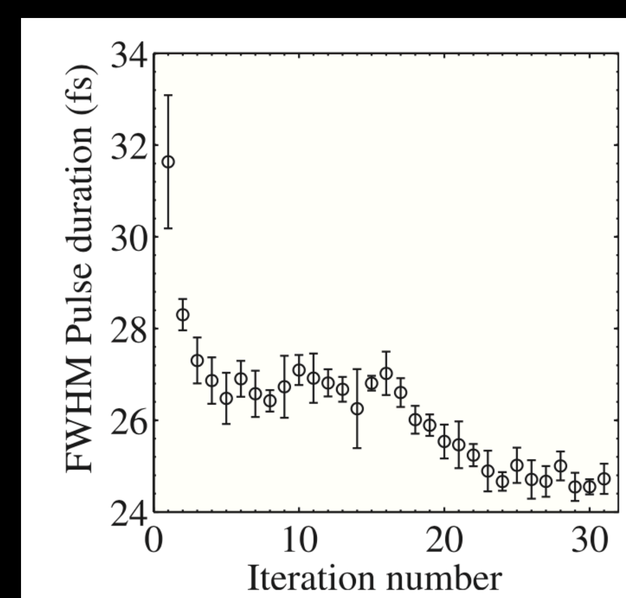
3. transverse emittance



2. Energy spectra

$$\mathrm{FOM} = \left(1 - \frac{\text{mean intensity outside mask}}{\text{mean intensity of whole image}}\right) \times \text{mean intensity inside mask}$$

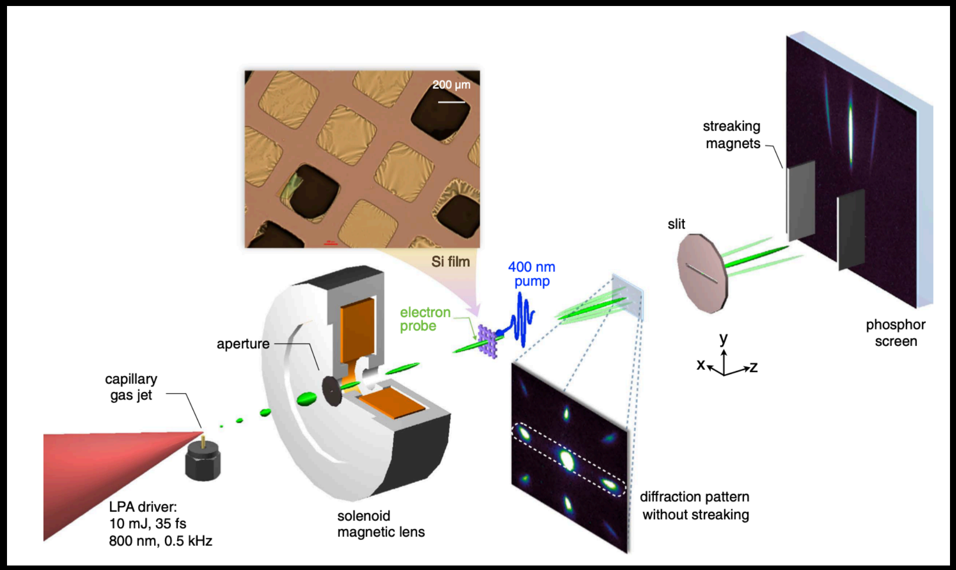


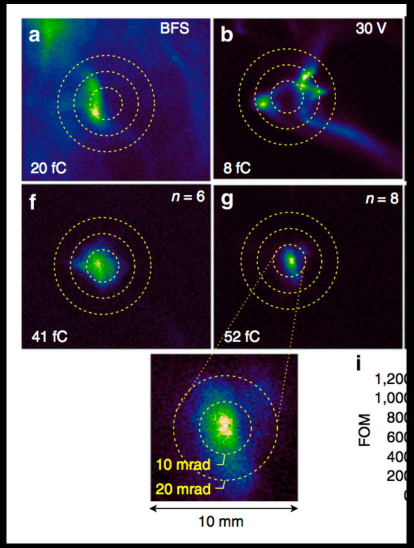


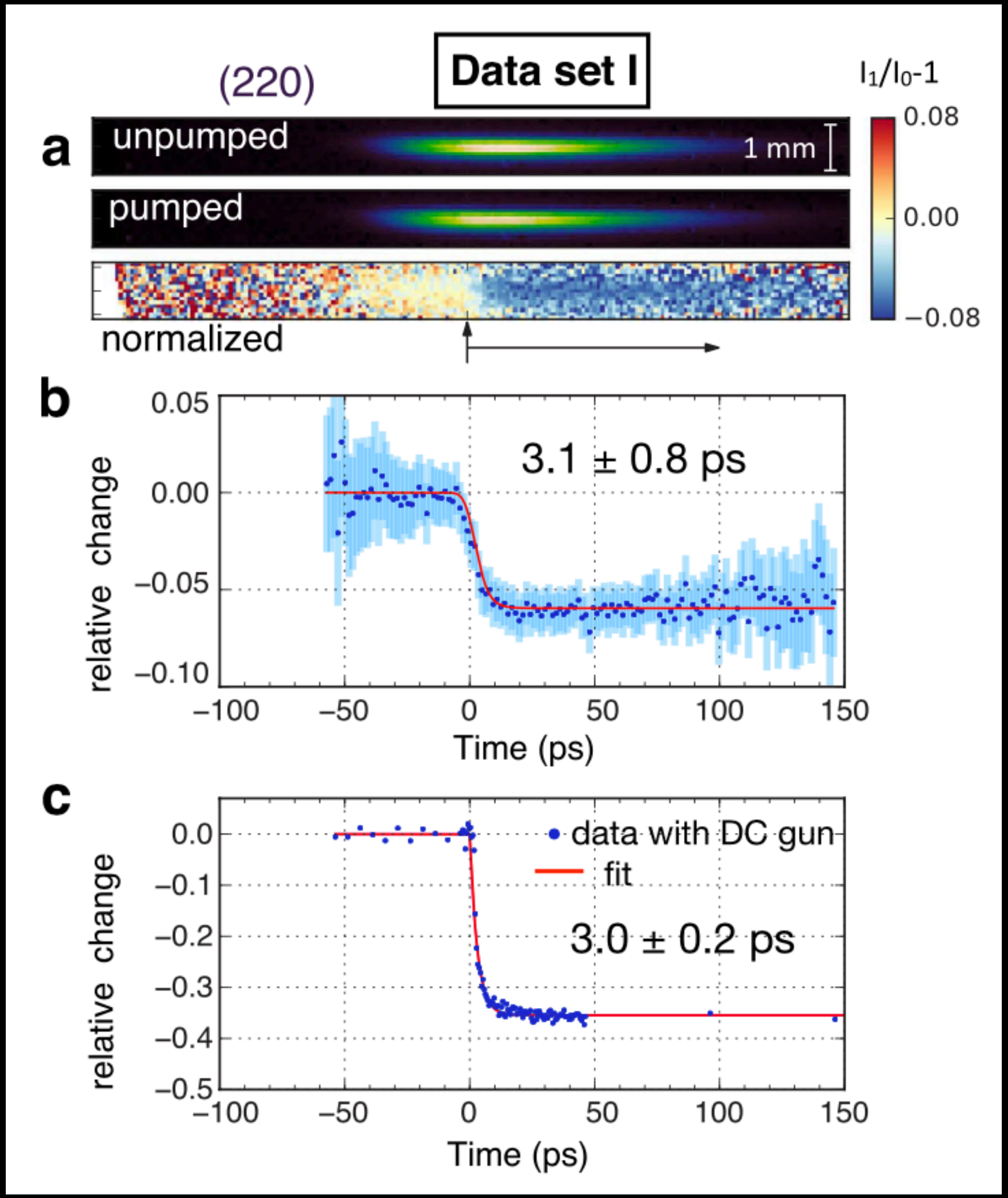
4. Pulse duration

Z.-H. He, *et al.* **Nat. Commun. 6**:7156 (2015).
Z.-H. He, *et al.* **Physics of Plasmas, 22**, 056704 (2015).

Time-resolved pump-probe with streaked electron diffraction at kHz







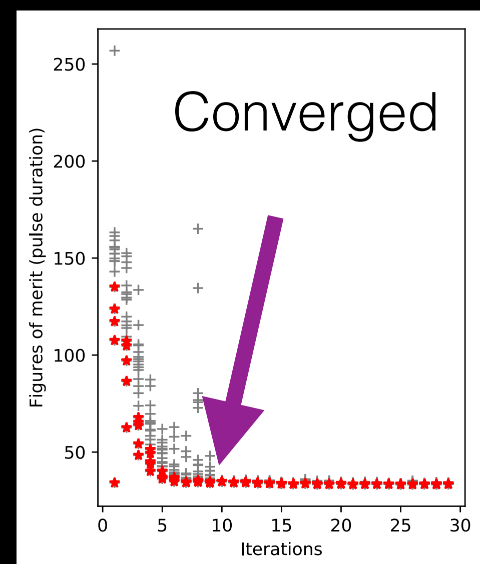
- time-resolved electron diffraction experiments have been performed using a kHz laser-wakefield accelerator
- with superior stability, delivering electrons in the 100 keV range, with the transverse coherence required for electron diffraction
- along with dramatic beam quality improvements enabled by active feedback control

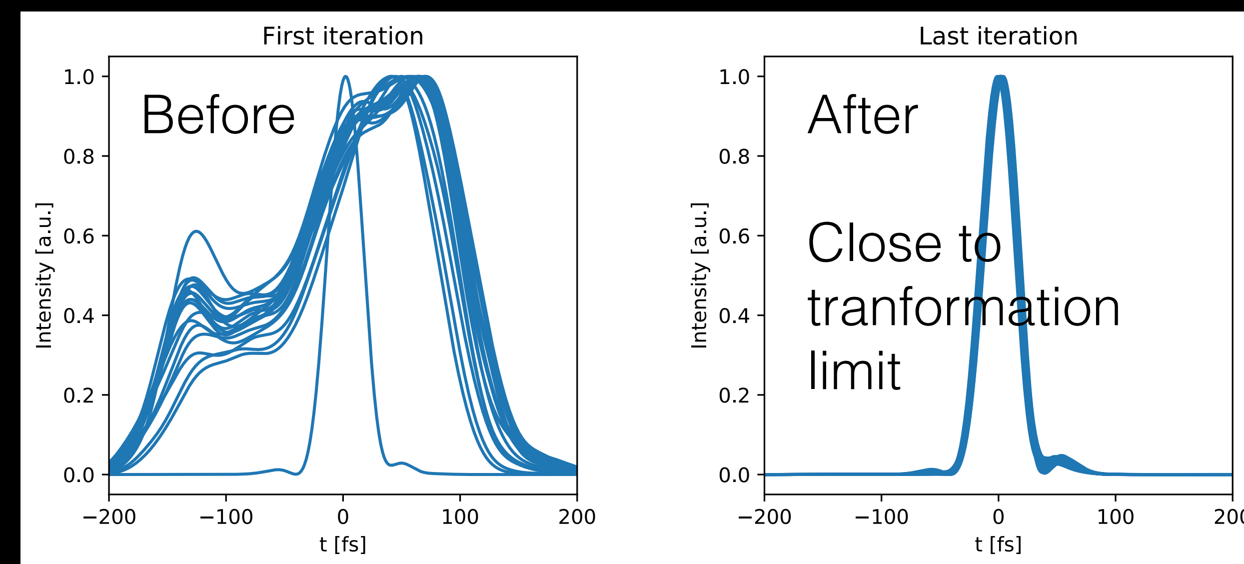
He, Z.-H. *et al. Sci. Rep.* **6**, 36224 (2016)

Optimization of laser pulse shape with DAZZLER via GA

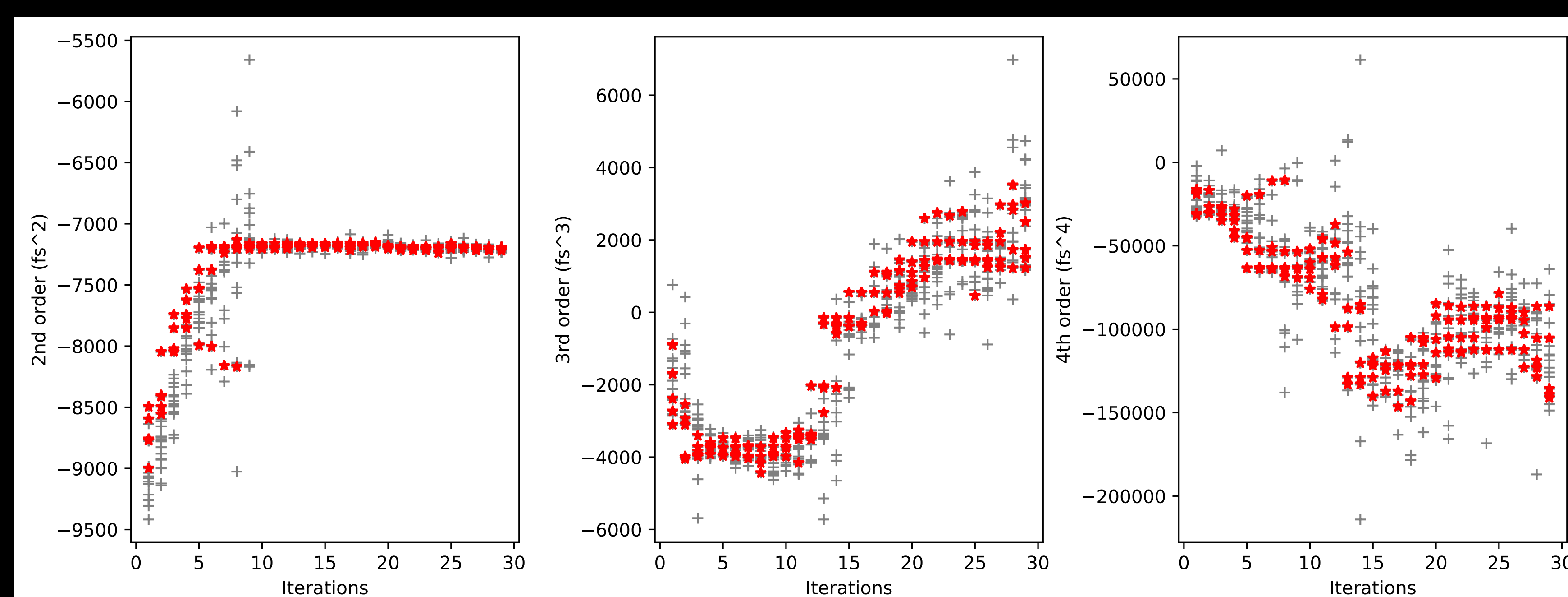
FOM: FWHM pulse duration.
Goal: minimization

Red: 5 elites as parents of new generation
Gray: all 20 in one generation, each data is an average of 250 laser shots





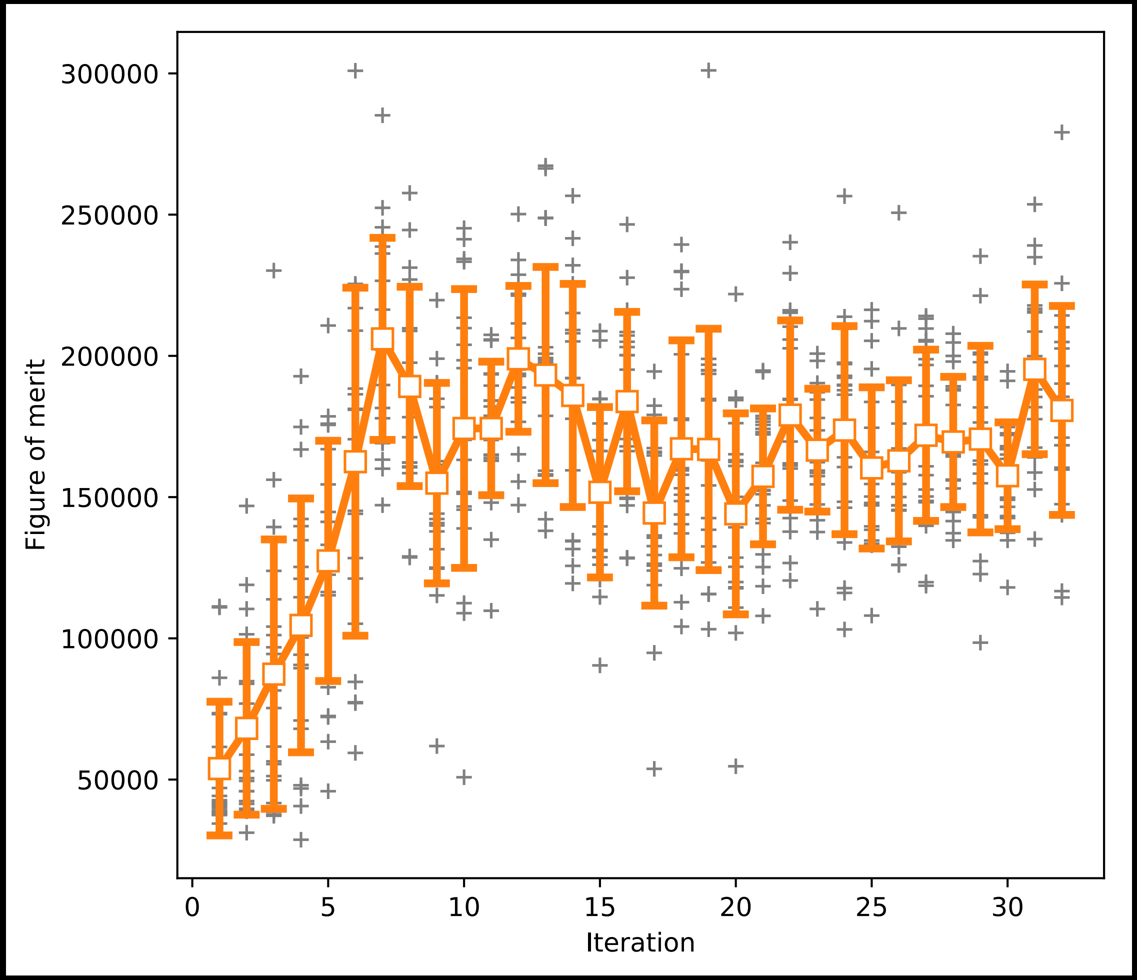
- Convergence of Dazzler Phases
- Pulse duration most sensitive to 2nd order phase



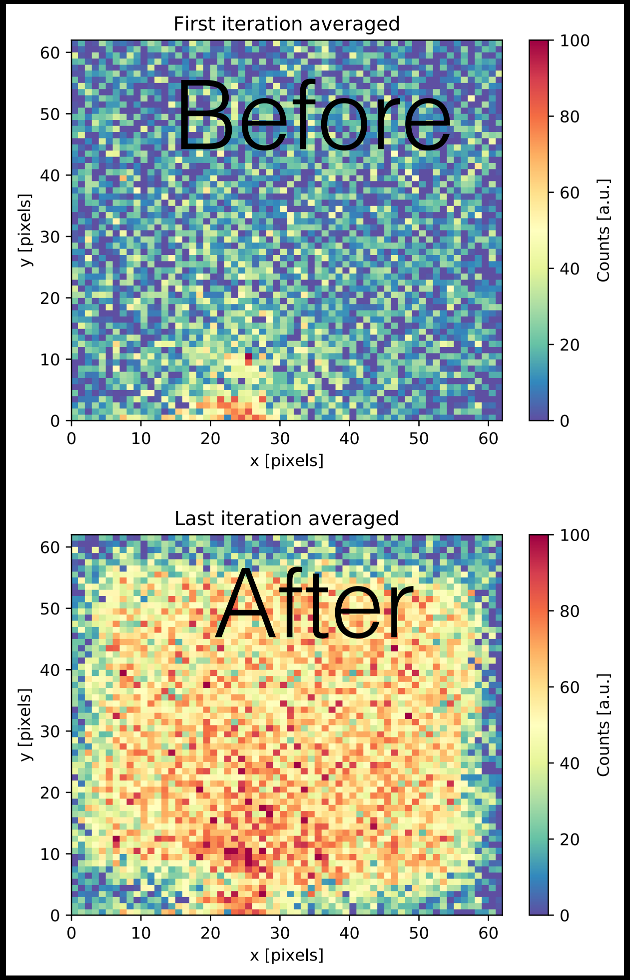
Optimization of electron beam quality with DAZZLER via GA

FOM: Electron beam charge

<10 iterations to convergence
Takes no more than 5 minutes



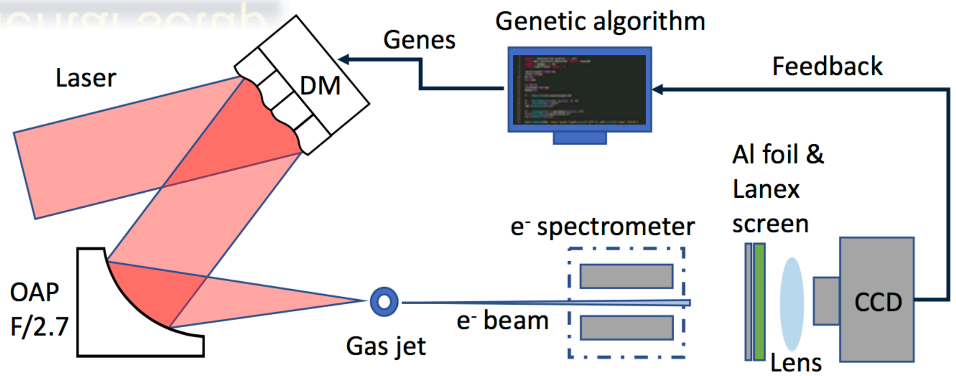
CCD image



Adaptive control of laser-wakefield accelerators driven by mid-IR laser pulses

4um, 20Hz, OPA/OPCPA laser @ University of Maryland

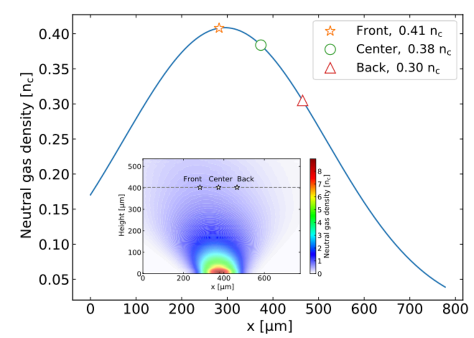
Experimental setup



Laser: @Maryland
λ_L: 3.9μm*,
E: 15 mJ,
τ_{FWHM}: 100 fs
w_0: 15 μm,
a_0: 0.7

DM (Xenetics):
2-inch,
4μm stroke,
37 actuators

Target:
H gas jet nozzle cooled with liquid N_2 @1Hz
n_{max}= 3×10^{19}cm^{-3}
(0.4n_c)



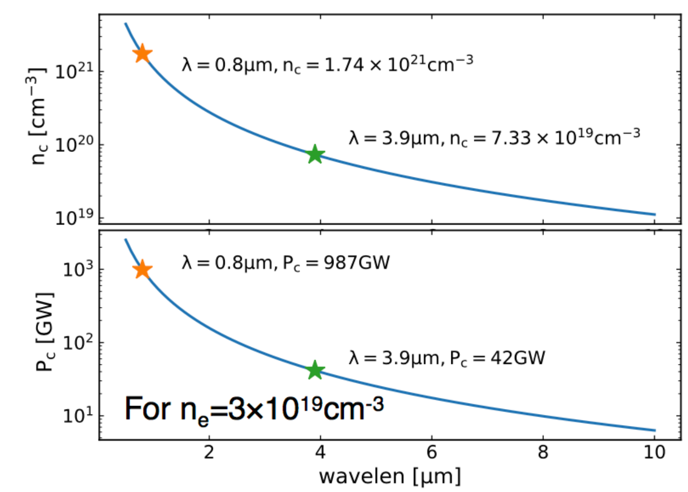
*G. Andriukaitis, et. al., Optics Letters, 36, 15, 2755, (2011)

Mid-IR laser

➢ $n_c = \frac{m_e \varepsilon_0}{e^2} {\omega_L}^2 \propto \frac{1}{{\lambda_L}^2}$

➢ $P_c = 17\left(\frac{n_c}{n_e}\right)[GW] \propto \frac{1}{{\lambda_L}^2}$

➢ $a_0 \propto \sqrt{I\lambda_L^2}$

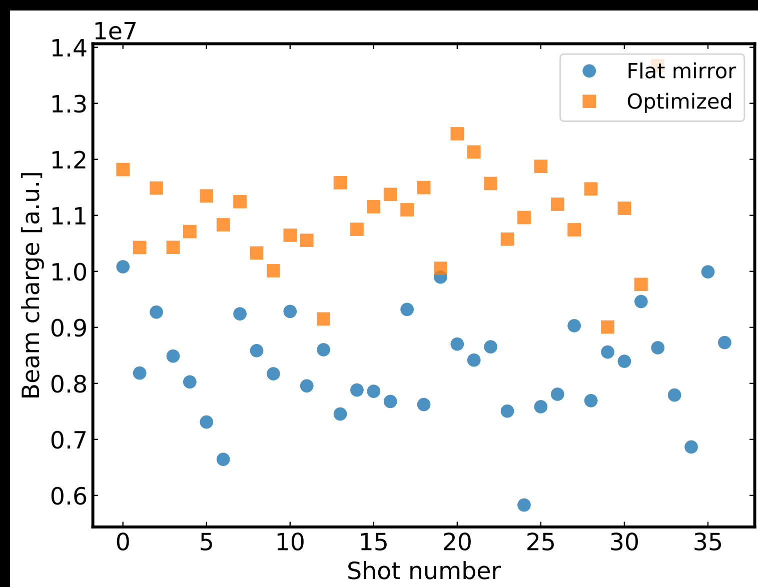


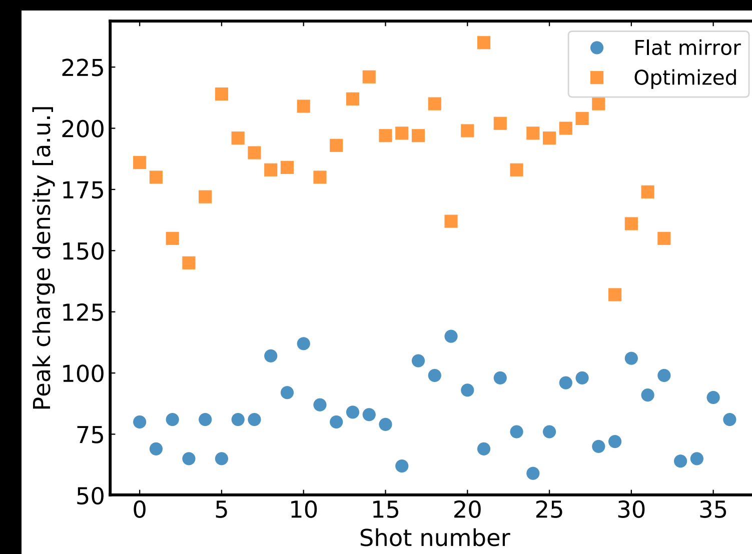
- Near-critical-density achievable with regular gas target
- Much lower critical power for self-guiding
- Higher a_0

Adaptive control of laser-wakefield accelerators driven by mid-IR laser pulses

4um, 20Hz, OPA/OPCPA laser @ University of Maryland

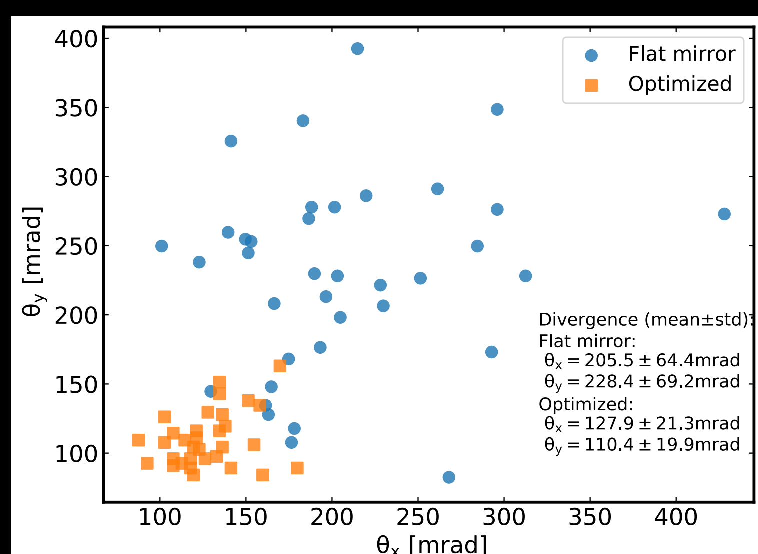
Total beam charge ~40%↑

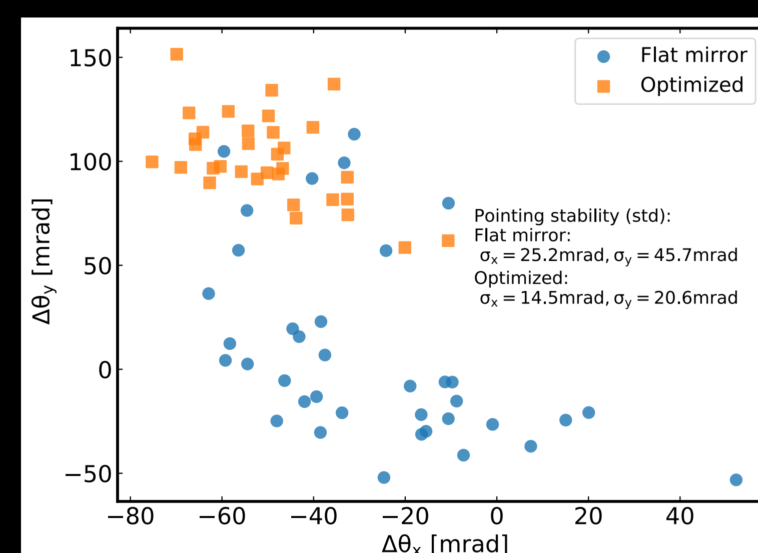




Peak charge density ~3 times ↑

Divergence angle ⇩ to 50%





Pointing instability ⇩ to 50%

J. Lin, Y. Ma, R. Schwartz, D. Woodbury, J. Nees, M. Mathis, A. Thomas, K. Krushelnick, and H. Milchberg, **Opt. Express 27**, 10912 (2019).

Adaptive control of laser-wakefield accelerators driven by mid-IR laser pulses

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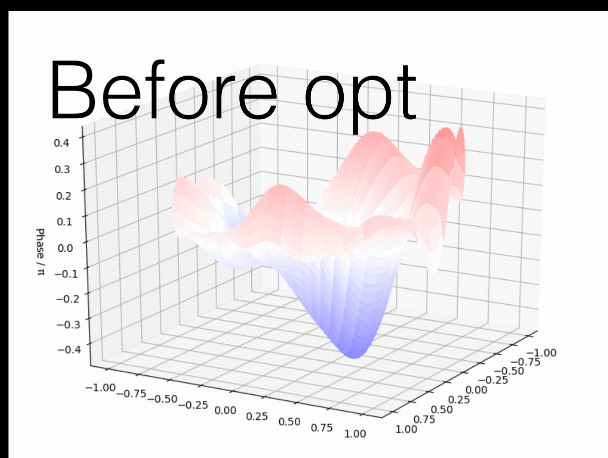
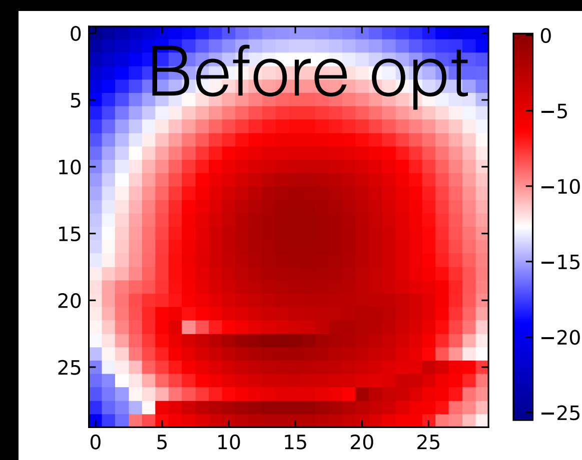
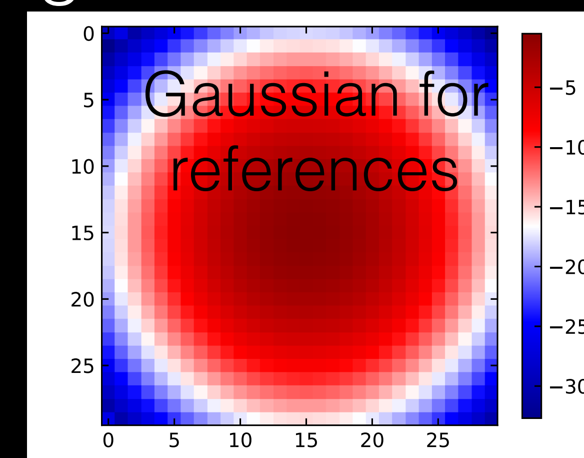
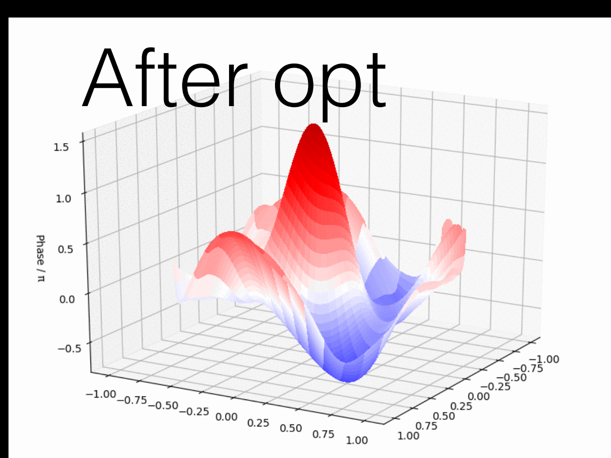
Laser Wavefront on DM

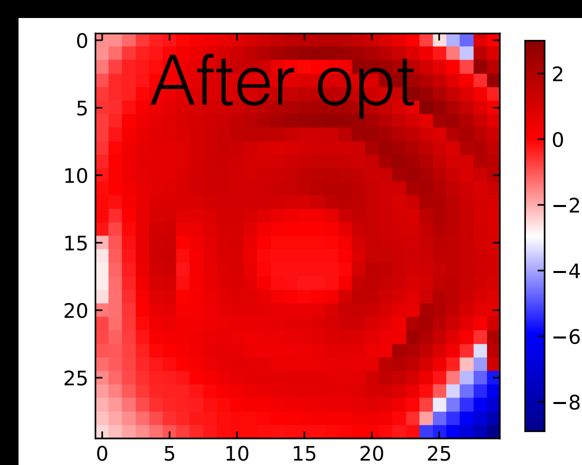
Laser Wavefront on target -500um

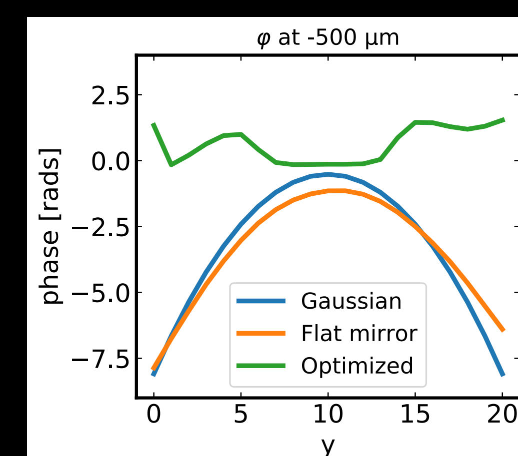












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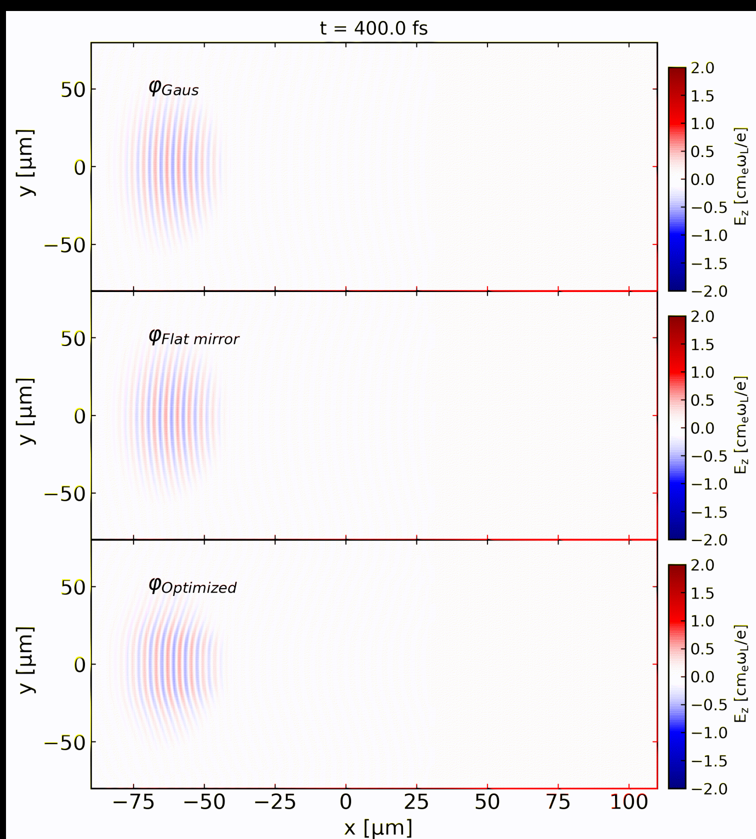
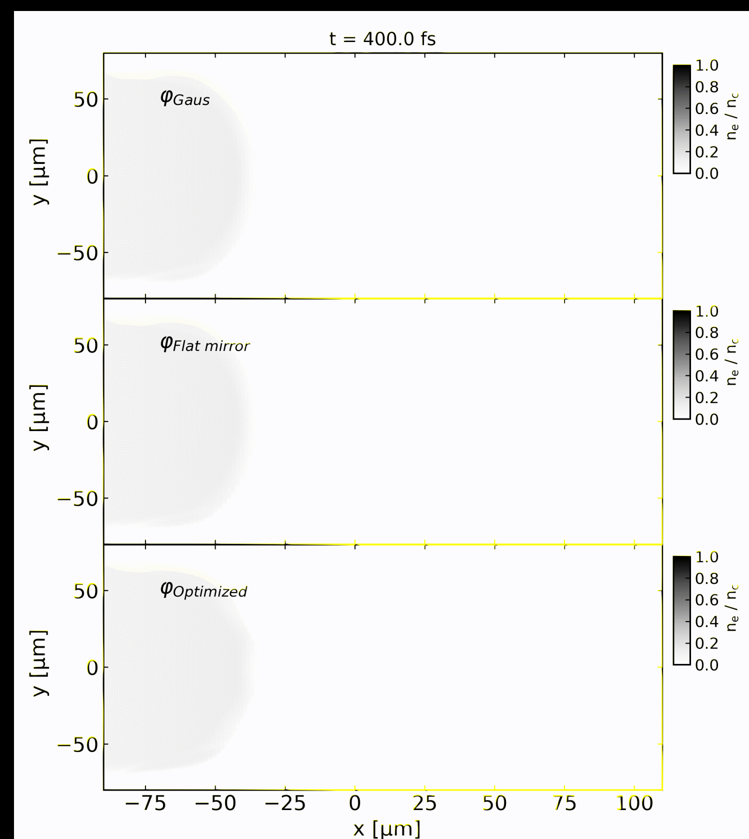
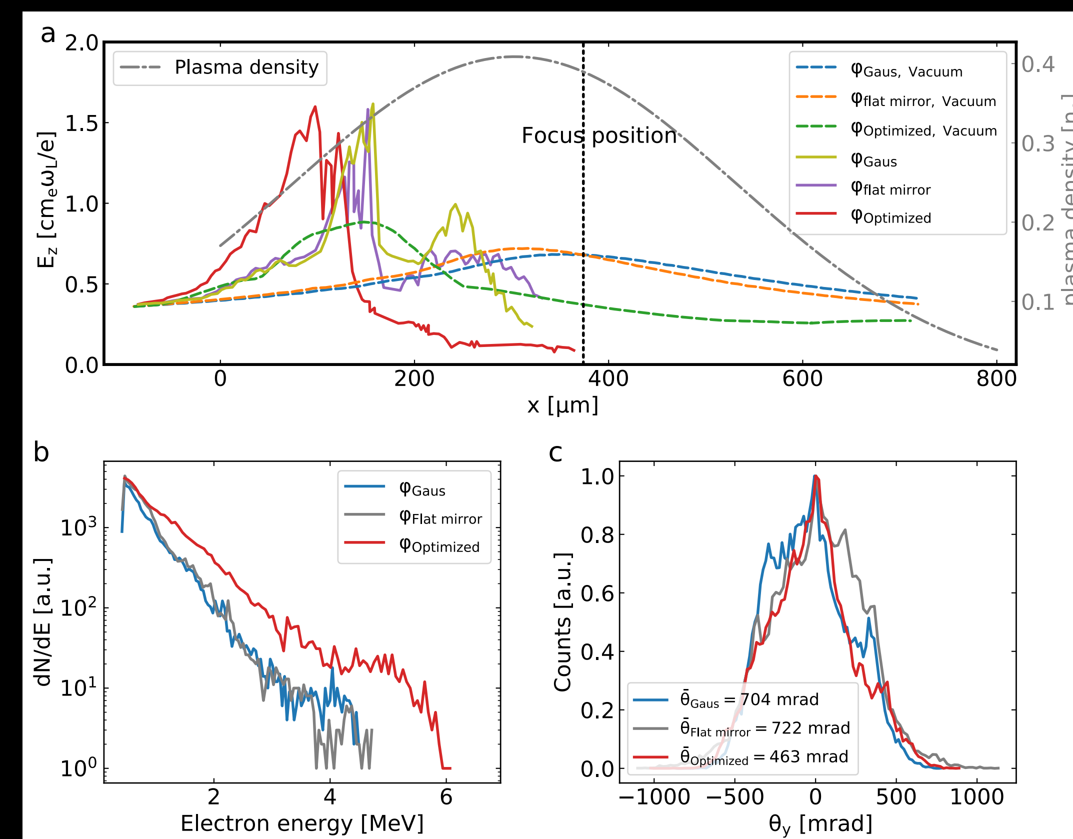


Laser field evolution (with reconstructed wavefronts as input)



Plasma density & particle momentum



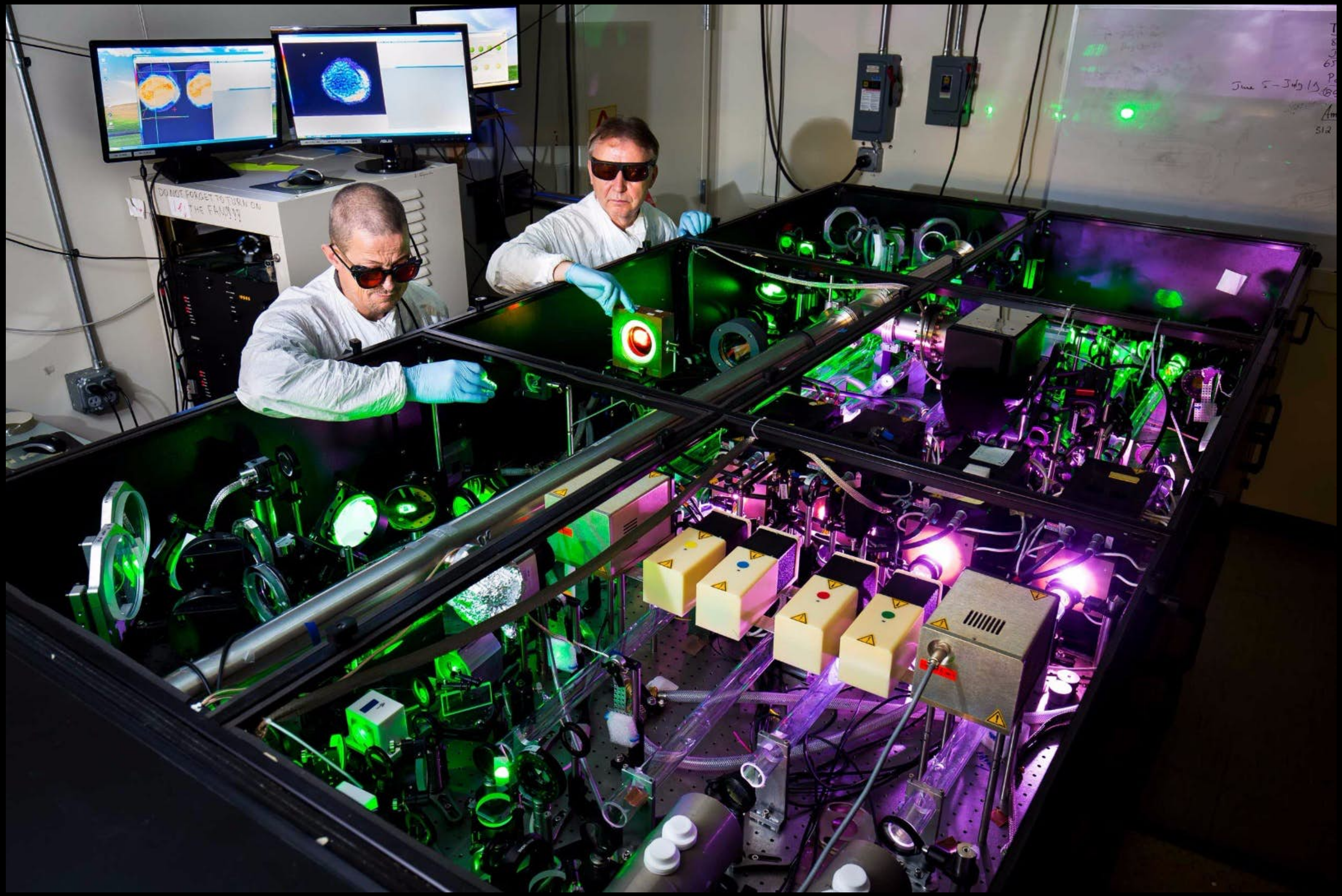
Optimized wavefront results in faster laser focusing and higher peak field strength

LWFA starts at lower density might results in higher energy gain

J. Lin, Y. Ma, R. Schwartz, D. Woodbury, J. Nees, M. Mathis, A. Thomas, K. Krushelnick, and H. Milchberg, **Opt. Express** **27**, 10912 (2019).

An upcoming platform: Hercules PW-scale high rep-rate LWFA @ CUOS

Hercules final amplifier 2017



Delivery of Atlas 100 (100J) and GAIA (5 Hz) pump lasers from Thales in 2019 (via MRI grant funded by National Science Foundation)

An exciting news

THE MICHIGAN ENGINEER NEWS CENTER

RESEARCH | CAMPUS & COMMUNITY | BY DEPARTMENT

Most powerful laser in the US to be built at Michigan

by Kate McAlpine • Michigan Engineering • September 19, 2019

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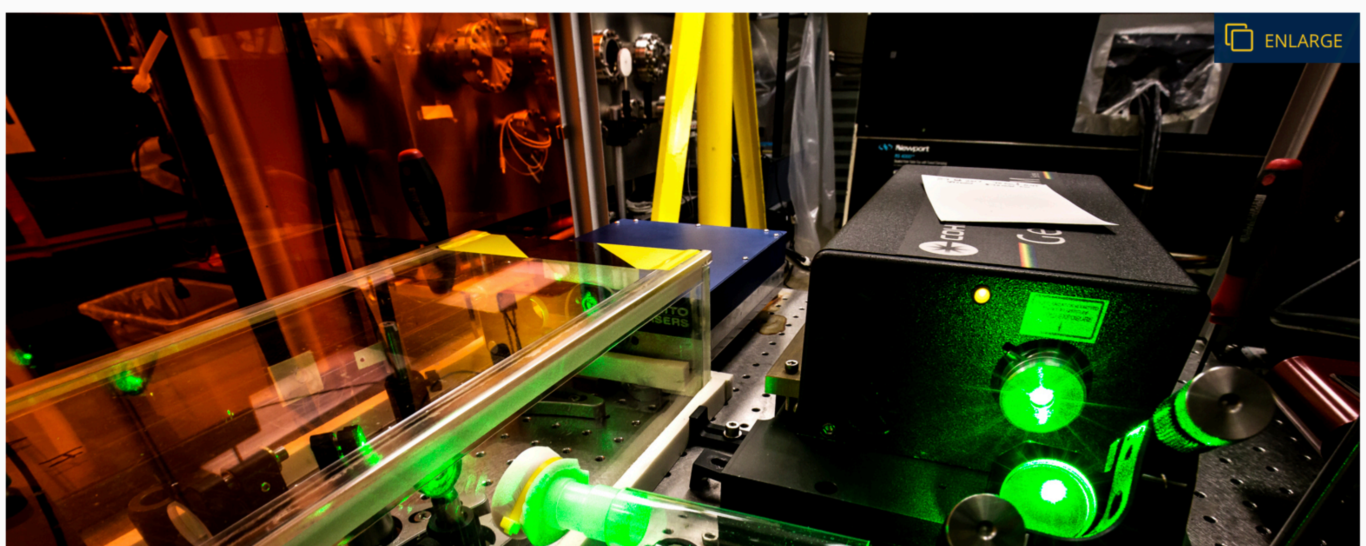
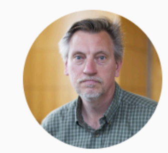
Using extreme light to explore quantum dynamics, advance medicine and more. | **Medium Read**

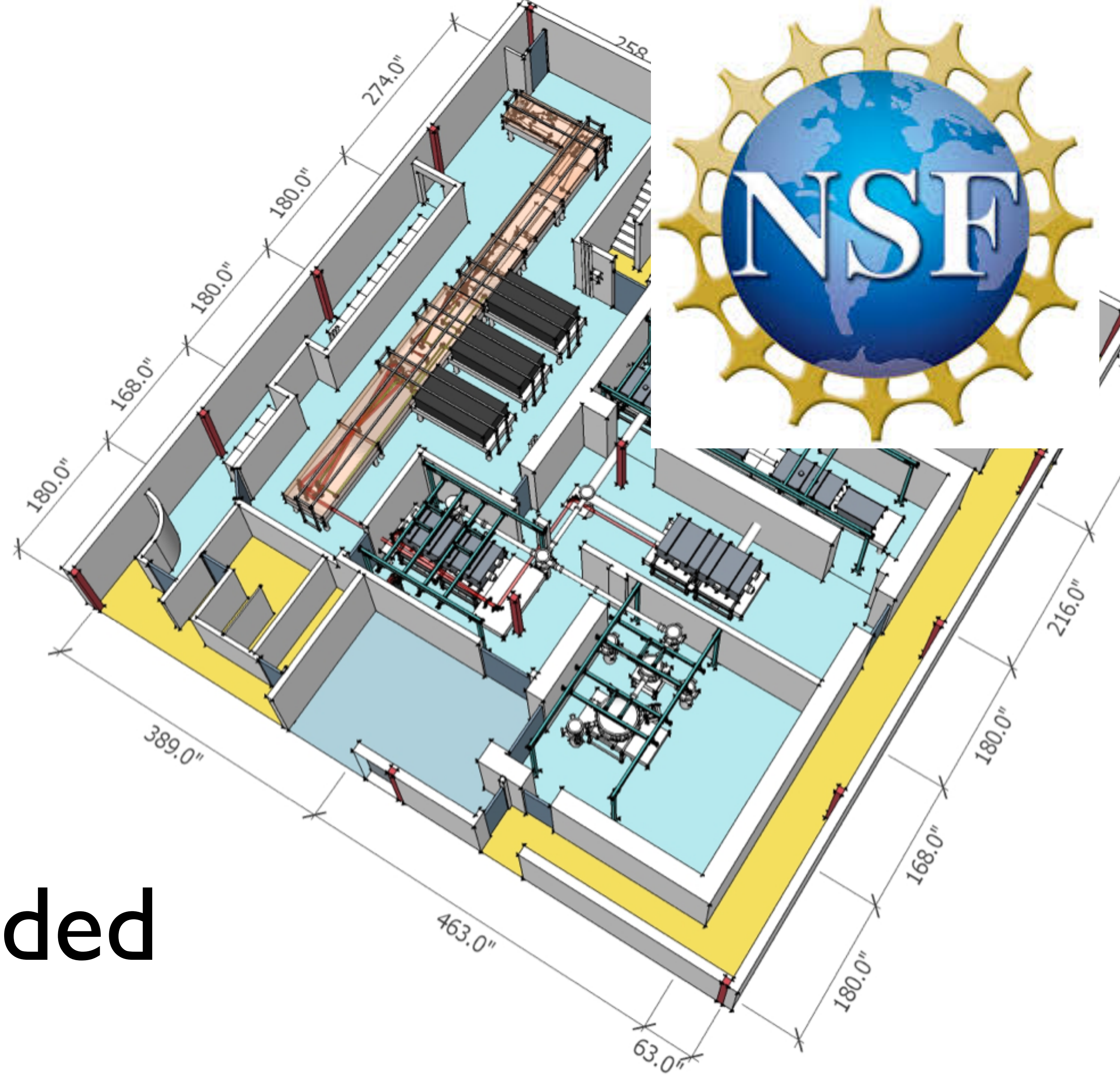


RESEARCHERS



Karl Krushelnick
Professor of Electrical Engineering and Computer Science

Zettawatt
Equivalent
Ultra
Short

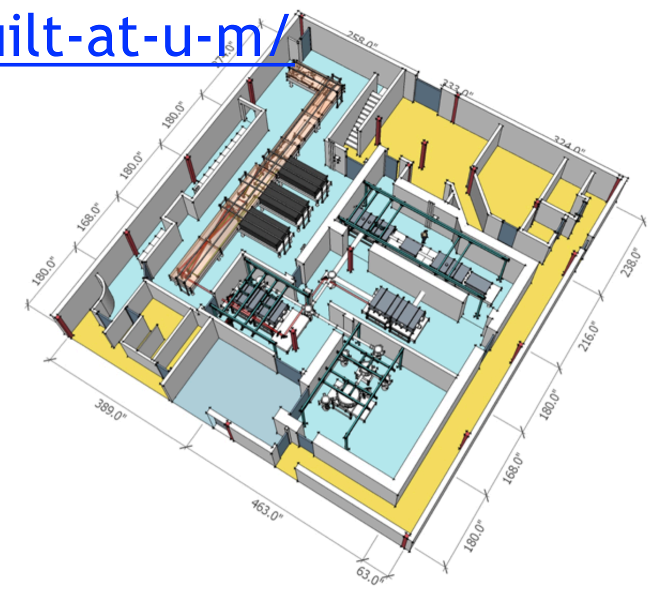


$16 million NSF funded facility @ Michigan

Towards high rep rate 10 GeV beams and QED-Strong Fields with ZEUS

ZEUS: Zettawatt-Equivalent Ultra Short laser

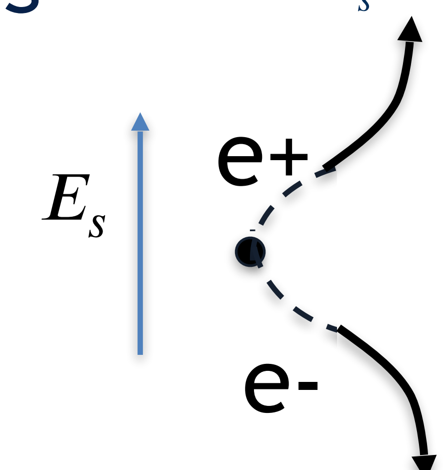
https://news.umich.edu/most-powerful-laser-in-the-us-to-be-built-at-u-m/

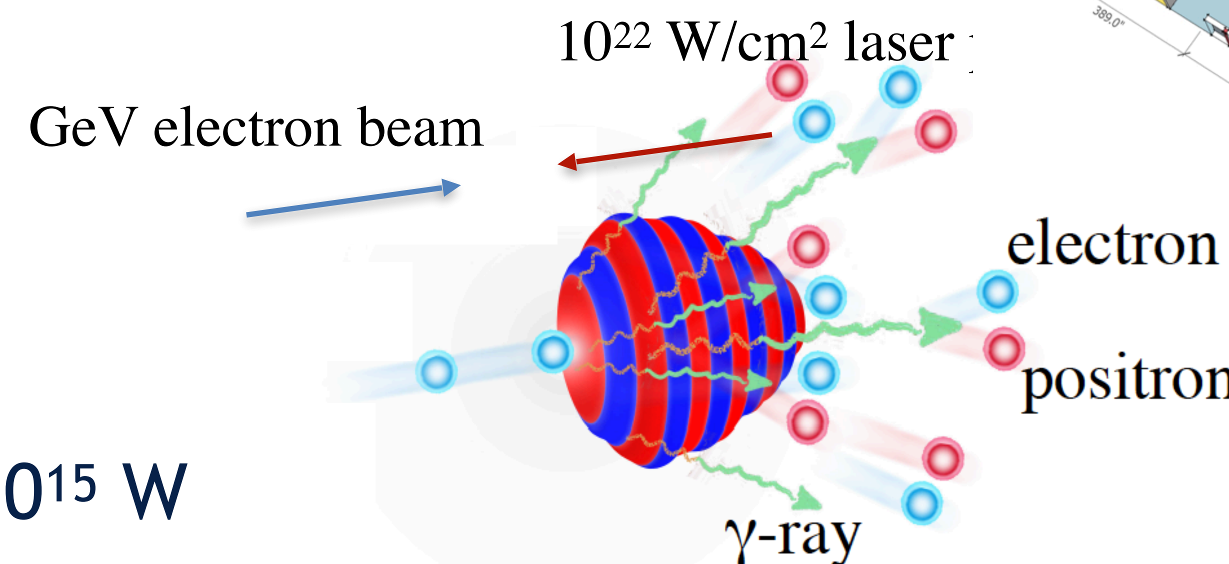


$16 million NSF user facility just announced!

Zettawatt = 10^{21} Watts

Schwinger field $E_s \sim 10^{18}$ V/m

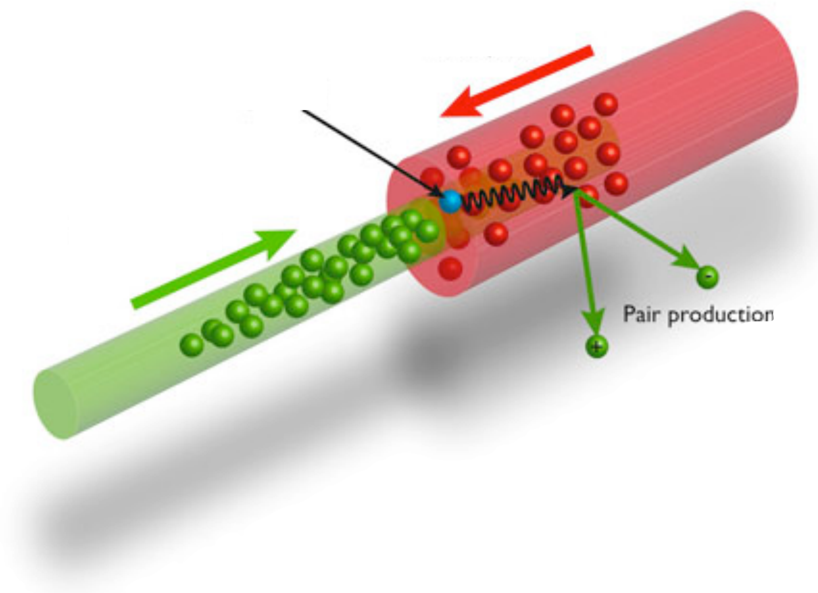




Actual power = 3 PW = 3 x 10^{15} W

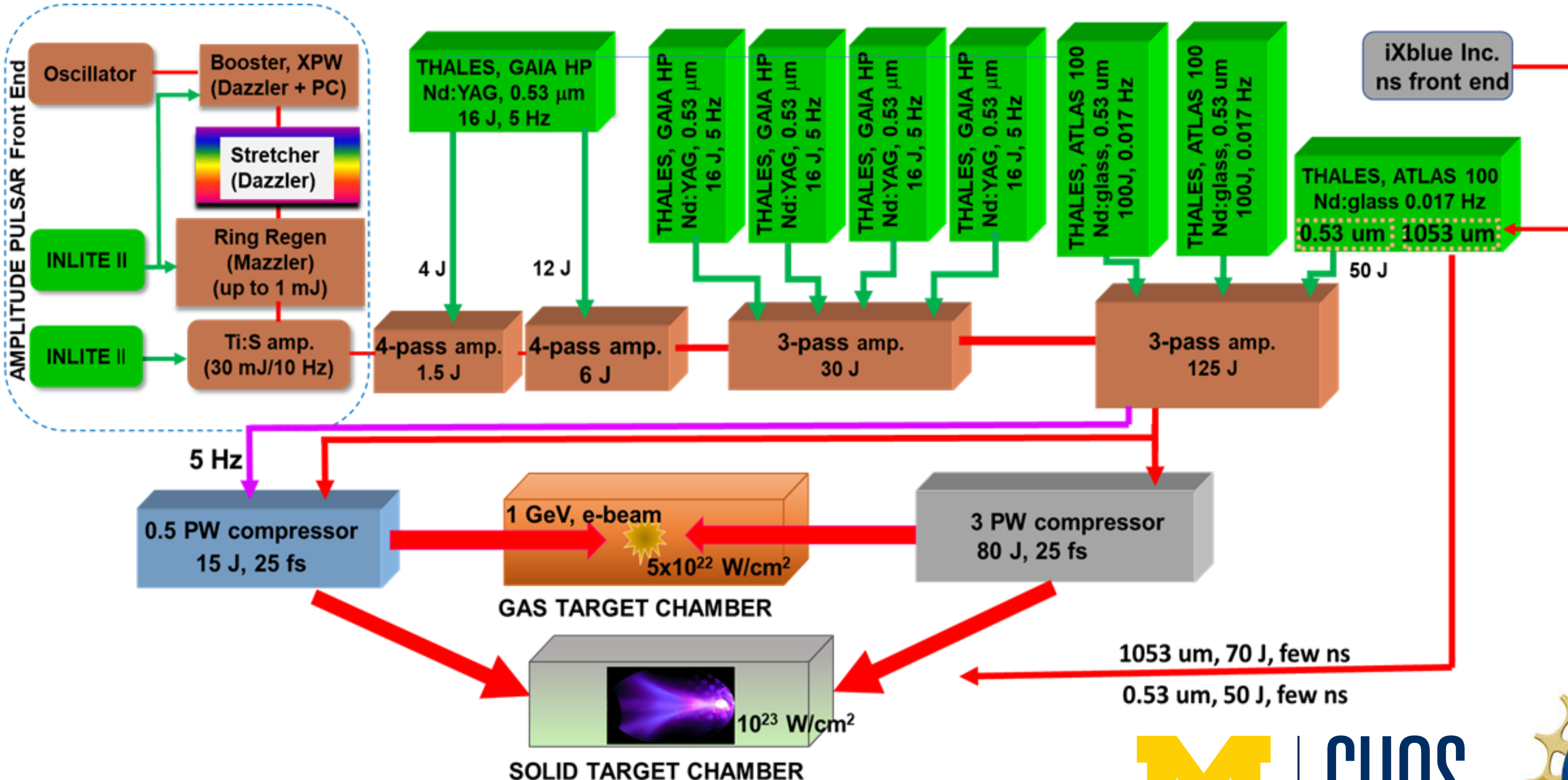
In the rest frame of reference a GeV electron beam the intensity experienced will be equivalent to a Zettawatt power pulse!

What is ZEUS?



- ZEUS is a combined wakefield accelerator / 3 PW laser system building on significant NSF investment at Michigan
- to operate as a 70% user facility, funded by NSF
  - A 500 TW (5 Hz) laser can generate electron beams up to 5 GeV
  - 2.5 PW laser can be focused to 10^{23} $\mathrm{Wcm^{-2}}$, greatly exceeding the Schwinger field (in electron rest frame)

ZEUS: Zettawatt-Equivalent Ultra Short laser



M | CUOS

NSF

ZEUS: Approximate timeline

System design

Building construction

Laser assembly

Target area assembly

Commissioning experiments

NSF user facility
70% outside user time

2020 | 2021 | 2022 | 2023 | 2024

Upgrade Hercules operating

Summary

- High rep-rate LWFA at University of Michigan, RAL, University of Maryland (Mid-IR)
- Adaptive control of LWFA with DAZZLER & DM via Genetic Algorithm
- ZEUS is on the way!

Outlook

- Include target control rather than just the laser pulse into the active feedback optimization
- Implement Convolutional Neural Network Architecture (collaborating with Prof. Sandra Biedron and Aasma Aslam from UNM)

Thank you!