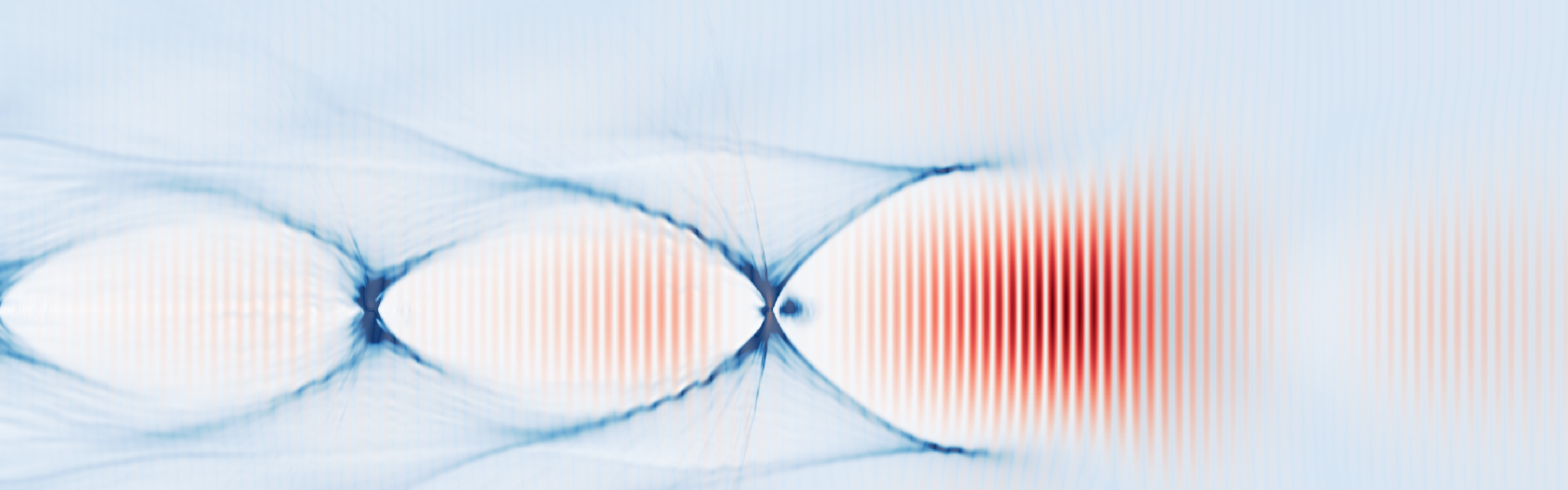

BEETLE

LPA using an industrial Yb-laser system with 1kW average power

Timo Eichner

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on behalf of BEETLE project team

HELMHOLTZ

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DESY.

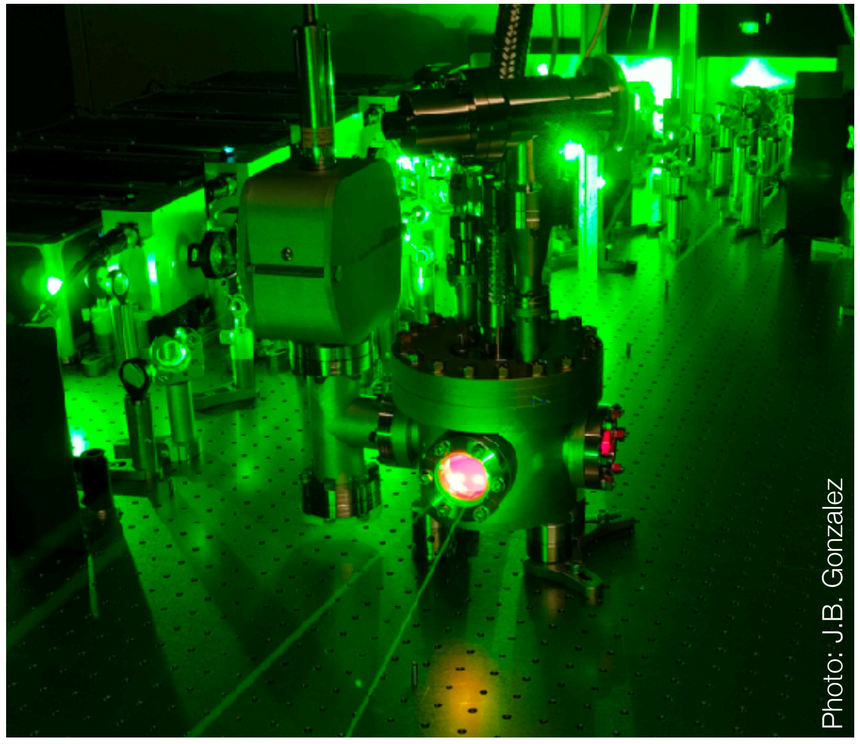
Lasers for high rep-rate LPA

Ti:Sapphire: workhorse-technology but challenging to scale

KALDERA tries to push the boundaries of Ti:Sapphire

Goal:

- 3J, 30fs, 100TW @ up to kHz repetition rate
- GeV-level, few-% energy spread & stability



Lasers for high rep-rate LPA

Ti:Sapphire: workhorse-technology but challenging to scale

KALDERA tries to push the boundaries of Ti:Sapphire

Goal:

- 3J, 30fs, 100TW @ up to kHz repetition rate
- GeV-level, few-% energy spread & stability

… but other laser technologies exist too.

(Especially for more moderate e^--parameters)

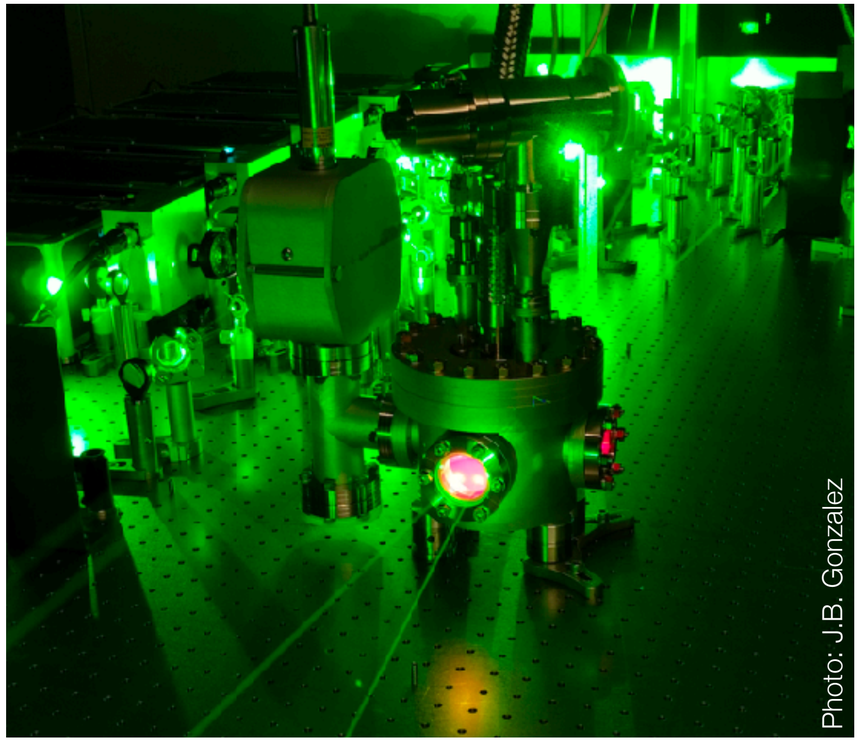
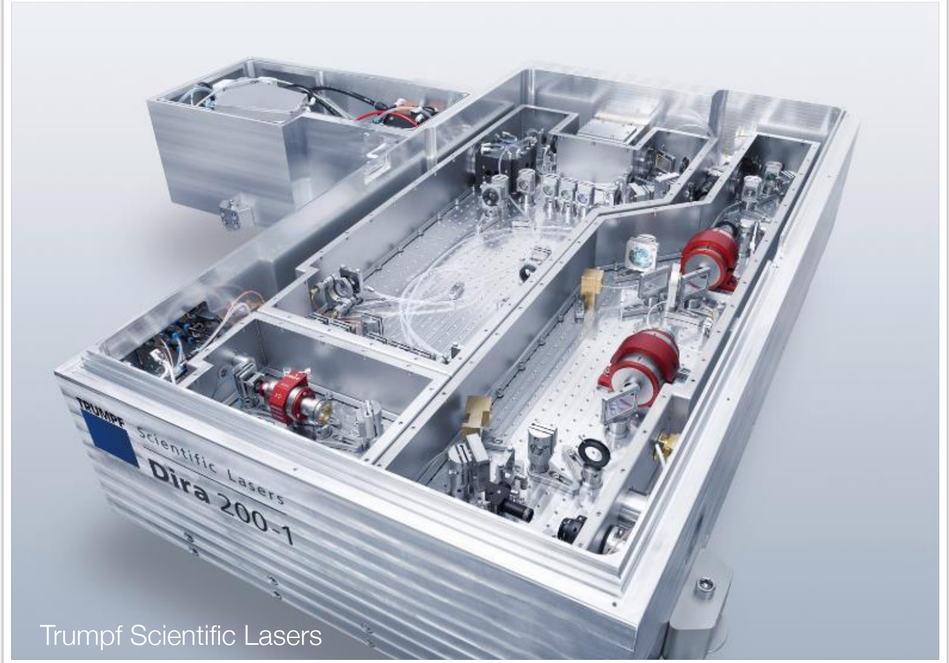


Photo: J.B. Gonzalez

Potential solution

Yb for efficiency, reliability & high repetition rate

- **Yb-based lasers** are available for various **industrial applications**
  - Can deliver **sub-ps pulses at kW level**
- **Post-compression to tens of fs** pulse durations is possible
  - Energy scaling is challenging…
  - … but should be sufficient for 100MeV-level LPA
- Could enable **LPA at kHz repetition rates** for industrial and medical applications



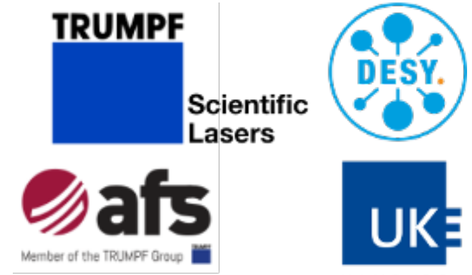
Trumpf Scientific Lasers

Y. Pfaff, *et al* "Nonlinear pulse compression of a 200 mJ and 1 kW ultrafast thin-disk amplifier," Opt. Express 31, 2023

BEETLE

kHz-level LPA using post compressed laser pulses

- Using **post-compressed industrial Yb-lasers** for kHz LPA
- **BMFTR** funded project, started early 2024
  - **Trumpf Scientific Laser & AFS**: Laser and spectral broadening
  - **DESY**: Pulse compression & LPA
  - Hamburg University Hospital **UKE:** initial VHEE/FLASH experiments



Bundesministerium
für Forschung, Technologie
und Raumfahrt

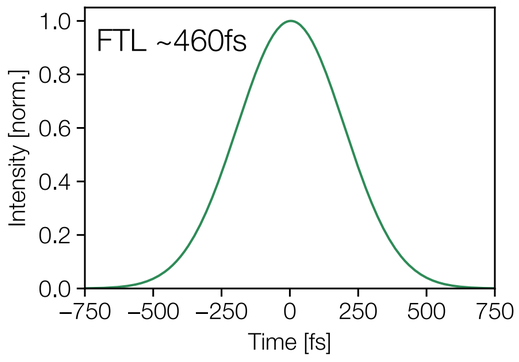
BEETLE

Project overview

TRUMPF

afs
Member of the TRUMPF Group

Dira Laser
200mJ, kW average power,
~500fs pulses



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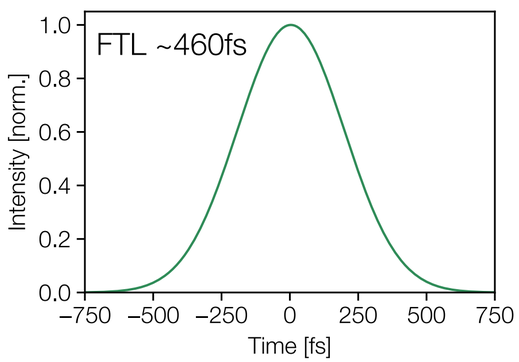
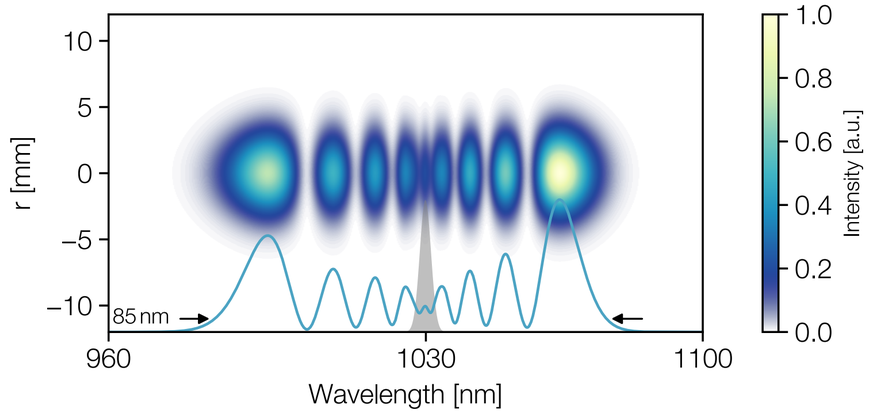
Project overview

TRUMPF

Dira Laser
200mJ, kW average power,
~500fs pulses

TRUMPF Multi-pass cell (MPC)*
Spectral broadening





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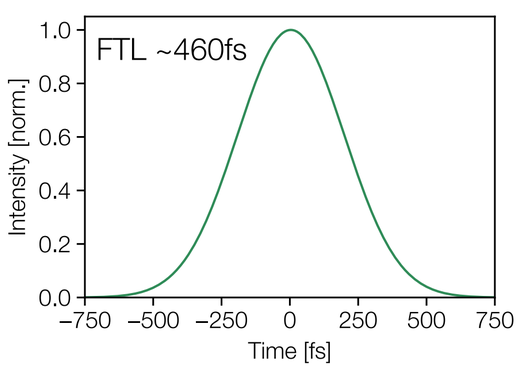
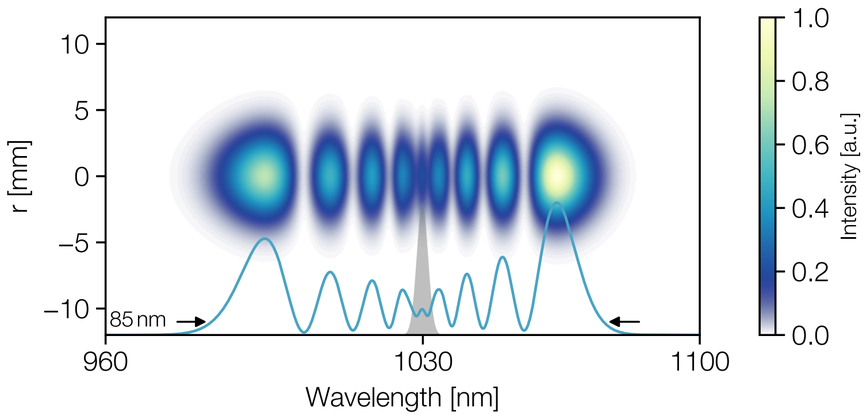
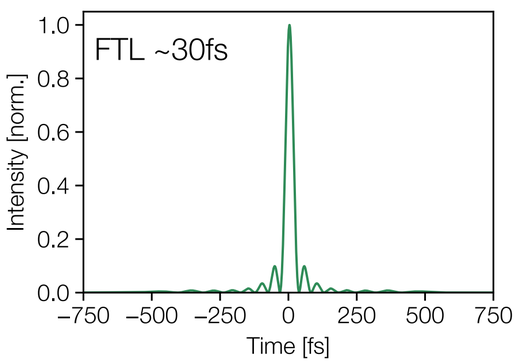
DESY.

Pulse compressor
Compression to ~30 fs







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BEETLE

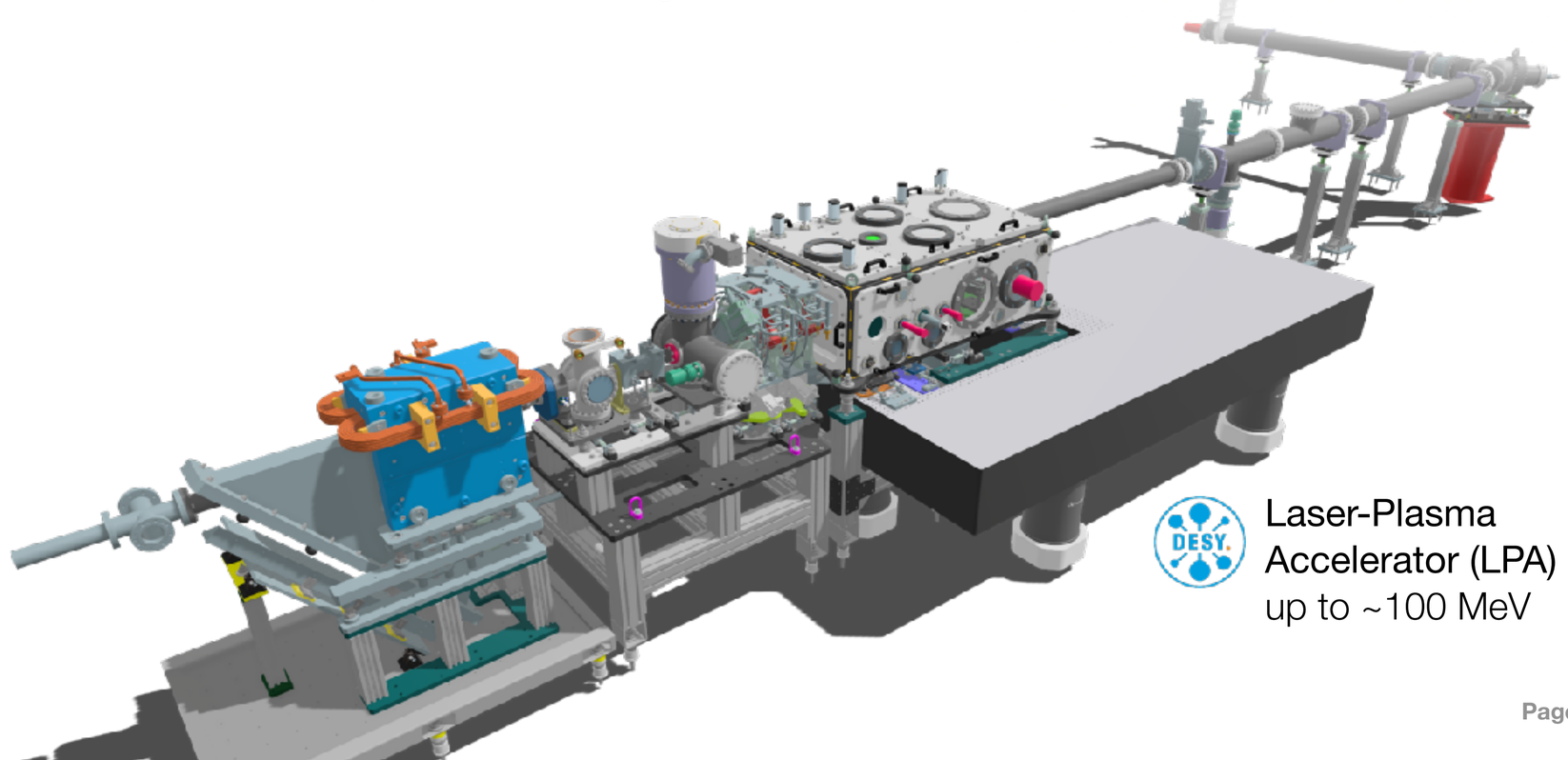
Project overview

Dira Laser
200mJ, kW average power,
~500fs pulses

Multi-pass cell (MPC)
Spectral broadening

Pulse compressor
Compression to ~30 fs

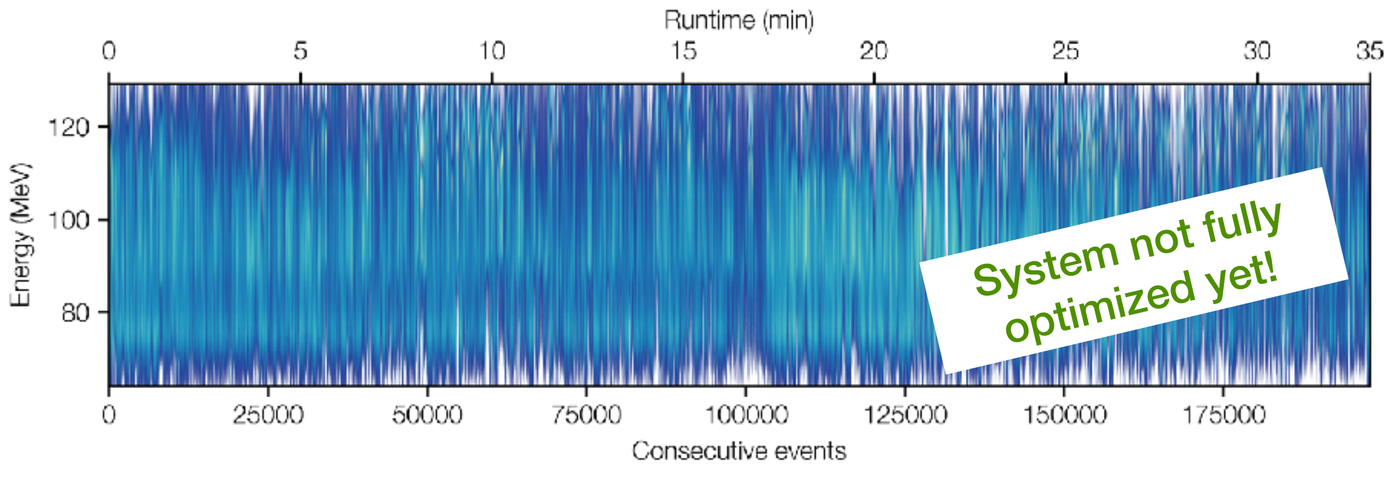
- **Existing** accelerator **setup**
- Already delivering up to
  ~150MeV, 10s of pC @100Hz
- Only **minor adaptations required**
  for BEETLE



Laser-Plasma Accelerator (LPA)
up to ~100 MeV

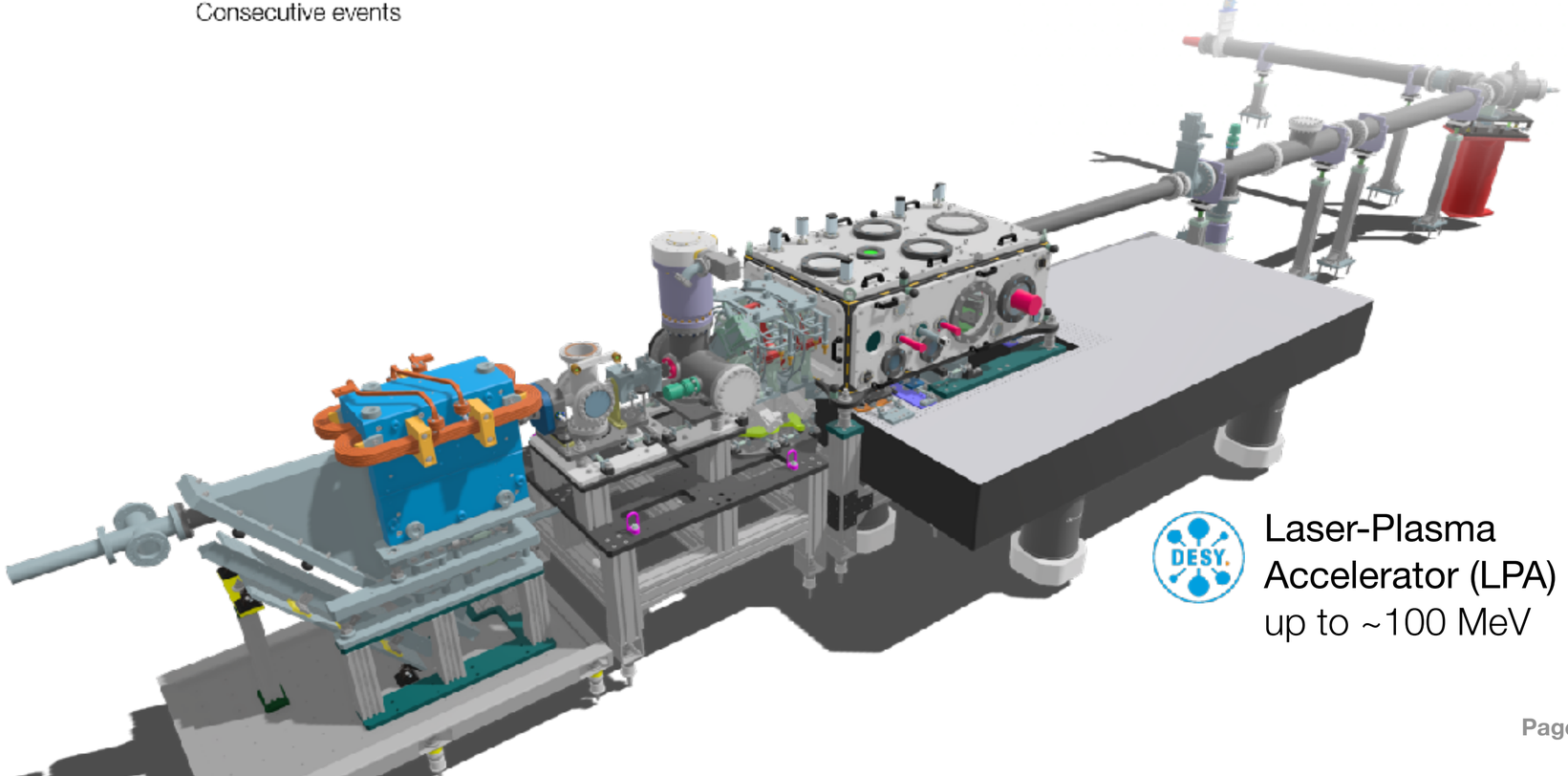
BEETLE

Project overview



LPA development & operation:
Manu & team

- **Existing** accelerator **setup**
- Already delivering up to ~150MeV, 10s of pC @100Hz
- Only **minor adaptations required** for BEETLE



Laser-Plasma Accelerator (LPA) up to ~100 MeV

Spectral broadening

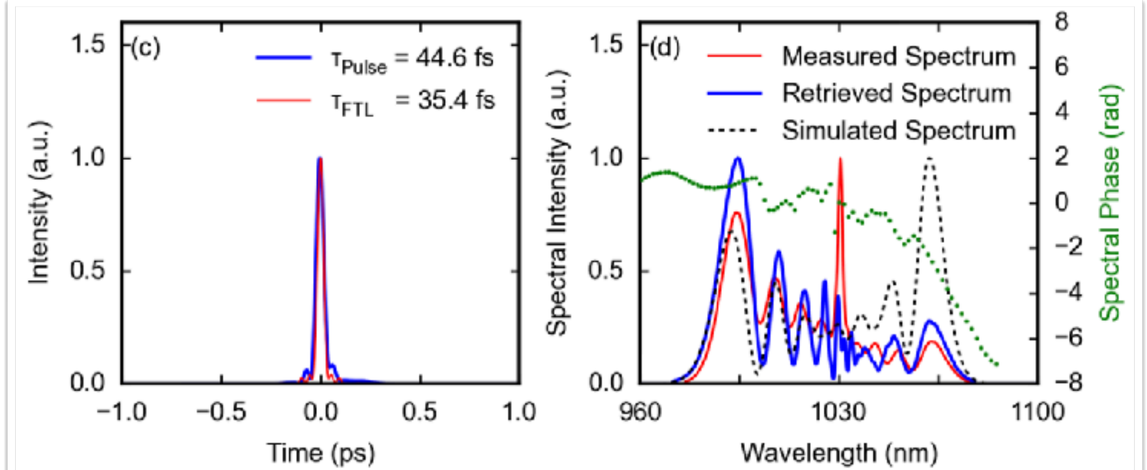
kW laser system & Multipass cell

Spectral broadnening
DIRA laser system

- Industrial, Yb-thin disk laser system
- Custom high contrast frontend
  - OPCPA based, free space stretcher
  - 200mJ pulse energy
- Up to 5kHz repetition rate
- 460fs duration
- 1030nm

Spectral broadnening

High energy, gas-filled multi-pass cell



- 10m mirror separation
- ~800mbar Helium
- 24 passes

Down to ~35fs FTL @ 200mJ demonstrated:

Y. Pfaff, *et al* "Nonlinear pulse compression of a 200 mJ and 1 kW ultrafast thin-disk amplifier," Opt. Express 31, 2023

Optimization for BEETLE ongoing

Compression

GTI compressor for 200mJ, 1kW pulses

R. Hanednousavian

GTI based pulse compression

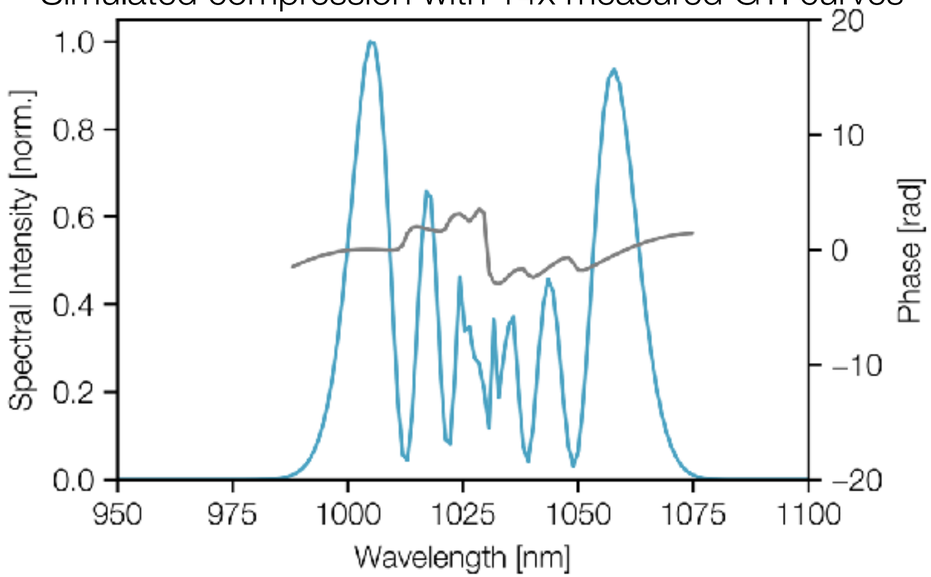
Compressor concept

- GTI mirror based compressor
  - Up to 20 6” mirrors required
  - To compensate ~4000fs^2
- Thorough evaluation of potential vendors done
  - GDD/Reflectivity
  - LIDT
  - Surface defects, absorption

GTI based pulse compression

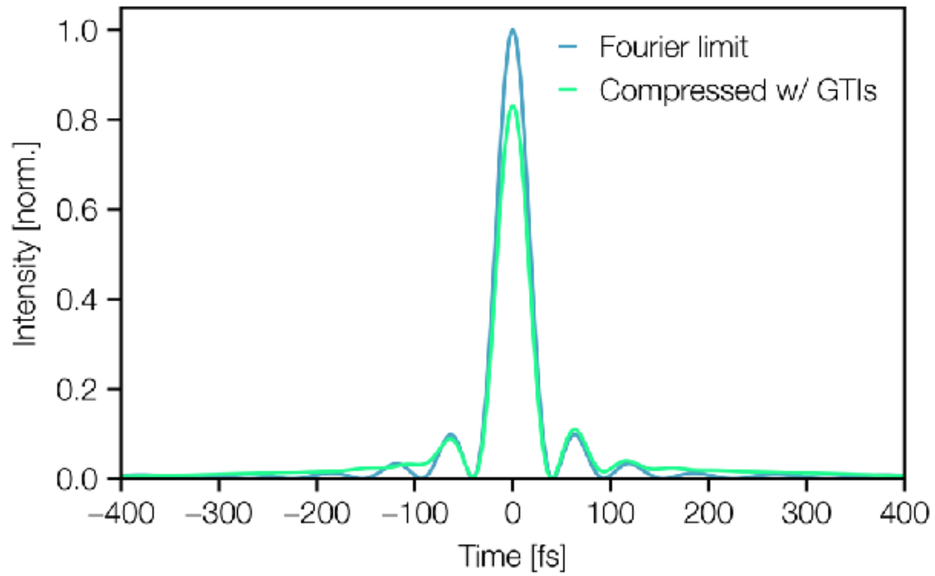
Phase & compression quality

Simulated compression with 14x measured GTI curves



- Temporal quality mostly limited by:
  - Spectral shape
  - Higher order phase out of MPC

Simulated temporal profile



- Compressed duration: ~36fs
- Peak power: 83% of FTL

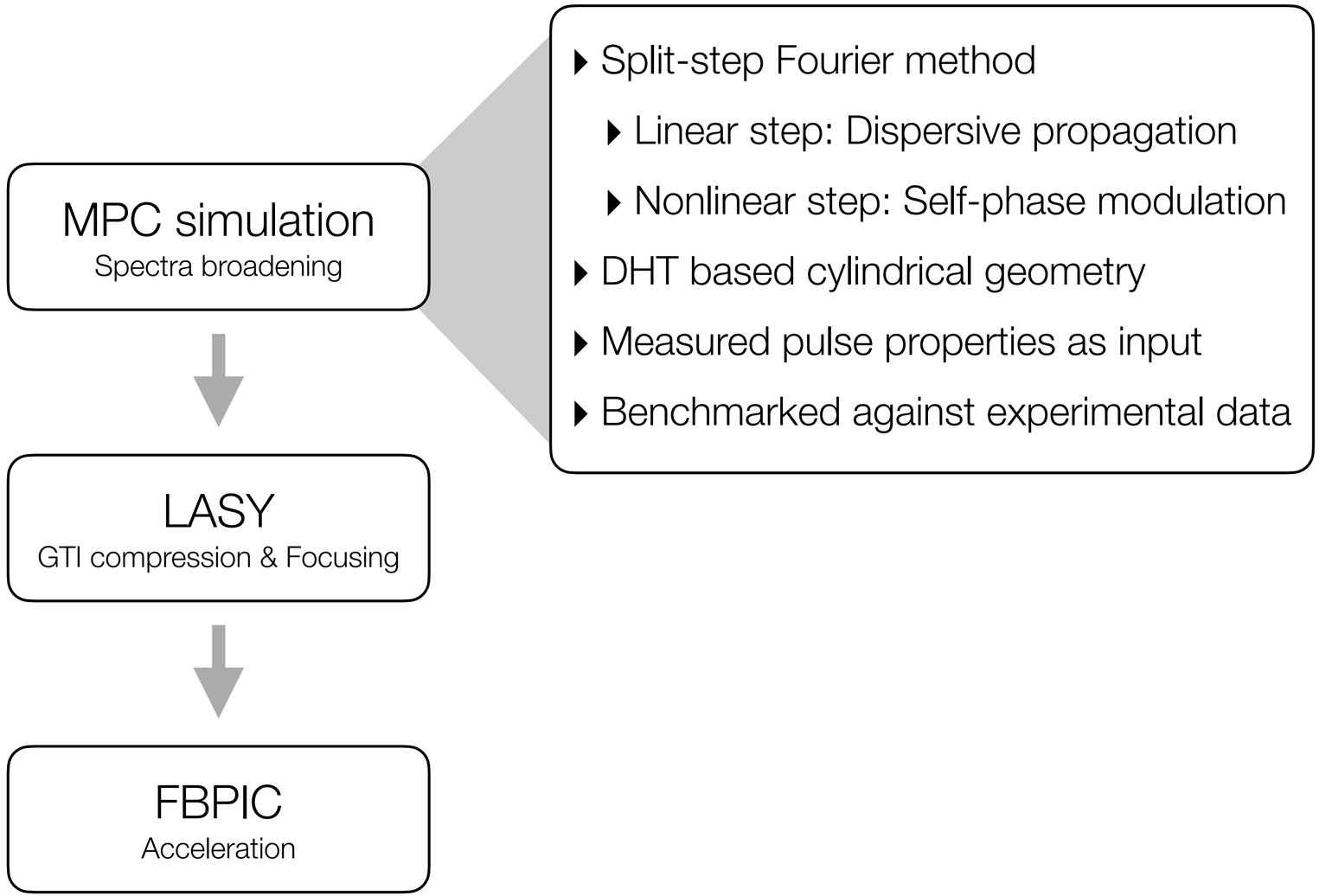
Acceleration

Adapting the proven MAGMA accelerator to 5kHz operation

Fig: S. Jalas

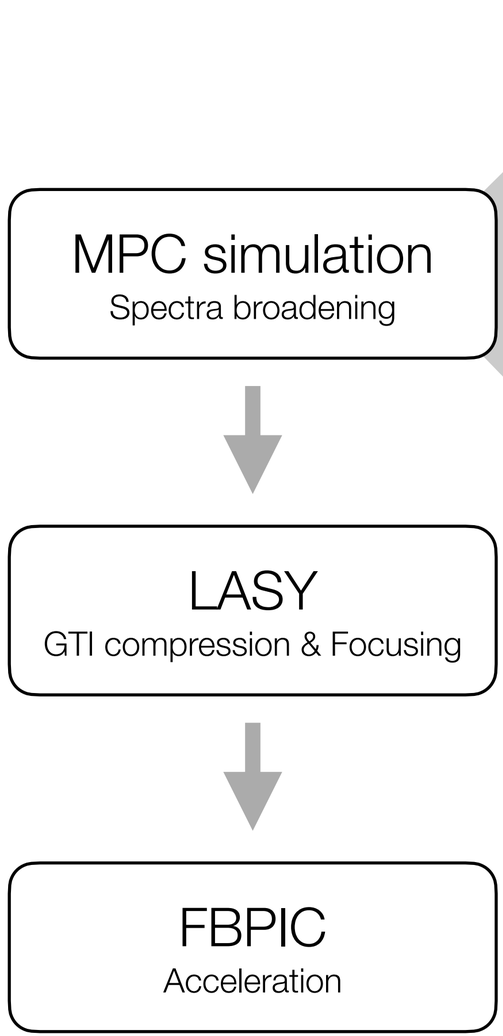
Start-to-end simulation toolchain

Realistic simulation using post compressed pulses



Start-to-end simulation toolchain

Realistic simulation using post compressed pulses



- Split-step Fourier method
  - Linear step: Dispersive propagation
  - Nonlinear step: Self-phase modulation
- DHT based cylindrical geometry
- Measured pulse properties as input
- Benchmarked against experimental data

- Only ~8min for a full simulation on 4 GPUs
  - Despite large simulation box to cover temporal background
- Allows fast simulation studies for optimization & exploration of experimental parameters

Start-to-end simulation toolchain

Optimization & Exploration of parameter space

Exploration of parameter space

- Bayesian multi-objective optimization helps to
  - understand trade-offs between electron parameters
  - explore parameter space
  - optimize MAGMA for new drive laser

Start-to-end simulation toolchain

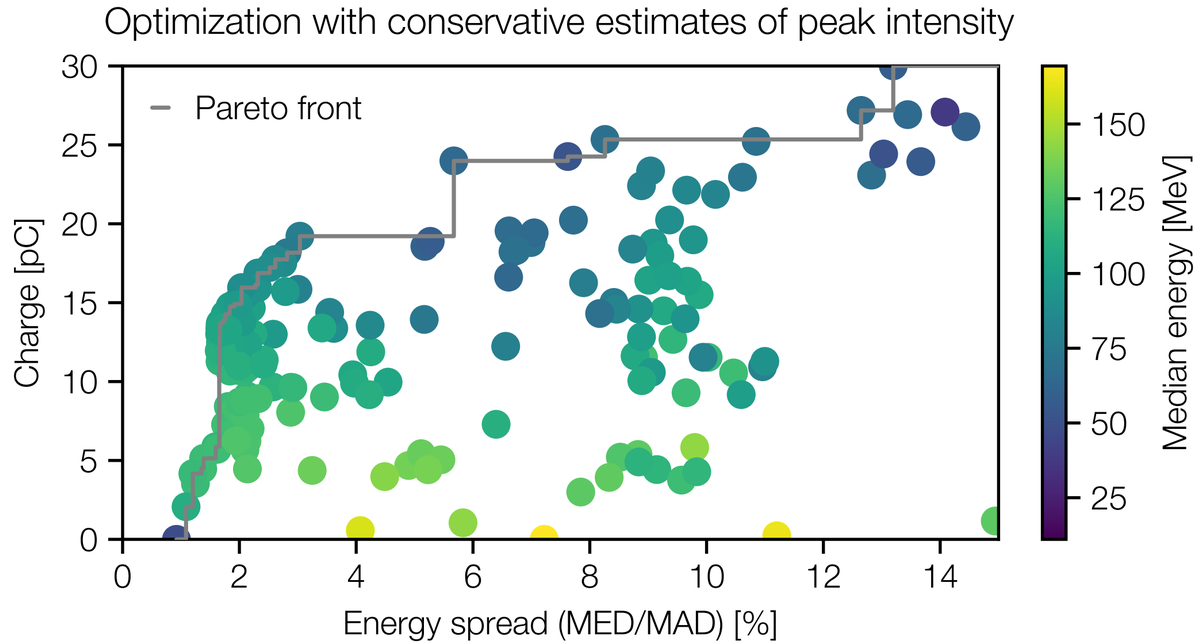
Optimization & Exploration of parameter space

Bayesian multi-objective optimization

- MAGMA-type LOCII target
  - Scaled to allow for higher density

Varied parameters:

- Plasma density
- Ar-doping concentration
- Focal length
- Focus position



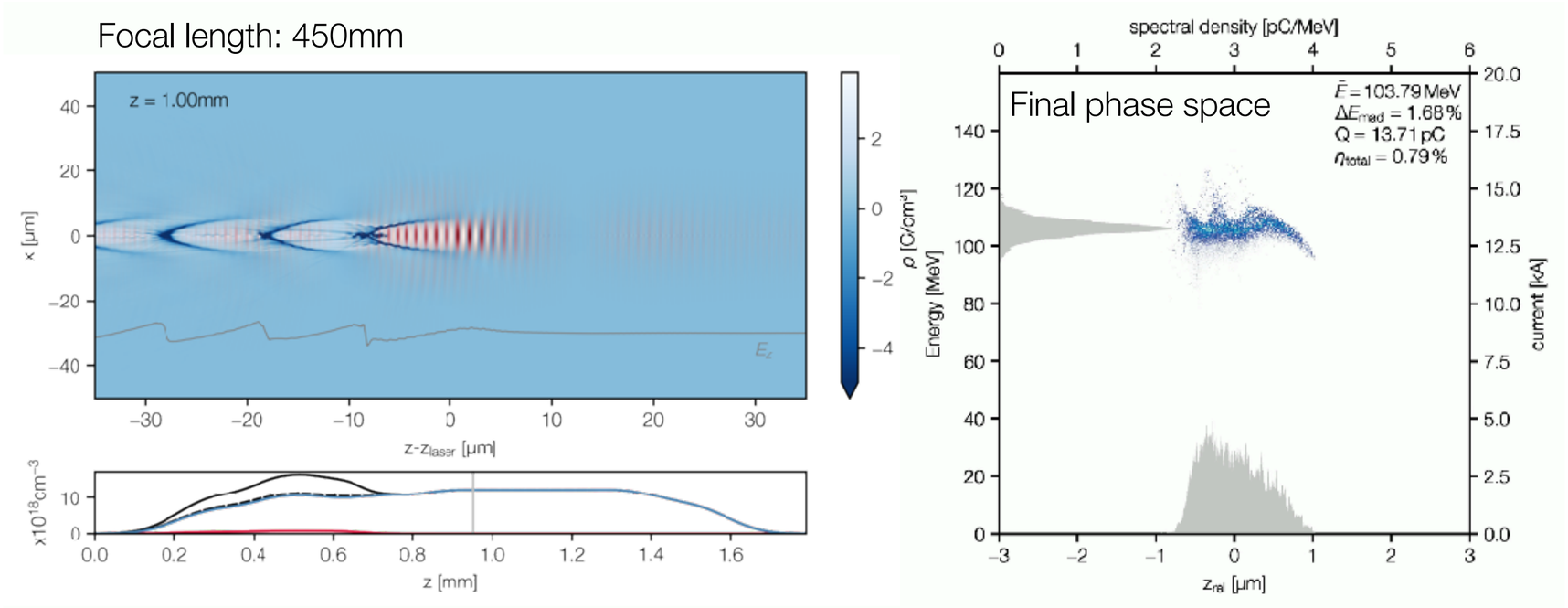
Expected electron parameters:

- <20pC, ~100MeV, few-% MAD/MED @ up to 5kHz

Start-to-end simulation

Example working point

Simulation with conservative estimates of laser peak intensity



- Relatively high density required
  - Potentially not ideal for stability, but sufficient for LPA demonstration

Summary

BEETLE: Pursuing multi-kHz LPA using industrial Yb-lasers

- Close collaboration with Trumpf Scientific Lasers & DESY
- Post-compression poses unique challenges for LPA
  - … but 100MeV, 10-20pC bunches seem reasonable

Next steps:

- Conceptual design ready, detailed preparations ongoing
- Experiments scheduled to start late 2026 / early 2027

Thanks for your attention

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HELMHOLTZ

DESY.