The HED instrument at European XFEL: Unique capabilities to study material properties of laser-compressed matter

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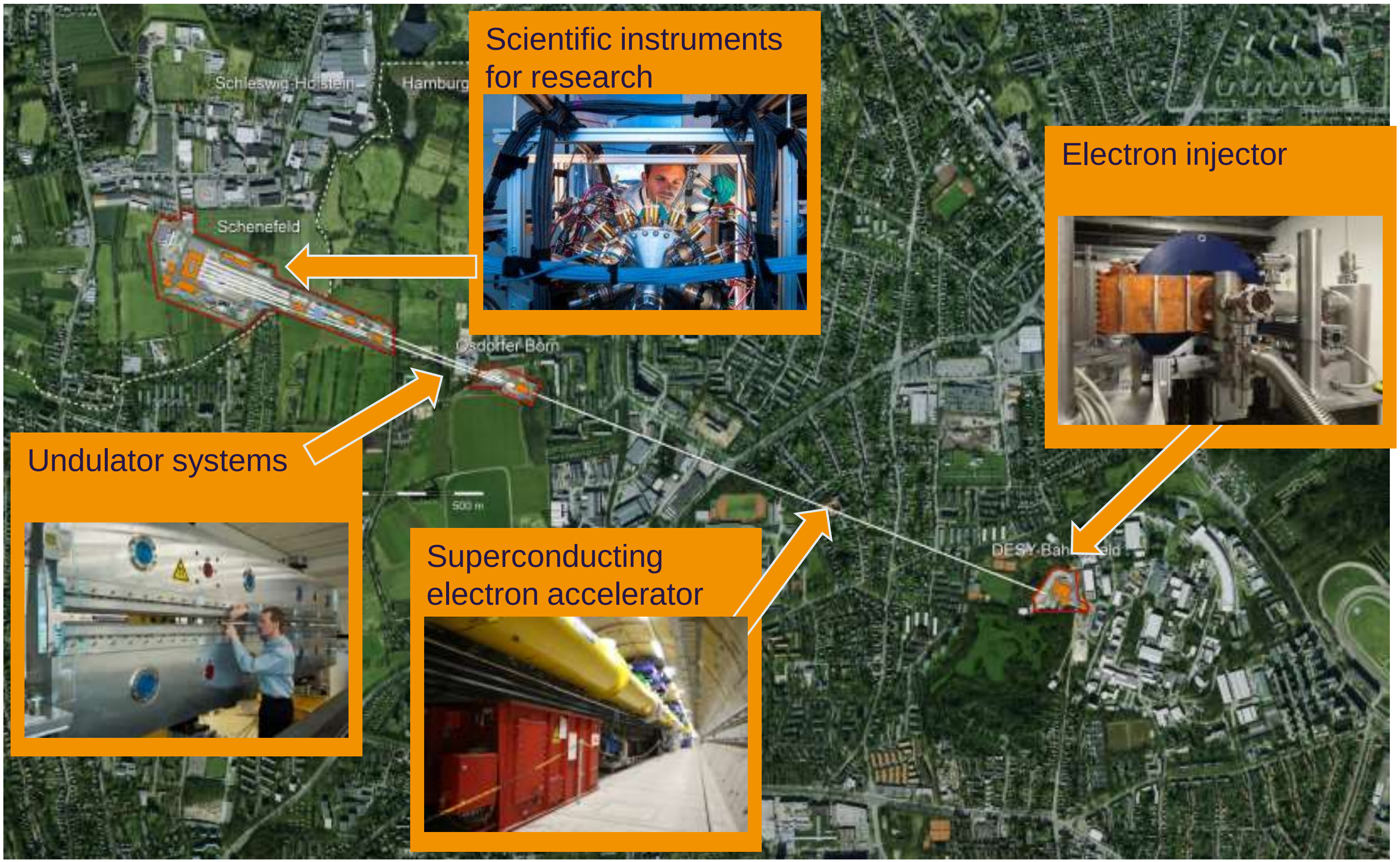
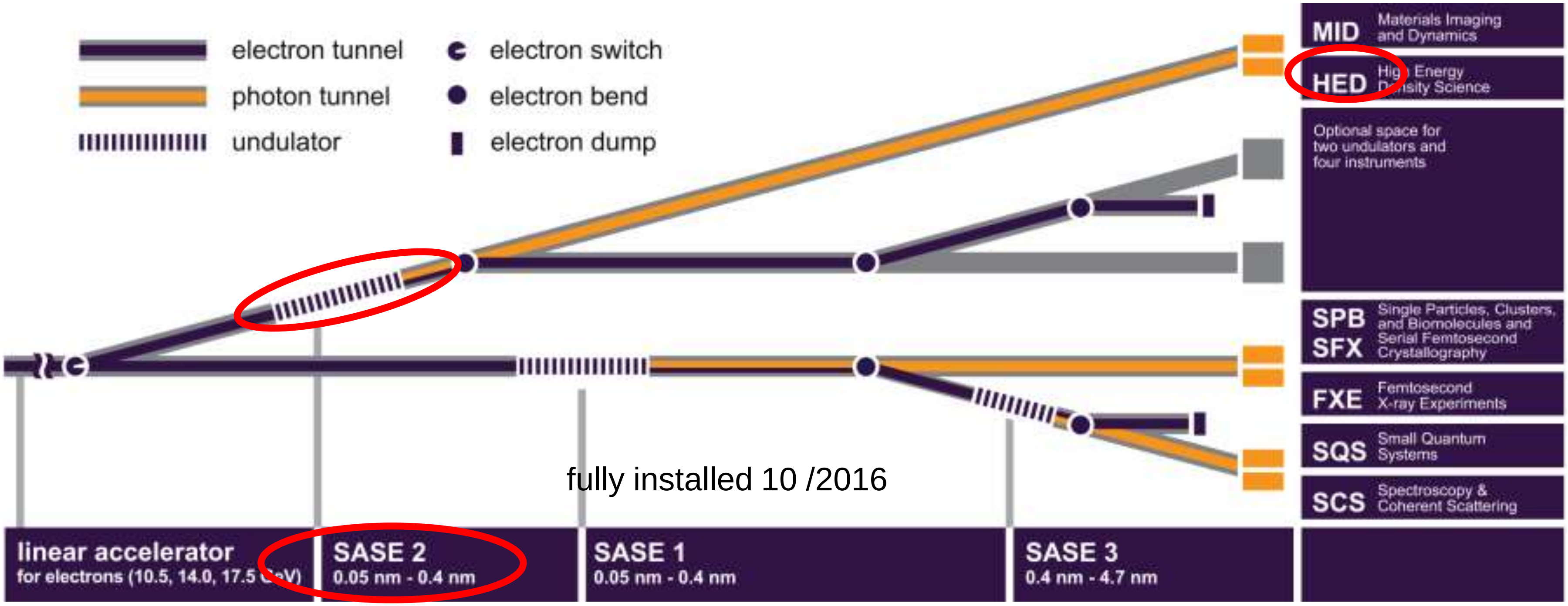
For the HED-HiBEF instrument

European XFEL – overview



European XFEL: beamlines and instruments

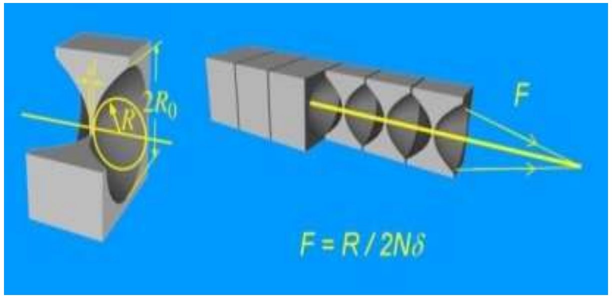


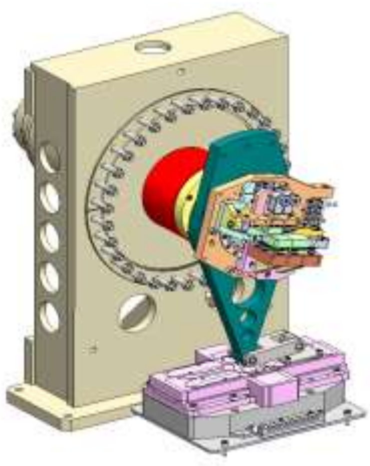
HED – some numbers

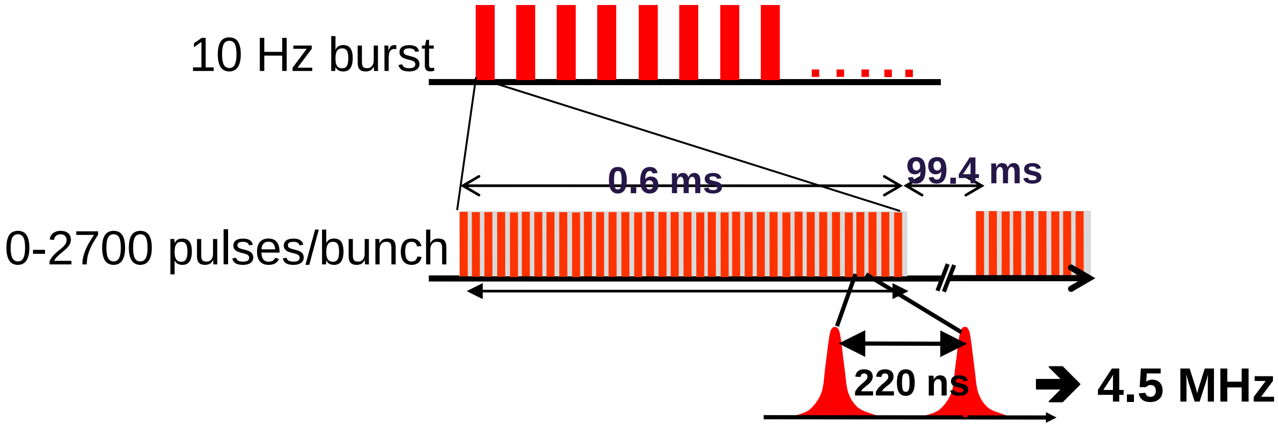
- Beamline commissioning 2019, first user experiments spring 2019
- Typically 20 experiments/year
- Photon energies: 5-25+ keV
- Pulse energies: > 3 mJ @ 8 keV

XFEL properties at the HED instrument

- Burst mode with 220 ns spacing between x-ray pulses
- Mirrors for harmonic supression
- Focussing of x-ray beam with CRLs, mm to sub-mum possible
- Monochromators to reach 10^{-4} to 10^{-6} bandwidth

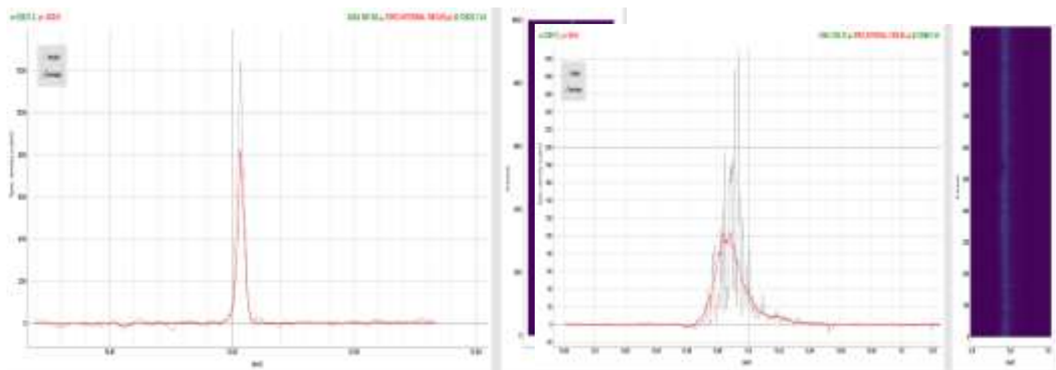
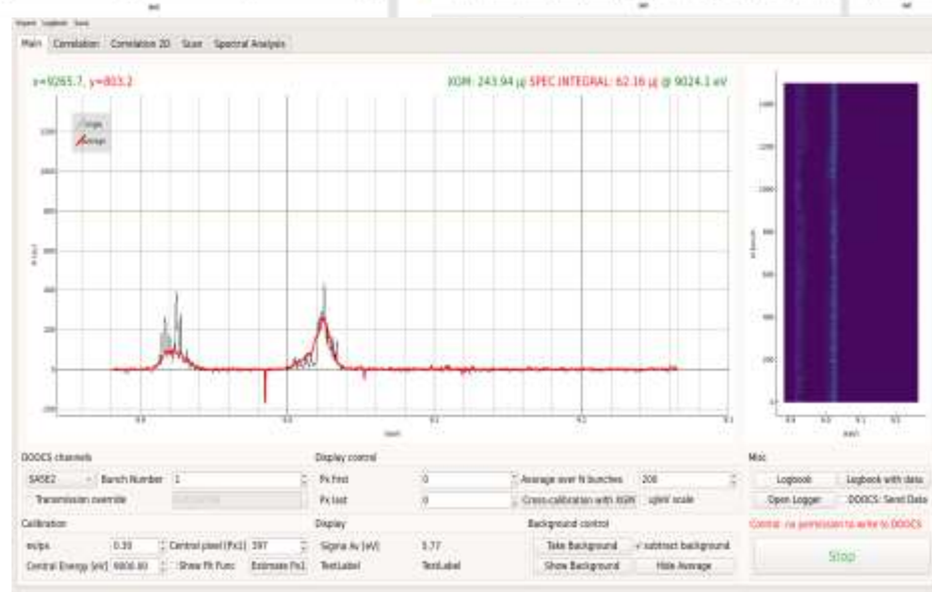






Special operation modes

- Self-seeded beam
  - Reduces spectral width ~20x
  - Increases spectral brightness ~10x
  - Reduced thermel load on monochromators
- Two color mode
  - Generation of two pulses ~100 eV separation
  - Variable delay 5-300 fs
  - Nearly overlapping focus

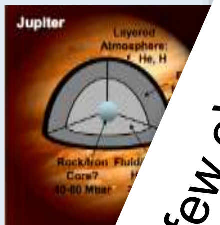
two colors

color 1 only

HED – research at extremes

Laser Compression

Shock & ramp compr



XRD, IX

Long-p laser

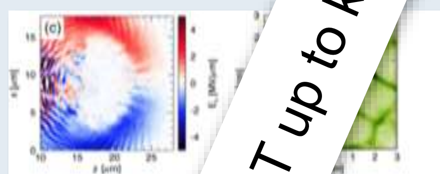
Relativistic Laser-Plasmas

Electron transpor

Instabilities and filam ,

Particle acceler

High EM fi



Multi-10 laser

Pulsed Magne ields

Solid state s

New quan tes

Superc vity

> 40 d coil, 600 µs

d , goniometer

Diam vil Cells

Fast piezo DAC

Puls heated DAC

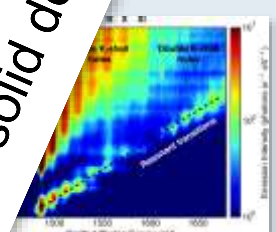
eated DAC

18 to 25 keV

Isochor excitation

Tra roperties,

H oms, rates



XES, IXS, XRD

Tight focusing

X-ray spectrometers

Cryogenic jet targets

High-rep solids targets

EMP-hard X-ray detectors

High-purity polarimetry

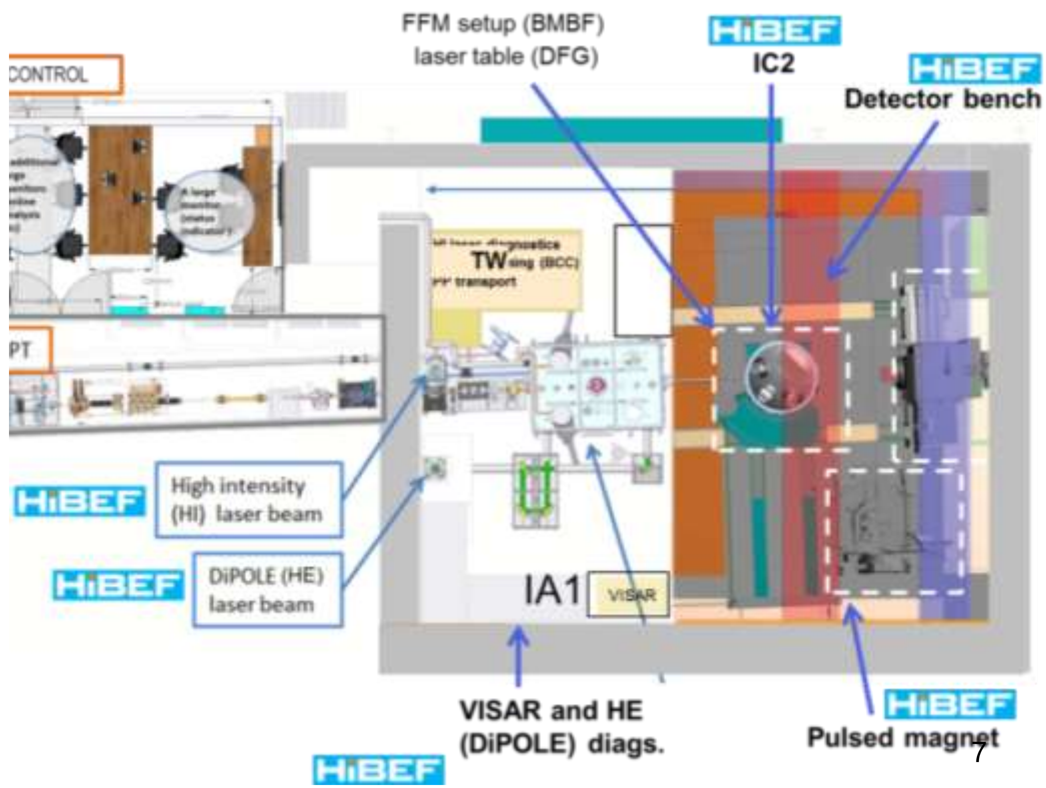
Laser-shocked DAC

GISAXS

Hibef user consortium

Helmholtz international beamline for extreme fields

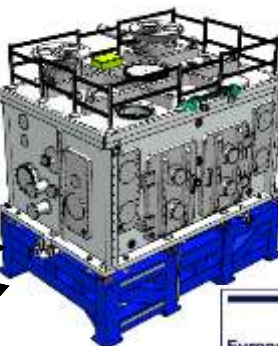
- Installation and operation of lasers and part of the HED instrument
- 80 institutions, 20 countries
- > 40 M€ budget



Drive capabilities at HED

- Diamond Anvil Cells (DAC)
  - dynamic DAC; pulsed laser heated DAC; double-stage DAC
- Powerful optical lasers
  - DiPOLE100 (100 J – 15 ns – 10 Hz)
  - Amplitude (200 TW – 30 fs – 10 Hz)
  - PP-laser (800 nm: 0.2-2 mJ – 15 fs – 1 MHz,
    1030 nm: 1-40 mJ – 800 fs – 1 MHz)
- XFEL split&delay line (x-ray pump-probe)
- Up to 60 T pulsed magnetic field coil

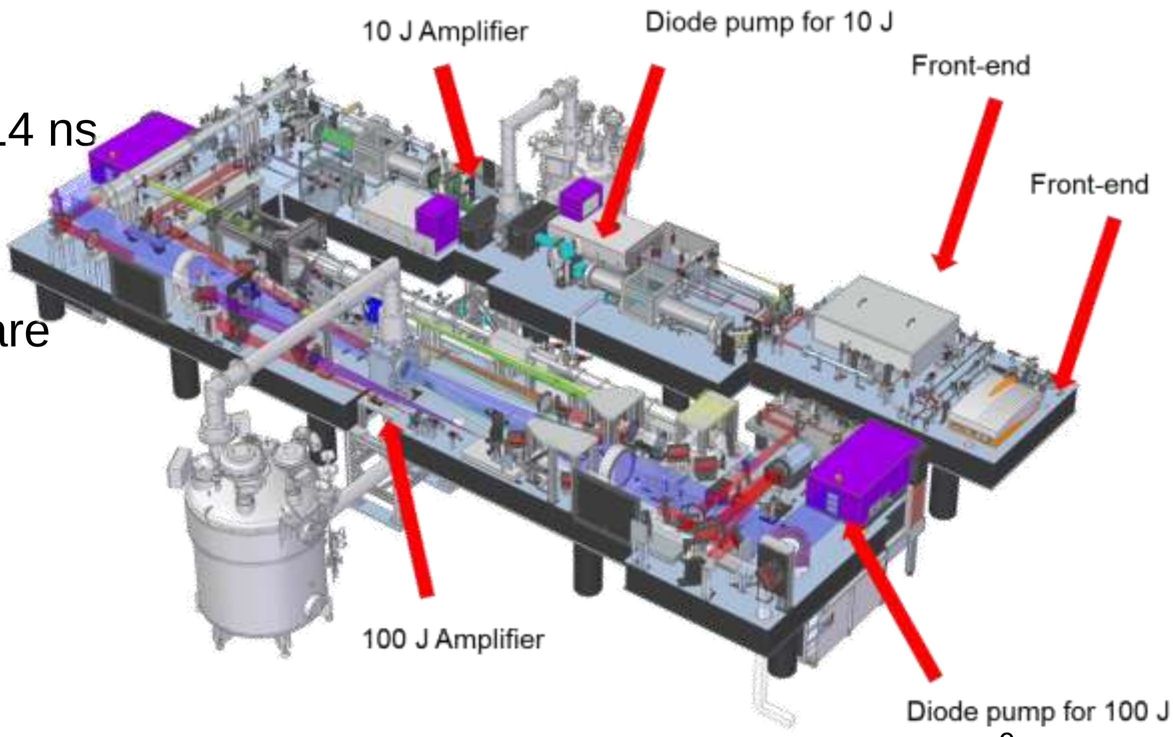
IC1



IC2

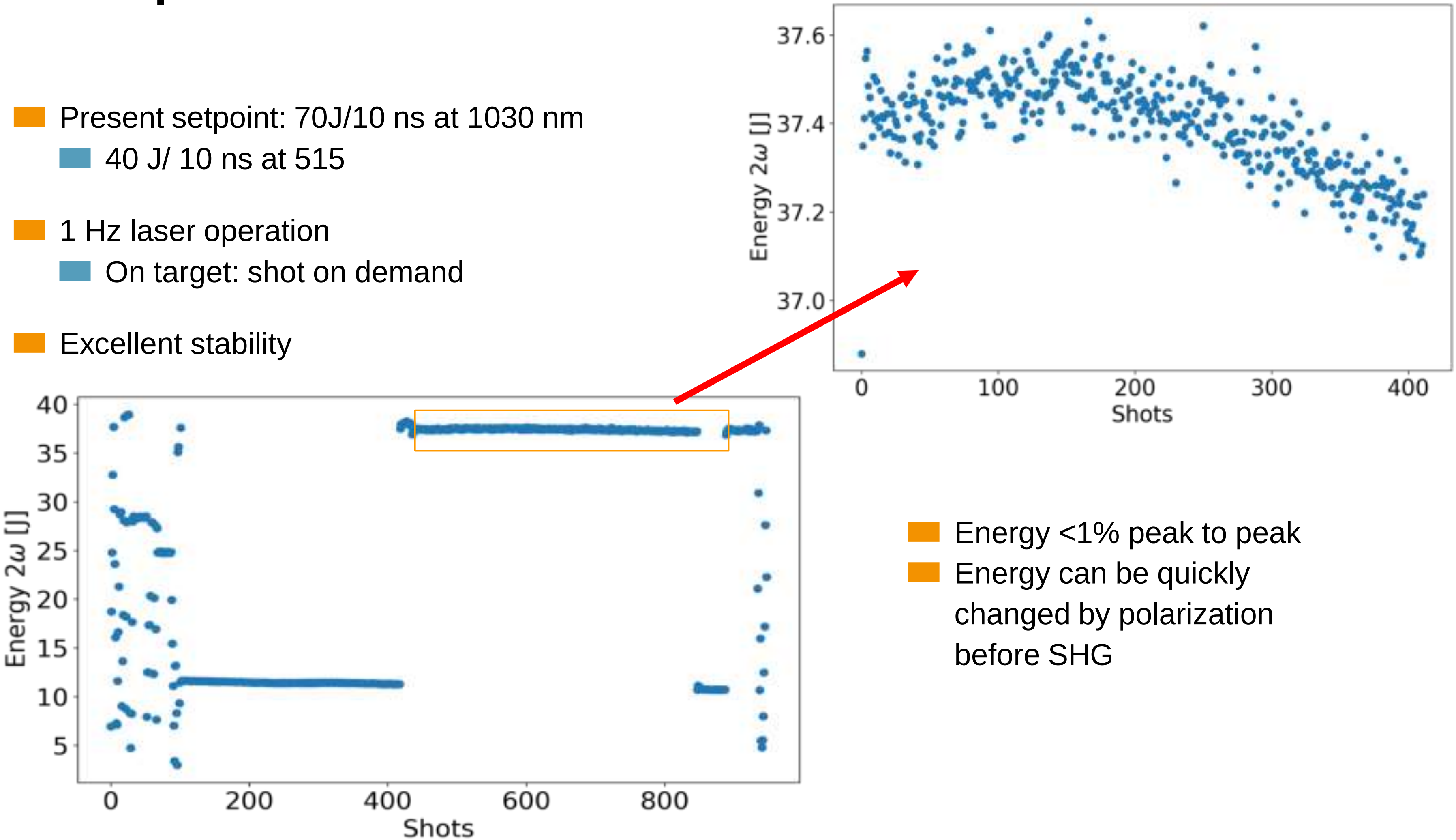
DiPOLE 100-X

- Developed by CLF as a STFC in-kind contribution to HiBEF
- Diode pumped Yb:YAG (1030 nm)
- Up to 100 J (w), 70 J (2w)
- Arbitrary pulse profile up to 14 ns
- 10 Hz operation
- Final beam size 80 mm square



Laser performance

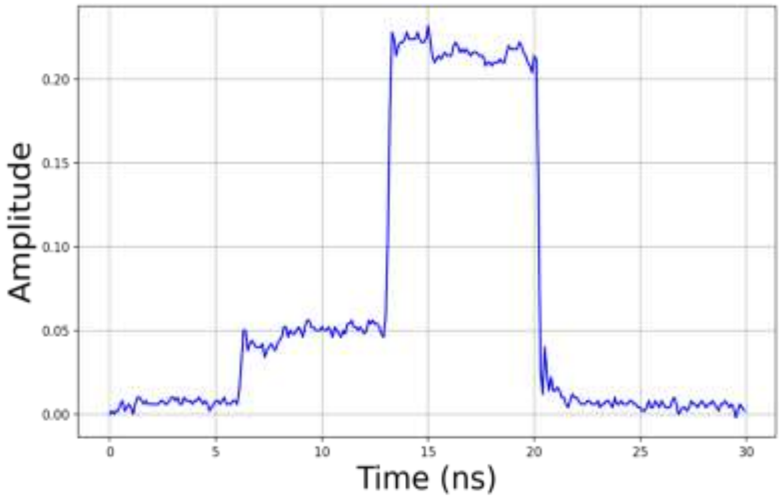
- Present setpoint: 70J/10 ns at 1030 nm
  - 40 J/ 10 ns at 515
- 1 Hz laser operation
  - On target: shot on demand
- Excellent stability

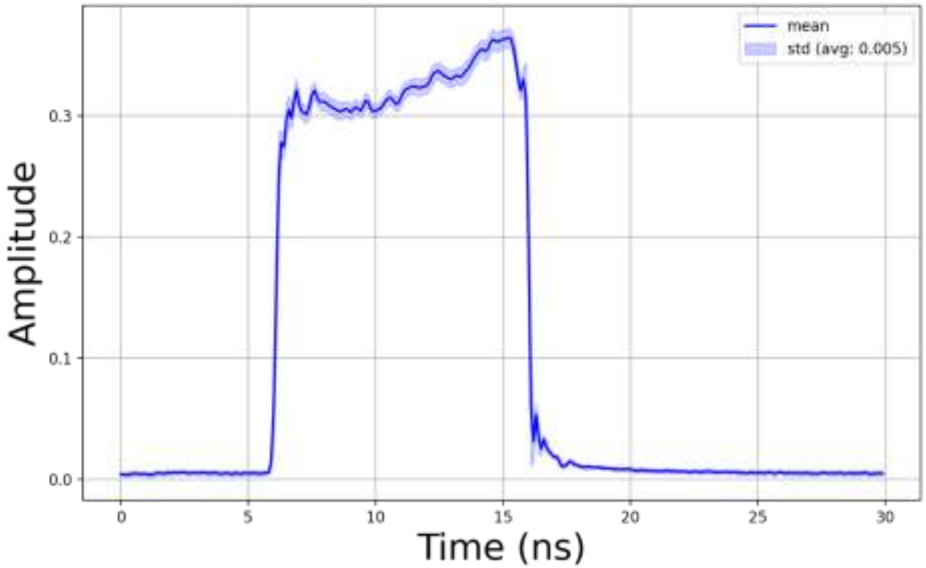


- Energy <1% peak to peak
- Energy can be quickly changed by polarization before SHG

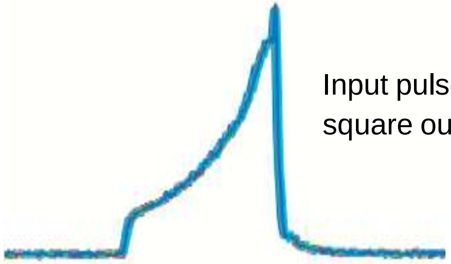
Pulse shaping capabilities

- Arbitrary pulse shaping 2-14 ns
- Ramp and double shock pulses for off-hugoniot states





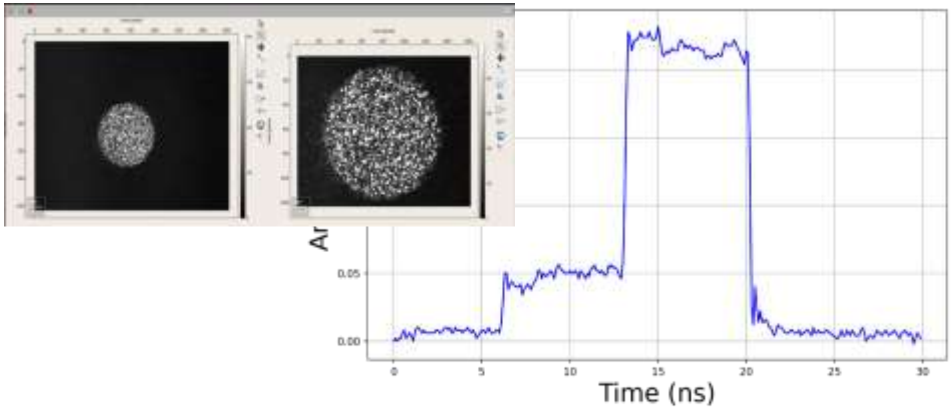
- Saturation in the amplifiers requires iterative pulse shaping
- Partially automated
- Pulse shape extremly reproducible

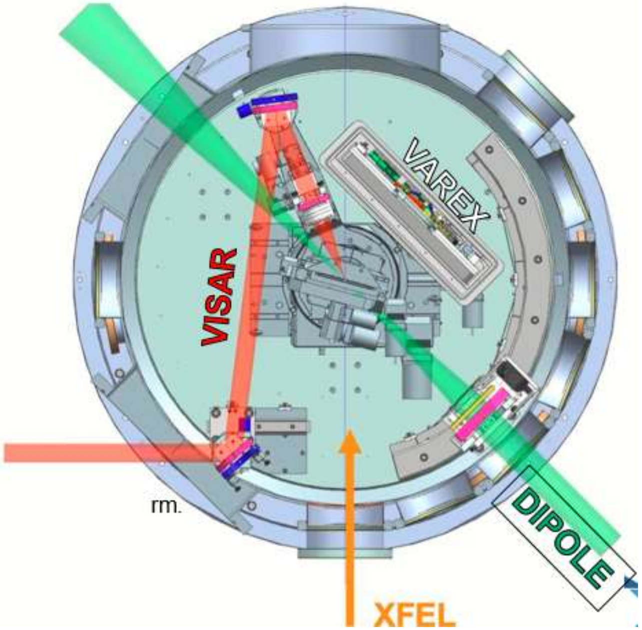


Input pulse for square output

Direct laser compression platform for diffraction

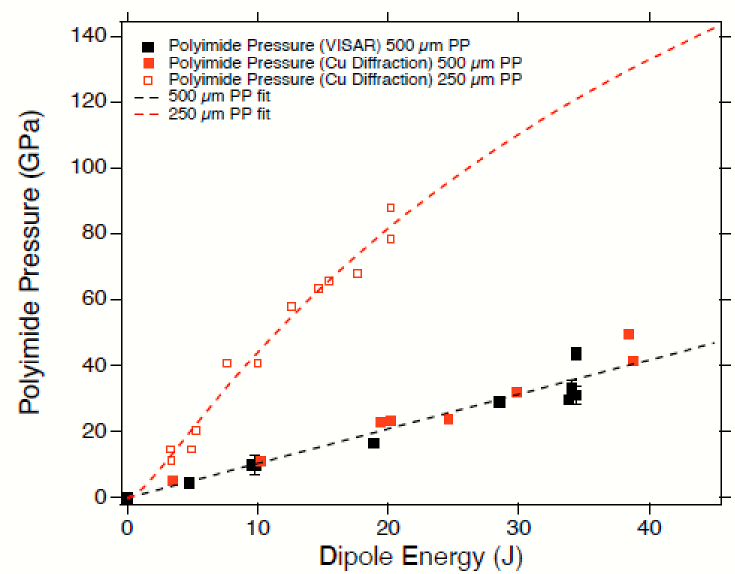
- Dedicated setup for diffraction with large area x-ray detector.
- Variable geometry for shock propagation vs. X-ray direction
- F/5 focussing optic, phase plates for 500, 250 and 100 mum focal spot available
- No noise on the detector due to laser plasma interaction

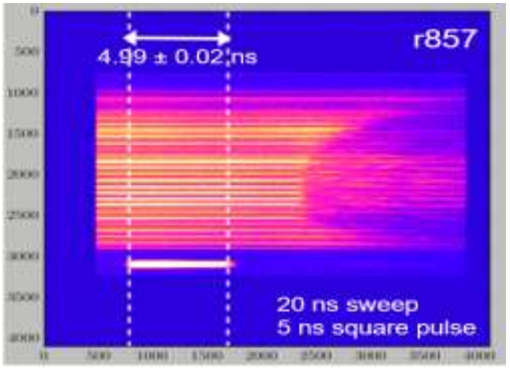




Capabilities

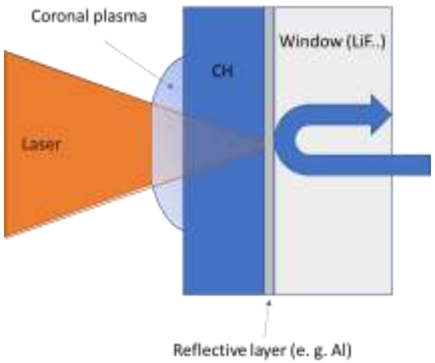
- VISAR system to get indepentdent pressure information for spatial and temporal evolution
- Ablation pressures for 10 ns pulses > 300 Gpa (100 mum phase plate)
- Timing fiducials on the streak camera for both laser and x-rays
- Full automatic scan of timing and energy reaching shot rates < 1 min

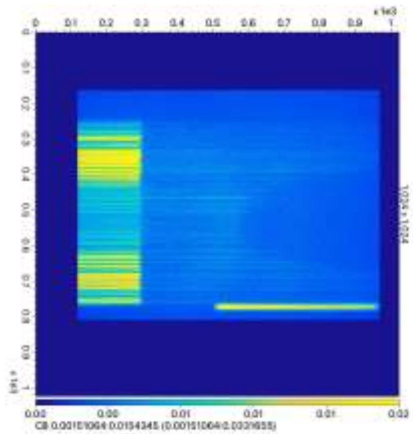




Operation experience

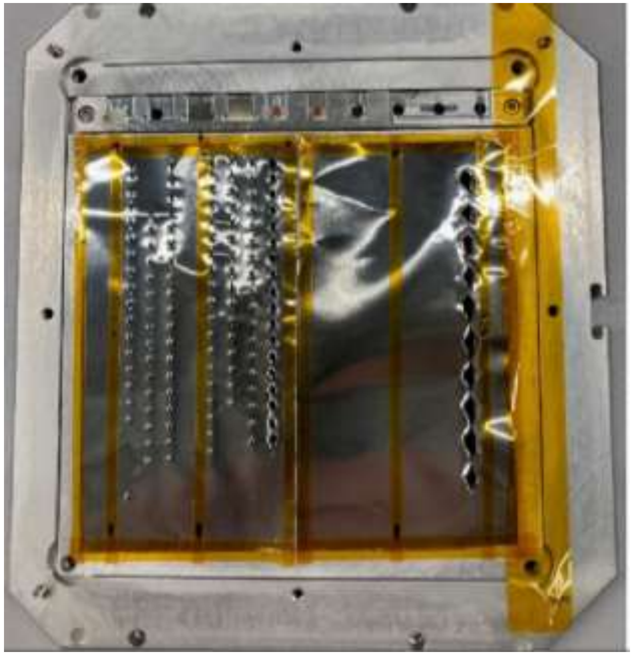
- Laser runs 24/7 without major interruptions
  - Cryogenic amplifier freezing – heat cycle at sample exchange (~30 min)
  - Occasionally trips of pump lasers or machine interlock -> restart (5 min)
- Up to now 3 user experiments
- Identified a prepulse issue, possibly related to reflectivity loss during shots
- Typical 200 shots per experiment day
  - Limitations: user decisions, procedures not yet optimal, control system limitations
  - Could be still improved x2…x3 in shot-on-demand mode
- Very limited access to target area and experimental setup
  - Chamber has to move out for other experiments
  - Hutch access not possible during other experiments
  - Total of 10 weeks laser up to sample, including user beam time and setup

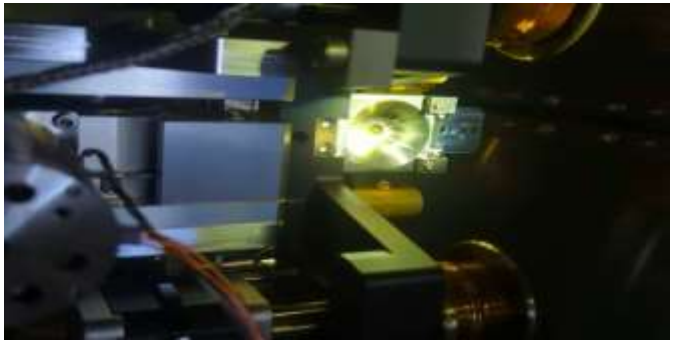




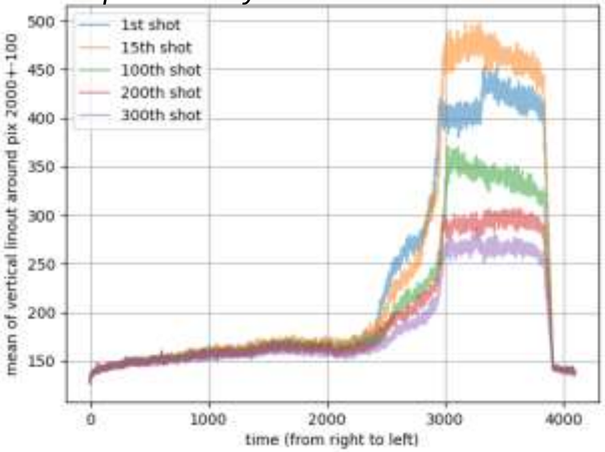
High-rep rate target delivery

- Low cross-section experiments require large shot numbers (100…1000)
- Important bottleneck (amongst other): sample delivery
- First test during first user experiment: 1 Hz on a 10 cm stripe
- Tape target run for 10 minutes @ 1 Hz: VISAR data stable, no x-ray data
- R&D project for next steps: integration, debris management, alignement verification





Breakout reproducibility:



THRILL: Technology for High-Repetition-rate Intense Laser Laboratories

- EU project (Horizon-infra 2022, 4 year project, 10 M€ budget)
- Development of a laser amplifier with more than 1 kJ pulse energy with repetition rate of ~1 shot/minute (presently ~1 shot/h)
- Partners: GSI, FAIR, HZDR, LULI, ELI, XFEL, Amplitude, Laserlab
- Objectives:
  - Actively cooled amplifiers
  - Beam transport design and optimization
  - Optical elements adapted to these conditions
- Status:
  - Project started 01/2023
  - Recruiting (HZDR postdoc for beamline)
  - Defining laser requirements for end users
  - Evaluating existing systems for scalability

Conclusion and outlook

- HED is a versatile platform for High Energy Density Physics and dynamic compression experiment
- X-ray energies from 5 to 25 keV, monochromators and focusing devices available
- Multiple drivers available like lasers, DAC, pulsed magnetic fields, x-ray excitation
- Upcoming commissioning of DiPOLE 100-X in IC1
  - Spectroscopy on laser-compressed samples
  - Imaging (~10 keV, <500 nm resolution)
  - Combination with short pulse laser
- Continuous Improvement Program
  - Improving focal spot quality
  - Predictive pulse shaping capabilities
  - Increasing laser energy (>70 J @ 2ω)
  - Online analysis