ELISS2023

ELI Summer School | 29 Aug – 1 Sep 2023
Dolní Břežany, Czech Republic

From XFEL basics to advanced synergy:

Integrating ELI-class lasers with a cutting-edge x-ray source

Dimitri Khaghani

SLAC National Acceleration Laboratory

September 1st, 2023

Dolní Břežany, Czech Republic

eli IMPULSE

IMPULSE is funded by the European Union's Horizon 2020 programme under grant agreement No. 871161

plasma

ns-laser

x-ray free electron laser

inertial fusion energy

electron beam

particle in-cell simulation

warm dense matter

ion acceleration

shock compression

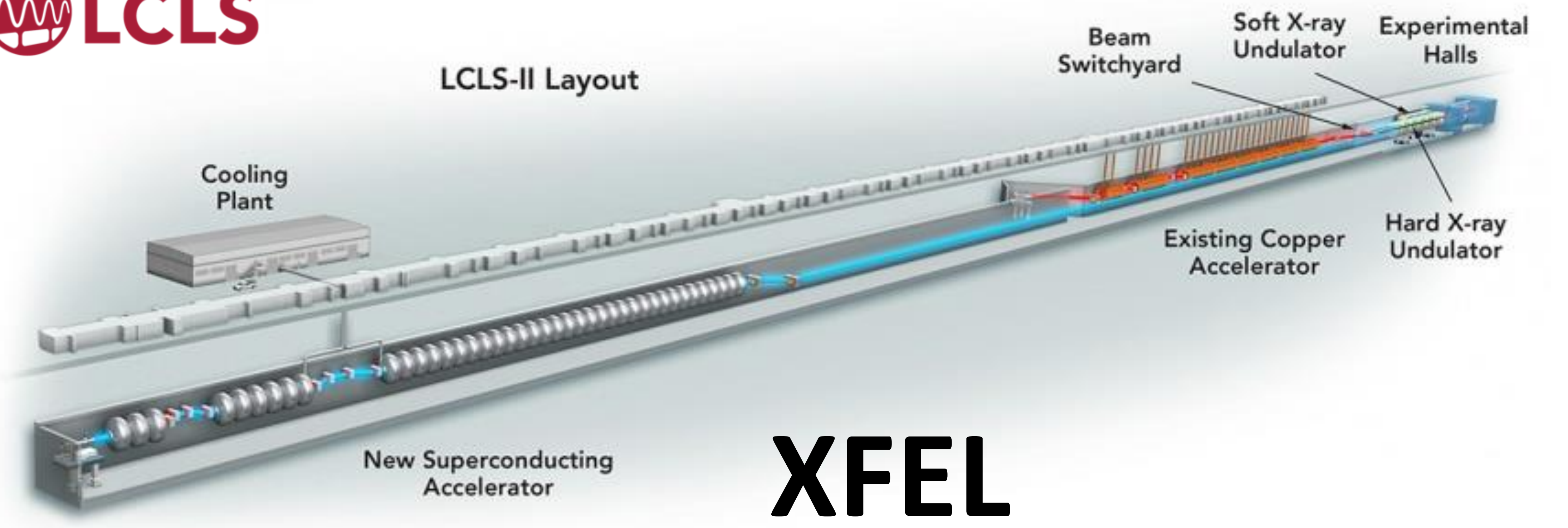
relativistic processes

x-ray sources

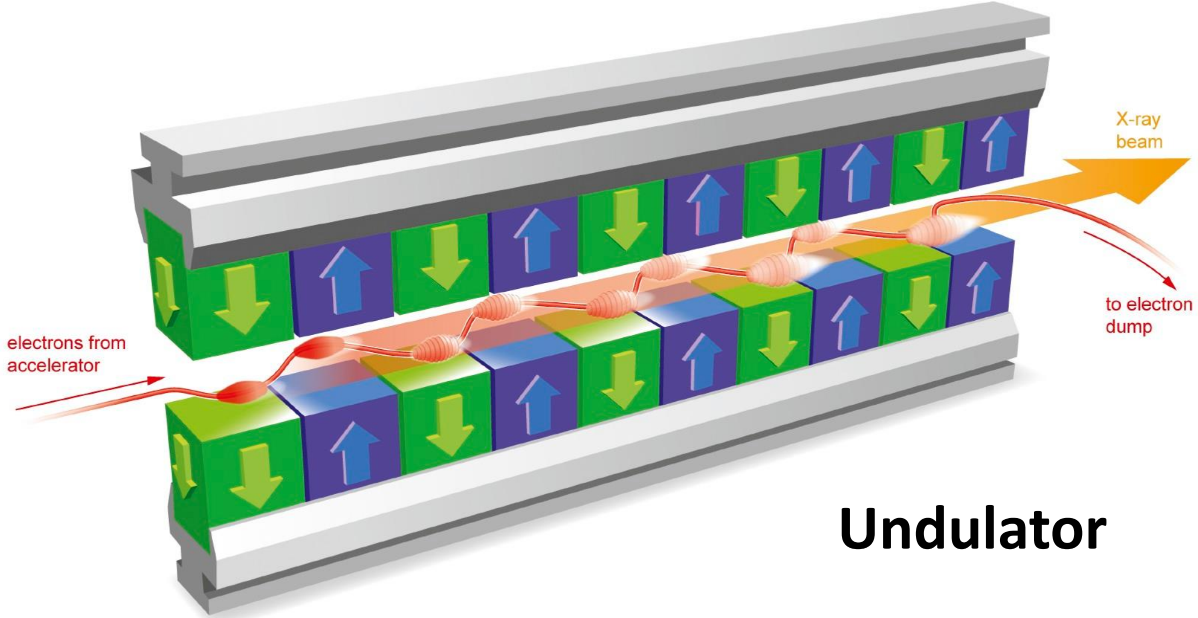
fs-laser

laboratory astrophysics

x-ray imaging

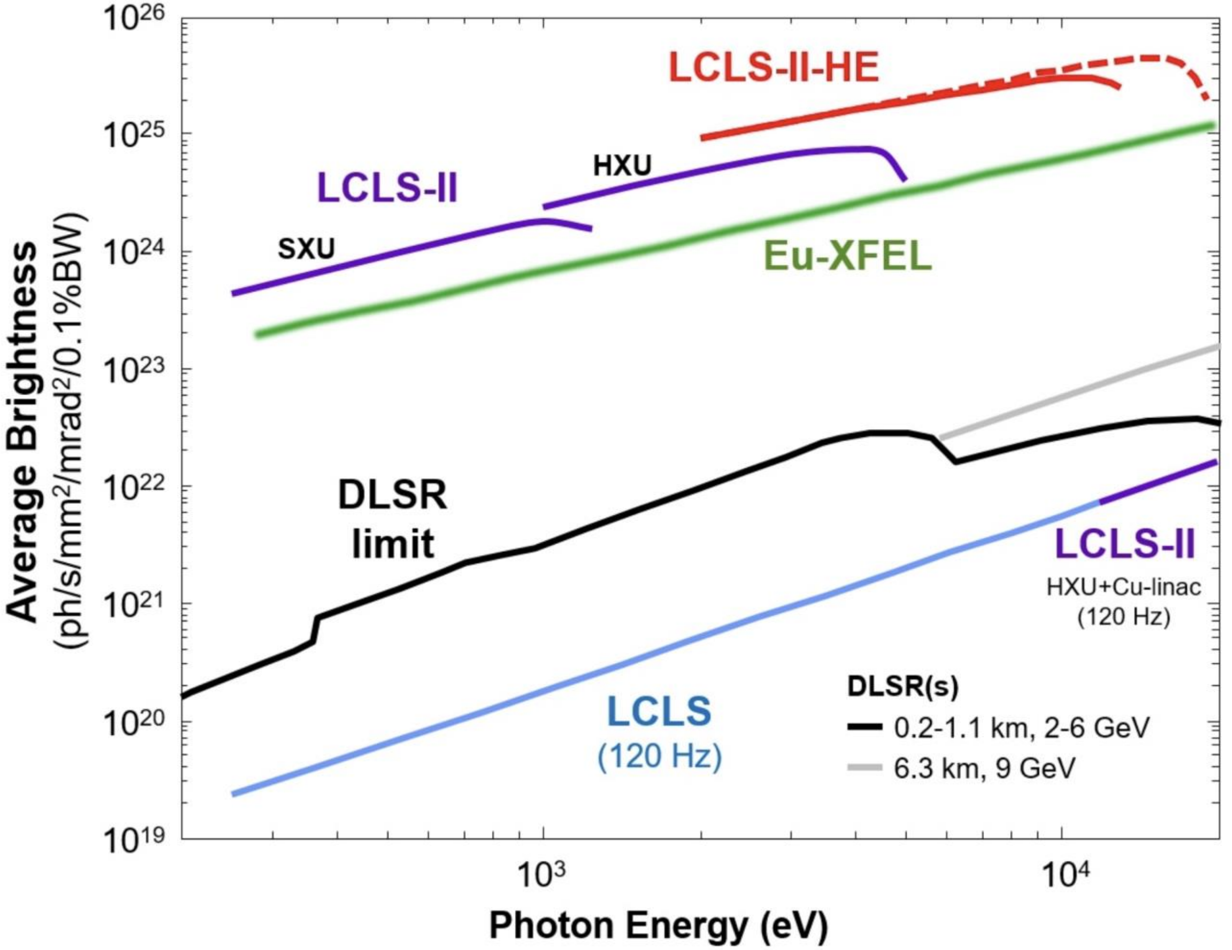


XFEL

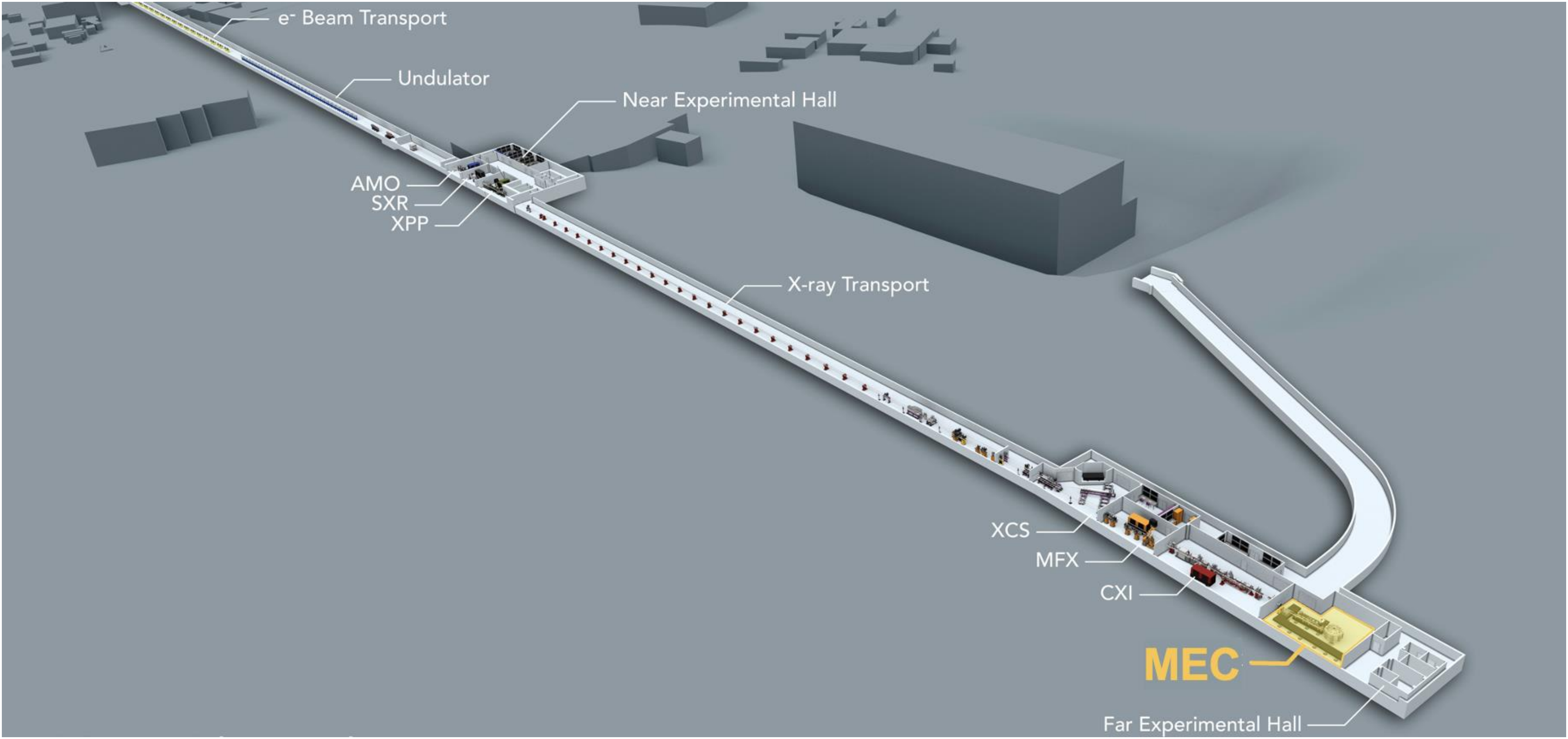


Undulator

LCLS-II

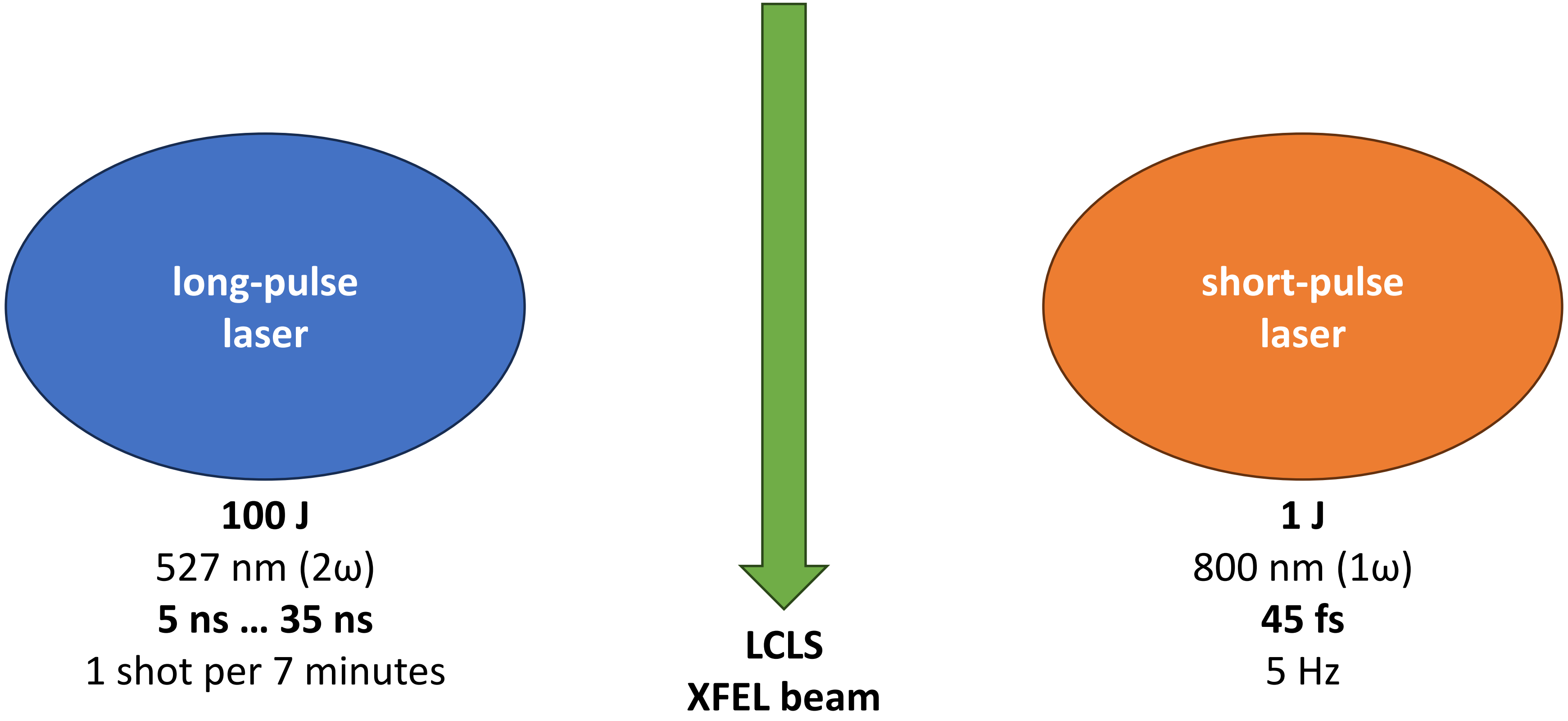


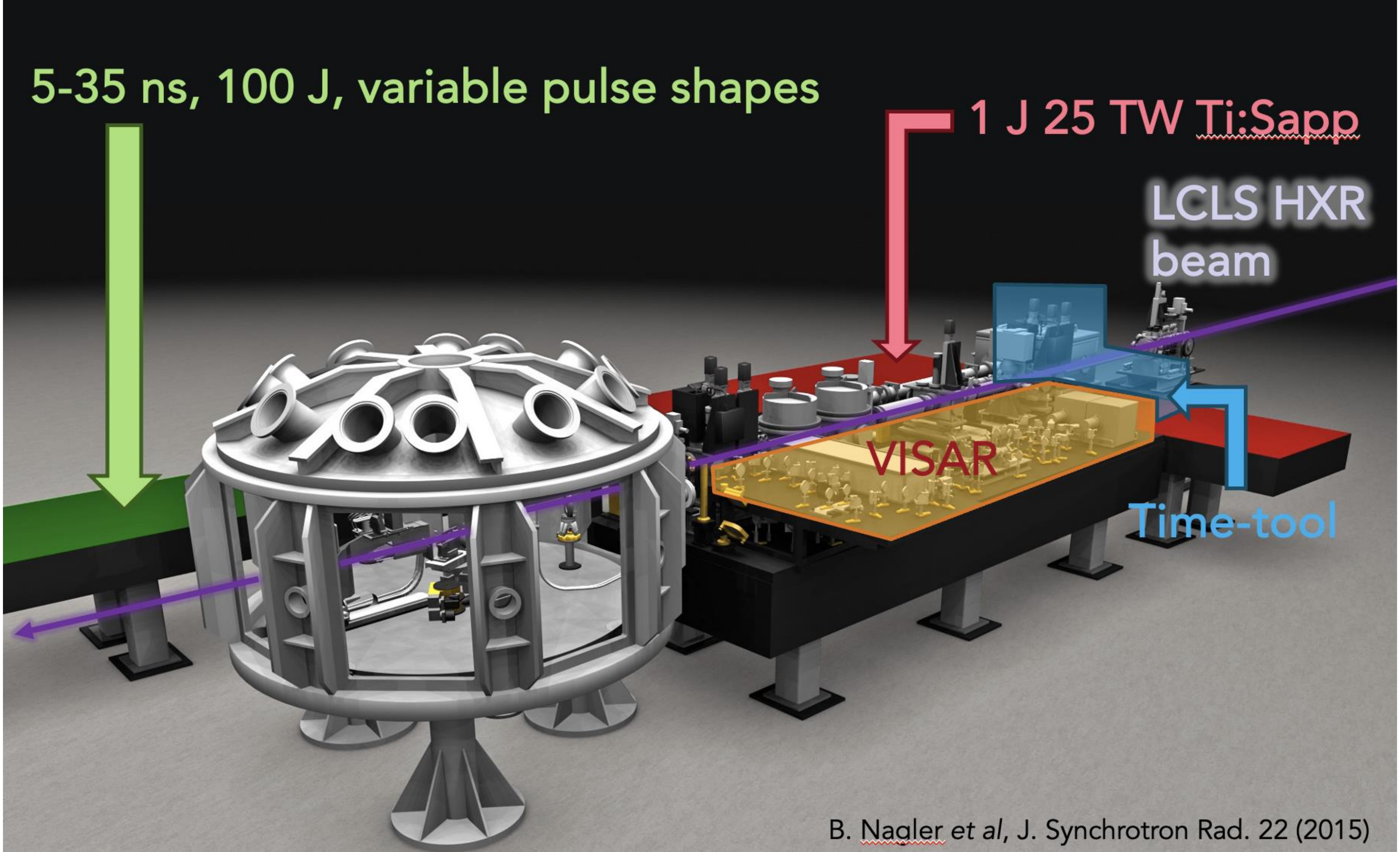
- Two all-new variable gap X-ray undulators: SXU and HXU
- Increases available beam time
- HXU photon energy extended to 25 keV


e- Beam Transport
Undulator
Near Experimental Hall
AMO
SXR
XPP
X-ray Transport
XCS
MFX
CXI
MEC
Far Experimental Hall

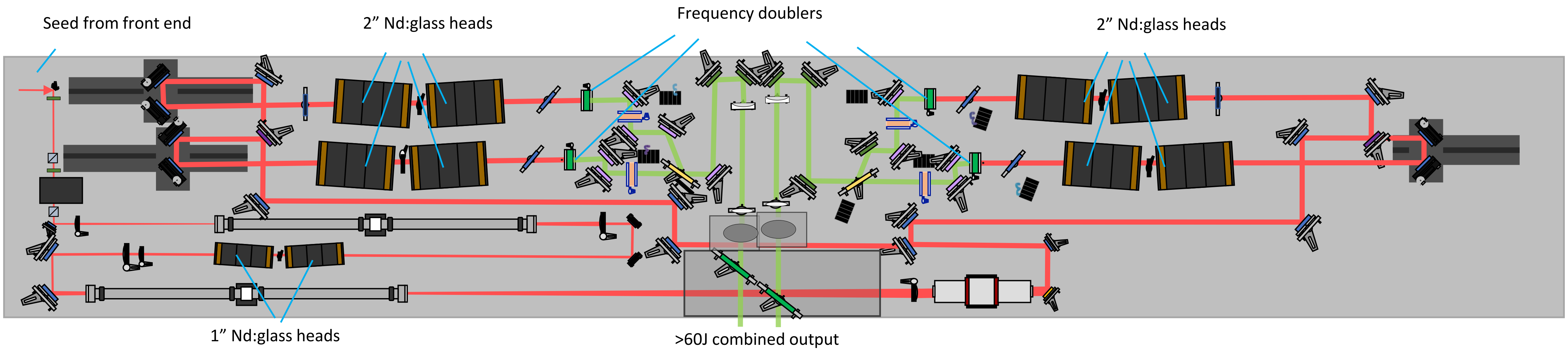
Matter in Extreme Conditions (MEC)

beamlines




5-35 ns, 100 J, variable pulse shapes
1 J 25 TW Ti:Sapp
LCLS HXR beam
VISAR
Time-tool
B. Nagler et al, J. Synchrotron Rad. 22 (2015)

Long-pulse laser



Seed: custom diode-pumped Nd:YLF

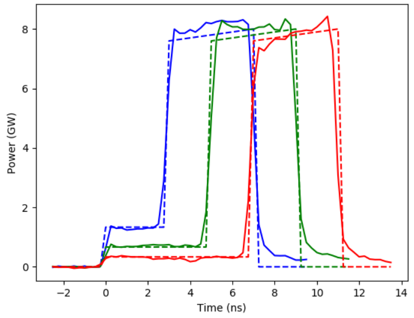
- > 100 mJ, 5-35 ns (arbitrary), 10 Hz

Pre amp: 2 x 25 mm Nd:Glass

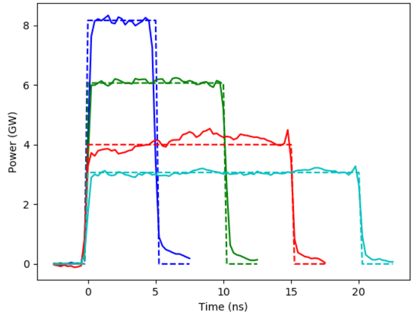
- 1 J, shot / 2 min

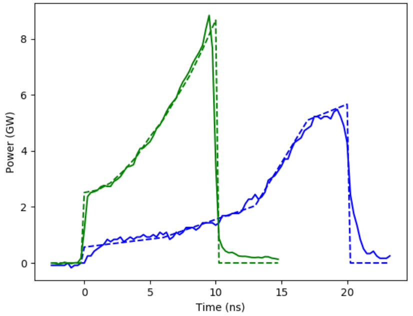
Power amp: 4 x 50 mm Nd:Glass

- 50 J → 25 J post-SHG, shot / 7 min
- Total 100 J for ≥ 10 ns, 10 J/ns for ≤ 10ns
- typical shapes: flat-top, ramp, step, etc.
- CPPs: 150 μm, 300 μm, 600 μm diameter (intensity > 10^{13} W/cm^2 with 150 μm CPPs)

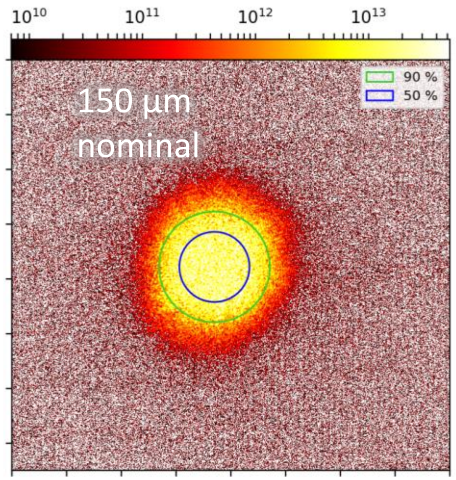


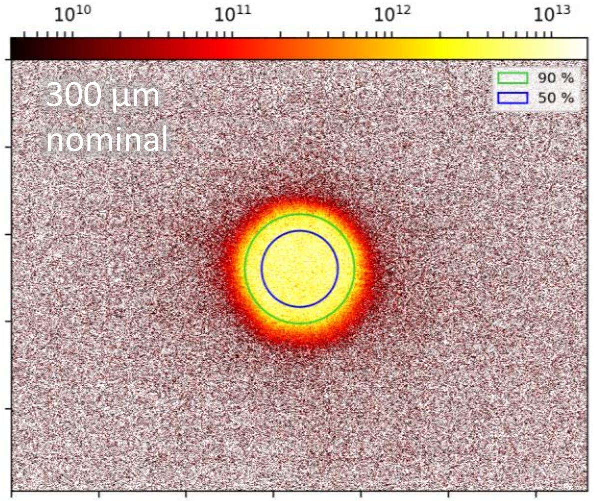
Pulse shaping

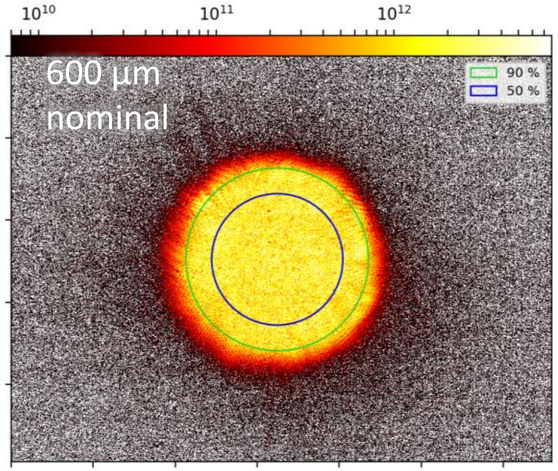




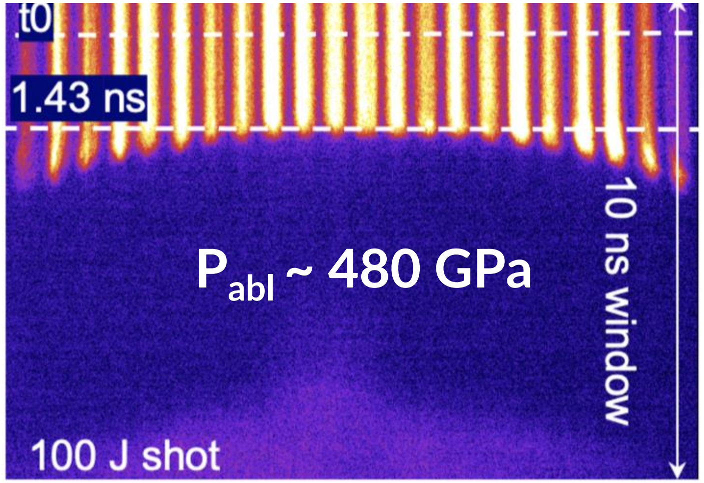
Long-pulse laser







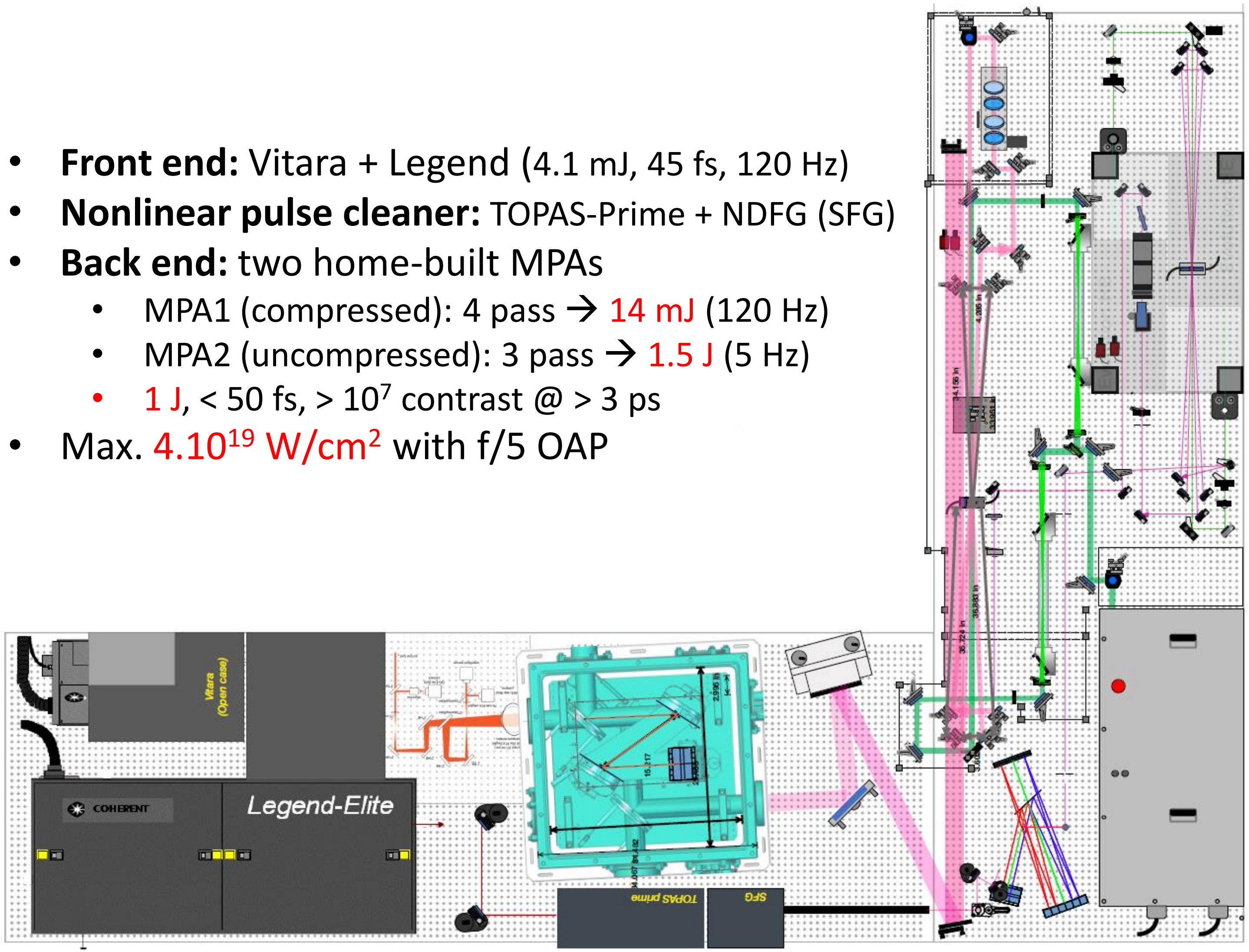
Laser-driven
shock compression
100 J → 4.8 Mbar



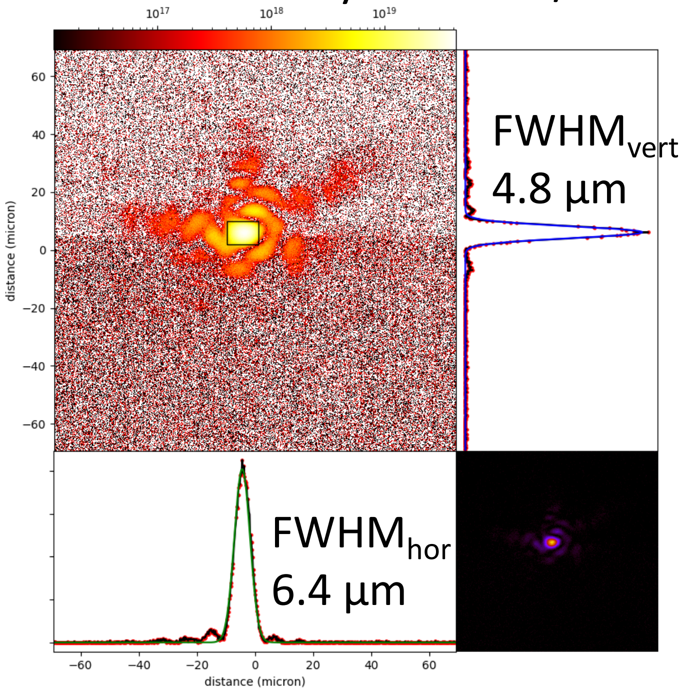
VISAR data:
CPP 150 μm
10 ns flat top
Al 25 μm

Short-pulse laser

- **Front end:** Vitara + Legend (4.1 mJ, 45 fs, 120 Hz)
- **Nonlinear pulse cleaner:** TOPAS-Prime + NDFG (SFG)
- **Back end:** two home-built MPAs
  - MPA1 (compressed): 4 pass → 14 mJ (120 Hz)
  - MPA2 (uncompressed): 3 pass → 1.5 J (5 Hz)
  - 1 J, < 50 fs, > 10^7 contrast @ > 3 ps
- Max. 4.10^{19} W/cm^2 with f/5 OAP



Peak intensity: 4.10^{19} W/cm^2



XFEL parameters

pulse duration

3 fs … **50 fs** … 250 fs

photon energy

4 keV … 25 keV
(hard x-rays in FEH)

spectral bandwidth

15 eV (SASE at 8 keV)
1 eV (seeded)

pulse energy

0.6 mJ … 2 mJ

pulse trains

Two bucket (Δt = 350 ps up to 120 ns)
4-8 pulses (Δt = 700 ps)

XFEL beam diagnostics

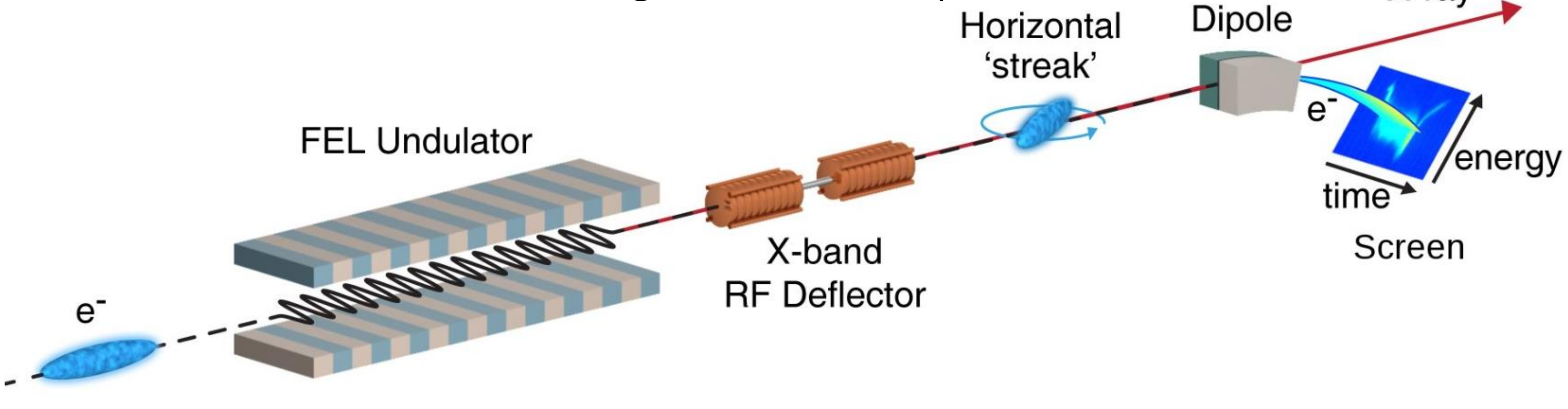
performance measurements

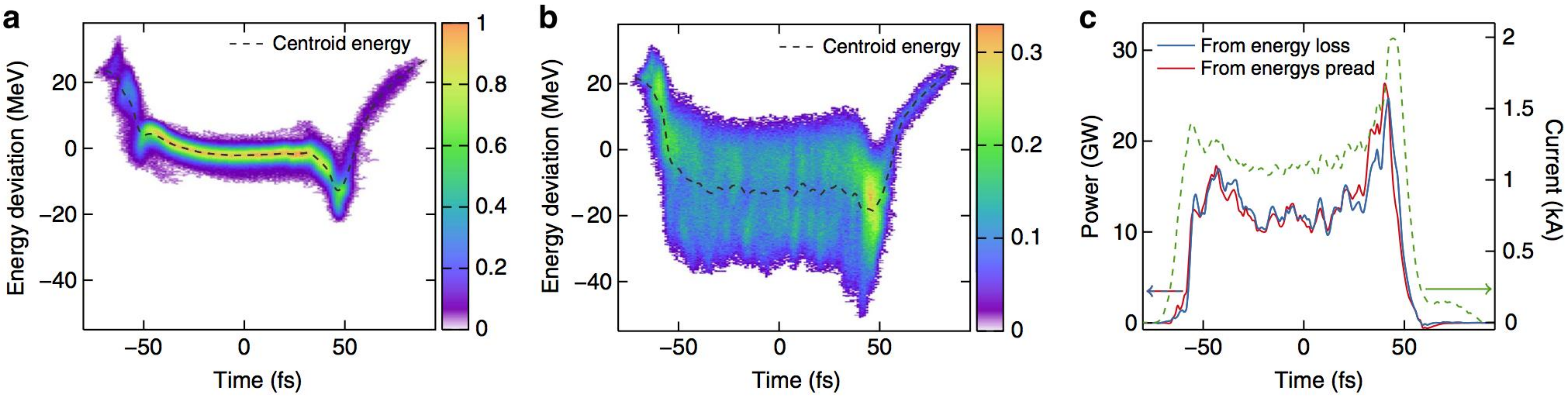
XTCAV

X-band Transverse deflecting mode CAVity

pulse duration

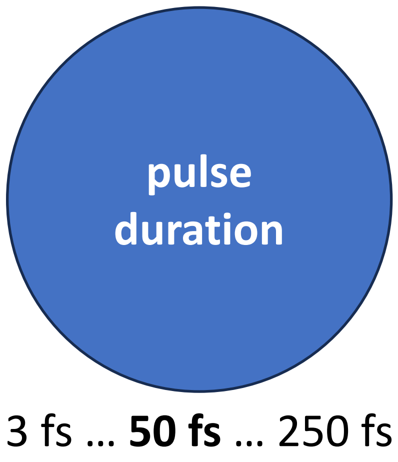
3 fs … **50 fs** … 250 fs

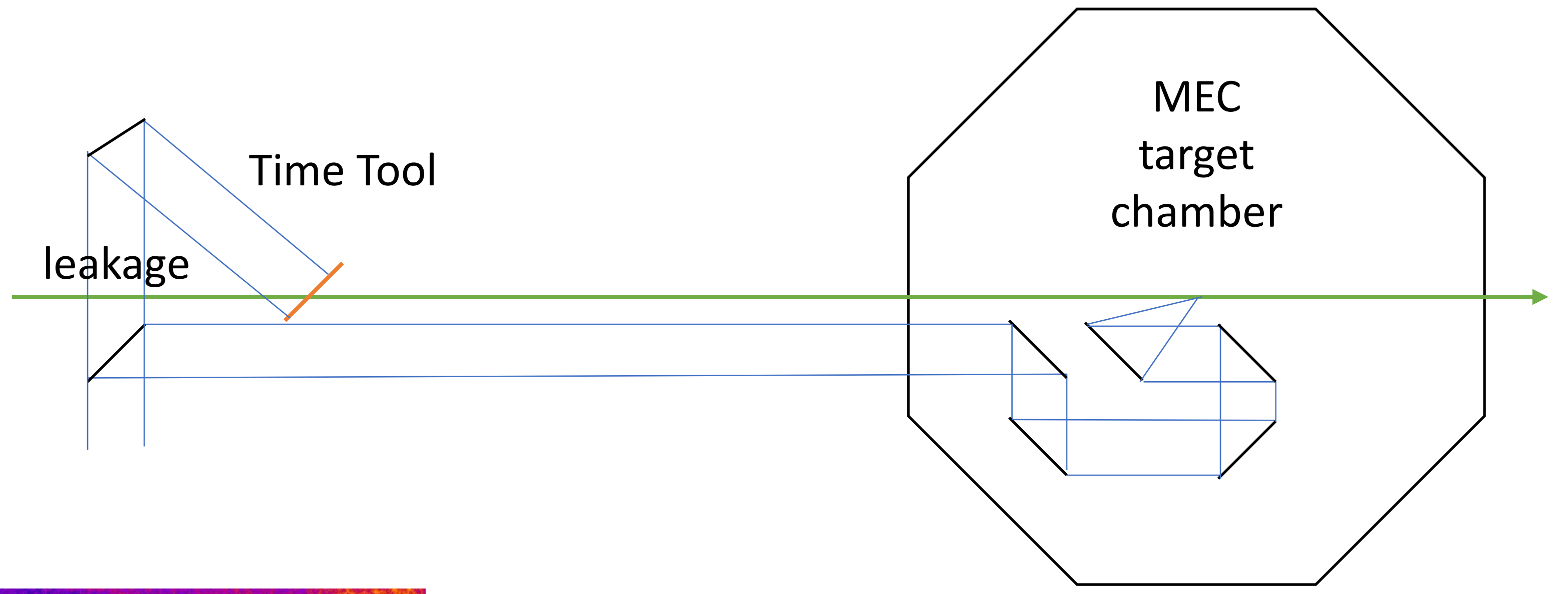


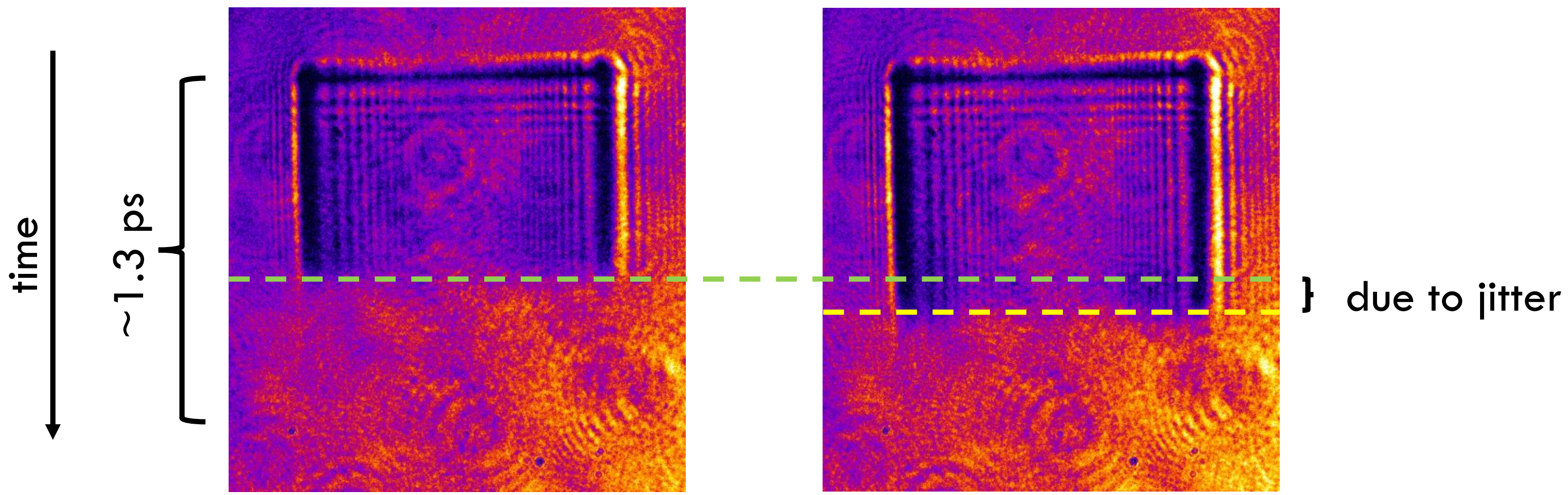


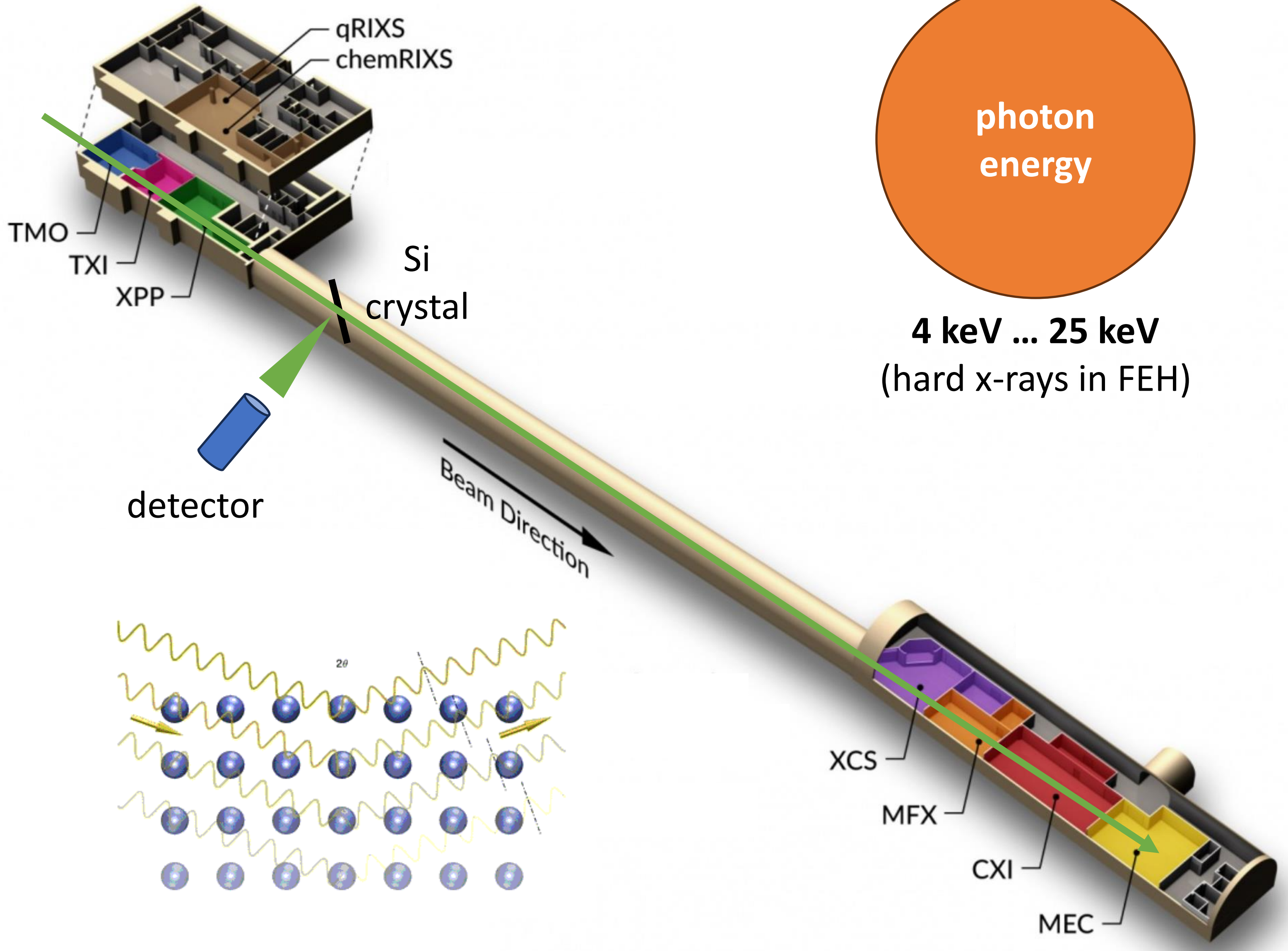
Time Tool

Timing the x-rays with the short-pulse laser









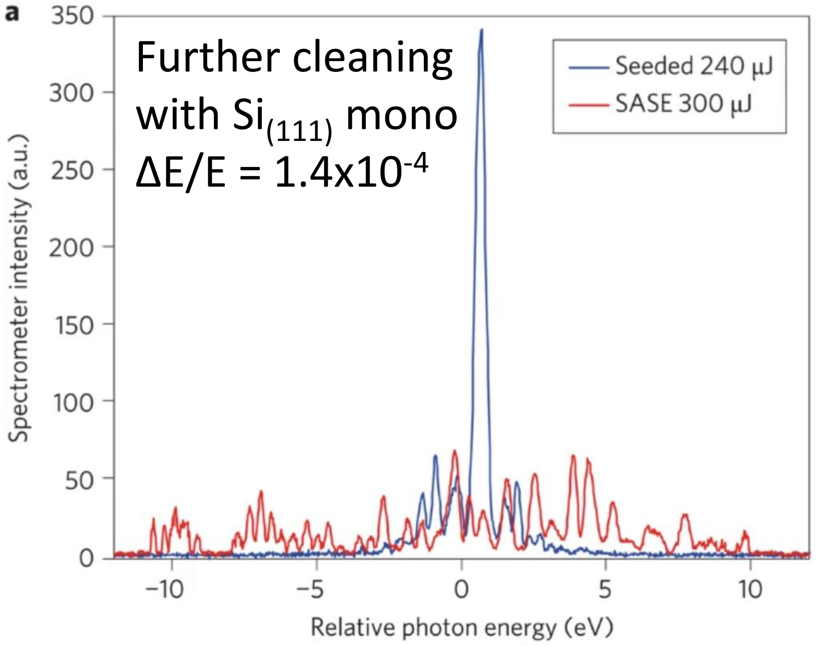
photon energy

4 keV … 25 keV
(hard x-rays in FEH)

spectral bandwidth

15 eV (SASE at 8 keV)
1 eV (seeded)

Further cleaning with $Si_{(111)}$ mono
$\Delta E/E = 1.4 \times 10^{-4}$



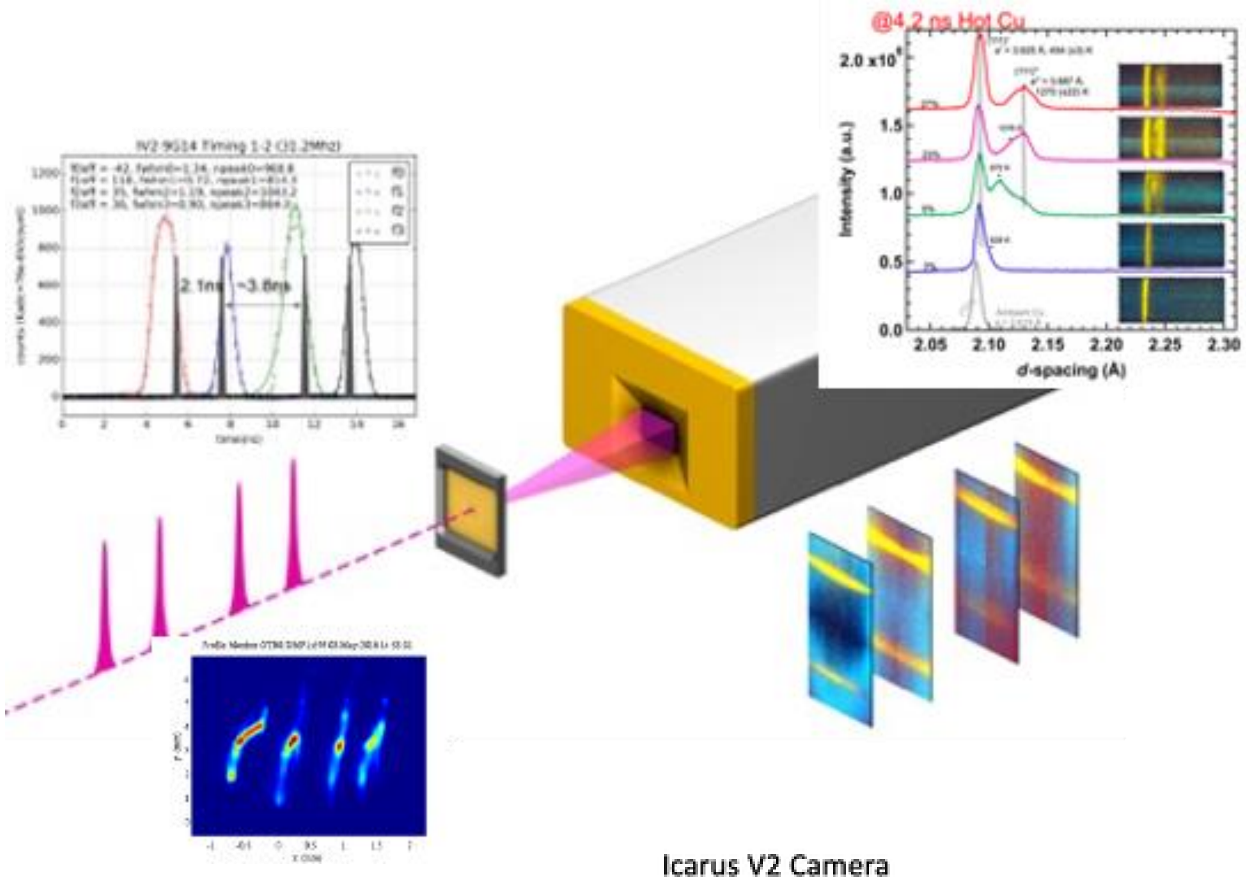
Icarus Camera

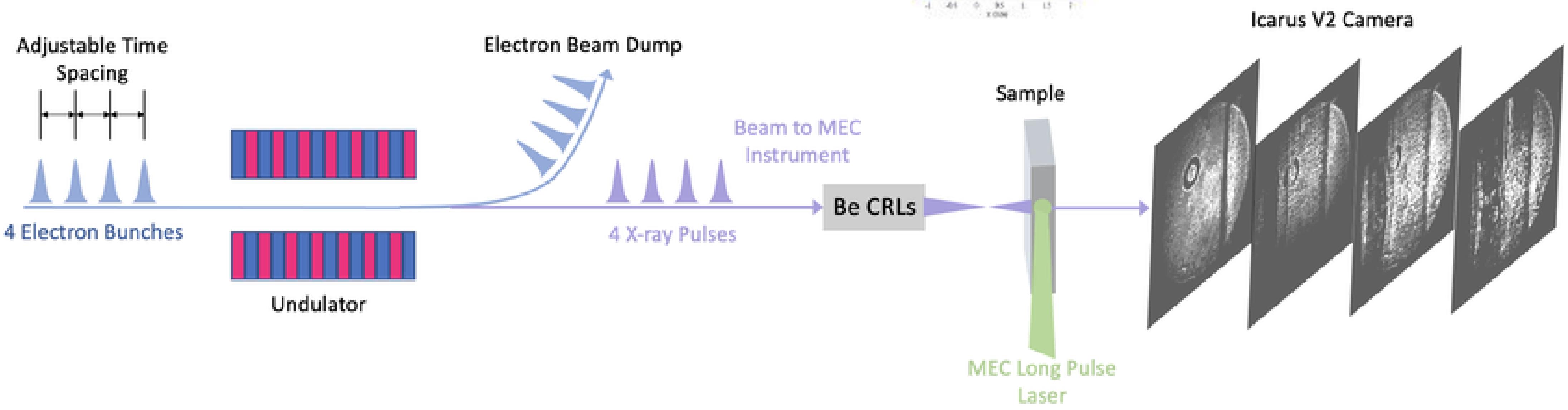
Multi-pulse detection

pulse trains

Two bucket (Δt = 350 ps up to 120 ns)

4-8 pulses (Δt = 700 ps)





Gas Monitor Detector

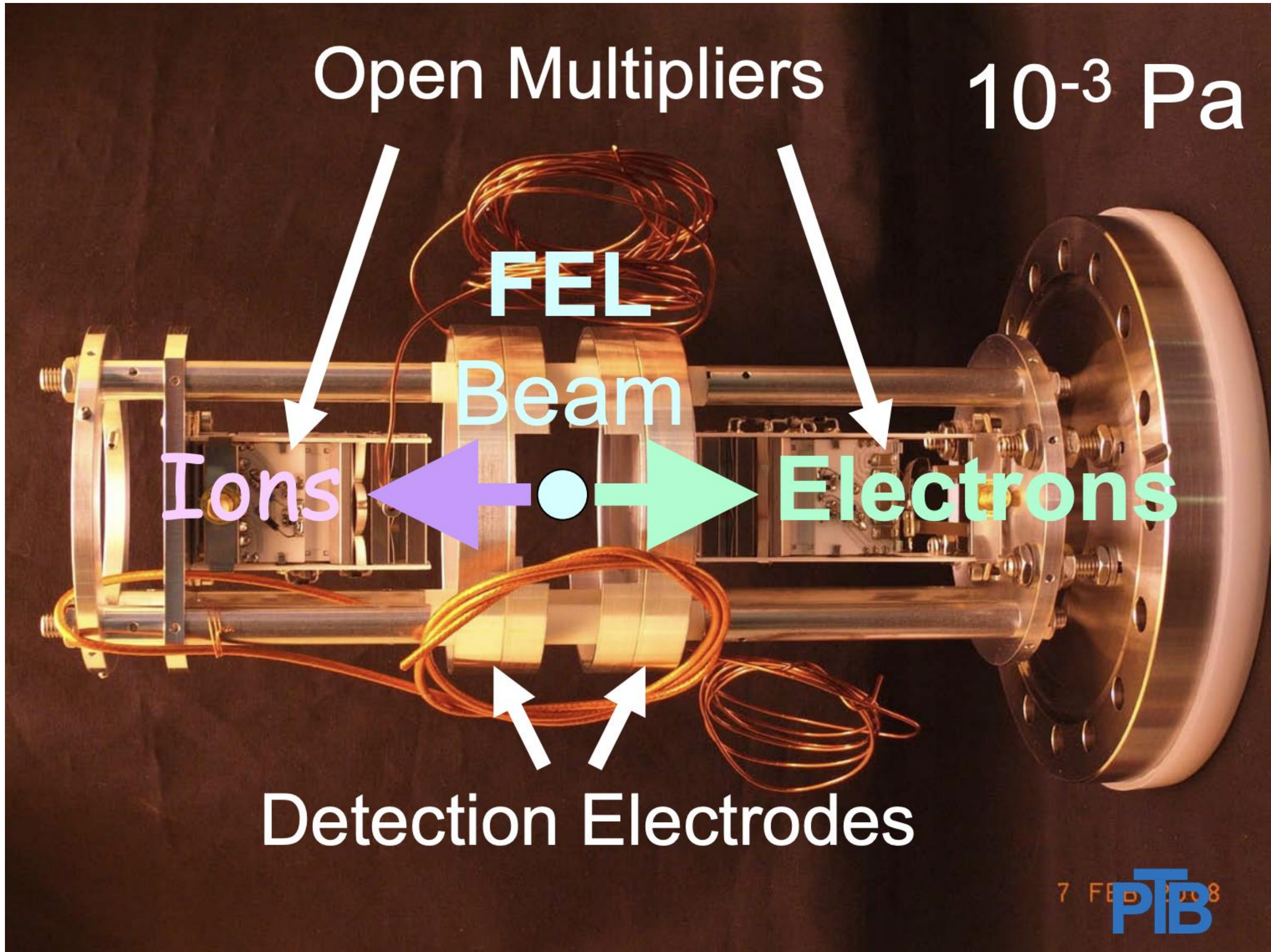
GDM

pulse energy

0.6 mJ … 2 mJ

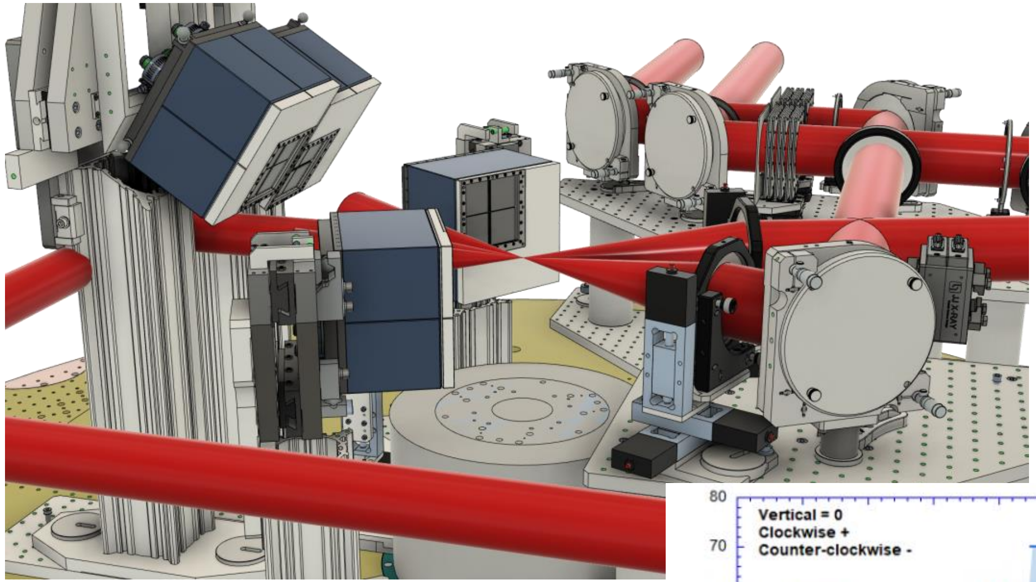
Atomic ionization of rare gases at low pressures (1E-5 to E-7Torr)

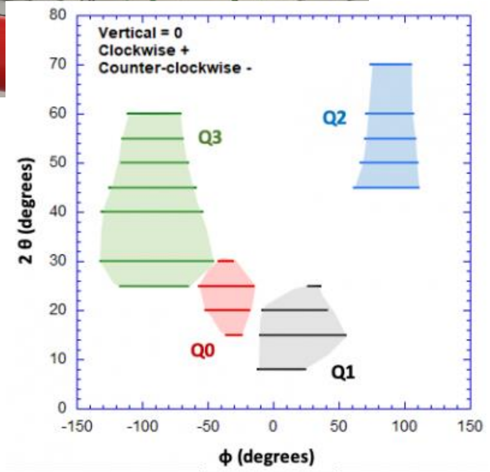
- atomic ionization of rare gases (Ar, Ne, Kr) at low pressure (10^{-5} to 10^{-7} mbar)
- Charge detection of ions and electrons (Faraday cup)
- Pulse by pulse measurement
- Cross calibrated to photon flux

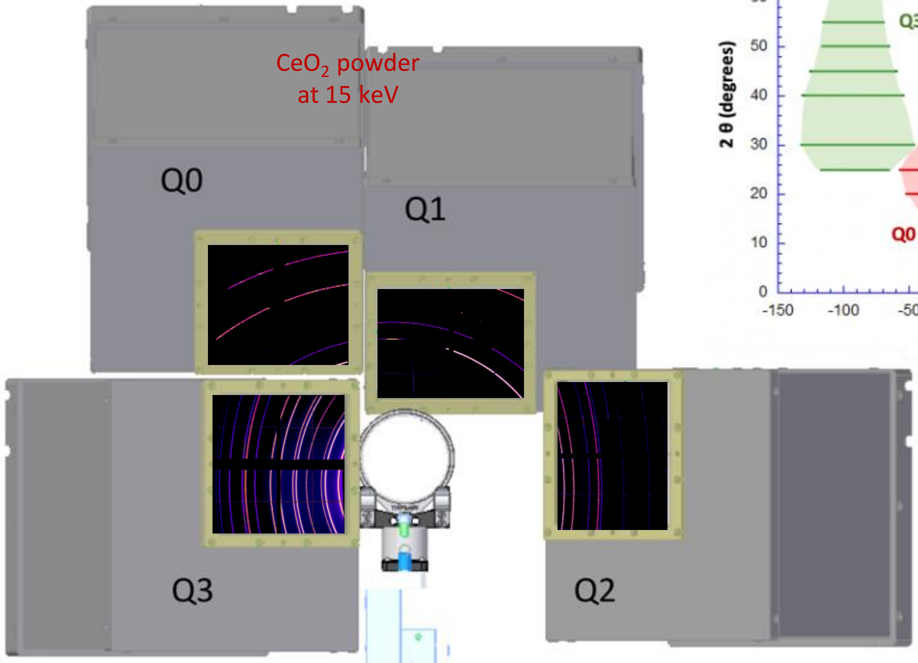


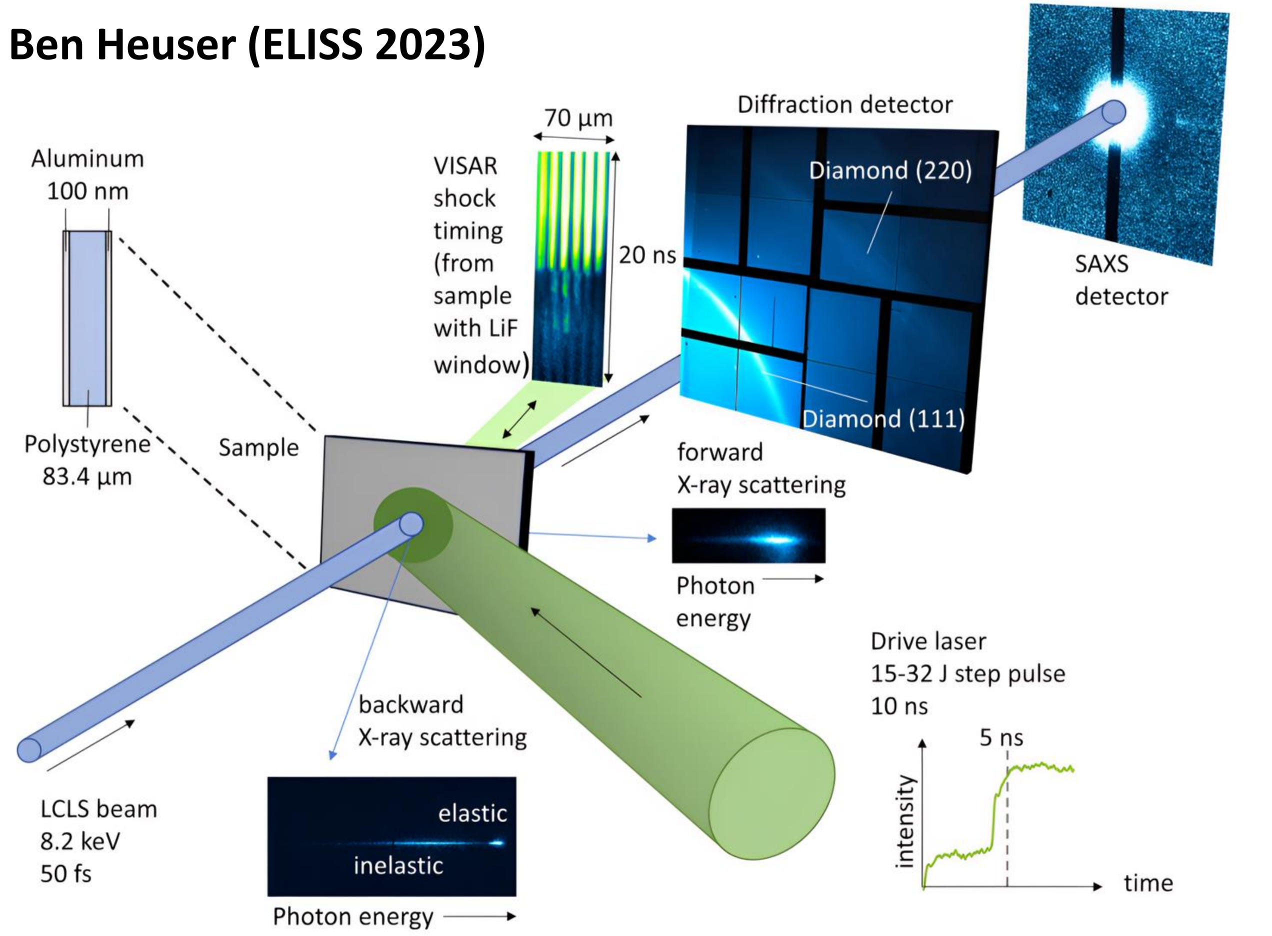
Scientific Cases

X-ray Diffraction Experiments









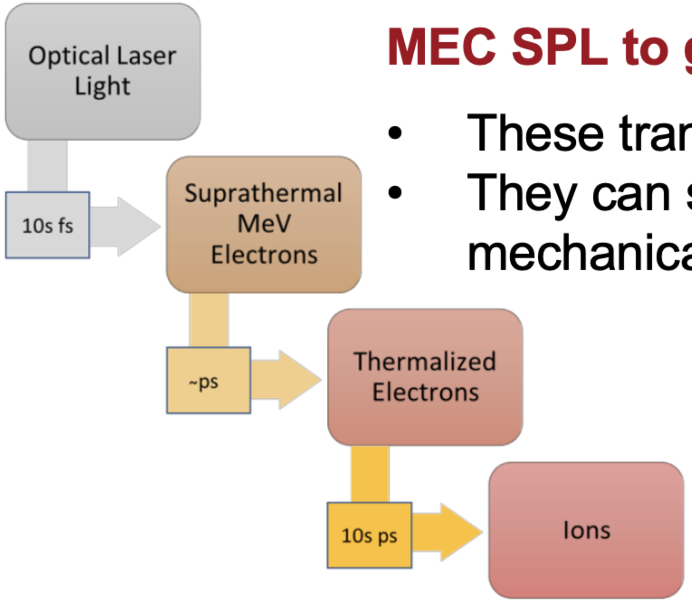
Concept:

- Standardization of XRD technique with LCLS and the MEC long pulse laser
- Provides simultaneous lattice structure and sample pressure measurements

Diagnostic capabilities:

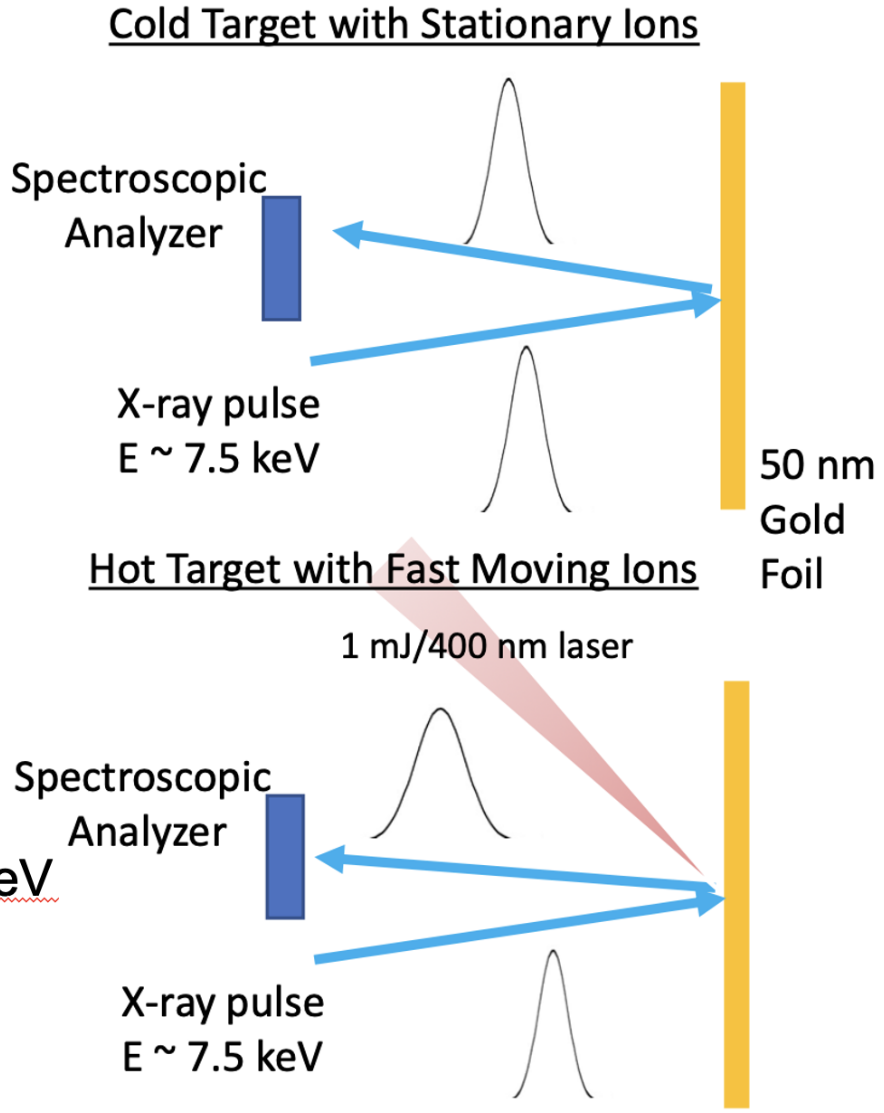
- 4 ePix10k quads provides a 2θ coverage of about 10° to 75° and a Φ coverage of ±100°
- Dual line VISAR allows for pressure measurement from 10 GPa up to 5 Mbar

Warm Dense Matter Studies



MEC SPL to generate WDM conditions

- These transient plasmas are a precursor to WDM
- They can serve as a testbed to validate quantum mechanical theories of electron-ion interactions

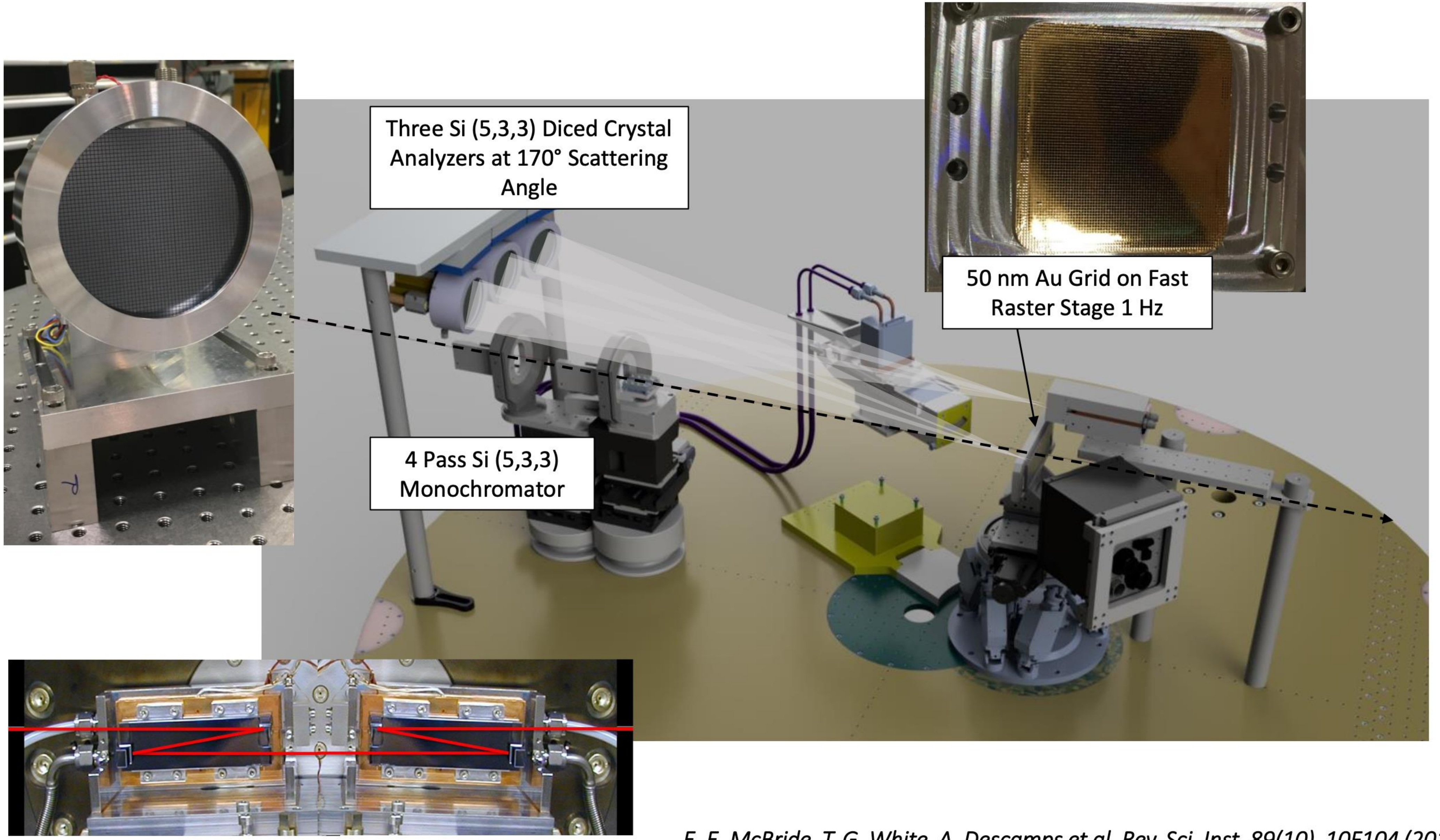


LCLS for a direct measurement of ion temperature in plasmas

- XFEL: brightest x-ray sources on the planet (10^9 x synchrotrons)
- LCLS standard probe is 40 fs with 10^{12} photons in a pulse
- Bandwidth in seeded mode is ~ 0.5 eV, but it can be reduced to meV range with 4-pass Si (533) monochromator

→ Allows Ultra-high resolution inelastic X-ray Scattering for direct T_i measurement

Warm Dense Matter Studies

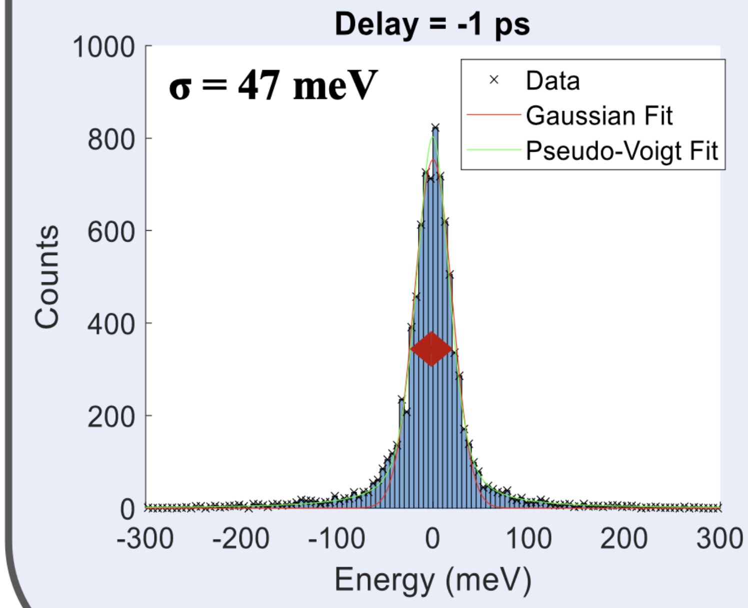


E. E. McBride, T. G. White, A. Descamps et al. Rev. Sci. Inst. 89(10), 10F104 (2018)

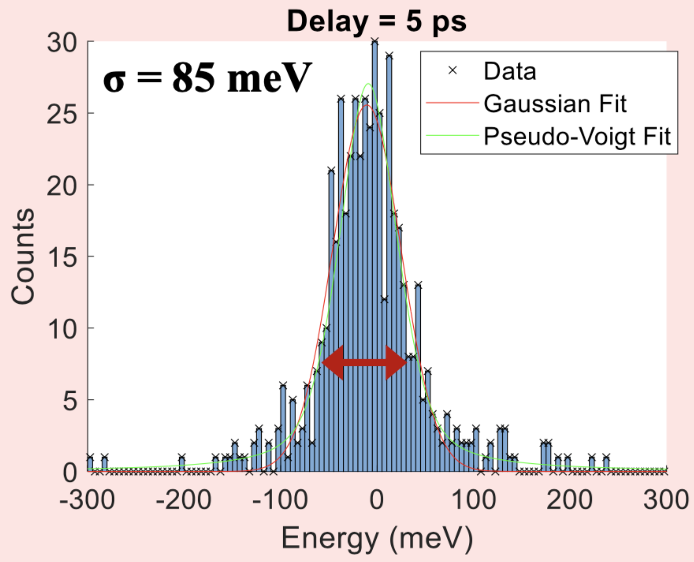
Warm Dense Matter Studies

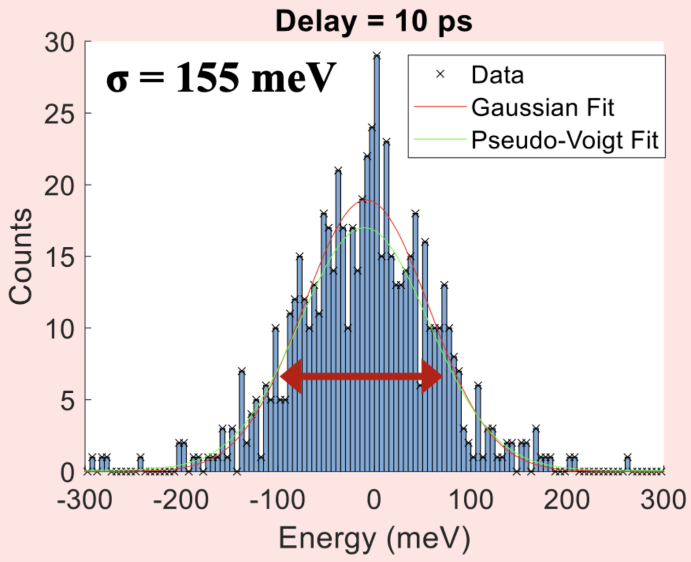
Experimental Results from Gold

Cold



Hot



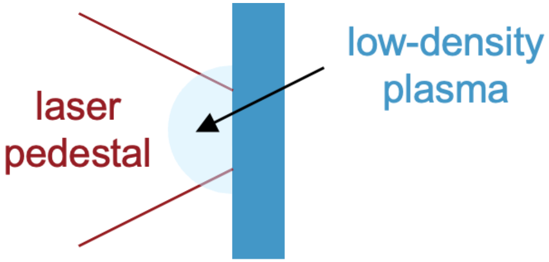


The spectrum from a cold target contains around ~10,000 photons and was collected at 10 Hz. It is well fit by a Voigt profile with a FWHM of 47 meV, close to the theoretical instrument function

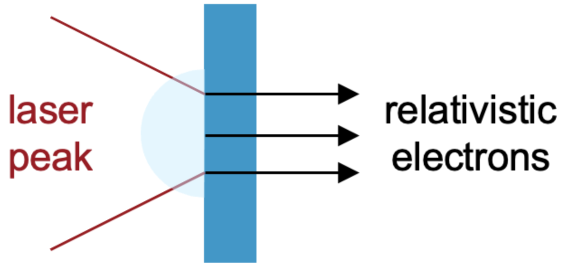
These 'hot' spectra are taken at 5 ps and 10 ps after laser irradiation. The instrument function is additionally broadened by a Gaussian with a width corresponding to the velocity distribution of the ions. As the target was destroyed on each shot, the shot rate for these spectra was 1 Hz and Each spectrum contains around 500 photons.

Daniel Haden (UNR)

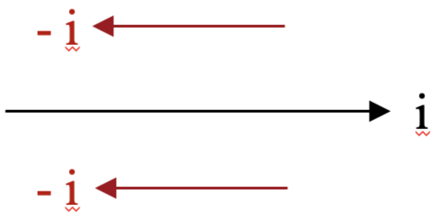
Relativistic Electron Transport



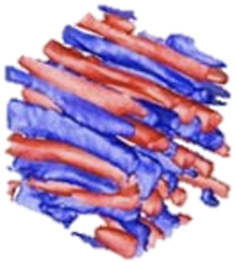
Above 10^{18} W/cm^2, the pedestal of the laser pulse creates a low-density plasma at the interaction surface.



At peak intensity, electrons of this pre-plasma are accelerated to relativistic energies into the over-dense target.

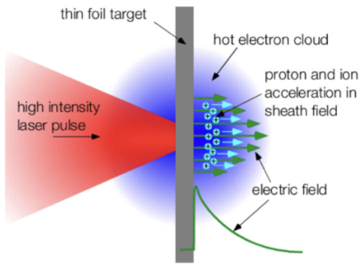


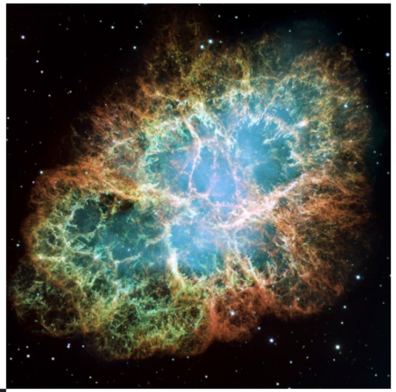
This electron beam is characterized by a large current, which is compensated by a counter-propagating return current.



This creates magnetic fields that trap electrons and divide the initial beam into smaller filaments.

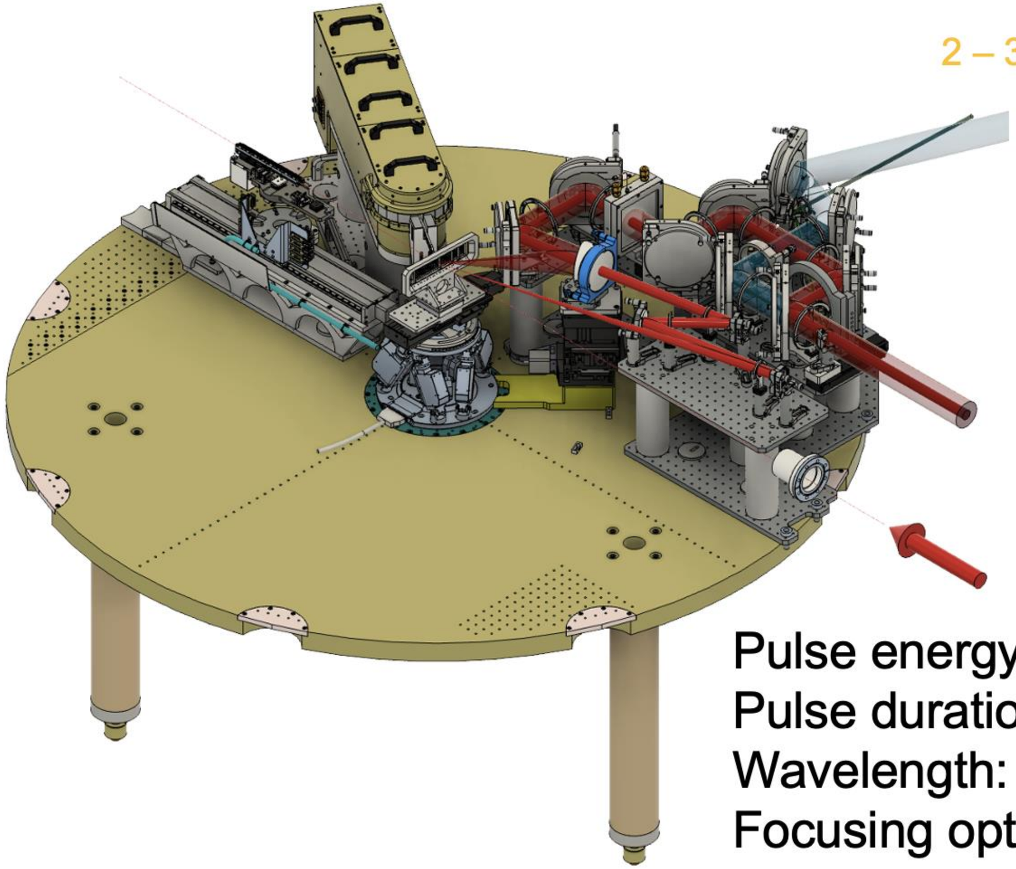
This process, called **resistive filamentation**, is a corollary to the **Weibel instability** found in counter-propagating collisionless plasma flows.

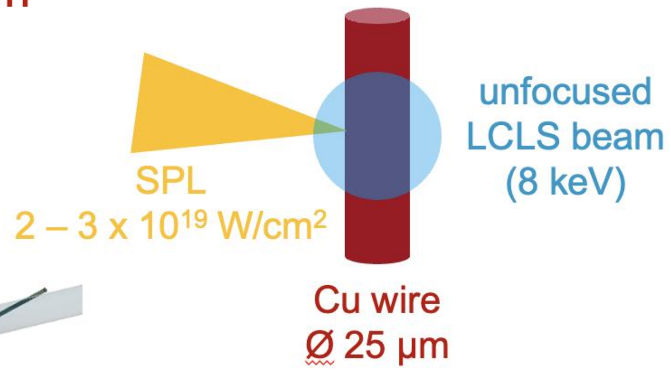




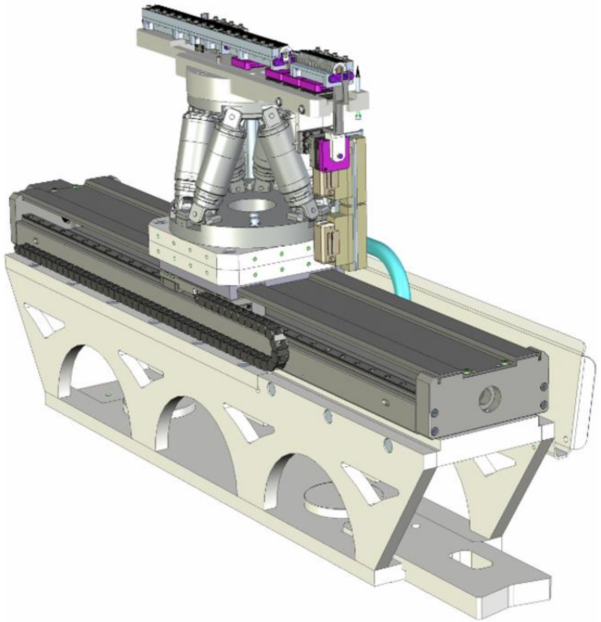
Relativistic Electron Transport

MEC SPL standard beam delivery platform
(up to 2 - 3 x 10^{19} W/cm^2)





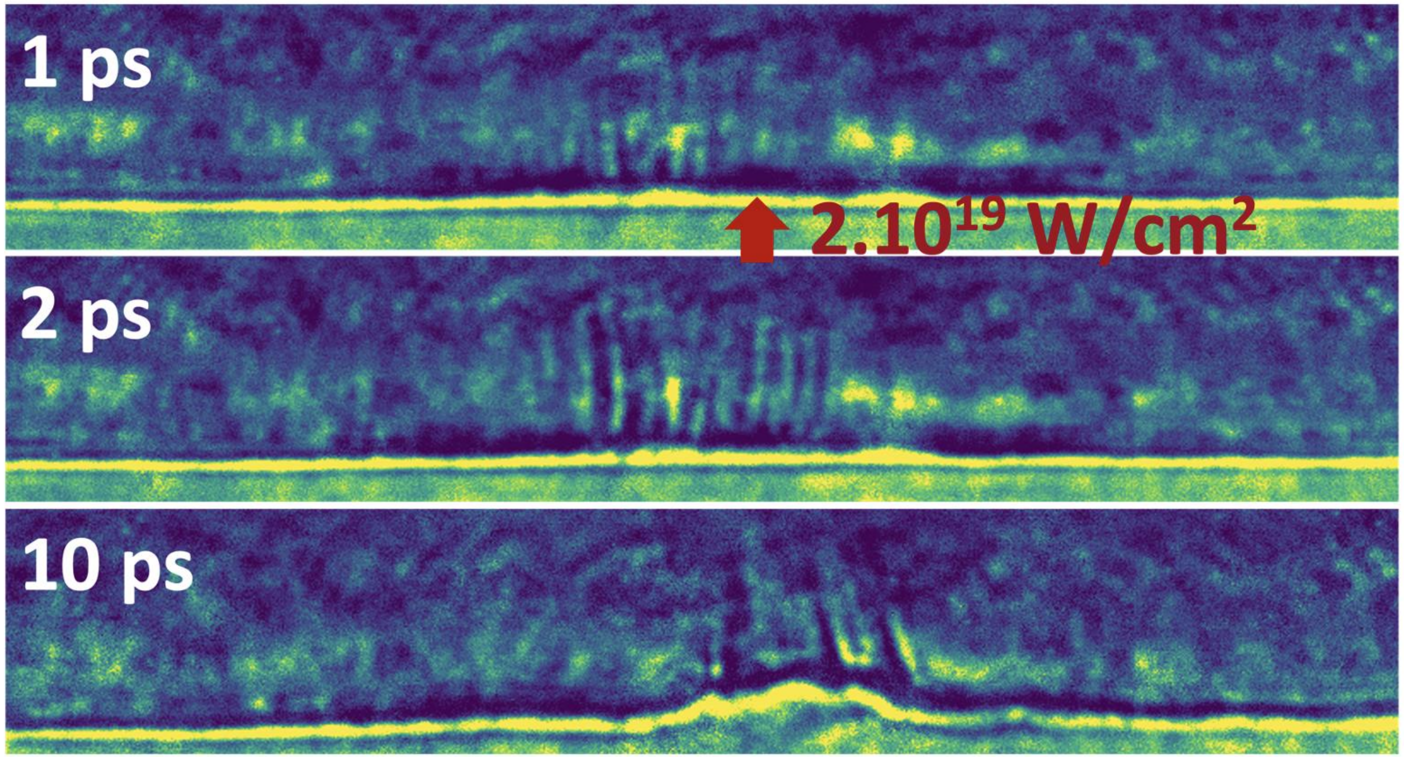
Pulse energy: ~1 J
Pulse duration: 50 fs
Wavelength: 800 nm
Focusing optics: f/5 OAP

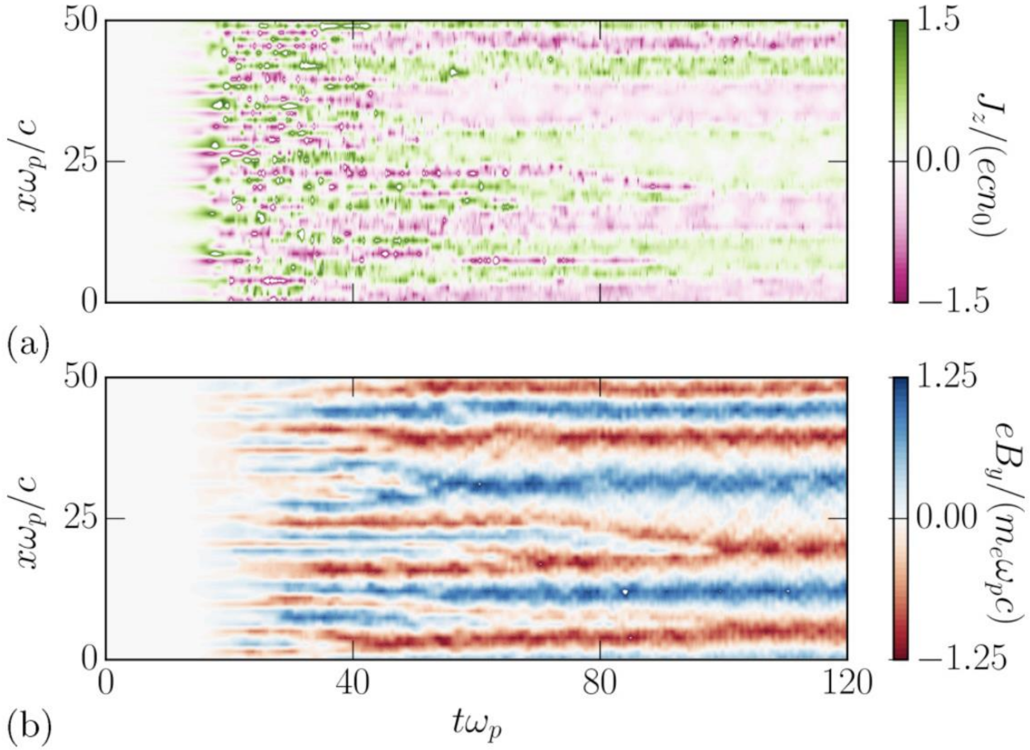


MEC X-ray Imager (MXI)

The MXI can perform direct x-ray imaging of laser-driven dynamic phenomena backlit by the LCLS beam. The spatial resolution is better than 400 nm, and the temporal resolution is better than 100 fs when coupled with the time tool.

Relativistic Electron Transport



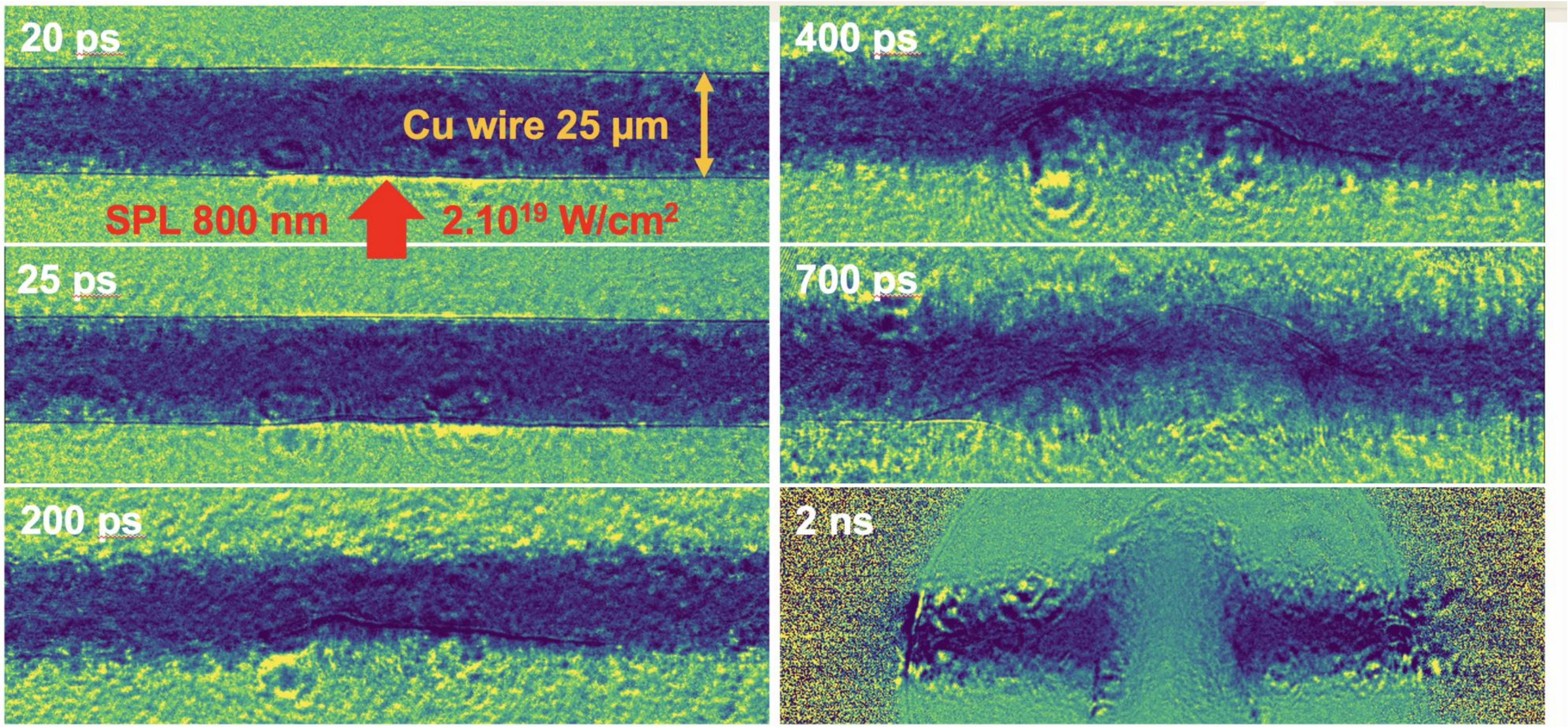


Grassi, A., et al. Physical Review E 95.2 (2017): 023203.

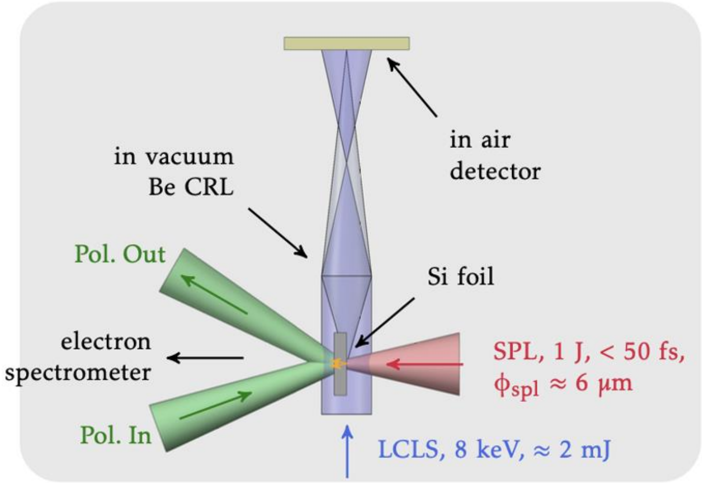
What do we really see?

- density contrast cannot explain this observation (ion motion is not expected yet)
- we could be observing the filament structures with phase contrast (x-ray beam transport and CRLs)

Hydrodynamic Evolution

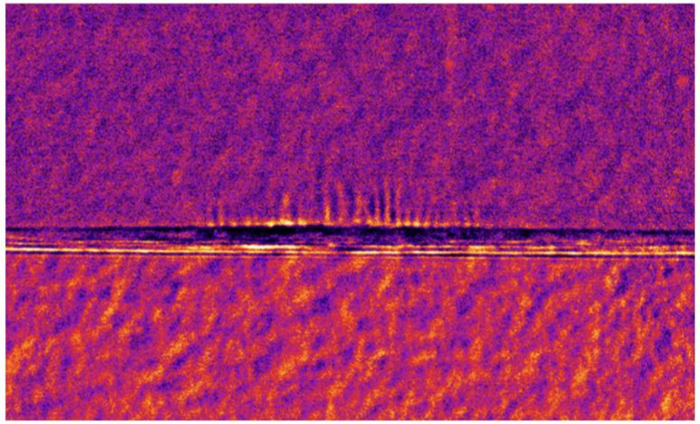


Future Investigations

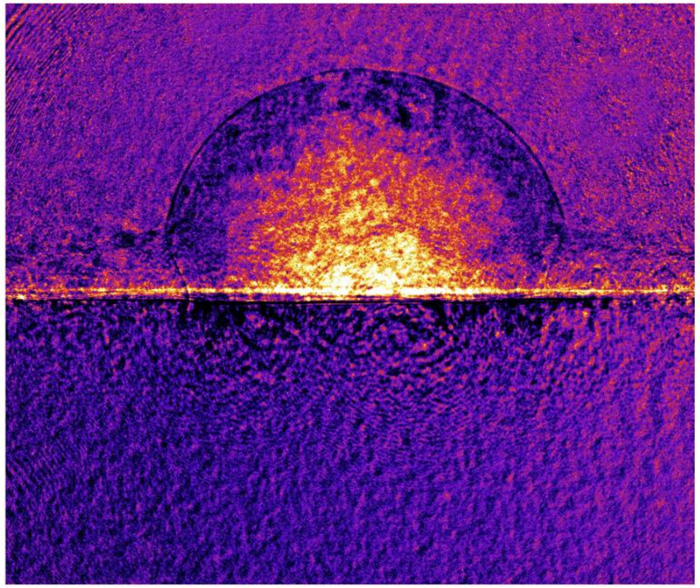


Further studies coming with Si foils

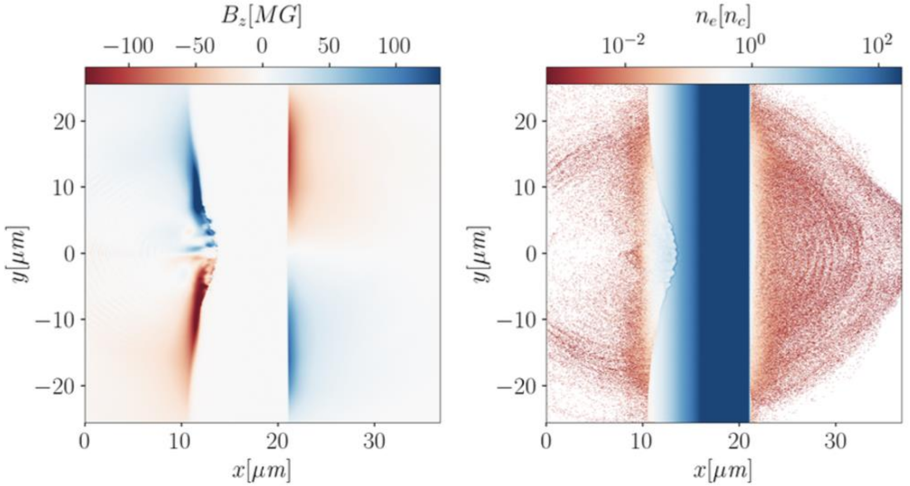
- Simplified interaction geometry
- Alignment precision easy to fulfil
- Adding magnetic field measurement with optical polarimetry



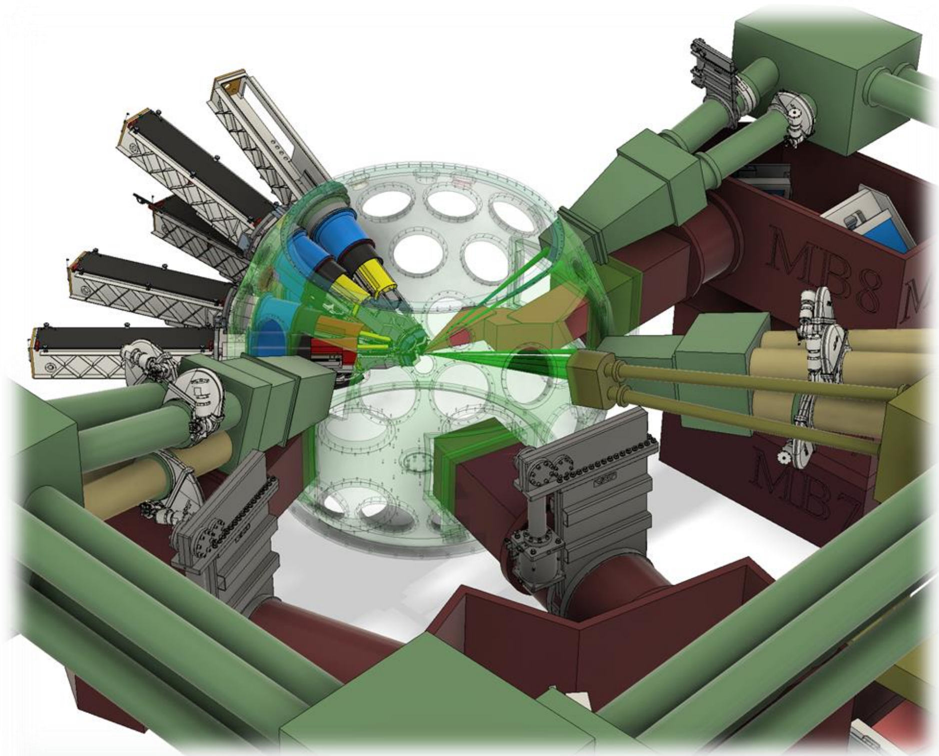
2 ps



2 ns



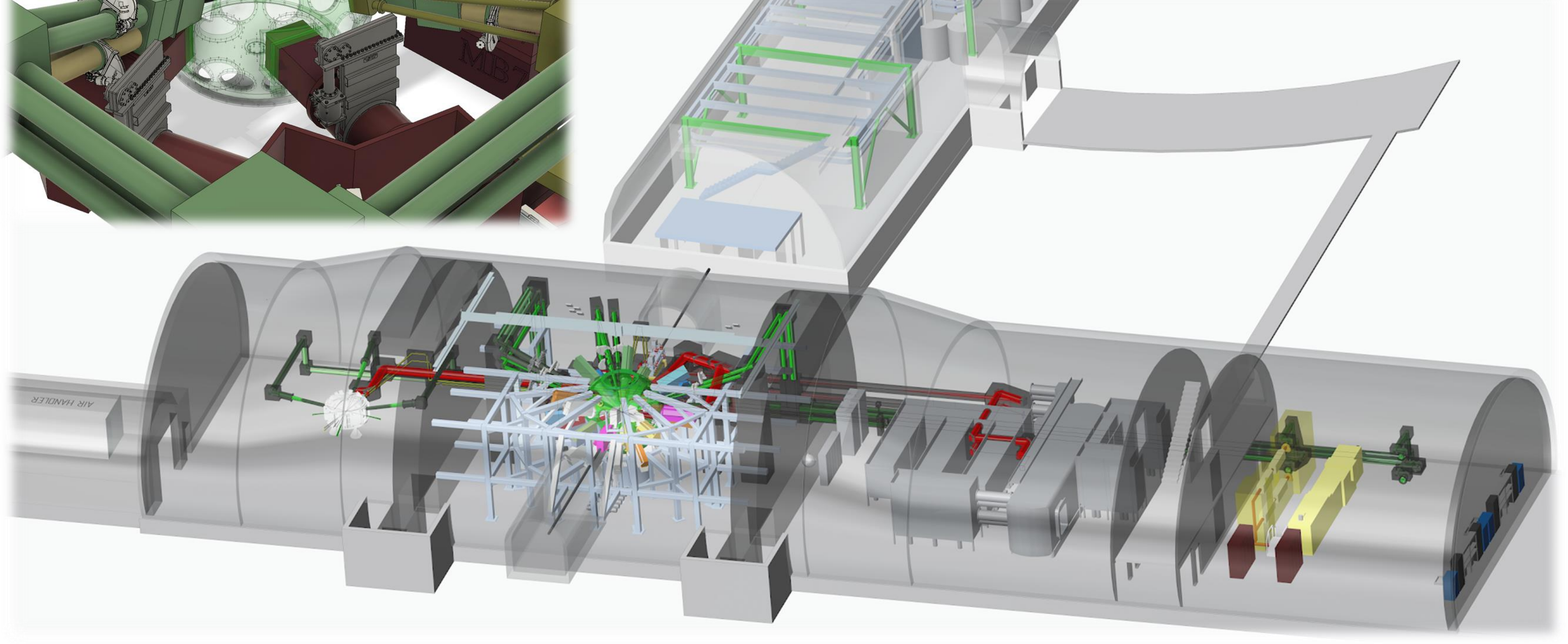
Starting collaboration with LULI for PIC simulations (Smilei)



MEC-U

MEC Upgrade Project

- LCLS-II : 5-40 keV, 120 Hz, multi-pulse mode
- LPL : 1 kJ, 5-35 ns, shot / 30min
  ~200 J, 5-35 ns, 10 Hz
- SPL : 150 J, 150 fs, 10 Hz
- Optimized X-ray end-station
- Dedicated Optical only end-station



MEC and MEC-U Team

Bob Nagler
Inst. Scientist

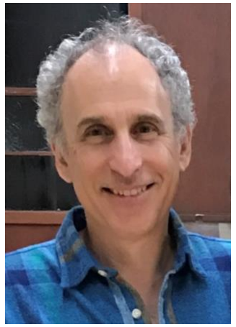
Philip Hart
Scientist, Detectors POC

Hae Ja Lee
Inst. Scientist

Meriame Berboucha
PhD Student

Eric Cunningham
Laser Scientist

Alan Fry
Senior Staff Scientist SLAC
MEC-U Project Director



Phil Heimann
Inst. Scientist
➛ X-ray Beam Delivery

Gilliss Dyer
Department Head

Eric Galtier
Instrument Lead

Dimitri Khaghani | khaghani@slac.stanford.edu