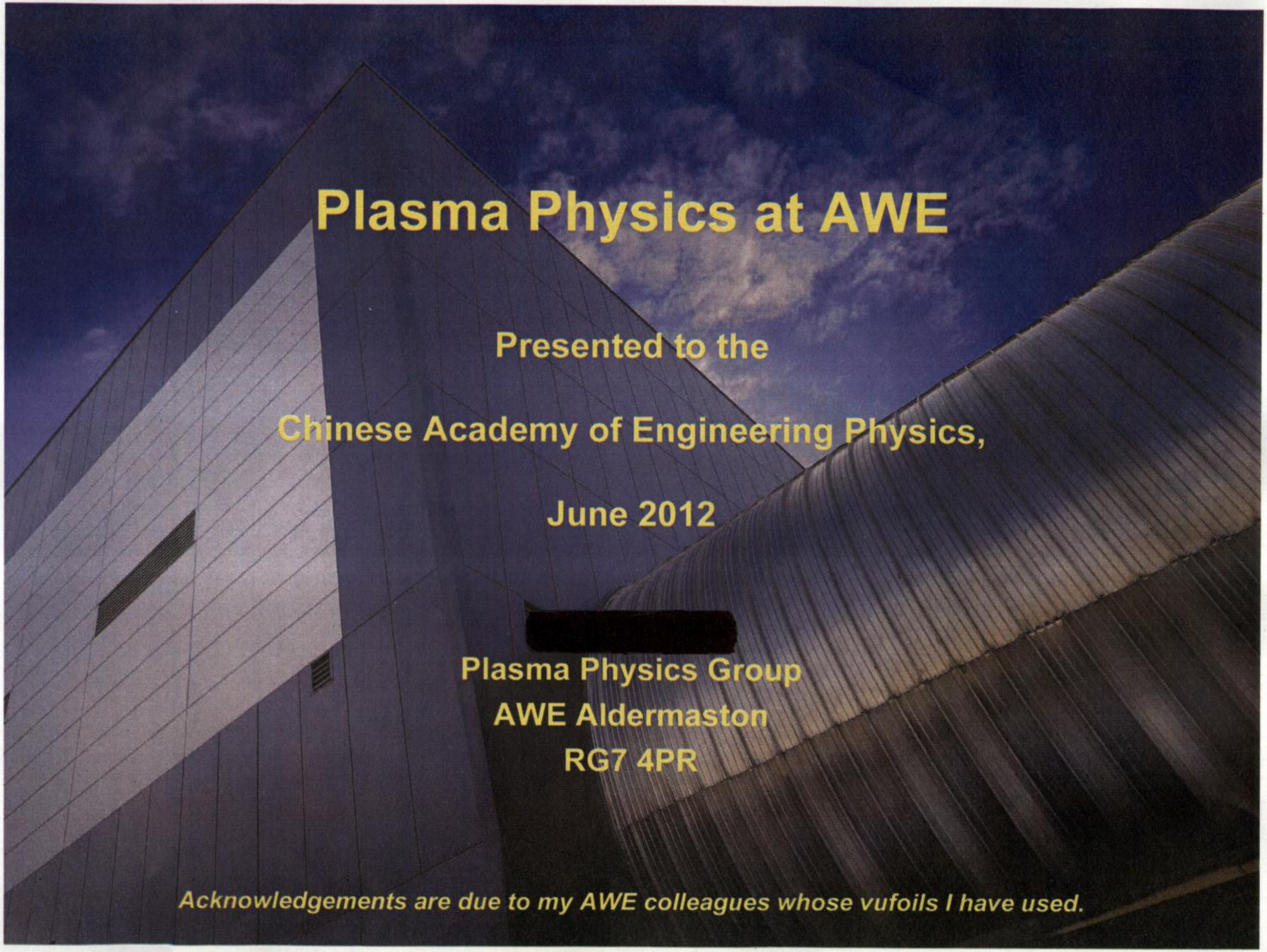

Plasma Physics at AWE
Presented to the
Chinese Academy of Engineering Physics,
June 2012
[redacted]
Plasma Physics Group
AWE Aldermaston
RG7 4PR
Acknowledgements are due to my AWE colleagues whose vufoils I have used.

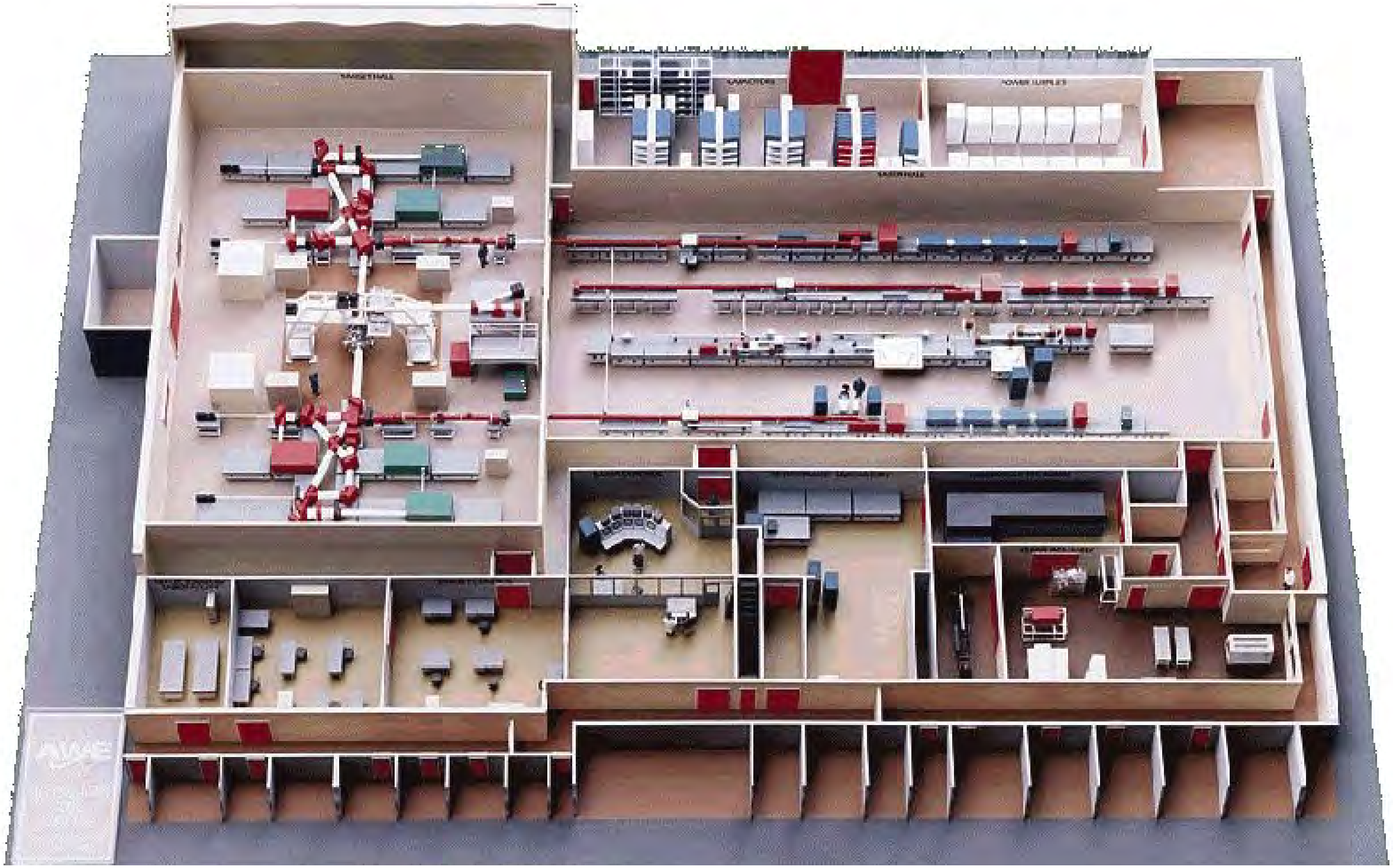
Contents

- Brief history of lasers at AWE
  - Helen
  - ORION
- The ORION laser
  - Configuration
  - Diagnostics
- ORION experiments
- Target fabrication

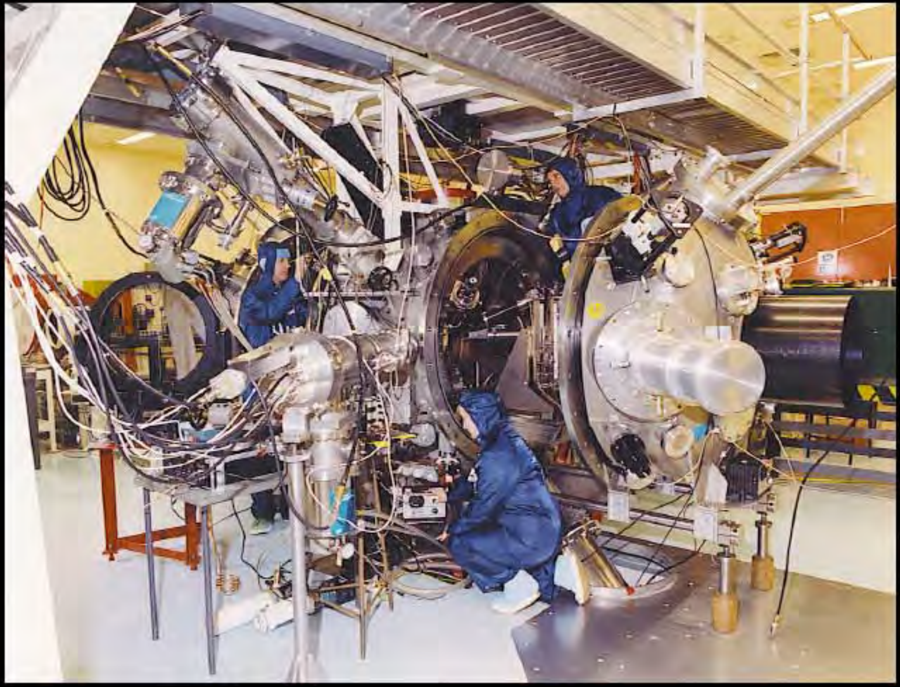
Laser work started at AWE in 1962.
The AWE HELEN laser opened in 1979.

- 1960 Laser invented
- 1962 Fusion study at AWE
- 1971 AWE paper on proposed programme for Laser Fusion studies
- 1972 LLNL publishes work on Laser Fusion
- 1975 AWE paper on a route to laser fusion (hohlraums)
  - potential for study of materials properties in near-term
- 1979 HELEN opened

HELEN had two long-pulse (~1 ns, 500 J) beams and a CPA backlighter beam (~500 fs, 50 J, 1.05 μm)



AWE's HELEN laser: opened 1979

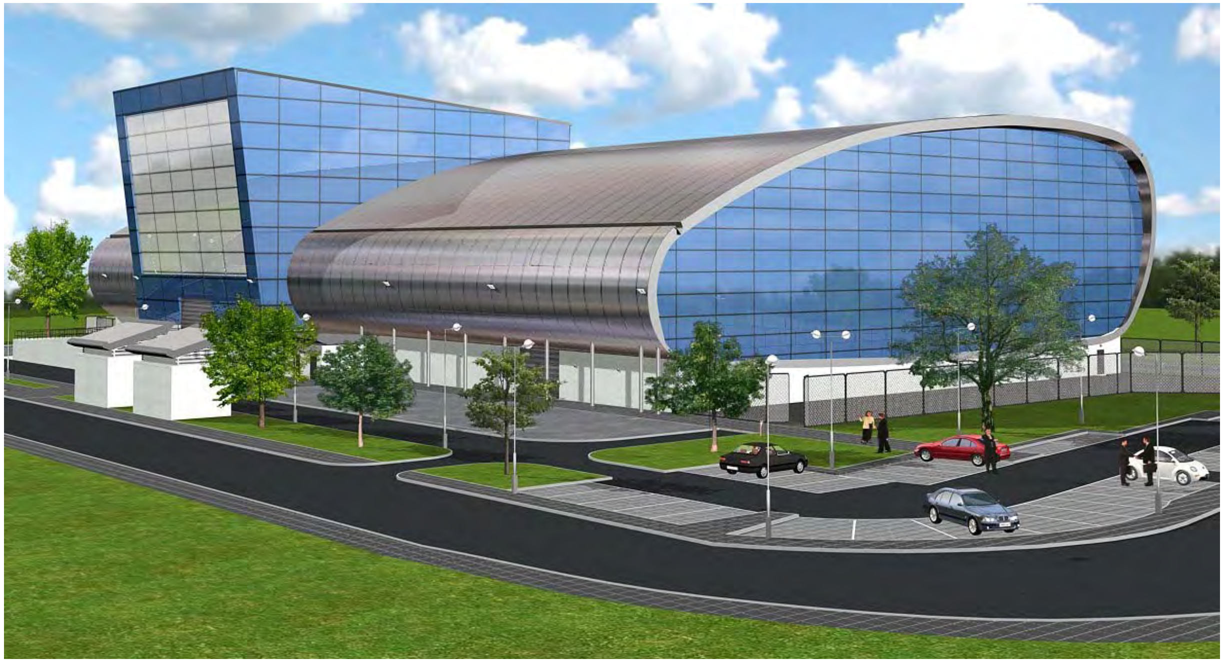


Laser work started at AWE in 1962
HELEN laser opened in 1979

- 1960 Laser invented
- 1962 Fusion study at AWE
- 1971 AWE paper on proposed programme for Laser Fusion studies
- 1972 LLNL publishes work on Laser Fusion
- 1975 AWE paper on a route to laser fusion (hohlraums)
  - potential for study of materials properties in near-term
- 1979 HELEN opened
- **2009 HELEN closed**
- **2012 ORION open**

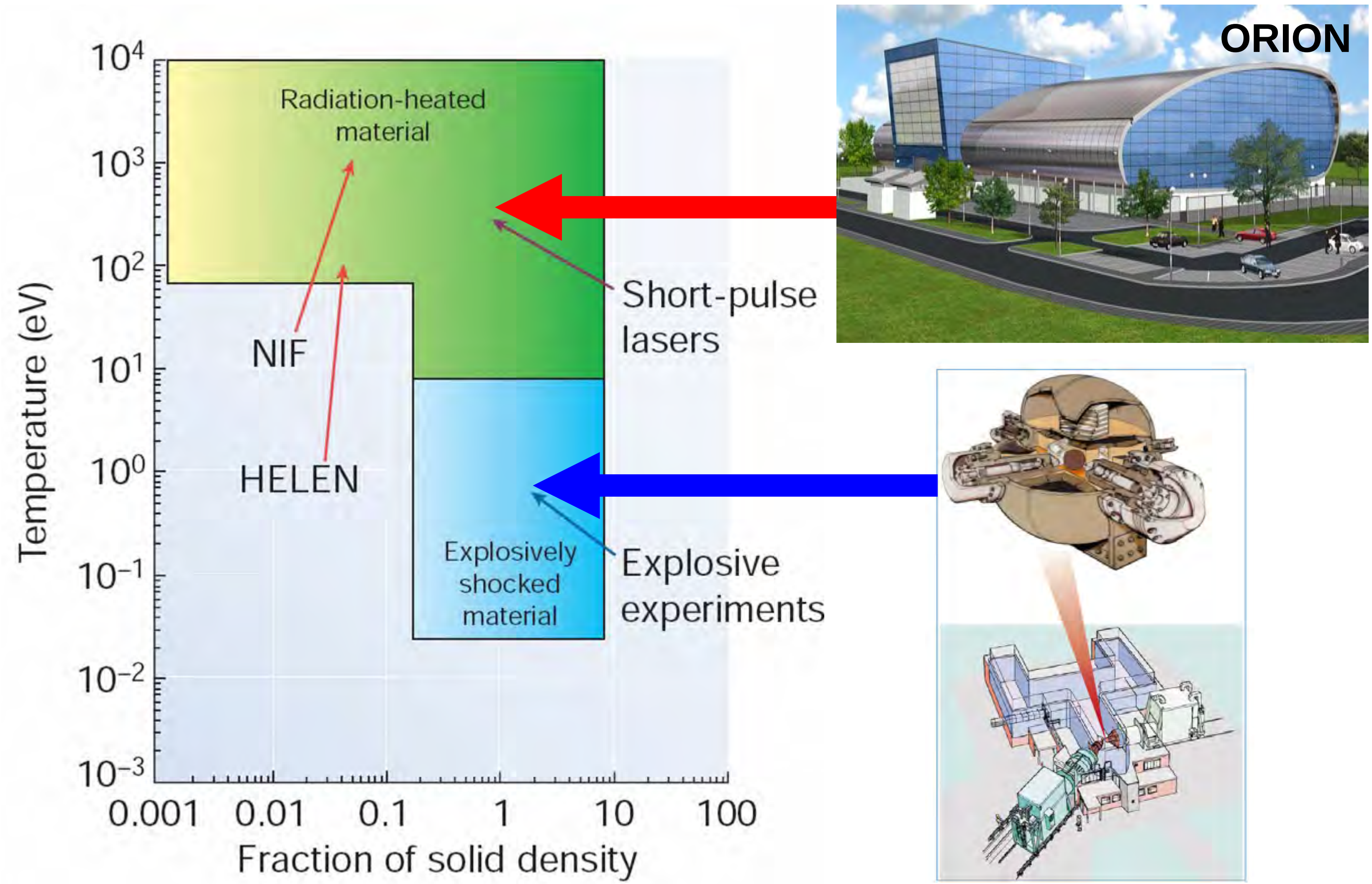
The ORION laser is under construction. Its combination of long-pulse and short-pulse beams will allow us to study materials properties at relevant high densities and temperatures.

- Long pulse beam for compression
- Short pulse beams for temperature
- Combine to achieve extreme conditions
- ~ 15% of Orion beam-time will be available for collaborators from academia.



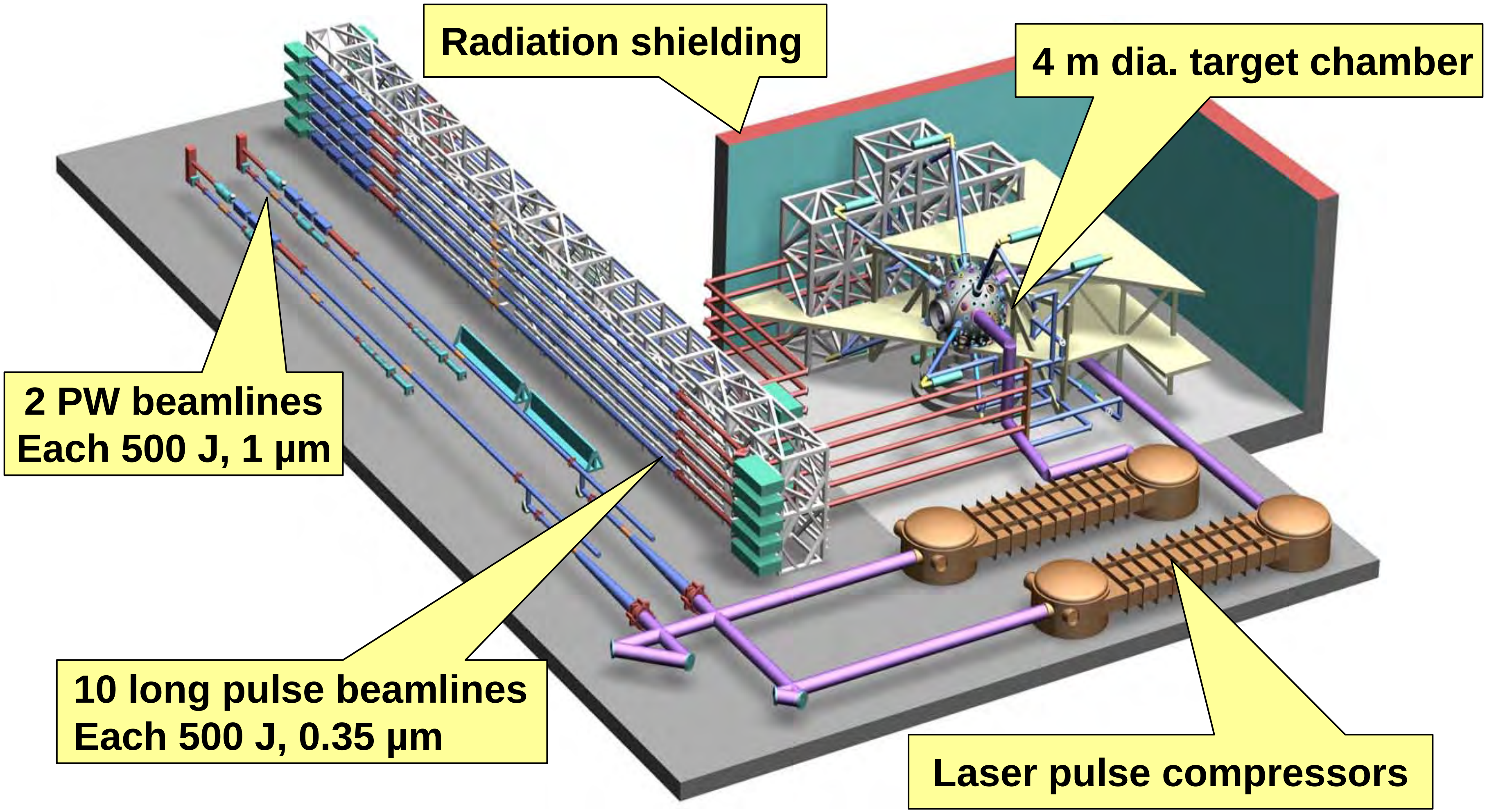
- Ten long-pulse beams
  - 300 mm dia.
  - 500 J per beam
  - 351 nm
  - 1 ns square pulse.
- Two short pulse beams
  - 600 mm dia.
  - 500 J per beam
  - 1053 nm
  - 0.5 ps pulse.
  - 10^{21} W cm^{-2} using f/3 off-axis focus parabola
  - horizontal on-axis and orthogonal layout
- Extensive diagnostics

ORION will allow us to explore conditions similar to those reached during the phases of operation of a nuclear warhead.



Nature, 415, 853, 21 Feb 2002

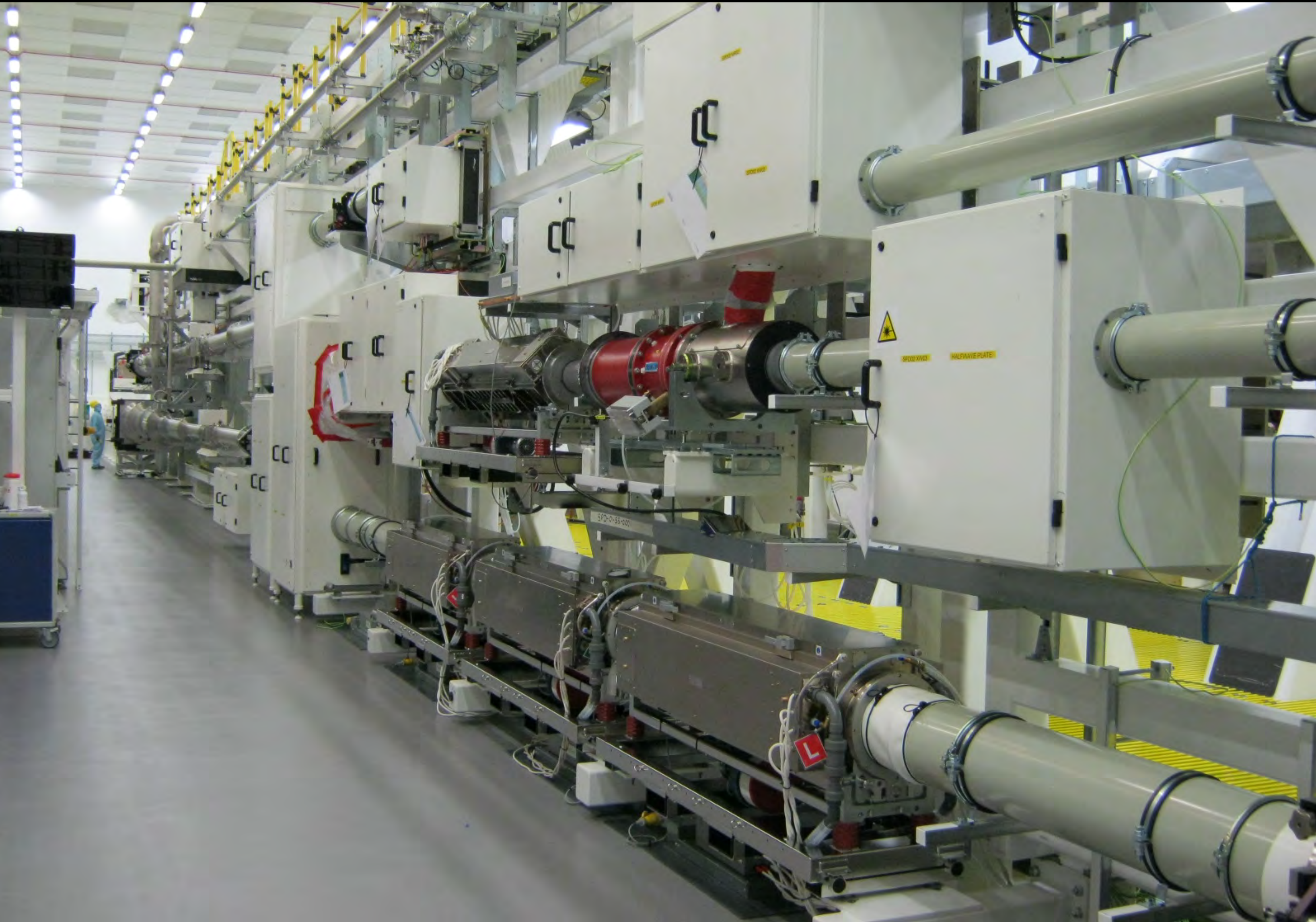
Schematic of ORION laser and target halls.



The laser hall, seen through a laser-light-absorbing filter.

The ten long-pulse beam-lines are complete and working.

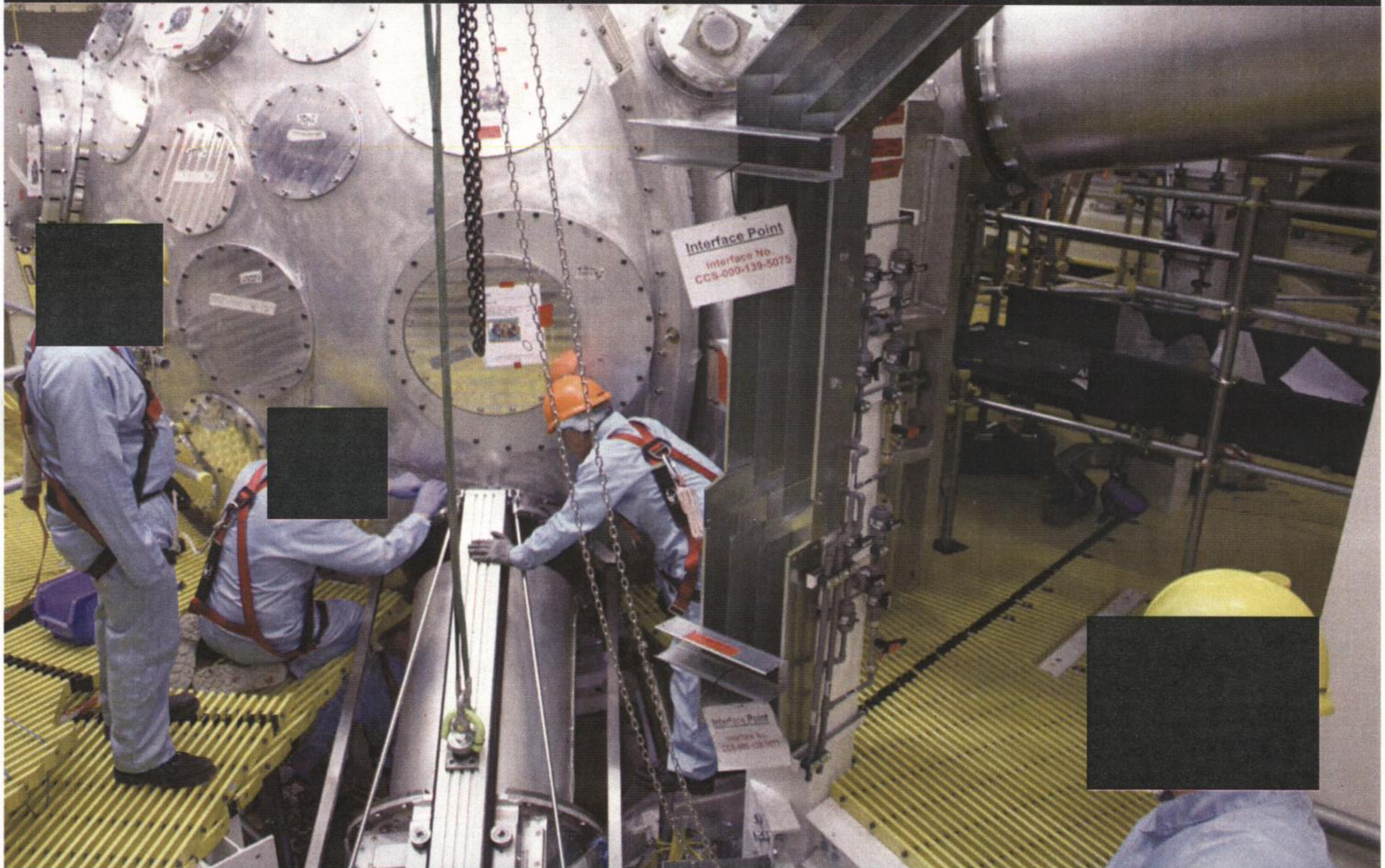
The two short-pulse beam-lines are complete and working.



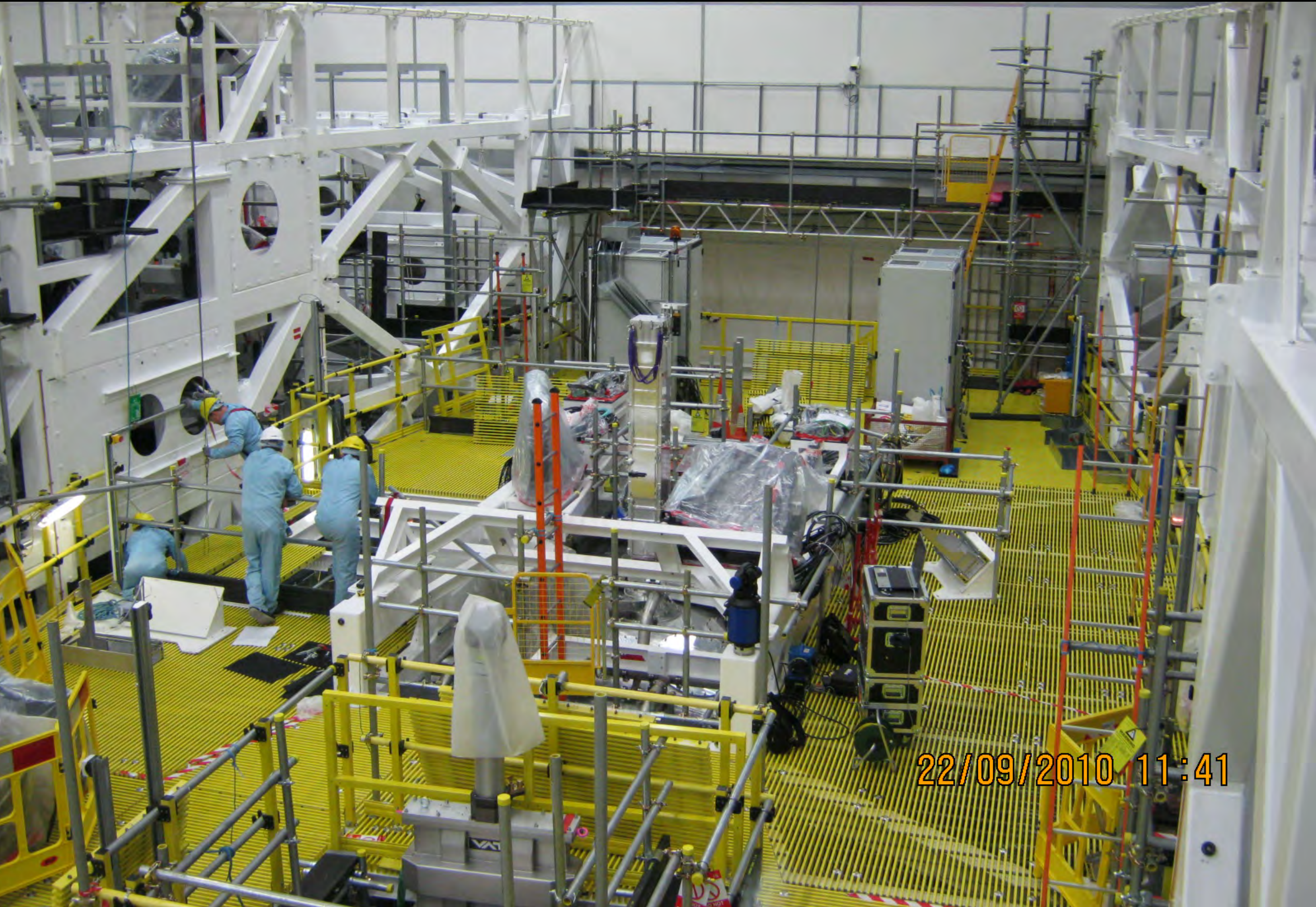
Compressor hall

Inside compressor vessel setting up large aperture grating.

First long-pulse final optics assembly being installed.

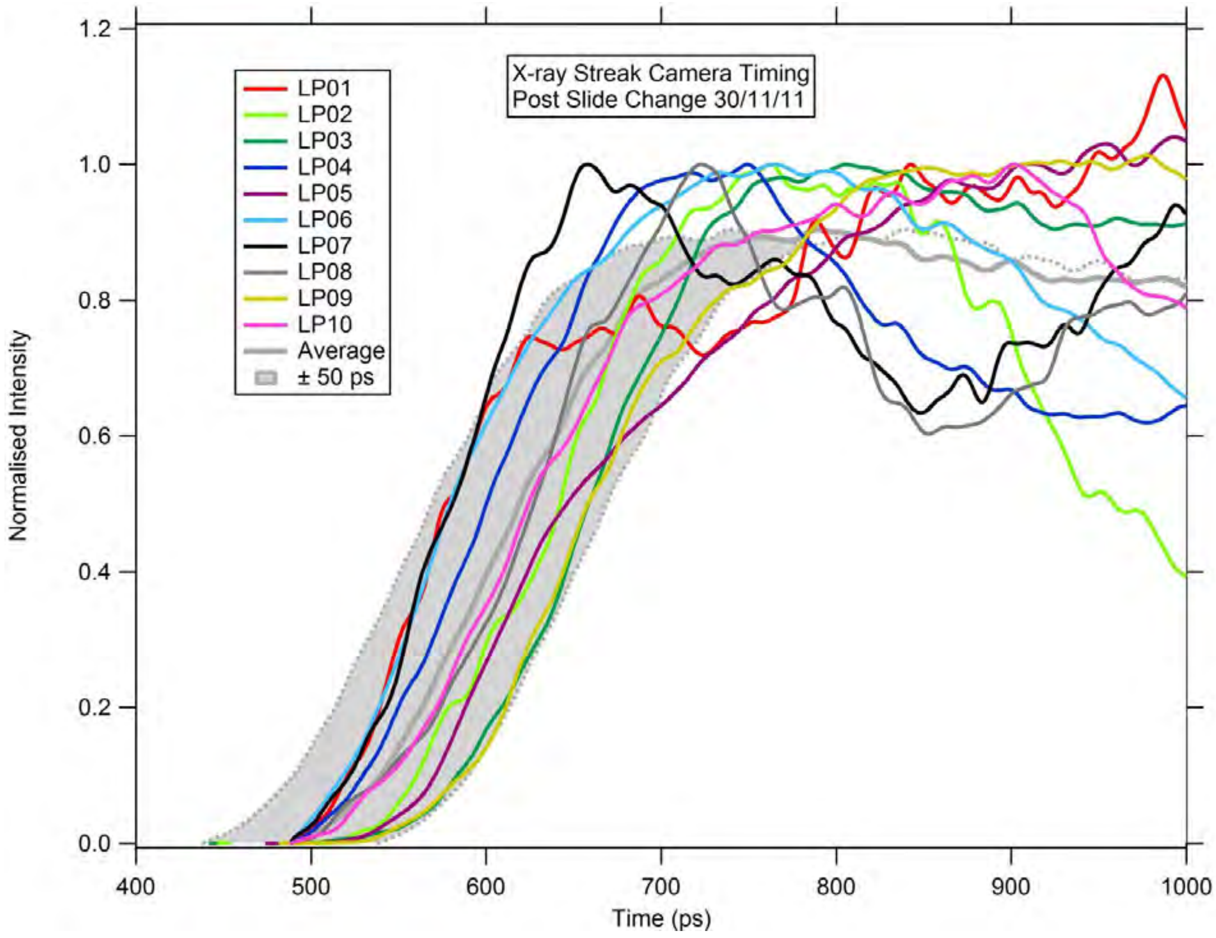


Above target chamber after installation of target inserter.



ORION target chamber during commissioning

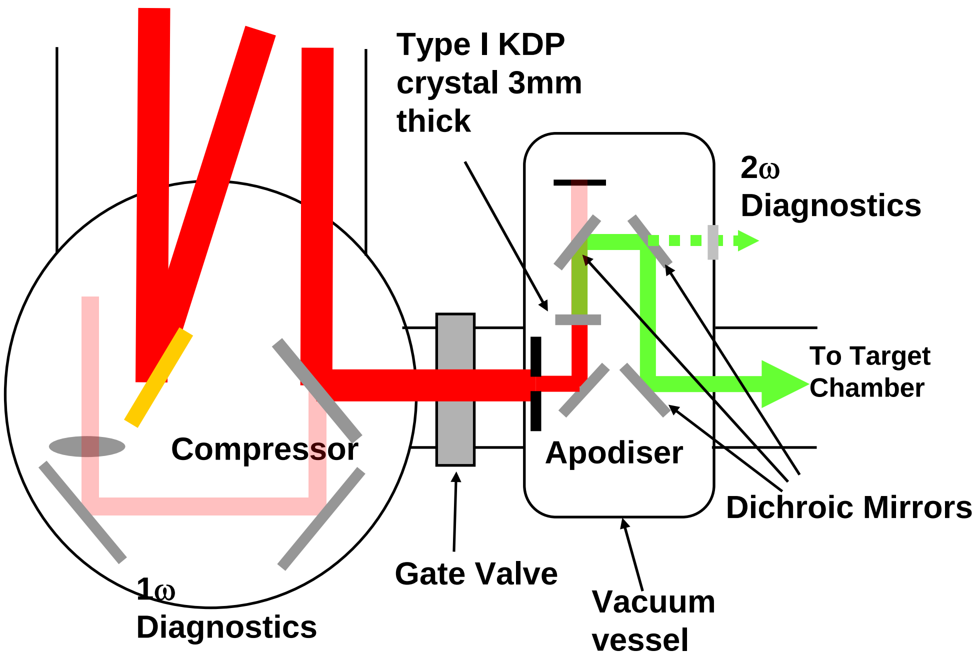
Long-pulse synchronisation to within ±50 ps has been achieved on all 10 beams.

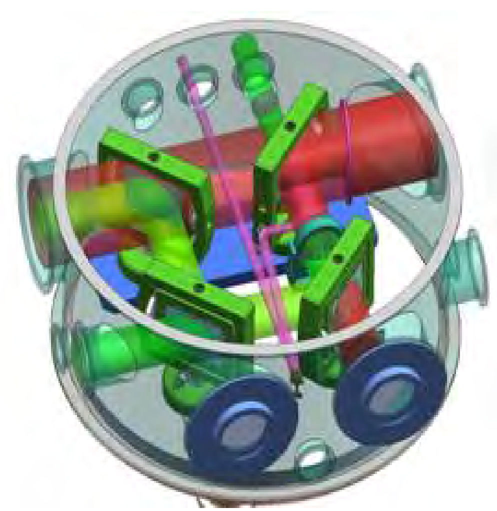


Pulse-contrast will be an issue for some experiments but is addressed by the availability on ORION of 2ω light at sub-aperture.

Some experiments will require the best possible contrast for the PW beams, rather than maximum intensity. Non-linear nature of conversion to 2nd harmonic provides large enhancement in contrast.

- **The option for conversion to the second harmonic at reduced aperture will be provided in a vessel immediately following the compressor.**
- **Dichroic mirrors leak away residual 1ω energy.**
- **2ω campaigns on HELEN CPA influenced the Orion design.**

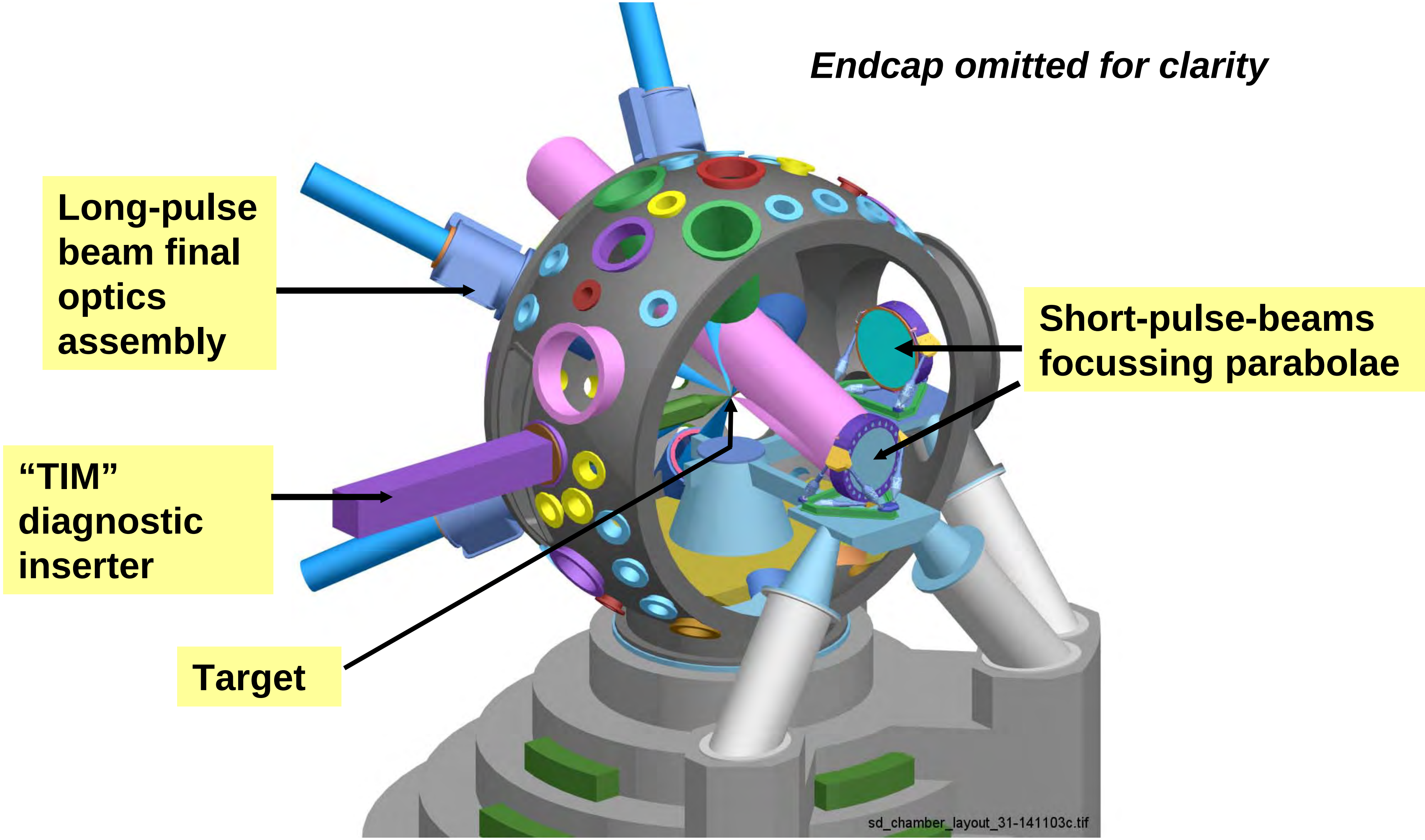




ORION diagnostics provided by the project include:

- **OPTICAL**
  - Optical streak cameras
  - Passive shock breakout
  - Optical pyrometry
  - Active shock breakout
  - VISAR interferometer
  - Backscatter – SRS + SBS
- **PARTICLE**
  - Electron spectrometers
  - Neutron time-of-flight
  - Total neutron yield
  - Neutron spectrometer (later)
- **X-RAY**
  - X-ray microscopes
  - Dante
  - Filter Fluorescer
  - Framing cameras (TIM-compatible)
  - Streak cameras (TIM-compatible)
  - Transmission grating spectrometer
  - Harada grating spectrometer
  - Hard X-ray spectrometer

The Orion target chamber (4 m dia. Al)



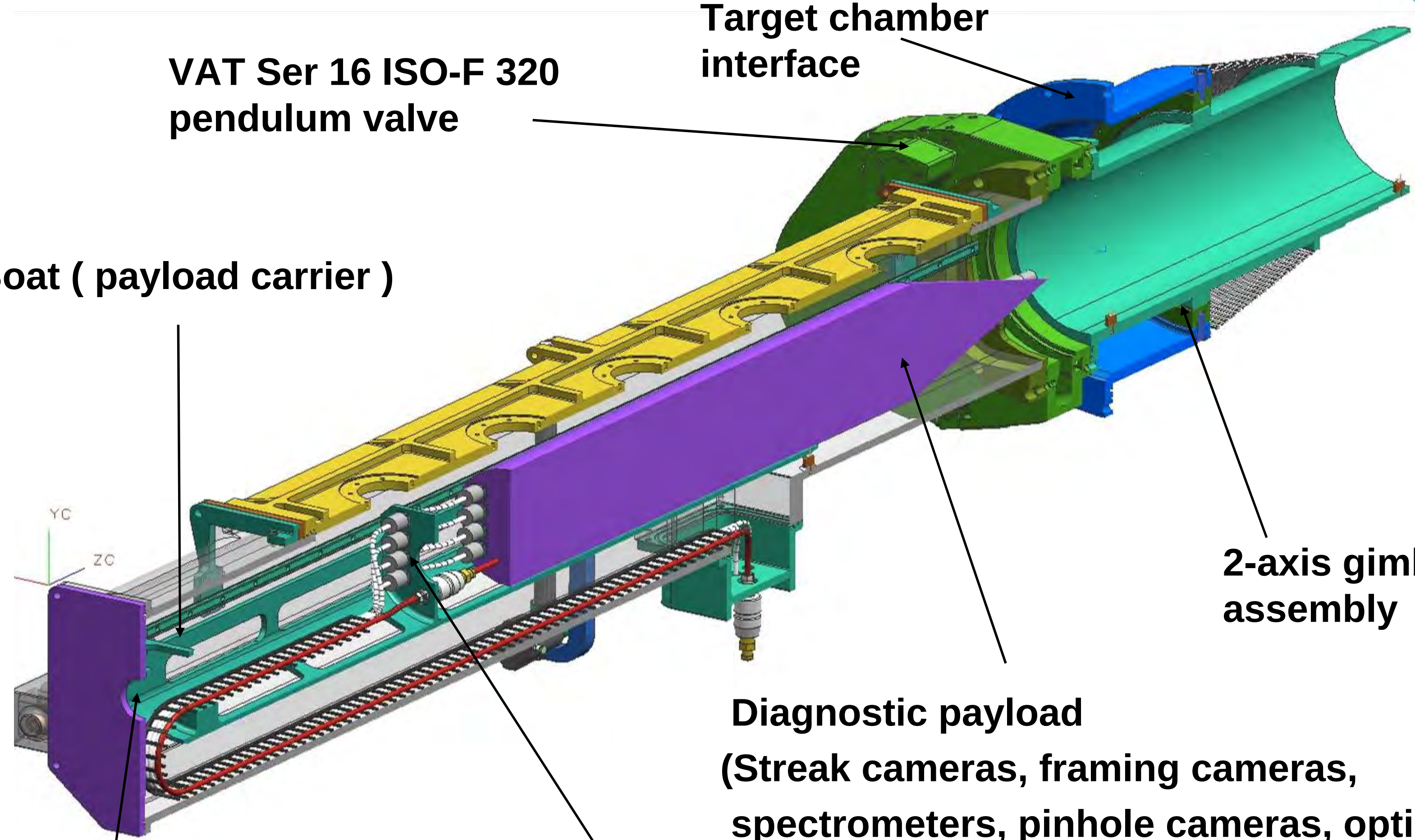
Orion has a number of permanently-mounted diagnostics.

Diagnostic	Specification
Optical diagnostic system	PASBO (passive shock breakout), ASBO (active shock breakout), VISAR, pyrometry and probe beam. (NB: front ends of this diagnostic are TIM-mounted)
Dante	Absolutely calibrated, time-resolved soft X-ray (100 eV - few keV) diodes
Filter-fluorescer	Absolutely calibrated, time-integrated X-ray (20 - 100 keV) detector
KB X-ray microscope	Time-integrated imaging (few keV, 10 μm resolution)
Full-aperture SRS/SBS backscatter	Long pulse, short pulse and NBI (near-backscatter optical imaging). Time resolved absolute power and spectrum
nTOF neutron diagnostic	Useful range 10^7 – 10^{11} neutrons. Scintillator / photomultiplier
Total yield neutron diagnostic	Copper activation uses rapid transfer and coincidence-counting techniques
Hard X-ray spectrometer	Absolutely calibrated, time integrated X-ray (100 keV - 2 MeV) detectors
Transmission grating spectrometer	Absolutely calibrated time-resolved or time-integrated X-ray diagnostic 120 eV - 1.2 keV
Electron spectrometer (High energy)	50 MeV - 1 GeV energy range

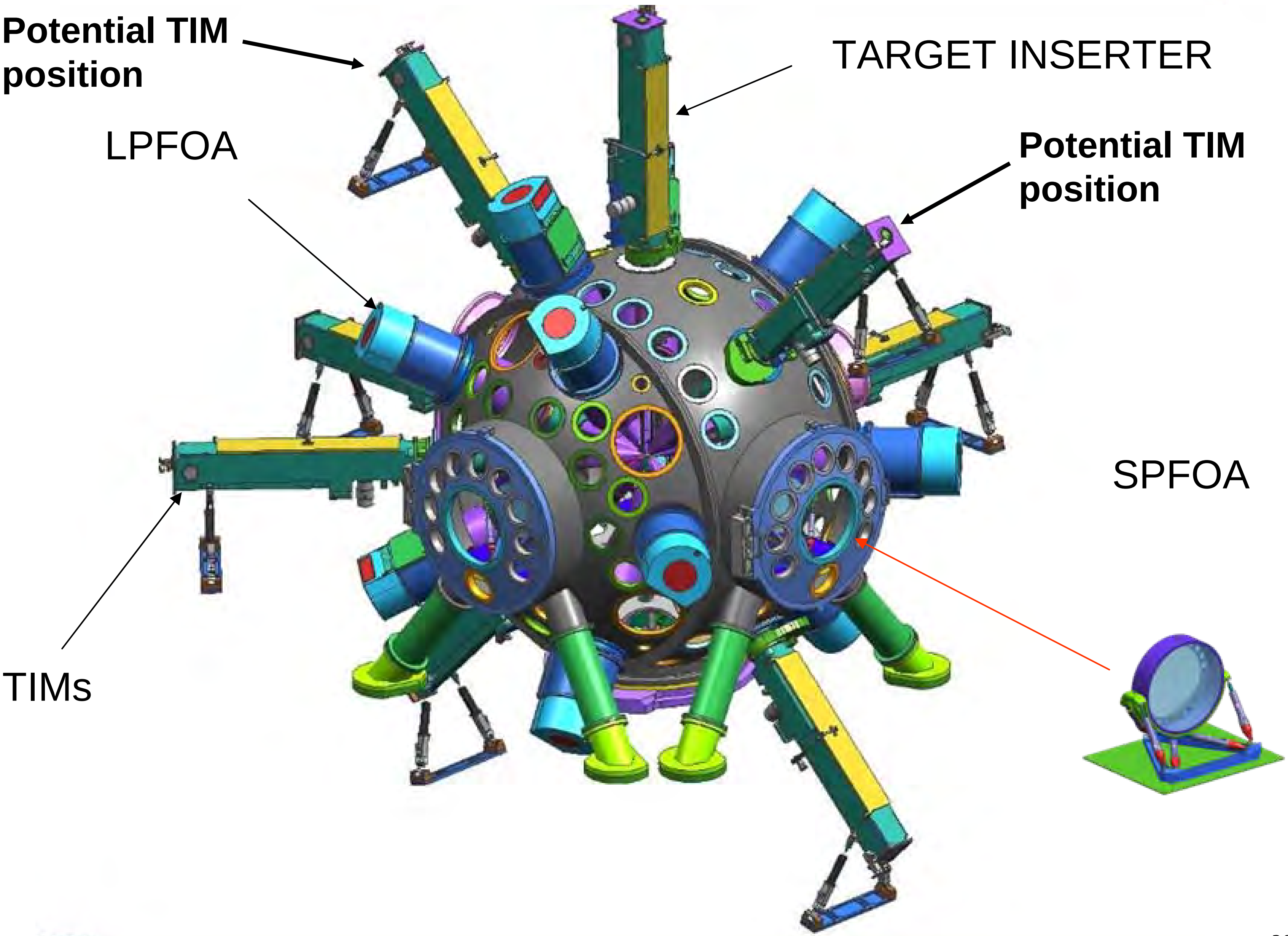
Some of the diagnostics will be fielded in insertion devices known as TIMs ("ten-inch manipulators").

Gated X-ray detector (3 off)	100 eV – few keV with pinhole camera array providing <100 ps gating capability
X-ray streak camera (4 off)	With imaging snout and crystal spectrometer providing ps and sub-ps resolution 100 eV – few keV
Time-integrated (film) spectrometer	X-ray crystal spectrometers
Thompson parabola	Proton spectra 100 keV – 10 MeV
XUV grating spectrometer	Time-integrated or time-resolved measurements 1 nm – 40 nm
Thermoluminescent dosimeters (TLD)	Hard X-ray dose 100 keV – 20 MeV
CR39 & radiochromic film (RCF)	Charged-particle dose and emission profiles
Faraday cups	Time-resolved charged-particle flux measurement

Many diagnostics are deployed on the “Ten-inch manipulator”. It allows them to be inserted without breaking chamber vacuum.



There are 6 TIMs on the ORION target chamber.



A laser is used to re-create the extreme conditions encountered in an operating nuclear weapon, but on a much smaller scale.

Weapon

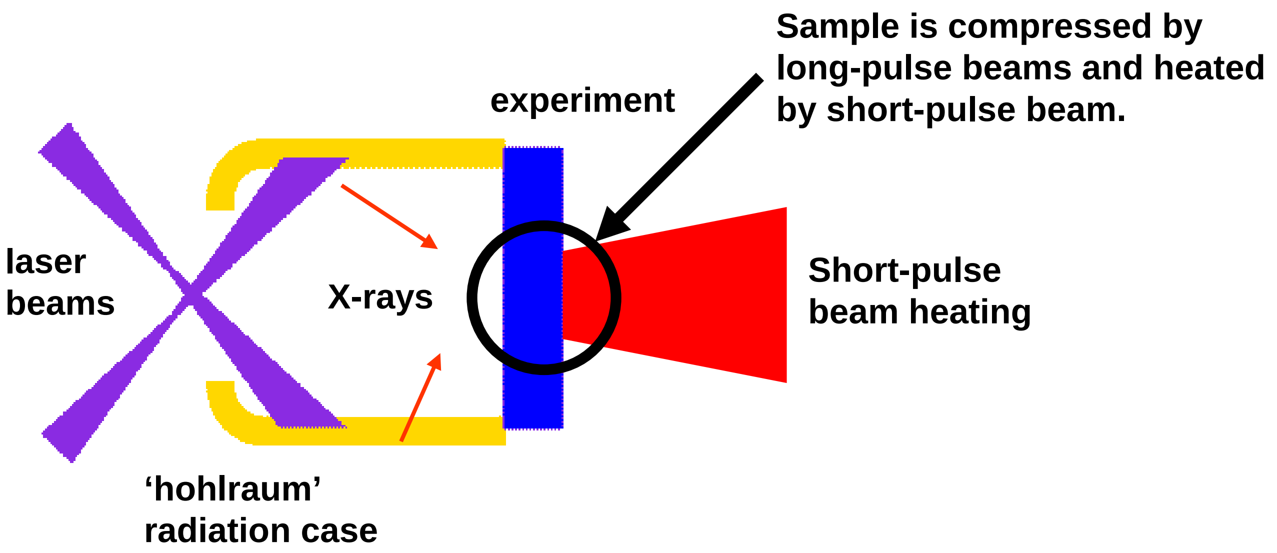
Temperature ~ 1000 eV (10 million degrees)
Density ~10’s g/cc
Timescales ~ << microsecond
Sizes ~ 10’s cm

Laser experiment
Conditions are close (but not quite) like a UGT

Temperature ~ 100 - 1000 eV
Density ~0.01 – few g/cc
Timescales ~ 0.001 - 50 ns
Sizes ~ 0.01 - 1 cm

1eV ≈ 11,600 Kelvin

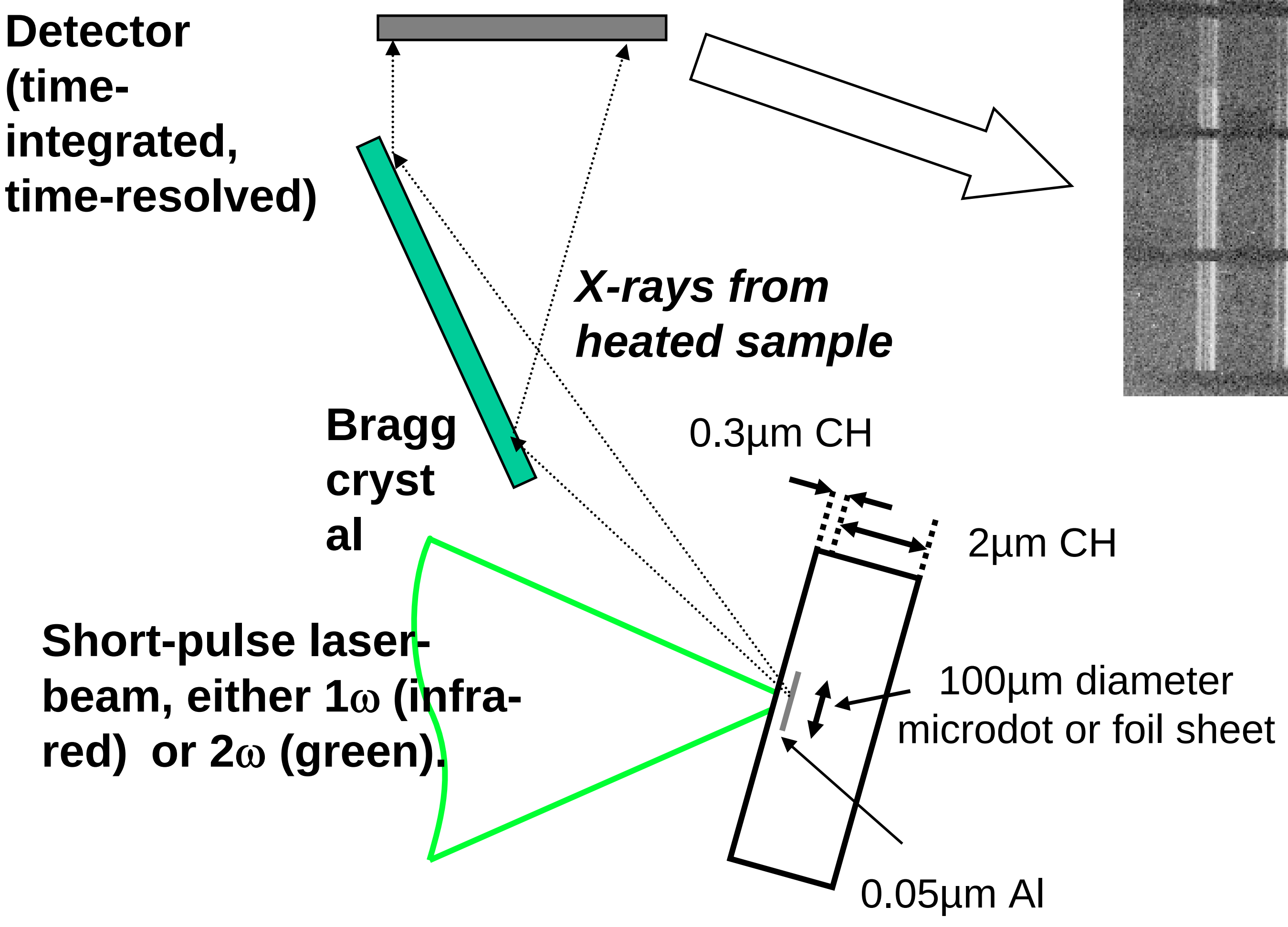
Concept cartoon

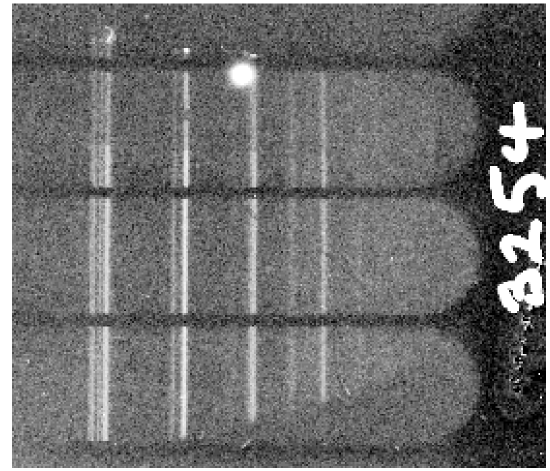


Likely ORION experiments

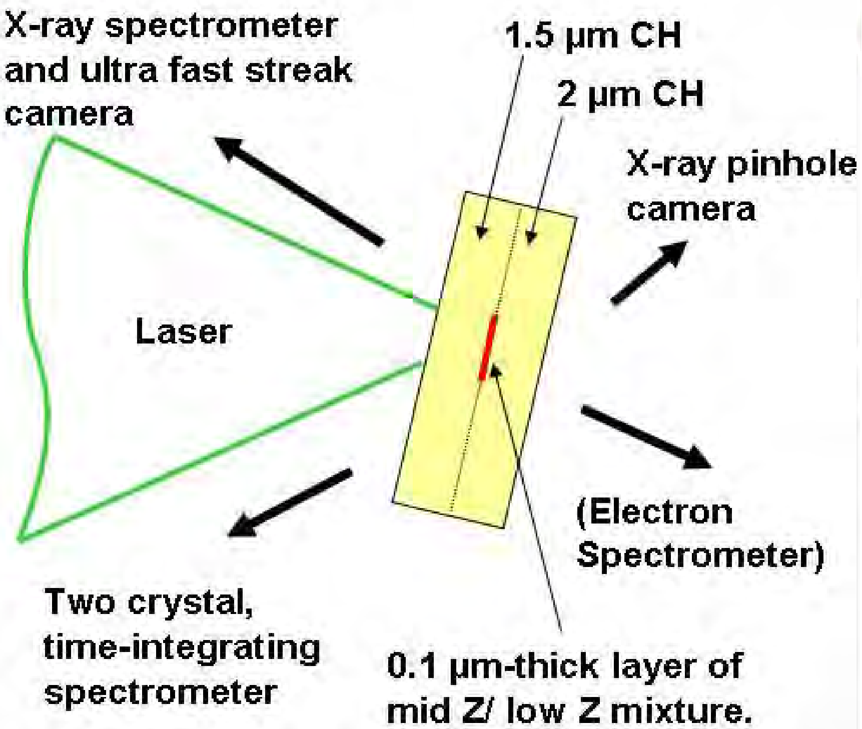
- Opacity
- Warm dense matter
- Strength

We used the CPA beam on HELEN to perform ORION precursor opacity experiments.

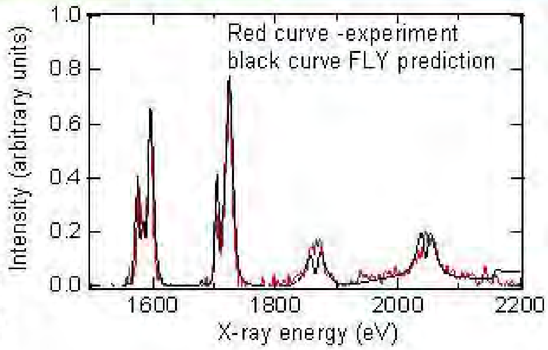




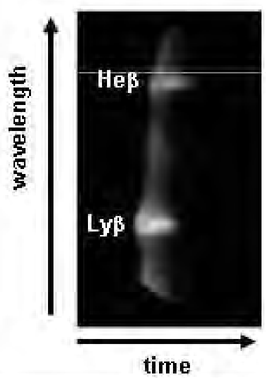
Buried micro-dot samples were heated by the 100 TW HELEN beam. The micro-dot was heated by the cold return current.

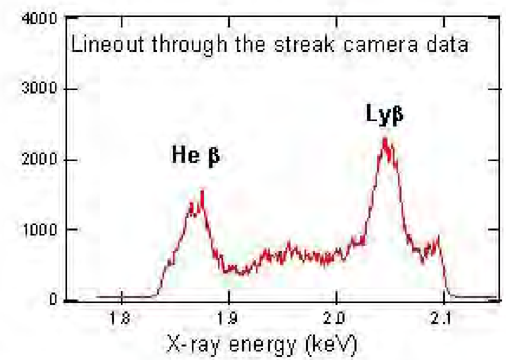


The Heβ /Ly β ratio and the line widths are compared to FLY calculations to infer the plasma temperature and density.



ultra-fast streak camera data show the peak emission lasting ~7ps.

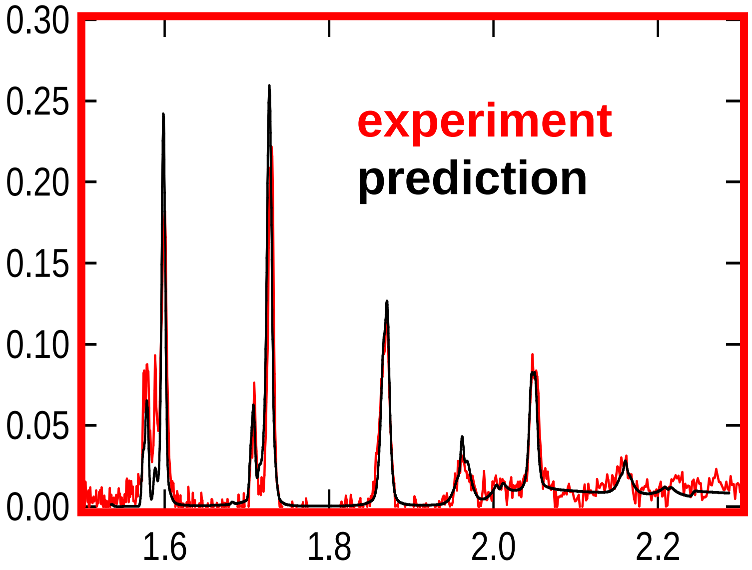




On HELEN we approached conditions of interest, provided that we reduced the effects of preheat.

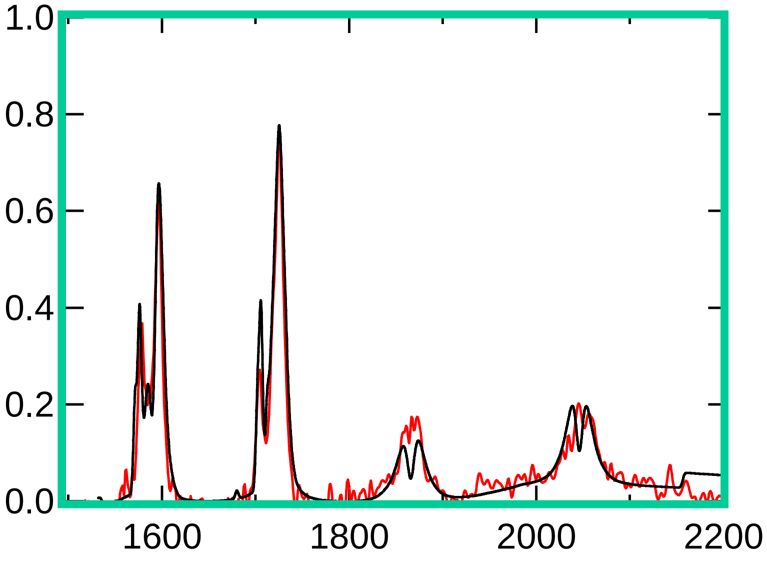
RED LIGHT (i.e. with prepulse)

Best-fit FLY calculation:
300 eV, 0.25 g/cc



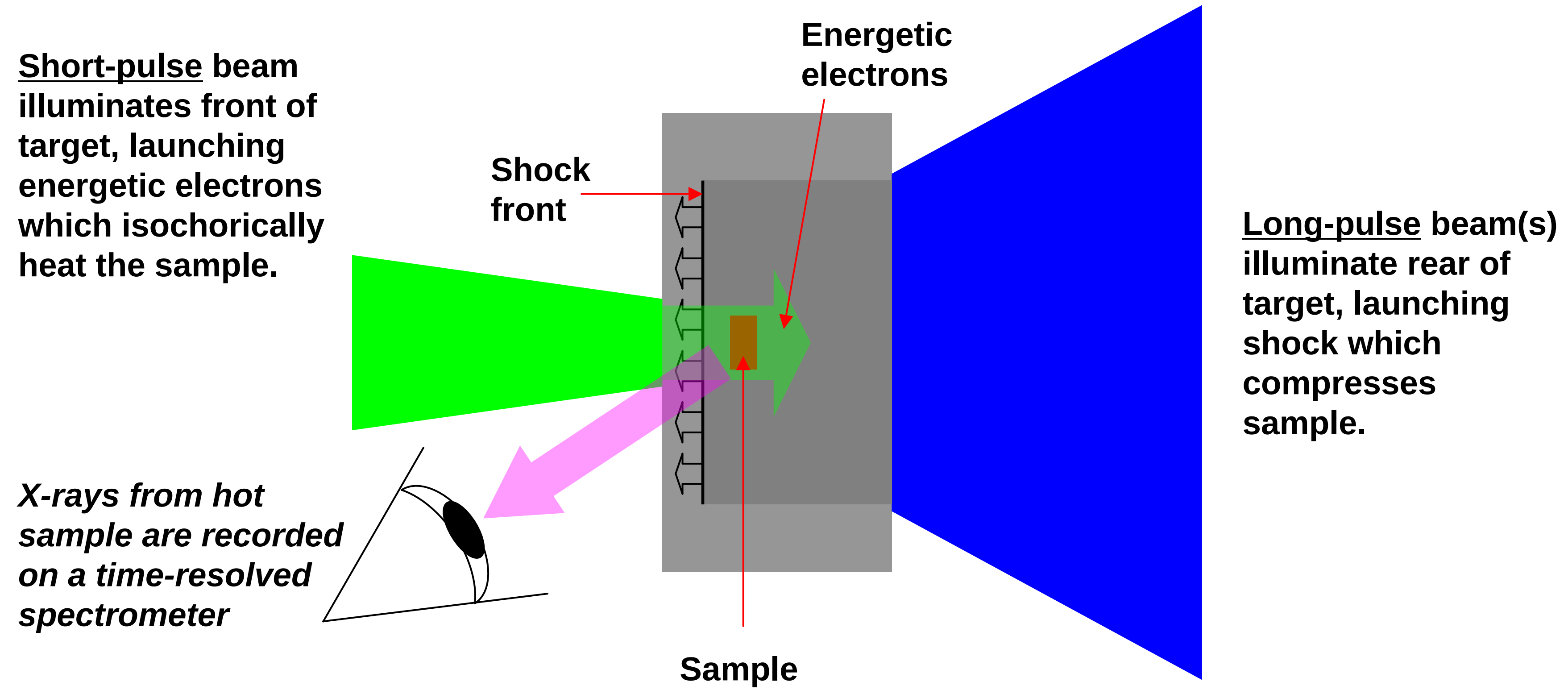
GREEN LIGHT (i.e. significantly reduced prepulse)

Best-fit FLY calculation:
450 eV, 2.7 g/cc



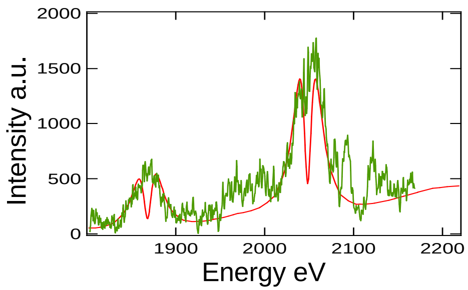
We need to measure the opacity of materials at greater than normal solid density and temperatures above 100 eV (10^6 K).

- **Furthermore, the sample has to be at a well-defined density and temperature – i.e. no significant *T*, ρ gradients within it.**
- **We can achieve this by shock-compressing it, then heating it essentially instantaneously so that the material does not have time to decompress during the experiment – *isochoric heating*.**

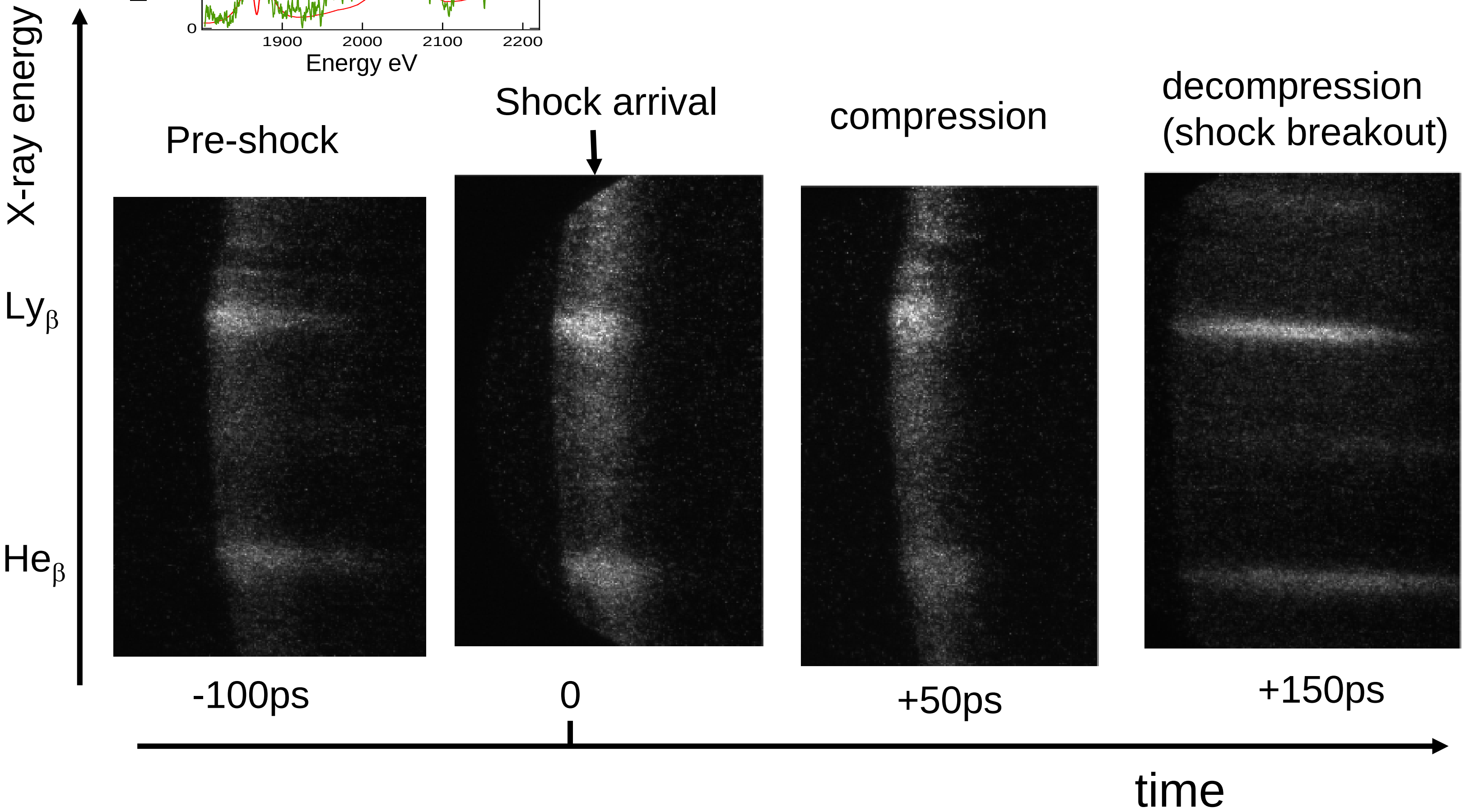


Shocked aluminium experiment streak data: line-broadening is used to diagnose shock compression of an aluminium layer.

Fits indicate compression to 3 g/cc.



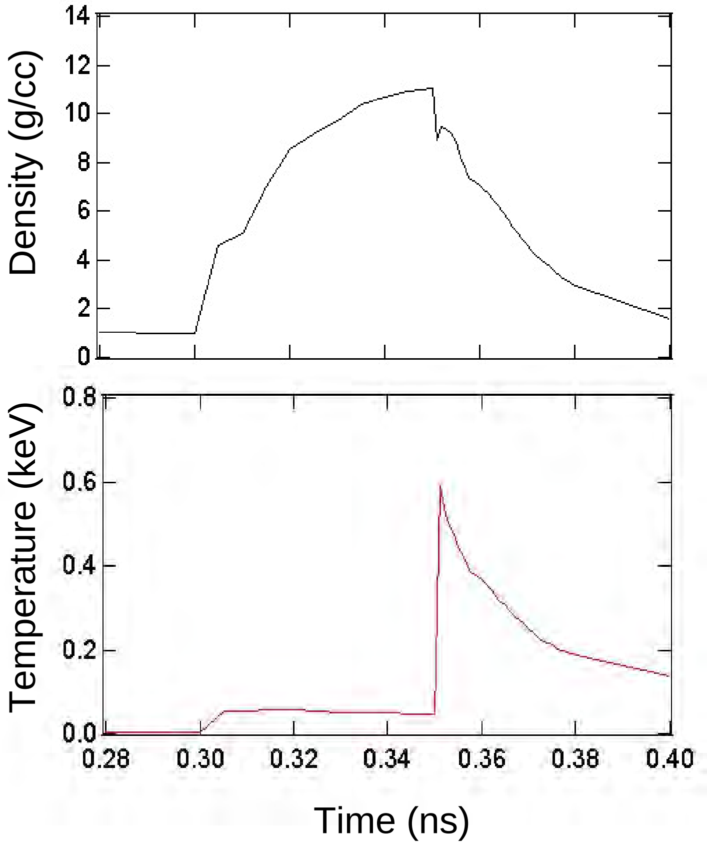
Fits to peak compression indicate density 3 g/cc and peak temperature 600 ± 50 eV.



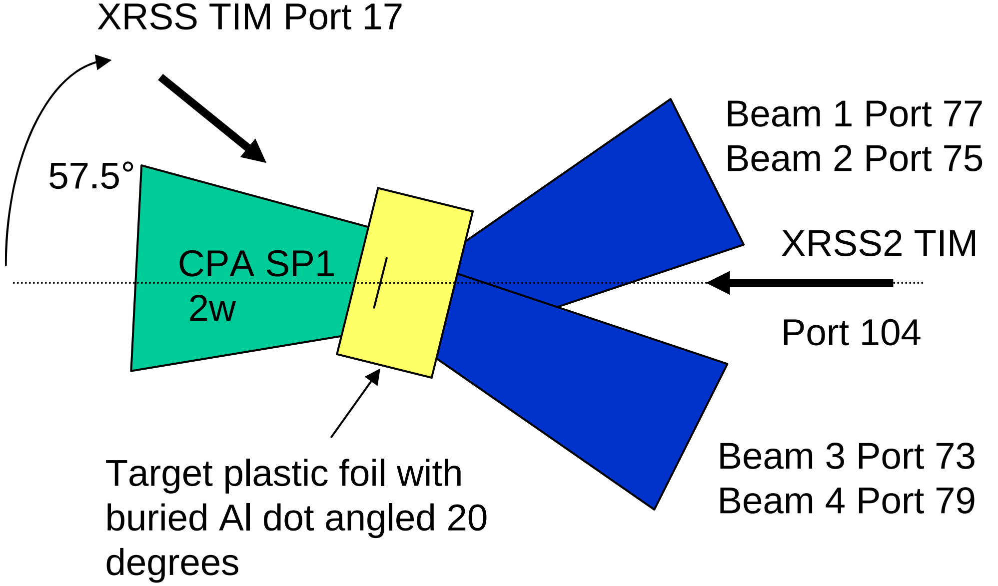
A shock compression and CPA heating experiment will be among the first measurements on Orion.

Predicted conditions up to 3 x solid at 500-600eV using multiple Orion beams to produce shock coalescence.

Experimental setup schematic

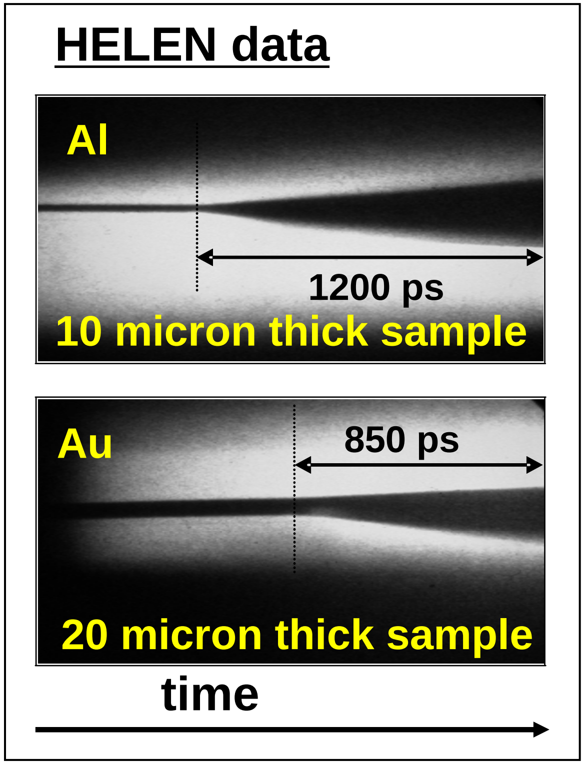


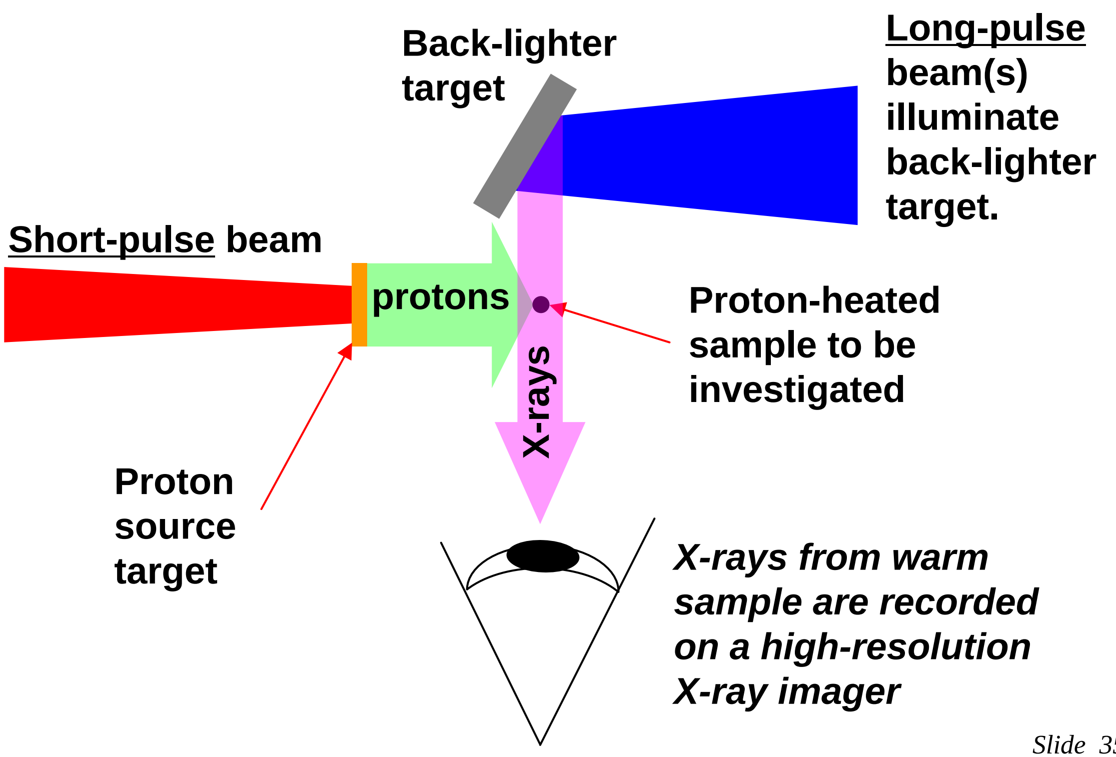
SP energy ~100J
LP energy ~ 1.5kJ, square pulses.



We have measured using HELEN the expansion of proton-heated targets to obtain equation-of-state data. Similar experiments are being planned for ORION.

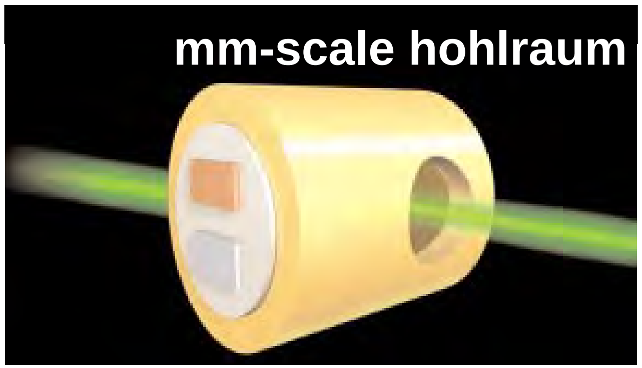
- Short-pulse beam illuminates front of target, launching energetic electrons which electrostatically drag protons from front surface of target.
- Protons strike sample, depositing energy, thus heating it isochorically.
- Backlit images provide expansion data



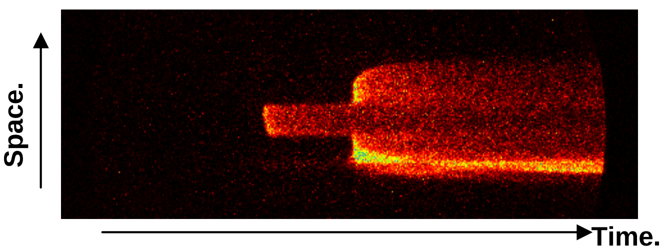


We have measured shock-driven EoS at 10-20 Mb - the most accurate measurements available in this régime.

A material's EoS describes its response to hydrodynamic events (e.g.shocks)

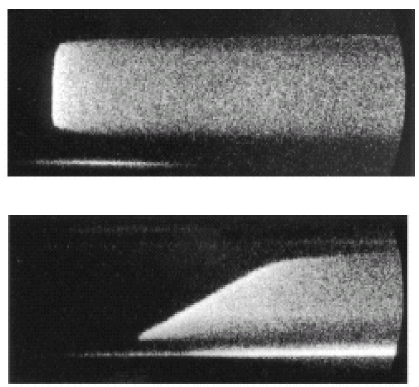


Impedance match steps

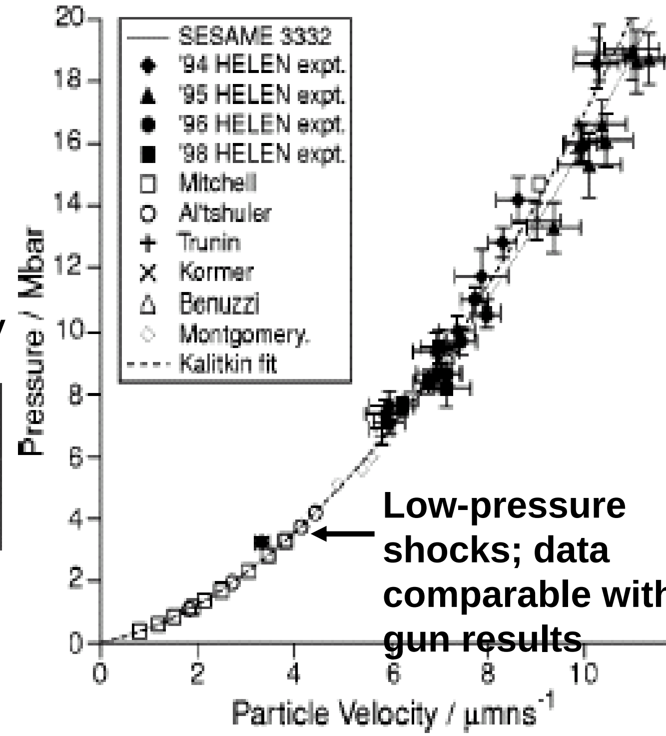


Streak-camera image of shock breakouts.

Spatial and temporal uniformity

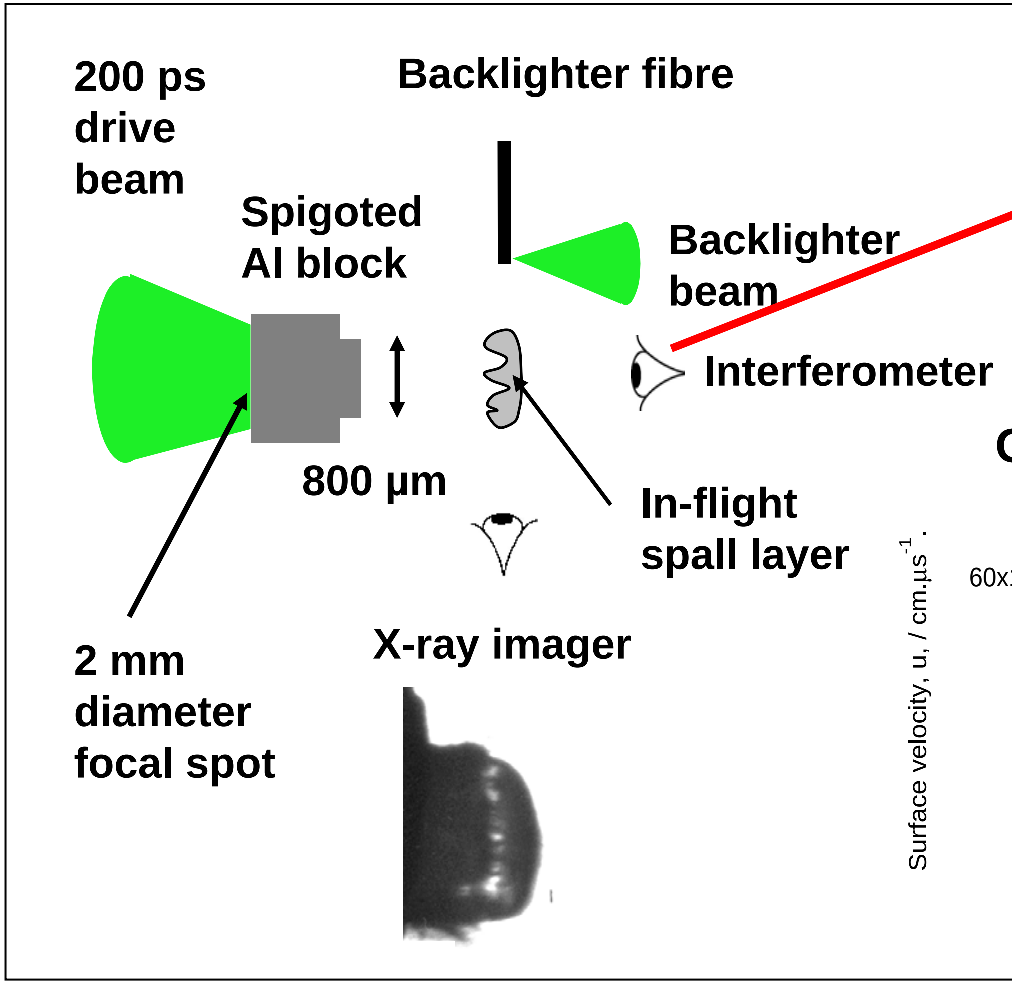


Copper Hugoniot accuracy ~ 2%

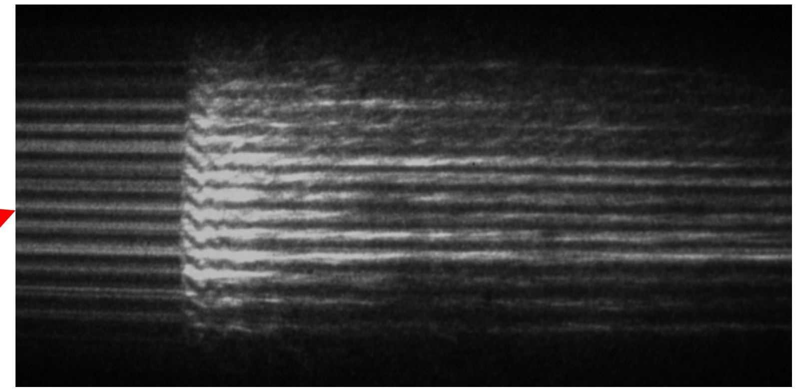


Low-pressure shocks; data comparable with gas-gun results

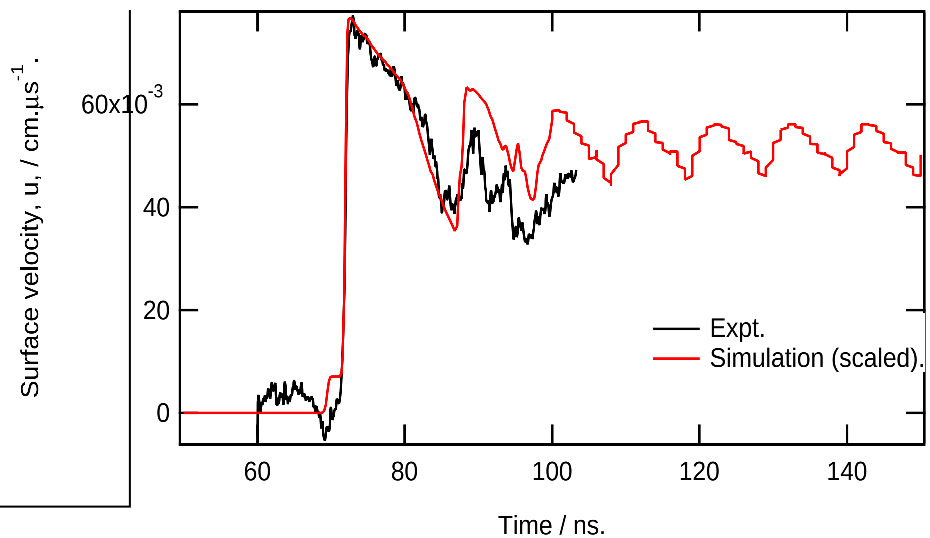
We have performed spall experiments to examine strain-rate dependent strengths.



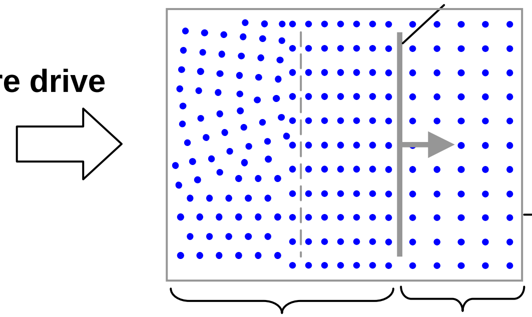
Interferogram

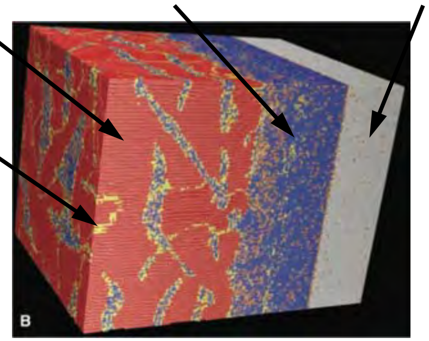


Comparison between expt & model

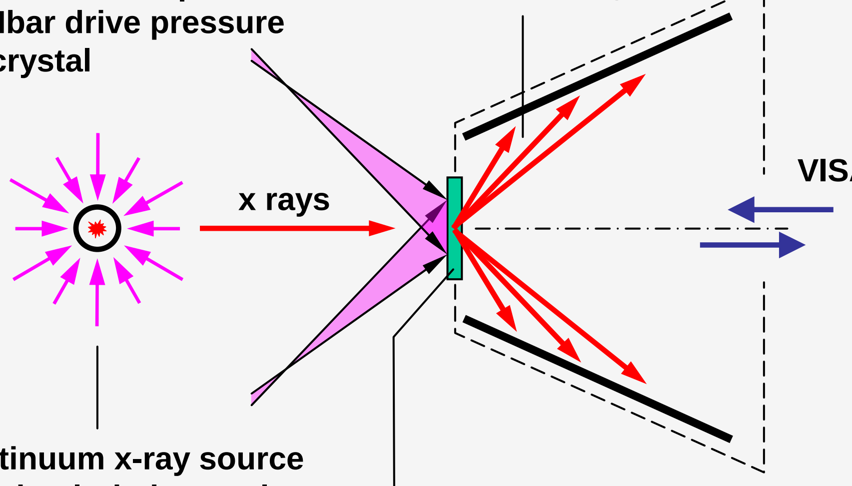


Transient-diffraction measurements of material response, resolved at the level of the crystal lattice, are being performed on OMEGA and may be performed on ORION.

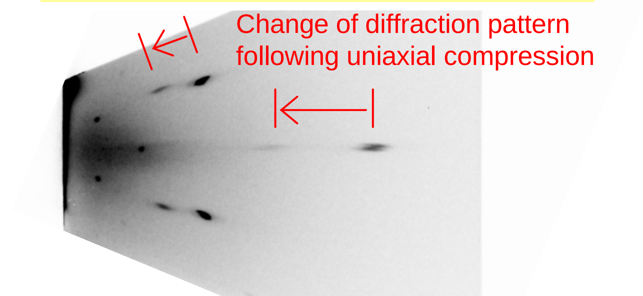




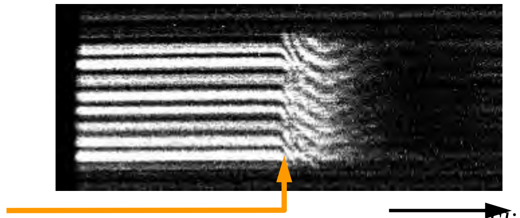
Iron MD simulation, from Kadau *et al*. Science, 296, 1681 (2002)



X-ray diffraction data

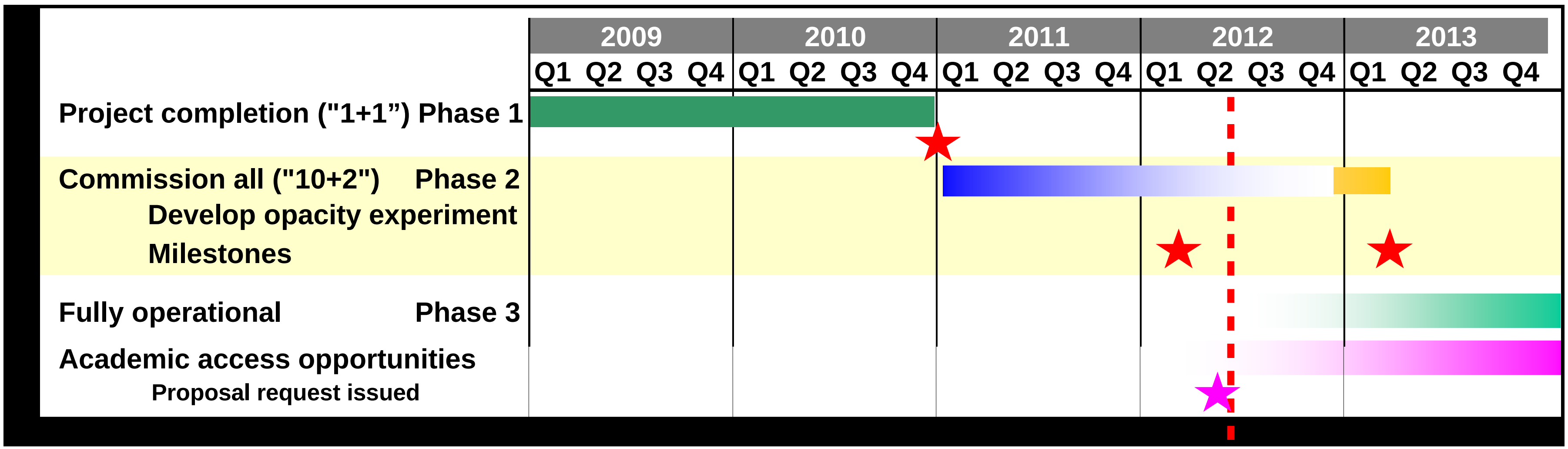


VISAR records shock breakout at tantalum/diamond interface

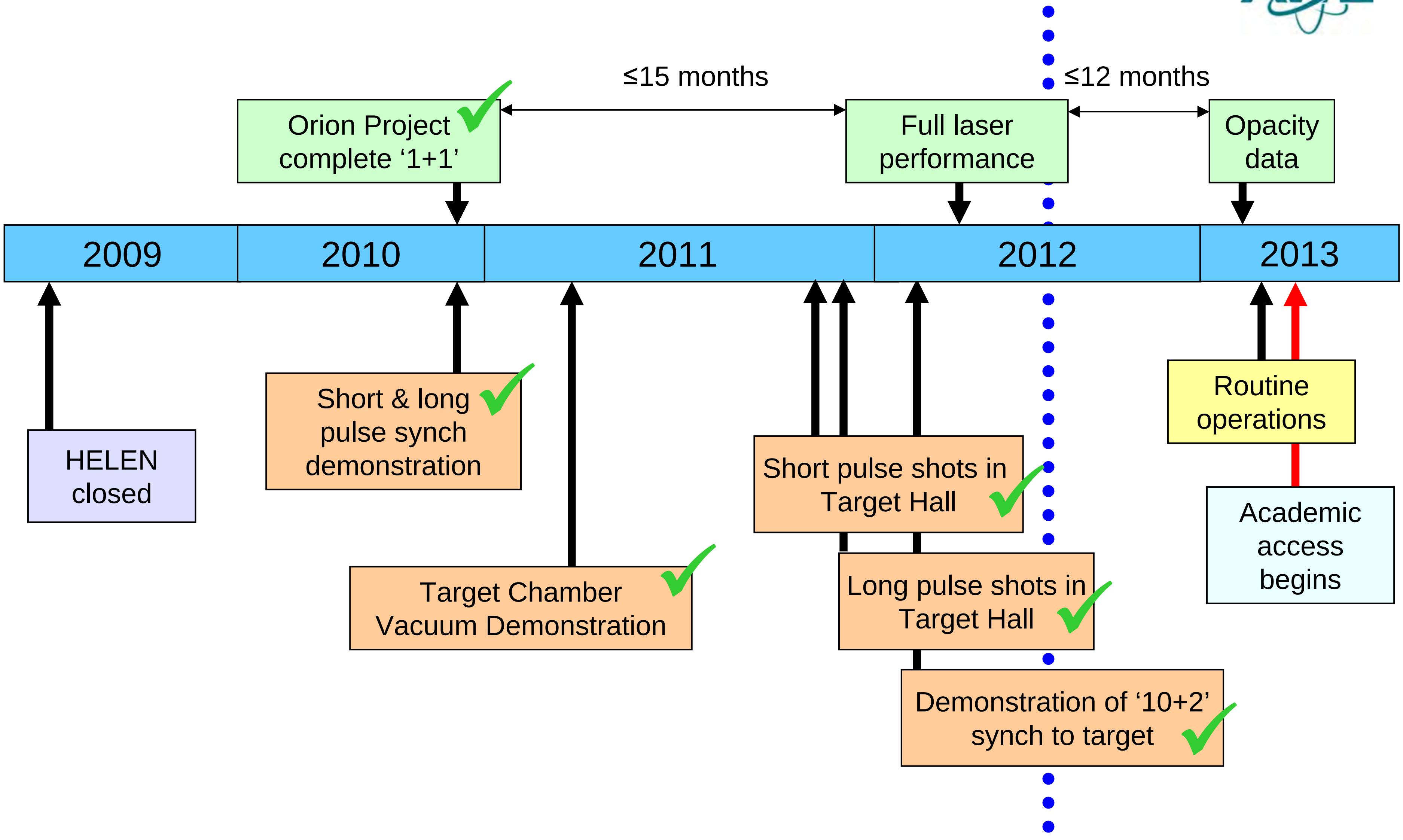


Up to 15% ORION time will be available to UK academia for collaborative experiments.

Access available from April 2013

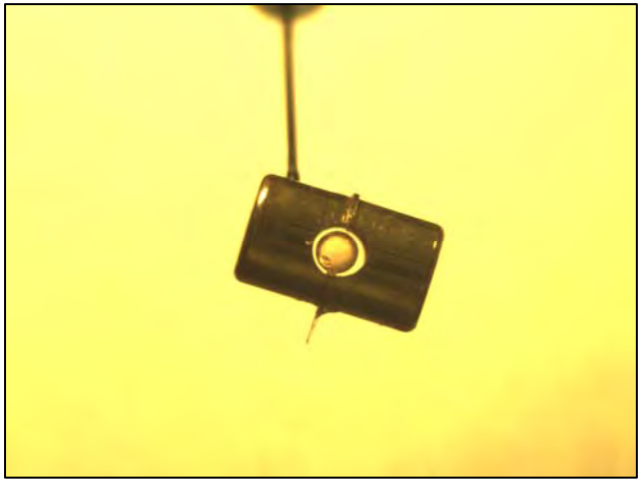


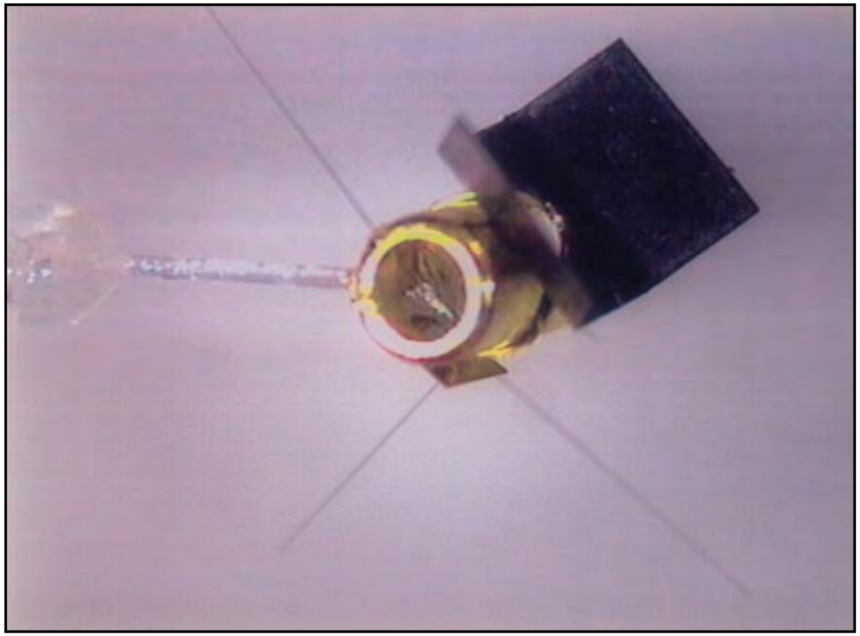
We are currently commissioning ORION, with a major milestone in April 2013.



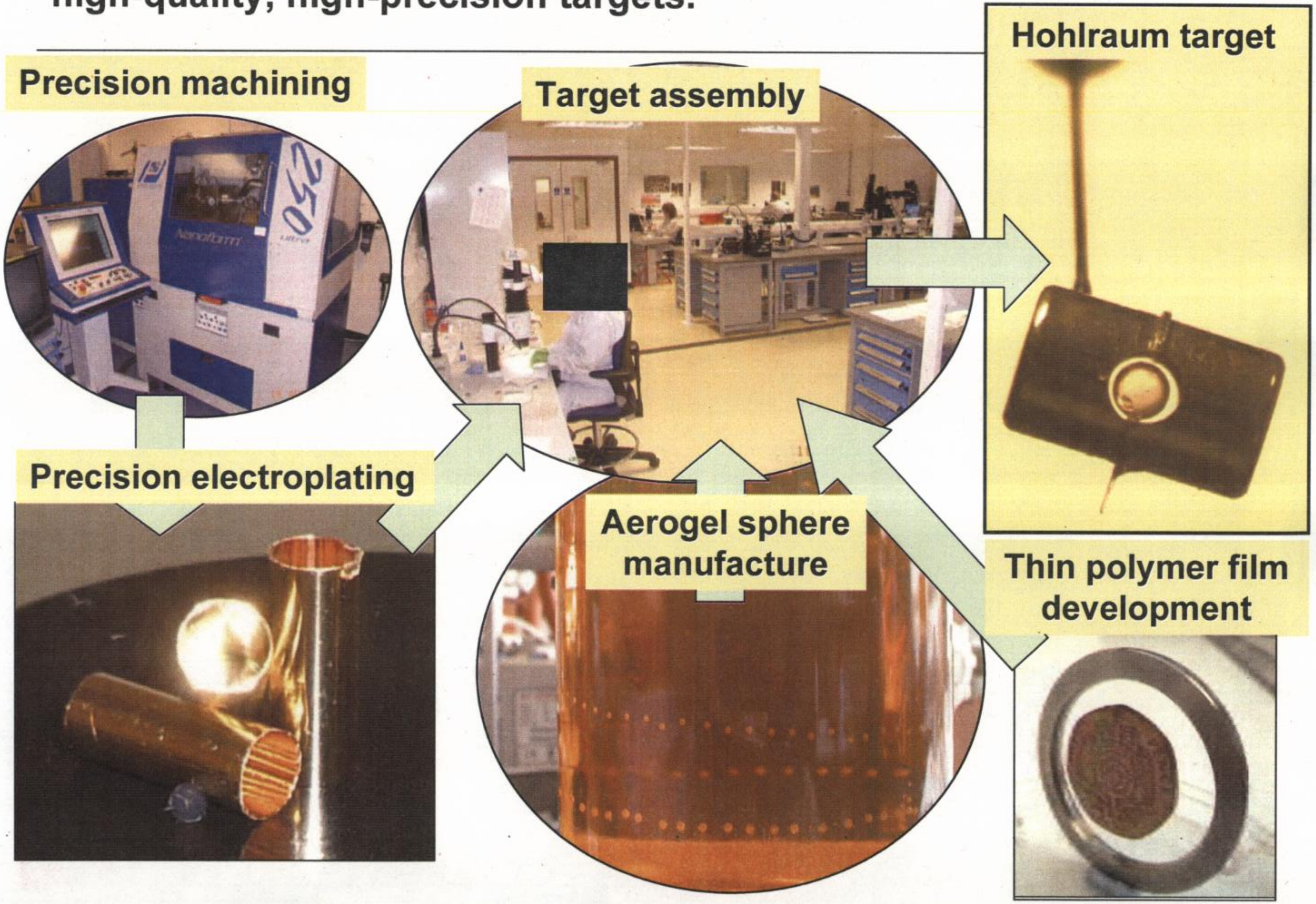
AWE has an excellent target fabrication capability.

- **Laser targets can be very small and complex:**
  - **µm to mm scale**
  - **Flat (layered) structures or 3D assemblies**
  - **Close tolerances - µm to nm**





Many technologies and skills are needed in order to produce high-quality, high-precision targets.



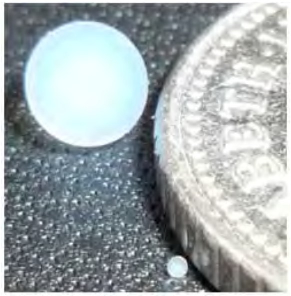
Target fabrication involves four key themes:

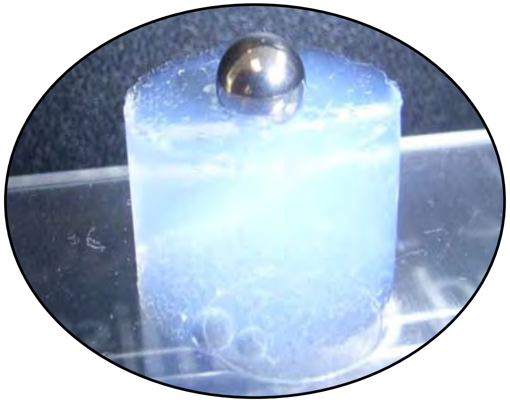
- **Materials Science** - ***make the raw materials***
- **Engineering** - ***form it to the shape we need***
- **Characterisation & metrology** - ***do the components meet requirements?***
- **Production** - ***assemble the targets***

AWE has expertise in aerogel foams, low-density polymer foams, metal foams, polymeric film development and electroplating.

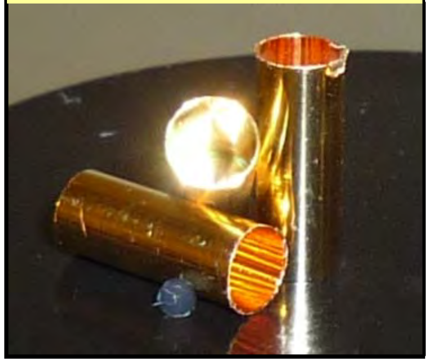
HIPE foam development

Aerogel technology

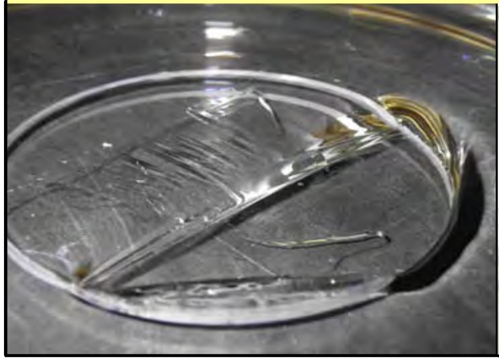




Precision electroplating

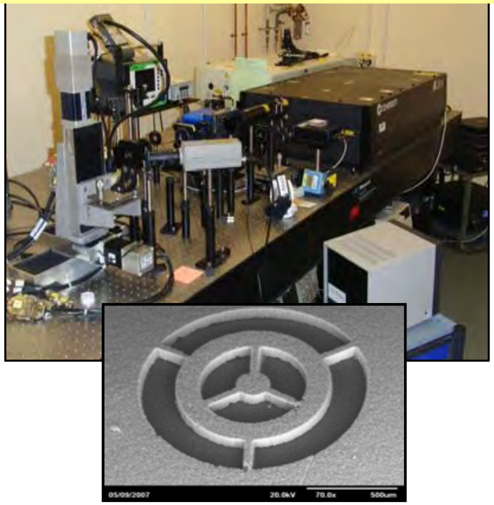


Sub-micron polymer film development



AWE has capabilities in micro-precision turning and milling, femto-second laser machining, and thin-film coating.

Femto-second laser micro-machining



Micro-precision diamond turning

Micro-precision milling

Thin film magnetron sputtering

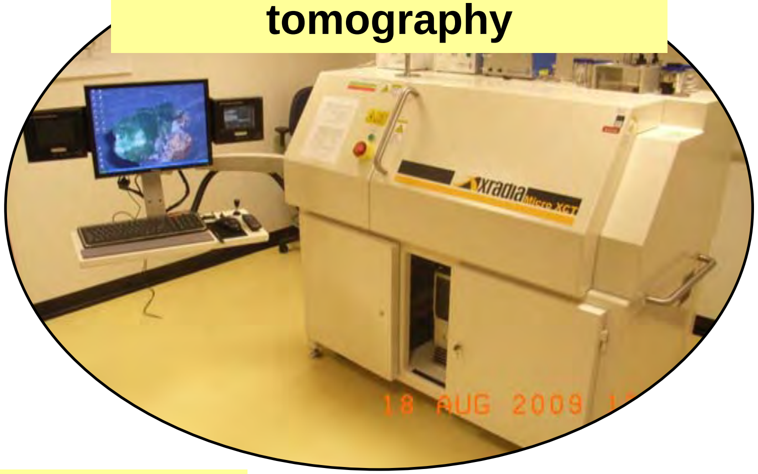
Thin film polymer coating

Characterisation & Metrology

AWE has a good variety of analysis and measurement techniques for characterising targets and their components.

Scanning electron microscopy

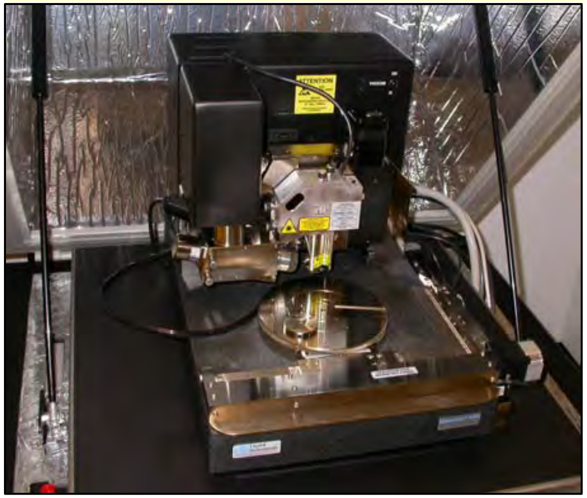
Real time precision x-ray tomography



Laser scanning microscopy

White light interferometry

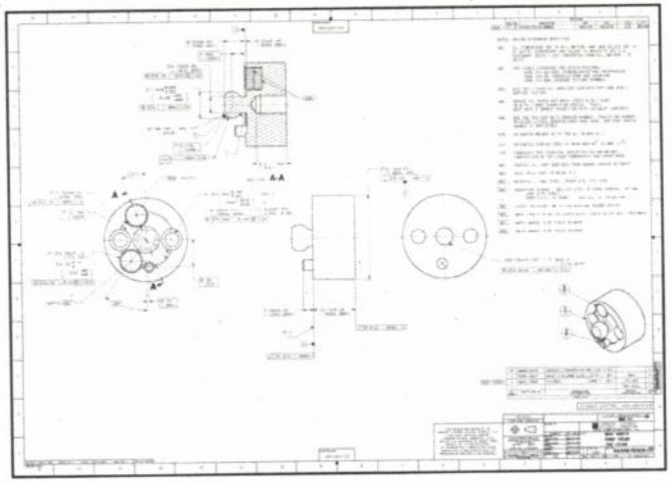
Atomic force microscopy



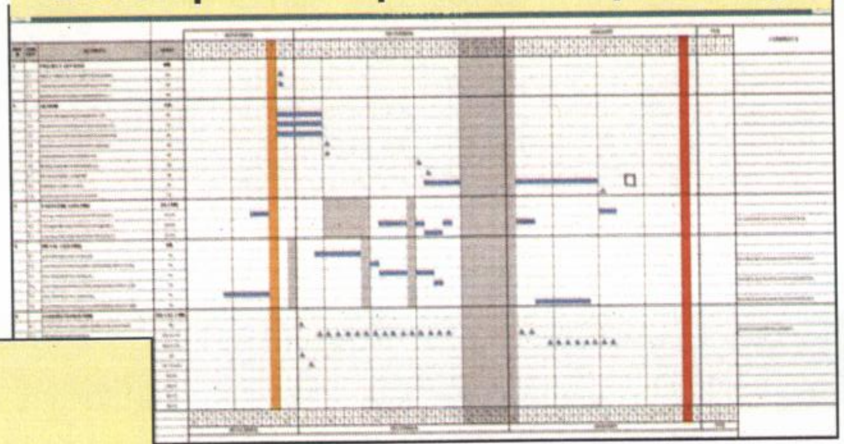
Production

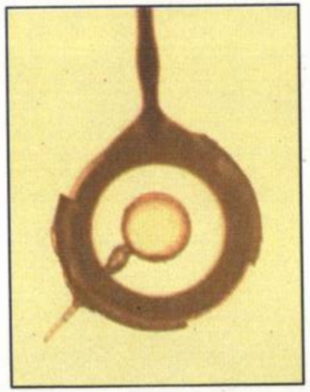
AWE Target design, development & production planning, assembly, quality assurance.

CAD design capability



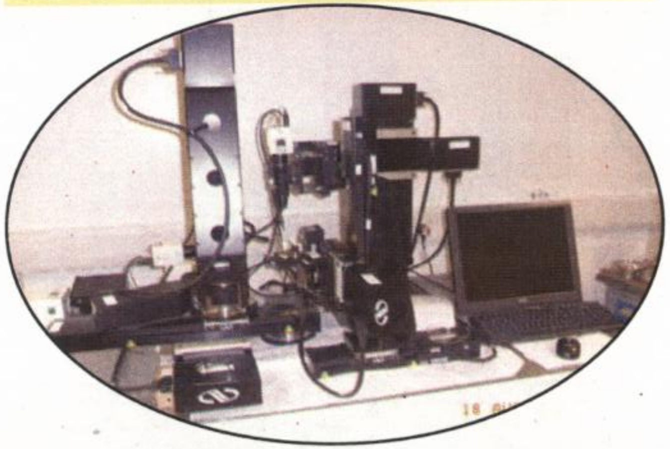
Development & production planning





Target assembly clean room

Target assembly manipulator



Summary

- ORION commissioning underway; commissioning milestone is March 2013
  - All 10 long-pulse beams are available (~400 J in 1 ns)
  - Both short-pulse beams are available (~300 J in 0.5 ps)
  - All have been synchronised to within ± 50 ps.
- During 2012 we are working towards an MoD-mandated experiment milestone (deadline: March 2013) to show that the laser can generate appropriate data
- Academic access starts 2013, with 15% of ORION time available.