Development of High-Energy & High-Intensity Multi-Hz Laser Systems at the Central Laser Facility DiPOLE

Paul Mason, Klaus Ertel, Saumyabrata Banerjee, Jonathan Phillips, Steve Blake, Justin Greenhalgh, Cristina Hernandez-Gomez, John Collier

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paul.mason@stfc.ac.uk
STFC Rutherford Appleton Laboratory,
R1 2.62 Central Laser Facility, OX11 0QX, UK
+44 (0)1235 778301

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Motivation

- Develop next generation high-energy PW-class lasers
  - Multi-J to kJ, multi-Hz, multi-% efficiency
- Enhance laser plasma research capabilities
  - Ultra-intense light-matter interactions
- Develop real world applications
  - Ultra-intense light-matter interactions
  - Compact laser driven particle accelerators
  - Laser driven UV & X-ray sources
  - Inertial confinement fusion
- Diode-pumped solid-state laser (DPSSL) amplifiers needed
  - Pumping fs-OPCPA or Ti:S amplifiers
  - ns-drive laser for ICF

Beamline Facility

CALTA
Centre for Advanced Laser Technology & Applications

High-Energy Amplifier Design

- Gain Medium

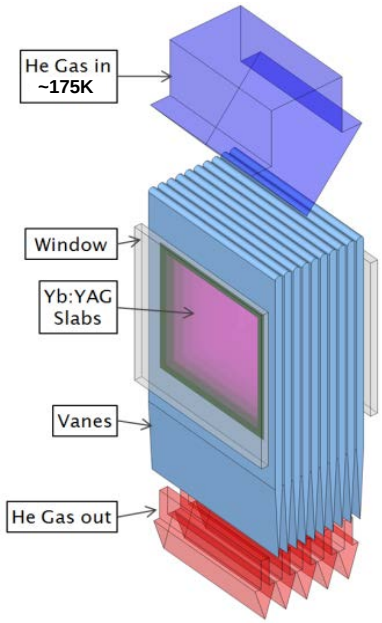
Long fluorescence lifetime	Higher energy storage potential Minimise number of diodes (cost)	Yb^{3+}
Low quantum defect	Increased efficiency & reduced heat load	Yb^{3+}
Good thermo-mechanical properties	Handle high average power	YAG
Sufficient gain cross section	Efficient energy extraction	YAG
Available in large size	Handle high energies	Ceramic

- Amplifier Geometry

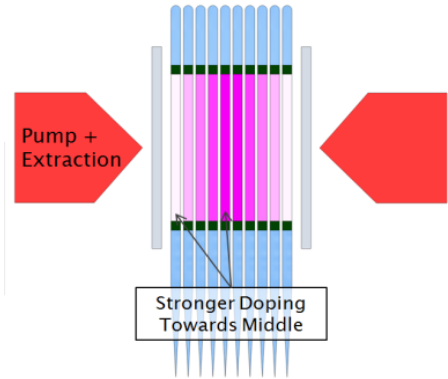
High surface-to-volume ratio	Efficient cooling
Low (overall) aspect ratio	Minimise ASE
Heat flow parallel to beam	Minimise thermal lens

DiPOLE Amplifier Concept

- Diode-pumped multi-slab amplifier
  - Ceramic Yb:YAG gain medium
  - Co-sintered absorber cladding for ASE suppression
- Distributed face-cooling by stream of <u>cold</u> He gas
  - Low overall aspect ratio & high surface area
- Operation at cryogenic temperatures
  - Higher o-o efficiency – reduction of re-absorption
  - Increased gain cross-section
  - Better thermo-optical & thermo-mechanical properties
- Graded doping profile
  - Equalised heat load in each slab
  - Reduces overall thickness (up to factor of ~2)
- Scalable design
  - 10 J, 100 J & 1 kJ



Schematic of 1 kJ head design

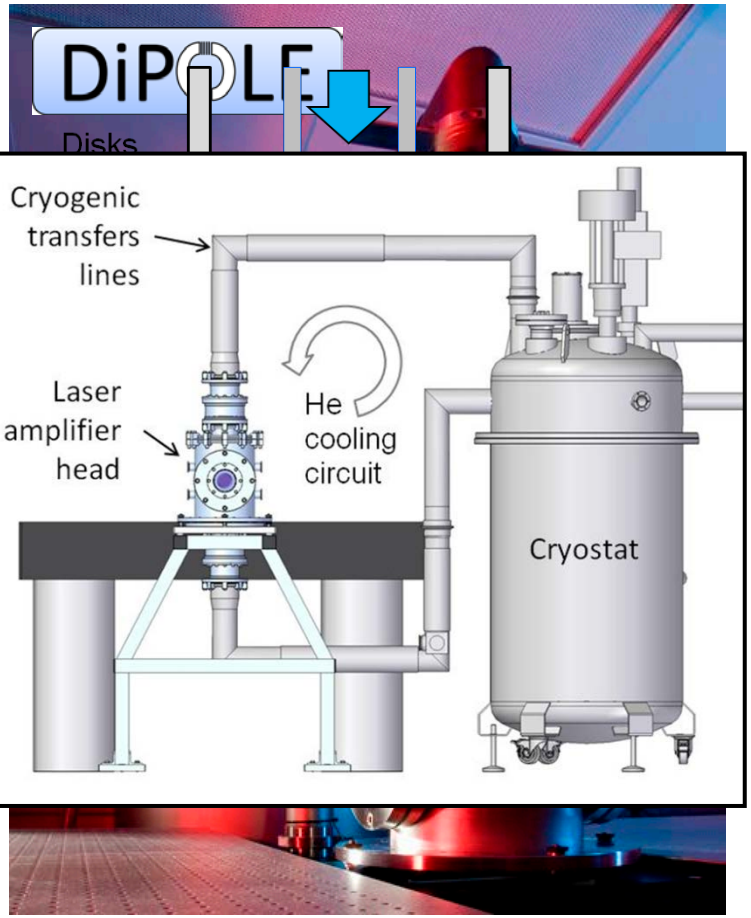


Scalable Design

	HiPER Beamlet	ELI Pump	DiPOLE Prototype
Extractable energy	~ 1 kJ	~ 100 J	**~ 10 J**
Beam size	14 cm	6 cm	**2 cm**
Slab size	22 cm	12 cm	**5.5 cm**
No. of slabs	10	6	**4**
Slab thickness	1 cm	0.8 cm	**0.5 cm**
No. of doping levels	5	3	**2**
Average doping level	0.33 at.%	0.79 at.%	**1.65 at.%**

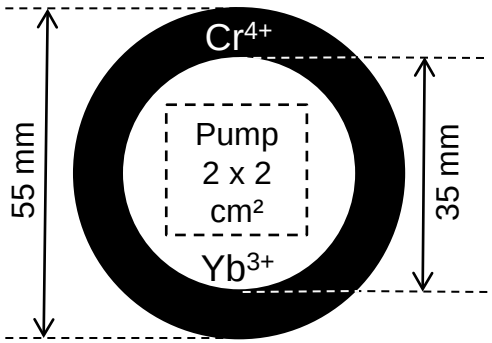
DiPOLE Prototype Amplifier

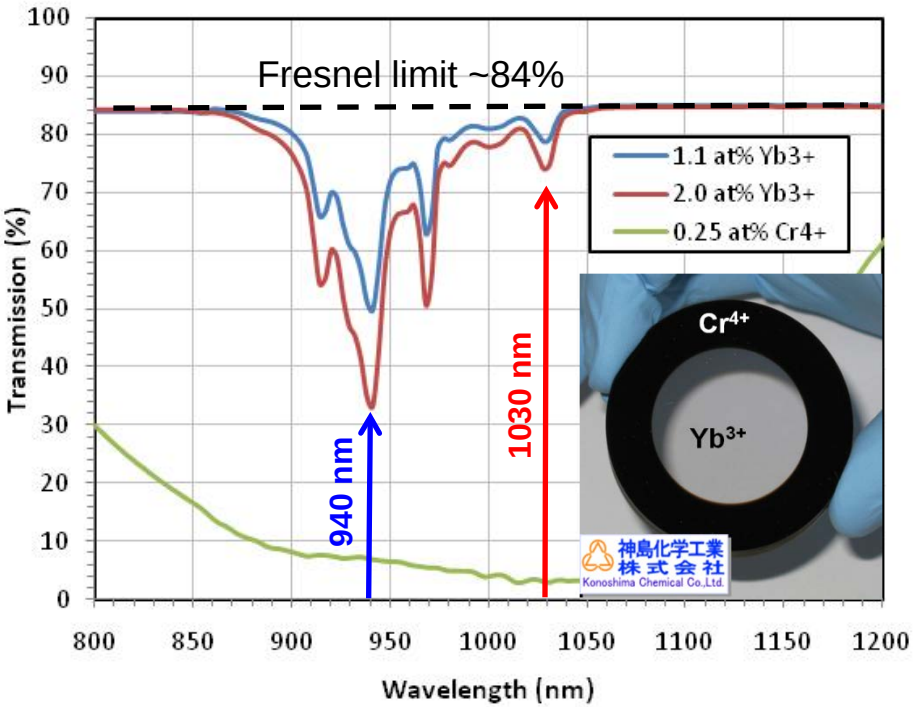
- Aims
  - Demonstrate viability of concept
  - Validate & calibrate numerical models
  - Test cryogenic gas-cooling technology
  - Test (other) ceramic gain media
- Specification
  - 10 J @ 10 Hz, 25% o-o efficiency
- Design
  - Ceramic Yb:YAG disks held in aerodynamically shaped vanes
    - CFD modelling $\Delta T \sim 3$ K
    - Design temperature ~ 175 K
  - End-pumped by 2 x 20 kW diode lasers
  - LN_2 based cryogenic gas cooling system

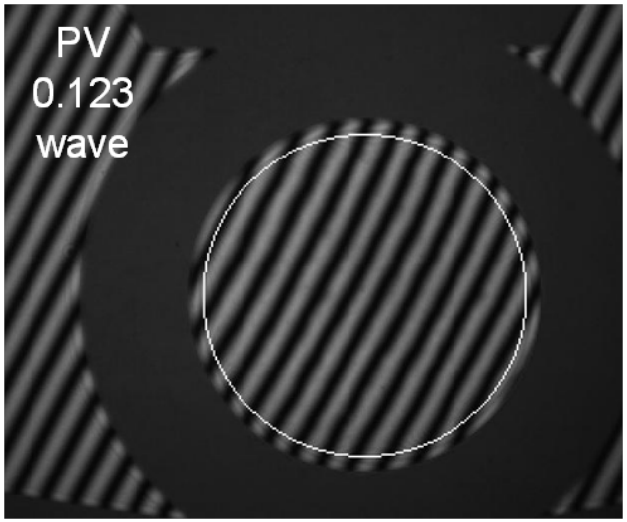


Optical Gain Material

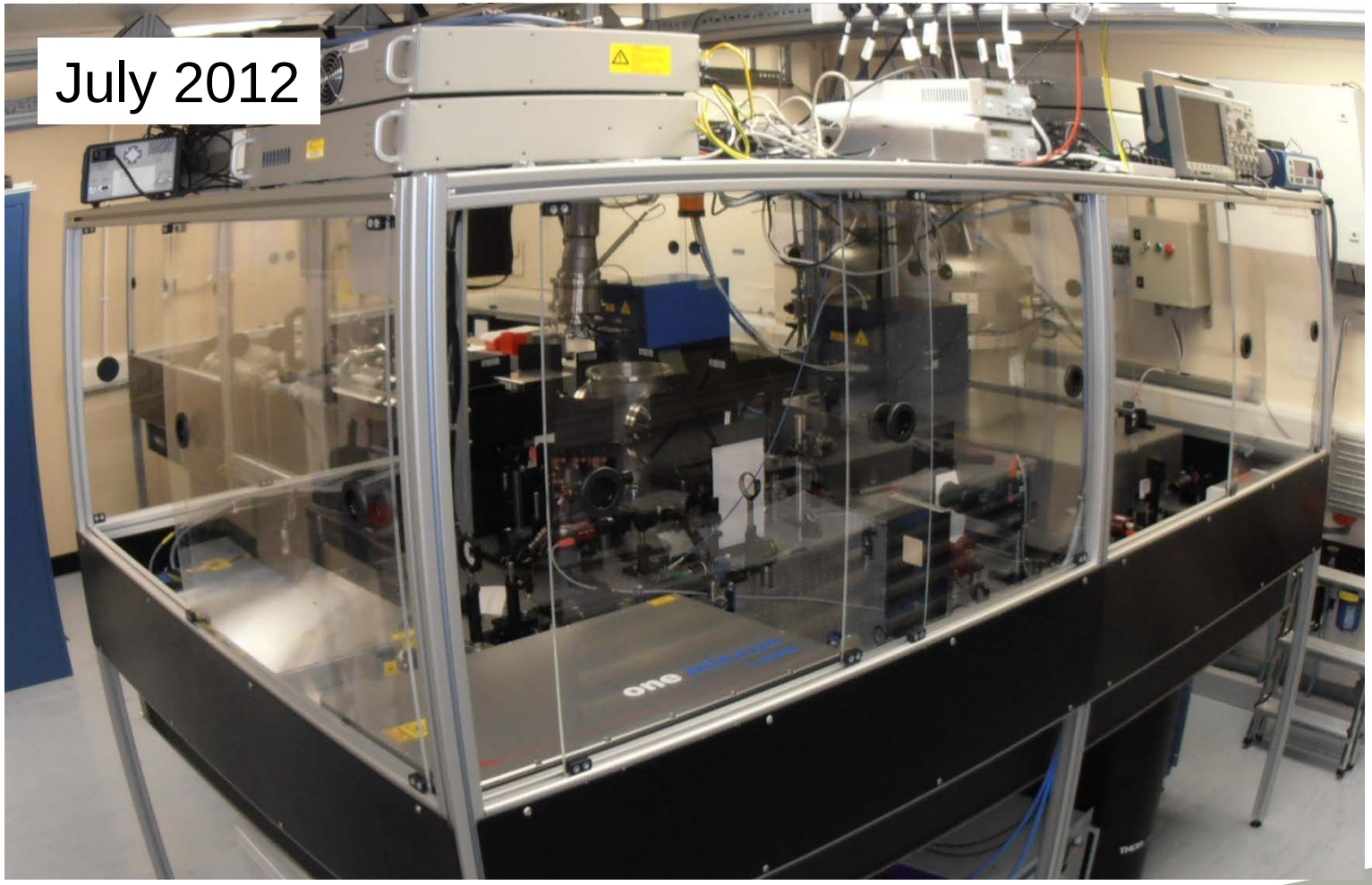
- 4 x co-sintered ceramic Yb:YAG disks
  - Circular 55 mm diameter x 5 mm thick
  - Cr^{4+} absorbing cladding
  - Two doping concentrations (1.1 & 2.0 at.%)







DiPOLE Laboratory



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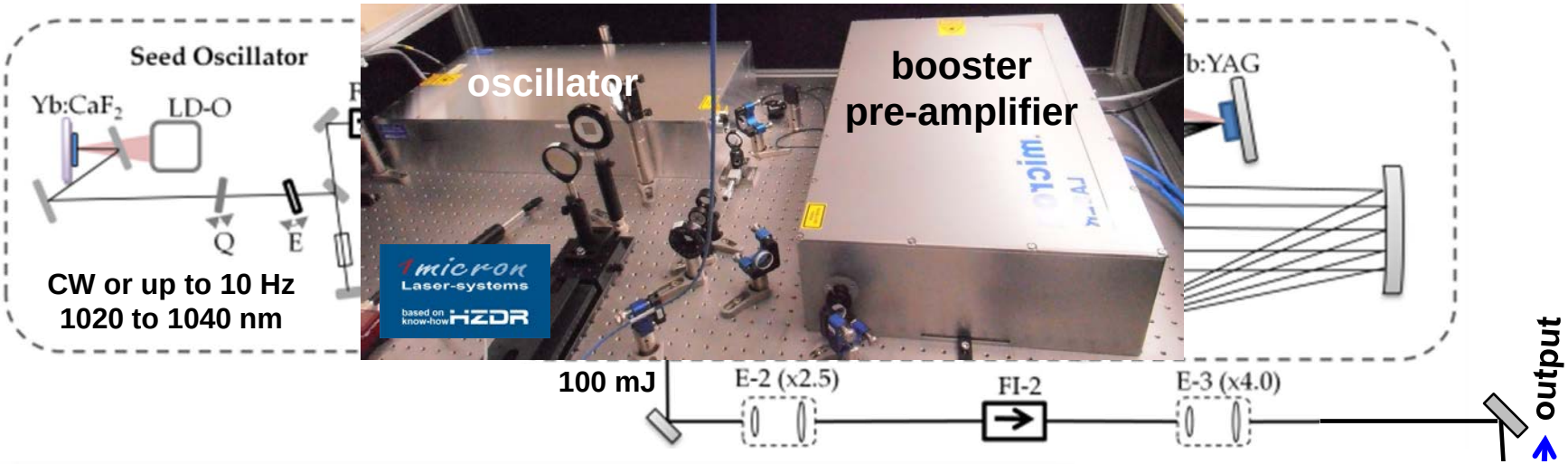
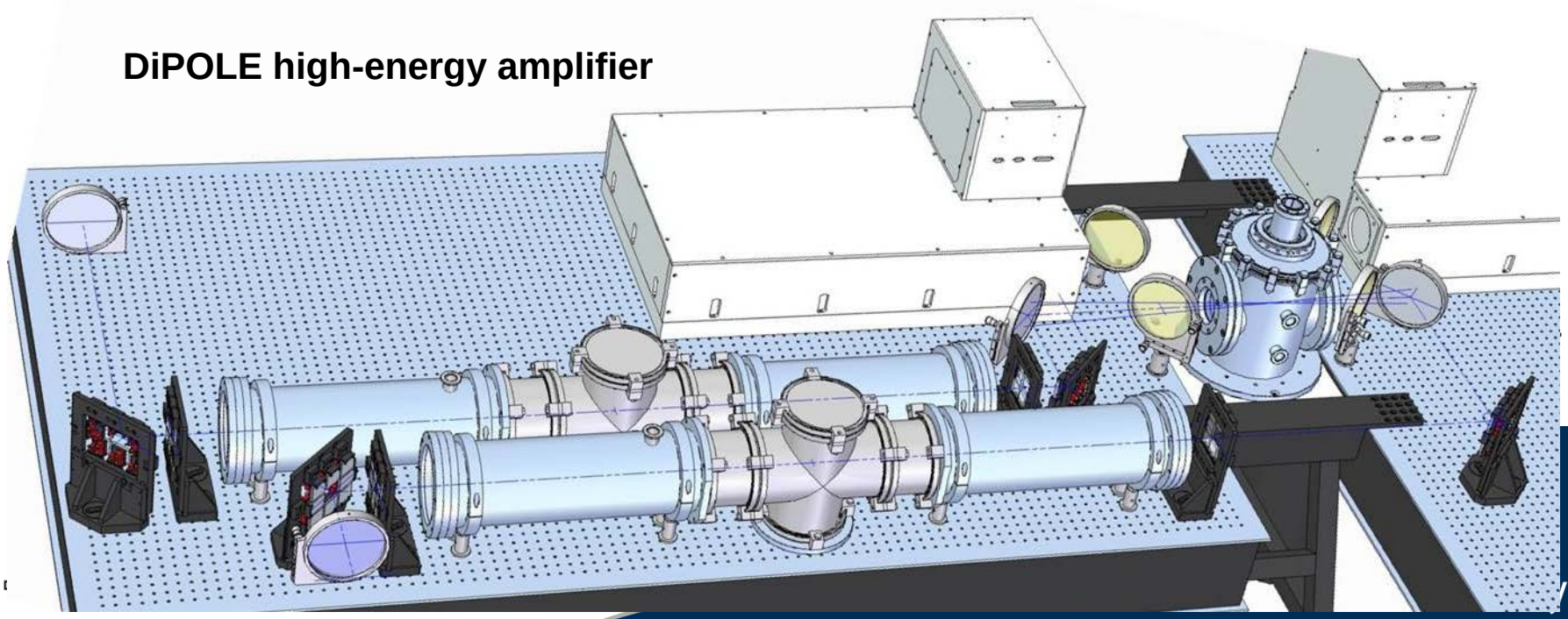
Recent Amplification Results

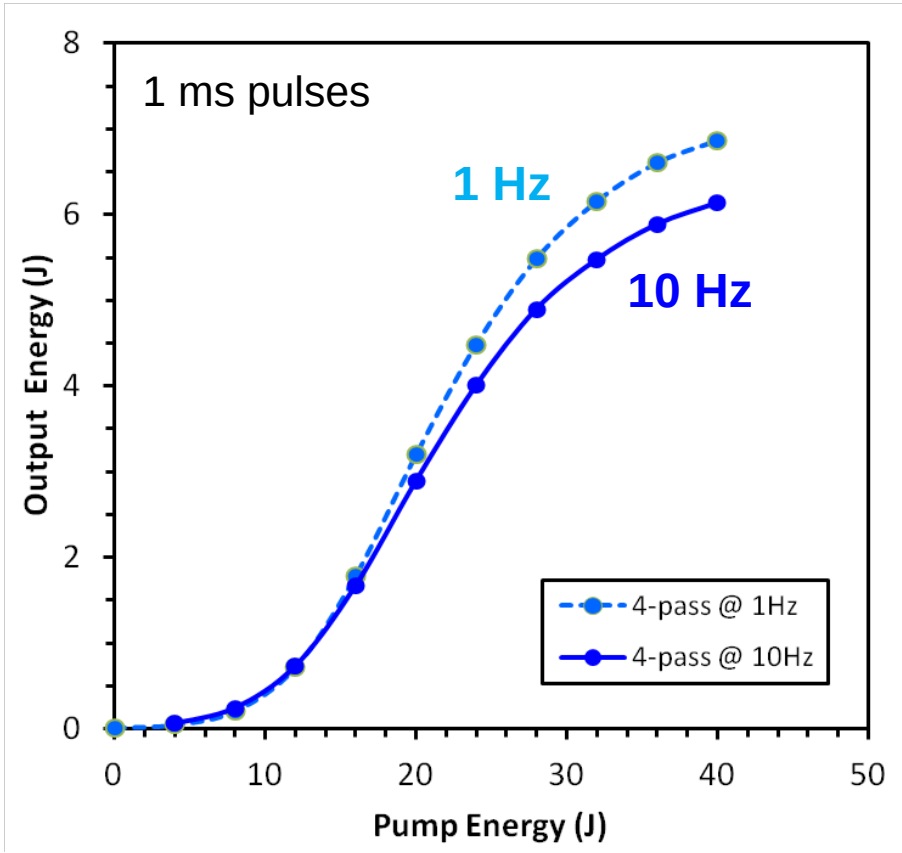


DiPOLE high-energy amplifier

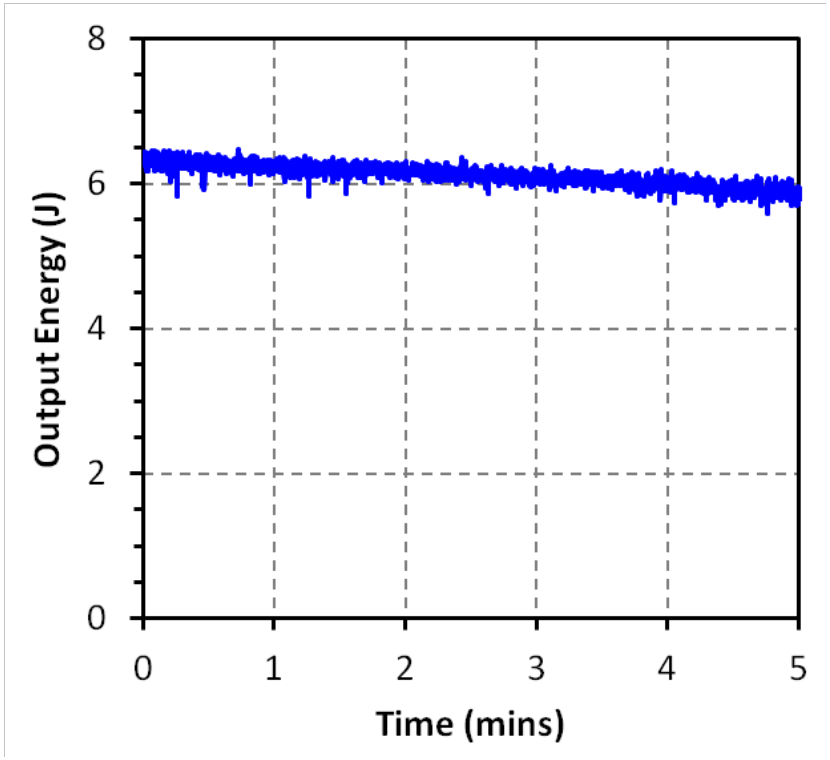


4-pass Performance at 1 Hz & 10 Hz

- 4-pass conversion at 110 K

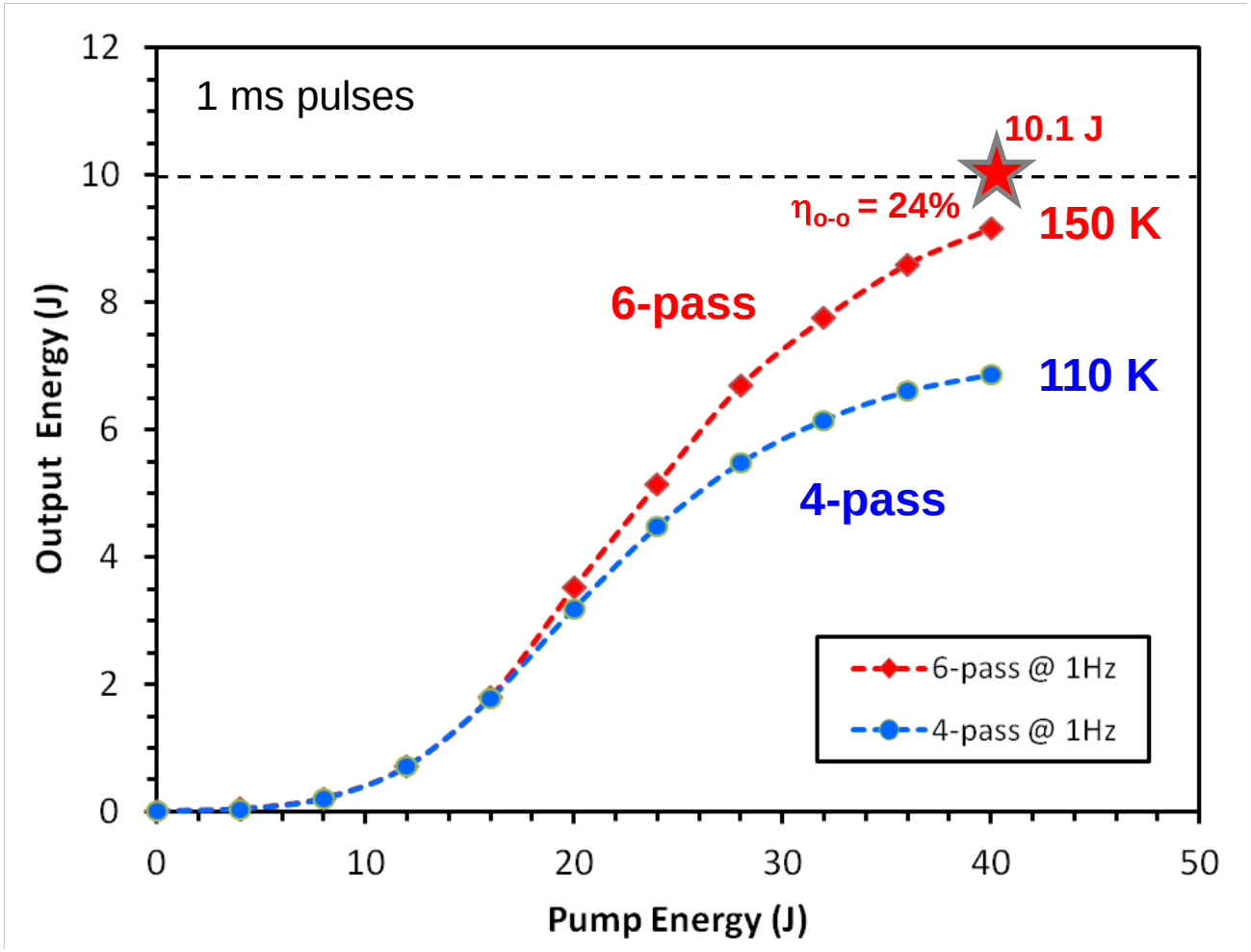


- Energy stability at 10 Hz



- Earlier 3 & 4-pass results detailed in Optics Letters, 2175, 37, No.12 (2012)

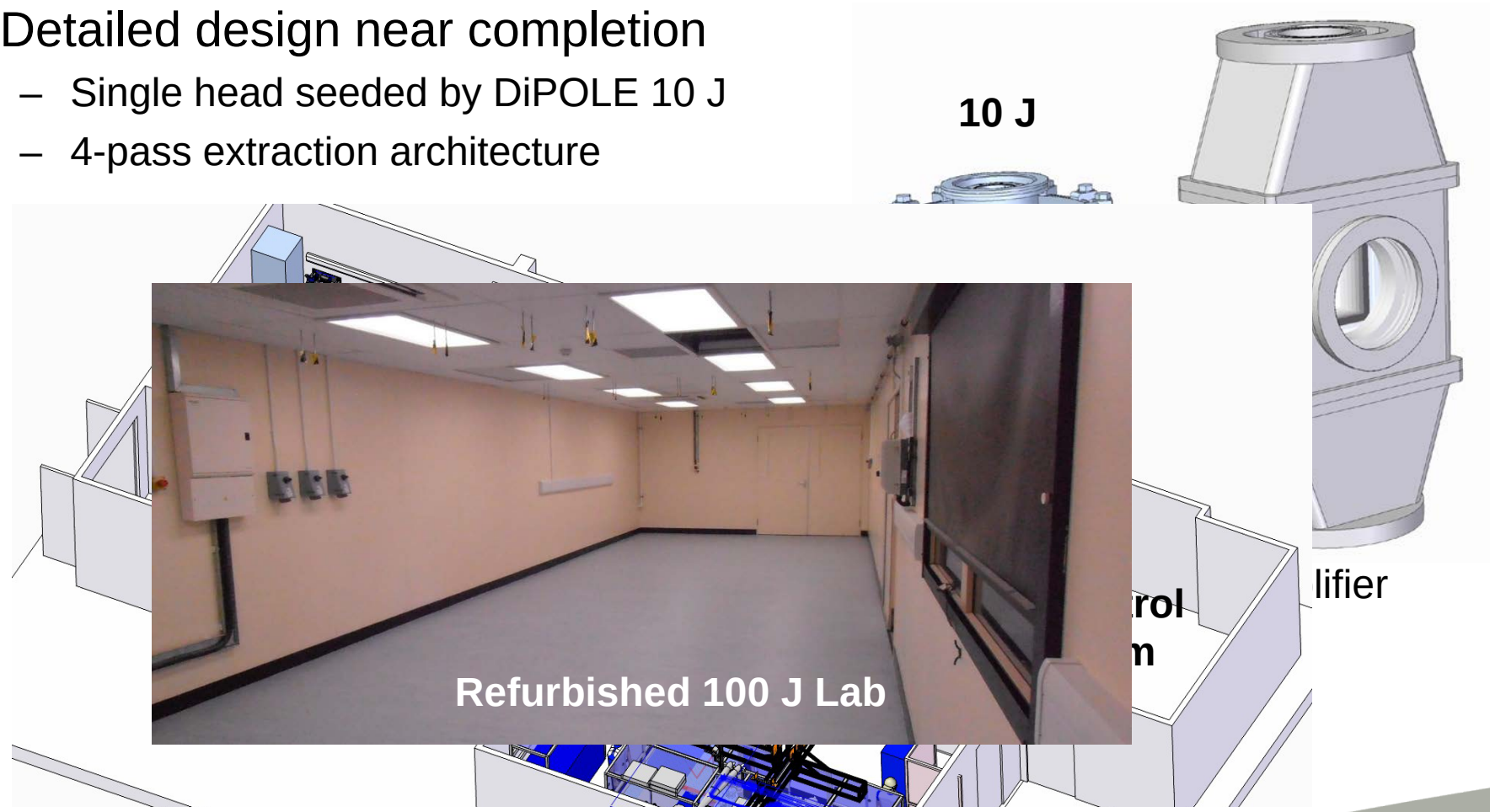
6-pass Performance at 1 Hz



- Booster preamplifier currently being serviced prior to 10 Hz experiments

Next Generation 100 J Amplifier

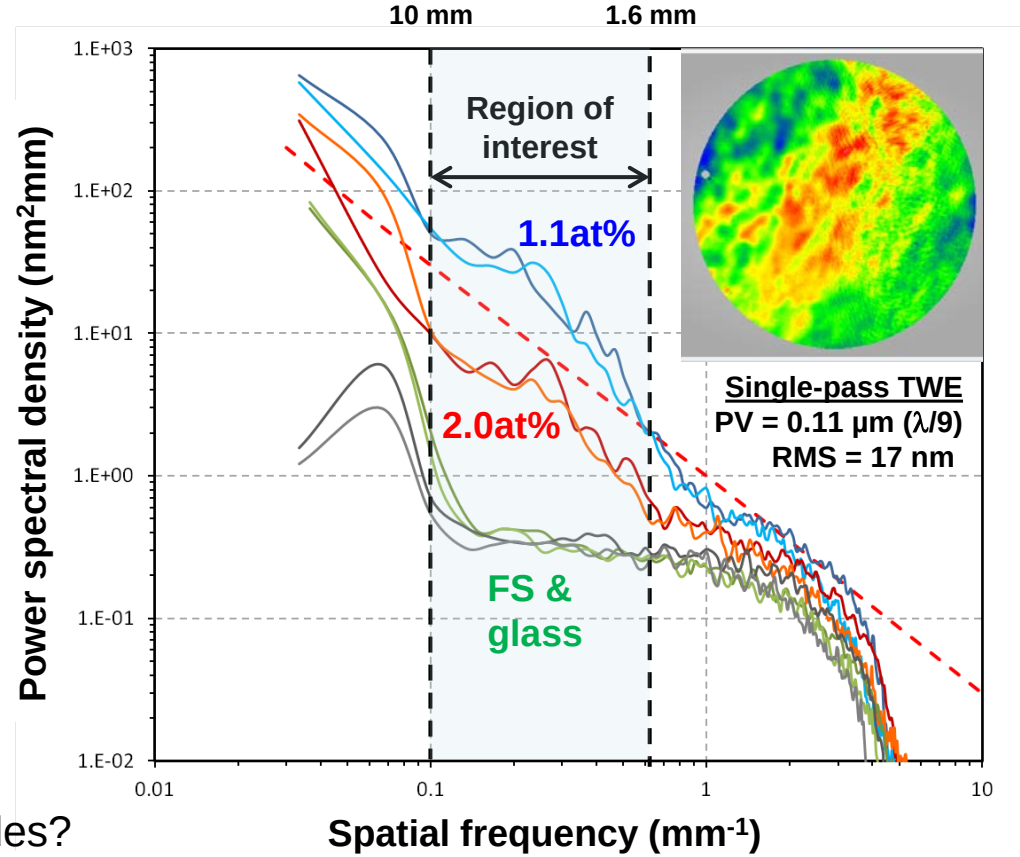
- Detailed design near completion
  - Single head seeded by DiPOLE 10 J
  - 4-pass extraction architecture



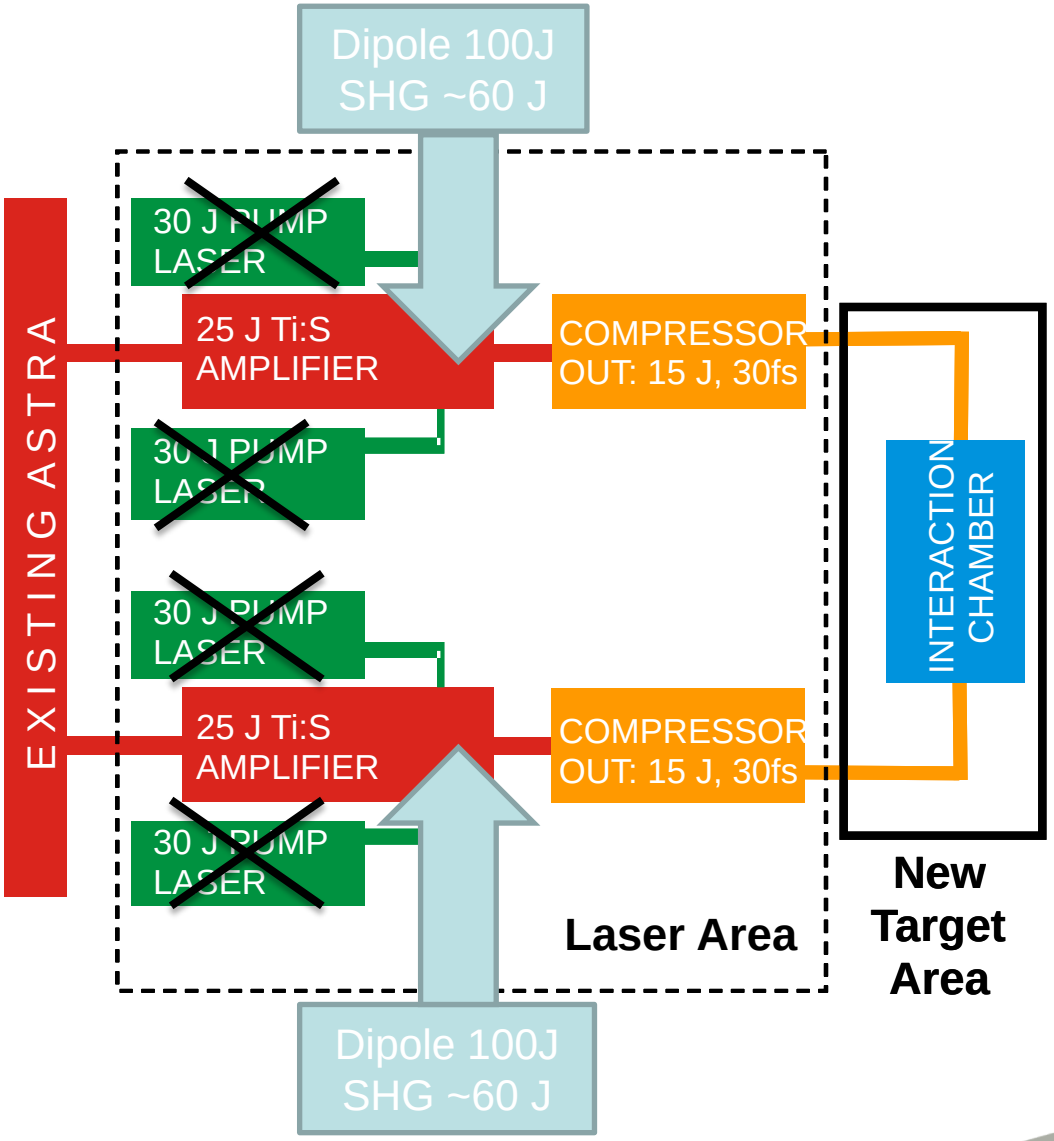
- Tenders for key components underway
  - Gain media, pump diodes, cryo-system

Gain Media Tender (In Progress)

- Specification
  - 6 x Yb:YAG ceramic slabs
  - 120 mm x 120 mm square
  - Yb-doped region
    - 100 mm x 100 mm
    - Doping 0.4, 0.6 & 1.0 at.%
  - Cr^{4+} cladding 10 mm wide
    - Attenuation = 3 ± 1 cm^{-1} at 1030 nm
- Issues
  - Feasibility of cladding
    - Uniform absorption on all 4 sides?
    - Will co-sintering induce stress?
  - Optical homogeneity & surface finish
    - Can lead to spatial non-uniformity in output beam



Future Upgrade to Astra-Gemini

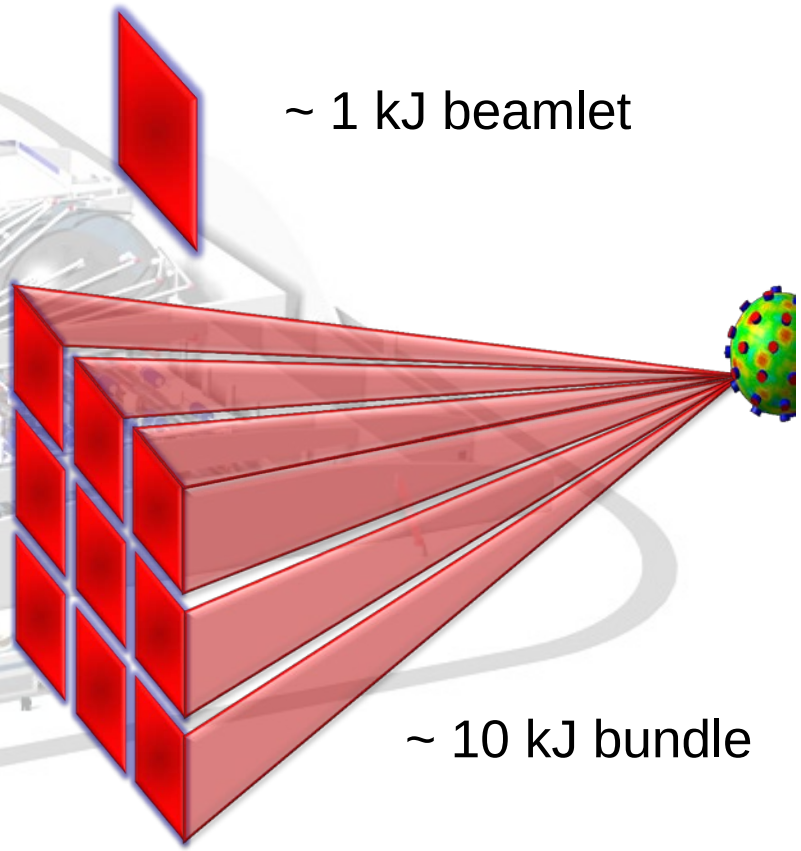


- Replace flashlamp based pump lasers with frequency-doubled DiPOLE 100 J
- New Ti:sapphire amplifier head design
  - Ceramic sapphire ?
- Two synchronised beams, independently configurable
  - Multi-Hz PRF
  - Contrast > 10^{10}
  - Intensity ~ 10^{22} W/cm^2

Requirements for HiPER

Laser gain material

- 1 kJ beamlet
  - 10 off 22 cm aperture slabs
  - 5000 cm^3 ceramic Yb:YAG
- 10 kJ bundle
  - 10 beamlets = 100 slabs
  - 50,000 cm^3 ceramic Yb:YAG
- IFE plant with 50 beamlines (0.5 MJ)
  - 50 beamlines = 10,000 slabs
  - 2.5 m^3 ceramic Yb:YAG



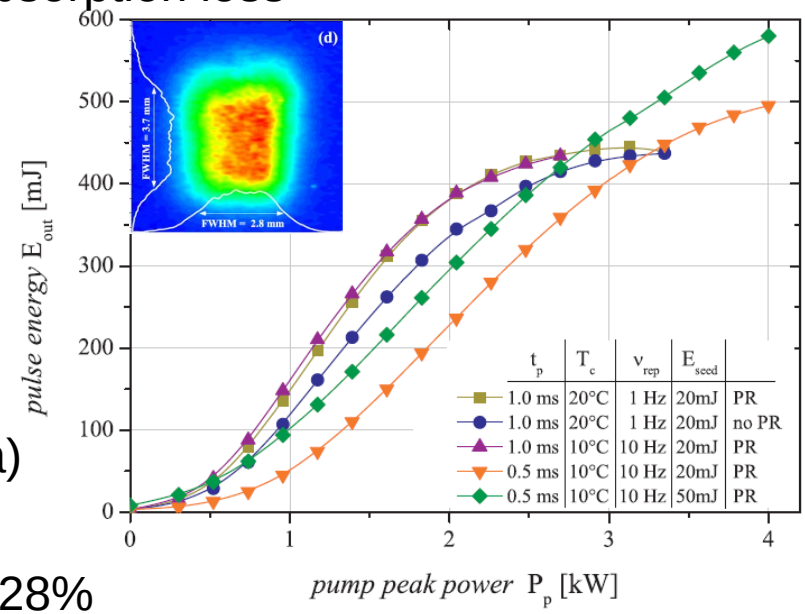
Large aperture Faraday rotator

- Aperture 10 to 20 cm capable of handling 10 kW average power
- Ceramic TGG/GGG ?

Alternative Laser Host Materials

Yb:LuAG

- Advantages over Yb:YAG
  - Higher thermal conductivity & lower reabsorption loss
    - More efficient operation at higher P_{avg}
  - Broader pump absorption spectrum
    - Relaxes pump diode linewidth



Siebold et al, Optics Express, 21992, 20, No.20 (2012)

- Room temperature evaluation in pre-amplifier completed
  - Ceramic Yb(10 at.%):LuAG (Konoshima)
  - 18 mm dia. x 1 mm thick
  - 0.5 Joule ns-pulses at 10 Hz with $\eta_{o\text{-}o}$ = 28%

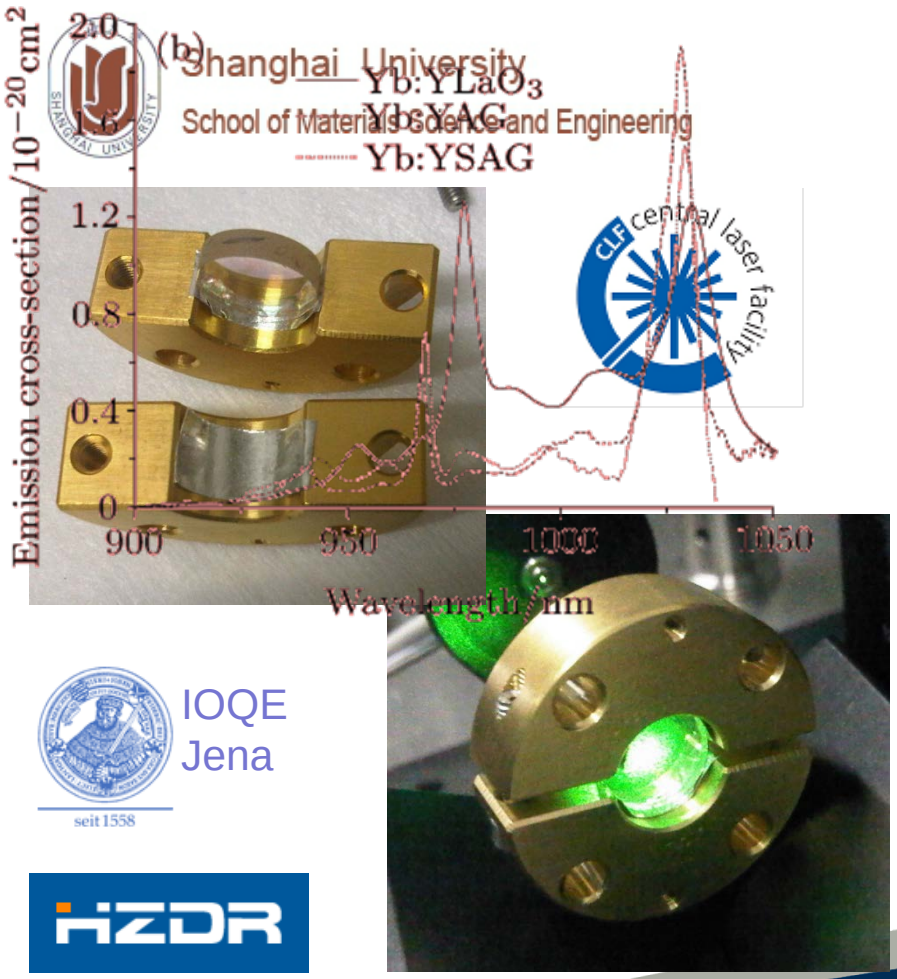
- Larger aperture samples to test in DiPOLE amplifier
  - >35 mm dia. x 5 mm thick with Cr-cladding ?

Alternative Laser Host Materials

Yb(La):Y_2O_3

- Advantages over Yb:YAG
  - Broader emission/gain bandwidth
  - Potential for shorter pulse generation

- Testing of small-scale ceramic samples begun
  - 11 mm dia. x 3 mm thick
  - Doping: Yb 5 at.%, La 10 at.%
  - Kindly provided by Prof Quihong Yang – Shanghai University
  - Temperature dependence of gain
    - RT → 80 K



IOQE Jena

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HZDR

Summary

- Cryogenic gas cooled Yb:YAG amplifier offers potential for efficient, high energy, high repetition rate operation
  - 24% optical-to-optical efficiency demonstrated
  - Multi-slab architecture scalable to at least 1 kJ
- DiPOLE prototype amplifier shows promising results
  - Expect to demonstrate 10 J @ 10 Hz shortly
- Development of next-generation 100 J amplifier begun
  - Plan to use this as a pump for new Ti:S head
  - Develop multi-Hz PW capability at CLF
- Requirement for large aperture, high quality optical ceramics
  - Laser gain media, Faraday rotators, etc.

Thank you for your attention!

Any Questions?

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