Intense Laser Developments at the CLF

Advanced Summer School “Laser-Driven Sources of High Energy Particles & Radiation”

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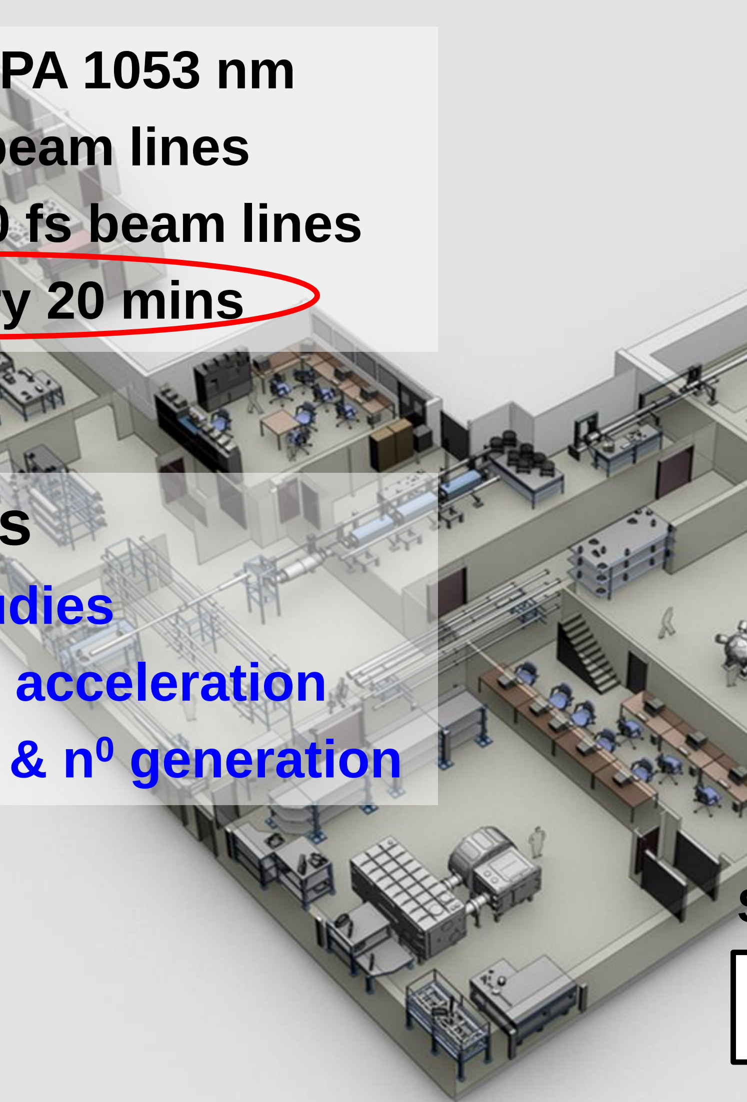
Science & Technology Facilities Council
Central Laser Facility

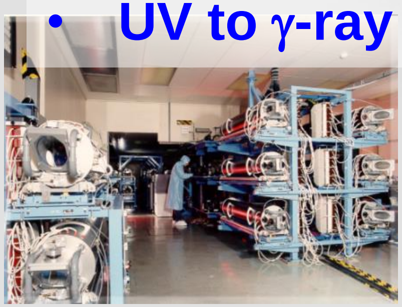
Vulcan Laser @ CLF

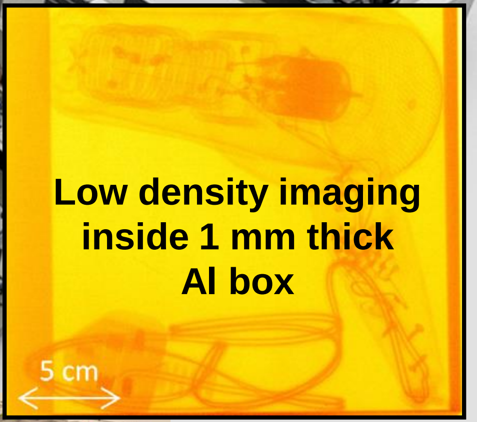


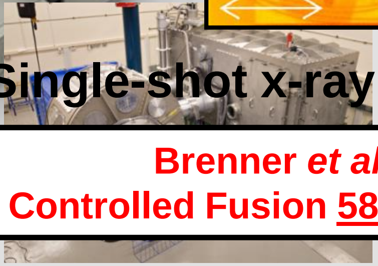
- Nd:glass CPA 1053 nm
- 6 x kJ, ns beam lines
- 2 x PW, 500 fs beam lines
- 1 shot every 20 mins

Applications

- Ignition studies
- e⁻, p^+ & ion acceleration
- UV to γ-ray & n^0 generation





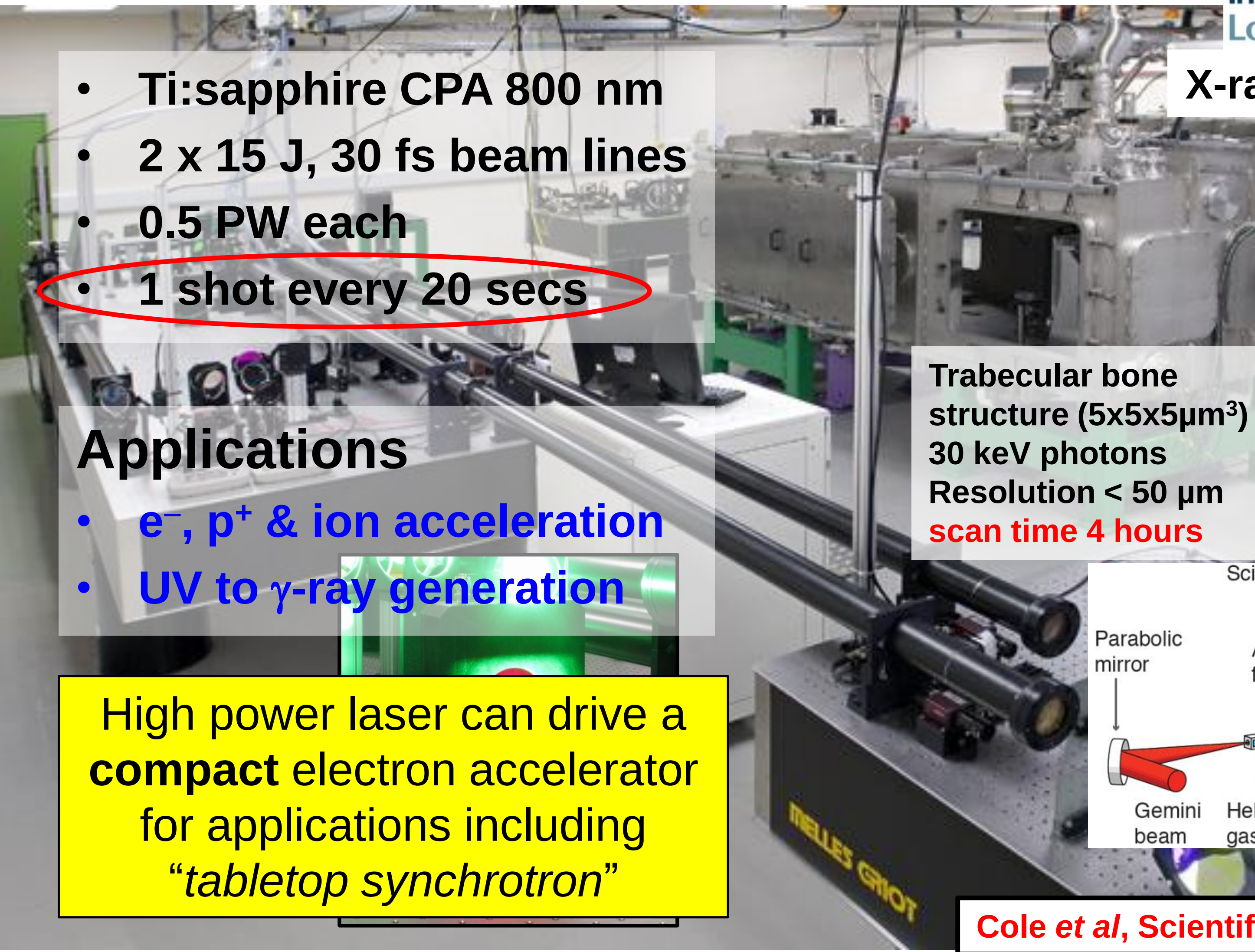


Single-shot x-ray radiography

Brenner *et al*, Plasma Phys. Controlled Fusion 58, 014039 (2016)

Danson *et al*, J. Nucl. Fusion 44 S239 (2004)

Gemini Laser @ CLF



- **Ti:sapphire CPA 800 nm**
- **2 x 15 J, 30 fs beam lines**
- **0.5 PW each**
- **1 shot every 20 secs**

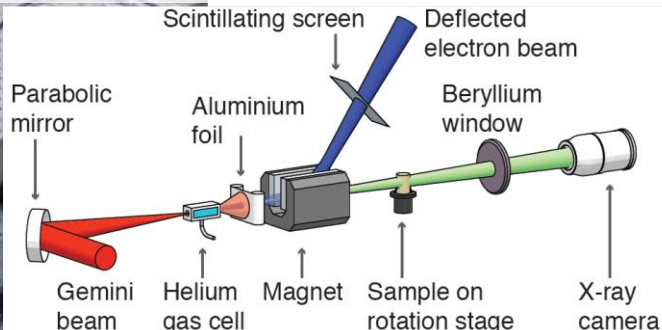
Applications

- **e^-, p^+ & ion acceleration**
- **UV to γ-ray generation**

High power laser can drive a **compact** electron accelerator for applications including "*tabletop synchrotron*"

X-ray tomography scan

Trabecular bone structure (5x5x5μm³)
30 keV photons
Resolution < 50 μm
scan time 4 hours

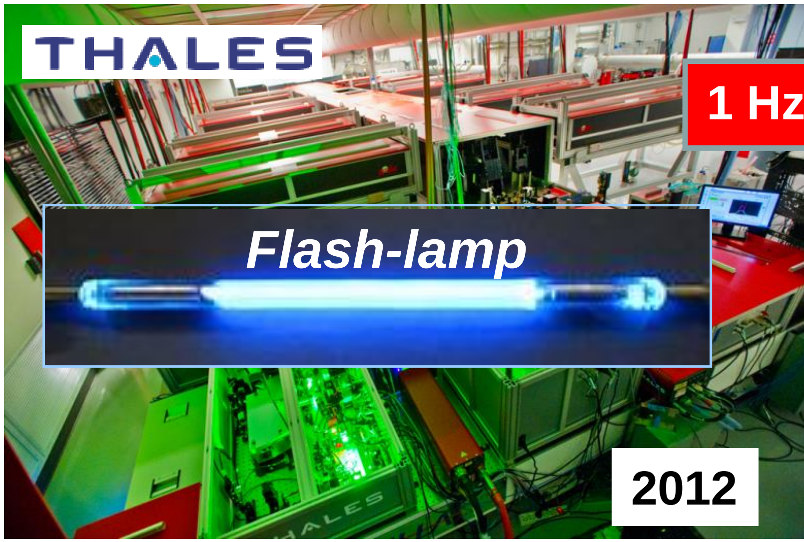


Cole *et al*, Scientific Reports 5, 13244 (2015)

Hooker *et al*, Rev. of Laser Eng. 37, 6 (2009)

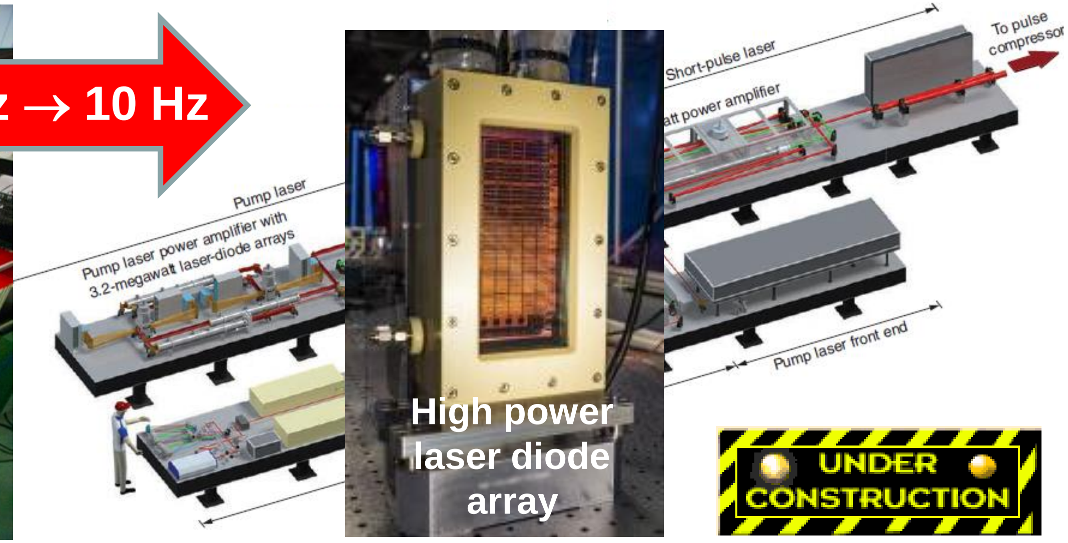
Coming Soon PW lasers @ 10 Hz

BELLA (LBNL) — BERKELEY LAB



1 Hz → 10 Hz

HAPLS (LLNL)



Flash lamp pumping

- Ti:sapphire CPA
- 40 J, 30 fs, 1 Hz
- **Cost: ~$10M**

Diode pumped solid-state laser (DPSSL)

- Ti:sapphire CPA
- 30 J, 30 fs, 10 Hz
- **4.6m x 17m, Cost: $45M**

http://newscenter.lbl.gov/2012/07/27/bella-laser-record-power/
https://www.llnl.gov/news/llnl-meets-key-milestone-delivery-worlds-highest-average-power-PW-laser-system

Centre for Advanced Laser Technology & Applications (CALTA)

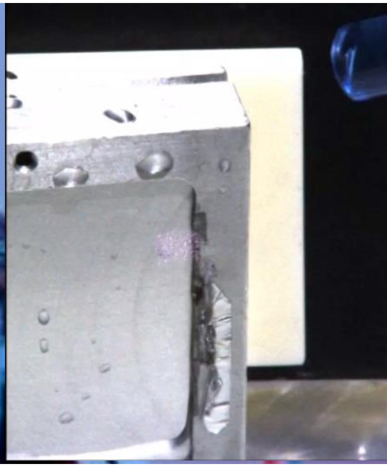
Laboratory science → Practical applications

DiPOLE

- **Efficient DPSSL amplifier technology**
- **Cryo-cooled Yb:YAG 1030 nm**
- **10 to 100 J, ns pulses**
- **10 shots per second**

Applications

- **Next generation pump for PW-class (OP)CPA lasers**
- **Industrial materials processing**
  - **Laser shock peening**

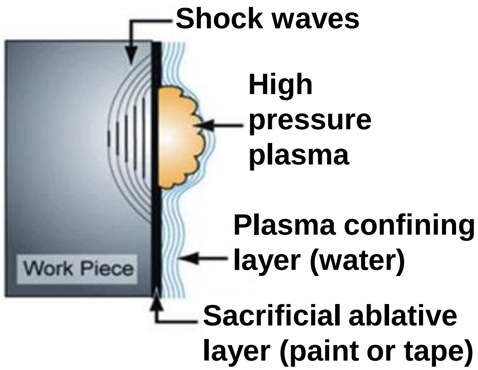


Laser-driven shock waves

Compressive stress

Plastic deformation

Improved fatigue resilience



Kalainathan *et al*, Optics & Laser Tech. 81, (2016)

Why Yb-doped YAG ?

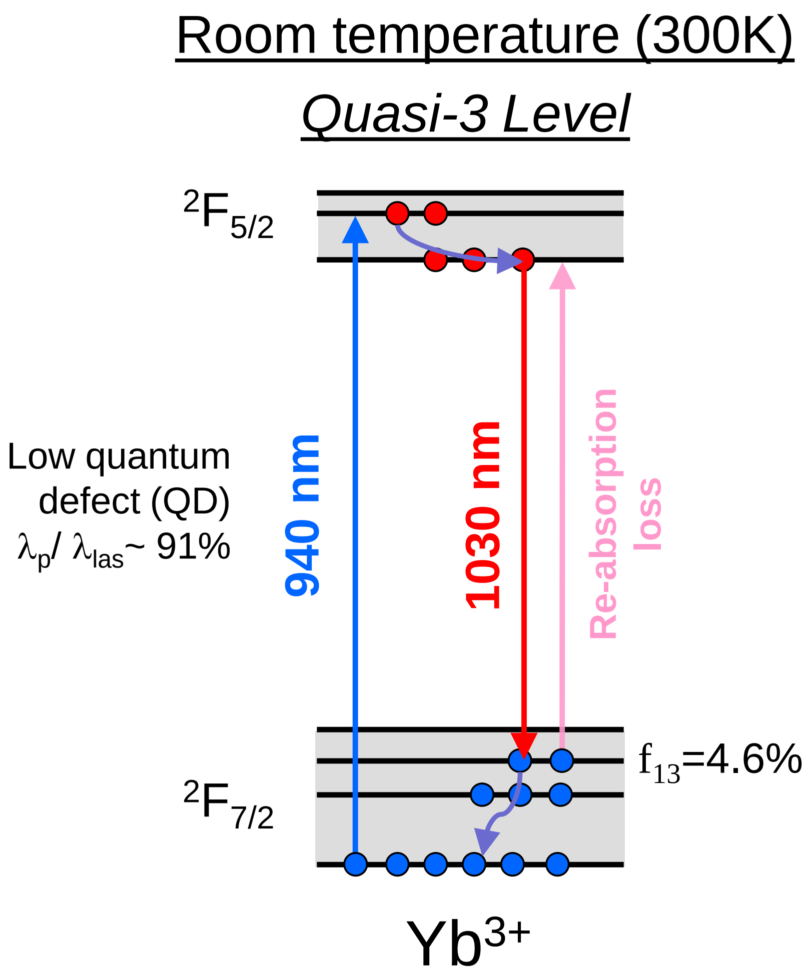
Parameter (at RT)	Glass	S-FAP	YAG	CaF_2
Wavelengths (pump/emission in nm)	940-980 / 1030	900 / 1047	940 / 1030	940-980 / 1030
Fluorescence lifetime (ms)	~ 2.0	~ 1.3	~ 1.0	~ 2.4
Emission cross-section (peak $\times 10^{-20}$ cm^2)	0.7	6.2	3.3	0.5
Gain	Low	High	Medium	Low
Non-linear index ($n_2 \times 10^{-13}$ esu)	0.1 to 1.2	1.5	2.7	0.43
Bandwidth	High > 50 nm	Low	OK?	High > 50 nm
Availability of large aperture	Good	Limited	OK (Ceramic)	Limited (Ceramic)
Thermal properties (K in $Wm^{-1}K^{-1}$)	Poor 1.0	OK 2.0	Good 10.5	OK 6.1

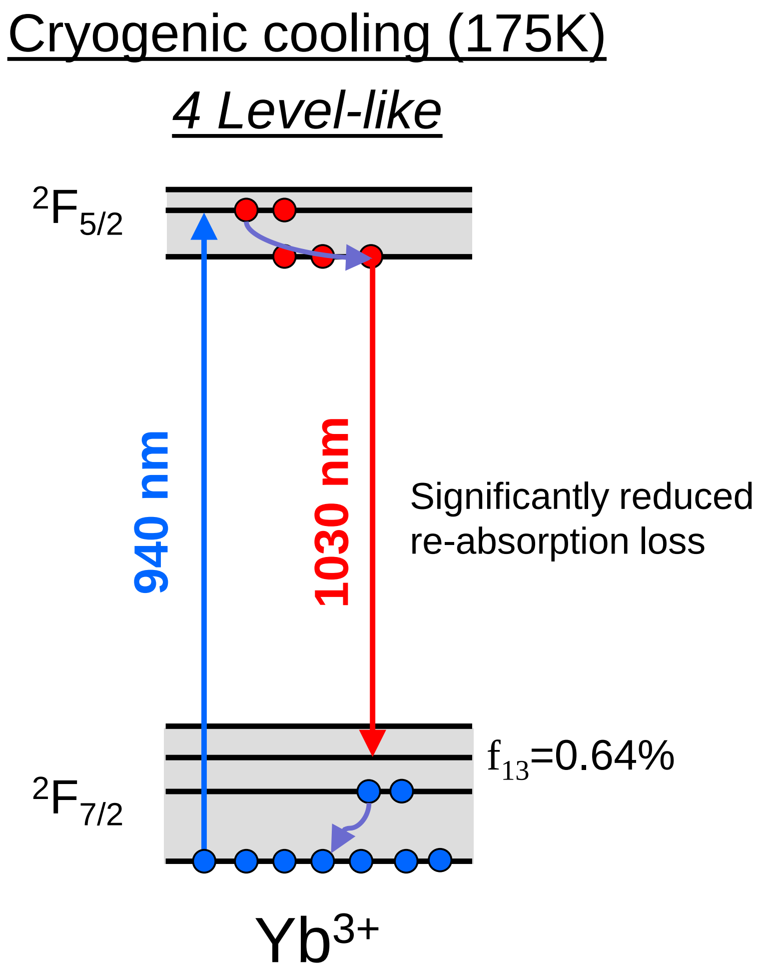
Good OK Poor

Best compromise

Why Cryogenic Cooling?

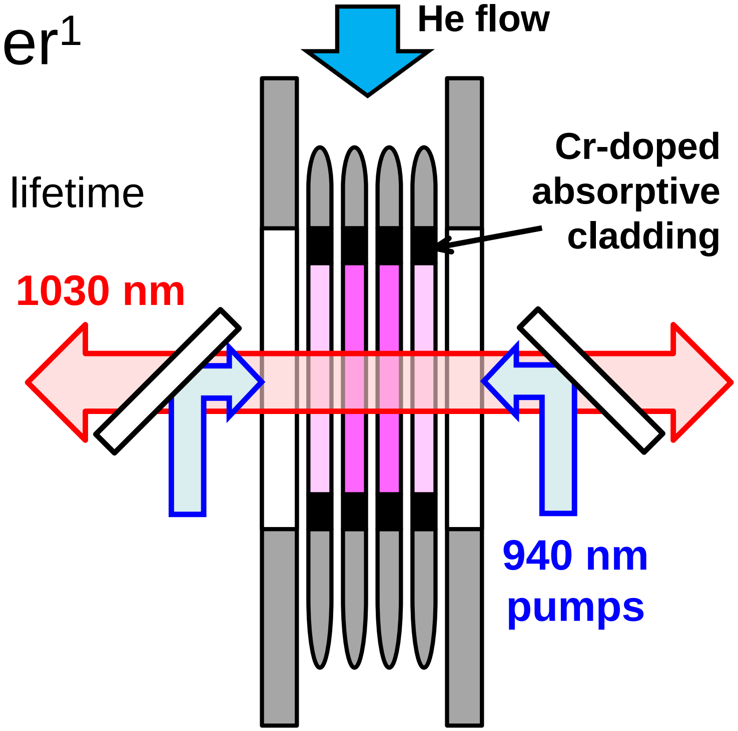
- Significantly reduced re-absorption loss

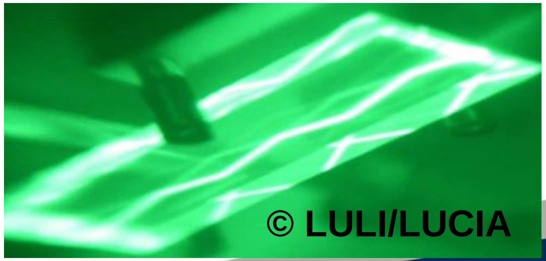




DiPOLE Cryo-Amplifier Concept

- Diode end-pumped multi-slab amplifier[1]
  - Ceramic Yb:YAG gain medium
    - Low quantum defect (91%), long fluorescence lifetime (1 ms), ceramic scalable in size
  - Composite structures ASE suppression
- Graded doping profile
  - Equalised heat load in each slab
- Face-cooled by cryogenic He gas
  - Improved efficiency & gain cross-section
    - Significantly reduced reabsorption loss
    - Emission x-section ~ 2 x RT
  - Better thermo-optical & thermo-mechanical[2]
    - Thermal conductivity (100K) ~ 4 x RT
    - dn/dT (100K) ~ 8 x smaller than RT
- Scalable design (10 J, 100 J & 1 kJ)

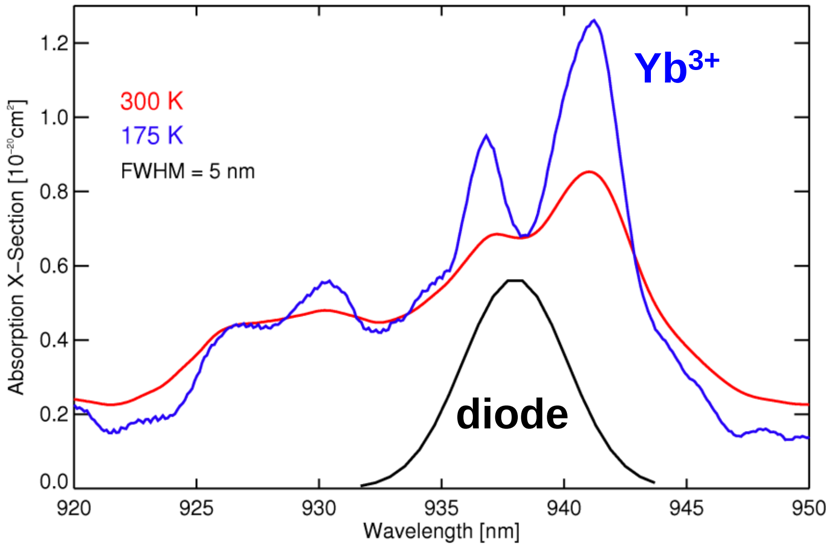


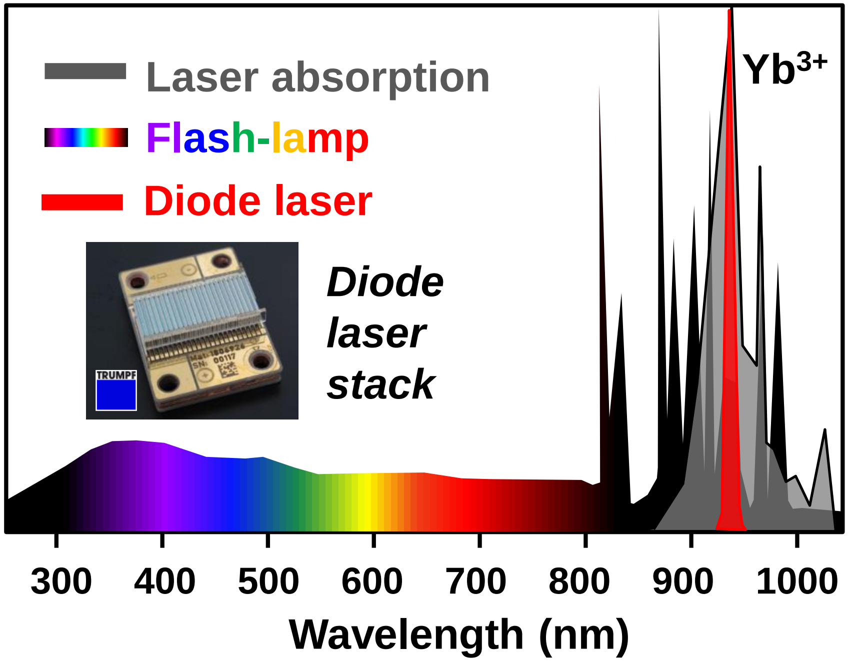


[1]Mason *et al*, Applied Optics 54, 4227 (2015)
[2]Aggarwal et al, J. Appl. Phys. 98, 103514 (2005)

Why Diode Pumping?

- Diode spectrum better matched to laser absorption
  - Improved efficiency
  - Reduced thermal load
  - Enhanced by cryo-cooling[1,2]



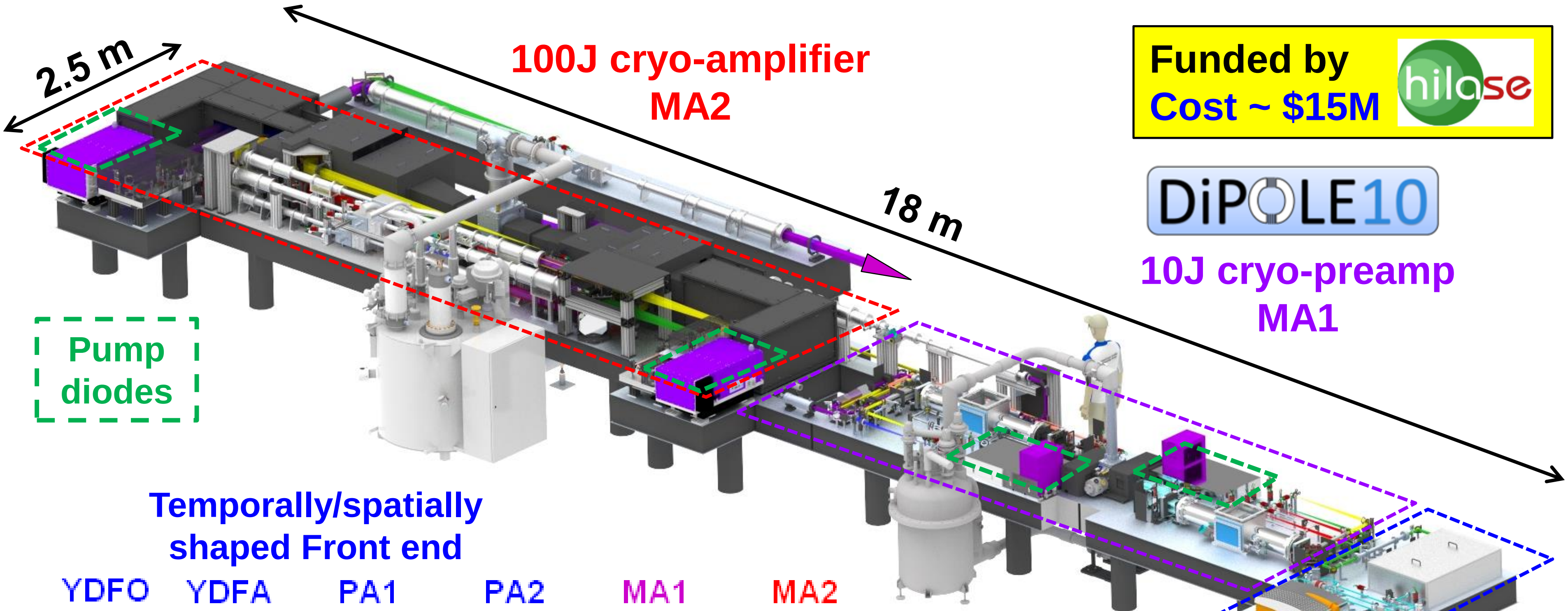


- Longer lifetime
  - Billions of shots
  - Higher pulse rates
  - Redundancy
- High brightness
  - Efficient coupling & uniform shaped profile

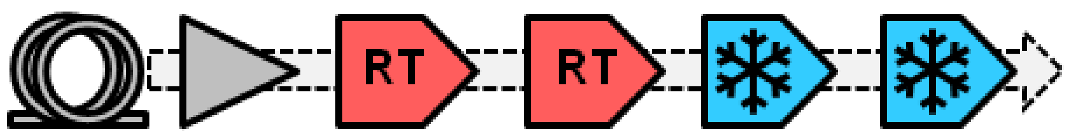
[1] *Brown et al, IEEE J. of Select. Topics in Quant. Elect. 11, No.3 (2005)*
[2] *Ertel et al, Optics Express, 19, No. 27, 26610 (2011)*

DiPOLE100 Architecture

Funded by hilase
Cost ~ $15M



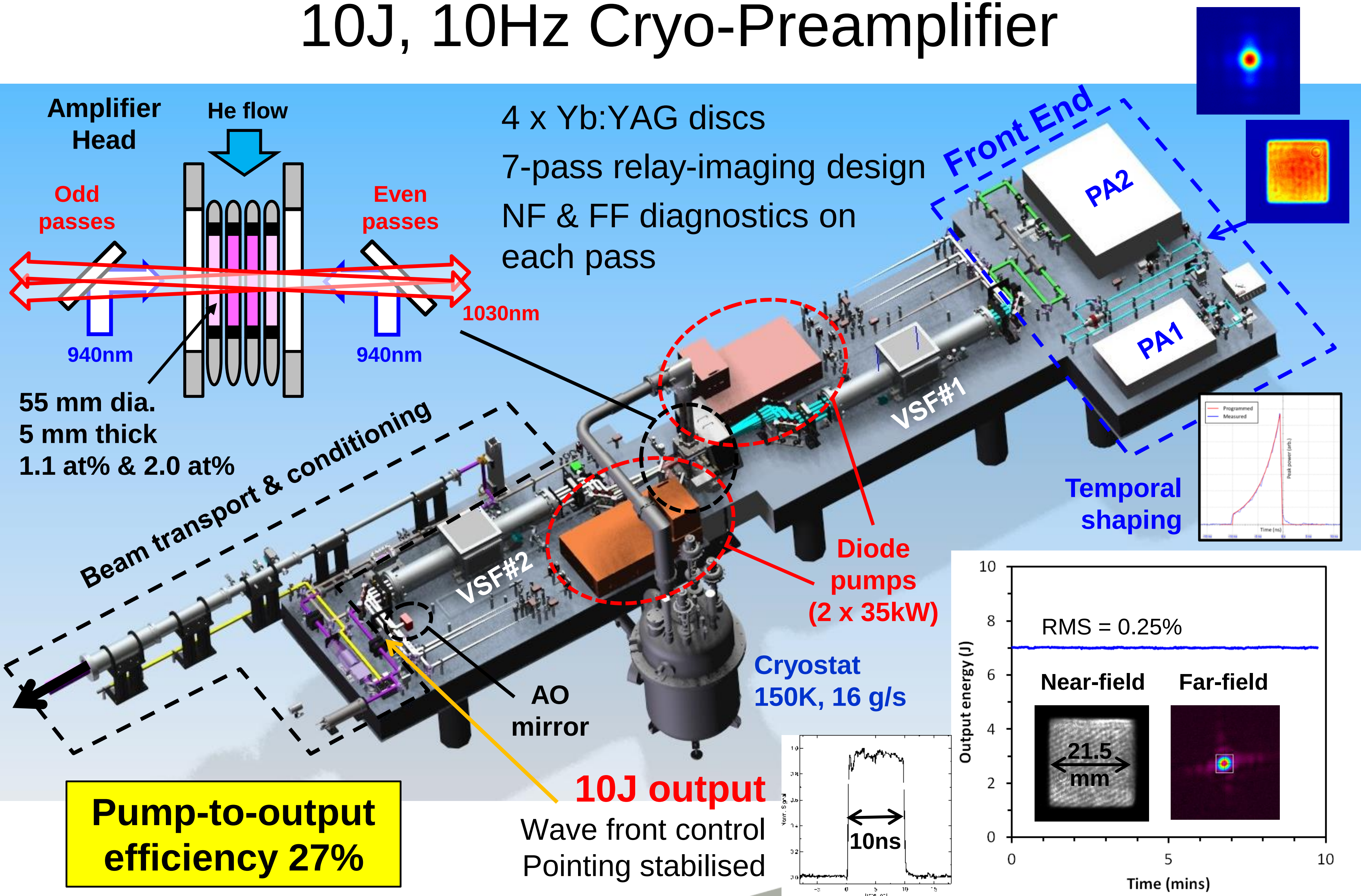
Temporally/spatially shaped Front end



	YDFO	YDFA	PA1	PA2	MA1	MA2
Energy :		7 nJ	3 mJ	100 mJ	9 J	100 J
PRF :		10 kHz	10 Hz	10 Hz	10 Hz	10 Hz
P_{avg} :		10 µW	30 mW	1 W	90 W	1 kW
Beam size:			2 mm	8 mm	22 mm	75 mm

DiPOLE100

10J, 10Hz Cryo-Preamplifier



Pump-to-output efficiency 27%

DiPOLE10

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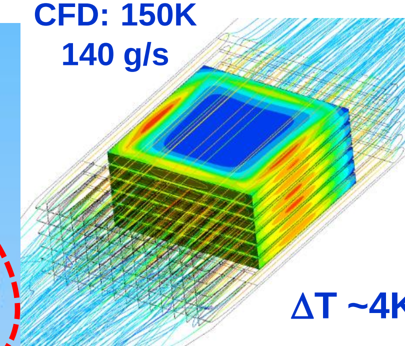
100J, 10Hz Cryo-Amplifier

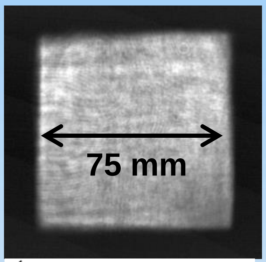
- 6 x Yb:YAG slabs
- 4-pass relay-imaging design
- NF, FF diagnostics on each pass

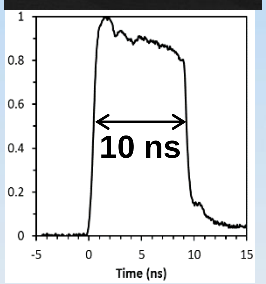
Konoshima Chemical Co.,Ltd.

120 mm square
8.5 mm thick

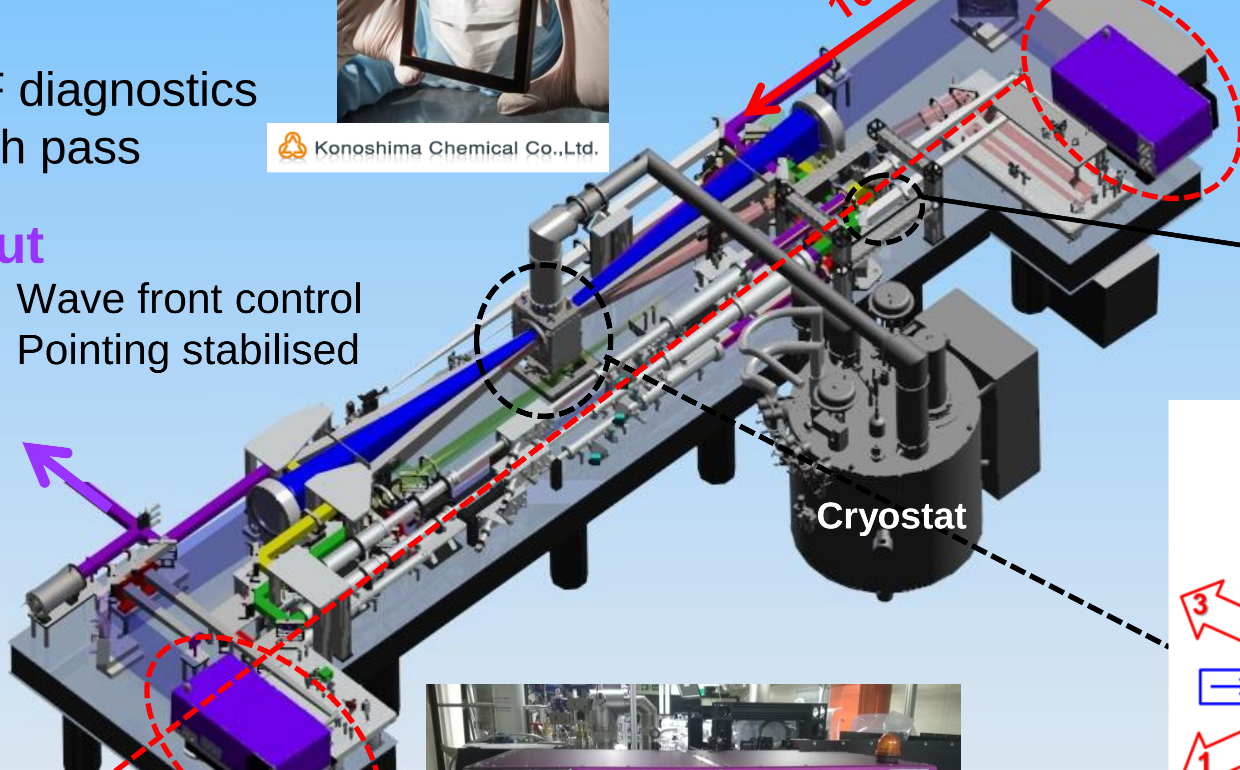


100J output

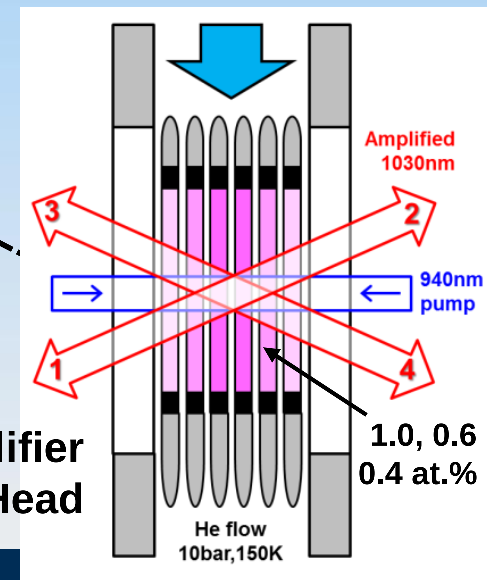




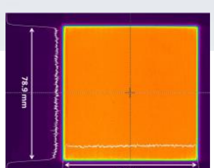
Wave front control
Pointing stabilised



He flow



Amplifier Head



ingeneric

DiPOLE100

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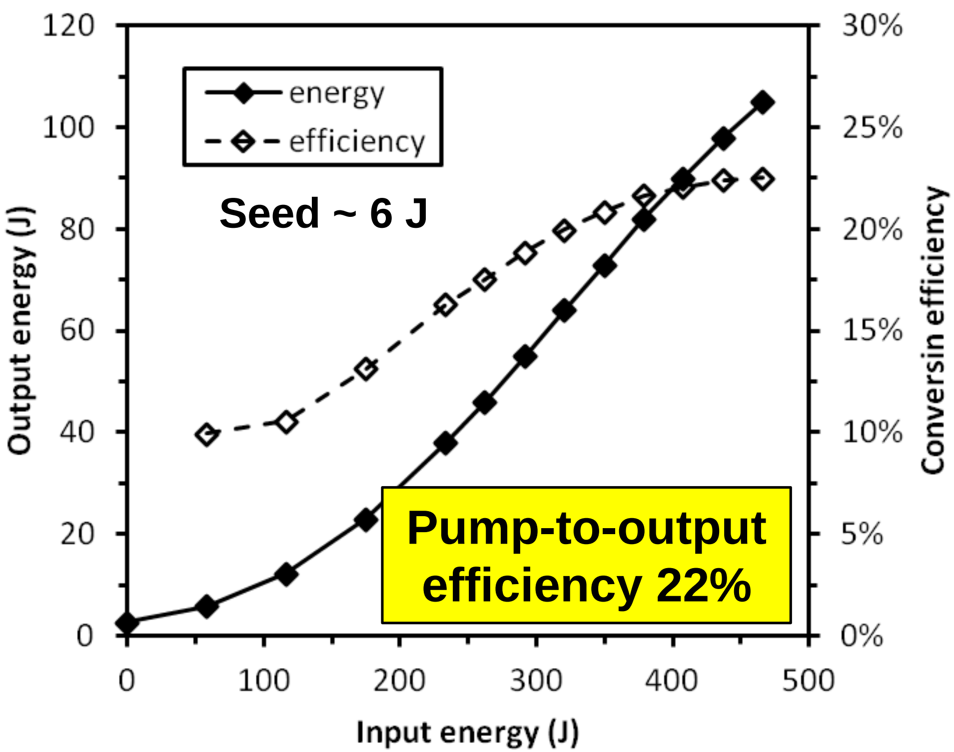
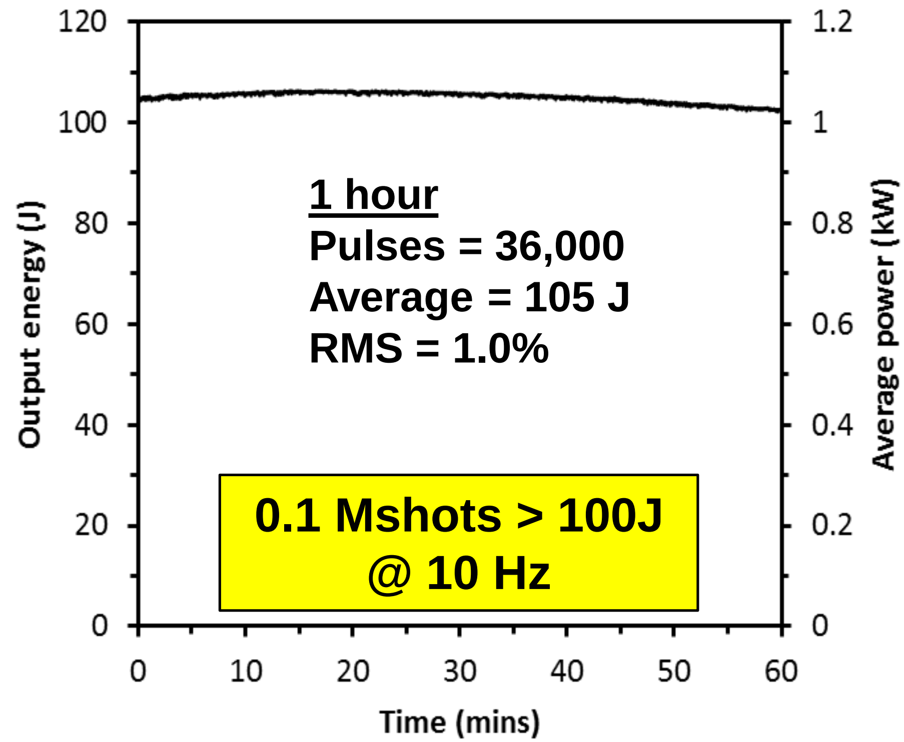
DiPOLE100 @ HiLASE

- Operational December 2016
  - 105 J @ 10 Hz, 10 ns



  - Energy stability



- First kW average power high-energy DPSSL

Mason *et al*, Optica 4, 438 (2017)

DiPOLE100

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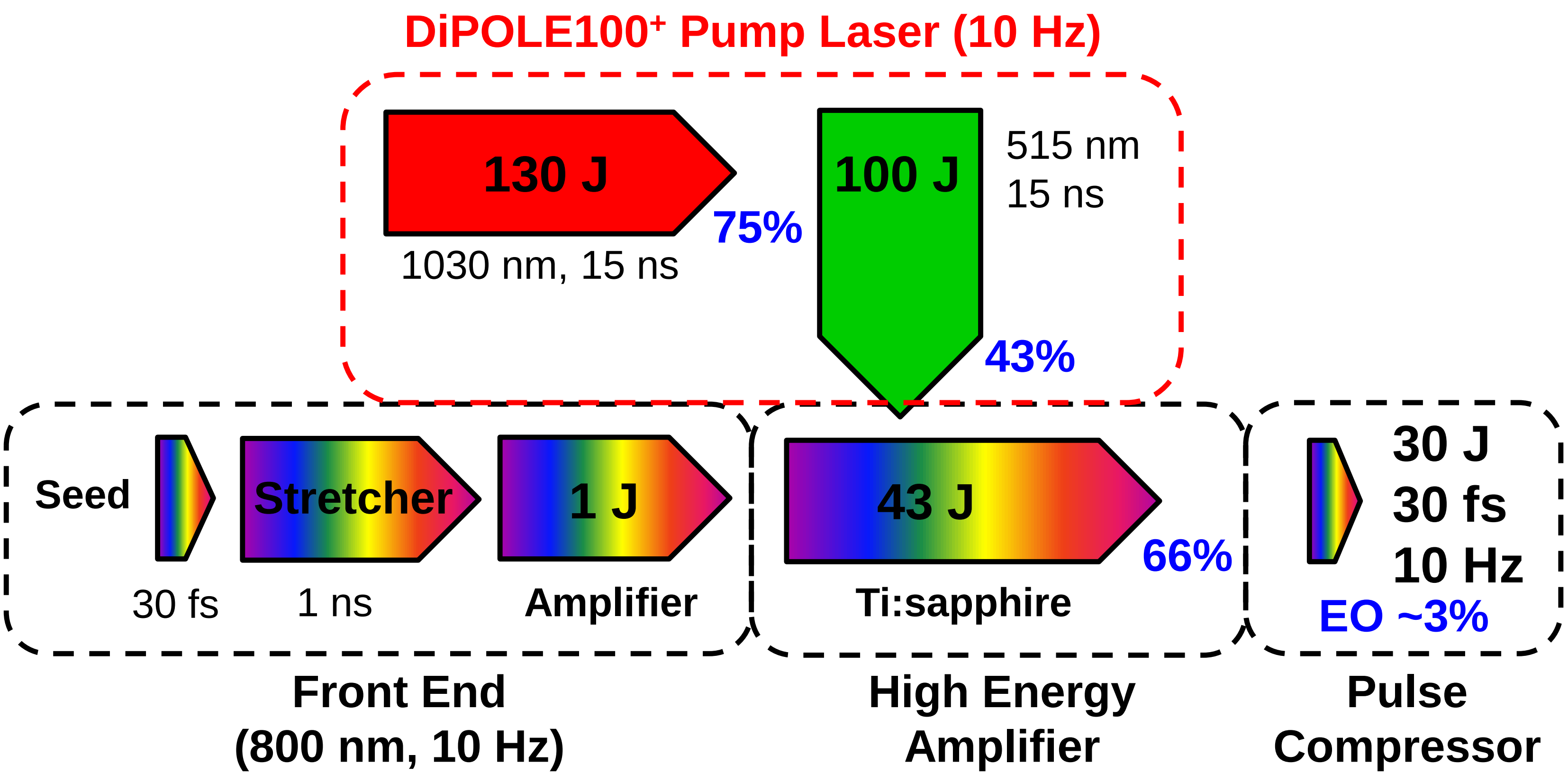
Operational DiPOLE Systems

Parameter	DiPOLE10	DiPOLE100
Wavelength	1029.5 nm	
Pulse energy	9 J	107 J
Energy stability	0.3% RMS	≤ 1% RMS
Pulse rate	10 Hz	
Average power	90 W	> 1 kW
Run time	> 50 hr (~2 Mshots)	> 2.5 hr (~0.1 Mshots)
Efficiency (o-o)	27%	22%
Pulse duration	Shaping @ 10 ns	10 ns
Beam shape	Square SG (order ~10)	
Beam size	22 mm	75 mm
Pointing stability	±15 µrad PV < 4% RMS	

Proposed Gemini Facility Upgrade @ CLF

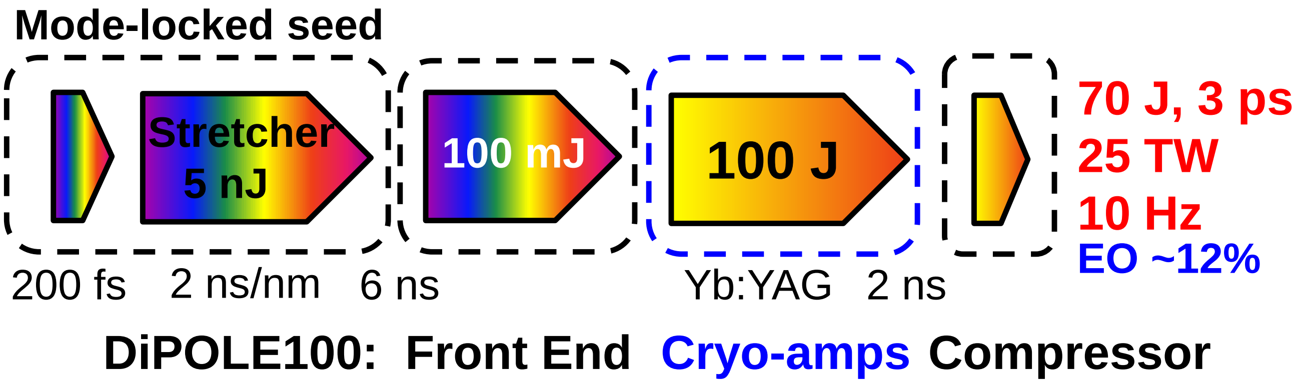
- 10 Hz PW Ti:S indirect CPA laser: 30 J, 30 fs, 10 Hz



- Technical design report completed
  - Published soon
  - Funding being sought

ps-DiPOLE

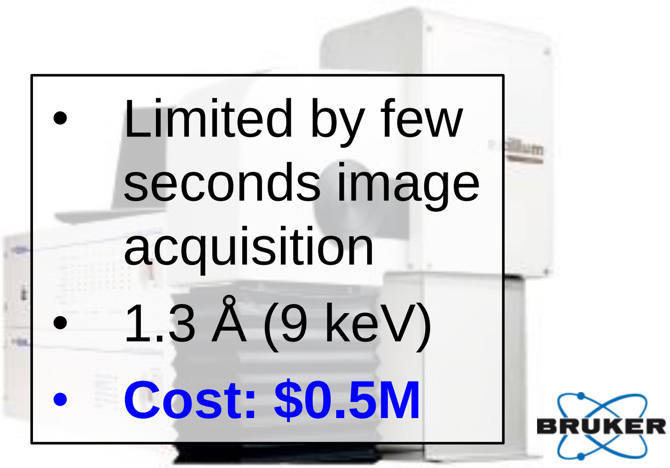
- Direct CPA in cryo-cooled Yb:YAG
- Architecture
  - Mode-locked fs seed source
  - Grating <u>or</u> cFBG stretcher + spectral shaping
  - Existing DiPOLE100 cryo amplifier chain



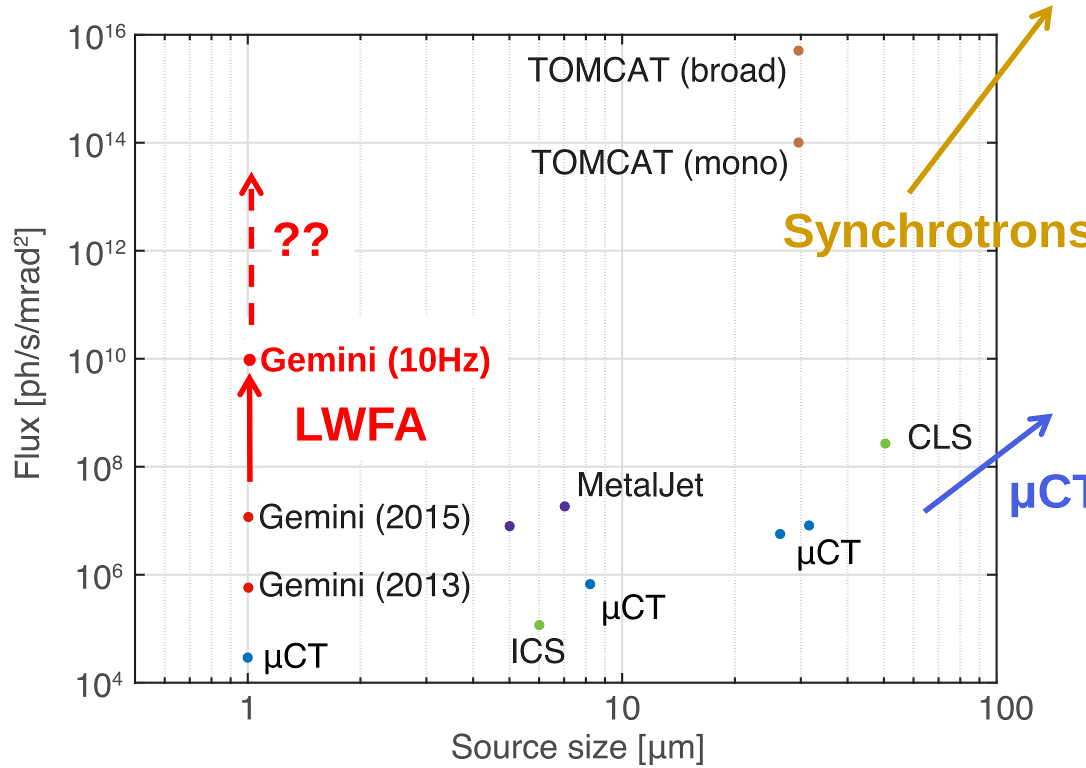
- Reduced complexity & improved efficiency
  - Potential applications

Lab-Scale X-ray Source Technology

MetalJet µCT



- Limited by few seconds image acquisition
- 1.3 Å (9 keV)
- **Cost: $0.5M**



Inverse Compton Scatter

- Limited by source size (30 µm)
- **Cost $10M**

Gemini LWFA (Betatron)

- Flux competitive with lab-scale sources
- Scales to higher flux @ same source size
- **Limited by pulse rate: Cost $5M**

Practical X-ray Imaging System Design

- Laser (333 TW)
  - 30 fs, 10 J, ≥ 30 Hz (DPSSL pump ~ 30 J)
- X-ray imaging source
  - ≥ 30 fps, sub-micron resolution
  - 0.4 Å (35 keV) phase contrast

Small footprint & low cost (few $M)

- Driven by applications
  - Rapid tomographic imaging
  - Low dose phase contrast radiography
- Commercialisation
  - Improvements in reliability & robustness

βCT image mouse embryo
Good resolution & SNR

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Summary & Future Plans

LWFA compact accelerators can generate extreme brightness short pulse x-rays for radiography

High power lasers are constantly improving

- Second DiPOLE100 for European XFEL
  - Closed-loop temporal shape control
  - Completion summer 2018
- Funded DiPOLE development (5 years)
  - Scaling energy (**~ 150 J**) & PRF (**10 J @ 100 Hz**)
  - Second & third harmonic generation
- New DPSSL-based laser designs
  - PW-class indirect CPA & ps direct CPA
- Compactisation
  - New geometries & cooling schemes

HiBEF EPSRC Engineering and Physical Sciences Research Council University of Oxford European XFEL Science & Technology Facilities Council

H2020

hilase

SHG in LBO

5 J @ 10 Hz

>80%, 7 J/cm²

0.7% RMS

DiPOLE100 @ HiLASE

Thank you
Any
questions?