The Abdus Salam International Centre for Theoretical Physics

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IAEA International Atomic Energy Agency

2132-44

Winter College on Optics and Energy

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Laser technology for laser fusion: the HiPER project

J. Collier

Rutherford Appleton Laboratory
U.K.

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

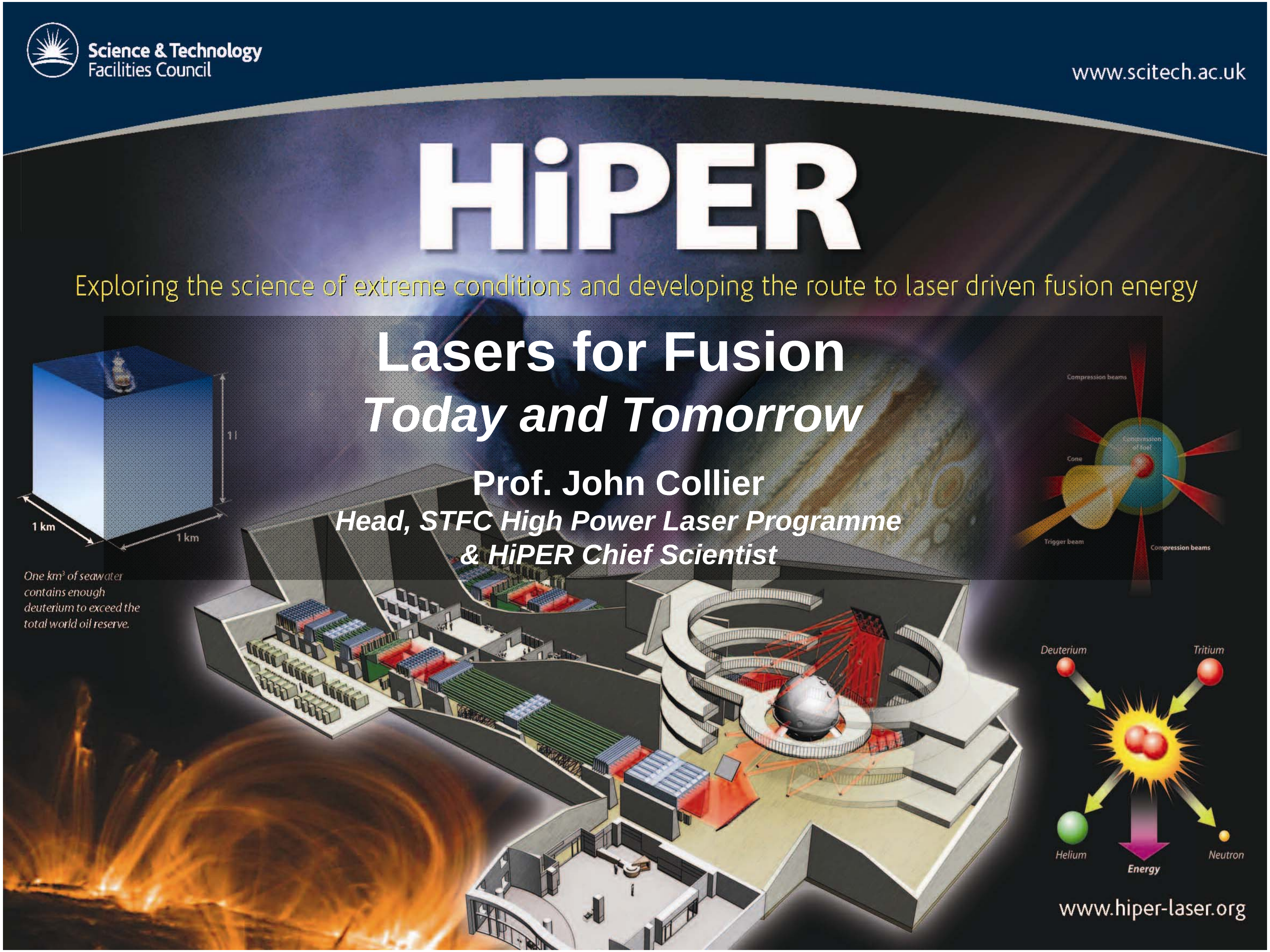
Lasers for Fusion

Today and Tomorrow

Prof. John Collier

Head, STFC High Power Laser Programme

& HiPER Chief Scientist



HiPER A multi-national partnership

Project partners (at the national agency level):

UK, France, Spain, Italy, Portugal, Czech Republic, Greece, European Commission (FP7)

Other partners (at the institutional level):

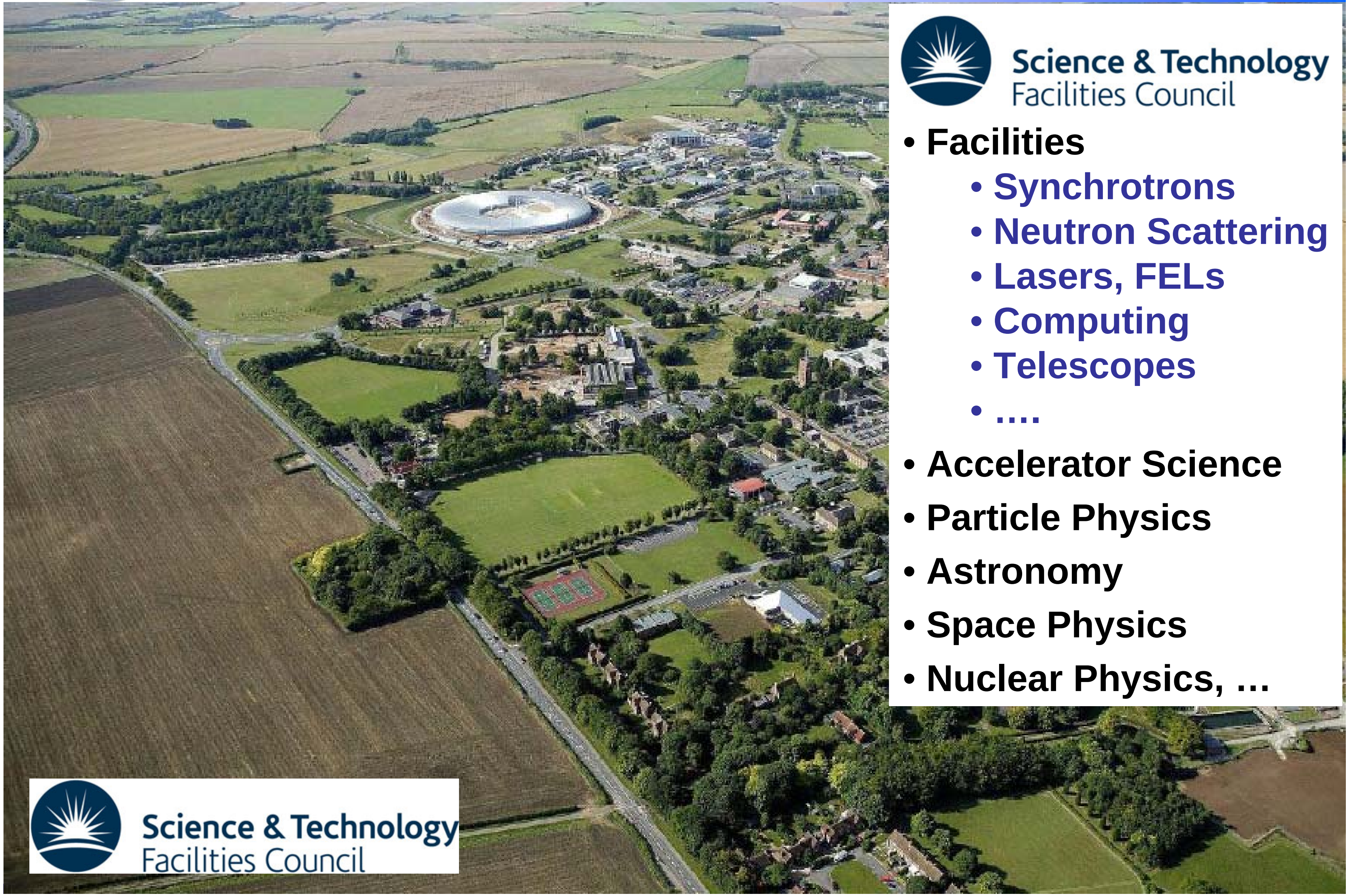
Germany, Poland, Russia

International links:

Japan, China, South Korea, USA, Canada

SEVENTH FRAMEWORK PROGRAMME

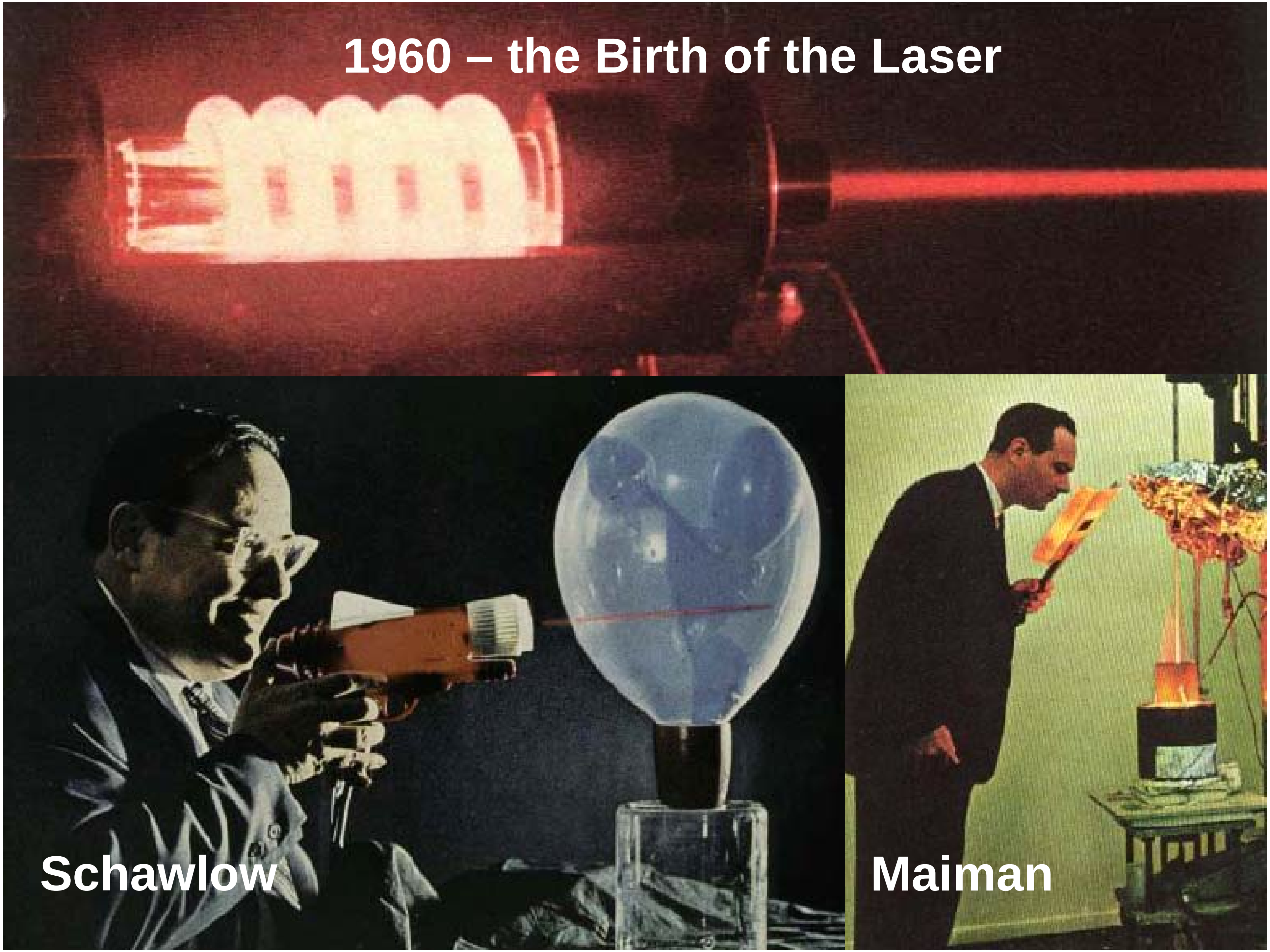
Rutherford Appleton Laboratory, UK

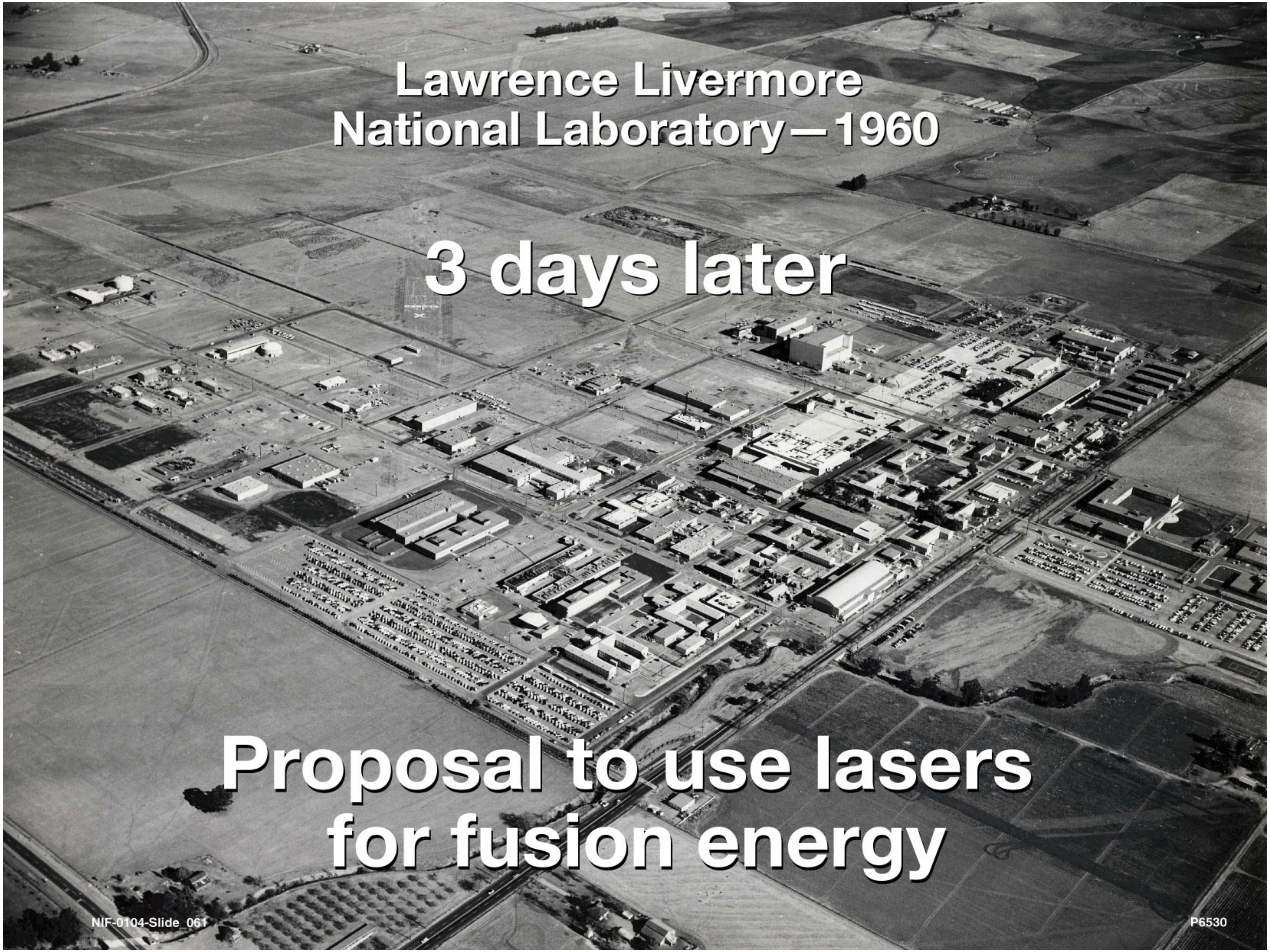


Science & Technology Facilities Council

- Facilities
  - Synchrotrons
  - Neutron Scattering
  - Lasers, FELs
  - Computing
  - Telescopes
  - ....
- Accelerator Science
- Particle Physics
- Astronomy
- Space Physics
- Nuclear Physics, …

1960 – the Birth of the Laser




Lawrence Livermore
National Laboratory—1960
3 days later
Proposal to use lasers
for fusion energy
NIF-0104-Slide_061
P6530

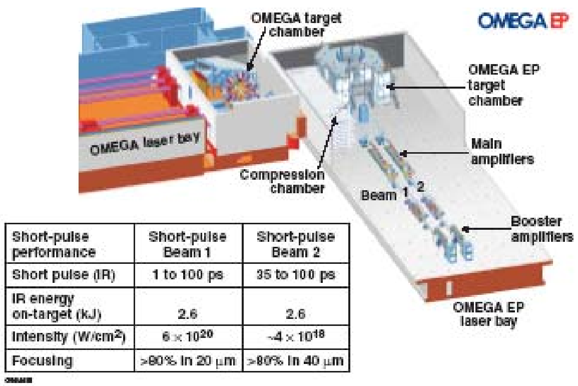
HiPER International effort in Laser / Inertial Fusion

Recent Large Scale laser systems

2002 Vulcan, UK
1kJ, 1PW

2006 LIL facility France 60kJ $3\omega_0$ + 4kJ PW (2013)

2007 FIREX laser Japan 10kJ PW + 10kJ $2\omega_0$



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm²)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	>80% in 20 μm	>80% in 40 μm

2007 OMEGA EP laser 5.2kJ PW + 30kJ $3\omega_0$

2009 - NIF facility in the USA 1.8MJ $3\omega_0$

2012 – LMJ facility France 2.4MJ $3\omega_0$

Laser numbers into perspective

- **Energy**: pitifully small
  - Largest lasers in the world have comparable energy to a cup of tea!
- **Timescale**: really quite short
- **Power**: staggeringly large
- 1 Petawatt
- (1,000,000,000,000,000 Watts)

> 10,000x UK National Grid

> 10x global photosynthesis

Imagine this power focussed to a spot 10x smaller than the width of a human hair……

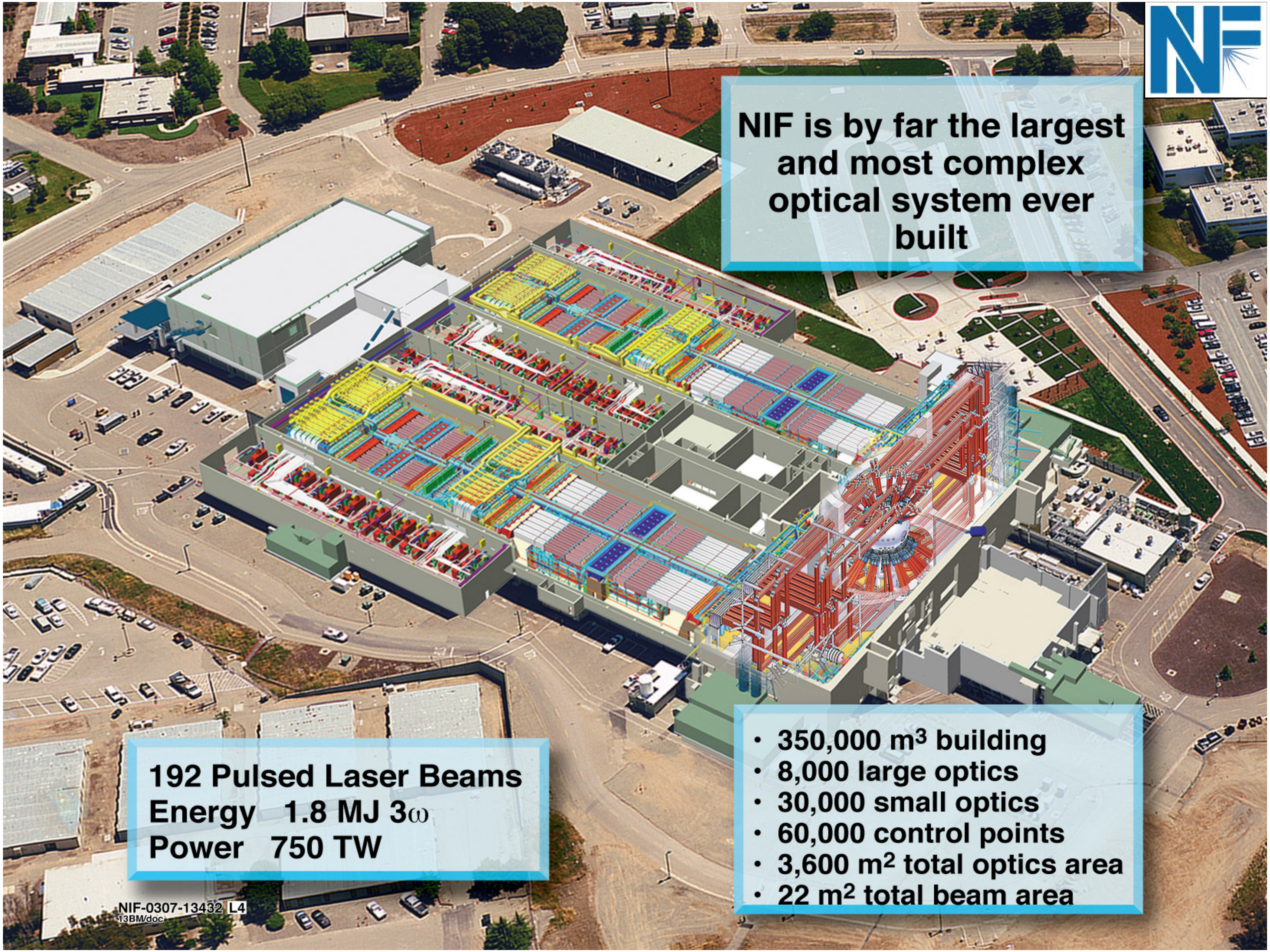
National Ignition Facility

$4 Billion US National Ignition Facility – Lawrence Livermore National Laboratory, California, USA *(plus also €4B for LMJ, France)*

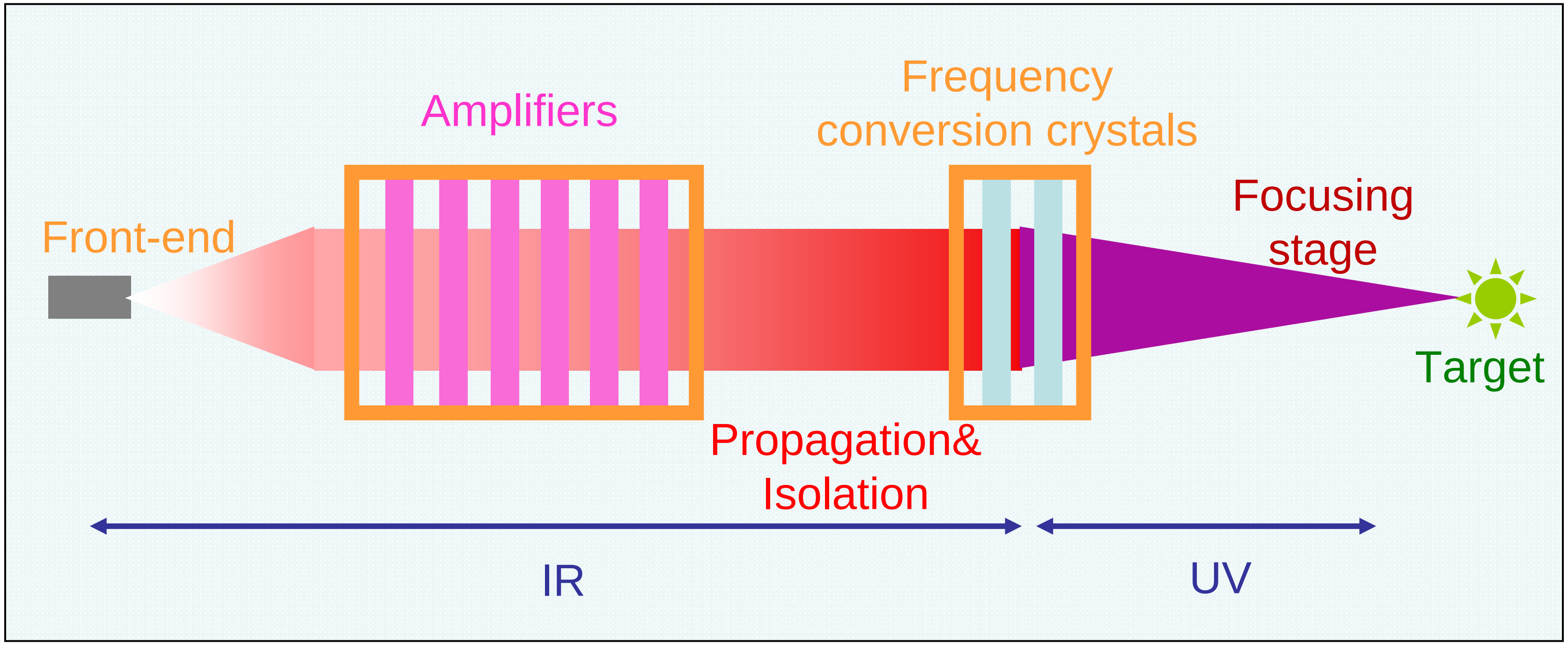
Completed in March 2009

Culmination of over 50 years' research


NIF 1104 09763


NIF is by far the largest and most complex optical system ever built
192 Pulsed Laser Beams
Energy 1.8 MJ 3ω
Power 750 TW
• 350,000 m³ building
• 8,000 large optics
• 30,000 small optics
• 60,000 control points
• 3,600 m² total optics area
• 22 m² total beam area
NIF-0307-13432 L4
13BM/doc

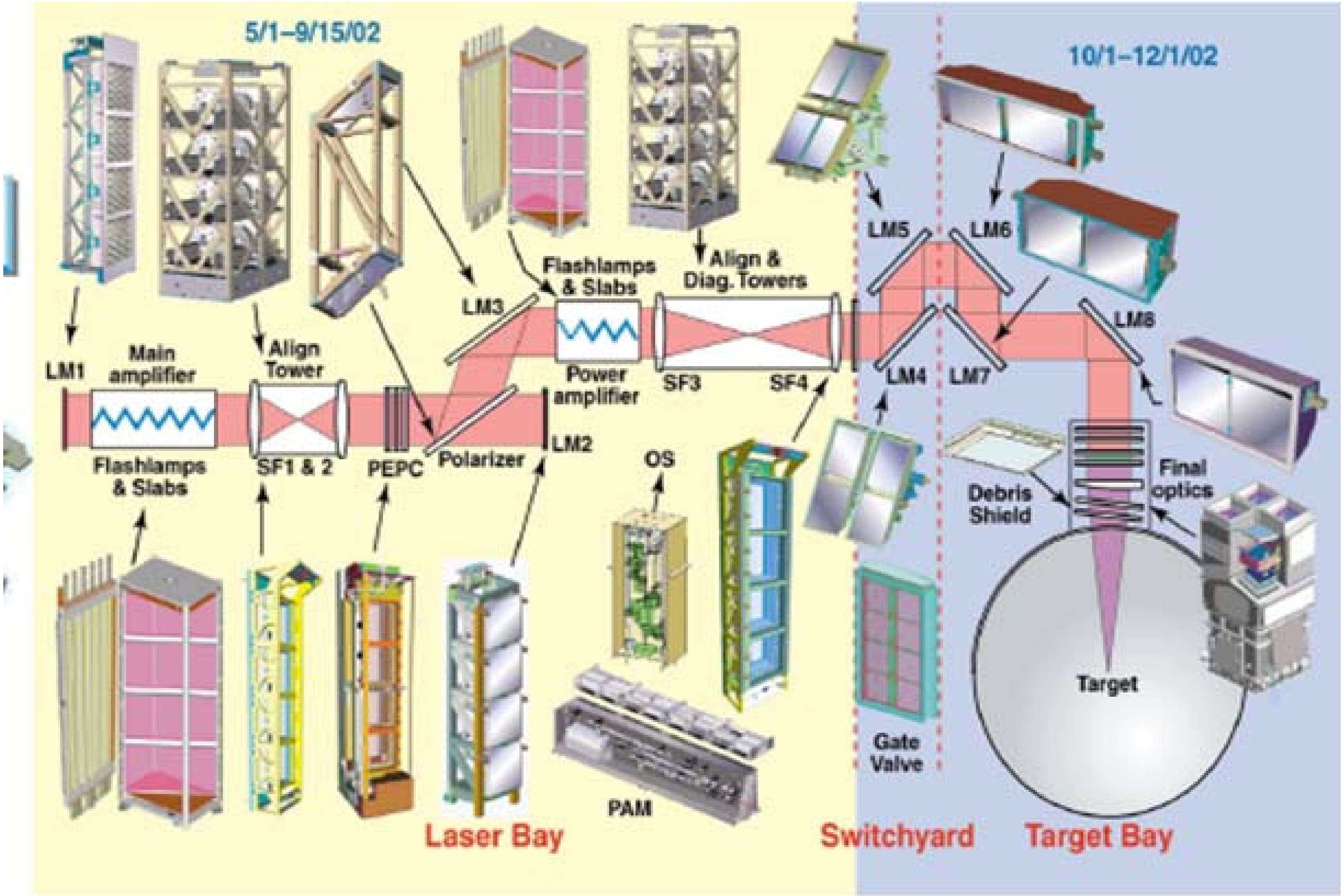
NIF Optical Architecture



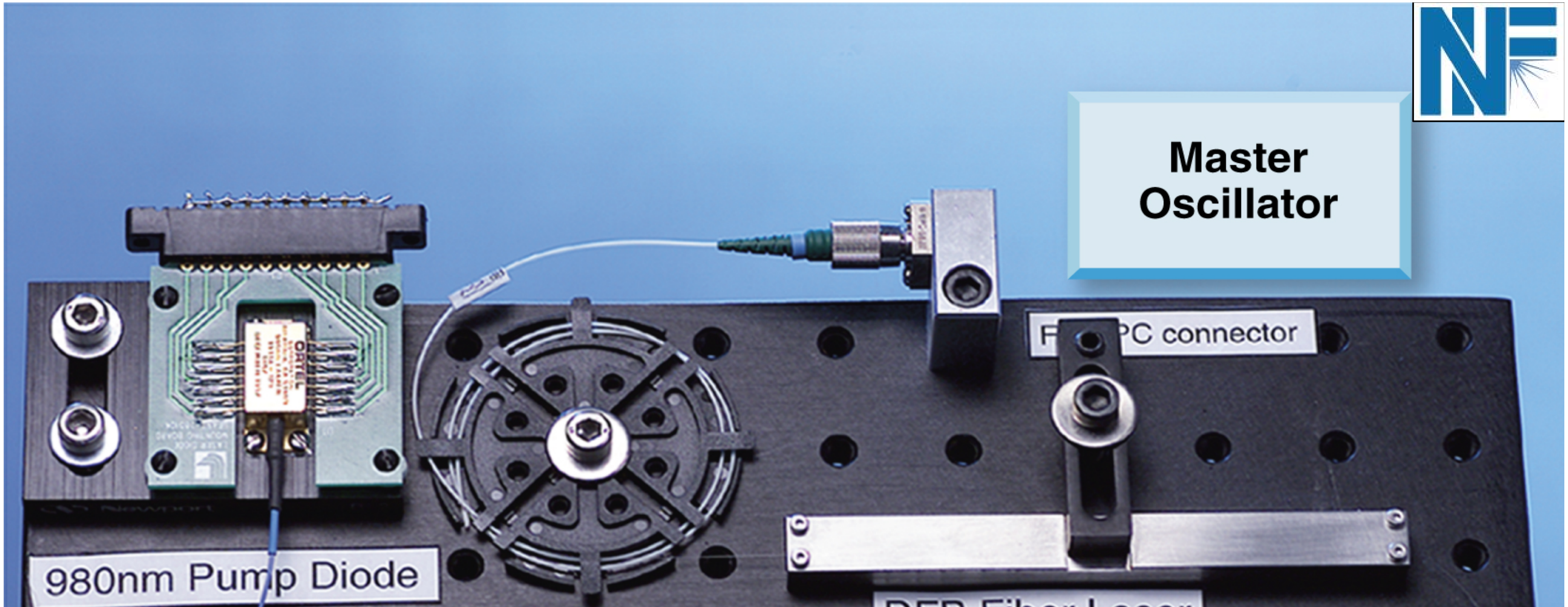
Basic NIF beam elements : Master oscillator, preamplifier, disc amplifier chain, adaptive optic mirror , beam propagation, switchyard and final optics assembly

Designed with Line Replaceable Units (LRU's) = arrays of components

IFE drivers are highly modular

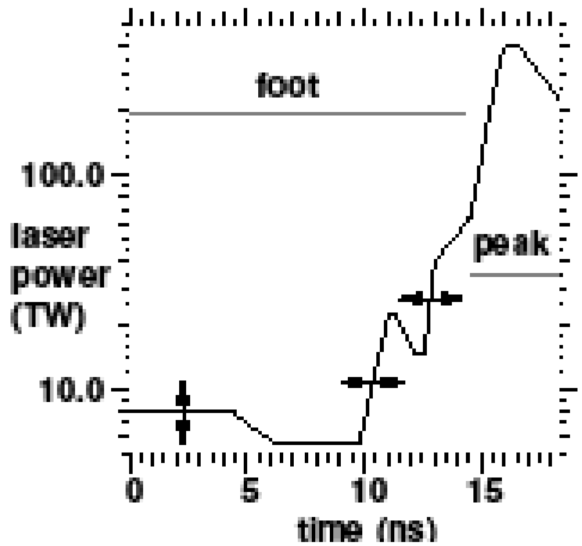


Master Oscillator

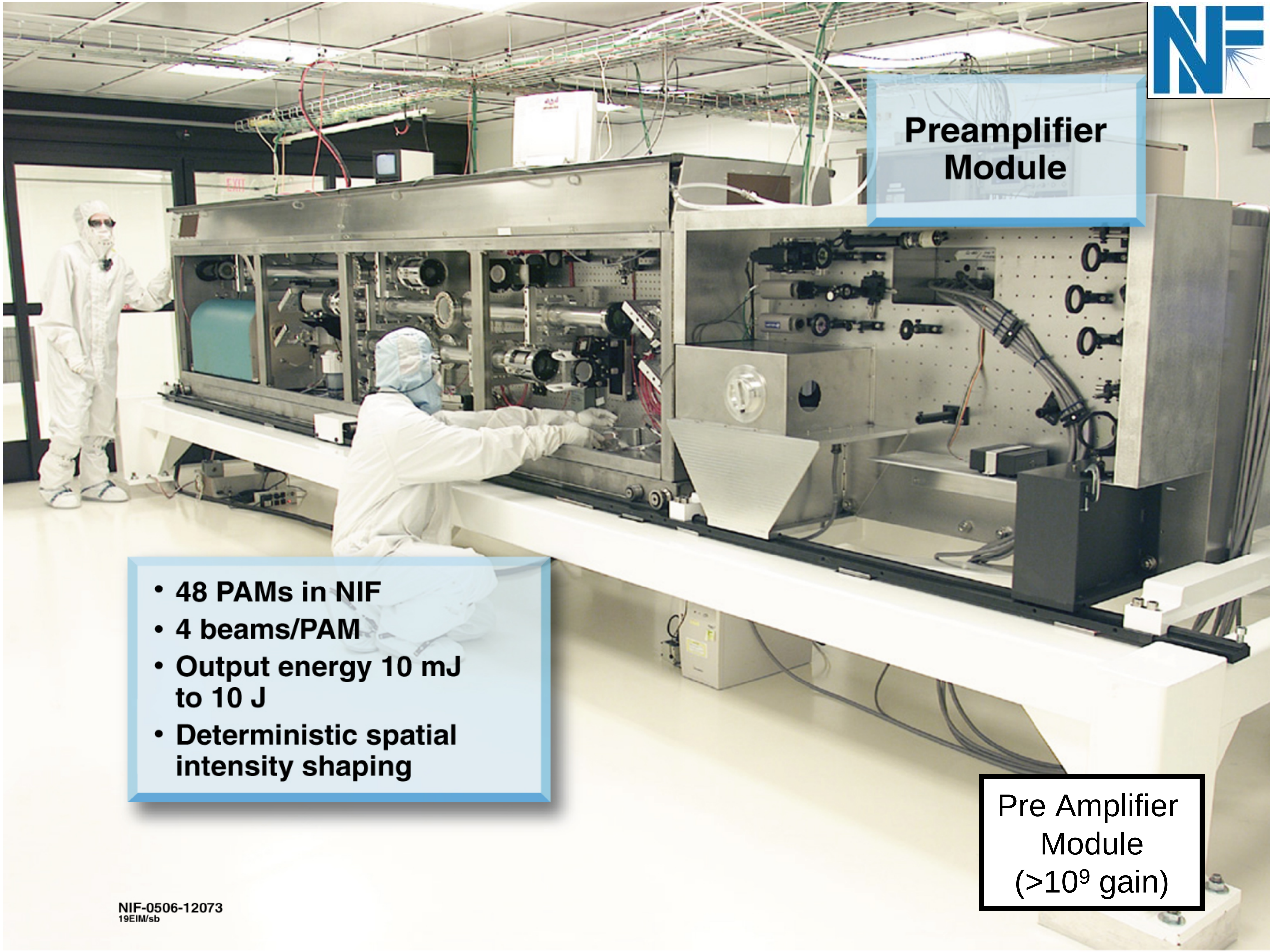


- **Power** **100 mW**
- **Bandwidth** **~10 Hz**
- **Two-color operation**
- **Tunability** **± 5Å**

Pulse shaping is critical



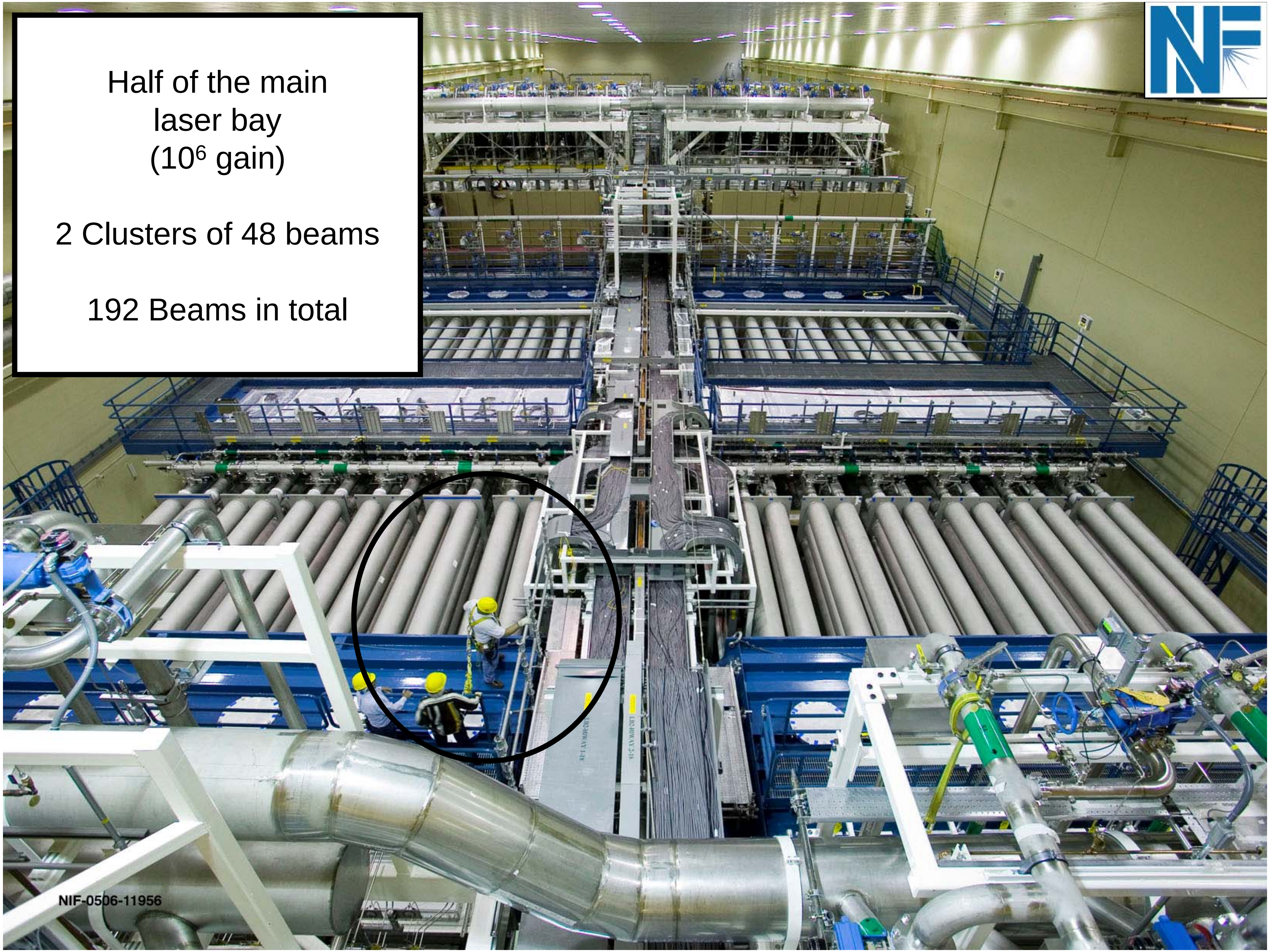
NIF-0506-12079
20EIM/fm

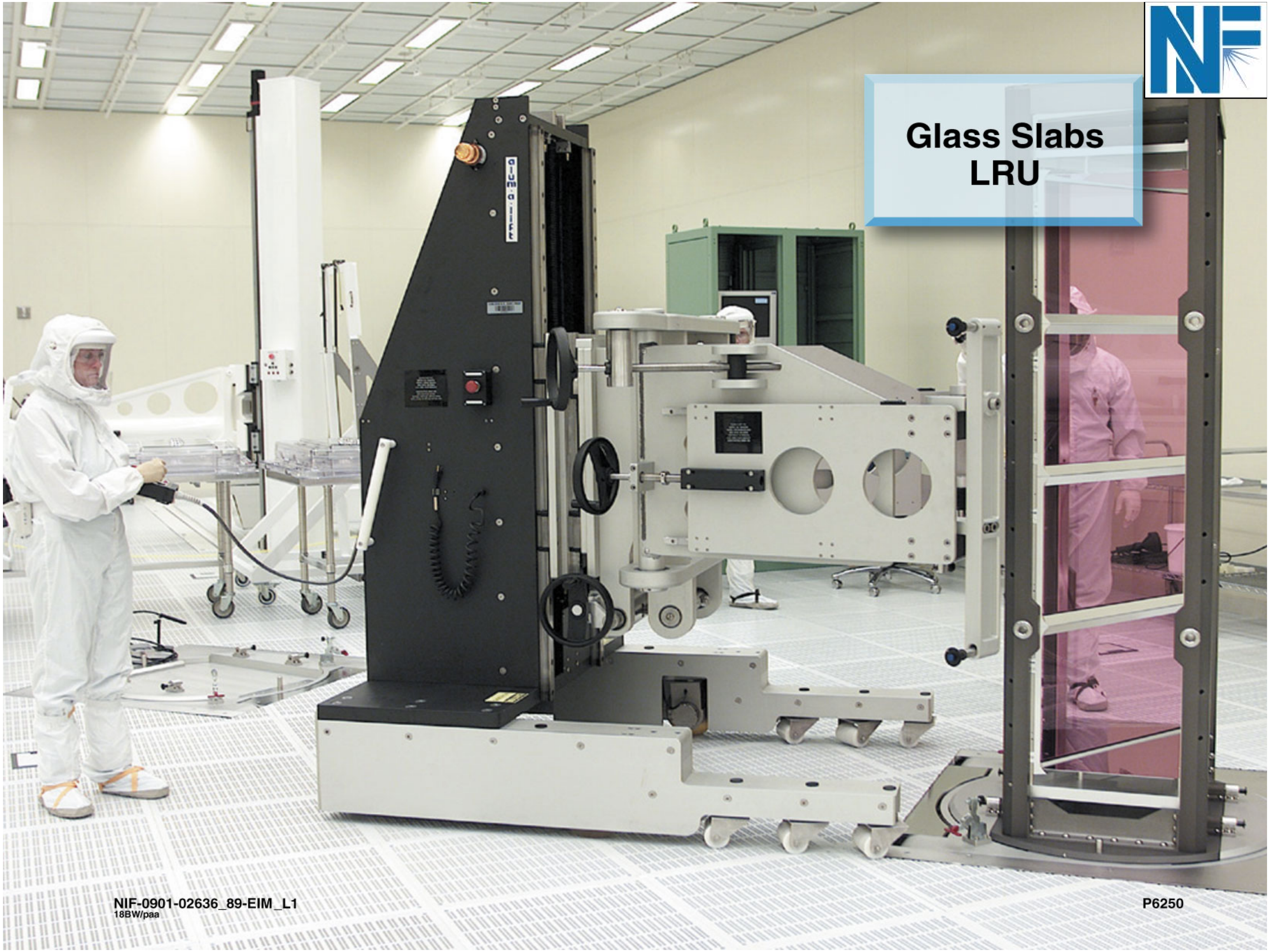

Preamplifier Module
• 48 PAMs in NIF
• 4 beams/PAM
• Output energy 10 mJ to 10 J
• Deterministic spatial intensity shaping
Pre Amplifier Module ($>10^9$ gain)

Half of the main laser bay
(10^6 gain)

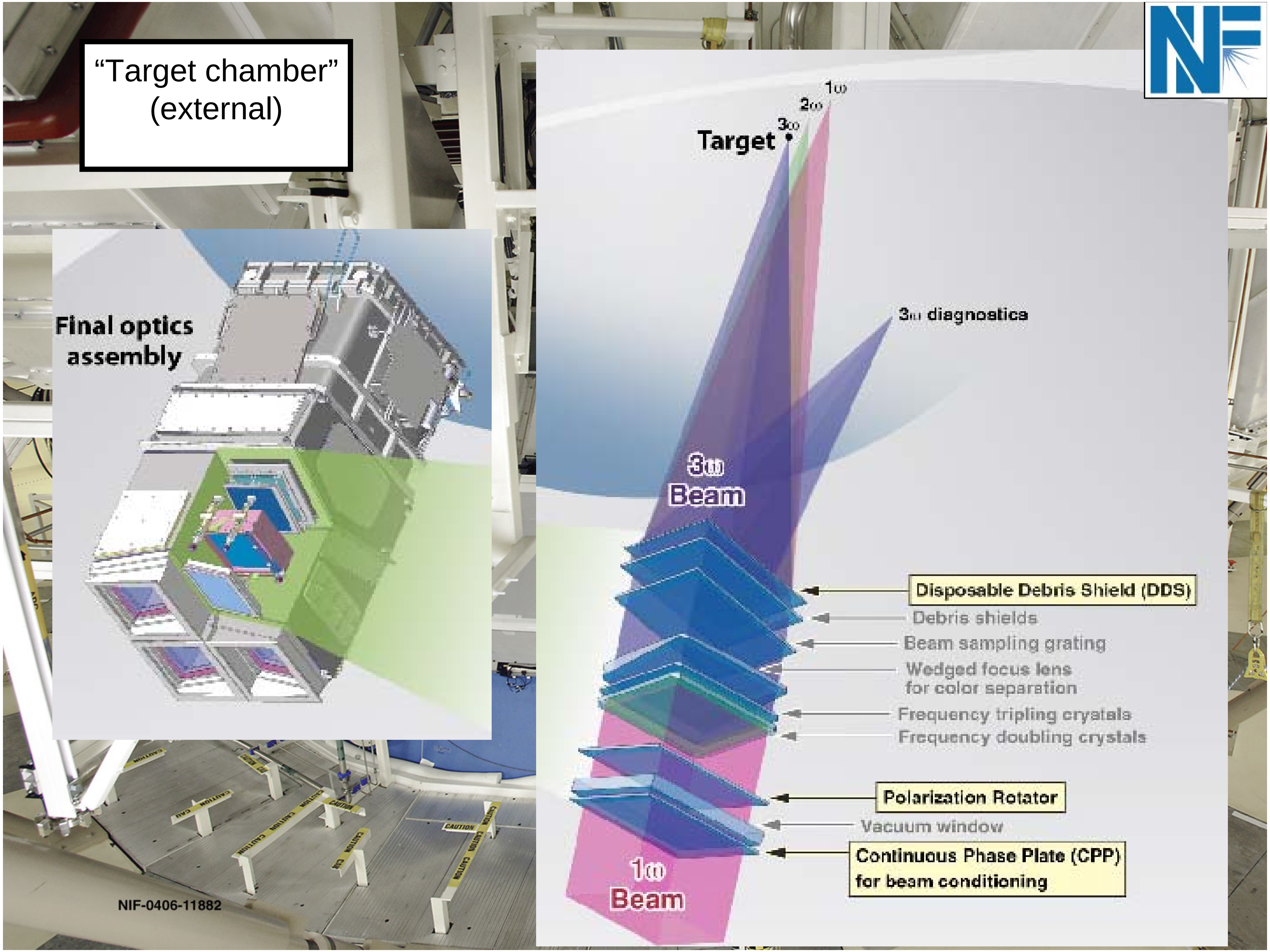
2 Clusters of 48 beams

192 Beams in total

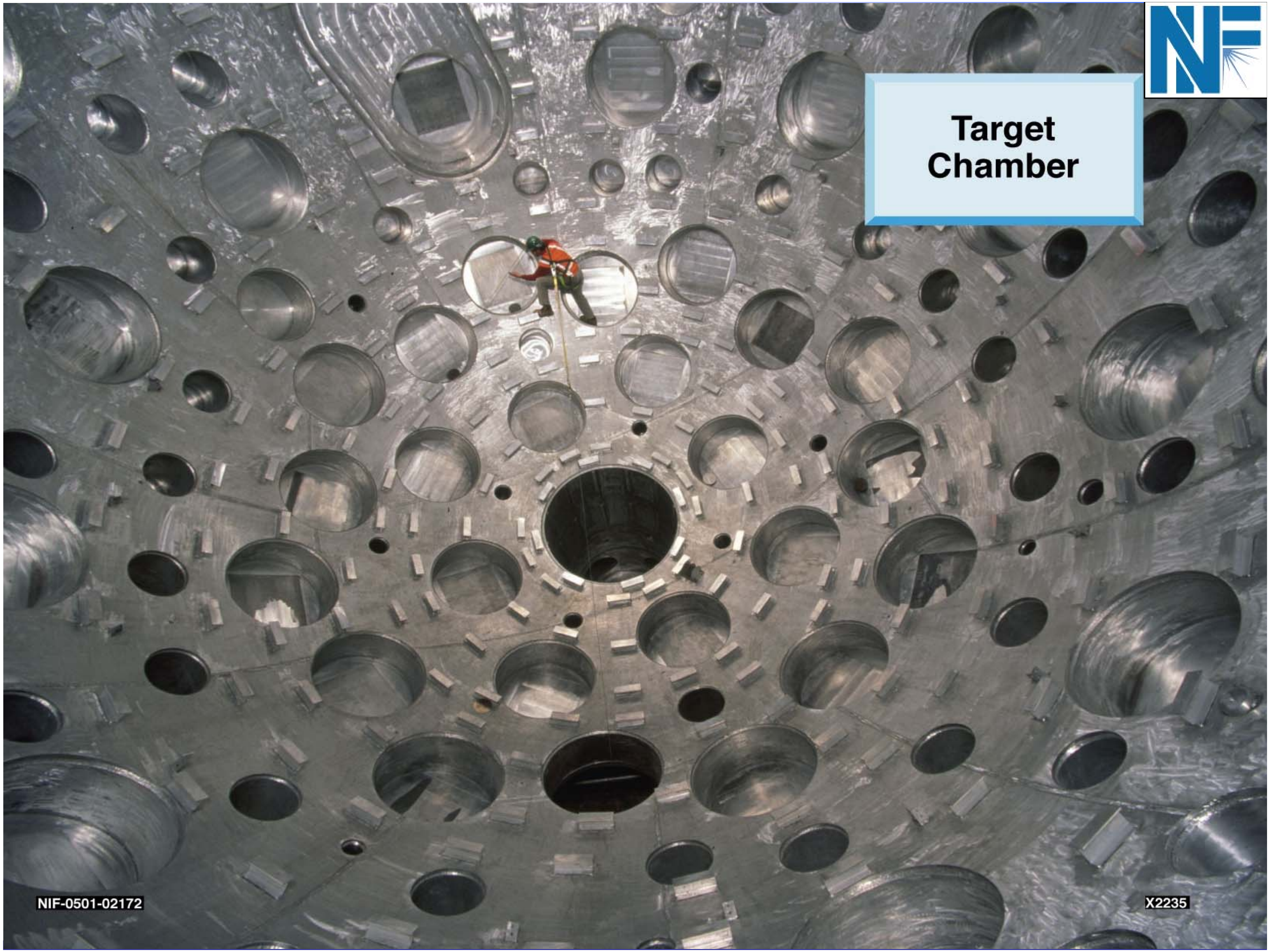



Glass Slabs
LRU
NIF-0901-02636_89-EIM_L1
18BW/paa
P6250

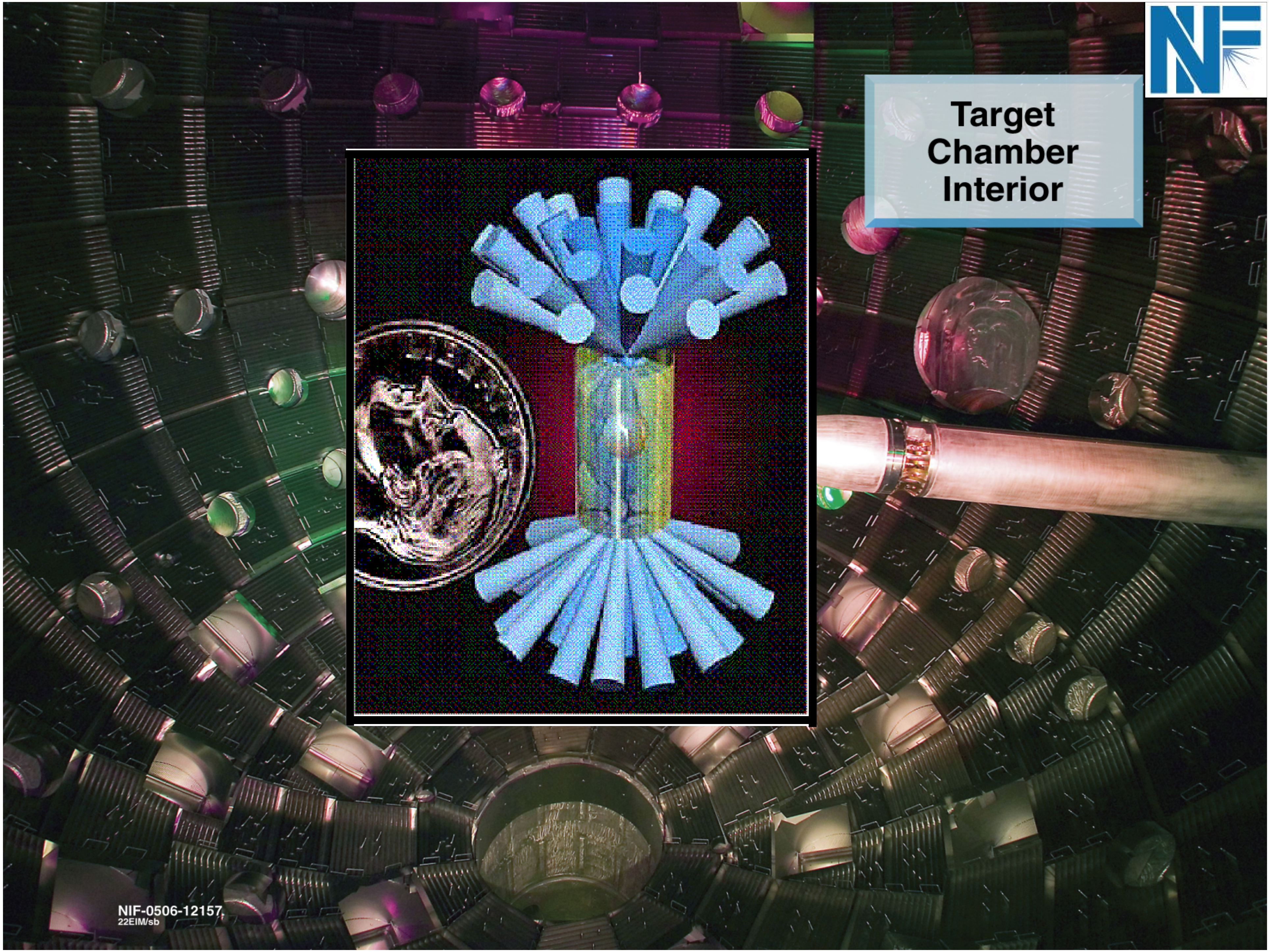

Target
Chamber
NIF-0105-10124
31EIM/dj
P8136


"Target chamber"
(external)
Final optics
assembly
Target
3ω
2ω
1ω
3ω diagnostics
3ω
Beam
Disposable Debris Shield (DDS)
Debris shields
Beam sampling grating
Wedged focus lens
for color separation
Frequency tripling crystals
Frequency doubling crystals
Polarization Rotator
Vacuum window
Continuous Phase Plate (CPP)
for beam conditioning
1ω
Beam
NIF-0406-11882

Target Chamber



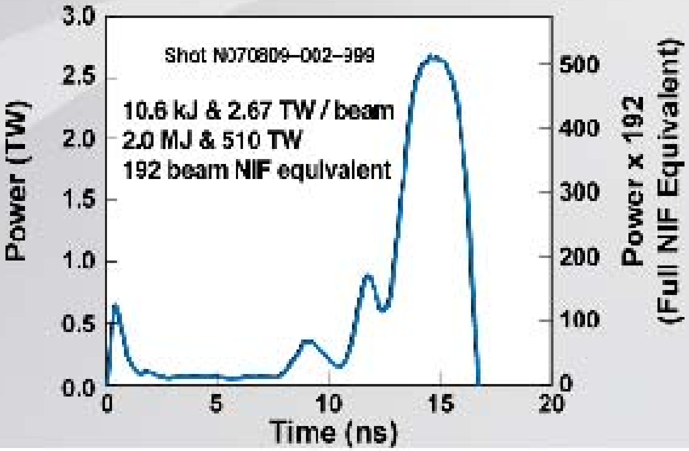
Target Chamber Interior



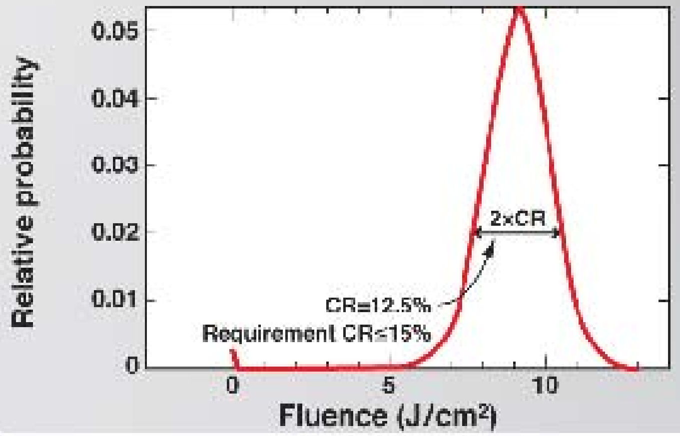
NIF-0506-12157
22EIM/sb

>1.8 MJ ignition point design, energy, power, pulse shape & smoothing were achieved simultaneously on PDS*

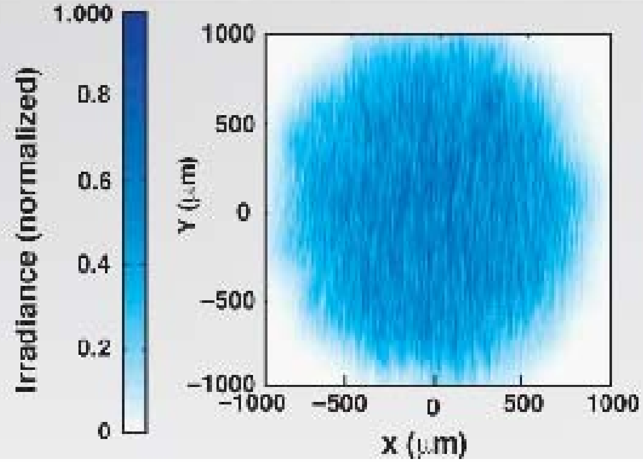
3ω Pulse Shape (2 MJ & 510 TW)



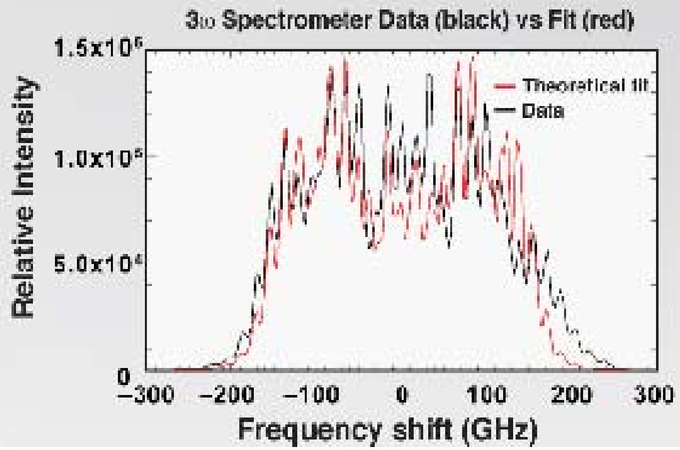
3ω Near Field Fluence Histogram



3ω Focal Spot (1.91 × 1.64 mm²)

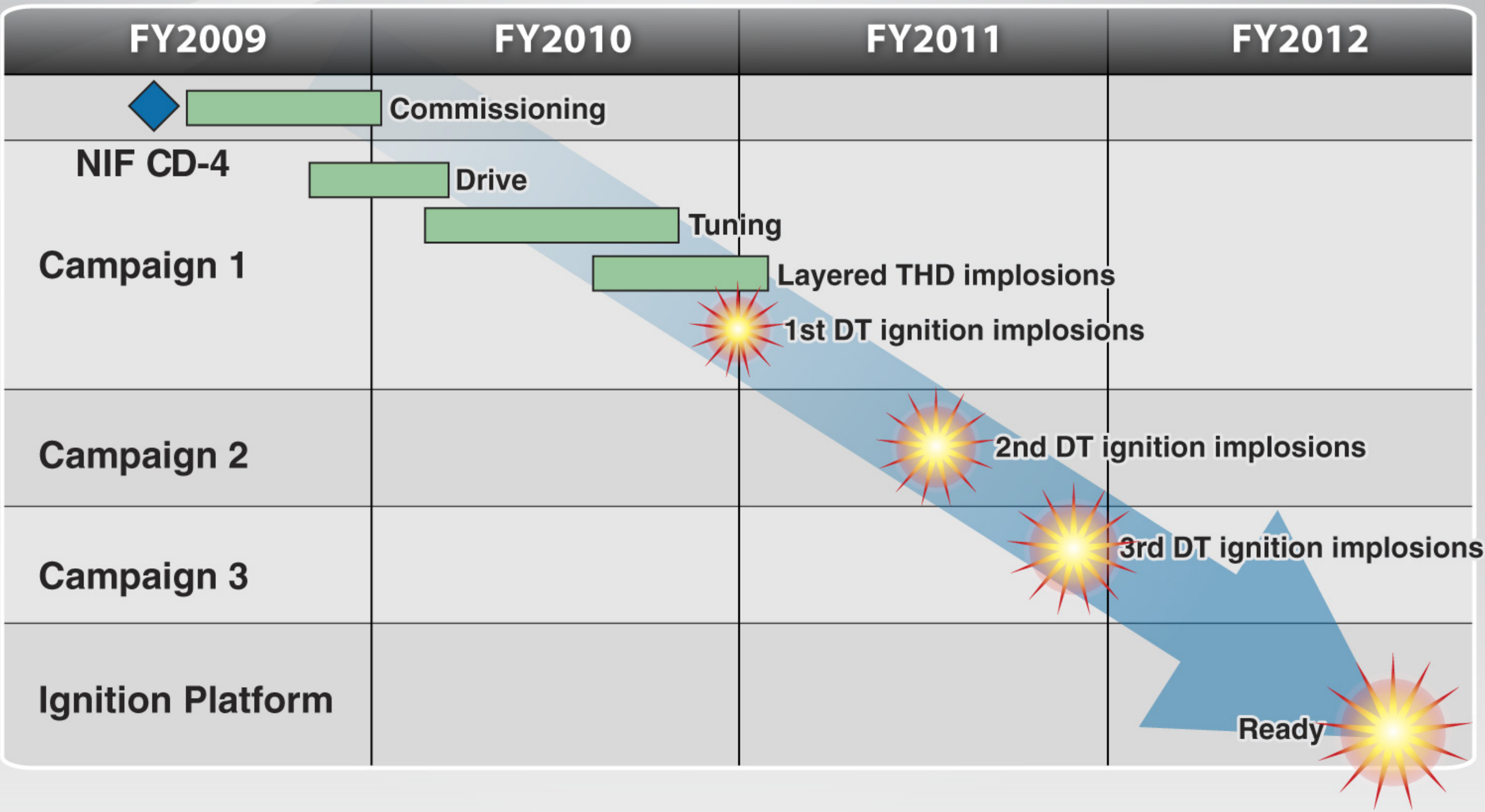


3ω SSD Bandwidth (270 GHz)

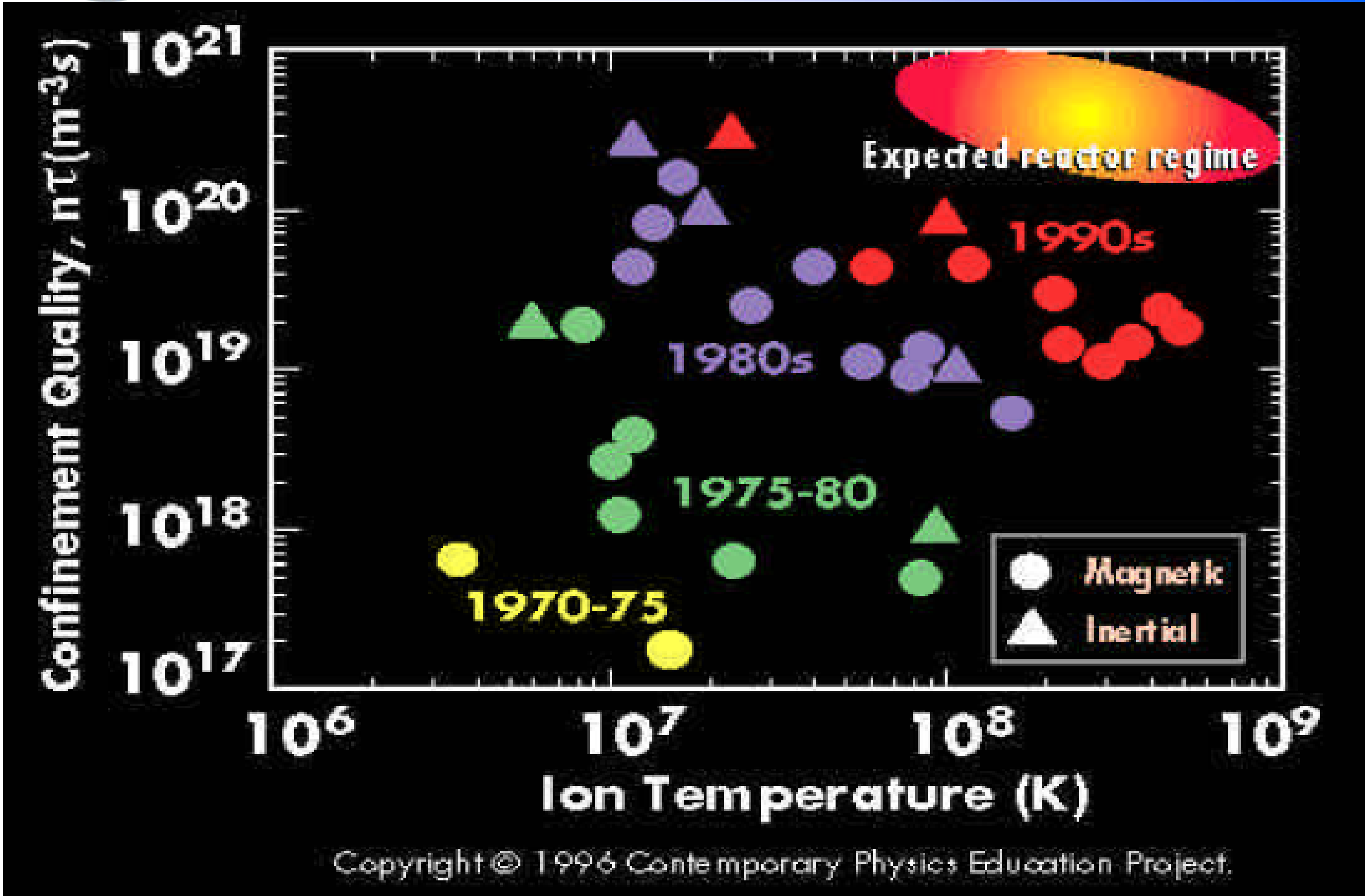


* Precision Diagnostic System

NIF will execute four major ignition campaigns in the next four years



Progress with Fusion



HiPER

What's next ?

- Commitment to fusion via NIF, LMJ (multi-$B investment)
- Inertial Confinement Fusion (ICF) is a demo of physics
- Credible path for future exploitation of laser fusion energy
- Inertial or Laser Fusion Energy (IFE) is a demo of technology

Defining features of the next step:

High repetition rate

Advanced Ignition Scheme

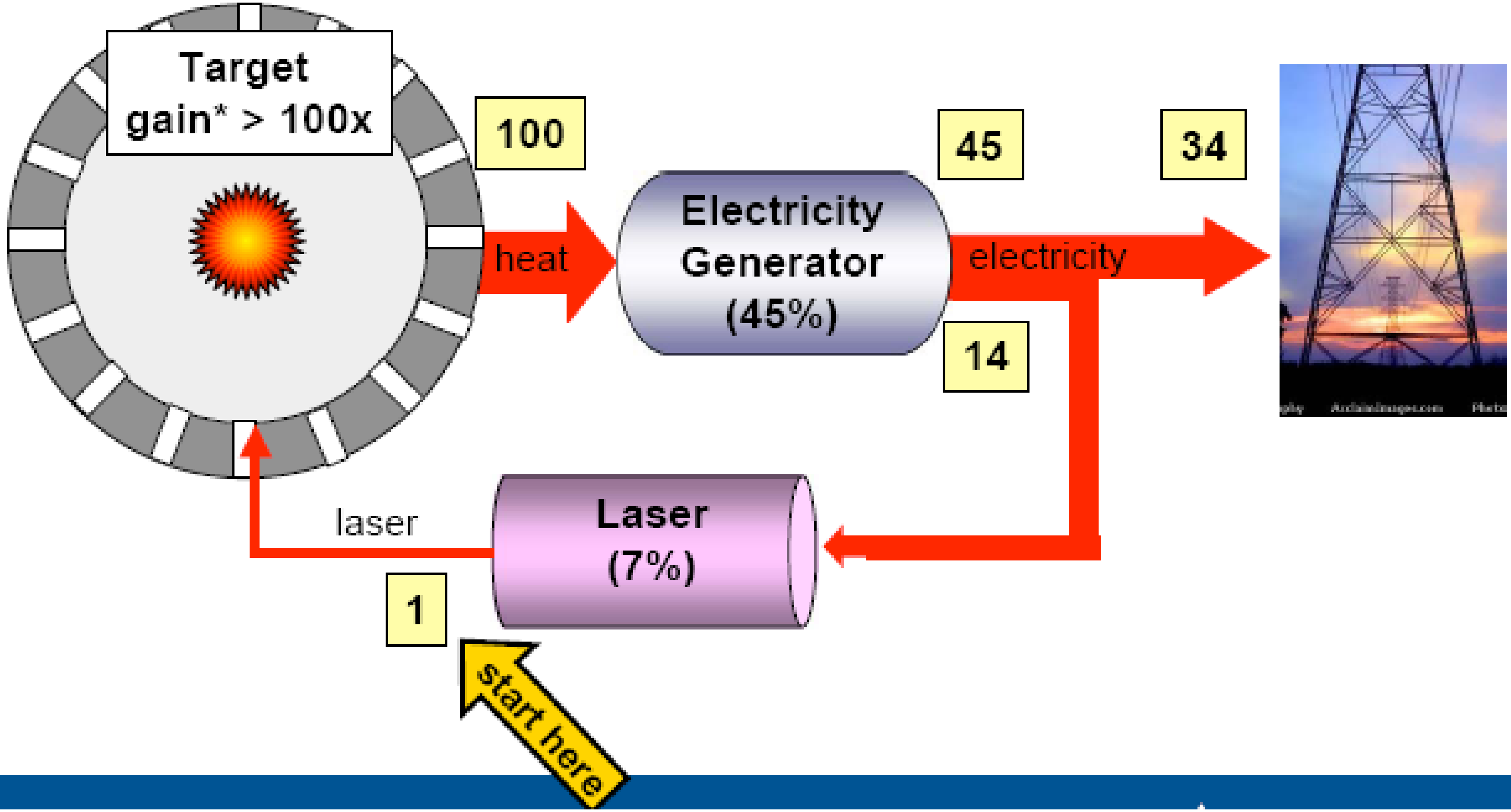
Reduced tolerances on laser

International, collaborative approach

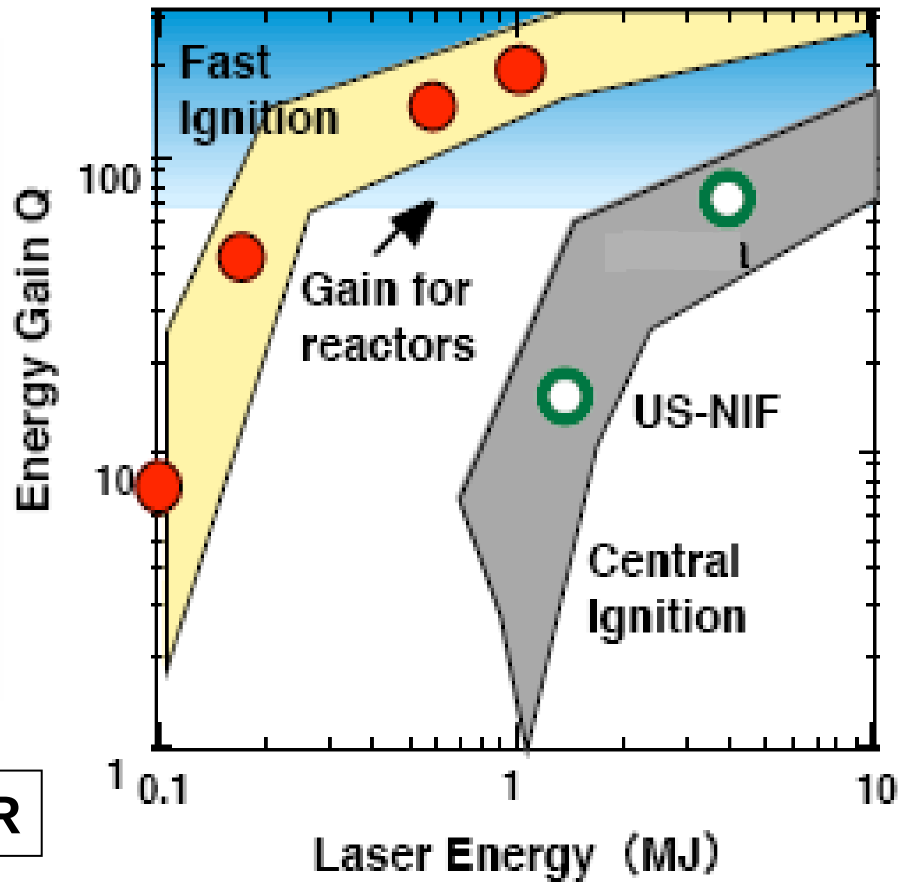
In Europe - HIPER
In America - LIFE
In Japan - LIFT

Fusion power plants need to generate an energy gain > 100

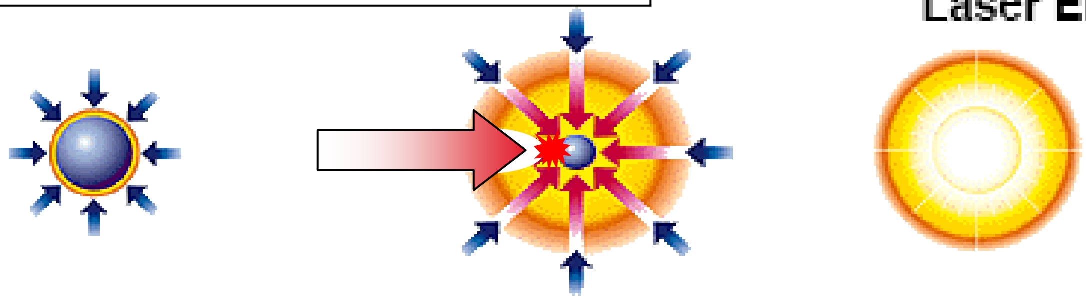
Inertial Fusion Energy (IFE) vs Inertial Confinement Fusion (ICF)
= Average Power, Efficiency, Scale, Simplicity, …



'Fast Ignition' route to reduced scale



One approach advocated by HiPER



Compress **Heat** **Energy output**

European step-HiPER

~500 kJ laser (Fundamental)

- Compression laser 250 kJ, 4ns, 3ω
- Shock Ignition laser 60 kJ, 400 ps, 3ω
- Fast Ignition laser 100kJ, 15ps, 2ω

~5-10 Hz

2.5 -5 MW average power !!

Major Challenge

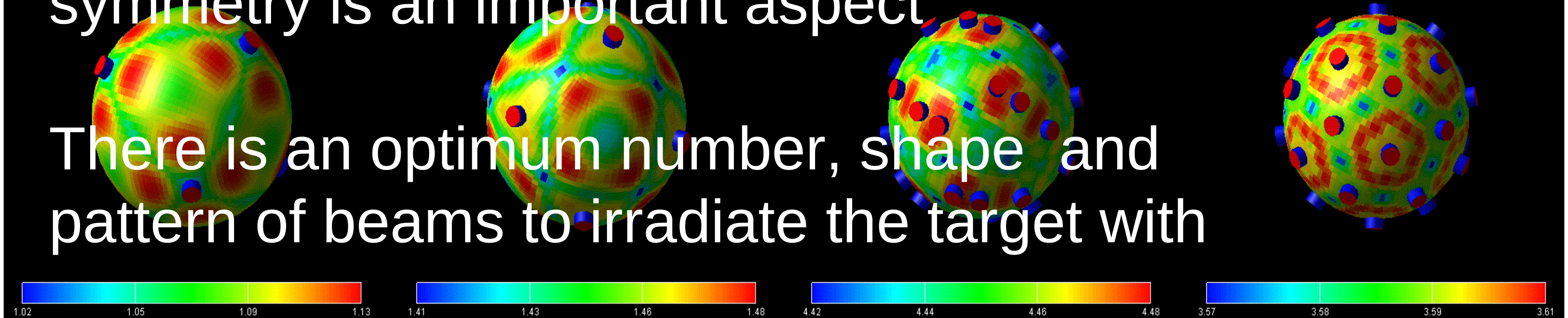
Will require a ~10kJ demonstrator

How? What are some of the issues?

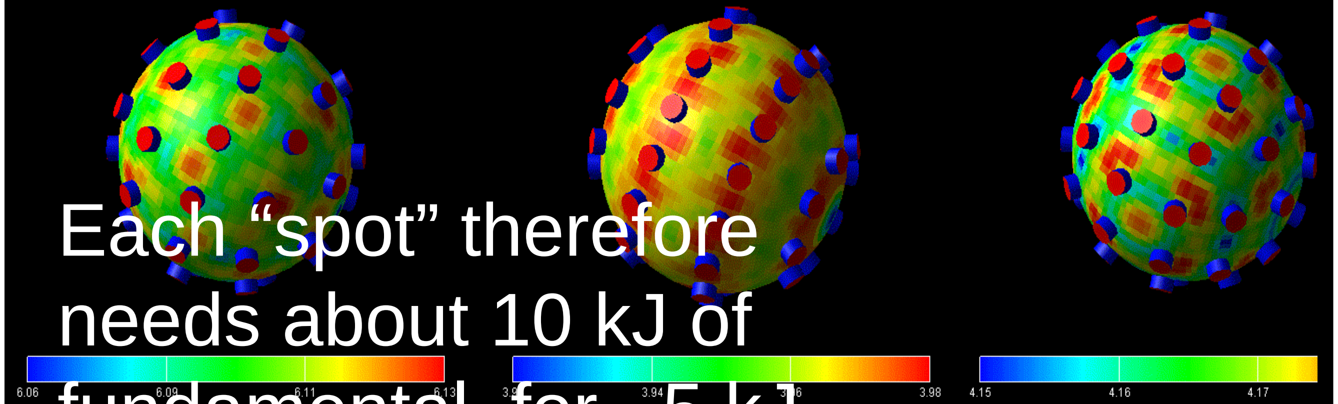
HiPER Beam Irradiation Pattern

In driving the compression phase of the capsule, symmetry is an important aspect

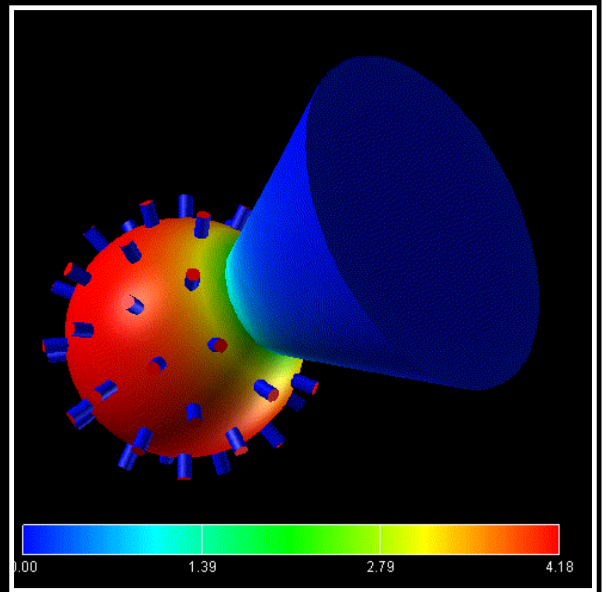
There is an optimum number, shape and pattern of beams to irradiate the target with



250 kJ in 48 beams is optimum

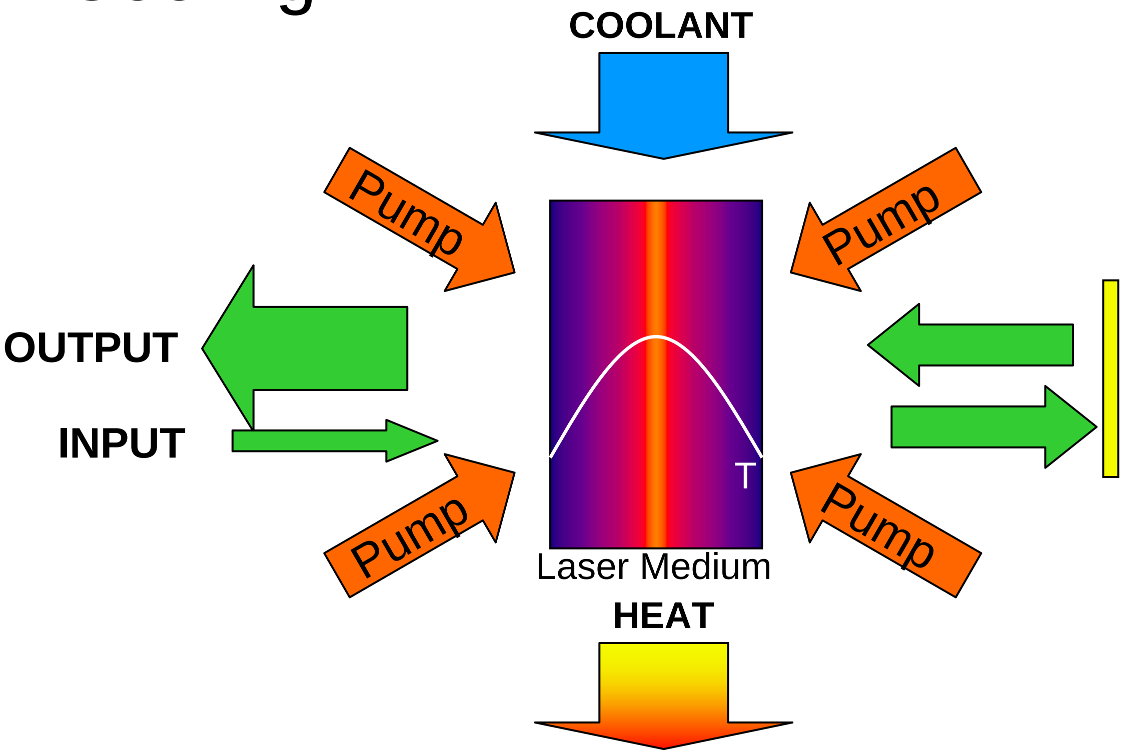


Each "spot" therefore needs about 10 kJ of fundamental, for ~5 kJ of UV



HiPER General Scheme

- Energy provided in beam lines
- 3 Primary issues to be resolved for a beamline
  - Laser Gain Material
  - Laser Pumping Method
  - Cooling



- Assume ~ 10 kJ per SPOT
- 1 SPOT – 1 BEAMLINE
- 10 Hz operation

HiPER Laser Pumping Method - DPSSL

Grid

Current Pulse ~1s

Capacitor

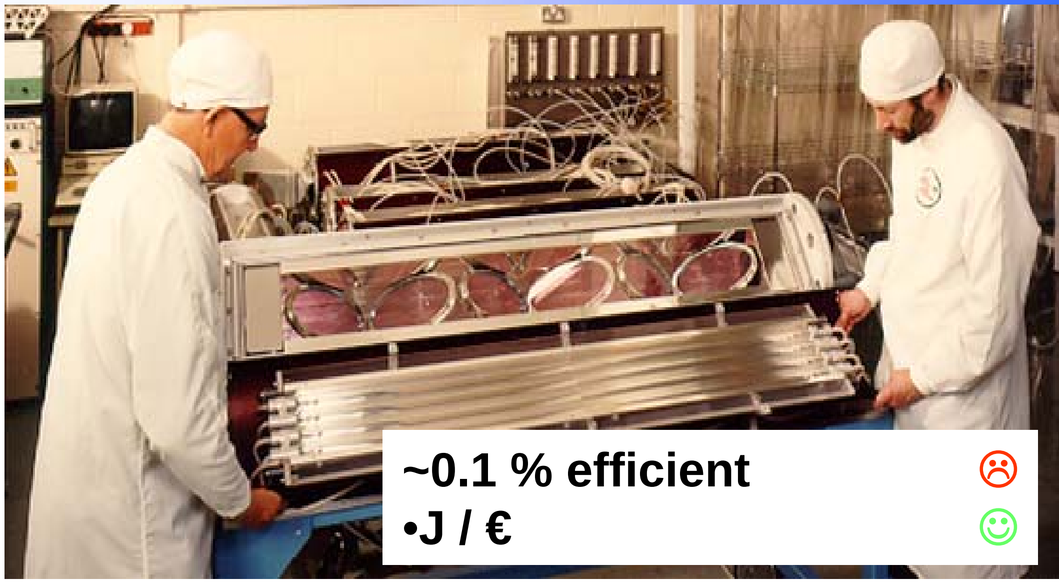
Current Pulse ~1ms

Lamp/Diode

Light Pulse ~1ms

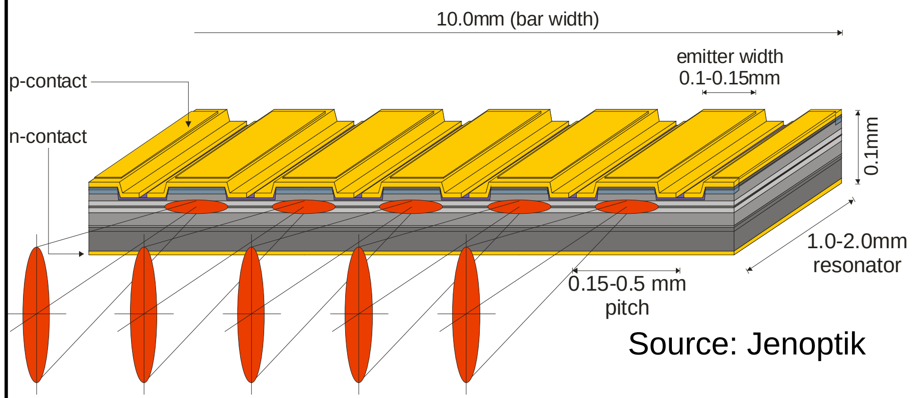
Gain Material

Laser Pulse ~3ns



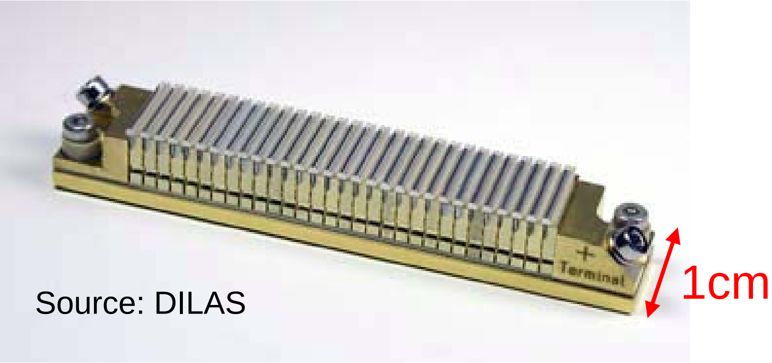
Diodes - Current Stat of the Art

Elementary building block: **Bar**
Monolithic, epitaxially grown
Has 10s of single emitters



Source: Jenoptik

Bars assembled into **Stacks**
Up to 30 bars par Stack



Source: DILAS

Properties (comment for IFE) :

☺ Narrow spectrum (~3nm)
☺ High e-o efficiency (> 50%) – **NOT REALLY ENOUGH**
☺ Long lifetime (~1Gshot) – **DEFINITELY NOT ENOUGH**
☺ High(ish) brightness, compact –
☹ Not cheap today

HiPER Arrays of Stacks

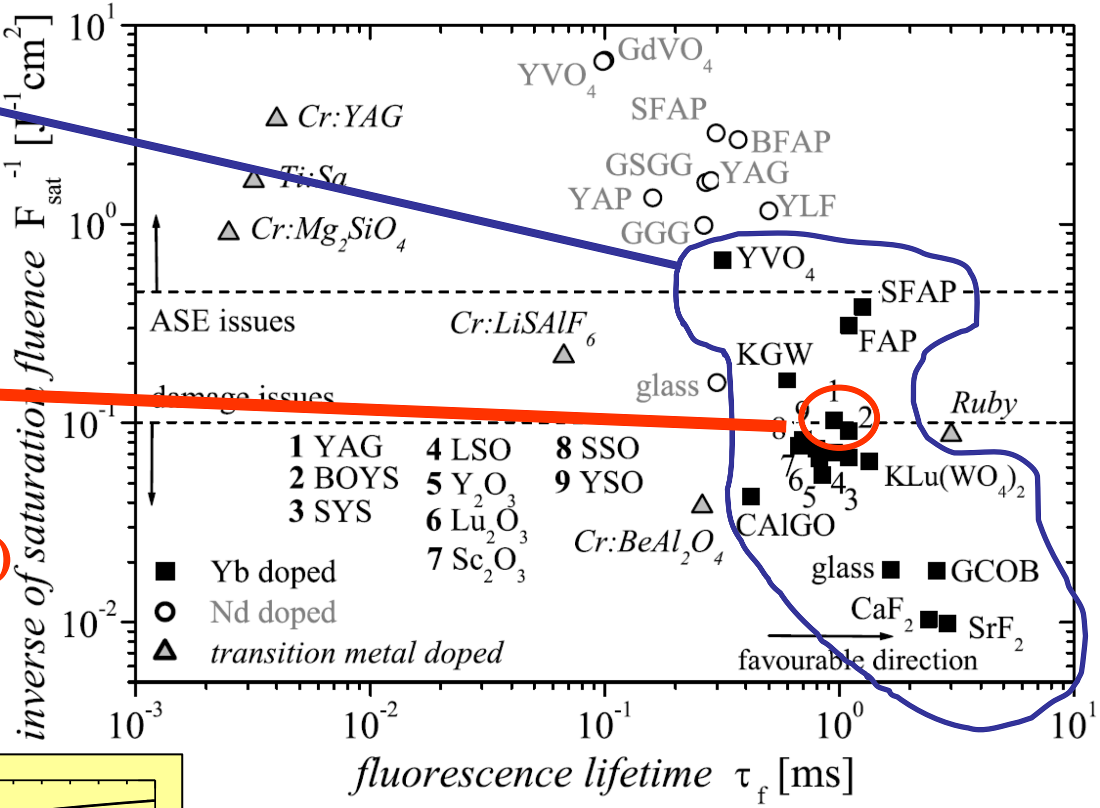
- Multiple EU manufactures of stacks and bars
- Stacks have been arranged into arrays
- Complex, time consuming and labour intensive

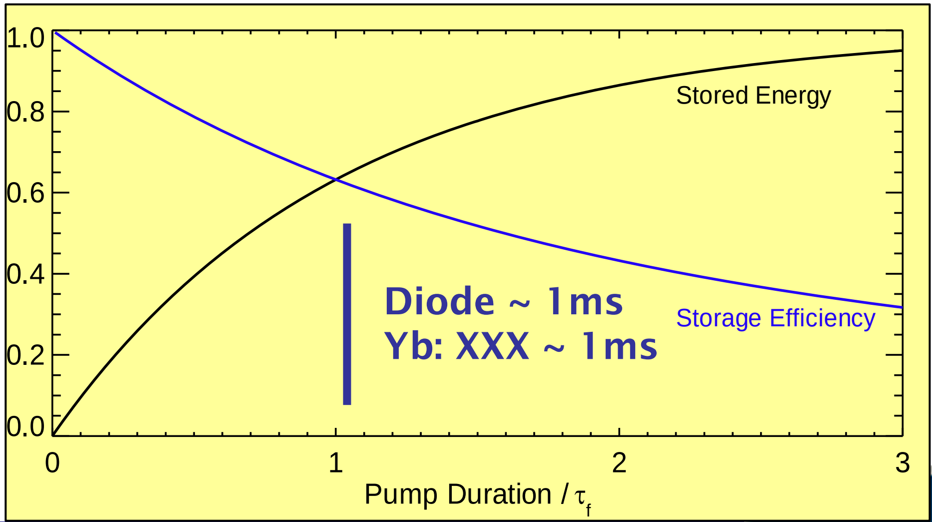
- <u>1 BEAMLINE example</u>
- For 40x40cm^2 at 10 kWcm^{-2}
- Requires ~20 MW of diode pump light
- Equal to 8000 stacks @ 2.5kW
- Equivalent to ~100 *Lucia* Panels

HiPER Available DPSSL Materials

Yb doped materials
Long lifetimes
Well suited to QCW diodes
Low Quantum defect

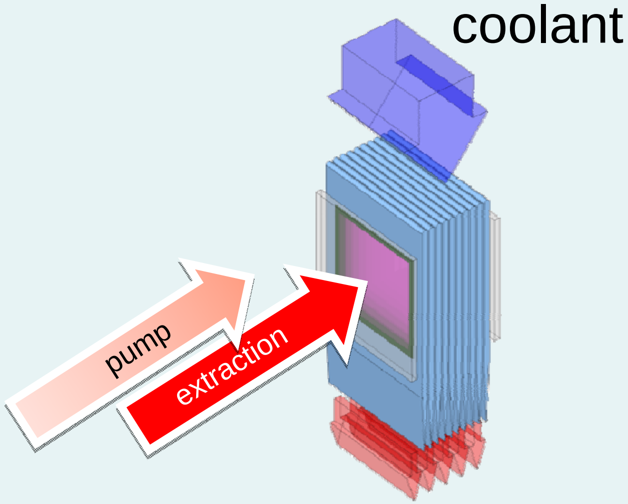
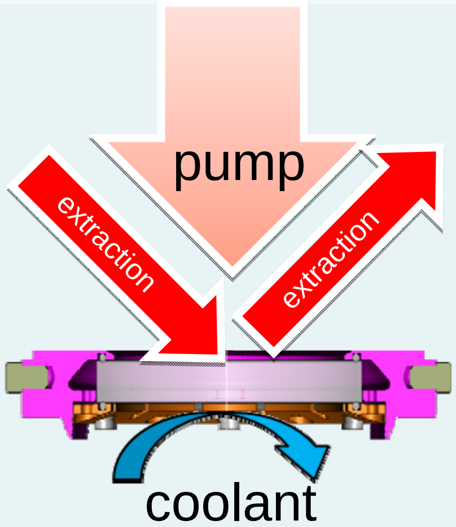
Yb:YAG
Crystals availabe (cm's)
Cubic Material - scaleable
Ceramics – availabe (10+ cm)





Q. How best to implement ?

Demonstration

IOQ, Germany	STFC, UK	CNRS, France	CEA, France
seit 1558			
CaF_2	YAG		Glass
Gas cooled plates		Active mirror	fibre
			

HiPER Yb:YAG Ceramic Gain Medium

- Needs good thermo-mechanical properties ➔ crystal
- Need large sizes ➔ glass
- Ceramics combine best of both
- Can be made with optical quality

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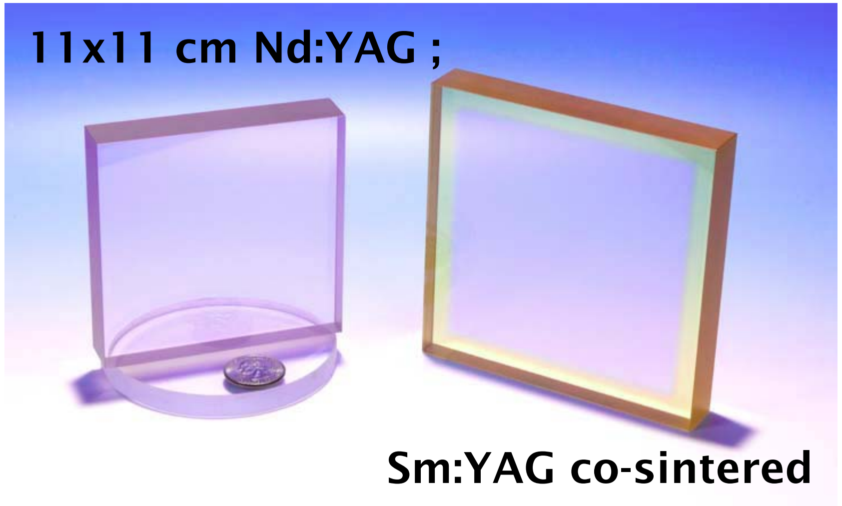
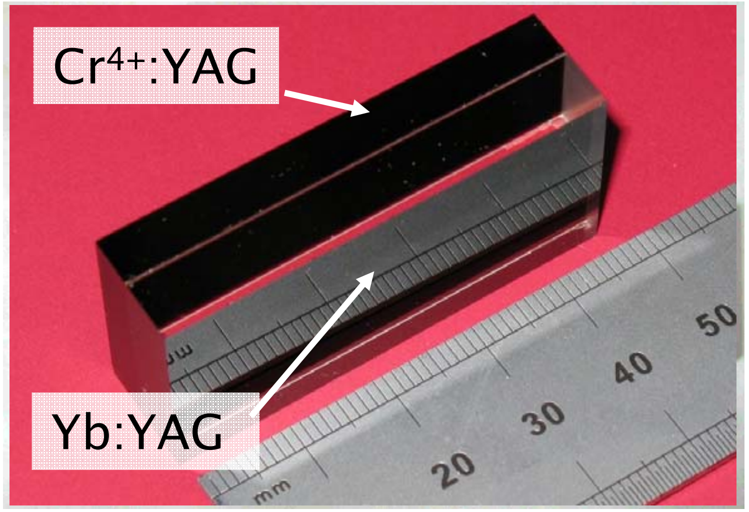
MF1.pdf

New Generation of Laser Ceramics with Anisotropic Materials

J.Akiyama, Y. Sato and T. Taira

Laser Research Center for Molecular Science, Institute for Molecular Science, 38 Nishigonaka, Myodaiji, Okazaki 444-8585, Japan
Phone:81-564-55-7246, Fax: 81-564-53-5727,
e-mail:akiyama@ims.ac.jp, yoichi@ims.ac.jp, taira@ims.ac.jp

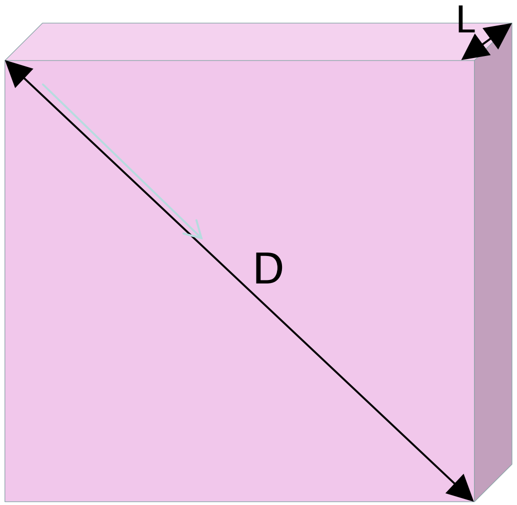




- 1 kJ per beam would require ~ 15 x 15 cm aperture slabs
- Feasible - 11 cm available now – scaleable to larger
- 10 kJ requires 40 x 40 cm – possible in principle
- Co-sintered cladding possible & variable doping
- Non-cubic demonstrated

HiPER Longitudinally Variable Doping

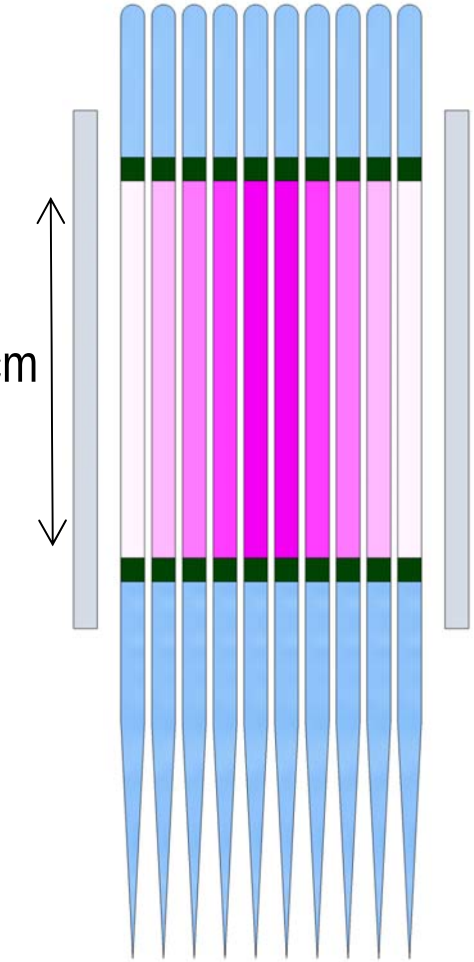
- **Doping of each slab is different**
- **Slabs in centre more highly doped**
- **Pseudo-constant longitudinal pumping and gain**
- **Excellent Transverse ASE control**



Longitudinal gain (useful): $G_{lon} = \exp\left(2\int g \, \mathrm{d}l\right)$

Transverse gain (ASE loss): $\exp(g_{\max} D)$

Rule of thumb: $g_{\max} D < 3$

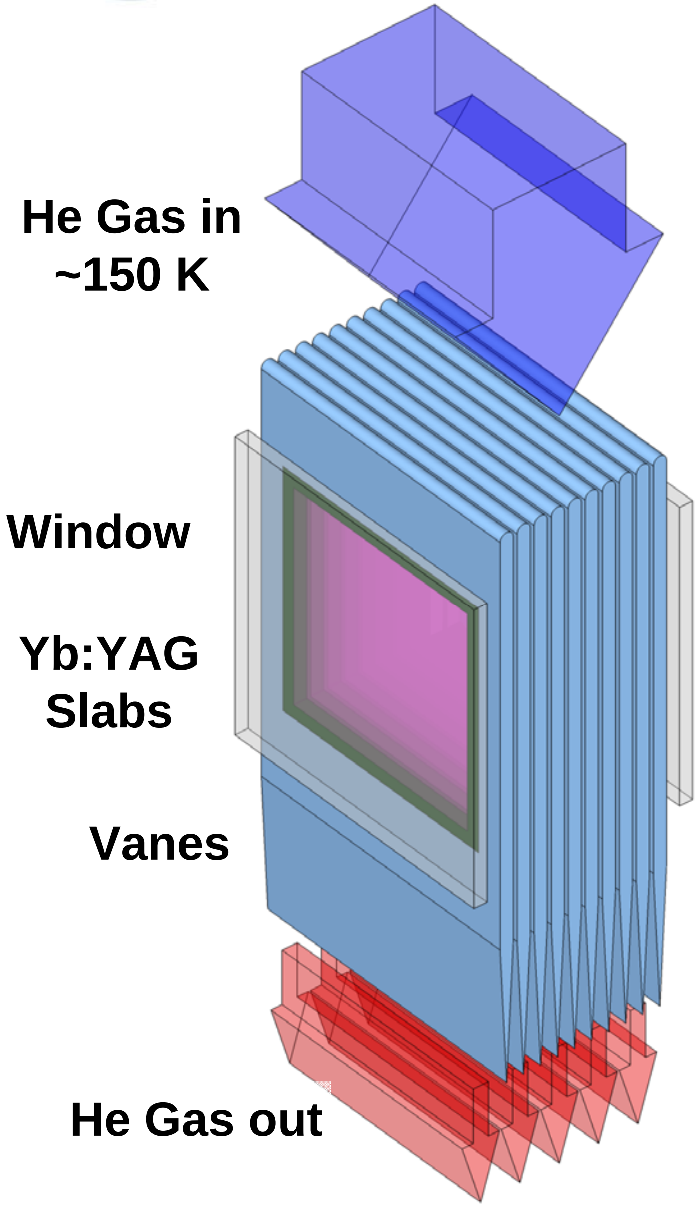


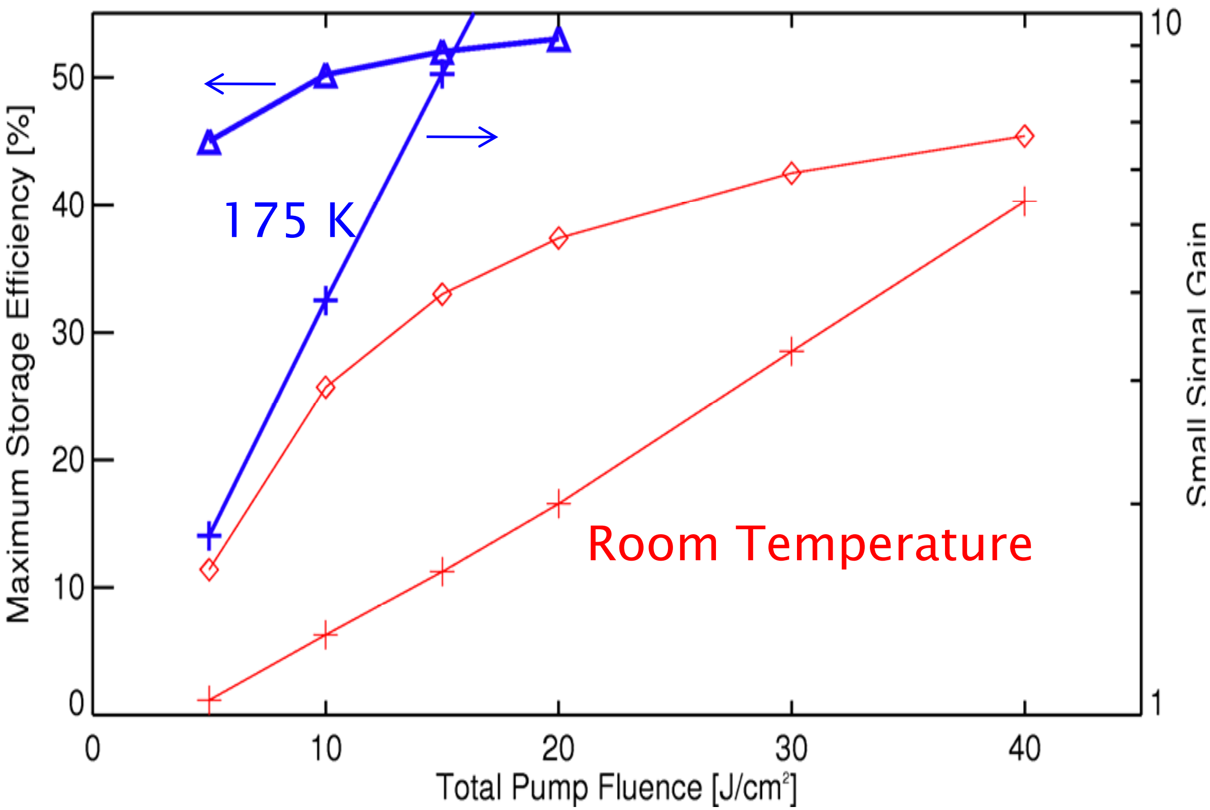
➔ For given G_{lon}, aspect ratio D/L is limited

➔ For thin disc essentially limits the maximum aperture

➔ Must retain ability to cool

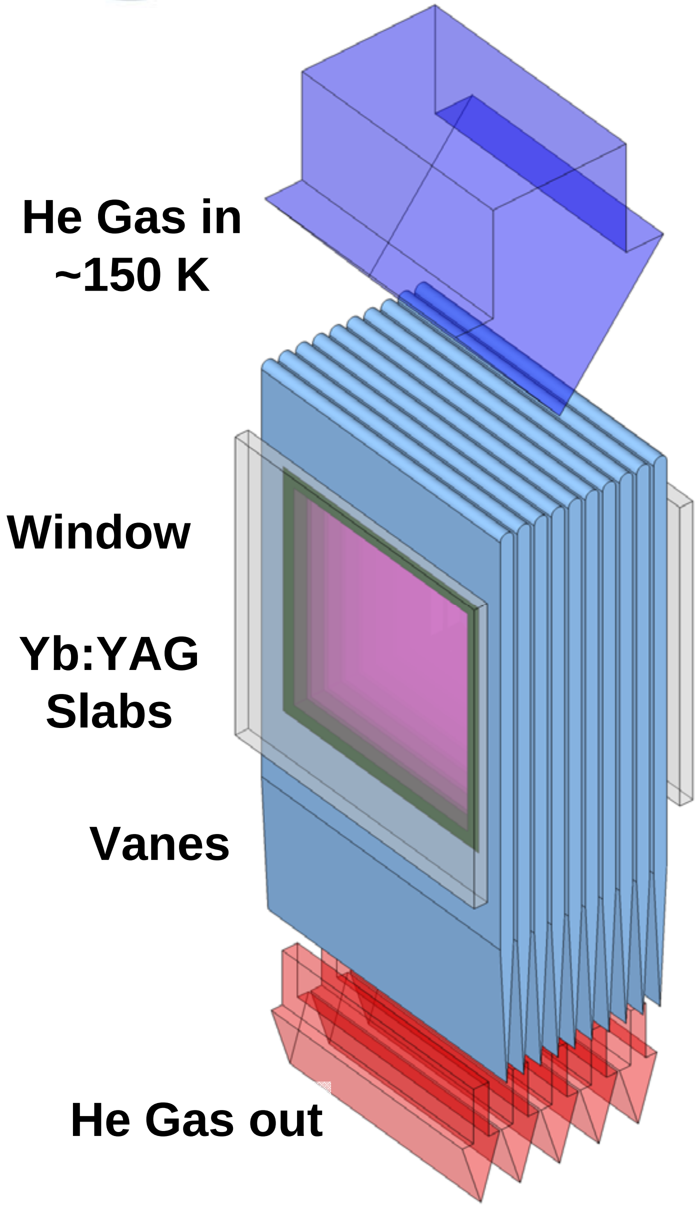
HiPER Heat Management I





· **Rutherford concept "*DIPOLE*" – others also under development**
· **Experimental programme underway**

Heat Management I



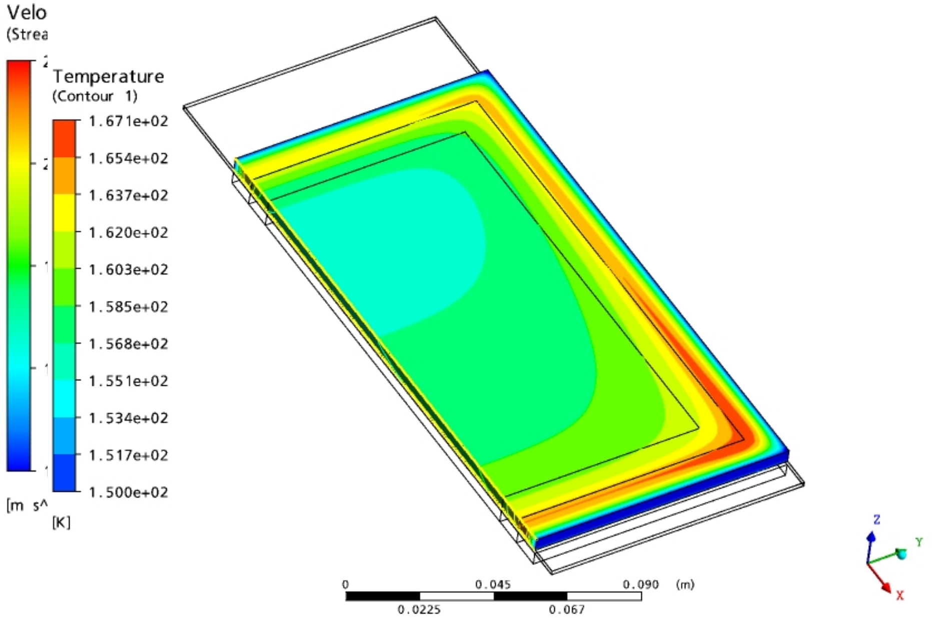
- Rutherford concept "*DIPOLE*" – others also under development
- Experimental programme underway

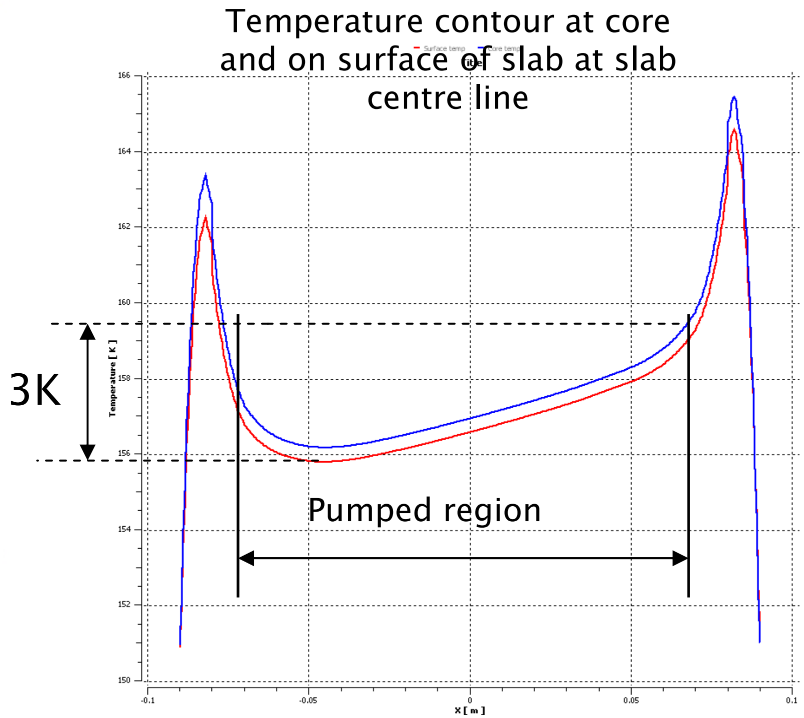
Heat Management II

STFC Computational Fluid Dynamics modelling

Cladded YAG – edges of slab held at 150K - Conjugate Heat Transfer (CHT)

YAG surface temperature contours

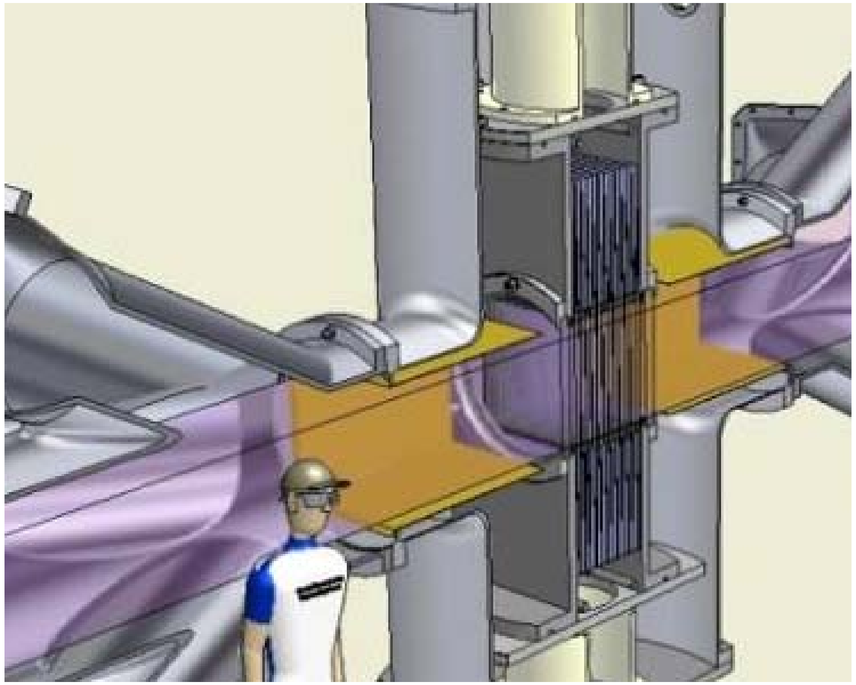


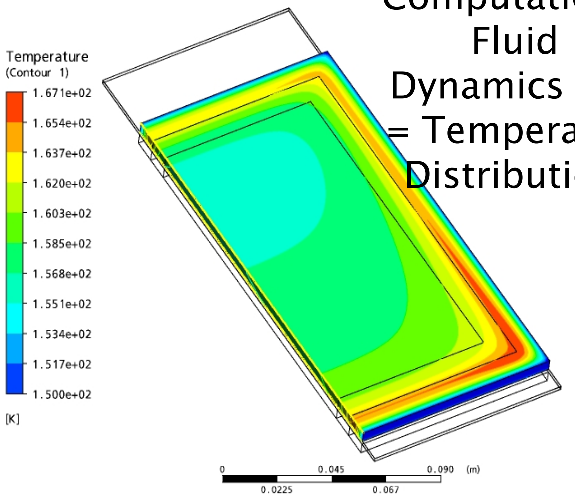


Temperature jump per pulse :
in absorber = 0.73K
in pumped region 0.05K

- Experimental Programme underway on this concept
- Tests at the few cm scale (~10J) underway

Concept Beamline

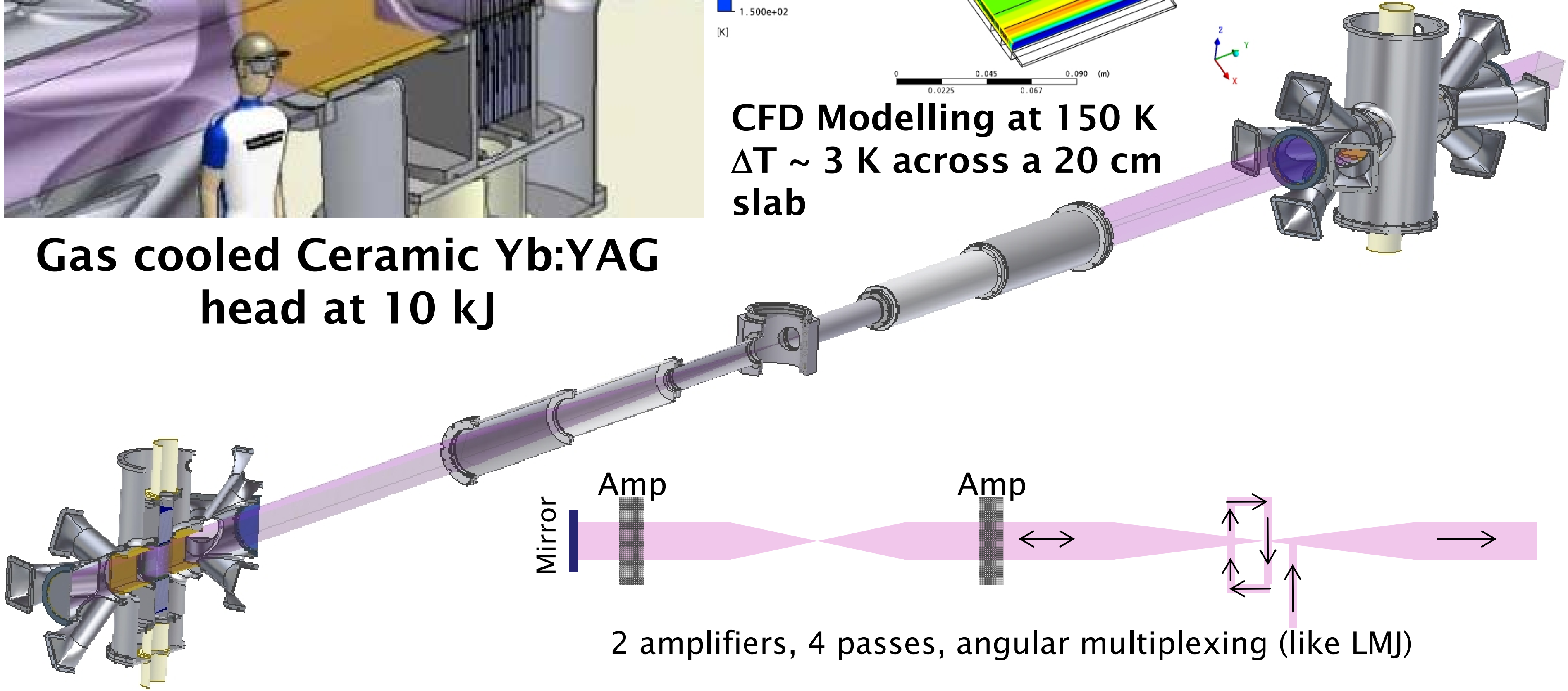




Computational Fluid Dynamics (TD) = Temperature Distributions

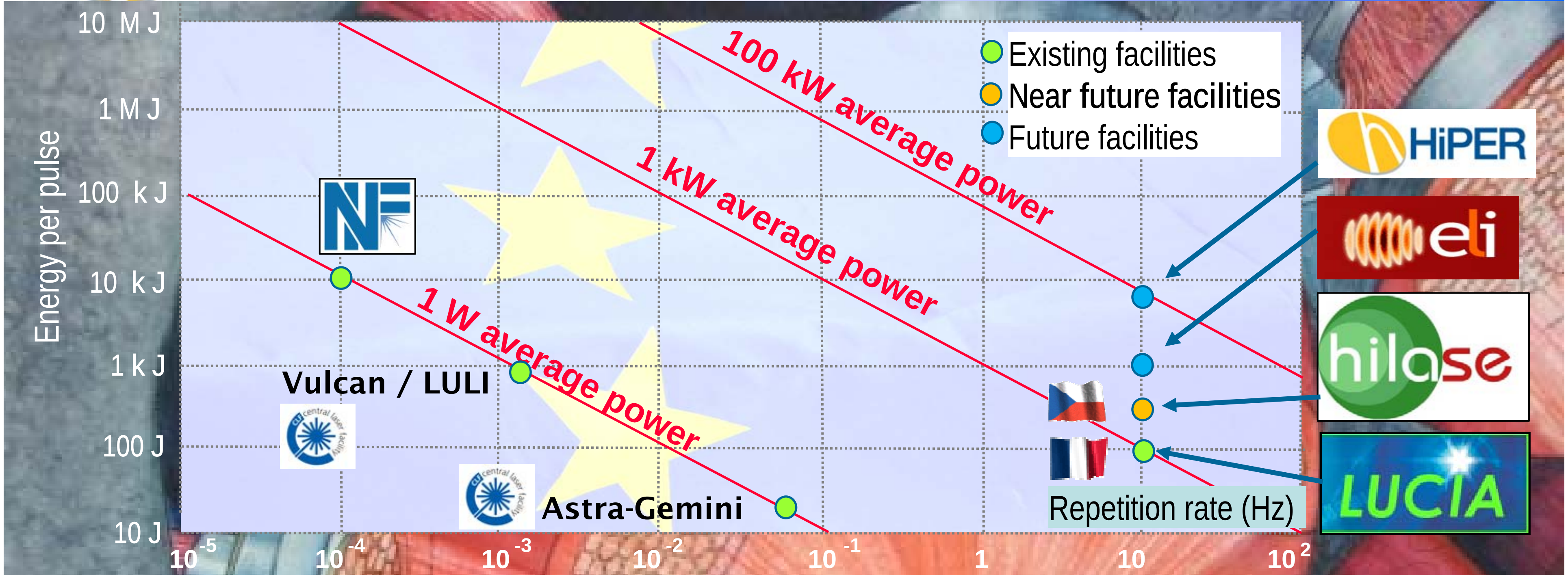
CFD Modelling at 150 K
ΔT ~ 3 K across a 20 cm slab

Gas cooled Ceramic Yb:YAG head at 10 kJ



2 amplifiers, 4 passes, angular multiplexing (like LMJ)

DPSSL Technology Context

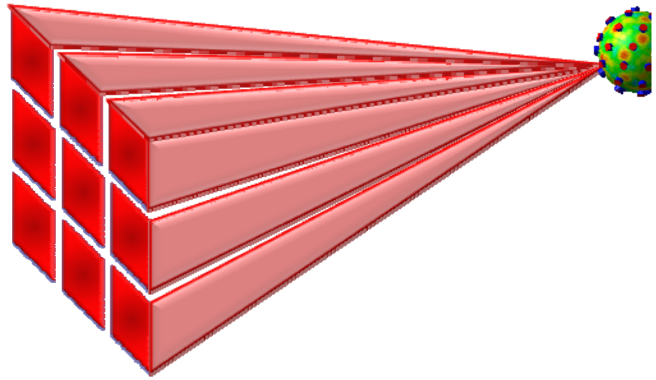


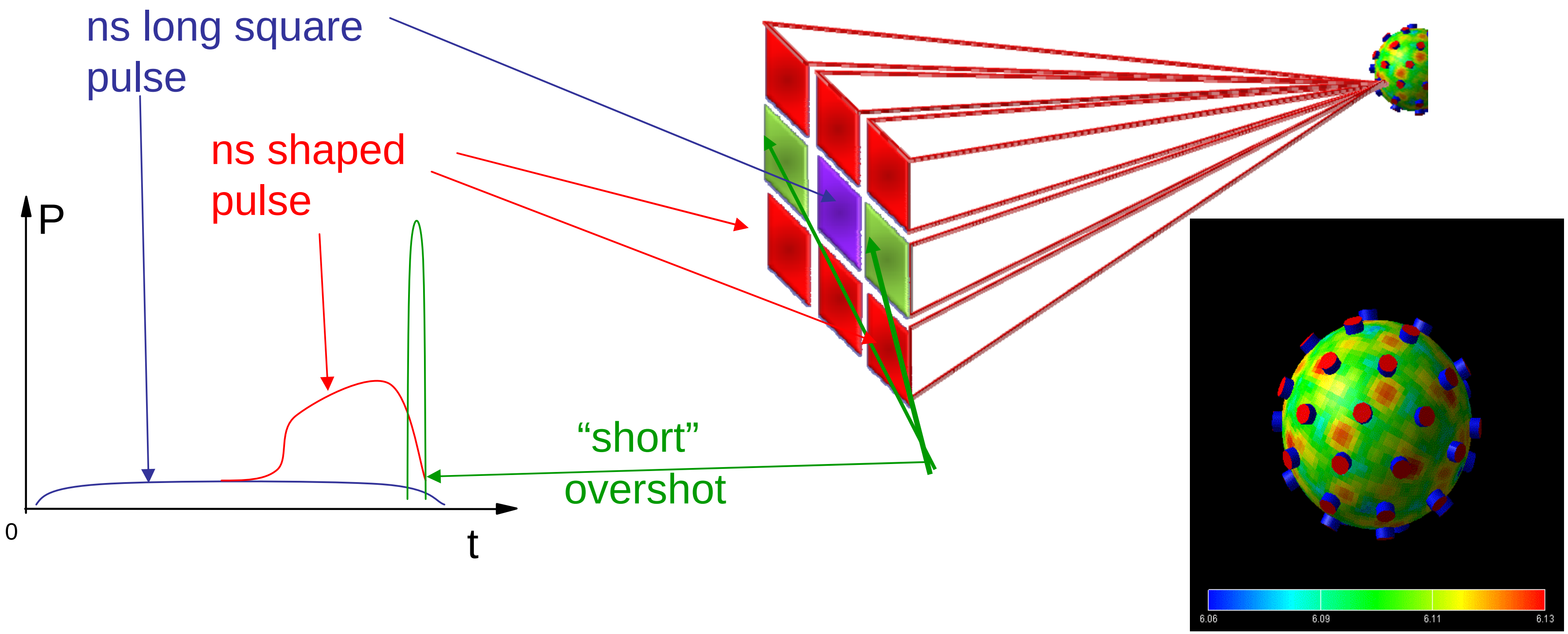
MERCURY
Pulsed
US Nat Lab
1 kW

JHPSSL
CW
Industry
100 kW

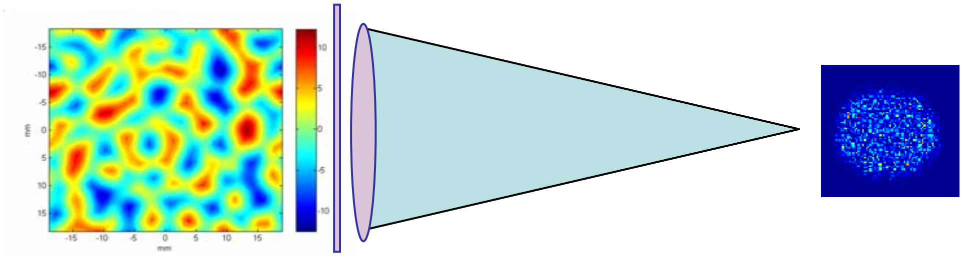
HiPER Using Beamlets - Temporal shaping

- Each “spot” formed from several beamlets
- Temporal shaping with multiple pulse profiles addition
- Each beamlet has its own arbitrary waveform generator

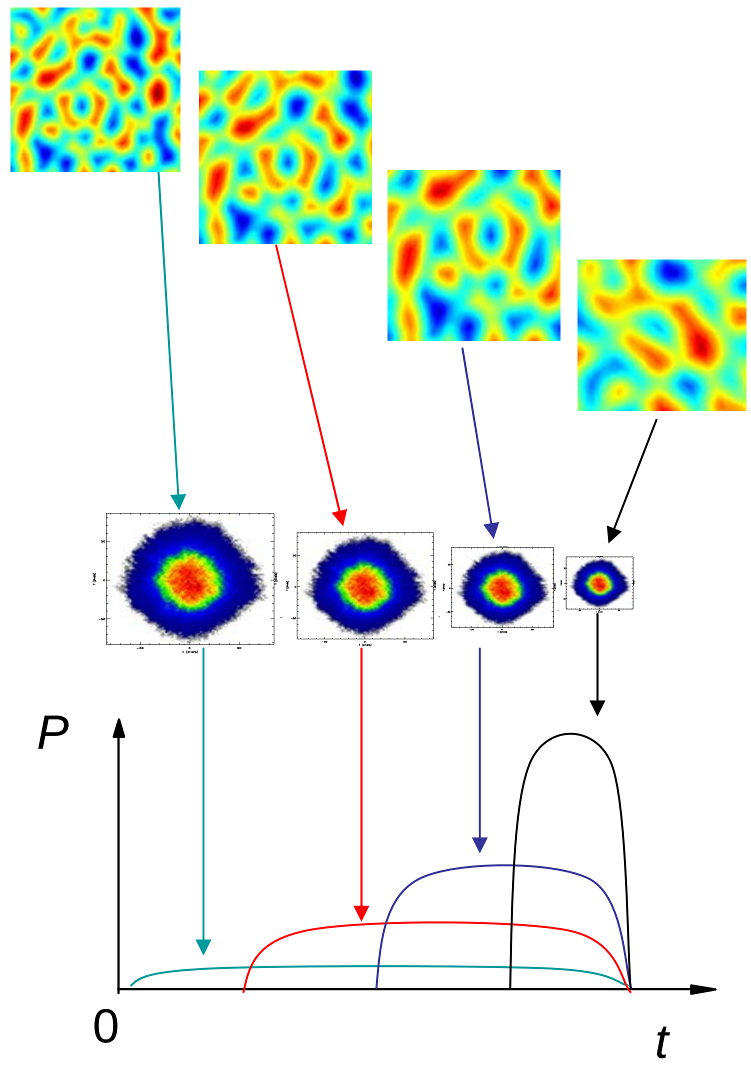




HiPER Beamlets – Smoothing and Zooming



Phase plate + lens => beam conditioning
⇒ Speckle pattern
⇒ Focal spot shape (envelope)
⇒ “smoothed” profile



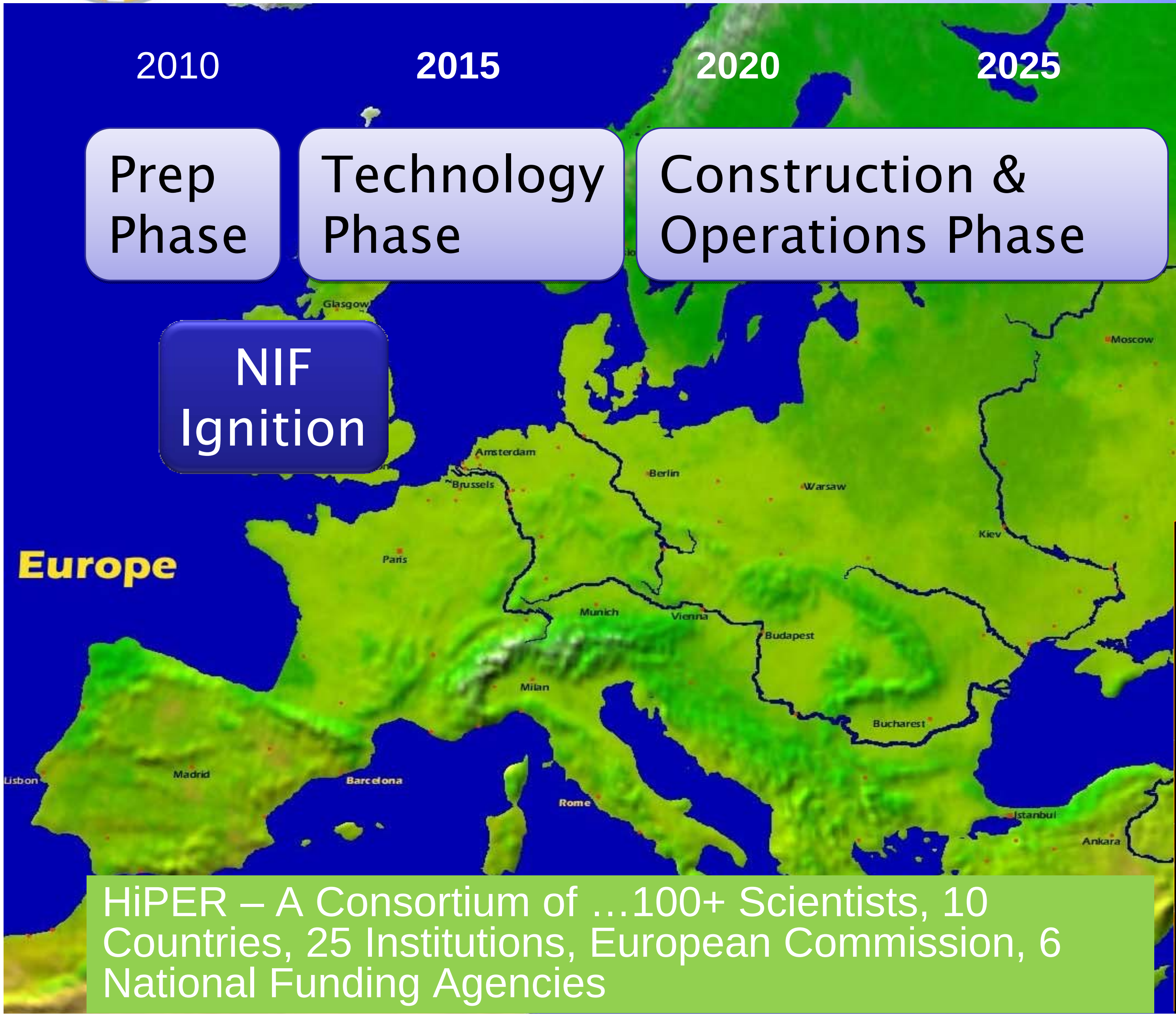
- Each beamlet has a phase plate and an Arbitrary Waveform Generator associated with.
- Introducing adequate timing between beamlets together with temporal shaping and focal spot overlap leads to optical zooming : spot size is moving during the pulse
- ** B. Canaud and F. Garaude”, Nucl. Fusion **45** (2005) L43-*

HiPER Pathway to Inertial Fusion Energy

2010	**2015**	**2020**	**2025**	2030

Prep Phase | Technology Phase | Construction & Operations Phase | Electricity Phase

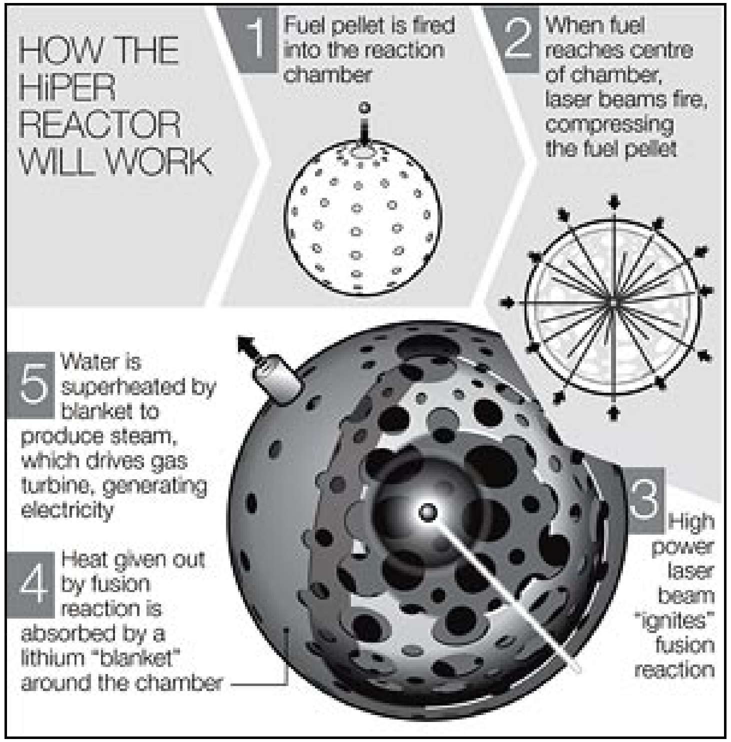
NIF Ignition



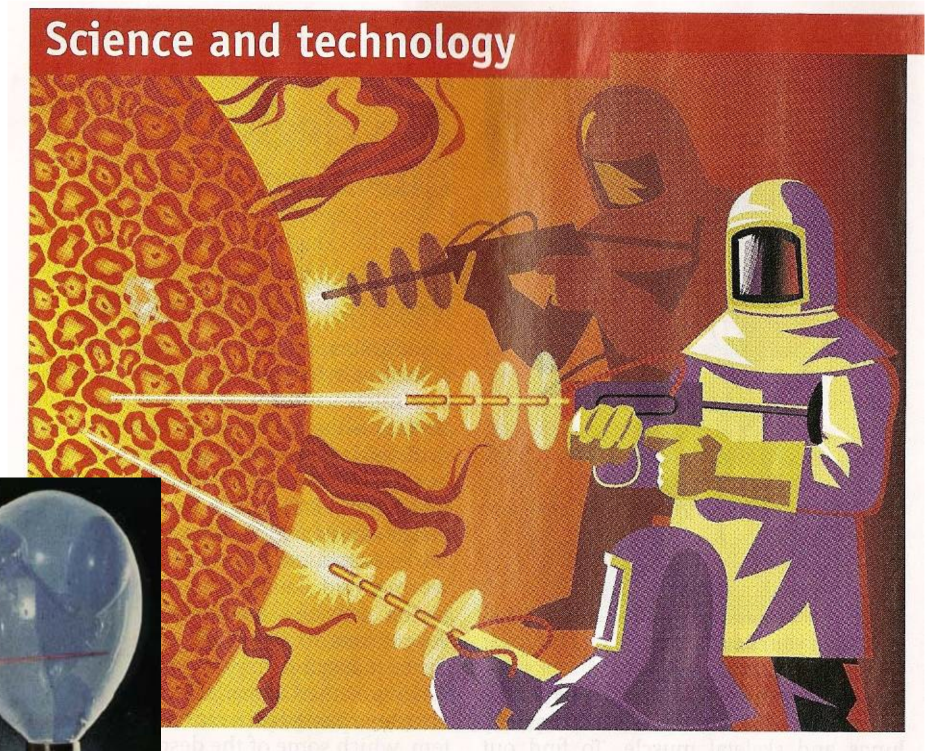
HiPER – A Consortium of …100+ Scientists, 10 Countries, 25 Institutions, European Commission, 6 National Funding Agencies

IFE viewed by the popular press …

Telegraph.co.uk



The Economist



HiPER

Summary

- We are entering a new era for Fusion Energy
- Ignition and net gain are within 6-18 months away
- A concept for a next-generation European IFE facility has been proposed
- Included on national & European roadmaps
- Next stage is primarily one of technology development