High Extraction Efficiency, Short Pulse, Laser Architecture for Gamma-Gamma Colliders

ICFA Workshop on Gamma-Gamma Colliders
Beijing

Dr. C. P. J. Barty
Chief Technology Officer - NIF and Photon Science Directorate
Chair - International Committee on Ultrahigh Intensity Lasers

April 24, 2017

LLNL-PRES-
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

About ICUIL

Objectives

The International Committee on Ultra-High Intensity Lasers (ICUIL) is an organization concerned with international aspects of ultra-high intensity laser science, technology and education.

History

Charter

Committee

The objectives of ICUIL

- To provide a venue for discussions among representatives of high-intensity laser facilities and members of user communities, on international collaborative activities such as the development of the next generation of ultrahigh intensity lasers, exploration of new areas of fundamental and applied research, and formation of a global research network for access to advanced facilities by users.
- To promote unity and coherence in the field by convening conferences and workshops dedicated to ultrahigh intensity lasers and their applications.
- To accelerate progress in the field by sharing information, exploring opportunities for joint procurement, and exchanging equipment, ideas and personnel among laser laboratories world-wide.
- To attract students to high-field science by promoting their education and training, their interactions with prominent scientists, and access to the latest equipment, results and techniques.
- To strengthen and exploit synergy with other relevant fields and techniques, notably accelerator-based free electron lasers.

The International Committee on Ultra-High Intensity Lasers

Home | ICUIL Newsletter | ICUIL Story | ICUIL Life | ICUIL Docs | ICUIL Contact

About ICUIL

Objectives

The International Committee on Ultra-High Intensity Lasers (ICUIL) is an organization concerned with international aspects of ultra-high intensity laser science, technology and education.

History

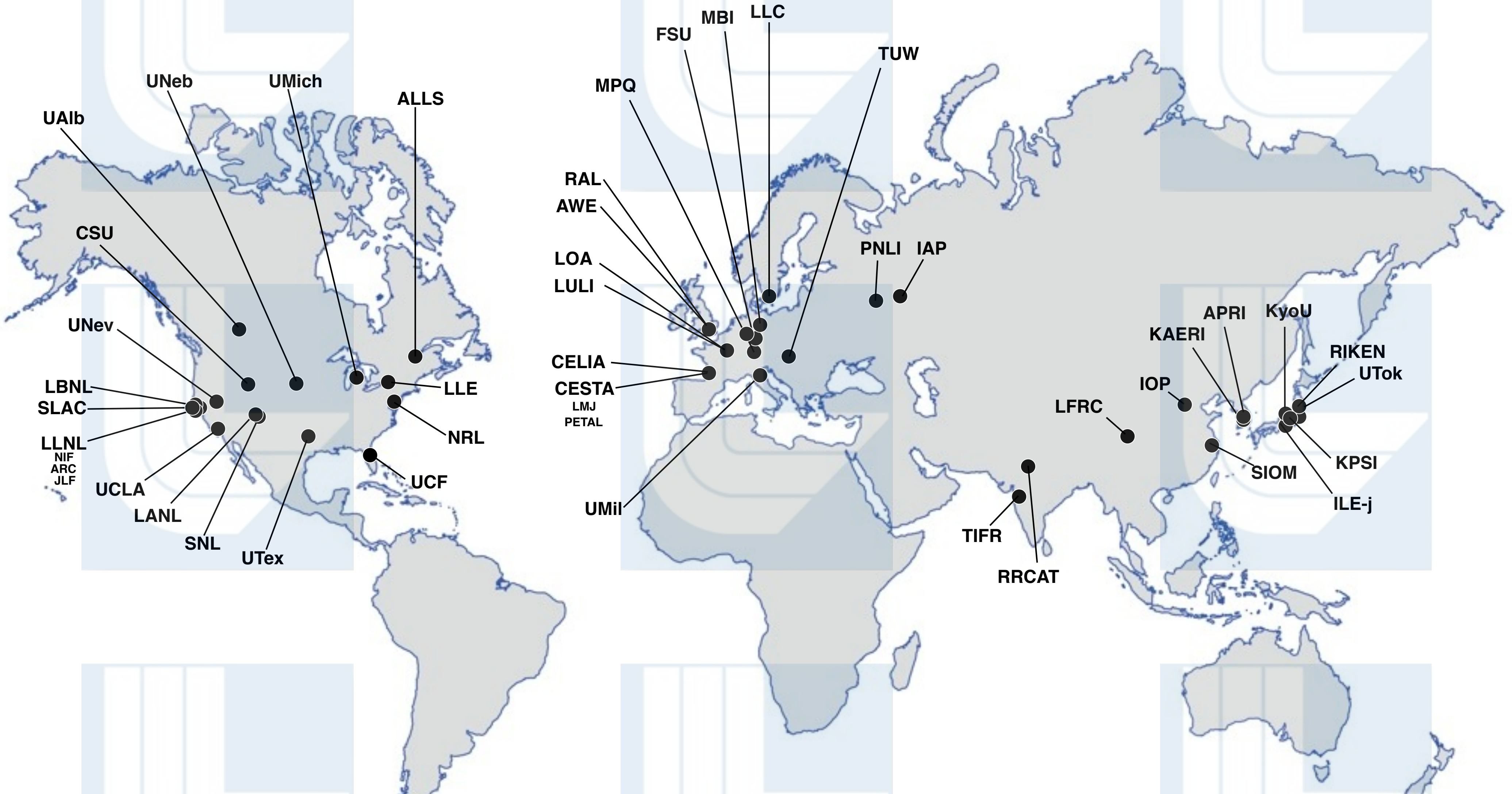
Charter

Committee

The objectives of ICUIL

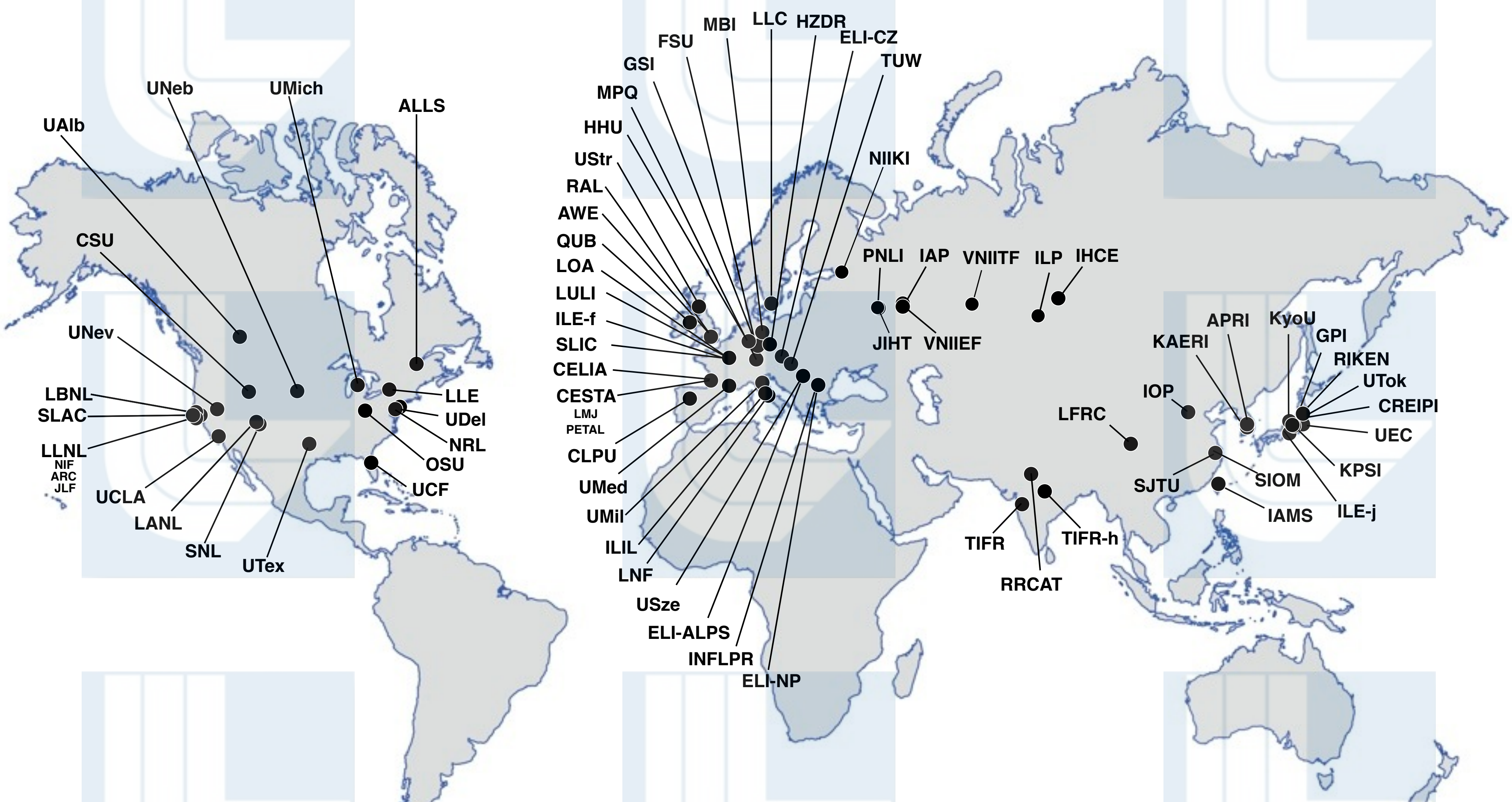
- To provide a venue for discussions among representatives of high-intensity laser facilities and members of user communities, on international collaborative activities such as the development of the next generation of ultrahigh intensity lasers, exploration of new areas of fundamental and applied research, and formation of a global research network for access to advanced facilities by users.
- To promote unity and coherence in the field by convening conferences and workshops dedicated to ultrahigh intensity lasers and their applications.
- To accelerate progress in the field by sharing information, exploring opportunities for joint procurement, and exchanging equipment, ideas and personnel among laser laboratories world-wide.
- To attract students to high-field science by promoting their education and training, their interactions with prominent scientists, and access to the latest equipment, results and techniques.
- To strengthen and exploit synergy with other relevant fields and techniques, notably accelerator-based free electron lasers.

2009 ICUIL World Map of Ultrahigh Intensity Laser Capabilities



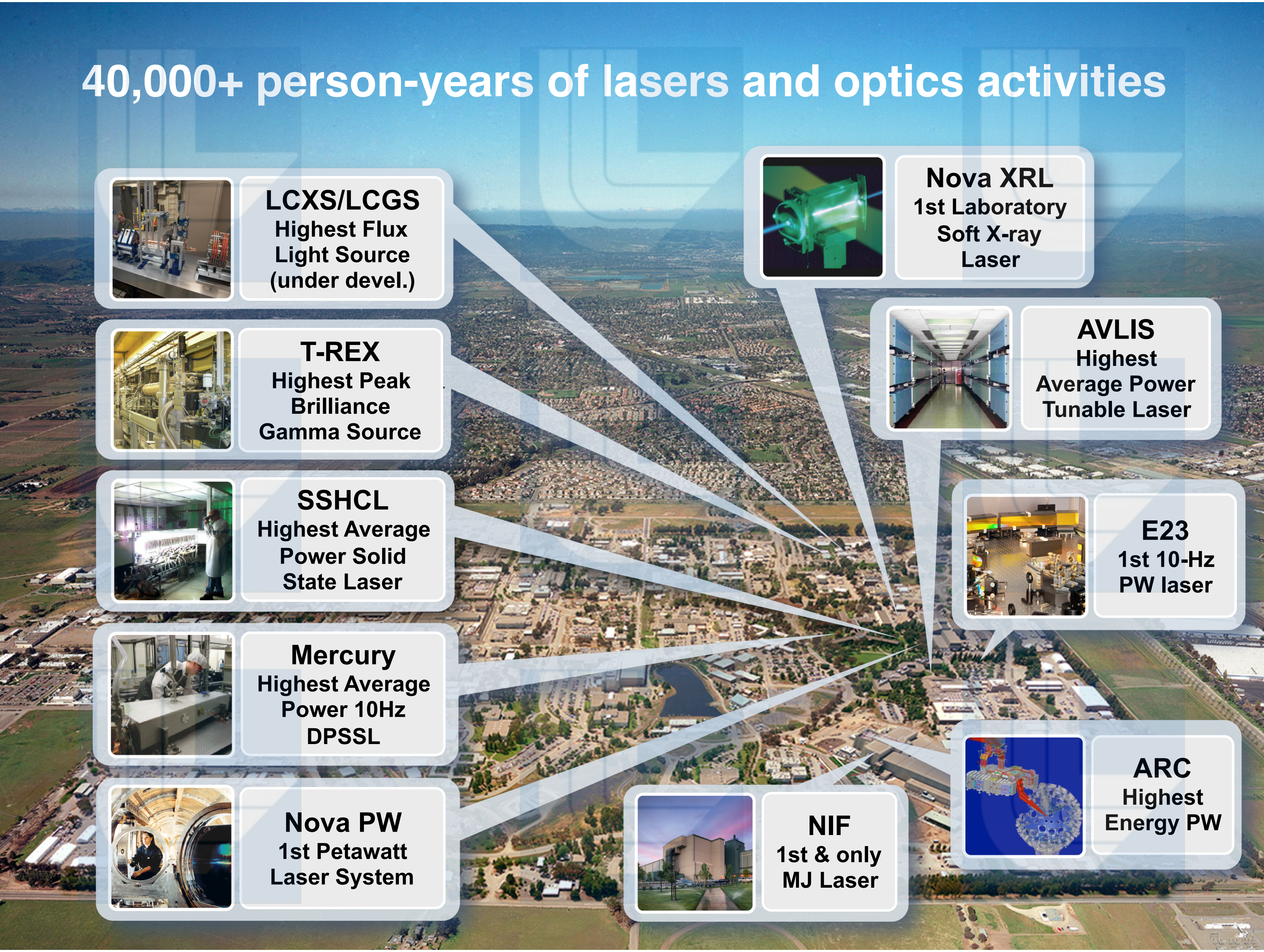
Labels represent the establishments with physical and administrative responsibility for the ultrahigh intensity laser system or facility

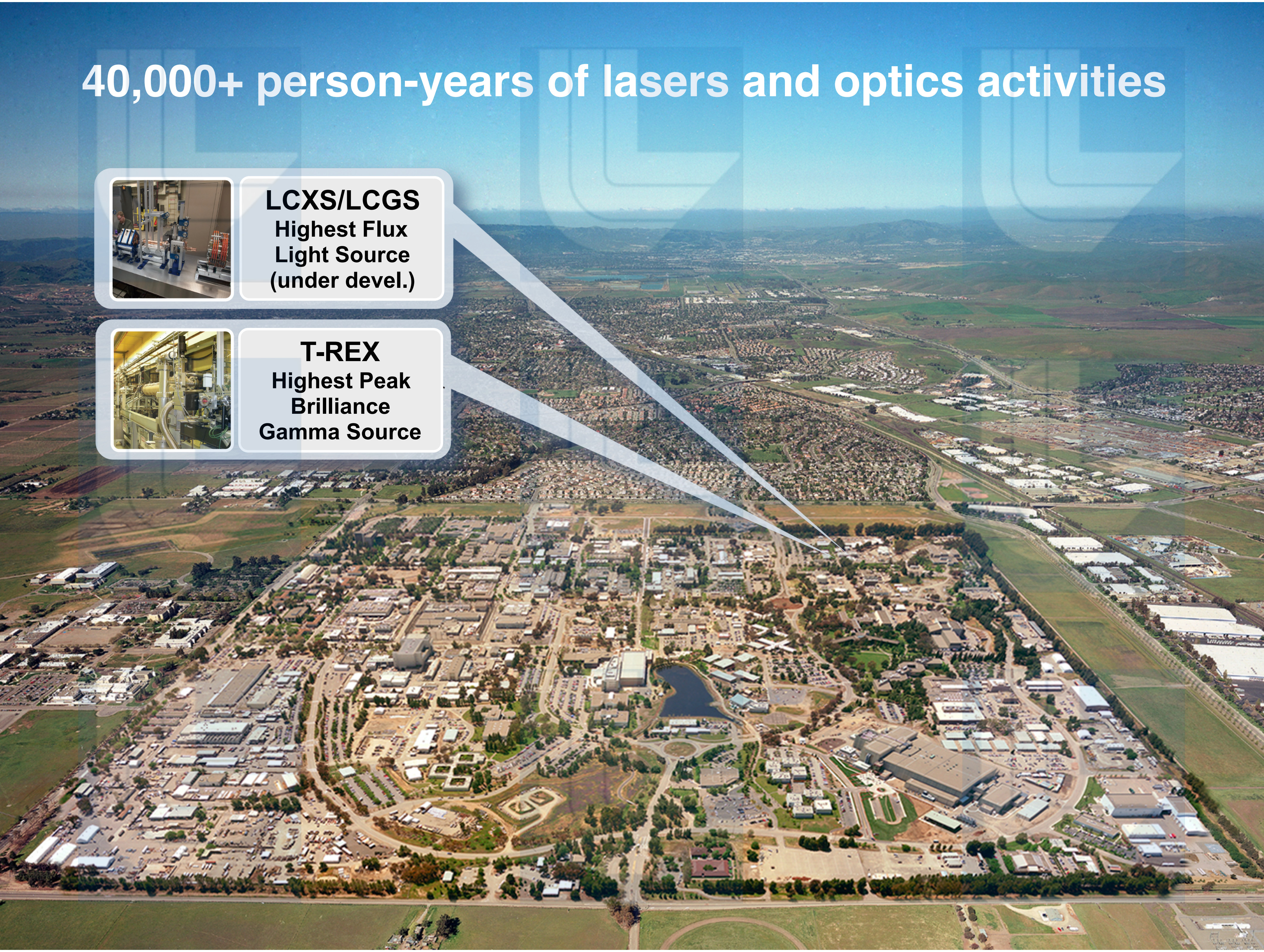
Present ICUIL World Map of Ultrahigh Intensity Laser Capabilities



Labels represent the establishments with physical and administrative responsibility for the ultrahigh intensity laser system or facility

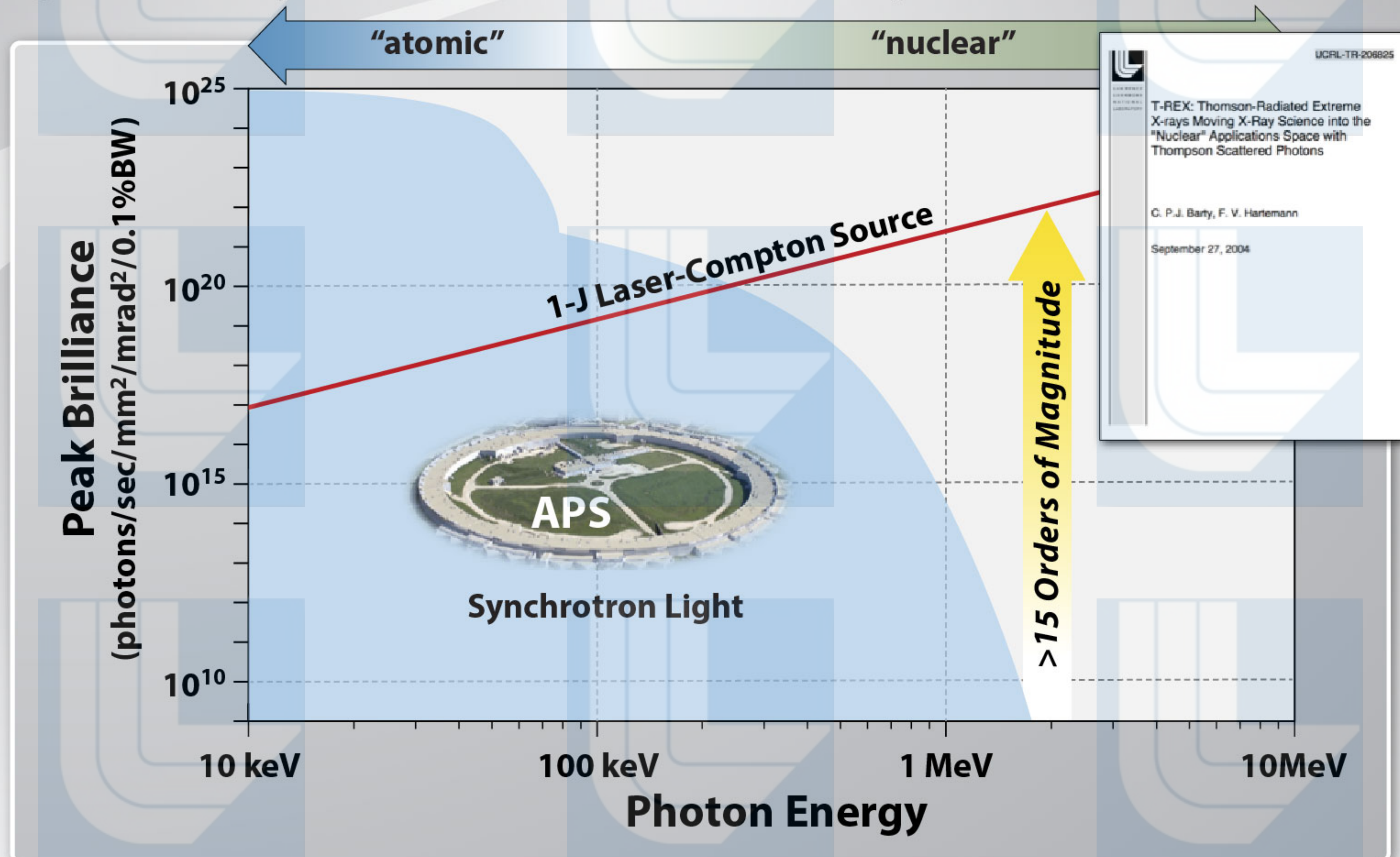

San Francisco
LLNL


40,000+ person-years of lasers and optics activities
LCXS/LCGS
Highest Flux
Light Source
(under devel.)
T-REX
Highest Peak
Brilliance
Gamma Source
SSHCL
Highest Average
Power Solid
State Laser
Mercury
Highest Average
Power 10Hz
DPSSL
Nova PW
1st Petawatt
Laser System
NIF
1st & only
MJ Laser
Nova XRL
1st Laboratory
Soft X-ray
Laser
AVLIS
Highest
Average Power
Tunable Laser
E23
1st 10-Hz
PW laser
ARC
Highest
Energy PW

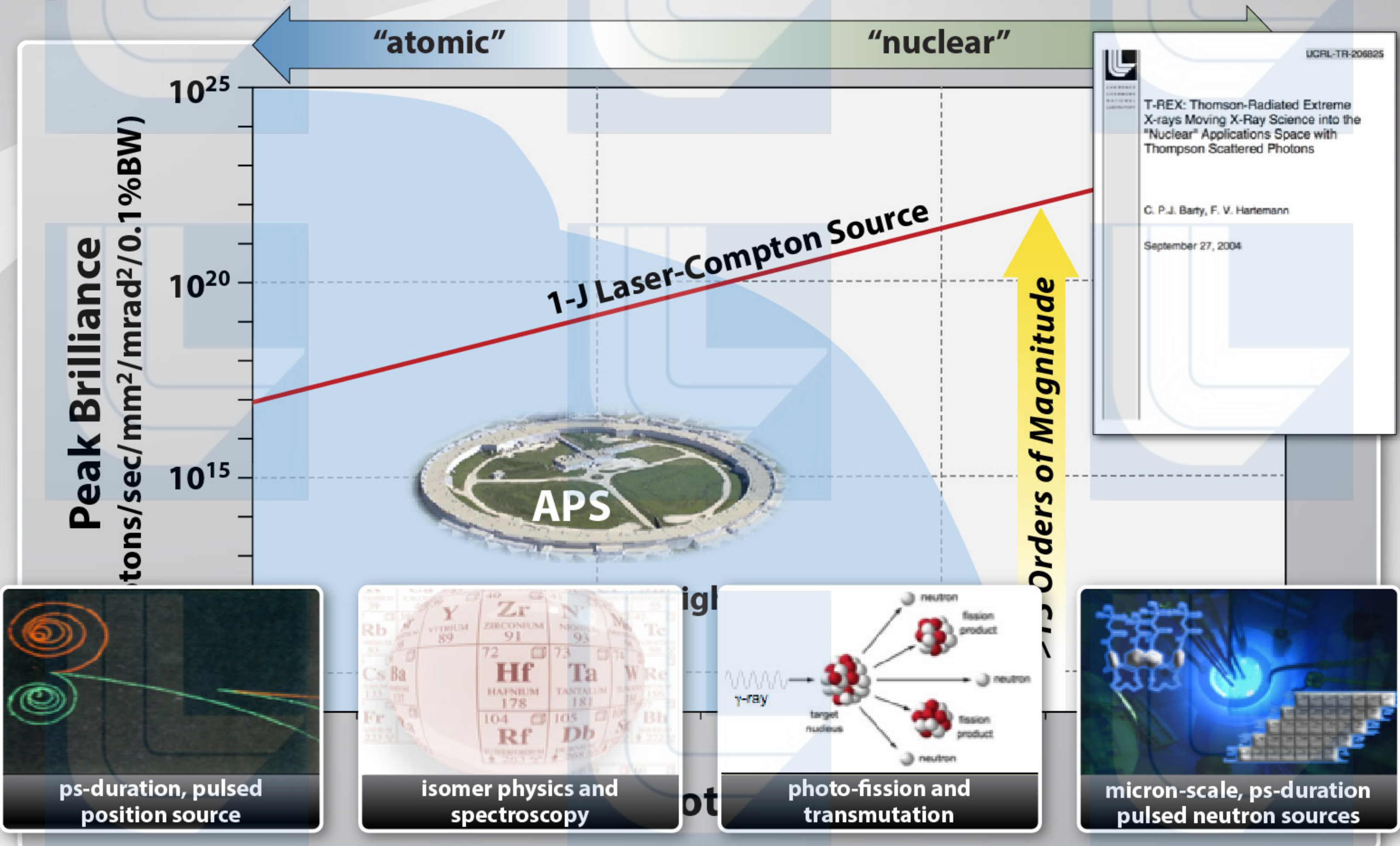

40,000+ person-years of lasers and optics activities
LCXS/LCGS
Highest Flux
Light Source
(under devel.)
T-REX
Highest Peak
Brilliance
Gamma Source

LLNL's Laser-Compton Test Station enables validation of novel, compact, high-flux, narrow-band architectures and technologies

The characteristics of optimized laser-Compton gamma-ray sources enable "nuclear photonics"

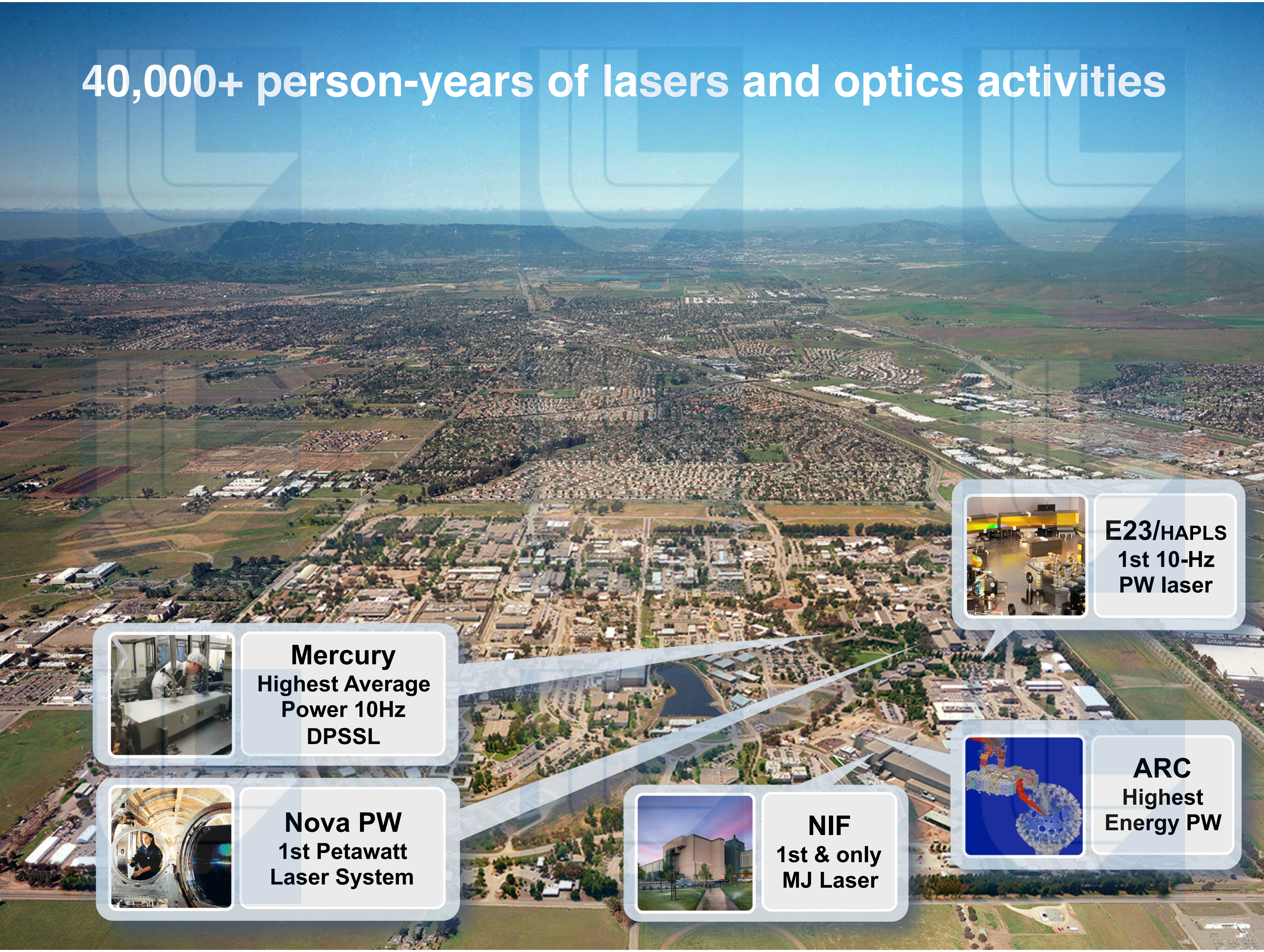


The characteristics of optimized laser-Compton gamma-ray sources enable "nuclear photonics"

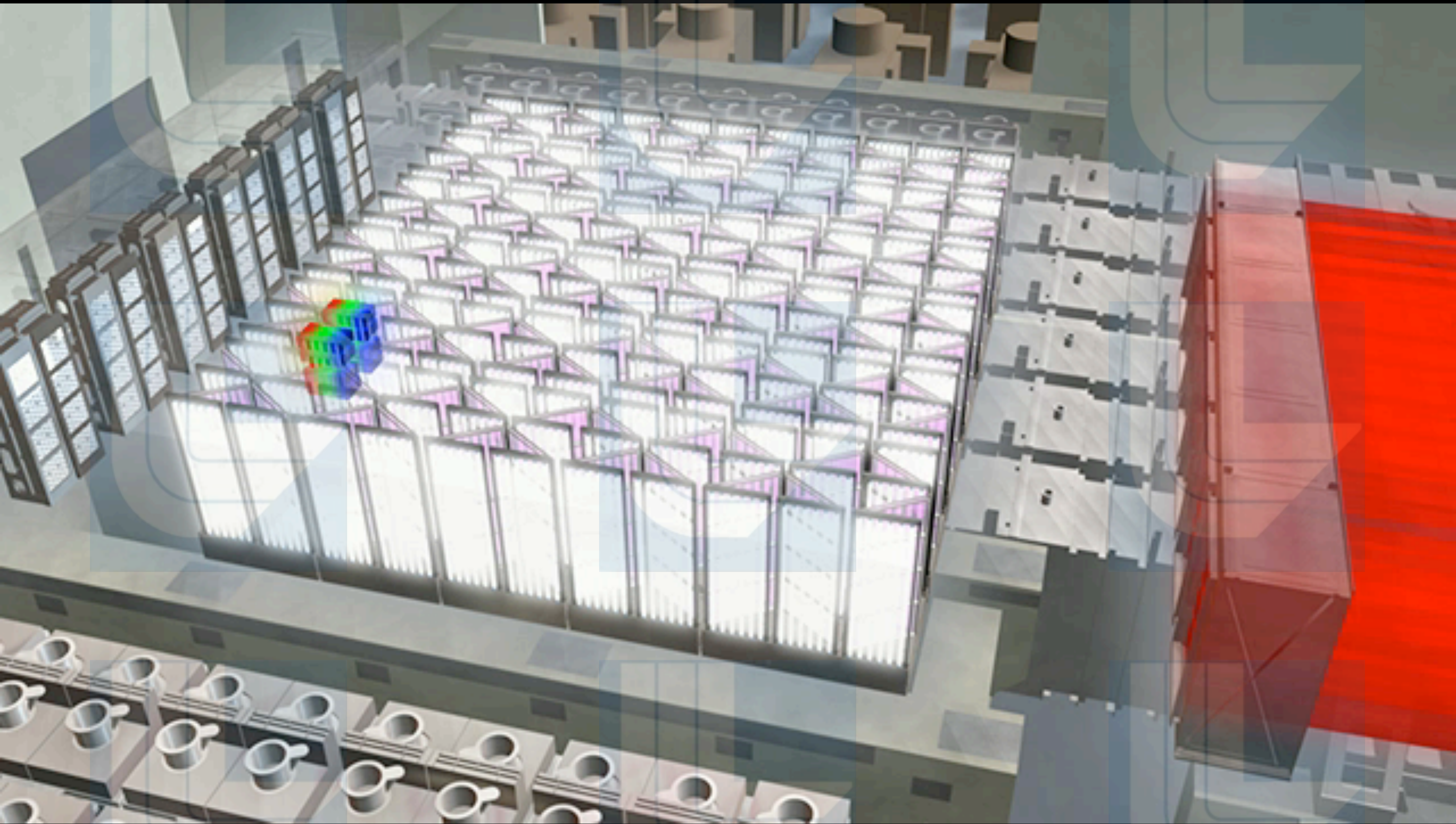


D. Habs, T. Tajima, J. Schreiber, C. Barty, M. Fujiwara & P. Thirolf, "Vision of nuclear physics w/ photo-nuclear reactions by laser-driven gamma beams," EPJ D 55, '09

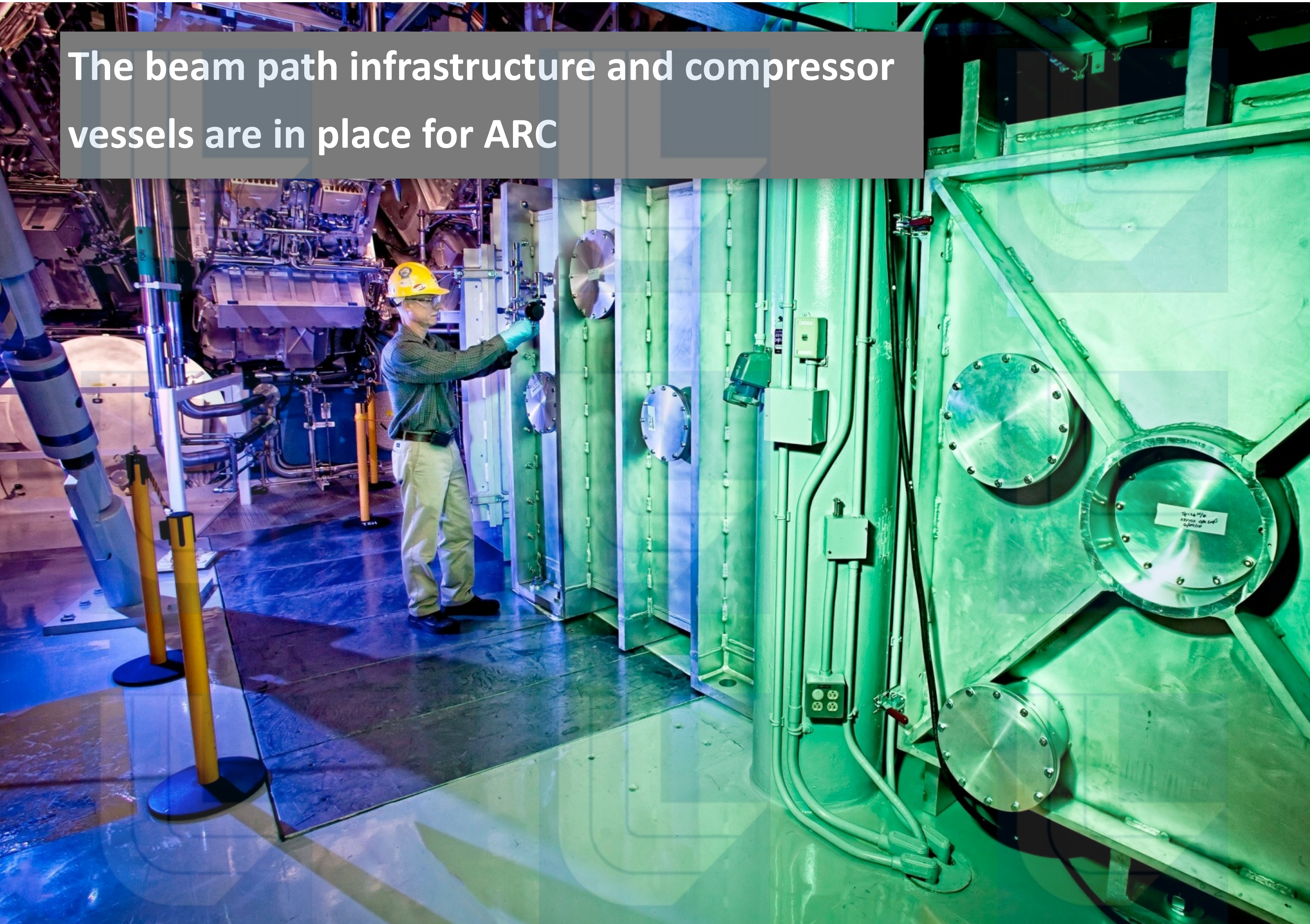

Nuclear
Photonics
2016


40,000+ person-years of lasers and optics activities
E23/HAPLS
1st 10-Hz
PW laser
Mercury
Highest Average
Power 10Hz
DPSSL
ARC
Highest
Energy PW
Nova PW
1st Petawatt
Laser System
NIF
1st & only
MJ Laser

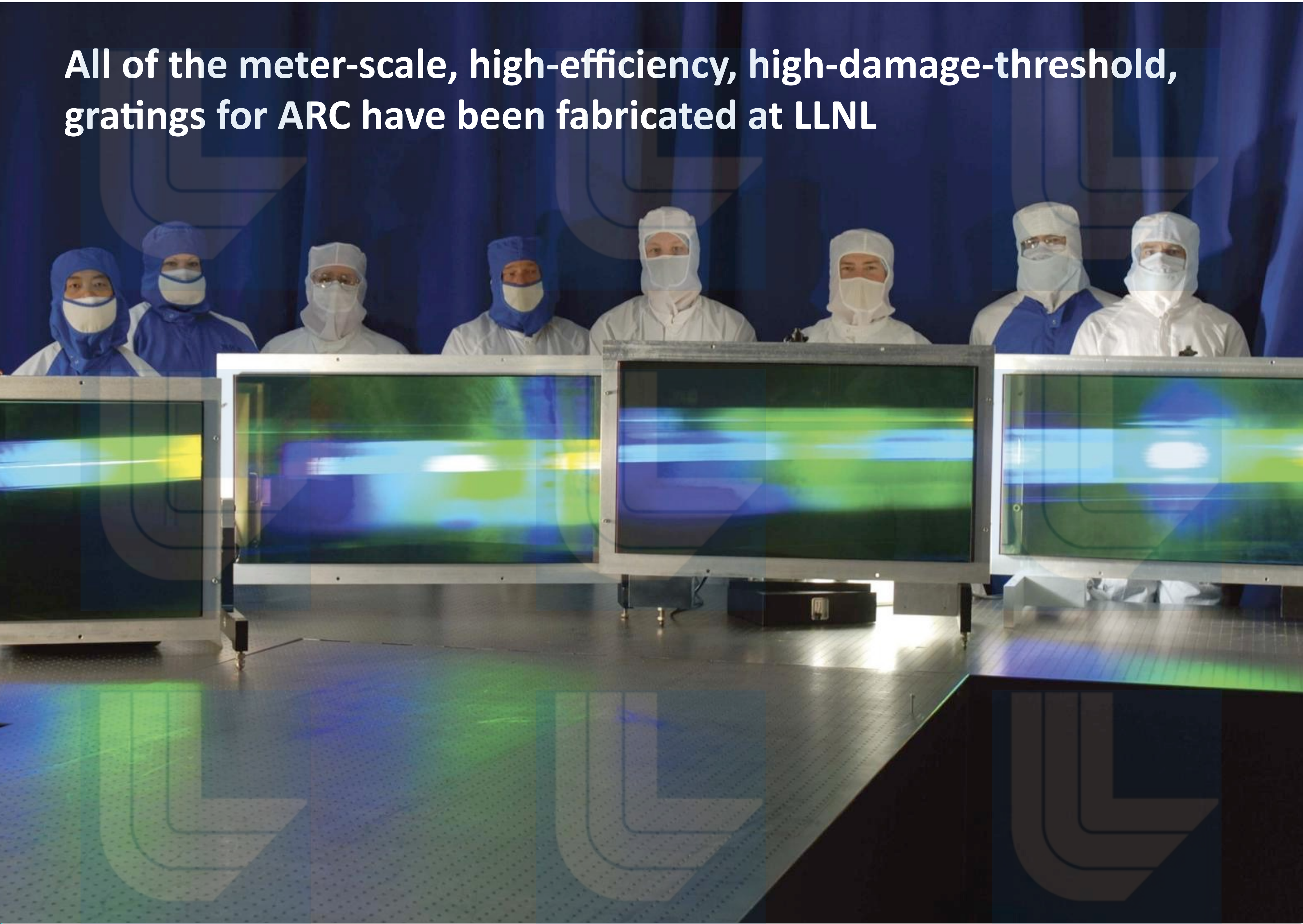
NIF's Advanced Radiographic Capability (ARC) PW system converts 4 of the 192 NIF beams into 8 separate, adjustable, kJ, ps pulses



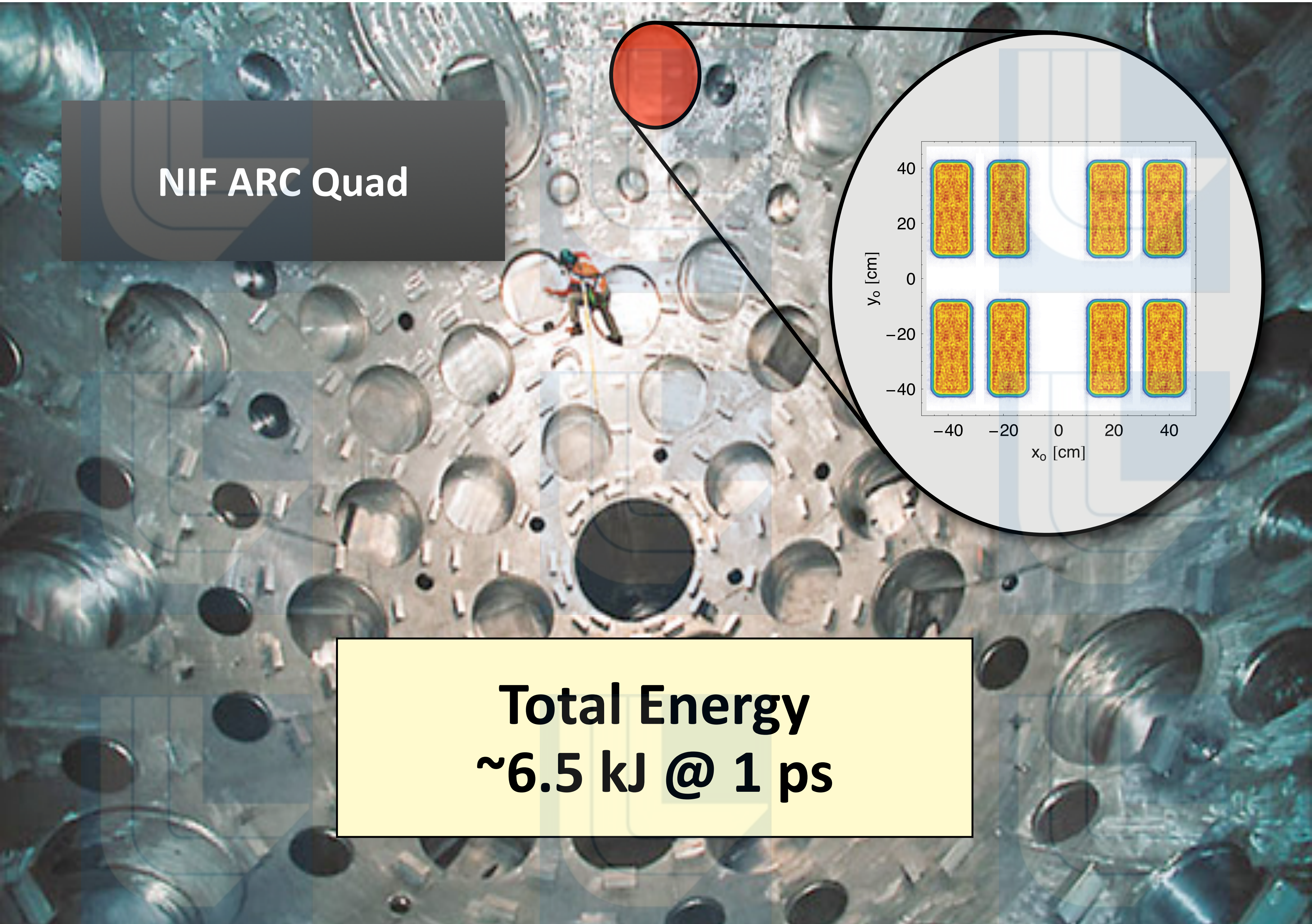
The beam path infrastructure and compressor vessels are in place for ARC



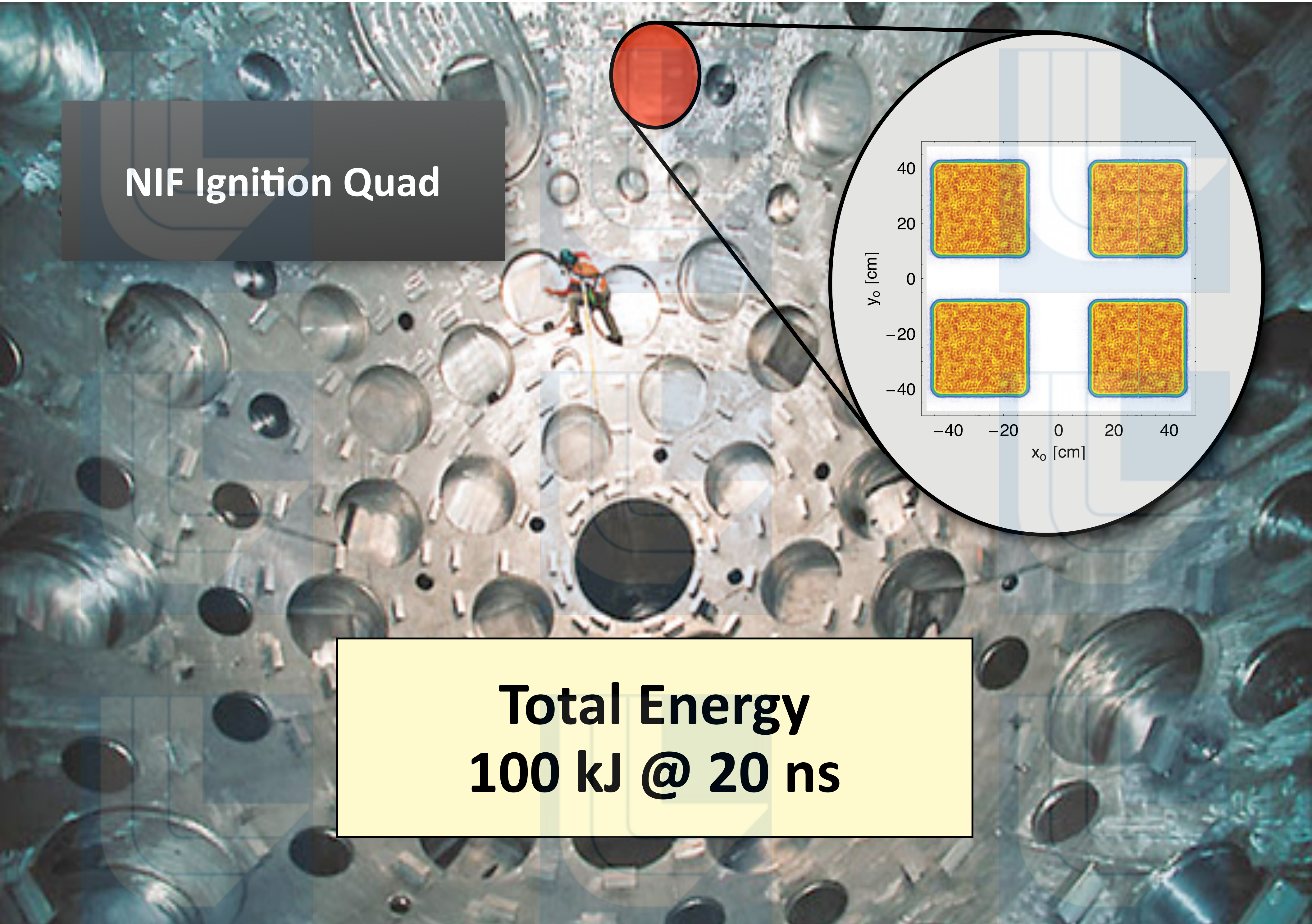
All of the meter-scale, high-efficiency, high-damage-threshold, gratings for ARC have been fabricated at LLNL



NIF ARC Quad

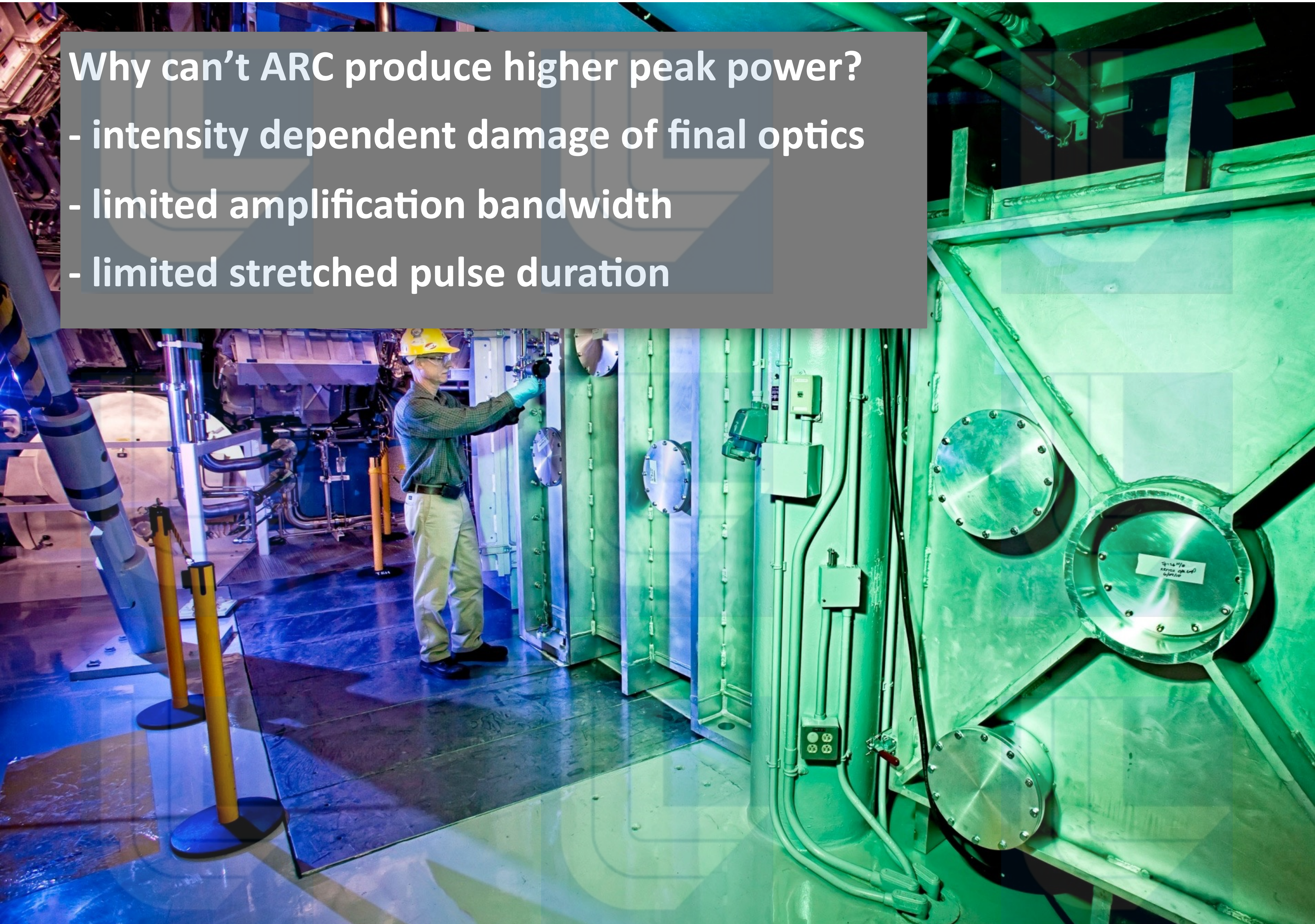


Total Energy
~6.5 kJ @ 1 ps

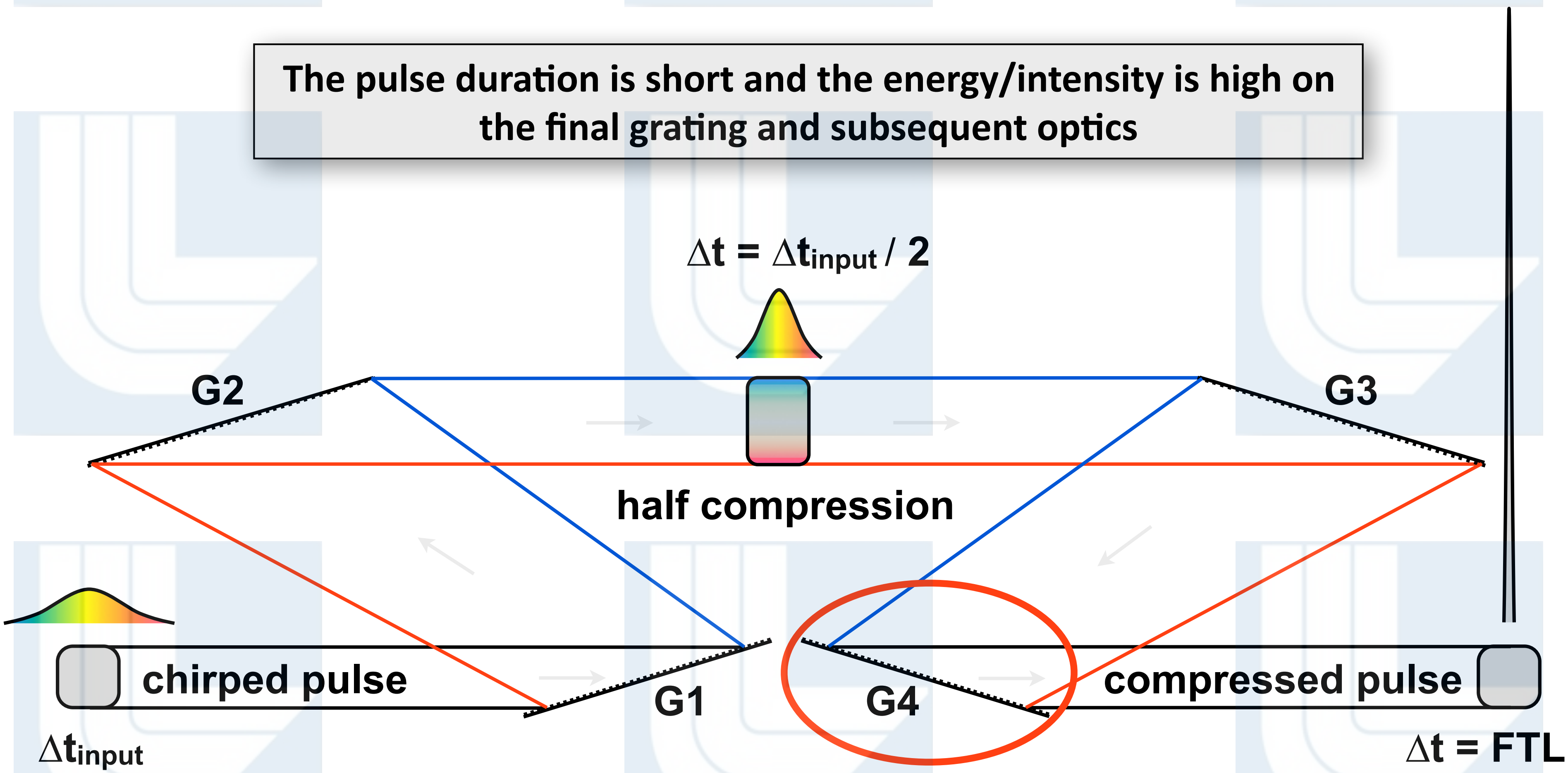

NIF Ignition Quad
40
20
0
−20
−40
y₀ [cm]
−40
−20
0
20
40
x₀ [cm]
Total Energy
100 kJ @ 20 ns

Why can’t ARC produce higher peak power?

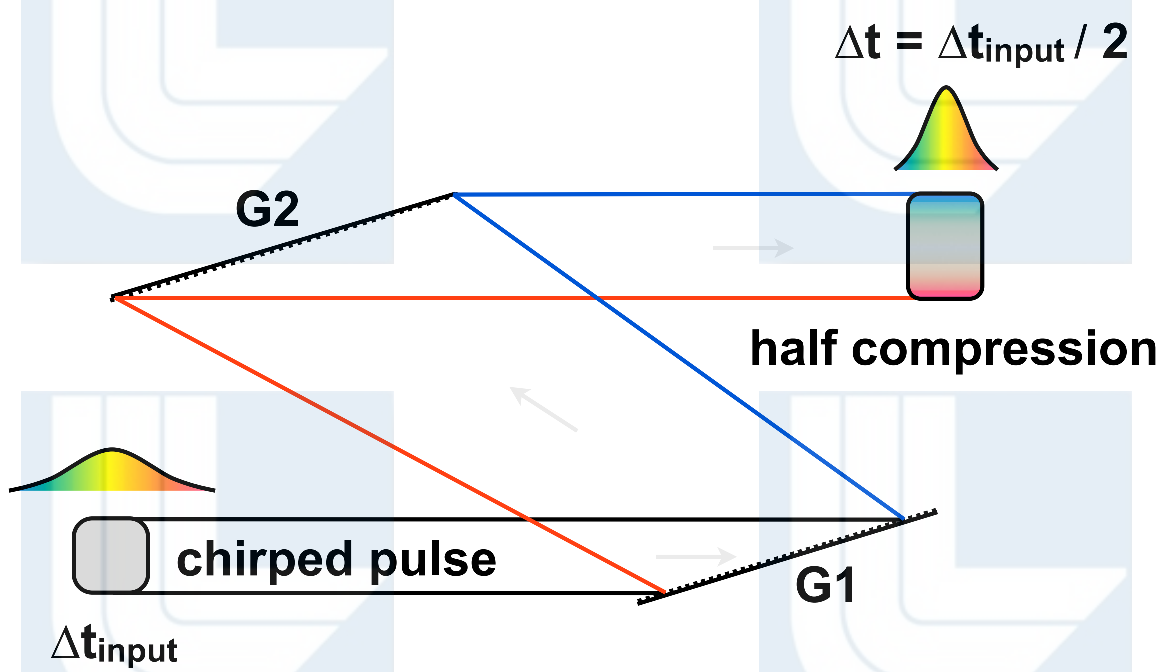
- intensity dependent damage of final optics
- limited amplification bandwidth
- limited stretched pulse duration



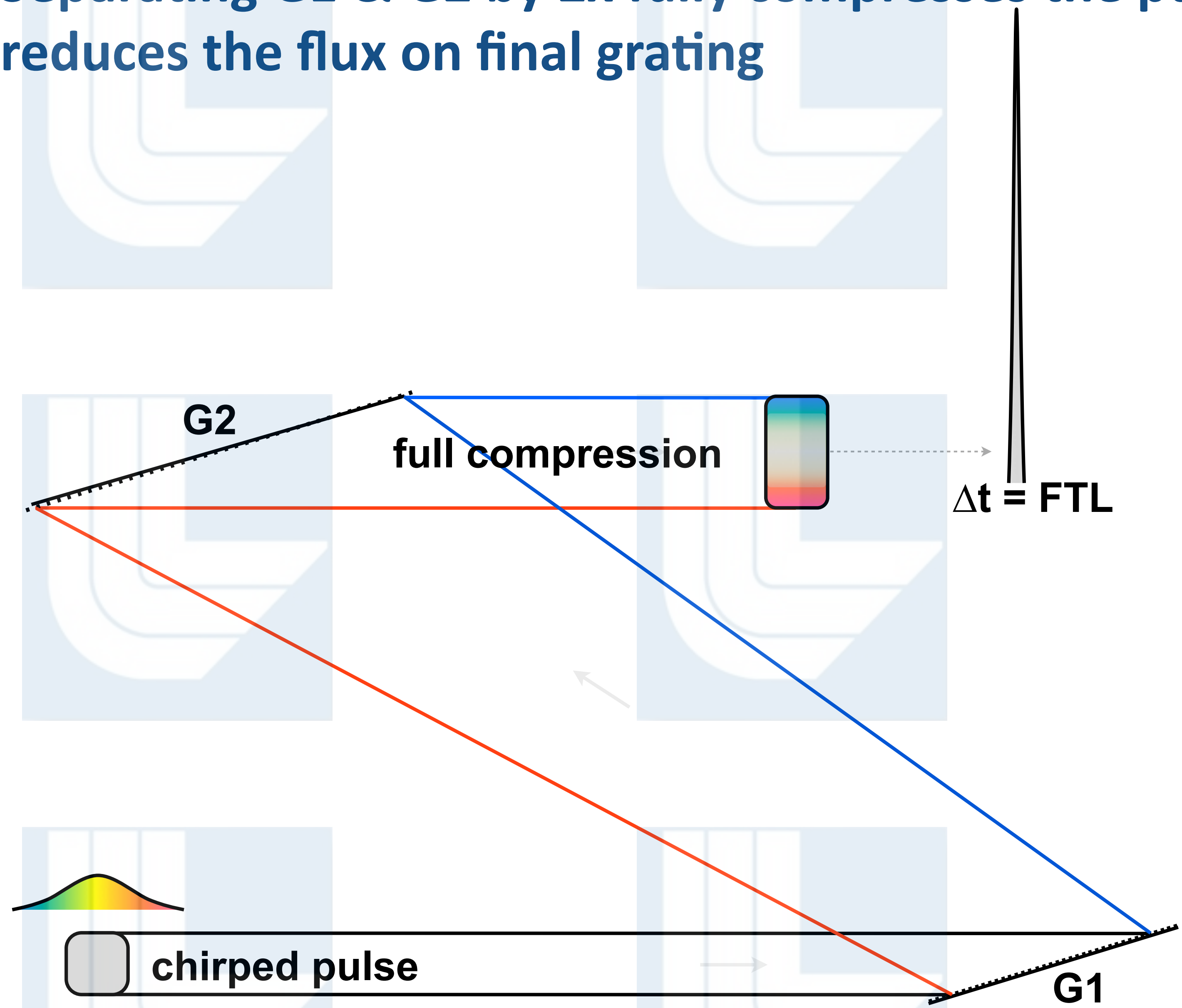
Conventional chirped pulse amplification produces high intensity on the final optics



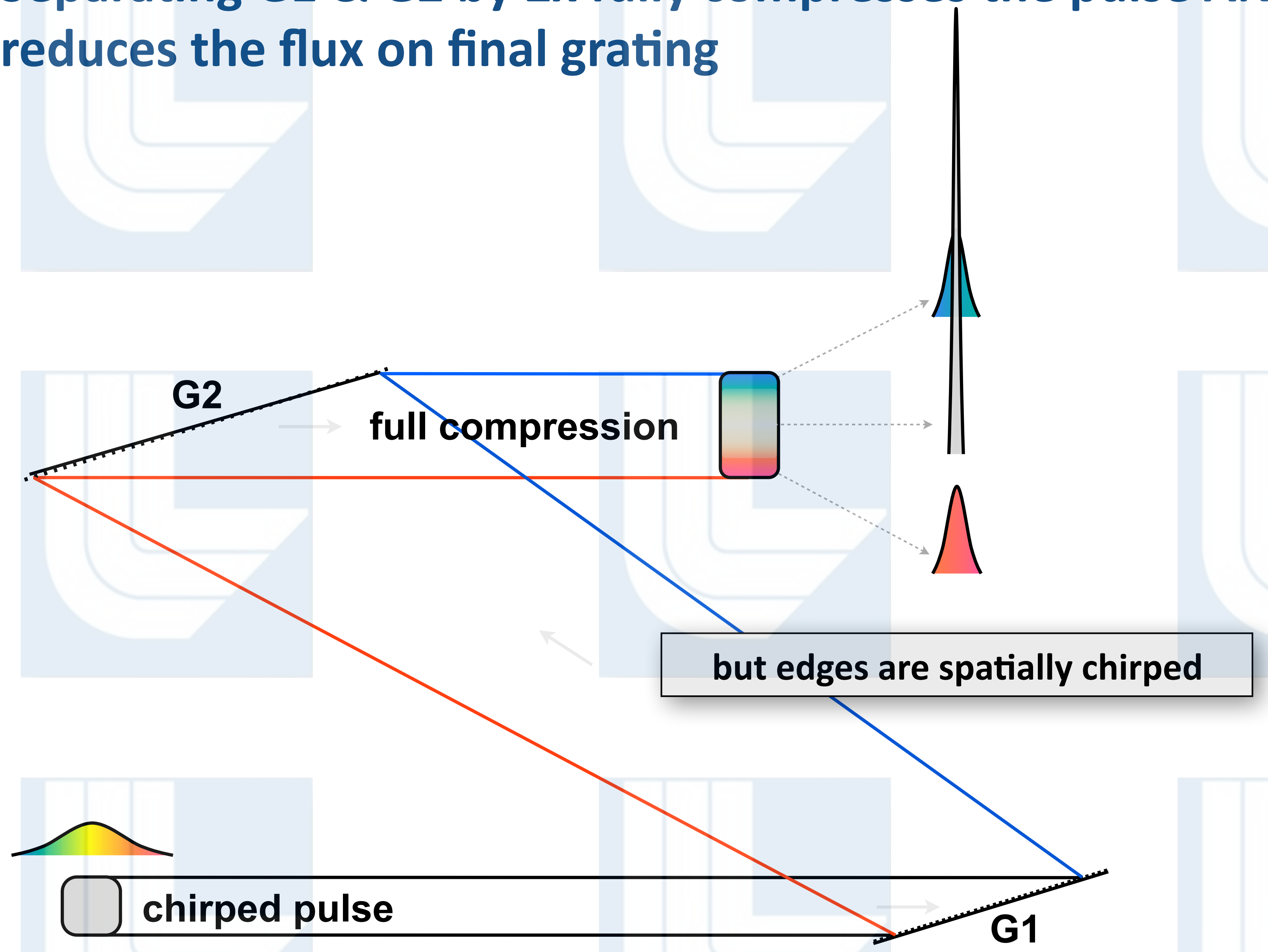
Now consider the first half of the traditional 4 grating compressor



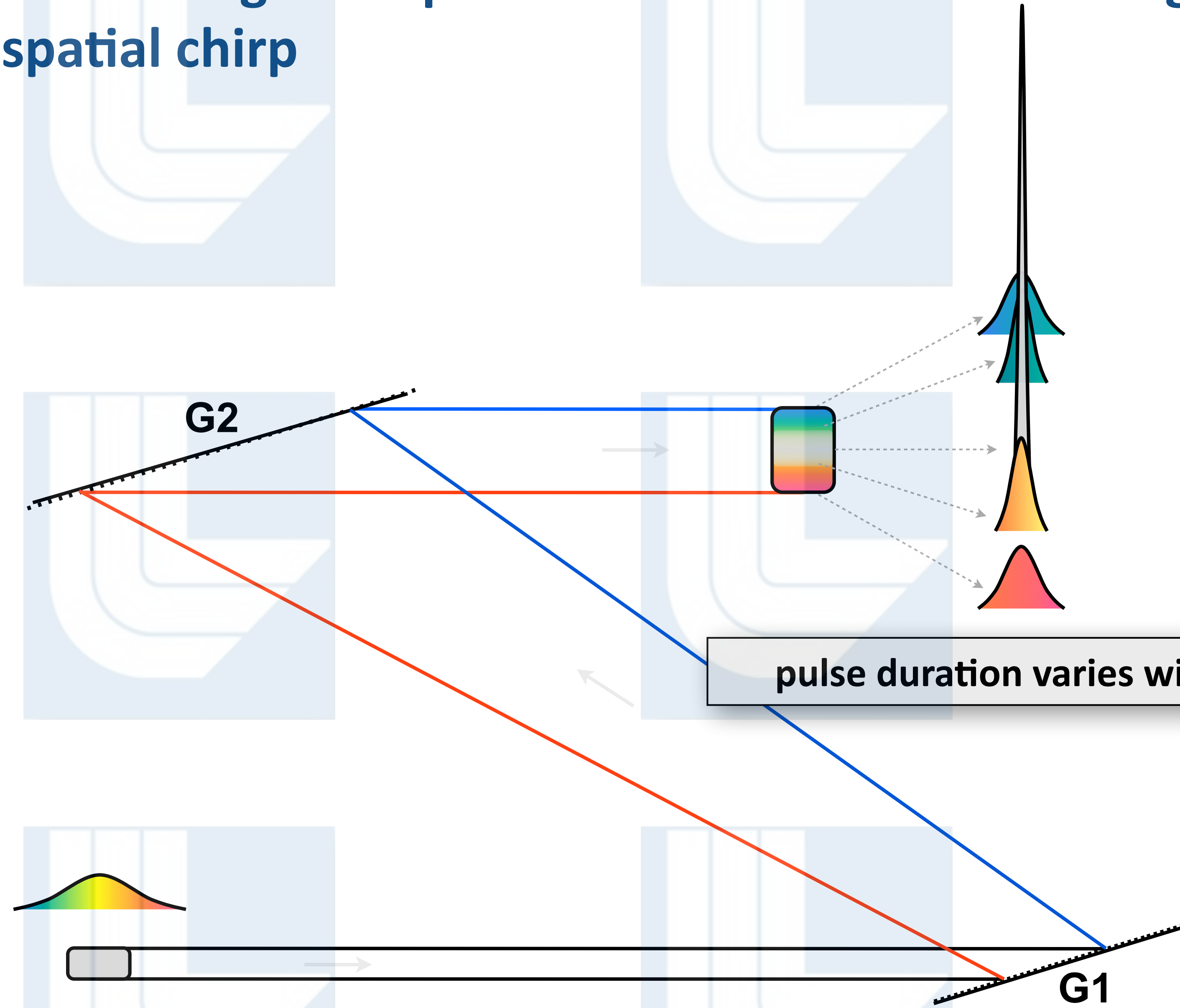
Separating G1 & G2 by 2x fully compresses the pulse AND reduces the flux on final grating



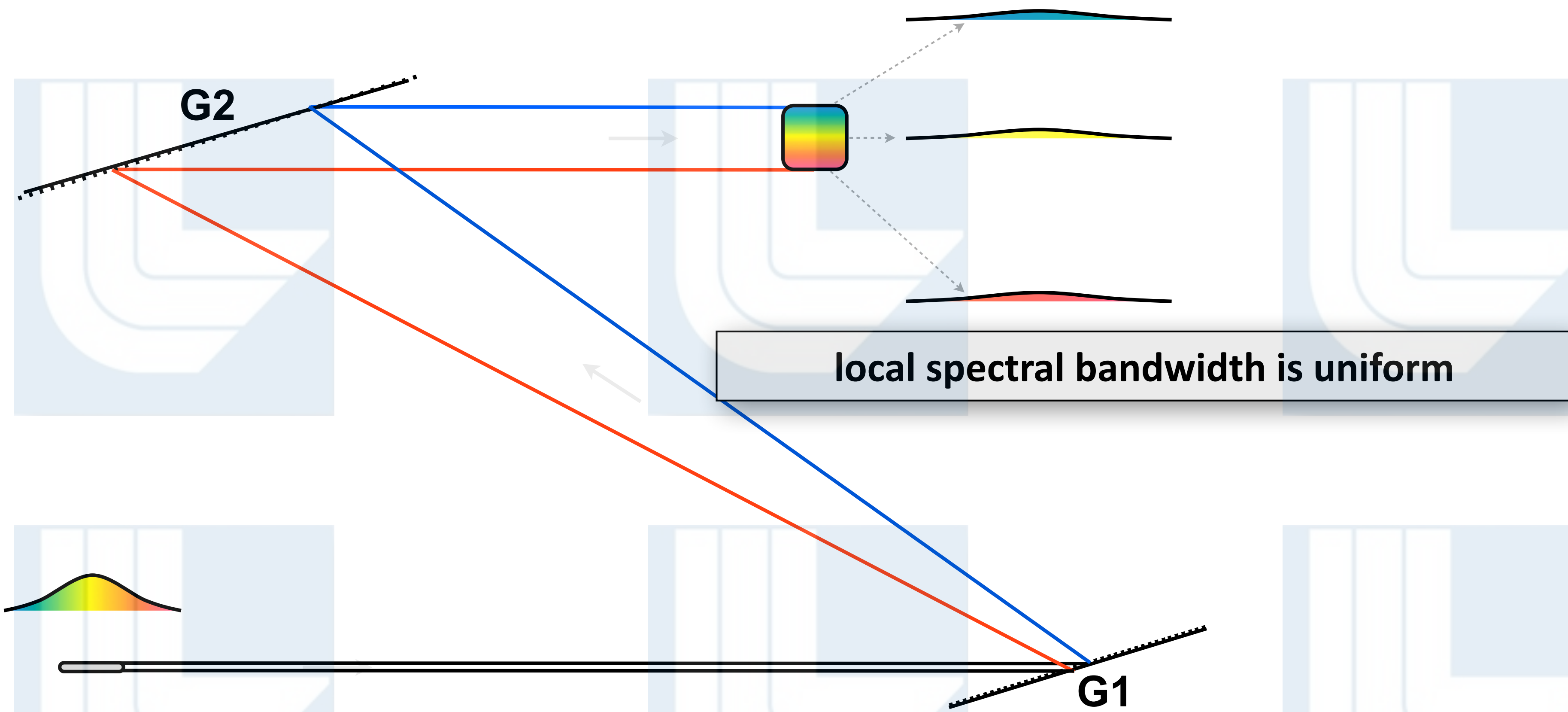
Separating G1 & G2 by 2x fully compresses the pulse AND reduces the flux on final grating



Decreasing the input beam size increases the degree of output spatial chirp

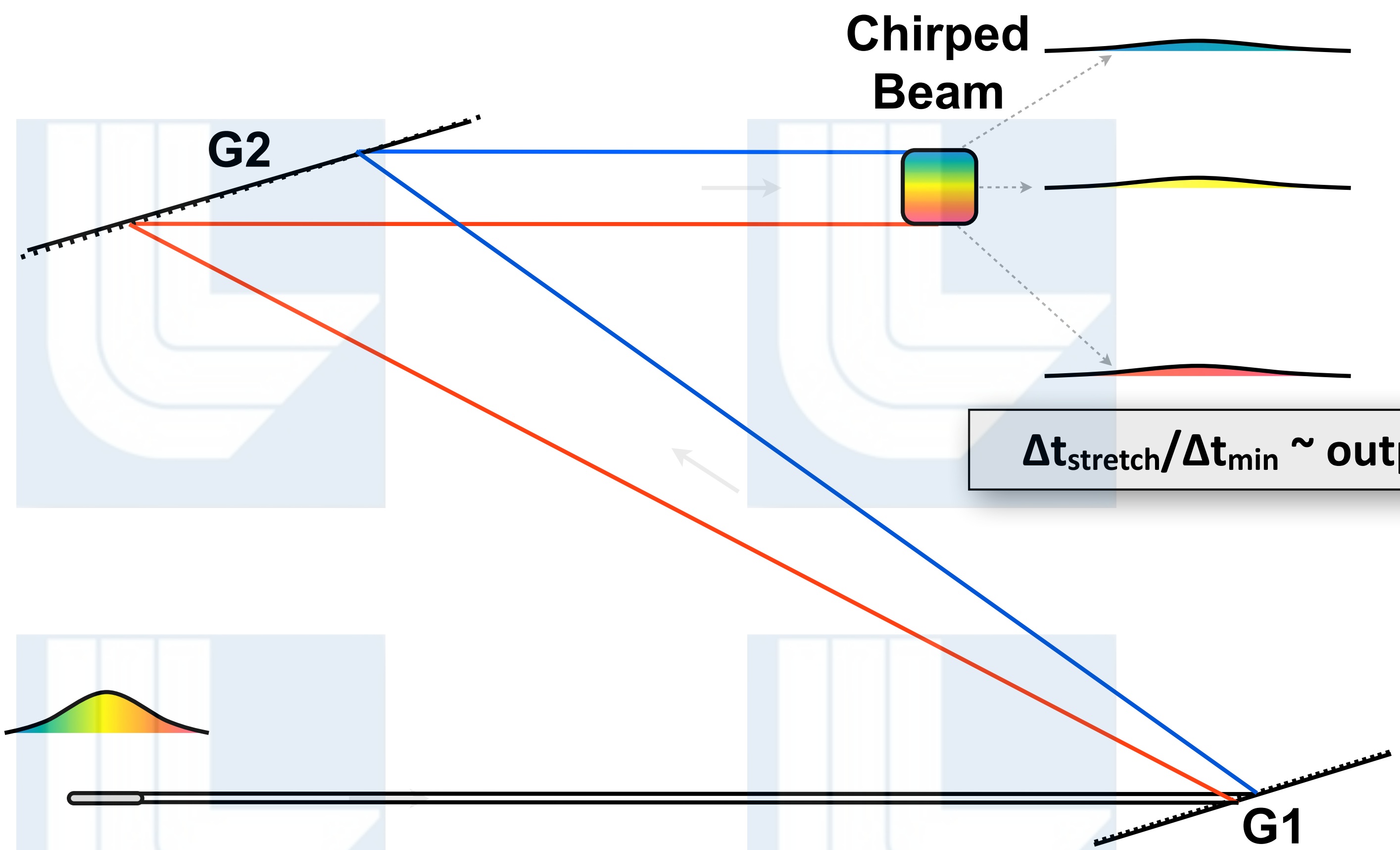


For small enough input beams, the output beam spatially lacks the spectral content to produce a short pulse



US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

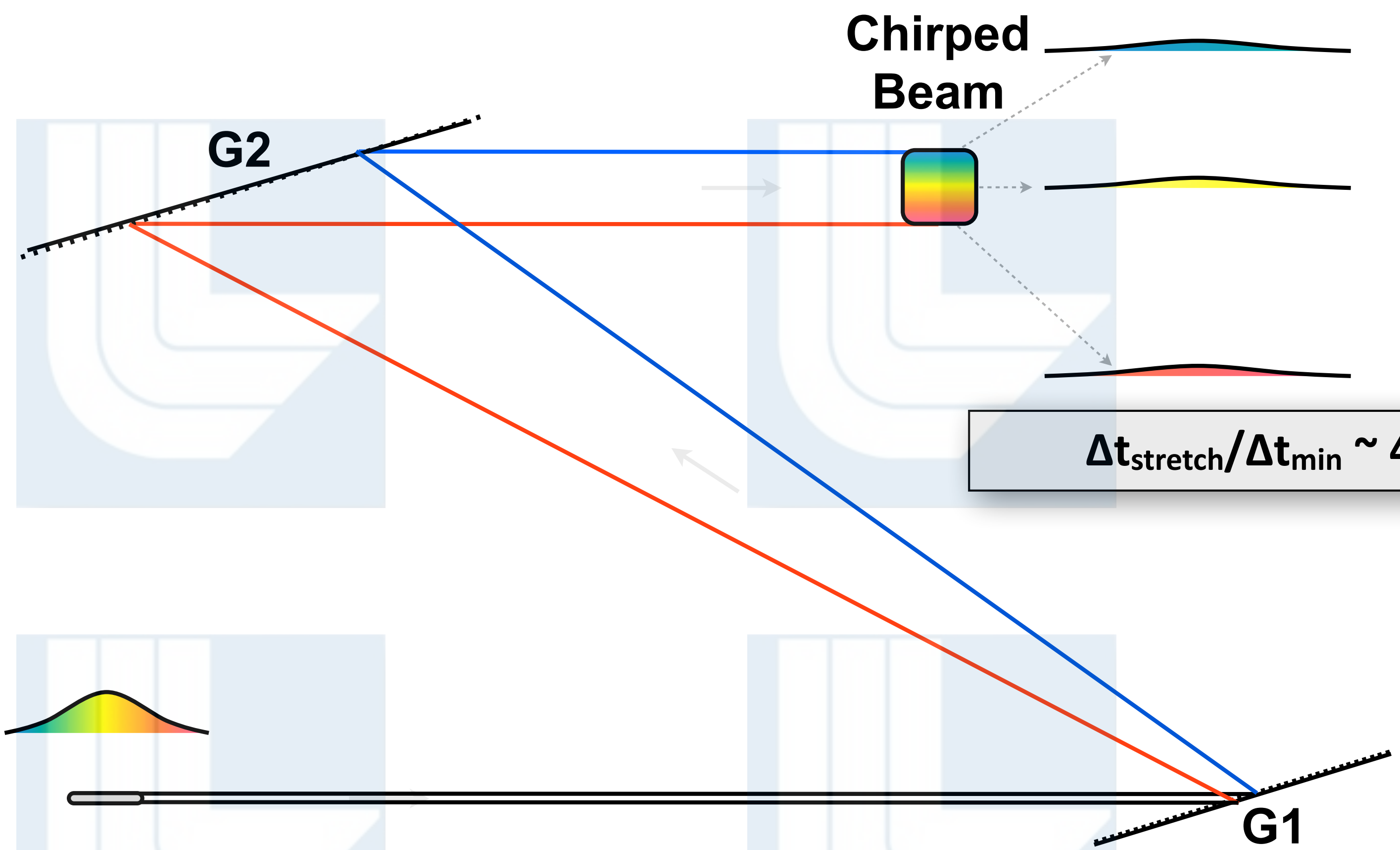
For small enough input beams, a uniform, long-duration “chirped” beam results



$\Delta t_{stretch}/\Delta t_{min}$ ~ output size/input size

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

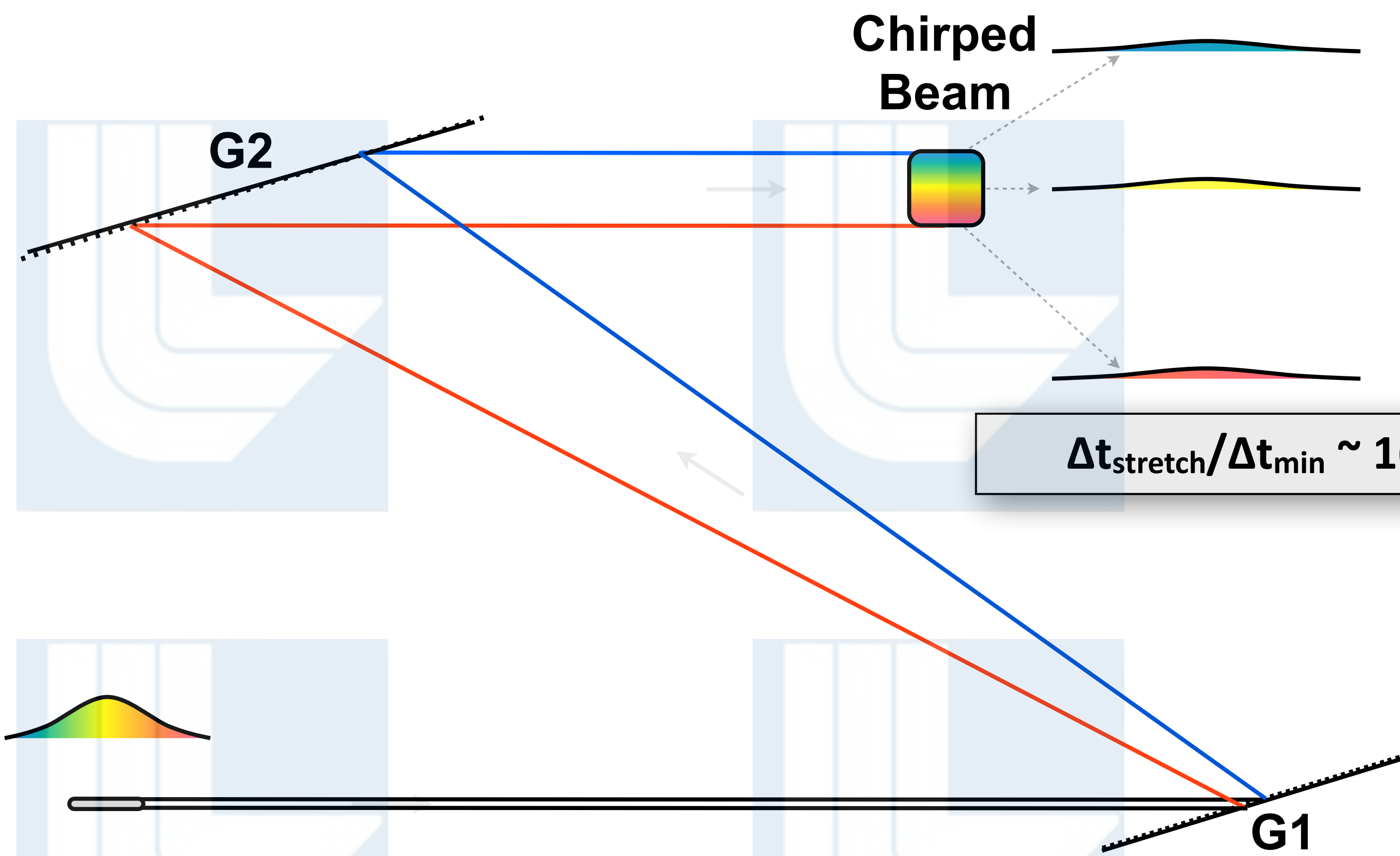
For small enough input beams, a uniform, long-duration "chirped" beam results



$\Delta t_{stretch}/\Delta t_{min}$ ~ 40 in 1D for NIF

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

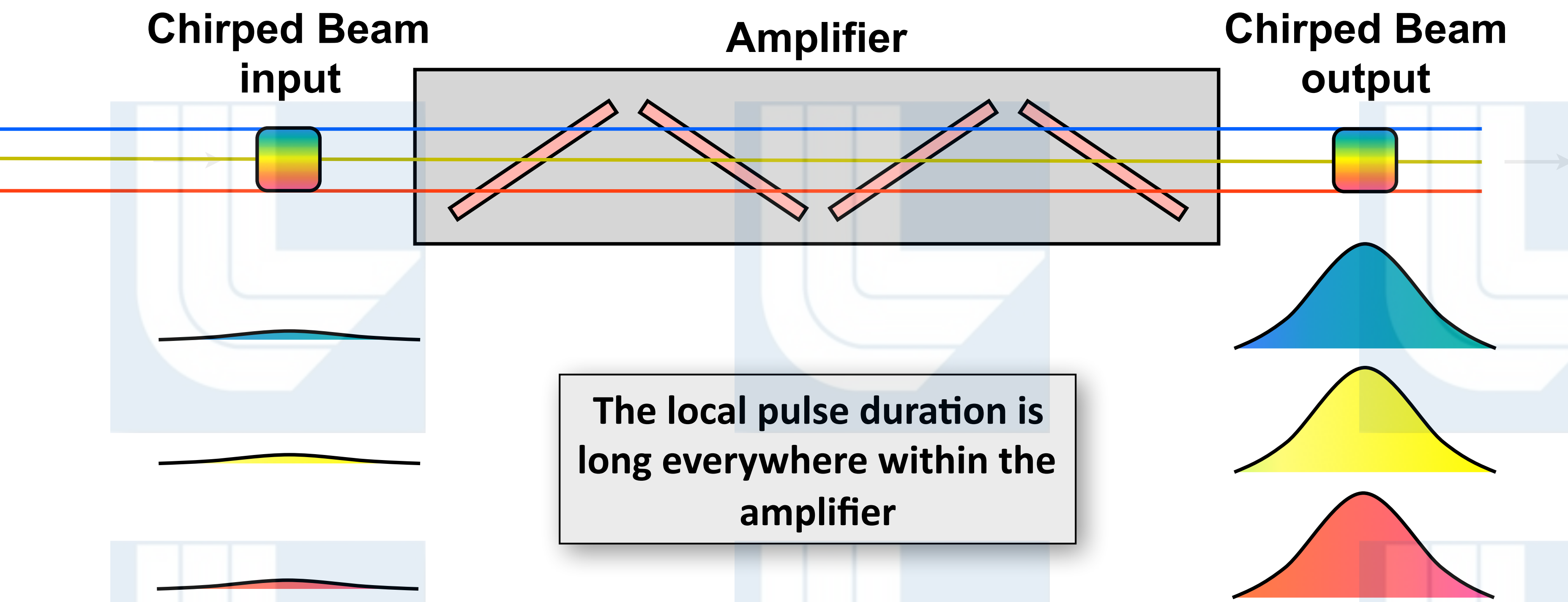
For small enough input beams, a uniform, long-duration “chirped” beam results



$\Delta t_{stretch}/\Delta t_{min}$ ~ 1600 in 2D for NIF

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

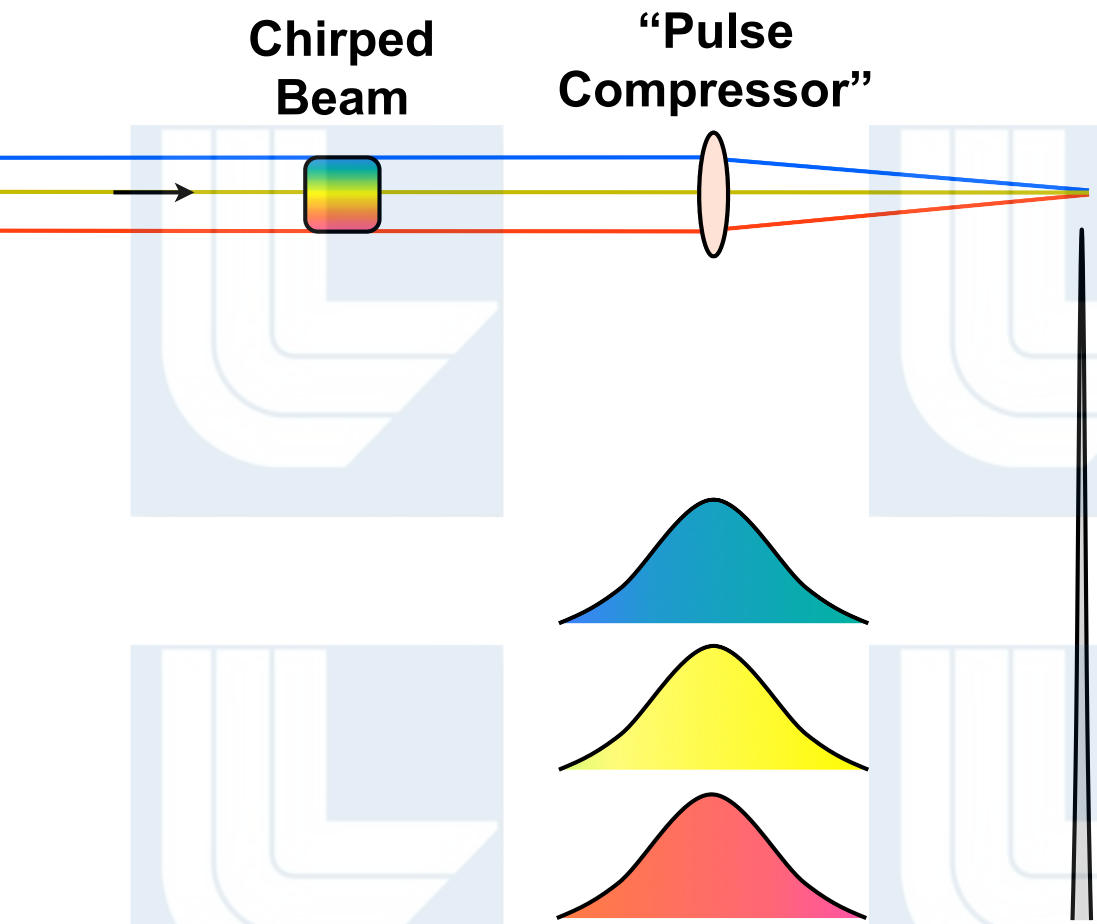
As in CPA, amplification of a "chirped beam" avoids intensity dependent amplifier damage



The local pulse duration is long everywhere within the amplifier

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

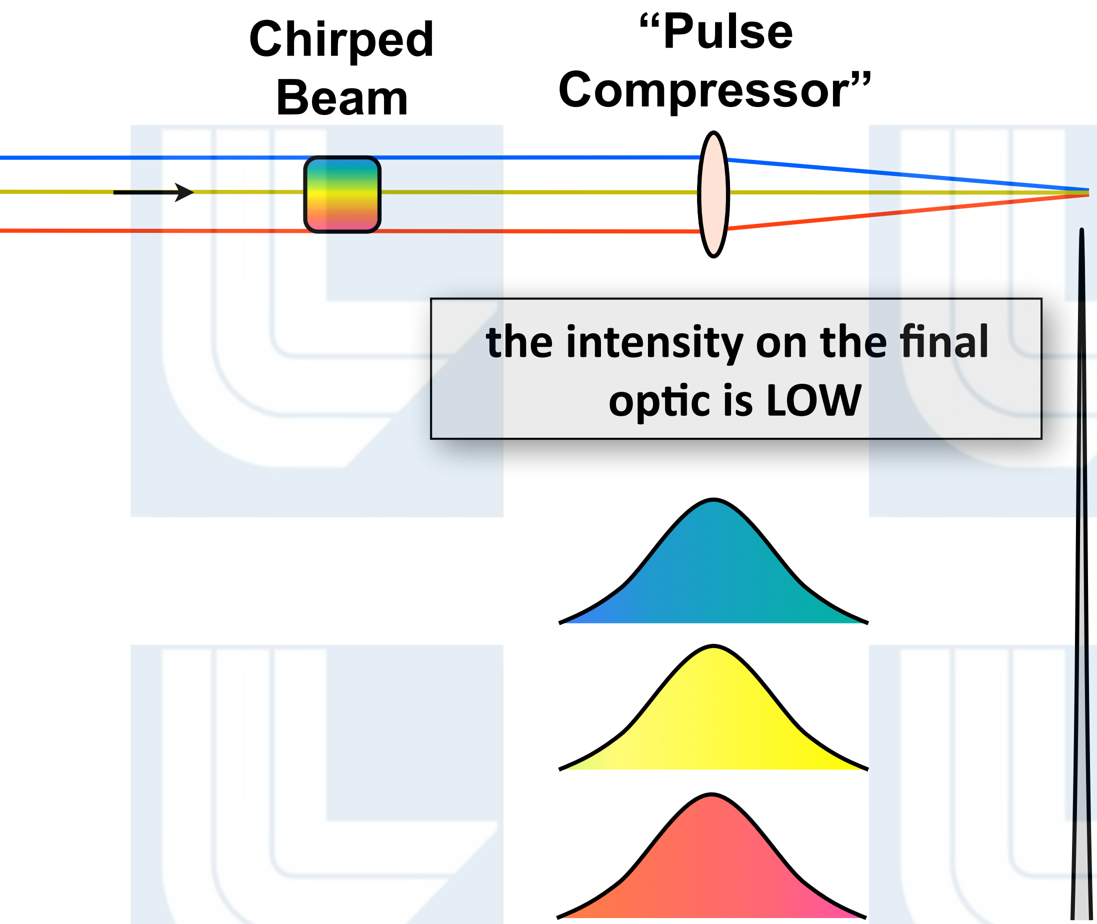
However the "pulse compressor" for a chirped beam can be a simple "lens"



All frequencies coherently overlap at the focus and are properly phased to produce a short duration pulse

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

However the "pulse compressor" for a chirped beam can be a simple "lens"

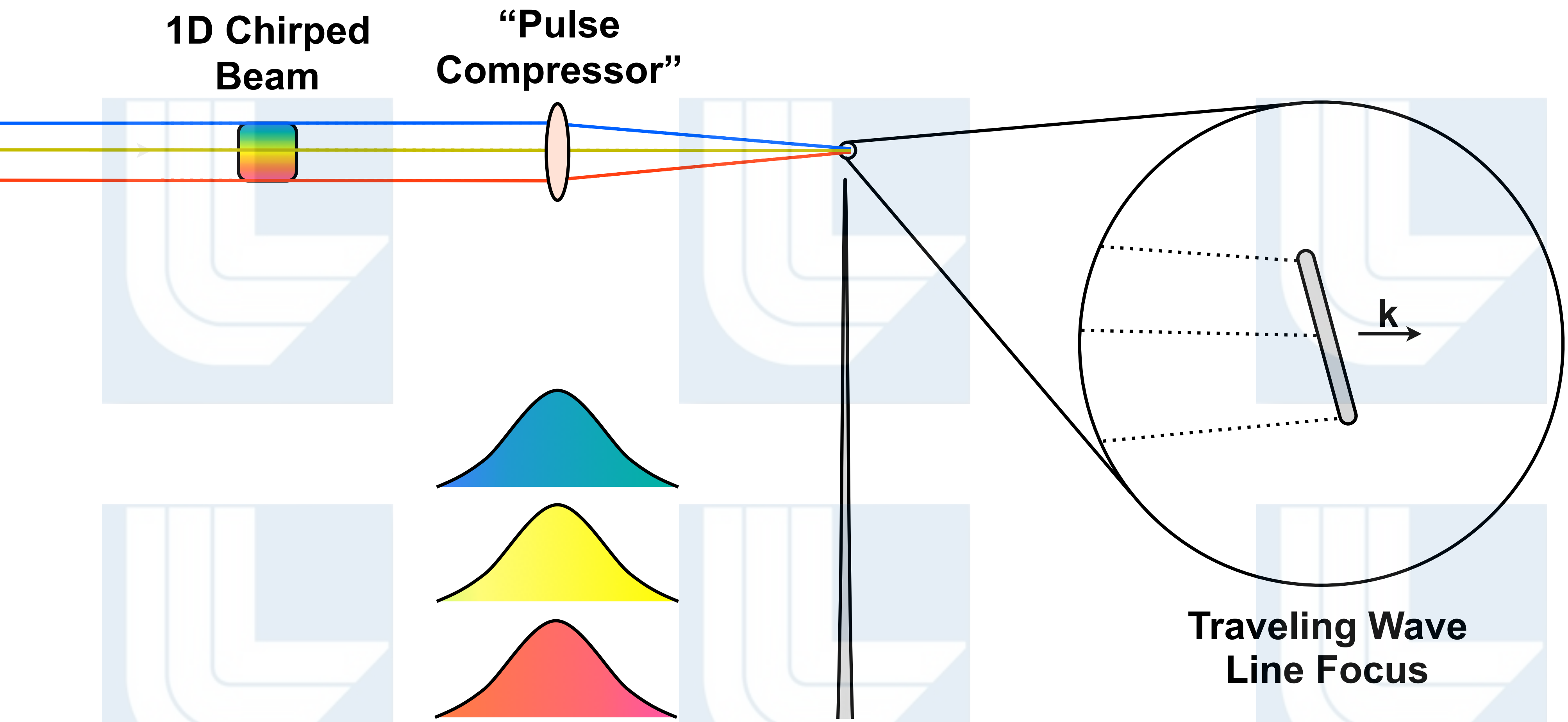


All frequencies coherently overlap at the focus and are properly phased to produce a short duration pulse

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

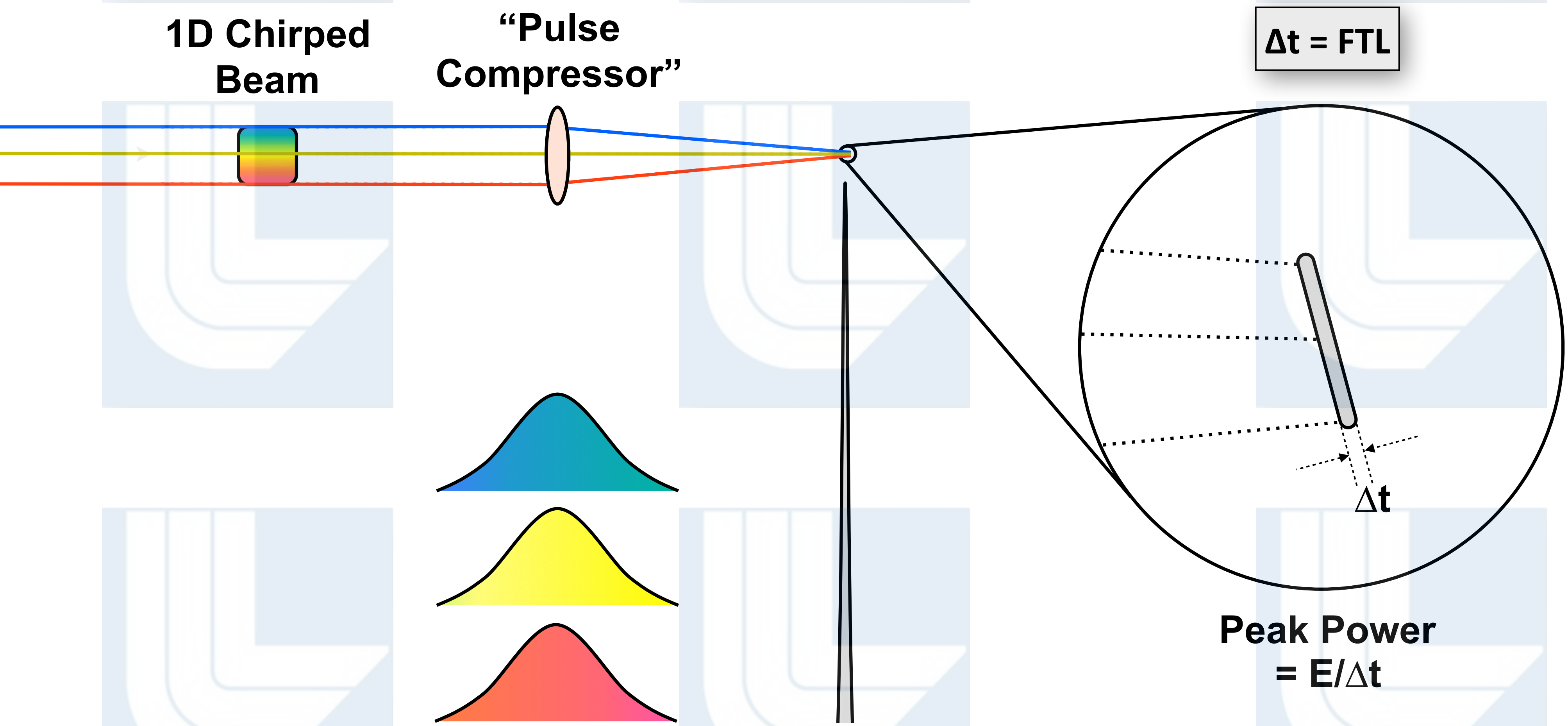
Theoretically a multiplexed Chirped Beam Amplification system using the ARC front end & NIF amplifiers could produce > 25 PW/beam or 4.8 EW

Unfortunately, the focus of a chirped beam does not produce high intensity



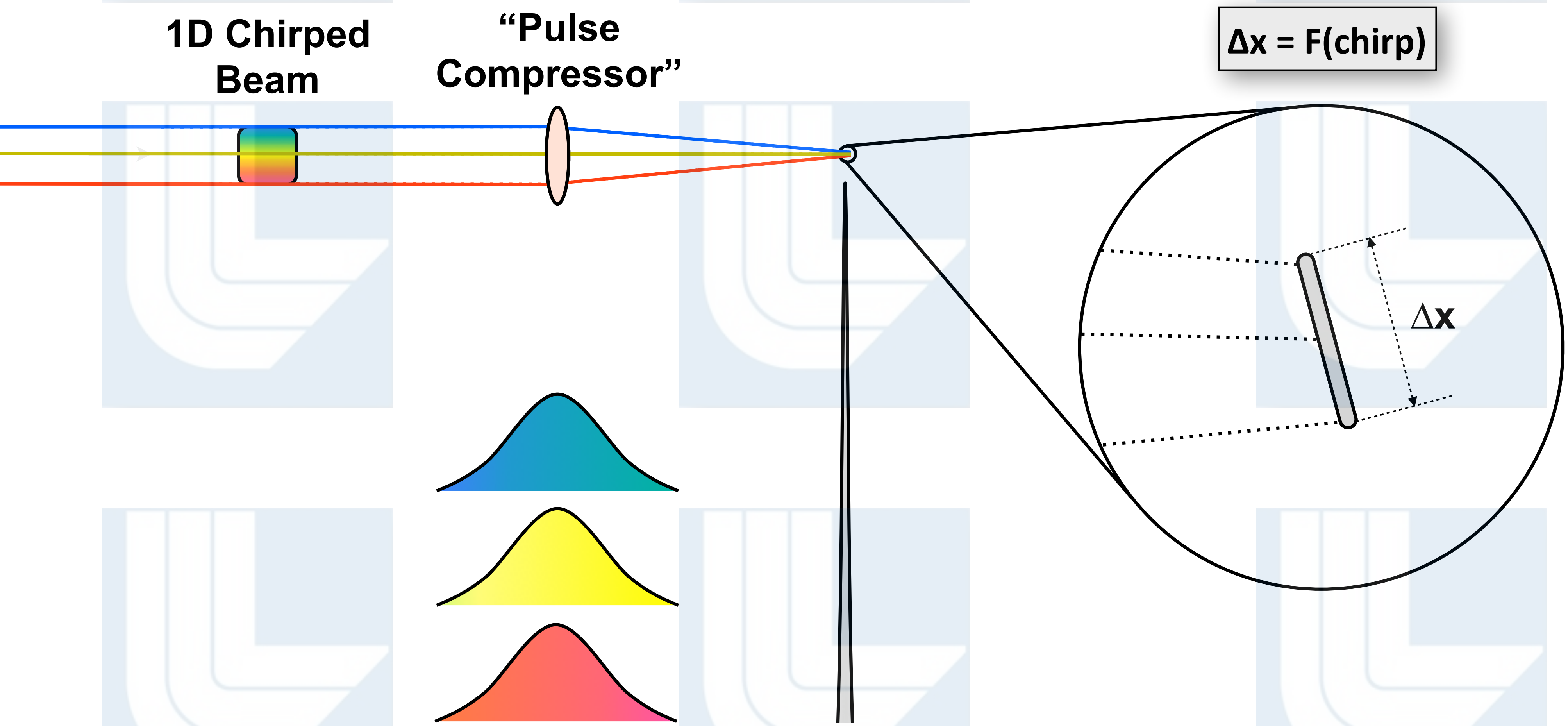
US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

The duration of the of the line focus is the Fourier limit of the total input bandwidth



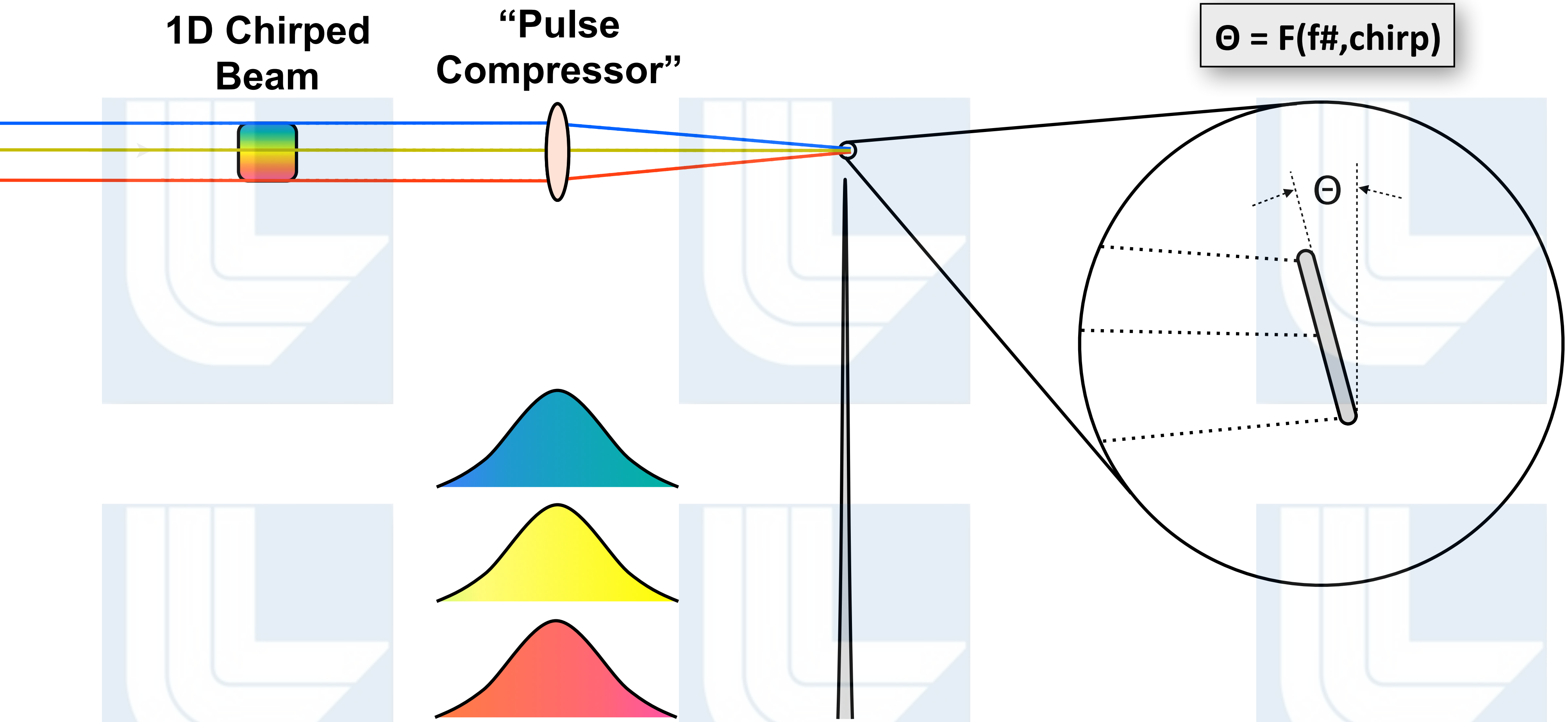
US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

The width of the line focus is a function of the beam chirp



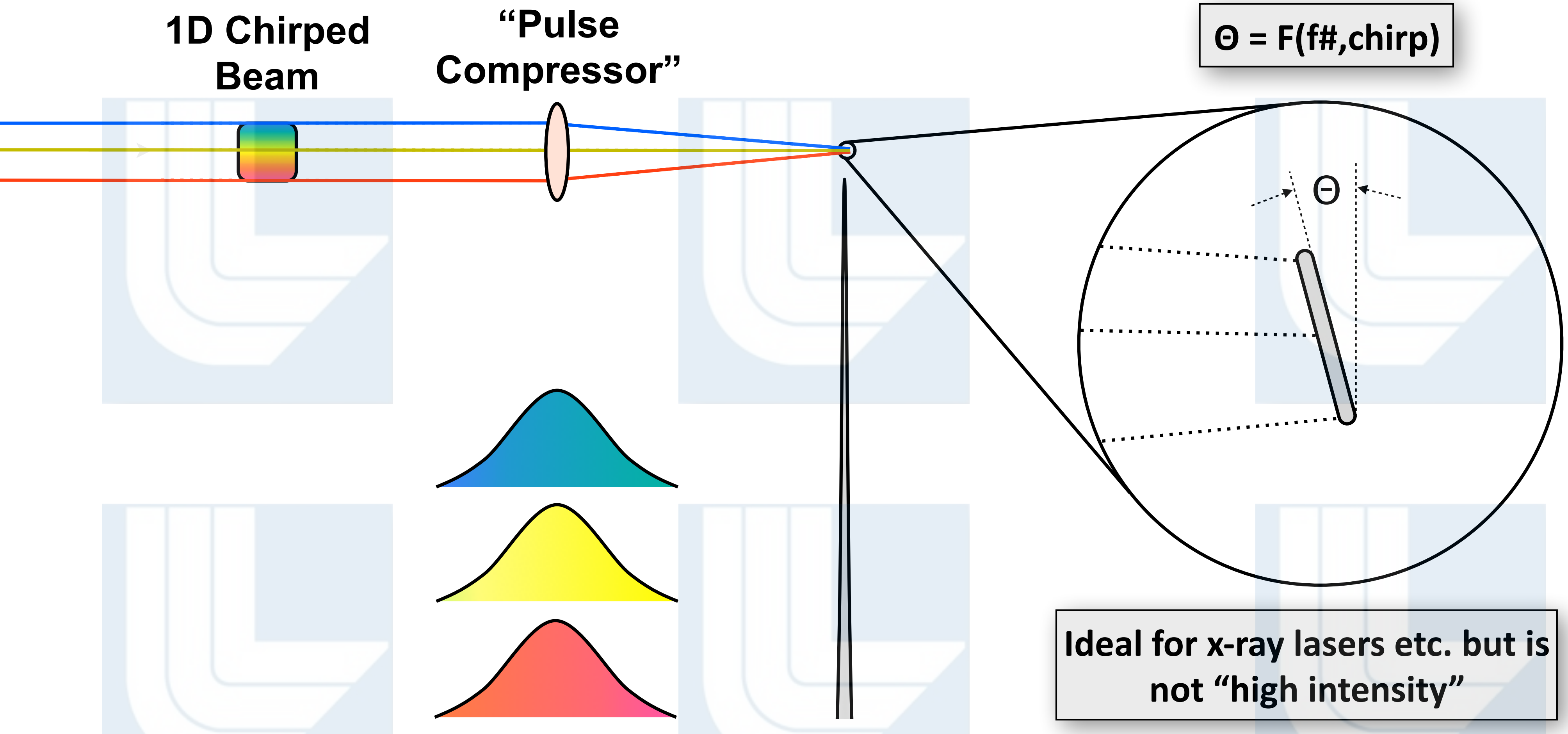
US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

The tilt of the line focus is a function of the f-number and beam chirp



US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

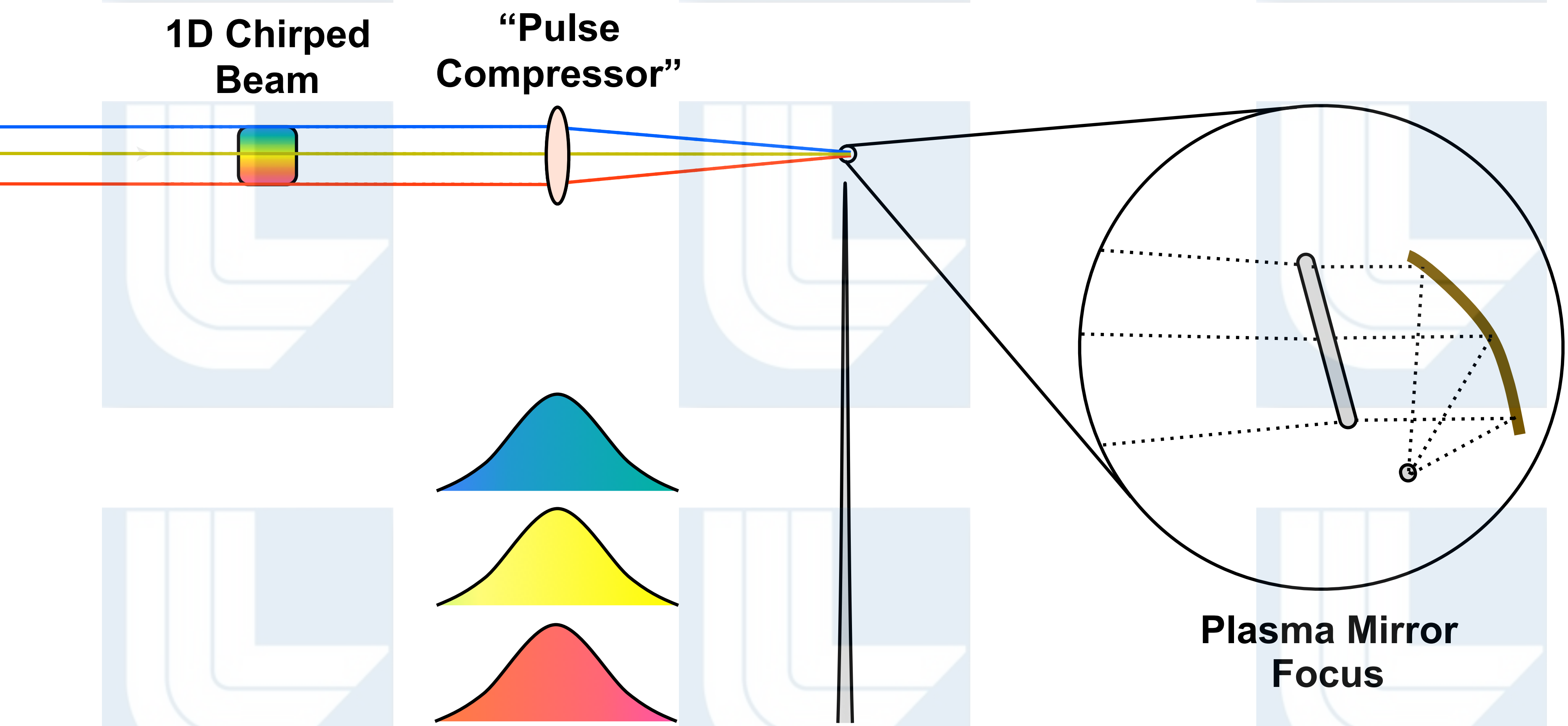
The tilt of the line focus is a function of the f-number and beam chirp



Ideal for x-ray lasers etc. but is not "high intensity"

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

A non-imaging concentrator, plasma mirror however might enable high intensity



US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

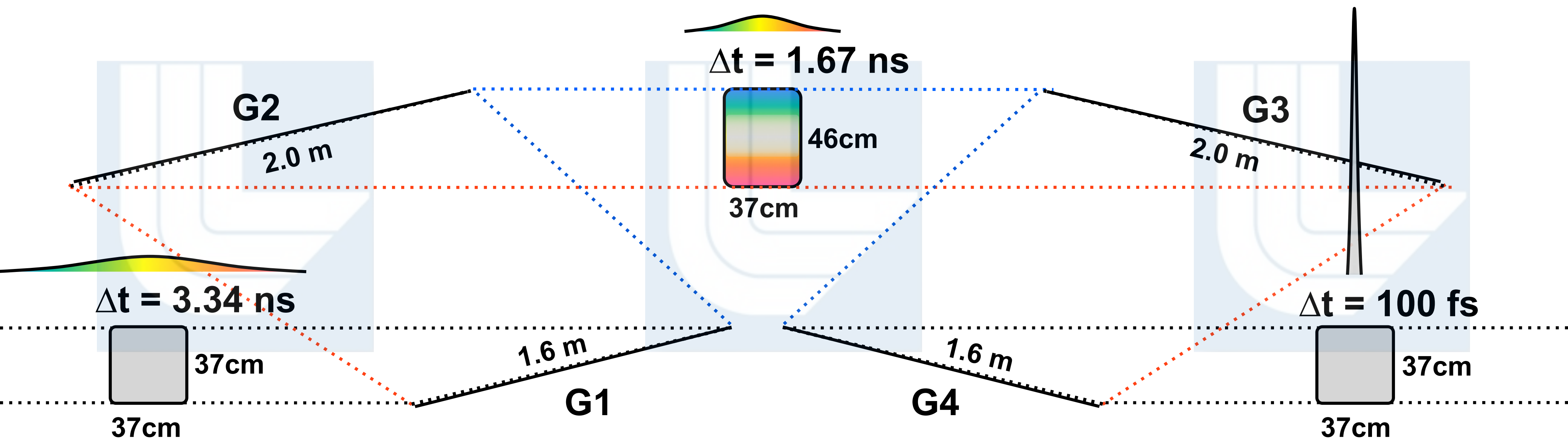
Formula for a "high intensity" NIF Exawatt:

- Use mixed media amplifiers to enable shorter pulses
- Upgrade grating fabrication from 0.9m to ~2m
- Combine chirped pulse AND chirped beam amplification
- Create multiple beams before final pulse compression
- Coherently add the compressed beams

Formula for a "high intensity" NIF Exawatt:

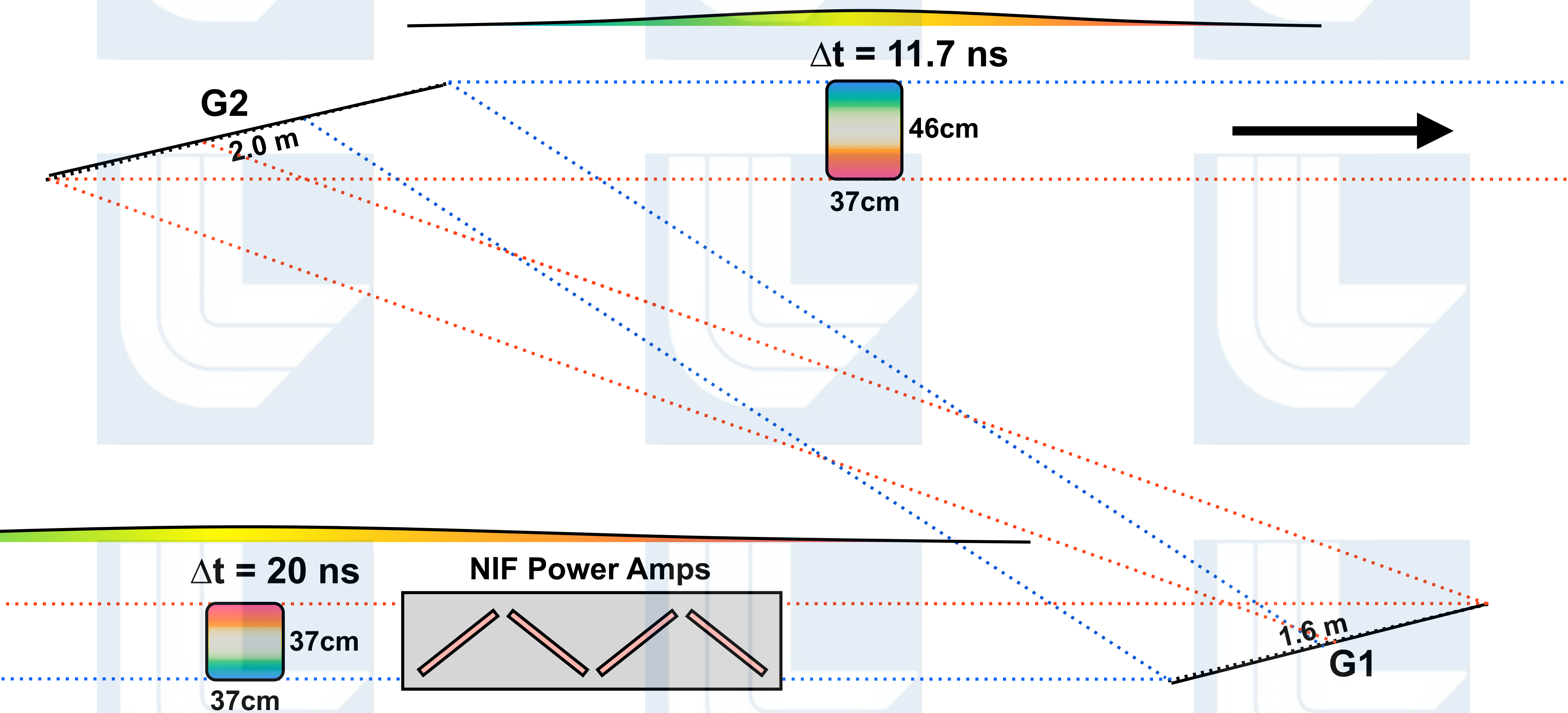
- Use mixed media amplifiers to enable shorter pulses
- **Upgrade grating fabrication from 0.9m to ~2m**
- **Combine chirped pulse AND chirped beam amplification**
- Create multiple beams before final pulse compression
- Coherently add the compressed beams

Full beam chirped pulse amplification with 2 m wide gratings ...



... would enable extraction of ~ 3kJ or 2x more energy than ARC

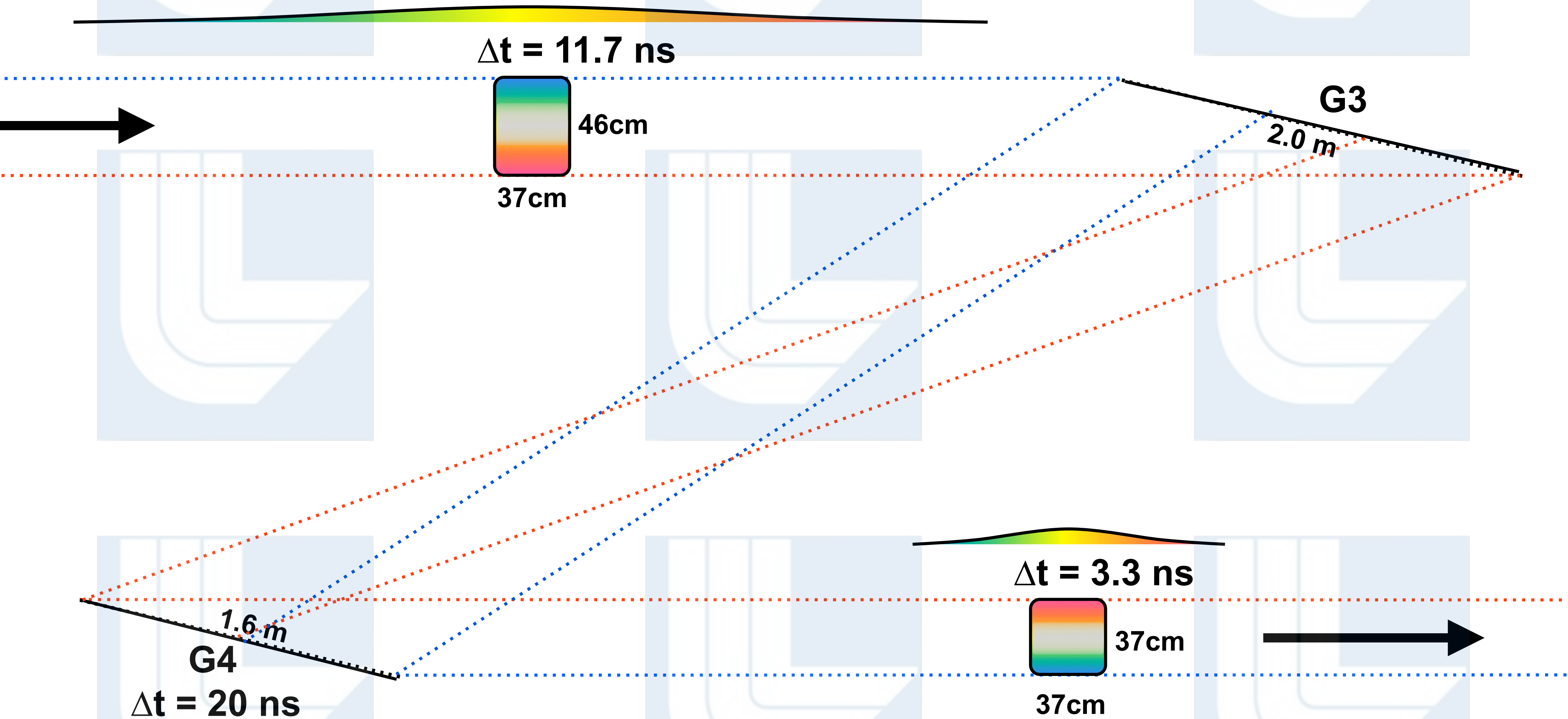
However, chirped pulse + chirped beam amplification …



… would enable full extraction of 25 kJ from one NIF beam line

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

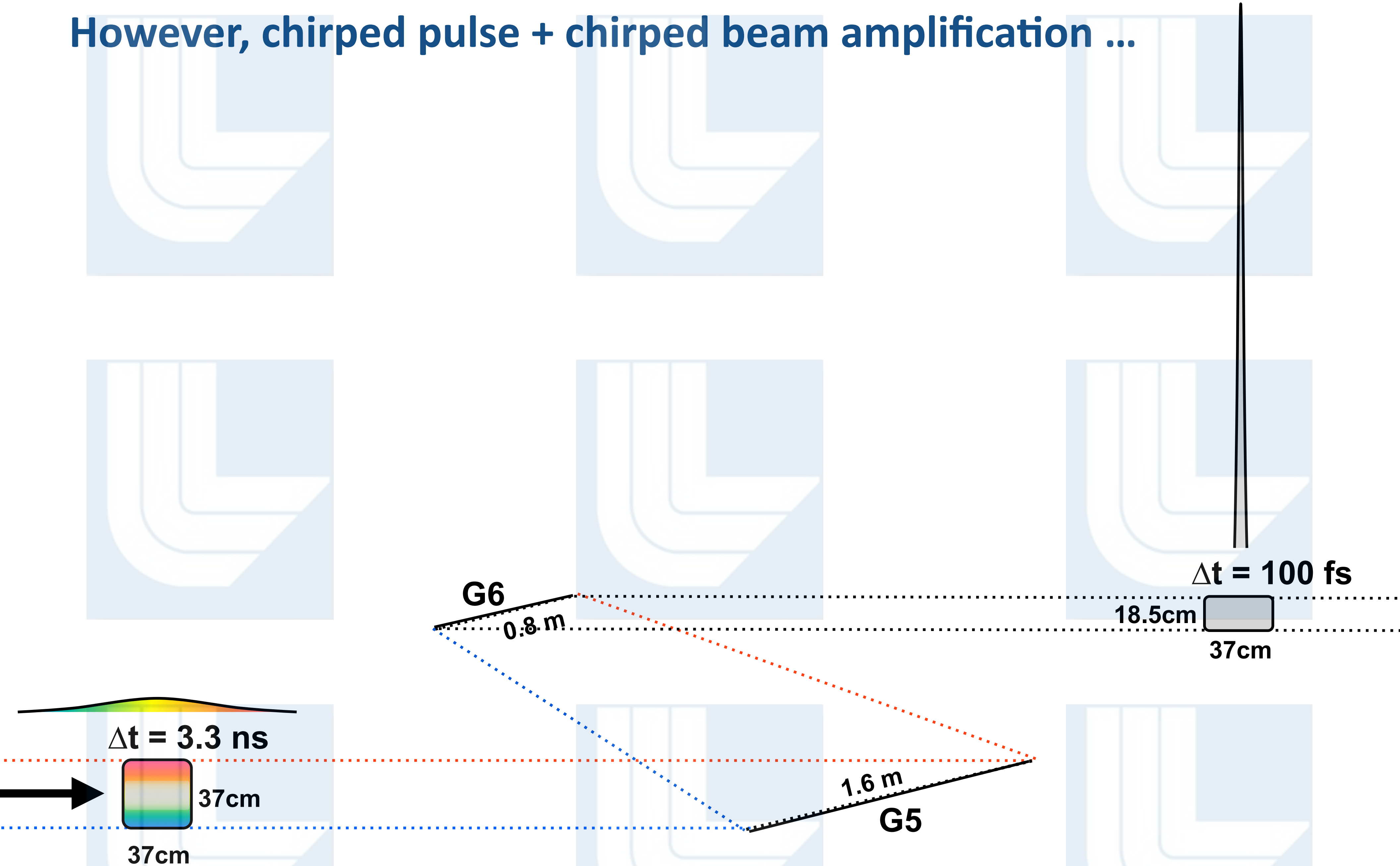
However, chirped pulse + chirped beam amplification …



… would enable full extraction of 25 kJ from one NIF beam line

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

However, chirped pulse + chirped beam amplification ...

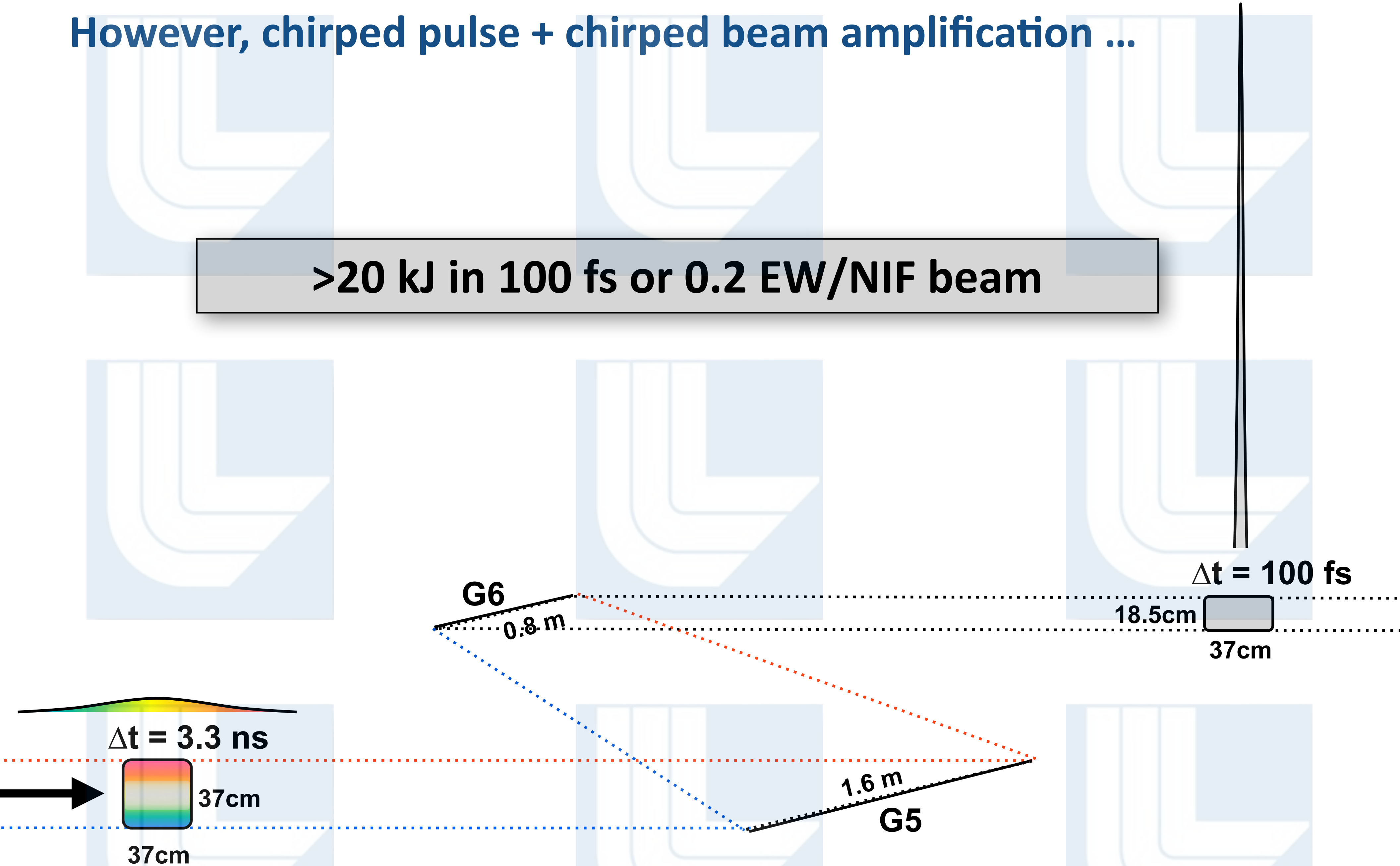


... would enable full extraction of 25 kJ from one NIF beam line

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

However, chirped pulse + chirped beam amplification …

>20 kJ in 100 fs or 0.2 EW/NIF beam



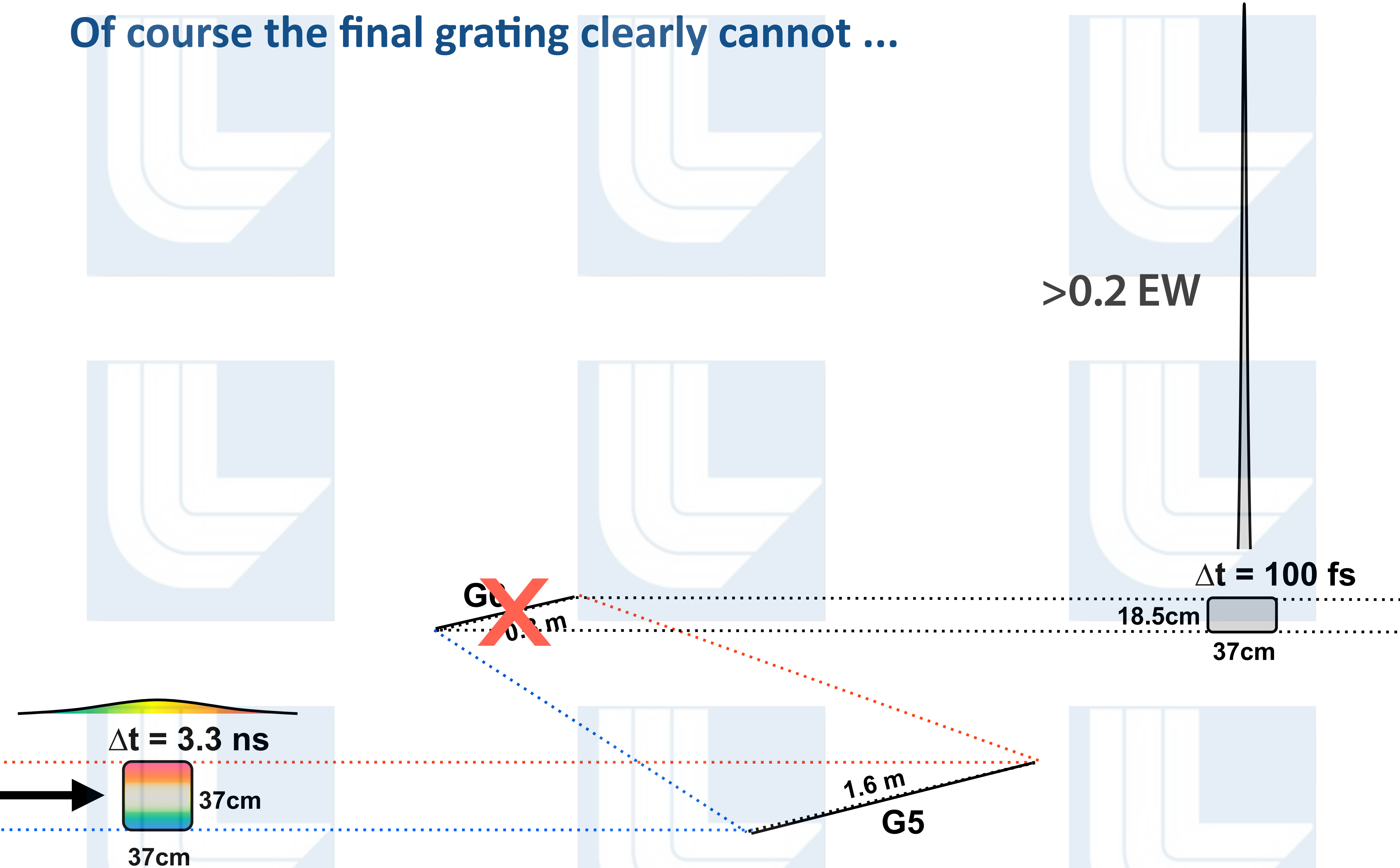
… would enable full extraction of 25 kJ from one NIF beam line

US Patent 6804045 B2, Barty, C. P. J. (2004). Optical Chirped Beam Amplification and Propagation.

Formula for a "high intensity" NIF Exawatt:

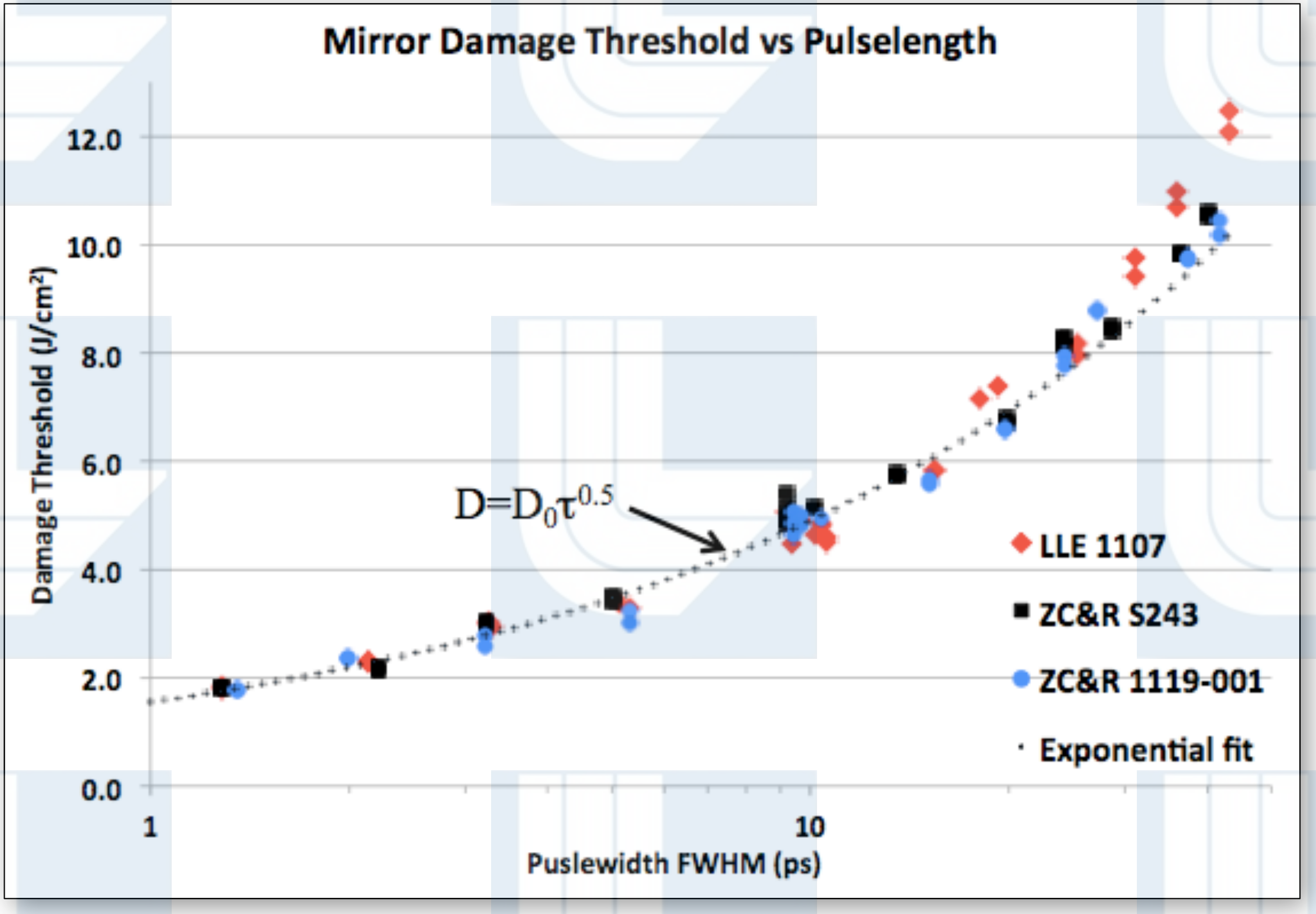
- Use mixed media amplifiers to enable shorter pulses
- Upgrade grating fabrication from 0.9m to ~2m
- Combine chirped pulse AND chirped beam amplification
- **Create multiple beams before final pulse compression**
- Coherently add the compressed beams

Of course the final grating clearly cannot ...



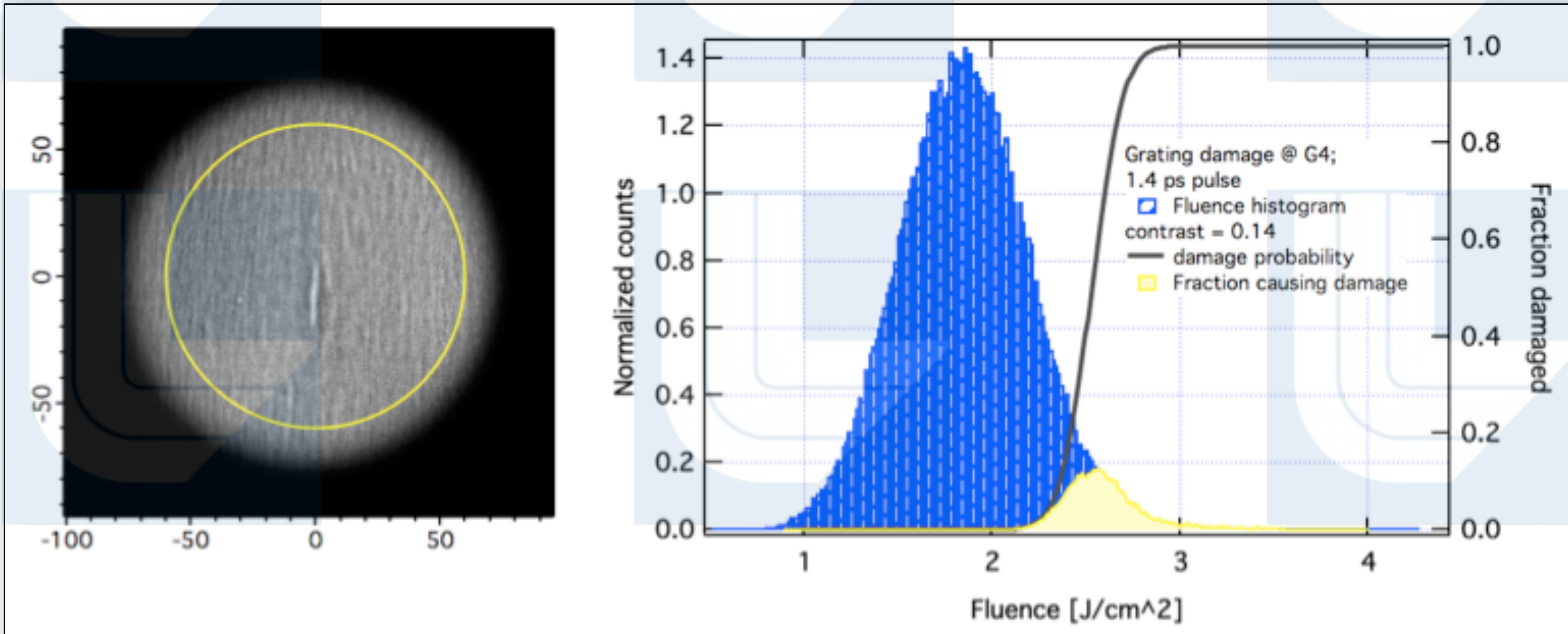
... handle a >20 kJ, 100 fs pulse!!!

Final optic damage limits machine performance



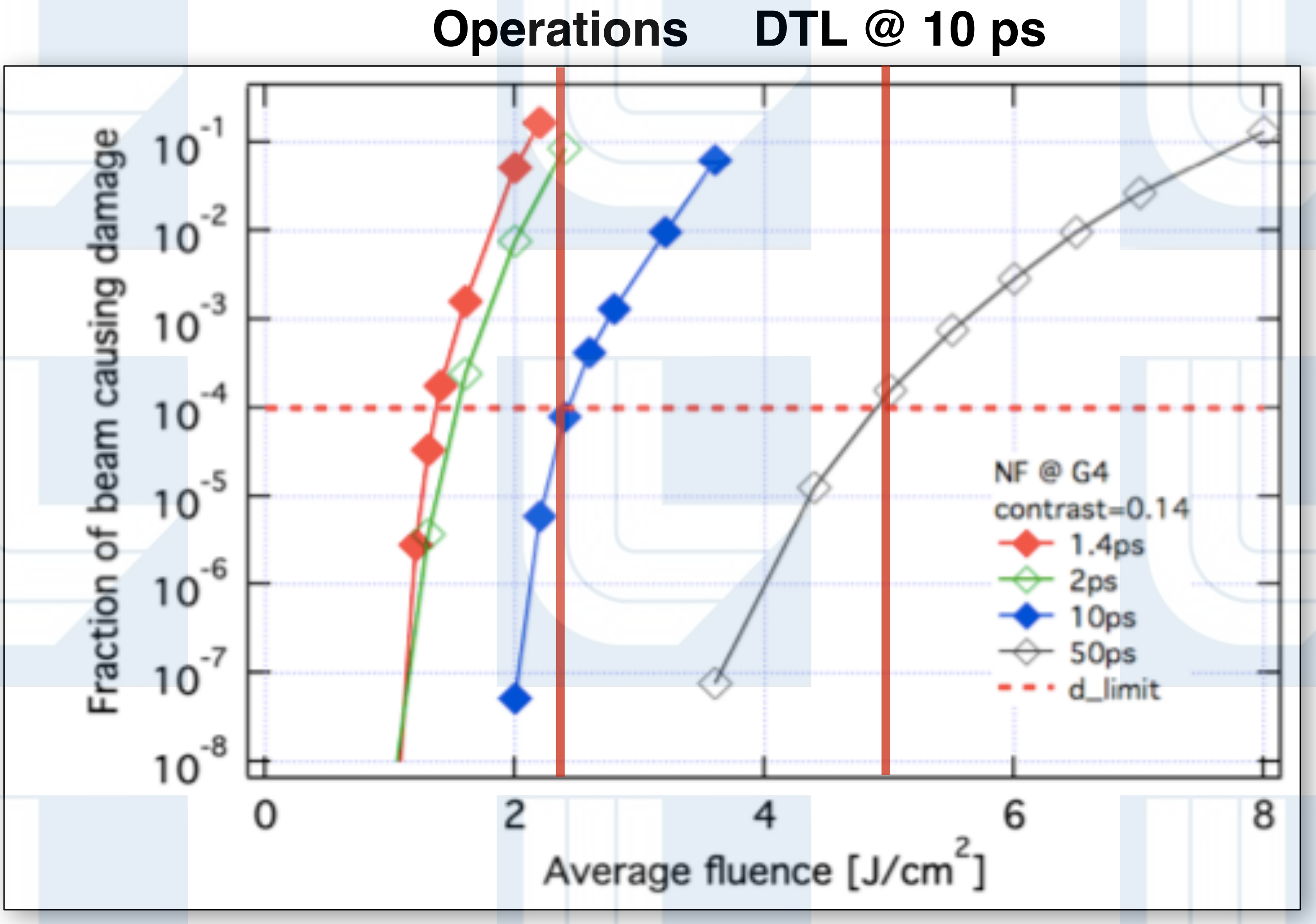
"Damage Threshold" = unity probability of damage !!!

Real systems with real beam contrast must ...



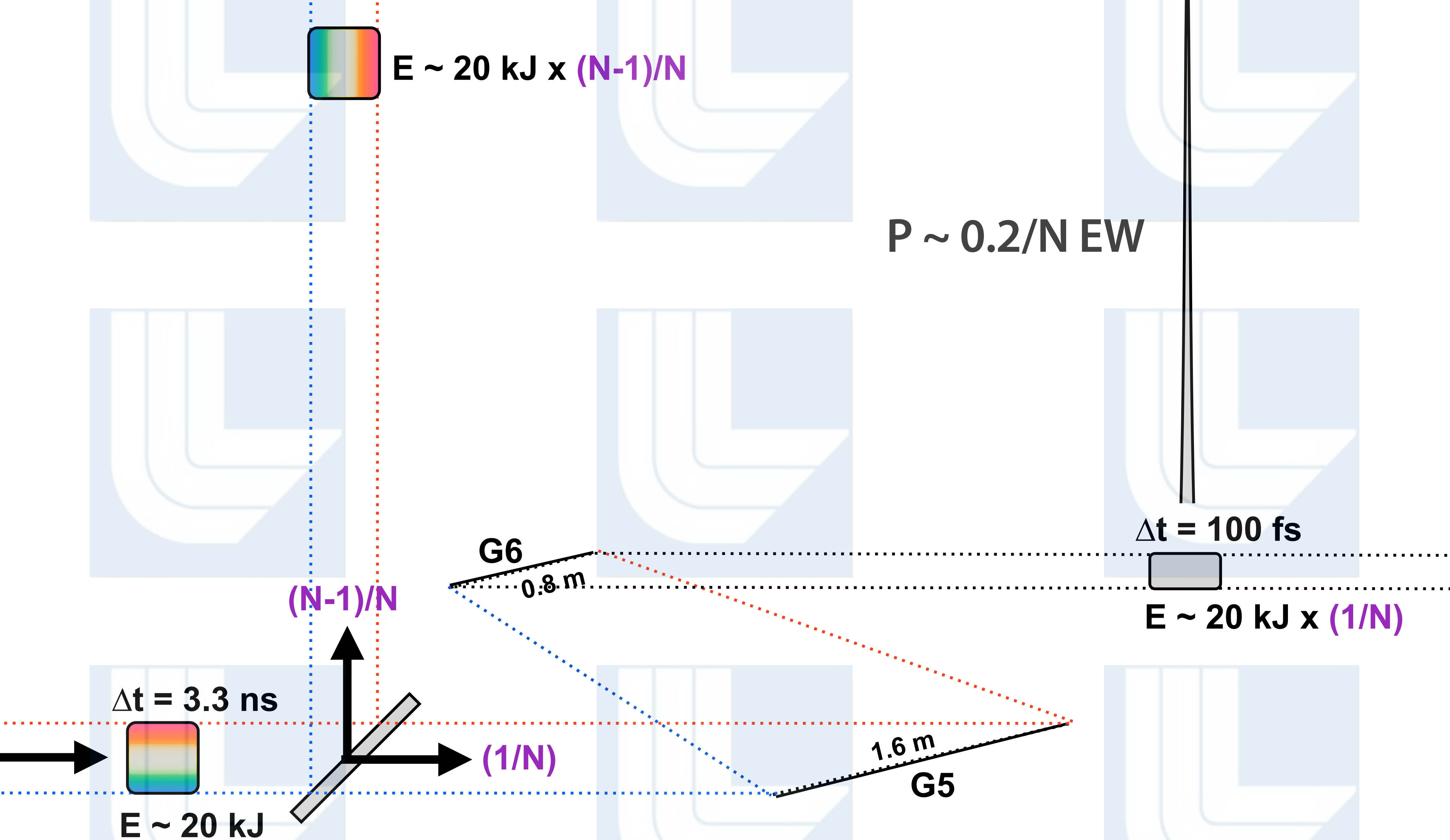
... operate below the damage threshold limit

For ARC, an operating point at which ...



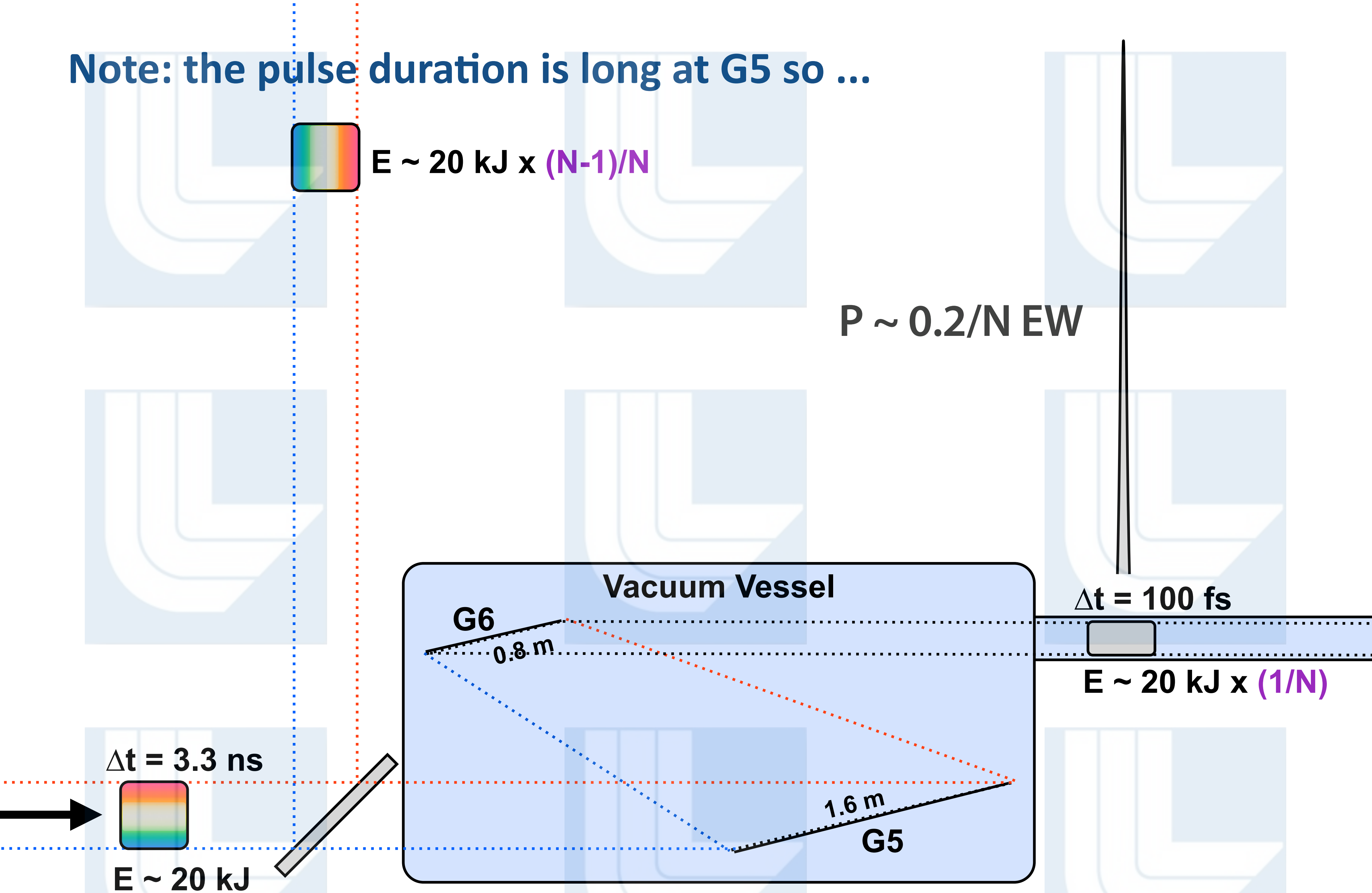
... optic damage is < 10^{-4} per shot is chosen

Beam splitting "N" times before compression ...



... enables safe operation of G6

Note: the pulse duration is long at G5 so ...

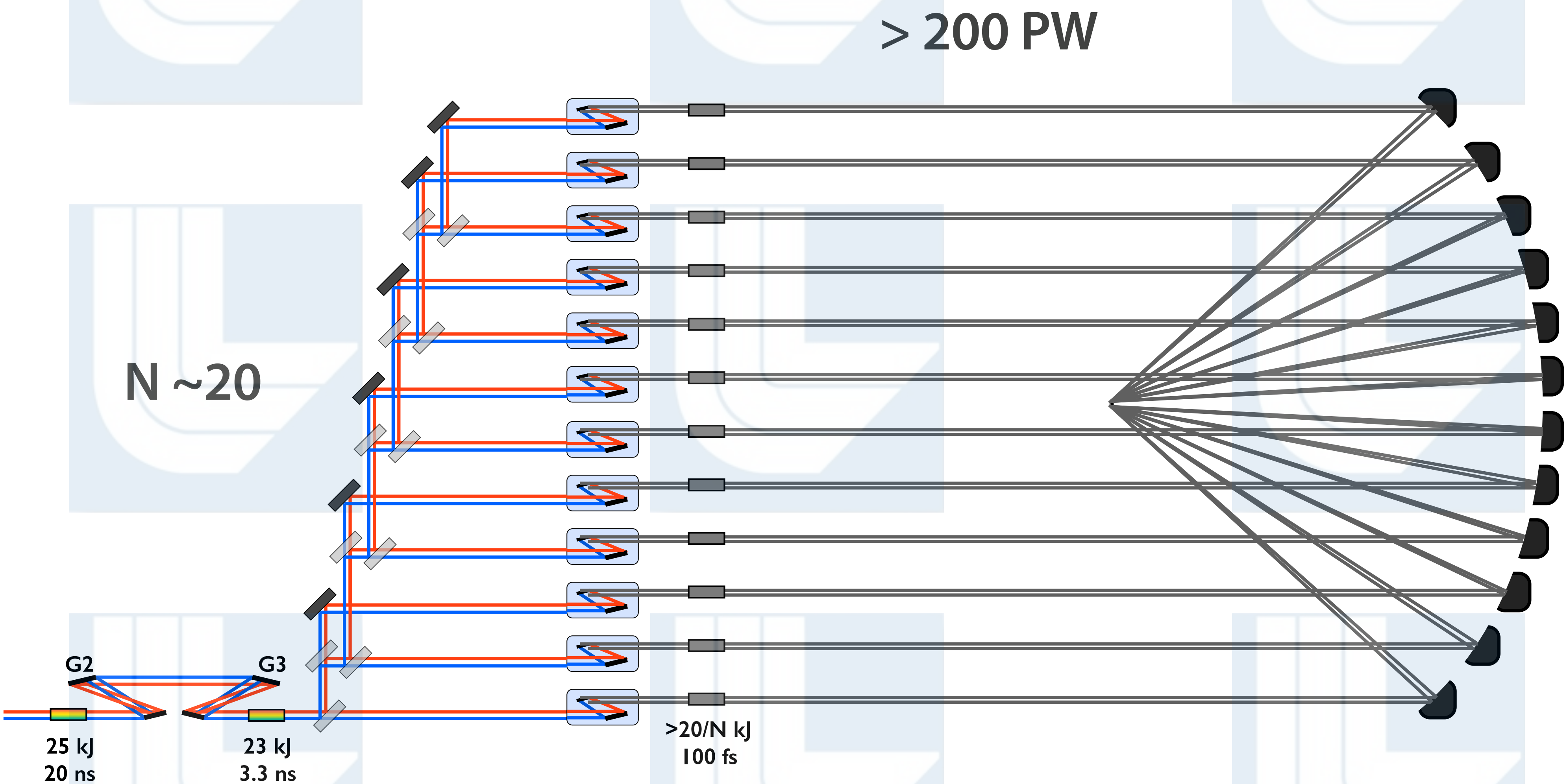


... only the last 2 gratings need to be in vacuum

Formula for a “high intensity” NIF Exawatt:

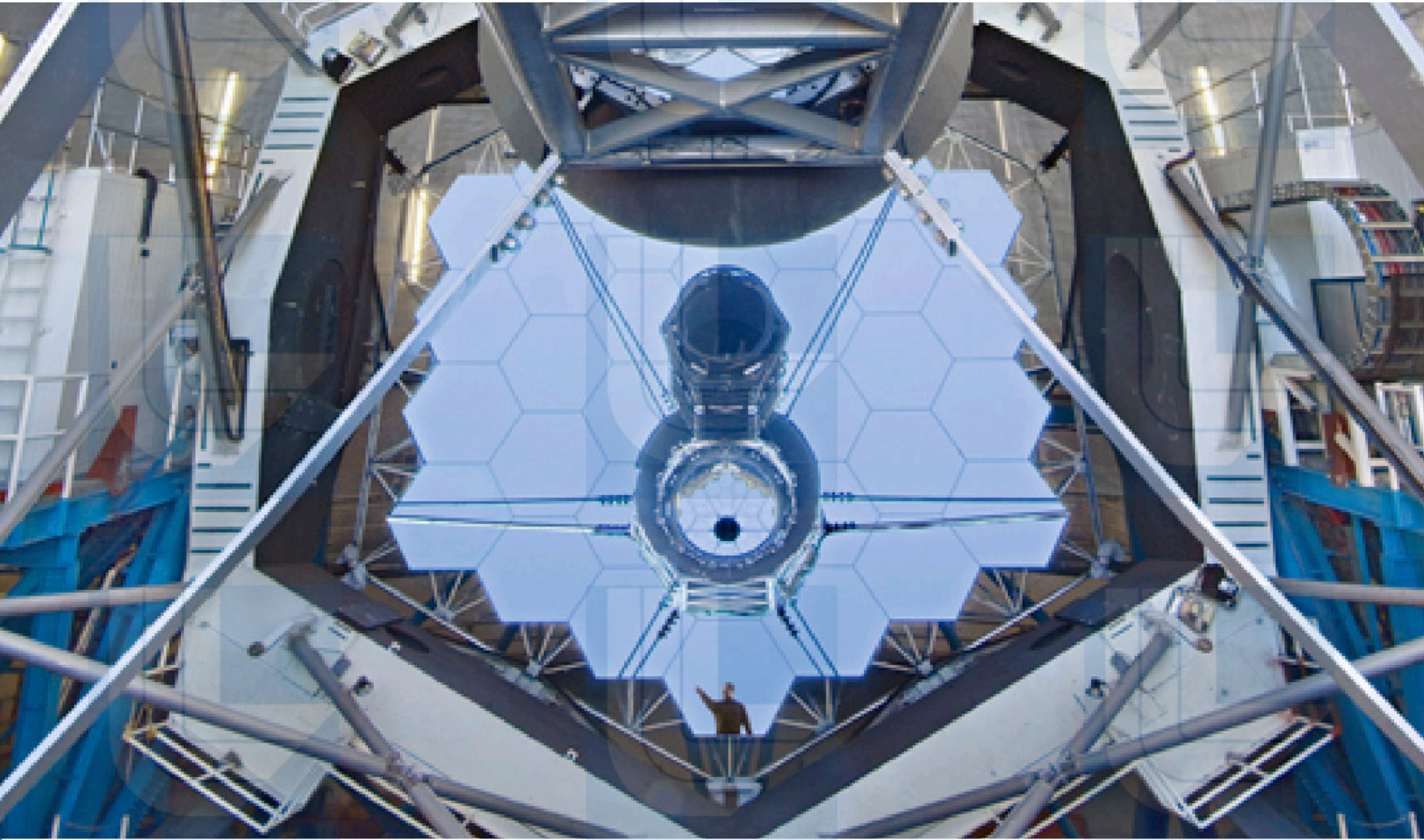
- Use mixed media amplifiers to enable shorter pulses
- Upgrade grating fabrication from 0.9m to ~2m
- Combine chirped pulse AND chirped beam amplification
- Create multiple beams before final pulse compression
- **Coherently add the compressed beams**

The Nexawatt focusing system would coherently ...

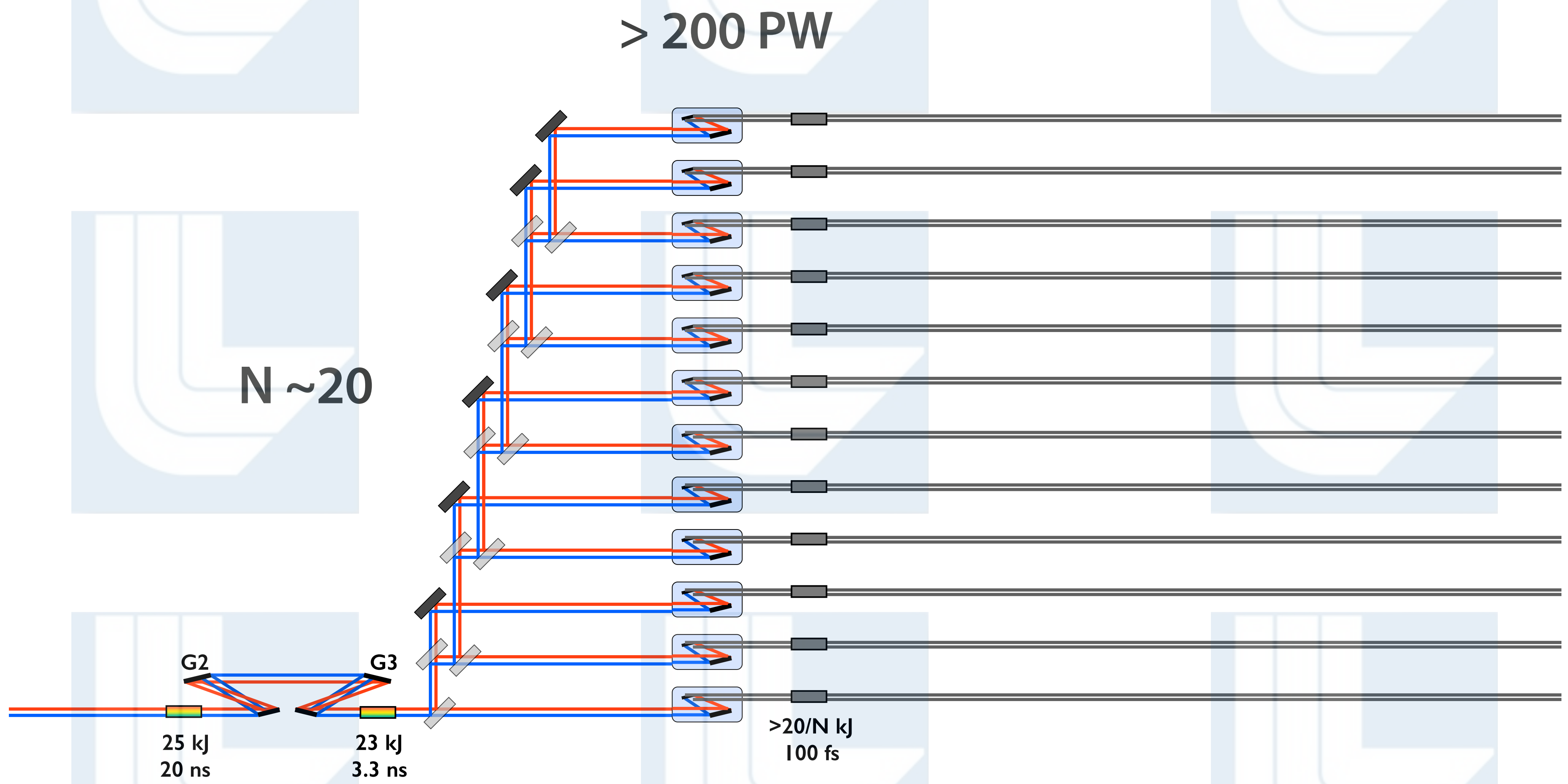


... combine N identical beams AFTER amplification

Nexawatt beam phasing tasks are similar in many ways to those already solved by the large telescope community



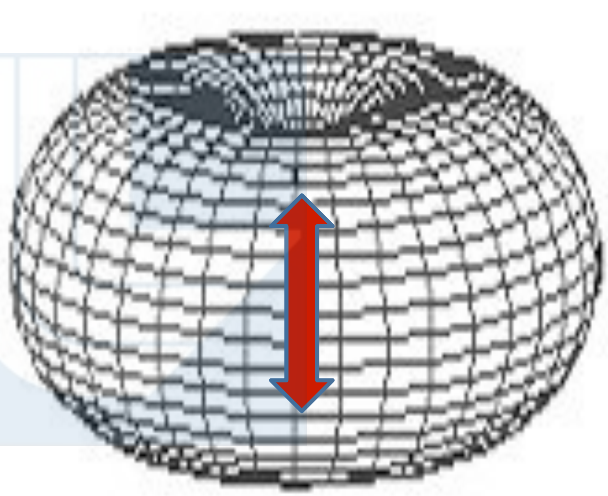
The Nexawatt architecture is also compatible ...



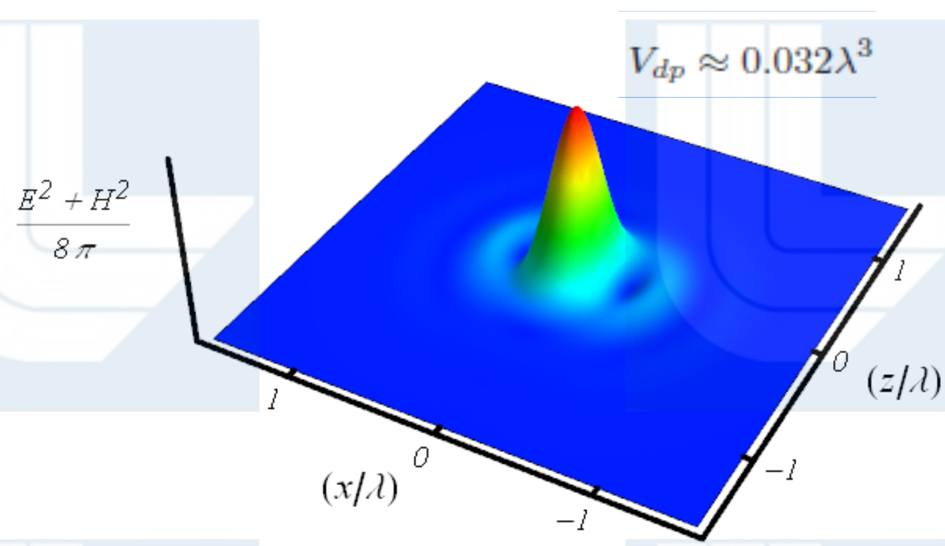
... with "other" focusing arrangements

A converging dipole wave creates ...

Converging dipole wave maximizes focal intensity and is an exact solution to Maxwell's equations



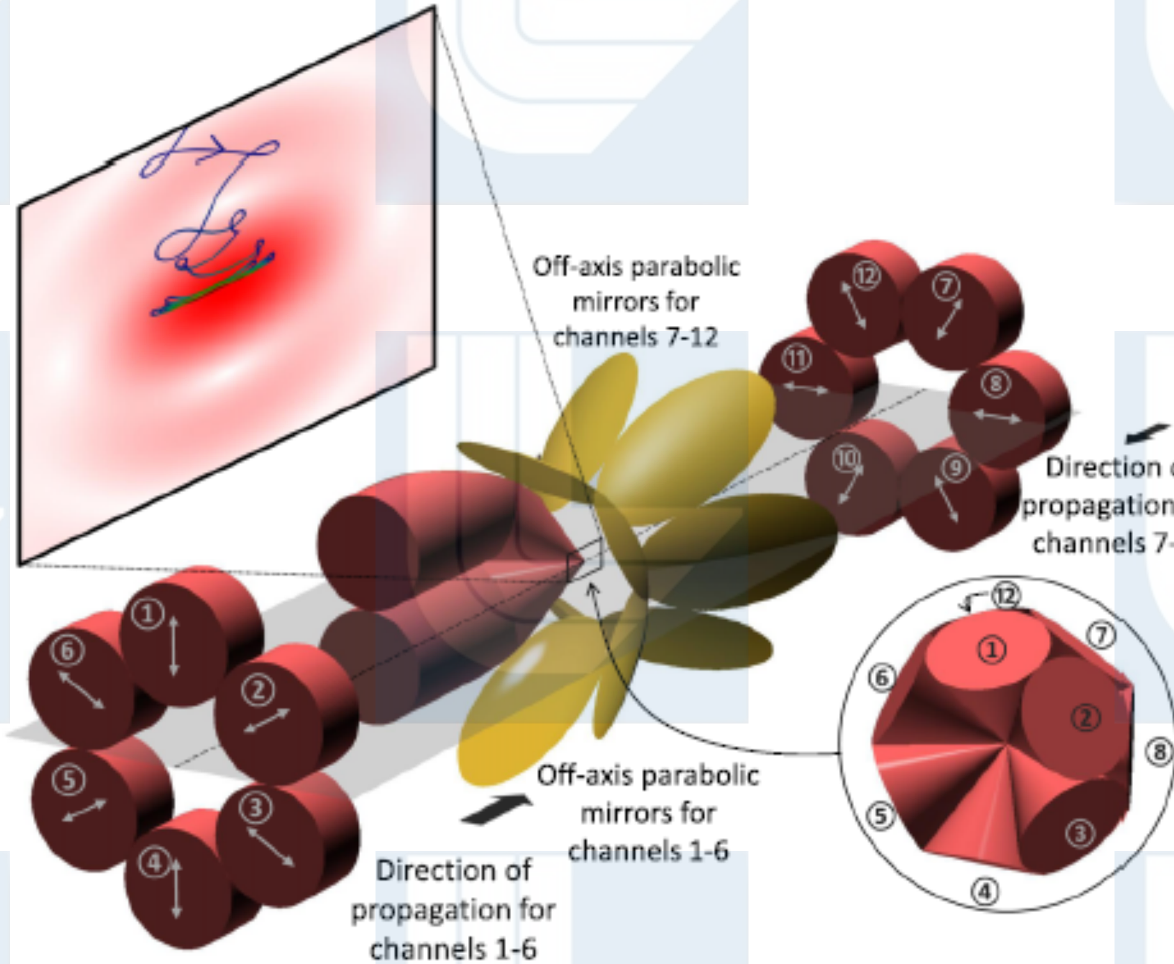
Minimum focusing volume



... the minimum possible focal volume

I. Gonoskov, A. Aiello, S. Heugel, and G. Leuchs, Phys. Rev. A (2012)

Dipole focusing can be approximated ...



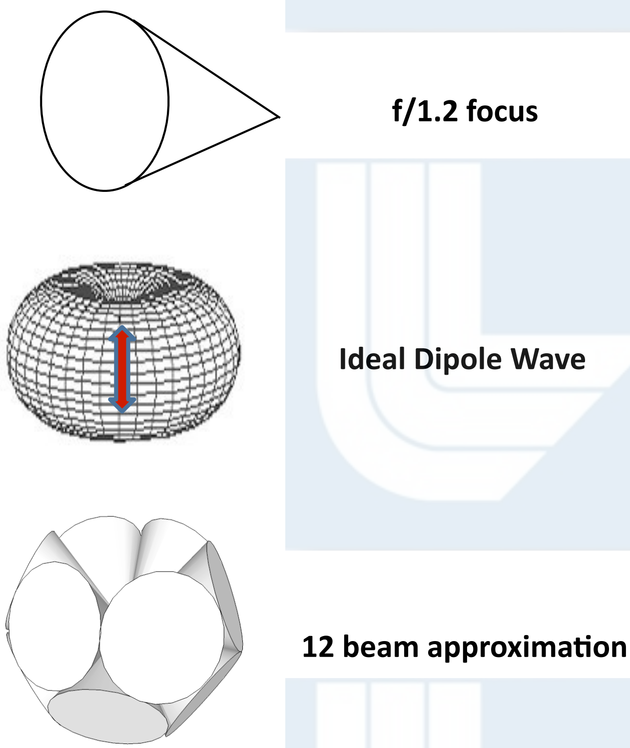
... with as few as a dozen beams

A.Gonoskov, A. Bashinov, I. Gonoskov, C. Harvey, A. Ilderton,A. Kim, M. Marklund, G. Mourou, and A. Sergeev Phys.Rev.Lett. 113, 014801 (2014)

Dipole-wave focusing enables "EW" intensity ...

Geometry	Intensity, $\times 10^{25}$W/cm^2	I/I(f=1.2)	Equivalent power (f=1.2)
Single beam (f=1.2)	1.2	1	200 PW
Dipole-Wave	16.7	13.9	2.8 EW
Double-Belt-12 12x (f=0.96)	13.4	11.2	2.2 EW

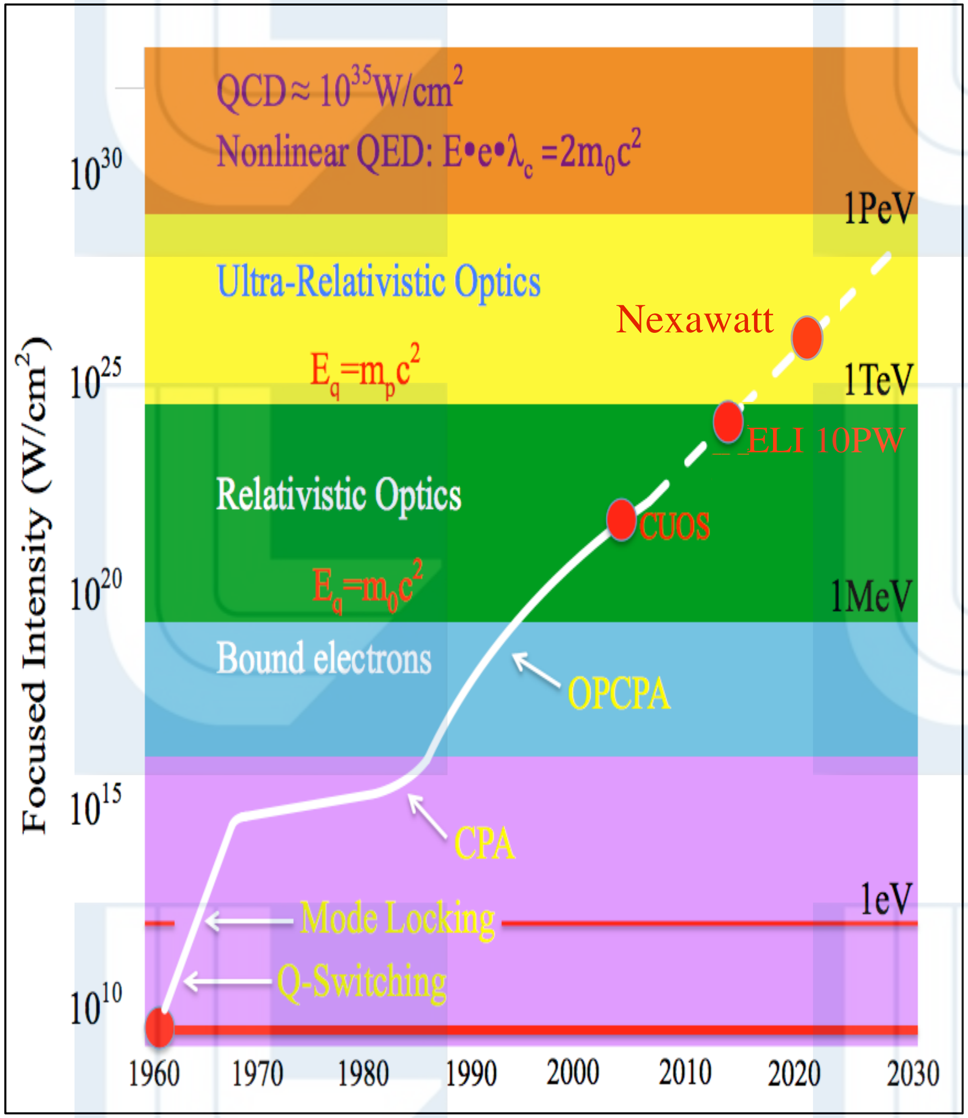
P_{total} = 200 PW



courtesy of Dr. Alexander Sergeev

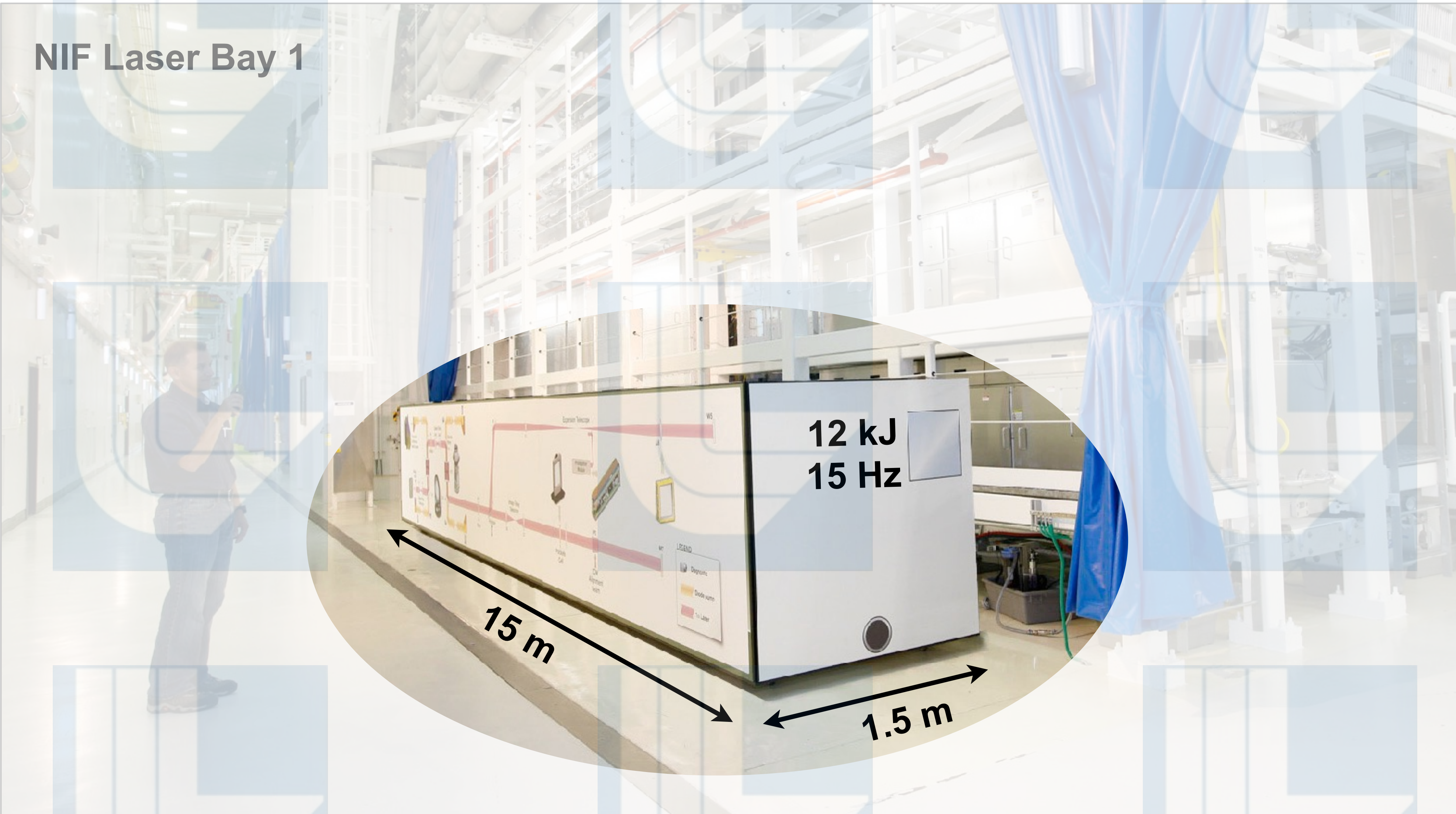
... from a 10x lower peak power system

Nexawatt summary:



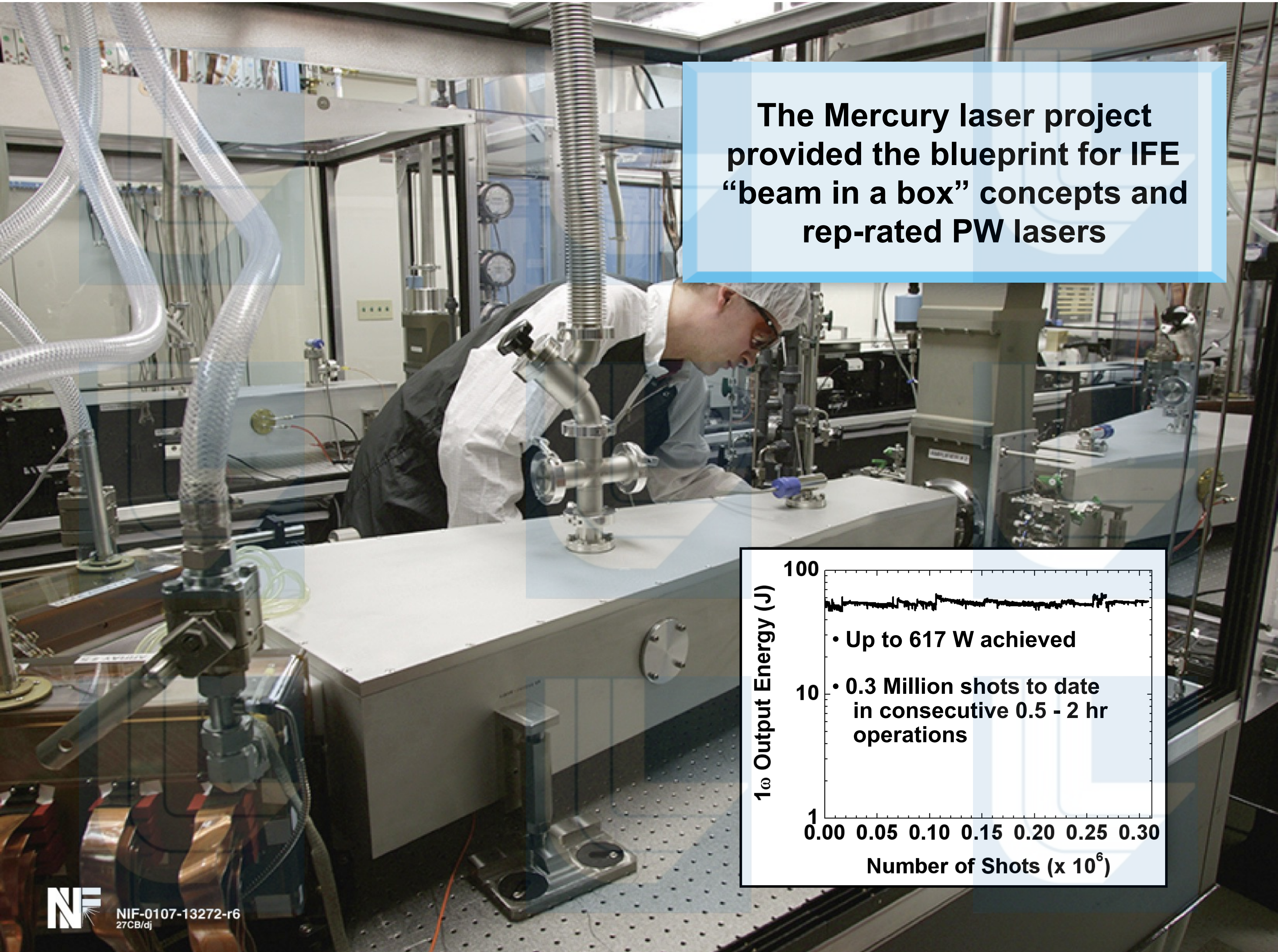
- Uses existing high efficiency, high damage threshold, high dispersion MLD gratings
- Is compatible with existing tools for fabrication of compressor gratings
- Operates within established damage limits
- Requires only two, 2-meter wide gratings
- Extracts all of the NIF beam line stored energy
- Phases "identical" beams created after amplification
- Is compatible with existing beam phasing technologies
- Could produce exawatt-scale intensities from a single, NIF or NIF-like beam line
- Is compatible with high-efficiency, high-repetition, fusion "energy" laser technology

"Beam in a Box" concepts for 100 kW IFE beams ...



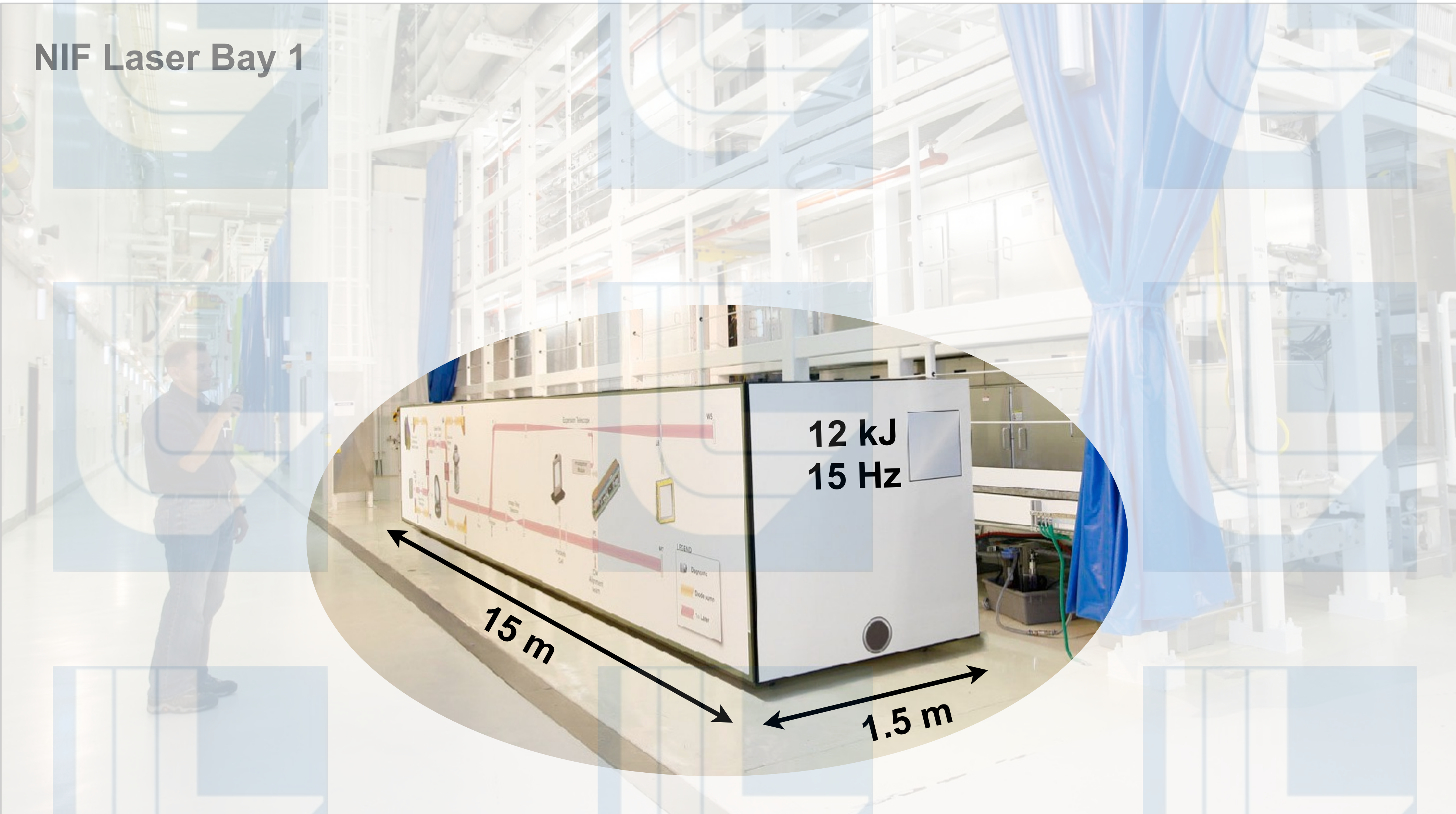
... exist and would enable a 15 Hz Nexawatt!

The Mercury laser project provided the blueprint for IFE “beam in a box” concepts and rep-rated PW lasers



NIF-0107-13272-r6
27CB/dj

“Beam in a Box” concepts at been demonstrated at...



... up to 3 kW levels & at appropriate thermal loadings for 100 kW