A New Regime of High Energy Density (HED) Physics: Coupling High-Rep-Rate Lasers with Cognitive Simulation

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- **CSU:** Reed Hollinger, Shoujun Wang, Jaebum Park, Jorge Rocca
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- **California State University Channel Islands:** Scott Feisiter
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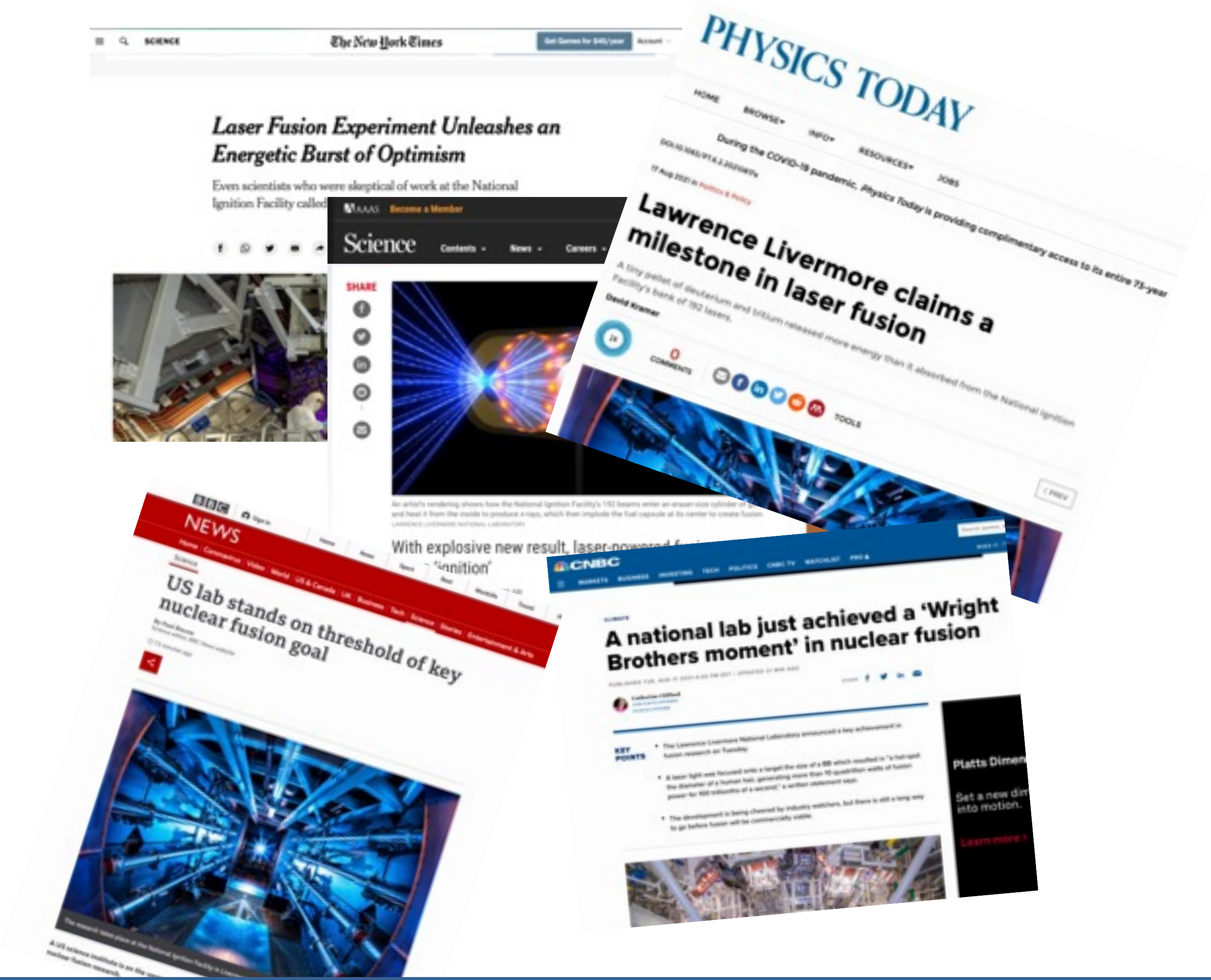
- **U. Osaka/ILE:** Natsumi Iwata, Alessio Morace, Yashuhiko Sentoku
- **STFC:** Dave Neely, Chris Armstrong
- **The NIF and ICF team!**
- ***And many, many more…***

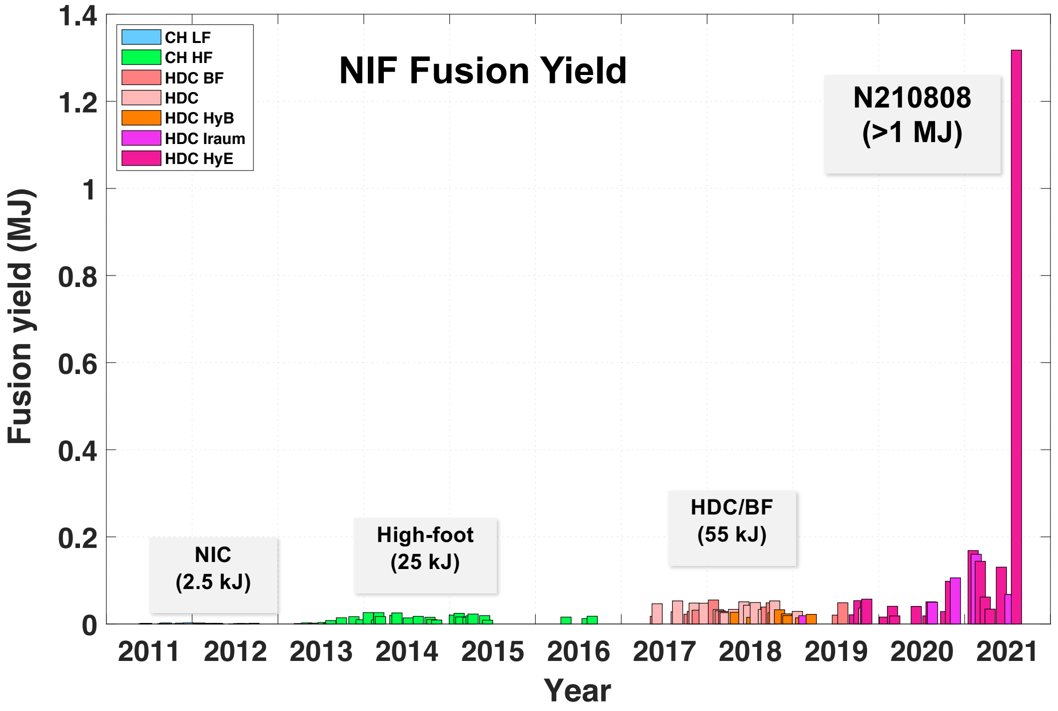
DOE Early Career Research Program

Outline

- High Energy Density (HED) experimental physics is starting to move towards high repetition rate
- Next-gen, high-rep-rate (HRR) laser facilities are already coming online around the world
  - HRR laser science is an opportunity to accelerate the rate of knowledge acquisition in HED
- An integrated HED experimental capability means feedback control loops within the laser, experiment, and simulation to simultaneously optimize the entire system in real-time
- Many emerging technologies are being leveraged to make this vision a reality
  - Suite of HRR diagnostics, automated analysis, and active feedback being developed
  - Novel cognitive simulation techniques will push the forefronts of scientific machine learning
  - Collaborations with scientists inside and outside the field
- Setting the stage for Inertial Fusion Energy

We recently demonstrated more than 1.3 MJ of fusion yield on the NIF – a significant advance in ICF research



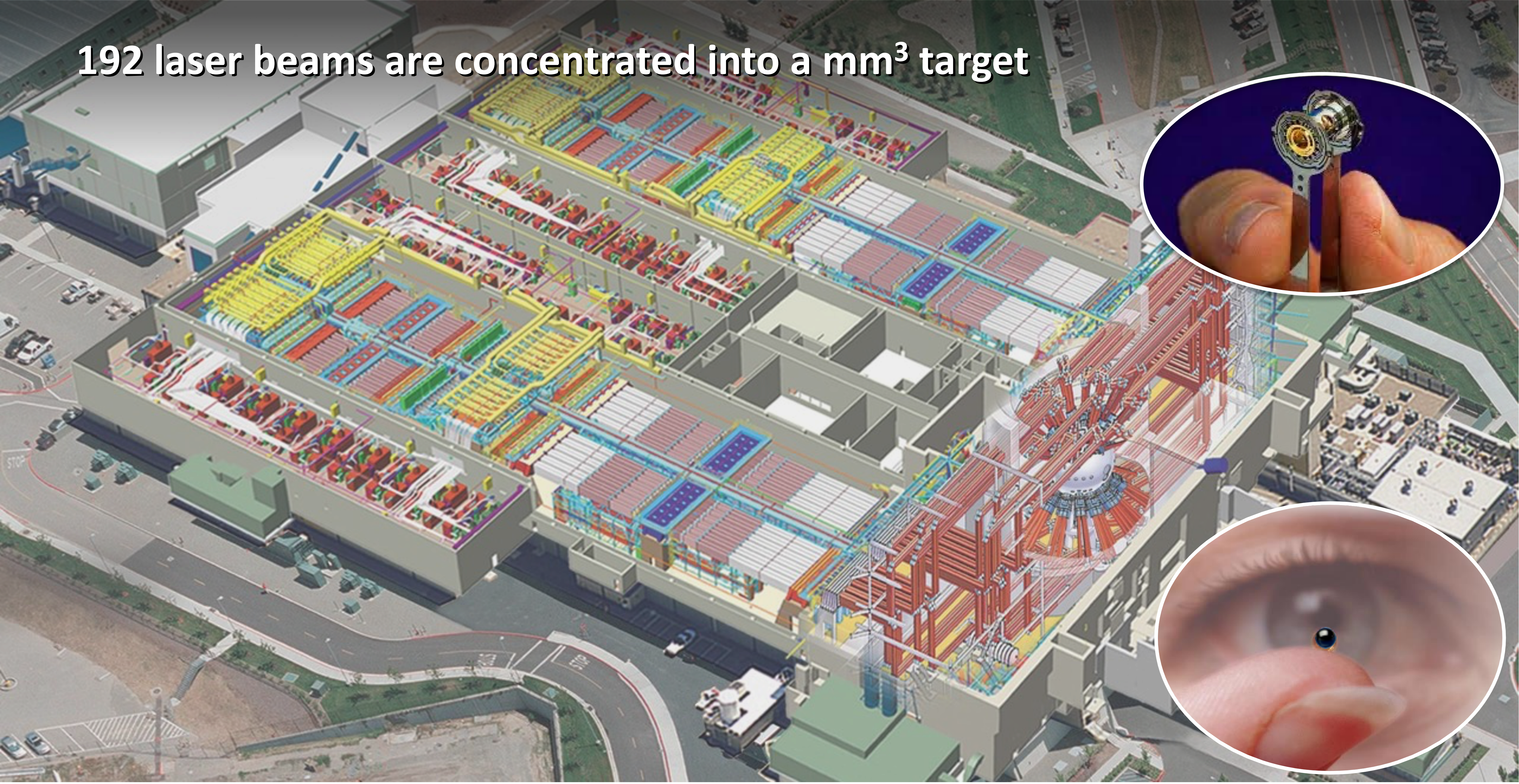


This shot was ~8x higher yield than the previous NIF record, and was the first NIF shot to achieve capsule gain (yield/absorbed energy) ~5+, and propagating burn!

The National Ignition Facility (NIF) is the world's most energetic laser enabling the study of extreme HED conditions

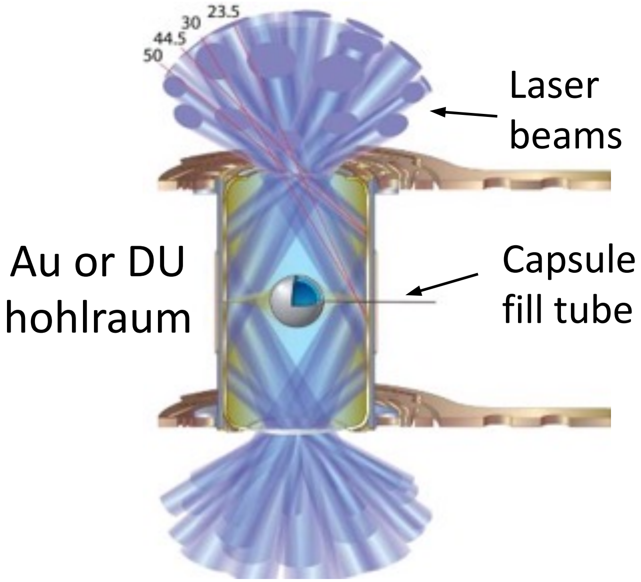
- 192 Beams, 1.9 MJ Energy, 500 TW Power
- Matter temperature >10^8 K
- Radiation temperature >3.5×10^6 K
- Densities >10^2 g/cm^3
- Pressures >10^{11} atm

192 laser beams are concentrated into a mm^3 target

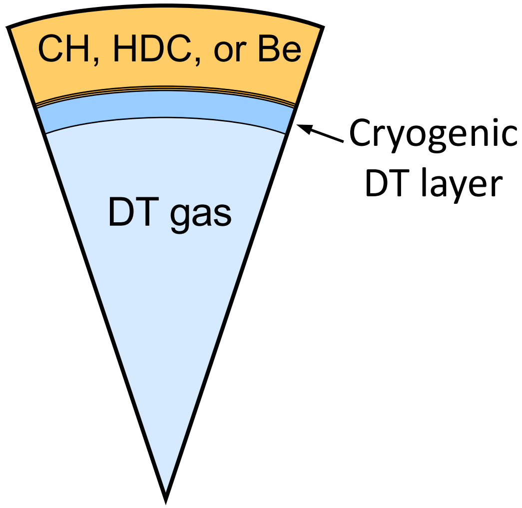


NIF uses a laser driven hohlraum to compress a fuel pellet to achieve the conditions for ignition

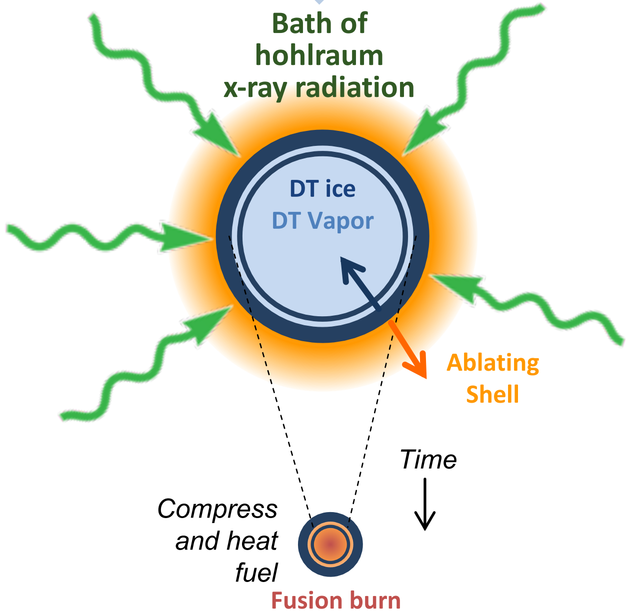
The hohlraum is a cylindrical cavity that serves as an x-ray "oven"



The fuel capsule consists of an ablator surrounding DT ice and gas



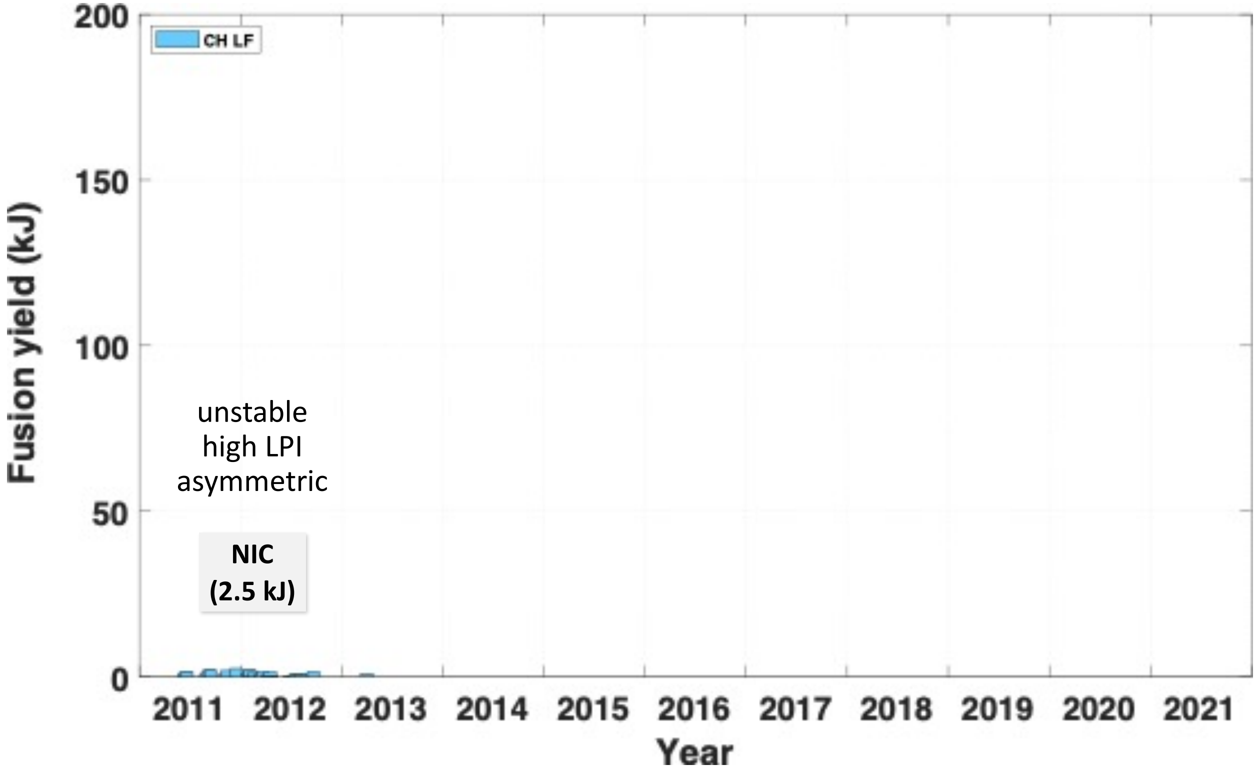
Turn 100 million atmospheres of pressure into 300 billion



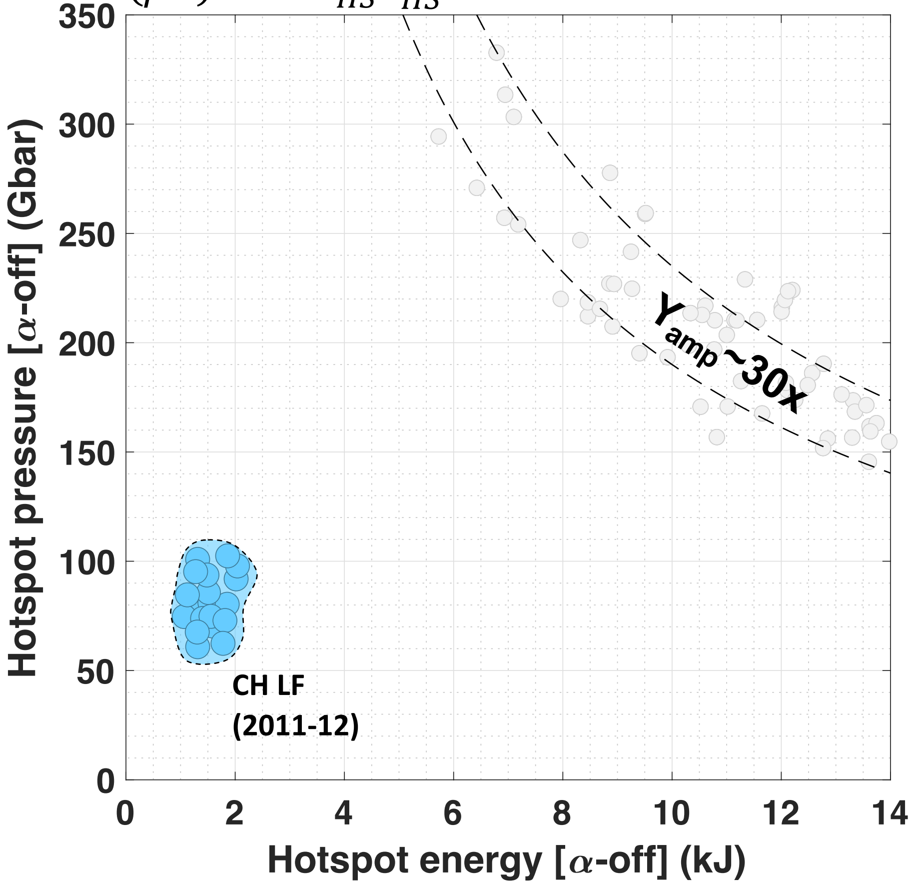
Achieving the conditions for ignition demands precise control of laser and target parameters for a high convergence implosion with low ablator fuel mix

J. Lindl, *PoP*, 1995; S. Haan, *et al.*, *PoP*, 2011
J. Nuckolls et al., *Nature*, 1972

The program has steadily advanced our physics understanding and the technology over the last decade to improve performance



Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



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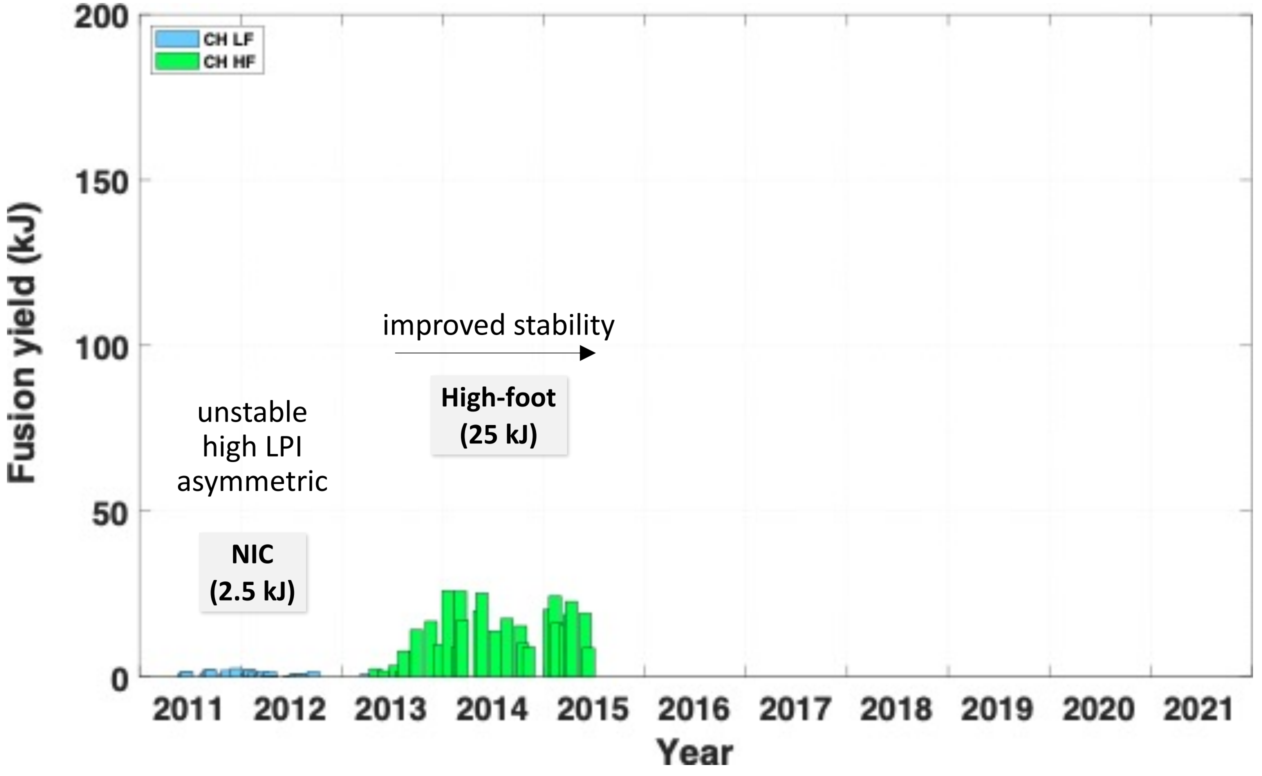

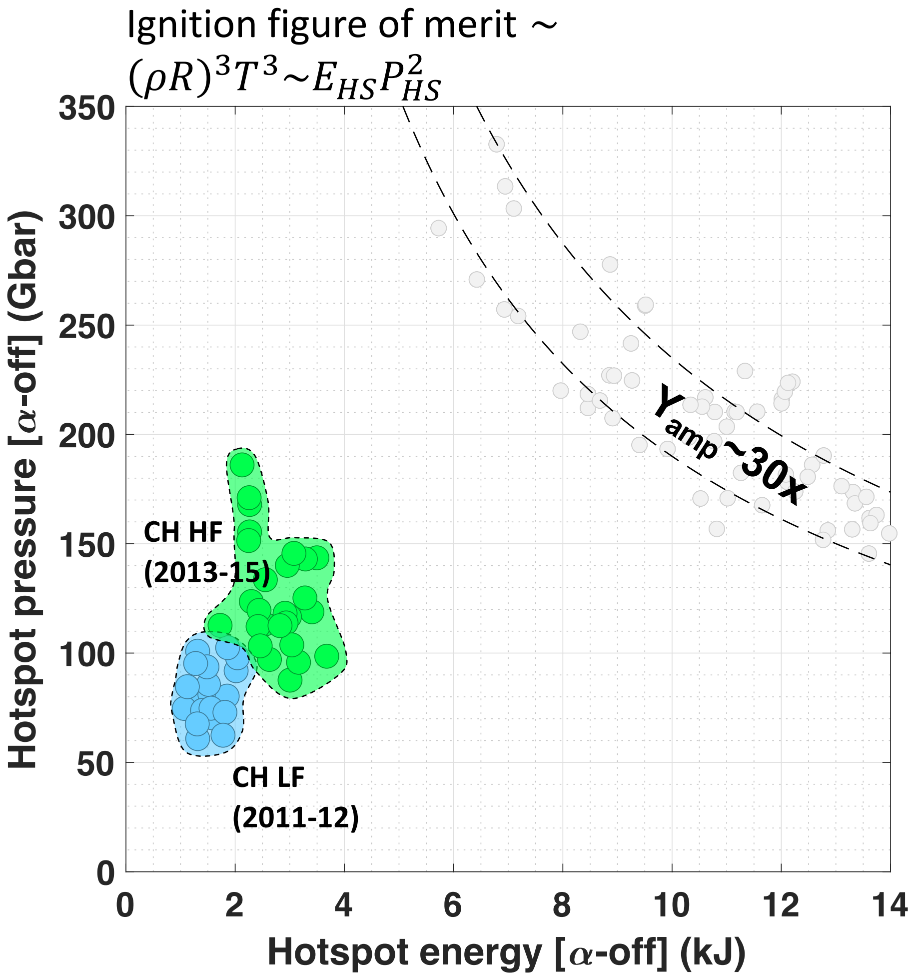

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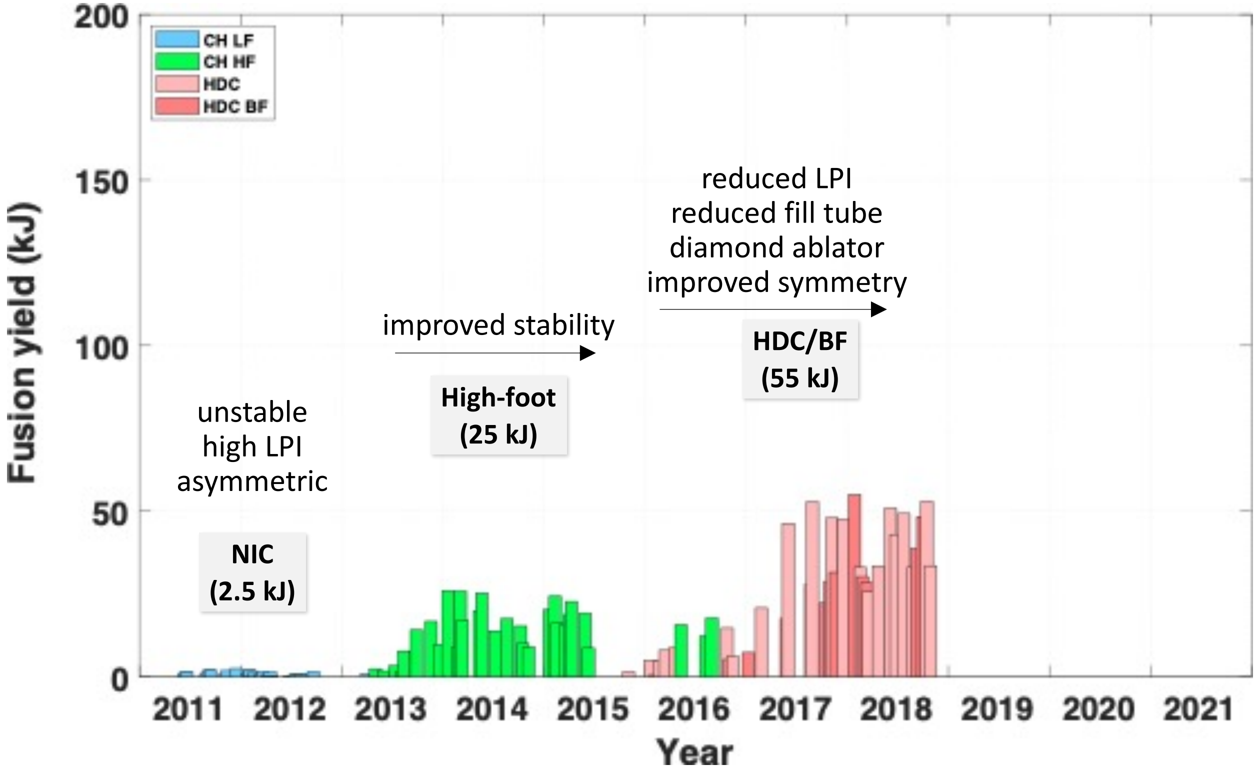

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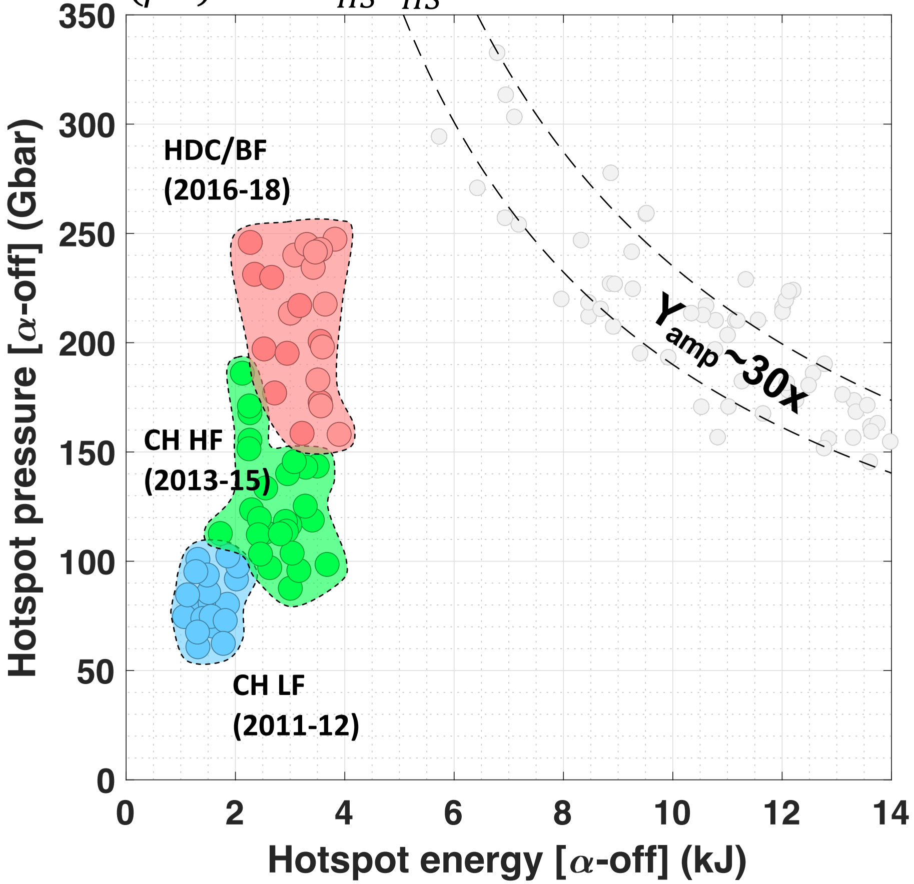

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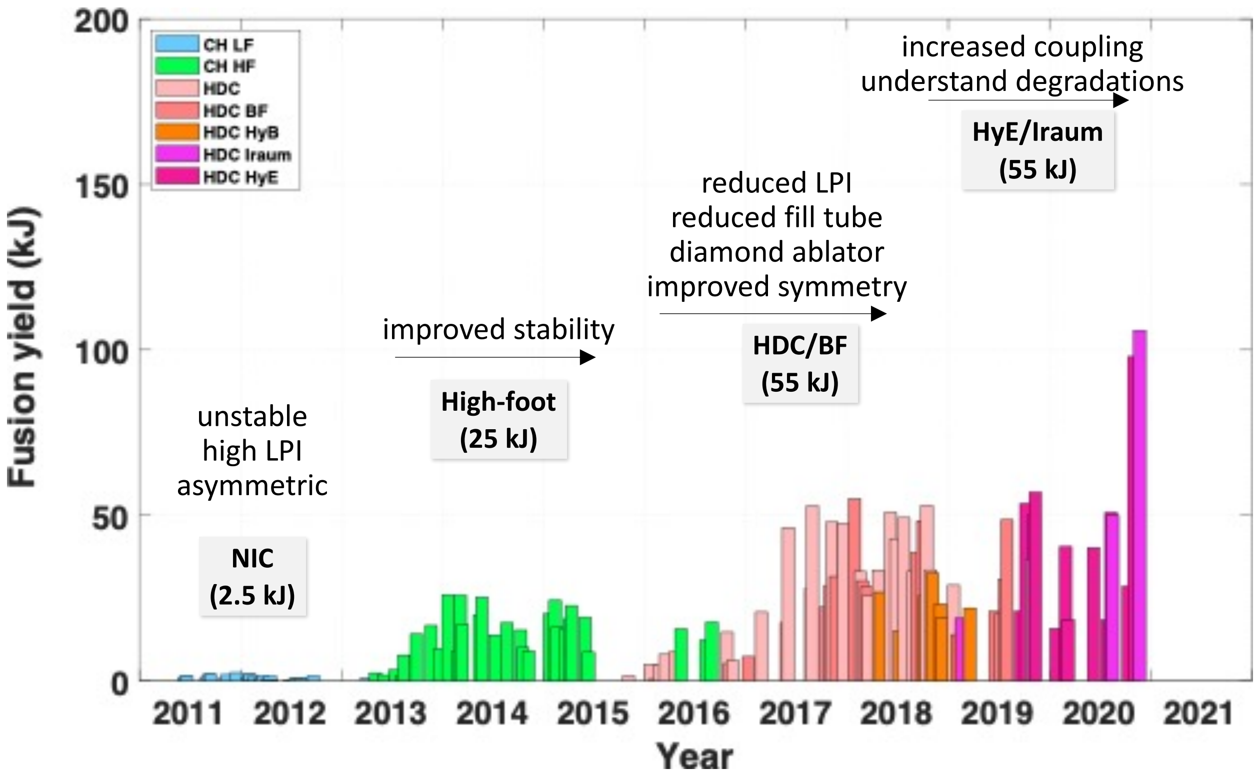

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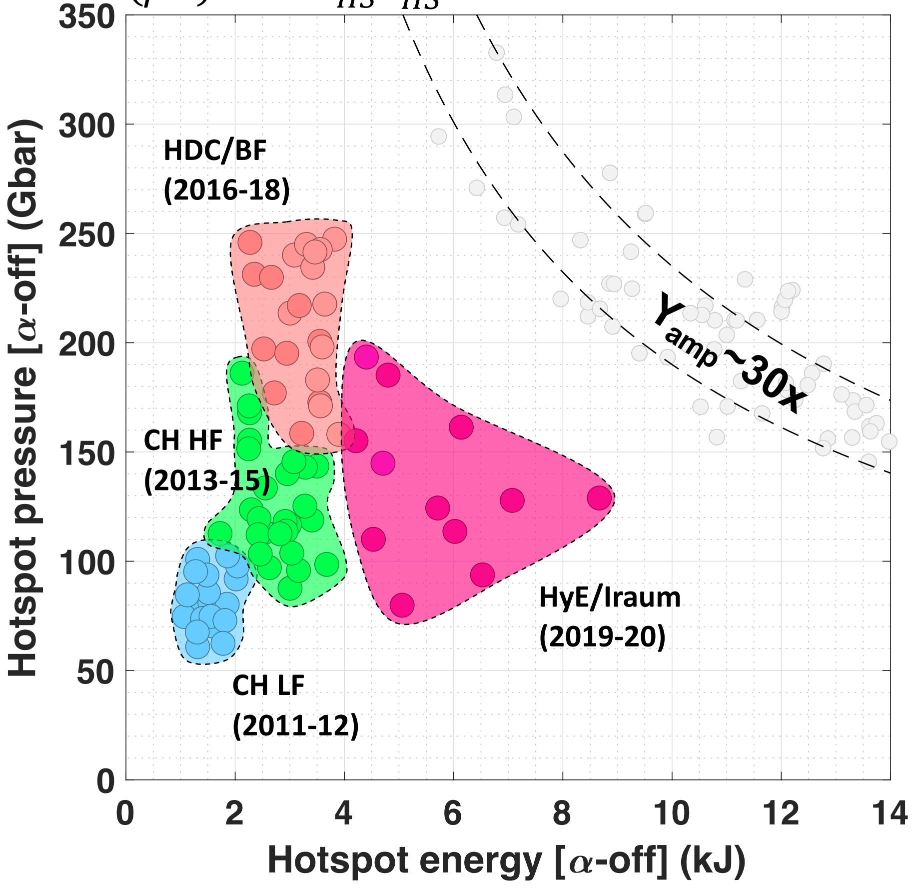

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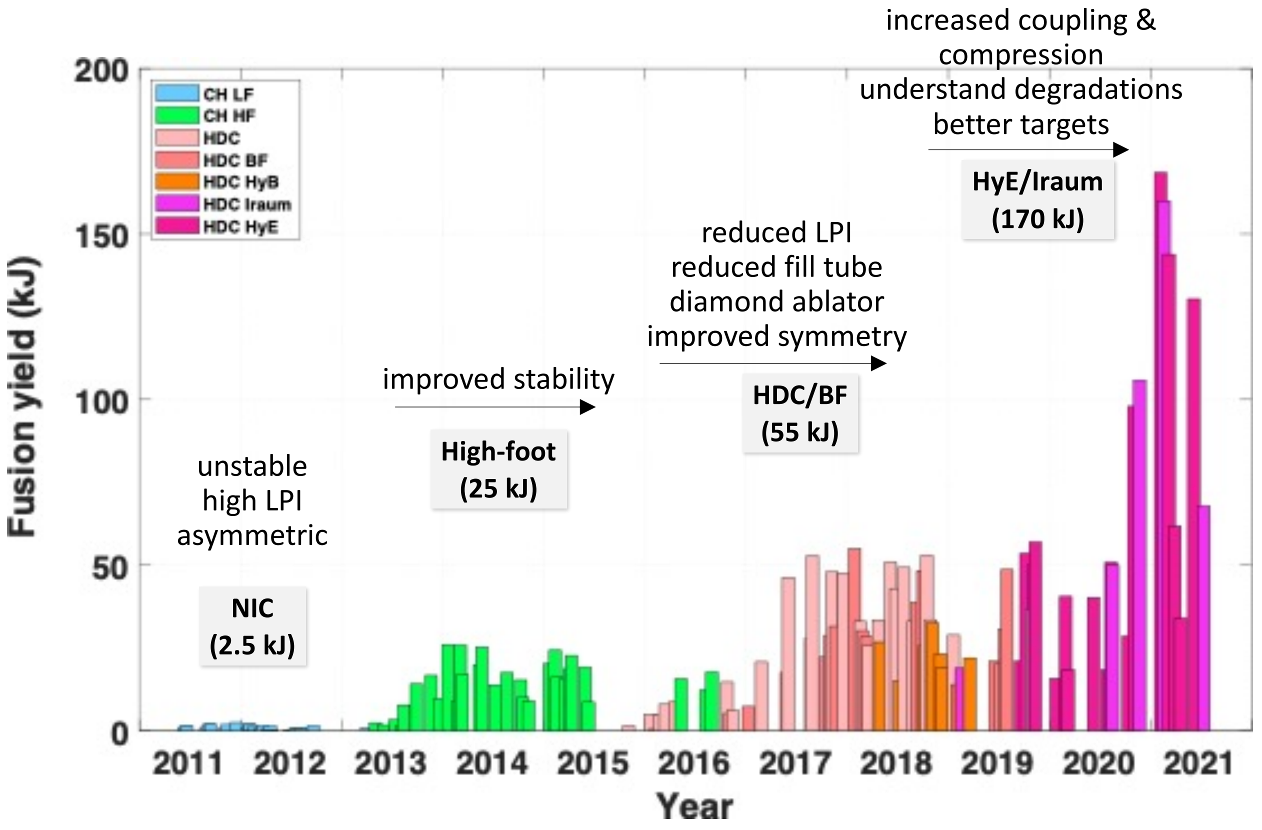

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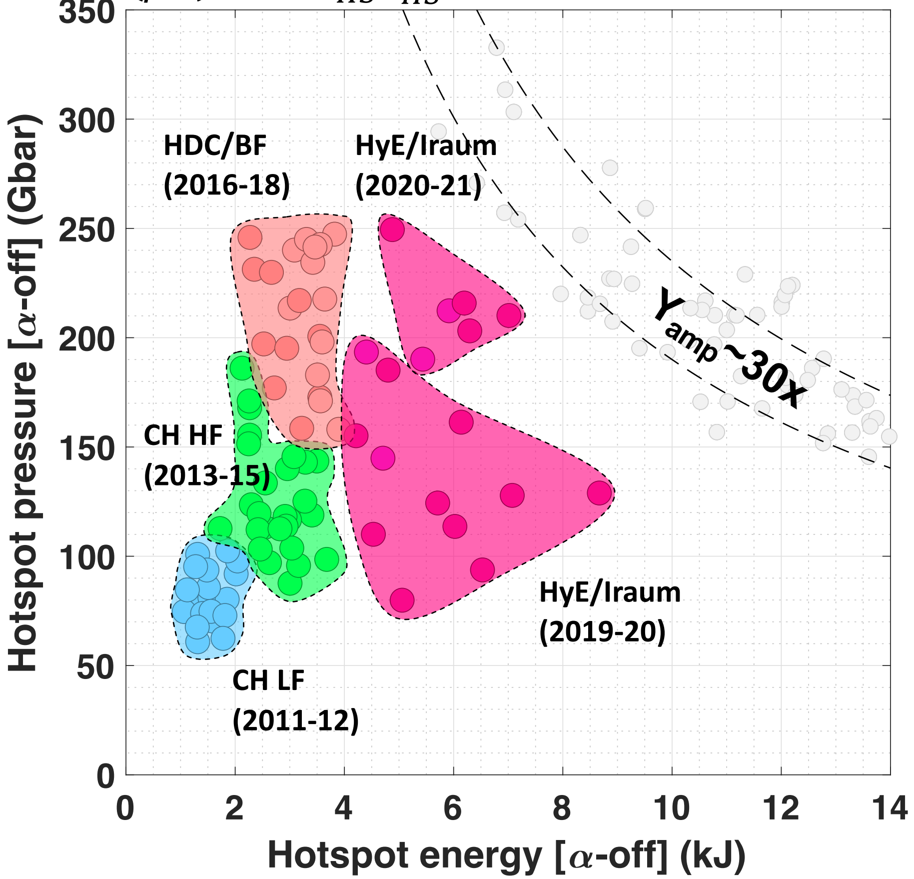

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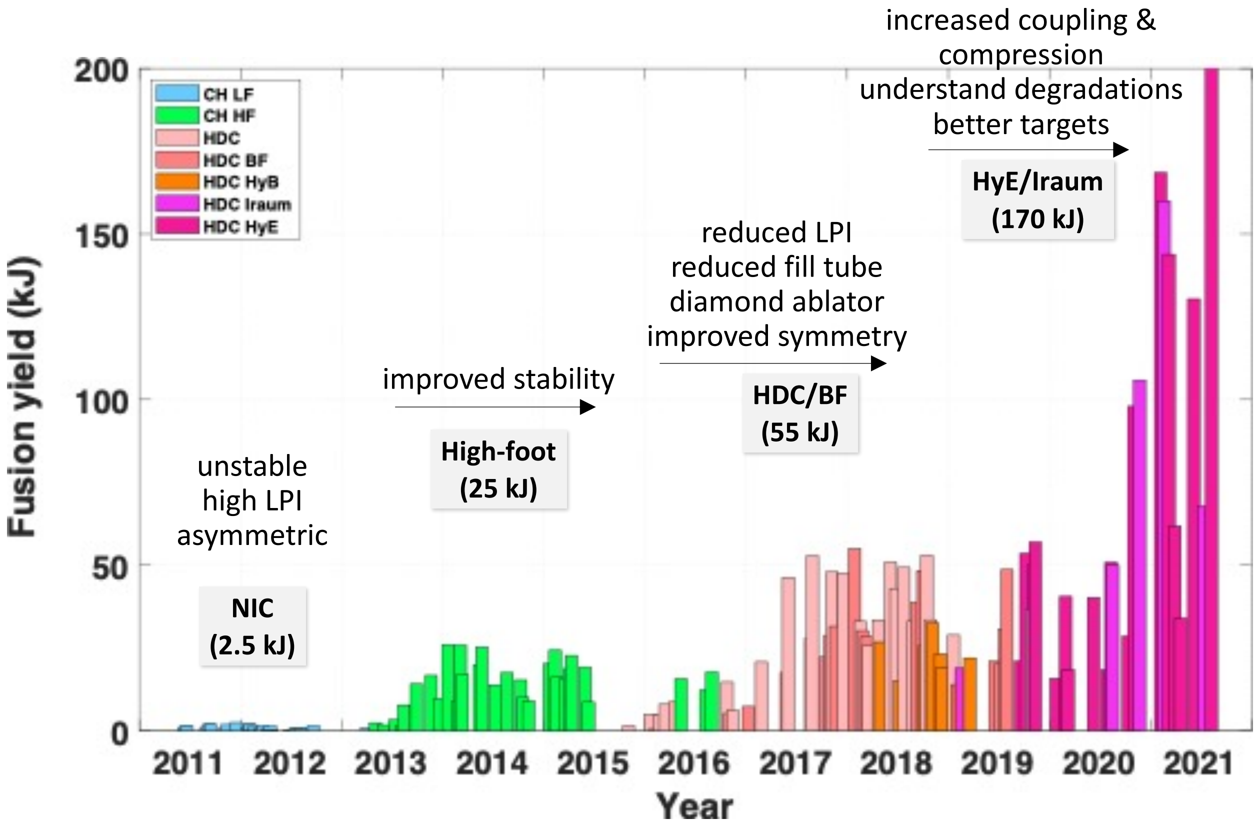

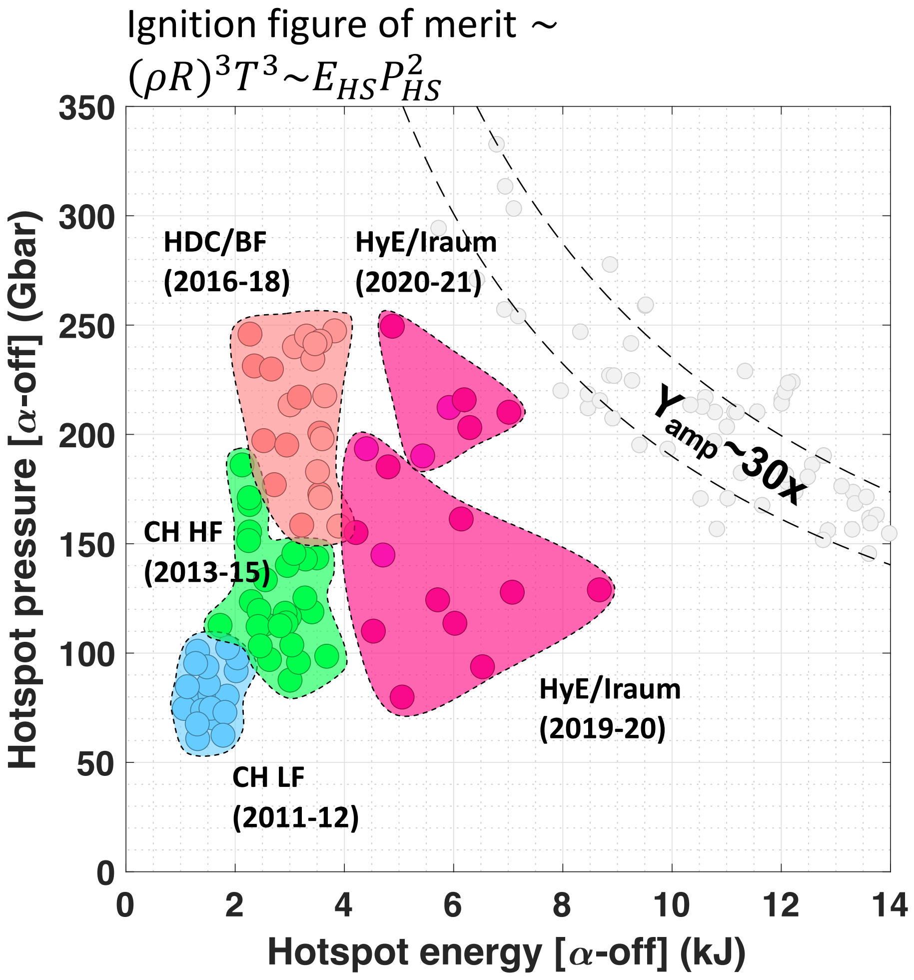

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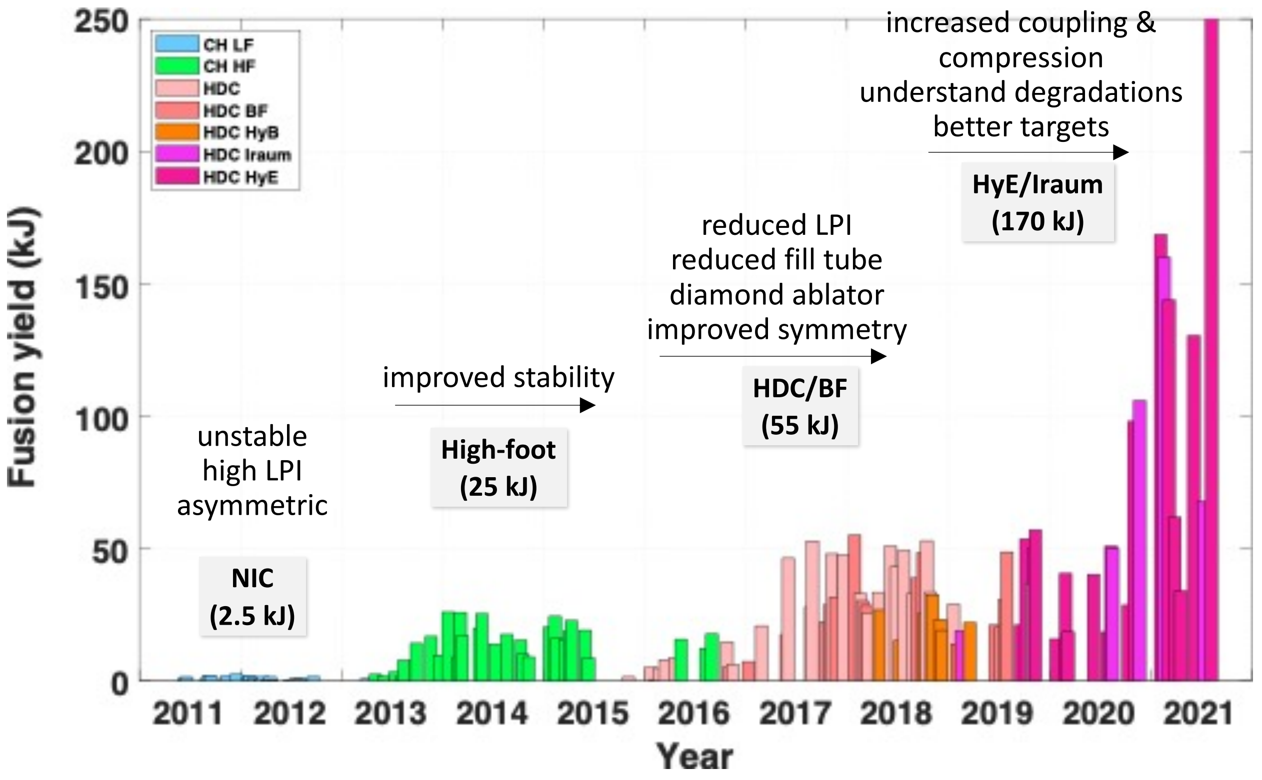

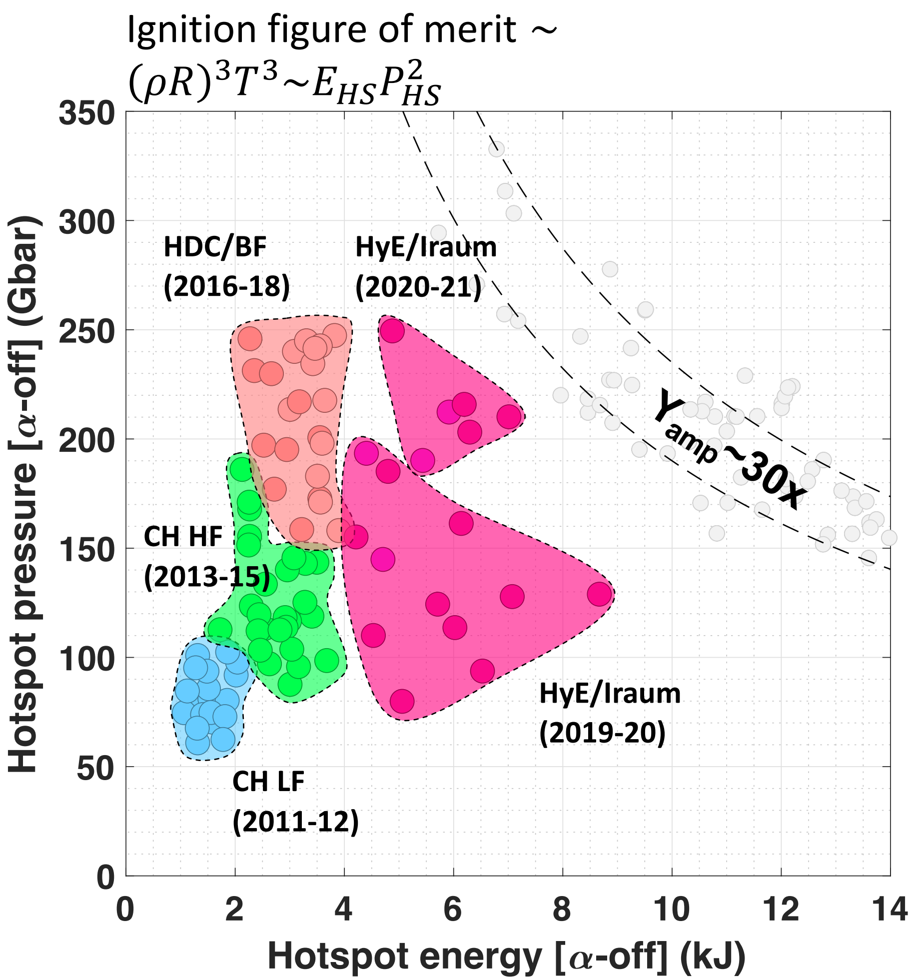

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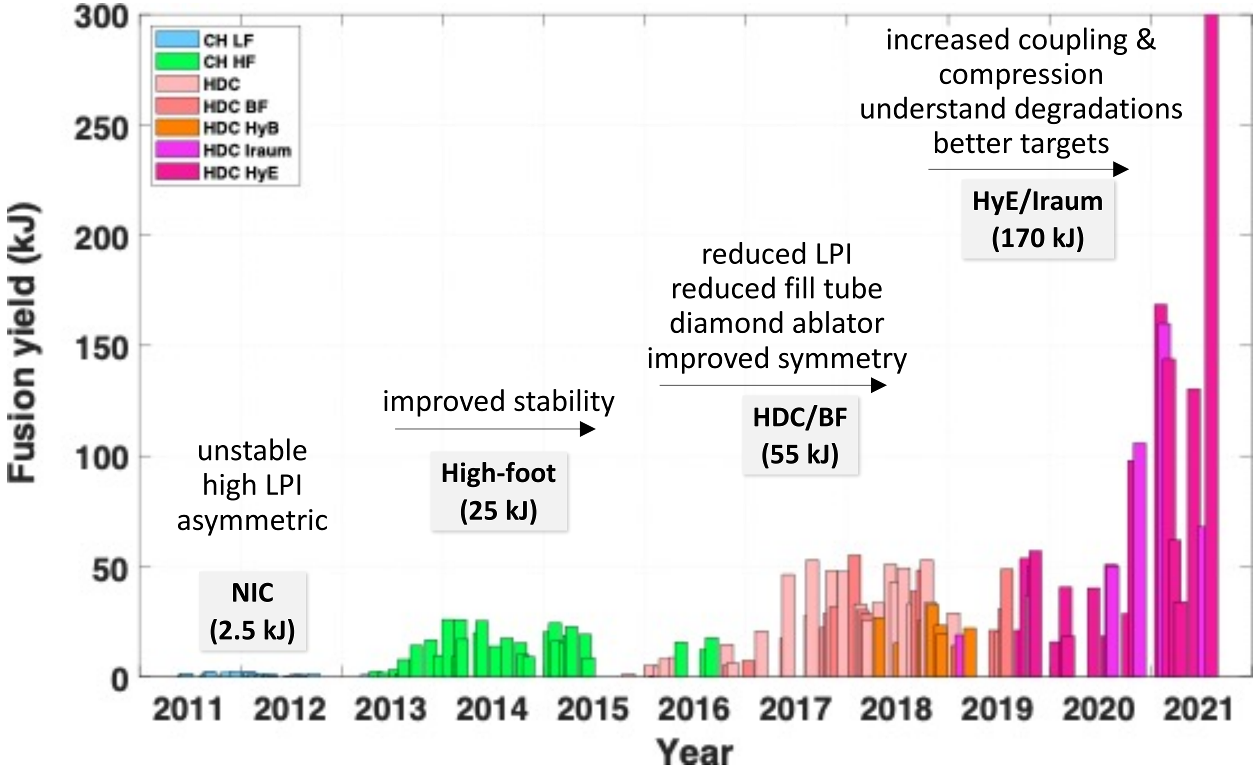

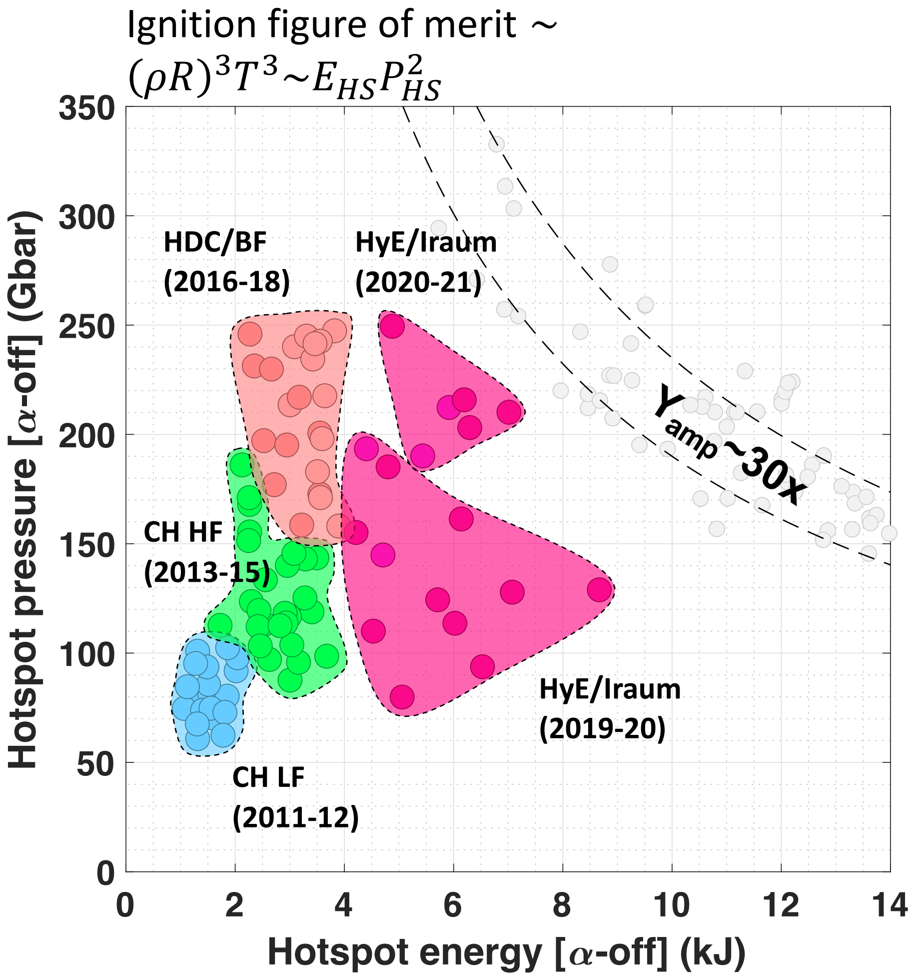

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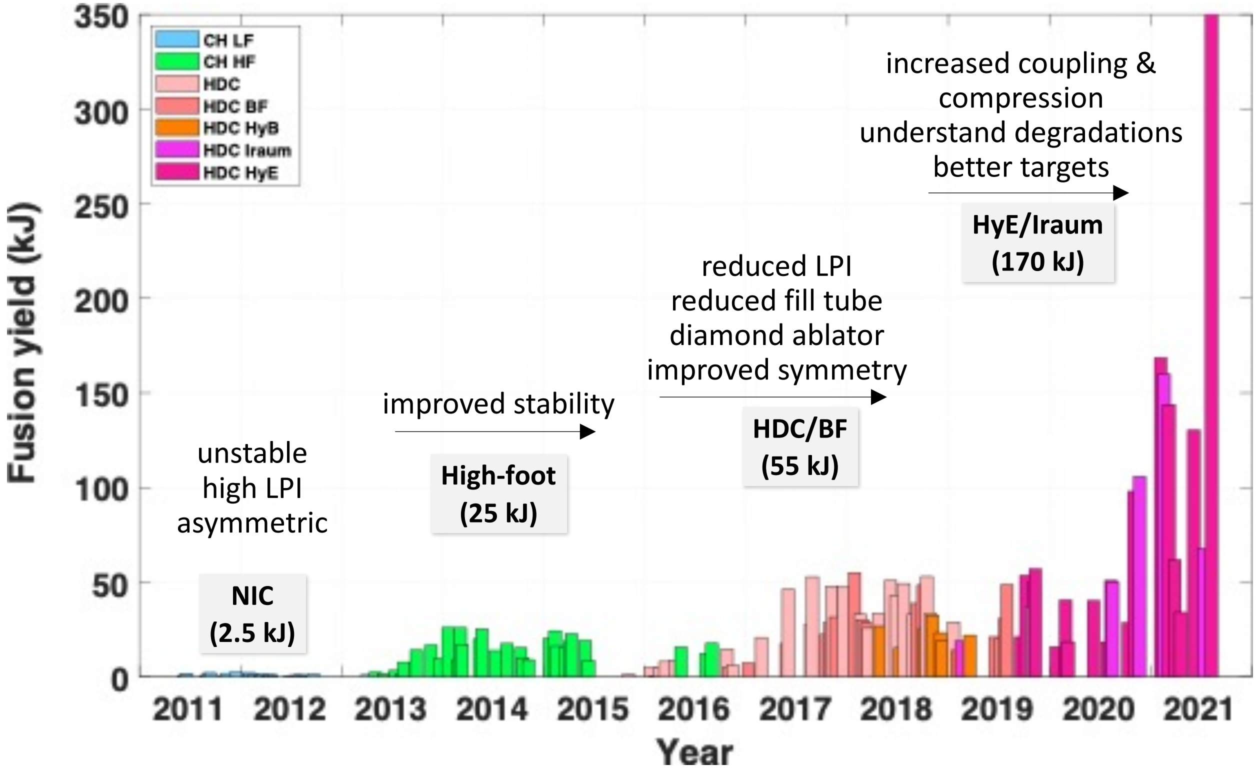

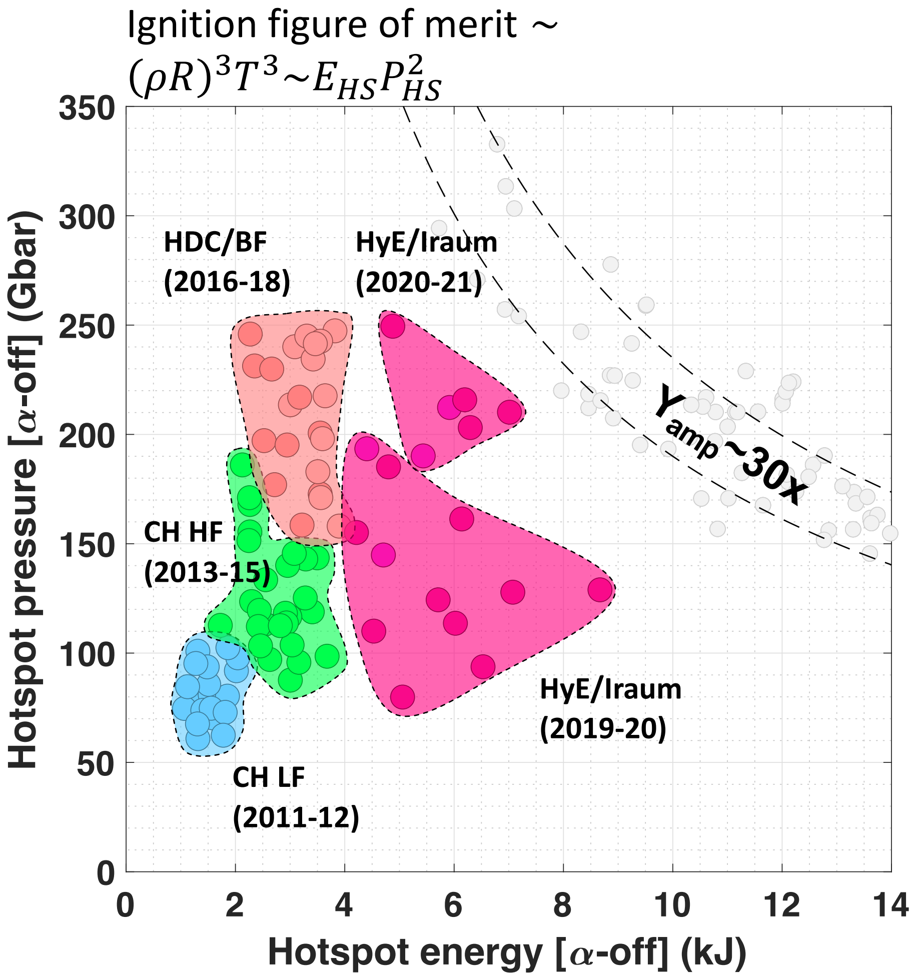

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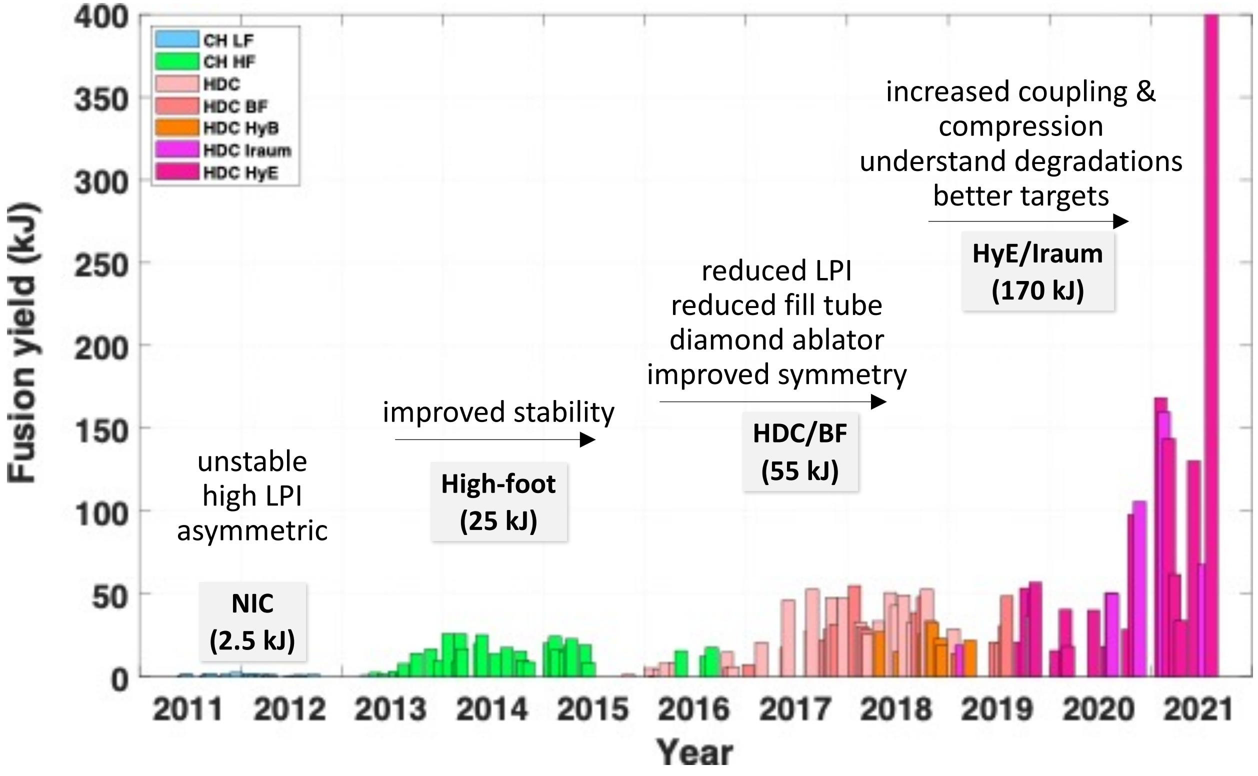
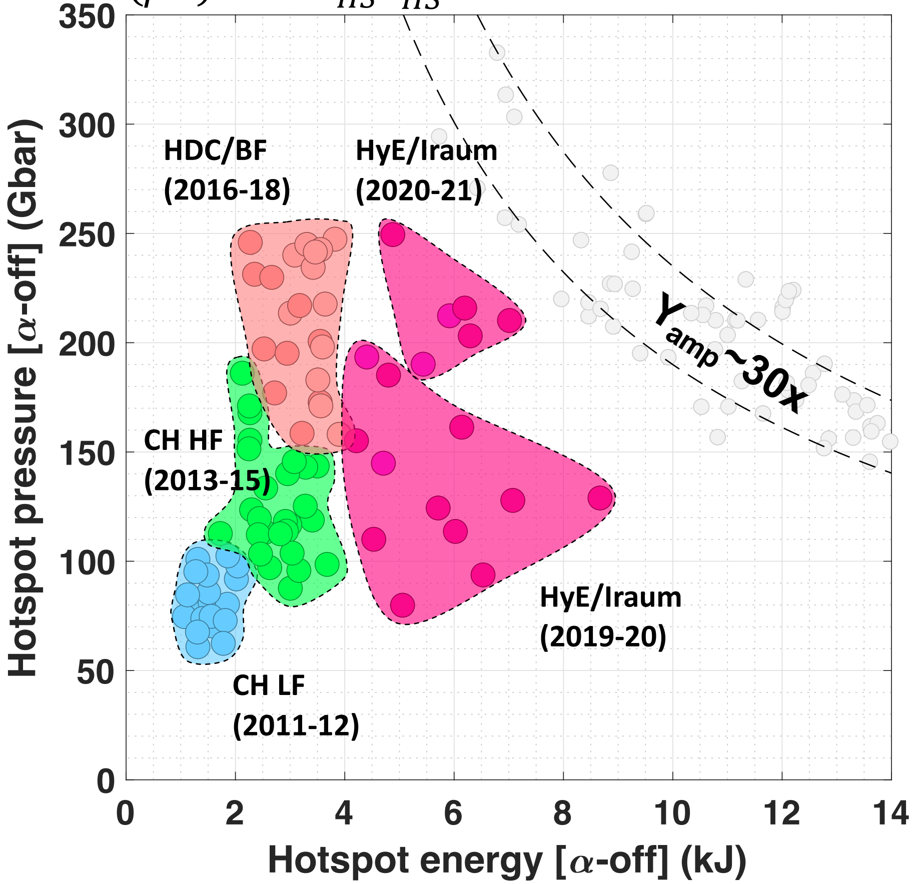


Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



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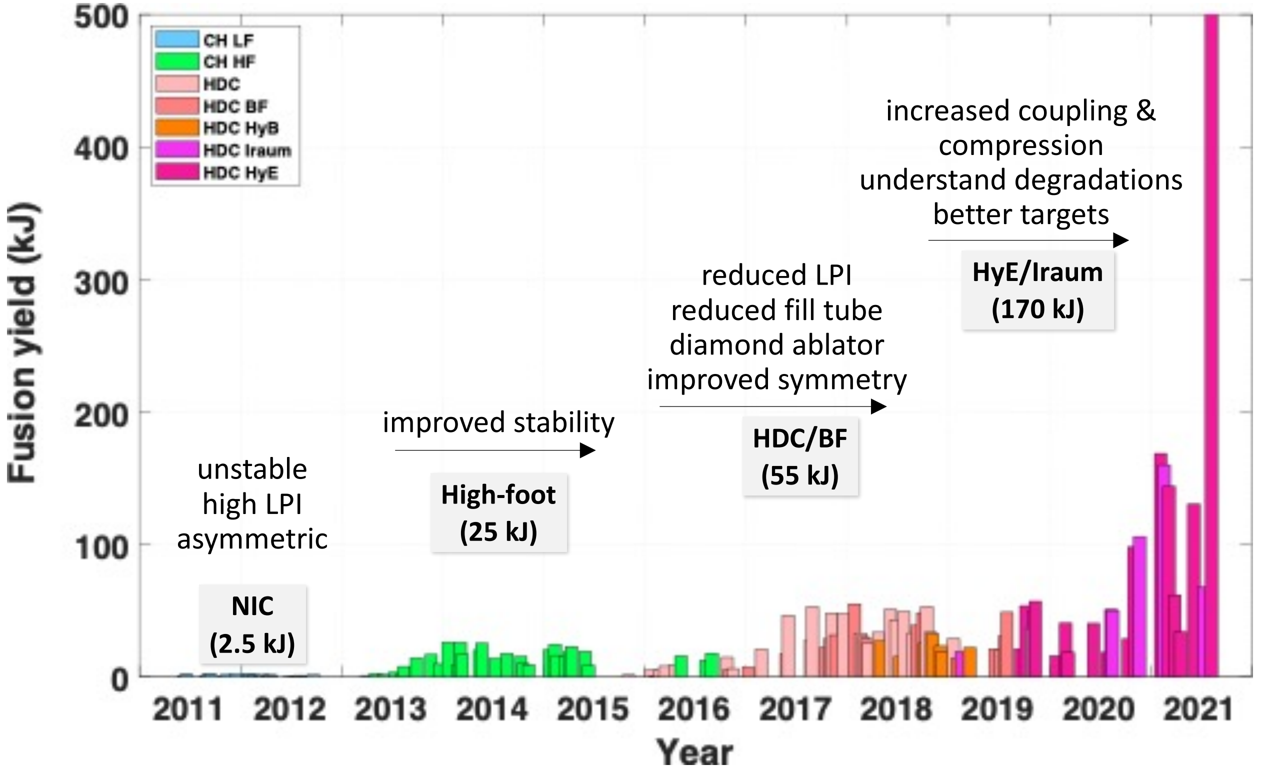

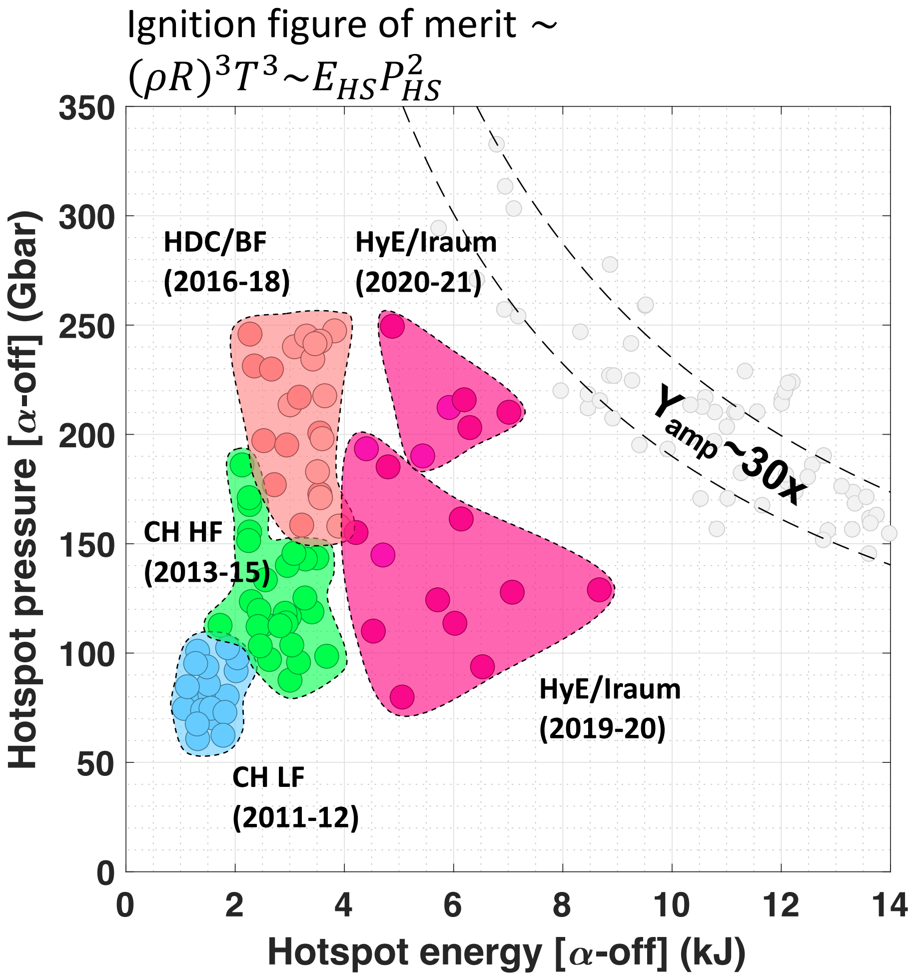

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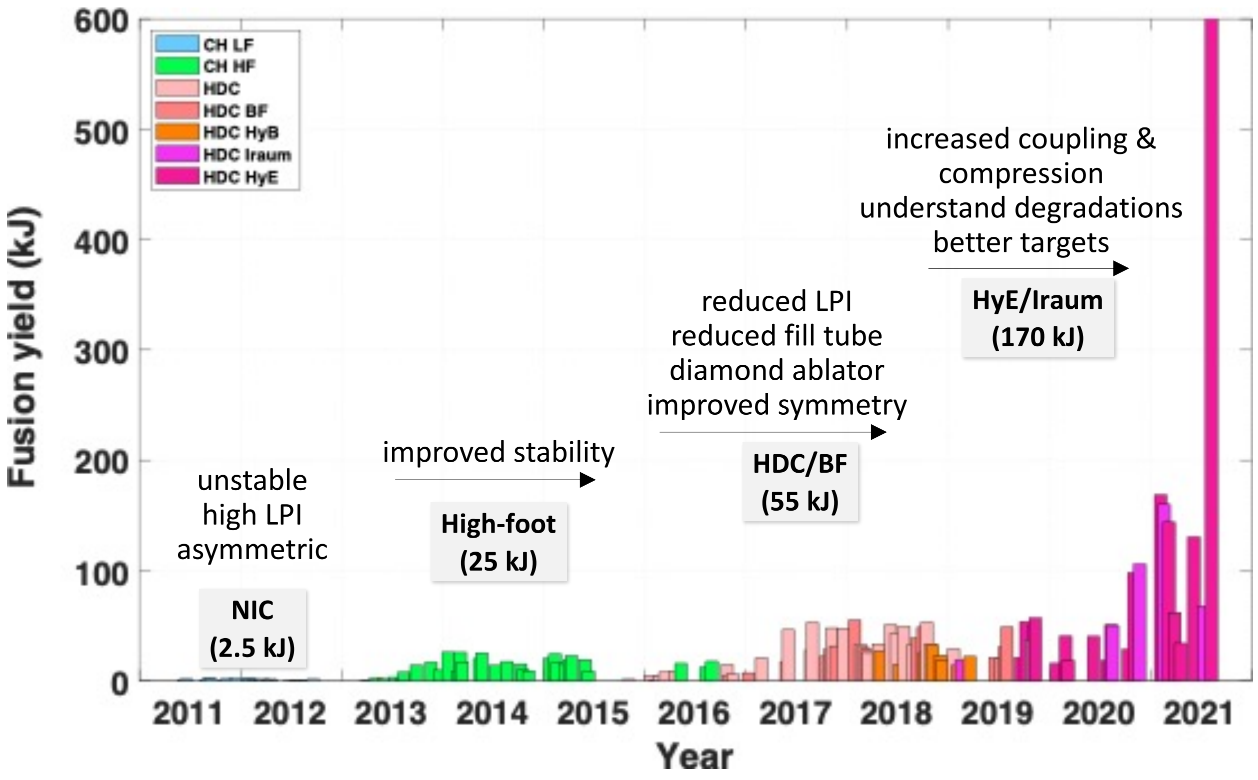

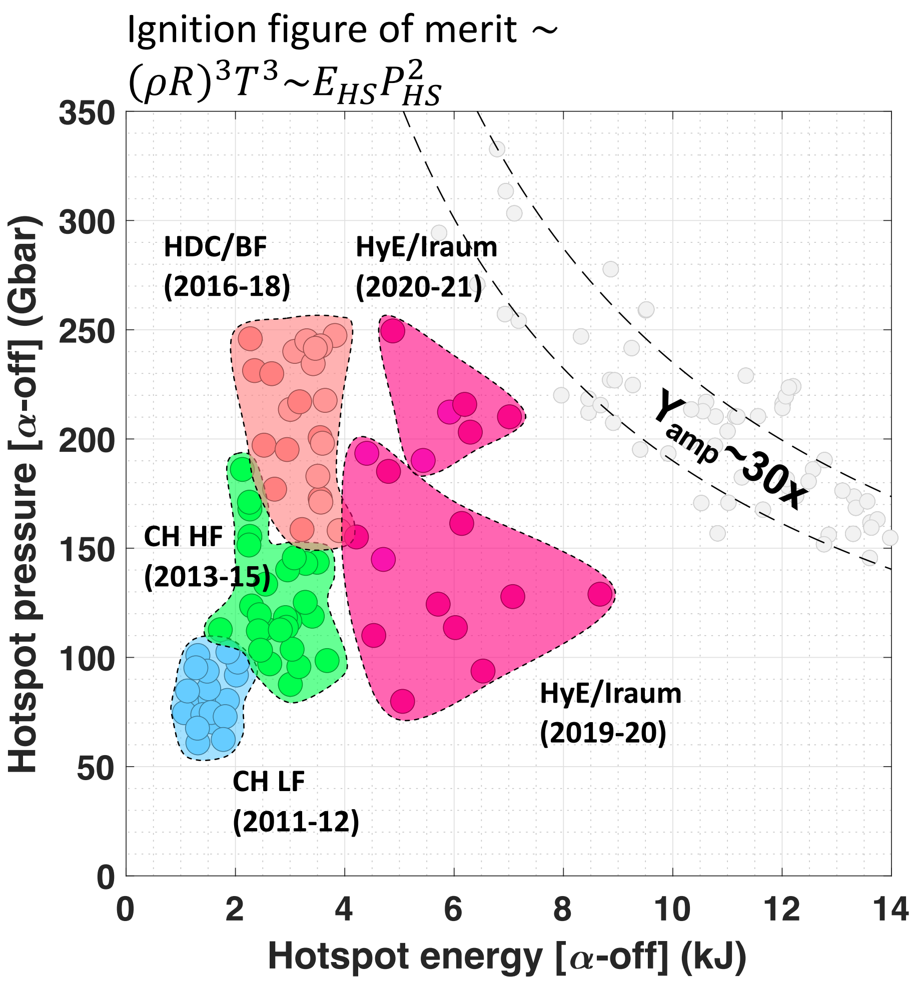

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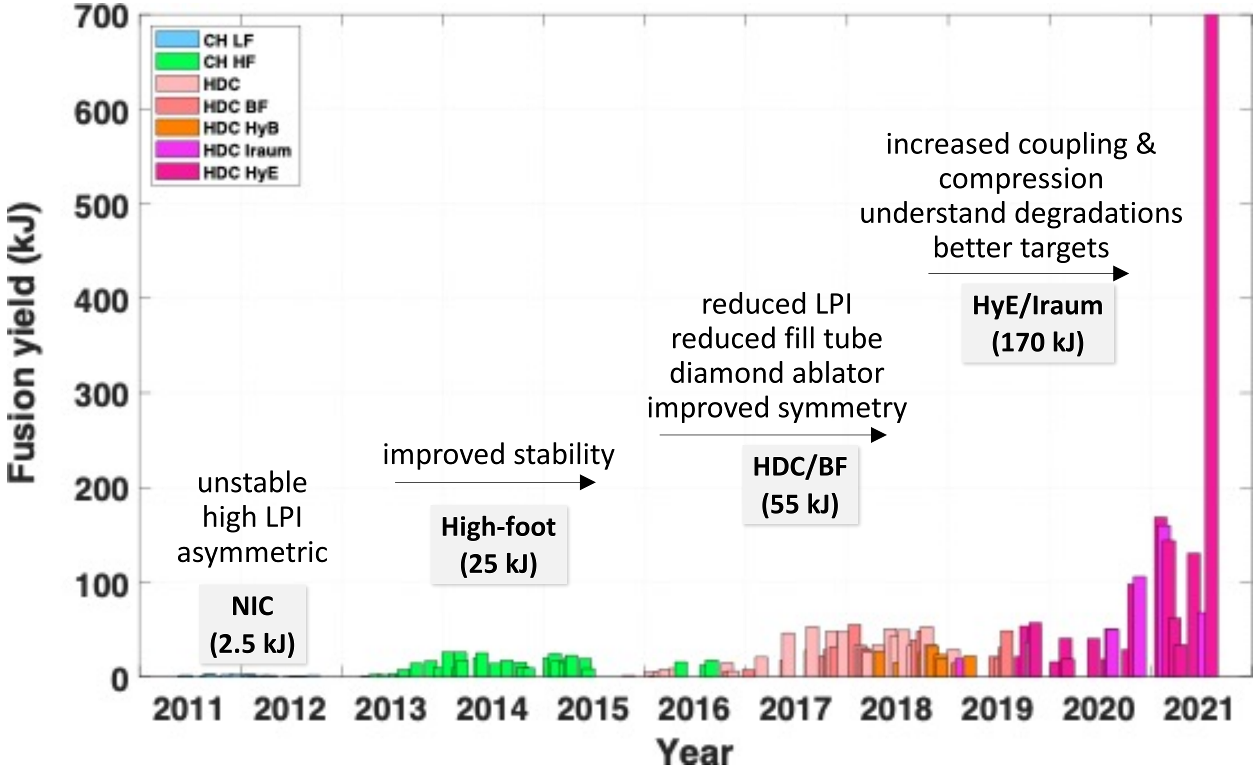
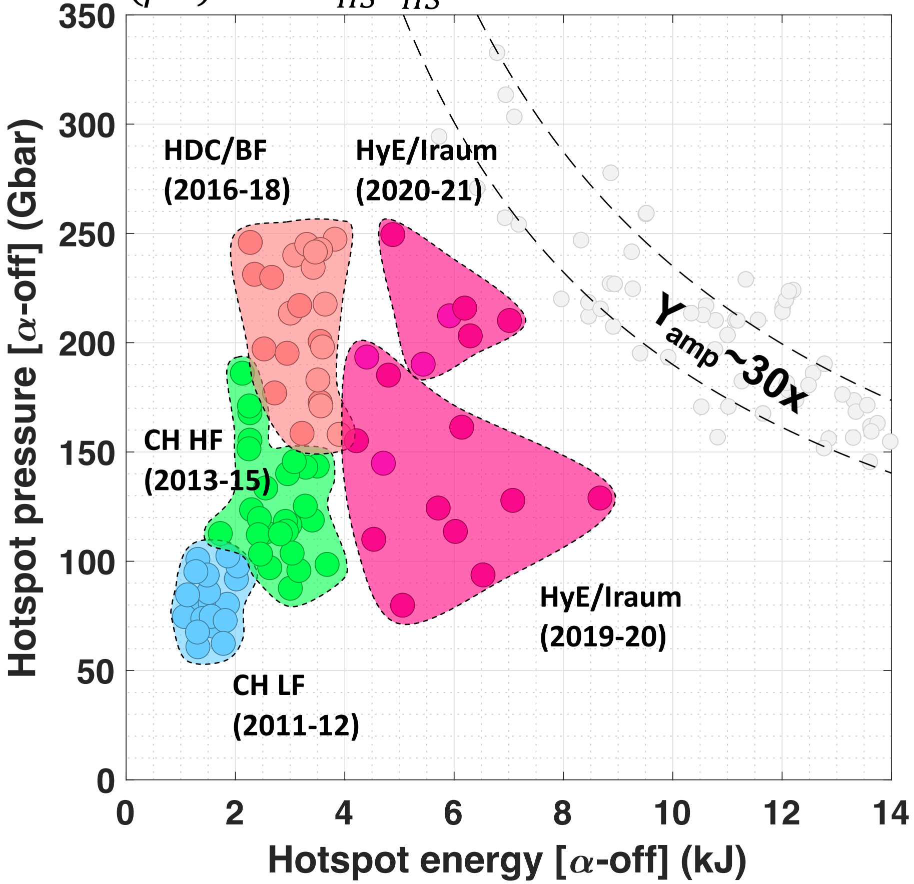


Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



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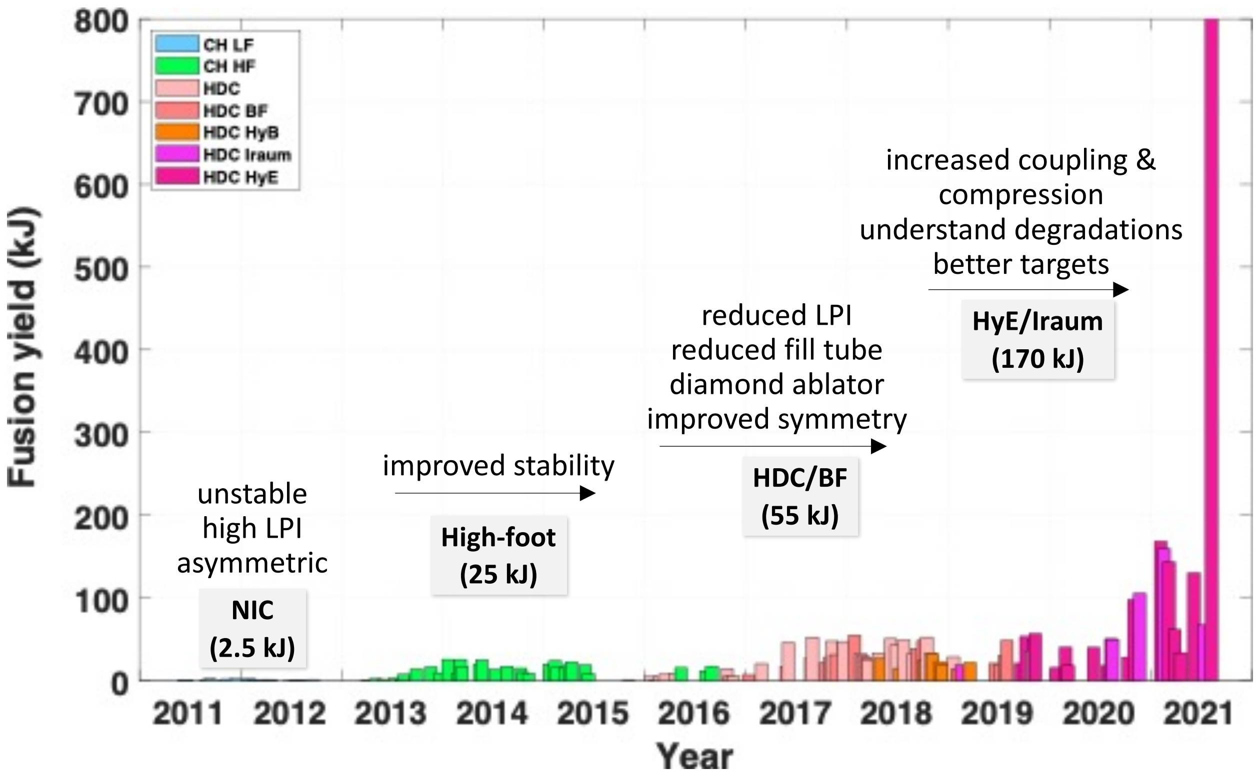

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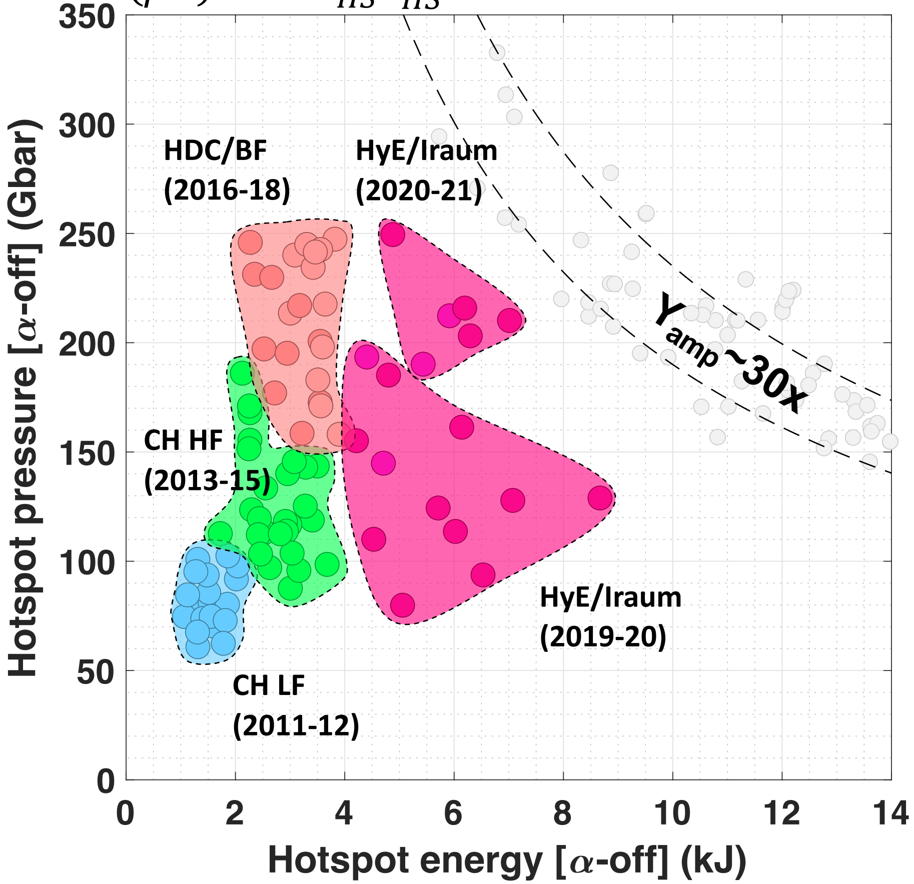

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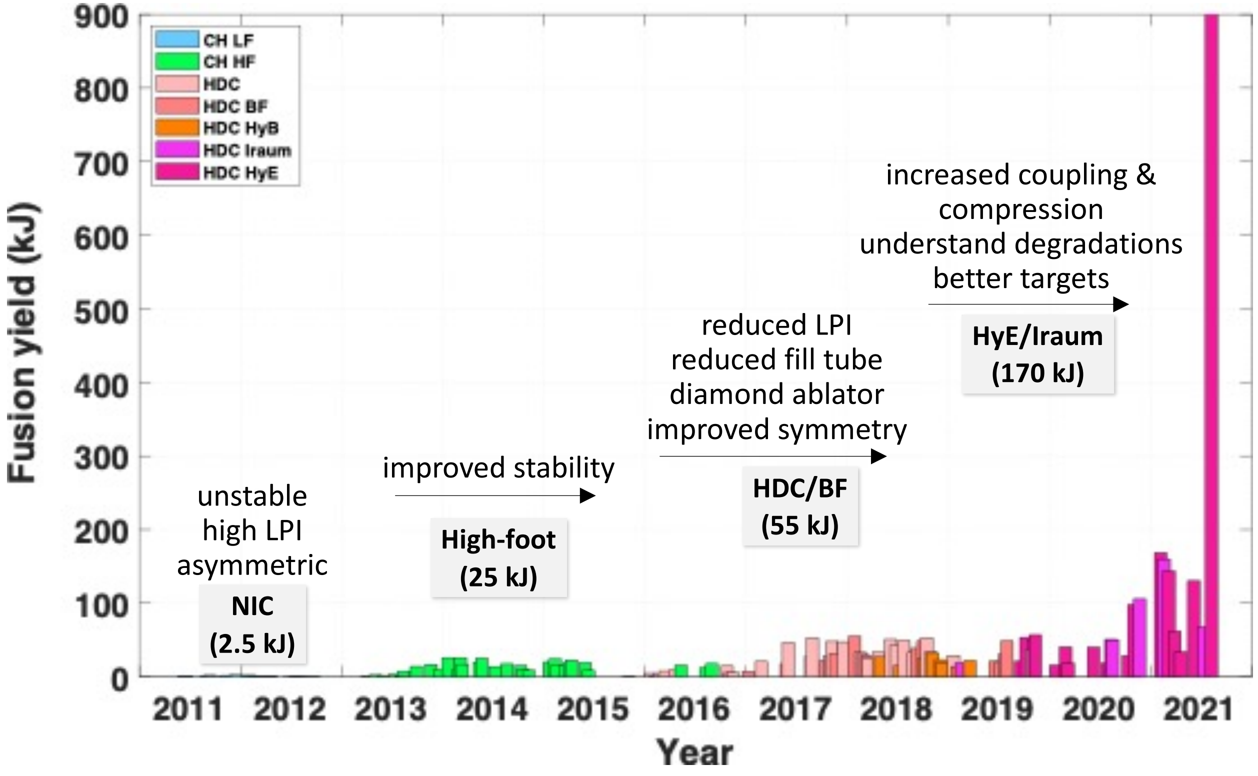

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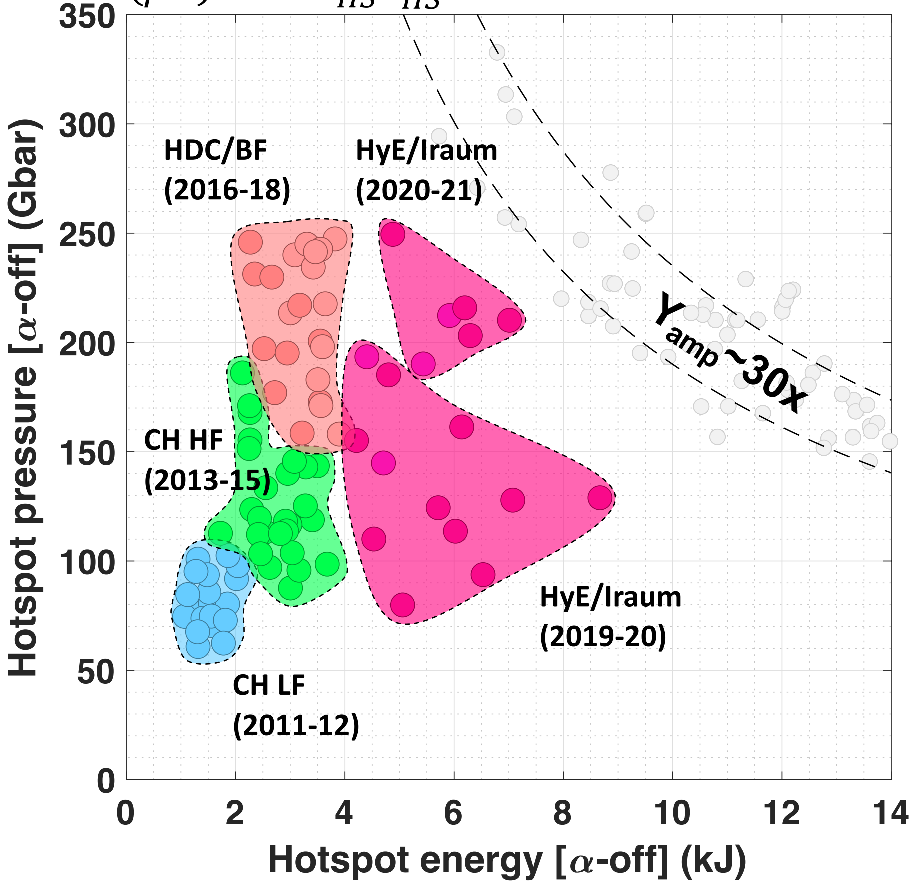

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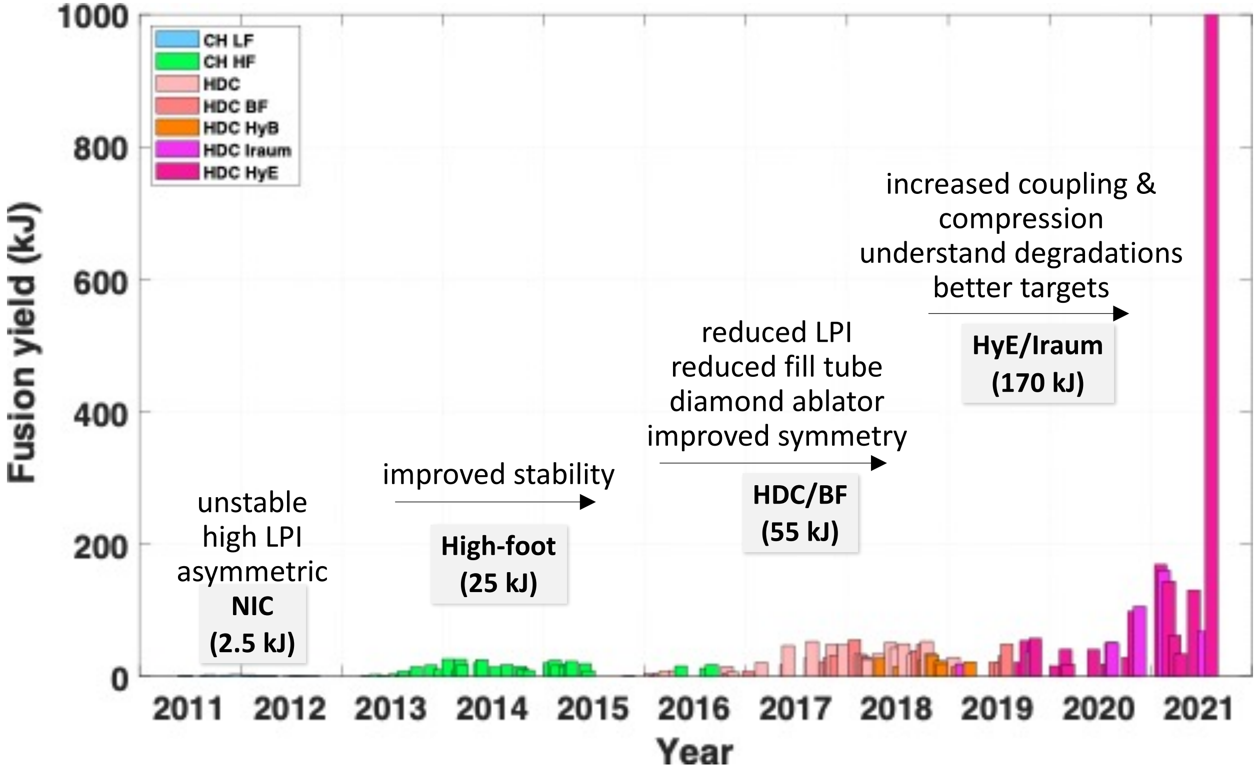

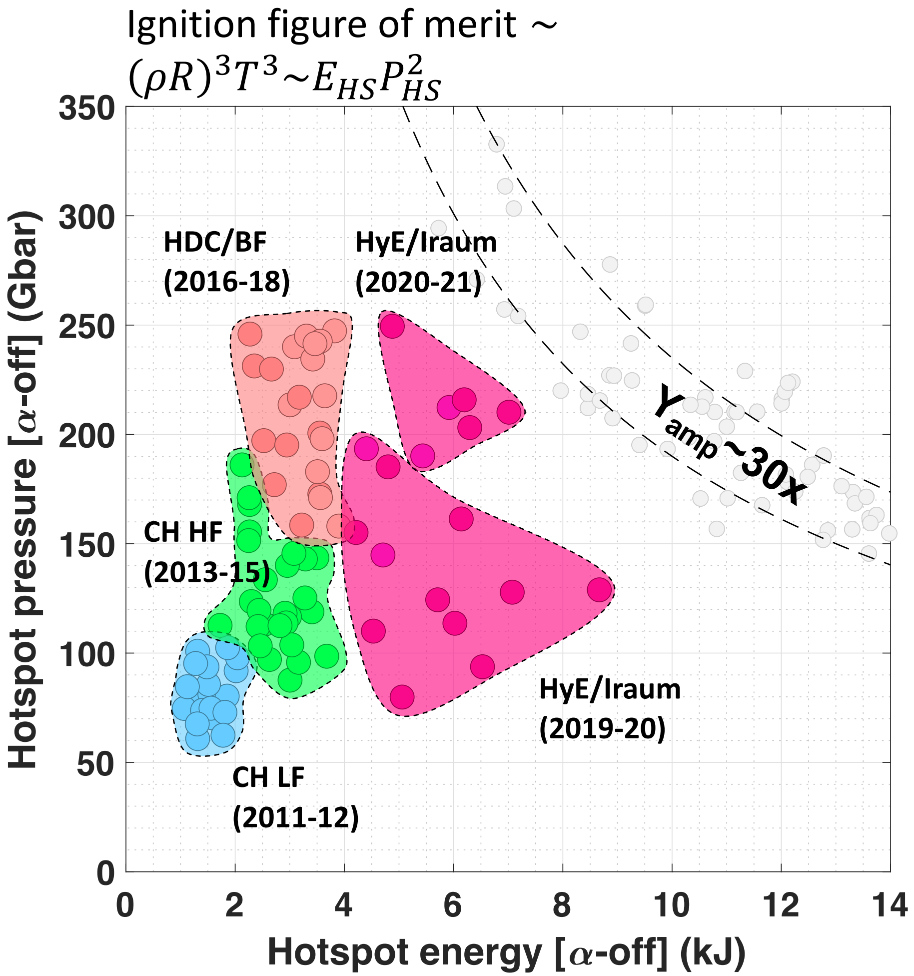

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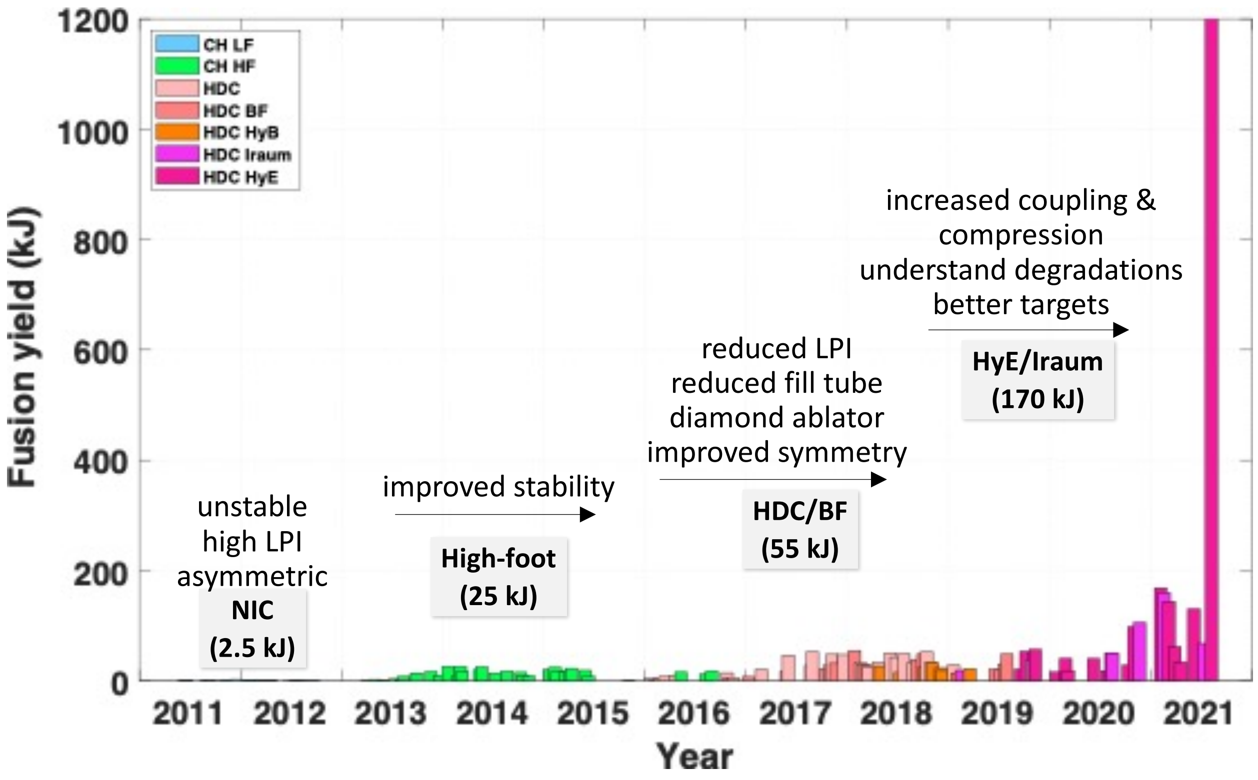

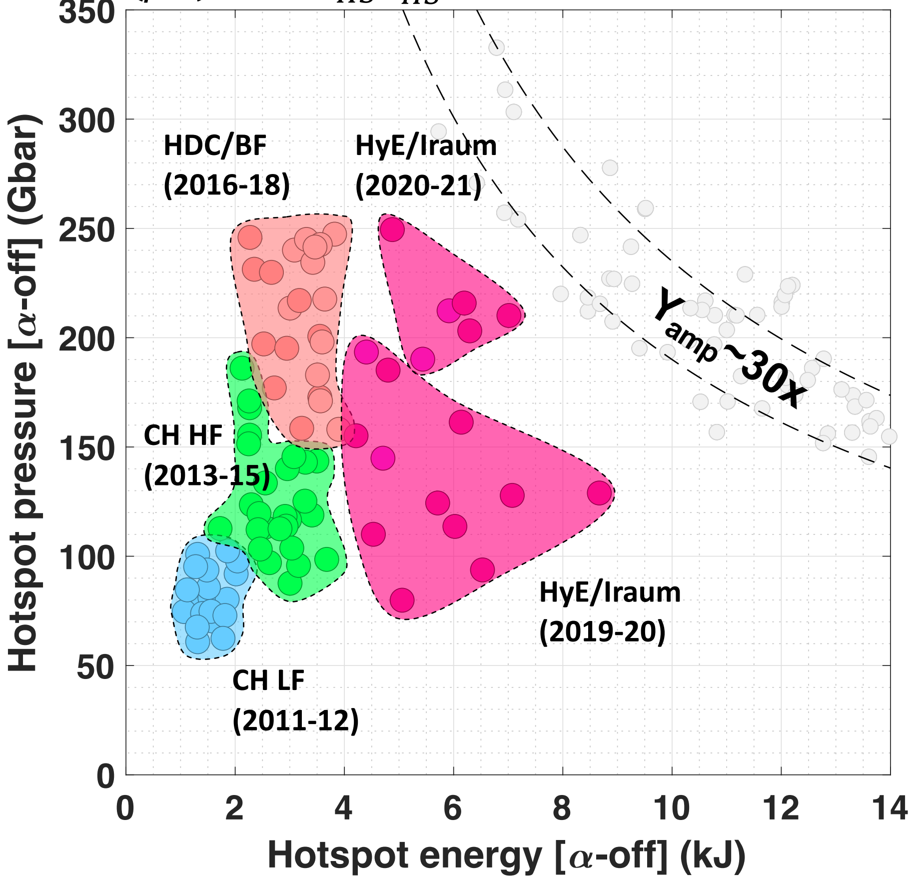

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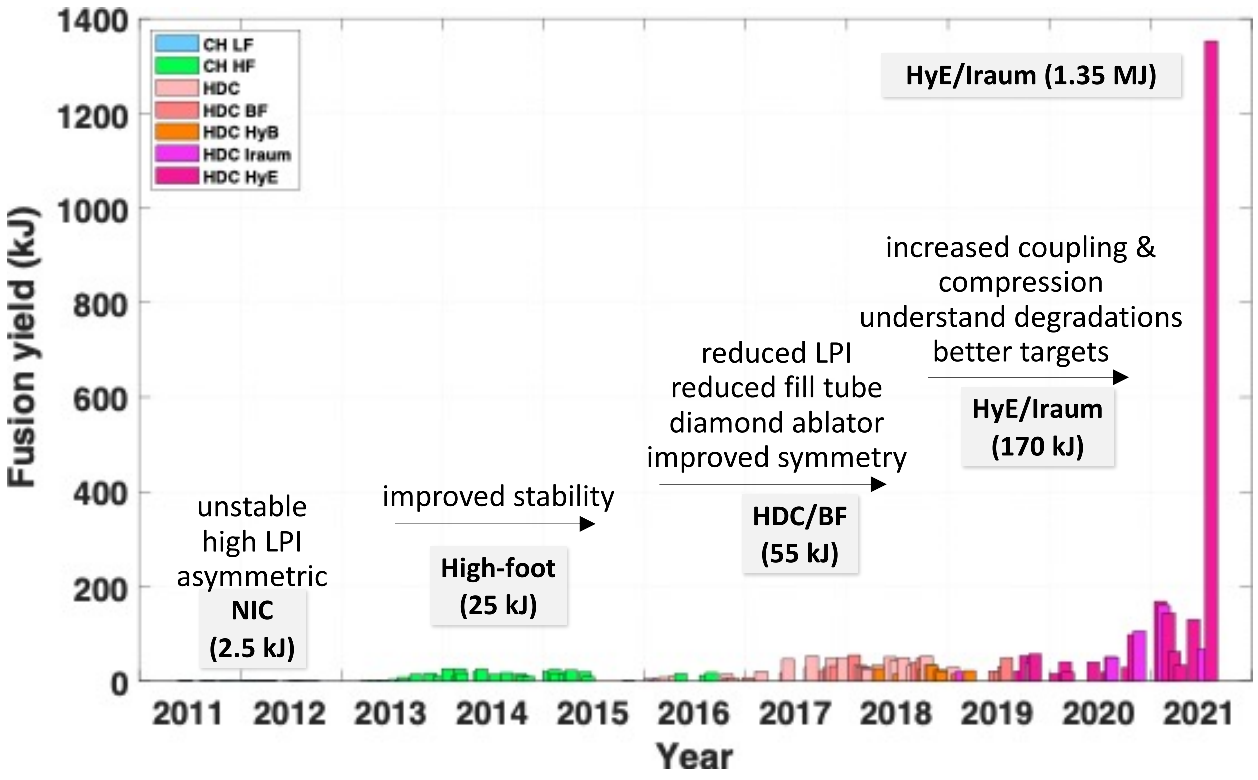

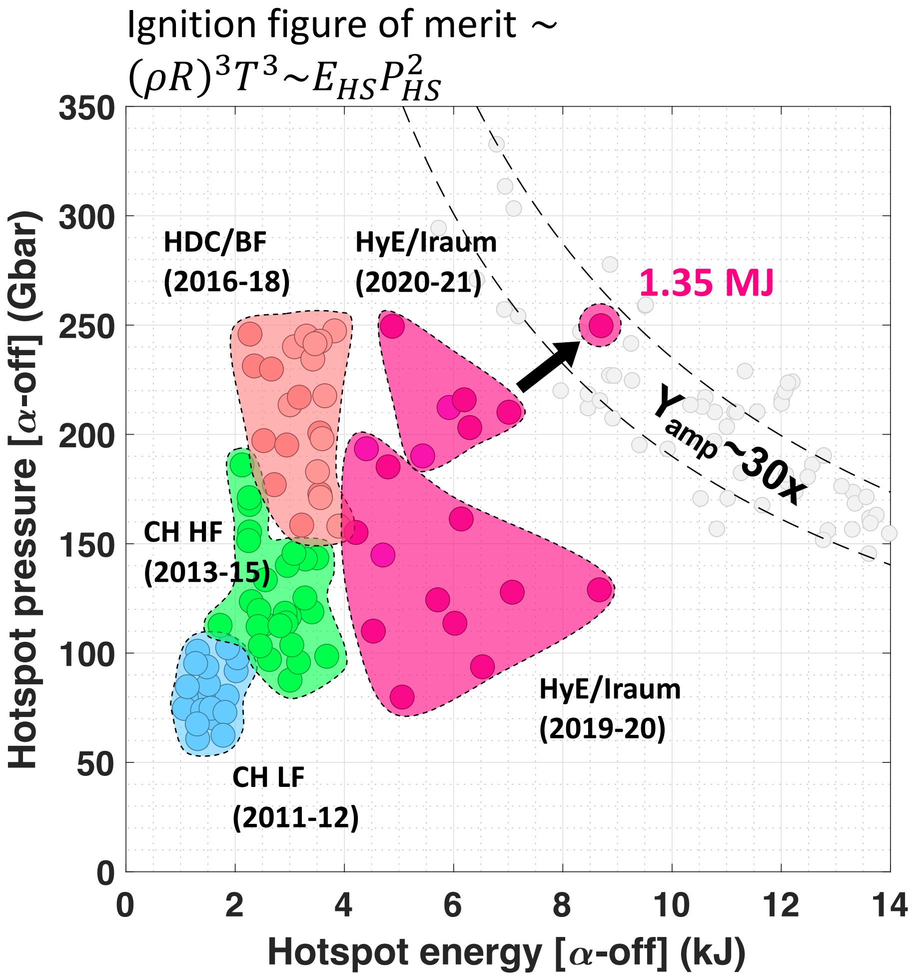

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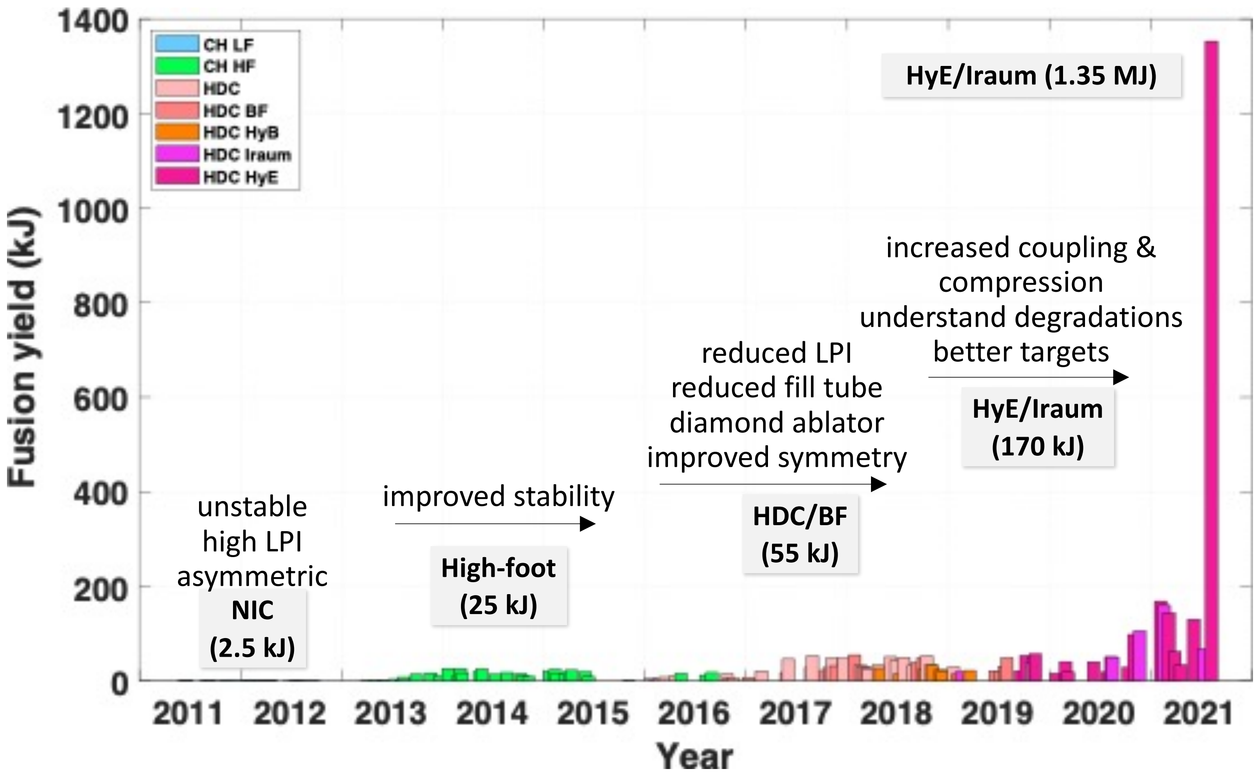
171 DT shots over ~10 years



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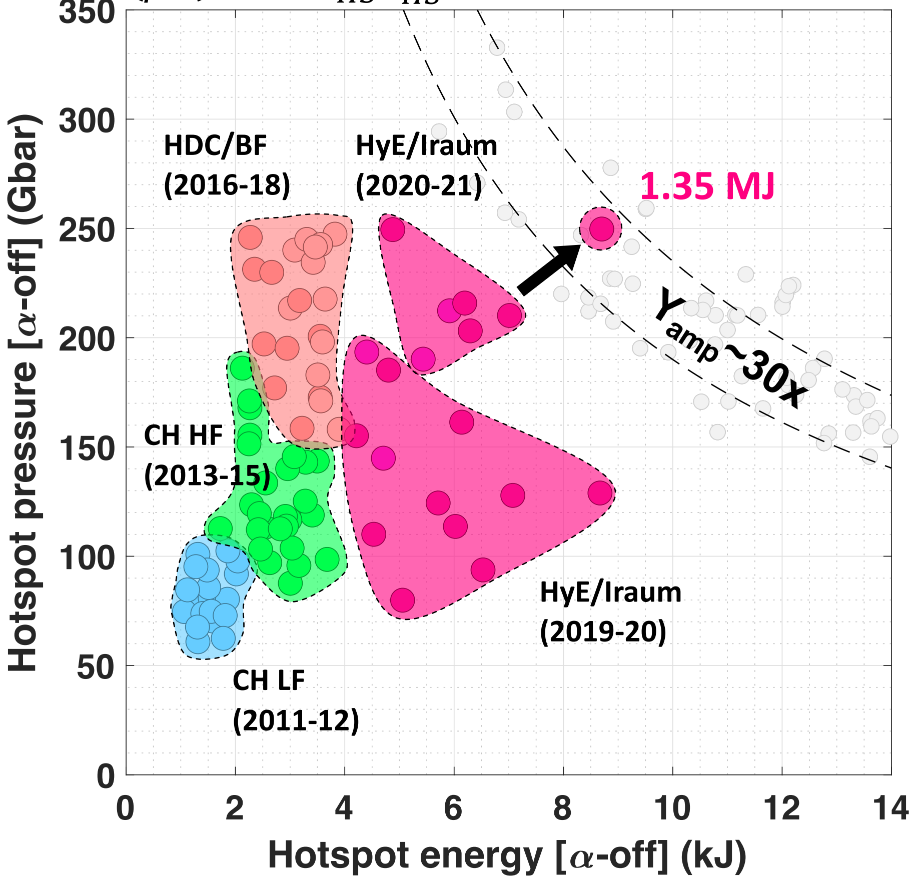
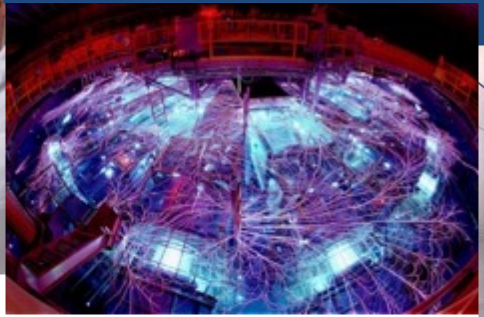


Built on a decade+ of research on the NIF, N210808 demonstrated burn propagation and a gain of 0.7

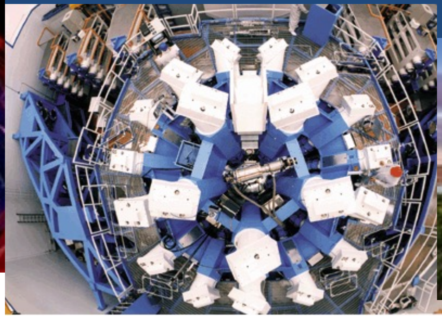
Currently we make use of a number of premier facilities around the US & the world to conduct forefront HED science

MEC SLAC

Z Machine

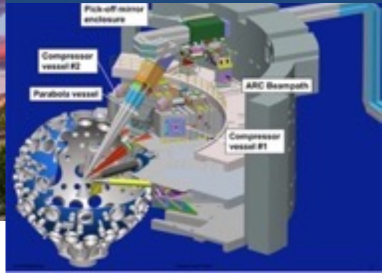


OMEGA-60



NIF

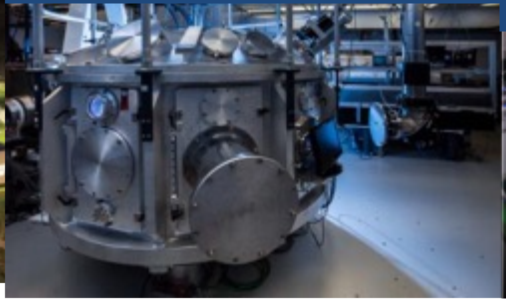
NIF-ARC



TUNL

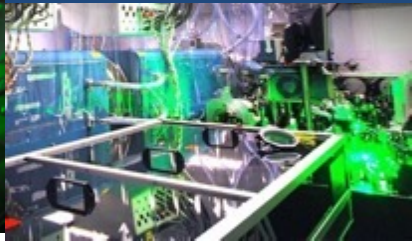
DCS

Jupiter Laser Facility



OMEGA EP

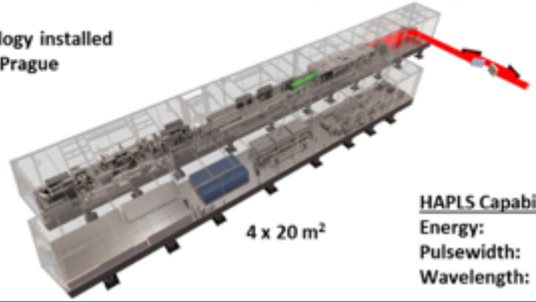
Texas PW



Until recently, much of HED has focused on large, energetic drivers that are mostly single-shot. However, next-gen lasers coming online are already rep-rated (>10 Hz)

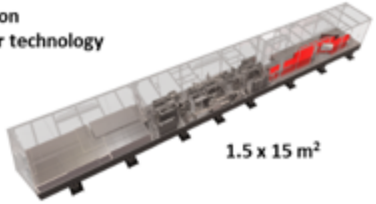
Numerous rep-rate-capable laser facilities have recently come online, and more are on the way

High-repetition-rate Advanced Petawatt Laser System (HAPLS)
1 PW @ 10 HZ
Operational technology installed at ELI-Beamlines in Prague



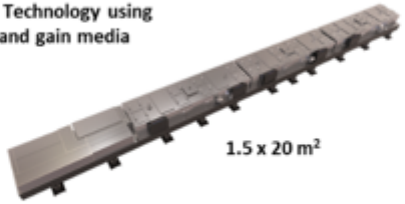
HAPLS Capabilities
Energy: 30 J
Pulsewidth: 28 fs
Wavelength: 820 nm

Scalable High-power Advanced Radiographic Capability (SHARC)
1 PW @ 10 HZ
Direct implementation of HAPLS pump laser technology



SHARC Capabilities
Energy: 150 J
Pulsewidth: 150 fs
Wavelength: 1.053 µm

Big Aperture Thulium (BAT) System
0.3 PW @ 10 kHZ
High TRL HAPLS-like Technology using Commercial Diodes and gain media



BAT Capabilities
Energy: 30 J
Pulsewidth: 100 fs
Wavelength: 1.95 µm

300 W
Indirect CPA
Max E-O Efficiency 1.5%

↓

1,500 W
Direct CPA
Max E-O Efficiency 7.6%

↓

300,000 W
Direct CPA
Multi-pulse Extraction
Max E-O Efficiency 21%

Zettawatt-Equivalent Ultrashort Pulse Laser System
ZEUS

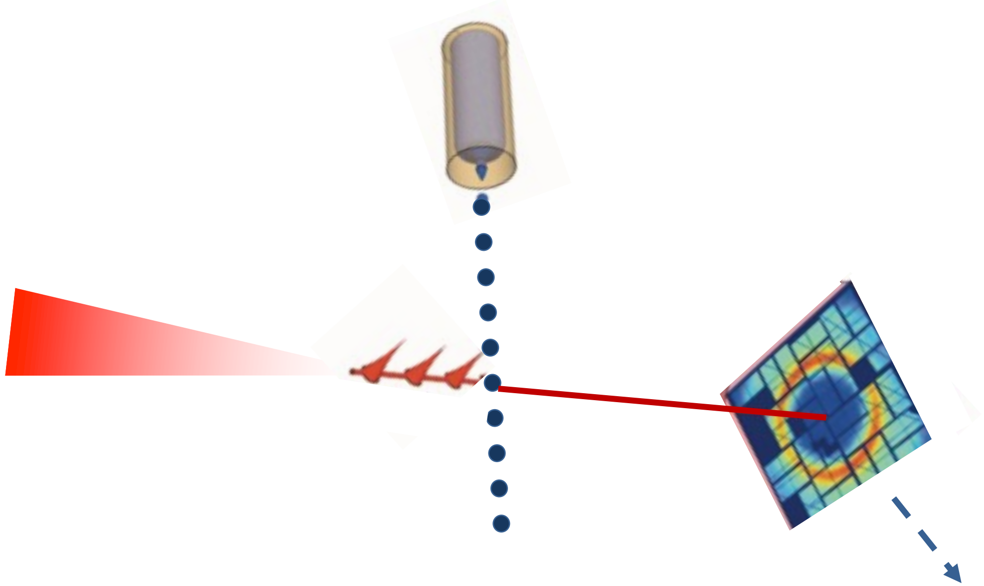
Zettawatt Equivalent Ultrashort laser System

- ZEUS will be the highest power U.S. laser system to allow exploration of fundamental physics

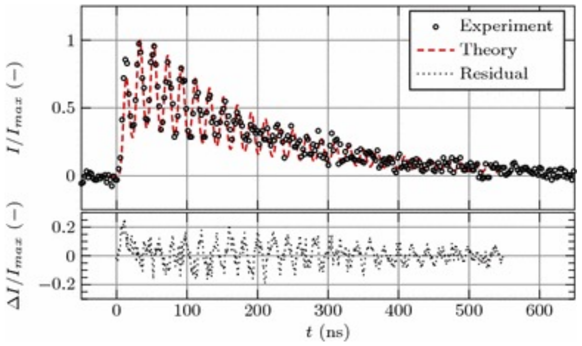
- 3 PW, shot/min
- <0.5 PW, 4 Hz

The US leads in laser technology development; pursuing new and very innovative laser technologies which will enable additional science opportunities

High-rep-rate laser science represents a radical paradigm shift in the way we do HED experiments



J.A. Sellberg et al., Nature **510** (2014)



High-rep-rate means:

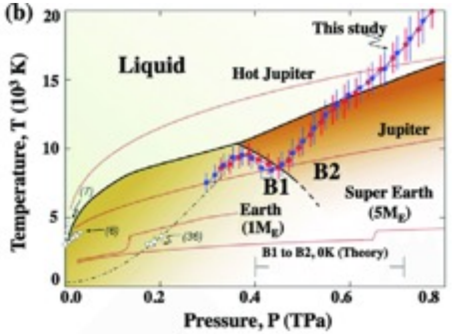
- More shots
- More data
- More statistics
- More precision
- More phase space
- More experiments
- More exploration
- Faster response to close mission need gaps

*Scientific knowledge = (**Drive** + **Probe**) x Repetition rate x time*

Many HED experiments will benefit from high throughput science enabled by high repetition rate lasers

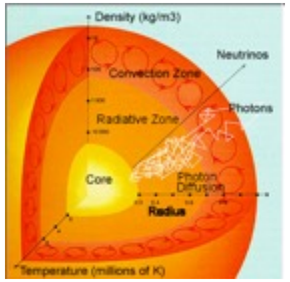
High Pressure Material Properties

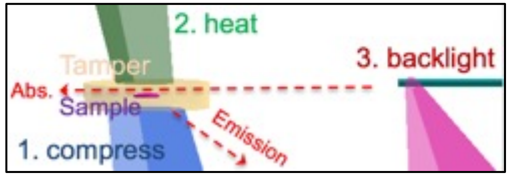
McWilliams et al., Science 2012



More shots to take measurements across larger phase space

Opacities and Radiative Properties

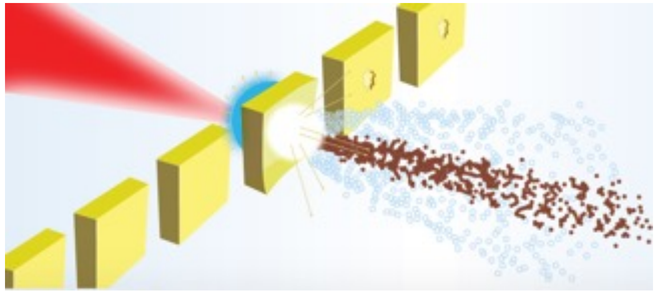




Heeter, LLNL

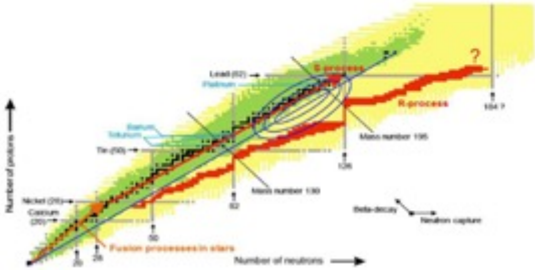
Increase measurement confidence through high statistics and constrain complex models used for stockpile assessments

Secondary Source Particle + Radiation Beams



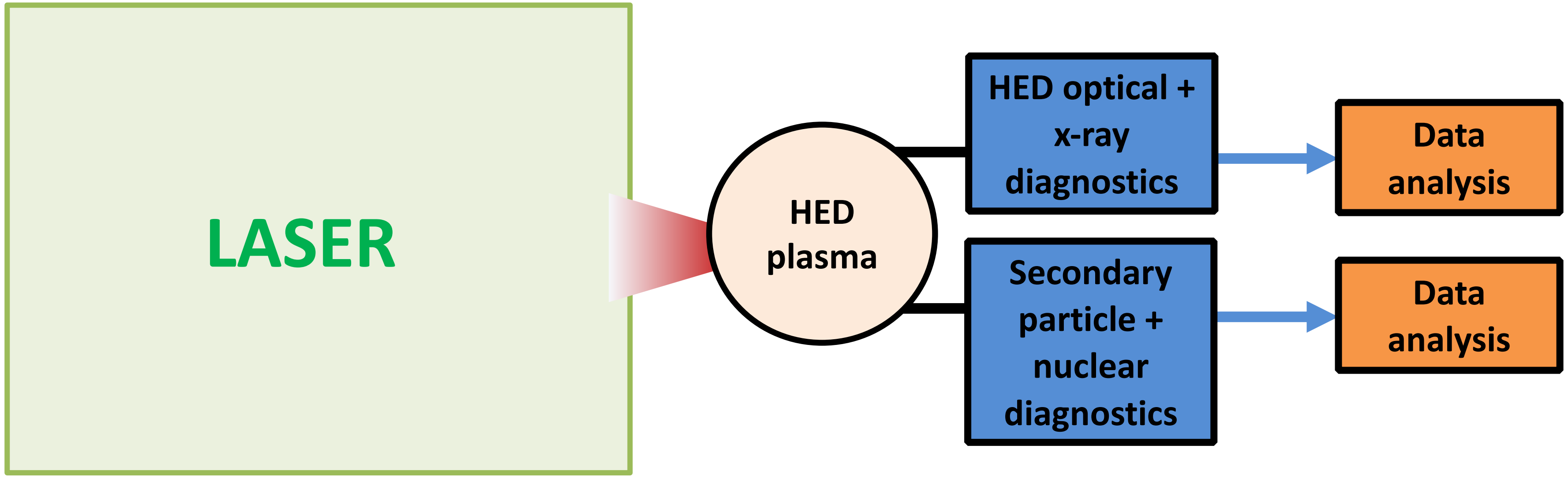
High brightness, tuned, reproducible beams for probing, heating, radiography

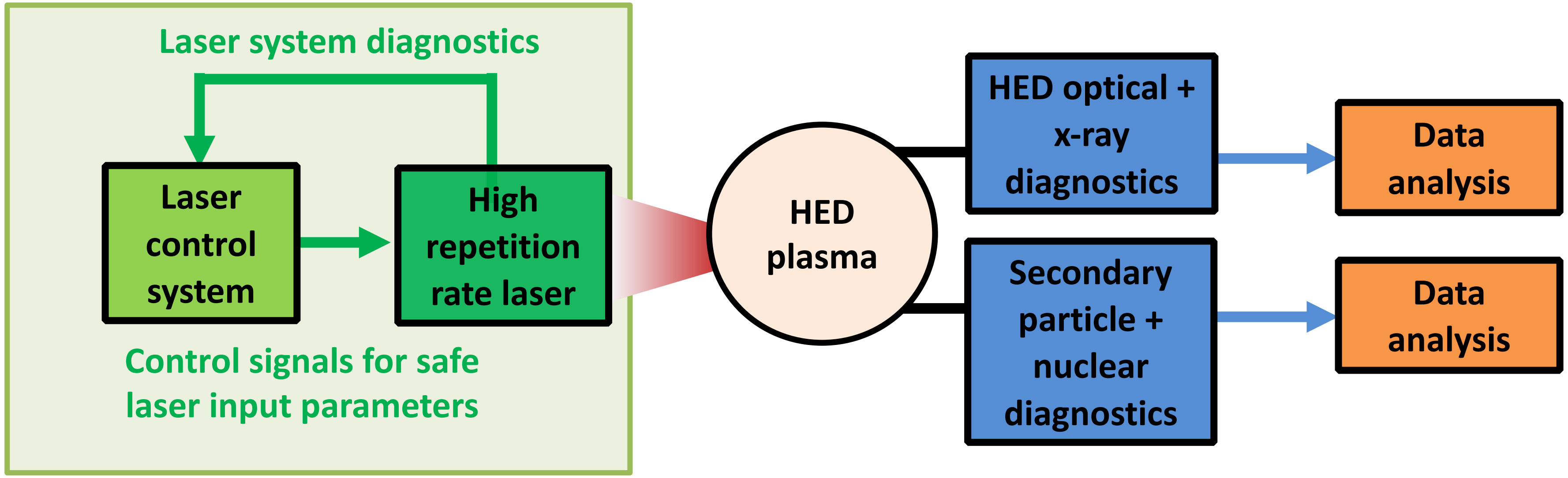
Plasma Nuclear Physics

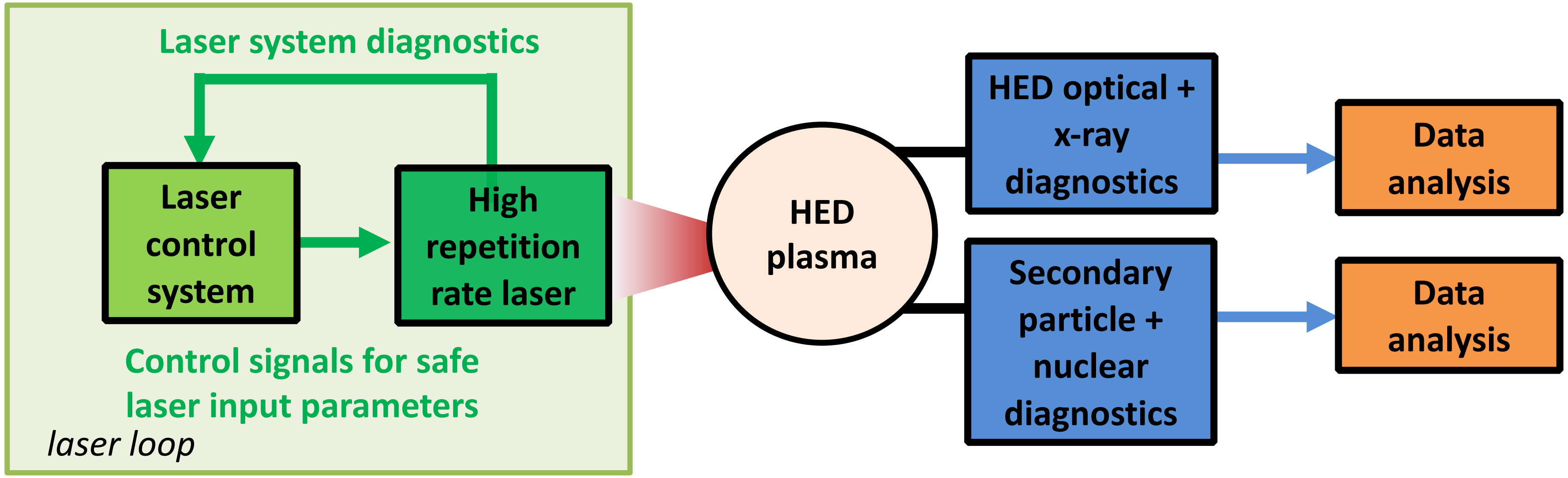


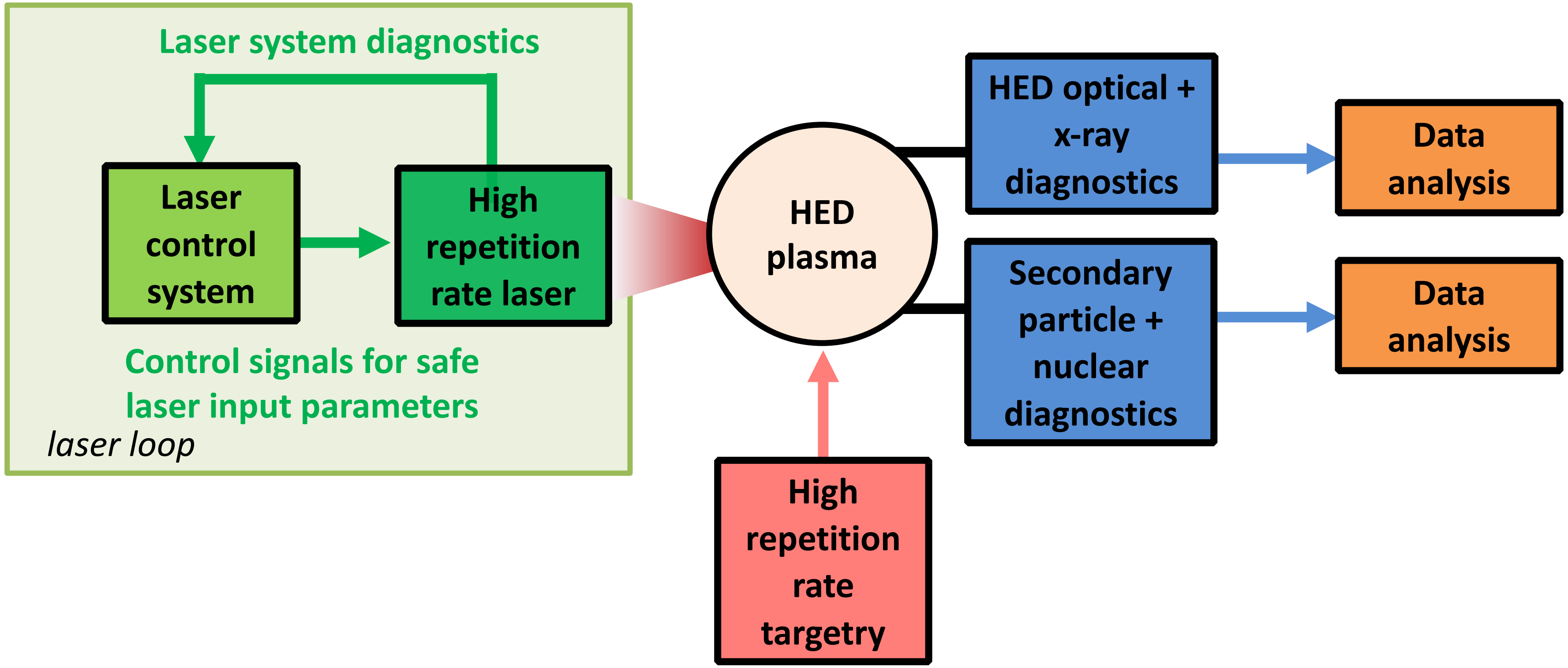
D. Habs et al., Appl Phys B 103: 471 (2011)

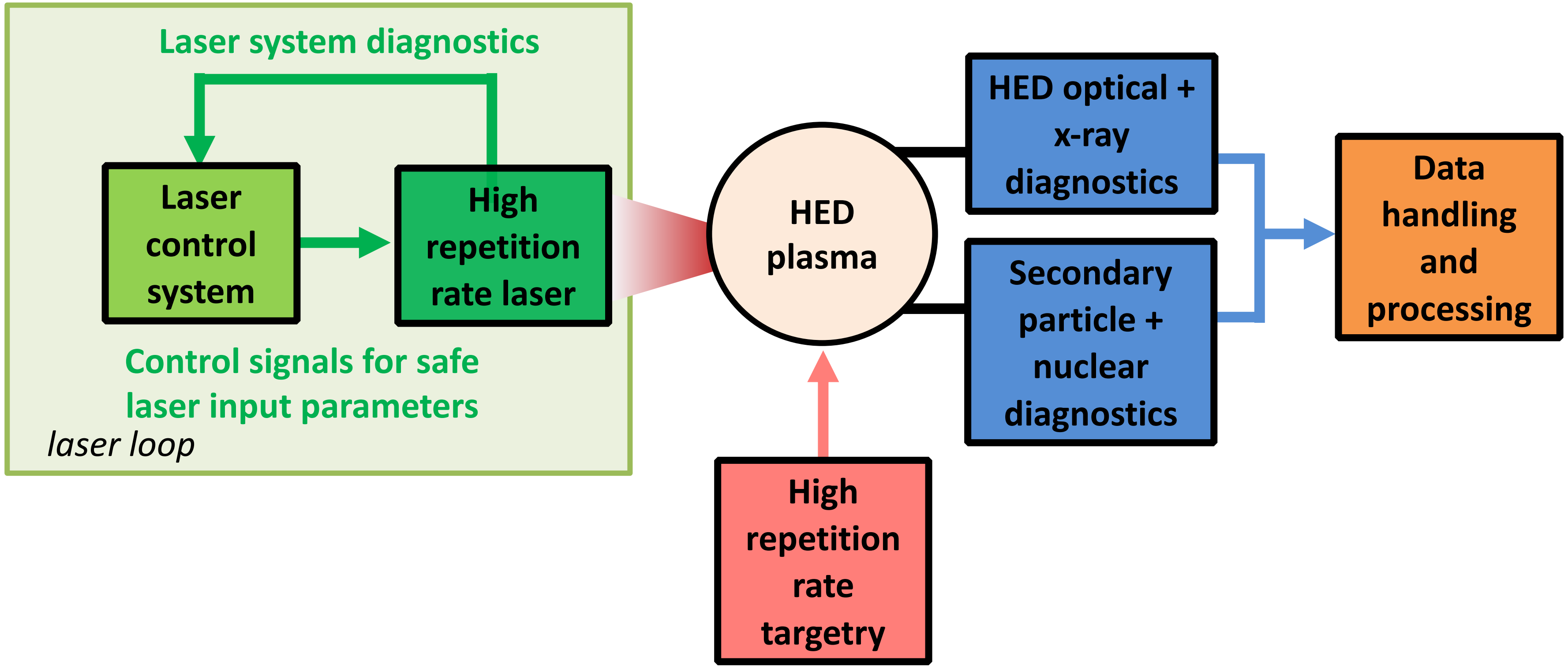
High average numbers to probe subtle, rare nuclear reactions


LASER
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data analysis
Data analysis

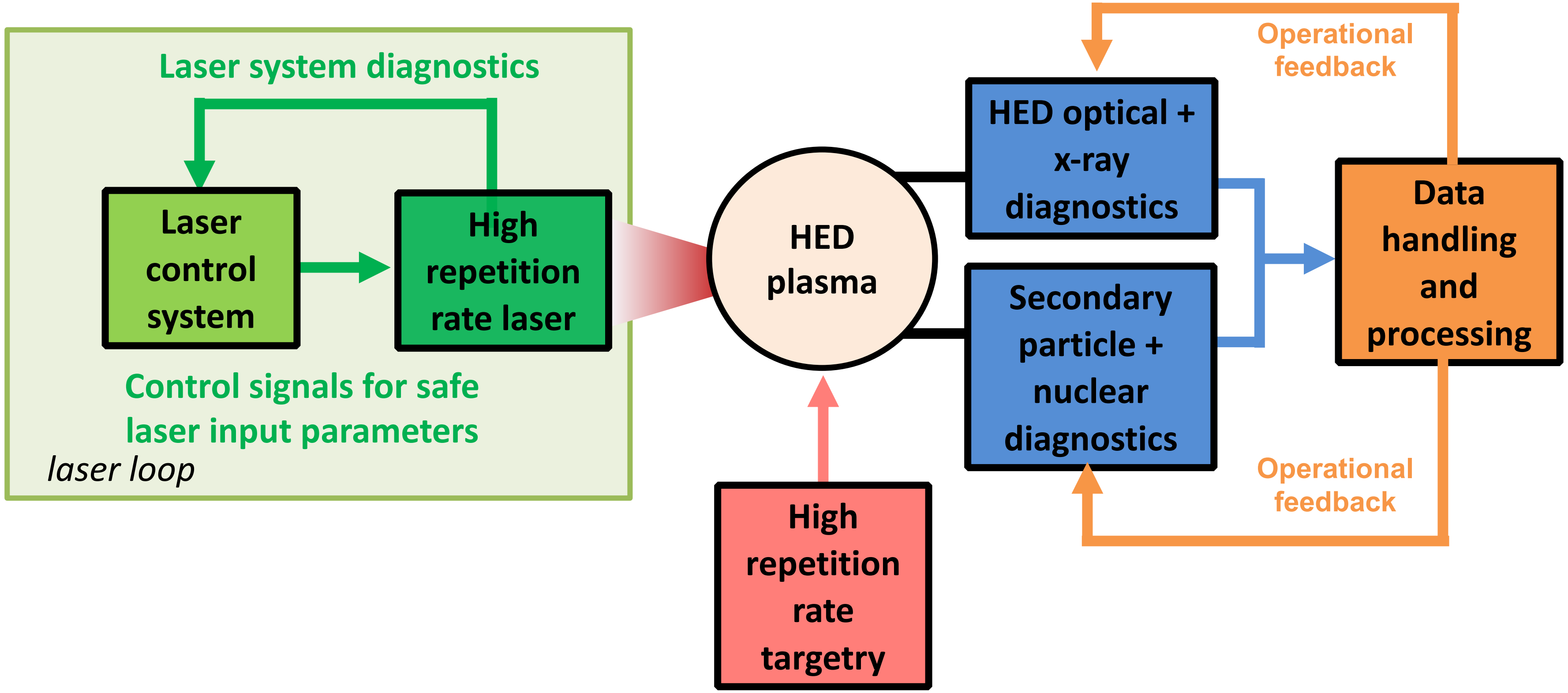

Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data analysis
Data analysis

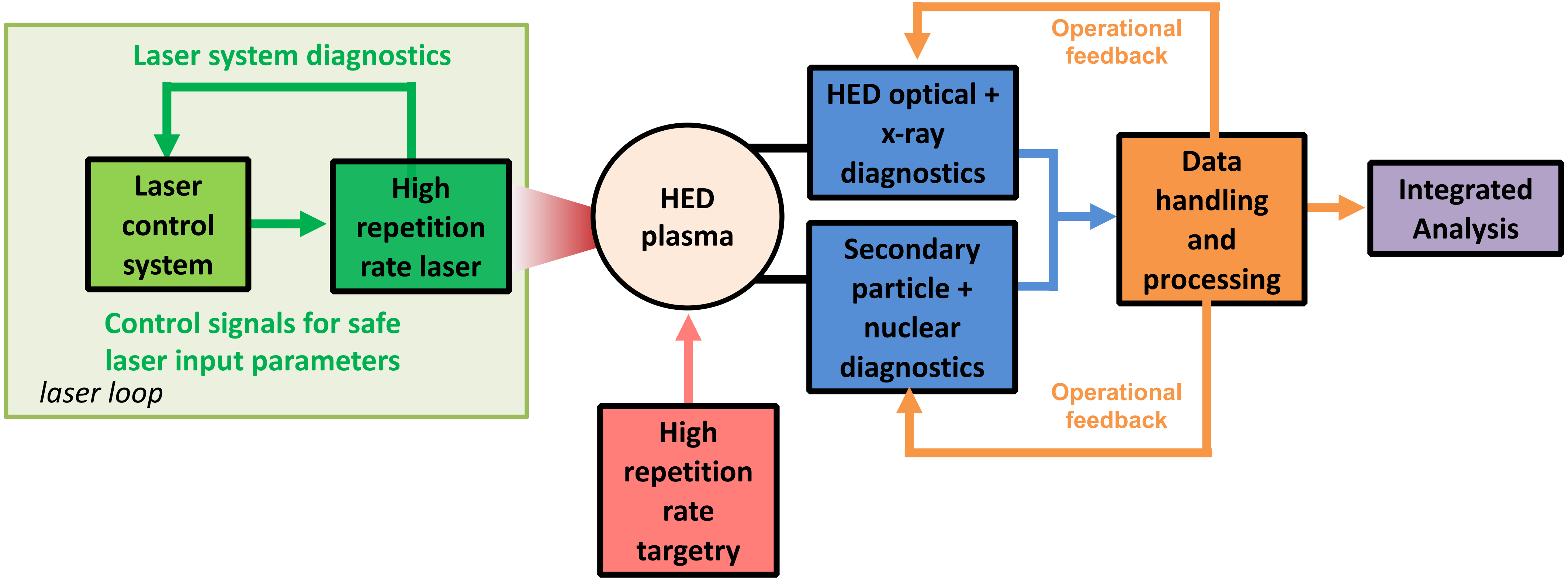

Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data analysis
Data analysis


Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data analysis
Data analysis
High repetition rate targetry

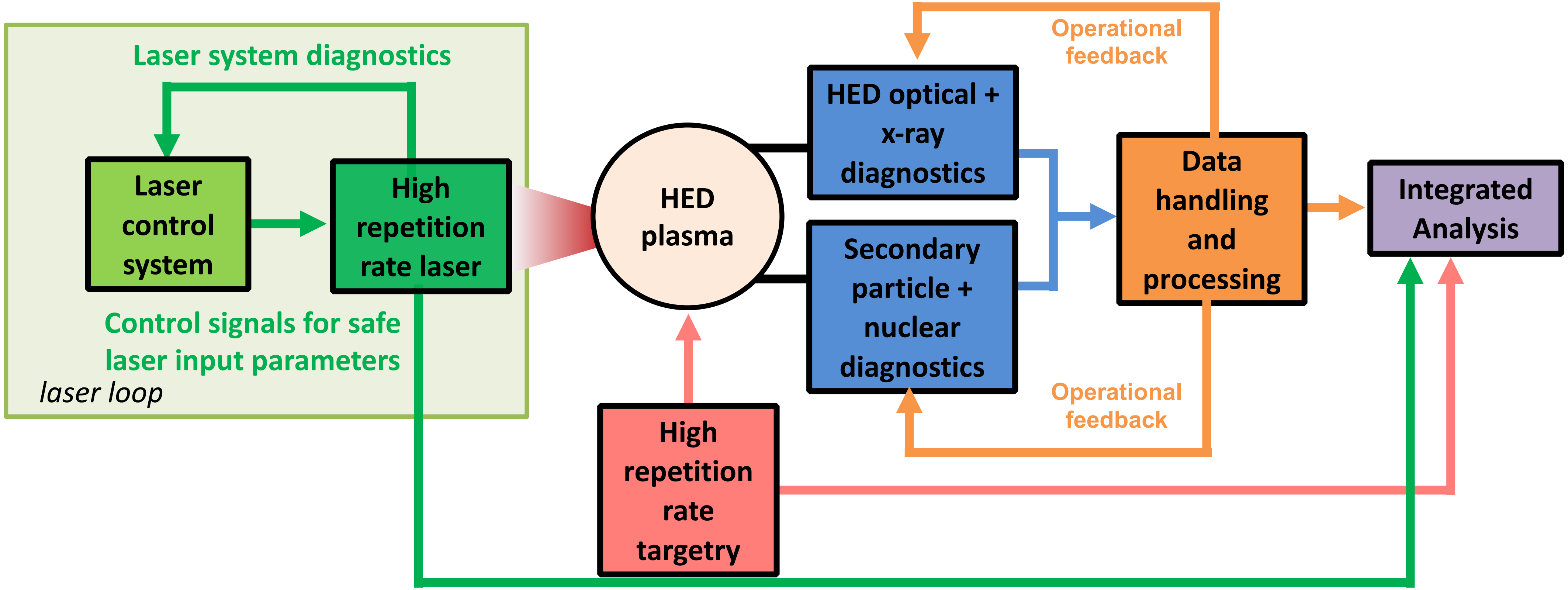


Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data handling and processing
High repetition rate targetry


Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
High repetition rate targetry
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data handling and processing
Operational feedback
Operational feedback



Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
High repetition rate targetry
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Operational feedback
Data handling and processing
Operational feedback
Integrated Analysis


Laser system diagnostics
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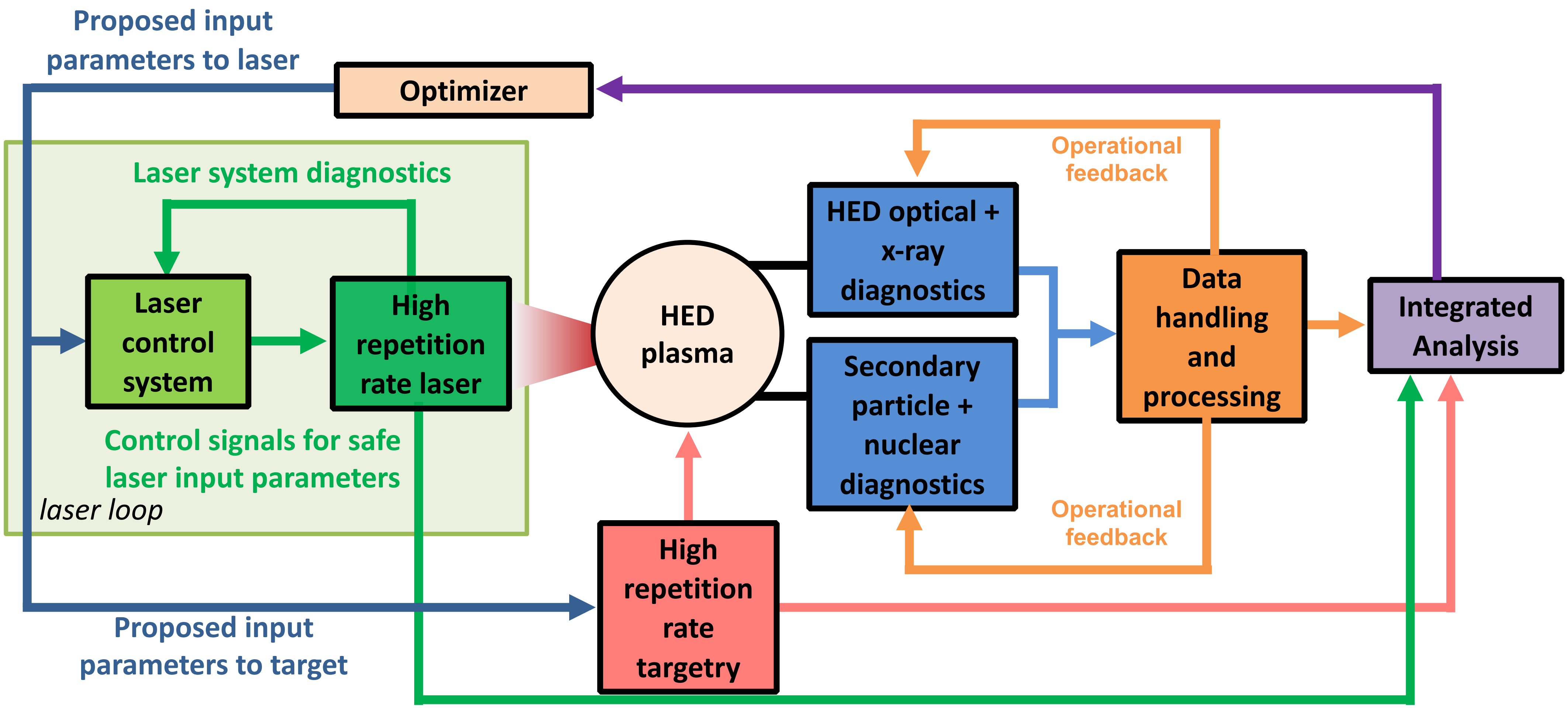
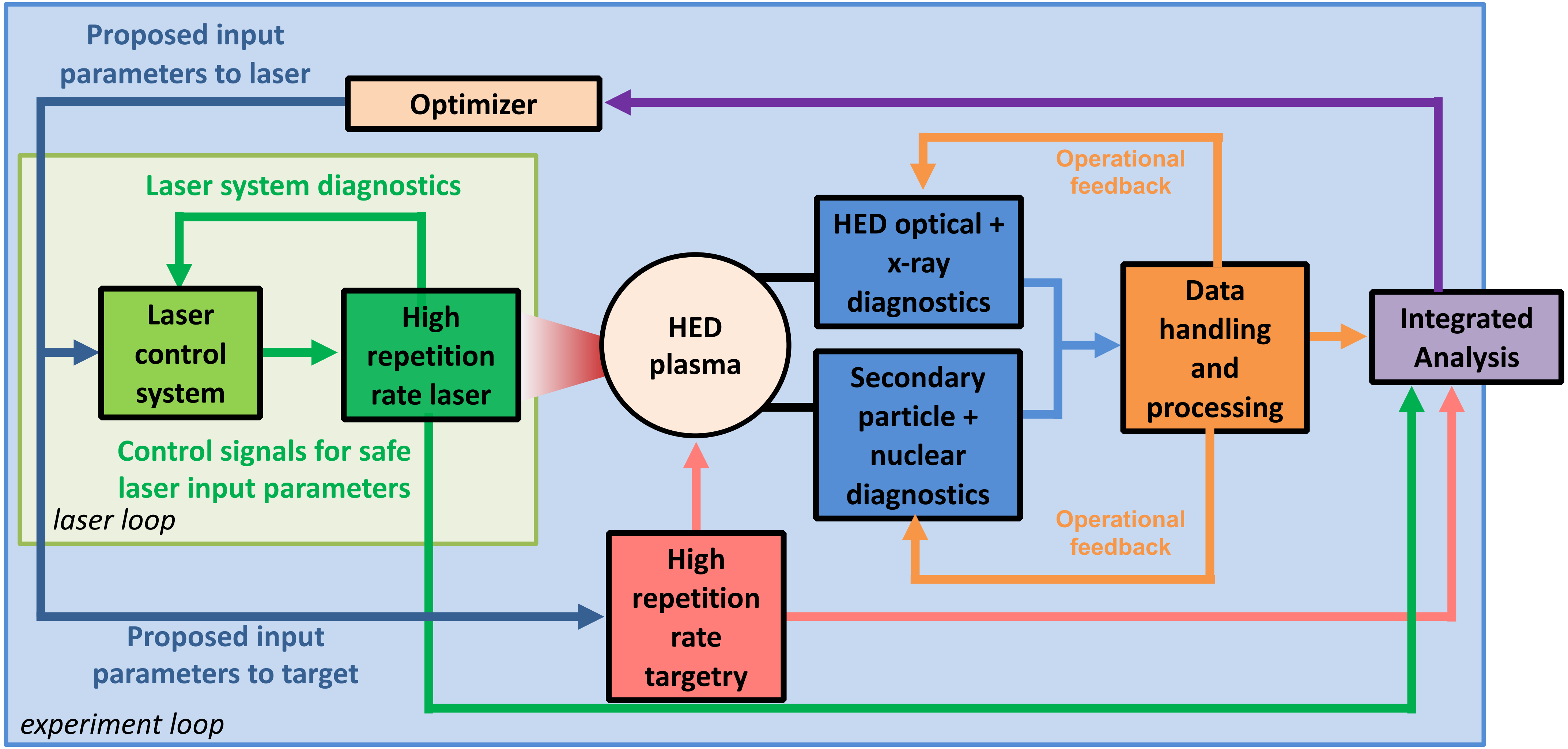
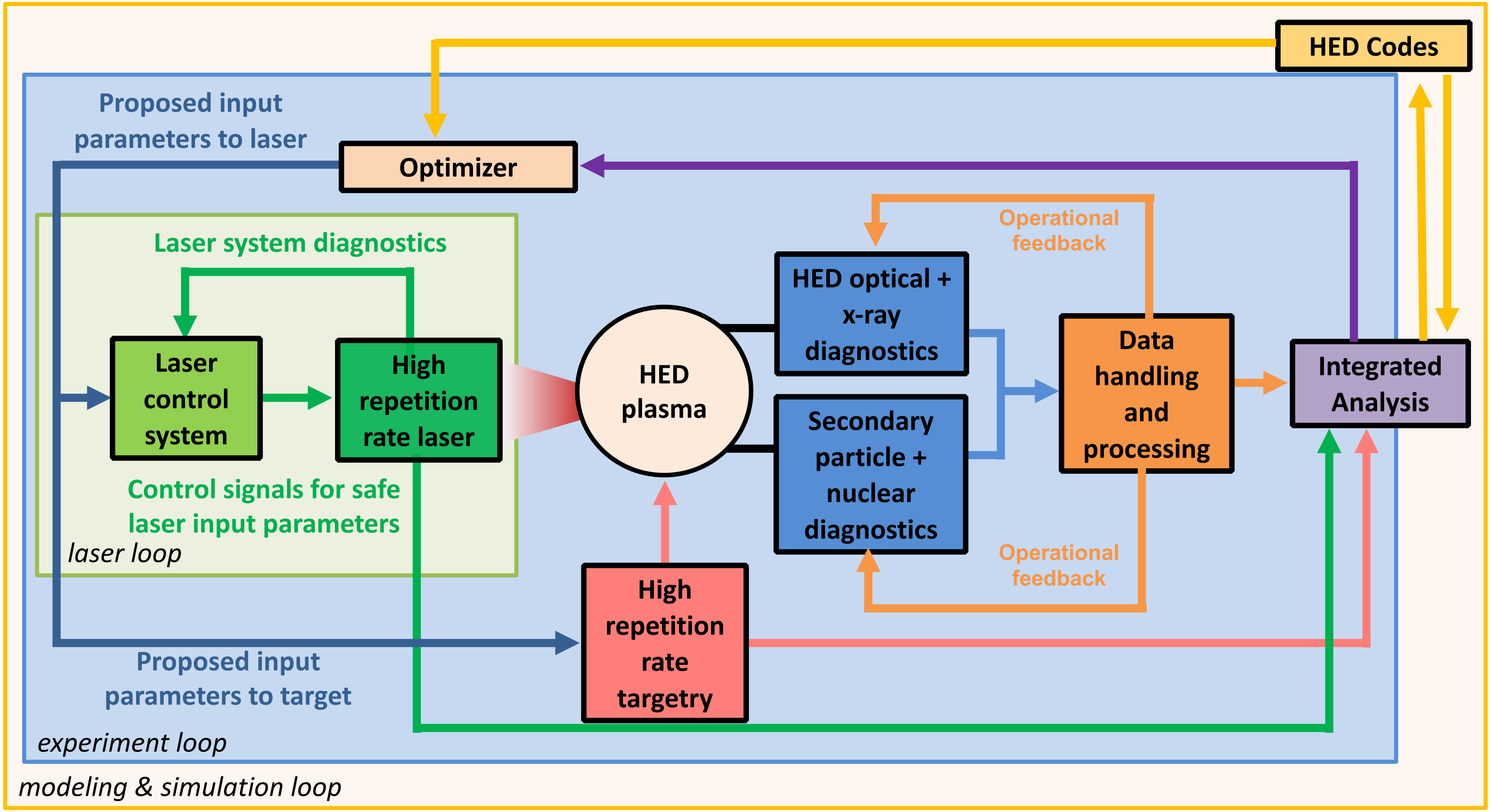
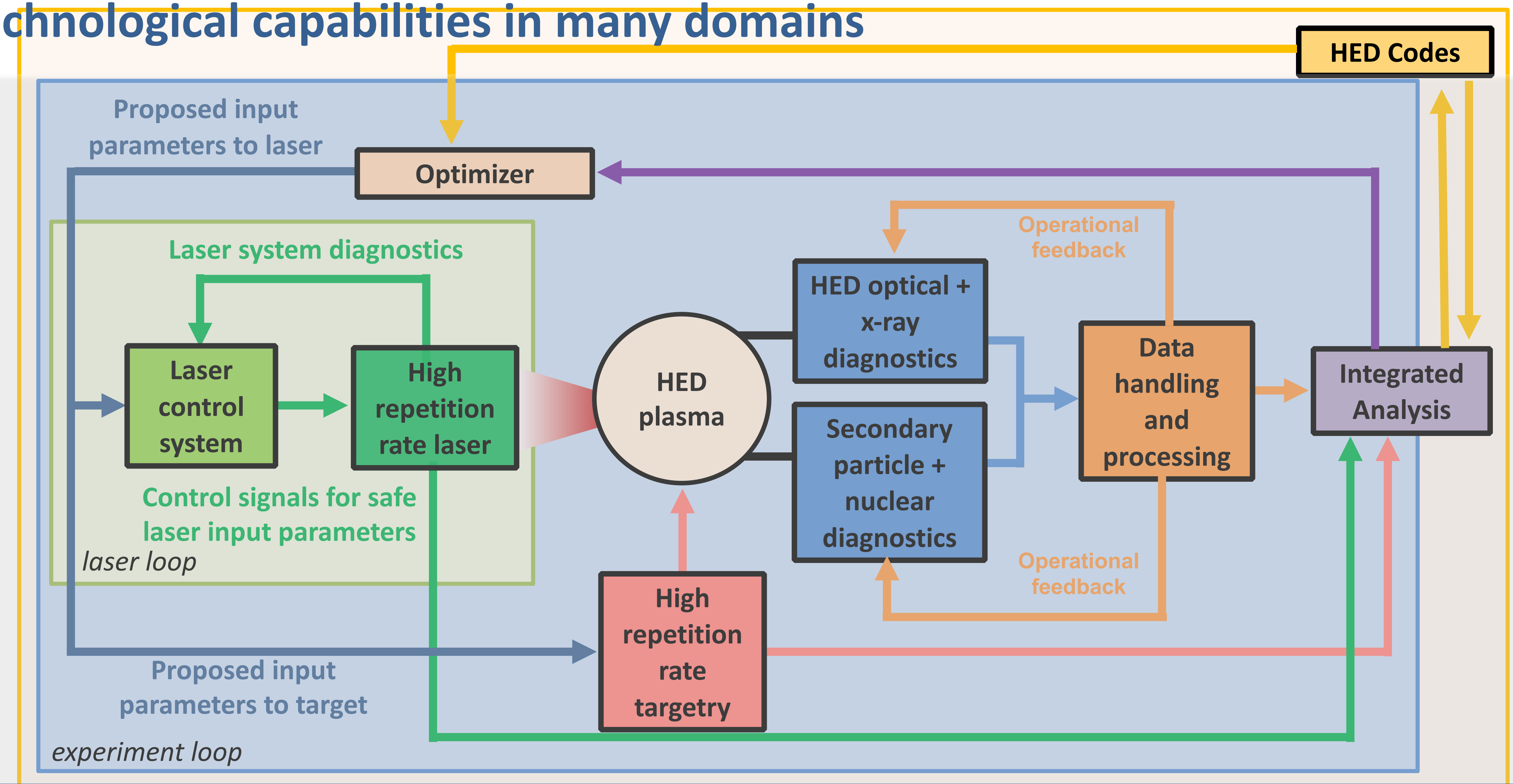
Operational feedback
High repetition rate targetry


Proposed input parameters to laser
Optimizer
Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Operational feedback
Data handling and processing
Operational feedback
Integrated Analysis
High repetition rate targetry
Proposed input parameters to target


Proposed input parameters to laser
Optimizer
Laser system diagnostics
Laser control system
High repetition rate laser
Control signals for safe laser input parameters
laser loop
HED plasma
Operational feedback
HED optical + x-ray diagnostics
Secondary particle + nuclear diagnostics
Data handling and processing
Integrated Analysis
Operational feedback
High repetition rate targetry
Proposed input parameters to target
experiment loop


HED Codes
Proposed input parameters to laser
Optimizer
Laser system diagnostics
Operational feedback
HED optical + x-ray diagnostics
Laser control system
High repetition rate laser
HED plasma
Data handling and processing
Integrated Analysis
Secondary particle + nuclear diagnostics
Control signals for safe laser input parameters
laser loop
Operational feedback
High repetition rate targetry
Proposed input parameters to target
experiment loop
modeling & simulation loop

High-rep-rate laser science means a fully integrated system that leverages technological capabilities in many domains



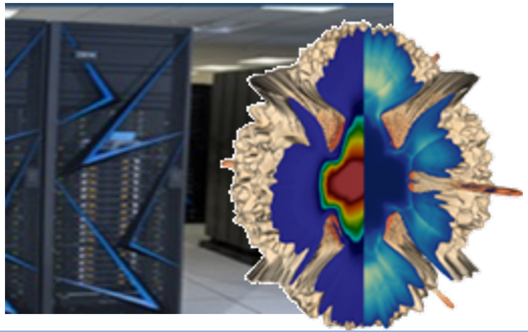
Challenges that stem from high-rep-rate experiments are starting to be addressed

A number of emerging technologies and capabilities can be leveraged to complement and enhance high-throughput HED experiments

Optical Technology

Large optics

HPC & HED Codes

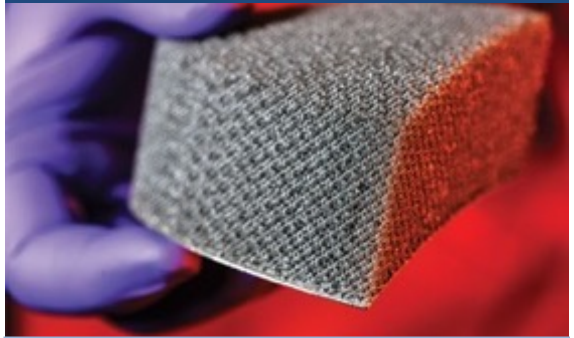


Advanced modeling, codes, machine learning

Target Fabrication

Exquisite & complex

Additive Manufacture



Novel materials, adaptive preparation

Laser Facilities

JLF & NIF

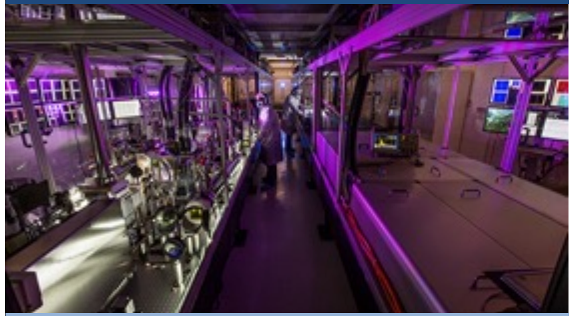
Community Ties

Discovery Science & User Group Meetings

Diagnostics

Transformative experimental capability

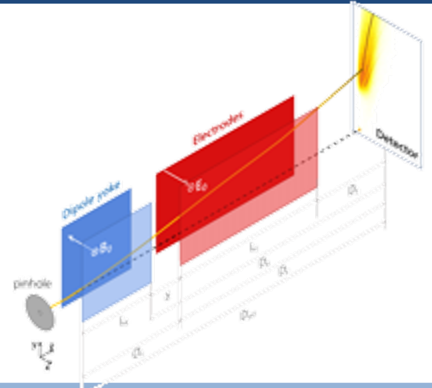
Frontier Laser Technology



kW-MW Petawatt Lasers

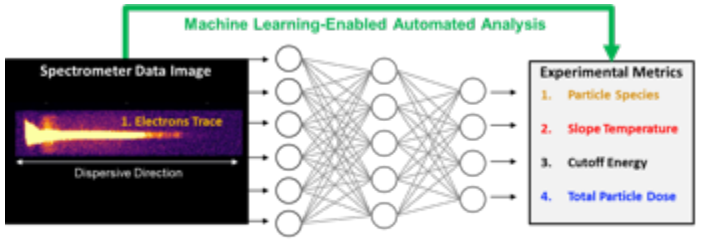
Currently, the lack of appropriate diagnostics is a major bottleneck to making HRR HED science a reality

Diagnostic Development



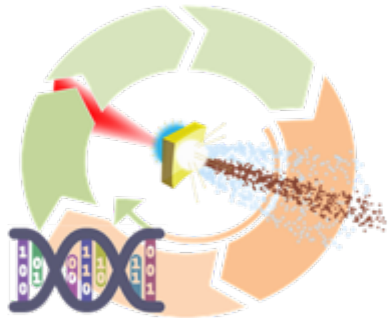
Rep-rate-capable diagnostics for x-ray and particle beams that are robust to HED environments

High-throughput Analysis

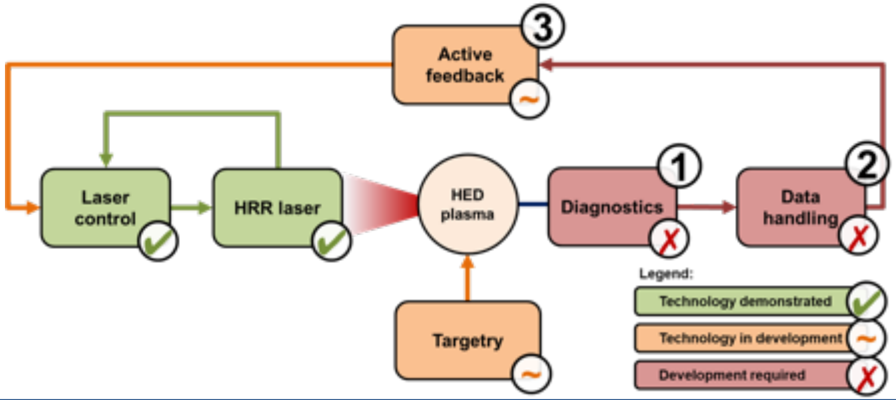


ML-based algorithms for *real-time analysis* of experimental metrics

Active Feedback

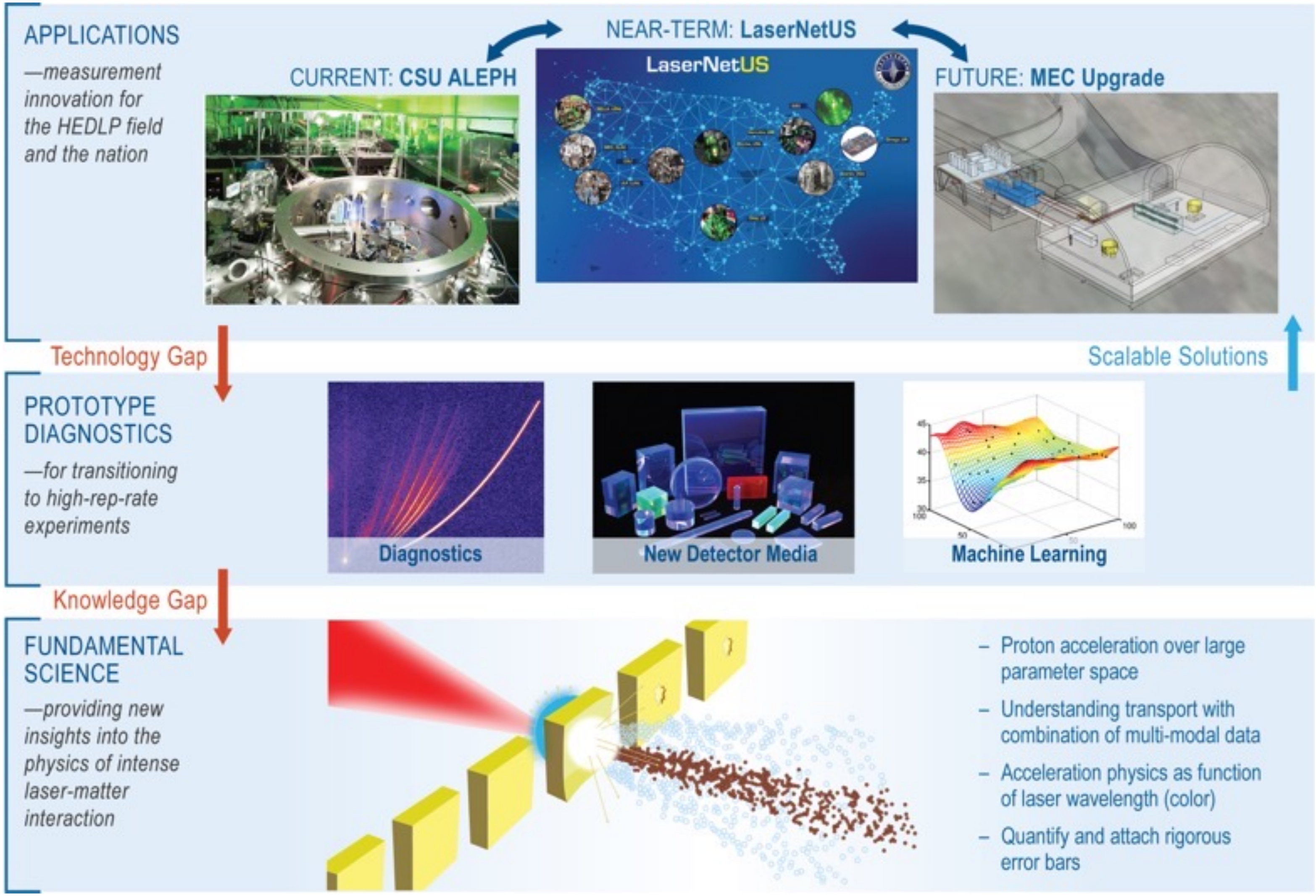


Feed back experimental data to the laser system and demonstrate secondary source optimization

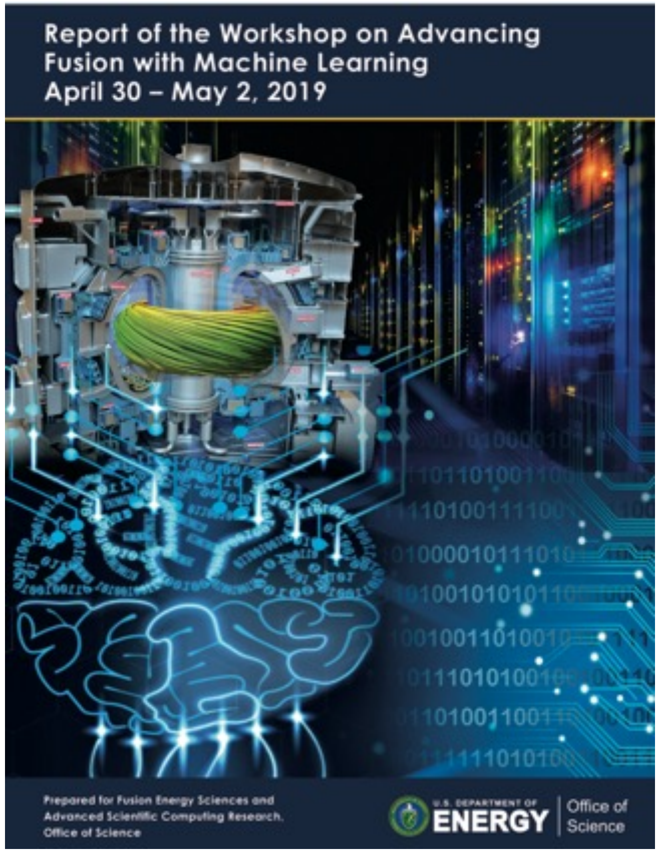


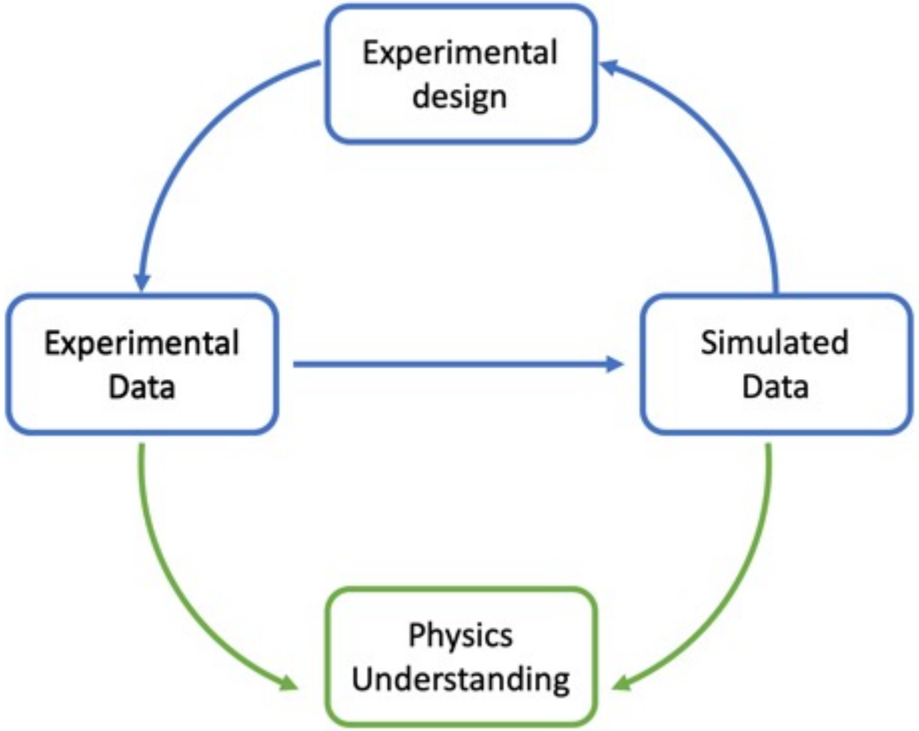
We are developing a suite of high repetition rate diagnostics coupled to high-throughput analysis and active feedback

These new HRR diagnostics will be deployed at CSU ALEPH (3.3 Hz) laser as a blueprint for scaling these capabilities to other LaserNetUS facilities



The application of Cognitive Simulation to HED means an integrated modeling tool that both learns from and guides experiments

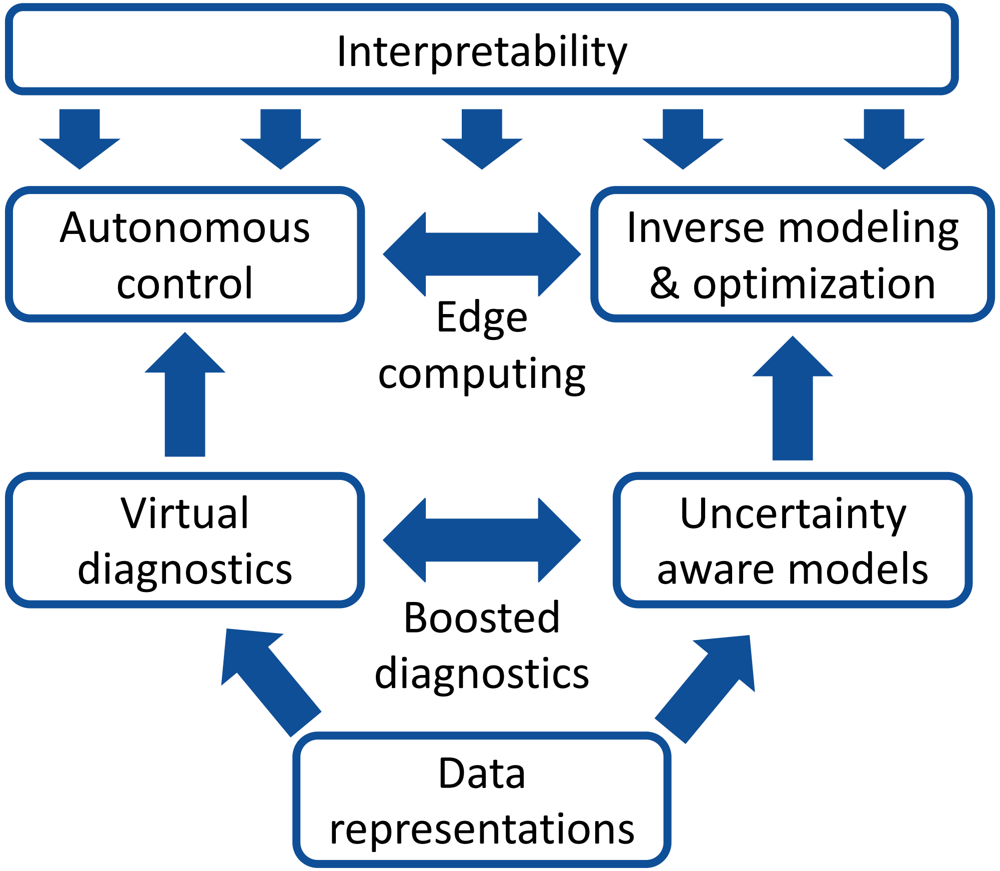




The revolution in computational power and machine learning techniques paves the way for new approaches in cognitive simulation

HED is ripe for the application of novel machine learning and AI techniques

- Multimodal data representations:
  - Representation learning & holistic treatment of diagnostics
- Enhanced diagnostics:
  - Transfer learning & virtual diagnostics
- Modeling and optimization under uncertainties:
  - UQ for ML & reliable control loop
- Advanced architectures at the edge:
  - System integration & autonomous control
- On-the-fly model elevation
  - ML interpretability & accelerated insights by assimilating live experimental data

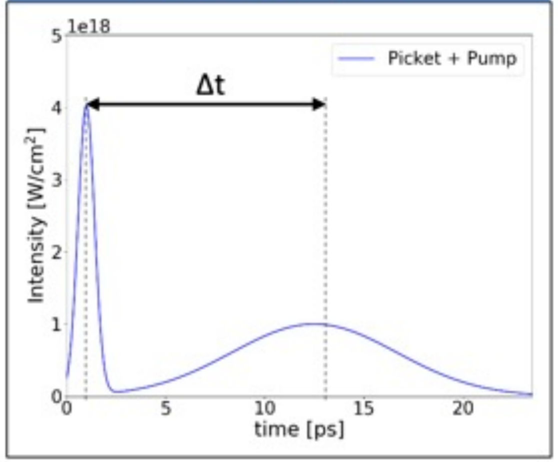


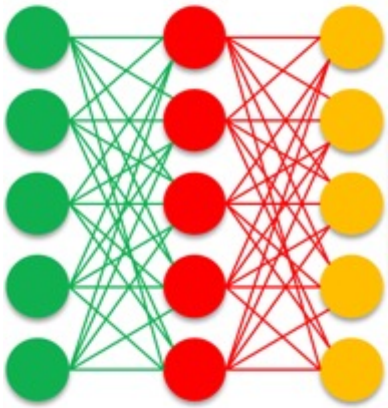
We are combining cutting-edge machine learning with operations to demonstrate a real-time feedback HRR integrated experimental and simulation HED capability

We are exploring the manipulation of particle acceleration at fs-ps timescales for precise control over secondary source characteristics

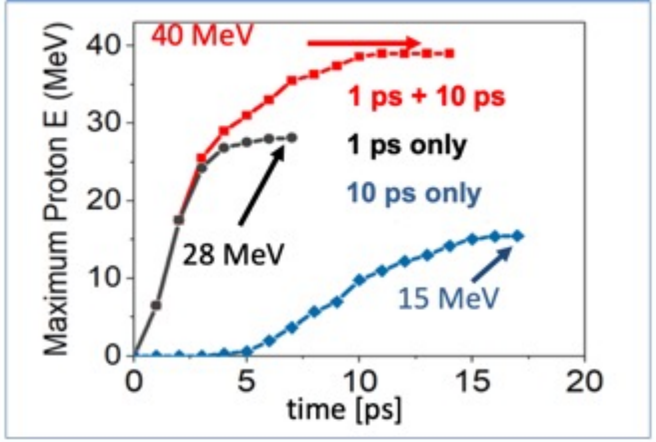
Inputs → "Big Data" + ML → Outputs

Shaped short-pulses





Time evolution of max proton energy



*J. Kim, Phys. Plasmas 25, 083109 (2018)

- High data throughput modeling/experimental methods enable rapid exploration of massive parameter space
- Shaped short pulses could be used to enhance efficiency and fluence of particle & X-ray sources → probing/driving experiments and interesting fundamental physics

New techniques/tools to modulate laser pulse shapes with ps resolution + predictive capability + ML to explore huge phase space = very cool new fundamental science in laser-matter interaction, and direct applications

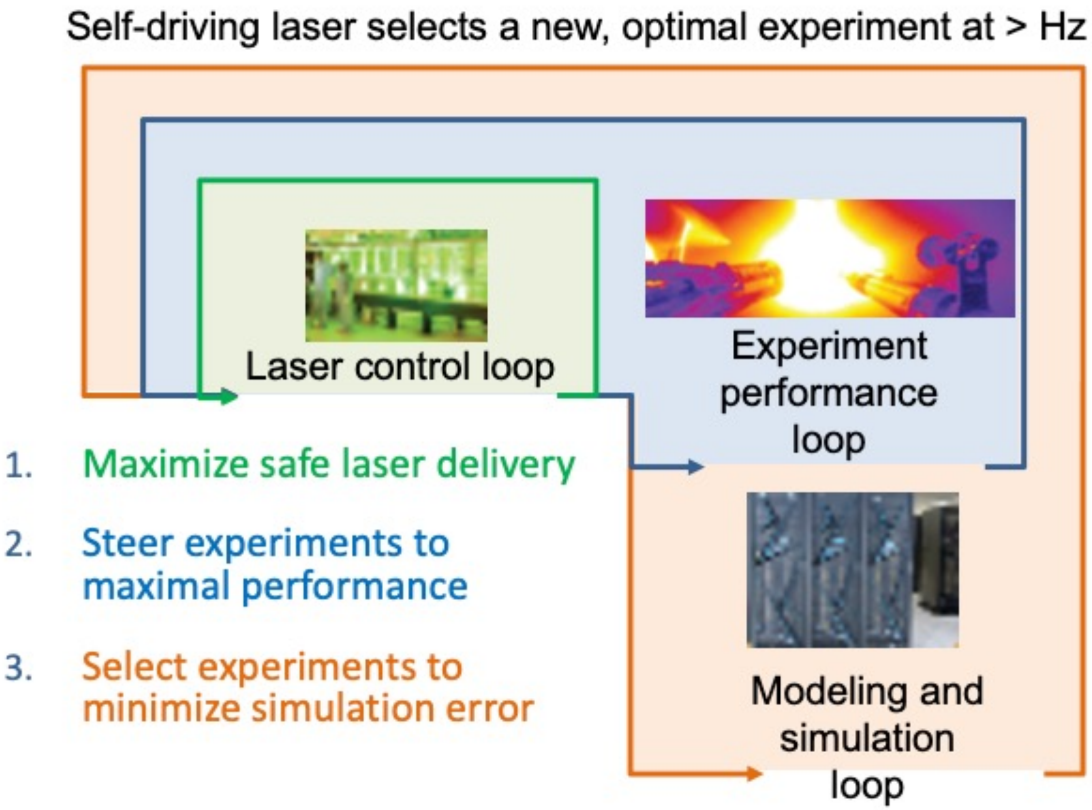
The challenges are many, and we are looking to learn from others

- A commonly voiced concern is that AI will remove expert judgement. How do we mitigate this?
  - Domain-aware, interpretable, and robust scientific machine learning needed to support progress
  - Constant iterative cycle with tight coupling and validation between experiments and modeling
  - Work across-facilities + scale between them

- Some of the biggest challenges we see in applying AI solutions to this work:
  - Machine and data interfaces + Communication across different tools/control systems
  - Standardization
  - Data volume
  - Reliability/robustness
  - Distributed debugging
  - Data provenance

The goal is to develop a high-throughput capability that is demonstrated to rapidly respond to HED questions

We are seeking to revolutionize the way that HED science data is captured and consumed

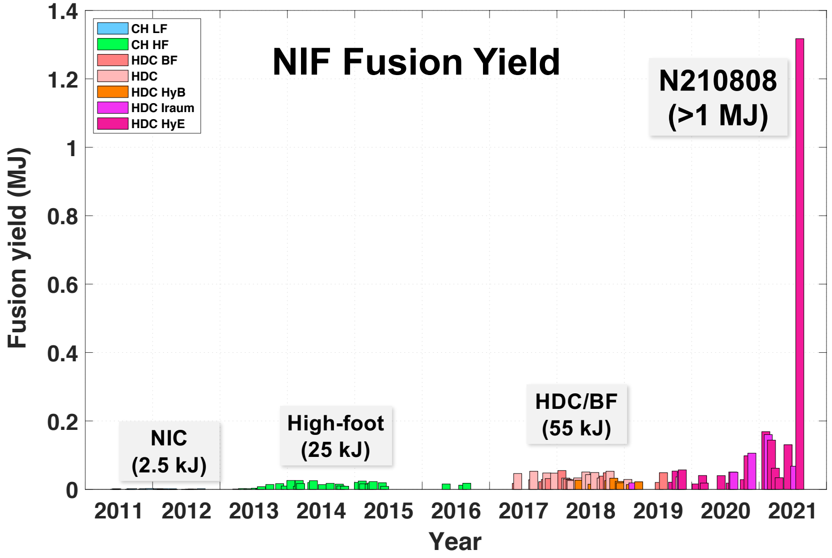


Key Technical Opportunities

- Ability to use all the data
- Quantify uncertainty in predictions
- Detect and remove bias between simulation and experiment
- Compute on time scales commensurate with experiment
- Optimization strategies to seek out desired performance

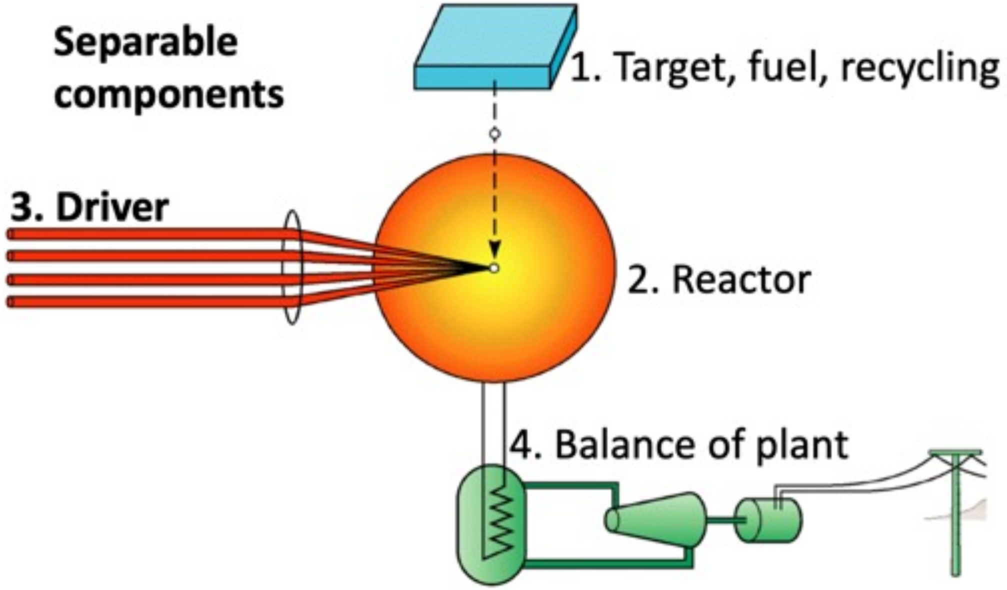
Tightly coupled advanced laser technology with state-of-the-art experiments and cognitive simulation leads to *intelligent experimentation* and *faster learning*

The recent NIF results establish the basic scientific feasibility of laser-driven inertial fusion energy (IFE)



The excitement around the world (and immediate extrapolation to energy) was invigorating to see!

Realizing IFE will require new advances in science and technology



Key components of an IFE system that need to be addressed:

- Drivers
- Target fabrication
- Target injection
- Engagement
- Chamber technologies
- Final optics
- Tritium processing
- Economics

Because IFE is a pulsed energy source, it is envisioned a power plant would require a reaction ~10 Hz

Both large-scale and smaller-scale facilities have a role to play: current ICF research on NIF offers the opportunity to experiment at "fusion scale," while we can push other technologies (high avg power lasers, rep rate technologies, AI, targets, etc) to advance the science and technology of IFE

High repetition rate HED experimental physics coupled to cognitive simulation will accelerate the rate of knowledge acquisition

- ICF experiments on the NIF are demonstrating very exciting progress
  - The scale and complexity of these experiments means progress is slow
- Next-gen, high-rep-rate (HRR) laser facilities will provide a different paradigm for HED experiments
- An integrated HED experimental capability means feedback control loops within the laser, experiment, and simulation to simultaneously optimize the entire system in real-time
- Many emerging technologies are being leveraged to make this vision a reality
  - Suite of HRR diagnostics, automated analysis, and active feedback being developed
  - Novel cognitive simulation techniques will push the forefronts of scientific machine learning
- Building on the recent great NIF results, we are pushing the technologies for IFE, with HRR playing a role

This is a very exciting time for fusion and plasma research!

LLNL postdoc program

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  - Research that is complementary to funded project
  - Maintain university collaborations
  - Travel and professional training activities
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  - Publishing is a priority
- Emphasis on mentoring
  - One-on-one meetings to help postdocs succeed


2017 Diving Dog Event

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Short Pulse HEDP- Postdoctoral Experimental Physicist

Entry Level | Full-time
Postdoctoral/Fellowship | livermore, CA | 10/18/2021

Reference #: REF1644R
Job Code: PDS.1 Post-Dr Research Staff 1
Organization: NIF and Photon Science
Position Type: Post Doctoral
Security Clearance: Not applicable
Drug Test: Required for external applicant(s) selected for this position (includes testing for use of marijuana)
Medical Exam: Not applicable

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Job Description

We have an opening for a **Postdoctoral Experimental Physicist- Short Pulse HEDP** to execute experiments, develop unique diagnostics and diagnostic techniques, and lead frontier research in the area of high-intensity short-pulse laser science and applications and high-energy-density plasmas (HEDP). Areas of active research are high-intensity laser interactions with matter, laser-driven secondary sources, plasma optics, future light sources, and the development of high-repetition-rate diagnostics, targetry, modeling, and machine learning. This position is in the HED (high energy density) S&T (science and technology) organization in the Short-Pulse Laser Science & Applications Group in the National Ignition Facility and Photon Science Principal

Contact
ma8@llnl.gov

https://www.llnl.gov/join-our-team/careers

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In 2019, more than 1,150 students engaged in research at LLNL that focused on our core mission areas

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- Data Science Summer Institute
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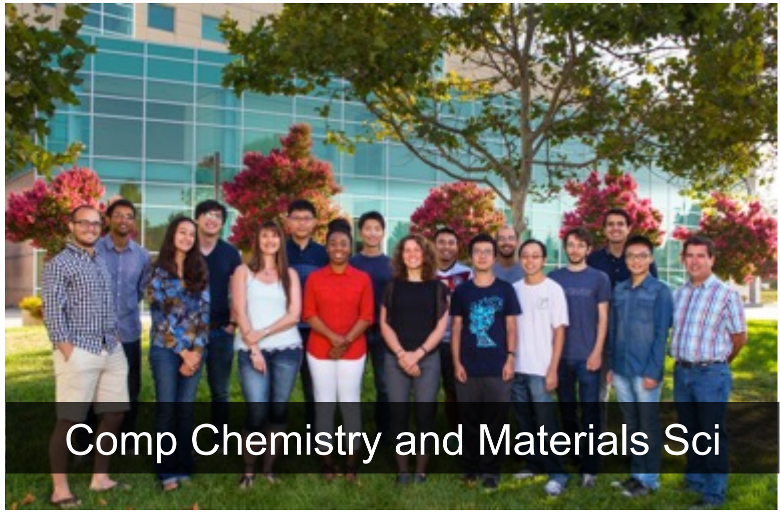
- Computation Scholar Program
- HED Science and WCI Summer Programs
- DHS Global Security Summer Program
- DOE Science Undergraduate Laboratory Internship (SULI)
- Science undergraduate lab interns


Seaborg Institute Nuclear Forensics


Cyber Defenders


Radiochemistry


Comp Chemistry and Materials Sci

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  - Faculty hired 1–3 months
  - Hosted by staff scientist and approved by committee
  - Paid a monthly salary and travel costs
  - Faculty learns new research capabilities and gains greater knowledge set
- LLNL has an existing sabbatical program for staff
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Andrew Gillette
Mathematics / Univ. Arizona

Farhat Beg
Engineering / U.C. San Diego

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Lawrence Livermore National Laboratory