上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Predictive simulations for laser direct-drive implosion experiments empowered by AI

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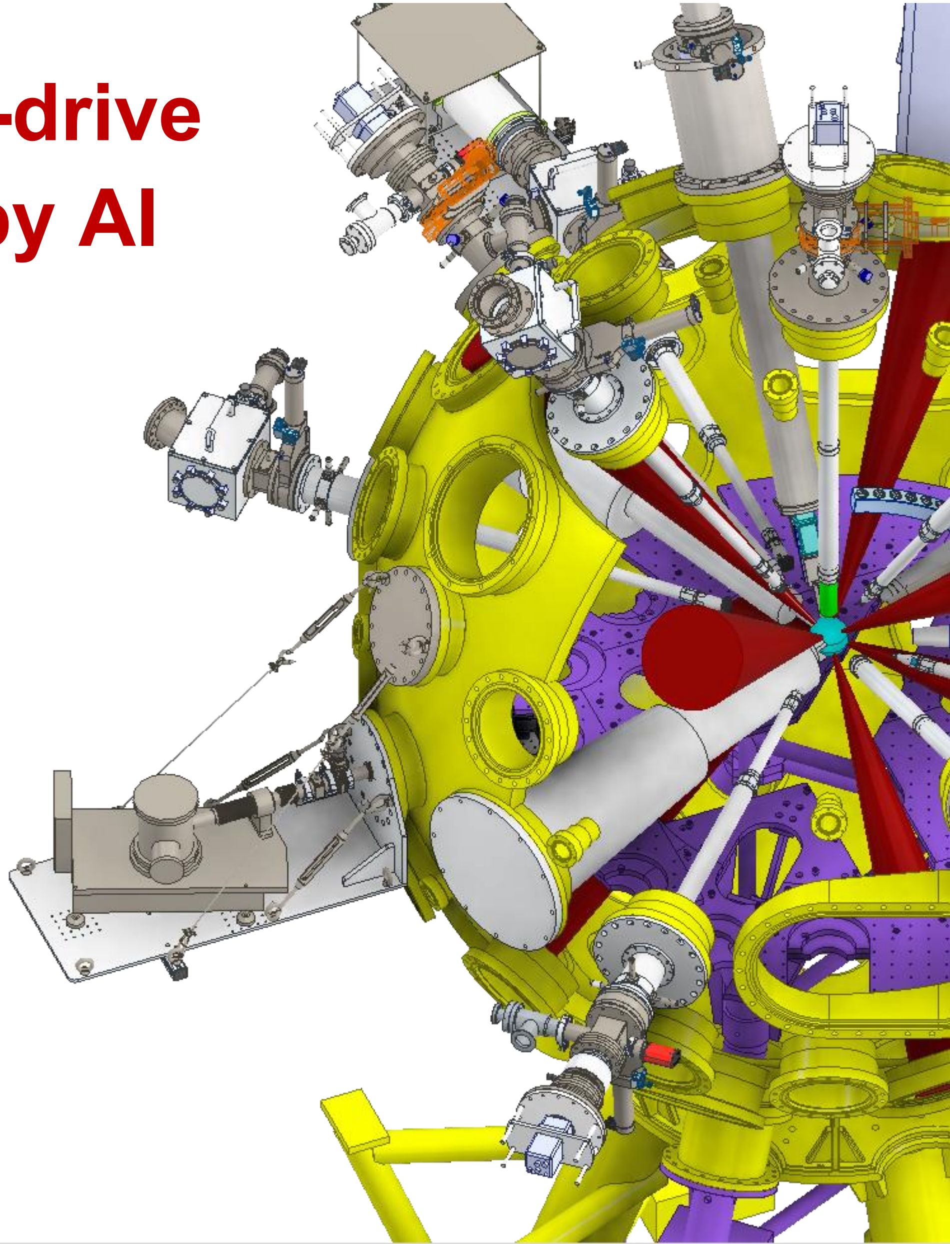


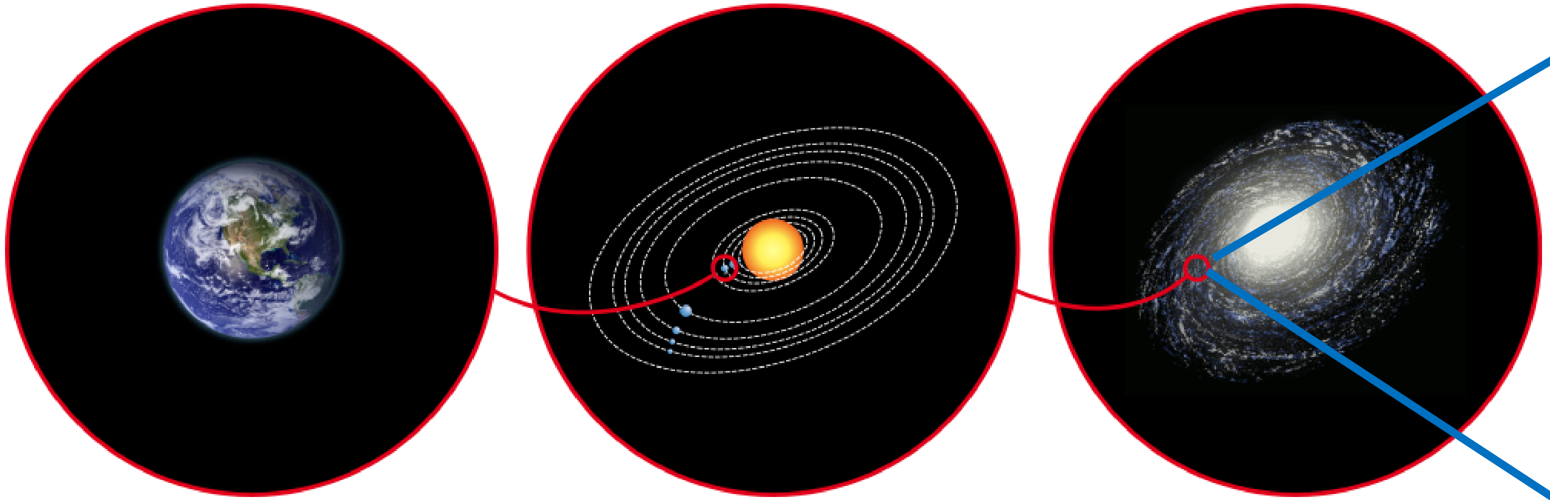
Outline

1. Introduction
2. Investigation method
3. Physical results
4. Summary

Laser fusion is good for all human being

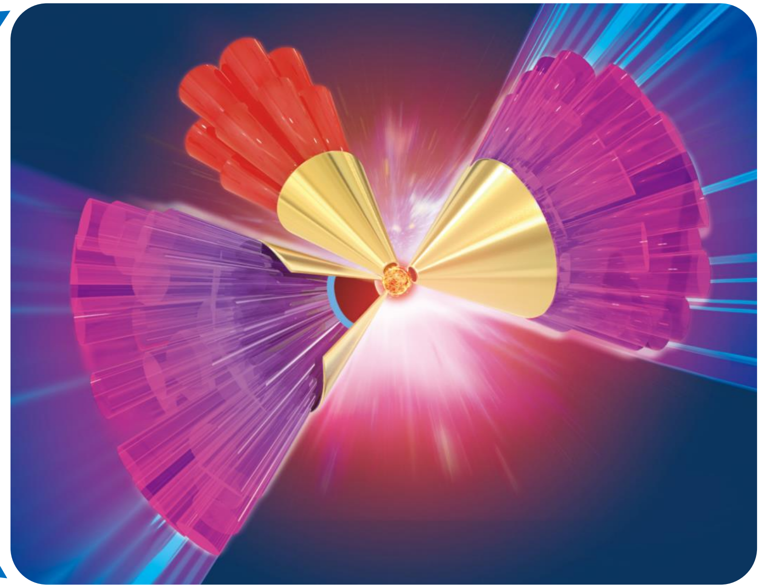
- Laser fusion is a promising method for the leap of human civilization from Kardashev scale I(Planet energy) to Kardashev scale II (Star energy).
- The Double-Cone Ignition(DCI) scheme proposed by Academian Jie Zhang is particularly suitable for laser fusion energy due to its high efficiency, high stability and low-cost.

Kardashev scale for human civilization



Type I: Planet   Type II: Star(Fusion)   Type III: Galaxy

Double-Cone Ignition scheme

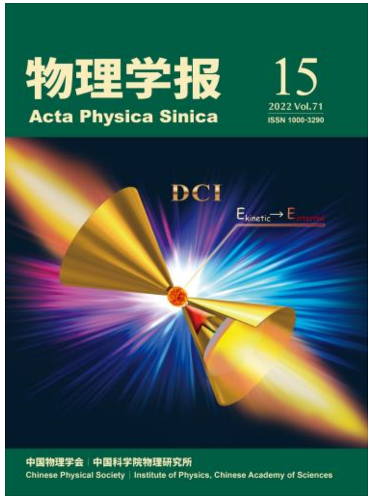


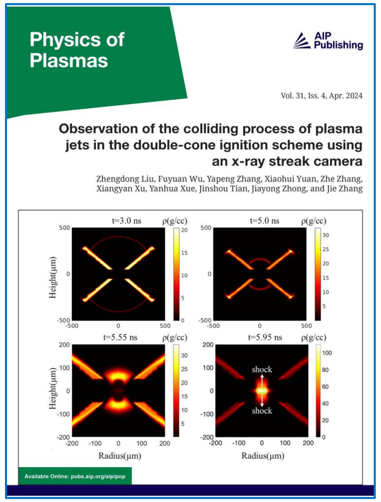
The Progress of Double-Cone Ignition Scheme

- ✓ **In the past 5 years, simulation abilities empowered by AI were developed, critical physical studies were performed, and 10 rounds experimental campaigns were completed.**
- ✓ **The results effectively support the high efficiency of the DCI scheme and validate all the four key physical processes.**

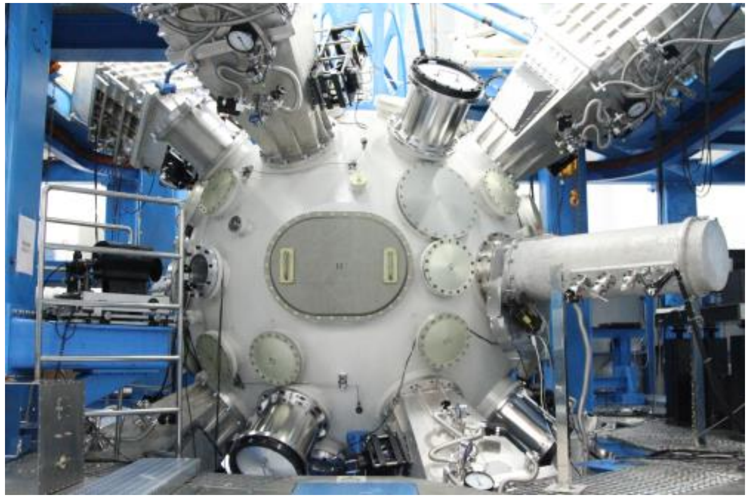
DCI joint research team

DCI results on the covers

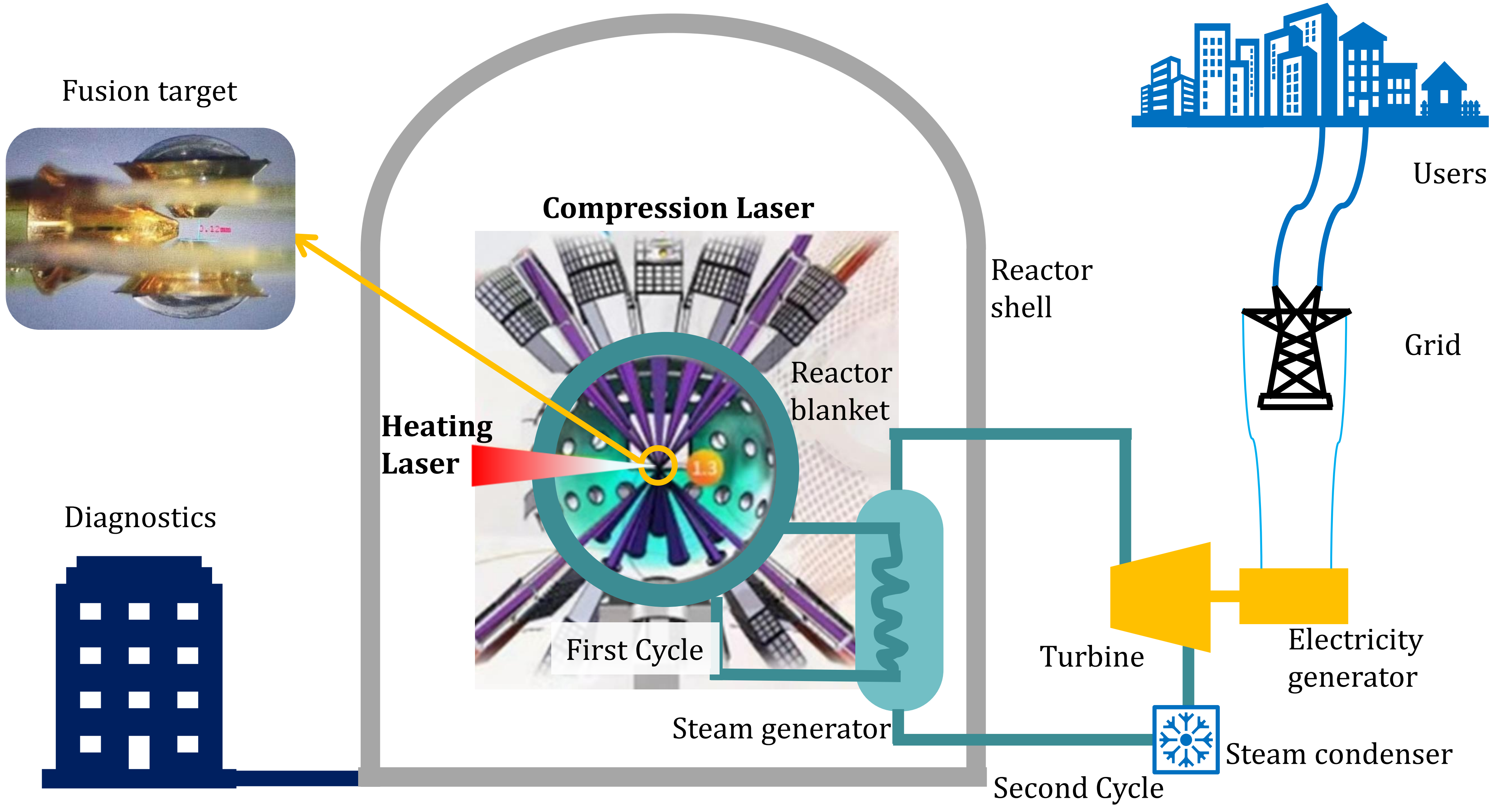




Experiments on SG-II Upgrade



Fusion Power Plant Based on Double-Cone Ignition Scheme

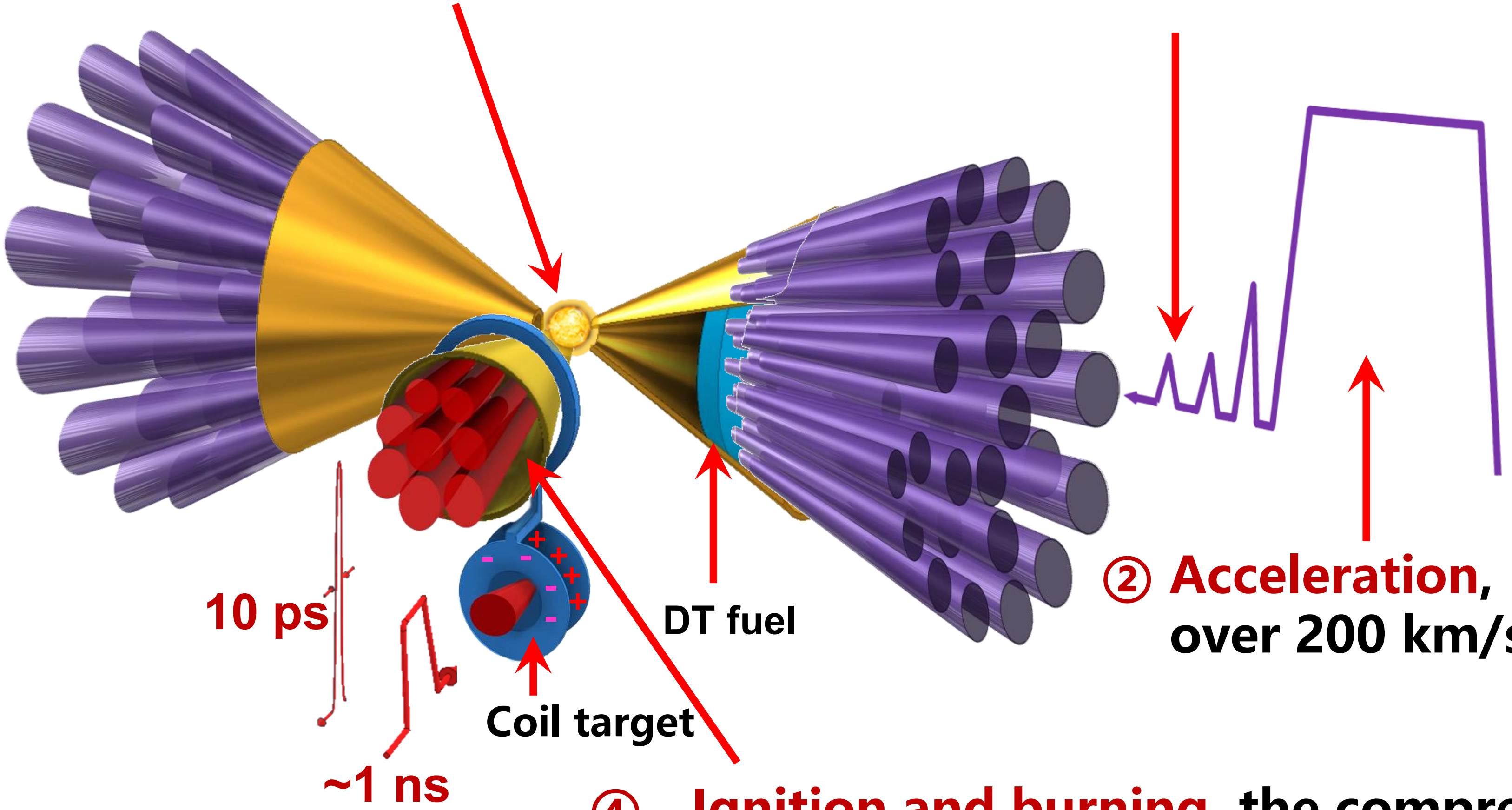


Zhang Jie, Yuan Xiaohui, Zhang Zhe, Li Yutong, Wu Fuyuan et al., Chines Patent, ZL 2024 1 1665249.4

The recent progress of the DCI Experiments

③ **Collision**, the density is compressed to 100g/cc and the temperature increase dramatically.

① Isentropic **compression**, with a density amplified by 50 times.

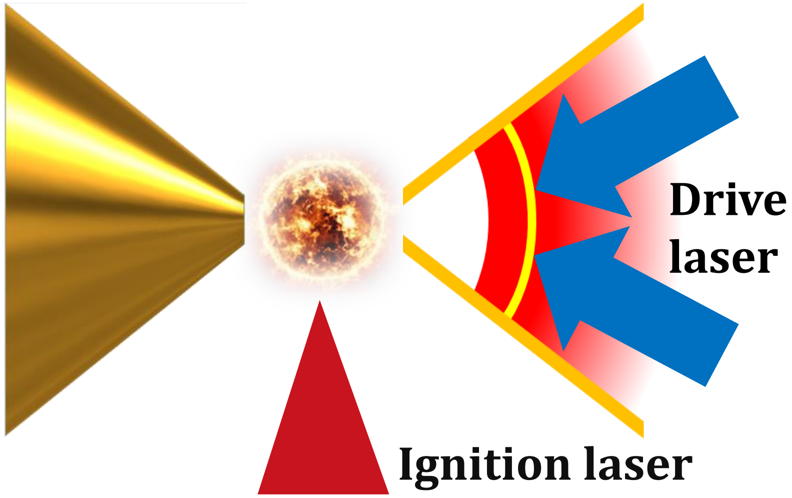


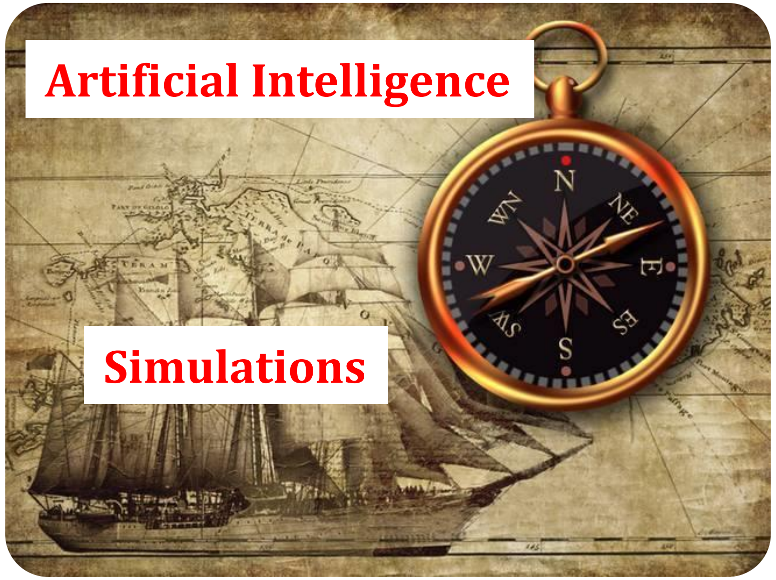
② **Acceleration**, with a speed over 200 km/s.

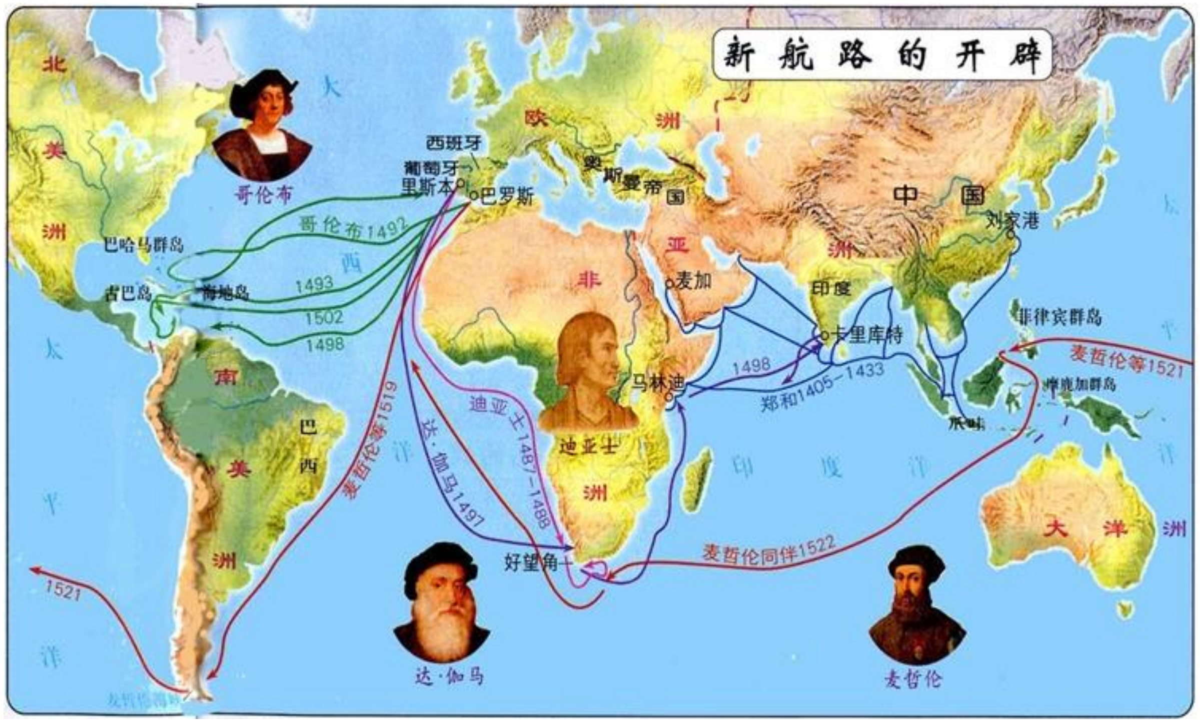
④ **Ignition and burning**, the compressed fuel is fast heated to over 600 eV by the picosecond laser.

How to discover the promised land efficiently?

Double-Cone Ignition Scheme







Scientific Faith: There are lots of continents made of laser pulse and target structure where fusion energy exists.

Question: How to discover routes to these continents efficiently?

Answer: Simulations(Boat) + Artificial Intelligence(Compass)

The Boat: The hydro code MULTI-1D/2D/3D

Author： Rafael Ramis(Spain), Meyer-ter-Vehn(Germany), ..., Fuyuan Wu(China)

Introduction: A two-dimensional, two-temperature, radiation magnetohydrodynamic program, considering laser ablation and fusion burning in Arbitrary Lagrangian-Eulerian(ALE) coordinates.

Mass： $\rho = m/V$

Momentum： $\rho \frac{du}{dt} = -\nabla(P_e + P_i + P_v) + J \times B$

Ion energy： $\rho \frac{de_i}{dt} = -(P_i + P_v)\nabla \cdot u - Q_{ei} + S_{exi}$

Eletron energy： $\rho \frac{de_e}{dt} = -P_e \nabla \cdot u + \nabla \cdot q_e + Q_{ei} + \eta J^2 + Q_{rad} + S_{exe}$

Toroidal field： $\frac{\partial B_\theta}{\partial t} = \nabla \times (u \times B_\theta) - \nabla \times \left(\frac{\eta}{\mu_0} \nabla \times B_\theta\right) + \nabla \times \left(\frac{1}{en_e} \nabla P_e\right)$

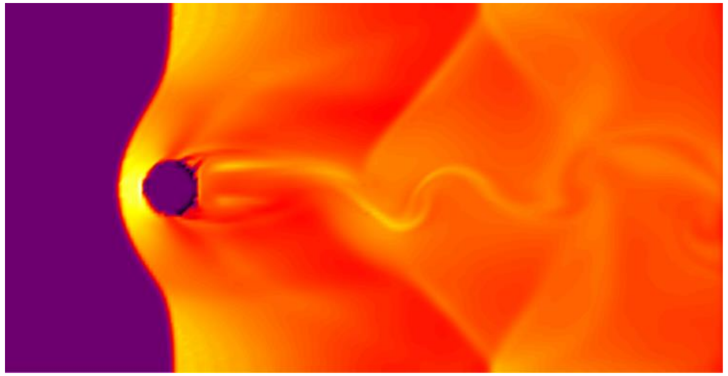
Parallel field： $\frac{\partial A_\theta}{\partial t} = -u \times \nabla \times A_\theta - \frac{\eta}{\mu_0} \nabla \times (\nabla \times A_\theta), (B_z, B_r) = \nabla \times A_\theta$

Radiation field： $\vec{n} \cdot \nabla I = -\frac{I^P - I}{\lambda}$

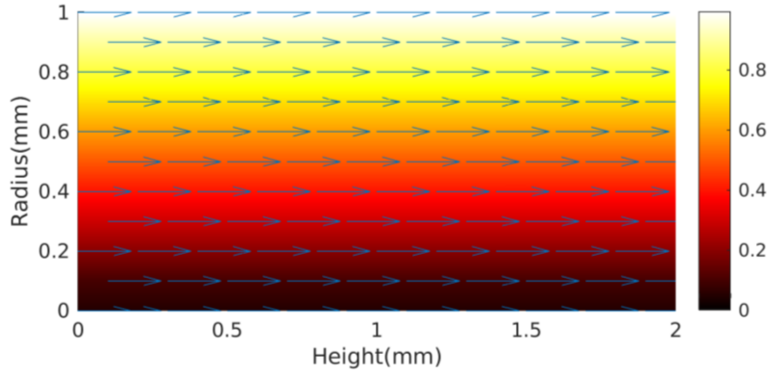
Fusion burning： $\frac{dn_{DT}}{dt} = -<\sigma v> n_{DT}^2, <\sigma v> = f(T_i)$

Alpha particle： $\frac{dE^\alpha}{dt} = -\nabla \cdot \vec{S}^\alpha - Q^\alpha + <\sigma v> n_{DT}^2 \varepsilon_0^\alpha$

Von Karmen Vortex Street(ALE)



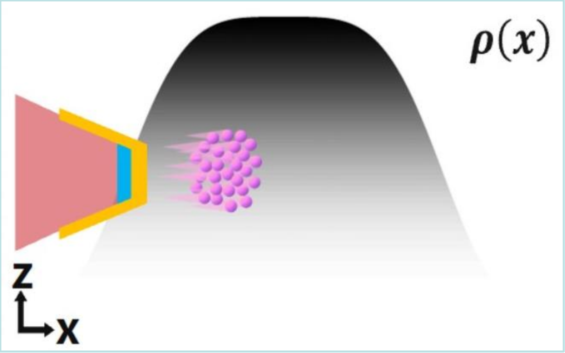
Axial magnetic field for fast ignition



The Boats: Integrated simulations for DCI

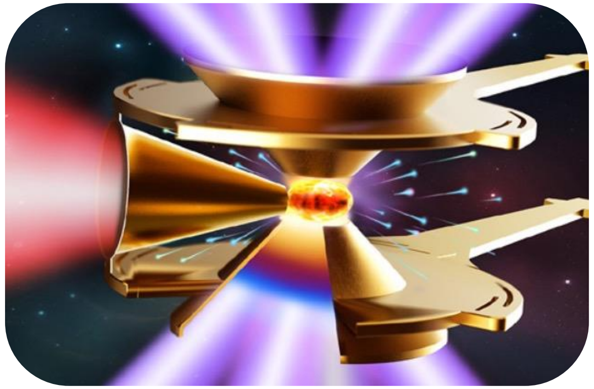
1) MULTI-IFE/2D/3D
Implosion by nanosecond laser

2) KLAPS
Generation of fast electrons

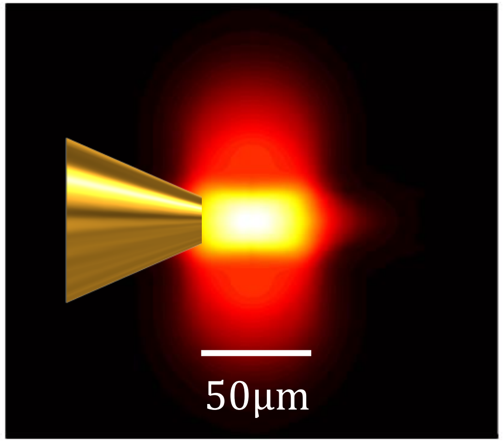


Density and Temperature

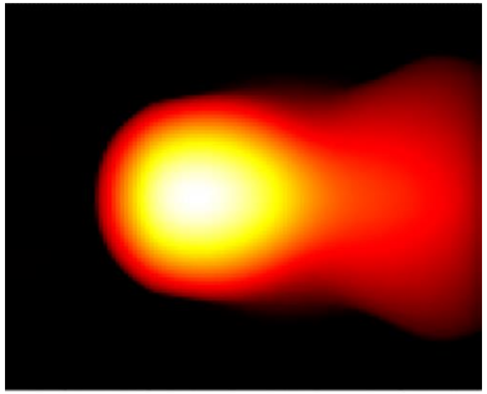
Optimize laser and target



REB Density



Density and Temperature

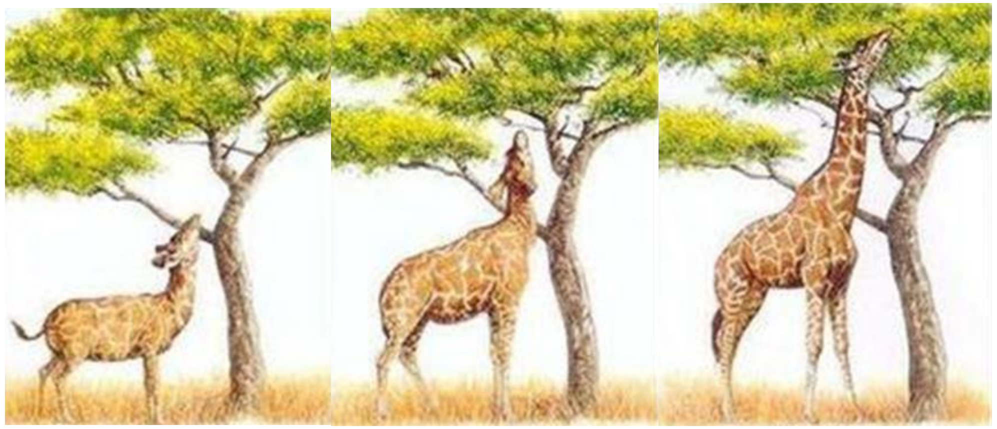


4) OSUKI/MULTI-3D
Fusion burning to release energy

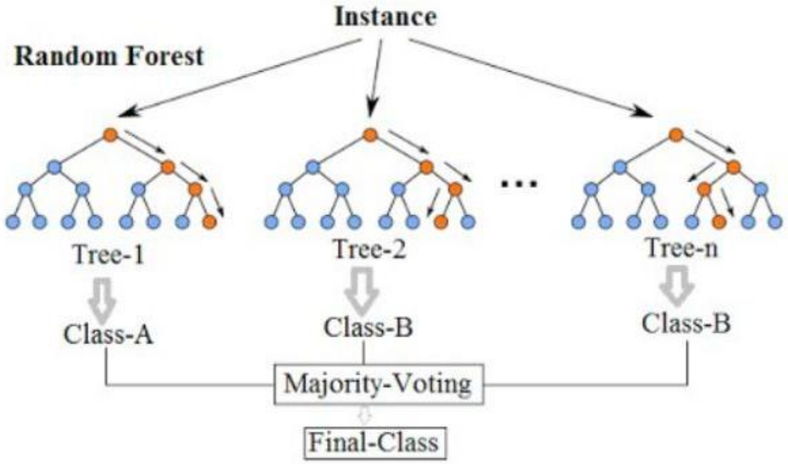
3) HEETS
Fusion ignition by fast electrons

The Compass： Artificial Intelligence

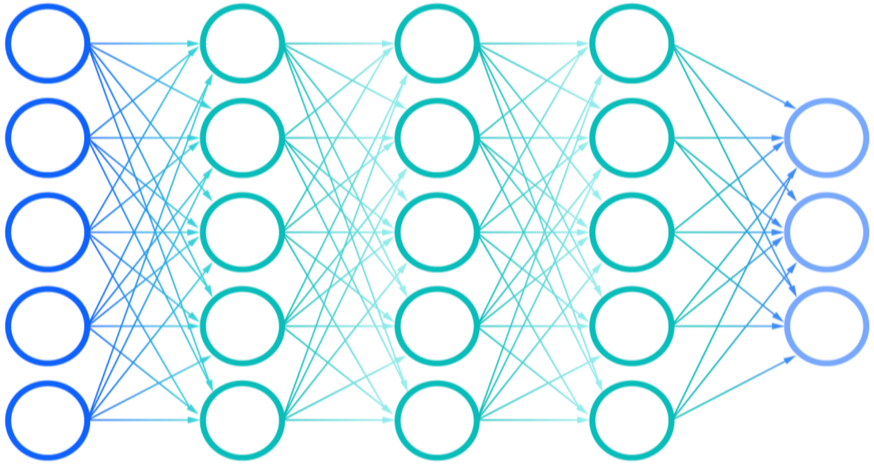
The Genetic Algorithm for global optimization



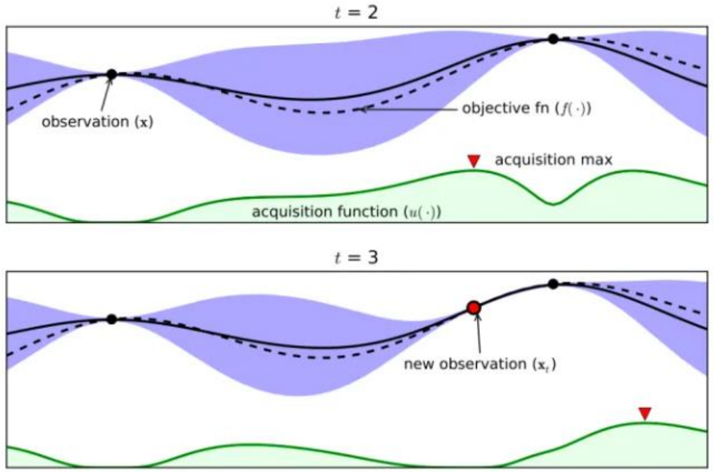
Random Forest for feature importance



The neural network for prediction



The Bayesian inference for Probability

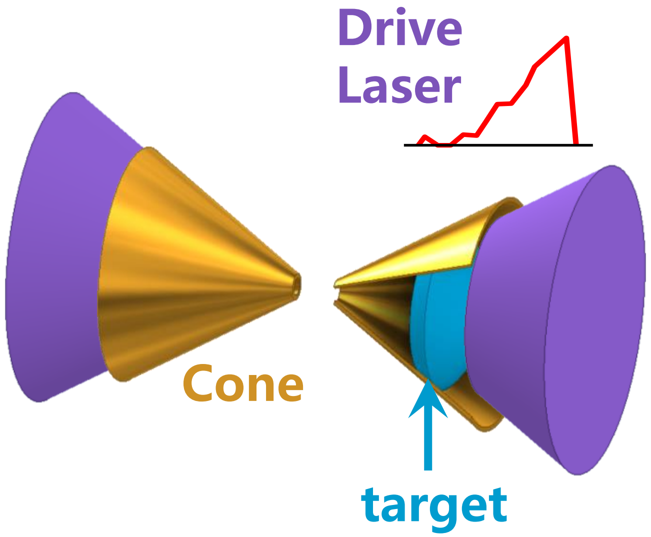


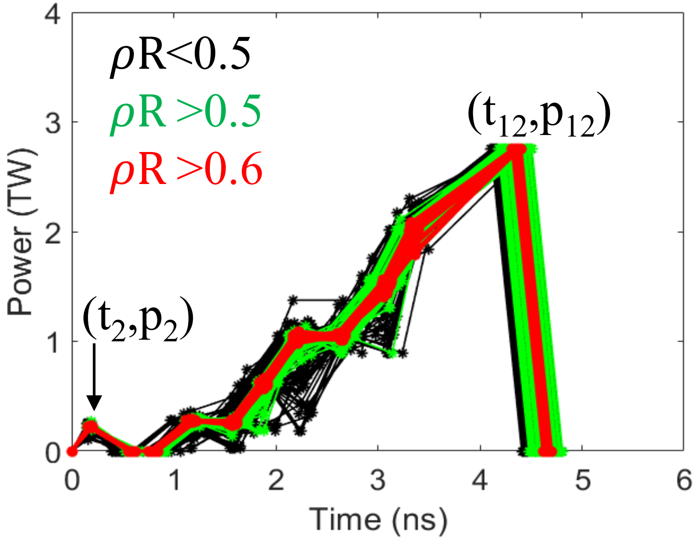
Poster 1: Yangyi Lei, Genetic Algorithm for waveform optimization to suppress RT instability
Poster 2: Yuhan Wang, Input Calibration for DCI Experiments with Transformer-Based Surrogate Models

Optimize the laser pulse with artificial intelligence

- Challenges:. It is important but very difficult to find a laser pulse that that satisfy isentropic compression, high-speed implosion and low instability.
- Methods: We employ the artificial intelligence to optimize 24 variables describing laser waveforms with a goal of high density, high speed and low in-flight aspect ratio. The optimization quality and efficiency is then improved greatly.

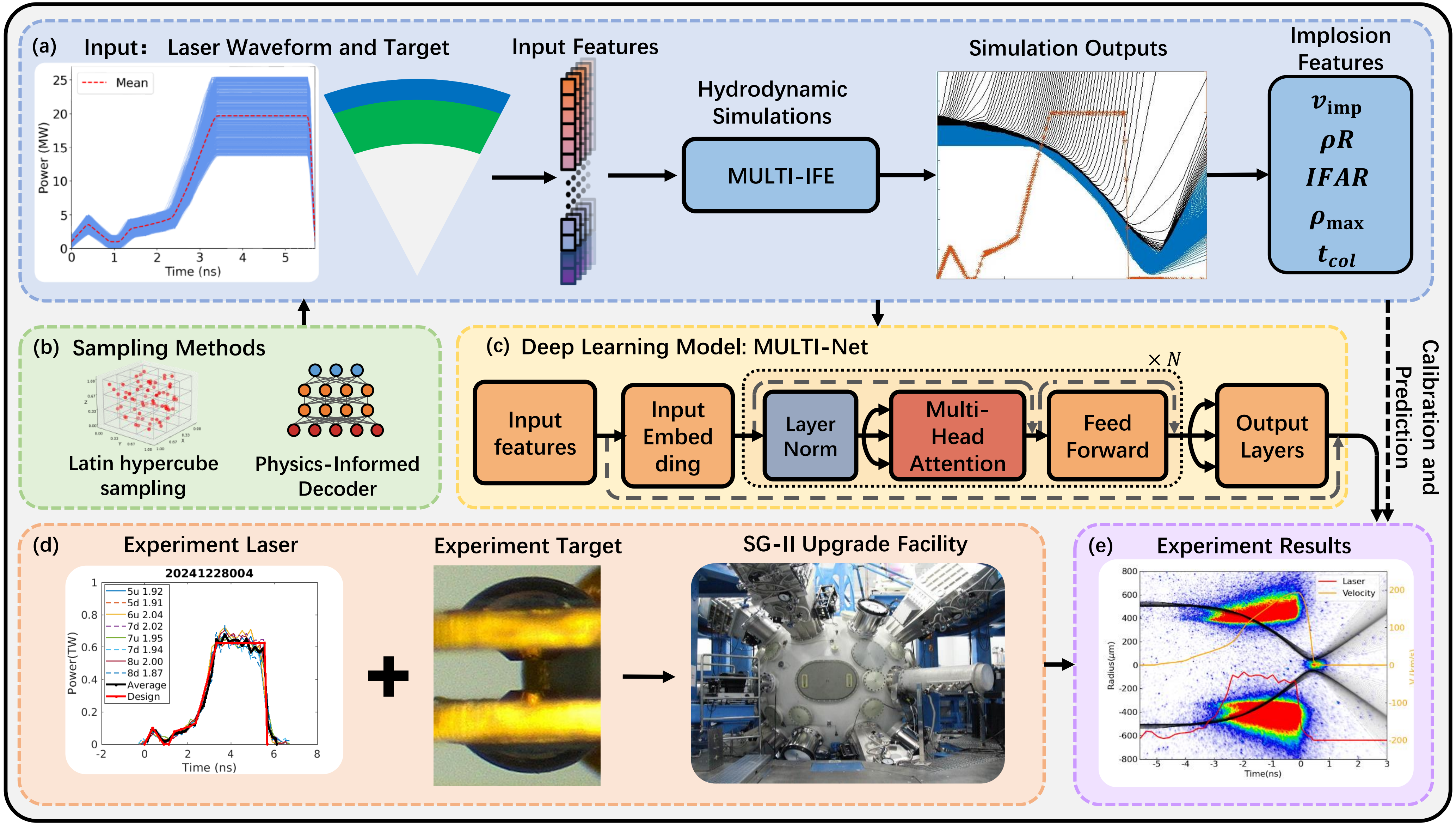
Object: Laser power pulse → **Evolution: black→red** → **The performance with AI**





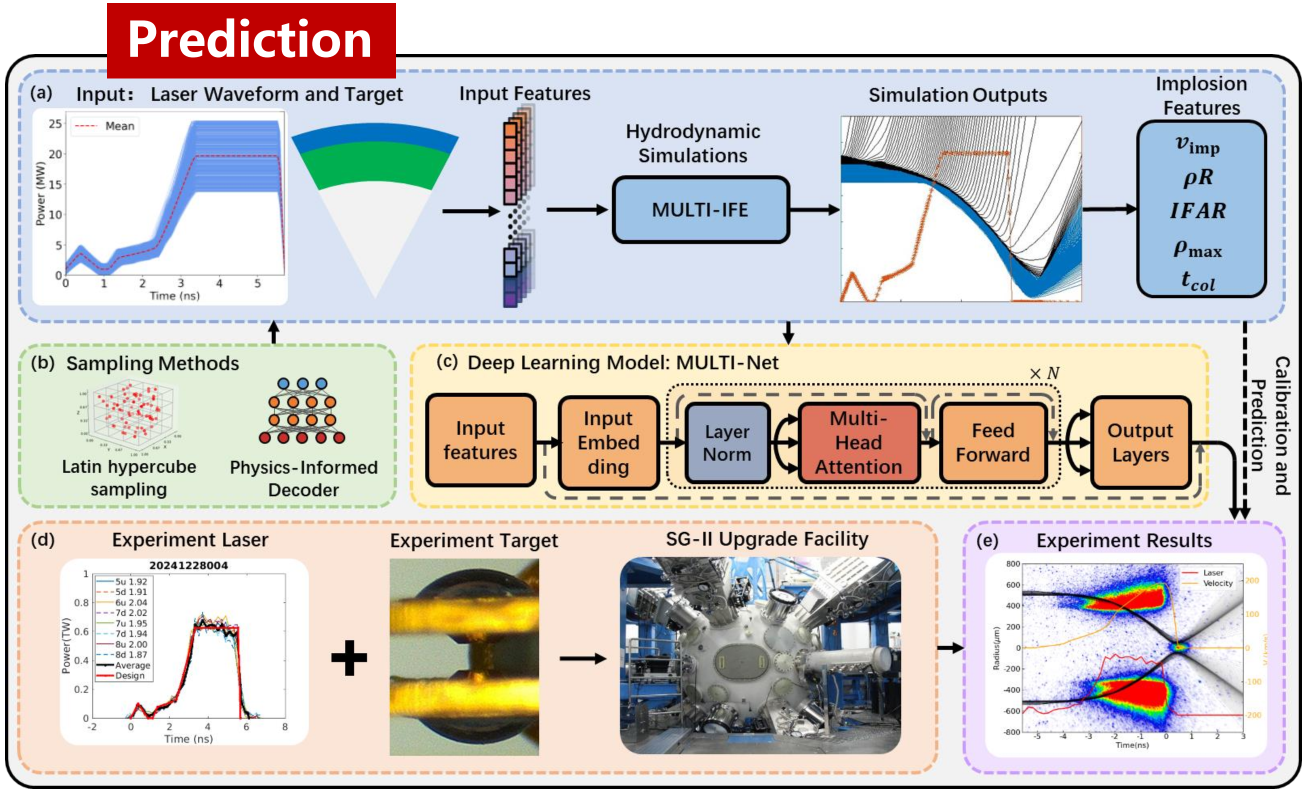
Variables	Before	AI	Effects
Density (g/cm^2)	0.13	0.32	↑ 2.5x
Speed (km/s)	135	210	↑ 1.6x
Time (Day)	30	7	↑ 4.3x

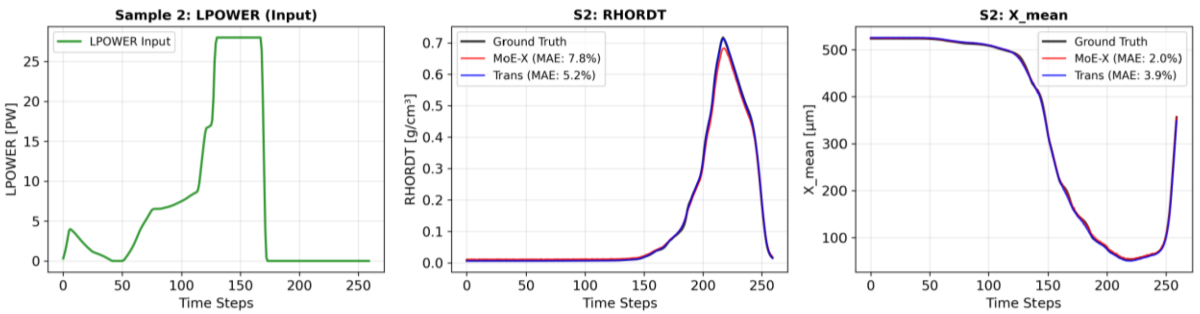
双锥对撞点火 祝融聚变大模型 An effort for the Zhurong fusion foundation model



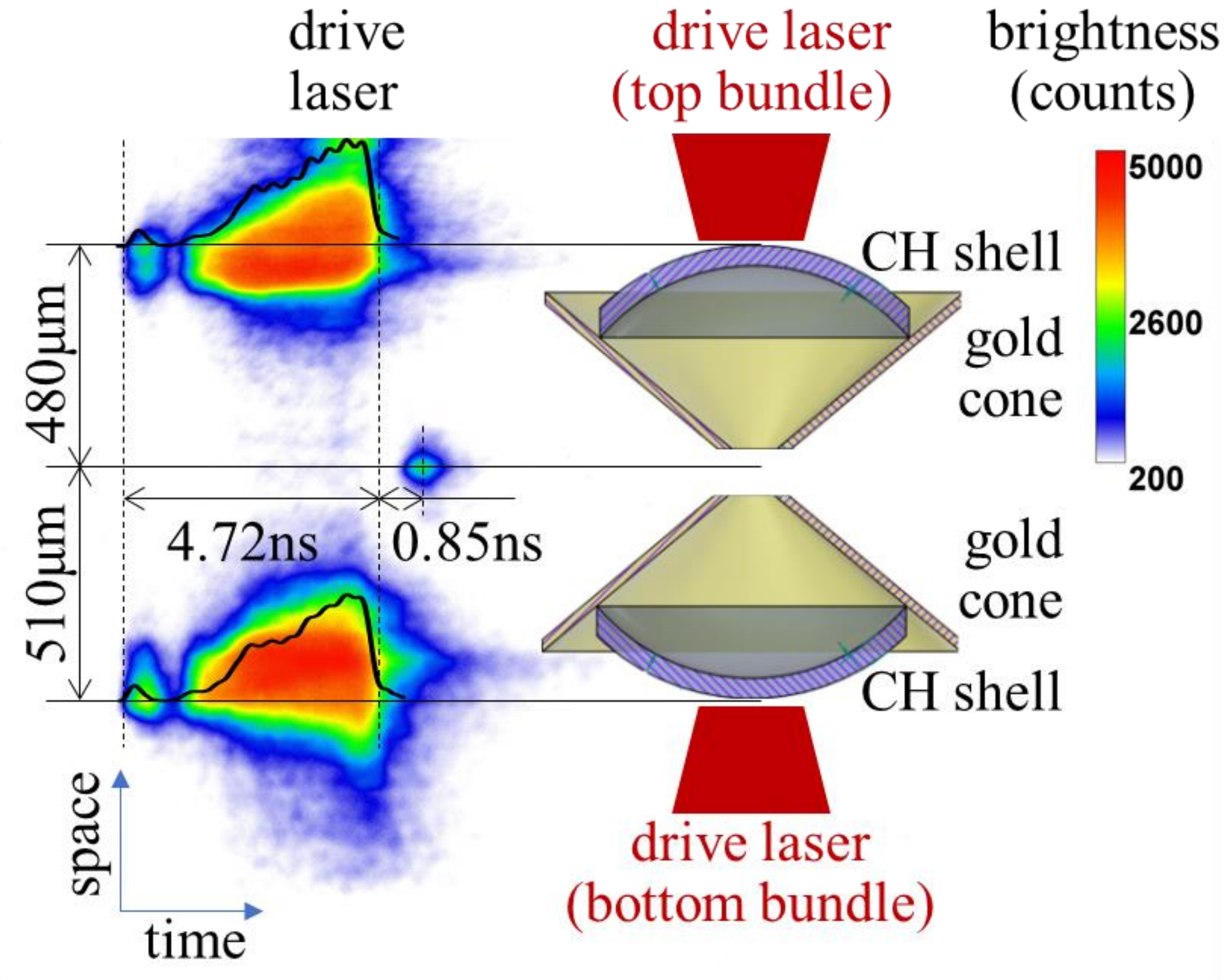
An effort for the Zhurong fusion foundation model

Prediction

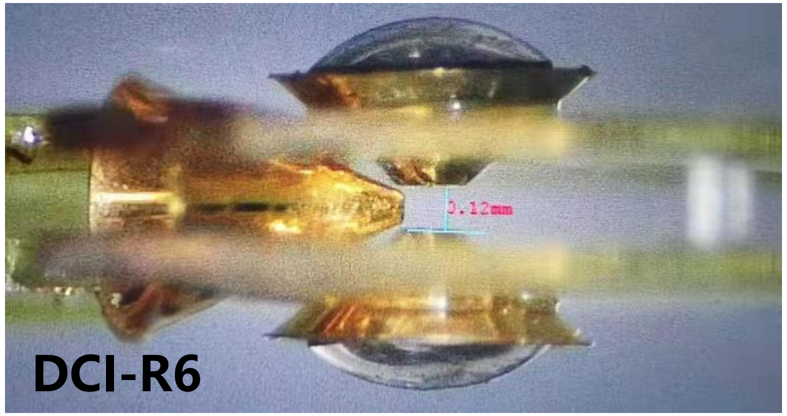


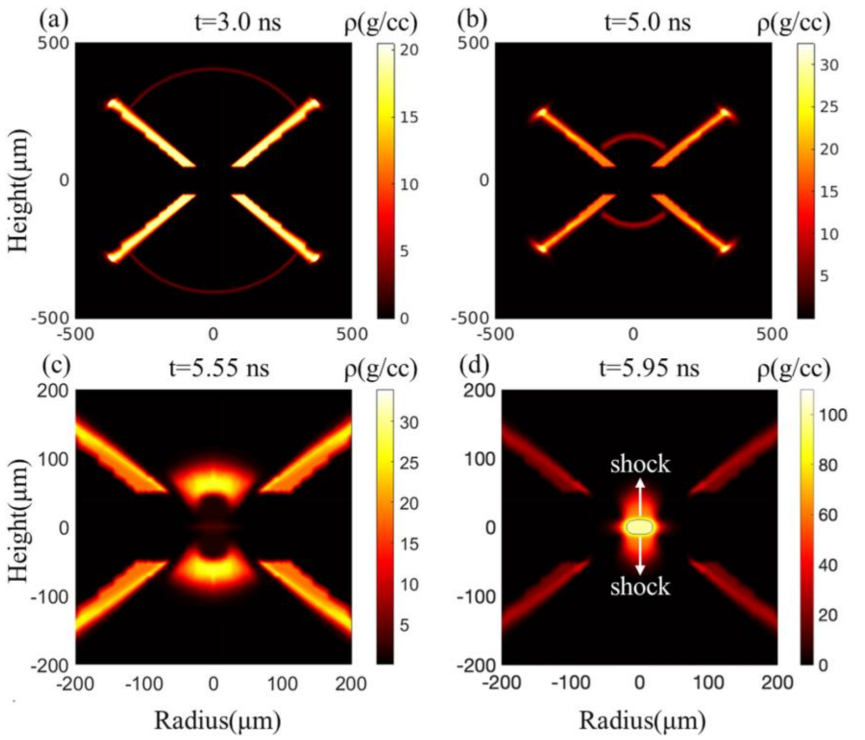


Formation of high density isochoric plasmas with the DCI

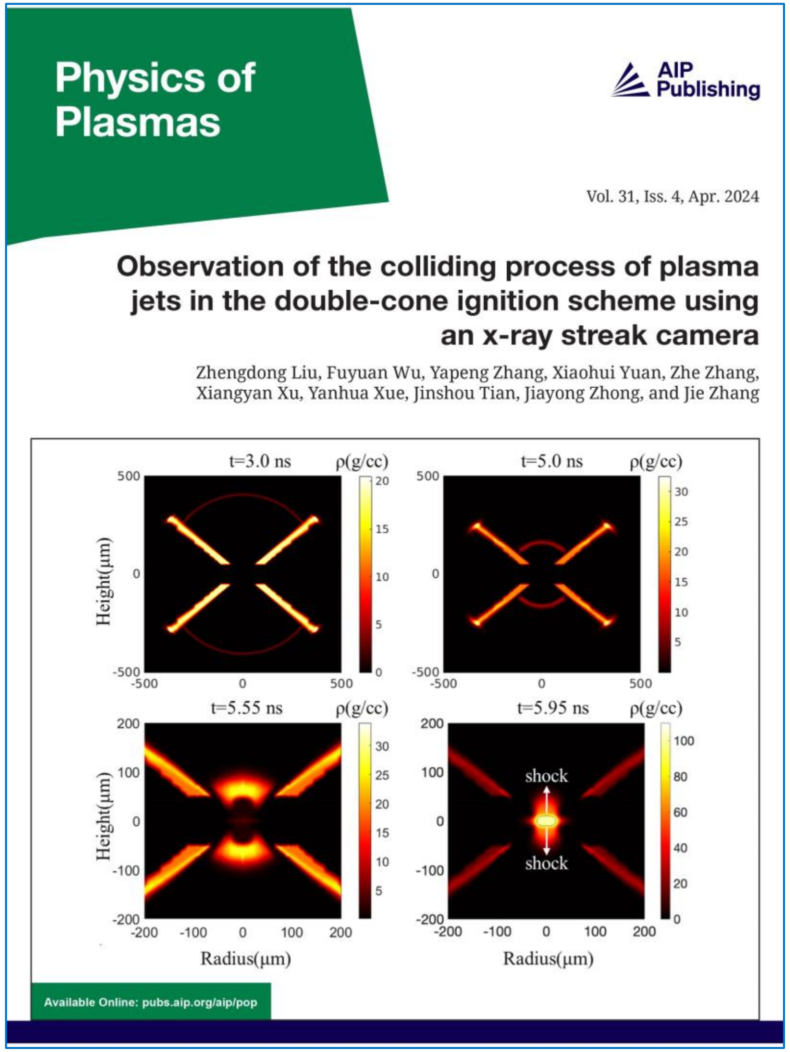


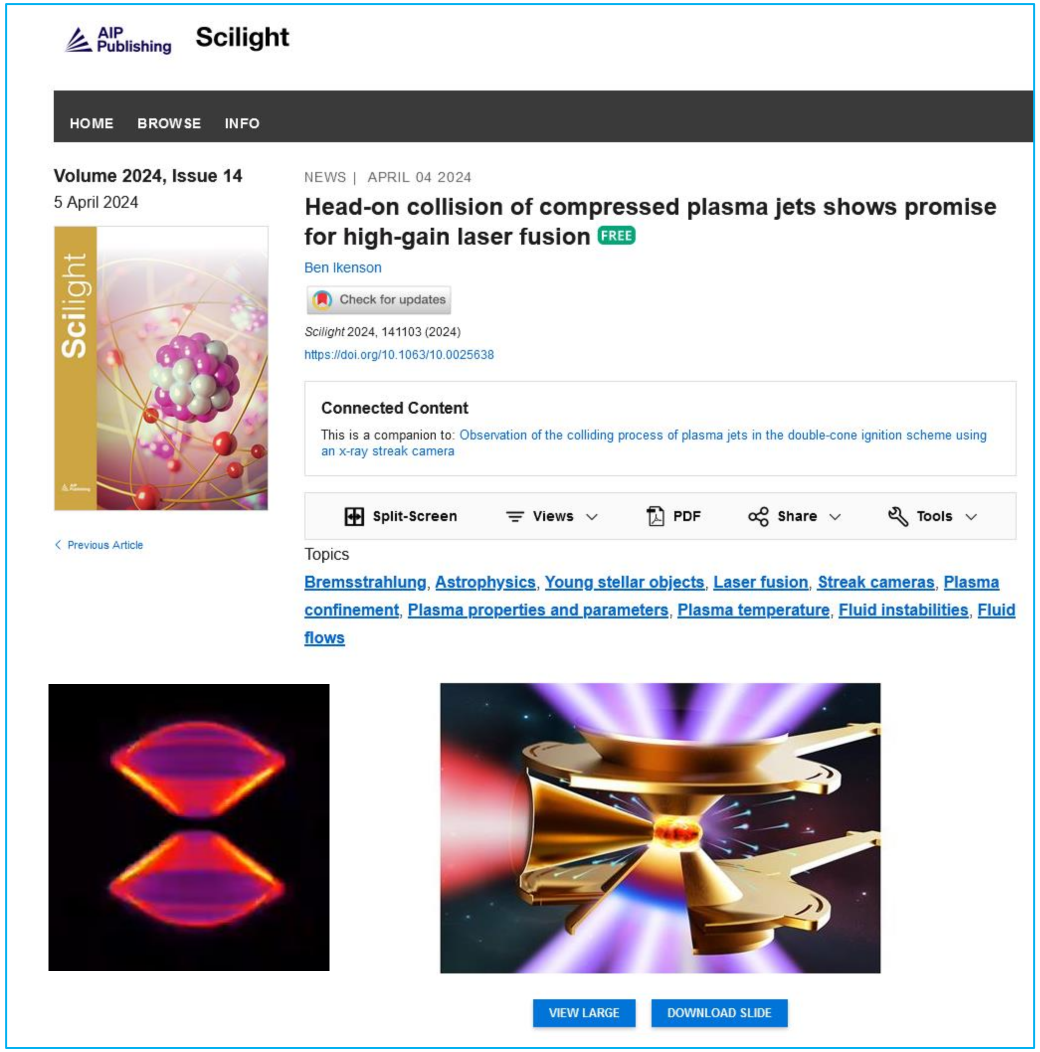
X-ray emissions from the ablated and collision plasma





More details about the DCI simulations and experiments

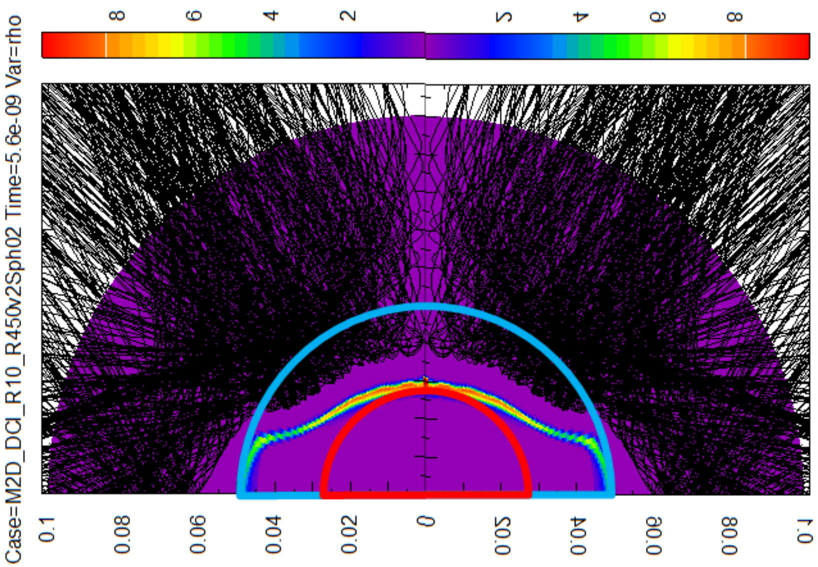


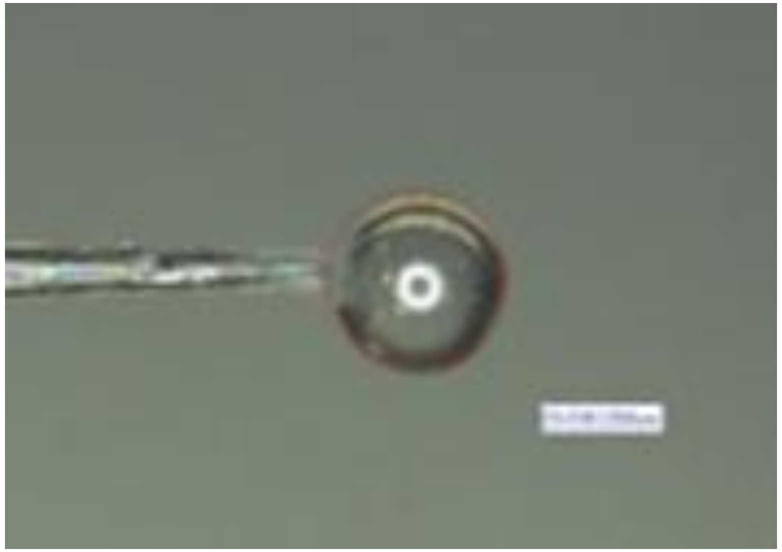


<u>Liu Z</u>, <u>Wu F</u>, Zhang Y, et al. Observation of the colliding process of plasma jets in the double-cone ignition scheme using an x-ray streak camera[J]. Physics of Plasmas, 2024, 31(4), 141103.

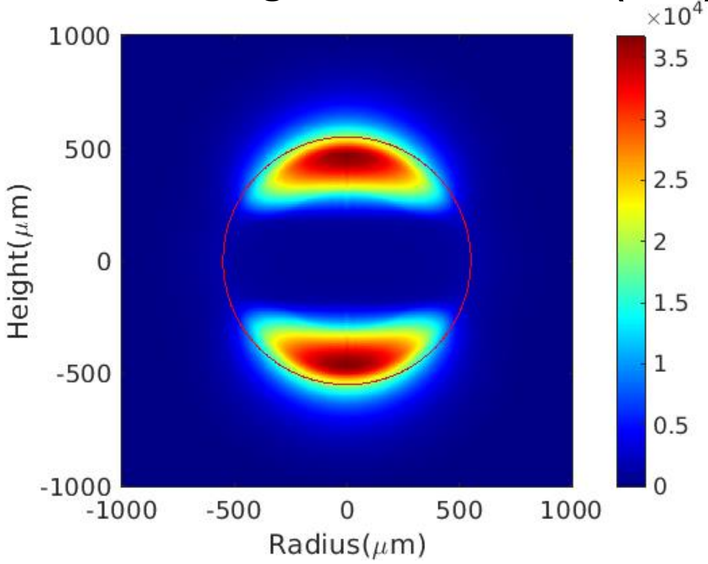
Spherical implosions and R10-Shot 30 experiments

Implosion of spherical ball

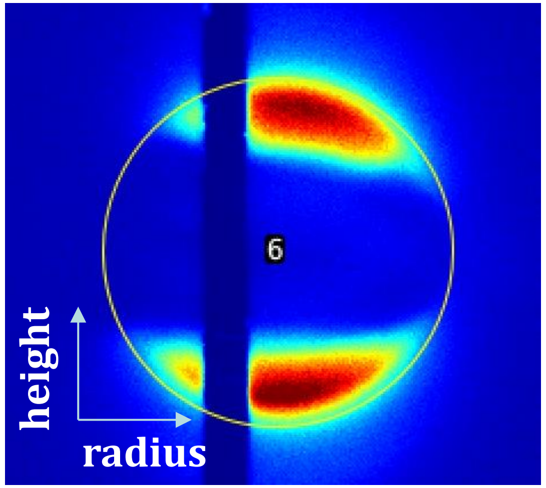




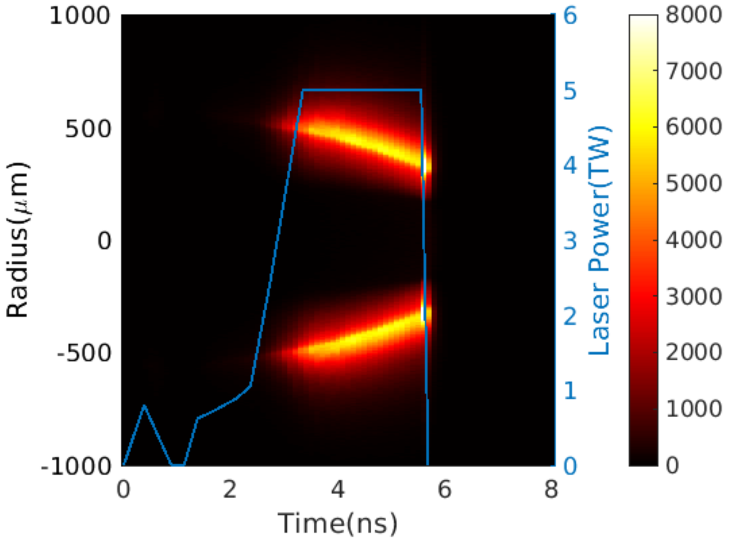
Time-Integrated emissions(Sim)



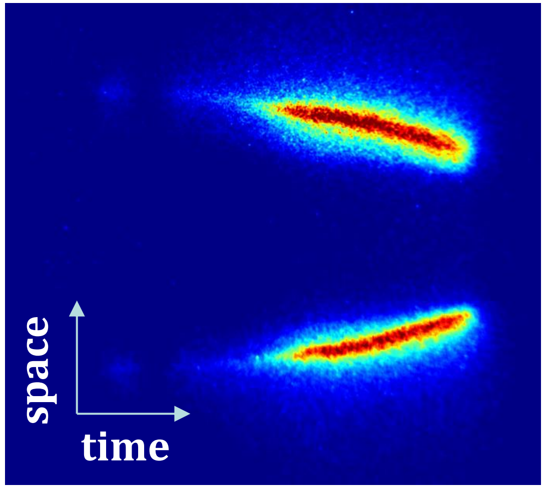
Time-Integrated emissions(Exp)



Time-Resolved emissions(Sim)

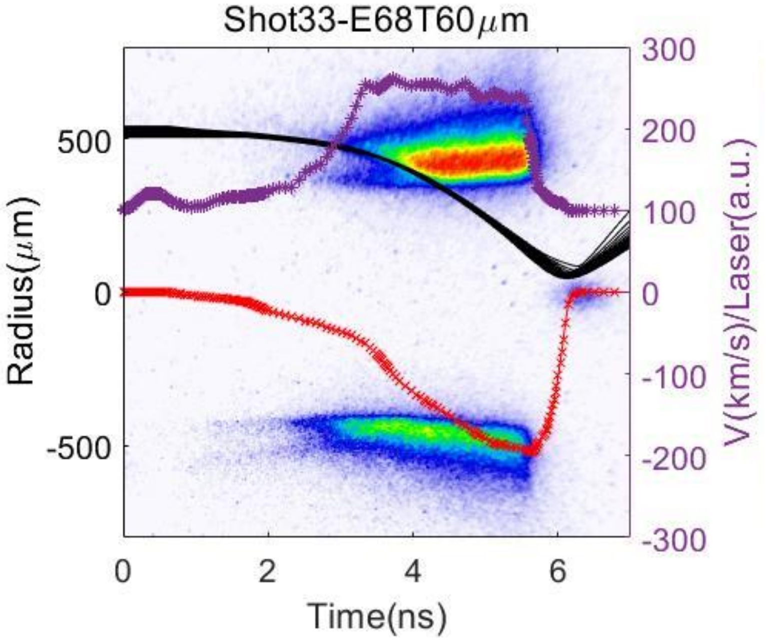


Time-Resolved emissions(Exp)

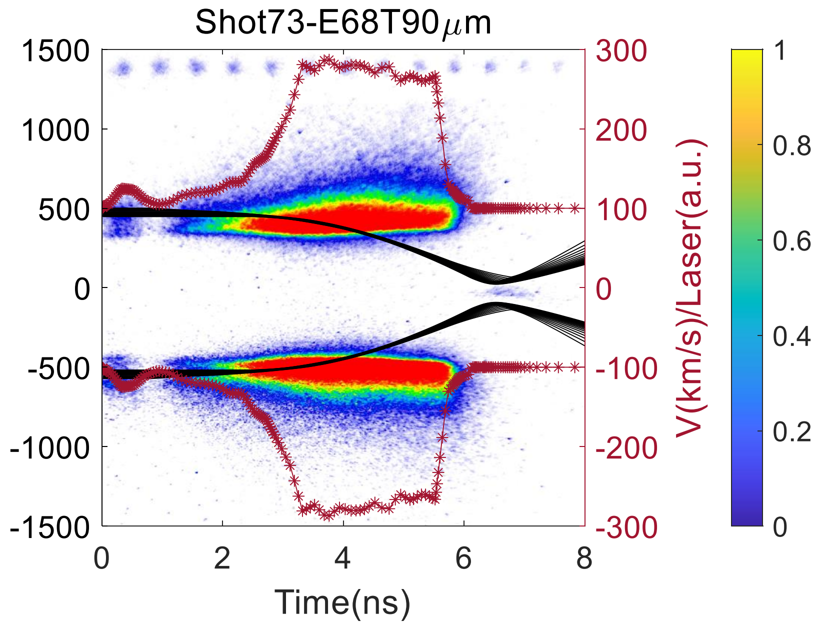


The plasma implosion is calibrated by Bayesian optimization

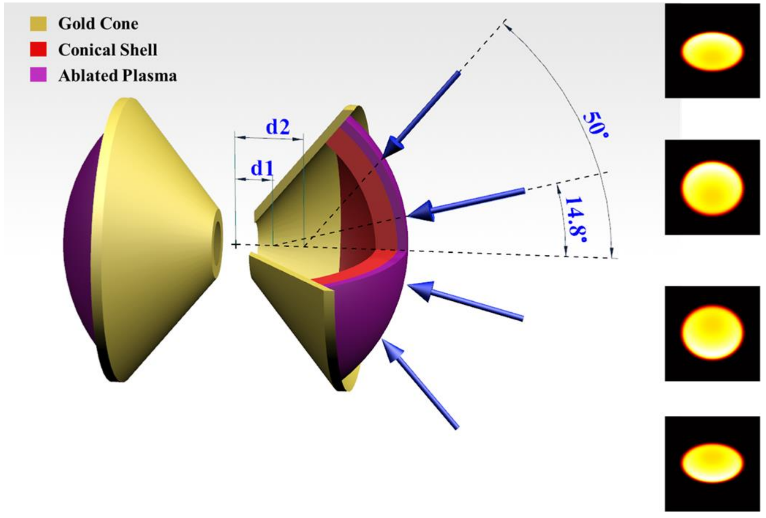
Calibration of shot 33



Prediction of shot 73



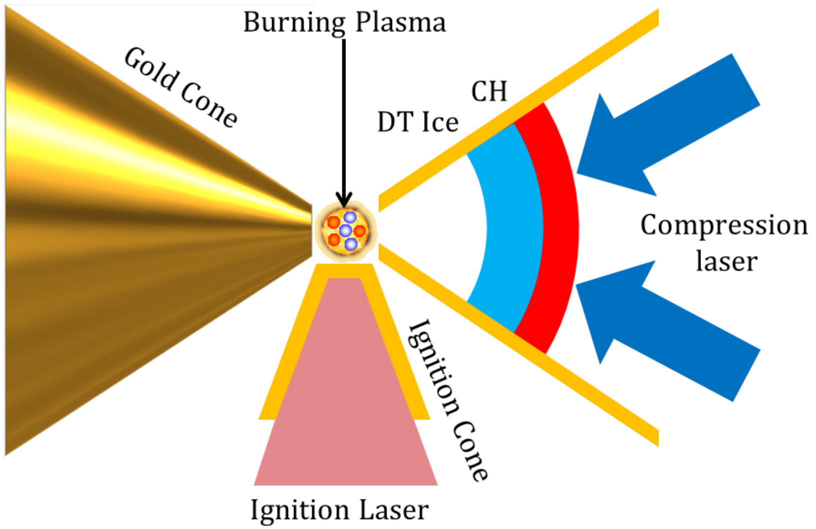
Laser irradiance of DCI



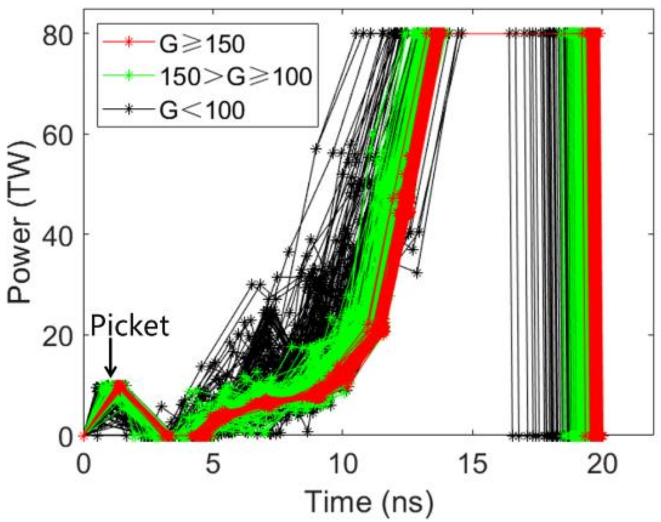
1. **The simulation is calibrated by shot 33 and successfully predict the shot 73.**
2. **Four experimental phenomena is well predicted by the simulation. a) the x-ray emission at the picket, b) the cooling time of the ablated plasma, c) the quasi-uniform acceleration with a parabolic curved trajectory, d) the collision time of the plasma jets at 6.2 ns.**
3. **Reasons: Some laser energy is lost due to the geometry and laser-plasma scatters.**

Optimization of Laser pulse for High Gain DCI scheme

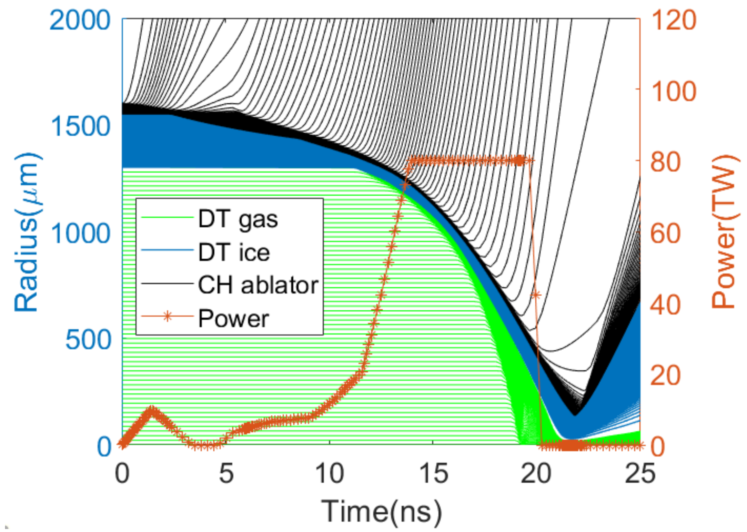
Optimization of laser puslse



Evolution of laser pulses



The baseline target and pulses



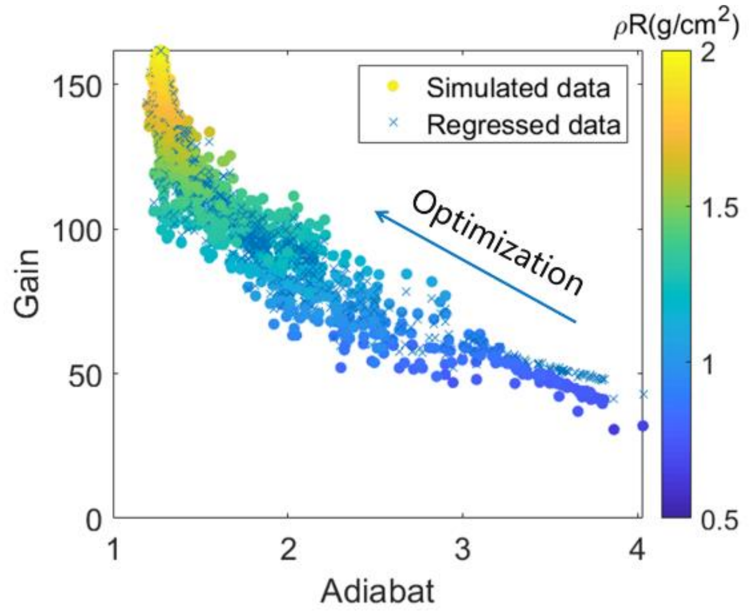
$$G_{fusion} = \frac{E_{fusion}}{E_{ns} + E_{ps}} = \frac{q_{fuel} M_{fuel}}{E_{ns} + 560(100/\rho)^{1.85}} \frac{\rho R}{\rho R + H_B}$$

Variable	M(μg)	ρR(g/cm²)	ρ(g/cc)	IFAR	E_{ns}(kJ)	E_{ps}(kJ)	E_{fusion}(MJ)	G_{fusion}
DCI	571	1.95	345	24	240	57	41	138

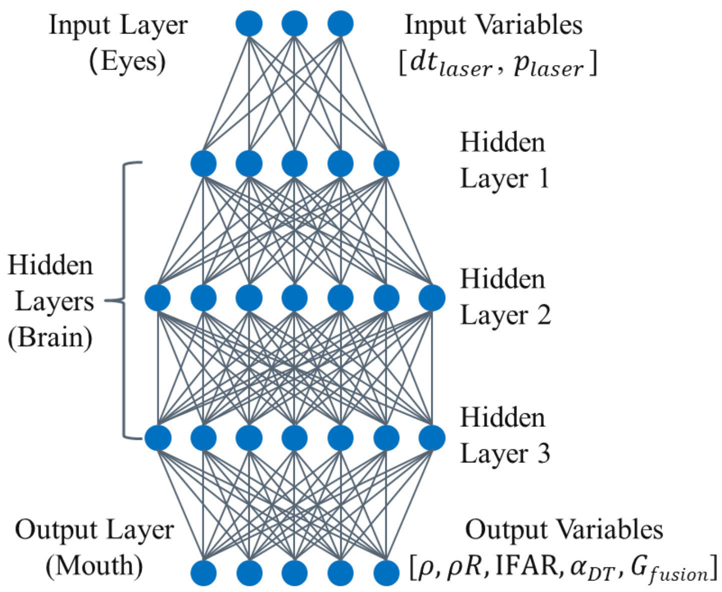
Wei S, Wu F, Zhu Y, et al. A Machine Learning Method for the Optimization Design of Laser Pulse in Fast Ignition Simulations[J]. Journal of Fusion Energy, 2024, 43(1): 6.

Construct a surrogate model for the hydro simulations

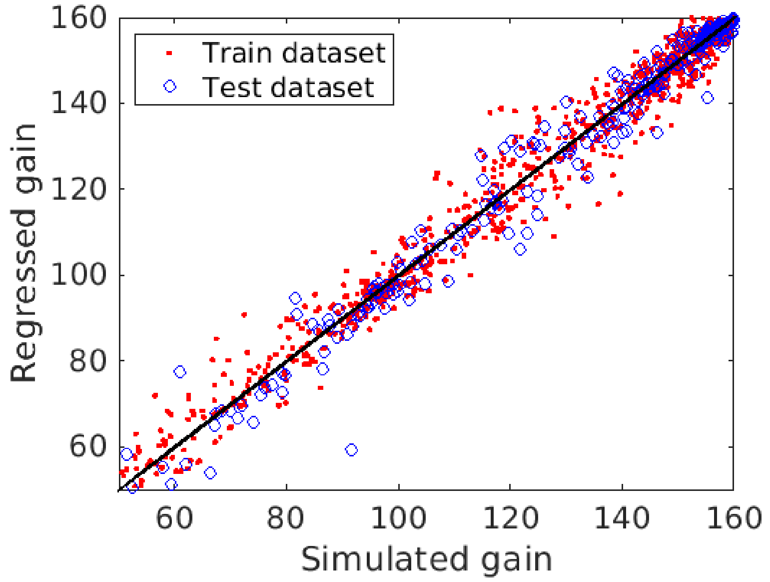
Dataset obtained by GA



Surrogate model for fusion



The ability of the trained model

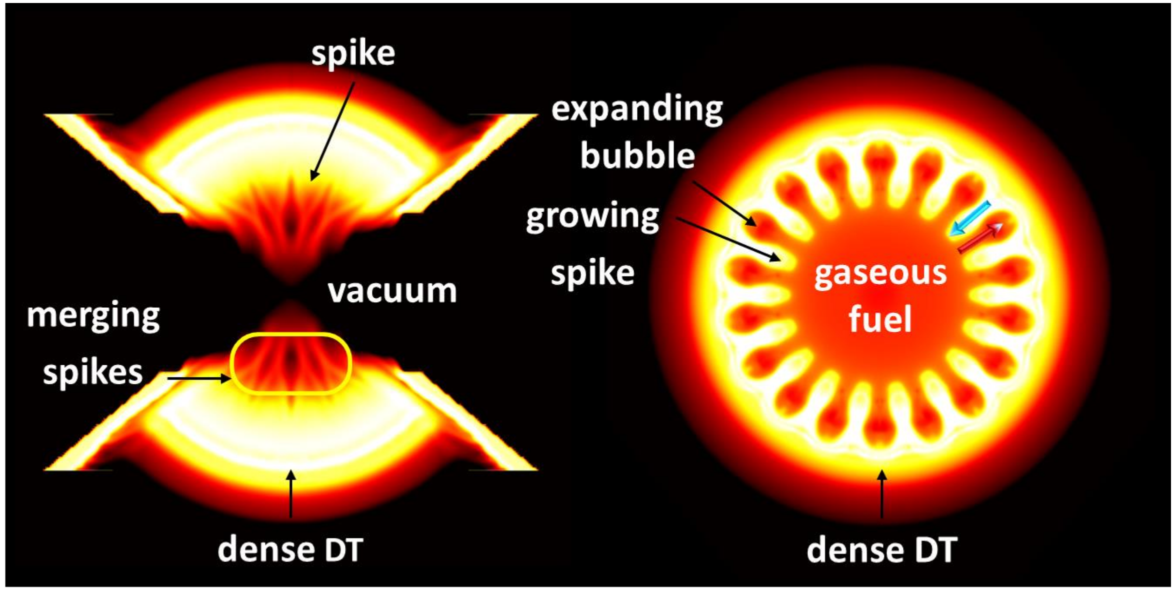


IAEA AI4Fusion CRP project

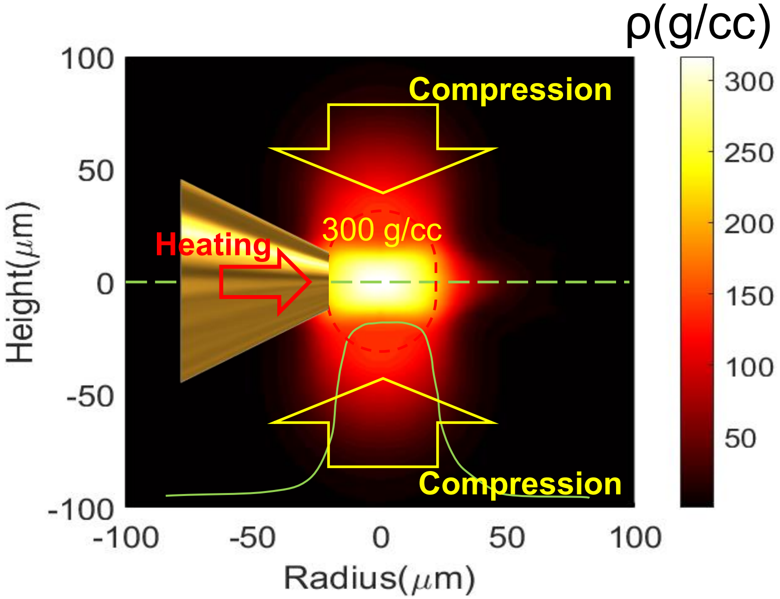
1. **The implosion dataset produced by the genetic algorithm is rather suitable for the training of a deep neural network model with multiple input and outputs.**
2. **When the surrogate model called by the Bayesian optimization, an implosion with a fusion gain larger than 100 can be found within 5 minutes.**

Formation of isochoric plasma insensitive to RT instability

RTI instability in the DCI and central ignition schemes



Isochoric plasma formed in DCI



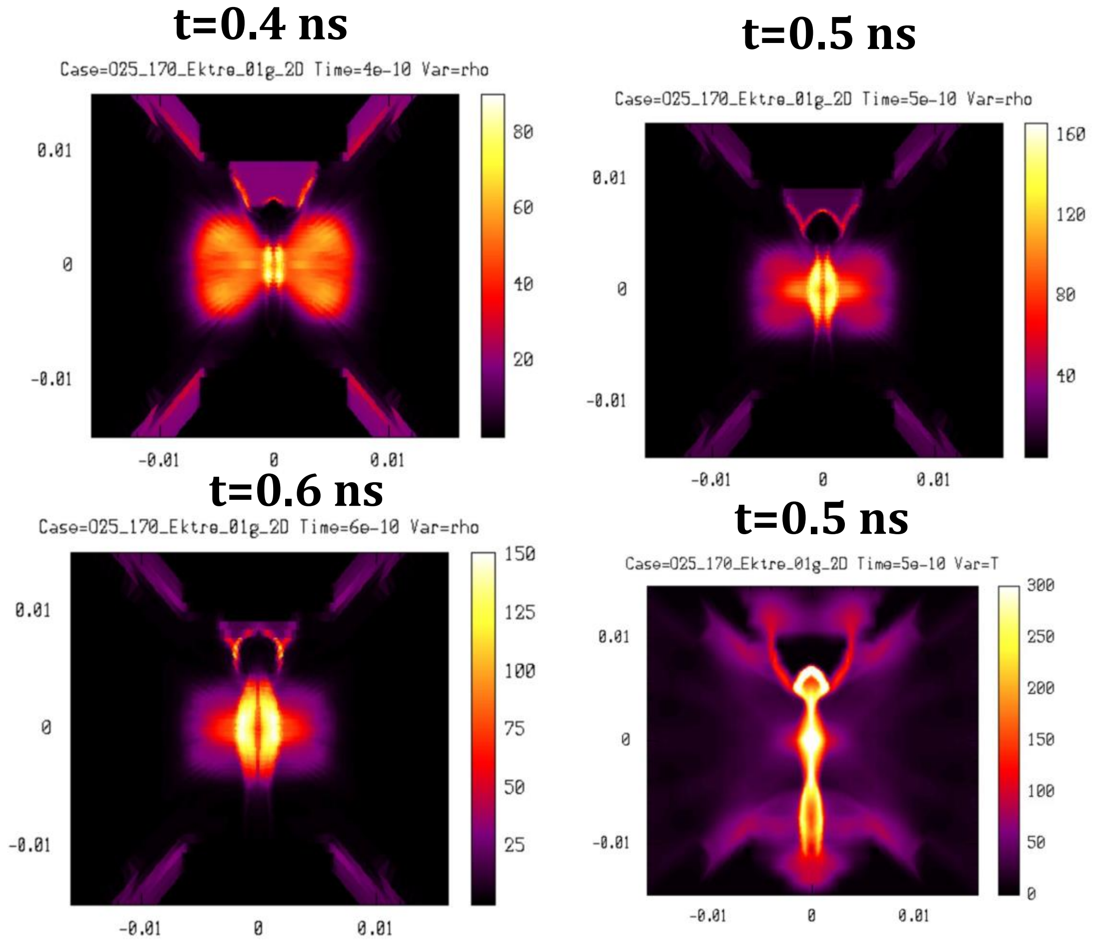
- **There is no central gas inside the DCI scheme, which can effectively suppress the growth of RT instability during sliding, forming a high-density isochoric plasma (ρ_{max} = 420 g/cm^3, ρR = 2.18 g/cm^2)**
- **In the central ignition scheme, the RT Instability develops significantly, a hotspot is formed with relatively small areal density($\rho_{hotspot}$ = 53 g/cm^3, ρR_{shell} = 0.99 g/cm^2)**

Lei YY, Wu FY, Ramis R, et al. Comparison of the evolution of Rayleigh-Taylor instability during the coasting phase, *Phys. Plasmas* 31, 012108 (2024)

The heating cone can survive until the peak compression

Features: ZRΘ Axial symmetrical grid, with the tip of heating Cone, Carbon and Gold material, Symmetric boundary at X=0, with heat conduction and radiation transport. Carbon Plasma jets with 10 g/cc, 5eV and 200 km/s, Gold cone with 19 g/cc, 0.1 eV and 0 km/s.

Results: The plasmas collides before the broken of heat cone, with rho>150 g/cc, T>300 eV.



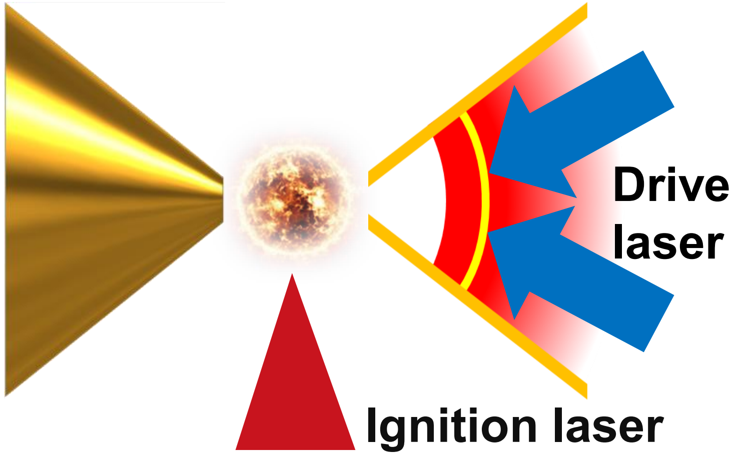
M3D_DCI_Collision-010 **O25_170_DCItre_01g**

Summary

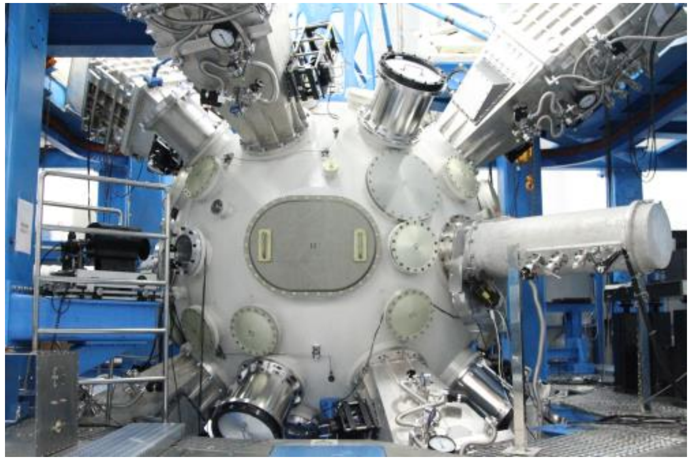
1. High-speed implosion plasma jets with a velocity of 200 km/s has been created with Double-Cone Ignition(DCI) scheme. A high-density isochoric plasma is formed after the collision on the SG-II Upgrade facility.
2. The laser pulse is optimized with machine learning, with a goal to achieve high-density, moderate velocity and high stability implosion for the DCI experiments.
3. A point design of the DCI baseline target indicates a fusion gain >100 with a drive energy of 300 kJ, which is promise for laser inertial energy fusion(LIFE).

Simulations on supercomputer

AI empowered DCI Fusion



Experiments on SG-II Upgrade



IAEA
International Atomic Energy Agency

Thank You!

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Via Fusion, Towards Space!

"Earth is the cradle of humanity, but one cannot remain in a cradle forever! "