Laser para confinamiento inercial

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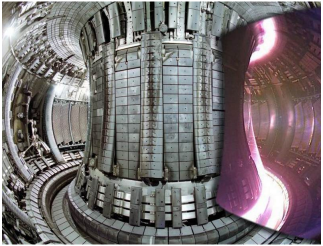
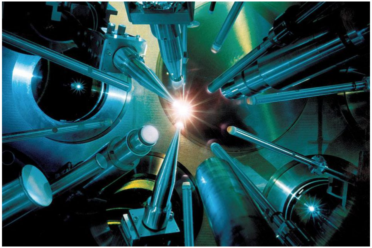
Introducción

Existen actualmente varios métodos mediante los cuales se intenta lograr la fusión nuclear controlada. T $>$ 10 keV

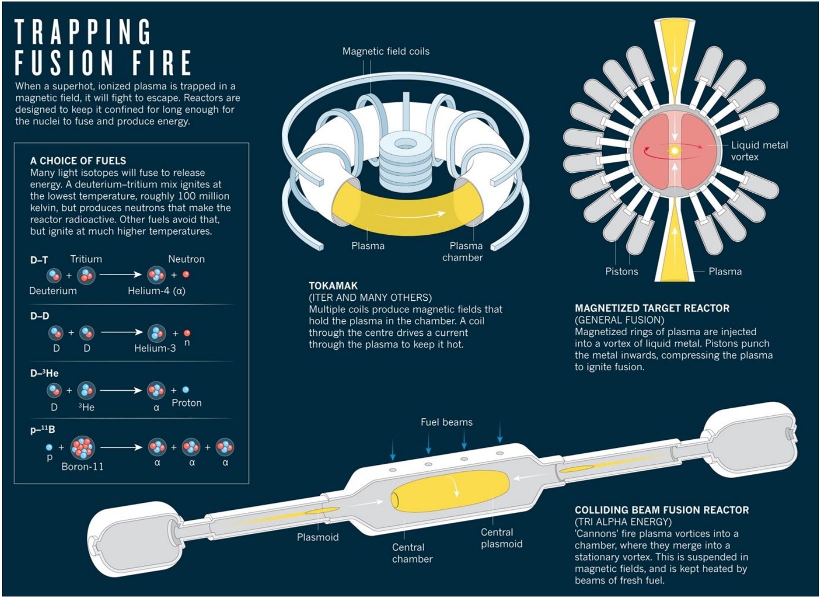
- Fusión por confinamiento magnético
- Fusión por haces de partículas
- Fusión láser



(a) ITER International Thermonuclear Experimental Reactor, Oxford, Reino Unido



(b) NIF National Ignition Facility, Lawrence Livermore National Laboratory


TRAPPING FUSION FIRE
When a superhot, ionized plasma is trapped in a magnetic field, it will fight to escape. Reactors are designed to keep it confined for long enough for the nuclei to fuse and produce energy.
A CHOICE OF FUELS
Many light isotopes will fuse to release energy. A deuterium–tritium mix ignites at the lowest temperature, roughly 100 million kelvin, but produces neutrons that make the reactor radioactive. Other fuels avoid that, but ignite at much higher temperatures.
D–T
Tritium
Neutron
Deuterium
Helium-4 (α)
D–D
D
D
Helium-3
n
D–³He
D
³He
α
Proton
p–¹¹B
p
Boron-11
α
α
α
Magnetic field coils
Plasma
Plasma chamber
TOKAMAK
(ITER AND MANY OTHERS)
Multiple coils produce magnetic fields that hold the plasma in the chamber. A coil through the centre drives a current through the plasma to keep it hot.
Liquid metal vortex
Pistons
Plasma
MAGNETIZED TARGET REACTOR
(GENERAL FUSION)
Magnetized rings of plasma are injected into a vortex of liquid metal. Pistons punch the metal inwards, compressing the plasma to ignite fusion.
Fuel beams
Plasmoid
Central chamber
Central plasmoid
COLLIDING BEAM FUSION REACTOR
(TRI ALPHA ENERGY)
'Cannons' fire plasma vortices into a chamber, where they merge into a stationary vortex. This is suspended in magnetic fields, and is kept heated by beams of fresh fuel.

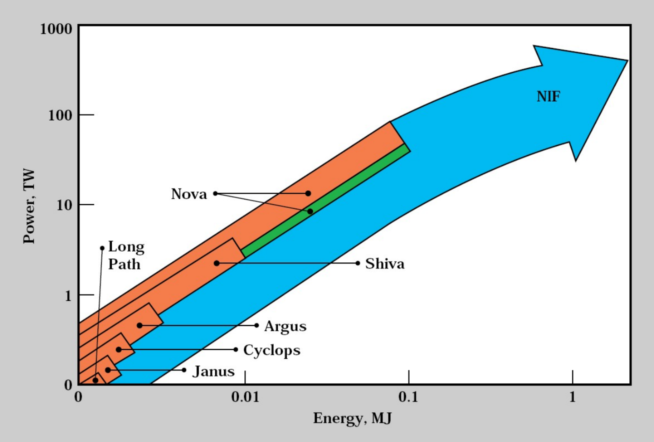


Figura: El progreso en los niveles de energía y energía alcanzables por los láseres de confinamiento inercial ha aumentado dramáticamente desde principios de los años setenta.

LETTER

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Fuel gain exceeding unity in an inertially confined fusion implosion

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Ignition is needed to make fusion energy a viable alternative energy source, but has yet to be achieved[1]. A key step on the way to ignition is to have the energy generated through fusion reactions in an inertially confined fusion plasma exceed the amount of energy deposited into the deuterium–tritium fusion fuel and hotspot during the implosion process, resulting in a fuel gain greater than unity. Here we report the achievement of fusion fuel gains exceeding unity on the US National Ignition Facility using a 'high-foot' implosion method[2,3], which is a manipulation of the laser pulse shape in a way that reduces instability in the implosion. These experiments show an order-of-magnitude improvement in yield performance over past deuterium–tritium implosion experiments. We also see a significant contribution to the yield from α-particle self-heating and evidence for the 'bootstrapping' required to accelerate the deuterium–tritium fusion burn to eventually 'run away'

The high-foot implosion is designed to reduce ablation-front-driven instability growth and thereby inhibit ablator plastic (carbon–hydrogen and silicon dopants) from mixing into and contaminating the D–T hotspot. The laser pulse shape is designed to obtain a relatively high hohlraum radiation temperature ($T_{rad} \approx 90$–100 eV) during the 'foot' of the pulse (Fig. 1) and launches three shocks. In contrast, the NIC implosion pulse shape drives a lower radiation temperature ($T_{rad} \approx 60$ eV) in the foot (hence 'low-foot') for longer and launches four shocks. The essential stability benefits of the high-foot scheme can be understood from examining an expression for the linear growth rate of the ablation-driven Rayleigh–Taylor instability[10]

$$\gamma_{A-RTI} = \alpha_2(\mathrm{Fr}, \nu)\sqrt{\frac{kg}{1+kL_\rho}} - \beta_2(\mathrm{Fr}, \nu)kv_a \quad (1)$$

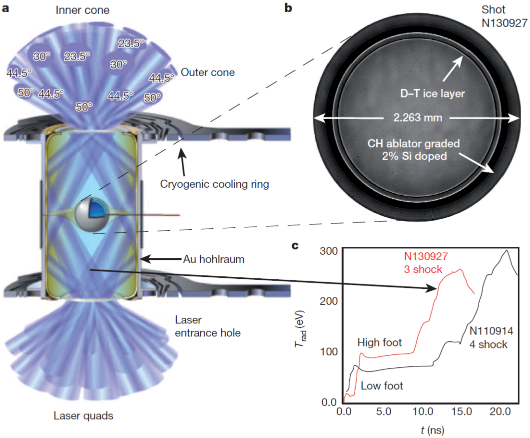
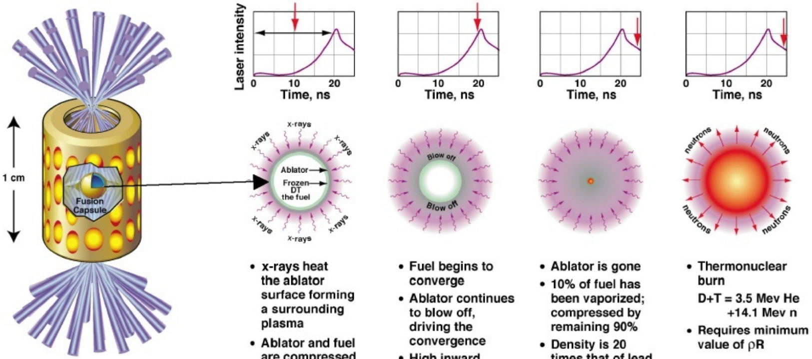


Figure 1 | Indirectly driven, inertially confined fusion target for NIF. **a**, Schematic NIF ignition target showing a cut-away of the gold hohlraum and plastic capsule with representative laser bundles incident on the inside surface of the hohlraum. **b**, X-ray image of the actual capsule for N130927 with D–T fuel layer and surrounding CH (carbon–hydrogen) plastic ablator. **c**, X-ray radiation drive temperature versus time for the NIC low-foot implosion and the post-NIC high-foot implosion.



- x-rays heat the ablator surface forming a surrounding plasma
- Ablator and fuel are compressed by blow off of the hot surface material

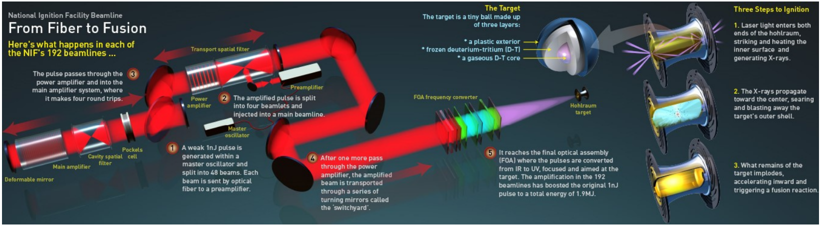
- Fuel begins to converge
- Ablator continues to blow off, driving the convergence
- High inward radial velocity

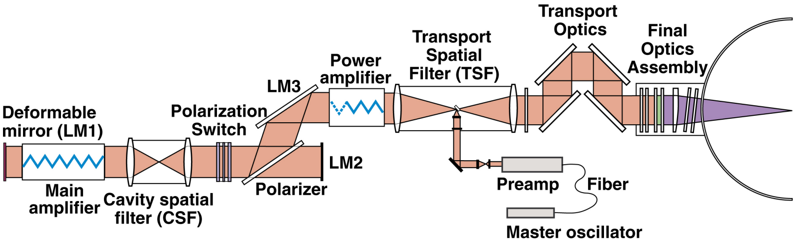
- Ablator is gone
- 10% of fuel has been vaporized; compressed by remaining 90%
- Density is 20 times that of lead
- Ignition begins at 100,000,000 K
- $R_{init}/R_{final} > 30$

- Thermonuclear burn

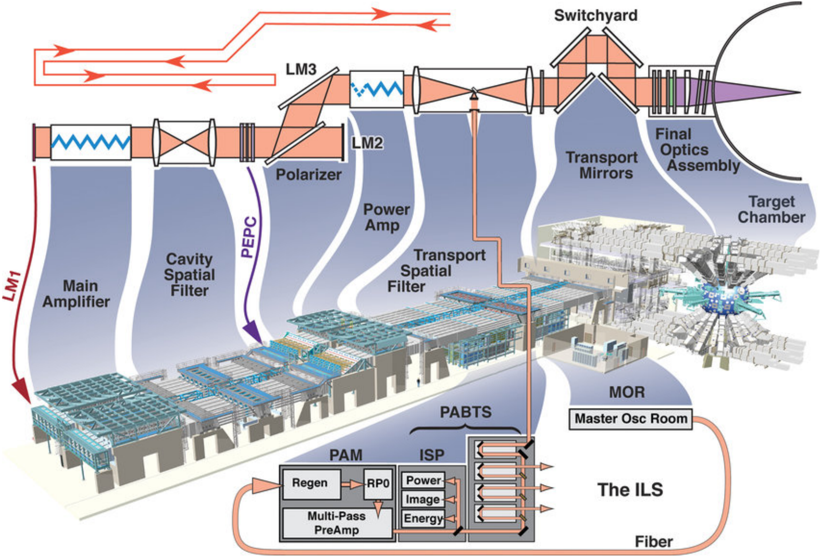
  D+T = 3.5 Mev He +14.1 Mev n
- Requires minimum value of ρR

Diagrama simplificado de la trayectoria del láser.





Vista esquemática de los sistemas y componentes del láser.



Figura

Full-aperture backscatter station on Shenguang-II Laser Facility

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神光Ⅱ激光装置的全口径背向散射测量系统*

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摘　要： 报道了基于神光Ⅱ激光装置的全口径背向散射测量系统。系统通过激光聚焦透镜收集激光等离子体相互作用产生的散射光；两个热能量卡计分别测量波长 348～354 nm 范围的受激布里渊散射和波长 400～700 nm 范围的受激拉曼散射产生的散射光。该系统可以测量散射光的能量、功率和光谱图像，提供优于 0.5 nm 光谱分辨和 10 ps 时间分辨的光谱物理信息。同时采用 PIN 二极管阵列对聚焦透镜外侧附近的近背向散射光信息进行测量。

关键词： 全口径背向散射；激光等离子体；受激布里渊散射；受激拉曼散射

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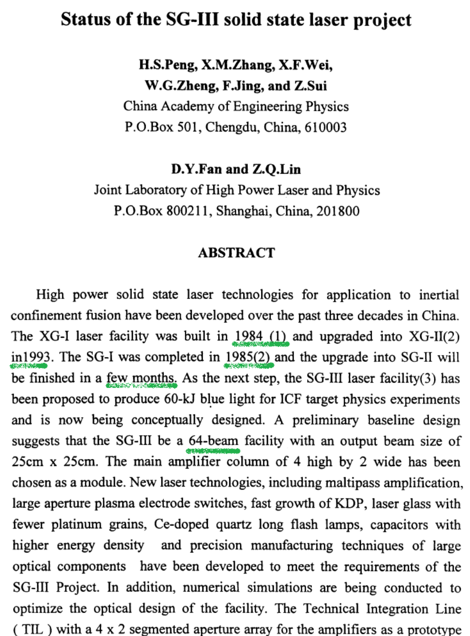
激光惯性约束聚变(ICF)等离子体点火物理研究中，激光能量与靶的耦合效率是十分重要的一个参数[1-3]。其中一个重要的能量损失机制是靶物质电离产生的等离子体中激光的散射。入射光波能共振地衰变为一个背向散射光波和一个等离子体中的本征波模——离子声波或电子等离子体波。背向散射光和入射光在某一频率上的拍频可以进一步驱动这个本征波模，提高它的幅度，从而进一步增大散射效率，如此形成了一个不稳定的反馈循环使得本征波模和散射光波的幅度在 0.1～10.0 ps 时间尺度内以指数增长。在电子等离子体波上的散射称为受激拉曼散射(SRS)，在离子声波上的散射称为受激布里渊散射(SBS)[4-7]。激光散射是惯性约束聚变实验长期关心的问题之一。因为散射不仅会增加入射激光的流失，降低靶的吸收，而且在间接驱动内爆实验中散射激光还会直接打击氘氚靶丸，影响内爆压缩，降低内爆效率，对内爆产生破坏作用。SRS，SBS 散射的大量能量如果在光束之间随机分布，将会使点火激光装置束间功率平衡小于 8%的要求更加难以满足，而这种功率平衡是保证高压缩比内爆时对称性条件所必需的。

本文介绍了神光Ⅱ激光装置的全口径背向散射测量系统(FABS)，该系统由收光系统和能量卡计组合而成，在每路伺服反射镜后加上收光系统，采用能量卡计对 SRS，SBS 散射光能量进行时间积分测量。对于大角



Status of the SG-III solid state laser project

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ABSTRACT

High power solid state laser technologies for application to inertial confinement fusion have been developed over the past three decades in China. The XG-I laser facility was built in 1984 (1) and upgraded into XG-II(2) in1993. The SG-I was completed in 1985(2) and the upgrade into SG-II will be finished in a few months. As the next step, the SG-III laser facility(3) has been proposed to produce 60-kJ blue light for ICF target physics experiments and is now being conceptually designed. A preliminary baseline design suggests that the SG-III be a 64-beam facility with an output beam size of 25cm x 25cm. The main amplifier column of 4 high by 2 wide has been chosen as a module. New laser technologies, including maltipass amplification, large aperture plasma electrode switches, fast growth of KDP, laser glass with fewer platinum grains, Ce-doped quartz long flash lamps, capacitors with higher energy density and precision manufacturing techniques of large optical components have been developed to meet the requirements of the SG-III Project. In addition, numerical simulations are being conducted to optimize the optical design of the facility. The Technical Integration Line (TIL) with a 4 x 2 segmented aperture array for the amplifiers as a prototype

Status of SG-III solid state laser project

1. SG-III LASER FACILITY

According to the requirements on laser performance for application to inertial confinement fusion and the development level of high power solid-state laser technologies , the SG-III laser facility has been proposed to build which will deliver 60-kJ blue light to targets. We have been working on the conceptual design of the facility for a couple of years and preliminary performance requirements for the SG-III facility have been suggested, based on the results of simulations and experiments to date, as shown in Table 1.

Table 1. Suggested specifications for SG-III

Laser pulse energy	60 kJ / 0.35μm
Peak power	60 TW
Pulse duration	1~5 ns
Pulse shaping	Flexible
Beam number	64
Beam power balance	≤ 10% rms
Beam pointing accuracy	≤ 30μm rms
Target chamber diameter	5 m
Shot rate	4 hours

The SG-III facility consists of a 64-beam Nd:glass laser, switchyard, target area and diagnostics housed in the main building with two laser bays. Technical support systems for construction, operation and maintenance of the facility are installed in an auxiliary building.

Because the SG-III is a multibeam laser facility, two significant principles for design, as in the case of NIF(4) and LMJ (6), are followed. First, the multisegment- aperture- array architecture with a 4-pass amplification for cavity amplifiers is adopted to greatly reduce the cost. Second, most of the

Status of SG-III solid state laser project

aperture of 30cm x 30cm has been chosen to match the manufacturing capability of large aperture precision optics in China. Each laser bay contains 4 independent beam bundles with a 2-meter space between two neighbours for easy access. The laser beams emerging from the transport spatial filters are directed to the switchyard and arranged there to enter the target chamber, after frequency conversion, either in a few beam cones for indirect drive targets or in a spherically-symmetrical distribution for direct drive target illuminations, as shown in Figure 2 and Figure 3, respectively . The target chamber is a 5-m-diameter sphere with many ports for both final optical assemblies and diagnostic instruments mounting.

2. TECHNICAL INTEGRATION LINE

Conceptual design of the SG-III facility shows that many new laser technologies have to be used for performance and cost effectiveness. Some of them are being examined on the existing facilities or even still under development. To reduce the risk, a technical integration line (TIL) as a prototype for the SG-III facility has been planned to build first in the next few years. The TIL is actually a 4 x 2 beam bundle of the SG-III facility with Nd:glass slabs for only two apertures and dummy slabs for the rest six apertures.

The TIL consists of six major systems which are front-end and preamplifier system, maim amplifier system, beam control system, frequency conversion system, laser diagnostic system and integrated computer control system. Figure 4 depicts the optical schematic of one beamline of the TIL from pulse injection to final focus on target.

The front-end consists of a master oscillator, low-voltage KTP waveguide modulator, fiber distributor and amplifiers, and diode-pumped regenerative amplifiers which provides high quality optical pulses at an energy level of a few millijoules. Then the pulse enters the preamplier optical chain composed

Table 2. Designed Specifications for TIL

Laser pulse energy	1500J/0.35μm
Beam aperture	25cm x 25cm (hard aperture 30cm x 30cm)
Beam number	2 (6 with dummy glass)
Pulse duration	1-3 ns (rectangular or shaped)
Beam pointing accuracy	≤ 30μm rms
Beam divergence	± 25μrad
Beam power balance	~10% rms

An adaptive optics system was firstly tested on SG-I laser facility in Shanghai late in 1980's. Here again ,we have designed a new adaptive optics system for the TIL to compensate for wavefront and thermal distortions in order to improve the beam quality and reduce the fabrication tolerances of optical components. Figure 5 shows the schematic of the system and the main components: deformable mirror, Hartmann sensors, processor and wavefront controller. The system is designed to correct 2-3λ static aberrations due to component fabrication and mounting errors and 3-6λ dynamic aberrations induced by the flashlamp thermal load so that the output beam divergence could be controlled to <±50μrad to meet the requirement for a high frequency conversion efficiency. The deformable mirror will be installed prior to the injection of the laser pulse into A1 as in the Beamlet (6)

The main amplifier stage has a cavity amplifier (A1) for four-pass amplification and a booster amplifier (A2) for energy extraction. The four-pass architecture is basically similar to that for NIF(3) and LMJ(5). The laser pulse (<10J) is injected into A1 at the focal plane of the cavity spatial filter for the first double-pass amplification, then directed into the optical chain of the beam reverser with a small aperture Pockels cell switch and then re-injected for the second double-pass amplification by A1. The pulse from A1 is finally amplified by A2 to the required output energy.

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beam reverser is designed to turn on for isolating the optical path since the onset of the flashlamps' pumping until the arrival of the laser pulse to be amplified. While the large one in the cavity is designed to work for interstage isolation after the amplification of the laser pulse by A1. When the laser pulse travel through the Pockels cells, there is no voltage applied to them. To the laser pulse, the switches work in a static regime. However, if the large Pockels cell once fails to work, optical damage could be brought by the reflected light. A prototype plasma-electrode Pockels cell of 80mm x 80mm has been successfully developed at CAEP, while larger ones for the TIL still under development.

Numerical simulations are still being conducted for optical design and the results have shown that glass slabs'numbers of 9 for A1 and of 5 for A2 are preferred. The Nd-doped phosphate glass is newly developed (5) and has been put in pilot production.

Table 3. Nd-Doped Phosphate Glass(N_{31})

Stimulated emission cross section	$4.5 \times 10^{-20} cm^2$
Fluorescence lifetime	400μm (2.2% Nd_2O_3)
Absorption coefficient	0.1% / cm
Nonlinear refractive index	1.2×10^{-13} e.s.u.
Damage threshold (1.06μm,3ns)	$\geq 20J / cm^2$
Platinum grain	≤ 0.2 / liter

The power conditioning systems will also be modularized, each pumping the flashlamps of one 4 x 2 x1 amplifier module. Capacitors using the self-healing, metallized dielectric technology are being developed by a number of vendors and an energy density of 0.5J/cc has been reached. Ce-doped quartz flashlamps 140-cm long, 3cm in inner diameter are now under test and pilot production will soon begin. A few options of laser current switches are

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Abstract. SG-III laser facility beam begins with a nanojoule energy laser pulse from the master oscillator and a fiber front-end system that can provide a variety of pulse shapes suitable for a wide range of experiments. The chirped pulse stacking method is used in the front-end system to generate arbitrarily shaped pulse with a rise time less than 50ps. The system stacks a set of 100-ps chirped pulses in fiber time-delay lines to obtain a 5-ns flat-top pulse with a spectral bandwidth of 1.2nm. The pulse is then transported to preamplifier modules under the middle of CSF for amplification and beam shaping. There is a total of 48 preamplifier modules on SG-III, each feeding a single laser beams. The main amplifier column of 4 high by 2 wide has been chosen as a module and the clear optical aperture is 40cm×40cm. Small PEPC are chosen for system isolation and beam can be rotated by 90 degree in U-turn beam reverser located in the middle of TSF. After main amplifier, beams are subsequently redirected to final optics assembly in switchyard and are focused on the center of the target chamber with the diameter of 6m.

Laser description

SG-III's laser system, the heart of the facility, is comprised of 48 high-power laser beams. For inertial fusion studies, these laser beams will produce 180,000 joules (approximately 60 trillion watts of power for 3 nanoseconds) of laser energy in the near-ultraviolet (351-nanometer wavelength).

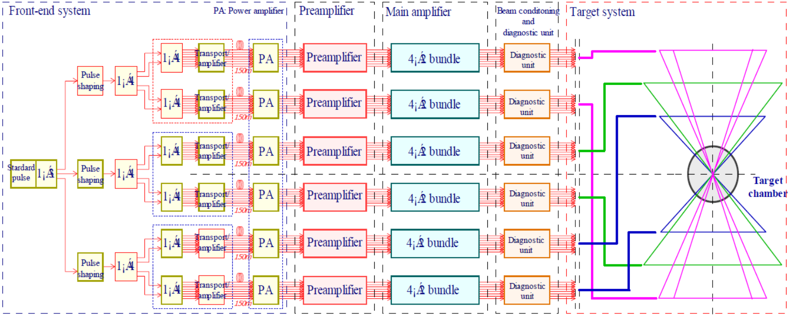

Figure 2. Configuration of SG-III's laser system

Front-end system

The front-end system mainly consists of four parts: 100-ps standard pulse unit pulse shaping unit, fiber transport amplify unit and power amplifier unit. The pulse begins in a passively mode-locked Yb-fiber laser which generates a train of stable 200-fs pulses at the central wavelength of 1053 nm with a bandwidth of 10 nm. A polarization-independent waveguide modulator is used as the pulse selector to decrease the pulse repetition rate from 20 MHz to 1 Hz. The selected pulses are coupled into an Yb-fiber amplifier with a 1 nm fiber grating filter centering at 1053 nm, and after passing through a chirped fiber grating the amplified pulse is stretched to 100 ps called standard pulse. These 100 ps standard pulses are input into a compact pulse shaping system based on temporal stacking of pulses. The system can generate shape-controllable pulses with fast rise time of 50 ps with a spectral bandwidth of 1.2nm.

Preamplifier system

Each of the 48 pulses from the Front-end enters the Preamplifier system on a single-mode optical fiber, where it is amplified first by a repetition amplifier module, then by a LD-array pumped thin-slab amplifier and a double-pass rod amplifier. After aligned and isolated, the pulse from the Front-end system is first injected into the high-gain amplifier where experiences a gain that raises its energy from $10\ \mu$J to 10 mJ. After being switched out of the high-gain amplifier, the pulse traverses a spatial shaping module that transforms the Gaussian spatial shape to a profile that is designed to compensate for the spatial nonuniformity of the gain throughout the rest of the laser. The ability to accurately shape the spatial profile allows the SG-III to produce beams at the output of the system that have a flat irradiance distribution across the central part of the beam. After passing through the beam-shaping module, the pulse is injected into thin-slab amplifier pumped by LD array, where the pulse makes 12 round trips and improves its energy from 10 mJ to 1J. Then the pulse makes double pass through a flashlamp-pumped rod amplifier, yielding a nominal net energy gain of 5. The overall energy gain of the preamplifier system is of the order of 10^6.

Main amplifier system

The beam from the preamplifier is injected into the main amplifier from the pinhole of the cavity spatial filter (CSF). In this way, the total gains of the main amplifier can be increased. It also can ease the pressure to system isolation and simplify the process of alignment. The beam traverses the main amplifier (MA), reflects off a deformable mirror that is used to correct wavefront distortions, and then goes through the MA and CSF again. It then passes through the booster amplifier, and enters U-turn beam reverser through the inject pinhole located near the focal plane of the transfer spatial filter (TSF). The amplifiers, with 16 glass slabs per beam, are arranged with 9 slabs in the main amplifier section and 7 slabs in the boost amplifier section. The laser glass slabs, measuring 46 cm x 81 cm x 4 cm, consist of neodymium-doped phosphate glass.

Final optics assembly

After the transfer spatial filter (TSF), the main pulse proceeds to the switchyard where four or five transport mirrors direct it to one of a number of final optics assemblies (FOAs) symmetrically located about, and mounted on, the target chamber. Each FOA contains a 1w vacuum window, focal-spot beam-conditioning optics, three frequency conversion crystals to reach 351 nm wavelength, a focusing lens, a beam sampling grating (BSG) that serves as a beam diagnostic pickoff to measure energy and power, and a 1-3 mm thick disposable debris shield.

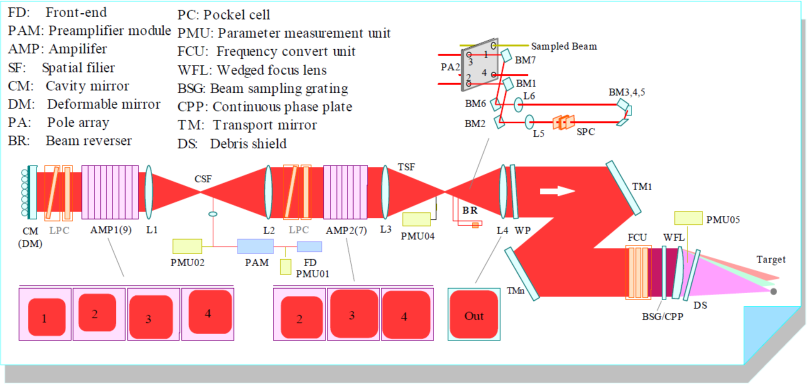

Figure 3. Schematic of one of the 48 beamlines in the SG-Ш facility