

第八章 激光放大技术

激光放大技术，又称为行波放大技术，是获得强激光必不可少的技术手段。

棒状放大器，片状放大器，板条状放大器；

单程放大器，多程（双程、三程、四程），
再生放大器，啁啾脉冲放大技术CPA技术等。

描述放大器的理论由涉及的激光时间特性不同
可分为三方面：

1、 $T \gg T_1$, 连续波运转及长脉冲运转,
 $d\Delta n/dt=0$, 稳态激光放大器理论;

2、 $T_2 < T < T_1$, 调Q运转,
 $\Delta n = \Delta n(x, t)$, 脉冲激光放大器理论;

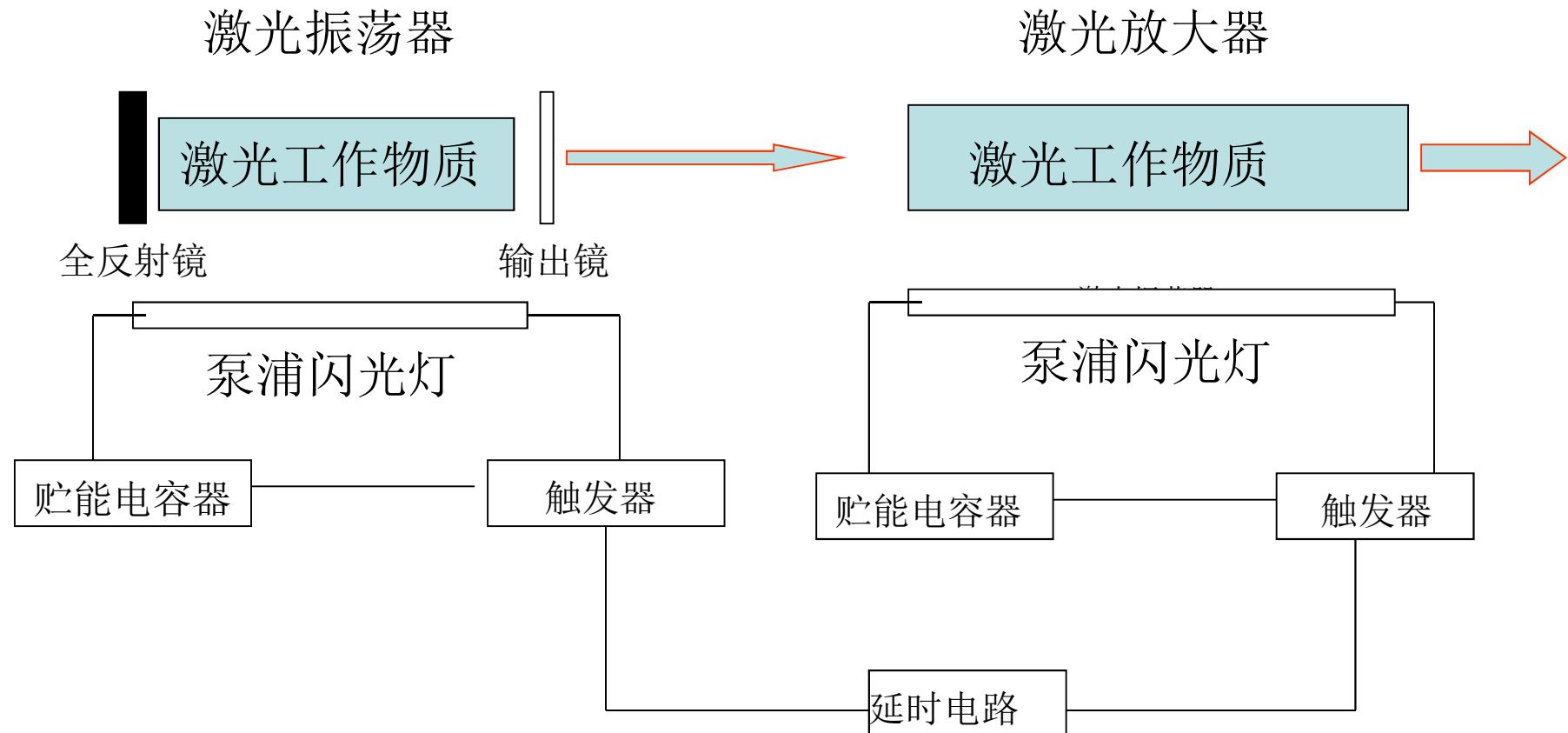
3、 $T < T_2$, 锁模运转, 半经典理论; 现在大多经啁啾脉冲放大技术CPA技术转换成纳秒或
亚纳秒脉冲, 而采用脉冲激光放大器理论;

τ 为光脉冲持续时间；

T_1 为纵向弛豫时间，由放大介质中激活粒子允许的跃迁能级寿命决定；对于固体 $\sim 10^{-3}s$ 。

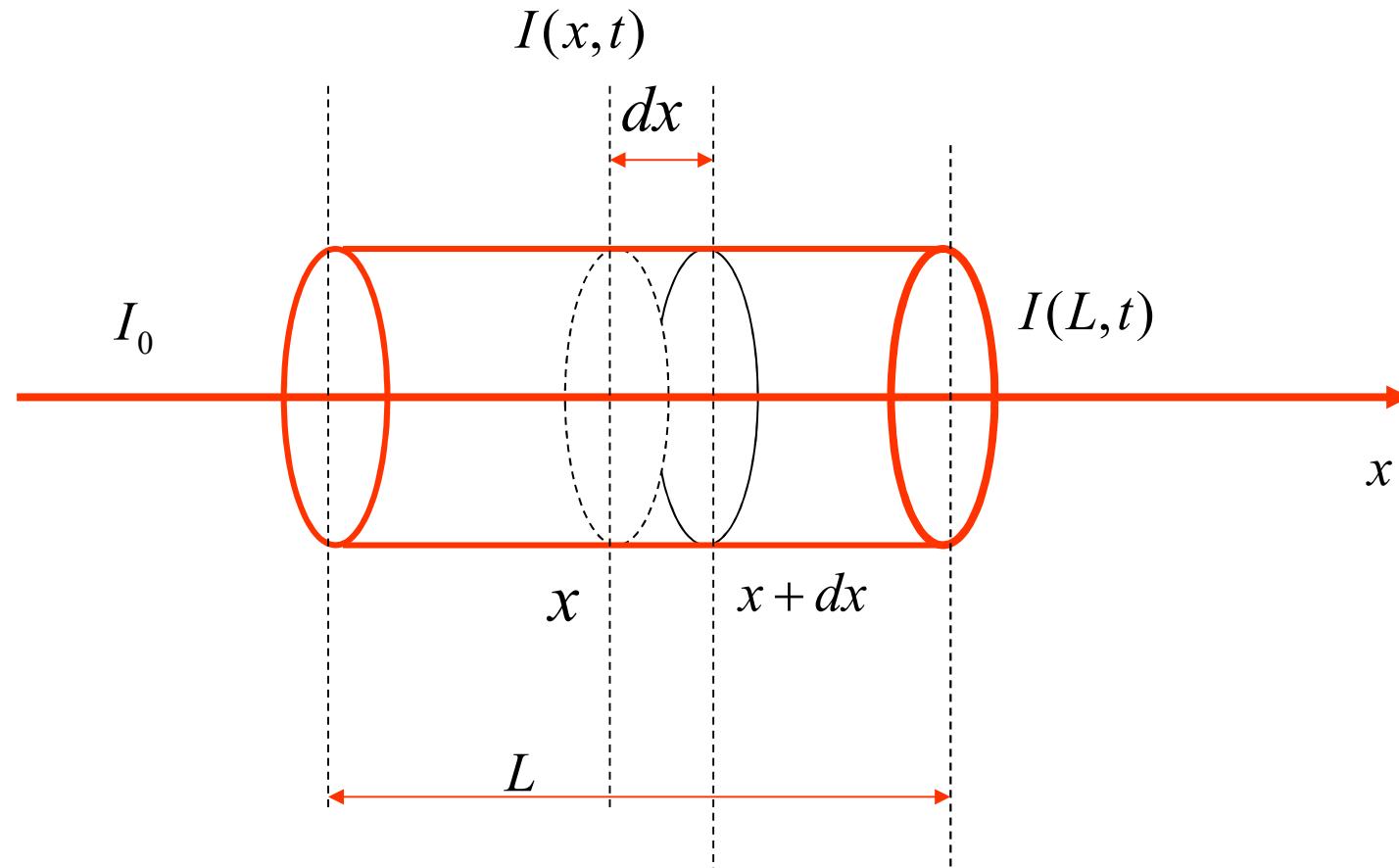
T_2 为横向弛豫时间，由放大介质中激活粒子相互交换能量过程引起的无辐射跃迁寿命决定；对于固体 $\sim 10^{-10}s$ 。

• 固体激光放大器



- 主振荡--功率放大器(MOPA)

- 第一节 脉冲放大器理论简介
- 一、脉冲放大器速率方程及其解



- 单位体积的光子数和反转粒子数都是时间t和空间x的函数；
- 假设反转粒子数分布均匀，不考虑线型和线宽的影响（单模光场）。
- 引入光子流强度 $I(x, t)$ ，单位时间流过单位横截面的光子流。光强表示为： $I'(x, t) \hbar v_0$ 。光子数密度 $\phi(x, t)$ ，
- $I(x, t) = c \phi(x, t)$, c 为受激辐射截面。

$$\text{三能级: } \frac{\partial \Delta n(x, t)}{\partial t} = -2\sigma \Delta n(x, t) I(x, t)$$

$$\text{四能级: } \frac{\partial \Delta n(x, t)}{\partial t} = -\sigma \Delta n(x, t) I(x, t)$$

$$\text{光子数密度的变化率: } \frac{\partial \phi(x, t)}{\partial t} + c \frac{\partial \phi(x, t)}{\partial x} = \sigma c \Delta n(x, t) \phi(x, t)$$

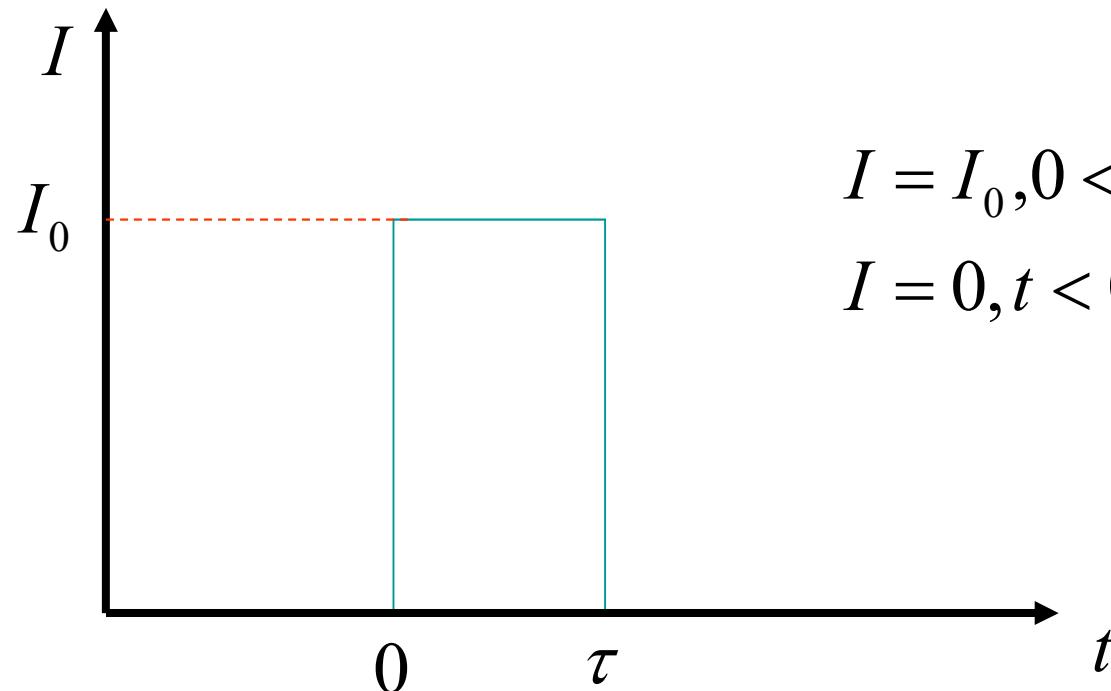
$$\text{光子流强度的变化率: } \frac{1}{c} \frac{\partial I(x, t)}{\partial t} + \frac{\partial I(x, t)}{\partial x} = \sigma \Delta n(x, t) I(x, t)$$

- 边界条件: $I(0, t) = I_0(t), \dots$ (在 $x = 0$ 处)
- $\Delta n(x, t < 0) = \Delta n_0(x), \dots$ (在 $0 < x < L$ 处)
- 上述边界条件, 联立求解上面的方程, 可以求得入射脉冲激光进入放大器中任意位置、在任何时刻的光子流利用强度、反转粒子数变化、输出脉冲能量和放大器的增益。

$$I(x, t) = \frac{I_0\left(t - \frac{x}{c}\right)}{1 - \left\{1 - \exp\left[-\sigma \int_0^x \Delta n_0(x') dx'\right]\right\} \exp\left[-2\sigma \int_{-\infty}^{t - \frac{x}{c}} I_0(t') dt'\right]}$$

$$\Delta n(x, t) = \frac{\Delta n_0(x) \exp\left[-\sigma \int_0^x \Delta n_0(x') dx'\right]}{\exp\left[2\sigma \int_{-\infty}^{t - \frac{x}{c}} I_0(t') dt'\right] + \exp\left[-\sigma \int_0^x \Delta n_0(x') dx'\right] - 1}$$

- 二、对矩形脉冲放大的分析
- 假设放大介质均匀泵浦、均匀掺杂。 Δn_0 可以视为常数。
- $\int_0^x \Delta n_0(x') dx' = \Delta n_0 x$



$$I = I_0, 0 < t < \tau,$$

$$I = 0, t < 0, t > \tau$$

在... $0 < t - \frac{x}{c} < \tau$...区间内光子流强度：

- $I(x, t) = \frac{I_0}{1 - [1 - \exp(-\sigma \Delta n_0 x)] \exp\left[-2\sigma I_0 \cdot \left(t - \frac{x}{c}\right)\right]}$

功率放大系数（单程功率增益）：

$$G_p \equiv \frac{I(x, t)}{I_0} = \frac{1}{1 - [1 - \exp(-\sigma \Delta n_0 x)] \exp\left[-2\sigma I_0 \cdot \left(t - \frac{x}{c}\right)\right]}$$

$$\text{脉冲前沿: } t = \frac{x}{c}, \dots G_p(x) = \frac{I(x, \frac{x}{c})}{I_0} = e^{\sigma \Delta n_0 x}$$

$$x = L, \rightarrow G_p(L) = e^{\sigma \Delta n_0 L},$$

- 呈指数增长, G_p 与 I_0 无关, 类似于小信号增益。
-

$$\text{脉冲后沿: } t = \frac{x}{c} + \tau,$$

$$G_p(x) = \frac{I(x, \frac{x}{c} + \tau)}{I_0} = \frac{1}{1 - [1 - \exp(-\sigma \Delta n_0 x)] \exp[-2\sigma I_0 \cdot \tau]}$$

$$x = L,$$

$$\rightarrow G_p(L) = \frac{1}{1 - [1 - \exp(-\sigma \Delta n_0 L)] \exp[-2\sigma I_0 \cdot \tau]}$$

要得到指数增长的必要条件：

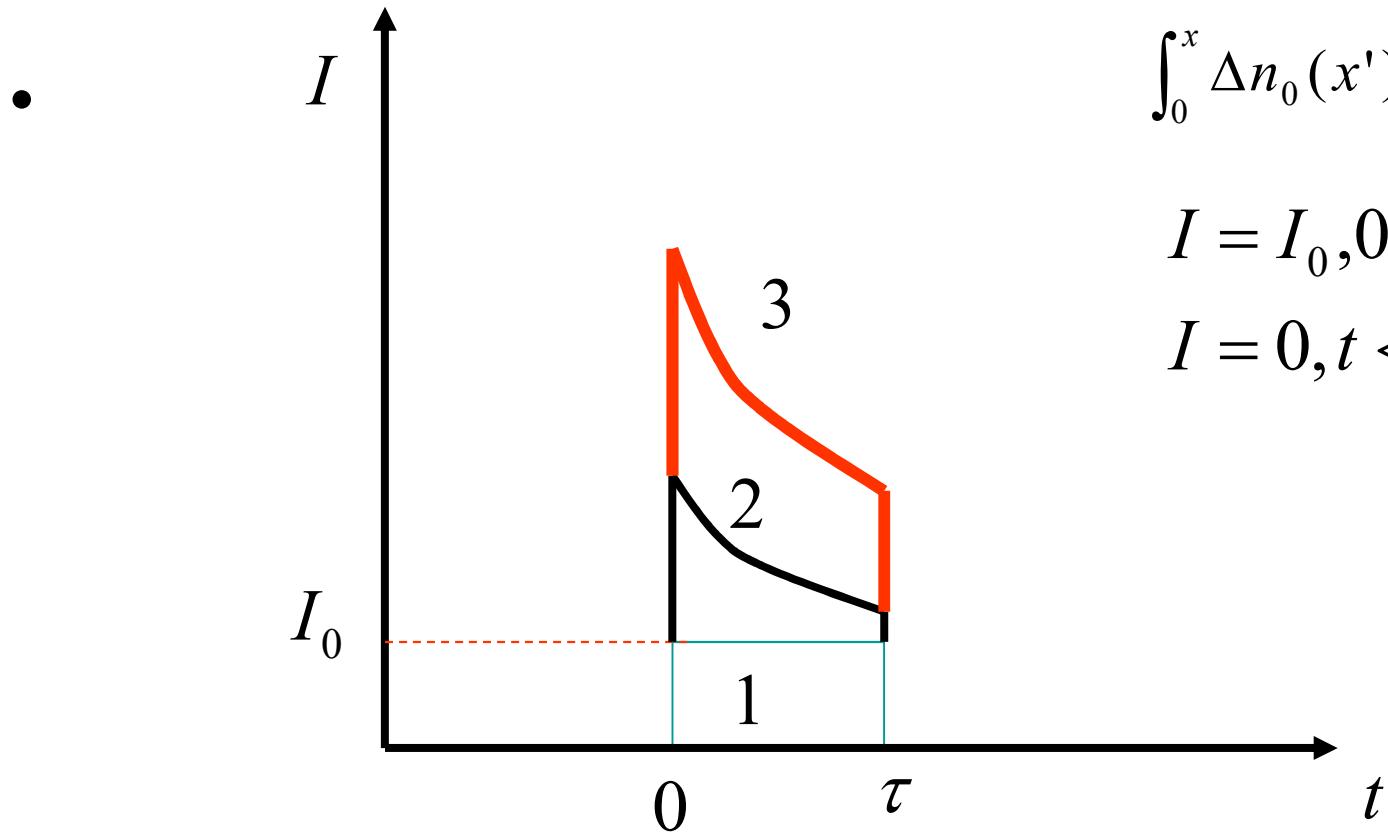
$$2\sigma I_0 \tau < 1, \text{ 和 } 2\sigma I_0 \tau \ll e^{-\sigma \Delta n_0 L}, \dots \rightarrow G_p(L) \approx e^{\sigma \Delta n_0 L},$$

•

只有在小信号 (I_0 很小) 或脉宽极窄的信号 (τ 很小) 时，才能获得指数的增益；

反之，当入射信号很强或脉宽较宽时，脉冲后沿难以放大。

(其根本原因在于增益饱和)



$$\int_0^x \Delta n_0(x') dx' = \Delta n_0 x$$

$$I = I_0, 0 < t < \tau,$$

$$I = 0, t < 0, t > \tau$$

- 1、入射脉冲；
- 2、 $\sigma\Delta n_0 L = 1$ 时，出射脉冲
- 3、 $\sigma\Delta n_0 L = 2$ 时，出射脉冲

- 脉冲能量增益:
- $G_E \equiv \frac{\int_{-\infty}^{+\infty} I(L, t) dt}{\int_{-\infty}^{+\infty} I(0, t) dt}$ -- 时间积分增益 .

对于矩形脉冲有 : $t < 0, t > \tau, \rightarrow I(0, t) = 0,$

$$t < \frac{L}{c}, t > \tau + \frac{L}{c}, \rightarrow I(L, t) = 0.$$

$$G_E \equiv \frac{\int_{\frac{L}{c}}^{\tau + \frac{L}{c}} I(L, t) dt}{\int_0^\tau I(0, t) dt} = \frac{1}{I_0 \tau} \cdot \int_{\frac{L}{c}}^{\tau + \frac{L}{c}} I(L, t) dt$$

- $I(L, t) = \frac{I_0}{1 - [1 - \exp(-\sigma \Delta n_0 L)] \exp\left[-2\sigma I_0 \cdot \left(t - \frac{L}{c}\right)\right]}$

$$G_E = \frac{1}{I_0 \tau} \int_{\frac{L}{c}}^{\tau + \frac{L}{c}} \frac{I_0}{1 - [1 - \exp(-\sigma \Delta n_0 L)] \exp\left[-2\sigma I_0 \cdot \left(t - \frac{L}{c}\right)\right]} \cdot dt$$

$$= \frac{1}{\tau} \int_0^\tau \frac{1}{1 - [1 - \exp(-\sigma \Delta n_0 L)] \exp[-2\sigma I_0 \cdot t]} \cdot dt$$

$$= \frac{1}{\tau} \int_0^\tau \frac{1}{1 + Ae^{\alpha t}} \cdot dt, ..$$

其中: $\alpha \equiv -2\sigma I_0, .. A \equiv e^{-\sigma \Delta n_0 L} - 1,$

- 利用积分公式：

$$\int \frac{1}{1+ Ae^{\alpha t}} \cdot dt = t - \frac{1}{\alpha} \ln(1 + Ae^{\alpha t}), ..$$

$$\rightarrow G_E = \frac{1}{\tau} \left[t - \frac{1}{\alpha} \ln(1 + Ae^{\alpha t}) \right]_0^\tau = \frac{1}{\tau} \left[\tau - \frac{1}{\alpha} \ln\left(\frac{1 + Ae^{\alpha \tau}}{1 + A}\right) \right]$$

$$= \frac{1}{\tau \alpha} \left[\ln e^{\alpha \tau} - \ln\left(\frac{1 + Ae^{\alpha \tau}}{1 + A}\right) \right] = \frac{1}{\tau \alpha} \left[-\ln\left(\frac{1 + Ae^{\alpha \tau}}{(1 + A)e^{\alpha \tau}}\right) \right]$$

$$= -\frac{1}{2\sigma I_0 \tau} \ln \frac{1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau}}{\left[1 + (e^{-\sigma \Delta n_0 L} - 1) \right] e^{-2\sigma I_0 \tau}}$$

$$= -\frac{1}{2\sigma I_0 \tau} \ln \frac{1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau}}{\left[1 + (e^{-\sigma \Delta n_0 L} - 1) \right] e^{-2\sigma I_0 \tau}}$$

利用 .. $\alpha \equiv -2\sigma I_0$, .. $A \equiv e^{-\sigma \Delta n_0 L} - 1$,

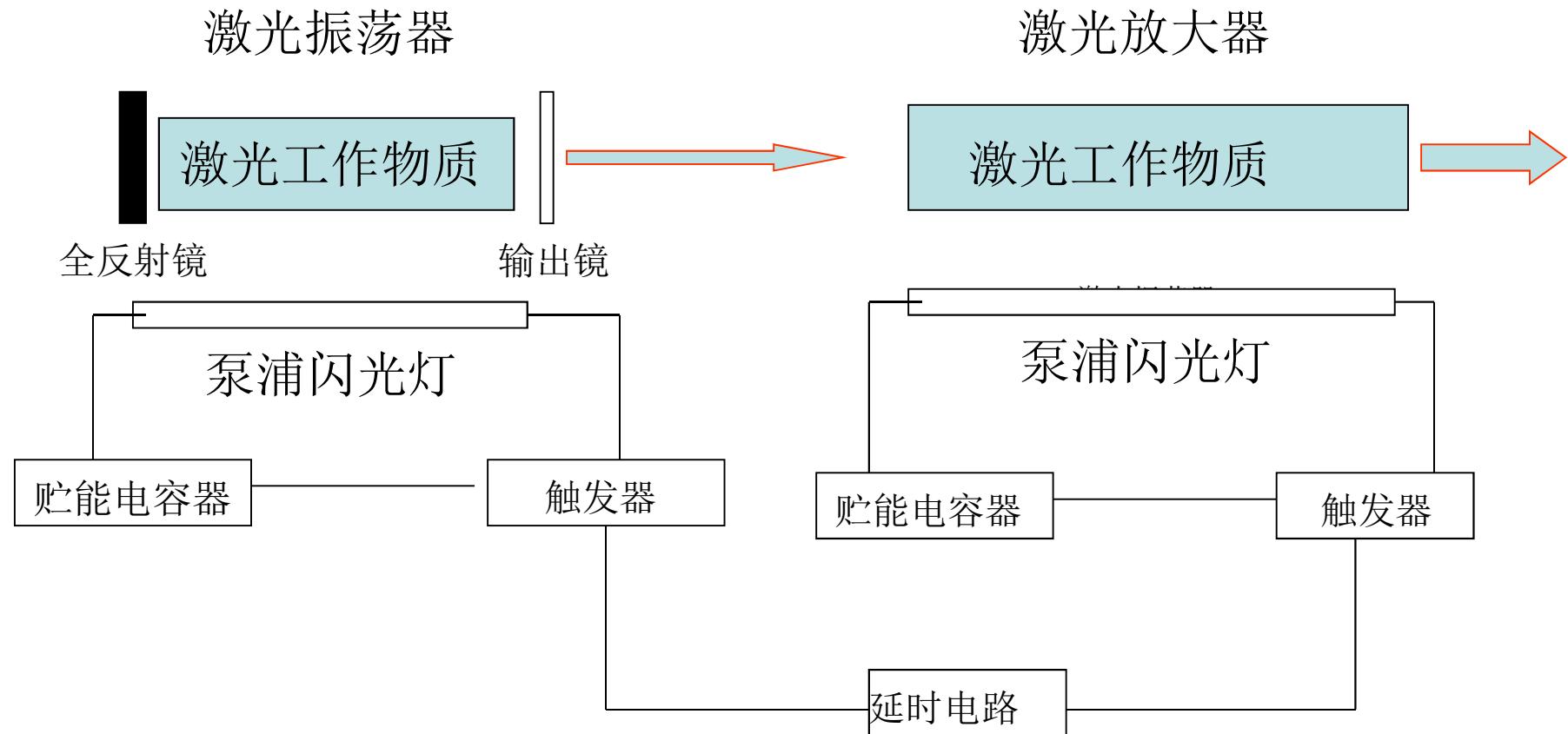
$$\begin{aligned}
&= -\frac{1}{2\sigma I_0 \tau} \ln \frac{1 + e^{-\sigma \Delta n_0 L - 2\sigma I_0 \tau} - e^{-2\sigma I_0 \tau}}{e^{-\sigma \Delta n_0 L - 2\sigma I_0 \tau}} \\
&= -\frac{1}{2\sigma I_0 \tau} \ln \left[1 - e^{\sigma \Delta n_0 L} + e^{2\sigma I_0 \tau + \sigma \Delta n_0 L} \right] = -\frac{1}{2\sigma I_0 \tau} \ln \left[1 + (e^{2\sigma I_0 \tau} - 1)e^{\sigma \Delta n_0 L} \right]
\end{aligned}$$

$$\begin{aligned}
G_E &= \frac{1}{\tau} \left[\tau - \frac{1}{\alpha} \ln \left(\frac{1 + Ae^{\alpha \tau}}{1 + A} \right) \right] = 1 - \frac{1}{\alpha \tau} \ln \left(\frac{1 + Ae^{\alpha \tau}}{1 + A} \right) \\
&= 1 + \frac{1}{2\sigma I_0 \tau} \ln \frac{1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau}}{1 + (e^{-\sigma \Delta n_0 L} - 1)} \\
&= 1 + \frac{1}{2\sigma I_0 \tau} \ln \left[1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau} \right] + \frac{1}{2\sigma I_0 \tau} \ln e^{\sigma \Delta n_0 L} \\
&= 1 + \frac{1}{2\sigma I_0 \tau} \ln \left[1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau} \right] + \frac{\Delta n_0 L}{2I_0 \tau}
\end{aligned}$$

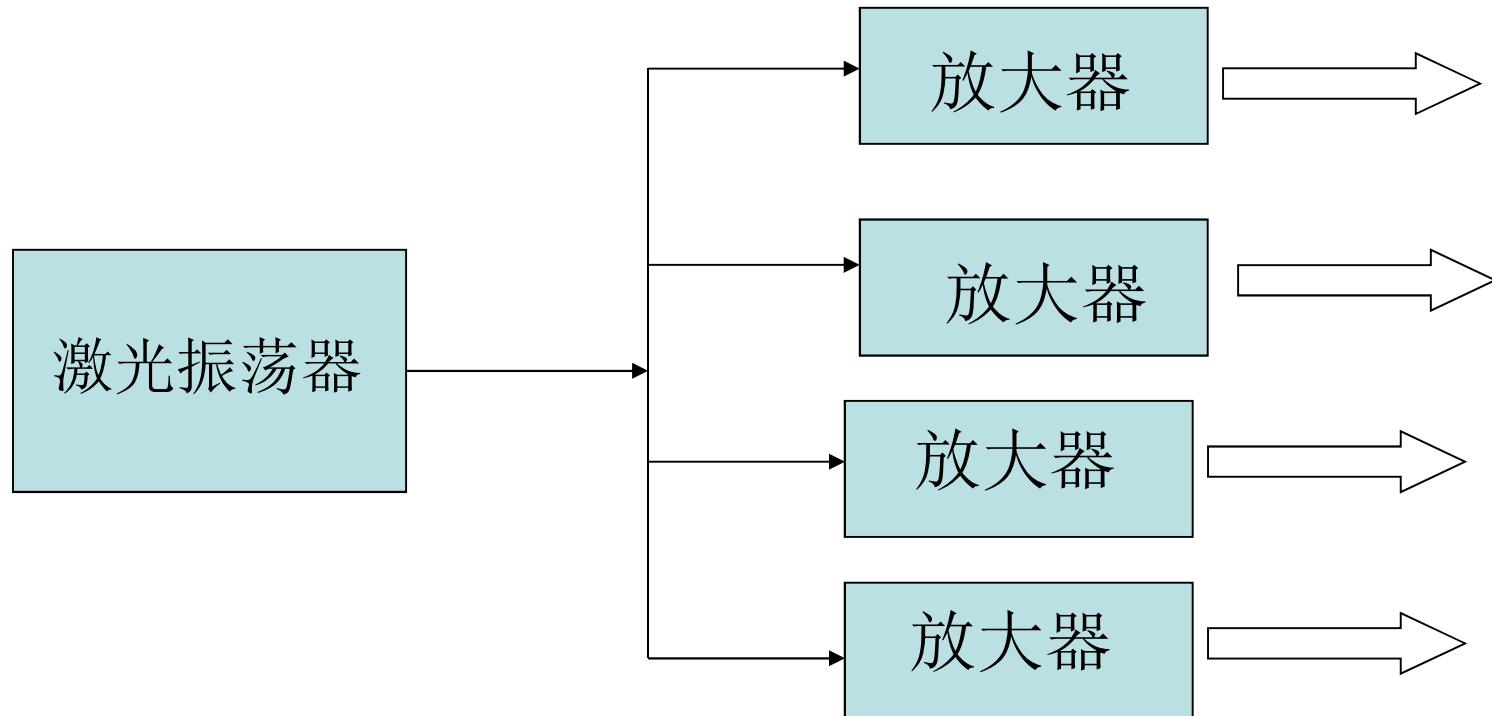
$$G_E = -\frac{1}{2\sigma I_0 \tau} \ln \left[1 + (e^{2\sigma I_0 \tau} - 1)e^{\sigma \Delta n_0 L} \right]$$

或 $G_E = 1 + \frac{1}{2\sigma I_0 \tau} \ln \left[1 + (e^{-\sigma \Delta n_0 L} - 1)e^{-2\sigma I_0 \tau} \right] + \frac{\Delta n_0 L}{2I_0 \tau}$

• 第二节 激光放大器实例分析

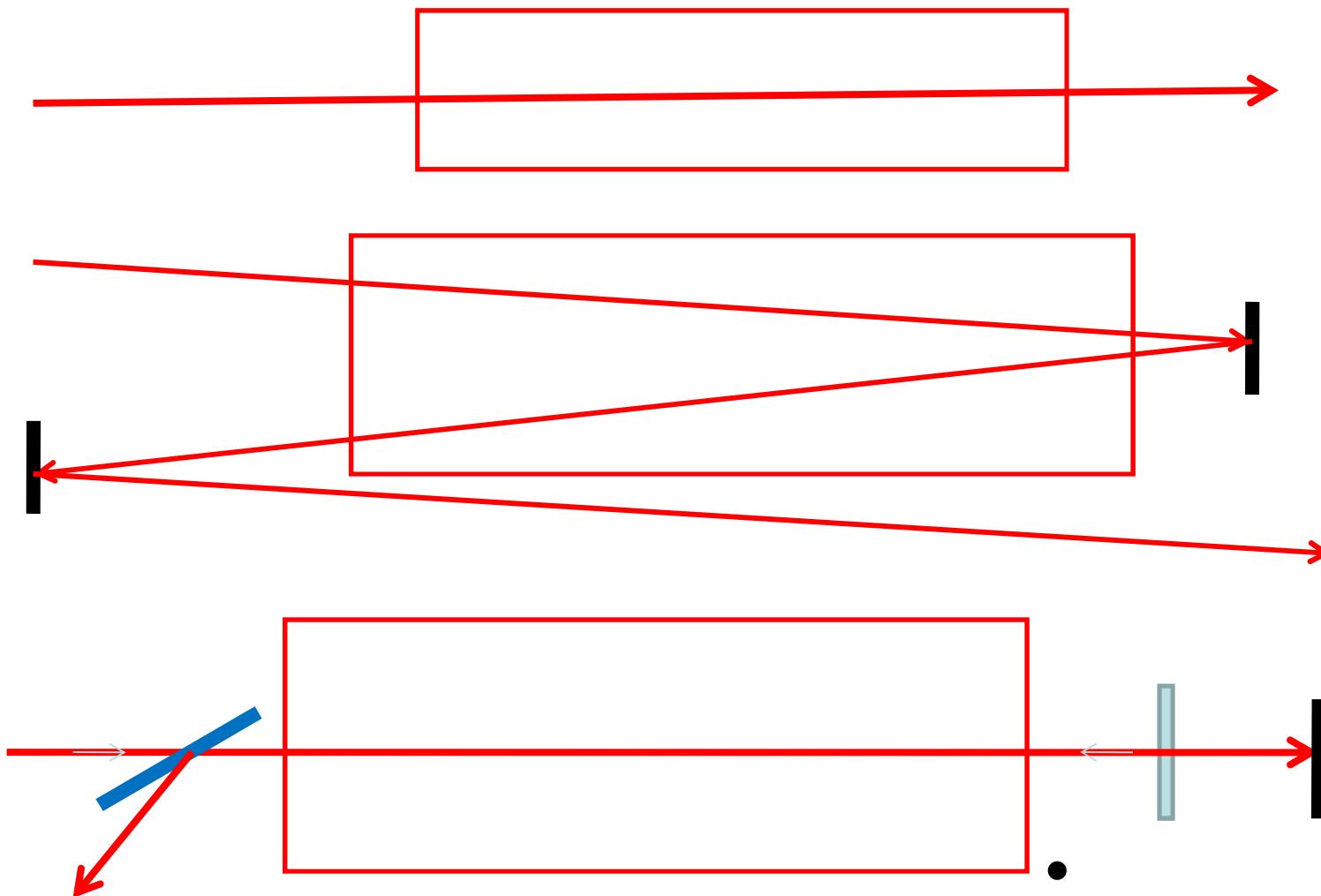


主振荡--功率放大器(MOPA)



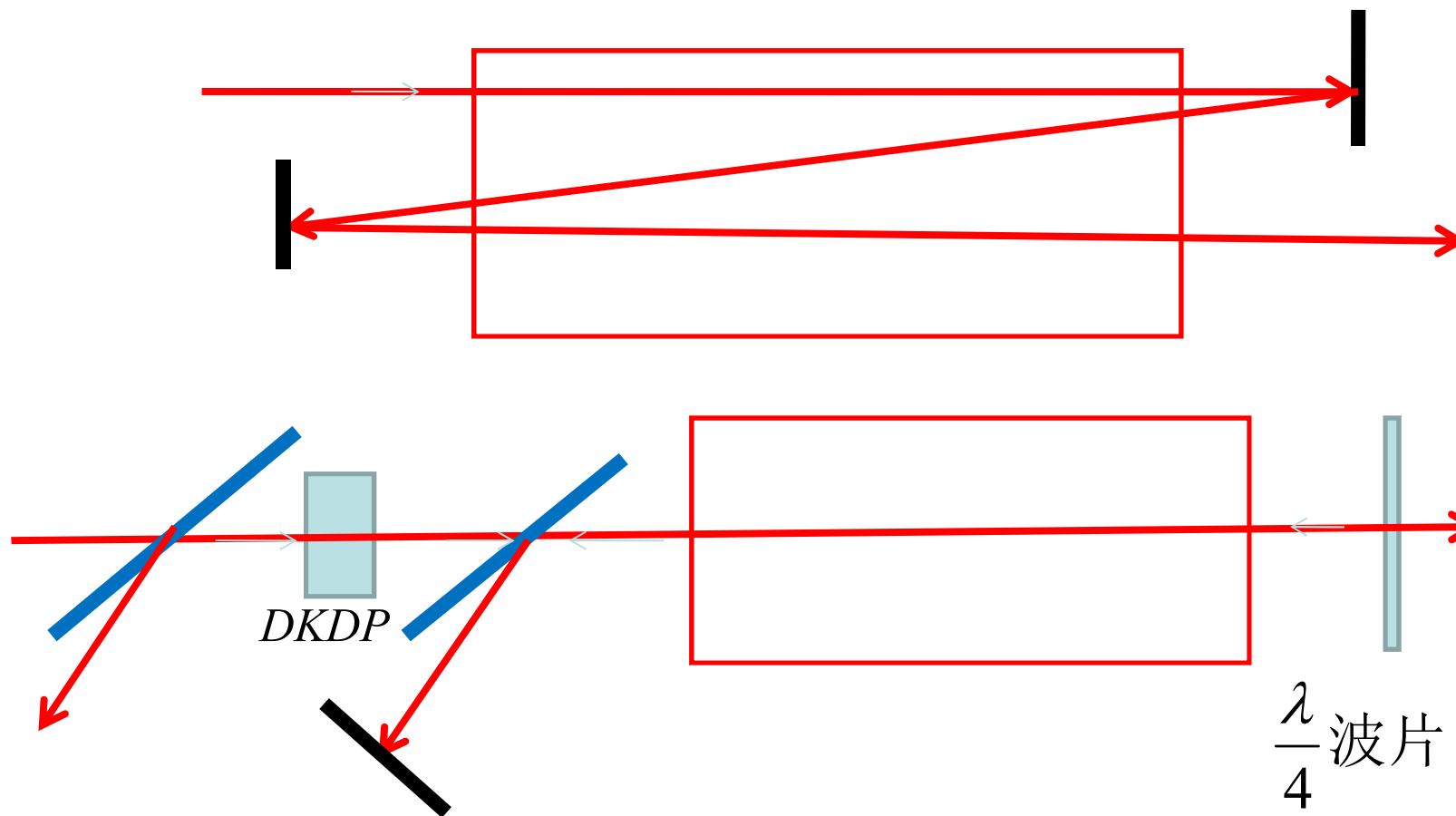
并接式激光放大器

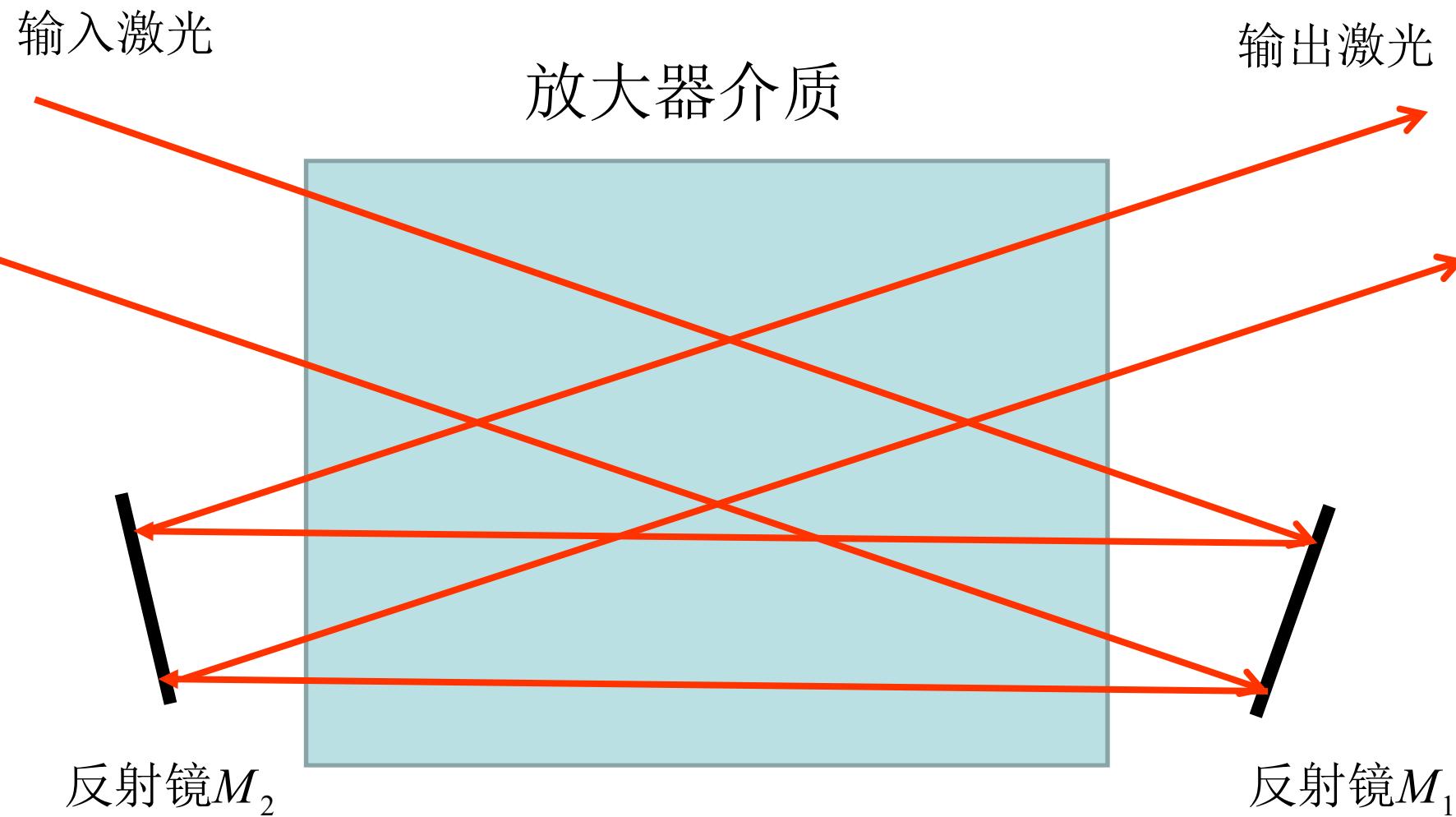
单程、双程放大器



$\lambda/4$

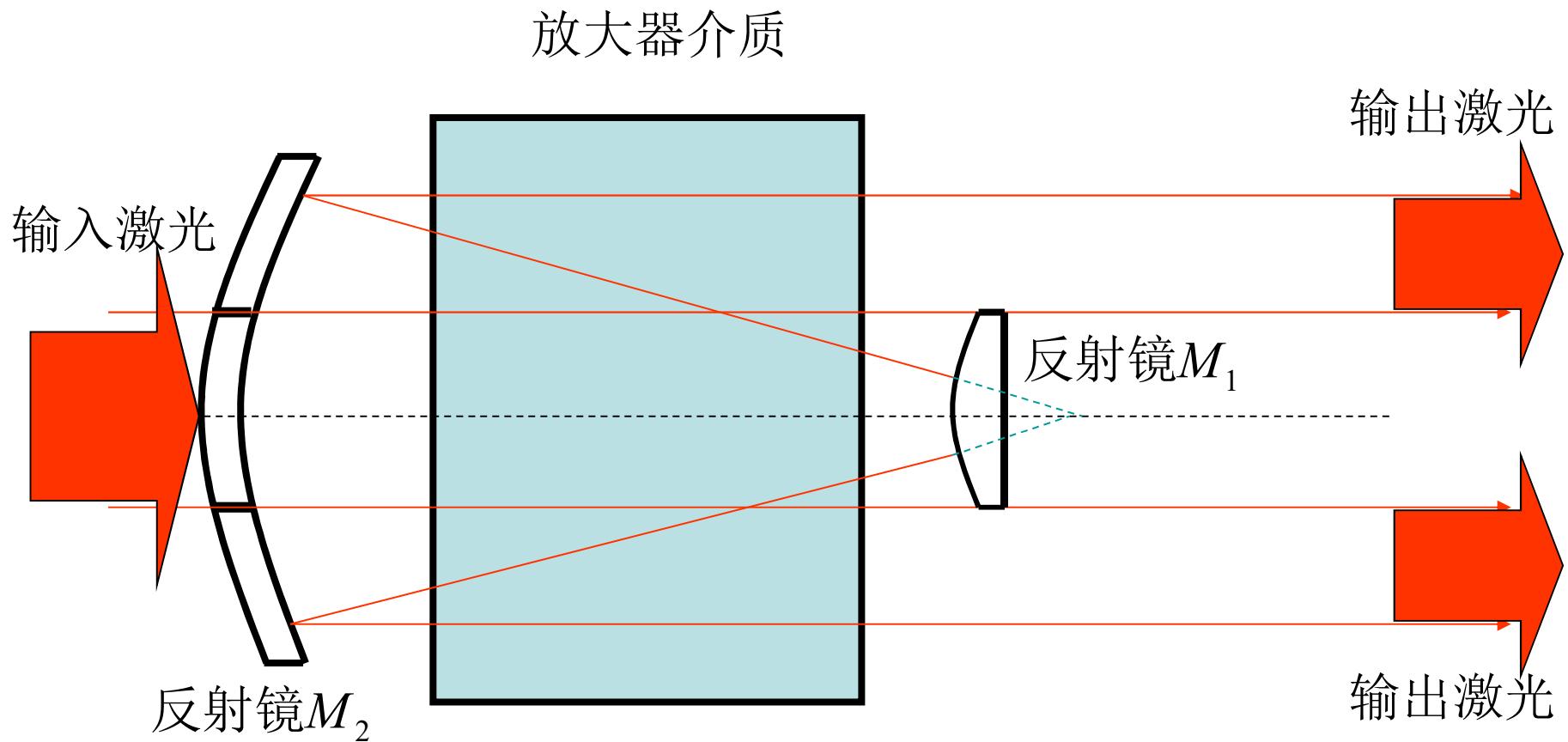
三程、四程放大器





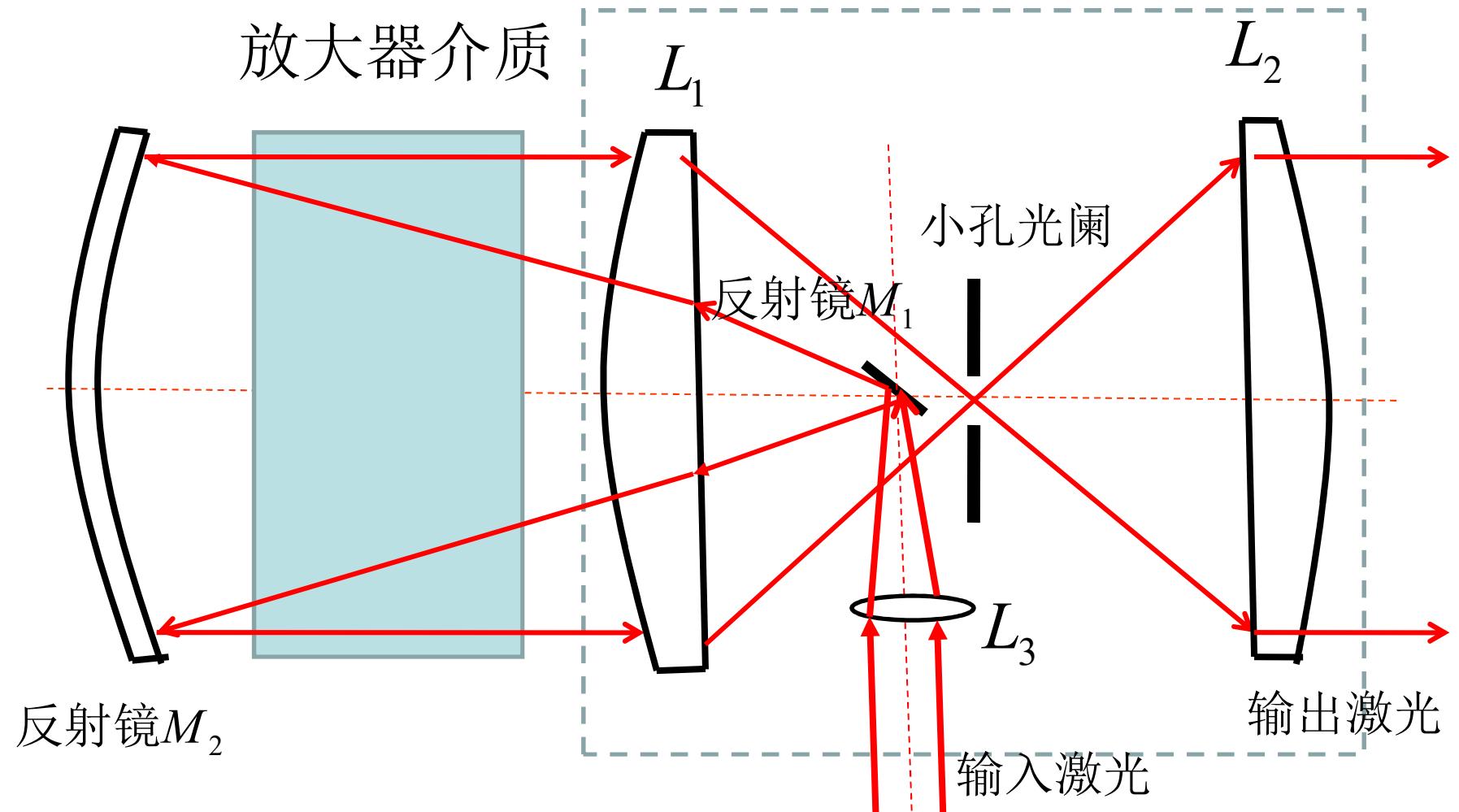
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激光三程离轴放大器



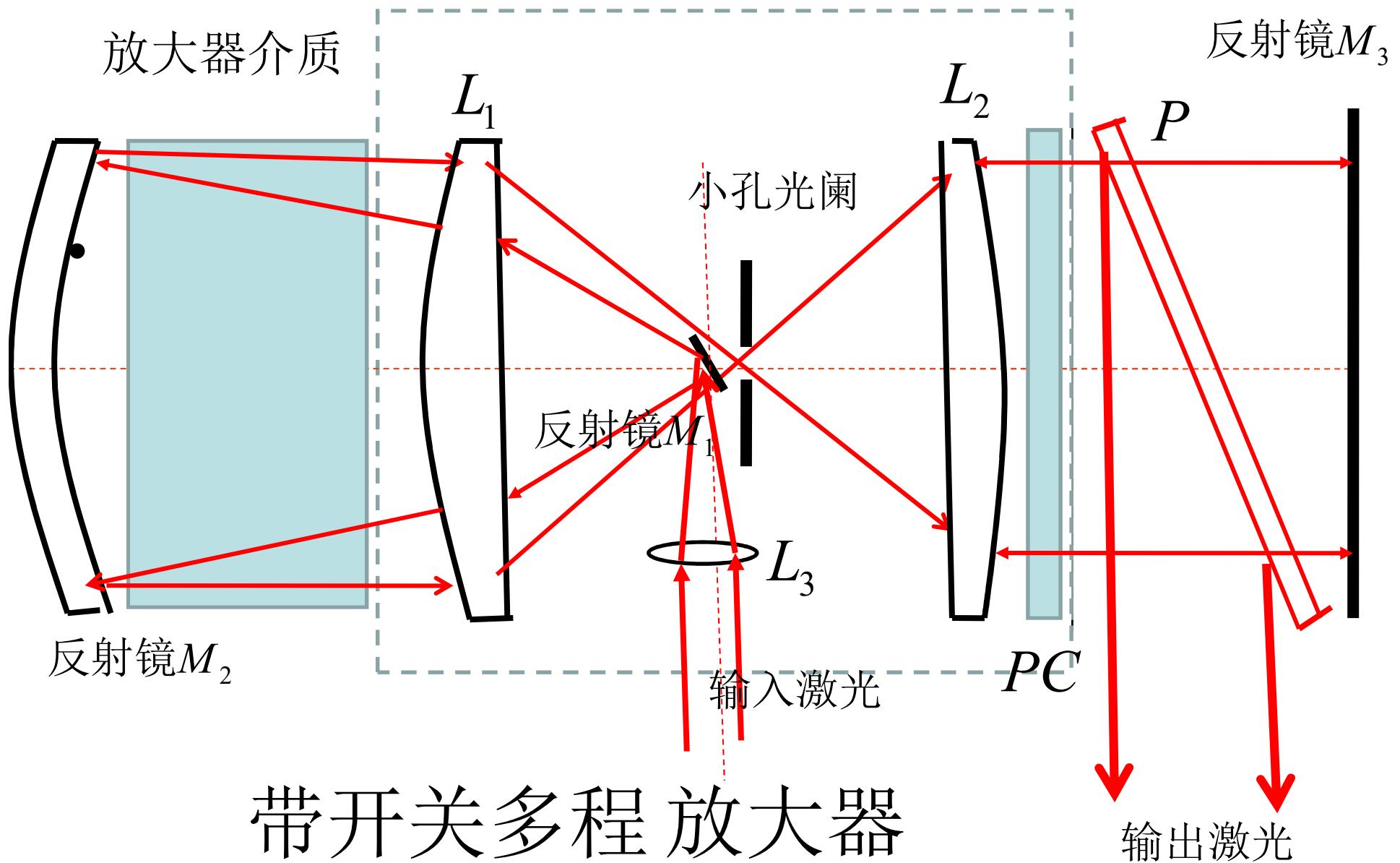
卡塞格林望远镜式激光三程放大器

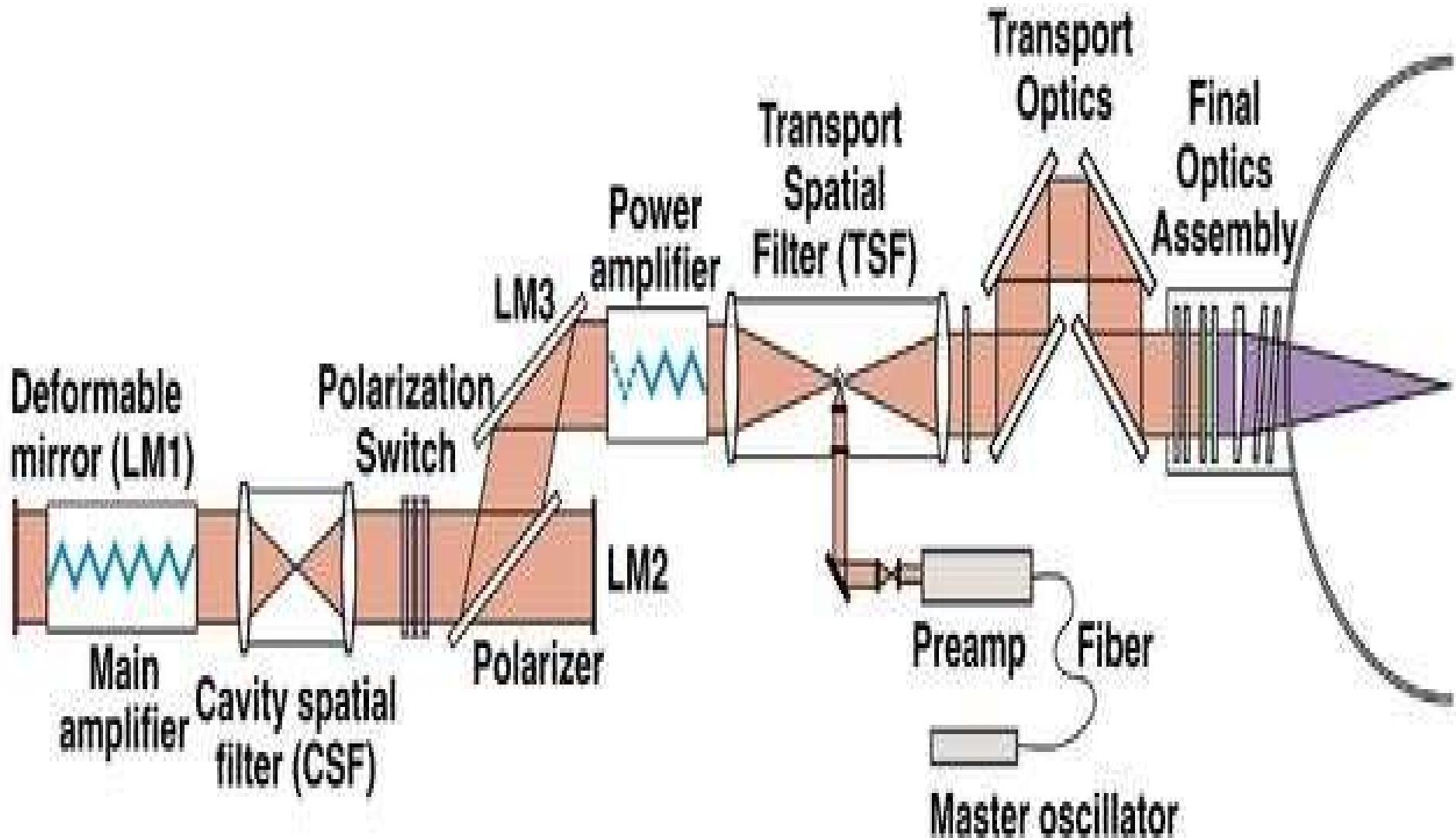
空间滤波器



同轴型无开关双程 放大器

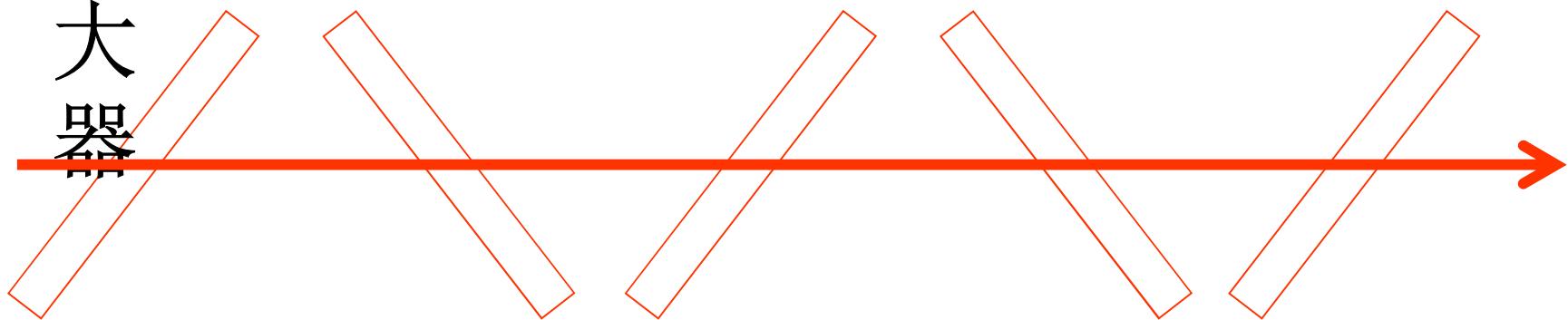
空间滤波器





片状放大器

片状
放大器



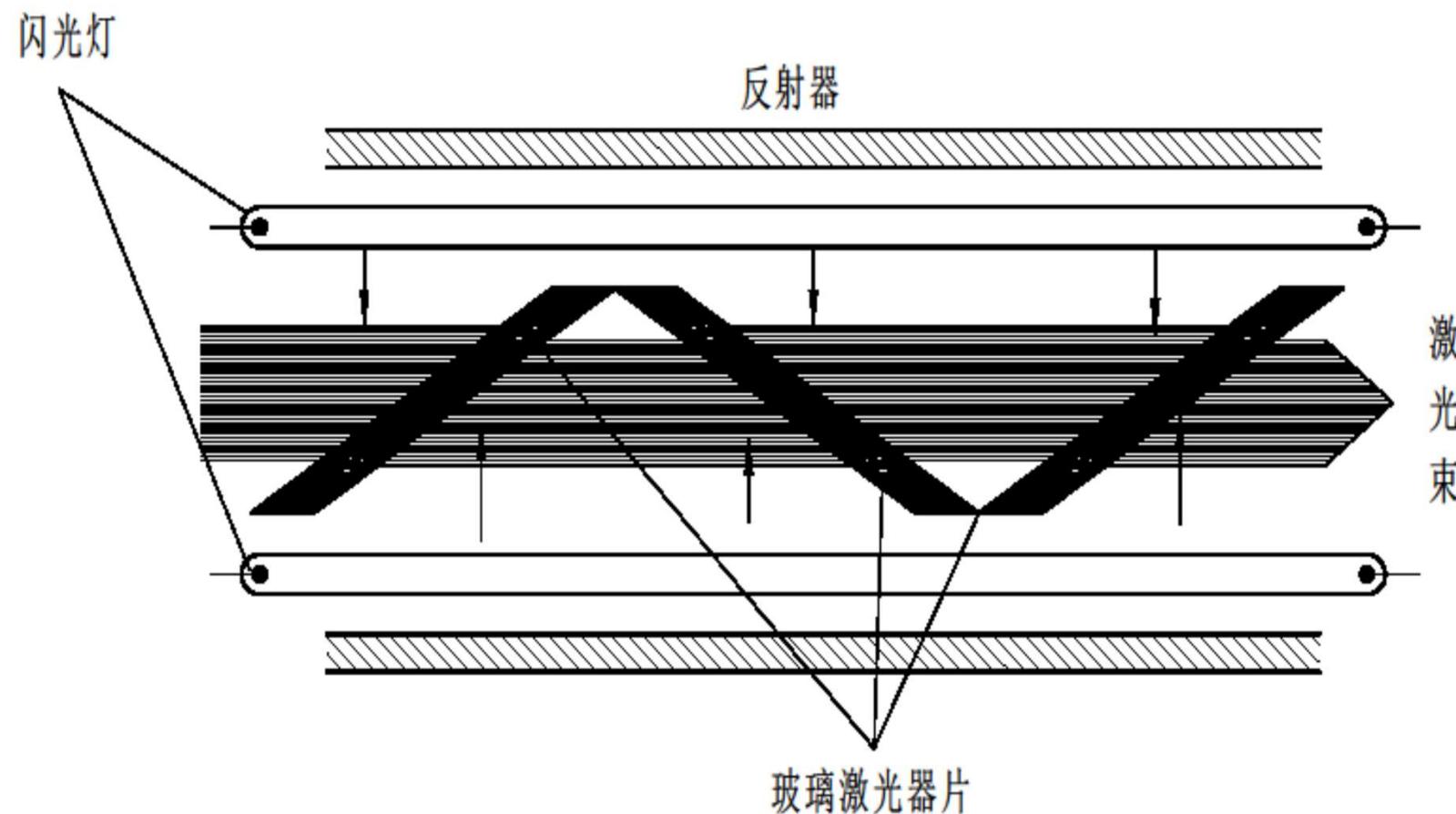
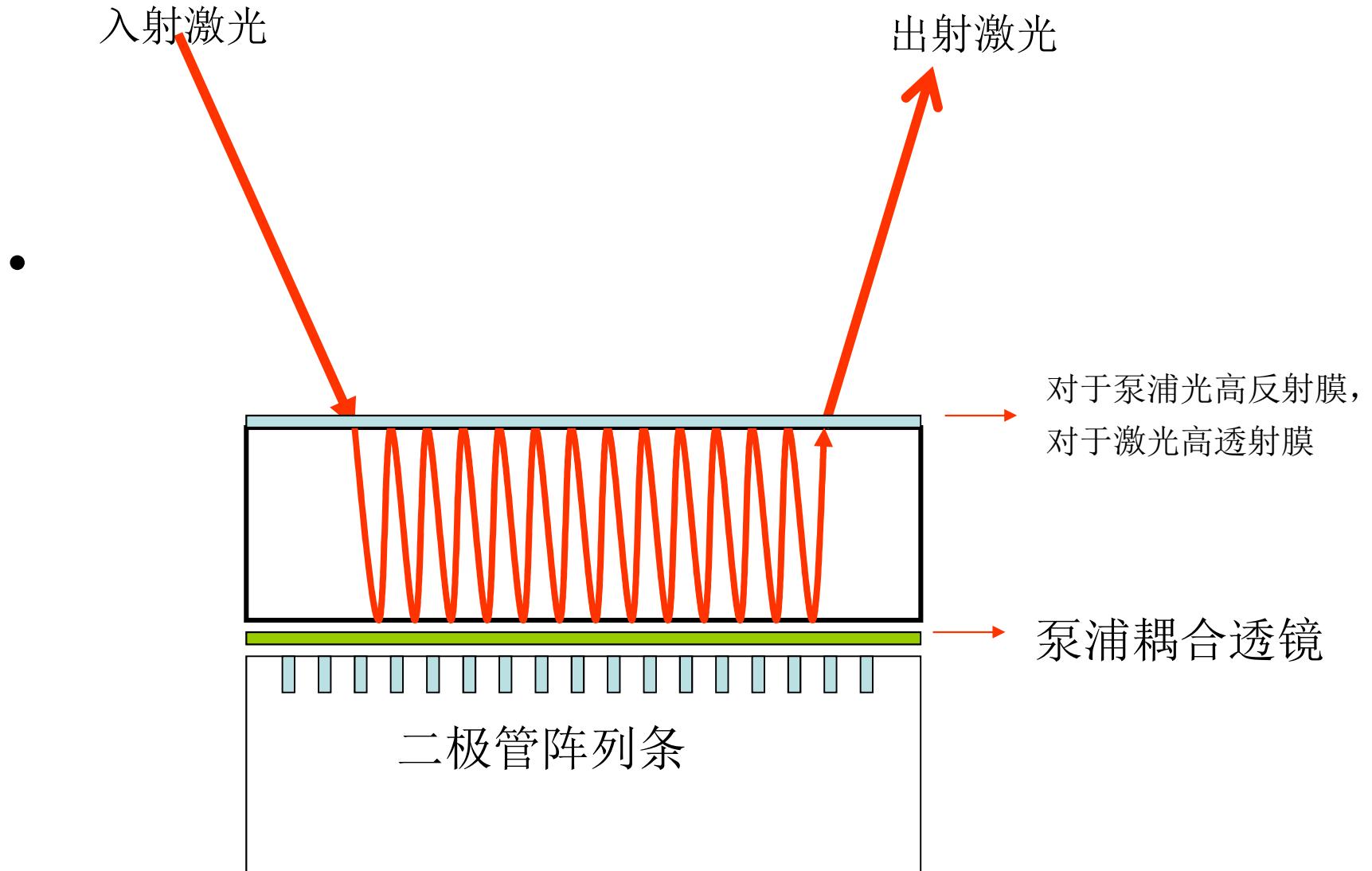
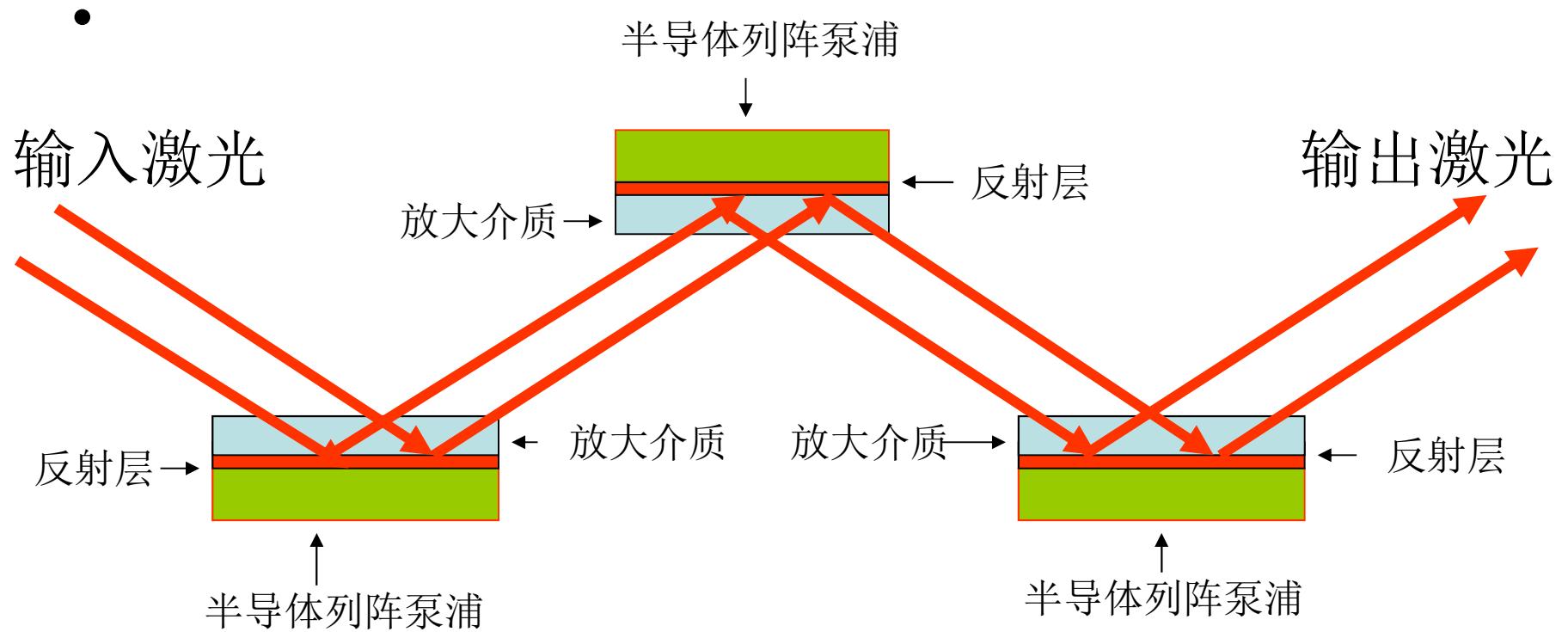


图7.8 面泵浦钕玻璃圆盘激光器结构



基于内反射的泵浦（紧凑折叠多程放大器）

N级串联系统，采用多片晶体薄片放大器



- 单脉冲选取后放大

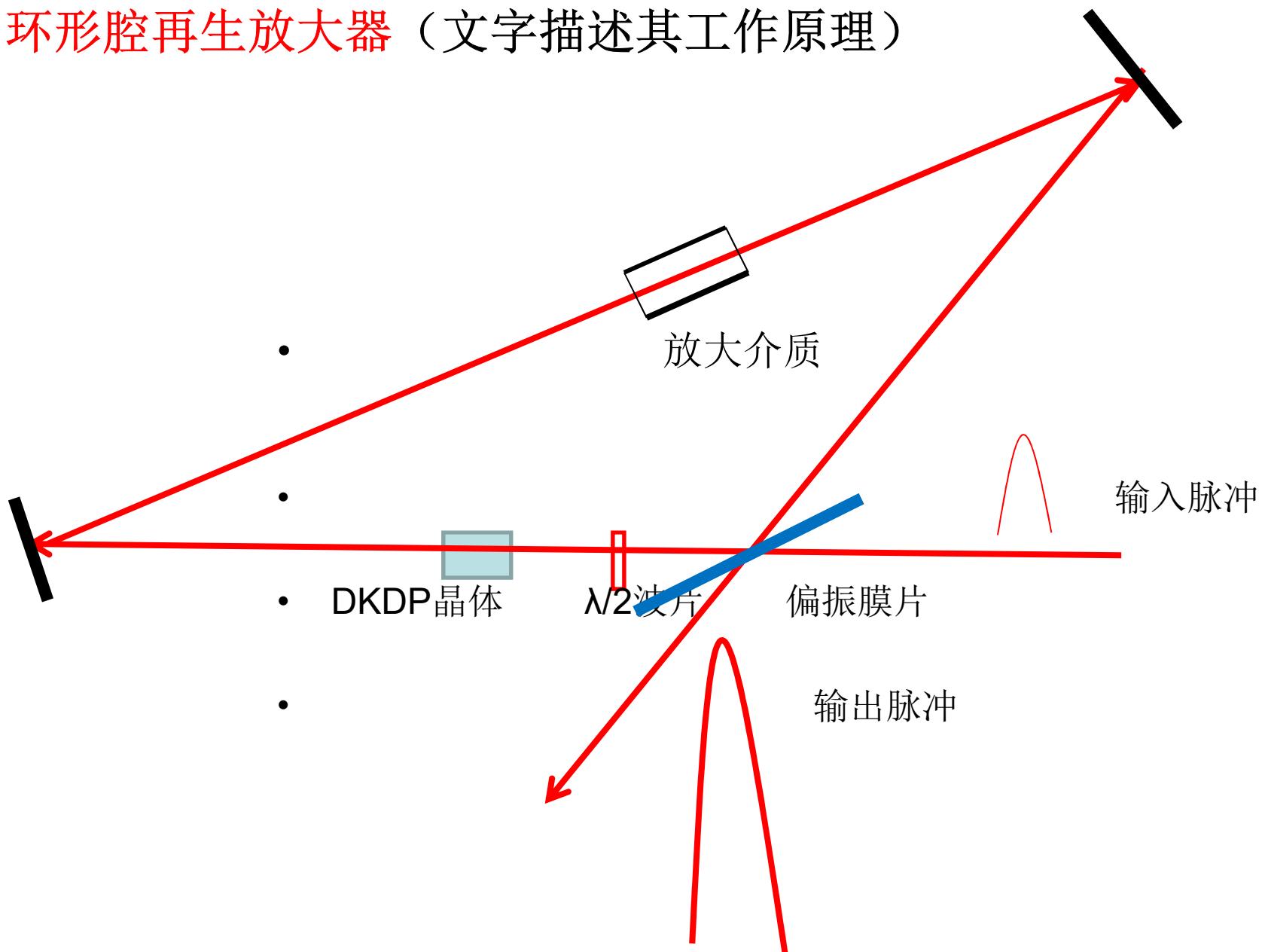
通常从锁模序列脉冲中选出一个脉冲作为种子脉冲进行放大后获得强脉冲激光

- 腔外脉冲压缩

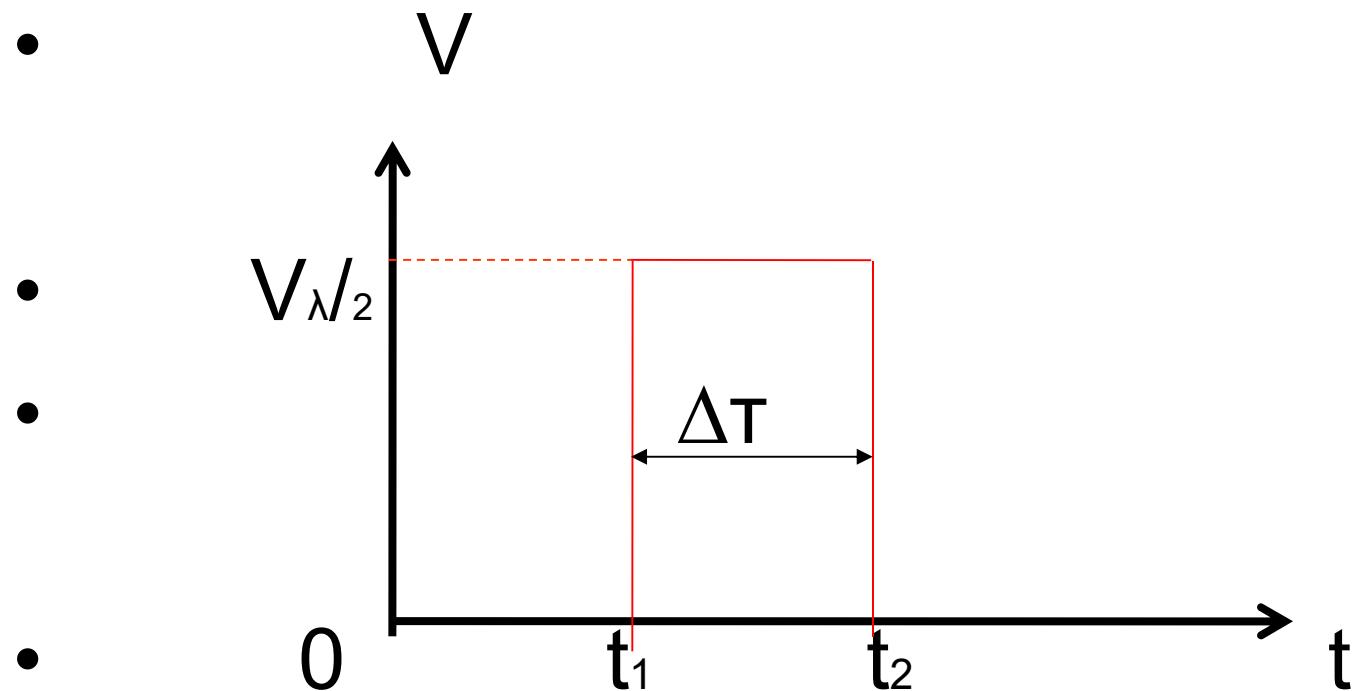
由自相位调制(SPM)产生的啁啾脉冲(Chirped pulse)通过具有一定的群速色散(GVD)的光学元件后可实现对光脉冲的展宽或压缩

再生放大器技术和啁啾脉冲放大技术

环形腔再生放大器（文字描述其工作原理）

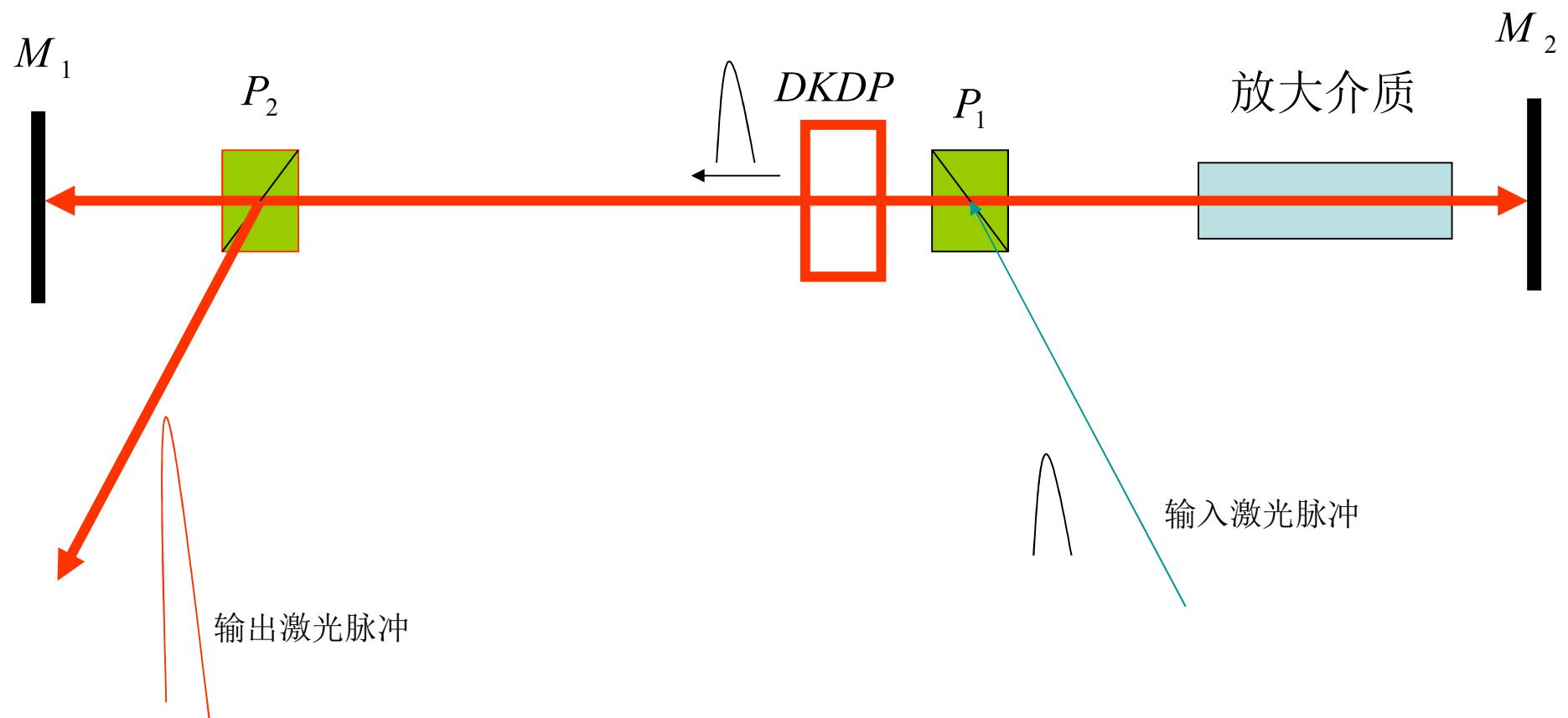


$$\Delta T = t_2 - t_1 = \frac{mL}{c}, .. I = I_0 e^{mG_0 L}$$

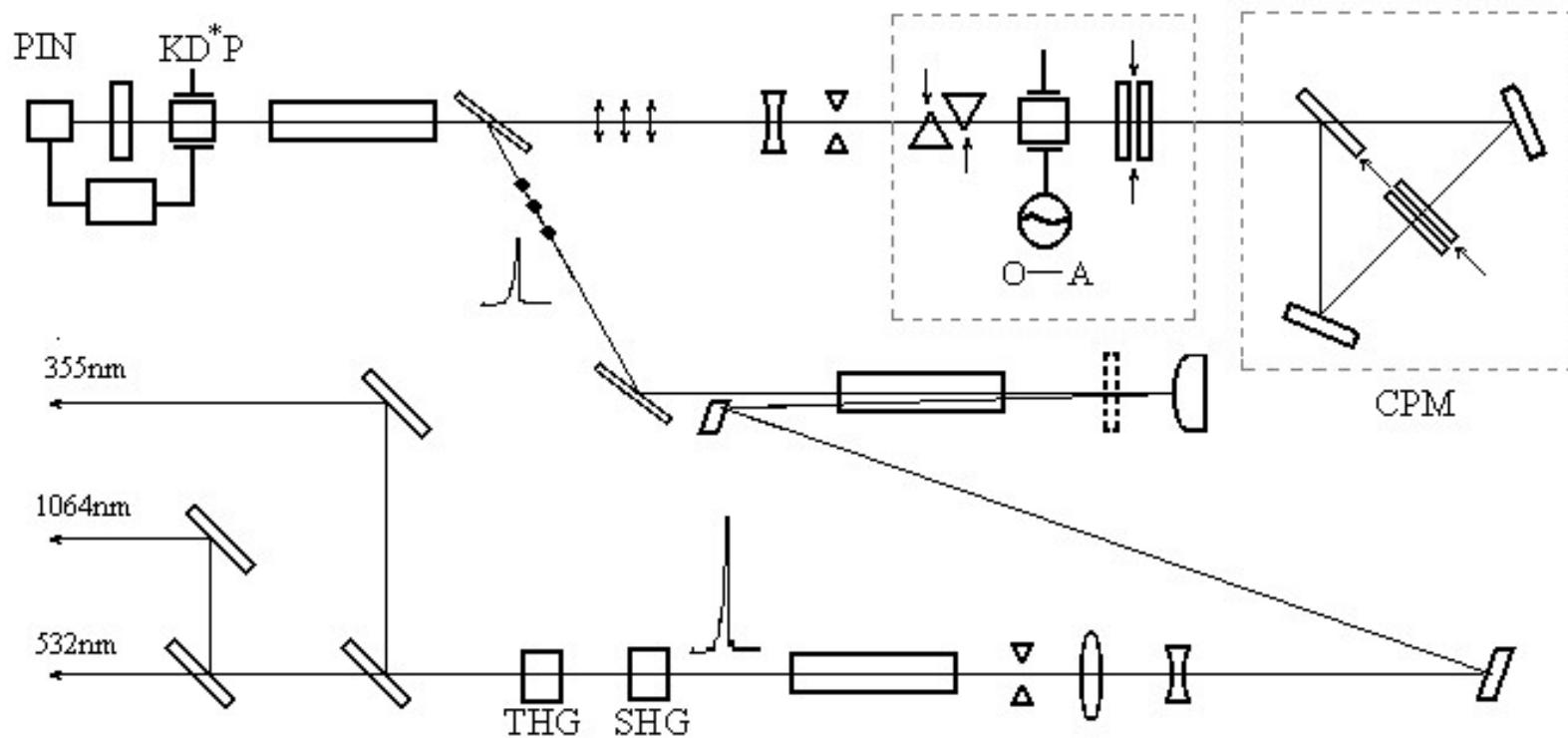


- 直腔式再生放大器（文字描述其工作原理）

$$P_1 \perp P_2$$



一种实际的多波长锁模脉冲皮秒激光器方案



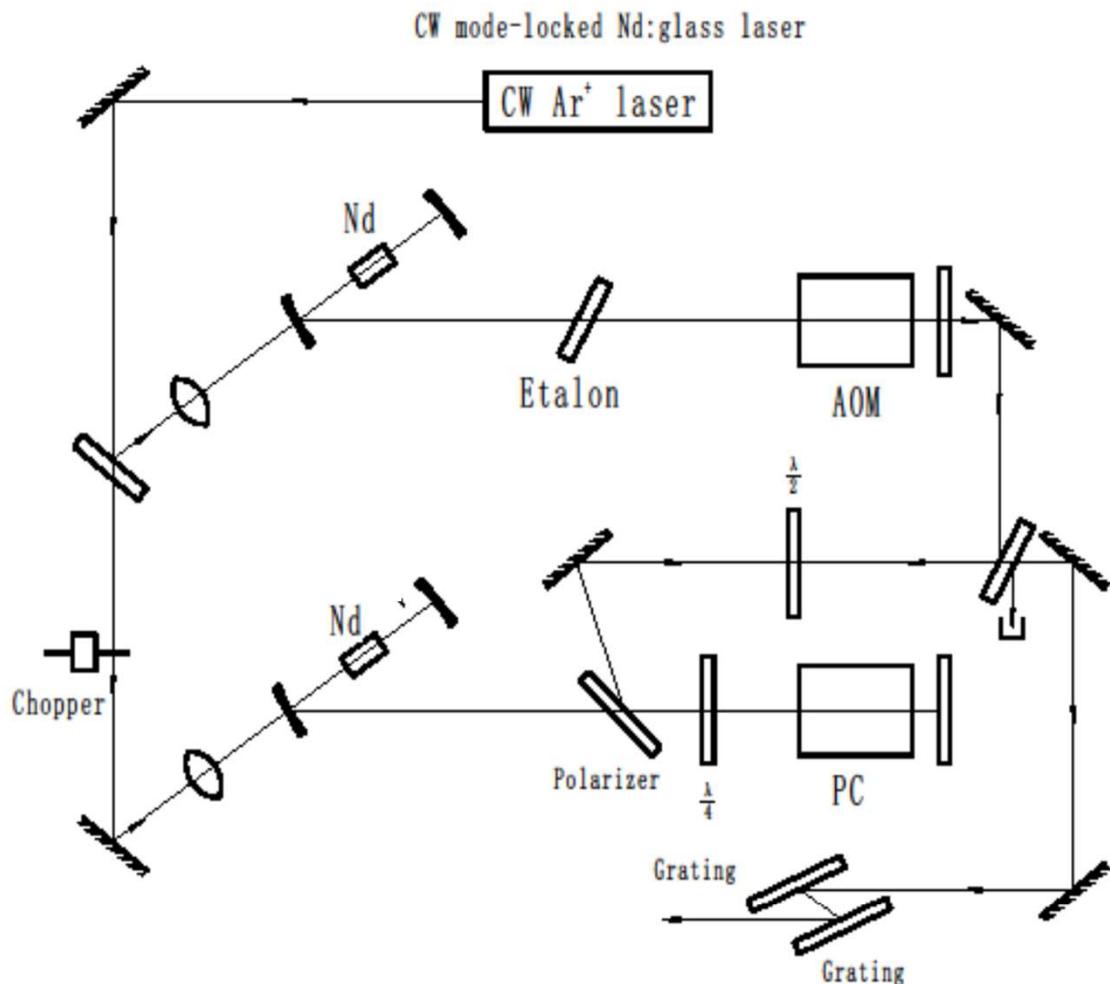
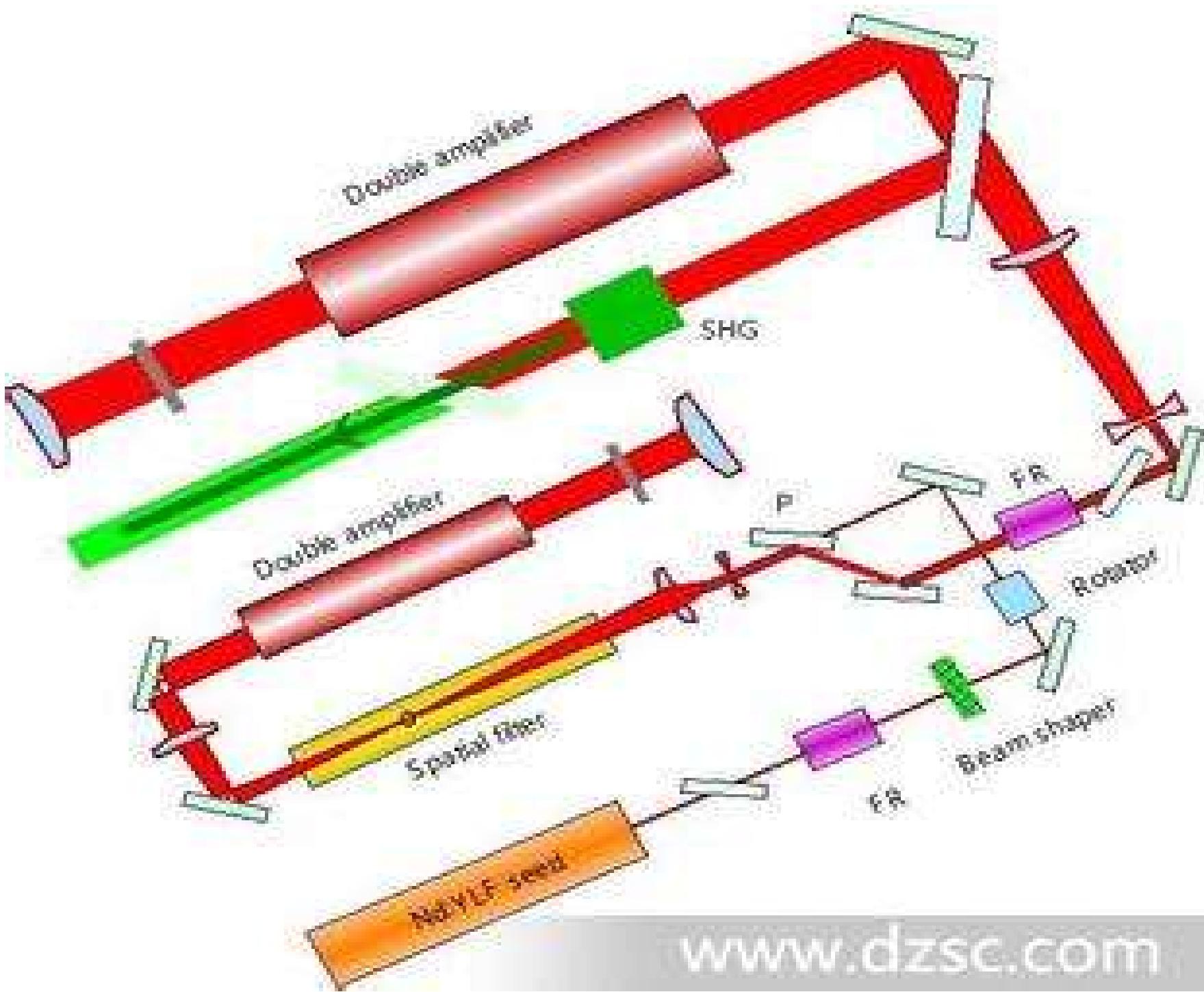
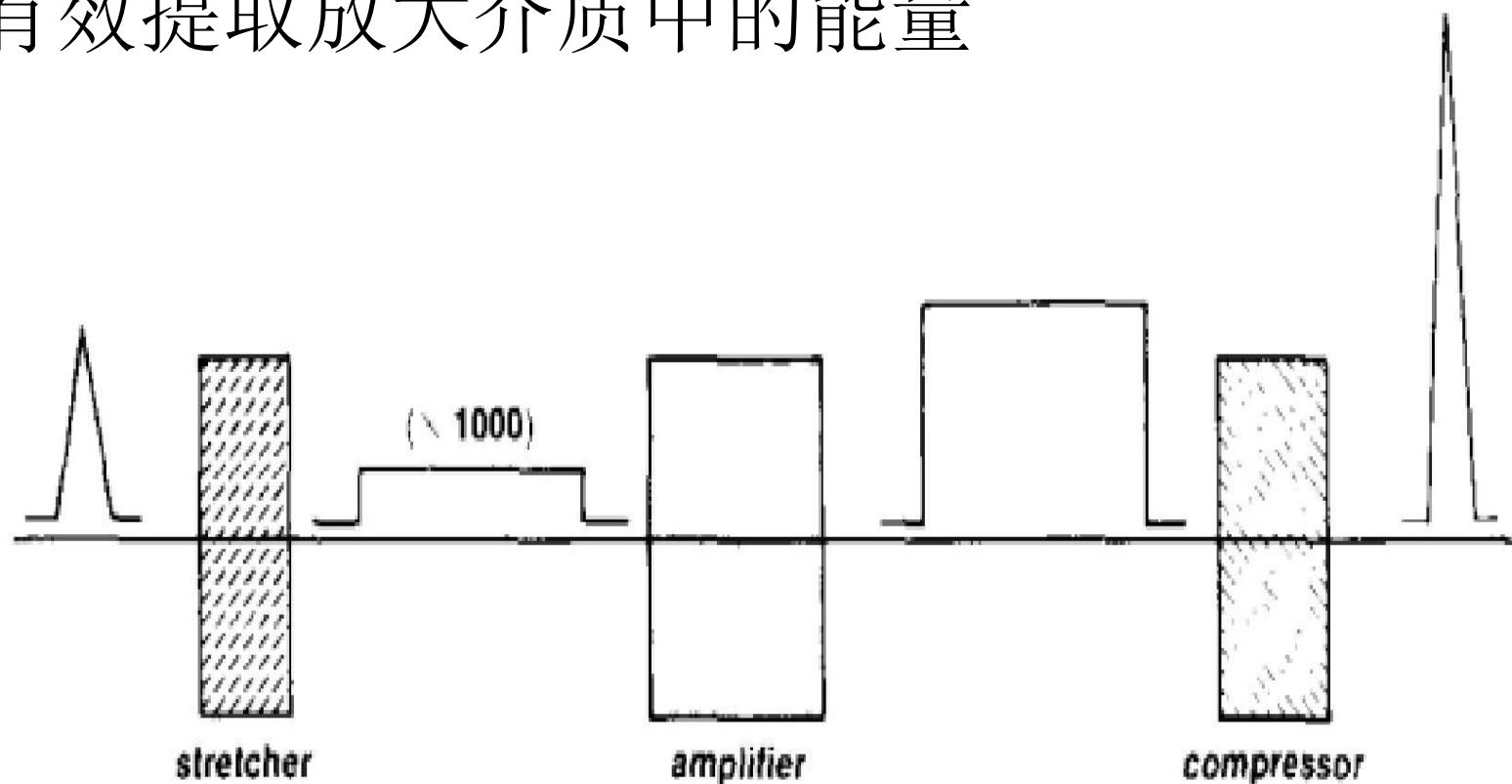


Fig. 7.11. System for generating ultrashort pulses from a neodymium glass laser system^[7,1]. The CW Ar⁺ laser pumps a Nd:phosphate glass laser that is mode-locked with an acousto-optic modulator (AOM). The mode-locked pulses are further amplified in a regenerative amplifier where they may make at least 60 round trips before being switched out of the cavity with the Pockels cells (PC) (an electro-optic crystal that can switch the polarization state of the beam). (Courtesy of Professor Chi H. Lee.)



- 咨啾脉冲放大技术**CPA**技术
- 避免光学元件被破坏;
- 有效提取放大介质中的能量



CPA

CPA : Chirped Pulse Amplifier

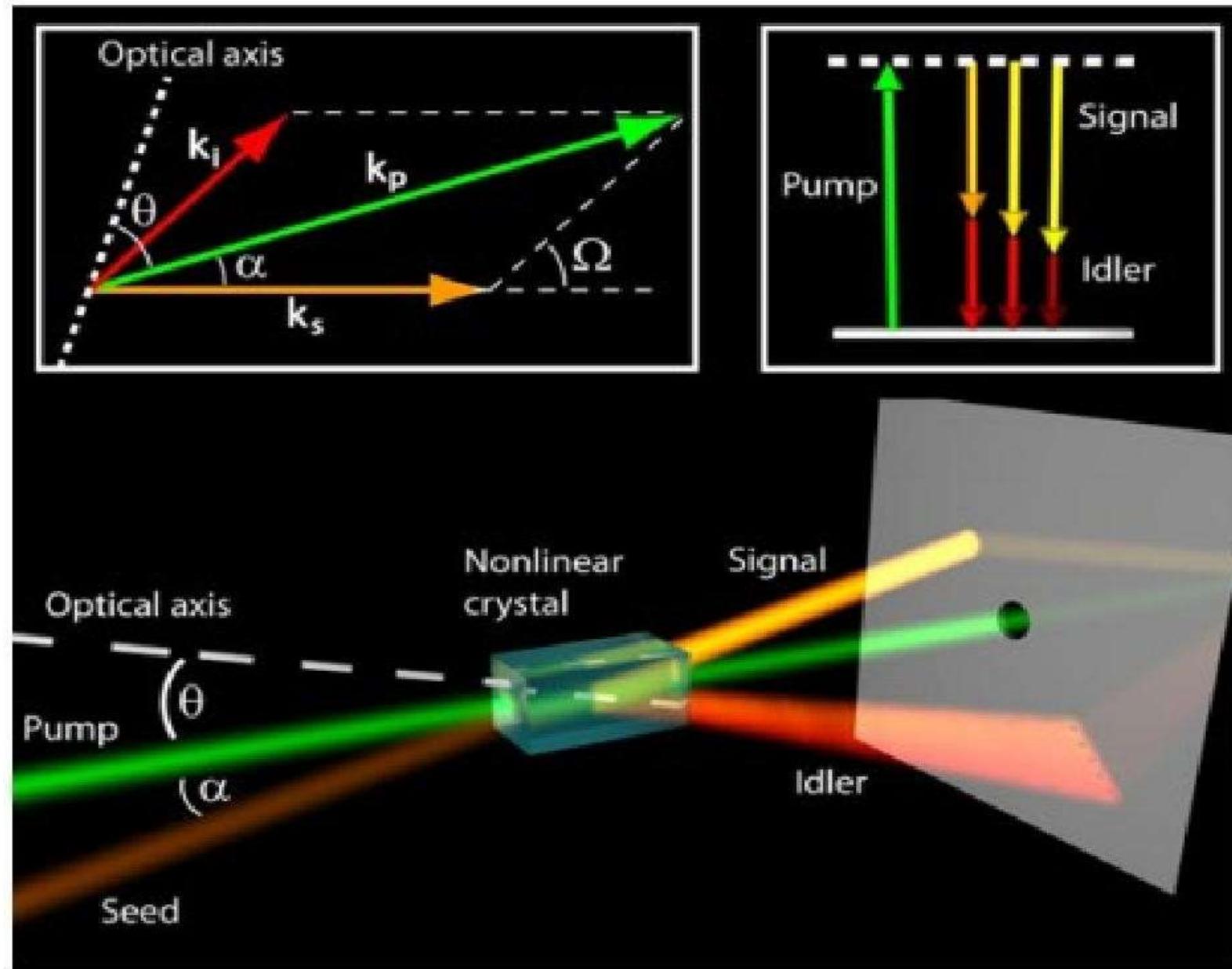
stretcher

Amplifier

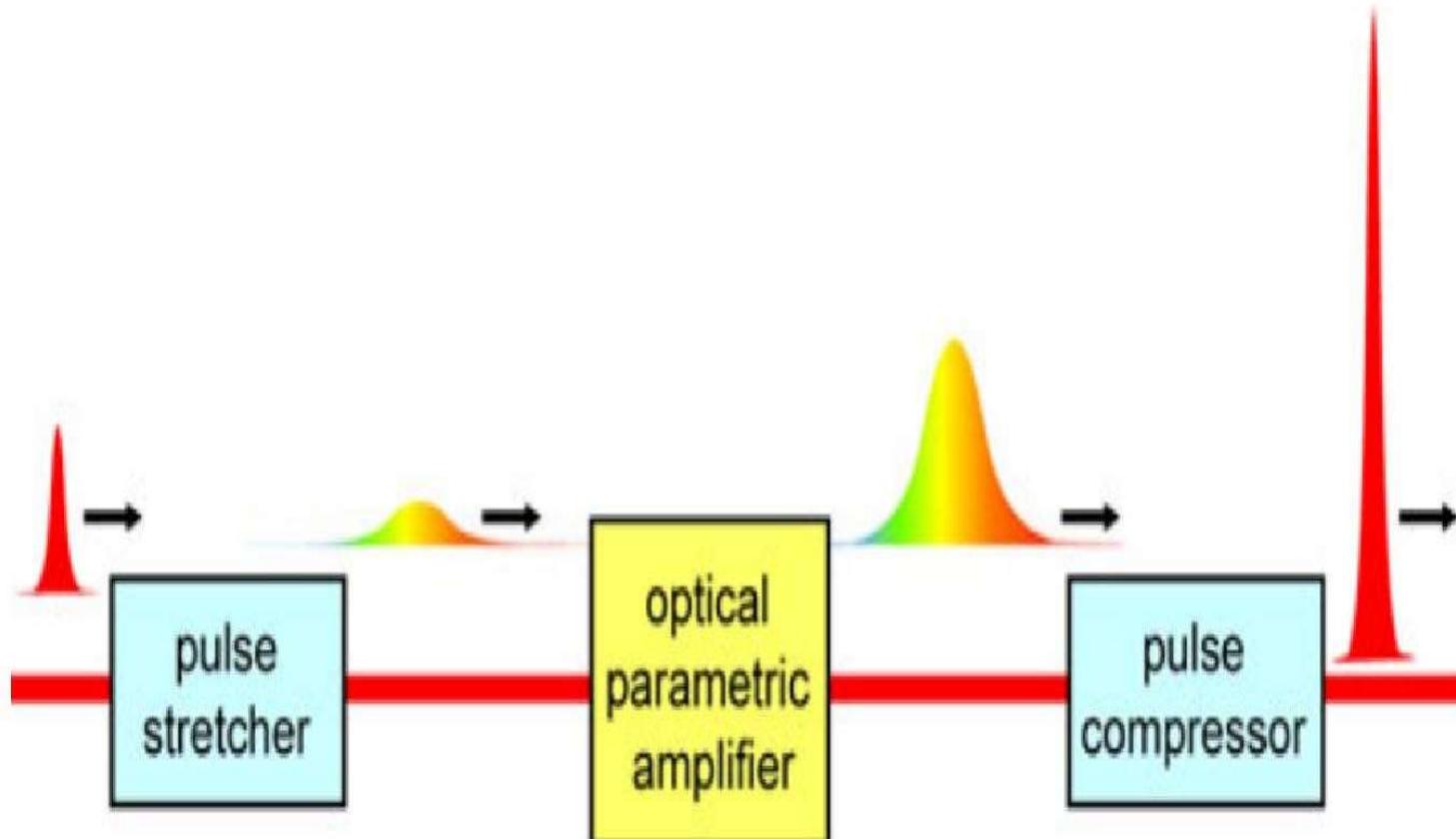
Compressor



• OPA技术

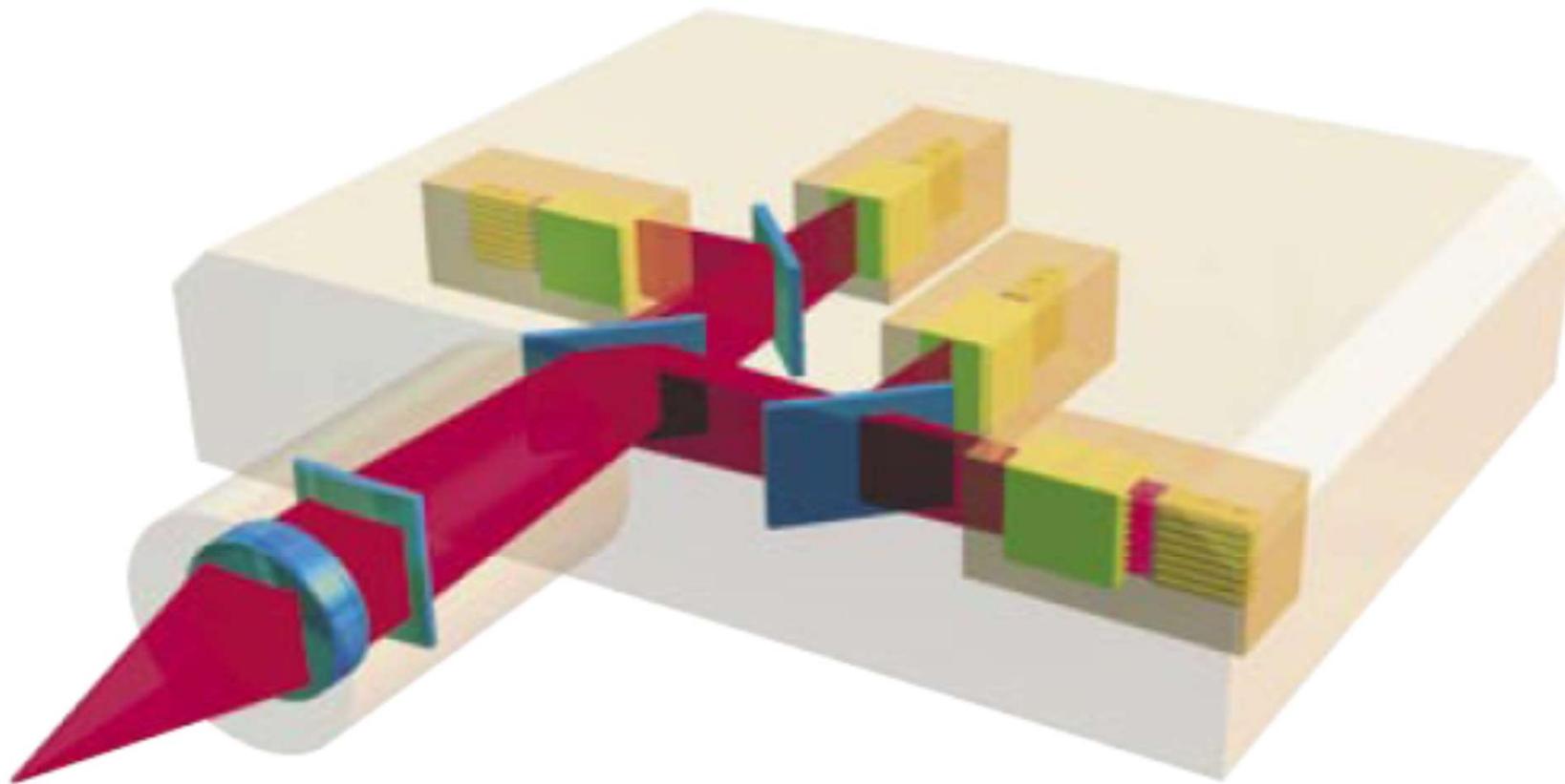


OPCPA技术

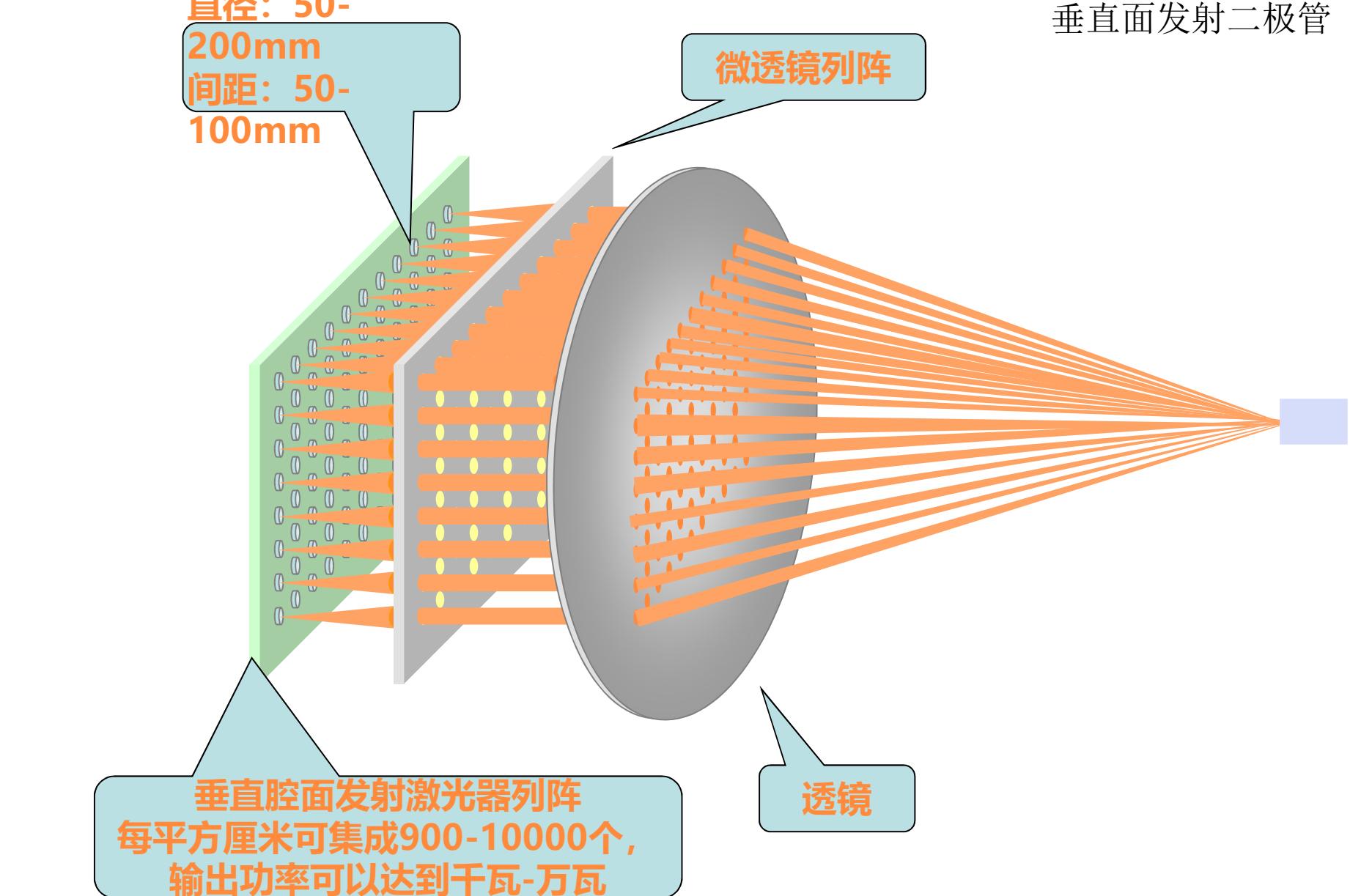


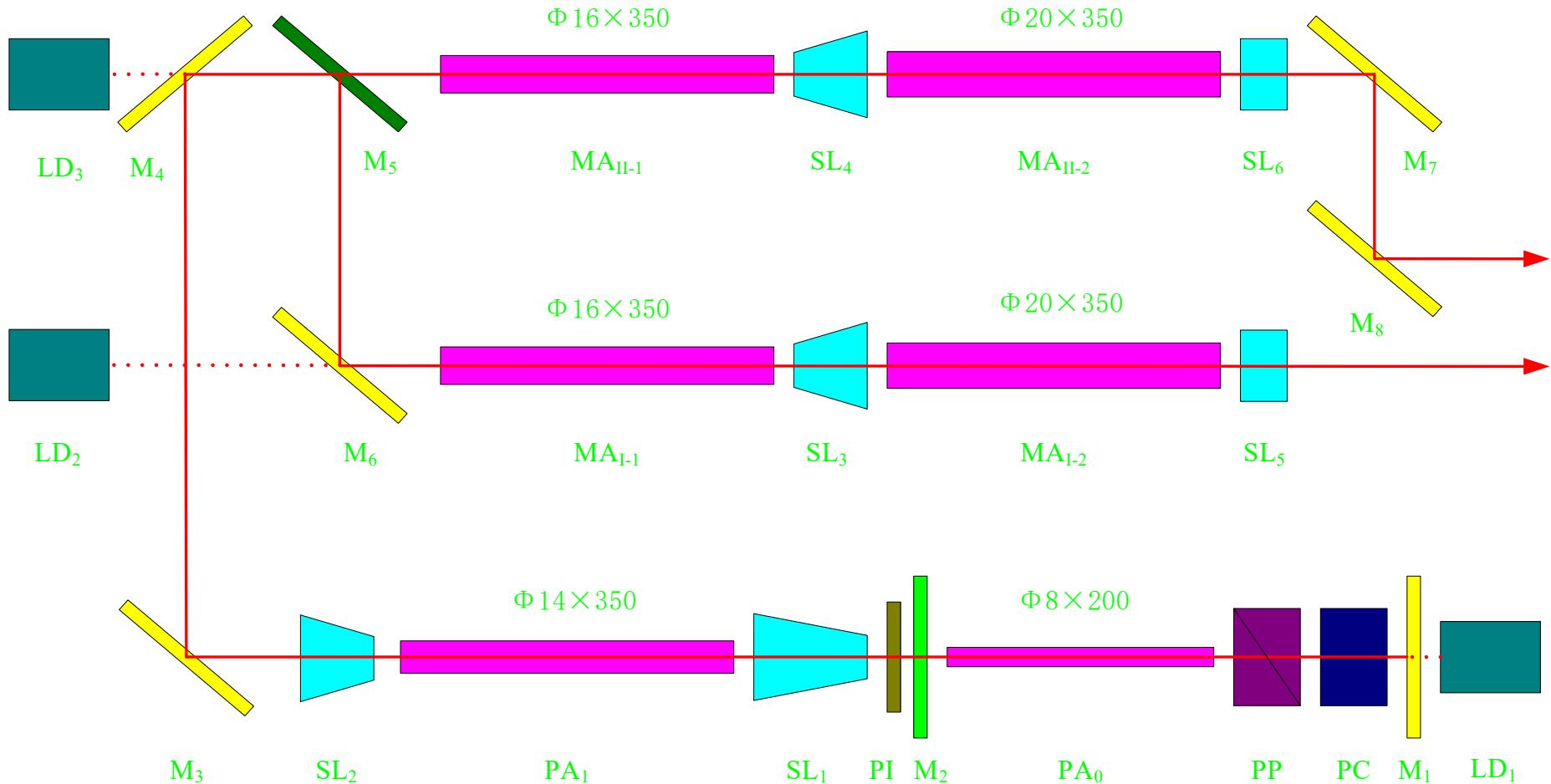
多路激光合束问题

(下图为板条或片光光束的合束)



直径: 50-
200mm
间距: 50-
100mm





LD₁~LD₃: 半导体激光器

M₁: 0°全反射镜

M₂: 输出镜

M₃,M₄,M₆,M₇,M₈: 45°全反射镜

M₅: 45°半透半反射镜

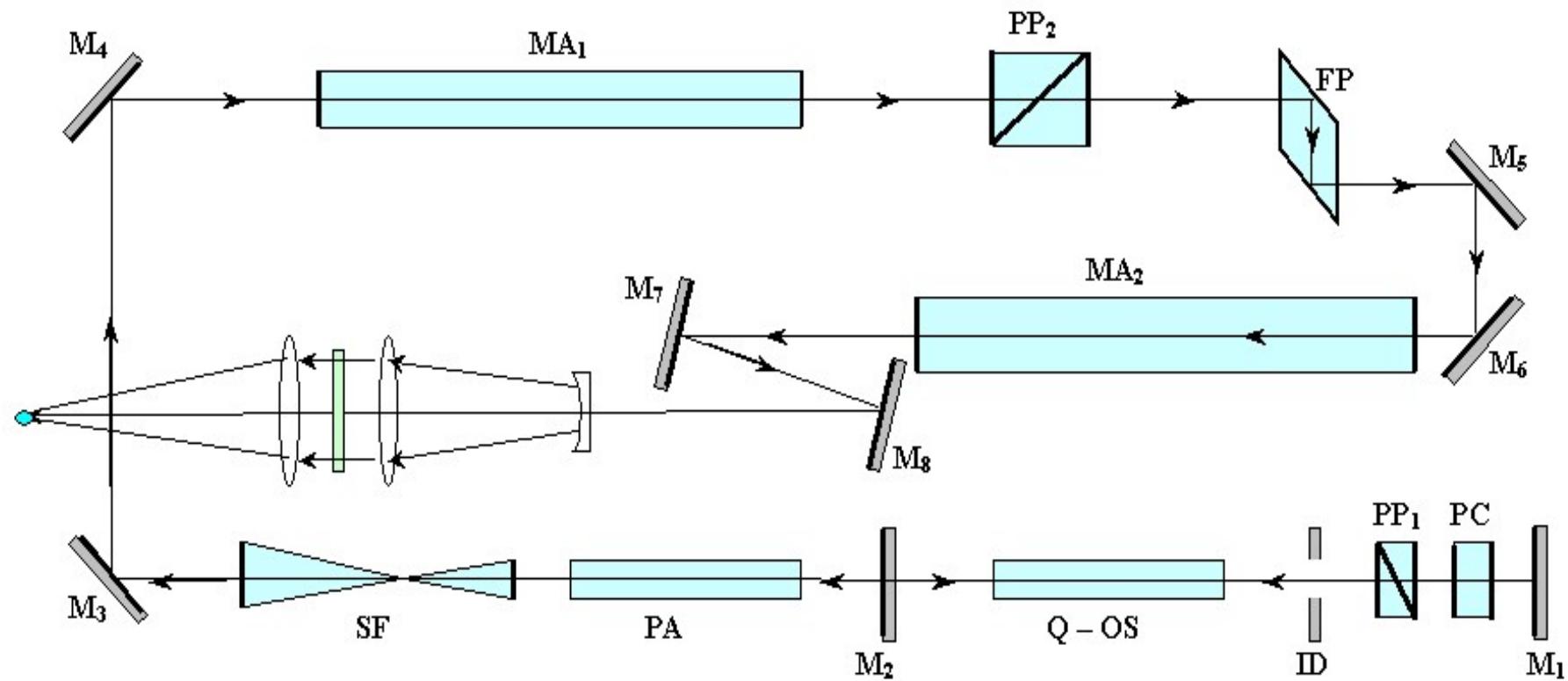
PC: KD*P电光晶体

PP: 偏振镜

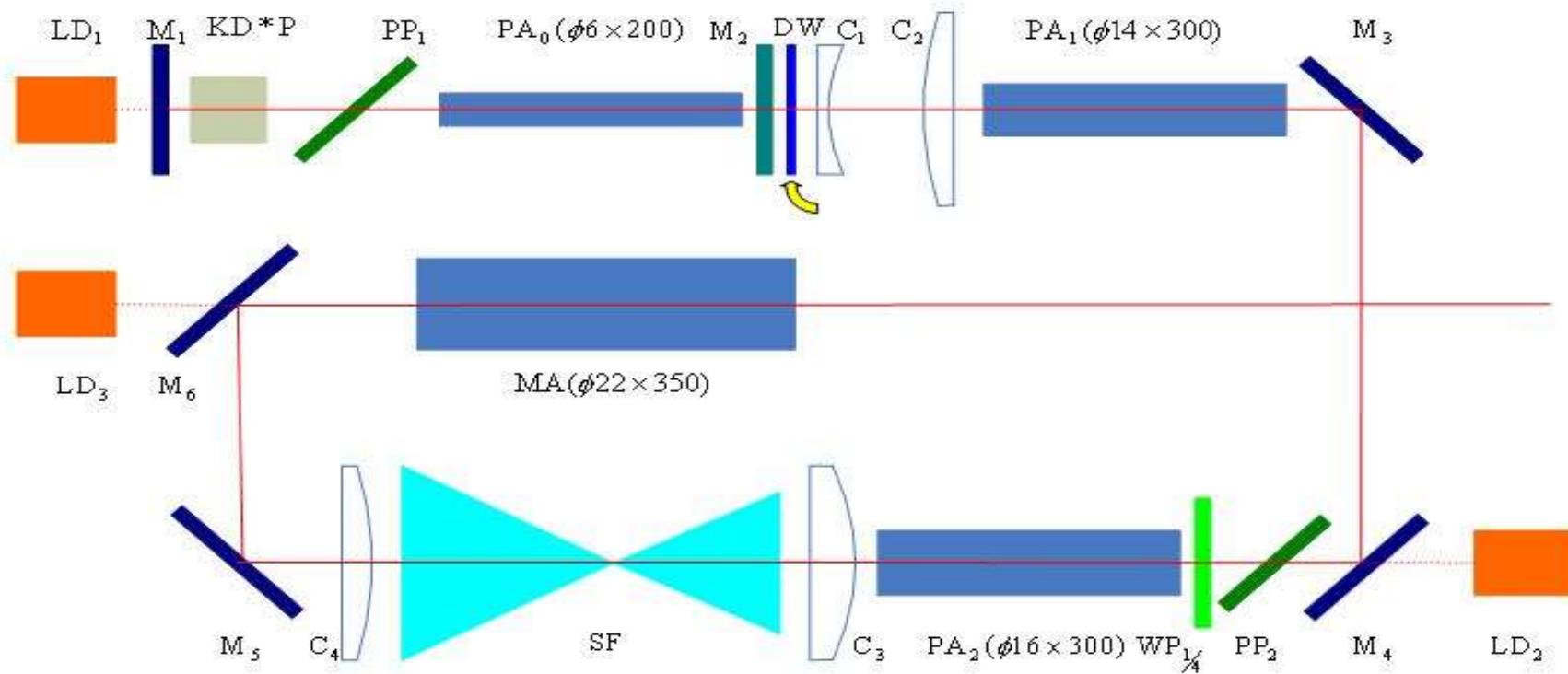
PI: 隔离器

SL₁~SL₆: 扩束镜

PA_m, MA_{m-n}: 钕玻璃棒



脉宽 ≤ 25 ns
 能量 ≥ 25 J
 峰值功率 ≥ 1 GW



LD₁ ~ LD₃: 二极管激光光源

M₁: 1054nm90°全反; M₃ ~ M₆: 1054nm45°全反

KD * P: 光电调Q晶体

PP₁, PP₂: 偏振片

PA₀ ~ PA₂, MA: N₂₁钕玻璃棒

M₂: 半板玻璃

DW: Cr⁴⁺: YAG染料晶片

WP_{1/4}: 1/4波片

SF: 空间滤波器

C₁ ~ C₄: 凸(凹)透镜

第三节 激光放大器设计中应考虑的方面

- 1、放大器工作物质光谱匹配；
- 2、放大器工作物质端面反馈的消除；
- 3、级间去耦（级间隔离）；
- 4、级间孔径匹配及空间滤波；
- 5、各级泵浦时间延迟的选定；
- 6、泵浦不均匀性的消除或补偿；
- 7、自聚焦效应的降低（B积分的选择）。

1、放大器工作物质光谱匹配(工作物质选择)

待放大的激光束的频率或波长一定要落在放大器工作物质增益线宽范围内（最好是谱线中心附近）。

振荡器工作物质可以和放大器工作物质不同，只要光谱匹配即可。

放大器工作物质激活粒子的浓度要合适（在避免“浓度淬灭”的情况下，要尽可能高）。

选择合适的几何尺寸放大器工作物质：1、使得激光能量和功率低于工作物质的破坏阈值；2、有效提取放大介质中贮存的能量。



HPLD——三类类型

目前，国内外的高(峰值)功率激光驱动器(HPLD)，按输出激光脉冲宽度，大致上可以分为以下三类：



【纳秒量级高能激光驱动器】

单脉冲宽度为数百ps~数ns，脉冲能量高达百万焦耳以上，如Nova、NIF等。



【皮秒量级高能拍瓦(PW)激光驱动器】

单脉冲宽度为数百fs~数ps，脉冲能量为数百焦耳，如Nova-PW、Gekko XII装置的第13路等。



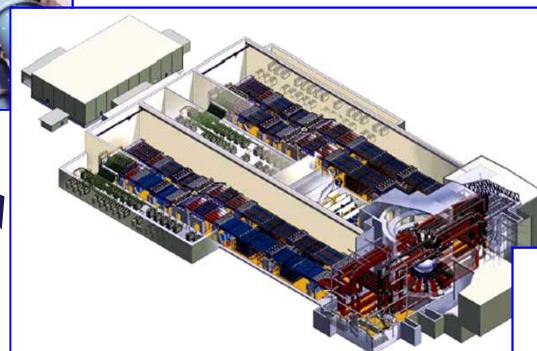
【飞秒量级拍瓦激光驱动器】

单脉冲宽度为数十fs~100fs，脉冲能量为数焦耳以上，如LLNL的JanUSP装置、中国Silex-I装置等。

HPLD——三代技术



【第一代】以Nova装置为代表，主要技术特征：圆光束，单口径，MOPA技术路线，分离式器件，较低通量、较低效率。

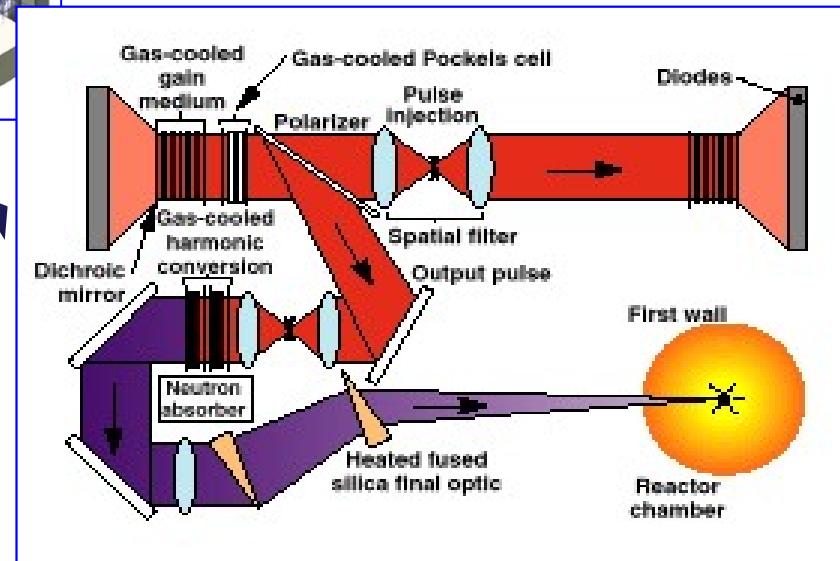


【第二代】以NIF为代表，主要技术特征为：方形光束，组合口径，多程放大技术路线，模块化结构，较高通量、较高效率。

第一代已成为历史；

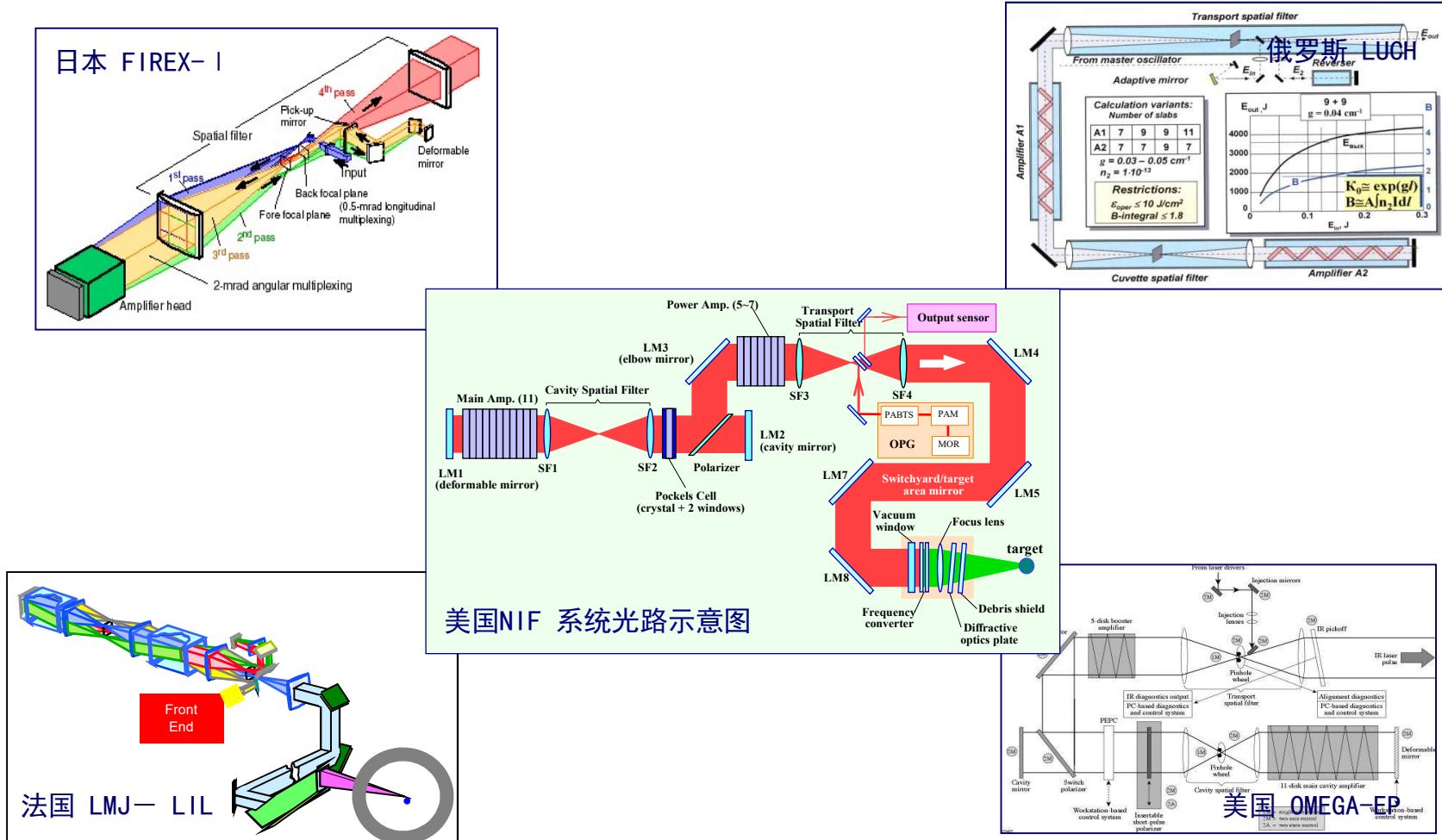
第二代已欣欣向荣、势不可挡；

第三代已成为哇哇待哺的婴儿！



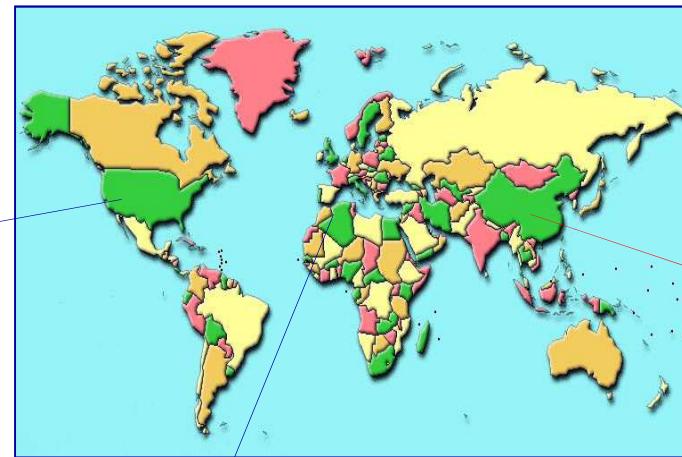
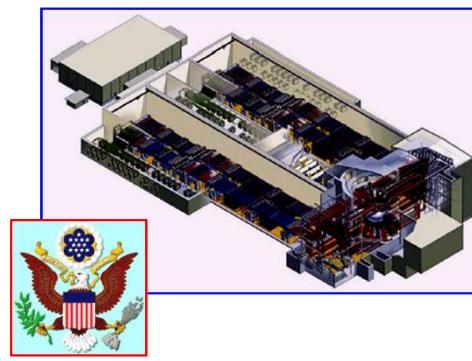
【第三代】以Helios为代表，主要技术特征为：用半导体激光器替代氙灯，高效率，可重复频率（10Hz）工作。

HPLD———三类技术

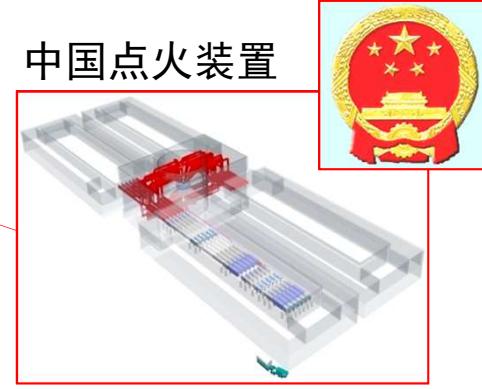


“方形光束+组合式口径+四程放大”以成为当今国际上新建高功率激光驱动器的“主流”总体技术路线。

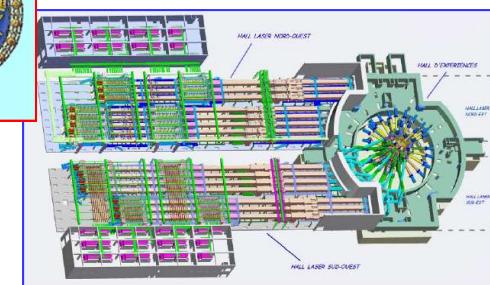
美国NIF (200903)



中国点火装置



法国LMJ (2012)



【我们面临的重大命题】

1. 在没有外援的条件下，自力更生，按时完成国家重大专项！
2. 激光驱动点火装置不但在总体规模上达到美国NIF、法国LMJ的水平，在综合性能方面也将达到NIF/LMJ的水平，并在关键技术方面有所创新！？

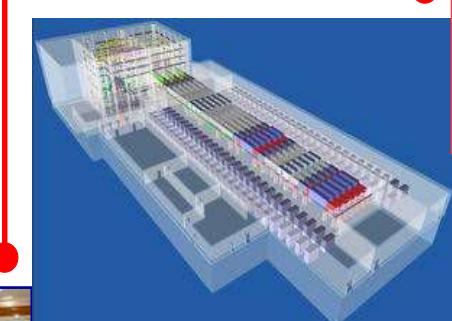
聚变级高功率激光驱动器基本技术特点

方形光束
组合口径
多程放大技术路线
较高能量转换效率
较高通量
模块化结构

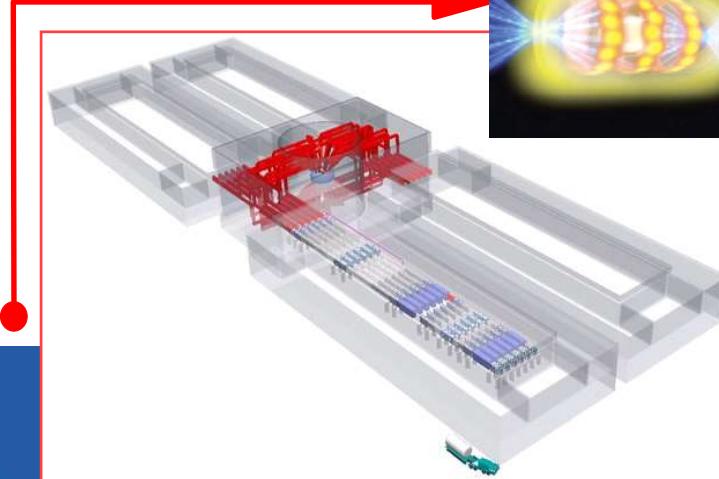


神光-II升级装置 神光-III原型装置
2007年 10kJ/8束

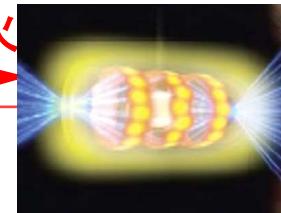
神光系列高功率激光驱动器



神光-III主机装置
2013年 200kJ/48束



聚变点火



激光驱动点火装置 2020年 1.4MJ/192束

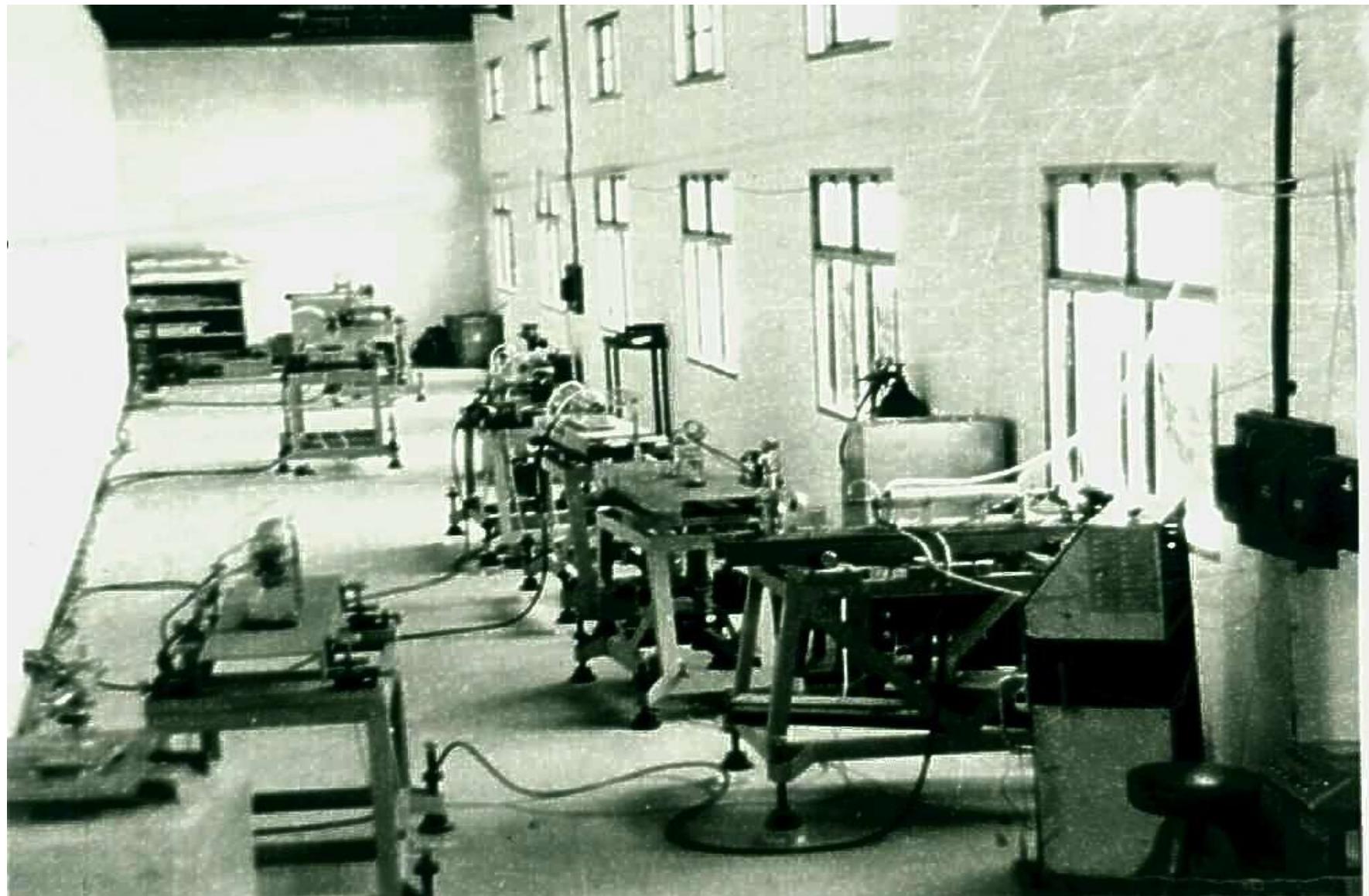
先进激光工程支撑体系

先进光学材料 精密光学检测
先进光学制造 光学元件前期处理
强光薄膜 精密装校

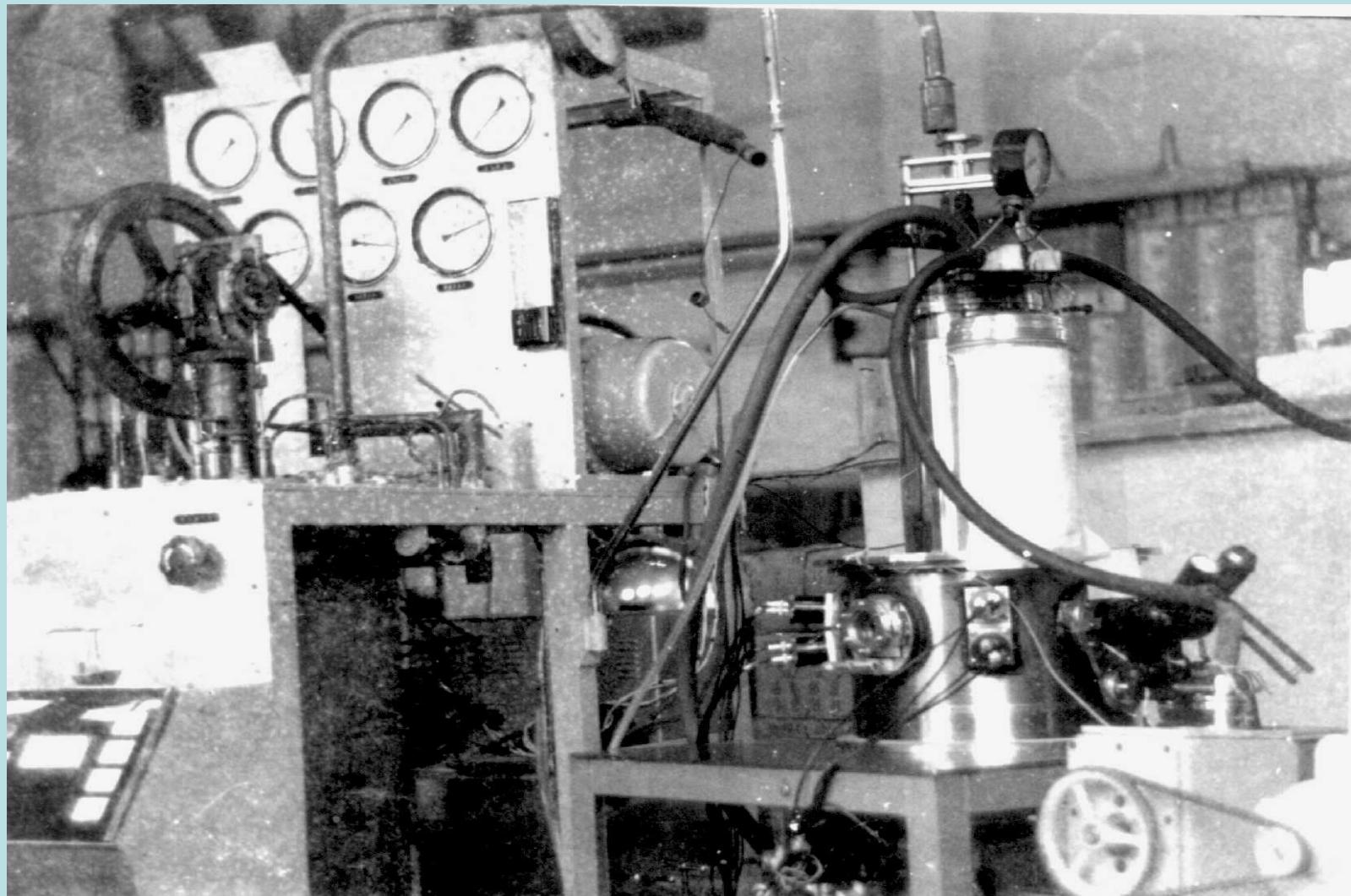
先进激光实验室与技术保障体系

“三个台阶、三步走！”

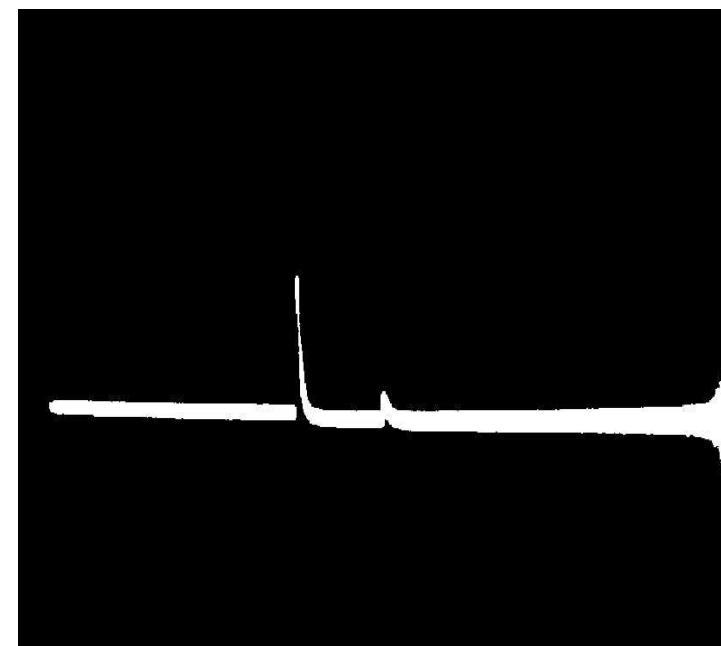
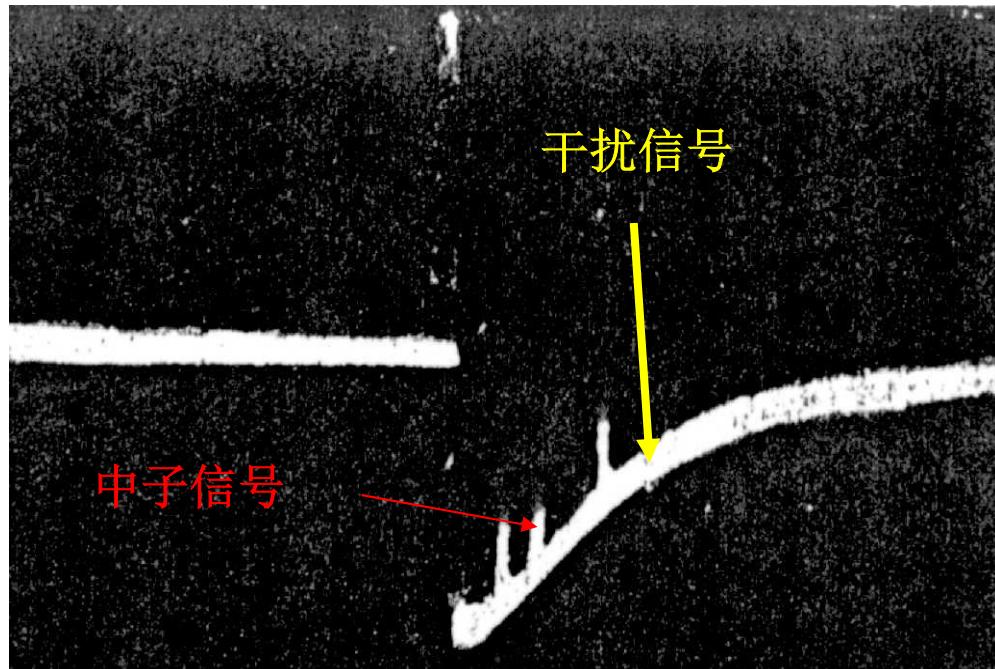
万兆瓦装置的激光系统（1973，闵行电机厂）



万兆瓦装置的低温(液氮)靶室 (1973, 闵行电机厂)

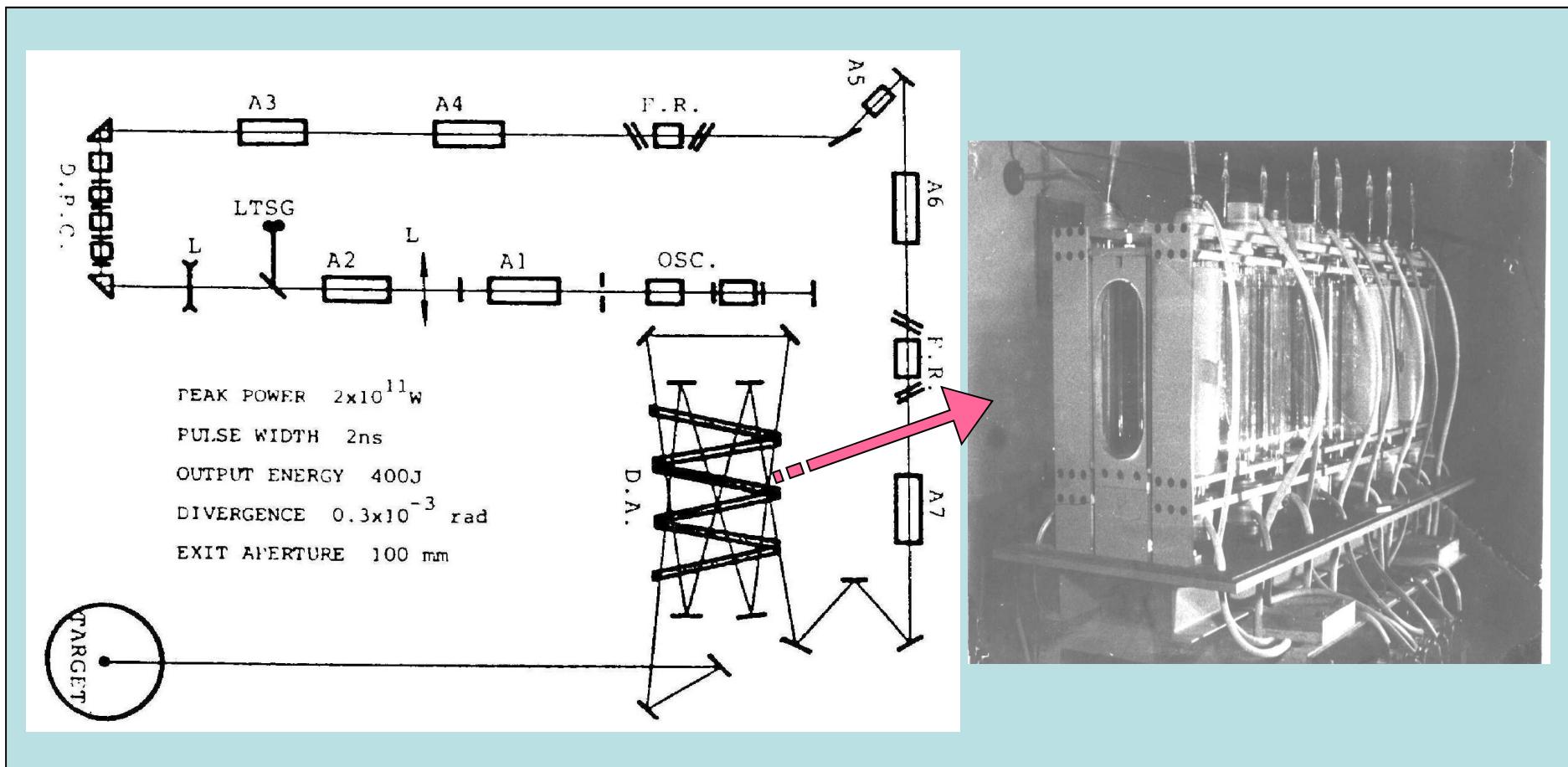


1973年4月25日—实现零的突破： 激光辐照氘冰靶获得中子

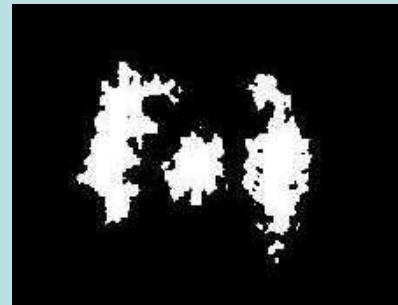
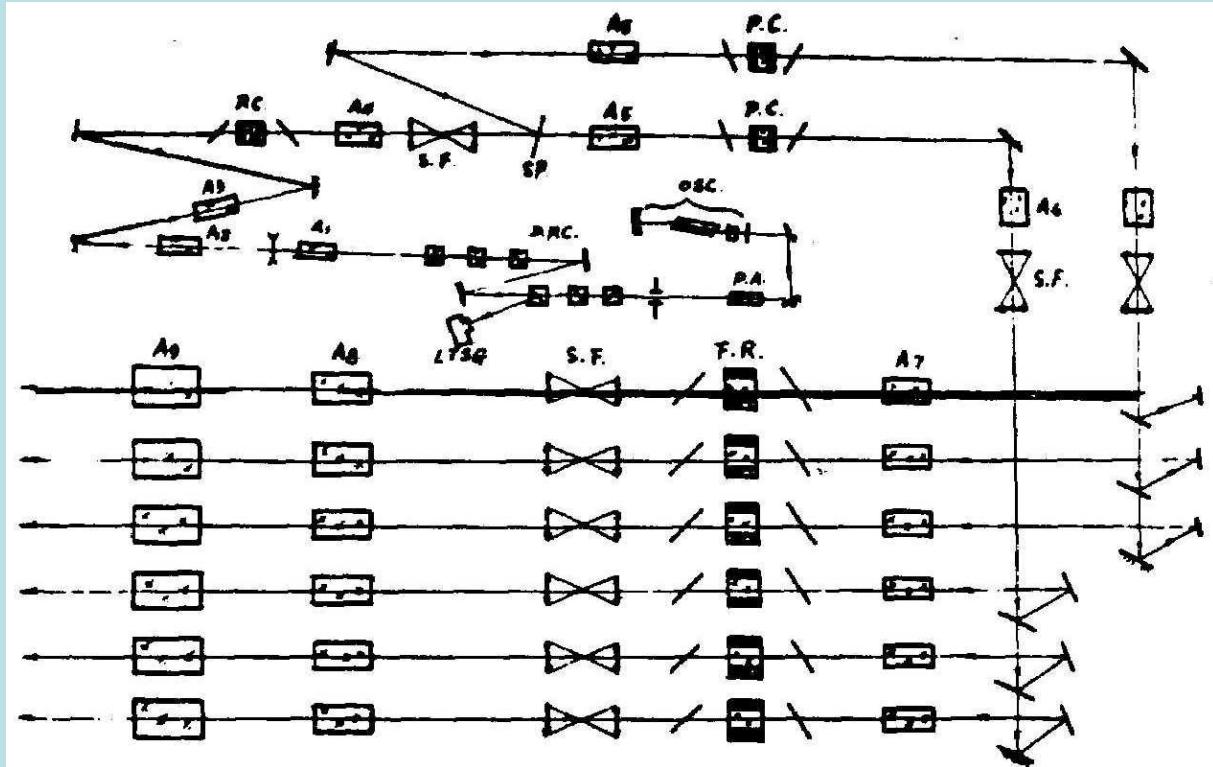


1974年激光功率增大二十倍： 2×10^{11} 瓦

中子产额提高二十倍： 2×10^4



1978年建成 10^{11} 瓦的六路激光装置 —实现空心玻璃壳靶的向心压缩



1986年建成TW级高功率钕玻璃激光系统
——神光-I 装置，双束， 10^{12} 瓦/束

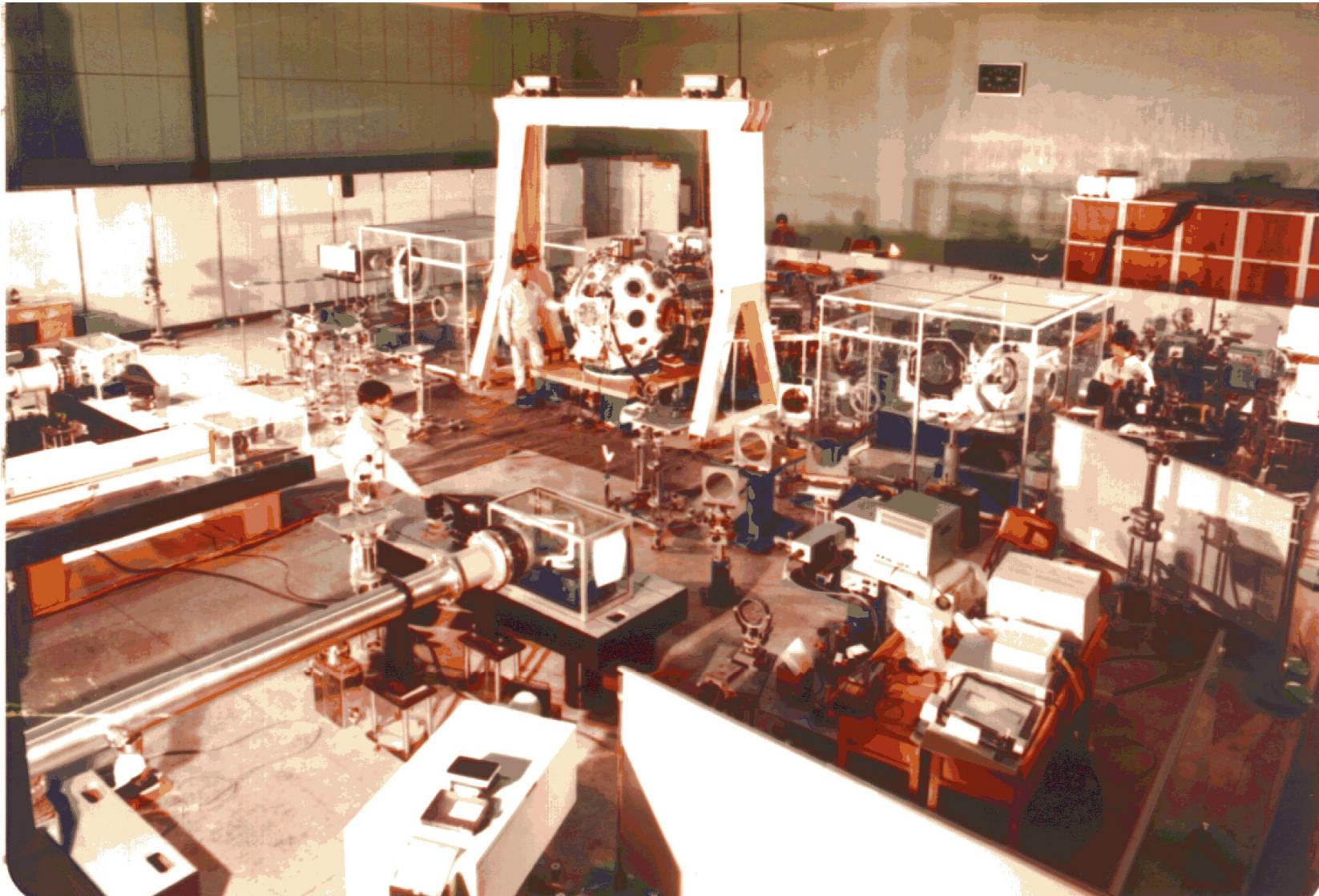


神光-I 装置的两路激光系统

(built in 1986 2beam /φ200mm, 1.6KJ/1ω/1ns)



神光-I 装置的靶室系统



“神光Ⅱ”装置的八路激光系统

(2000 8 beams/ $\phi 200\text{mm}$, 6KJ/1 ω ~2.5KJ/3 ω /1ns)



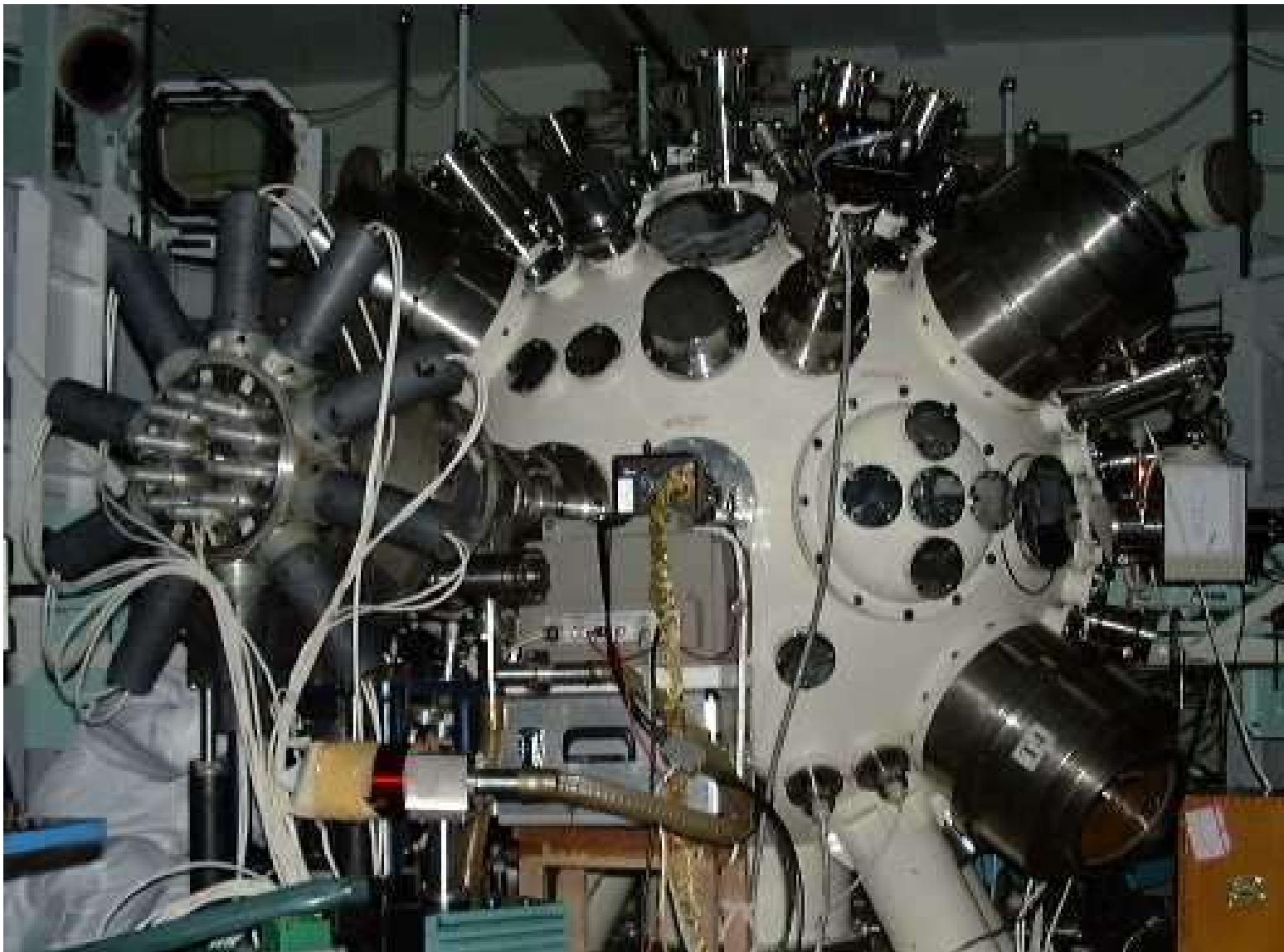


神光Ⅱ装置放大部分

神光-II 装置的双靶室系统



神光Ⅱ装置的ICF靶室和物理诊断设备



1992~94 建成星光-II 激光装

置



- 光束数: 1
- 光束口径: 150mm
- 波长: 0.35μm
- 激光能量:
130J/3ω
- 工作脉宽: ~1ns

星光-II 激光装置——倍频器和靶室



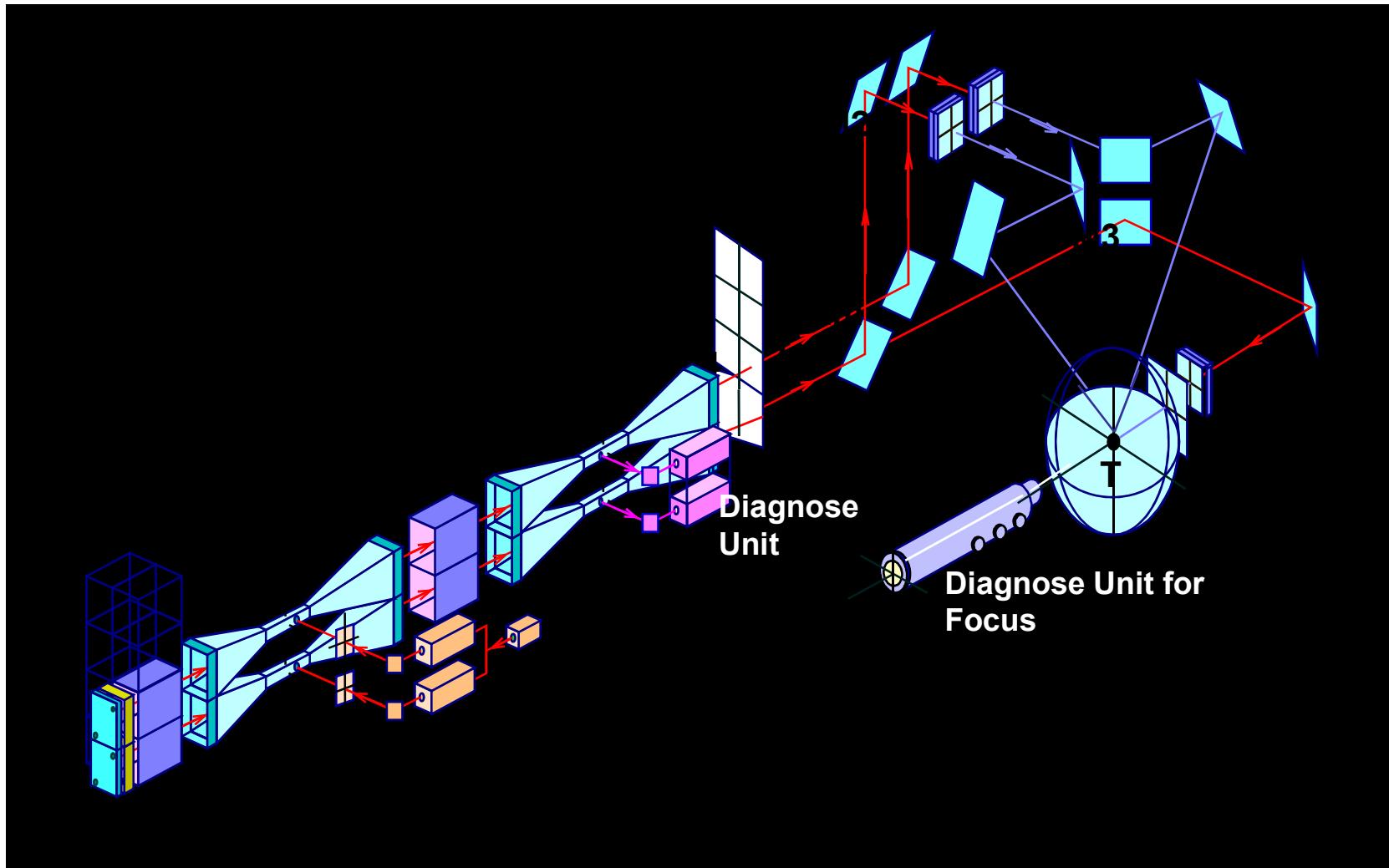
三次谐波转换器



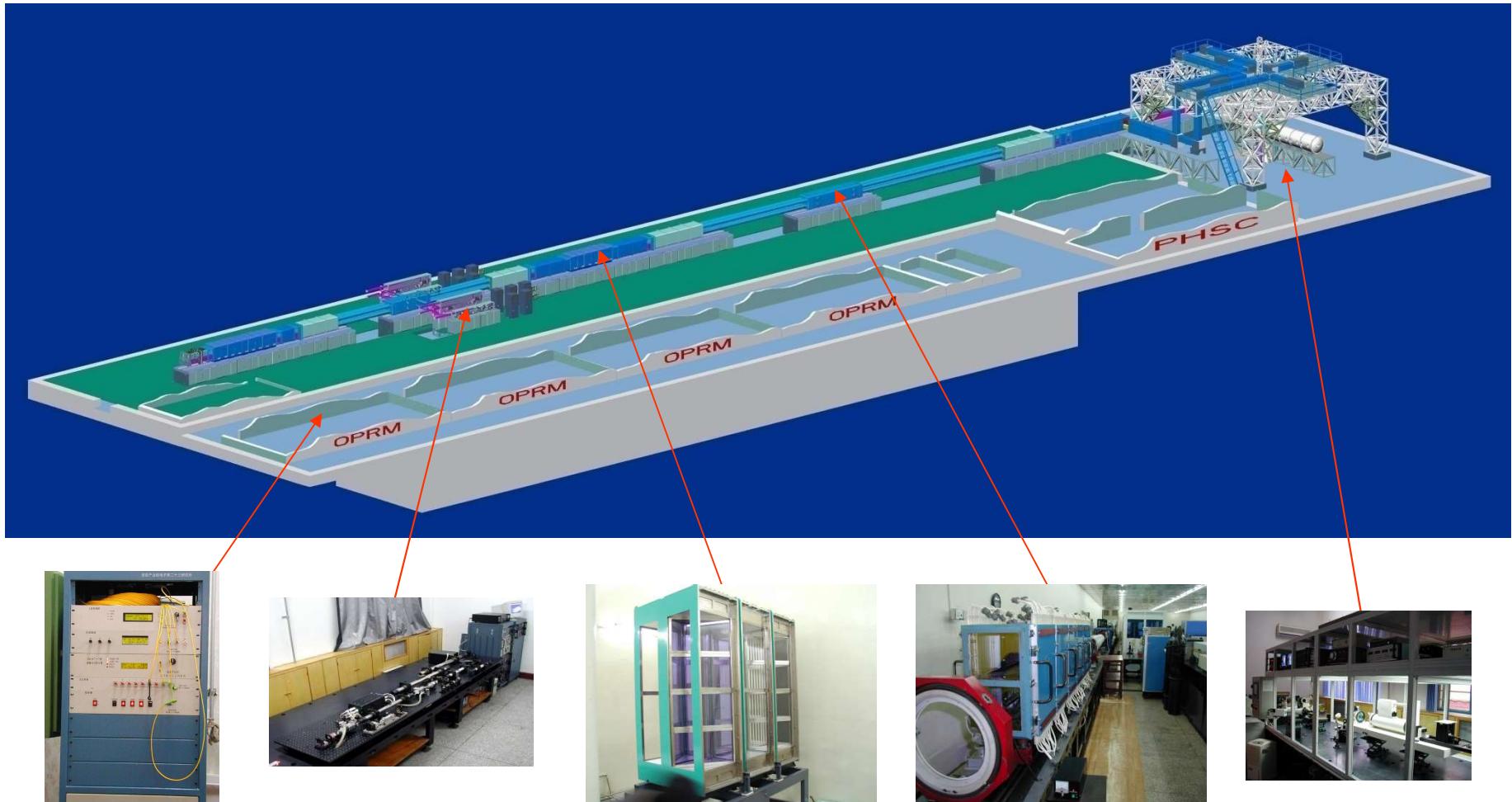
物理实验靶室

神光-III原型装置光路图

(8束/ 300mm, ~10KJ/3ω/1ns)



神光III原型装置总体效果图



神光-III原型首束出光并达标



钕玻璃片超净安装

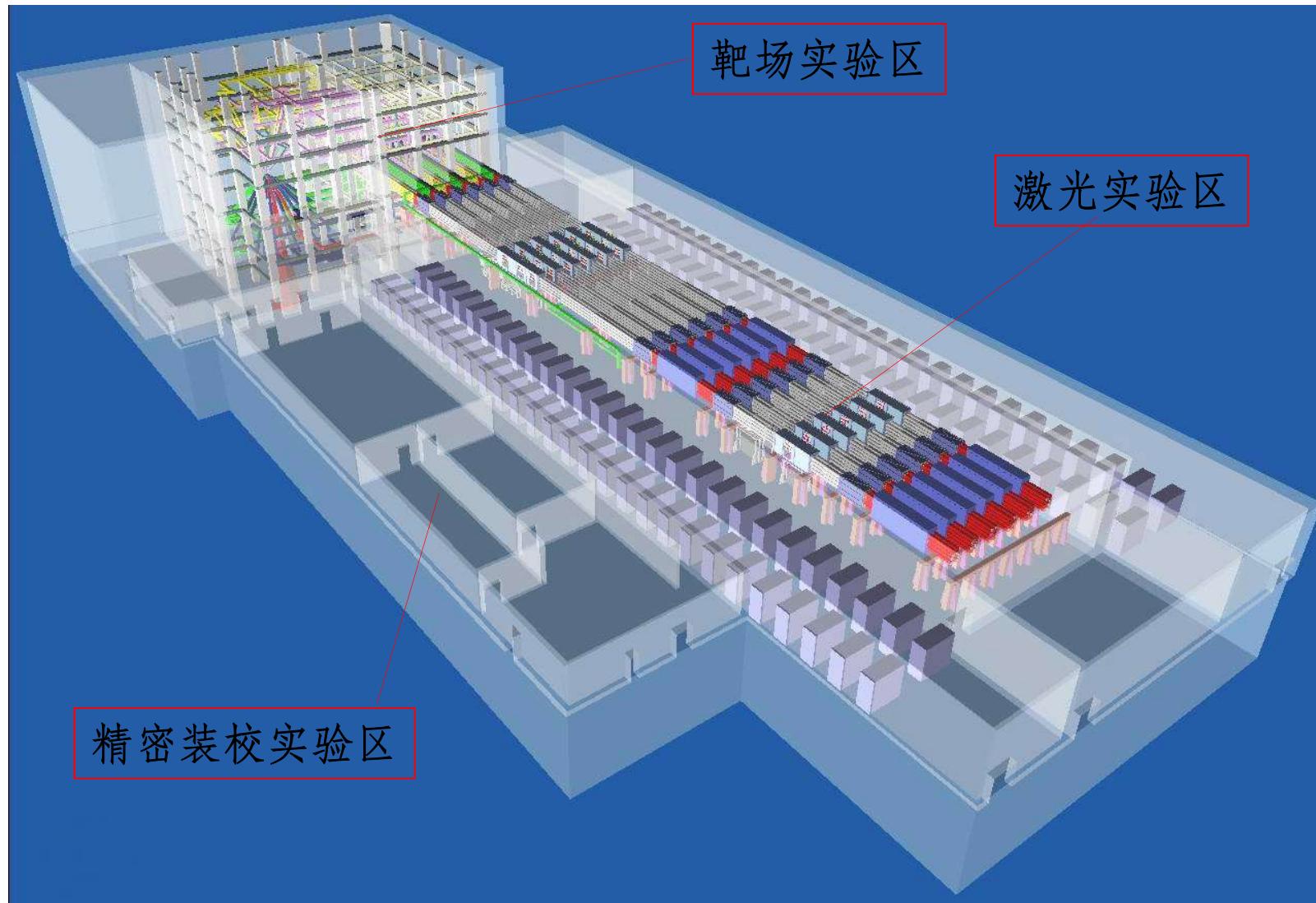


四程放大器



Main amplifier modules

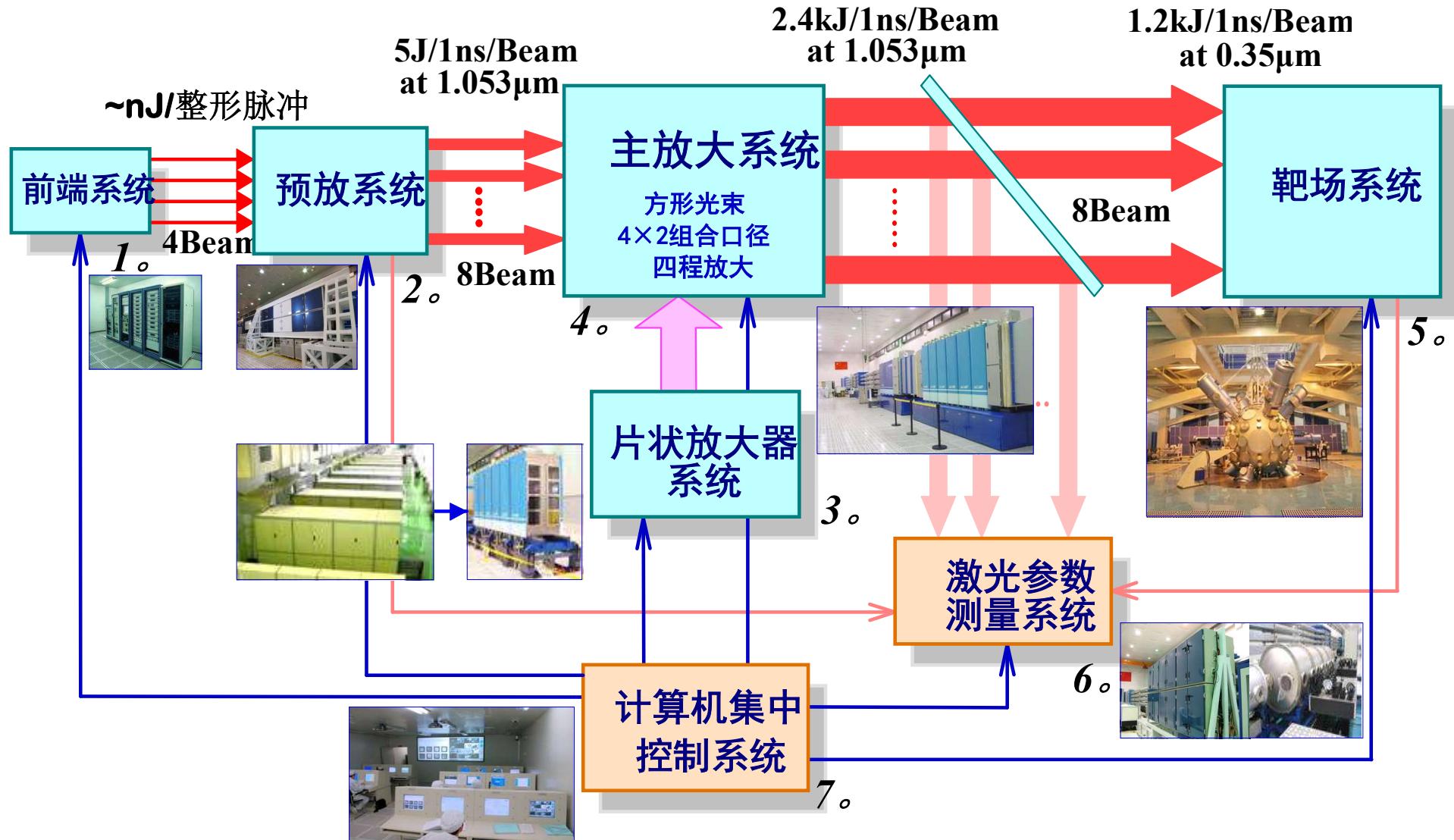
神光III计划



神光-III原型装置是我国第二代高功率激光驱动器的科学与工程样机，总体设计中采用了一系列新原理、新技术。

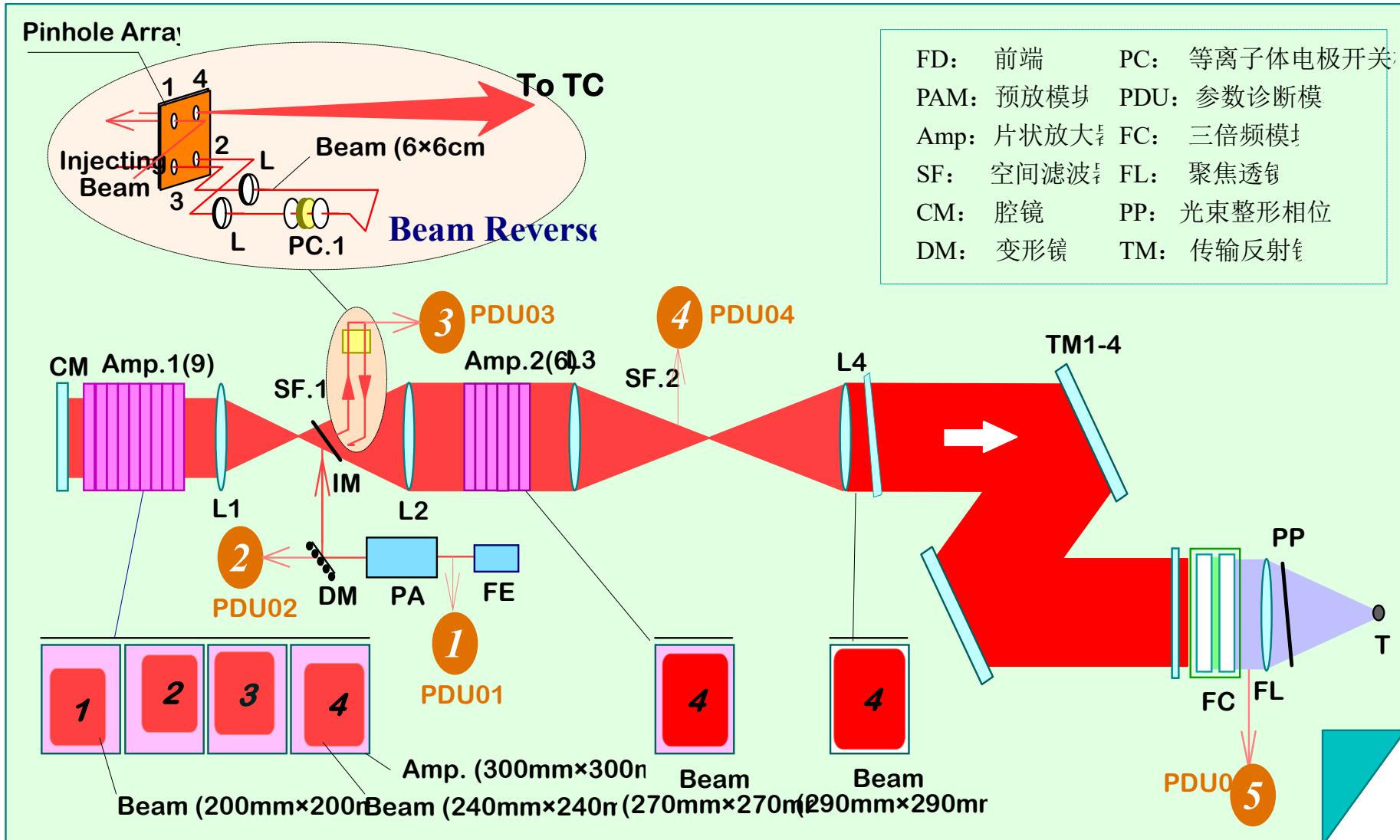


HPLD总体构型研究与总体技术方案设计不但决定了整个装置的输出能力(包括增益与负载能力)、光束质量、综合控制能力、可靠性等关键性能，同时也决定了装置性价比，是研究与设计神光-III原型装置首先应解决的总体类科学技术与与工程问题，是突破二代技术、掌握核心、跨上台阶的主要标志之一！

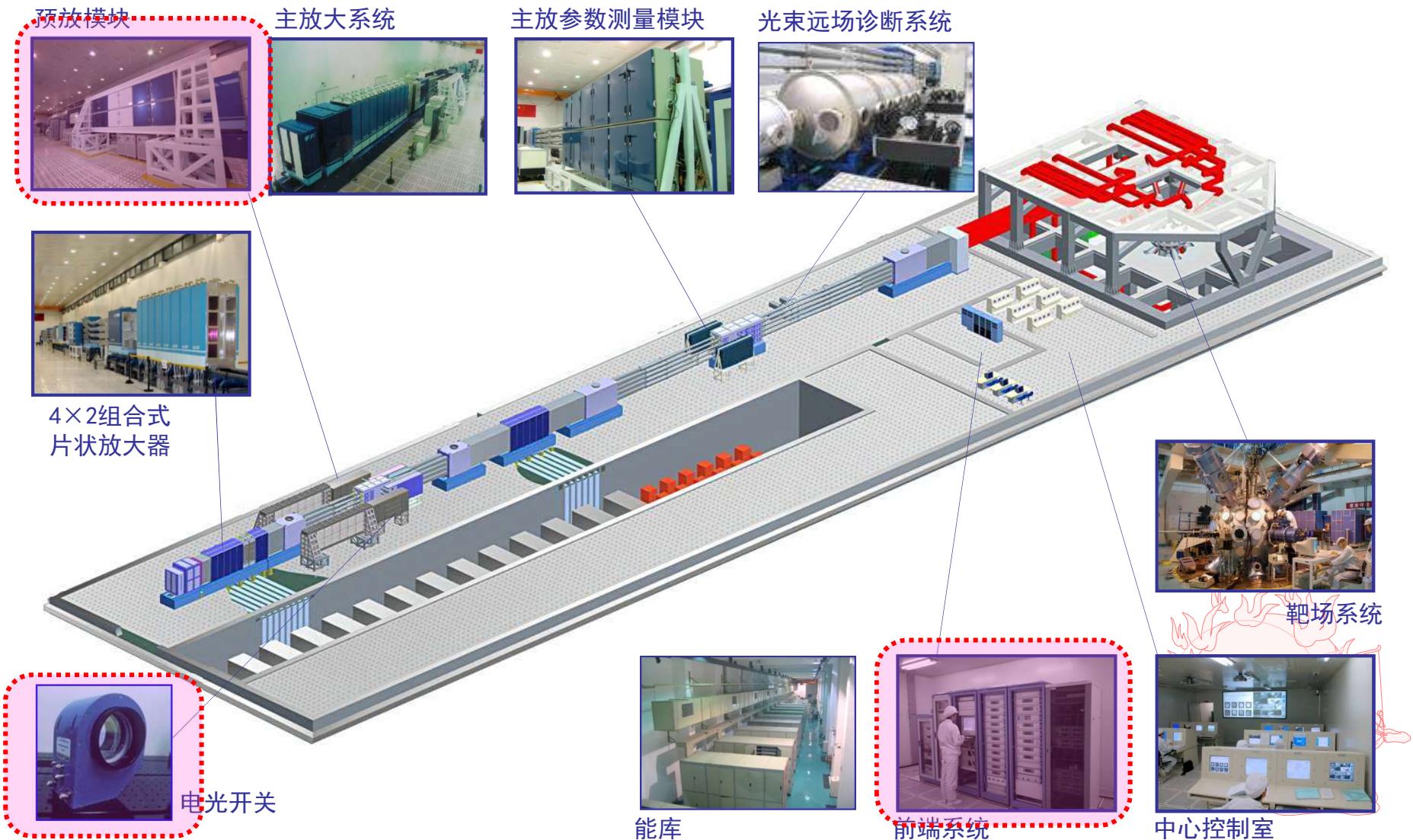


神光-III原型装置主要由前端、预放、片状放大器、主放、靶场、激光参数测量和计算机集中控制等七大系统组成，可输出八束 $300\text{mm} \times 300\text{mm}$ 口径、能量高达万焦耳的三倍频激光。

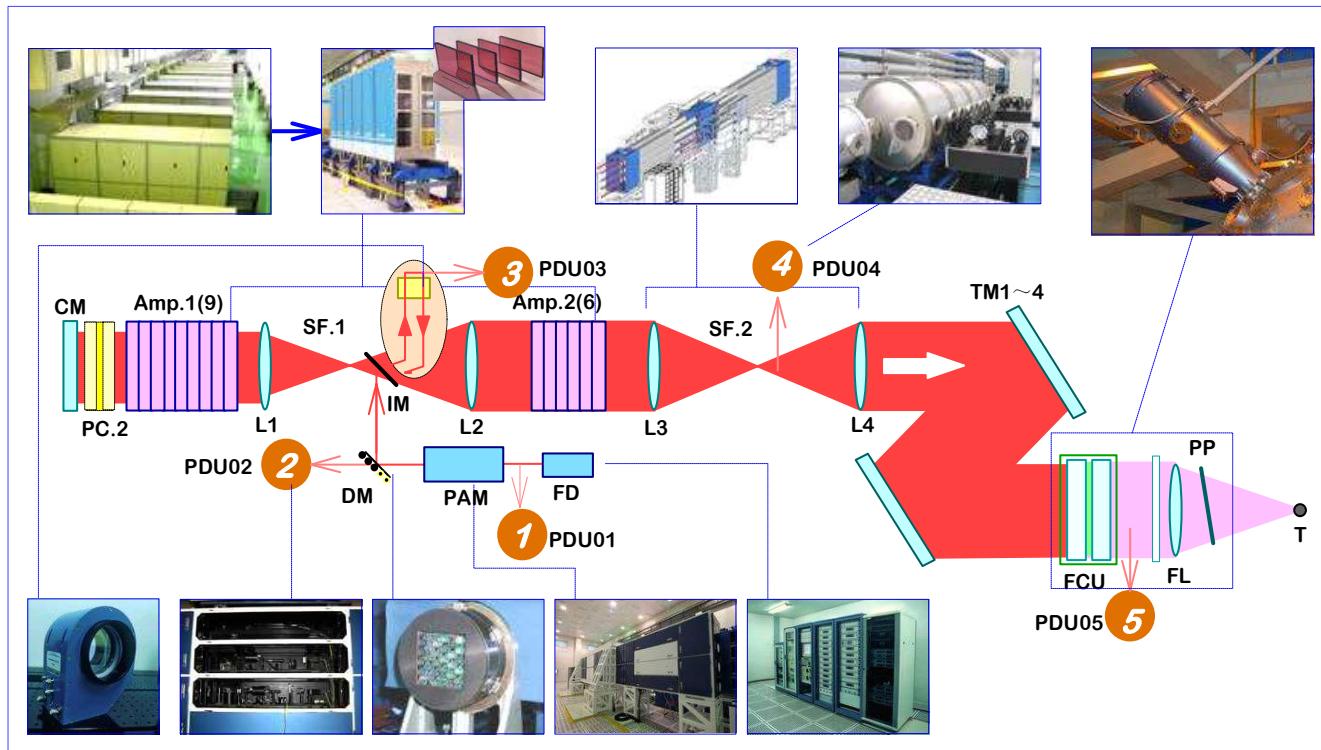
深入、系统地研究并掌握了以“方形光束+组合口径+多程放大技术”为主要标志的第二代高功率激光驱动器总体技术路线。



“方形光束+4×2组合口径+内腔四程放大/助推单程放大”构型



系统地研究了第二代高功率激光驱动器的核心与关键技术，并成功地应用于原型装置，全面奠定了设计、建设、运行和维护第二代高功率激光驱动器的科学技术与工程基础。

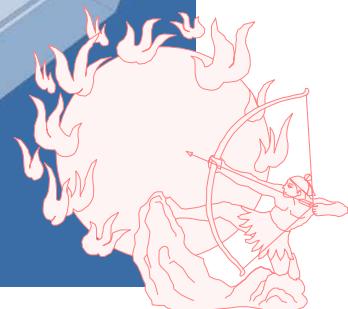


神光-III主机装置
总体设计效果图

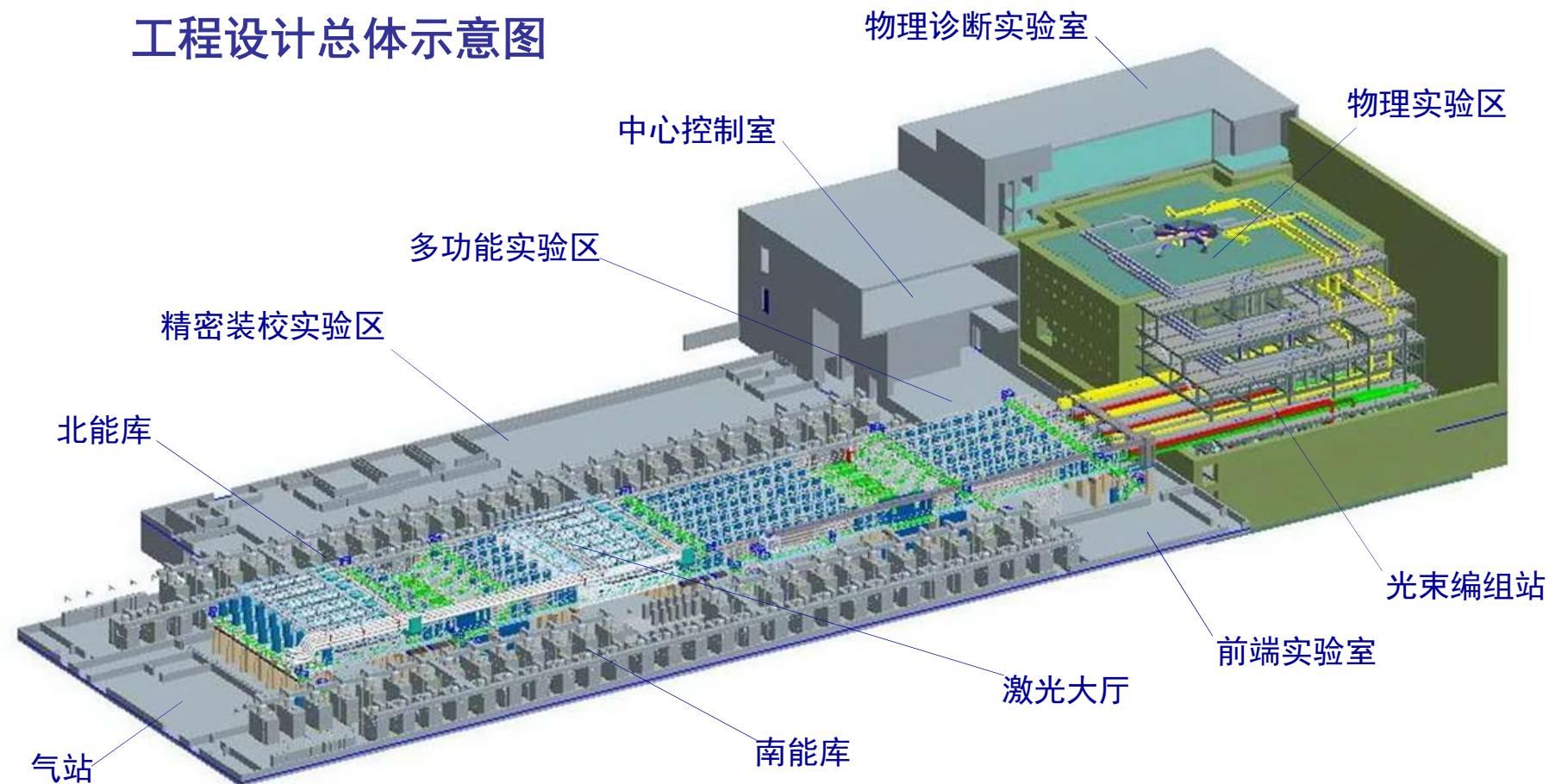


标志性技术指标

- * 光束束数：48束
- * 激光能量：0.2MJ
- * 激光波长：351nm
- * 脉冲宽度：1ns～10ns
- * 功率平衡：10%



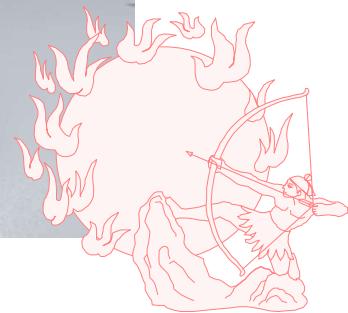
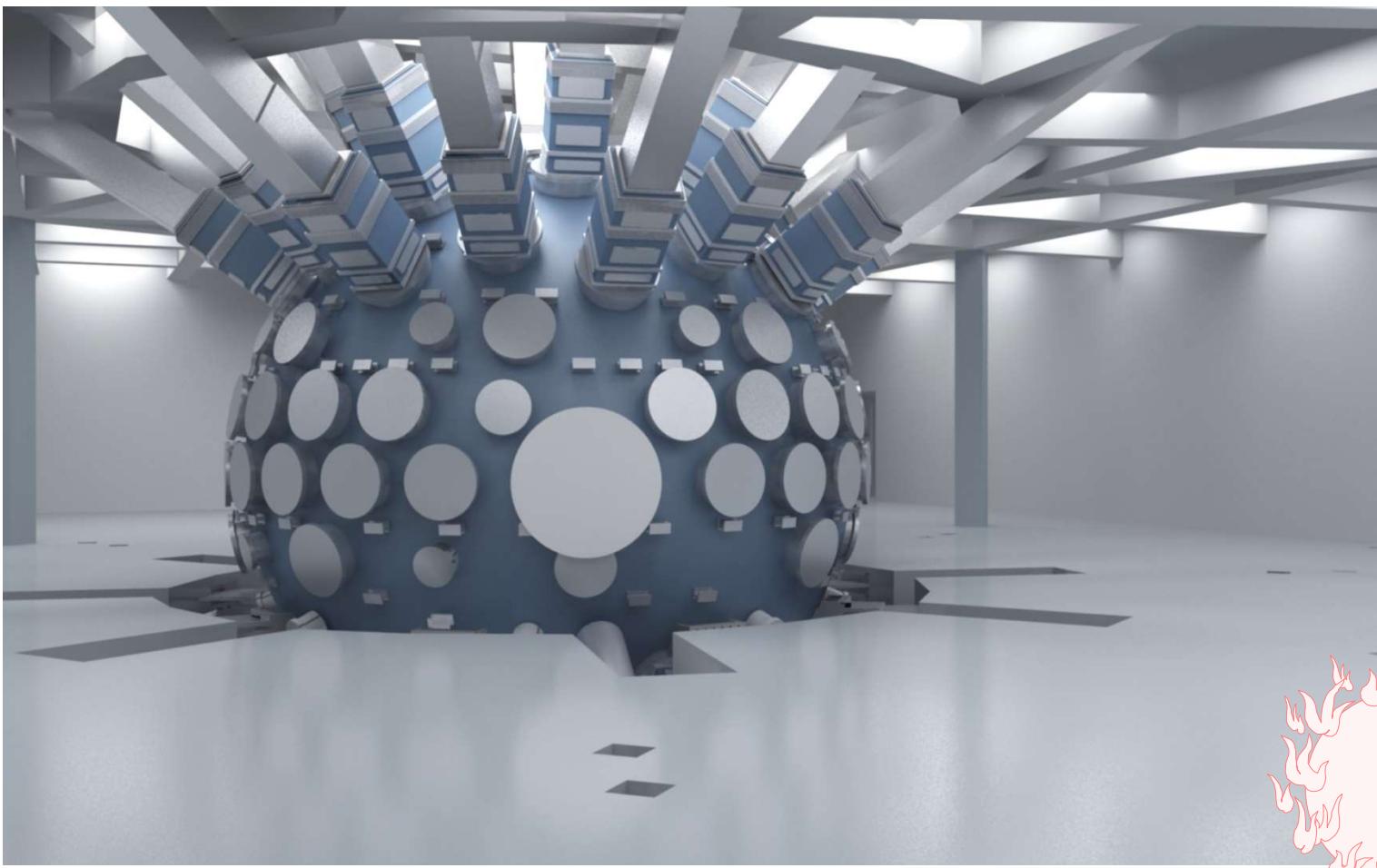
神光-III主机装置 工程设计总体示意图



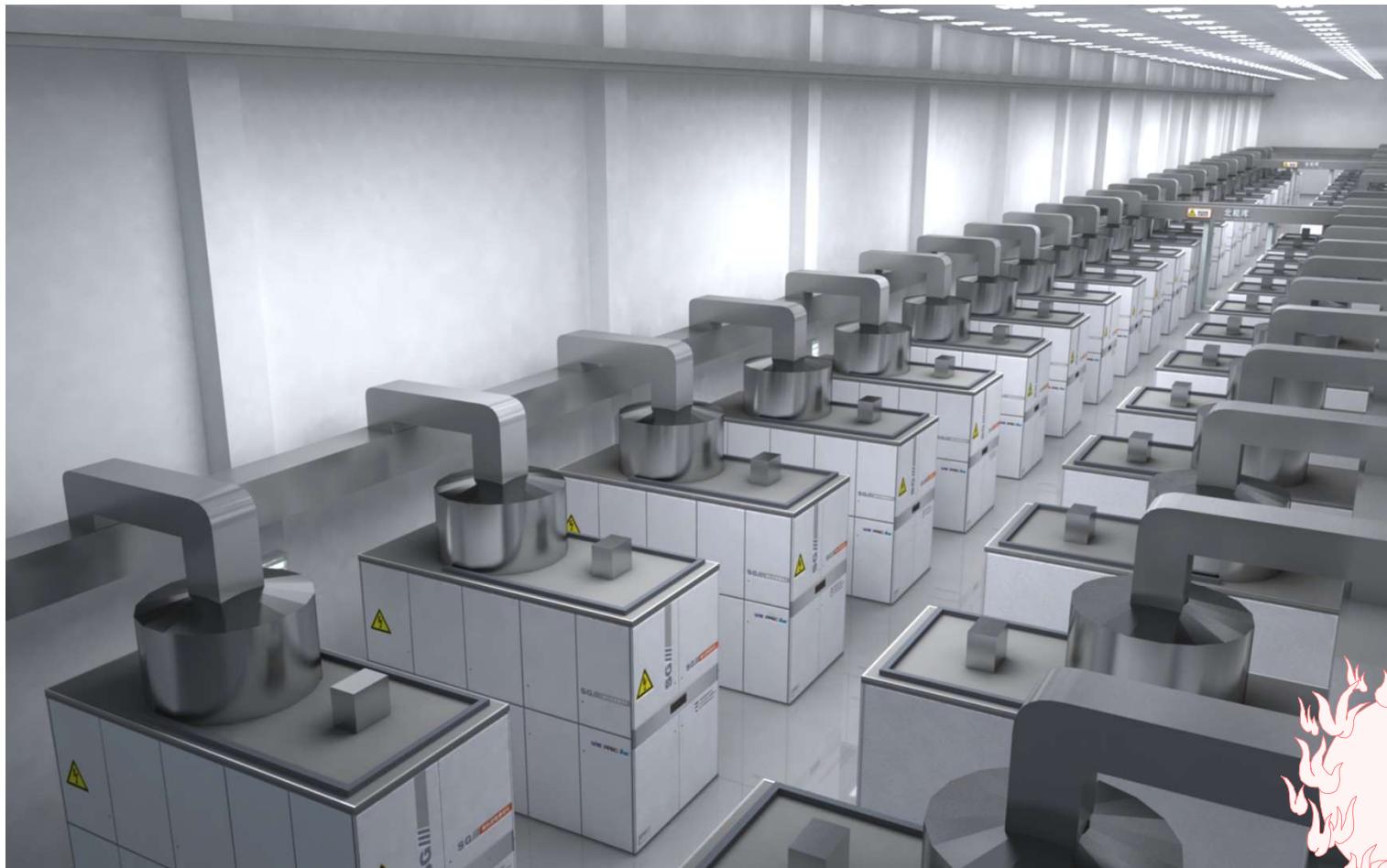
神光-三主机装置激光大厅



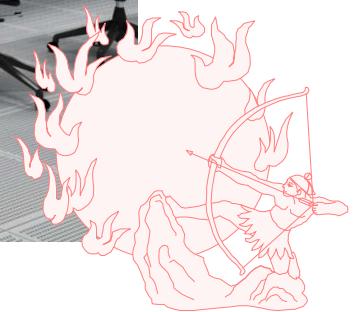
神光-三主机装置靶场实验室



神光-三主机装置能源系统



神光-三主机装置中心控制室



美国国家点火装置（NIF）



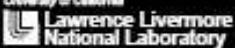
The image shows an aerial view of the National Ignition Facility (NIF) complex, featuring several large industrial buildings and a surrounding area with roads and parking lots.

Our Mission *Science in the National Interest*

Energy
NIF is designed to demonstrate fusion ignition and energy gain — two key milestones along the path to limitless fusion power production.

National Security
Data from NIF experiments will help scientists to understand the complex physics of nuclear weapons, ensuring the safety and reliability of our strategic deterrent.

Basic Science
NIF experiments can create immense pressures and temperatures similar to those in stars and supernova. These experiments bring the study of astrophysical phenomena, materials science, and nuclear physics into a controlled laboratory setting.

University of California
 Lawrence Livermore National Laboratory

任务目标

- 聚变能源
- 国家安全
- 基础科学



NIF concentrates all



Pressures

>10¹¹ atm

NIF-0506-12065
19EIM/dj



坐落在LLNL的NIF装置外景

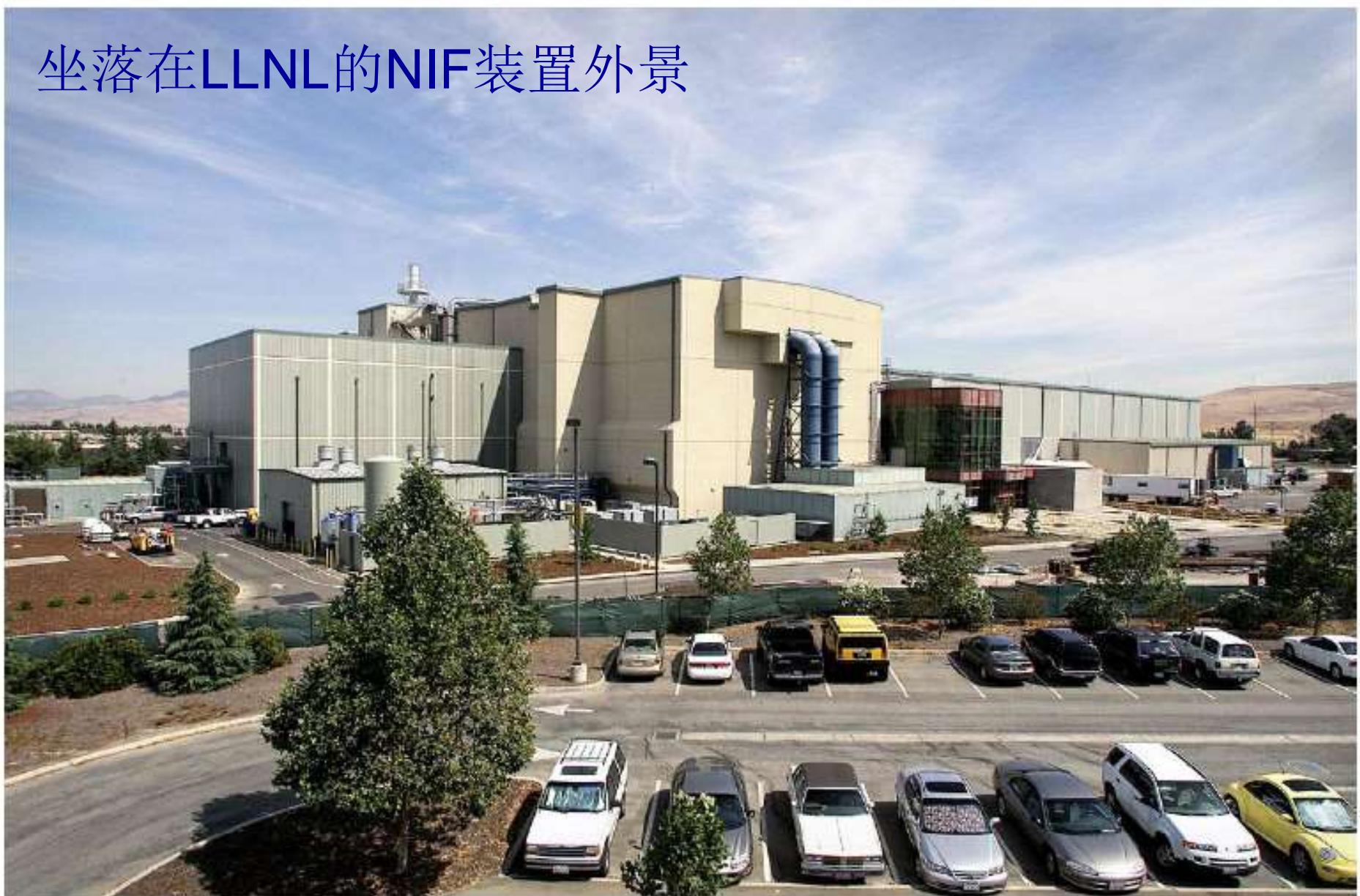
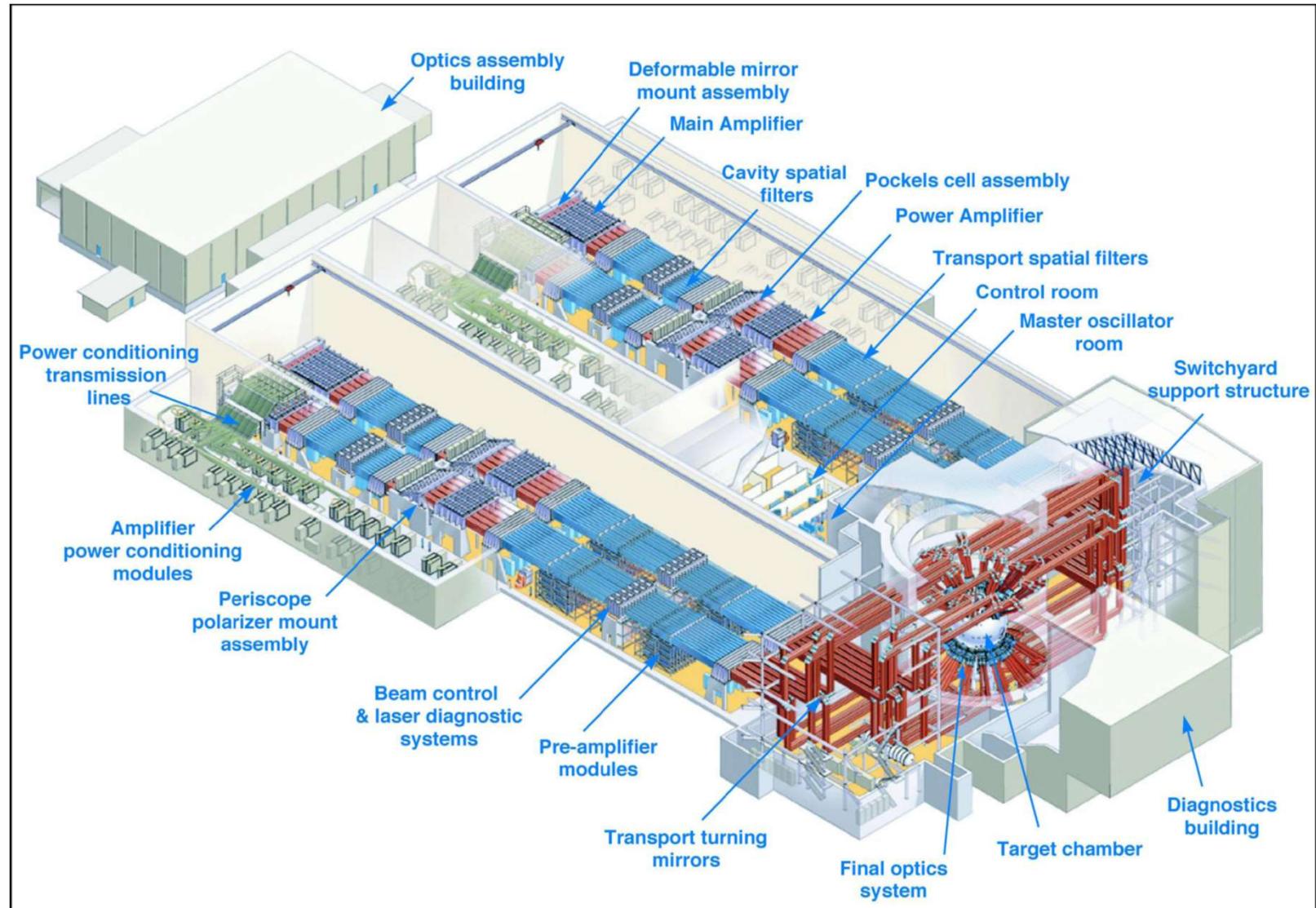


Fig. 1. The National Ignition Facility at Lawrence Livermore National Laboratory.

美国国家点火装置（NIF）



Inertial Fusion Energy

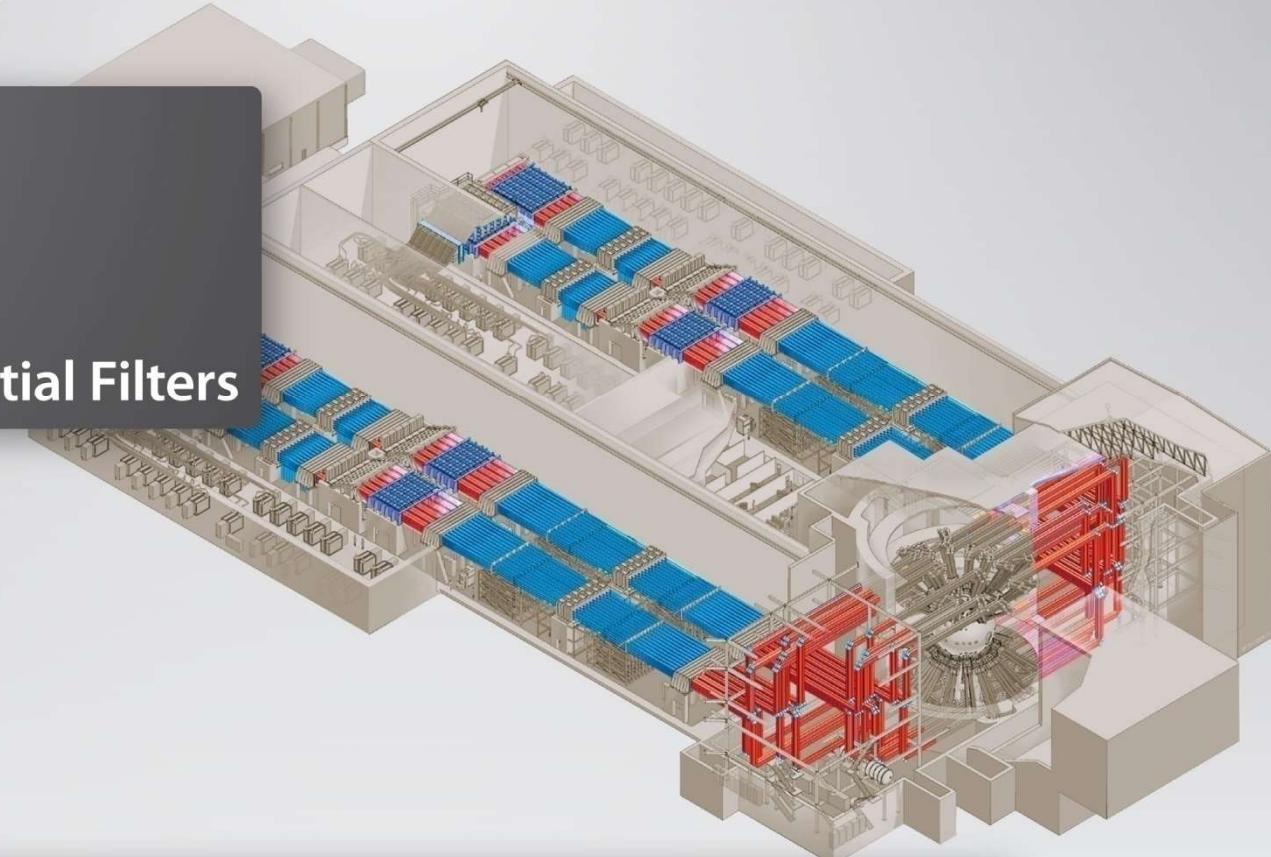
- High neutron yield
- No greenhouse gasses
- Only low-level radioactive waste



Pure fusion solutions are technologically
and economically challenging

NIF is based on 1960's — 1990's laser technology

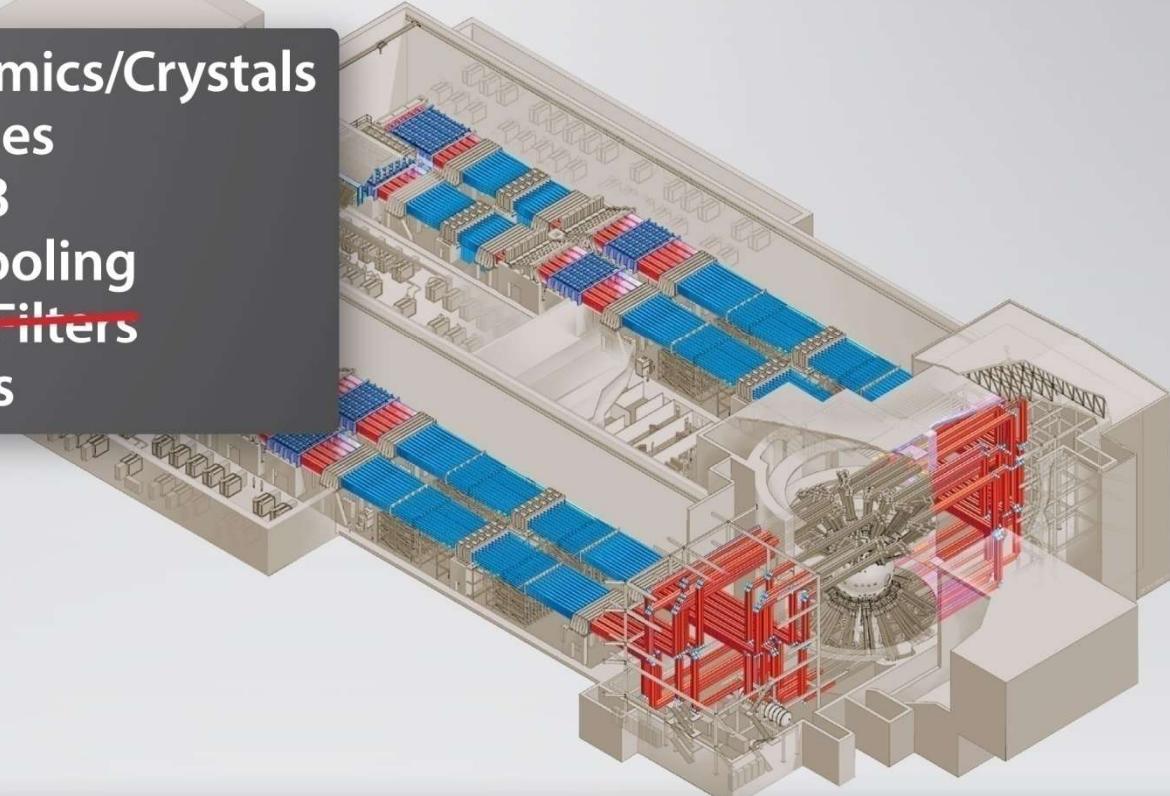
- Glass
- Flashlamps
- KDP
- Air cooling
- Discrete Spatial Filters



These technologies result in a low rep rate,
low efficiency laser fusion driver

IFE laser will be based on 1990's — 2020's technology

- ~~Glass~~ Glass/Ceramics/Crystals
- ~~Flashlamps~~ Diodes
- ~~KDP~~ DKDP, YCOB
- ~~Air cooling~~ He cooling
- ~~Discrete Spatial Filters~~
Rugate reflectors



These “plug and play” modifications to NIF architecture could increase rep rate by 100,000x and efficiency by 40x



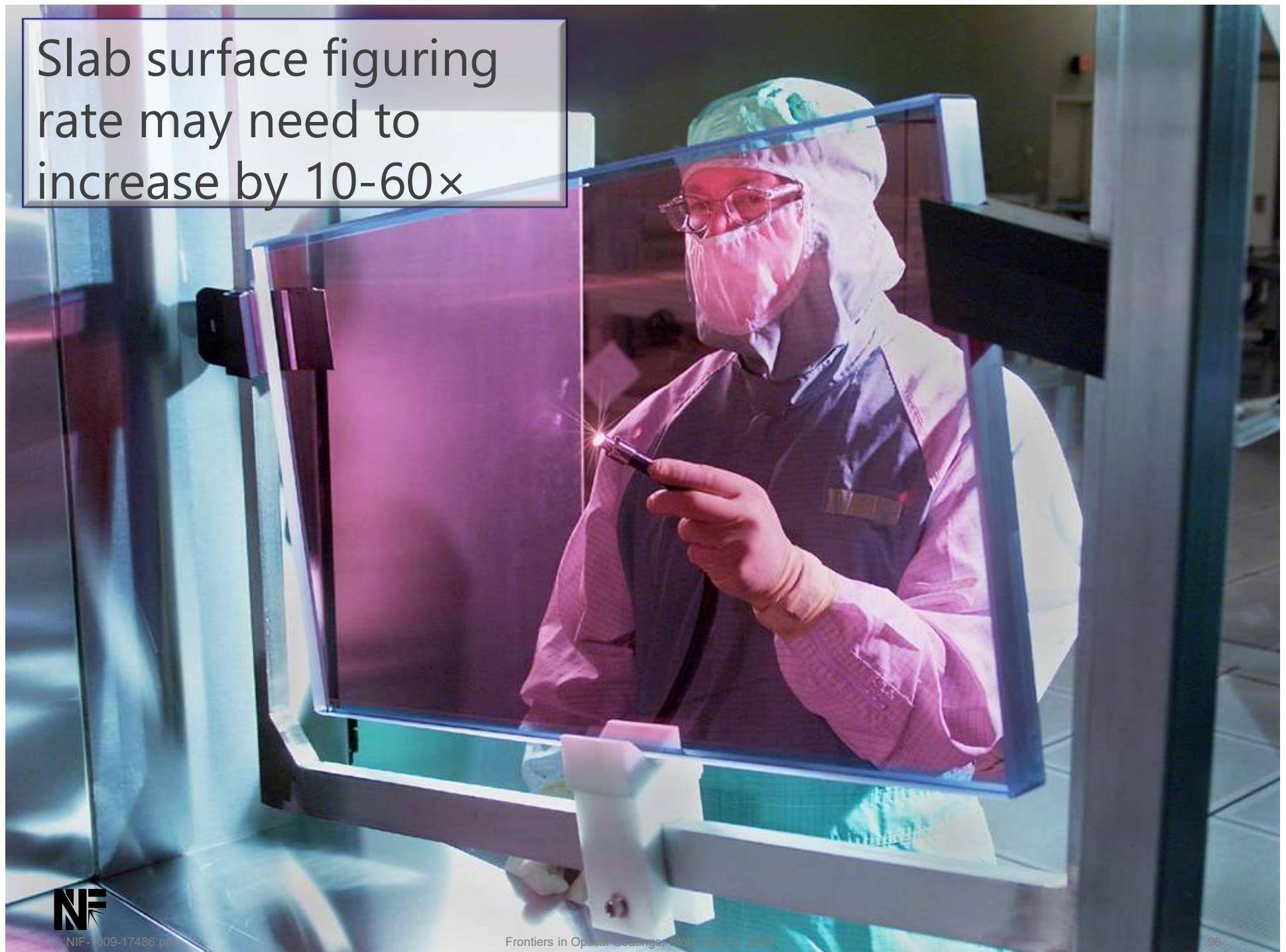
A new laser glass
composition or crystalline
material will be needed for
~10 Hz repetition rate



NIF-0506-12187r3
23EIM/dsm

NIF-1009-17486.ppt

Slab surface figuring
rate may need to
increase by 10-60×



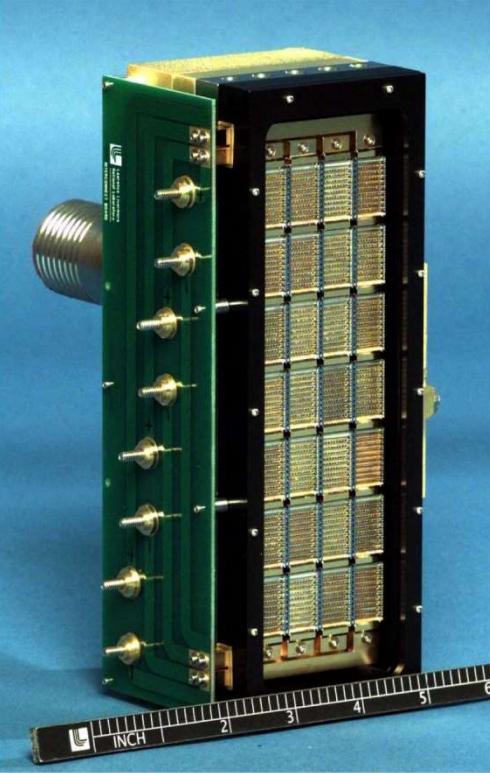
Diodes are significantly more energy efficient than flashlamps

Flashlamps



**400 W average power
electrical-optical efficiency**

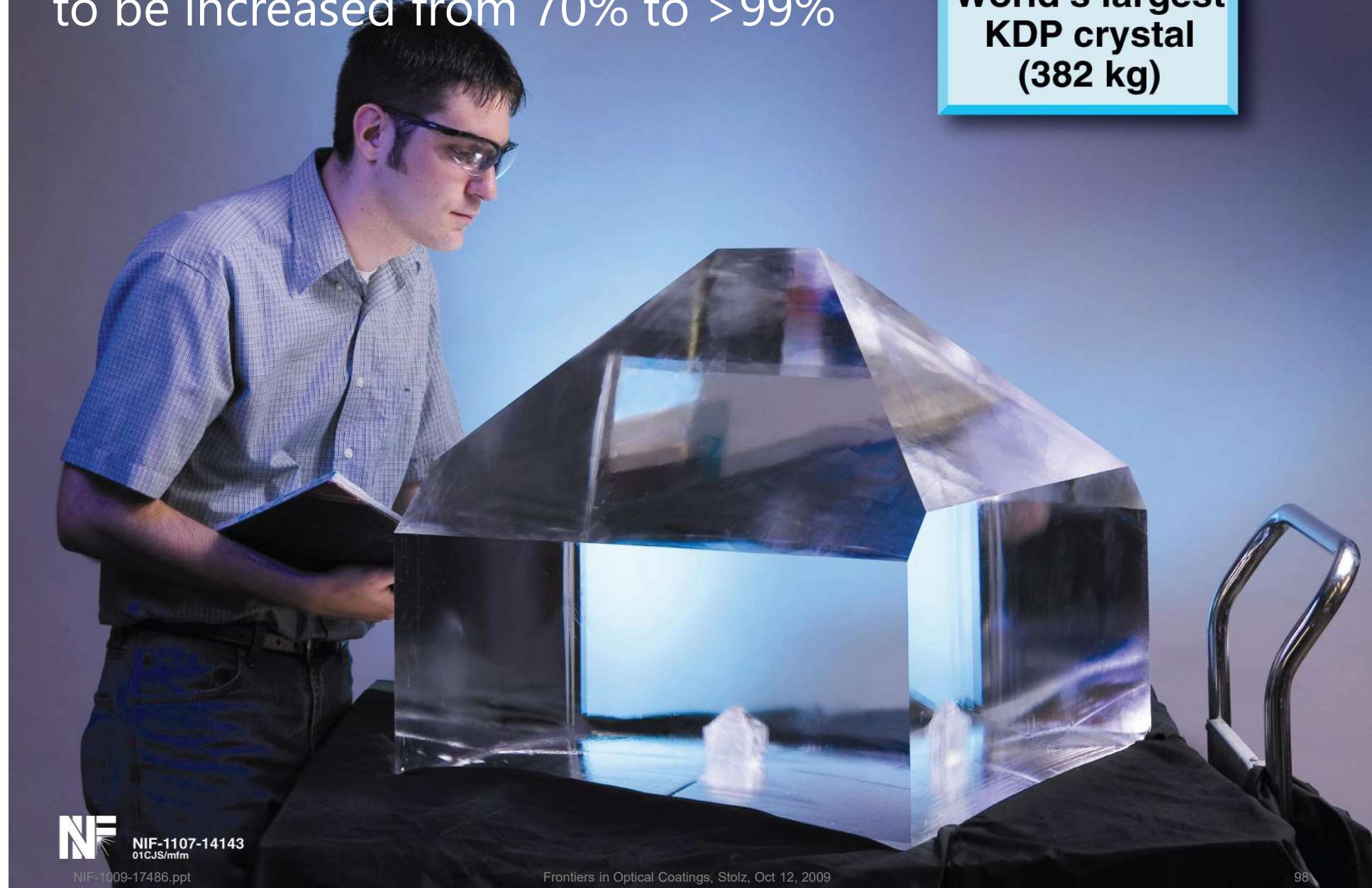
Diodes



**30 kW average power
electrical-optical efficiency**

DKDP deutiration levels will need
to be increased from 70% to >99%

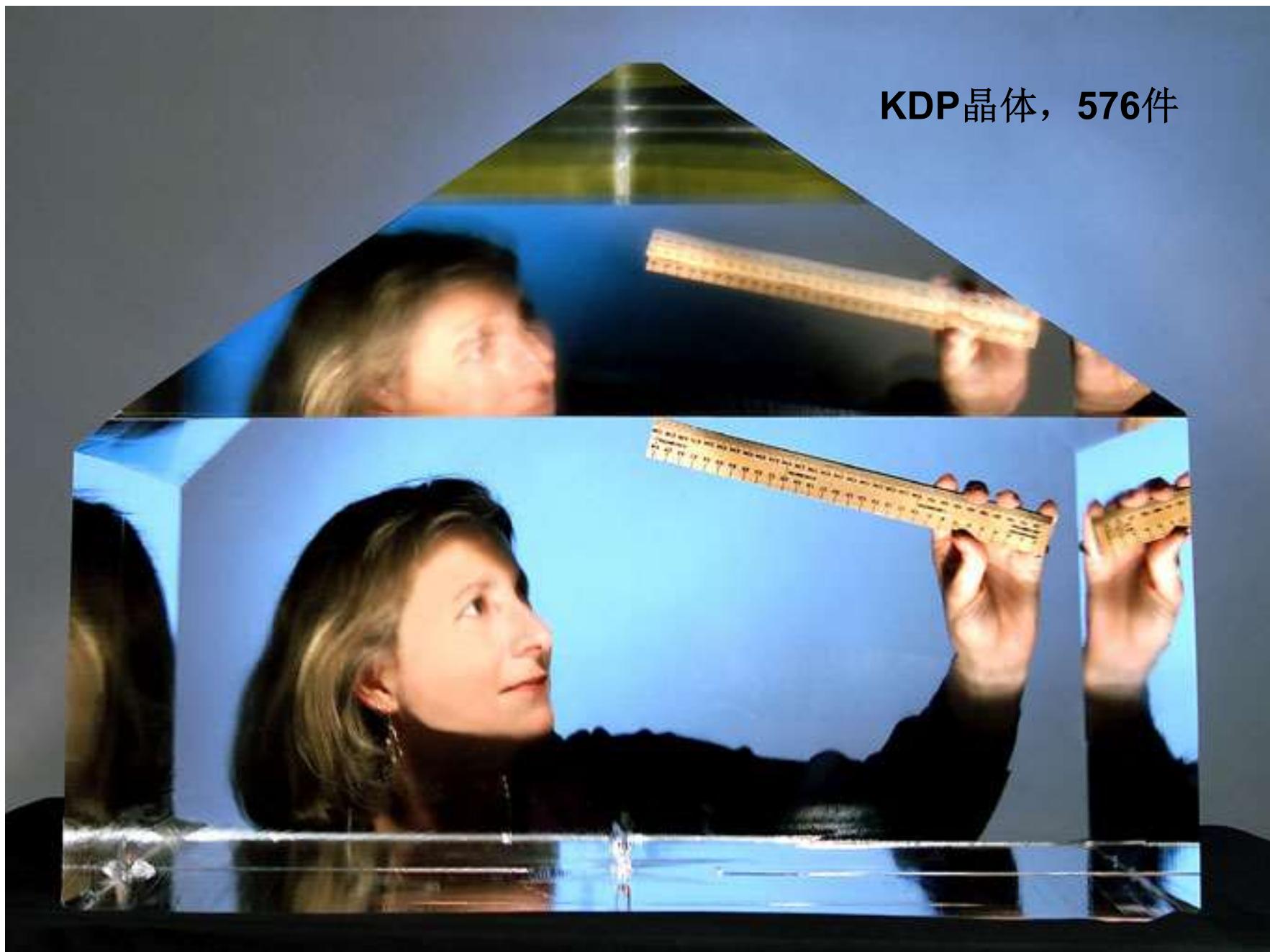
**World's largest
KDP crystal
(382 kg)**



NIF-1107-14143
01CJS/mfm

NIF-1009-17486.ppt

KDP晶体，576件





等离子体电极电光开关

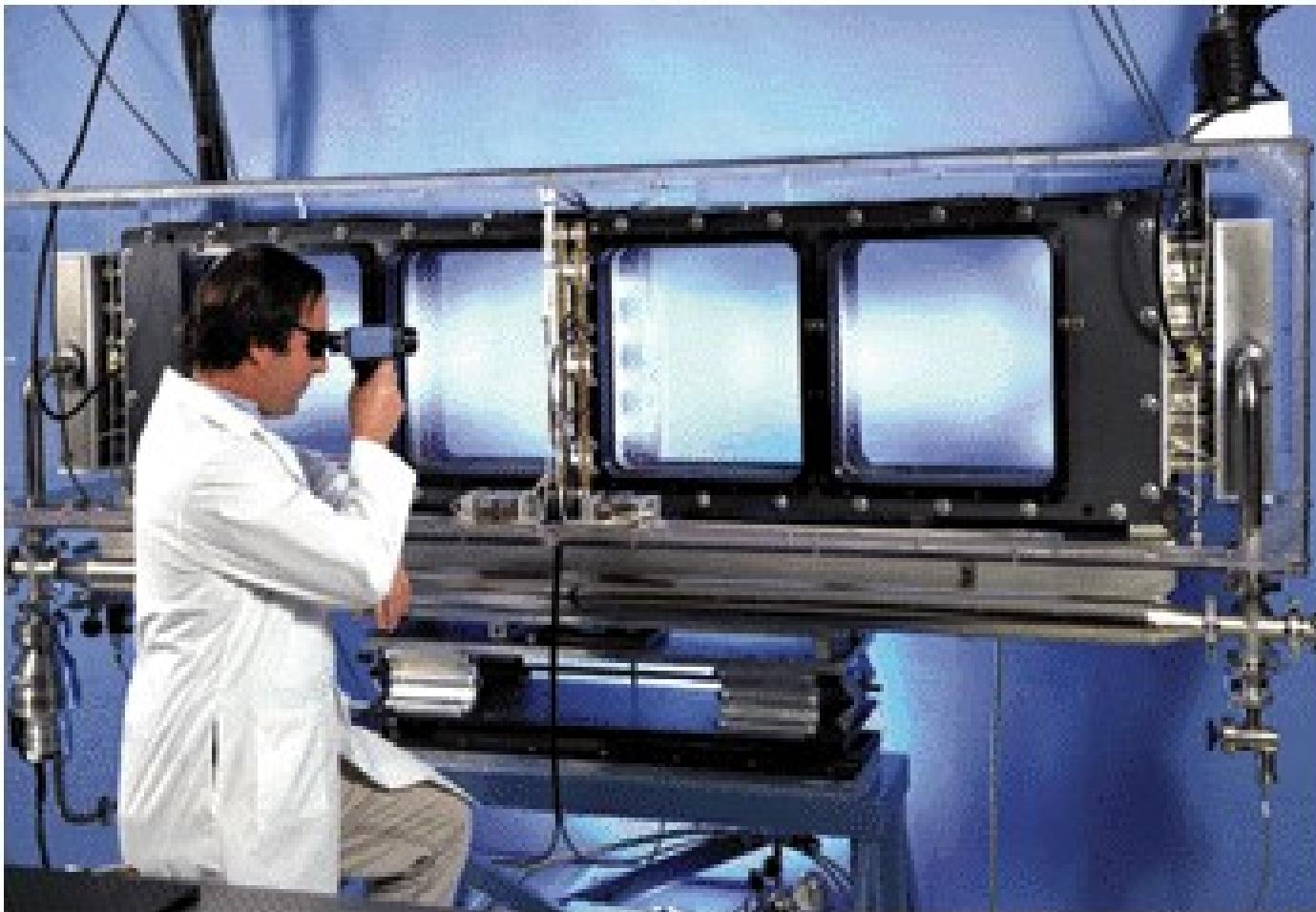


Figure 8. Each of NIF's plasma electrode Pockels cells (being tested here horizontally), acting as a giant light switch for four beams, will be arranged vertically in a single replaceable unit.

一米级大口径镀金光栅

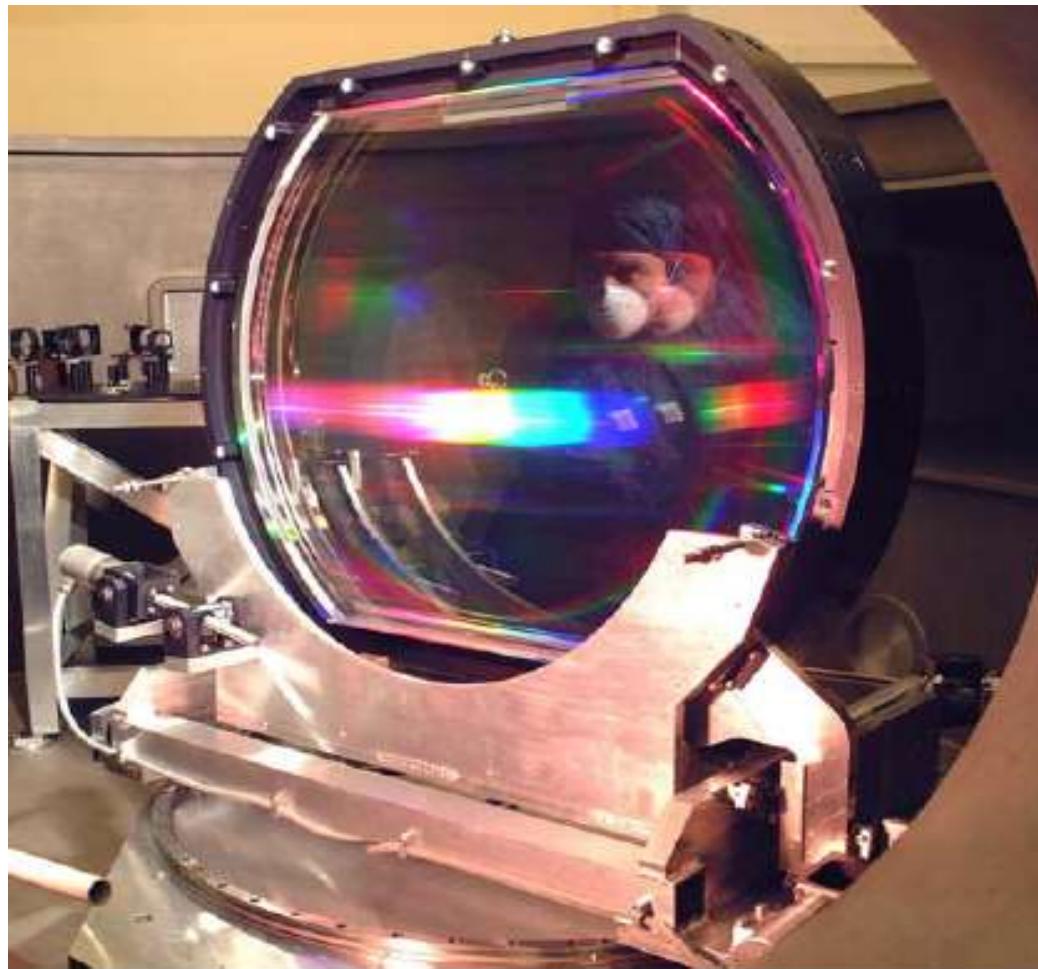
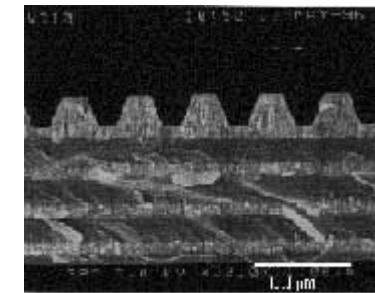
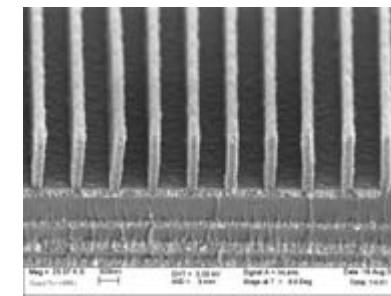
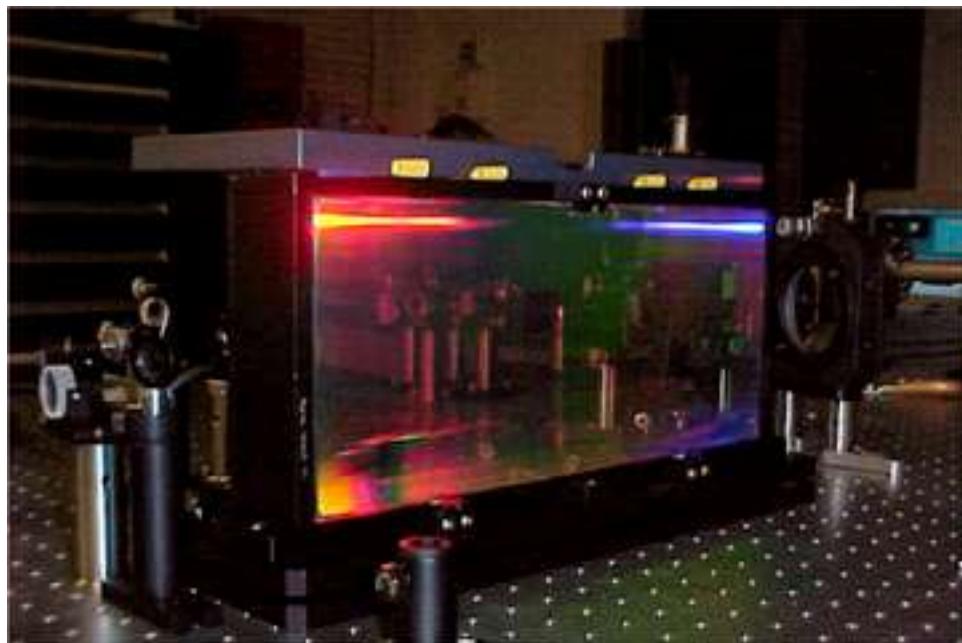
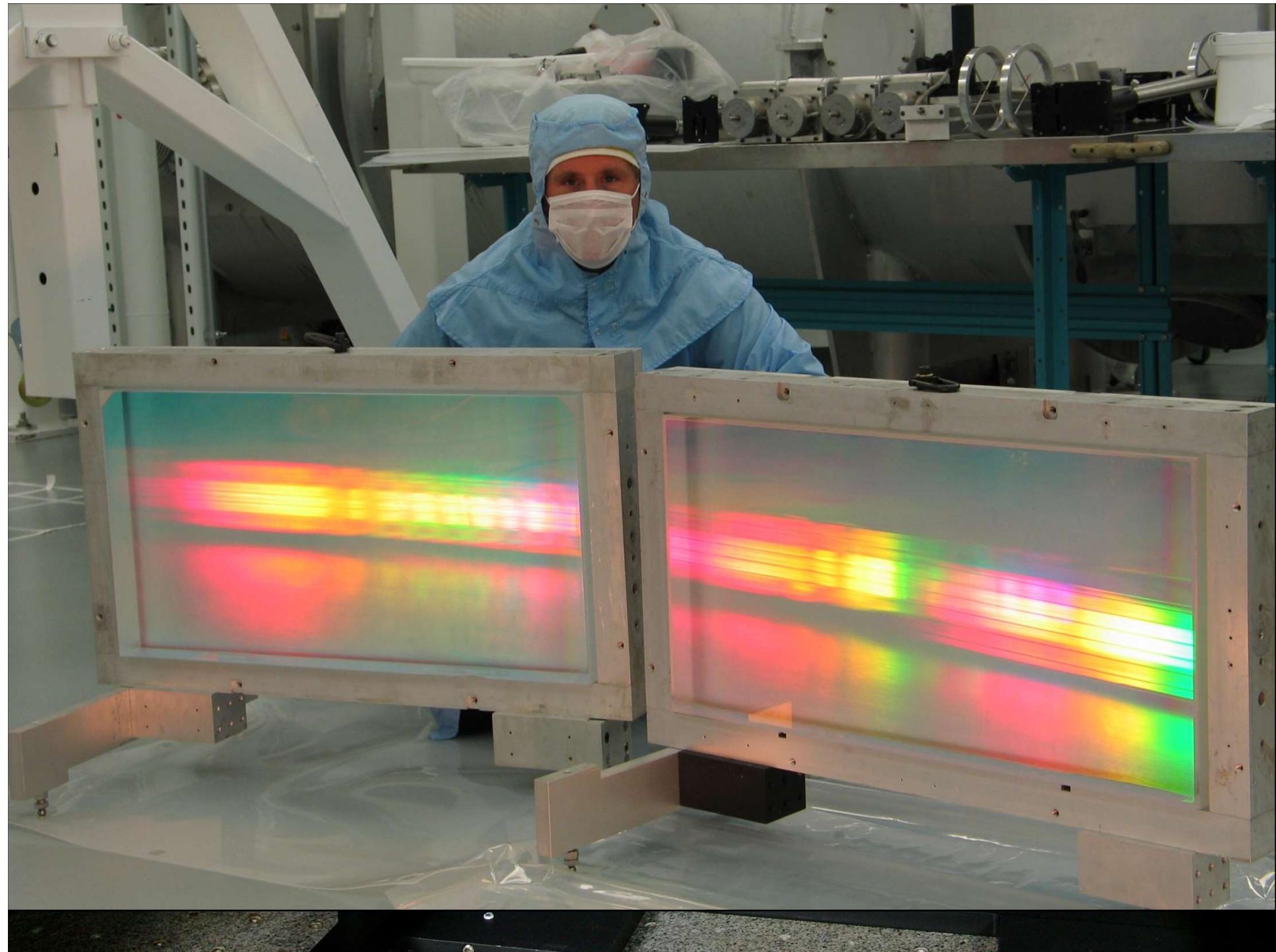


Figure 1. Petawatt Compression Grating.

大口径介质膜光栅



Microstructure of multilayer dielectric HfO₂/SiO₂ grating with 675-nm period grooves ion-beam-etched 300 nm into the top HfO₂ layer



第三个“奇迹”

美国NIF等离子体电极普克尔开关，解决寄生振荡和隔离问题。

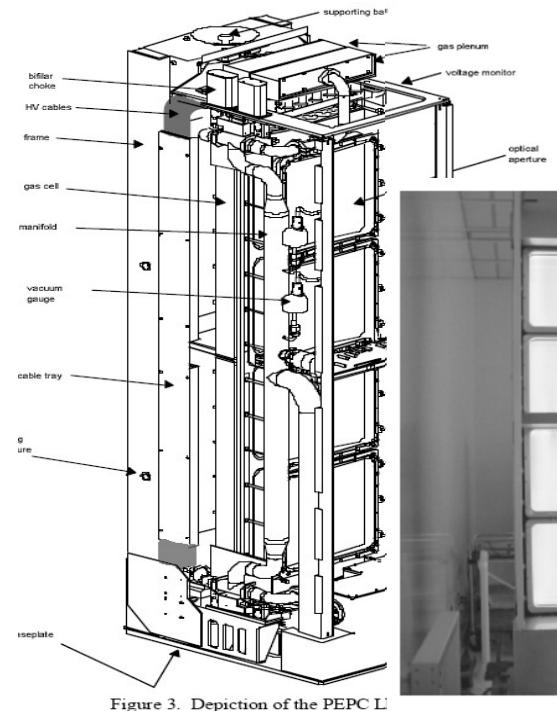


Figure 11. Main plasma discharge in the Pockels cell.

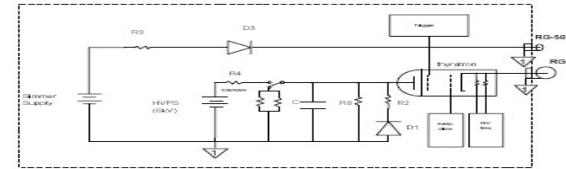
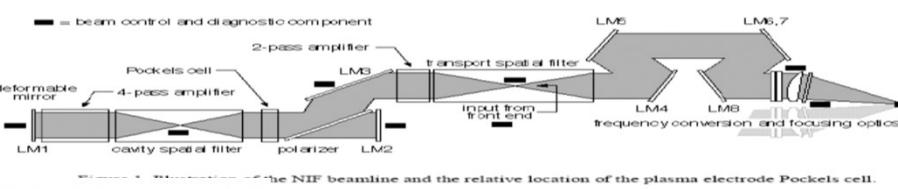


Figure 5. Schematic of PEPC Plasma Pulse Generator (PPG).

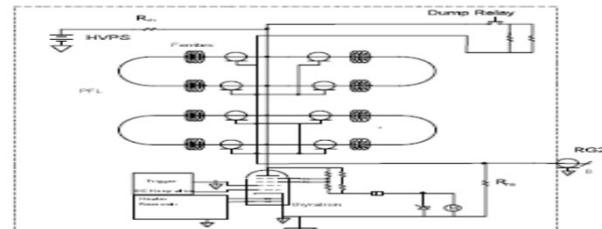
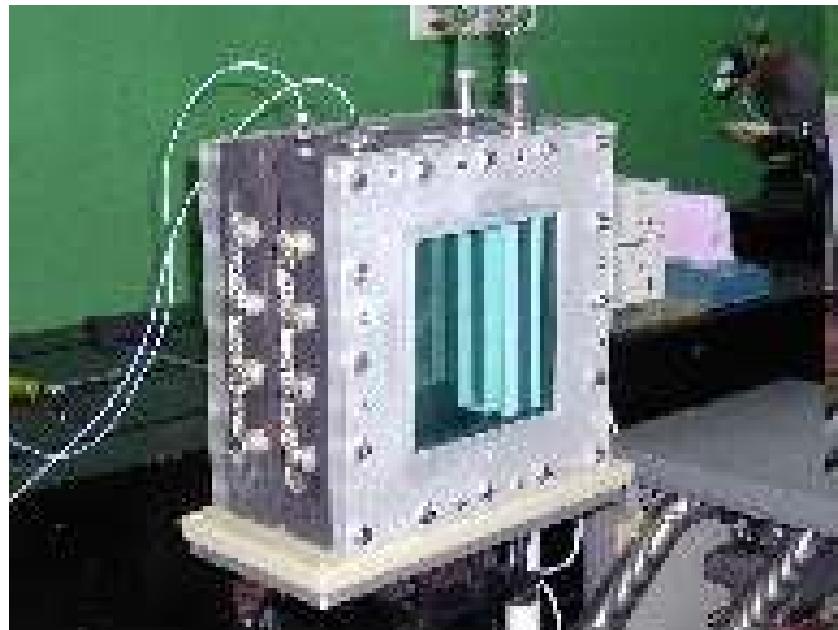
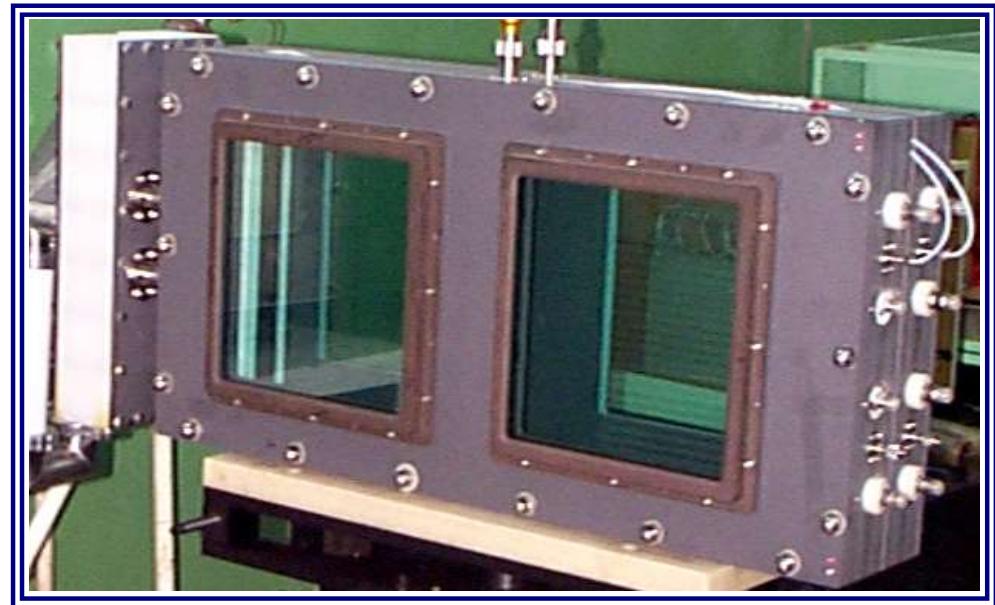


Figure 6. Schematic of the PEPC Switch Pulse Generator (SPG).

我国中物院八所中大口径PEPC初步取得成功



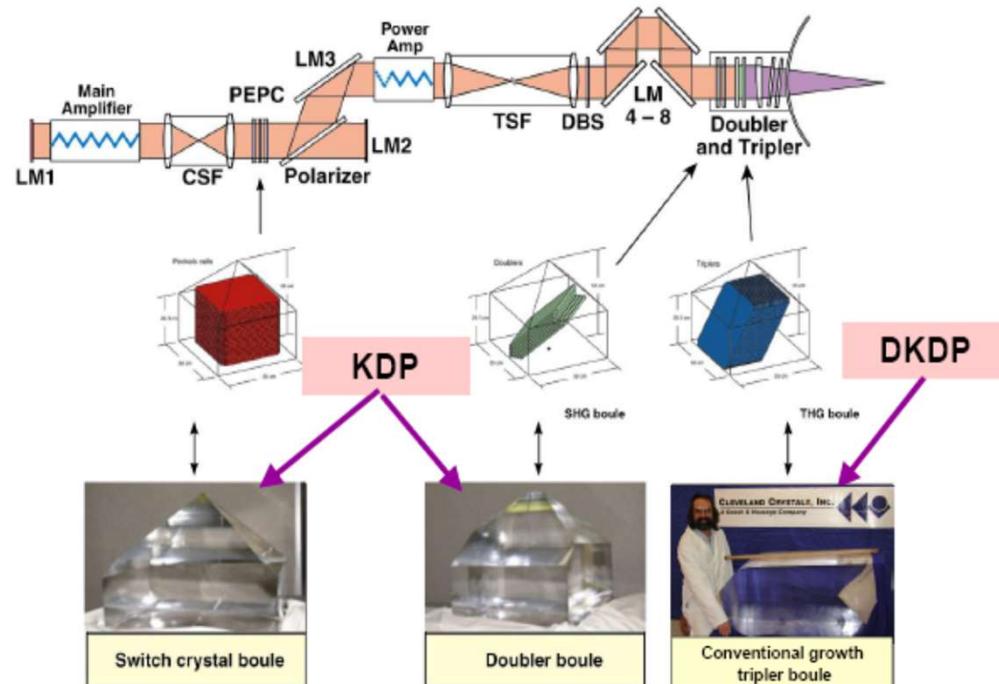
300 x 300mm 口径



1×2组合
240×240mm口径

美国NIF第四个“奇迹”

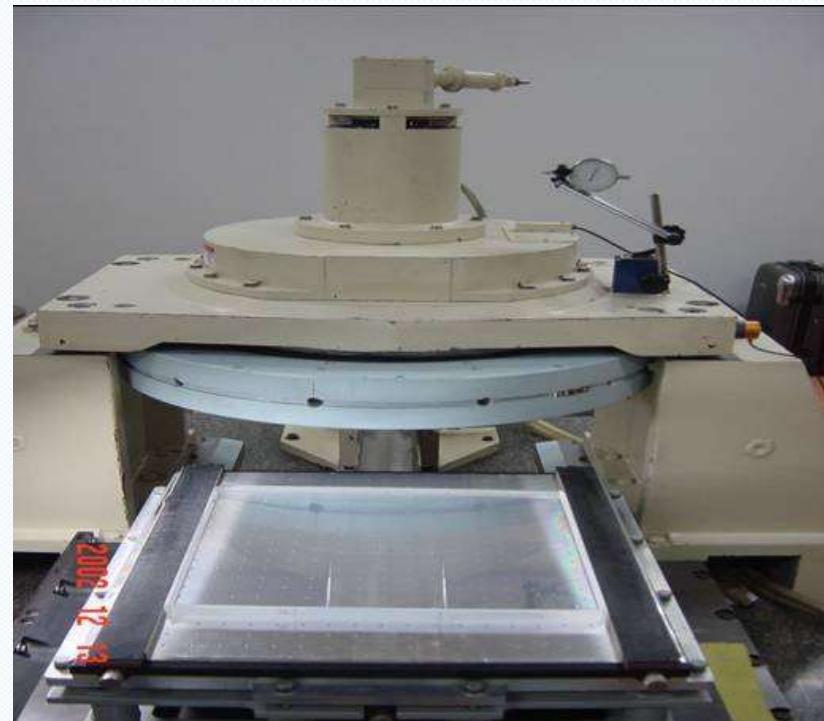
大口径KDP生长和加工，解决
PEPC和倍频需求。



	NOVA	Beamlet	NIF
Size (cm)	27 x 27	37 x 37	42 x 42
Roughness	<5 nm RMS	<5 nm RMS	<1.5 nm RMS
Roughness PSD2	No spec	No spec	$<15\text{v}^{-1.55}$, 2.5-0.12 mm
Scratch/dig	60/20	60/20	40/15
Transmitted Wavefront @ 633 nm	<0.25 lambda	<0.25 lambda	5 nm Rq, >33 mm
PSD1	No spec	No spec	$<15\text{v}^{-1.55}$, 33-2.5 mm
Transmitted Wavefront Gradient	<0.25 lambda	<0.25 lambda	11 nm/cm RMS, >33 mm
Orientation	<30 μR	<15 μR	<20 μR
Wedge (sec)	<2	<1	2±1
Surface Flatness (microns)	6	6	3.16



我国中科院物构所(福州) 和山东大学KDP快速及中速生长已经成功， KDP飞刀切割抛光接近 $\lambda/2$ (p-v)透过波前的要求



美国NIF第五个“奇迹” 39单元可变形反射镜

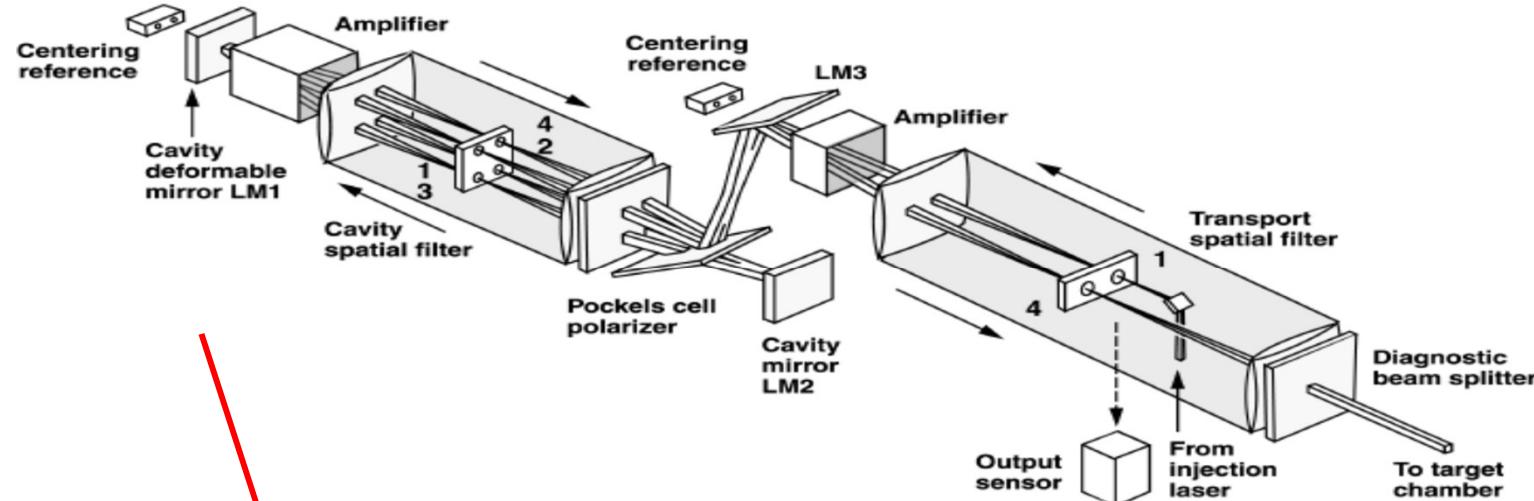


Fig. 2. The NIF 4-pass architecture incorporates alignment references, adaptive optics, and multiplexed sensor packages.

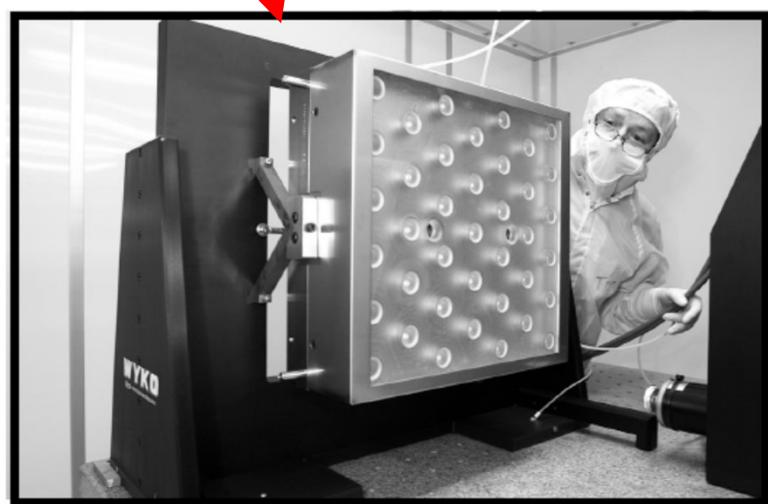


Fig. 12. Photograph of the NIF DM and concept sketch showing major components.

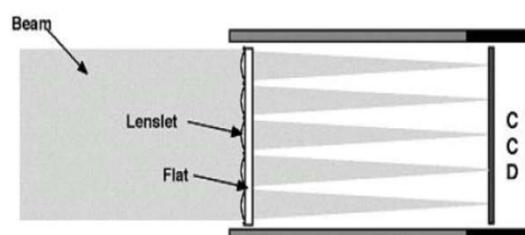
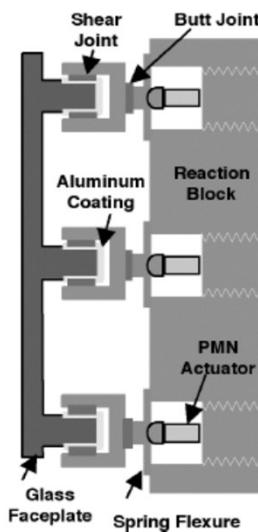


Fig. 13a. Shack-Hartmann sensor concept sketch.

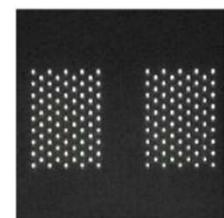


Fig. 13b. Focal plane image of dual-beam Hartmann sensor.

高功率脉冲氙灯

(a)



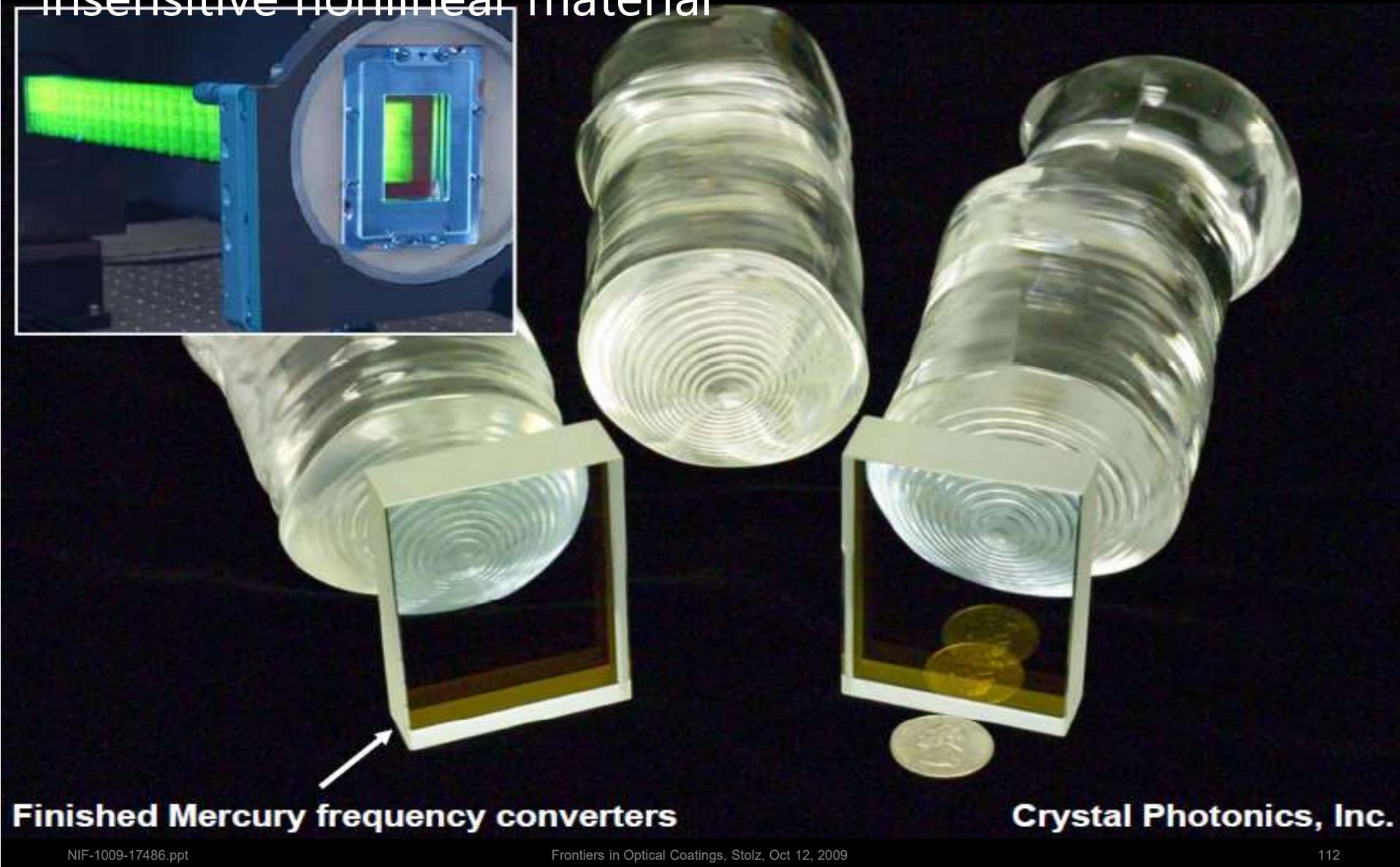
(b)



Figure 5. (a) Technician Wanda Dallum holds a flashlamp, the largest commercial unit ever manufactured. (b) Technicians install a cassette of flashlamps in Livermore's Amplab.



Frequency conversion efficiency >70% was demonstrated on Mercury using YCOB, a thermally insensitive nonlinear material



Finished Mercury frequency converters

Crystal Photonics, Inc.

Deterministic finishing technologies such as MRF will be needed for crystal and glass finishing



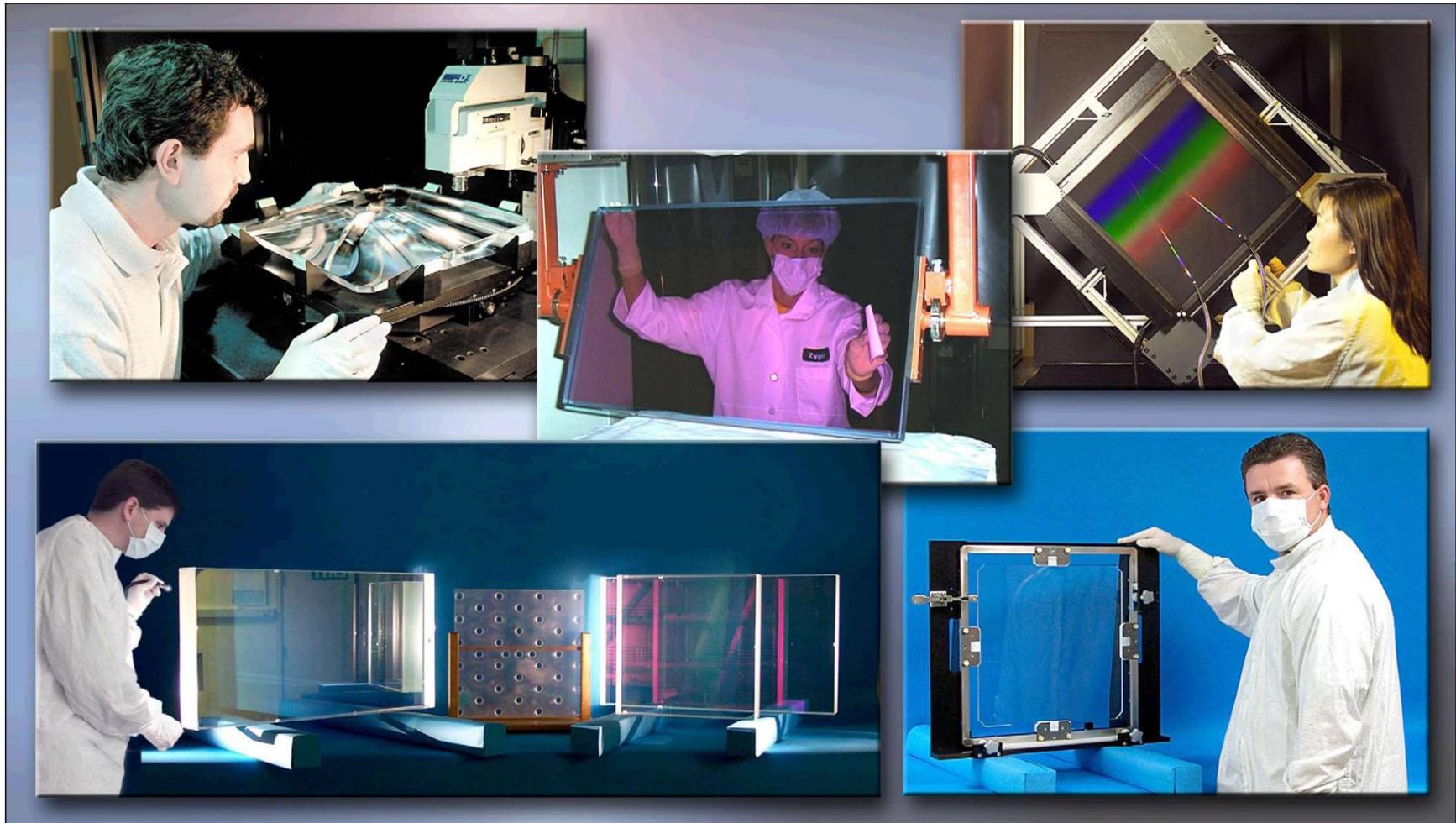
Optical coatings will need to withstand
~10 Hz operations at high fluence for decades



Preconditioning & damage
stabilization of optical
coatings will be needed to
achieve lifetimes

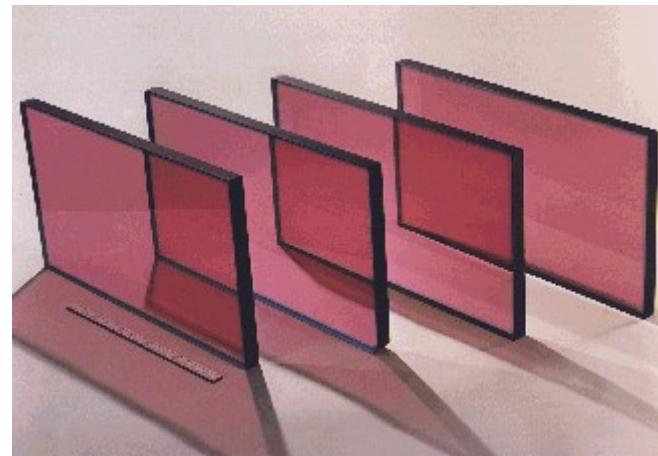
Laser
conditioning







磷酸盐钕玻璃片
3072件



The National Ignition Facility

The NIF building complex was completed in September 2001. Spanning the length of two football fields, the facility will house 192 laser beams in two bays in precision-aligned and environmentally controlled conditions. The aerial photograph of the NIF facility has been combined with a computer-generated model revealing one bay of the laser system. NIF is scheduled to deliver its first laser light to the target chamber in 2003 and will be completed with all 192 laser beams operational in 2008. You are invited to follow the progress of NIF on our web site <http://www.llnl.gov/nif>.

7 A 360-degree panorama of the Class 100 clean room facility in the Optics Assembly Building.



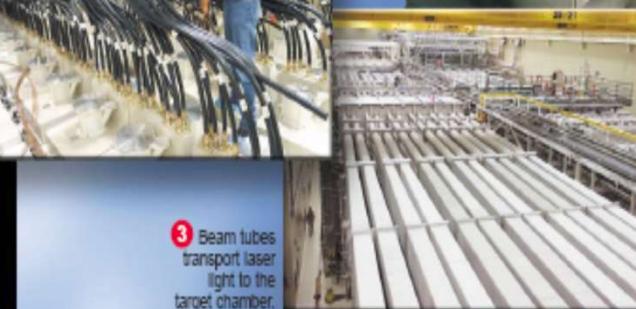
1 The NIF laser contains more than 3000 pieces of amplifier glass. They are cleaned and assembled into modules before automated guided vehicles install them into the laser system.



2 The cable plant delivers electrical power to the flashlamps in the amplifier system.



3 Beam tubes transport laser light to the target chamber.



6 The NIF Control Room controls all aspects of the laser system and target experiments.



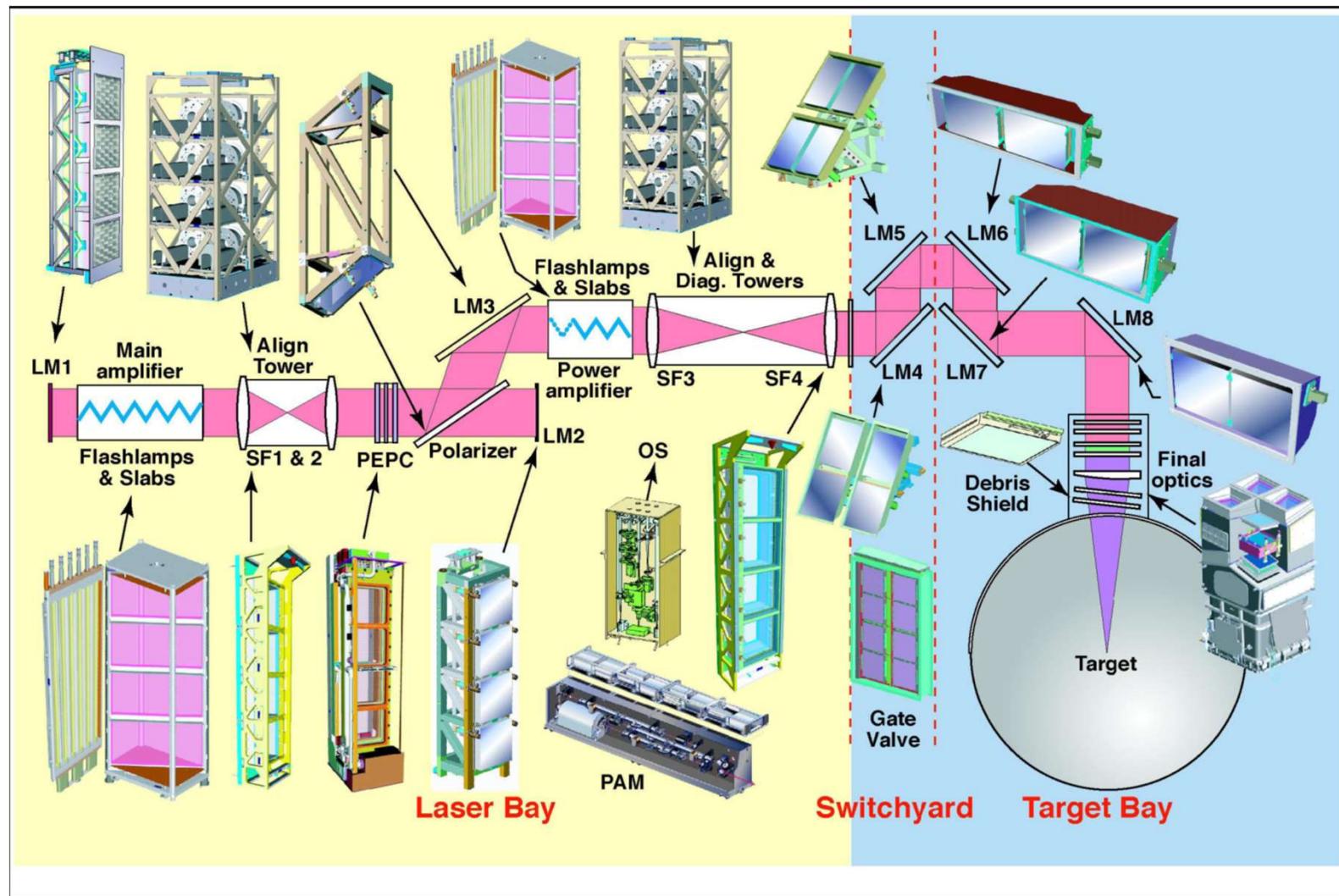
5 At the center of the 10-meter-diameter target chamber, the 192 ultraviolet laser beams converge on the target.

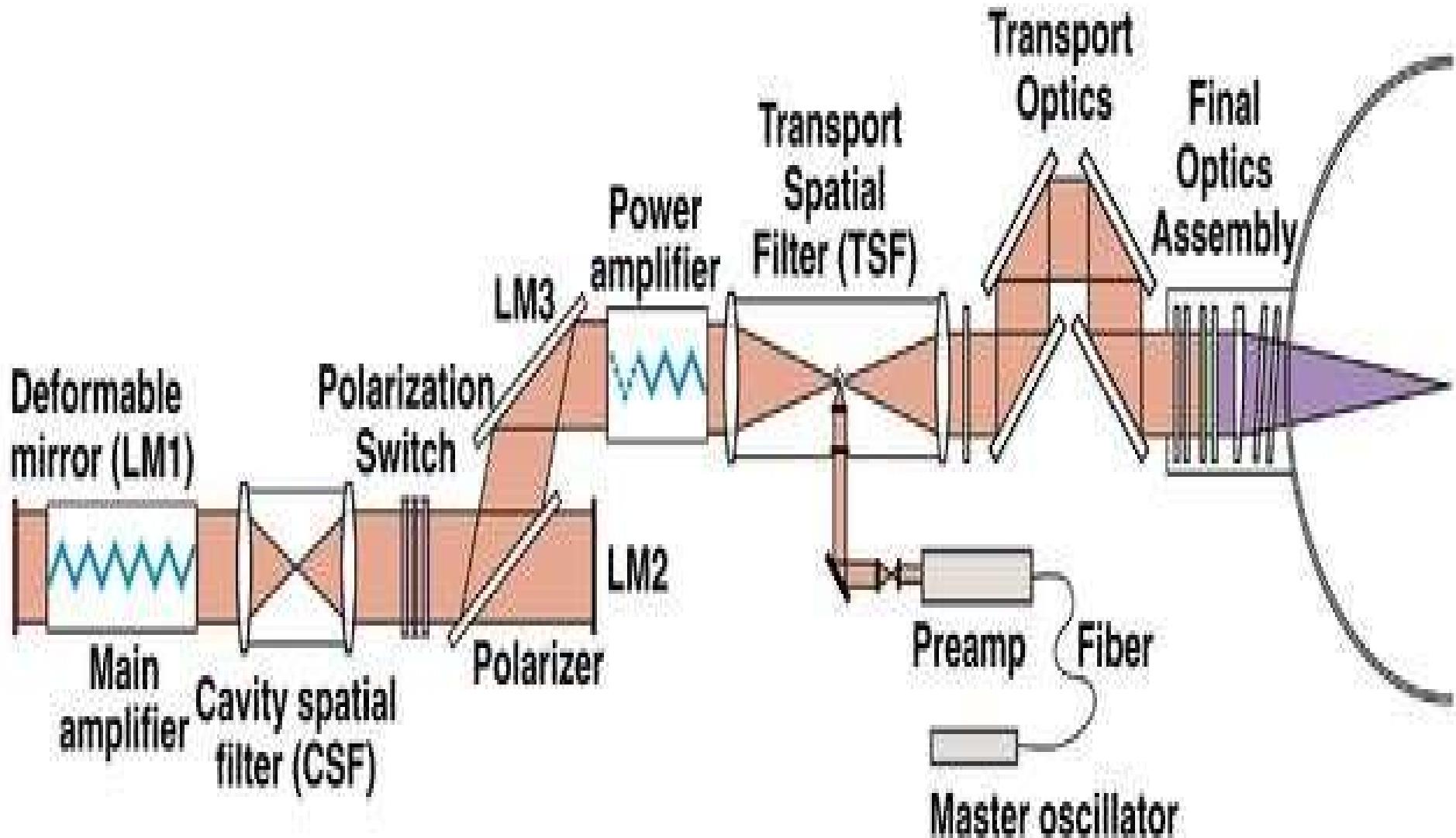


4 Slices of giant crystals convert the infrared lasers to ultraviolet light before the beams enter the target chamber.



34亿美元投入，带动了激光与光电子产业的发展

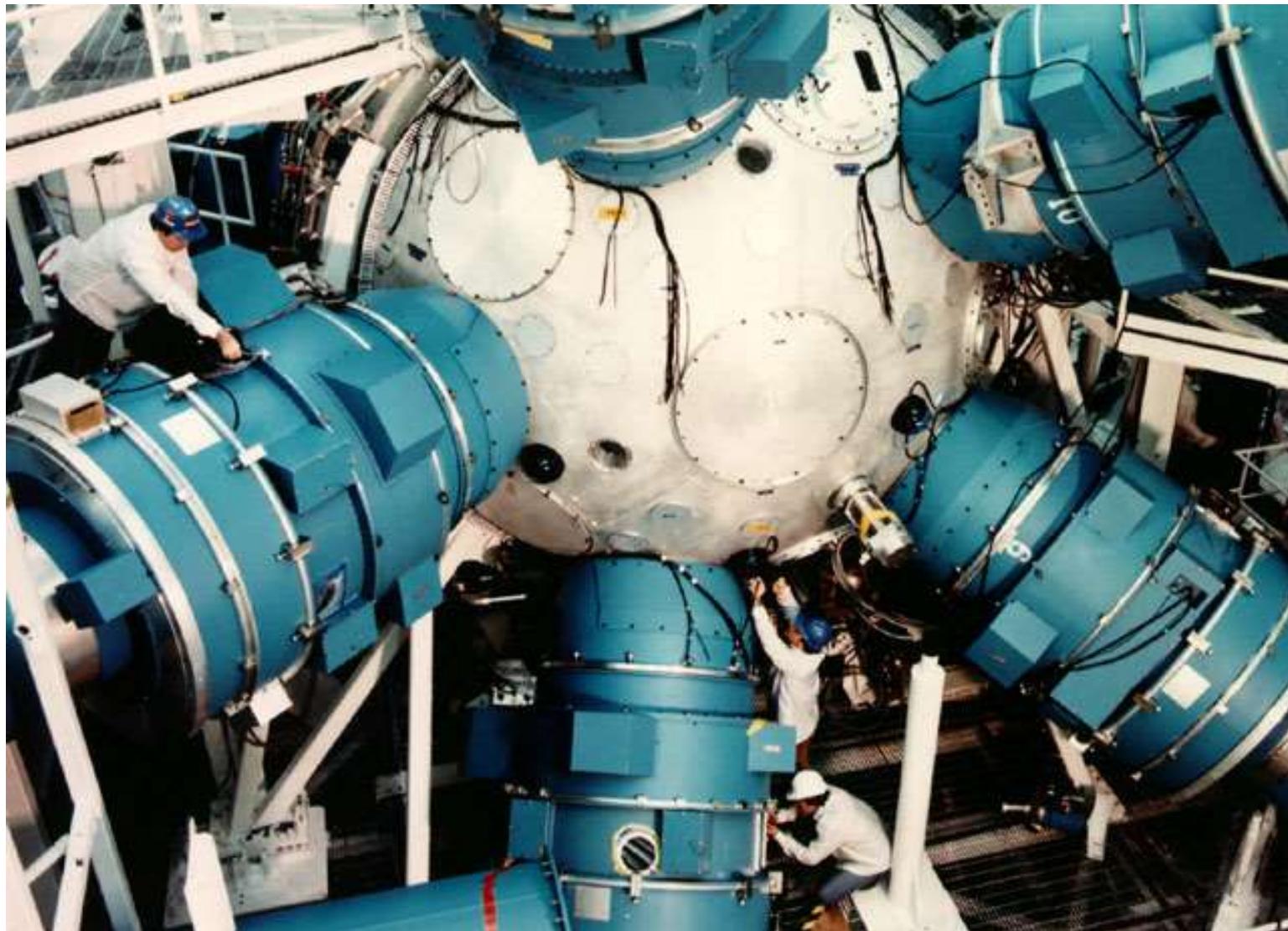




日本大阪大学“激光-XII”装置
(1983 12beam/Φ200mm , 15KJ/3ω)

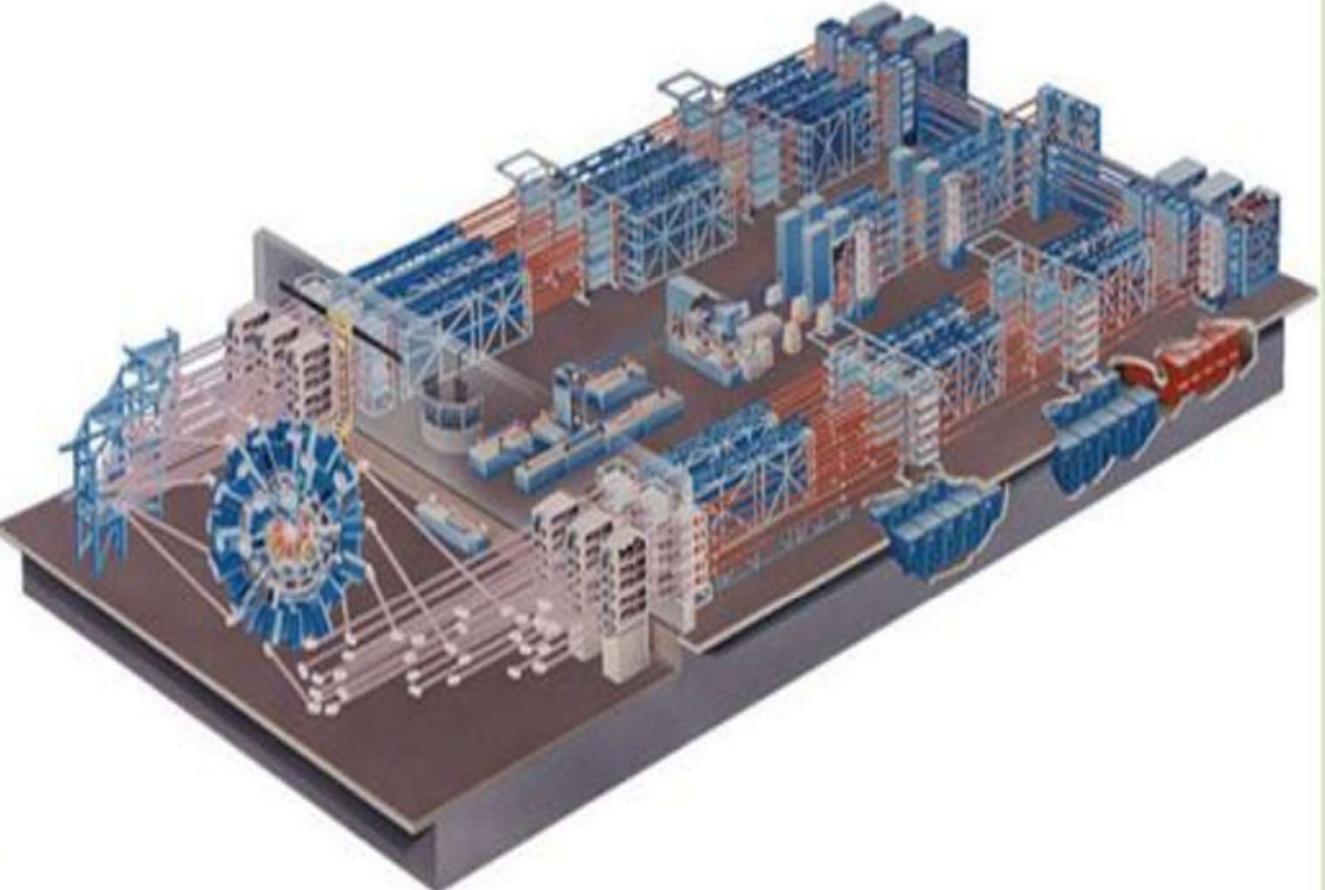


NOVA 装置的十路激光靶室

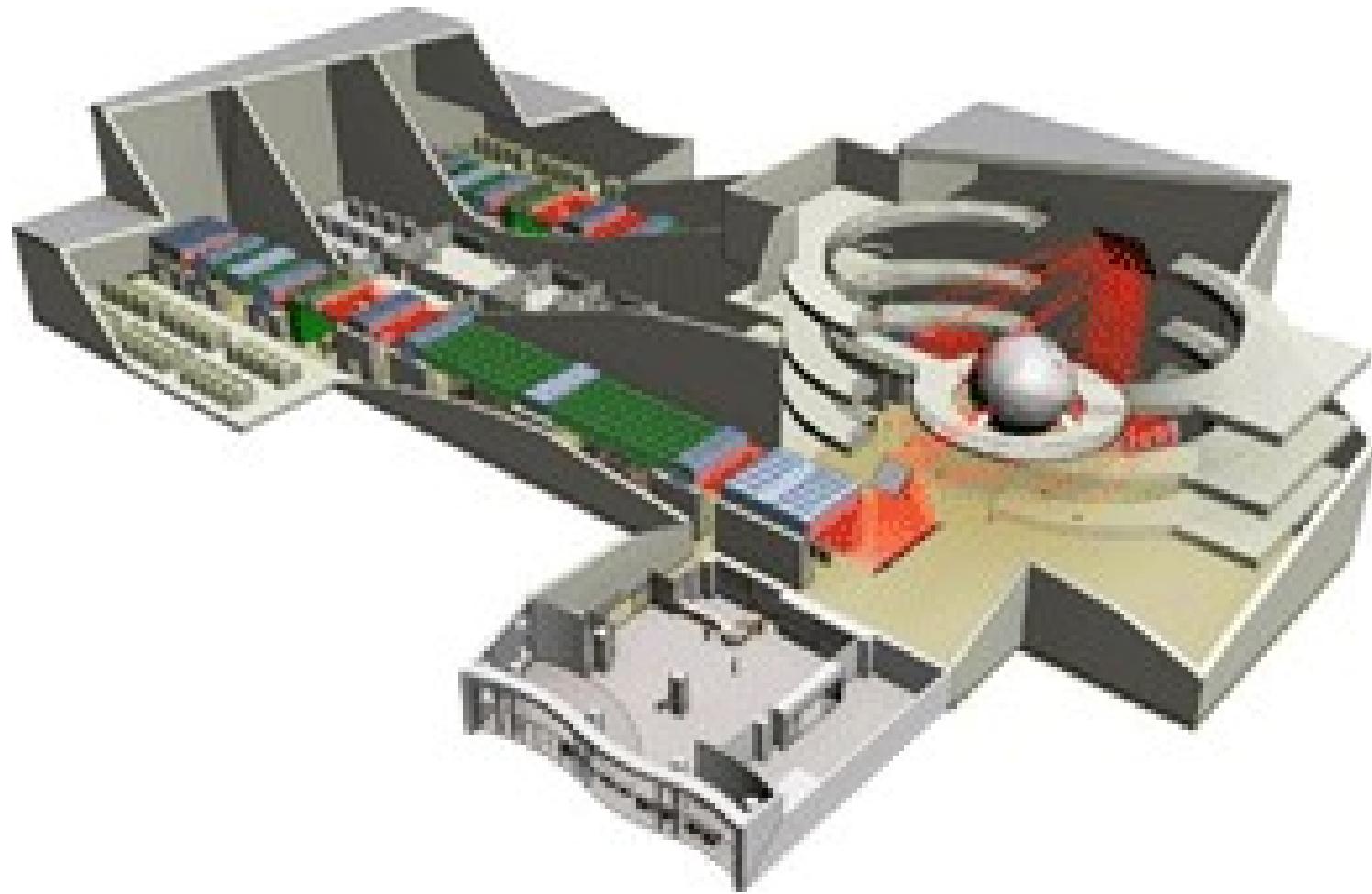








NOVA 装置的内部（左）与 OMEGA 装置图（右）



欧盟的 HiPER 装置图



日本GEKKO-XII 激光器输出脉宽 1ns，12 路激光束，输出能量为 5~8kJ

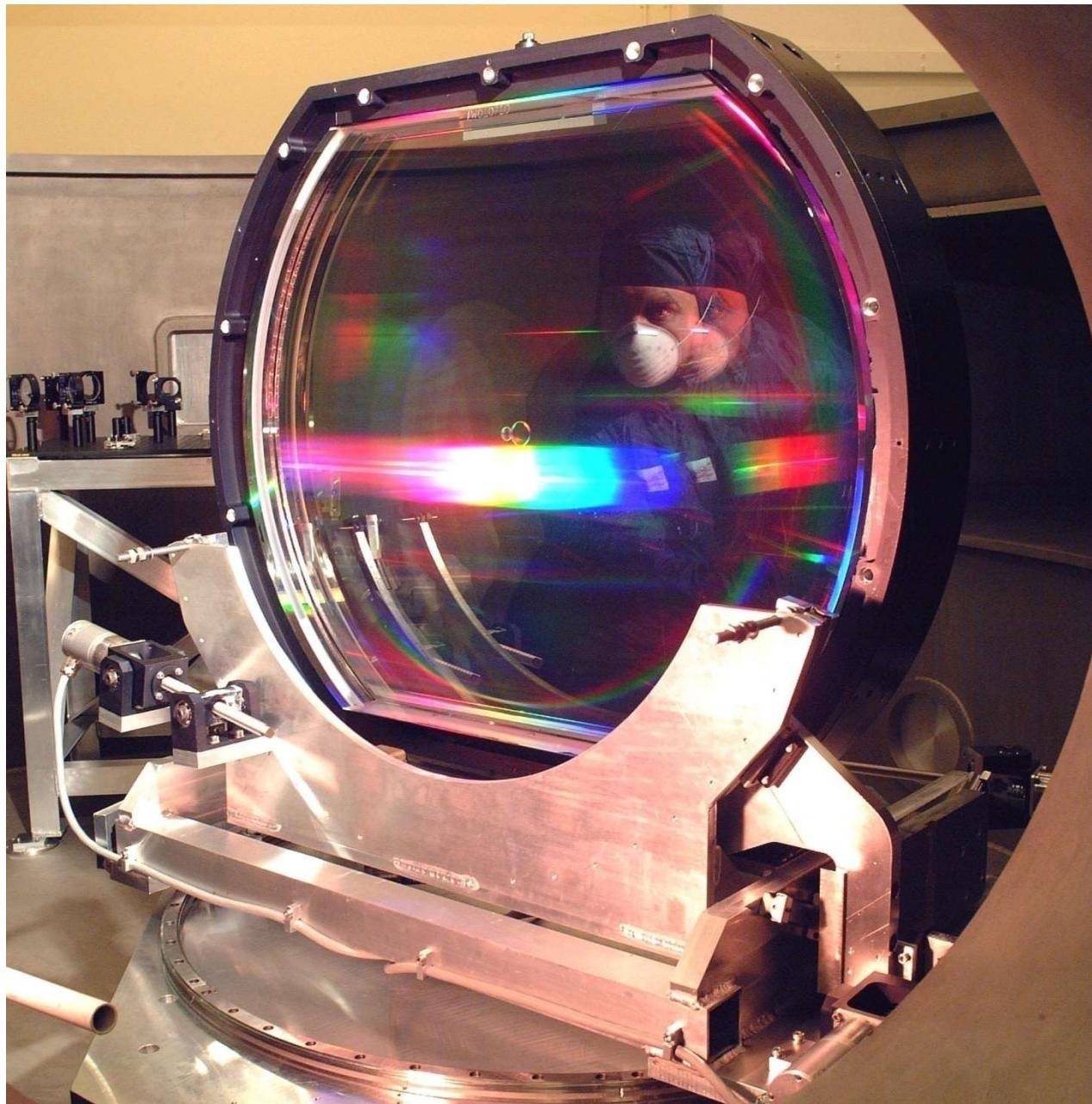


NEW PETAWATT TARGET AREA JUNE 2002









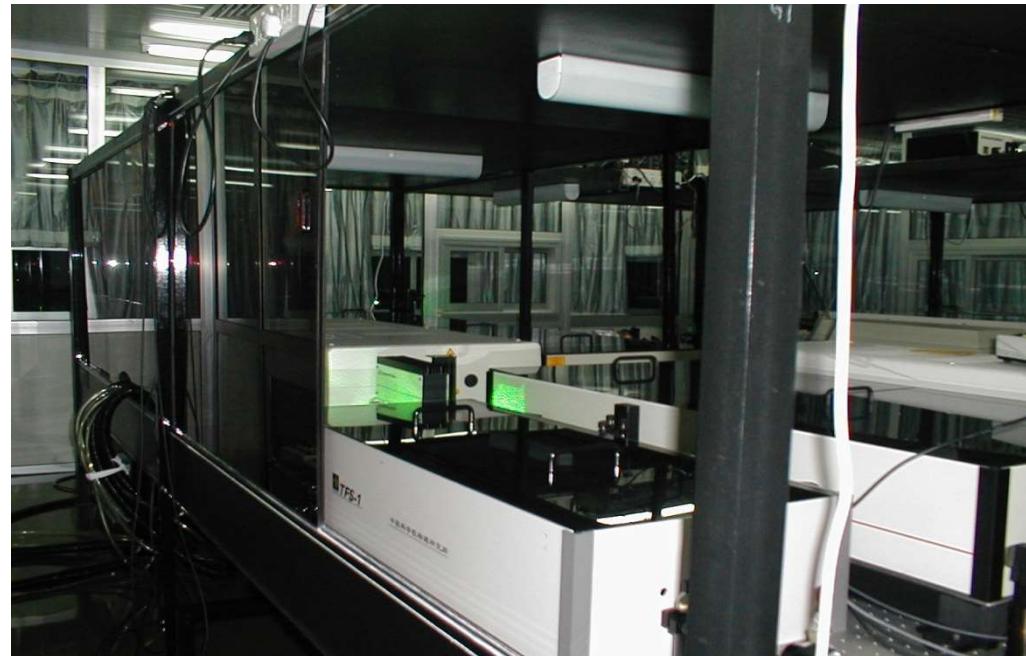
日本JAERI的100TW/10Hz的激光装置



C103 High peak power T-cube laser laboratory

中科院物理所极光二号—20TW飞秒激光装置

建成20TW级的
飞秒激光装置
聚焦功率密度
超过 10^{19}W/cm^2
成为世界上为
数不多的可以进
行相对论光强
实验的装置



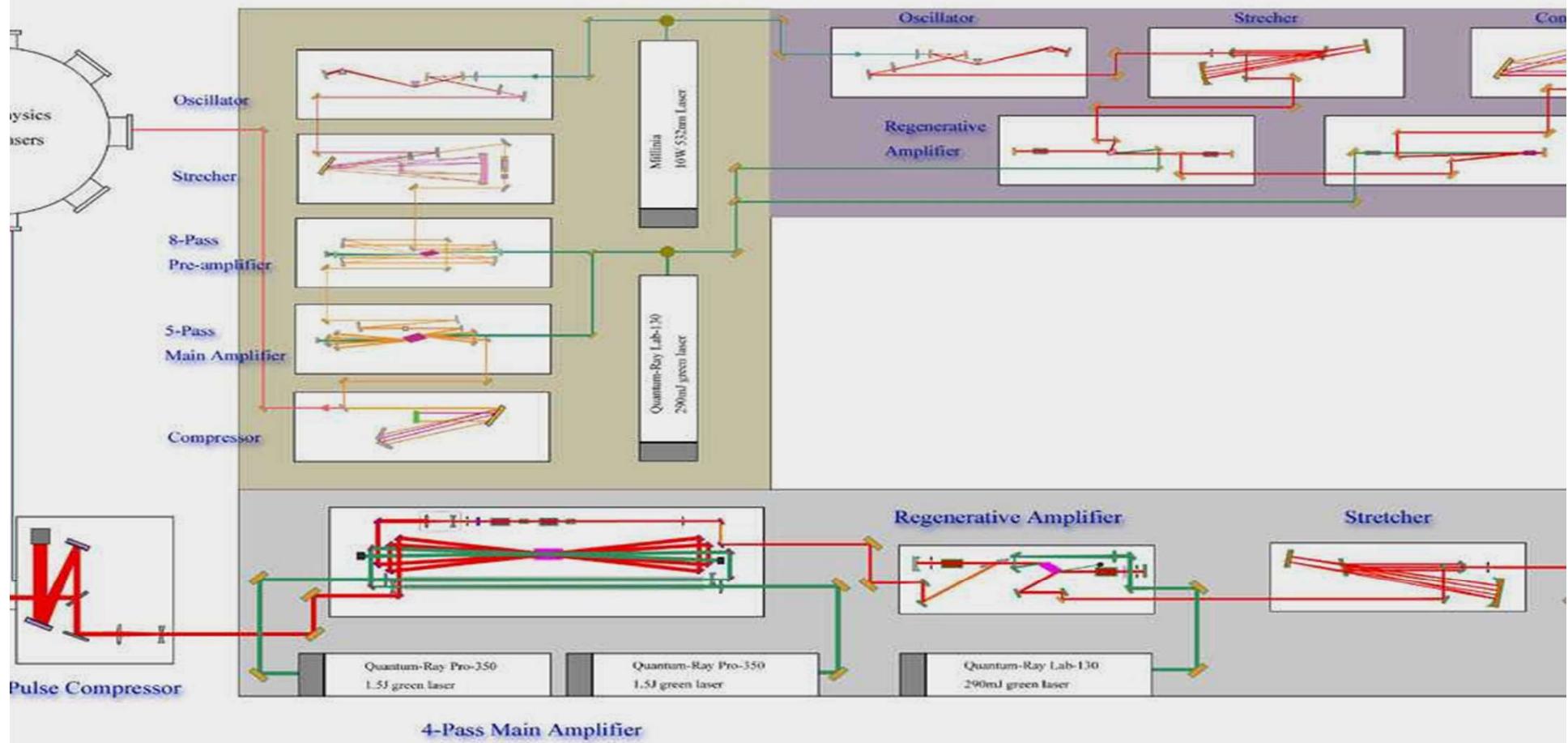
640mJ/30fs, 20TW= $2 \times 10^{13} \text{W}$, 聚焦功率密度> 10^{19}W/cm^2

JG LASER FACILITY FAMILY

Laboratory of Optics

JG-I Laser Facility

>1TW, 35mJ/25fs, 10Hz



Milli-Joule Laser Facility

5mJ, 150fs, 10 Hz

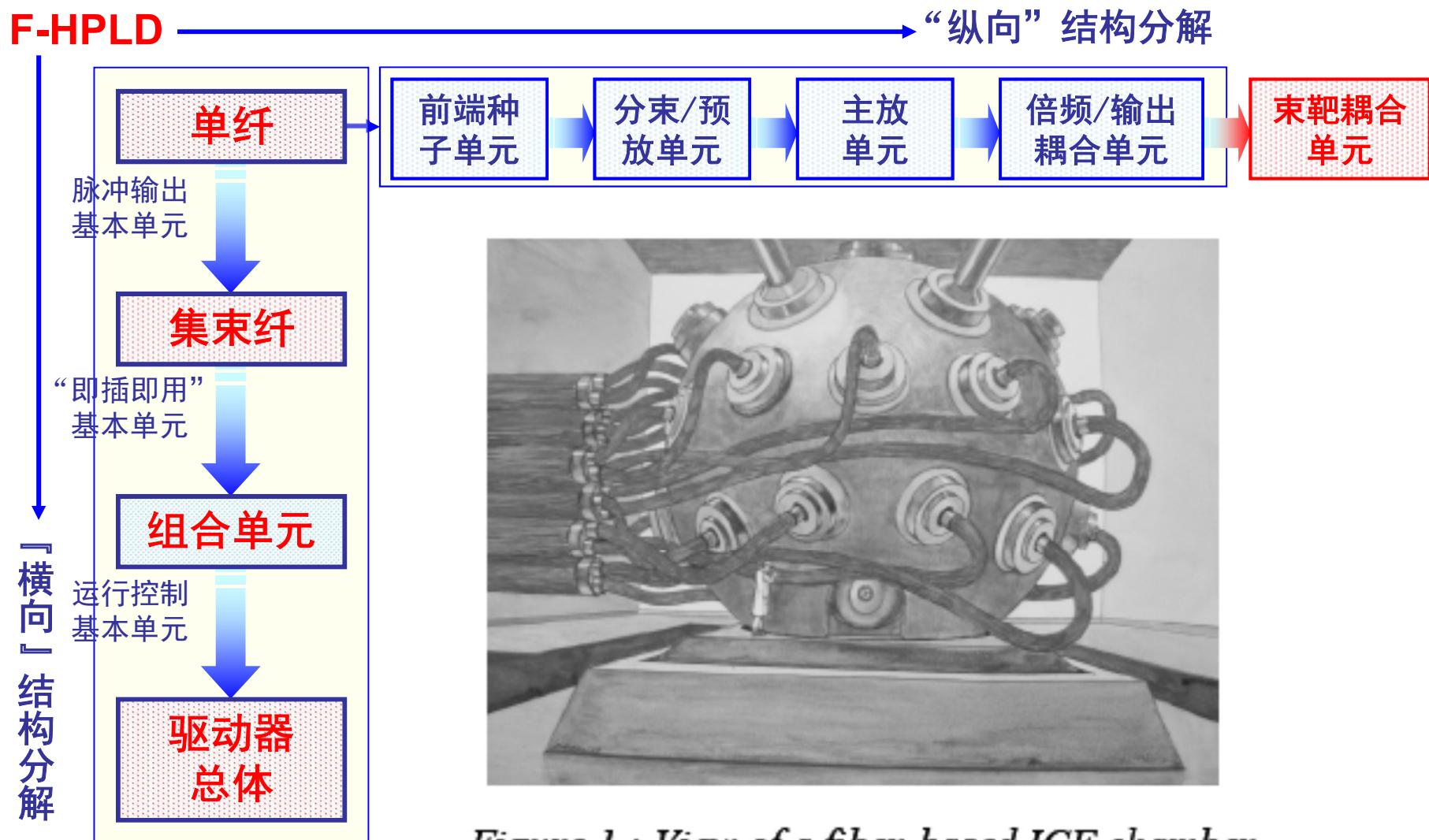
JG-II Laser Facility

20TW, 600mJ/30fs, 10Hz

世界上现有的超短超强激光装置

国家	研究机构	峰功率 (TW)	能量 (J)	脉冲宽度 (fs)	聚焦光强 (W/cm ²)	建成年代
美国	LLNL—Petewatt	1500	660	440	7×10^{20}	1994-97
	LLNL—JanUSP	200	15	75-80	2×10^{21}	2000
	MI —ALFA-2	240	6	25	10^{20}	1998
日本	ILE —PWM	60-100	45	800	5×10^{19}	1998
	JAER1	100		19	10^{20}	1999
法国	LULI	100	30	300	10^{19}	1998
英国	RAL—Vulcan	100	70	700	5×10^{19}	1998
	RAL—VulcanPW	1000	500	500		2002
中国	中科院物理所	20	0.65	30	3×10^{19}	2001
中国	上海光机所	15	0.5	40		2001
中国	中物院八所	(100)	(10)	(100)		(建造中)

“波导之路”



- 光纤激光放大器
- 摻铒光纤放大器(1550nm)
- 摻钕光纤放大器 (900nm, 1050nm, 1300nm)
- 摻镨光纤放大器 (1300nm)

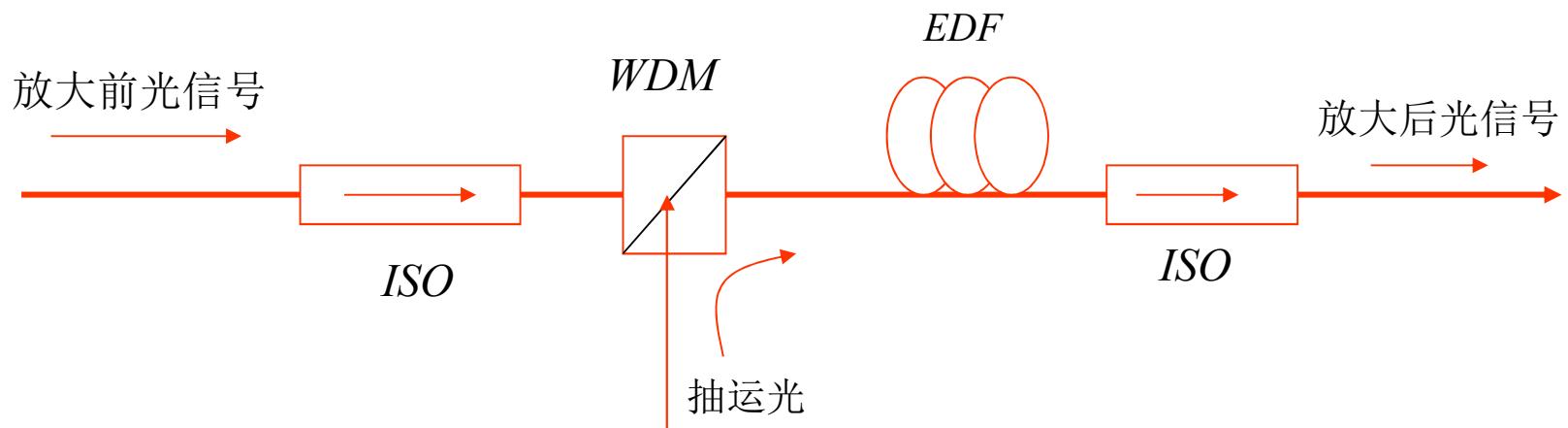
分布式光纤放大器：

光纤拉曼放大器--利用光纤中受激拉曼散射

光纤布里渊放大器-利用光纤中受激布里渊散射

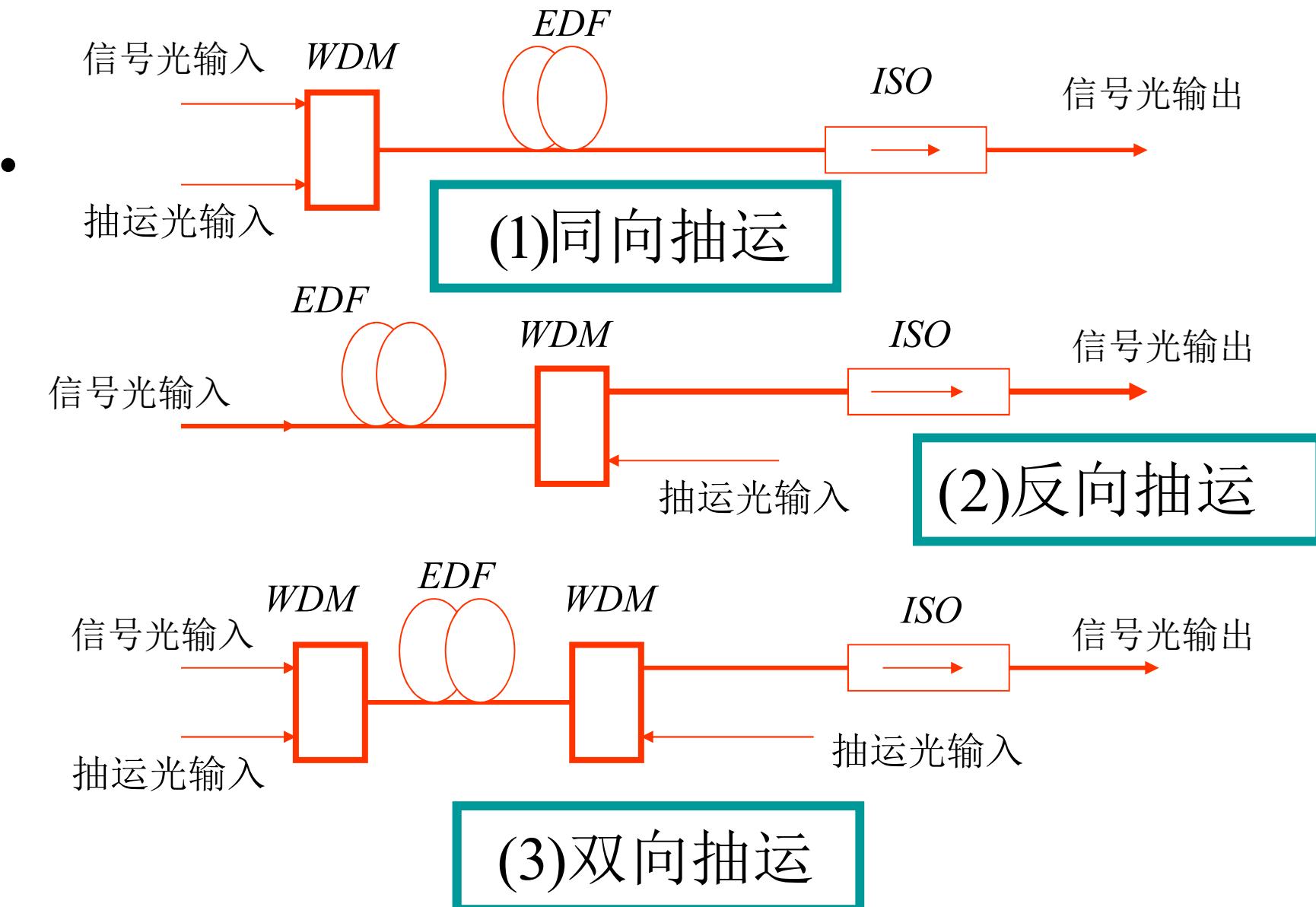
-
-

- 摊铒光纤放大器(1550nm)
- 光波信号经光隔离器后与抽运光一起在合波器的耦合下进入掺杂（如摊铒）光纤，在光纤中抽运光把能量转换到信号光上，实现信号光的放大。

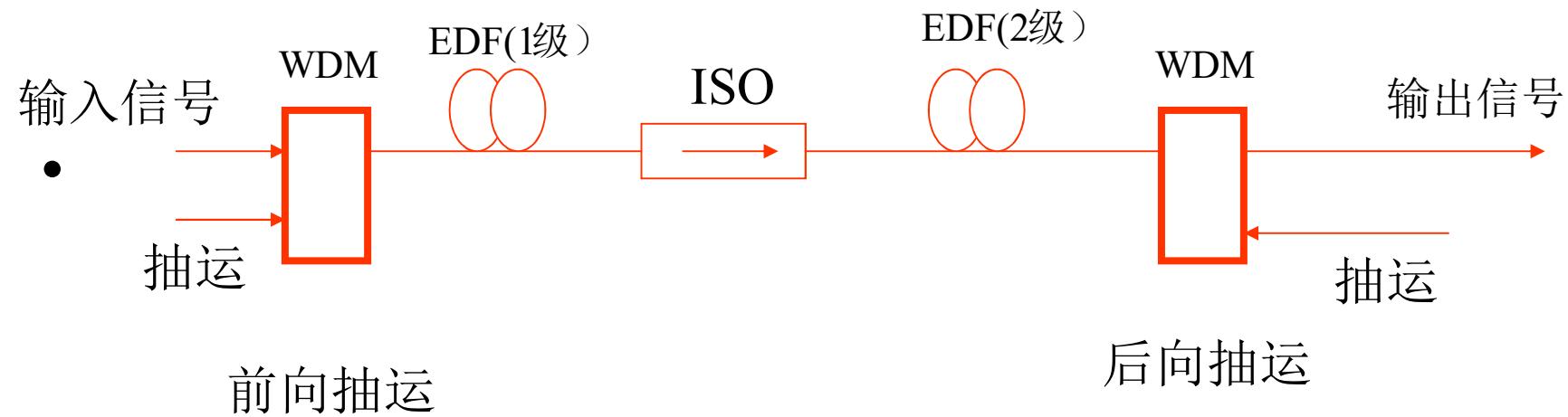


光纤放大器的基本结构

单级掺铒光纤放大器的不同抽运方式

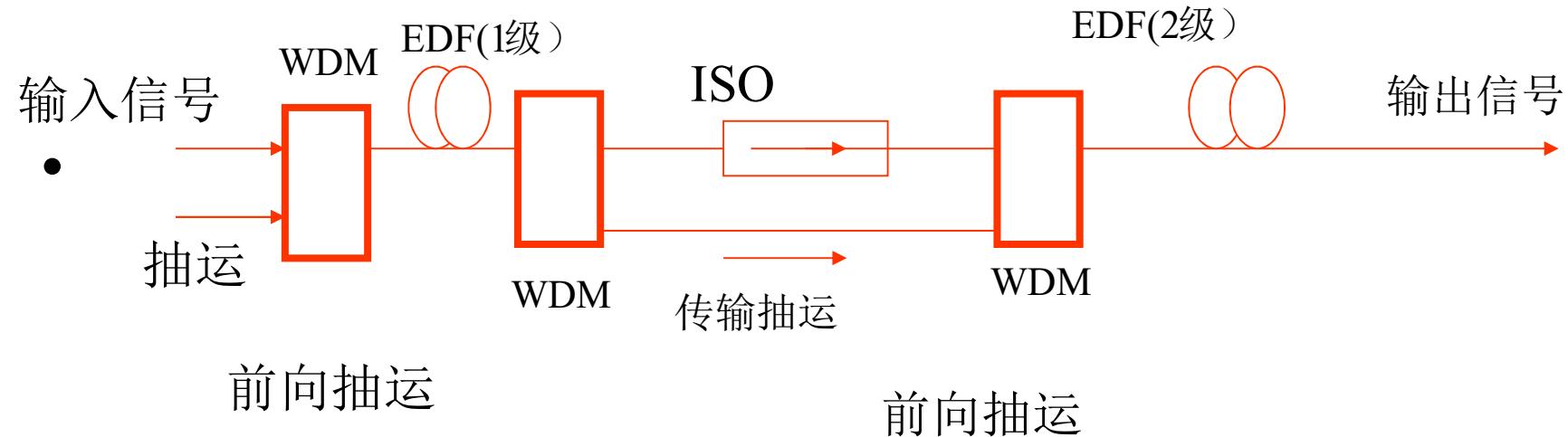


两级光纤放大器



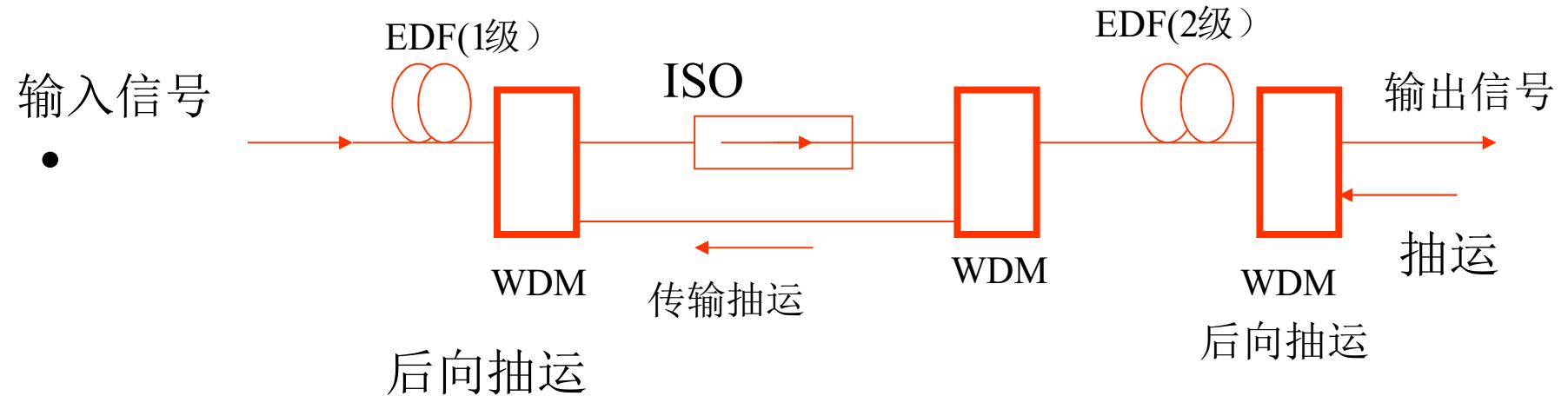
同向（信号光与抽运光 同向）和反向（信号光 与抽运光反向）抽运方式

两级光纤放大器



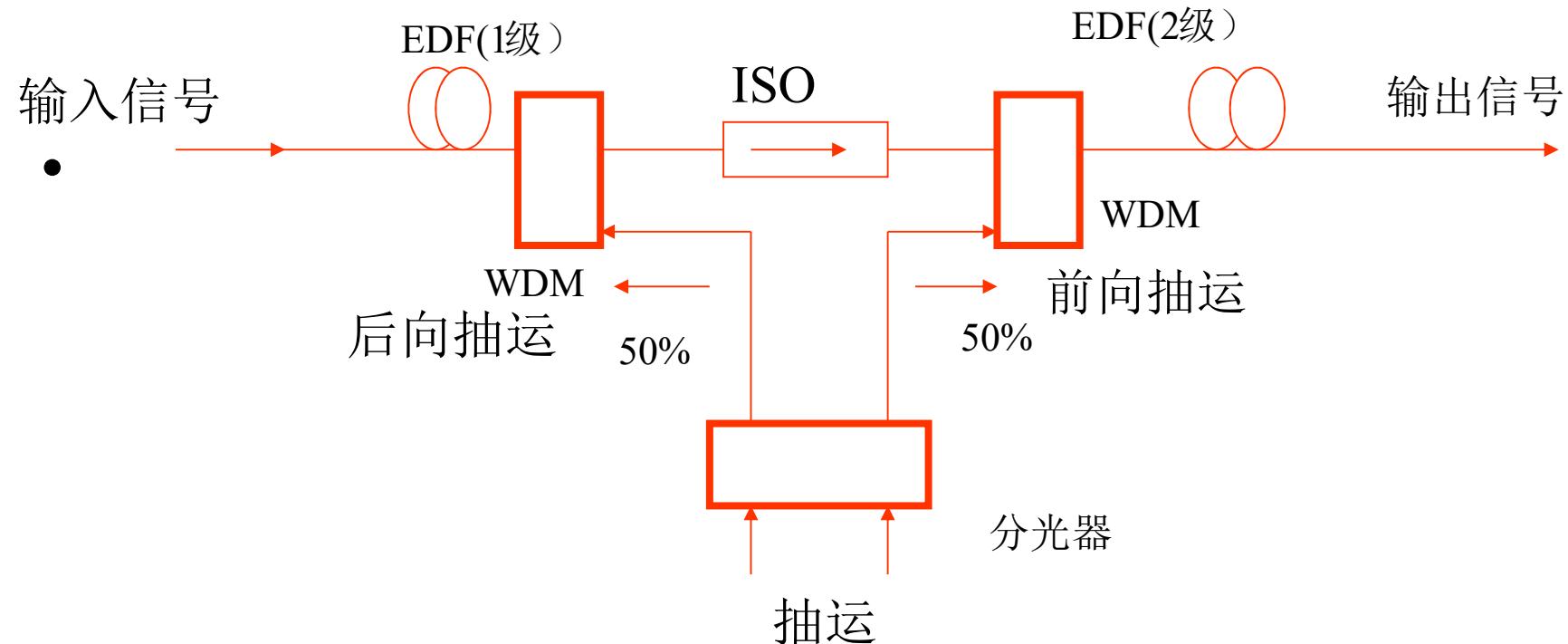
同向（信号光与抽运光 同向）和同向（信号光 与抽运光同向）抽运方式

两级光纤放大器



反向（信号光与抽运光 反向）和反向（信号光 与抽运光反向）抽运方式

两级光纤放大器



反向（信号光与抽运光 反向）和同向（信号光 与抽运光同向）抽运方式