強光雷射與強場物理

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強光雷射

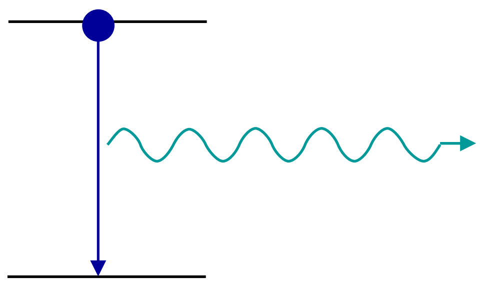
- 飛秒脈衝的產生
- 飛秒脈衝的放大
- 飛秒脈衝的測量
- 飛秒脈衝的波形控制
- 中研院的10兆瓦雷射
- 中央大學的100兆瓦雷射

強場物理

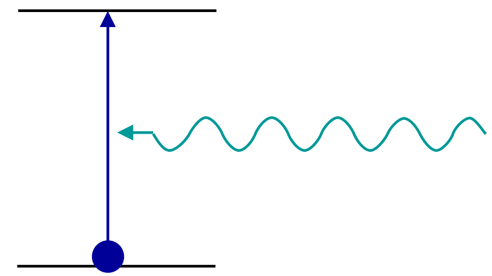
- X光雷射
- 電子加速器
- 質子加速與中子源
- 在實驗室模擬黑洞
- 雷射驅動核融合

原子如何發光？

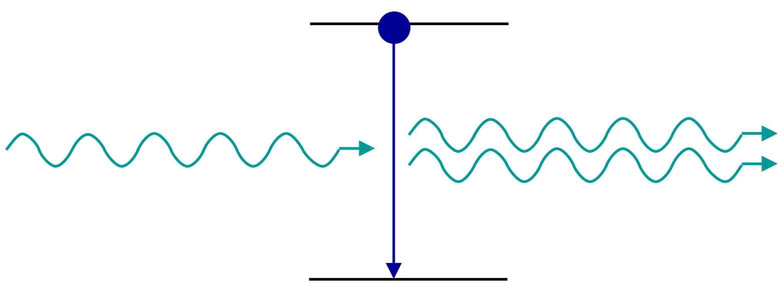
自發放光



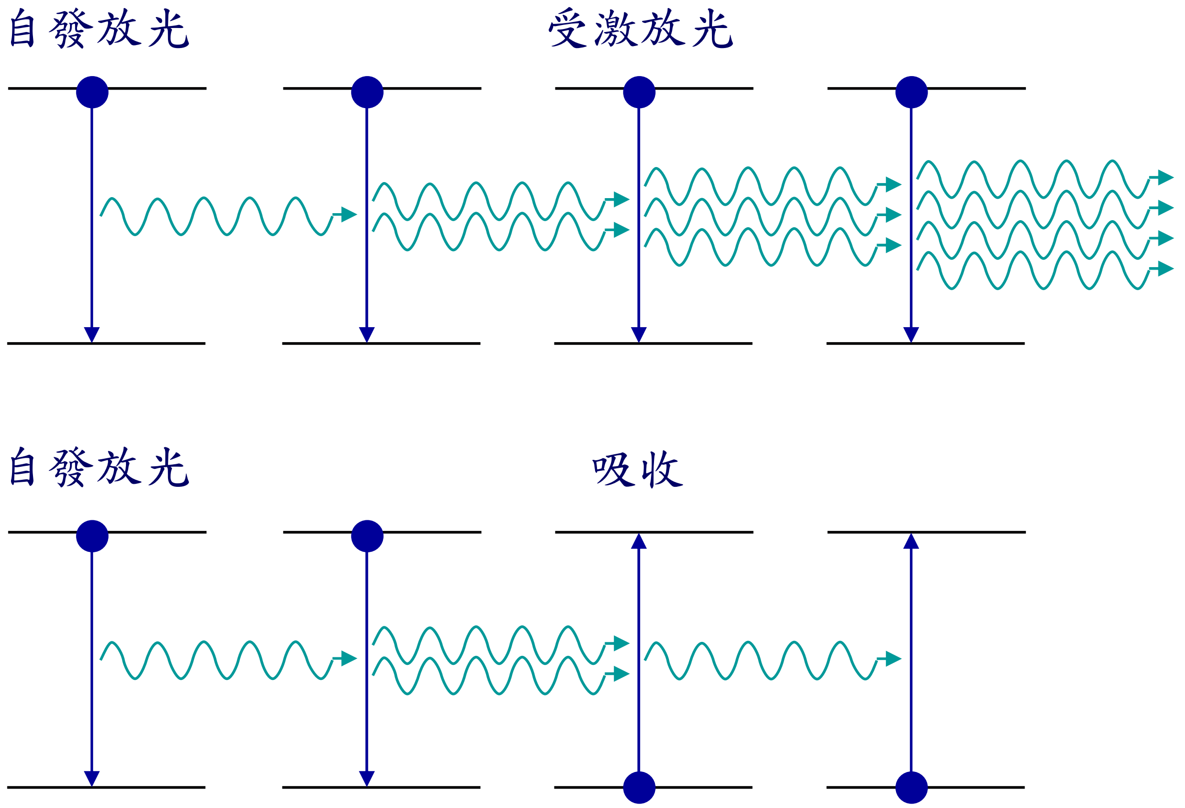
吸收



受激放光

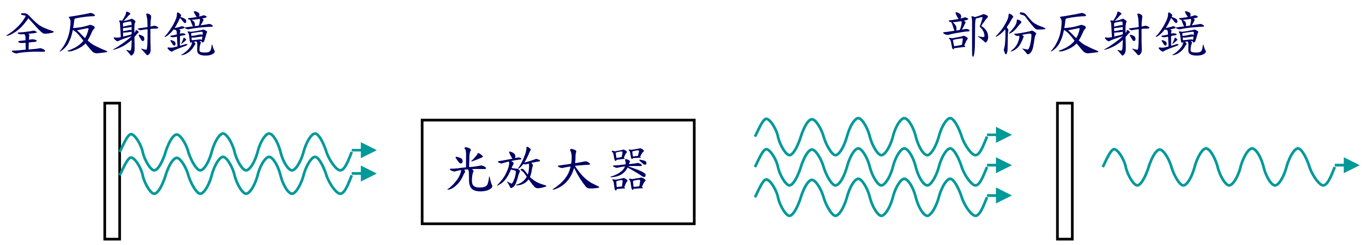


光放大器



光放大的條件：高能階的原子數大於低能階的原子數(居量反轉)

雷射的原理



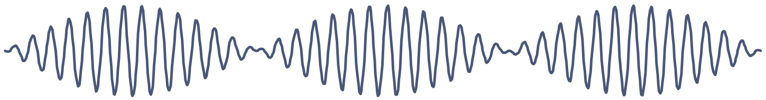
共振腔的功能：(1)限制雷射光的行進方向

(2)限制雷射的頻率

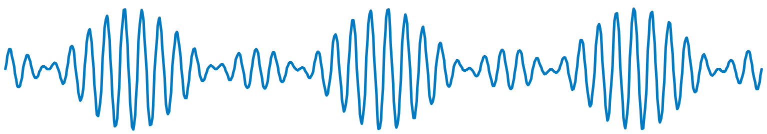
共振條件： $L = \frac{n\lambda}{2}$

光脈衝的組成

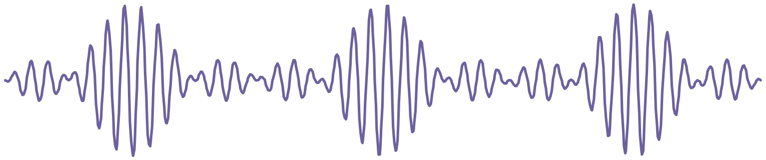
二個頻率的波相加



三個頻率的波
同相相加



四個頻率的波
同相相加



十個頻率的波
同相相加

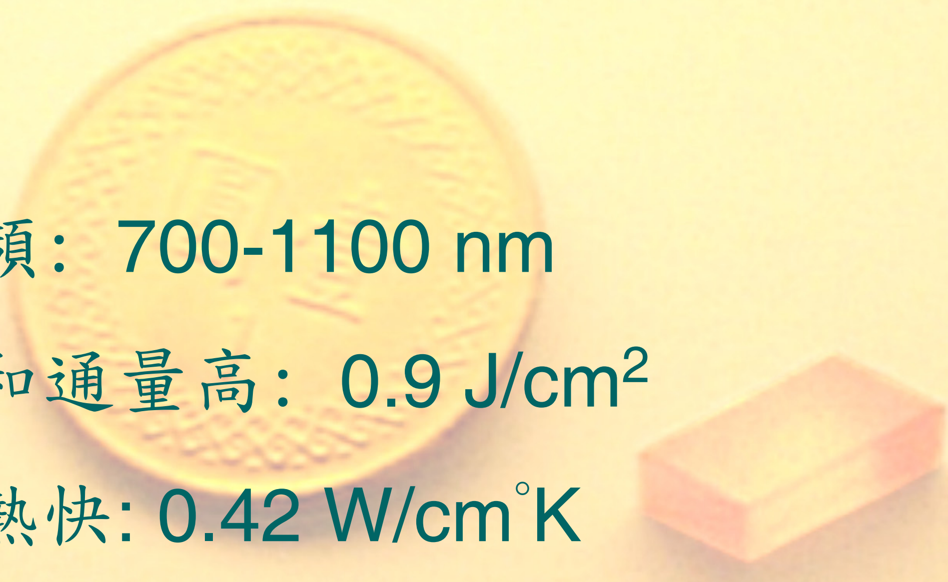
十個頻率的波
亂相相加

飛秒脈衝的產生

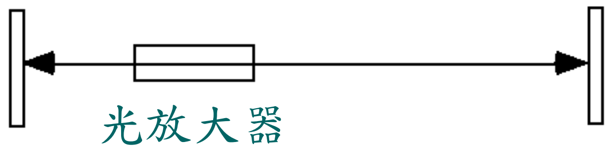
- 寬頻雷射介質
- 脈衝壓縮機制
- 腔內色散補償

摻鈦藍寶石晶體

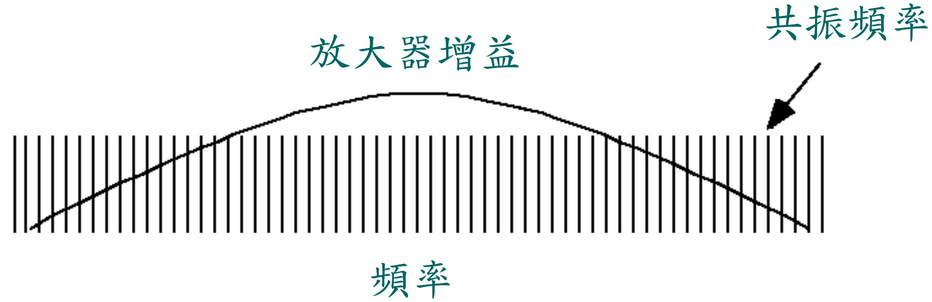
- 寬頻：700-1100 nm
- 飽和通量高：0.9 J/cm^2
- 散熱快: 0.42 W/cm°K
- 耐強光：23 GW/cm^2 at 200 ps



寬頻鎖模雷射



共振條件：$\frac{n\lambda}{2} = L$



增益頻寬 $= 10^{12} - 10^{14}$ Hz

頻率間距 $= \frac{\omega_c}{2\pi} \approx 10^8$ Hz

所有頻率同相相加：

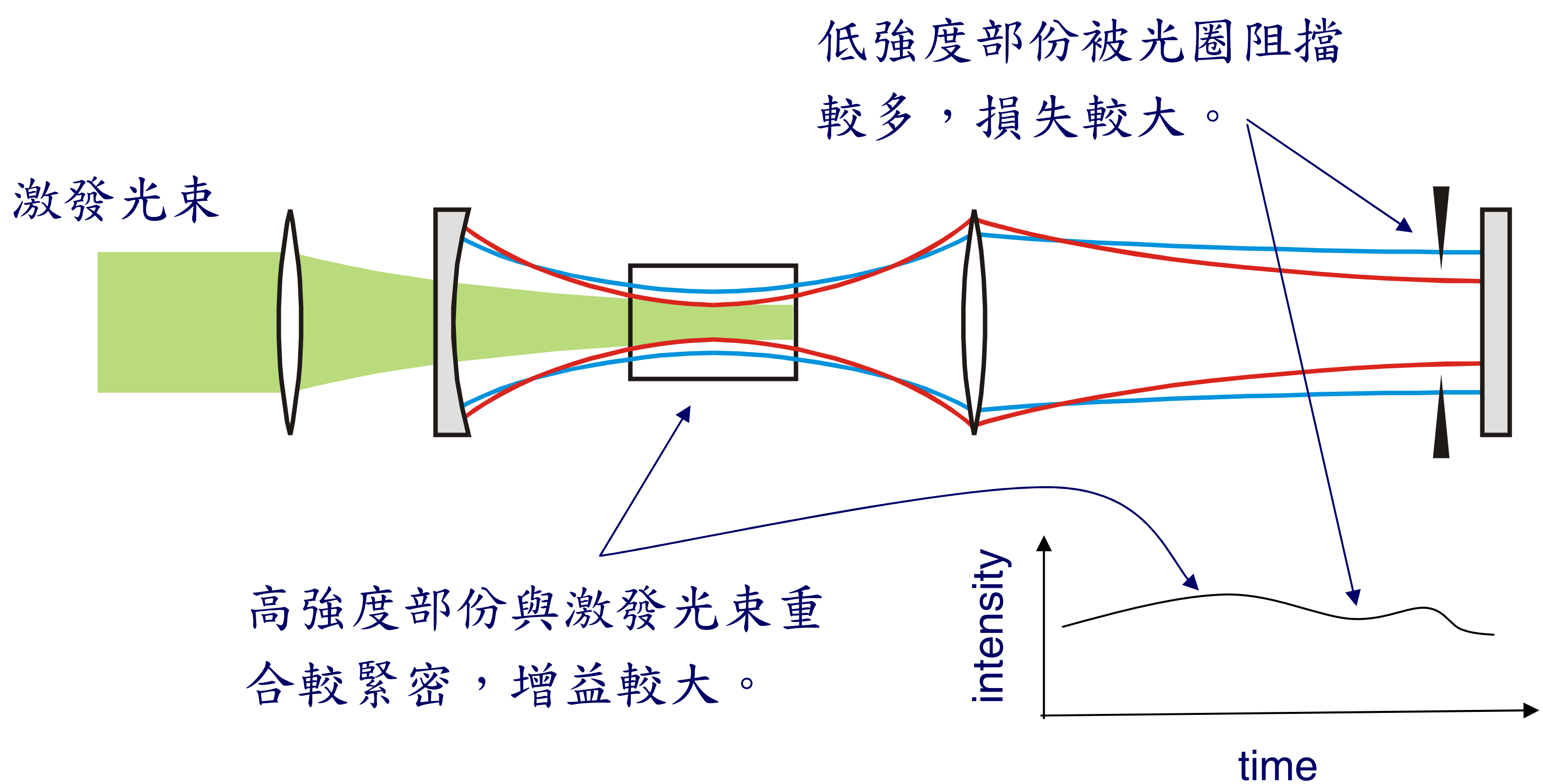
$$\left| \sum_{m=-n/2}^{n/2} e^{i(\omega_0 + m\omega_c)t} \right| = 1 + 2\sum_{m=1}^{n/2} \cos(m\omega_c t) = \frac{\sin\left[\frac{(n+1)\omega_c t}{2}\right]}{\sin\frac{\omega_c t}{2}}$$

高度 $\propto n$

寬度 $\propto n^{-1}$

自聚焦脈衝壓縮原理

光學克爾效應: $n = n_0 + n_2 I$



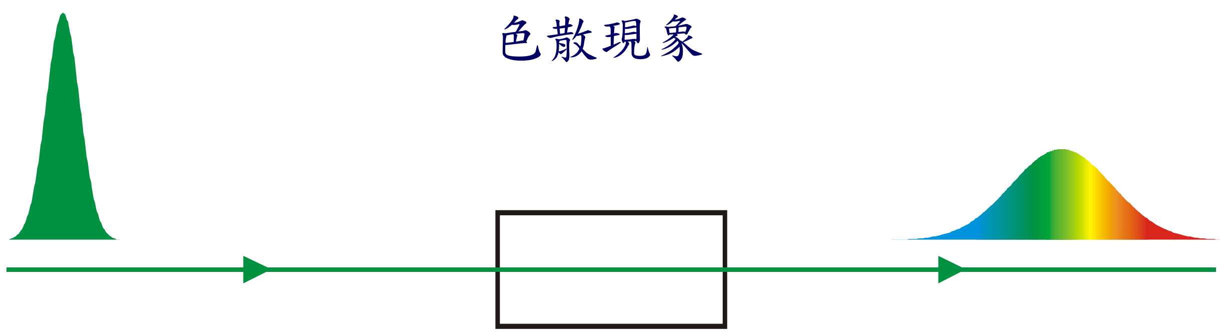
在介質中光速隨頻率改變

紅光折射率: 1.5145

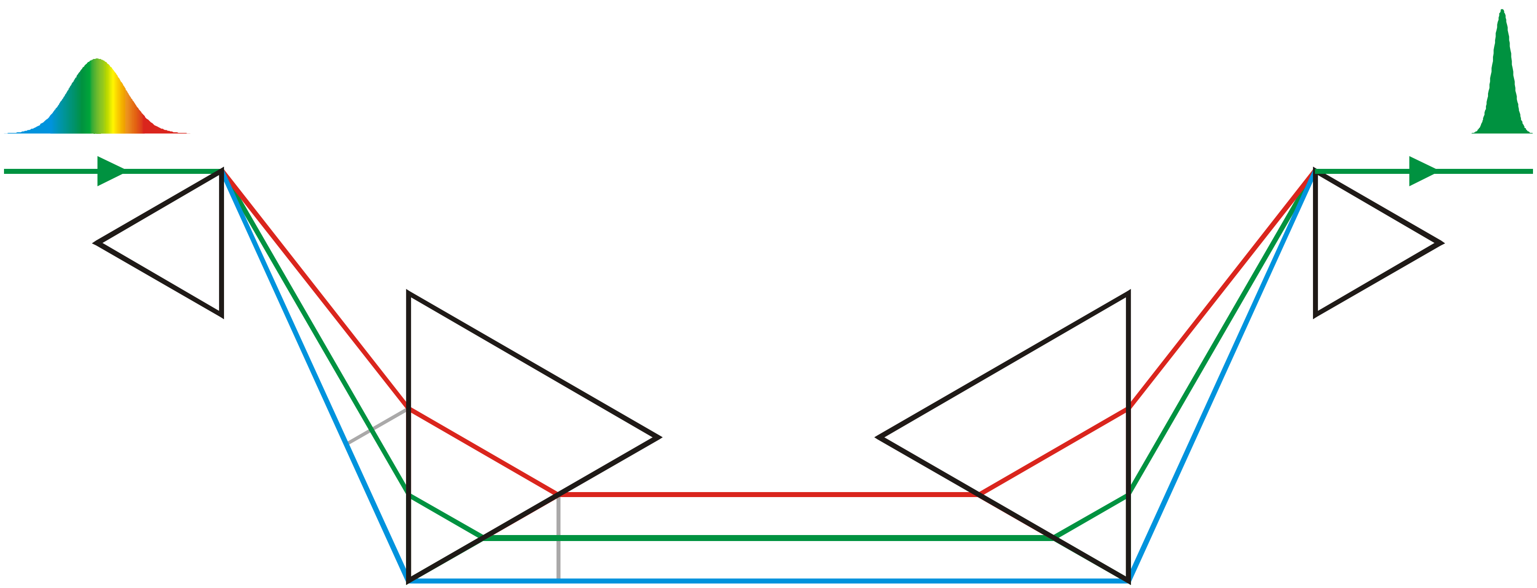
（BK7玻璃）

藍光折射率: 1.5253

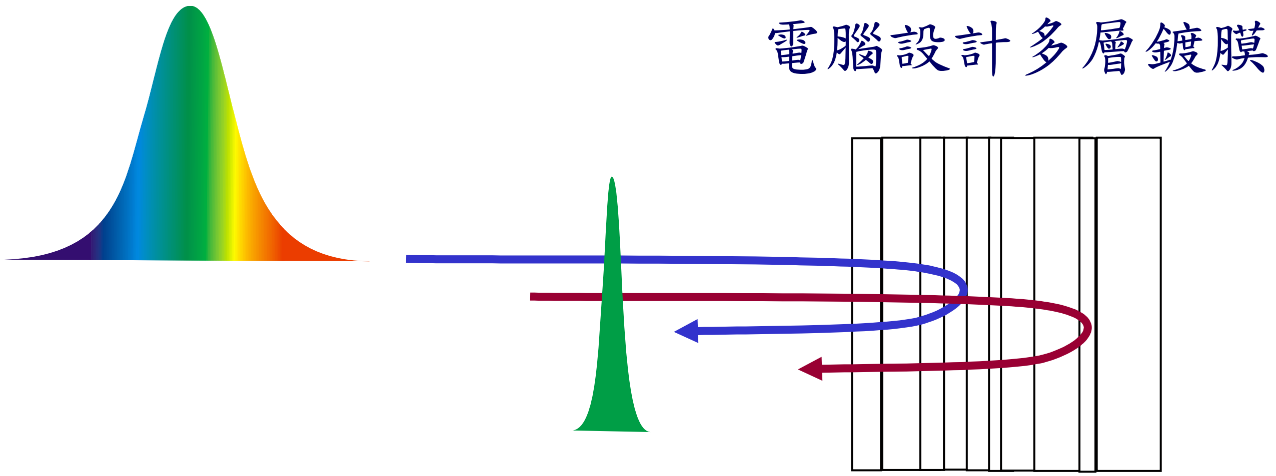
色散現象



腔內色散補償



線性變頻反射鏡

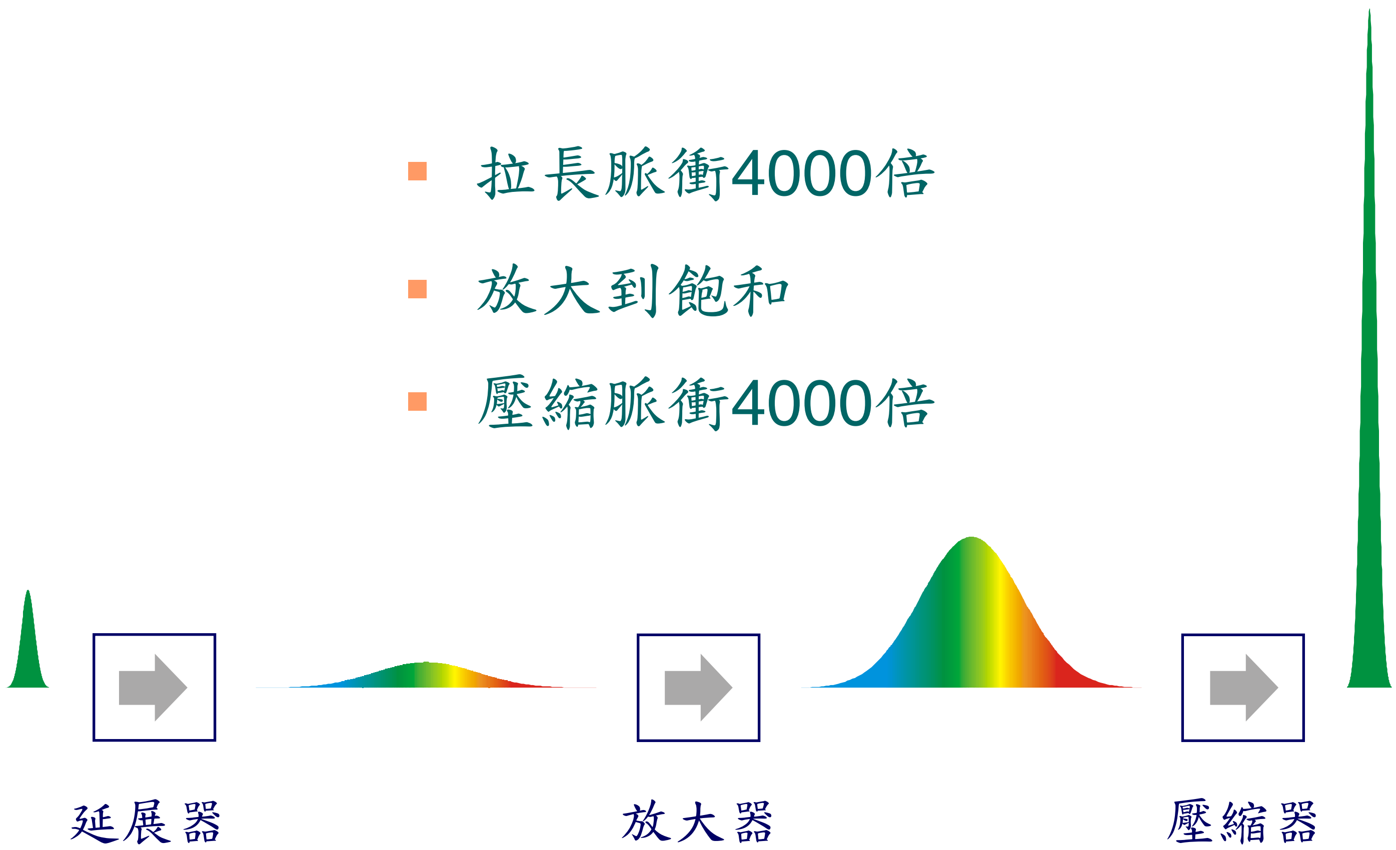


飛秒脈衝的放大

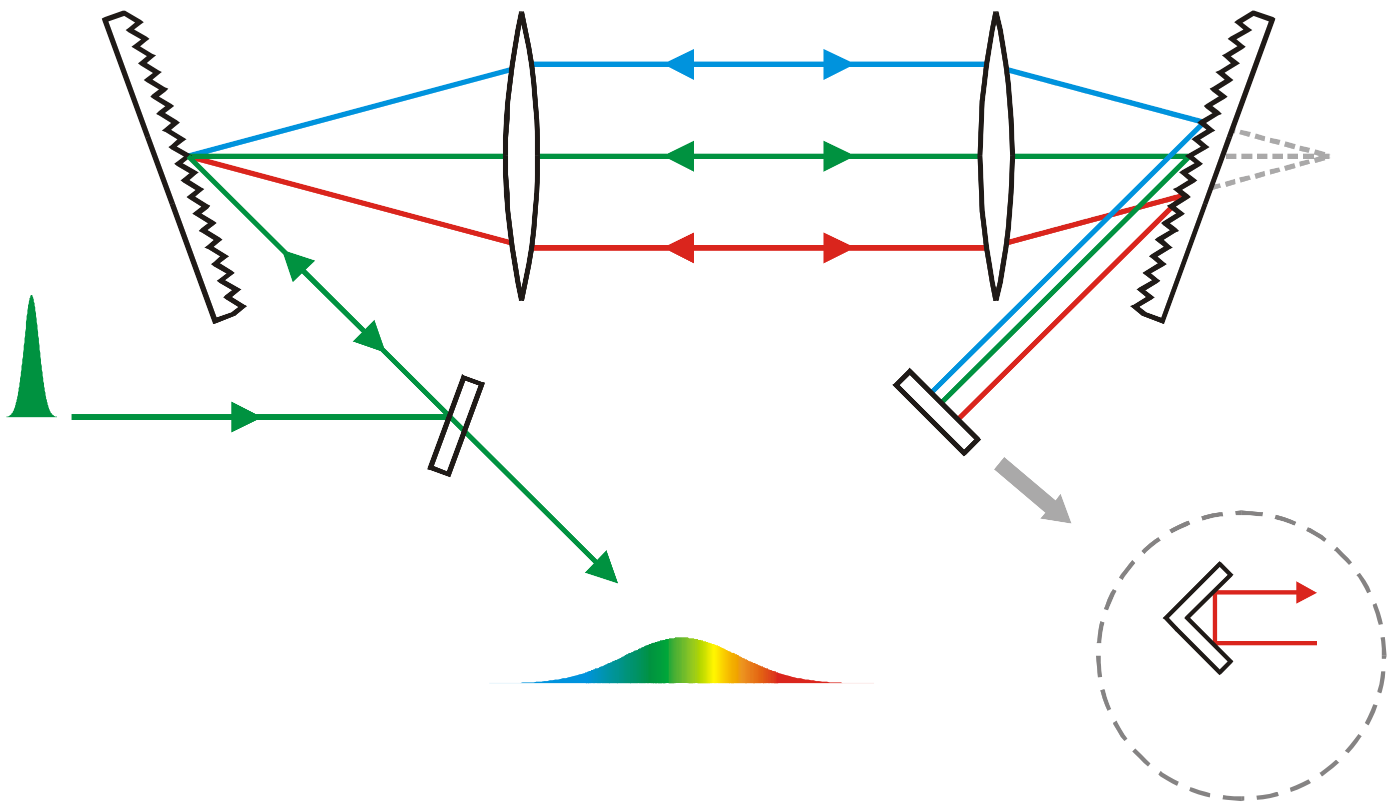
- 寬頻雷射介質
- 色散補償
- 防止非線性效應

線性變頻放大

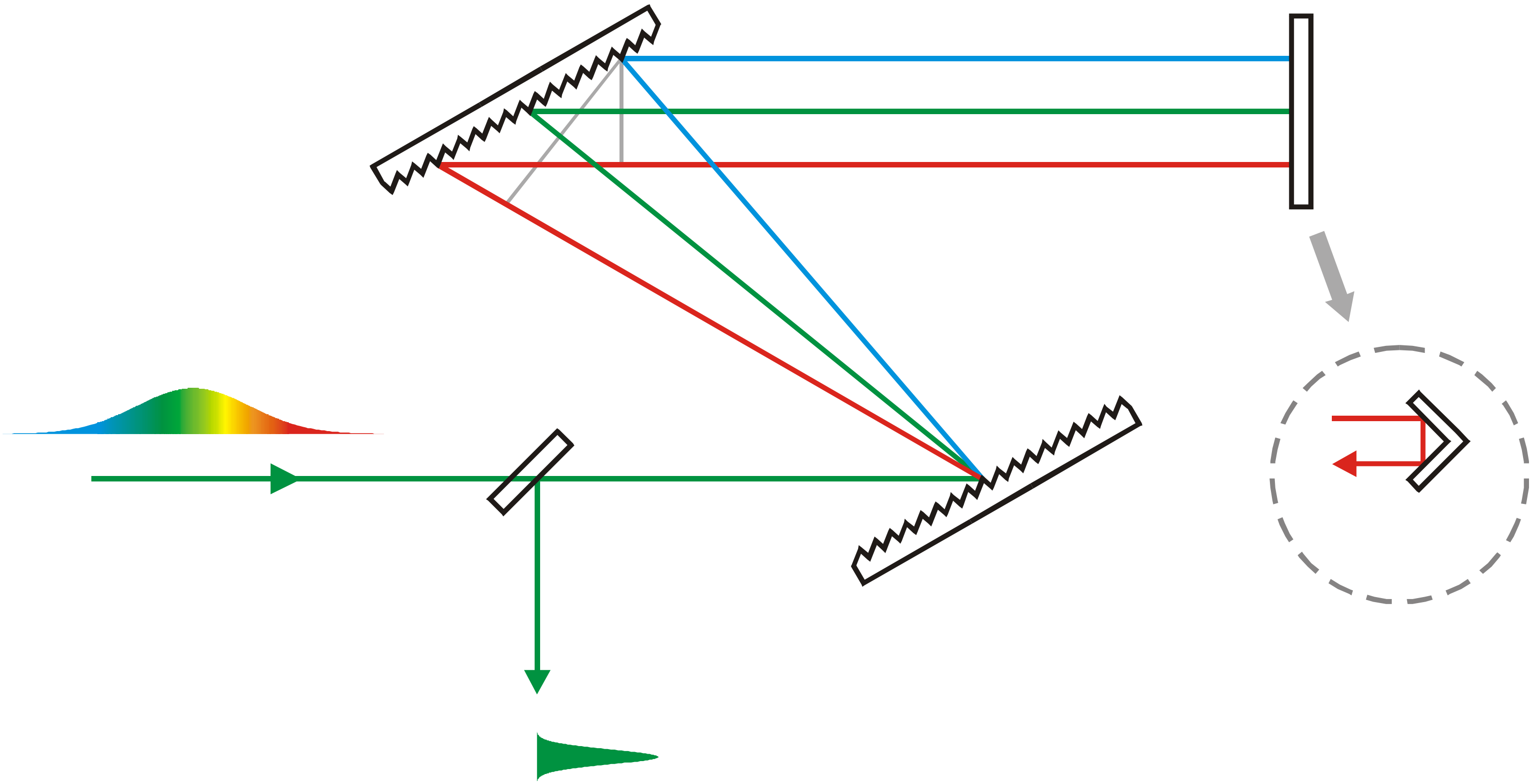
- 拉長脈衝4000倍
- 放大到飽和
- 壓縮脈衝4000倍



脈衝延展器原理

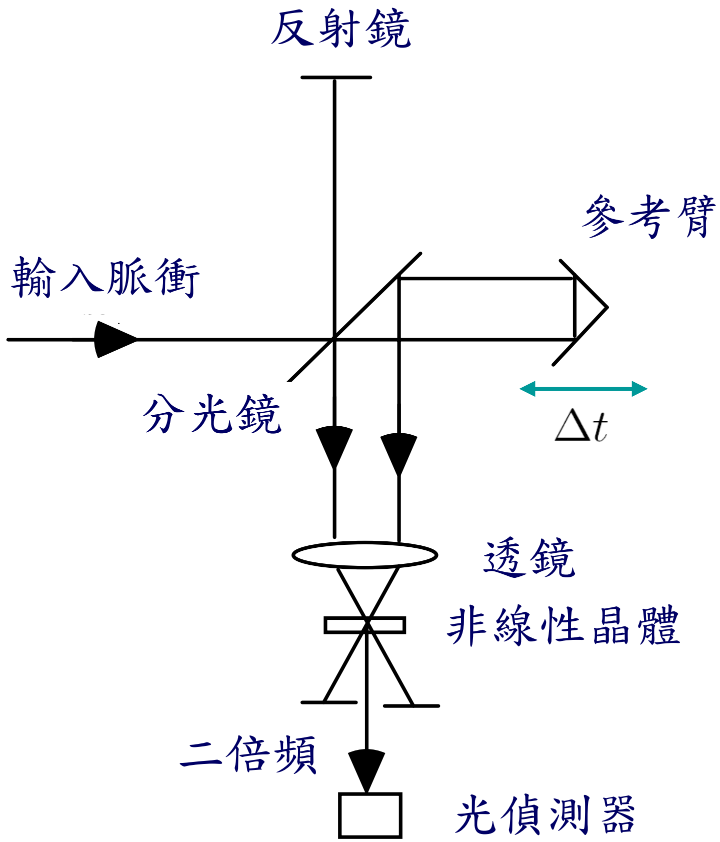


脈衝壓縮器原理



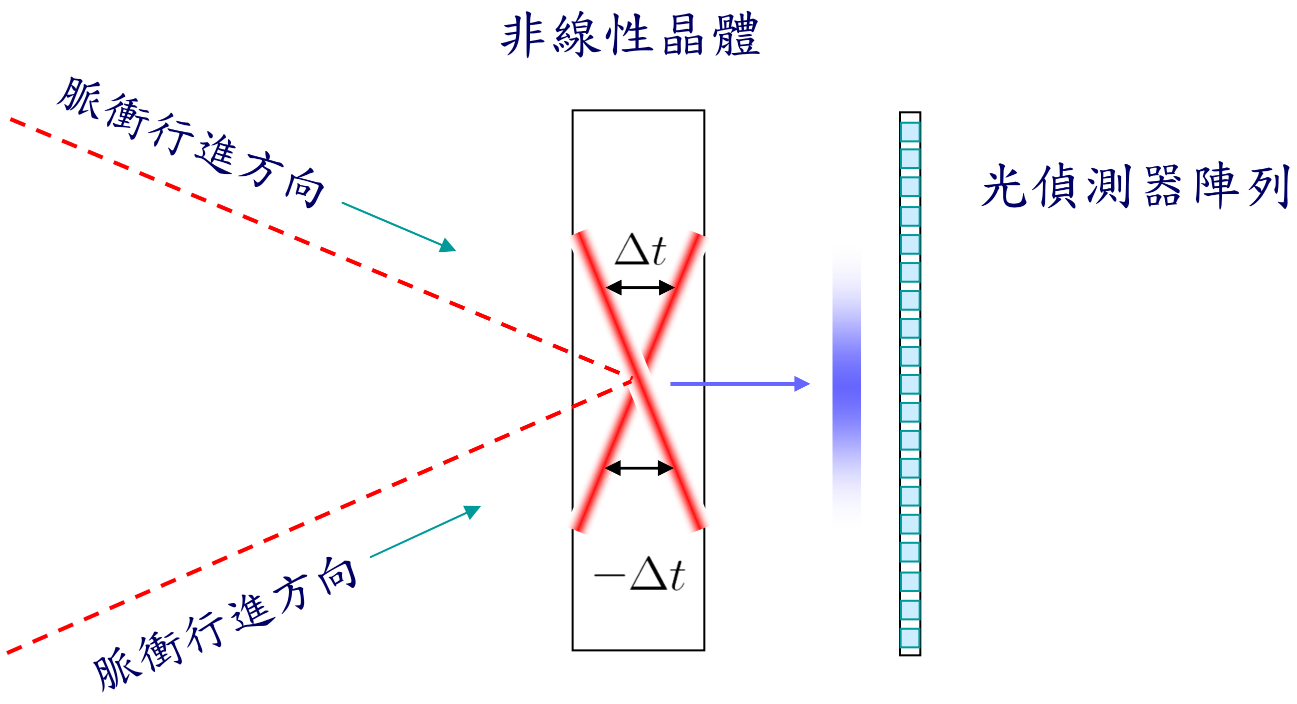
飛秒脈衝的測量

掃描式自相關儀



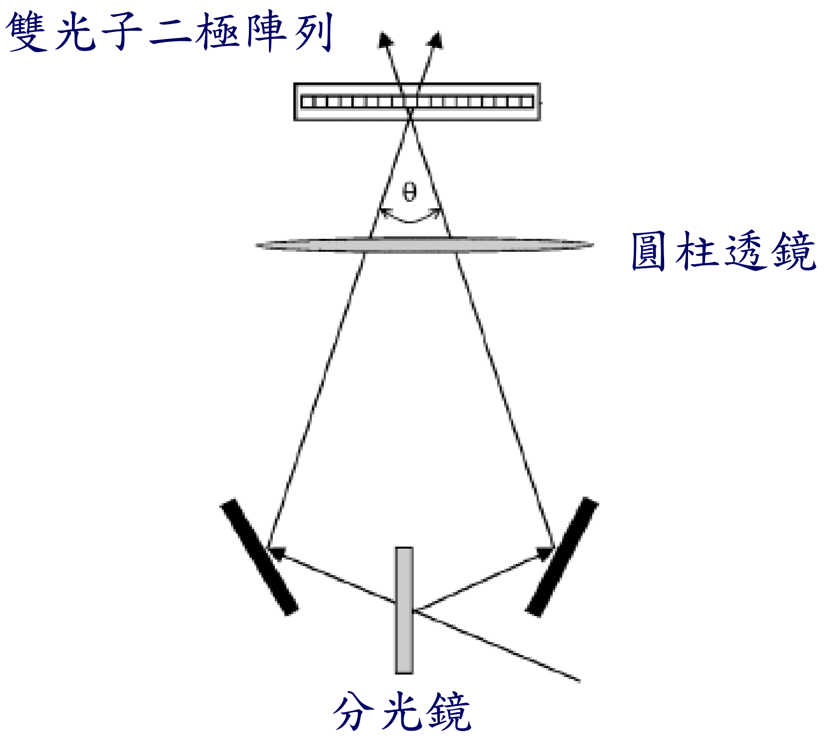
$$A(\Delta t) = \int I(t)I(t-\Delta t)dt$$

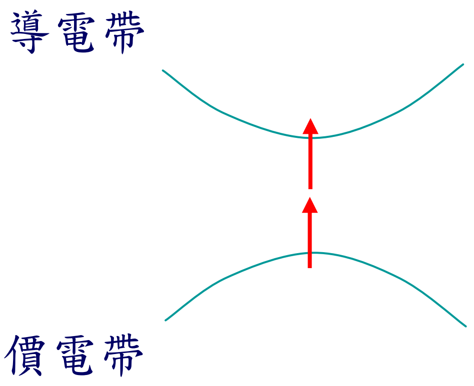
單擊式自相關儀

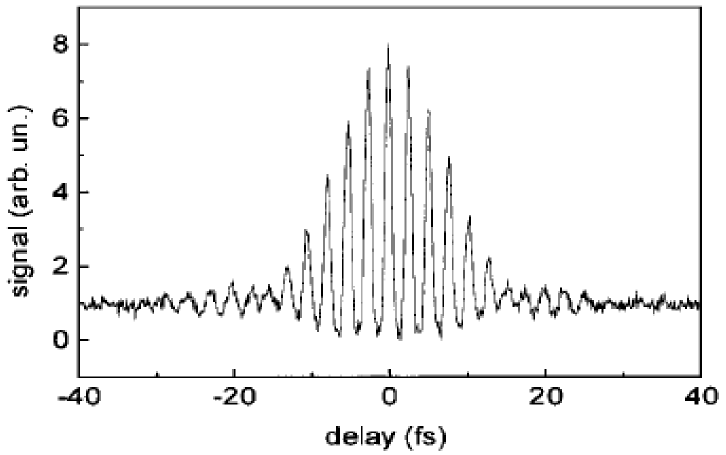


$$A(\Delta t) = \int I(t)I(t-\Delta t)dt$$

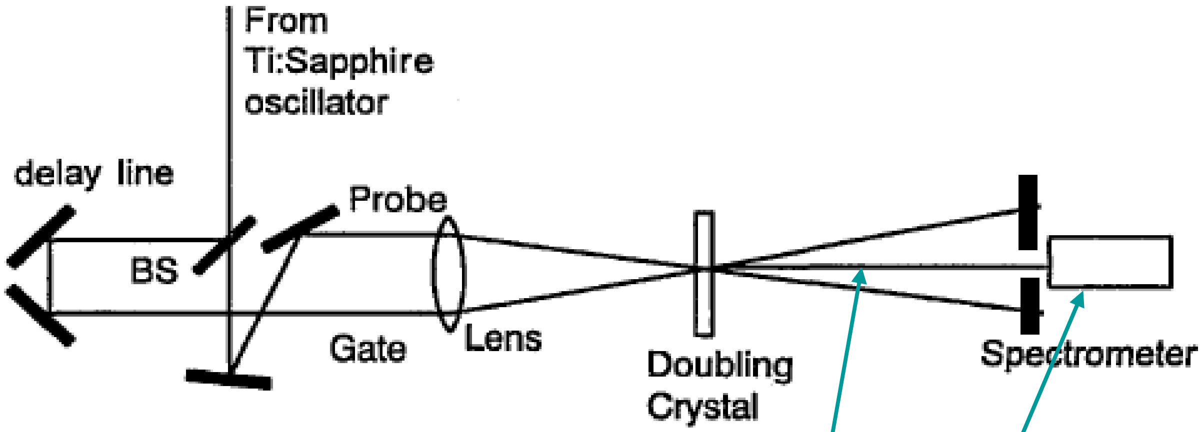
雙光子二極體


雙光子二極陣列
θ
圓柱透鏡
分光鏡


導電帶
價電帶


signal (arb. un.)
0
2
4
6
8
-40
-20
0
20
40
delay (fs)

Frequency-Resolved Optical Gating

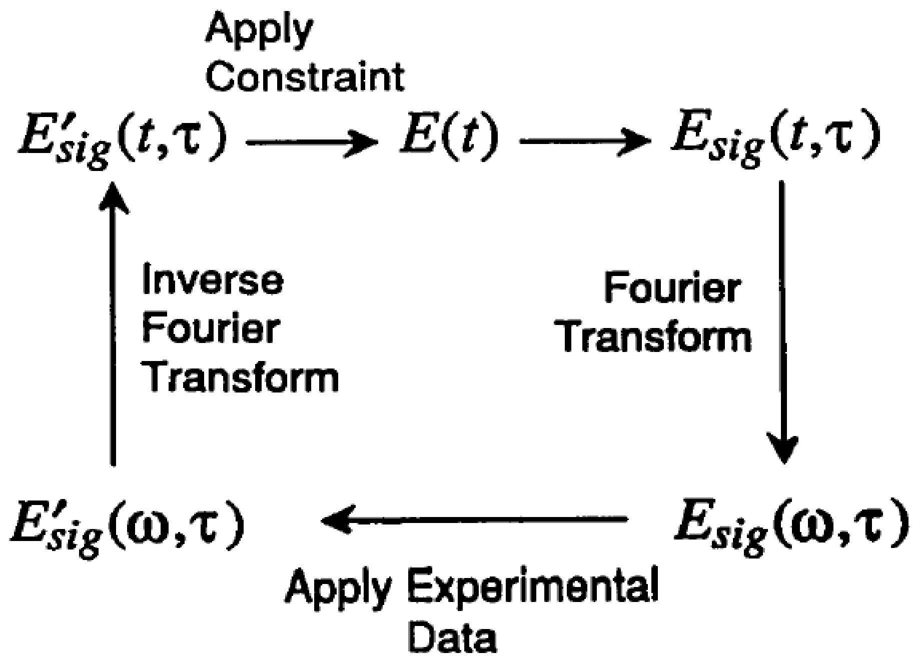


$$E_{\mathrm{sig}}(t,\ \tau) = E(t)E(t-\tau)$$

$$I_{\mathrm{FROG}}(\omega,\ \tau) = \left| \int_{-\infty}^{\infty} \mathrm{d}t\ E_{\mathrm{sig}}(t,\ \tau) \exp(i\omega t) \right|^2$$

$$= |E_{\mathrm{sig}}(\omega,\ \tau)|^2 .$$

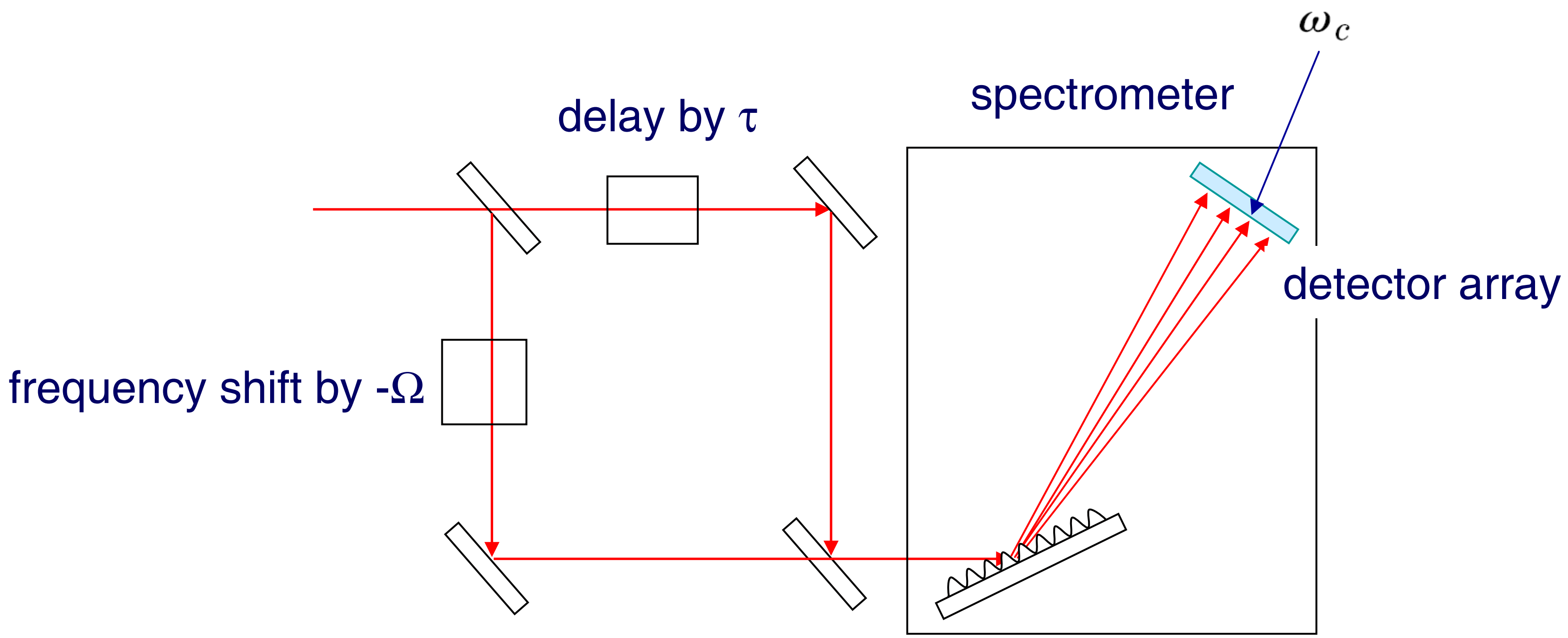
Reconstruction Algorithm



constraint: minimizing Z

$$Z = \sum_{t,\tau=1}^{N} |E_{\rm sig}'(t,\tau) - E(t)E(t-\tau)|^2$$

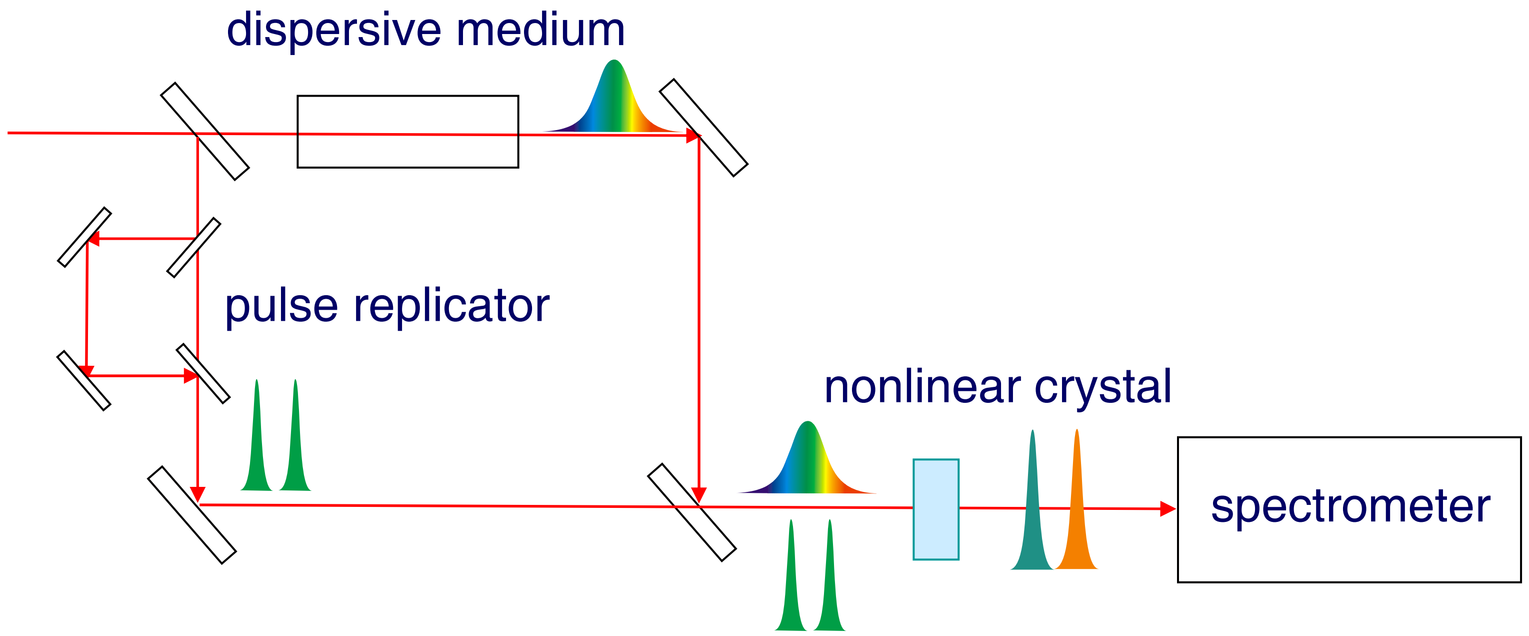
Frequency-Domain Shear Interferometry



$$S(\omega_c, \tau) = |\tilde{E}(\omega_c)|^2 + |\tilde{E}(\omega_c + \Omega)|^2 + 2|\tilde{E}(\omega_c)\tilde{E}(\omega_c + \Omega)|$$

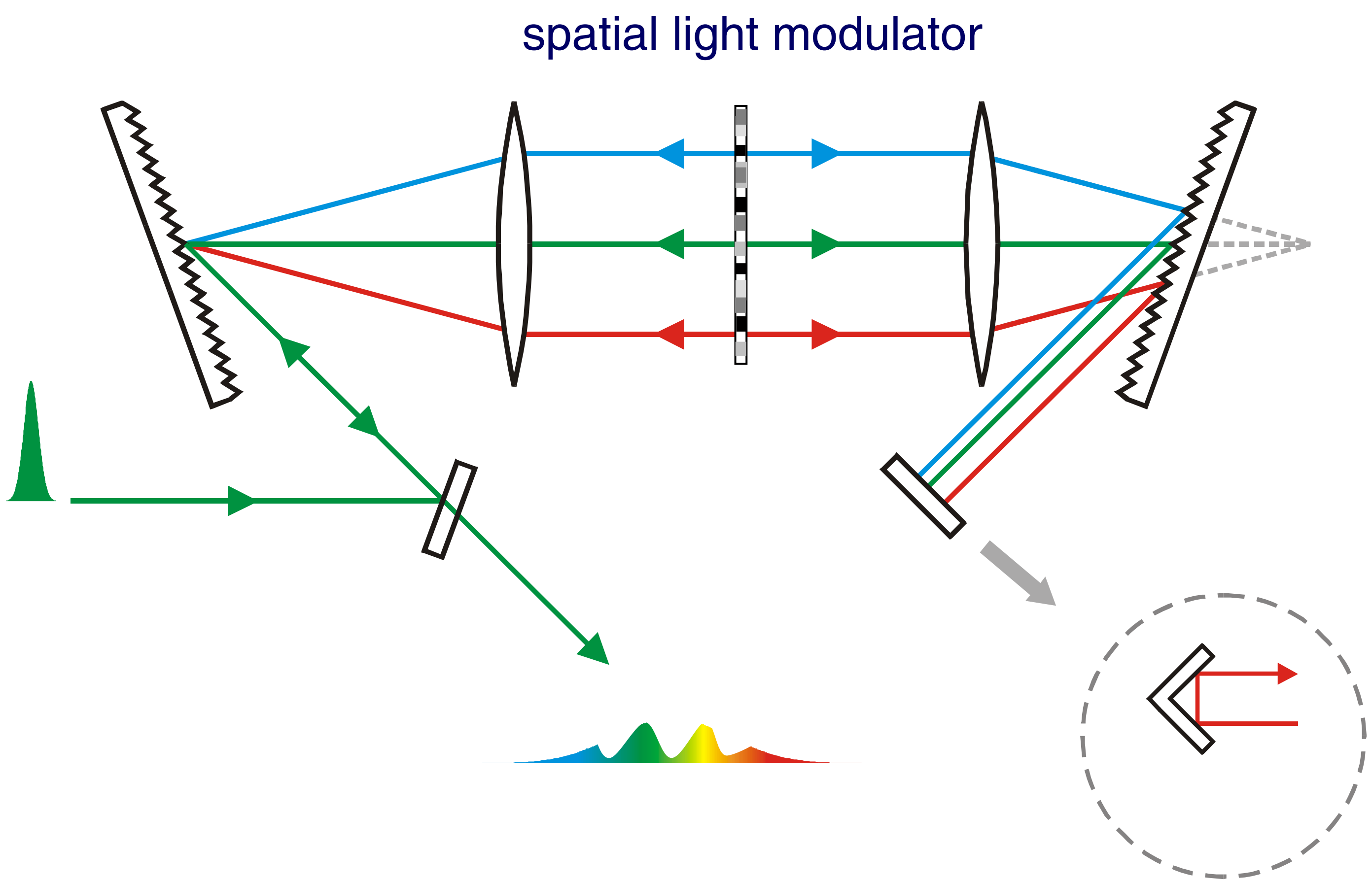
$$\times \cos[\phi_\omega(\omega_c + \Omega) - \phi_\omega(\omega_c) + \omega_c \tau]$$

Frequency-Domain Shear Interferometry



飛秒脈衝的波形控制

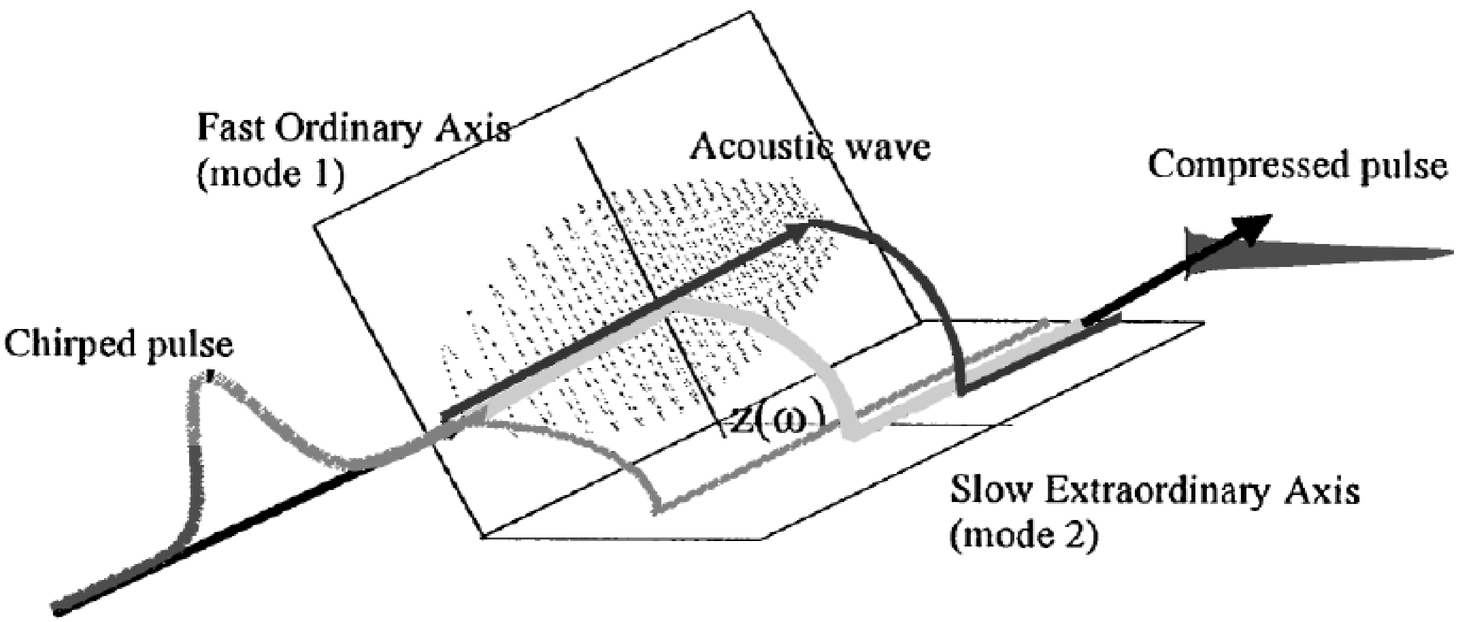
波形合成



Acousto-optic programmable dispersive filter

$$E_{\mathrm{out}}(\omega) \propto E_{\mathrm{in}}(\omega) S(\alpha\,\omega) \qquad \alpha = \Delta n(V/c)$$

speed of sound



中研院的10兆瓦雷射

主脈衝： 500 mJ, 40 fs–2 ps, 10 Hz

副脈衝： 400 mJ, 80 ps, 10 Hz

時空品質：

- 時寬與頻寬乘積： 1.2 倍傅利葉極限
- 可聚焦性： 1.2 倍繞射極限
- 最大照度： 4×10^{19} W/cm^2

對比度：

- –10 ns: 5×10^{8}
- –200 ps: 1.5×10^{7}
- –40 ps: 2×10^{6}
- –1 ps: 1×10^{4}

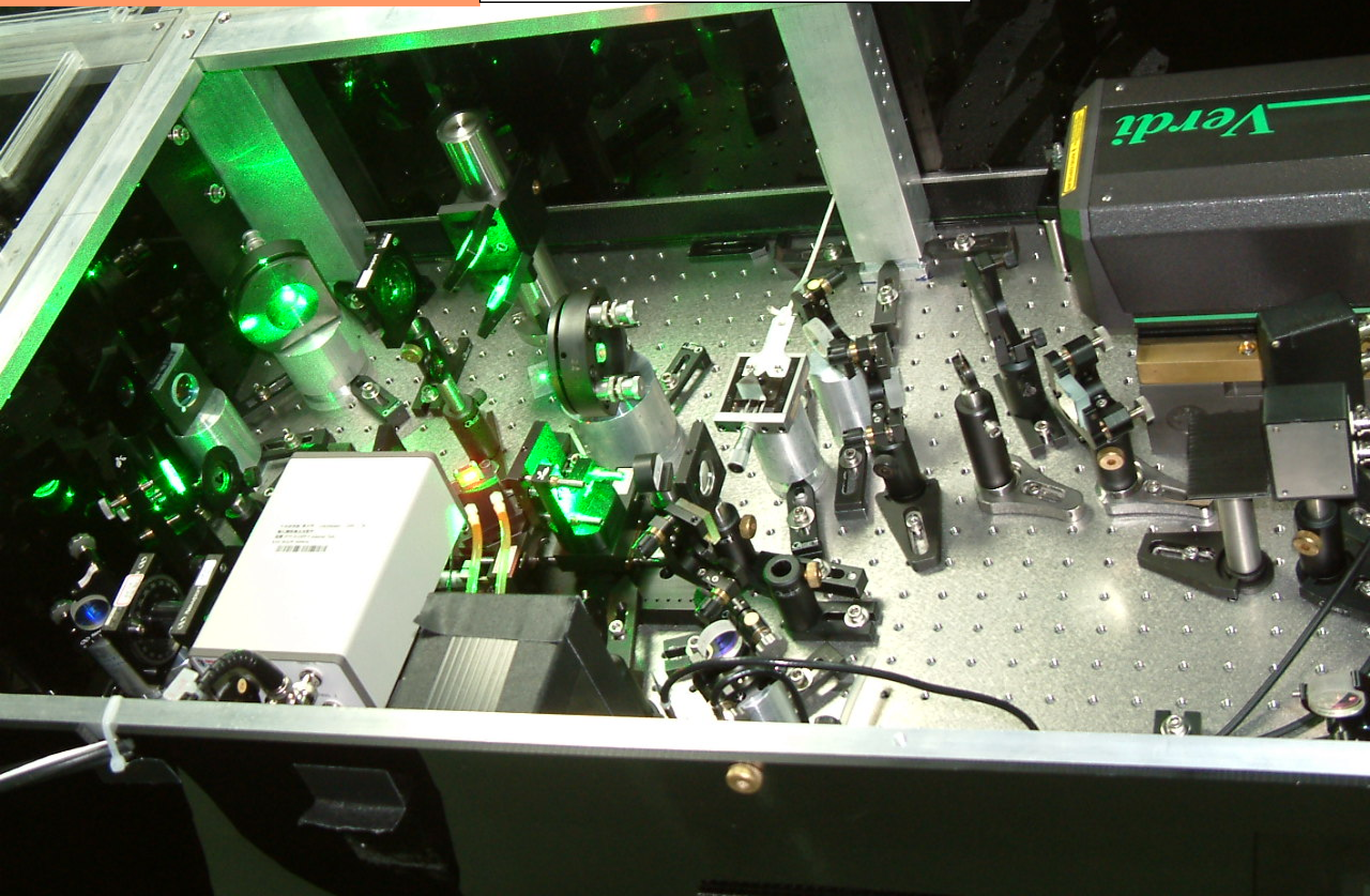
穩定度：

- 能量: 1.3%
- 波形： < 2.4%
- 指向性： 13 μrad

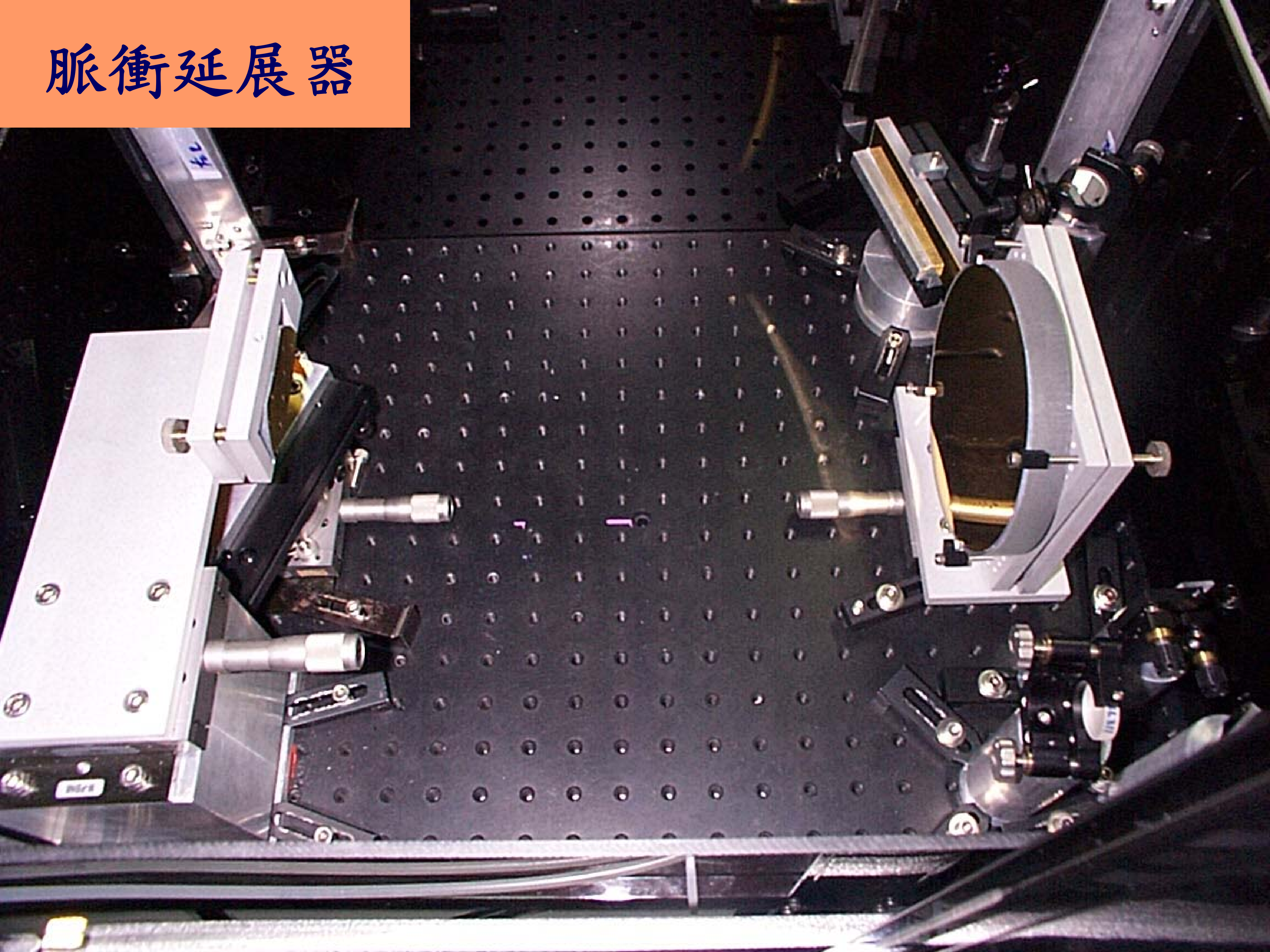
Appl. Phys. B **79,** 193 (2004)

25-fs 振盪器

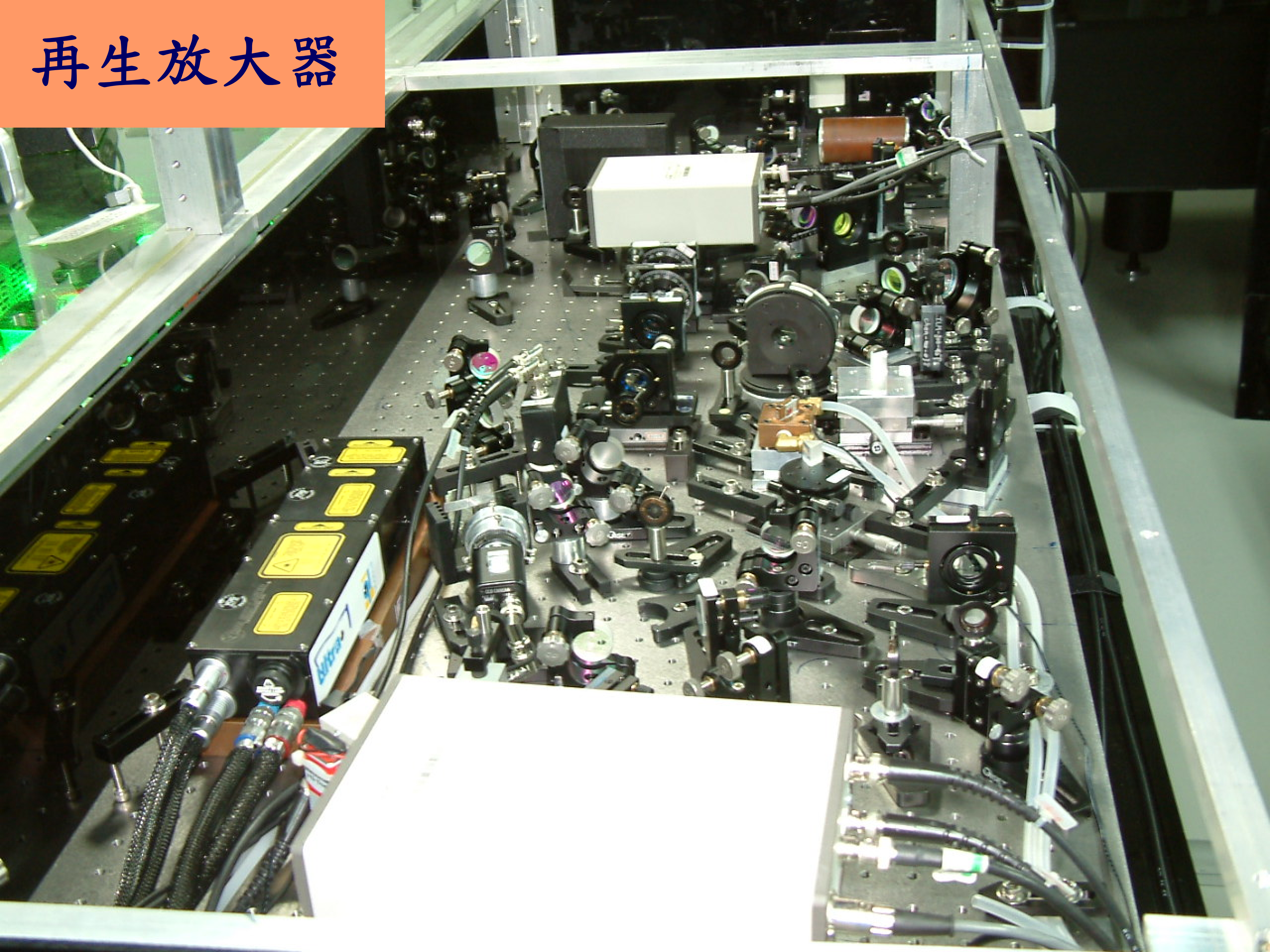
1秒：1 fs = 3000萬年：1秒



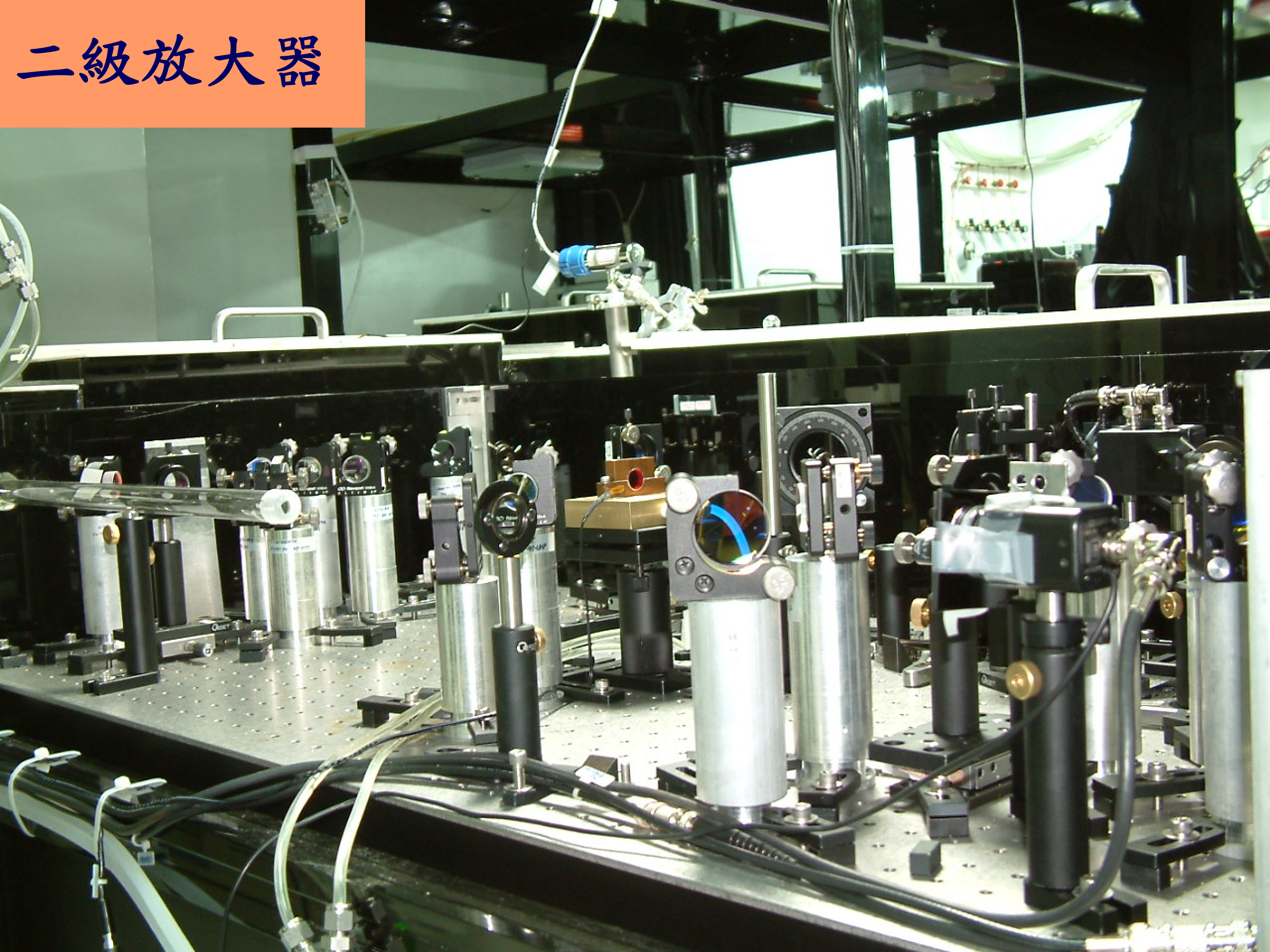
脈衝延展器



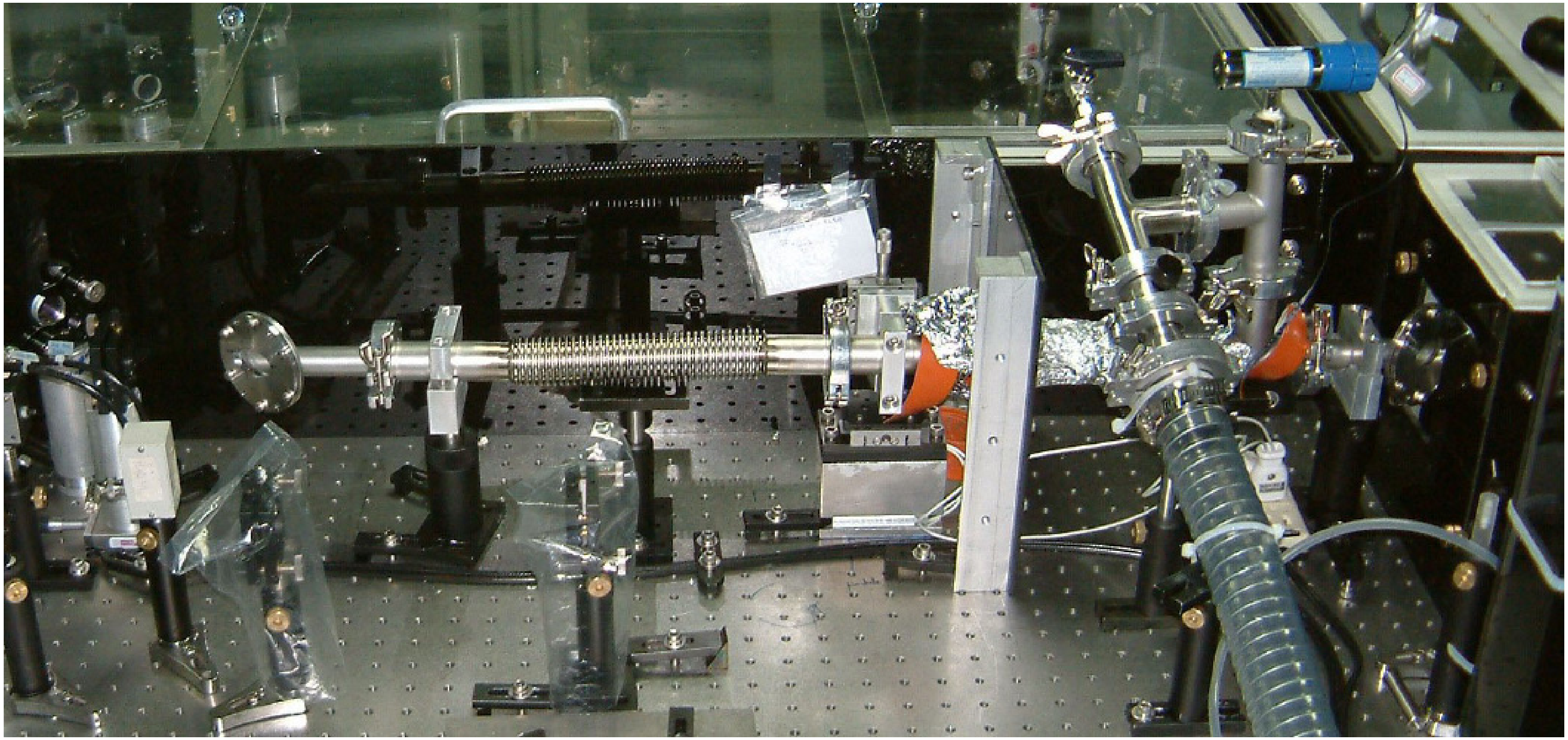
再生放大器



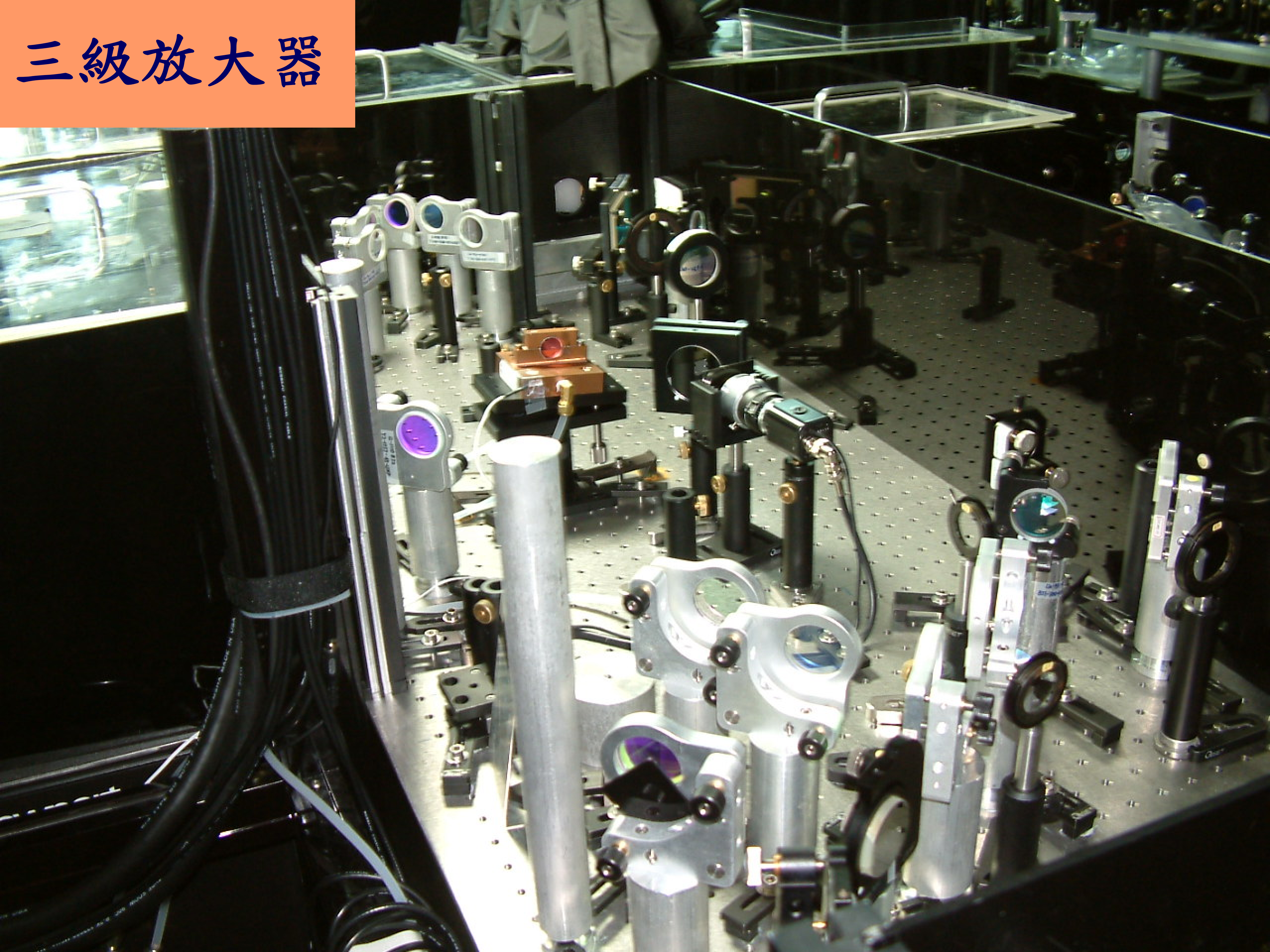
二級放大器



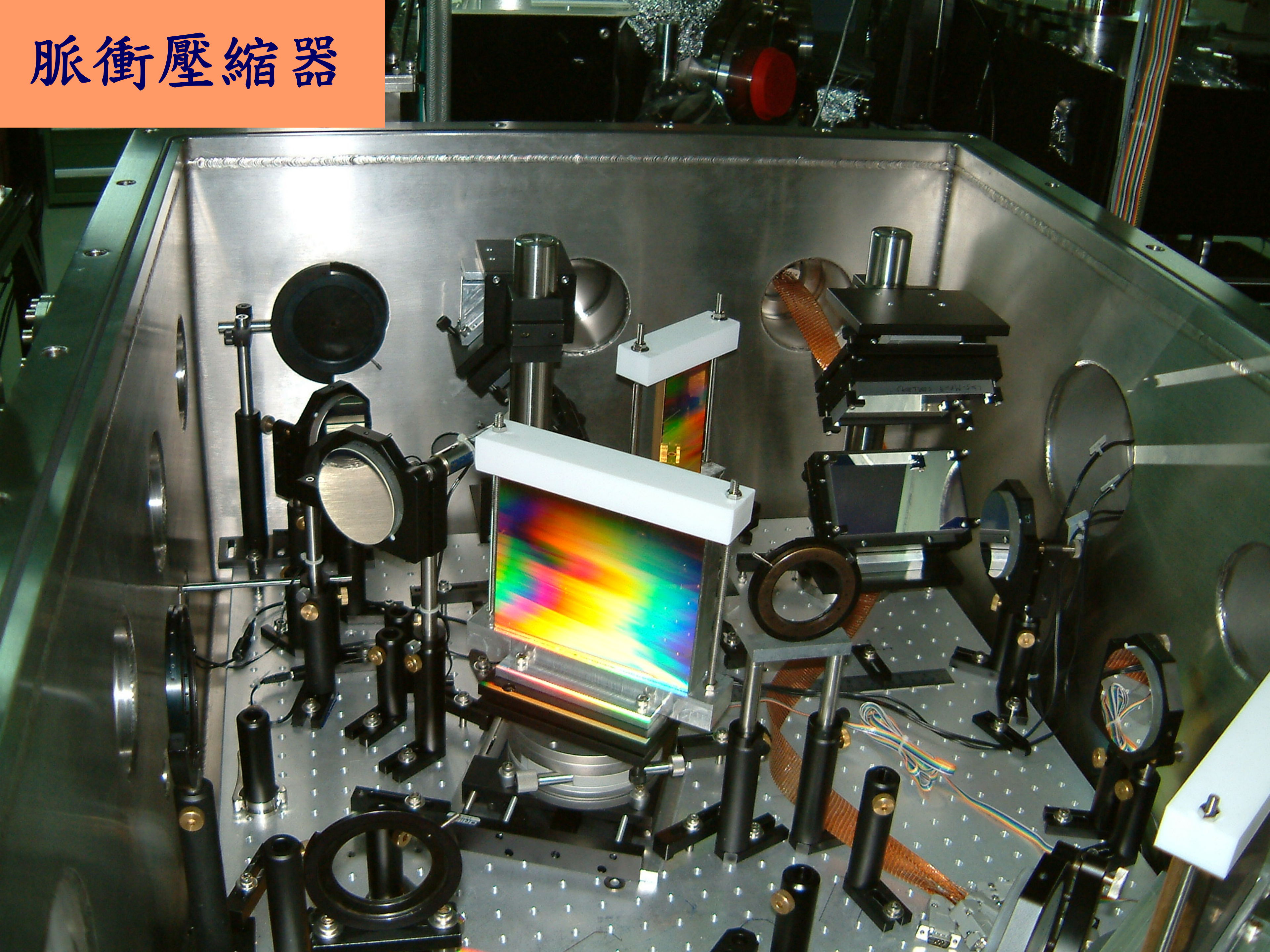
空間濾波器



三級放大器

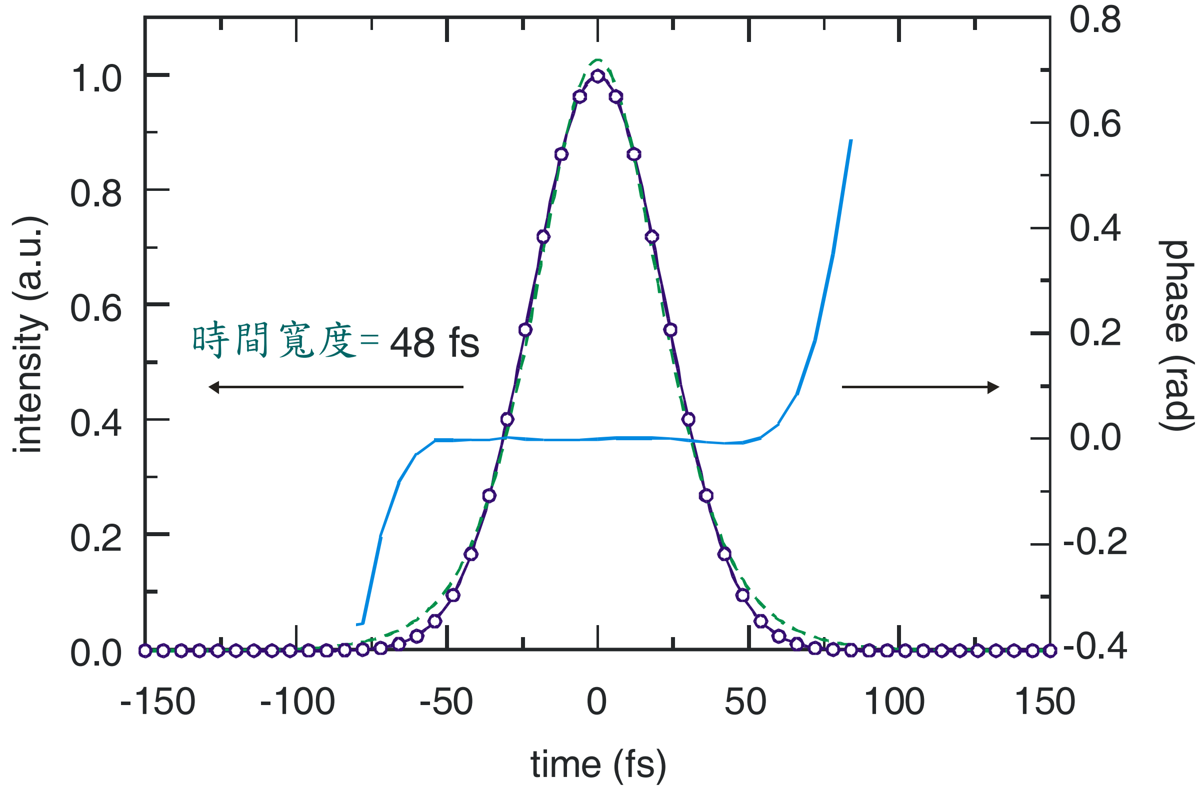


脈衝壓縮器



全景

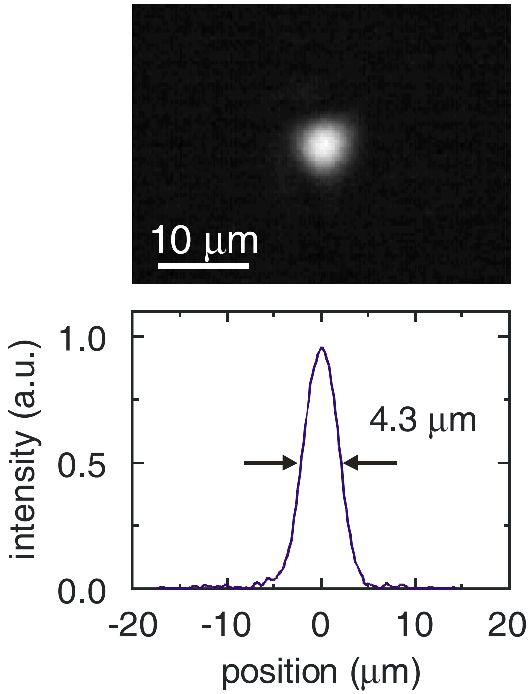
振幅與相位



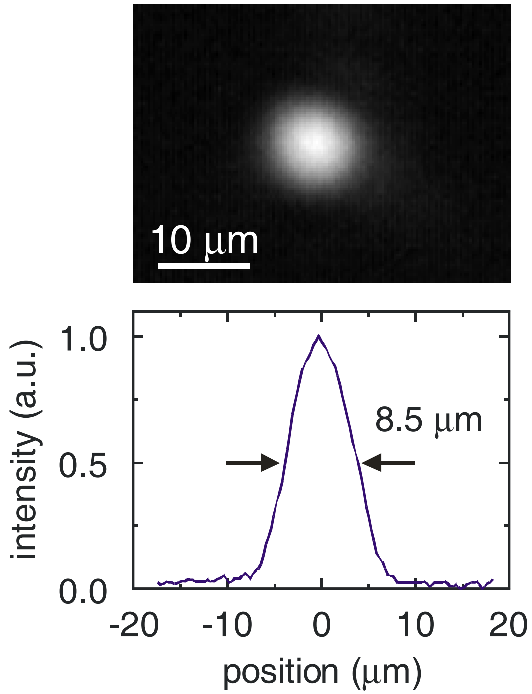
1.2倍傅立葉轉換極限

焦點的光束截面

以F/3.8拋物面鏡聚焦



以F/7.7拋物面鏡聚焦

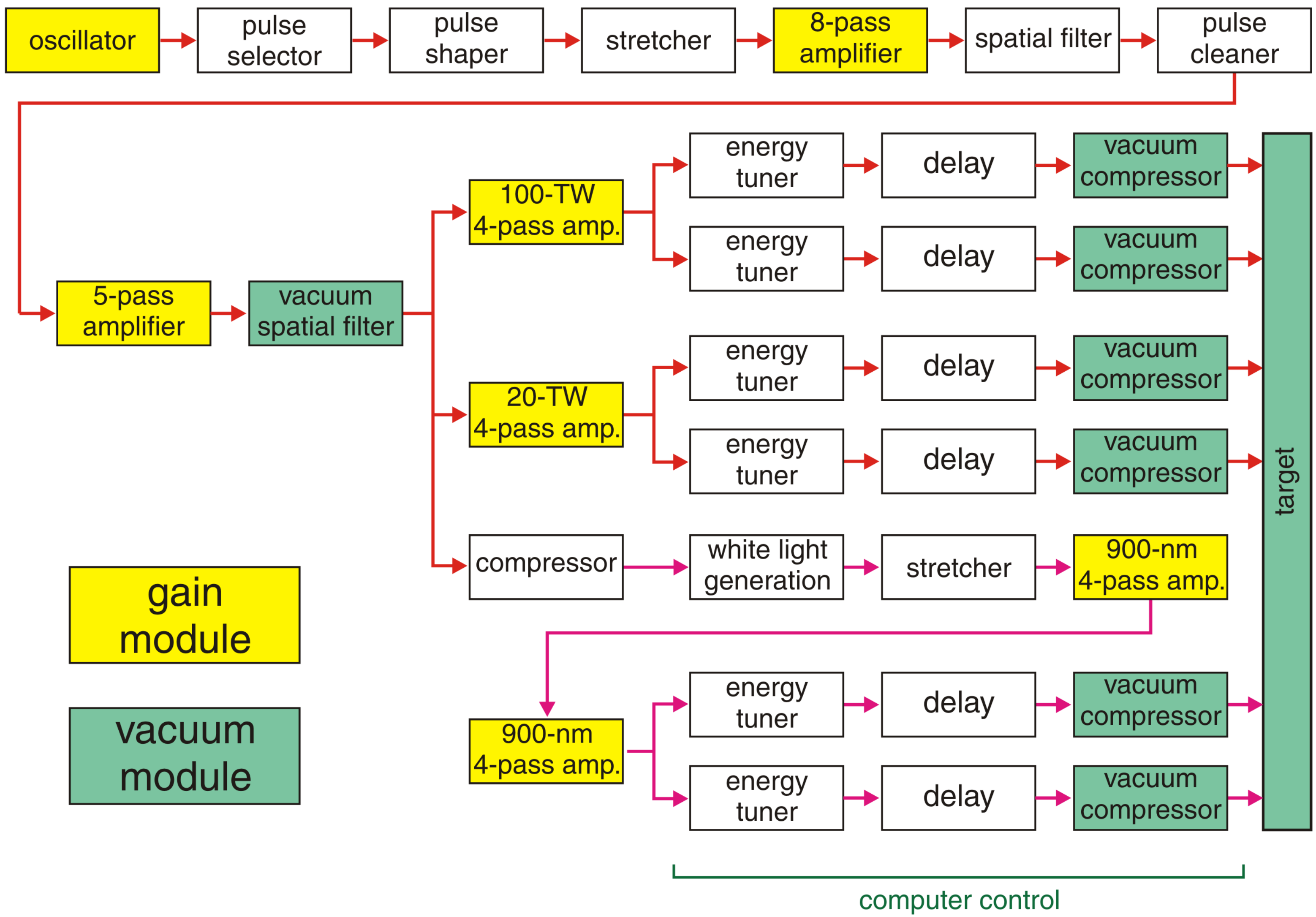


1.2倍繞射極限

主脈衝聚焦後

- 功率： 500 mJ/50 fs =10^{13} W (1000個核能電廠)
- 照度： 4×10^{19} W/cm^2 (正午的太陽 = 0.1 W/cm^2)
- 電場： 2×10^{11} V/cm (30倍氫原子內部的電場)
- 磁場： 6.7×10^{4} tesla (10億倍地球表面磁場)
- 光壓： 1.4×10^{10} 大氣壓 (1/10太陽中心的壓力)
- 照射固體表面產生的溫度： 10^{7} 度 (太陽中心的溫度)
- 對電子造成的加速度： 3×10^{23} g (g = 地表重力加速度)

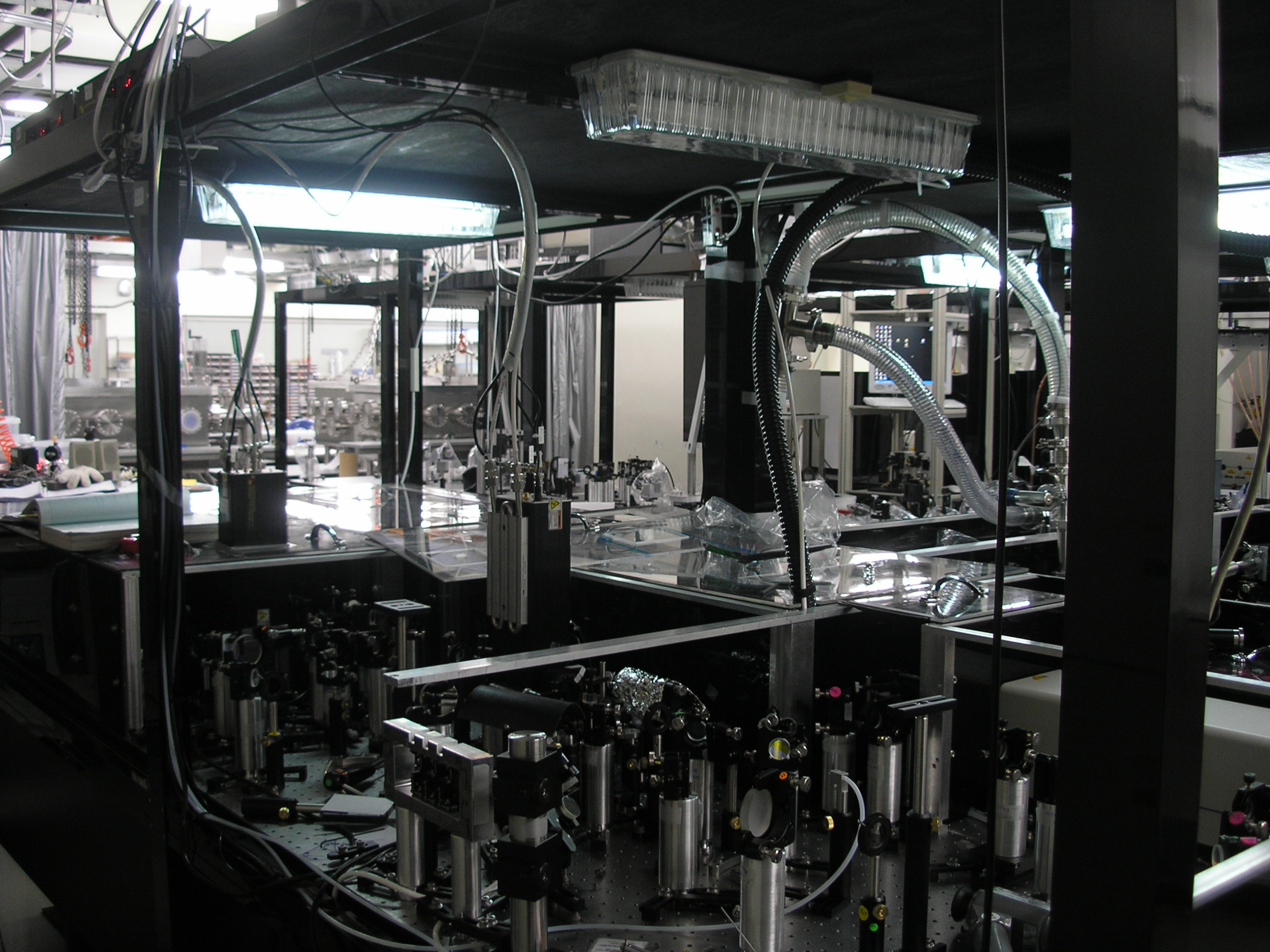
中央大學的100兆瓦雷射

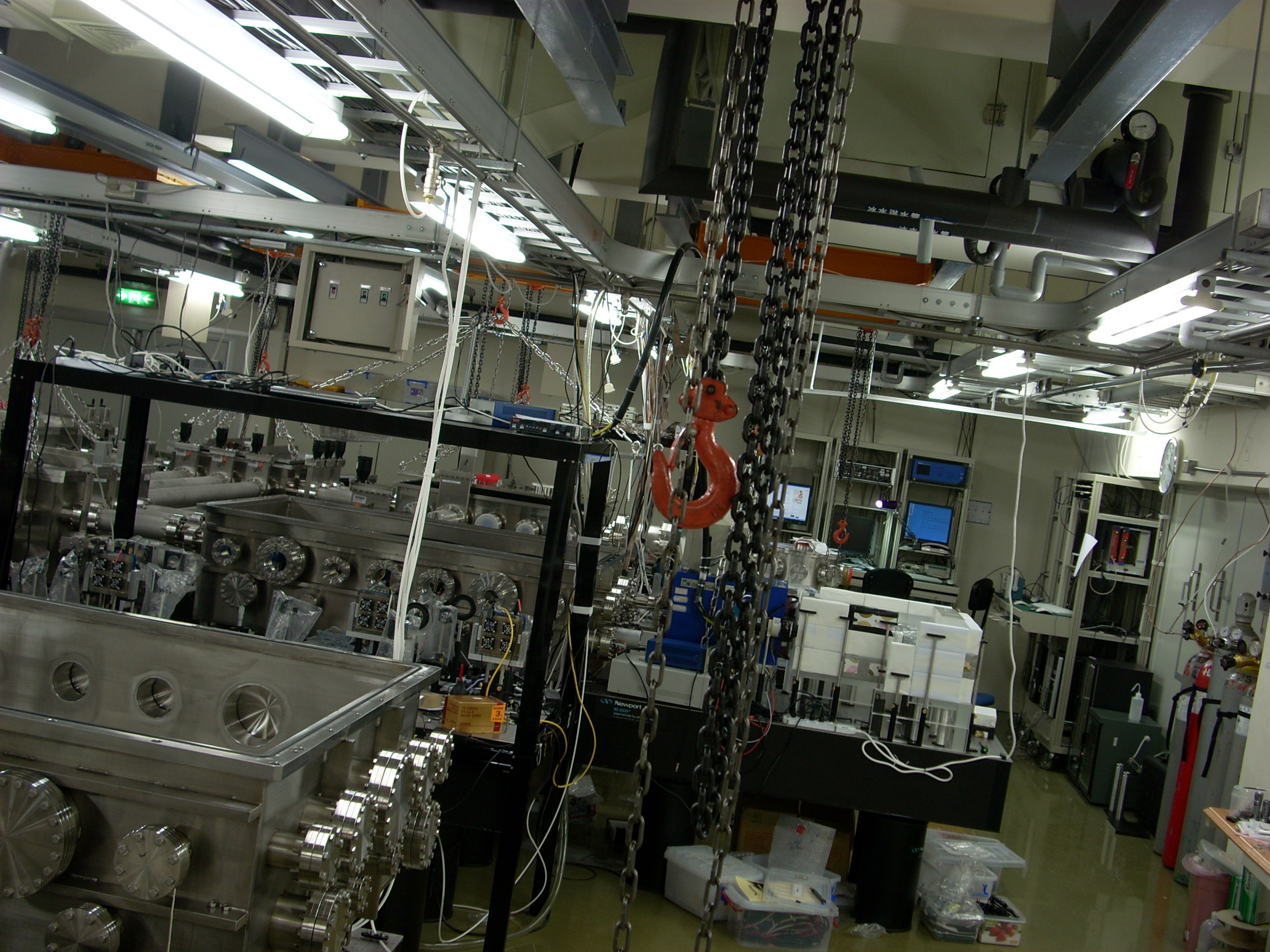


Current Status

rep. rate: 10 Hz	energy	duration	peak power	contrast	stability	focusibility*
100-TW beamline (800 nm)	3.3 J	30 fs	110 TW	$> 10^8$	2.1%	72%
20-TW beamline (800 nm)	600 mJ	30 fs	20 TW	$> 10^8$	1.9%	86%
5-TW beamline (900 nm)	200 mJ	40 fs	5 TW	$> 10^7$	3.4%	72%

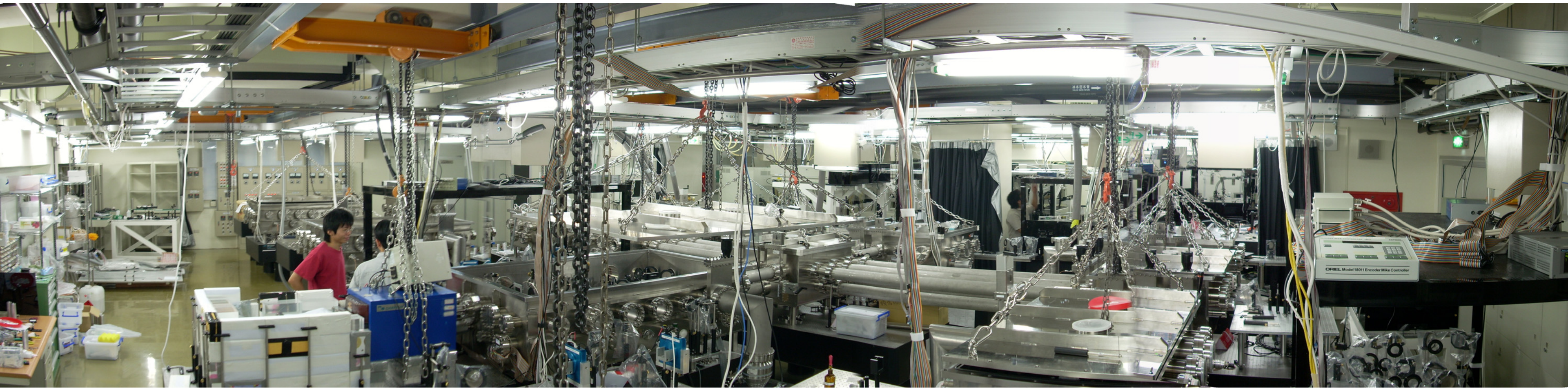
*energy enclosed in an F/7.7 Gaussian focal spot




Newport

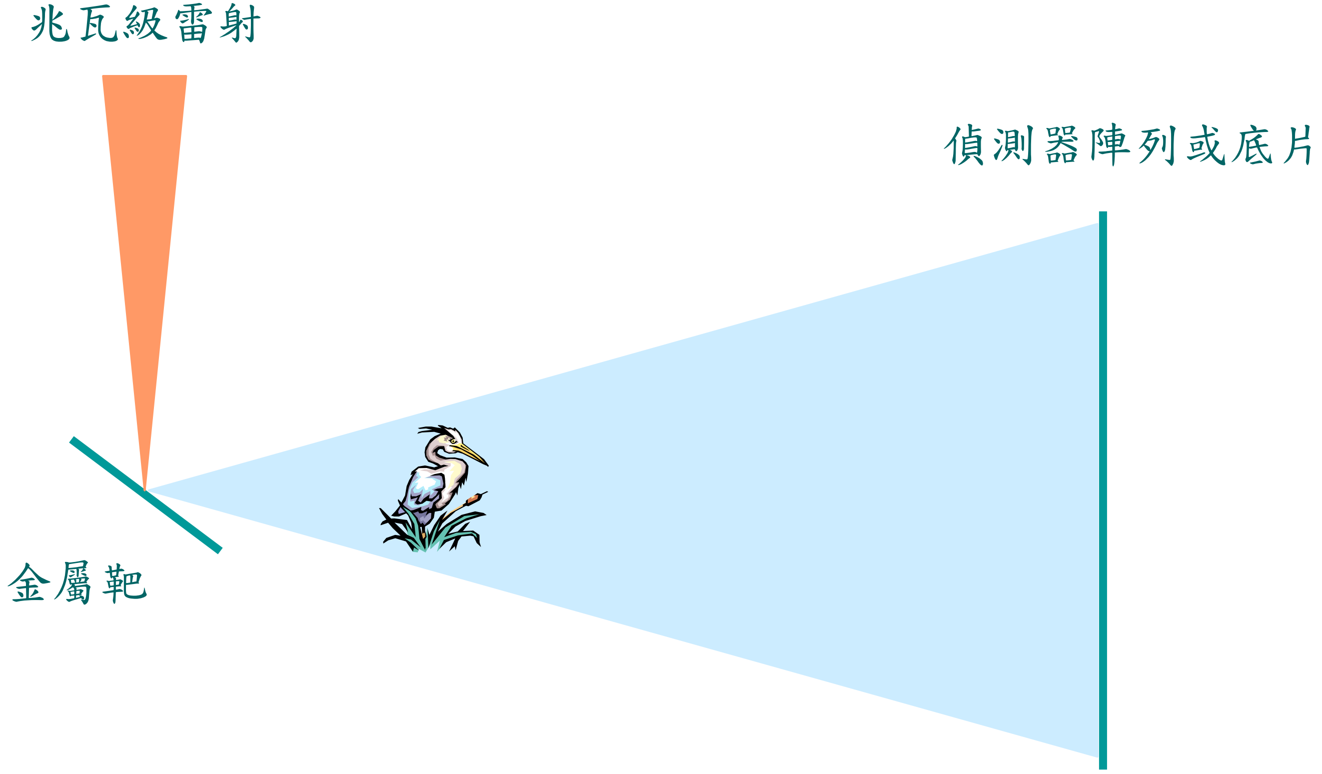

In vaccum


20AP6 PANEL


ORIEL Model 18011 Encoder Mike Controller

強場物理

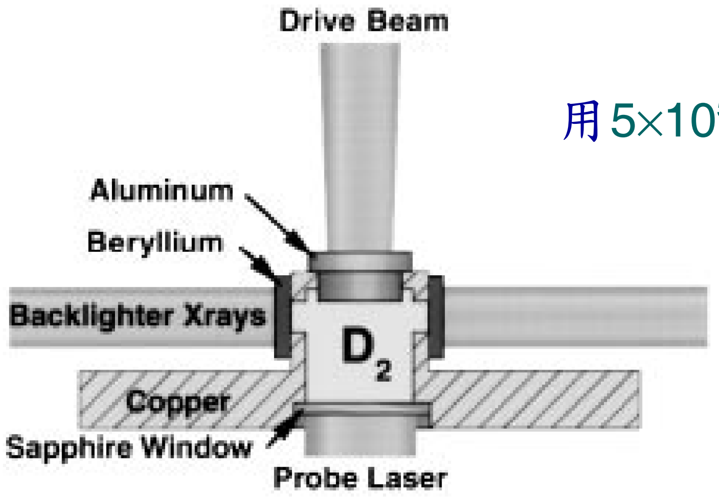
高解析率 X 光攝影



Rev. Sci. Instrum. 74, 2300 (2003)

強大光壓的展示

Nova laser in Lawrence Livermore National Laboratory

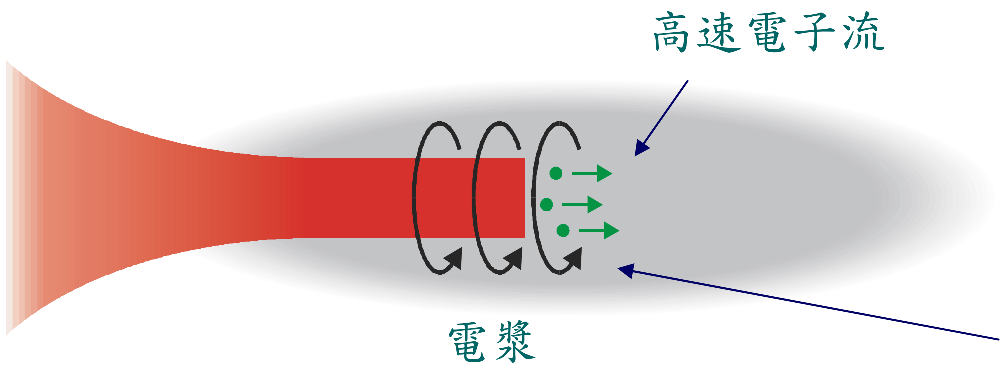


用5×10^5大氣壓的光壓將氘壓成金屬態

Phys. Rev. Lett. **84,** 5564 (2000)

人造磁場的最高紀錄

Vulcan laser in Rutherford Appleton Laboratory



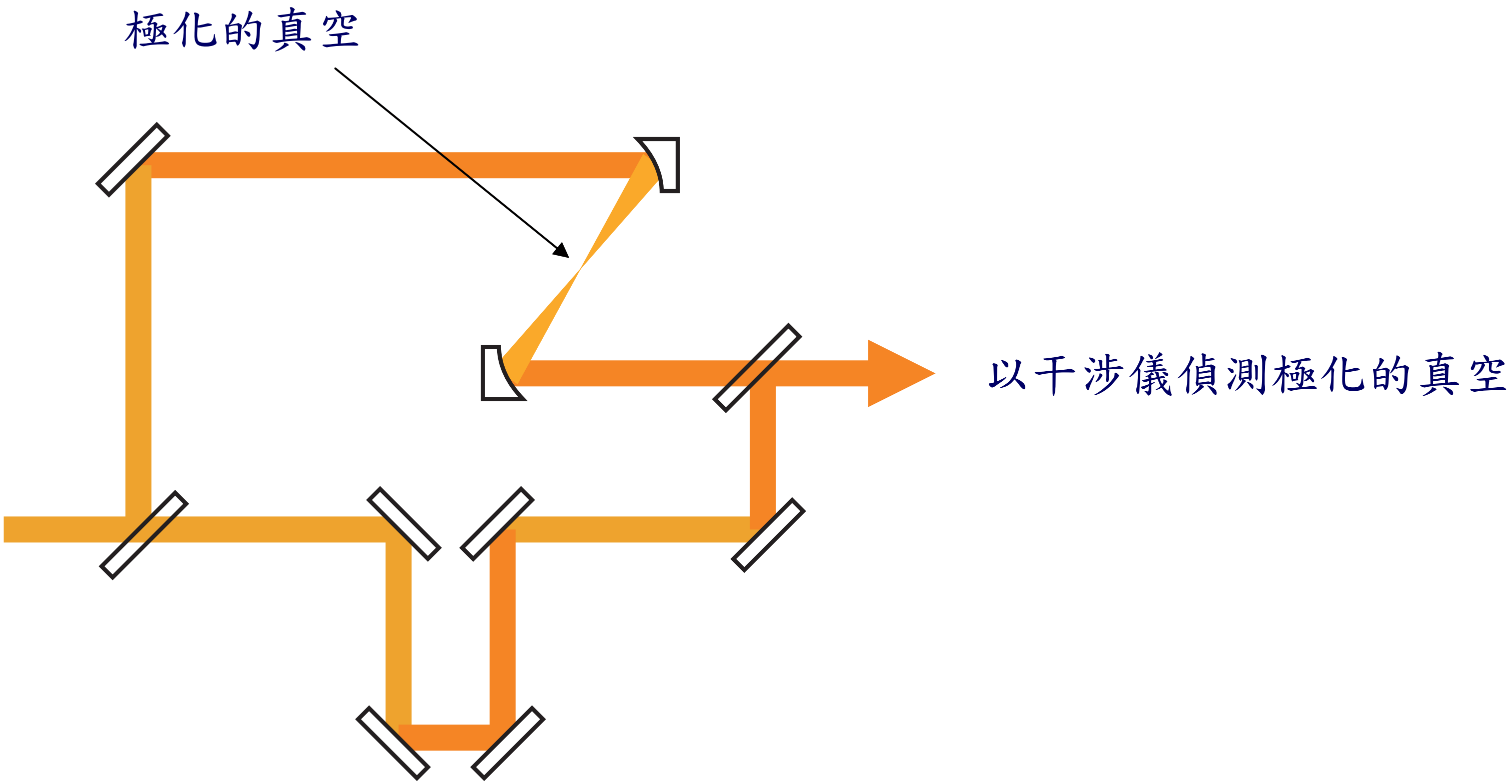
環形磁場 $\approx 3.4 \times 10^4$ T

Nature **415,** 280 (2002)

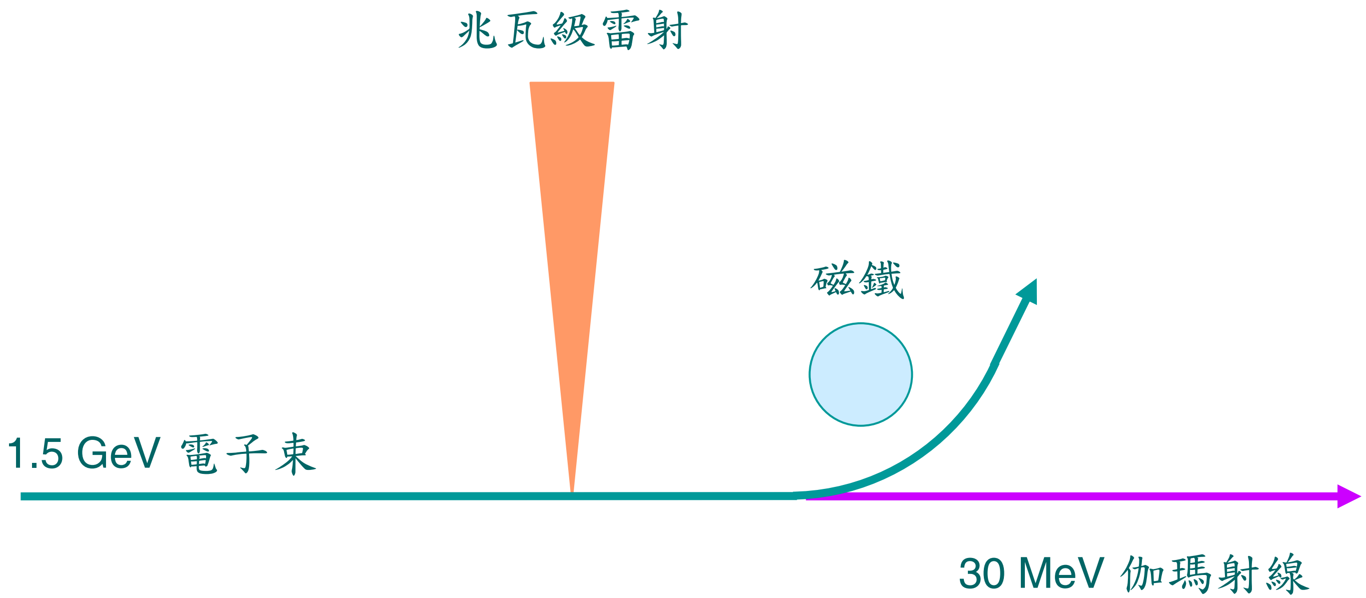
超導磁鐵的磁場 ≈ 10 T

在真空中產生正負電子對?

所需電場 = $\dfrac{2m_e^2c^3}{eh} \approx 4.2 \times 10^{17}$ V/m



核子物理的新光源



用途：觸發核反應，製作同位素，研究元素形成途徑。

光與光相撞產生反物質

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

S. C. Berridge, W. M. Bugg, K. Shmakov, and A. W. Weidemann
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996

C. Bula, K. T. McDonald, and E. J. Prebys
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(Received 2 June 1997)

A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]

PACS numbers: 13.40.–f, 12.20.Fv, 14.70.Bh

用雷射來改變基本粒子的生命期?

PRL **98,** 251803 (2007) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2007

Laser-Assisted Muon Decay

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(Received 2 February 2007; published 20 June 2007)

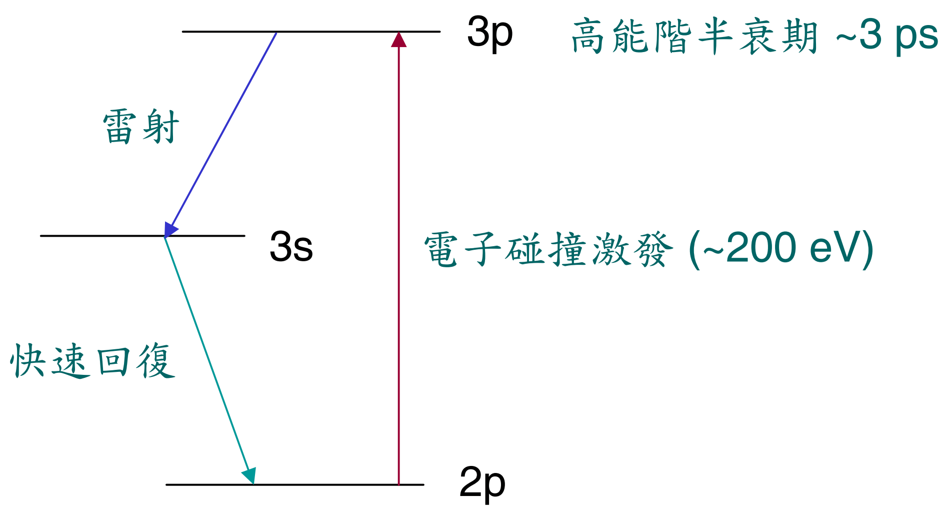
We show theoretically that the muon lifetime can be changed dramatically by embedding the decaying muon in a strong linearly polarized laser field. Evaluating the S-matrix elements taking all electronic multiphoton processes into account we find that a CO_2 laser with an electric field amplitude of $10^6\ \mathrm{V\,cm^{-1}}$ results in an order of magnitude shorter lifetime of the muon. We also analyze the dependencies of the decay rate on the laser frequency and intensity.

DOI: 10.1103/PhysRevLett.98.251803 PACS numbers: 13.35.Bv, 13.40.Ks, 14.60.Ef, 42.62.−b

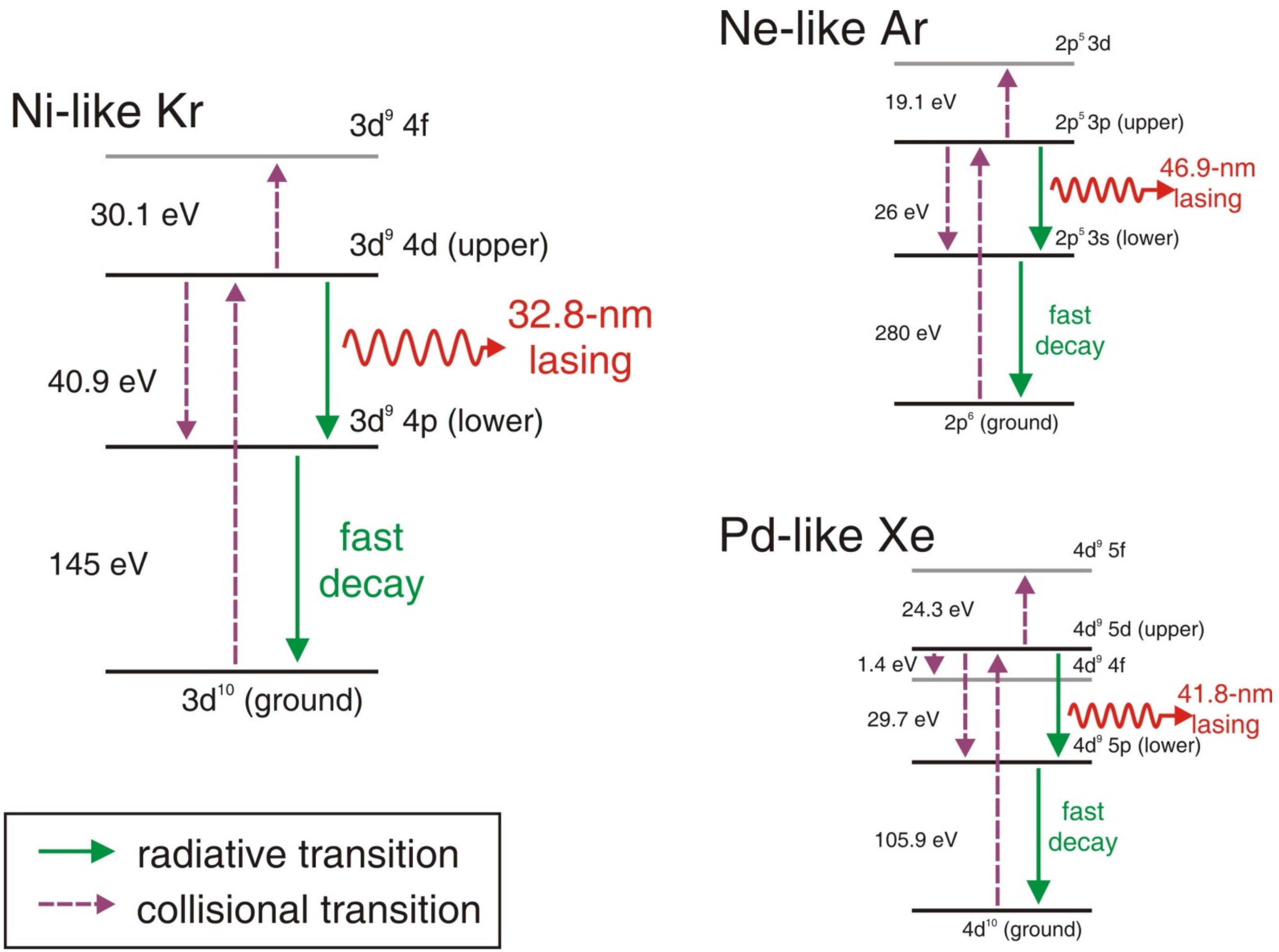
X 光雷射

X 光雷射的能階

類氖離子 (Ar^{8+}, Ti^{12+}, Fe^{16+})



Energy levels of soft x-ray lasers



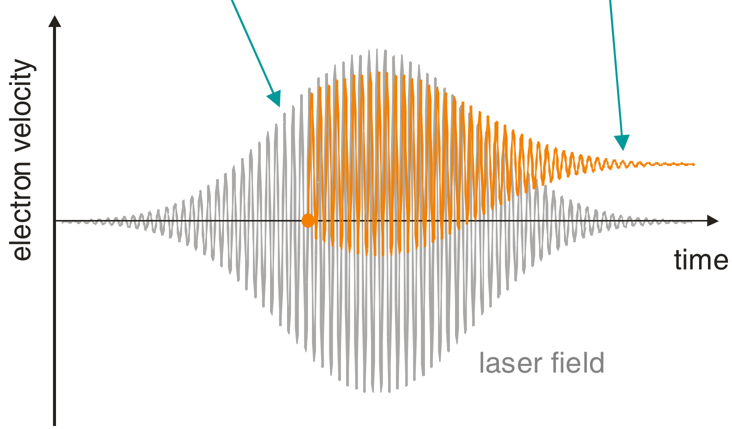
光場游離激發X光雷射

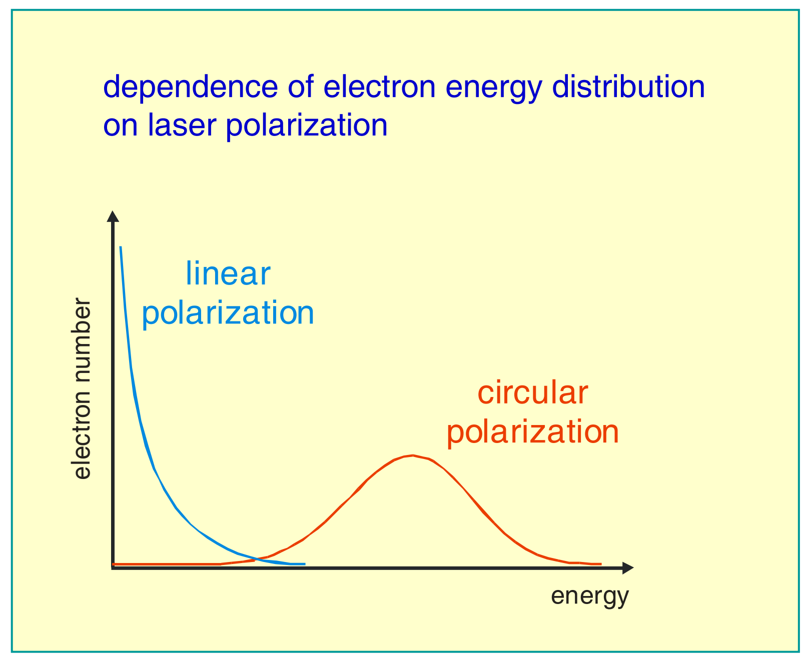
雷射穿隧游離原子到特定游離態

電子受到雷射的電場加速

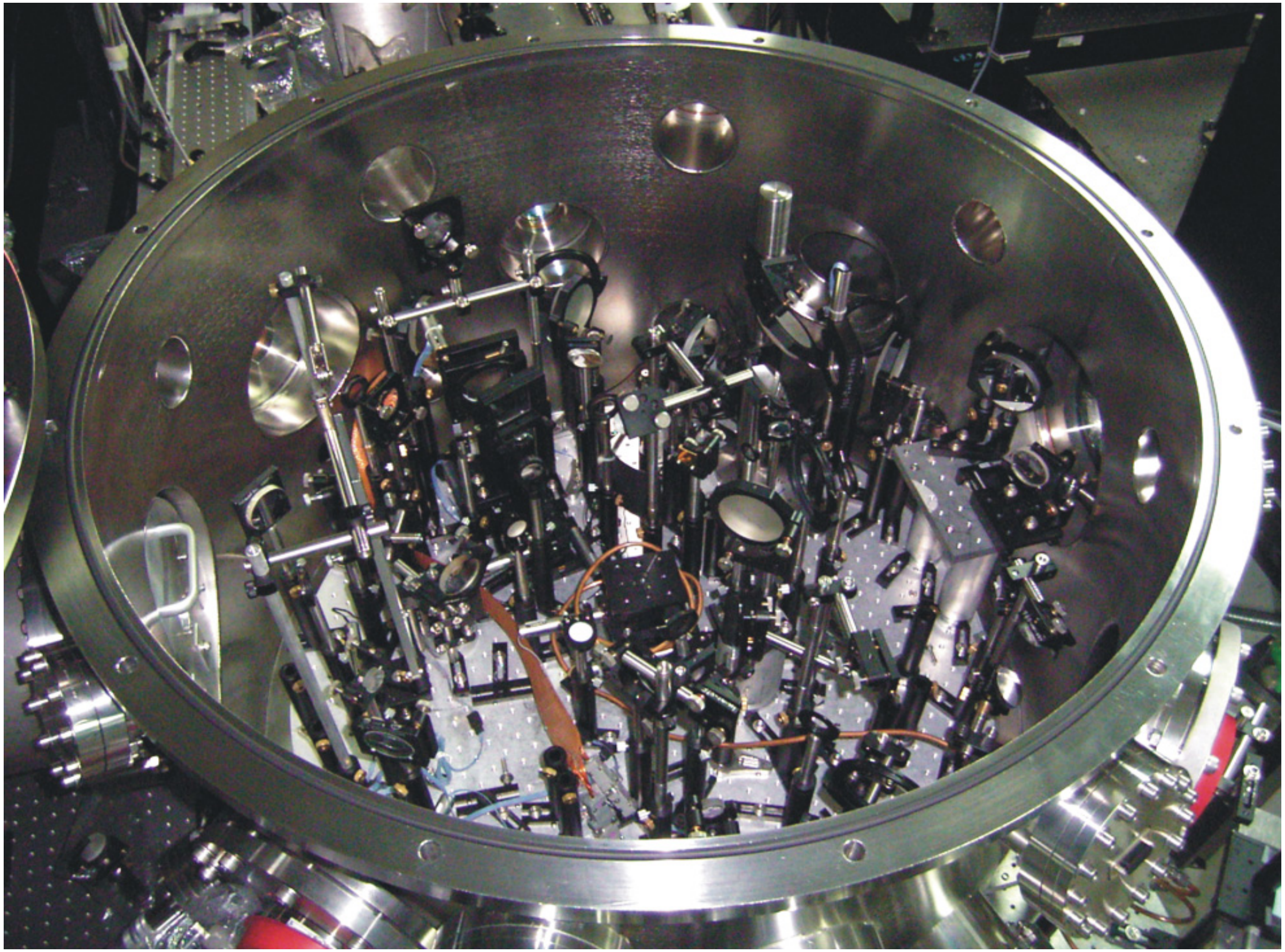
電子與離子碰撞使離子躍遷到激發態

居量反轉

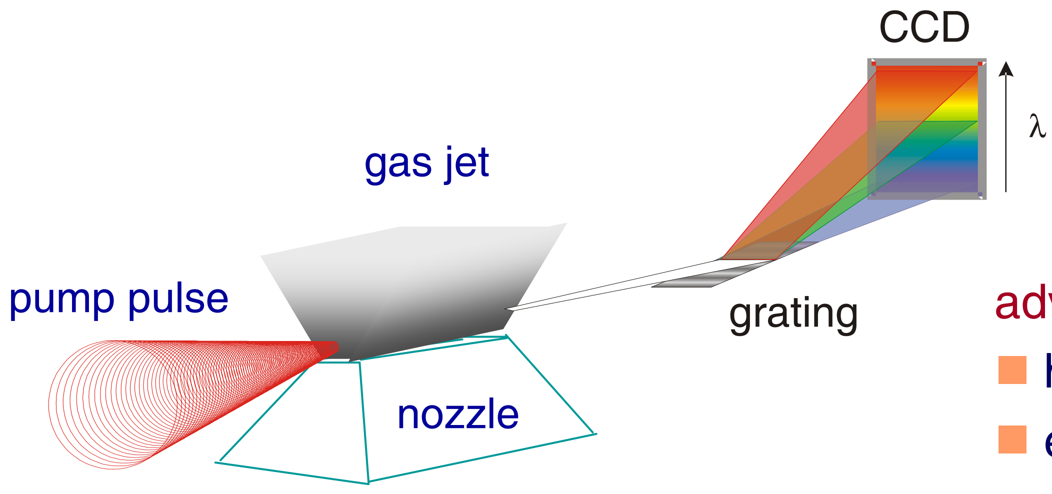




氣體靶X光雷射



Longitudinally pumped optical-field-ionization x-ray lasers

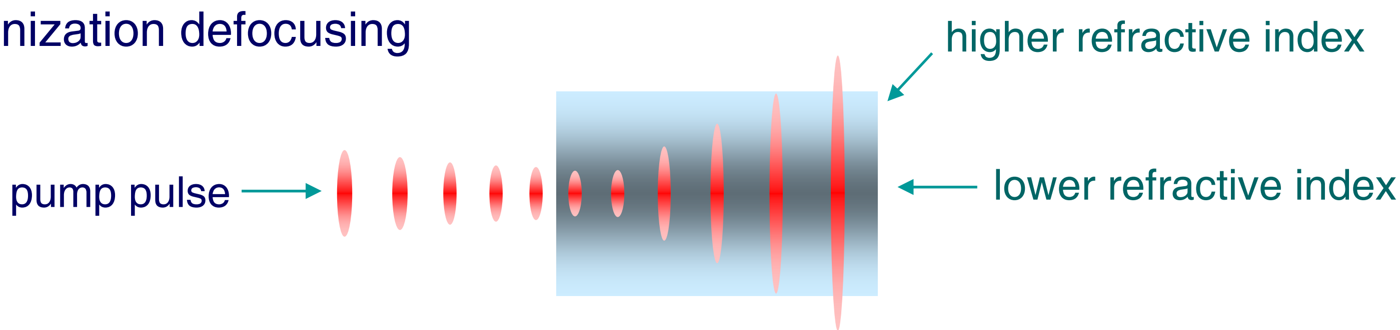


advantages:

- high efficiency
- excellent beam profile
- no debris

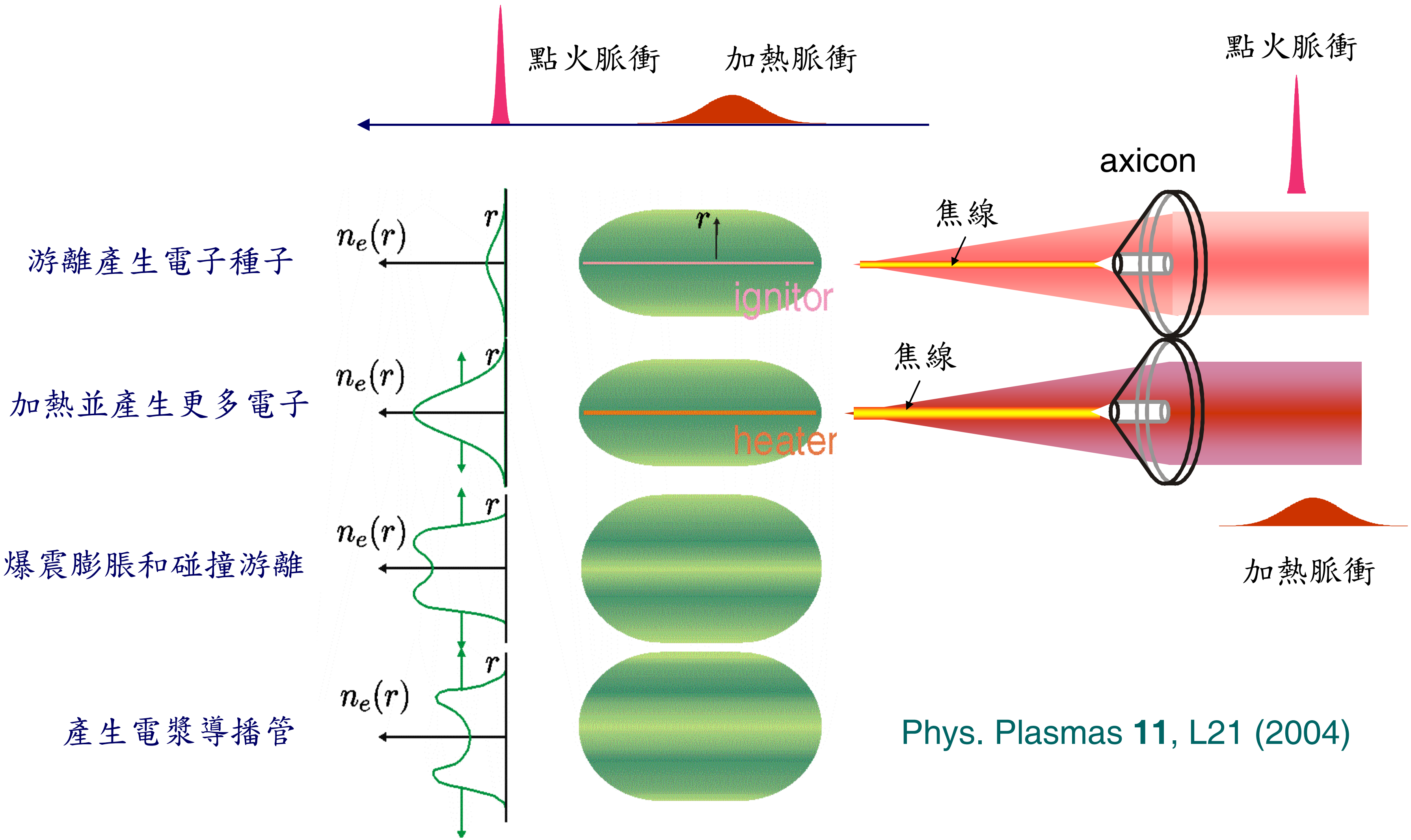
problem:

- ionization defocusing



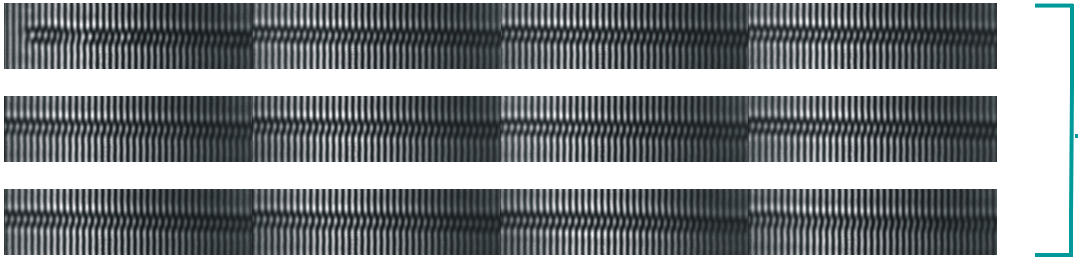
defocusing quickly reduces intensity

以線形聚焦製作電漿導波管



Phys. Plasmas **11**, L21 (2004)

Laser drilled plasma waveguide



length > 1.2 cm

density variation < 20%

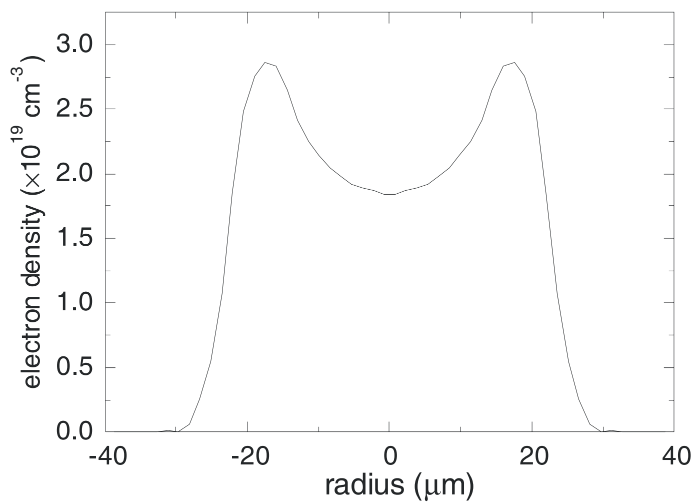
ignitor: 15 mJ, 55 fs

heater: 85 mJ, 80 ps (1.1 ns delay)

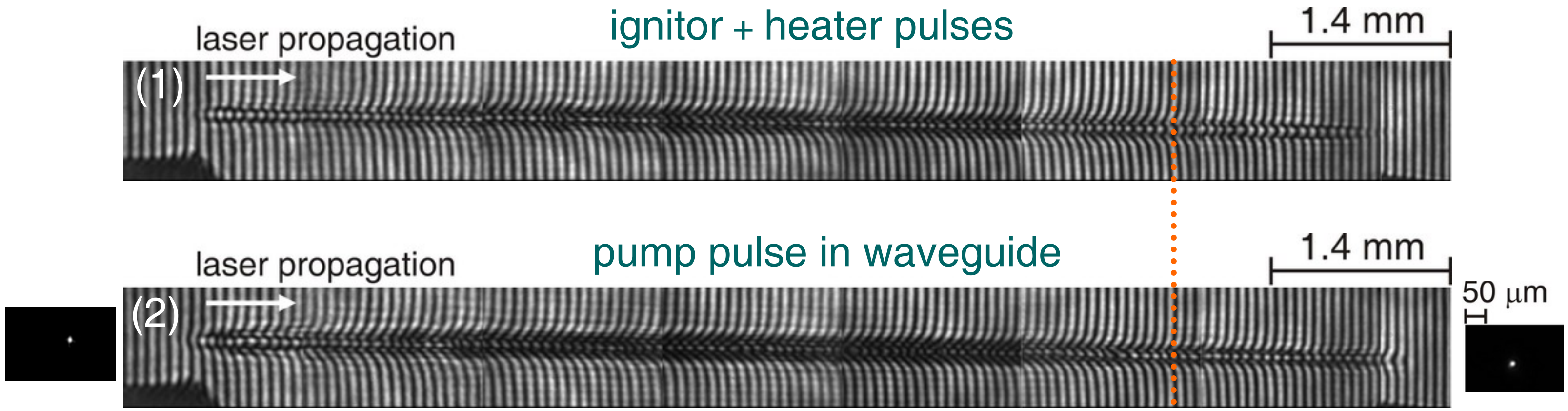
probe: 1.2 ns after heater

Phys. of Plasma **11,** L21 (2004)

electron density profile

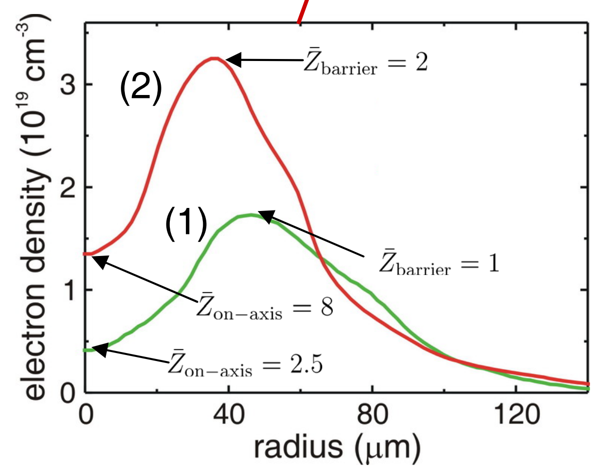


Unexpected immunity to ionization defocusing



pump pulse: 45 fs, 235 mJ
ignitor: 45 fs, 45 mJ
heater: 80 ps, 225 mJ
ignitor-heater separation: 200 ps
hearer-pump delay: 2.5 ns
atom density: 1.6×10^{19} cm^{-3}

radial electron density profile

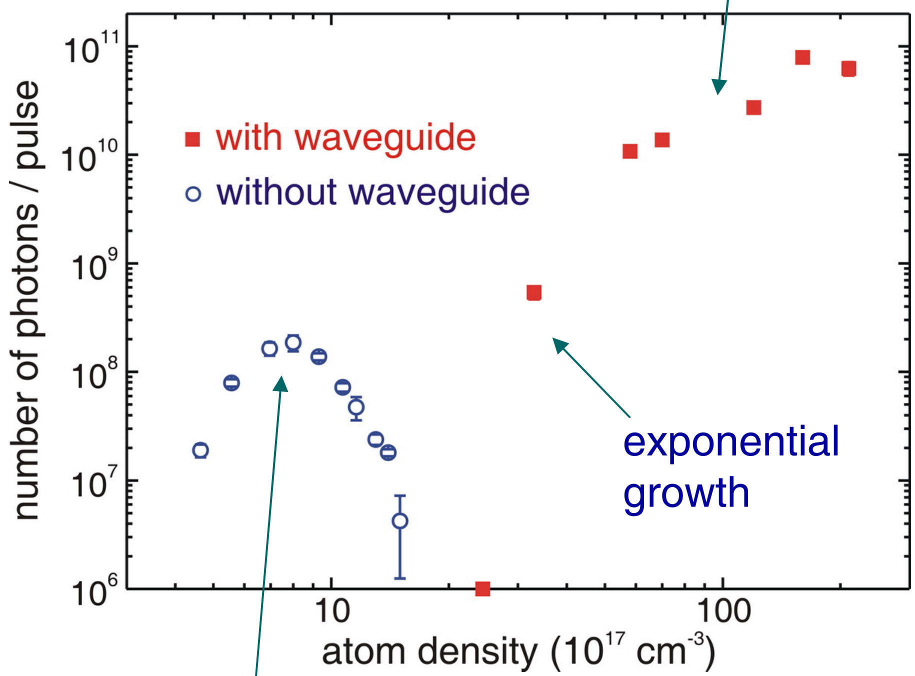


A uniform plasma waveguide of 9-mm length is produced with the axicon-ignitor-heater scheme. The guided beam size is smaller than 15 μm.

Atom density dependence for Ni-like Kr lasing at 32.8 nm

400-fold enhancement by waveguide

linear growth (reaching saturation)



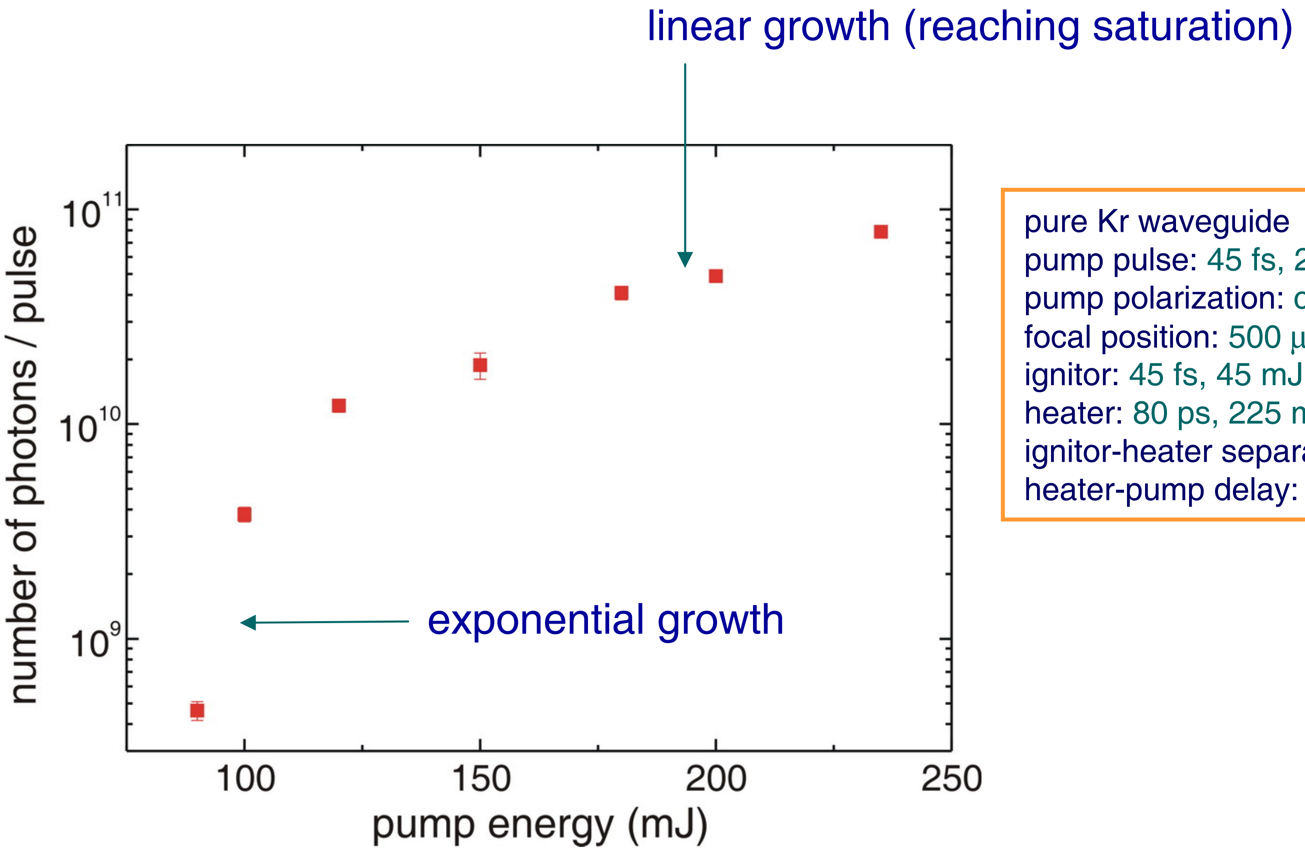
without waveguide
pump pulse: 45 fs, 235 mJ
focal position: 2.75 mm
pump polarization: circular

pure Kr waveguide
pump pulse: 45 fs, 235 mJ
pump polarization: circular
focal position: 500 μm
ignitor: 45 fs, 45 mJ
heater: 80 ps, 225 mJ
ignitor-heater separation: 200 ps
heater-pump delay: 2.5 ns

trade-off between larger gain coefficient
and more severe ionization defocusing

Phys. Rev. Lett. **99**, 063904 (2007)

Pump power dependence for Ni-like Kr lasing at 32.8 nm



pure Kr waveguide
pump pulse: 45 fs, 235 mJ
pump polarization: circular
focal position: 500 µm
ignitor: 45 fs, 45 mJ
heater: 80 ps, 225 mJ
ignitor-heater separation: 200 ps
heater-pump delay: 2.5 ns

Phys. Rev. Lett. **99**, 063904 (2007)

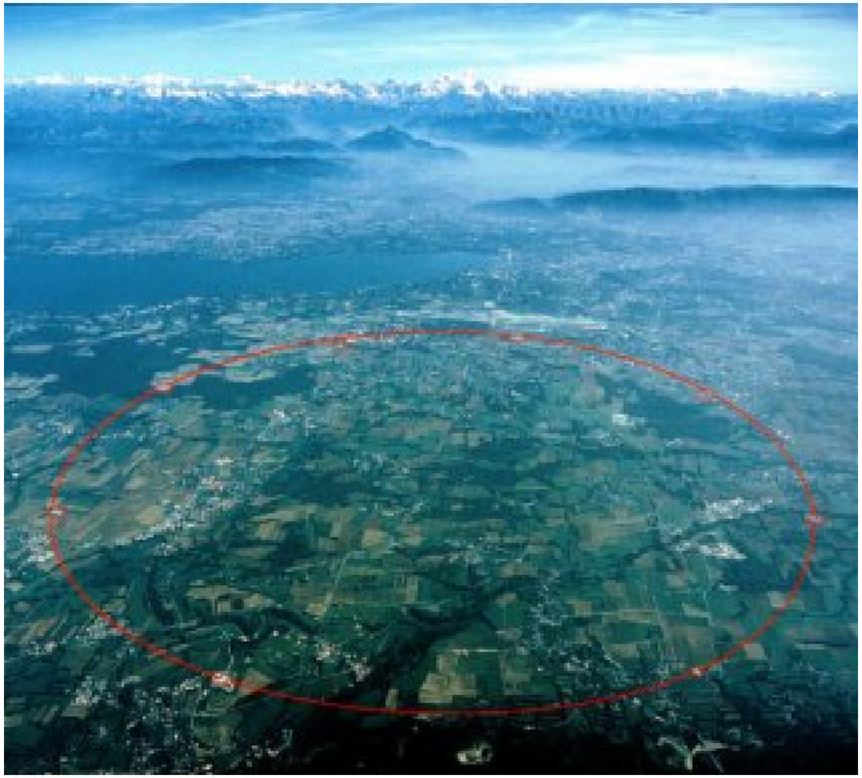
與同步輻射比較

spectral brightness (photon/sec/mm²/mrad²) for $\frac{\Delta\lambda}{\lambda} = 10^{-4}$

	NSRRC (Taiwan)	x-ray laser
pulse duration	100 ps	100 fs (with HHG seeding)
repetition rate	10^6 Hz	10 Hz
wavelength	tunable	discrete set
average spectral brightness at 32.8 nm	9.8×10^{12}	2.0×10^{13}
peak spectral brightness at 32.8 nm	7.9×10^{14}	3.9×10^{25}

電子加速器

CERN的27公里環形加速器



傳統加速器的材料極限： 10^8 V/m

雷射電子加速器概念

10兆瓦雷射脈衝聚焦到10微米的光點

↓

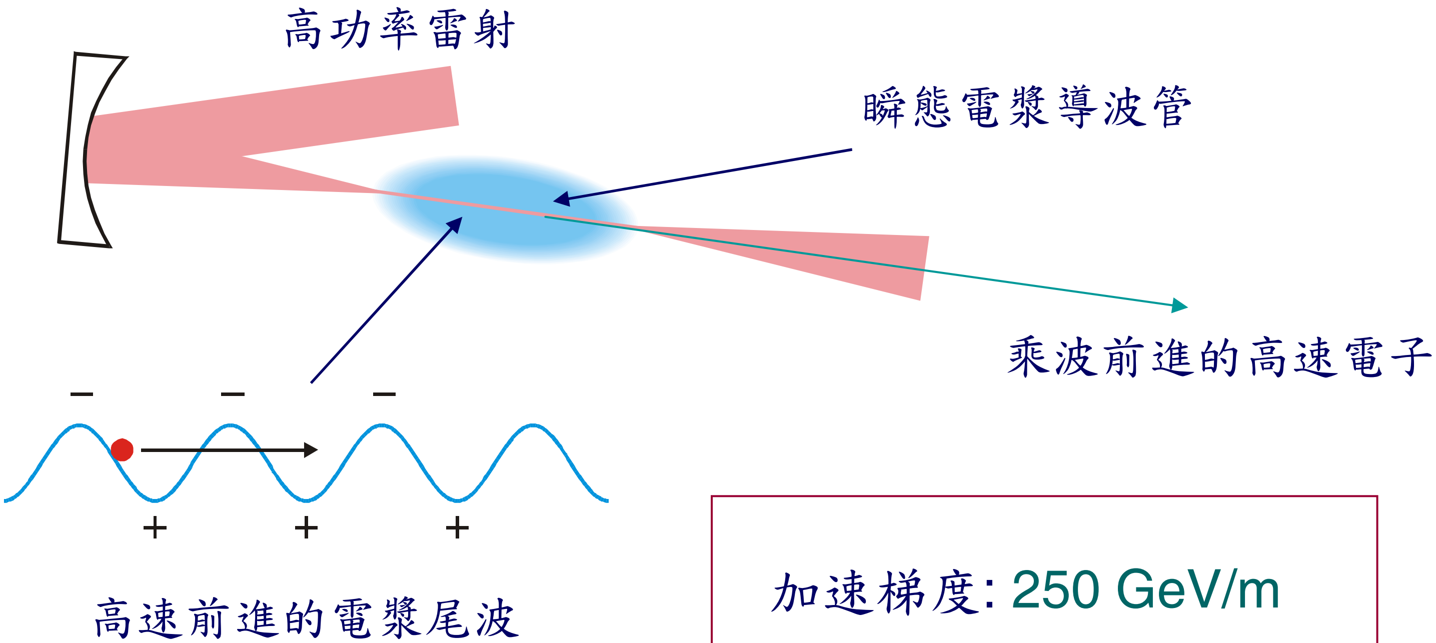
照度: 10^{19} W/cm^2

電場: 10^{13} V/m

加速度: 10^{24} m/sec^2

傳統加速器的材料極限： 10^{8} V/m

雷射電漿波電子加速器



加速梯度: 250 GeV/m

傳統加速器: 50 MeV/m

雷射脈衝激發電漿波

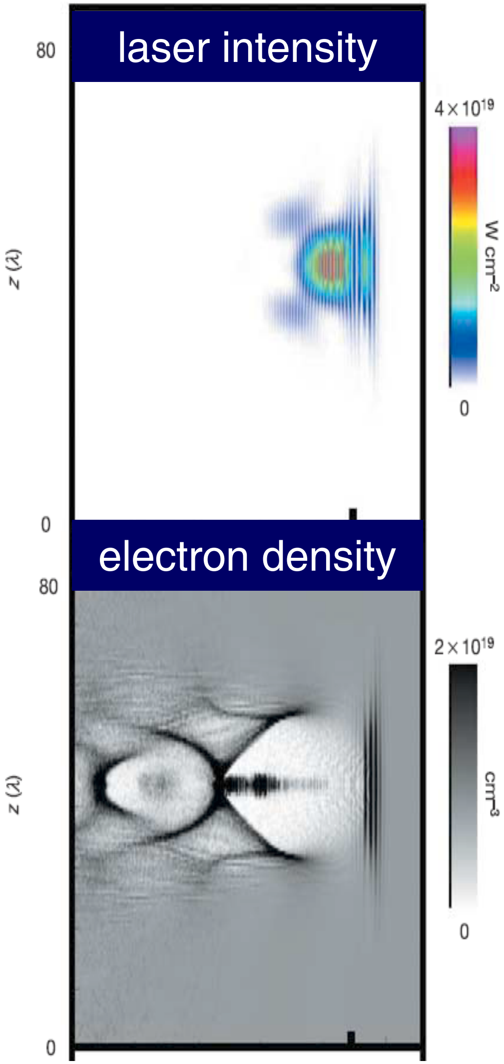
劃雪車機制

(脈衝長度小於電漿振盪週期)

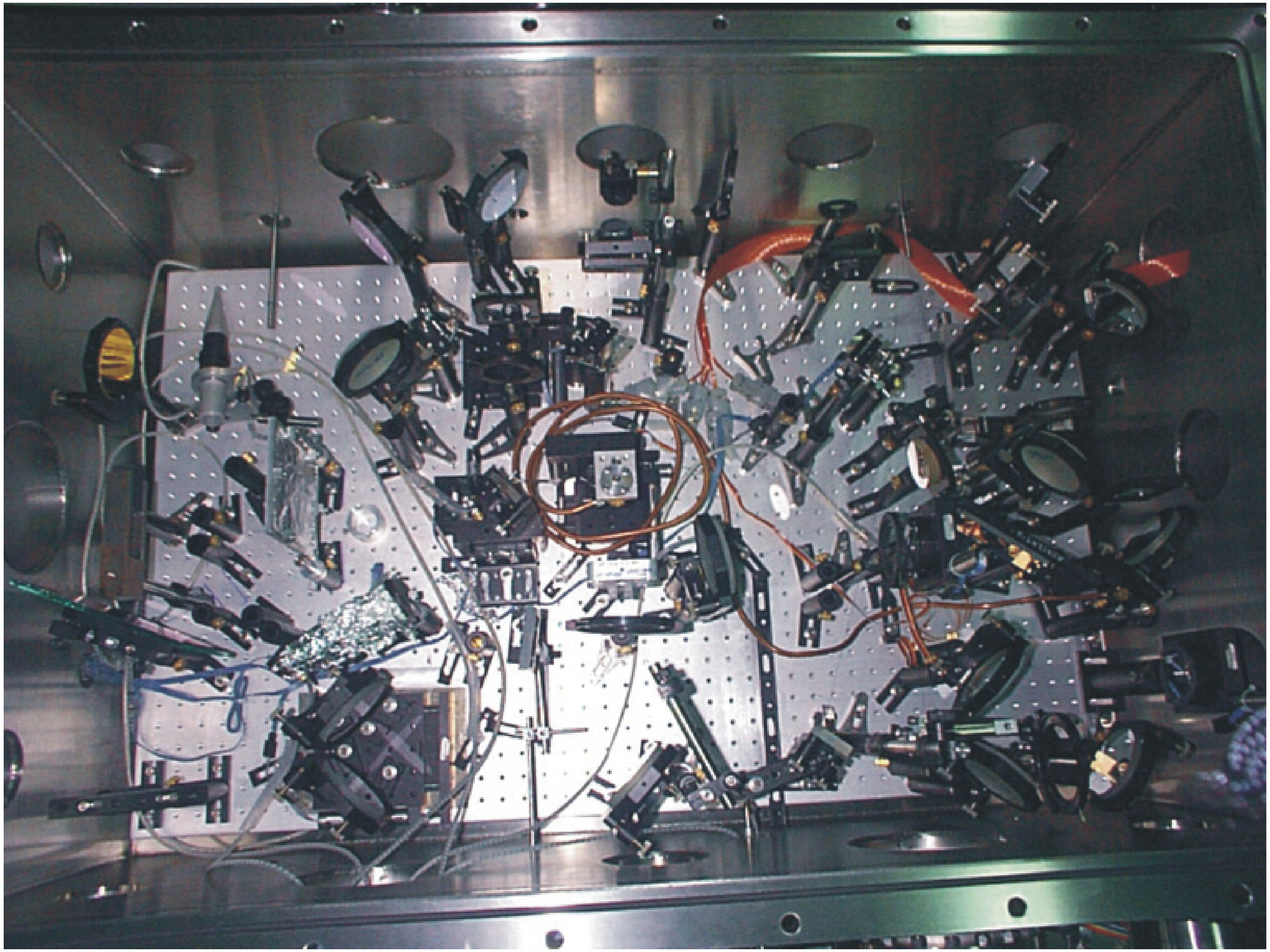
電子被光壓排開

→ 正電空洞跟隨雷射脈衝前進

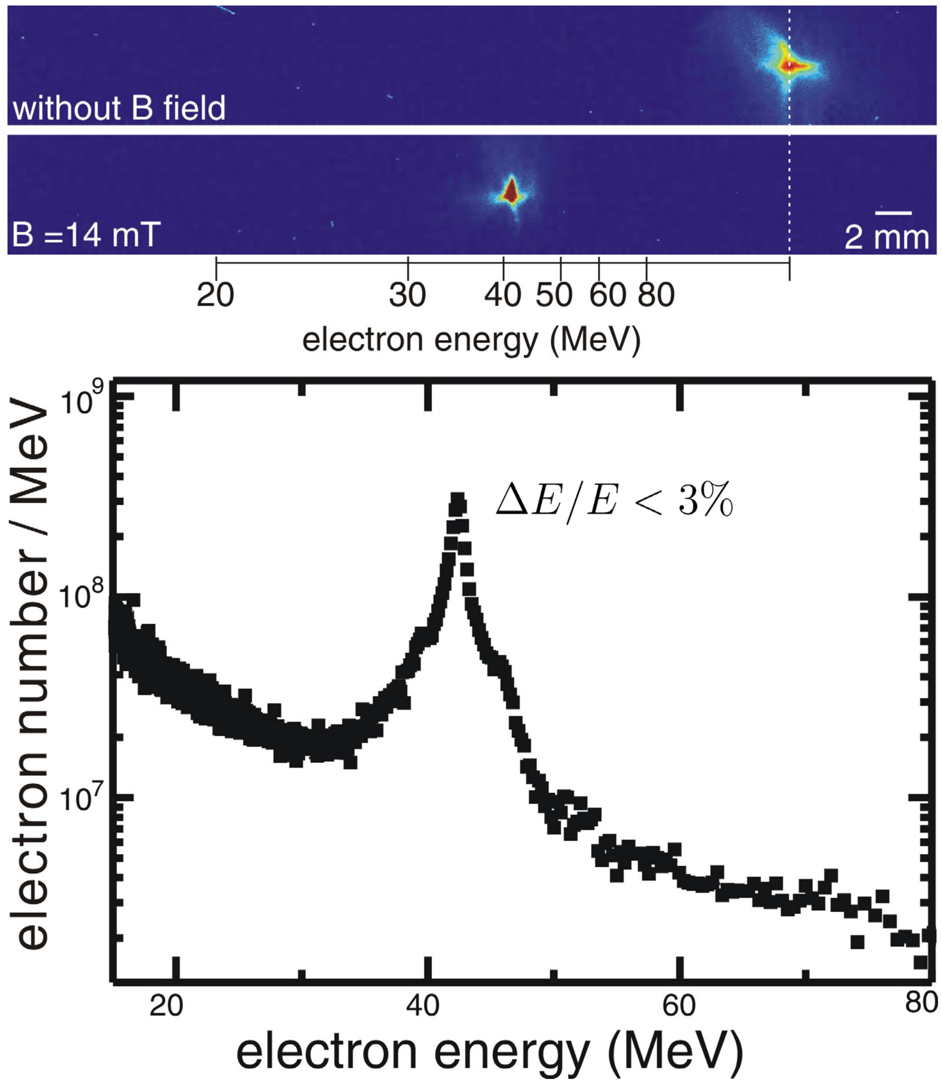
Nature **431,** 541 (2004)



發展中的電子加速器



單一能量加速



plasma density:

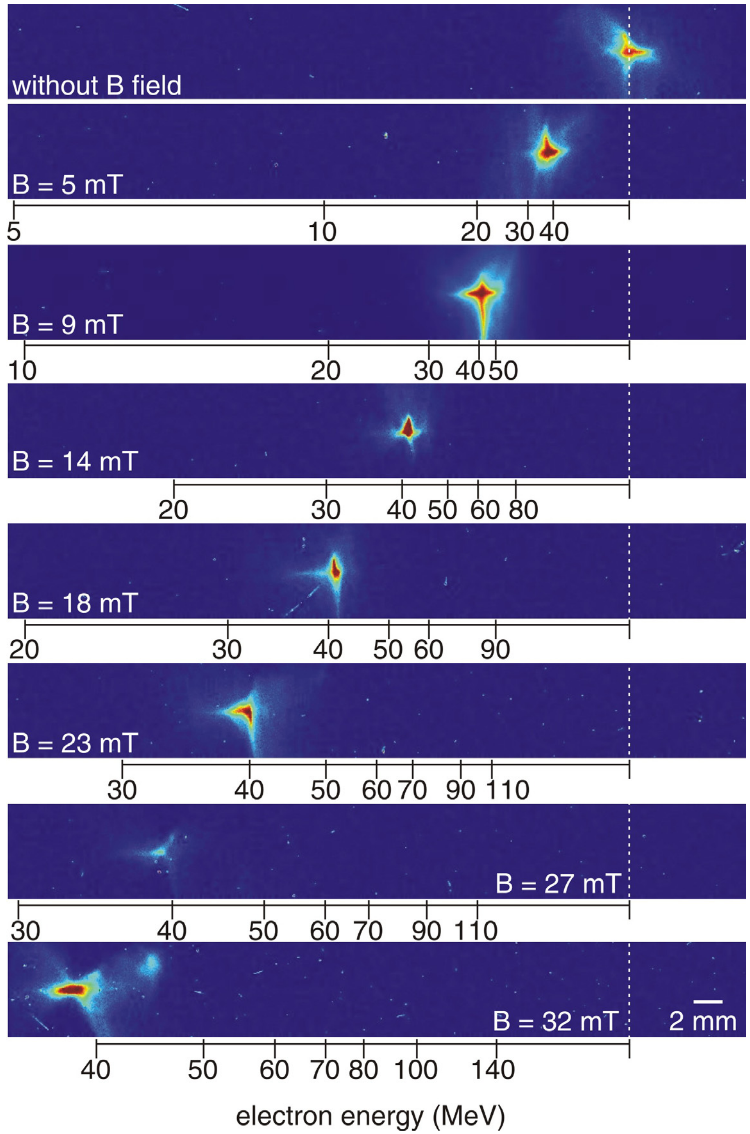
$4 \times 10^{19}\ \mathrm{cm}^{-3}$

pump pulse:

230 mJ, 45 fs,

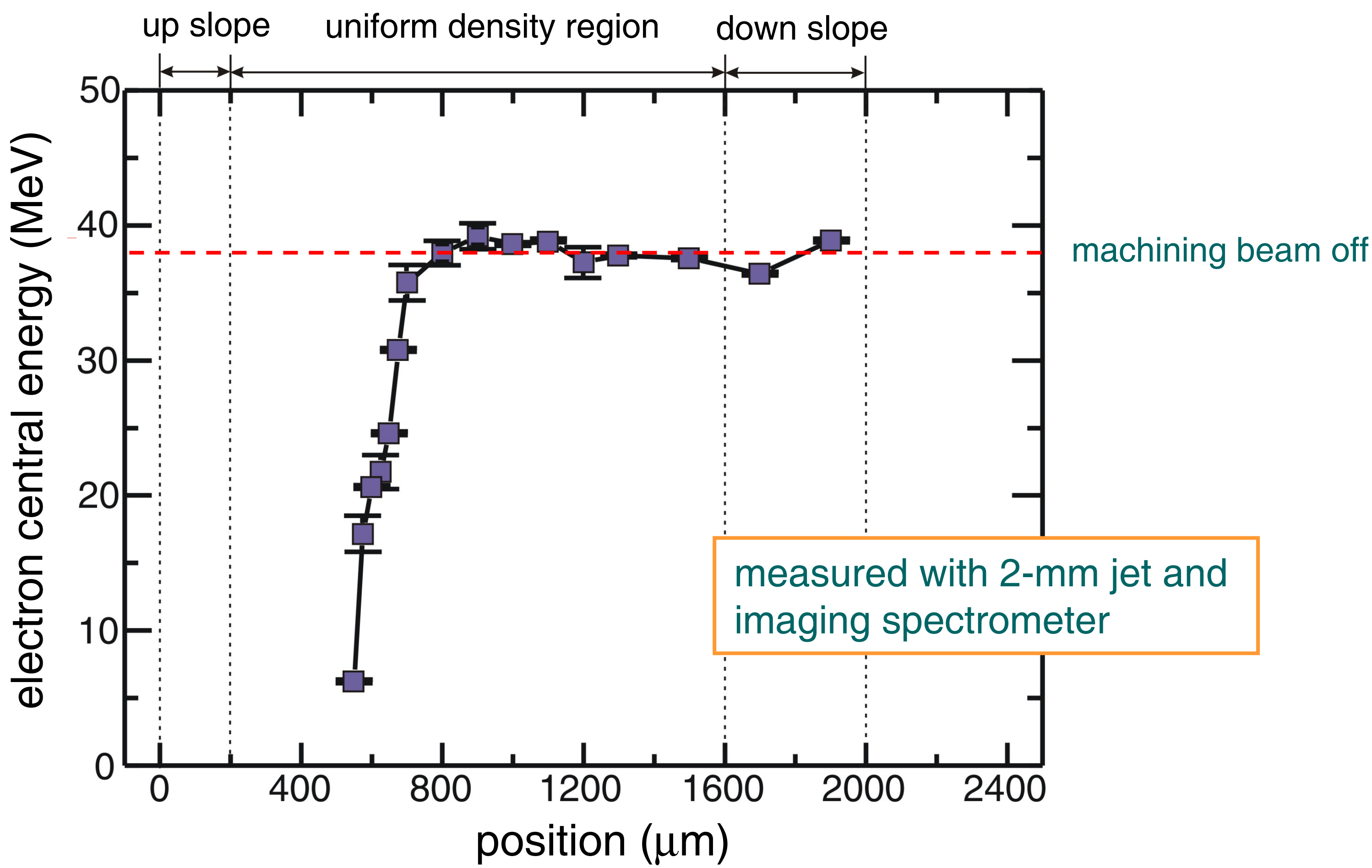
focused to 8-μm diameter

能譜儀上的電子影像



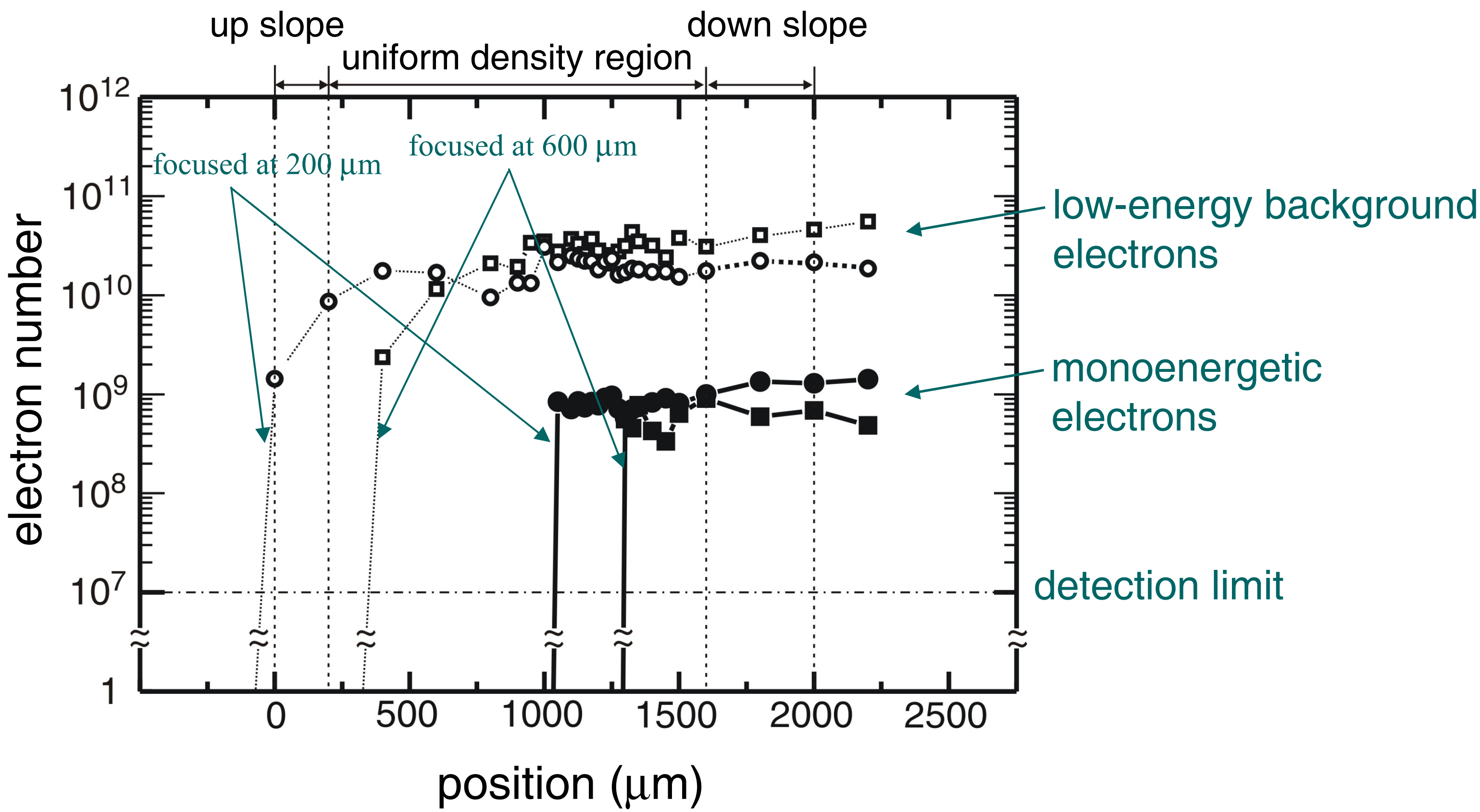
without B field
B = 5 mT
5
10
20
30
40
B = 9 mT
10
20
30
40
50
B = 14 mT
20
30
40
50
60
80
B = 18 mT
20
30
40
50
60
90
B = 23 mT
30
40
50
60
70
90
110
B = 27 mT
30
40
50
60
70
90
110
B = 32 mT
2 mm
40
50
60
70
80
100
140
electron energy (MeV)

解析加速與飽和的過程



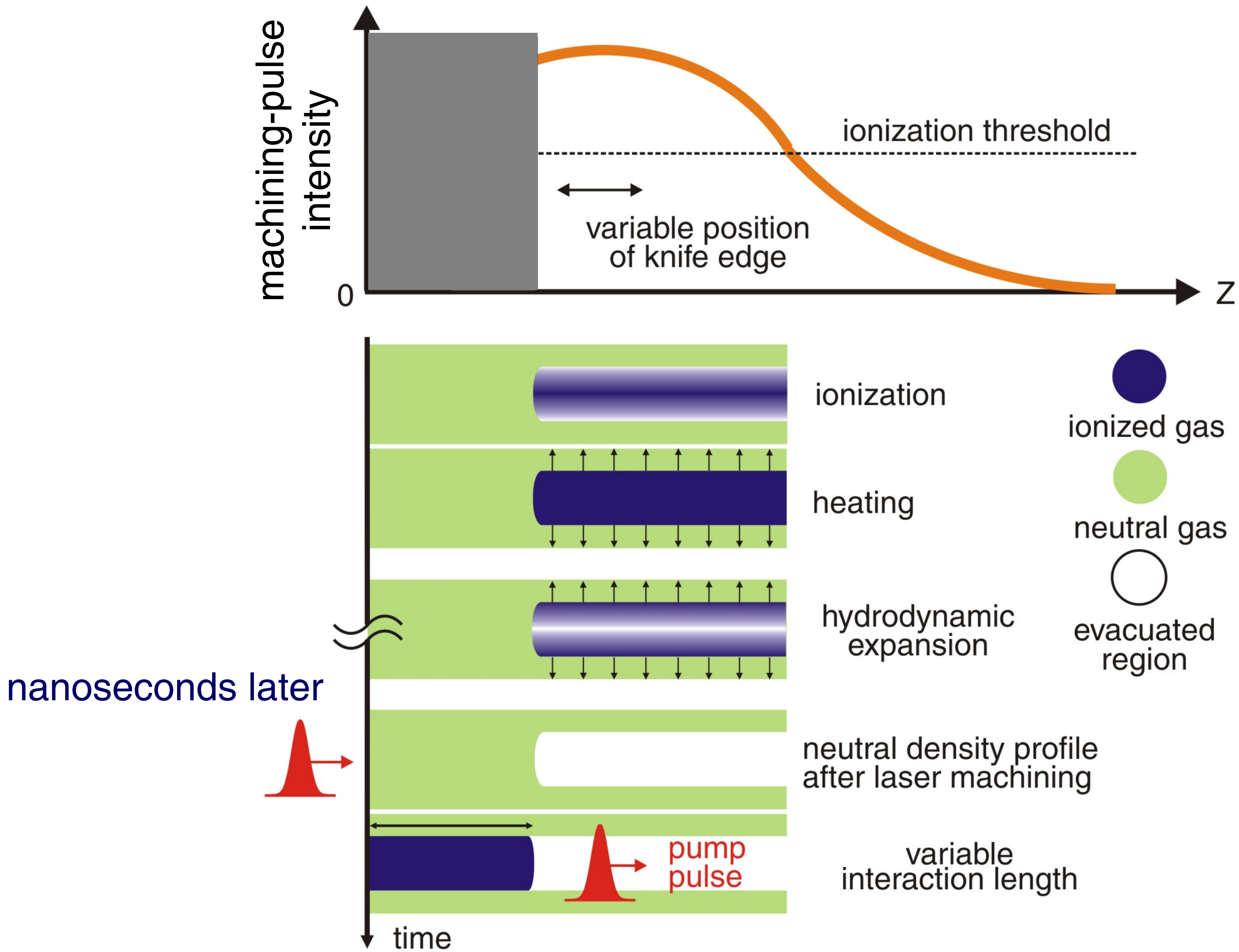
Saturation of electron energy occurs after about 200-μm acceleration distance.

解析電子的注入過程



- It takes a finite distance for the pump beam to evolve into the condition for injection.
- Mono-energetic electrons are injected at a localized location.

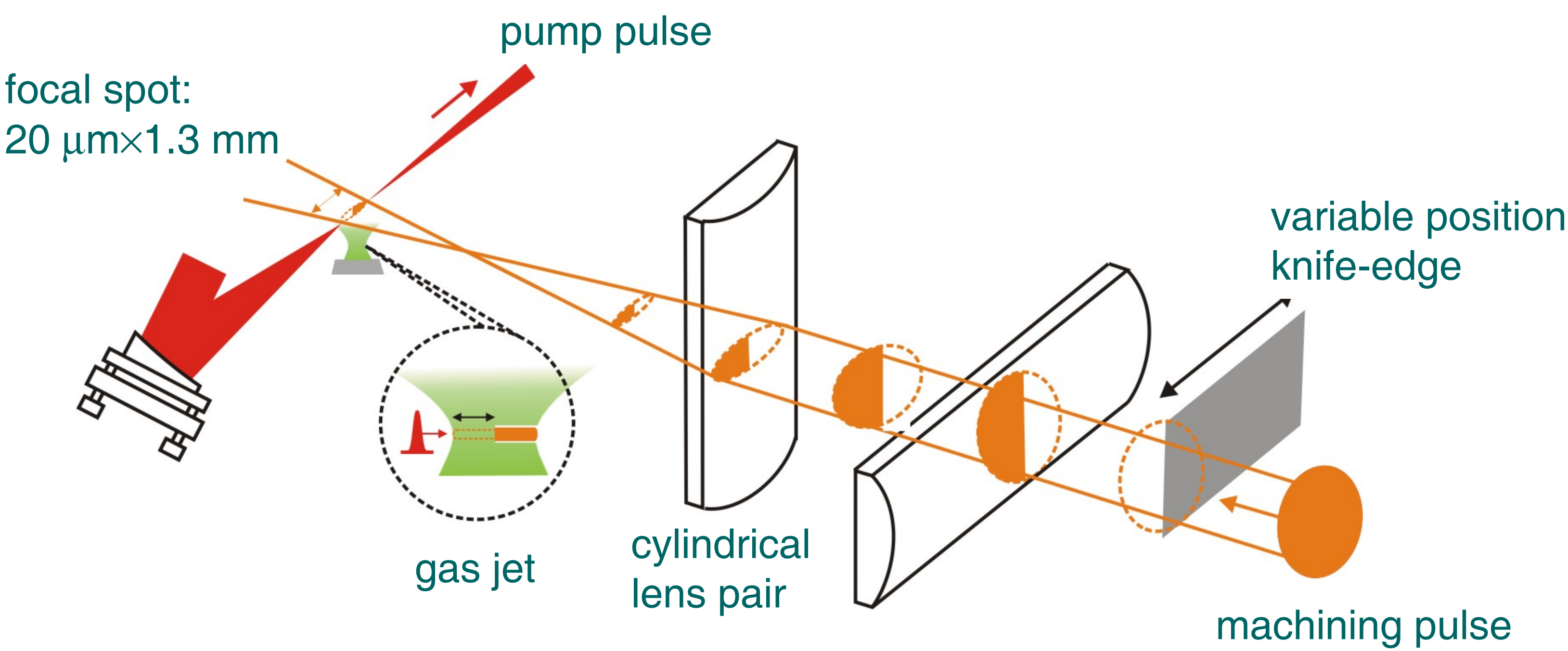
電漿斷層掃描術



machining-pulse intensity
0
Z
ionization threshold
variable position of knife edge
ionization
heating
hydrodynamic expansion
neutral density profile after laser machining
variable interaction length
pump pulse
nanoseconds later
time
ionized gas
neutral gas
evacuated region

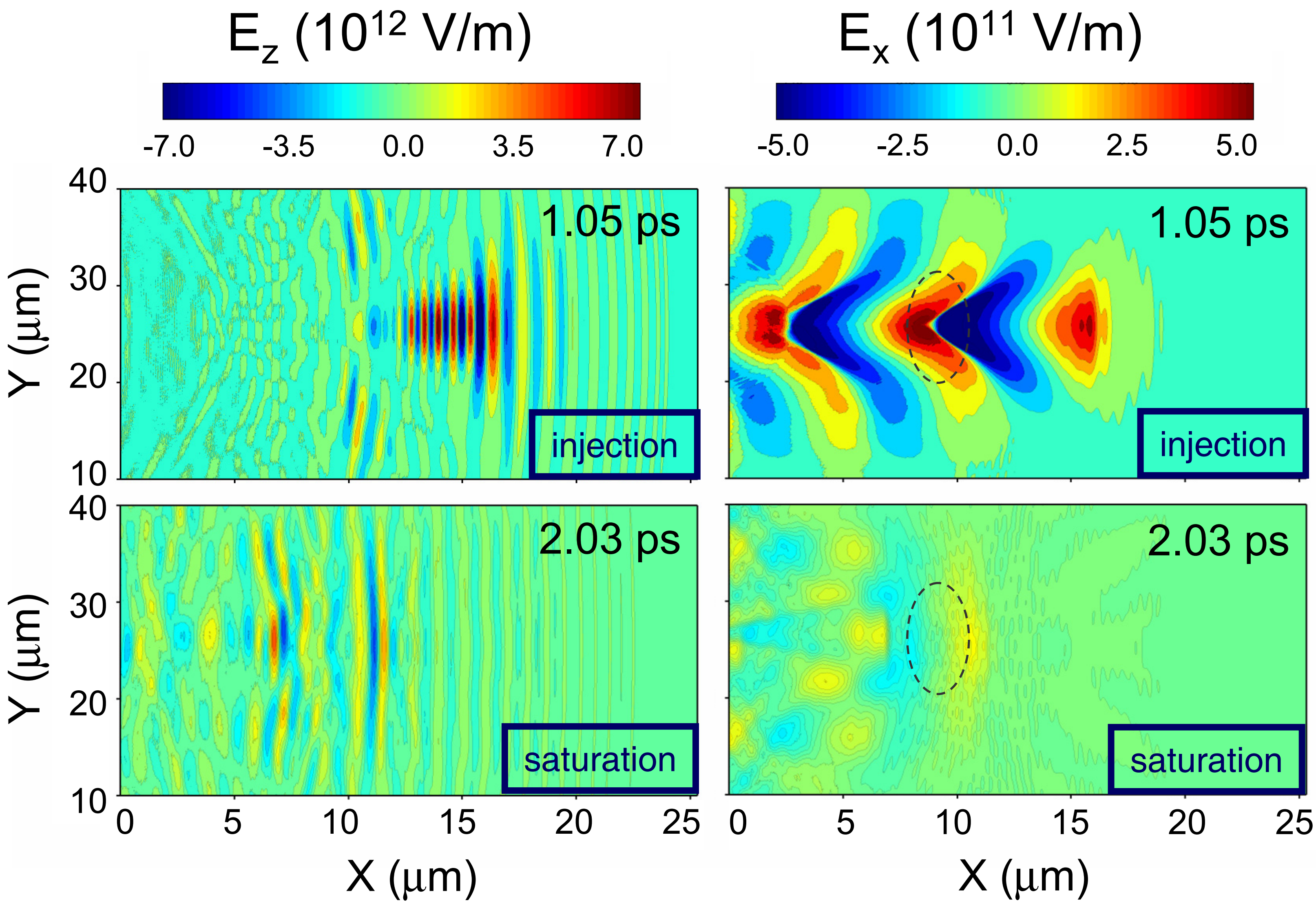
Setup of the machining beam for tomographic measurements

function of the knife-edge: setting the interaction length



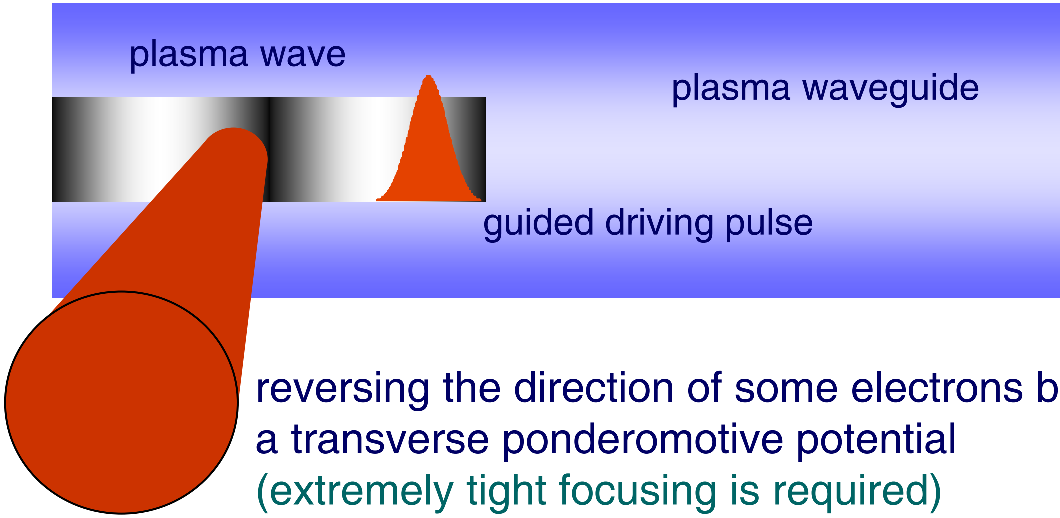
Phys. Rev. Lett. **96**, 095001 (2006)

Evolution of the laser field and the wakefield

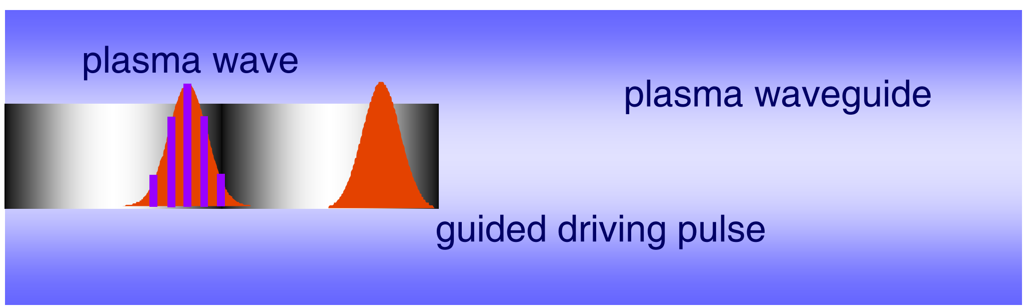


simulation by Prof. Shih-Hung Chen (陳仕宏)

結合光控電子注入與波導中加速



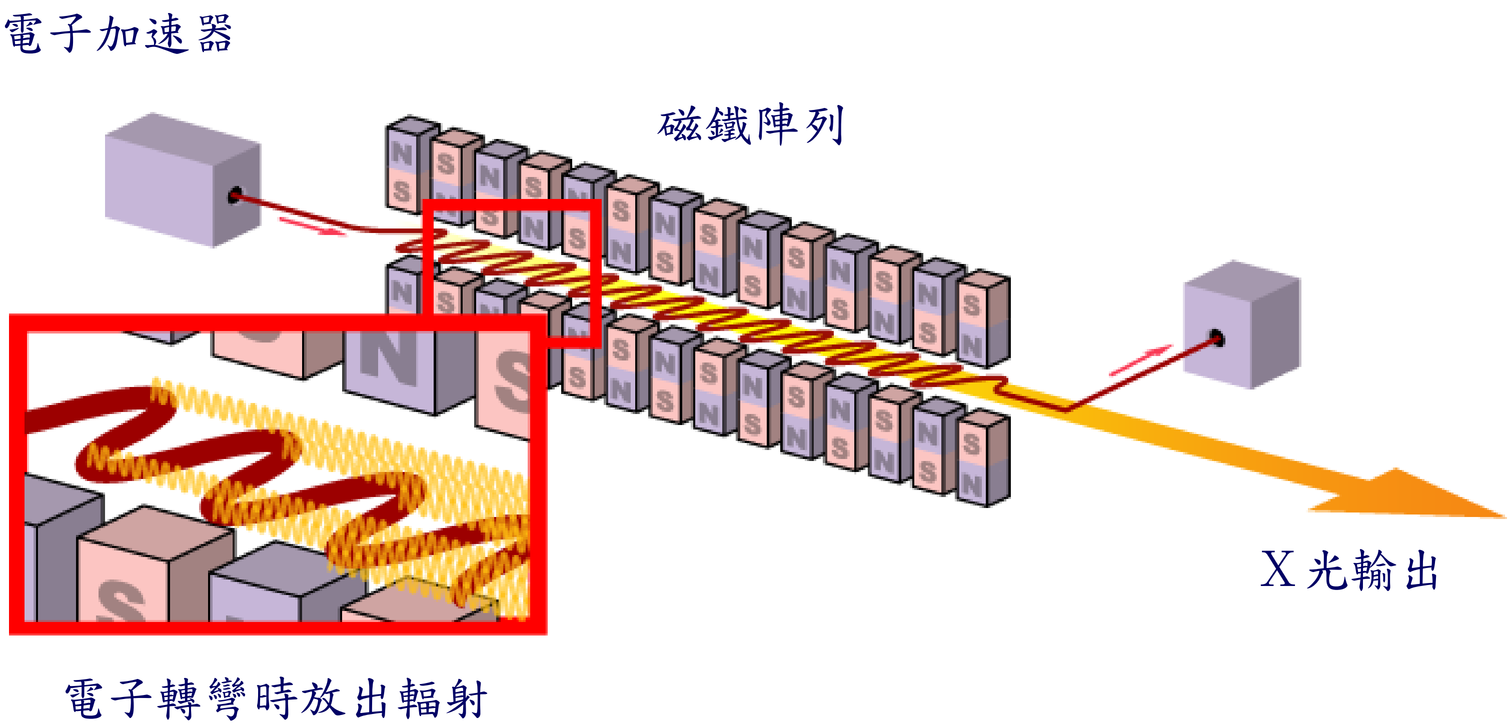
reversing the direction of some electrons by a transverse ponderomotive potential
(extremely tight focusing is required)



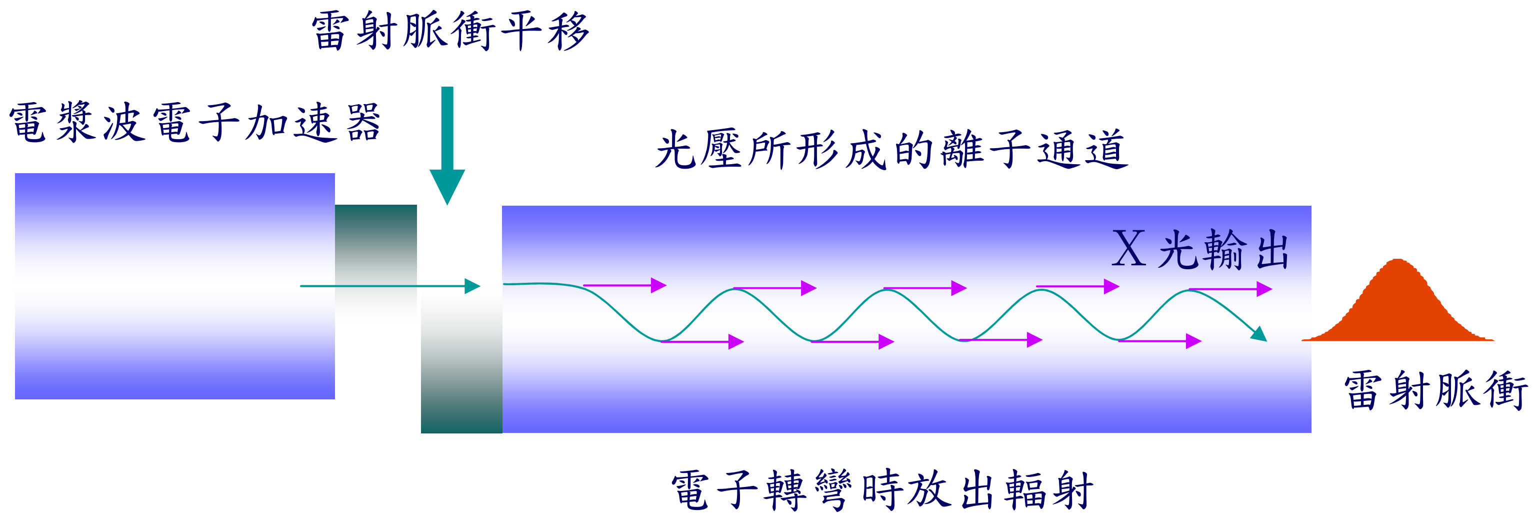
reversing the direction of some electrons by a beat wave between 900-nm and-800 nm pulses

Phys. Rev. Lett. **79,** 2682 (1997)

傳統的X光自由電子雷射



離子通道X光自由電子雷射



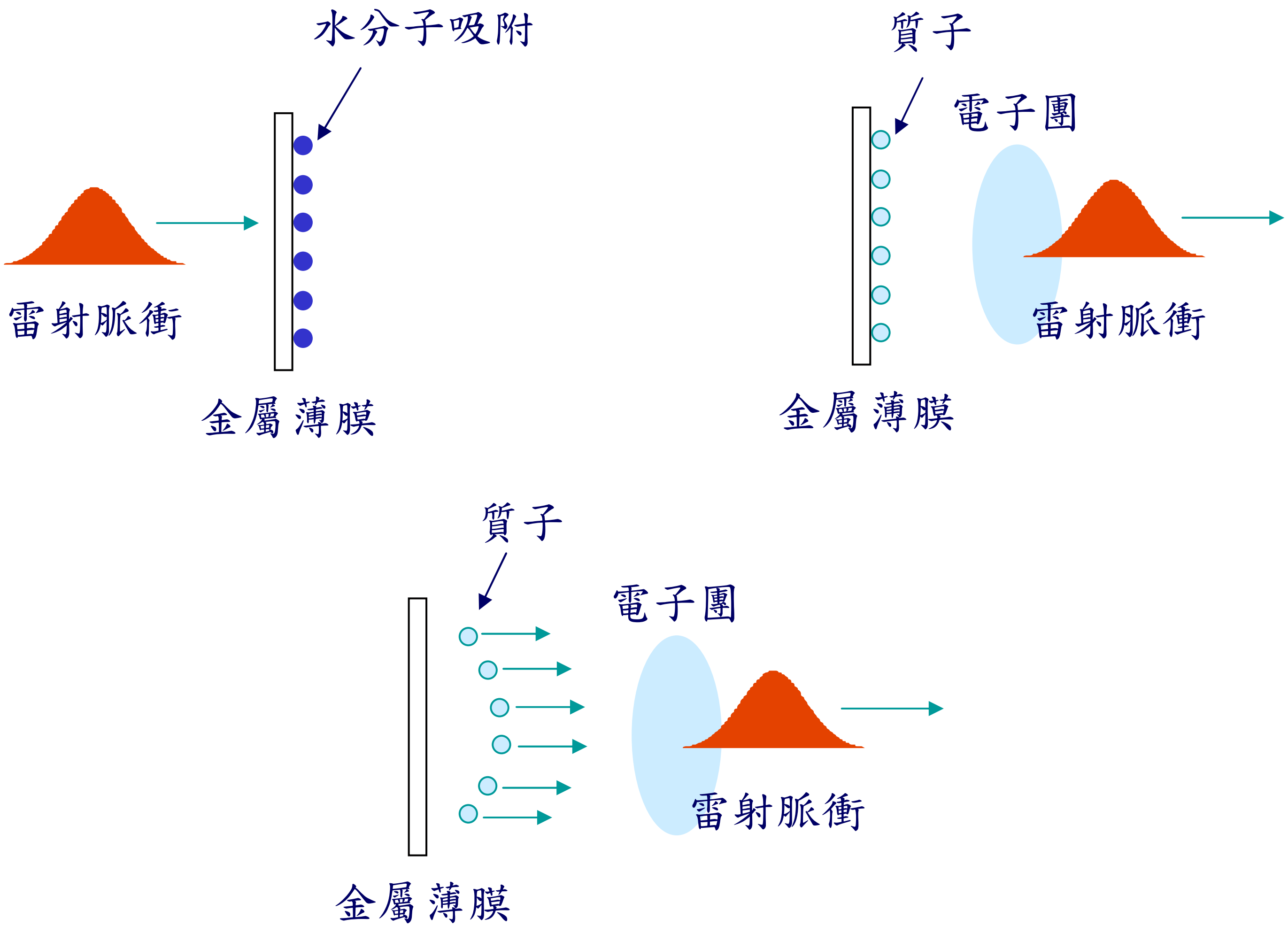
Theoretical estimation:

With 500-MeV 1-nC input electron beam, 1-μW 10-KeV x-ray can be produced.

Phys. Rev. Lett. **93**, 135005 (2004)

質子加速器與中子源

雷射質子加速器



Phys. Rev. Lett. **88,** 215006 (2003)

Dose Localization

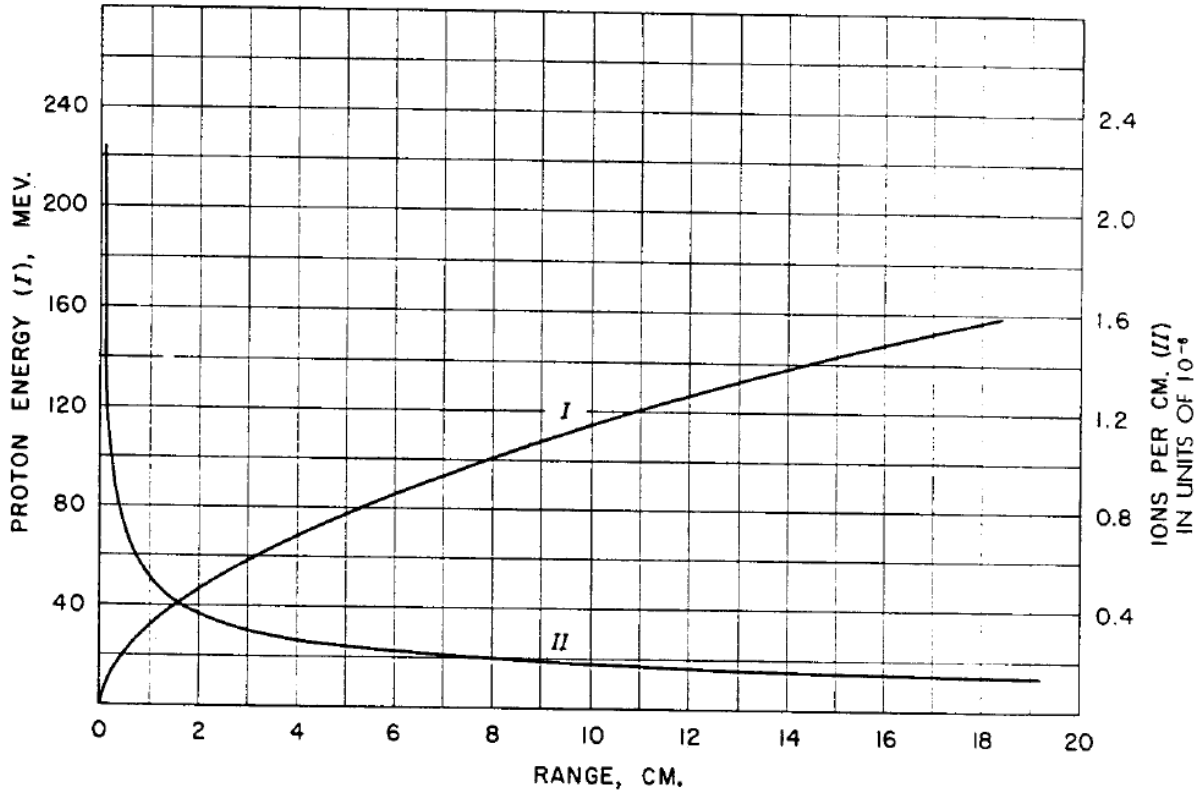


Fig. 1. Curve I is the range-energy relation in tissue. Curve II shows the specific ionization as a function of the residual range of a proton in tissue.

Range straggling ~ 1% **Beam spread ~ 5%**

Radiology **47,** 487 (1946)

Comparison with other radiation sources

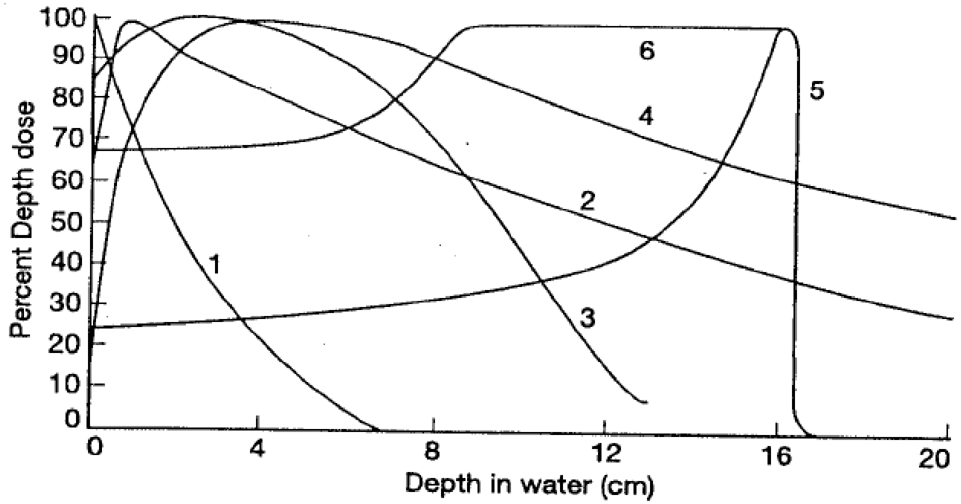
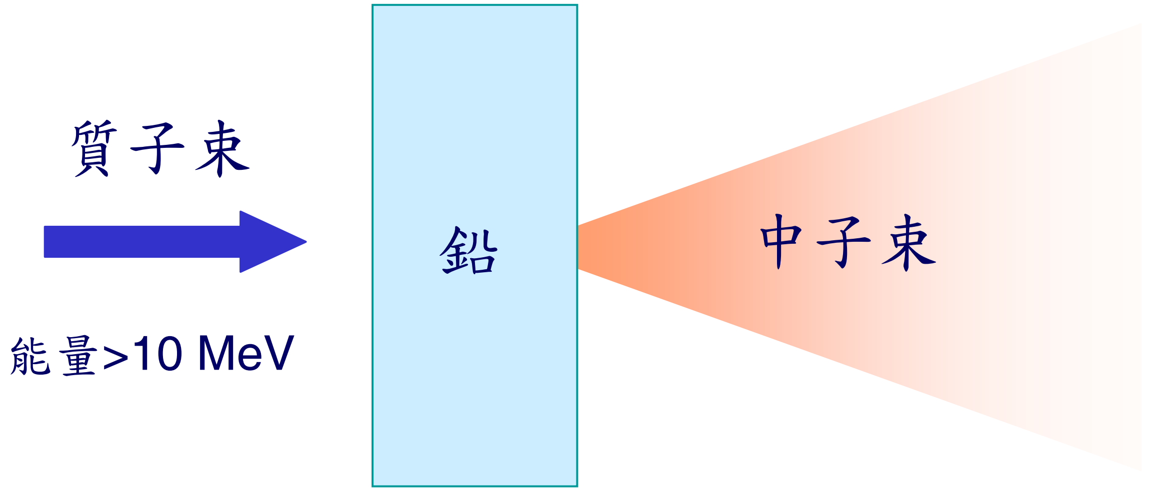


Figure 1. Depth dose distributions of gamma quanta, electron and proton beams. Curve 1, 140 kV x-rays; curve 2, 1.17 MeV gamma radiation (^{60}Co); curve 3, 25 MeV electron beam; curve 4, 25 MeV gamma radiation; curve 5, monochromatic 160 MeV proton beam (Bragg curve); curve 6, spread out Bragg peak (the energy spectrum optimized for the irradiation of a target spreading from 9 cm to 16 cm deep).

Eur. J. Phys **19,** 523 (1998)

雷射中子源



$$轉換效率 \approx 4 \times 10^{-3}$$

New Journal of Physics **7,** 253 (2005)

加速座標系的物理

等速座標 → 狹義相對論

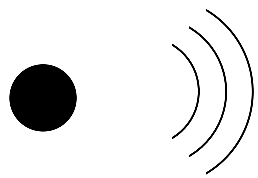
加速座標 → 廣義相對論

廣義相對論　　量子力學

黑洞

在實驗室裡模擬黑洞

黑洞



霍金輻射

愛因斯坦的等效原理：重力=加速度?

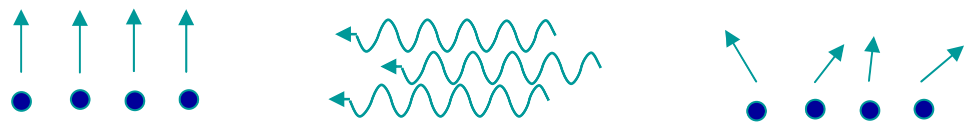
加速度中的電子

$$kT = \frac{\hbar a}{2\pi c}$$

泡在昂魯－霍金輻射中

前人的提議

加速器中電子極化的消散 (J. S. Bell and J. M. Leinaas, 1983)



昂魯—霍金輻射

快速改變的折射率等於加速度 (E. Yablonovitch, 1989)

等效加速度 10^{21} m/s^2

雷射引起的快速電漿增長

$$kT = \frac{\hbar a}{2\pi c}$$

真空溫度: 6 K

藉由散射偵測昂魯－霍金輻射？

雖然:

加速度: 10^{24} m/sec^2

真空溫度: 6000 K

$$kT = \frac{\hbar a}{2\pi c}$$

但是:

電子－光子散射截面積: 8×10^{-30} m^2

等效發光時間: 5×10^{-14} sec

散射光子數: 6×10^{-4}

在加速座標系的電子－光子散射理論？

Laboratory soft x-ray emission due to the Hawking–Unruh effect?

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[2] Centre for Fundamental Physics, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, UK
[3] Space Science & Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, UK
[4] Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, UK
[5] Physics Department, Imperial College, London, UK

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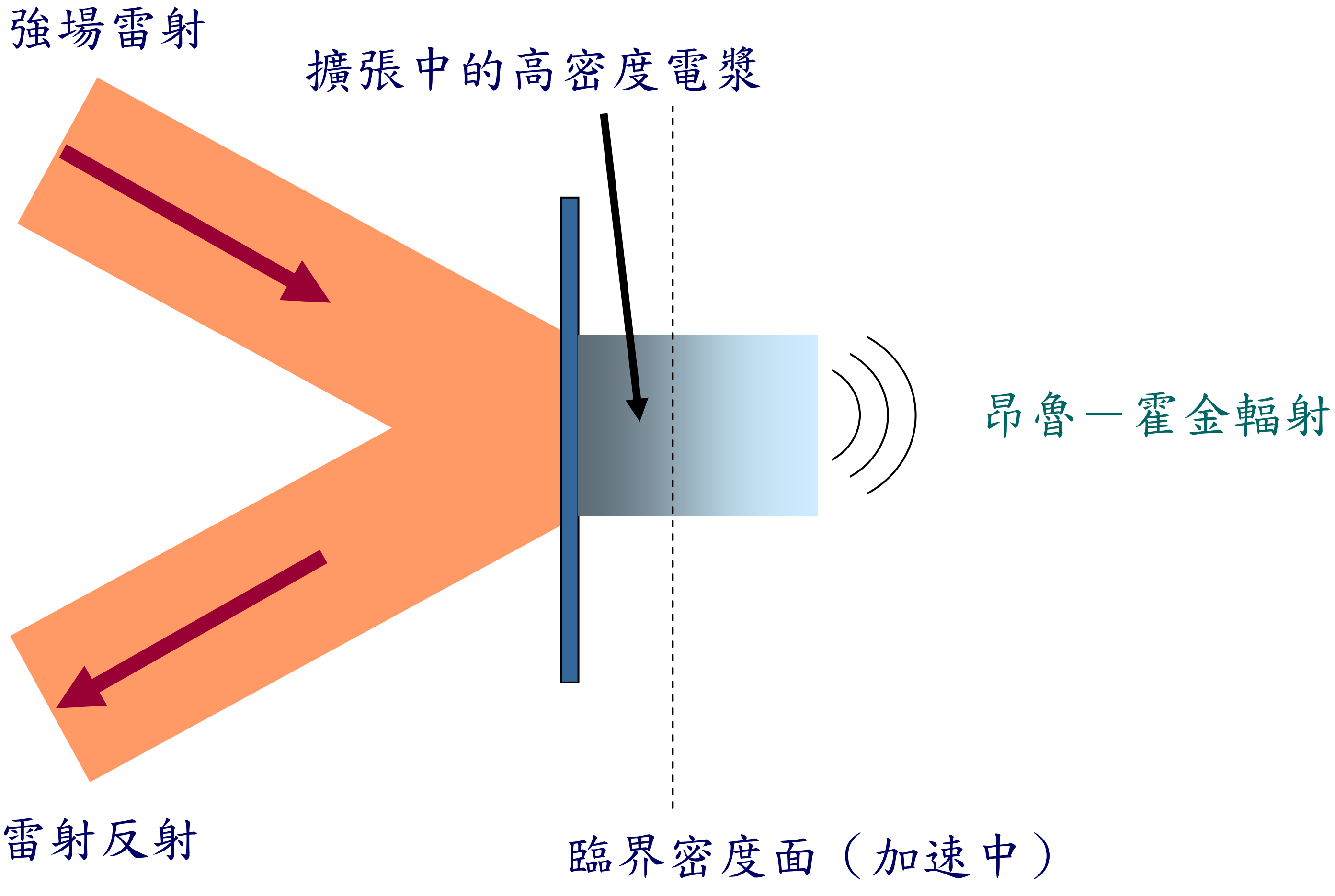
Online at stacks.iop.org/CQG/25/145005

2500J, 0.25PW

Abstract

The structure of spacetime, quantum field theory, and thermodynamics are all connected through the concepts of the Hawking and Unruh temperatures. The possible detection of the related radiation constitutes a fundamental test of such subtle connections. Here a scheme is presented for the detection of Unruh radiation based on currently available laser systems. By separating the classical radiation from the Unruh response in frequency space, it is found that the detection of Unruh radiation is possible in terms of soft x-ray photons using current laser-electron beam technology. The experimental constraints are discussed and a proposal for an experimental design is given.

加速中的鏡子



尚待回答的問題

是否可以在實驗室座標系中偵測到昂魯—霍金輻射，
而非在電子的座標系?

加速度中的電子

泡在昂魯—霍金輻射中

雷射控制核融合反應

能源與文明

- 石油＋天然氣存量約可使用100年（數量級）
- 煤炭存量約可使用100年（數量級）
- 溫室效應（如果有很多石油，你敢燒嗎？）
- 核分裂燃料存量約可使用100年（數量級）
- 太陽能電池（20% 效率）→ 四分之一國土覆蓋（台灣）
- 核融合反應：無污染、無存量問題

核融合反應

$D + D \rightarrow {}^3He$ (0.8 MeV) $+ n$ (2.4 MeV)

$p + B \rightarrow 3{}^4He$ (3 MeV)

動能愈大，密度愈大，反應機會愈大。

基本條件： $\sigma v n t \approx 1$

100 KeV (10^9 K), 1 ATM $\rightarrow t \approx 1$ ms

傳統方法：以高溫獲得動能

- 長時間低密度反應
- 輻射損失
- 侷限困難

強場方法：以加速獲得動能

- 以光壓達成燃料壓縮
- 高密度快速反應
- 以慣性達成侷限

100兆瓦雷射的下游應用