國家同步輻射研究中心
National Synchrotron Radiation Research Center

Beam manipulation with high energy laser in accelerator-based light sources

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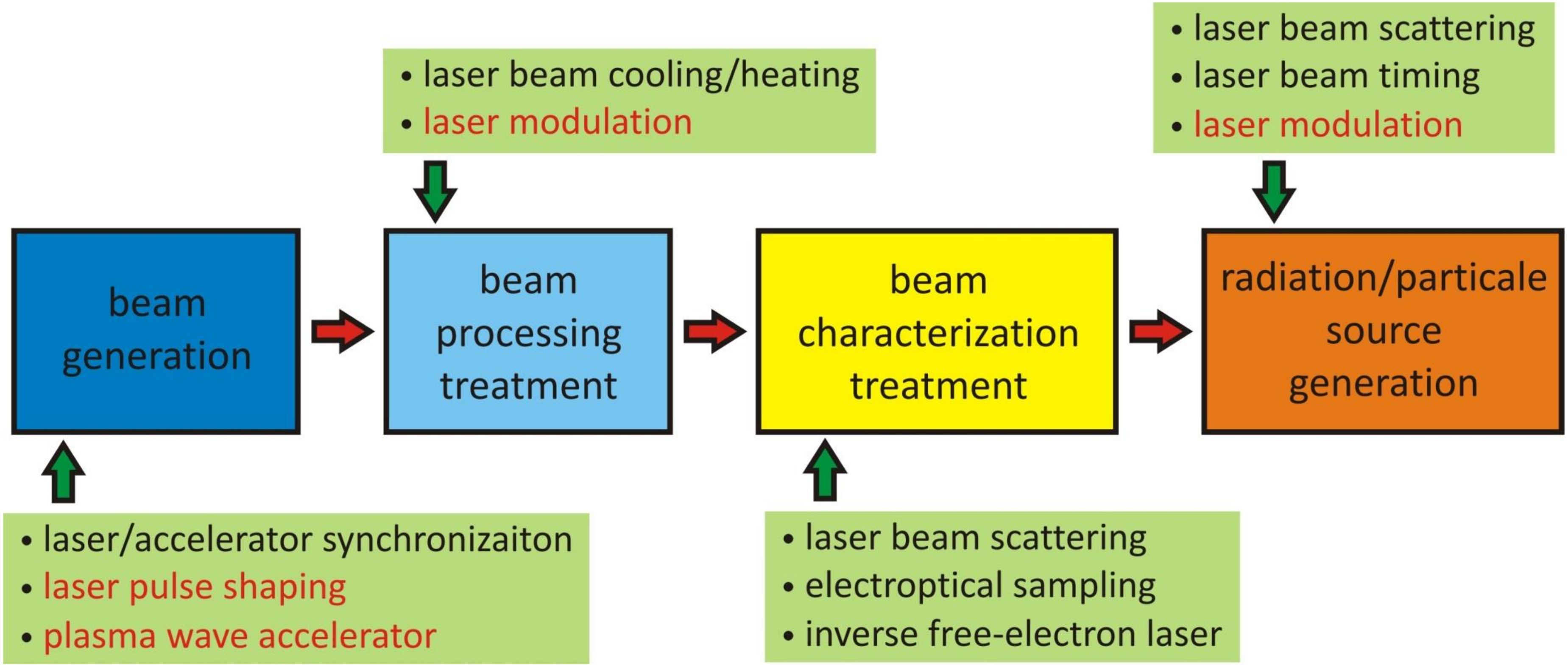
FEL winter school, Jan. 14～Jan. 18, 2019

A map for laser applications in accelerators



Outline

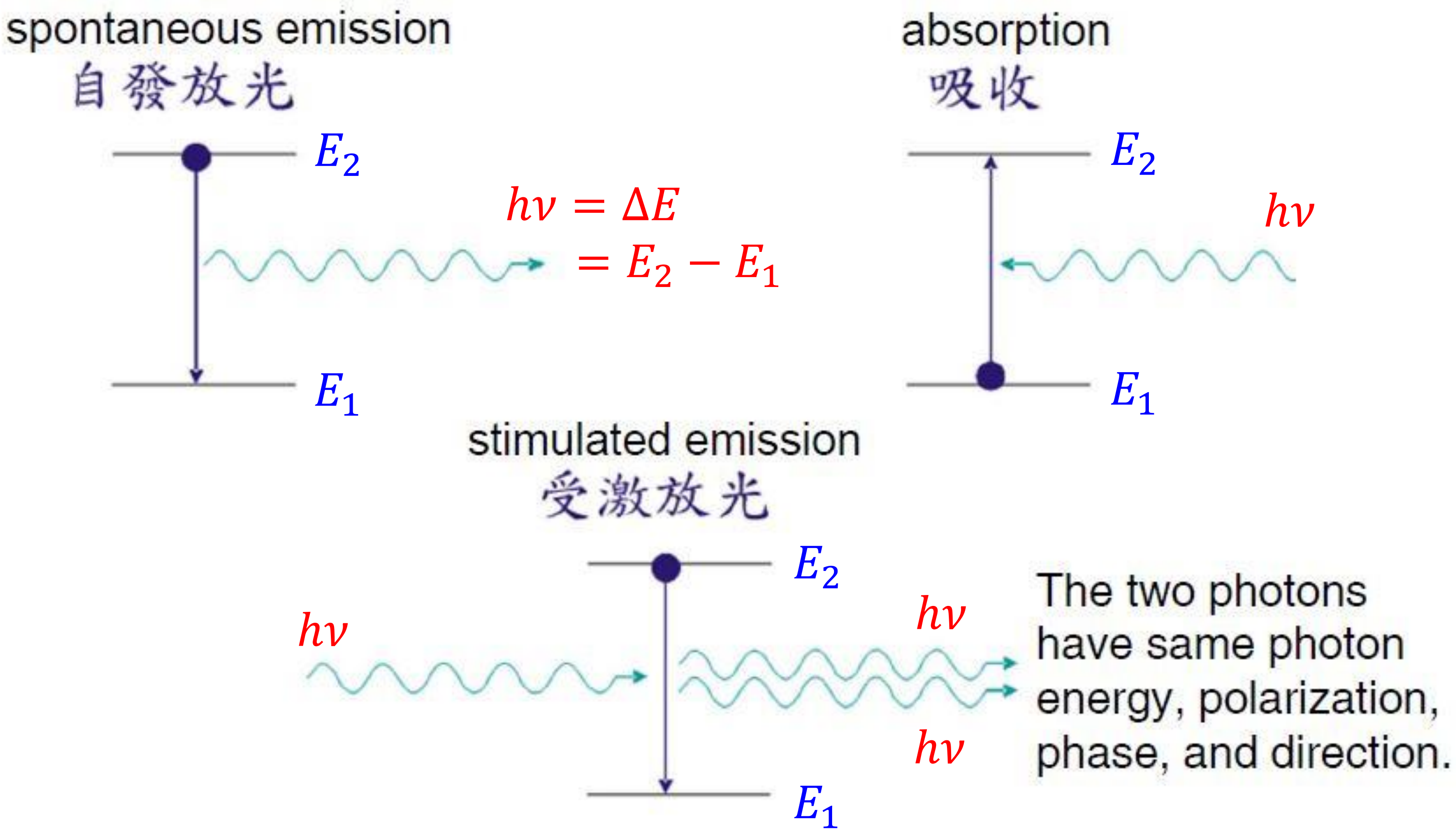
I. Laser basic

II. Laser shaping

III. Beam manipulation using lasers

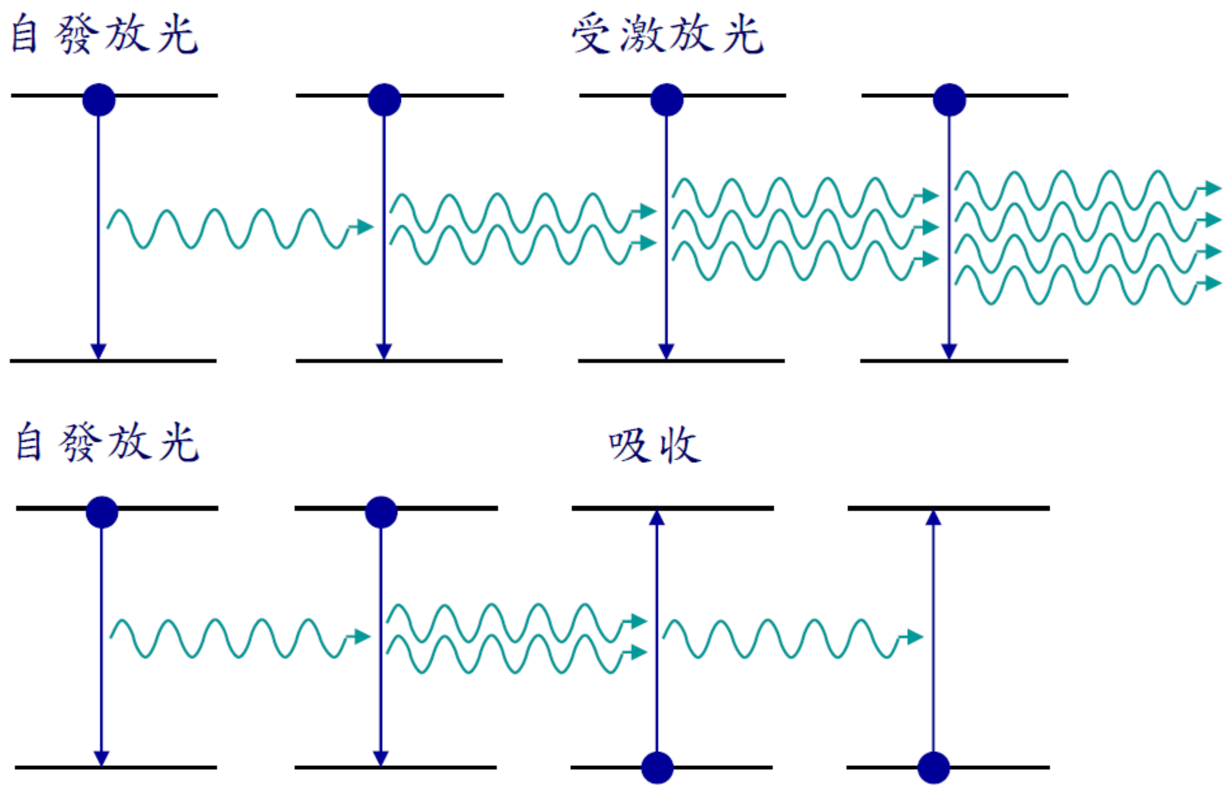
IV. Innovative accelerator with lasers

原子如何發光？


spontaneous emission
自發放光
E_2
E_1
$h\nu = \Delta E$
$= E_2 - E_1$
absorption
吸收
E_2
$h\nu$
E_1
stimulated emission
受激放光
E_2
$h\nu$
$h\nu$
$h\nu$
E_1
The two photons have same photon energy, polarization, phase, and direction.

What is a laser?

LASER: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

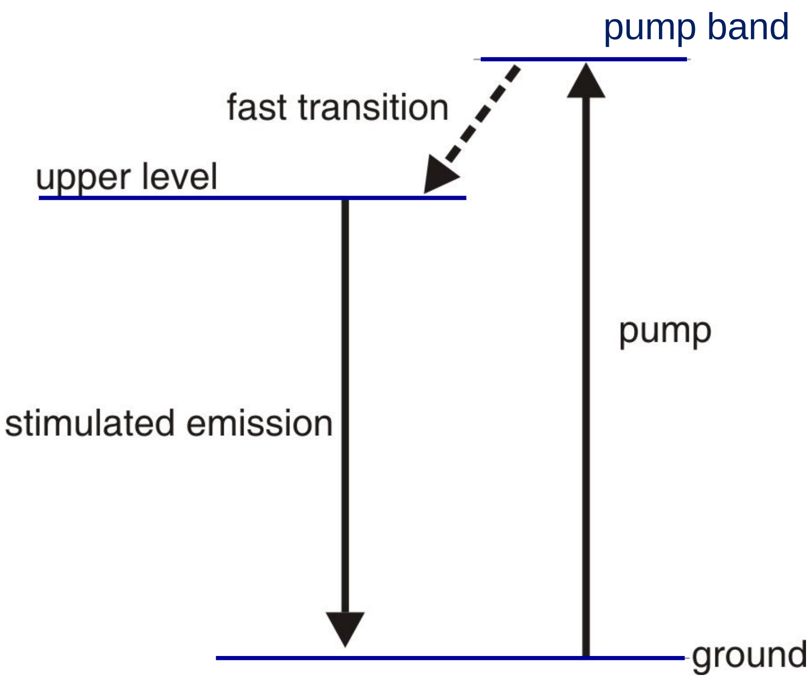


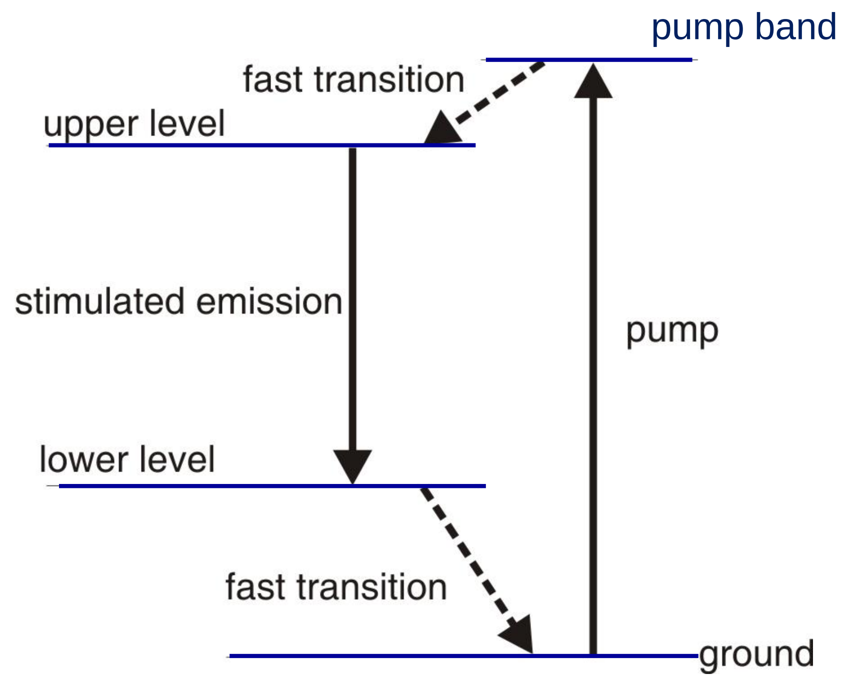
光放大的條件：高能階的原子數大於低能階的原子數(居量反轉)

population inversion

Energy diagram of lasers

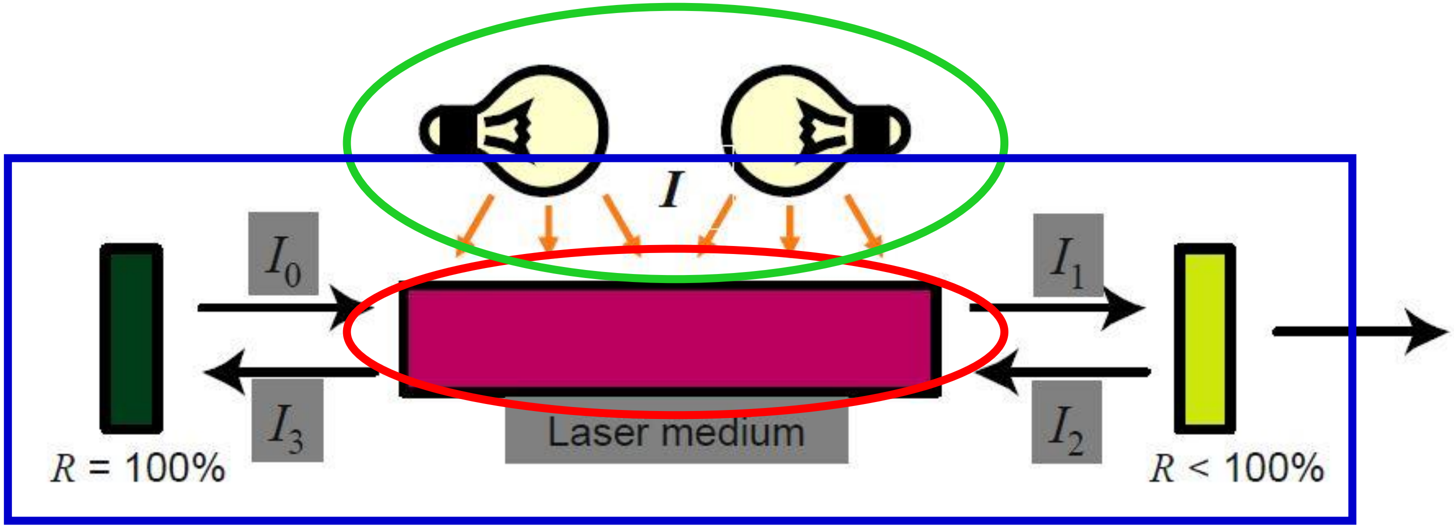
3-level lasers **4-level lasers**





$$\textbf{quantum efficiency of fluorescence} = \frac{\#\ \text{of emitted photons}}{\#\ \text{of absorbed photons}}$$

How to build a laser?



- Laser gain medium
  – depend on wavelength, pulse duration, power
- Pump source
- Optical resonator
  – laser oscillation

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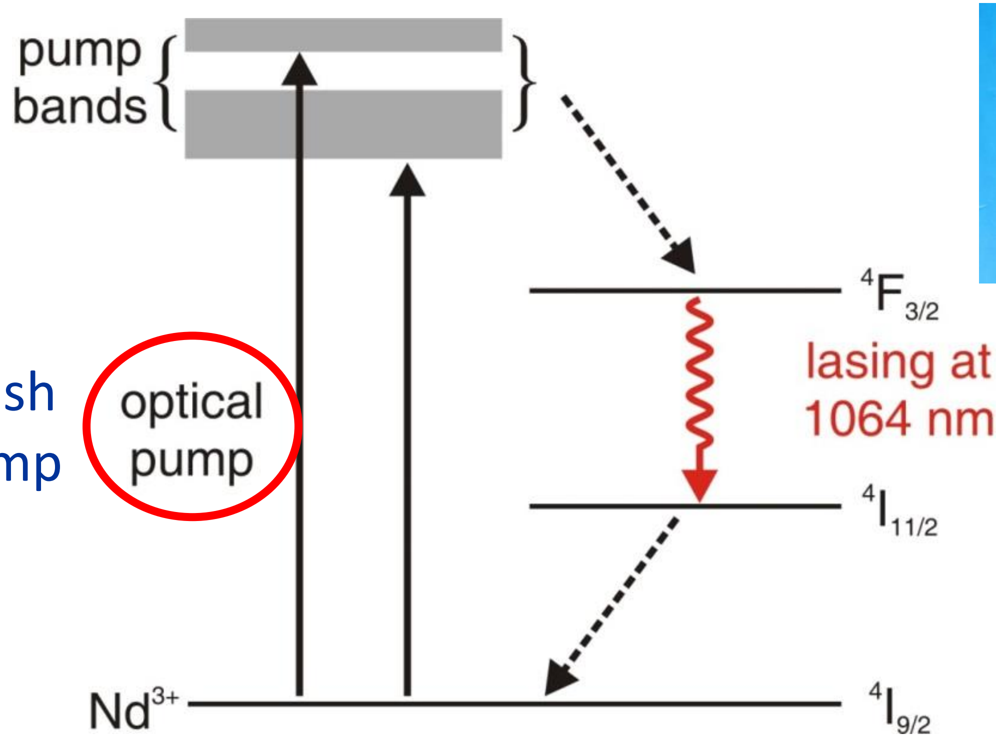
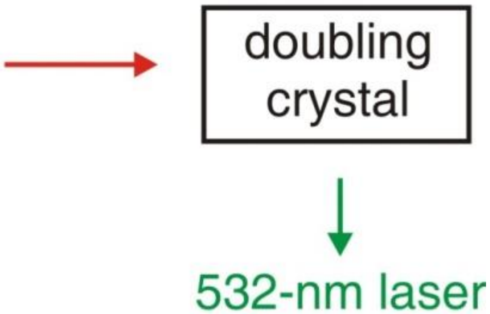
Nd:YAG laser

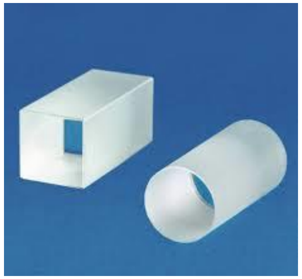
Nd:YAG rods

flash lamp





KD*P crystal



Principle of a high-peak-power laser system

$$Power = \frac{energy}{pulse\ duration} \qquad Intensity = \frac{power}{beam\ size}$$

Generation of femtosecond laser pulses

– broadband gain medium

– pulse compression mechanism

– dispersion compensation

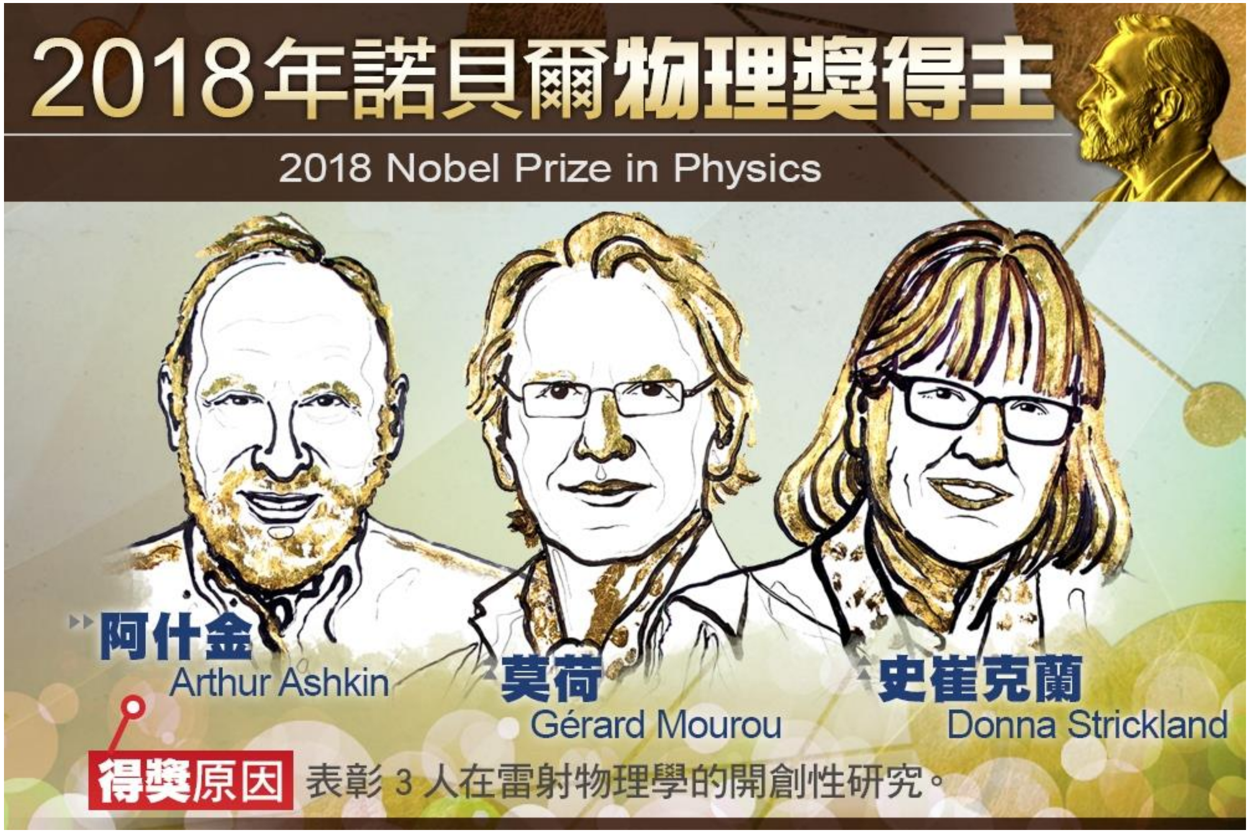
Chirped pulse amplification (CPA) technique

– stretch the femtosecond laser pulse

– amplify the stretched laser pulse

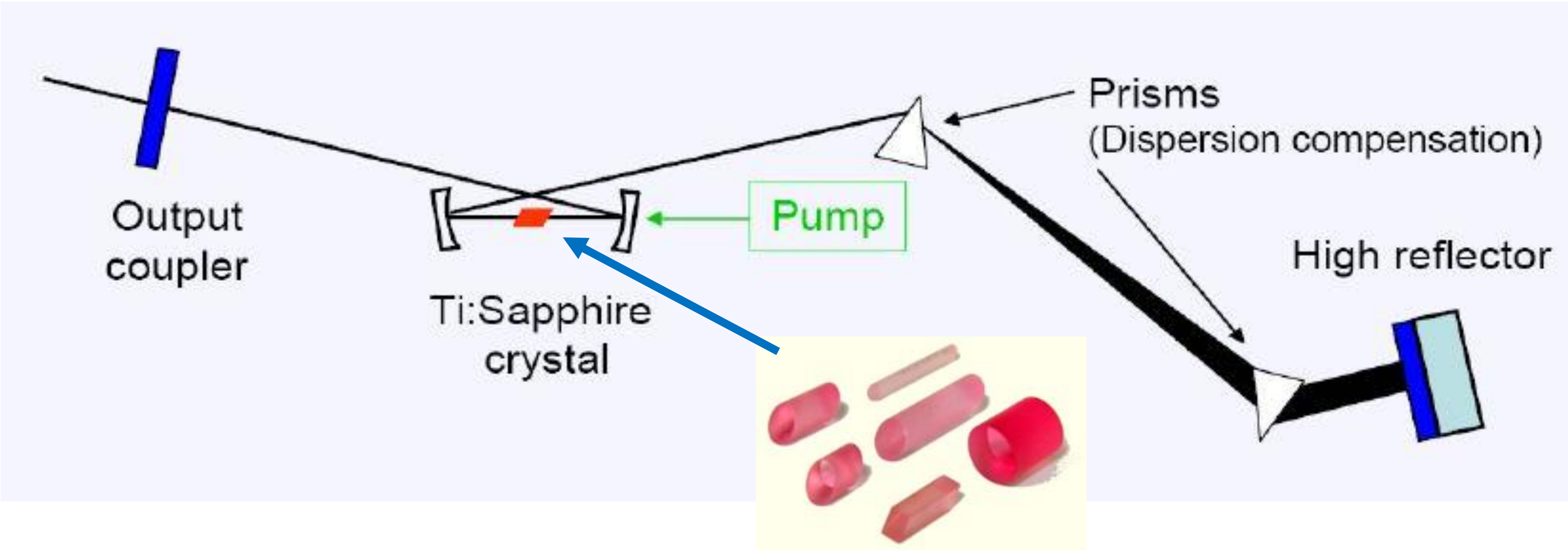
– compress the amplified laser pulse

2018 Nobel Prize in Physics



The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses."

Ti:Sapphire oscillator



- Gain medium: Ti:sapphire crystal
  - broad fluorescence linewidth (600–1050 nm)
  - efficiently pumped at 532 nm
  - High saturation fluence (0.9 J/cm^2)
  - Good thermal conductivity (0.42 W/cm*K)
  - high damage threshold (23 GW/cm^2 at 200 ps)
- Kerr-lens mode-locking
- Dispersion compensation by using prism-pairs

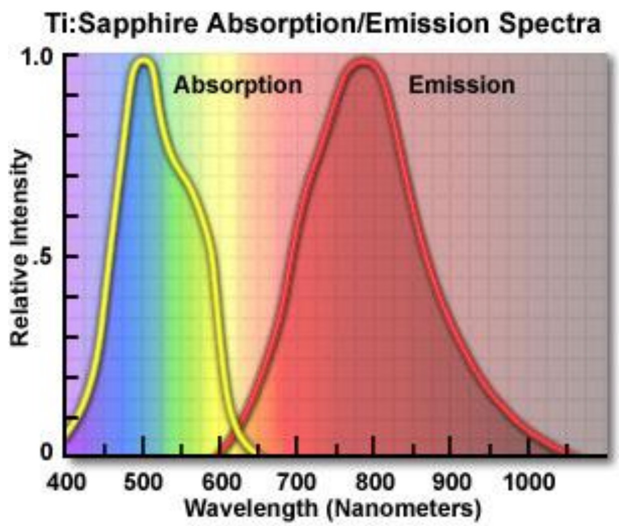
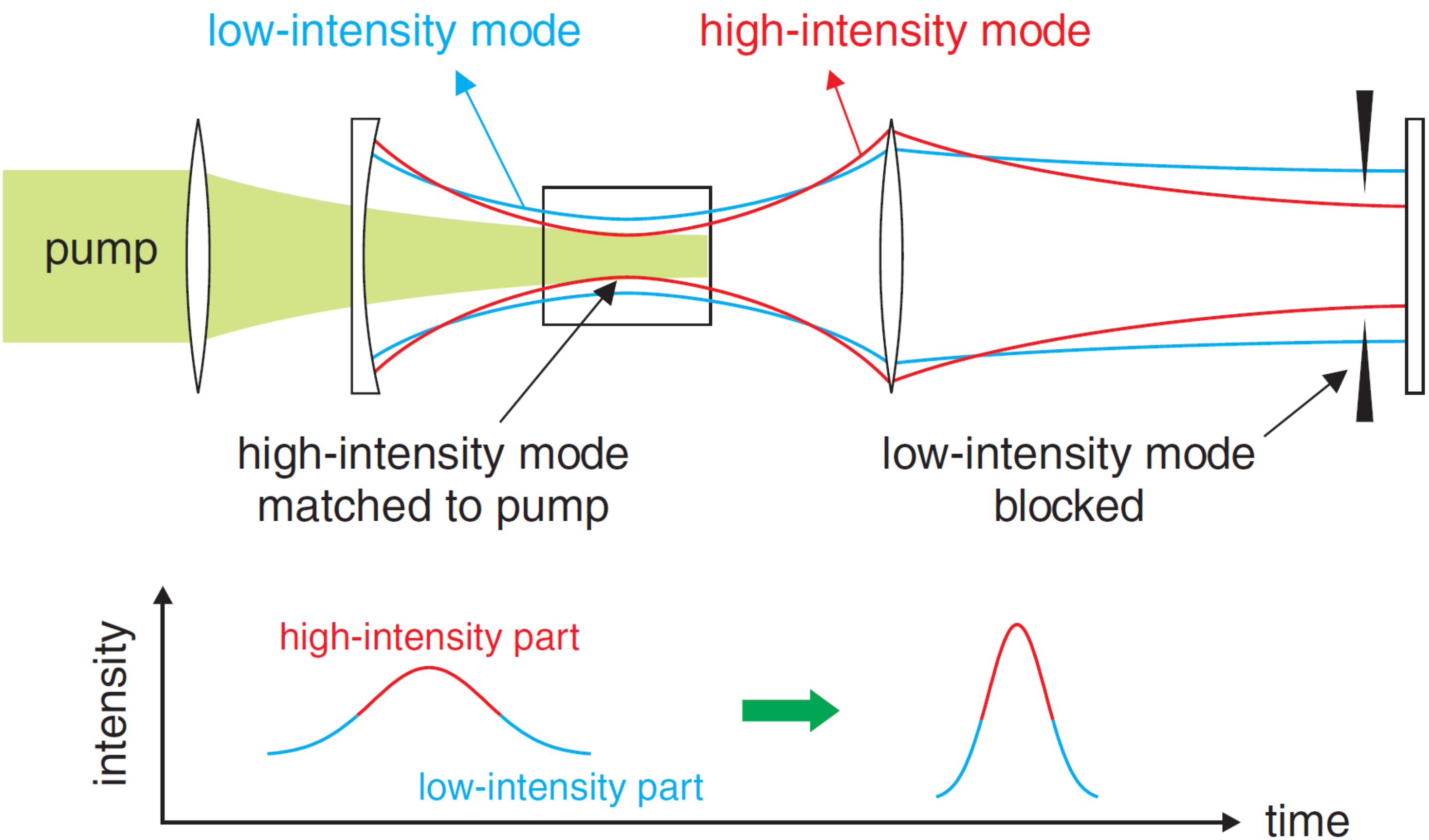


Figure 1

Pulse compression – Kerr-lens mode-locking

optical Kerr effect: $n = n_0 + n_2 I$

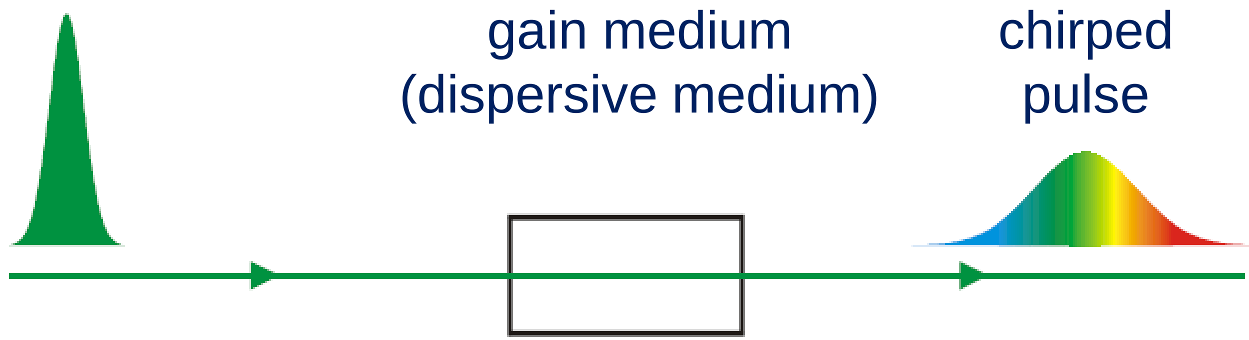


在介質中光速隨頻率改變

紅光折射率: 1.5145

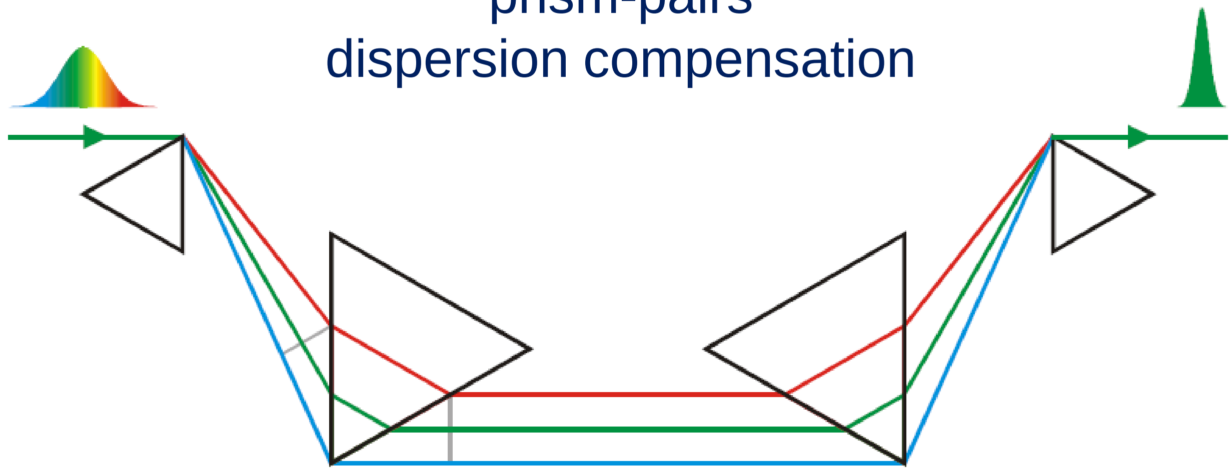
（BK7玻璃）

藍光折射率: 1.5253

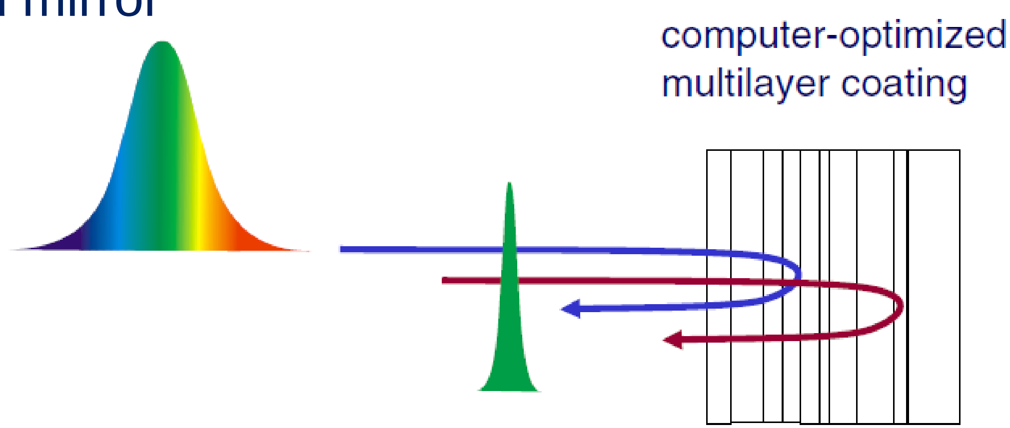


Dispersion compensation

prism-pairs
dispersion compensation



chirped mirror



Chirped Pulse Amplification

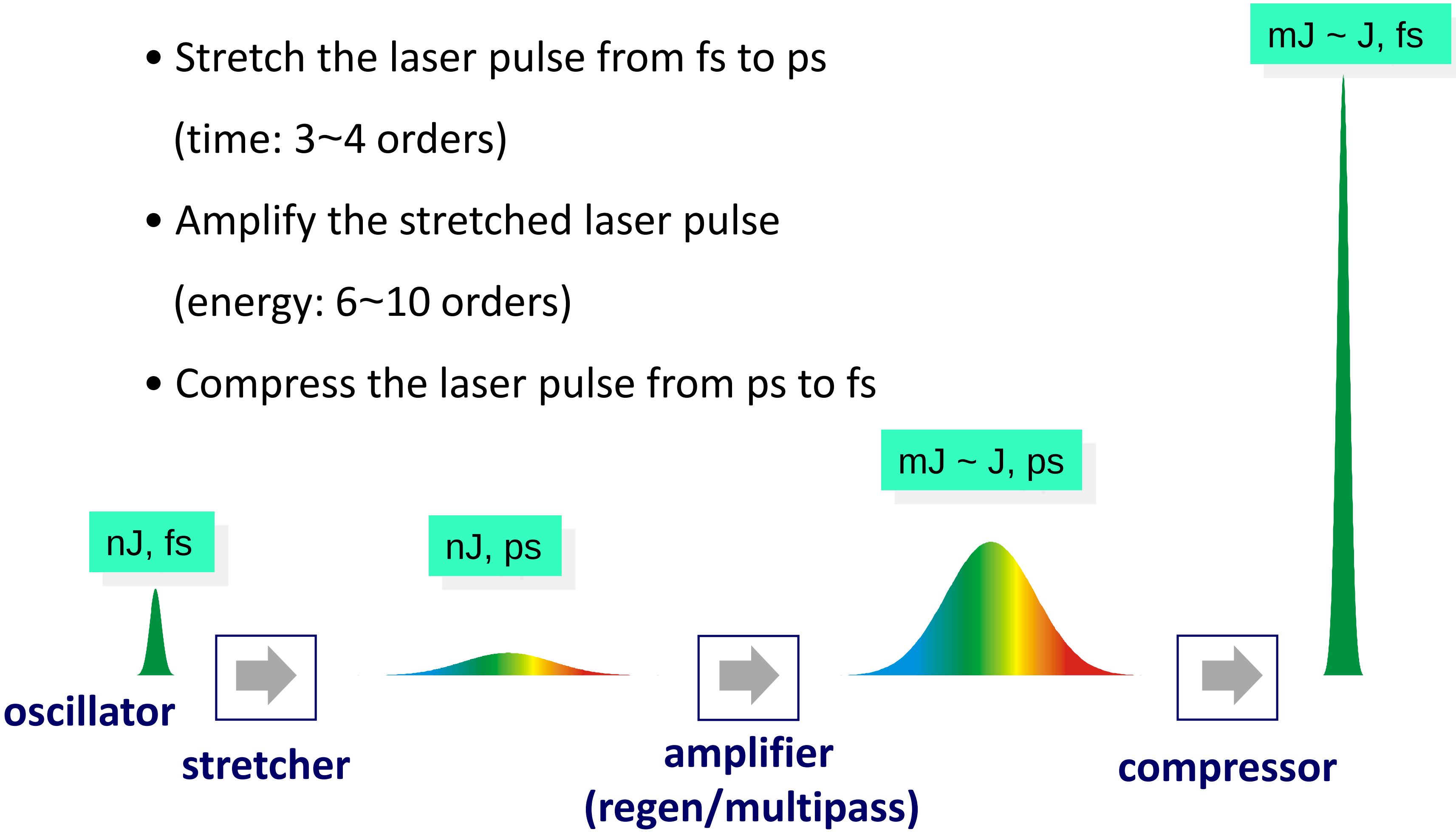
- Stretch the laser pulse from fs to ps

  (time: 3~4 orders)

- Amplify the stretched laser pulse

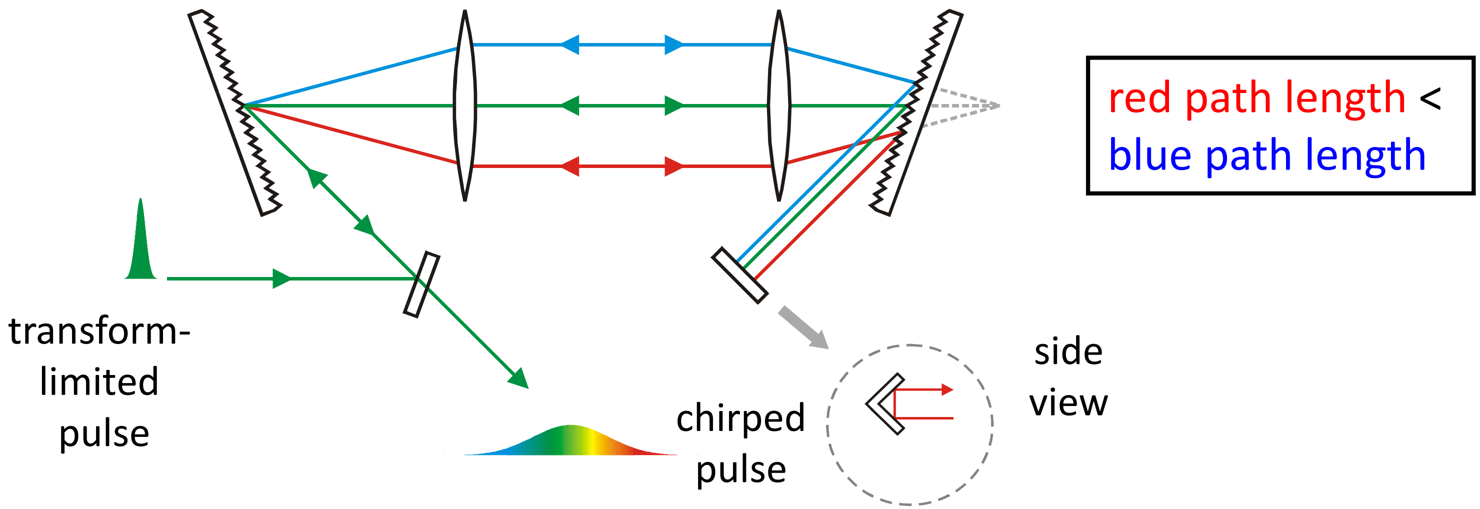
  (energy: 6~10 orders)

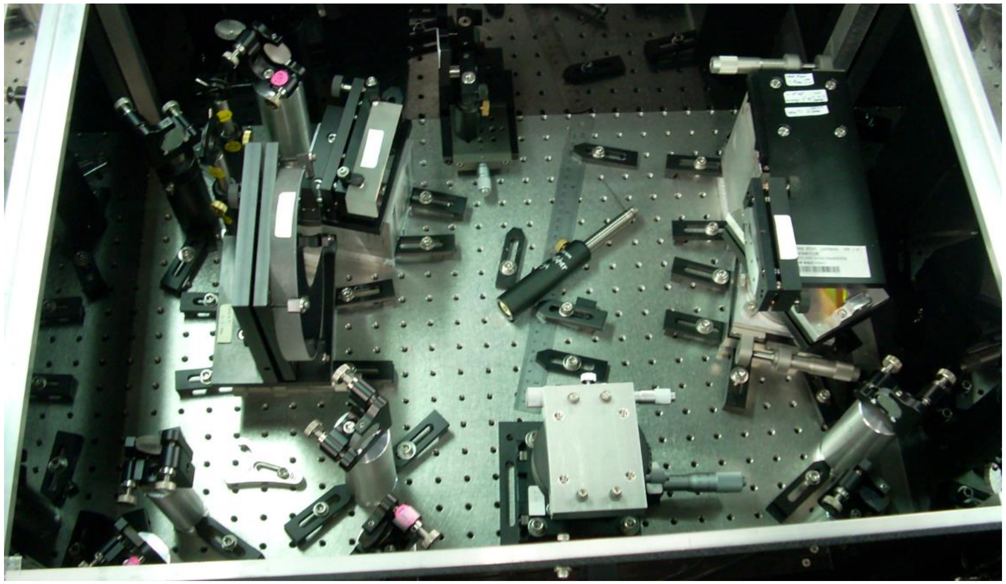
- Compress the laser pulse from ps to fs



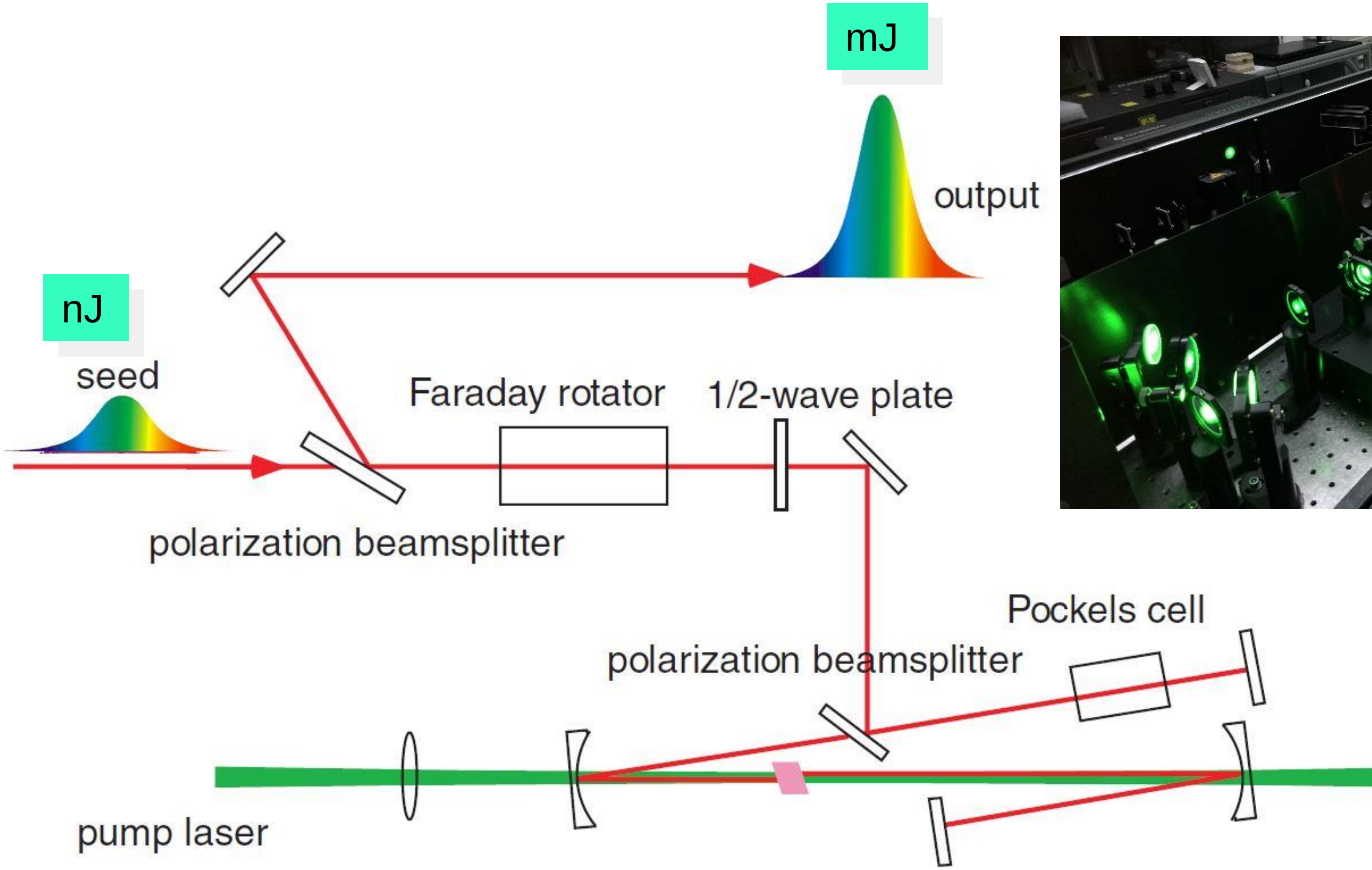
Pulse stretcher

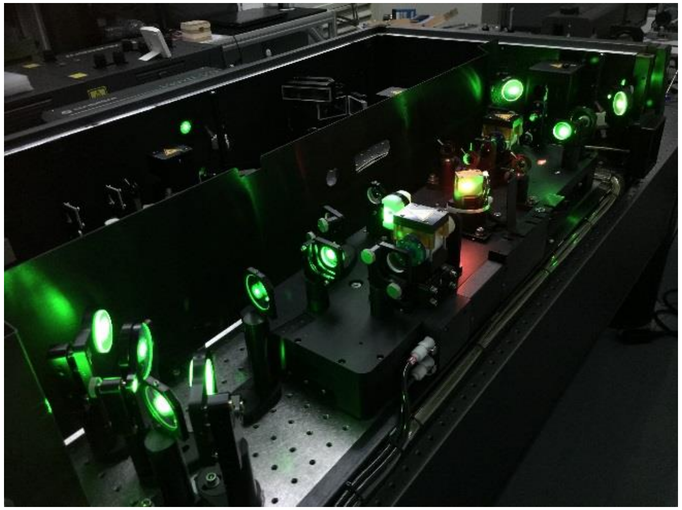
grating stretcher





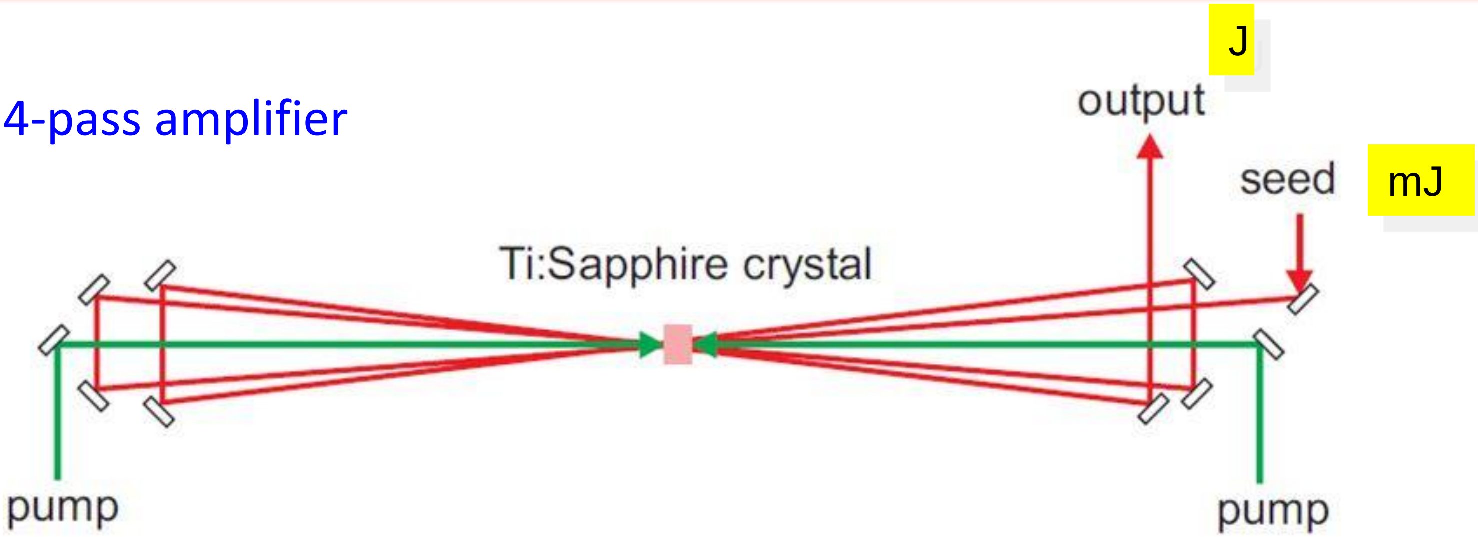
Laser amplifier – regenerative amplifier

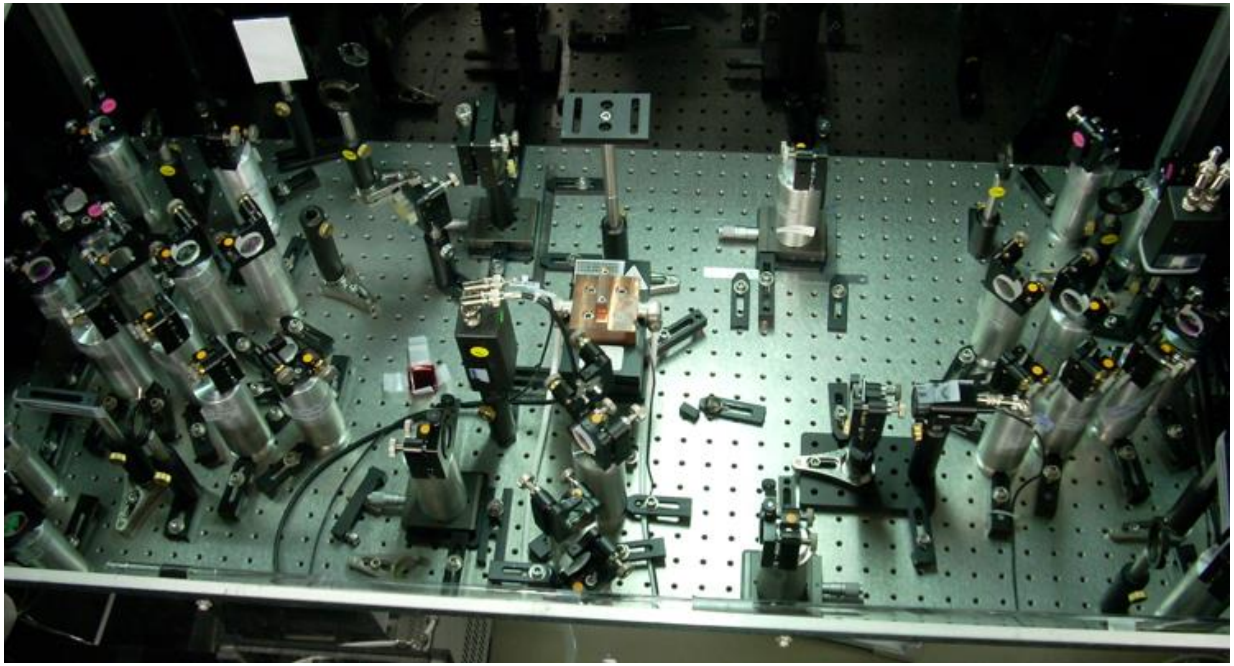




Laser amplifier – multi-pass amplifier

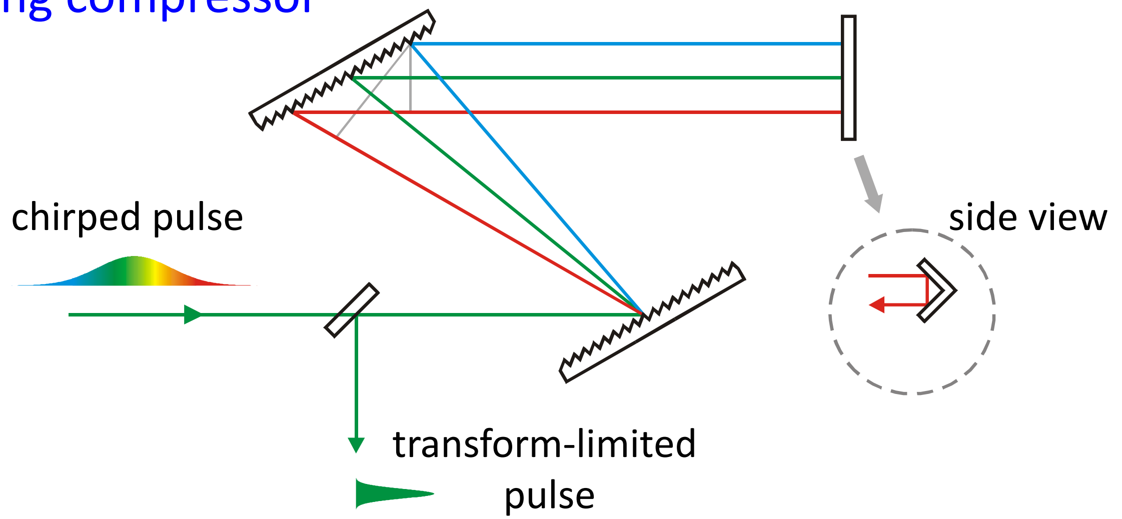
4-pass amplifier



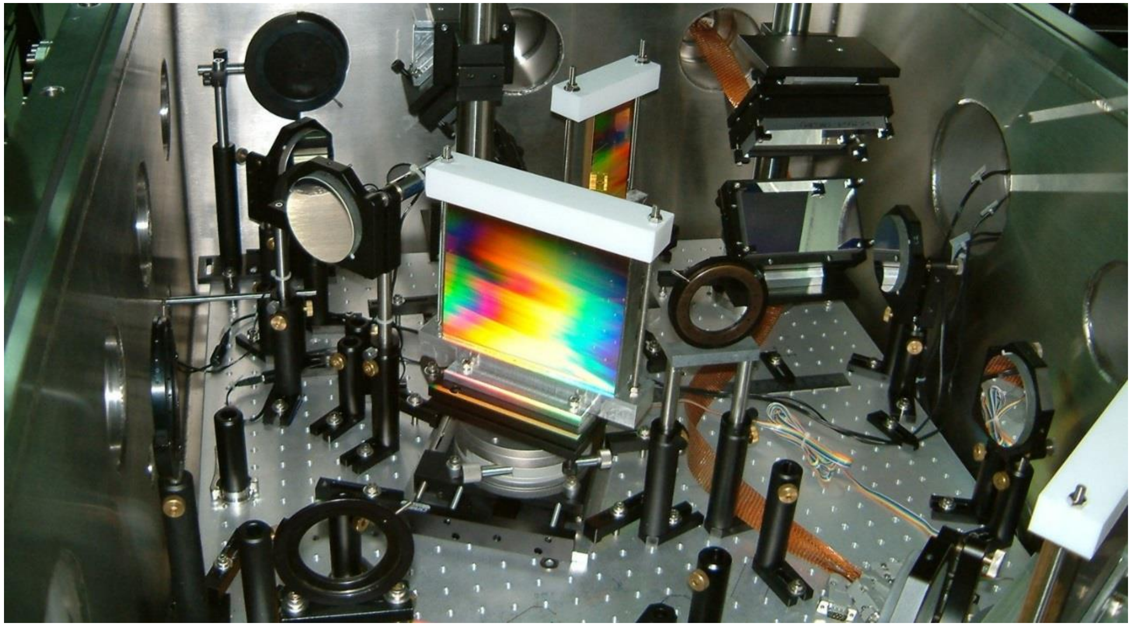


Pulse compressor

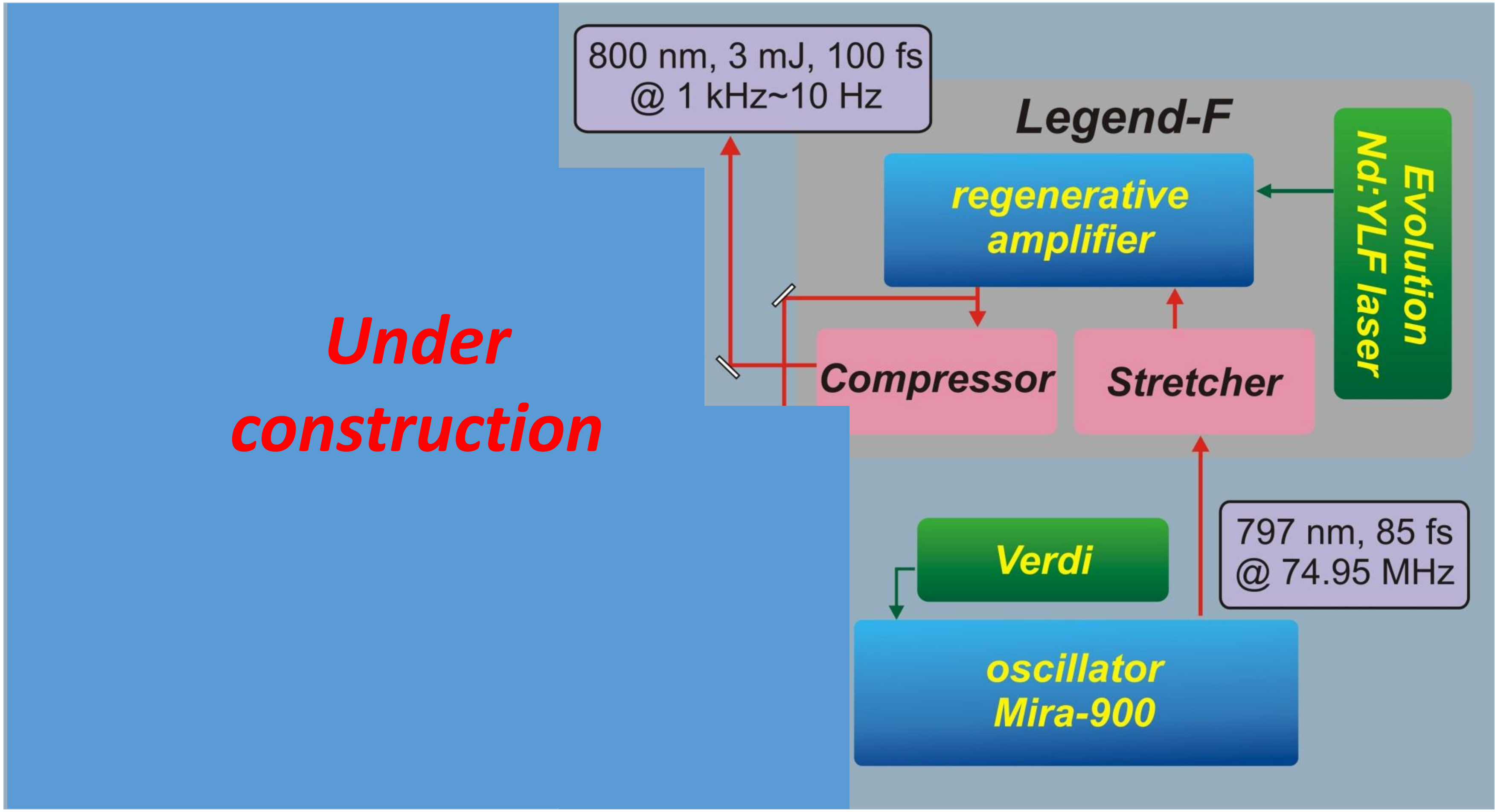
grating compressor



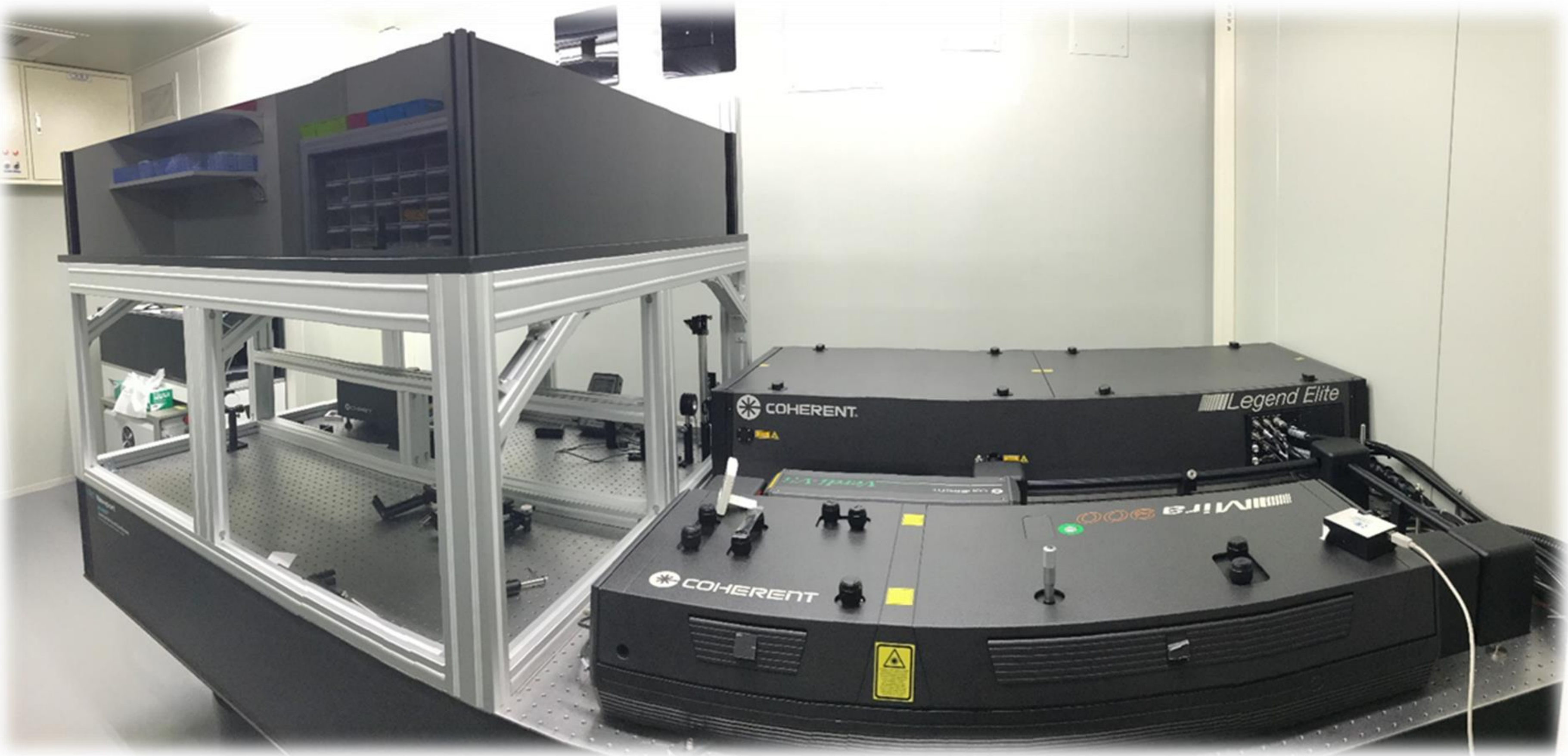
red path length >
blue path length



NSRRC femtosecond laser system

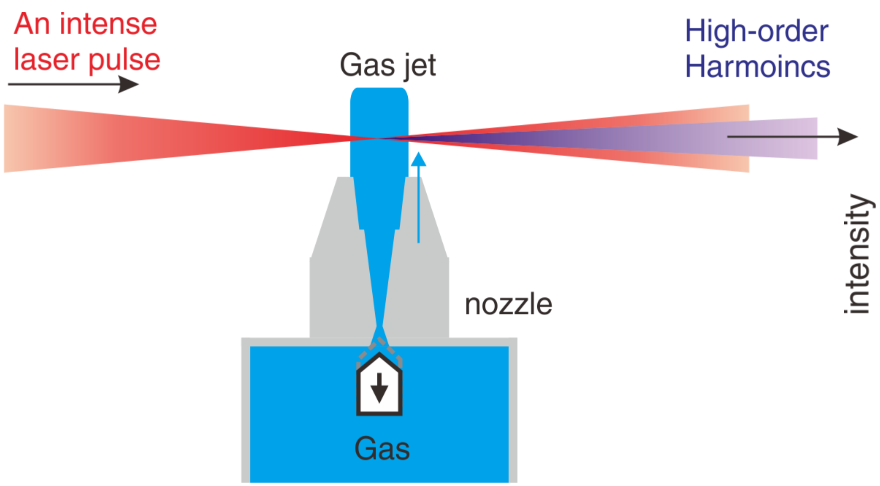


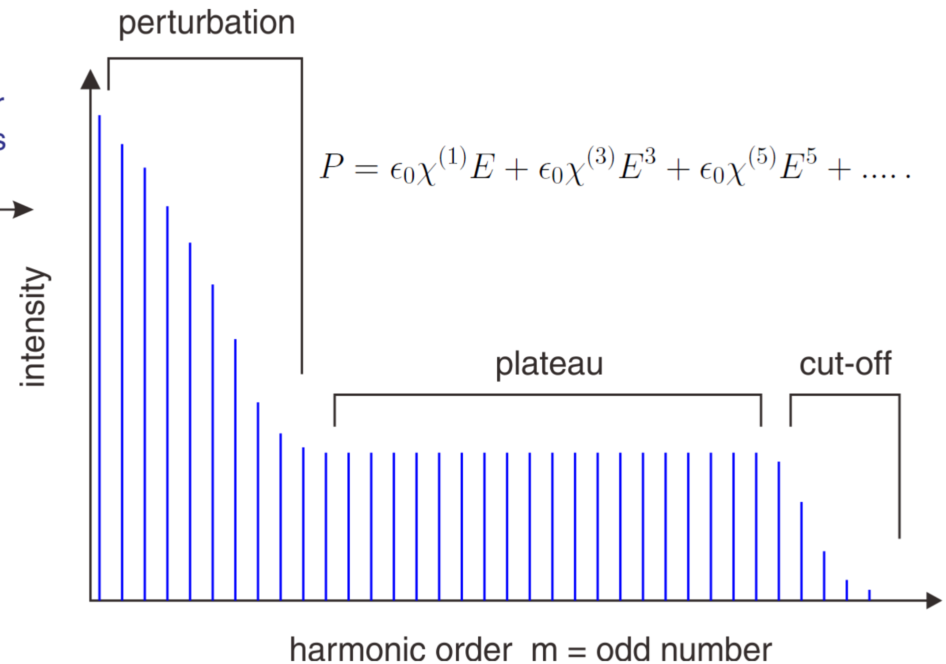
NSRRC femtosecond laser system



Short wavelength lasers – frequency conversion

Frequency conversion: High order harmonics generation (HHG)





- Atoms as the nonlinear media.
- Carry over the spatial coherence of the driving laser.
- Of short pulse duration comparable or shorter than the drive laser up to attoseconds.
- Cut-off is intensity- and atom-dependent.

Semi-classical model of HHG

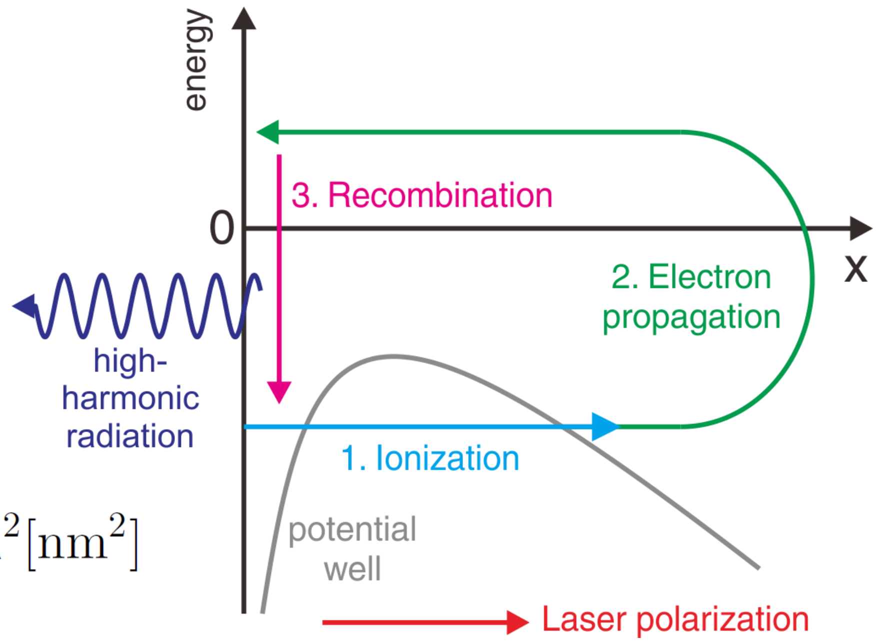
photon energy of the
highest harmonic order :

$$E_{\mathrm{cutoff}} = I_p + 3.17\ U_p$$

I_p : ionization potential

U_p : ponderomotive potential

$$U_p[eV] = 9.33 \times 10^{-20} I[\mathrm{W/cm^2}]\lambda^2[\mathrm{nm^2}]$$



for 810-nm driving laser

atom	I_p (eV)	ionization intensity (W/cm^2)	U_p (eV)	cut-off energy (eV)	cut-off wavelength (nm)
He (Z=2)	24.59	1.46×10^{15}	89.56	308.5	4.02
Ar (Z=18)	15.76	2.47×10^{14}	15.12	63.7	19.5
Ne^{1+} (Z=10)	40.96	2.82×10^{15}	172.5	588	2.11

Ref: S. Augst *et al.,* Phys. Rev. Lett., **63**, 2212 (1989)

Higher harmonics

Longer λ is Better for reaching higher harmonics

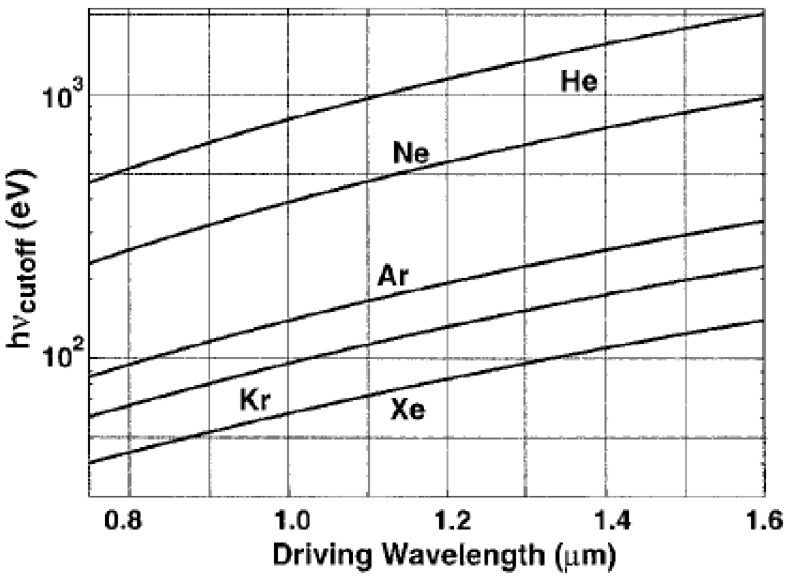
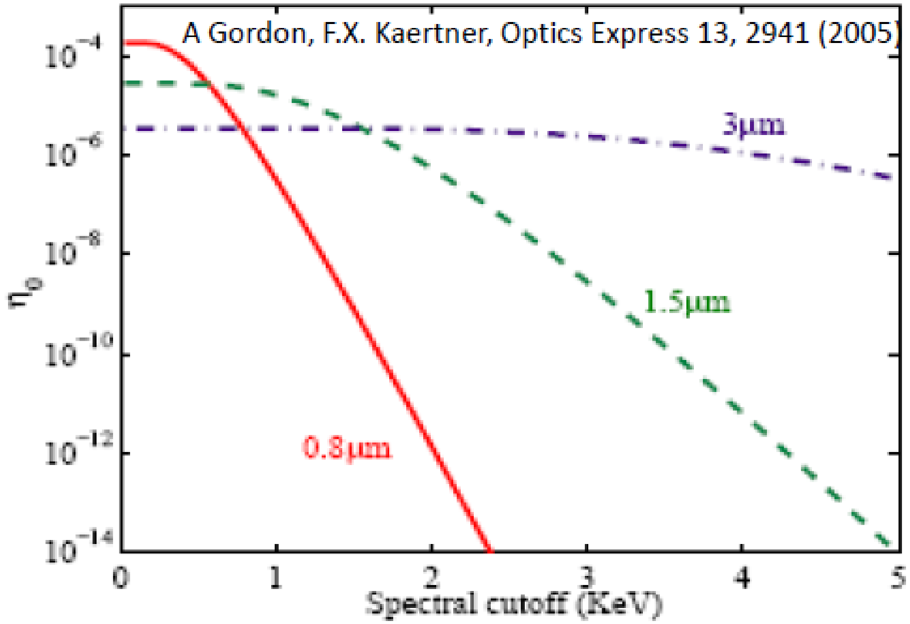


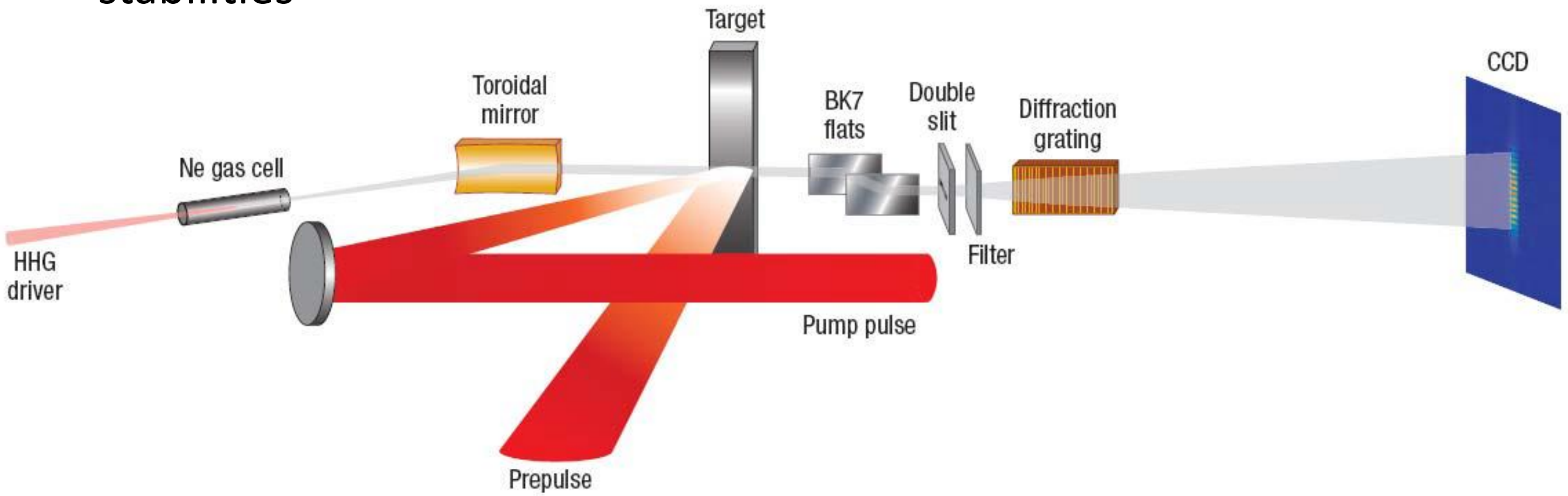
FIG. 1. Calculated relationship between single-atom HHG cutoff photon energy and the driving wavelength.
From Shan and Chang PRA **65** 011804 (2001)

Single atom efficiency at the harmonic cutoff, effect of fundamental wavelength



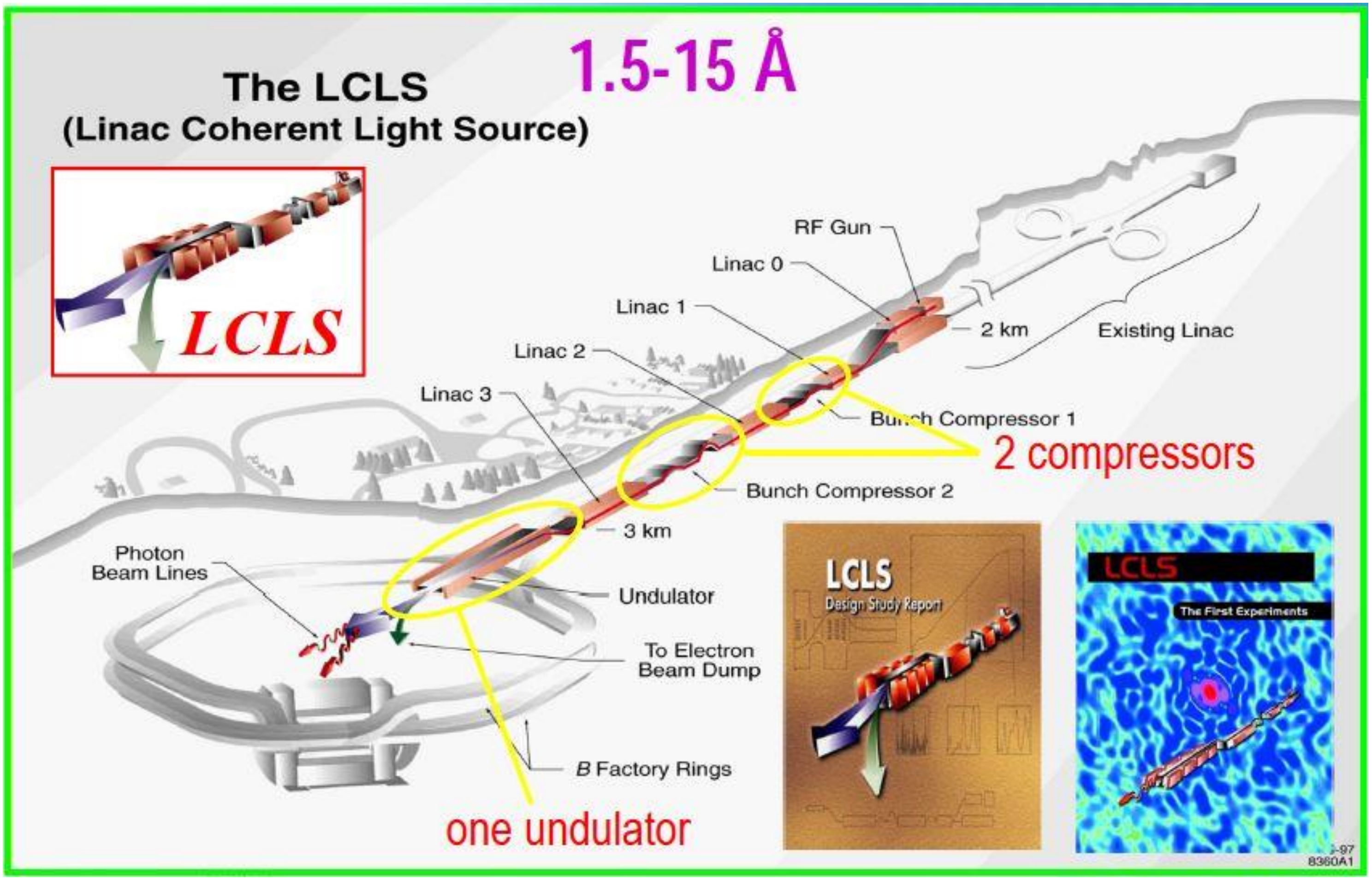
Plasma based soft-x-ray lasers

- Still a traditional laser based on population inversion, but in hot dense plasma to accommodate the high energy difference between atomic levels, wavelength from 1 nm to 100 nm.
- Can be pumped by laser or discharge.
- Laser beam quality can be improved by HHG seeding.
- Challenges: tunability and capability for shorter wavelengths, stabilities



X-ray free electron laser (XFEL)

X-ray Free electron lasers: 1.5-0.15 nm, high brightness, high transverse coherence, etc.



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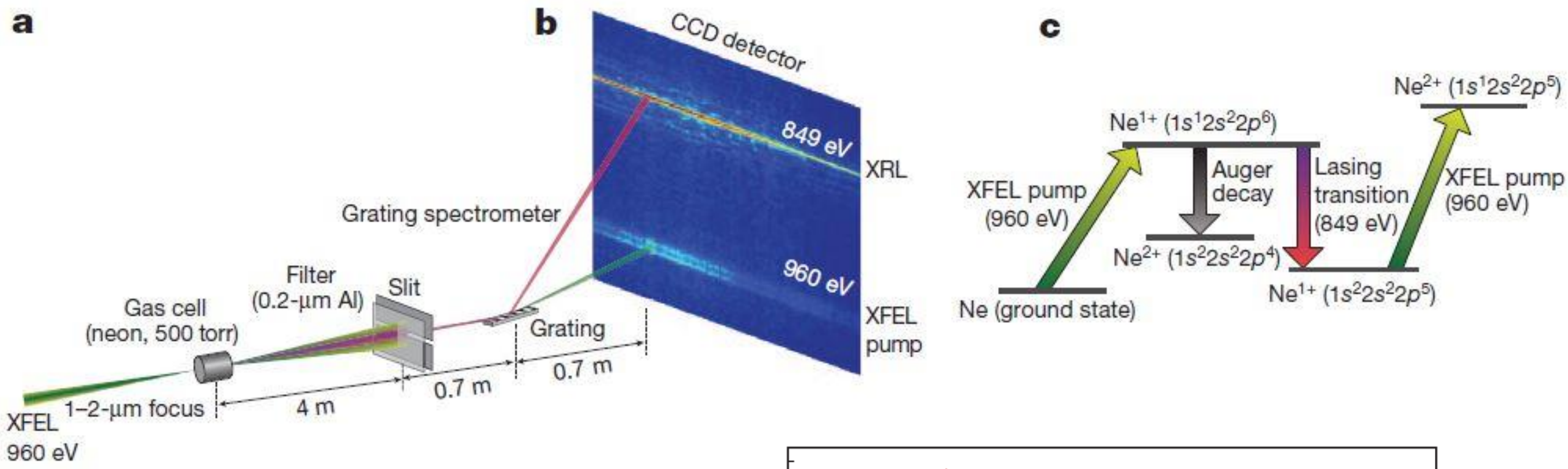
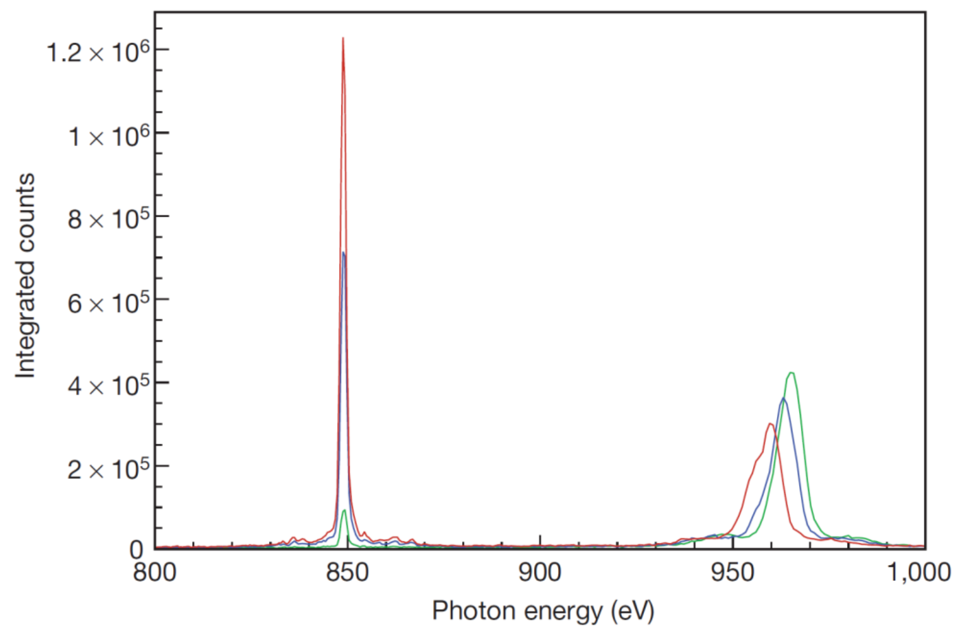
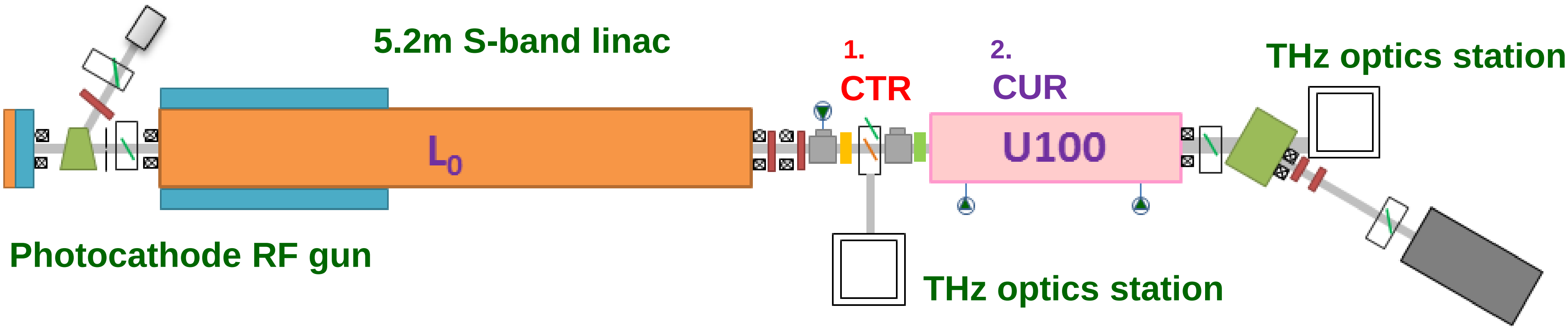
Atomic inner-shell X-ray laser pumped by an XFEL





Ref: N. Rohringer *et al.*, Nature **481**,488 (2012)

The NSRRC 100 MeV Photo-injector



Generation of 100 fs ultrashort electron bunches →

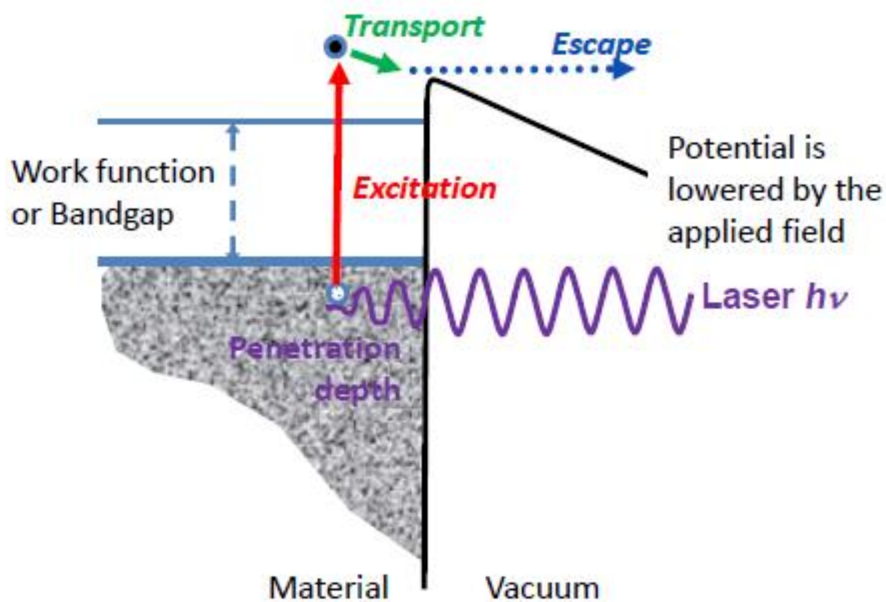
1. broad-band, fs THz light by CTR (coherent transition radiation)
2. tunable, narrow-band, ps THz light by U100 CUR (coherent undulator radiation)

Photoemission in metal

- **Metal photocathodes**
- Copper, magnesium, lead, niobium
- Require UV photons (>4.5 eV)
- $<10^{-4}$ quantum efficiency
- Short penetration depth (~14 nm)
- Prompt electron emission
- **Semiconductor photocathodes**
- Cesiated antimonide, GaAs, telluride
- Require visible or UV photons
- $>10^{-2}$ quantum efficiency
- Long penetration depth (~mm)
- Delayed electron emission

Three steps of photoemission:

- Electron excitation
- Electron transport to surface
  - electron-electron scattering
  - electron-phonon scattering
- Electron escape
  - escape over the barrier



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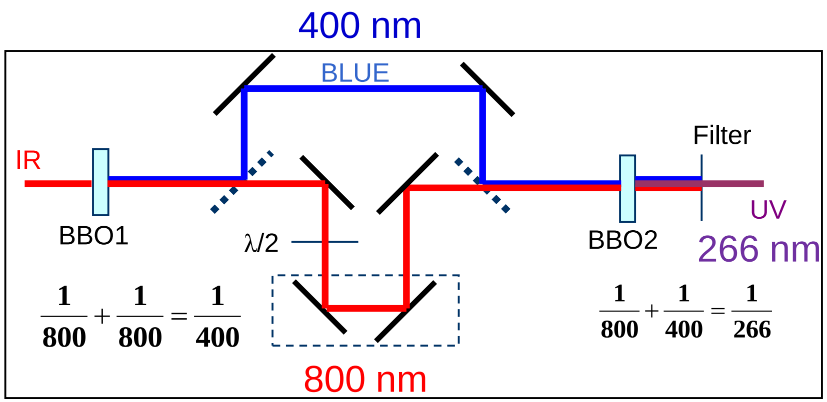
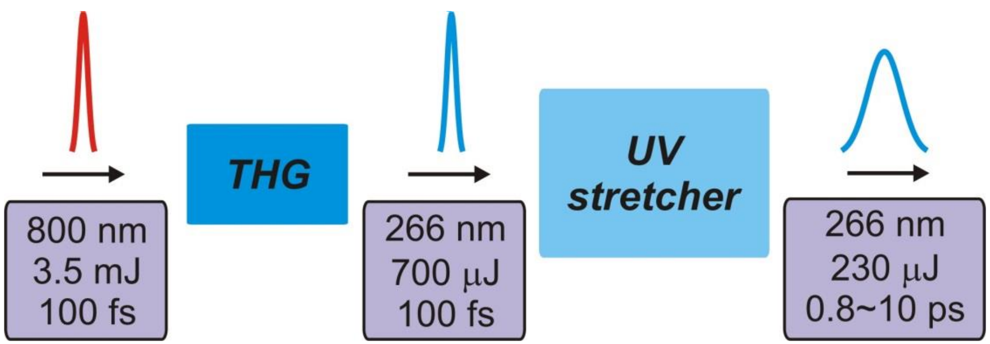
Third harmonic generation and UV stretcher

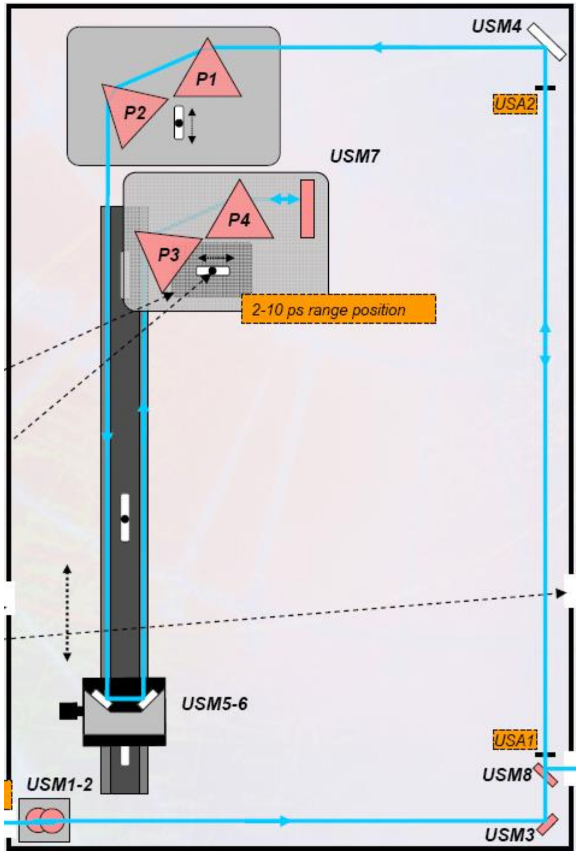
Third harmonic generation



The third harmonic generator consists of two type-I BBO crystals with 1-mm thickness. The overall efficiency is about 20%.

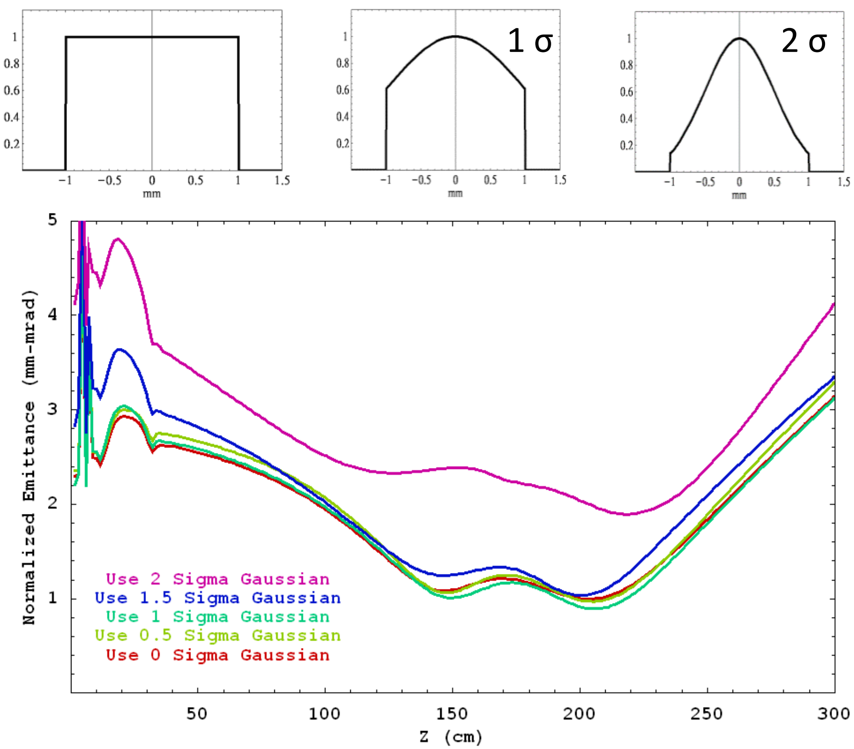


UV stretcher

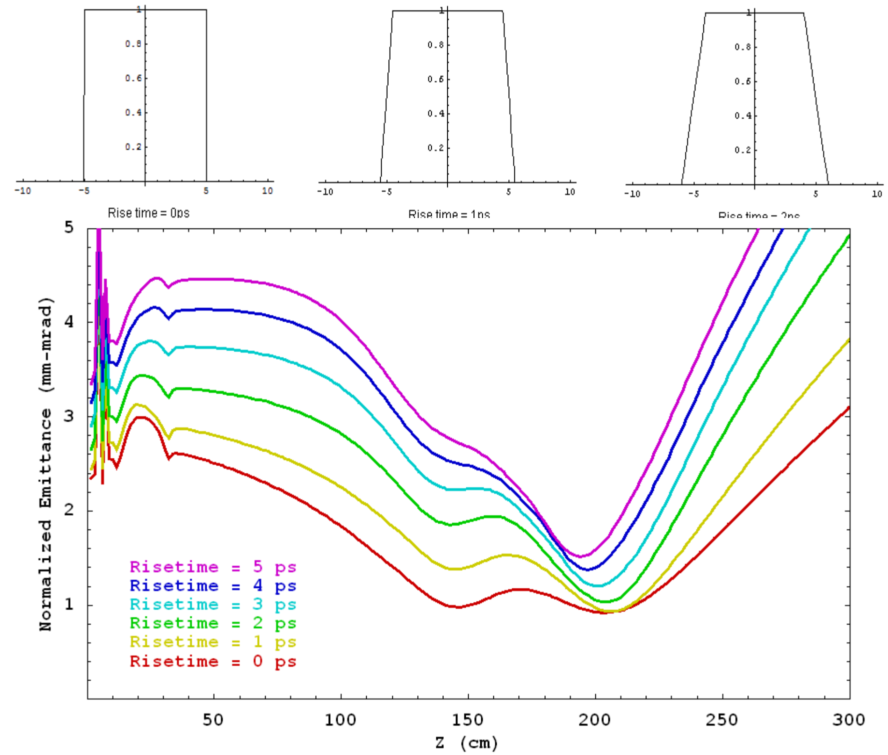


Minimizing emittance

transverse profile



longitudinal profile

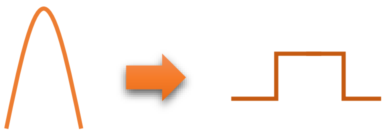


- Space charge forces increase beam emittance.
- Emittance compensation requires linear space charge force, which is dependent on the e-beam geometry.
- In a photoinjector, e-beam carries over the laser geometry.
- Laser pulse geometry is the key.

Laser shaping

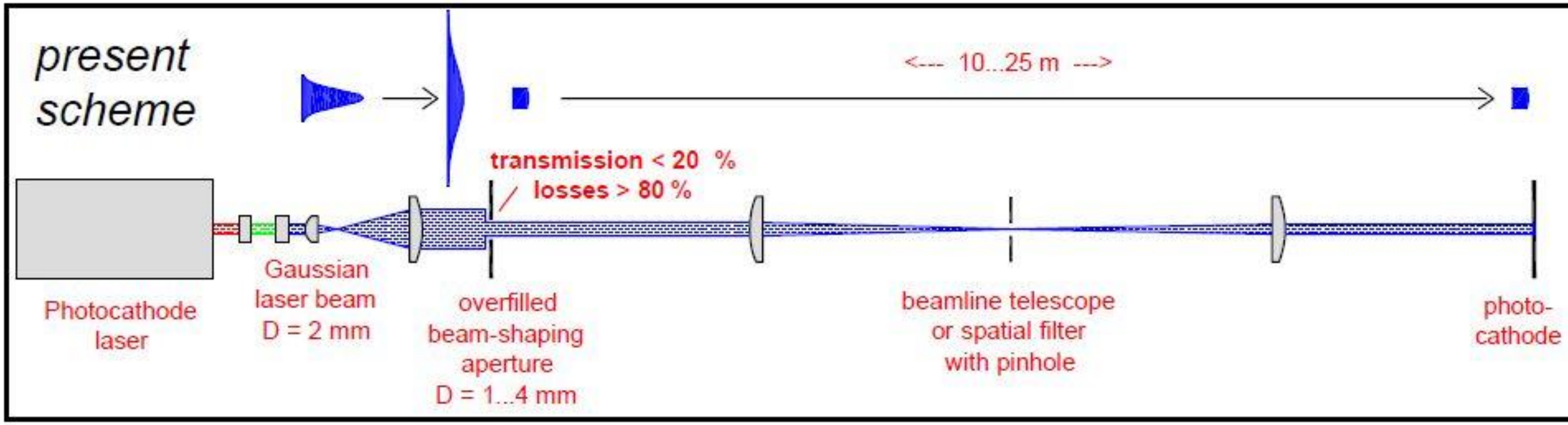
- **Spatial shaping**
  - – Clipping a Gaussian
  - – Beam flattener optics
  - – Deformable mirror
  - – spatial light modulator (SLM)

Gaussian pulse --> flat-top pulse

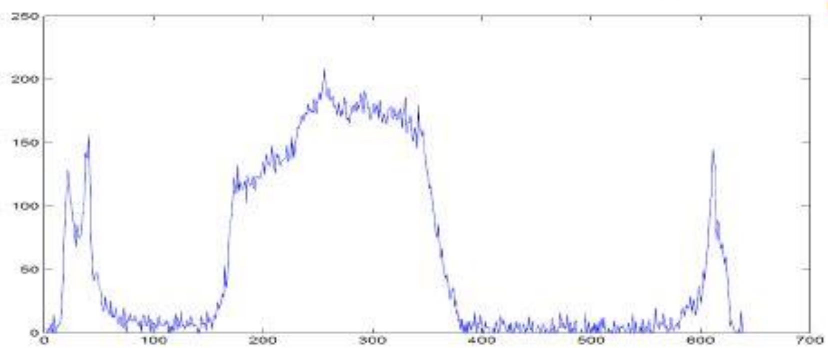


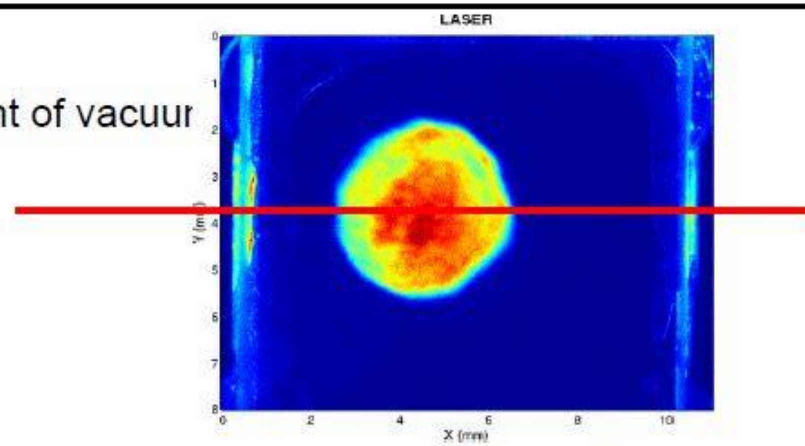
- **Temporal shaping**
  - – spatial light modulator (SLM)
  - – acousto-optic programmable dispersive filter (AOPDF or DAZZLER)
  - – Pulse stacking

Gaussian to flat-top clipping



- Imaging the overfilled iris on laser table
- Problem: larger pointing jitter than iris in front of vacuur
- Jitter about 0.5 of diameter min/max





Ingo Will, Max-Born Institute

S. Schreiber, DEZY

PITZ mini pulse shaping workshop, 2007

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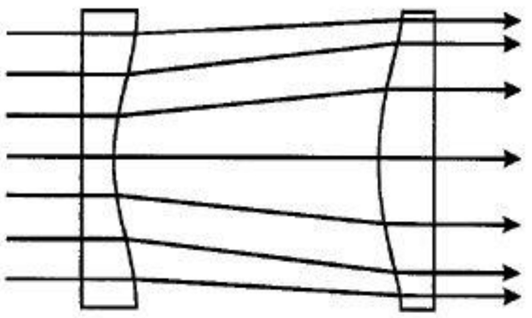
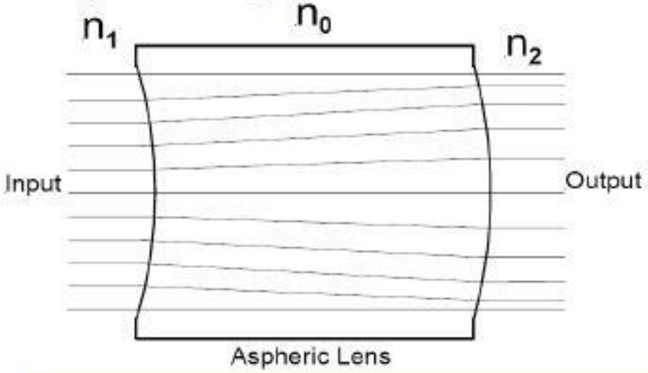
Laser beam shaper design

Newport design



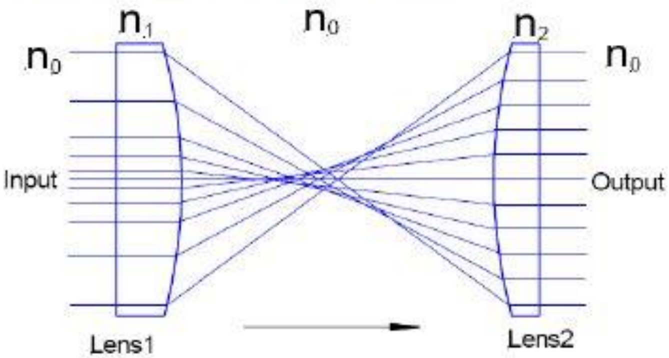
Hoffnagle et al, Apll. Opt. 39, 6488 (2000).

Singlet design 1



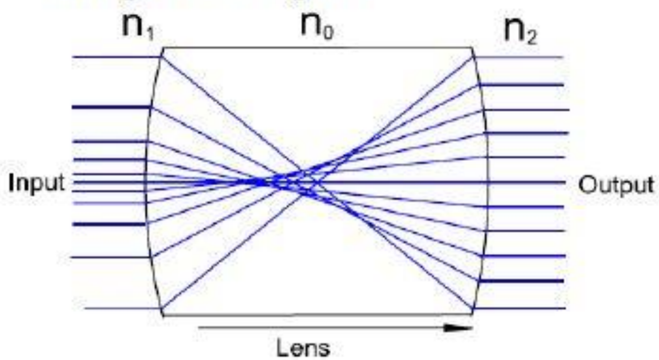
Zhang et al., Opt Express 11, 1942 (2003).

Another 2-lens design



Liu and Zhang et al., Opt. Express 16, 6675 (2008).

Singlet design 2



Zhang et al., J. Opt. A9, 945 (2007).

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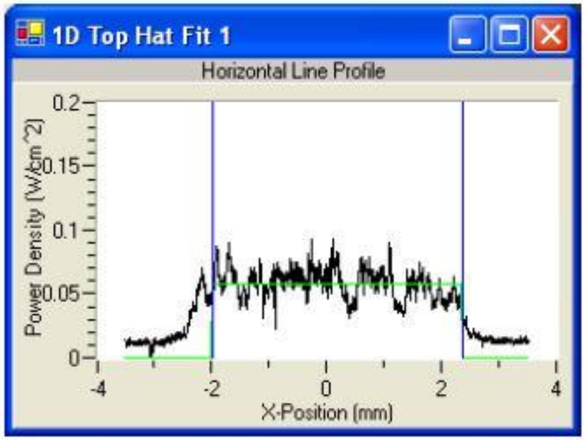
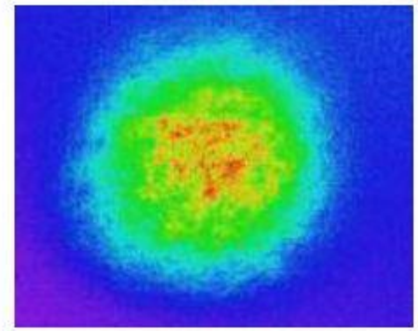
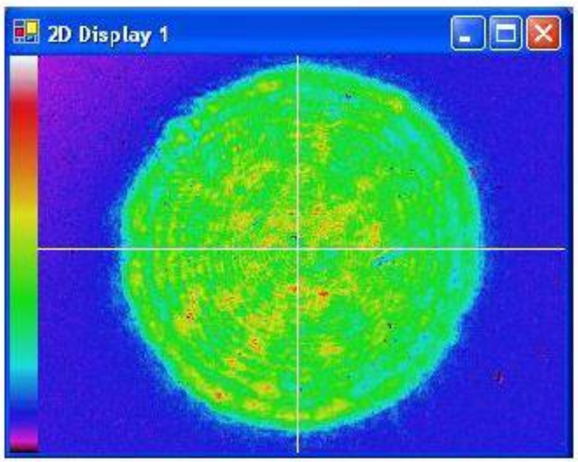
Newport refractive UV shaper

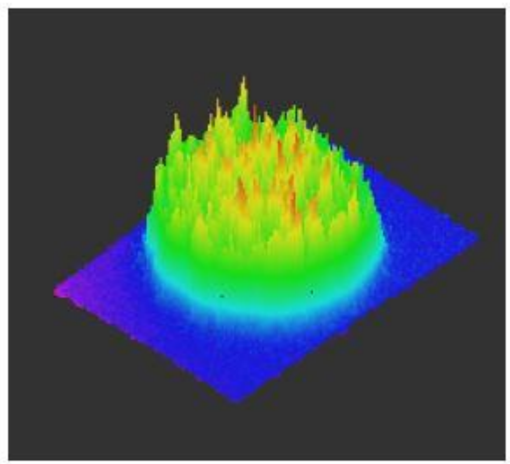


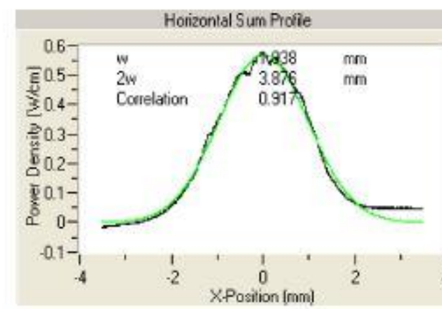
require nearly perfect Gaussian beam!!



laser transverse profile before shaper



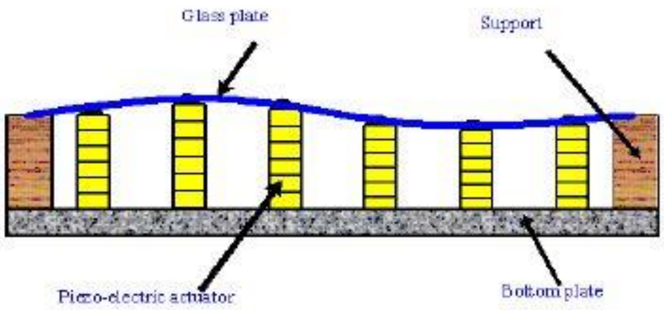


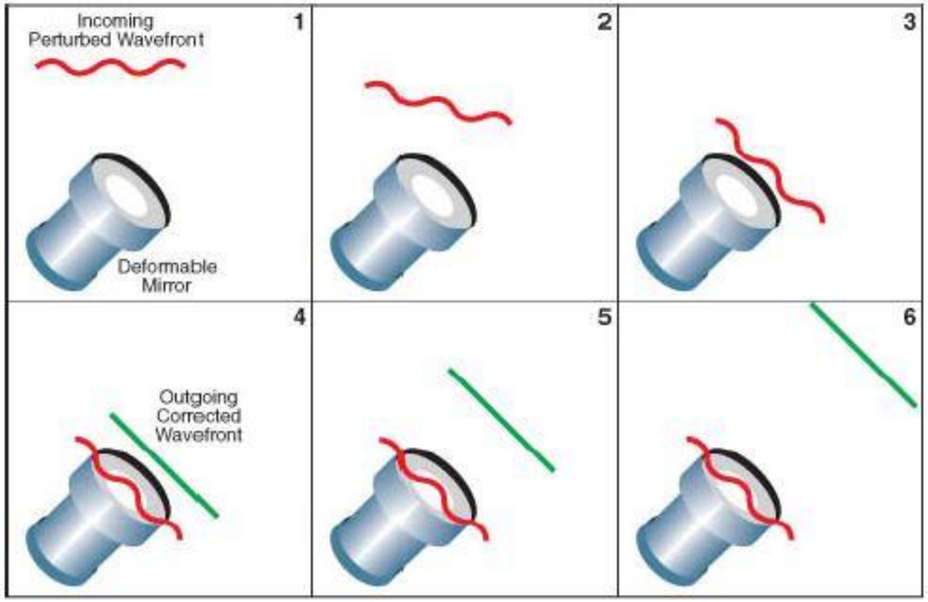


laser transverse profile after the Newport refractive UV shaper

Deformable mirror

- For wave front (aberration) correction
- Can be used for minor homogeneity adjustment
- Commercially available, widely
- Many applications
  - Laser beam shaping/correction
  - Large telescopes
  - Microscopes
  - Vision

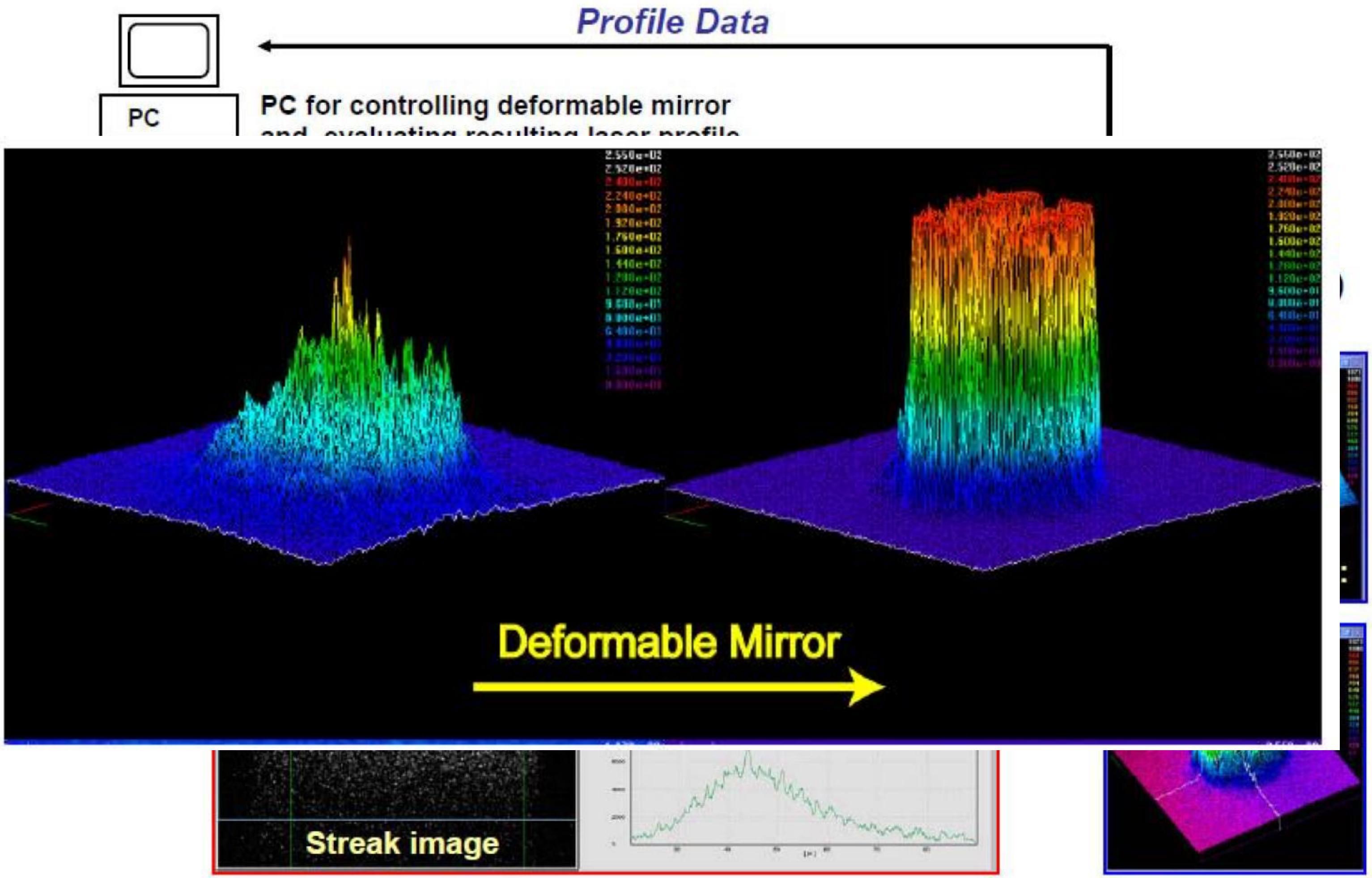




http://www.agiloptics.com

curtsy of Dr. Yuelin Li

Deformable mirror: testing @Spring8



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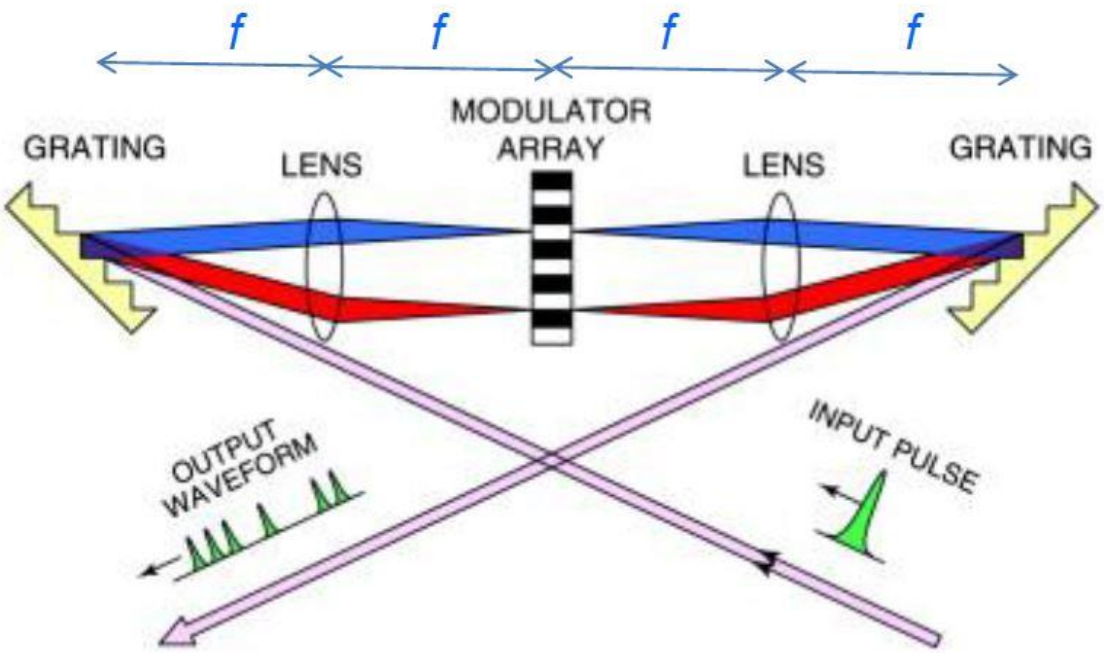
Fourier transform temporal shaping

Basic setup for Fourier transform temporal shaping



- Gratings are at a distance f from the lenses → 0 length stretcher.
  – separating the frequencies in the focal plane without introducing any path length difference.
- Grating 1 maps freq. → angle, lens 1 maps angle → position; after modulation, lens 2 and grating 2 invert the maps.

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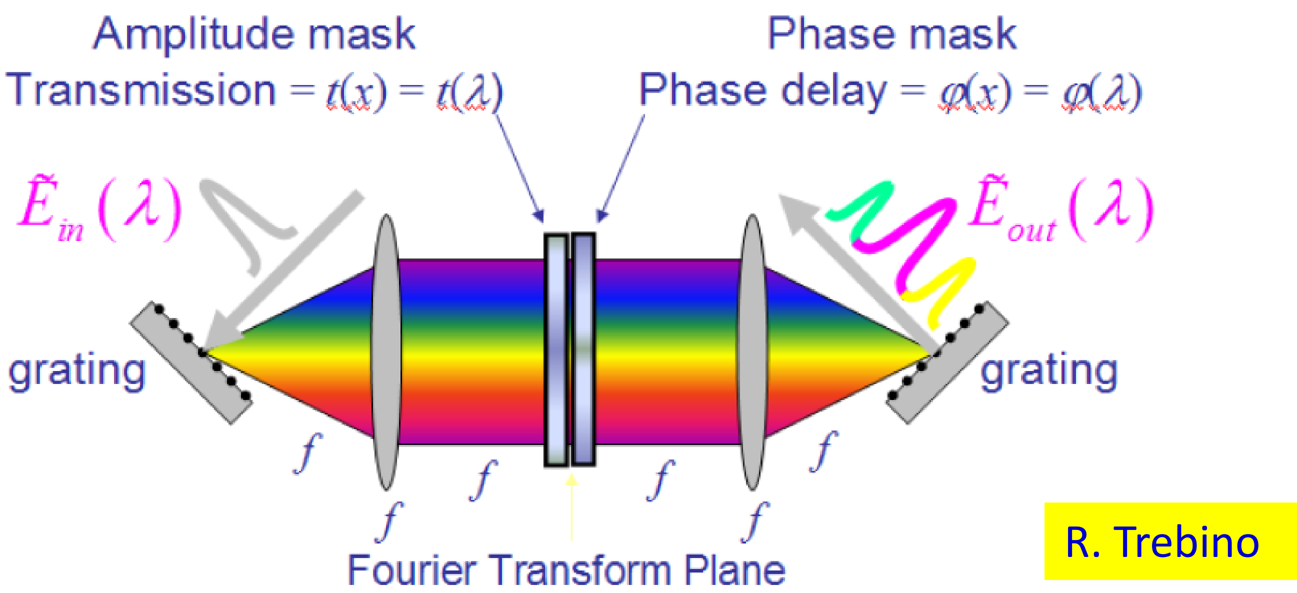
Fourier transform temporal shaping



$$\boxed{H(\lambda) = t(\lambda)\exp[i\varphi(\lambda)]}$$

- Modulator array can alter both intensity and phase of addressable frequency components. For example: 2 SLMs & 2 polarizers
- Multiply by transfer function and transform back to time domain to obtain temporal pulse shaping.

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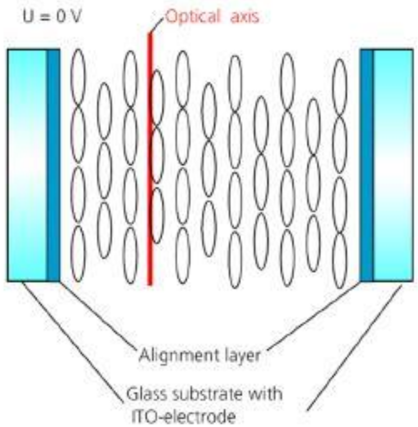
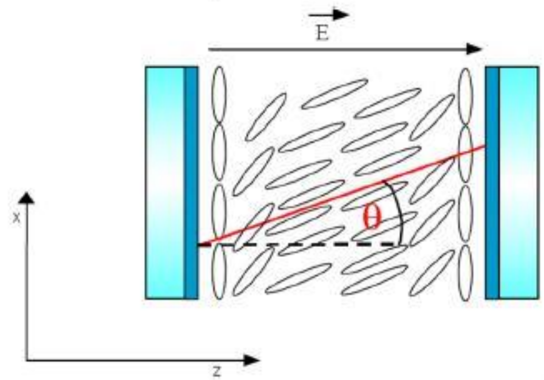
Spatial light modulator (SLM)

phase retardation: $\delta = \dfrac{2\pi d \cdot \Delta n(V, \lambda_0)}{\lambda_0}$

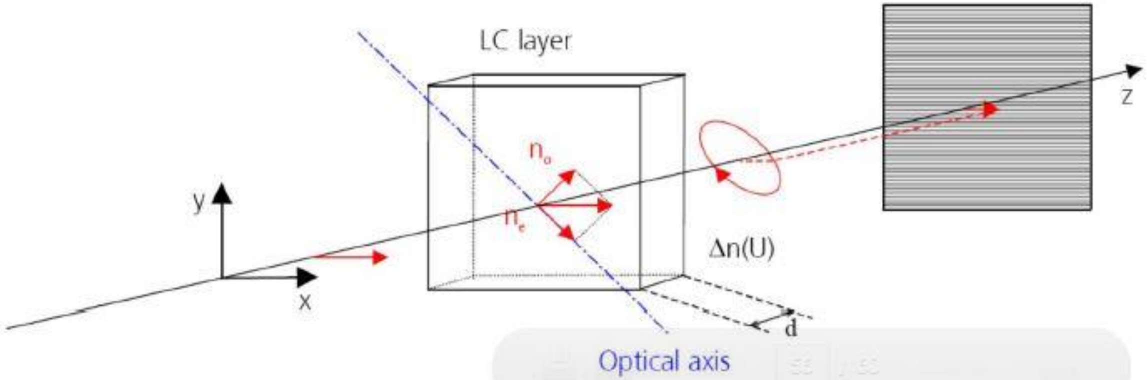
$$\Delta\phi(V,\lambda) = \frac{2\pi d}{\lambda}\Delta n(V,\lambda)$$





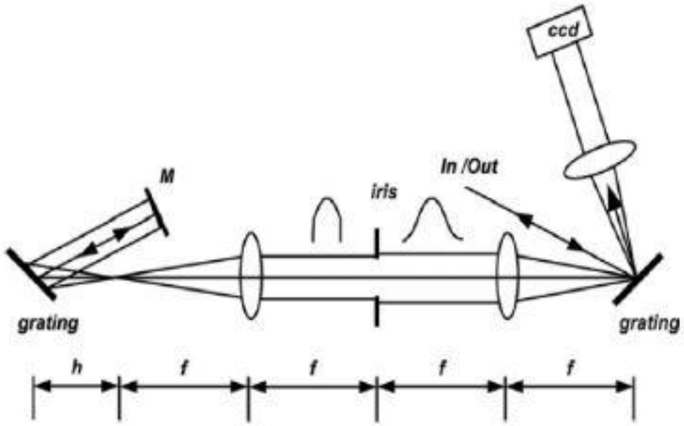
$$\Delta n = \frac{0.2002\lambda}{\sqrt{\lambda^2 - \lambda_0^2}}$$

$$\Delta n(V,\lambda) = \Delta n(\lambda) f(V)$$

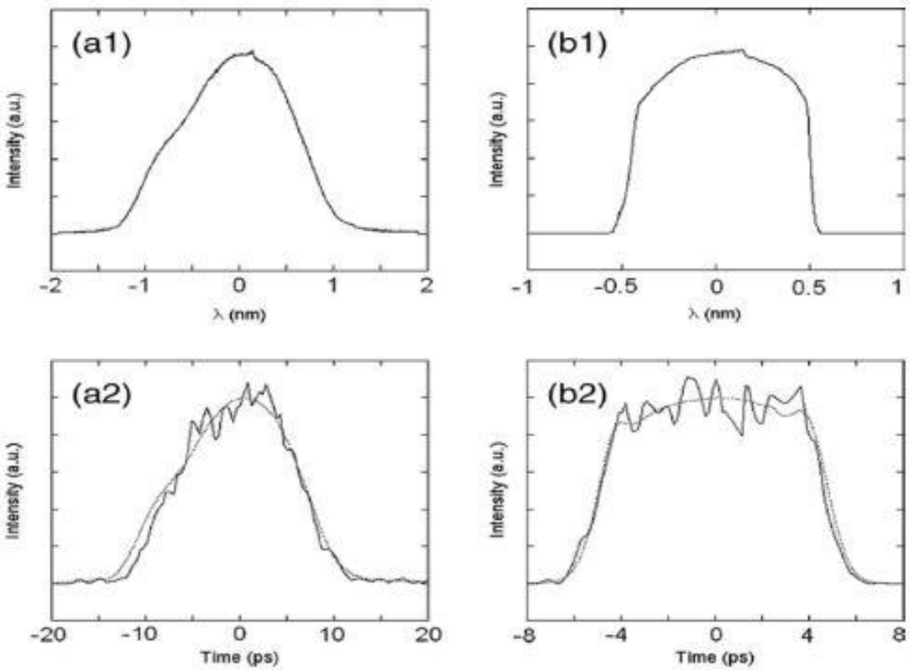


Temporal shaping for PC guns @SPARC

- SPARC, SLM iris and chirp of a 100 fs laser system
- Directly in UV



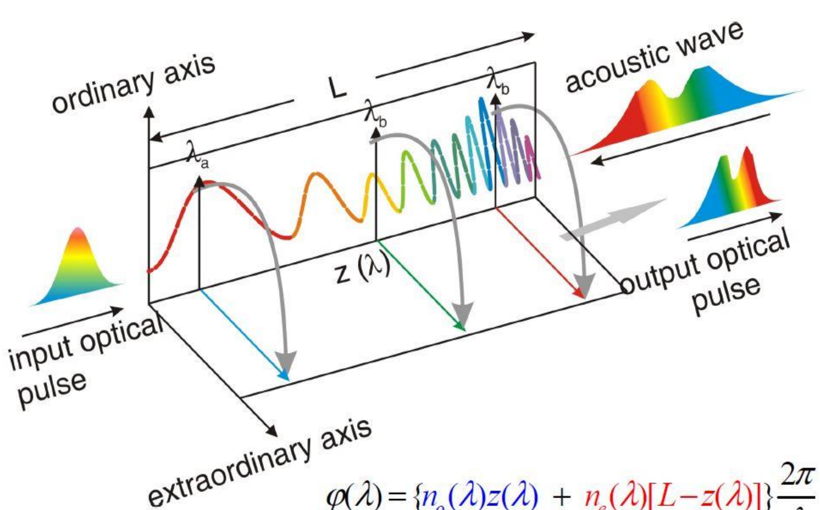
Initial spectrum (a1), spectrum after the mask (b1), and relative measured cross correlations (a2 and b2). The dotted curves represent the theoretical cross correlations obtained, taking into account that the probe pulse used for the measurement is actually 750 fs long.



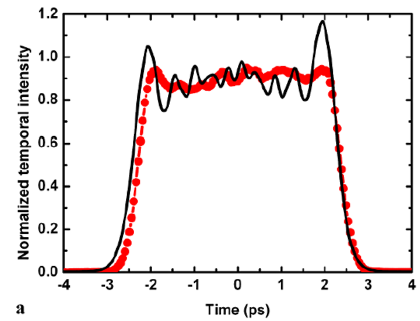
Cialdi et al, Appl. Opt. 46, 4959 (2007)

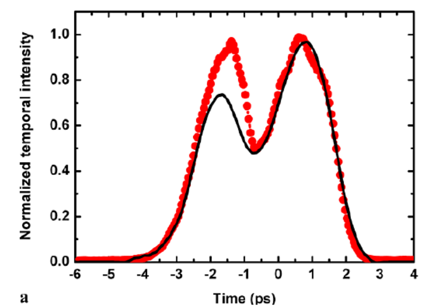
curtsy of Dr. Yuelin Li

Acousto-optic programmable dispersive filter

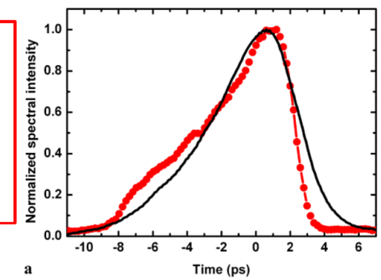


$$\varphi(\lambda) = \{n_o(\lambda)z(\lambda) + n_e(\lambda)[L - z(\lambda)]\}\frac{2\pi}{\lambda}$$

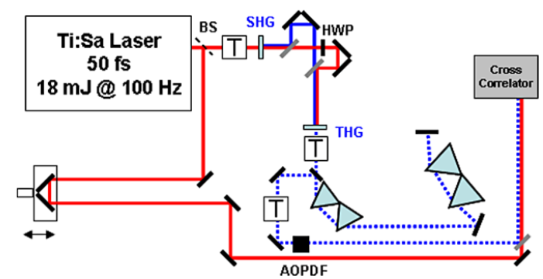




Pulses shaped directly in the UV using stretcher + UV AOPDF at PSI. red measured, black theory



- wavelength-selectively scatter between e- and o-wave using RF-generated acoustic wave
- continuous modulation, no pixel boundaries
- high bandwidth -> high wavelength resolution
- can now work directly in UV (less resolution than IR)
- low efficiency (~20%)
- damage threshold (10's MW peak power)
- length-limited; need pre-stretching for τ > 4ps



Tisorio et Appl Phys B 105, 255 (2011)

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Pulse stacking: temporal profile

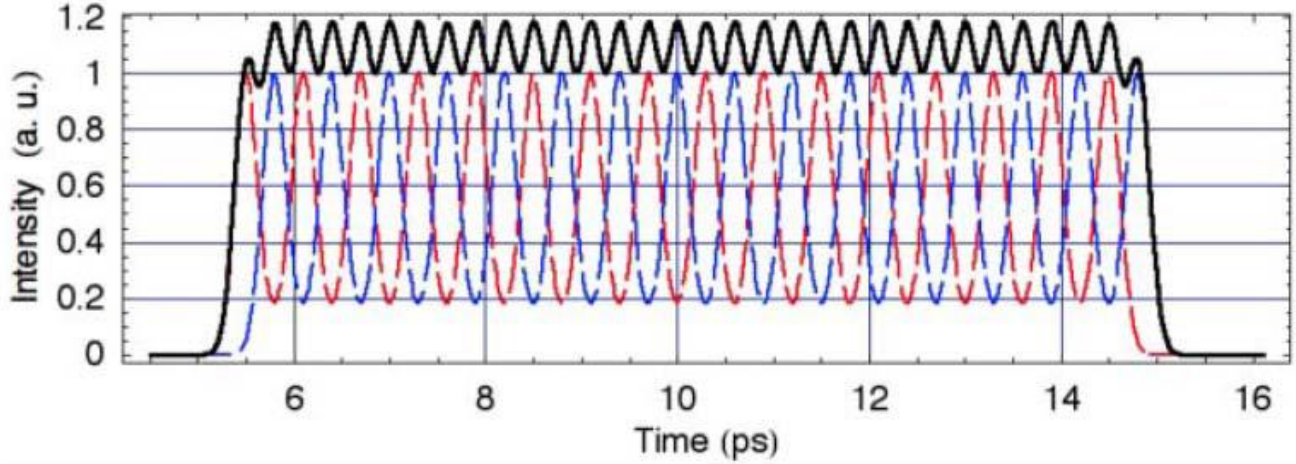
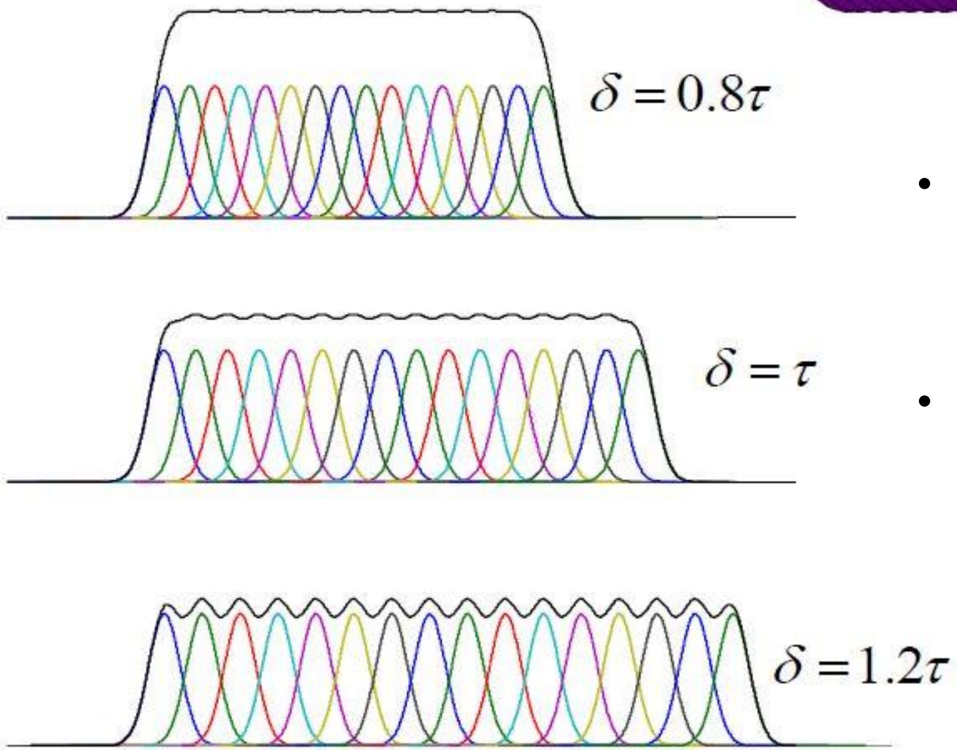


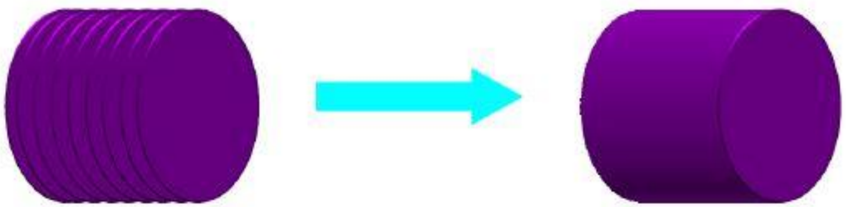
Figure 3: Simulation of the shaped UV pulse after the pulse-stacker. Red and blue dashed lines indicate p and s-polarized pulse trains. The resulting UV pulse on the photocathode is shown by the thick black line. Simulations of the electron beam propagation done in Parmela suggest that the intensity modulation in the resulting laser pulse does not degrade the emittance of the electron bunches.

Ref: M. Y. Sheverdin, Proc. PAC07, p. 533 (2007) (LLNL PC gun drive laser)

Pulse stacking: temporal profile

$$\sum_{n=0}^{15} e^{-2\left(\frac{t-n\delta}{\tau}\right)^2}$$





- Summing multiple pulse replicas shifted in time, closely separated enough that they merge into one continuous pulse.
- Gaussians give flat-top with little ripple for $\delta < \tau$.

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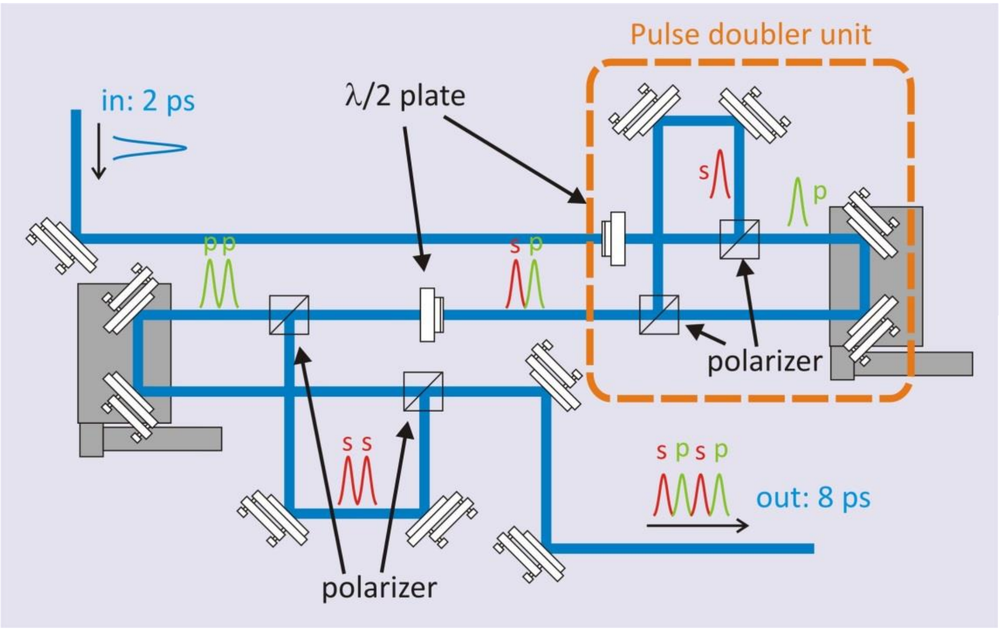
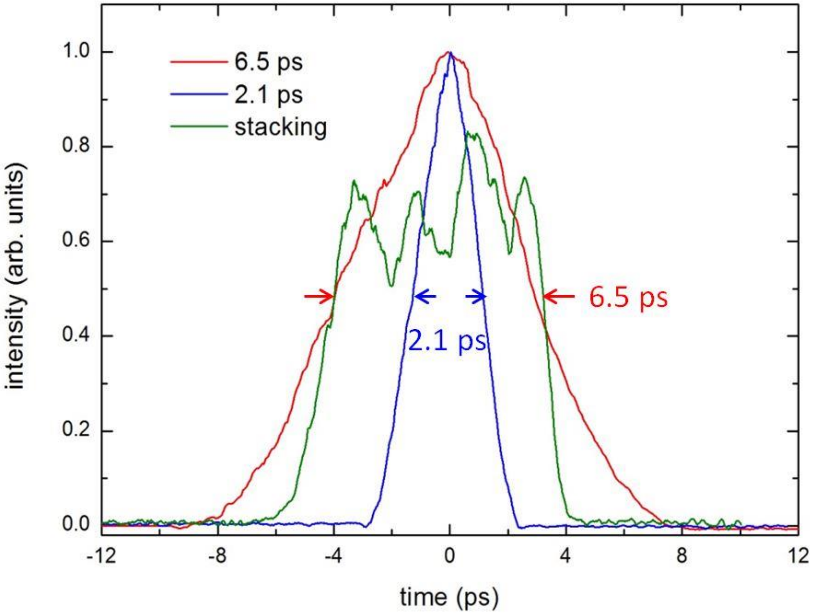
2 stages pulse stacking @NSRRC





Other pulse stacking methods

interferometer design

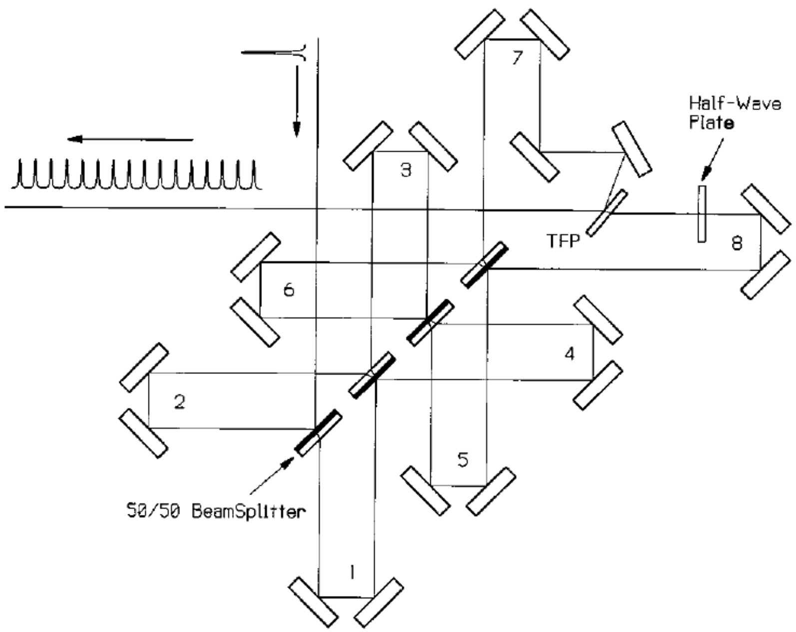
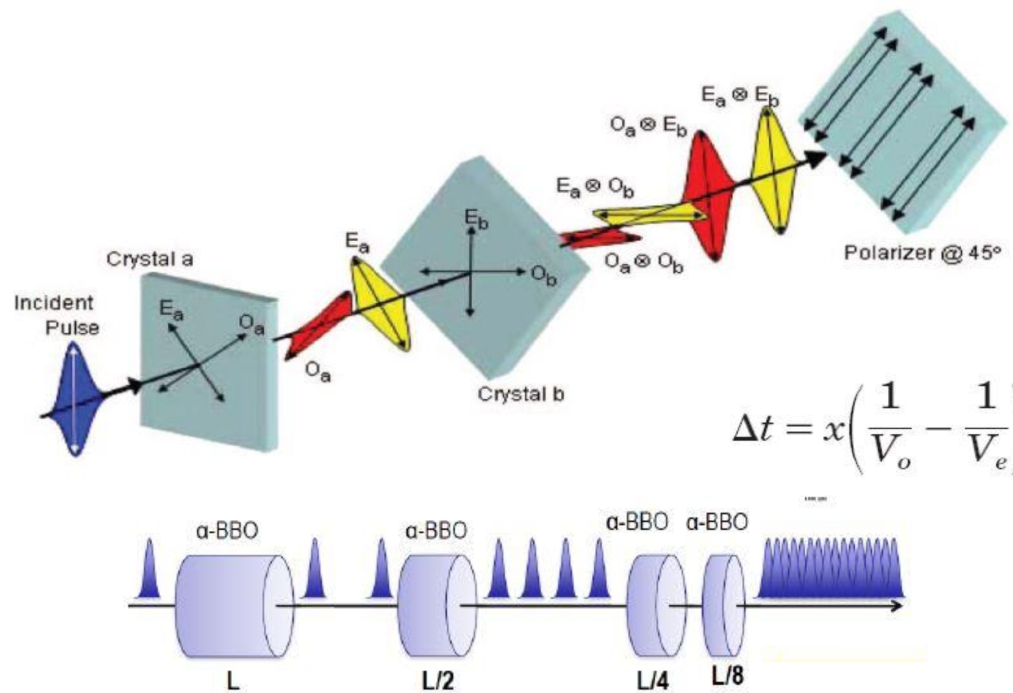


Fig. 1. Interferometer design for generation of a train of 16 pulses. For equally spaced pulses, arm 2 is lengthened by half a unit, arm 3 by one unit, arm 6 by two units, and arm 8 by four units.

Ref: M. Y. Sheverdin, Proc. PAC07, p. 533 (2007) (LLNL PC gun drive laser)

birefringent pulse stacking

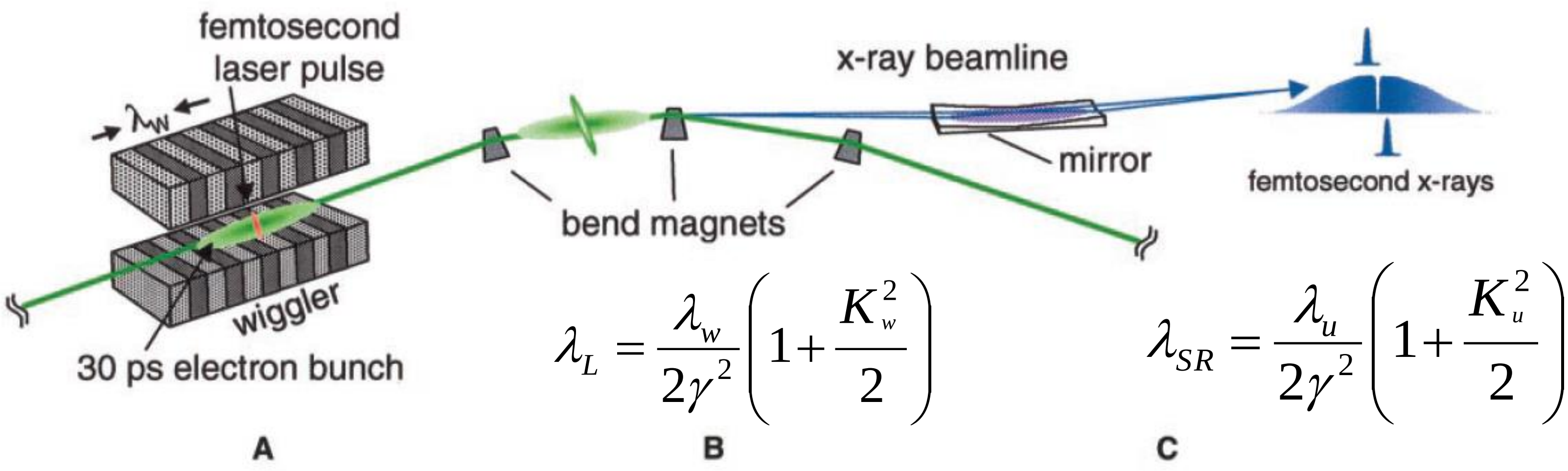


Ref: B. Dromey *et al.,* Appl. Opt., **46** 5142 (2007)

Short pulse x-ray sources

- Scientists want short pulse, short wavelength light sources for ultrafast science. (~100 fs)
- Existing laser based light sources
  – laser plasma sources
  – high order harmonics (as, 100 eV)
  – Thomson scattering
- Ways to generated short pulse radiation from beam based sources
  – free electron lasers
  – deflecting a beam
  – slicing a beam (laser slicing)
- Some light sources have become standard to make a user facility with femtoslicing: ALS, BESSY II, SLS, SOLEIL

Laser slicing principle



$$\lambda_L = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K_w^2}{2}\right)$$

$$\lambda_{SR} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K_u^2}{2}\right)$$

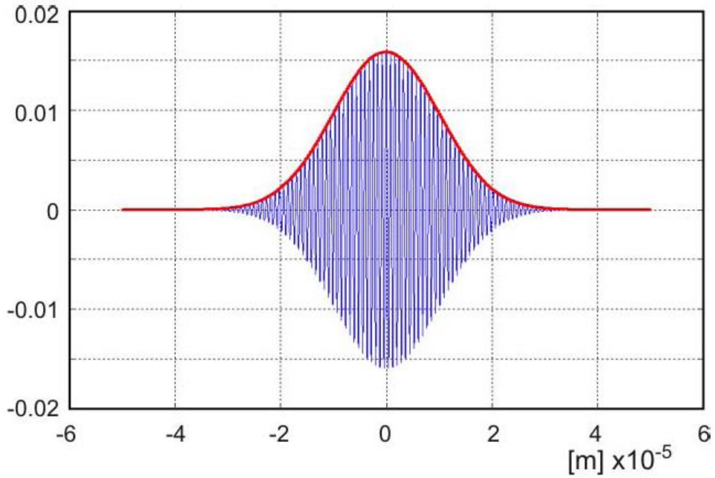
A. The short laser pulse is overlapped with bunch center in a wiggler and when meeting the resonant condition it produces an energy modulation in the short "slice".
B. The modulated electrons are separated transversely from the rest of the bunch in a dispersive bend of the storage ring.
C. The femtosecond synchrotron radiation at the beamline image plane is spatially separated from the radiation from the "core" (rest of the bunch).

Ref: A. A. Zholents, M. S. Zolotorev, Phys. Rev. Lett. **76**, 912, (1996)
R. W. Schoenlein *et al*., Science **287**, 2237 (2000)

Energy modulation of an electron beam

$$\boxed{(\Delta E)^2 \simeq 4\pi\alpha A_L \hbar\omega_L \frac{K^2/2}{1+K^2/2}\frac{\Delta\omega_L}{\Delta\omega_R}}$$

The electron modulation envelope after laser-beam interaction



A_L: laser pulse energy

α: the fine structure constant

$\omega_L = 2\pi c/\lambda_L$

λ_L: laser wavelength

K: the deflection parameter

$\Delta\omega_L$: bandwidth of the laser pulse

$\Delta\omega_R$: bandwidth of the undulator radiation

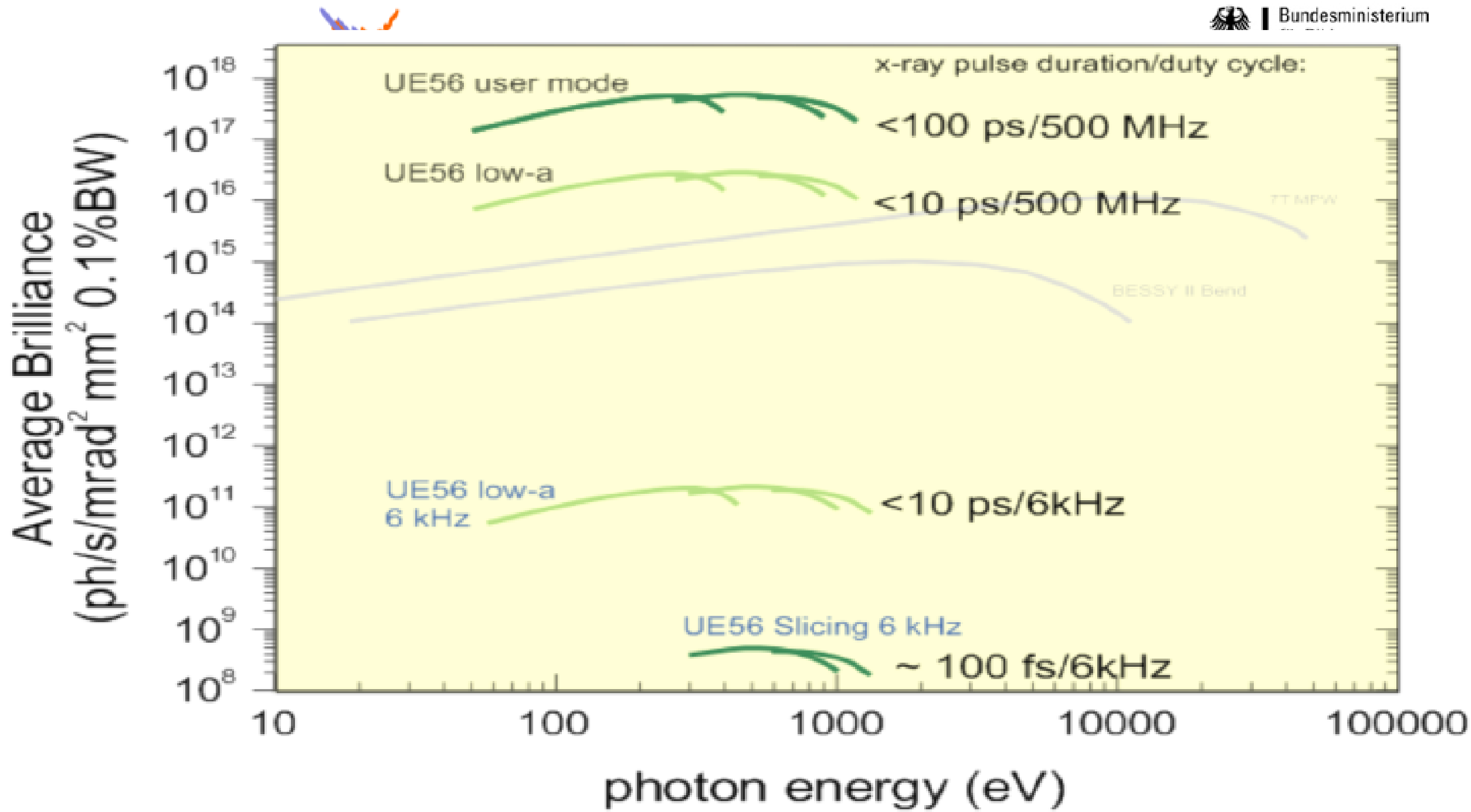
$$\frac{\Delta\omega_L}{\Delta\omega_R} \sim \frac{M_U}{M_L}$$

M_U: number of undulator period

M_L: optical cycles of laser pulse

- Stronger modulation will be required for higher energy ring for good beam separation depending on photon beamline design. It means that higher laser energy is required for fixed modulator specifications.

FEMTOSPEX – femtoslicing facility at BESSY II

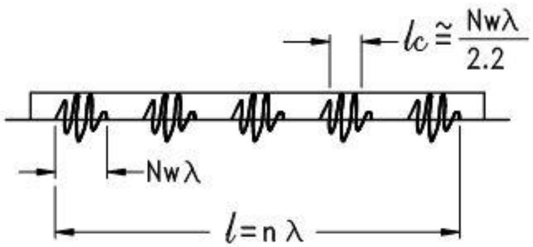


UV-VIS-NIR-FIR OPTICAL PUMP – X-RAY PROBE SETUP AFTER THE FEMTOSPEX - UPGRADE

curtsy of Dr. K. Holldack

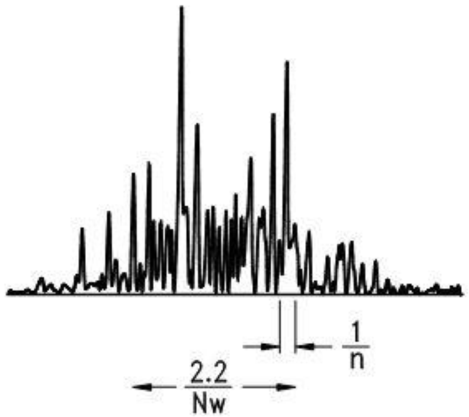
Self-amplified spontaneous emission (SASE) FEL

- In the X-ray wavelength range, most FELs are operated in the self-amplified spontaneous emission (SASE) mode.
- Although the radiation from a SASE FEL has excellent transverse coherence, it typically has rather poor temporal coherence and relatively large statistical fluctuations due to starting up from the random shot noise.



bunch length l, slipage $Nw\lambda$
and coherence length l_c

train of pulses with independent phase



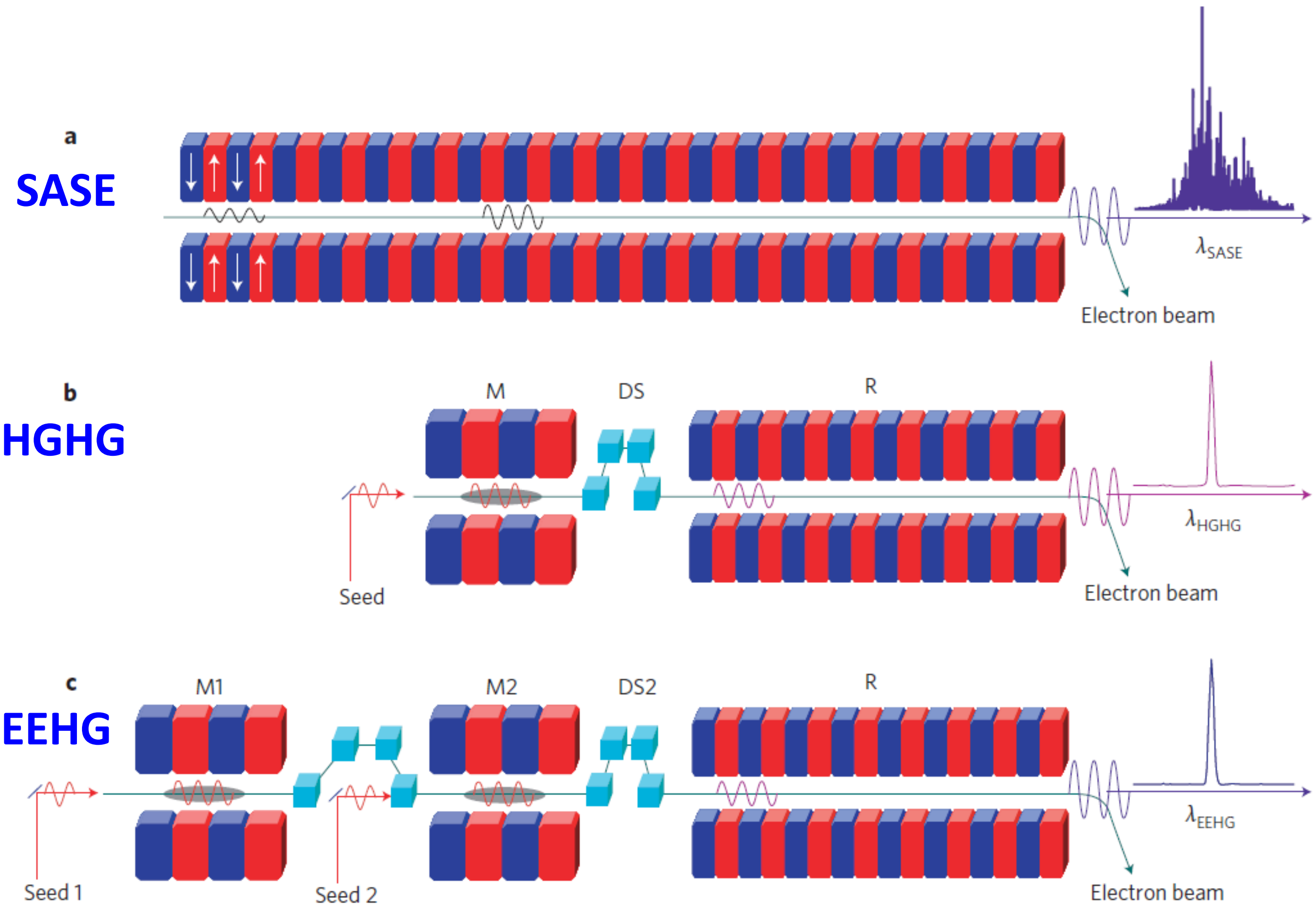
single shot spectrum

spectrum consists spikes

→ Need seeded FEL for full temporal coherence!!

Seeded FEL vs. SASE FEL

SASE



poor temporal coherence

HGHG

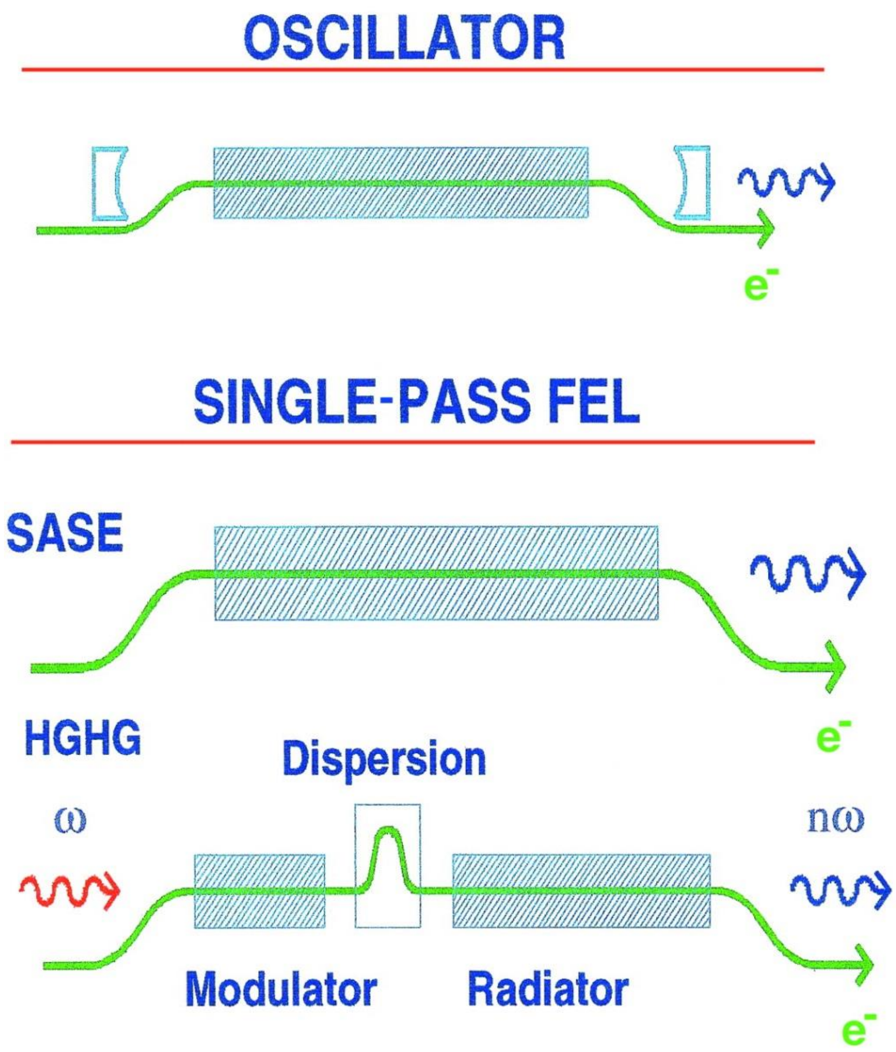
full temporal coherence with limited harmonic number (N~10)

EEHG

full temporal coherence with a very high harmonic number

Ref: Z.T. Zhao *et al.,* Nat. Phot. **6**, 360 (2012)

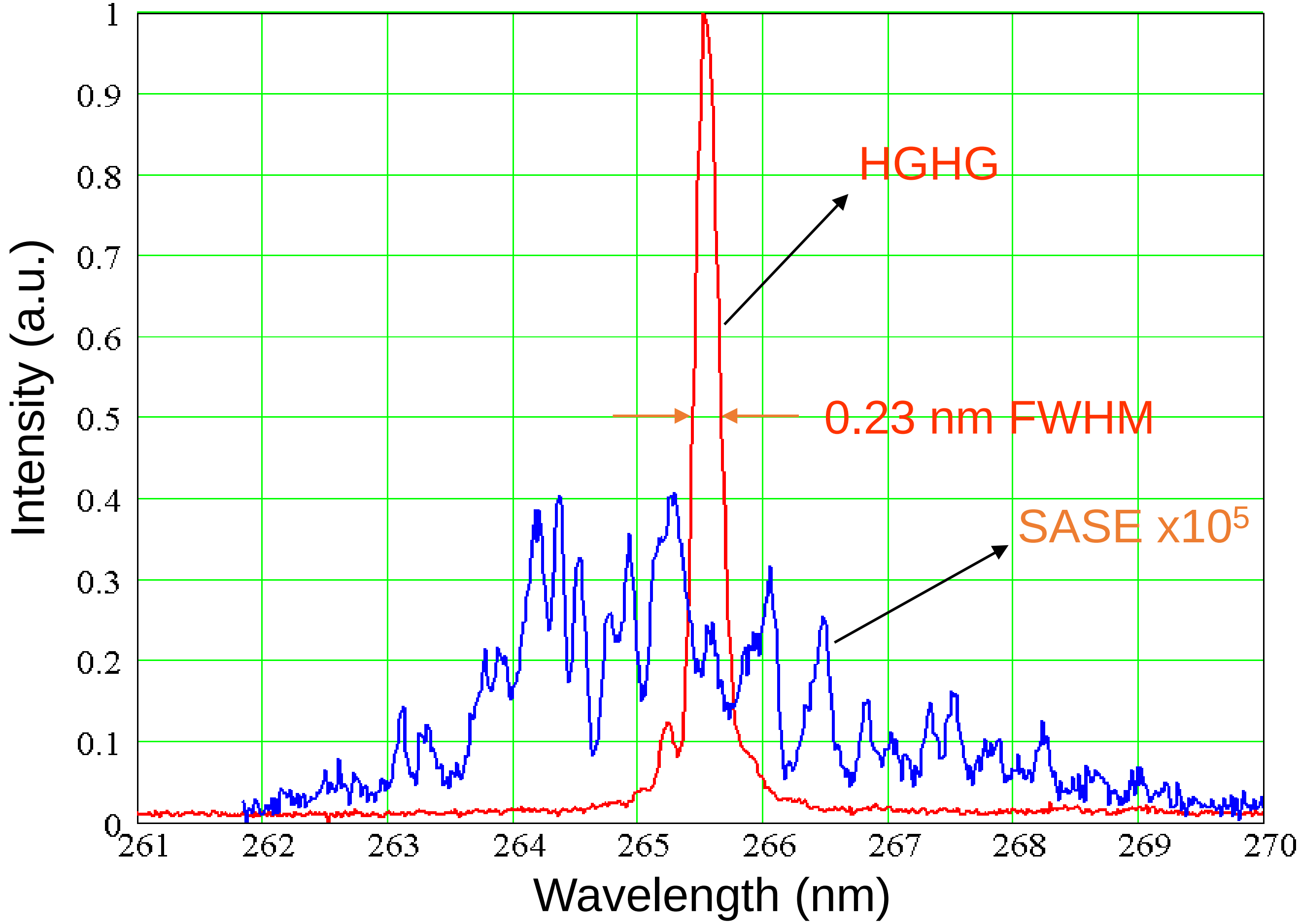
High gain high harmonic (HGHG) FEL



Ref: L.H. Yu et al., Science **289**, 932 (2000)

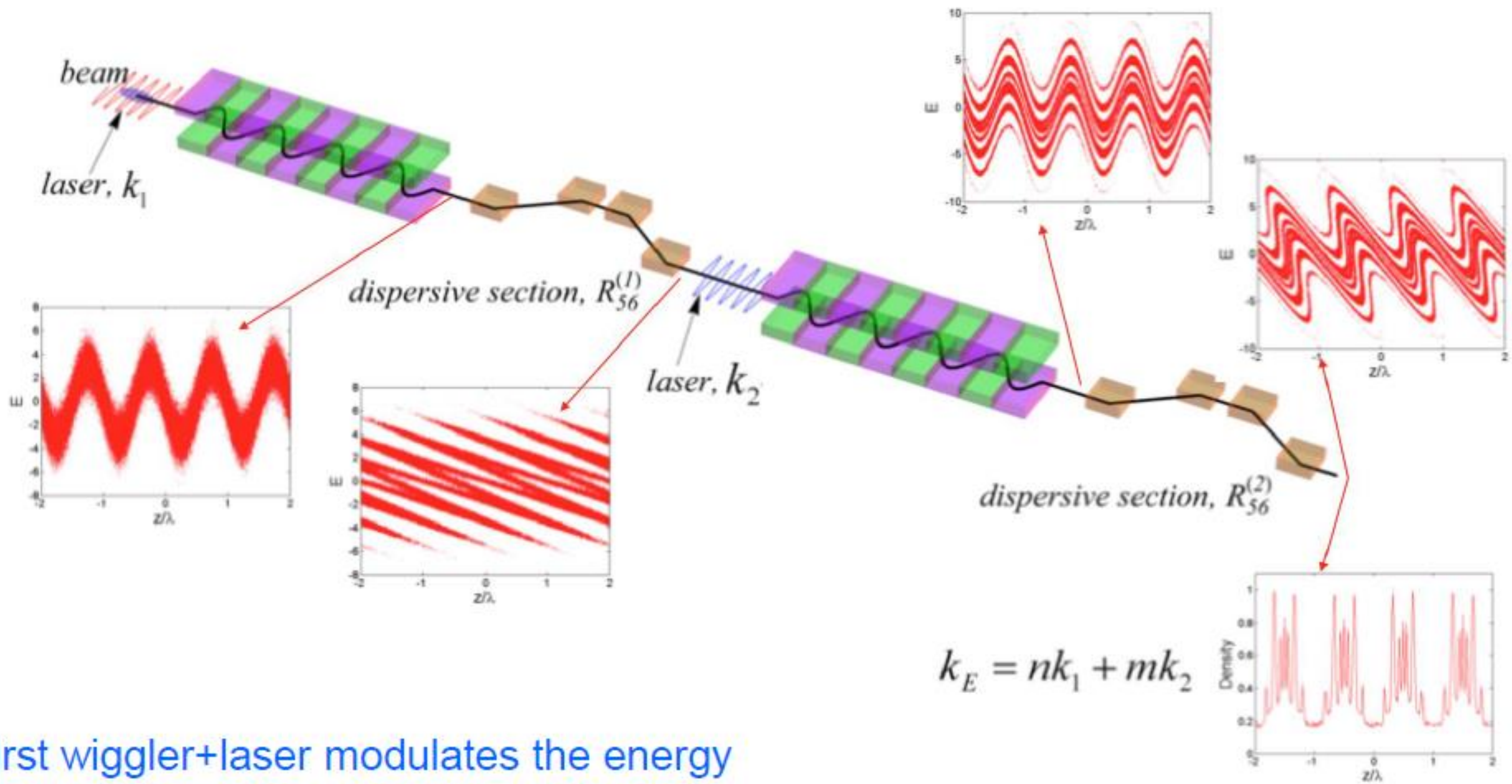
High gain high harmonic (HGHG) FEL

Spectrum of HGHG and SASE at 266 nm under the same electron beam condition



curtsy of Dr. L.H. Yu

Echo-enabled high harmonic (EEHG) FEL



- First wiggler+laser modulates the energy
- First chicane creates energy bands of narrow width ($<<\sigma_{E0}$) at each z
- Second wiggler+laser modulates all of the bands
- Second chicane converts these modulations into density modulations at harmonics of the laser

curtsy of Dr. Brian Sheehy

EEHG FEL @Shanghai DUV-FEL

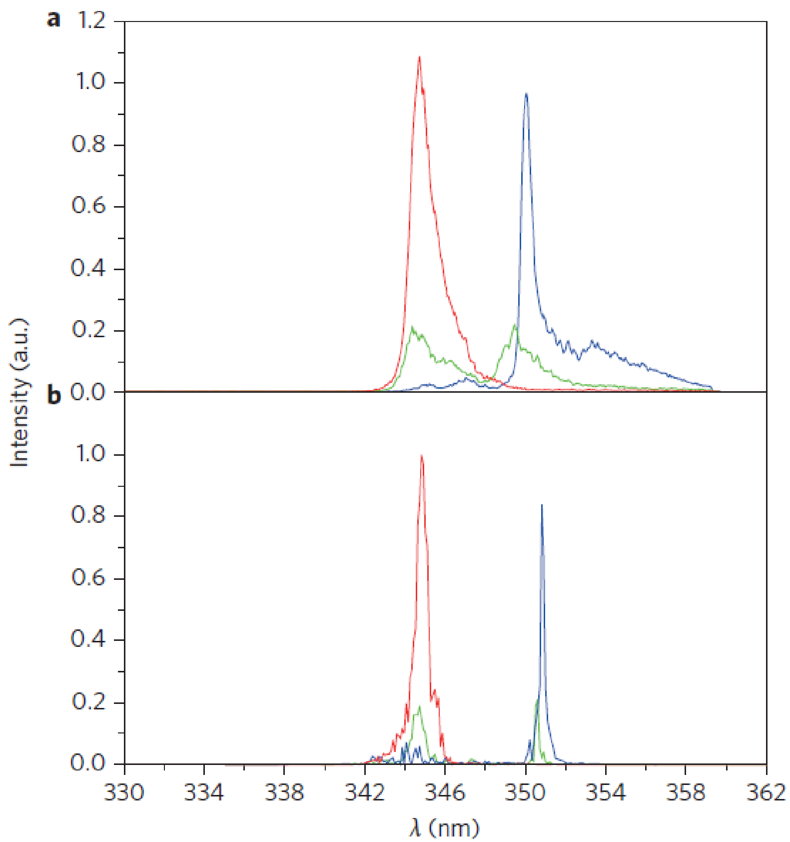


Figure 3 | Spectra for FEL radiation. a, Experimental results (red line, HGHG; blue line, EEHG; green line, intermediate state between HGHG and EEHG). **b**, Simulation results (red line, HGHG; blue line, EEHG; green line, intermediate state between HGHG and EEHG).

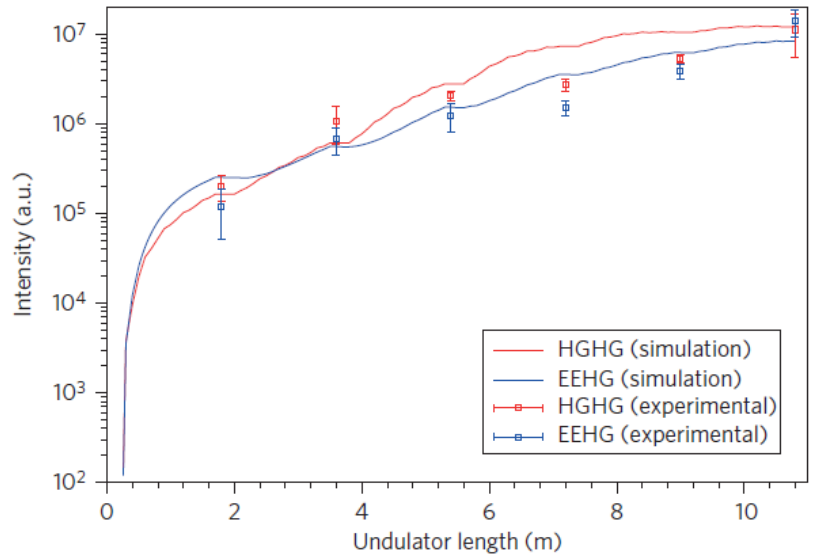
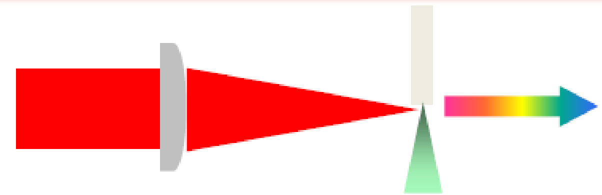
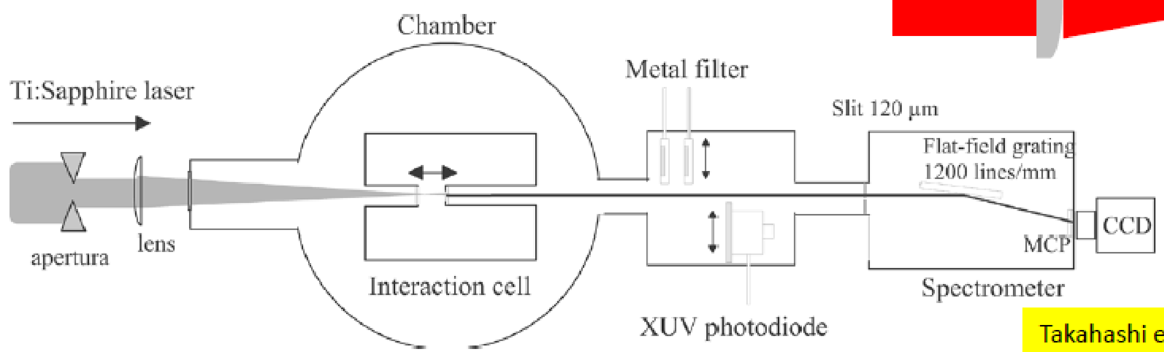


Figure 5 | Gain curves of the EEHG and HGHG FEL at SDUV-FEL. Intensity is measured with a calibrated CCD at the end of the radiator (red open squares, HGHG; blue open squares, EEHG). Error bars correspond to the peak-to-peak intensity statistics of 100 measurements. Simulation results are shown as a red line (HGHG) and a blue line (EEHG).

Ref: Z.T. Zhao *et al.,* Nat. Phot. **6**, 360 (2012)

FEL seeding with high harmonics

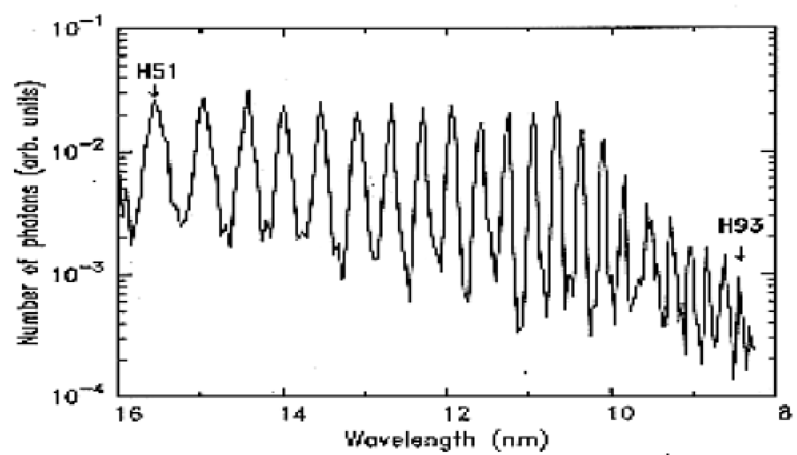




Takahashi et al, IEEE JQE 10,1315 (2004)

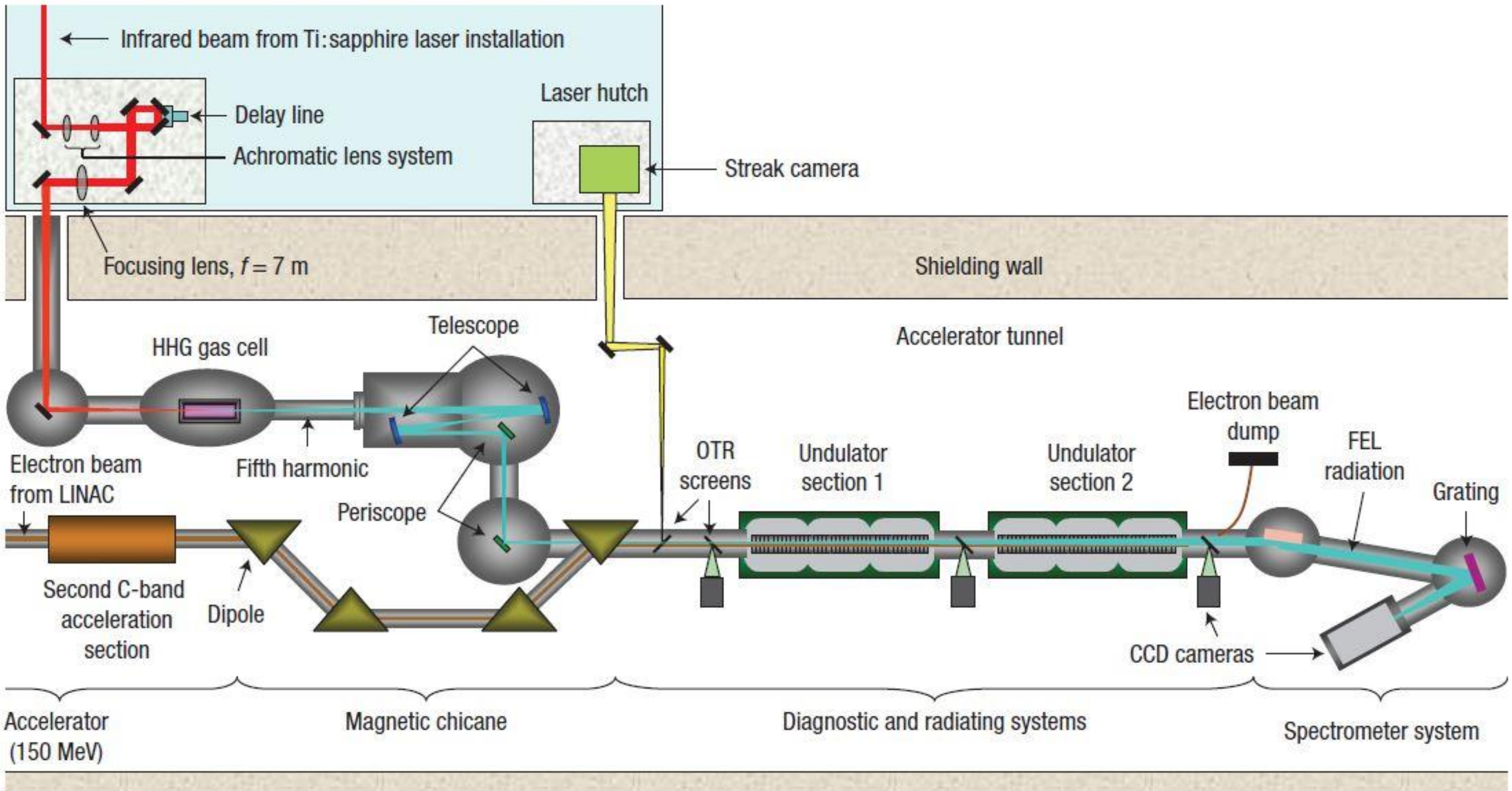
<u>Ultrafast pulse focused into a gas sample</u>

- Xe, Ar, Ne, He
- Intensity ~ $10^{14} – 10^{15}$ W/cm^2
    - ionization plays a role both in quenching (saturation) & phase-matching
- sample may be in a jet, capillary (waveguide) , or cell
    - phase matching
- Cutoff is intensity- and atom-dependent



curtsy of Dr. Brian Sheehy

FEL directly seeded at 160 nm @Spring8

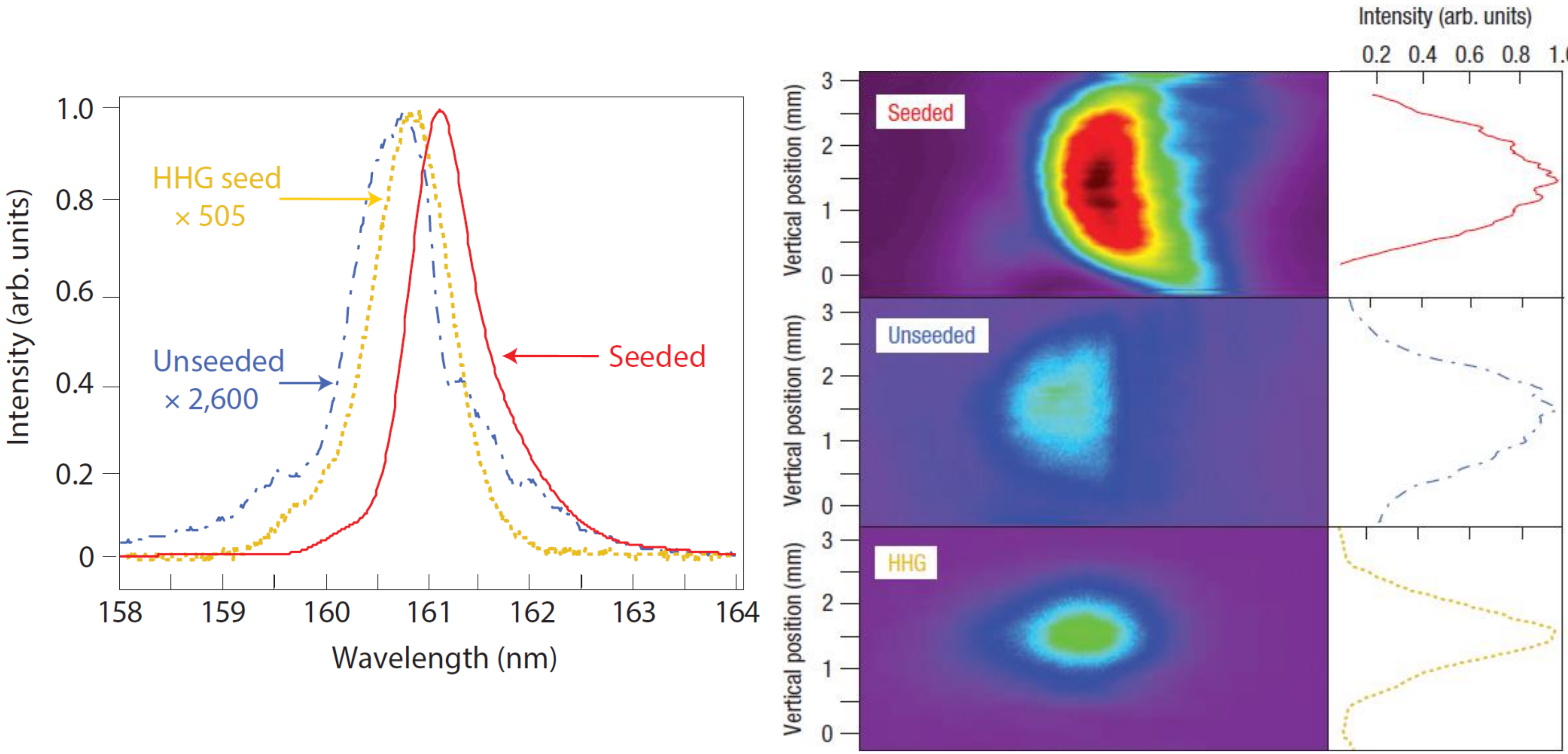


- laser: 800 nm, 100 fs, 20 mJ, 10 Hz
- H5: 160 nm, ~50 fs, ~ 1 μJ, Xe gas cell
- e-beam: 150 MeV, 1 ps, 10 Hz

Ref: G. Lambert *et al*., Nat. Phys. **4**, 296 (2008)

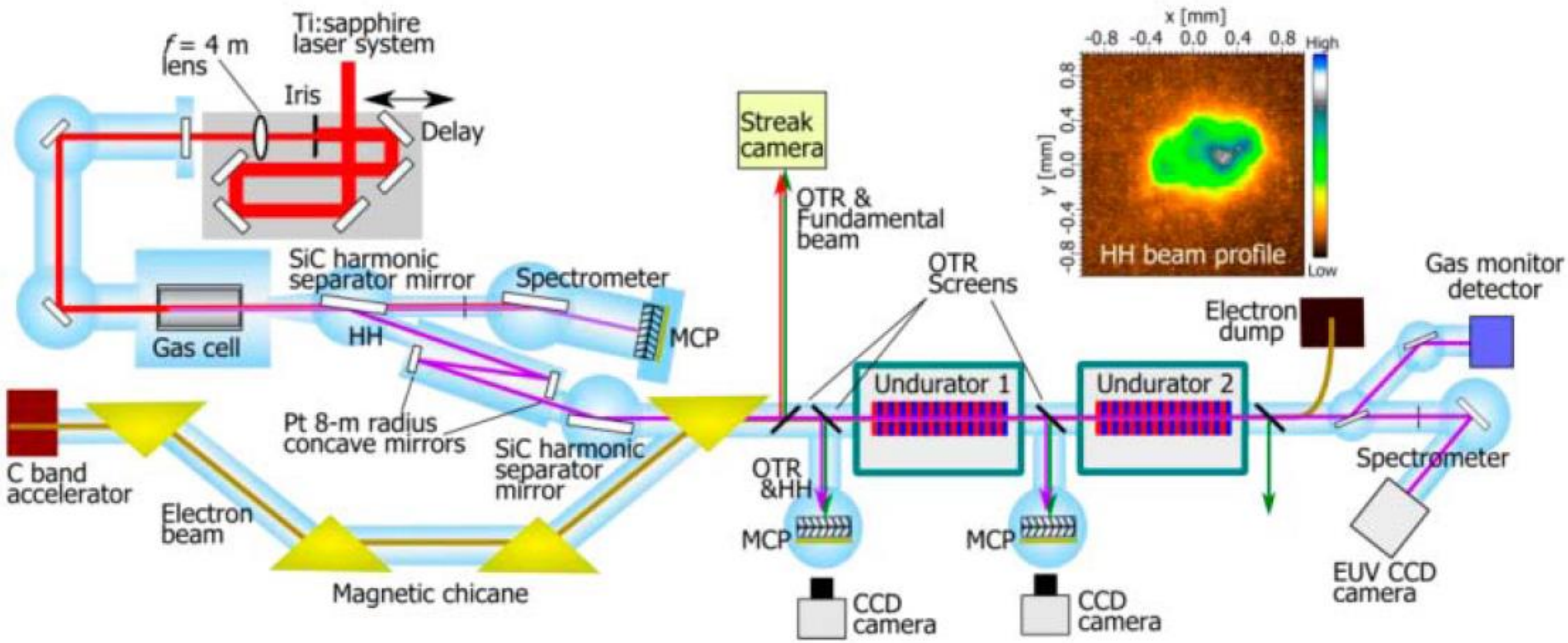
FEL directly seeded at 160 nm @Spring8

Spectra and spatial distributions of seeded and SASE FEL



Ref: G. Lambert *et al*., Nat. Phys. **4**, 296 (2008)

FEL directly seeded at 61 nm @Spring8



- laser: 800 nm, 160 fs, 100 mJ, 30 Hz
- H13: 61.2 nm, ~ 2 nJ, Xe gas cell
- e-beam: 250 MeV, 300 fs, 30 Hz

Ref: T. Togoshi *et al.,* Opt. Express **19**, 317 (2011)

FEL directly seeded at 61 nm @Spring8

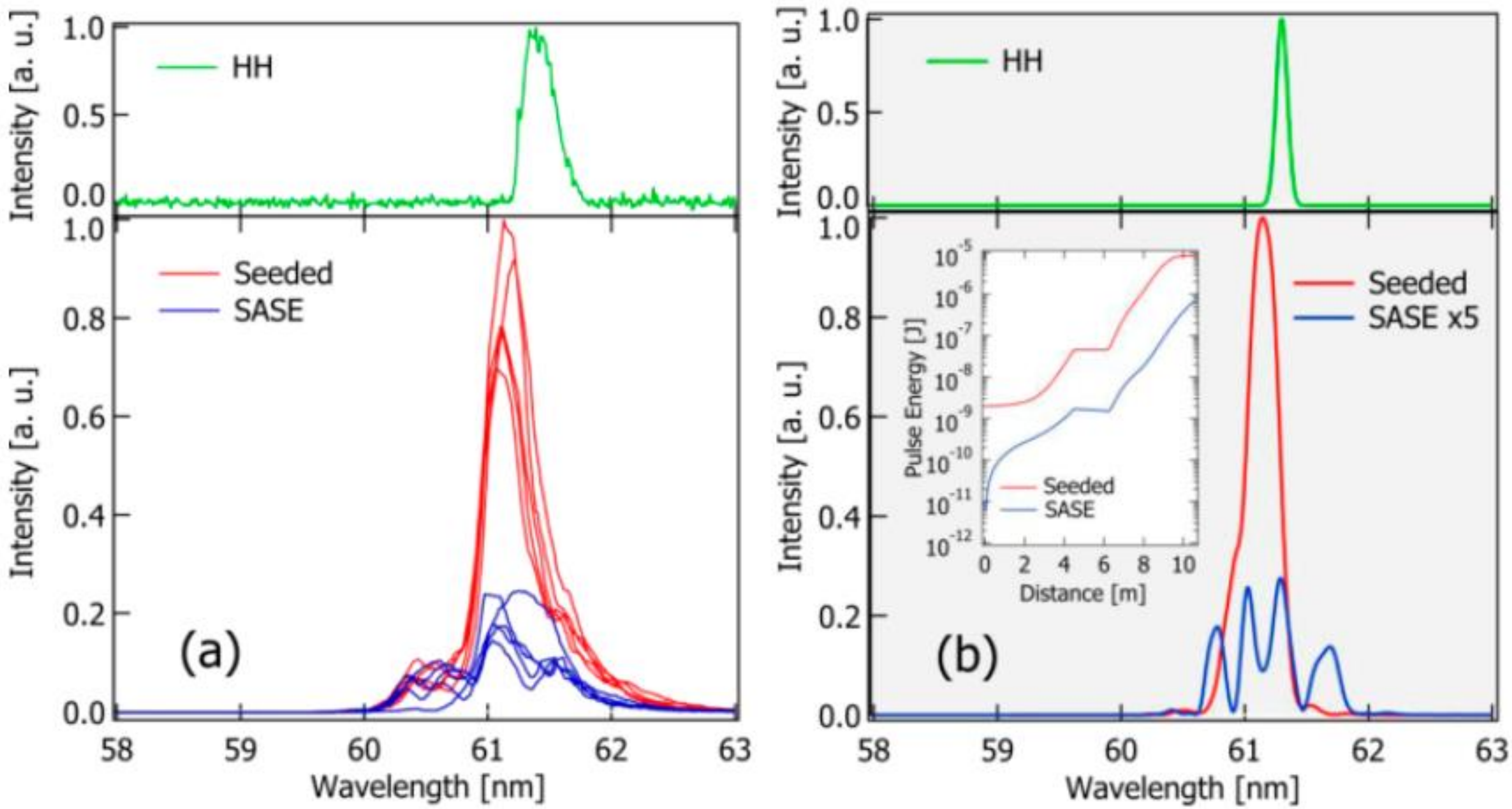
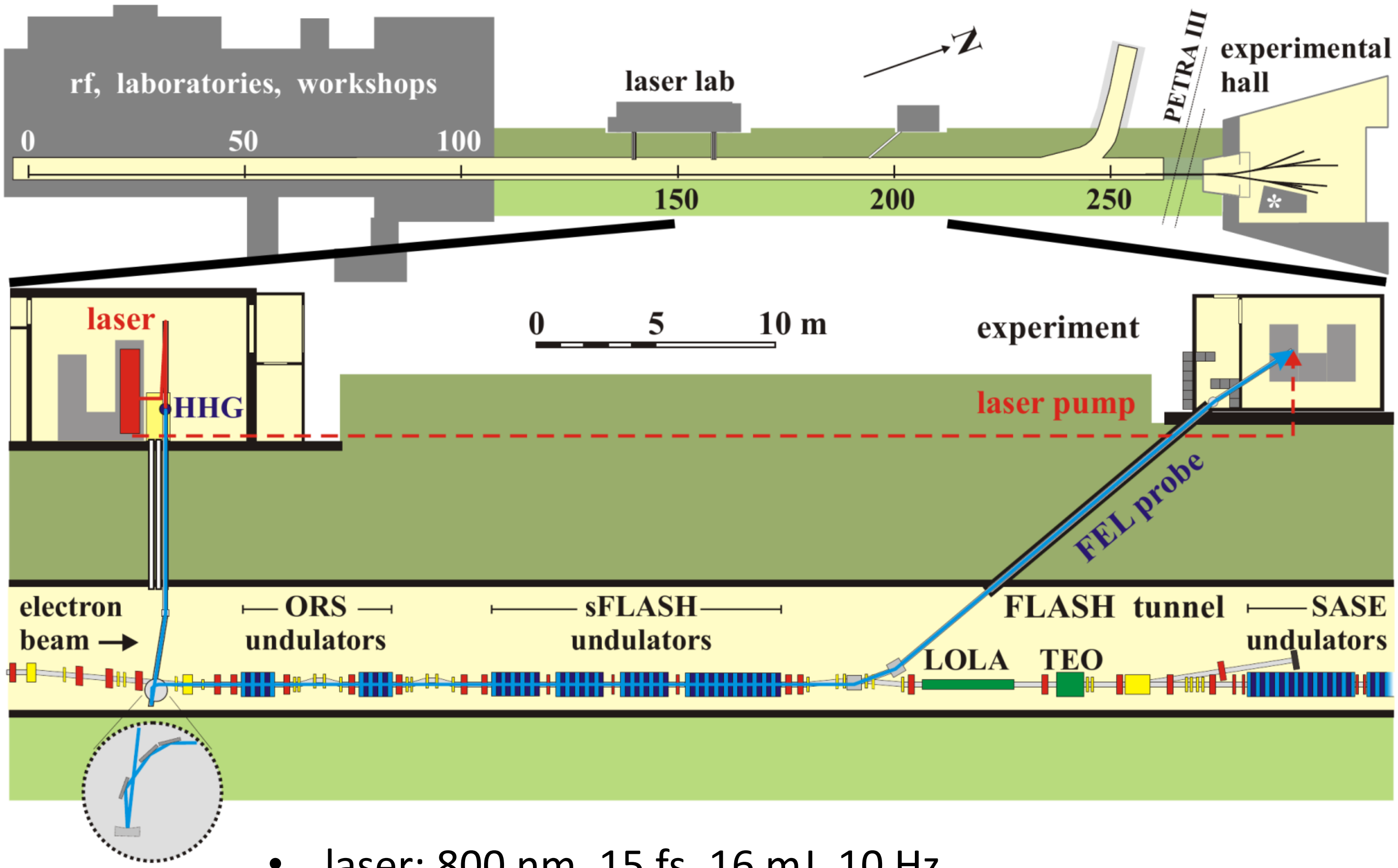


Fig. 3. Spectra of seeded (red lines) and unseeded (blue lines) conditions, as well as that of HH radiation (green line), given by experiment (a) and simulation (b). The inset of (b) shows intensity growths along the undulator for seeded (red line) and unseeded (blue line) conditions.

Ref: T. Togoshi *et al.,* Opt. Express **19**, 317 (2011)

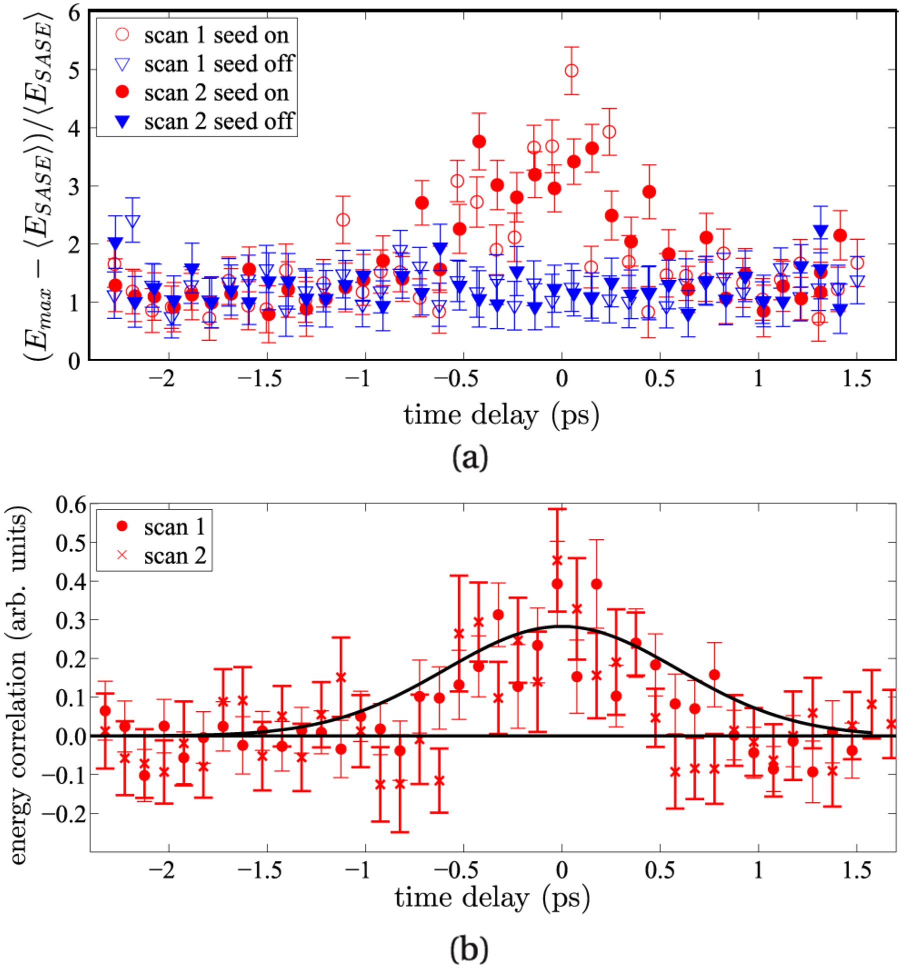
FEL directly seeded at 38 nm @FLASH

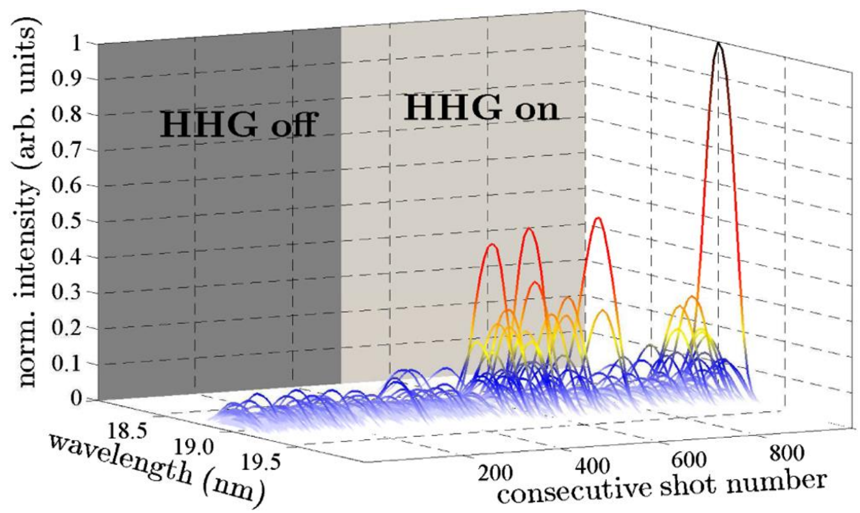


- laser: 800 nm, 15 fs, 16 mJ, 10 Hz
- H21: 38.1 nm, 9 nJ, Ar gas
- e-beam: 700 MeV

curtsy of Dr. C. Lechner

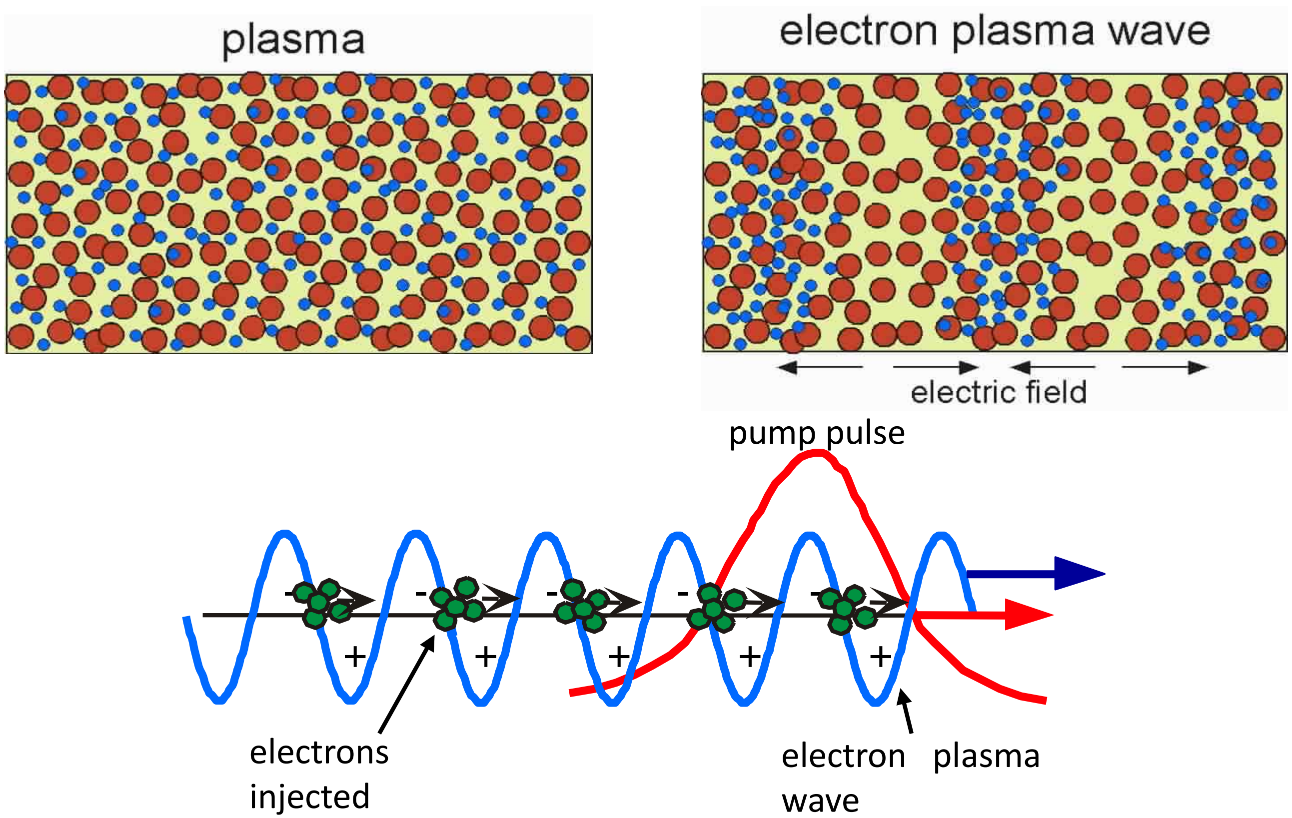
FEL directly seeded at 38 nm @FLASH





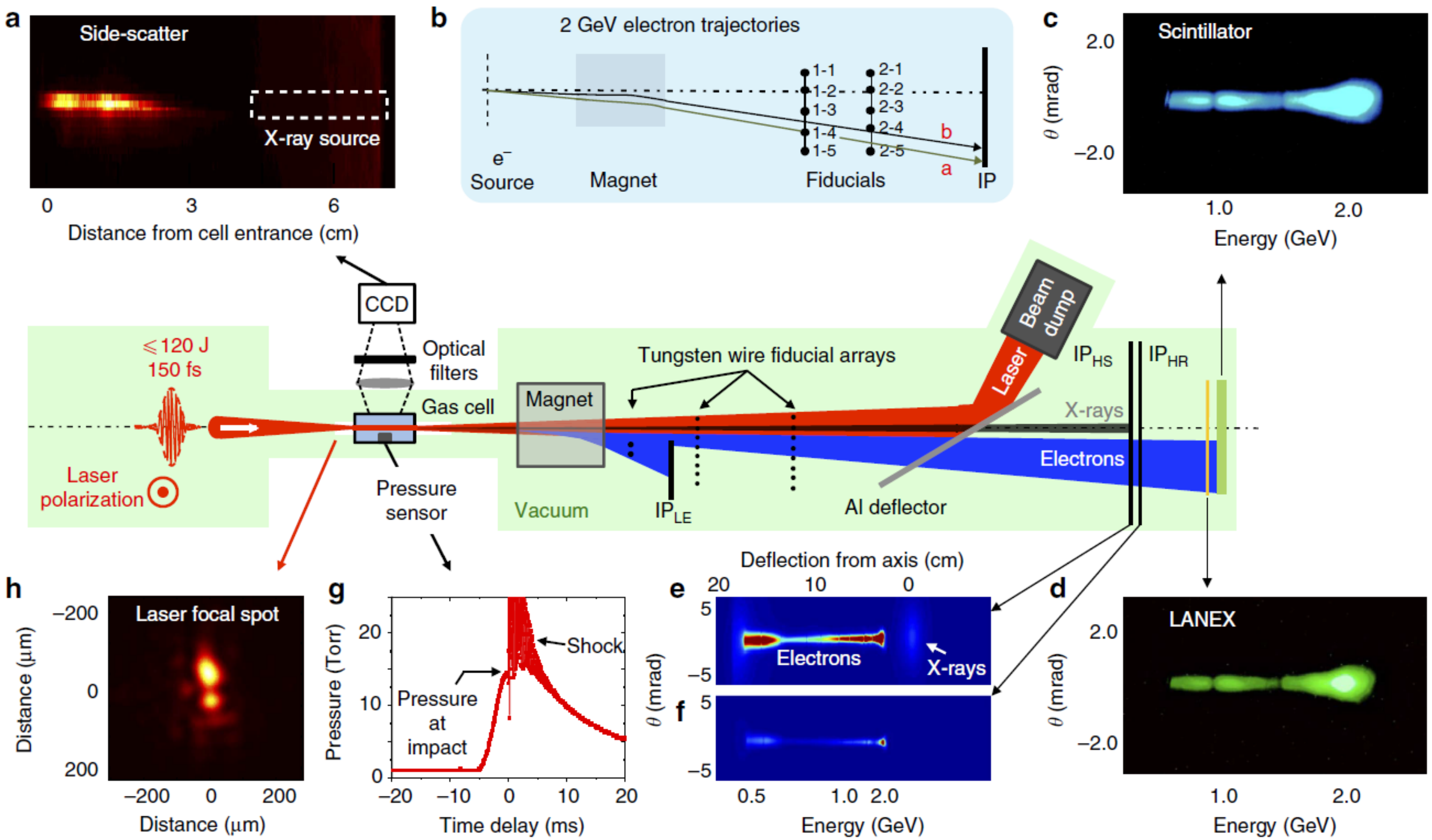
Ref: S. Ackermann *et al.,* Phys. Rev. Lett. **111**, 114801 (2013)

Laser plasma accelerator (LPA)



- Compared to conventional accelerator:
  high acceleration gradient (~ 1 GeV/cm, three orders of magnitude higher)
  short pulse duration (~ 3 fs, three orders of magnitude shorter)

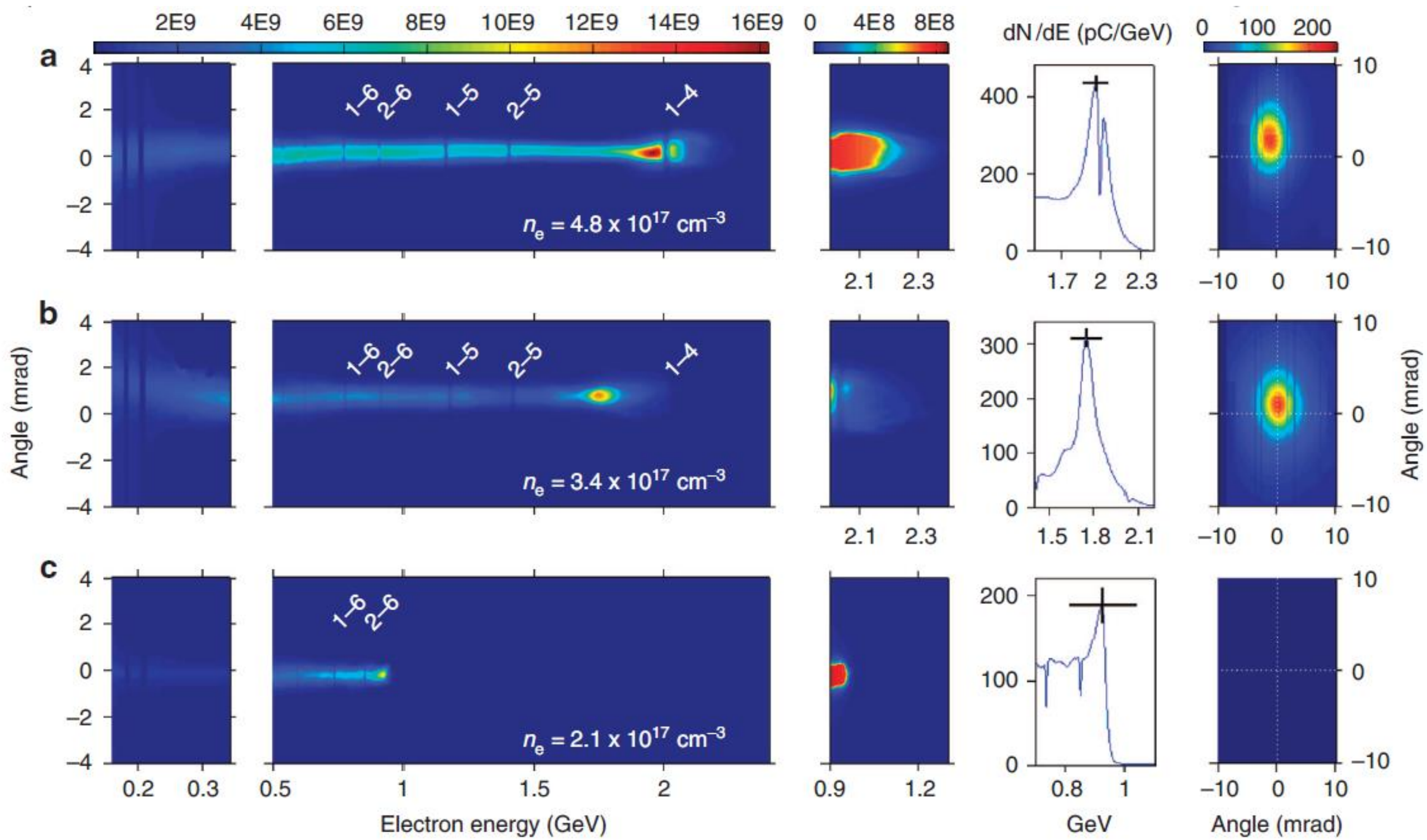
PW laser-driven LPA @University of Texas, Austin



Laser parameter:
1.057 μm, 1.1 PW (170 J, 150 fs)

Ref: X. Wang *et al.,* Nat. Comm. **4** Article number: 1988 (2013)

PW laser-driven LPA @University of Texas, Austin



e-beam: 2 GeV, 540 pC, 0.5 mrad divergence
10% energy spread

Ref: X. Wang *et al.,* Nat. Comm. **4** Article number: 1988 (2013)

4.2 GeV electron beam driven by LPA @LBNL

Selected for a Viewpoint in *Physics*

PRL **113,** 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

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Multi-GeV electron beams with energy up to 4.2 GeV, 6% rms energy spread, 6 pC charge, and 0.3 mrad rms divergence have been produced from a 9-cm-long capillary discharge waveguide with a plasma density of $\approx 7 \times 10^{17}$ cm^{-3}, powered by laser pulses with peak power up to 0.3 PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. A detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.

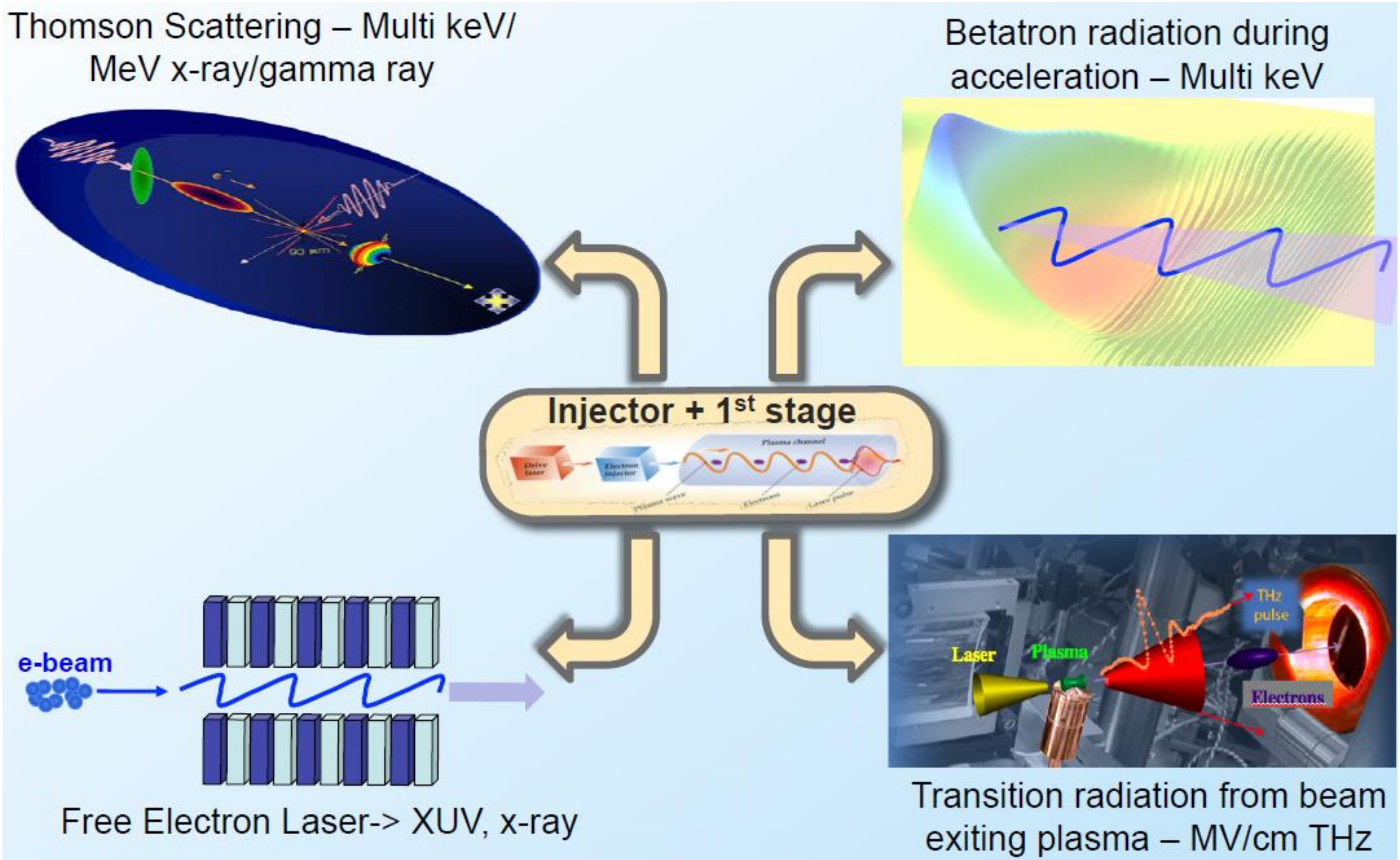
DOI: 10.1103/PhysRevLett.113.245002 PACS numbers: 52.38.Kd

BELLA Laser: 815 nm, 0.3 PW (16 J, 40 fs)

e-beam: 4.2 GeV, 6 pC, 0.3 mrad divergence
6% energy spread

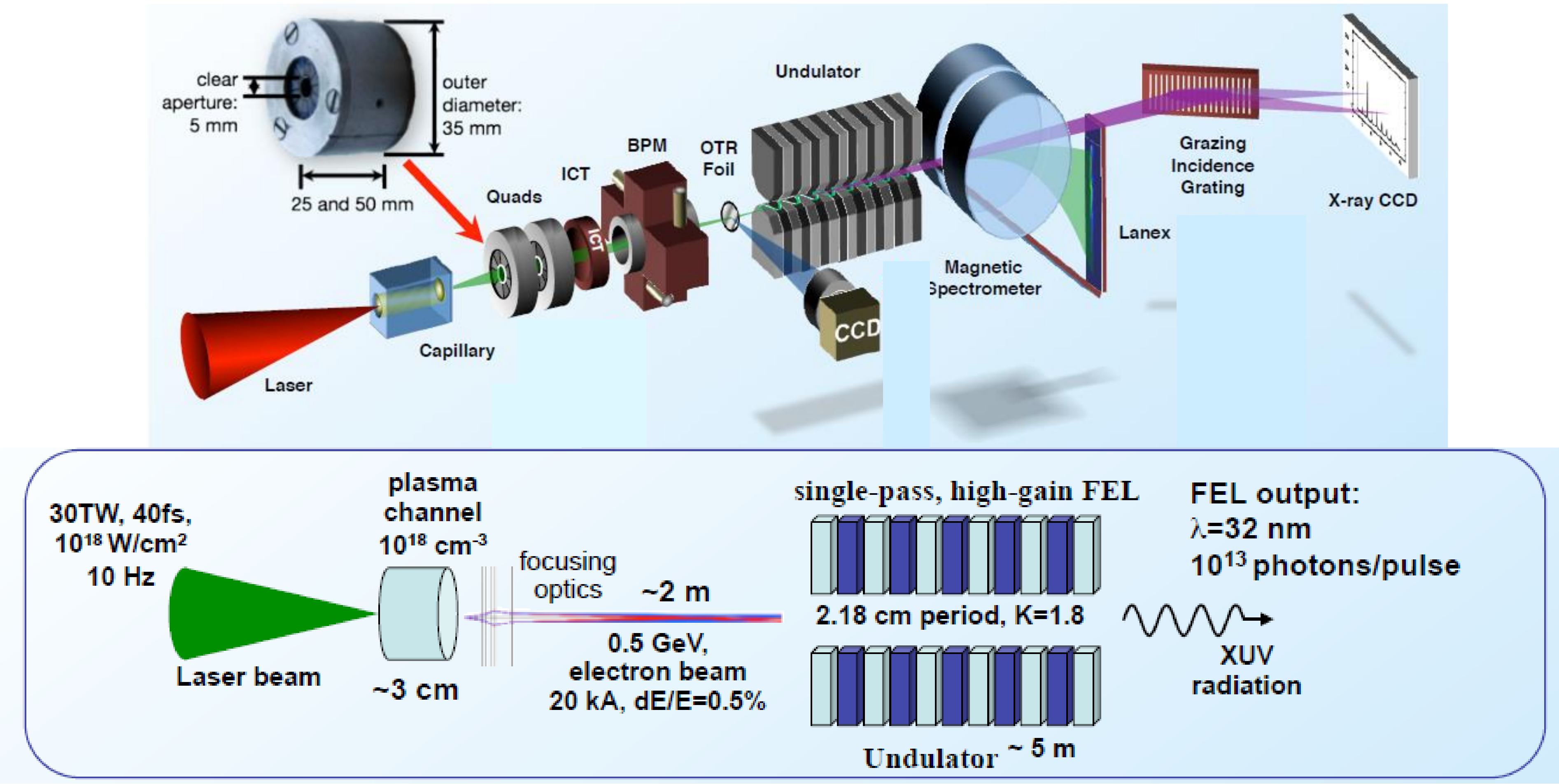
Ref: W.P. Leemsns *et al.,* Phys. Rev. Lett. **113,** 245002 (2014)

Radiation from THz to gamma ray driven by LPA



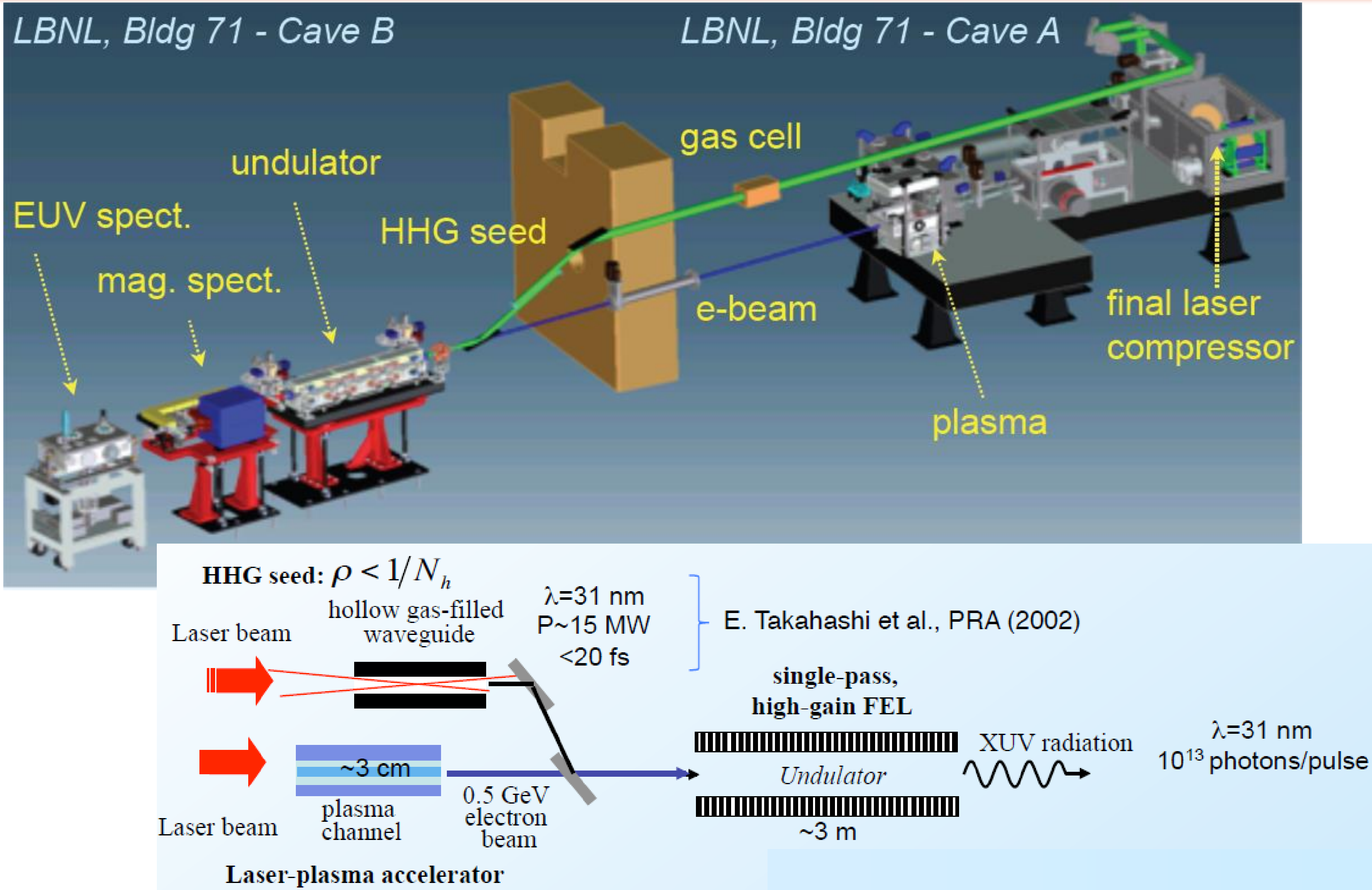
curtsy of Dr. W.P. Leemans

LPA driven XUV FEL @LBNL



curtsy of Dr. Carl B. Schroeder

HHG-seeded XUV FEL @LBNL



curtsy of Dr. W.P. Leemans

國家同步輻射研究中心
National Synchrotron Radiation Research Center

Thank you!