IPAC14

Advanced Concepts and Challenges in Compton Radiation Sources

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OUTLINE

INTRODUCTION

HIGH-BRIGHTNESS COMPTON GAMMA SOURCES

INTRA-CAVITY HIGH-REPETITION COMPTON SOURCES

- **High-Finesse Super-Cavities**
- **Active Laser Cavity**

ALL-OPTICAL COMPTON SOURCES BASED ON PLASMA ACCELERATORS

- **Plasma Accelerators**
- **Radiation from a Plasma Accelerator**
- **All-Optical Compton Sources**
- **Towards Compton FEL**

OTHER RESEARCH OPPORTUNITIES

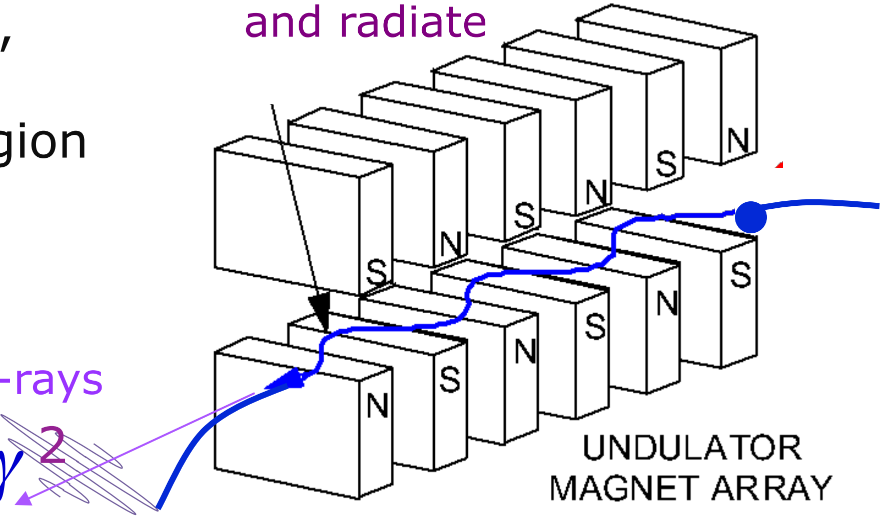
- **Continuum of Compton Harmonics**
- **Channeled Compton Sources**
- **Colliding Laser Pulses**

CONCLUSIONS

Synchrotron light source

With λ_w ~ several centimeters, attaining XUV region requires electron energy in the GeV region delivered by a stadium-size accelerator.

$\lambda_x = \lambda_w / 2\gamma^2$



Electrons wiggle and radiate

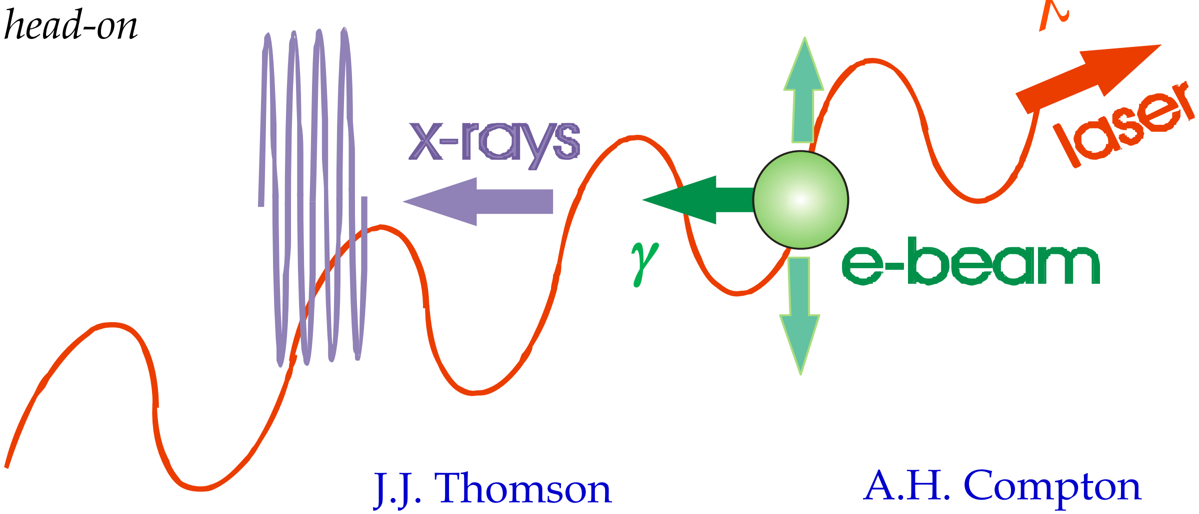
X-rays

UNDULATOR MAGNET ARRAY

Laser – a virtual wiggler

Scattered photon satisfies undulator equation with period λ/2 for head-on collisions

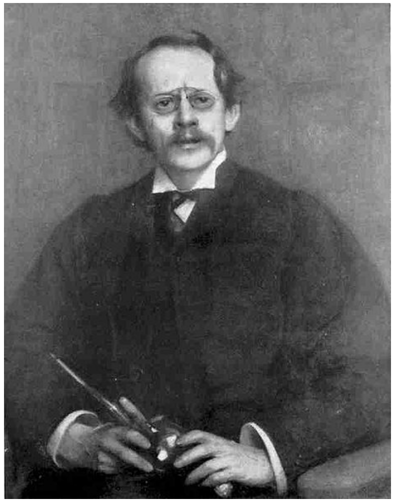
$$\lambda_x = \lambda / 4\gamma^2$$



Advantages of a Laser Synchrotron Source:

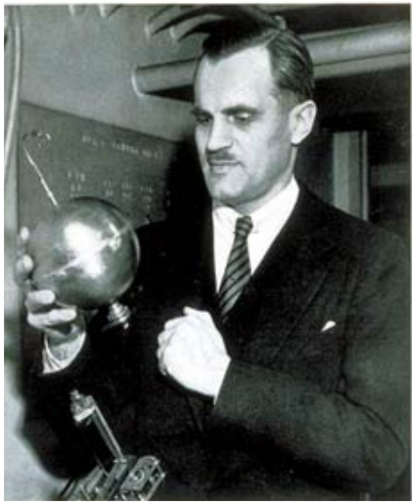
- access to hard-x-ray and gamma regions with a **compact linac**
- polarization control
- femto-second pulses
- ultra-high peak brightness

J.J. Thomson



@ $h\nu << mc^2$

A.H. Compton

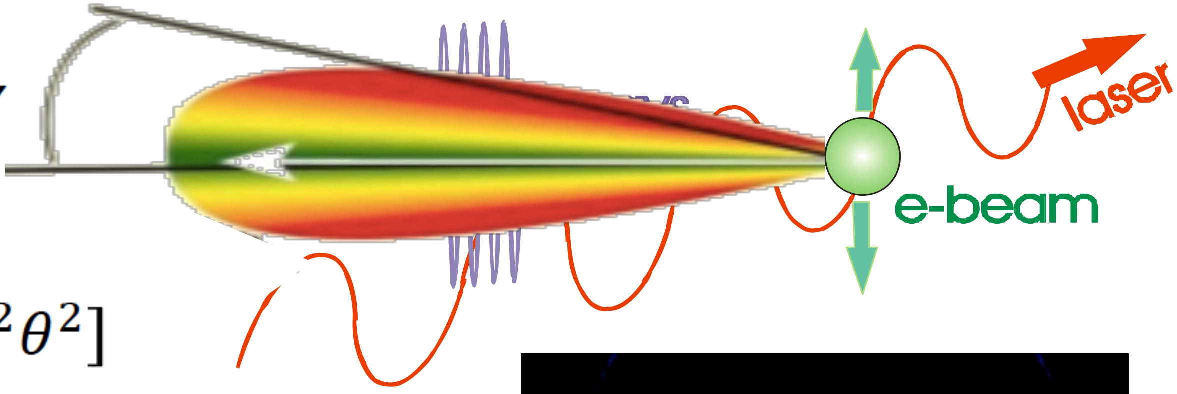


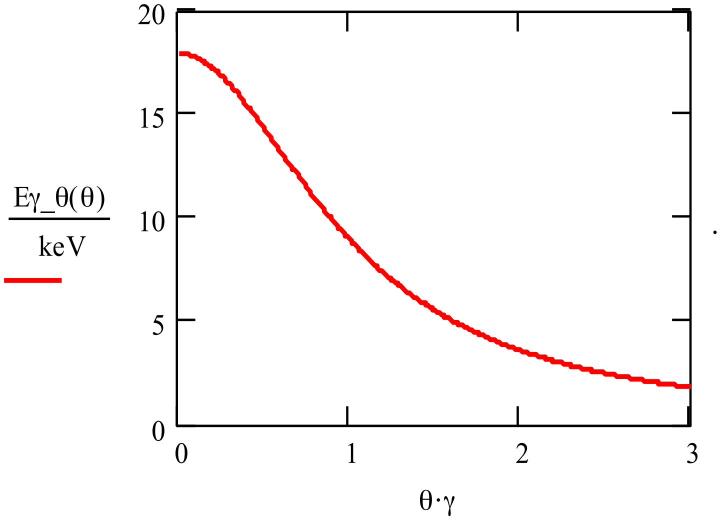
@ $h\nu \sim mc^2$

Properties

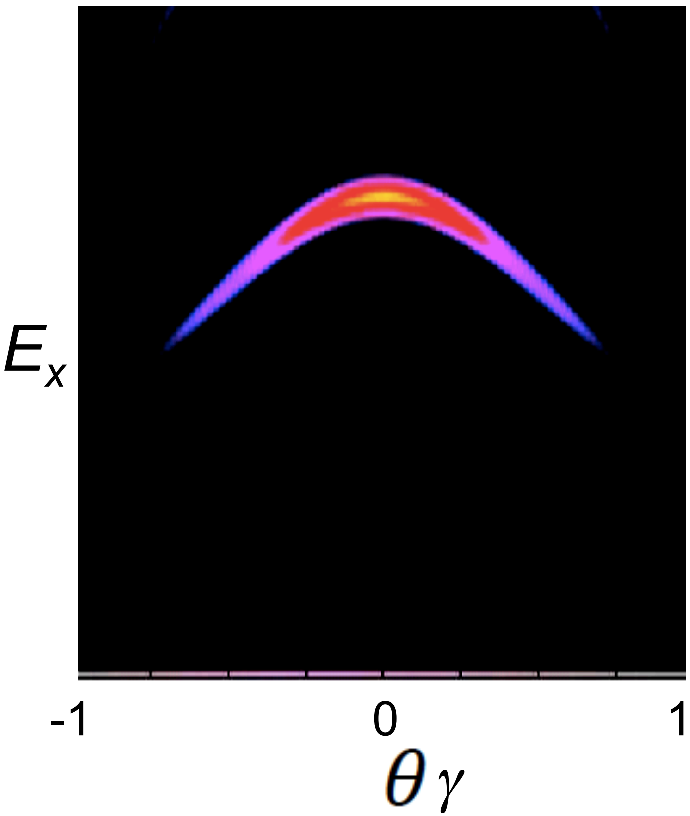
$$\theta_0 = {}^{1}/_{\gamma}$$

$$\lambda_x \approx \frac{\lambda_L}{4\gamma^2}\left[1 + \gamma^2\theta^2\right]$$



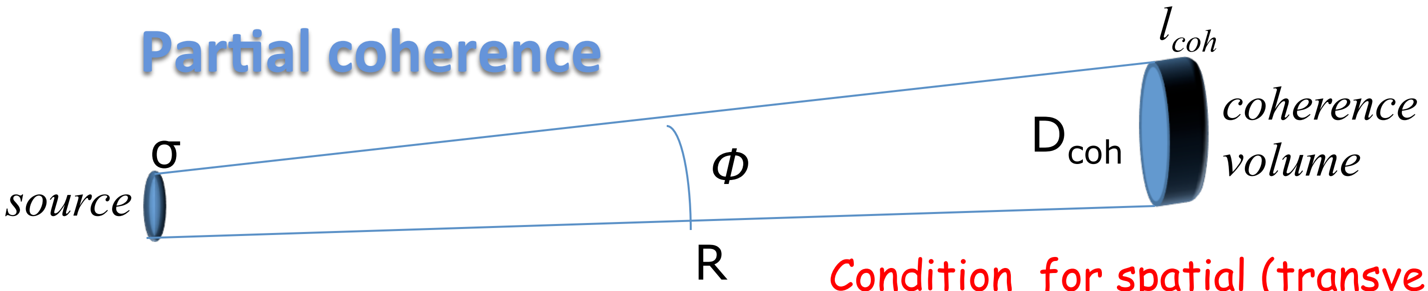


Azimuthal distribution of spectral density



Spatial coherence

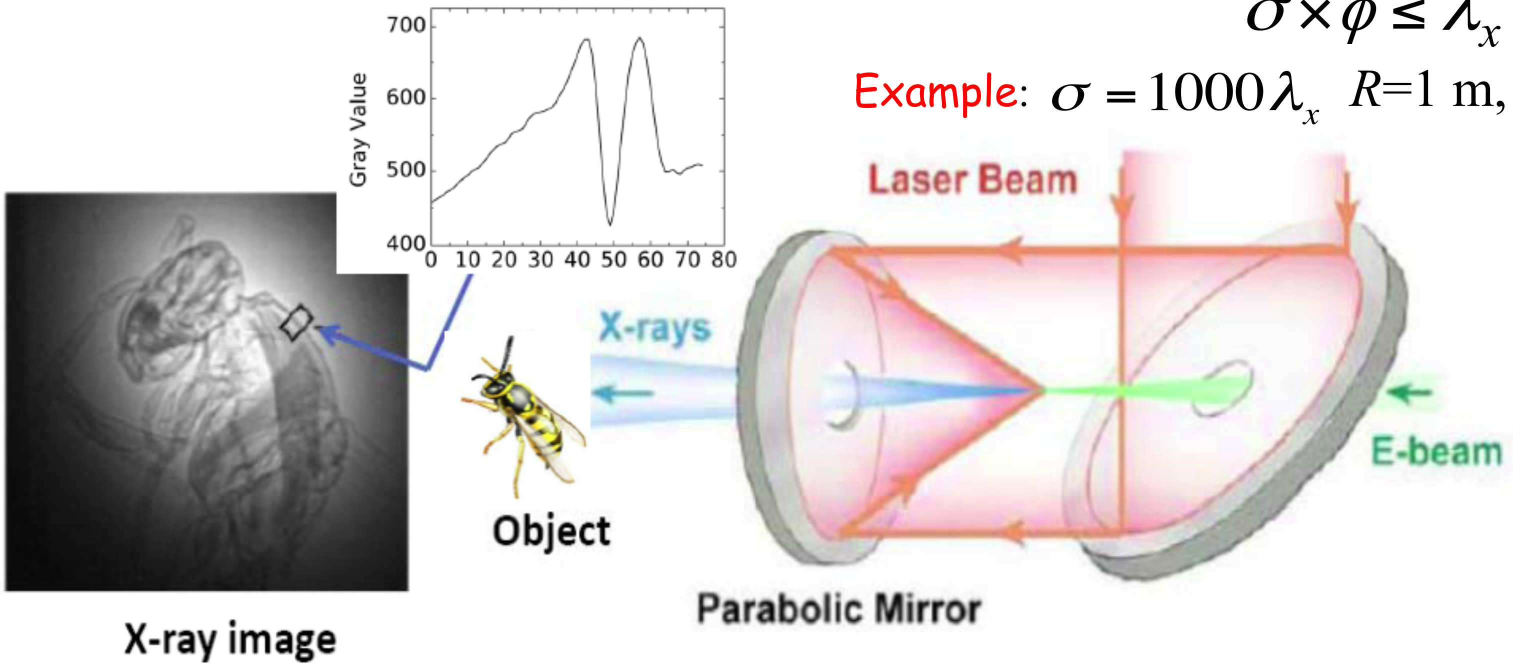
Partial coherence



Condition for spatial (transverse) coherence

$$\sigma \times \phi \leq \lambda_x$$

Example: $\sigma = 1000\lambda_x$ R=1 m, D=1 mm

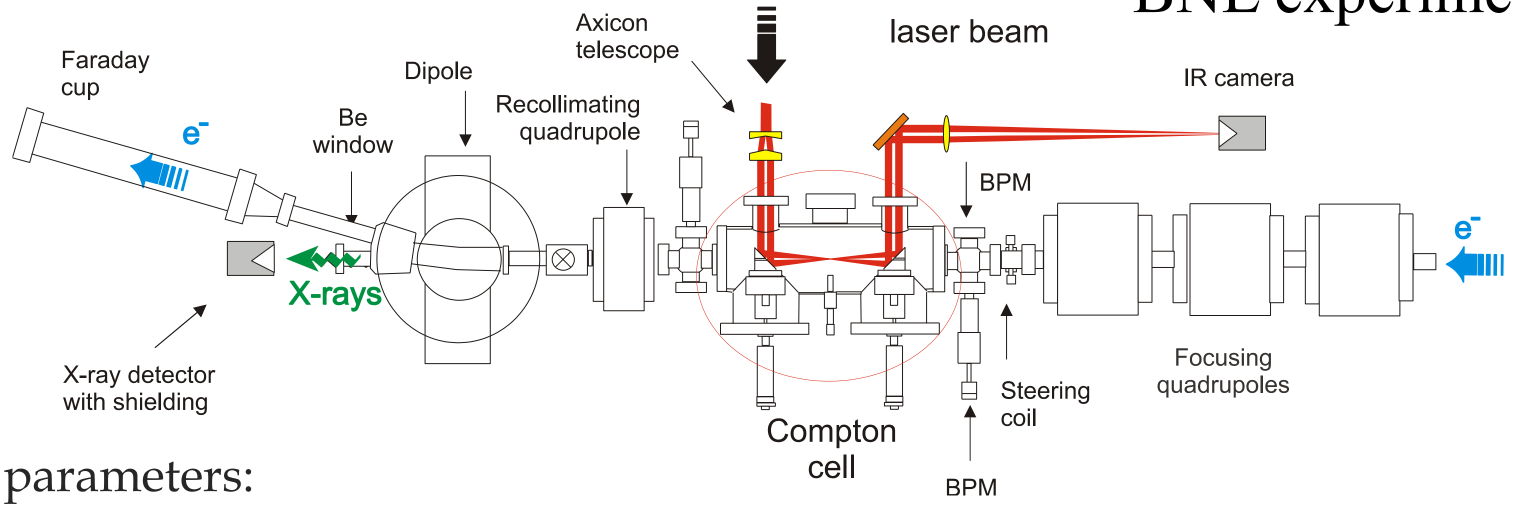


Single-shot phase-contrast X-ray image with 1-ps exposure

P. Oliva, et al, Appl. Phys. Lett. 97, 134104 (2010).

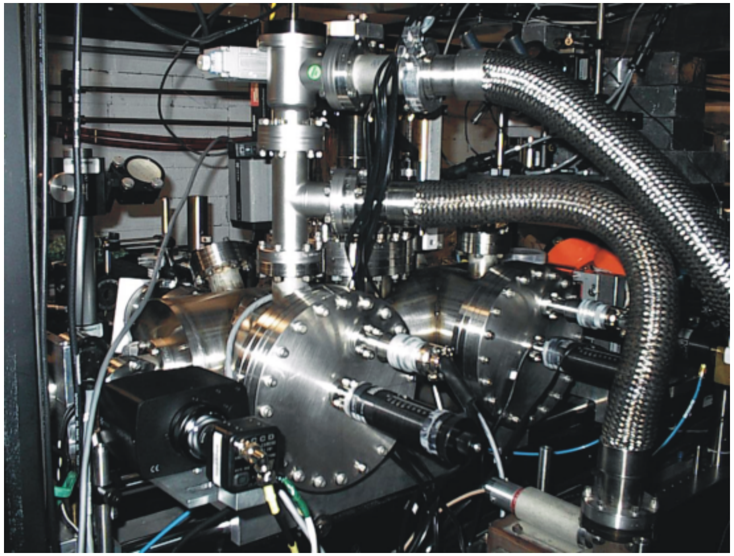
Photon Yield and Brightness

BNL experiment



Laser parameters:

$\tau = 5$ ps, $E = 5$ J, $P = 1$ TW, focused to $\sigma = 35\ \mu$m,

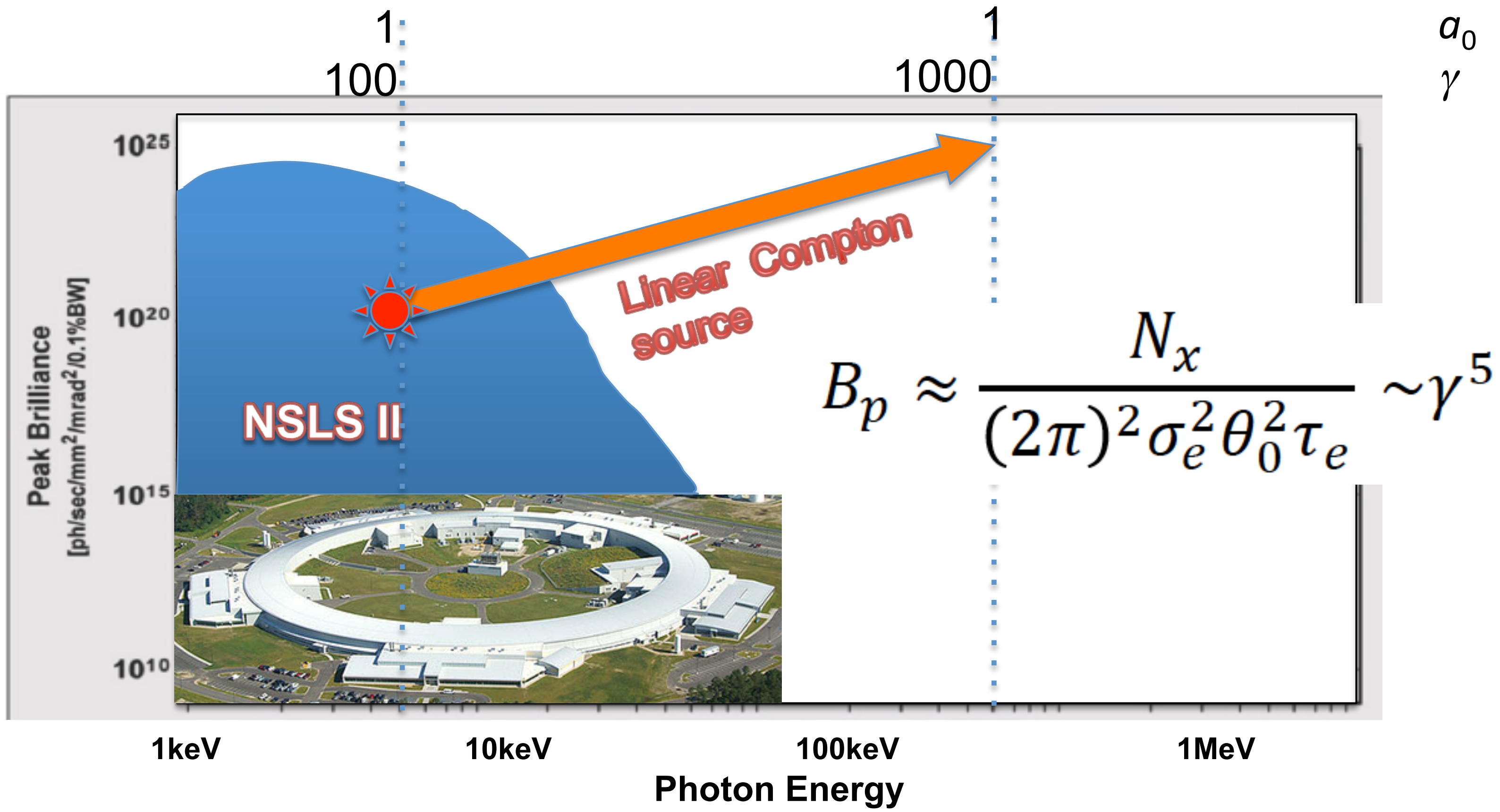


$$N_x = \frac{N_e N_L \sigma_T}{2\pi\sigma_L^2} \qquad \frac{N_x}{N_e} \sim 1$$

$$B_p \approx 1.5\times10^{-3}\frac{N_x\gamma^2}{(2\pi)^2\sigma_e^2\tau_e}$$

10^{20} ph/s-mm^2-mrad^2-0.1%BW

Peak Brightness

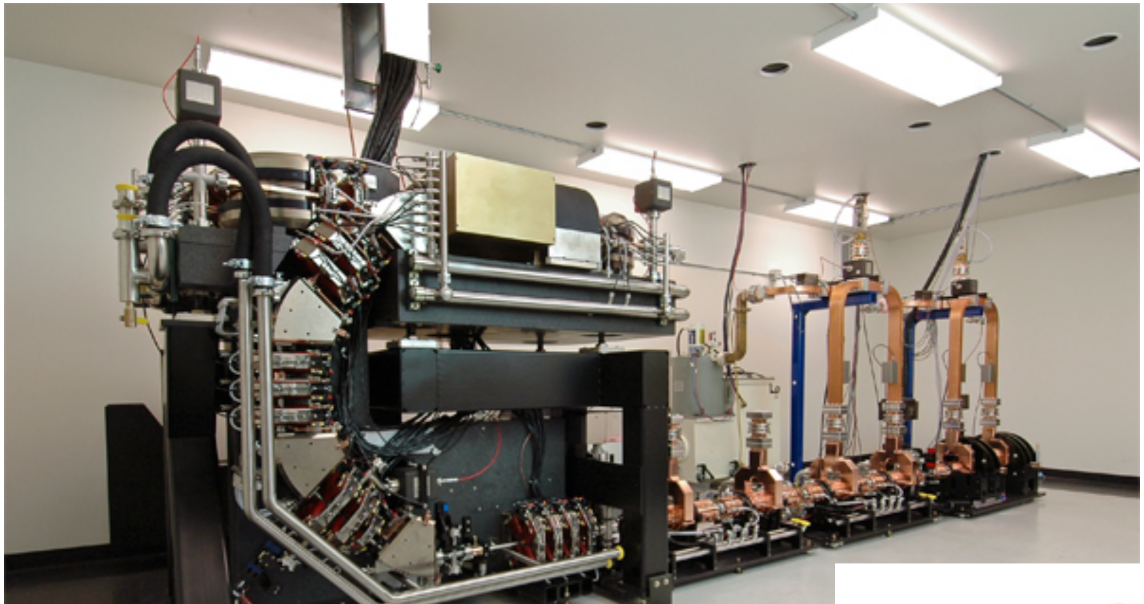


$$B_p \approx \frac{N_x}{(2\pi)^2 \sigma_e^2 \theta_0^2 \tau_e} \sim \gamma^5$$

- *Peak* brightness comparable to 3rd-generation Synchrotron Light Sources (SLSs) in *x-ray* region, and become unsurpassed by other techniques in the *gamma* range.
- *Average* brightness of Compton sources is orders-of-magnitude below that of the SLSs. This limits their potential for application.

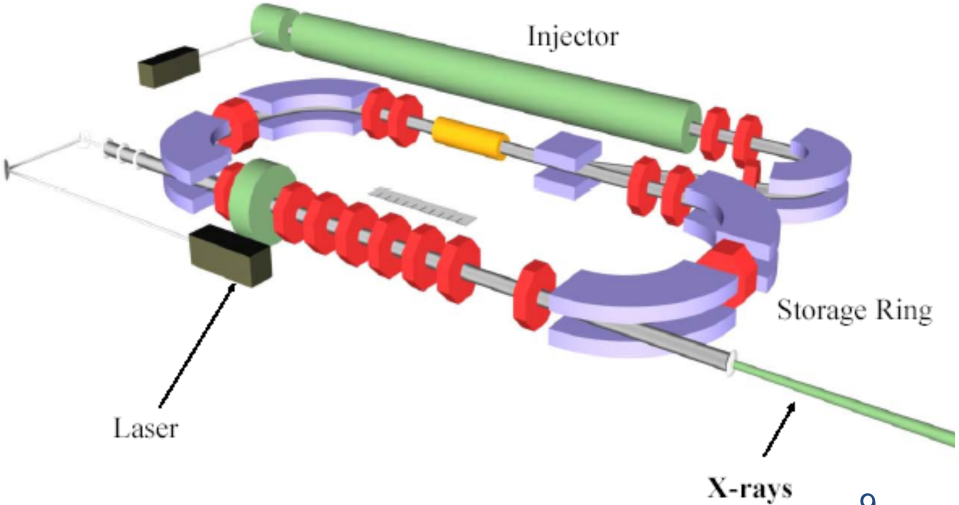
Compact light source

by Lyncean Technologies, Inc.



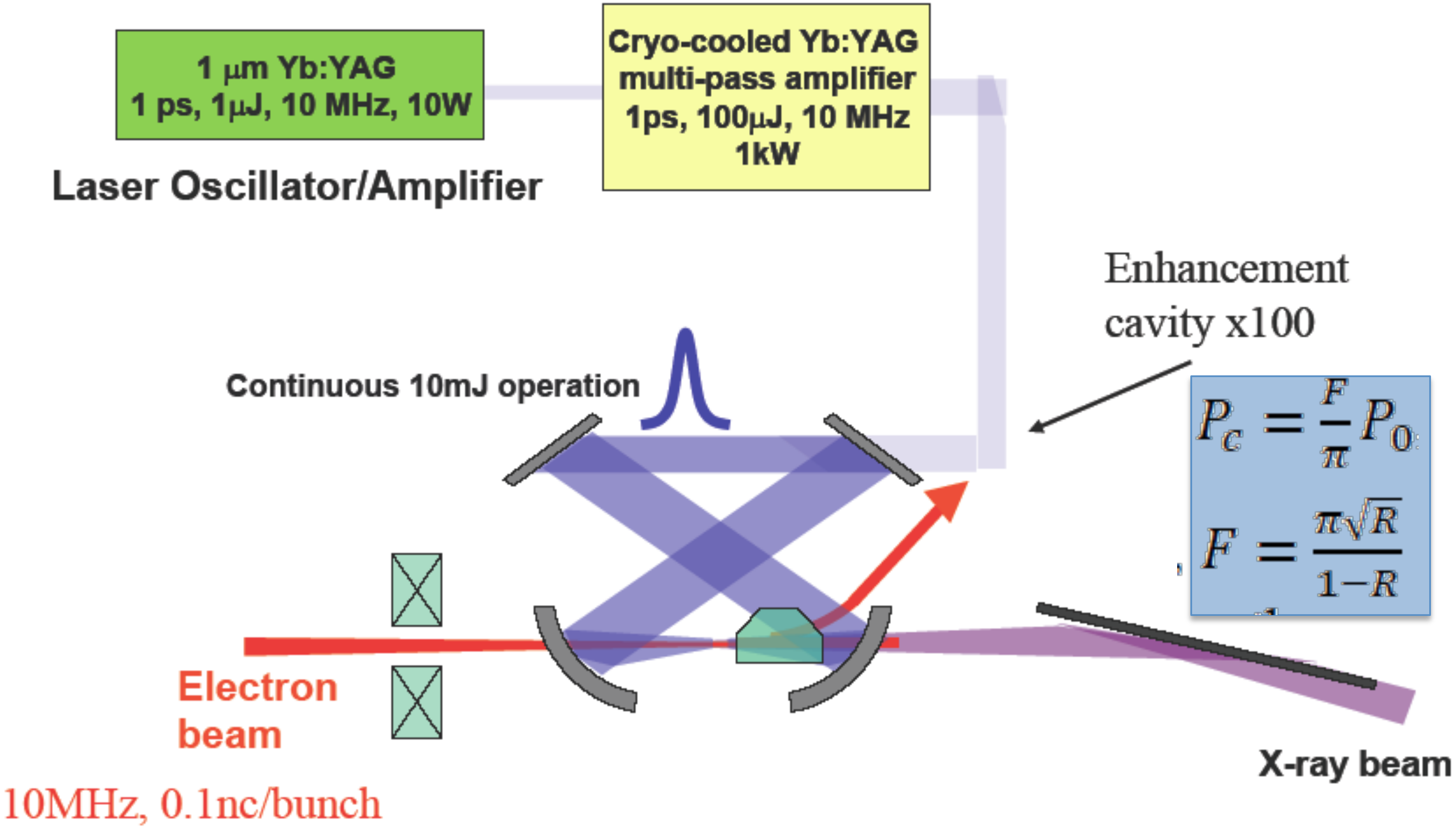
$$B_{avg} = B_p f \tau_e$$

$B_{avg}=10^{12}$ ph/s-mm^2-mrad^2-0.1%BW



Used for crystallography and phase-contrast imaging

Super-cavity Compton source (MIT)



1 µm Yb:YAG
1 ps, 1µJ, 10 MHz, 10W

Laser Oscillator/Amplifier

Cryo-cooled Yb:YAG
multi-pass amplifier
1ps, 100µJ, 10 MHz
1kW

Enhancement
cavity x100

$$P_c = \frac{F}{\pi} P_0$$

$$F = \frac{\pi\sqrt{R}}{1-R}$$

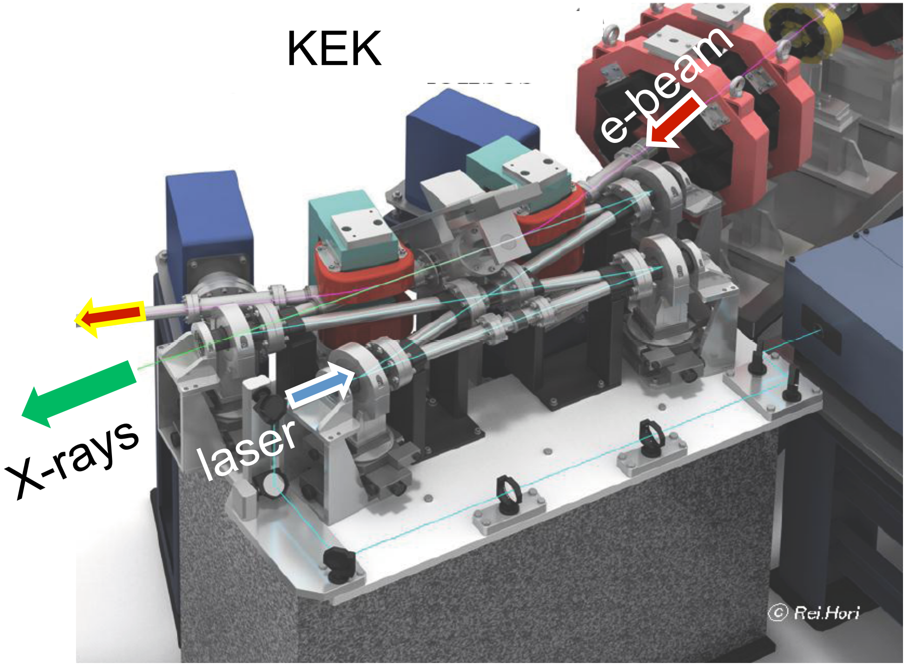
Continuous 10mJ operation

Electron beam

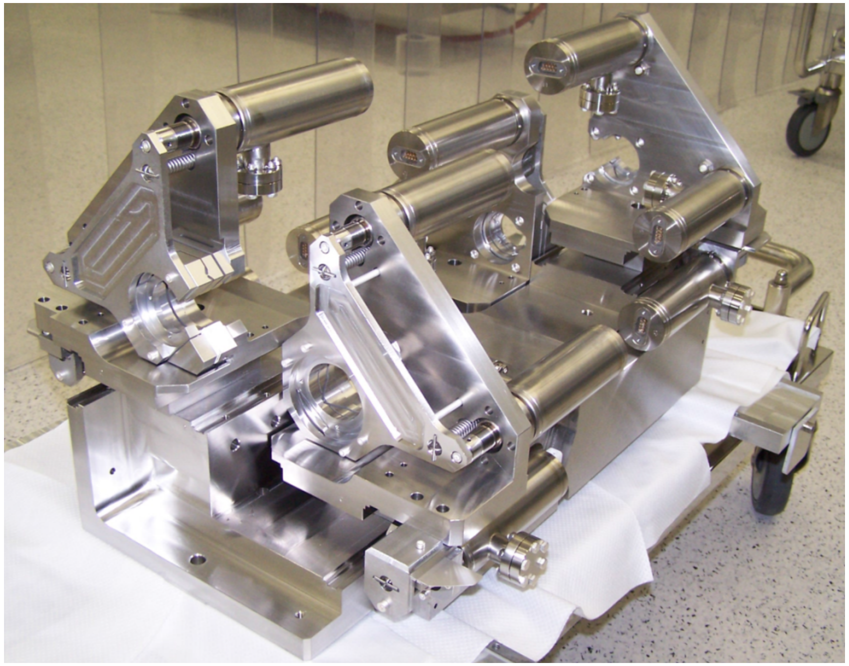
10MHz, 0.1nc/bunch

X-ray beam

Super-cavity Compton source (KEK and LAL)



Laboratoire de l'Accélérateur Linéaire

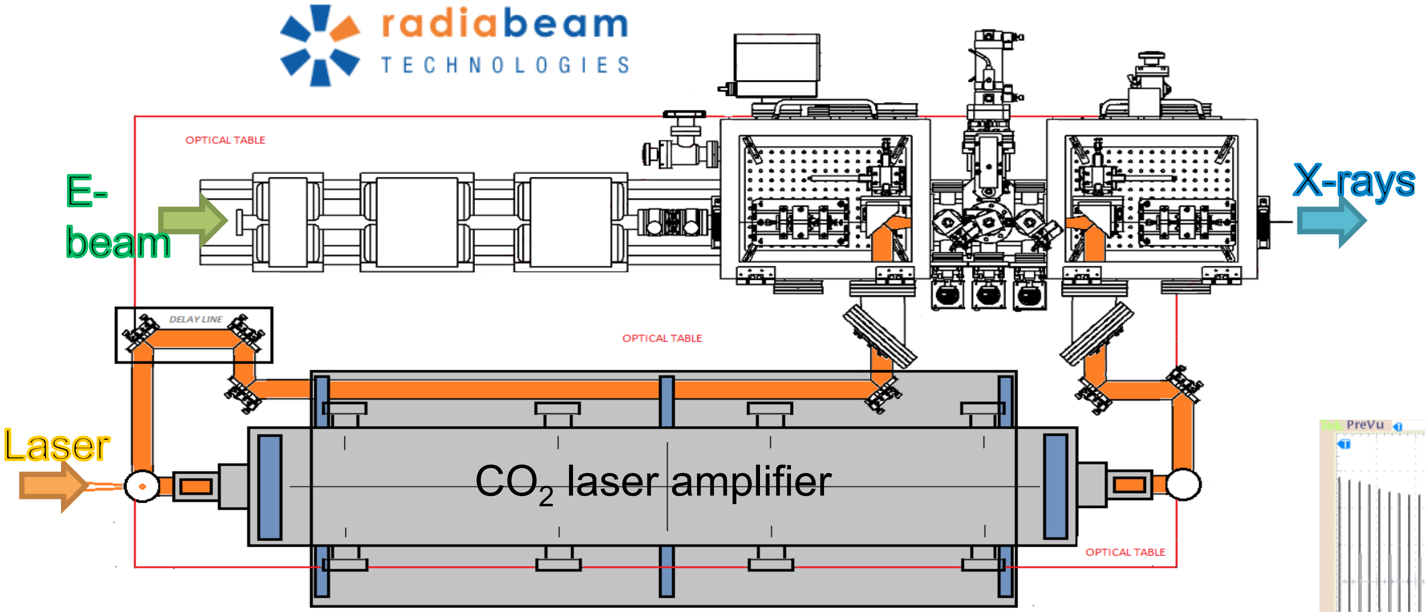


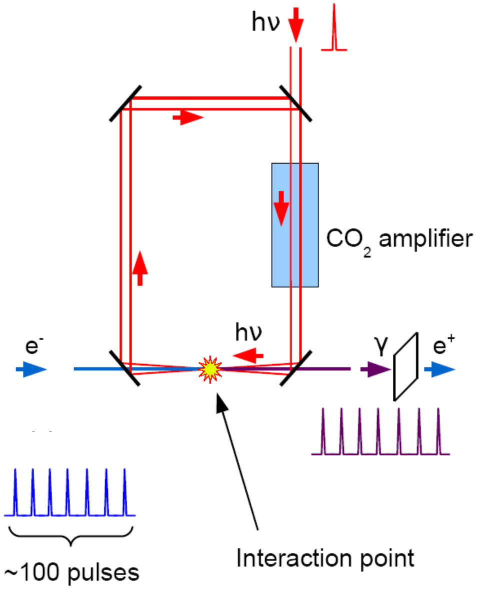
- Prospects for $B_{ave}=10^{13}-10^{14}$ photons/s-mm^2-mrad^2-0.1%BW (comparable with 2nd generation SLSs) upon the cavity finesse increase to 10,000.
- However, the extreme tolerances to the components' stability and alignment, the optical-diffraction losses, and reduced efficiency of crossed-beam interaction (compared to counter-propagation) make this goal very challenging.

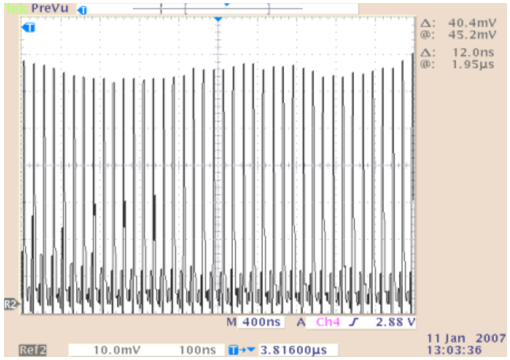
Intra-cavity Compton source (BNL)

- 25 ns cavity round trip = spacing between electron bunches.
- 100 interactions per a laser shot

- E-beam - 0.5 nC/bunch
- E-beam – 60 MeV
- CO_2 Laser - 0.5 J/pulse
- X-ray– 6.4 keV







- Demonstrated total laser energy - 30 J
- Expected photons per train in 0.1%BW - $4x10^7$
- Peak brightness - $3x10^{18}$ (ph/s-mm²-mrad² -0.1%BW)

High-repetition CO_2 laser

CO_2 laser:

• Pressure	10 atm
• Repetition Rate	1 kHz
• Average Power	1 kW

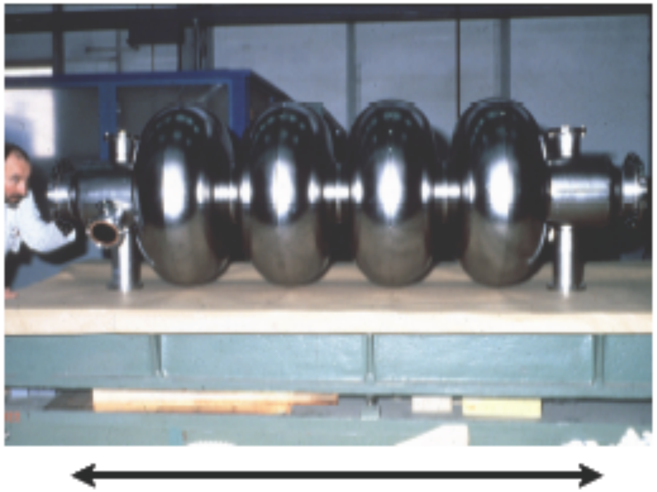
X-ray (γ-rays):

- Prospective $B_{ave} = 10^{13}$ @10keV
  to 10^{19} @10MeV
  (ph/s-mm^2-mrad^2 -0.1%BW)

It is anticipated that compact light sources affordable to any university will make a similar impact as PCs complementing main-frame computers.

Plasma accelerators

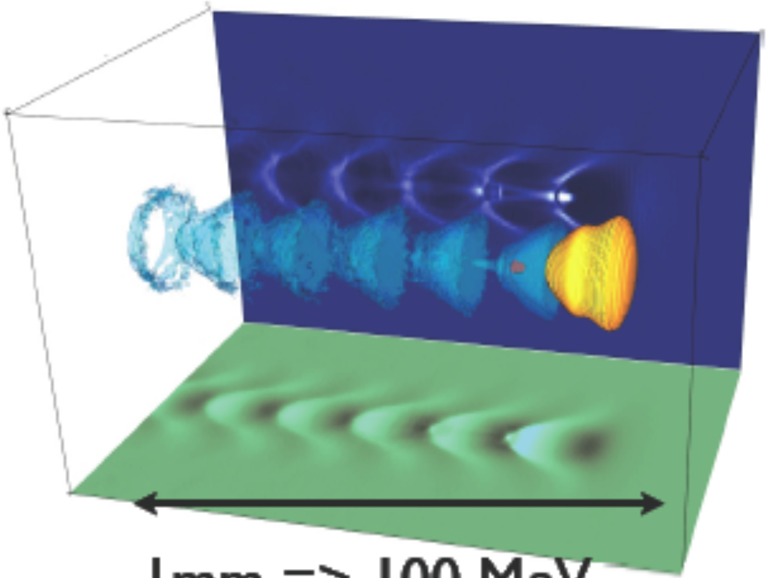
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

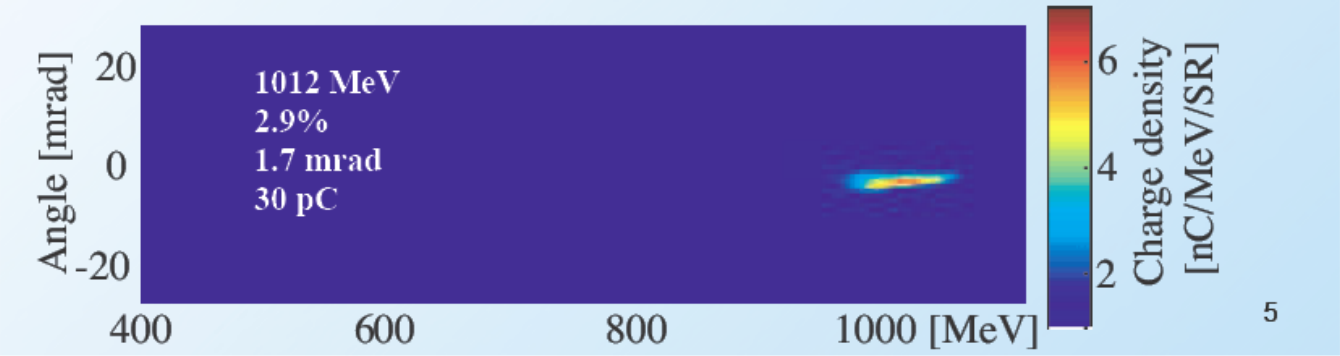
Plasma Cavity



1mm => 100 MeV

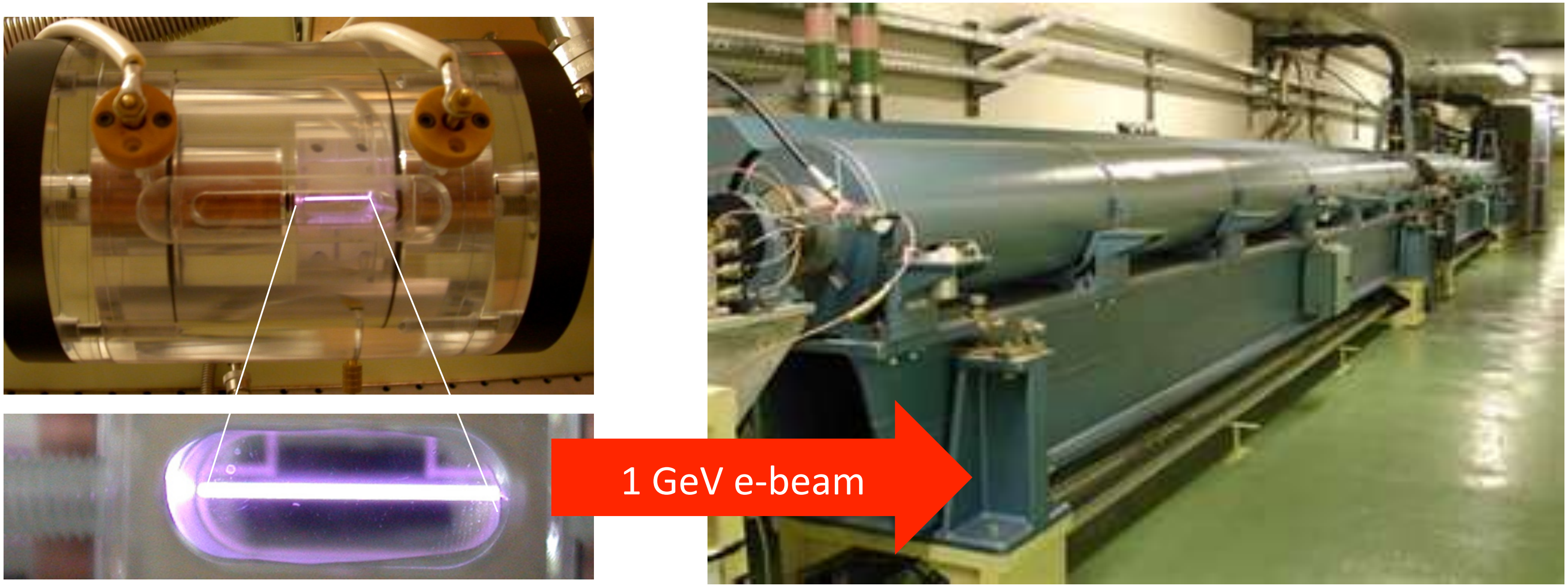
Electric field > 100 GV/m

Laser wake field accelerator (LWFA)

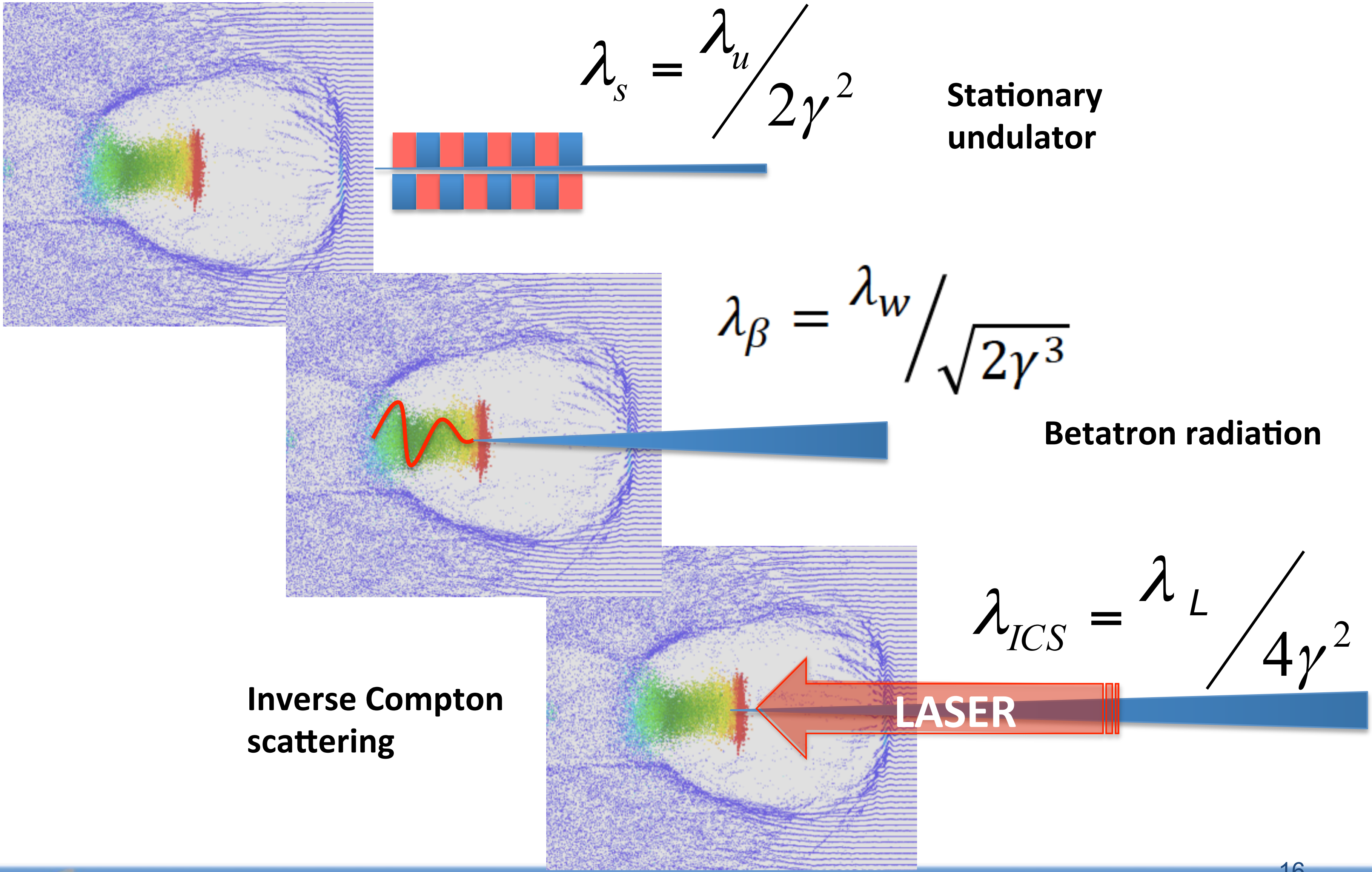


ΔE ~ 0.5%

ε_n~ 1 mrad



LWFA synchrotron sources



$$\lambda_s = \lambda_u / 2\gamma^2$$

Stationary undulator

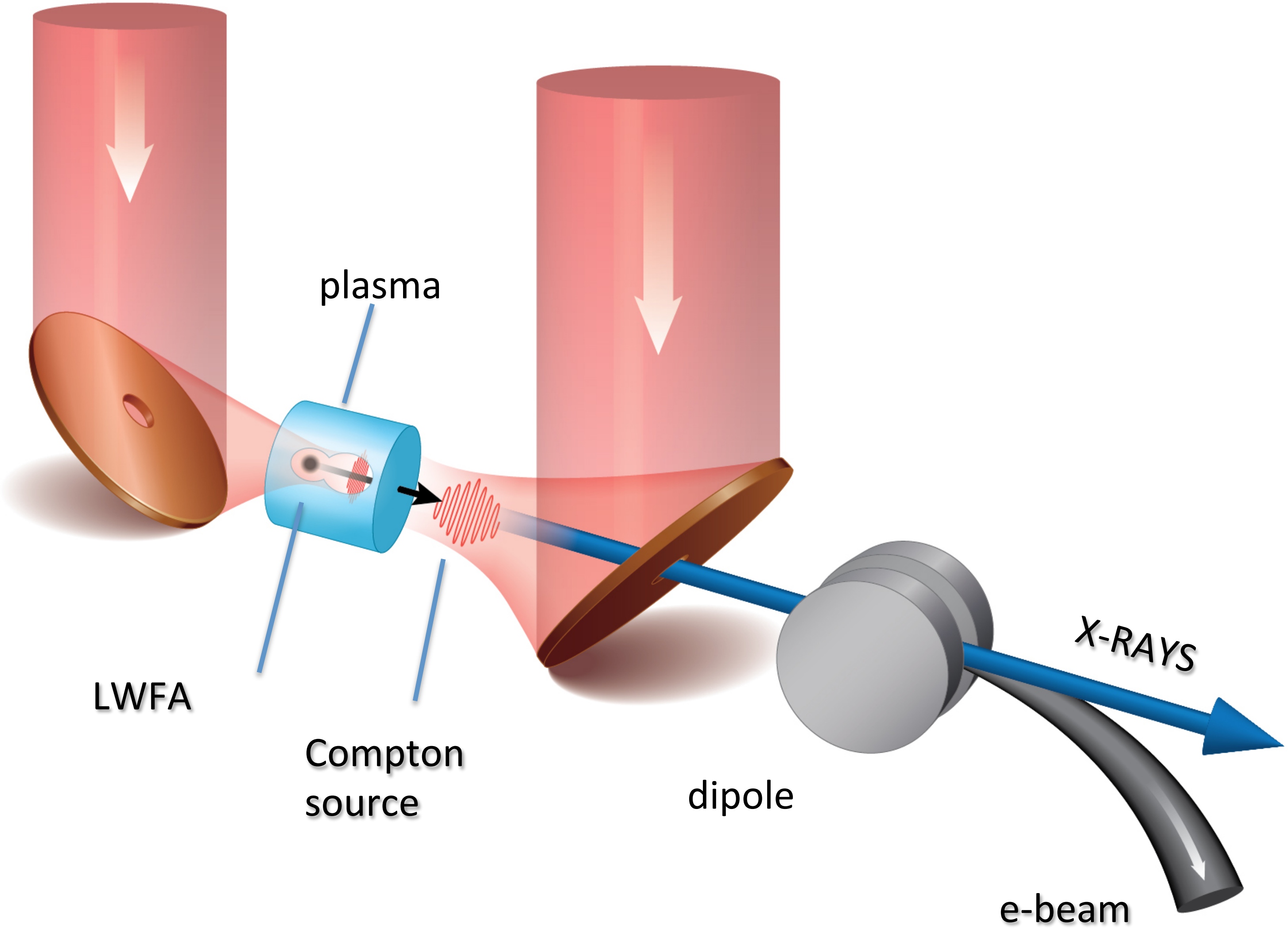
$$\lambda_\beta = \lambda_w / \sqrt{2\gamma^3}$$

Betatron radiation

$$\lambda_{ICS} = \lambda_L / 4\gamma^2$$

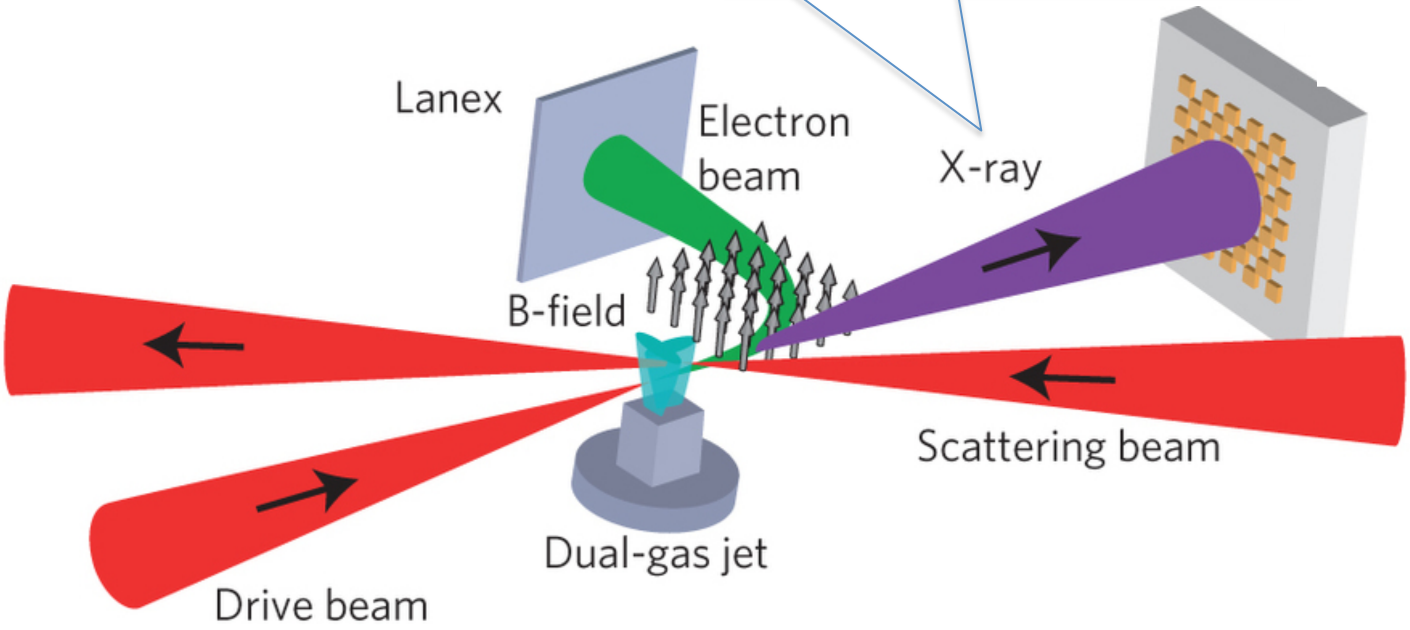
Inverse Compton scattering

All-optical Compton source



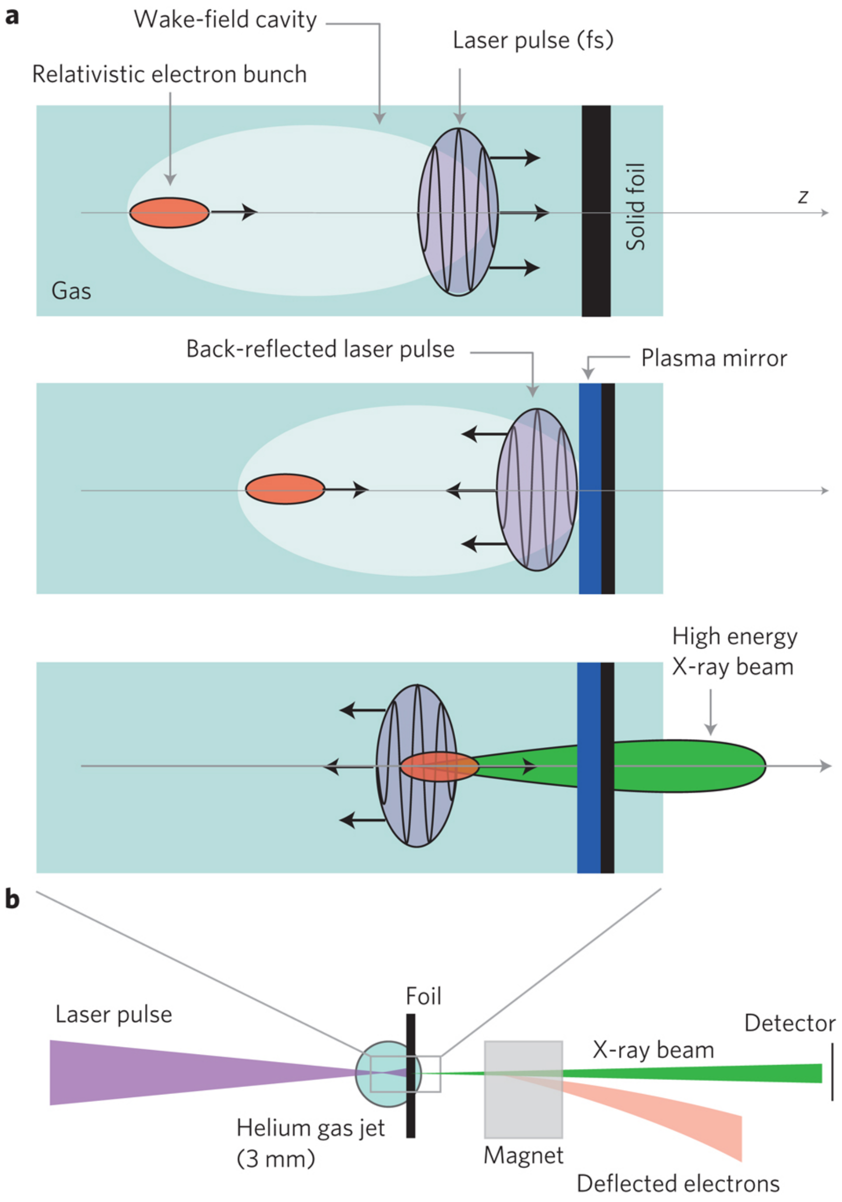
All-optical Compton source

Tunable 50 keV-1 MeV
Peak B=10^{19} (0.1%BW)
@ Charge 30 pC



NATURE PHOTONICS | VOL 8 | JANUARY 28 2014
University of Nebraska–Lincoln

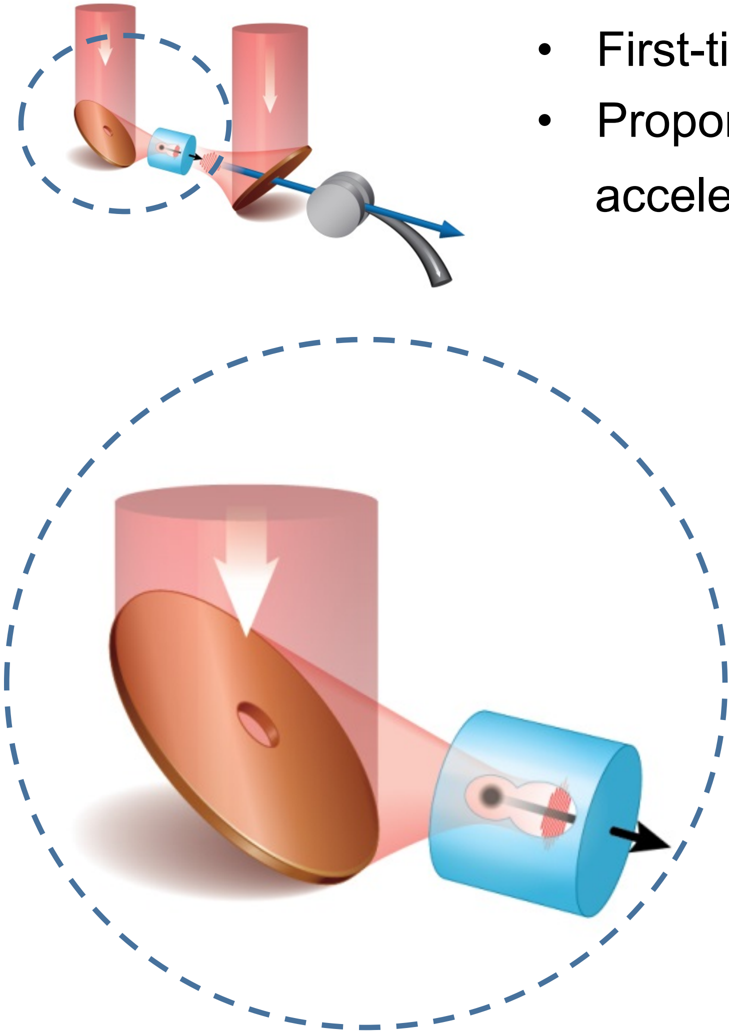
All-optical Compton source



- Interesting demonstration of the all-optical Compton source: The same laser that drives the LWFA e-beam was reflected by a foil at the side of the plasma jet to interact with the electron bunch producing Compton photons.
- Tuneable to 1 MeV at peak brightness, B_p=10^{21}.

K. Ta Phuoc et al., *Nature Photon*. **6**, 308 (2012)

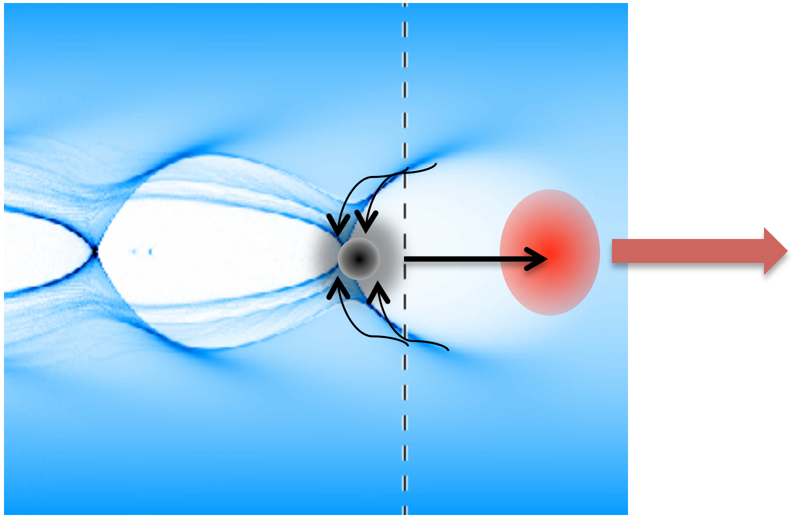
High-current bubble LWFA



Benefits from using prospective 100 TW CO_2 laser:

- First-time opportunity for bubble LWFA @ λ=10 μm.
- Proportional to λ increase of the bubble size allows higher accelerated charges

$$N_{mono} \approx \frac{1.8}{k_0 r_e}\left(\frac{P}{P_{rel}}\right)^{1/2} \approx 10^{11}$$ = 6 nC !



Courtesy of Wei Lu (Tsinghua Univ.)

All-optical Compton source

Benefits from using CO_2 laser:

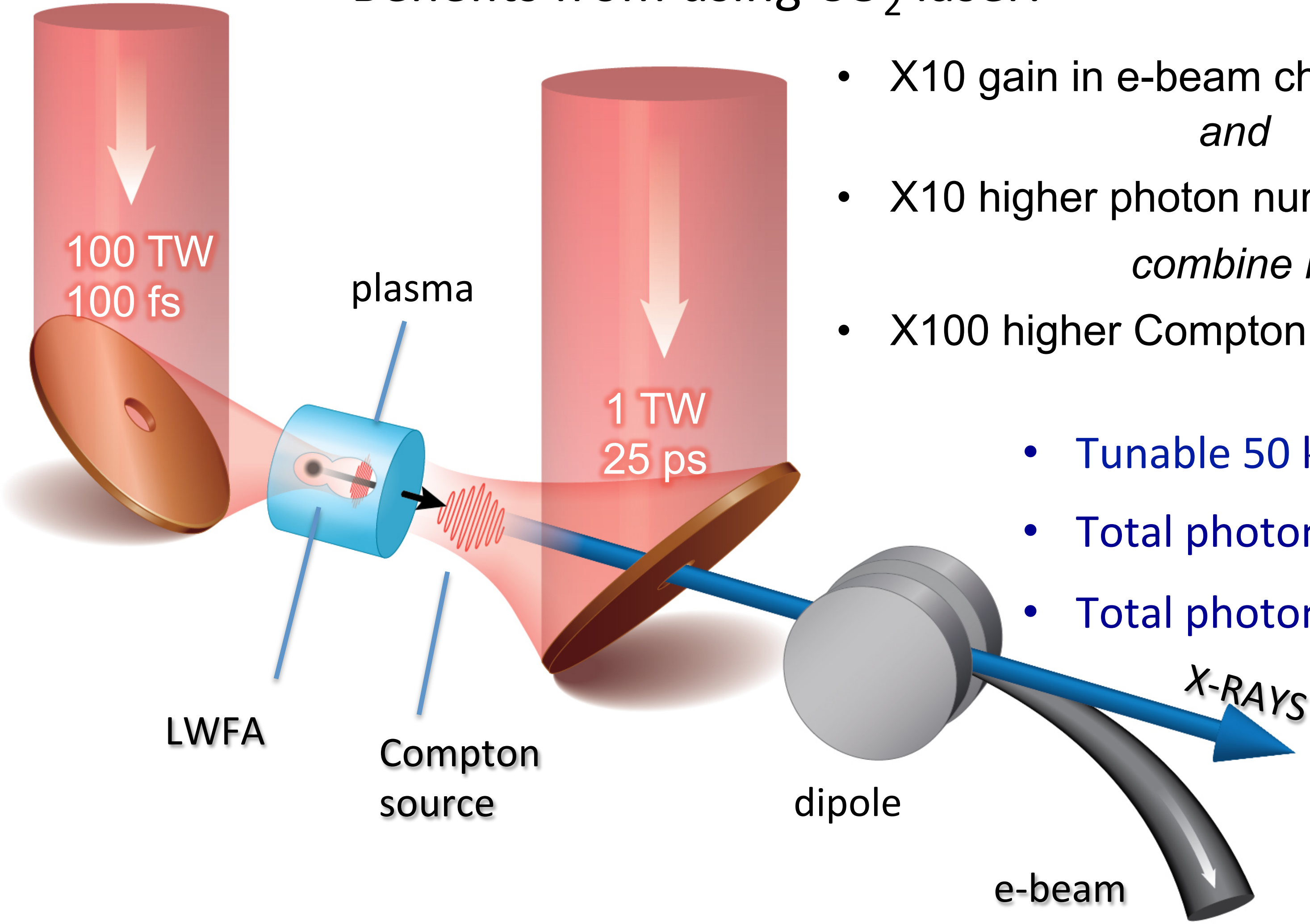
- X10 gain in e-beam charge

and

- X10 higher photon number per Joule

combine in

- X100 higher Compton yield



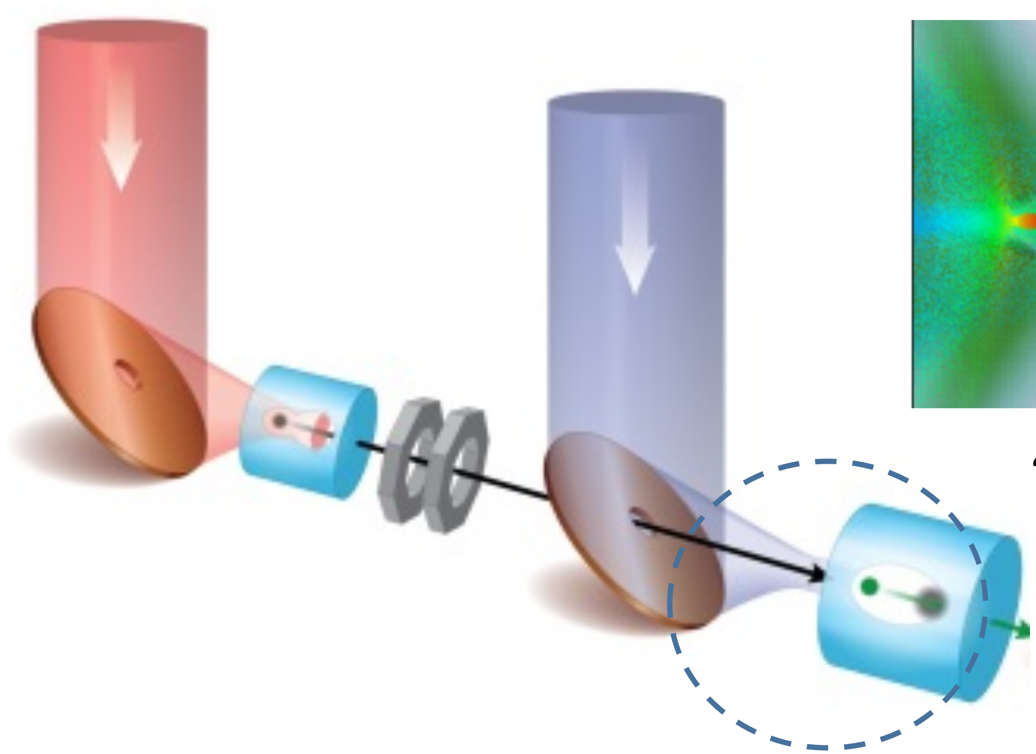
- Tunable 50 keV - 50 MeV
- Total photon yield 10^{11}
- Total photon flux 10^{24}/s

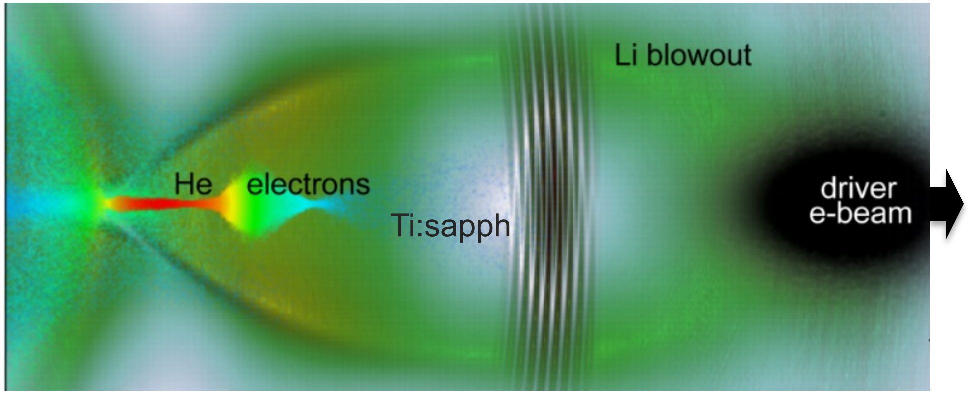
"Trojan Horse" PWFA

Path to low emittance:

− LWFA – *ponderomotive* action by a laser pulse results in electron heating to several MeV.

+ PWFA – electrons are expelled by the *Coulomb* force of the driver-bunch with negligible heating.



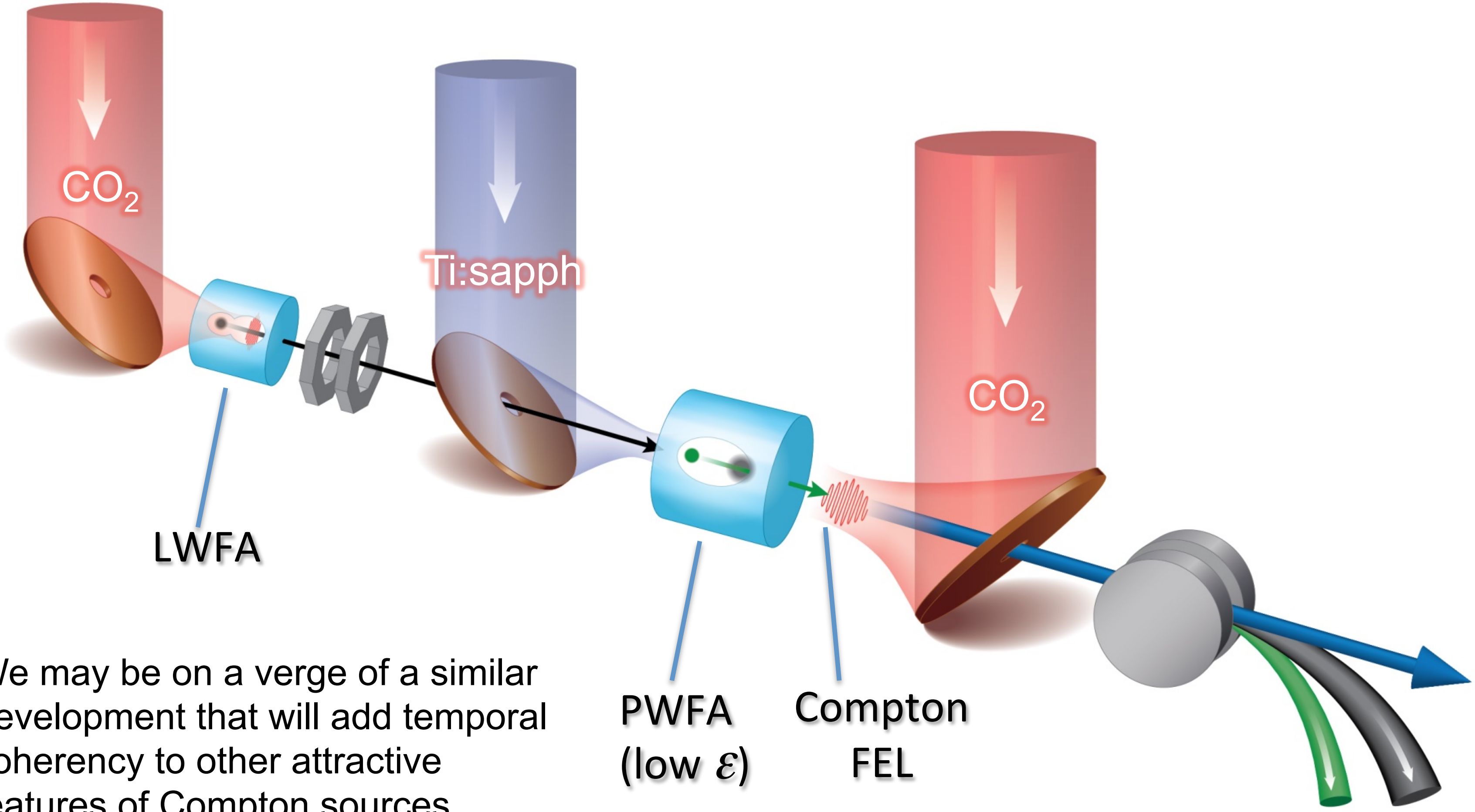


"Trojan Horse" – concept of brightness transformer predicts ε_n=30 nm

PRL **108**, 035001 (2012)

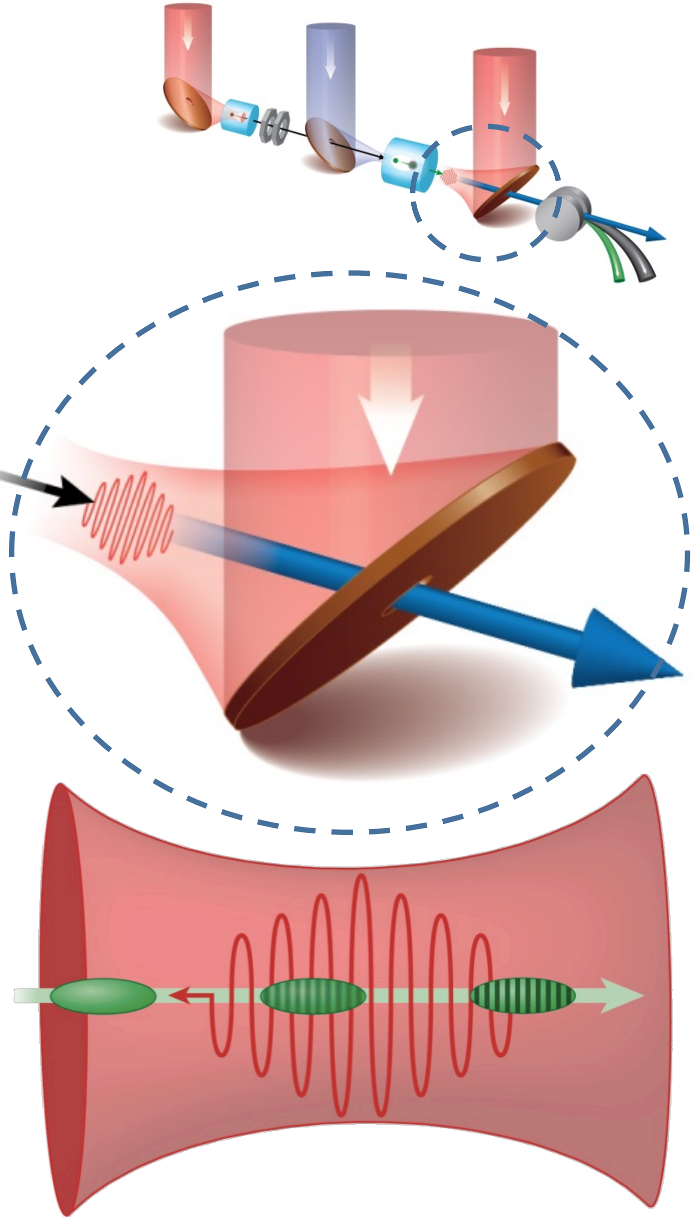
Concept of all-optical FEL

- Using low-emittance linacs, instead of synchrotrons, resulted in inception of 4th generation coherent light-sources – FELs.



- We may be on a verge of a similar development that will add temporal coherency to other attractive features of Compton sources.

Compton FEL



- Longer wavelength – higher gain

1^{st} example – RF linac;
PRST-AB **9**, 060704 (2006)

Electrons: 30 MeV, 3 nC, 3ps, $\Delta E/E=10^{-4}$, $\varepsilon_n=0.6$ μm

CO_2 laser: 100 GW, $a_0=0.3$, 100 ps

FEL: 7.6Å, $L_s=3$ cm, 10^{10} photons (X100 over incoherent),
2 MW, $B_{pk}=10^{26}$

2^{nd} example – plasma linac

Electrons: 30 MeV, 0.3 nC, 50fs, $\Delta E/E=10^{-2}$, $\varepsilon_n=0.03$ μm

CO_2 laser: 1TW, $a_0=0.5$, 10 ps

FEL: 7.6Å, $L_s=3$ mm, 10^9 photons, 30 MW, $B_{pk}=10^{27}$

Ponderomotive potential

Energy of the electron quiver motion in laser field E

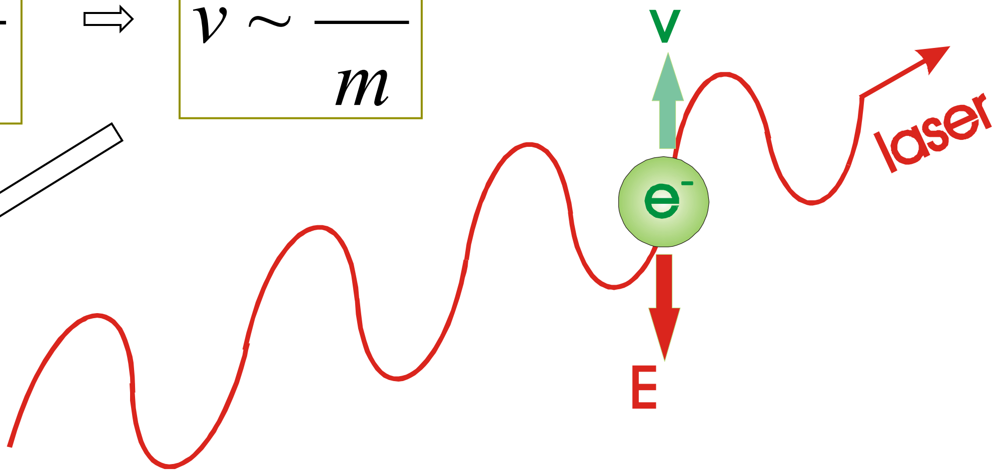
$$\boxed{\Phi = \frac{mv^2}{2}} \Rightarrow \boxed{v \sim \frac{\dot{v}}{\omega}} \Rightarrow \boxed{\dot{v} \sim \frac{eE}{m}}$$

$$\boxed{\Phi \sim \frac{e^2E^2}{2m\omega^2}}$$

$$\Downarrow$$

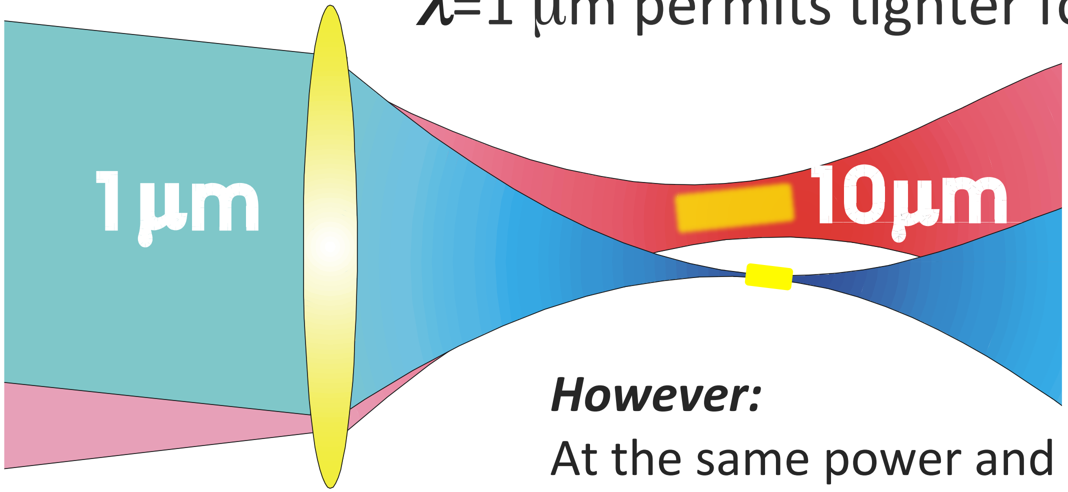
$$\boxed{\Phi \sim \frac{I}{\omega^2}}$$

note the ω^2 dependence



Access to nonlinear regime

λ=1 μm permits tighter focusing



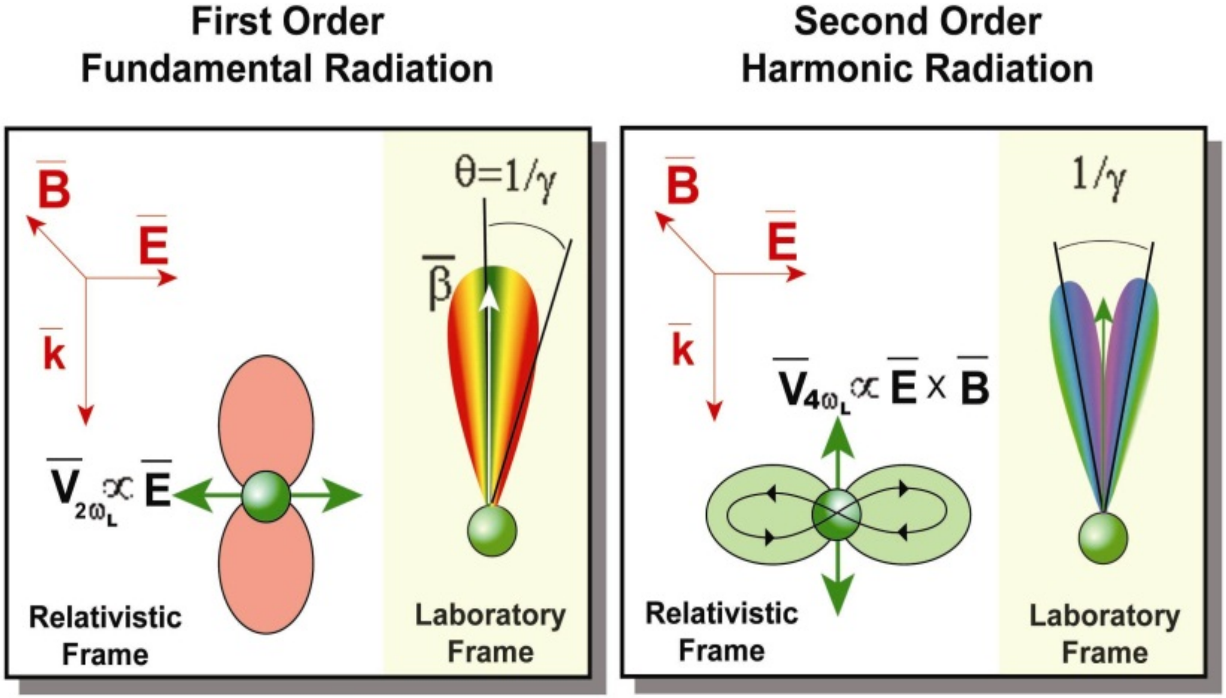
However:

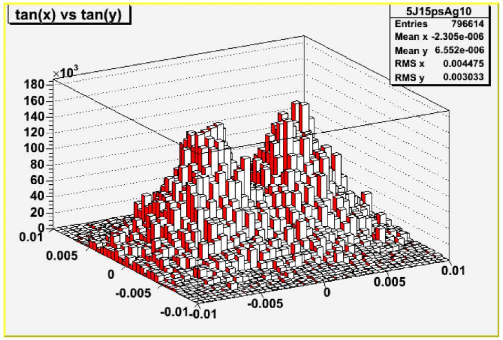
At the same power and energy, CO_2 laser provides the same ponderomotive action within ~λ^2 (100 times) bigger area or ~ λ^3 (1000 times) bigger volume.

Interacting with e-beam you do not want to focus laser tighter than e-beam (decreases acceleration quality or x-ray yield).
CO_2 laser focusing is sufficient to interact with low-emittance e-beams.

1 TW CO_2 laser could be equivalent to 1 PW solid state laser!

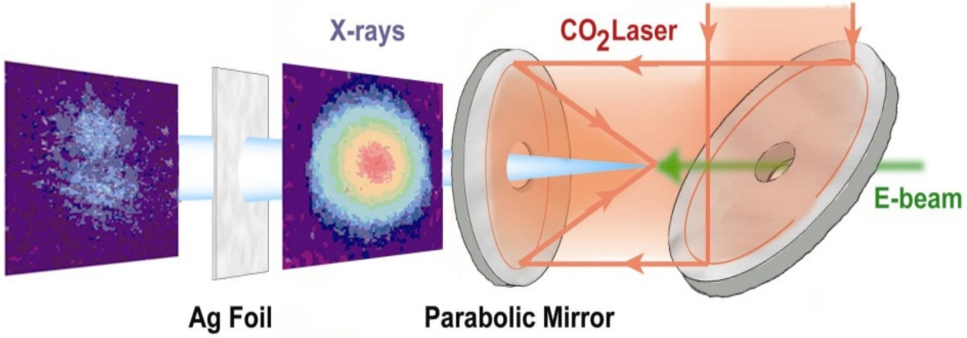
2nd harmonic



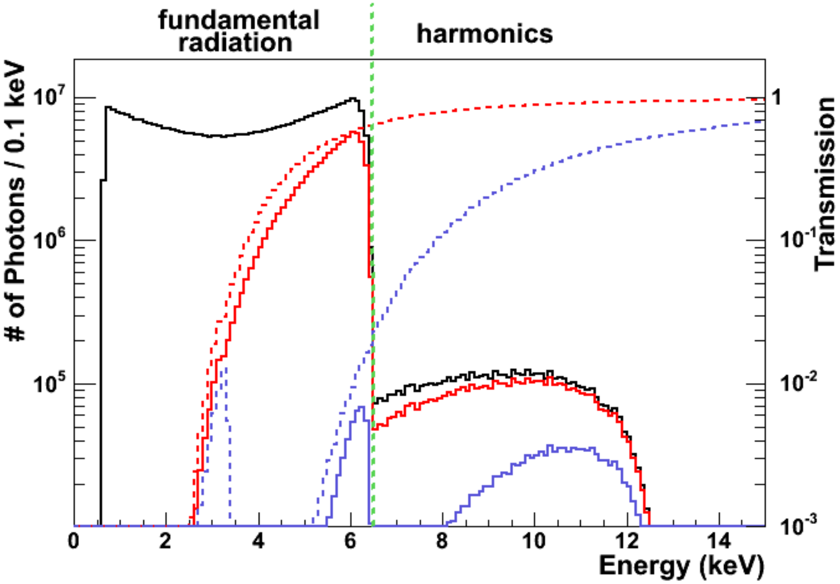


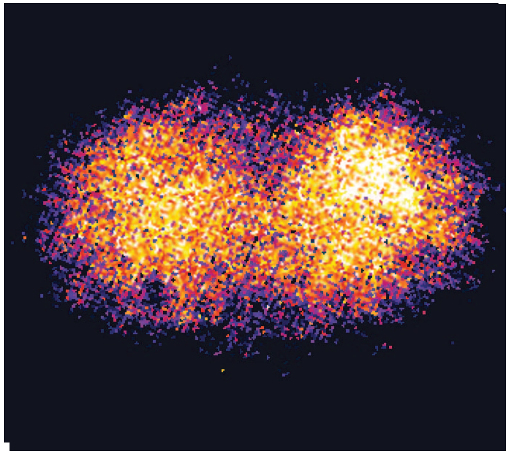
- The first direct observation of a nonlinear component in relativistic Thomson x-ray scattering

Phys. Rev. Lett. **96**, 054802 (2006)



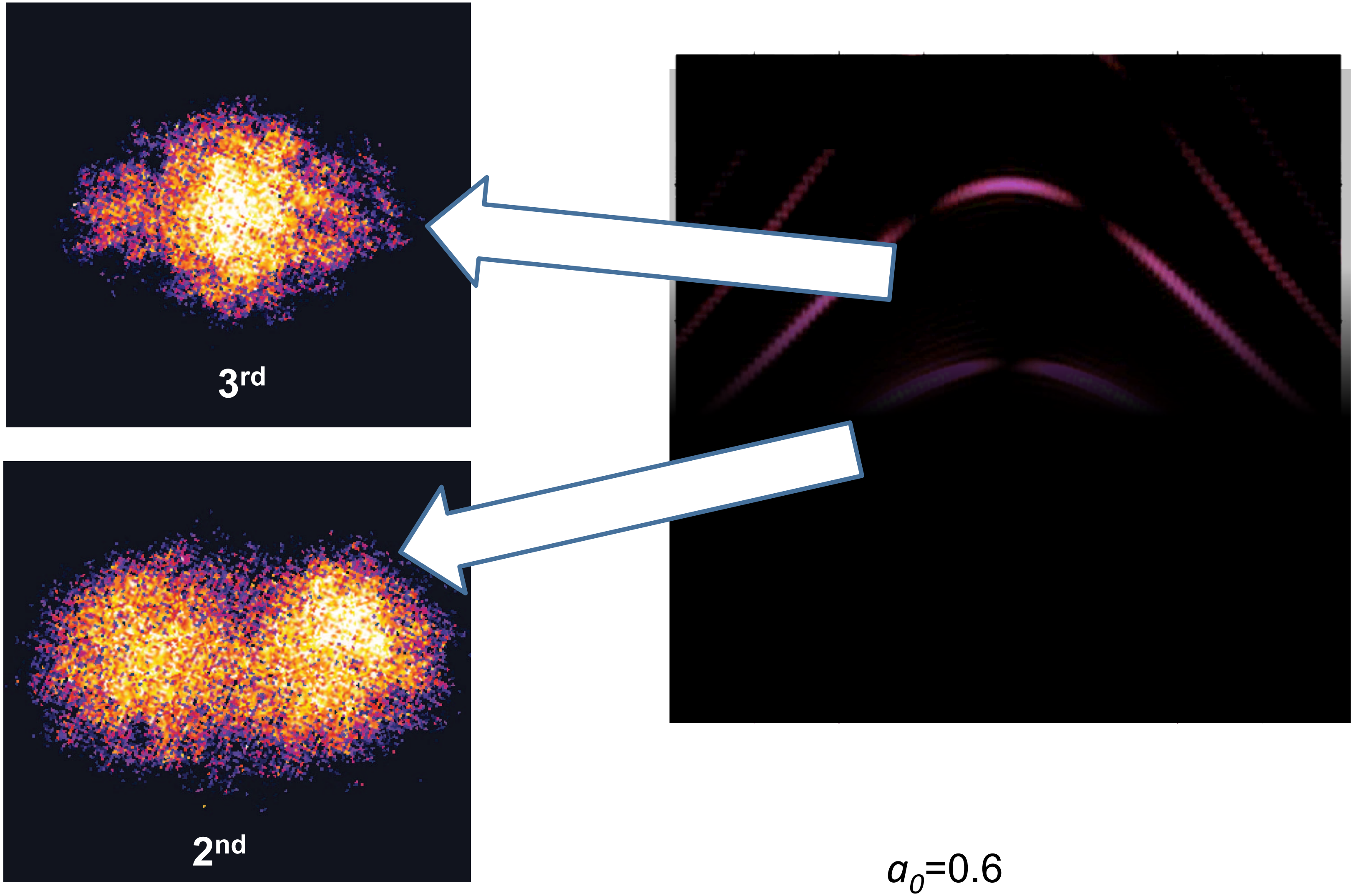
2nd harmonic





a_0=0.6

Higher harmonics



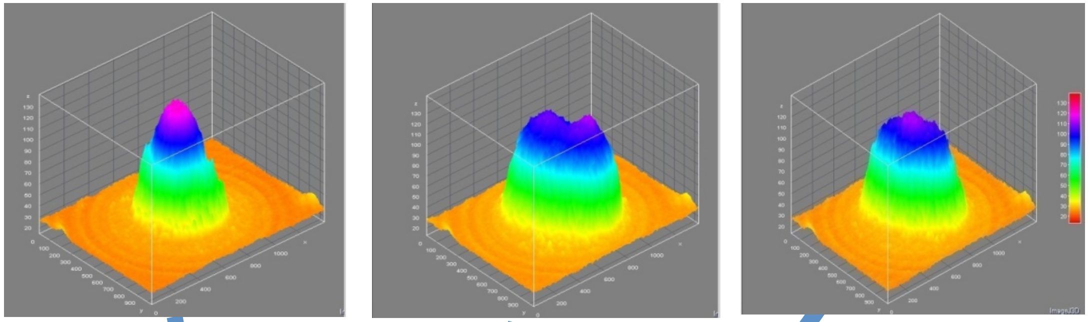
a_0=0.6

Mass shift

Recent unpublished results in nonlinear Compton scattering

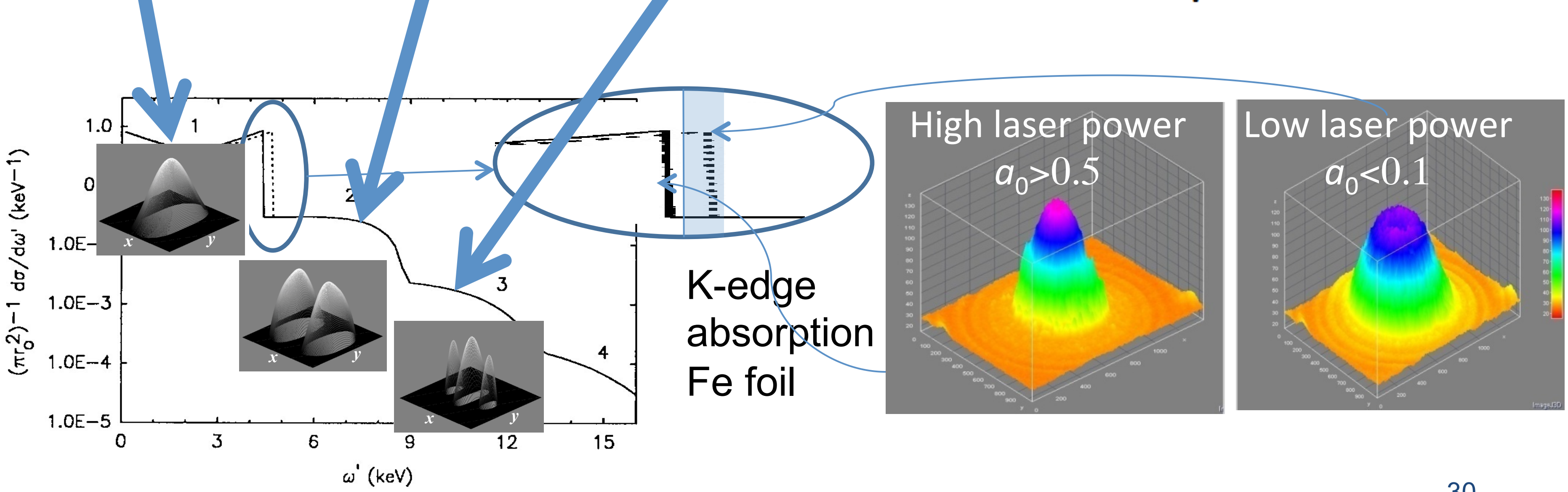
harmonics

mass shift



$$\bar{m} = m\sqrt{1 + a_0^2}$$

$$\lambda_x \approx \frac{\lambda_L}{4\gamma^2}\left[1 + a_0^2\right]$$



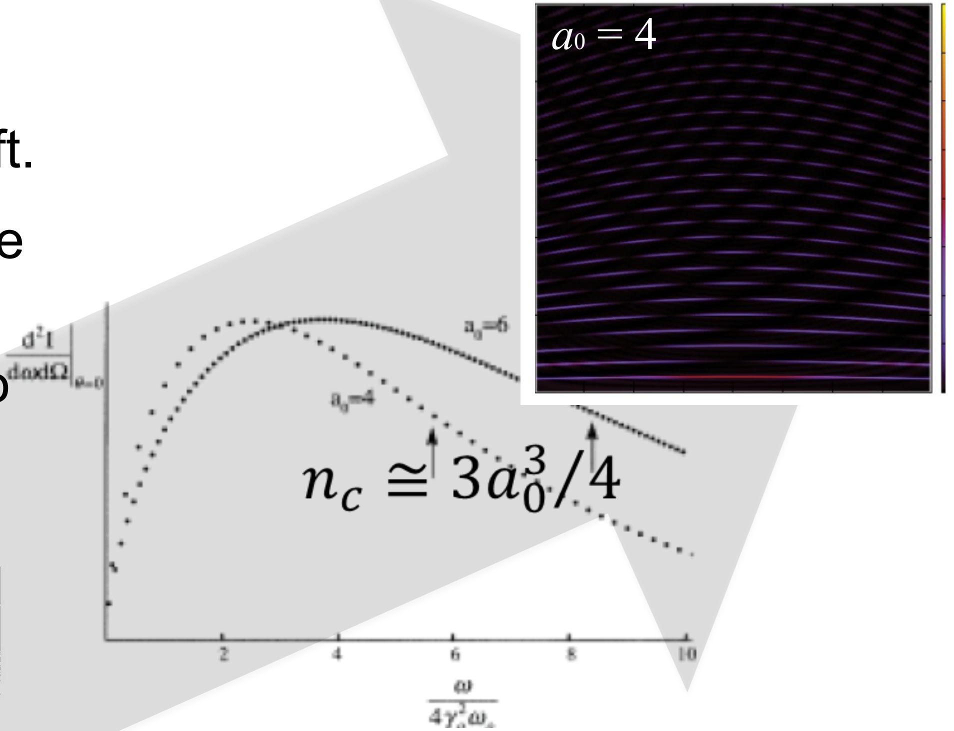
K-edge absorption Fe foil

High laser power $a_0 > 0.5$

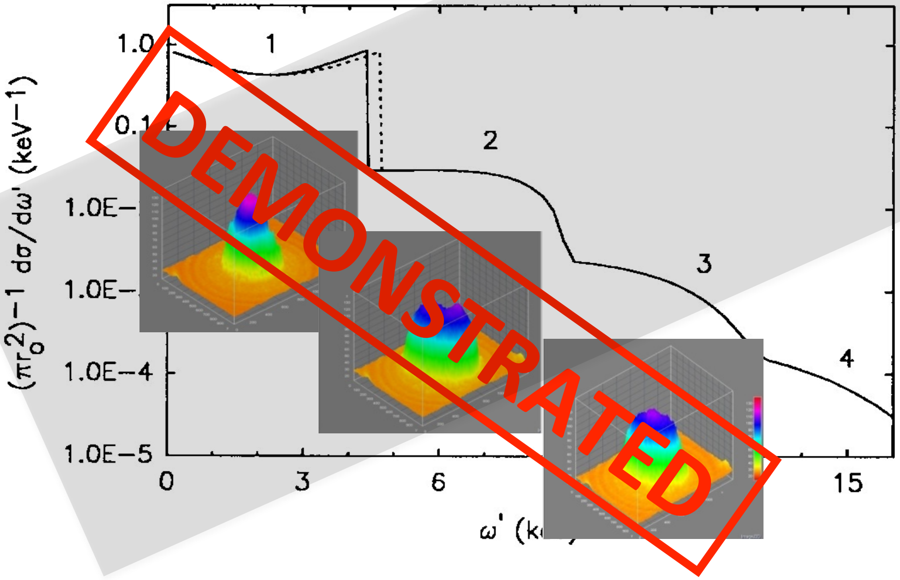
Low laser power $a_0 < 0.1$

Very high Compton harmonics

- New avenue to shorter wavelengths based on harmonic frequency up-shift.
- For a_0 >>1, numerous harmonics are generated, yielding a continuum.
- Harmonics increasing in intensity to some critical harmonic number n_c

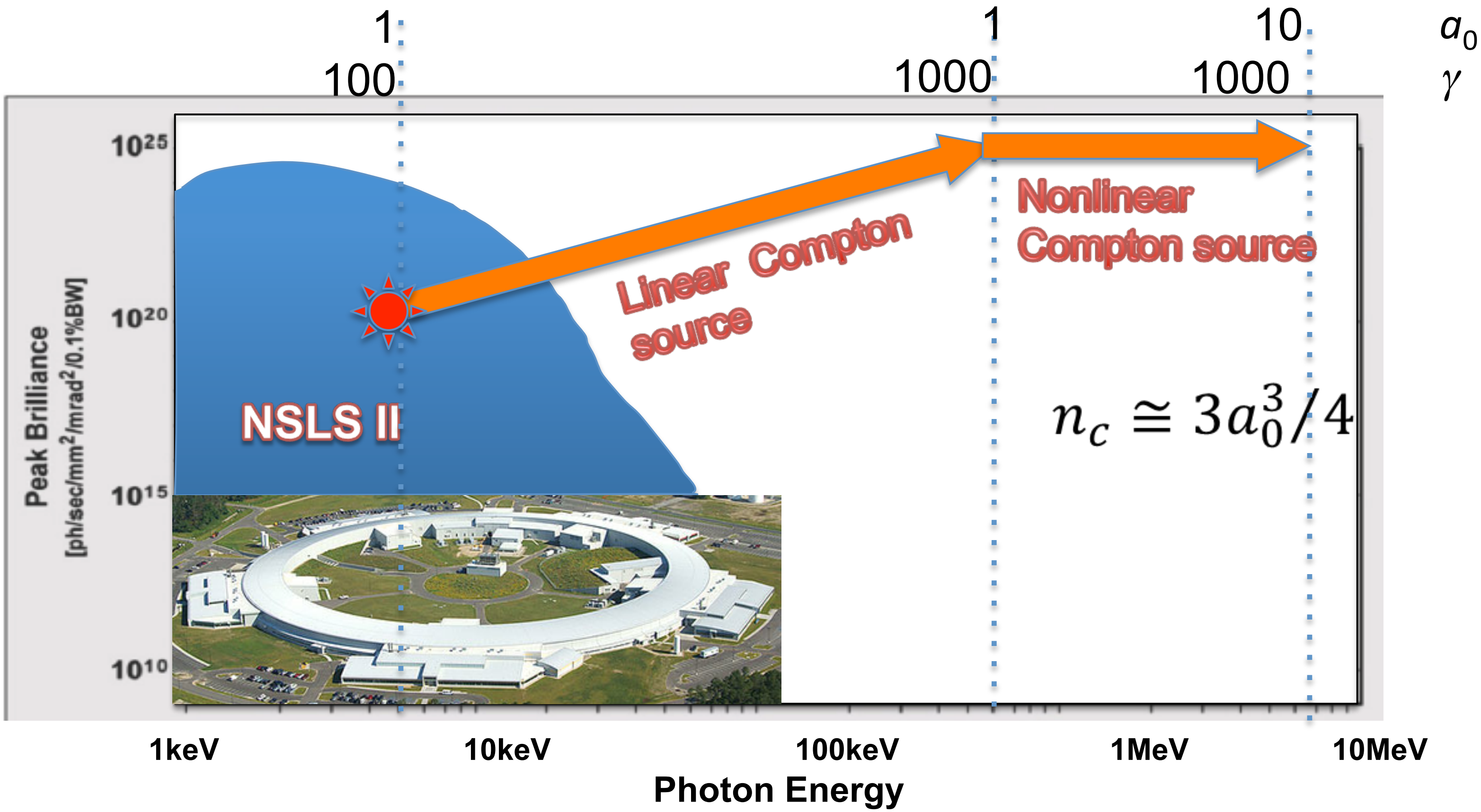


$$n_c \cong 3a_0^3/4$$



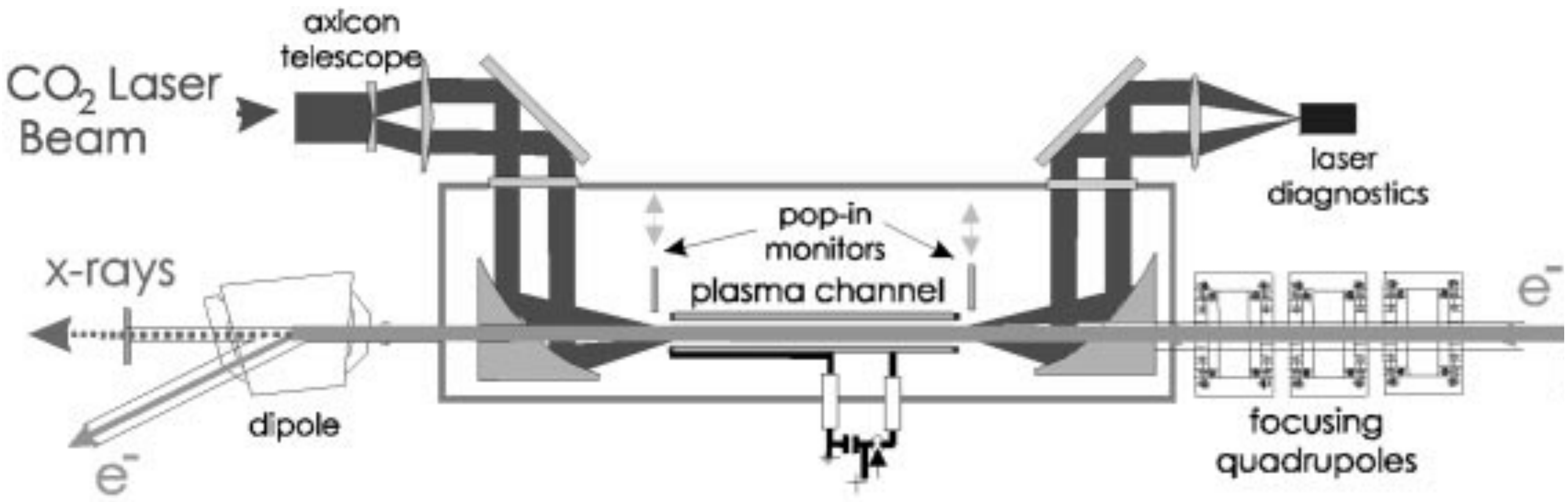
- n_c is close to 1000 for a_0 =10.
- 3 MeV gamma-rays with 500 MeV electrons.

Peak Brightness

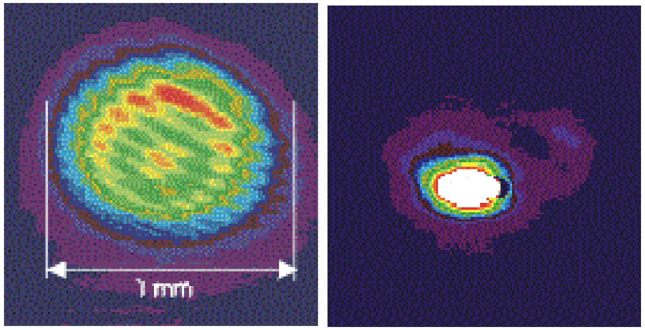


Further spectrum extension through harmonics continuum

Plasma guided beams

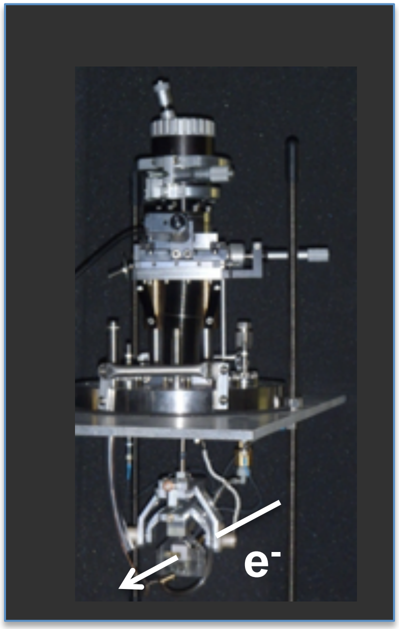


CO_2 laser channeling in plasma capillary



without discharge

with discharge



Capillary discharge plasma source

Expect ×10
in x-ray flux/ shot

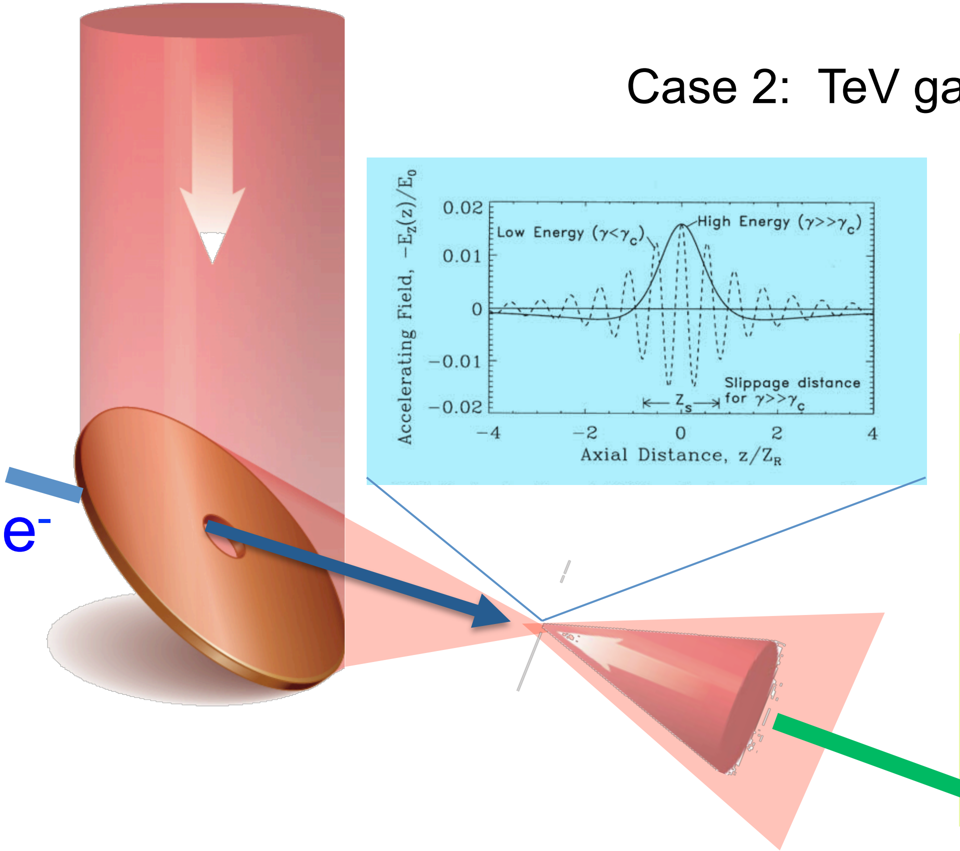
NIM A **455**, 176 (2000)

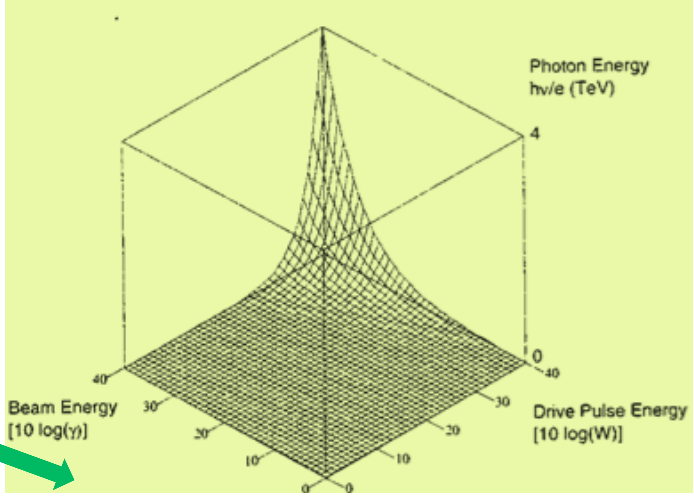
Transient Compton

Lawson-Woodward theorem prohibits net acceleration in vacuum; however, transient energy gain over slippage distance πZ_r could be significant:

Case 1: ΔE=100 MeV over 100 μm with 20 TW
Phys. Rev. E **52**, 5443 (1995)

Case 2: TeV gammas with 500 MeV e-beam and $a_0=20$
Phys. Plasmas **5**, 2037 (1998)



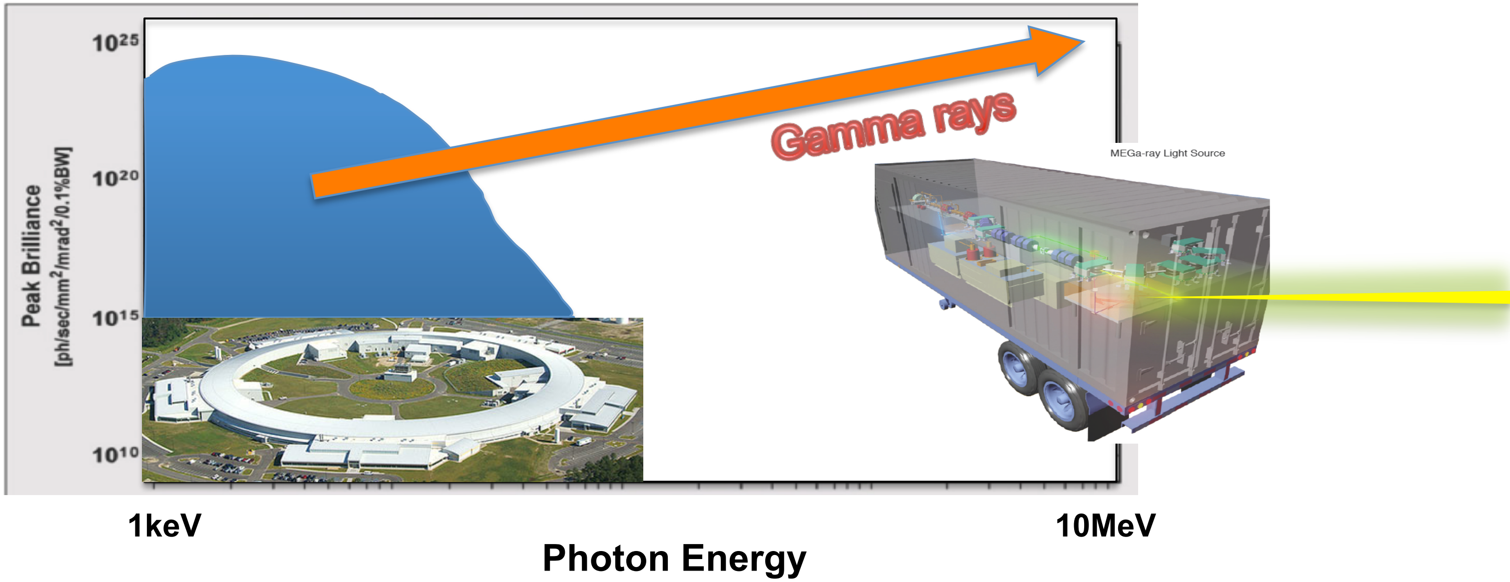


Summary

Current challenges in Compton sources:

#1

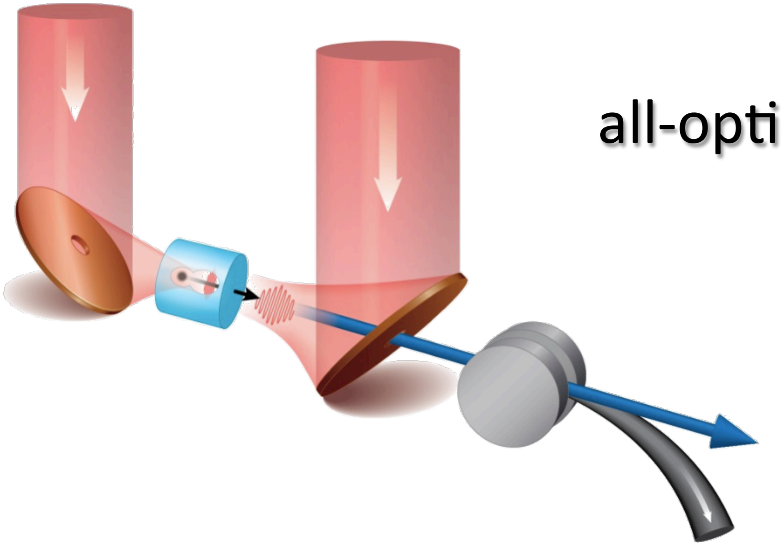
#2



Summary

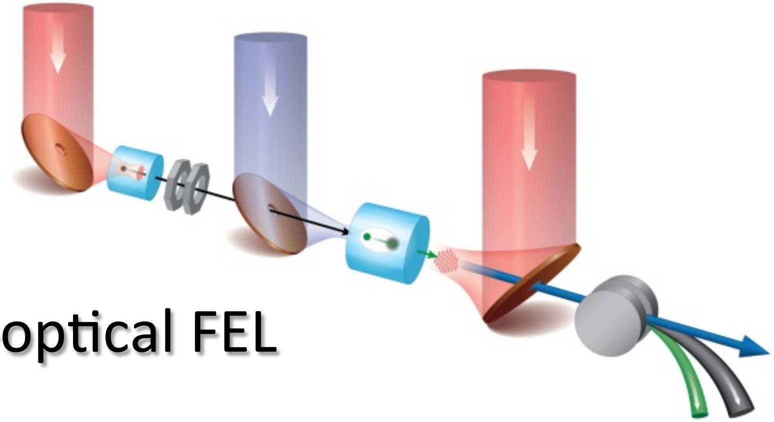
Current challenges in Compton sources:

#3

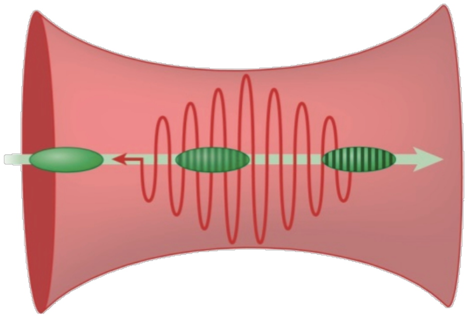


all-optical Compton source

#4

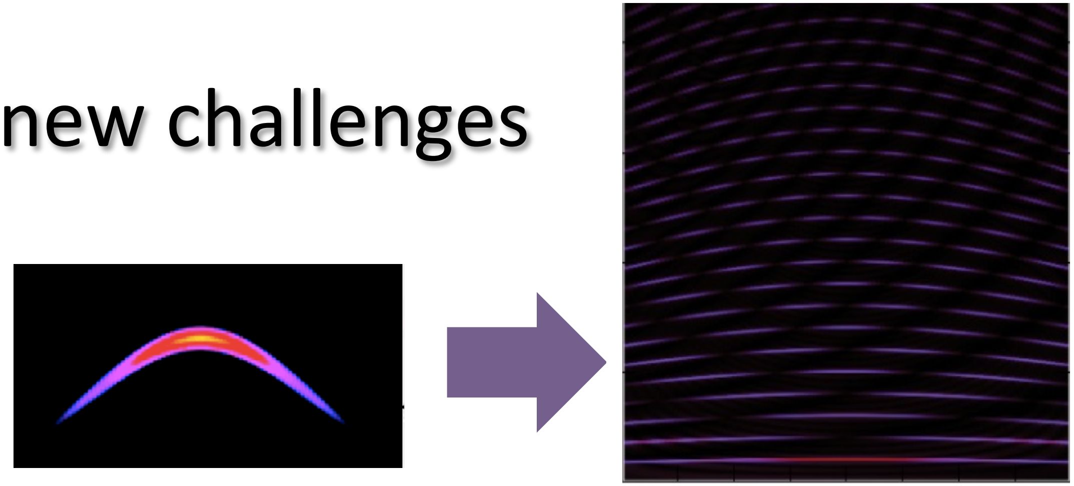


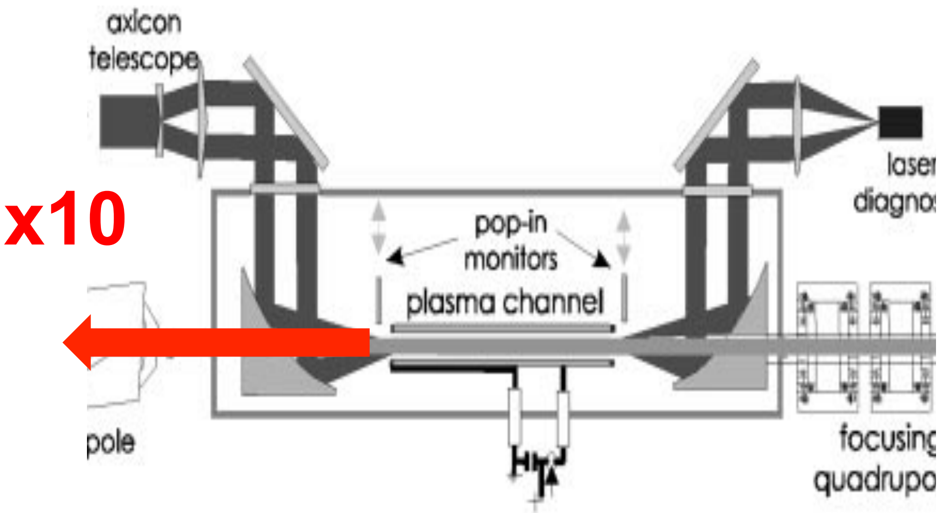
all-optical FEL

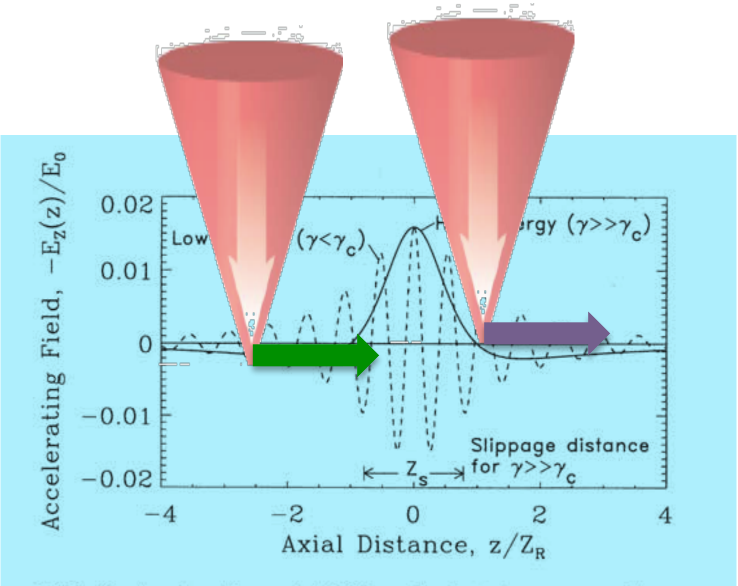


Summary

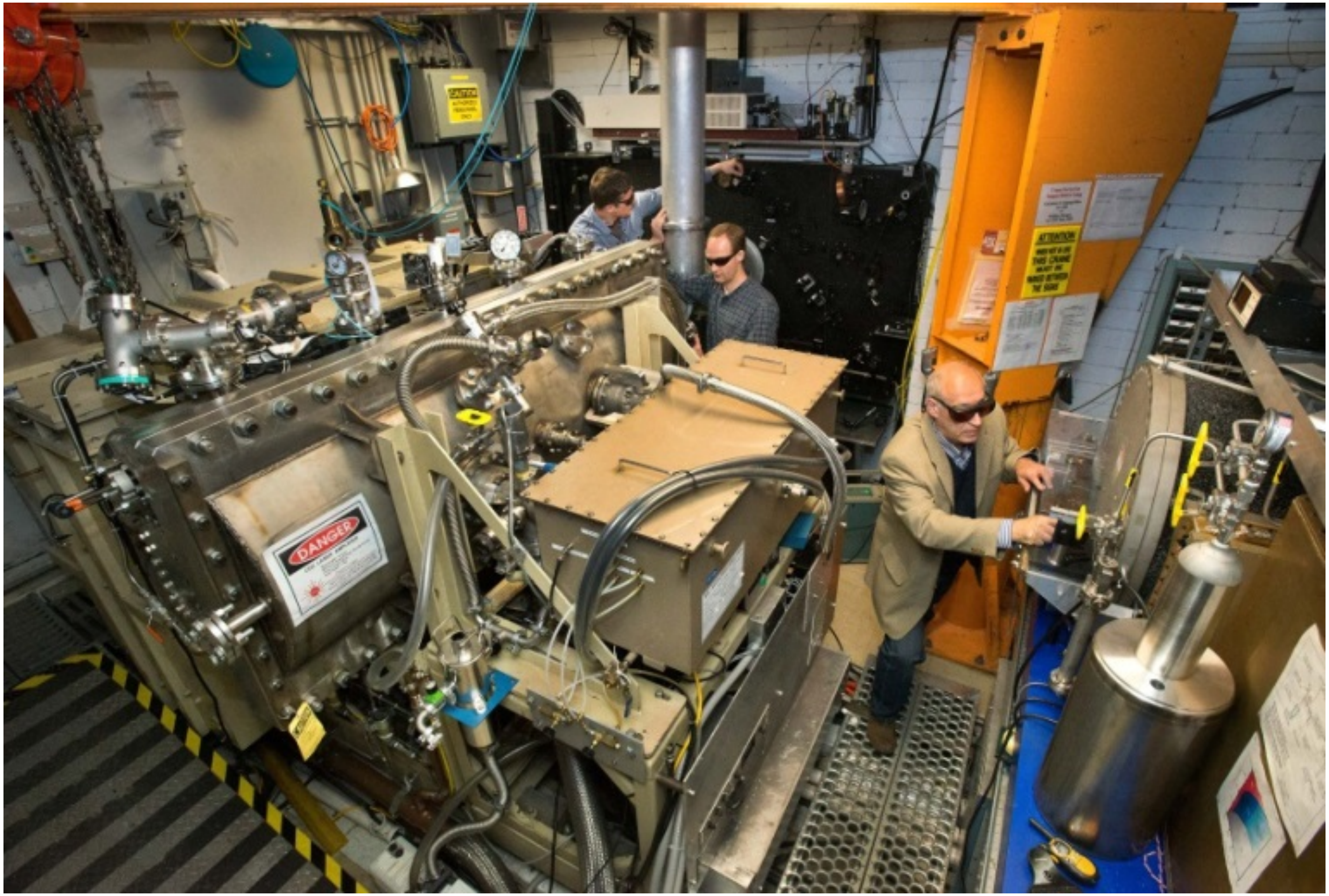
Searching for new challenges







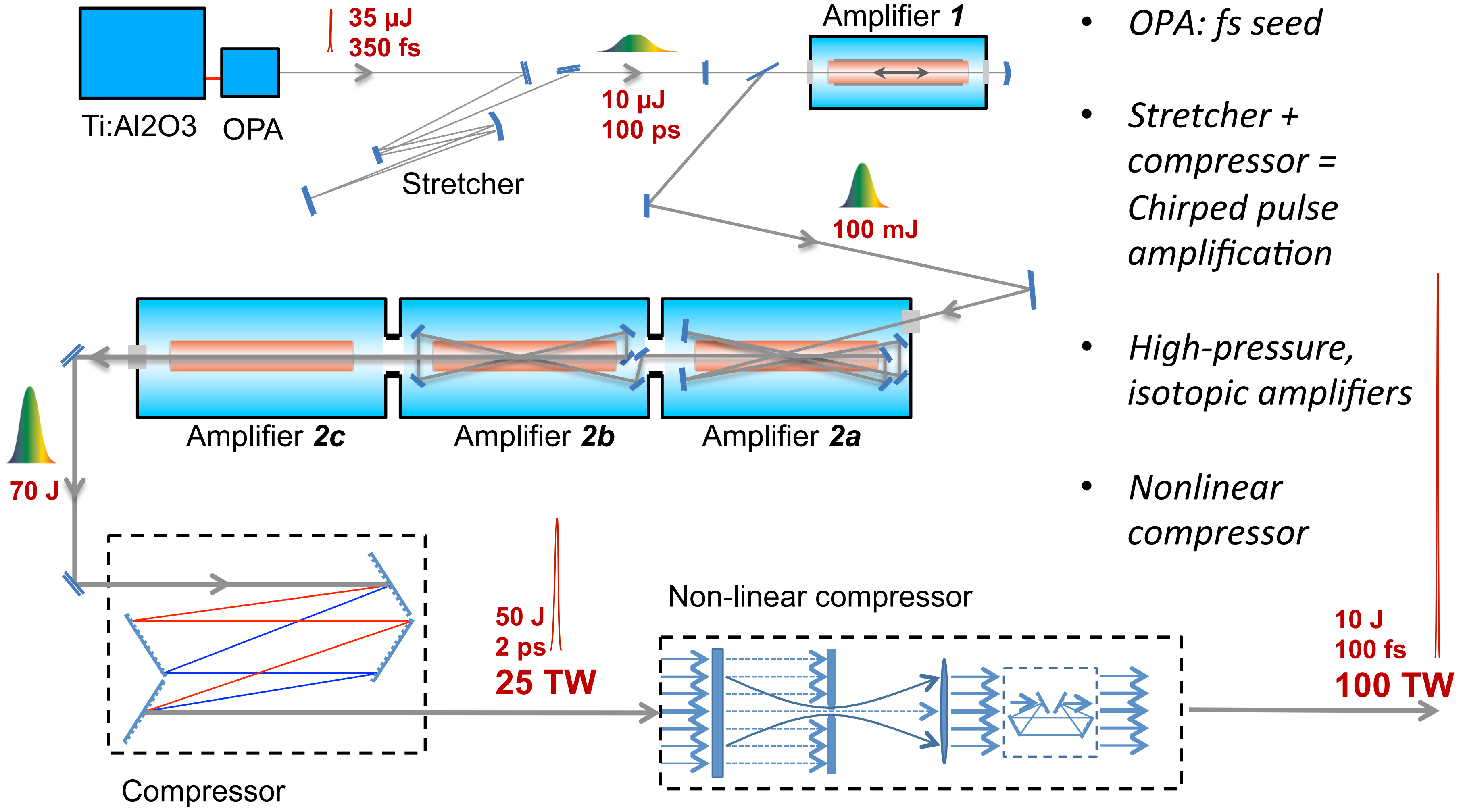
Developing 100 TW CO_2 laser



100TW CO_2 concept laser

Collection of innovations:

- OPA: fs seed
- Stretcher + compressor = Chirped pulse amplification
- High-pressure, isotopic amplifiers
- Nonlinear compressor



Multi-TW CO_2 laser

Those and many other new developments will be enabled by the future ATF 100-TW 100-fs CO_2 laser that will open the first-time opportunity to study strong-field effects in mid-IR spectral domain not accessible with high-power lasers previously

Visit the ATF website
www.bnl/atf
to explore current
research opportunities

Send proposals for experiments
to Meeting coordinator
Kathleen Tuohy
tuohy@bnl.gov

ATF Program Committee:
Wim Leemans, LBL, Chairman
Kathy Harkay, ANL
Karl Krushelnick, U.Michigan
Sergei Nagaitsev, FNAL
James Rosenzweig, UCLA
Vitaly Yakimenko, SLAC

FIRST ANNOUNCEMENT

Active program of user experiments and new
proposals will be reviewed at the next
ATF User Meeting
at Brookhaven National Laboratory
Upton, New York, USA

17th ATF User Meeting

October 14-15, 2014

BACK TO BACK EVENTS

October 16-17, 2014

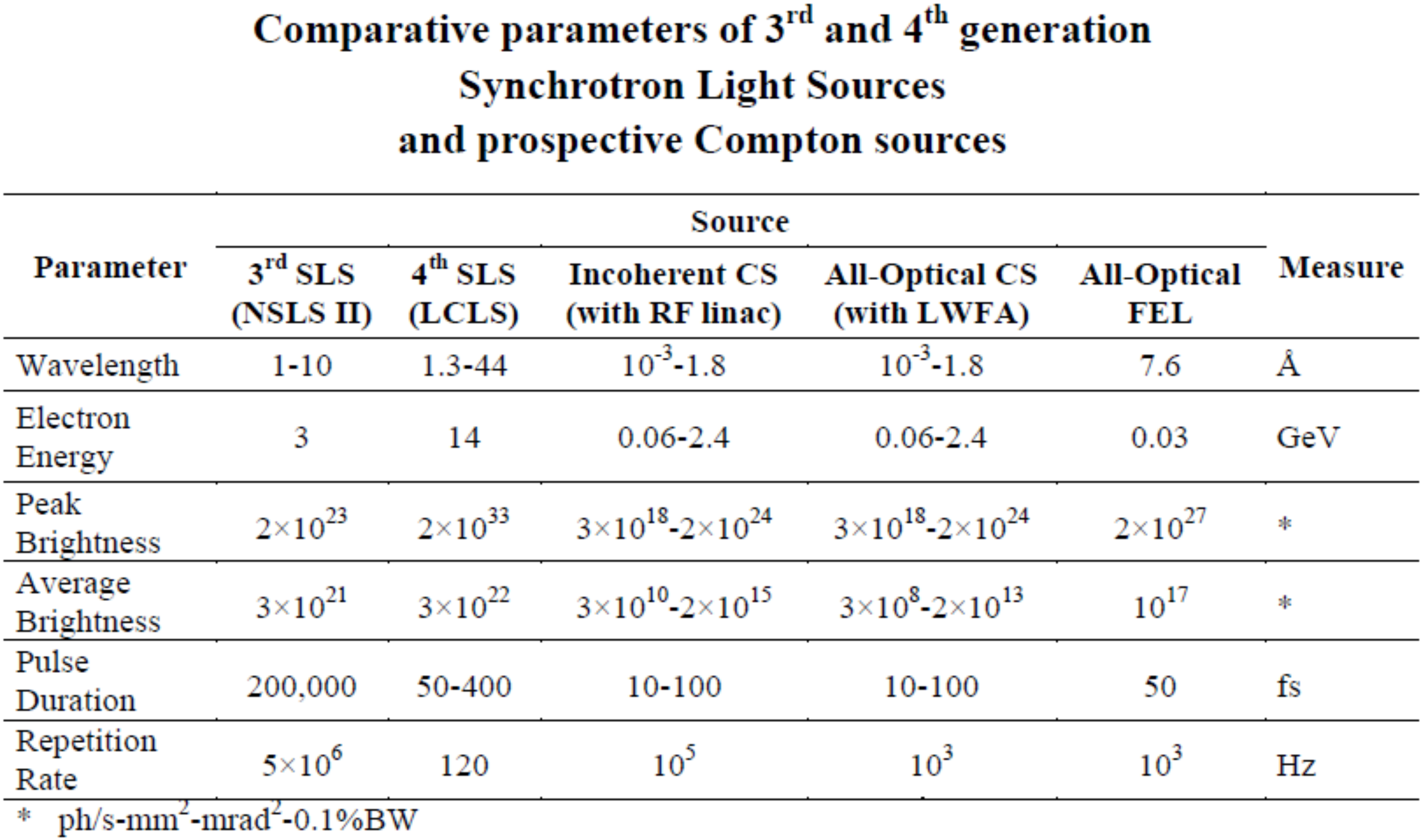
ATF II Upgrade Workshop

Explore new opportunities for research
in advanced accelerators and radiation sources
offered by future ATF upgrade
to 500 MeV electron beam energy and
100 TW peak power from a femtosecond CO_2 laser

See ATF Upgrade Proposal at
www.bnl.gov/atf/docs/
ATFupgrade.pdf

Workshop organizers:
Ilan Be-Zvi, ATF Scientific Program Director, BNL,
Igor Pogorelsky, ATF Interim Director, BNL
Mikhail Fedurin, ATF User Coordinator, BNL

For more information contact
Workshop coordinator
Kathleen Tuohy
tuohy@bnl.gov



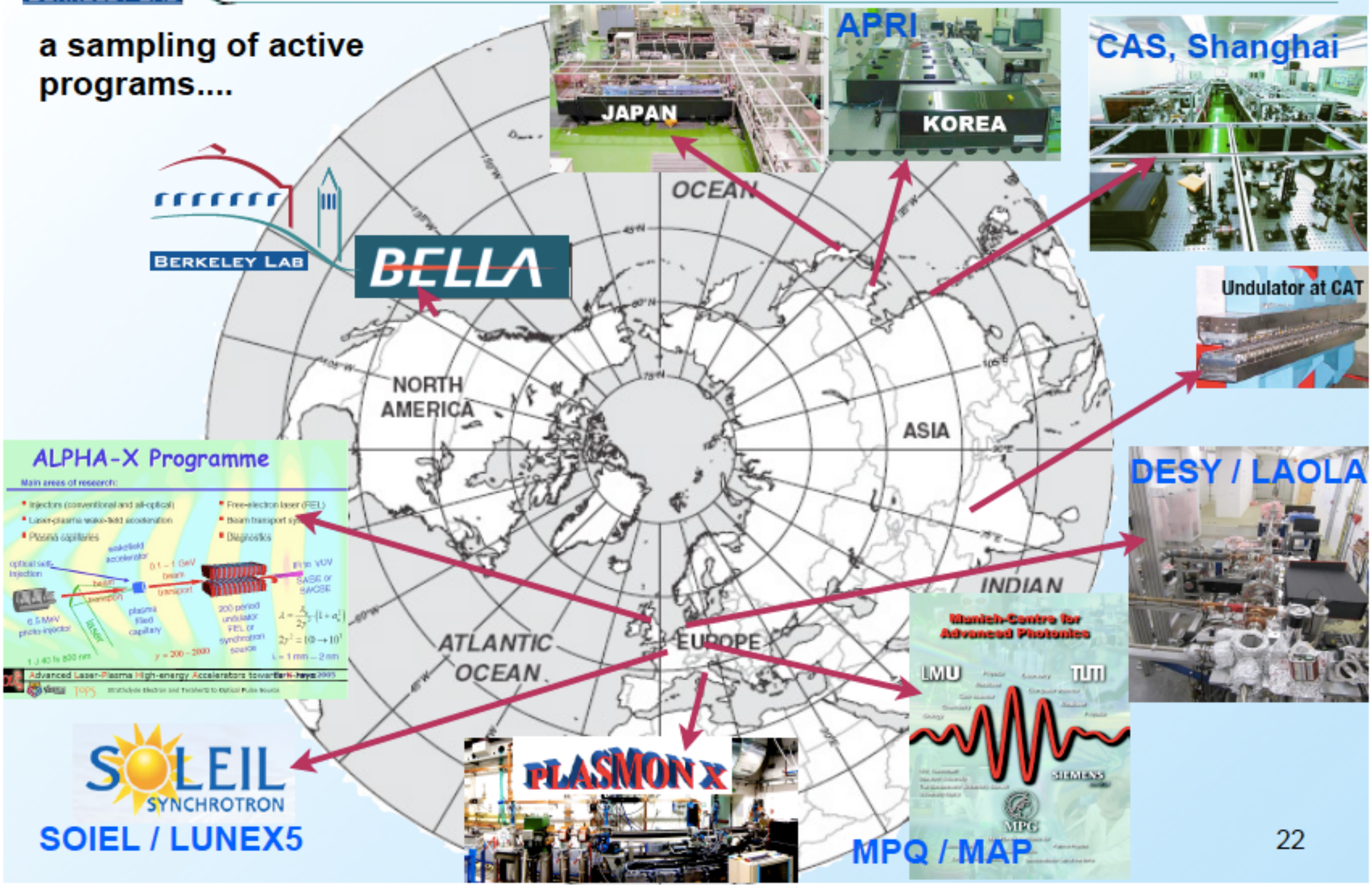
Comparative parameters of 3rd and 4th generation Synchrotron Light Sources and prospective Compton sources

Parameter	Source					Measure
	3rd SLS (NSLS II)	4th SLS (LCLS)	Incoherent CS (with RF linac)	All-Optical CS (with LWFA)	All-Optical FEL	
Wavelength	1-10	1.3-44	10^{-3}-1.8	10^{-3}-1.8	7.6	Å
Electron Energy	3	14	0.06-2.4	0.06-2.4	0.03	GeV
Peak Brightness	2×10^{23}	2×10^{33}	3×10^{18}-2×10^{24}	3×10^{18}-2×10^{24}	2×10^{27}	*
Average Brightness	3×10^{21}	3×10^{22}	3×10^{10}-2×10^{15}	3×10^{8}-2×10^{13}	10^{17}	*
Pulse Duration	200,000	50-400	10-100	10-100	50	fs
Repetition Rate	5×10^{6}	120	10^{5}	10^{3}	10^{3}	Hz

* ph/s-mm^2-mrad^2-0.1%BW

World-wide interest in light sources driven by laser-plasma accelerator

a sampling of active programs....



ALPHA-X Programme

Main areas of research:

- Injectors (conventional and all-optical)
- Laser-plasma wake-field acceleration
- Plasma capillaries
- Free-electron laser (FEL)
- Beam transport sys
- Diagnostics

Advanced Laser-Plasma High-energy Accelerators towards X-rays 2005

Strathclyde Electron and TeraHertz to Optical Pulse Source