Day 8 – Lecture 2

The New Radiation Science:
Progress toward the Attosecond Frontier

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We are at the doorway
of the New Radiation Science

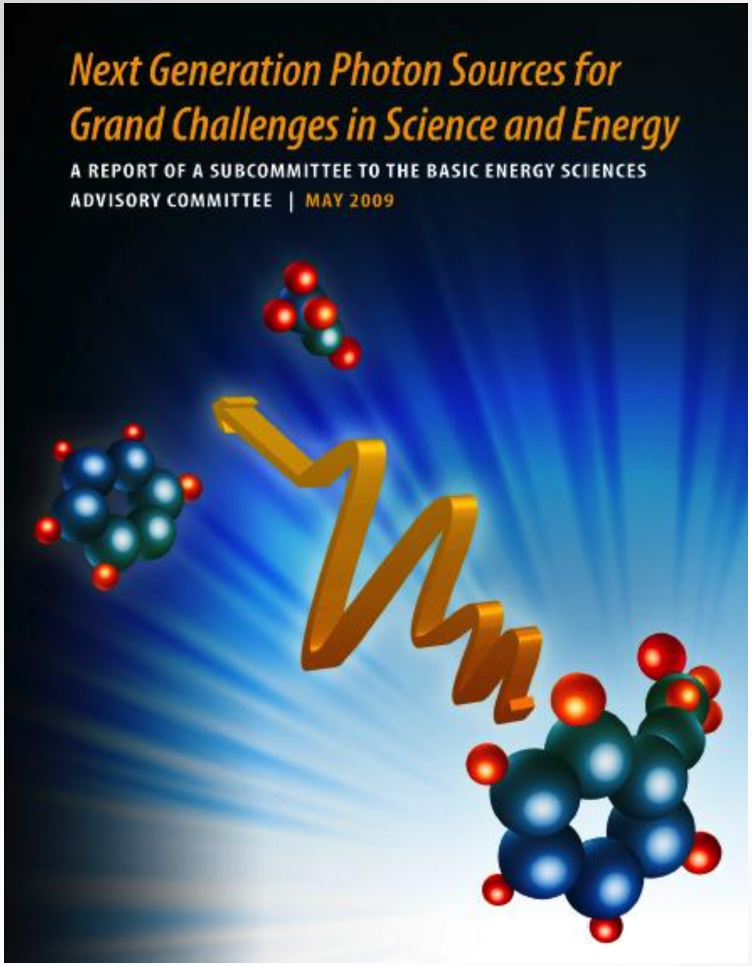
- Uncertainty relation:

$$\Delta E \Delta t \sim E(eV)\ t(fs) \sim 1$$

Energy scale of electronic states

- Bohr orbital time scale ~ 150 as
- 100 attoseconds ~30 nm
- Full set of keys requires coherent radiation probes

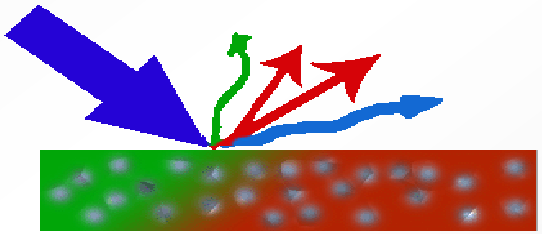
Key science issues
for the new radiation science



- Observe flow of information & energy on fundamental time scales
- Atomic resolution in energy, space & time (meV, nm, as)
- Image real time processes at nm spatial scales, tomographically
- Measure energy scales relevant to function of complex materials
- Move from observation to control of materials & chemistry

Grand challenge science with X-rays
Two general modes of experiments

- Image molecular structures with *atomic resolution*
  - "Diffract before destroy"
- Unprecedented studies of dynamics parameters combining spectroscopy & diffraction using X–rays
  - Typically "pump-probe"



Figures of Merit:

Brilliance v. λ (B = ph/s/mm^2/mrad^2/0.1%BW)

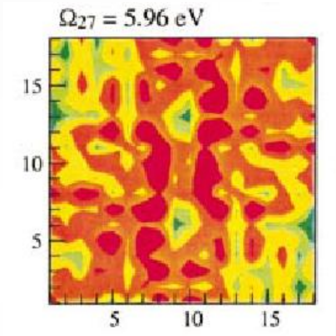
Time structure of x-ray pulses

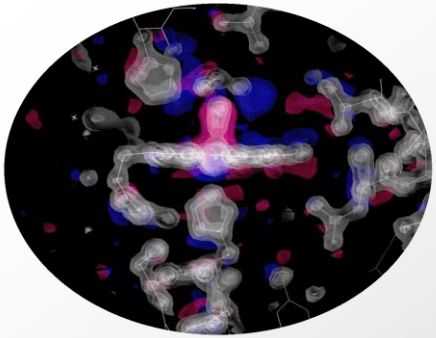
Expanding the Frontier:
Time-resolved experiments

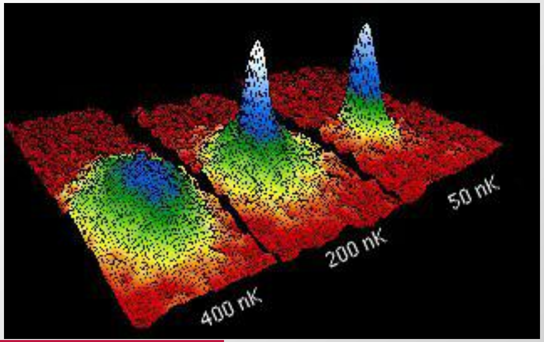
- Science and the multiple relationships between time, spectroscopy, and diffraction

- Combining diffraction and spectroscopy (nuclear positions & electronic, chemical or structural probes), will yield outstanding new science in the X-ray regime.

- Temporal dynamics parameters have not been exploited in the X–ray, mostly due to lack of sources.

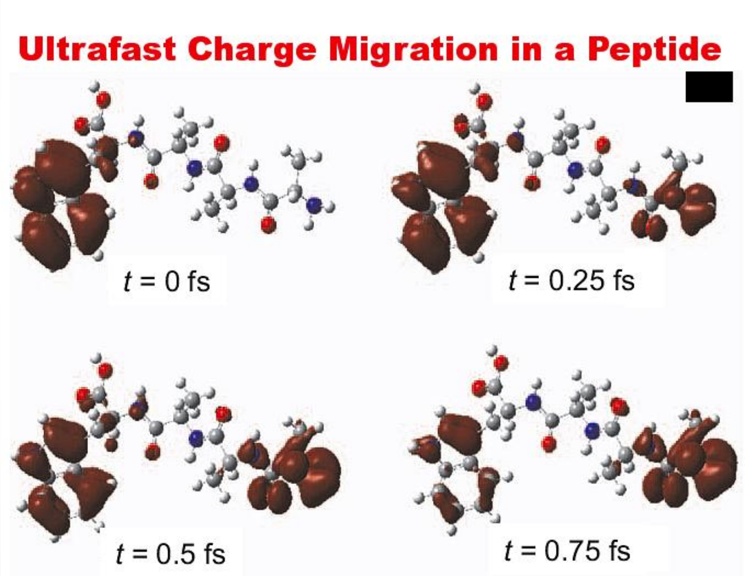






Example: Reveal electron dynamics

- Probe molecules at intrinsic time scale of electron dynamics
  - Bohr orbit period ~ 150 attoseconds
- Follow correlated motion of electrons
- Understand correlation of electronic & nuclear motion
- Many-fold-improvement needed over brightness of bench-top sources
  - tunability for chemical specificity
  - as - to - ps, time-bw-limited pulses
  - coherence

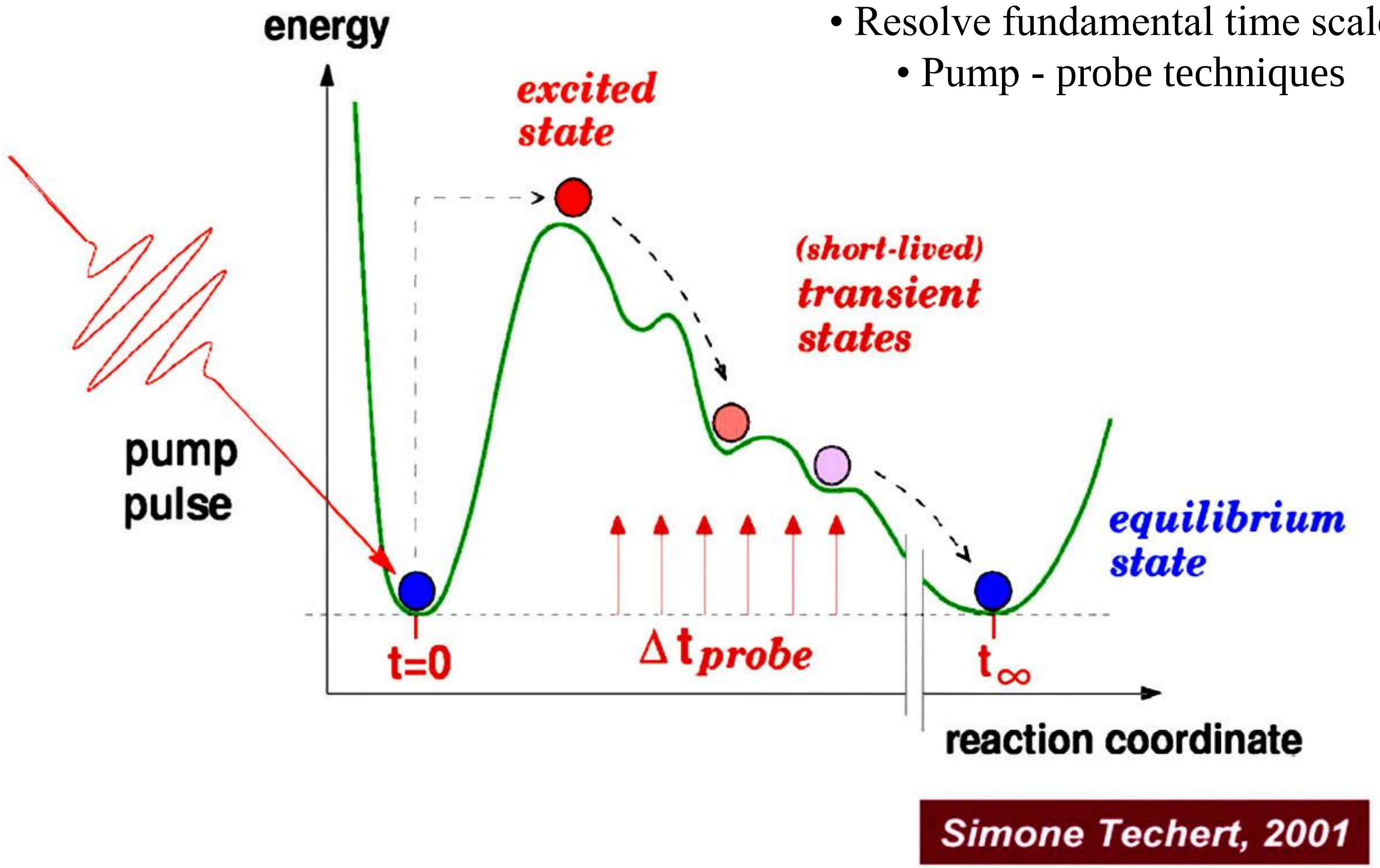


Foundation for energy and environmental sciences & technologies of the future

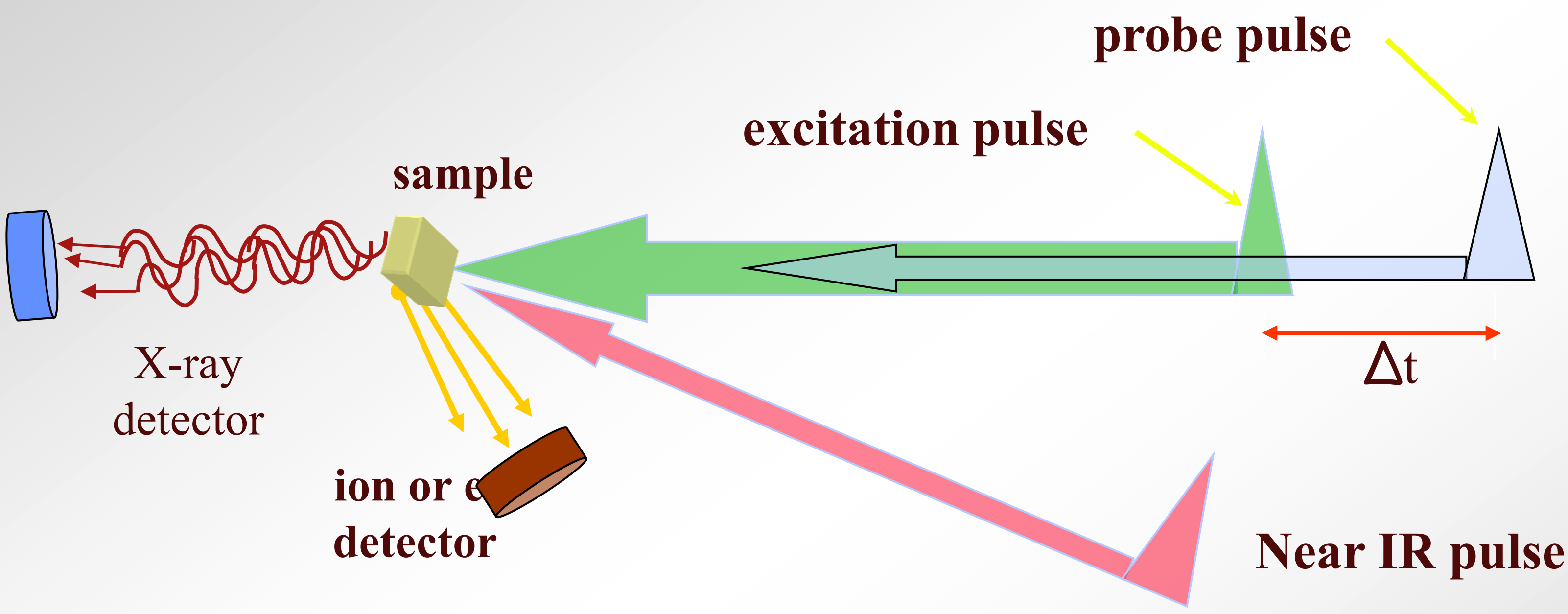
Courtesy of R. Falcone

Example:
Resolve non-equilibrium dynamics

- Resolve fundamental time scales
- Pump - probe techniques



Pump-probe experiment concept
for ultra-fast science and/or imaging



- Pulses can be x-rays, VUV, electrons or ions
- Requires control/measurement of Δt with a resolution << x-ray pulse duration (possibly as small as 100 attoseconds)

What matters most for ultra-fast science

(searching for weak, dynamically changing signals amidst large, time-invariant signals)

- Timing: most experiments initiate a time evolving process with another laser or x-ray pulse - tight time synchronization is expected
  - *0.1 to 10's of fs*
- Pulse-to-pulse stability: essential since only a small fraction of the molecules or materials are excited
  - *Expectation of 3rd generation 0.1% stability,*
  - *Real time subtraction - pump on/pump off*
- Bandwidth & chirp: minimum BW, without violating transform limit, to isolate spectral shifts, chirp to correlate energy with time in new ways
  - *Core level shifts 0.1-0.5 eV typical: RIXS < 5 meV bandwidth*

Con't

Ultrafast scientists' needs

- Tunability
  - *Spectroscopy demands tuning to near edge transitions*
- Repetition rate
  - *High repetition rates desirable for samples that can be refreshed, low damage, as high as conventional electronics*
- Pulse duration
  - *50 - 200 fs for many processes, 0.1 - 10 fs for future applications*
- Pulse energies
  - *Sufficient to obtain photoemission signals, absorption contrast changes, without sample damage*

Con't

Further needs for ultrafast science

- Polarization
  - *Complete rhc & lhc components needed for polarization blocking & dichroism experiments*
- Coherence
  - *True phase control (Spatial, temporal, phase coherence)*
  - *Need complete phase control for efficient modulation of electron beam at short periods ==> generation of fsec/asec pulses*
- Focusability
  - *Near-diffraction limit for seeded systems, 10's nm at 1 keV*
- Power density
  - *10^{15} W/cm^2 readily achievable*
- Trade off between power density & repetition rate
  - *Maintain linear probing for many experiments*
  - *Multi-photon versus single photon*

LINAC based designs give best opportunity to achieve goals

Spatial & Temporal Coherence

- Need complete phase control for efficient modulation of electron beam at short periods.
  - Permits the generation of *fs/as* pulses

- Spatial and temporal coherence are essential for some imaging techniques, but partial coherence is better for some.
  - *Experiments which utilize and indeed require full phase coherence include Fourier transform holography, coherent diffractive imaging, coherent zone plate imaging.*
  - *Partial coherence is more appropriate for full-field zone plate imaging.*
  - *A further class of experiments such as wave mixing, lies ahead, which will require true phase coherence at the sample.*

Operating modes for fs/as FEL

With Photoelectrons

- space charge issue
- 10^8 photons/pulse
- high repetition rate
- as/fs highly desirable, enabling science
- tradeoff of time duration vs. spectral bandwidth $(\Delta E \cdot \Delta\tau)|_{FWHM} = 1.82\ \text{eV} \cdot \text{fs}$

With Photons

- single pulse imaging
- 10^{11} photons/pulse at sample
- illumination/polarization control
- as/fs highly desirable, enabling science
- tradeoff of duration vs. ph flux, e.g.
  - 1 fsec and 10^{10} ph/pulse @ 2nm OR
  - 10 fsec and 10^{11} ph/pulse @ 2nm

Integrated photon flux needed
in condensed matter physics experiments

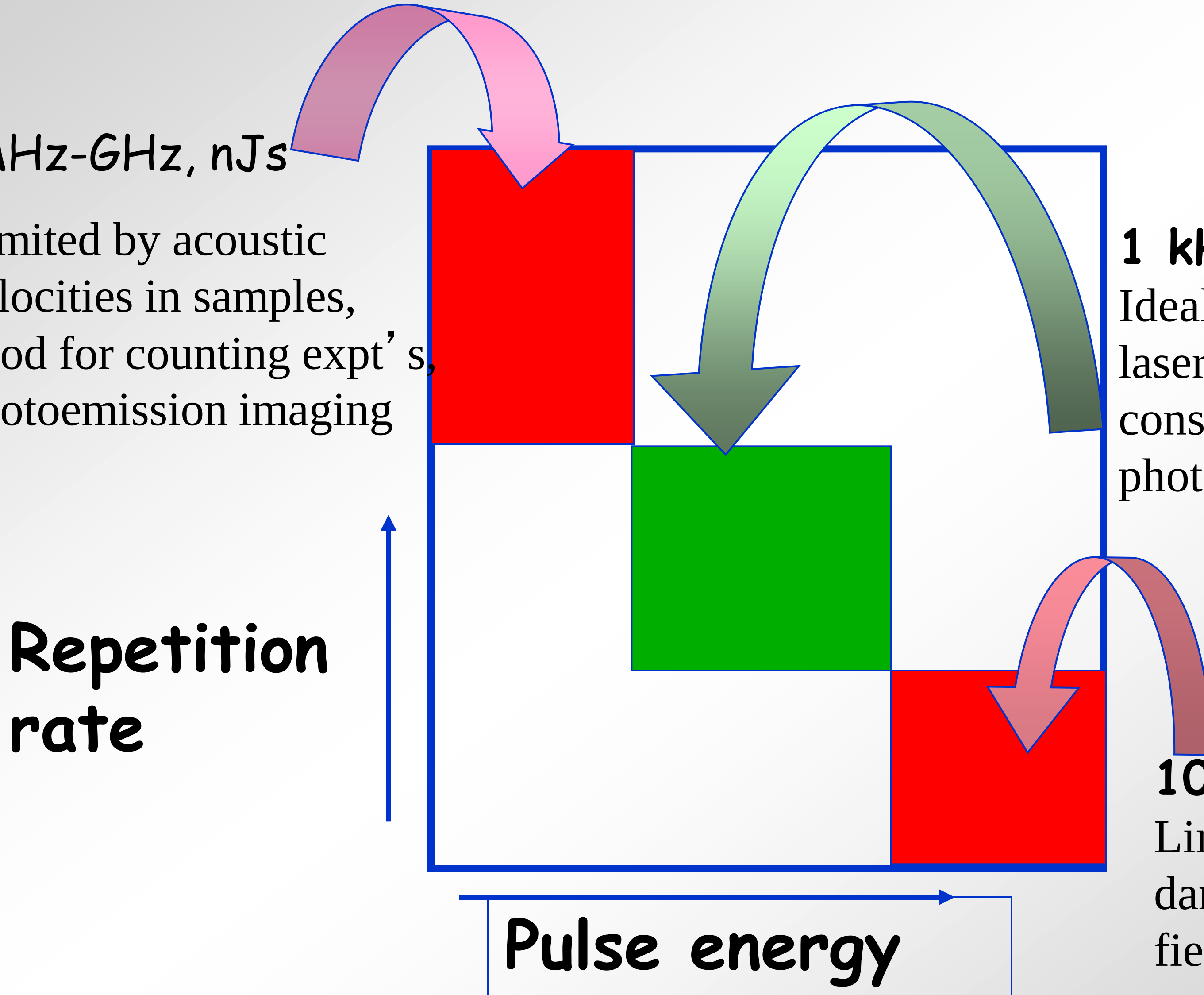
- Angle resolved photoemission: volume datasets
  - 10^{17} photons (20 – 100 eV)
- Microscopy
  - 10^{13} photons (280 – 1200 eV)
- Spectro-microscopy
  - 10^{15} photons (280 – 1200 eV)
- Time resolved microscopy
  - 10^{16} photons (280 – 1200 eV)
- Time resolved spectroscopy
  - 10^{10} photons (280 – 1200 eV)

From H. Padmore

Regimes of repetition rate vs. pulse energy

MHz-GHz, nJs

Limited by acoustic velocities in samples, good for counting expt’s, photoemission imaging



1 kHz-1 MHz, μJs

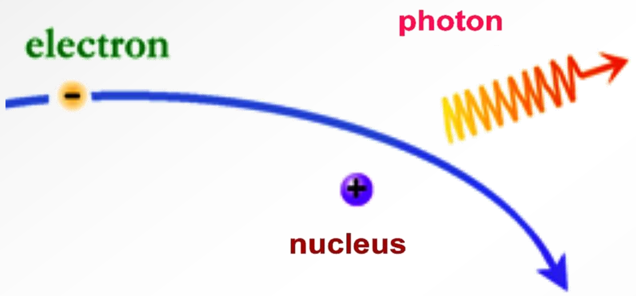
Ideal match to ultrafast lasers & sample considerations, single photon regime

10-100Hz, mJs,

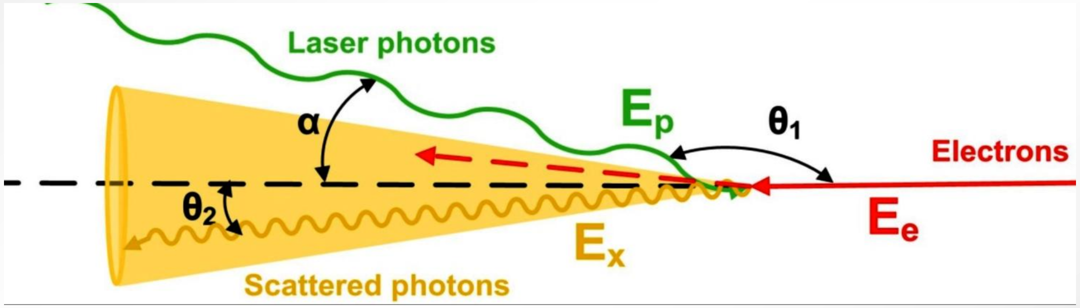
Limited by sample damage, many high field effects

Three approaches to get VUV to hard X-rays with accelerators

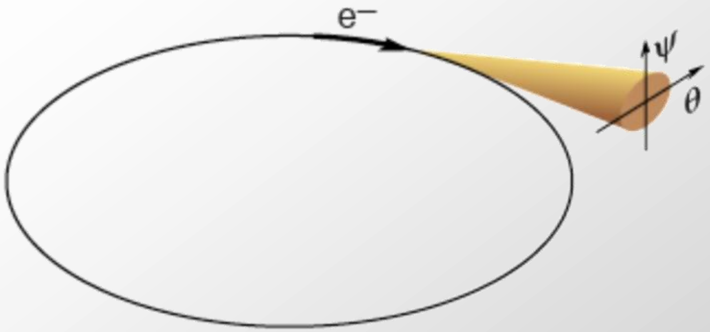
- Bremsstrahlung



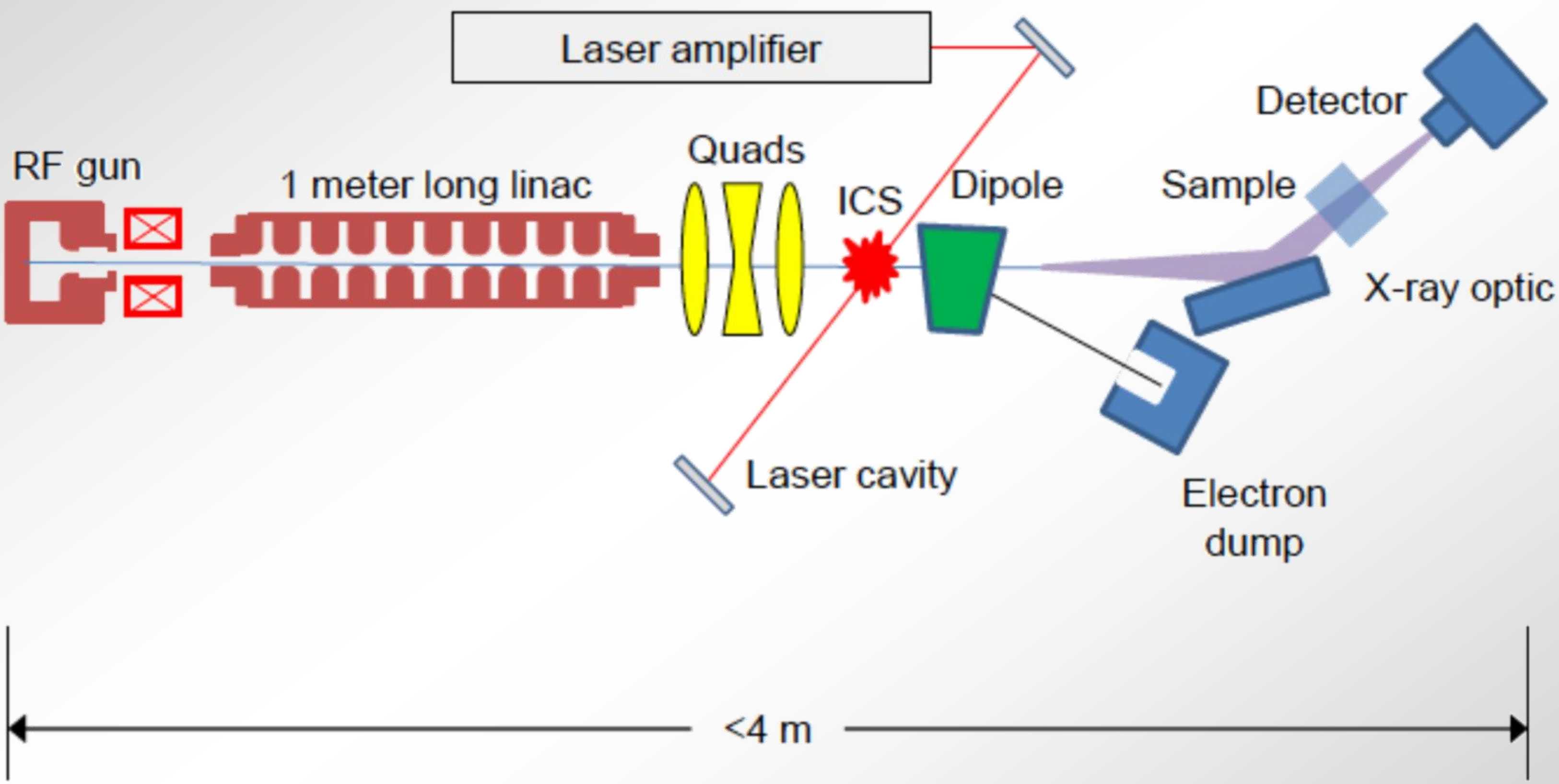
- Compton scattering



- Synchrotron radiation



Basic layout of Compton source



Source: W. Graves, MIT

X-rays from a Compton source

- Photon scattering cross section is approximately

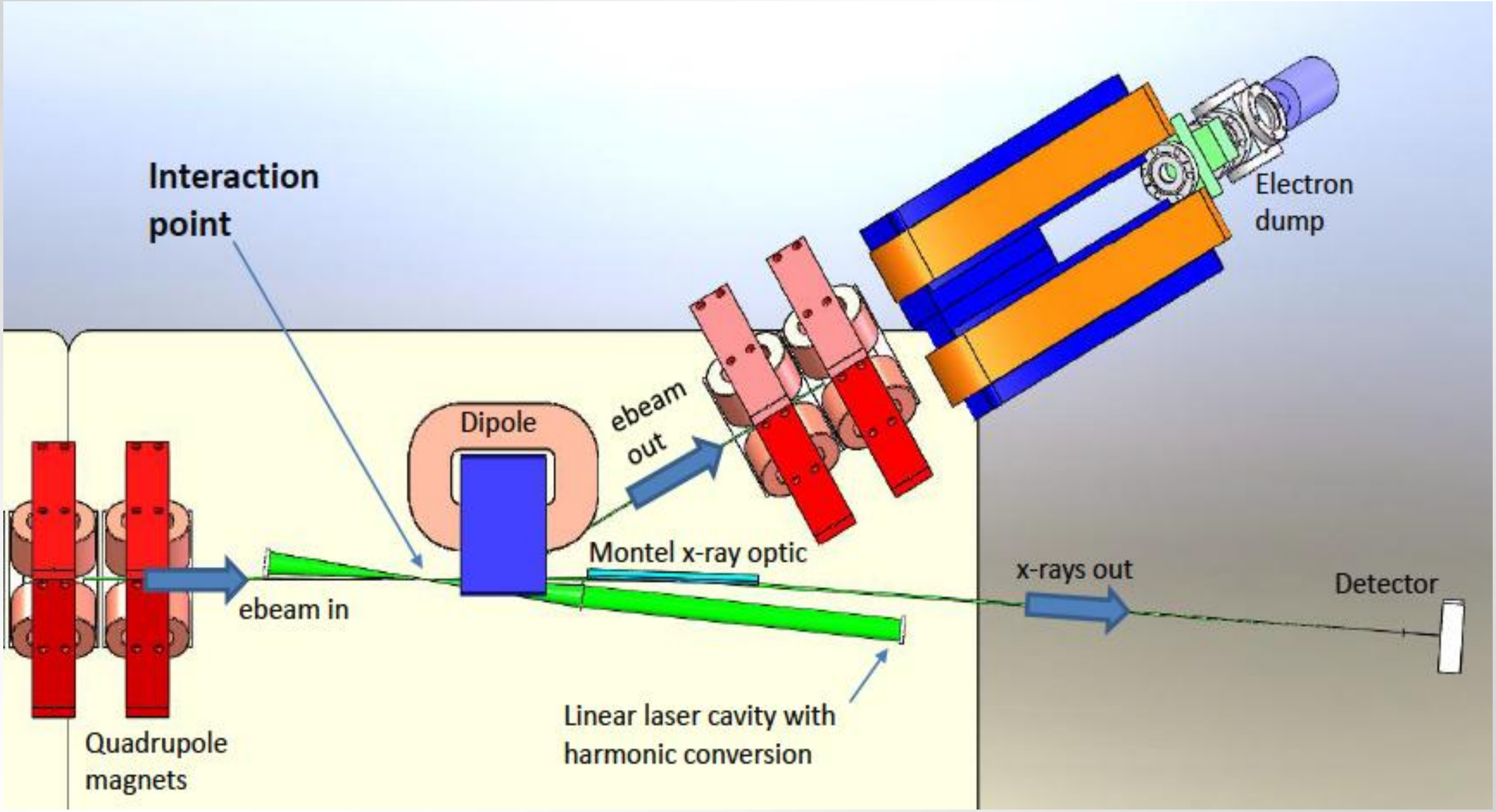
$$\sigma_{TH}=6.65\text{x}10^{-29}\ \text{m}^2.$$

- The number of X-ray photons is the product of the luminosity and the interaction cross section:

$$N_X = \frac{N_e N_g \sigma_{TH} f_{rep}}{4\pi s^2}$$

where N_e is the number of electrons, N_g the number of laser photons, f_{rep} the repetition rate, and s the rms beam

Interaction region of the Compton source



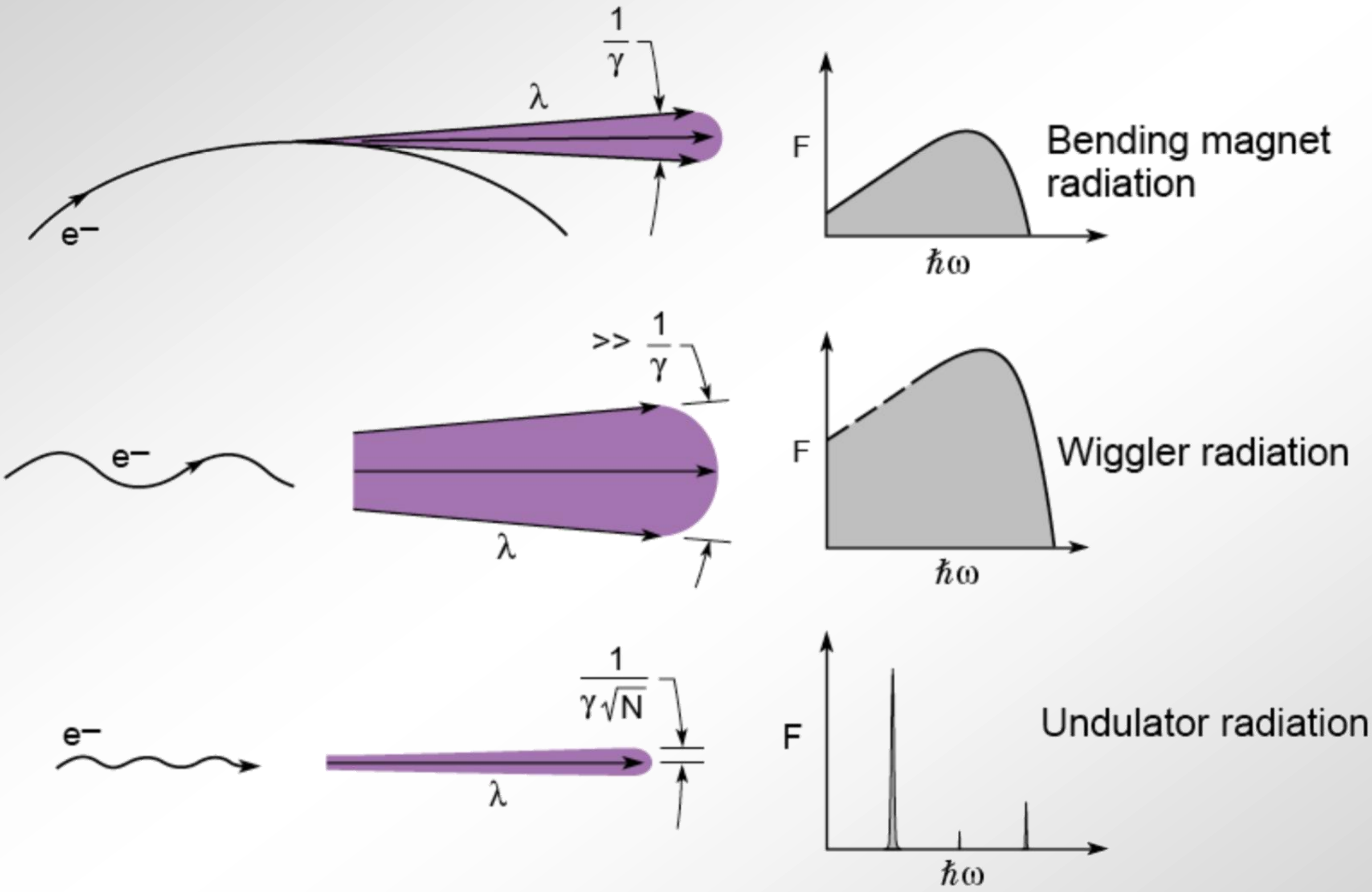
Source: W. Graves, MIT

Parameters of proposed MIT source @ 12 keV

Parameter	0.1% Bandwidth	5% Bandwidth	Units
Average flux	2×10^{10}	5×10^{11}	photons/s
Average brilliance	7×10^{12}	2×10^{12}	photons/(s .1% mm^{2}mrad^2)
Peak brilliance	3×10^{19}	9×10^{18}	photons/(s .1% mm^{2}mrad^2)
RMS horizontal size	2.4	2.5	microns
RMS vertical size	1.8	1.9	microns
RMS horizontal angle	3.3	4.3	mrad
RMS vertical angle	3.3	4.3	mrad
Photons per pulse	2×10^5	5×10^6	
RMS pulse length	490	490	fs
Repetition rate	100	100	kHz

Can be useful for some experiments

Light sources provide three types of SR



Number of photons emitted

- Since the energy lost per turn is

$$U_0 \sim \frac{e^2 g^4}{r}$$

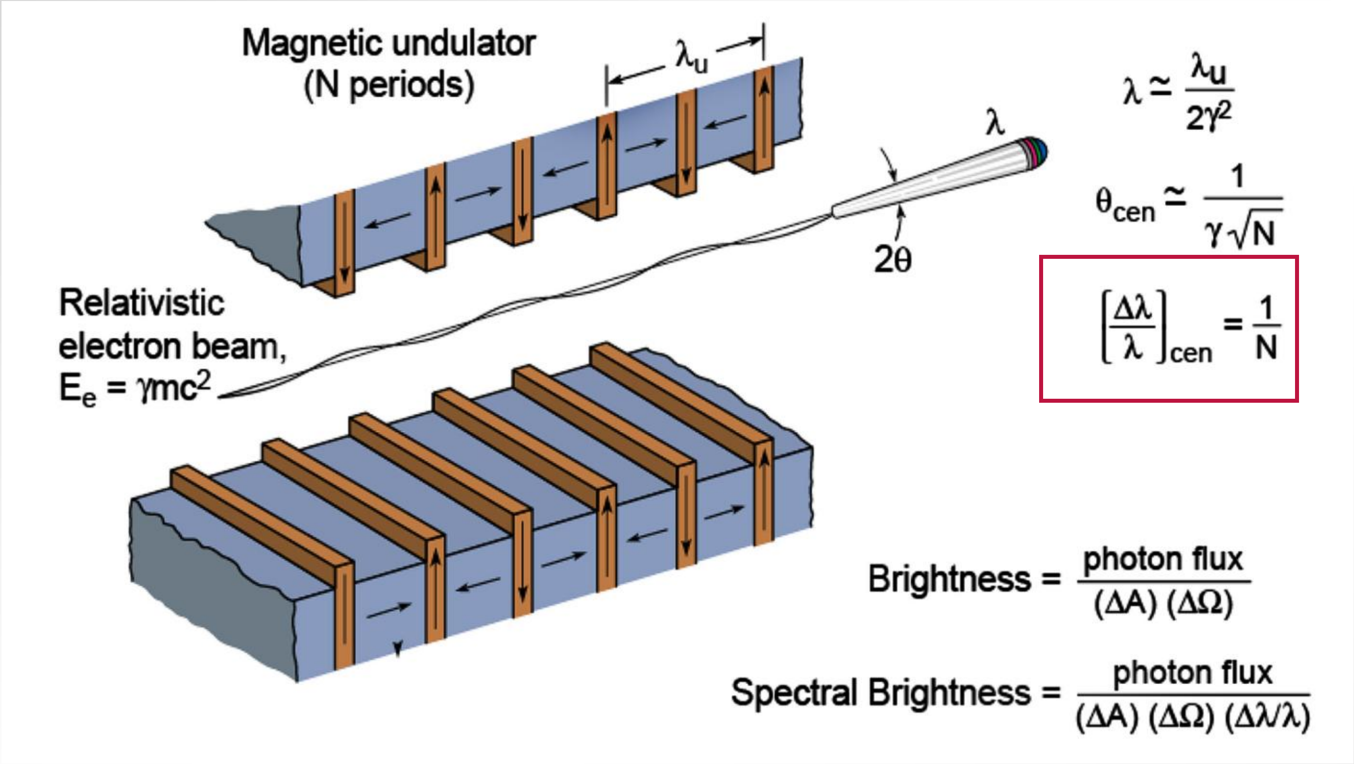
- And average energy per photon is the

$$\langle e_{photon} \rangle » \frac{1}{3} e_c = \frac{\hbar w_c}{3} = \frac{1}{2} \frac{\hbar c}{r} g^3$$

- The average number of photons emitted per revolution is

$$\langle n_{photon} \rangle » 2pa_{fine} g$$

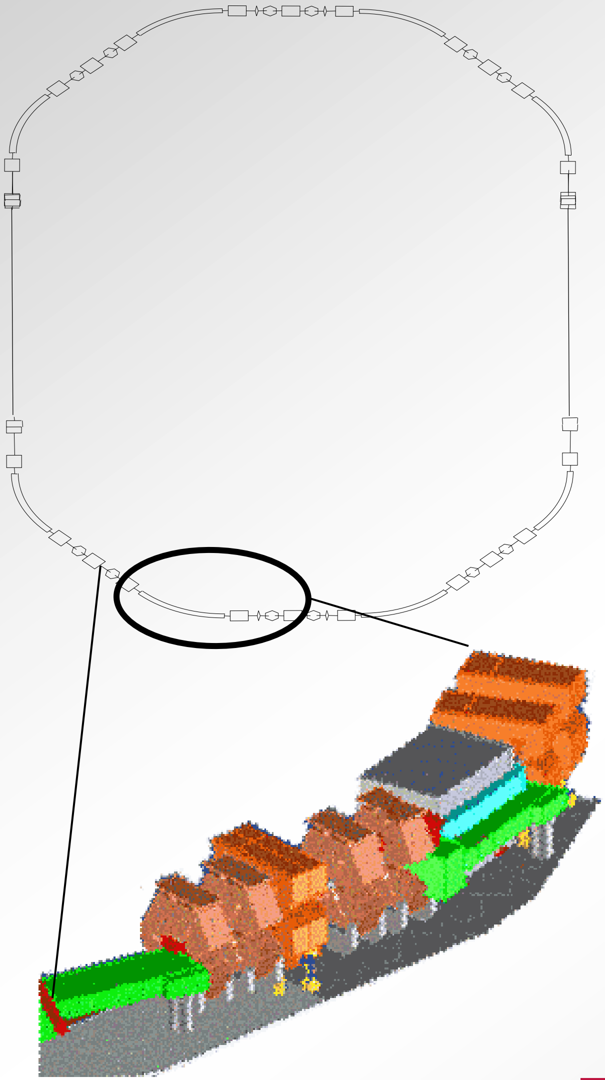
Light sources add radiation from many small bends for brighter X-rays



- But the number of undulator photons is still limited by

$$\langle N_\gamma \rangle \approx \Theta_{bending}\, \alpha_{fine}\, \gamma N_e$$

Approach 1:
Diffraction limited storage rings



- 100 x brighter than existing rings
  - Ideal for structural studies
  - Extremely stable, Many simultaneous users

The U.S. needs a diffraction limited,

hard X-ray source to remain competitive

BUT cannot access ultra-fast processes

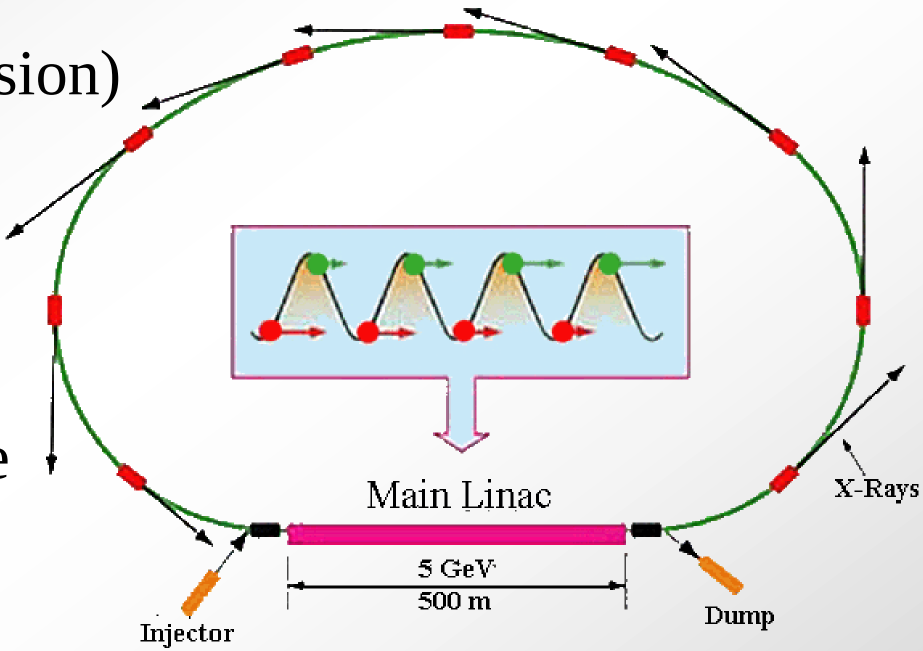
- Pulse length in rings (2p - 50 ps) is set by
  - Natural energy spread
  - Coherent synchrotron radiation
  - Instabilities

These effects take many revolutions
to spoil the beam

==> *Discard the beam after using*

Approach 2: Energy Recovery Linacs
(Hard X-rays ==> ~ 5 GeV electrons)

Synchrotron light source
(pulsed incoherent X-ray emission)



Pulse rates – kHz => MHz

X-ray pulse duration ~ 1 ps

High average e-beam brilliance & e-beam duration ~ 1 ps

⇒ One pass through ring
⇒ Recover beam energy
⇒ High efficiency

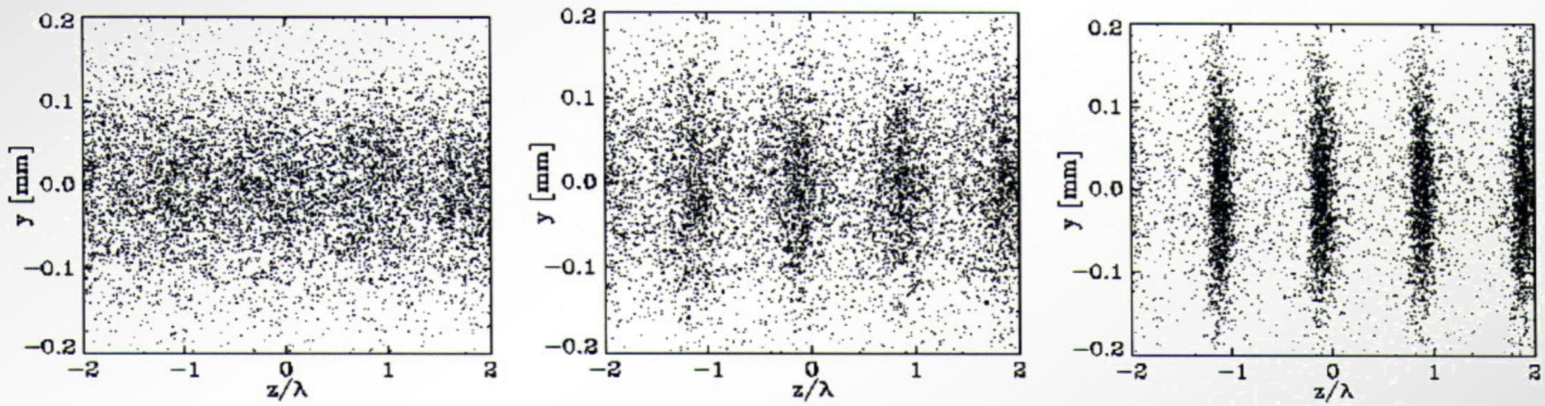
⇒ Superconducting RF optimized for CW operation

Pulse duration & ΔE limited (> 50 fs at 0.1% bandwidth) by coherent synchrotron radiation in the arcs

To get brighter X-ray beams
we need another great invention

- The Free Electron Laser (John Madey, Stanford, 1976)

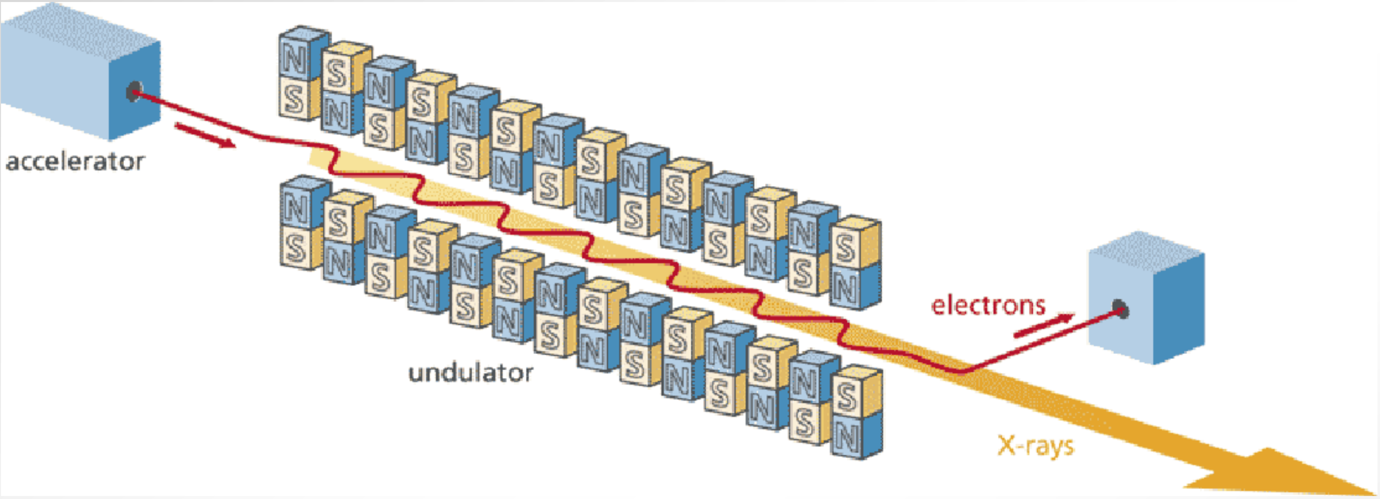
- Physics basis: *Bunched electrons radiate* *coherently*



START *MIDDLE* *END*

- Madey's discovery: the bunching can be self-induced!

The undulator couples the EM field & beam



- Wiggling the electron beam ==> $J_\perp$
- $J_\perp \bullet E_\perp$ transfers net energy from the electron beam if the radiation slips 1 optical period per wiggler period
- This bunches the beam ==> coherent emission & gain

EM field can be external imposed OR
it can be the incoherent synchrotron radiation from the beam

The pendulum equation of the FEL

- The equations of motion for individual electrons,

$$\frac{d^2x}{dt^2} = |A|\sin(x + j)$$

- Is coupled to the wave equation for the electromagnetic field.

$$\frac{dA}{dt} = - J\left\langle e^{-ix} \right\rangle$$

- Non-dimensional parameters, A and J, are proportional to the optical field strength and the current density, respectively.
  - The current density, J, determines the rate of change of the laser field, A.
  - The EM field phase, ϕ, is the phase of the complex scalar, A.
  - The electron phase, x, with respect to the EM and wiggler field is

$$x=(k_w-k)z - \omega t.$$

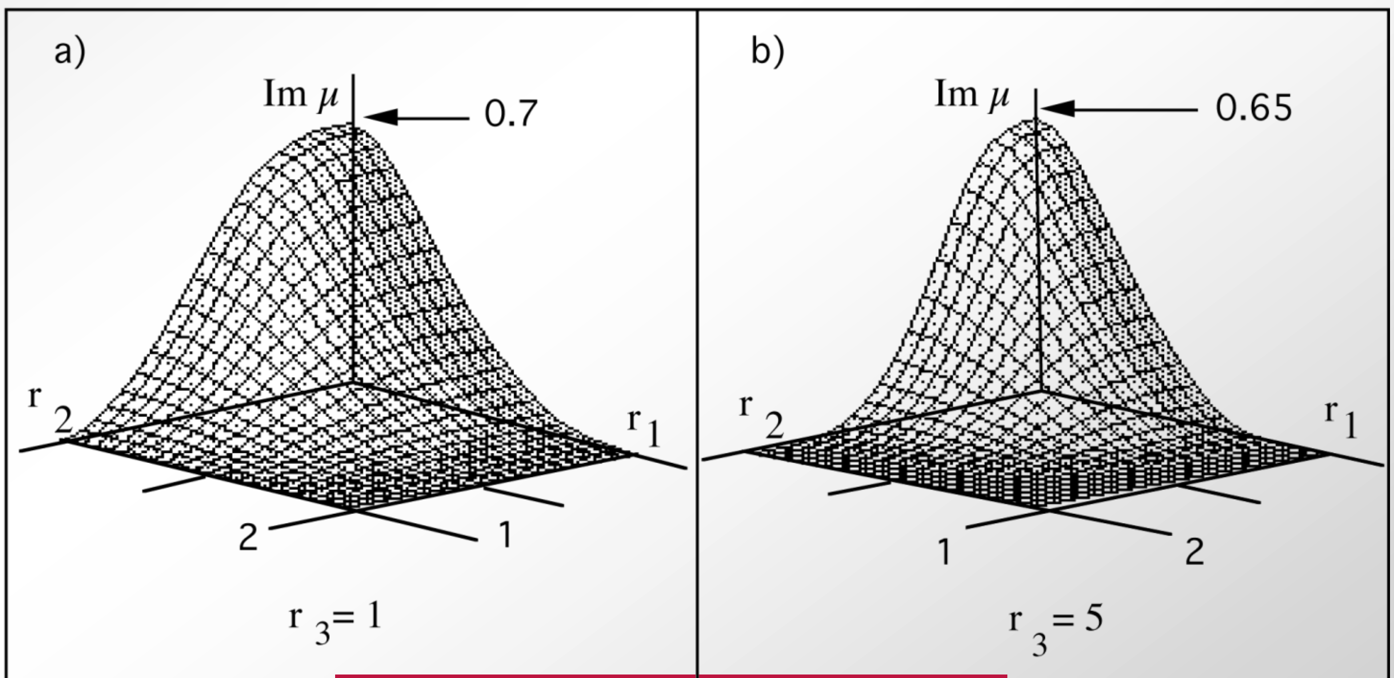
The simulation will show us the bunching & signal growth

Scaling FEL performance:
1-D, cold beam limit

❖ Exponential growth length

$$P = P_o e^{z/L_g} \quad \text{where} \quad L_G \approx \frac{\lambda_w}{4\pi\rho\ \mathrm{Im}(\mu)}$$

In the cold-beam, 1-D limit, Im(μ) = √3/2.



- The dimensionless vector potential is

$$a_w = \sqrt{2} * K = \sqrt{2} * 0.934 * B(T) * \lambda_w(cm)$$

- The relativistic plasma frequency is $\omega_p^2 = \dfrac{4\pi n_e r_e c^2}{\gamma^3}$

$$\rho = \left(\frac{a_w \omega_p \lambda_w}{8\pi c} \right)^{2/3} \propto \frac{I^{1/3} B_w^{2/3} \lambda_w^{4/3}}{\gamma}$$

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + a_w^2\right) \quad \textit{(resonance condition)}$$

Basic Free Electron Laser Physics

Resonance condition:

Slip one optical period per wiggler period

FEL bunches beam on an optical wavelength at *ALL* harmonics

Bonifacio et al. NIM A293, Aug. 1990

Gain-bandwidth & efficiency ~ ρ

Gain induces $\Delta E \sim \rho$

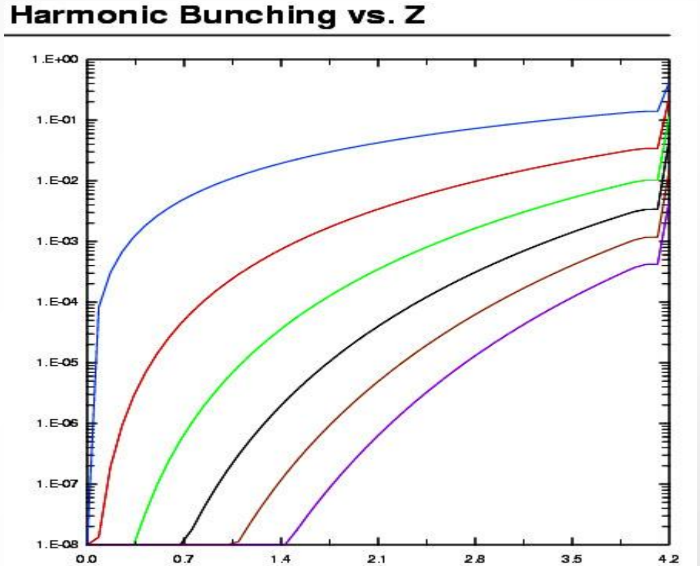
1) Emittance constraint

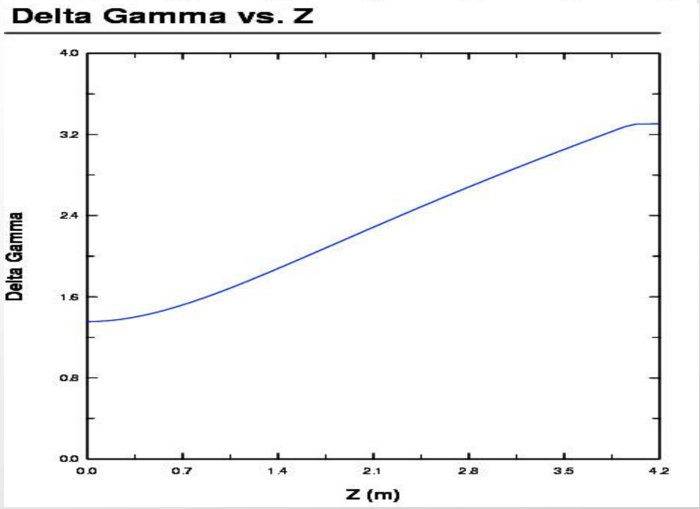
Match beam phase area to diffraction limited optical beam

2) Energy spread condition

Keep electrons from debunching

3) Gain must be faster than diffraction



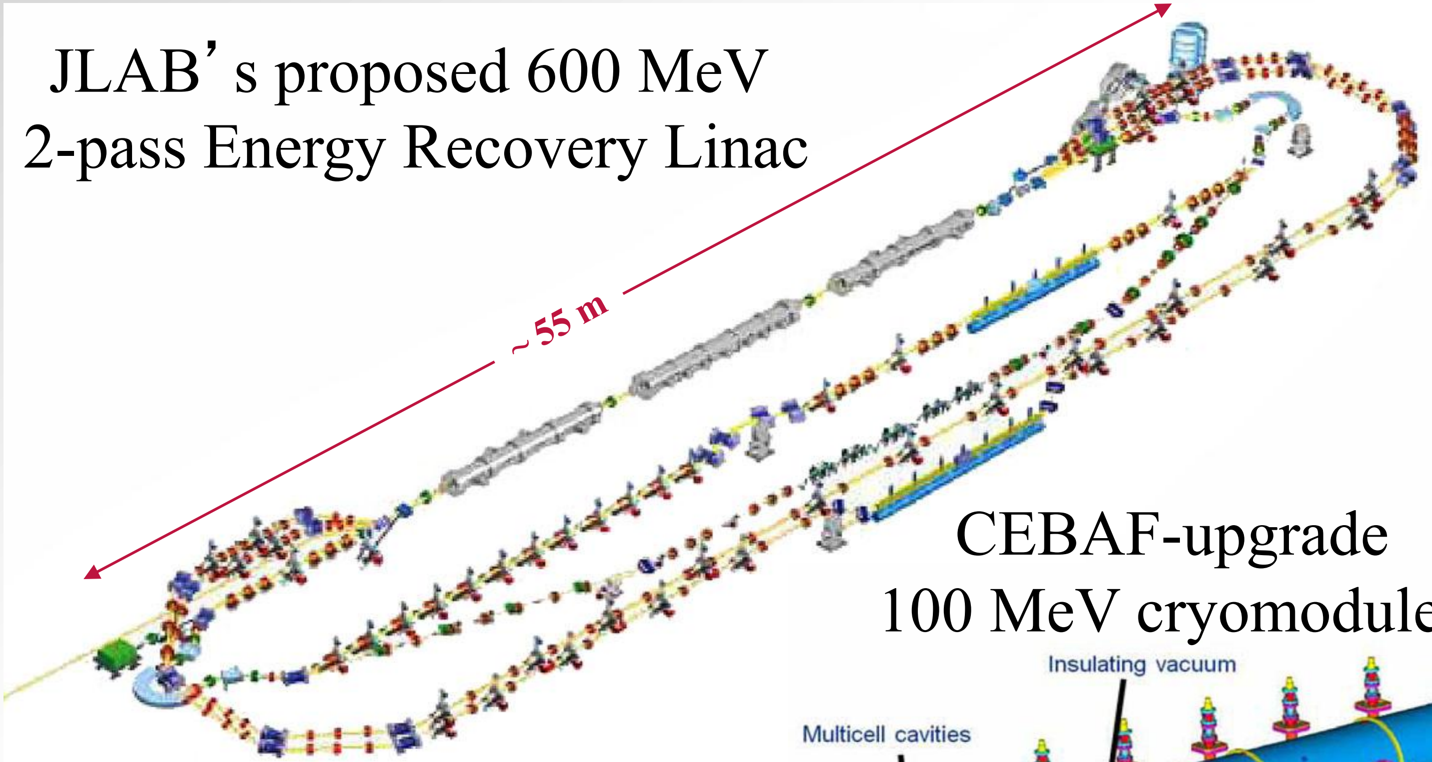


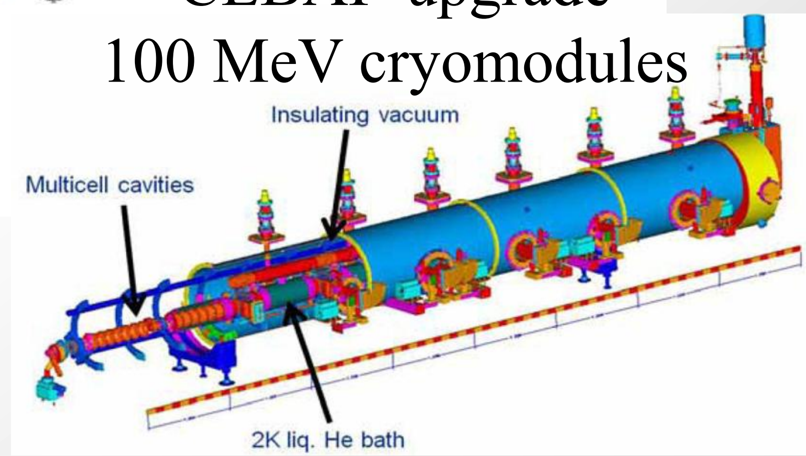
A sample 92 eV FEL
(modified 1-D estimate)

BEAM parameters			**FEL inputs**		**FEL performance**	
Italics denote inputs						
Accelerator			**Wiggler**			
Energy (GeV)	6.00E-01	*	*Wiggler period (cm)*	2.0	Wavelength (nm)	**13.48**
Peak current (kA)	1.20	*	*B-actual (T)*	0.70	photon energy (eV)	92.0
Pulse length (ps)	5.0E-01		Limiting B (T) SmCo	0.8		
Norm Emit (mm-rad)	0.0004		Limiting B(T) NdFe	0.9	rho-electron	**6.59e-03**
rep rate (Hz)	1.25E+06		Wiggler gap (cm)	0.58	L-gain (power) (m)	**0.34**
Pulse length (mm)	0.1		A-w	**0.93**	N-wig/L-g	**17**
N-part	3.8E+09		Wiggler length (m)	**5.1**	(N-w/L-g) - Zol	194
Charge (nC)	0.60		N-periods, sat	255	(N-wig/L-g) - 1D	7
P-beam (GW)	720		Gain lengths)	15.03		
Num. Bunches	1				P-sat-empirical (GW)	**0.8**
Bunch spacing (ns)	2.5	*	**Focusing**		Convert efficiency	0.04%
<I>-macro (kA)	2.4E-04		*h*nat-focus =*	0.2	P-empir/P-1D	0.17
Average I (A)	**7.50E-04**		f-c	4.4e-06	P-noise (W)	92.7
Σ-p to wiggler(%)	0.130		R/r-nat	0.45	Coherent energy (mJ)	0.40
ZemitN (m)	7.2E-08		h-"opt" (ß*=1)	**1.00**	I-sat-pk (W/cm^2)	7.5e+13
					Brightness (W/Str)	8.9e+15
Derived beam values			**FEL constraints**			
Gamma	1175		4ΔE/rho*E - R1	**0.79**	Photons / pulse	**2.7e+13**
Emittance (m-rad)	3.0E-10		4π*emit/lambda- R2	**0.28**	Photons/cm^2	1.3E+18
Pulse energy (J)	0.36		L1-g/Z-r - R3	**1.76**	Spectral brilliance	**3.6e+27**
Brightness (a/m2-r2)	2.0E+15				Pulse energy (μJ)	4.0e+02
					Average power (W)	**5.0e+02**

However, *the beam power is 450 kW to produce 500 W of EUV*

The key to efficiency:
Recovery of used beam energy





Dumping beam at 5 MeV recovers >98% of the beam power

Some typical CW cost estimators (based on JLab upgrade)

- Frequency 1.5 GHz
- 15-20 MV/m CW (~10 MV/m real estate gradient)
  - $Q_o \sim 10^{10}$ at 20 MV/m (has been demonstrated)
- CM Cost ~$2.6M*/100 MeV (Jlab upgrade module)
- RF ~$1.7M/cryomodule (8x13kW RF stations) @~1mA
  - At 10 mA (claiming some efficiency) use $10M
- 2K cryogenic plant ~$30M/GeV (4.5 kW CHL2)
  - Excl. distribution & cold box . Use $50M for new site?

==> ~$176M per GeV of cryomodules (excluding tunnel costs)

- ~$17.6/watt beam power (10ma @ 1GeV =10MW)

*FY08 loaded dollars, actual 12 GeV project costs will be known soon

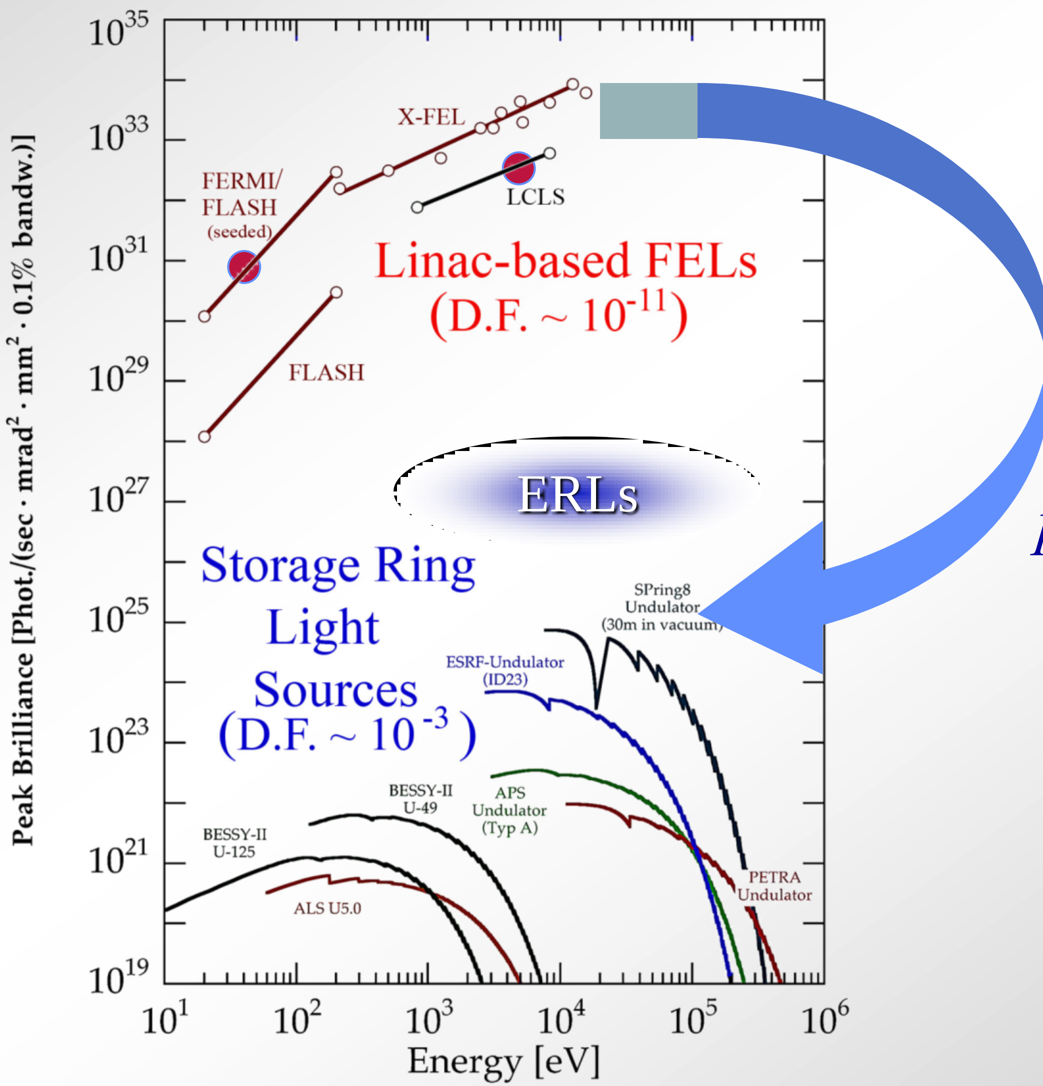
Source: R. Rimmer

Rough estimate of hardware costs
Based on Rimmer guidelines

Cost element	
Injector	$3,000,000
Linac structure	$8,000,000
RF	$5,100,000
Linac mechanical	$3,000,000
Cryoplant	$15,000,000
Low energy arc	$6,200,000
High energy arc	$5,000,000
FEL / wiggler	$5,000,000
Return Legs	$4,700,000
Spreaders	$5,000,000
Beamines	$3,000,000
Beam dump	$150,000
Diagnostics	$500,000
Controls	$750,000
Mgmt & Commissiong	$6,440,000
Sub-total	$70,840,000
35% Contingency	$24,794,000
Total	$95,634,000

Such a machine is largely within the capabilities of US industry

State of technology: VUV to X-ray sources



Duty factor correction for pulsed linacs

Short pulse techniques

Ultra-short X-ray pulses with low charge electron bunches 1- 10 pC

UCLA studies:

Smaller emittance (by 10 x) & very short, ~ 1 fs or less, electron bunches can be produced by dropping the bunch charge to 1 -10 pC

Electron beam brightness can be increase by a factor 10 - 100 x

peak current

$$B = \frac{I}{\varepsilon_{\perp}^{2}\,\sigma_{\gamma}}$$

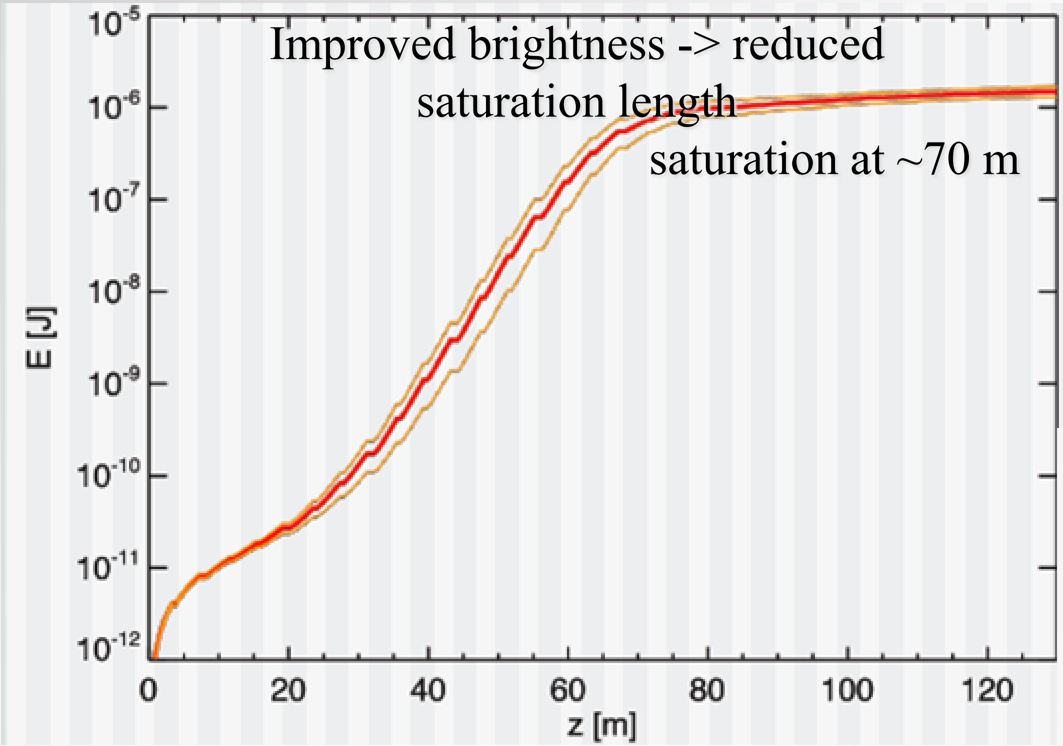
Normalized slice emittance

Slice energy spread

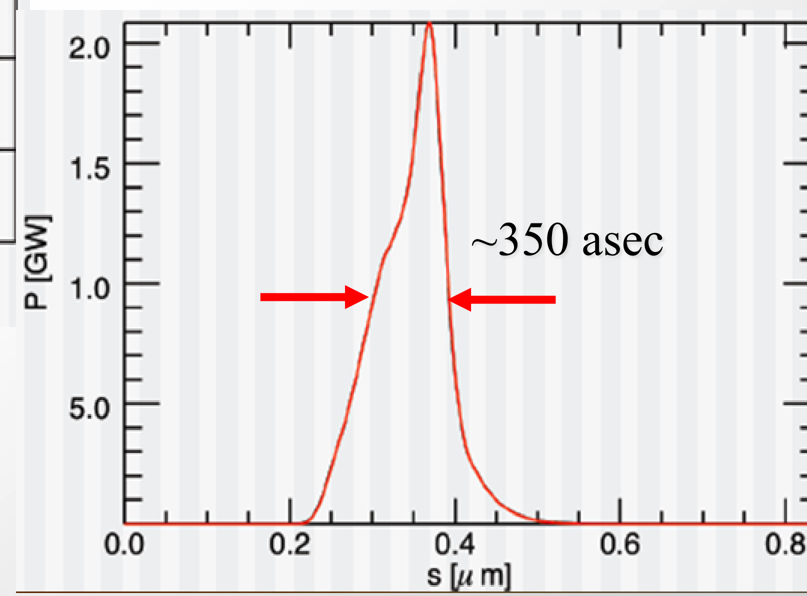
Road to compact FELs

J.B. Rosenzweig et al., NIM A 593, 39 (2008

Simulation for LCLS with 1 pC



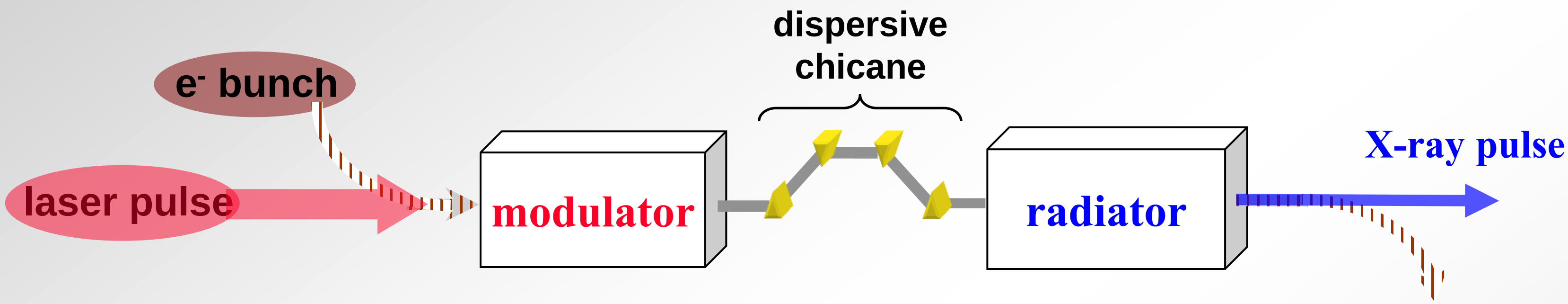
Difficult to synchronize to external source due to electron bunch arrival time jitter



Allows for multi-bunch operation in non-SLED configuration

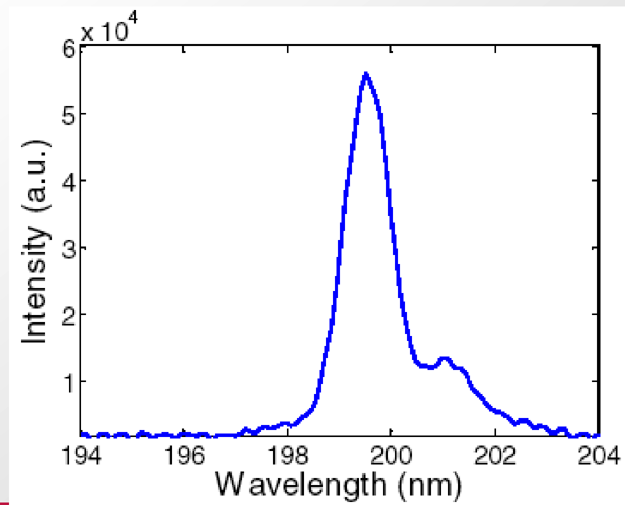
J.B. Rosenzweig, FEL workshop, LBNL, November 2008

High-gain harmonic generation (HGHG)



$$\lambda_{laser} = \lambda^{modulator}_{x-ray} = \frac{\lambda^{modulator}_{undulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

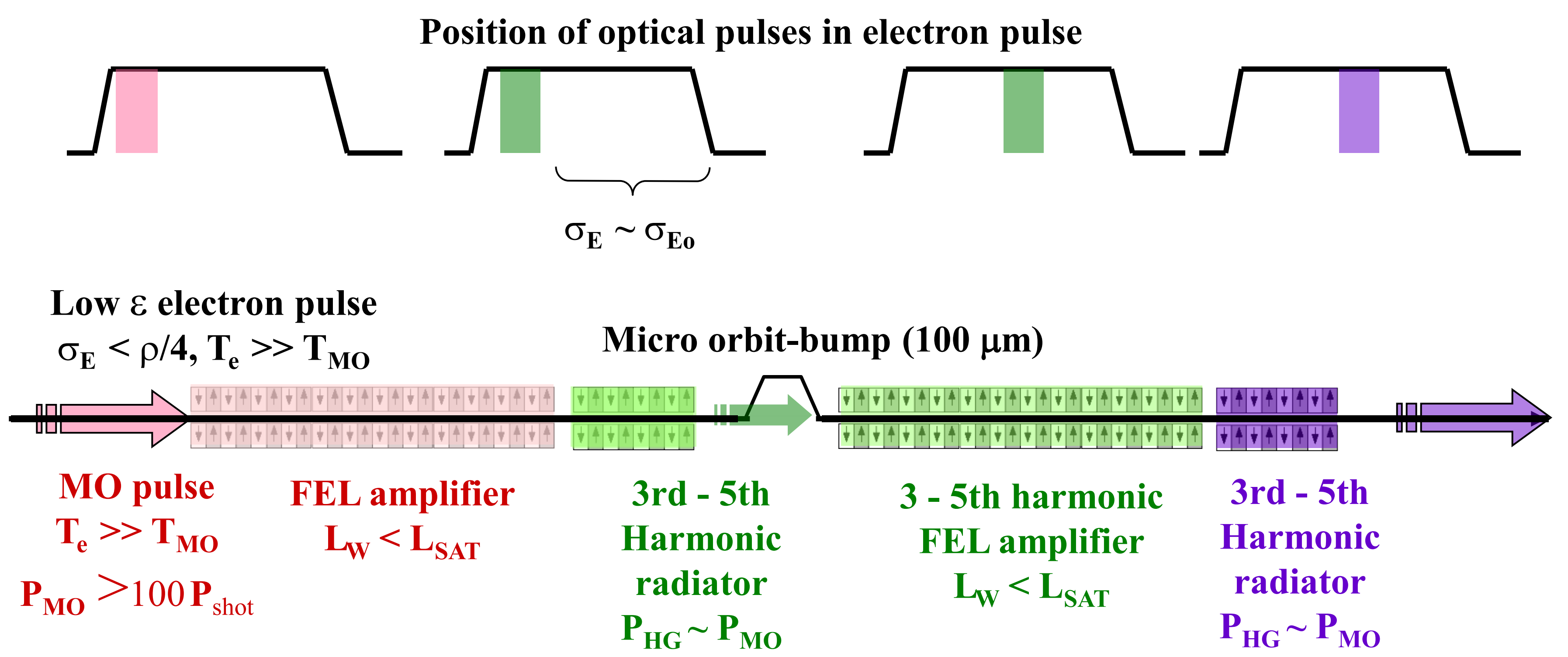
$$\lambda^{radiator}_{x-ray} = \frac{\lambda^{modulator}_{x-ray}}{n} = \frac{\lambda^{radiator}_{undulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



L.-H. Yu et al, Science 289 932-934 (2000)
L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)

Multiple-stage, Super-Radiant Harmonic Cascade Amplifier

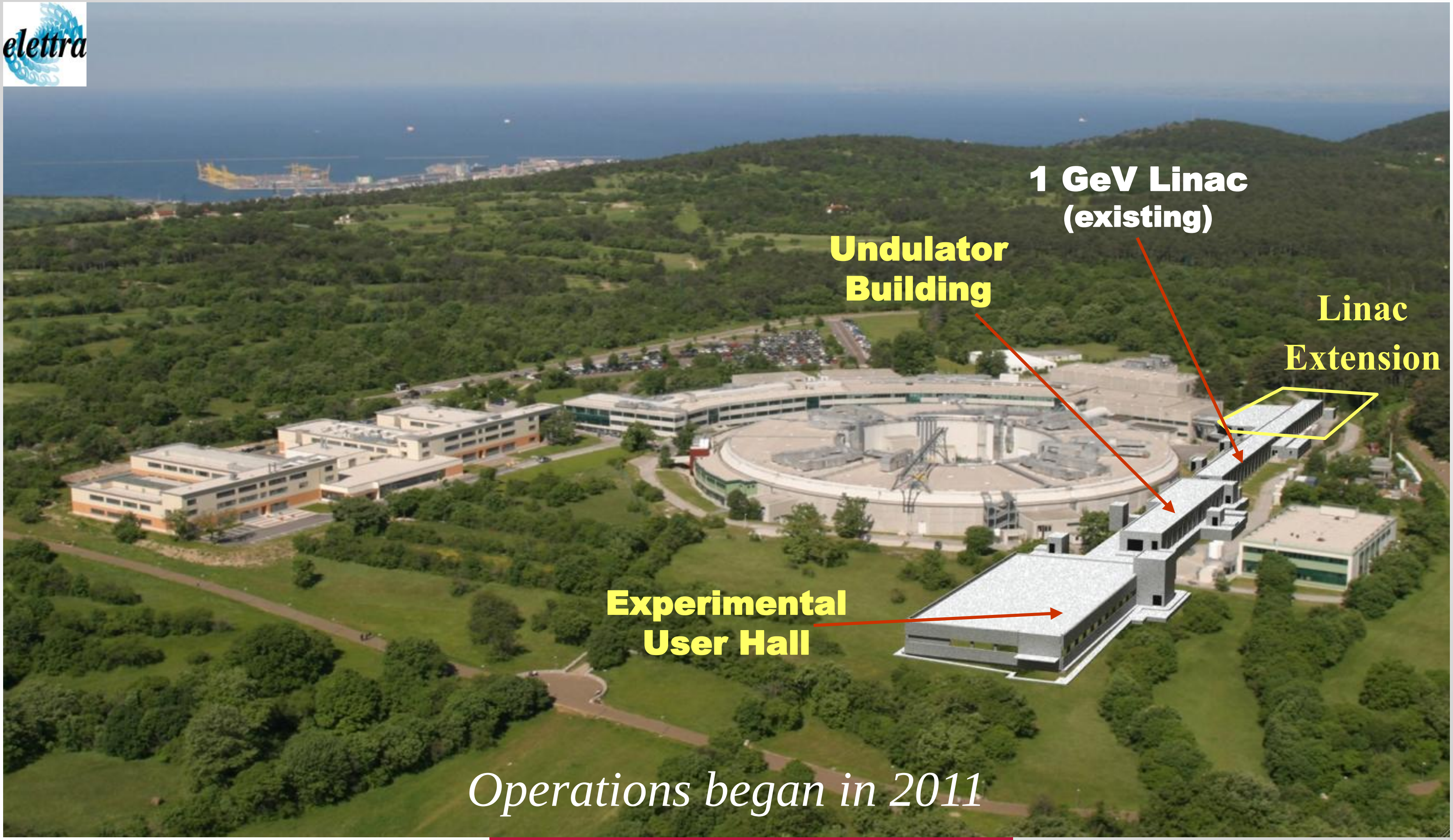
Requirements:



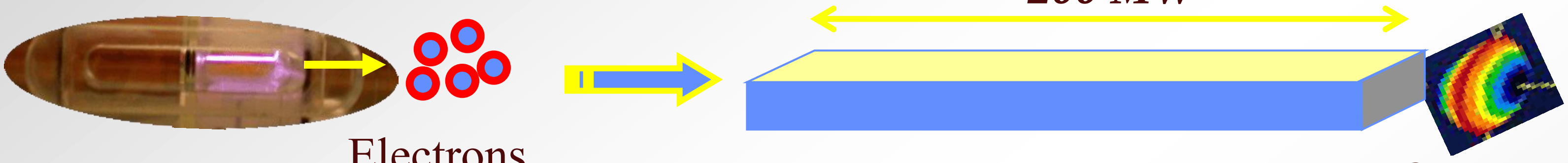
FEL scheme for generation of precisely timed pulses of 10^8 - 10^{12} photons/pulse over range of 20 - 2 nm

Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

FERMI @ Elettra: a seeded, HGHG cascade



Simple undulator for water window FEL

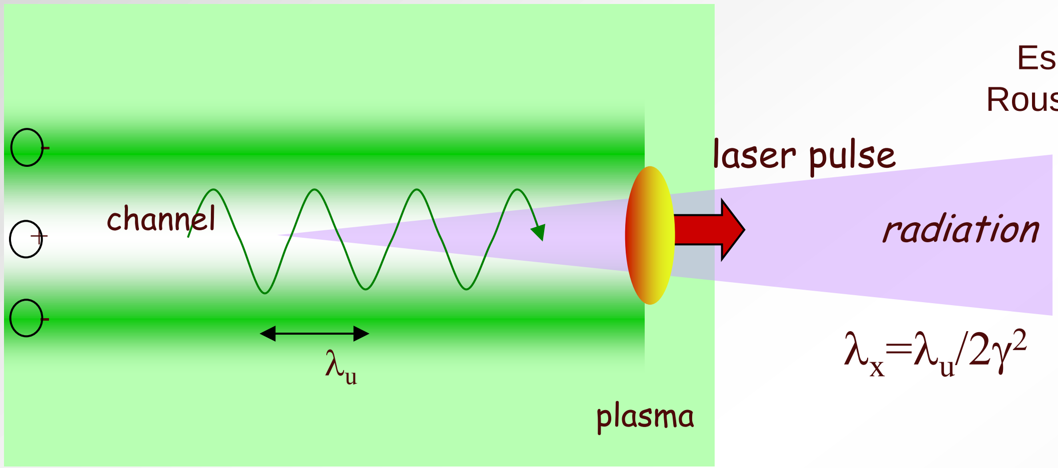


- Channel guided LWFA with capillary:
    - 1 GeV, ~ 10 fs electron beam
    - Charge in femtosecond bunch ~0.5 nC*
- TW-waveguide undulator for fs x-ray generation

Pellegrini

NX-rays from betatron motion & Thomson scattering

Betatron oscillations:



Esarey et al., Phys. Rev E (2002)
Rousse et al., Phys. Rev. Lett. (2004)

<u>Strength parameter</u>

Betatron: $a_\beta=\pi(2\gamma)^{1/2}r_\beta/\lambda_p$

Thomson scattering: $a_0 = e/mc^2A$

Radiation pulse duration = bunch duration

Dawn of a new age of radiation science

- Tailor accelerator types to meet user requirements
  - SCRF: High average data rates, ultra-stable
  - S-band & C-band RF: compact, faster, cheaper (?) 1st generation
  - Laser driven: Very compact, hyperspectral

We have the keys in hand