Nuclear Engineering 282, UC Berkeley

Charged Particle Sources and Beam Technology

Light Sources II
Future Accelerators / Current Topics of R+D

Christoph Steier

Lawrence Berkeley National Laboratory
Accelerator and Fusion Research Division

November 23, 2009

Topics

- Light Sources
  - —4th generation
    - Ultimate Storage Rings
    - ERLs
    - FELs (seeded)
  - —R+D issues
    - Sources
    - Beam Dynamics

- Summary

Lectures are posted at
http://als.lbl.gov/als_physics/robin/Teaching/NUC%20282c.html

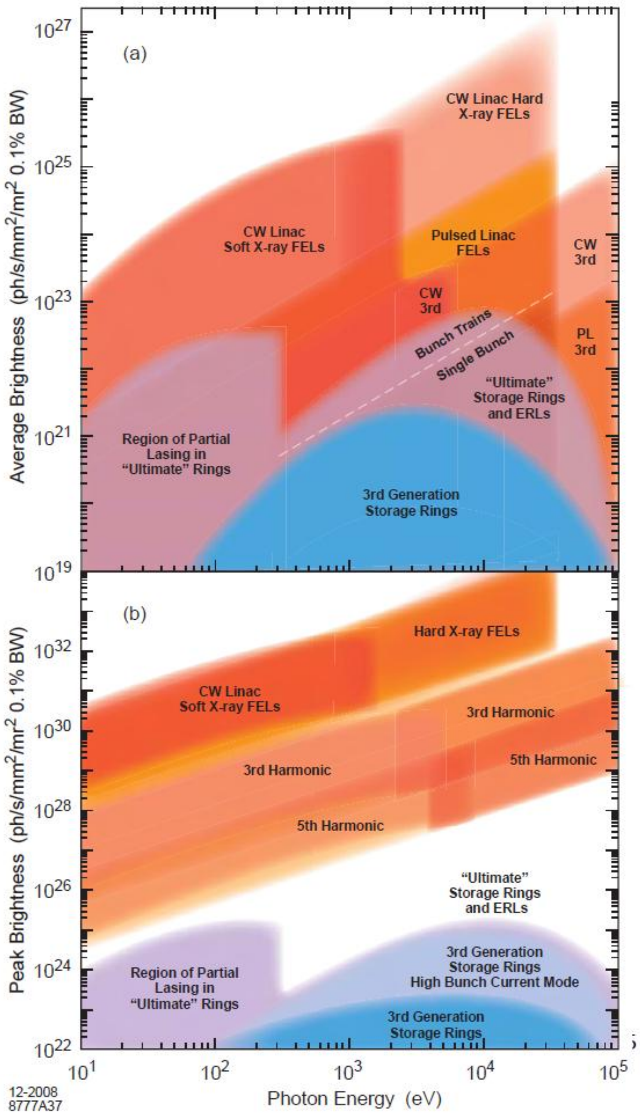
Synchrotron Radiation Facilities

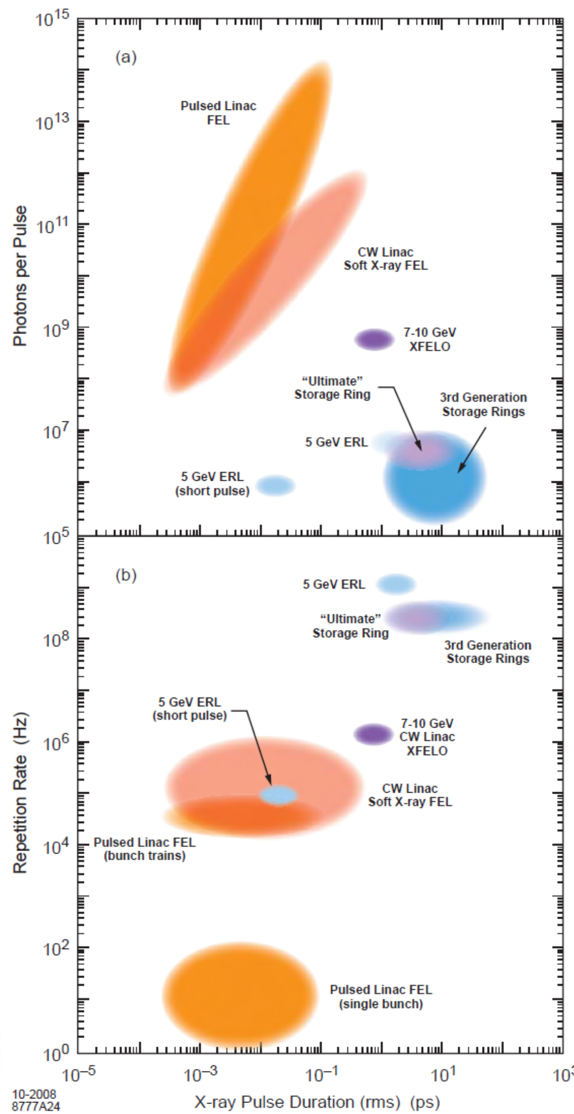
~ 50 Synchrotron Facilities in the world

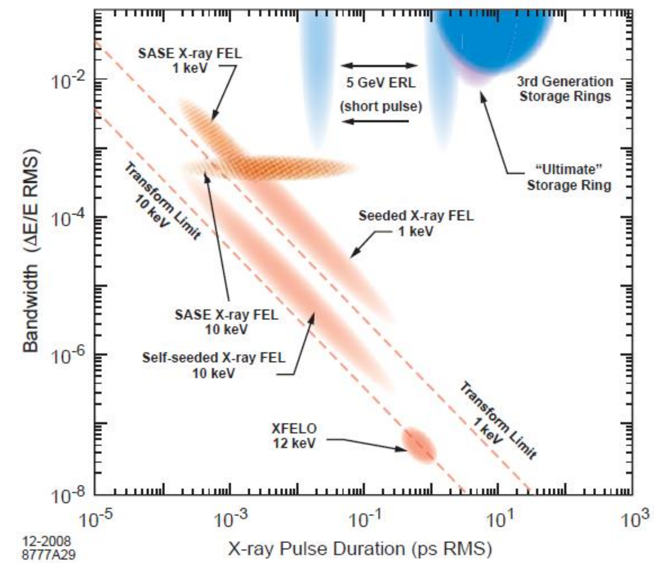
Motivation

- 3rd generation light sources are extremely successful
- Several other concepts exist and a first generation of FEL facilities is in operation or under construction
- Two new major projects are under way in DOE (LCLS starting user operations, NSLS-II under construction)
- Recent ideas open potential for facilities with capabilities beyond those currently under way – currently formulating accelerator R+D program to get there
- It is important to understand the science case and the needs of user experiments in terms of performance parameters and trade-offs of future facilities to prioritize the R+D program

Parameter Range of SR Sources







3rd generation light sources

- Highly successful and productive scientific facilities
- Decades of development, highly optimized
  - ⇒ Optimized performance for many applications - difficult to achieve additional order of magnitude improvement

- Flux is constrained
  - ~ constant x current x i.d. length
- Brightness then determined by optics
  - – lattice squeezes electron beam close to diffraction limit
- Undulator bandwidth limited by electron beam energy spread!! – Limited number of useful undulator periods.

✓ Average flux
▪ Average brightness
✓ Pulse repetition rate (~500 MHz)
✓ Tunability
✓ # beamlines
✓ Beam stability
• Spatial coherence
⇓ Temporal coherence
⇓ Ultra-short pulses
⇓ Synchronization

3rd Generation Rings (Current and Future)

SLS (2002) 2.4GeV

ε_x= 3.9 nm, ε_y=72 pm, I=300 mA

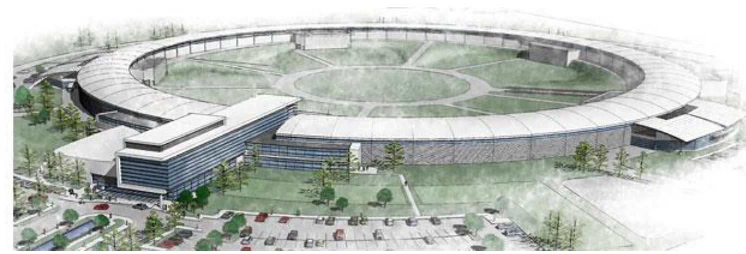
ALS (1993) 1.9GeV

ε_x= 6.3 (2.0) nm, ε_y=30 pm, I=500 mA

SpearIII+CLS (2004)

3/2.9GeV

ε_x= 18.9 nm, ε_y=100 pm, I=200(500) mA



NSLS-II (2013) 3GeV

ε_x= 0.5 nm, ε_y= 10 pm, I=500 mA

Soleil (2006) 2.75 GeV

ε_x= 3.7/5.6 nm, ε_y=37 pm, I=500 mA

APS (1995) 7GeV

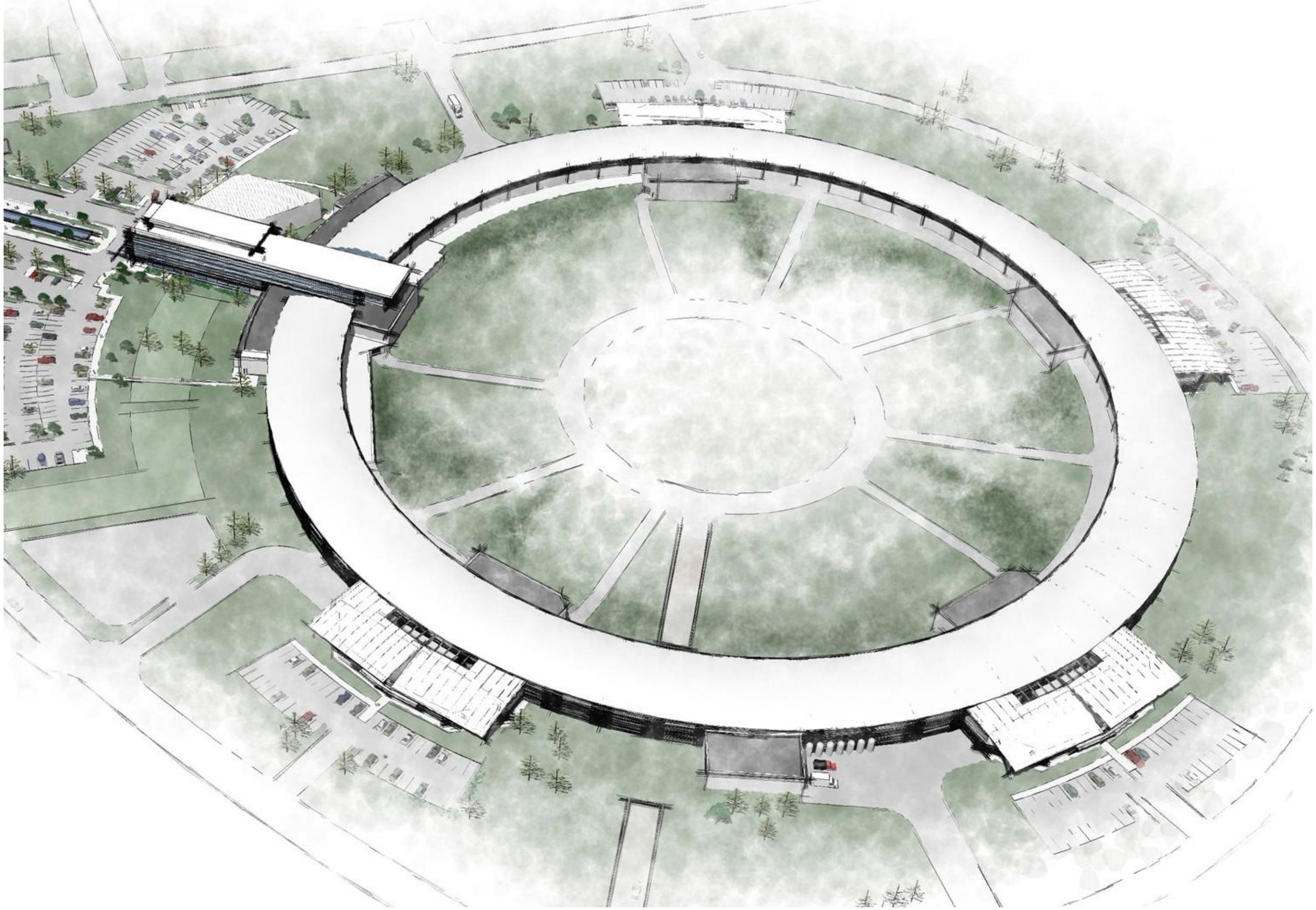
ε_x= 2.5/3 nm, ε_y=25 pm, I=100 mA

Diamond (2007)

3.0 GeV

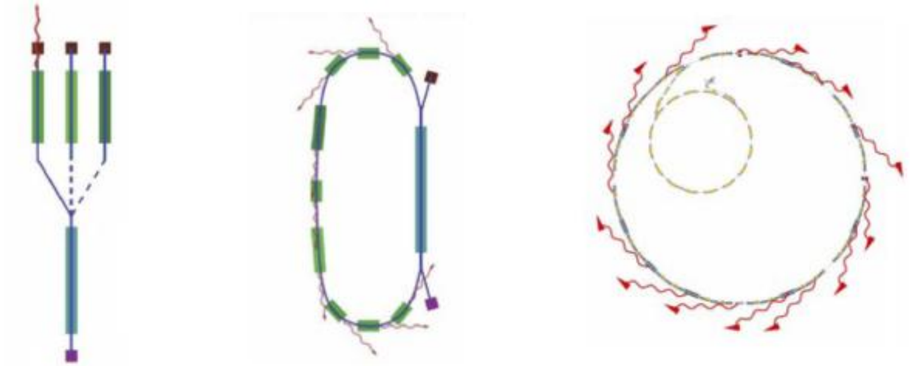
ε_x= 3.0 nm, ε_y= 30 pm, I=300(500) mA

Newest US Light Source: NSLS-II at Brookhaven (2013)



Outline - a variety of synchrotron radiation source concepts to pursue

- **(Ultimate) Storage rings**
- **Energy recovery linac (ERL)**
- **Free electron laser (FEL)**
- Laser wakefield accelerator
- Optical manipulation of electron beams



Figures of merit

- Average and peak flux
- Average and peak brightness
- Pulse repetition rate
- Temporal coherence
- Bandwidth
- Spatial coherence
- Pulse duration
- Synchronization
- Tunability
- # beamlines
- Beam stability

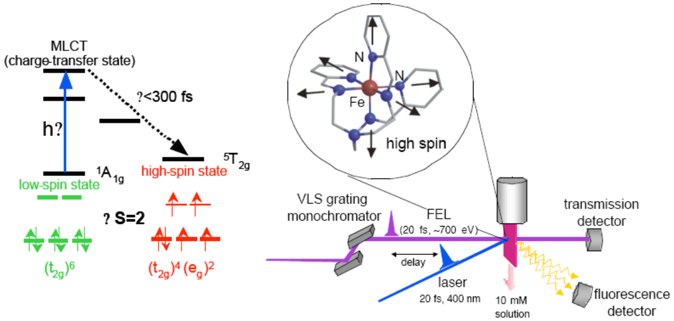
Future generations of light sources will likely utilize novel techniques for producing photons tailored to application needs

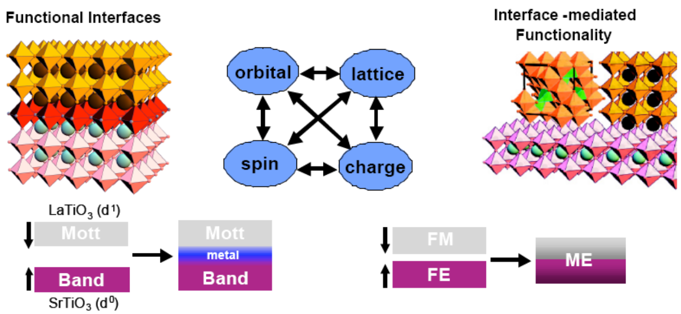
Different operating modes

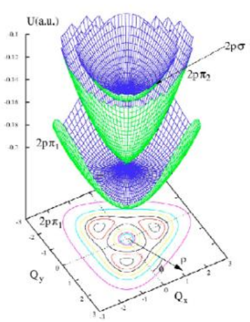
Different facilities

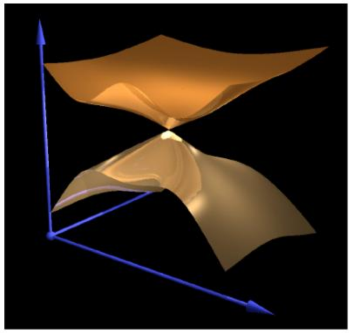
Science Drivers

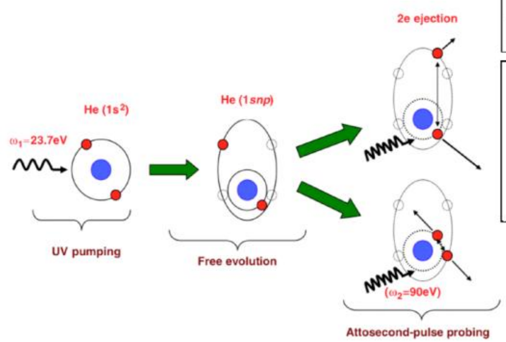
Performance Category	Quantification	Required for:
Ultrafast Time Resolution and Laser Synchronization	<100 fs and ~100 as	All dynamics studies - attosecond to picosecond time scales - duration/bandwidth control
High Repetition Rate	10-100 KHz	Time-resolved spectroscopy - high repetition rate for signal averaging - repetition rate limited by sample recovery/replacement - flux per pulse limited by damage and non-linear efffects Inelastic x-ray scattering Lensless imaging
High Average Flux	~10^{15} ph/s/0.1% BW (~ 3rd Gen. SR)	Time-resolved spectroscopy X-ray emission spectroscopy—RIXS/XES (at 0.5 eV resolution) - flux per pulse limited by damage and nonlinear effects
Very High Average Flux	>>10^{15} ph/s/0.1% BW (>> 3rd Gen. SR)	Inelastic x-ray scattering—IXS X-ray emission spectroscopy—RIXS/XES (<10 meV resolution) Lensless imaging - flux per pulse limited by damage and nonlinear effects
Tunability	100 eV – 10 KeV	X-ray spectroscopy (electronic/atomic structure) - soft x-ray: XANES, EXAFS (TM L-edges) - hard x-ray: EXAFS (TM K-edges)
Polarization Control	adjustable circular/linear	All x-ray dichroism spectroscopy
Coherence	Full transverse and longitudinal	Energy resolution (temporal transform limit) Chirped/shaped pulse experiments Lensless imaging (transverse coherence)
Stability	<10% pulse amplitude <$0.1\sigma_{x,y}$ alignment	Extraction of small signals from background

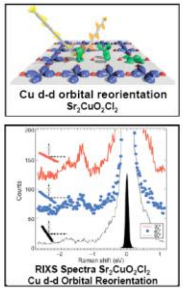


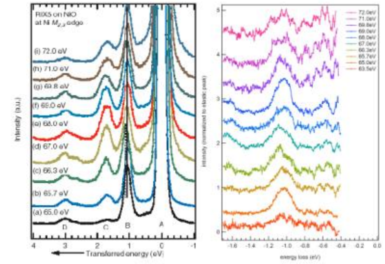






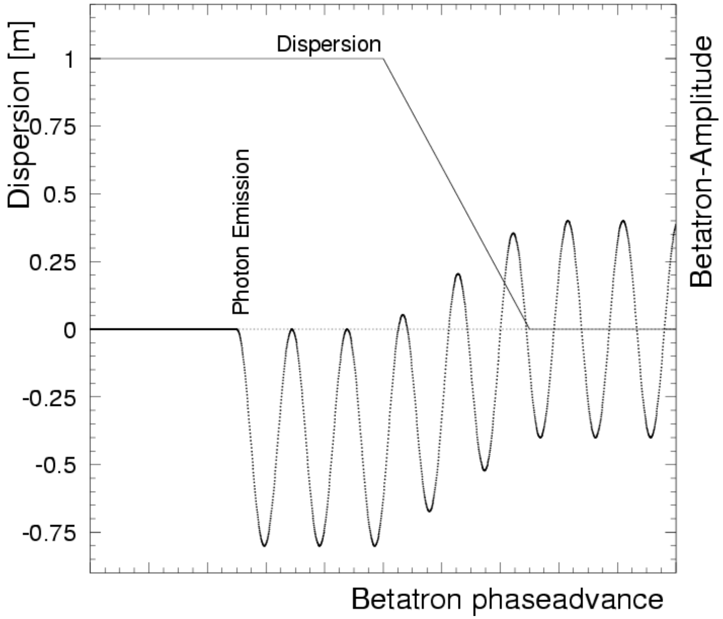






Reminder: Quantum Excitation

Particles change their energy in a region of dispersion undergoes increase transverse oscillations. This balanced by damping gives the equilibrium emittances.



The beam size is $\sigma_x = \sqrt{\beta_x \varepsilon + \left(D_x \frac{\sigma_e}{E} \right)^2}$

Horizontal emittance

- Horizontal Emittance is determined by random excitation and damping induced by synchrotron radiation in the magnetic fields (bending magnets and wigglers).

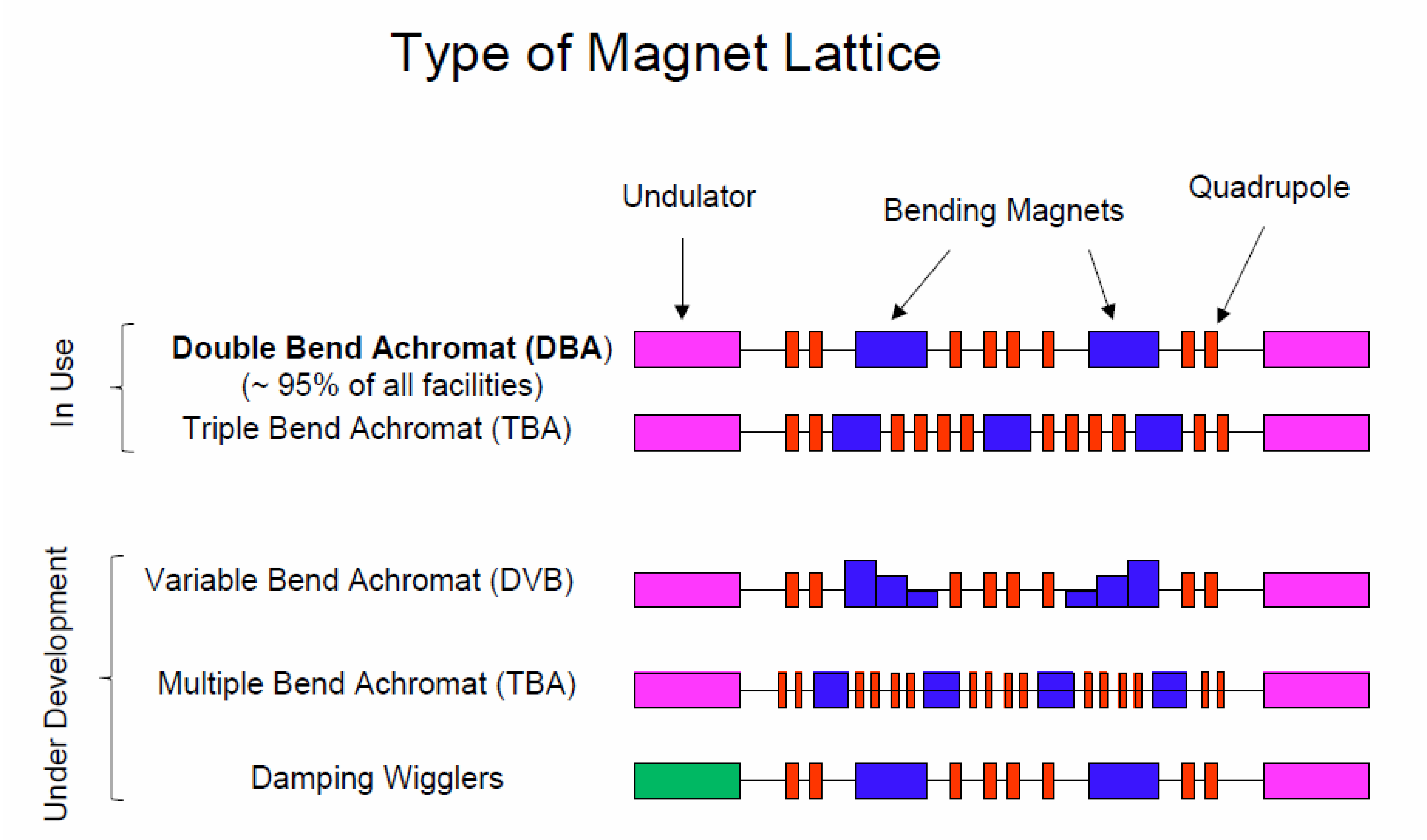
$$\varepsilon_x = Q_x \tau_x \,, \qquad Q_x \approx E^5 \oint B^3 \frac{\eta^2 + \left(-\frac{\beta_x'}{2}\eta + \beta_x \eta'\right)^2}{\beta_x} ds \,, \qquad \frac{1}{\tau_x} \approx J_x E^3 \oint B^2 ds$$

- => Minimize dispersion and horiz. beta function in the bending magnets and wigglers
- => Refocus the beam horiz. in each bending magnet
- => **Need space between each bending magnet !**
- For a lattice with no wiggler and N identical uniform field bending magnets :

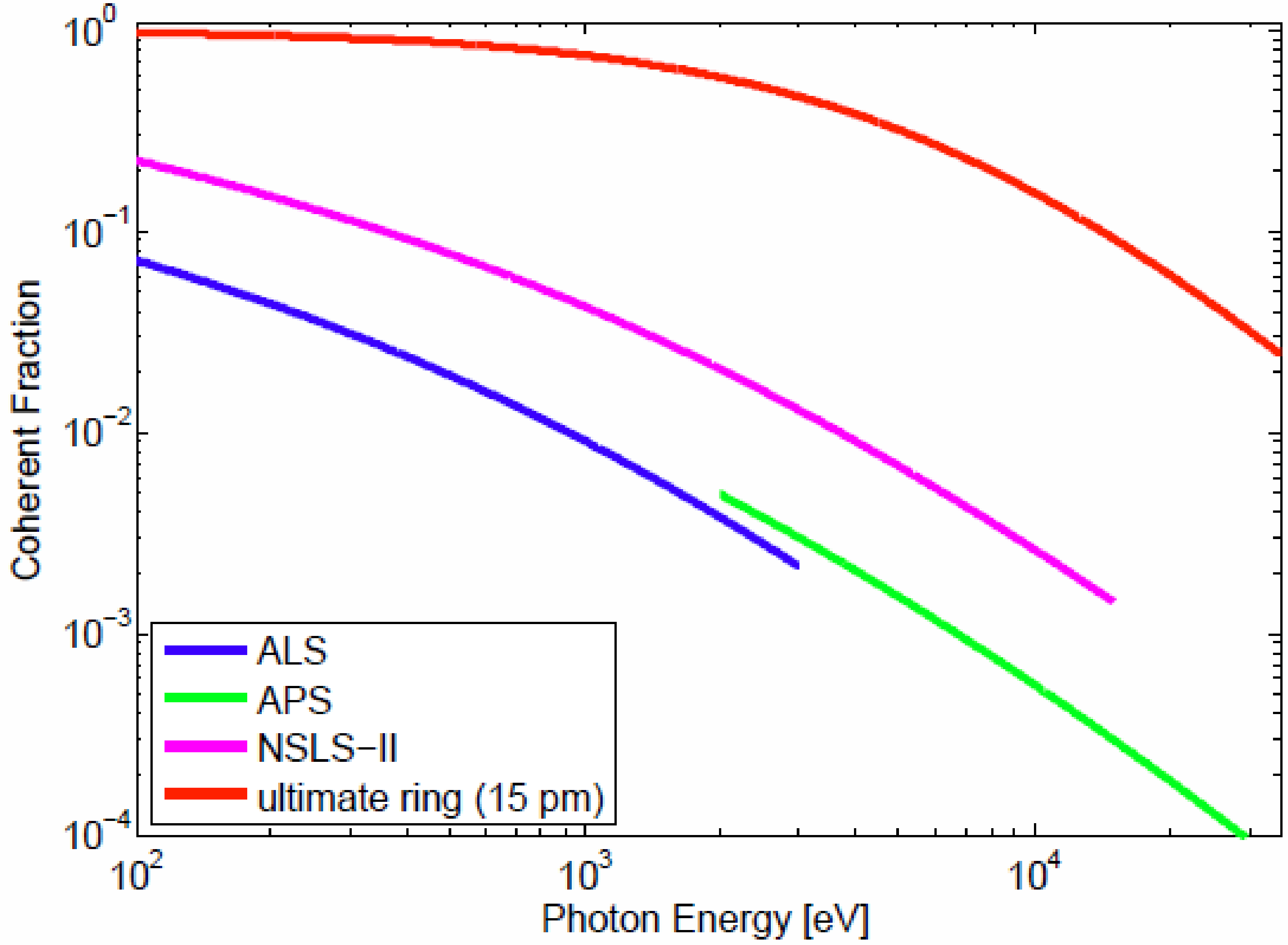
$$\varepsilon_x \approx F(Lattice)\frac{E^2}{N^3}$$

- Damping wigglers generate less dispersion => Lower emittance (for the same rms field)

Actual Lattice Options



Distinguishing Feature of ERL and Ultimate Storage Ring Proposals: Transv. Coherence



Challenge: Nonlinear Dynamics

Resonances can lead to irregular and chaotic behavior for the orbits of particles which eventually will get lost by diffusion in the outer parts of the beam.

Rule of thumb => Avoid low order resonances **(<~ 12th for protons and <~ 4th for electrons)**

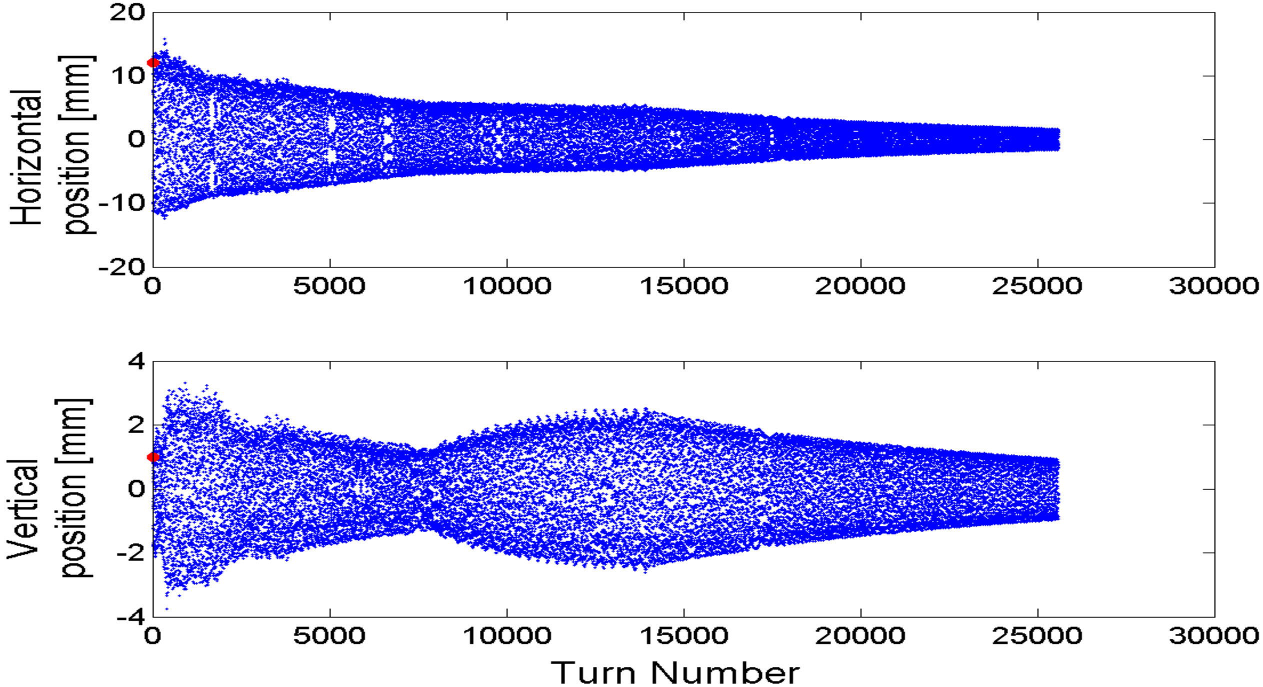
Unfortunately there is no simple way to forecast the real strength of a resonances without using a tracking code or through measurements

=> Tune scans
=> Frequency Map Analysis

Vertical orbit diffusion – On-energy example

Particles are lost in the vertical plane

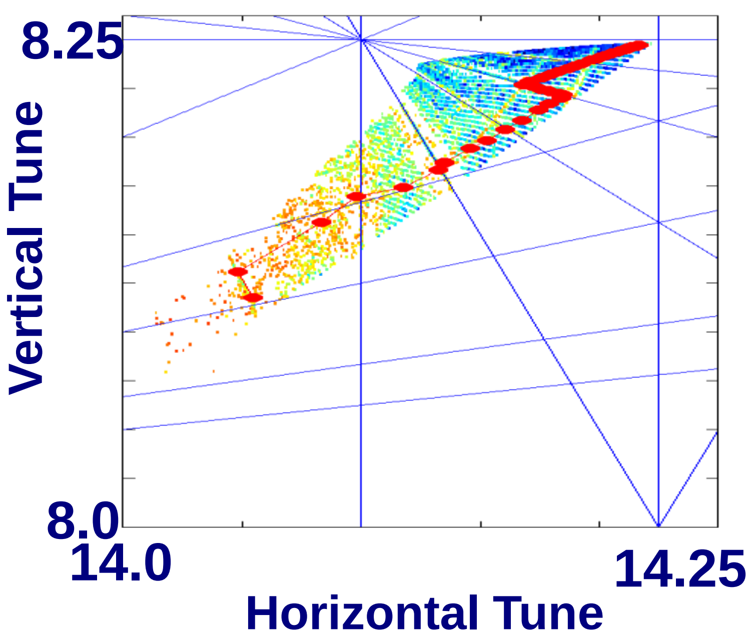
- *via nonlinear coupling and diffusion of the trajectory*.



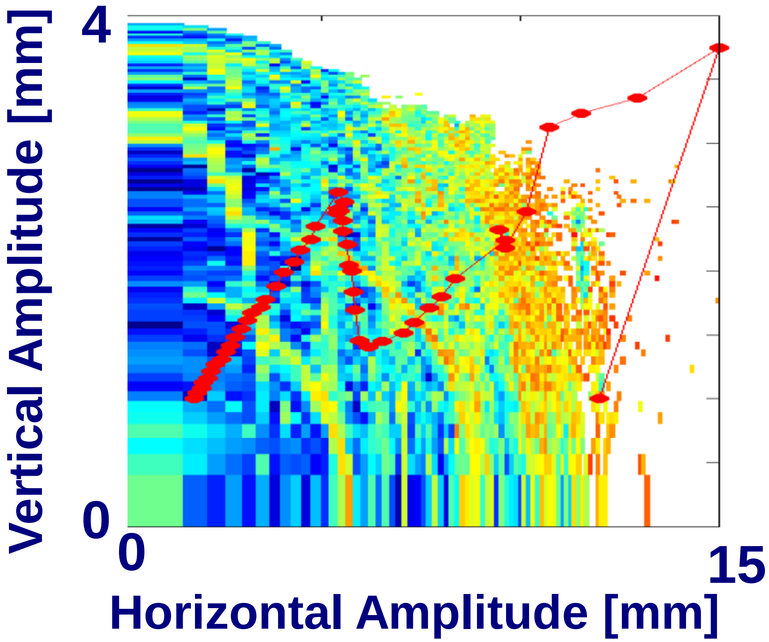
Example : Particle la
1 mm vertically and tracked with damping and synchrotron oscillations. (Simulated injection)

Frequency Map Analysis

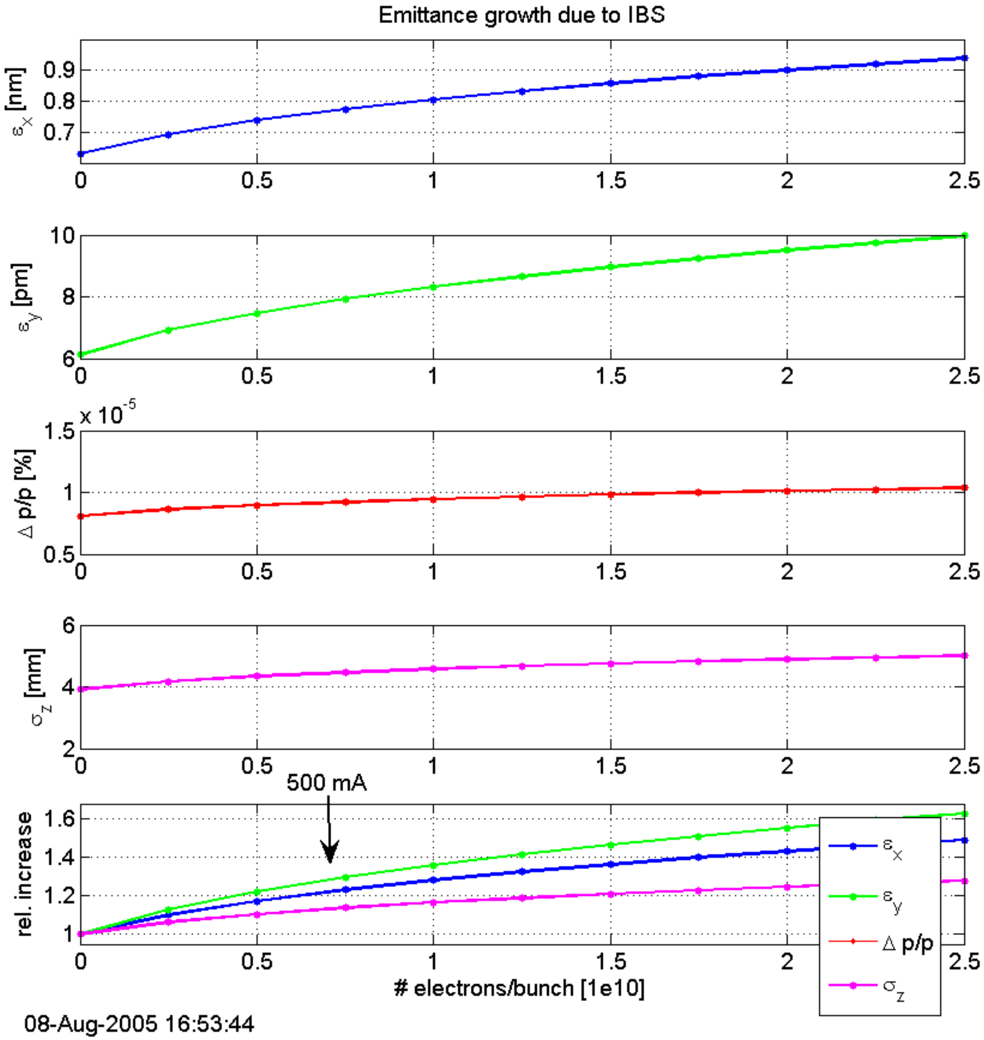
Frequency Space



Amplitude Space



Challenges: Intra Beam Scattering



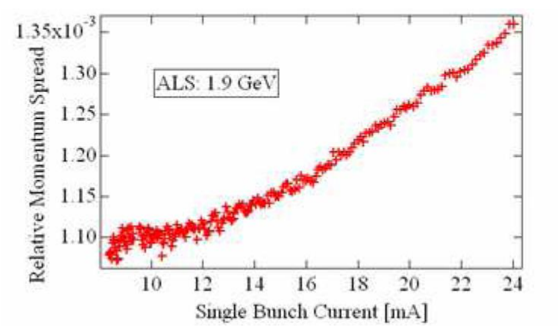
- **Calculations of intra beam scattering (IBS) shows it is significant, but no show-stopper**
- **There will be significant non-gaussian tails in the beam distribution**

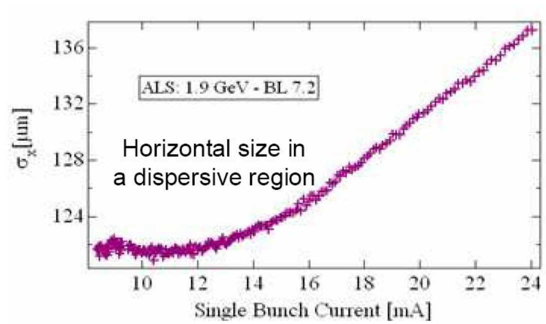
Challenges: Short Bunches/Instabilities

- **The total broad band impedance of a storage ring cause a longitudinal single bunch instability known as the microwave instability.**
- **When the current per bunch is larger than the instability threshold the longitudinal oscillation amplitude grows exponentially. Because of non-linearities, the oscillation frequency changes with amplitude limiting the maximum amplitude and in most of the cases no particle loss happens.**

$$I_{peak} > \frac{2\pi\alpha_C E_0 (\sigma_E / E_0)^2}{e|Z_{//}/n|}$$

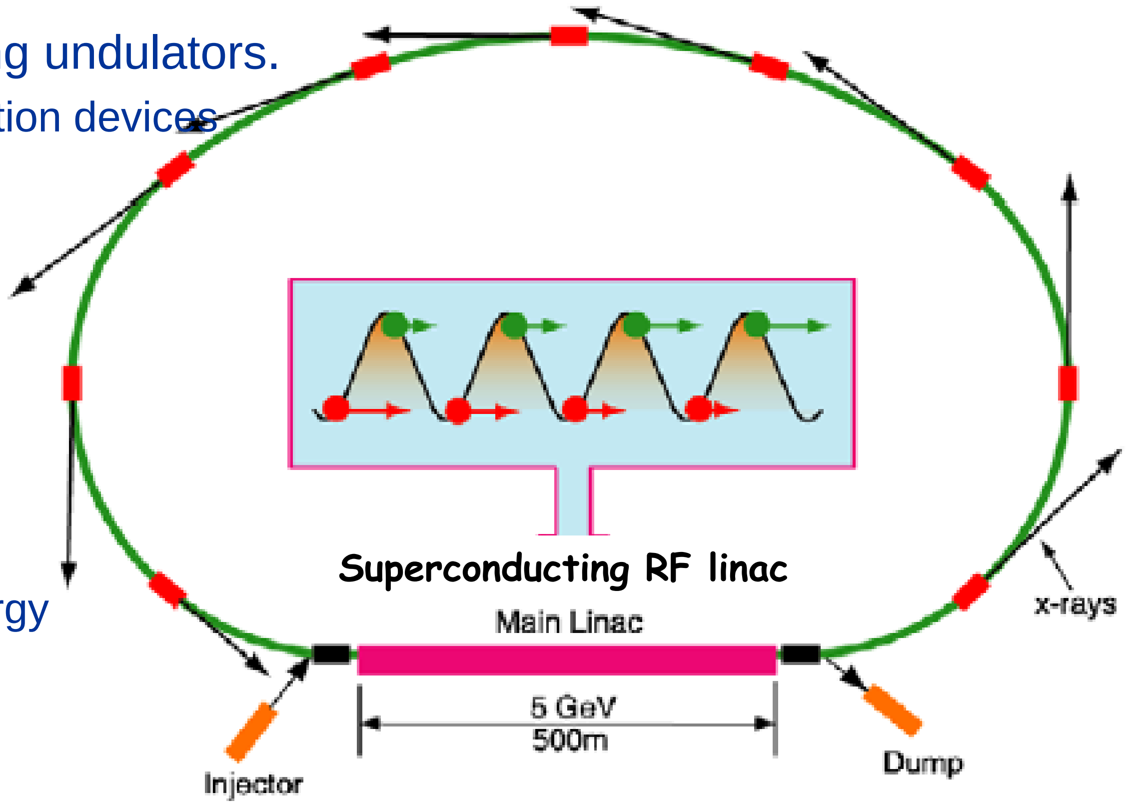
- **The net effect on the bunch is an *increase of the energy spread* above threshold with a consequent *increase of the bunch length* and of the beam *transverse size in dispersive regions.* This limits the achievable bunch length (or beam current at short bunch lengths) in storage rings.**





Energy Recovery Linac (ERL)

- An ERL accelerates high-brightness electron beams in a linac and recovers the energy from the beam after it radiates
- High-brightness electron bunches from a photocathode gun + adiabatic damping!
- Diffraction-limited radiation into the hard x-ray regime (with a high-energy electron beam)
- Small energy spread = very long undulators.
  – Spontaneous emission in insertion devices
  – Multiple operating modes
    • Spatial coherence
    • High brightness
    • Short pulses
  – High bunch repetition rate
    ~ MHz - GHz
  – High average power
    • Need to recover beam energy
    • 100 mA @ 5 GeV
      – 500 MW



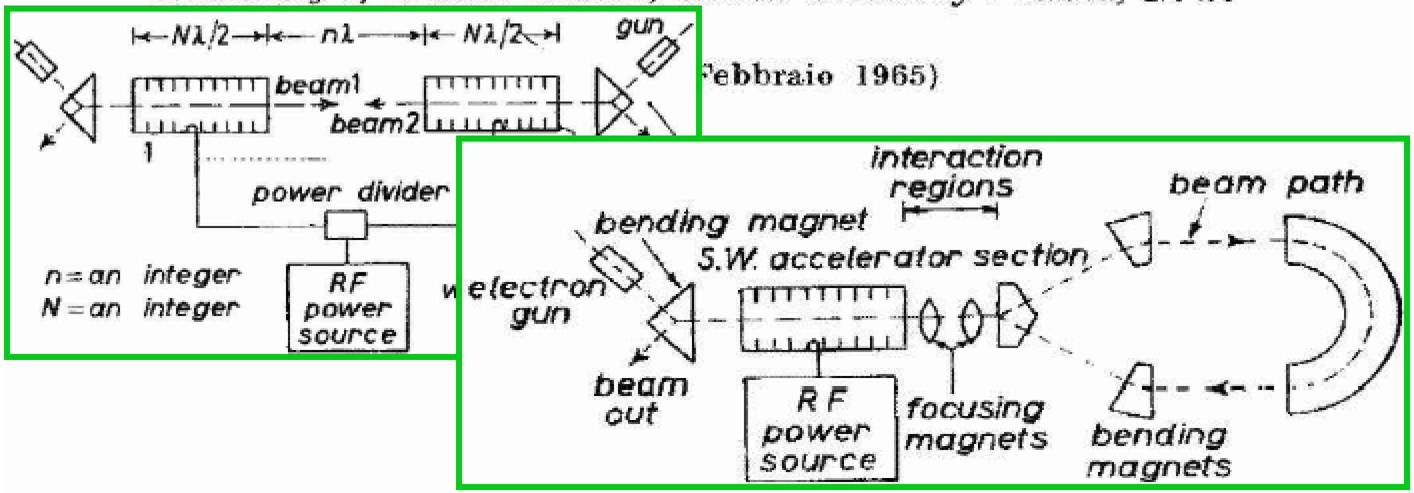
Very early Proposal of ERL (Cornell/Tigner)

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

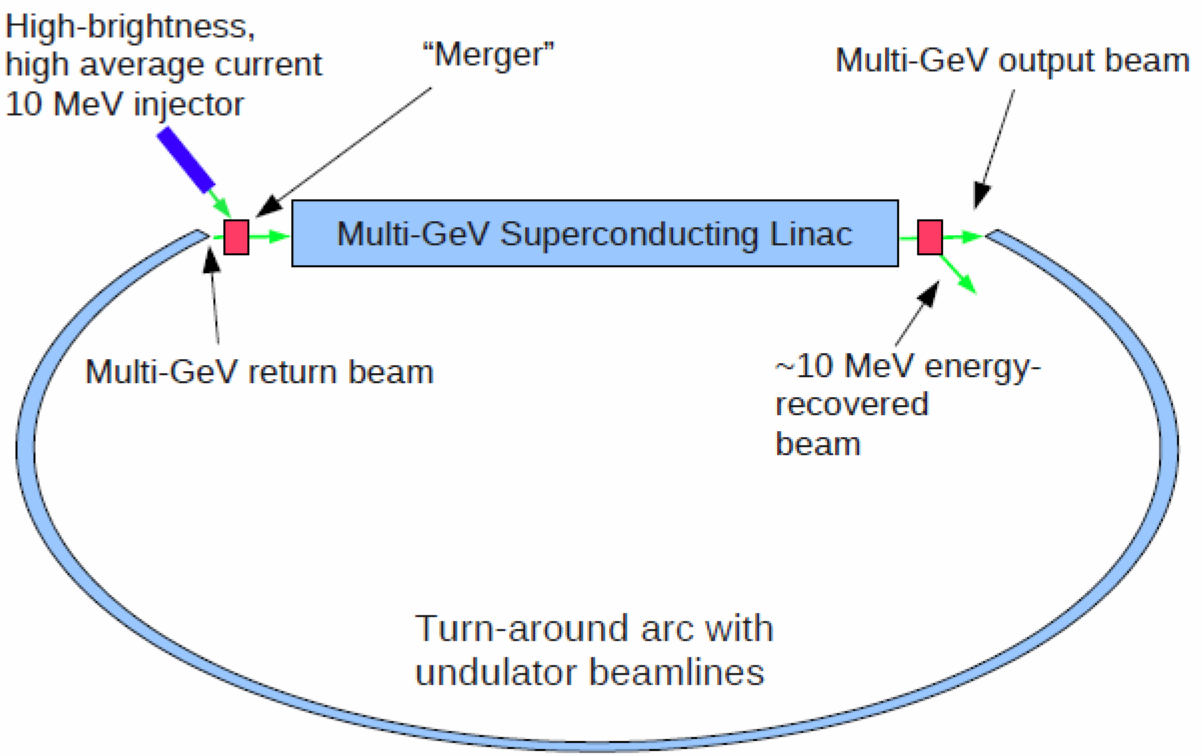
Febbraio 1965)



Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

Important Ingredients for an ERL

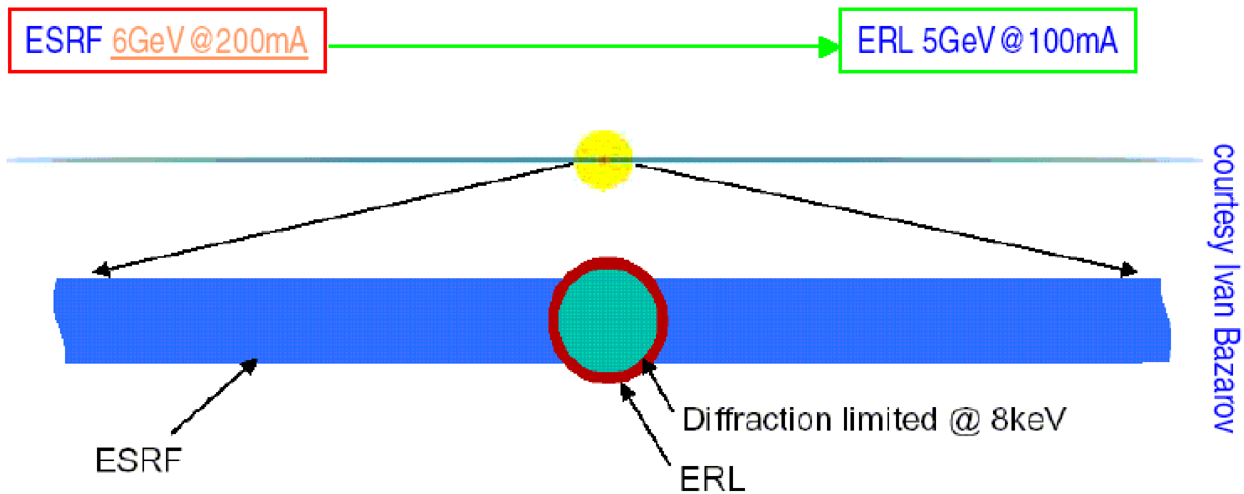


Energy recovery addresses the most significant advantage of rings over linacs.

[1]M. Tigner, *Nuovo Cimento* **37**, 1965.
[2]I. Bazarov *et al.*, PAC 2001, 230.
[3]I. Ben-Zvi *et al.*, PAC 2001, 350.

Energy Recovery Linac (ERL)

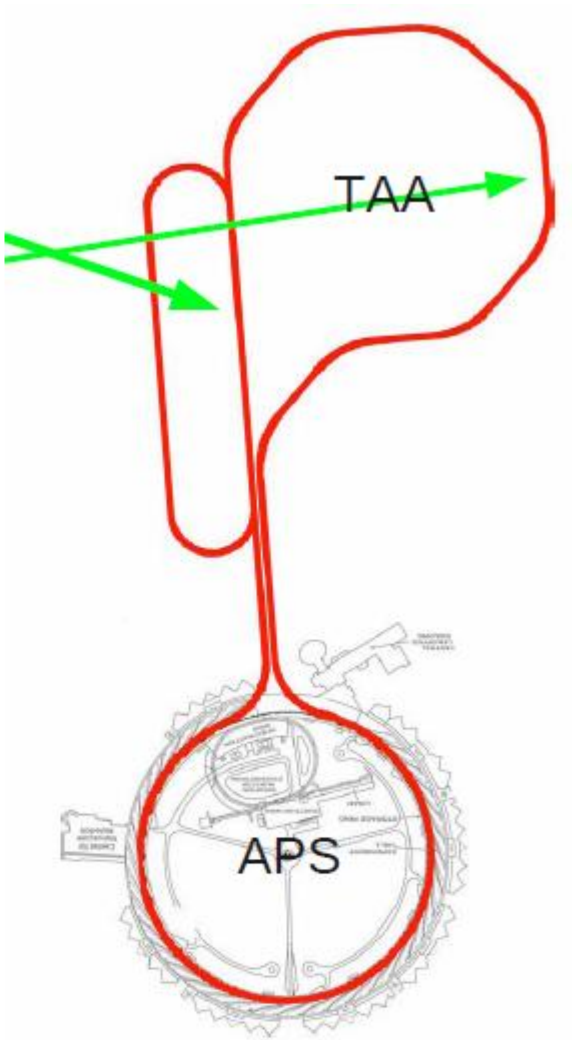
- Goal - small beamsize
  - The horizontal beamsize can be made much smaller than in a ring
  - Take advantage of future developments in electron sources
- Short bunches
  - Bunch length much shorter then typical storage ring

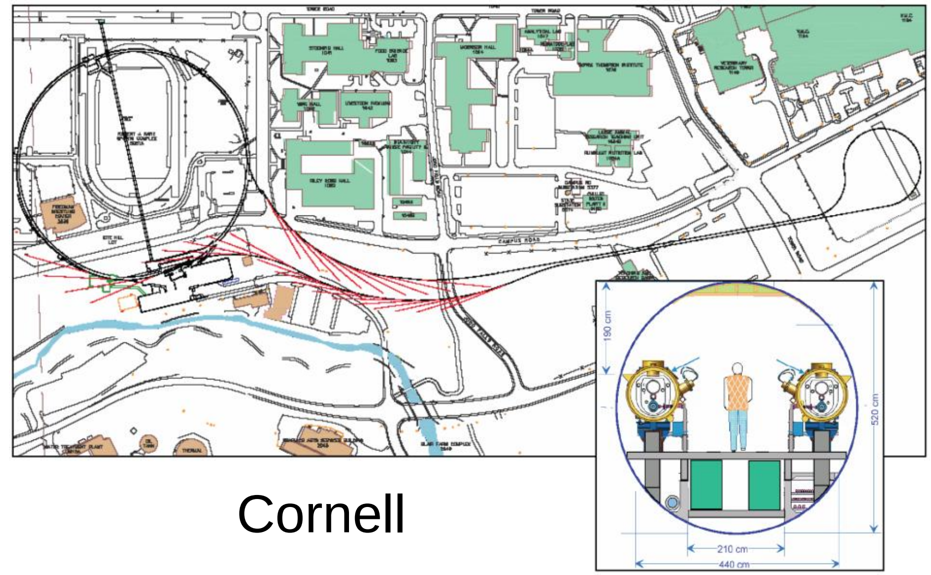


- Difficulties
  - Injector
  - Instabilities in the e-beam
  - Energy recovery

US hard x-ray ERL proposals

Argonne





Cornell

Energy Recovery Linac (ERL) - e.g. Cornell proposal

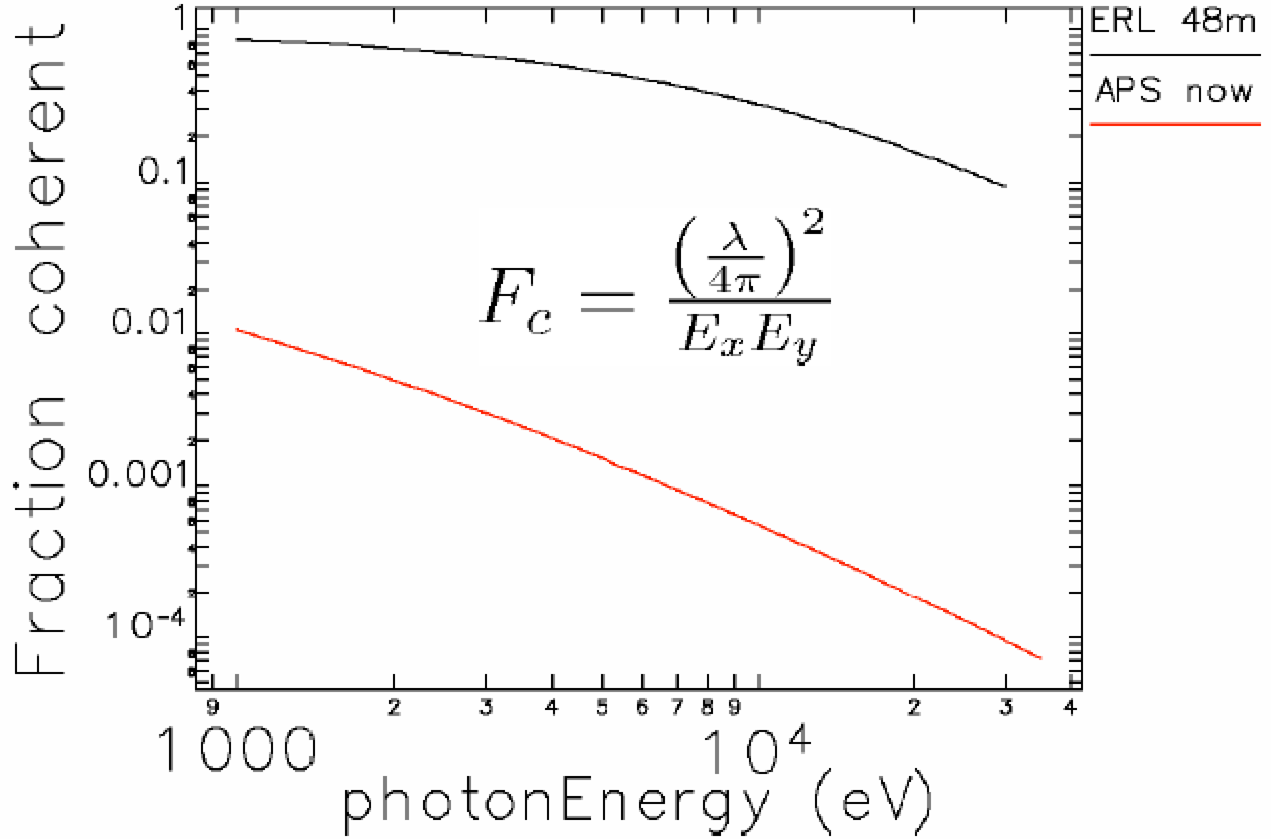
Multiple operating modes

		Cornell ERL-II			Cornell ERL-IIa		
Mode of operation		Hi-flux	Hi-coh	Ultrafast	Hi-flux	Hi-coh	Ultrafast
Machine energy	E (GeV)	5.3	5.3	5.3	5.3	5.3	5.3
Charge per bunch	q (nC)	0.077	0.008	1	0.154	0.0192	1
Repetition rate	f (MHz)	1300	1300	1	1300	1300	10
Machine current	I (mA)	100	10	1	200	25	10
Horizontal emittance	ε_x (nm-rad)	0.1	0.015	0.1	0.1	0.008	0.1
Vertical emittance	ε_y (nm-rad)	0.1	0.015	0.1	0.1	0.008	0.1
Rms bunch length	σ_t (ps)	3.0	3.0	0.1	2.0	2.0	0.02
Energy spread	σ_E/E	0.0004	0.0004	0.0027	0.0002	0.0002	0.0027
Undulator length	L (m)	25	25	4.1	25	25	4.1
Number of periods	N_u	1470	1470	240	1470	1470	240
Deflection parameter	K	1.34	1.34	1.34	1.34	1.34	1.34
Fundamental energy	E_1 (keV)	8.27	8.27	8.27	8.27	8.27	8.27
Average flux	F_n (p/s/0.1%)	5.11E+15	5.31E+14	7.65E+12	1.76E+16	2.20E+15	7.65E+13
Average brilliance	B_n (std units)	9.08E+21	1.86E+22	1.10E+19	3.13E+22	1.40E+23	1.10E+20
Peak flux	F_p (p/s/0.1%)	4.91E+17	5.10E+16	2.86E+19	2.54E+18	3.16E+17	1.43E+20
Peak brilliance	B_p (std units)	8.72E+23	1.78E+24	4.10E+25	4.51E+24	2.02E+25	2.05E+26
Photons per pulse	n_p (p/0.1%)	3.93E+06	4.09E+05	7.65E+06	1.36E+07	1.69E+06	7.65E+06
Coherent flux	F_c (p/s/0.1%)	5.10E+13	1.04E+14	6.15E+10	1.76E+14	8.20E+14	6.15E+11
Peak coherent flux	F_{cp} (p/s/0.1%)	4.90E+15	1.00E+16	2.30E+17	2.53E+16	1.13E+17	1.15E+18
Coherent flux fraction	p_c (%)	1.0	19.6	0.8	1.0	37.3	0.8
Photons per coherent volume	δ_D	2	5	115	13	57	576
Total undulator output power	P_0 (W)	31,679	3,291	51.7	63,358	7,899	517
On-axis power density @20m	dP/dA (W/mm^2)	2,655	276	4.3	5,311	662	43
Peak coh. electric field @ exit	E_c (V/m)	1.42E+06	4.56E+05	5.71E+04	2.00E+06	7.07E+05	1.81E+05

Qun Shen, CHESS

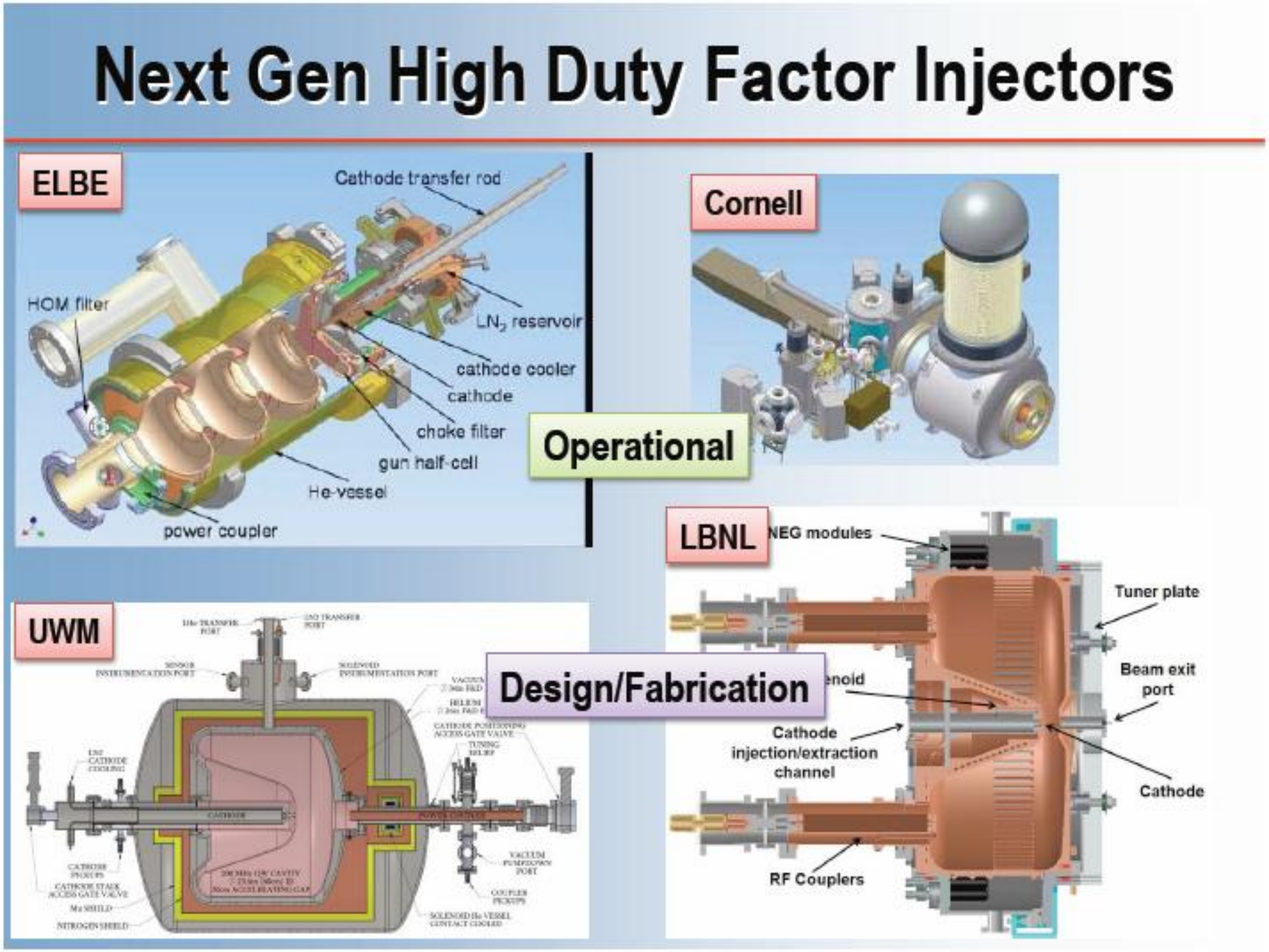
Distinguishing Feature of ERL and Ultimate Storage Ring Proposals: Transv. Coherence

X-Ray Performance: Transverse Coherence



$$F_c = \frac{\left(\frac{\lambda}{4\pi}\right)^2}{E_x E_y}$$

ChallengesElectron Sources (compare Fernando's Lecture)



Challenges: Wakefields and Beam Dynamics

Wakefields & Beam Dynamics

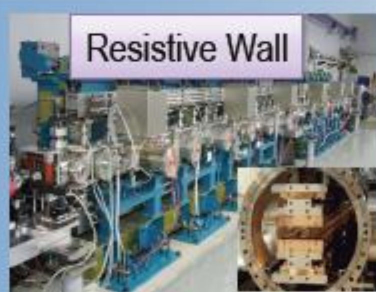
Longitudinal Space Charge

$$Z_{LSC}(k) \approx \frac{iZ_0 c}{4\pi\gamma^2}\left(1 + 2\ln\frac{r_w}{r_b}\right)k$$

Coherent Synchrotron Radiation

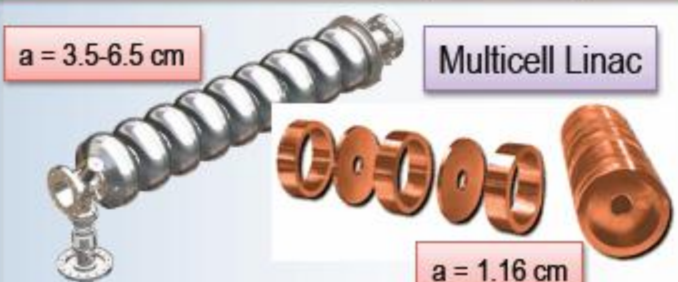
$$Z_{CSR}(k) \approx \frac{2Z_0\Gamma\left(2/3\right)}{3^{1/3}\rho^{2/3}}\left(\frac{\sqrt{3}}{2} + i\frac{1}{2}\right)k^{1/3}$$

Resistive Wall



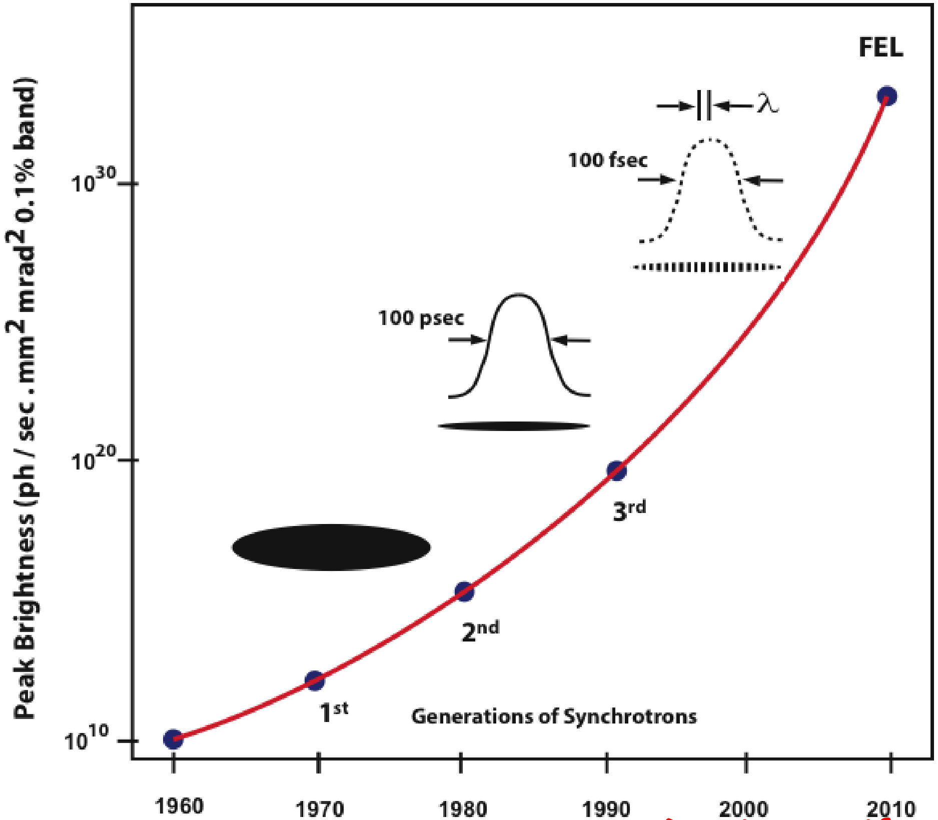
$$Z_{RW}(k) \approx \frac{2s_0}{cb^2}\left(\frac{i\,\mathrm{sgn}(ks_0) + 1}{(ks_0)^{1/2}} - \frac{i(ks_0)}{2}\right)^{-1}$$

Multicell Linac



$$Z_{Linac}(k) \approx i\frac{Z_0}{\pi a^2 k}\left[1 + \frac{\alpha(1+i)L}{a}\left(\frac{\pi}{kg}\right)^{1/2}\right]^{-1}$$

Evolution of light sources - seeded FEL provides capabilities not available from other sources



Dominates if $\sigma_z < \lambda$

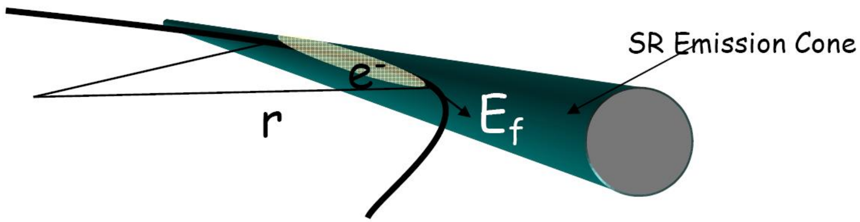
$$I_{total}(\omega) = \{N + N(N-1)|g(k)|^2\} I_e(\omega)$$

$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz} dz$$

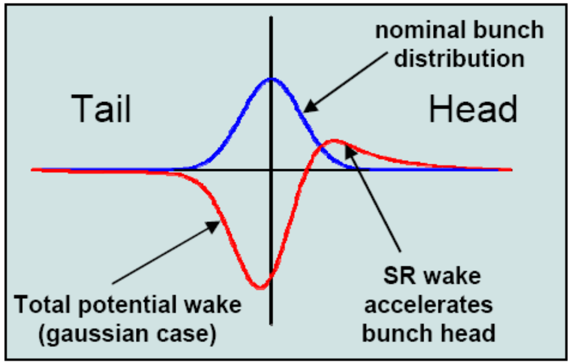
- **Free Electron Laser (FEL)**
  - **Enhance coherence at shorter wavelengths by modulation of the charge within a bunch**
- ***Seeded* FEL provides additional capabilities essential to explore the proposed science:**
  - **Control of pulse duration**
  - **Temporal coherence and narrow linewidth**
  - **Harmonic generation of shorter wavelengths**
  - **Precise synchronization**
  - **Shorter gain length**

Reminder: SR Wake Field

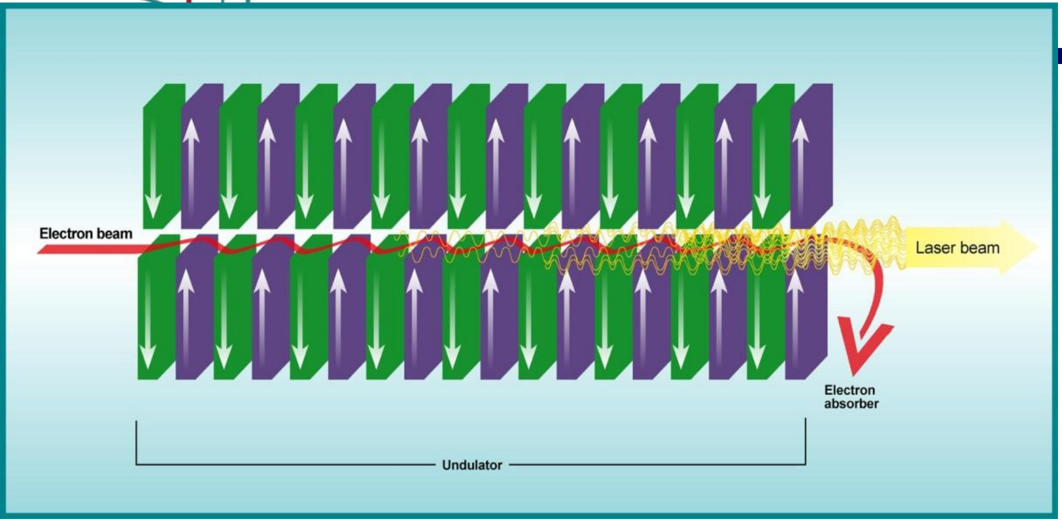
- The wake field due to synchrotron radiation, belongs to the category of the wakes that propagates with the beam. Such a wake is important only for the relativistic particle case.
- Relativistic particles on a curved trajectory emit synchrotron radiation (SR). The SR fields propagates in a cone of emission centered on the tangent to the beam trajectory at the emission point and with ~ $1/\gamma$ aperture.

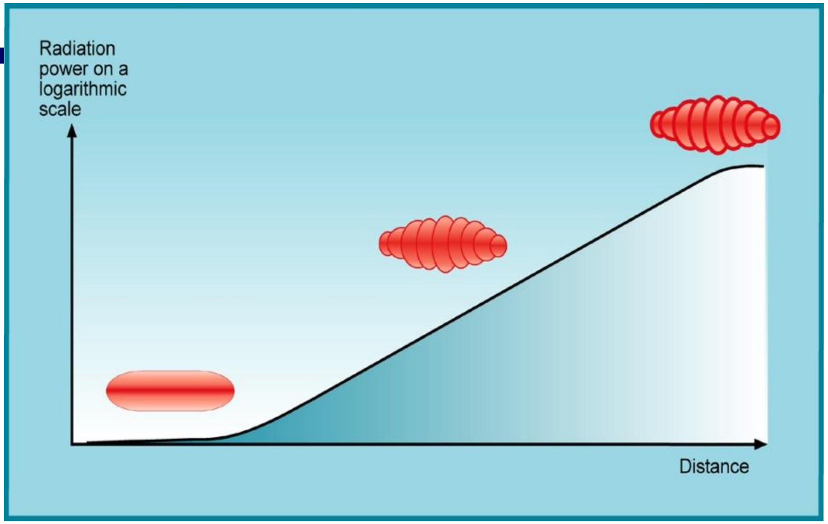


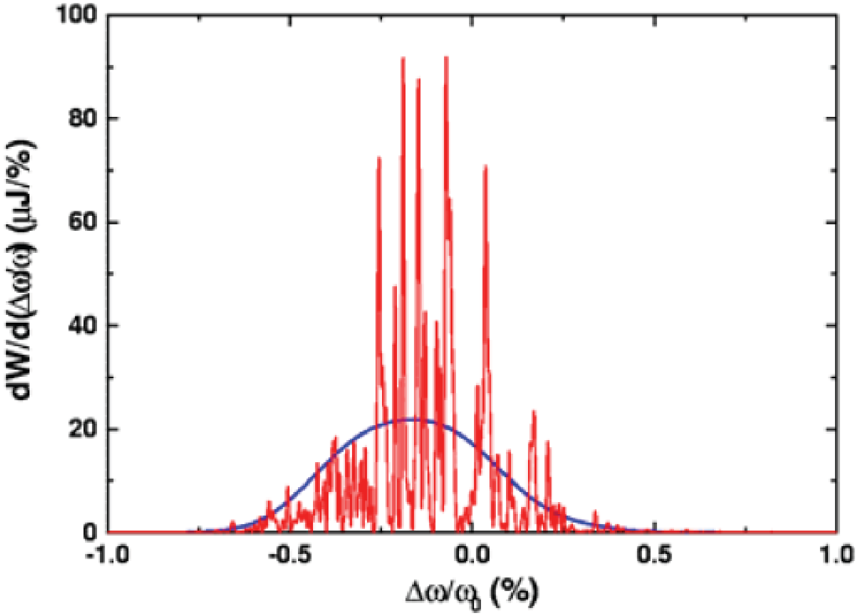
- The fields propagate at the speed of light, while the particles move on the curved trajectory. For this reason, even if the particles are relativistic the projection of their speed on the tangent direction is smaller than *c*.
- In other words, the SR wake field due to a particle in the tail of the bunch can reach and interact with a particle in the head! This is exact the opposite of what happens with vacuum chamber wakes.



SASE FEL

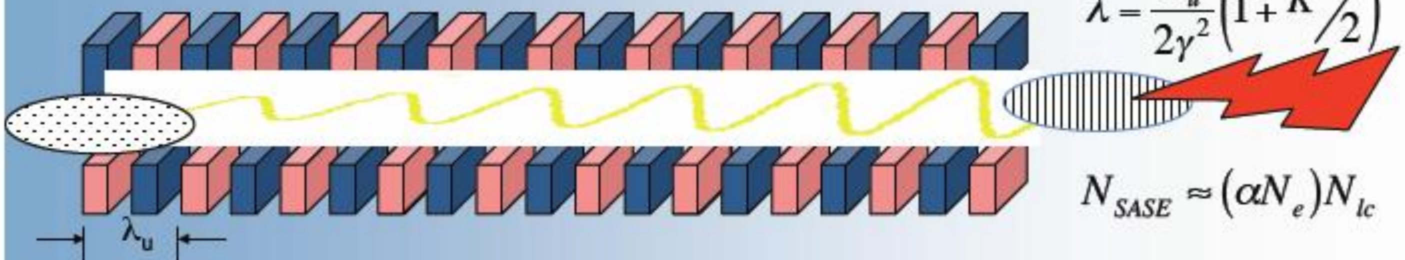






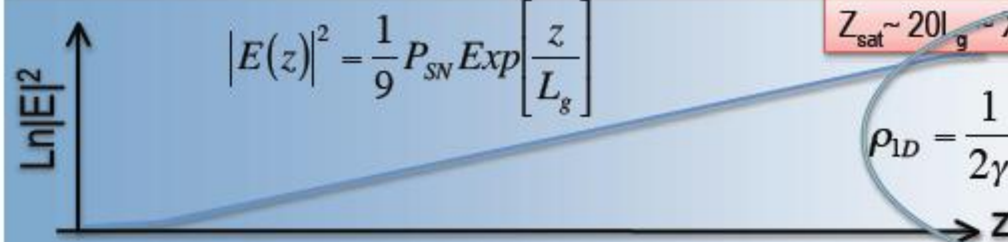
- Beam entering undulator emits spontaneous synchrotron radiation
- Radiation interacts with bunch, creating microstructure
- Particle within microstructure start to emit coherently – exponential gain until saturation
- Critical: Bunch length, energy spread, emittance (transverse size*divergence)

SASE: Self Amplified Spontaneous Emission



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)$$

$$N_{SASE} \approx (\alpha N_e) N_{lc}$$



$$\left|E(z)\right|^2 = \frac{1}{9} P_{SN} Exp\left[\frac{z}{L_g}\right]$$

$Z_{sat} \sim 20 l_g \sim \lambda_u/\rho_{1D}$

$$\rho_{1D} = \frac{1}{2\gamma}\left[\frac{I_{peak}}{I_A}\frac{\lambda_u^2 K^2 \left[JJ(K)\right]^2}{8\pi^2 \varepsilon_x \beta_x}\right]^{1/3}$$

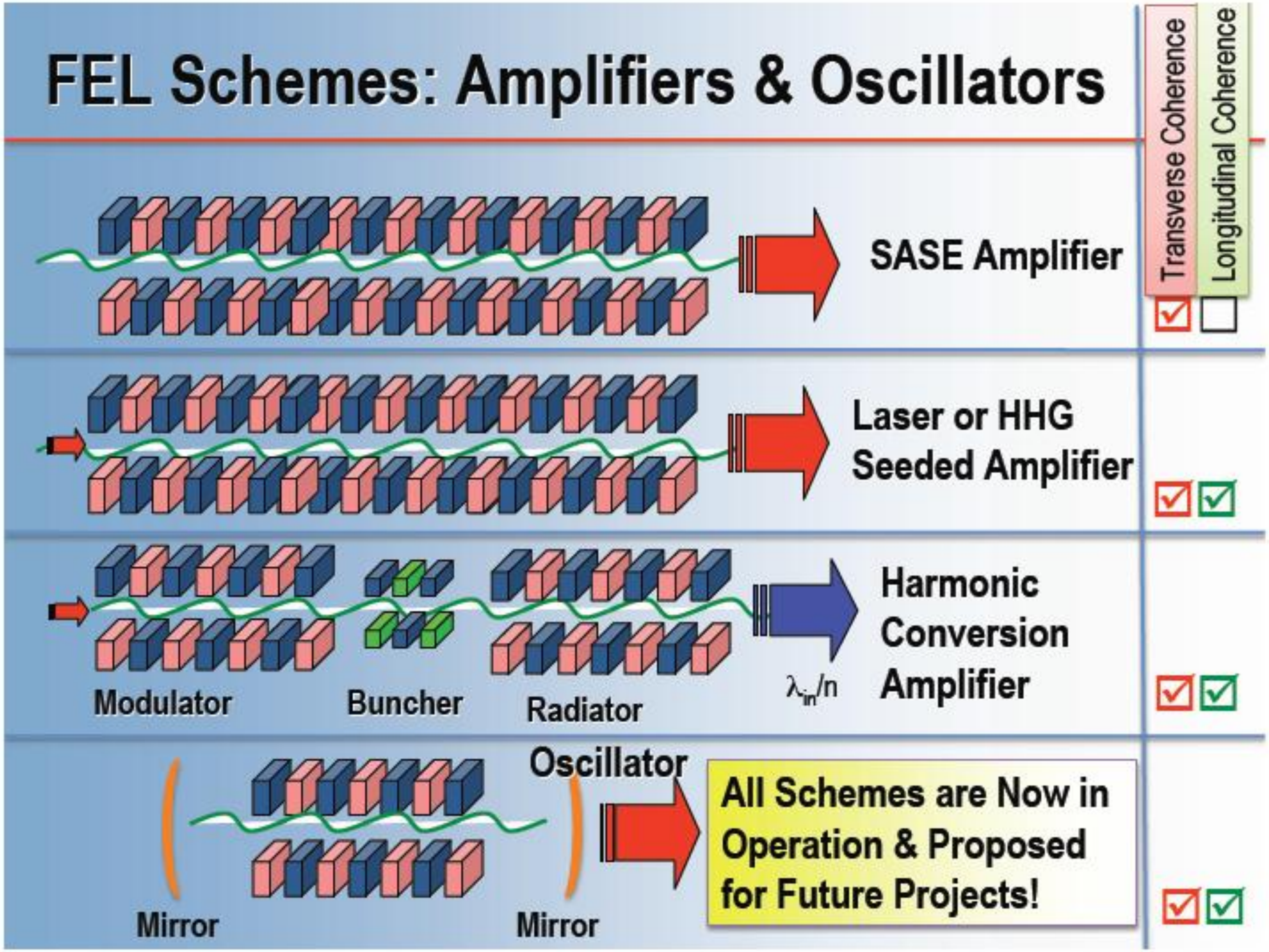
Power Gain Length: $L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}}$

FEL Bandwidth: $\frac{\sigma_\omega(z_{sat})}{\omega} \approx \rho_{1D}$

Cooperation Length: $L_c \approx \frac{\lambda}{\lambda_u} L_g = \frac{\lambda}{4\pi\sqrt{3}\rho_{1D}}$

FEL Efficiency: $P_{peak}(z_{sat}) \approx \rho_{1D} E_e I_{peak}$

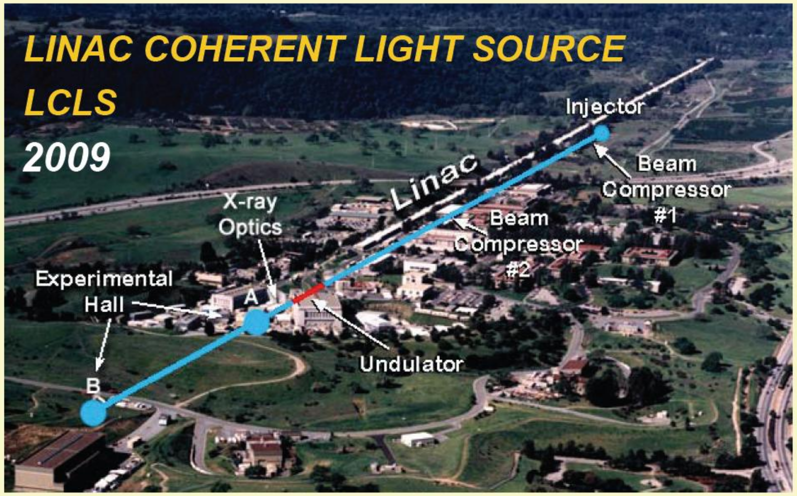
Bonifacio, Pellegrini & Narducci 1984

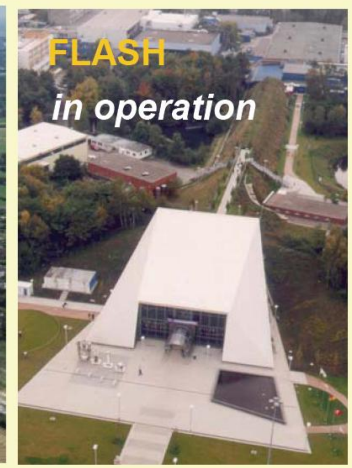

FEL Schemes: Amplifiers & Oscillators
Transverse Coherence
Longitudinal Coherence
SASE Amplifier
Laser or HHG Seeded Amplifier
Harmonic Conversion Amplifier
Modulator
Buncher
Radiator
λ_{in}/n
Oscillator
Mirror
Mirror
All Schemes are Now in Operation & Proposed for Future Projects!

Challenges

- Challenges generally are a superset of ERL and Ulimate Rings
- High brightness guns
- Low emittance beam transport
- Stability
- Details of seeding processes.

‘1st generation’ SASE FEL Facilities





Summary

- Light Sources have greatly evolved over time
- About 10,000 users annually at US DOE light sources alone
- Major further development potential exists
  - Ultimate Storage Rings
    - Highly stable, high capacity, high average brightness, low-moderate risk
  - ERLs
    - High coherence, high average brightness, substantial development program (risk)
  - FELs
    - Extremely high peak brightness, potential for very high average brightness, potentially full (longitudinal + transverse) coherence up to short wavelengths, ultimate performance requires substantial development program (risk)
- Many interesting topics (for theses) in all areas, Berkeley (LBNL) and Stanford (SLAC) are heavily involved in multiple areas.

Thanks to P. Elleaume, J. Corlett, J. Murphy for several illustrations