The Quest for Bright, Coherent X-Ray:
A Personal Story

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ANL

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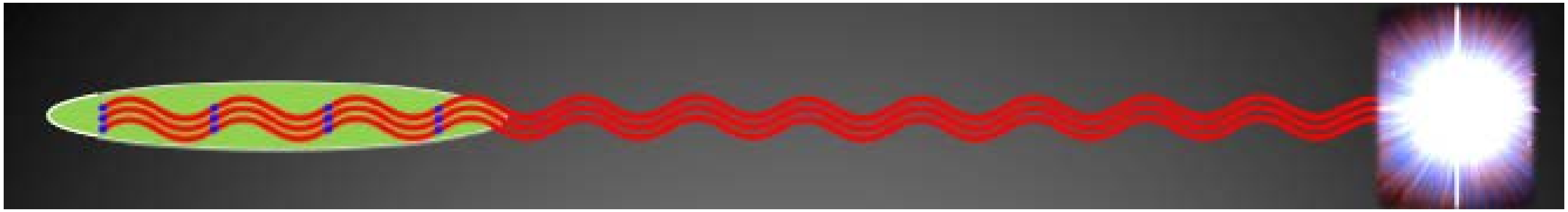
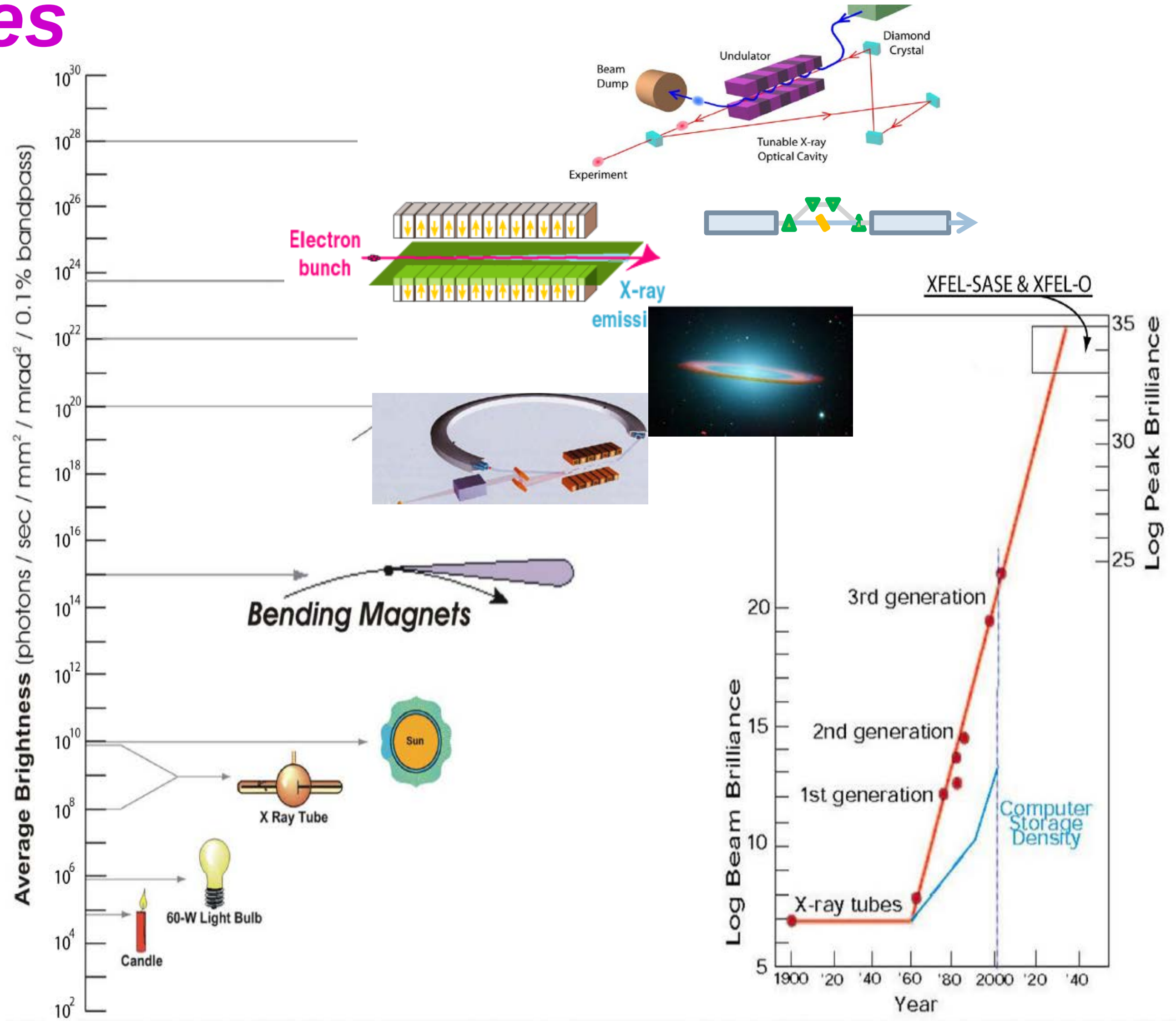
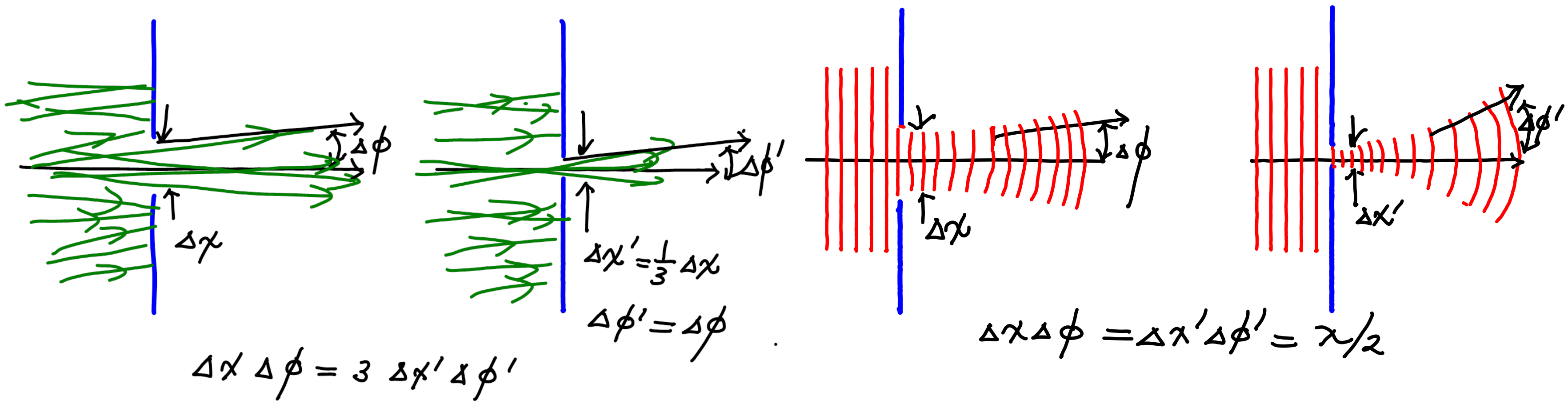


Legend of evolving bright & coherent x-ray sources

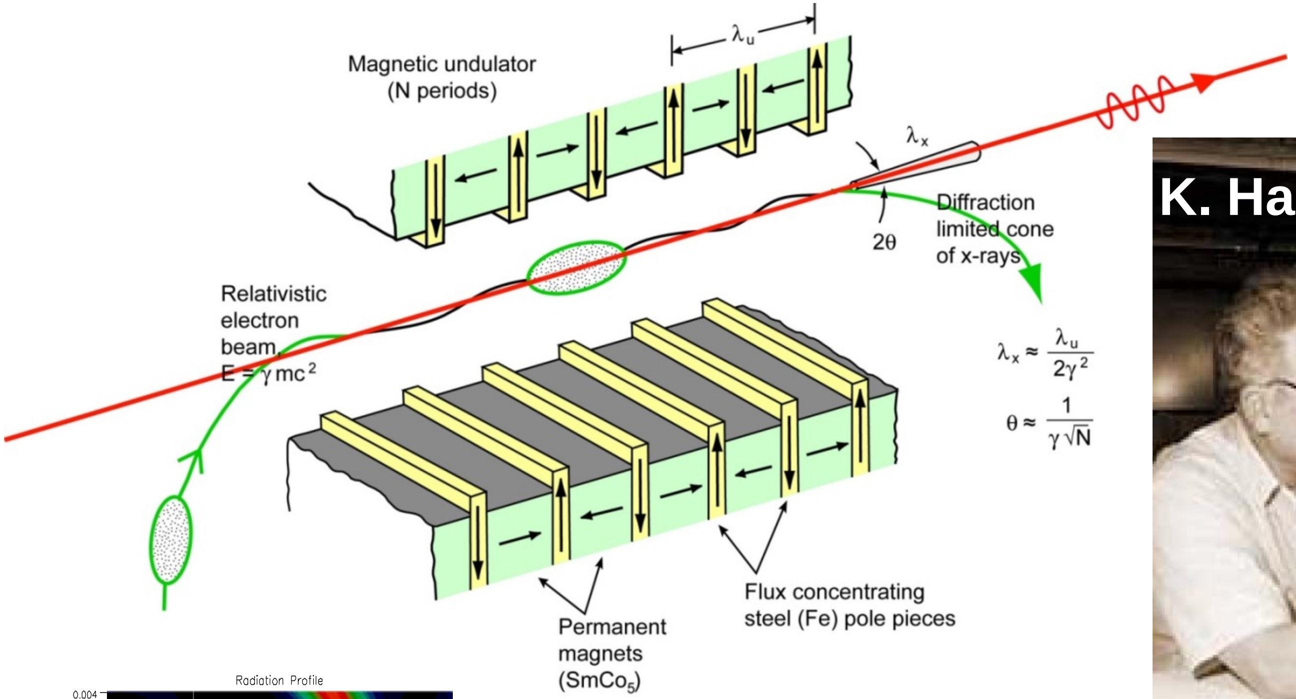


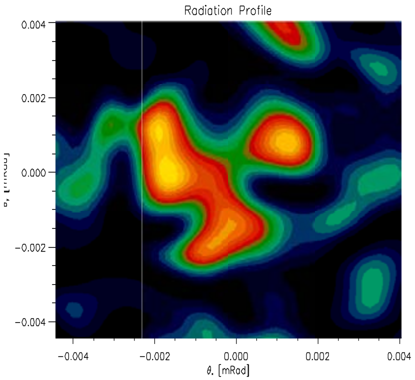
Incoherent and coherent beam

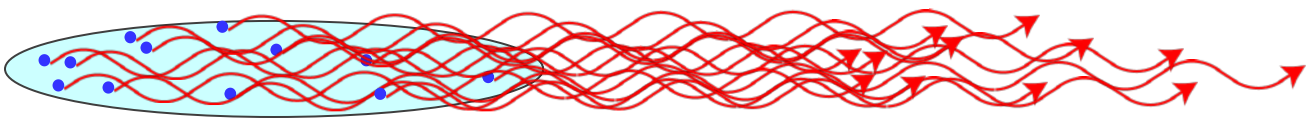


- **The phase space area $\varepsilon=(\Delta x\Delta\phi)$ of incoherent beam can be divided into smaller and smaller area (electron beam)**
- **With coherent beam the phase space area cannot be divided to area smaller than $\Delta x\Delta\phi = \lambda/2$**
- ***A unified description* of coherent and incoherent phase space concept is needed for a correct description of brightness, *B*=phase space density of flux, for modern electron-beam-based radiation sources**

Bright radiation by electron beams passing through an undulator







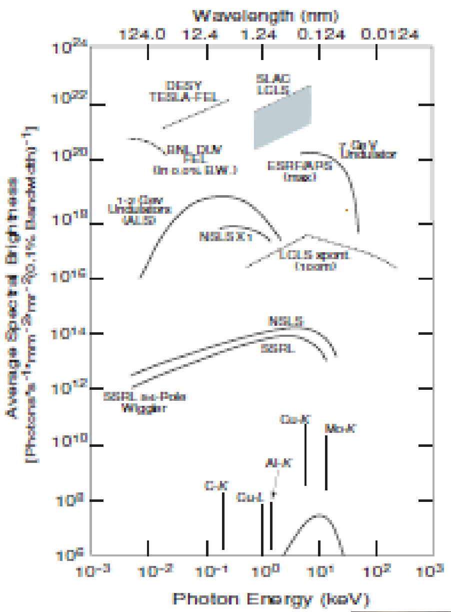
What is brightness?

- **The brightness for the bending magnet radiation was first introduced by G.K. Green in the original NSLS proposal (1976) and for the undulator radiation in the "blue book" of ESRF proposal (R.Coisson) in 1979, but these are at intuitive level**

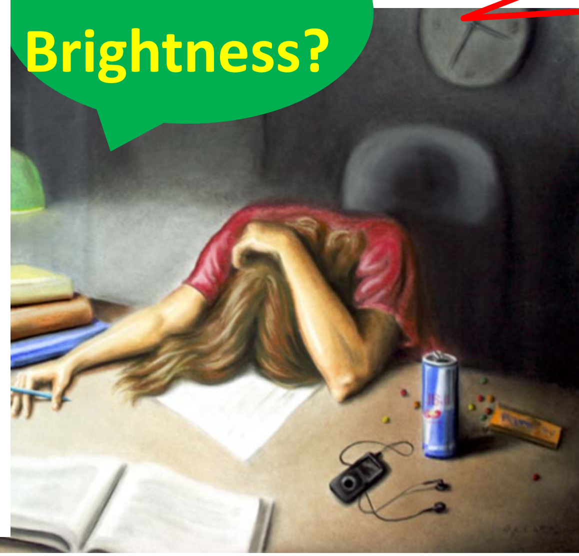
- $$B(\mathbf{x},\phi_\perp) = \frac{dF}{d\Omega \times \mathrm{Area}}$$

$$\frac{dF}{d\Omega} = const\left|\tilde{E}(\phi_\perp)\right|^2, \frac{dF}{d\mathbf{x}} = const\left|E(\mathbf{x})\right|^2, \tilde{E}(\phi_\perp) = \int d\mathbf{x}\, e^{ik\phi_\perp \cdot \mathbf{x}} E(\mathbf{x})$$

- ***We know how to compute** $\tilde{E}(\phi_\perp)$ **but E&M books do not discuss formula for** $B(\mathbf{x},\phi_\perp)$*

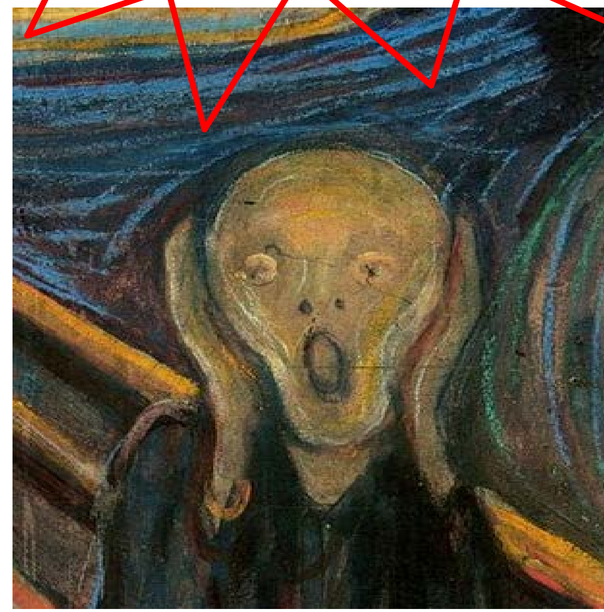


What is Brightness?



Eureka!!!!!

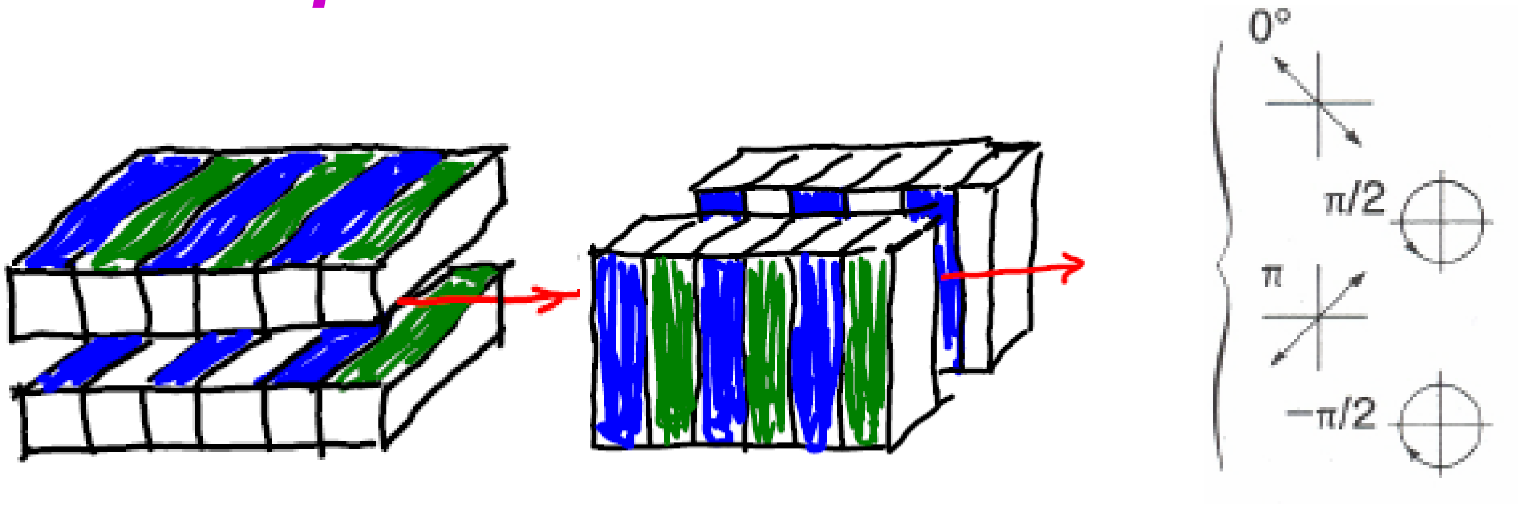
$$B(x, \phi; z) = \int dy \, \exp(iky\phi) < E^*(x+y/2;z) \, E(x-y/2;z) >$$



The quantity so defined transformed correctly as it go through free space and focusing elements. The way to include the electron beam emittance also became straightforward! I was in a high level of excitement (1985)

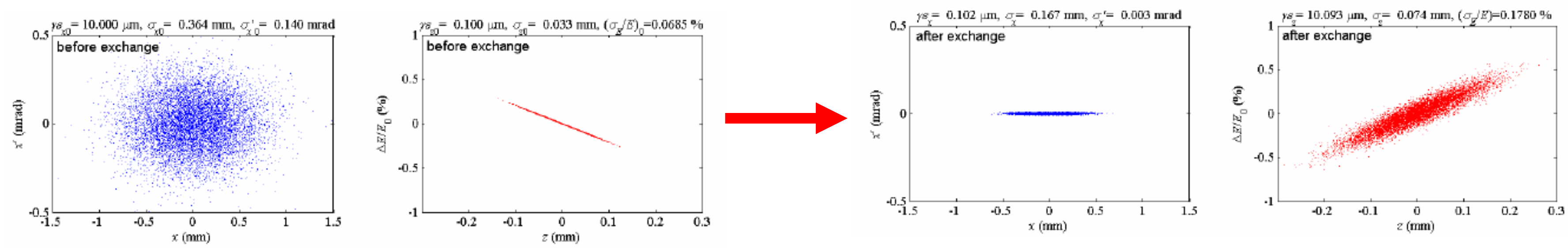
At a seminar at NSLS, Marty Blume (a prominent solid state theorist) noted that this was introduced by E. Wigner in 1930s for quantum statistical mechanics

Variable polarization device

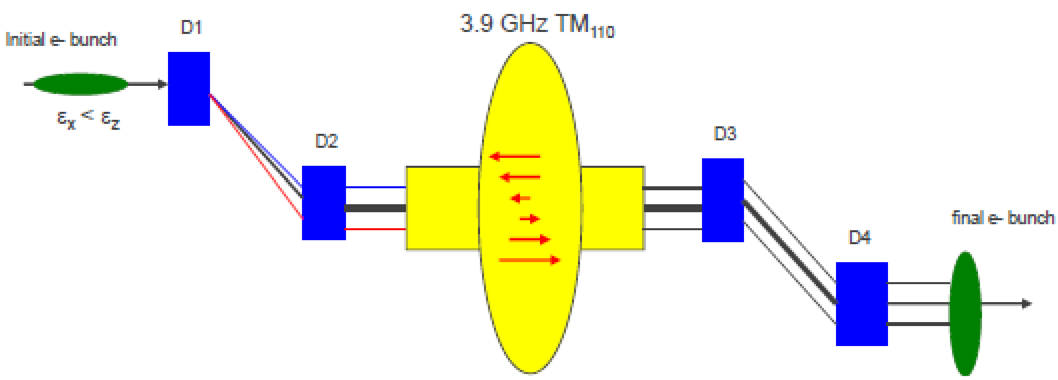


- **Eureka moment while listening to Prof. Tinoco, UCB biochemist at “new ring’s WS” at Stanford in 1983, explaining the need for variable polarization**
- **Prototype built at BESSY by A. Gaupp (1986) and J. Bahrdt and at Duke ring (Y. Wu, 2010)**
- **Will work better with FEL devices, especially seeded, such as XFELO (Shanghai Seeded VUV FEL, 2013)**

It is sometimes useful to swap the x-phase space with z-phase space



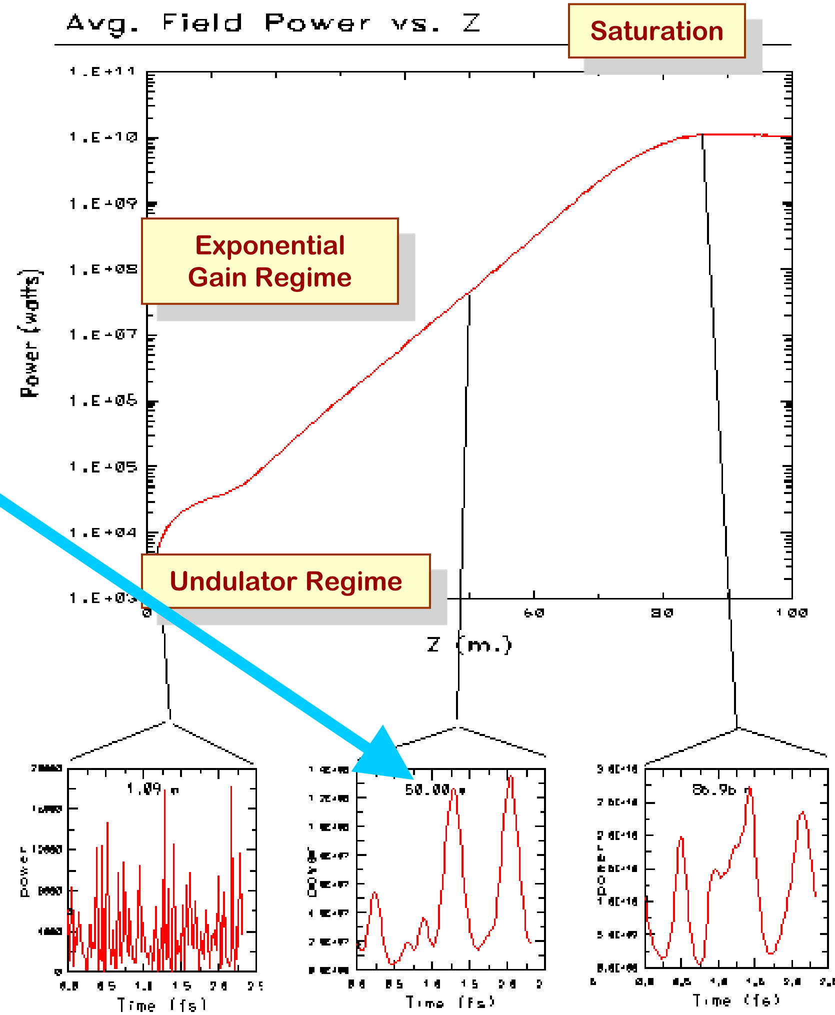
- **Approximate scheme by P. Emma and M. Cornacchia (2002)**



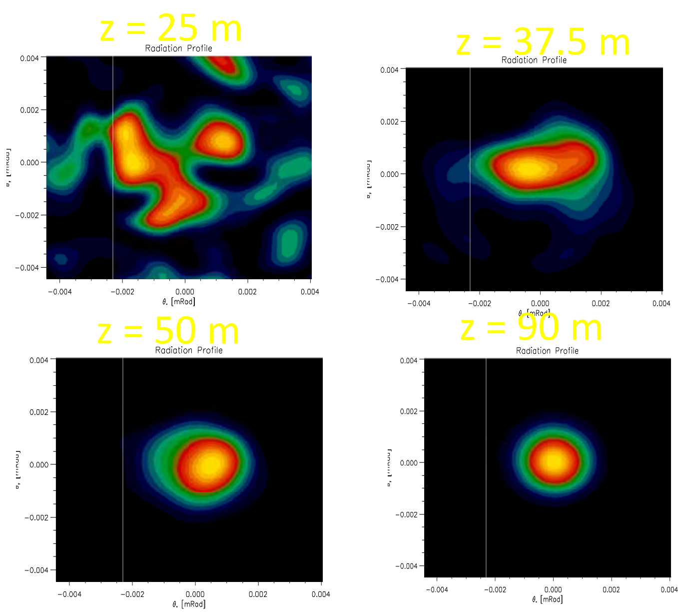
This scheme turns out to be exact (2006)! Demonstrated at Fermilab A0 (T. Koeth, Y.e. Sun,..) . Conditioning DWA beam for FEL (J. Power, et al)

Self-Amplified Spontaneous Emission (SASE)

High-single pass gain → Do not need mirrors
High transverse coherence
Limited temporal coherence ($\Delta\omega/\omega$ ~10^{-3})



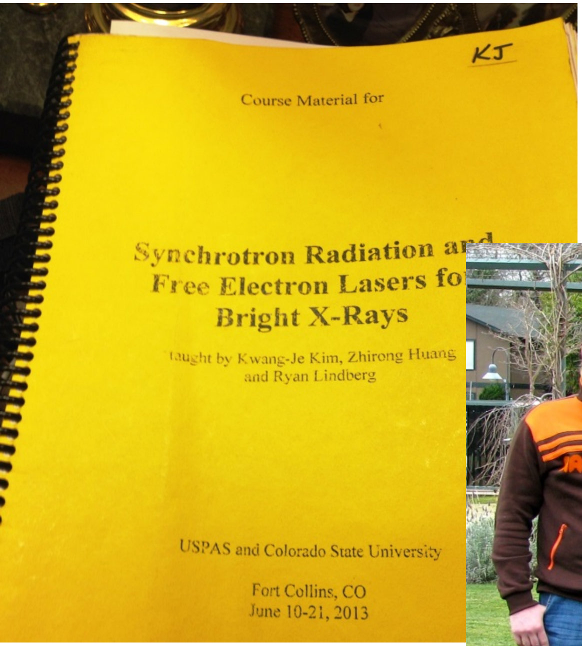
Transverse mode evolution
Courtesy S. Reiche



A short personal history of FEL theory

- At 1983 BNL Workshop, Bonifacio, Narducci, Pellegrini studied SASE by collective variable analysis as a mirror-less XFEL, earlier (1980) by Kondratenko & Saldin in USSR
- I was able to develop a more general 1D Maxwell-Klimentovich eqs and solve them to show explicitly the evolution from undulator rad to SASE including electrons' energy spread (1985)
- Succeeded in generalizing the eqs to 3D and solving the initial value problem by Van-Kampen method (1986)
- Variational solution of 3D eqs by S. Krinsky and L.-H. Yu (1990) agreed well with simulation (1990)
- Exact numerical solution by M. Xie and his interpolation formula greatly expedited the XFEL design (1996)
- (Even without smart phones, which were not born yet!)

FEL theory has been continually refined from USPAS teachings jointly first with Z. Huang and later R. Lindberg.



Lecture notes 2013

2008 USPAS at Santa Rosa, CA

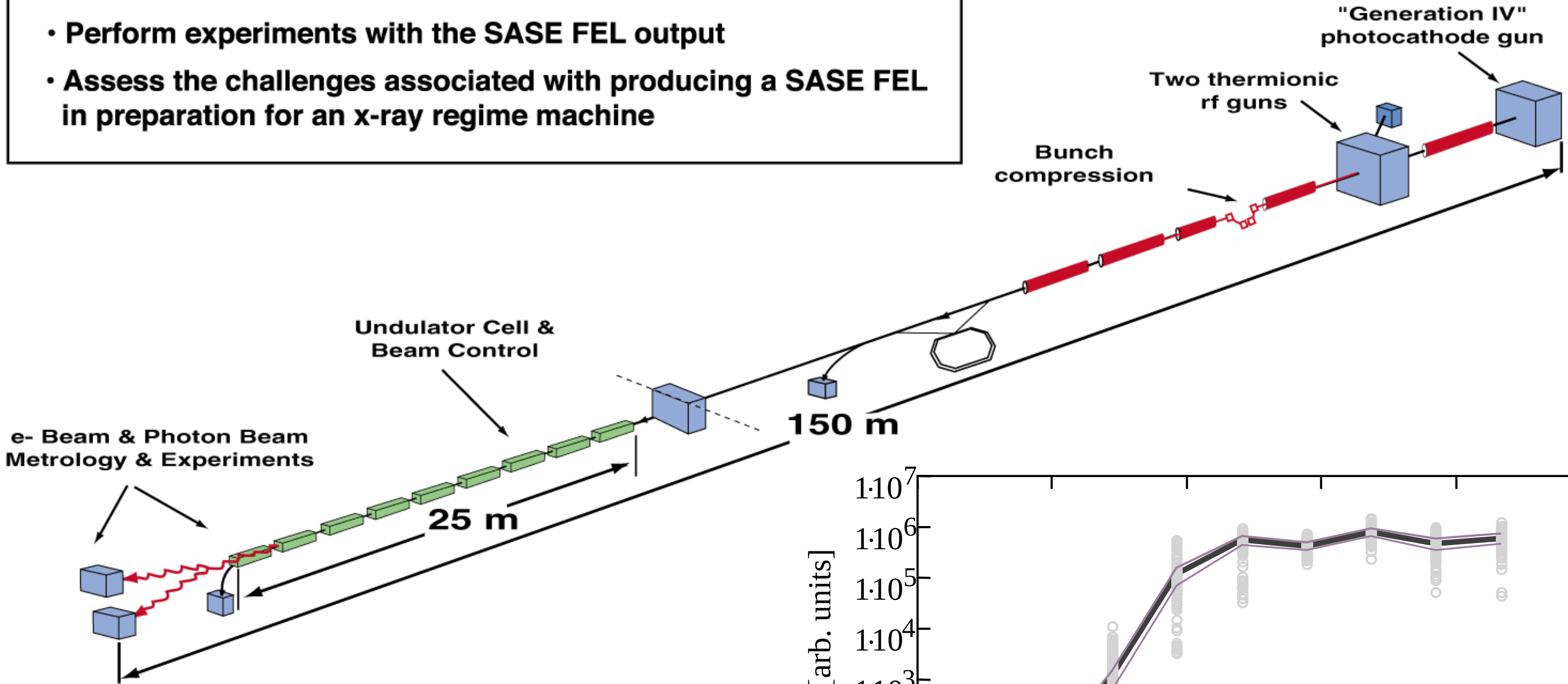
A short personal history of XFEL development

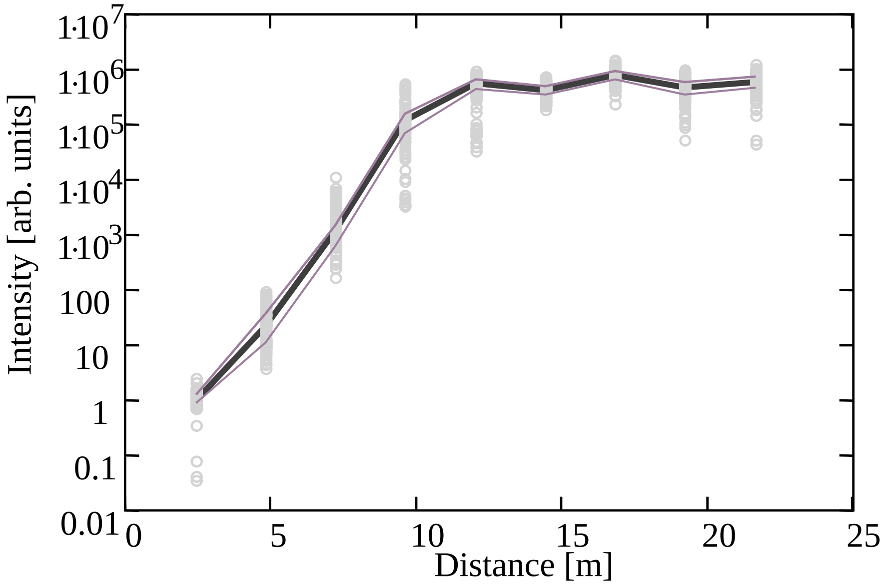
- **FEL theory was mature by 1990. But it became clear by then that storage rings can not provide the needed longitudinal emittance. (Sag Harbor Workshop)**
- **A linac with a photocathode injector invented at LANL looked more promising. But the emittance growth due to RF and space charge effect appear to preclude 1 Å SASE**
- **However, C. Pellegrini, in his talk at 1992 SLAC WS, proclaimed, "*The emittance shall be <1 mm-mrad !* "**
- **And so it was! The emitttance can be compensated, and the LCLS ushered us into the era of x-ray FEL**
- **APS LEUTL experiment demonstrated the reality of a large scale, high-gain FEL (1999)**
- **High-gain XFEL user facilities are in construction and in operation around the world**

LOW-ENERGY UNDULATOR TEST LINE PARAMETERS

PROJECT GOALS

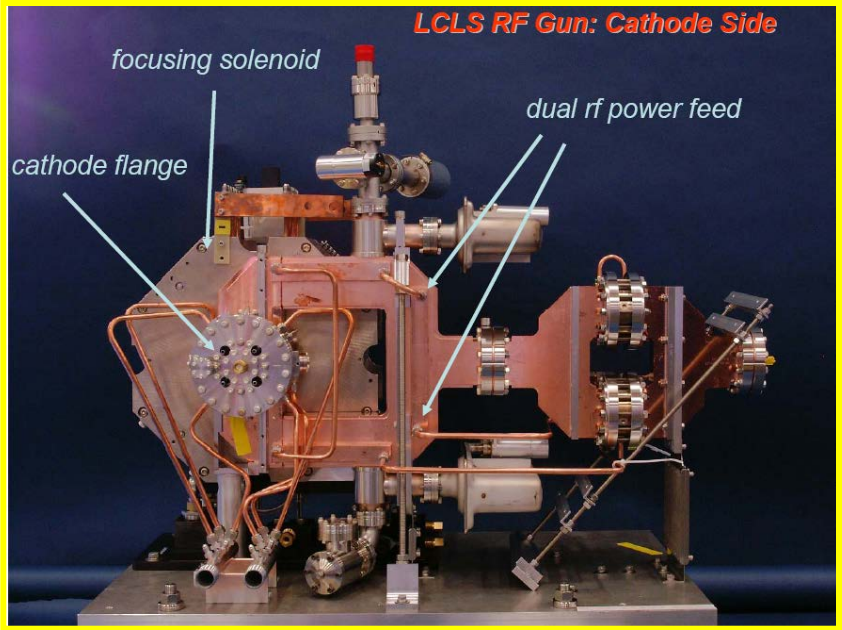
- Perform experiments with the SASE FEL output
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine





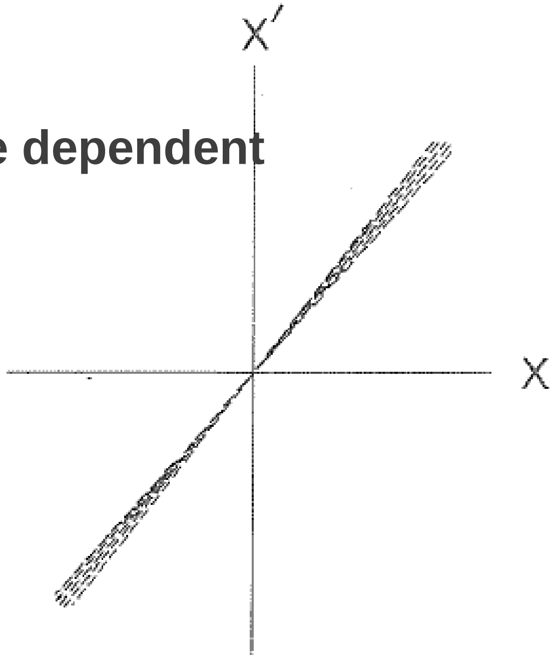
Advanced Photon Source
Argonne National Laboratory
APS/00-2

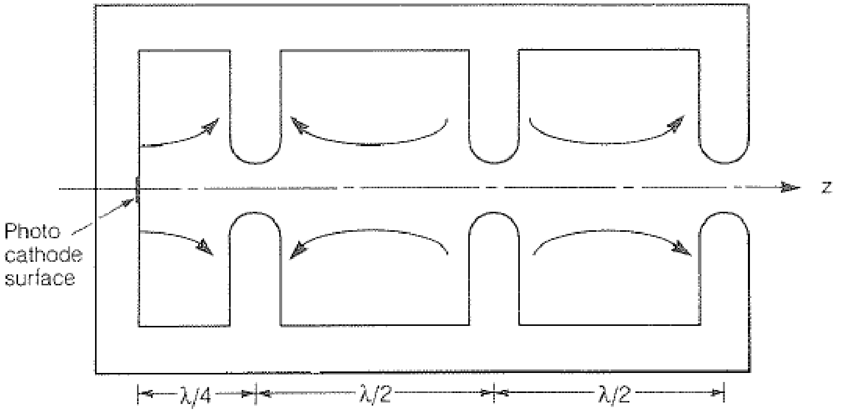
Beam Dynamics in an RF Photocathode (1988)



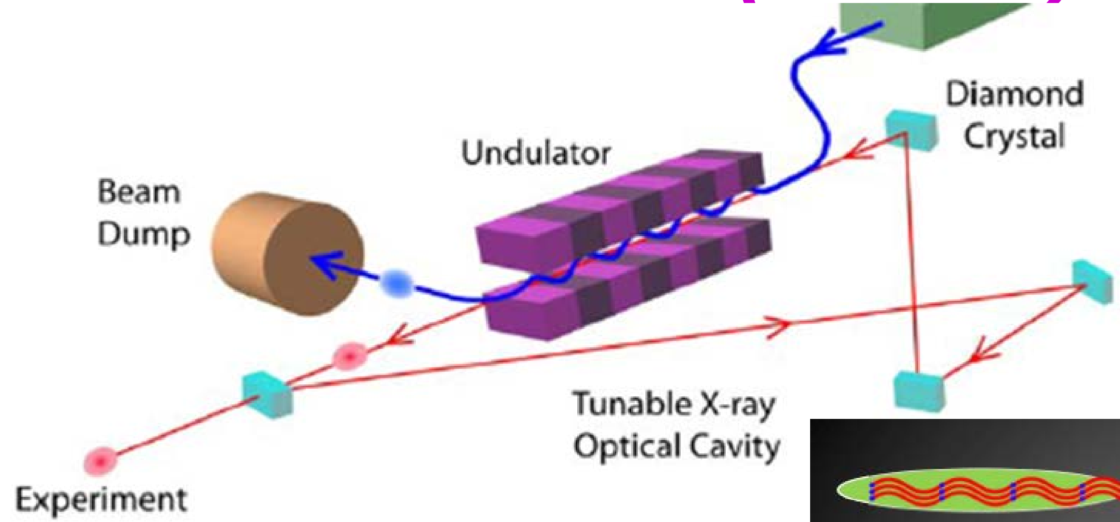
BNL type LCLS S-band RF Photocathode

Effect due to time dependent RF focussing

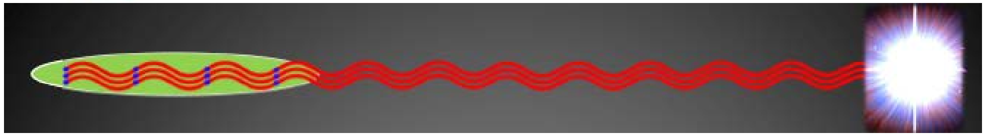




The full complement of XFELs should include oscillators (XFELO)

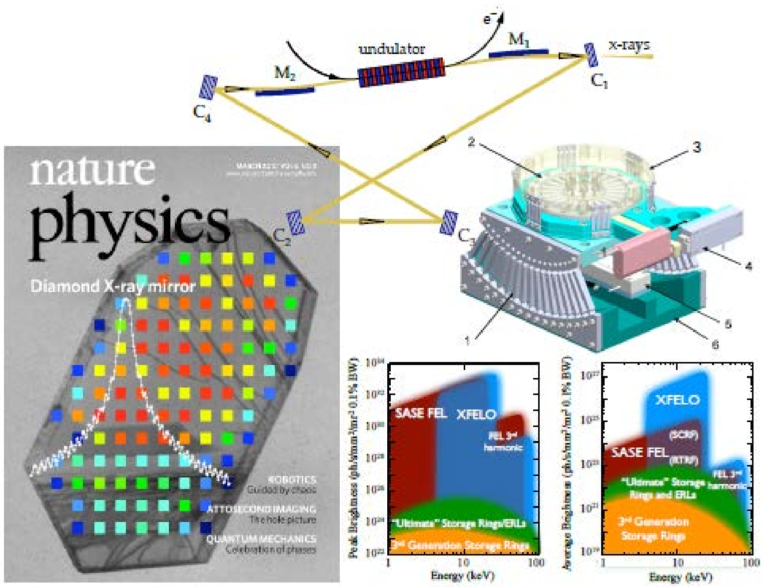


KJK, Yuri Shvyd'ko, Ryan Lindberg, Stan Stoupin, Deming Shu, Vladimir Blank,

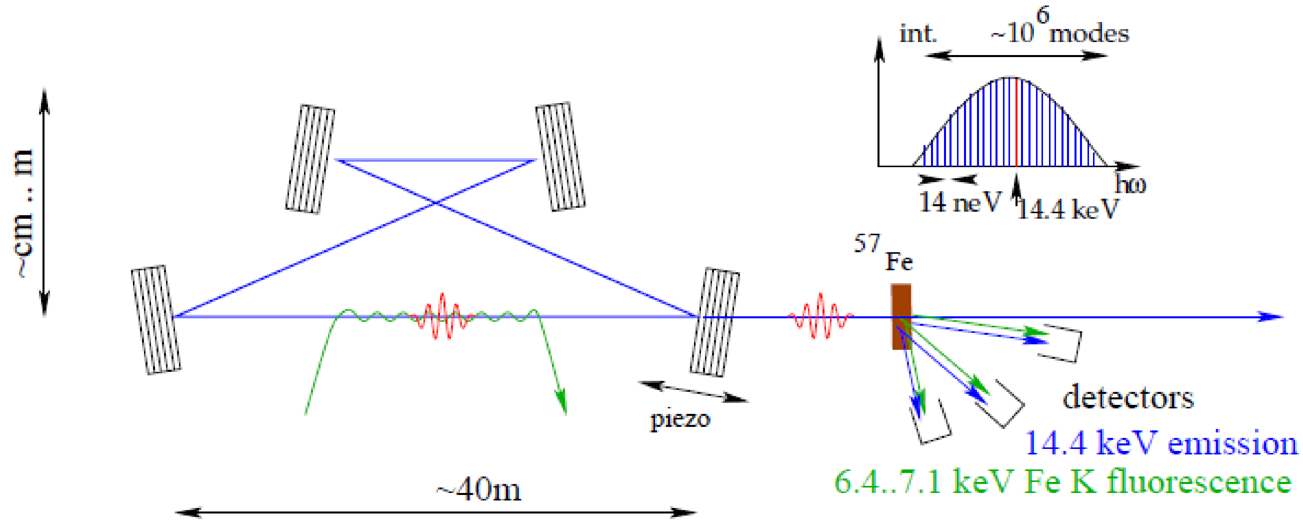


- **Bragg reflectors as suggested at the 1983 BNL WS**
- **Highly stable, fully coherent, ps pulses with ultra-high spectral purity (10^{-7}) with MHz rep rate XFELO looks feasible (2008)— "a real laser"**
- **XFELO may be implemented at LCLS-II by using harmonic lasing (X. Deng, R. Lindberg, 2013)**

We are happy to work on XFELO!



XFELO can be regarded as seeded FEL with an identical seed



- **By stabilizing the XFELO cavity length referenced to a narrow nuclear resonance(^{57}Fe), x-ray spectral combs may be generated, allowing experimental x-ray quantum optics for fundamental physics, x-ray metrology, etc (Bernhard Adams, KJK, 2012)**

A Short Lesson in Korean and Chinese (the latter learned from Yuan T. Lee)

- **Kwang (광, 光)--light**
- **Je (제， 齊)– ordered**
- **Kwang-Je → *Coherent Radiation***

Some random samples of past moments

Quest for higher brightness has given me opportunities to meet scientists & engineers & students around the world, to learn and deepen my sciences and enrich my life.

Thank you all for excitement, and for good times!