Lecture 1:

Introduction

Yunhai Cai
SLAC National Accelerator Laboratory

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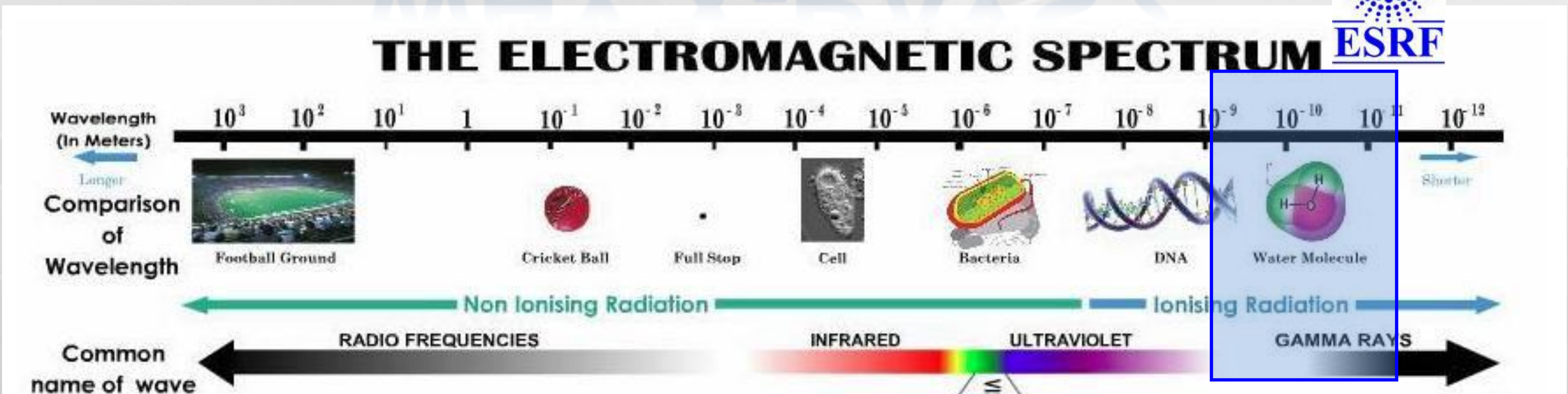
USPAS June 2017, Lisle, IL, USA

WHY X-RAYS?

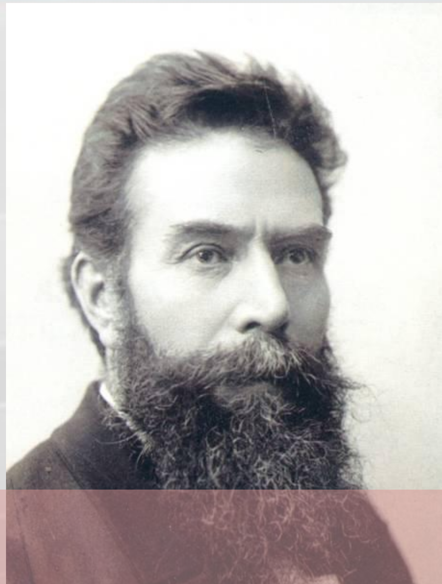


X-rays – as electrons – are ideally suited to achieve ***sub-nano-*metre** spatial resolution:

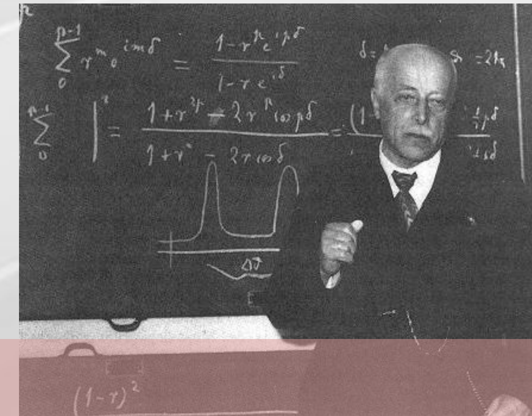
- ***No diffraction limit*** (visible light)
- ***X-ray Synchrotron nano-imaging*** achieved already ***resolution below 10x10 nm²***

X-rays

2012
SLAC: 50 years
X-ray Diffraction: 100 years

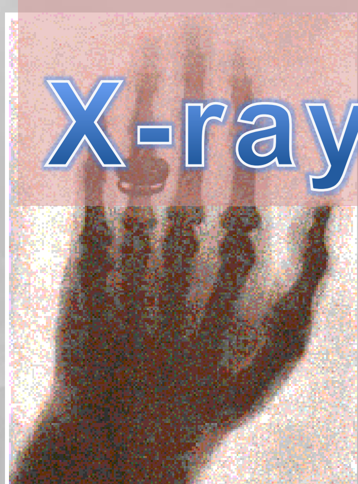


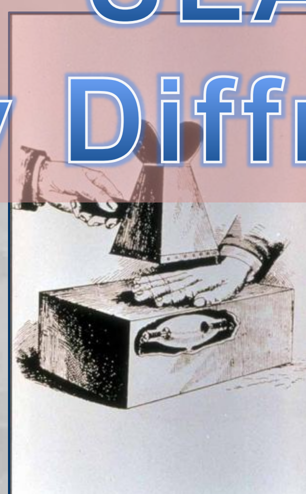
Röntgen discovered X-rays in 1895 and received the FIRST NOBEL PRIZE in Physics in 1901.



Max von Laue

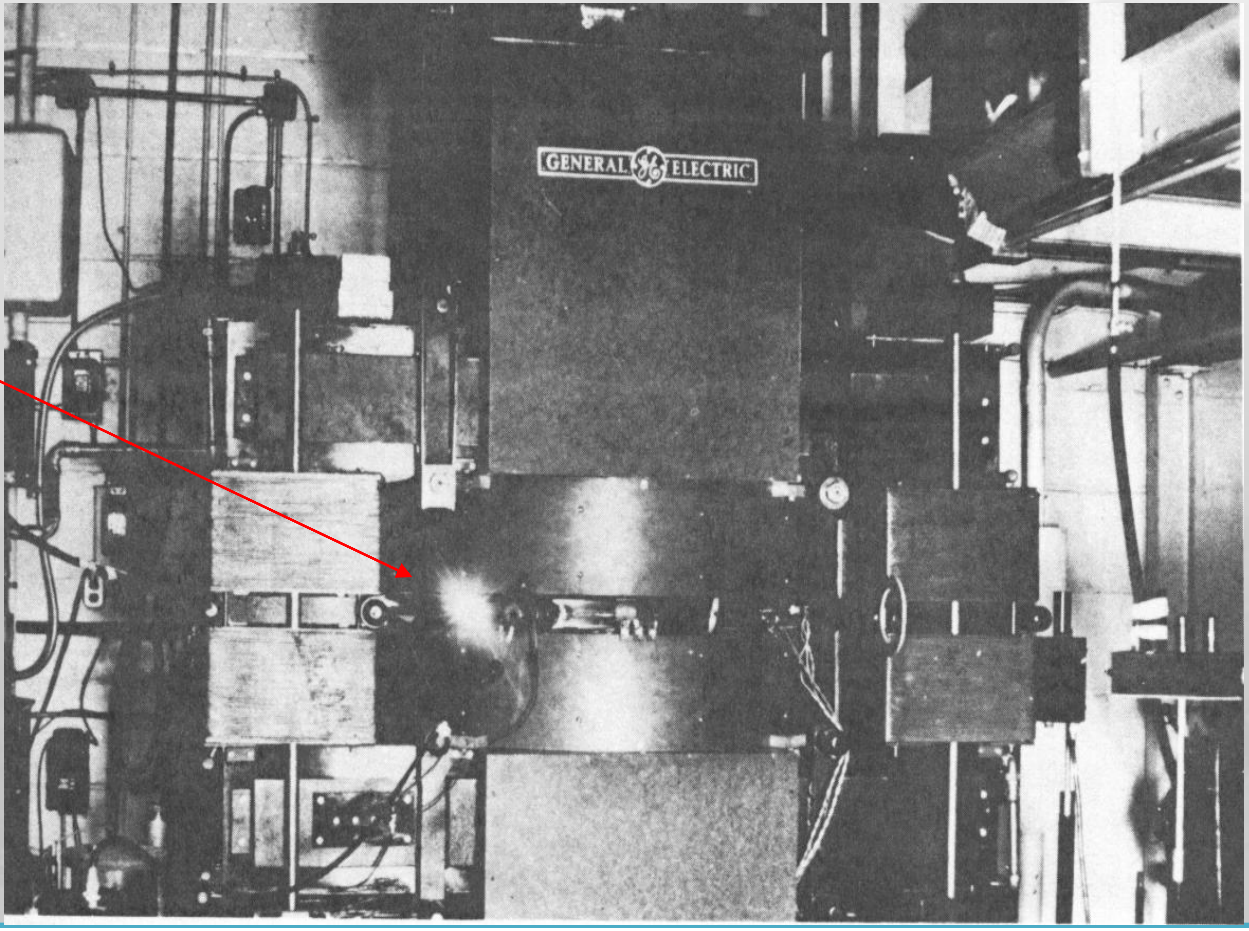
W. Bragg father and son





Laue and the Braggs discovered in 1912-13 that X-rays can be used to study atomic structures and properties of materials. They received Nobel Prizes in physics in 1914 and 1915, respectively.

First Observation of Synchrotron Radiation



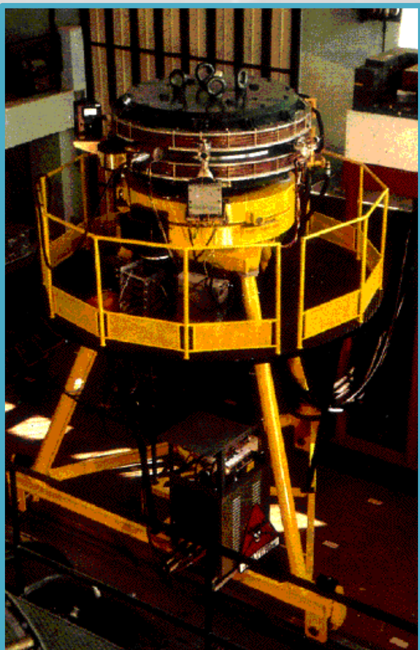
The General Electric team (Langmuir, Elder, Gurewitsch, Charlton and Pollock) looking at the vacuum chamber of the 70 MeV synchrotron (1947).

Synchrotron X-rays

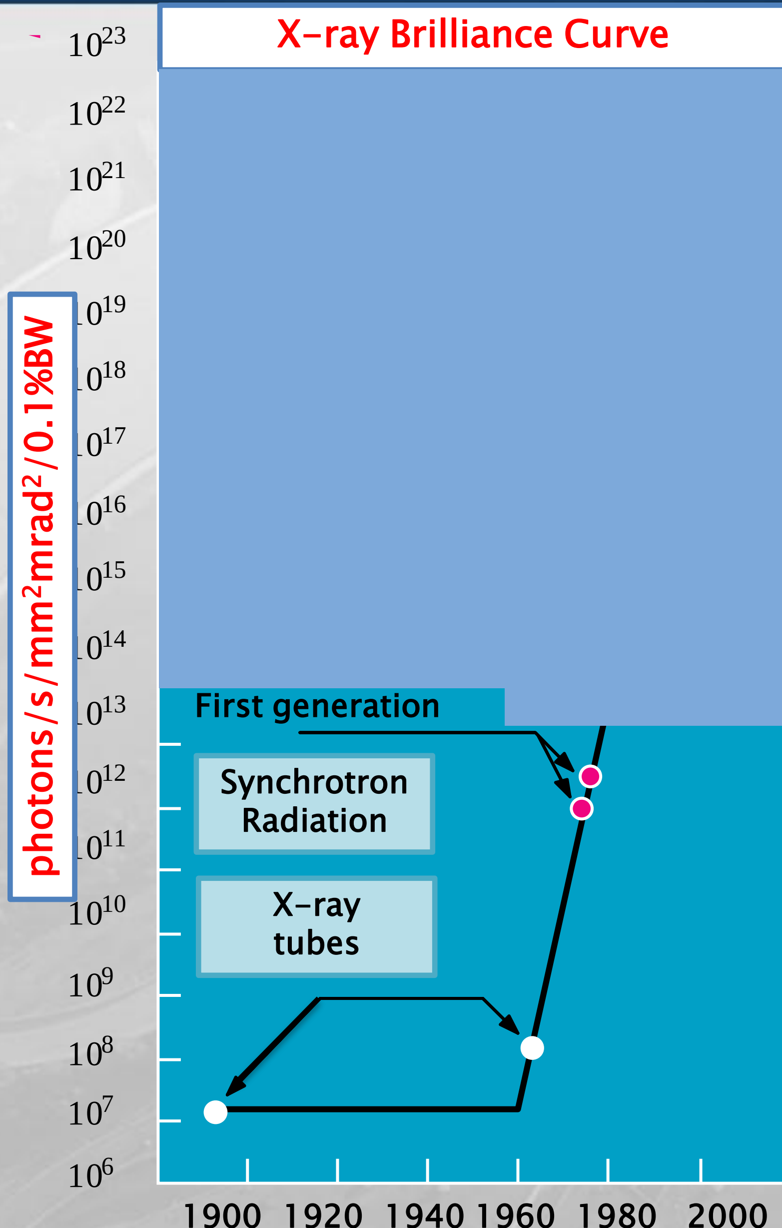
Synchrotron Radiation:

A Revolution in the use of X-rays

Storage Ring, 1961-1964
Key Time for Synchrotron Radiation



Construction of ADA,
the first storage ring for electron and positron beams rotating in opposite Directions.
Proposed by Bruno Touschek (1921-1978), in 1960

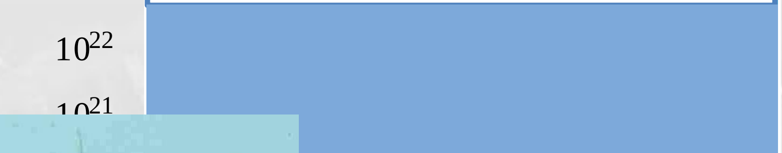


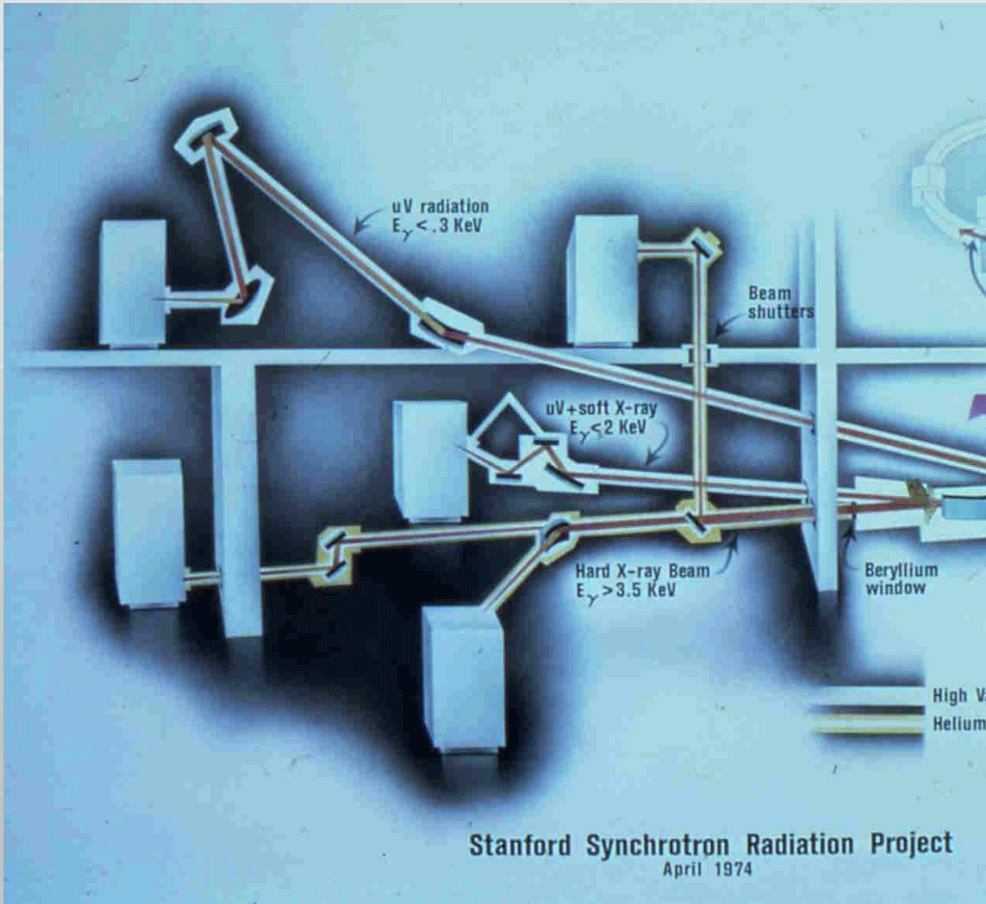
Synchrotron X-rays

Synchrotron Radiation:

A Revolution in the use of X-rays

X-ray Brilliance Curve



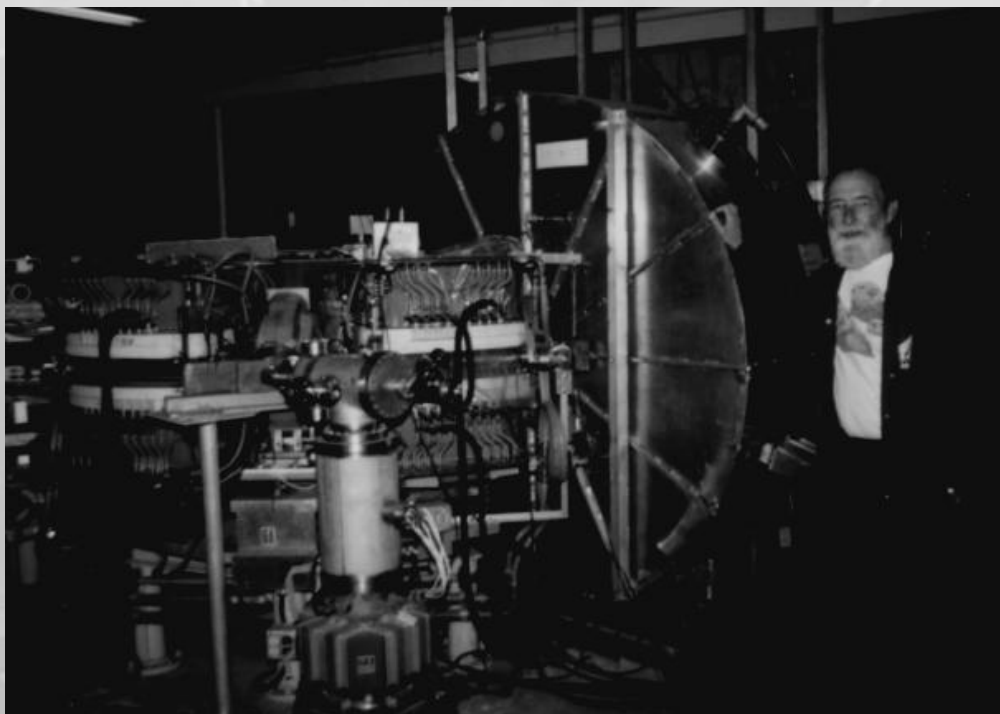


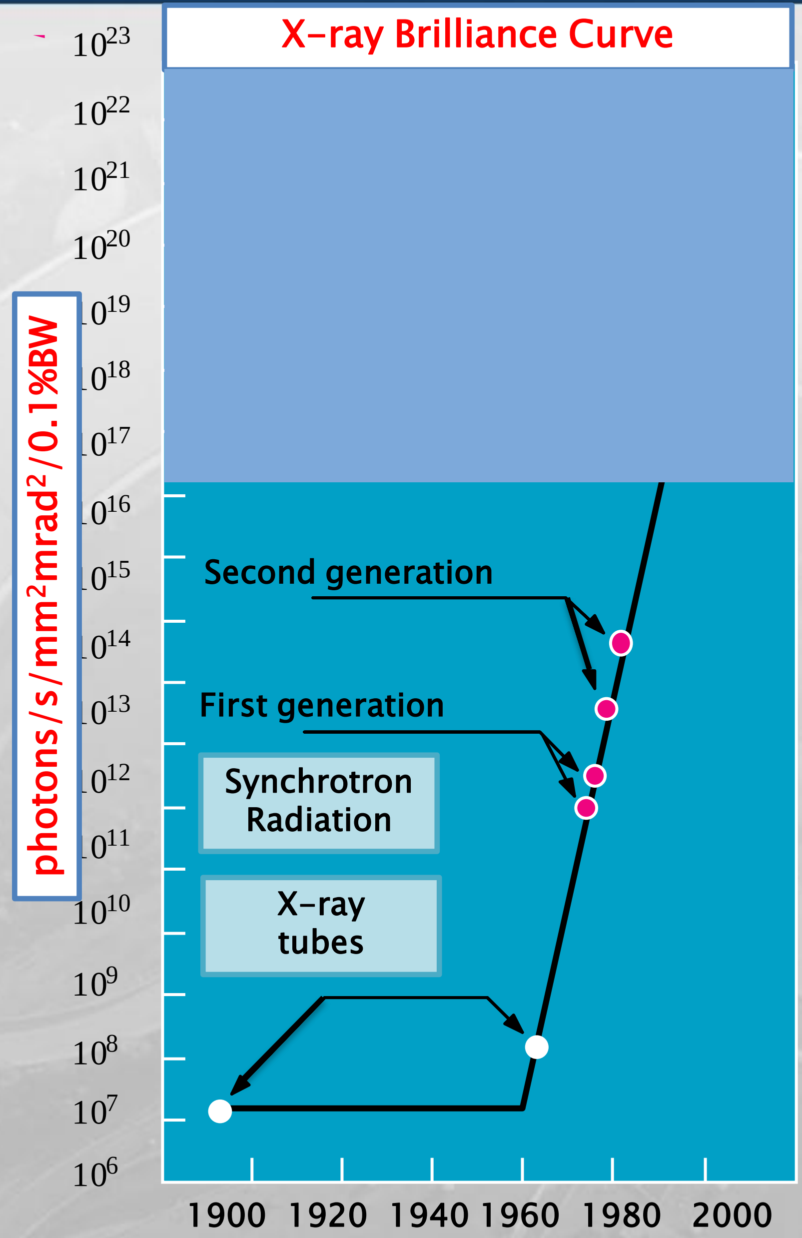
Synchrotron X-rays

Synchrotron Radiation:

A Revolution in the use of X-rays

Tantalus I:
The first dedicated source of Synchrotron Radiation, 1968

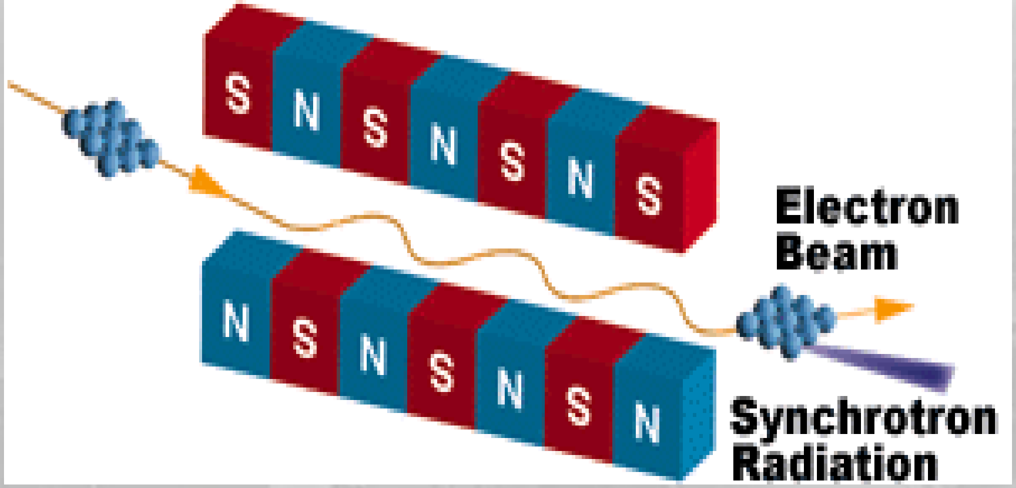


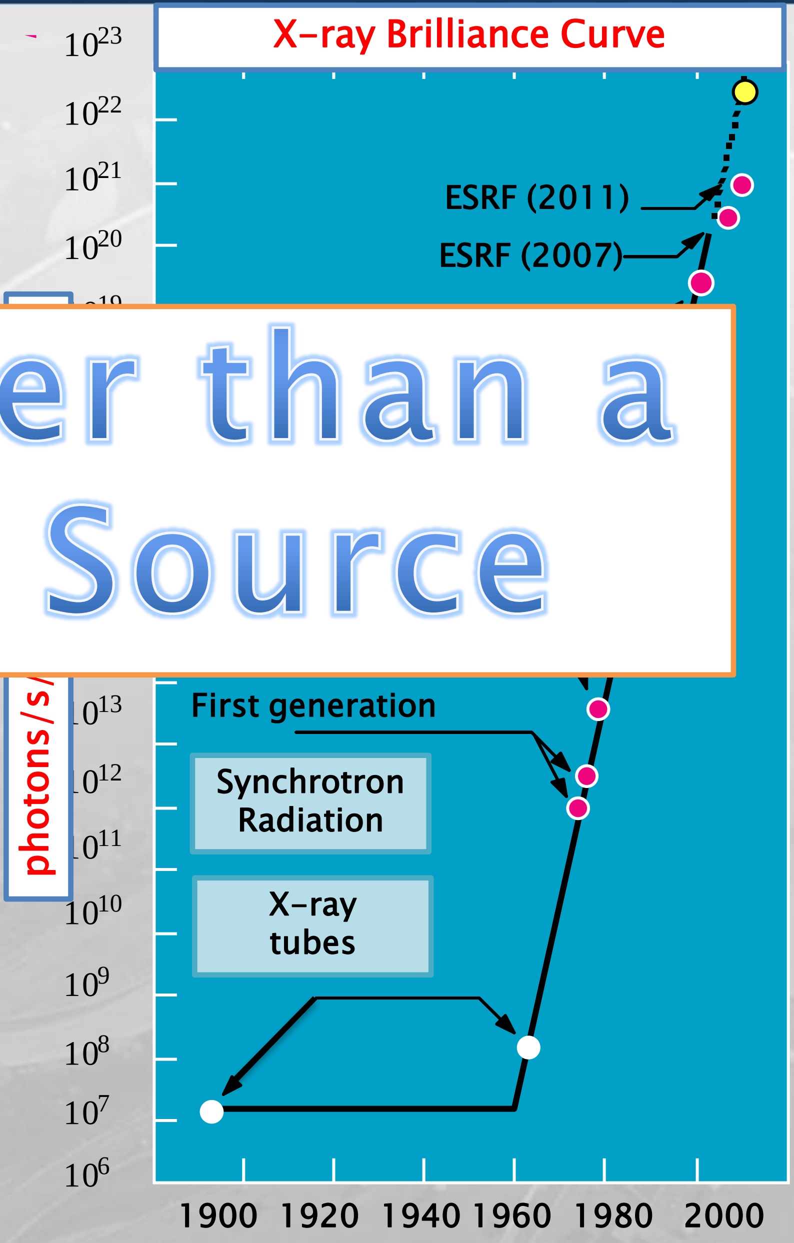


Synchrotron Radiation:

A Revolution in the use of X-rays

~10^{11} brighter than a Laboratory Source





The ESRF in Grenoble

The European Synchrotron Radiation Facility: the 1st Third Generation Source

Investigating matter, materials and living matter

Fields of application

Understanding matter down to the single atom links many scientific disciplines at Synchrotrons:

Solid-state physics

- Atomic structure
- Magnetic / electronic properties of materials

Chemistry

- Structure / dynamics of new materials
- Structure of interfaces

Medicine

- Pharmaceutical molecules
- New therapy protocols

Life sciences

- Protein cristallography
- Protein dynamics

Investigating matter, materials and living matter

Fields of application

Understanding matter down to the single atom links many scientific disciplines at Synchrotrons:

Engineering

- Development of new manufacturing / processing technologies
- Material failure

Material science

- Structural properties of high-performance materials
- Soft-condensed matter

Earth sciences

- Structure and formation of earth's crust
- Geo-dynamics

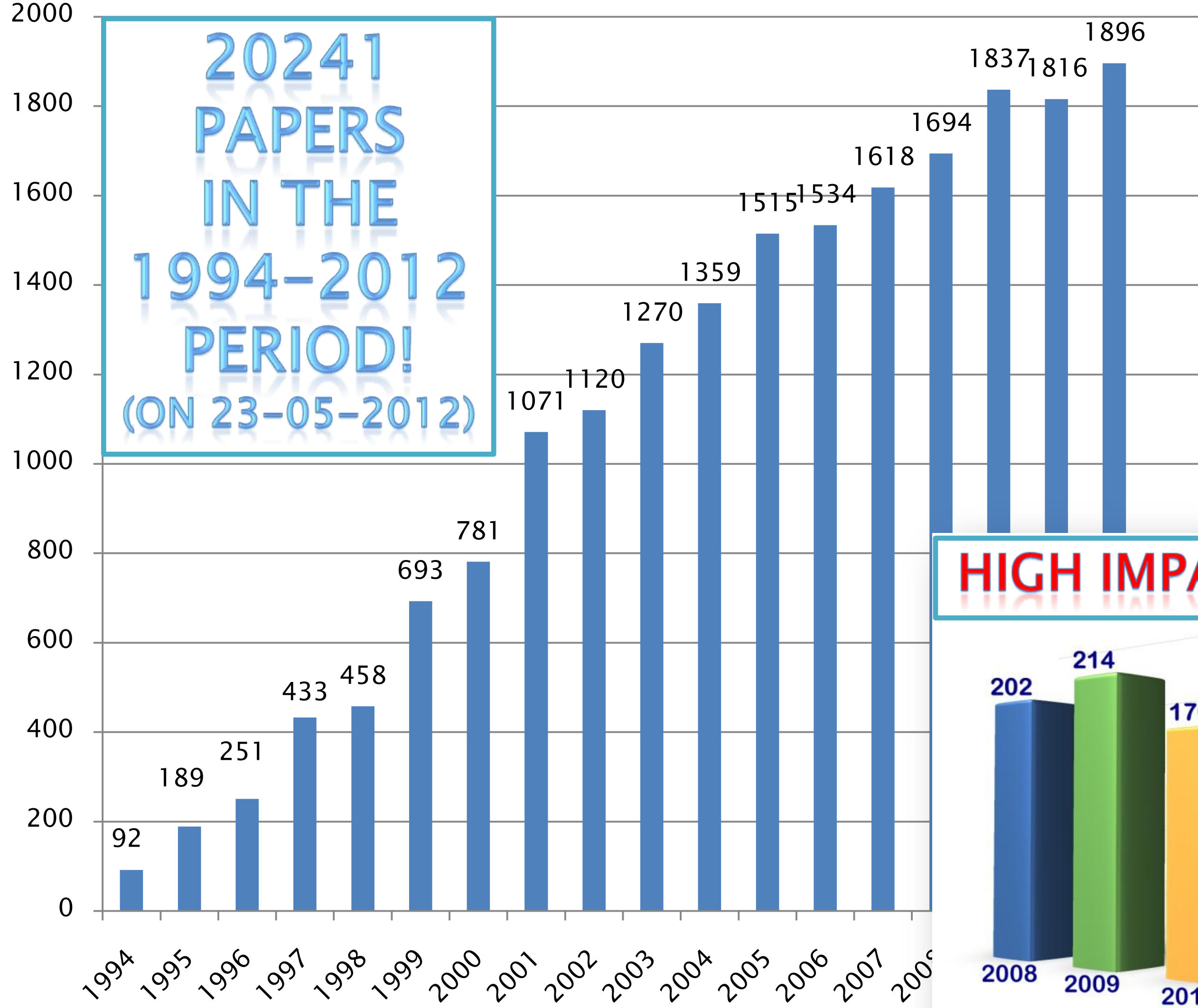
Environment

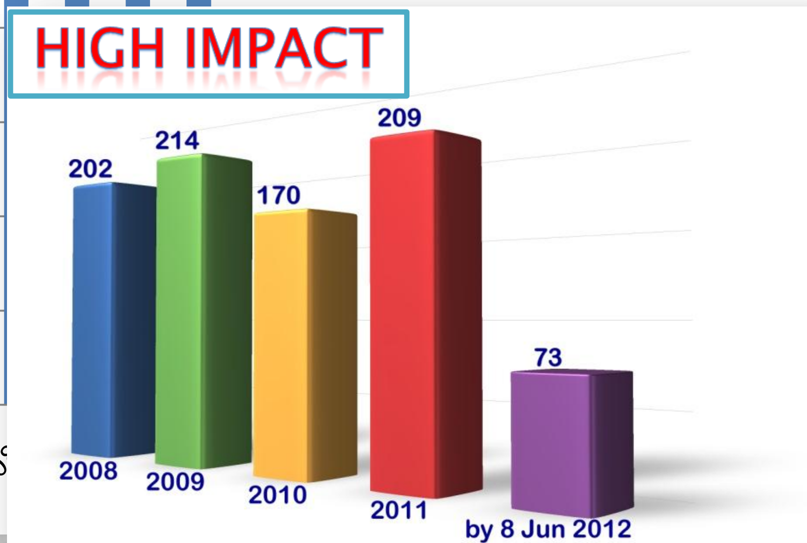
- Behaviour of bacteria under extreme conditions
- Heavy Metals in the Environment: origin, interaction and remediation

Cultural heritage

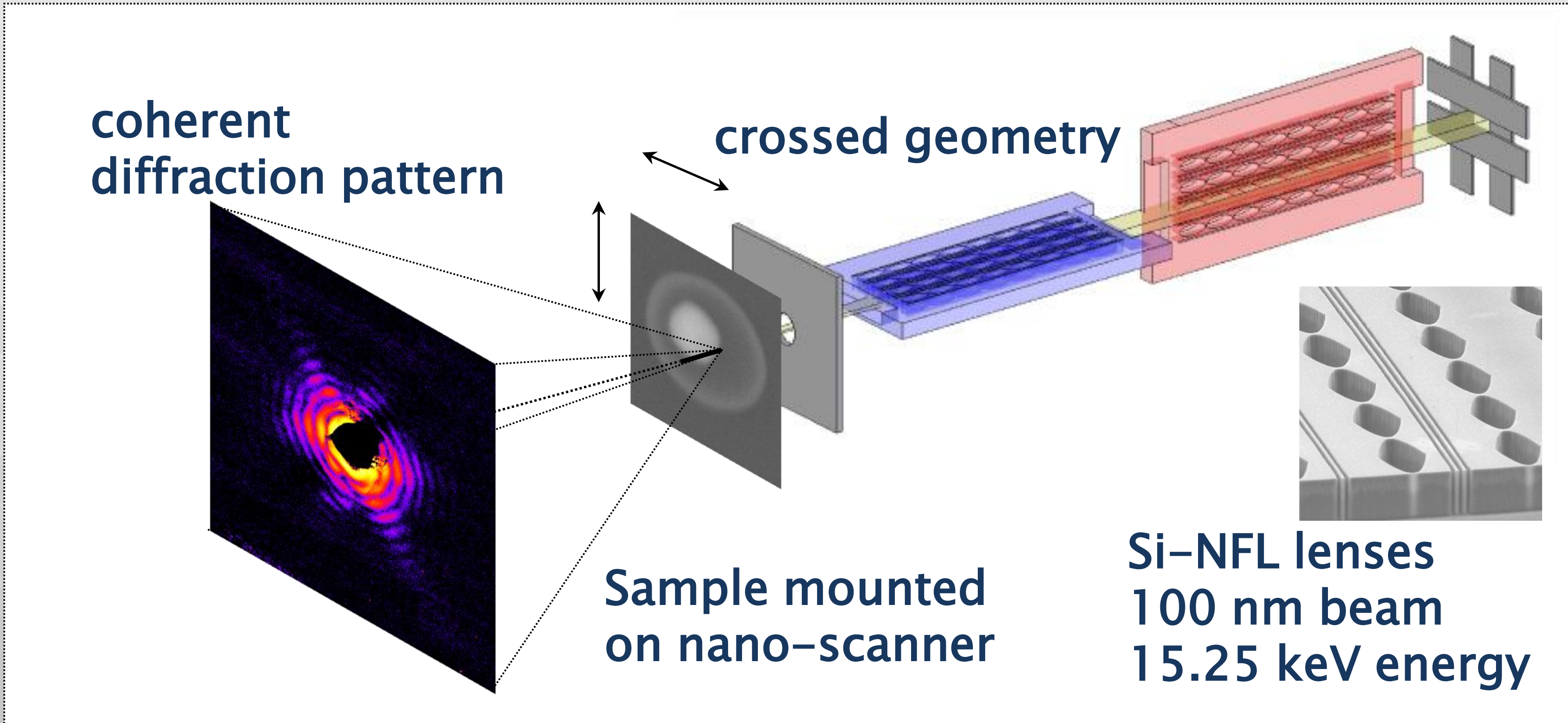
- Non-destructive X-ray imaging
- Artefacts
- Palaeontology

Refereed Publications from work at the ESRF



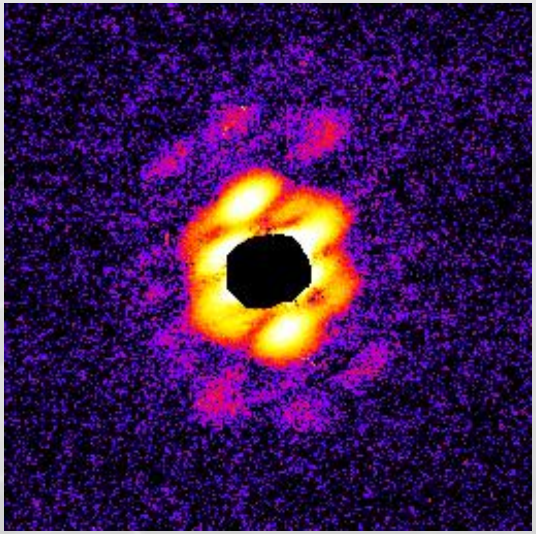


X-ray Imaging: *nano*-scale and coherent X-rays

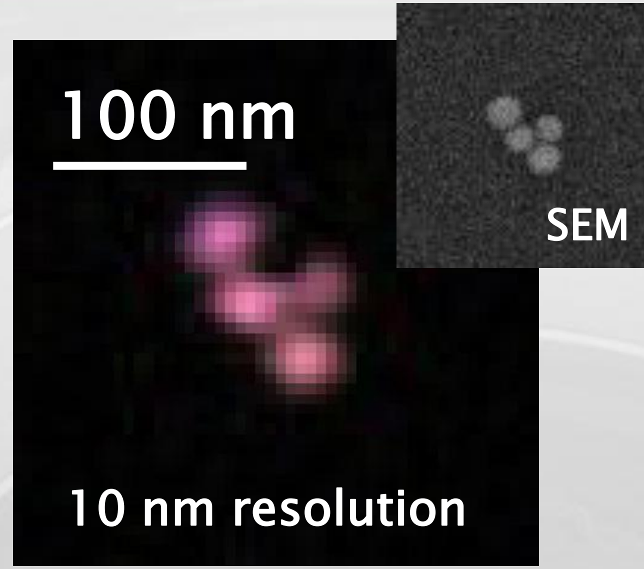


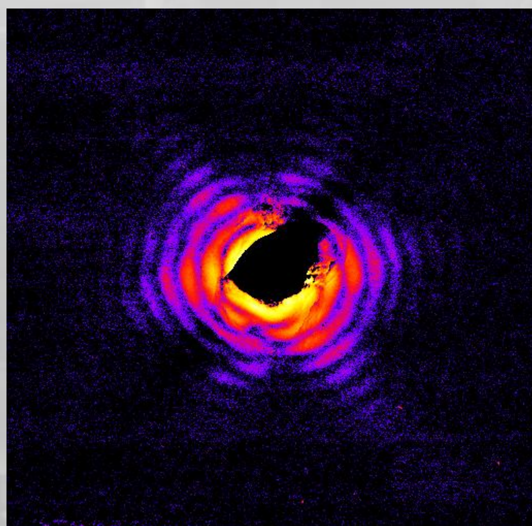
- *nano*-beam coherent X-ray diffraction imaging (CXDI)
- 100 nm beam generating gaussian illumination function
- *nano*-focusing silicon compound refractive lenses (NFL)

X-ray Imaging: *nano*-scale and coherent X-rays

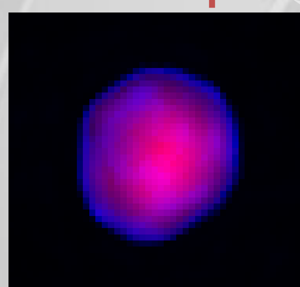


reconstruction
via
iterative
phase retrieval

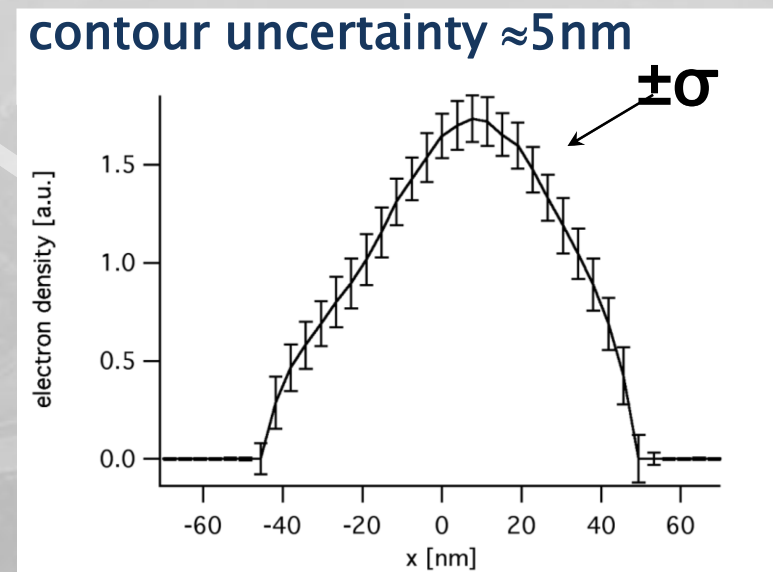




gold *nano*-particle

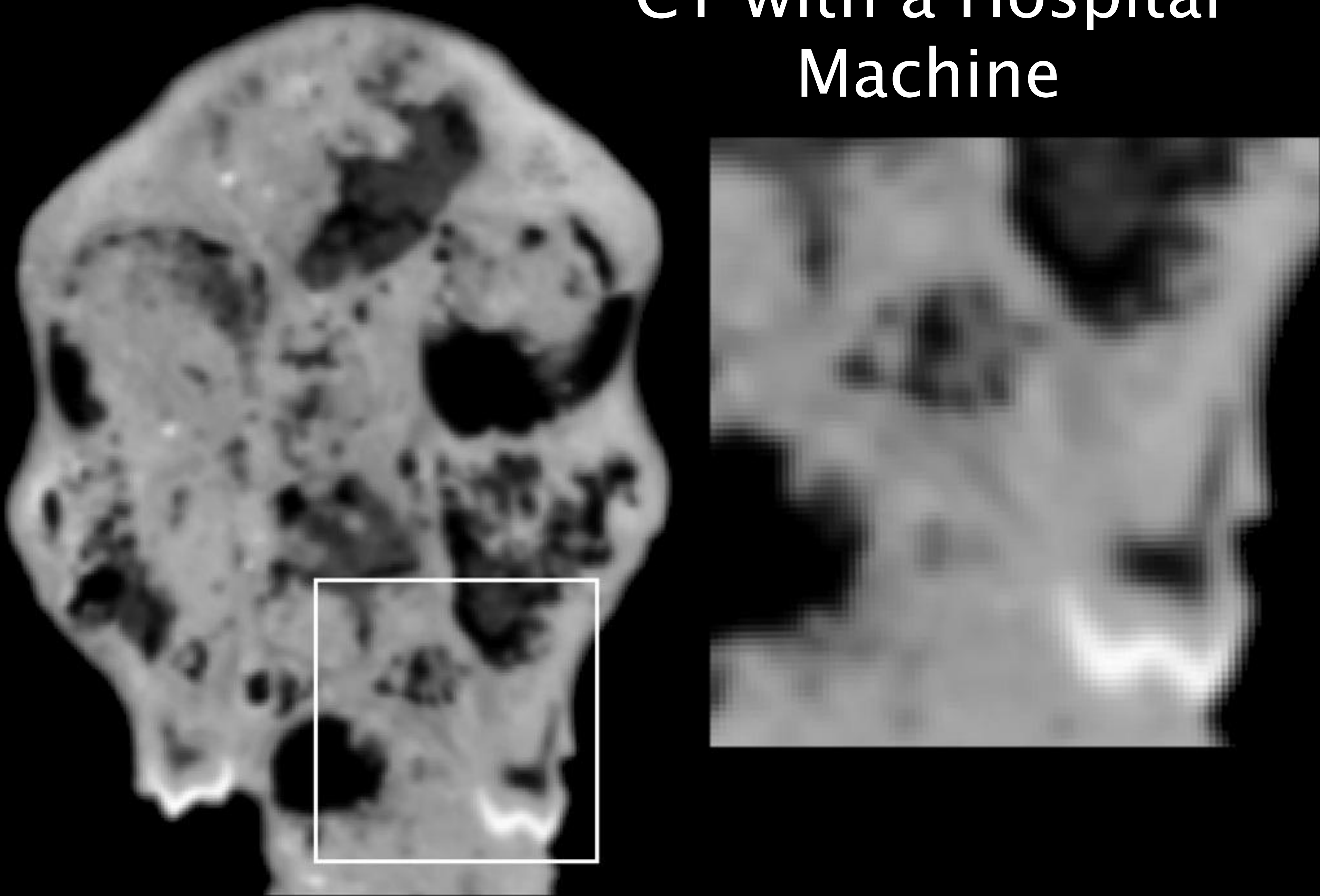


reconstructed
projection
5 nm resolution



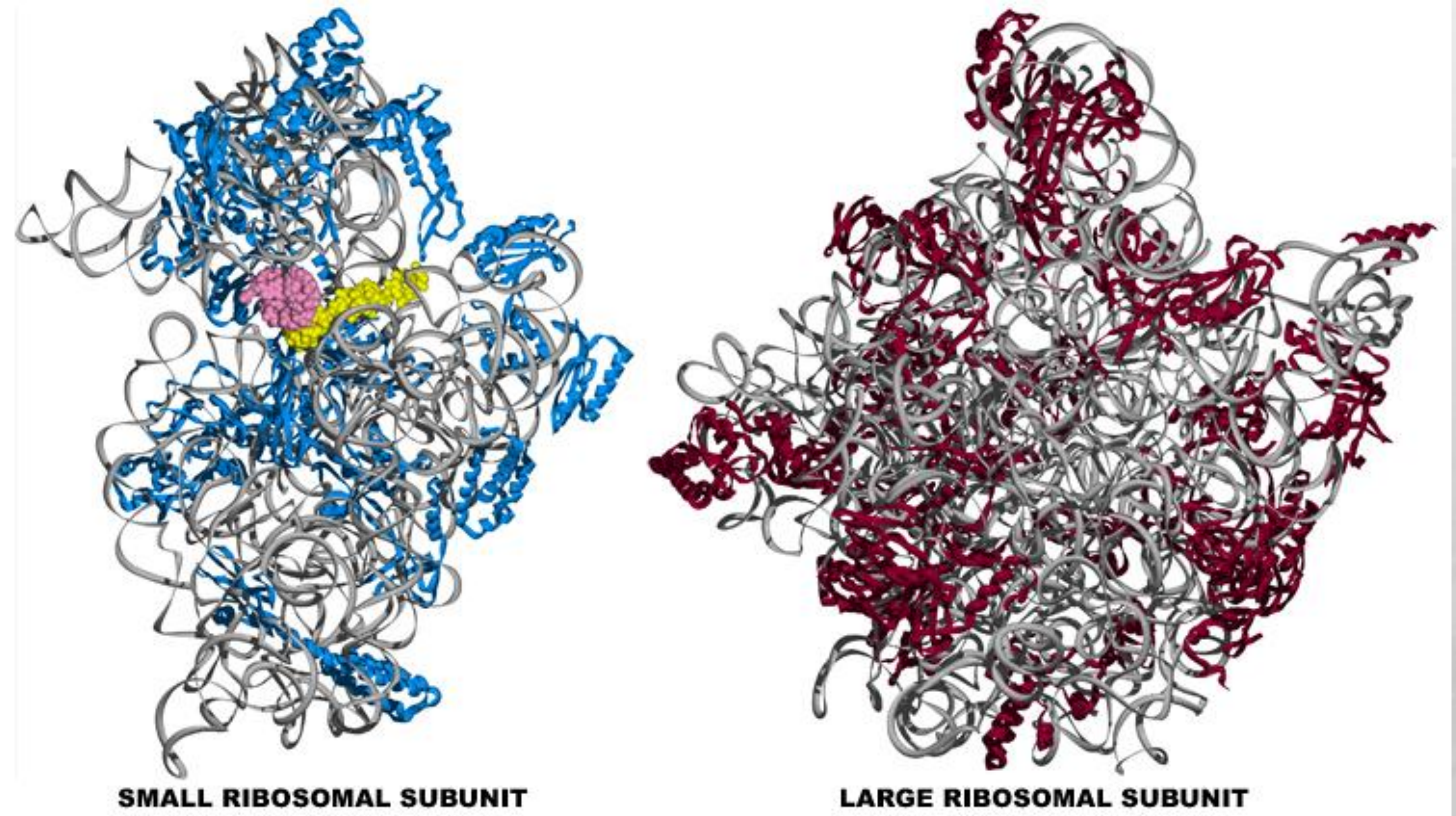
C. G. Schroer et al. Phys. Rev. Lett. 101, 090801 (2008)

CT with a Hospital Machine

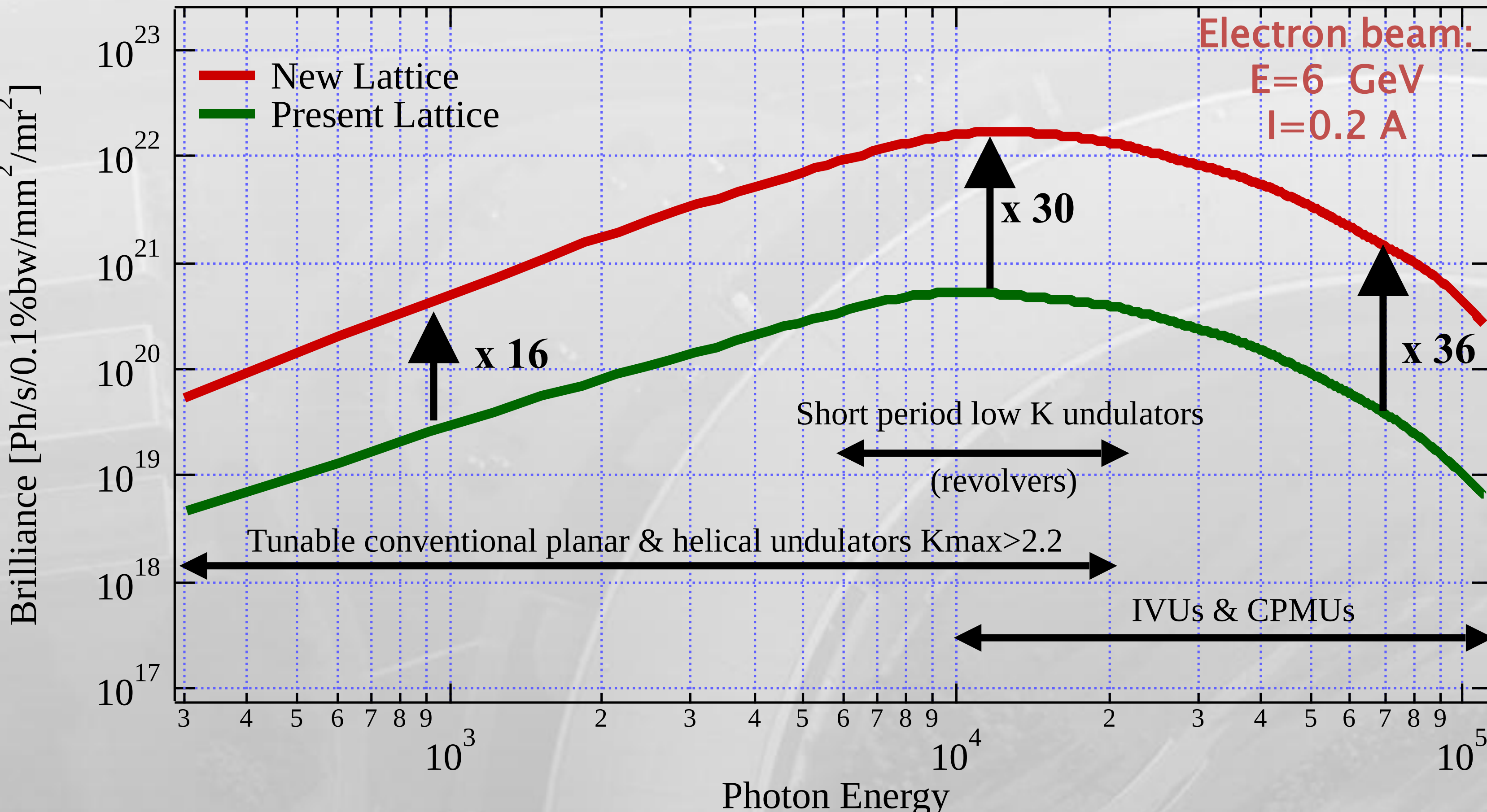


CT with Synchrotron Light on the ID17 Line at ESRF

Ribosome sub-units at atomic resolution.

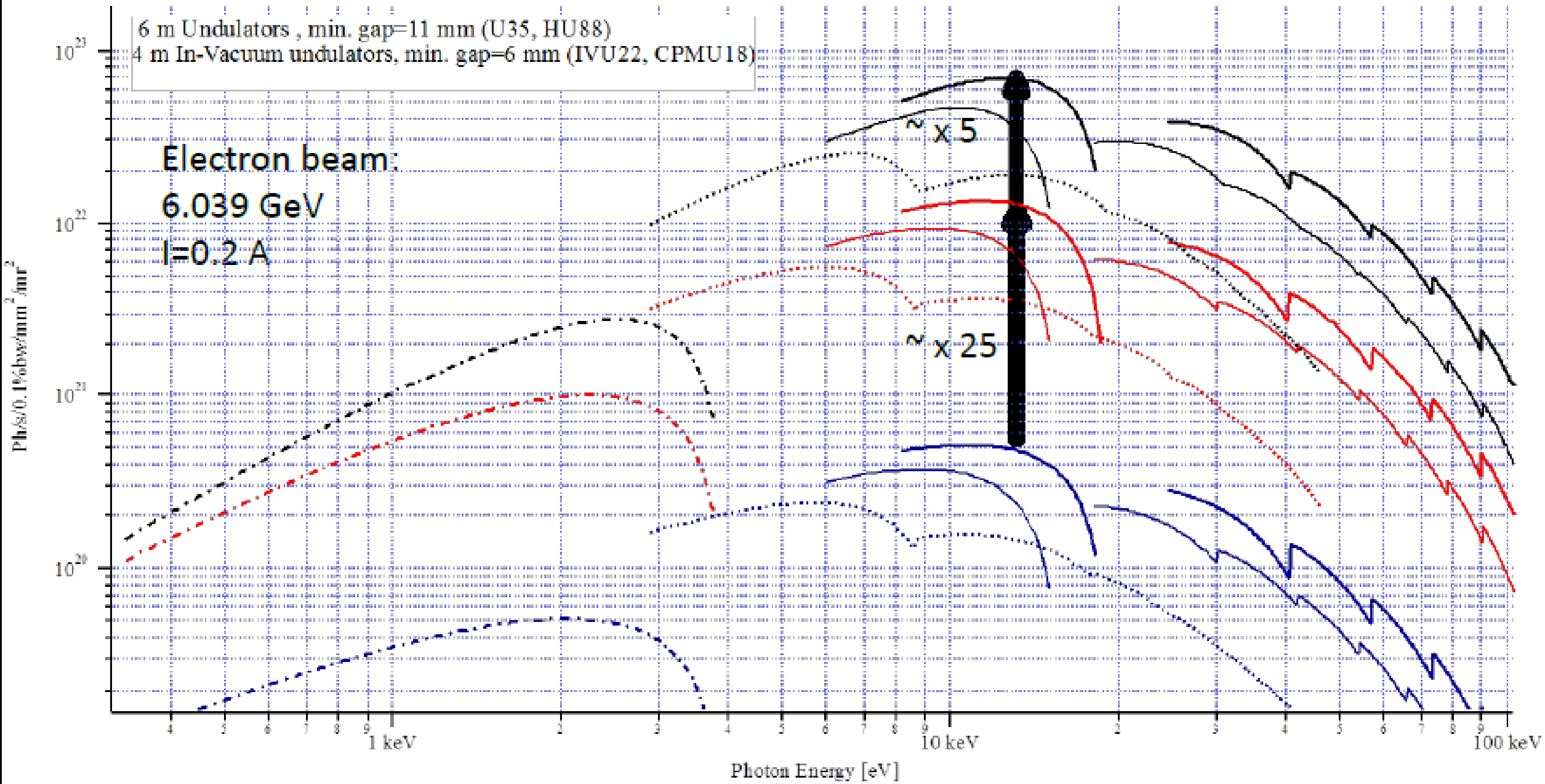


SSU from Ramakrishnan's work with A-site Anticodon Stem Loop bound and mRNA LSU from Steitz and Moore labs



	Emittance	Coulping [%]	Energy spread [%]
Present	4 nm	0.12	0.1
New lattice	0.13	1	0.09

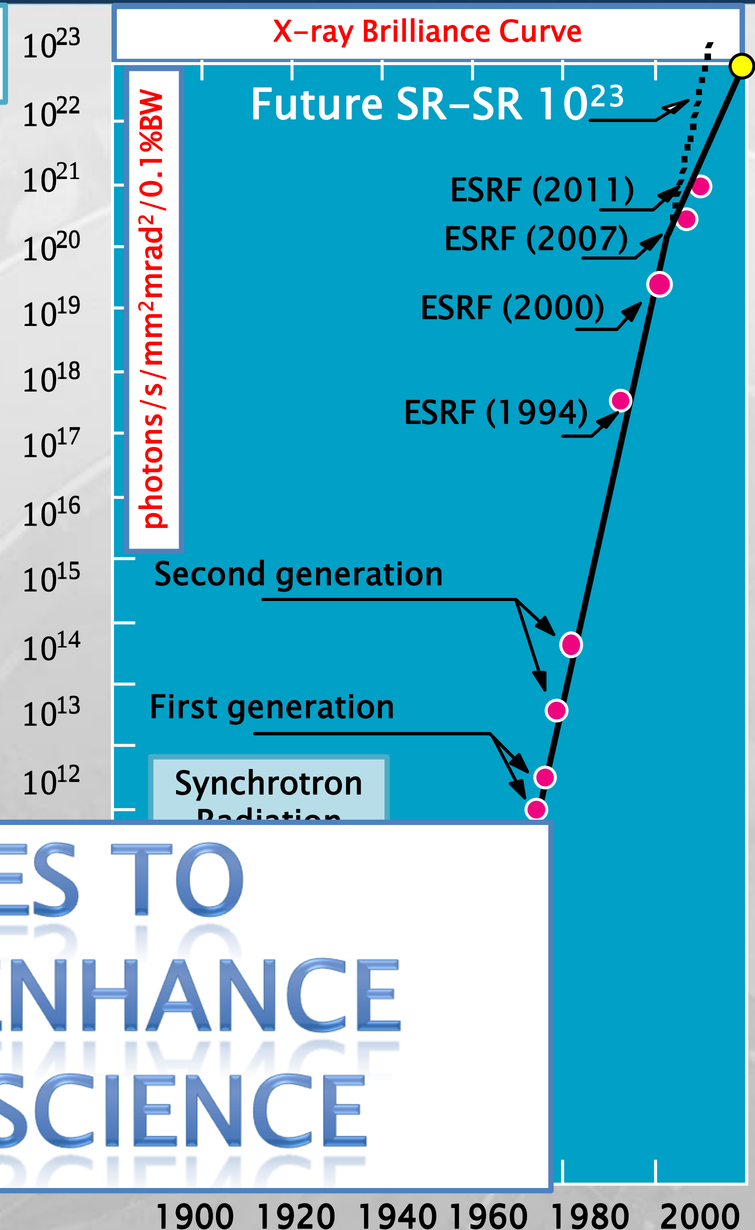
Gain in brilliance due to reduction of horizontal emittance



Hor. Emittance [nm]	4	0.15	0.01
Vert. Emittance [pm]	3	2	2
Energy spread [%]	0.1	0.09	0.09
Betax[m]/Betaz [m]	37/3	6/2	6/2

The SR Grand Challenges

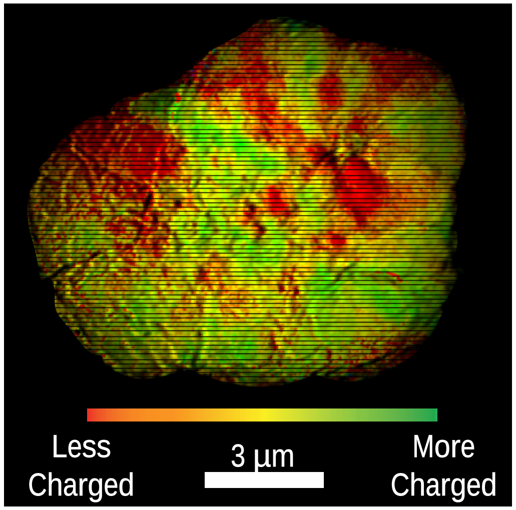
- **To be increasingly useful:**
  - Powered by scientific excellence
  - Faithful and committed Users' service
- **To enlarge the Users' Community:**
  - More then PHOTONS!
- **Quest for the "Future SR-SR source":**
  - Improved horizontal emittance: 10x10 pm^2 ??
  - 10^{23} Brilliance ($ph/s/mm^2mrad^2/0.1\%BW$) ??



OPPORTUNITIES TO QUALITATIVELY ENHANCE SYNCHROTRON SCIENCE

Motivation: Desire to Probe Nature at Atomic Length (Å) & Time (fs) Scales

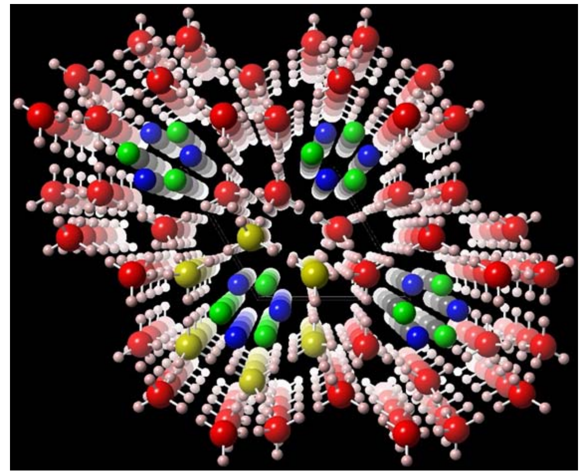
Seeing the Invisible in Real Materials



Compositional heterogeneity in a $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ battery hundreds of hours after charging

Adv. Materials (2016)

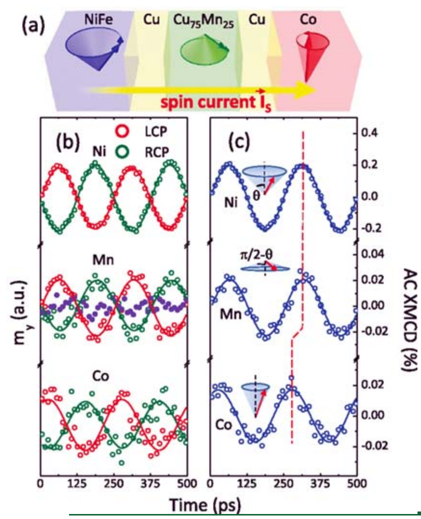
Where are the Atoms?



Newly discovered structure of a hydrogen-stuffed, quartz-like form of ice

JACS (2016)

Where are the Electrons & Spins?



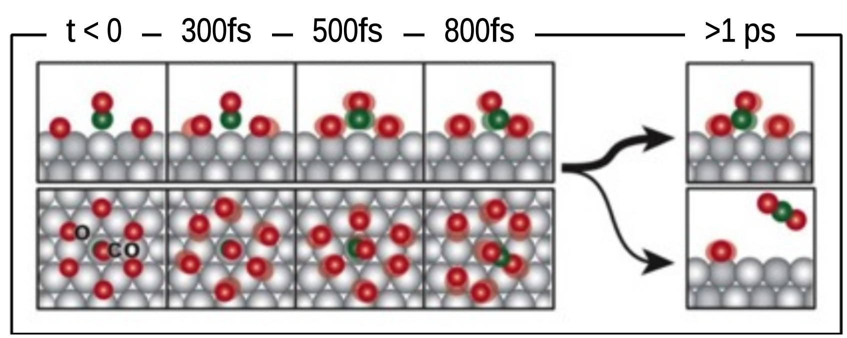
Direct measurements of "pure" ac spin currents (flow of spin angular momentum without flow of charge)

PRL (2016)

What are the Dynamics?

Capturing the transient behavior of catalytic bond formation

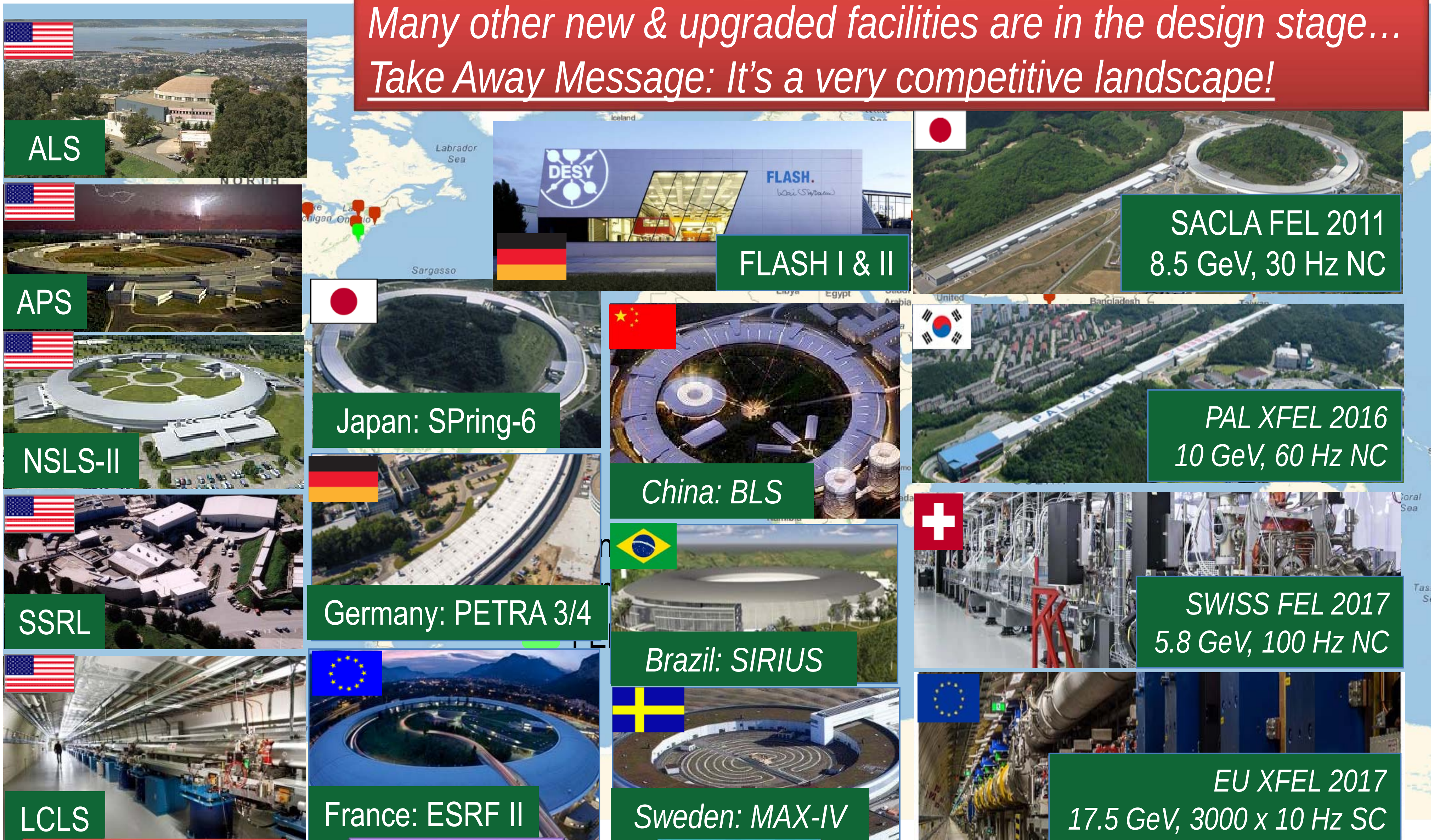
Science (2015)



Goal: Control Matter & Energy on These Scales!

Light Sources Are Alive & Kicking: 60⁺ Facilities Worldwide & Growing

Many other new & upgraded facilities are in the design stage…
Take Away Message: It's a very competitive landscape!



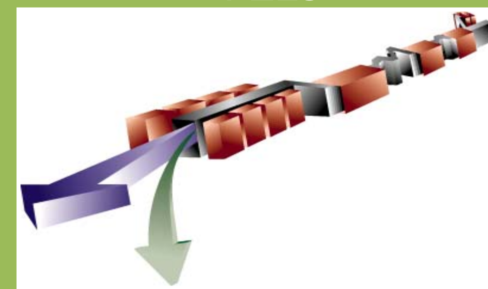
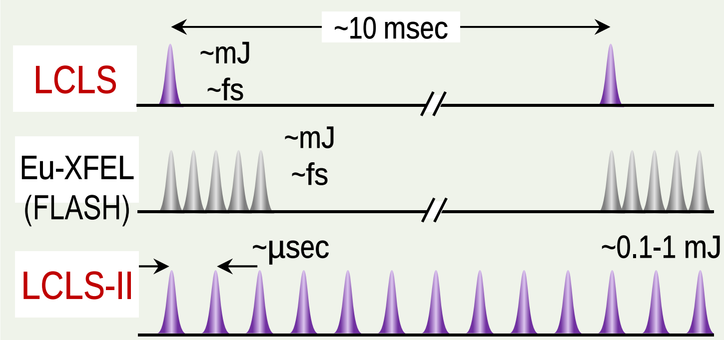
BES Light Sources | Ring Upgrades | *New Rings* | Upgraded & *New FELs*

USA Response: BESAC Report on Light Source Facility Upgrades (June 2016)

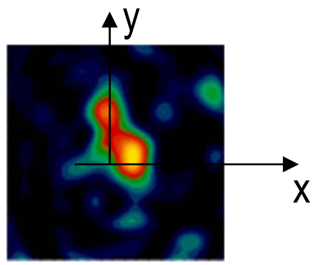
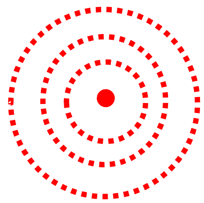
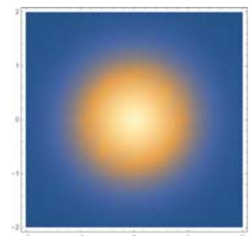
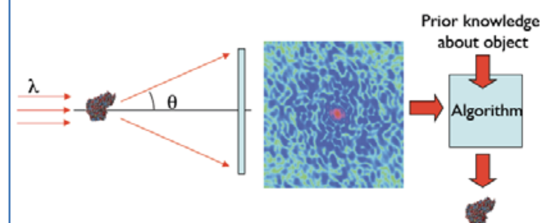
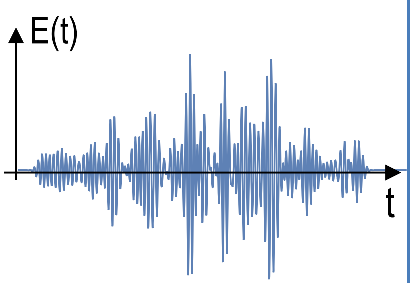
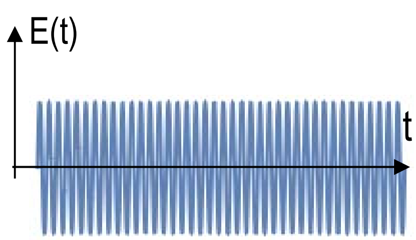
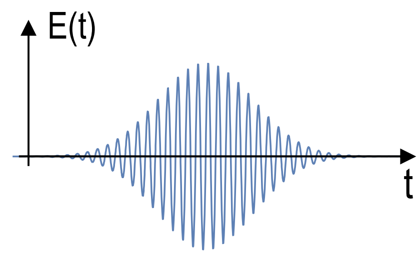
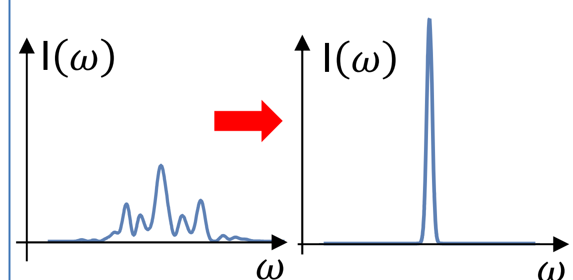
	Storage Rings		FEL
Project	ANL APS-U	LBNL ALS-U	SLAC LCLS-II-HE
Project Scope	Hard X-ray ~Diffraction Limited 6 GeV Multi-Bend Achromat (MBA) Ring	Soft X-ray ~Diffraction Limited 2 GeV Multi-Bend Achromat (MBA) Ring	High Rep-Rate, High Energy X-ray FEL, 8 GeV SC Linac
Current Status of Facility	APS is operational since 1996; ring will be replaced	ALS is operational since 1993; ring will be replaced	LCLS is operational since 2010; LCLS-II is under construction
Worldwide Competition	EU ESRF Germany PETRA 3,4 Japan SPring-6 China BLS	Sweden MAX-IV Brazil SIRIUS CH SLS-II	EU XFEL Japan SACLA Korea PAL XFEL CH Swiss FEL
Dark Time	~1 yr	~0.75 yr	0 yr
Status FY2017	CD-3b	CD-0	CD-0

The ALS-U, APS-U & LCLS-II-HE proposals were each deemed “absolutely central to contribute to world leading science & ready to initiate construction”

Storage Rings & Free Electron Lasers are Complementary

Parameter	Storage Rings	FELs
		
Beam Stability	Excellent	Very Good
Number of Beamlines	Up to 70+	1-5
Brightness (Ave, Peak)	(High, Low)	(Up to Very High, Extreme)
Transverse Coherence	Partial-Full	Full (@ Saturation)
Longitudinal Coherence	Poor	Moderate (SASE)-Very Good (seeding)
Pulse Time Structure Pulse Energy		

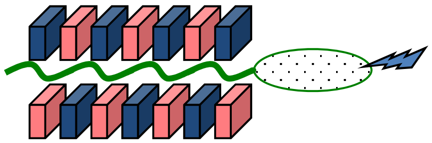
New Sources Will Provide Enhanced Transverse & Longitudinal Coherence

Coherence Level	Realistic Partial	Idealized Full	Realistic Full	Coherence Advantages
Transverse (Spatial Profile)	Multi-Mode  $\Delta x \cdot \Delta\theta_x > \lambda/_{4\pi}$	Point Source (Spherical Waves)  $\Delta x, \Delta y \rightarrow 0$	Gaussian Laser Mode  $\Delta x \cdot \Delta\theta_x = \lambda/_{4\pi}$	Coherent Diffractive Imaging, Ptychography & Nanoprobes  Imaging w/o Lenses
Longitudinal (Temporal Profile)	Noisy Pulse  $c\,\Delta t \cdot \frac{\Delta\omega}{\omega} > \lambda/_{4\pi}$	Monochromatic Wave Train  $\Delta\omega \rightarrow 0, \Delta t \rightarrow \infty$	Gaussian Laser Pulse  $c\,\Delta t \cdot \frac{\Delta\omega}{\omega} = \lambda/_{4\pi}$	FEL SASE vs Seeded Spectrum  Maximize Number of Photons in Minimum BW

Physics & Technology for Maximizing the Photon Beam Brightness, B_{ave}

Rings ~ 10^{22}

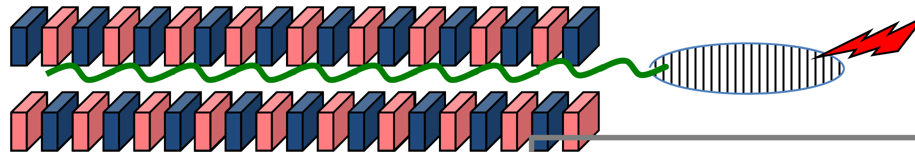
Spontaneous Emission from a Random Beam



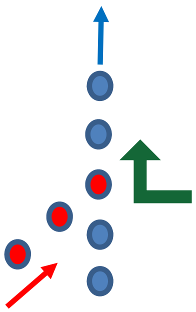
$$N_{ph}^{spon} \approx \alpha N_e \approx \frac{N_e}{137}$$

FELs ~ 10^{25}

Stimulated Emission from a Self Bunched Beam (SASE)

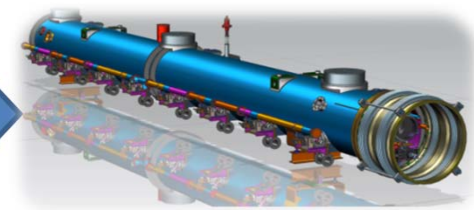


$$N_{e/coop} \approx 10^6$$
$$N_{ph}^{stim} \approx 10^6 N_{ph}^{spon}$$



On Axis Injection
Bunch-by-Bunch
or Bunch Trains

$$B_{ave} = \frac{f_{reprate}}{4\pi^2} \frac{photons/\ pulse/\ 0.1\%\ BW}{(\varepsilon_{ex} \oplus \varepsilon_{Lx})(\varepsilon_{ey} \oplus \varepsilon_{Ly})}$$

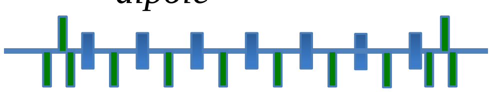


SC RF CW Linac (1.3 GHz)

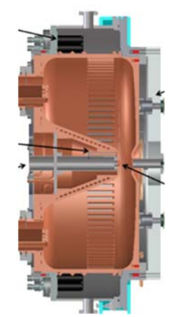
Diffraction Limit

$$\varepsilon_{Lx}\varepsilon_{Ly} \rightarrow \left(\lambda/2\right)^2$$

$$\varepsilon_x \propto \frac{E_e^2}{N_{dipole}^3}, \quad N_{MBA} \approx 2,3 \rightarrow 7,9$$

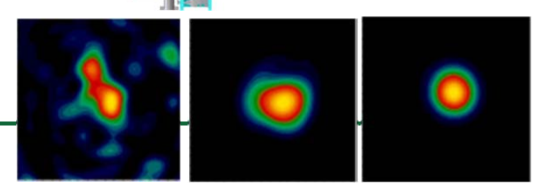


Multi-Bend Achromat (MBA)



High Brightness
High Rep Rate
Photoinjector

$$B_{peak} = \frac{B_{ave}}{\tau_e \cdot f_{reprate}} \xrightarrow{FEL} 10^{10} B_{ave}$$

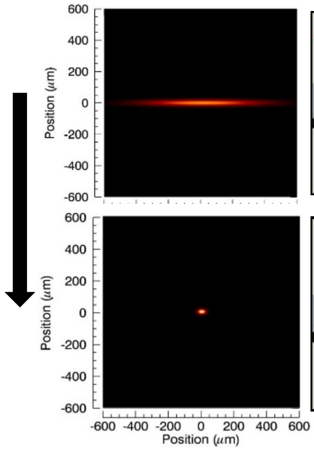


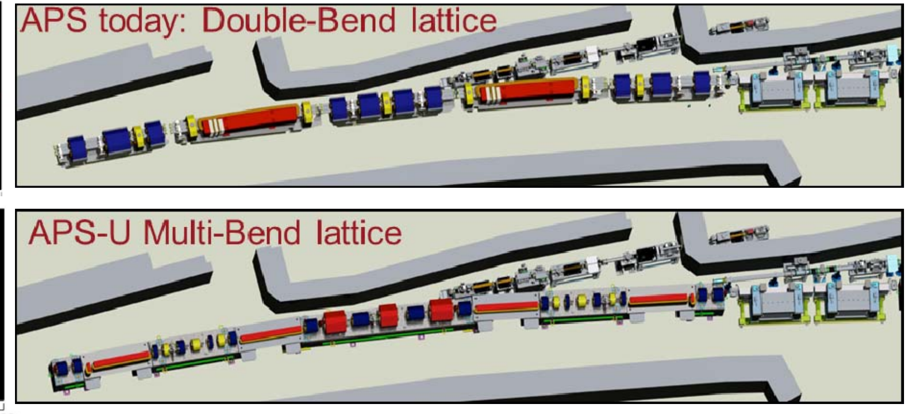
Advanced Photon Source Upgrade (APS-U) at ANL

Project Developments:

- Design optimized to provide penetrating high-energy x-rays
- MBA-7 lattice incorporating reverse bends to reduce emittance from 67pm to 41pm
- Beamline proposal selection and roadmap complete
- Technical prototypes well along; Preliminary Design Report underway; ready for next step

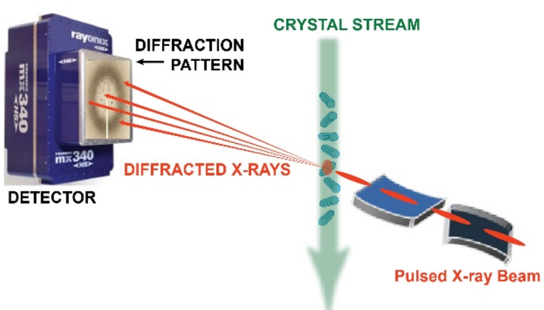
APS-U MBA-7 lattice uses 7 bending magnets/sector (was 2)





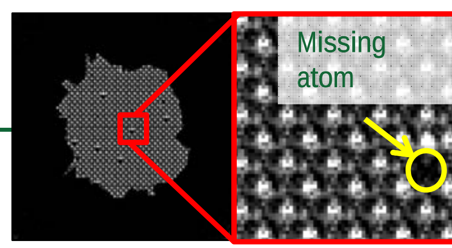
Small-Beam Scattering & Spectroscopy

- Nanometer imaging with chemical and structural contrast; few-atom sensitivity
- Room-temperature, serial, single-pulse pink beam macromolecular crystallography



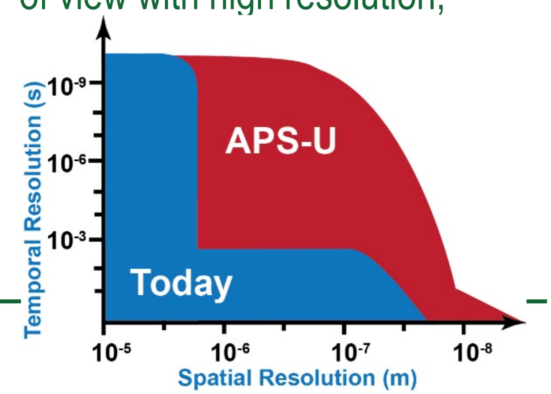
Coherent Scattering & Imaging

- Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
- XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,



Resolution @ Speed

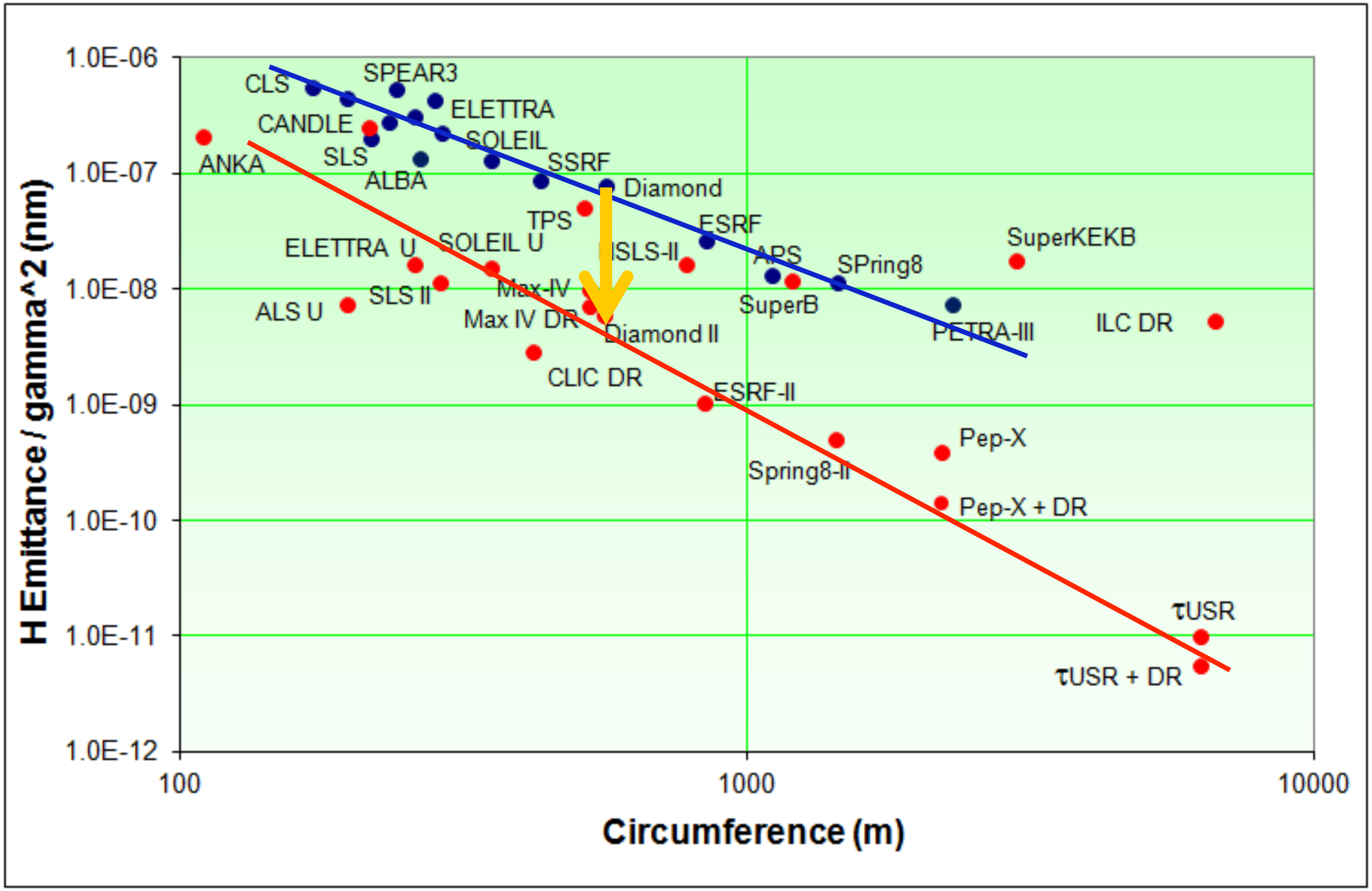
- Mapping all of the critical atoms in a cubic millimeter
- Detecting and following rare events
- Multiscale imaging: enormous fields of view with high resolution;



Ring Based Light Sources

Start a new trend:
MBA

Survey of low emittance lattices



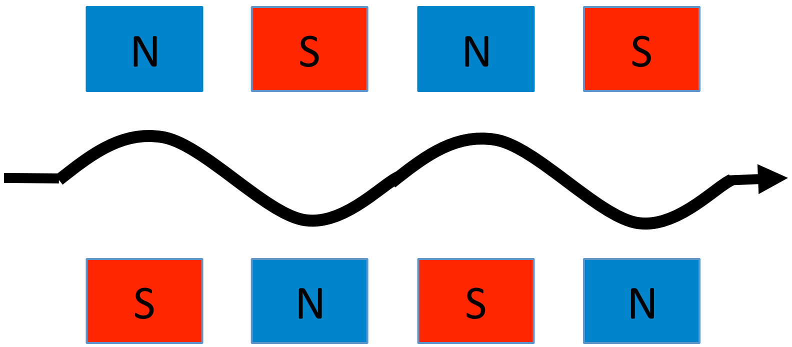
Courtesy of Bartolini

John Adams Institute for Accelerator Science

diamond

Synchrotron Radiation

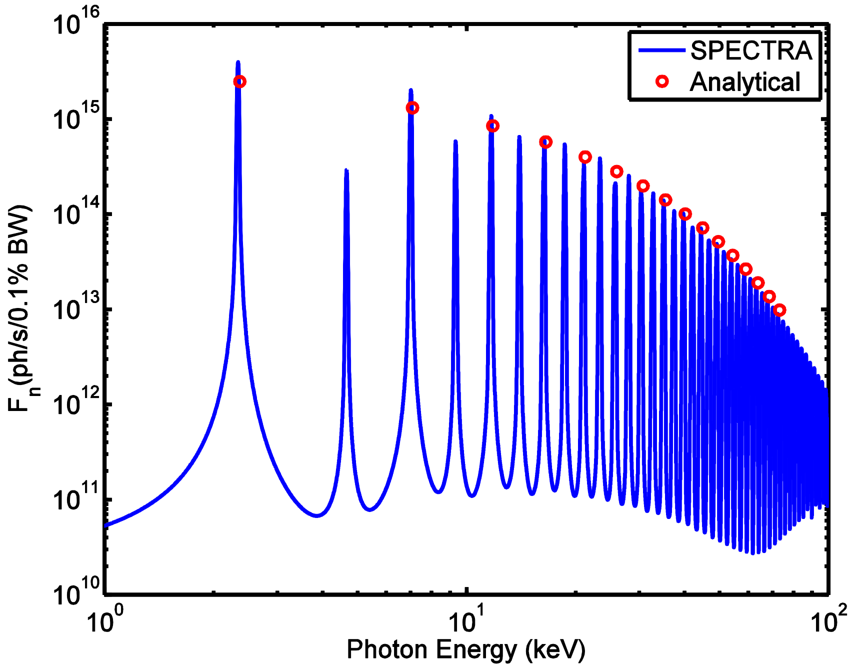
Electron beam in undulator



nth harmonic wavelength:

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

Photon spectral flux in 0.1% BW



$$F_n = \frac{\pi}{2}\alpha N_u Q_n\left(\frac{nK^2}{4+2K^2}\right)\frac{\Delta\omega}{\omega}\frac{I}{e}$$

Spectral Brightness

Brightness of electron beam radiating at nth (odd) harmonics in a undulator is given by

$$B_n = F_n / (4\pi^2 \Sigma_x \Sigma_x^{'} \Sigma_y \Sigma_y^{'})$$

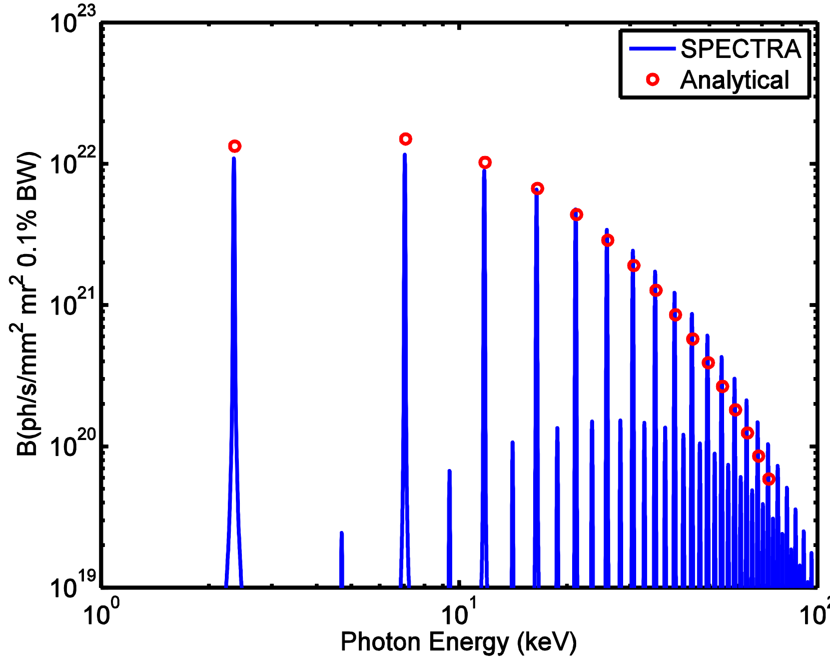
If the electron beam phase space is matched to those of photon's, the brightness becomes optimized

$$B_n = \frac{F_n}{4\pi^2 (\varepsilon_x + \lambda_n / 4\pi)(\varepsilon_y + \lambda_n / 4\pi)}$$

Finally, even for zero emittances, there is an ultimate limit for the brightness

$$B_n = \frac{4F_n}{\lambda_n^2}$$

Spectral brightness of PEP-X



A diffraction limited ring at 1 angstrom or 8 pm-rad emittance

Energy Spread and Emittance

Balance between the quantum excitation and radiation damping results in an equilibrium Gaussian distribution with relative energy spread σ_δ and horizontal emittance ε_x:

$$\sigma_\delta^2 = \frac{\tau_s}{2E_0^2} < \dot{N}_{ph} < u^2 >>_s = C_q \frac{\gamma^2}{J_s} \frac{\langle 1/\rho^3 \rangle_s}{\langle 1/\rho^2 \rangle_s},$$

$$\varepsilon_x = \frac{\tau_x}{4E_0^2} < \dot{N}_{ph} < u^2 > H_x >_s = C_q \frac{\gamma^2}{J_x} \frac{\langle \mathcal{H}_x / \rho^3 \rangle_s}{\langle 1/\rho^2 \rangle_s},$$

where and

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}, \qquad \mathcal{H}_x = \beta_x \eta_{px}^2 + 2\alpha_x \eta_x \eta_{px} + \gamma_x \eta_x^2$$

- The quantum constant C_q = 3.8319x10^{-13} m for electron
- γ is the Lorentz factor (energy)

Minimization of Emittance

For an electron ring without damping wigglers, the horizontal emittnace is given by

$$\varepsilon_0 = F_c \frac{C_q \gamma^2}{J_x} \theta^3$$

where F_c is a form factor determined by choice of cell and θ is bending angle of dipole magnet in cell. In general, stronger focusing makes F_c smaller. Often there is a minimum achievable value of F_c for any a given type of cell. For example, we have

$$F_{min}^{DBA} = \frac{1}{4\sqrt{15}}$$

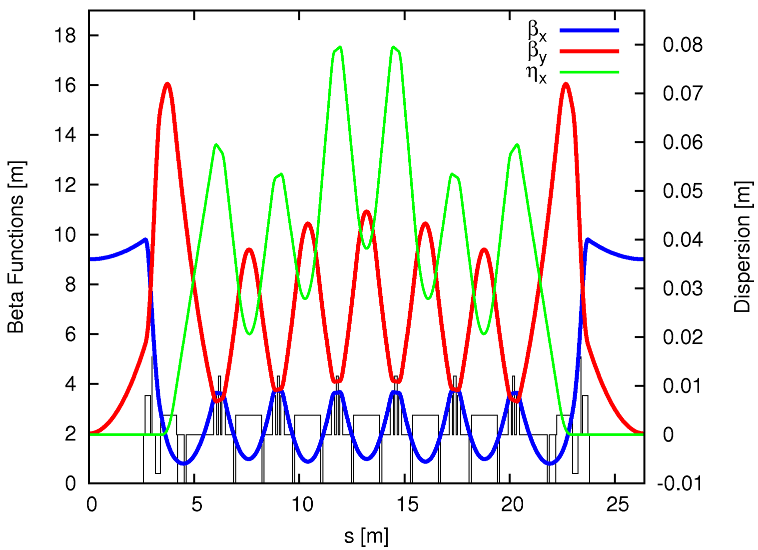
$$F_{min}^{TME} = \frac{1}{12\sqrt{15}}$$

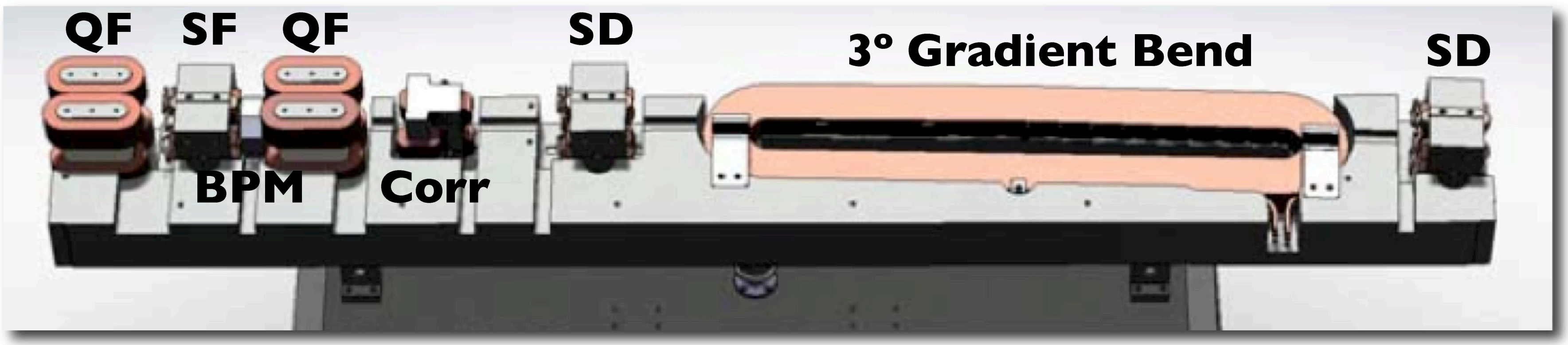
There is a factor of three between the minimum values of DBA and TME cells. That's the price paid for an achromat, namely fixing the dispersion and its slop at one end of dipole.

MAX-IV Synchrotron Light Source

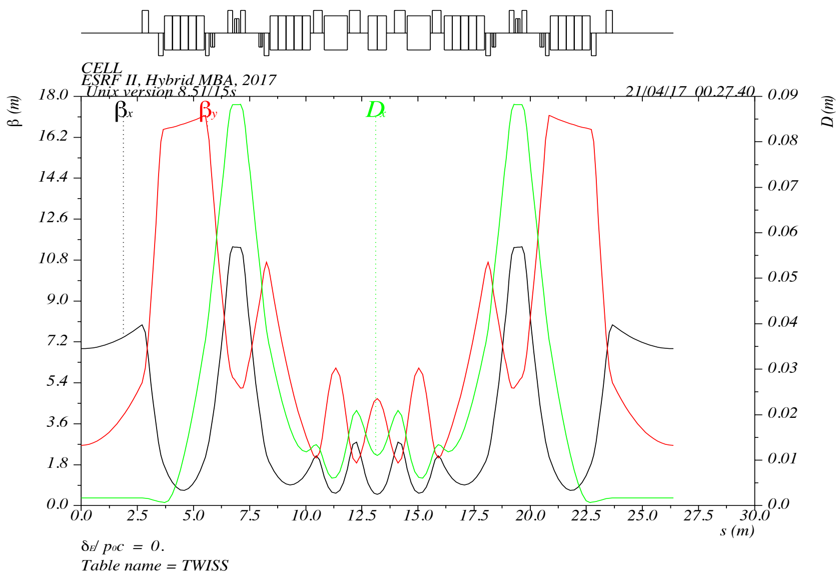
Innovation:

- 7 bend achromat
- Combine function dipoles
- Compact magnets
- Resonance minimization
- OPA optimization code
- Harmonic Sextupoels
- Octupoles





ESRF-II Synchrotron Light Source

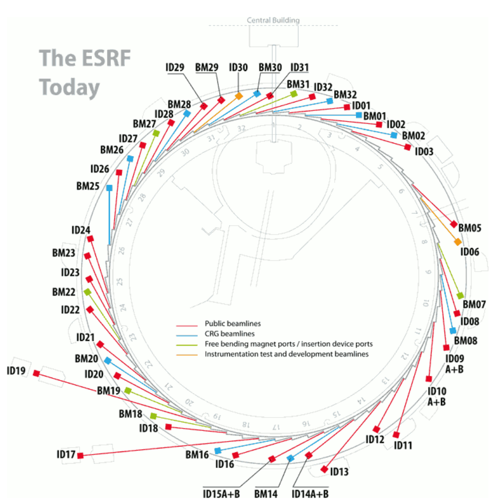


Innovations:

- Hybrid 7 bend achromat
- Dispersion bump
- "-I" paired sextupoles
- Variation dipoles

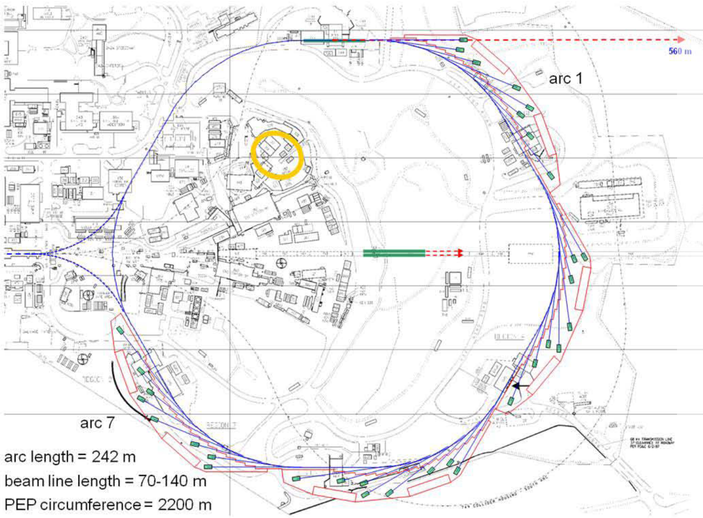
An approximated symmetry:

μ_x~(2+3/8) x 360^0, μ_y~(1-1/8) x 360^0



PEP-X Layout & Parameters

An ultimate storage ring

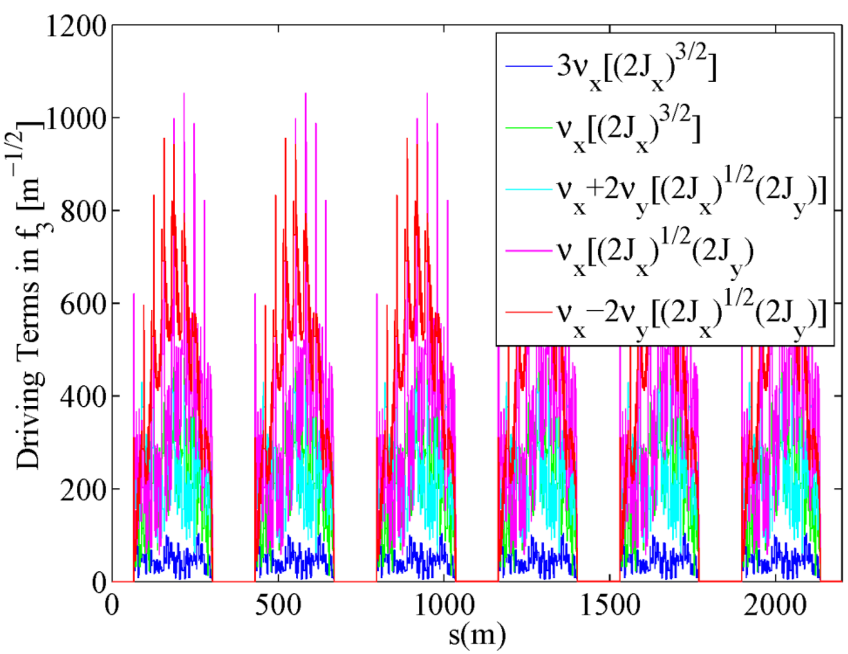


Energy, GeV	4.5
Circumference, m	2199.32
Natural emittance, pm	11
Beam current, mA	200
Emittance at 200 mA, x/y, pm	12 / 12
Tunes, x/y/s	113.23 /65.14/0.007
Bunch length, mm	3.1
Energy spread	1.25×10^{-3}
Energy loss per turn, MeV	2.95
RF voltage, MV	8.3
RF harmonic number	3492
Length of ID straight, m	5.0
Wiggler length, m	90.0
Beta at ID center, x/y, m	4.92 / 0.80
Touschek lifetime, hour	10
Dynamic aperture , mm	10

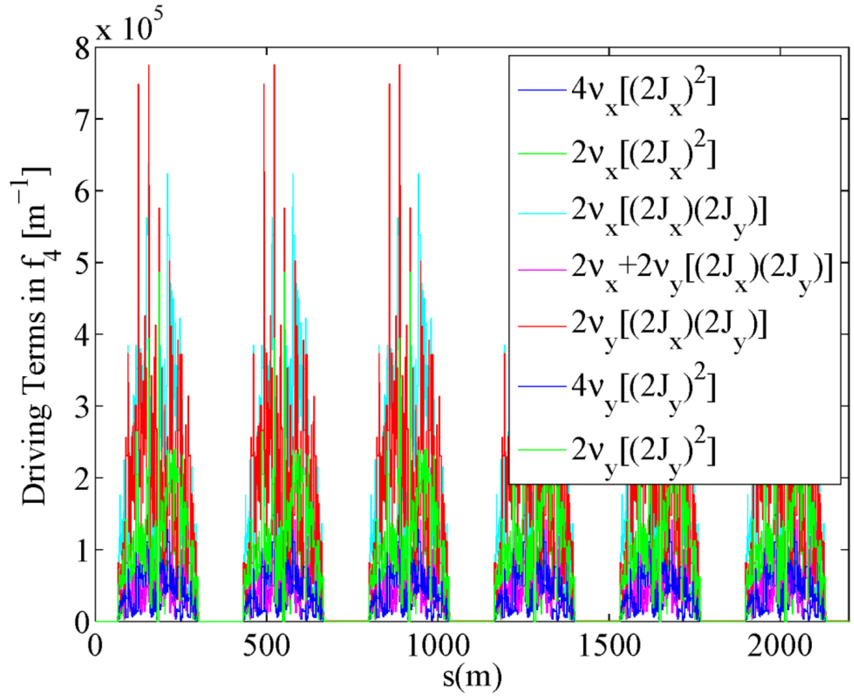
To be Built with 4th-order geometrical achromats in the PEP tunnel.

Cancellation of All Geometric 3rd and 4th Resonances Driven by Strong Sextupoles
except $2\nu_x$-$2\nu_y$

Third Order



Fourth Order



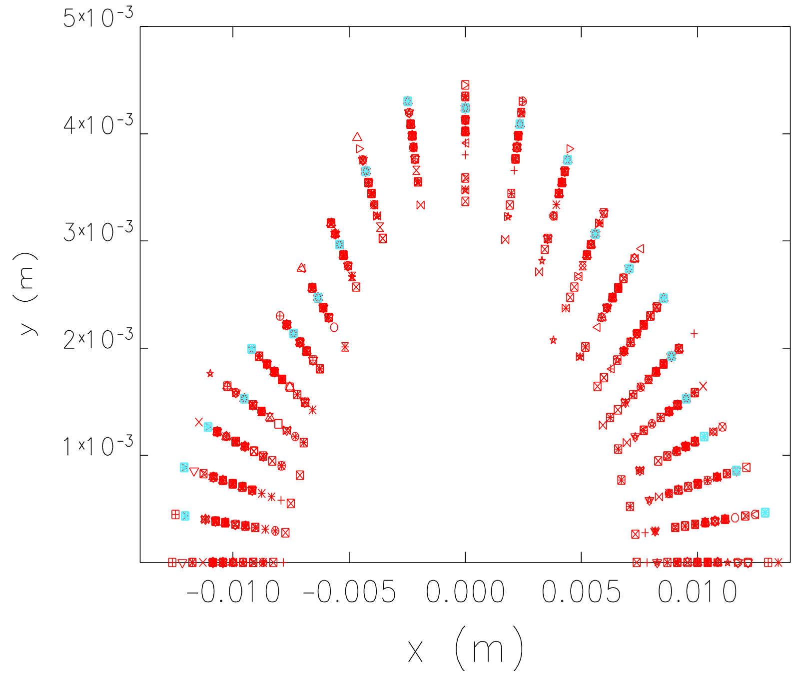
K.L. Brown & R.V. Servranckx
Nucl. Inst. Meth., A258:480–502, 1987

Yunhai Cai
Nucl. Inst. Meth., A645:168–174, 2011.

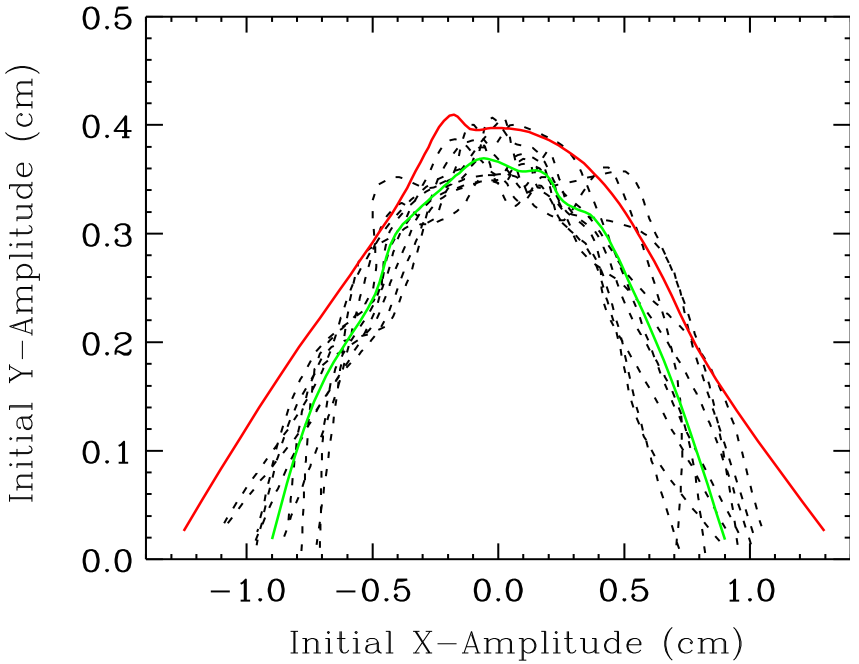
Cell phase advances: μ_x=(2+1/8) x 360^0, μ_y=(1+1/8) x 360^0 (8 cells for cancellation)

Dynamic Aperture

ELEGANT Tracking



LEGO Tracking



Presentations for Magnetic Elements

Lie factors $\mathrm{M}^{1} e^{:f_3:} e^{:f_4:} \ldots$

- engine in MARYLIE (A. Dragt)
- violates symplecticity when evaluates

↑ Dragt-Finn

Taylor map $\mathrm{M}^{n}(z)$

- engine in TRANSPORT, MAD, COSY (K. Brown and M. Berz), simple R-matrix
- but high-order one violates

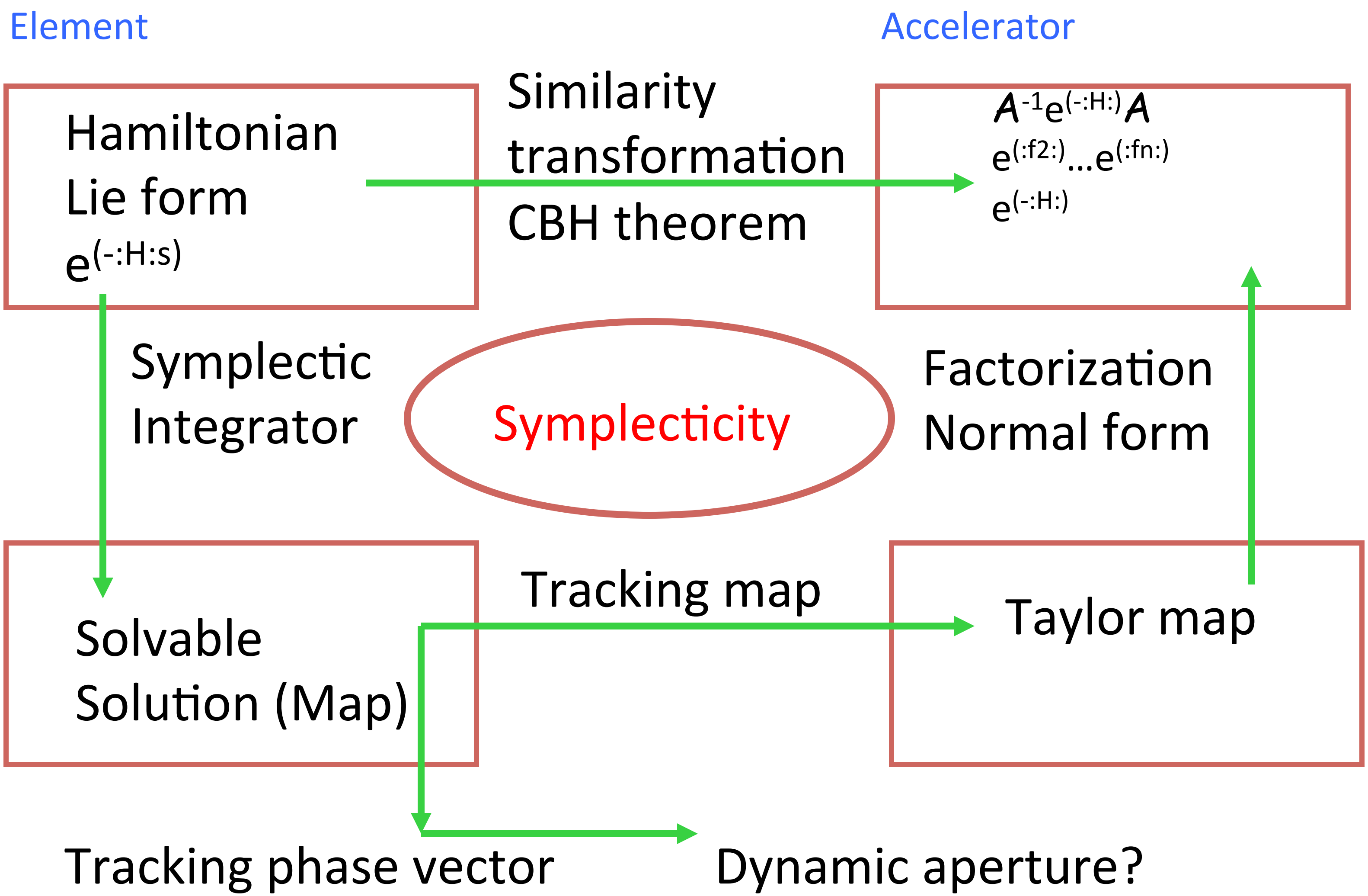
↑ TPSA

Symplectic Integrator

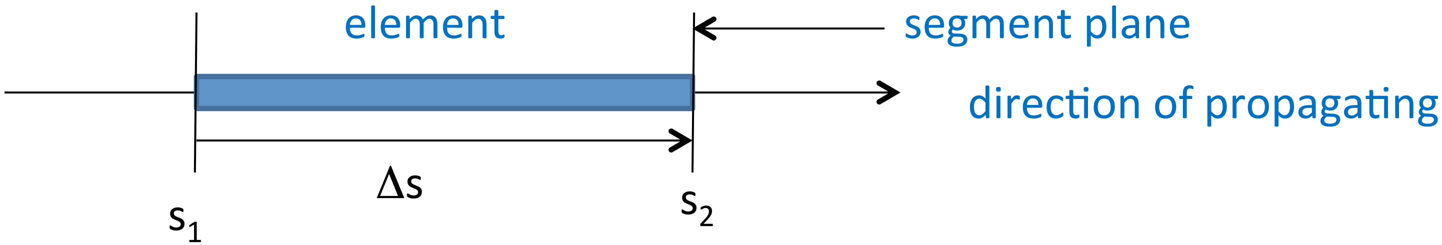
$$\prod_{i=1}^{n} e^{-\frac{:H_0:}{2}\Delta s} e^{-:H_1:\Delta s} e^{-\frac{:H_0:}{2}\Delta s}$$

- engine in TEAPOT, SAD, TRACY, **LEGO**, PTC (E. Forest, R. Ruth, and K. Hirata)
- preserves symplecticity
- simple and based on several known solutions
- emphasis on numerical process

Lie Method Bases Analysis and Tracking Code



Concept of Transfer Map



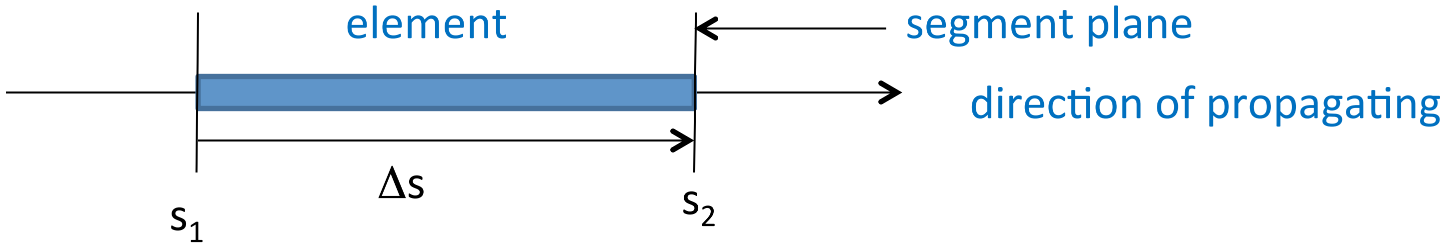
$$z(s_1) = \begin{pmatrix} x \\ p_x \\ y \\ p_y \\ \delta \\ \ell \end{pmatrix}_{|s_1} \quad \mathrm{M}_{1\to 2} \quad \begin{pmatrix} x \\ p_x \\ y \\ p_y \\ \delta \\ \ell \end{pmatrix}_{|s_2} = z(s_2)$$

$$z(s_2) = \mathrm{M}_{1\to 2}(z(s_1)).$$

abbreviated map notation

A set (six) of functions of canonical coordinates. It's called symplectic if its Jacob is symplectic.

Exponential Lie Operator



For any function f(s), we have the Taylor expansion

$$f(s_2) = \sum_{n=0}^{\infty} \frac{\Delta s^n}{n!} \frac{d^n f}{ds^n}\Big|_{s_1} \equiv e^{\Delta s \frac{d}{ds}} f(s)\Big|_{s_1}$$

← a symbolic notation

In particular, if there is no explicit dependent of s in the function f(s), namely f(s) = f(x(s),p_x(s),…), we have

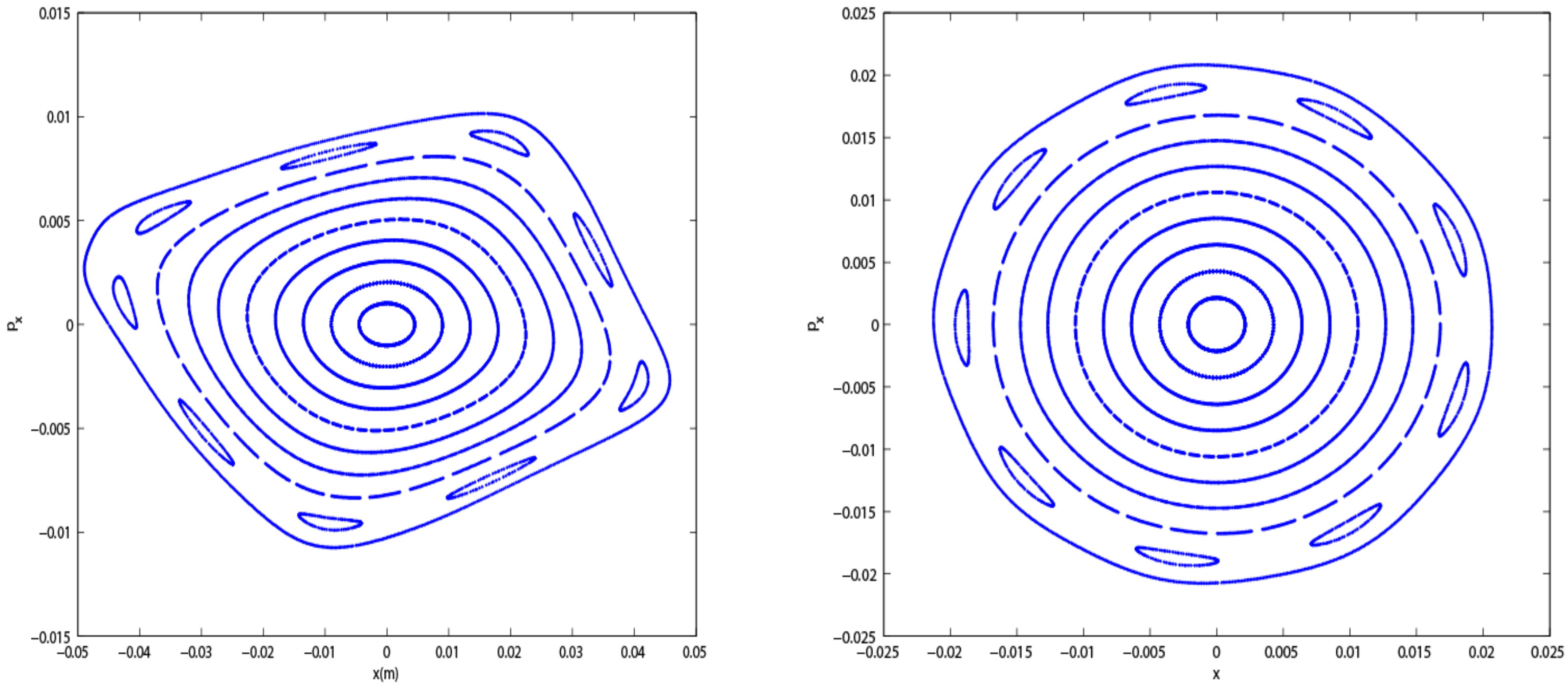
$$\frac{df}{ds} = -[H, f] \equiv -:H:f,$$

← another symbolic notation

Used Hamiltonian equation and the definition of the Poisson bracket. Combining these symbolic notations, we have the exponential Lie operator

$$f(s_2) = e^{-\Delta s:H:} f(s)\Big|_{s_1}$$

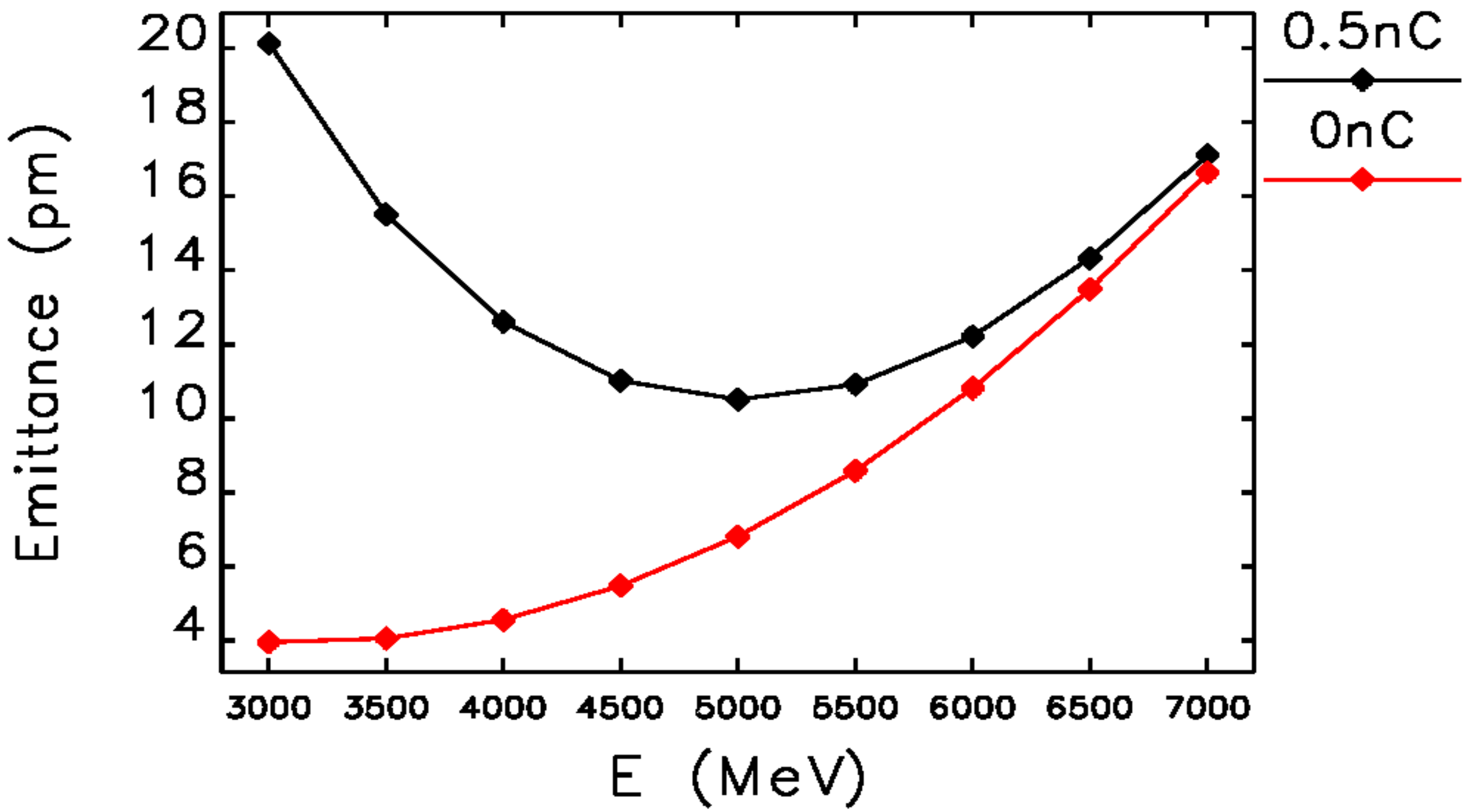
Nonlinear Normal Form



Physical coordinates ⟶ Normalized coordinates

Transformation approximated by a 10th order Taylor map

Intra-Beam Scattering



Touschek Lifetime

When a pair of electrons go through a hard scattering, their momentum changes are so large that they are outside the RF bucket or the momentum aperture. This process results in a finite lifetime of a bunched beam. The lifetime is given by

$$\frac{1}{T} = \frac{r_e^2 c N_b}{8\sqrt{\pi}\gamma^4 \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta} < \sigma_H F(\delta_m) > ,$$

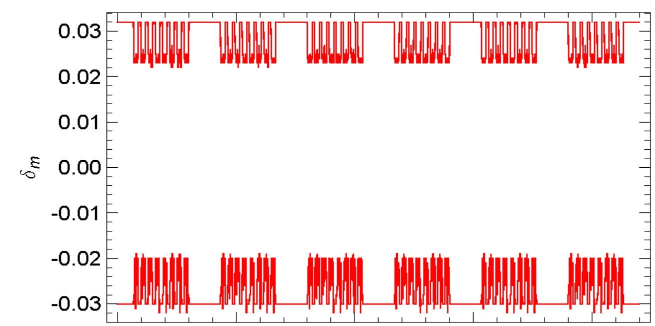
with

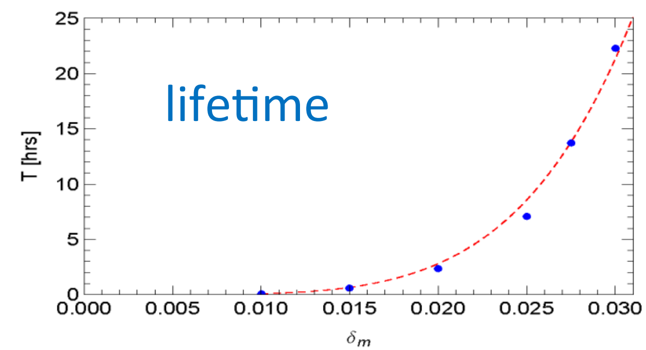
$$F(\delta_m) = \int_{\delta_m^2}^{\infty} \frac{d\tau}{\tau^{3/2}} e^{-\tau B_+} I_0(\tau B_-)\left[\frac{\tau}{\delta_m^2} - 1 - \frac{1}{2}\ln\left(\frac{\tau}{\delta_m^2}\right)\right],$$

$$B_\pm = \frac{1}{2\gamma^2}\left|\frac{\beta_x(\beta_x\varepsilon_x + \eta_x^2\sigma_\delta^2)}{\varepsilon_x(\beta_x\varepsilon_x + \beta_x\mathcal{H}_x\sigma_\delta^2)} \pm \frac{\beta_y}{\varepsilon_y}\right|,$$

where d_m is the momentum acceptance.

momentum aperture



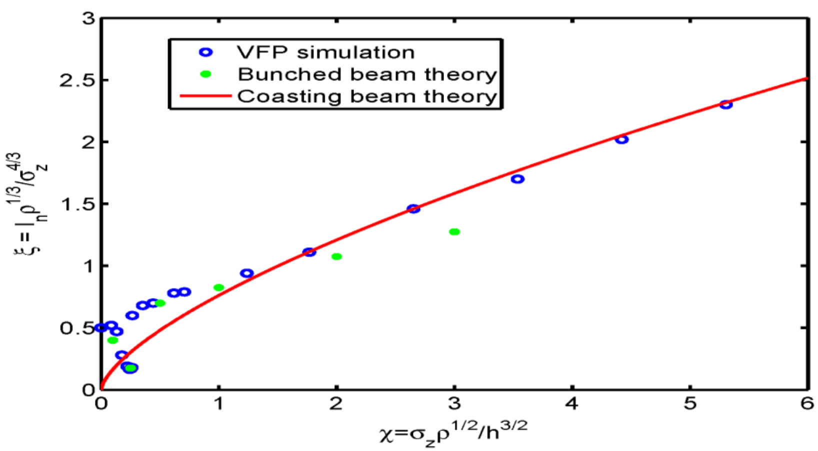


Threshold of Instability
Driven by CSR

Based on the bunched beam theory, the threshold can be written as

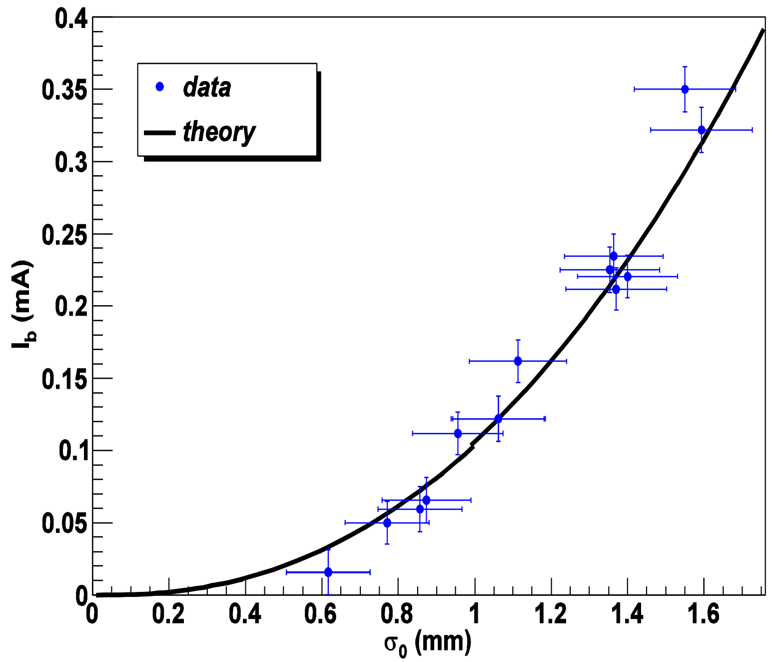
$$\sigma_z^{7/3} = \frac{c^2 Z_0}{8\pi^2 \xi^{th}(\chi)} I_b^{th} \rho^{1/3} / (V_{rf} \cos\varphi_s f_{rf} f_{rev})$$

where ξ^{th} is given by



My talk, IPAC 2011, San Sebastian, Spain

Measured bursting threshold at ANKA
See M.Klein et al. PAC09, 4761 (2009)



(courtesy of M. Klein, ξ^{th}=0.5 used.)

Acknowledgements

- PEP-X: Karl Bane, Michael Borland, Robert Hettel, Yuri Nosochkov, Min-Huey Wang
- Beam optics: Karl Brown, Donald Edwards, Mike Syphers, Roger Servranckx
- Maps and Lie algebra: Alex Chao, John Irwin, Etienne Forest, Yiton Yan
- Microwave instability and coherent synchrotron radiation: Karl Bane, Robert Warnock, Gennady Stupakov

- Francesco Sette, SLAC 50th Anniversary talk, 2012
- Persis Drell, BESAC talk, 2017