The Jefferson Lab Free Electron Laser Project

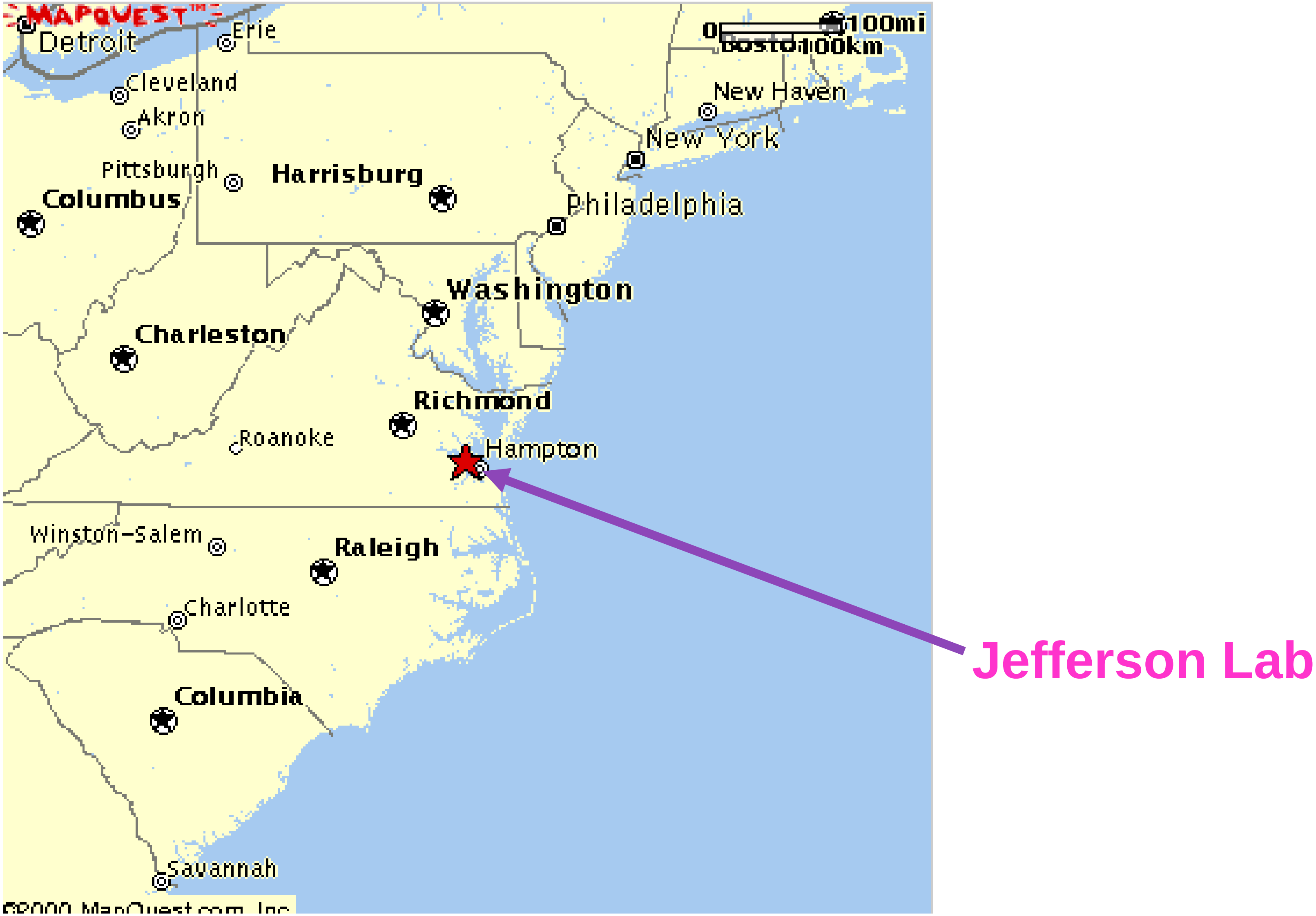
Gwyn P. Williams and the JLab Team
Jefferson Lab
12000 Jefferson Avenue
Newport News, Virginia 23606

Argonne, March 6, 2009

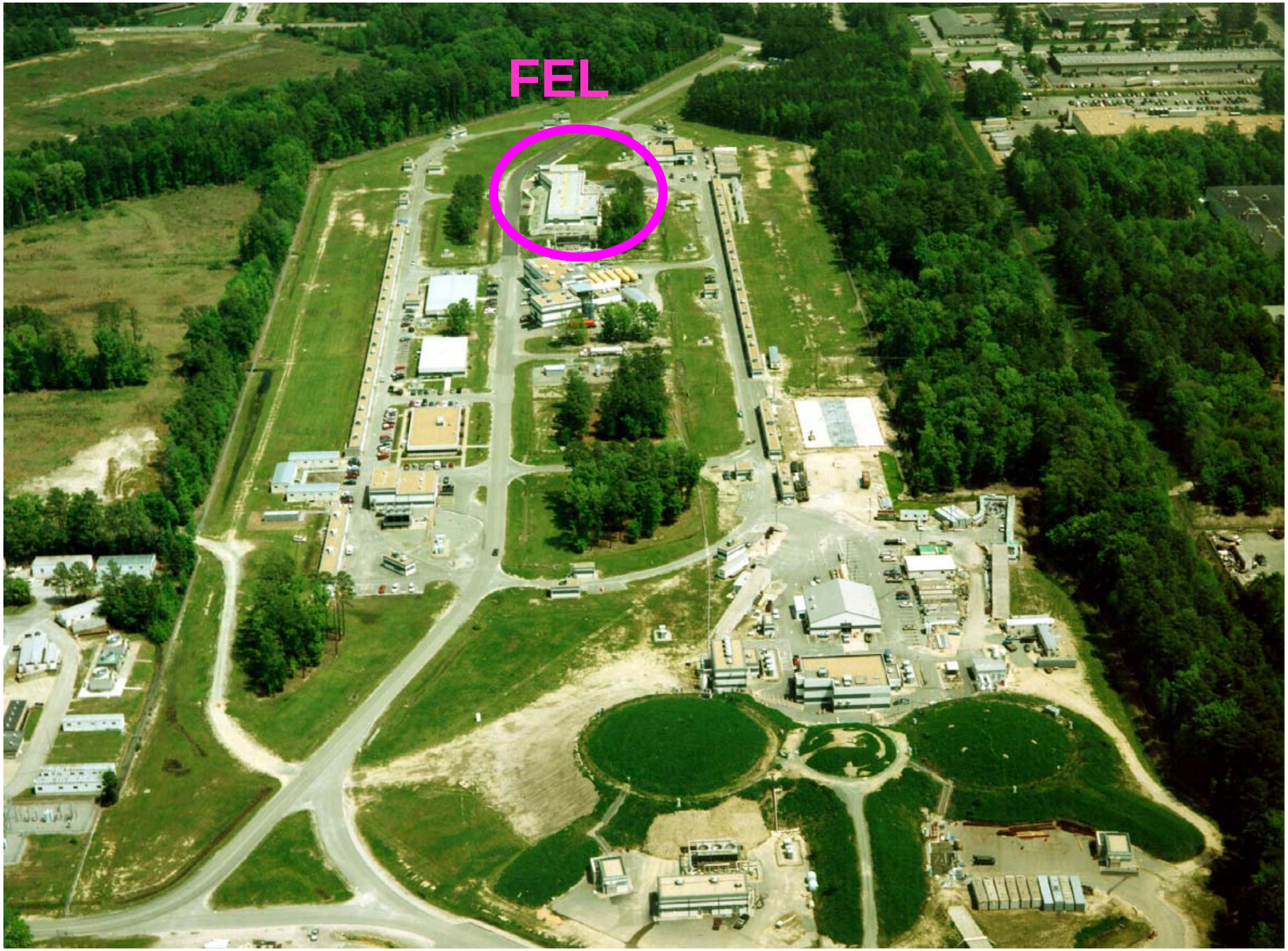
Talk Outline

- Background/motivation for 4^{th} generation light sources
- The Jefferson Lab FEL
- Highlights from the JLab scientific program
- Coherent Synchrotron Radiation
- Some thoughts about the future

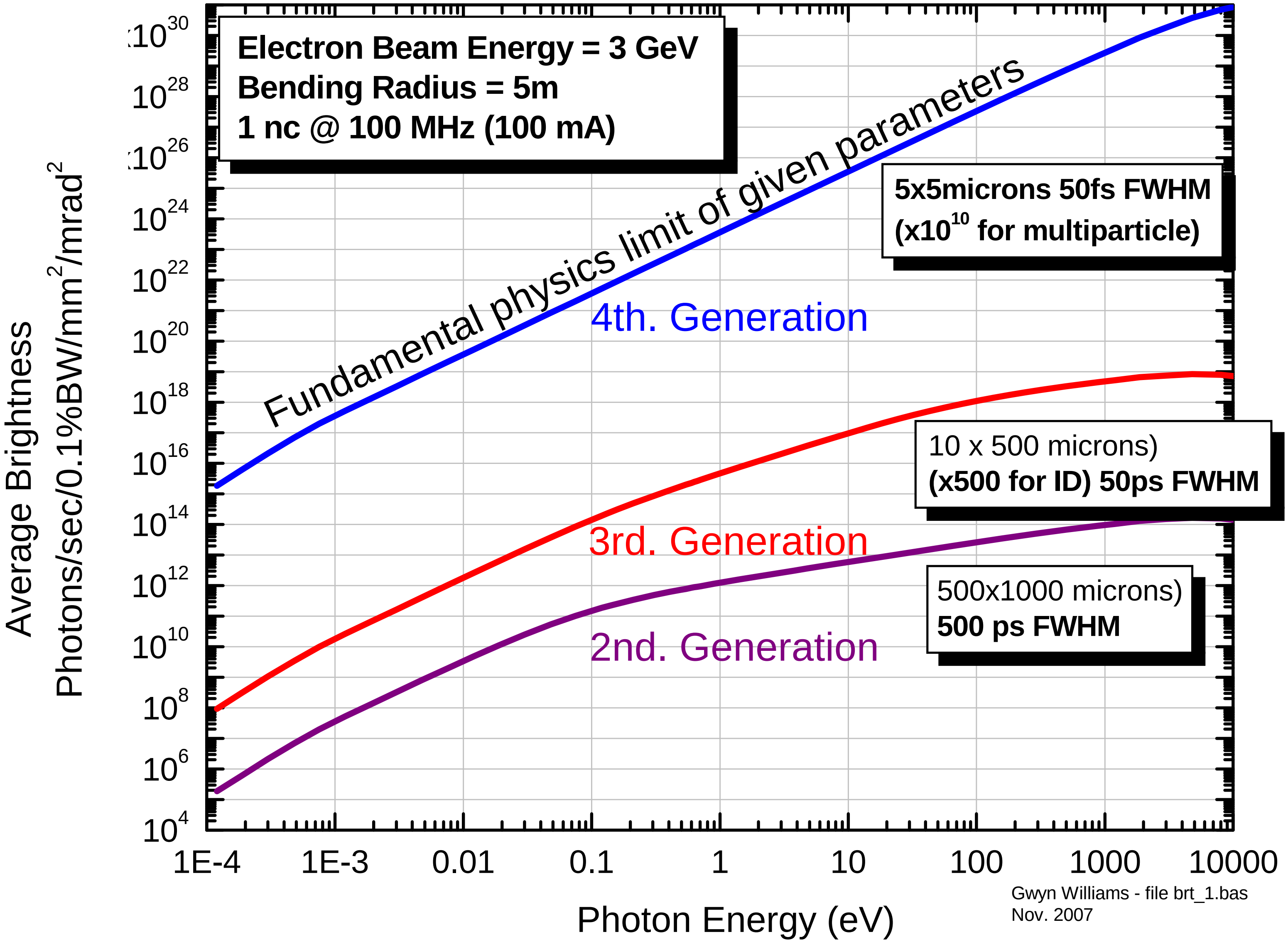
Jefferson Lab - where are we?



Jefferson Lab, Newport News, VA

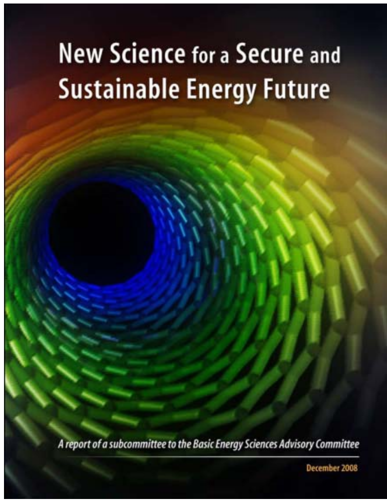


Potential major advantage for coherence…transverse, longitudinal, multiparticle



The 10 DOE "Basic Research Needs" Workshops

10 workshops; 5 years; more than 1,500 participants from academia, industry, and DOE labs



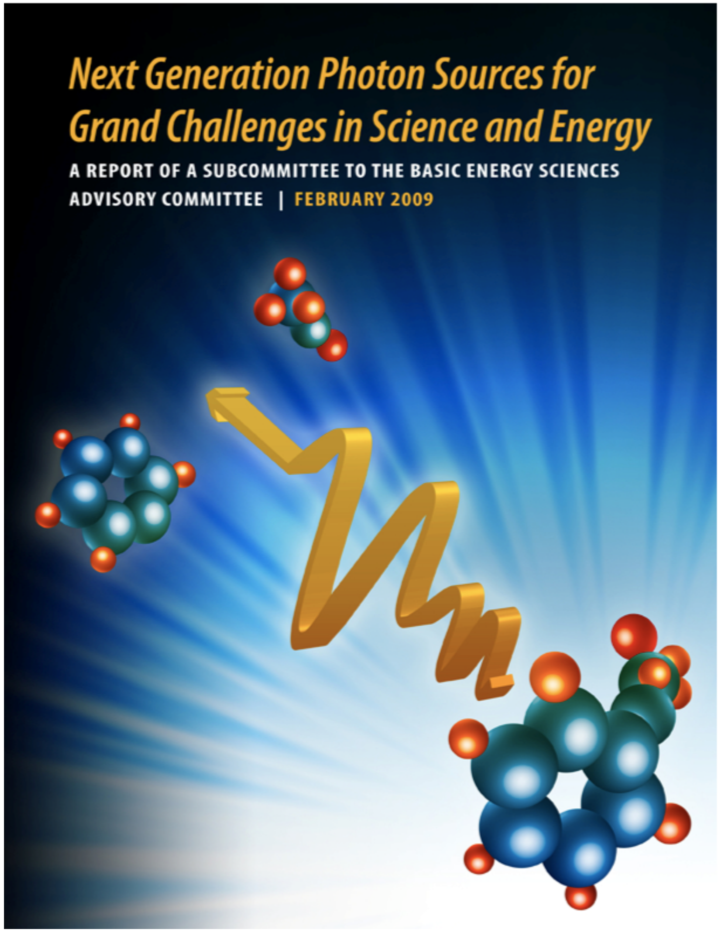
- Basic Research Needs for the Hydrogen Economy
- Basic Research Needs for Solar Energy Utilization
- Basic Research Needs for Superconductivity
- Basic Research Needs for Solid State Lighting
- Basic Research Needs for Advanced Nuclear Energy Systems
- Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels
- Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems
- Basic Research Needs for Electrical Energy Storage
- Basic Research Needs for Catalysis for Energy Applications
- Basic Research Needs for Materials under Extreme Environments

www.science.doe.gov/bes/reports/list.html

courtesy Pat Dehmer

The reports make a compelling case for use of high power and brightness for fundamental studies of equilibrium and non-equilibrium properties of novel materials.

A second report, due in April 2009, will discuss photon sources.



What are (4th) Next Generation Light Sources?

1. First of new generation – they do not displace 3rd generation.
2. Superconducting radio-frequency linac based.
3. Use multiparticle coherence (or “gain”).

- Big discussion over whether all of above, and if 3, then how - SASE, oscillators, seeded amplifiers?
- Big discussion over average current (do we need ERL for example), and power per pulse.
- Use science to define machine parameters.
- JLab is the first of the 4th generation light sources operating in the THz/IR/(UV) range in the USA.

Next Generation Light Sources USA Programs

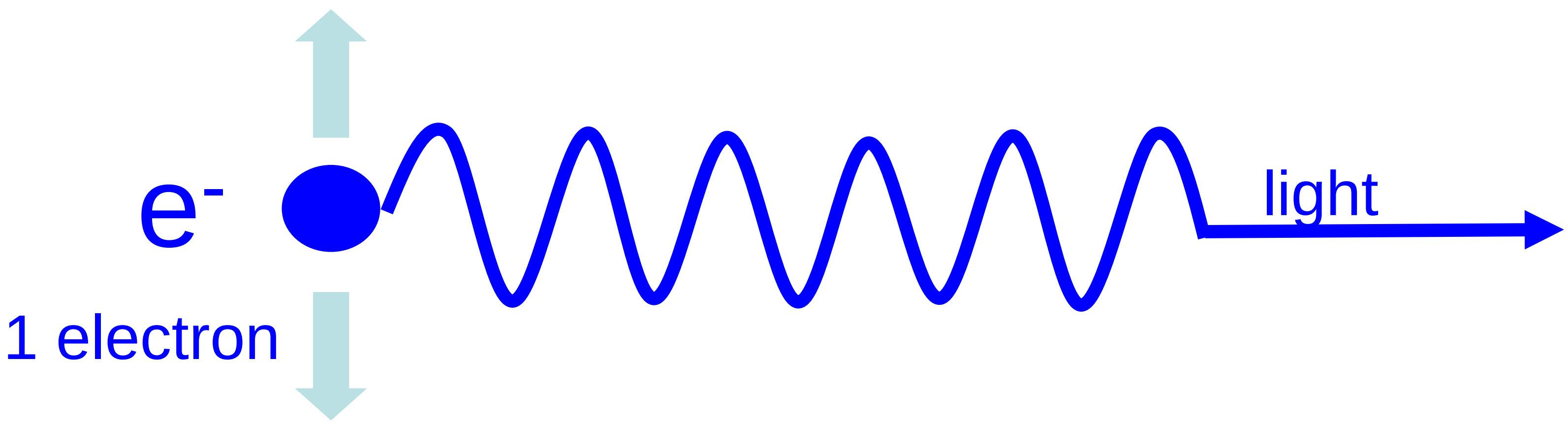
1. Jefferson Lab, UV/IR/THz ERL, operational
2. LCLS, Stanford, USA, hard x-ray, DOE-BES under construction
3. Cornell University, hard x-ray ERL, proposal to NSF, initial funding
4. Florida State University, IR/THz ERL, proposal to NSF, initial funding
5. WiFEL, Stoughton, Wisconsin, soft x-ray, proposal to NSF
6. Advanced Light Source, Berkeley, soft x-ray, ideas phase
7. Advanced Photon Source, Argonne, hard x-ray ERL, ideas phase
8. LSU, THz – soft x-ray, white paper preparation to State and DOE
9. Light Source of the Future, DOE-BES, TBD

Next Generation Light Sources – International

1. FZR-Dresden, IR/THz, operational
2. Budker Institute, Novisibirsk, Russia, THz ERL operational
3. FLASH, Hamburg, Germany, soft x-ray, operational
4. Daresbury & Rutherford UK, THz-x-ray, proposal in process
5. Paul Scherrer Inst. Switzerland, hard x-ray, proposal
6. Maxlab, Lund, Sweden, soft x-ray, proposal
7. XFEL, Hamburg Germany, hard x-ray, European project constr. phase
8. XFEL, Spring-8, Japan
9. Arc-en-Ciel, French ERL, proposal
10. XFEL, Pohang Light Source, Korea, proposal
11. IRFEL, Nijmegen, Netherlands, funded
12. IRFEL, Fritz-Haber Inst. Berlin, funded

Multiparticle Coherent Synchrotron Radiation

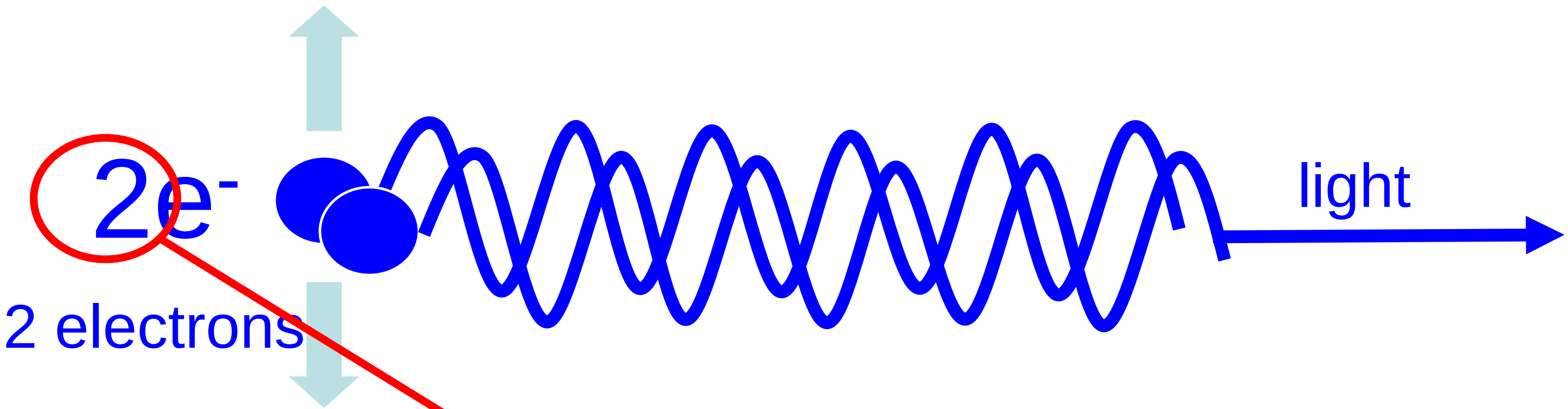
………aka longitudinal coherence



$$\text{Larmor's Formula: Power} = \frac{2(\quad e)^2 a^2 \gamma^4}{3c^3} \text{ (cgs units)}$$

Multiparticle Coherent Synchrotron Radiation

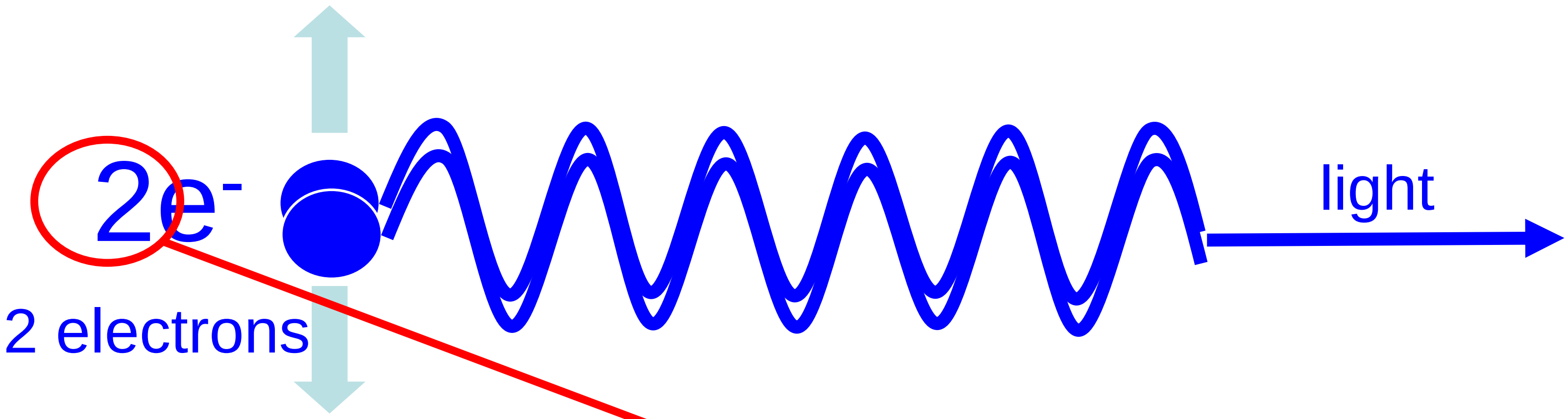
………aka longitudinal coherence



Larmor's Formula: Power $= 2\left(\frac{2(e)^2 a^2 \gamma^4}{3c^3}\right)$ (cgs units)

Multiparticle Coherent Synchrotron Radiation

………aka longitudinal coherence

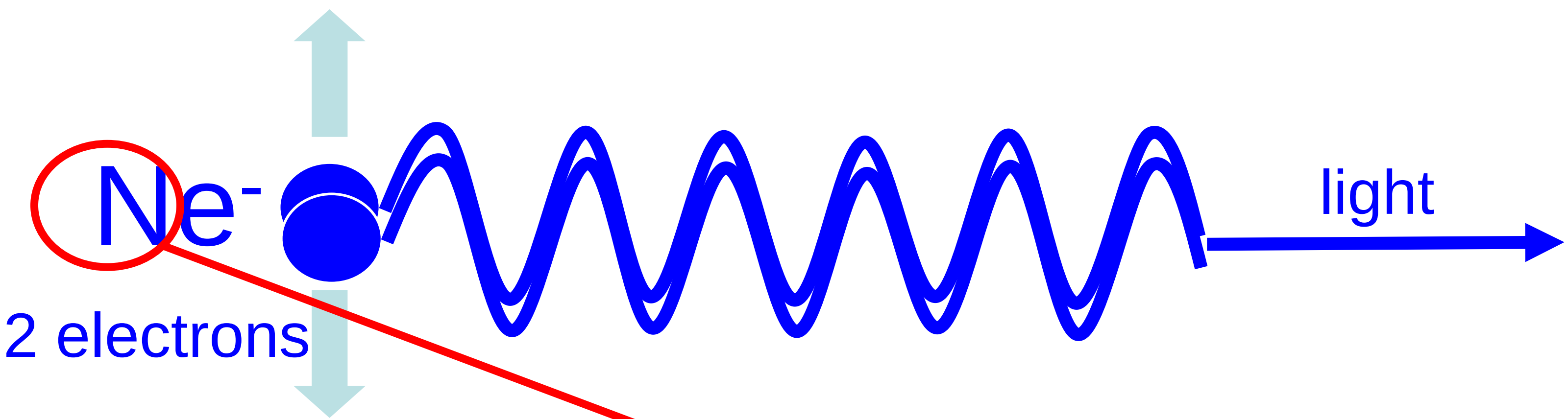


Larmor's Formula: $\text{Power} = \left(\dfrac{2(2e)^2 a^2 \gamma^4}{3c^3} \right)$ (cgs units)

So 2 electrons give 4 times the power of 1 electron

Multiparticle Coherent Synchrotron Radiation

………aka longitudinal coherence



Larmor's Formula: $\text{Power} = \left(\frac{2(Ne)^2 a^2 \gamma^4}{3c^3} \right)$ (cgs units)

So N electrons give N^2 times the power of 1 electron

Multiparticle Coherent Synchrotron Radiation Generation

………aka longitudinal coherence

Jackson, Classical Electrodynamics, Wiley, NY 1975

Near-field term not normally considered for synchrotron calculations

Electric field for single particle:-

$$\vec{E}_\omega = ec^{-1}\int_{-\infty}^{+\infty} \frac{\vec{n}\times[(\vec{n}-\vec{\beta}_e)\times\dot{\vec{\beta}}_e] + cR^{-1}\gamma^{-2}(\vec{n}-\vec{\beta}_e)}{(1-\vec{n}\vec{\beta}_e)^2 R} \exp[i\omega(\tau + R/c)]d\tau$$

REFERENCES

R.A. Bosch, Nuclear Instr. & Methods **A431** 320 (1999).

M. Buess, G.L. Carr, O. Chubar, J.B. Murphy, I. Schmid & G. P. Williams "Exploring New Limits in Understanding The Emission of Light from Relativistic Electrons" presented at the SRI conference, Stanford, 1999.

O. Chubar, P. Elleaume, "Accurate And Efficient Computation Of Synchrotron Radiation In The Near Field Region", proc. of the EPAC98 Conference, 22-26 June 1998, p.1177-1179.

Multiparticle Coherent Synchrotron Radiation Generation

………aka longitudinal coherence

$$\frac{d^2 I}{d\omega\, d\Omega} = \left[N[1 - f(\omega)] + N^2 f(\omega) \right] \times \left[single\ particle\ intensity \right]$$

$f(\omega)$ is the form factor – the Fourier transform of the normalized longitudinal particle distribution within the bunch, S(z)

$$f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \hat{n} \cdot \vec{z}/c} S(z)\, dz \right|^2$$

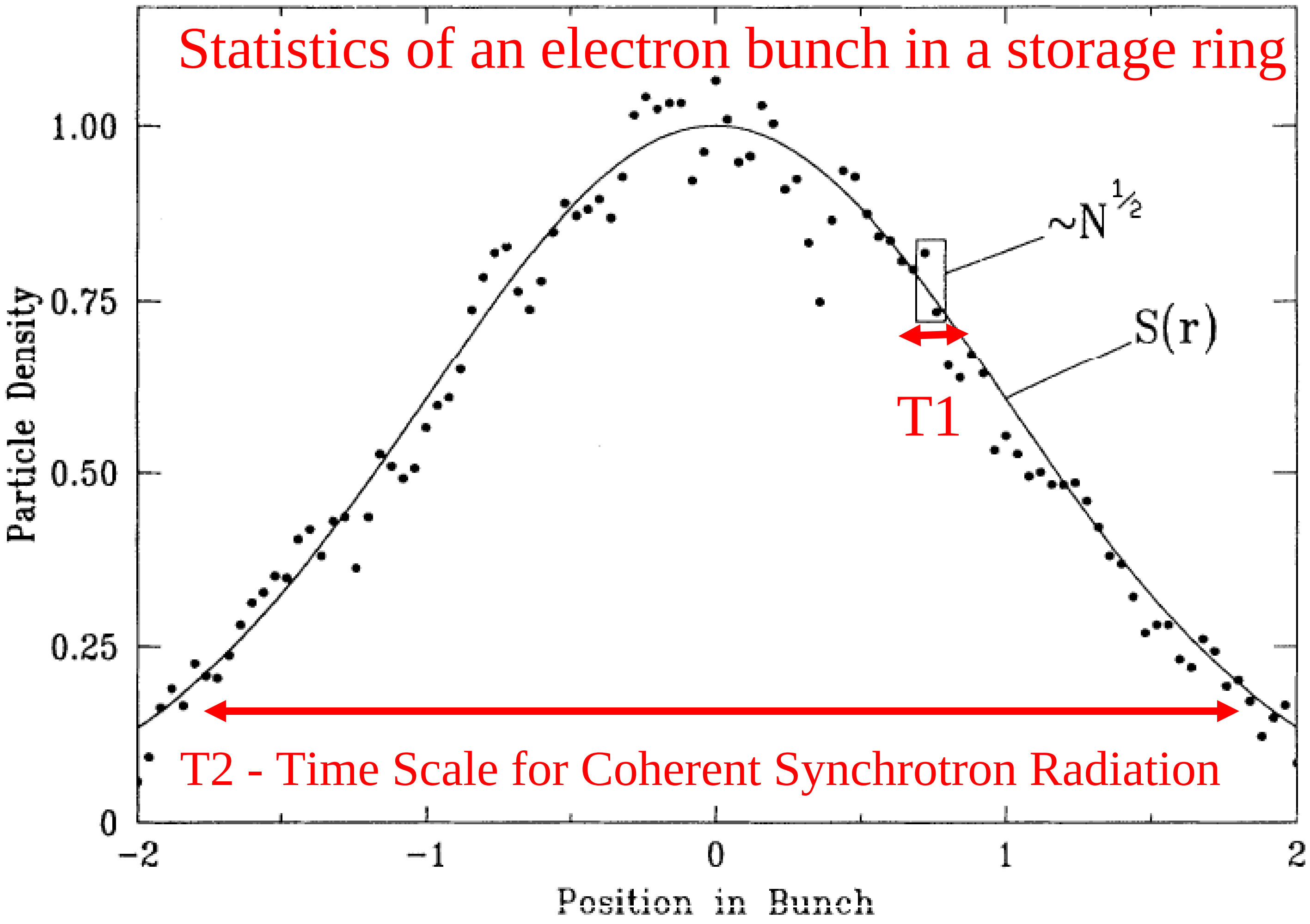
REFERENCES

S.L. Hulbert and G.P. Williams, Handbook of Optics: Classical, Vision, and X-Ray Optics, 2nd ed., vol. III. Bass, Michael, Enoch, Jay M., Van Stryland, Eric W. and Wolfe William L. (eds.). New York: McGraw-Hill, 32.1-32.20 (2001).

S. Nodvick and D.S. Saxon, Suppression of coherent radiation by electrons in a synchrotron. Physical Review **96**, 180-184 (1954).

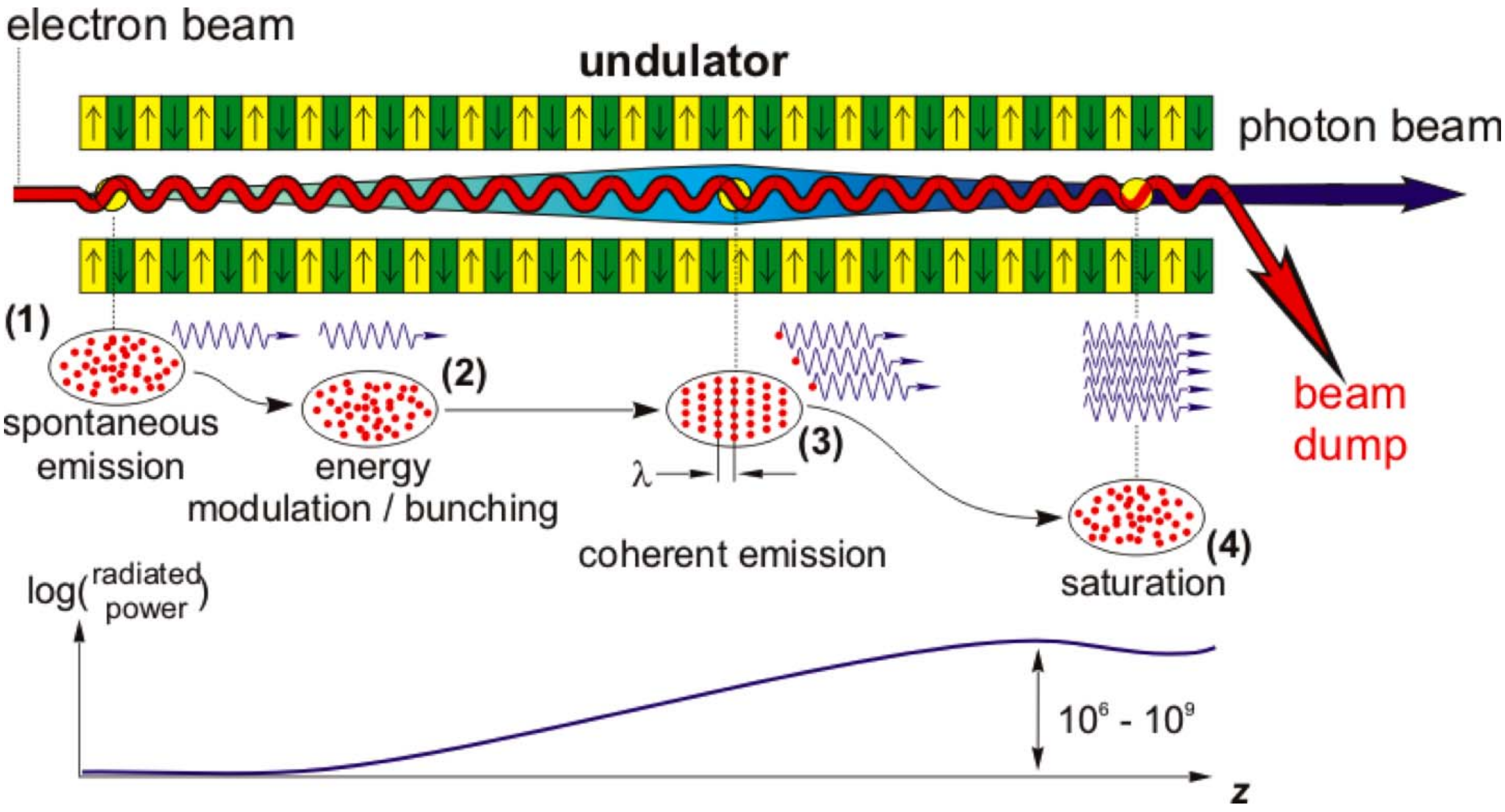
Carol J. Hirschmugl, Michael Sagurton and Gwyn P. Williams, Multiparticle Coherence Calculations for Synchrotron Radiation Emission, Physical Review **A44**, 1316, (1991).

Synchrotron Radiation Generation - 2 time-scales



Hirschmugl, Sagurton and Williams, Physical Review **A44**, 1316, (1991).

Photon Sources ---- FEL's - oscillator, seeded, SASE

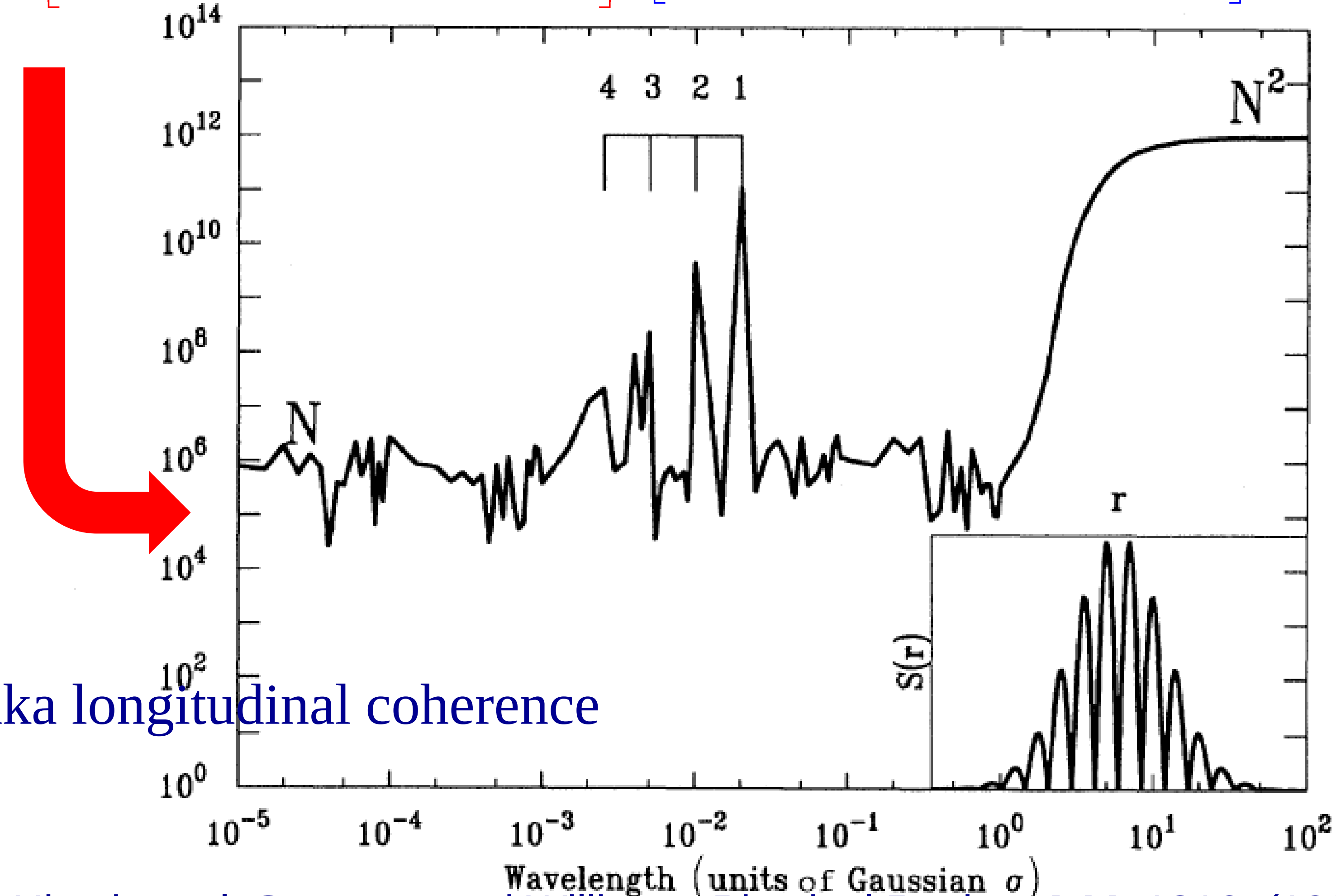


All electrons emit coherently ---- brilliance proportional to N_{el}^2

extremely high peak brilliance ----- fully coherent beam ----- fs pulses

Multiparticle coherence – Free Electron Laser

$$\frac{d^2 I}{d\omega\, d\Omega} = \left[N[1 - f(\omega)] + N^2 f(\omega) \right] \times \left[single\ particle\ intensity \right]$$

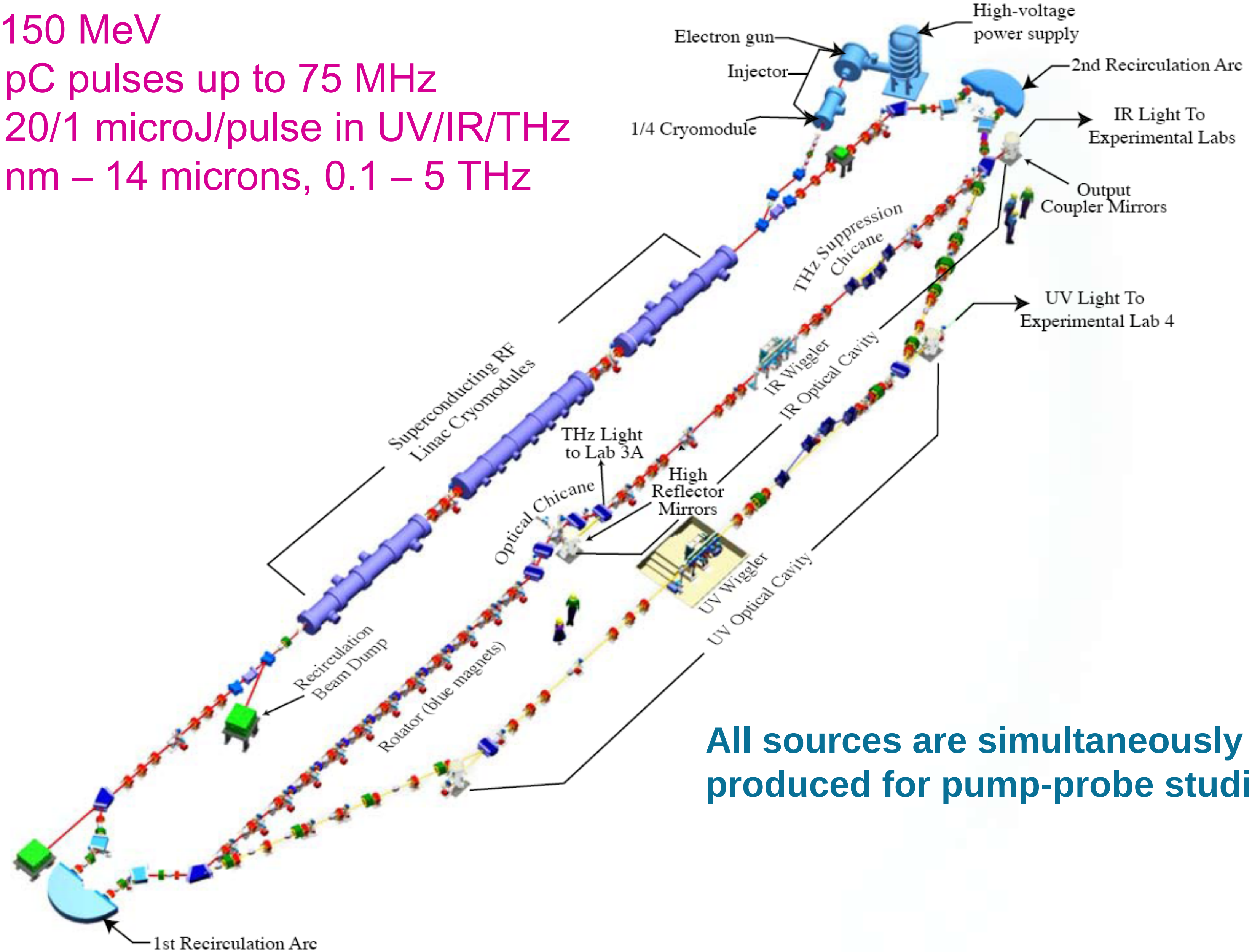


………aka longitudinal coherence

Hirschmugl, Sagurton and Williams, Physical Review **A44**, 1316, (1991).

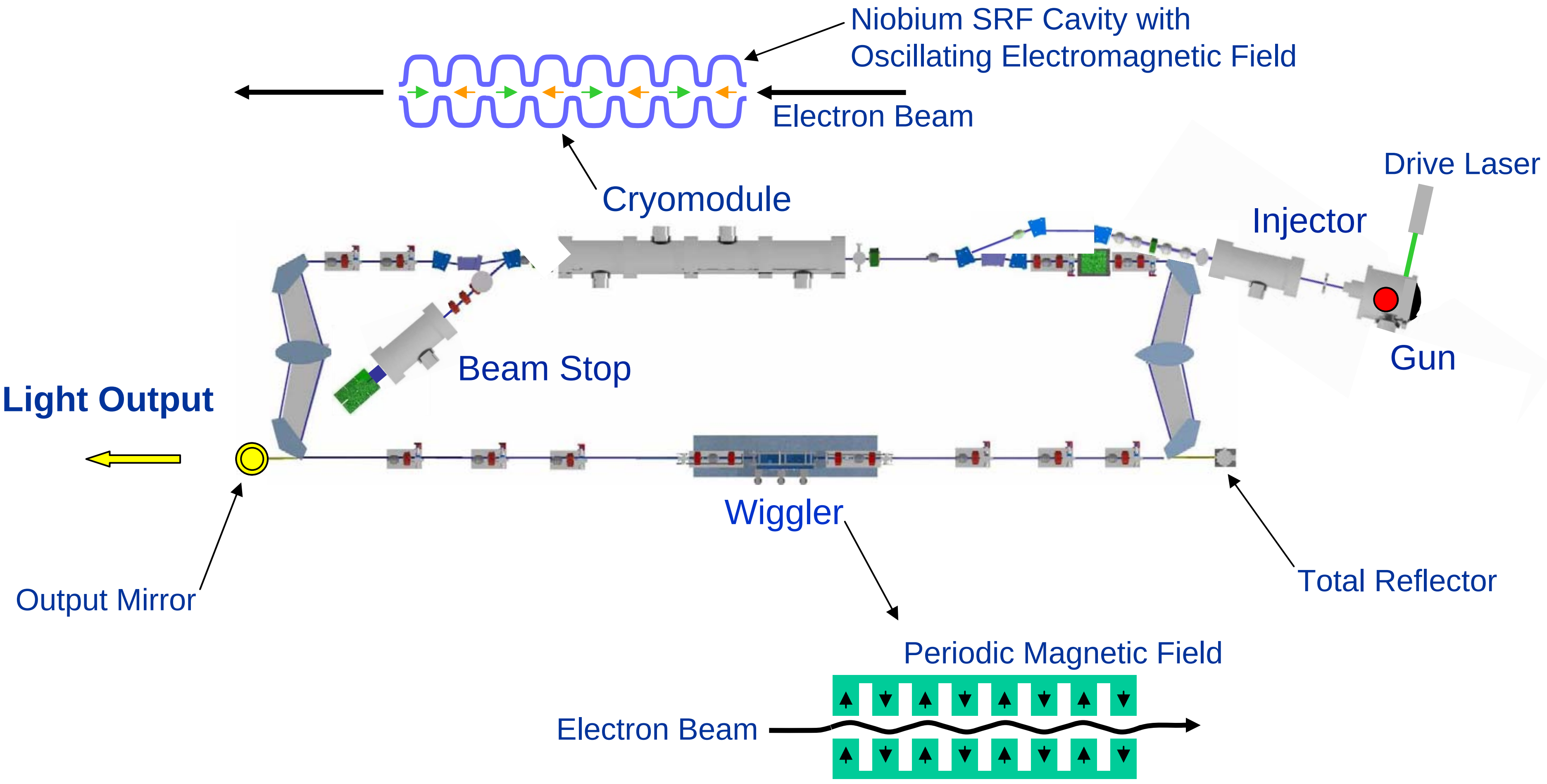
JLab Energy Recovered Linac (4GLS) facility schematic

E = 150 MeV
135 pC pulses up to 75 MHz
20/120/1 microJ/pulse in UV/IR/THz
250 nm – 14 microns, 0.1 – 5 THz



All sources are simultaneously produced for pump-probe studies

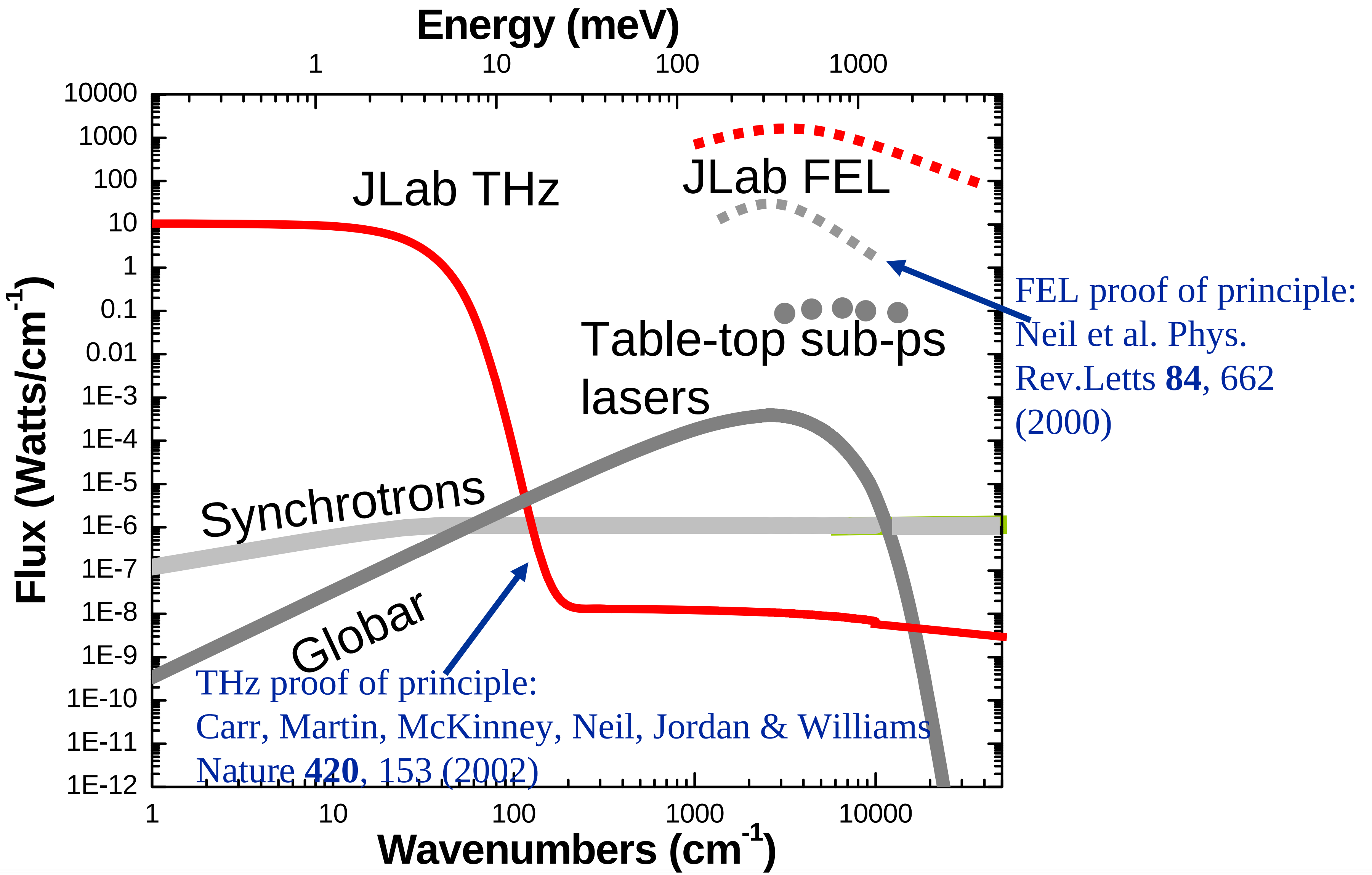
Schematic of JLab 4th. Gen. Light Source Operation



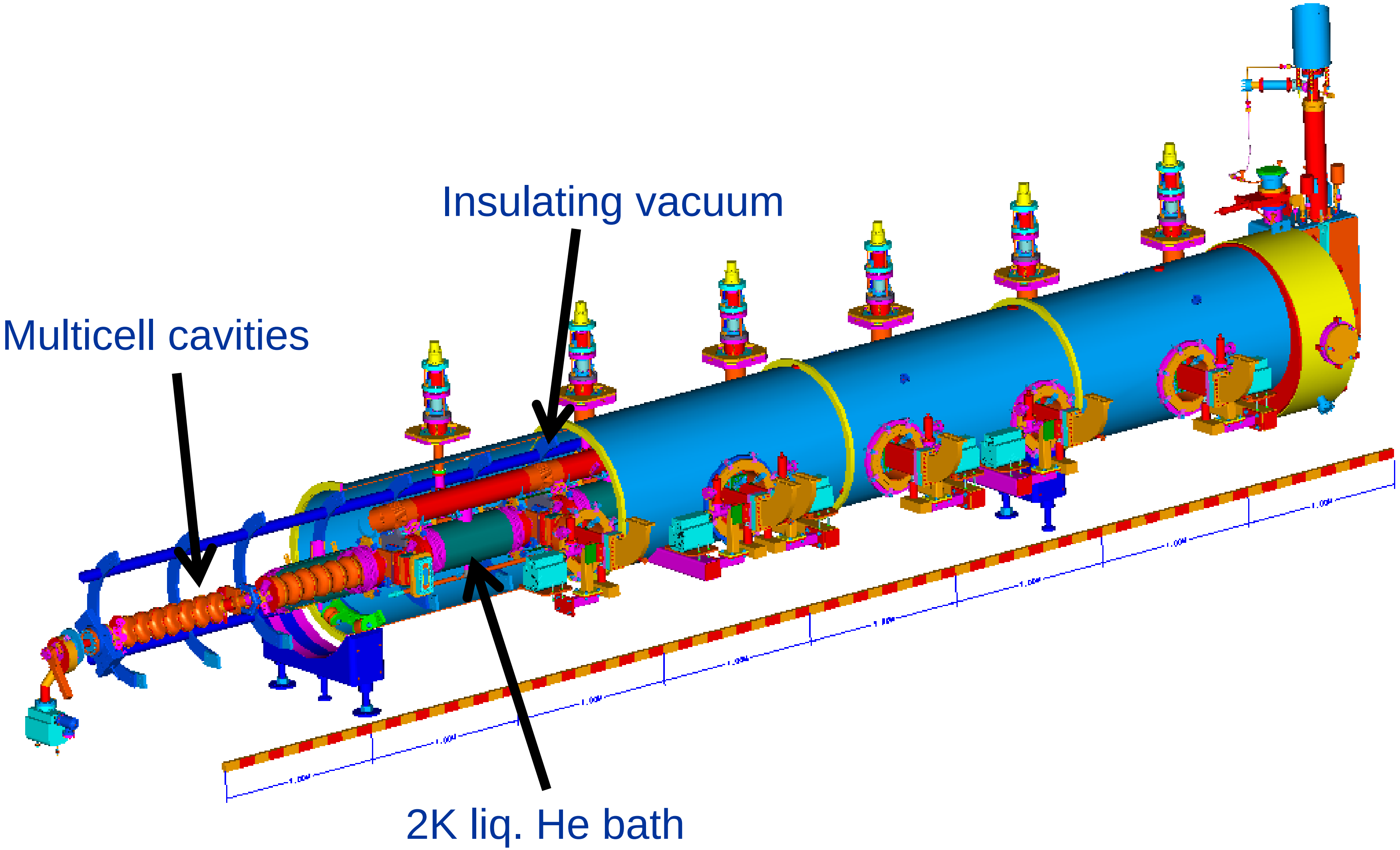
Laser Wavelength ~ Wiggler wavelength/(2Energy)^2

Superconducting FEL for high rep rate

Jefferson Lab Facility Spectroscopic Range and Power

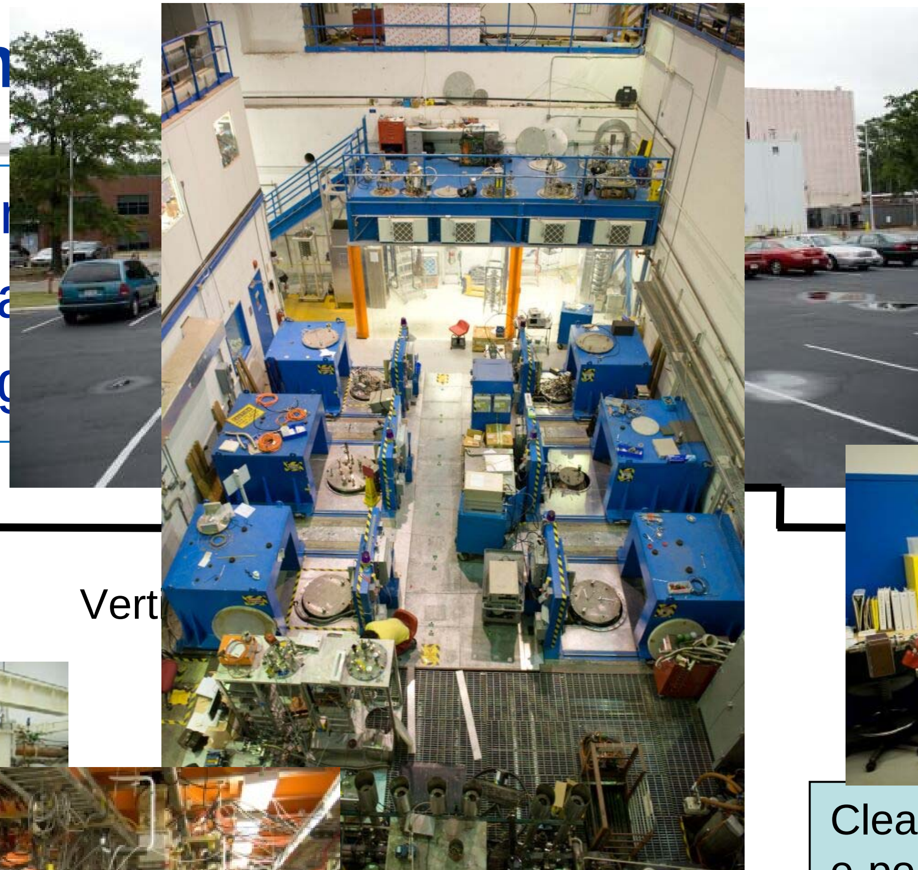


100 MeV Superconducting Linac – Jefferson Lab



Supercon ... ferson Lab

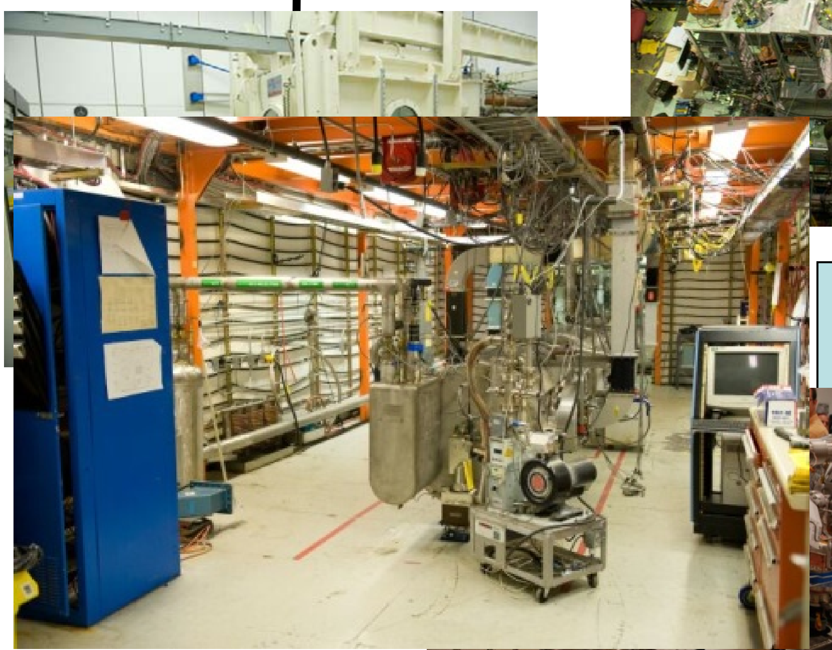
- 3000 square ...
- Cryo-test area ...
- Manufacturing ... cryo-testing.



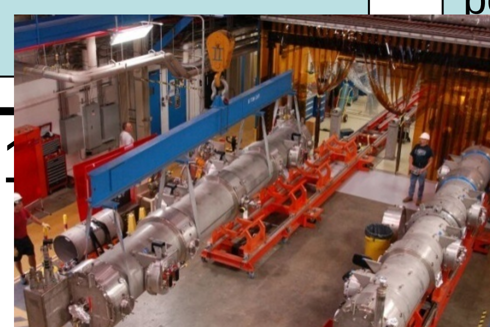
Vert

Clean-rm
e-polish/
chemi...
polish/
...nse

50m



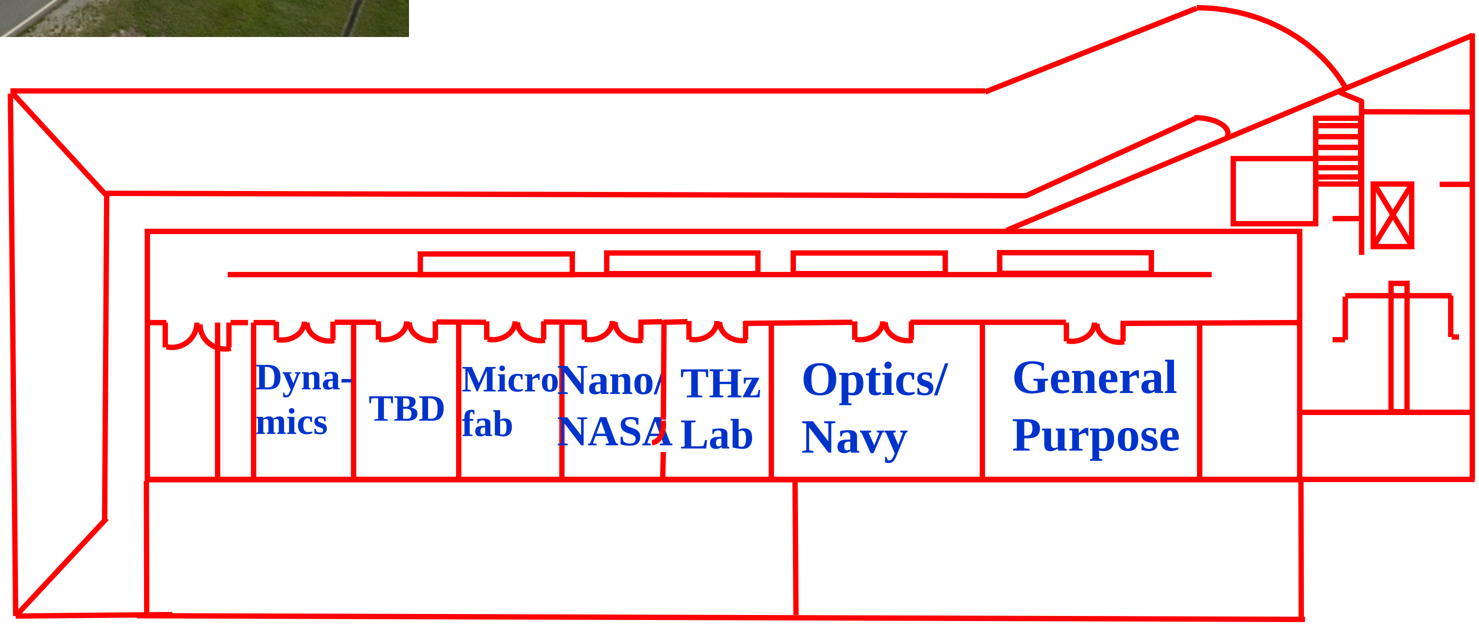
Horizontal



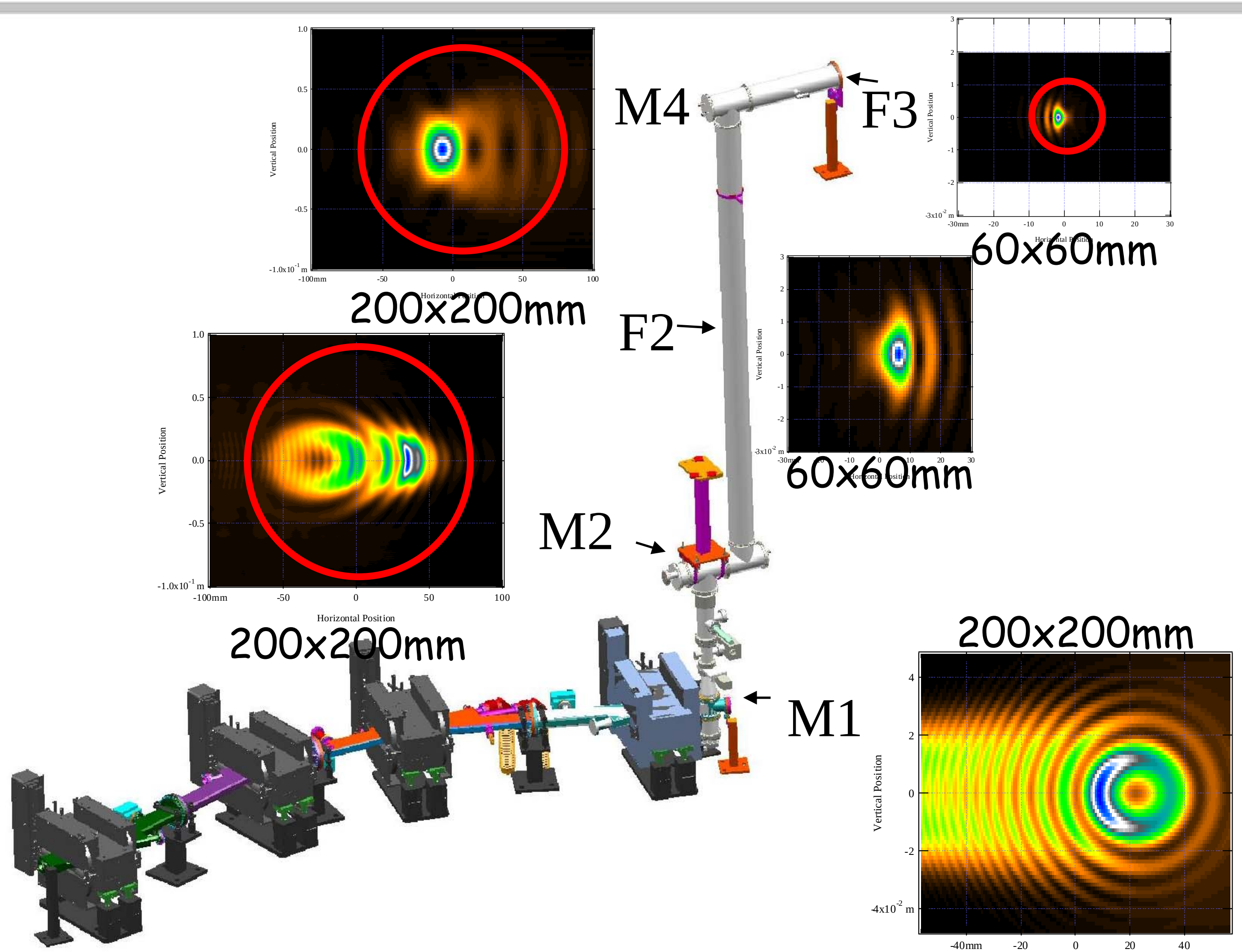
The JLab FEL User Facility

Current User Facility has 7 Labs

- Lab1 General set-ups and prototypes
- Lab 2 Initial propagation studies (Navy)
- Lab 3 THz dynamics and imaging
- Lab 3b NASA nanofab
- Lab 4 Aerospace LMES
- Lab 6 FEL + lasers for dynamics studies



JLab THz Beam Schematic with Optical Beam Ray-tracing



SRW calcs courtesy Paul Dumas, Oleg Chubar

JLab FEL Research Strategy

Choose some high profile experiments unique to our source.

1. **Relaxation dynamics in solids.**

   Key experiment: Relaxation dynamics of high Tc superconductor YBCO selectively pumped out of the superconducting state in a cold lattice.

2. **Strong-field atomic and molecular physics.**

   Key experiment: FEL selective excitation of molecules in mid-IR and observation of high harmonics in UV/visible.

3. **High Pressure as a reversible thermodynamic probe.**

   Key experiment: metallic hydrogen.

4. **Laser-bio interactions: photodynamic therapy, erythemal action.**

   Key experiments: Selective tissue ablation using tunable high-power FEL; photo-induced cancer; protein landscape determination

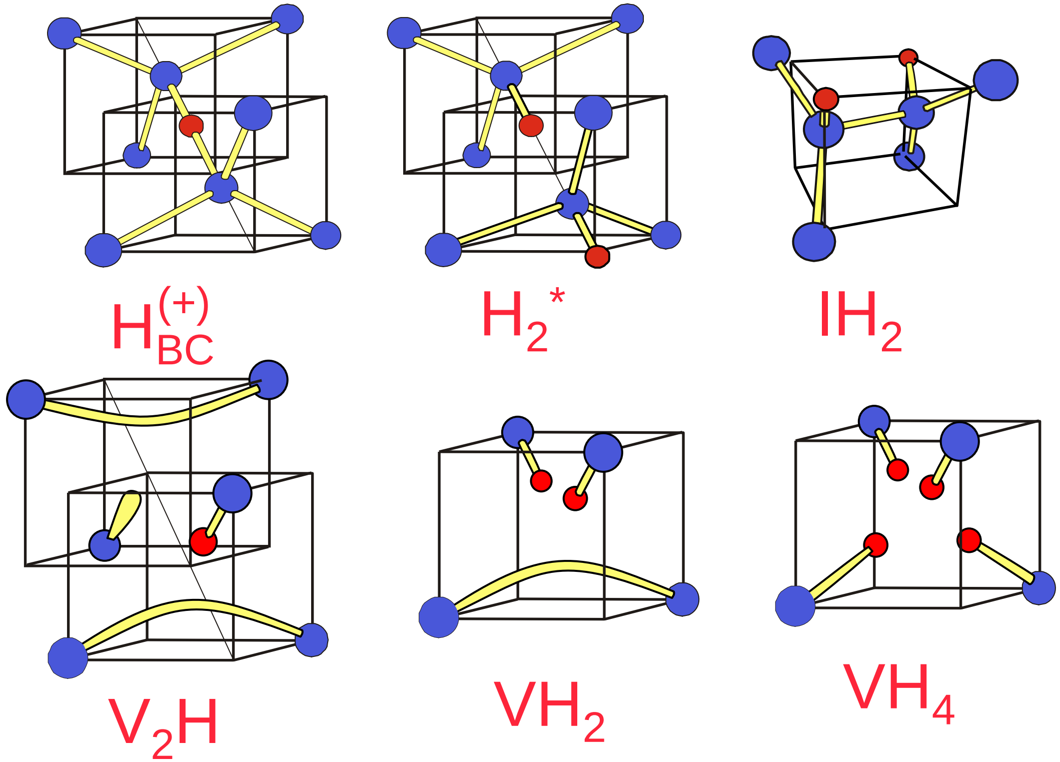
5. ***Search for Dark Matter of the Universe.***

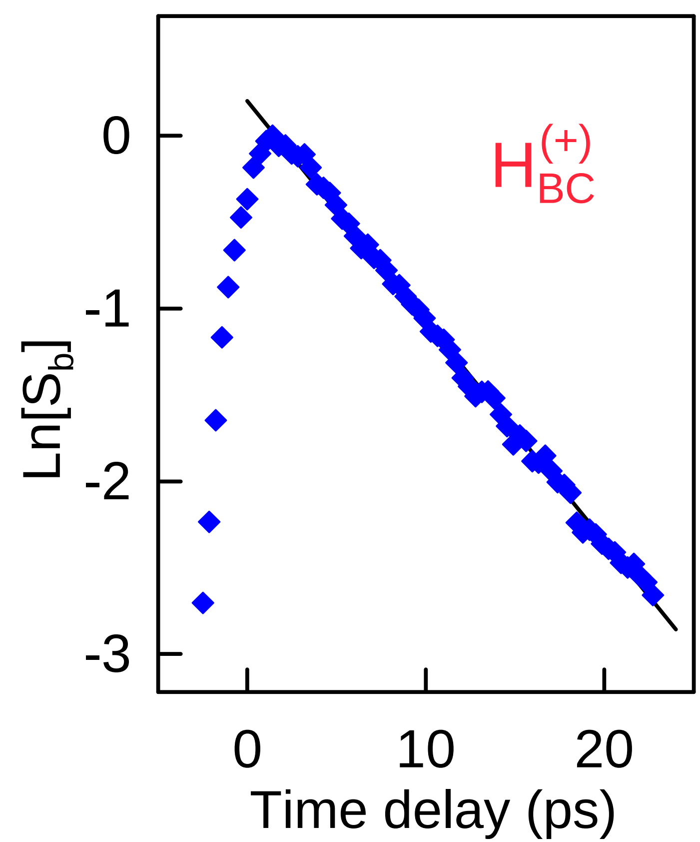
   Key experiments: Search for axions

Example of niche of 4th. Generation $\rightarrow$ Si:H

Defect Dynamics

Luepke et al. CWM/Vanderbilt





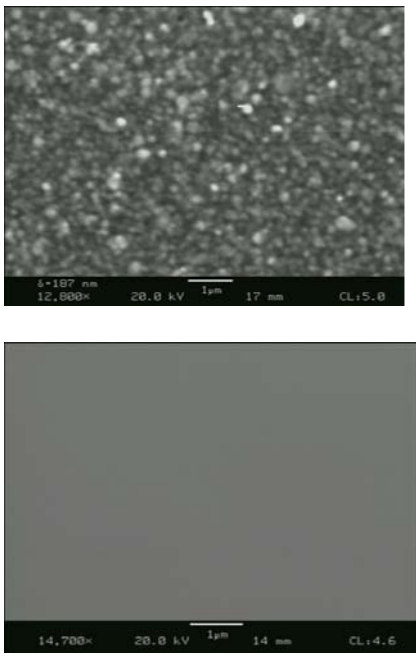
$T_1 = 7.8 \pm 0.2$ ps

Luepke et al. Phys. Rev. Letts **85**, 1452 2000
Wm. & Mary Phys. Rev. Letts **88**, 135501, 2002
Vanderbilt Phys. Rev. Letts **87**, 145501, 2001
Phys. Rev. **B63** 195203 2001
J. Appl. Phys. **93** 2316, 2003

JLab FEL - PLD High Rep Rate

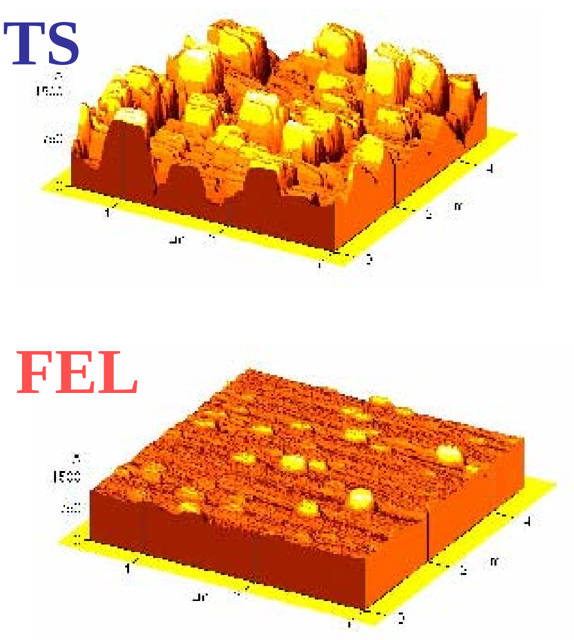
Pulsed laser deposition of $Ni_{80}Fe_{20}$ "Permalloy" films with the JLab-FEL

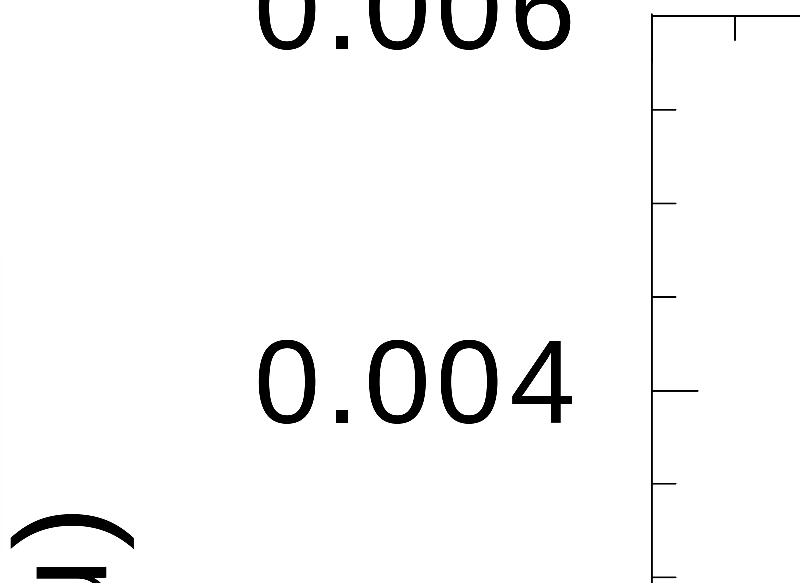
A. Reilly et al. CWM
J. Appl. Phys. 95 3098 (2003)



TS

FEL





SEM

AFM

Magnetic Hysteresis

Direct Laser Synthesis of Functional Coatings by FEL treatments

Peter Schaaf [a)], M. Shinn [b)], E. Carpene [a)], J. Kaspar [c)]

a) GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN
Zweites Physikalisches Institut

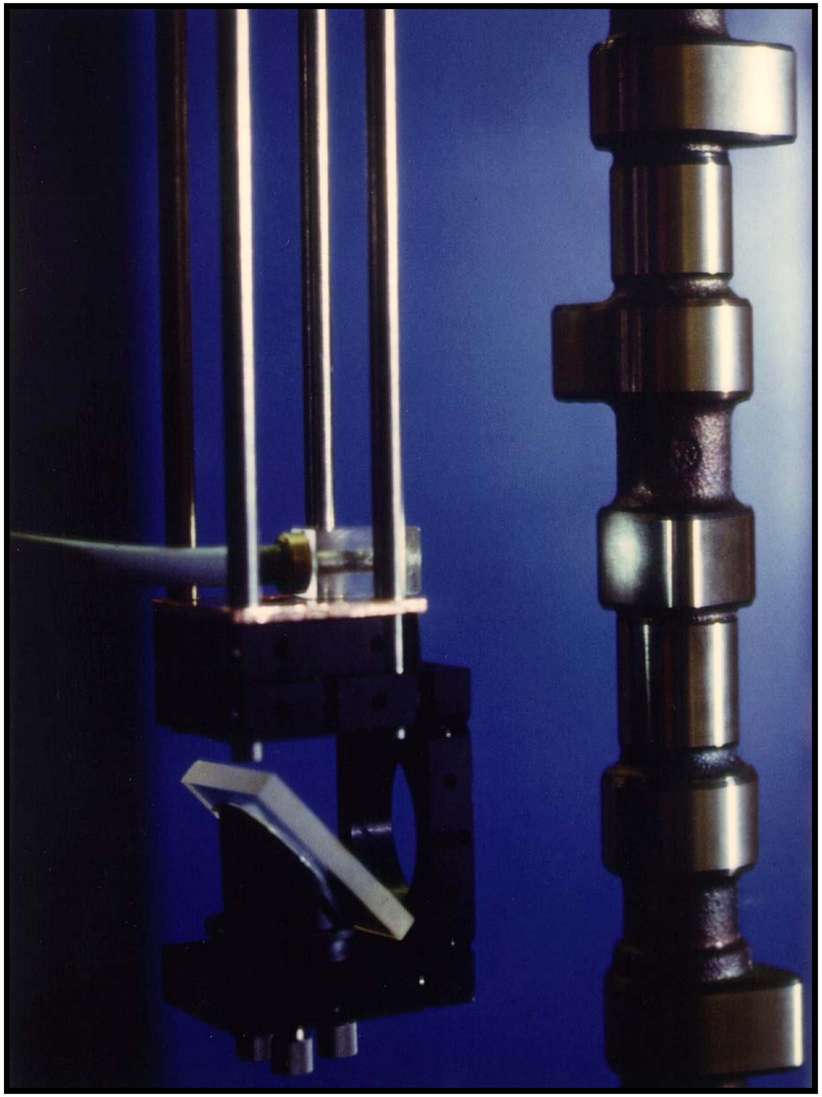
b) Jefferson Lab
Free-Electron Laser

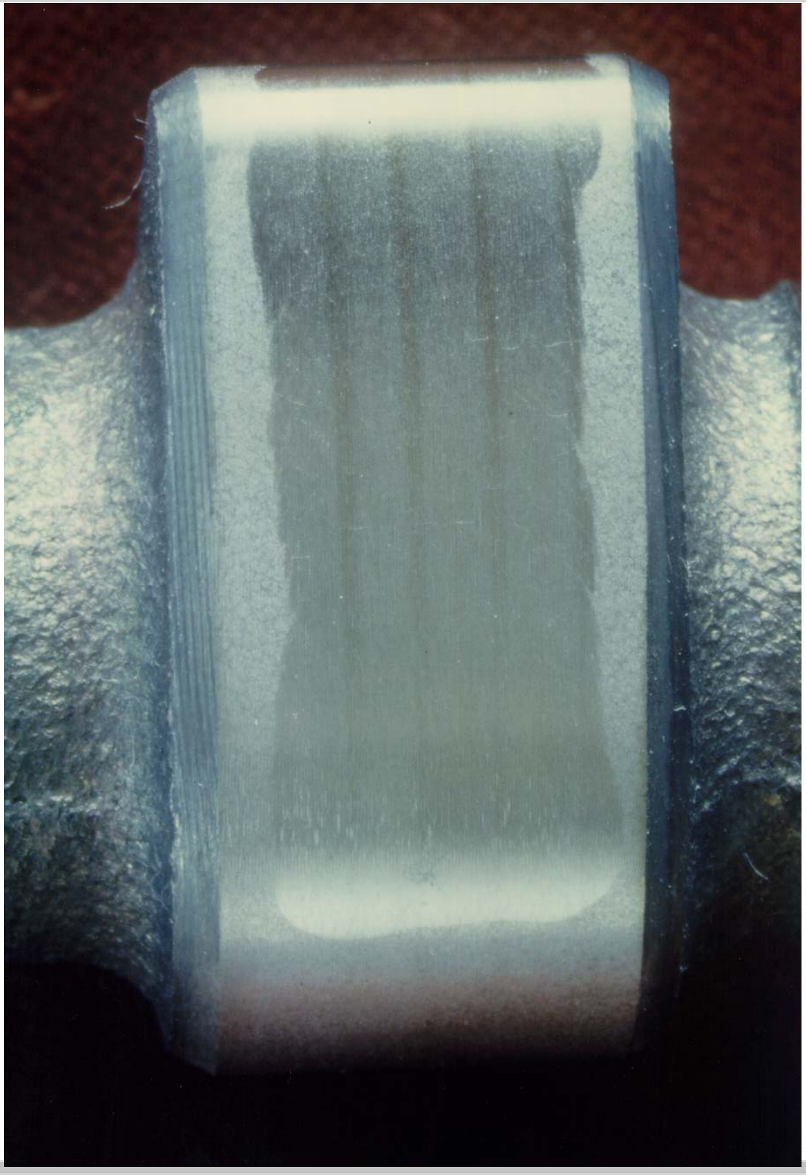
c) Fraunhofer IWS Institut Werkstoff- und Strahltechnik

Laser Synthesis

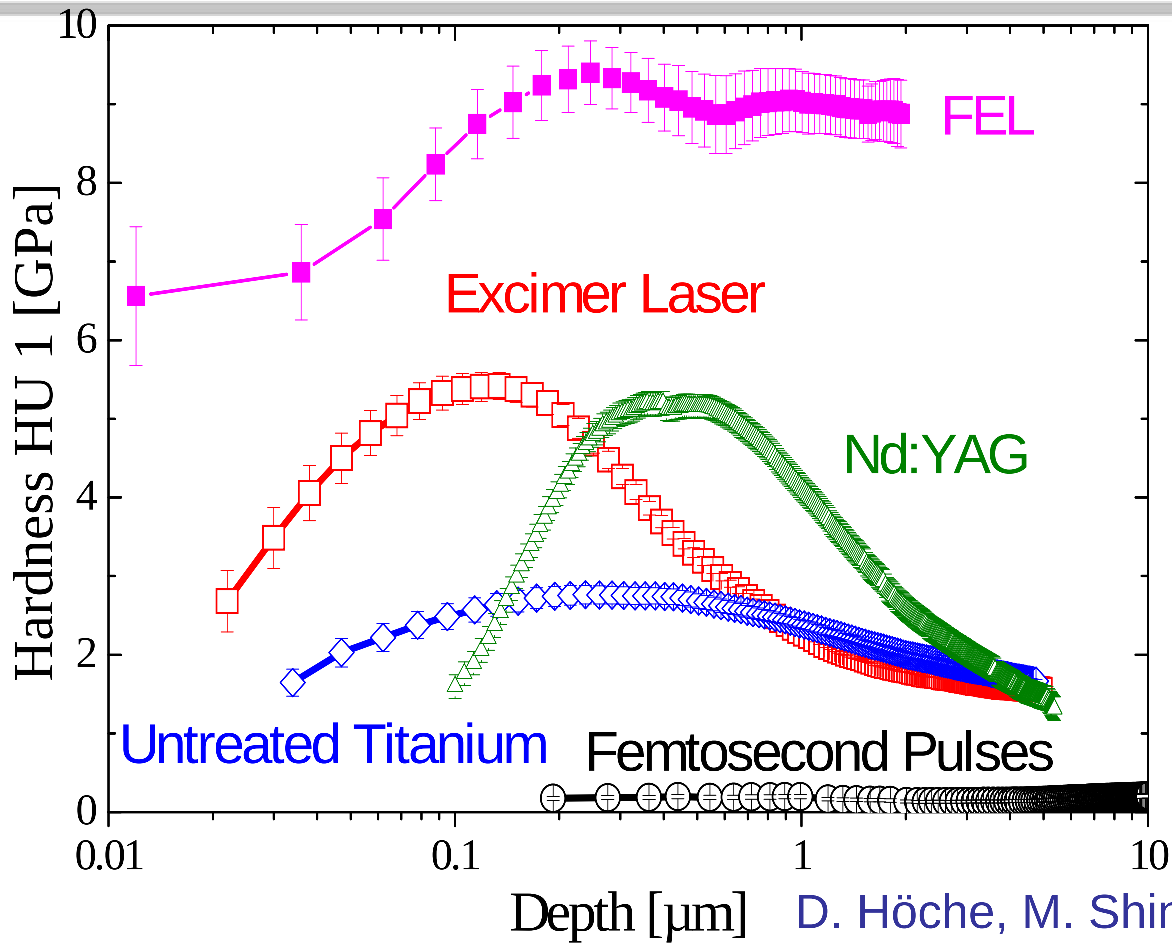
Reactive or non-reactive atmosphere

Laser surface modification Application: Cam Shafts





TiN: hardness – comparison laser



D. Höche, M. Shinn, J. Kaspar, G. Rapin, and P. Schaaf, "Laser pulse structure dependent texture of FEL synthesized TiNx coatings", J. Phys. D: Applied Physics **40** 818 (2007).

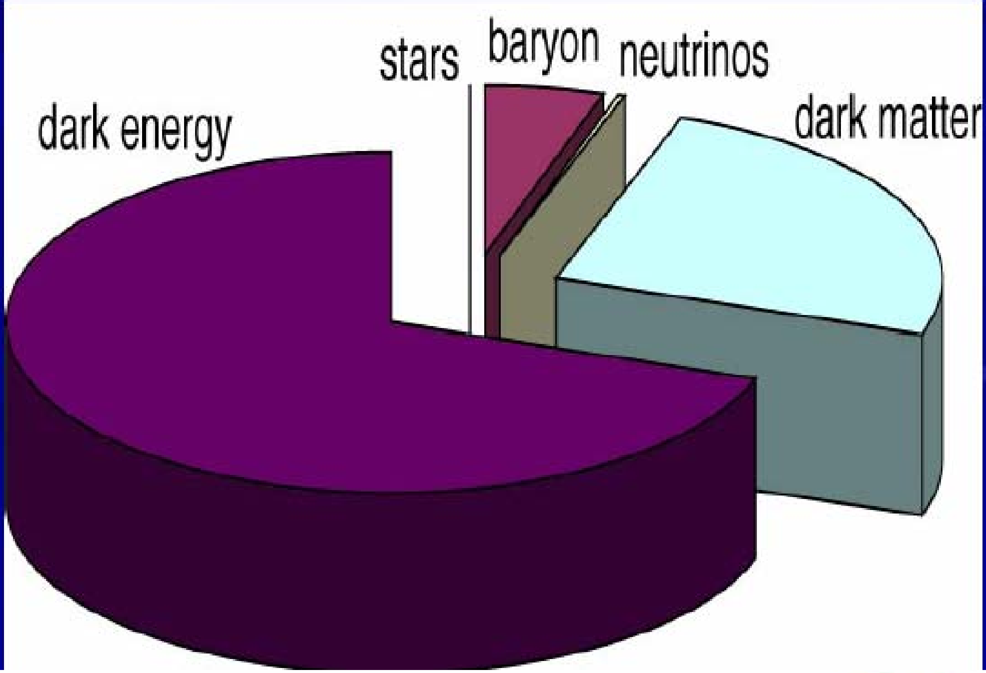
matter/energy budget of universe

Schirber, Science **311** 1535 (2006)
Zavattini E. *et al*. *Phys. Rev. Lett.* **96**, 110406 (2006)
Lamoreaux, Nature **441** 31 (2006)

Courtesy K. Baker Yale U.

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%

axion a dark matter candidate



PRL 96, 110406 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Experimental Observation of Optical Rotation Generated in Vacuum by a Magnetic Field

E. Zavattini,[1] G. Zavattini,[2] G. Ruoso,[3] E. Polacco,[4] E. Milotti,[5] M. Karuza,[1] U. Gastaldi,[3] G. Di Domenico,[2] F. Della Valle,[1] R. Cimino,[6] S. Carusotto,[4] G. Cantatore,[1,*] and M. Bregant[1]

(PVLAS Collaboration)

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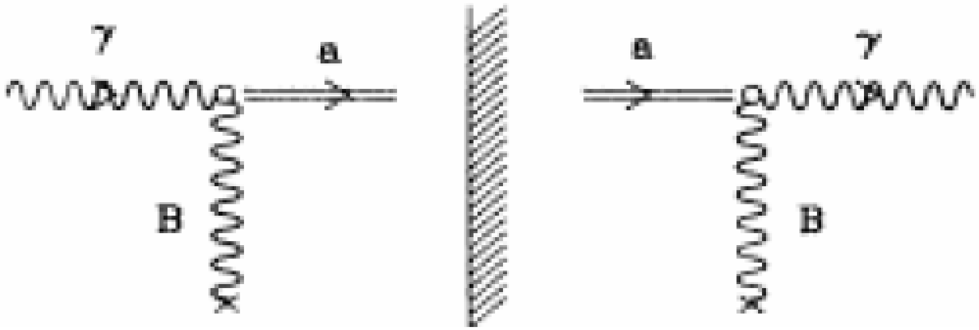
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Ferrara and Università di Ferrara, Ferrara, Italy*
[3]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Legnaro, Legnaro, Italy*
[4]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa and Università di Pisa, Pisa, Italy*
[5]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione Trieste and Università di Udine, Udine, Italy*
[6]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, Frascati, Italy*
(Received 29 July 2005; revised manuscript received 8 February 2006; published 24 March 2006)

We report the experimental observation of a light polarization rotation in vacuum in the presence of a transverse magnetic field. Assuming that data distribution is Gaussian, the average measured rotation is $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass, at 5 T with 44 000 passes through a 1 m long magnet, with $\lambda = 1064$ nm. The relevance of this result in terms of the existence of a light, neutral, spin-zero particle is discussed.

DOI: 10.1103/PhysRevLett.96.110406 PACS numbers: 12.20.Fv, 07.60.Fs, 14.80.Mz

Light, Neutral, Spin-zero Boson Search



Light Shining Through Walls

Advantages of FEL
•High average power
•Stable operation
•Low-emittance beam
•Bunched beam
•Coherence between bunches
•High polarization
•Tunability
•Infrastructure

FEL photons couple to the virtual photons in a high field magnet to create the spin-zero particles (labeled *a*). These weakly interacting bosons travel through a light shield to a second high field magnet where photons of light are regenerated.

A. Afanasev, O.K. Baker, K.B. Beard, G. Biallas, J. Boyce,
B. M. Minarni, R. Ramdon, M. Shinn, P. Slocum,
C. "New Experimental limit on Optical Photon Coupling to
D. Neutral, Scalar Bosons", Phys. Rev. Lett. **101** 120401 **2008**

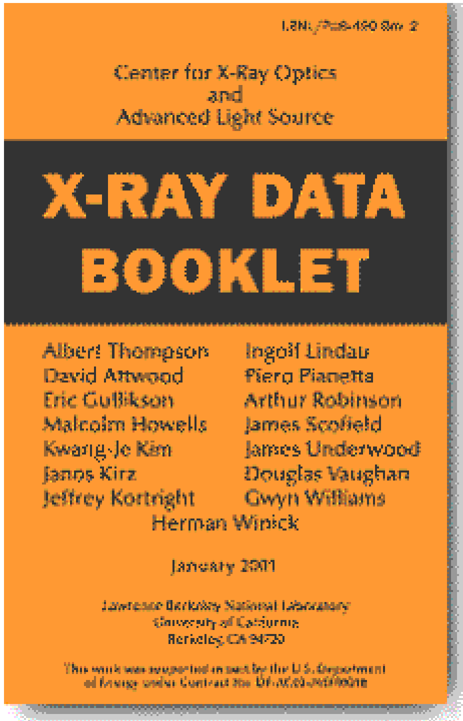
Synchrotron radiation in transverse coherent limits…………

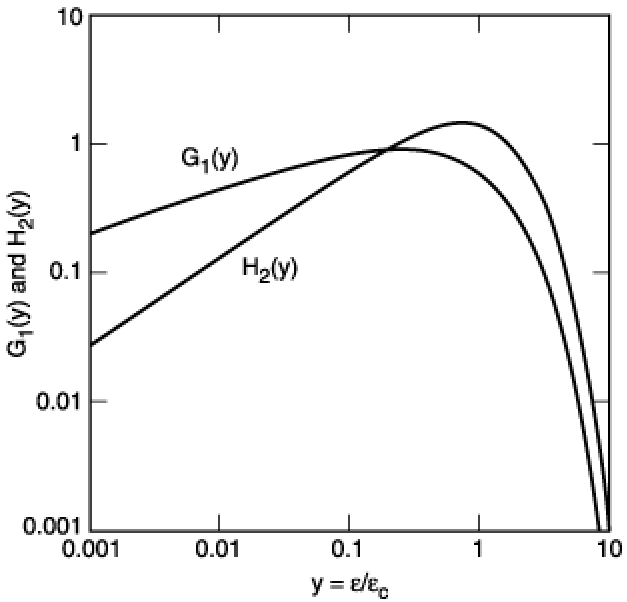
4^{th} generation light sources have extremely small, round electron bunches.

There is a need to look at SR calcs in this limit.

Extensively using Kwang-Je's work, and working with Jim Murphy, Steve Hulbert, Larry Carr………….

Incoherent synchrotron radiation





Synchrotron radiation: power given by $G_1(y)$
brightness by $H_2(y)$

Power and coherent fraction

Photons/sec integrated over all vertical angles K.J. Kim, AIP Conf Proc **184** 565 1989

$$F = 2.46\times10^{13}.\theta(mrads).E(GeV).I(amps)G_1(y)\ photons/\sec/mr/0.1\%BW$$

where: $G_1(y) = y\int_y^\infty K_{\frac{5}{3}}(y')dy'$ with y = ω/ω_c, and $K_{5/3}$ a modified Bessel function of the 2nd kind

The asymptotic limit of the Bessel function integral is given by:
Sokolov and Ternov, "Radiation from Relativistic Electrons", AIP Translation Series, translated by S. Chomet and edited by C.W. Kilmister, New York 1986
Hofmann "The Physics of Synchrotron Radiation", Cambridge University Press, Cambridge, England, 2004 in the following form:

$$f(y) = \frac{9\sqrt{3}}{8\pi}G_1(y) = 1.33\left(\frac{\omega}{\omega_c}\right)^{\frac{1}{3}} \qquad G_1(y) = \frac{1.33\times8\times\pi}{9\times\sqrt{3}}\left(\frac{\omega}{\omega_c}\right)^{\frac{1}{3}} = 2.144\left(\frac{\omega}{\omega_c}\right)^{\frac{1}{3}}$$

Thus the formula for angle integrated flux for $\omega < \omega_c$ can be written as:

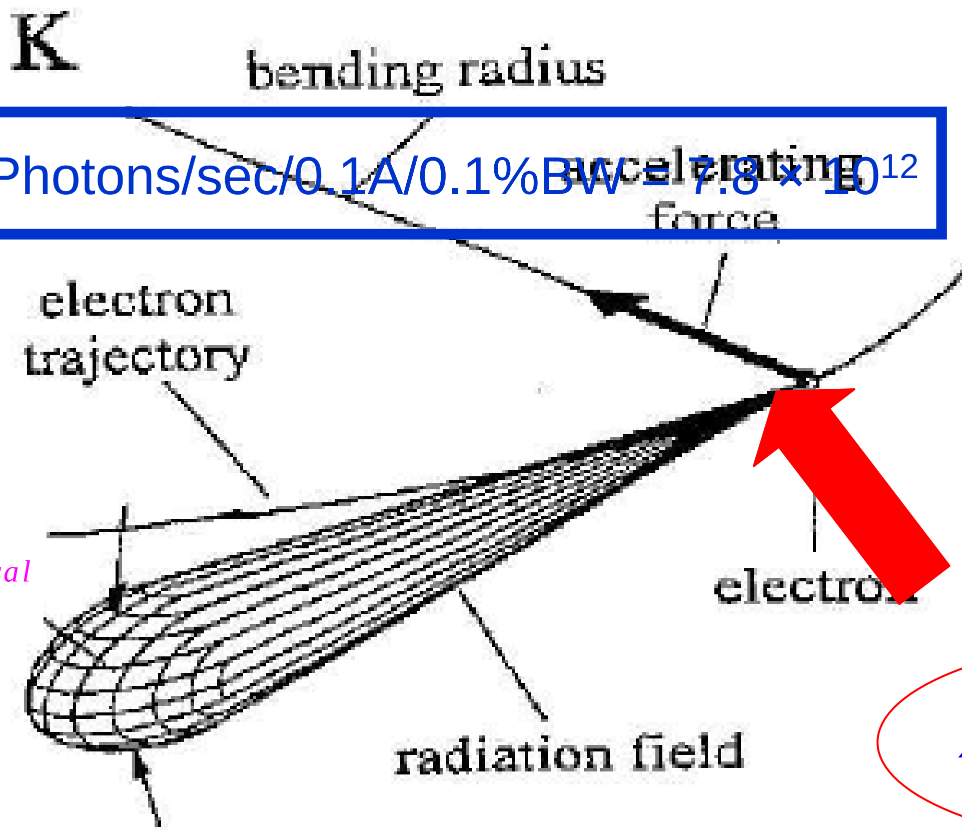
$$F = 5.3\times10^{17}.\left(\frac{\omega}{\omega_c}\right)^{\frac{1}{3}}.\theta(rads).E(GeV).BW(\%).I(amps)\ photons/\sec$$

Power with full transverse coherence

Photons/sec/0.1A/0.1%BW = 7.8×10^{12}

$$\theta^{\frac{1}{2}}_{rms\ (NATURAL)} = 0.8282\left(\frac{\lambda}{2\pi\rho}\right)^{\frac{1}{3}}$$

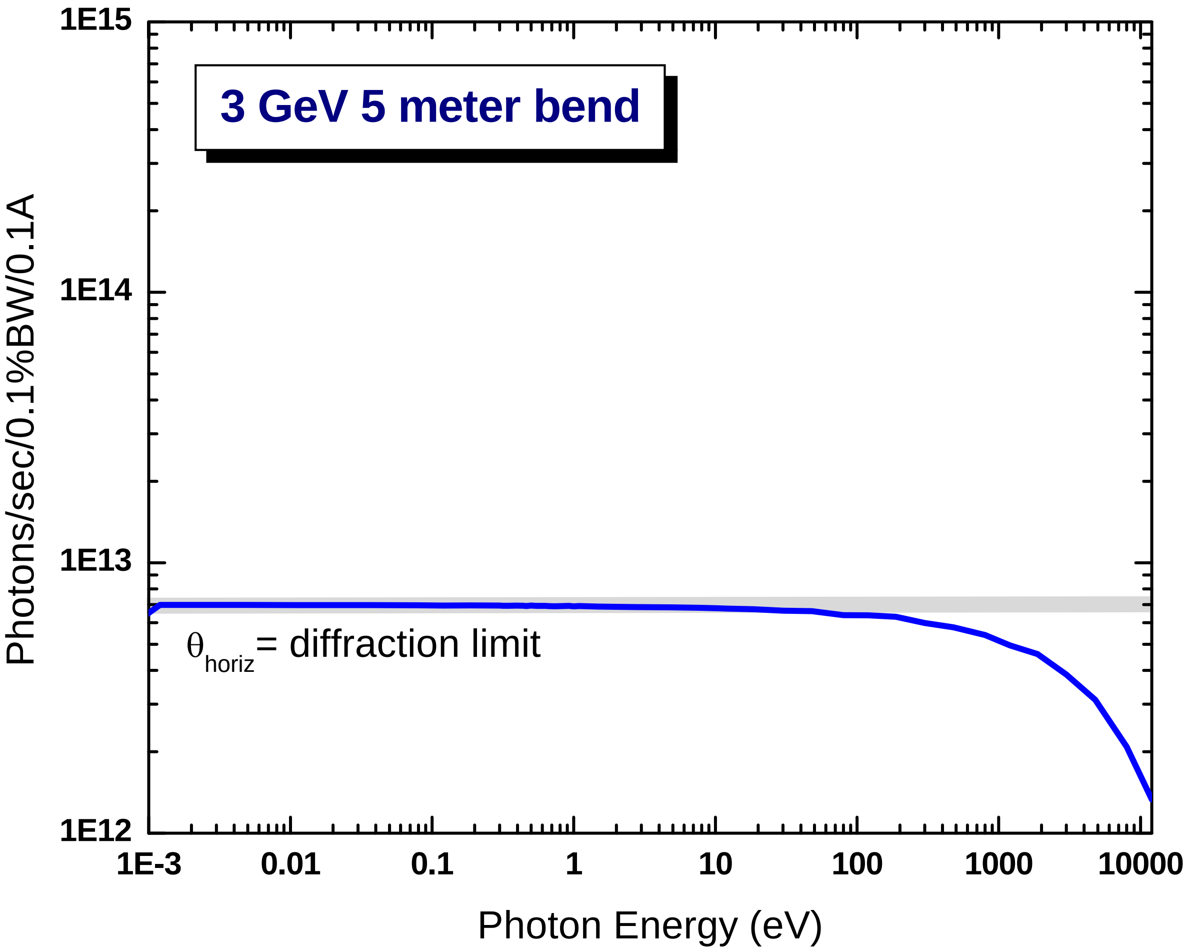
$\theta_{natural}$



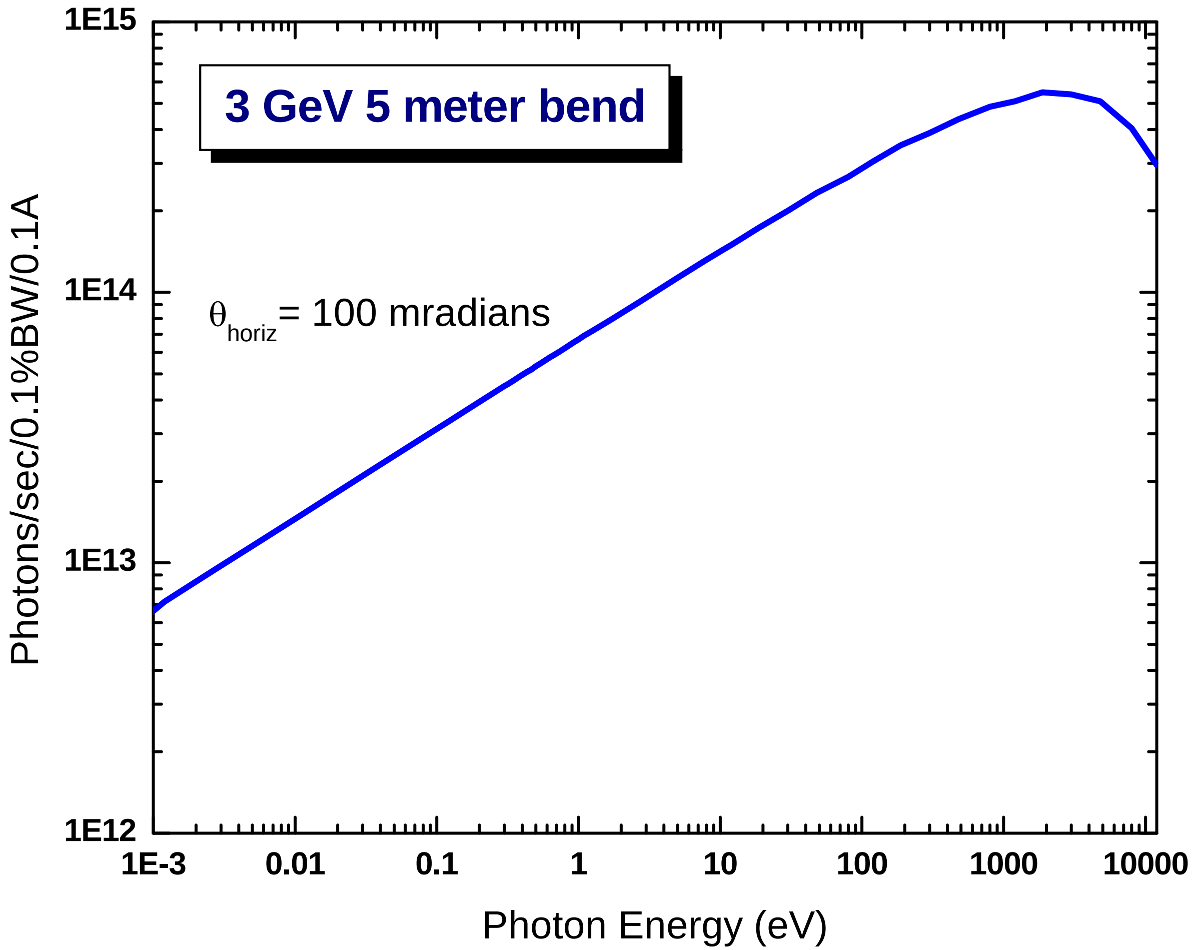
$$\lambda_c(\overset{0}{A}) = \frac{5.59\rho(meters)}{E^3(GeV)}$$

Photons/sec integrated
over all vertical angles = $5.3\times10^{17} E(GeV) I(Amp) \vartheta_{full}[rad] BW[\%]\left(\frac{\omega}{\omega_c}\right)^{1/3}$

Synchrotron Radiation – transverse coherence



Synchrotron Radiation – transverse incoherence



Relationship to user requirements

User requirements can be expressed either as peak power (peak E-field), or photons/pulse.

Question for the accelerator is the bunch charge/time (peak current) and emittance.

We can relate this to machine parameters quite easily if we assume transverse spatial coherence.

Games with numbers – to get a feel for things….

So, 1 amp gives 7×10^{13} photons/sec/0.1% BW
Thus each electron gives 1.1×10^{-5} photons!!!

Assume:

1. Undulator gives 1.1×10^{-3} photons/electron
2. We need 1 GW peak power
3. Wavelength is 1 eV (1.24 microns)
4. 100 fs FWHM pulse

What peak current would we need?

Well a 1 eV photon carries 1.6×10^{-19} joules, so we'd need 6.24×10^{14} of them to make 100 microJ.

This would require 7.54×10^{8} electrons, which is a peak current of 1.21 kA

BUT – for 10 keV photons, we would need only 7.54×10^{6} electrons – 12.1A

IT GETS EASIER AS PHOTON ENERGY INCREASES!!

The Future?

1. DOE will build a new light source.
2. Likely to be superconducting radio-frequency linac based.
3. Jefferson Lab would like to be engaged.
4. Use existing facility to test components, study beam dynamics, go to higher photon energies.

JLab Current Thoughts

- Use existing FEL as a test bed to address technology drivers.
  - Replace existing SRF cryomodules with ones optimized for high real estate gradient and recirculation.
  - Investigate limits of multipass operation and deal with CSR, LSC, compression methodologies, etc.
  - Opportunity for world class condensed matter research using this tool.

Conclusions

Jefferson Lab has an ERL-based light source, that could provide important tools for solving DOE's new scientific challenges.

We are starting to engage with the community under our new leadership, and look forward to collaborations wherever possible.

Some of the JLab Team

Photo taken Jan 16, 2007

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.