Light Source Advancement at the JLab FEL

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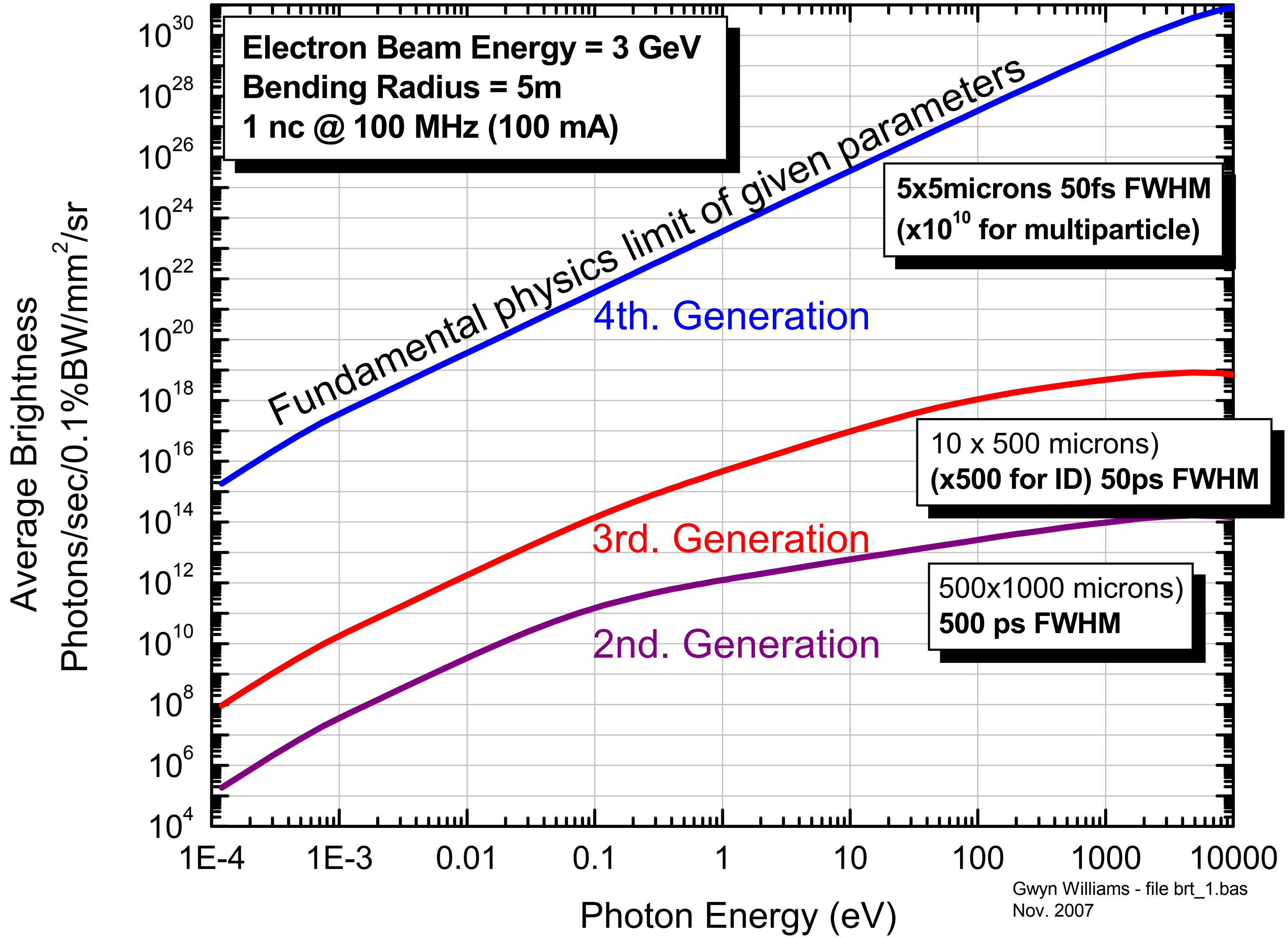
Outline

- Context - the emergence of linac-based light source technology
- Jefferson Lab ERL development
- 21st Century Light Source Program at DOE-BES
    - "Science Grand Challenges"
- Jefferson Lab program development, evolution & engagement
    - Leveraged advancement of light source technology
    - New Opportunities - "Nobel class experiments"

Bottom lines

- Improving the performance and cost-effectiveness of linac based light sources has enormous implications for scientific reach, competitiveness and facility costs.
- There is a role for meso-scale light source facilities which has not been supported in the past
- There are substantial opportunities for top science in wavelength ranges in addition to the X-ray region

Light Sources – "The World Stage"



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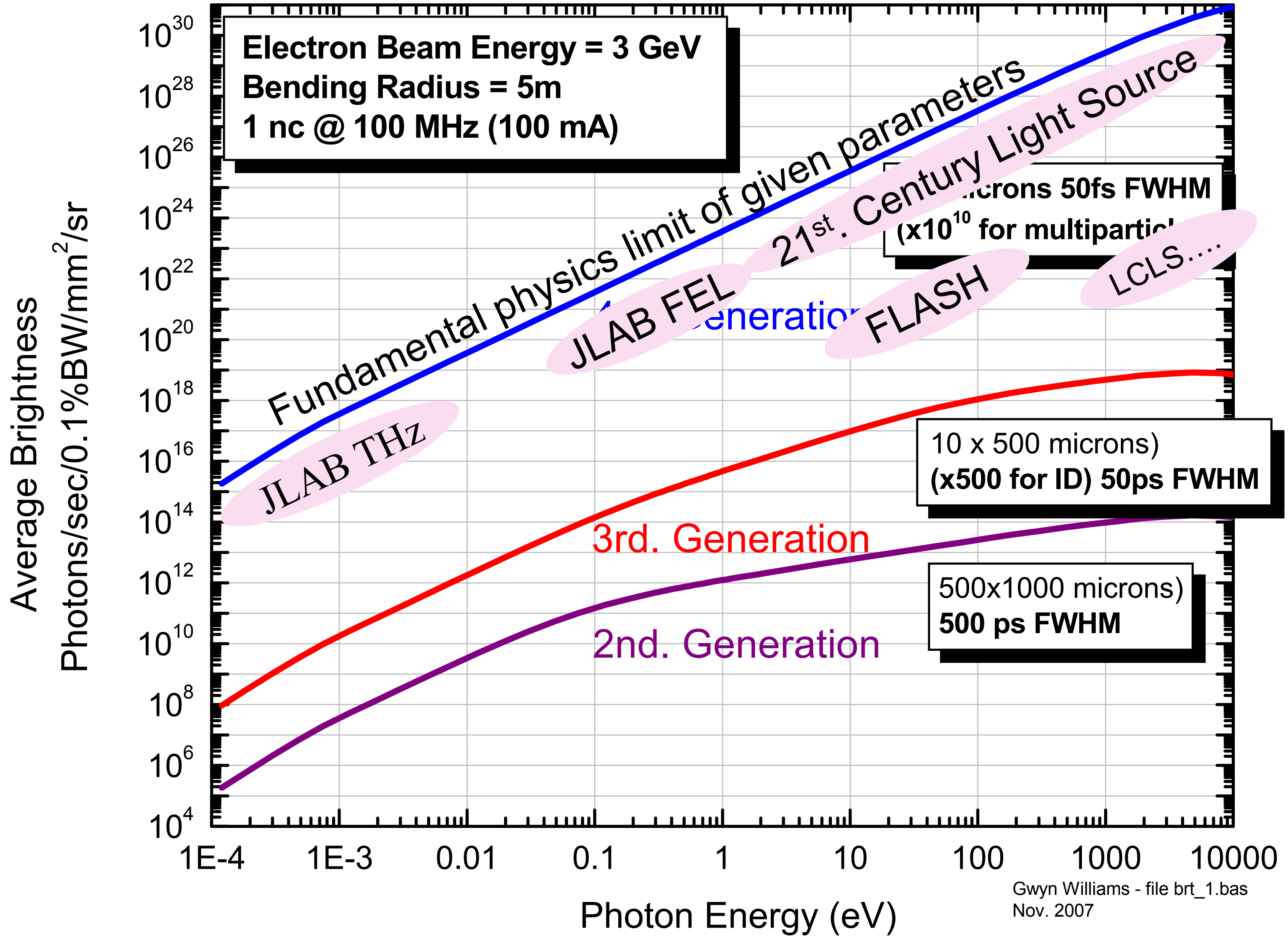


What are Next Generation Light Sources?

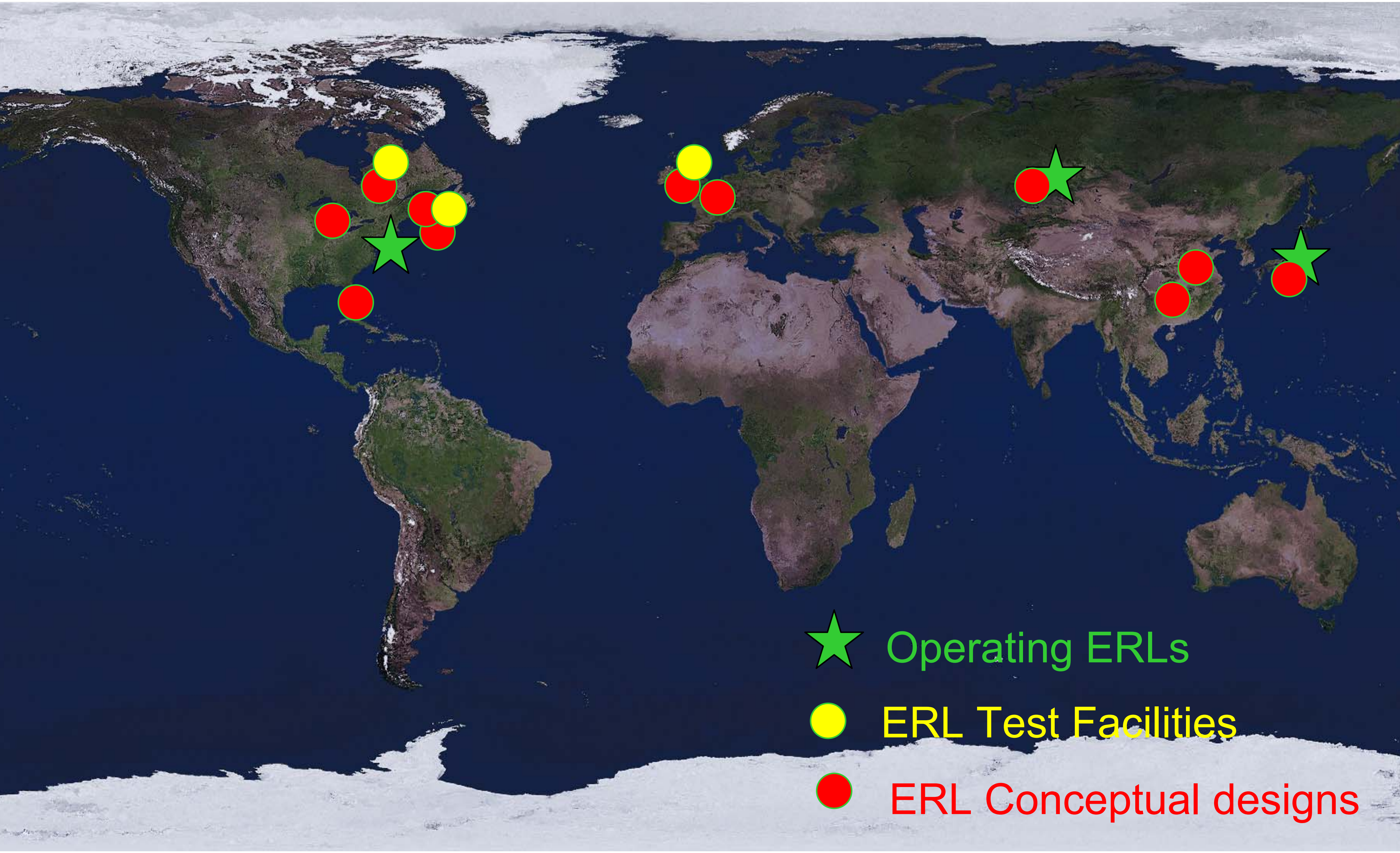
1. Brighter than 3rd generation.
2. Linac based.
3. Using multiparticle coherence (or "gain").

- 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.

Accelerator community response to need

- Pulse slicing on 3rd generation machines
- High brightness linac with single or multiple wigglers
  - SASE, Amplifiers with HG sources, HGHG
- High brightness ERLs with
  - Compton sources
  - Synchrotron sources
  - FELs: SASE, Amplifiers with HG sources, HGHG, possibly even oscillators

Operating and Future ERLs



Physics advances are required

Injectors: ultimate brightness limits at low (100 pC in 100 fs gives 1 GW for 1 keV photon energy) and high (> ~ 1 nC) charge

- Approaches: DC gun, copper RF gun, SCRF gun

Brightness preservation:

- Solutions to CSR, LSC, pulse compression (chicanes are bad: curvature terms are wrong sign for rf and they always have a parasitic compression) - really want 1 nC in < 100 fs = 10 kA

Halo control

HOM & BBU control

Wakefield and propagating mode damping

Engineering development also has high leverage

- Multipass BPMs for beam control
- Cost/MeV for cryomodule (increasing gradient reduces capital expense of cryomodules - potentially $100M savings)
- Good real estate gradient to minimize conventional facilities (several $10Ms possible)
- Low loss (high Q_0) to reduce He refrigeration capital and operating costs (>$10M potential capital savings and several $M/year in operating costs)
- LHe plant design and process cycle optimization to minimize capital and operating cost (Ganni cycle by JLab introduced to BNL saves > $100k of electric operating costs/week)
- Multiple cavity drive from single rf source (rf systems cost > $1M/srf module and have only weak power dependence)

Proposed National Strategy

Improvements in all these areas are needed to make next generation light sources both practical and useful without breaking the bank

Jefferson Lab Response

Rather than propose an X-ray light source at this time, JLab is leveraging technology development from our funded ONR effort to address technologies key to making next generation light sources successful and practical

1) Validate design for high real-estate gradient, high average current cavities by testing in FEL injector

2) Produce prototype accelerator modules and test in ERL

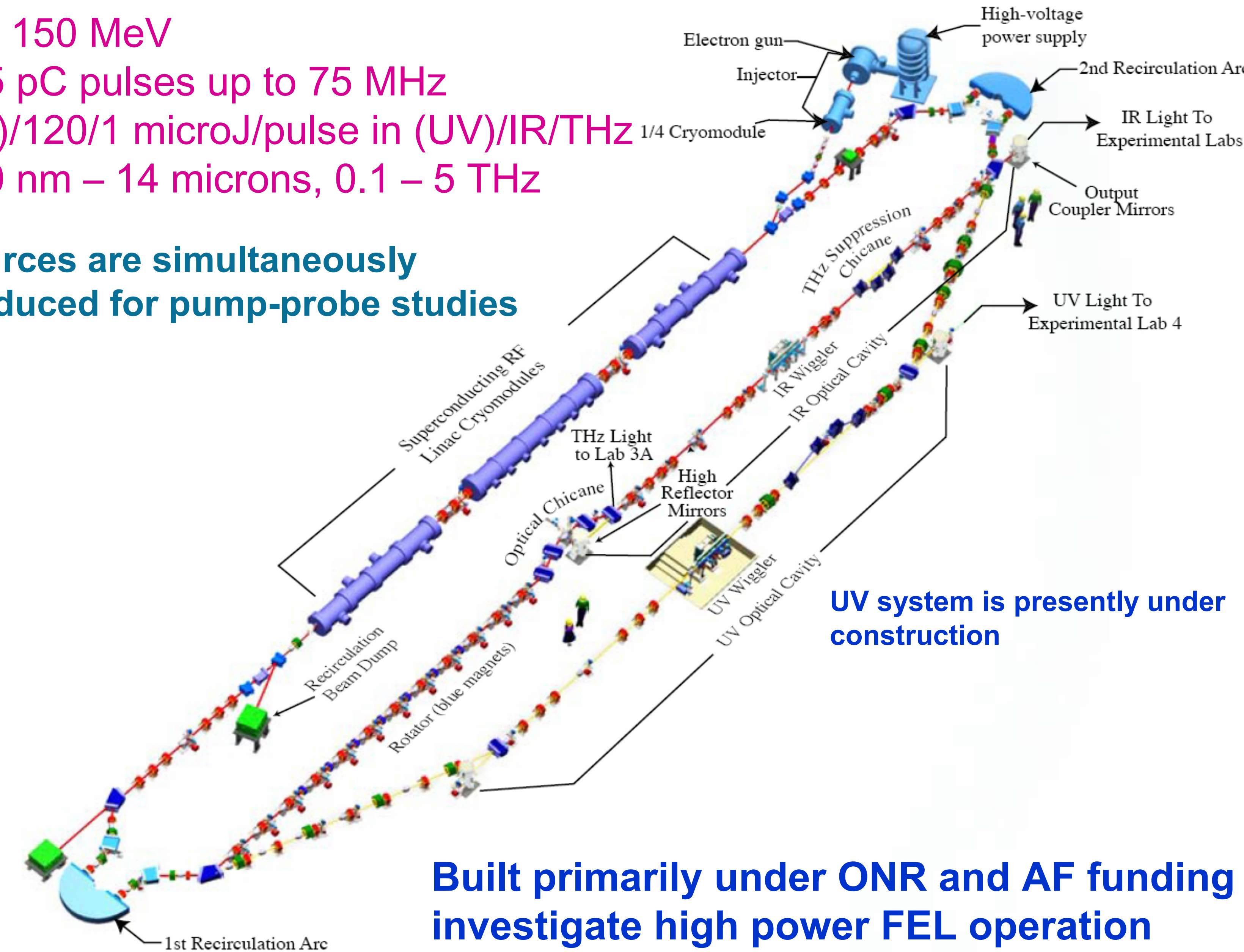
3) Test physics of high brightness and high charge transport including CSR, longitudinal space charge, recirculation

In parallel, under modest funding, we intend to utilize our IR/THz/(UV) source for the best possible science

JLab's Existing 4th Generation Light Source

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

Sources are simultaneously produced for pump-probe studies



UV system is presently under construction

Built primarily under ONR and AF funding to investigate high power FEL operation

Achievements of the JLab FEL effort

- Accelerator physics and technology test bed for electron source, srf linac, and diagnostics development:

- In addition, JLab has processed over half of the world's srf cavities and we have over 50 cavity-centuries of operating experience with these systems

What do we presently provide?

- World best-in-class facility for basic science studies with <100 fs output in the THz, IR, (UV) region combined with a productive technology test bed for a 4th generation X-ray machine

- Recently we completed design of a system for the National High Magnetic Field Lab at FSU designed to provide IR-THz capability for condensed matter research

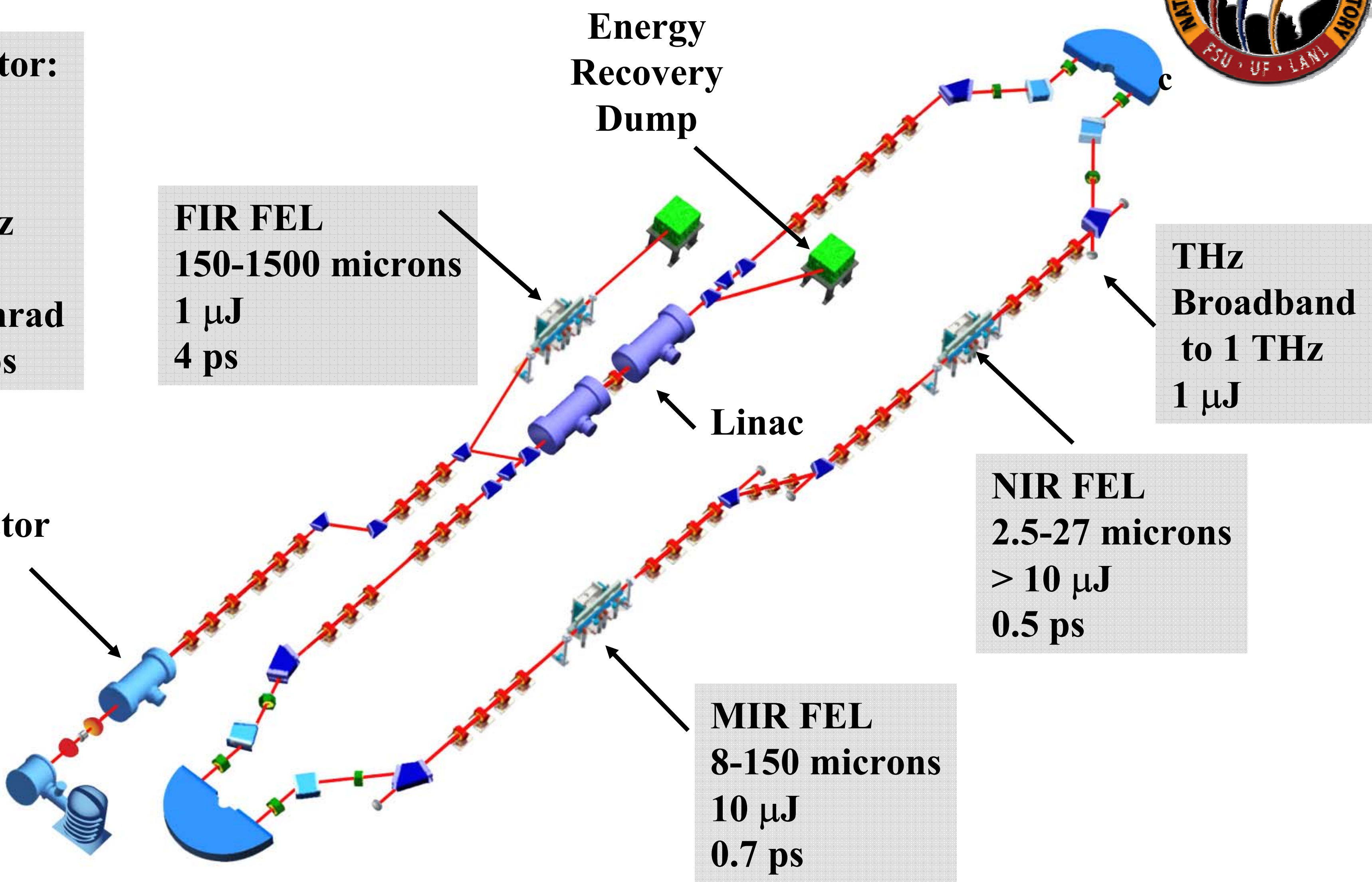
Caveat

- However, there has historically been a lack of support for meso-scale light sources. This needs to change
  - such facilities fill a niche that major light sources and university laser labs cannot meet
  - such facilities provide technical capabilities unavailable elsewhere and are cost-effective at producing valuable research

BigLight FEL for NHMFL

Accelerator:

60 MeV
2 mA
11.8 MHz
135 pC
10 mm mrad
80 keV-ps



In context of DOE light sources: What's next?

- Leverage successful test bed to address next generation technology drivers: shorter pulses, emittance minimization (longitudinal and transverse), improve key cost drivers for femtosecond X-ray production at high prf
  - Injector test stand and upgrade of existing injector for higher brightness generation
  - Replacement of existing cryomodules with ones optimized for high real estate gradient
    - (yields machine with > 300 MeV energy in single pass)
  - Investigation of limits of multipass operation while dealing with CSR, LSC, compression methodologies, etc.
    - (is recirculation in addition to energy recovery possible, at least at lower energies?)
  - RF control studies leading to multiple cavities driven from one tube

In context of DOE light sources: What's next?

- Leverage successful test bed to address next generation technology drivers: shorter pulses, emittance minimization (longitudinal and transverse), improve key cost drivers for femtosecond X-ray production at high prf

- Due to the installed infrastructure, we can achieve significant performance advances for a fraction of the cost required elsewhere (e.g., 600 MeV test bed < $50M)

21st Century Light Sources:

An assessment of needs driven by new scientific opportunities

- The BES suite of storage-ring-based light sources is one of the largest and most scientifically productive complex of user facilities in the world, serving more than 8,500 users each year.
- The Linac Coherent Light Source at SLAC, the first hard x-ray, linac-based light source, will be added to this complex in FY 2009. It will be fully operational a year or two later.
- The National Synchrotron Light Source – II at BNL, an advanced ultra bright storage-ring-based light source, will be added to the complex a few years later, in approximately 2015.
- By 2015, with LCLS and NSLS-II newly operating, the youngest of today's BES light sources will be approaching its 20th birthday. Now is the time for DOE and the scientific community to begin the process of strategic planning for the 21st century light sources that will be as impactful as today's light sources and address the scientific needs of the community in the 21st Century.
- The scientific opportunities and mission needs – as developed over the past five years in ten Basic Research Needs workshops and in the BESAC Grand Challenges study – are the major drivers for the specifications of new and upgraded light sources.

Ray Orbach September 20, 2007

"Basic Research Needs" Workshops

- **Basic Research Needs to Assure a Secure Energy Future**
  BESAC Workshop, October 21-25, 2002
  The foundation workshop that set the model for the focused workshops that follow.
- **Basic Research Needs for the Hydrogen Economy**
  BES Workshop, May 13-15, 2003
- **Nanoscience Research for Energy Needs**
  BES and the National Nanotechnology Initiative, March 16-18, 2004
- **Basic Research Needs for Solar Energy Utilization**
  BES Workshop, April 18-21, 2005
- **Advanced Computational Materials Science: Application to Fusion and Generation IV Fission Reactors**
  BES, ASCR, FES, and NE Workshop, March 31-April 2, 2004
- **The Path to Sustainable Nuclear Energy: Basic and Applied Research Opportunities for Advanced Fuel Cycles**
  BES, NP, and ASCR Workshop, September 2005
- **Basic Research Needs for Superconductivity**
  BES Workshop, May 8-10, 2006
- **Basic Research Needs for Solid-state Lighting**
  BES Workshop, May 22-24, 2006
- **Basic Research Needs for Advanced Nuclear Energy Systems**
  BES Workshop, July 31-August 3, 2006
- **Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels**
  BES Workshop, October 30-November 1, 2006
- **Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems**
  BES Workshop, February 21-23, 2007
- **Basic Research Needs for Electrical Energy Storage**
  BES Workshop, April 2-5, 2007
- **Basic Research Needs for Materials under Extreme Environments**
  BES Workshop, June 10-14, 2007
- **Basic Research Needs for Catalysis for Energy**
  BES Workshop, August 5-10, 2007

DOE BES Science Grand Challenges

Controlling Matter and Energy; 5 Challenges for Science & the Imagination

1. How do we control materials processes at the level of the electrons?
   Pump-probe time dependent dynamics
2. How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties?
   PLD, photo-chemistry, XRS
3. How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties?
   Pump-probe time dependent dynamics, XRS
4. How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?
   Pump-probe time dependent dynamics, XRS
5. How do we characterize and control matter away -- especially very far away -- from equilibrium?
   Non-linear dynamics, ultra-bright sources

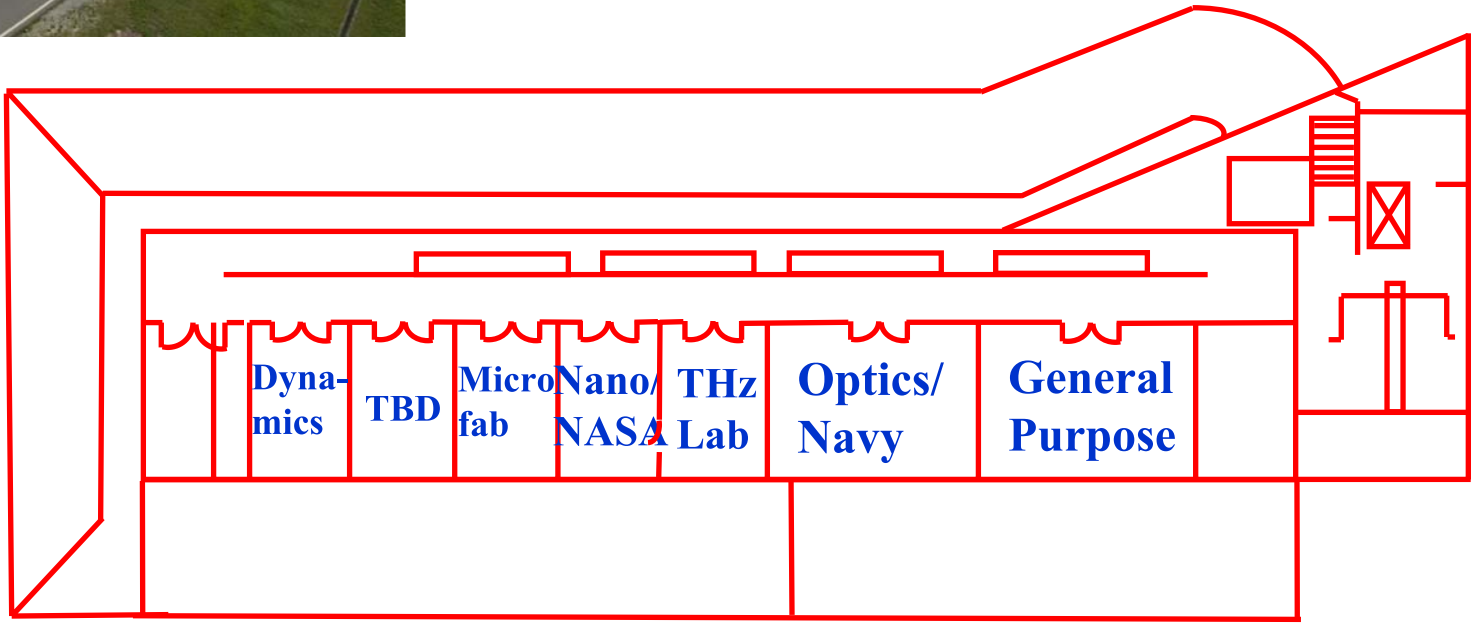
New Report in process - Graham Fleming and Mark Ratner (Chairs).

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light

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



Key Recent User Results from FEL Upgrade

Laser Microengineering Station (Helvajian)

- remote operation over internet

Harvard/Mass. General: differential heating/necrosis of tissue

(R. Anderson)

- very important application to dermatology and potentially heart disease:

NASA-LaRC: carbon nanotube (CNT) production (M. Smith)

- highest production rate (~7 g/hr) of high purity SWCNT using laser ablation, also interesting BN results

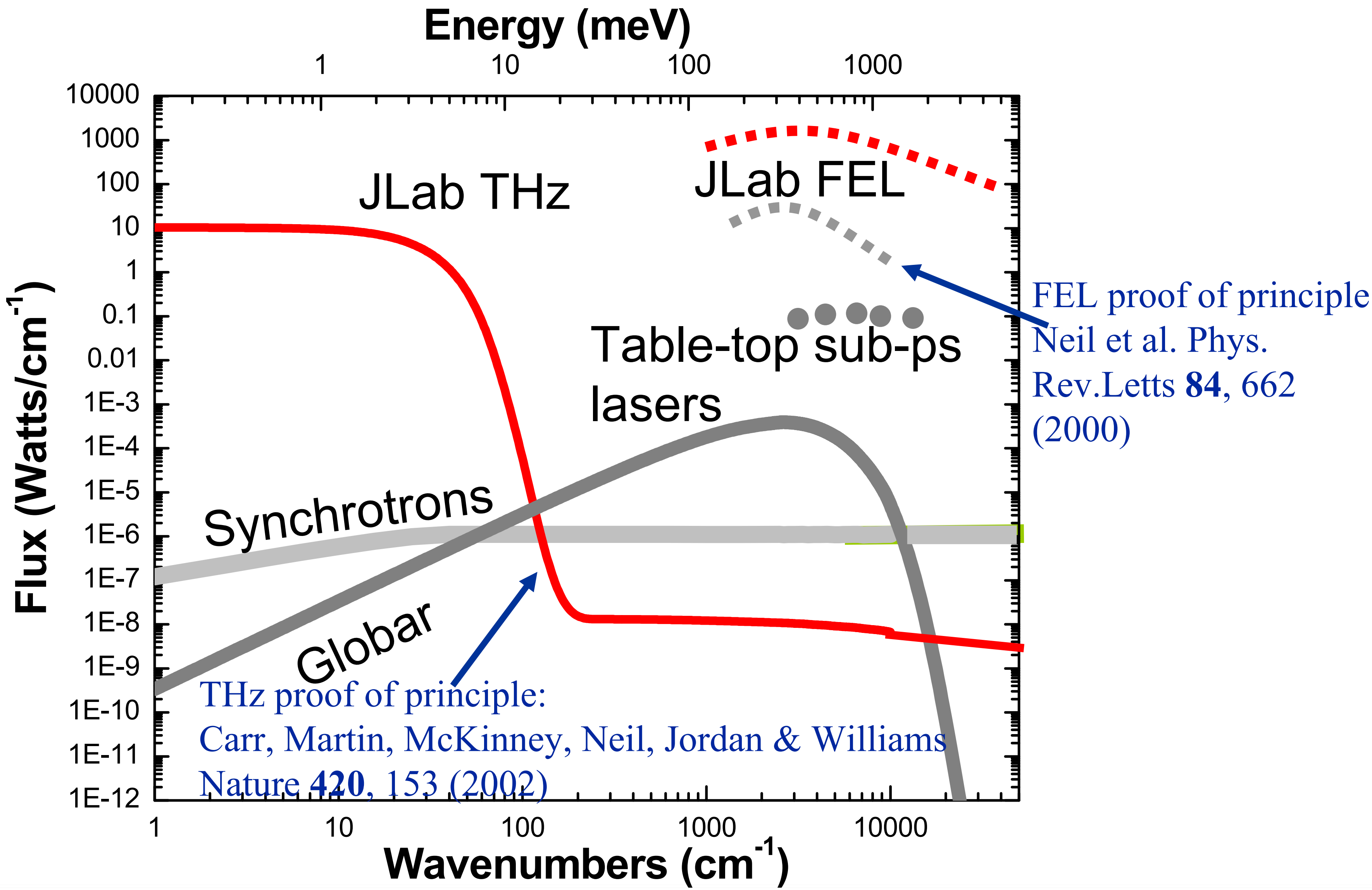
U. Delaware: THz imaging and spectroscopy:

- first THz real time movie

Yale/HU/JLab: Search for light neutral spin zero boson:

- uses tunable high power source with high magnetic field

Jefferson Lab Spectroscopic Range and Power



Specific Niche of Existing JLab FEL

- Wide frequency range (THz $\rightarrow$ IR $\rightarrow$ UV).
- High power per pulse (1 μJ $\rightarrow$ 120 μJ $\rightarrow$ (20 μ J)).
- Rapid tunability (1 – 10 μm in 5 seconds).
- Ultrafast (100 fs – 2 ps).
- Average power capability > table-top (x 1000)
- Supported with numerous other lasers synchronized to the FEL for pump/probe or comparison studies

6 Major Scientific Initiatives for the JLab FEL

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

   Key experiment: - metallic hydrogen.

   Collaborators: Hemley, Mao, Goncharov Carnegie Geophysical Inst.

2. **Relaxation dynamics in solids.**

   Key experiment: – Relaxation dynamics of High Tc selectively pumped out of the superconducting state with the lattice cold.

   Collaborators: Luepke, William 7 Mary; Khodarapast, VT

3. **Strong-Field Atomic and Molecular Physics.**

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

   Collaborators: Jones, UVa; Sukenik, ODU

6 Major Scientific Initiatives for the JLab FEL

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

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

   Collaborators: Sutherland, ECU; Anderson, Harvard & Mass. Gen.

5. High Magnetic Fields as a non-invasive and reversible thermodynamic probe.

   Key experiments: – *Dynamics of giant and colossal magnetoresistive (GMR and CMR) materials.*

   Collaborators: Singleton, LANL, Boebinger, NHMFL.

6. Search for dark matter.

   Key experiment: – *Photon/virtual photon/axion scattering.*

   Collaborator: Keith Baker, Yale U.

The Periodic Table - Hydrogen is a metal

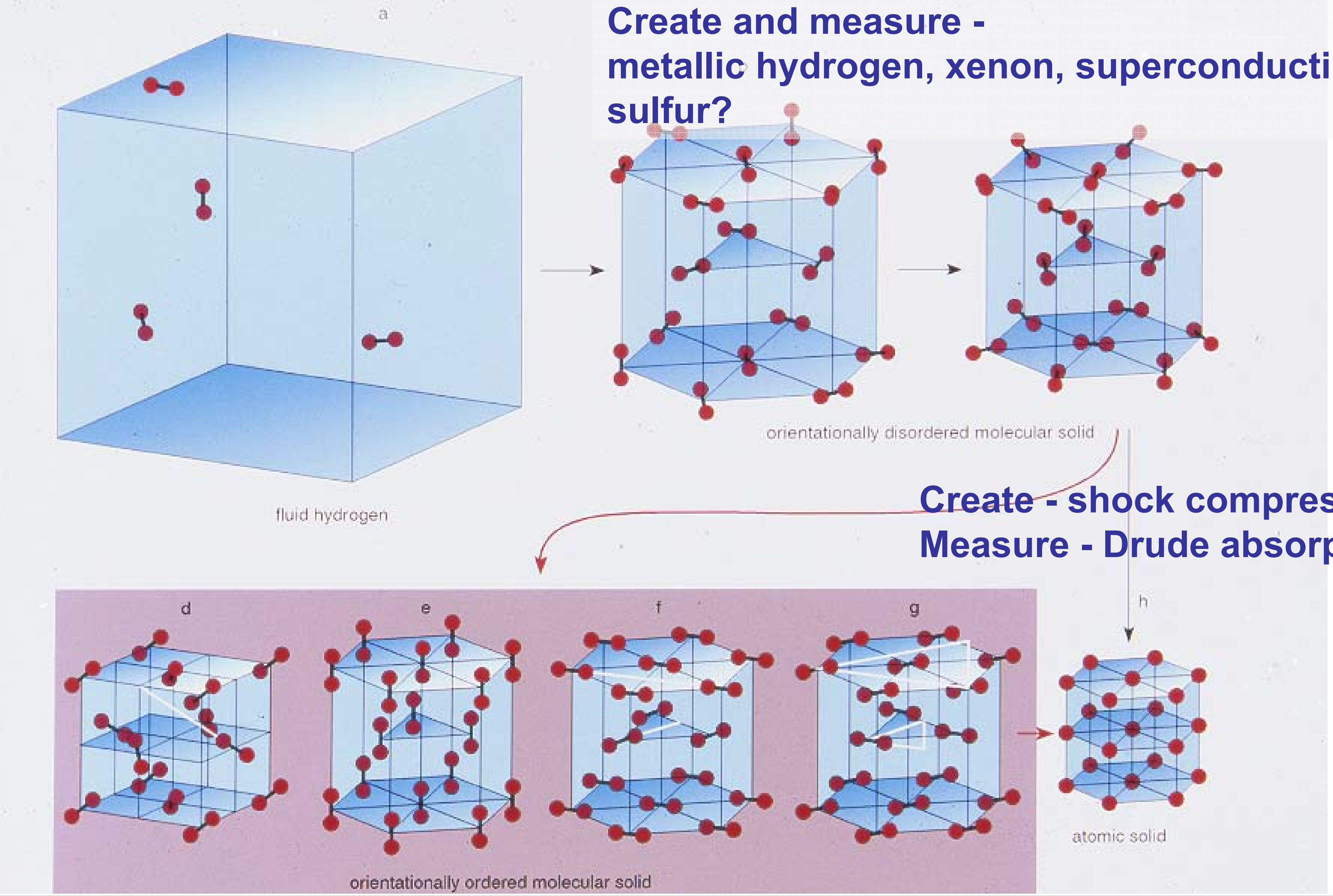
Group / Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 ** Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo

- Non Metals
- Alkali Metals
- Alkaline Metals
- Transition Metals
- Rare Earth Elements
- Noble Gases
- Metalloids
- Halogens
- Other Metals

*Lanthanides	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
**Actinides	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

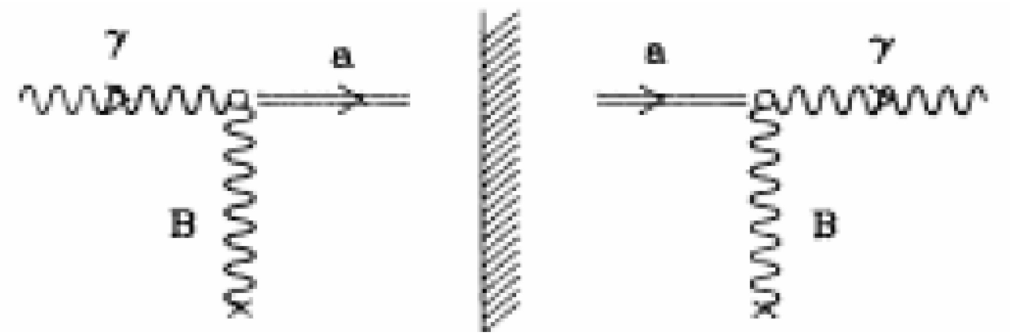
Grand Challenge – matter under extreme conditions

Create and measure -
metallic hydrogen, xenon, superconducting sulfur?



Create - shock compression
Measure - Drude absorption

Create and measure light, neutral, spin-zero Bosons



Light Shining Through Walls

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.

Advantages of FEL

- **High average power**
- **Stable operation**
- **Low-emittance beam**
- **Bunched beam**
- **Coherence between bunches**
- **High polarization**
- **Tunability**
- **Infrastructure**

Courtesy K. Baker, Yale U.

Summary

- JLab has developed Energy Recovering Linac technology for 4th generation light sources.
- Our existing machine with upgrades is
  - a productive technology test bed to determine economic approaches for 4th generation X-rays
  - a productive accelerator physics test bed to determine physics limitations to high brightness and short pulse generation
  - a useful interim facility for basic science studies with <100 fs, high prf, output in the THz, IR, UV and soft X-ray region
- We encourage the involvement of outside researchers to utilize the full potential of the facility although we have been limited by the lack of operation funding

Some of the JLab Team

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