Gregory S. Boebinger
National High Magnetic Field Laboratory

Conceptual Design for "BIG Light"

Proposed Fourth-Generation Light Source:
a Terahertz -to- Infrared Free Electron Laser
at the National High Magnetic Field Laboratory

NATIONAL HIGH MAGNETIC FIELD LABORATORY FSU • UF • LANL

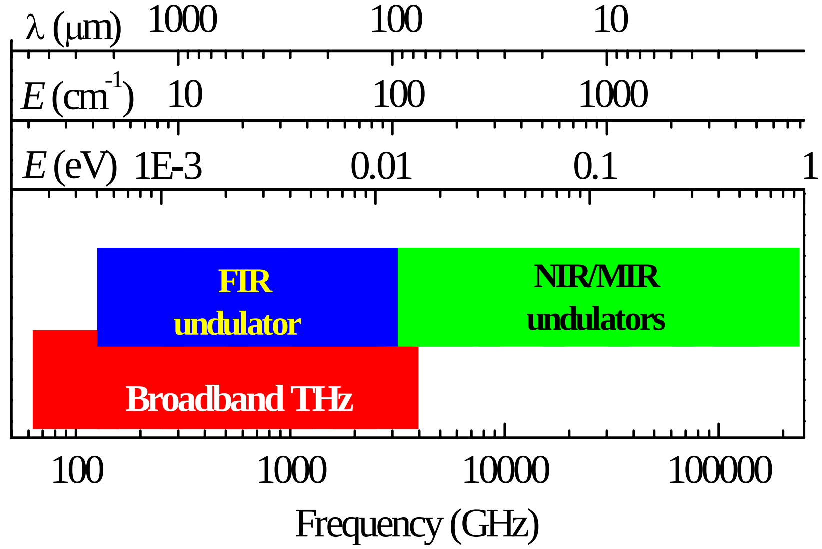
Jefferson Lab

UCSB

NSF

A Fourth Generation Terahertz-to-Infrared Free Electron Laser National User Facility

Three undulators covering 1mm to 1.5 microns



Broadband THz source covering 50GHz to 3 Terahertz

Using Existing JLab Designs to Minimize Risk, Cost, and Time to First Light

$25-30M Cost and Commission BigLight FEL
$10-15M FEL Specific Infrastructure
$ 20M FEL Building

If funded mid-2009, if building ready by mid-2010, then first light in 2012

National High Magnetic Field Laboratory

Multi-site Facilities: Tallahassee FL, Gainesville FL, Los Alamos NM

Multi-disciplinary and Inter-disciplinary Scientific Research

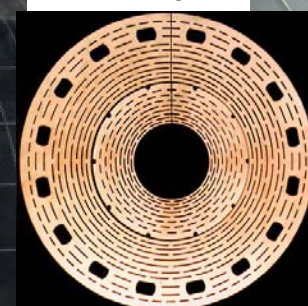
Annual User Program: ~1000 Scientists, ~400 Refereed Publications

www.magnet.fsu.edu

Proposed site for BigLight

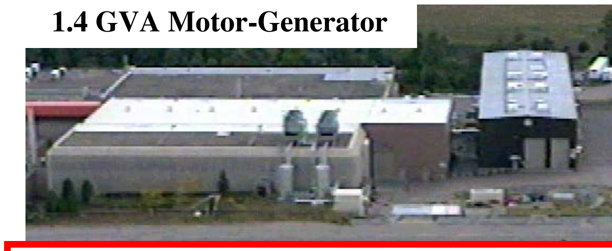
Florida State University

45T Hybrid DC Magnet



900MHz 105mm bore NMR Magnet

1.4 GVA Motor-Generator

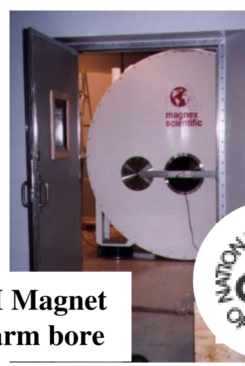


Los Alamos National Laboratory

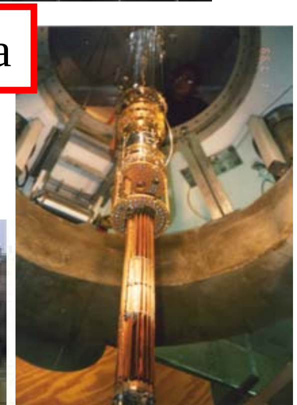
65T Pulse Magnet 15mm bore

University of Florida

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



11.1T MRI Magnet 400mm warm bore



High B/T Facility 17T, 6wks at 1mK

NATIONAL HIGH MAGNETIC FIELD LAB

Five Science Drivers for High Magnetic Field Research

All would benefit from BigLight

Quantum Matter – ***Addressing our limited understanding of strongly interacting quantum systems***

- **Magnetism in Model Systems** *(low-dimension, frustration)*
- **Correlated States** *(High-Tc Superconductivity, Quantum Hall Effect, Bose-Einstein Condensation)*

Complex Fluids – ***Studying nature as it presents itself, complex and unrefined fluids and mixtures***

- **Petroleum** *(pollution reduction, refining sour crude)*
- **Bio-fluids** *(disease markers in urine, blood, cerebro-spinal fluid)*

Structure, Dynamics and Function – ***Exploiting Nuclear and Electron Magnetic Resonance***

- **Condensed Matter Physics** *(nanoscale structure and determining phase diagrams)*
- **Membrane proteins** *(critical for function, yet change morphology if crystallized)*
- **Bio-molecules** *(dynamics and function of metal ions in bio-systems)*

Materials Chemistry – ***Element specific nuclear and electron spins, including Quadrupolar Nuclei***

- **Condensed Matter Technologies** *(glasses, ceramics, catalysts, zeolytes, batteries and fuel cells)*

Materials for Magnets *and* by Magnets –

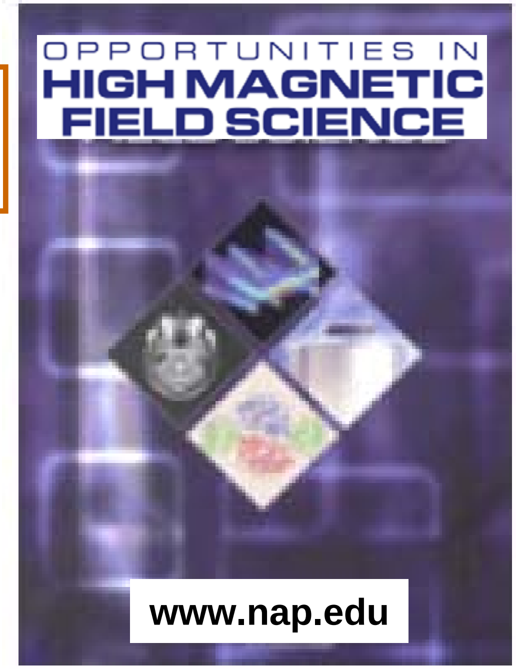
- **Superconductor Revolution** *(High-Tc for 30T and ultra-stable cable-in-conduit designs; Magnesium Diboride for inexpensive, cryo-free MRI to rural areas and the third world)*
- **Manufacturing Magnets** **(***high-strength copper composites, insulators, and structural materials)*
- **Manufacturing in Magnetic Fields** *(high-strength alloys and nano-tube composites)*

Increasing the Scientific Impact of High Magnetic Field Research

PARTNER with NATIONAL LABORATORIES

to marry Magnetic Fields with other Spectroscopies:

Neutrons, X-rays, Infrared, and Terahertz



From scientific and budgetary considerations :

1. **Take the magnets to the…** **Neutrons at the Spallation Neutron Source**
2. **Take the magnets to the…** **X-rays at the Advanced Photon Source**
3. **But bring the Infrared and Terahertz to the Magnets:**

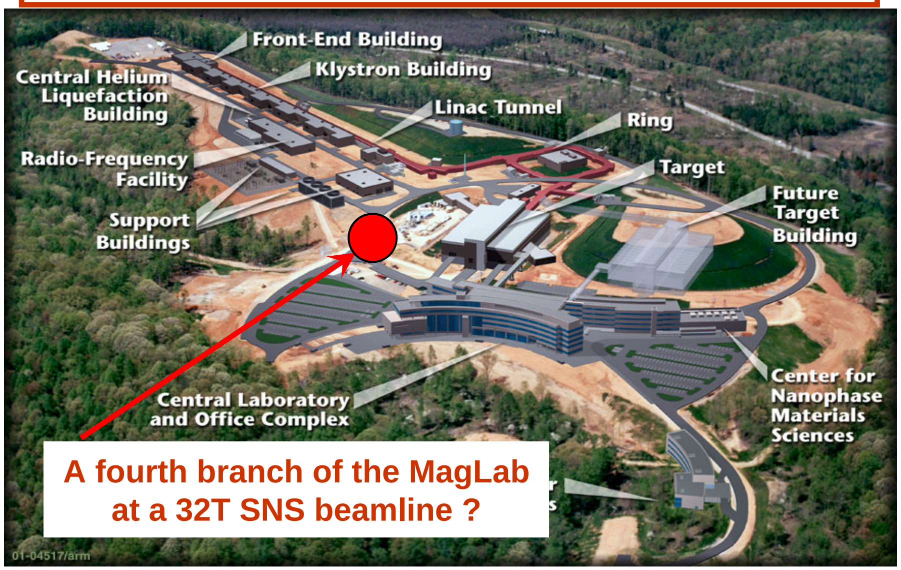
THz-IR Free Electron Laser at the NHMFL

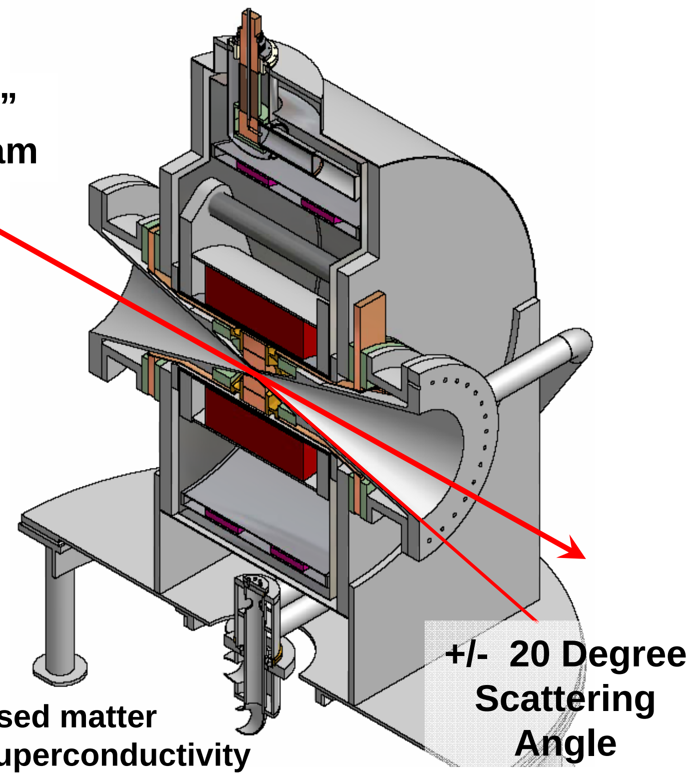
“ZEEMANS” : Ze Extreme Magnetic Neutron Spectrometer

Collaboration with Johns Hopkins and the Spallation Neutron Source

(Design Proposal is Funded…*similar proposal submitted with Hahn-Meitner Institute)*

SERIES CONNECTED HYBRID TECHNOLOGY
x3 lower power than resistive magnets
~32T, 32mm bore, 10MW





Nano-scale Materials Sciences
- Magnetic multilayers…for magnetic field sensors
- Metallurgical nano-structure and macro-properties
- Phase-separation in correlated electron materials

Hard condensed matter
- High Tc Superconductivity
- Vortex matter
- Model magnet systems (1D, 2D, and frustrated 3D)
- Multi-ferroics
- Charge, lattice and spin correlations

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> ***“New instruments for studying the neutron and x-ray scattering properties of materials in high magnetic fields should be developed in the United States.”***
> ***COHMAG, p.5***

SNS SPALLATION NEUTRON SOURCE

NATIONAL HIGH MAGNETIC FIELD LAB

X-rays and Series Connected Hybrids

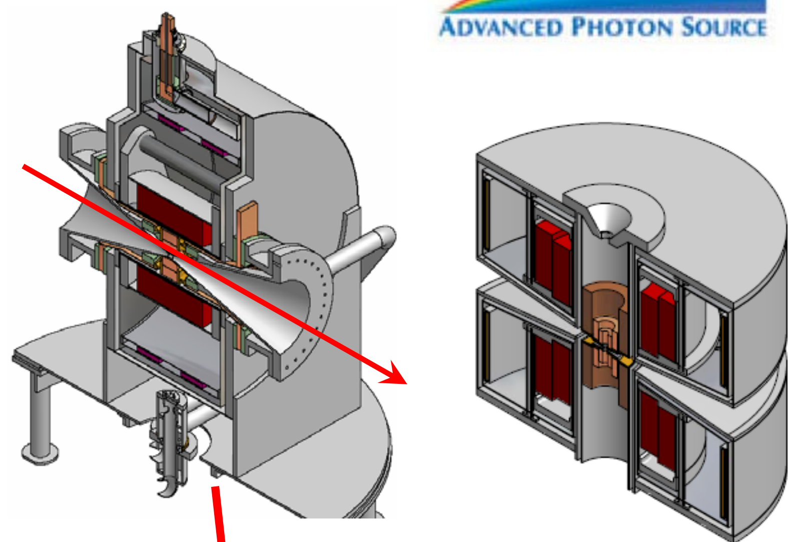
Collaboration with MIT and Advanced Photon Source
(Design Proposal has been Submitted)

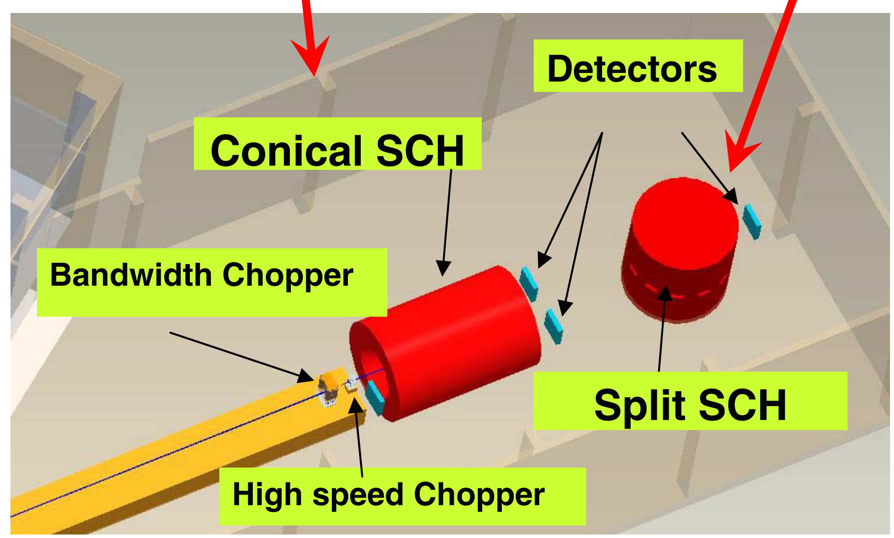
ADVANCED PHOTON SOURCE

SERIES CONNECTED HYBRID TECHNOLOGY

- *Lower power (10MW) than resistive magnets*
- *~30T, 32mm bore*
- *Split magnet (gap at magnet's equatorial plane)*

Possible location for Series Connected Hybrid Magnet(s)



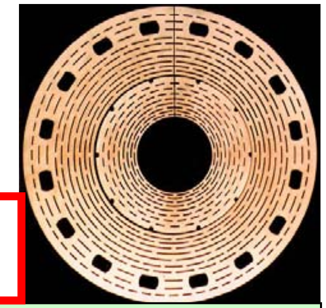


USER PROGRAMS at the MagLab / FSU

Condensed Matter Physics, Materials Research and Engineering, Magnet Engineering, Chemistry, Biochemistry, Biology, Biomedicine

900MHz 105mm Bore NMR Magnet

Florida State University



1

"world's highest steady-field resistive (35 T) and hybrid (45 T) magnets"

4

"highest frequency and largest bore size [NMR/MRI] magnet"

3

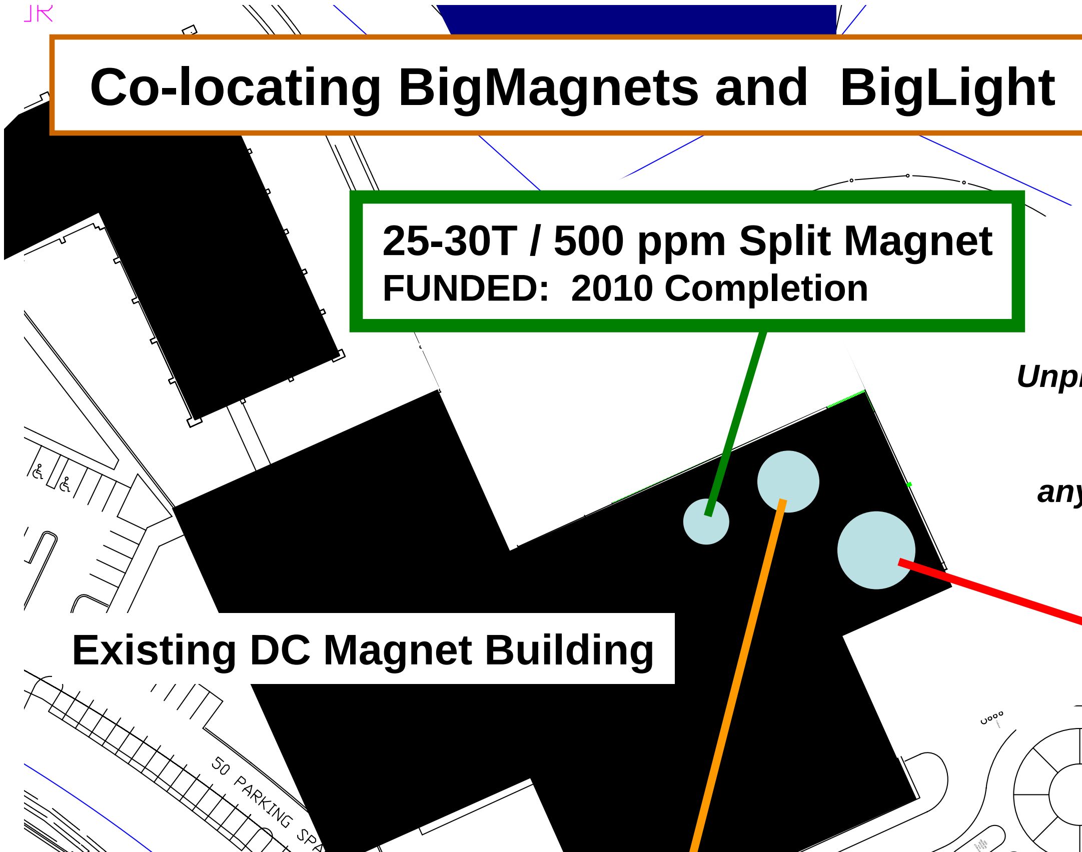
"ICR, where Tallahassee is the world leader"

2

"uniquely high [EMR] frequency of 670 GHz"

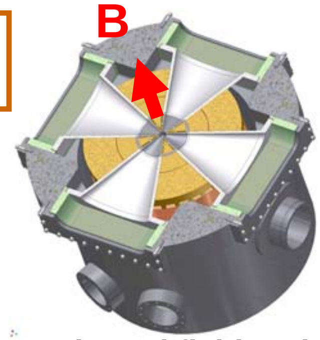
Quotes are from the NHMFL External Advisory Committee, Dec 2006

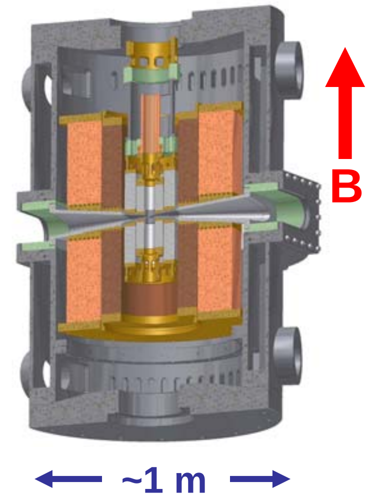
Co-locating BigMagnets and BigLight



25-30T / 500 ppm Split Magnet
FUNDED: 2010 Completion

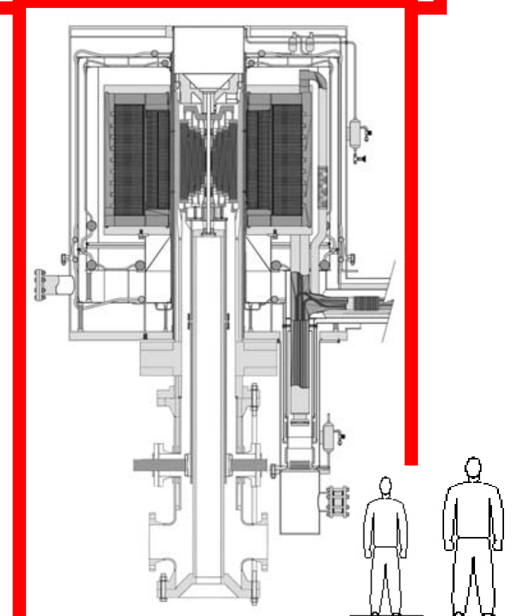
Existing DC Magnet Building





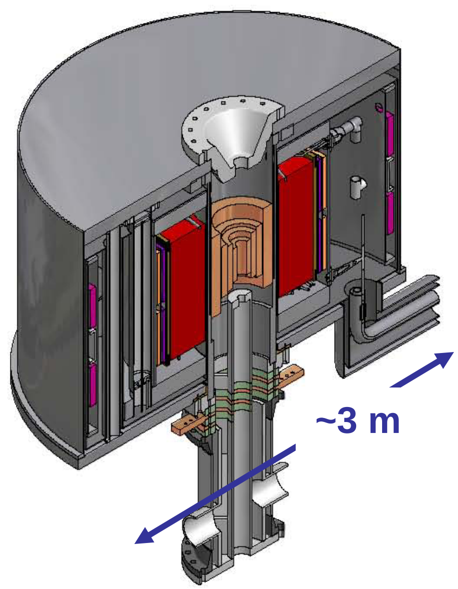
Unprecedented field and access for optical scattering
Four 45° openings : any scattering angle attainable

Existing 45T Hybrid Magnet
Highest DC field world-wide



36T / 1ppm Series Connected Hybrid
FUNDED: 2012 Completion

Unprecedented field and homogeneity for resonance experiments



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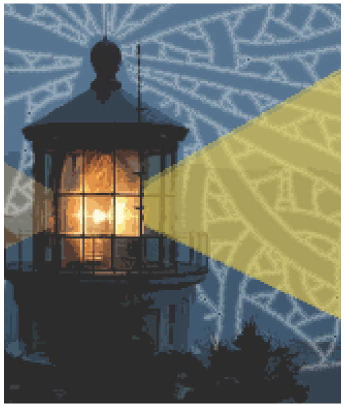


BIG LIGHT:
How did we get here…?

The MagLab / JLab / UCSB collaboration on the "Big Light" Free Electron Laser

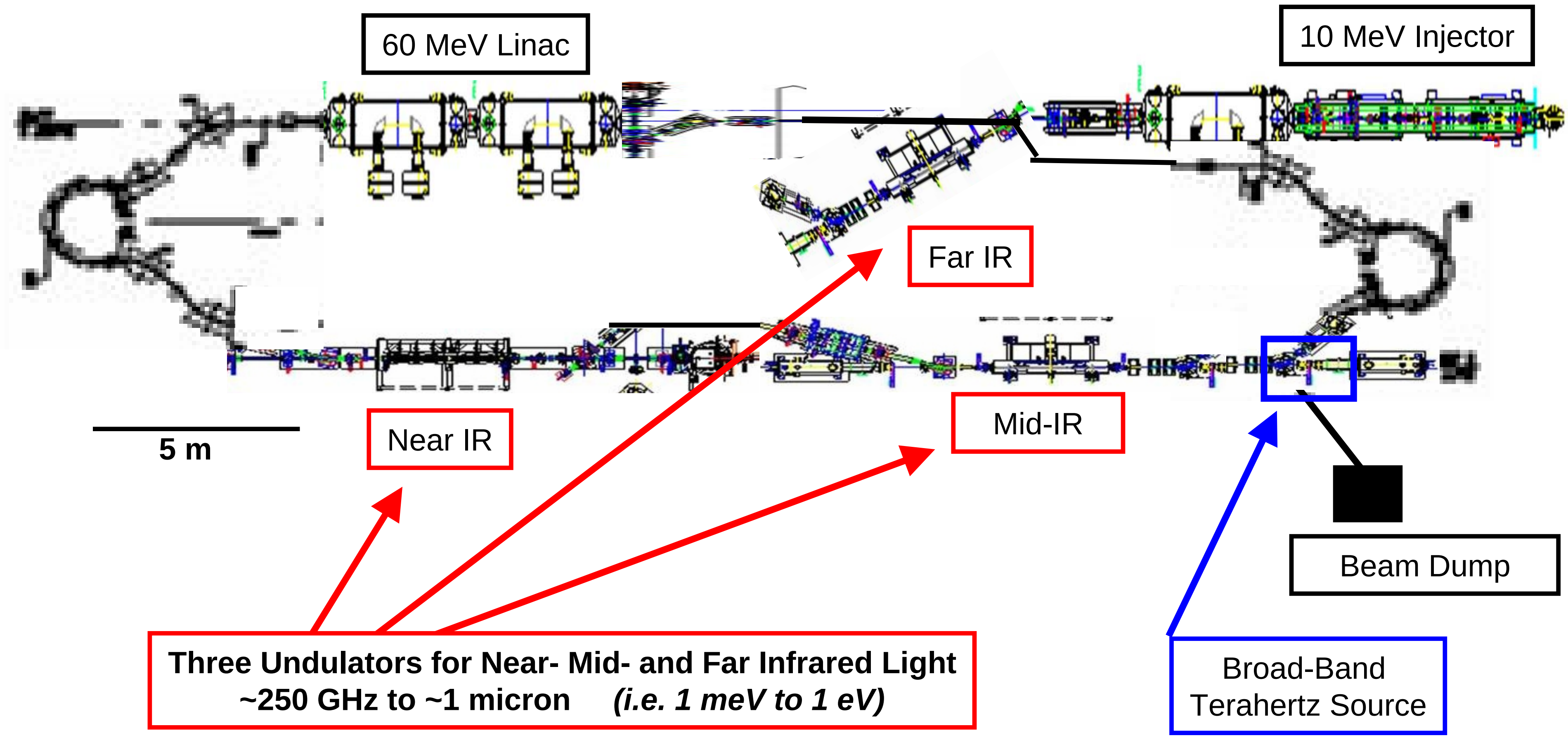
May 2004: First "BigLight" Workshop
July 2005: FEL design proposal funded
Florida State University and National Science Foundation
(no formal commitments for construction at this time)

Late 2006: Endorsement of FEL as part of MagLab Vision
by MagLab Users Committee
by MagLab External Advisory Committee

Jan 2007: NSF Site Visit review of MagLab's 2008-2012 renewal proposal
featured MagLab's highest strategic priorities:
Series Connected Hybrid Magnet
"Big Light" Free Electron Laser
FEL supported by the NSF Site Visit Committee

Presently: BIG LIGHT Conceptual and Engineering Design Completed

MagLab's "Big Light" Source - Initial Draft Layout



NOTE: Near IR, Mid-IR and Broadband THz sources are automatically synchronized
(<20 fsec jitter for pump-probe experiments)

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HIGH MAGNETIC
FIELD LAB

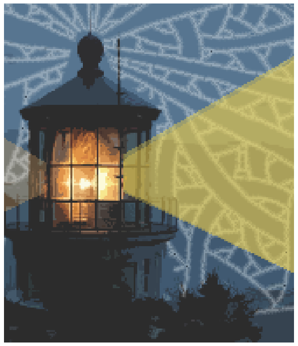
BIG LIGHT

Terahertz-to-Infrared Free Electron Laser National User Facility

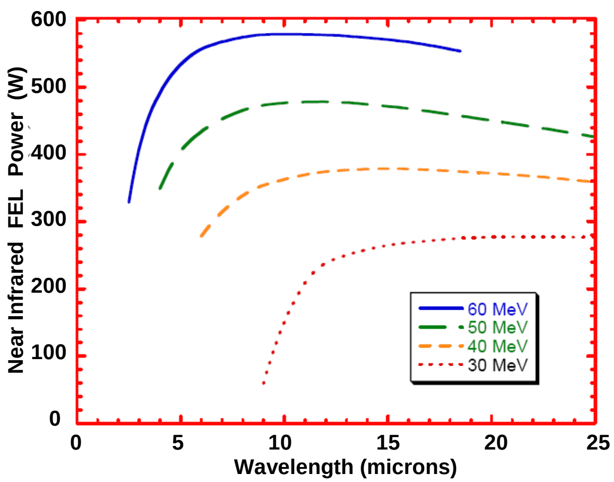
Conceptual Design for "BIG Light"

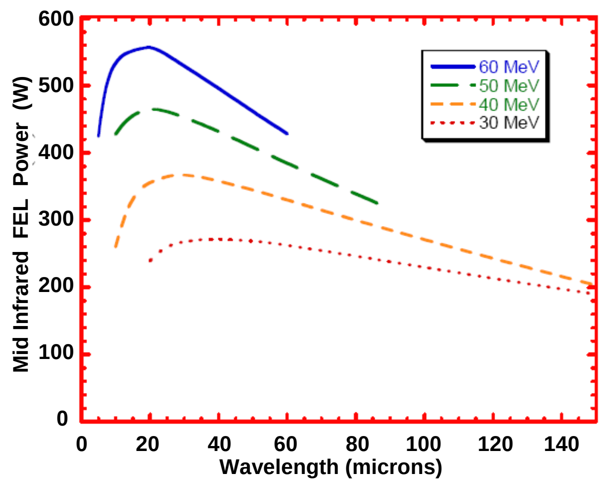
A Proposed Terahertz -to- Infrared Free Electron Laser at the National High Magnetic Field Laboratory

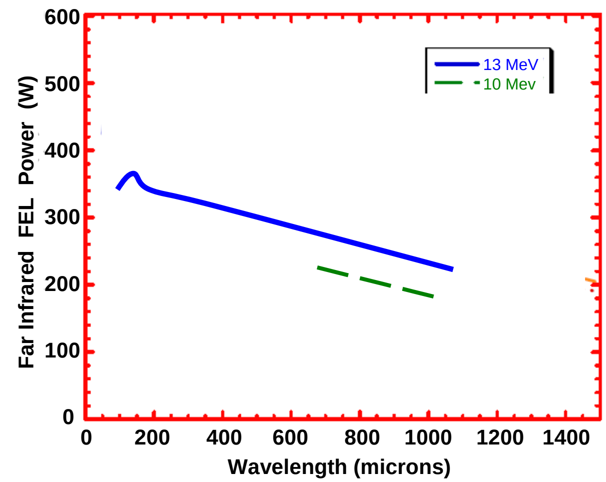
Parameter	NIR FEL	MIR FEL	FIR FEL
Wavelength (µm)	2.5 to 27	8 to >150	100 to 1100
Average Power (W)	> 100	> 100	> 10
Micropulse energy (µJ)	> 10	10	1-6
Micropulse Width (ps)	0.5	0.7	1.6 to 4
Bandwidth	Fourier-Transform Limited	Fourier-Transform Limited	Fourier-Transform Limited
Beam Mode	Annular, Scraper Out-coupled	Annular, Scraper Out-coupled	Variable slot in waveguide; others?
Beam Pulse Rate (MHz)	10.7	10.7	10.7
Macropulse format	100 µs - CW (arbitrary prf)	100 µs - CW (arbitrary prf)	100 µs - CW (arbitrary prf)
e^- Beam Energy (MeV)	≤ 60	≤ 60	7-13
Wiggler Wavelength (mm)	55	100	80
Wiggler K^2	8	9	0.3 to 2
Periods	36	30	40

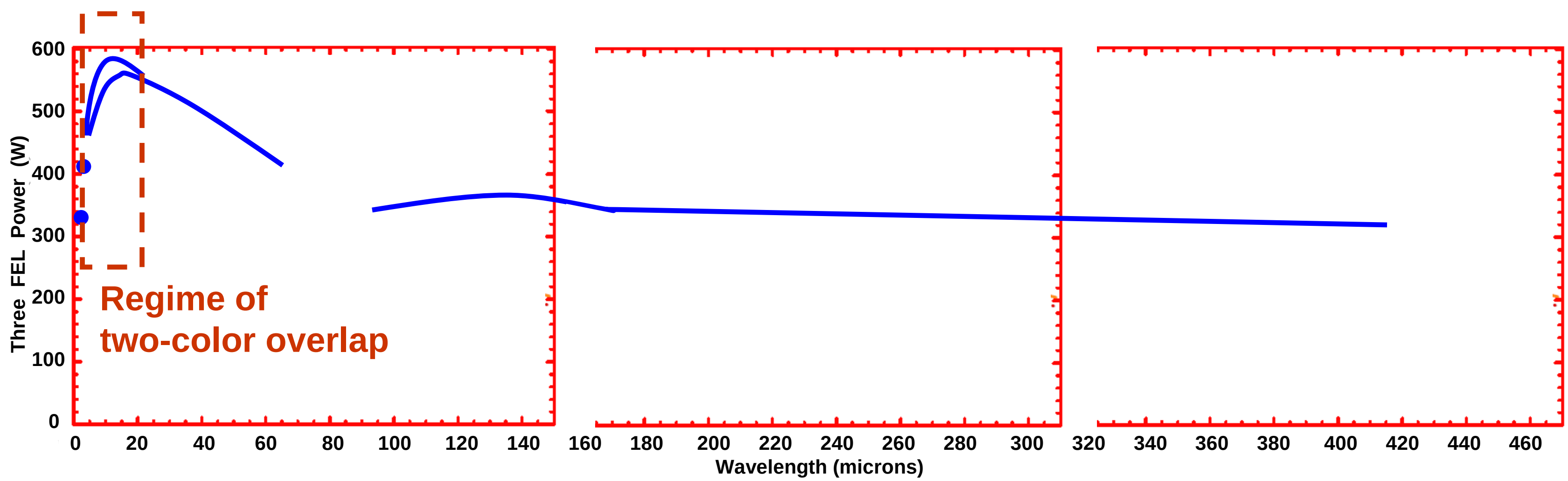


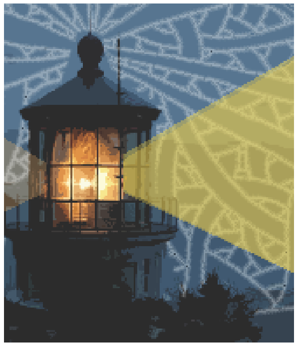
Conceptual Design Completed



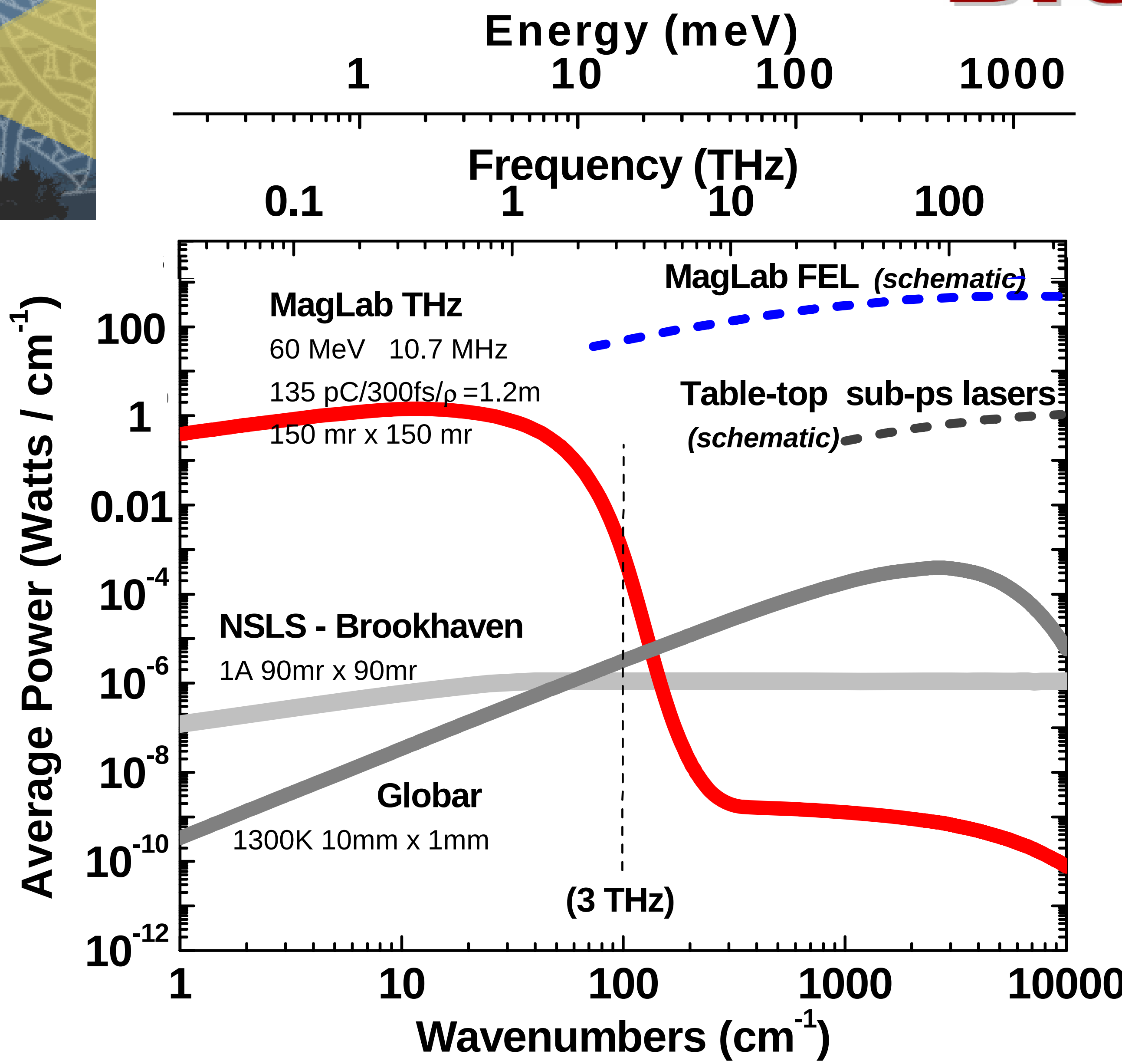








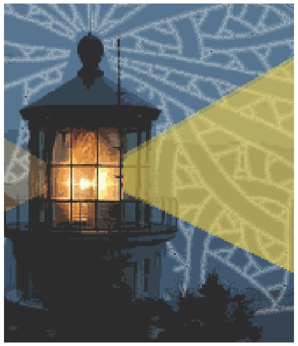
Broadband Terahertz Source

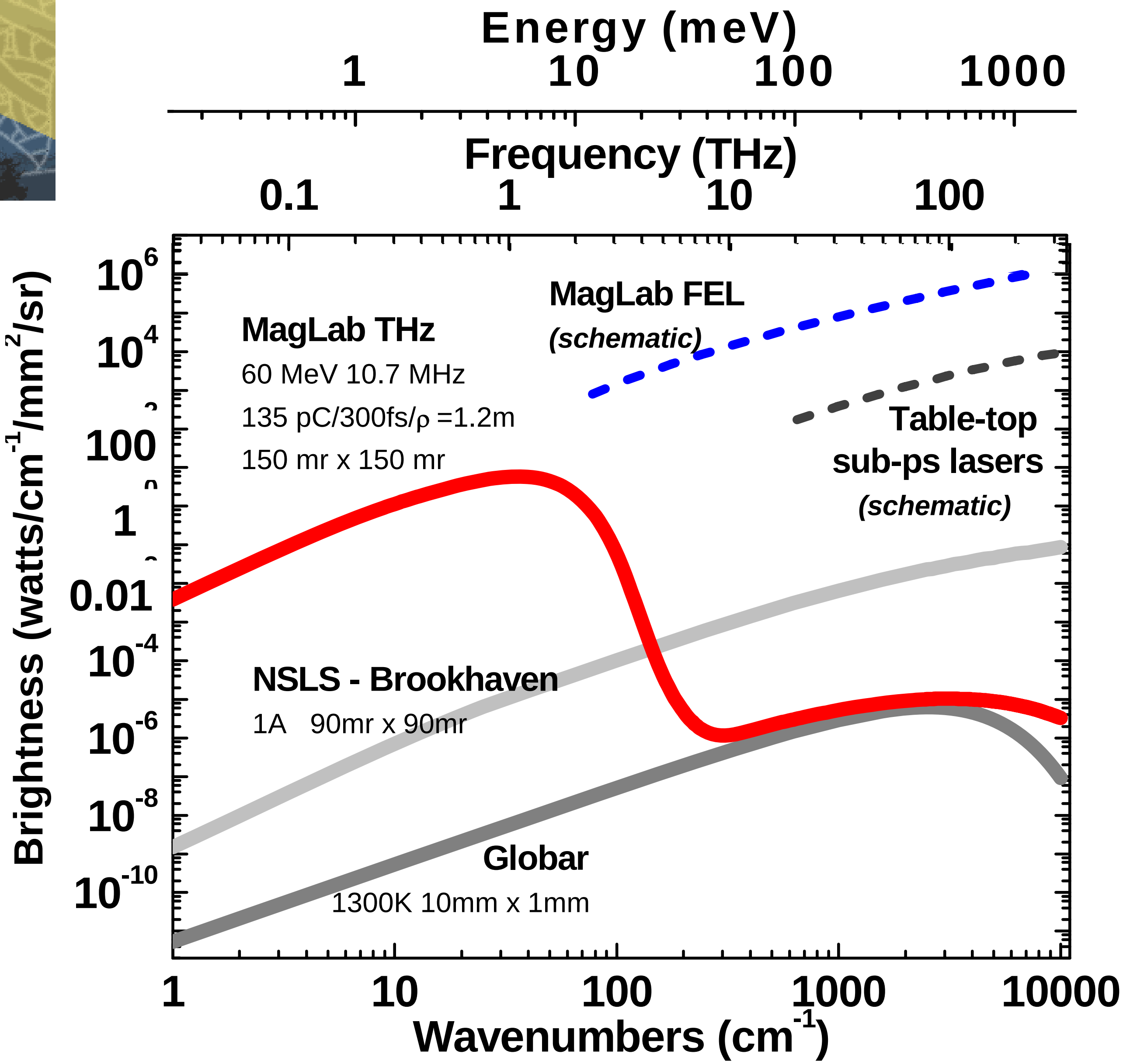


For Peak Power, multiply MagLab by 10,000, multiply NSLS by 20

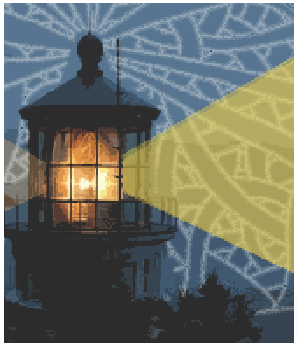
Broadband Terahertz Source

BIG LIGHT



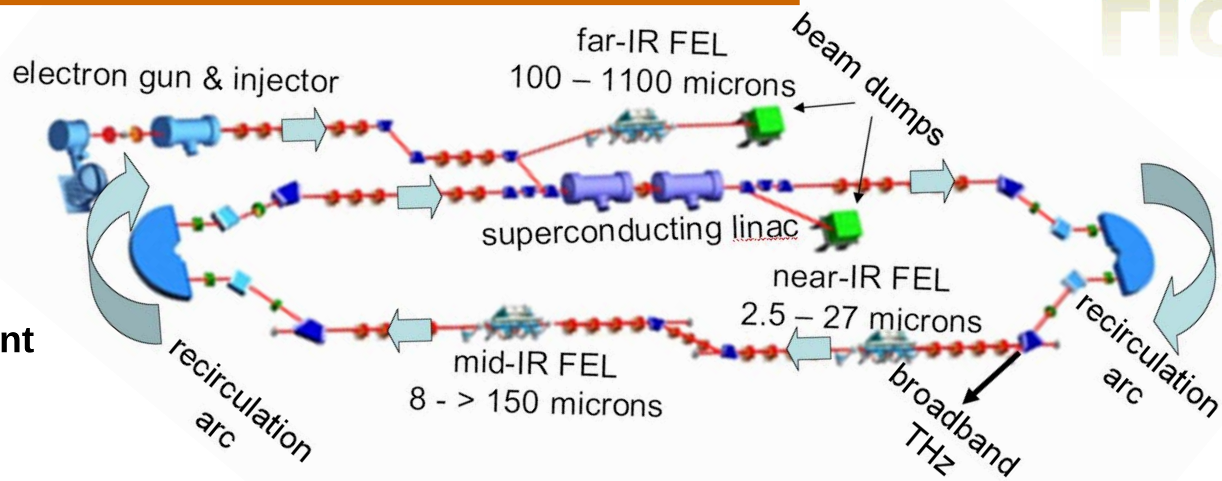


For Peak Brightness, multiply MagLab by 10,000, multiply NSLS by 20

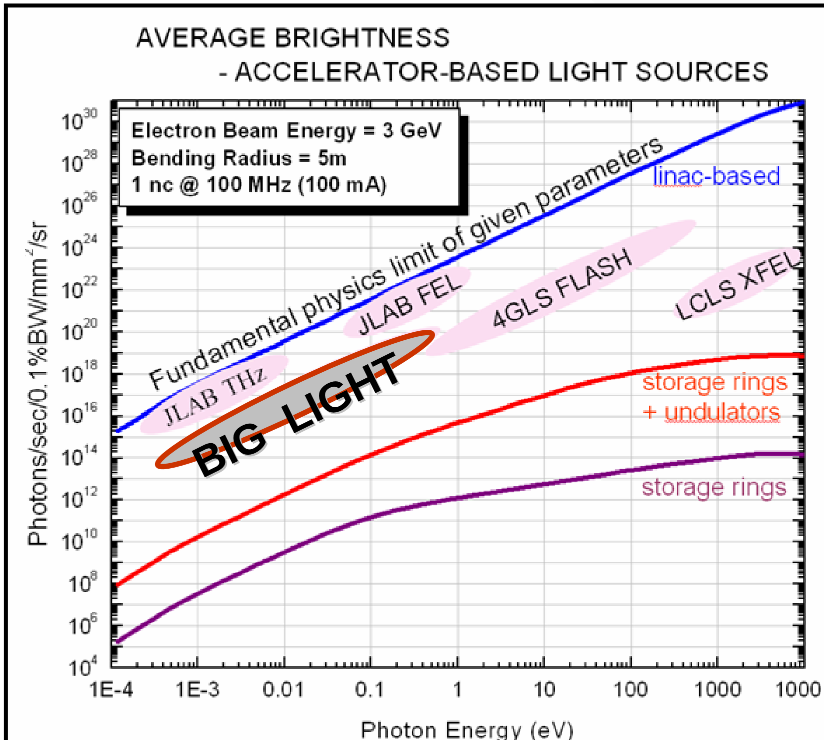


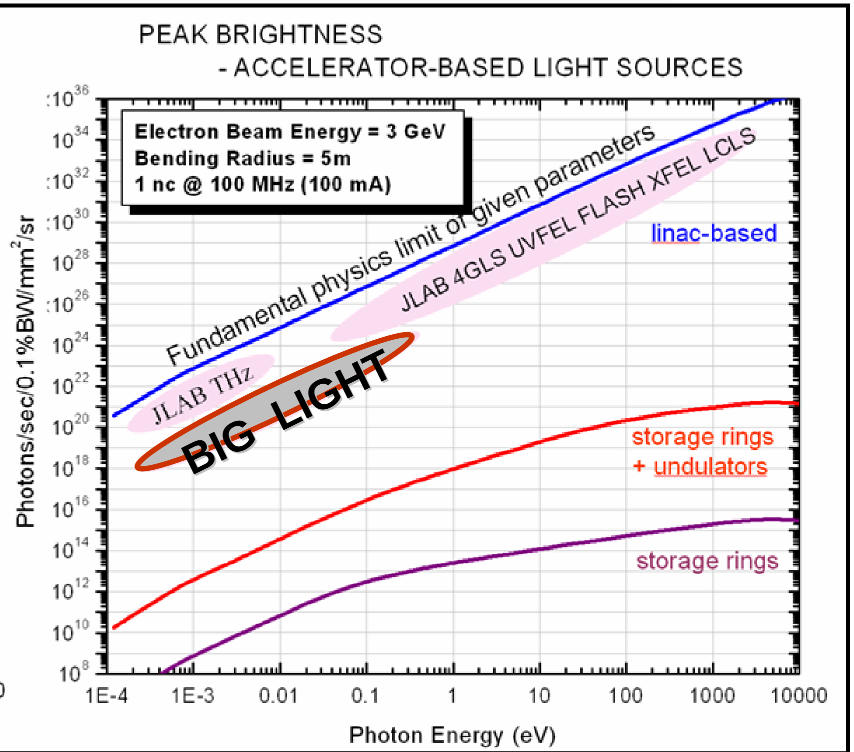
Conceptual Design Completed

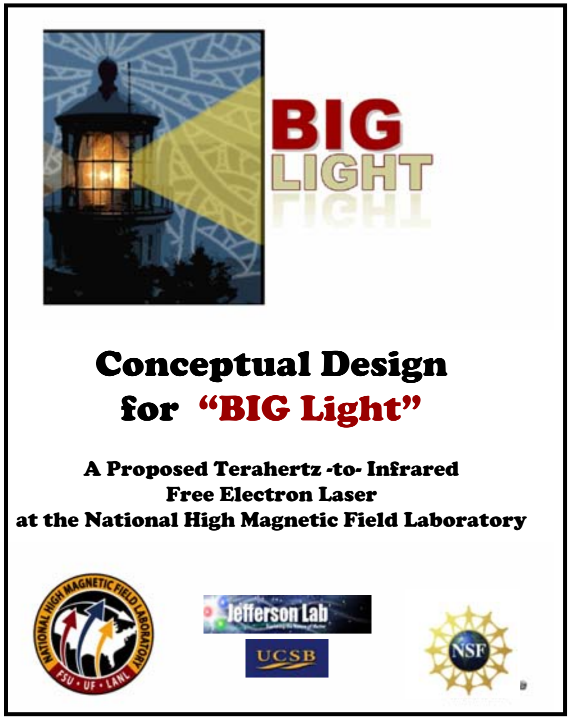
BIG LIGHT



10m x 40m footprint







¤ Using Existing Designs ¤ to Minimize Risk, Minimize Cost, and Minimize Time to First Light

Near-IR similar to JLab IR Upgrade

Mid-IR similar to Australian Light Source

Far-IR is highest risk
(psec pulse, and 100's micron wavelength)

Dipole Magnets

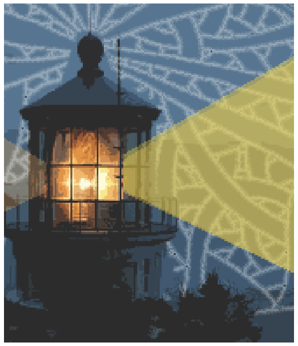
Purpose	Required	Available	Status	
Injection - Low Momentum Bump	9	0	Morph design from GV	¤
Injection - Low Momentum Combiner	2	0	Morph design from GU	¤
Linac/Arc Bend	2	0	Morph design from DX	¤
Arc Reverse Bend	4	0	Morph design from DQ	¤
Pi (180°) Bend - DY	2	2	Available	¤¤
Optical/Arc Bend	2	0	Morph design from GX	¤
Chicane Bend	2	0	Morph design from GW	¤
Total	23			

Focusing Magnets

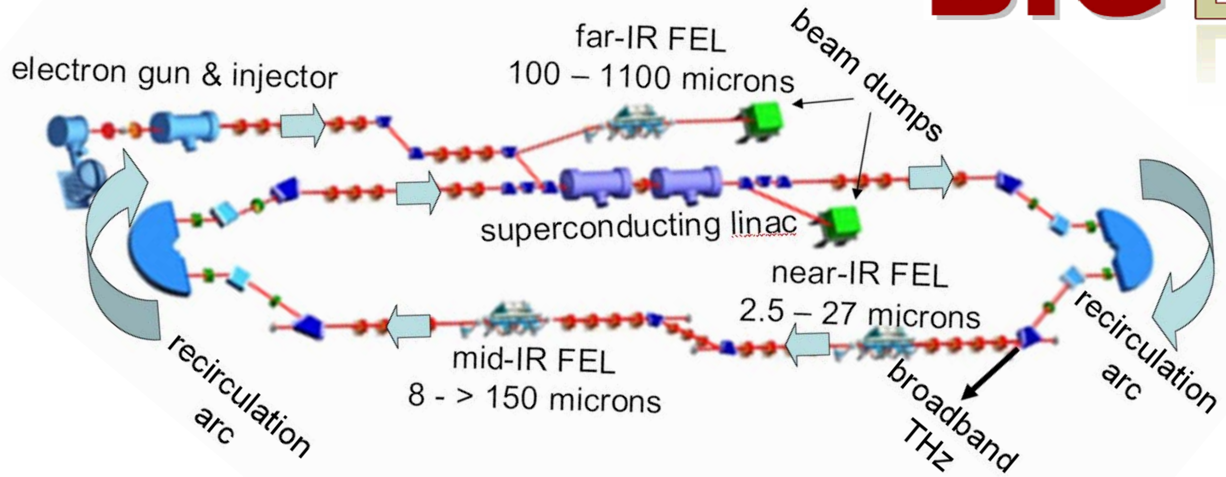
Purpose	Quantity	Required Strength	Status	
Injector Solenoids	2	TBD	Design Needed	
Injector & FIR Panofsky	15	1100 Gauss-cm/cm @ 1 cm R	Design available, QI, 1150 Gauss-cm/cm @ 1 cm R	¤
Dump's Double length Panofsky	4	1100 Gauss-cm/cm @ 1 cm R	Design available, QI, 1150 Gauss-cm/cm @ 1 cm R	¤
Panofsky Trim Quadrupole – Arcs	8	600 Gauss-cm/cm @ 10 cm R	Design available, QH, 661 Gauss-cm/cm @ 10 cm R	¤
Small Diameter Beam Line Quadrupole	14	7500 Gauss-cm/cm @ 1 cm R	Design available, QG, 7330 Gauss-cm/cm @ 1 cm R	¤
Medium Diameter Beam Line Quadrupole	12	7500 Gauss-cm/cm @ 1 cm R	Design available, QX, 10000 Gauss-cm/cm @ 1 cm R	¤
Large Diameter Beam Line Quadrupole	7	7505 Gauss-cm/cm @ 1 cm R	Design Needed	
Sextupole	4	4200 Gauss-cm/cm^2 @ 10 cm R	Design available, SF, 8083 Gauss-cm/cm^2 @ 10 cm R	¤
Total	66			

Correction Dipoles, Skew Quadrupoles, Raster Magnets

Purpose	Required	Available	Status	
Gun & Injector, Haimson Nested Horizontal & Vertical	14	0	Commercial Coils	¤
DH, DB, DJ FEL Beam Line Horizontal & Vertical & Raster	53	0	Design Available	¤
Large FEL Beam Line Style, Horizontal & Vertical	8	0	Design Needed	
Skew Quadrupole	?	0	Design Available	¤
Path Length Corrector System	1 set of 4	1 set of 4	Magnets available	¤¤
Arc Vertical combined with Trim Quad	4	0	Design Needed	
Arc Horizontal combined into DQ Dipoles	4	0	Design Needed	
Total (without Skew Quads)	87			



BIG LIGHT



Accomplishments and Partnerships in BigLight design phase:

MagLab: Electron resonance to 45T and pulsed EPR on C60 qubits
Jefferson Lab: New magnet beamline: actinide molecular complexes, ion dissociation
UCSB Electrostatic FEL: First injection locked (single-mode) operation ***Resulted in $1.75M grant from Keck Foundation***
Brookhaven THz/IR beamlines: Experiments on semiconductors, co-developing optically-pumped EPR
United Kingdom 4GLS: Consult on science and engineering, future BigLight engineering team ?
Netherlands FELIX: Co-developing Ion Cyclotron Resonance using FEL, ICR now relocated to JLab
Korean THz FEL: Plans to test output coupler, dielectric mirrors, high-Q external cavity

Existing Faculty Developing Experimental Techniques

MagLab/UF faculty: Eyler, Hill, Reitze, Tanner
MagLab/FSU faculty: **Brunel,** Dalal, Fajer, **Krzystek, McGill, Smirnov, van Tol, Wang**
Future FEL users: Ardavan, Basov, Kono, Rodgers, **Singleton**

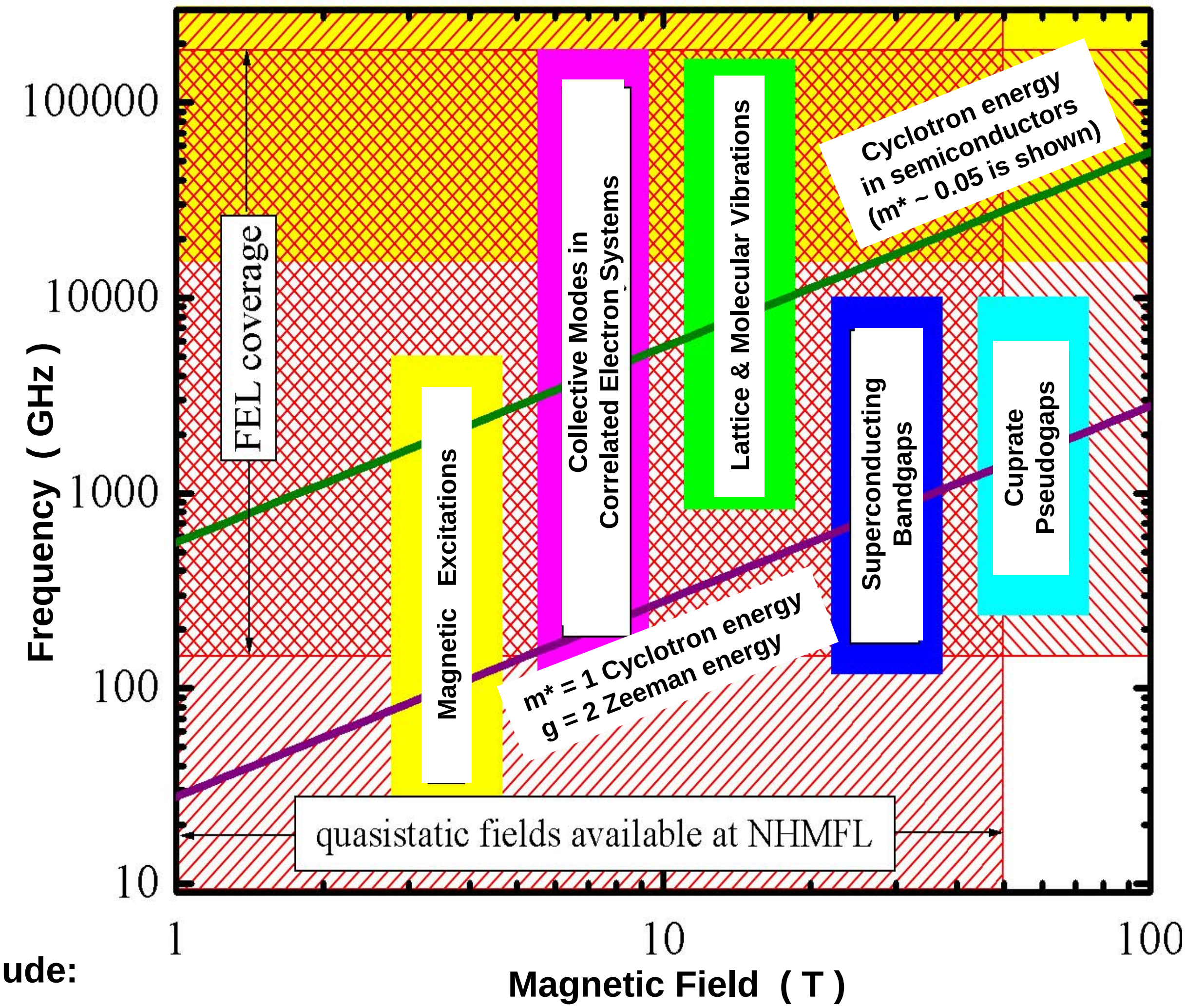
The seven people in ***bigger boldface type*** *already have* ***user support responsibilities***

BIG LIGHT

….at the National High Magnetic Field Laboratory

1. Resonance among BigLight and the MagLab's BigMagnets
($2M-$15M each)

-- 45T Hybrid DC Magnet
-- 25T/20ppm Magnetic Resonance "Keck" Magnet
-- 30T Optical Scattering Split Magnet (2010)
-- 36T/1ppm Series Connected Hybrid Magnet (2011)



Scientific Opportunities include:

A. broadband magneto-spectroscopy

fill the blindspot between infrared and gigahertz to measure continuous spectra
metal-insulator transitions (including f-electron local moment vs delocalization)
scaling of quasiparticle lifetimes near quantum critical points
dither FEL wavelength to remove IR-THz artifacts from geometrical resonances

B. tunable resonance spectroscopy

probe vibrational and electronic excitations in the myriad of m ~ 1 materials*
Kondo resonances in heavy fermions, actinides, nano-structure impurities
low-dimensional magnetism and fluctuations in oxides, superconductors, organics
nanostructures, including spin-charge separation in carbon nanotubes

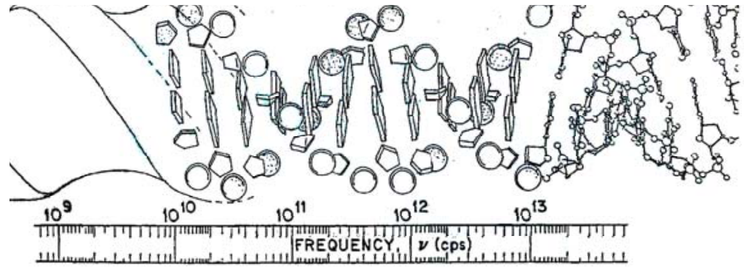
BIG LIGHT

….at the National High Magnetic Field Laboratory

2. Synergy among BigLight and the MagLab's User Programs:

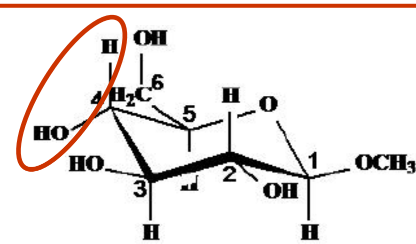
-- DC Magnet: ***Infrared Fourier, Quantum Cascade Lasers, Backward Wave Oscillators***
-- Pulsed Magnet: ***Broadband THz, Gigahertz Network Analyzers***
-- Electron Magnetic Resonance: ***300-700 GHz, time-domain EPR***

Frequency response of DNA ***(courtesy of L.L. Van Zandt, Purdue)***
matches BigLight to study excitations, vibrations and couplings across the entire spectrum using four co-located and time-synchronized sources

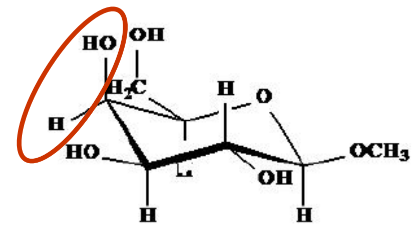


Sub-THz: *relative motion of large molecular components*

Super-*THz: vibration and bond energies of individual atoms and bonds*



Glucose



Galactose

Sugars 'coat' proteins and play a role in cell-cell recognition, e.g. antibodies recognizing antigens
Infra-Red Multi-Photon Dissociation (IRMPD) resolves isomeric structures, because IR absorbed through molecular vibrational modes (not electronic transitions). Hence need a tunable IR source with high *peak* brightness

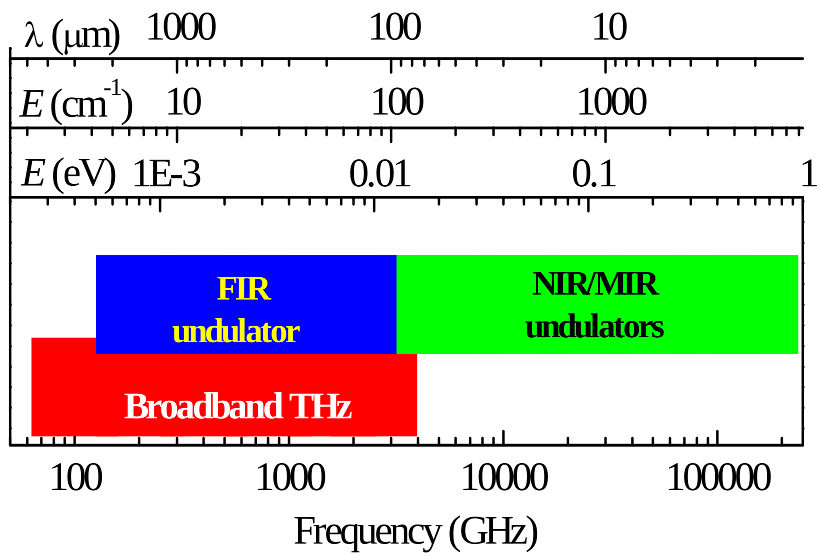
Scientific Opportunities include:

C. time-resolved pump-probe (THz/infrared and infrared/THz)
quantum matter (oxides, metals, semiconductors, superconductors)
molecular magnets, crystal field levels
vibrations, electron and ion transfer, tunable bond-breaking in chemical and biochemical systems
membrane proteins (nerves, viral capsids), metallic-ion proteins (hemoglobin, photosynthesis),
time-domain EPR: mimicking NMR techniques but in THz regime for electrons (e.g. manipulating qubits)

D. nonlinear magneto-spectroscopy
multi photon absorption, optically-induced phase transitions,
disruption of localized states, bandstructure, real-space morphology of bio-molecules

Terahertz-to-Infrared
Free Electron Laser
National User Facility

Three undulators
covering 1mm to 1.5 microns



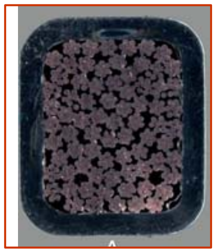
Broadband THz source
covering 50GHz to 3 Terahertz

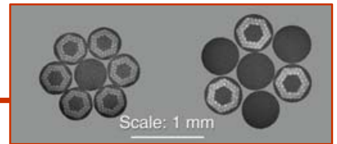
Using Existing JLab Designs
to Minimize Risk, Cost,
and Time to First Light

$25-30M Cost and Commission BigLight FEL
$10-15M FEL Specific Infrastructure
$ 20M FEL Building

If funded mid-2009, if building ready by mid-2010, then first light in 2012

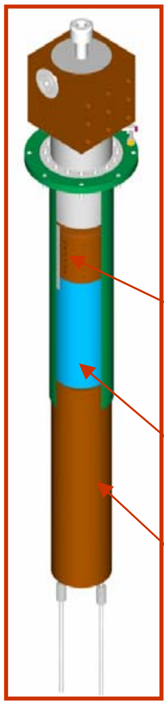
Recent MagLab Technology Advances
Enabled the Series Connected Hybrid Concept





CABLE-in-CONDUIT

Circulates superfluid liquid-He inside the conductor
- **Greater cooling of conductor**
- **Greater stability against quenches**
- **ABILITY TO SCALE CONDUCTOR TO LARGER CROSS-SECTIONS**



HIGH-Tc LEADS

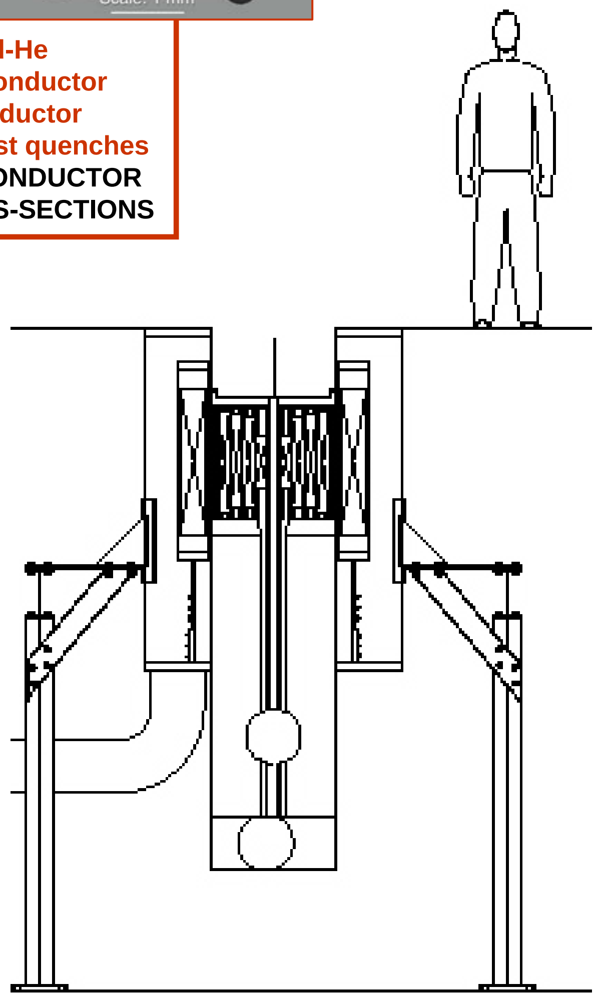
Allow high current through superconducting coil

Reduced helium losses due to Joule heating

Interface block with integral LN_2 reservoir

HTS element with integral shunt

Liquid He reservoir and lower bus (Copper can with superconductor tracing)



The Problem Solved:
How to connect in series
a 20kA Resistive Magnet
and a Superconducting
Outsert Magnet

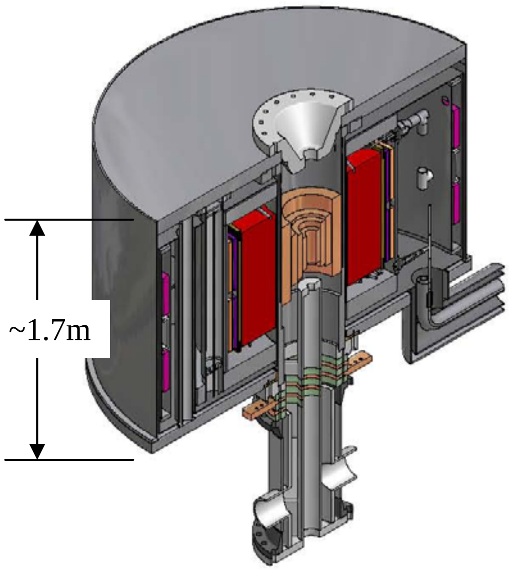
"High Homogeneity" Insert
Magnet specifications
10 MW power consumption
36T central field
40 mm clear bore
~ 1 ppm in 10mm DSV homogeneity

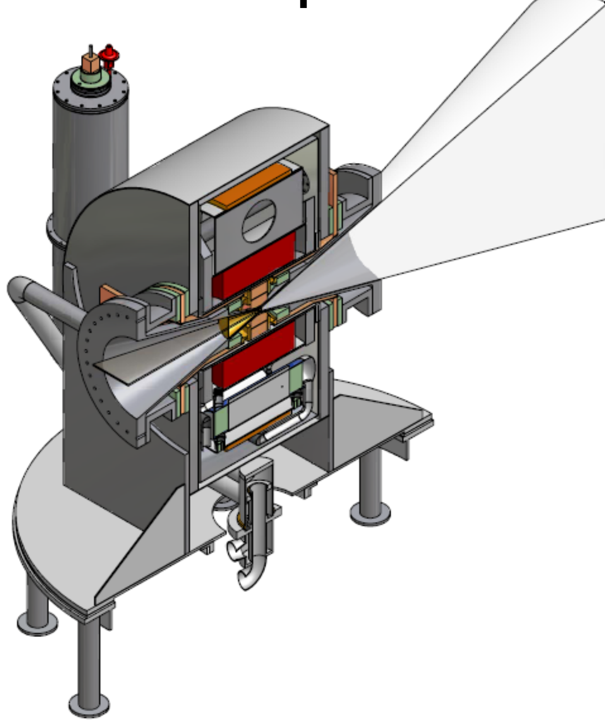
For experiments requiring
- high homogeneity
- high temporal stability
- long times at peak field

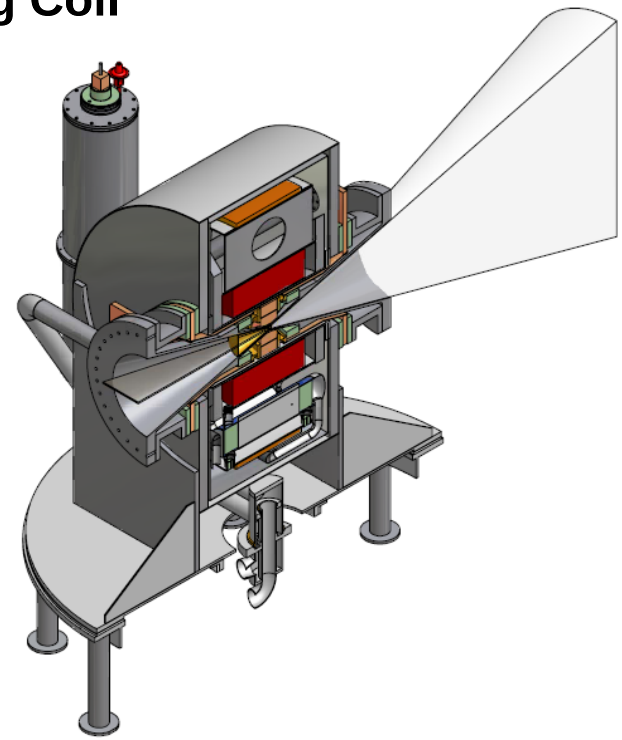
Engineering advantages of SCH:
Reduced engineering required for fault protection
~ 1/3 power of all-resistive magnet
Fits standard resistive-magnet cell
Swap multiple insert magnets
eg 40T "Highest Field" Configuration

Existing Series - Connected Hybrid Magnet Projects

Three Magnets under development using the same Superconducting Coil



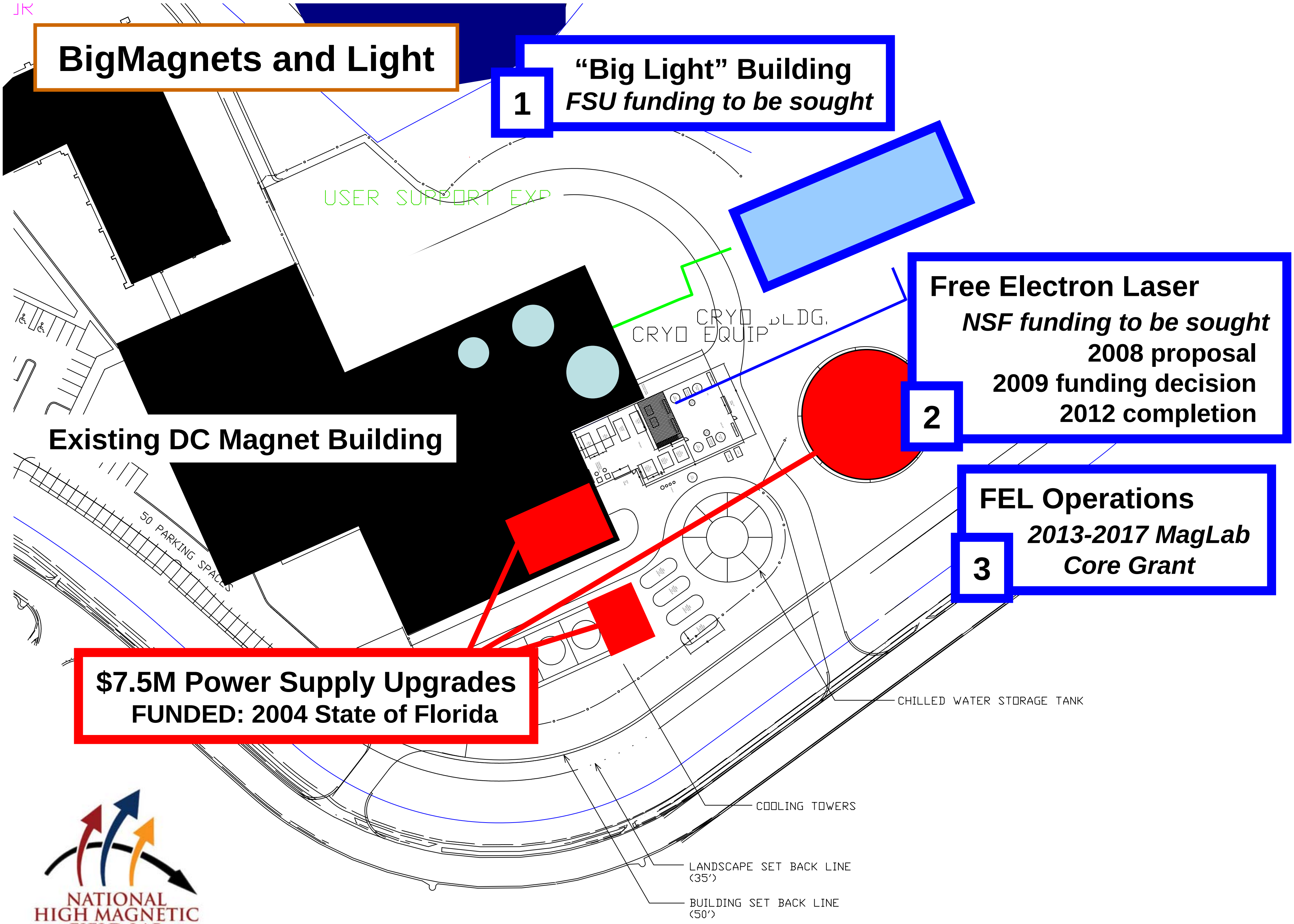




NHMFL
Tallahassee, FL
36T High-Homogeneity and 40T Highest-Field
Construction Funded by NSF

HMI
Berlin, Germany
25-30 T
Neutron Scattering
Construction Funded by Germany

SNS
Oak Ridge, TN
30 T
Neutron Scattering
Design Funded by NSF



NATIONAL
HIGH MAGNETIC
FIELD LAB