Prospects for US Advanced Accelerator R&D After the HEPAP P5 Subpanel Report

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Abstract

An accelerator R&D sub-panel of the US High Energy Physics Advisory Panel (HEPAP) was set up to examine the research portfolio of the current HEP accelerator R&D program, and to identify the most promising research areas to support the advancement of particle physics in synergy with the P5 roadmap for discovery in the field. This presentation will describe the major findings and recommendations issued in the sub-panel report, with emphasis on new accelerator concepts, and will highlight the prospects for advanced accelerator R&D in the US.

This is an overview; many details are included in EAAC contributions

Looking to the Future in US High Energy Physics

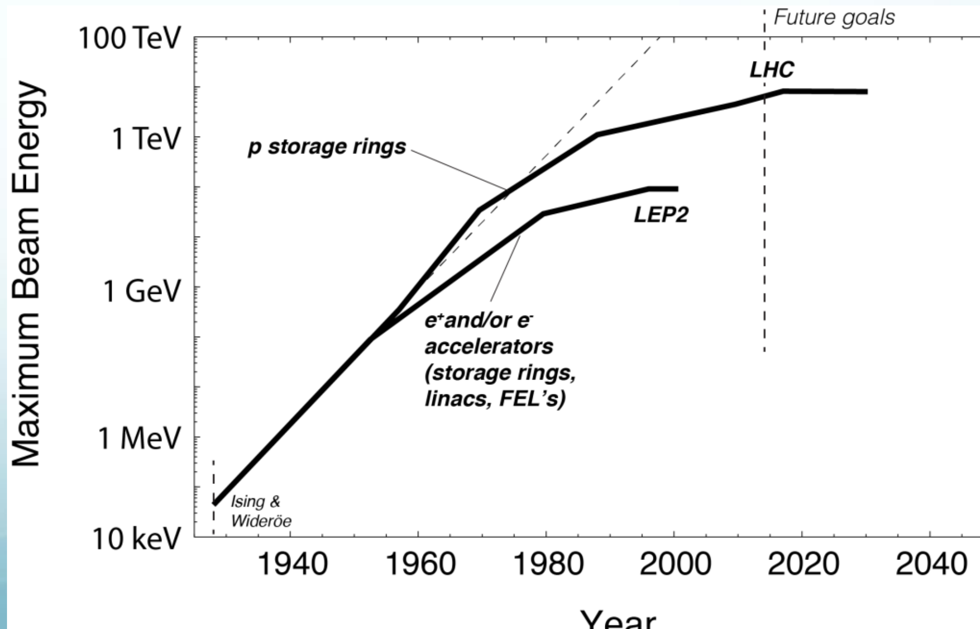
- High Energy Physics Advisory Panel (HEPAP) P5 report: roadmap for particle physics research in the US (2014)
- **Accelerator based** HEP, emphasis on
  - *Intensity Frontier* in US in near term
  - *Energy frontier*: future LC’s at 0.5-3 TeV, VLHC (100 TeV-class)
  - Re-align national **accelerator R&D** towards HEP goals
  - New HEPAP GARD subpanel, report in May 2015
    - Report accepted, implementation underway

Accelerator R&D in the US: HEP-centered

- **Historic legacy**: US accelerator research *mainly* supported by, and dominated by needs of, Department of Energy, High Energy Physics (HEP) Division
- GARD panel examines priorities of DoE HEP Accel R&D
  - "Stewards" of accelerator physics for Office of Science
  - Some in NSF ($10M), very little in other DOE OS offices

Energy is not only concern…
Not cost effective

Look for AA concepts? Explore other experimental pathways…



Guidance from HEPAP P5 Committee

- **Science Drivers**
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Explore unknown: new particles, interactions, and physical principles (e.g. cosmic acceleration, dark energy)
- **Projected startup dates for existing/known projects**
  - LHC: Phase 1 upgrade ~ 2020
  - HiLuminosity-LHC ~ 2025
  - Long Baseline Neutrino Facility (LBNF) ~ mid 2020s
  - International Linear Collider ~ late 2020s
- **Possible future projects (Next Steps and Further Future Accelerators)**
  - Multi-MW proton source, 1 TeV e+e- collider, VLHC, $\geq$ 3 TeV e^+e^- collider, neutrino factory (physics case not yet established)
- **10 years R&D for major project**
- **10 years physics prime era for new physics in project**

Specific Charge to GARD Subpanel

- **Recommendation 26**: *Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.*
- A HEPAP subcommittee on accelerator R&D will provide detailed guidance on the implementation of accelerator R&D aligned with P5 priorities.

Members of P5-GARD Subpanel

Bill Barletta	MIT	Young-Kee Kim	(U of Chicago)
Ilan Ben-Zvi	BNL/Stonybrook •	Tadashi Koseki	KEK/J-PARC
Marty Breidenbach•	SLAC	Geoff Kraft (NP Obs.)	JLAB
Oliver Bruning	CERN	Andy Lankford*• (ex officio)	UC Irvine
Bruce Carlsten*	Los Alamos	Lia Merminga•	TRIUMF
Roger Dixon	Fermilab	James Rosenzweig	UCLA
Steve Gourlay	LBNL	Mike Syphers	MSU
Don Hartill (Chair)	Cornell	Bob Tschirhart*	Fermilab
Georg Hoffstaetter*	Cornell	Rik Yoshida	Argonne
Zhirong Huang (BES Obs.)	SLAC		

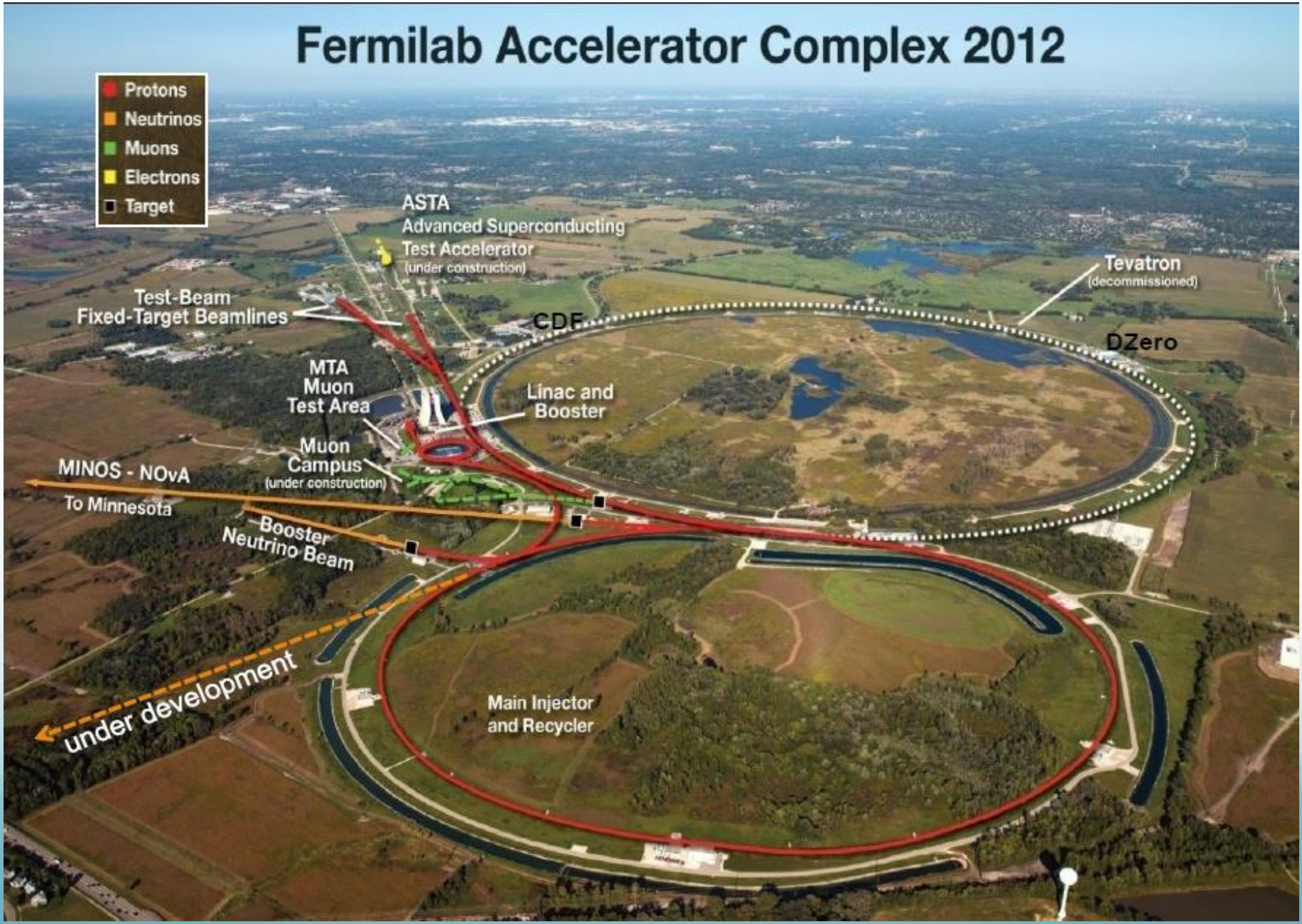
* Members of HEPAP • Members of P5

International membership, national labs, universities
Note nominal representation outside of HEP accelerators

Some background

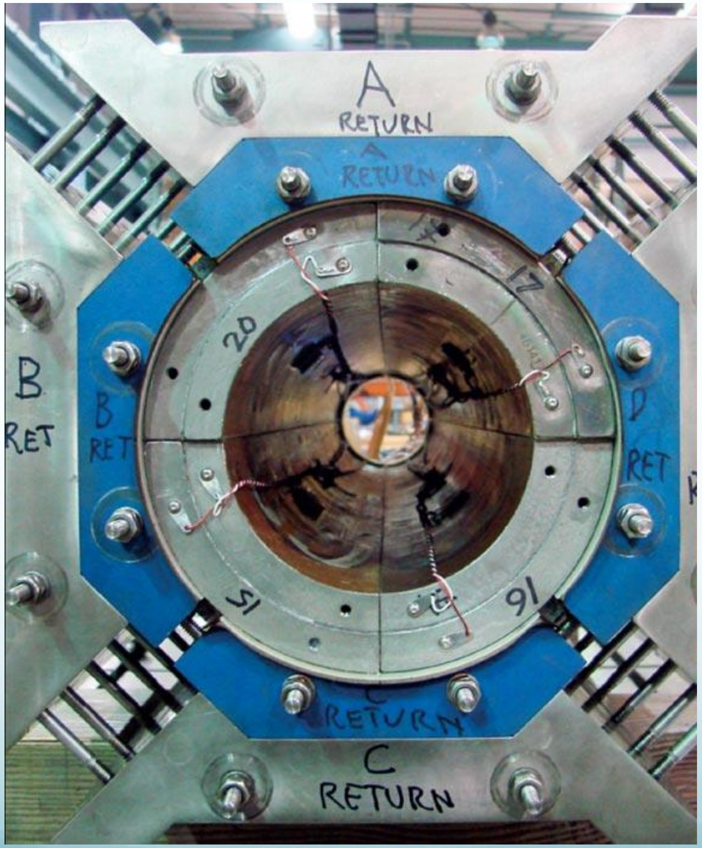
- Current/under construction machines
- High energy physics and non-HEP
  - Light source emphasis
  - Need for accelerator science stewardship…
- Financial implications and boundary conditions

What is after the Tevatron?
-last energy frontier machine in US



US contributions to CERN

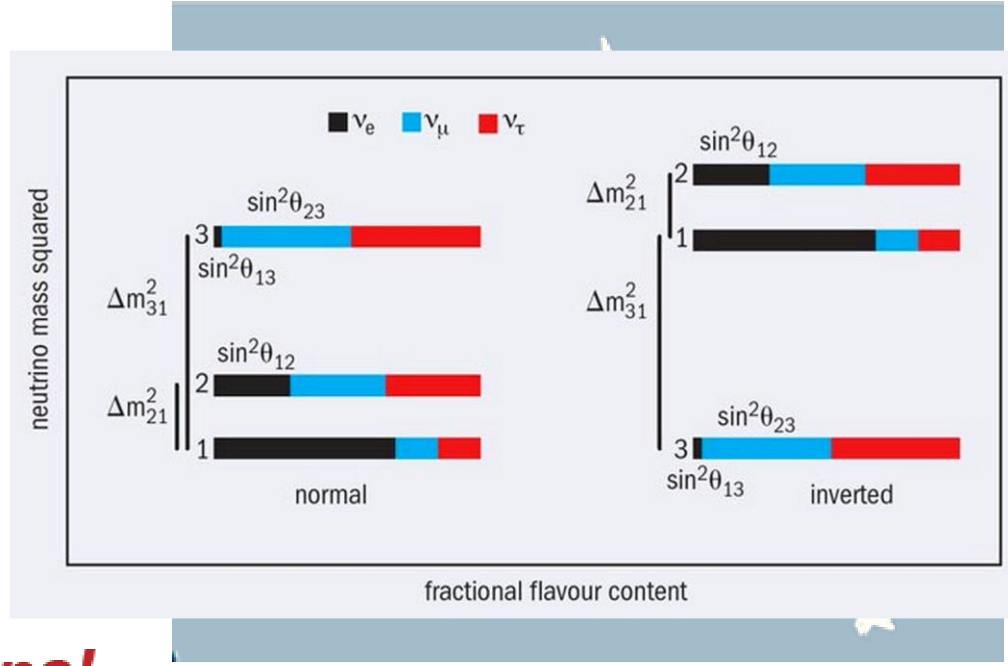
- LARP program in accelerator science (know-how)
- Superconducting magnets (HiLumi upgrade)



Near Future: *Intensity Frontier*

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - MINOS+, NOvA @700 kW
  - LBNF @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities



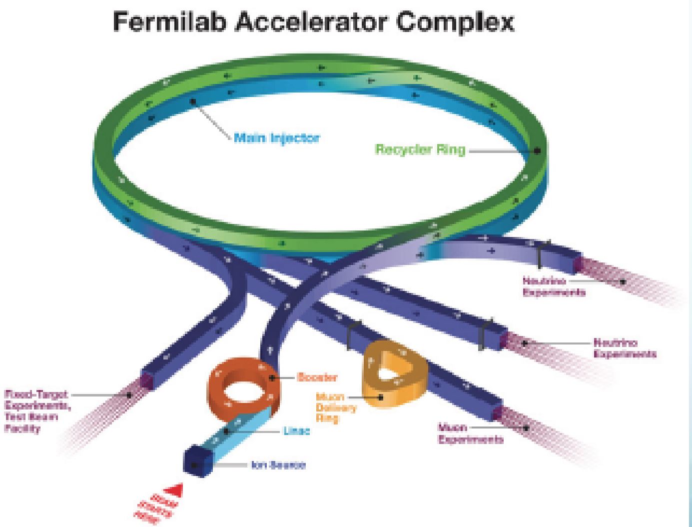
⇒ This requires more protons!

- Proton Improvement Plan II (PIP II)

Fermilab's Present Accelerator Complex

- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability*:
  - Booster: 4.2×10^{12} protons @ 8 GeV @ 7.5 Hz = 40 kW
  - MI: 3.5×10^{13} protons @ 120 GeV @ 0.75 Hz = 500 kW

- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
    - However the RF system is only capable of operating at ~7.5 Hz
  - Booster protons per pulse
    - Limited by space-charge forces at Booster injection, i.e. the linac energy
  - Target systems capacity
    - Limited to ~700 kW by a large number of factors



- Choke points to break through: PIP II

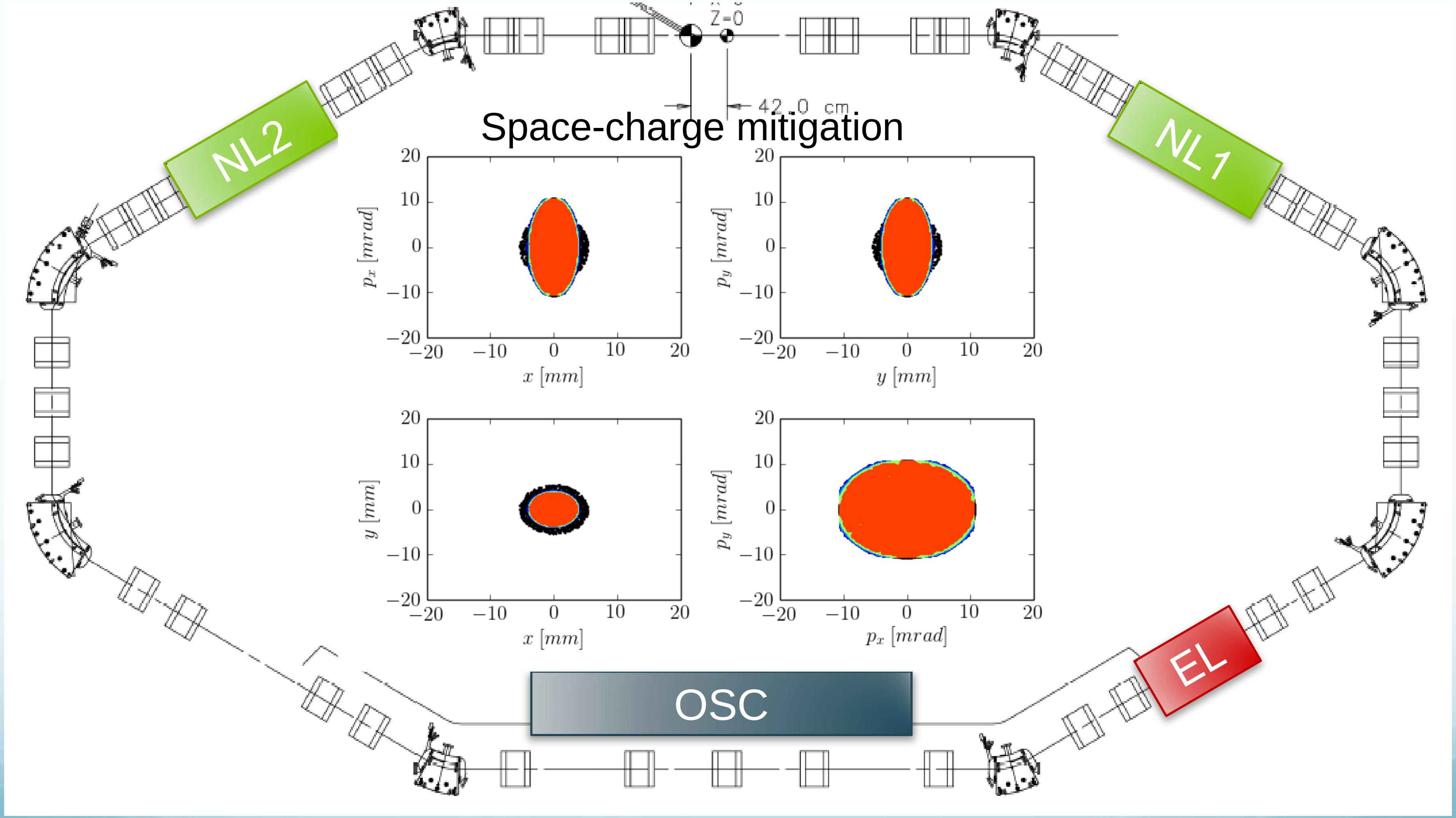
Proton Improvement Plan (PIP)

Central elements: 800 MeV SC pulsed linac, extendable to CW for MW beams @ LBNF. Improve Booster performance

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Beam Power	8	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{12}	
Booster Puls			Hz
Booster Bea			kW
Beam Powe			kW
Main Injecto			
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
LBNF Beam Power @ 120 GeV	0.7	1.2*	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

- **Many high flux fixed target physics specific issues**
- **Linac development is generally applicable**
- **High power rings also applicable for nuclear apps (neutrons, fusion, ATW)**

Example R&D facility IOTA: Test facility for *integrable optics*



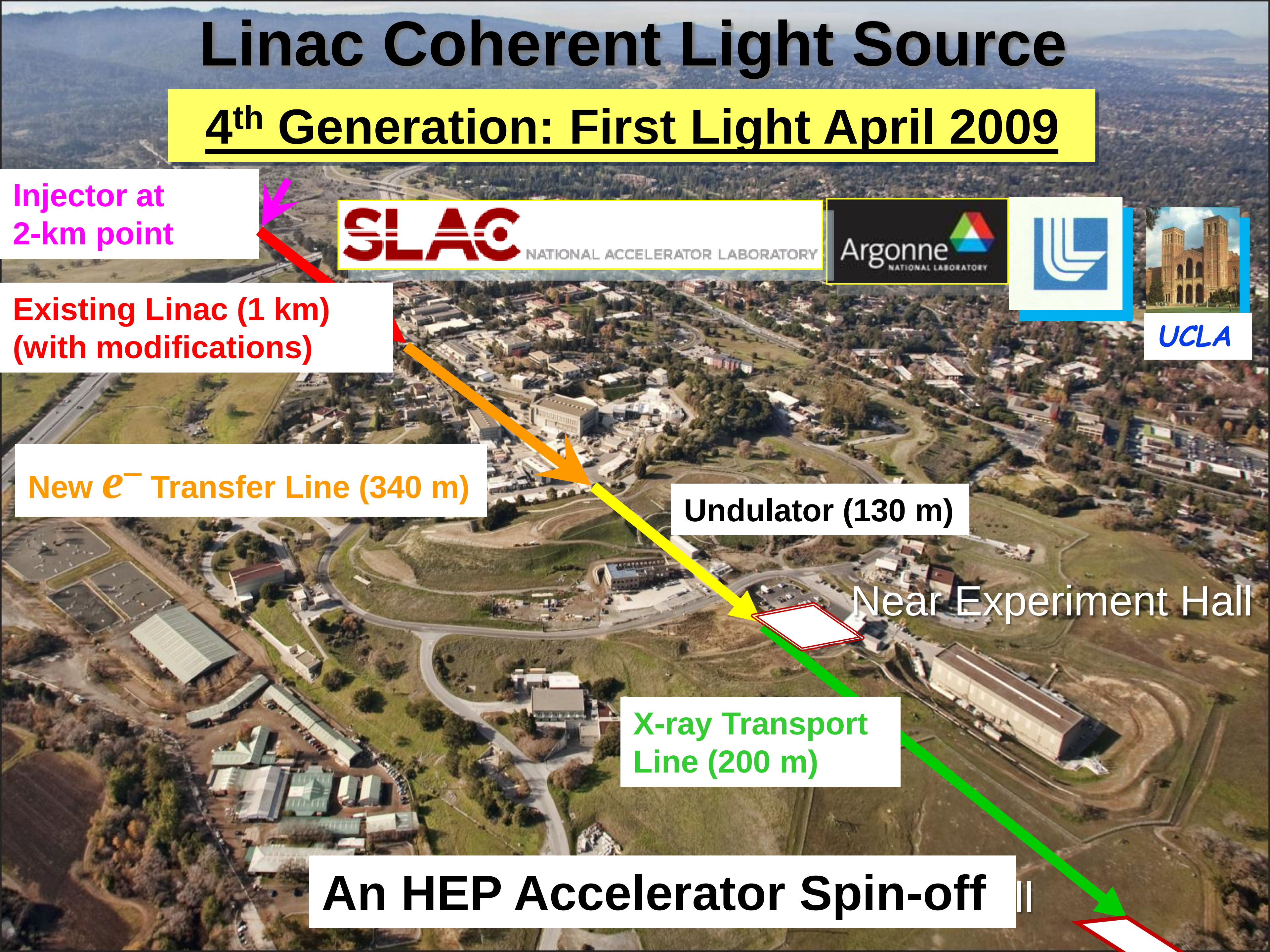
Judicious use of nonlinearities gives integrable system. Employs electron lens

Major non-HEP Emphasis Synchrotron Light Sources

- 3rd Generation synchrotron rings still active
- APS leads current state of art in US.
- NSLS II is latest 3rd generation light source with double bend achromatic lattice plus damping wigglers to produce x-rays with world leading flux and brightness. $1B investment.

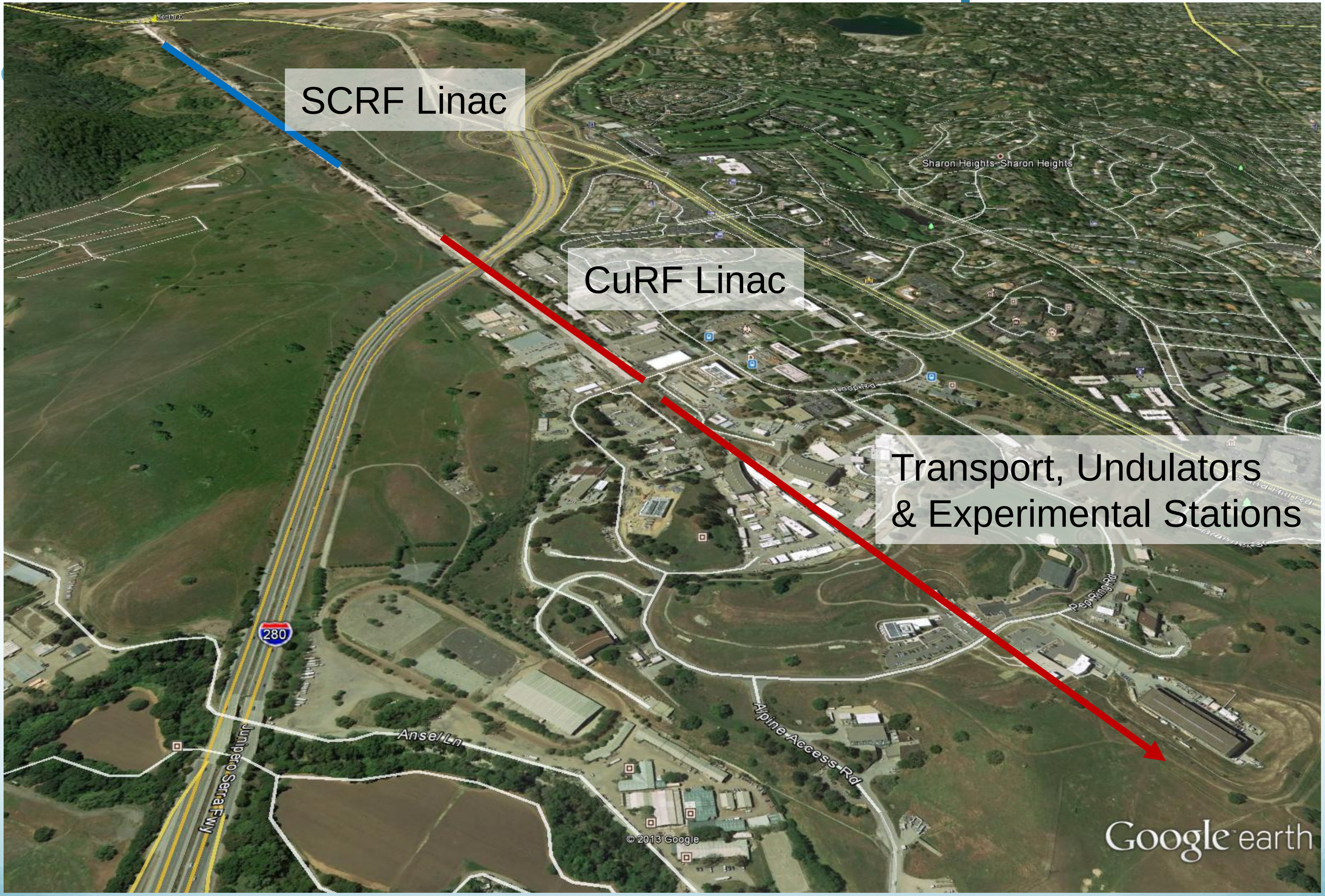
Linac Coherent Light Source

4th Generation: First Light April 2009



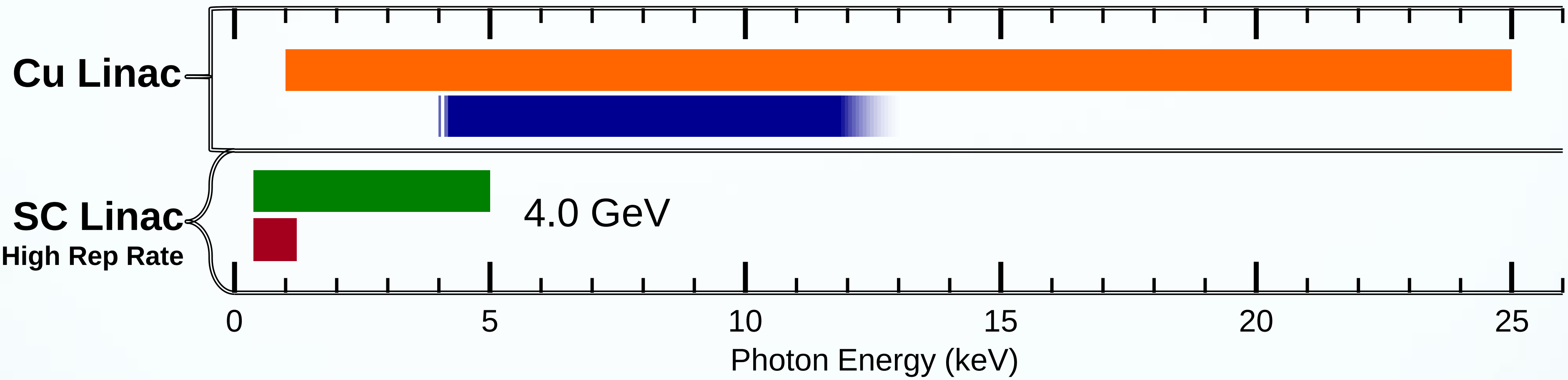
An HEP Accelerator Spin-off

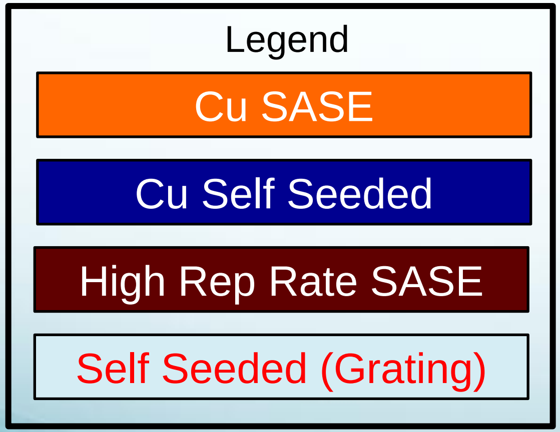
LCLS-II Concept



$1B-class project – tiny pre-R&D expenditures

Future Coherent Photons for BES: Material, Condensed Matter, Biology, Chemistry…



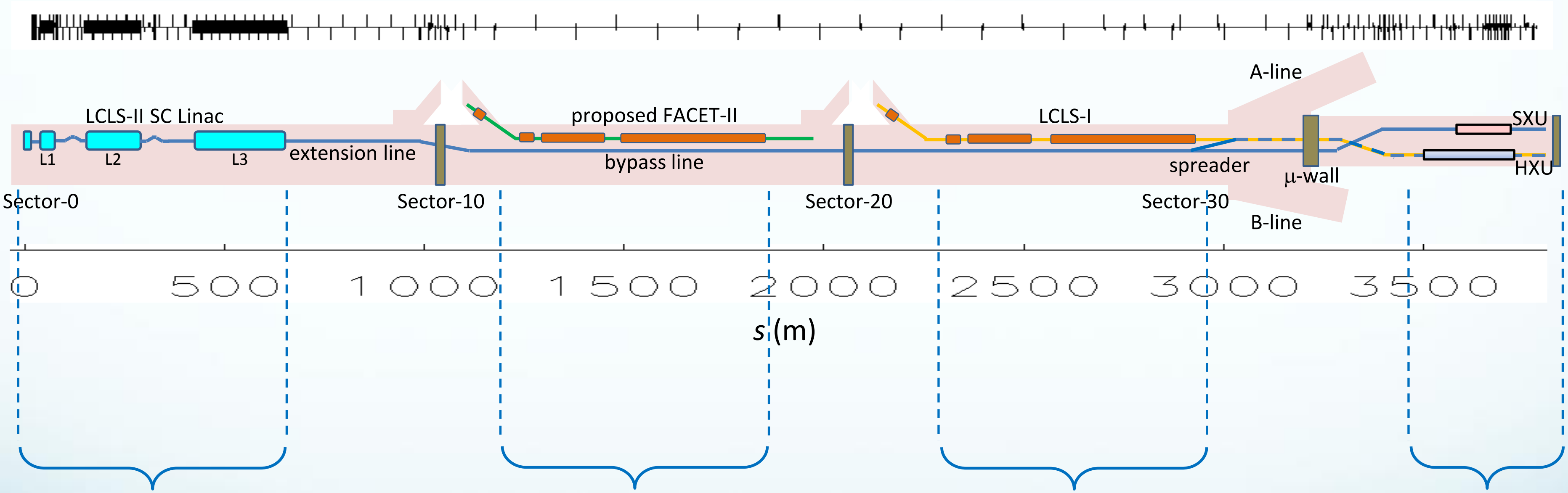


- Hard X-Ray Source:
  - 1-5 keV w/ new 4 GeV SC linac
  - Up to 25 keV with LCLS Cu Linac
- Soft X-Ray Source:
  - 250 eV-1.2 keV w/ 4 GeV linac
- ***Both linacs feed HXR undulator***

SC linac synergistic with proton apps (FNAL is lead)

LCLS-II Layout in SLAC Linac Tunnel

Conserves LCLS I infrastructure, and ***place for FACET II***



New SCRF Linac (4 GeV) FNAL collab.

Proposed FACET-II and Bypass Line

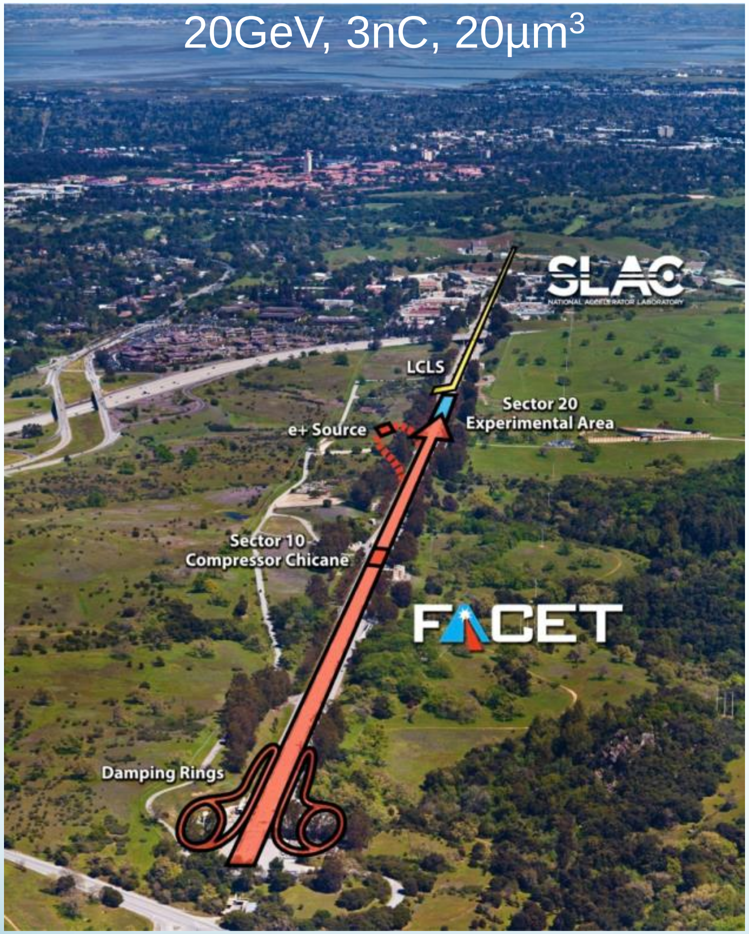
Existing LCLS-I Linac

Undulators (LCLS-I & -II)

Advanced Accelerator R&D Program in the US

- Search for GeV/m gradients for HEP *and* light sources (5th generation)
  - HEP application mainly directed at e+e- LCs
- Long tradition in US, beginning early 1980's
- National lab-based facilities (important!)
  - FACET: charged particle beam-based wakefields
  - ATF: broad-based user facility (e-beam, CO_2 laser)
  - BELLA: PW-class laser-driven plasma wakes
- Vigorous participation by universities
  - Smaller facilities, users, student training

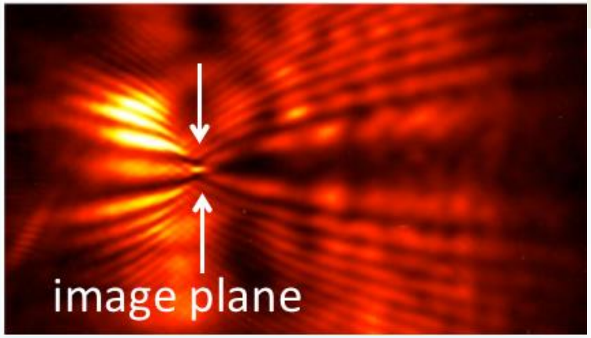
FACET National User Facility

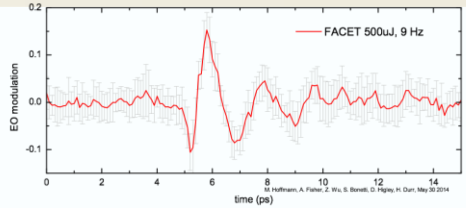


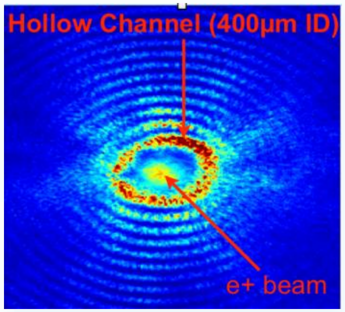
- Primary Goal: demonstrate a single-stage high-energy wakefield accelerator for electrons.
  - Meter scale ✓
  - High gradient ✓
  - Preserved emittance
  - Low energy spread ✓
  - High efficiency ✓
- Timeline:
  - Commissioning (2012) ✓
  - Drive & witness e^- bunch (2012-2013) ✓
  - Optimization of e^- acceleration (2013-2015)
  - First high-gradient e^+ PWFA (2014-2016)
  - First high-gradient DWA (2013-16)

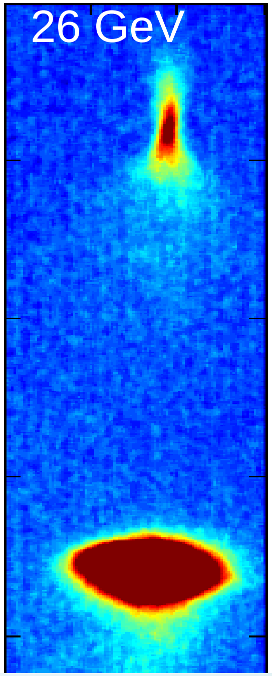
FACET user program is based on high-energy high-brightness beams and their interaction with plasmas, dielectrics and lasers

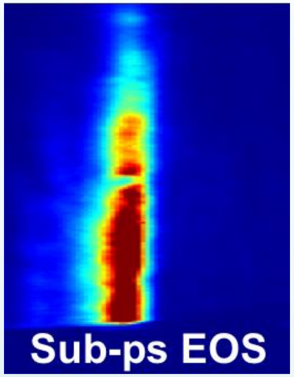
FACET Portfolio Emphasizes Very High Fields

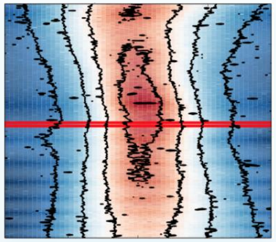


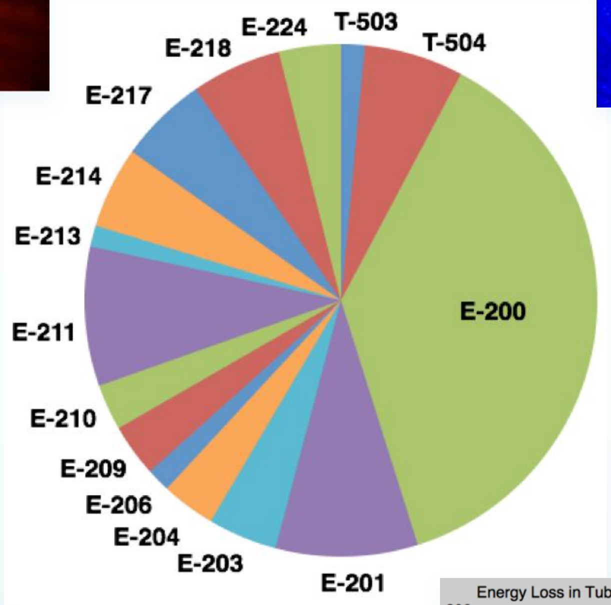


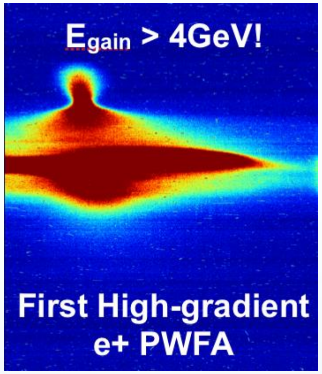


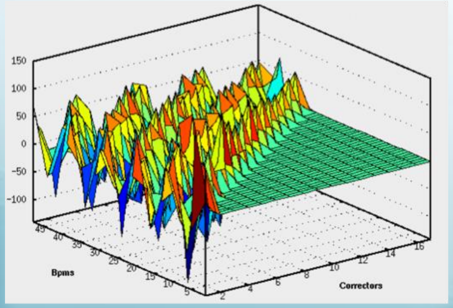


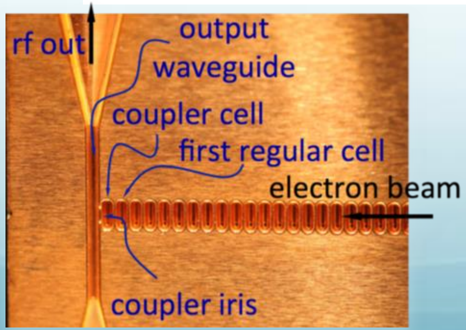


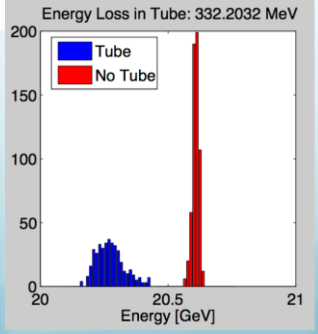


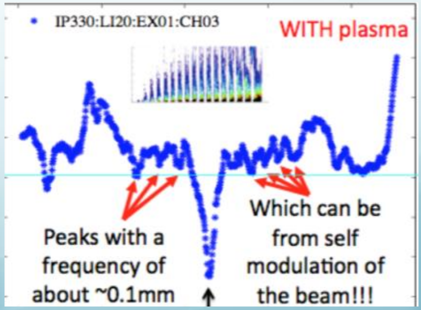










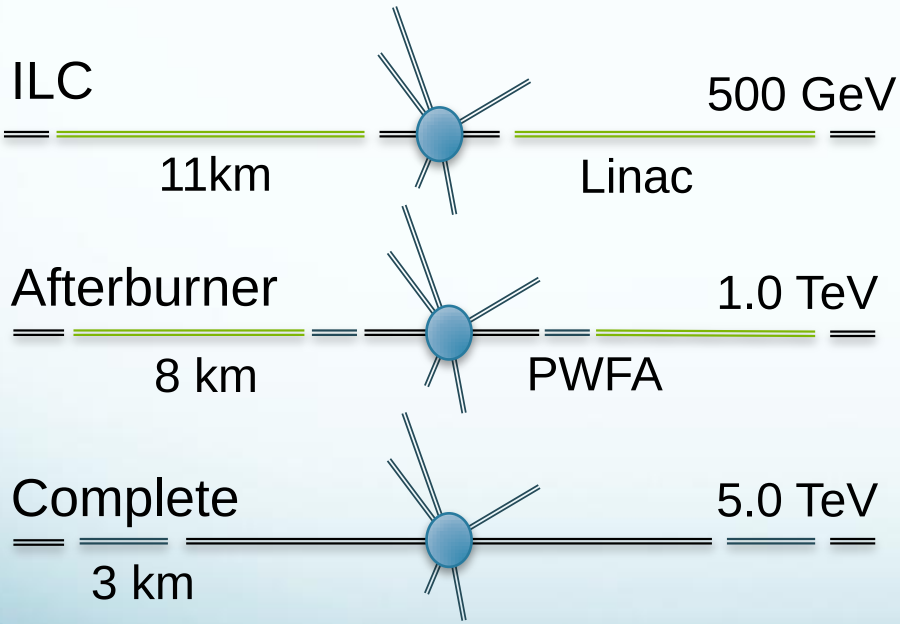


FACET-II Plans

HEP Mission

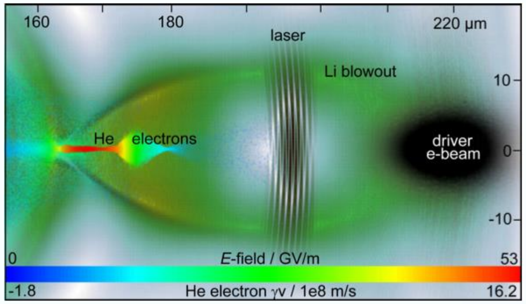
- Demonstrate Plasma Wakefield Acceleration Stage

Vision for PWFA as ILC upgrade path:



User Facility

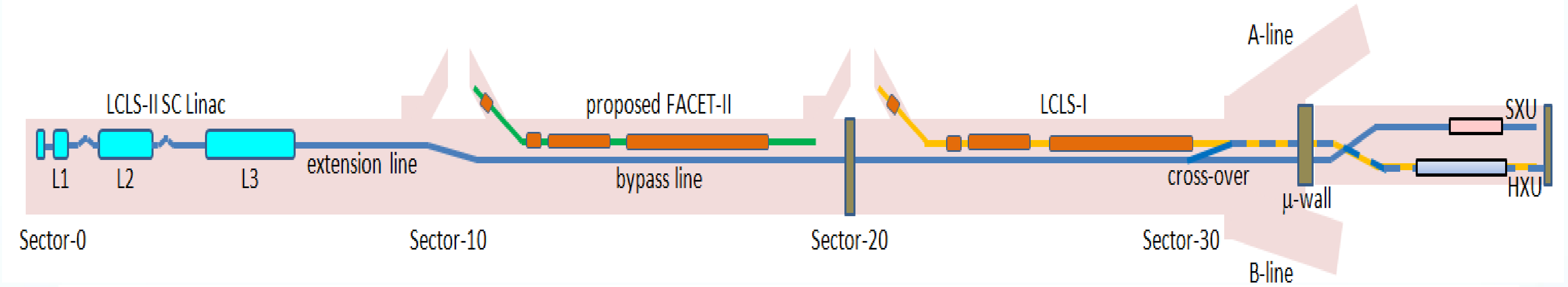
- High-energy high-density electron beams for user experiments



- Generation of e^- beams of unprecedented brightness
- Delivering highest intensity THz fields with V/Å strength
- Unmatched gamma ray source

A cornerstone for worldwide advanced accelerator R&D leading to future HEP collisions, delivering broad range of user experiments

FACET-II by the numbers



Three main stages:

- electron beam photoinjector (e$^-$ beam only) $23M FY17-18
- positron damping ring (e$^+$ or e$^-$ beams) $13M FY18-19
- "sailboat" chicane (e$^+$ and e$^-$ beams) $9M FY20

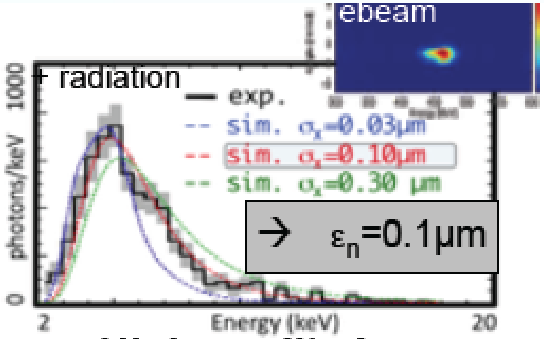
FACET II operating budget:

- 6 months operations $8.0M
- Minimum maintenance state $3.0M
- AIP $2.5M
- Mission readiness $1.0M

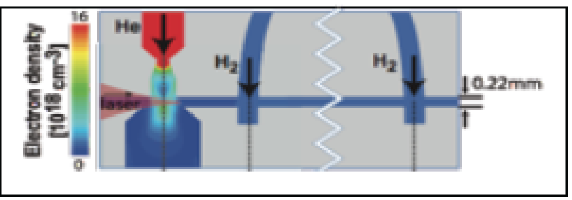
Total **$14.5M**

Nontrivial project cost

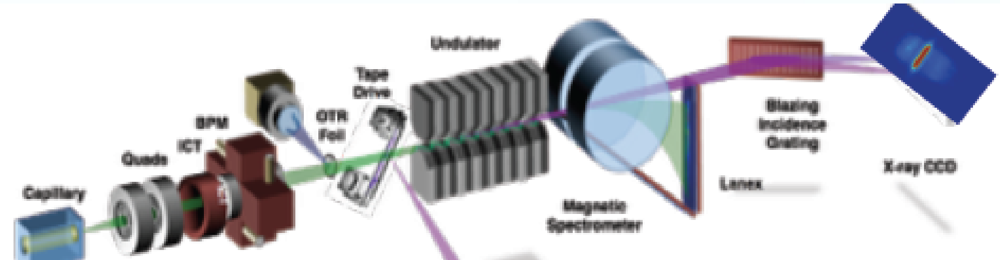
L'OASIS/BELLA at LBNL



High quality beams



G. Plateau et al., PRL 2012
A.J. Gonsalves et al., Nature Phys. 2011
W.P. Leemans et al., Nature Phys. 2006
C.G.R. Geddes et al., Nature 2004

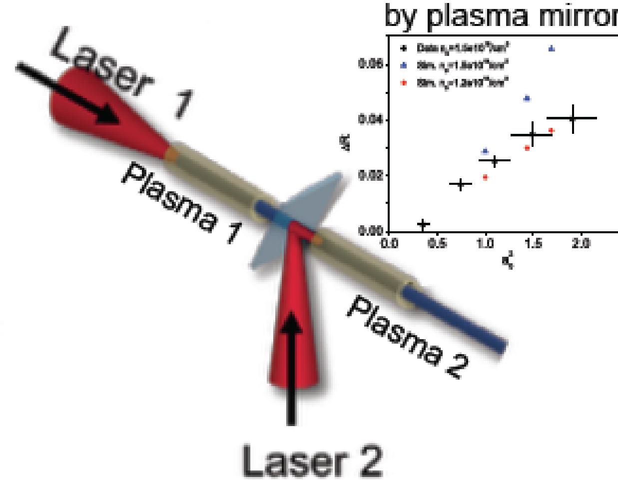


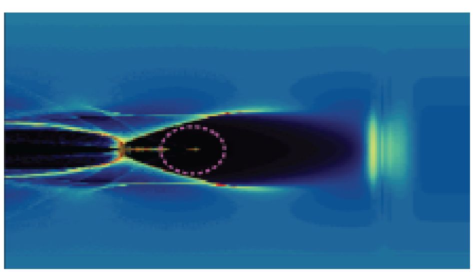
Laser Plasma Accelerator

Diagnostics/Radiation sources

J. van Tilborg et al., PRE 2014
J. van Tilborg et al., Optics Lett 2013
B. Shaw et al., J. Applied Phys. 2013
L. Chen et al., PRL 2012

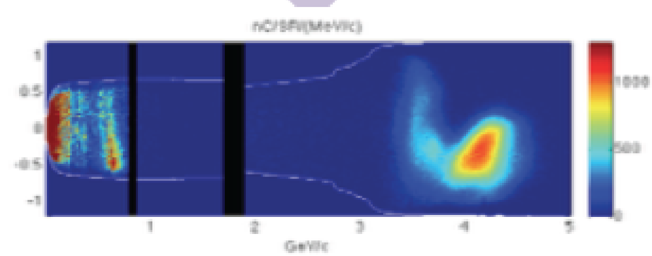
2nd stage powered by plasma mirror





Theory/Modeling

C. Benedetti et al., Phys. Plasmas 2014
L.L. Yu et al., PRL 2014
C.B. Schroeder et al., Phys. Plasmas 2013
C. Benedetti et al., Phys. Plasmas 2013



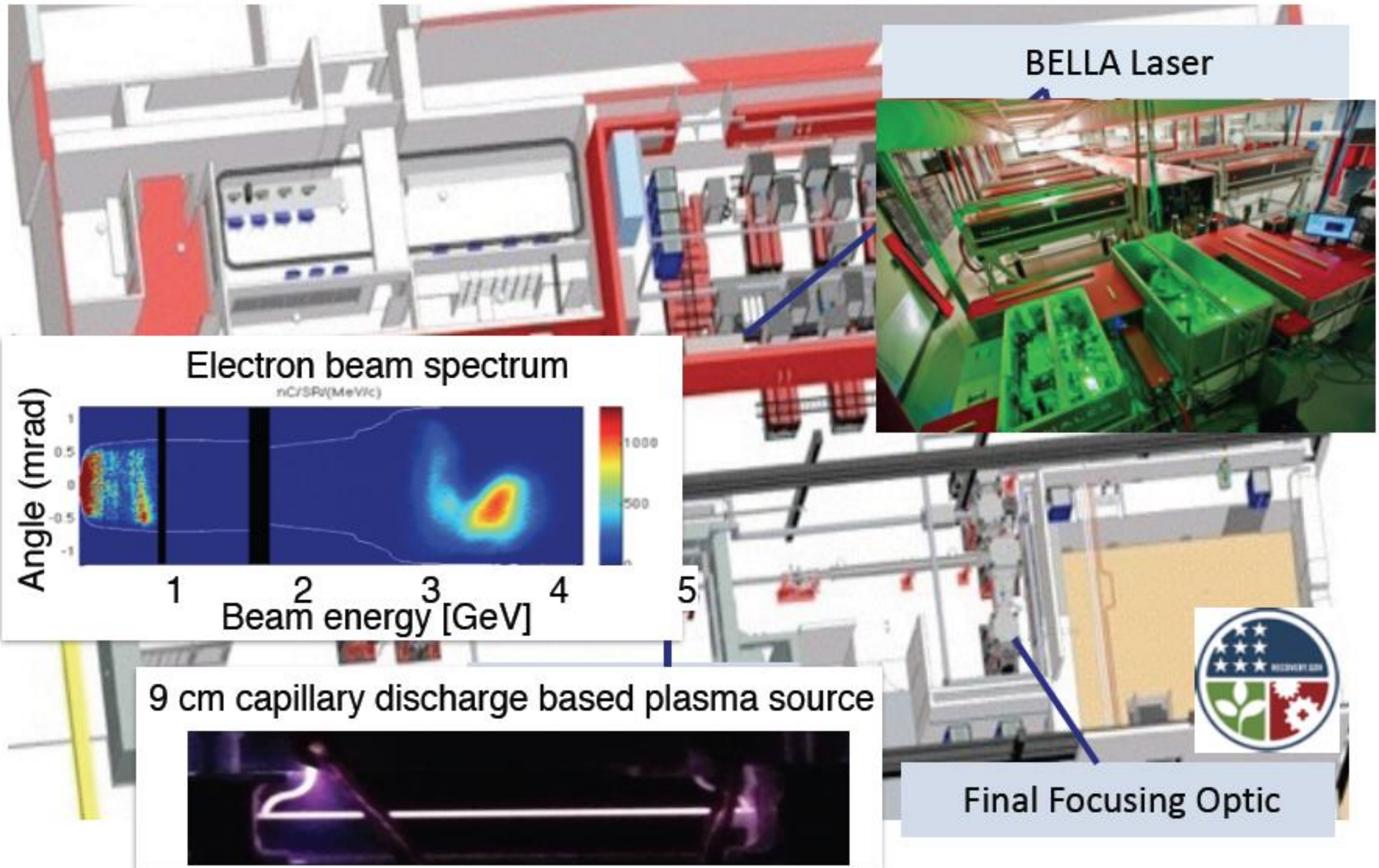
Multi-GeV beams

W.P. Leemans et al., submitted 2014
N. Bobrova et al., Phys. Plasmas 2013
C. Benedetti et al., Phys. Plasmas 2012

Staging, optimized structures

S. Shiraishi et al., Phys. Plasmas 2013

BELLA houses a state-of-the-art high repetition rate PW-laser for laser plasma accelerator science – demonstrator for 10 GeV



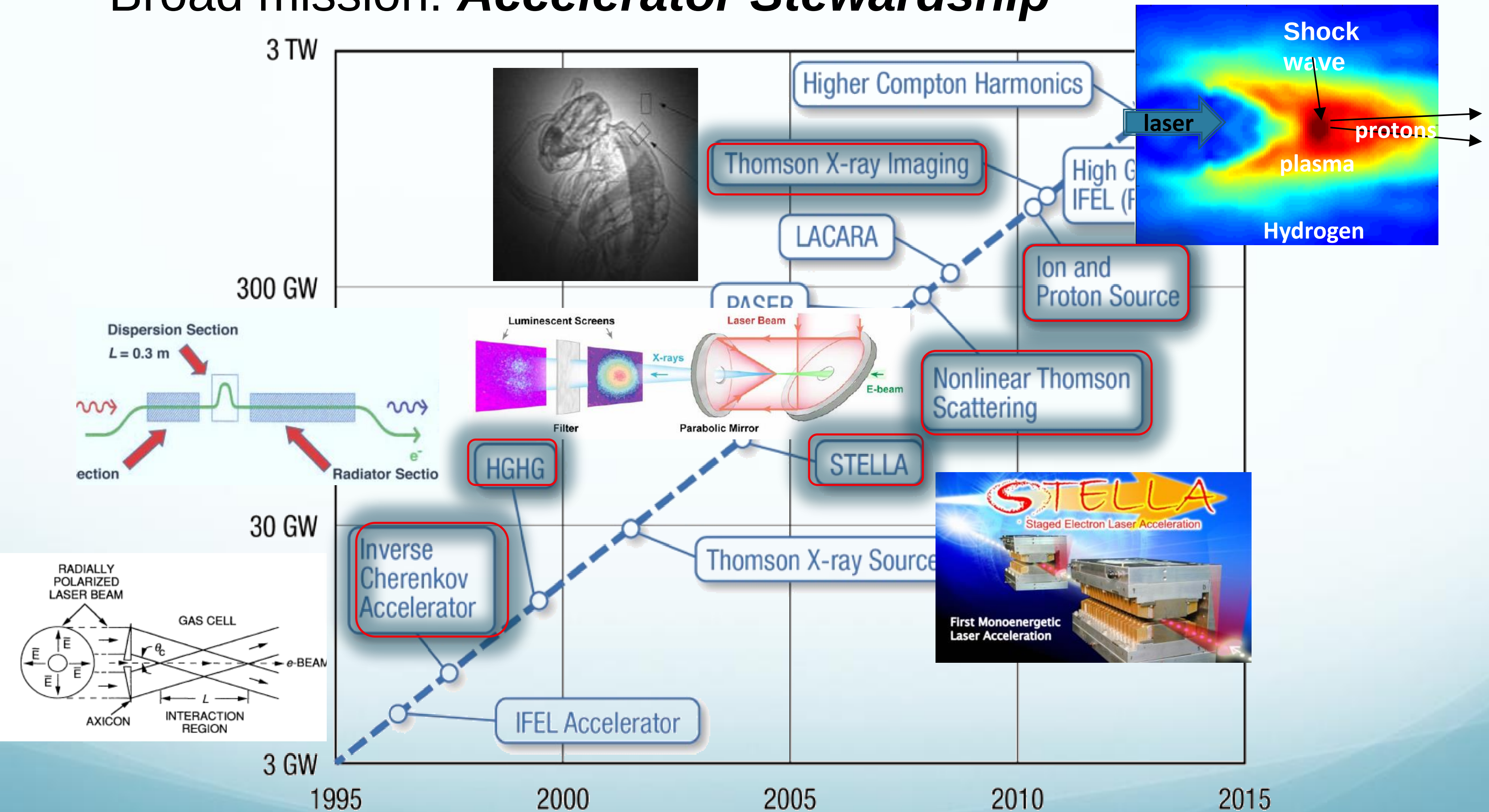
BELLA Upgrade in Global Context

- European Extreme Light Infrastructure investment:
  - > $1 B from 2012-2017
- Comprehensive US program through critical investments:
  - BELLA: 2009-2012 -- ~$30 M investment
    - World record setting PW class laser at 1 Hz
    - First results: > 4.2 GeV from 9 cm structure

  - Maintain and grow current program of laser plasma accelerator science
    - Beam quality, staging, efficiency
  - New demonstrator investments:
    - BELLA-II: high average power demonstrator at kW-level
      - FY15-FY20, $30-35 M, requires development of new laser
      - Opens up near-term applications
    - BELLA-III: multi 10's of kW FY20-25, $50-100 M level
      - Full-scale demonstrator module for collider

BNL ATF is test-bed for advanced e-beam, laser interaction research

-Broad mission: ***Accelerator Stewardship***

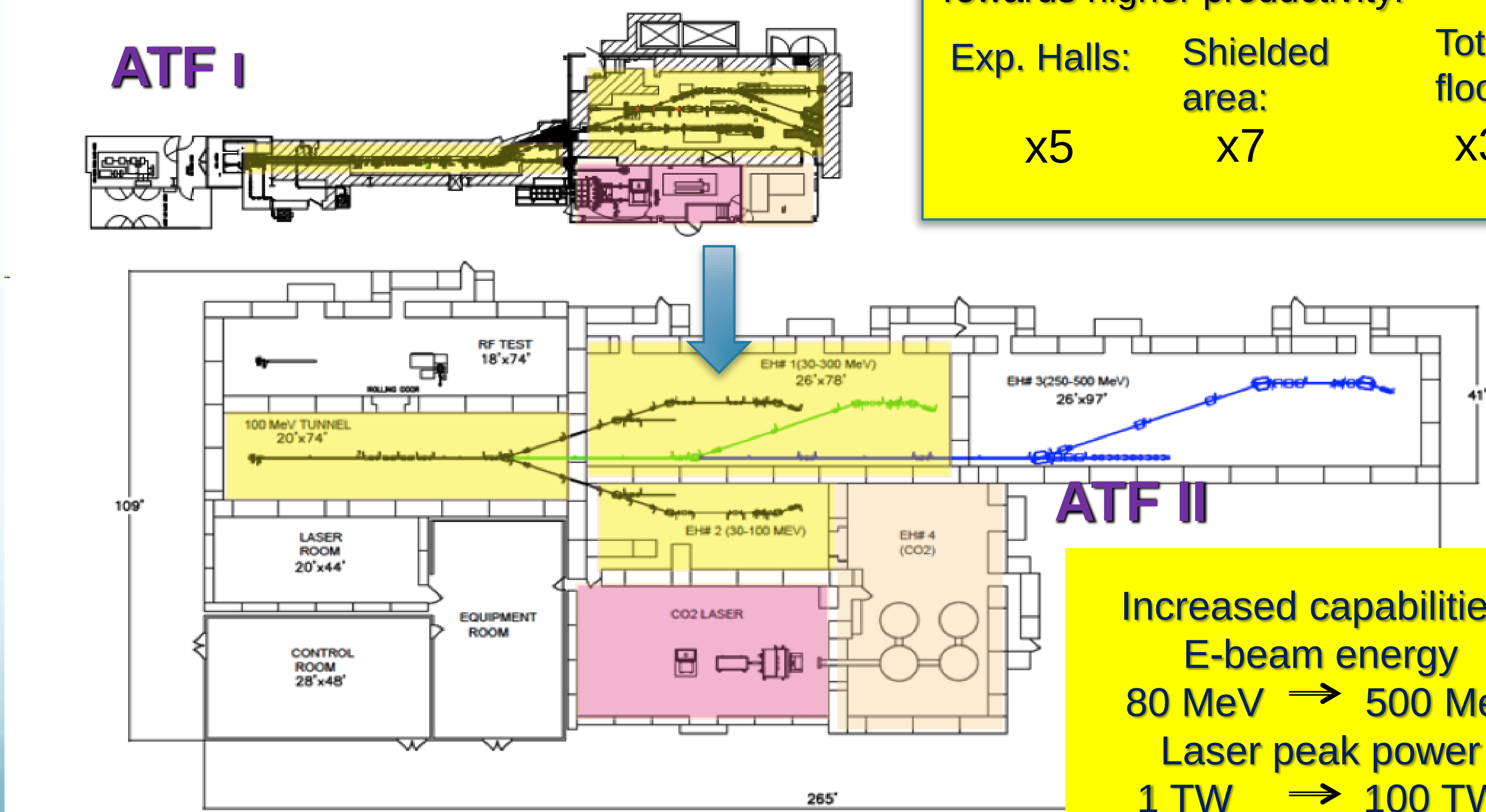


Applications across the Office of Science

ATF II facility upgrade : keystone of stewardship

Towards higher productivity:

Exp. Halls:	Shielded area:	Total floor:
x5	x7	x3



Increased capabilities:

E-beam energy

80 MeV → 500 MeV

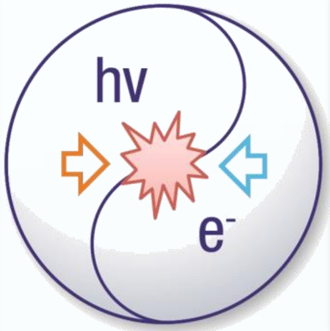
Laser peak power

1 TW → 100 TW

ATF upgrade opens up new accelerator and high field science opportunities

Science of strong field λ-scaling

- HHG
- Laser-matter interaction studies at $I\lambda^2 > 10^{20}$ W/cm^2 in unexplored mid-IR spectral domain



Advanced accelerator studies

- Ion acceleration – gas targets; H, D, He, Ne, etc.
- High bunch-charge LWF electron acceleration.

Combining ATF laser with high brightness e-beam:

- Probing or seeding of laser-driven plasma wakes
- IFEL technology reaching the GeV level
- Advanced studies of Inverse Compton scattering, e.g. non-linear interactions, pulse recirculation, etc.

Analysis of HEP GARD Thrust Areas

Superconducting RF Cavities

Accelerator Beam Physics

Particle Sources

Beam Instrumentation and Controls

NC RF and High Gradient Accelerating Structures

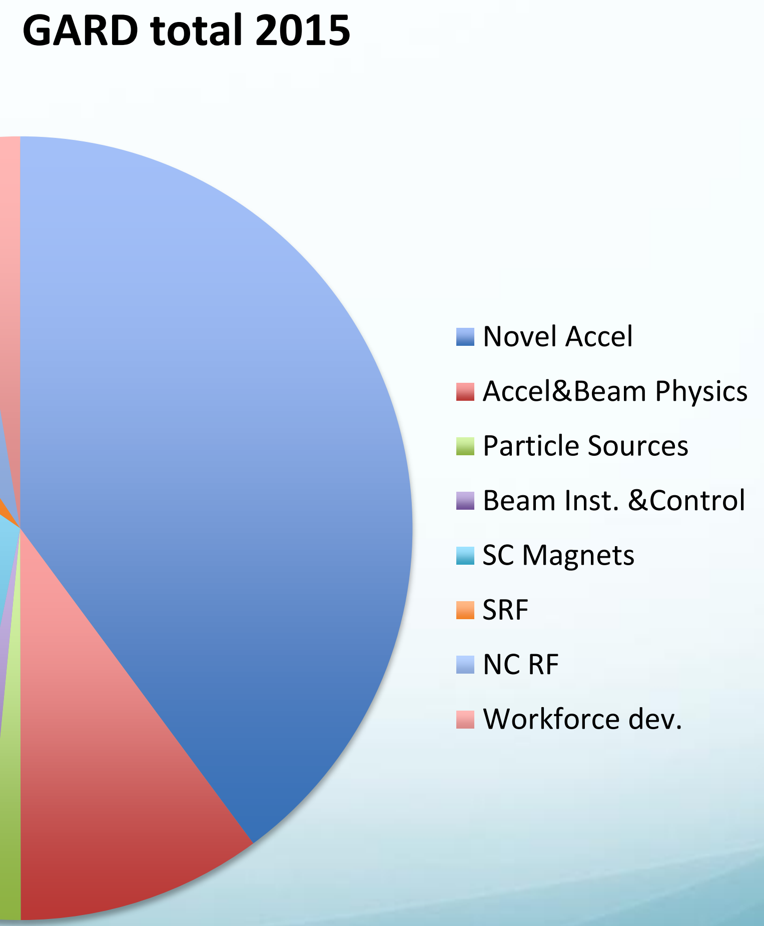
New Accelerator Concepts

Superconducting Magnets and Materials

How to split the pie to achieve HEP goals?
What are the effects on AA research?

GARD at present

- Total 2015 budget $68M. Projects (HEP) excluded
- Includes facilities

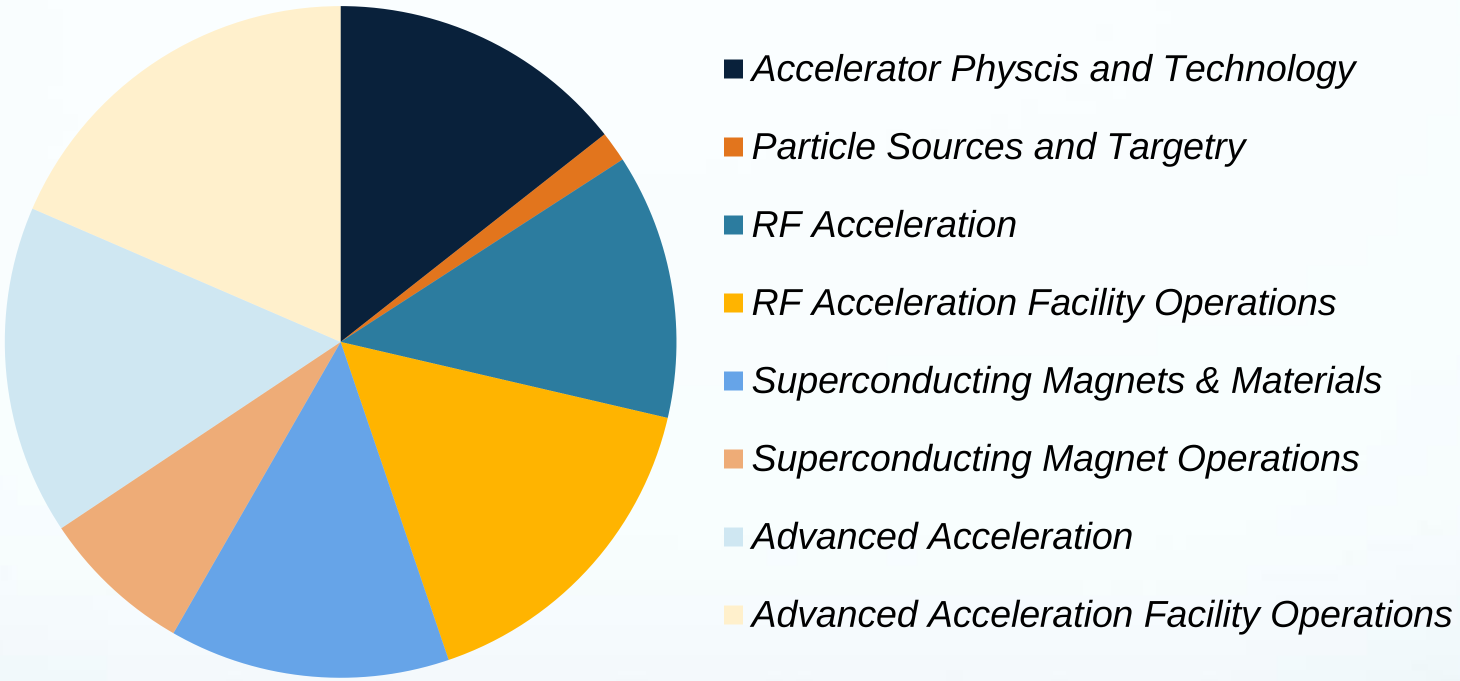


Novel accelerator *high* percentage

Challenges in rebalancing R&D

- Limited funding for the GARD program
- Time scales for construction starts in next gen accelerator facilities long
- Next generation multi-MW proton sources, very high-energy TeV pp colliders, 1 TeV e^+e^- colliders, and $\geq$ 3 TeV e^+e^- colliders will be **complex**
- Current designs for these accelerators have broad spectrum of maturity
- Very high stored energy of the beams and the magnet systems of a ~ 100 TeV pp collider provides design difficulties
- Intense synchrotron radiation from the beams in a very high-energy TeV pp collider presents very significant challenges
- Cost of using known technologies for these machines is very high
- **The applicability of the advanced acceleration technologies to HEP colliders is at an early stage of understanding**
- **Cost of R&D facilities** (both construction and operating costs)
- Key driver for GARD is to develop strategies to signficantly reduce the costs of construction/operation for future facilities

Current GARD Program: Rebalanced and Reclassified



Advanced accelerators down in "Scenario A" (no budget increase), Magnets, SRF and targetry up (Intensity Frontier support)

- **Case made for Scenario B (across the board 20% increase)**
- **Scenario C: New initiatives (FACET II,** HTS magnets etc.**)**

Scenario C exercise for FACET II already underway

Recommendations summarized

For the multi-MW proton beam:

High power components, IOTA (space charge), simulations, and SRF

For a very high-energy proton-proton collider:

Design effort, simulation, high field magnets, Nb_3Sn, HTS, and industrialization for cost reduction

For up to 1 TeV ILC:

Higher Gradient SRF (80 MV/m)

For a >3 TeV e^+e^- collider:

Facilities to continue beam-driven and laser-driven wakefield acceleration; develop a roadmap for advanced accelerators; efficient RF sources; component test facilities; next step plan for NC RF technology (e.g. cryo)

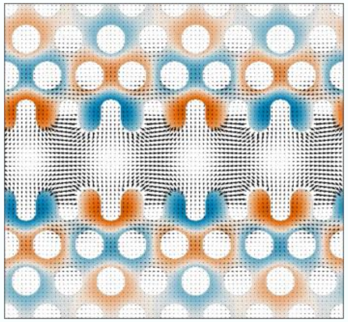
Note: dielectric laser accelerators, muons de-emphasized

Organizational activity in AA

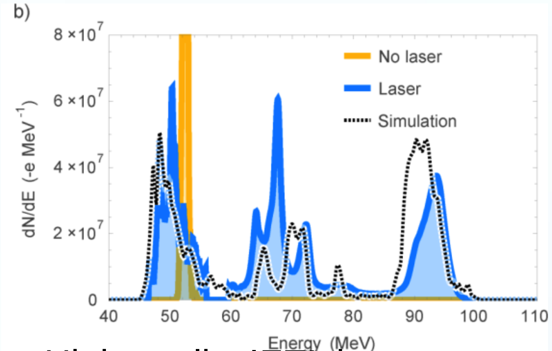
- Recommendations for going forward explicitly given
- FACET II proposal moving toward CDI
- FACET II physics workshops in October
- BELLA preparing new user facility role
- Reorganization of USPAS
- Milestone exercises/meetings
  - Preliminary PWFA, DWA and LWFA meetings
  - Collider suitability discussed in early 2016

Opportunities beyond HEP

- Expand activities in BES/NP. No EUPRAXIA yet.
- Other federal agencies have non-trivial role
  - DARPA AXiS DLAs
  - DNDO all-optical ICS

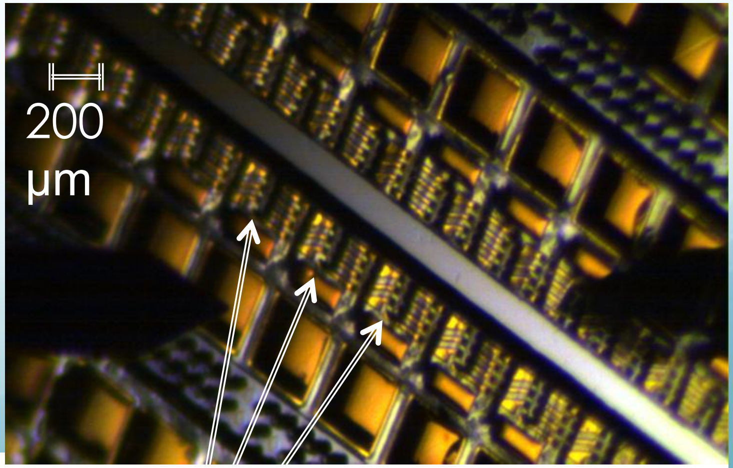


GALAXIE DLA structure



High quality IFEL beam

- New initiatives in private foundations promising
  - Purposefully complementary
  - Keck Foundation μFEL at UCLA
  - Moore Foundation DLA/LWFA



Batch-fabricated electromagnets

Outlook

- Present facilities meeting physics needs for users and R&D, but funding is not high
- US particle accelerator R&D aimed at next generation facilities is undergoing redirection
- New projects in light sources healthy; long term research is not
- Accelerator Stewardship is in early stages, must continue evolving
- Frontier HEP machines will concentrate on intensity in near term
- **Energy frontier is not abandoned**; fundamental research (mid and far term) needed