U.S. DEPARTMENT OF ENERGY | Office of Science

High Luminosity LHC Accelerator Upgrade HL-LHC AUP

HiLumi Collaboration Meeting

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Outline

- The Energy Frontier at the LHC
  - DOE/HEP Mission
  - The P5 Strategy
  - DOE Construction Plans and Physics Timeline
  - The US involvement in the LHC
- The US Role in the HL-LHC Accelerator Upgrade (AUP)
  - Alternatives for participation
  - From LARP to AUP; Detector Upgrades
  - Scope proposal & approval
  - DOE Projects process and AUP status
- A Look to the Future
- Conclusions

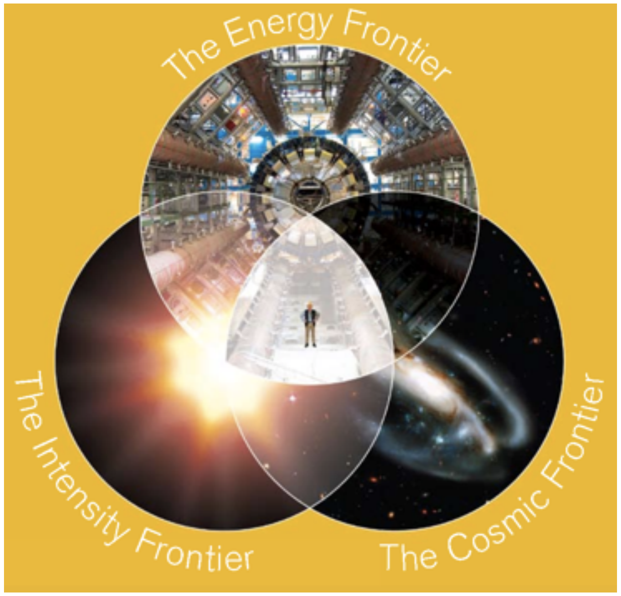
DOE/HEP Mission

Understand how the universe works at its most fundamental level:

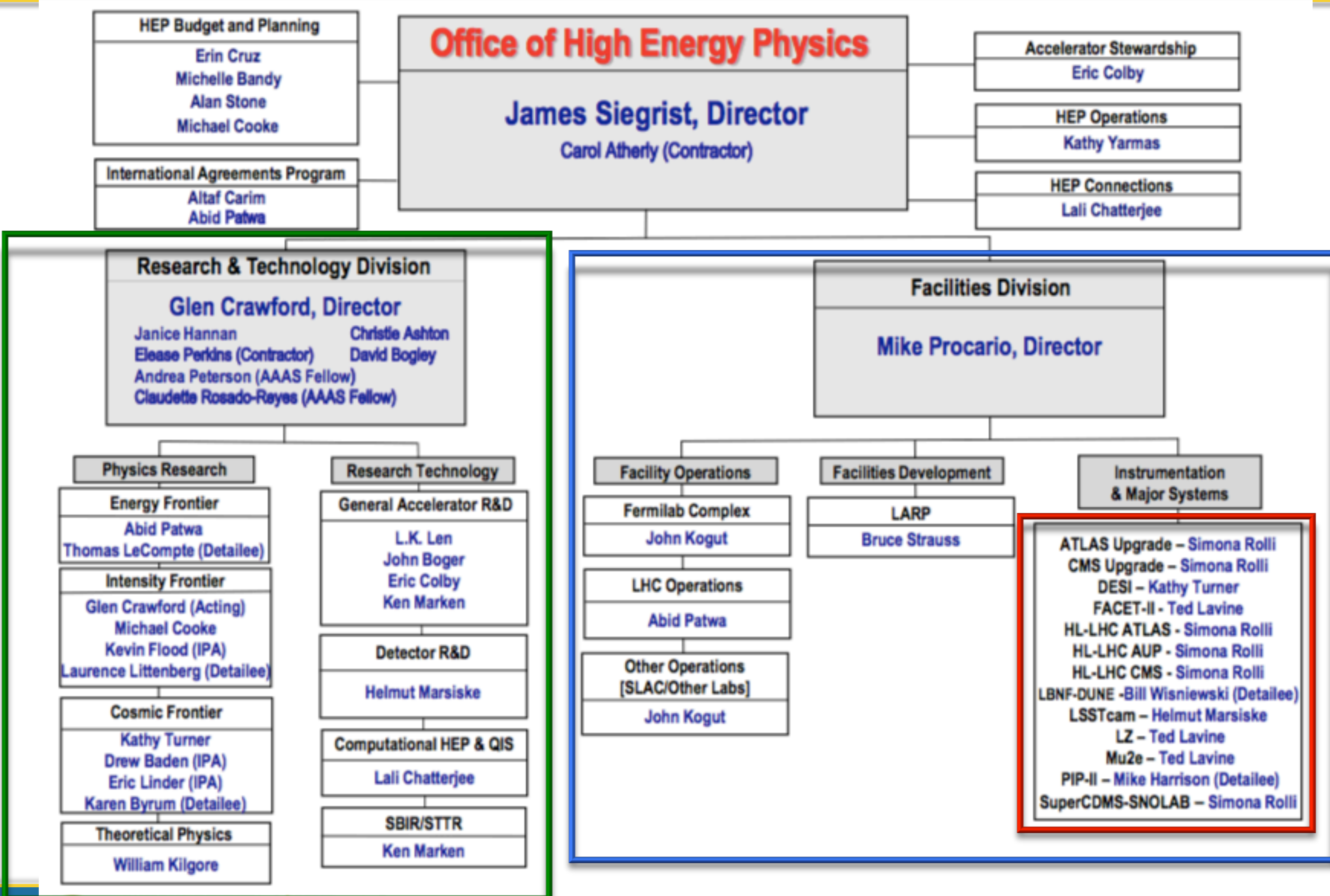
- Discover the most elementary constituents of matter and energy
- Probe the interactions between them
- Explore the basic nature of space and time

We carry out this mission through experiments on the Energy, Intensity and Cosmic Frontier by:

- building projects that enable discovery science
- operating facilities that provide the capability to perform discovery science
- supporting a balanced research program that produces discovery science



DOE/HEP Org Chart



Priority Within DOE/HEP

The The Particle Physics Project Prioritization Panel (P5) report (2014) identifies the following 5 major science drivers in particle physics:

- ***✔1. Use the Higgs boson as a new tool for discovery***
  - Exclusive realm of LHC
- ***2. Pursue the physics associated with neutrino mass***
  - Addressed by the U.S. LBNF program, *LSST, IceCube*
- ***✔3. Identify the new physics of dark matter***
  - Many complementary experiments including the LHC
- ***4. Understand cosmic acceleration: dark energy and inflation***
  - Addressed by e.g. LSST
- ***✔5. Explore the unknown: new particles, interactions and physics principles***
  - LHC is at the "Energy Frontier" and is in the best position to explore the unknown!
    - Complementary to e.g. LIGO (an NSF MREFC project)

P5 Construction & Physics Timeline

- P5 provided a ten- year strategic plan in the context of a twenty-year global vision

- Carefully chosen investments will enable a steady stream of exciting new results for many years to come

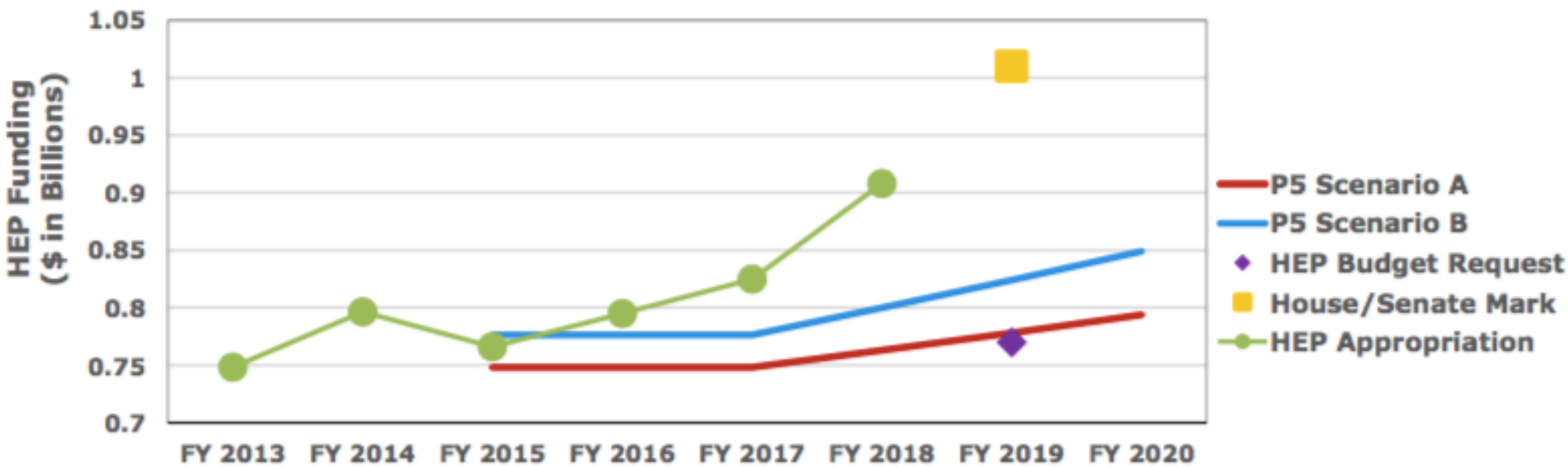
Legend:

- ***Approximate Construction***
- ***Expected Physics***
- ***LBNF/DUNE Early Science***

DOE/HEP Projects

Subprogram	TPC ($M)	CD Status	CD Date
INTENSITY FRONTIER			
Long Baseline Neutrino Facility / Deep Underground Neutrino Experiment (LBNF/DUNE)	1,260 – 1,860	CD-3A	September 1, 2016
Proton Improvement Project (PIP-II)	653 - 928	CD-1	July 23, 2018
Muon g-2	44	CD-4	January 16, 2018
Muon-to-Electron Conversion Experiment (Mu2e)	274	CD-3	July 14, 2016
ENERGY FRONTIER			
LHC ATLAS Detector Upgrade	33	CD-3	November 12, 2014
LHC CMS Detector Upgrade	33	CD-4A	September 19, 2017
High-Luminosity LHC (HL-LHC) Accelerator Upgrade	208 - 252	CD-1/3A	October 13, 2017
High-Luminosity LHC (HL-LHC) ATLAS Detector Upgrade	125-155	CD-1	September 21, 2018
High-Luminosity LHC (HL-LHC) CMS Detector Upgrade	125-155	CD-0	April 13, 2016
COSMIC FRONTIER			
LUX-ZEPLIN (LZ)	56	CD-3	February 9, 2017
Super Cryogenic Dark Matter Search - SNOLAB (SuperCDMS-SNOLAB)	18.6	CD-2/3	May 2, 2018
Dark Energy Spectroscopic Instrument (DESI)	56	CD-3	June 22, 2016
Large Synoptic Survey Telescope Camera (LSSTcam)	168	CD-3	August 27, 2015
ADVANCED TECHNOLOGY R&D			
Facility for Advanced Accelerator Experimental Tests II (FACET-II)	24.6	CD-2/3	June 8, 2018

DOE/HEP Budget



- The US budget is always on a year + 6 months schedule –
  - We are working now on the 2020 budget (public in Feb 2019)
- The recent increases allow for a healthy level of projects funding

US Involvement in HL-LHC

- The principal laboratory for the LHC program is CERN, which assumes the ultimate responsibility for mounting and guiding the HL-LHC upgrades

- The DOE contribution to HL-LHC consists of **upgrades to the accelerator** and to both the **ATLAS and CMS detectors** totaling ~ $550M
  - HL-LHC AUP $200-250M
  - HL-LH ATLAS Upgrade $125-155M (not including I&C)
  - HL-LHC CMS Upgrade $125-155M (not including I&C)

- NSF guidance = $150M MREFC (plus development funds in 2017-20) to ATLAS & CMS ($75M each)
  - MREFC funding is targeted to begin April 2020, pending National Science Board and Congressional approvals.

Potential Approach

- **Option 1 Develop a suite of in-kind contributions that utilize the expertise of the U.S. accelerator community including the national laboratories.**
  - These contributions should be in a form that utilizes U.S. expertise that CERN does not already have.
  - **This option best addresses the goals and priorities for HEP at the Energy Frontier outlined by the 2014 P5 strategic plan including the international partnership of the U.S. on the LHC program at CERN.**
- **Option 2 Provide CERN with cash payments for contributions to the upgrade or pay annual operating costs to CERN during the operation of the HL-LHC.**
  - Currently, the U.S. does not have a comparable user facility in particle physics to host European researchers, so the historical reciprocal relationship whereby facilities in different global regions hosted foreign users without charging user fees or operating costs no longer exists.
  - **This cash payment option does nothing to advance the skills of the U.S. accelerator building community** and may slow the upgrade of the HL-LHC since the U.S. is currently ahead of CERN in high field superconducting magnet technology.
- **Option 3 Do nothing.**
  - **This option would severely impact the international partnership of the U.S. on the LHC program at CE**RN and would result in HEP being unable to maintain a meaningful Energy Frontier research program, which P5 affirms is necessary for mission success. . It is also possible that this approach could damage the U.S.'s standing in the international scientific community.

The US is contributing to areas where there is recognizable US technical expertise.

Scope Proposal & Approval

- The project will deliver technical components to CERN for incorporation into the LHC, which CERN is interested in acquiring from the U.S.
- Since 2003 DOE supported the LHC Accelerator Research Program (LARP) to allow U.S. accelerator physicists to participate in the ongoing development of the LHC.
  - Strong coordination with CERN
- Since 2012 – CERN-DOE converge on the following:
  1. **Nb_3Sn low-beta focusing magnets (triplets)**
  2. High Bandwidth Feedback System for SPS (define acronym)
  3. **Crab Cavities**
  4. 11 Tesla Dipole (cold mass, no cryostat)
  5. *Electron lenses*
- Electron Lenses are not yet part of the HL-LHC baseline at this time only due to financial constraints.

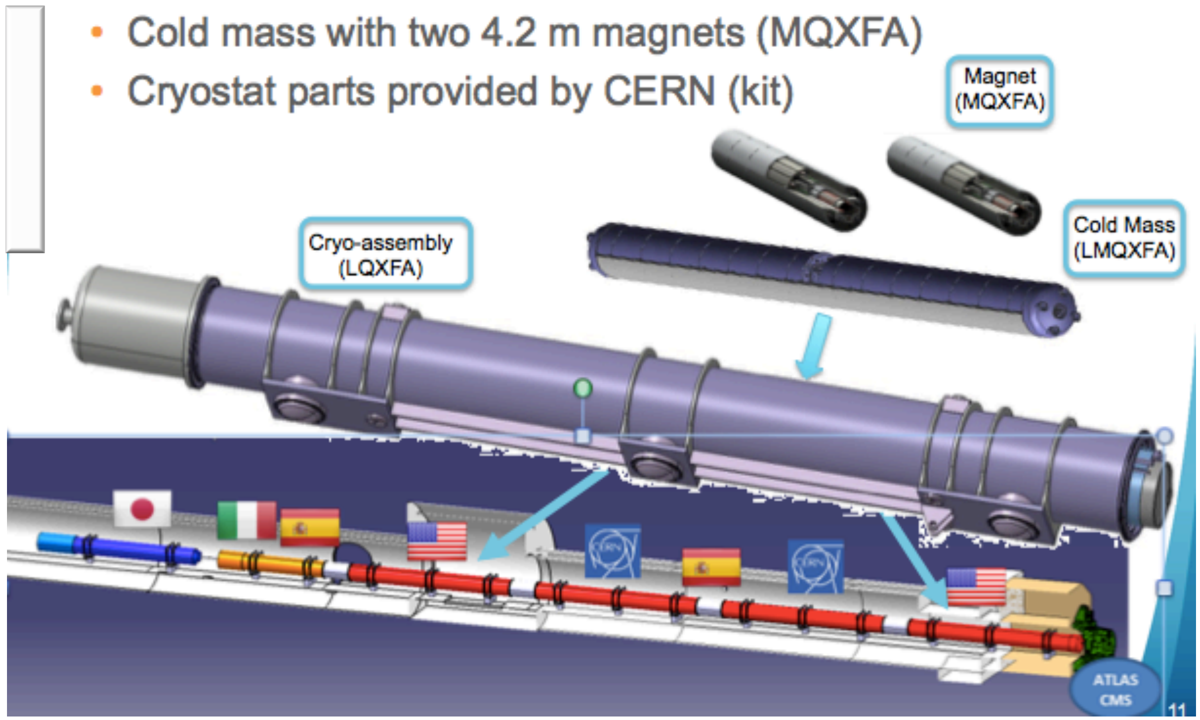
Based upon cost considerations and further iteration with CERN, the HL-LHC down selected to quadrupole magnets and crab cavities as the technical scope to be developed as in-kind contribution to the project.

DOE Role in the HL-LHC Accelerator Upgrade

Focusing Magnets

A classical route for a luminosity upgrade is to reduce a quantity related to the transverse size of the beam at the interaction point (β^*)

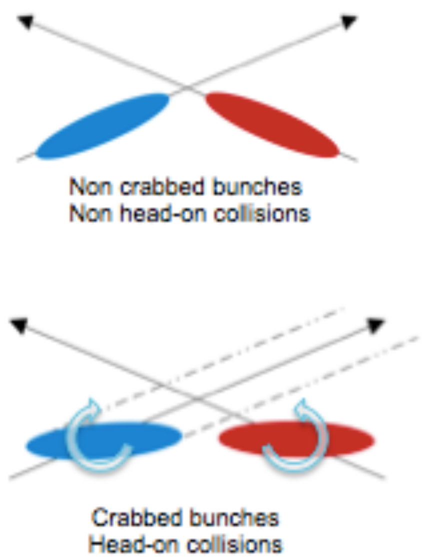
Such reduction implies larger beam sizes and the use of **new superconducting technology for the construction of larger bore quadrupoles in the HL-LHC.**

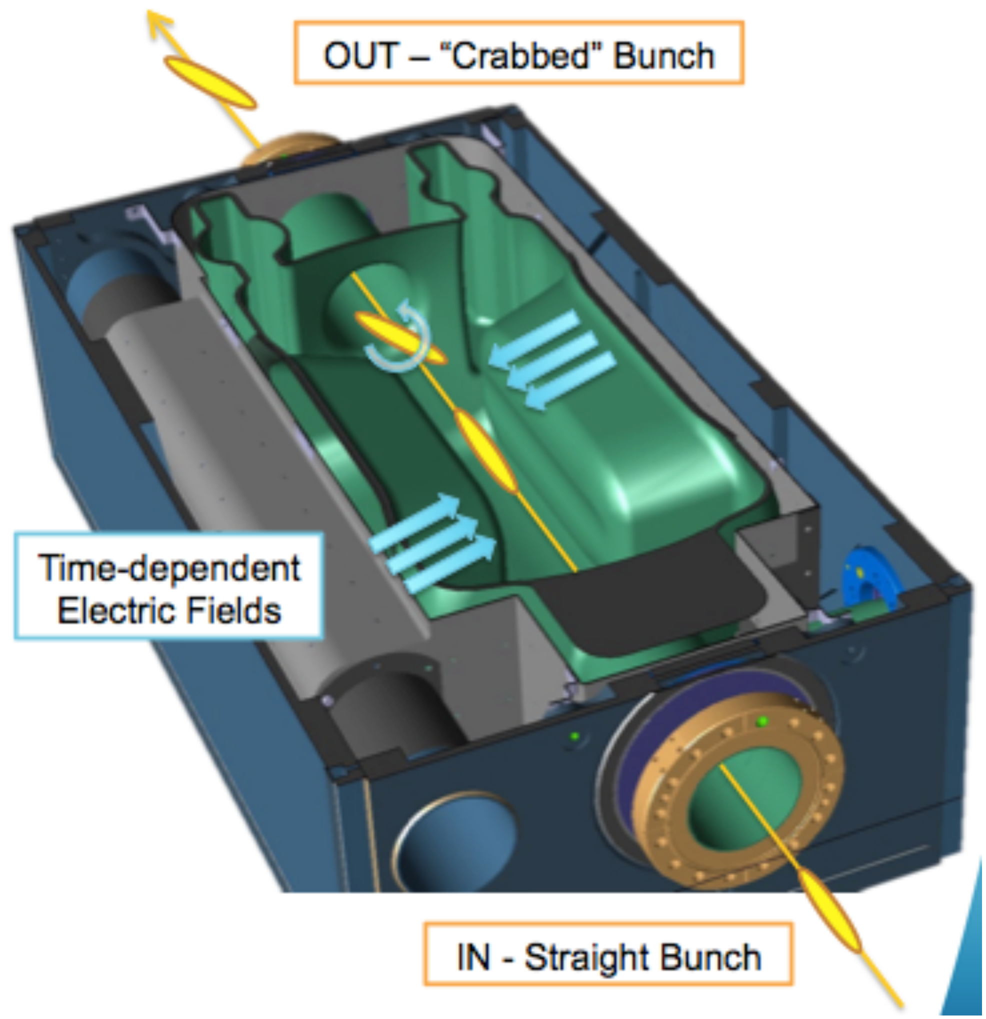


DOE Role in the HL-LHC Accelerator Upgrade

Crab Cavities

The drawback of very small β^* is that it also requires a larger crossing angle. Increasing the crossing angle decreases geometric overlap of the beams. **Rotating the beam bunches with crab cavities** before and after collision can reduce this.





Multi-lab Collaboration

- HL-LHC AUP activities funded by DOE will take place at:
  - **Fermi National Accelerator Laboratory**
  - **Brookhaven National Laboratory**
  - **Lawrence Berkeley National Laboratory**
- Technical efforts at BNL, FNAL and LBL are almost evenly split among the Laboratories on magnet efforts
- WFO/Contractual activities will happen with other US Institutions such as:
  - Old Dominion University
  - Florida National High Field Magnet Laboratory
  - Argonne National Laboratory
  - Jefferson Laboratory
  - Stanford Linear Accelerator Laboratory

From LARP to AUP

- DOE created **focused R&D Program (LARP)** in ~2003 (with sizable funding from ~2006 to 2018) to enable development of leading-edge technologies (Nb_3Sn magnets, SRF Crab Cavities) aimed at LHC Luminosity increase
  - LARP driven as project-like activity in last ~3 years to converge on final developments and design for potential US in-kind contributions to HL-LHC

- **Cutting edge-technology was brought to fruition for Energy Frontier by US-LARP**

- First usage in accelerator for Nb_3Sn Superconductor
  - ~50% higher fields than present LHC. Forces higher by x4-6
  - Brittle superconductor, stress management a must
  - Challenging technology with enabling features for future of HEP field (FCC, CepC,…)

- First usage in hadronic collider of “crabbing” technology

- Value Engineering has focused on reducing and minimizing risk:
  - Insure performance achievement
  - Manufacturability
  - Availability of manufacturing facilities
  - Long turn-around time for major “design improvements” (~3 years from conductor to tested magnet) will allow continued VE only on the above-mentioned elements of manufacturability and optimized usage of facilities

DOE Project Proposal & Approval

- HL-LHC AUP is a **formal DOE Construction Project**
  - Governed by DOE Order 413.3B
    - https://www.directives.doe.gov/directives-documents/0413.3-BOrder-b
    - Applies to capital assets projects having a Total Project Cost greater than or equal to $50M
- A DOE construction project proceeds through **several critical decision gateways**:
  - **CD-0: Mission Need (April 2016)**
    - ***Total Project Cost Range: $180-$250 Millions***
  - **CD-1: Approve Alternative Selection and Cost Range & *CD-3a: Approval of Long-lead Procurements (September 2017)***
    - ***Preliminary Cost Point Estimate ~$227M***
  - **CD-2/3b, Approve Performance Baseline & *Approve Fabrication Start of coils and magnets* Planned for Q1 FY19**

We are now here!

  - **CD-3**, Approve Full Construction Start of balance of Project (CryoAssemblies and Crab Cavities Fabrication) Planned for Q3F2021
  - **CD-4**, Approve Project Completion Planned for Q4FY27

Funding

- Funding supports:
  - Planned Scope (including *Objective KPPs*)
  - First 8 Cryo-assemblies and dressed cavities delivered to CERN by "Need by" date.
  - The baseline budget will be finalized by the December 2018 gate review:

- TPC: ~240 M$
  - BAC of ~178-180 M$
  - **~36%** Cont. on work-to-go
- Schedule Float:
  - Minimum **11** Months to CERN "Need-by" date
  - 36 Months to DOE CD-4

Technical Progress

- All models and prototypes built in US to demonstrate AUP Scope of Work (supported by LARP and CERN) performed better than required for HL-LHC.

- **The LARP Team transitioned smoothly to HL-LHC AUP – LARP has concluded**

- **More in Giorgio’s talk tomorrow!**

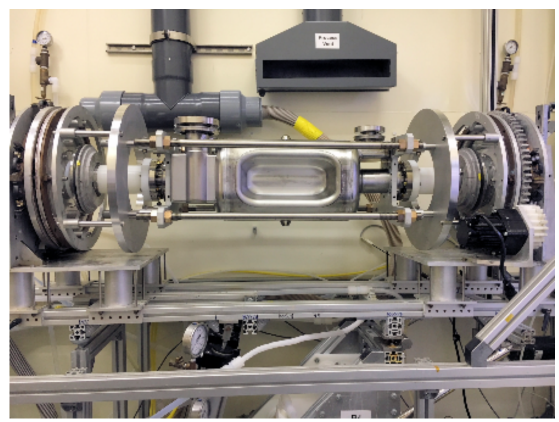
Technical Progress (cont'd)

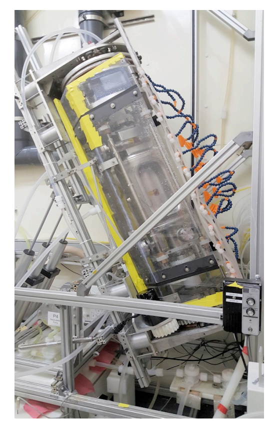
Magnets

- Nb_3Sn procurement in full execution
- Final MQXFAP2 Vertical Test at BNL before baseline
- Other activities progressing as usual
  - Cables, Coils and Magnets Assemblies
  - Prototype order placed

Cavities

- Validated new rotational-BCP tool at ANL
- Newly fabricated HOM dampers by JLab
  - Warm and cold tests performed at Jlab/ODU
- Continued cold-tests on LARP prototypes
  - Exceeded requirements of field and quality factor (FNAL)
  - Still troubleshooting damper losses (ODU/Jlab/FNAL)
- Placed contract for bare cavity fabrication





A Look At The Future

- DOE is coordinating with the international community towards development of the next collider program
  - U.S. looks forward to a decision this year by Japan to host the ILC as an international project
  - Global strategy for circular collider awaits 2020 European Strategy Update for Particle Physics

- Interest from HEP community to pursue R&D studies for future collider options
  - Circular collider: DOE efforts focused on high-field magnet technology to enable higher energy
  - ILC: DOE efforts focused on cost reduction R&D, *e.g.*, nitrogen treatment in SRF cavities has potential for up to 10% cost reductions in 3-5 years, up to 15% in 5-10 years

- Near-term priorities aim to support the LHC program including HL-LHC upgrades

Superconducting Magnets R&D

The US HEP Superconducting Magnet Programs are now integrated into the **US Magnet Development Program**

The program has well-defined goals and is structured with leads who are responsible for delivery

The MDP is fully functioning, with management oversight and technical reviews

HEP is now focusing on successful execution of the important LHC project(s)

Future dedicated R&D a la' LARP will be selected following the next steps in strategic planning – for now we will concentrate on overcoming technological barriers

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Advanced Technology R&D

Advanced Technology R&D supports and advances research at all three experimental Frontiers

Fosters cutting-edge research in the physics of particle beams, accelerator R&D, and particle detection

Three broad categories:

- **Near- to mid-term** directed R&D for facilities/technologies in support of current DOE projects
- **Mid-term**, facility-inspired R&D focused on concepts or technologies to demonstrate feasibility
- **Long-term**, proposal-driven research on the fundamental science to enable breakthroughs in size, cost, beam intensity, beam energy, and control

Recent results:

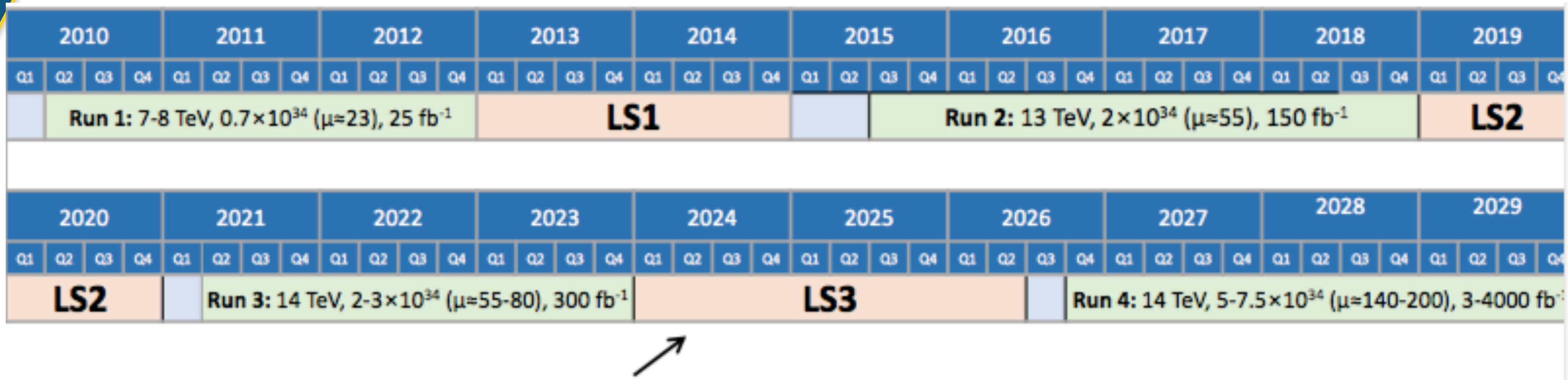
- **Low-Loss Superconducting Radio-Frequency (SRF) Cavities using new processes developed by Fermilab**
  - Linac Coherent Light Source II (LCLS-II), under construction by Basic Energy Sciences (BES), will be first beneficiary
- **Advances in laser-driven and beam-driven plasma wakefield accelerators**
  - Could produce high-gradient accelerators for future machines
- **Record current in high-temperature superconductors**
  - Could enable magnetic field levels that double existing particle collision energies

Conclusions

- The High Luminosity Accelerator Upgrade is now in full execution mode
  - The US part of the project will be baselined in December 2018 and construction will start on magnets, followed by cavities in 2019/2020
- The project transitioned seamlessly from the LARP R&D phase, and it is a testimony to the importance of targeted R&D
- Future dedicated R&D a will be selected following the next steps in strategic planning – for now we will concentrate on overcoming technology challenges

Backup

LHC Schedule



- Long Shutdown 3 (LS3) – a 2.5-year shutdown and installation period beginning in Jan 2024 -- is the overall milestone that drives the upgrade construction completion schedule.

Run	Years	Energy (TeV)	Bunch Spacing (ns)	Peak Lumi (x 10^{34} $cm^{-2}s^{-1}$)	Pileup (pp collisions/crossing)	Total Int. Lumi (fb^{-1})
1	2010-12	7,8	50	0.75	20	30
2	2015-18	13,14	25	1.9	55	150
3	2021-23	14	25	2-3	55-80	300
4	2026…	14	25	5-7.5	140-200	3,000

Mission Need & Capability Gap

- In order to achieve the goals of the LHC research program, it will be **necessary to increase both the energy of the accelerator and the brightness of the colliding beams**.
  - The LHC is now operating at a center of mass collision energy of 13 TeV and it is expected that in the near future (Run 2 & Run 3, by 2019) the energy can be increased to the design energy of 14 TeV.
  - Increasing the beam brightness is more challenging. Over a period of two and a half years in 2024-2026, an upgrade to the LHC will be installed (HL-LHC). After this work, the beam brightness will be approximately three times higher than is currently possible.
- The expected instantaneous luminosity (beam brightness) is expected to have an ultimate value of 7.5 x 10^{34} $cm^{-2}s^{-1}$.
- **The increase from 2–3 x 10^{34} $cm^{-2}s^{-1}$ through 2023 to an ultimate value of 7.5 x 10^{34} $cm^{-2}s^{-1}$ in 2026 is the capability gap described in the Mission Need for the AUP project**
- A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling** will allow to integrate **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade - *more than ten times the luminosity reach of the first 10 years of the LHC lifetime*

Project Scope & KPP

Parameters	Threshold Performance	Objective Performance
302.2 Inner Triplet Focusing Quadrupoles (Q1 and Q3)	a) 5 Q1-Cryoassemblies and 4 Q3-Cryoassemblies are accepted by CERN after testing at HL-LHC nominal temperature and ultimate gradient for the magnets, and functionality for the Cryoassembly. The Cryoassemblies will be assembled from Cold Masses built by HL-LHC AUP and Cryostat kits and tools provided by CERN. b) Procurement of components for 1 additional Q3 Cold Mass	1 additional Q3-Cryoassembly is accepted by CERN after testing at HL-LHC nominal temperature and ultimate gradient for the magnets, and functionality for the Cryoassembly. The Cryoassembly will be assembled from Cold Masses built by HL-LHC AUP and Cryostat kits and tools provided by CERN
302.3 SRF Crab Cavities	a) 8 Radio Frequency Dipoles (RFDs) Dressed cavities for the HL-LHC Crab Cavity System are accepted by CERN after being tested at HL-LHC nominal temperature, nominal frequency, and ultimate cavity voltage. Dressed cavities include HOM couplers, pick-ups, He Vessel and magnetic shields. b) Procurement of components for 2 additional RFD Dressed Cavities	2 additional Radio Frequency Dipoles (RFDs) Dressed cavities for the HL-LHC Crab Cavity System are accepted by CERN after being tested at HL-LHC nominal temperature, nominal frequency, and ultimate cavity voltage. Dressed cavities include HOM couplers, pick-ups, He Vessel and magnetic shields.

Deliverables:
5 Q1 and 5 Q3 Cryoassembly

50% of the **Q1**/Q2a & b/ **Q3** Final Focusing Triplets of HL-LHC

Deliverables:
10 Dressed RFD Cavities

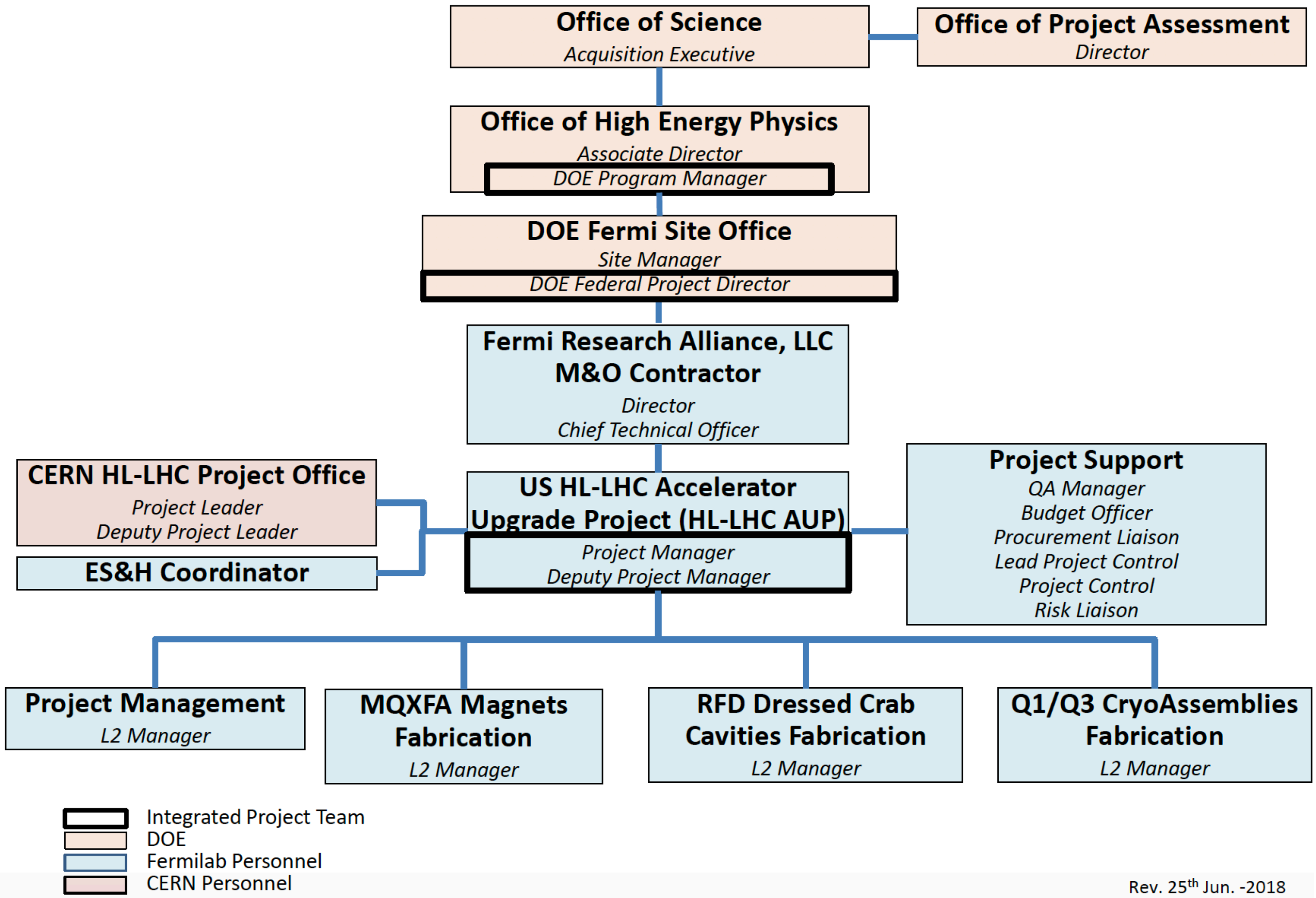
RFDs are 50% of the total number of Crab Cavities for HL-LHC

Need-by Delivery Date (from CERN):

Q1/Q3 — Cryoassembly #8 at CERN by Summer '24

RFD — Dressed Cavity #8 at CERN by Summer-Fall '23

Project Organization



Rev. 25th Jun. -2018

Analysis of Alternatives

- **Overarching criteria used to select preferred option**:
  - agreement from CERN on the selected option including their evaluation of the quality of the technical solution,
  - benefits to the U.S. accelerator community,
  - Life-cycle costs.
- **Options**:
  1. Develop Suite of in-kind Contributions
  2. Provide CERN with Cash Payment (1a) or Associate Membership (2b)
  3. Do Nothing
- **Pre-conceptual & Conceptual development on basis of 2 additional criteria**:
  - The contribution needs to be compatible with the CERN needs in terms of scope contribution and planned schedule.
  - The contribution need to maximize scientific return for both CERN and U.S. scientists active in the accelerator physics community and … should maximally exploit the U.S. scientific expertise and DOE investment in technology R&D, providing components for which CERN doesn't (yet) have the same competence and/or proficiency.

DOE/HEP Major lab investments

Argonne National Laboratory

- Cross-disciplinary R&D with material science and advanced computing, including instrumentation
- Dielectric accelerator R&D with the Argonne Wakefield Accelerator
- Computational Cosmology
- High performance computing applications in HEP, leveraging Argonne Leadership Computing Facility (ALCF)

Berkeley Lab

Lawrence Berkeley National Laboratory

- Laser-driven plasma wakefield accelerator technology (BELLA)
- Silicon detectors for LHC, dark matter, and dark energy experiments
- Leveraging NERSC for high-throughput computing & large-scale simulations and Energy Sciences Network (ESnet) for big data transfer, including LHC
- Host Lab for LZ experiment and Dark Energy Spectroscopic Instrument (DESI)

Brookhaven National Laboratory

- Brookhaven Accelerator Test Facility
- Detector R&D and readout development, leveraging Instrumentation Division
- Host Lab for U.S. ATLAS, hosting ATLAS Tier-1 computing center

Fermilab

- Fermilab Accelerator Complex User Facility supports beam-driven neutrino science and precision science experiments
- Superconducting RF accelerator technology, high-intensity particle beams and high-power targets
- Extensive infrastructure for accelerator and detector R&D, including specialized facilities for design, fabrication and testing
- Host Lab for LBNF/DUNE and U.S. CMS, hosting CMS Tier-1 computing center

SLAC National Accelerator Laboratory

- Beam-driven plasma wakefield accelerator technology (FACET)
- Kavli Institute for Particle Astrophysics and Cosmology
- Host Lab for SuperCDMS-SNOLAB dark matter experiment and Large Synoptic Survey Telescope