HEPAP view and
U.S. activities on future colliders

FCC Week 2016;   11 April 2016

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Chair, High Energy Physics Advisory Panel
University of California, Irvine

Credits & Apologies

I thankfully acknowledge all of the scientists who have helped me to assemble this talk. There have been too many for me to list individually here. I apologize.

I would like to acknowledge Steve Gourlay, who unfortunately had to cancel his attendance here and his presentation on high-field magnet development.

This presentation shows some specific examples of detector, experiment, and machine studies relating to future colliders with which I am familiar.

It misses some, or perhaps many, others

Please recall also that much R&D occurring for "nearby" colliders such as HL-LHC & ILC, as well as generic R&D, in the realms of accelerators and detectors are of relevance to "future" colliders such as FCC.

I will show some important examples in the realm of accelerator technology.

HEPAP "View"

What is HEPAP, and how is the HEPAP view formed?

HEPAP = High Energy Physics Advisory Panel for DOE & NSF

A HEPAP subpanel, P5, was responsible for developing a strategic plan, executable over 10 years, in the context of a 20-year global vision, in *realistic* budget scenarios

- P5 = Particle Physics Project Prioritization Panel
- The P5 plan built upon a year-long HEP community study of scientific opportunities ("Snowmass" study).
- The P5 plan is science-driven.
- The P5 plan was developed under very strict budget guidance.
- P5 Report was submitted by HEPAP in May 2014.
- The P5 plan is now being executed by the agencies.

☐ **The P5 report discussed future colliders, and it noted the need to align accelerator R&D with the program's strategic vision.**

☐ **An Accelerator R&D Subpanel was formed to deliver a plan for R&D that is aligned with the P5 plan. It reported in April 2015.**

Three Overarching Recommendations of P5

Particle Physics is a Global Field of Discovery

- The scientific program required to address all of the most compelling questions of the field is beyond the finances and technical expertise of any one nation or region.
- **The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions**
  - if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere.
  - Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision.
- *P5-1:* ***Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.***

The HEP program must be science-driven.

- **P5 identified 5 science *drivers* and recommended:**
- *P5-2:* ***Pursue a program to address the 5 science drivers.***

Temporarily cut R&D to invest in projects for the next discoveries.

- ***P5-5: Increase the budget fraction invested in construction of projects to the 20%–25% range.***

P5: Near-term and Mid-term High-Energy Colliders - LHC

LHC thru HL-LHC

The enormous physics potential of the LHC should be fully exploited.

P5-10 Complete the LHC phase-1 upgrades *and*

continue the strong collaboration in the LHC with

the phase-2 (HL-LHC) upgrades *of the*

accelerator *and*

both general-purpose experiments *(ATLAS and CMS)****.***

The LHC upgrades constitute our highest-priority near-term large project.

U.S. R&D for the Hi-Lumi LHC accelerator upgrade is performed by LARP.

P5: Near-term and Mid-term High-Energy Colliders - ILC

Interest expressed in Japan in hosting the ILC is an exciting development.

- **An e+e- collider can provide the next outstanding opportunity [after LHC/HL-LHC] to investigate the properties of the Higgs in detail.**
- The ILC is the most mature in its design and readiness for construction.
- As the physics case is extremely strong, all scenarios include ILC support at some level through a decision point within the next 5 years.
- Participation by the U.S. in project construction depends on a number of important factors, some of which are beyond the scope of P5 and some of which depend on budget scenarios.

P5-11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

ILC in Scenario C (the ‘unconstrained” budget scenario)**:**

> ***Should the ILC go forward, Scenario C would enable the U.S. to play world-leading roles in the detector program as well as provide critical expertise and accelerator components.***

- **Historically, U.S. investment in ILC has been high, particularly in SRF.**
- **At present, R&D investment is very modest in light of budget priorities, but generic SRF development continues.**

P5: Far-term Future-Generation Accelerators

The motivation for future-generation accelerators must be the Science Drivers

A very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window.

Participate in global design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.

A multi-TeV *e+e–* collider could be based on either the Compact Linear Collider (CLIC) or plasma-based wakefield technology.

Muon colliders can reach higher energies than *e+e–* accelerators, but have many technical challenges. Addressing all of the necessary challenges would require a very strong physics motivation based on results from ongoing or future accelerators. *[In part, this rationale led to winding down the Muon Accelerator Program directed R&D project.]*

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.

P5 Vision of Possible Future HEP Facilities

Three techniques for inquiry:

	Intensity Frontier Accelerators	Hadron Colliders	Lepton Colliders
Current Efforts	**PIP**	**LHC**	
	PIP-II	**HL-LHC**	**ILC**
Next Steps	**Multi-MW proton beam**	**100 TeV class *pp* collider**	1 TeV class energy upgrade of ILC*
Further Future Goals	Neutrino factory*	higher energies*	Multi-TeV e^+e^- collider*

**dependent on how physics unfolds*

Accelerator R&D – in Scenario C

P5 Scenario C presents 3 options. One focuses on accelerator R&D:

Move boldly forward with transformational accelerator R&D.

- **A primary goal = dramatically lower cost.**
- **For example,**
  - **pp colliders - high-field accelerator magnets**
  - **e^+e^- colliders - improving the accelerating gradient and lowering the power consumption.**
  - Although these topics are R&D priorities in the constrained budget scenarios, larger investments could make these far-future accelerators technically and financially feasible on much shorter timescales.

○ **Large, positive impacts beyond particle physics.**

As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.

ILC

DOE Goals for ILC Work

- Japan has expressed interest in hosting the International Linear Collider (ILC) and is actively working through a decision making process
- As recommended in the P5 strategic plan, DOE plans to provide modest and appropriate support through the period of Japanese decision making
  - U.S. has played key roles in the design of the ILC accelerator, including leadership in the Global Design Effort
  - Continued intellectual contributions to the accelerator and detector design are still necessary to enable a site-specific bid proposal
  - P5 recommended ILC support at some level in all budget Scenarios through a decision point within the next 5 years
- DOE is making an effort to maintain ILC accelerator activities in balance with other programmatic priorities

Superconducting RF R&D

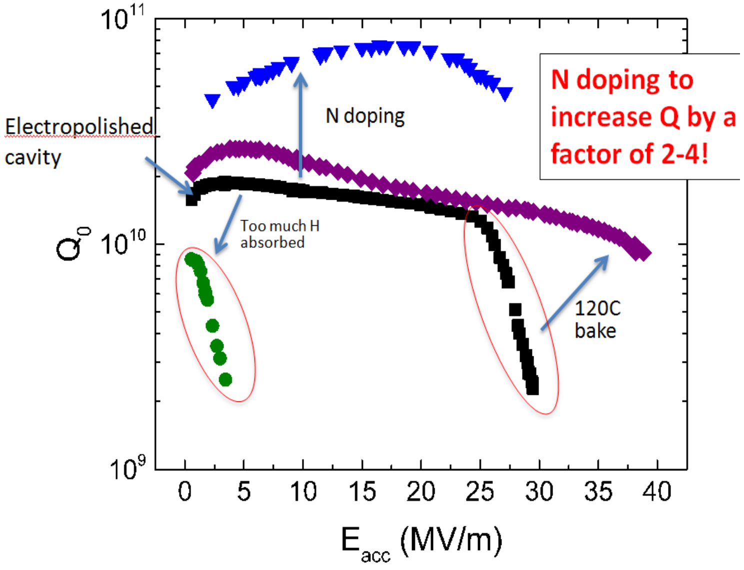
Ongoing SRF R&D is yielding developments valuable to ILC and other future colliders.
- in Generic Accelerator R&D (GARD) program
- for Linear Coherent Light Source II (LCLS-II) at SLAC
- for Proton Improvement Plan II (PIP-II) linac at Fermilab.

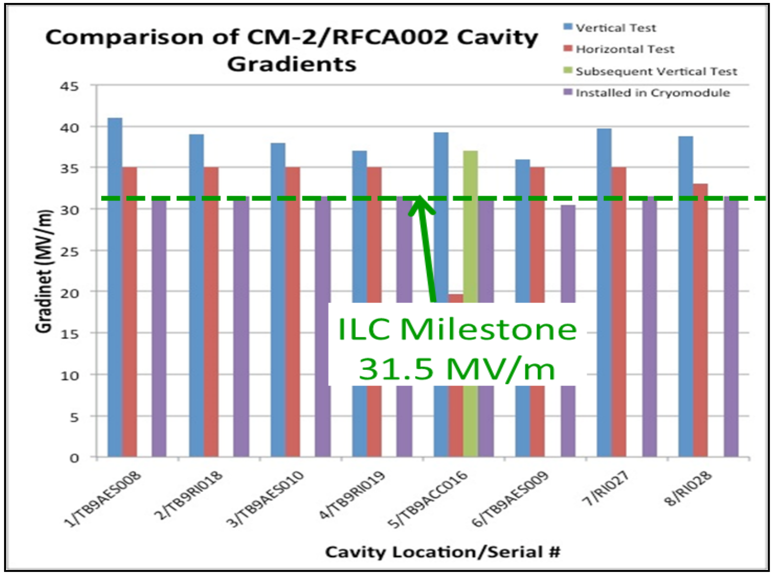
Q_0 Improvements

- Nitrogen doping improves Q by factor 2-4
- Technology has been successfully transferred to industry for LCLS-II production.

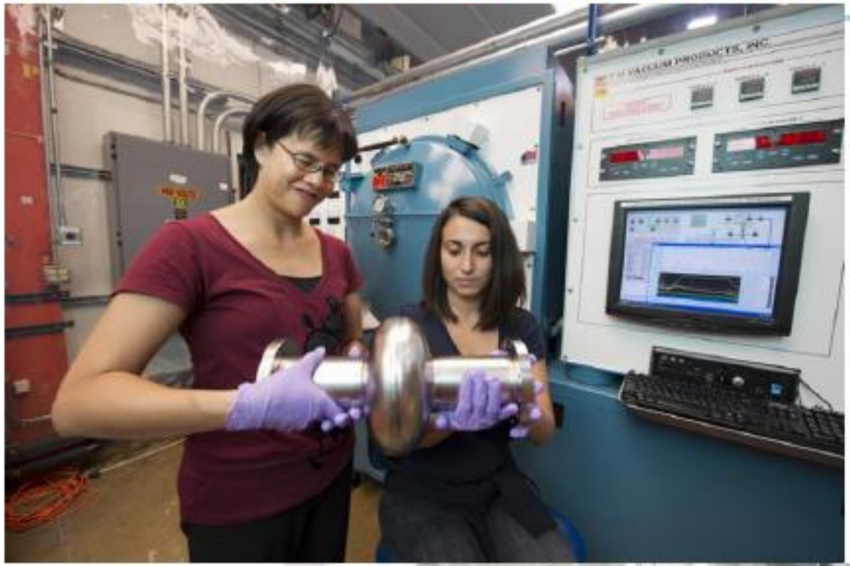
Gradient Improvements

- Complete U.S. cryomodule meets ILC specs.
- Ongoing R&D in GARD

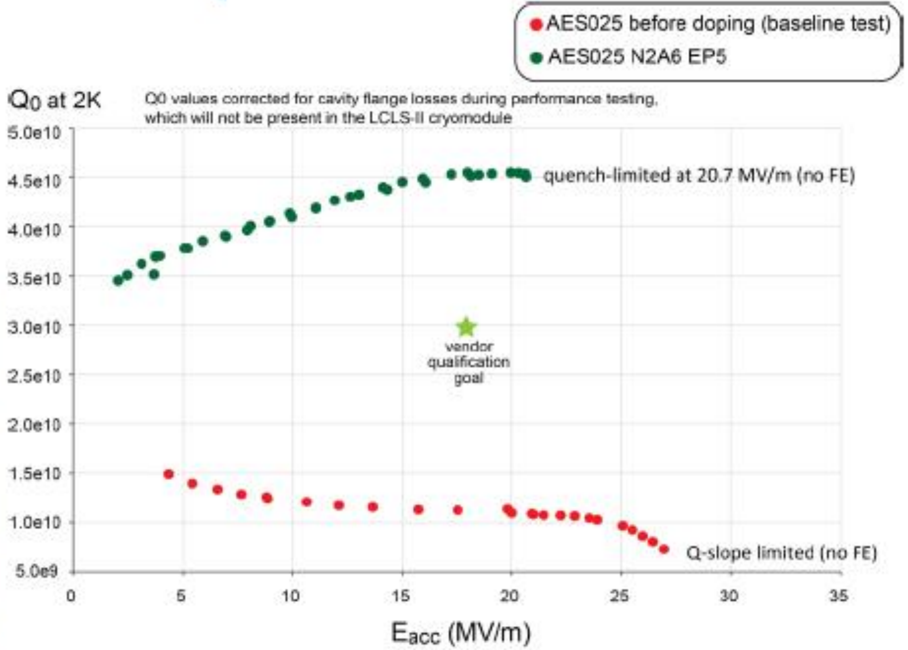




First Dressed Cavities Emerge from Clean Room for LCLS-II



Successful nitrogen doping technology transfer to industry for LCLS-II production



Q0 values corrected for cavity flange losses during performance testing, which will not be present in the LCLS-II cryomodule

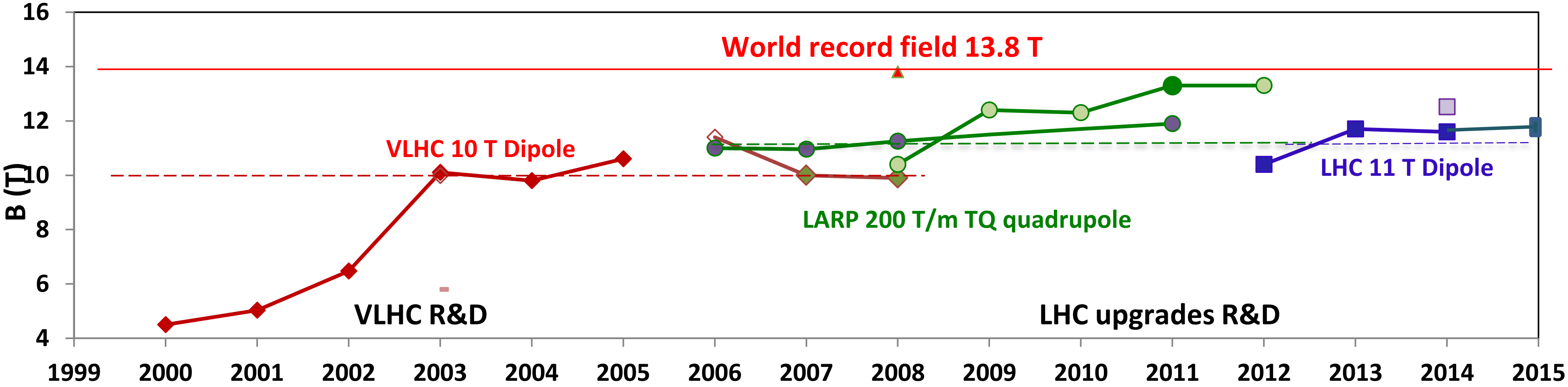
Project advances our hi-tech infrastructure & know how

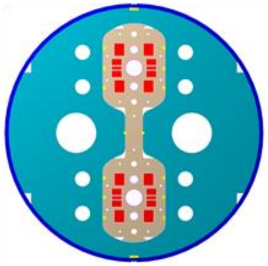
Debating whether we plan for additional projects…e.g. Brazil

HI-LUMI LHC

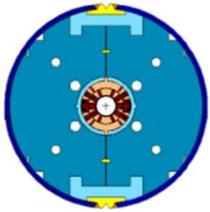
High Field Nb_3Sn Magnet R&D

- **U.S. has a history of collaboration with CERN and global partners in superconducting magnet R&D, with particular emphasis on Nb_3Sn technology**
  - **U.S. LHC Accelerator Research Program (LARP) aims to leverage this expertise to serve the needs of HEP community on the Hi-Lumi LHC.**

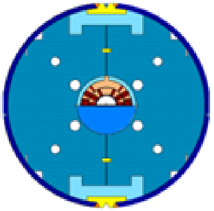




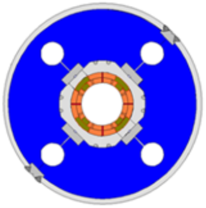
HFDC (R&W)
40 mm 10 T dipole



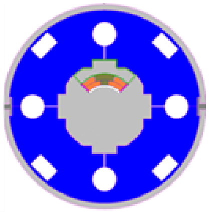
HFDA
43.5 mm
10 T dipole



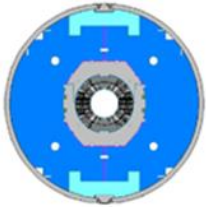
HFDM-LM
Dipole mirror



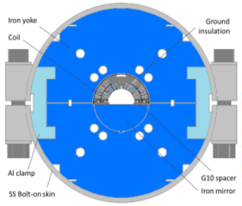
TQC
90 mm 200 T/m
quadrupole



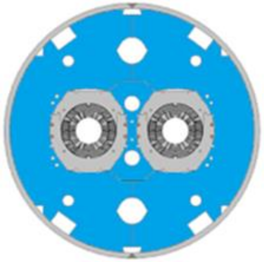
TQM-LQM
Quadrupole
mirror



MBHSP
60 mm 11 T dipole



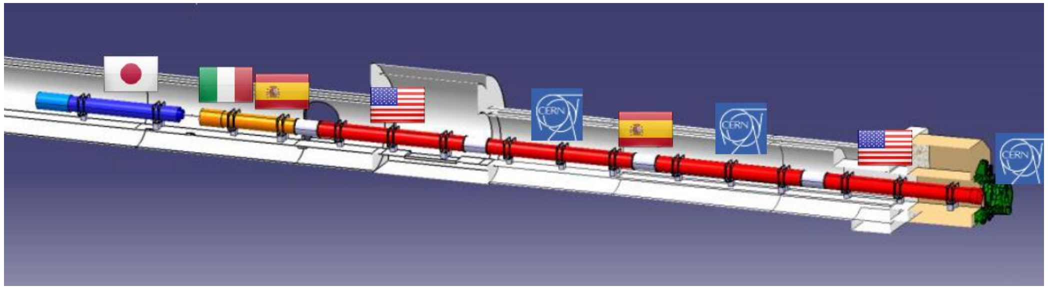
MBHSM
Dipole mirror



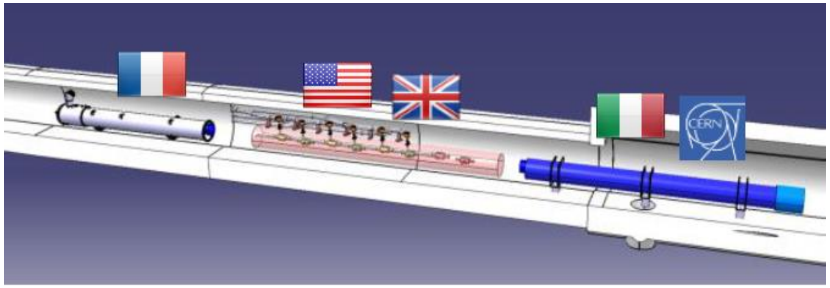
MBHDP
60 mm 11 T dipole

U.S. LHC Accelerator Research Program (LARP)

- LARP is a national R&D program managed from Fermilab with the goal of preparing the U.S. to actively participate in the LHC High-Luminosity Upgrade
    - **Collaborating U.S. National Laboratories: BNL, FNAL, LBNL, SLAC**
- Goals of the LARP program include:
    - Build and test prototype Intersection Region **(IR) quadrupoles**
    - **Commission the tooling production**
    - Deliver **crab cavities** for SPS test
    - Deliver **Wide Band Feedback System** for SPS test
    - Support studies of **hollow electron beam lens**
    - **Prepare** for U.S. contributions to the Hi-Lumi LHC through the **U.S. HL-LHC Accelerator Upgrade Project**



HL-LHC Intersection Region Magnets

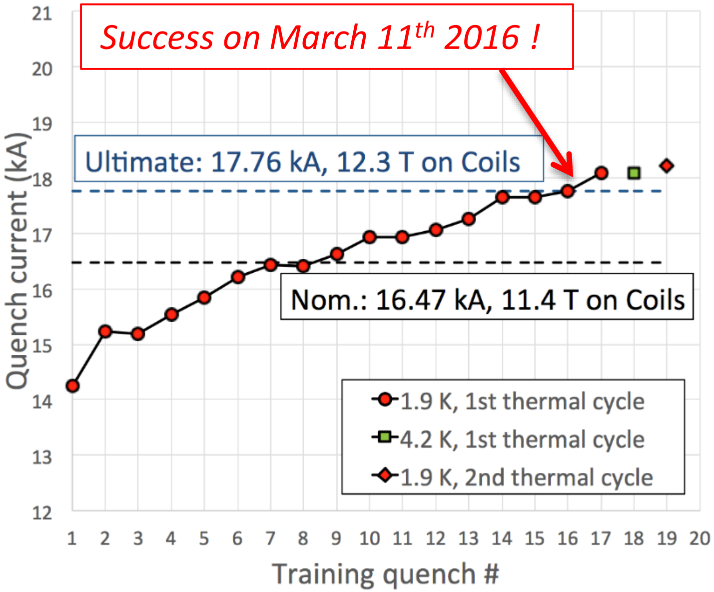


HL-LHC Crab Cavities

Success on First MQXF Magnet !

- **First full quadrupole model (1 m long – 150 mm ID,** labeled MQXFS1**) for HL-LHC assembled at LBL and tested at FNAL.**
    - The model contains 2 coils from US-LARP and 2 coils from CERN. One of the first accelerator magnets with coils from different manufacturers.
    - A coil in mirror configuration was tested at FNAL with good results earlier in ‘15.
- **MSQXFS1 achieved HL-LHC “operating current” (16.5kA) in ~7-8 quenches and surpassed the “ultimate current” level requested to insure appropriate margin for HL-LHC operations.**
    - Confirmation of MQXF design “soundness”
    - Confirmation of magnet “memory” after warm-up/cool-down cycle
    - Measurements being finalized in Apr. ‘16 on other magnet features: field quality, quench protection, etc.


Assembly at LBL – Summer-Fall ’15

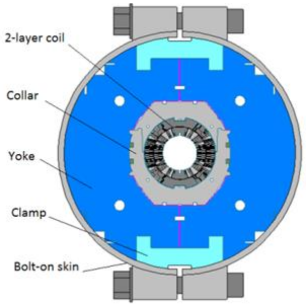

Success on March 11th 2016 !

Ultimate: 17.76 kA, 12.3 T on Coils

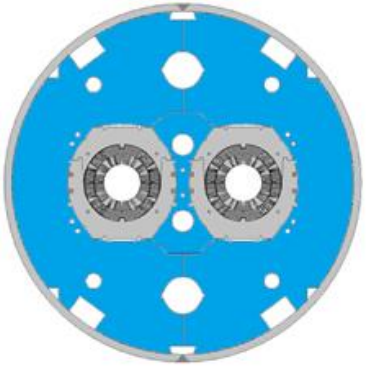
Nom.: 16.47 kA, 11.4 T on Coils

11 T Dipoles for Hi-Lumi LHC

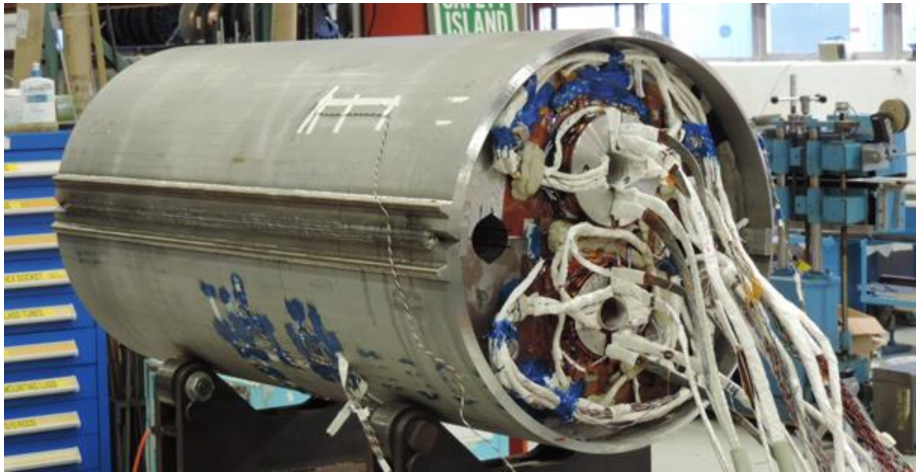
- Collaboration with CERN
- US role in development only
- US built:
  - ❑ 5 single-aperture models (1m):
    - ○ B_{max}= 11.6 T MBHSP02, MBHSP03
  - ❑ Twin-aperture model (2m):
    - ○ B_{max}= 11.5 T MBHDP01
    - ○ Testing ongoing

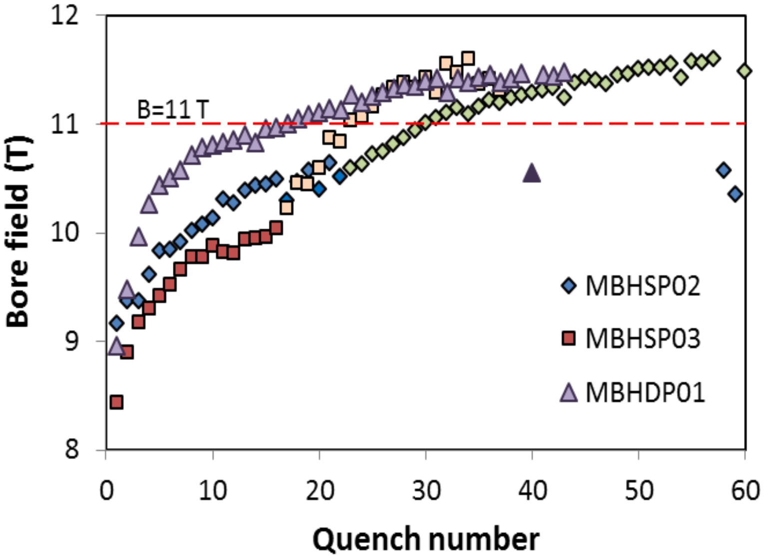


MBHSP02, MBHSP03



MBHDP01





SC Magnet Fabrication and Testing Facilities

LARP leverages US infrastructure to meet HL-LHC R&D goals.

- Nb_3Sn IR quadrupole magnet efforts build on strand and cable technology developed by the U.S. HFM R&D program

- The IR quads, along with the HFM 11T dipole, will be the first Nb_3Sn accelerator magnets


Strand and Cable Lab


Short Coil Winding Table

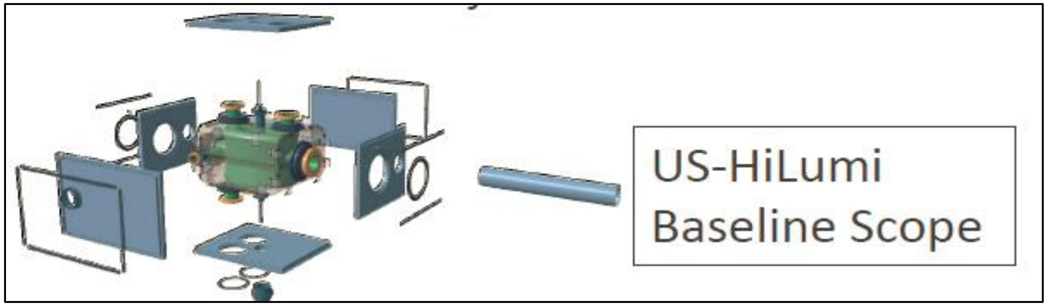

Coil Reaction Oven

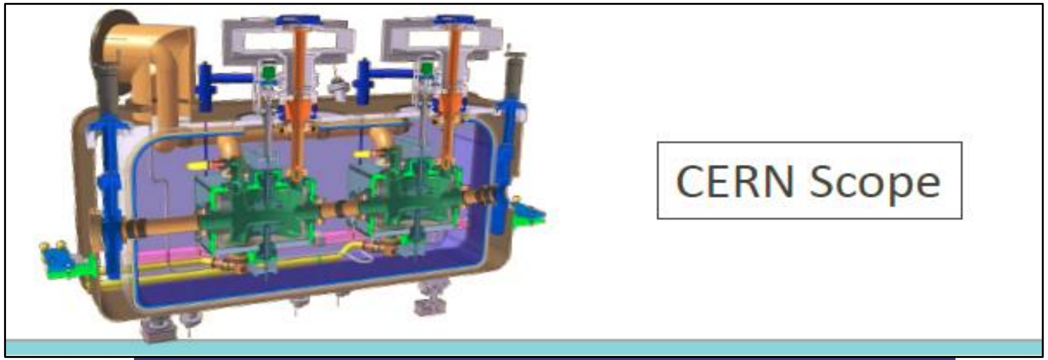

Coil Forming Press

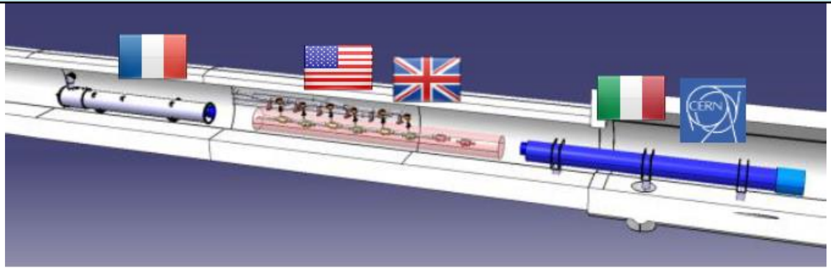

Vertical Magnet Test Facility

Crab Cavities for HL-LHC IR's

40 He-Vessel Dressed Crab Cavities
with HOM and tuners







LARP → U.S. HL-LHC Accelerator Upgrade Project

- **Transition from R&D to Project in 2018**
- US deliverables and Project scope not yet finalized.
- DOE approval of CD-0 “Mission Need” this week.
- **Tentative scope:**
  - (dependent on hollow e-lens being in baseline):

  50% of IR quad cold masses

  50% of crab cavities

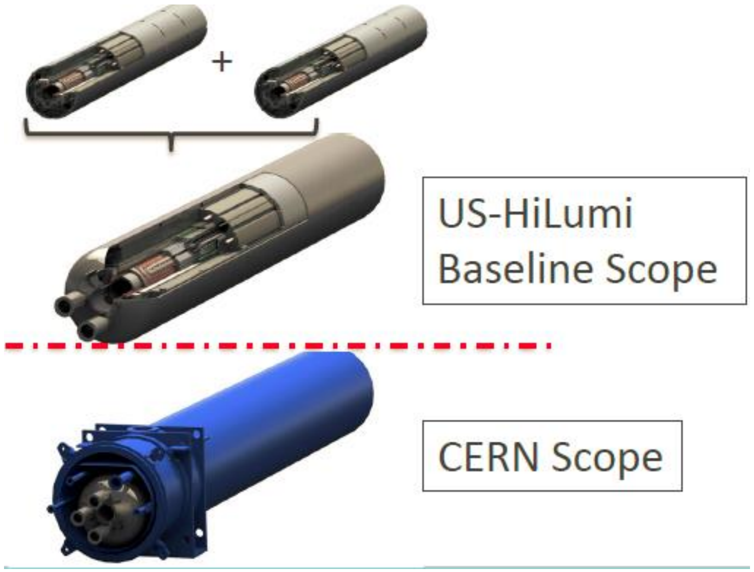
  hollow e-lens

  later (by LS4):

    50% of crab cavities

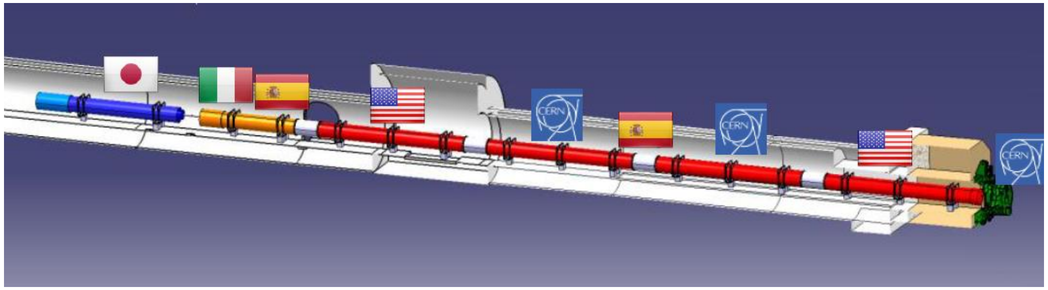
    compensator
- A major contribution from US-HEP to LHC infrastructure.

Magnets are principal US deliverable

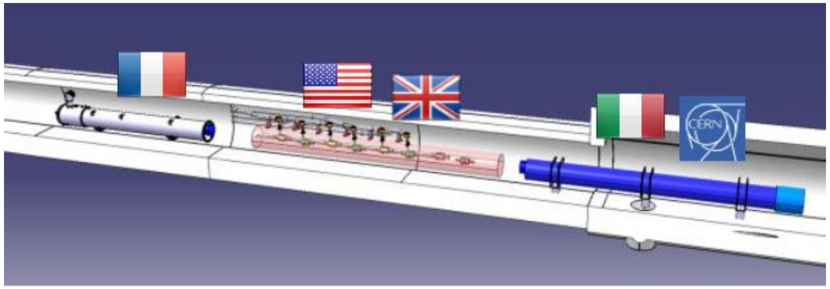


US-HiLumi Baseline Scope

CERN Scope



HL-LHC Intersection Region Magnets



HL-LHC Crab Cavities

PHYSICS AND DETECTOR STUDIES FOR FUTURE (CIRCULAR) COLLIDERS

EXTENSIVE HL-LHC & ILC STUDIES HAVE BEEN PERFORMED

SNOWMASS CSS 2013

ON THE MISSISSIPPI

JULY 29 – AUGUST 6, 2013

ORGANIZED BY THE DIVISION OF PARTICLES AND FIELDS OF THE APS

HOSTED BY THE UNIVERSITY OF MINNESOTA

STUDY GROUPS

Energy Frontier
  Chip Brock *(Michigan State)*,
  Michael Peskin *(SLAC)*
Intensity Frontier
  JoAnne Hewett *(SLAC)*,
  Harry Weerts *(Argonne)*
Cosmic Frontier
  Jonathan Feng *(University of California, Irvine)*,
  Steve Ritz *(University of California, Santa Cruz)*
Frontier Capabilities
  William Barletta *(MIT)*,
  Murdock Gilchriese *(LBNL)*
Instrumentation Frontier
  Marcel Demarteau *(Argonne)*,
  Howard Nicholson *(Mt. Holyoke)*,
  Ron Lipton *(Fermilab)*
Computing Frontier
  Lothar Bauerdick *(Fermilab)*,
  Steven Gottlieb *(Indiana)*
Education and Outreach
  Marge Bardeen *(Fermilab)*,
  Dan Cronin-Hennessy *(Minnesota)*
Theory Panel
  Michael Dine *(University of California, Santa Cruz)*

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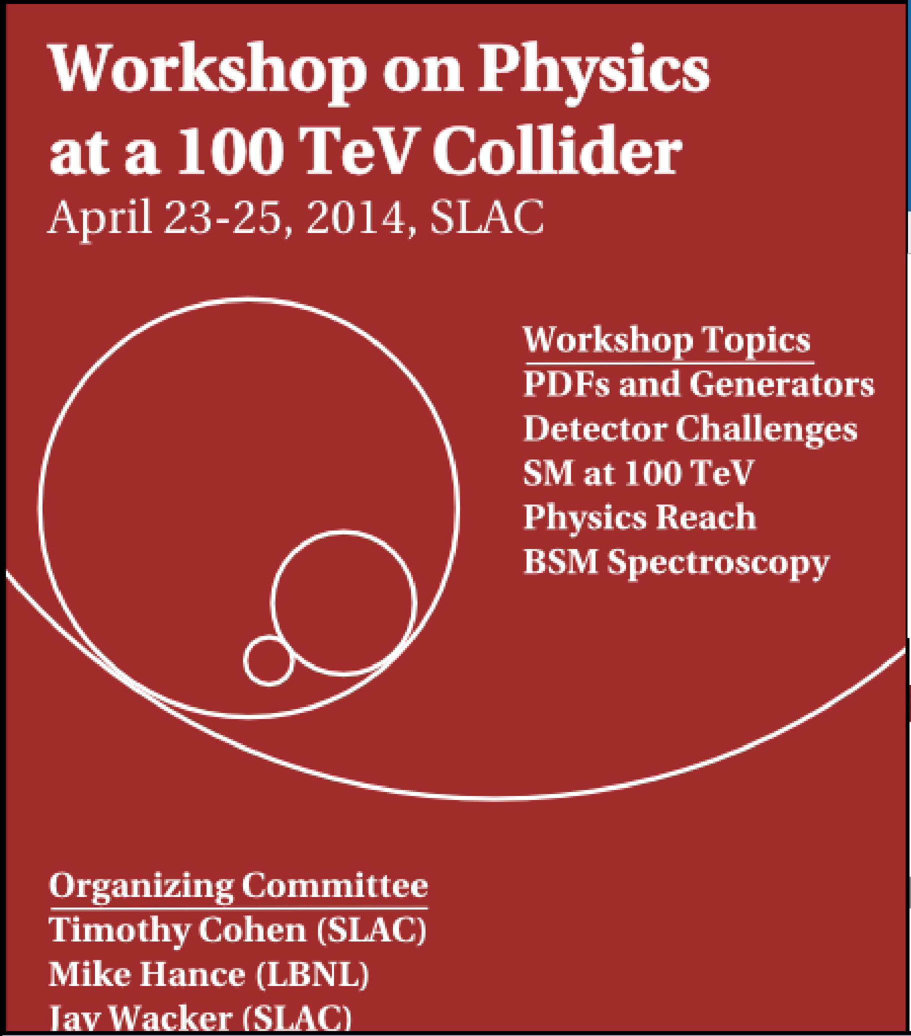
WWW.SNOWMASS2013.ORG

POSTER DESIGN BY KATIE SCHALOW

Studies restarted at Snowmass 2013

- HEP community study of compelling science opportunities in the coming decades
- This study provided the science basis for P5 prioritization.

http://www.slac.stanford.edu/econf/C1307292/

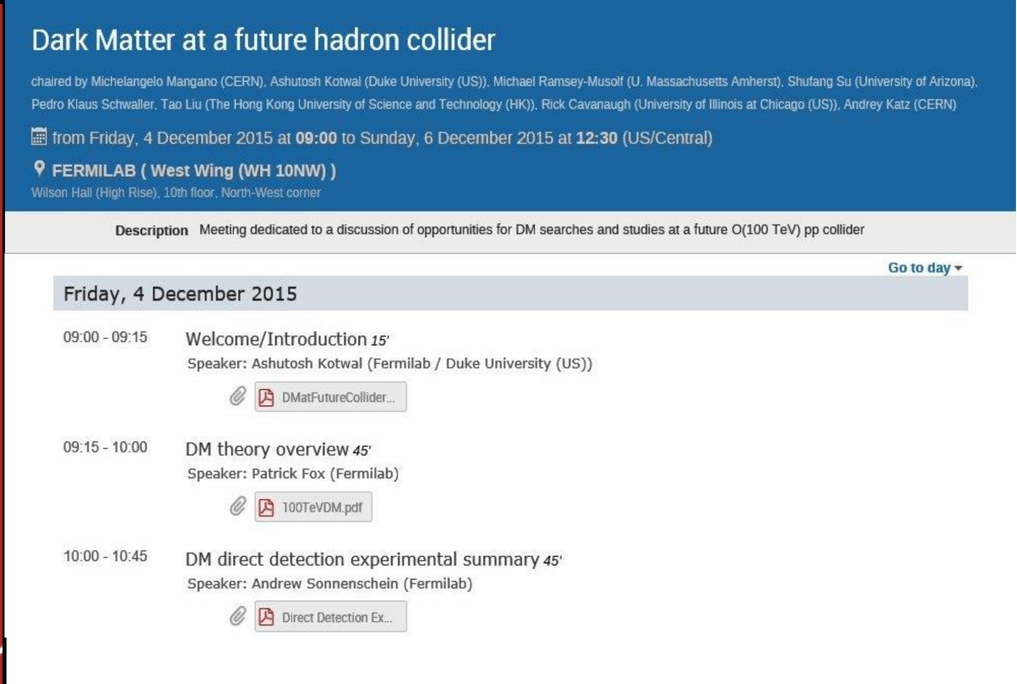


Workshop on Physics at a 100 TeV Collider

April 23-25, 2014, SLAC

Workshop Topics
PDFs and Generators
Detector Challenges
SM at 100 TeV
Physics Reach
BSM Spectroscopy

Organizing Committee
Timothy Cohen (SLAC)
Mike Hance (LBNL)
Jay Wacker (SLAC)



Dark Matter at a future hadron collider

chaired by Michelangelo Mangano (CERN), Ashutosh Kotwal (Duke University (US)), Michael Ramsey-Musolf (U. Massachusetts Amherst), Shufang Su (University of Arizona), Pedro Klaus Schwaller, Tao Liu (The Hong Kong University of Science and Technology (HK)), Rick Cavanaugh (University of Illinois at Chicago (US)), Andrey Katz (CERN)

from Friday, 4 December 2015 at **09:00** to Sunday, 6 December 2015 at **12:30** (US/Central)

FERMILAB (West Wing (WH 10NW))
Wilson Hall (High Rise), 10th floor, North-West corner

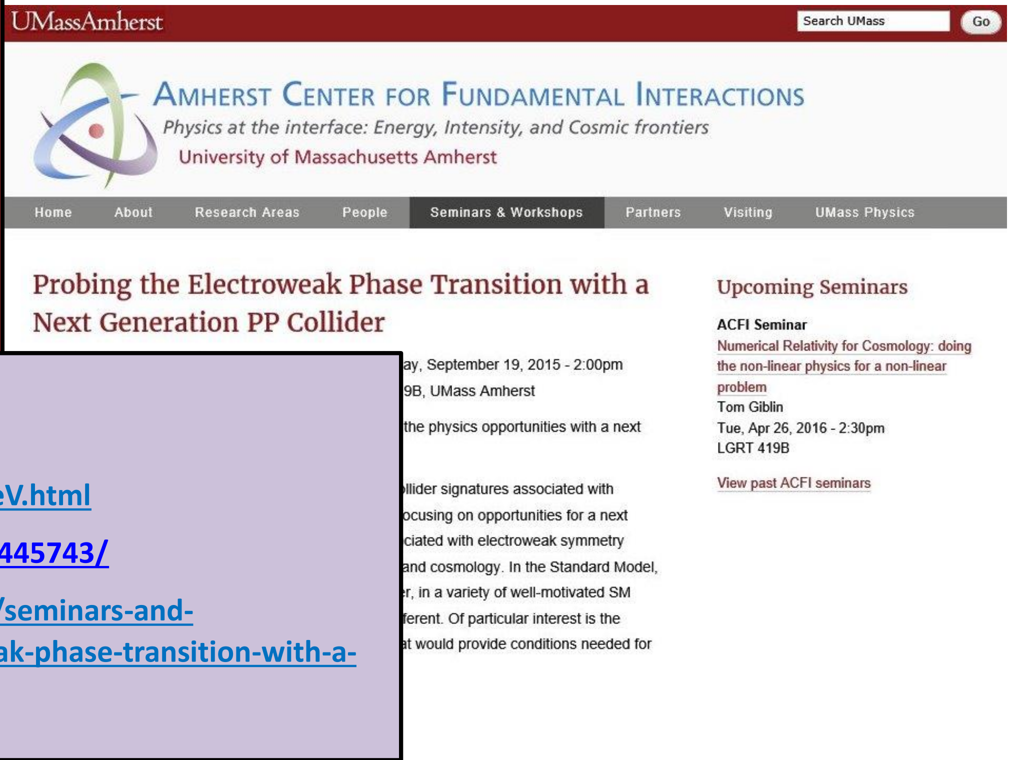
Description Meeting dedicated to a discussion of opportunities for DM searches and studies at a future O(100 TeV) pp collider

Friday, 4 December 2015

09:00 - 09:15 Welcome/Introduction *15'*
Speaker: Ashutosh Kotwal (Fermilab / Duke University (US))
DMatFutureCollider...

09:15 - 10:00 DM theory overview *45'*
Speaker: Patrick Fox (Fermilab)
100TeVDM.pdf

10:00 - 10:45 DM direct detection experimental summary *45'*
Speaker: Andrew Sonnenschein (Fermilab)
Direct Detection Ex...



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Probing the Electroweak Phase Transition with a Next Generation PP Collider

ay, September 19, 2015 - 2:00pm
9B, UMass Amherst

the physics opportunities with a next

llider signatures associated with
ocusing on opportunities for a next
ciated with electroweak symmetry
and cosmology. In the Standard Model,
r, in a variety of well-motivated SM
ferent. Of particular interest is the
t would provide conditions needed for

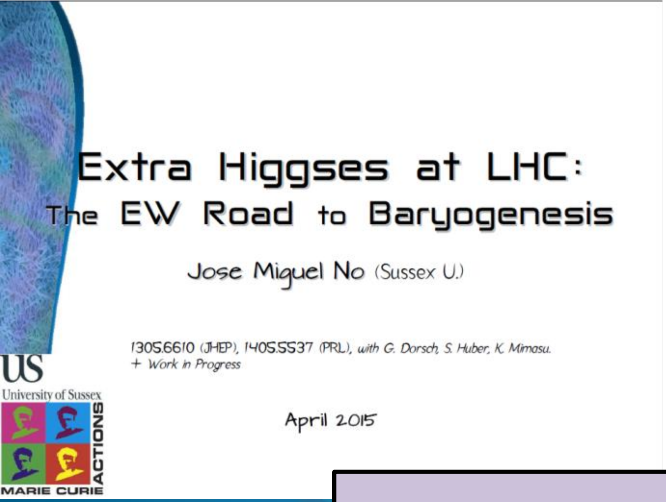
Upcoming Seminars

ACFI Seminar
Numerical Relativity for Cosmology: doing the non-linear physics for a non-linear problem
Tom Giblin
Tue, Apr 26, 2016 - 2:30pm
LGRT 419B

View past ACFI seminars

Physics Workshops

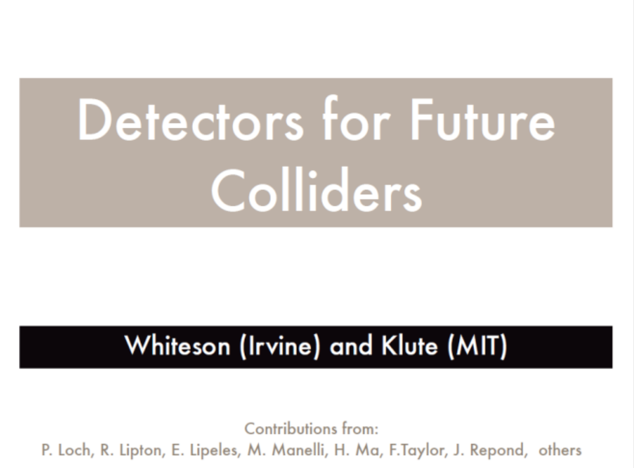
SLAC: www.slac.Stanford.edu/th/100TeV.html
Fermilab: https://indico.cern.ch/event/445743/
UMass: http://www.physics.umass.edu/acfi/seminars-and-workshops/probing-the-electroweak-phase-transition-with-a-next-generation-pp-collider


Extra Higgses at LHC:
The EW Road to Baryogenesis

Jose Miguel No (Sussex U.)

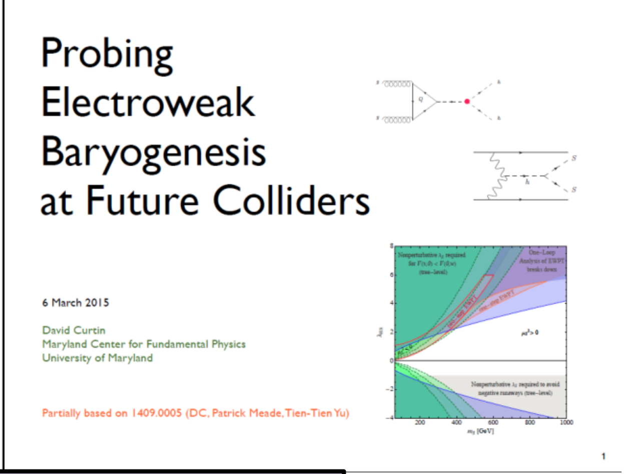
1305.6610 (JHEP), 1405.5537 (PRL), with G. Dorsch, S. Huber, K. Mimasu.
+ Work in Progress

April 2015


Detectors for Future Colliders

Whiteson (Irvine) and Klute (MIT)

Contributions from:
P. Loch, R. Lipton, E. Lipeles, M. Manelli, H. Ma, F.Taylor, J. Repond, others


Probing
Electroweak
Baryogenesis
at Future Colliders

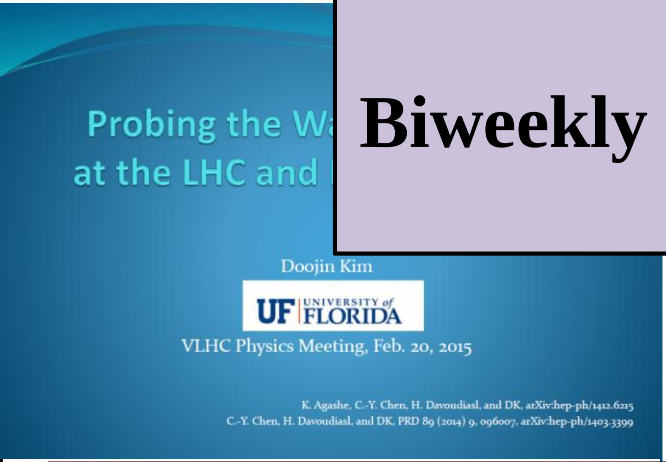
6 March 2015

David Curtin
Maryland Center for Fundamental Physics
University of Maryland

Partially based on 1409.0005 (DC, Patrick Meade, Tien-Tien Yu)

Biweekly Physics Seminars at Fermilab

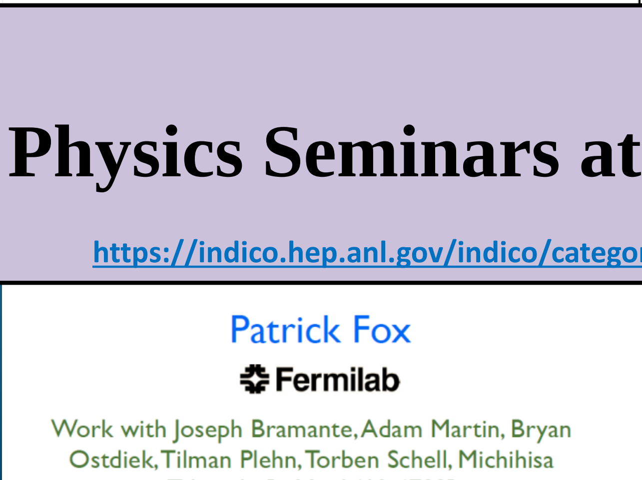
https://indico.hep.anl.gov/indico/categoryDisplay.py?categId=26


Probing the W
at the LHC and

Doojin Kim

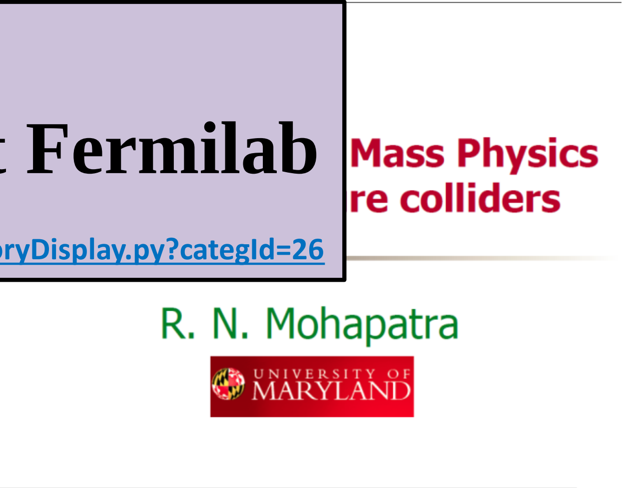
VLHC Physics Meeting, Feb. 20, 2015

K. Agashe, C.-Y. Chen, H. Davoudiasl, and DK, arXiv:hep-ph/1412.6215
C.-Y. Chen, H. Davoudiasl, and DK, PRD 89 (2014) 9, 096007, arXiv:hep-ph/1403.3399


Patrick Fox

Fermilab

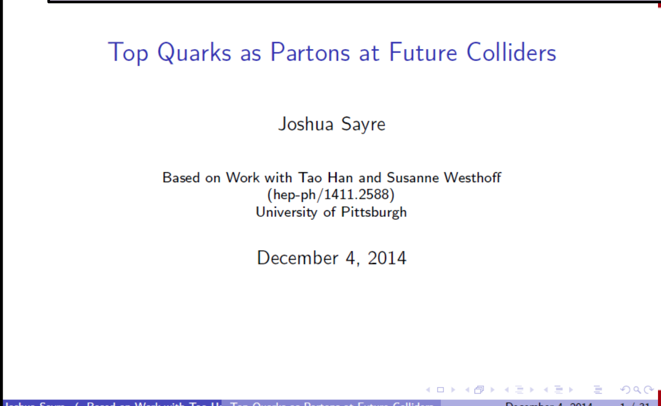
Work with Joseph Bramante, Adam Martin, Bryan Ostdiek, Tilman Plehn, Torben Schell, Michihisa Takeuchi [arXiv:1412.4789]


Mass Physics
re colliders

R. N. Mohapatra

UNIVERSITY OF MARYLAND

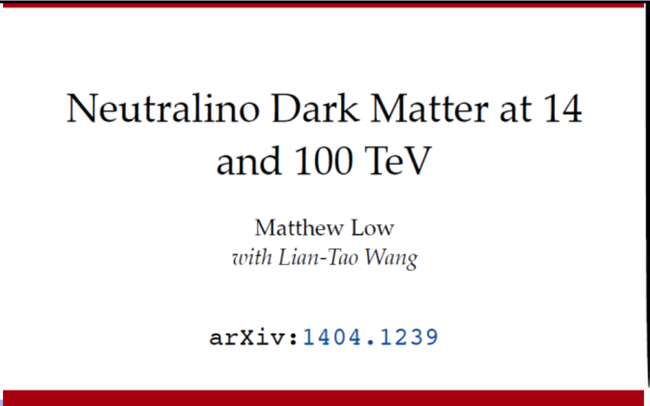
Many individual papers developed from, or as basis for, these workshops and seminars


Top Quarks as Partons at Future Colliders

Joshua Sayre

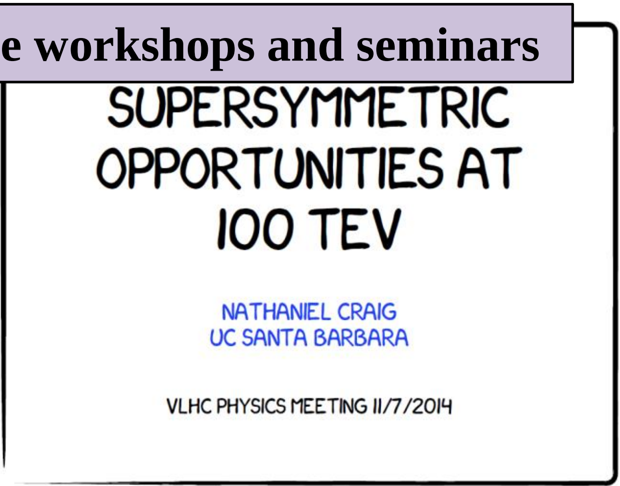
Based on Work with Tao Han and Susanne Westhoff
(hep-ph/1411.2588)
University of Pittsburgh

December 4, 2014


Neutralino Dark Matter at 14 and 100 TeV

Matthew Low
with Lian-Tao Wang

arXiv:1404.1239


SUPERSYMMETRIC OPPORTUNITIES AT 100 TEV

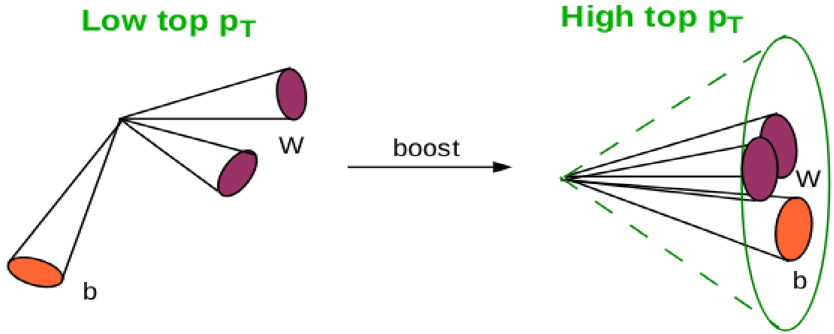
NATHANIEL CRAIG
UC SANTA BARBARA

VLHC PHYSICS MEETING 11/7/2014

High-granularity Calorimetry for FCC-hh

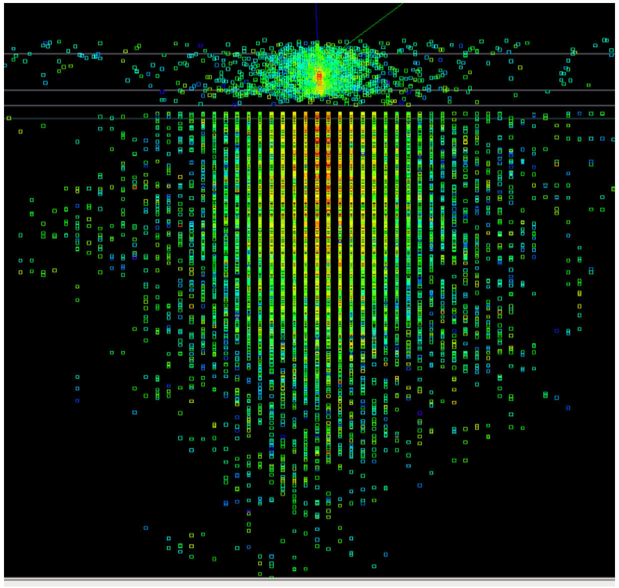
(a sample detector study)

For instance, for boosted jet studies at very-high energy



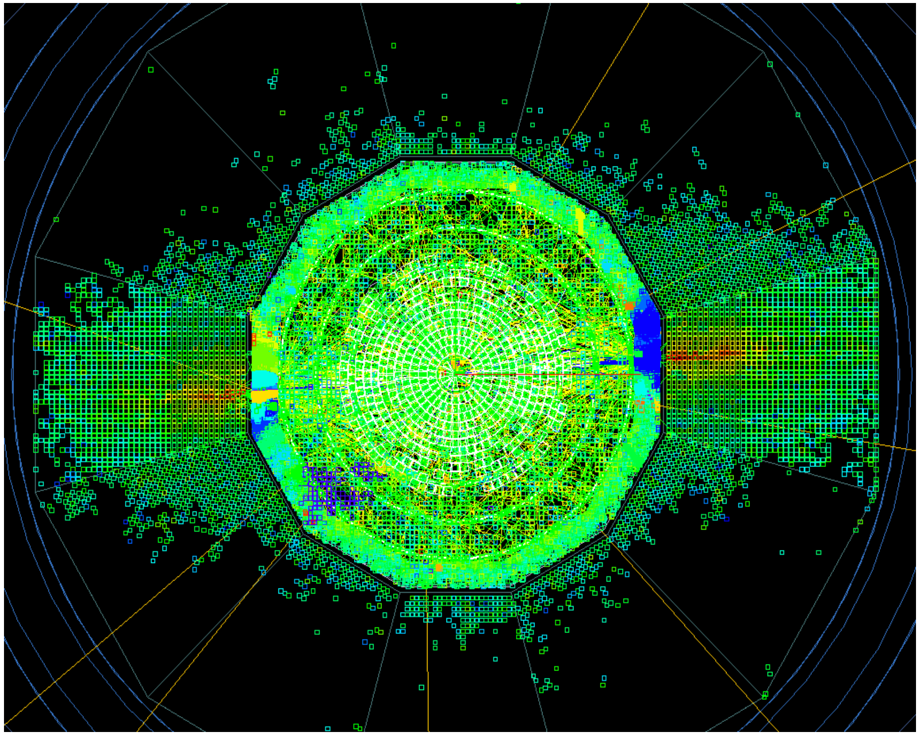
ANL, FNAL, *et al.*
Simulations at ANL

1 TeV π^+



rho-Z view

Z' (40 TeV) → qq



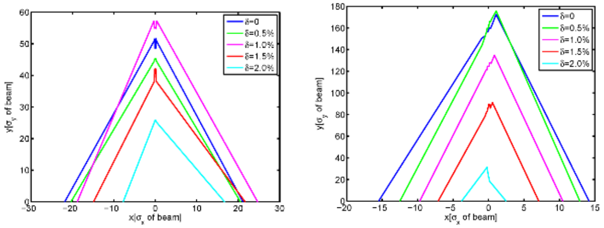
Some CepC-specific Experiment Studies
(examples from SLAC)

- ☐ Updated physics performance expectations, such as Higgs width precision, including alternative run plan scenarios
- ☐ Beam collision energy measurement techniques for ZH and Z pole energies
- ☐ Beam backgrounds, *e.g. wrt* beam pipe radius and detector location
- ☐ Silicon tracker layout

Some Specific FCC Machine Studies

(examples from SLAC)

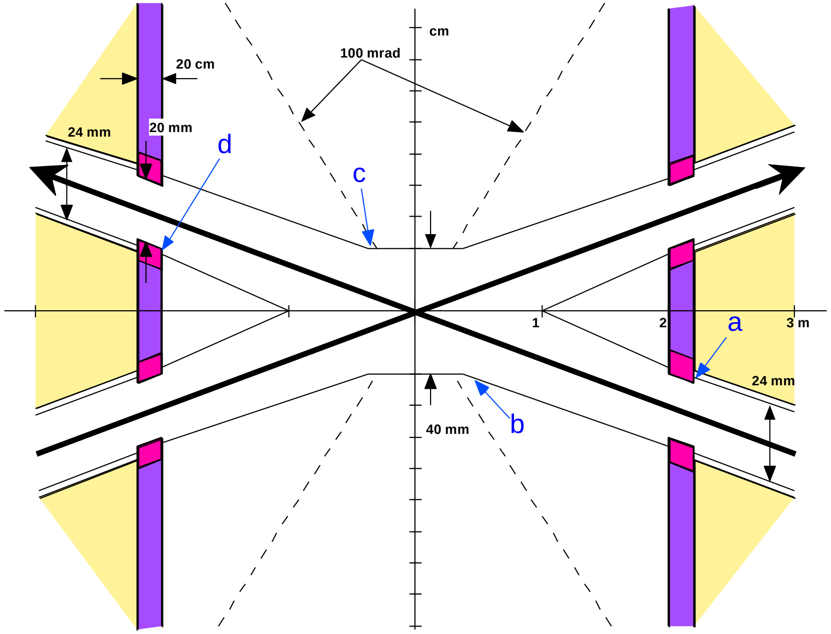
- ❑ **FCC-ee optics design and lattice optimization**



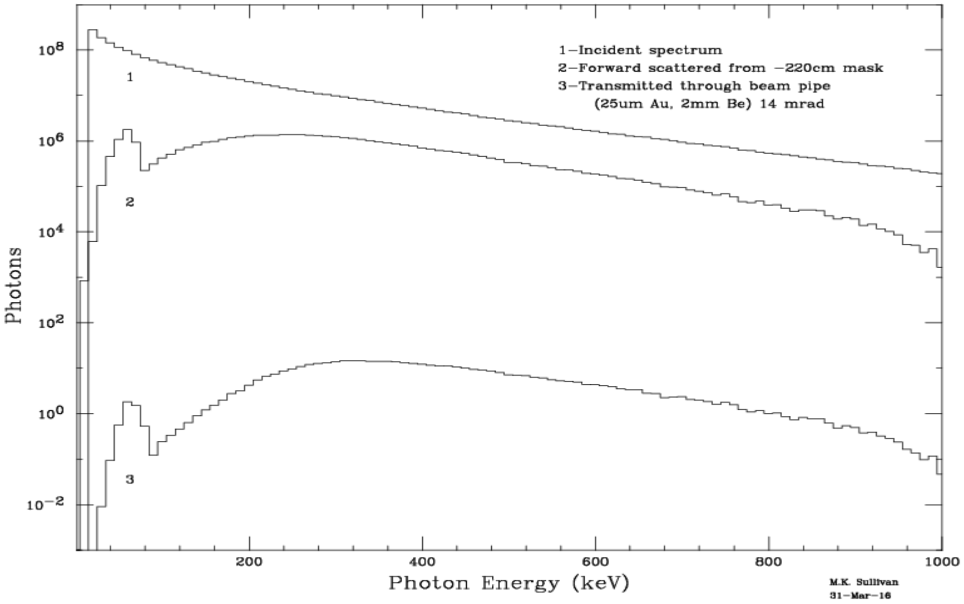
Dynamic apertures of lattices

- ❑ **Impedance and collective instabilities in FCC-ee and FCC-hh**

- ❑ **Modeling synchrotron radiation at FCC-ee IR**



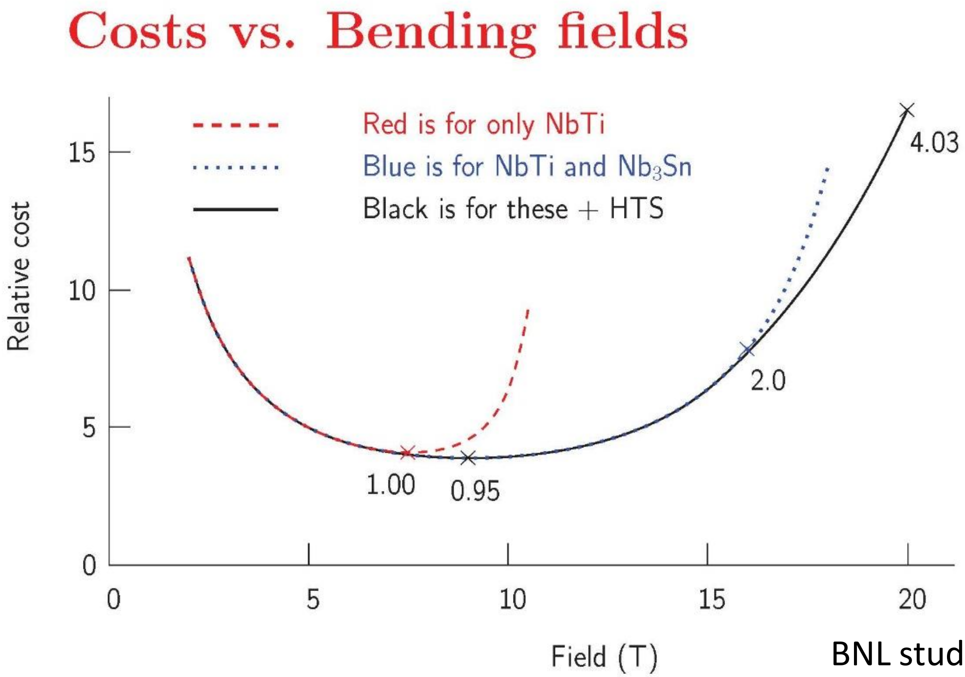
Photon spectrum



Study of VLHC Cost Optimization

Tunneling costs vs magnet costs

- **Some scientists believe that cost-performance will be optimized by a larger ring.**
  - A cost optimization exists at some radius.



BNL study

- **Optimum has a broad minimum.**
- **Optimization depends on local tunneling costs and on future magnet costs**

VERY HIGH-ENERGY PROTON-PROTON COLLIDERS

P5 on Very High-Energy p-p Colliders

- **“A very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window.”**

- **“The U.S. is the world leader in R&D on high-field superconducting magnet technology, which will be a critical enabling technology for such a collider.”**

Therefore,

- **“Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.”**

Accelerator R&D Subpanel on SC Magnet Development Program

- **5.** Participate in international design studies for a very high-energy proton-proton collider in order to realize this Next Step in hadron collider facilities for exploration of the Energy Frontier. Vigorously pursue major cost reductions by investing in magnet development and in the most promising superconducting materials, targeting potential breakthroughs in cost-performance.
- **5a.** Support accelerator design and simulation activities that guide and are informed by the superconducting magnet R&D program for a very high-energy proton-proton collider.
- **5b.** Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.
- **5c.** Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.
- **5d.** Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

- **5e.** Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.
- **5f.** Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.

- **C1a.** Ramp up research and development of superconducting magnets, targeted primarily for a very high-energy proton-proton collider, to a level that permits a multi-faceted program to explore possible avenues of breakthrough in parallel. Investigate additional magnet configurations, fabricate multi-meter prototypes, and explore low cost manufacturing techniques and industrial scale-up of conductors. Increase support for high-temperature superconducting (HTS) materials and magnet development to demonstrate the viability of accelerator-quality HTS magnets for a very high-energy collider.

Accelerator R&D Subpanel on SC Magnet Development Program

- 5. Participate in international design studies for a very high-energy proton-proton collider in order to realize this Next Step in hadron collider facilities for exploration of the Energy Frontier. Vigorously pursue major cost reductions by investing in magnet development and in the most promising superconducting materials, targeting potential breakthroughs in cost-performance.

- 5a. Support accelerator design and simulation activities that guide and are informed by the superconducting magnet R&D program for a very high-energy proton-proton collider.

- These two recommendations capture the principal emphasis.
  - Superconducting magnet technology
  - Accelerator studies that guide magnet program

- 5. Participate in international design studies for a very high-energy proton-proton collider in order to realize this
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U.S. Magnet Development Program

The Accelerator R&D Subpanel recommended:

- **Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.**

DOE-HEP held a workshop in July 2015 to survey the existing High Field Magnet R&D program

- Broad program in dipole design and conductor development
- Labs (BNL, FNAL, LBNL, HFML) and Universities

Magnet Development Program established early 2016

- **Aligned with recommendations of ARD Subpanel**
- **Builds on and focuses the expertise and infrastructure acquired by the generic High Field Magnet R&D and by LARP/Hi-Lumi Project**
- **Coordinated by Steve Gourlay (LBNL)**
- **DOE awaits its proposal** (this month)

Central Goals of US Magnet Development Program

- **Develop accelerator magnets at the limit of Nb_3Sn capabilities**

- **Investigate accelerator magnet designs with Low Temperature Superconductor (LTS) and High Temperature Superconductor (HTS) coils for fields beyond the capability of Nb_3Sn.**

- **Drive high-field conductor development, including Nb_3Sn and HTS materials for high-field accelerator magnets.**

- **Address fundamental aspects of magnet design, technology and performance that could lead to substantial reductions of magnet cost.**

4 Principal Initial Elements of US Magnet Development Program

Nb_3Sn

- **Demonstrate viability of 16T @ 90% short sample**
- Two approaches:
  - **High risk, high potential pay-off – Canted-Cos-theta (CCT)**
  - **Baseline reference design – Block Cos-theta (BCT)**

HTS

- **Study and develop both Bi-2212 technology and REBCO technology,** working with SBIR/industry and DOE university programs
- Bi-2212: to 5 T dipole to demonstrate HTS dipole technology
- REBCO: design and test CCT technology and quadrupole magnets

Technology development

- **Underlying program to develop technology to feed into 16T program,** including: Training studies, materials, diagnostics, etc.

Conductor Procurement and R&D

- **Provide MDP with “standard” conductor**
- **Conductor improvement as input to ultimate magnet design**

4 Principal Initial Elements of US Magnet Development Program

Nb_3Sn

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HTS

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- Bi-2212: to 5 T dipole to demonstrate [illegible]
- REBCO: design and test CCT technology and q[illegible]

Build Magnets

Technology development

- **Underlying program to develop technology to feed into 16T program,** including: Training studies, materials, diagnostics, etc.

Conductor Procurement and R&D

- **Provide MDP with “standard” conductor**
- **Conductor improvement as input to ultimate magnet design**

Outlook for MDP Initiative

Accelerator quality dipoles with an operating field of 16T are feasible.

Making them affordable is a challenge and will take time and require more resources than we have now. It will be a worldwide effort.

Very important:

- **Program must be coherent with worldwide efforts.**
- **Program must be integrated** (cryo, *etc*) **and take into account ancillary problems,** *e.g.* SR heat load, magnetization effects
- **HTS has many issues to understand and overcome in order to be a viable option**

  We need to prove feasibility, which could be demonstrated within the next year or two, then we can worry about the cost.

LOOKING BEYOND: MULTI-TEV LEPTON COLLIDER

Looking Beyond: Multi-TeV e^+e^- Collider

We are awaiting the science motivation, as well as the technology.

The LHC/HL-LHC could well make discoveries that would motivate a future multi-TeV lepton collider, but we are currently without such strong motivation or knowledge of the required energy.

Technology could be based on RF acceleration or Wakefield Acceleration.

NCRF (normal conducting) or **SRF** (superconducting)
DWFA (dielectric), **PWFA** (beam-driven plasma), **LWFA** (laser-driven plasma)

U.S. currently has R&D on each.
However, the technology path to affordable colliders is long.

Appropriate levels of R&D should be invested.

In part to prepare to realize such a machine if warranted

In part because it constitutes exciting accelerator science R&D and excellent training for accelerator scientists

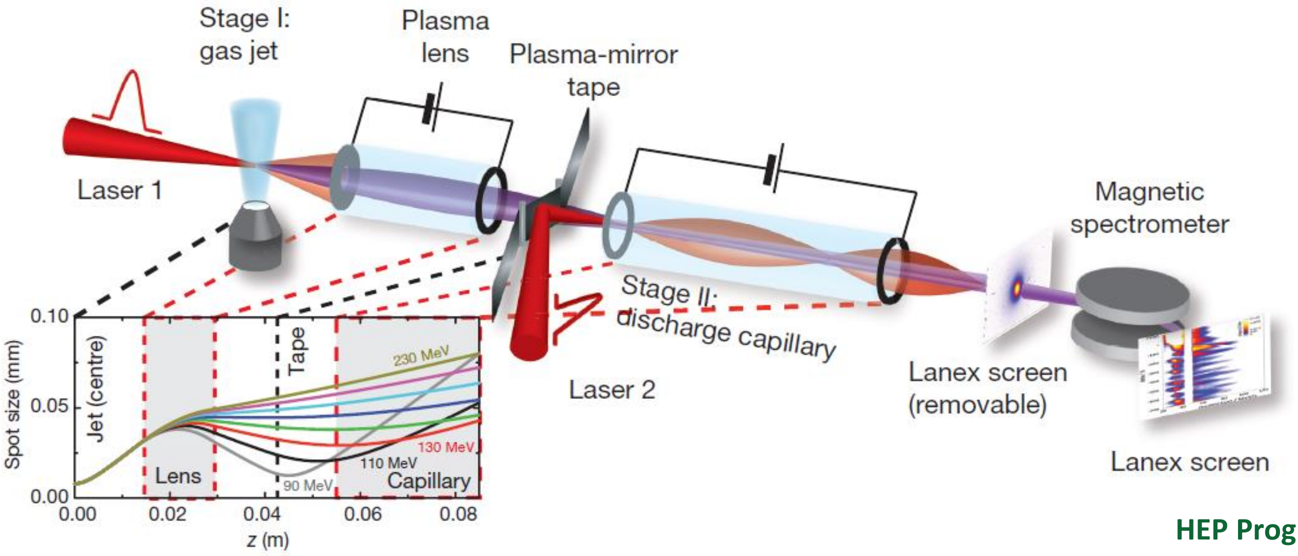
DOE recently hosted an Advanced Acceleration Concepts R&D Roadmap Workshop to map an R&D program towards a multi-TeV e+e- collider,

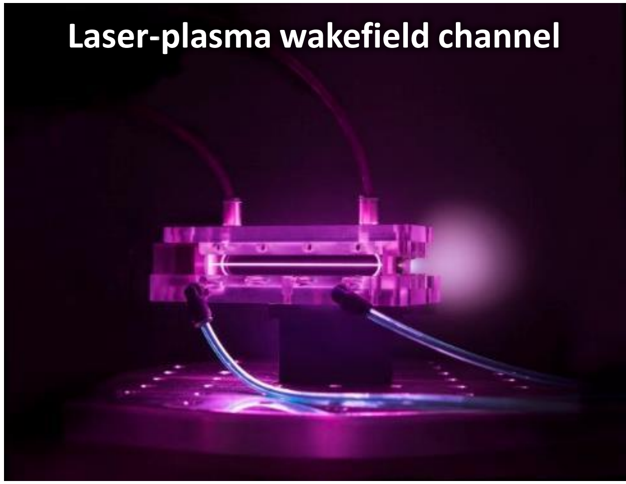
in response to recommendation of Accelerator R&D Subpanel.

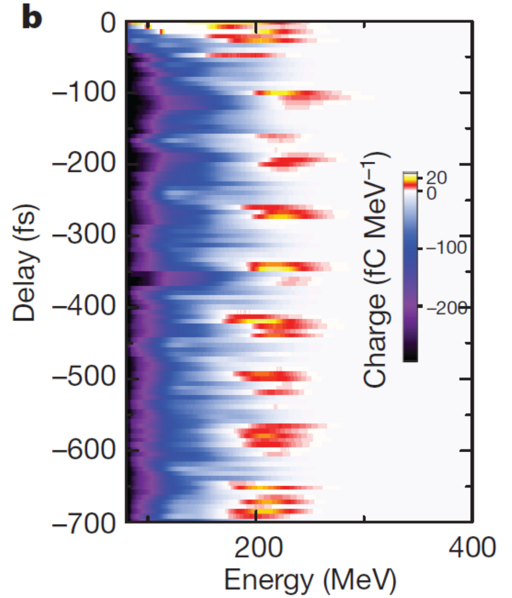
Advanced Technology R&D Highlight:

BELLA Demonstrates Plasma Accelerator Staging

- **BELLA has previously demonstrated single-stage Laser-plasma Particle Accelerators (LPA)**
  - Using world-record petawatt output laser, delivering 40 femtosecond pulses at 1 Hz
  - World-record gradient achieved in 2014 with 4.25 GeV acceleration in 9 cm laser-plasma channel
- **The Berkeley Lab Laser Accelerator (BELLA) at LBNL has successfully demonstrated two-stage laser-induced plasma wakefield acceleration**
  - Staging is a key step towards realizing future LPA colliders
- **Two LPA stages were coupled over a short distance by a plasma mirror**
  - After 1st stage acceleration to 200 MeV, acceleration by 2nd stage detected via energy gain of 100 MeV for subset of the electron beam
  - Results indicate that fundamental limitation to energy gain from laser depletion can be overcome using staged acceleration
- **Results published in Nature 530, 190–193 (11 February 2016)**




Laser-plasma wakefield channel



Beam Energy after 2nd Stage LPA vs. Laser Pulse Delay Time

Conclusion

Colliders pave the way to future discoveries at the high-energy frontier, from HL-LHC to ILC to very high-energy pp colliders.

The HEPAP subpanel P5 identified the future colliders of the most interest to the US HEP community, based on community's Snowmass study.

- **A very high-energy pp collider is the "most powerful future tool", under any scenario of physics results in the next decade.**
- **P5 recommended participating in global design studies and critical path R&D, especially SC magnet technology.**

The HEPAP Accelerator R&D Subpanel identified an R&D plan aligned with the P5 strategic vision.

A national Magnet Development Program is being established,

- in order to pursue the **cost-performance** for a 100-TeV scale collider,
- **based on expertise gained thru LARP and HFM & CDP programs,**

as a high-priority even during ambitious current U.S. program of projects.

THANK YOU

HEP is a highly successful, discovery-driven science

- **P5 emphasized that the field is driven by science.**
  - It distilled the 11 groups of physics questions from Snowmass into 5 compelling lines of inquiry, that show great promise for discovery over the next 10 to 20 years.
- **Subjects driving the science:**
  - **Use the Higgs boson as a new tool for discovery.**
  - **Pursue the physics associated with neutrino mass.**
  - **Identify the new physics of dark matter.**
  - **Understand cosmic acceleration: dark energy and inflation.**
  - **Explore the unknown: new particles, interactions, and physical principles.**

- **P5 recommended a balanced program to address all 5 drivers.**
  - ***Pursue a program to address the 5 science Drivers.***

- **Status: DOE & NSF have adopted a program to pursue all 5 science drivers via the suite of P5-recommended projects.**

Synopsis of Projects in P5 Plan

The P5 strategic plan includes a number of projects (and their time ordering).

  - These projects provide the opportunities to study the science drivers.
- **Large projects** (in time order)**:**
  - **Muon g-2 & Mu2e** (5)
  - **LHC Upgrades** (1,3,5)
  - **LBNF/DUNE & PIP-II** (2, 5)
- **Small and Medium projects** (in subject order)**:**
  - **Dark matter** (3)**: DM G2, DM G3**
  - **Cosmic surveys** (2,5)**: DESI, LSST, CMB-S4**
  - **Small Projects Portfolio**
  - **SBN** (2)
  - **Accelerator R&D**
- **ILC** (handled specially)

In order to accomplish these projects:

Increase the budget fraction invested in construction of projects to the 20%–25% range.

LHC, LBNF/DUNE, ILC are large projects & involve major int'l. partnerships.

  - **LHC was an int'l. partnership, by nature + US + JAPAN in particular**
  - **P5 recommended the transformation to LBNF/DUNE**
  - **ILC was conceived as global project**

P5's collider vision: ILC

Precision tool: "***Use the Higgs boson as a new tool for discovery***"

contributes also to: "*Identify the new physics of dark matter*"

"*Explore the unknown: new particles, interactions, and physical properties*"

Energy upgrade path to ~1 TeV,

Upgrade path differs from circular colliders, whose upgrade path is to *pp.*

Scientifically **motivated** by:

- **Higgs self-coupling** (~13%); precision Higgs-top coupling (~2%)
- Extended **search for new particles** coupling to γ & Z
- Motivation increased if **LHC/HL-LHC discovers new particles**

Status:

- TDR – June 2013 -> ***technically ready***
- **Japan** is considering whether or not to host ILC.
- Subject of discussion between DOE and MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology)
- Japanese decision before 2018 unlikely.

Very High-Energy Proton-Proton Collider

A very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window. – P5

Why start work on a very high-energy pp collider now?
Answer: Addressing the tremendous challenges must start now.

Challenges are formidable:

1. **Required technical performance must be achieved at affordable cost.**
   - ○ **Particularly, high-field superconducting dipole magnets**
2. **Adequate resources, financial & technical expertise, must be gathered.**
   - ○ **Support will be needed from science community and decision makers**
   - ○ **Scale of project will draw on international community, if not for resources, then for technical expertise.**

VHEPP work must be balanced *wrt* more immediate priorities, *e.g.* HL-LHC.

Begin now: Tackle high-priority R&D, beginning with SC magnets
Establish critical accel. Parameters, *e.g.* E, L_{int};
Articulate scientific motivation;

Accelerator R&D Subpanel on SC Magnet Development Program

- 5. Participate in international design studies for a very high-energy proton-proton collider in order to realize this Next Step in hadron collider facilities for exploration of the Energy Frontier. Vigorously pursue major cost reductions by investing in magnet development and in the most promising superconducting materials, targeting potential breakthroughs in cost-performance.

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- **5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.**

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Accelerator R&D Subpanel on SC Magnet Development Program

- **5e.** Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.

- **5f.** Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.

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- 5b. Form a
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- 5d. Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

- 5e. Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the
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high-temperature superconducting (HTS) materials and magnet development to demonstrate the viability of accelerator-quality HTS magnets for a very high-energy collider.

- **C1a. Ramp up research and development of superconducting magnets, targeted primarily for a very high-energy proton-proton collider, to a level that permits a multi-faceted program to explore possible avenues of breakthrough in parallel. Investigate additional magnet configurations, fabricate multi-meter prototypes, and explore low cost manufacturing techniques and industrial scale-up of conductors. Increase support for high-temperature superconducting (HTS) materials and magnet development to demonstrate the viability of accelerator-quality HTS magnets for a very high-energy collider.**

4 Principal Initial Elements of US Magnet Development Program (p1)

Nb_3Sn

- **Demonstrate viability of 16T @ 90% short sample**
- Two approaches:
  - **High risk, high potential pay-off – Canted-Cos-theta (CCT)**
  - **Baseline reference design – Block Cos-theta (BCT)**

HTS

- **Study and develop both Bi-2212 technology and REBCO technology,** working with SBIR/industry and DOE university programs
- The deliverables/milestones/activities in the next two years include:
- Bi-2212:
  - ○ from sub-scale magnets including both racetrack magnets and CCT to explore technology limits
  - ○ to 5 T dipole to demonstrate HTS dipole technology
- REBCO:
  - design and test CCT+CORC technology,
  - design and test quadrupole magnets made using racetrack coils and use that as a testbed to guide US conductor development.

4 Principal Initial Elements of US Magnet Development Program (p2)

Technology development

- **Underlying program to develop technology to feed into 16T program,** including: Training studies, capability development (insert infrastructure), materials (insulation, mandrels, impregnation), diagnostics, QP/D, Analysis and modeling tools, design comparison/code models, Field quality control.

Conductor Procurement and R&D

- Primarily driven by MDP needs
  - ○ Provide MDP with “standard” conductor
- In parallel, **develop goals and milestones for conductor improvement as input to ultimate magnet design** (Need a “bullet-proof” conductor)
  - ○ **Scalability** and **cost**
  - ○ Emphasis on **simplicity of manufacture** to enable worldwide capacity ramp-up. (This will eliminate start-up cost and allow more competition.)
  - ○ **Performance**