The US Effort for High Luminosity LHC

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HiLumi LHC-LARP Meeting, Nov 11-15, 2013

US Context

- The US HEP Community plays a substantial role in the scientific productivity of the LHC
- Substantial US involvement in the construction of detectors and the accelerator
  - The US contributed $164 million to the construction of the ATLAS detector and $167 million to the construction of the CMS detector.
  - The US contributed $200 million to the construction of the Large Hadron Collider.

US Context

- Approximately 2,000 scientists, students, engineers and technicians from 96 US institutions participate in the LHC.
  - 23 percent of the ATLAS collaboration members come from American institutions
  - 33 percent of the CMS collaboration members come from American institutions.
  - Since 2008, the work on the ATLAS and CMS experiments resulted in about 230 doctorate degrees for US students.
- The United States provides 23 percent of the computing power for the ATLAS experiment and 40 percent of the computing power for the CMS experiment.

US Planning Activities

Department of Energy Scientific Facilities
"Snowmass" Community Summer Study
Particle Physics Project Prioritization Panel (P5)

DOE/HEPAP Facilities Subpanel Report

Facilities Subpanel considered large scale scientific user facilities for High Energy Physics

Regarding Energy Frontier Facilities:

LHC Upgrades

- Science questions drive the need to upgrade luminosity and detectors at the LHC
  - Accelerator and upgrades of both detectors are **absolutely central** to world-wide goals of particle physics
    - Proposed US roles in accelerator and detector upgrades are compatible with US leadership areas, although actual roles have yet to be determined
    - Contributions to both ATLAS and CMS upgrades are essential to maintain ongoing US participation

Snowmass: The Higgs

The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.

3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

Origin of EWSB **Origin of matter** **Naturalness** **Unification** **New forces**
Dark matter **Elementary?**

Brock/Peskin Snowmass 2013

Chip Brock, Snowmass Energy Frontier Report

Snowmass: LHC Upgrades

LARP

High Luminosity LHC

(excerpted from "Snowmass 2013 Energy Frontier Working Group Report – HEPAP Sept. 5, 2013)

LHC: 3000 fb^{-1}

Higgs EW Top QCD NP/flavor

1. **The precision era in Higgs couplings: couplings to 2-10% accuracy, 1% for the ratio gamma gamma/ZZ.**
2. Measurement of rare Higgs decays: mu mu, Z gamma with 100 M Higgs.
3. **First measurement of Higgs self-coupling.**
4. Deep searches for extended Higgs bosons
5. Precision W mass to 5 MeV
6. **Precise measurements of VV scattering; access to Higgs sector resonances**
7. Precision top mass to 500 MeV
8. Deep study of rare, flavor-changing, top couplings with 10 G tops.
9. Search for top squarks & partners in models of composite top, Higgs in the expected range of masses.
10. Further improvement of q, g, gamma PDFs to higher x, Q^2
11. A 20-40% increase in mass reach for generic new particle searches - can be 1 TeV step in mass reach
12. **EW particle reach increase by factor 2 for TeV masses.**
13. **Any discovery at LHC–or in dark matter or flavor searches–can be followed up**

Snowmass Report

(excerpted from "Planning the Future of U.S. Particle Physics, Report of the 2013 Community Summer Study")

- We find the case for the high-luminosity stage of the LHC compelling.
  - This plan to deliver 3000 fb-1 has been listed in the European Strategy for Particle Physics as the highest priority accelerator project in Europe for the 2020's.
  - We find that it will provide a significant additional step in the search for new particles, and that it will provide other important capabilities.
  - The most important of these is the beginning of the era of precision Higgs boson measurements, to few-percent precision.
  - It is likely to give the first evidence of the Higgs boson self-coupling.
  - It will provide a program of precision measurement in the SM that will dramatically tighten our knowledge of the W boson and the top quark, with measurements sensitive to the predictions of a variety of new physics models.
- We have already noted that the additional luminosity will significantly enhance the capability of the LHC to search for new heavy particles.

Particle Physics Project Prioritization Panel (P5) Charge

The P5 Process has just begun, and is expected to answer the following charge by the Spring:

"…develop an updated strategic plan for U.S. HEP that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field."

"…examine current, planned, and proposed US research capabilities and assess their role and potential for scientific advancement; assess their uniqueness and relative scientific impact in the international context; and estimate the time and resources (the facilities, personnel, research and development and capital investments) needed to achieve their goals."

P5 Charge

"Your report should provide recommendations on the priorities for an optimized high energy physics program over the next ten years (FY14-23), under…three scenarios."

"The report should provide a detailed perspective on whether and how the pursuit of possible major international partnerships (such as LHC upgrades, Japanese-hosted ILC, LBNE, etc.) might fit into the program you recommend in each of the scenarios."

Potential US (Accelerator) Involvement in High Luminosity LHC

LHC Accelerator Research Program (LARP) History & Evolution

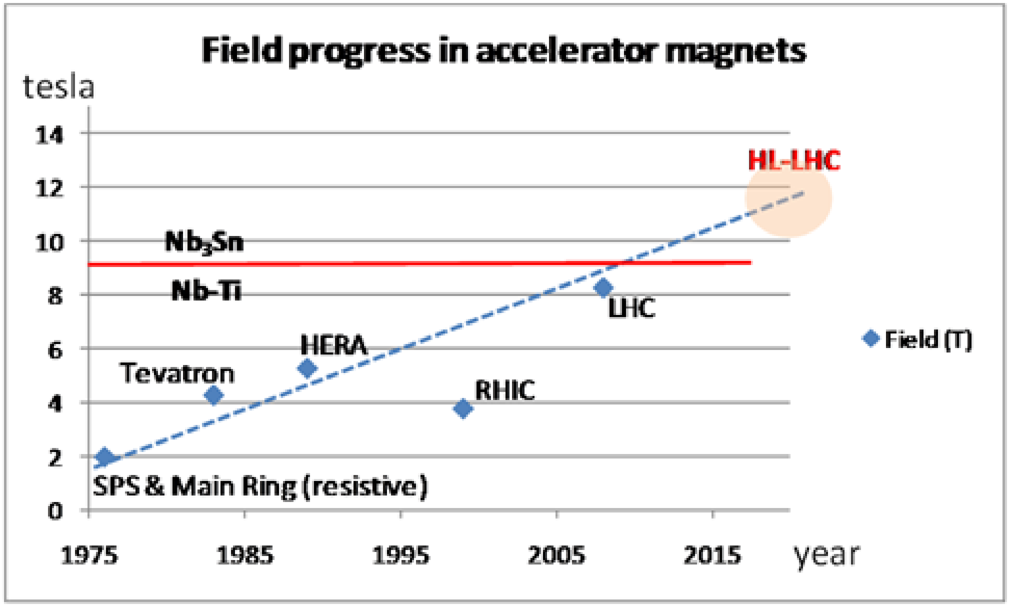
- The US LHC Accelerator Research Program (LARP) was formed in 2003 to coordinate US R&D related to the LHC accelerator and injector chain
  - partnership of Brookhaven Lab, Lawrence Berkeley Lab and Fermilab
  - SLAC joined shortly thereafter
  - Has also had some involvement from Jefferson Lab, Old Dominion University and UT Austin
- LARP contributed to the initial operation of the LHC, but much of the program has been focused on future upgrades
- The program is currently funded at a level of about $12-13M/year, divided among:
  - Magnet research (~half of program)
  - Accelerator research (Crab cavities, WBFS, Collimators, e-hollow lens,..)
  - Programmatic activities, including support for personnel at CERN
- Recent Evolution (2012 onward)
  - Initial convergence on deliverables for HL-LHC
  - Program now transitioning to a project-approach
  - Giorgio Apollinari has taken the lead as LARP Director

Potential US Involvement in HL-LHC: A Preliminary Look

- Several candidate scope elements have been under development
  - 150 mm aperture Nb_3Sn quadrupoles
  - Crab Cavities
  - High Bandwidth Feedback System
  - Collimation and hollow e-beams
  - 11 T Nb_3Sn dipoles
  - Large Aperture NbTi D2 separator magnets
- Process of convergence among CERN-DOE-U.S. Labs-LARP initiated in Dec '2012
- Initial consensus on core Priorities which makes good use of US accelerator expertise, and which makes critical contributions to LHC luminosity:
  - Committed to a major stake in Nb_3Sn quads
  - Crab cavities up to the SPS test and possibly beyond to production
  - High bandwidth feedback was seen as a high impact contribution for modest resources.
- Back up options:
  - 11 T dipoles
    - Proper "hand-off" if not continued in US
  - Hollow electron beams for halo removal
    - Support some modest R&D into this effort in the event that circumstances allow its inclusion
- Lower priority:
  - There was not much interest in pursuing the D2 separators.

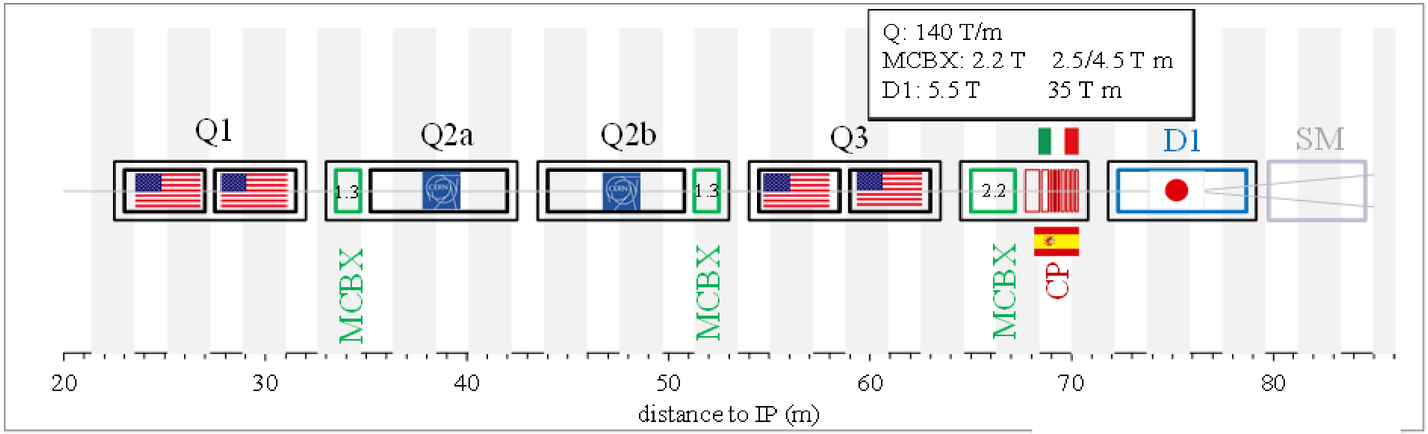
Increase Luminosity: High Field SC Magnets

- Quads for inner Triplets
  - Decision 2012 for low-β quads
    Aperture ∅ 150 mm – 140 T/m
  - B_{peak} ≈12.3 T, LHC: 8T, 70 mm
- More focus strength,
  - β* as low as 15 cm
  - LHC: 55 cm
- Dipoles for beam recombination/separation:
  - capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)
- Dipoles 11 T for LS2 (*presently not part of plans as a US deliverable*)



HL-LHC Nb_3Sn Magnets

- Interaction Region Magnets
  - 4 Q1 and 4 Q3 (2 per IR) plus 1 spare each from US
    - Q1 and Q3 will probably contain 2 ~4.5 m long magnets each, for a total of ~20 quadrupoles
  - 4 Q2a and 4 Q2b from CERN
    - Option still open on the length of Q2.



E. Todesco

LARP Magnet Development Tree

LARP

High Luminosity LHC

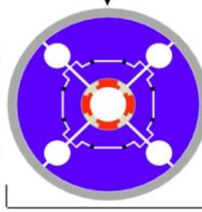
SQ Series: 19 coils, 11-12 T
SQ02: **54/61 MJR** J_c>1800
- 97% at 4.3/4.5 K
- 97% at 1.8 K

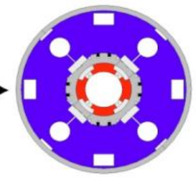
Subscale Quadrupole
SQ
0.3 m long
110 mm bore

Subscale Magnet
SM
0.3 m long
No bore

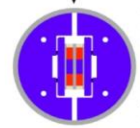
LR Series: xx coils, ~12 T
LRS02: 54/61 RRP J_c>2700
- 96% at 4.5 K

Technology Quadrupoles
TQS, TQC
1 m long
90 mm bore





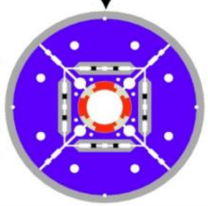
Long Racetrack
LRS
3.6 m long
No bore



TQ Series: 33 coils, 12-13 T
TSQ02**: 54/61 RRP** J_c>2800
- 88% to 97% at 4.3
- "Erratic" @ 1.9 K

TQS03: **108/127 RRP** J_c>2800
- 93% at 4.3 K
- 93% at 1.9 K

Long Quadrupole
LQS
3.7 m long
90 mm bore



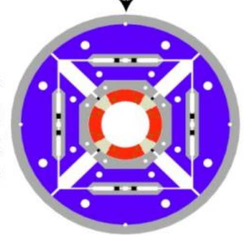
LQ Series: 19 coils, ~12 T
LSQ01**: 54/61 RRP** J_c>2700
- 93% at 4.5 K
- Marginal Increase at lower T

LQS03: **108/127 RRP** J_c>2800
- 91% at 4.6 K
- No increase at lower T

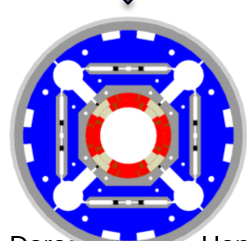
HQ Series: 25 coils, 13-15 T
HQ01e: **54/61 and 108/127 RRP**
- 85% at 4.5 K
- No Increase at lower T

HQ02: **108/127 RRP** J_c>2800
- 98% at 4.5 K
- Not fully trained at lower T

High Field Quadrupole
HQ
1 m long
120 mm bore



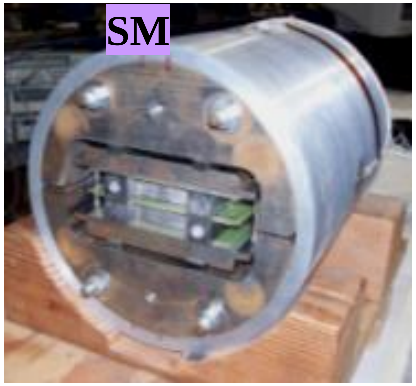
High Field Quadrupole
SQXF/LQXF
1 m / 4 m long
150 mm bore

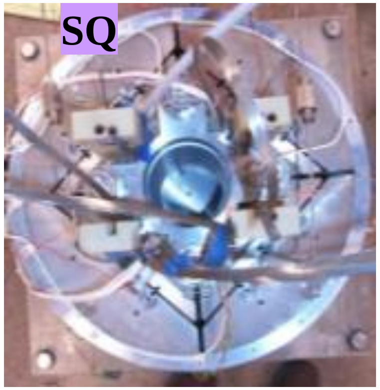


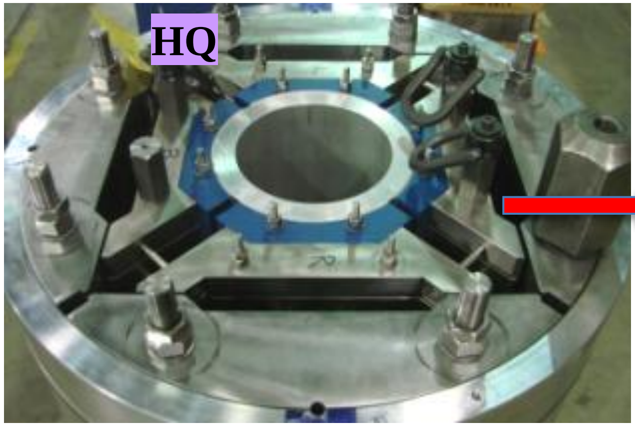
US SQXF Series: 13/18 Coils
- 2 or 3 1m long models
- 2014-2016

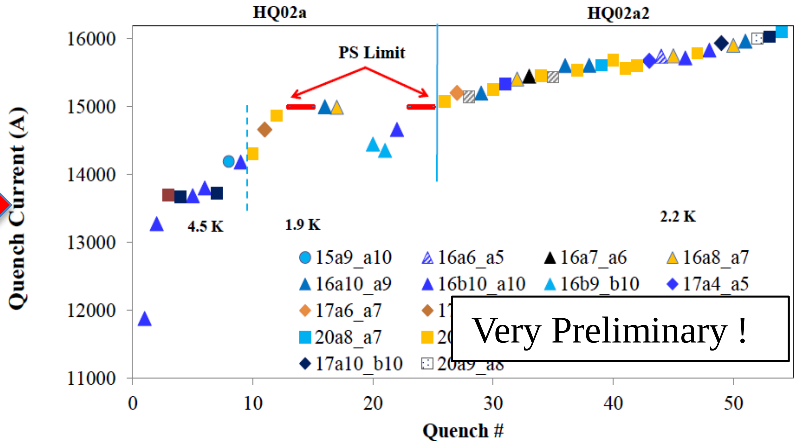
US LQXF Series: 18 Coils,
- 3 ~4.3 m Long Models
- 2015-2017

LARP Quadrupole Magnet Development





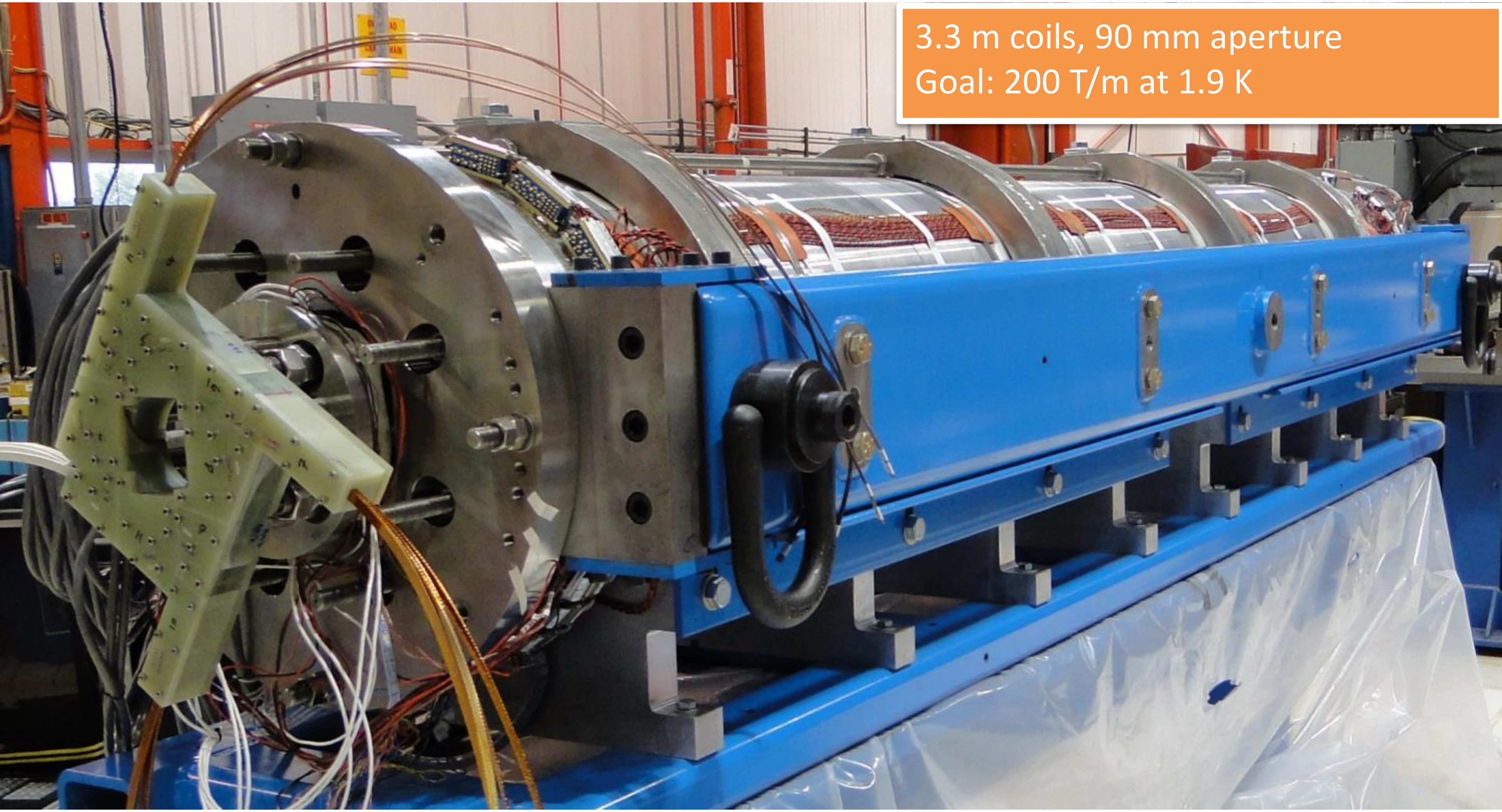




LARP

Long Magnets: LQS of LARP

High Luminosity LHC



3.3 m coils, 90 mm aperture
Goal: 200 T/m at 1.9 K

LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

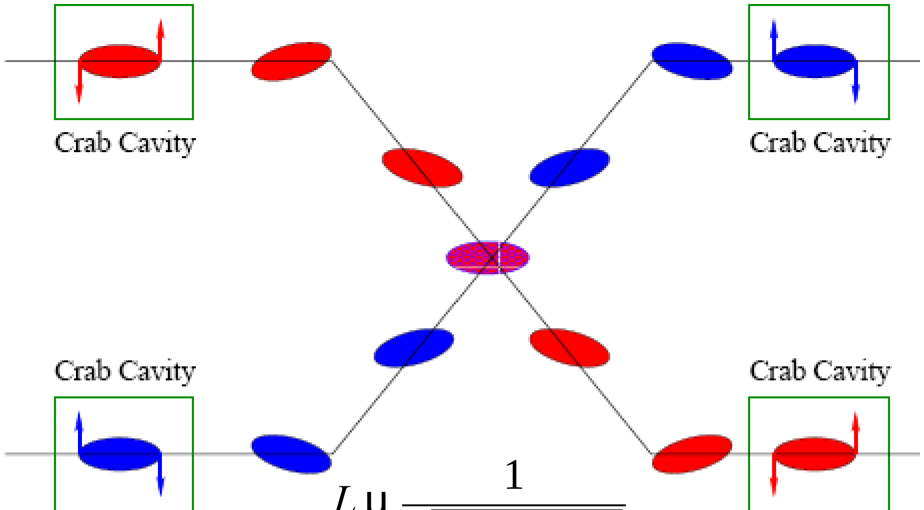
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

Evolution of the Magnet Plan

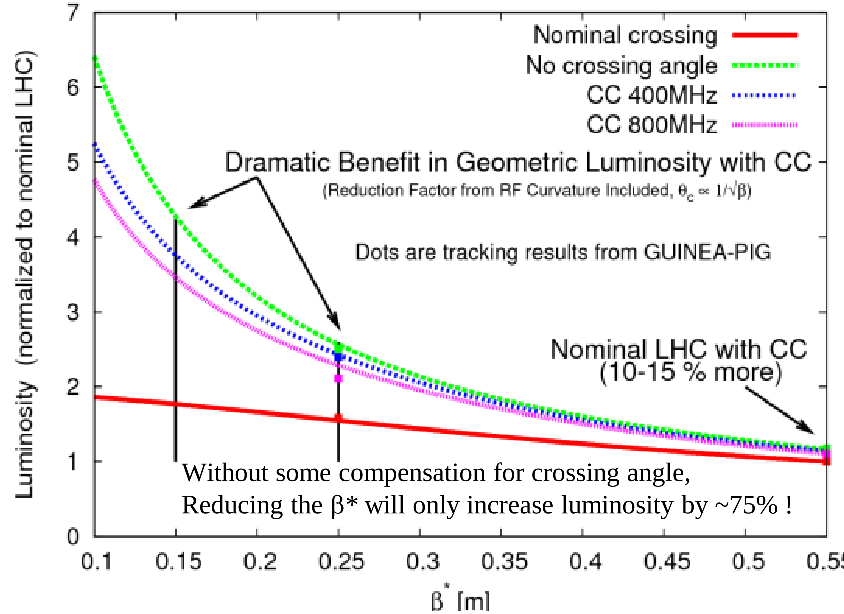
- Original plan
  - Follow HQ with 4m x 120 mm LHQ
  - Use this to demonstrate technology for 120 mm prototype as part of large scale construction project
- Recent Developments
  - In June 2012, CERN chose 150 mm as the aperture for the HL-LHC
  - July 2012 LARP review recommends abandoning LHQ to pursue 150 mm prototype
- New plan
  - Curtail 120 mm program to long ¼ magnet “mirror” tests
    - We feel there are still important things to learn
  - Begin working with CERN on 150 mm prototype as part of an integrated production plan for Nb_3Sn quads in LS3.

Crab Cavities

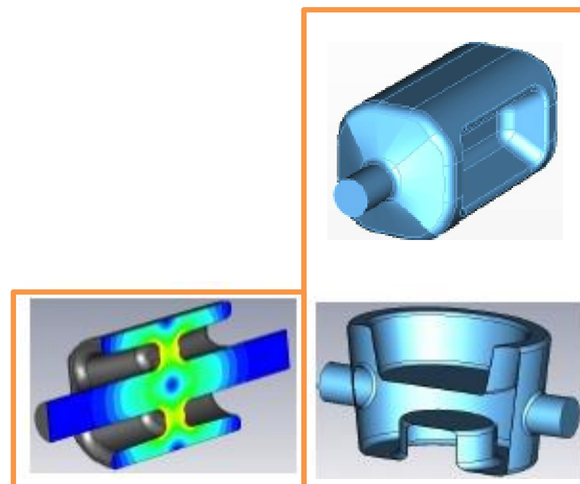


$$L \propto \frac{1}{\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_x}\right)^2}}$$

"Piwinski Angle"



- Technical Challenges
  - Crab cavities have only *barely* been shown to work.
    - Never in hadron machines
  - LHC bunch length requires low frequency (400 MHz)
  - 19.4 cm beam separation needs "compact" (exotic) design
- Additional benefit
  - Crab cavities are an easy way to level luminosity!
- Currently aiming for:
  - Down-select ~next year
  - Aiming for SPS test in 2015



UK LARP

Crab Cavities and Cryomodules

RF-Dipole Nb prototype

4-rod in SM18 for RF measurements

DQWR prototype
17-Jan-2013

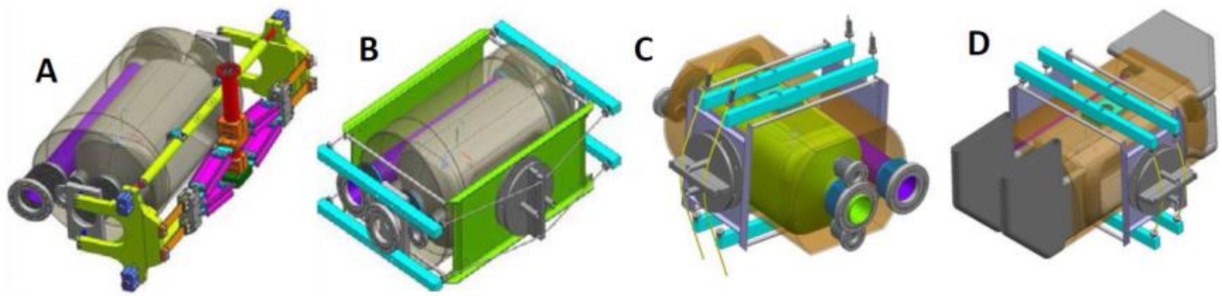
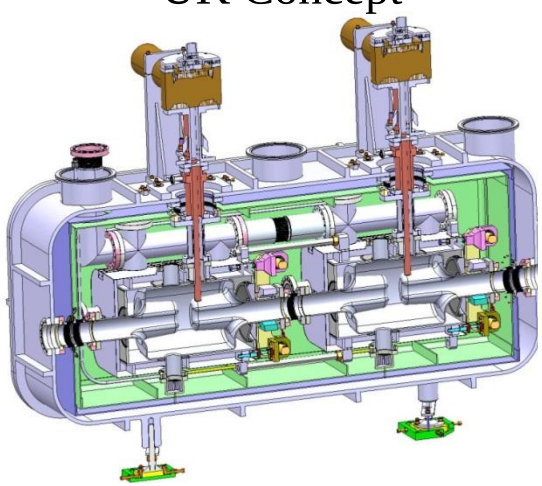
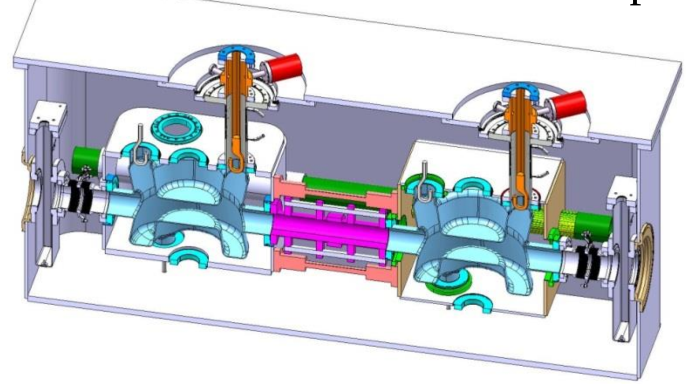


Figure 1: LHC crab cavity cryostat concept – A) JLab design, B) ANL design (helium pressure actuates bellows), C) ANL design (tuner deforms cavity outer surfaces), D) Waveguide

UK Concept



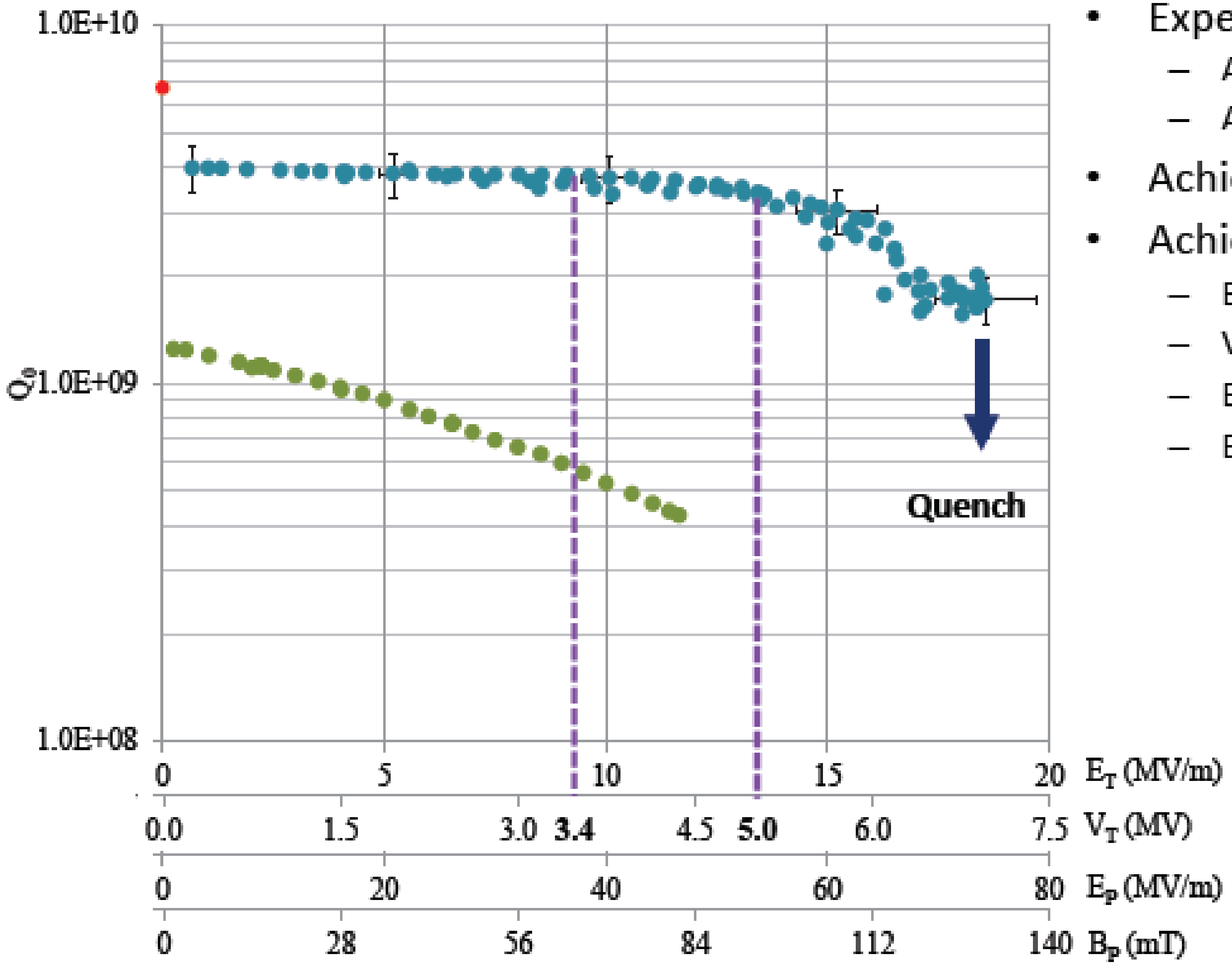
BNL Concept



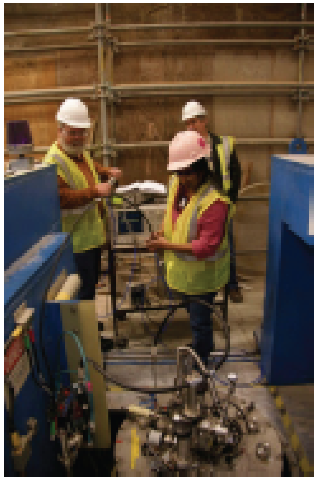
First test of CC (ODU-SLAC at J-LAB)

LARP

High Luminosity LHC



- Expected $Q_0 = 6.7\times10^9$
  - At $R_S = 22$ nΩ
  - And $R_{res} = 20$ nΩ
- Achieved $Q_0 = 4.0\times10^9$
- Achieved fields
  - $E_T = 18.6$ MV/m
  - $V_T = 7.0$ MV
  - $E_P = 75$ MV/m
  - $B_P = 131$ mT



Jefferson Lab

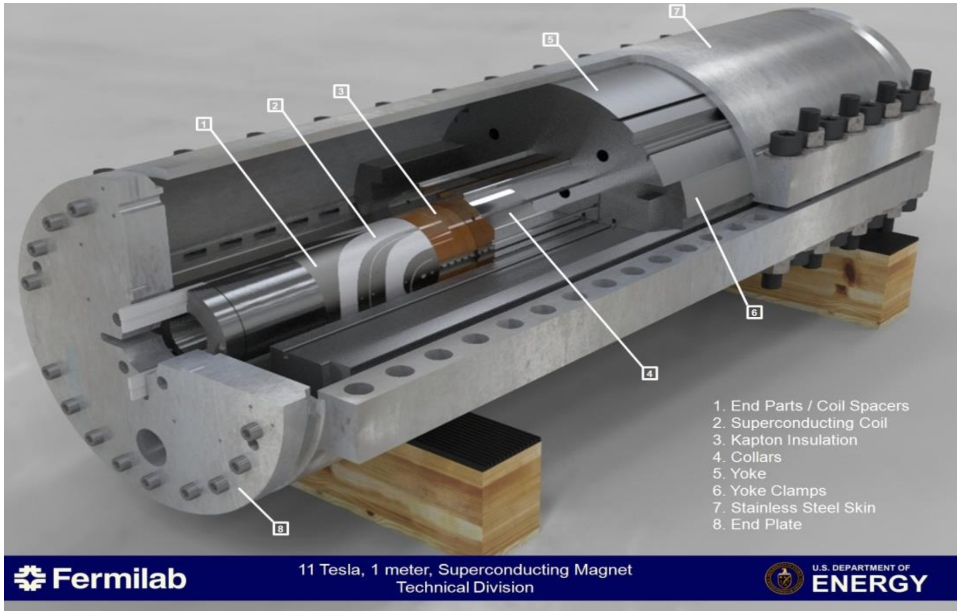
Old Dominion University

High Bandwidth Feedback System

- The high bandwidth feedback system is a proposed feedback system for the SPS, which leverages LARP experience with the LHC LLRF system, to address intra-bunch instabilities
- Proposal
  - LARP will continue R&D related to the system.
  - The deliverable would be a functional feedback system the SPS, for which
    - The US contribution would be the complete, full-function, instability control system hardware, firmware and software necessary to operate at the SPS (and potentially LHC, PS).
    - The CERN contribution will include the vacuum structures (pickup(s) and kicker(s)) and all tunnel related cable plant.

11 T Development

Not LARP



- Create space for additional collimators by replacing 8.33 T MB with 11 T Nb_3Sn dipoles compatible with LHC lattice and main systems.
  - 119 Tm @ 11.85 kA (in series with MB)

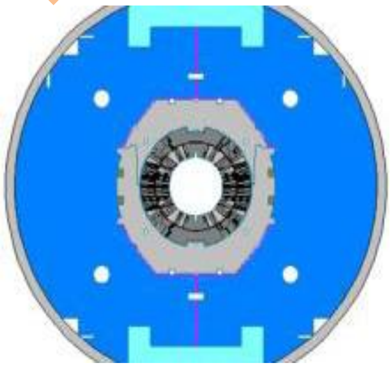
- At this time not proposed as a US in-kind contribution. Intellectually relevant as R&D program toward high field, accelerator quality, dipoles and, consequently, HE-LHC

11T Dipole R&D

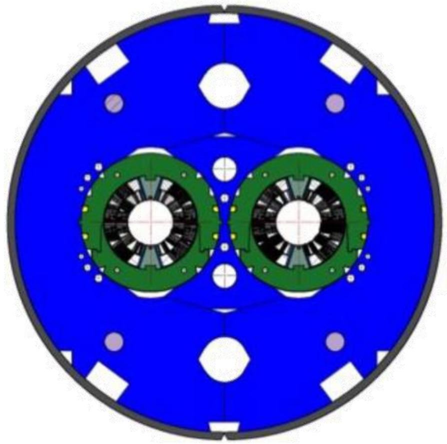
LARP

Not LARP

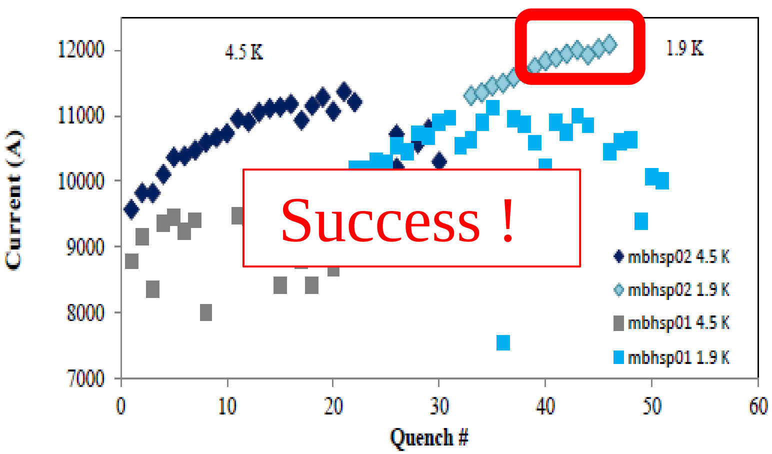
Si… erture model

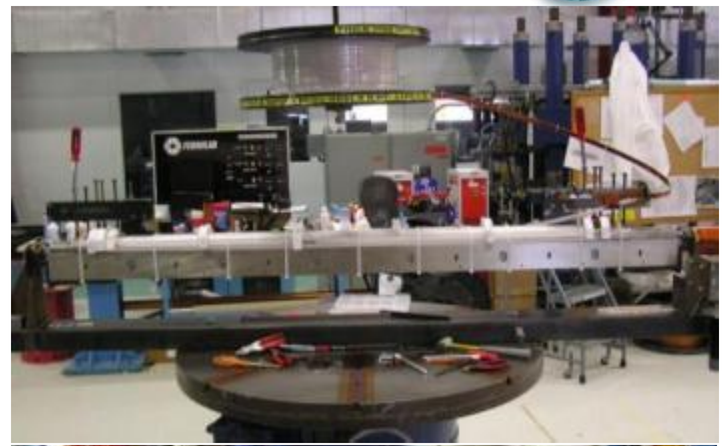


Twin aperture model



Second Nb_3Sn Accelerator Quality Dipole (1m long) – Dec '12





Fermilab

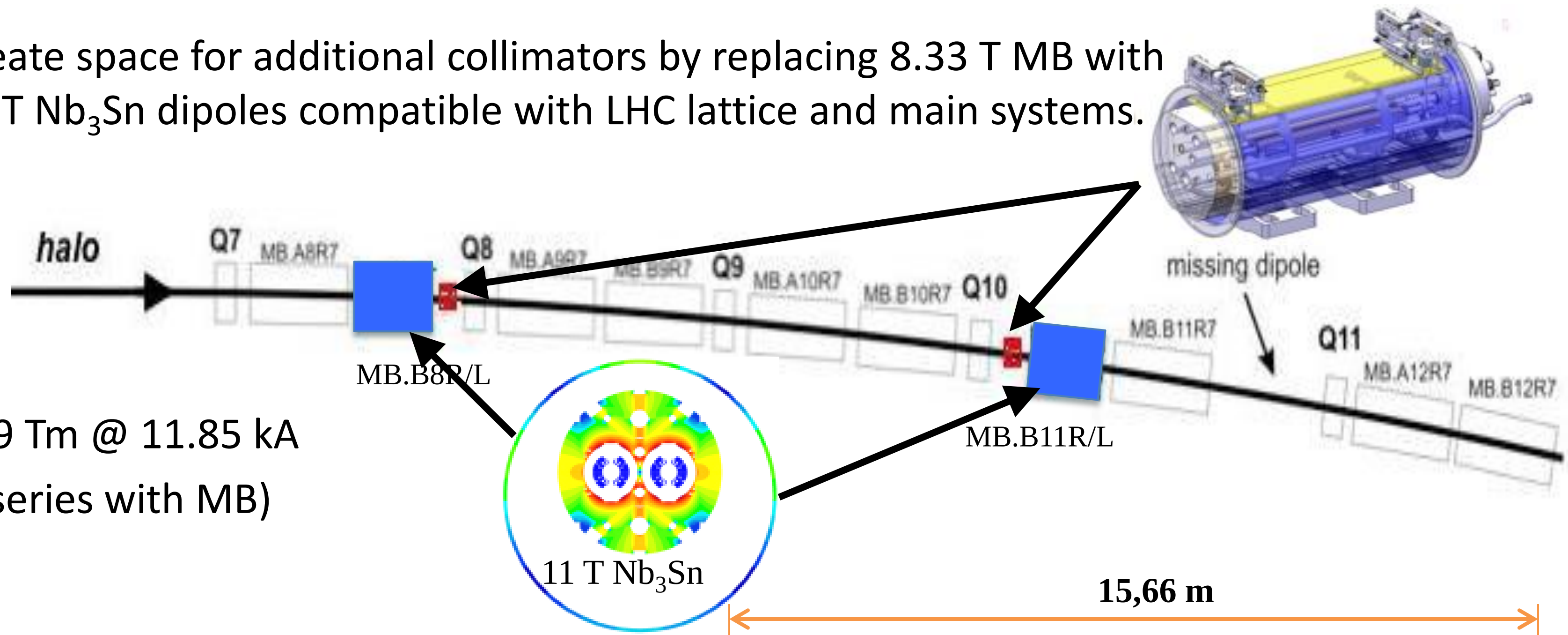
Summary

- The importance of the High Luminosity LHC Physics potential has been recognized in ongoing US Planning activities
- The assessment of the P5 Panel will be an important element in establishing the scale of US involvement in HL-LHC
- LARP is focusing on the Development of technology which is critical to increasing the luminosity of the LHC
- LARP has laid the groundwork for critical contributions in Nb3Sn magnet technology for IR quadrupoles
- LARP is developed crab cavity and feedback systems
- The US community is committed to realizing the full potential of the Large Hadron Collider

The US community is committed to realizing the full potential of the Large Hadron Collider

Collimators and 11T Dipoles

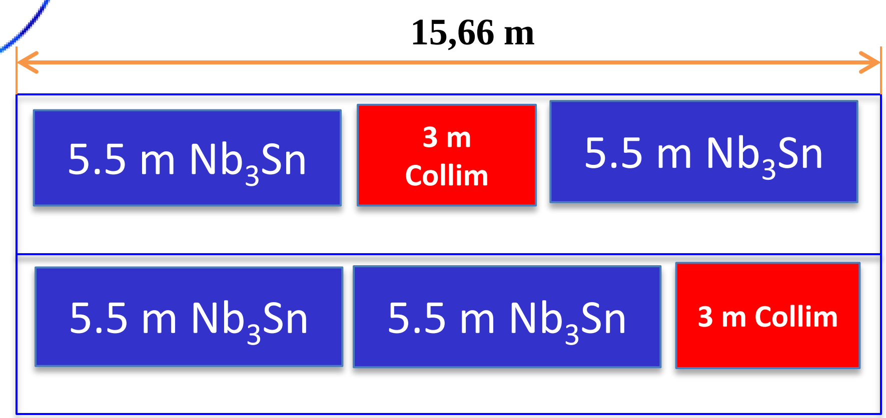
- Create space for additional collimators by replacing 8.33 T MB with 11 T Nb_3Sn dipoles compatible with LHC lattice and main systems.



- 119 Tm @ 11.85 kA

  (in series with MB)

- LS2 : IR-2
  - 4 MB => 8 x 5.5 m CM + spares
- LS3 : IR-1,5 and Point-3,7
  - 4 x 4 MB => 32 x 5.5 m CM + spares



- Focus of joint R&D program aimed at Accelerator Quality Magnets between CERN and US. R&D program to be completed in US with conclusion of Short (1m) Models.