11 T Dipole Project Overview and Status

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On behalf of CERN-FNAL collaboration

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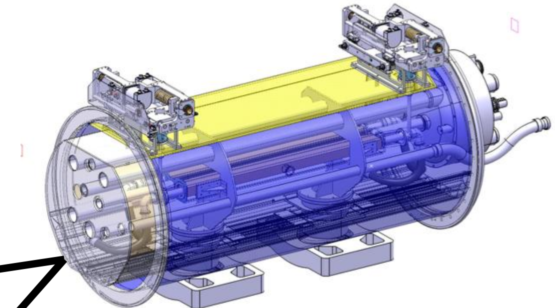
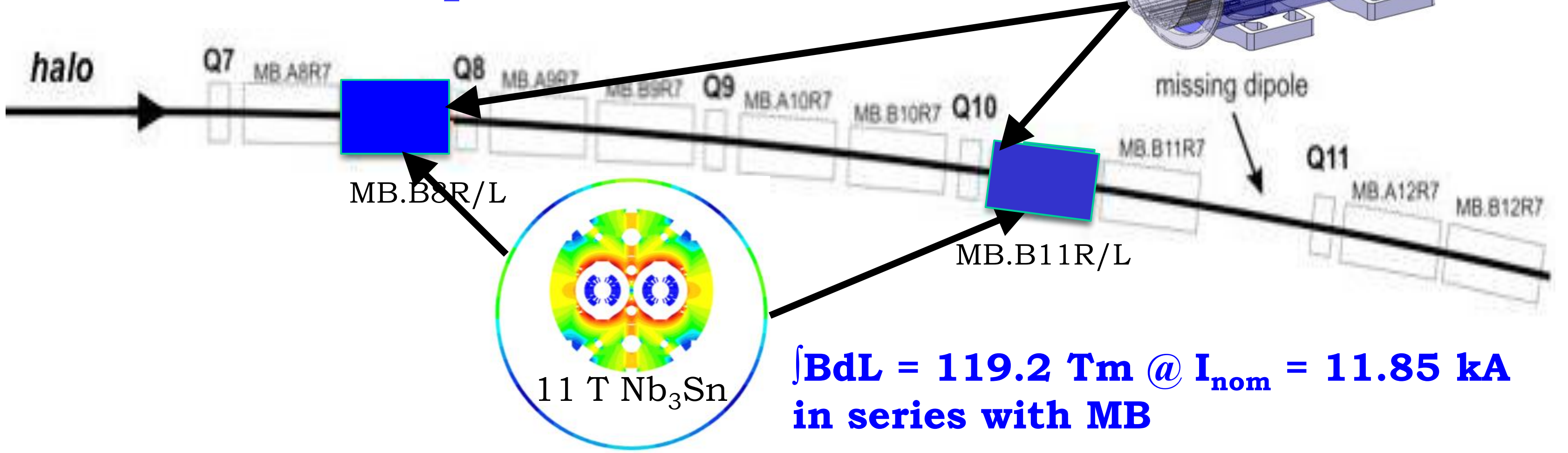
DS Upgrade

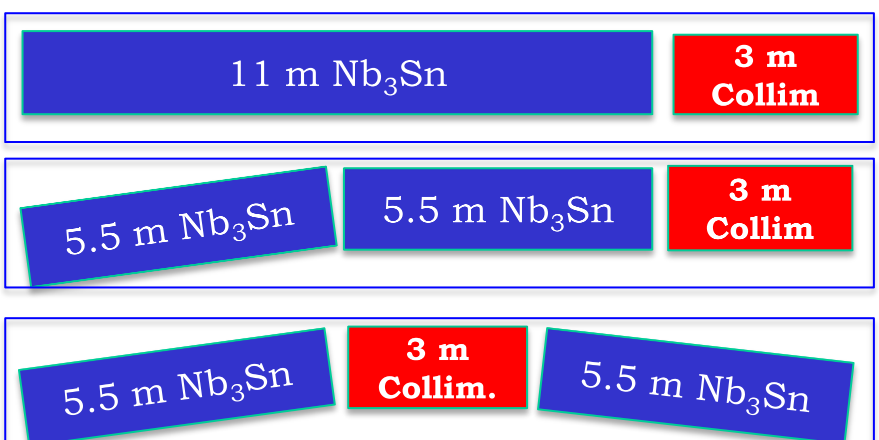
- 2017-18: Point-3,7 & IR-2

- 2020: IR1,5 as part of HL-LHC





$\int BdL$ = 119.2 Tm @ I_{nom} = 11.85 kA
in series with MB



(11.2 T x 10.6 m), L_{CM} ≈ 11 m, (MB -4.2 m)
=> 12 coldmass + 2 spares = 14 CM

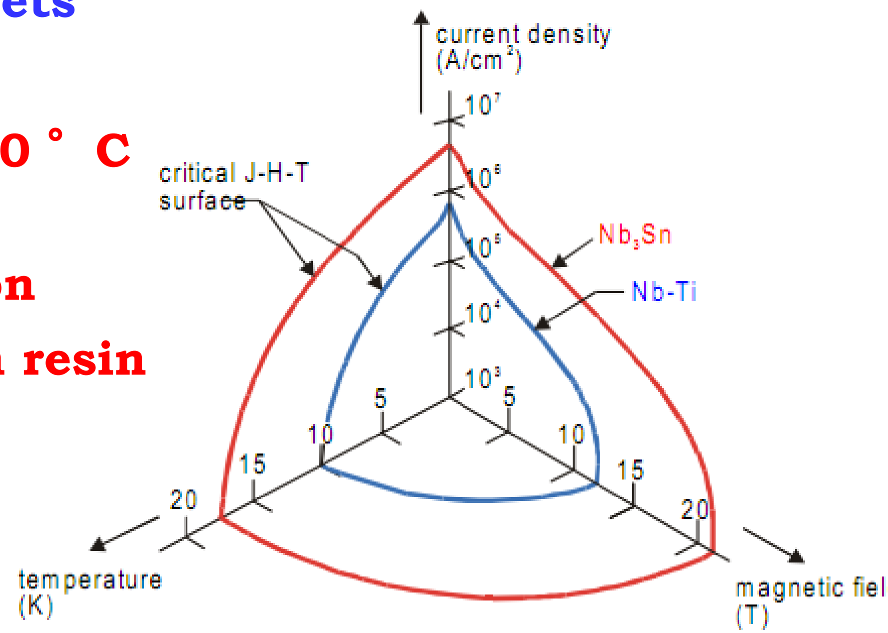
2 x (11.2 T x 5.3 m), L_{CM} ≈ 11.5 m, (MB -3.7 m)
=> 24 coldmass + 4 spares = 28 CM

11 T Dipole Cold Mass

- **Cold mass length 5.5 m:**
  - o **FNAL have coil fabrication and collaring tooling up to 6 m**
  - o **Handling of 11 m coils is risky (250 kCHF of cable)**
  - o **11-m-long coils require cable unit length of 1200 m**
- **Sagitta: 11 m – 5.0 mm, 5.5 m – 1.3 mm**
  - o **Ø60 mm aperture and straight cold mass**
- **Integration in the LHC**
  - o **2-in-1 design, intra-beam distance 194 mm**
  - o **Bus-bar routing and heat exchanger location as MB**
- **Schedule and cost**
  - o **Make use of existing tooling and infrastructure**
  - o **Parallel production lines at CERN and FNAL**

Nb_3Sn Superconductor

- **Nb_3Sn critical parameters (J_c, B_{c2} and T_c) very attractive for accelerator magnets**
- **Requires (long) heat treatment @ 680 ° C**
  - **=> Only inorganic insulation materials**
- **Brittle, strain sensitive after reaction**
- **Requires vacuum impregnation with resin**
  - **=> less efficient heat extraction by He**
- **Magneto-thermal instabilities**
  - **=> small filaments, small strands, high RRR**
- **Filaments ~50 μm (NbTi 6 μm)**
  - **⇒ Persistent current effects**
- **Cost ~5 x NbTi**
- **Limited supply and only few suppliers**

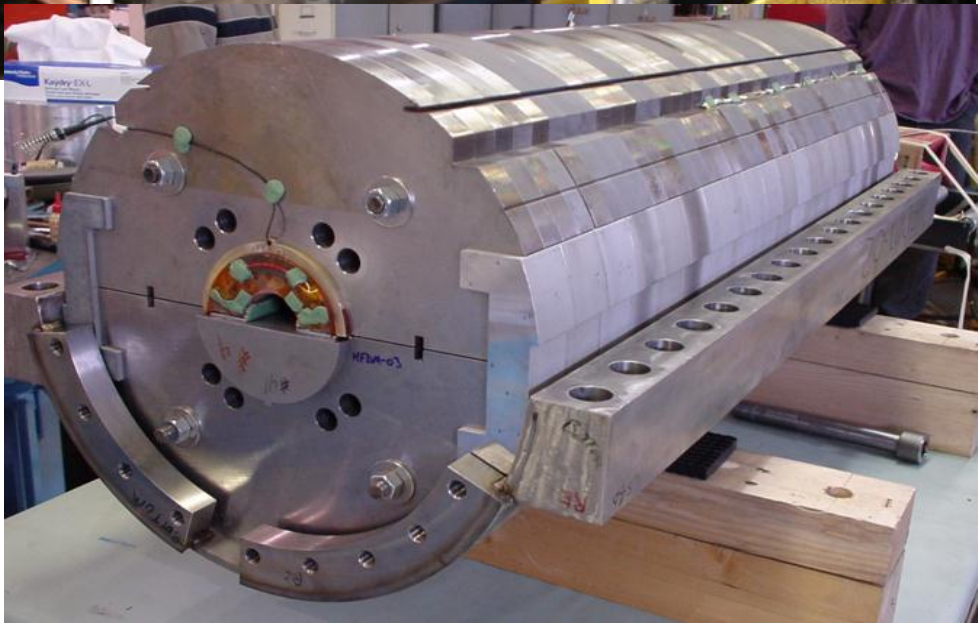


Nb_3Sn Accelerator Magnet R&D

Year	Laboratory	Magnet type (name)	Results
1967	BNL	quadrupole	85 T/m (3 T)
1979	BNL	dipole	4.8 T
1982	CERN	quadrupole	71 T/m
1983	CEN/Saclay	dipole	5.3 T
1985	LBNL	dipole (D10)	8 T
1986	KEK	dipole	4.5 T
1988	BNL	dipole	7.6 T
1991	CERN/ELIN	dipole	9.5 T
1995	LBNL	dipole (hybrid D19H)	8.5 T
1995	UT	dipole (MSUT)	11.2 T
1996	LBNL	dipole (D20)	13.3 T
2003	LBNL	dipole (RD3c)	10 T
2004-6	Fermilab	dipole (HFDA05-07)	10 T
2008	LBNL	dipole (HD2)	13.4 T

Both the performance and the technological aspects of the Nb_3Sn strands and accelerator magnets have significantly advanced.

FNAL Nb_3Sn Dipole Mirror (4 m)

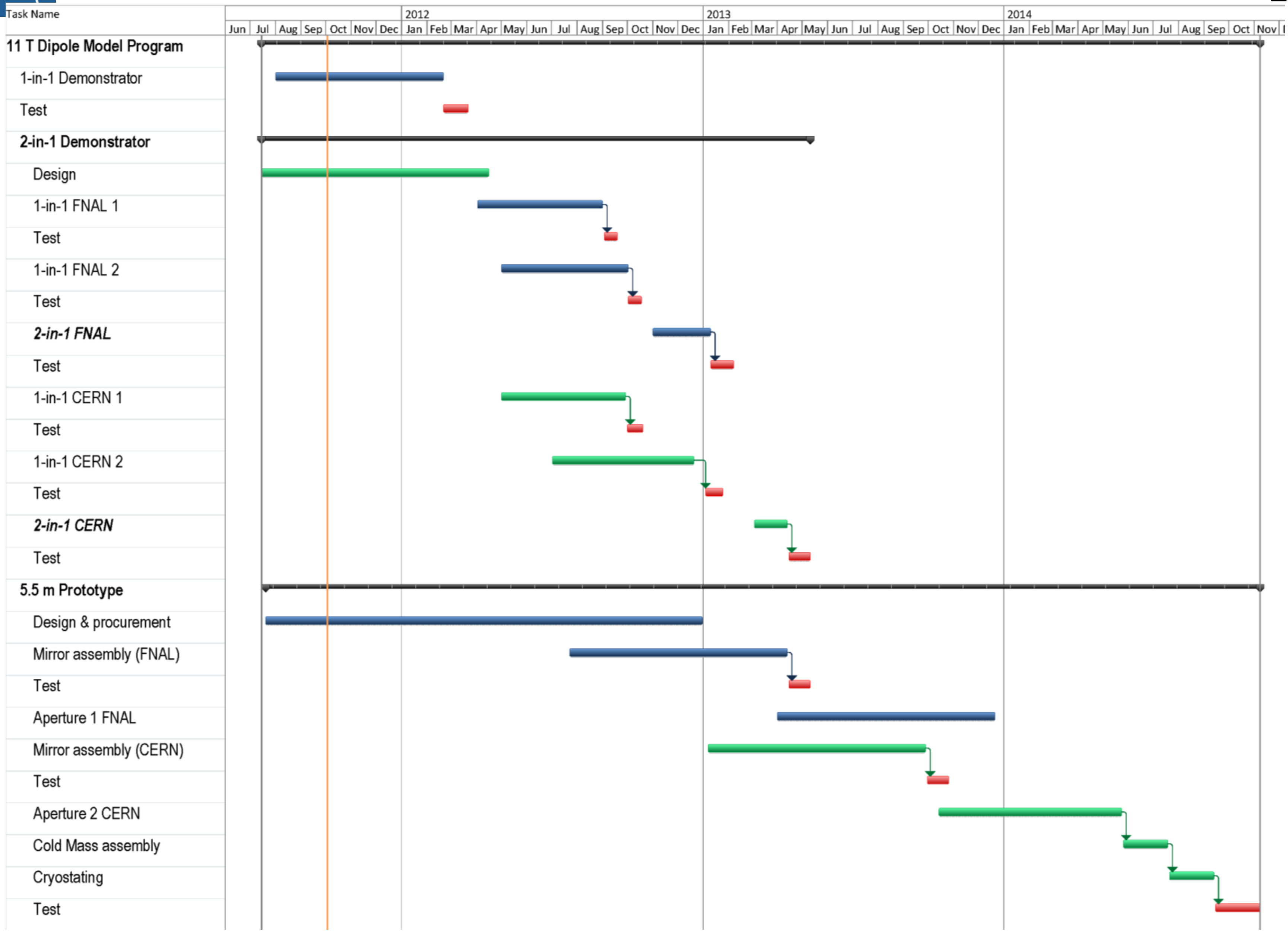


- **Fabrication methods**
- **Tooling**
- **Cold mass components**

11 T Model Program

Date	Description	Length	Remarks	Goals
End-2011	1-in-1 Demonstrator Magnet	2 m	Construction at FNAL	Cable technology Coil Technology Quench performance Magnetization effects
End-2012	2-in-1 Demonstrator Magnet 1	2 m	FNAL collared coils CM-Assembly at CERN	2-in-1 structure Field quality: - iron saturation - cross-talk - Magnetization effects Quench performance Reproducibility
Mid-2013	2-in-1 Demonstrator Magnet 2	2 m	CERN collared coils CM-Assembly at CERN	
End-2014	2-in-1 Prototype Cold Mass	5.5 m	Aperture 1 by FNAL Aperture 2 by CERN CM assembly at CERN	Scale-up Long tooling Fabrication of long coils CM assembly Magnetic performance

11 T Dipole Model Program



Production Phase 2014-17

- Coil production (CERN & FNAL)
- Collaring (CERN & FNAL)
- Cold mass assembly (CERN)
- Cryostat integration (CERN)
- Testing (CERN)
- Installation in the tunnel
- Material cost for 28 off 5.5 m CM ~35 MCHF

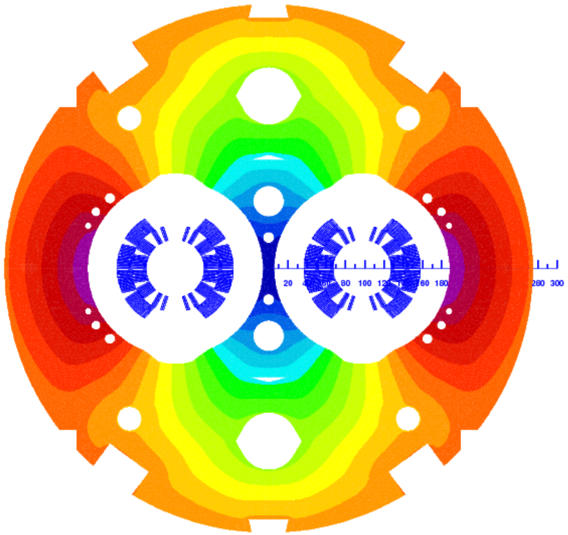
3..4 years



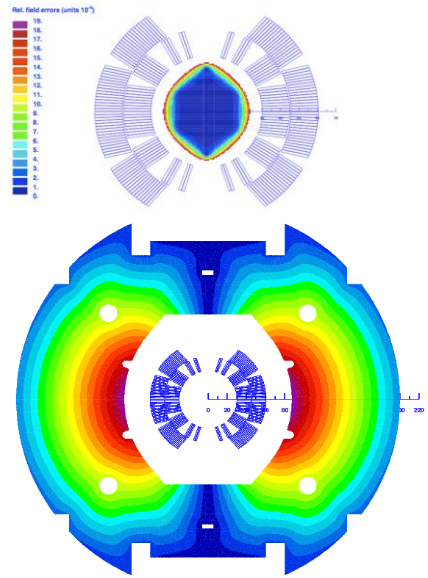
1-in-1 Demonstrator Goals

- Design and construction of a 2-m-long single aperture magnet, delivering 11 T at the LHC nominal operating current of 11.85 kA with 20% margin
- Cable technology
  - J_c degradation, I_s-data
- Coil technology
  - Fabrication procedures
  - Insulation technology
- Quench performance
  - Operation margin
  - Ramp-rate studies
- Magnet protection
  - Heater development
  - Heater efficiency and delays
- Coil Magnetization & coupling currents

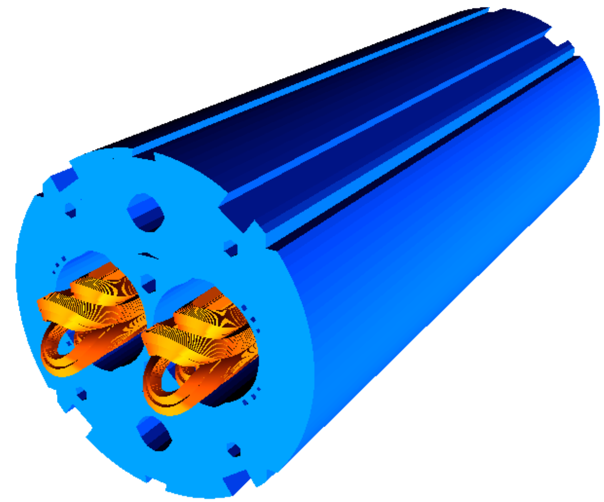
Coil Design



$B_0(11.85\ \text{kA}) = 11.21$ T



$B_0(11.85\ \text{kA}) = 10.86$ T



- **Coil optimization**
  - **>11 T at 11.85 kA with 20% margin at 1.9 K**
  - **Field errors below the 10^{-4} level**
- **6-block design, 56 turns**
  - **14.85 mm wide 40-strand Rutherford cable**
  - **Several X-sections were analyzed with and without core**
  - **Coil ends optimized for low field harmonics and minimum strain in the cable**

Cable Development & Strand Stock

- 40-strand Rutherford cable based on RRP-108/127 0.7 mm strand and with ~85% compaction for the 11 T Nb_3Sn demonstrator dipole has been developed
  - Issues - large aspect ratio, low compaction
  - FNAL roll the cable in two stages with an intermediate anneal (rectangular → trapezoidal cross-section).
  - CERN use single pass process.

- Cable samples with and without a SS core
  - I_c degradation well within the initial goal of 10 %
- Cable unit length 205 m (2 m coil) or 600 m (5.5 m)
- FNAL have 430 m cable
- CERN have strand for three 2 m coils
- FNAL ordered 2 x 45 km (Jan-12 & Jul-12)
- CERN in process of ordering 2 x 45 km (delivery TBC)
- Need ASAP low-performance strand for first practice coils at CERN

SC-strand & Cable needs

Model program:

1-in-1 Demo	**3 coils**	**26 km**
2-in-1 Demo FNAL	**4 coils**	**34 km**
2-in-1 Demo CERN	**2(*+4 coils**	**17(* +34 km**
5.5 m proto	**10 coils**	**240 km**

===

Total strand ***17+334 km***

Cable for series magnets:

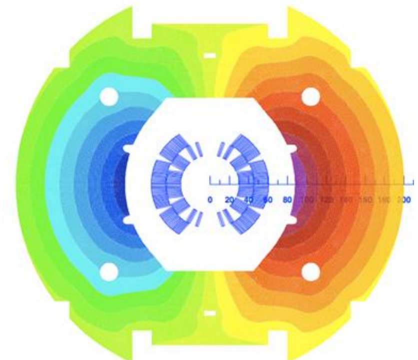
28 x 5.5 m **112 + 6 spare coils** **71 km**

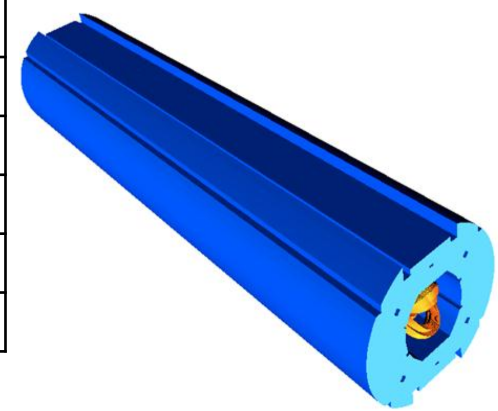
(+20% margin >3400 km of strand)

**) Practice coils*

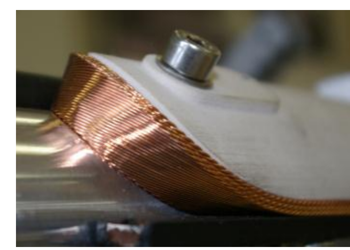
1-in-1 Demonstrator Parameters

Parameter	Value
Aperture [m]	60
Nominal current I_{nom} [A]	11850
Nominal bore field (with 400 mm yoke) [T]	10.86
Short-sample bore field at 1.9 K [T]	13.6
Margin B_{max}/B_{nom} at 1.9 K [%]	25.4
Ultimate design field [T]	12.0
Inductance at I_{nom} [mH/m]	5.6
Stored energy at I_{nom} [kJ/m]	473
F_x per quadrant at I_{nom} [kN/m]	2889
F_y per quadrant at I_{nom} [kN/m]	1570
Coil length [m]	1.9
Magnetic length [m]	1.79



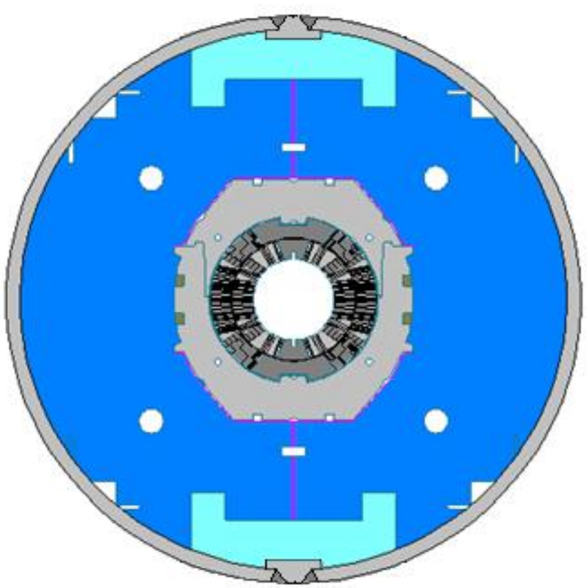


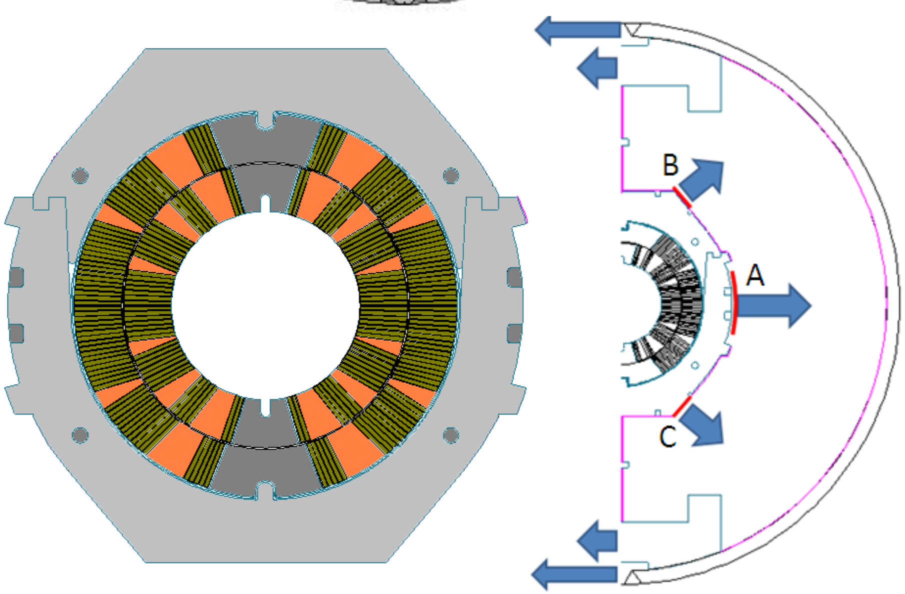
Coil Technology



- Coil technology developed at Fermilab
- Integrated Ti poles, st. steel end parts and wedges
- 2 m long practice coils:
  - PC#1: Cu cable
  - PC#2: Nb_3Sn cable (RRP-114/127)
  - Practice windings to check the optimized cable and end parts
- First real coil winding is being completed

1-in-1 Demonstrator Mechanical Structure





- Slightly elliptical stainless steel collar, 25-mm wide near mid-plane.
- The vertically split iron yoke clamped with Al clamps.
- The 12-mm stainless steel skin.
- Two 50-mm thick end plates.
- Maximum stress during assembly ~130 MPa to keep coil under compression up to 12 T bore field.
- The mechanical structure is optimized to maintain the coil stress below 165 MPa - safe level for brittle Nb3Sn coils

1-in-1 Demonstrator Status

- The engineering design and tooling are complete
- 40-strand cable developed and tested
- 2 unit lengths are available for coil winding
- Coil fabrication procedures established
- Coil fabrication tooling commissioned
- Assembly tooling being procured
- Winding of the first coil being completed
- Mechanical structure is being procured
- Next steps:

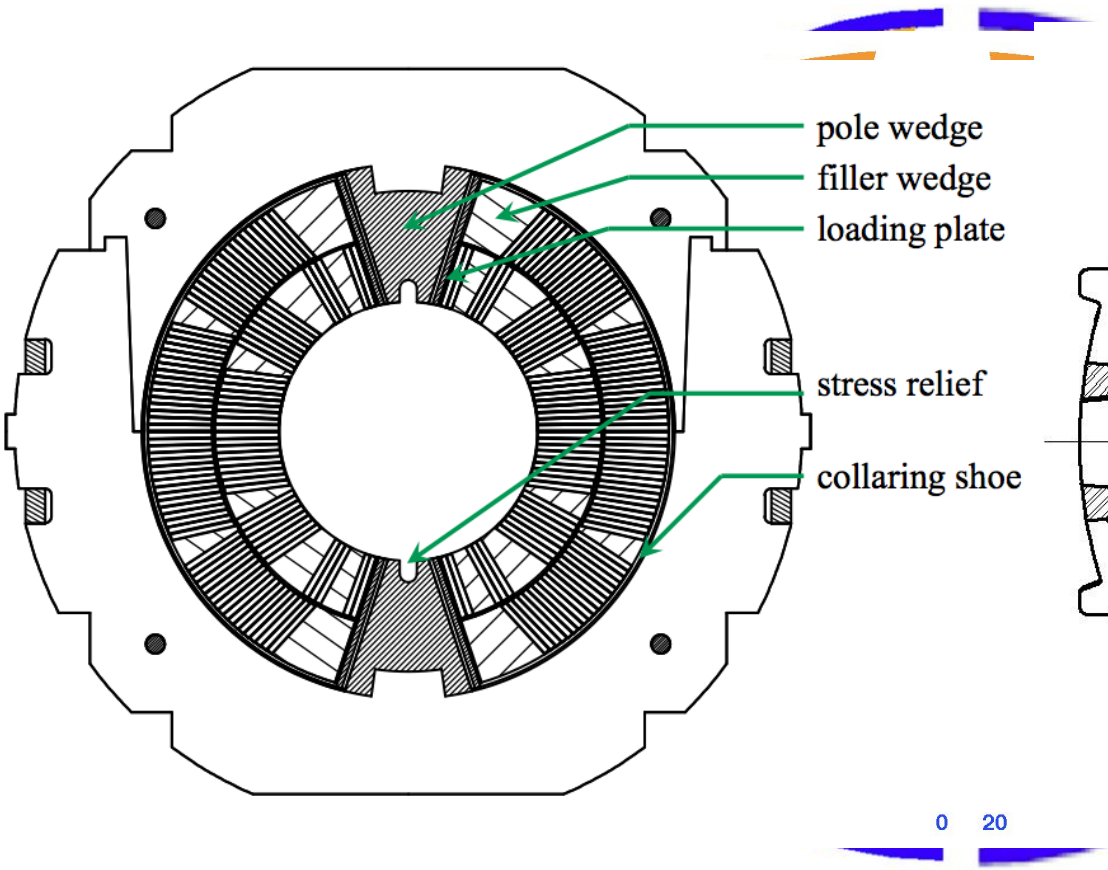
Short mechanical model assembly	End-Nov
Collaring	Jan-12
Yoke assembly	Feb-12
Magnet test at FNAL	Mar-12

2-in-1 Demonstrator Goals

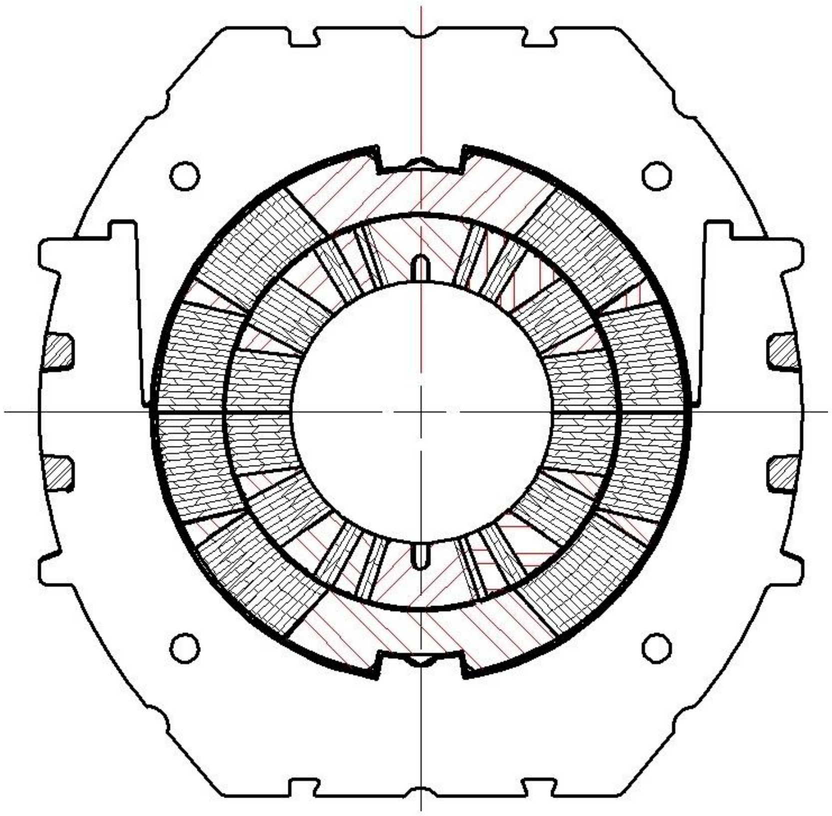
- Design and construction of a 2-m-long 2-in-1 magnet, delivering 11 T at the LHC nominal operating current of 11.85 kA with 20% margin
- Quench performance
  - Operation margin
  - Ramp-rate studies
- Transfer function matching with MB
- Field quality
  - Iron saturation
  - Persistent current effects & passive correction
  - Coupling current effects
  - Magnetic cross-talk between the apertures
- Magnet protection
  - Heater development
  - Heater efficiency and delays

2-in-1 Demonstrator Design

❖ **Two alternative design concepts**



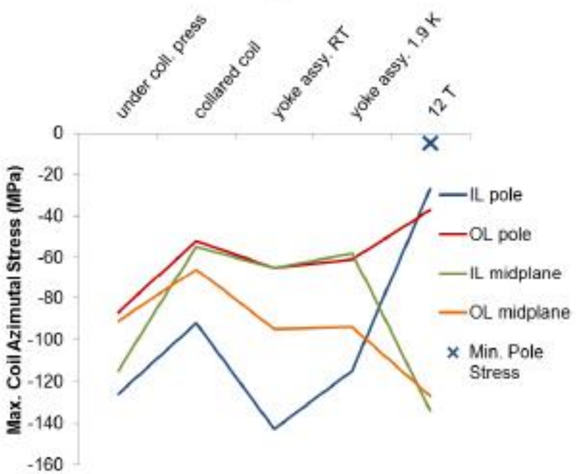
Removable Pole Design

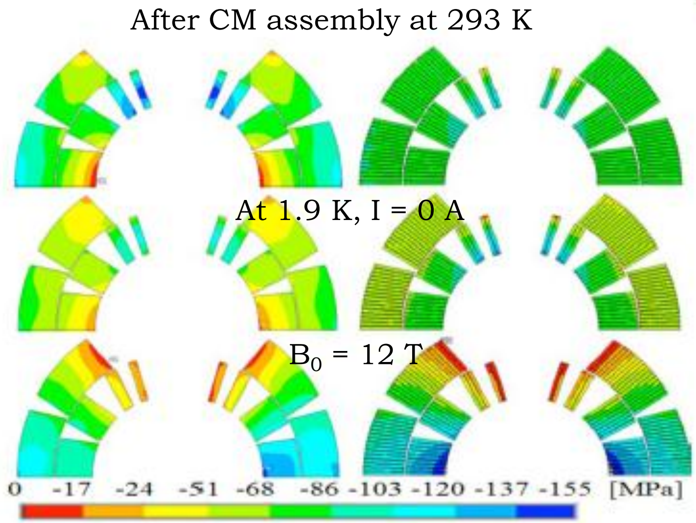


Integrated Pole Design

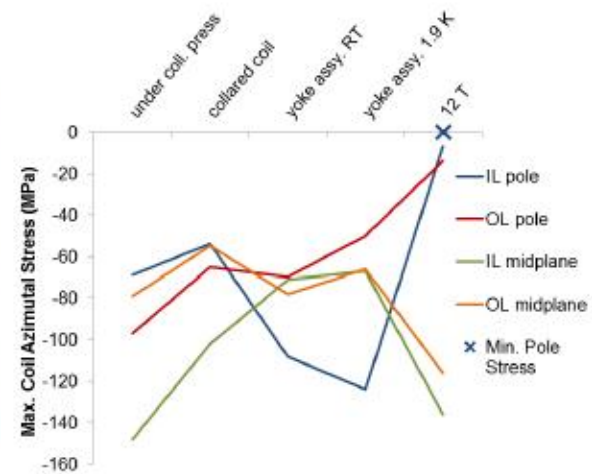
2-in-1 Demonstrator FEA

Removable Pole Design





Integrated Pole Design



- **Mechanical design challenges**
  - **First twin-aperture Nb_3Sn dipole**
  - **Coil pre-stress and Lorentz force management inside the LHC iron yoke.**
  - **Lorenz forces are almost 2X higher than in MB**
- **Both design concepts meet the mechanical design goals**
  - **Coil stress below 150 MPa during the assembly process**
  - **Coil remain under compression up to 12 T**

2-in-1 Demonstrator Paramteres

Parameter	Unit	Removable Pole Design	Integrated Pole Design
Nominal current I_{nom}	kA	11.85	11.85
Nominal bore field	T	11.23	11.25
Maximum coil field	T	11.59	11.6
Magnetic length	mm	1.537	1.54
Working point on the load-line at I_{nom}		81%	81%
Ultimate design field	T	12	12
Inductance at I_{nom}	mH/m	11.97	11.98
Stored energy at I_{nom}	kJ/m	966.3	968.6
F_x per quadrant at I_{nom}	MN/m	3.15	3.16
F_y per quadrant at I_{nom}	MN/m	-1.58	-1.59
F_z per aperture	kN	430	430
Overall length	mm	1960	1960
Coil overall length	mm	1760	1760
Yoke outer diameter	mm	550	550
Outer shell thickness	mm	10	10
Mass	kg	~2600	~2600

2-in-1 Demonstrator status & Plans (1/2)

- **Engineering design of the magnet is in progress**
  - **Collared coil from 1-in-1 demonstrator**
  - **"Conventional" collaring with coil pre-loading at the poles**

- **2-in-1 magnet with FNAL coils**

Coils for 1st aperture	Mar..Jul-12
Cold test of 1st aperture	Sep-12
Coils for 2nd aperture	Apr..Jul-12
Cold test of 2nd aperture	Oct-12
Mechanical model	Oct..Dec-12
2-in-1 CM assembly at CERN	Jan-13
2-in-1 cold test at CERN	Feb-13

2-in-1 Demonstrator status & Plans (2/2)

- **CERN tooling (based on FNAL design)**
  - **Winding tooling in procurement**
  - **Reaction, impregnation, and assembly tooling being designed**

- **2-in-1 magnet with CERN coils**

First practice coil (Cu)	Dec-12
First practice coil (Nb_3Sn)	Feb-12
Mechanical model (1-in-1)	Mar..Apr-12
Coils for 1st aperture	May..Aug-12
Cold test of 1st aperture	Oct-12
Coils for 2nd aperture	Jul-12..Nov-12
Mechanical model (2-in-1)	Oct..Dec-12
Cold test of 2nd aperture	Jan-13
2-in-1 CM assembly	Mar-13
2-in-1 cold test	Apr-13

5.5 m Prototype Plans

- **FNAL**
  - **Practice coils** — **Aug-12..Jan-13**
  - **Mirror assembly** — **Mar-13**
  - **Mirror test** — **Apr-13**
  - **Coils for FNAL aperture** — **May..Nov-13**
  - **Collared coil** — **Dec-13**
- **CERN**
  - **Practice coils** — **Jan..Jul-13**
  - **Mirror assembly** — **Aug-13**
  - **Mirror test** — **Oct-13**
  - **Coils for CERN aperture** — **Oct-13..May-14**
  - **Collared coil** — **Jun-14**

  - **CM assembly** — **Aug-14**
  - **Cryostat assembly** — **Sep-14**
  - **Cold test** — **Oct..Nov-13**

Summary

- 11 T Nb_3Sn dipole magnets for the LHC upgrades are being developed by Fermilab/CERN collaboration
  - additional cold collimators
  - other applications
- The construction of the **1-in-1 demonstrator** magnet has started and the engineering design of the **2-in-1 demonstrator** is well underway.
- Tooling design for **5.5 m coils** has started at FNAL
- **SC strand** supply is on the **critical path** of the model program
- The integration into the LHC is common effort with the (cryo-) collimator R&D.
- The time scale of the planned upgrade is challenging and requires parallel production lines at CERN and at FNAL.