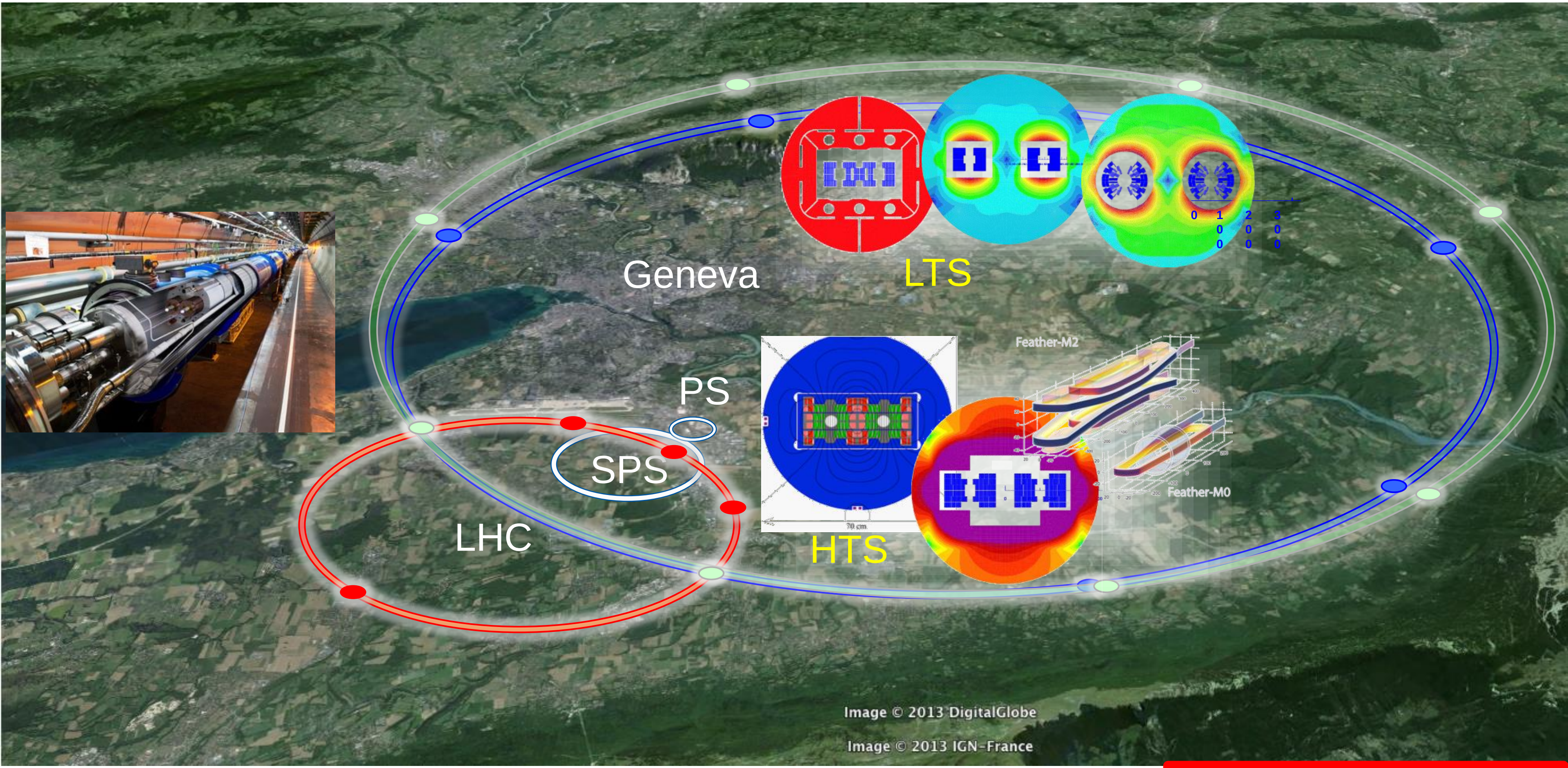
FCC SC magnet program

L. Bottura

FCC Week, Washington

March 22nd, 2015

The FCC playground



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LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

Outline

- **Magnet focus is on FCC-hh**: the other accelerators in the complex are within reach of present technology
- Identify **high priority items** and discuss R&D targets
- Outline a possible program

Wed 3/25

07:00 **Breakfast for all FCC participants** *Marriott Georgetown Hotel*

High Field SC Magnets: Machine Configuration & Magnet Specifications *GianLuca Sabbi* *ROOM C, Marriott Georgetown Hotel*

FCC-hh *Abid Patwa* *ROOM A, Marriott Georgetown Hotel*

10:00 **Coffee Break** *Marriott Georgetown Hotel*

High Field SC Magnets: Conductor R&D I *Carmine Senatore* *ROOM C, Marriott Georgetown Hotel*

FCC-hh experiments *Guido Emilio Tonel...* *ROOM A, Marriott Georgetown Hotel*

12:00 **Lunch break** *Marriott Georgetown Hotel*

Lunch break *Marriott Georgetown Hotel*

High Field SC Magnets: Conductor R&D II *Amalia Ballarino, ...* *ROOM C, Marriott Georgetown Hotel*

Contributed Talks - Accelerators 1: Experiments *Stephen Peggs* *ROOM A, Marriott Georgetown Hotel*

15:00 **Coffee break** *Marriott Georgetown Hotel*

High Field SC Magnets: HTS and opportunities of FCC developments *Pierre Vedrine* *ROOM C, Marriott Georgetown Hotel*

FCC-he: Physics and detector *Claire Gwenlan* *ROOM A, Marriott Georgetown Hotel*

17:00 **Teatime**

Thu 3/26

07:00 **Breakfast for all FCC participants** *Marriott Georgetown Hotel* 07:00 - 08:30

High field magnets challenges: Concepts, production, cost, radiation *Herman Ten ...* *ROOM B, Marriott Georgetown Hotel*

Infrastructure & Operation: Implementation, Operation, Power *Lluis Secundin...* *ROOM C, Marriott Georgetown Hotel*

Technologies R&D Working Group *Yasunori Tan...* *ROOM A, Marriott Georgetown Hotel*

Physics & Phenomenology: Discovery via precision EW/Higgs/flavour physics *Jonathan R. E...* *ROOM D, Marriott Georgetown Hotel*

10:00 **Coffee Break** *Marriott Georgetown Hotel* 10:00 - 10:30

High Field SC Magnets: Magnet Design Options I *Giorgio Apollinari...* *ROOM B, Marriott Georgetown Hotel*

Infrastructure & Operation: Cryogenics *Christoph Ha...* *ROOM C, Marriott Georgetown Hotel*

Beam Transfer Systems & Instrumentation *Egbert Fischer* *ROOM A, Marriott Georgetown Hotel*

Physics & Phenomenology: EWSB probes of BSM *Dmitri Denis...* *ROOM D, Marriott Georgetown Hotel*

12:00 **Lunch Break** *Marriott Georgetown Hotel* 12:00 - 13:30

High Field SC Magnets: Magnet Design Options II *Tatsushi Na...* *ROOM B, Marriott Georgetown Hotel*

Infrastructure & Operation: Controls & Safety *Ralf Trant* *ROOM C, Marriott Georgetown Hotel*

Beam Dump & Collimators: Materials & Engineering Breakthroughs *Olivier Brunn...* *ROOM A, Marriott Georgetown Hotel*

Physics & Phenomenology: (In)direct probes of the high-mass frontier *Raman Sund...* *ROOM D, Marriott Georgetown Hotel*

15:00 **Coffee Break** *Marriott Georgetown Hotel* 15:00 - 15:30

High Field SC Magnets: Magnet Design Options III *Stephen Gour...* *ROOM B, Marriott Georgetown Hotel*

FCC-hh experiments *Roy Aleksan* *ROOM C, Marriott Georgetown Hotel*

Magnets (Resistive) & Machine Protection *Mar Capeans ...* *ROOM A, Marriott Georgetown Hotel*

Physics & Phenomenology: Dark matter at FCC *Joseph David...* *ROOM D, Marriott Georgetown Hotel*

Physics & Phenomenology: What's next: general ...

17:00 **Teatime**

LTS magnets for FCC-hh

Task	Key targets	Description	Specific challenges
HH-MB	B=16 T D=50 mm L=15 m	Arc dipole	Magnet concept **Quench performance and margin** Field quality **Specific cost**
HH-MQ	G=450 T/m D=50 mm L=6 m	Arc quadrupole	High gradient Specific cost
HH-MBX	B=12 T D=60 mm L=12 m	Separation dipole	**Heat removal and radiation hardness**
HH-MBR	B=10 T D=60 mm L=10 m	Recombination dipole	
HH-MQY	G=300 T/m D=70 mm L=10 m	Matching/insertion quadrupole	
HH-MQX	G=225 T/m D=100 mm L=10 m	IR quadrupole	Field quality and alignment **Heat removal and radiation hardness**

NOTES

all values based on preliminary estimates, pending optics studies

HTS magnet options for FCC-hh

Task	Key targets	Description	Specific challenges
HTS-demo	B=5 T D=40 mm L=0.5 m	5 T magnet technology demonstrator (as from EuCARD2)	**Quench performance and margin** **Quench detection and protection** Field quality
HH-MB-HTS	B=20 T D=50 mm L=15 m	arc dipole for 80 km ring	**Quench performance and margin** **Quench detection and protection** Field quality **Specific cost**
HH-MQX-HTS	G=275 T/m D=100 mm L=10 m	IR quadrupole	Quench performance and margin Quench detection and protection Field quality and alignment **Heat removal and radiation hardness**

NOTES

all values based on preliminary estimates, pending optics studies

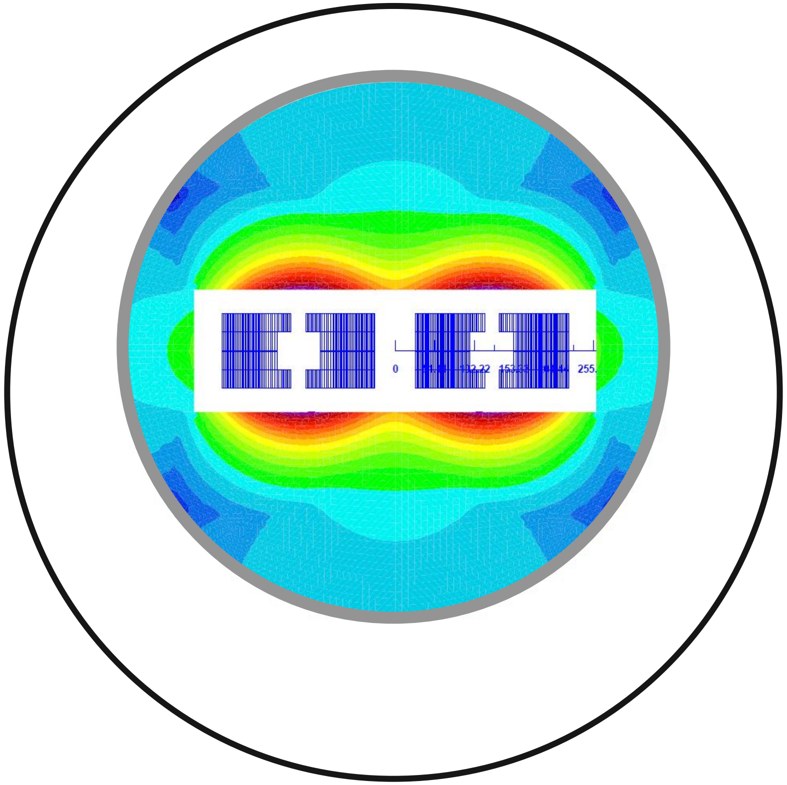
Other SC magnets for the FCC

Task	Key targets	Description	Specific challenges
SPS4FCC	B=11 T dB/dt = 35 mT/s	Injector dipole magnet for the SPS tunnel	Quench performance and margin Ramp-rate, powering and AC loss Specific cost and operation cost Fatigue
LHC4FCC	B=4 T dB/dt = 35 mT/s	Use of the LHC as FCC injector	Ramp-rate, powering, protection and AC loss Operation cost
FCC-HTS-INJ	B=1.1 T dB/dt = 50 mT/s H=120 mm(1)	Super-ferric booster magnet in the FCC tunnel based on HTS coils	Quench performance and margin Ramp-rate, powering and AC loss, SR load Specific cost and operation power/cost Compatibility with a FCC-ee booster
FCC-TL	B up to 5 T	Beam transfer lines, separate or combined function magnets	Cold mass and cryostat design for large magnet slope (8 %) and tilt (30 degrees) Specific cost
EE-MQX	TBD	IR SC quadrupole for FCC-ee	Magnet configuration (conical aperture) and design SR

NOTES

all values based on preliminary estimates, pending optics studies

MB – block @ 1.9 K



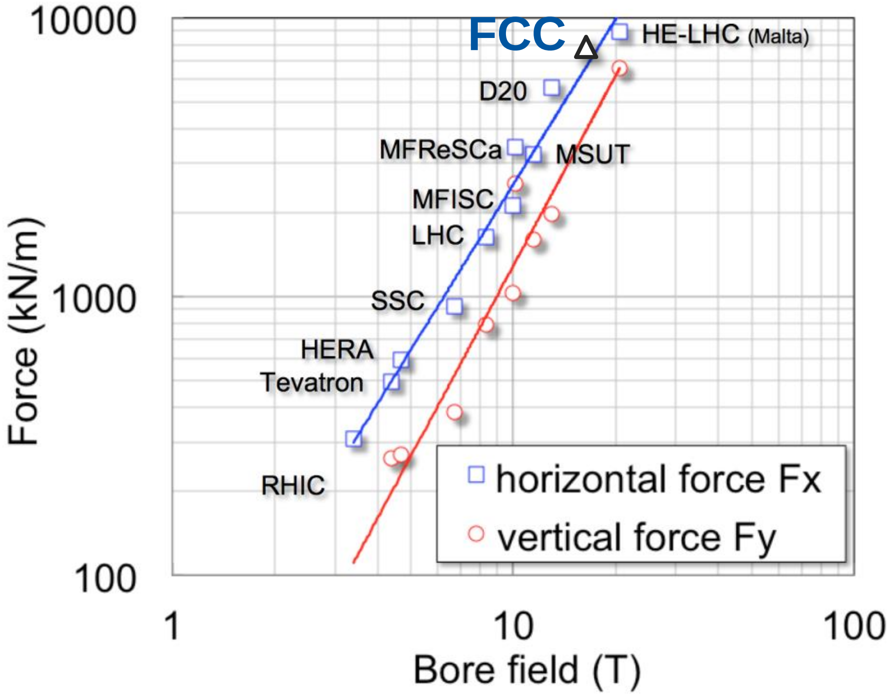
1 m diameter “cryostat” envelope
Mechanical concept: Collared coils

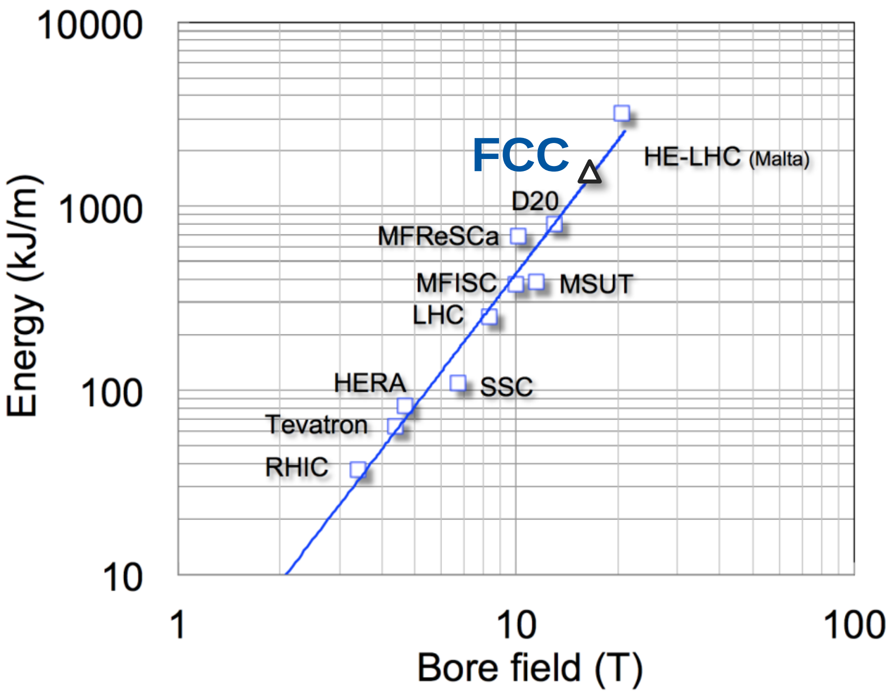
Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	250
Operating current	(kA)	16.4
Operating temperature	(K)	1.9
Nominal field	(T)	16
b_2 @ 2/3 Aperture	10^{-4}	40.5
b_3 @ 2/3 Aperture	10^{-4}	2.8
Peak field	(T)	16.3
Margin along the load line	(%)	~20
Stored magnetic energy	(MJ/m)	3.2
Fx (per ½ coil)	(kN/m)	7600
Fy (per ½ coil)	(kN/m)	-3800
Inductance (magnet)	(mH/m)	22.8
Yoke ID	(mm)	-
Yoke OD	(mm)	700
Weight per unit length	(kg/m)	2500
Area of SC	(mm^2)	6650
Area of cable low-Jc Nb_3Sn	(mm^2)	7180
Area of cable high-Jc Nb_3Sn	(mm^2)	10900
Area of cable Nb-Ti	(mm^2)	4000
Turns Low-J Nb_3Sn per pole	-	19
Turns High J Nb_3Sn per pole	-	41
Turns Nb-Ti per pole	-	15

Design by D. Schoerling, J. van Nugteren

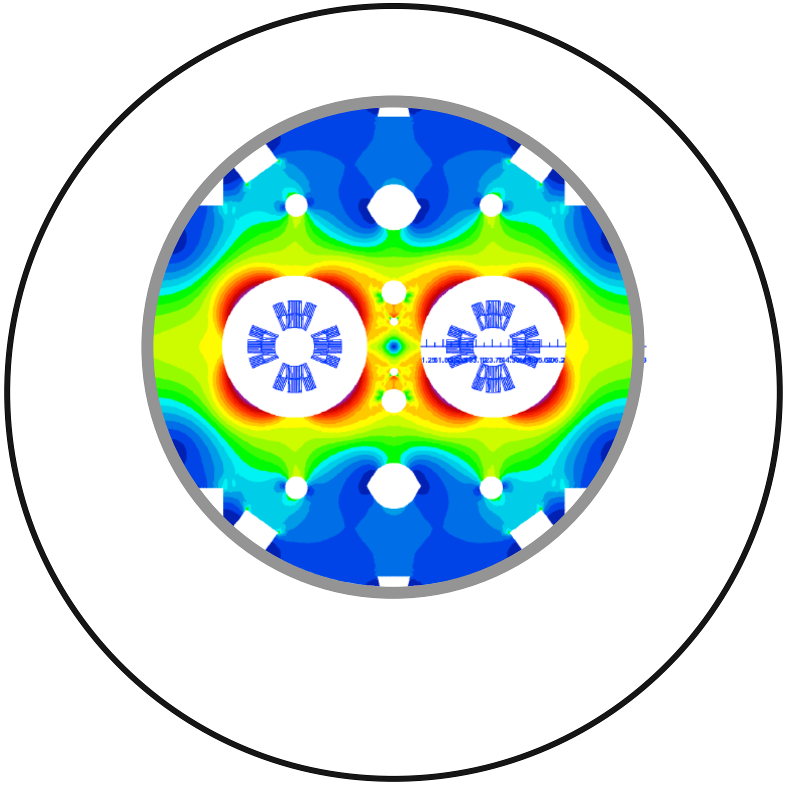
Note on scaling

- Forces in the FCC MB will be approximately 4 times larger, stored energy approximately 8 times larger than in the LHC





MQ – V4 @ 1.9 K



Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	250
Operating current	(kA)	26.1
Operating temperature	(K)	1.9
Nominal gradient	(T/m)	380
b_6 @ 2/3 Aperture	10^{-4}	0.0
b_{10} @ 2/3 Aperture	10^{-4}	2.6
Peak field	(T)	10.5
Margin along the load line	(%)	20
Stored magnetic energy/unit length	(MJ/m)	0.59
Fx (per ½ coil)	(kN/m)	1496
Fy (per ½ coil)	(kN/m)	-2095
Inductance (magnet)	(mH/m)	1.2
Yoke ID	(mm)	184
Yoke OD	(mm)	620
Weight per unit length	(kg/m)	2000
Area of SC	(mm^2)	1420
Area of cable Nb_3Sn	(mm^2)	3200
Area of cable Nb-Ti	(mm^2)	0
Turns per pole, inner layer	-	7
Turns per pole, outer layer	-	10

Design by M. Karppinen

Matters of high priority

- LTS magnets: can we make them, reliable and cost-effective ?
  - Design and prototype the magnets that are crucial for the FCC-hh baseline collider (100 km ring, 16 T dipoles)
  - Push the performance of graded LTS (Nb_3Sn) accelerator magnets to its practical limit
  - Reduce training and operating margin
- HTS magnets: can we make them at all ?
  - Prove the performance of a 5 T dipole as an insert to break the 20 T barrier
- What infrastructure is required to support the above tasks ?

Conductor R&D (LTS & HTS)

- Objectives:
  - Boost the performance of Nb_3Sn to meet the targets as set by magnet design for an LTS FCC-hh
  - Sustain HTS development for accelerator applications

Task	Key targets	Description
Nb_3Sn	D_{strand}: 0.7…1 mm J_C (16 T, 4.2 K) > 1500 A/mm^2 DM (1 T,4.2 K) <150 mT (D_{fil} < 20 μm) RRR > 150 UL > 5 km	Develop conductor for **increased J_C** with respect to HL-LHC specifications, maintain high RRR, reduce magnetization, increase stability, withstand cabling
LTS cost	Cost(16 T, 4.2 K) < 5 USD/kA m	Perform cost analysis and identify drivers Process innovation and potential for industrialization to increase yield and UL, **reduce cost**
HTS	J_E (20 T, 4.2 K) > 600 A/mm^2 UL > 100 m	Develop long length homogeneous YBCO tape and BSCCO wires, develop high current cables
Quench	Quench propagation speed and temperature limits characterization	Understand quench regimes and quench limits for LTS and HTS materials

Magnet technology R&D – 1/2

- Objectives:
  - Develop basic concepts and materials for the magnet technology required to achieve the LTS FCC-hh performance targets

Task	Description
Margin and training	Develop techniques and materials to **reduce training and operating margin**, covering conductor design, epoxy types, additives, bonding characteristics, glass charge homogeneity, impregnation technology. Understand and improve magnet training memory
Quench protection	Develop improved/alternatives for quench detection and protection, including interlayer quench heaters, inner layer heaters, pulsed current protection schemes
Heat transfer	Characterize and develop methods to increase heat removal from impregnated windings
Radiation and dose	Develop designs and materials that decrease the exposure to radiation loads, increase hardness, reduce activation

Magnet technology R&D – 2/2

- Objectives:
  - Develop existing and novel techniques and materials as necessary for a cost-optimized LTS FCC-hh

Task	**Description**
Winding	Winding with additives, winding tooling, automated winding
Splices	Technology for splices among cables (Nb_3Sn to Nb_3Sn and Nb_3Sn to NbTi)
Grading	Develop robust technology for the grading of Nb_3Sn magnet winding (coil assembly methods, including interlayer splices)
Insulation	Develop improved insulation schemes (fibers, resins) compatible with HT cycles, higher voltage withstand, radiation hardness
Heat treatment	Understand and allow for dimensional changes during heat treatment, and related dimensional tolerances
Structure	Develop existing concepts (collars, bladder-and-key) and novel concepts for the magnet support
Cost	Analyze the cost of **magnet manufacturing**, examine low cost designs, and manufacturing procedure for cost reduction

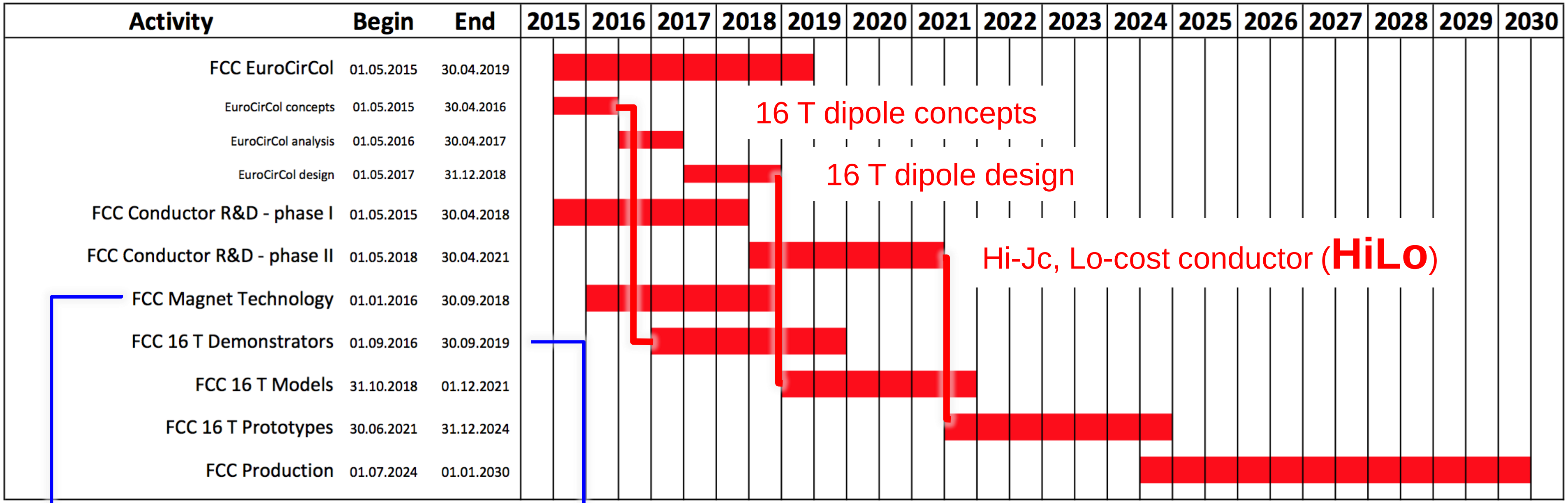
Infrastructure

- Objectives:
  - Material analysis, processing and diagnostic instruments appropriate to the advanced materials developed for the FCC magnets

Task	Description
SC materials testing	Very high field (18 T … 20 T) test facilities for high critical current (2 kA and above) and magnetization measurements
	Imaging (e.g. nano-tomography), microscopy (e.g. SEM/TEM), and analytical facilities (e.g. XRD, neutron diffractography) in support to material analysis
SC cables testing	Cable test facility for high field (15 T and above) and high current (30 kA and above)
Material and components processing	Ovens (600…900 °C, OPHT capability) for the processing of LTS and HTS materials.
Models and prototype magnet testing	SC magnet test facility for high current tests (30 kA and above), for HTS under variable temperature (up to 77 K)

A plan for discussion – 1/2

- Focus on the “piece de resistance” (improperly translated as “main course”): LTS 16 T MB and conductor R&D

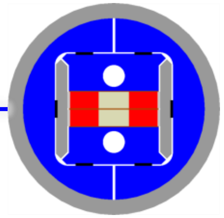


16 T dipole concepts

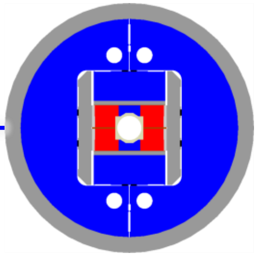
16 T dipole design

Hi-Jc, Lo-cost conductor (**HiLo**)

Activity	Begin	End
FCC EuroCirCol	01.05.2015	30.04.2019
EuroCirCol concepts	01.05.2015	30.04.2016
EuroCirCol analysis	01.05.2016	30.04.2017
EuroCirCol design	01.05.2017	31.12.2018
FCC Conductor R&D - phase I	01.05.2015	30.04.2018
FCC Conductor R&D - phase II	01.05.2018	30.04.2021
FCC Magnet Technology	01.01.2016	30.09.2018
FCC 16 T Demonstrators	01.09.2016	30.09.2019
FCC 16 T Models	31.10.2018	01.12.2021
FCC 16 T Prototypes	30.06.2021	31.12.2024
FCC Production	01.07.2024	01.01.2030

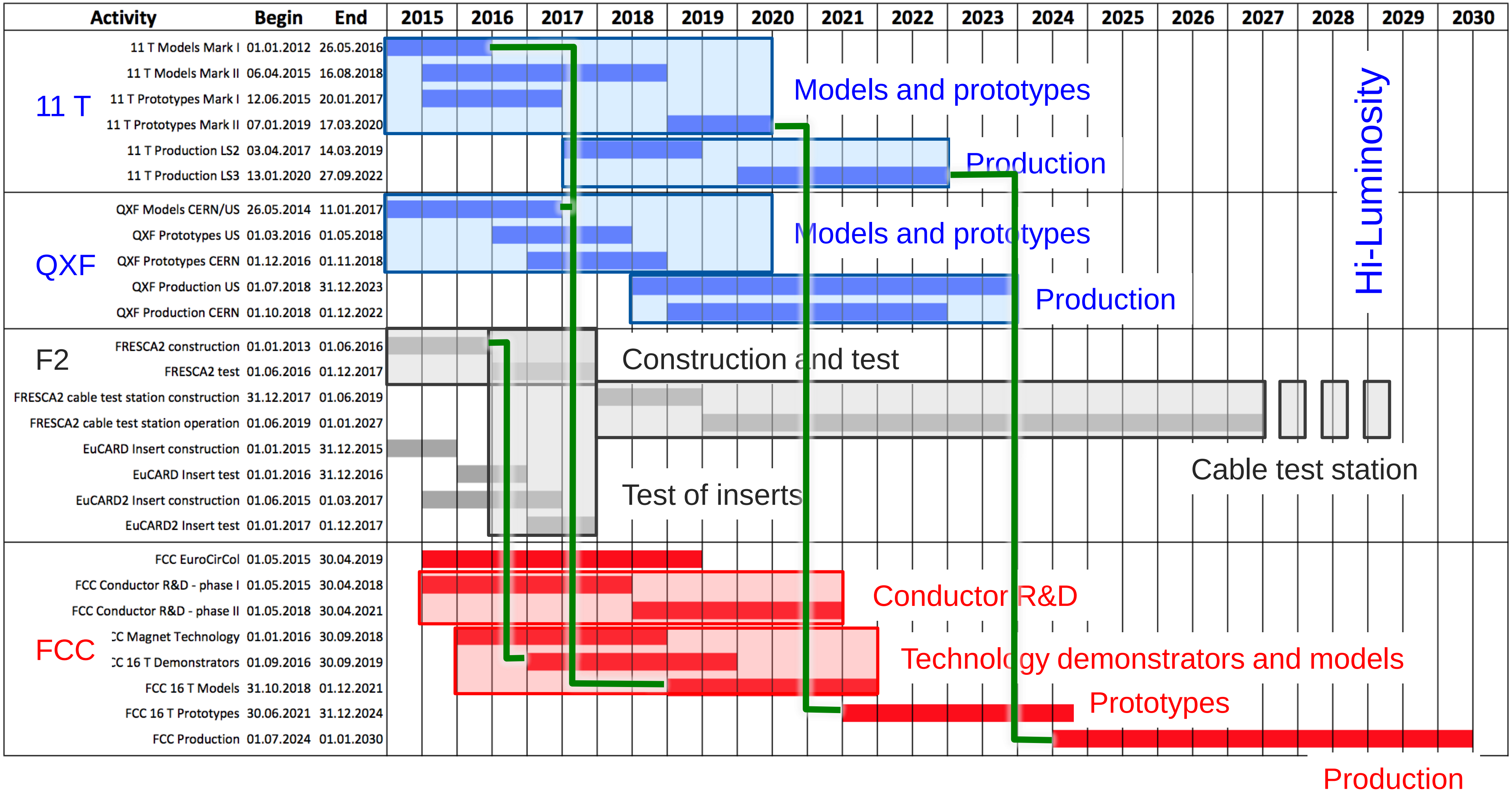


Technology:
SC, SMC/RMC



Demonstrator:
HD, *DMC*

A plan for discussion – 2/2



	Activity	Begin	End
11 T	11 T Models Mark I	01.01.2012	26.05.2016
	11 T Models Mark II	06.04.2015	16.08.2018
	11 T Prototypes Mark I	12.06.2015	20.01.2017
	11 T Prototypes Mark II	07.01.2019	17.03.2020
	11 T Production LS2	03.04.2017	14.03.2019
	11 T Production LS3	13.01.2020	27.09.2022
QXF	QXF Models CERN/US	26.05.2014	11.01.2017
	QXF Prototypes US	01.03.2016	01.05.2018
	QXF Prototypes CERN	01.12.2016	01.11.2018
	QXF Production US	01.07.2018	31.12.2023
	QXF Production CERN	01.10.2018	01.12.2022
F2	FRESCA2 construction	01.01.2013	01.06.2016
	FRESCA2 test	01.06.2016	01.12.2017
	FRESCA2 cable test station construction	31.12.2017	01.06.2019
	FRESCA2 cable test station operation	01.06.2019	01.01.2027
	EuCARD Insert construction	01.01.2015	31.12.2015
	EuCARD Insert test	01.01.2016	31.12.2016
	EuCARD2 Insert construction	01.06.2015	01.03.2017
	EuCARD2 Insert test	01.01.2017	01.12.2017
FCC	FCC EuroCirCol	01.05.2015	30.04.2019
	FCC Conductor R&D - phase I	01.05.2015	30.04.2018
	FCC Conductor R&D - phase II	01.05.2018	30.04.2021
	CC Magnet Technology	01.01.2016	30.09.2018
	CC 16 T Demonstrators	01.09.2016	30.09.2019
	FCC 16 T Models	31.10.2018	01.12.2021
	FCC 16 T Prototypes	30.06.2021	31.12.2024
	FCC Production	01.07.2024	01.01.2030

Not too bad… when is the C+S review ???

An agenda for this week

- FCC-hh **16 T arc dipole** and other magnets: discuss concepts, performance, margin, cost drivers
- HHMB-HTS 20 T arc dipole: follow-up developments
- LHC4FCC 4 T, 35 mT/s: is this an effective option ?
- FCC-INJ 1.1 T, 50 mT/s: I believe in this technology !
- **LTS conductor R&D**: need performance increase (x 1.5) and cost reduction (x 1/3), is this HiLo Nb_3Sn realistic ?
- Magnet technology: training and margin, protection, how can we improve ?


CERN