SC Magnet System for High Luminosity LHC Upgrade in View of Radiation Issues

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Reference

- LHC Performance Workshop (Chamonix 2017)
  https://indico.cern.ch/event/580313/
- 129th LHCC Meeting (open session)
  https://indico.cern.ch/event/609813/
- HL-LHC Collaboration Meeting 2016
  https://espace.cern.ch/HiLumi/2016/SitePages/Home.aspx

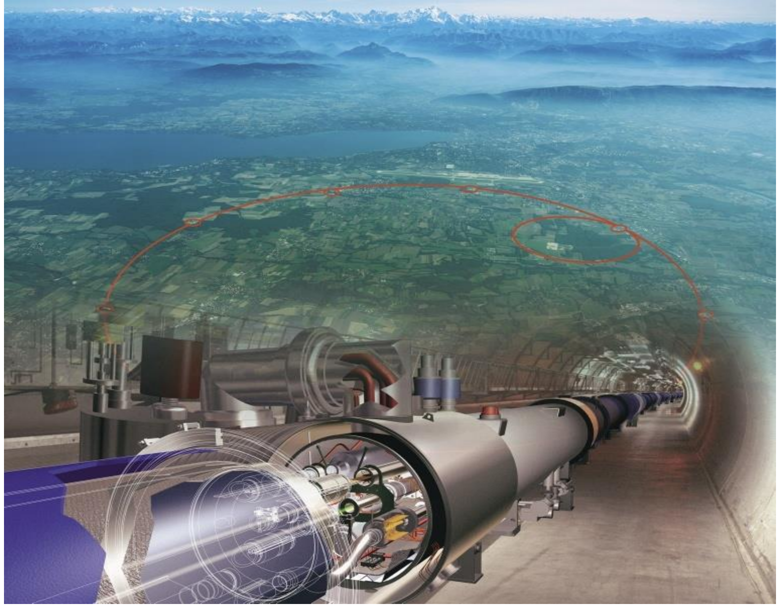
Special thanks to;

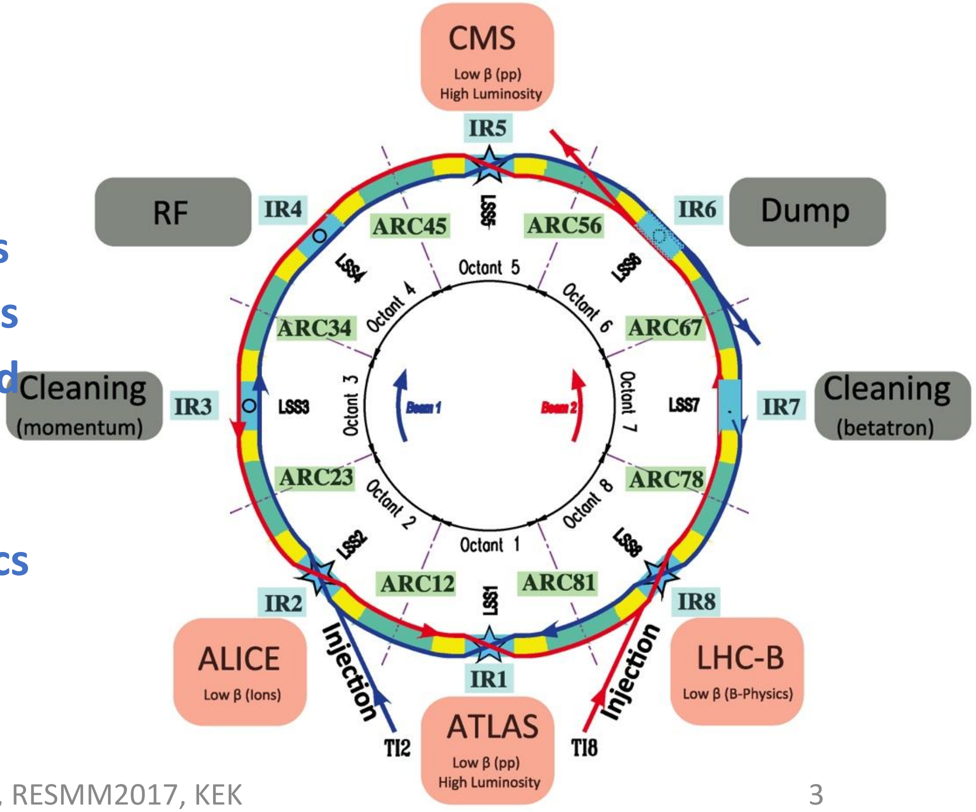
- **F. Cerutti (CERN) and N. Mokhov (FNAL) for particle transport simulations for the HL-LHC project.**
- **R. van Weelderen (CERN) for HeII cooling calculation.**

Overview: LHC

- Large Hadron Collider at CERN
- Circumference: 26.7 km
- Proton Beam Injection Energy: 450 GeV
- p + p Collision Energy:
  - 4 + 4 TeV (2012)

    Splice consolidation work in LS1 (2013-2014)
  - 6.5 + 6.5 TeV (2015)
  - 7 + 7 TeV (design)
- Nominal Luminosity: 1 x 10^{34} cm^{-2} sec^{-1}
- Superconducting Technology and Cryogenics
  - 2 in 1 main dipole at 8.3T: 1232 magnets
  - Cooled at 1.9 K by 100 tons of superfluid helium
  - Total weight of cold mass: 35,000 ton
  - Electrical power of 40 MW for cryogenics plant
- Construction budget: > 5000 MCHF





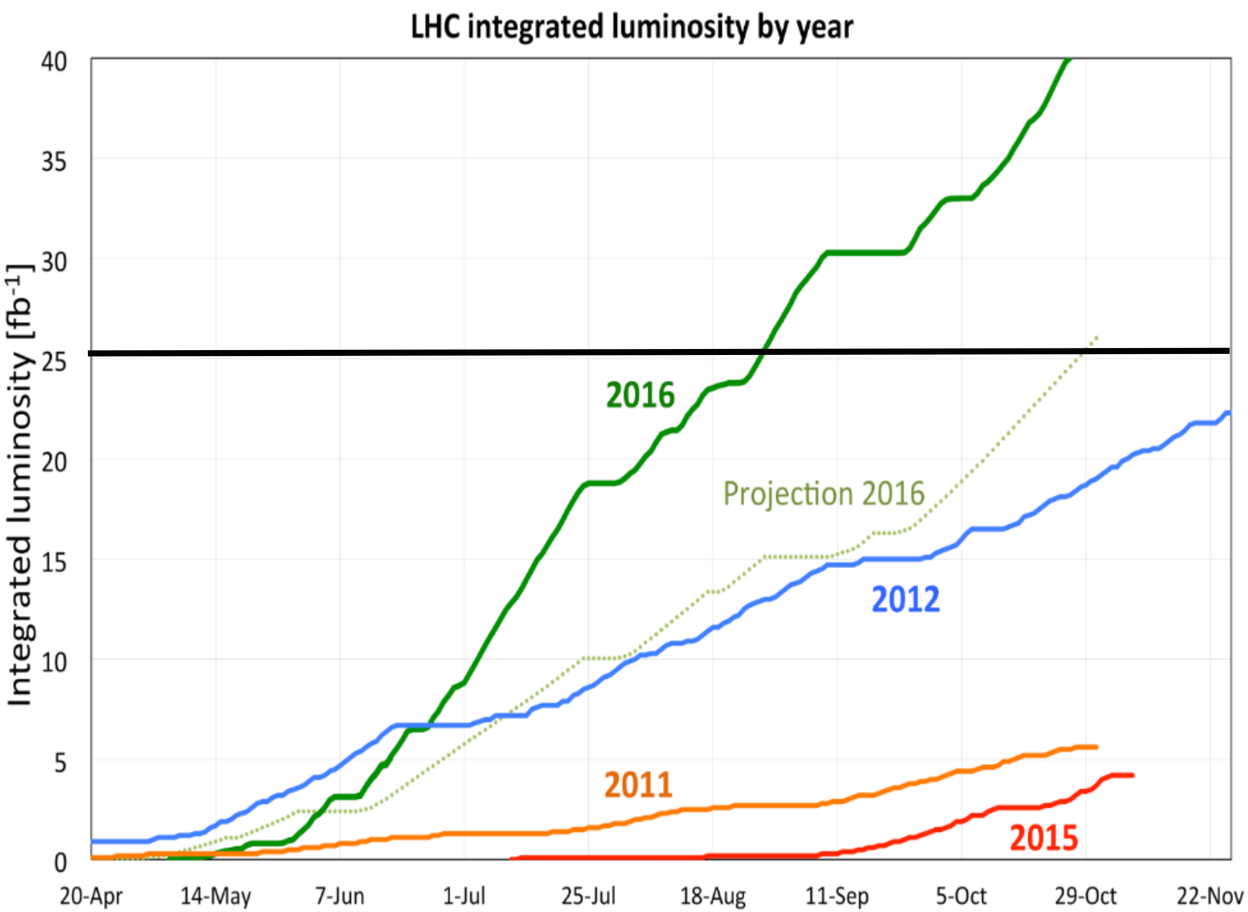
2016 LHC: Production year

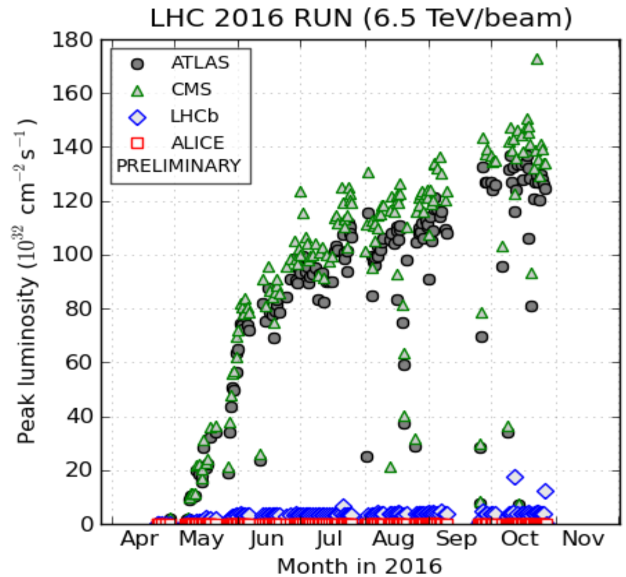
Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

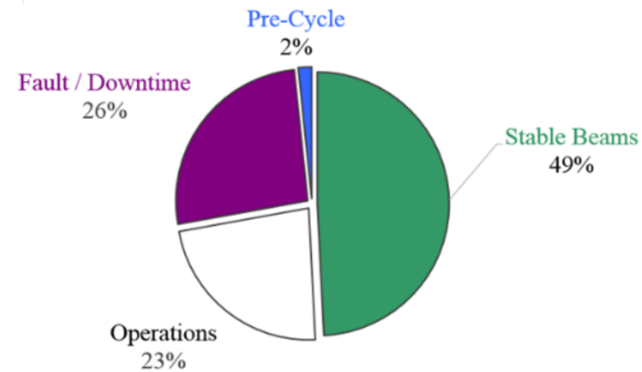
~40 fb^{-1} in both ATLAS and CMS

Higher Integrated Luminosity:

"Peak Lumi." & "Efficiency of Stable Beams"







≈153 days physics ≈3738.7 hours

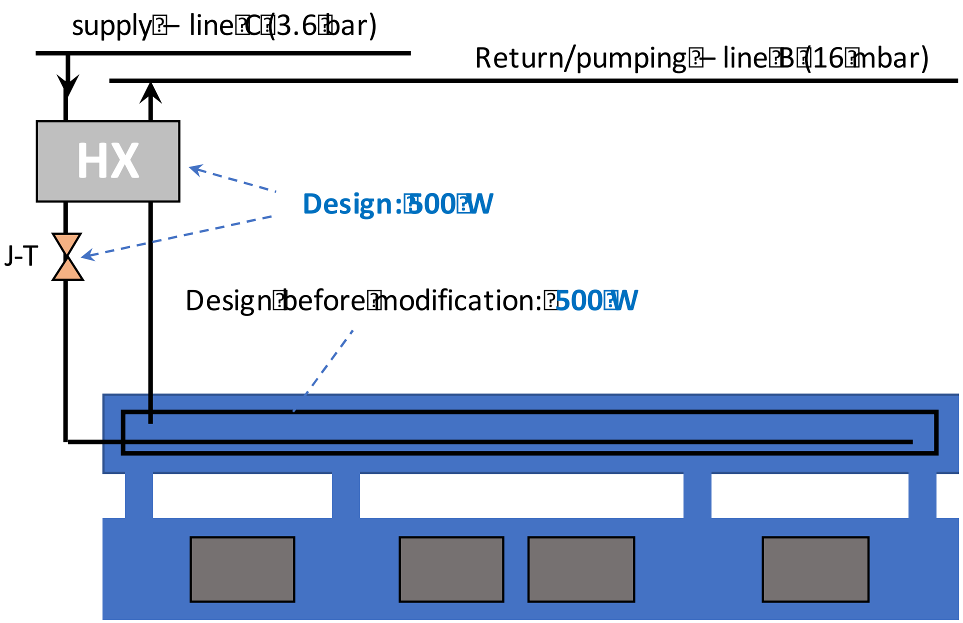
	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

F. Bordry

TS1 - TS2 : stable beams ***58 %***

TS2 - TS3 : stable beams ***54 %***

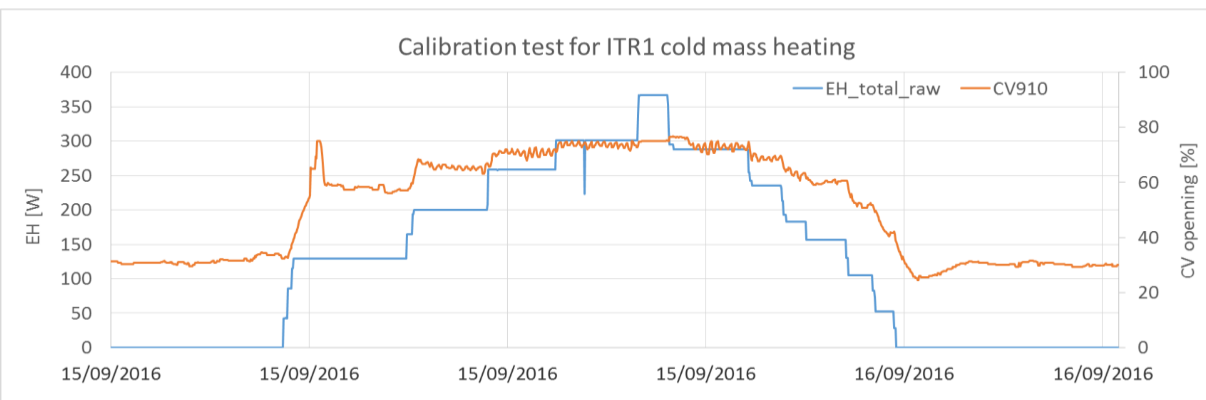
Cryogenics Limit for IT Quads.



IT Quads. for final beam focusing

K. Brodzinski

Due to global stability issues and related mechanical problems, the bayonet heat exchanger diameter was modified in 2007 reducing thermal performance of the system.

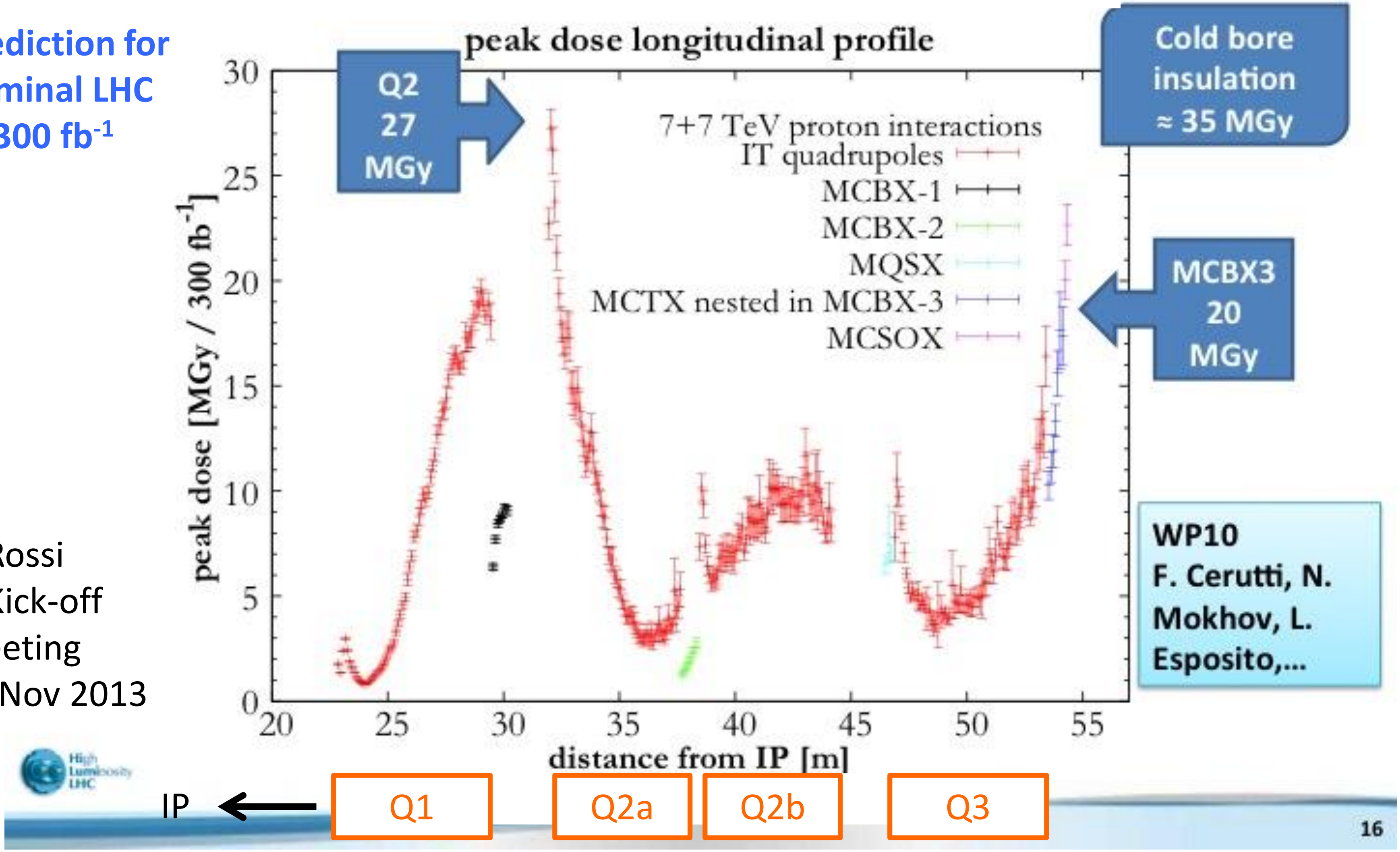


Recent calibration test for IT R1 cold mass heating showed that maximum dynamin heat load is **250 W.**

Peak luminosity of LHC will be limited around 1.75 e^{34} cm^{-2} s^{-1} for 6.5 TeV due to insufficient cooling capability at IT Quads.

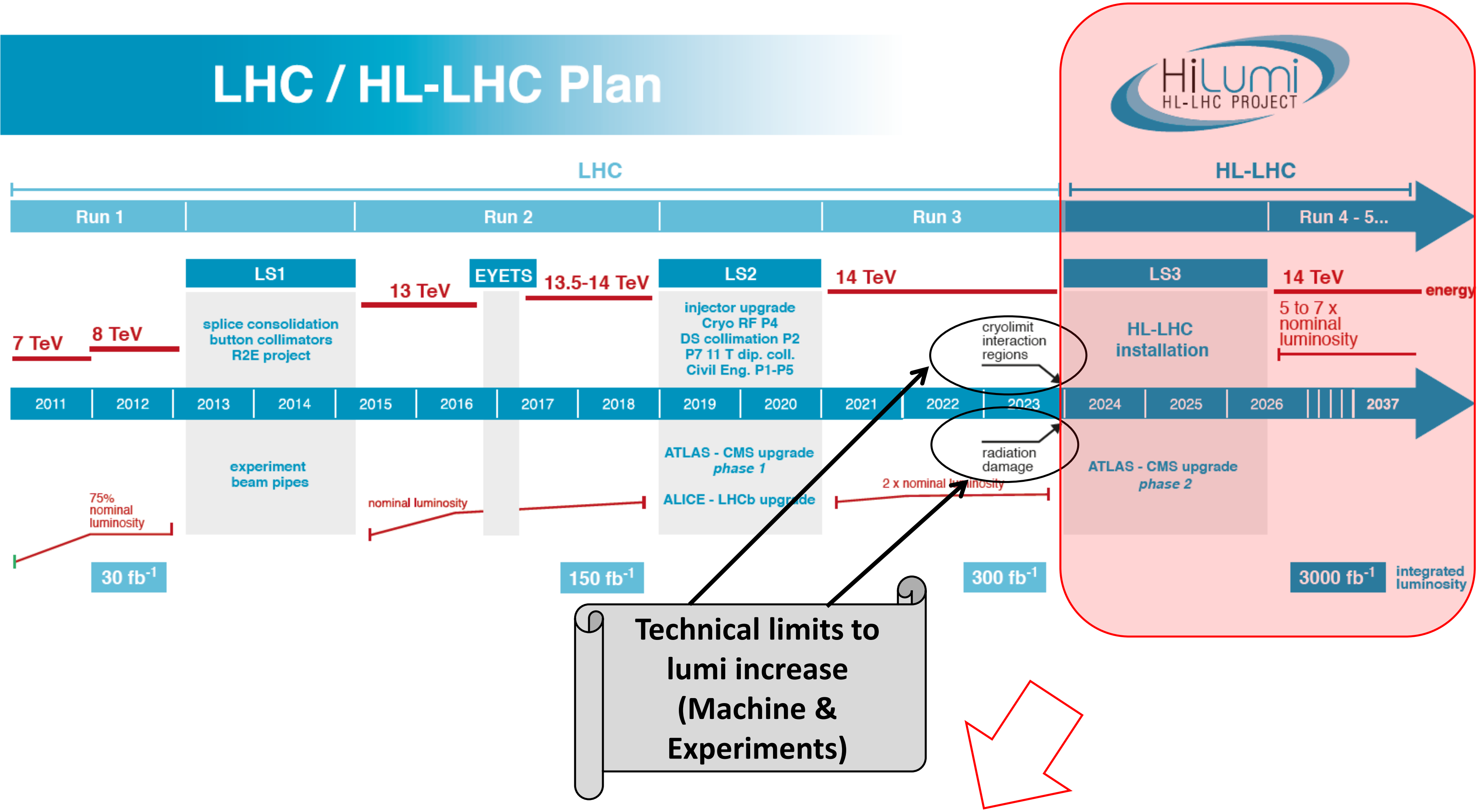
Limit of IT Quads. due to Radiation Damages

Prediction for nominal LHC at 300 fb^{-1}



WP10
F. Cerutti, N. Mokhov, L. Esposito,...

L. Rossi
@Kick-off Meeting
11 Nov 2013



Cooling, cryogenics

Radiation resistance of materials

HL-LHC: High Luminosity LHC

Target: 5×10^{34} cm^{-2} sec^{-1}, 3000 fb^{-1}

(Nominal LHC: 1×10^{34} cm^{-2} sec^{-1} ,300 fb^{-1})

HL-LHC Baseline Parameters

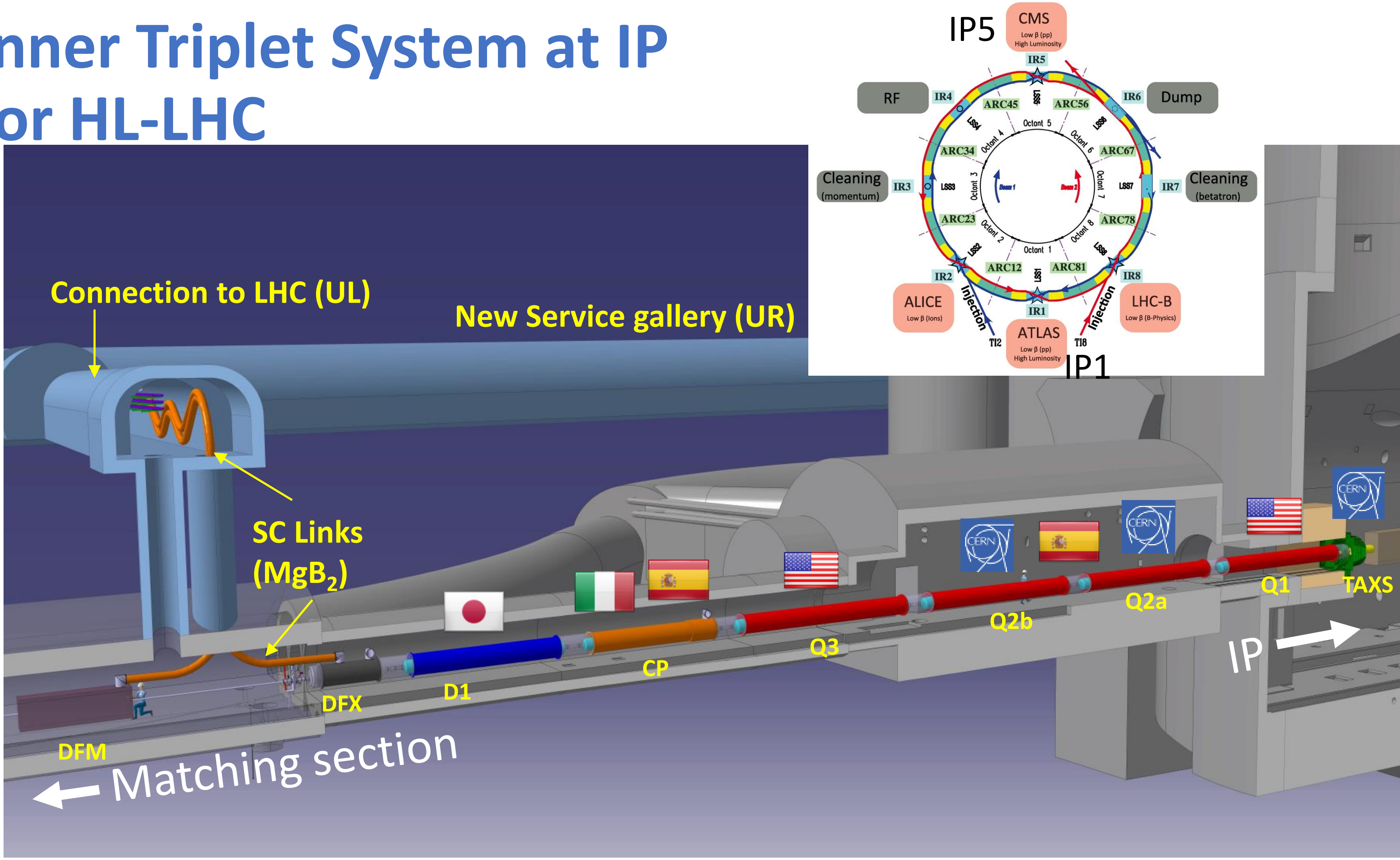
$$L = \gamma_r \frac{N_b^2 n_b f_{rev}}{4\pi\varepsilon_n \beta^*} R$$

Parameter	Nominal LHC	25ns HL-LHC
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches n_b	2808	2747
Beam current [A]	0.58	1.09
Crossing angle [mrad]	285	590
Beam separation [σ]	9.9	12.5
Minimum β^* [m]	0.55	0.15
Normalized emittance ε_n [mm]	3.75	2.5
ε_L [eVs]	2.5	2.5
r.m.s. bunch length [m]	0.0755	0.0755
Geometric loss factor R (w/o / w/ CC)	0.836 / (0.981)	0.305 / 0.829
Virtual Luminosity (w/o / w/ CC) [10^{34} cm^{-2}s^{-1}]	1.2 / (1.2)	6.73 / 19.54
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.00
Levelled Pile-up/Pile-up density [evt. / evt./mm]	27/0.2	140/1.2
Integrated luminosity [fb^{-1}/year]	45	260

Actions;

- LHC injectors upgrade (for N_b, n_b, ε_n)
- New insertion magnets with large apertures & higher fields (for β^*)
- SC crab-cavities first-ever in the proton collider (for R)

Inner Triplet System at IP for HL-LHC

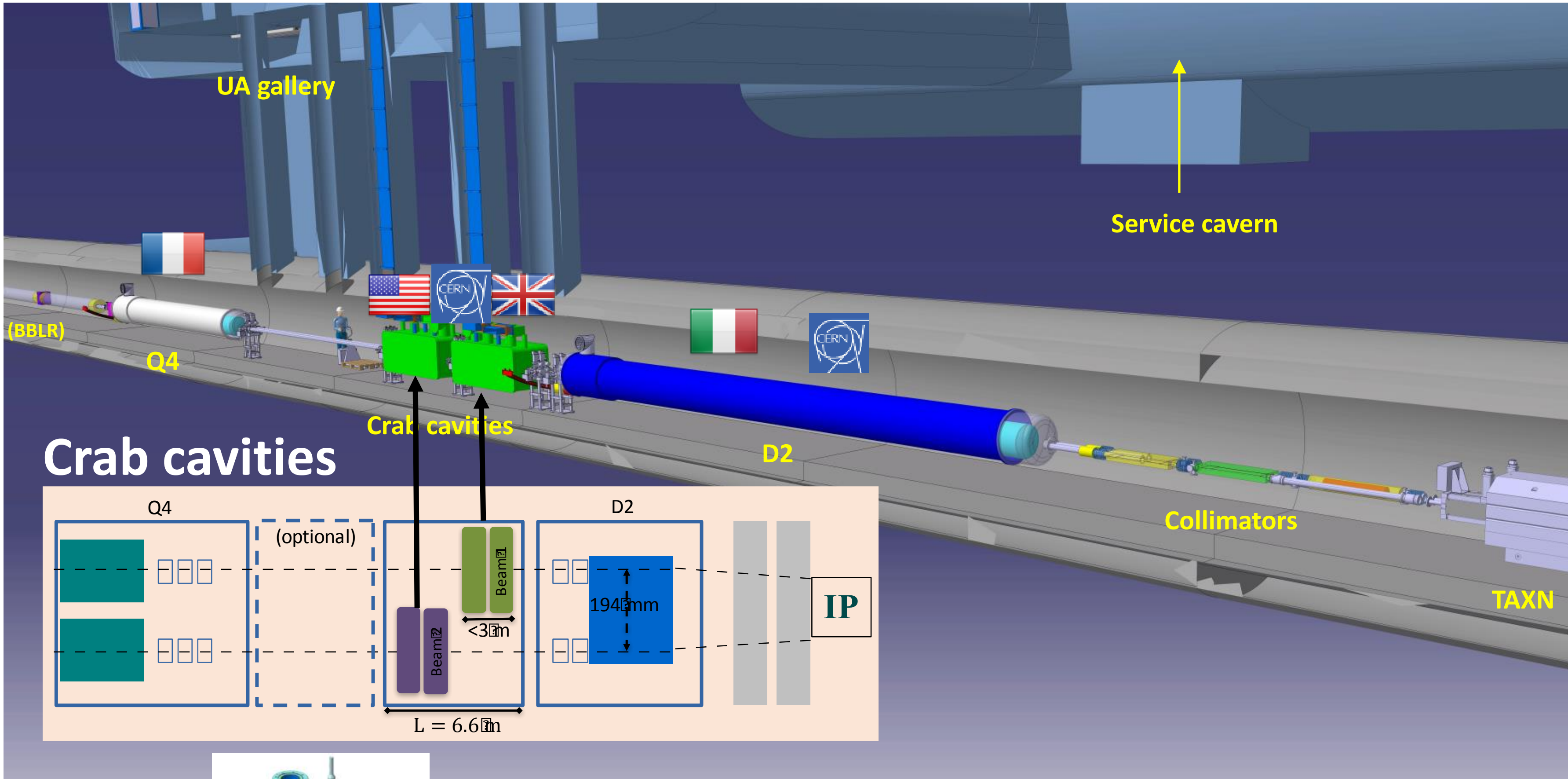


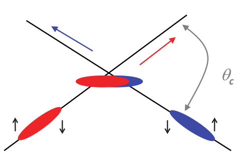
- Insertion regions for IP1 & 5 will be totally replaced for upgrade.
- New magnet system (IT Quad., D1, Correctors) 70mm → 150mm
- New Technology: Nb_3Sn Quad., SC Crab-cavities

L. Rossi

IR Matching Section at IP for HL-LHC

L. Rossi
R. Calaga





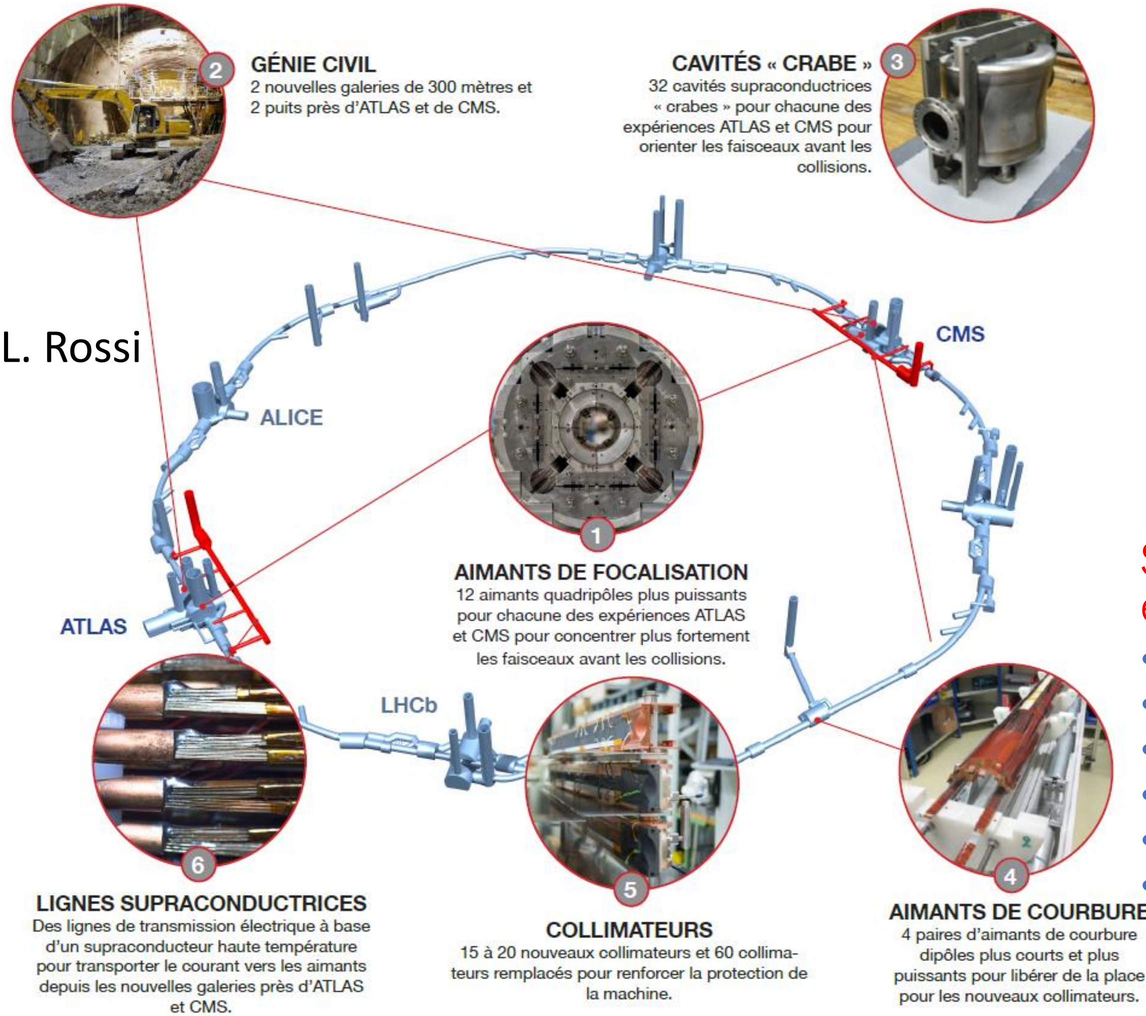
Double Quarter Wave (DQW) cavity at ATLAS (V)

RF-Dipole (RFD) cavity at CMS (H)

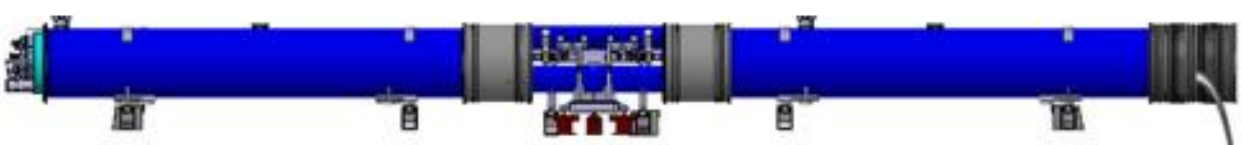
- Voltage $= 3.4\ MV$ /cavity (2 cavities /beam /IP side) – 16 total
- Frequency $= 400.79$ MHz
- $Q_{ext} = 5 \times 10^5$, $Q_0 \approx 10^{10}$
- RF power source $= 80$ kW (SPS ≤ 40 kW)
- Cavity tuning $= \pm 100$ kHz (LFD $\sim 0.5\ kHz$)
- Operating temperature $=\ 2.0$ K

Works around the LHC Ring

L. Rossi



11 T Nb_3Sn Dipole and LEN collimator



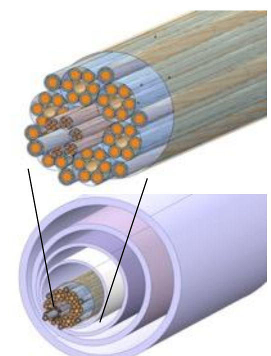
Cryo@P1&P5
2 x 18 kW
@ 4.5 K
(3kW@1.9K) (!!)

Cryo@P4
6 kW @ 4.5 K

"High Luminosity"

Significant increase of beam stored energy, heat loads, radiation

- **11 T Nb_3Sn Dipole and LEN collimator**
- **New service tunnel: "Double Decker"**
- **SC Link (MgB_2), R2E,**
- **New cryogenics plants**
- **Tungsten beam shield**
- **Etc…**



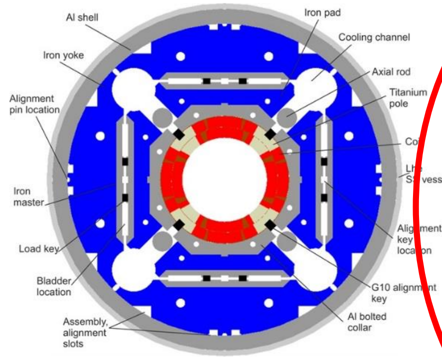
SC Link (MgB_2, 100m, 110kA)

Cross Sections of IR Magnets

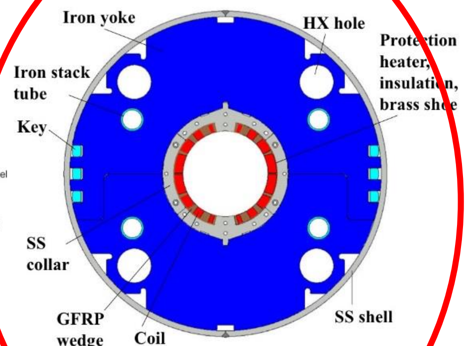
Cross-sections in scale

- 11 cross sections, 92 magnets (+spare)
- $L_{mech.}$: 0.1 m to 8 m
- ***Development programs for all model magnets are underway.***

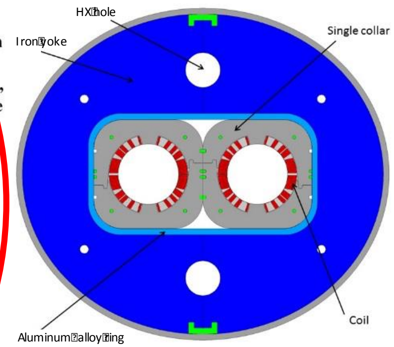
Main Magnets



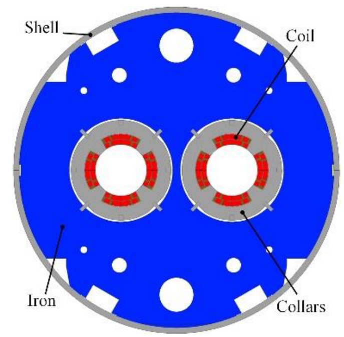
MQXF
Inner triplet quadrupole (Q1-Q3)



MBXF
Beam separation dipole (D1)

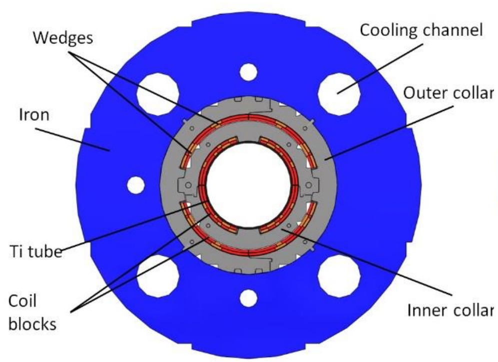


MBRD
Beam recombination dipole (D2)

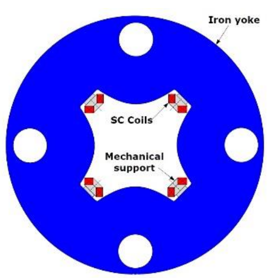


MQY
2-in-1 quadrupole (Q4)

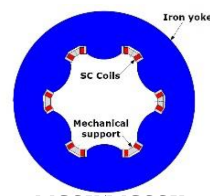
Corrector Magnets



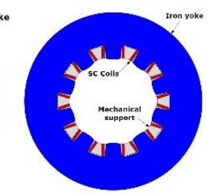
MCBXF
Orbit corrector at Q2 and CP



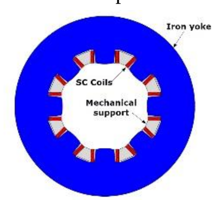
MCQSX
Skew quadrupole corrector at CP



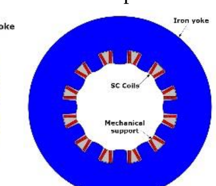
MCSX/MCSSX
Sextupole



MCDX/MCDSX
Decapole

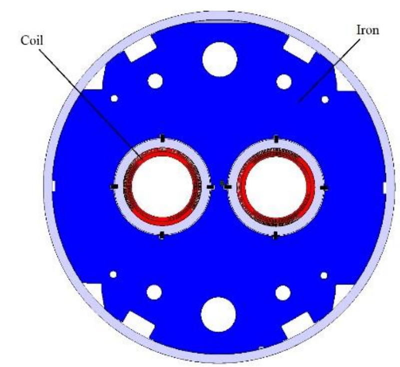


MCOX/MCOSX
Octupole



MCTX/MCTSX
Dodecapole

Non-linear correctors at CP

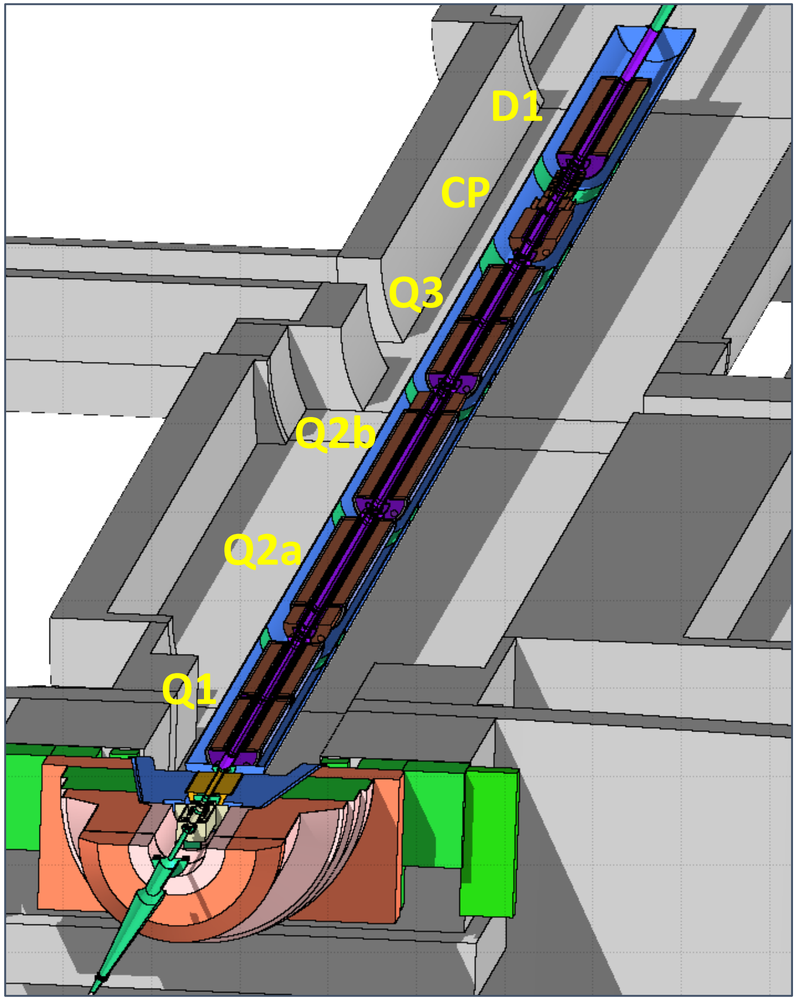


MCBRD
Orbit corrector at D2

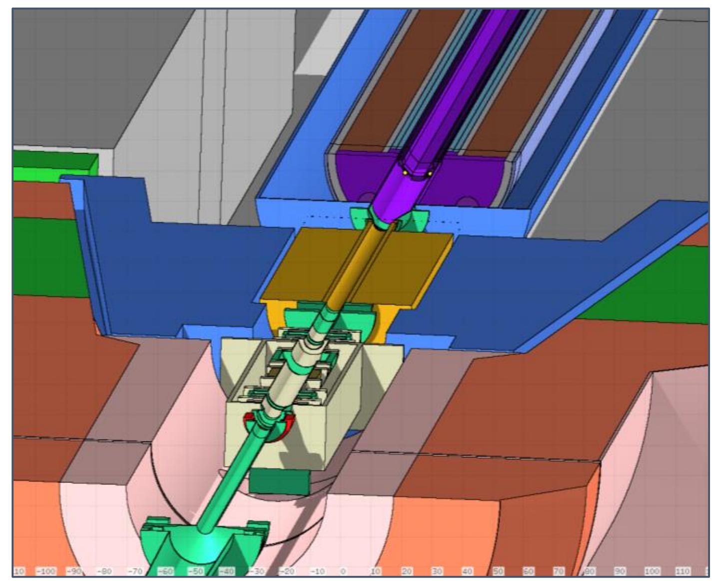
FULKA Simulation: Geometry (IT Quad. - D1)

Primary source of the energy deposition in the SC coil is pp collision debris

- HL-LHCV1.3 (255μrad half crossing angle, β^*=20cm)



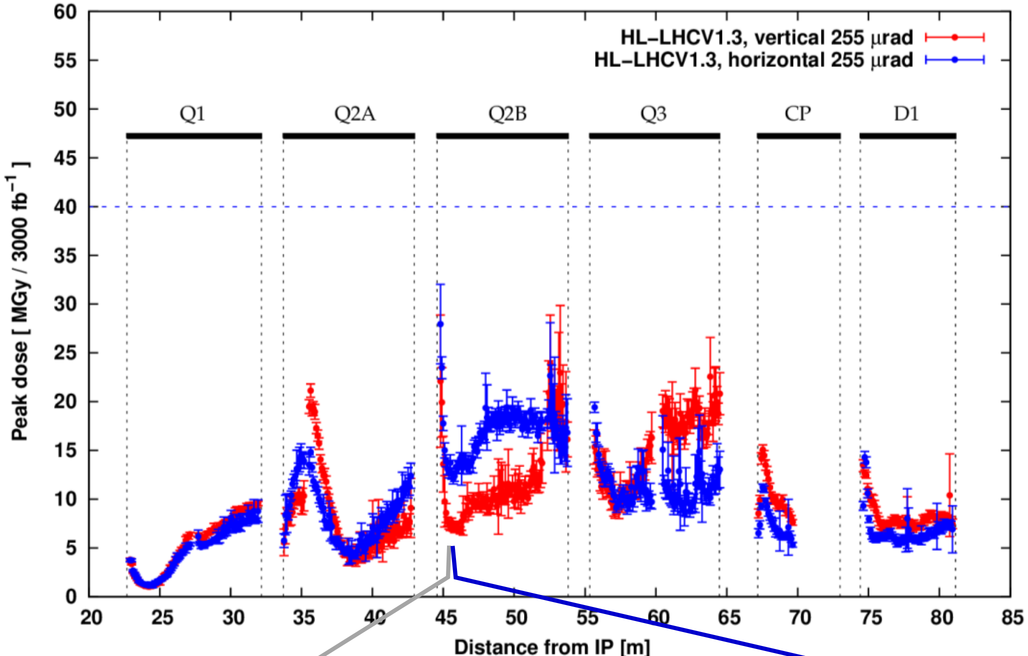
- Various updates:
  - Cryostat (position, composition) *(info from D. Ramos)*
  - Detailed VAX added
  - Realistic BS shielding extension to 45° (20% filling factor, explicitly modelled)
  - Interconnects (see next section)



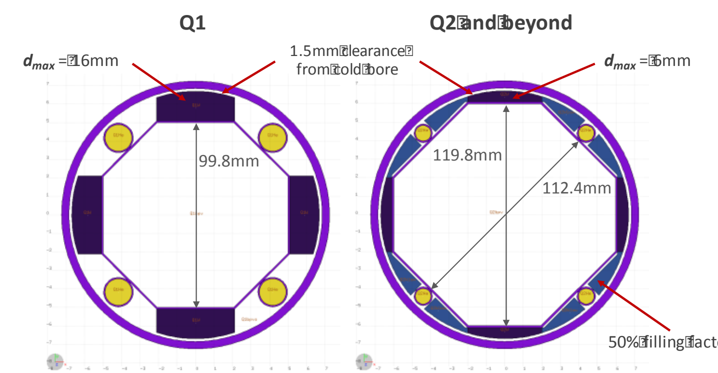
VAX model by I. Efthymiopoulos & I. Bergstrom

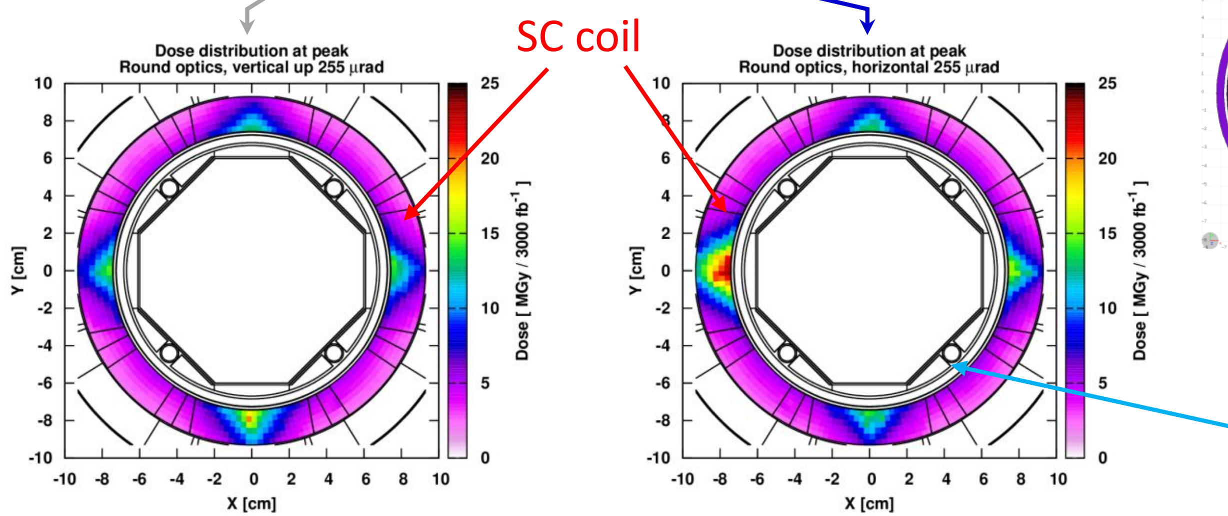
A. Tsinganis, F. Cerutti

FLUKA: Peak Dose Profile



- "Estimated dose" will determine materials in the SC magnet in view of radiation resistance.
  - ✓ Guideline for the HL-LHC: < 40 MGy
- Validation of components and layout.
  - ✓ Ex) BPM shielding at interconnect for the peak at Q2B.
- Requirements for "Beam Screen"



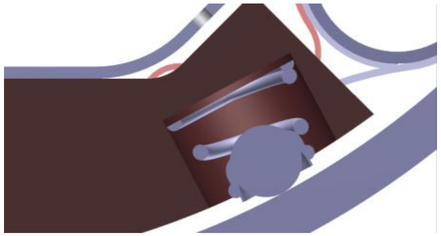


"Beam Screen" in the cold bore is crucial significantly to reduce the heat load and the dose in the cold mass (SC coil). If no BS, the peak dose would be 200 MGy or higher…

A. Tsinganis, F. Cerutti

Cold Bore and Beam Screen

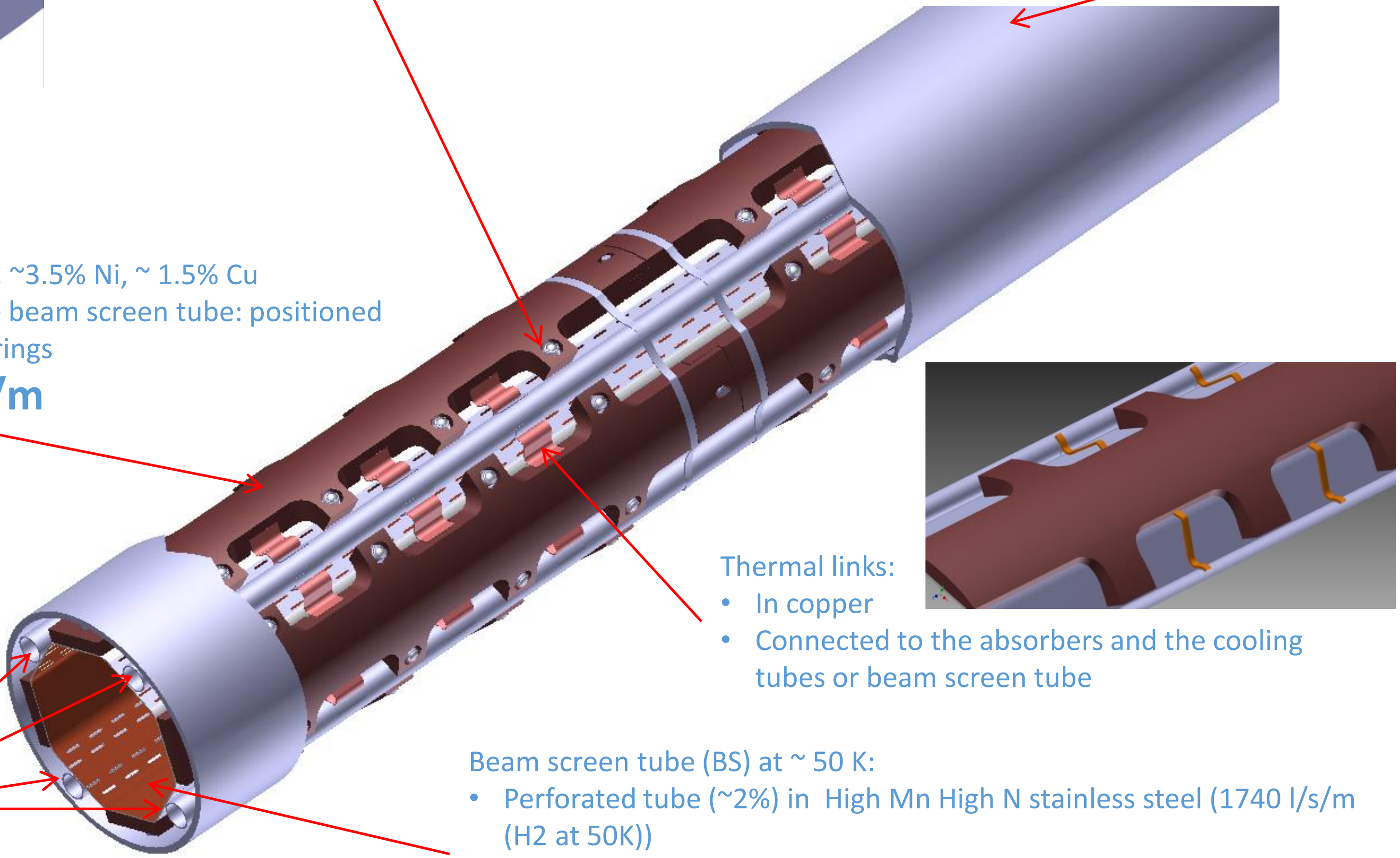
C. Garion



Elastic supporting system:
Low heat leak to the cold bore tube at 1.9K
Ceramic ball with titanium spring

Cold bore (CB) at 1.9 K:
4 mm thick tube in 316LN

Pressure boundary



Radiation Shield

Tungsten alloy blocks:

- Chemical composition: 95% W, ~3.5% Ni, ~ 1.5% Cu
- mechanically connected to the beam screen tube: positioned with pins and titanium elastic rings
- **Heat load: 15-25 W/m**

Thermal links:

- In copper
- Connected to the absorbers and the cooling tubes or beam screen tube

Beam screen tube (BS) at ~ 50 K:

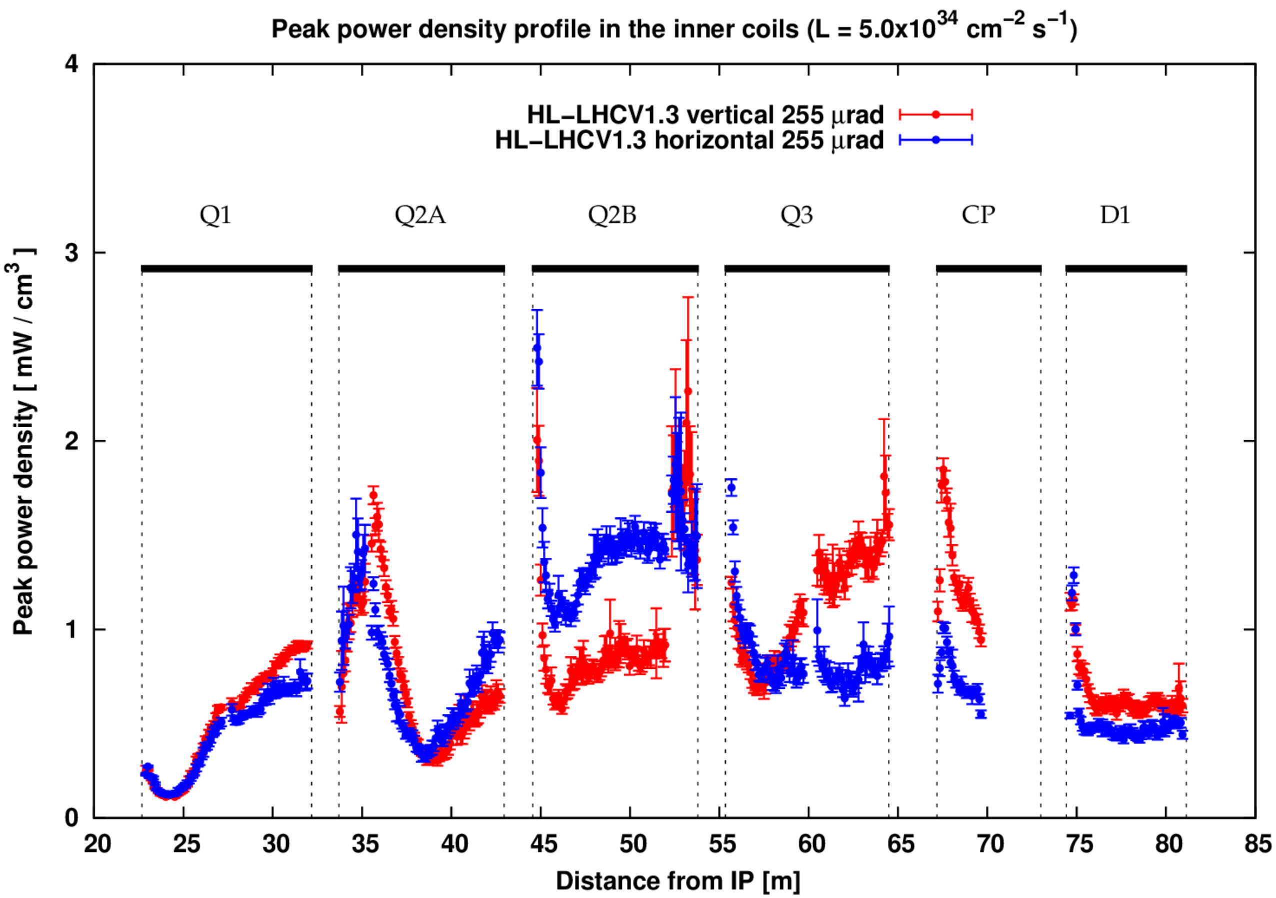
- Perforated tube (~2%) in High Mn High N stainless steel (1740 l/s/m (H_2 at 50K))
- Internal copper layer (80 μm) for impedance
- a-C coating (as a baseline) for e- cloud mitigation
- Laser treatments under investigation

Cooling tubes:

- Outer Diameter: 10 or 16 mm
- Laser welded on the beam screen tube

For Q1, production of BS will start at beginning 2018.

FLUKA: Peak Power Density



- **Peak power density values below 3 mW/cm^3 everywhere.**

➡ See slides of "Cable insulation" and "Magnet Structure" in view of ***temperature distribution in the SC coil*** later.

A. Tsinganis, F. Cerutti

FLUKA: Dynamic Heat Load

L=5.0x10^{34} cm^{-2} s^{-1}

	Vertical (IP1)		Horizontal (IP5)	
Magnets	**Magnet cold mass, 1.9 K**	**Beam screen, ~50 K**	**Magnet cold mass, 1.9K**	**Beam screen, ~50 K**
	Power [W]			
Q1A + Q1B	114	170	113	169
Q2A + corr.	101	68	99	65
Q2B + corr.	126	87	136	100
Q3A + Q3B	134	80	119	70
CP	54	62	42	46
D1	79	56	67	46
Beam pipe extensions	21	72	21	64
TOTAL	**629**	**595**	**597**	**560**

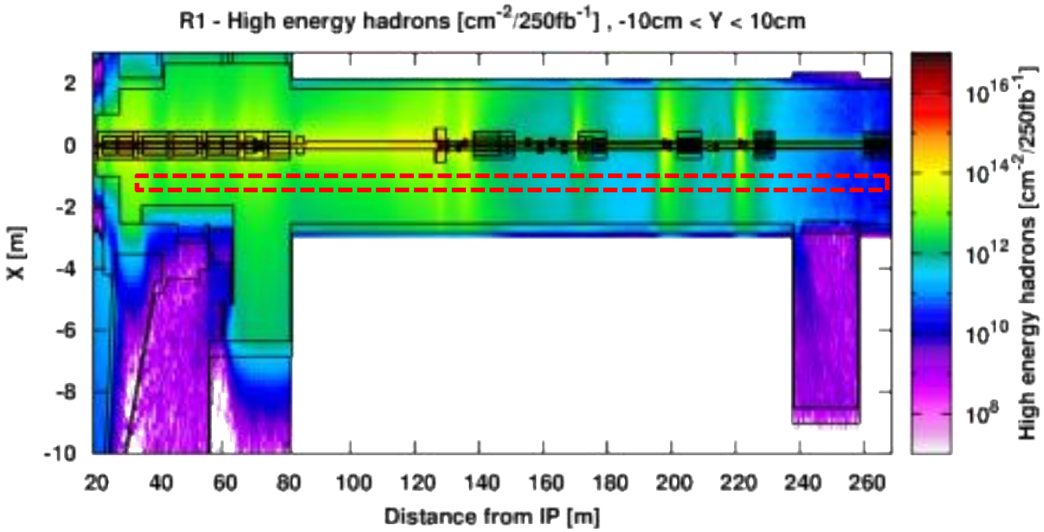
- Present cooling capability of IT Quad is only 250 W at 1.9 K.

⇨ ***Need of new cryogenic plants for IP1 & IP5 respectively.***
2 x 18 kW @ 4.5 K (3kW@1.9K) (!!)

A. Tsinganis, F. Cerutti

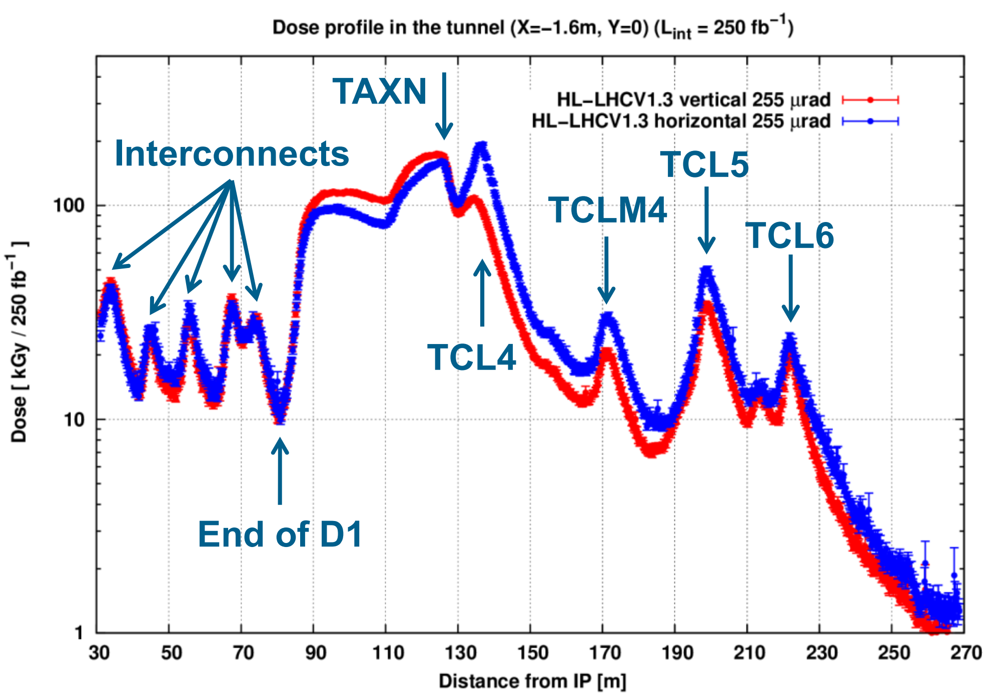
FLUKA: Radiation in the Tunnel

A. Tsinganis, F. Cerutti



1 year op. >> 250 fb^{-1}

- Dose, thermal and 1MeV neutron equivalent fluence & high energy hadron fluence estimated.
- Total Fluence: < ~10^{21} m^{-2} around beam pipe for 3000 fb^{-1} .

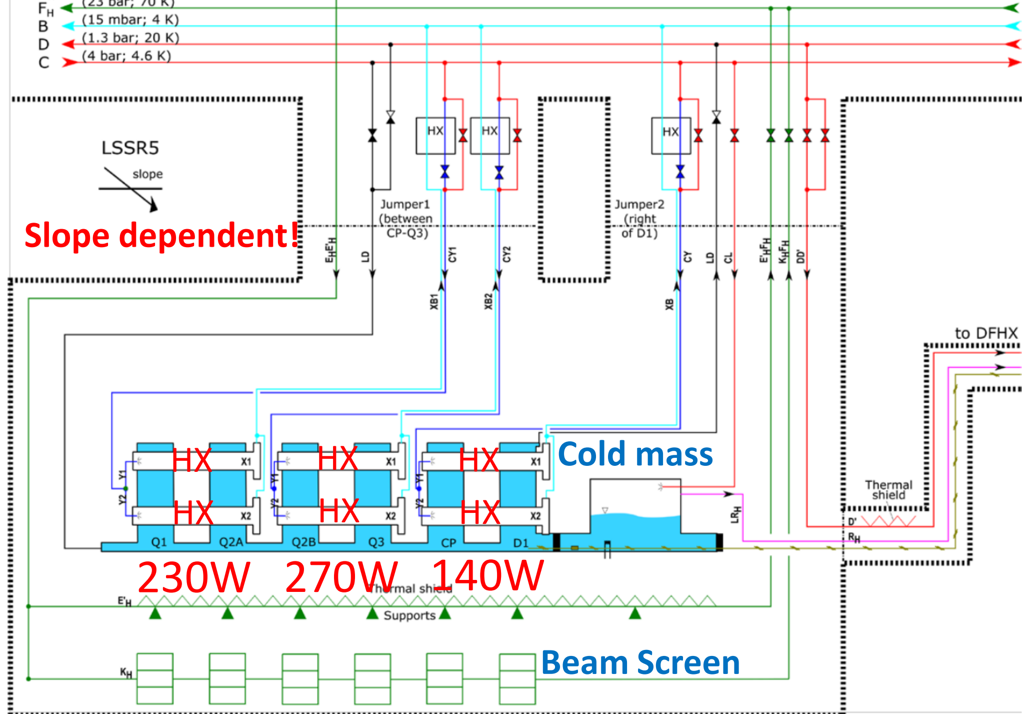


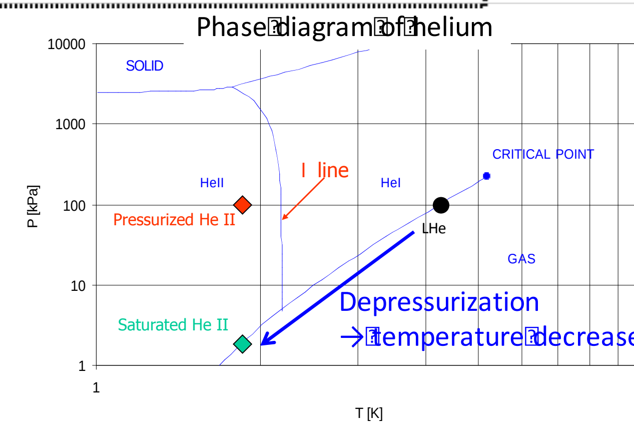
- In general, higher levels in the matching section (not IT or D1!!) for horizontal crossing.
  - ✓ > 1 MGy for 3000 fb^{-1}

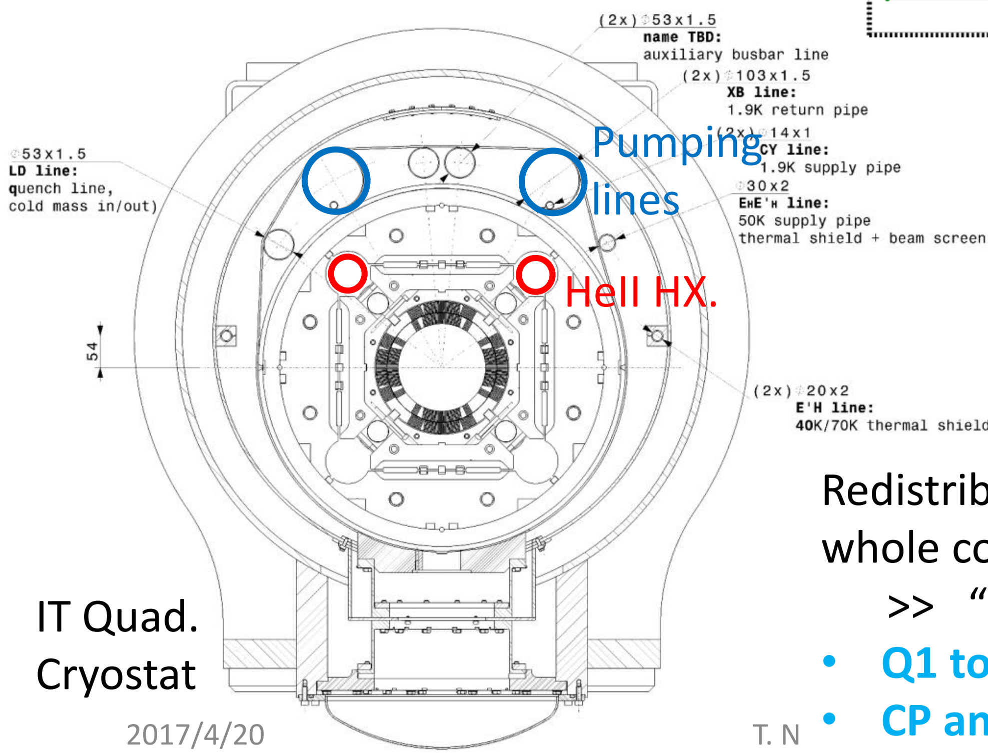
Cryogenics for HL-LHC IT Quads. & D1

- Baseline: Cold mass in pressurized HeII at 1.9 K, 1.3 bar w/ HX (Saturated HeII at 16 mbar)

  >> Same as today.
- But, total heat load increased to **~640W!!**
  - **3 x (2 x ϕ68 mm HX pipes)**
  - **2 x ϕ100 mm pumping lines**







IT Quad. Cryostat

Redistribution of heat loads along the whole cold masses (Q1 to D1)

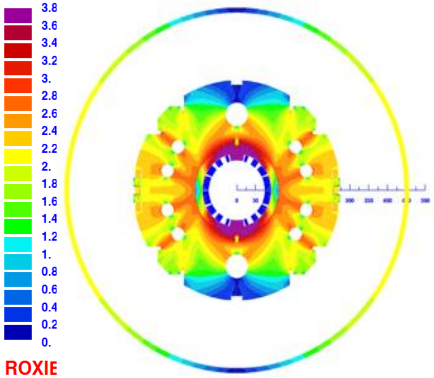
>> "Free area" in the cross section;

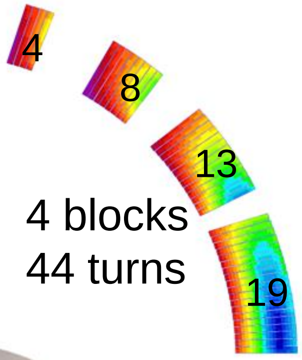
- **Q1 to Q3: > 150 cm^2**
- **CP and D1: > 100 cm^2**

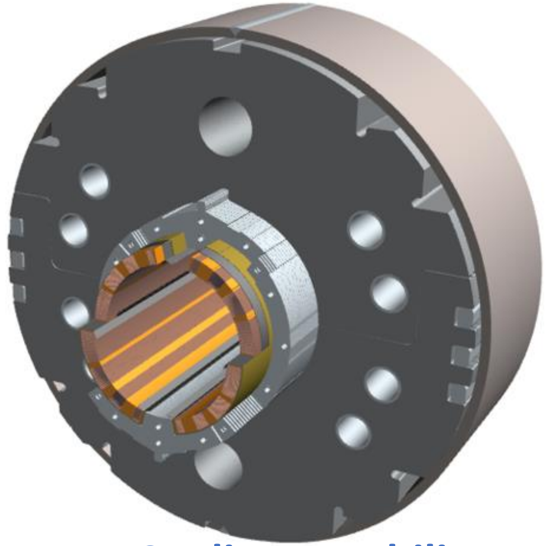
D. Ramos

HL-LHC Beam Separation Dipole (D1)

	A series production	2 m model
Coil aperture	150 mm	
Field integral	35 T m	9.8 T m
Nominal field	5.57 T	
Peak field	6.44 T (SS), 6.56 T (coil end)	
Operating current	12.0 kA	
Operating temperature	1.9 K	
Field quality	$<10^{-4}$ w.r.t B_1 (R_{ref}=50 mm)	
Load line ratio	75.4% （SS）, 76.6%(coil end） at 1.9 K	
Differential inductance	4.0 mH/m	
Conductor	Nb-Ti: LHC-MB outer cable	
Stored energy	340 kJ/m	
Magnetic length	6.33 m	1.73 m
Heat load	135 W (Magnet total) 2 mW/cm^3 (Coil peak)	
Radiation dose	> 25 MGy	







Technical challenges

- **Large aperture**： Management of coil size and pre-stress.
- **Radiation resistance**：Radiation resistant material for coil parts. Cooling capability.
- **Iron saturation**：Good field quality from injection to nominal current.

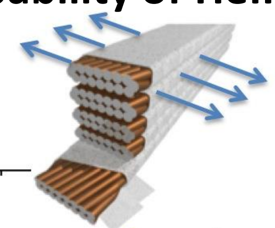
Plan of Japanese in-kind contribution (the budget is not approved yet.)

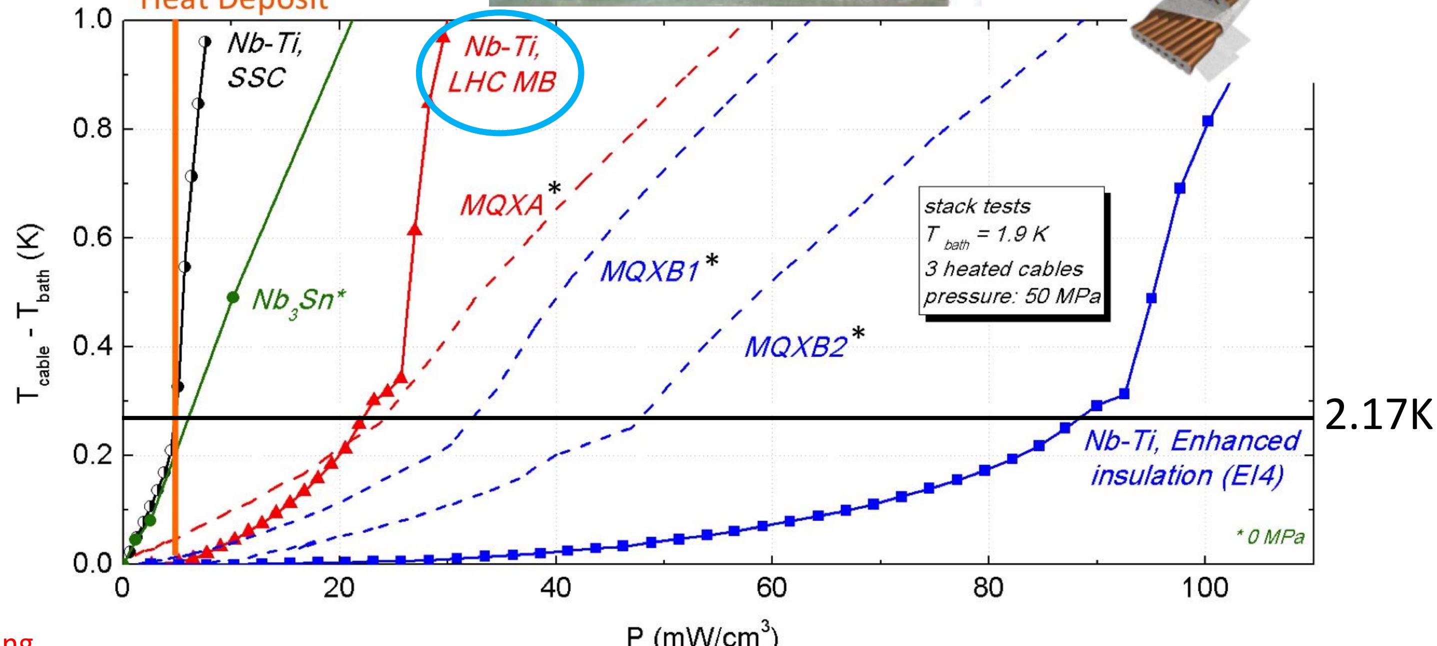
- Full scale prototype (magnet in cryostat): 1
- Series production: 6

Cable Insulation and Heat Transfer

- **Baseline for the D1: NbTi SC cable for LHC MB Outer layer (given)**
- Insulation: Standard for MB >> Apical tape, cured at 197 deg. C at > 15 MPa.
  - Screening in terms of;
    - ✓Radiation resistance up to **40 MGy** : **All polyimide. >> OK**
    - ✓Cooling capability below **3 mW/cm^3** : **T_{cable} < λ point (2.17K). See below. >> OK**

T_{max} must be below 2.17 K to exploit a good cooling capability of HeII.

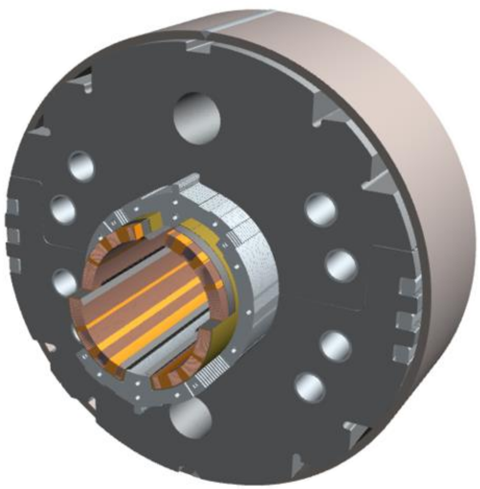




P.P. Granieri, 2nd HiLumi Meeting, Frascati, 2012

* unpublished measurements from D. Richter (5 SC heated cables, actual MQX cables)

D1 Structure for Cooling Requirement

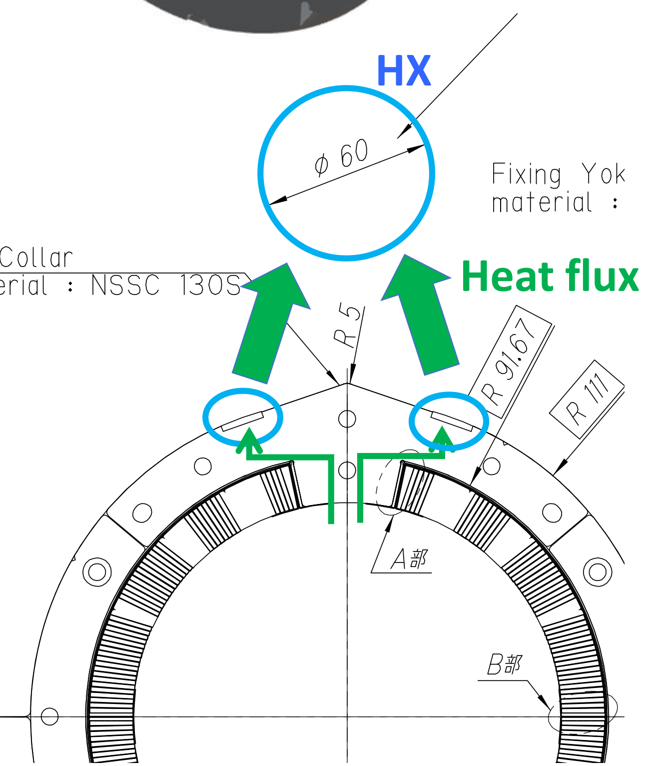


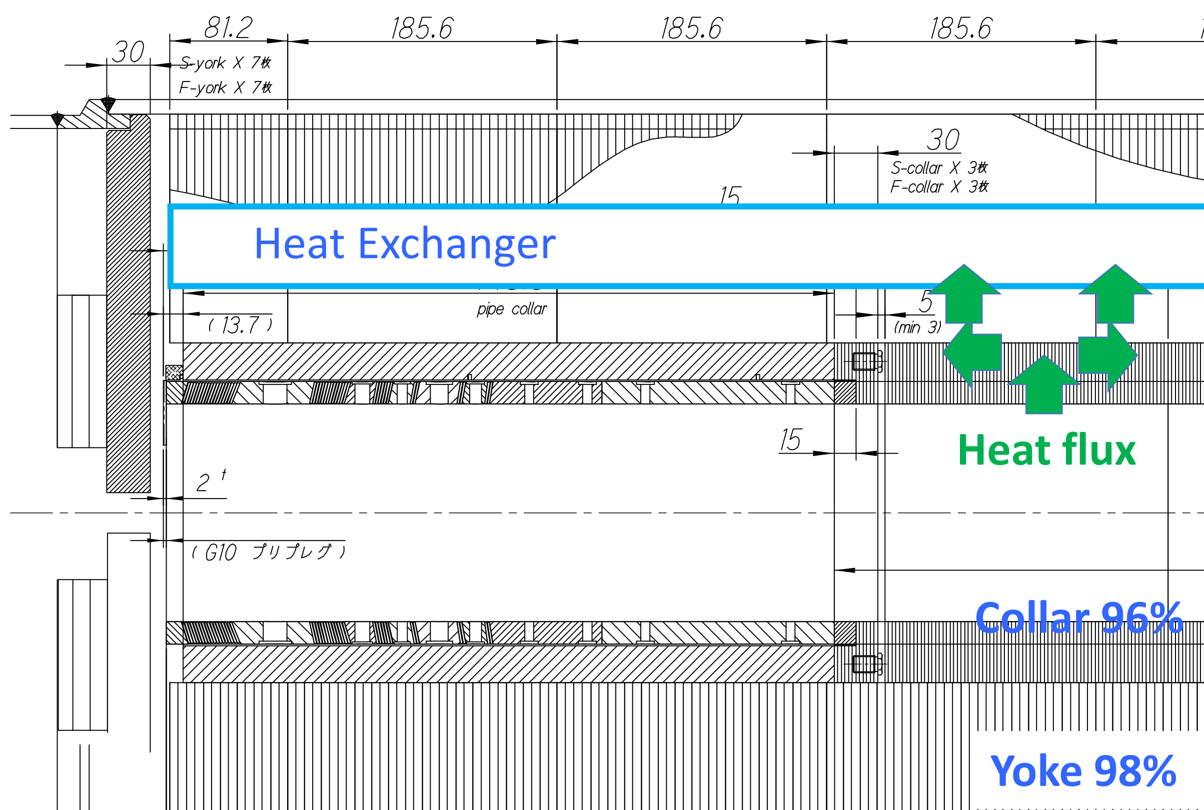
Design guideline:

- 2 x ϕ57 HeII HXs
- Radial gap of 4 % up to HX holes.
- Longitudinal free area >100cm²

➡

- **A single layer coil design**
- SS Collar lamination **w/ 0.2mm gap** by emboss: **PF=96 %**
- **Longitudinal grooves** on collar: **2 x d2 x w20**
- **Yoke PF (packing factor) = 98 %**
- **Free area: 150 cm²**

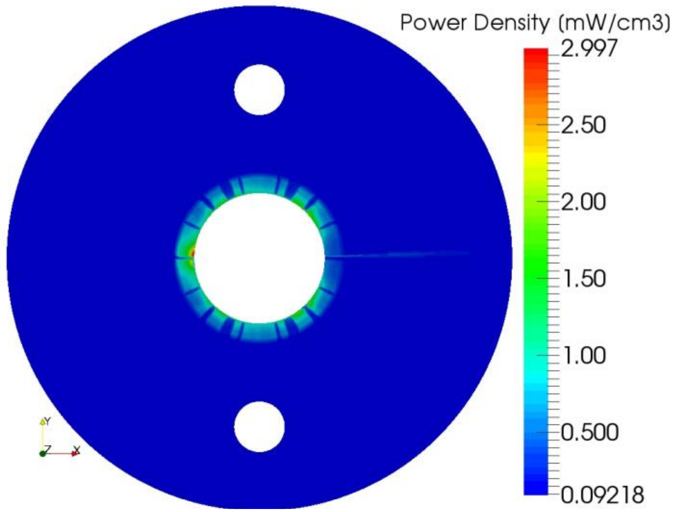


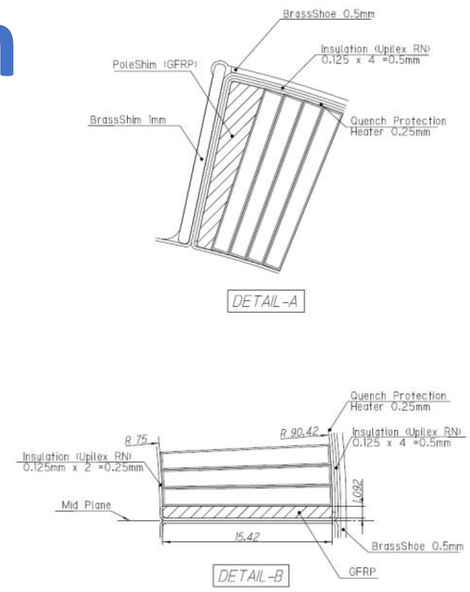


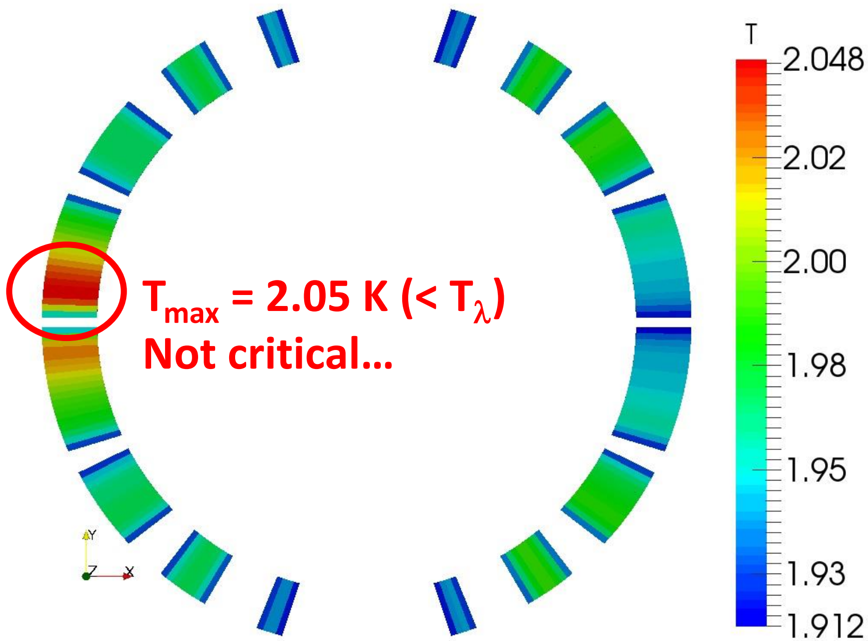
Calculation: T map and T margin

Rob van Weelderen,
5^{th} HiLumi Meeting, CERN, 2015

Power Density Map by FLUKA
Peak: 3 mW/cm^3
Ave.: 1.5 mW/cm^3

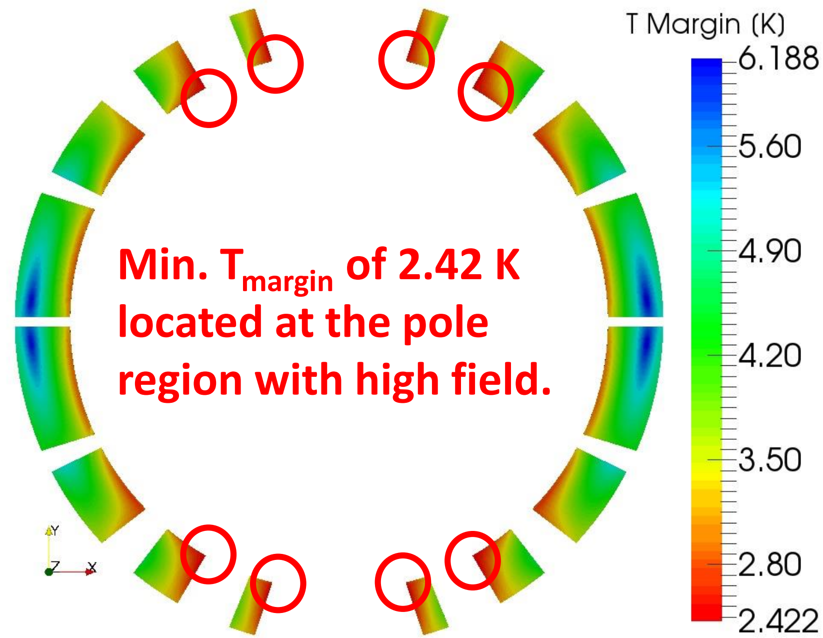






T_{max} = 2.05 K (< T_λ)
Not critical…

T map in the D1 coil

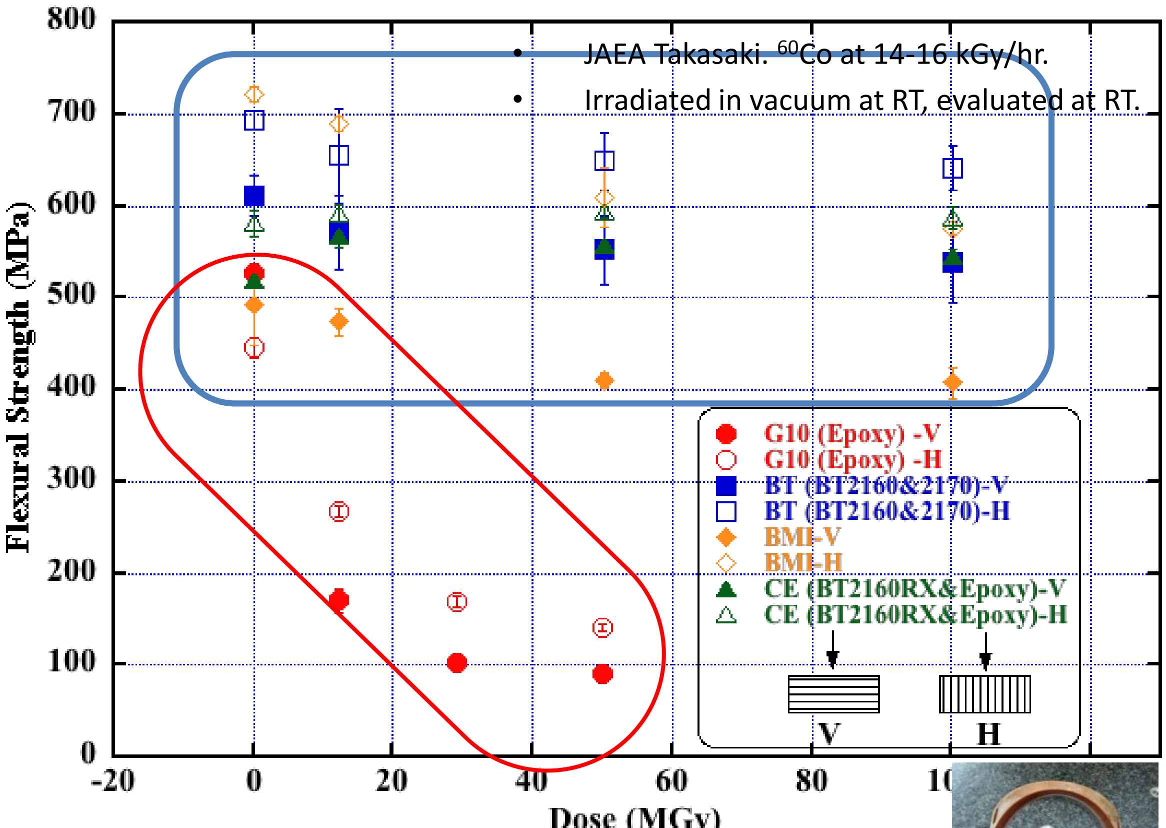


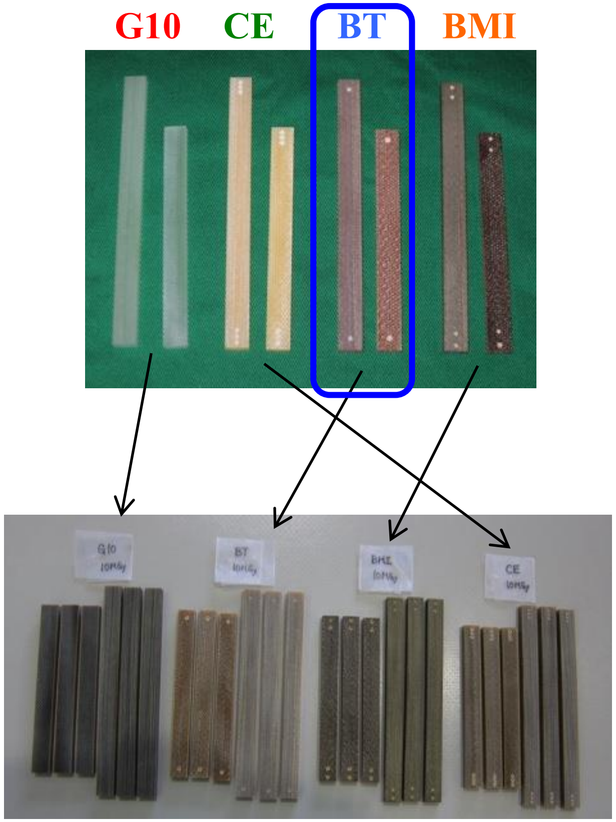
Min. T_{margin} of 2.42 K located at the pole region with high field.

T margin w.r.t. critical T

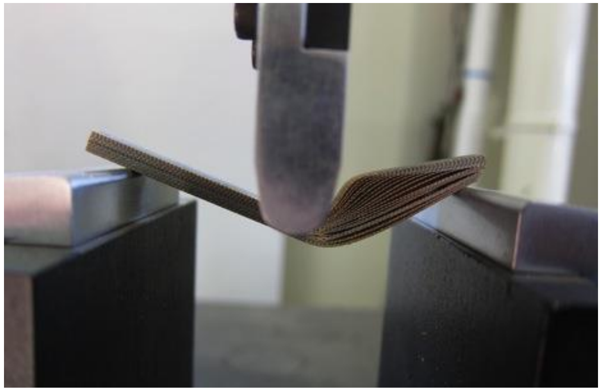
Radiation Resistance GFRP

Flexural Strength Meas. after Gamma-ray Irradiation:





After irradiation of 13 MGy


Flexural strength test （G10, 30MGy）

- Ordinary G10 (Epoxy) already showed significant degradation even at 10 MGy.
- New GFRPs (CE&Epoxy, BT, and BMI) show good radiation resistance up to **100 MGy**.

New GFRP (S2 glass & BT resin) will be adopted for the IR magnets (not only D1)

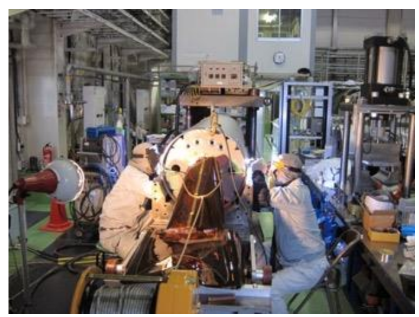
Development of the 1st D1 2m model at KEK

Coil winding

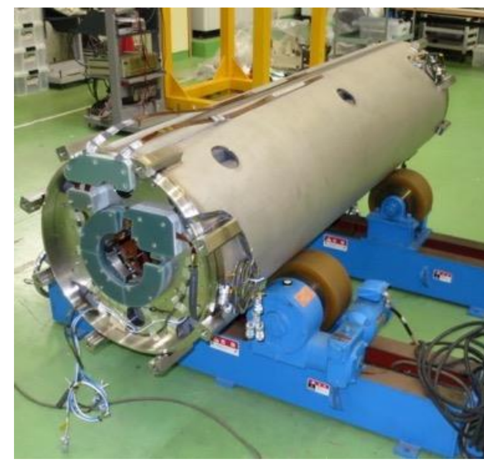
Curing

Collaring

Yoking



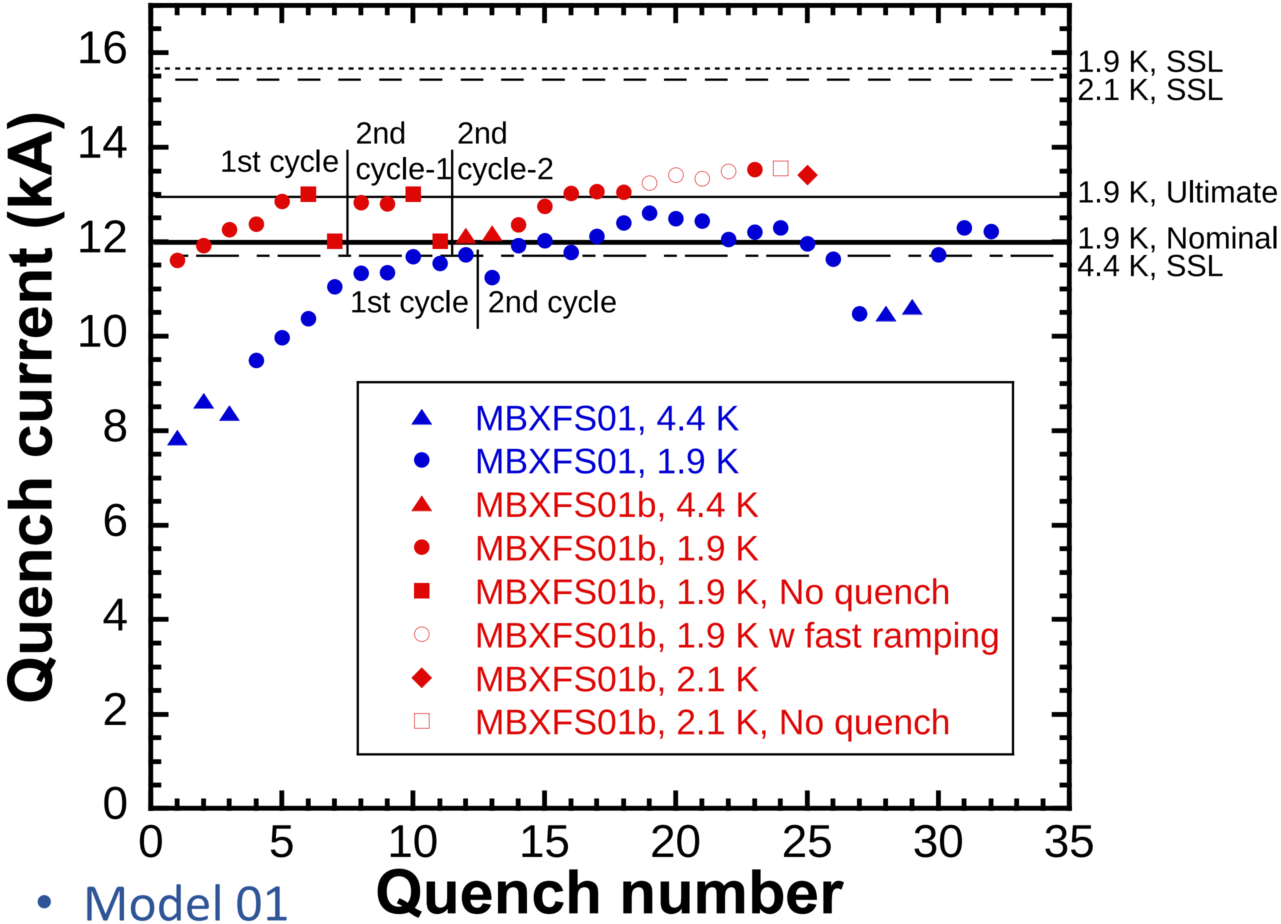
Shell welding



Completed magnet

Some minor technical issues found. But they were basically solved, or improvement will be applied to the 2nd model.

Quench Performance: D1 2m Models 01 & 01b



- Model 01
  - ➢ Unsatisfactory quench behavior due to insufficient preload at assembly.

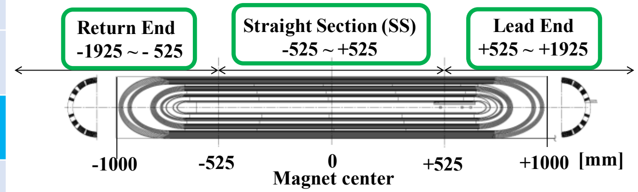
Decision to reassemble the model 01 with increasing preload on the SC coil.

- Model 01b
  - ➢ Significant improvement of quench behavior: reaching to the ultimate at 6^{th} ramp in the 1^{st} test cycle.
  - ➢ Good training memory after full thermal cycle.

MFM Results of Model 01

Field integral at 10kA

n	RE		SS		LE		Total	
	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$	$\widetilde{b_n}$	$\widetilde{a_n}$
1	1937.51 (1965.25)	2.53 (0.00)	6031.67 (6080.50)	−0.46 (0.27)	2030.82 (1954.25)	−28.55 (−17.11)	10000.00 (10000.00)	−26.47 (−16.80)
2	0.25 (0.00)	−2.50 (0.00)	−0.36 (0.00)	−0.23 (0.00)	0.25 (0.00)	−0.93 (0.00)	−0.17 (0.00)	−3.67 (0.00)
3	−9.26 (−7.70)	−0.24 (0.00)	18.76 (21.41)	0.29 (0.13)	−5.19 (−5.50)	6.74 (5.74)	4.30 (8.21)	6.78 (5.88)
4	0.21 (0.00)	−0.26 (0.00)	0.00 (0.00)	0.19 (0.00)	0.07 (0.00)	0.23 (0.00)	0.28 (0.00)	0.17 (0.00)
5	−1.12 (−1.73)	−0.07 (0.00)	−1.14 (−0.66)	0.05 (−0.02)	1.42 (−0.08)	−0.52 (−0.52)	−0.84 (−2.46)	−0.54 (−0.54)
6	0.14 (0.00)	−0.13 (0.00)	−0.04 (0.00)	0.03 (0.00)	−0.04 (0.00)	−0.02 (0.00)	0.06 (0.00)	−0.12 (0.00)
7	−1.34 (−1.49)	−0.01 (0.00)	0.18 (0.20)	0.08 (0.03)	−0.62 (−0.70)	0.36 (0.39)	−1.78 (−1.99)	0.43 (0.41)
8	0.12 (0.00)	−0.12 (0.00)	−0.10 (0.00)	−0.08 (0.00)	−0.19 (0.00)	0.07 (0.00)	−0.18 (0.00)	−0.12 (0.00)
9	−1.16 (−1.32)	−0.06 (0.00)	−0.02 (0.09)	−0.09 (−0.01)	−0.92 (−1.01)	0.00 (−0.15)	−2.09 (−2.23)	−0.16 (−0.16)
10	0.06 (0.00)	−0.05 (0.00)	−0.08 (0.00)	−0.03 (0.00)	−0.08 (0.00)	0.02 (0.00)	−0.10 (−0.81)	−0.06 (0.00)



$$\overline{b_n(I)} = \frac{\int B_n(I)dz}{\int B_1(I)dz} \times 10^4$$

Measurement
(ROXIE cal.)

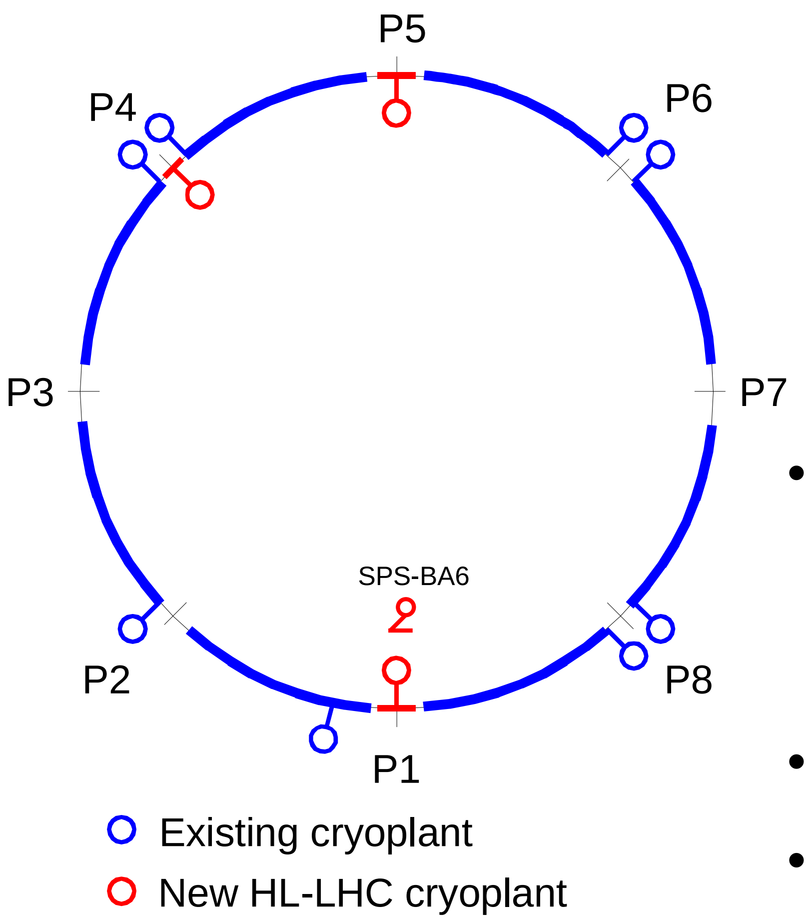
- *ROXIE3D calculations generally agree with the measurement.*
  - **Need improvement of ROXIE models for b_3 and b_5.**
- **Skew and un-allowed multipoles are sufficiently small.**

Summary

- LHC operation in 2016 was very successful.
  - 40 fb^{-1} @ 13 TeV with a peak luminosity of 1.4 e34 $cm^{-2}s^{-1}$
- High Luminosity LHC project is underway in CERN with international collaborations including Japan. Construction will be started around 2024, followed by physics run 2026-2037 (?).
  - $5x10^{34}$ cm^{-2} sec^{-1}, 250-300 fb^{-1}/year, 3000 fb^{-1}
  - Significant efforts are needed to cope with an increased luminosity (heat load, stored energy, radiation…).
- **Particle transport simulations (FLUKA, MARS) have provided the crucial information for the design guidelines of the HL-LHC systems.**
  - New helium cryogenic plant for IP1 & 5.
  - New service tunnels, layout in the tunnel.
  - Tungsten beam screen
  - Structure and materials of the SC magnet, etc.
- **Design of the HL-LHC beam separation dipole magnet (D1) and 2m model magnet development in view of radiation issues has been carried out by KEK.**
  - **New radiation resistant GFRP (BT-S2) successfully developed.**
  - Cold tests of Model 01b have shown positive results.

HL-LHC Cryogenic Upgrade

S. Claudet



- **2 new cryoplants (~18 kW @ 4.5 K incl. ~3 kW @ 1.8 K) at P1 and P5** for high-luminosity insertions
  - ✓ Enable to accept the max. heat loads of **2 x 950 W** for the **ultimate luminosity (7.5 x 10^{34} cm^{-2} s^{-1})** with some redundancy.
- 1 new cryoplant (~4 kW @ 4.5 K) at P4 for SRF cryomodules. (Alternative under study: upgrade of 1 existing LHC cryoplant and distribution)
- 11T + Q5@P6
- SRF test facility with beam at SPS-BA6 primarily for Crab-Cavities