



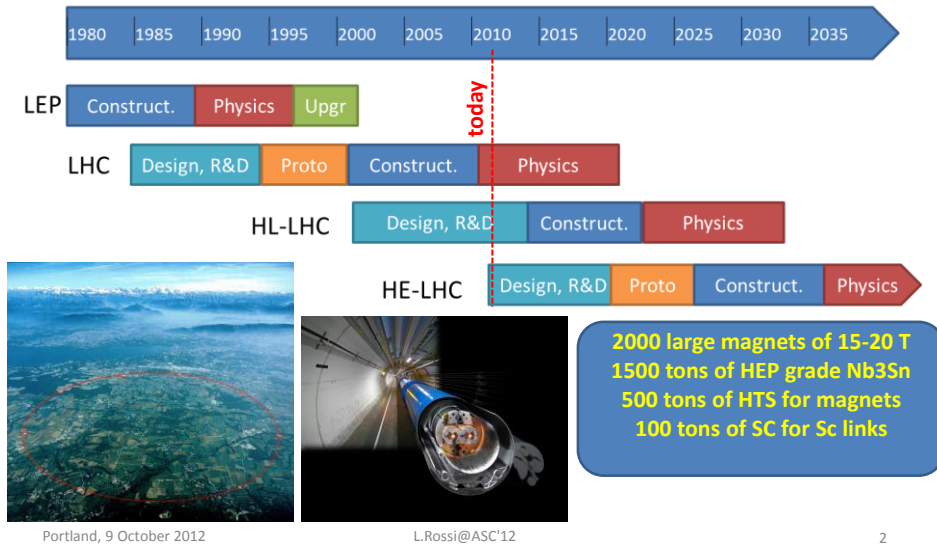
Advances in Applied Superconductivity Technologies for High Luminosity LHC Project

**High
Luminosity
LHC**
The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capabilities Specific Programme, Grant Agreement 284404


Lucio Rossi
CERN
HiLumi LHC Project Leader
ASC12 – App. SC Conference
Portland, OR, 9 October 2012



**The super-exploitation of the CERN complex:
Injectors, LEP/LHC tunnel, infrastructures**



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CERN has a plan for the exploitation of LEP/LHC tunnel: the last 30 years and may be the next 30 year of CERN will be based on this 27 km tunnel (see left picture). The today LHC SC magnets (central pictures) may be replaced by the SC magnet of a future High Energy HE – LHC: the needs in terms of advanced superconductors for the SC magnets of HE-LHC are reported in the right box (HTS may be either Bi2212 or YBCO). For SC links MgB2 would be the preferred option (but HTS would be considered as well)

However the new technology of HE-LHC is based on the success of the near future project, High Luminosity HL – LHC (see later for the definition)

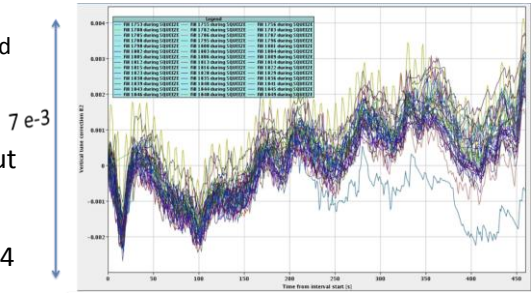


LHC present performance Superconductivity



- Sc effects are well mastered:
 - b_3 (sextupole) components by magnetization is well corrected
 - Snap back (sudden change of b_3 at low field) also controlled.
 - Experience accumulated should be useful for full energy operation
- Hysteresis is NOT negligible but a suitable cycle was found
- Global reproducibility of the 24 main circuits (8 dipoles + 16 quads) and of the hundreds other circuits is excellent.

LHC magnetically reproducible with rigorous pre-cycling - set-up remains valid from month to month



Tune corrections made by feedback during squeeze of the beam (many circuits varied)

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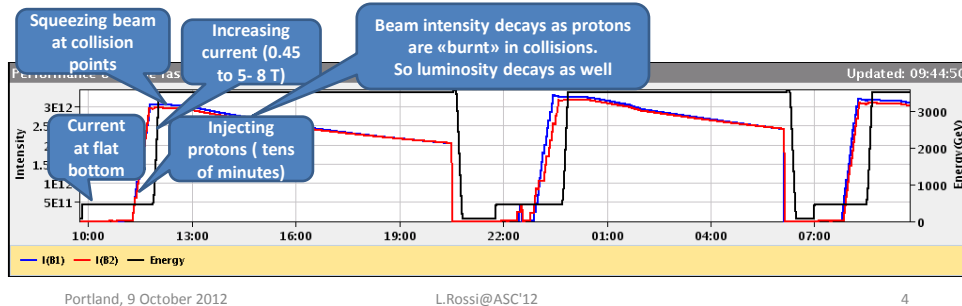
The various superconducting effects (diamagnetic and hysteretic behaviour) are well visible in the LHC operation, but they are mastered to the point that they are almost “invisible” for beam performance, confirming the success of the design.



LHC magnet ramp (magnet field is 50% nominal)



- Power converters (all magnet circuits), magnet model, RF, collimators, beam dump, transverse damper, orbit and tune feedback, BLM thresholds etc.
- Reproducible and essentially without loss



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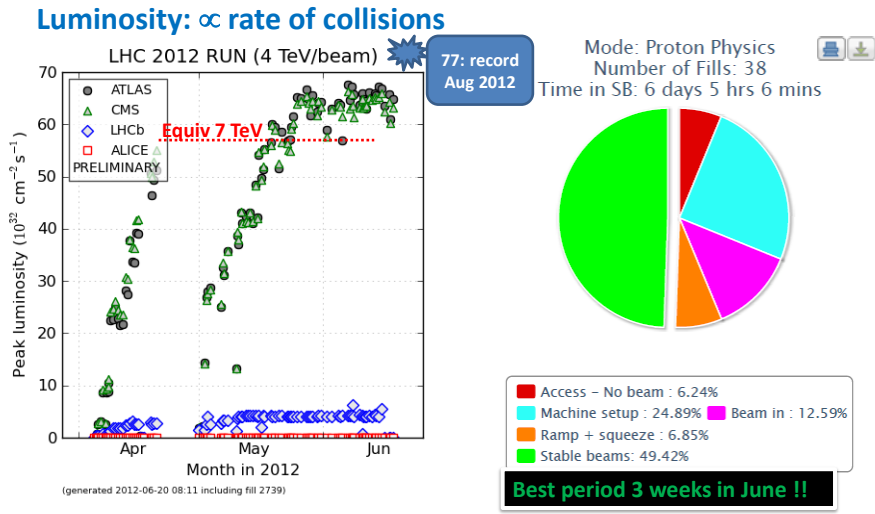
A typical cycle of the LHC accelerator:

1. The black curve represents the beam energy which is proportional the magnet current (to be read on the right ordinate axis).
2. The blue and red curves are proportional to the beam current (intensity), i.e. the proton population, of the two beams : blue is for beam 1 that circulates clockwise, while red is for beam 2 anticlockwise.

This run lasted about 10 hours: it started with magnet pre-cycle and then injection at h.10:00 with collision taking place from h.11:30 (when the beam are “squeezed” in the collision points) to h.22:00 when the beams were lost. Beam energy was 3.5 GeV/beam and population was 3×10^{12} proton/beam (the population decreases during collision because of proton burning).



LHC Performance



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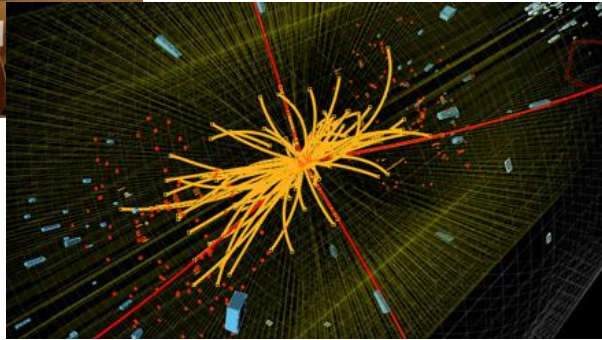
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Performance of a particle collider is measured by the luminosity (proportional to the rate of particle collisions). Beside the peak luminosity (which exceeded expectation from May 2012, see red line in left graph) it is important the time of stable beam, i.e., the time when detector can collect events: in right chart is shown that stable beam can reach 50% of the total time.



First job done: Higgs found!!



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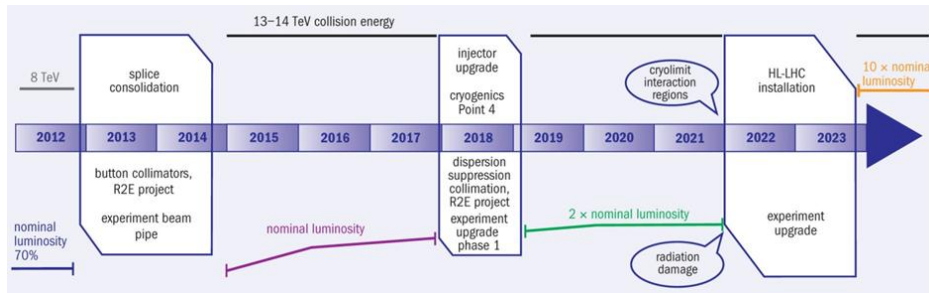
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The Scottish theorist Peter Higgs entering in the auditorium where the seminar announcing the Higgs discovery were held (CERN, 4th July 2012); see traces of Higgs particle decay (the four red traces, almost straight) in a LHC detector at the right.



From here: where to go? The CERN 10 y plan



Luminosity: number of events/seconds per unit of cross section.
 $N_{\text{event}}/s \propto \text{instantaneous luminosity, } L(t)$
 $N_{\text{event}} \text{ in a certain period} \propto \int L(t)dt$

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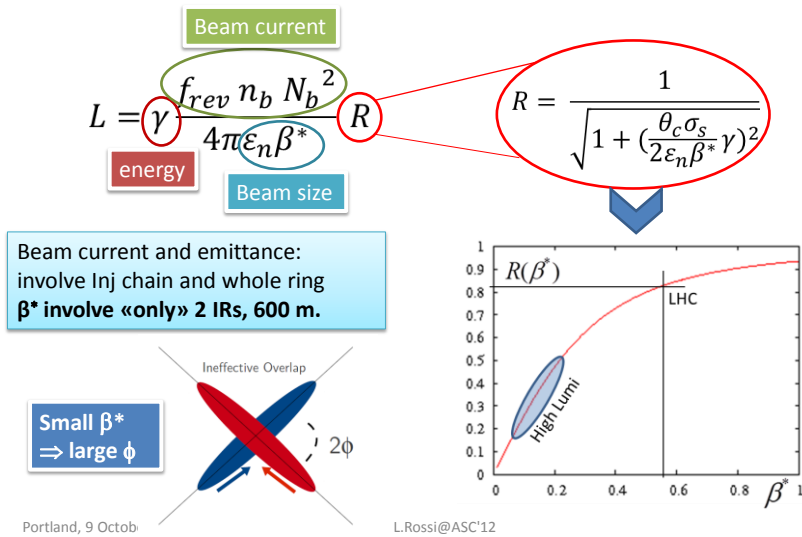
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The CERN plan to increase the performance of the LHC both in energy and luminosity

General definition of luminosity is reported (see next slide for more details)



Luminosity: main ingredients



Definition of luminosity in term of accelerator parameters:

f_{rev} is the revolution frequency, n_b the number of bunches, N_b the number of proton per bunch, ϵ_n is the beam normalized emittance and β^* is the betatron oscillation length (sort of focal length) at the collision point. R is a reduction factor that goes as the angle 2ϕ (see picture at bottom left).

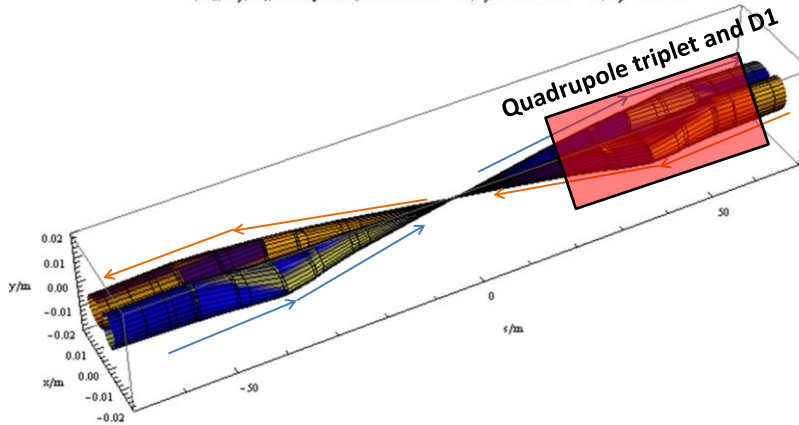
High luminosity requires small β^* , however one has to avoid a strong reduction R.



Beam envelope scales as $1/\sqrt{\beta^*}$



$(5\sigma_x, 5\sigma_y, 5\sigma_z)$ envelope for $\epsilon_x = 5.02646 \times 10^{-10}$ m, $\epsilon_y = 5.02646 \times 10^{-10}$ m, $\sigma_z = 0.000111$



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Beam envelope around a collision point. The light red rectangle shows the zone of the quadrupole triplet (and Dipole 1) that makes the small β^* , i.e. a small beam size, at the interaction point.

One axis is the distance from collision point (longitudinal coordinate s in m), i.e. the beam trajectory, while the other two axes form the transverse plane.



High Luminosity LHC project



- Increase lumi above the nominal design: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Increase luminosity **to 5 10^{34} or more, limited by:**
 - Pile up in the detectors. We have a pile up of 30-35, experiments design upgrade for 140 evts/crossing in average with a max of 200/crossing)
 - If energy deposition by collision debris in the nearest SC magnets (low. β triplet quads) allows it
- **Use of lumi levelling** to maximize integrated luminosity for a given max lumi.
- Commissioning of the High Luminosity machine: 2023
- **Final goal is : 3000 fb^{-1} in 10-12 years, by 2035.**
(LHC was designed for 300-400 fb^{-1} in 10-15 y)

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Scope of the HL-LHC project.

3000 fb^{-1} of integrated luminosity means about 300 billions of billions of proton collisions!

Pile up is the number of protons collisions happening at each bunch crossing

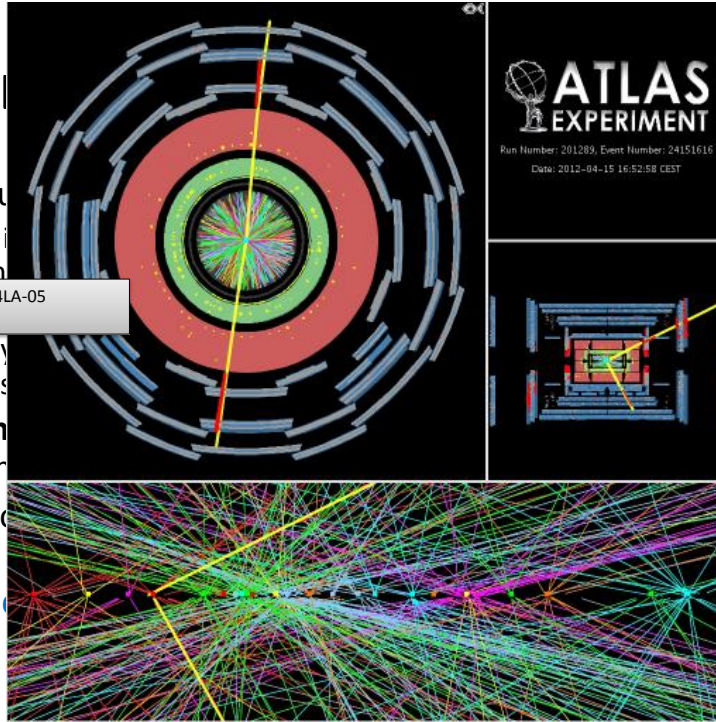
Energy deposition: heat deposited on the quadrupole triplets (see previous slides).



High Luminosity

- Increase luminosity
 - Pile up of events in the experiment
- Use of luminosity for a given energy
- Commissioning
- **Final goal** (LHC was...)

E. Todesco, CERN, talk 4LA-05
D. Bocian, 3LPY-01



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Example of pile up: a collision with about 30 events (happening at the same time), see picture at bottom which show a zoom of small zone enlargement of the full detector image at top.



Target parameters for HL-LHC run



Efficiency is defined as the ratio between the annual luminosity target of 250 fb⁻¹ over the potential luminosity that can be reached with an ideal cycle run time with no stop for 150 days: $t_{run} = t_{lev} + t_{dec} + t_{turn}$. The turnaround time after a beam dump is taken as 5 hours, t_{decay} is 3 h while t_{lev} depends on the total beam current

Parameter	Nom.	Target		LIU	
		25 ns	50 ns	25 ns	50 ns
N_b [10 ¹¹]	1.15	2.0	3.3	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	1.02	0.84	0.86	0.64
θ_c [μ rad]	300	475	445	480	430
β^* [m]	0.55	0.15	0.15	0.15	0.15
ϵ_n [μ m]	3.75	2.5	2.0	2.5	2.0
SC Magnets		2.5	2.5	2.5	2.5
		25	17	25	10
IBS I[h]	65	21	16	21	13
Piwnski	0.68	2.5	2.5	2.56	2.56
F red.fact.	0.81	0.37	0.37	0.37	0.36
b-b/IP[10 ⁻³]	3.1	3.9	5	3	5.6
L_{peak}	1	7.4	8.4	5.3	7.2
Crabbing	no	yes	yes	yes	yes
$L_{peak virtual}$	1	20	22.7	14.3	19.5
Prifup $L_{lev}=5L_0$	19	95	190	95	190
Eff. 150 days	=	0.62	0.61	0.66	0.67

SC RF Cavities

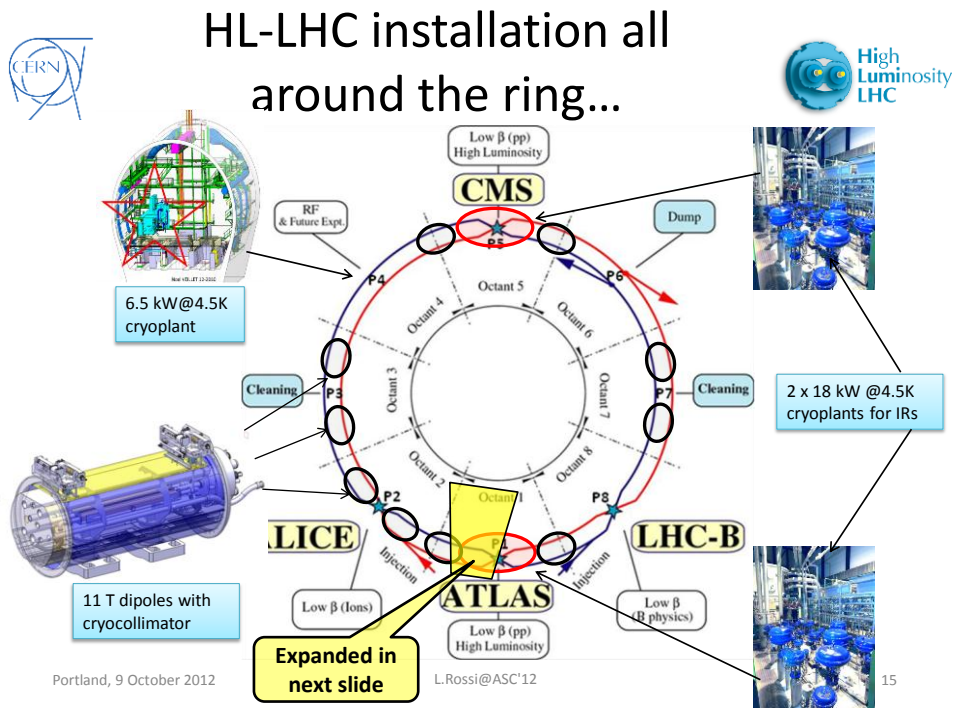
SC Links

baseline

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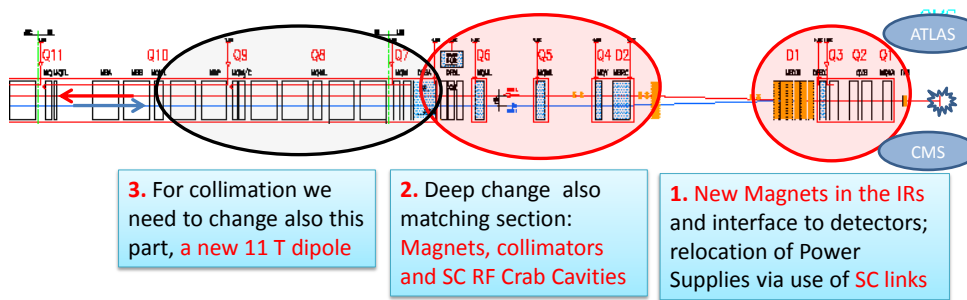
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Regions of LHC where modifications will be carried out for the HL-LHC project (not in scale). The yellow zone is just 1/4 of the length of the two red ovals that are the most important zones.

The critical zone: magnet changes, cryogenics +...

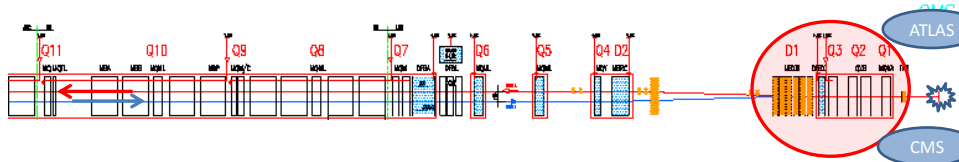


**300 m x 4 +... ~ 1.5 km long accelerator
In high radiation environment: 10...100 MGy**

Expansion of the most critical zone for the upgrade (only 1/4 is shown, see previous slide). This zone is repeated four times in the LHC.



The critical zone: HF quads/dips, cryogenics +...



Various talks in this session and 4LA session (Thursday)

1. New Magnets in the IRs and interface to detectors;

**Most critical magnets for the upgrade
In high radiation environment: 10...100 MGy**

R. Flukiger, CERN, talk 3MF-05
Irradiation both with neutron and protons

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In the critical zone the first thing that will happen is the removal of the present Q1-Q34 magnets (the inner triplet quadrupole) with more performing magnets (50% higher peak field) capable of high radiation resistance.



Here the magnets for the low β in the present LHC



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Pictures of the present LHC SC magnets that will be fully renovated for HL-LHC.



Magnets: the shopping list



Magnet type	NAME	SCOPE	Quantity	Peak Field (T)	Coil bore (mm)	Length (m)	Energy (MJ)	F _c (MN/m)	Deadline (year)
Dipole	FRESCA2	Ice Test station upgrade	1-2	13	120	1.5	3.6	15	2013
Twin dipole	LHC	=	=	8.3	56	14.3	7	3.4	=
Twin Dipole	11T	HL-LHC DS	10-20	11	60	11 (2x5.5)	11	7.3	2017-2020
Quad	Low-β Q1-Q3	HL-LHC IR	16	12	150	8-10	12	=	2020
Dipole	D1	HL-LHC IR	4	5	160	8	6	7	2020
Two-in-One Dipole	D2	HL-LHC IR	4	3-5?	100 ?	5-10	?	?	2019
Twin Quad	Q4	HL-LHC IR	4	8	85-90	4.5	1.2	=	2019
Twin Quad	Q5	HL-LHC IR	4	8 ?	70	4.5	0.6	=	2019
Dipole	LHC2D	HE-LHC demo	1	20	40	1	5	20	2016
Twin Dipole	LHC2T	HE-LHC demo	1	20	40	1	10	20	2017
Twin Dipoles	LHC2	HE-LHC	1232	20	40	14.3	100	20	2030

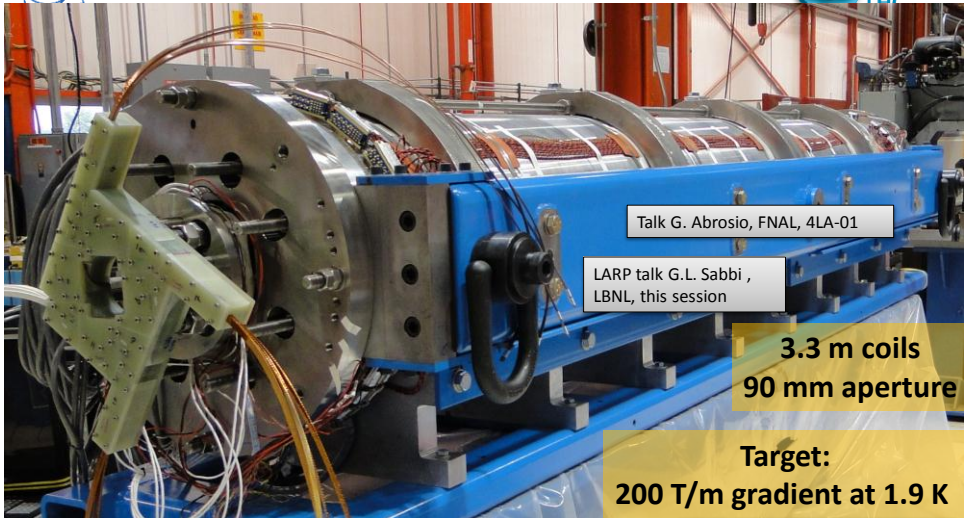
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The list of new advanced SC magnets under development at CERN and other HEP labs (CEA, US-LARP, etc.), with evidenced the ones needed for the HL-LHC projects. Magnets with peak field beyond 10 T requires use of Nb₃Sn conductor.

LARP Long Nb₃Sn Quadrupole



Talk G. Abrosio, FNAL, 4LA-01

LARP talk G.L. Sabbi ,
LBNL, this session

3.3 m coils
90 mm aperture

Target:
200 T/m gradient at 1.9 K

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

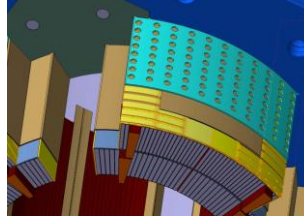
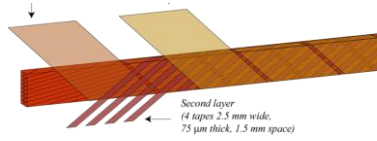
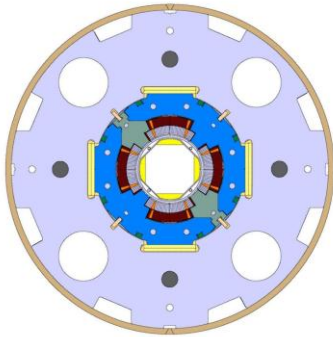
LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
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limited by one coil

LQS03: **208 T/m** at 4.6 K
210 T/m at 1.9 K
20
1st quench: 86% s.s. limit

US- LARP program has already build some models ad prototypes of high field quadrupoles in Nb₃Sn needed for the HL-LHC, here one example, the LQS magnet (three variants).



Improved Nb-Ti technology Low- β quad 120 mm aperture



new insulation scheme, more porous in the coils and in the structure

Higher heat removal (matching the gap to NbSn ?)

80% short sample quench limit (nominal operation) at 4th quench

Talk G. Kirby, CERN, this session

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Status of an advanced Nb-Ti quadrupoles recently built at CERN (as back-up of the baseline Nb₃Sn, in case of need) with enhanced heat removal features. This solution will be probably adopted for the various Nb-Ti magnets needed for HL-LHC.



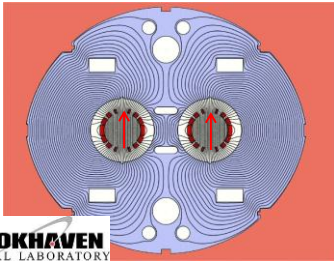
Separation dipoles (KEK, BNL)



The D1 : Large field 8 T in a very large bore.
Substituting 18 m long resistive magnets with
8 m long 6 T large aperture SC dipoles

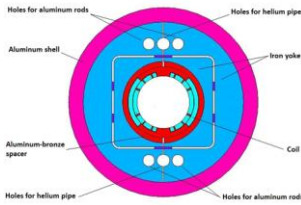


Q. Xu et al., this session



BROOKHAVEN
NATIONAL LABORATORY

D1 // field aperture dipole
To explore ant coils to reduce flux return



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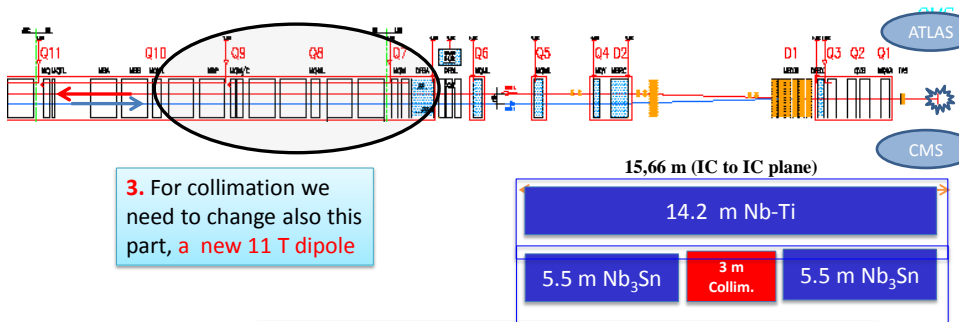
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Contribution of KEK and BNL to the HL-LHC: design of Nb-Ti special SC magnets.



The critical zone: magnet changes, cryogenics +...



3. For collimation we need to change also this part, a new 11 T dipole

RETROFIT : replace an LHC dipole with a shorter one of the same bending strength to make room for beam absorber (collimation)

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Another zone that needs new High Field magnets for the HL-LHC project: the 11 T dipole between Q7 and Q9.

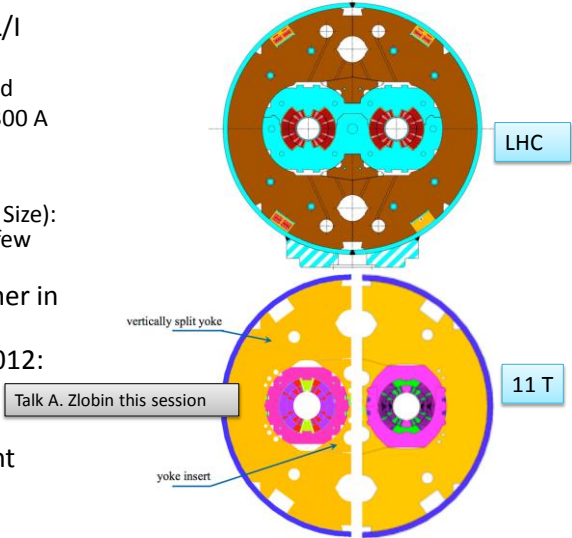


11 T : challenges

CERN-FNAL collaborations



- Series to LHC dipoles: BL/I = 120Tm/11.85kA
 - Cable, strand constrained
 - Nested power supply ± 300 A
- Field quality
 - Fe saturation 6.5 \rightarrow 0.5
 - Pers. Current (40 μ m fil. Size): 44 \rightarrow 20 \rightarrow 10? Enough (few magnet)
- Forces, energy 70% higher in same envelope
- Demo (single, 2 m) by 2012: tested!!
- Proto by 2013-14
- 1 unit = 2x5.5m \Rightarrow straight
- First NbSn in operation?



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Characteristics and status of the 11 T project carried out by Fermilab and CERN.



USA: Strand and Cable Design

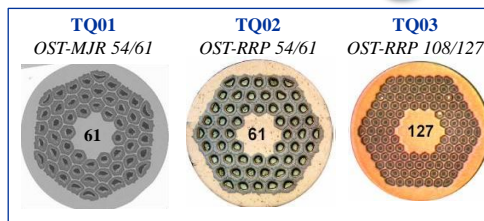


Conductor design:

- TQ01: OST MJR 54/61
- TQ02: OST RRP 54/61
- TQ03: OST RRP 108/127

Cable:

- 27 strands, 0.7 mm diameter
- Width: 10.05 mm
- Mid-thickness: 1.26 mm
- Keystone angle: 1.0 deg
- Insulation: S-2 glass sleeve



Based on the DOE-CDP
Conductor Development Program
 Launched in 1998 has doubled the J_c (1400 \rightarrow 3000 A/mm² @ 12T, 4.2K) in 2001...
 But to make it really usable in our magnets at 2700 A/mm² is still an endeavour...

G.L. Sabbi, LBNL
 A. Gosh, BNL, this session

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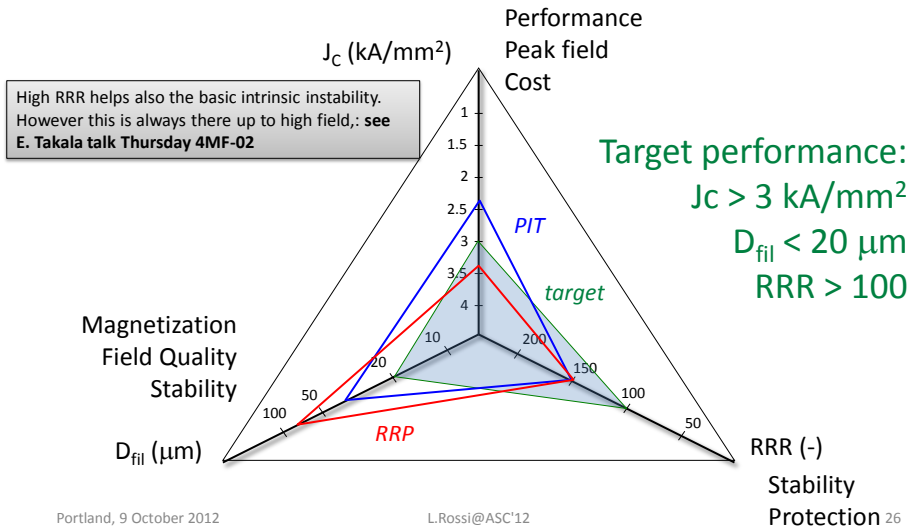
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The High Field magnet program for the HL-LHC requires a strong development of advanced Nb₃Sn with very high current density. Status of the conductor progress in USA (LARP program and DOE-CDP, Conductor Development Program).



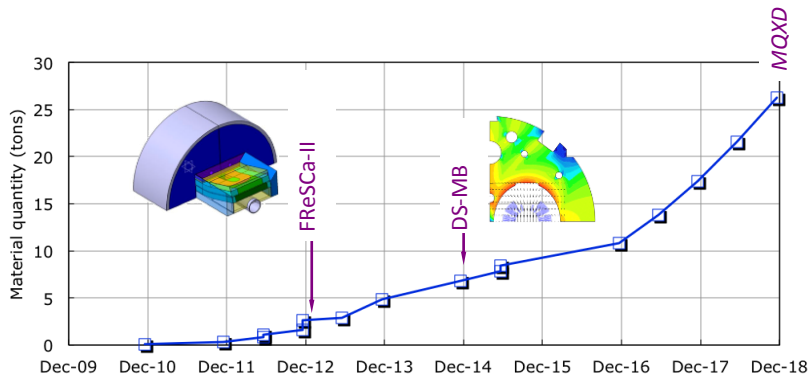
Performance targets for Nb₃Sn Near but not quite there: variation in RRR is critical



Picture originated by Luca Bottura illustrating the final target region for the HL-LHC project (HE-LHC is also included).



Material needs - LTS



- Approximately 26 tons of HEP-grade Nb₃Sn will be needed in the coming 10 years

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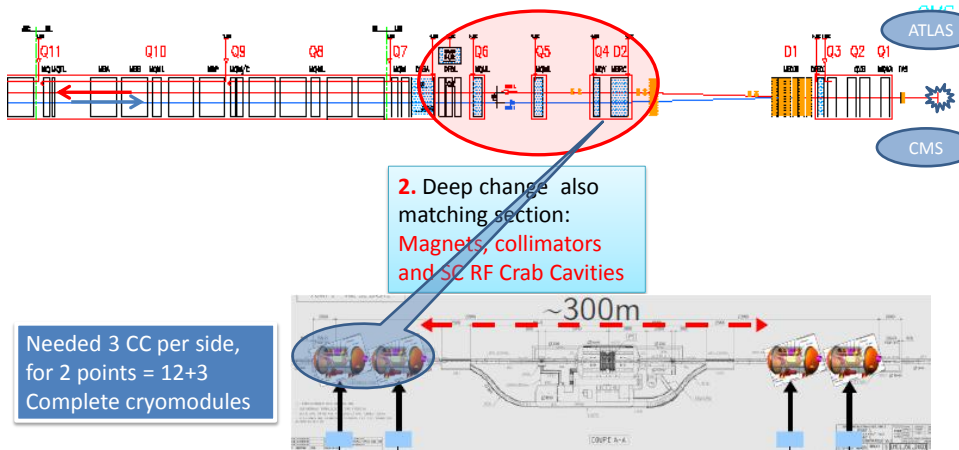
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Need of Nb₃Sn conductor for CERN projects in the next decennium.



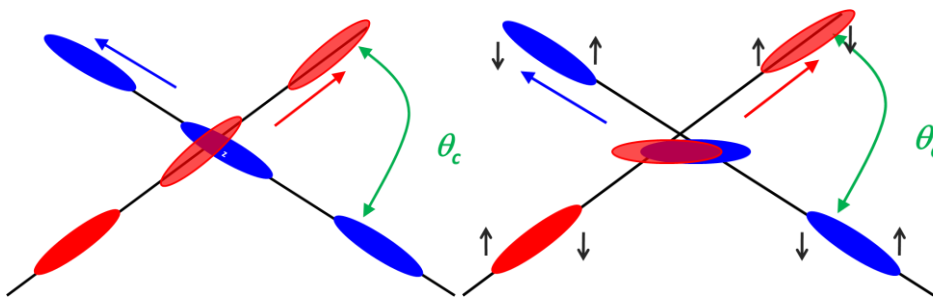
The critical zone: SC RF cavities in between magnets



In the critical zone we need to make room, in between Q4 and D2, for a new special SC RF device called Crab Cavity.



Effect of the crab cavity (recovering the lost of θ_c)



- RF crab cavity deflects head and tail in opposite direction so that collision is effectively “head on” and then luminosity is maximized
- *Crab cavity maximizes the lumi and can be used also for lumimosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the geometrical factor. Then they are slowly turned on to compensate the proton burning*

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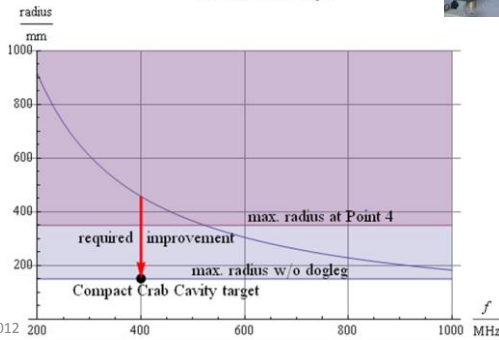
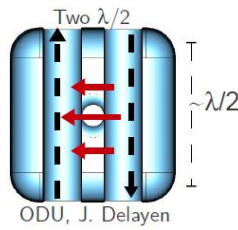
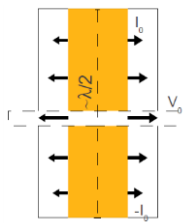
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Effect of crab cavity: elimination of the Reduction factor (see slide n.10) by local rotation of the beam before collision point and then, compensates by a counter-rotation after collision to re-establish natural beam position.



Crab Cavity, for p-beam rotation **at fs level!**



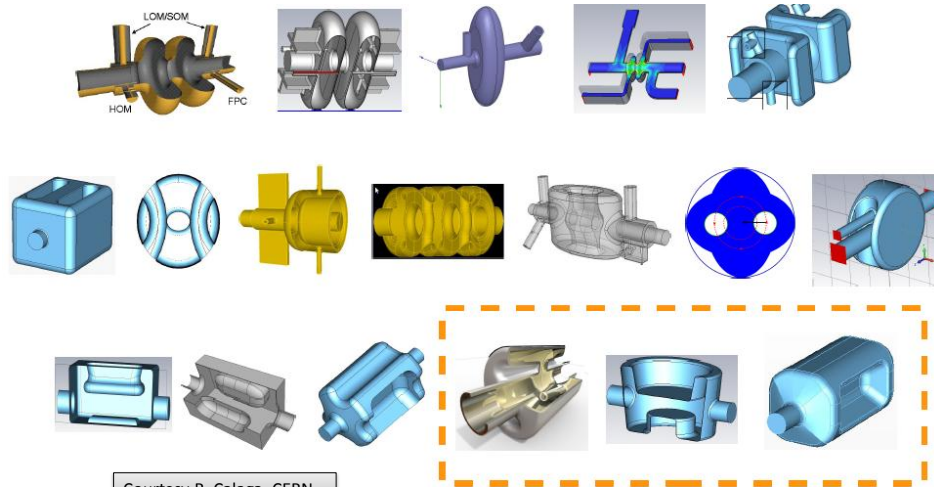
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Field line in a crab cavity. The graphs shown the transverse size (radius in mm) of compact crab cavity at 400 MHz vs. size of “standard” elliptical cavity (named Point 4 in the graph, where size vs. frequency is plotted). A classical elliptical cavity is shown in the picture at top right.



Crab Cavities for LHC



Courtesy R. Calaga, CERN

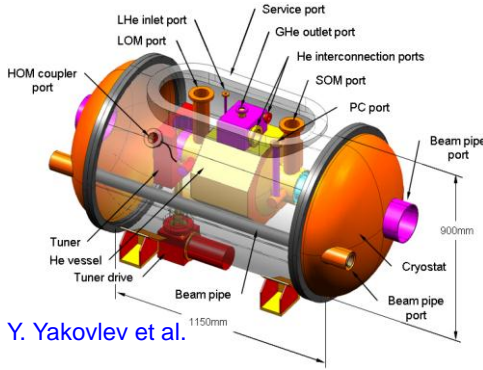
~4yr of design evolution

Exciting development of new concepts
(BNL, CERN, LU-CI-DL, FNAL, KEK, ODU/JLAB, SLAC)

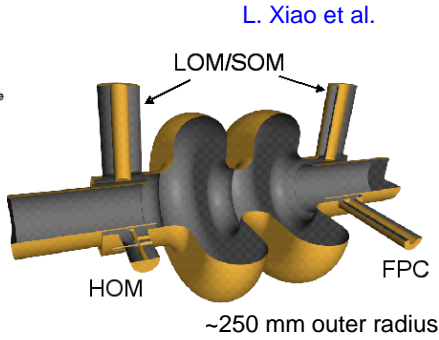
Many different design for Compact Crab Cavity have been examined: now, after down selection process, only the last three lay-outs (in the dashed box) are under development.



Crab cavity ; cryomodule and cavity all solid Nb – 2 K operations



Y. Yakovlev et al.



L. Xiao et al.

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Progress in SC Crab Cavities



UK – Cockcroft Int. –Lancaster U.



First test : Nov.@CERN

Finished cavity at Niowave

Jan 2012 → May 2012



USA (ODU-SLAC)



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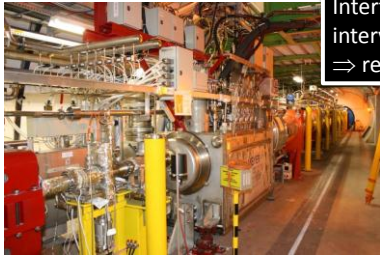
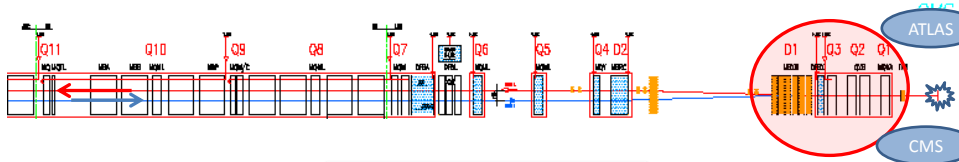
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First two prototypes of Crab Cavity after construction (bare cavity, without cryostat).



The critical zone: relocation of EPC and DFB to increase reliability



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Interface warm-cold requires intervention for maintenance
⇒ remove on surface

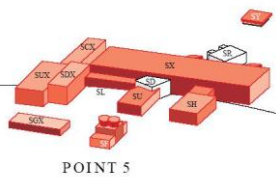
1. New Magnets in the IRs and interface to detectors;
relocation of Power Supplies via use of SC links

Power convertes are very vulnerable to radiation (SEU)



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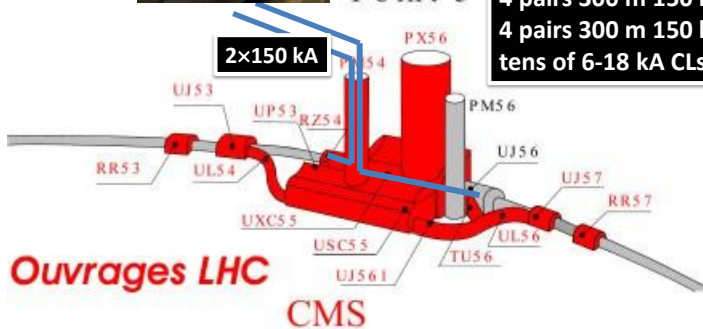
Because of the increase in radiation level (due to the higher luminosity) we need to relocate the magnet power supplies and the CFBs, the Cryogenic Feed Boxes containing the HTS current leads feeding the SC magnets) from the critical region in the tunnel up to surface, at ground level.



POINT 5

Point 5

1 pair 700 m 50 kA – 2016-17
4 pairs 300 m 150 kA – 2018
4 pairs 300 m 150 kA – 2021
tens of 6-18 kA CLs pairs in HTS



Ouvrages LHC

CMS

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A. Ballarino, 18 Nov. 2011

View of the tunnel where the power supplies and CFBs are today located (zone UJ56) and schematic for the 300 m long links (100 m is the tunnel average deepness).

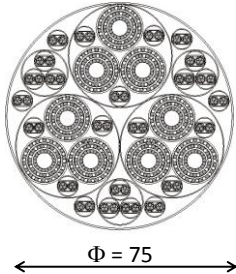


**CERN Superconducting Link for large current
Needs of round wire**



Cable structure using MgB₂ wires

27 cables 6000 A
48 cables 600 A
I_{tot} = **190 kA** (~2 × 95 kA)



~7 kg/m
~ 900 m_{HTS}/m_{cable}



3 × 6 kA



**Very good results –
recent to be confirmed**

Courtesy A. Ballarino

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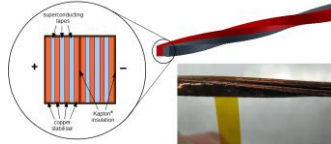
Schematic and first prototype of the MgB₂ round cable for SC links at CERN



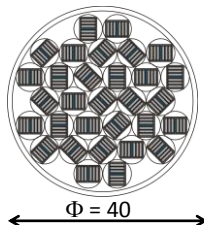
**“smaller cable”: 24 × 2 × 600 A (2 × 15 kA)
@ 25 K MgB₂
@ 65 K (YBCO and Bi-2223)**



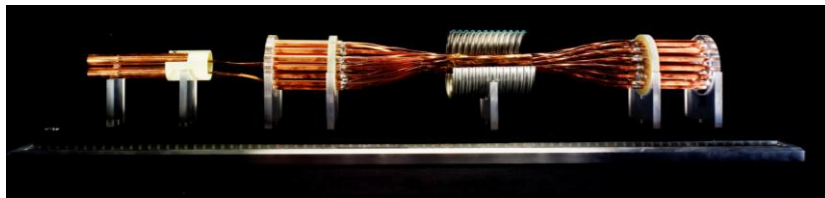
~2 kg/m
~ 200 m_{HTS}/m_{cable}



**Novel cable concept
using tapes (MgB₂,
YBCO or YBCO)**



A. Ballarino, CERN
See talk 2LPF-01

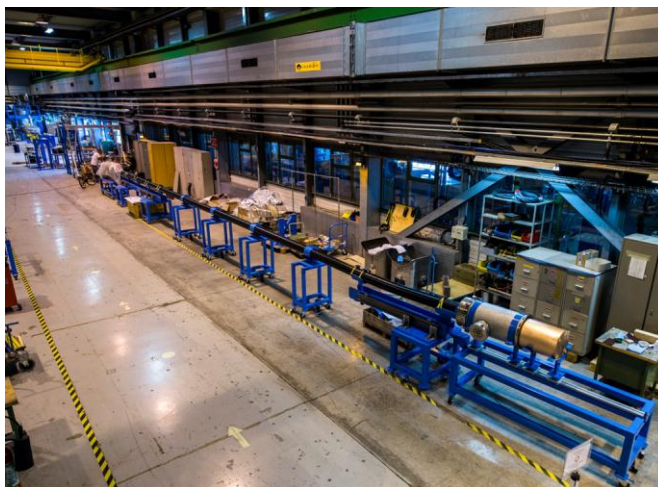


A. Ballarino, March 2012

Low amperage SC link cable can be manufactured also by means of tapes (HTS or MgB₂) as demonstrated at CERN on short lengths



A unique tool: 20 kA - 4-300 K test station



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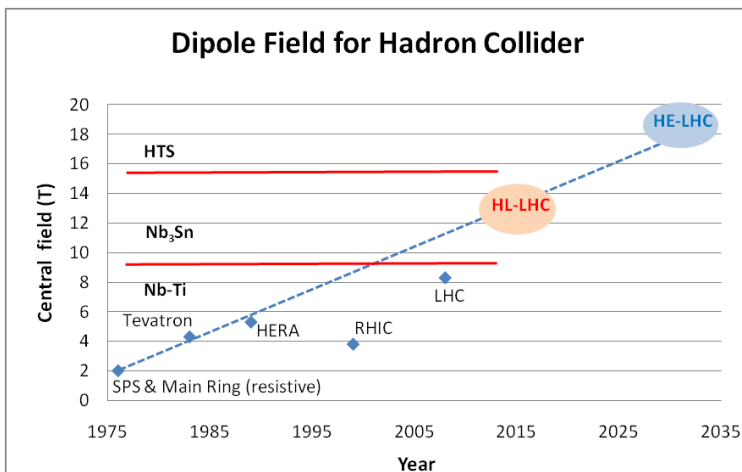
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Photo of the new CERN test facility, capable to measure high amperage cable at variable temperature. The 20 m long flexible cryostat is shown (black tube).



HE-LHC



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Accelerator magnet evolution, from resistive era to the future HE-LHC project. The jump in performance beyond LHC which is required for HL-LHC is impressive.



Magnets: the shopping list



Magnet type	NAME	SCOPE	Quantity	Peak Field (T)	Coil bore (mm)	Length (m)	Energy (MJ)	F _x (MN/m)	Deadline (year)
Dipole	FRESCA2	Ic Test station upgrade	1-2	13	120	1.5	3.6	15	2013
Twin dipole	LHC	=	=	8.3	56	14.3	7	3.4	=
Twin Dipole	11T	HL-LHC DS	10-20	11	60	11 (2x5.5)	11	7.3	2017-2020
Quad	Low-β Q1-Q3	HL-LHC IR	16	12	150	8-10	12	=	2020
Dipole	D1	HL-LHC IR	4	5	160	8	6	7	2020
Two-in-One Dipole	D2	HL-LHC IR	4	3-5?	100 ?	5-10	?	?	2019
Twin Quad	Q4	HL-LHC IR	4	8	85-90	4.5	1.2	=	2019
Twin Quad	Q5	HL-LHC IR	4	8 ?	70	4.5	0.6	=	2019
Dipole	LHC2D	HE-LHC demo	1	20	40	1	5	20	2016
Twin Dipole	LHC2T	HE-LHC demo	1	20	40	1	10	20	2017
Twin Dipoles	LHC2	HE-LHC	1232	20	40	14.3	100	20	2032

HiEnergy LHC

HiEnergy LHC

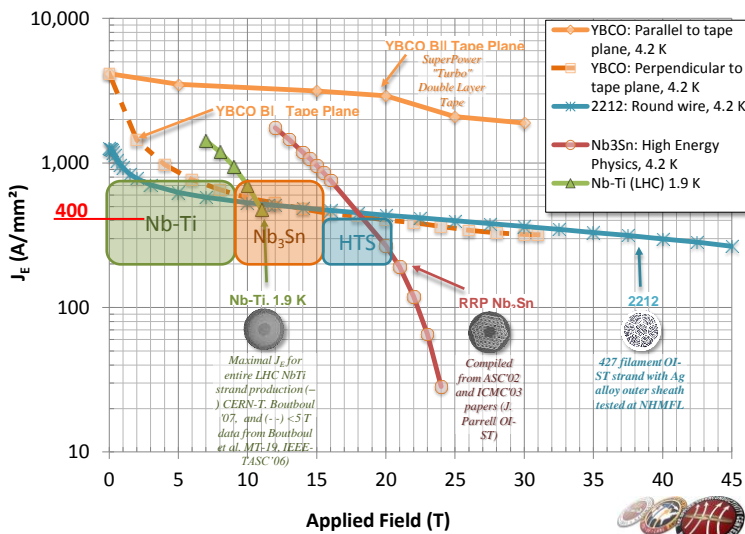
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The Superconductor « space » Minimise use of HTS



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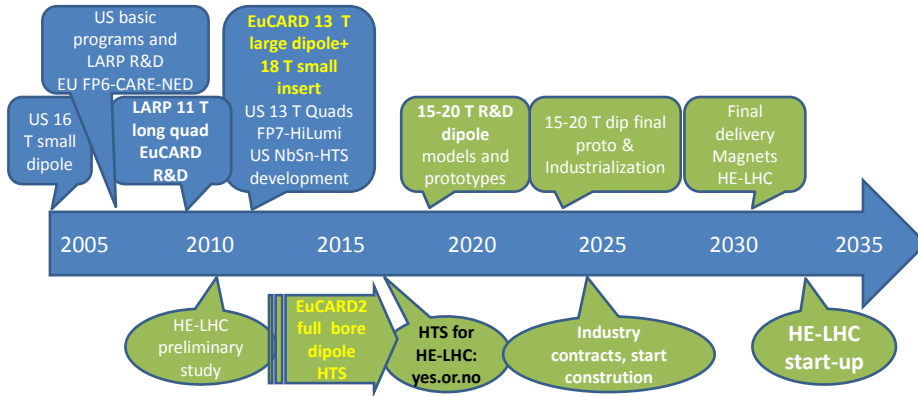
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Because for technical difficulty and especially because of their high cost, the use of HTS for high field magnet must be minimized. However it is clear that for accelerator magnets to go beyond 15-16 T one needs HTS. The graphs show $J_{\text{engineering}}$ rather than J_c .



Critical decision for HE-LHC Is HTS conductor usable in magnets with large current?



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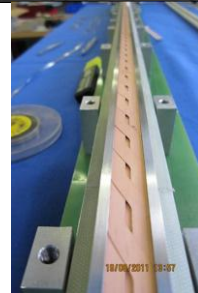
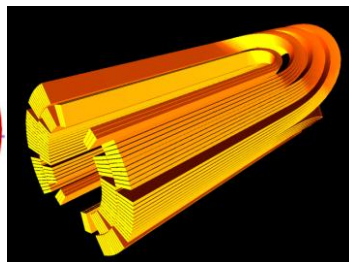
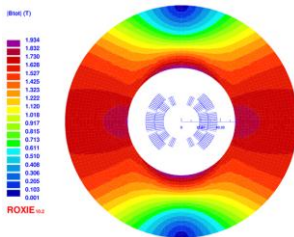
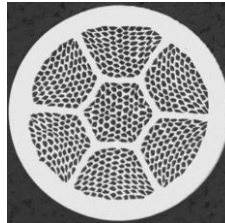
The timeline for the R&D and construction of HE-LHC magnets. Around 2017 one has to answer if the HTS can be used or not, allowing to reach 16-20 T domain.



Program FP7- EuCARD2 approved - starts May 2013



- Develop 10 kA class HTS accelerator cables **both Bi-2212 and YBCO**
 - Stability, Magnetization, strain resistance
 - Uniformity and High $J_{overall}$
- Test in a 5 T accelerator quality dipole



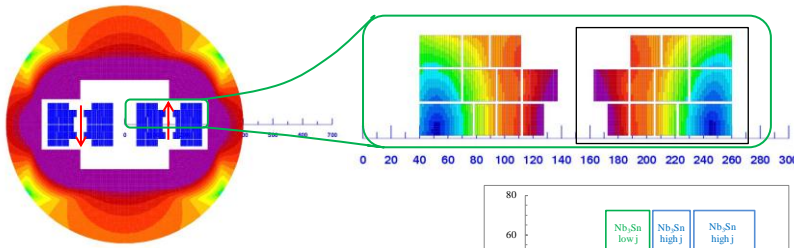
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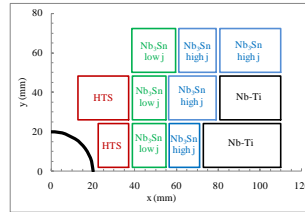
A few highlights on the recently approved program called Eucard2-Future Magnets , with R&D on HTS magnets.



Malta Workshop 14-16 Oct. 2010 HE-LHC @ 33 TeV



Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm ²)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380



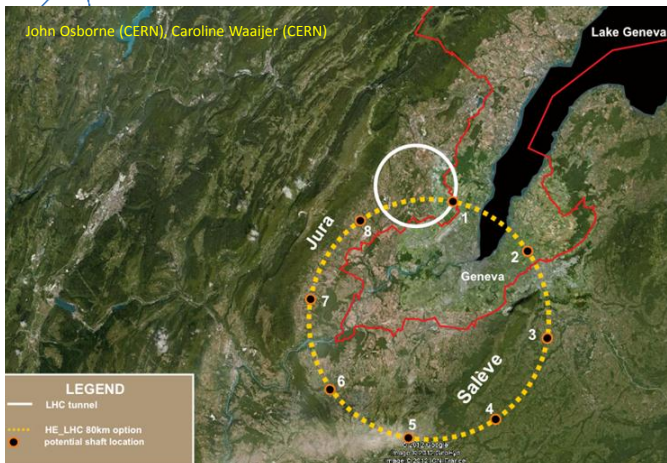
Magnet design: very challenging but feasible: 300 mm inter-beam; anticoincils to reduce flux
Multiple powering in the same magnet for FQ (and more sectioning for energy)

Higher INJ energy is desirable \Rightarrow pulsed magnets for the injectors (Ps and SPS) (synergy with FAIR SIS100 and INFN-GSI dipole for FAIR SIS300 **(session 1LE)**)

First sketch of a possible 20 T dipole (operative field) for HE-LHC presented at a workshop in Malta, 2010. The expansion of the coils shows the composition in terms of various superconductors.

The 20 Tesla field will enable to reach 33 TeV of particle energy in the center-of-mass (LHC is limited to 14 TeV).

The big leap forward: a 80 km tunnel for a VLHC



Optimization could be:
 16 T field level: collision energy 80 TeV
 20T field level: collision energy 100 TeV

Much better new infrastructure. However many costs go linearly, or more, with length. Magnet stored energy, beam energy also a concern

Whatever solution, only a vigorous SC & Magnet R&D for B ~ 16-20 T will enable to go beyond LHC energy

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Option 2

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A rather recent novel approach to HE-LHC: in case is possible the idea is to build a new tunnel about 80 km long near Geneva: in this way up to 100 TeV energy might be attained in the particle center-of-mass.



Conclusions



- HL-LHC project has started, building on an expanding international collaboration.
 - Project cost: about 850 MCHF (400 in SC and cryo components)
 - HFM for 11-12 T operative fields, SCRF cavities and long-high current SC links
- HL-LHC calls for hardware beyond state-of-the-art and as such, **it open a new territory and may pave the way toward a high energy LHC.**
- HE-LHC as ultimate upgrade of the LHC: **26-33 TeV c.o.m. (and ideas for a VLHC of 80-100TeV are taking ground...)**
 - Project relies on Very High Field Magnet Development: **16-20 tesla. HTS has a chance that we need to explore...**
 - **Quantity about 3000 tons of SC: 1000 NbTi, 1500 NbSn, 500 HTS**
 - Doubling the energy in SPS is highly desirable which will entail:
 - 3 T, 4 T/s magnets for the PS: about 500 m of magnets
 - 5 T, 1 T/s in the SPS; about 7 km of magnets

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Conclusions



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Collaboration is welcome!
(Labs & Industry)

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