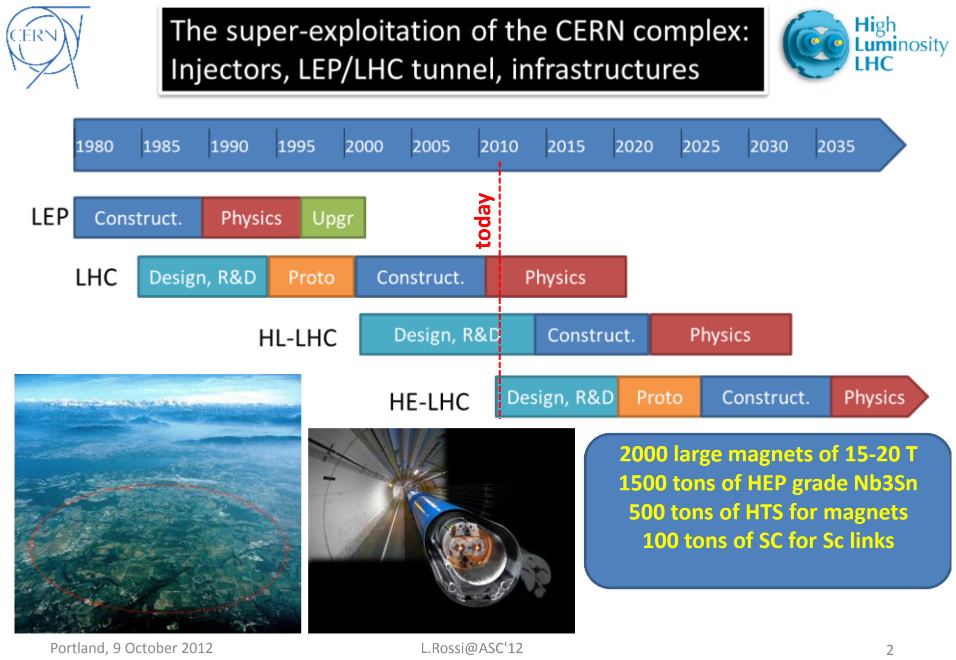

Advances in Applied
Superconductivity Technologies for
High Luminosity LHC Project
High
Luminosity
LHC
The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404
Lucio Rossi
CERN
HiLumi LHC Project Leader
ASC12 – App. SC Conference
Portland, OR, 9 October 2012



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 MgB_2 would be the preferred option (but HTS would be considered as well)

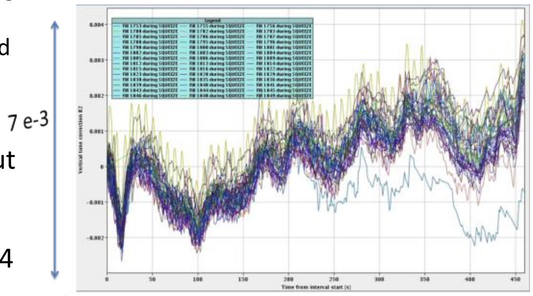
However the new technology of HE-LHC is based on the success of the near future project, High Luminosity HL – LHC (see later for the definition)

LHC present performance Superconductivity

High Luminosity LHC

- Sc effects are well mastered:
  - b_3 (sextupole) components by magnetization is well corrected
  - Snap back (sudden change of b3 at low field) also controlled.
  - Experience accumelated 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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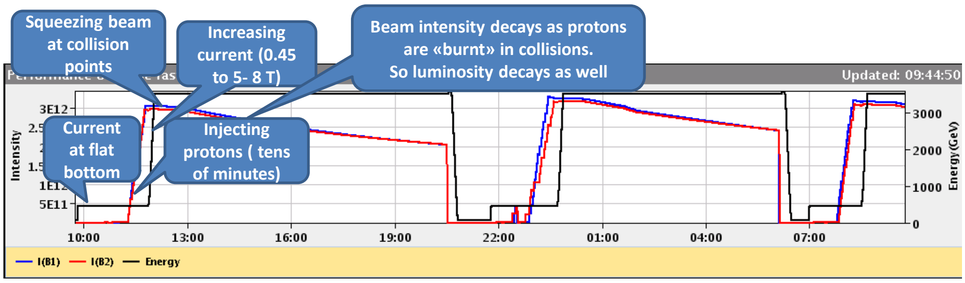
The various superconducting effects (diamagnetic and hysteretic behaviour) are well visible in the LHC operation, but they are mastered to the point that they are almost “invisible” for beam performance, confirming the success of the design.

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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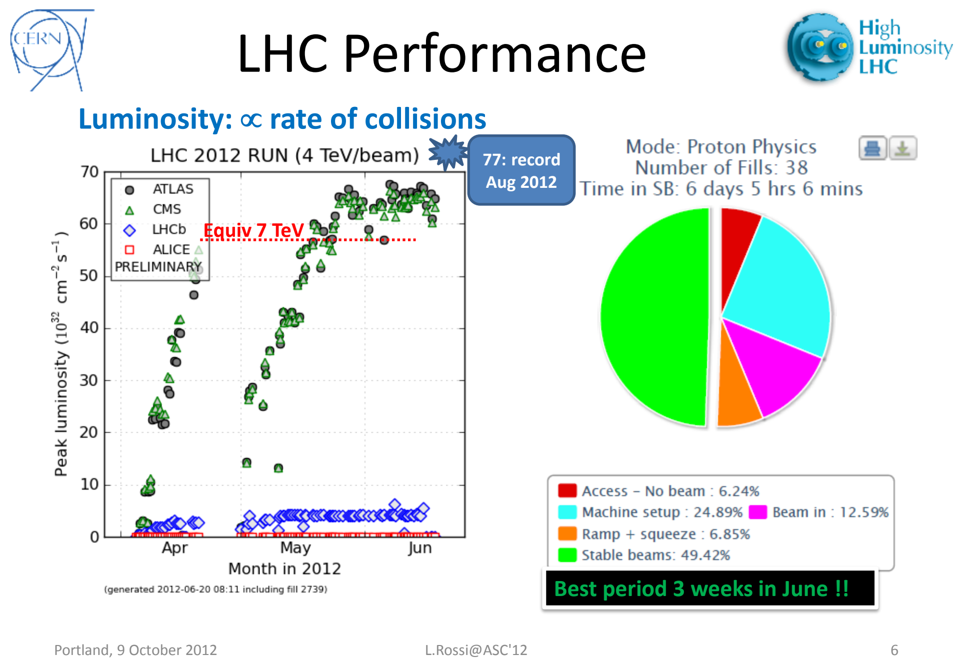
A typical cycle of the LHC accelerator:

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 read 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 read is for beam 2 anticlockwise.

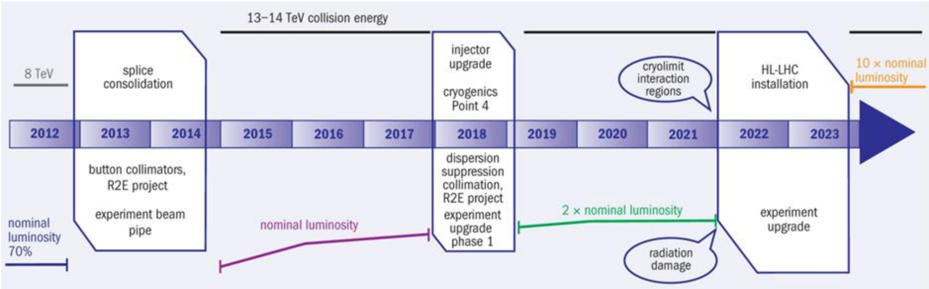
This run lasted about 10 hours: it started with magnet pre-cycle and then injection at h.10:00 with collision taking place from h.11:30 (when the beam are “squeezed” in the collision points) to h.22:00 when the beams were lost. Beam energy was 3.5 GeV/beam and population was 3×10^{12} proton/beam (the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



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.

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.
$N_{event}/s \propto$ istantaneous luminosity, L(t)
N_{event} in a certain period $\propto \int L(t)dt$

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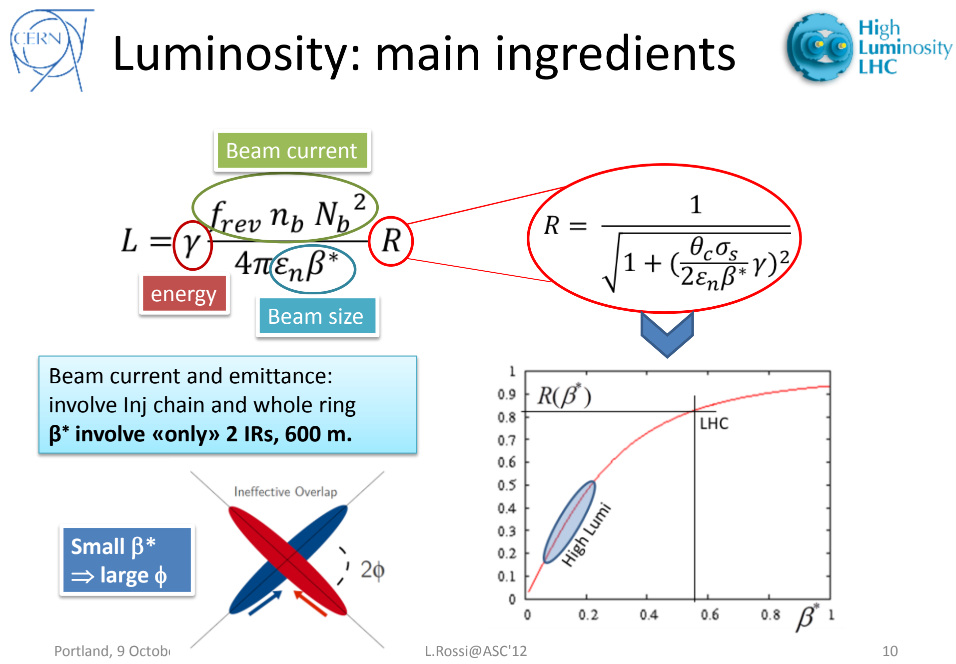
The CERN plan to increase the performance of the LHC both in energy and luminosity

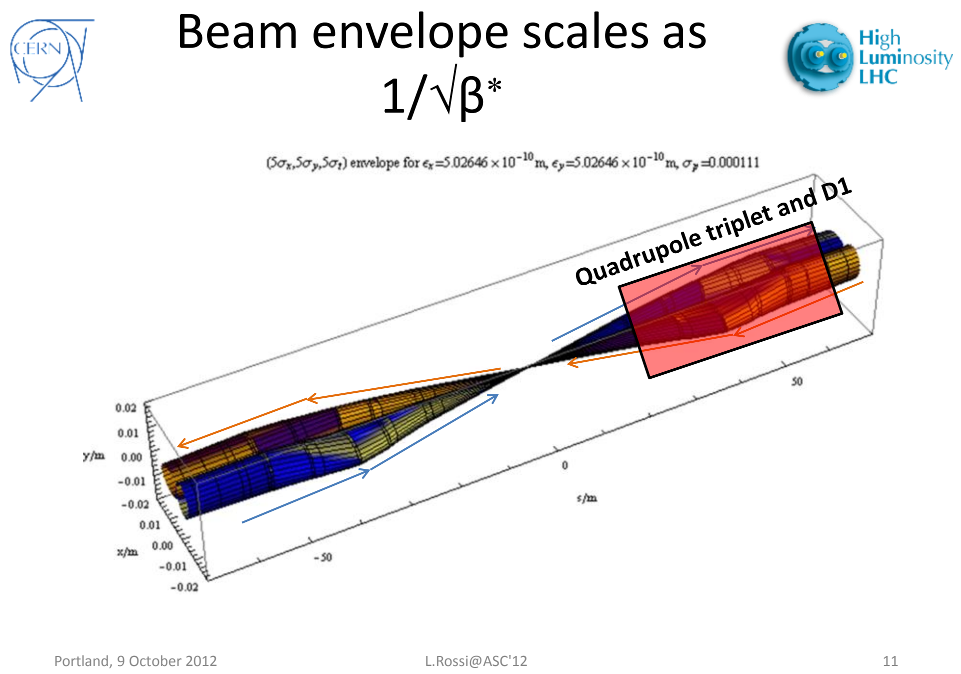
General definition of luminosity is reported (see next slide for more details)



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 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 form collision point (longitudinal coordinate s in m), i.e. the beam trajectory, while the other two axes forms the transverse plane.

High Luminosity LHC project

- Increase lumi above the nominal design: 10^{34} $cm^{-2}s^{-1}$
- 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.
- Commissionin 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)

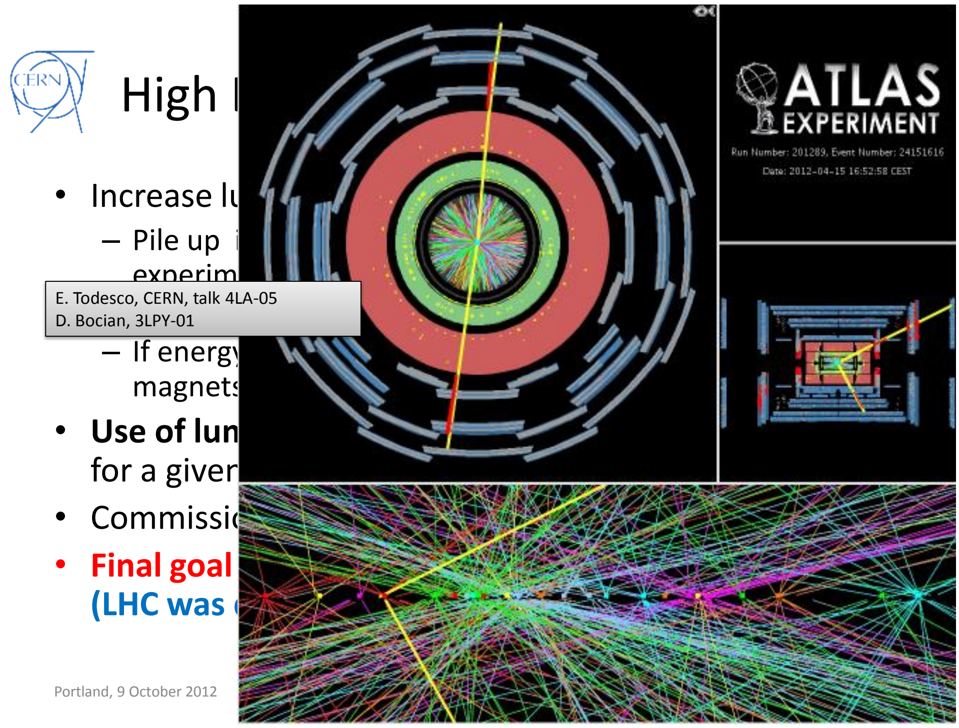
Portland, 9 October 2012 L.Rossi@ASC'12 12

Scope of the HL-LHC project.

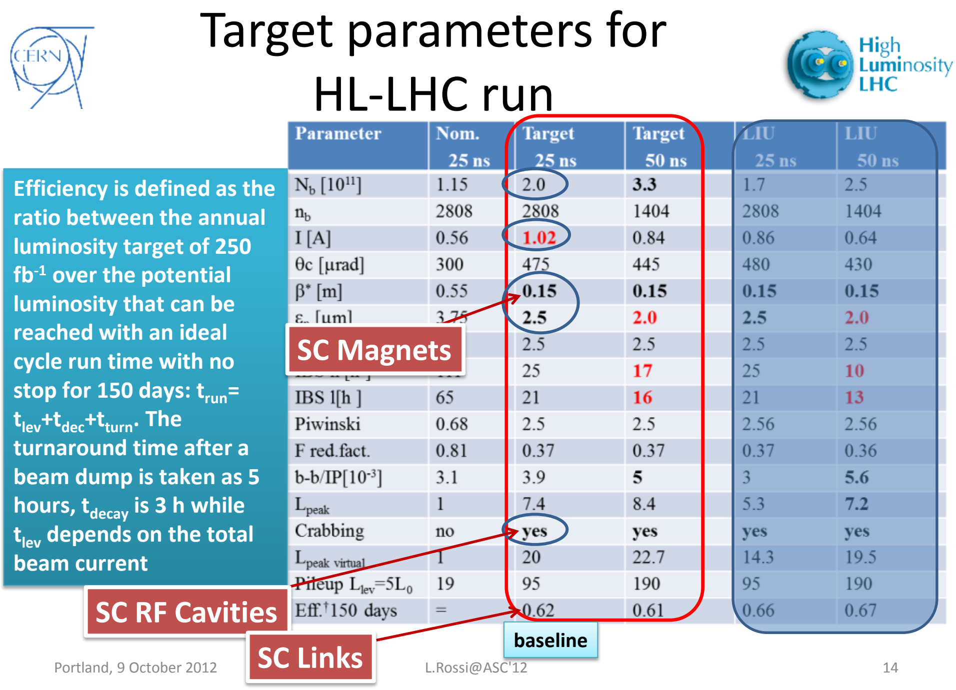
3000 fb-1 of integrated luminosity means about 300 billions of billions of proton collisions!

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

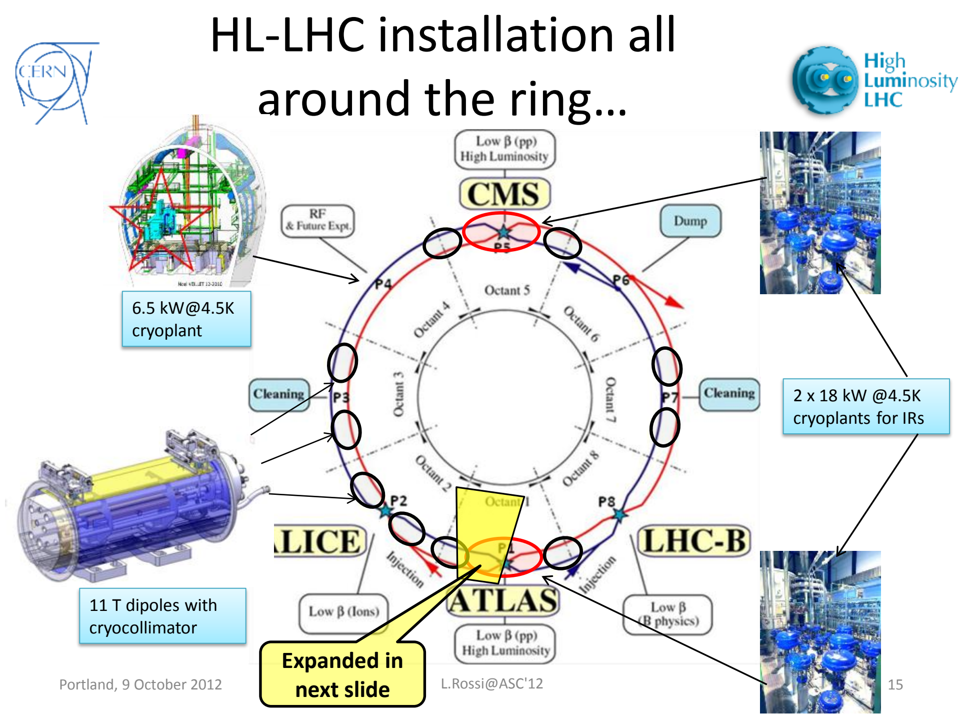
Energy deposition: heat deposited on the quadruple triplets (see previous slides).



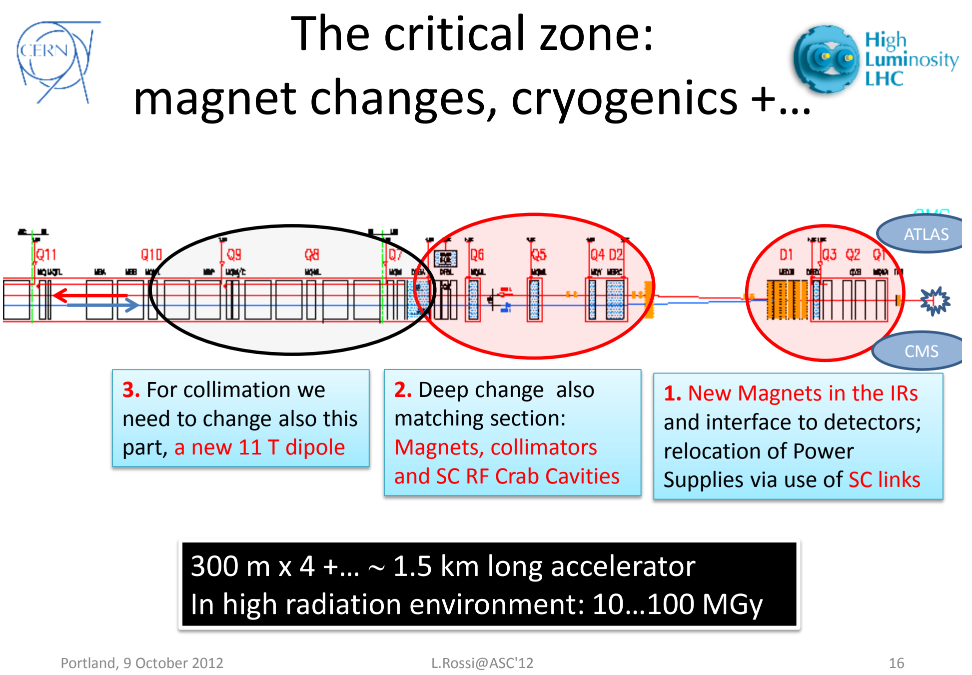
Example of pile up: a collision with about 30 events (happening at the same time), see picture at bottom which show a zoom of small zone enlargement of the full detector image at top.



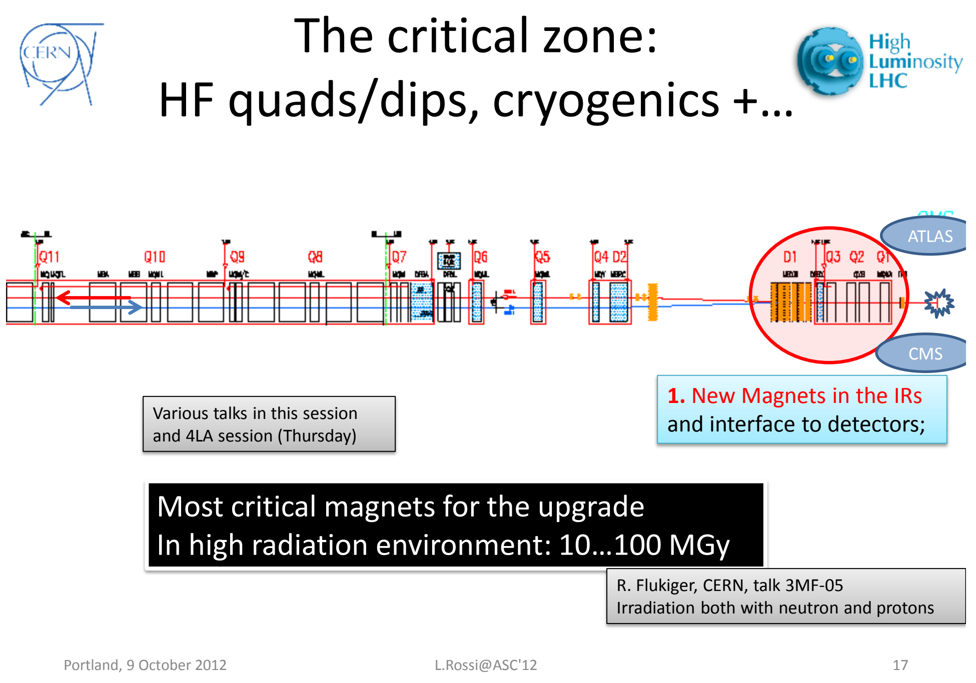
Parameter	Nom. 25 ns	Target 25 ns	Target 50 ns	LIU 25 ns	LIU 50 ns
N_b [10^{11}]	1.15	2.0	**3.3**	1.7	2.5
n_b	2808	2808	1404	2808	1404
I [A]	0.56	1.02	0.84	0.86	0.64
θc [μrad]	300	475	445	480	430
β* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	2.0	**2.5**	2.0
[illegible]	[illegible]	2.5	2.5	2.5	2.5
IBS [illegible]	[illegible]	25	17	25	10
IBS l[h]	65	21	16	21	13
Piwinski	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
Pileup $L_{lev}=5L_0$	19	95	190	95	190
Eff.†150 days	=	0.62	0.61	0.66	0.67



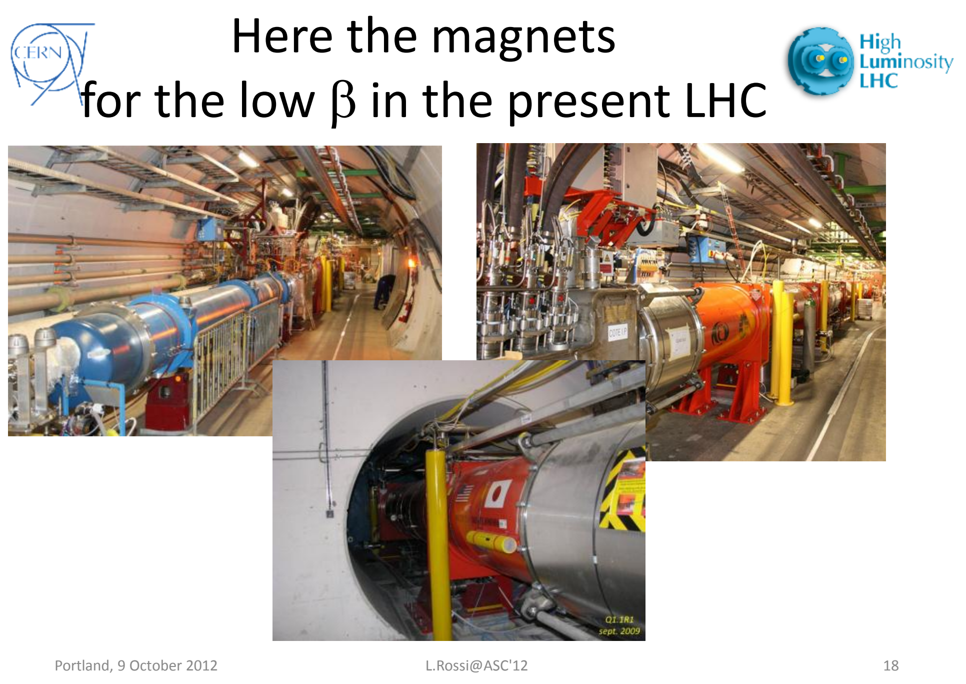
Regions of LHC where modifications will be carried out for the HL-LHC project (not in scale). The yellow zone is just ¼ of the length of the two red ovals that are the most important zones.



Expansion of the most critical zone for the upgrade (only ¼ is shown, see previous slide). This zone is repeated four times in the LHC.



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.



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

Magnets: the shopping list

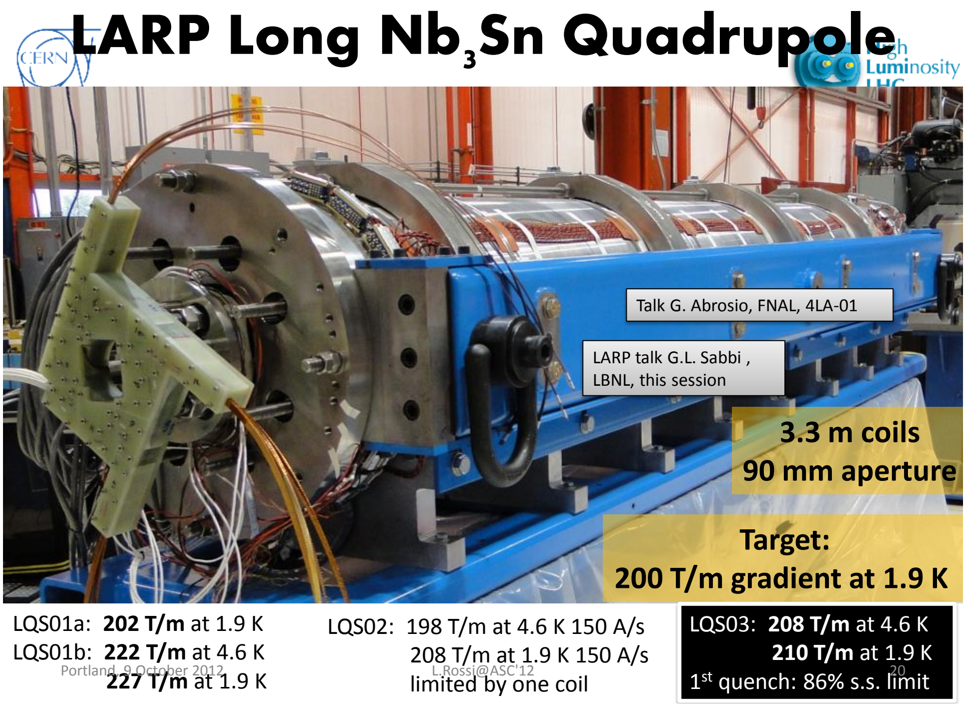
High Luminosity LHC

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 (2×5.5)	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**

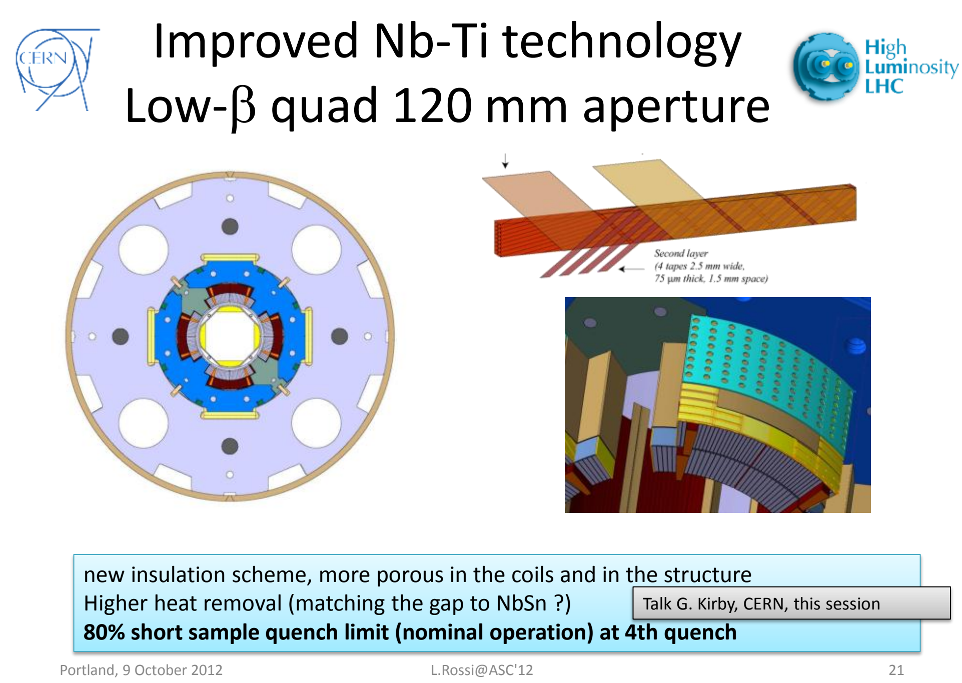
HiLumi LHC

Portland, 9 October 2012 L.Rossi@ASC'12 19

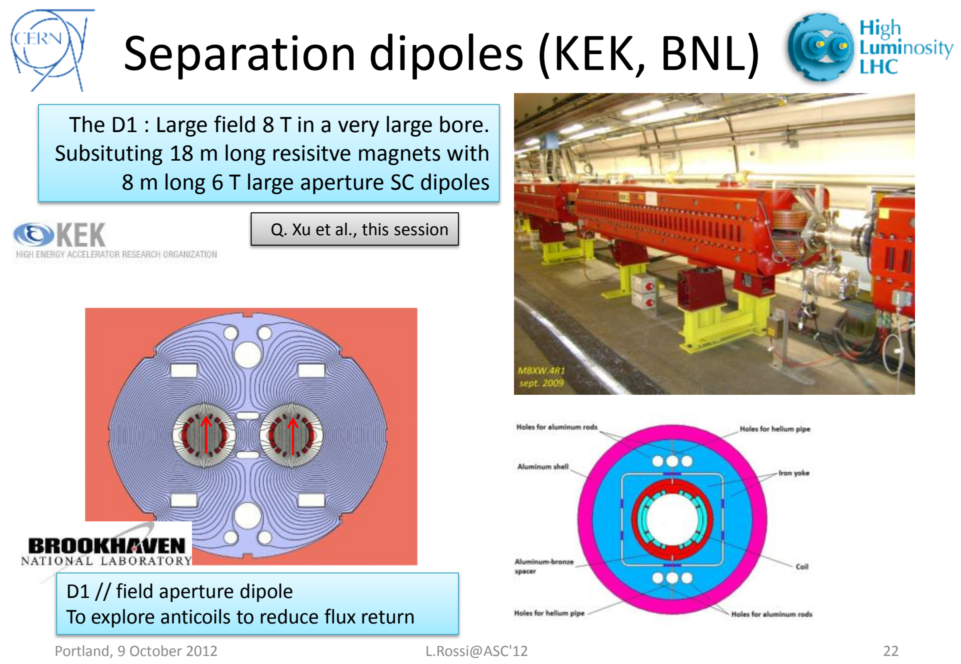
The list of new advanced SC magnets under development at CERN and other HEP labs (CEA, US-LARP, etc.), with evidenced the ones needed for the HL-LHC projects. Magnets with peak field beyond 10 T requires use of Nb_3Sn conductor.



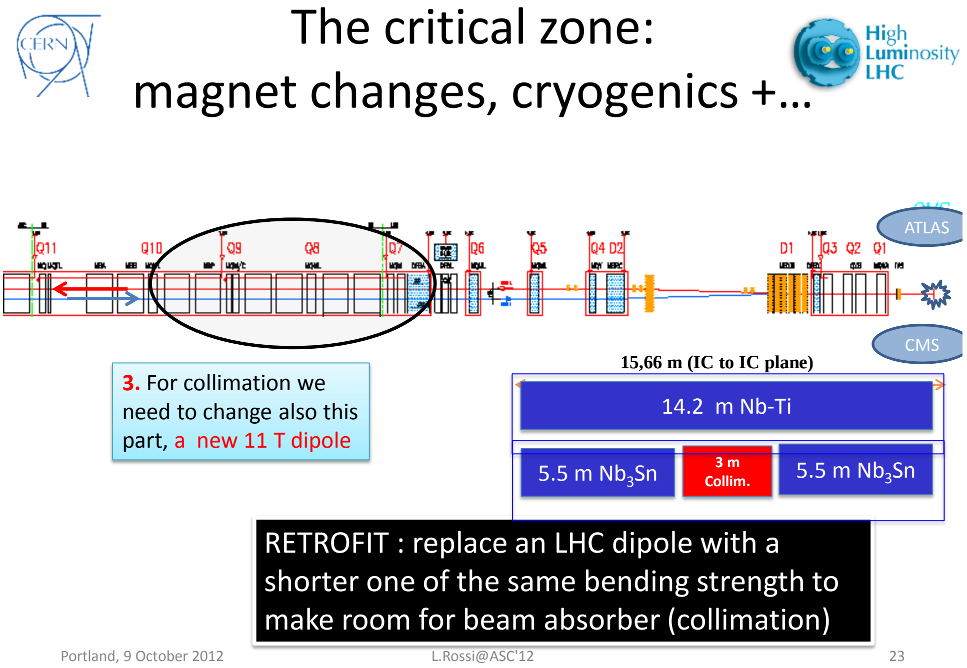
US- LARP program has already build some models ad prototypes of high field quadrupoles in Nb_3Sn needed for the HL-LHC, here one example, the LQS magnet (three variants).



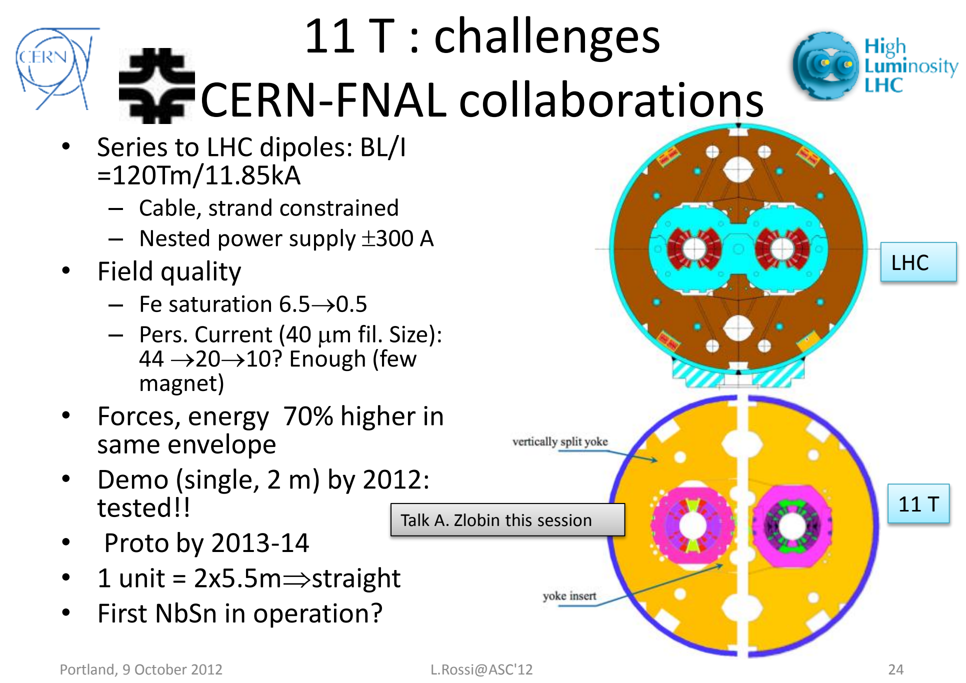
Status of an advanced Nb-Ti quadrupoles recently built at CERN (as back-up of the baseline Nb_3Sn, in case of need) with enhanced heat removal features. This solution will be probably adopted for the various Nb-Ti magnets needed for HL-LHC.



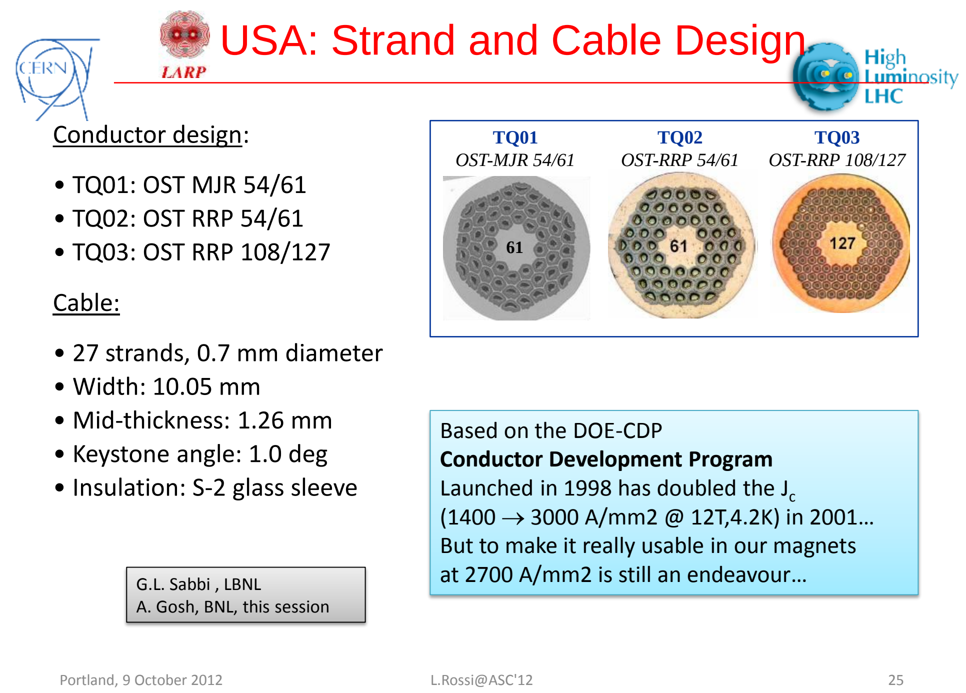
Contribution of KEK and BNL to the HL-LHC: design of Nb-Ti special SC magnets.



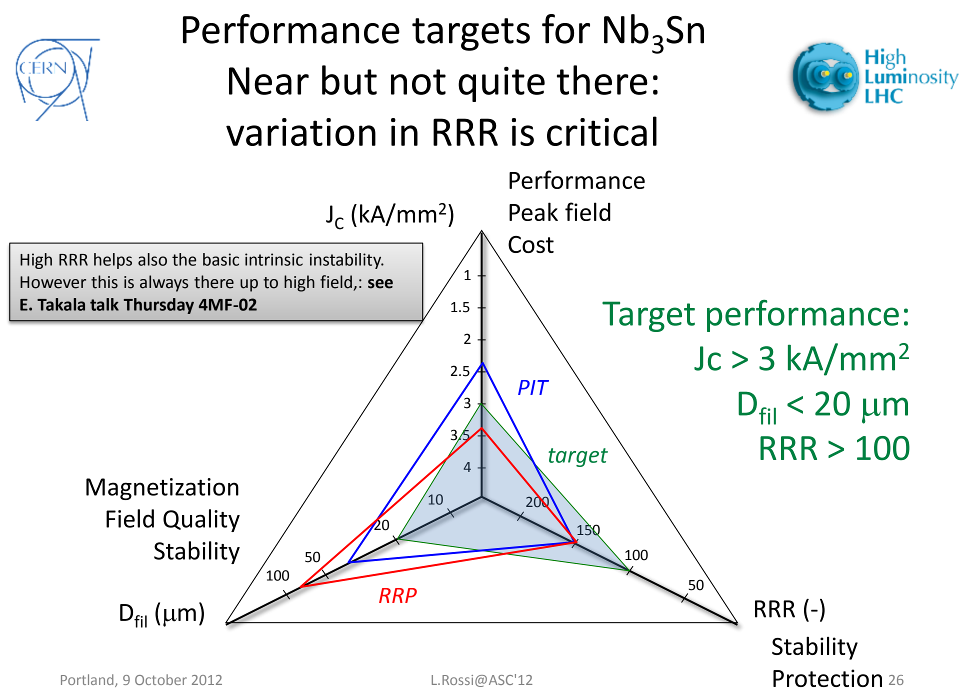
Another zone that needs new High Field magnets for the HL-LHC project: the 11 T dipole between Q7 and Q9.



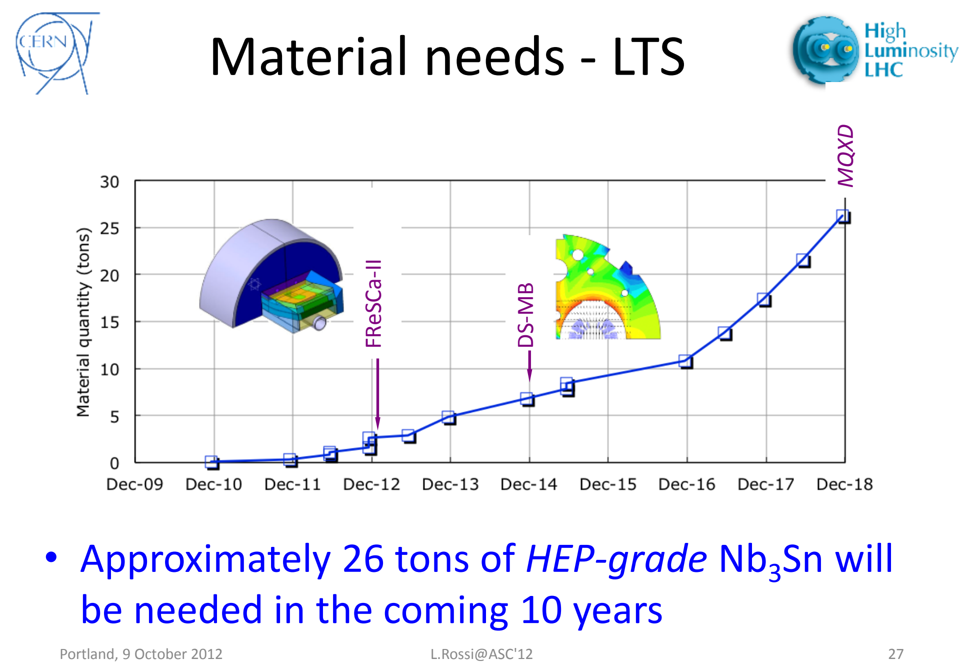
Characteristics and status of the 11 T project carried out by Fermilab and CERN.



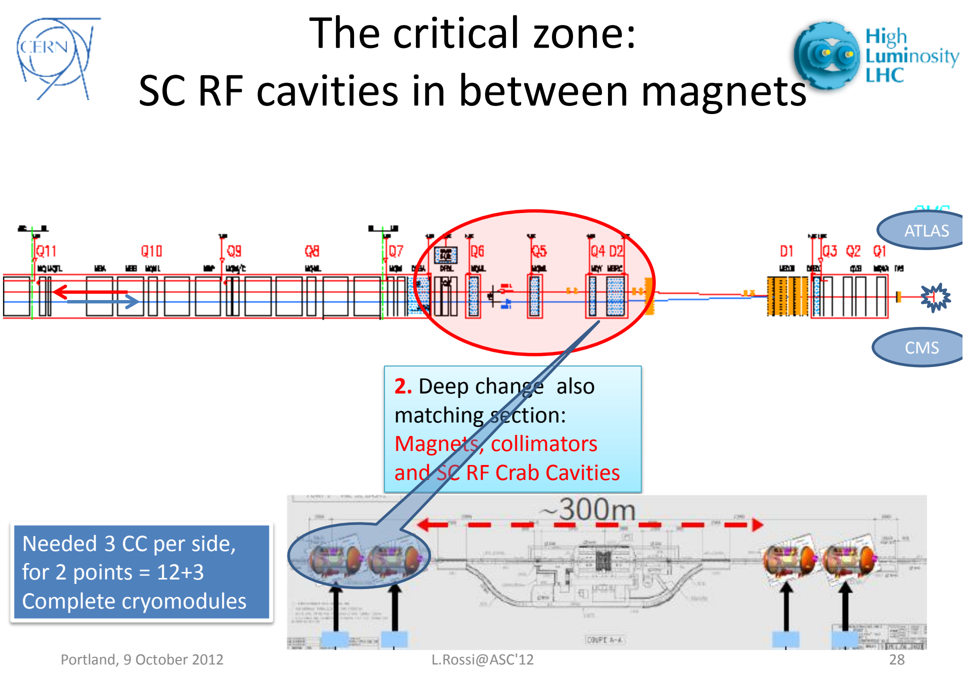
The High Field magnet program for the HL-LHC requires a strong development of advanced Nb_3Sn with very high current density. Status of the conductor progress in USA (LARP program and DOE-CDP, Conductor Development Program).



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

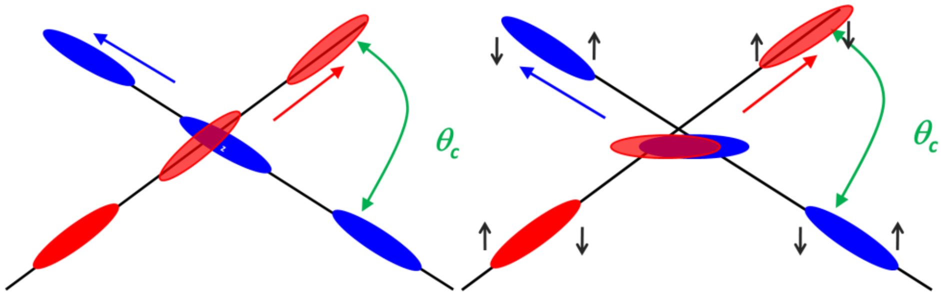


Need of Nb_3Sn conductor for CERN projects in the next decennium.



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

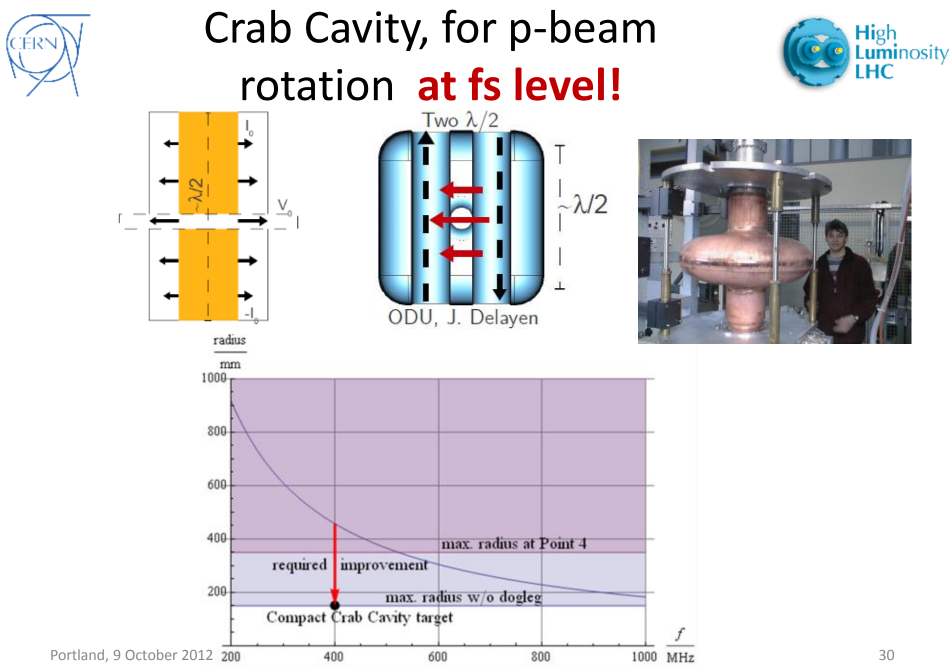
Effect of the crab cavity (recovering the lost of θ_c)



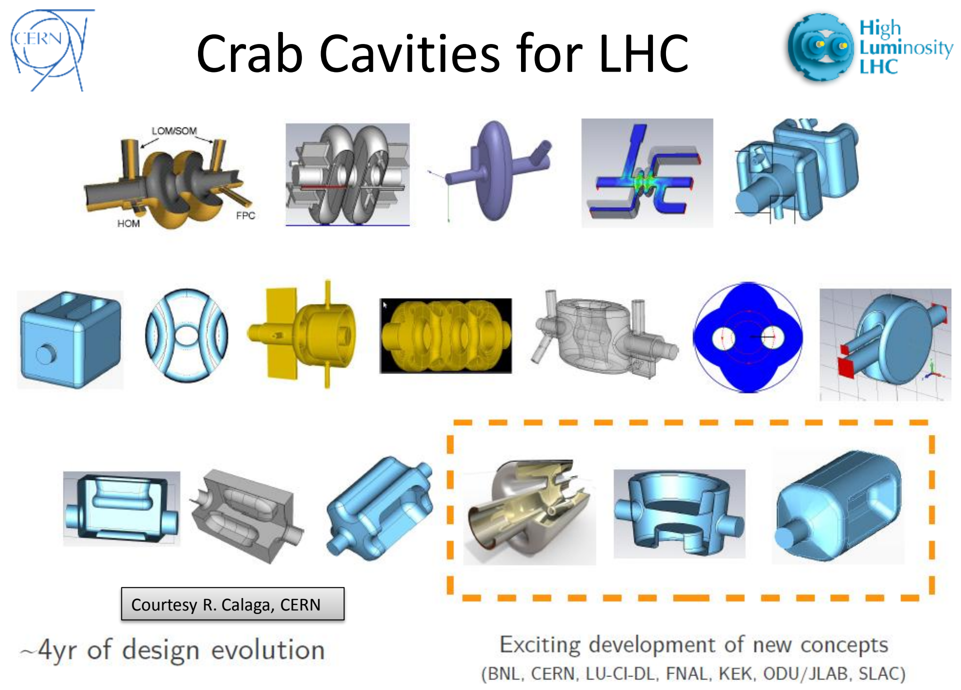
- **RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" and then luminosity is maximized**
- ***Crab cavity maximzes the lumi and can be used also for lumimosity levelling: if the lumi is too high, initially you don't use it, so lumi is reduced by the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

Portland, 9 October 2012 L.Rossi@ASC'12 29

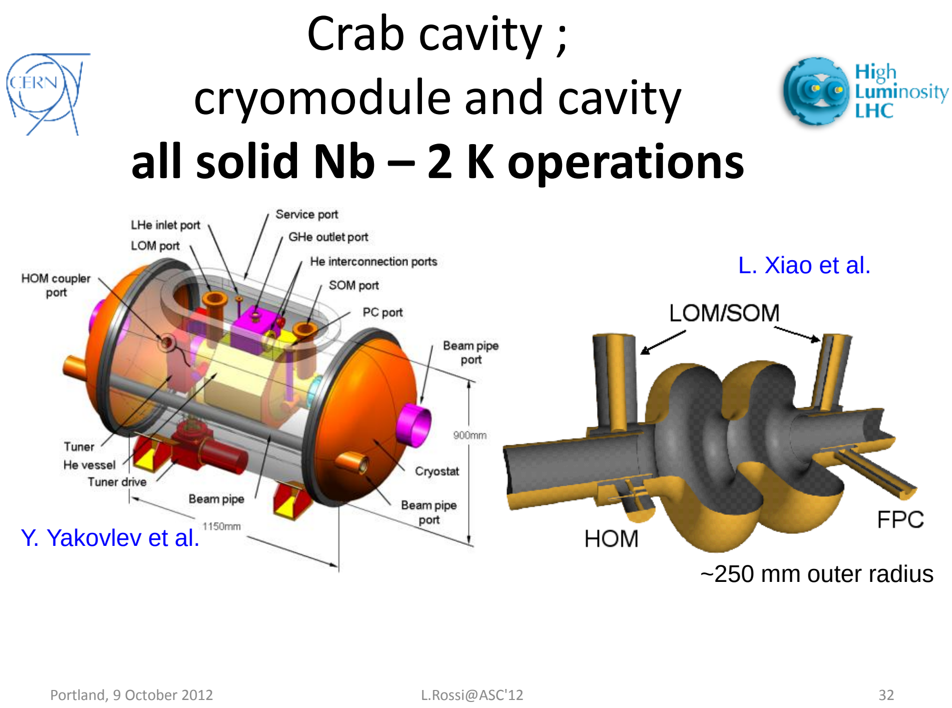
Effect of crab cavity: elimination of the Reduction factor (see slide n.10) by local rotation of the beam before collision point and then, compensates by a counter-rotation after collision to re-establish natural beam position.

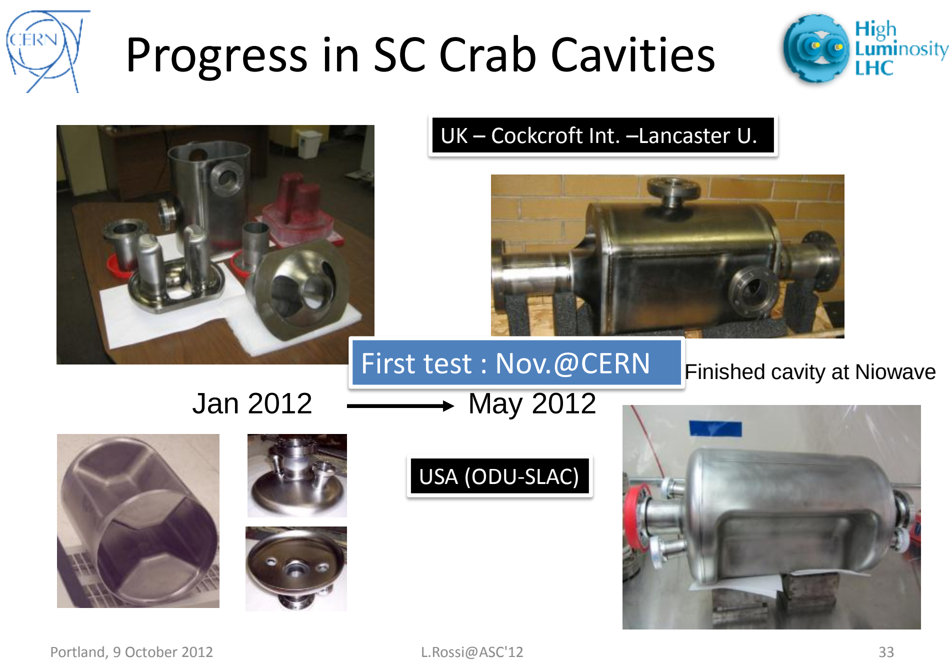


Field line in a crab cavity. The graphs shown the transverse size (radius in mm) of compact crab cavity at 400 MHz vs. size of "standard" elliptical cavity (named Point 4 in the graph, where size vs. frequency is plotted). A classical elliptical cavity is shown in the picture at top right.

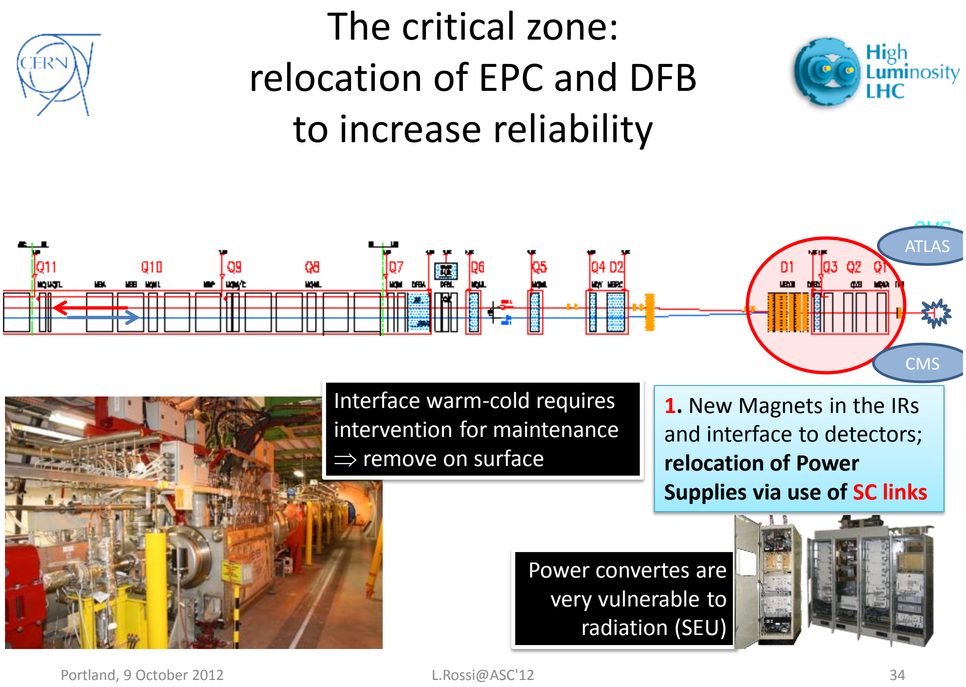


Many different design for Compact Crab Cavity have been examined: now, after down selection process, only the last three lay-outs (in the dashed box) are under development.

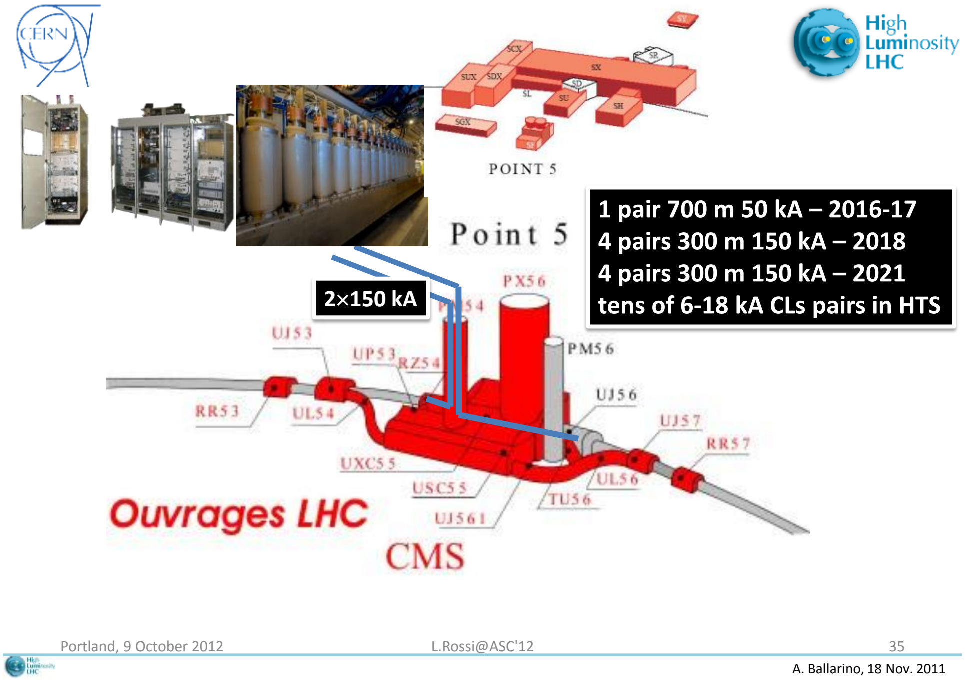




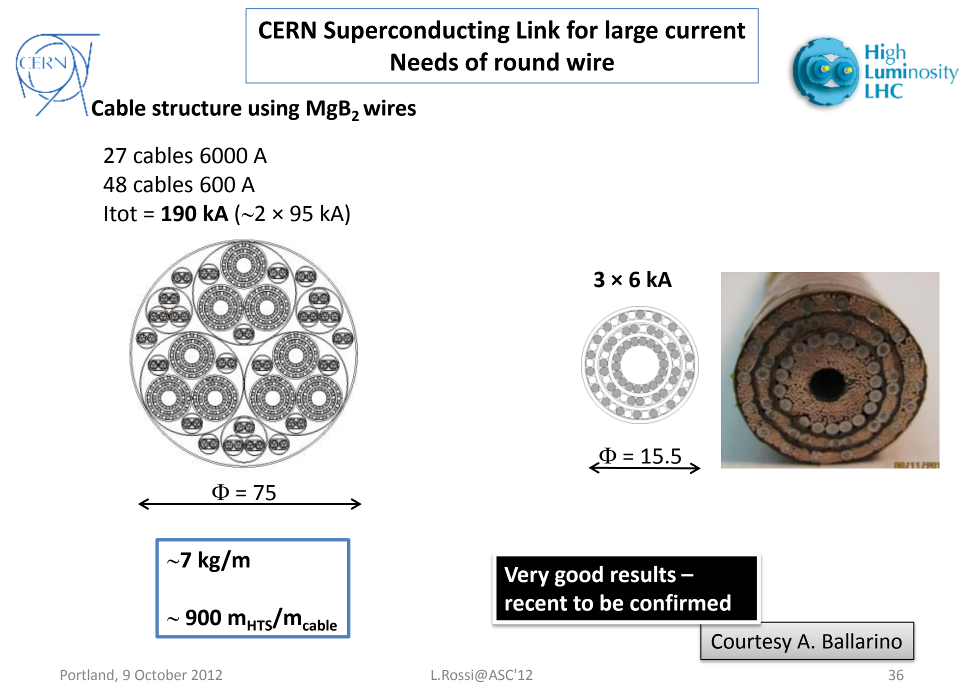
First two prototypes of Crab Cavity after construction (bare cavity, without cryostat).



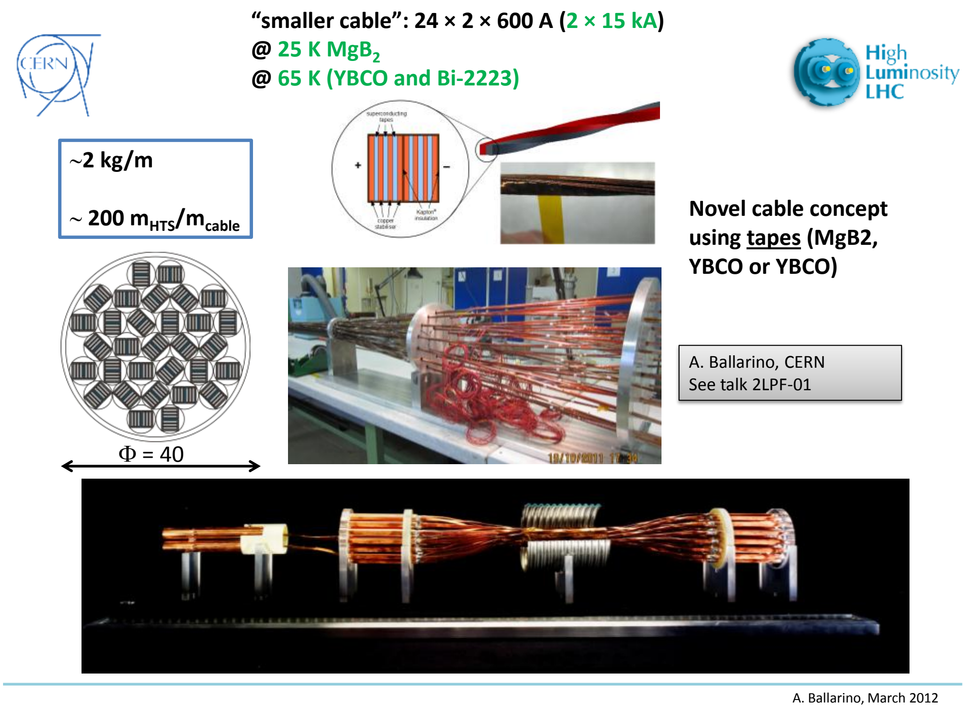
Because of the increase in radiation level (due to the higher luminosity) we need to relocate the magnet power supplies and the CFBs, the Cryogenic Feed Boxes containing the HTS current leads feeding the SC magnets) from the critical region in the tunnel up to surface, at ground level.



View of the tunnel were 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).



Schematic and first prototype of the MgB_2 round cable for SC links at CERN



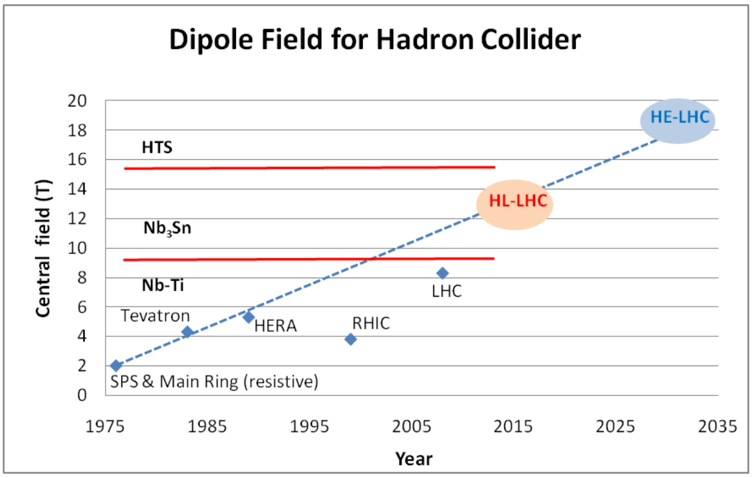
Low amperage SC link cable can be manufactured also by means of tapes (HTS or MgB_2) as demonstrated at CERN on short lengths

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

Portland, 9 October 2012 L.Rossi@ASC'12 38

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



Portland, 9 October 2012 L.Rossi@ASC'12 39

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.

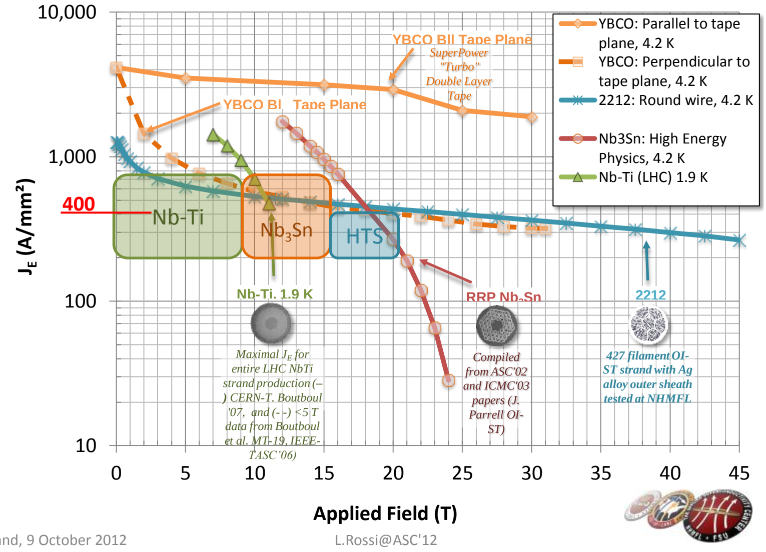
Magnets: the shopping list

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 (2×5.5)	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

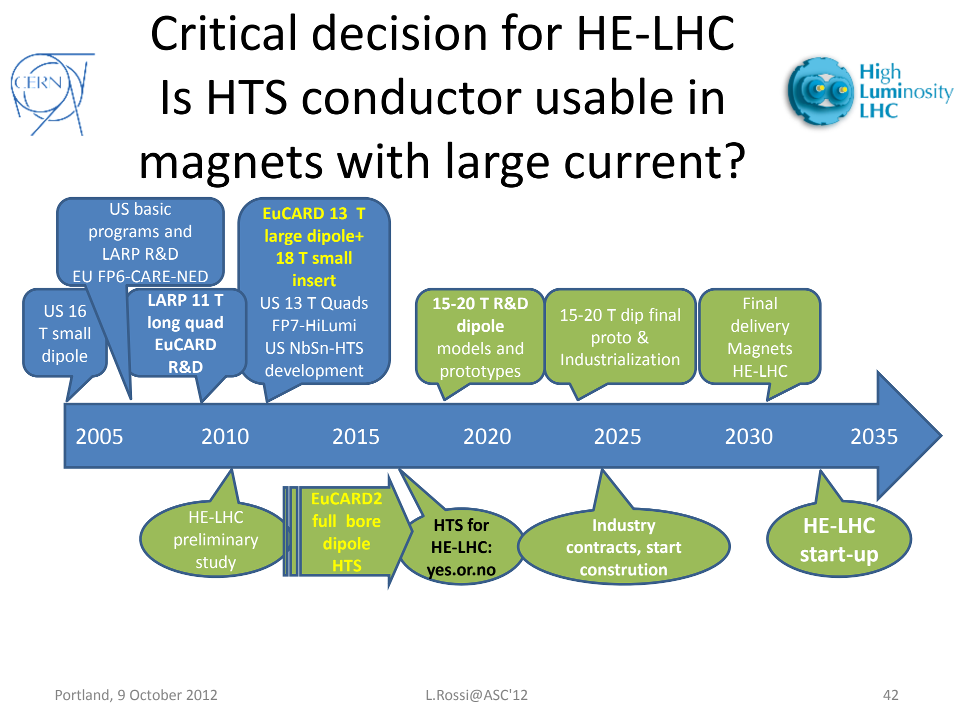
Portland, 9 October 2012 L.Rossi@ASC'12 40

The Superconductor « space » Minimise use of HTS

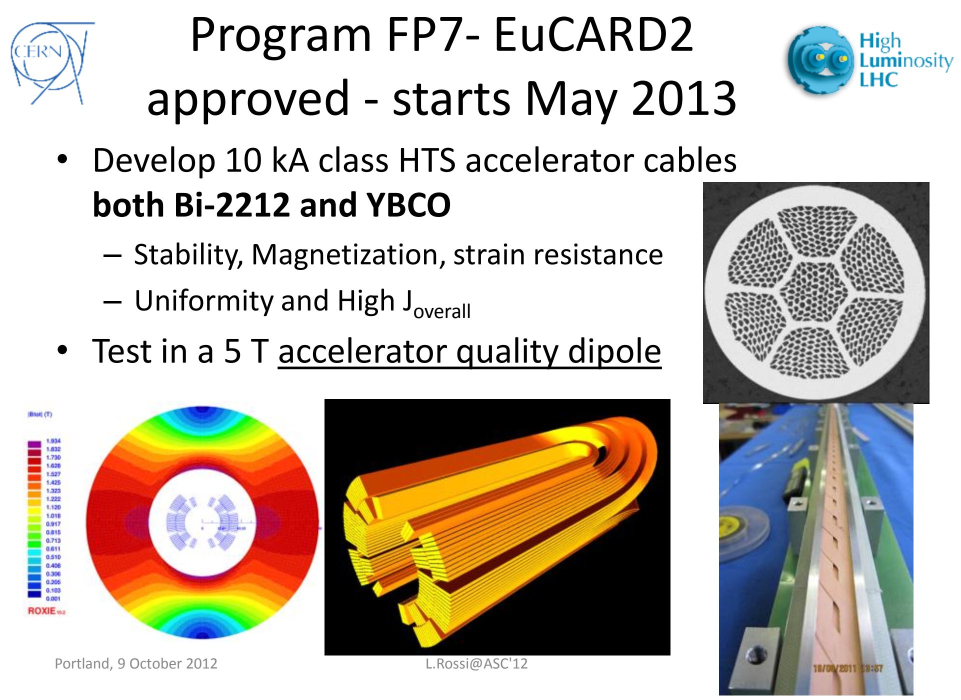


Portland, 9 October 2012 L.Rossi@ASC'12 41

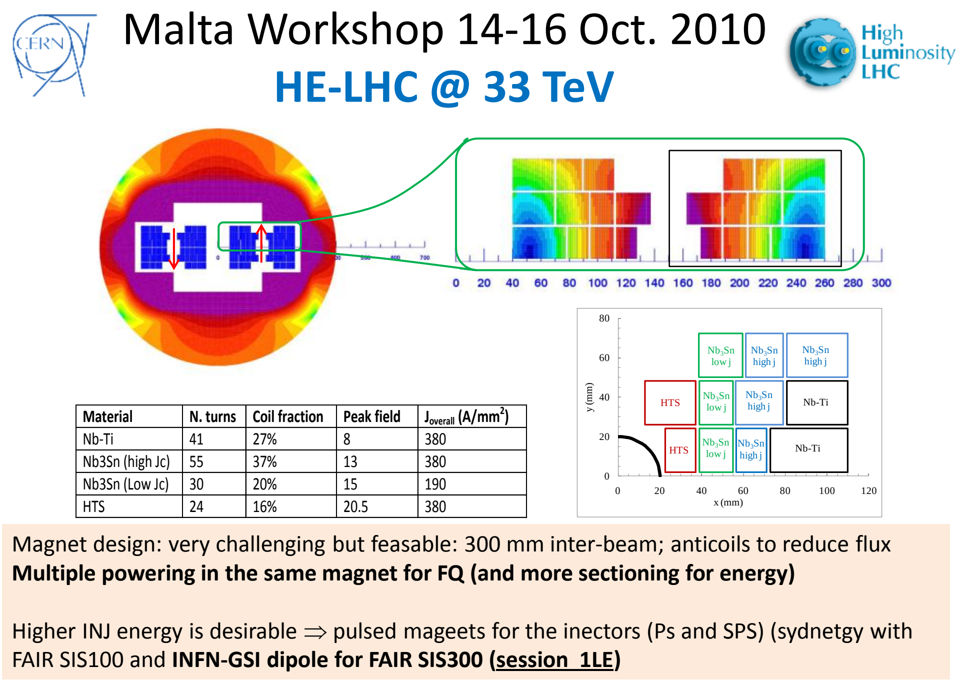
Because for technical difficulty and especially because of their high cost, the use of HTS for high field magnet must be minimized. However it is clear that for accelerator magnets to go beyond 15-16 T one needs HTS. The graphs show $J_{engineering}$ rather than J_c.



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.

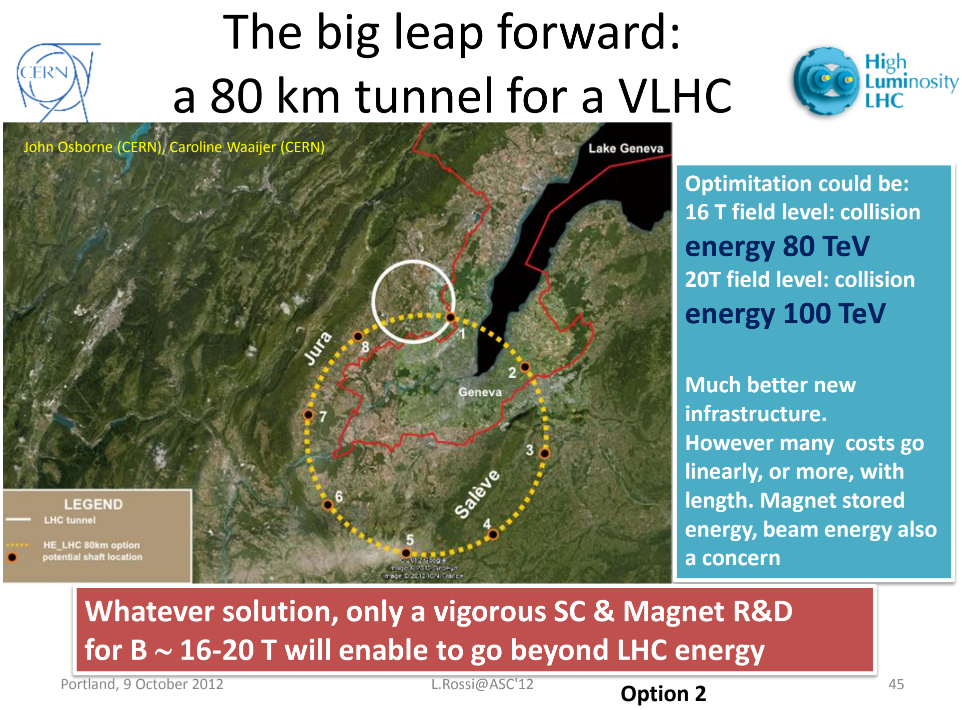


A few highlights on the recently approved program called Eucard2-Future Magnets , with R&D on HTS magnets.



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).



Option 2

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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  - Project cost: about 850 MCHF (400 in SC…)
  - HFM for 11-12 T operative fields … current SC links
- HL-LHC calls for hard… …as such, **it open a new t… …ward a high energy LHC…**
- HE-L… …: **26-33 TeV c.o.m.** **…eV are taking ground…)**
  - …Field Magnet Development: **16-20 tesla. …at we need to explore…**
  - **…t 3000 tons of SC: 1000 NbTi, 1500 NbSn, 500 HTS**
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Collaboration is welcome!
(Labs & Industry)

Portland, 9 October 2012 L.Rossi@ASC'12 47