www.cern.ch

LHC and HL-LHC
How do we reach the requirements?

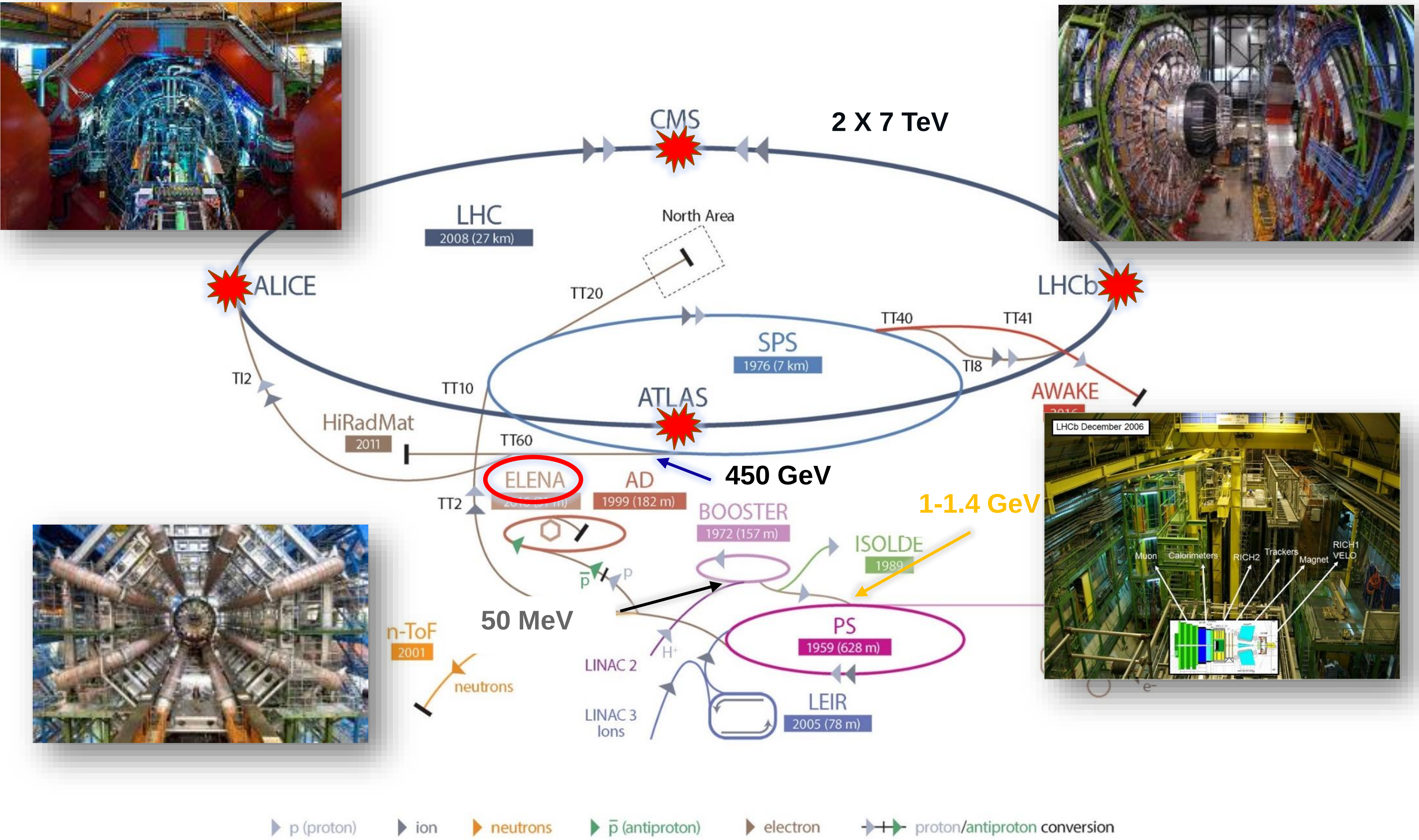
Giuseppe Bregliozzi
TE-VSC-BVO

Slides contribution from many VSC colleagues

Outline

- The vacuum system of the LHC
  - LHC Cryogenic beam vacuum.
  - LHC Room temperature beam vacuum.
  - Acceptance criteria.
  - Beam induced heating: Some examples.
- High Luminosity Upgrade (HL-LHC)

Introduction: CERN accelerators chain



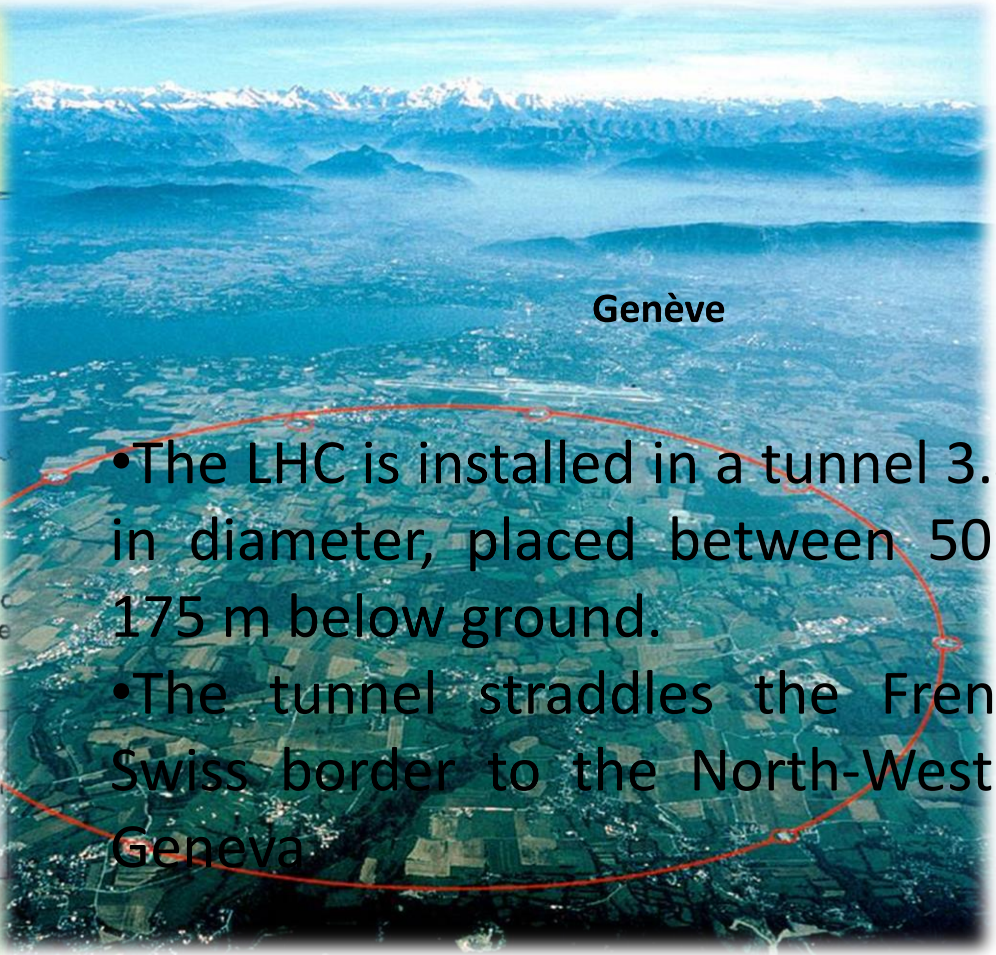
2 X 7 TeV

450 GeV

1-1.4 GeV

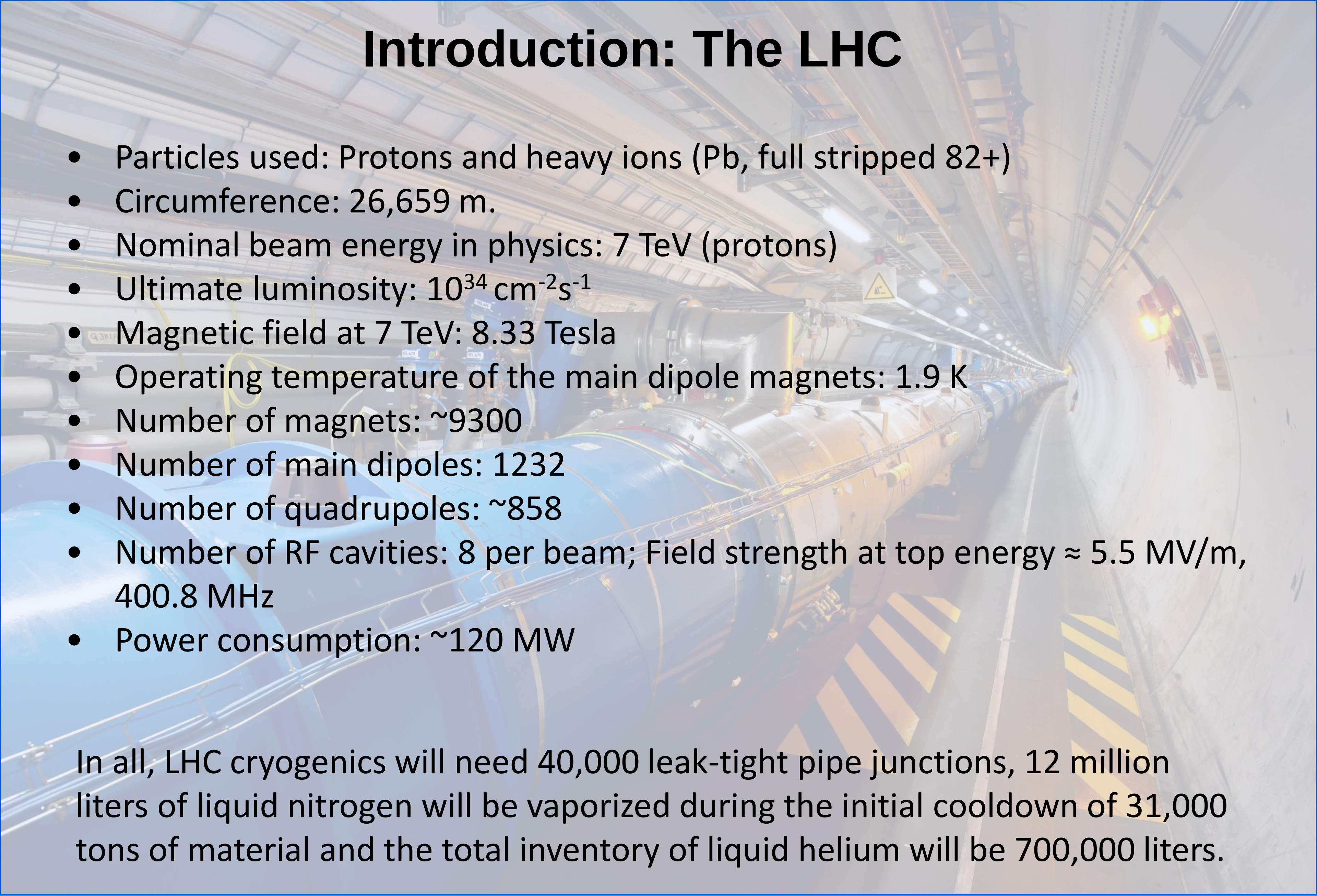
50 MeV

Introduction: The LHC



- The LHC is installed in a tunnel 3.8m in diameter, placed between 50 to 175 m below ground.
- The tunnel straddles the French-Swiss border to the North-West of Geneva

Introduction: The LHC



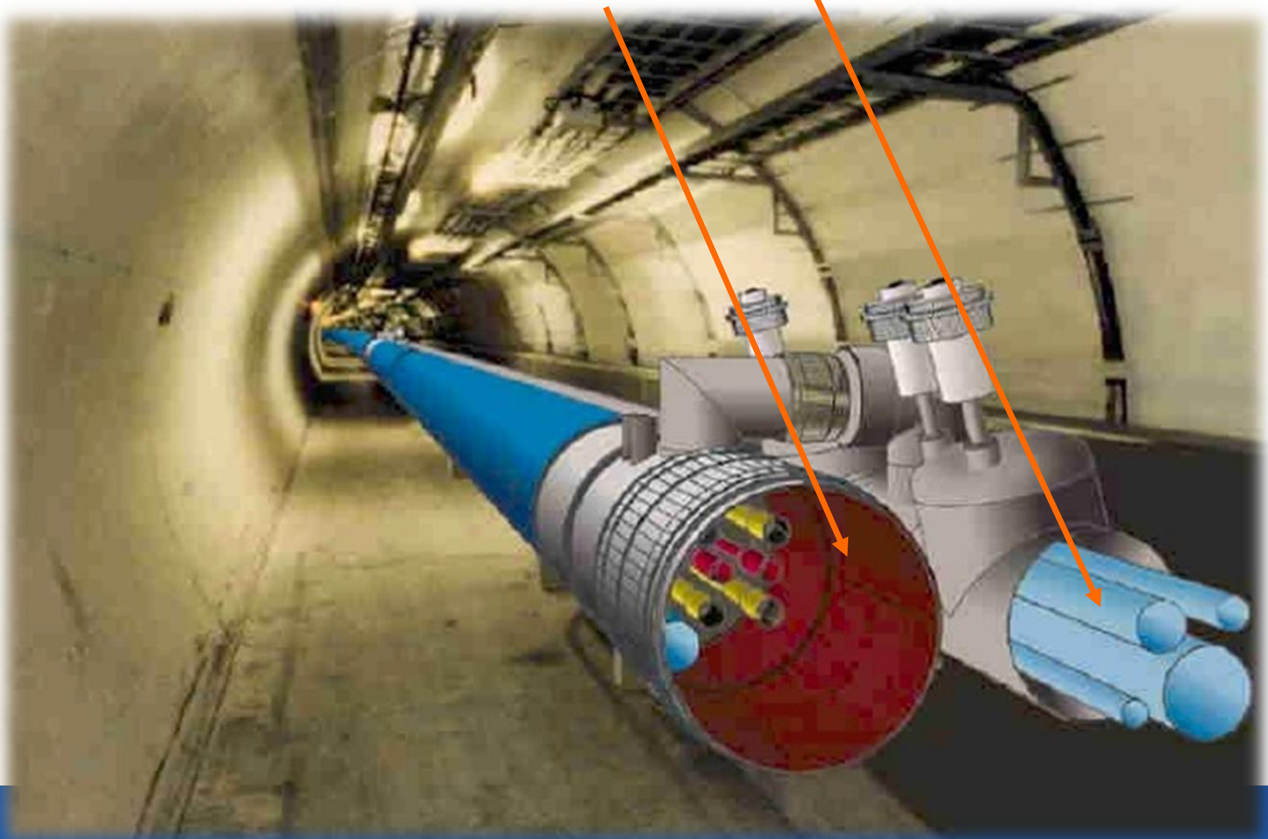
- Particles used: Protons and heavy ions (Pb, full stripped 82+)
- Circumference: 26,659 m.
- Nominal beam energy in physics: 7 TeV (protons)
- Ultimate luminosity: 10^{34} $cm^{-2}s^{-1}$
- Magnetic field at 7 TeV: 8.33 Tesla
- Operating temperature of the main dipole magnets: 1.9 K
- Number of magnets: ~9300
- Number of main dipoles: 1232
- Number of quadrupoles: ~858
- Number of RF cavities: 8 per beam; Field strength at top energy ≈ 5.5 MV/m, 400.8 MHz
- Power consumption: ~120 MW

In all, LHC cryogenics will need 40,000 leak-tight pipe junctions, 12 million liters of liquid nitrogen will be vaporized during the initial cooldown of 31,000 tons of material and the total inventory of liquid helium will be 700,000 liters.

Vacuum system of the LHC

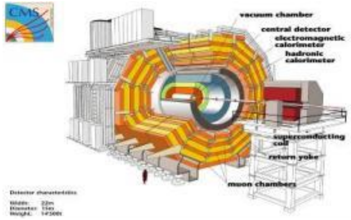
The LHC has three vacuum systems:

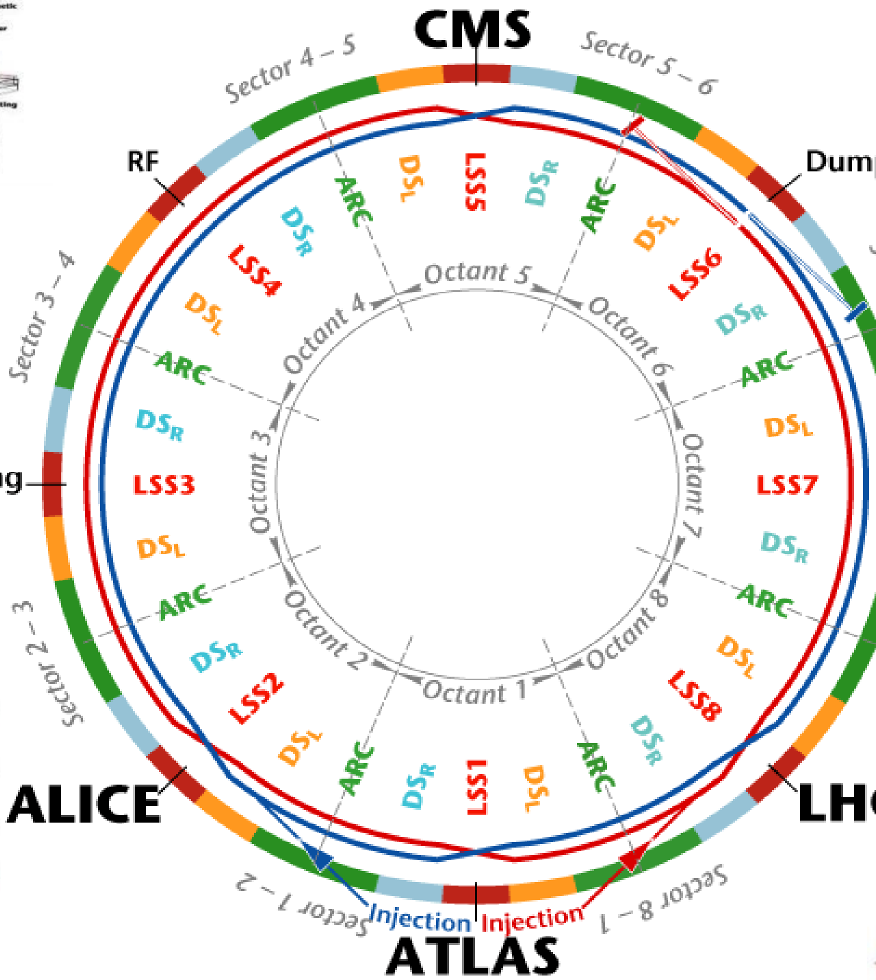
- ✓ insulation vacuum for helium distribution line
- ✓ insulation vacuum for the cryomagnets
- ✓ beam vacuum (requirement ≈ 10^7 molecules cm^{-3}).



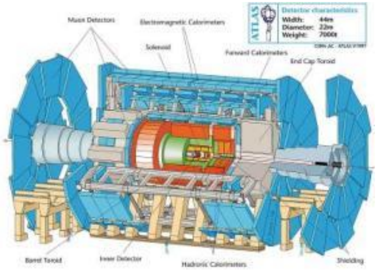
The LHC Vacuum System

The LHC Layout



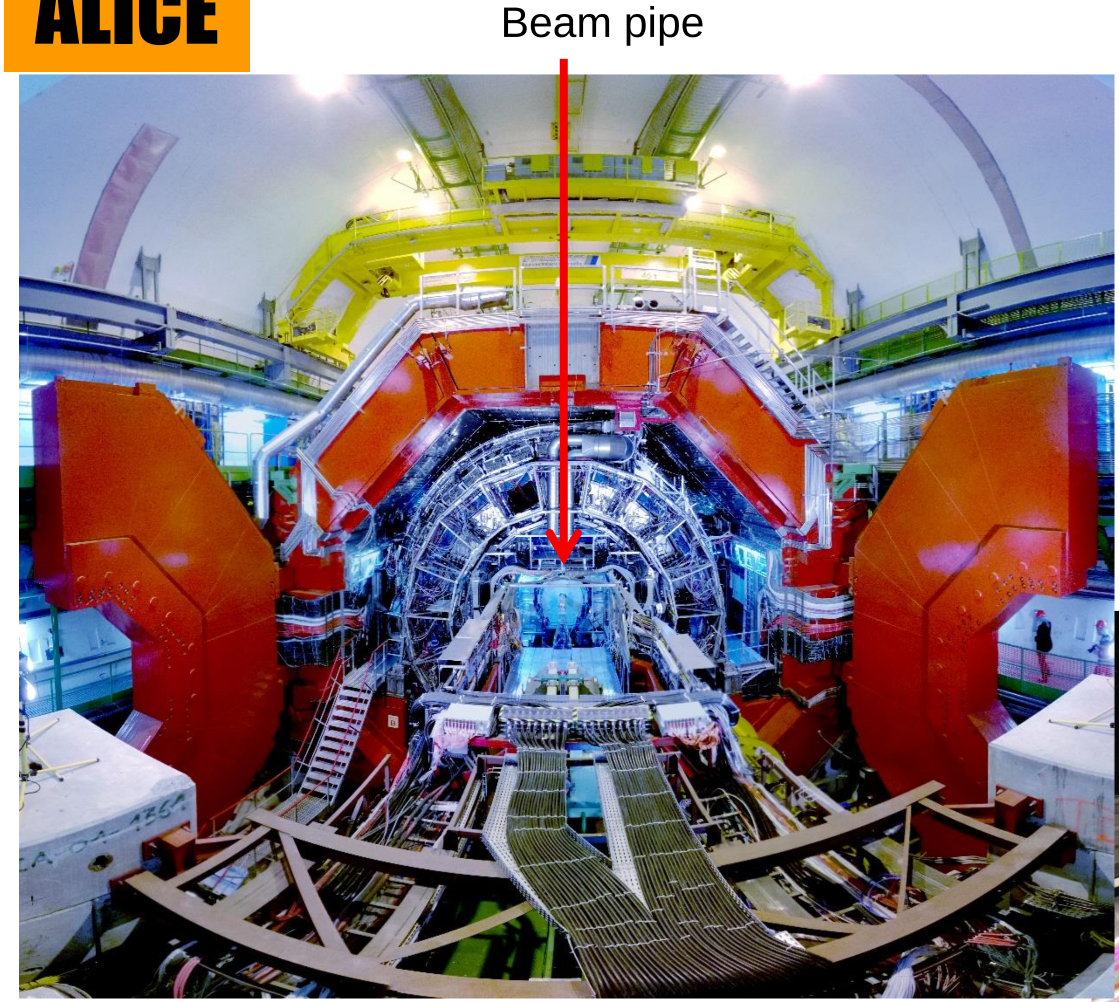


	IR MAIN FUNCTIONS
IR1	ATLAS EXPT
IR2	ALICE EXPT, INJECTION
IR3	CLEANING
IR4	RF
IR5	CMS EXPT
IR6	DUMP
IR7	CLEANING
IR8	LHC B EXPT, INJECTION

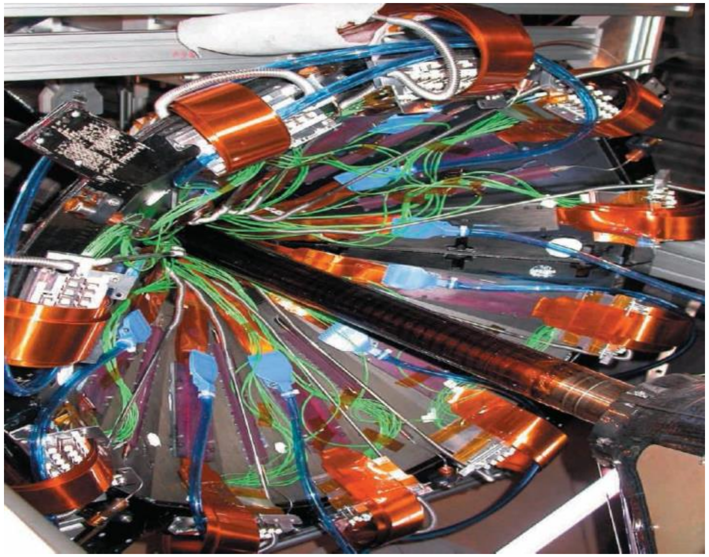


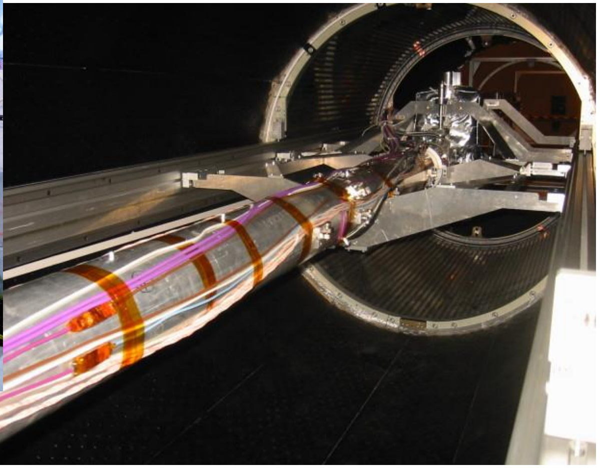
LHC Experiments

ALICE



(Josef Sestak's contribution)

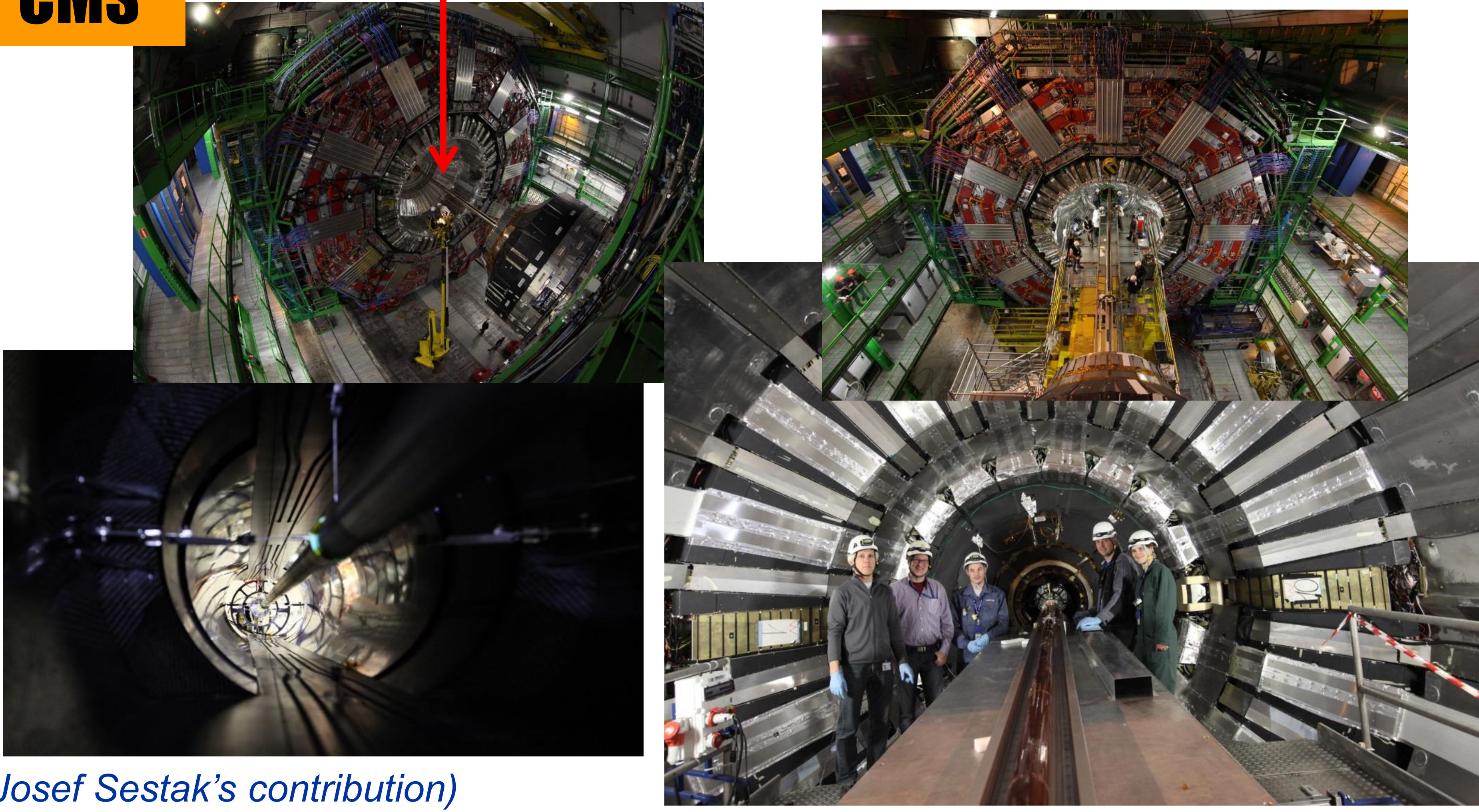




LHC Experiments

CMS

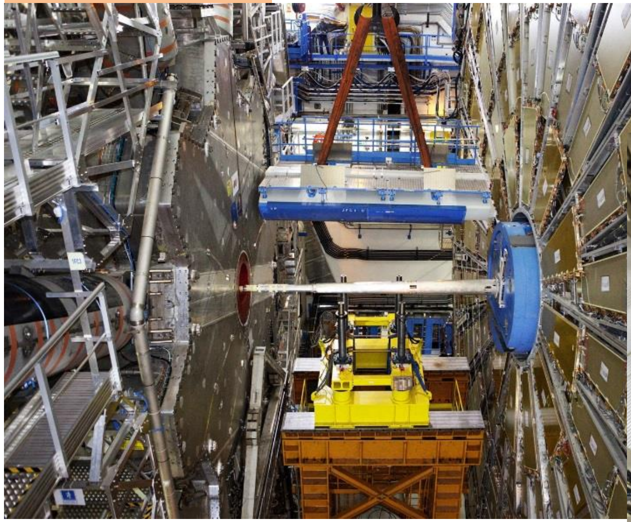
Beam pipe



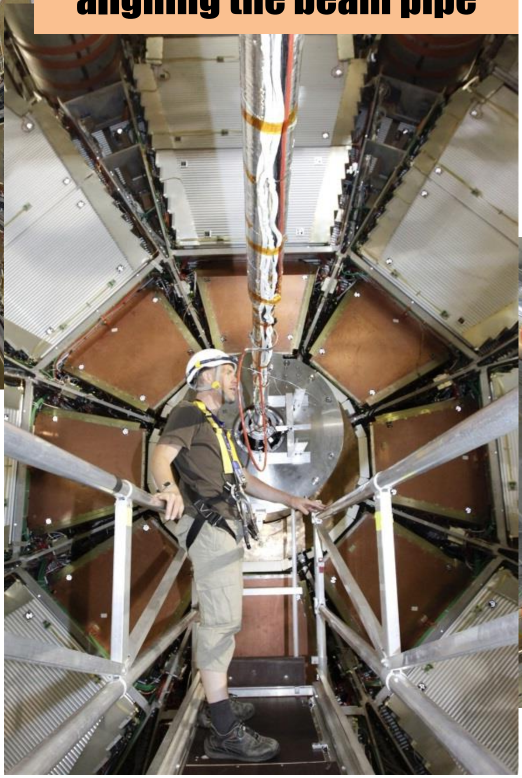
(Josef Sestak’s contribution)

LHC Experiments

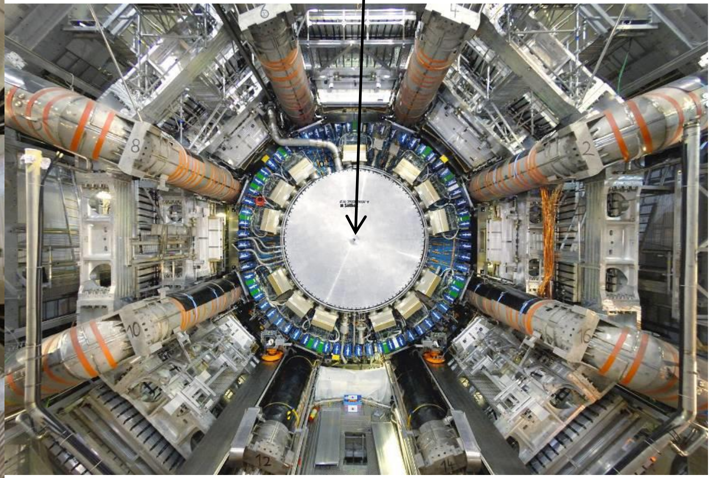
ATLAS



Vacuum technician aligning the beam pipe



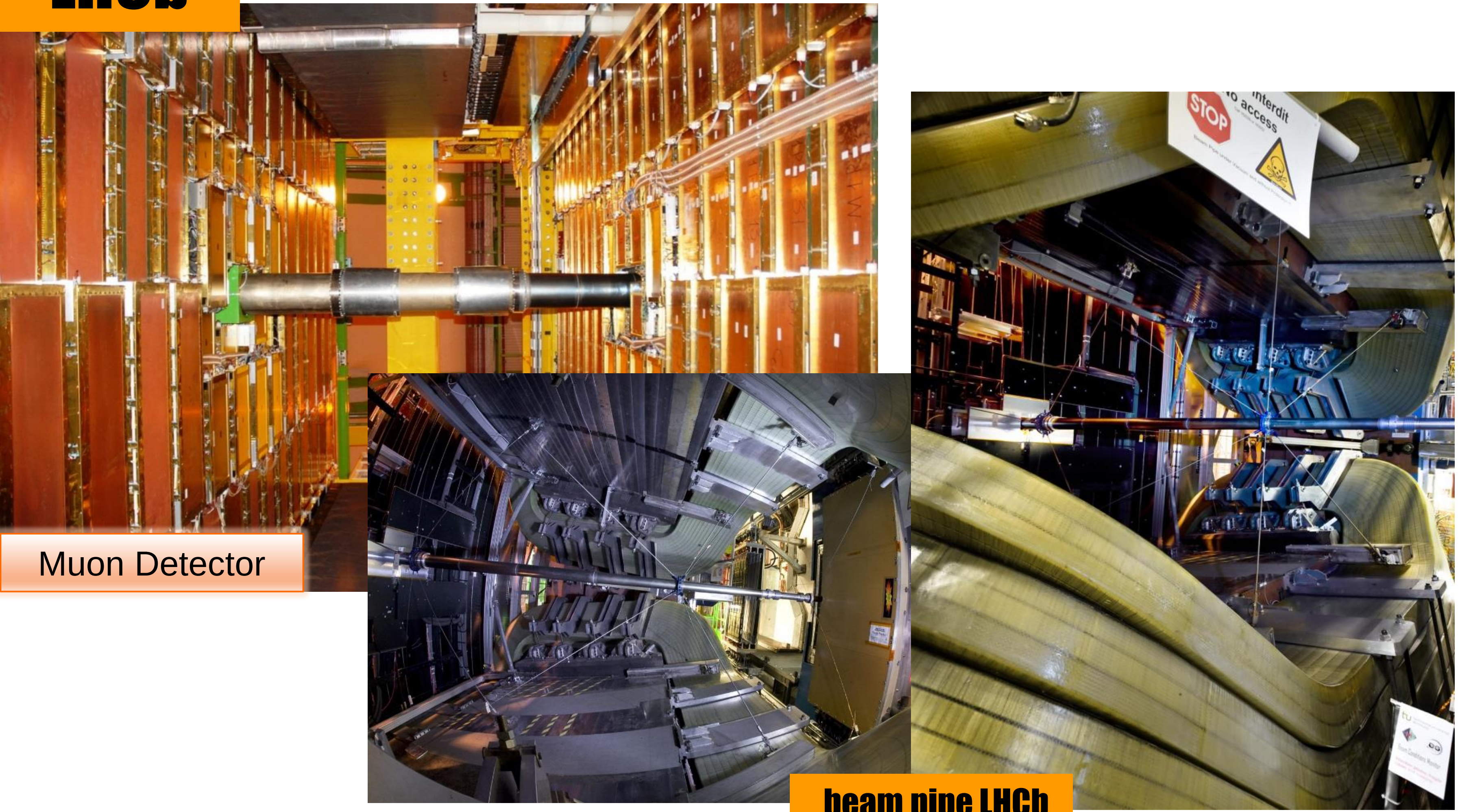
Beam pipe



(Josef Sestak’s contribution)

LHC Experiments

LHCb

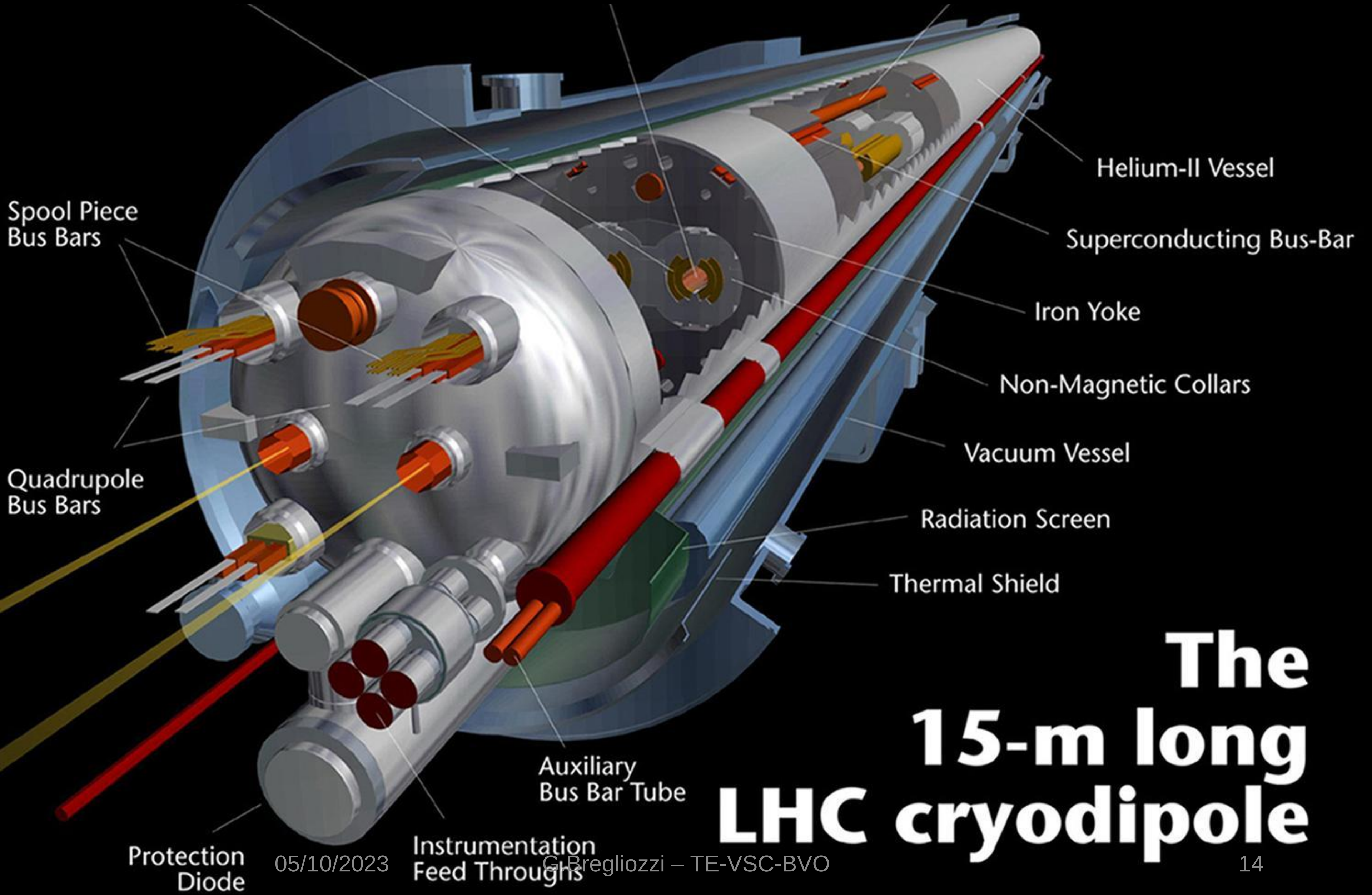


Muon Detector

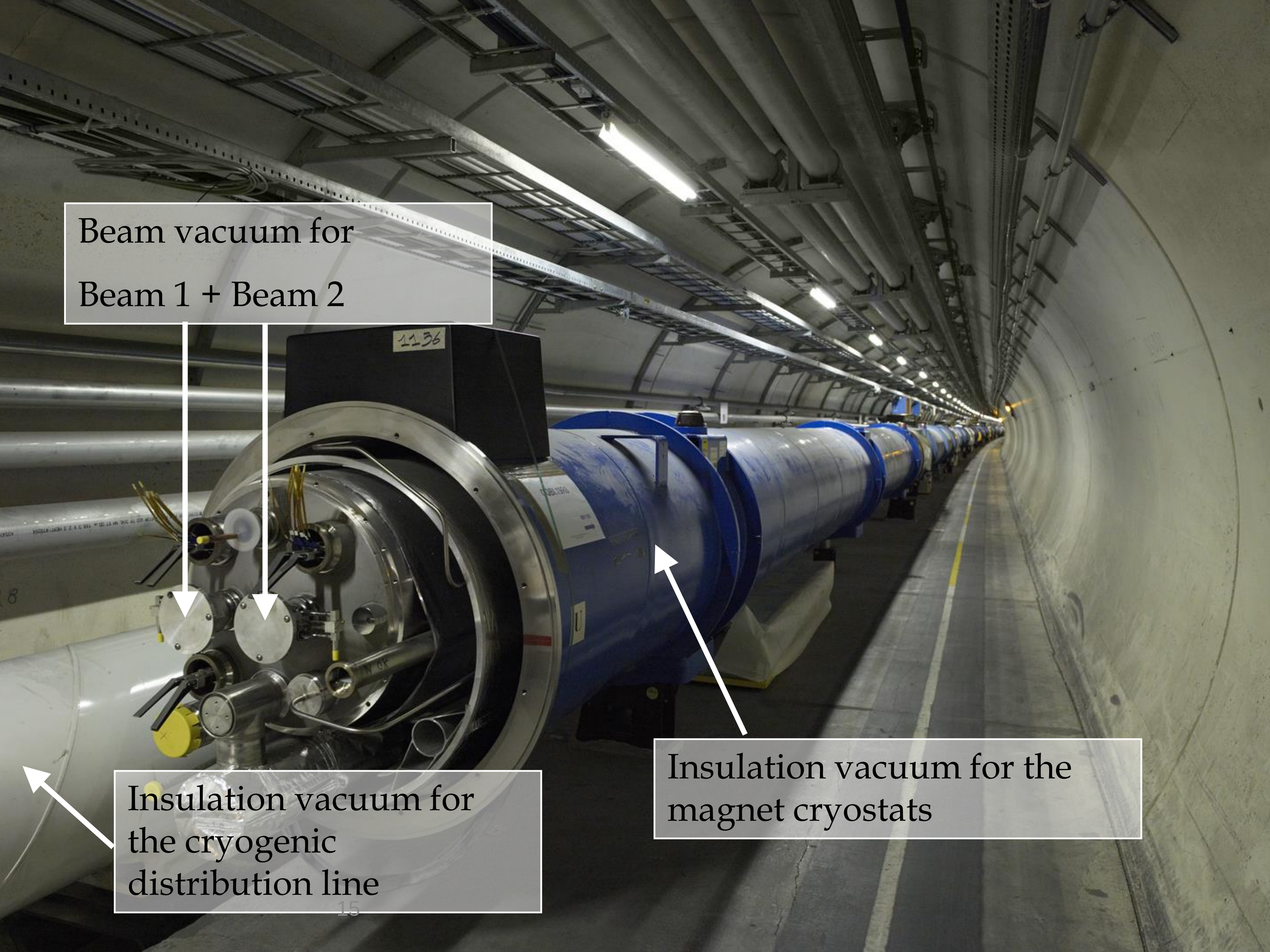
beam pipe LHCb

(Josef Sestak's contribution)

The LHC: Cold Beam Vacuum



The 15-m long LHC cryodipole



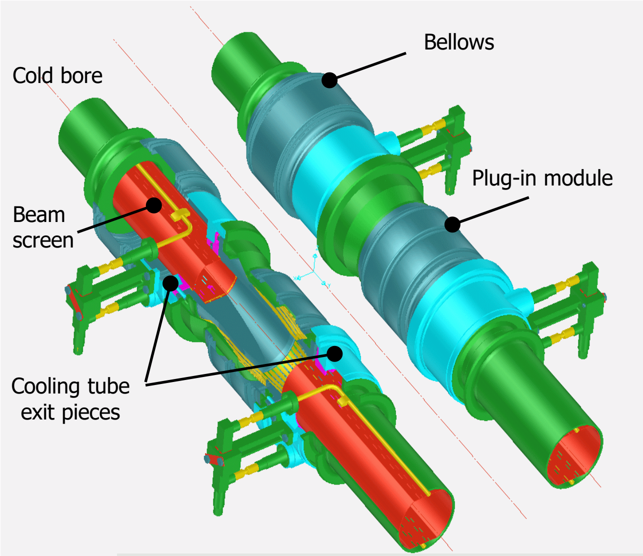
Beam vacuum for

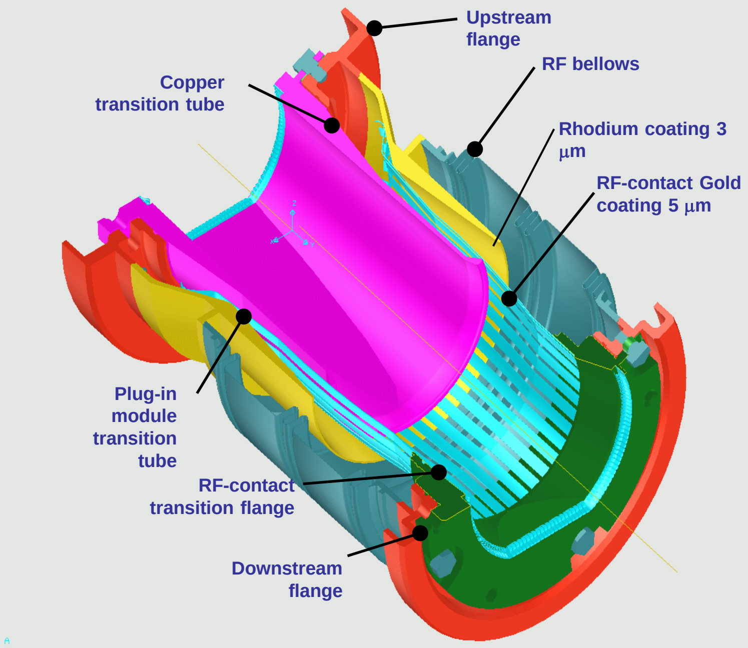
Beam 1 + Beam 2

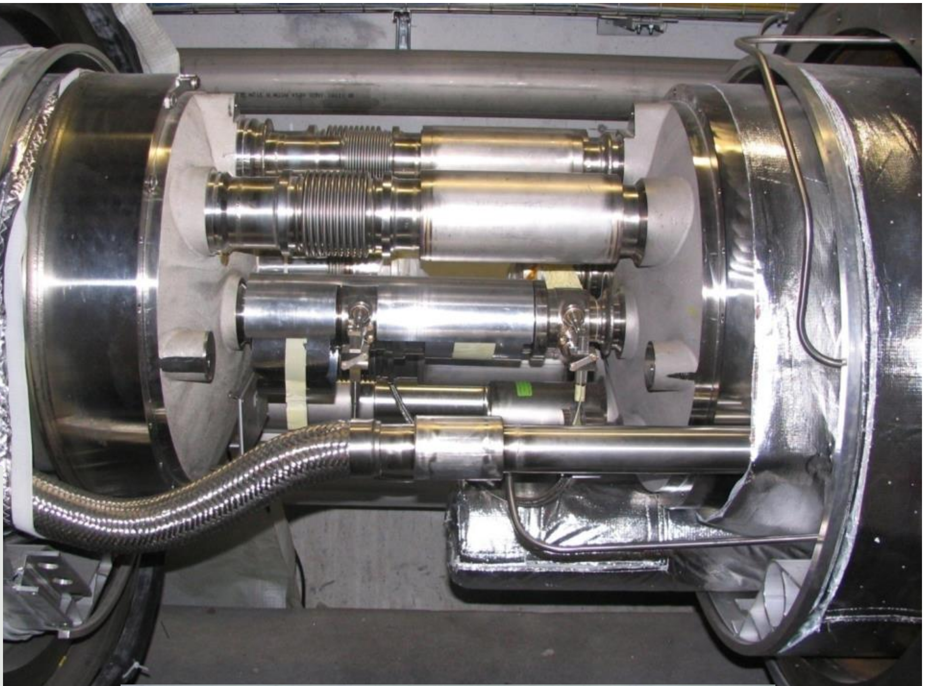
Insulation vacuum for the cryogenic distribution line

Insulation vacuum for the magnet cryostats

Dipole-Dipole Interconnection

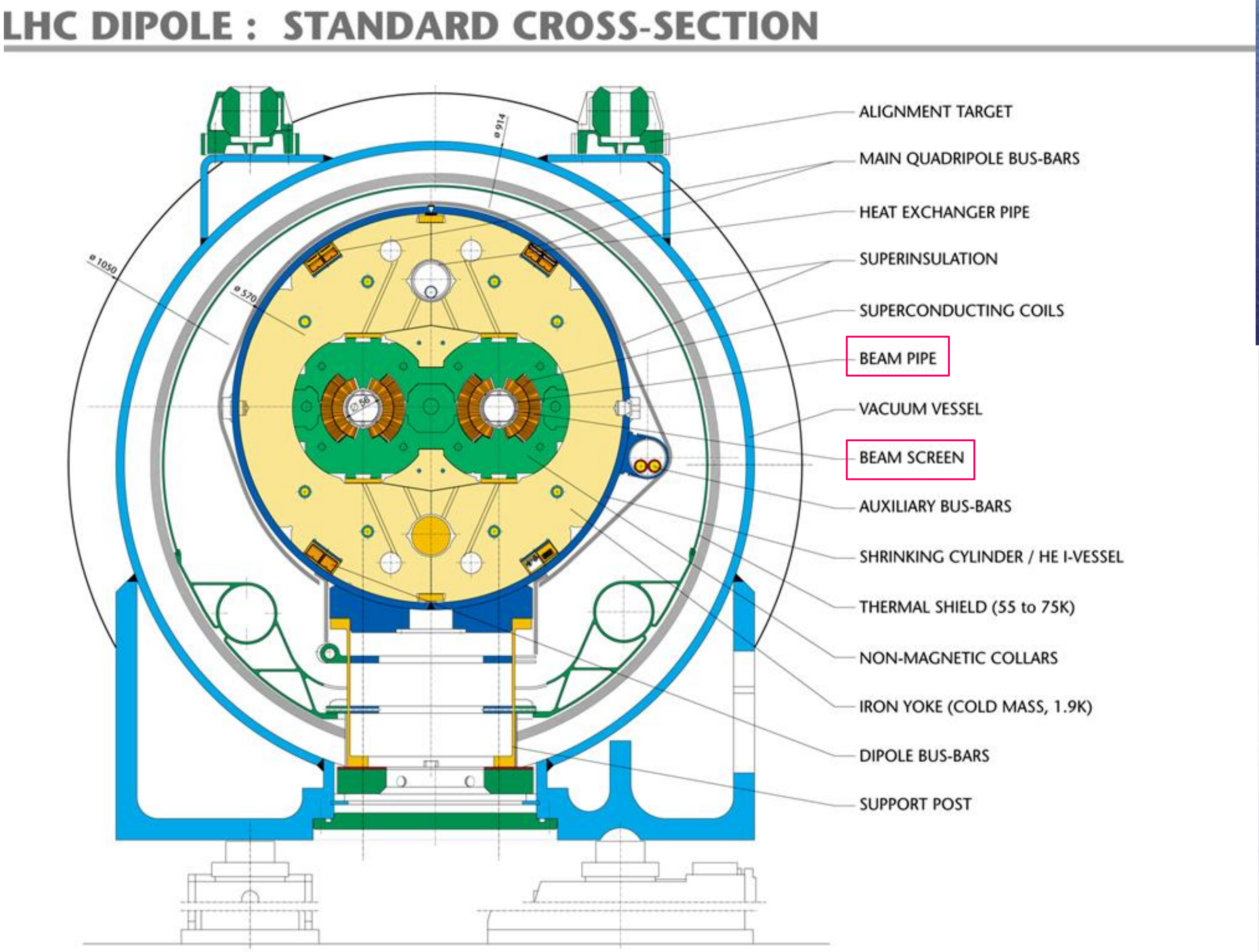




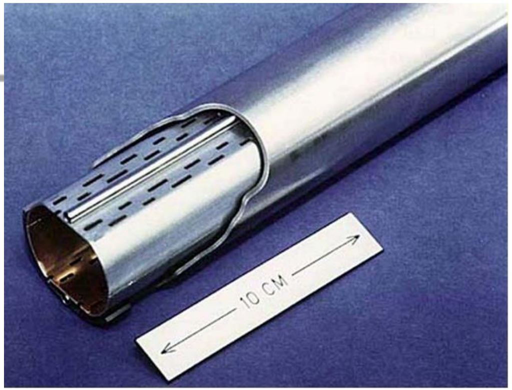


LHC Dipole Vacuum System

- Cold bore (CB) at 1.9 K which ensures leak tightness
- Beam screen (BS) at 5-20 K which intercepts thermal loads and acts as a screen



CERN AC/DI/MM - HE107 - 30 04 1999

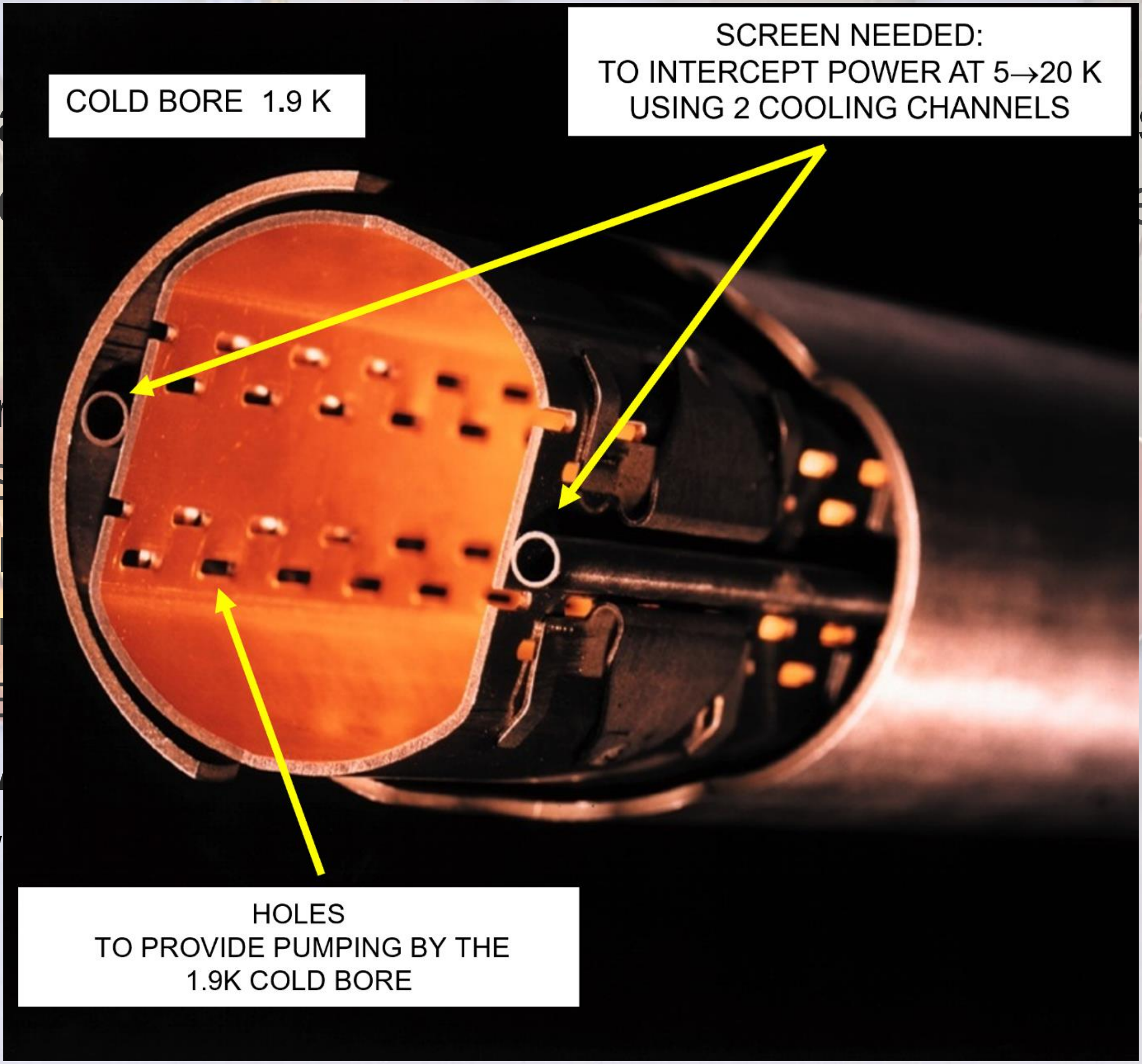


Beam Screen

Innova screen”

B et cold

- **Inter**
  - S
  - I
  - I
  - E
- **Prov**
- **Low**
- **Opti**



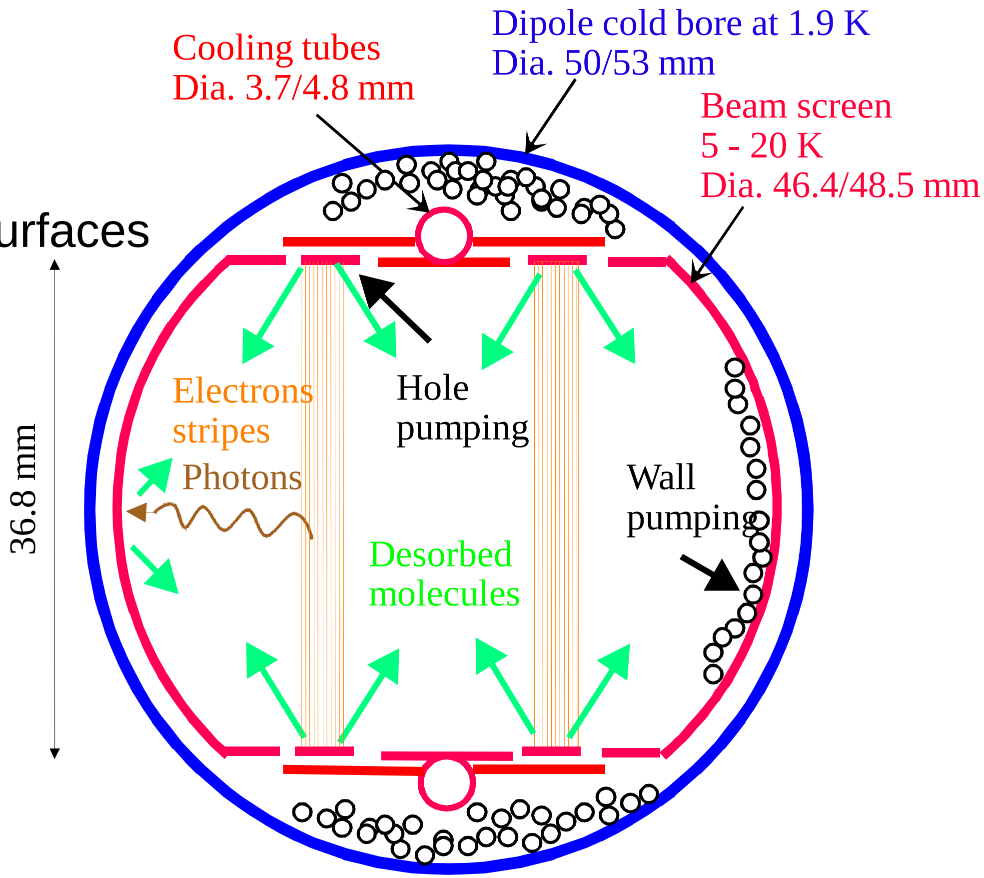
COLD BORE 1.9 K

SCREEN NEEDED:
TO INTERCEPT POWER AT 5→20 K
USING 2 COOLING CHANNELS

HOLES
TO PROVIDE PUMPING BY THE
1.9K COLD BORE

Vacuum Principle

- Molecular desorption stimulated by photon, electron and ion bombardment
- Desorbed molecules are pumped on the beam vacuum chamber
- 100 h beam life time (nuclear scattering) eq. to ~ 10^{15} H_2/m^3 (10^{-8} Torr H_2 at 300 K)



In cryogenic elements

- Molecular physisorption onto cryogenic surfaces (weak binding energy)

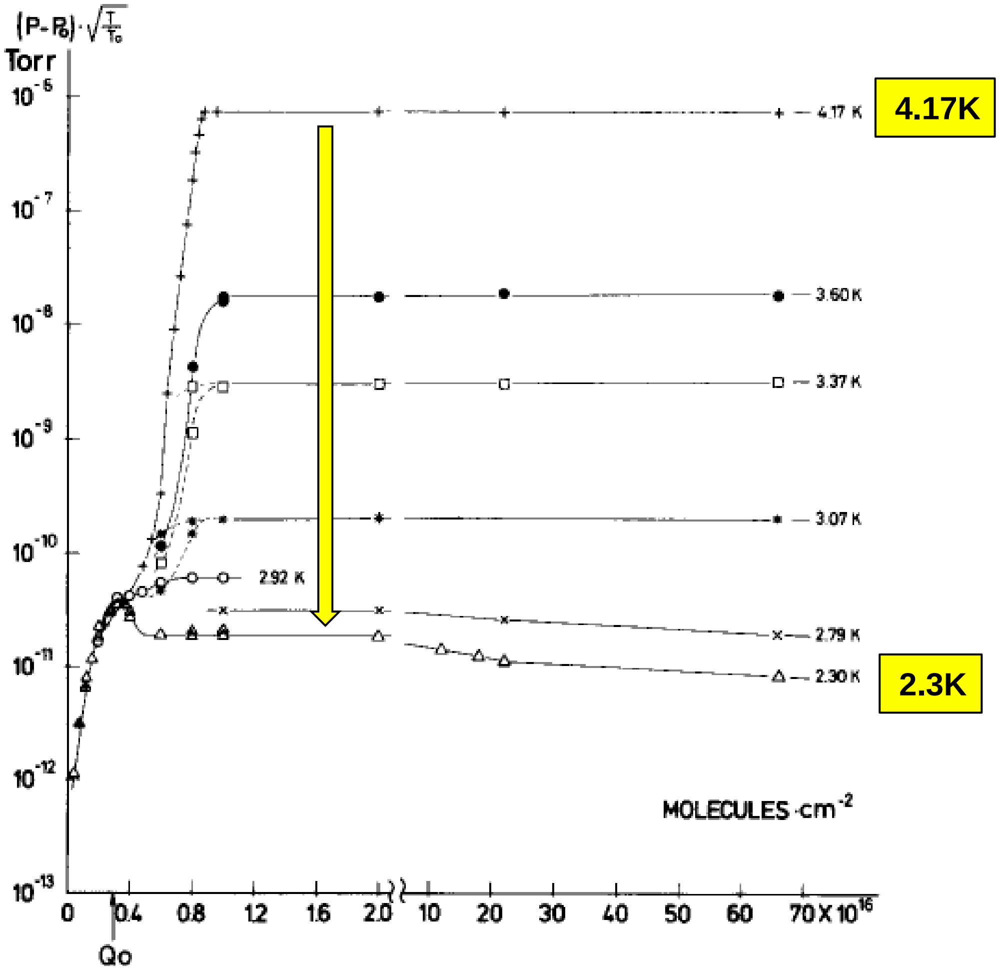
- Molecules with a low recycling yield are first physisorbed onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore

- H_2 is physisorbed onto the cold bore

Cold Beam Vacuum at Cryogenic Temperature

H_2 adsorption isotherms on stainless steel

Equilibrium pressure decreases by 5 orders of magnitude from ≈4.2K to ≈2.3 K

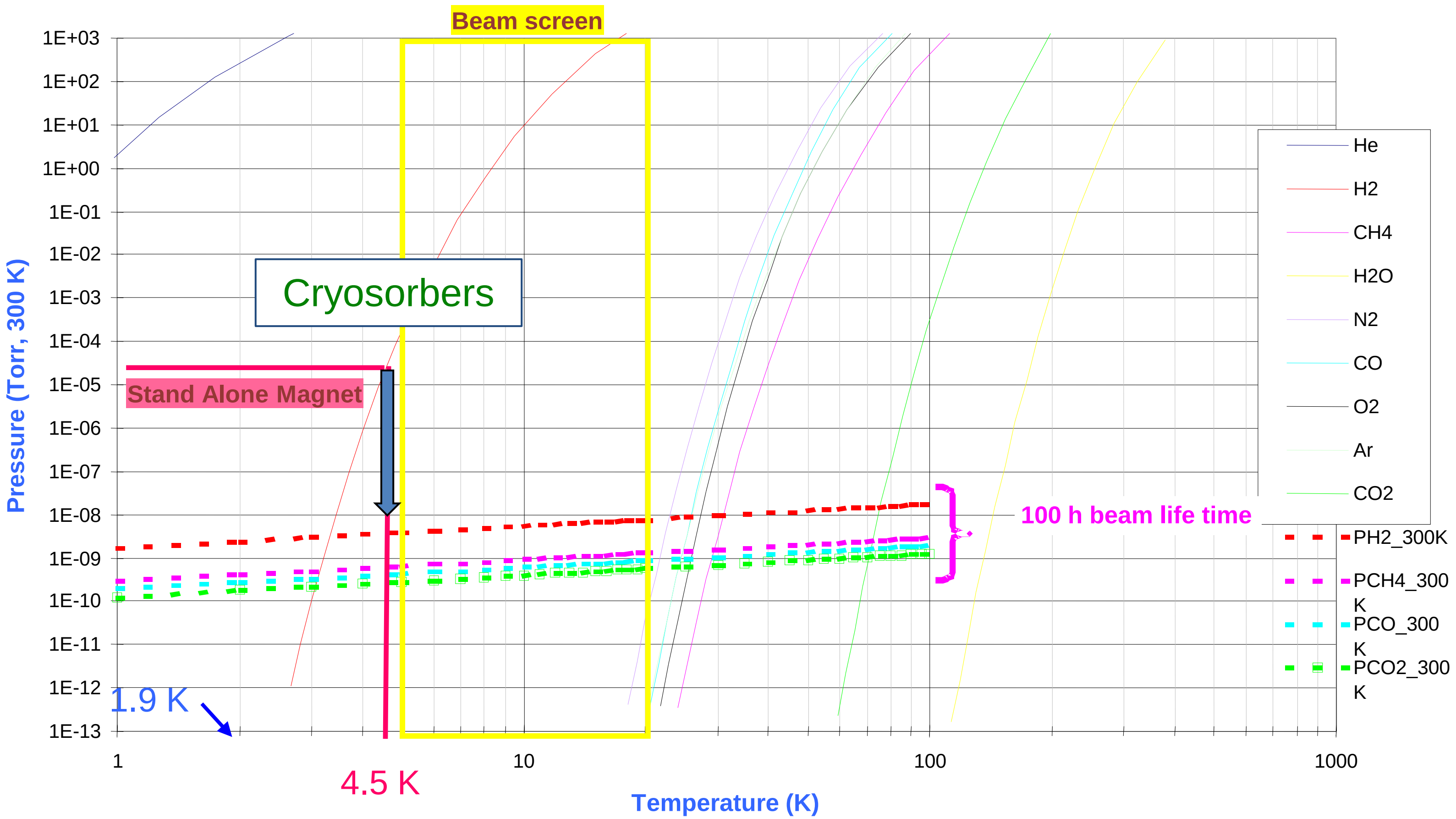


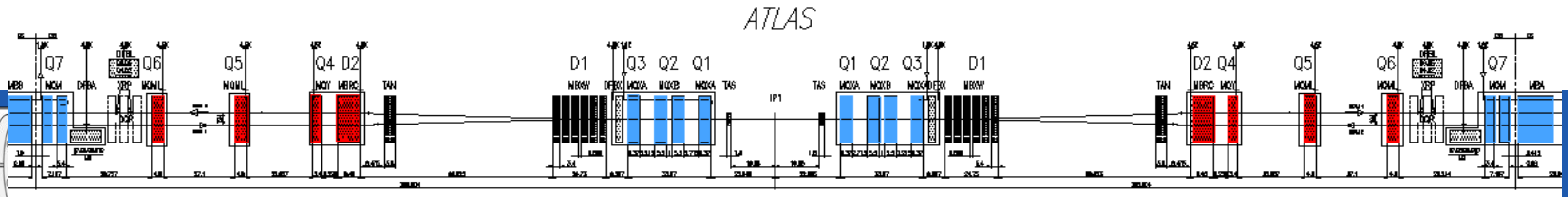
4.17K

2.3K

C. Benvenuti, R. S. Calder, and G. Passardi, J. Vacuum Science and Technology

Cold Beam Vacuum

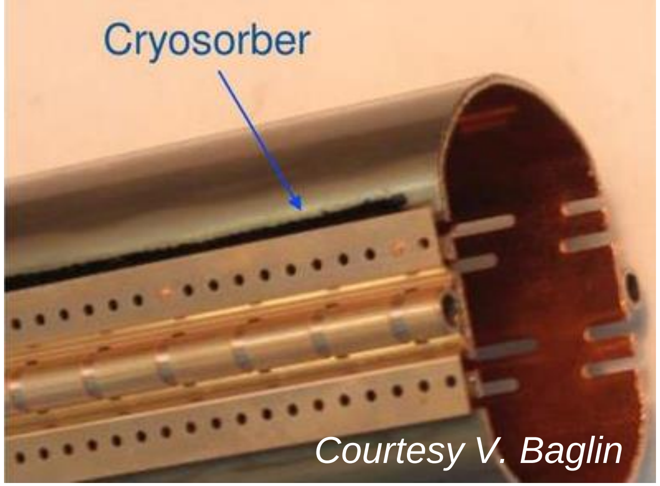

Saturated vapour pressure from Honig and Hook (1960)



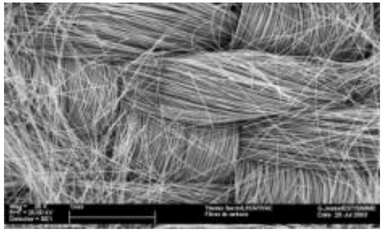
H_2 Pumping on Stand Alone Magnet

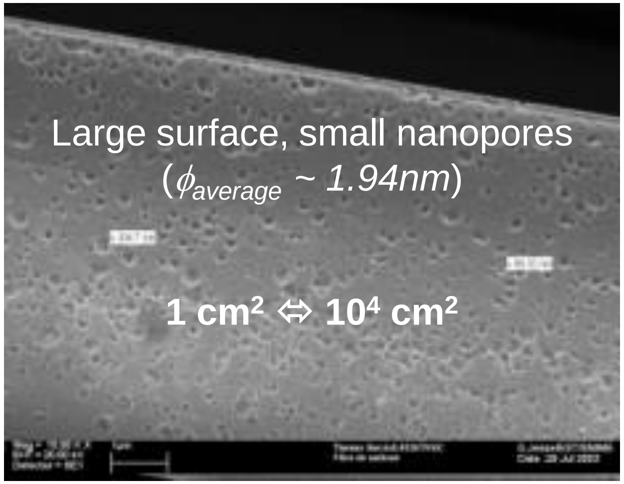
Stand alone magnets are equipped with cryosorbers

Woven carbon fibre material with high adsorption capacity



Courtesy V. Baglin





Large surface, small nanopores ($\phi_{average}$ ~ *1.94nm*)

1 cm^2 ⇔ 10^4 cm^2

V. Baglin, H. Dupont, T. Garcin, CERN, Geneva, Switzerland
Proceedings of EPAC 2004, Lucerne, Switzerland

The LHC: LSS Beam Vacuum Room Temperature

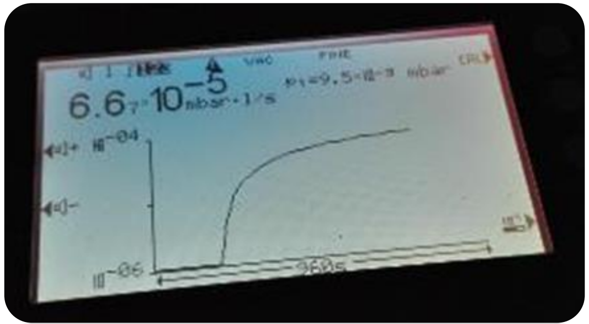
LSS Beam Vacuum

- ≈ 6 km of RT beam vacuum in the long straight sections
  - Except in standalone cryomagnets
- ≈ 303 sector valves as vacuum protection
  - Prevents saturation of the NEG coating during warming up
  - Allows interventions during shutdowns
- Extensive use of NEG coatings
  - All beam pipes are NEG coated
    - Baked-out allows the vacuum activation of NEG coatings
- ≈ 780 ion pumps to avoid vacuum instability
  - Provide pressure indications
    - Are used as sector valve interlocks
- ≈2600 Warm bellows module to easier the mechanical installation and the bakeout cycle

LSS Beam Vacuum

- Pre-testing as baseline
  - More than 2300 assemblies tested before installation
- Bake-out of beam vacuum
  - 230°C for NEG coated chambers / 250°C non coated parts
    - 350°C for vacuum instrumentation: ports, gauges and RGAs
- Pressure lower than 10^{-9} Pa after activation
  - Pressure reading limited by outgassing of the gauge port and by the gauge resolution

Vacuum Acceptance Criteria



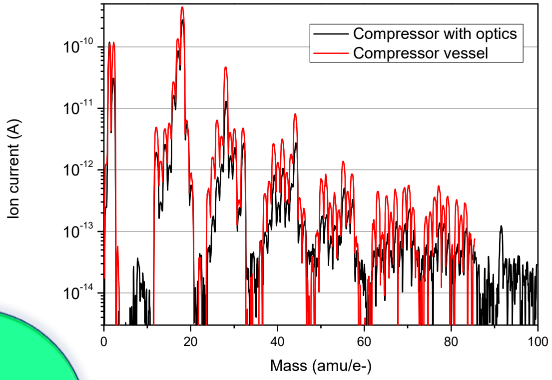
CONTAMINATION

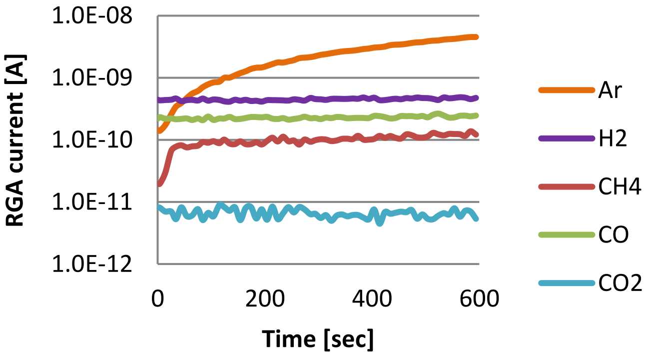
LEAK TIGHTNESS

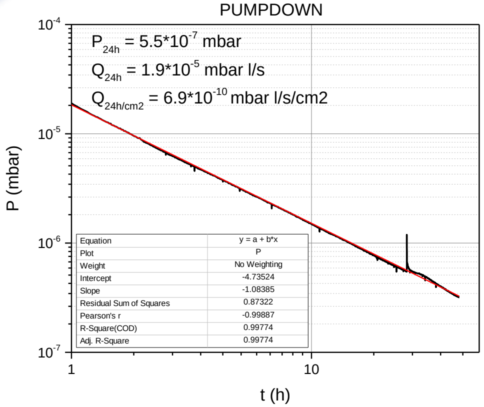
VACUUM COMPONENT

OUTGASSING RATE

VIRTUAL LEAKS







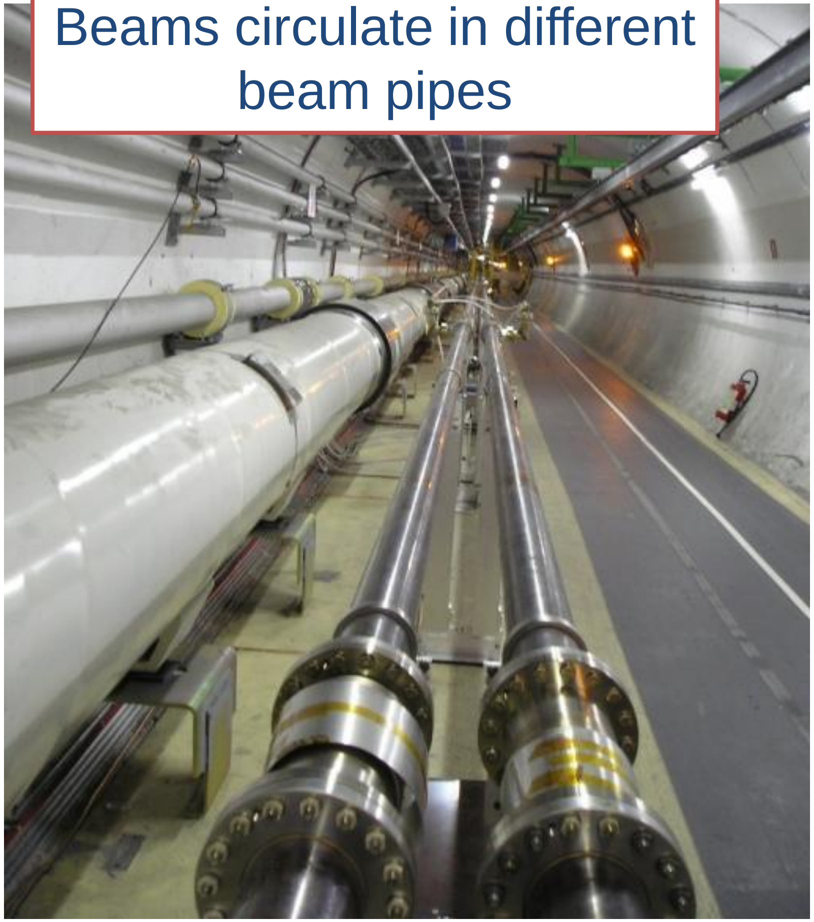
$P_{24h} = 5.5 \times 10^{-7}$ mbar

$Q_{24h} = 1.9 \times 10^{-5}$ mbar l/s

$Q_{24h/cm2} = 6.9 \times 10^{-10}$ mbar l/s/cm2

Equation	y = a + b*x
Plot	P
Weight	No Weighting
Intercept	-4.73524
Slope	-1.08385
Residual Sum of Squares	0.87322
Pearson's r	-0.99887
R-Square(COD)	0.99774
Adj. R-Square	0.99774

LSS Vacuum sectors



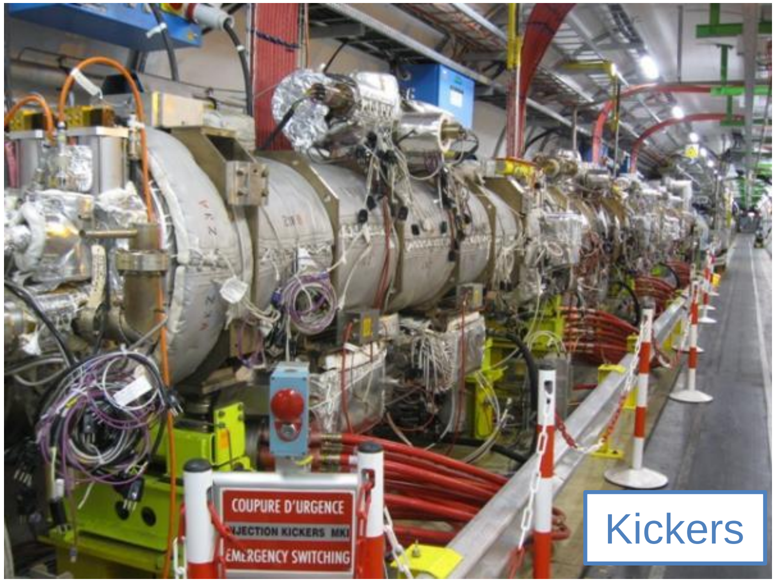
“Twin” sector
Beams circulate in different beam pipes

“Combined” sector
Both beams circulates in the same beam pipe

LSS Vacuum sectors


Warm magnets

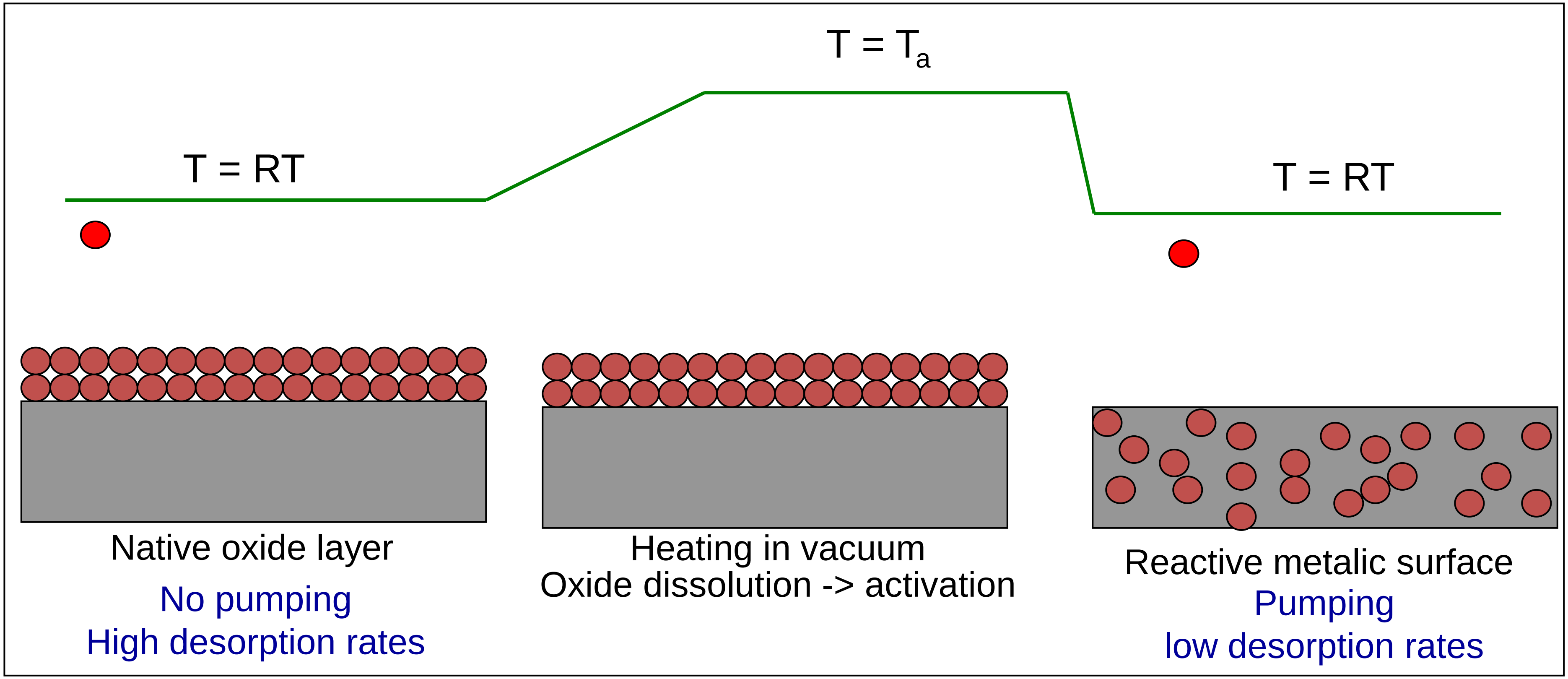

Collimators



Kickers

Beam Instrumentations

Non-Evaporable Getters (NEG)



Native oxide layer

No pumping

High desorption rates

Heating in vacuum
Oxide dissolution -> activation

Reactive metalic surface
Pumping
low desorption rates

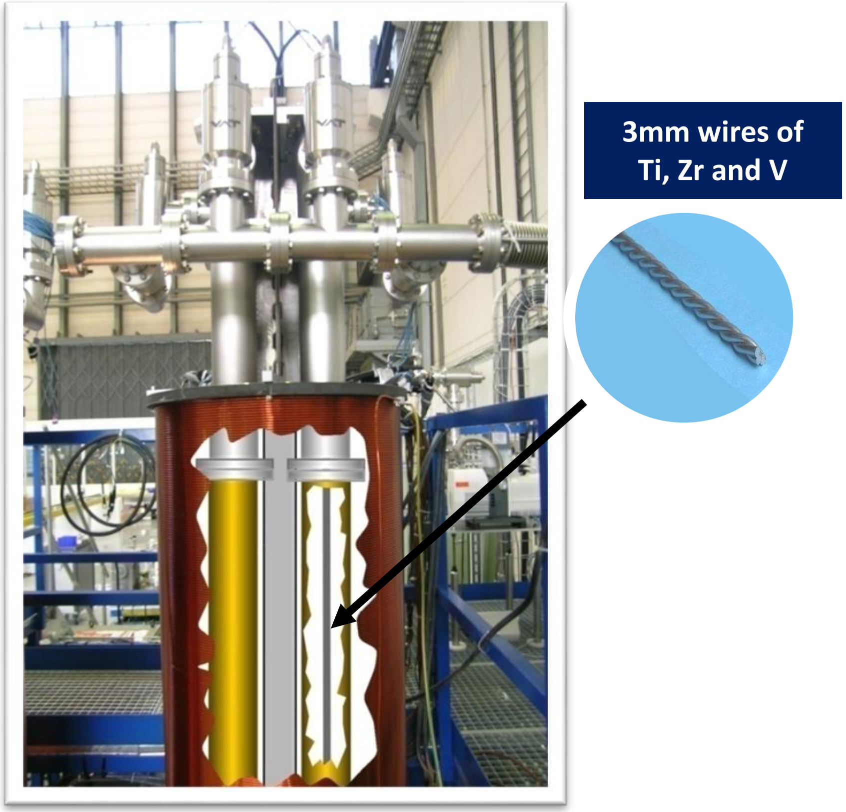
On activation the oxide layer at the surface of NEG is diffused to the bulk of the material creating clean, chemically active surface where gas molecules are captured.

NEG Coating Facilities

A dedicated coating facility is available at CERN since 2004:

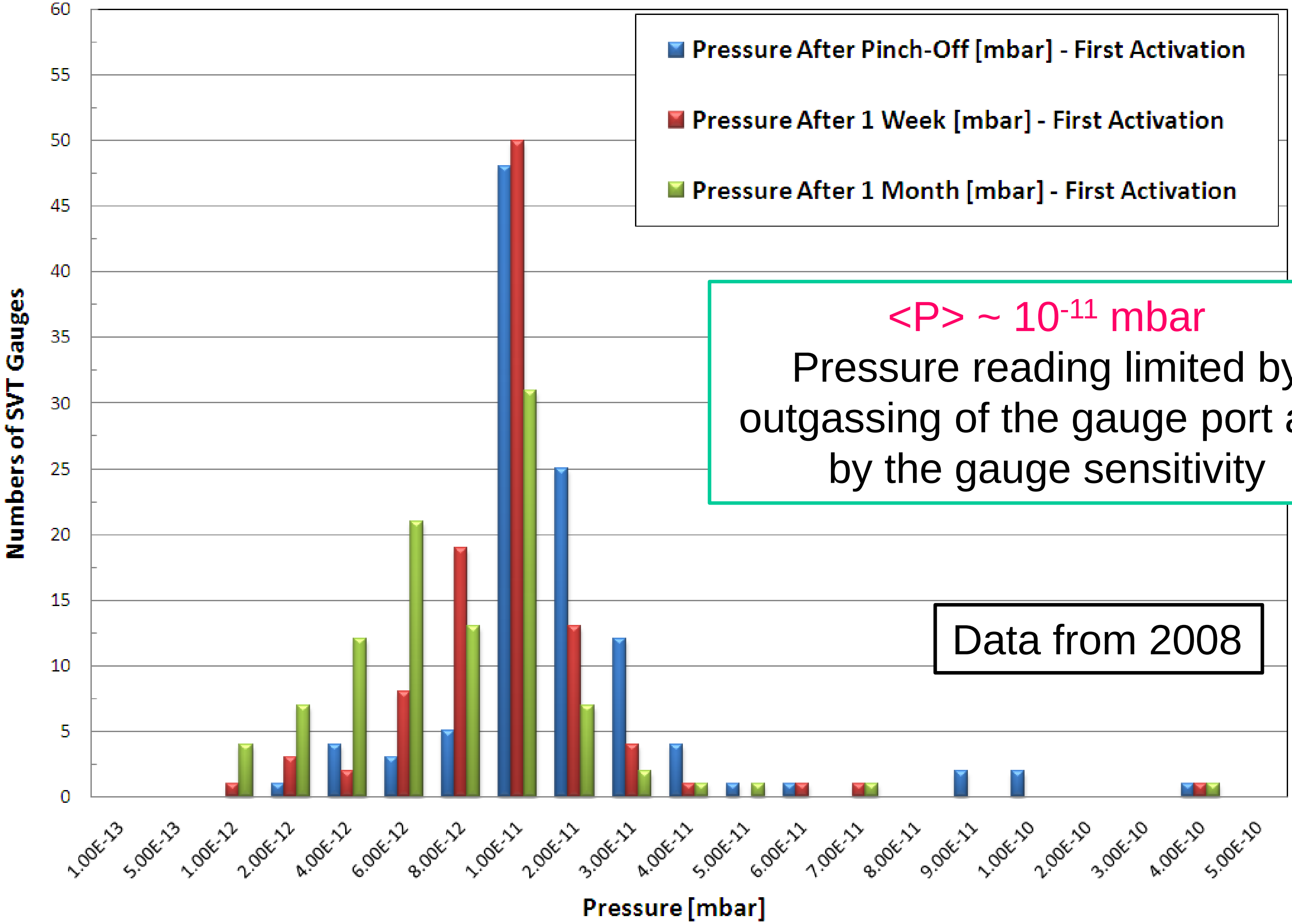
- ✓ 3 independent magnetron sputtering systems
- ✓ Maximum length: 7.5 m; maximum diameter: 60 cm
- ✓ Maximum production rate: 20 chambers of 7 meters per week.

Solenoid: L=8 m diam=0.6 m



3mm wires of Ti, Zr and V

Pressure Distribution with NEG

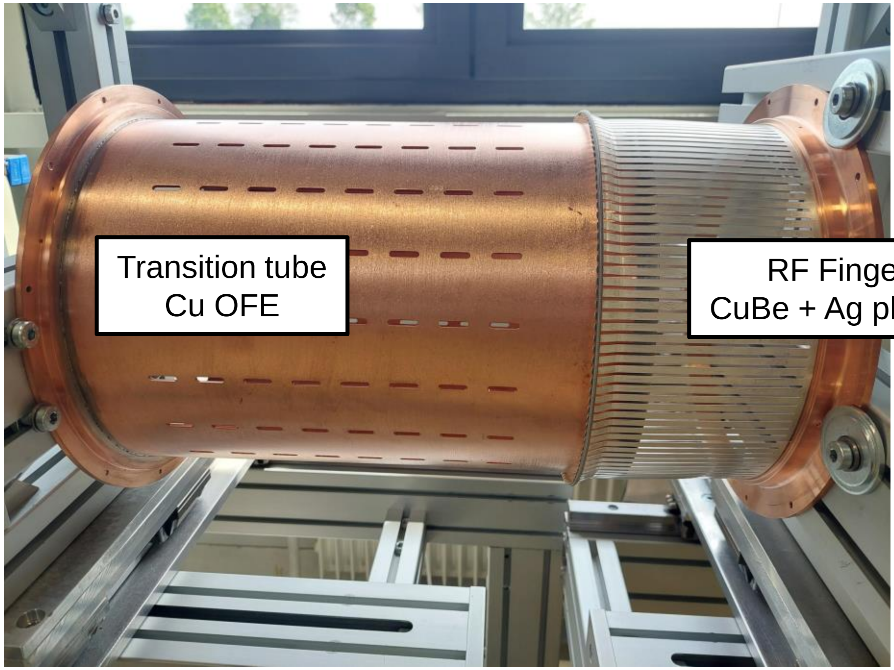


<P> ~ 10^{-11} mbar

Pressure reading limited by outgassing of the gauge port and by the gauge sensitivity

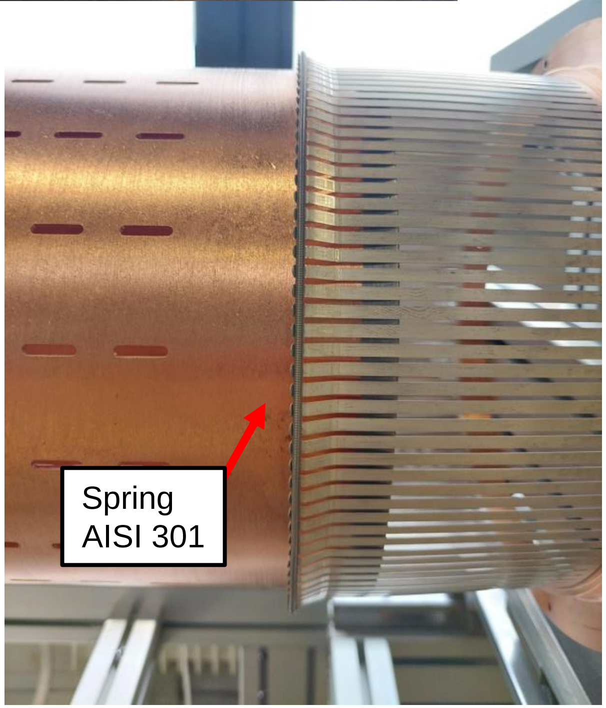
Data from 2008

Warm Bellows Modules



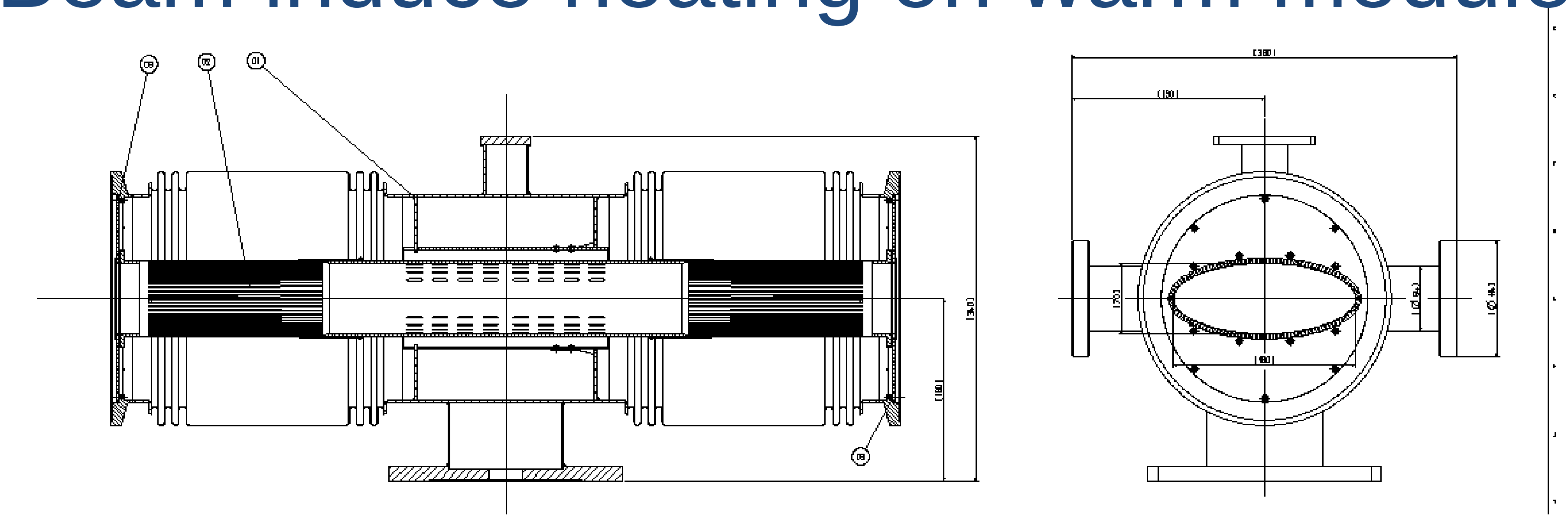
Transition tube
Cu OFE

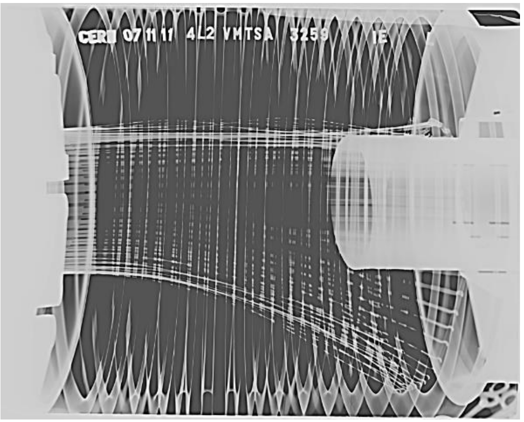
RF Finger
CuBe + Ag plating

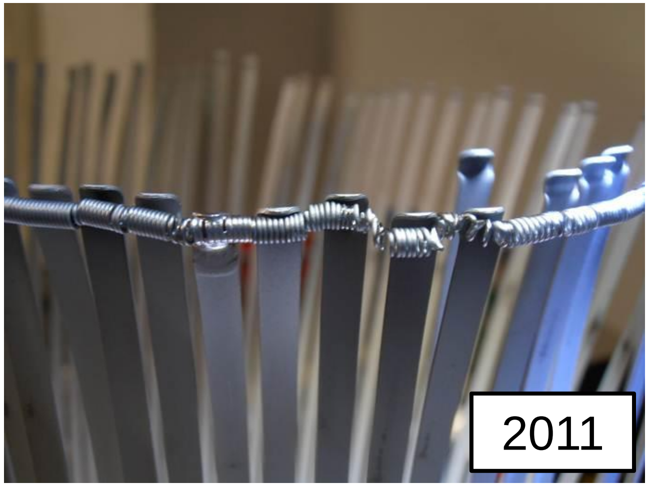


Spring
AISI 301

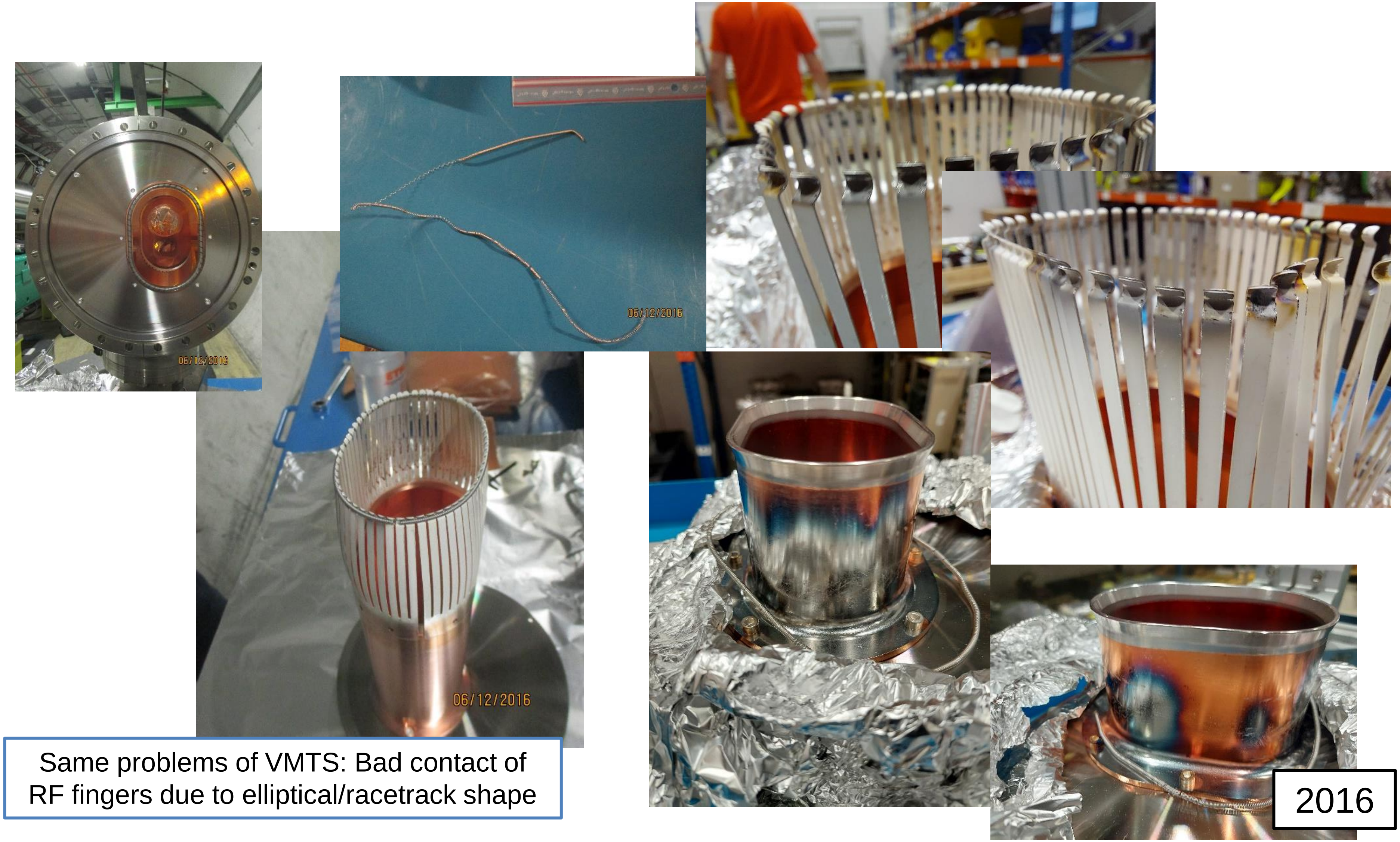
Beam induce heating on warm modules







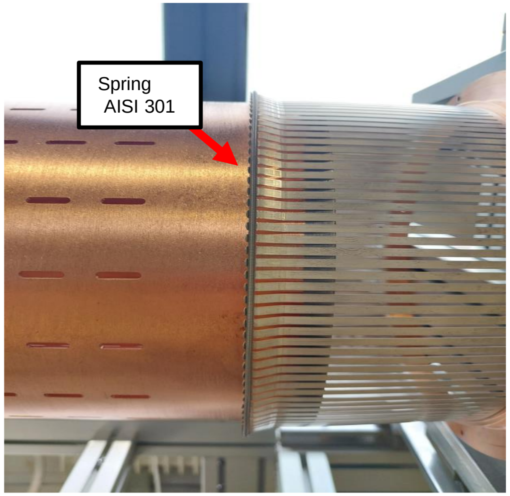
Beam induce heating on warm modules



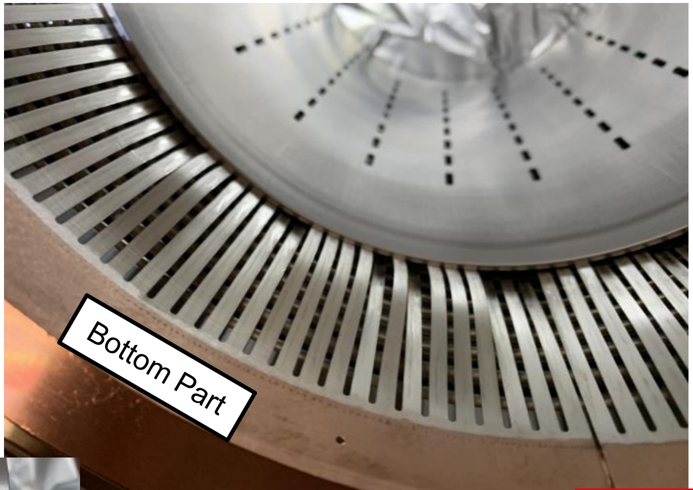
Same problems of VMTS: Bad contact of RF fingers due to elliptical/racetrack shape

2016

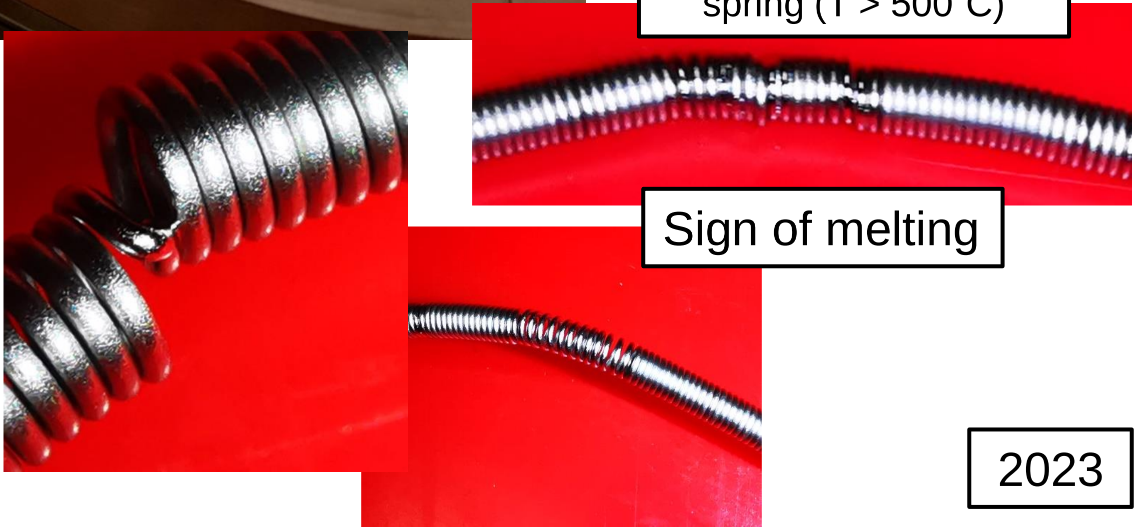
Beam induce heating on warm modules



RF finger clearly not anymore in contact with transition tube



Completely plasticized spring (T > 500°C)



Sign of melting

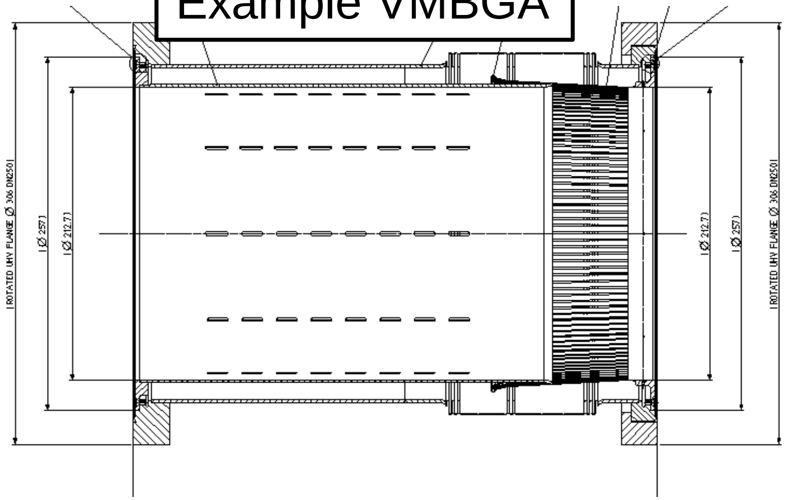
Sign of sparking or heating on the outside of the transition tube

2023

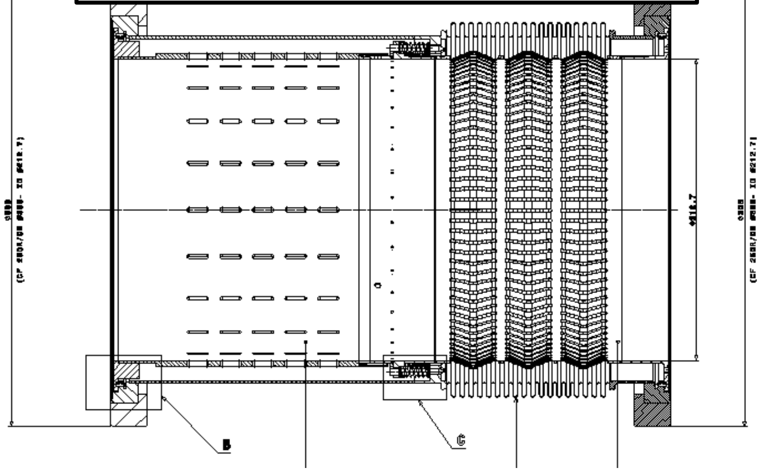
Consolidation project

Replace all the RF Contact ID212 with the new DRF (Deformable RF Finger)
Completely new design

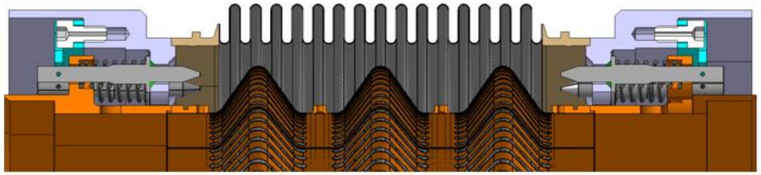
Example VMBGA



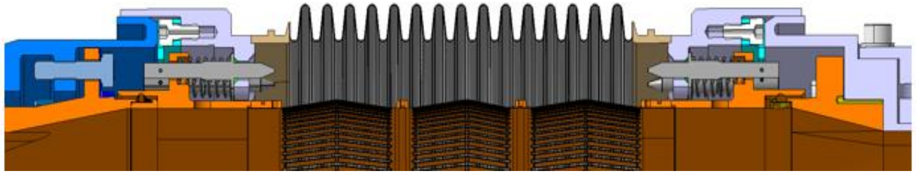
New DRF LHCVM___0098



Installation configuration



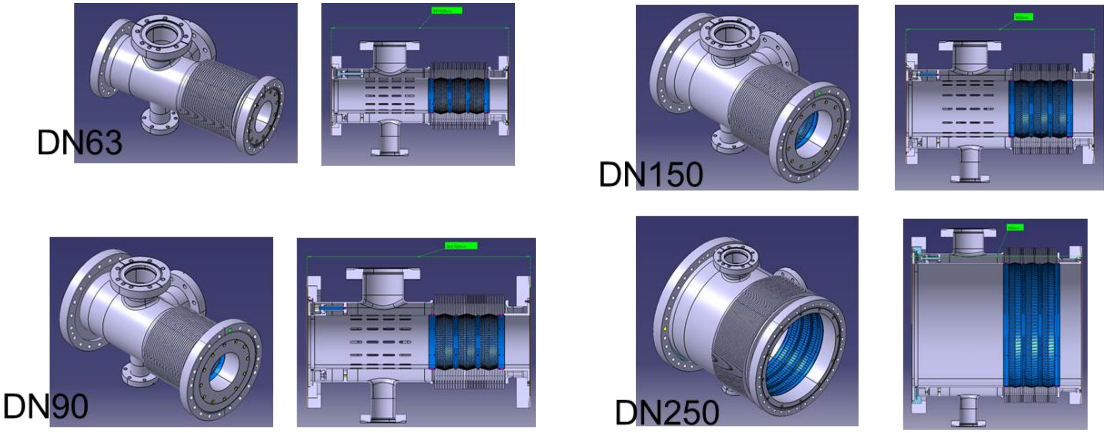
Operation configuration

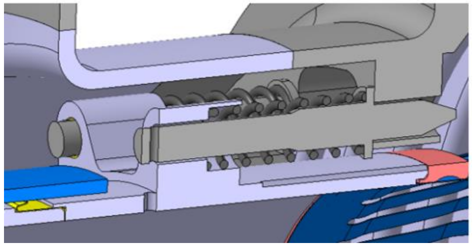


No spring and no possibility to lose electric contact

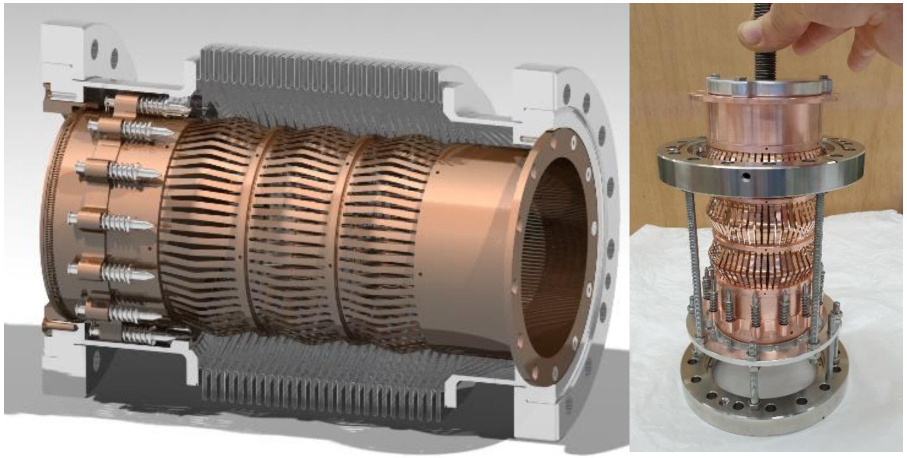
Non deformable RF bridge

- RF bridge prototype
- Studies &Tests
- Designs

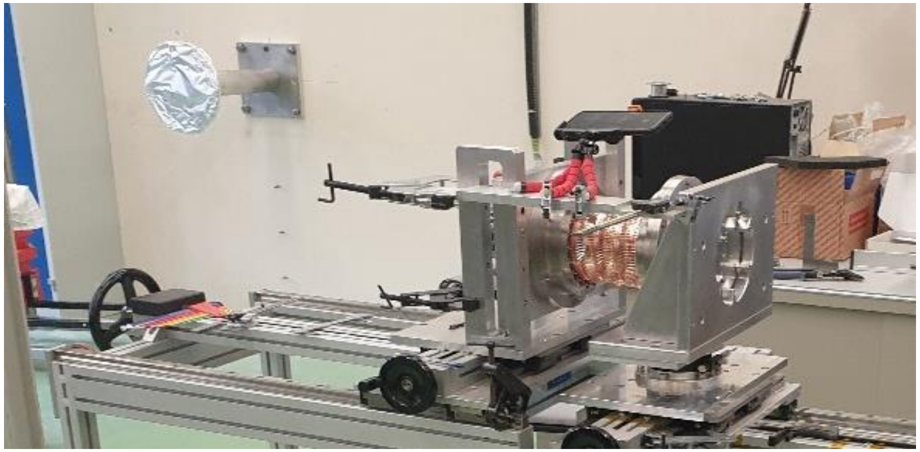




Compensation system

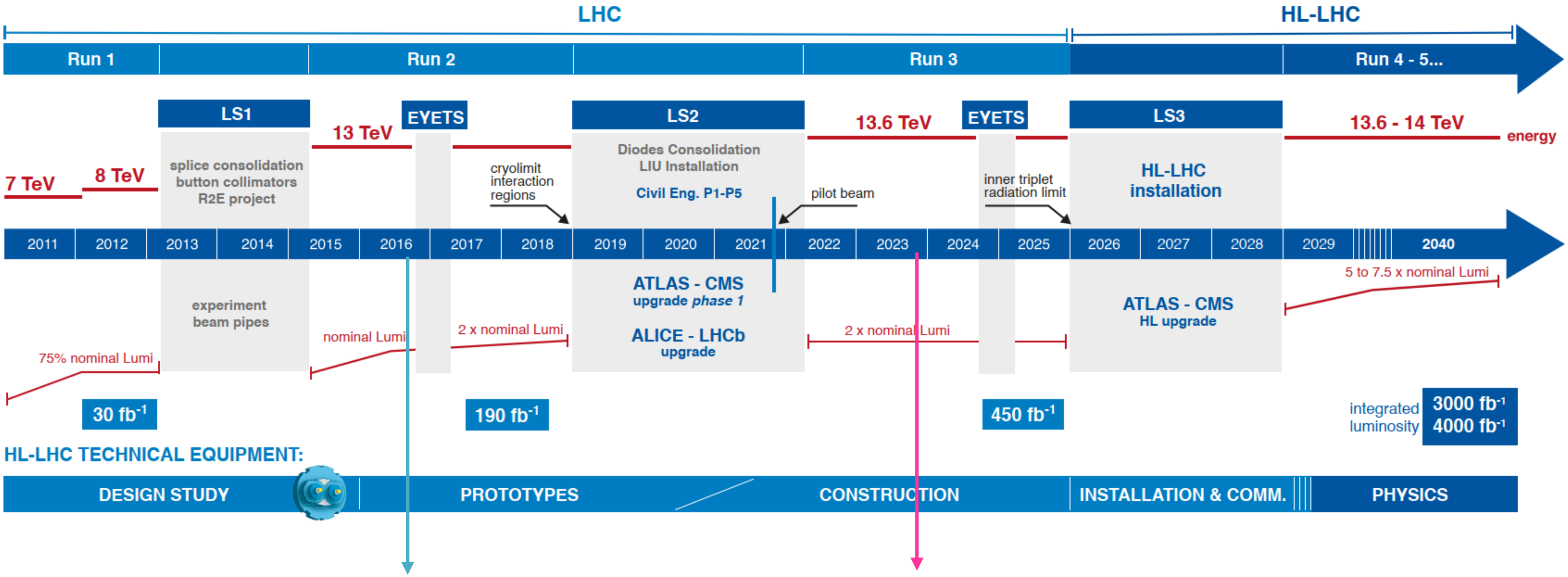


RT Deformable RF bridge



Elongation/transverse studies

LHC upgraded to HL-LHC: PLAN



Approval of
HL-LHC project

Today: 2 years before LS3 starts

O. Brüning

- Transition from prototypes tests to series production
- LS3 shifted by 1 year and extended to 3 years
- Construction schedule unchanged to keep momentum

HL-LHC Goals

From FP7 HiLumi LHC Design Study application in 2010

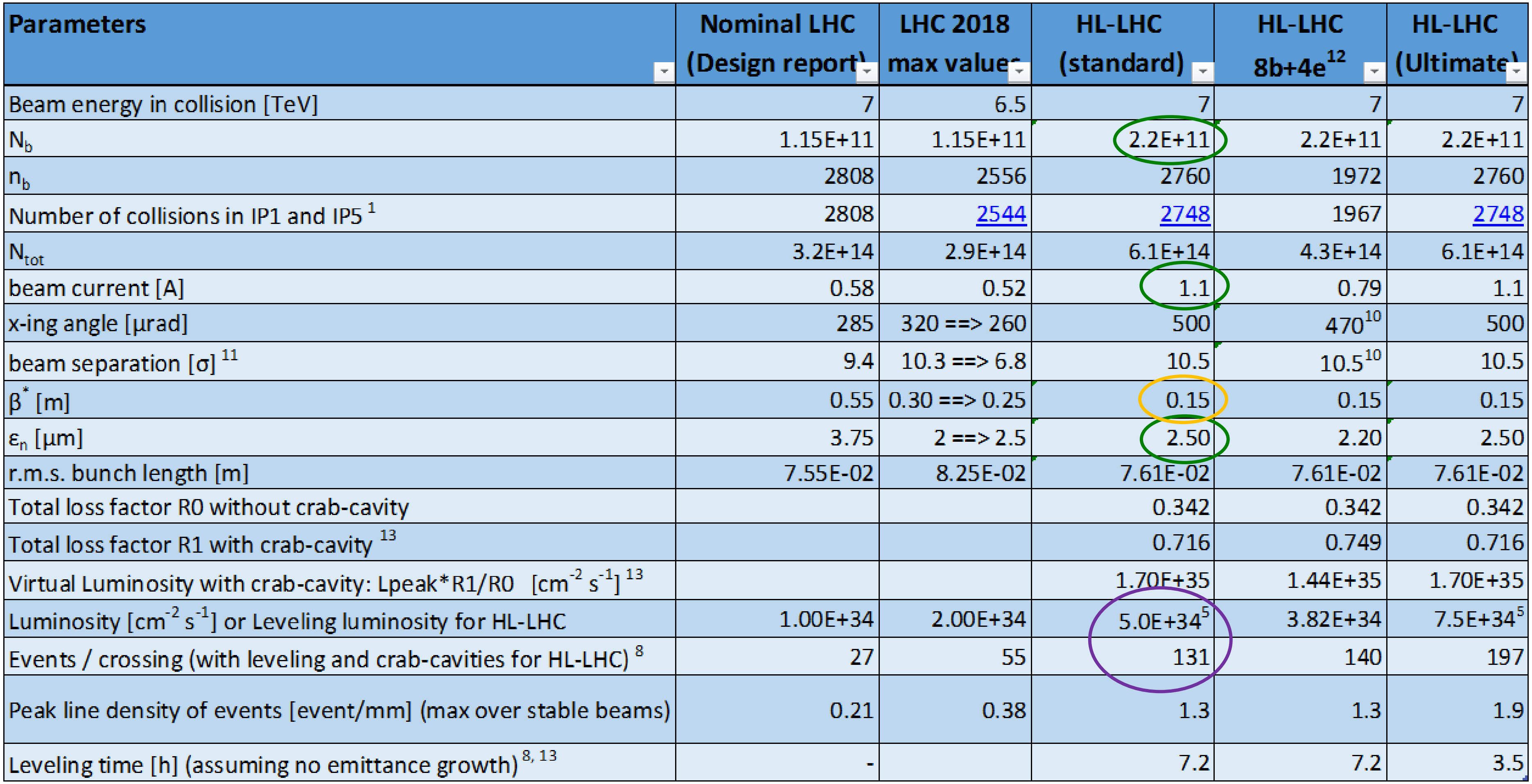
The main objective of HiLumi LHC Design Study is to extend the LHC lifetime by **another decade** and to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1} twelve years after the upgrade**.
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

HL-LHC Baseline Parameters

Back-up scenario



Parameters	Nominal LHC (Design report)	LHC 2018 max value	HL-LHC (standard)	HL-LHC 8b+4e[12]	HL-LHC (Ultimate)
Beam energy in collision [TeV]	7	6.5	7	7	7
N_b	1.15E+11	1.15E+11	2.2E+11	2.2E+11	2.2E+11
n_b	2808	2556	2760	1972	2760
Number of collisions in IP1 and IP5 [1]	2808	2544	2748	1967	2748
N_{tot}	3.2E+14	2.9E+14	6.1E+14	4.3E+14	6.1E+14
beam current [A]	0.58	0.52	1.1	0.79	1.1
x-ing angle [μrad]	285	320 ==> 260	500	470[10]	500
beam separation [σ] [11]	9.4	10.3 ==> 6.8	10.5	10.5[10]	10.5
β^* [m]	0.55	0.30 ==> 0.25	0.15	0.15	0.15
ε_n [μm]	3.75	2 ==> 2.5	2.50	2.20	2.50
r.m.s. bunch length [m]	7.55E-02	8.25E-02	7.61E-02	7.61E-02	7.61E-02
Total loss factor R0 without crab-cavity			0.342	0.342	0.342
Total loss factor R1 with crab-cavity [13]			0.716	0.749	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}] [13]			1.70E+35	1.44E+35	1.70E+35
Luminosity [cm^{-2} s^{-1}] or Leveling luminosity for HL-LHC	1.00E+34	2.00E+34	5.0E+34[5]	3.82E+34	7.5E+34[5]
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	55	131	140	197
Peak line density of events [event/mm] (max over stable beams)	0.21	0.38	1.3	1.3	1.9
Leveling time [h] (assuming no emittance growth) [8, 13]	-		7.2	7.2	3.5

Integrated luminosity [fb^{-1}/year]	**45**	**65**	**300**	**230**	**450**

LS2= **LIU**

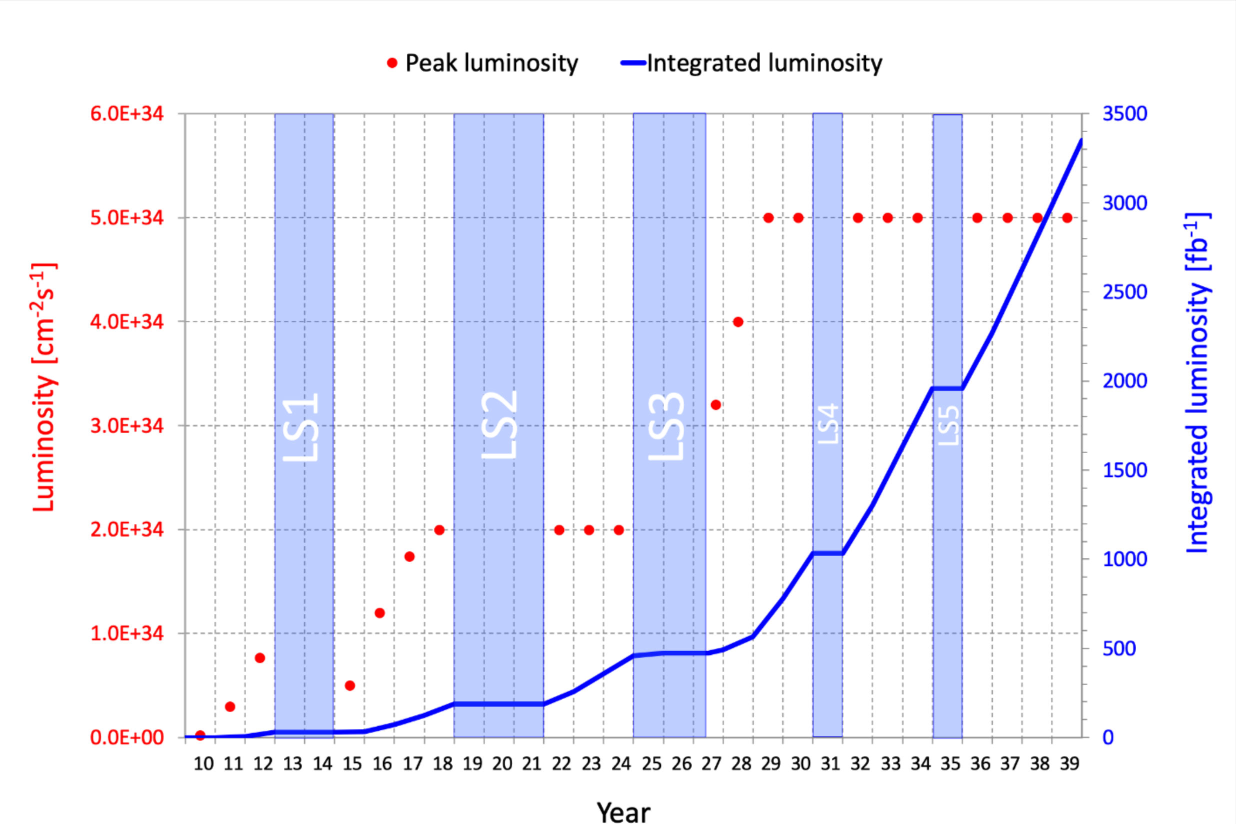
LS3= **New IT Quads & ATS** + **Crab Cavity with levelling**

Tech. Coord. Committee, V7.0

WP2

HL-LHC performance

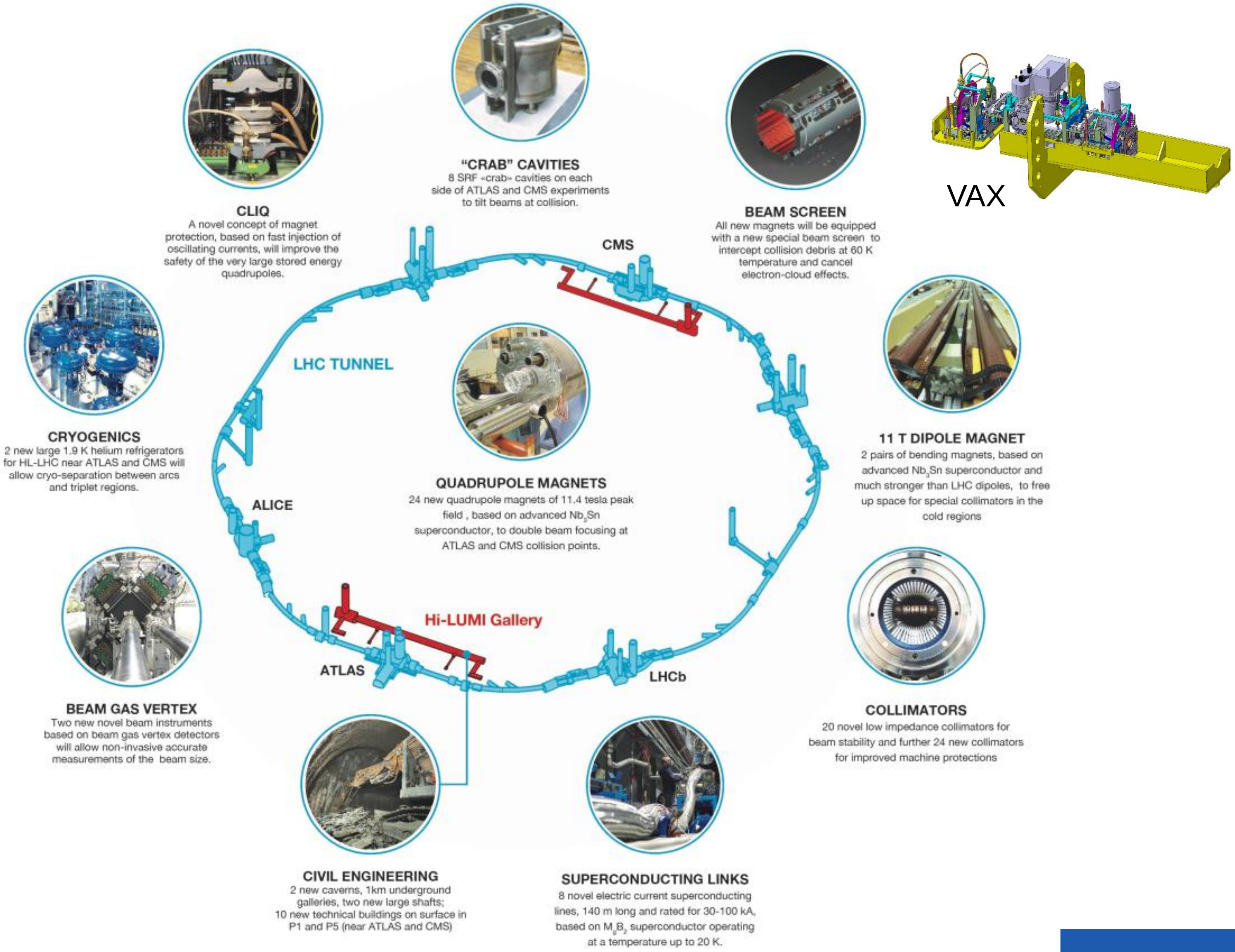
- LHC is projecting ~ 400 fb^{-1} by the end of RUN3:
  - ➔ delaying HL is not an option
  - ➔ mitigating the radiation damage from 35 to 25 MGy by variation of crossing angle
- 3 000 fb^{-1} is achieved 11 years after HL construction



O. Bruning, M. Lamont, L. Rossi

O. Brüning

HL-LHC Technology Landmarks



"CRAB" CAVITIES
8 SRF «crab» cavities on each side of ATLAS and CMS experiments to tilt beams at collision.

CLIQ
A novel concept of magnet protection, based on fast injection of oscillating currents, will improve the safety of the very large stored energy quadrupoles.

BEAM SCREEN
All new magnets will be equipped with a new special beam screen to intercept collision debris at 60 K temperature and cancel electron-cloud effects.

CRYOGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS will allow cryo-separation between arcs and triplet regions.

11 T DIPOLE MAGNET
2 pairs of bending magnets, based on advanced Nb$_3$Sn superconductor and much stronger than LHC dipoles, to free up space for special collimators in the cold regions

QUADRUPOLE MAGNETS
24 new quadrupole magnets of 11.4 tesla peak field, based on advanced Nb$_3$Sn superconductor, to double beam focusing at ATLAS and CMS collision points.

BEAM GAS VERTEX
Two new novel beam instruments based on beam gas vertex detectors will allow non-invasive accurate measurements of the beam size.

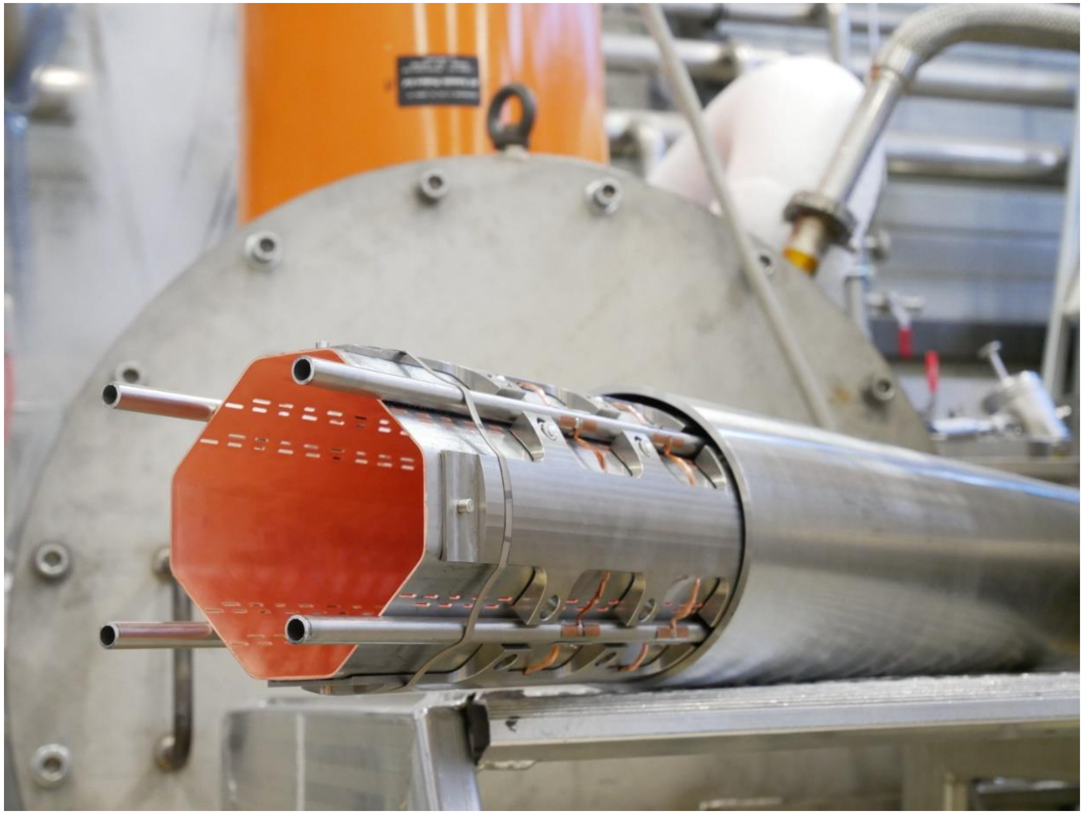
COLLIMATORS
20 novel low impedance collimators for beam stability and further 24 new collimators for improved machine protections

CIVIL ENGINEERING
2 new caverns, 1km underground galleries, two new large shafts; 10 new technical buildings on surface in P1 and P5 (near ATLAS and CMS)

SUPERCONDUCTING LINKS
8 novel electric current superconducting lines, 140 m long and rated for 30-100 kA, based on M$_g$B$_2$ superconductor operating at a temperature up to 20 K.

L. Rossi

New production: Beam screen



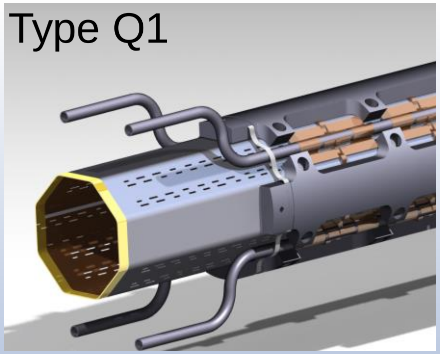
LHC Beam Screen

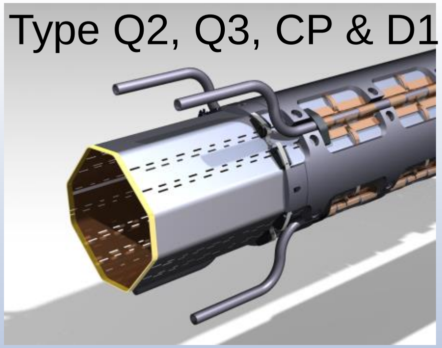
- Ensure vacuum performance
- Minimize and intercept beam induced heat loads
- Intercept collision debris

New production: Beam screen

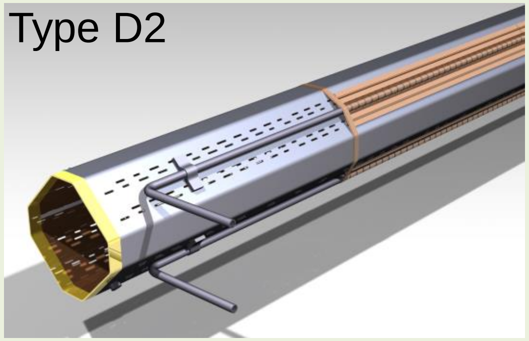
How many types are needed for HL-LHC project?
Where will we install them in the LHC machine?

TRIPLETS

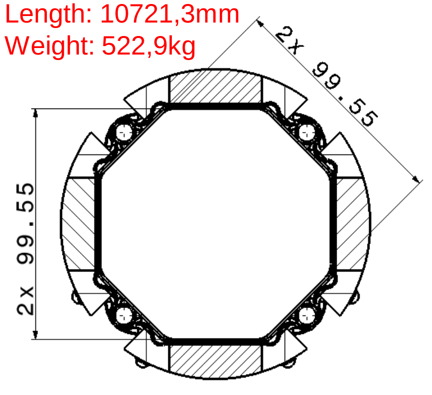

Type Q1


Type Q2, Q3, CP & D1

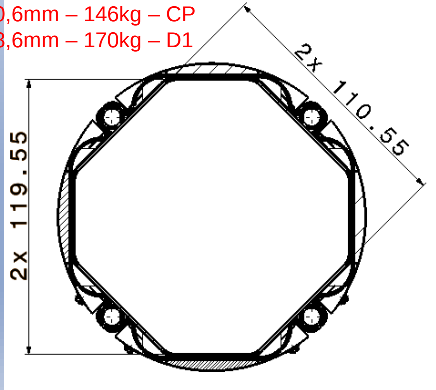
LSS


Type D2

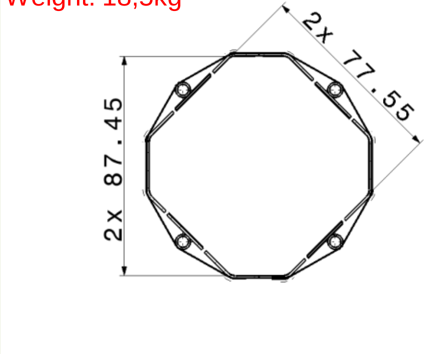
Length: 10721,3mm
Weight: 522,9kg



L:10291,6mm – 210,5kg – Q2
L:10606,6mm – 209kg – Q3
L:7460,6mm – 146kg – CP
L:8498,6mm – 170kg – D1



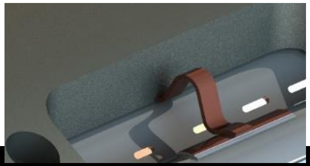
Length: 14083mm
Weight: 18,5kg

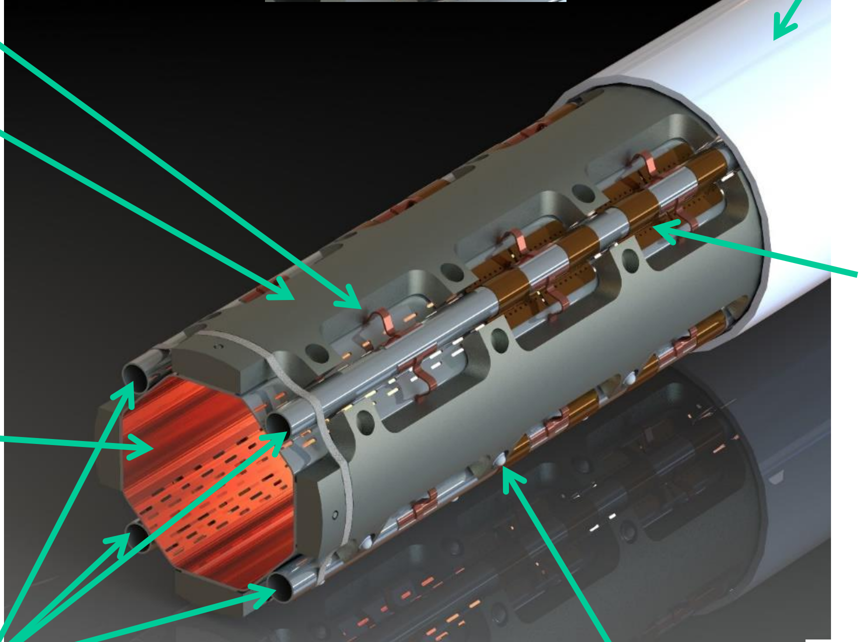


(From A. Vidal

New production: Shielded beam screen

- Objective
  - Provide vacuum stability, control gas density
  - Protect the Triplet cold mass against particle collision debris

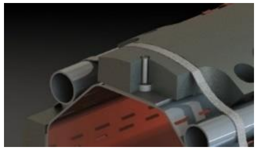




Thermal links:
- In copper
- Connected to the absorbers and the cooling tubes or beam screen tube

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

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
- 40 cm long

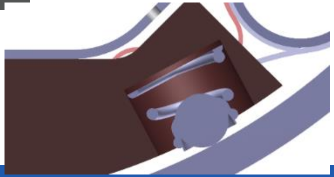


Pumping slot shield

Beam screen tube (BS) at 60-75 K:
- Perforated tube (~2%) in High Mn High N stainless steel (1600 l/s/m (H_2 at 300K))
- Internal copper layer (75 μm) for impedance
- a-C coating (as a baseline) for e- cloud mitigation

Cooling tubes:
- Outer Diameter: 10 mm
- Laser welded on the beam screen tube

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

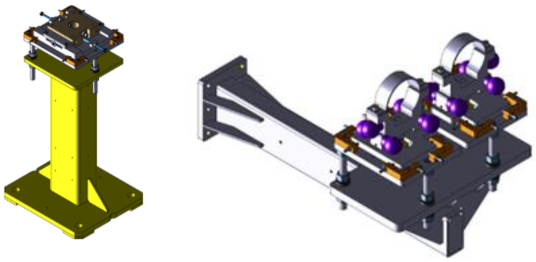


New production for RT area

- Vacuum modules:
  - all released, 20 variants
  - 672 manufacturing drawings
  - ≈ 280 total new units

- Vacuum chambers:
  - Recombination chamber
  - 28 variants
  - Production drawing to be finalized in Q3 2023
  - Start production

- Vacuum supports
  - 8 variants for sector valves
  - New version for FRAS compatibiltiy



Thanks you for your attention