

PERFORMANCE OF THE LHC BEAM VACUUM SYSTEM DURING PROTON RUNS

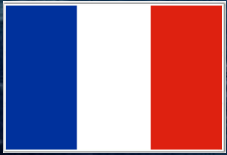
G. Lanza, V. Baglin, G. Bregliozi, J. M. Jimenez

3rd Vacuum Symposium UK
17/18 October 2012 - Ricoh Arena, Coventry

CERN - Vacuum, Surfaces and Coatings
European Organization for Nuclear Research
CH-1211 Geneva 23, Switzerland

The Large Hadron Collider

FRANCE



Leman lake

Geneva
airport

54 km

SWITZERLAND



Giulia Lanza

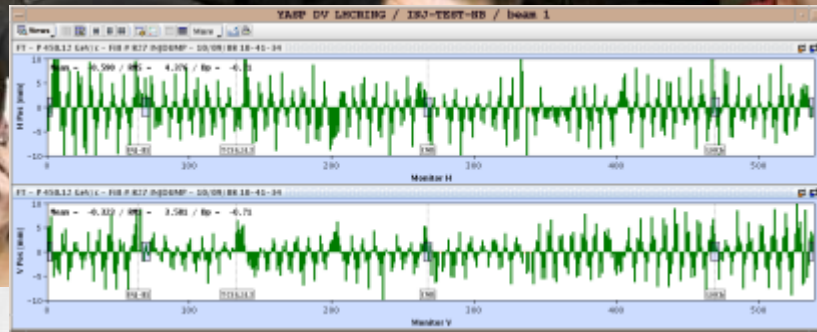
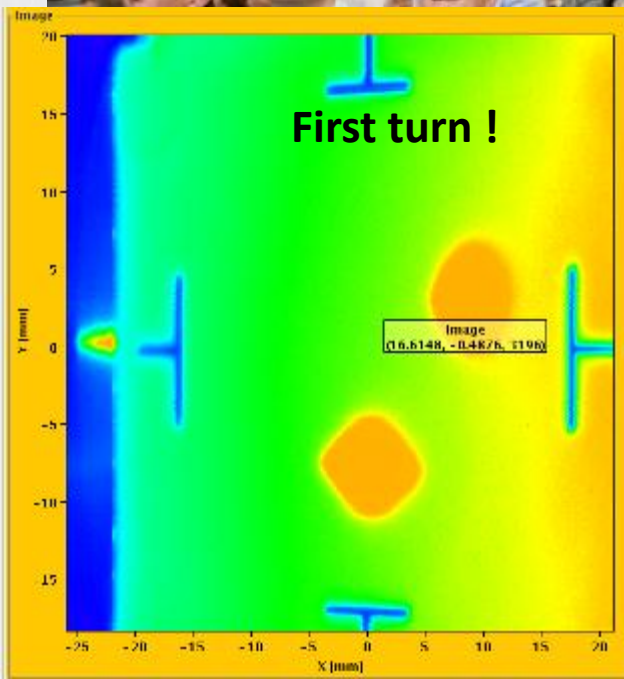
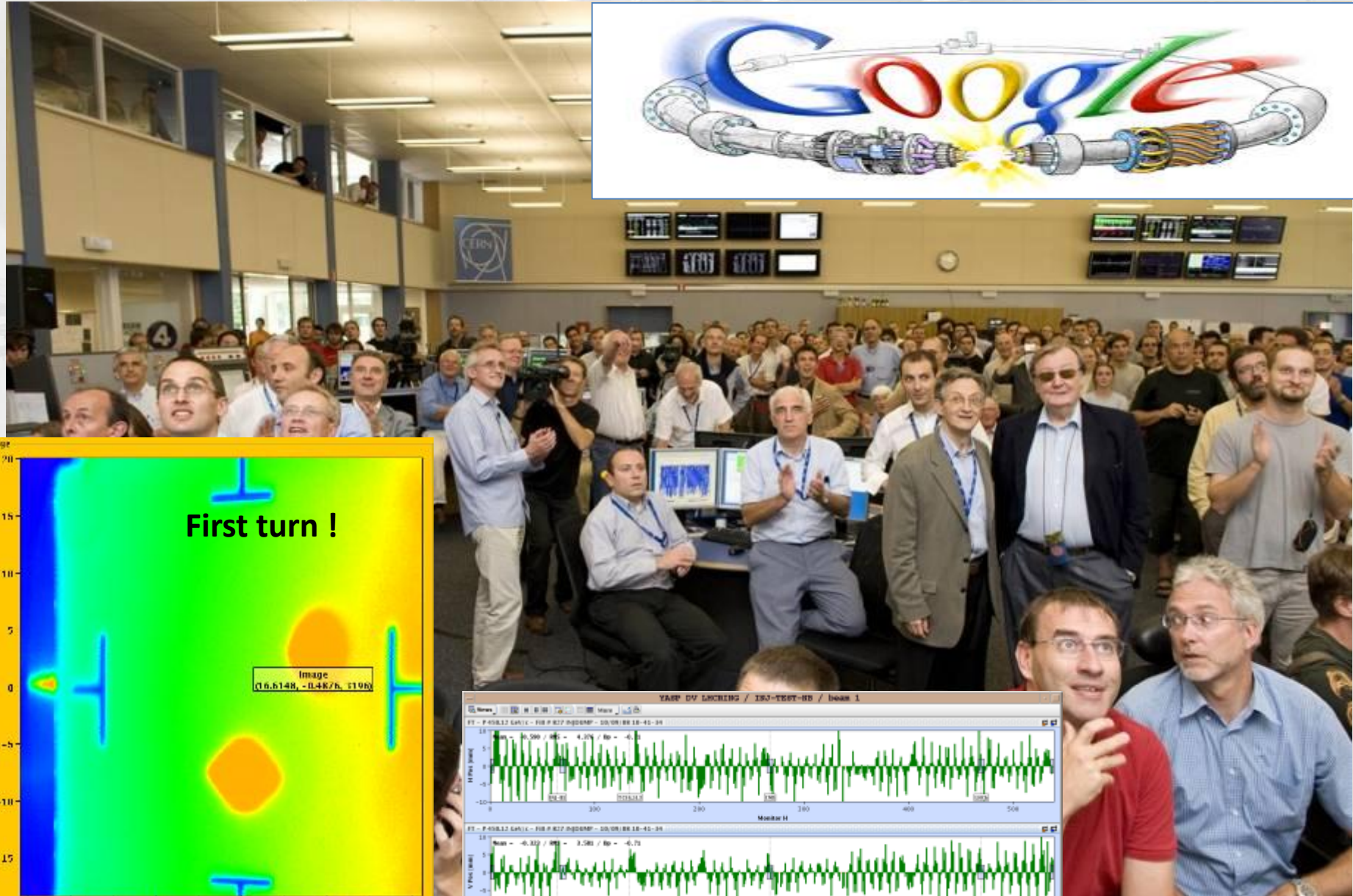
Present LHC Performance

Parameter	Nominal value	Present value August 2012
Proton Energy	7 TeV	4 TeV
Bunch Spacing	25 ns	50 ns
Bunch Intensity	1.1×10^{11} proton	1.6×10^{11} proton
Bunch Number	2808	1374
Beam Current	0.56 A	0.40 A
Peak Luminosity	1.0×10^{34} Hz/cm ⁻²	7.0×10^{33} Hz/cm ⁻²
Sync. Rad. Critical Energy	44 eV	8 eV
Photon Flux	1×10^{17} ph/m/s	0.5×10^{17} ph/m/s
Synchrotron Radiation Dose	$*1 \times 10^{24}$ ph/m	0.06×10^{24} ph/m

*assuming continuous operation for 150 days

LHC

First beams: 10th September 2008...



LHC

November 2009

1.18TeV

Geneva, 20 November 2009

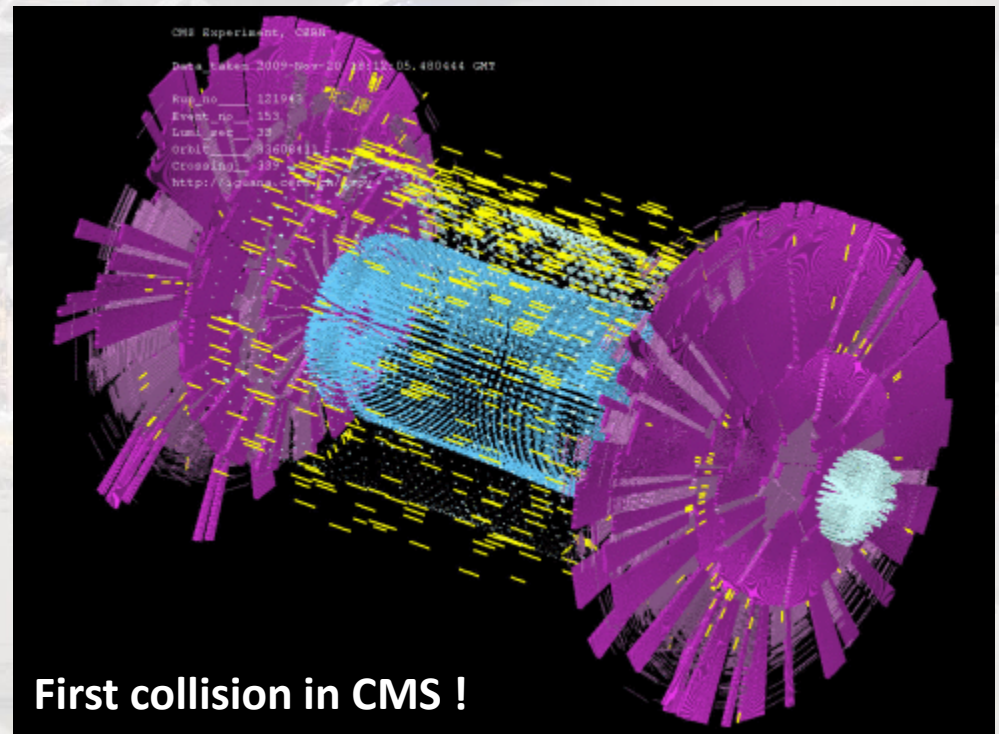
Particle beams are once again circulating in the LHC.

Geneva, 23 November 2009

In the LHC circulated two beams simultaneously for the first time, first chance proton-proton collisions

Geneva, 30 November 2009

LHC is the world's highest energy particle accelerator: twin beams of protons to an energy of 1.18 TeV



LHC

Luminosity

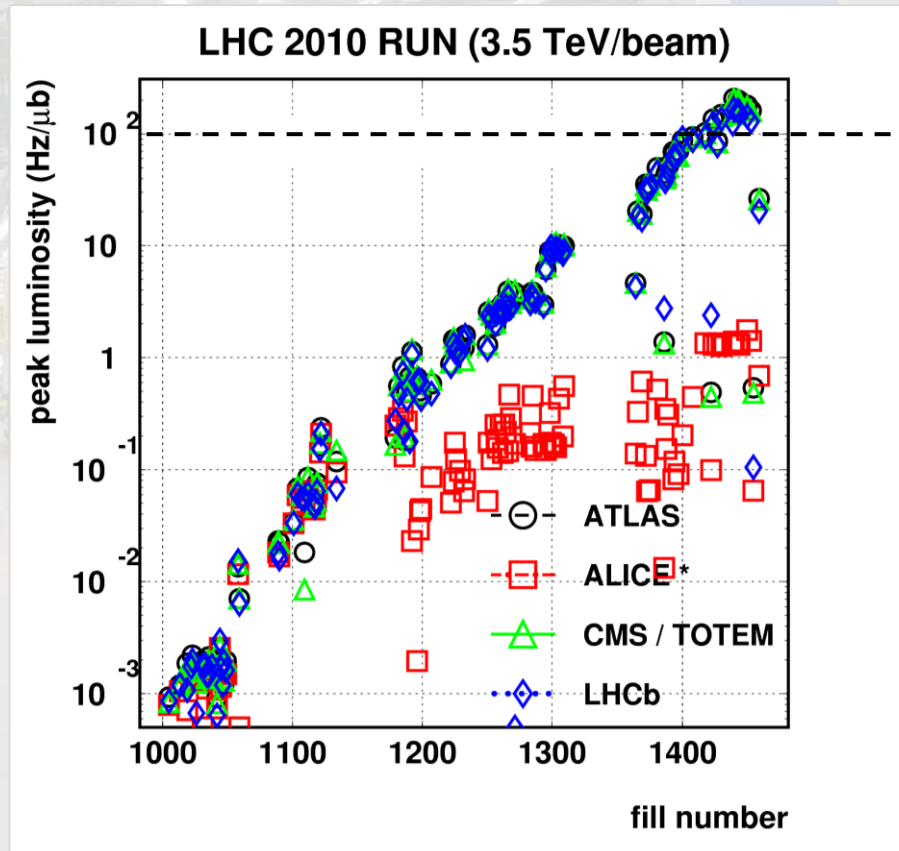
$$L = \frac{N^2 k_b f}{4 \pi \sigma_x^* \sigma_y^*} F = \frac{N^2 k_b f \gamma}{4 \pi \epsilon_n \beta^*} F$$

N	Number of particles per bunch
K _b	Number of bunches
f	Revolution frequency
σ _y	Beam size at interaction point
F	Reduction factor due to crossing angle
ε	Emittance
ε _n	Normalized emittance
β [*]	Beta function at IP

**Aim: maximize
peak luminosity**

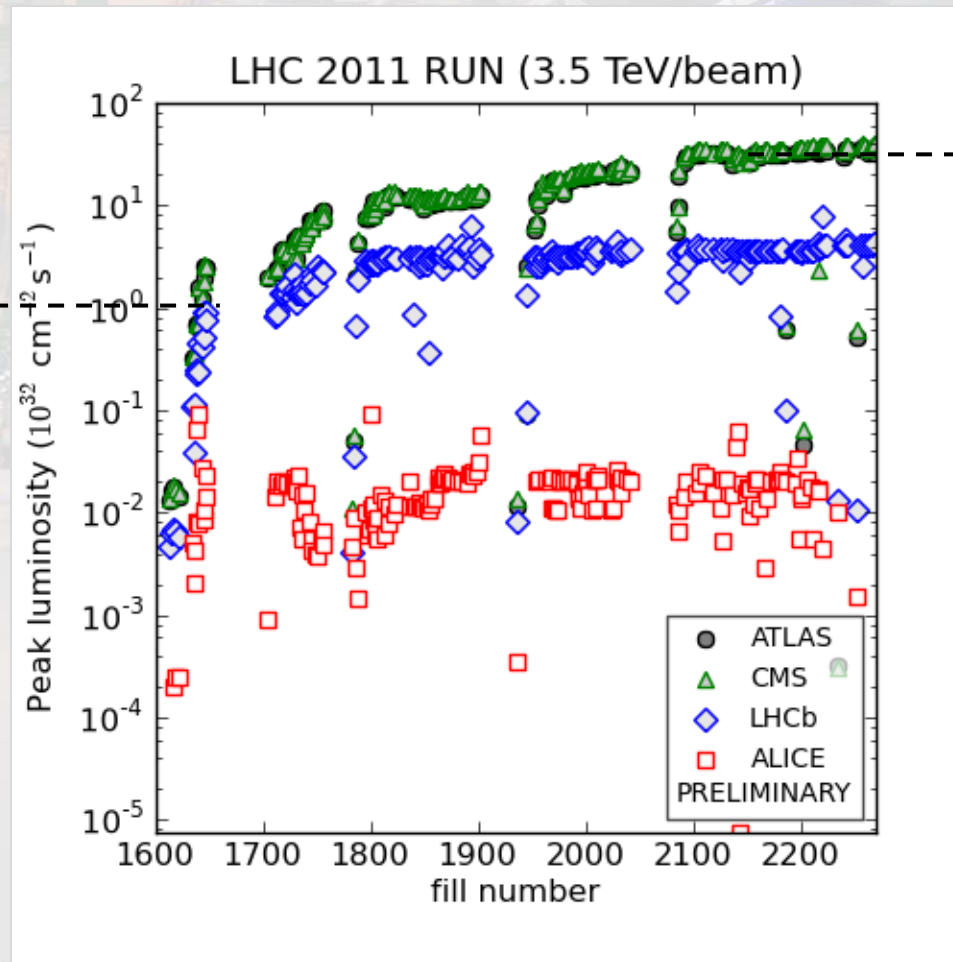
LHC
2010

3TeV



LHC
2011

3TeV



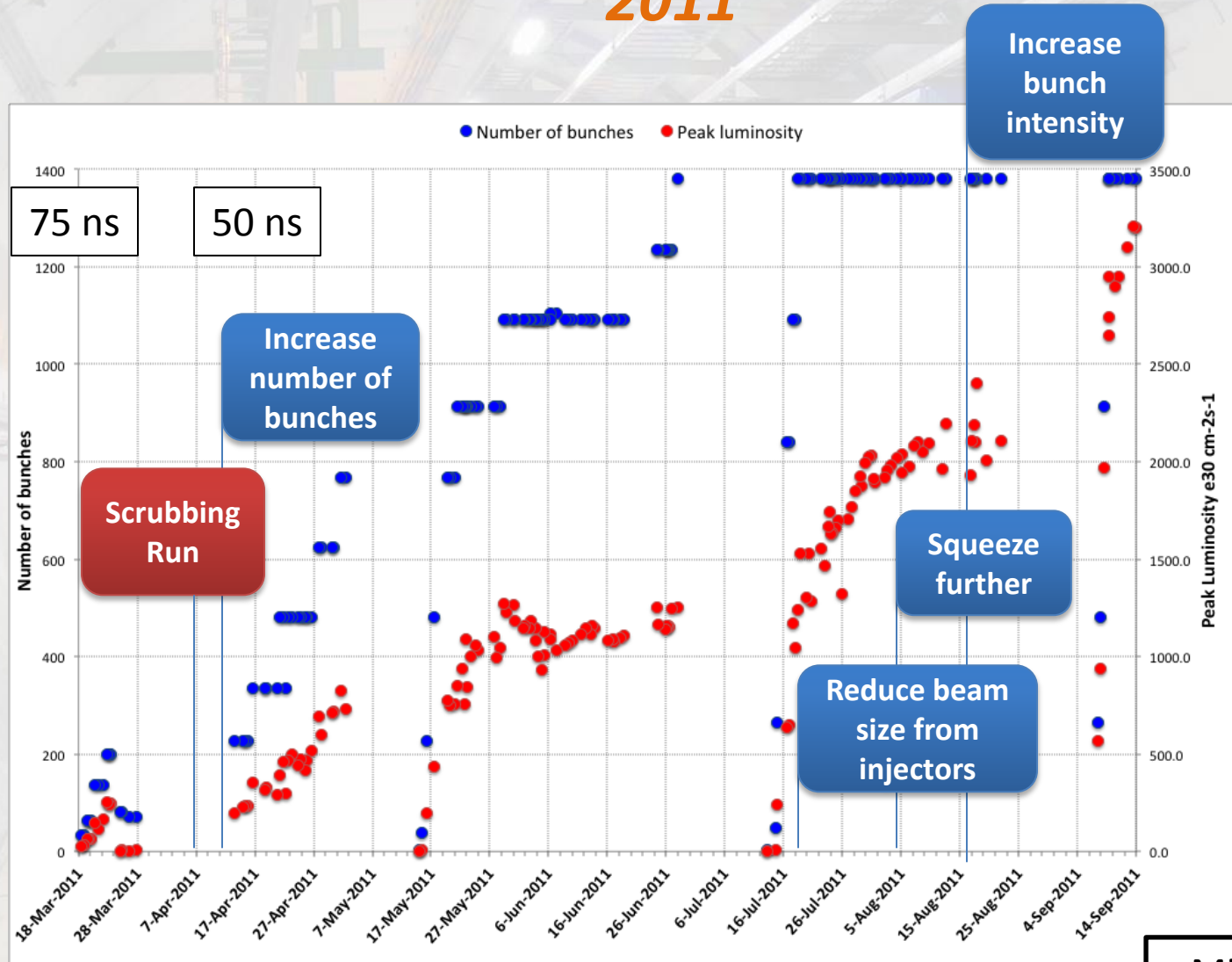
3×10^{33}
 Hz/cm^2

1×10^{32}
 Hz/cm^2

2010 peak luminosity re-established in in the first 9 days of 2011 physics operation

LHC
2011

3TeV



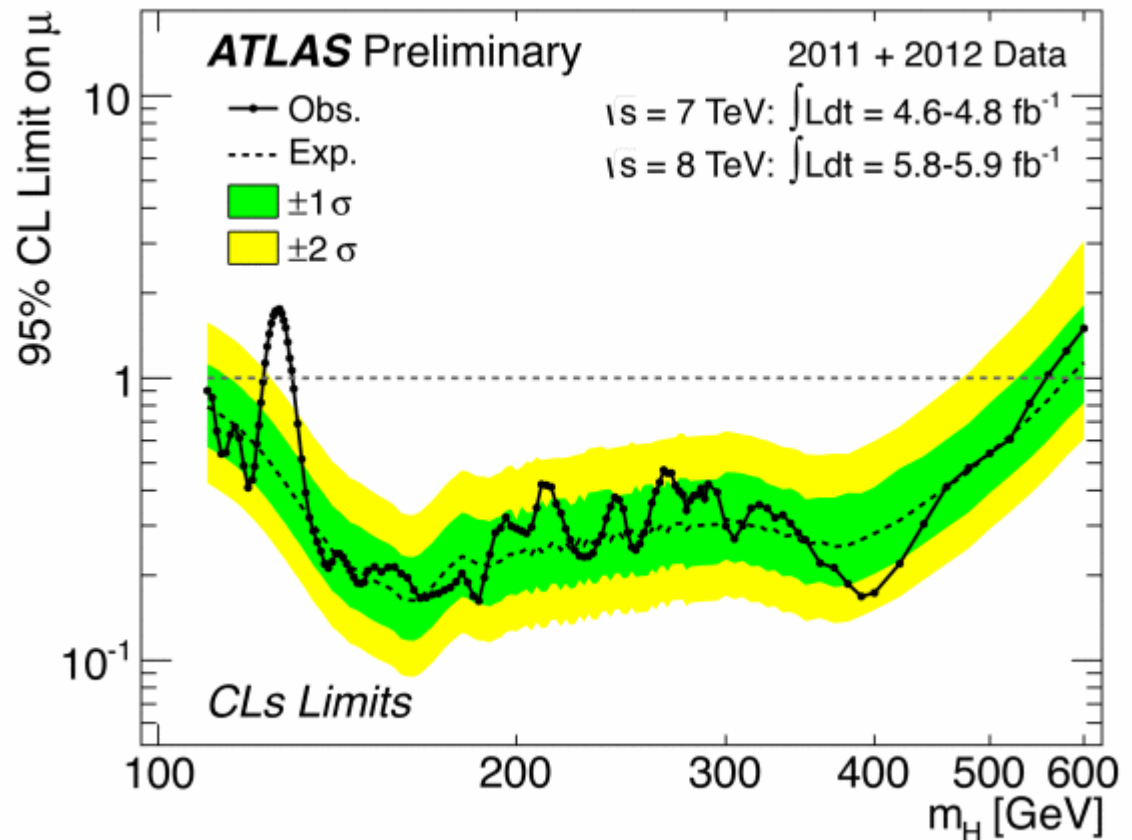
Mike Lamont
LHC operation perspectives

LHC
2012

Boson discovery

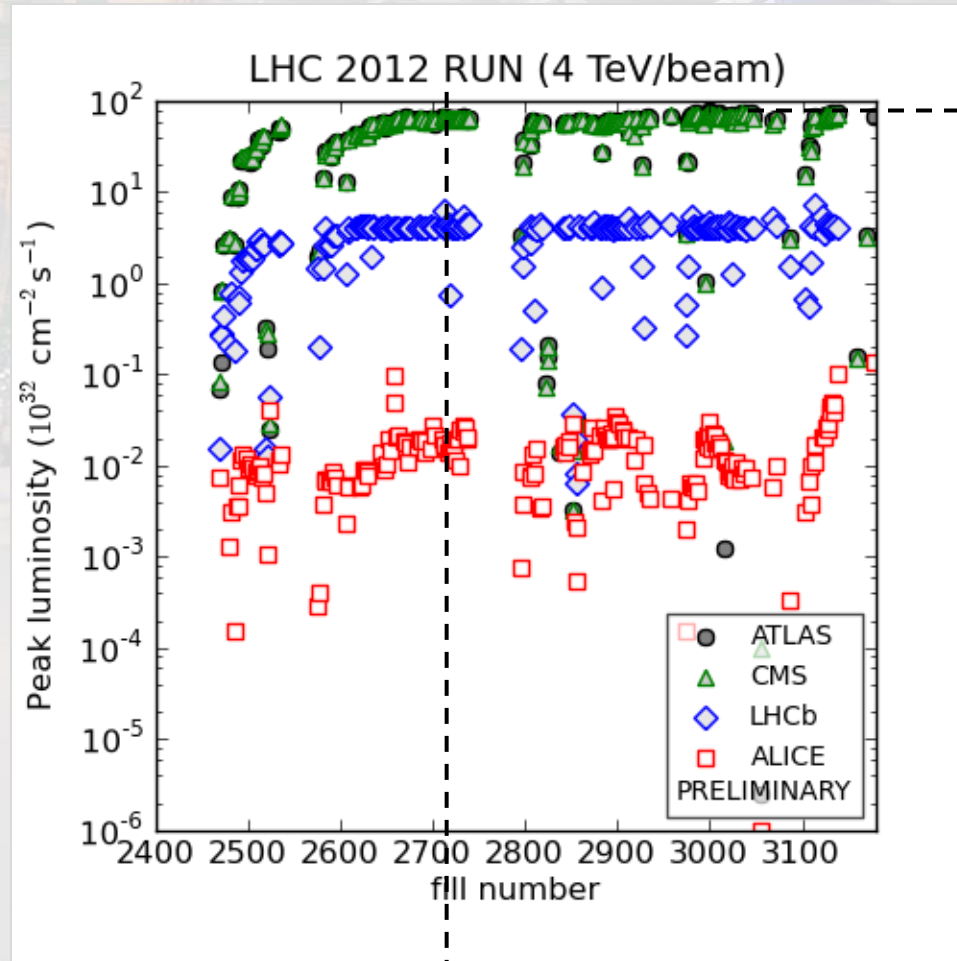


ATLAS and CMS
observed a new
particle in the mass
region around
125-126 GeV



LHC
2012

4TeV



7×10^{33}
 Hz/cm^2

Boson discovery



LHC VACUUM LAYOUT

Why is Vacuum needed in the LHC?

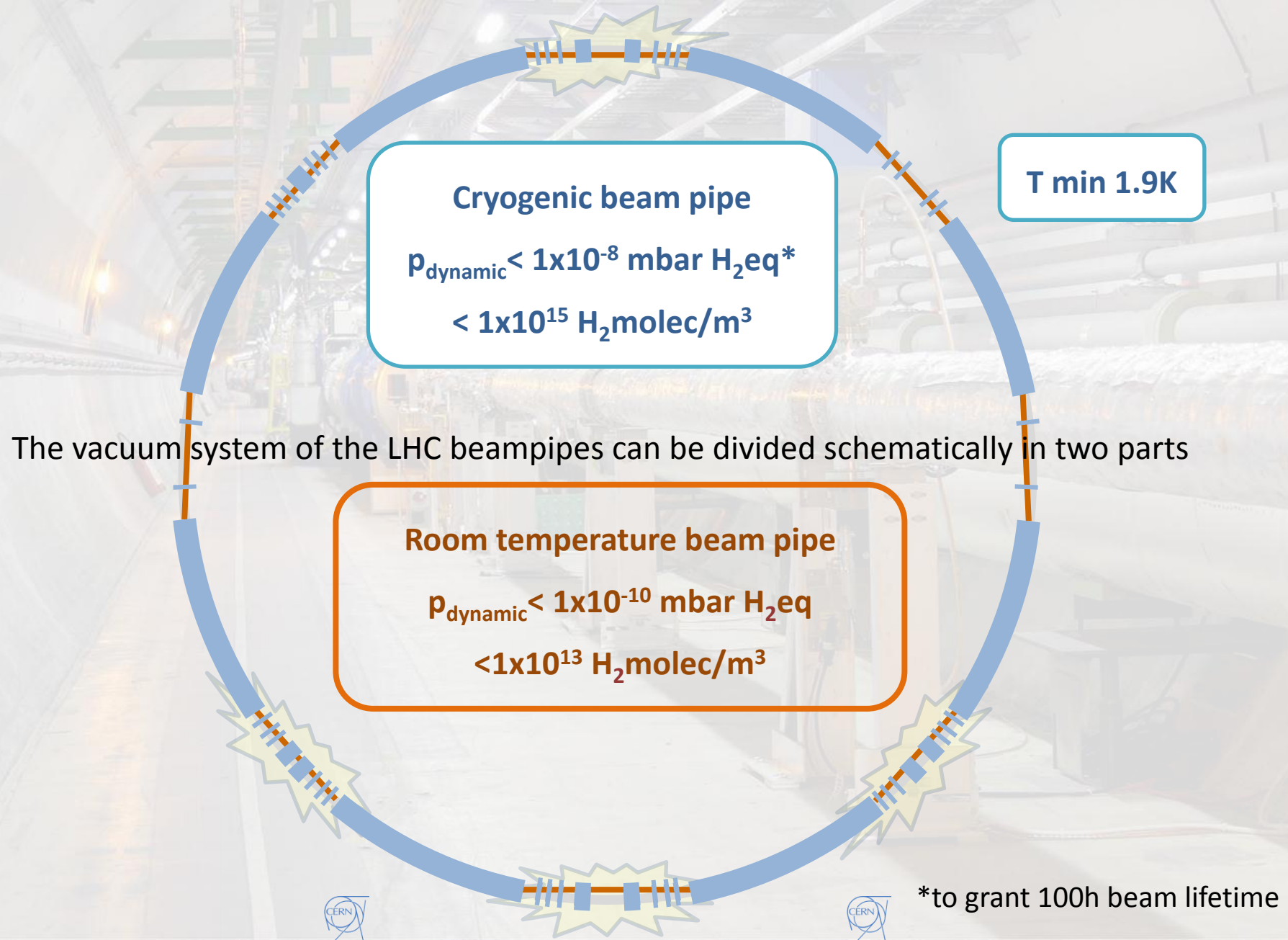
Vacuum aims to reduce beam-gas interaction which is responsible for:

- **Machine performance limitations**
 - nuclear scattering, multiple coulomb scattering, ionization
- **Background to the experiments**

Beam vacuum pipes are designed to:

- **Minimise beam impedance and HOM generation**
- **Optimise beam aperture**
- **Intercept heat loads (cryogenic machines)**
 - ⇒ Intercept most of the heat load, 1 W at 1.9 K requires 1 kW of electricity

The Large Hadron Collider Vacuum Layout



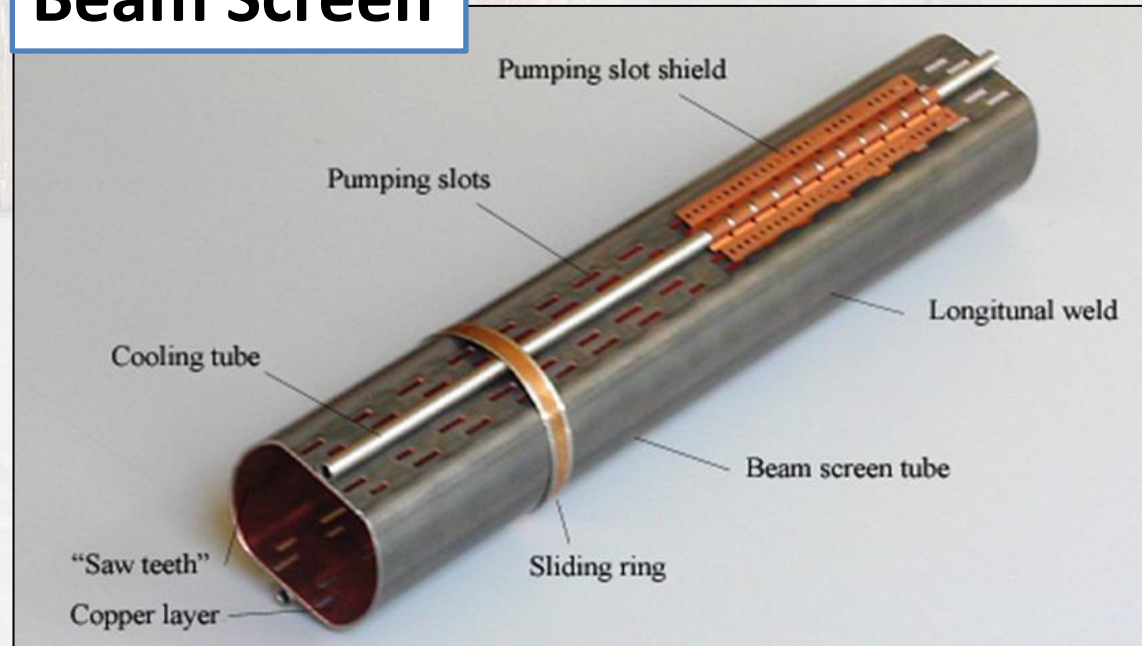
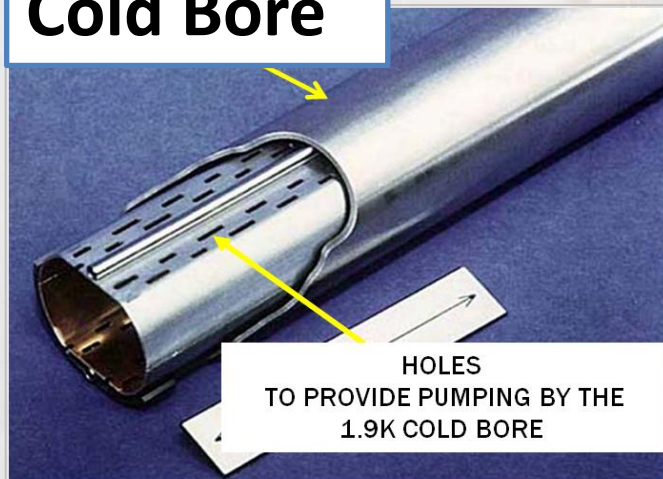
Cold Vacuum

Condensation on the cold bore by the cryogenic cooling of the superconducting magnets



Beam Screen

Cold Bore



Room Temperature Vacuum : the LHC long straight sections

- 6 km of RT beam vacuum in the long straight sections
 - Except in standalone cryomagnets
- 303 sector gate valves as vacuum protection
 - Prevents saturation of the NEG coating during magnets warming up
- 780 ion pumps to avoid ion instability
 - Are used as sector gate valve interlocks
- 397 pirani gauges, 610 penning gauges and 170 Bayard-Alpert
 - Provide pressure indications
 - Are used as sector gate valve interlocks

Vacuum Control and Monitoring

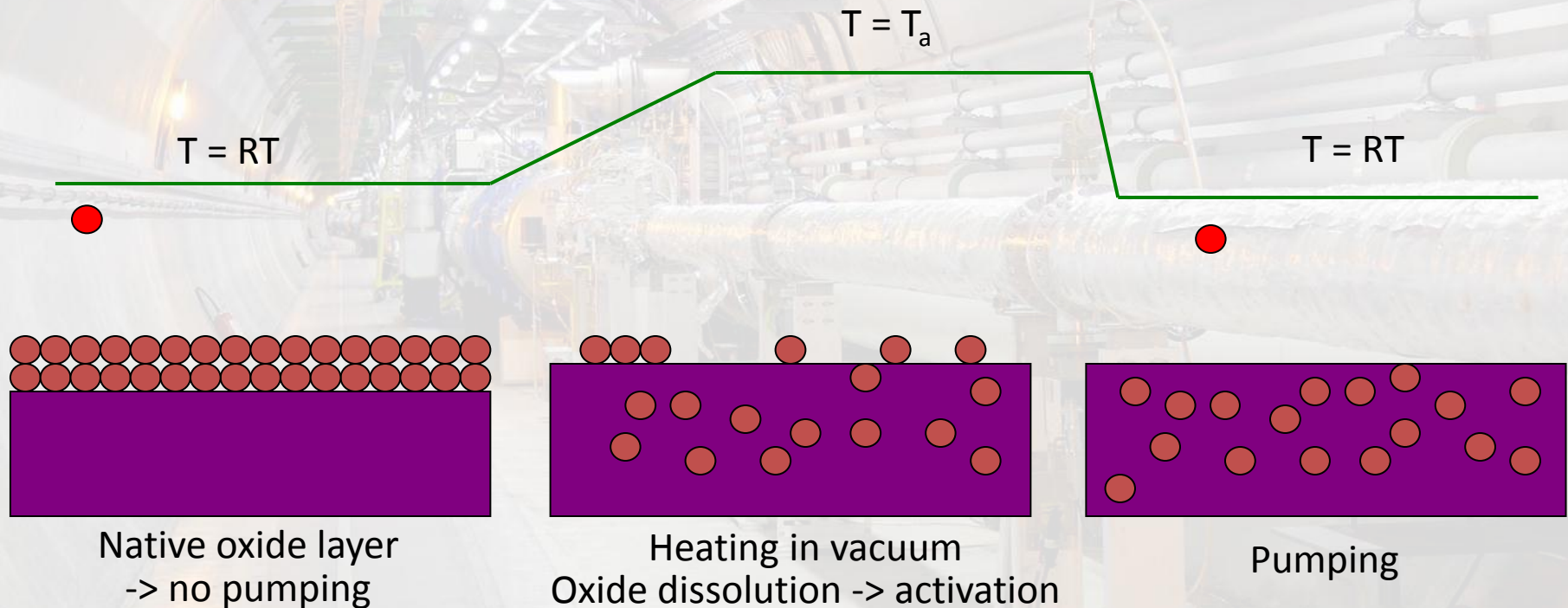


Room Temperature Vacuum : the LHC long straight sections

- Extensive use of NEG coatings
 - All beam pipes are NEG coated (~1,100)
 - Baked-out allows the vacuum activation of NEG coatings
- 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
 - 320°C for vacuum instrumentation: ports, gauges and RGAs
- Pressure lower than 10^{-9} Pa after vacuum activation
 - Pressure reading limited by outgassing of the gauge port
 - And by the gauge resolution

NEG

Getters are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean. For Non-Evaporable Getters a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.



NEGs pump most of the gas except rare gases and methane at room temperature

P. Chiggiato and P. Costa Pinto, Thin Solid Films, 515 (2006) 382-388

Room Temperature Vacuum: NEG coated

“Twin” sector

Beams circulate in different beam pipes

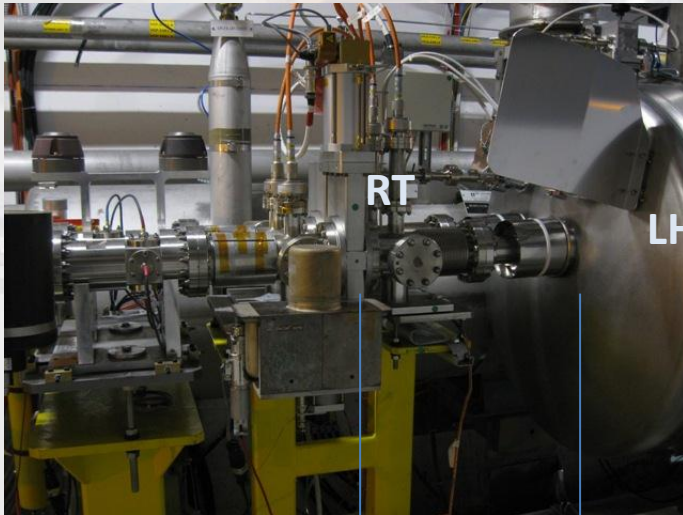


“Combined” sector

Both beams circulates in the same beam pipe

Room Temperature Vacuum: Uncoated

Cold-Warm transition in the long straight section



uncoated & unbaked

NEG coated & unbaked



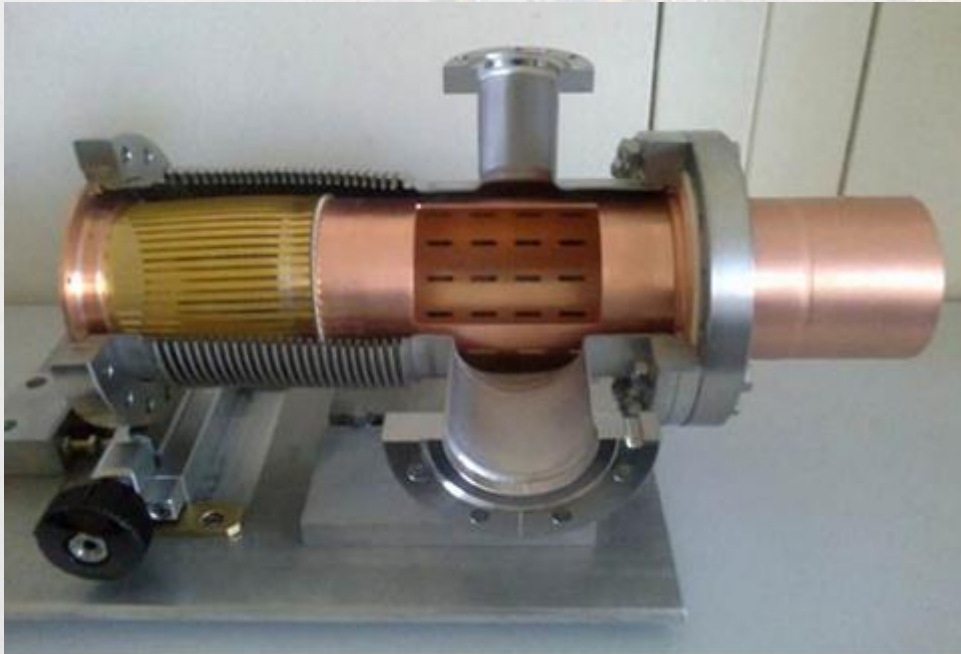
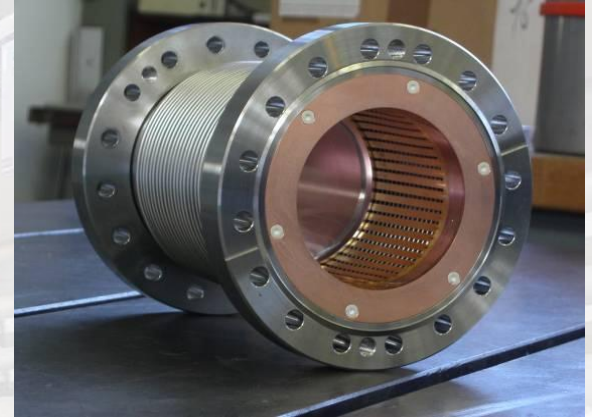
Uncoated parts in the room temperature beampipes



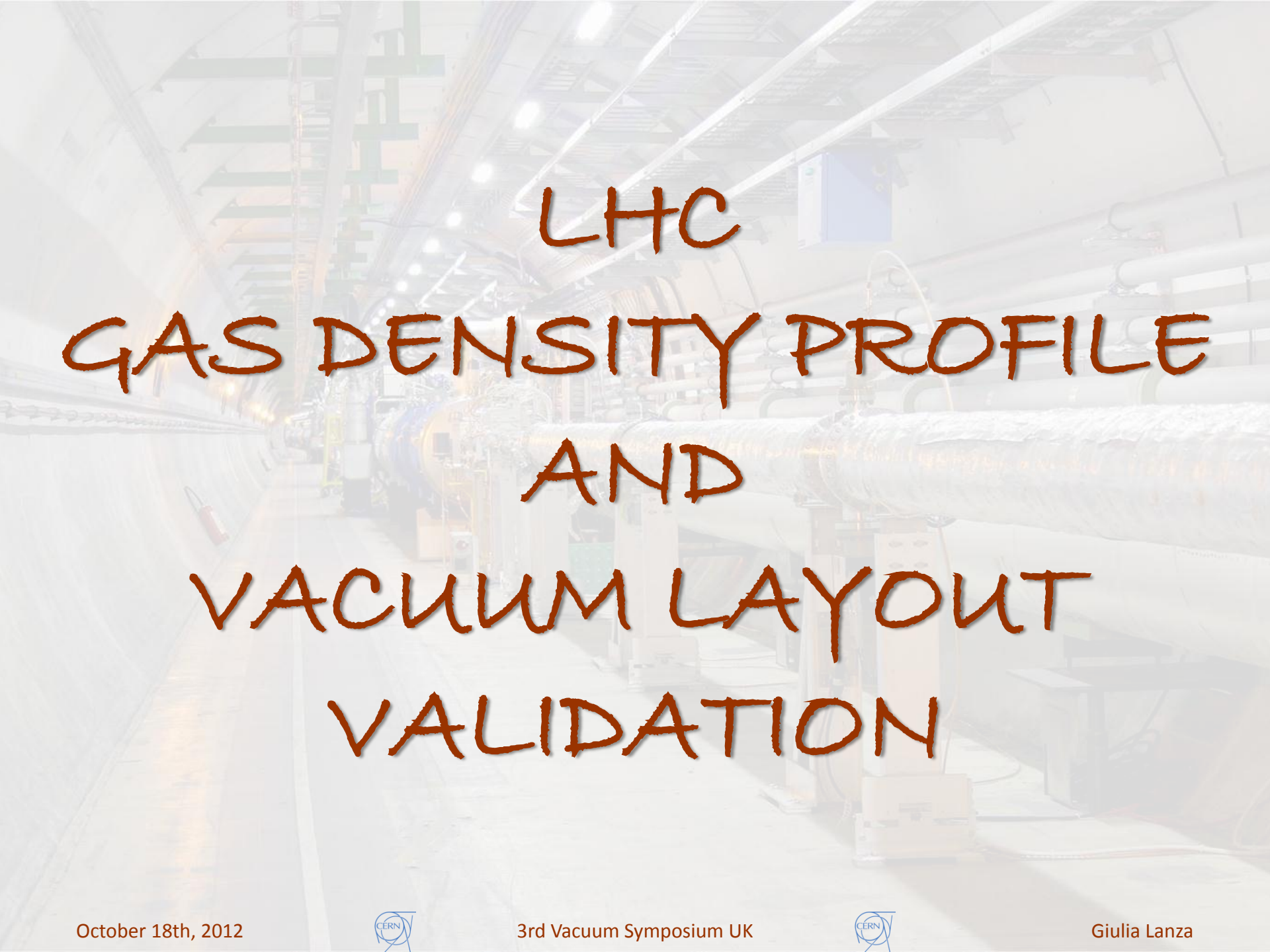
RF module



Bellow shielding :
copper-beryllium
contact fingers which
slide on a rhodium-
coated copper tube



- To allow thermal expansion during bake out
- To compensate the mechanical and alignment tolerances
- Low electrical resistance ($<0.1\text{m}\Omega$)
- Low inductance



LHC GAS DENSITY PROFILE AND VACUUM LAYOUT VALIDATION

VAcuum Stability Code: General Gas Density Equations

Static Vacuum

+

Dynamic Vacuum

$$V \frac{\partial n_g}{\partial t} = a \cdot D_g \cdot \frac{\partial^2 n_g}{\partial x^2} - \frac{I}{e} \sum_j \left\{ \eta_{i,j^+ \rightarrow g} \sigma_j^b \cdot n_j \right\} - \left(\frac{A \cdot v_g}{4} \cdot \alpha_g + C_g \right) \cdot n_g + \underbrace{\eta_{ph,g} \cdot \dot{\Gamma}_{ph}}_{\text{Desorption by photons}} + \underbrace{\eta_{e,g} \cdot \dot{\Gamma}_e}_{\text{Desorption by electron}} + \underbrace{A \cdot q_g}_{\text{Thermal desorption}}$$

Time variation of particles in volume V

Diffusion through surface a

Ionization by beam and desorption by the ions

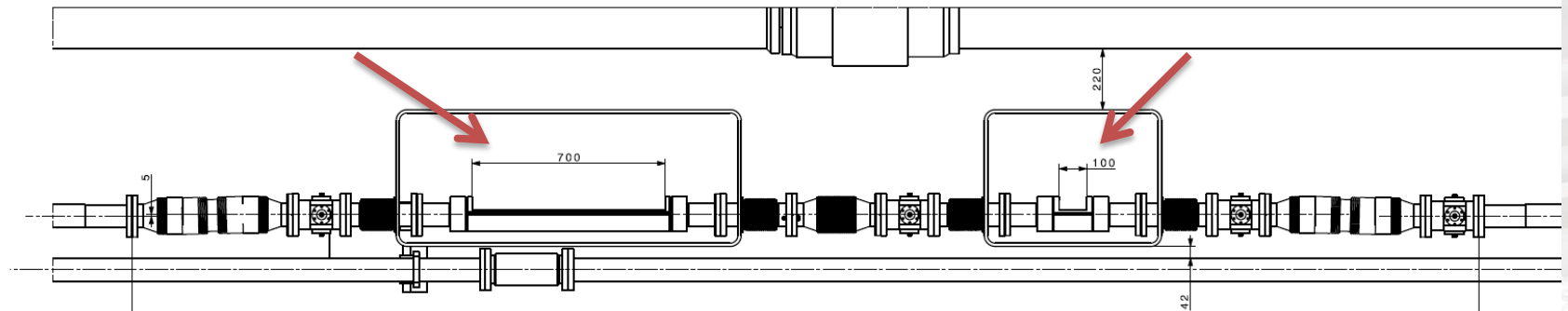
Distributed pumping of NEG or Cryo

Desorption by photons ***by electron***

Thermal desorption

Simulated pressure profile: VAcuum Stability Code

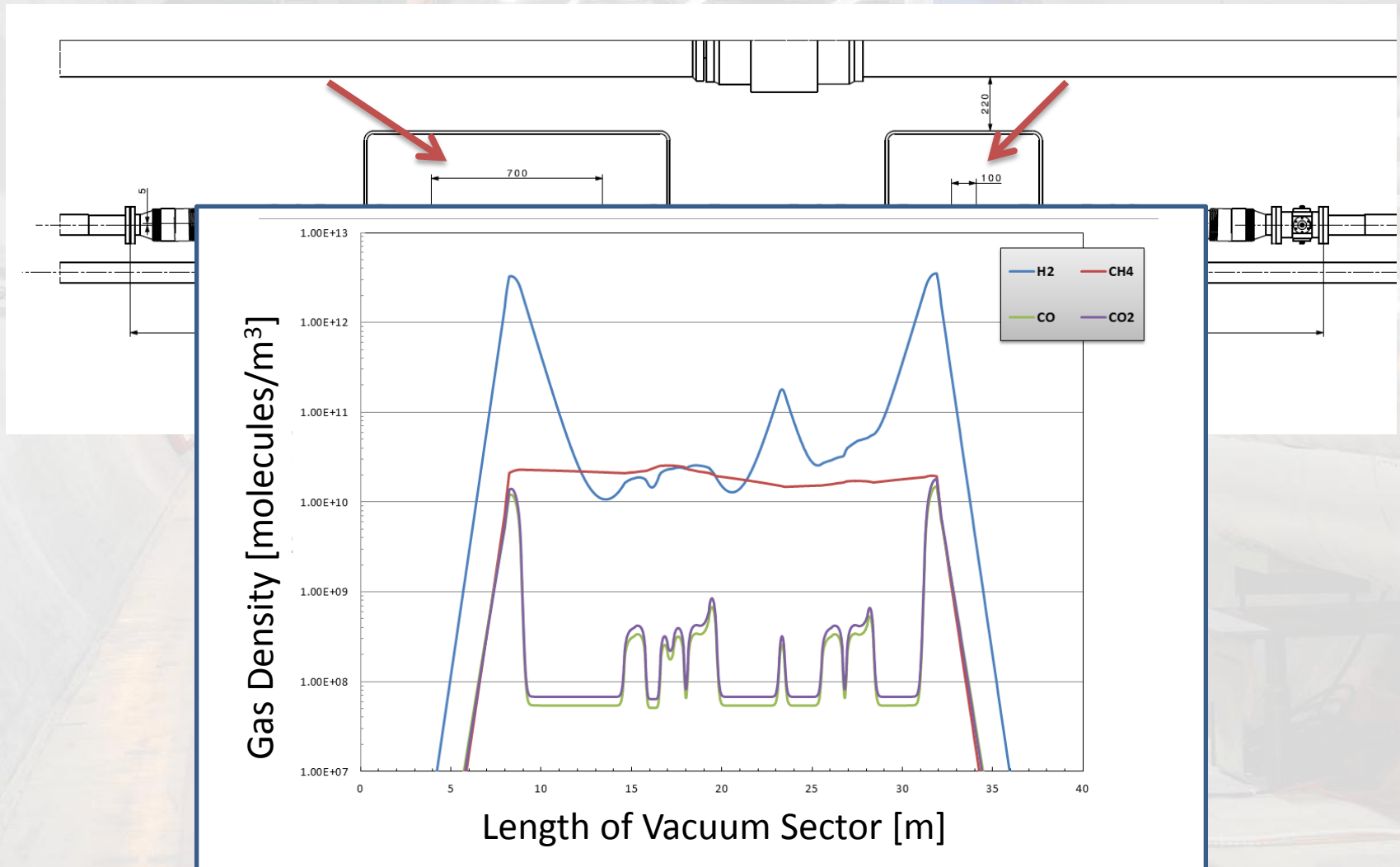
Integration of the Hamburg Beam Pipe in the LHC vacuum system



Integration of a rectangular shaped vacuum chamber on a vacuum sector
Analysis of the gas density profile

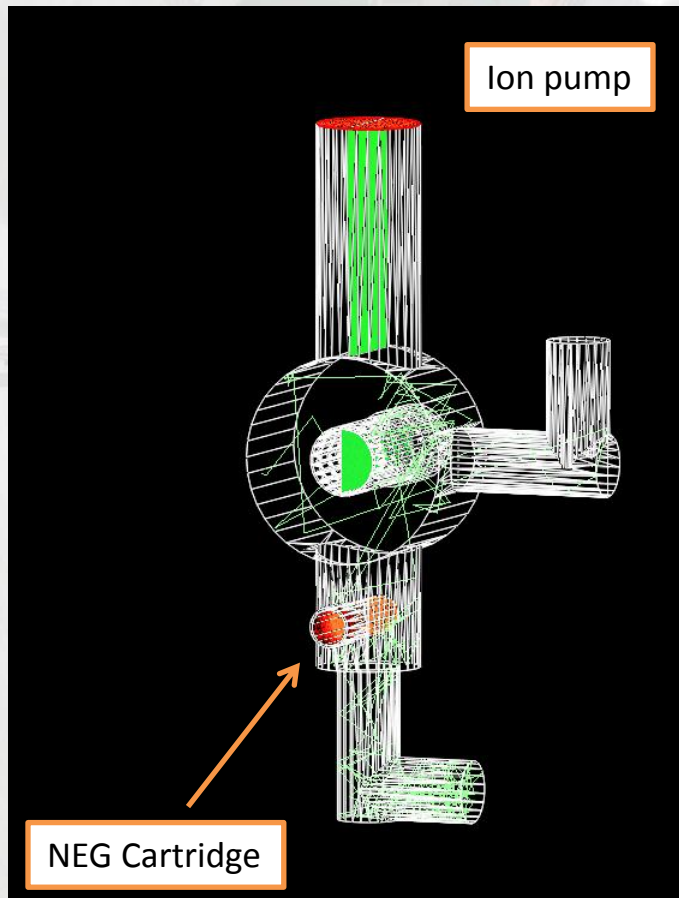
Simulated pressure profile: VAcuum Stability Code

Integration of the Hamburg Beam Pipe in the LHC vacuum system



Gas density profile simulation: Molflow+

A Test-Particle Monte-Carlo Simulator for Ultra-High Vacuum systems



Simulation done with a flow of 1×10^{-8} mbar*l/s coming from the VAX insert

	Pressure in the beam line [mbar]	Pressure in the SVT gauge [mbar]
Ion Pump	2×10^{-8}	2×10^{-8}
Ion Pump + D400 NEG cartridge	6×10^{-9}	6×10^{-9}

Data from G.Bregliozi – TE-VSC

For info: <http://test-molflow.web.cern.ch/content/about-molflow>



LHC OPERATION

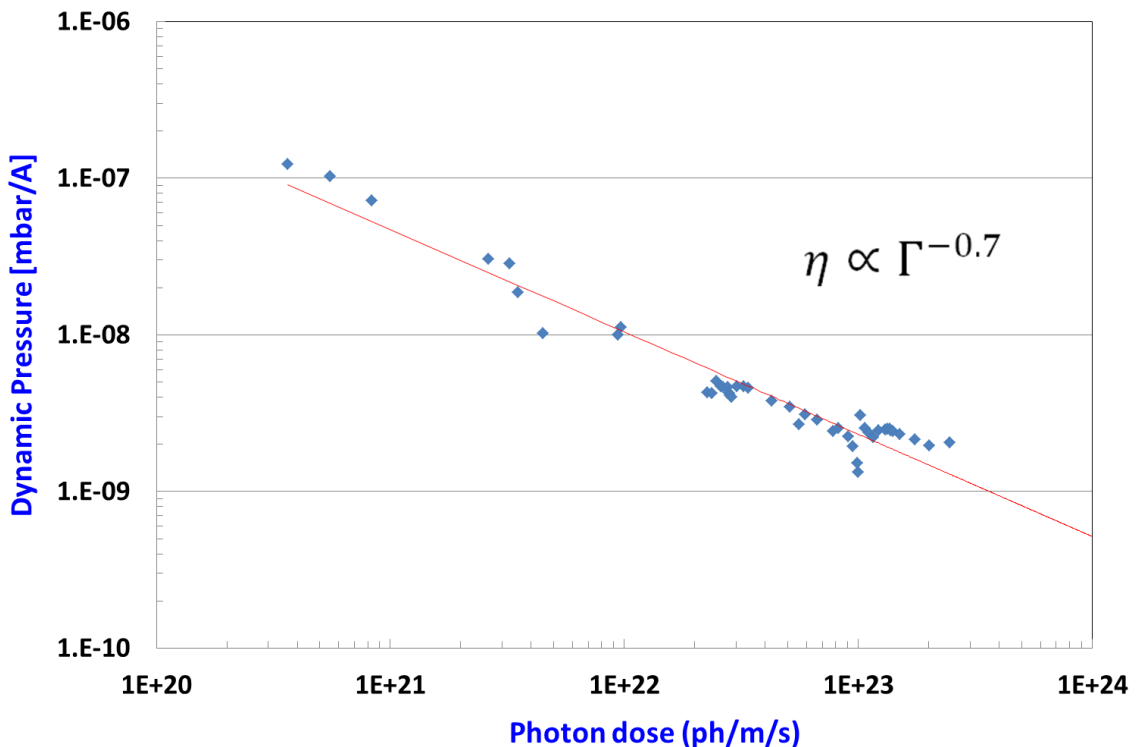
Synchrotron Radiation

Pressure increases due to
synchrotron light
irradiation

$$V \frac{\partial n_g}{\partial t} = \eta_{ph, g} \cdot \Gamma_{ph}$$

Vacuum cleaning
(photon desorption yield decreasing)
of the vacuum system

BEAM SCREEN AT 5→20 K
USING 2 COOLING CHANNELS



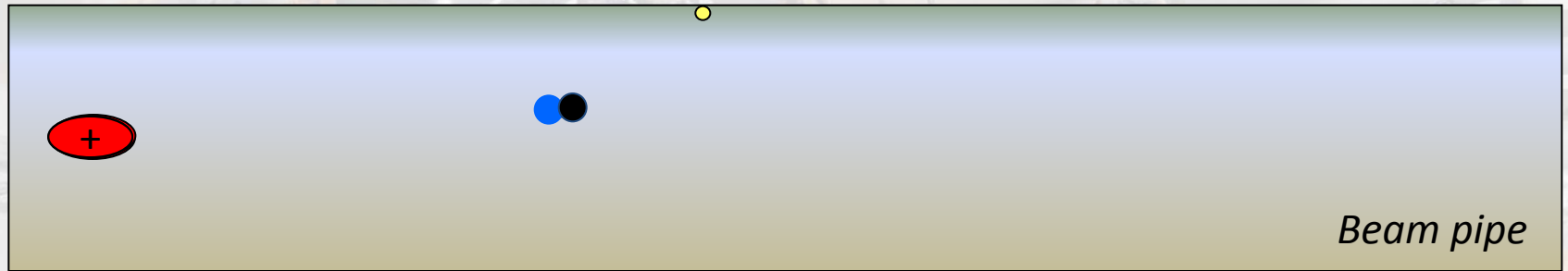
Key Message



PHOTON
IRRADIATION WILL
BE ALWAYS
PRESENT DURING
OPERATION

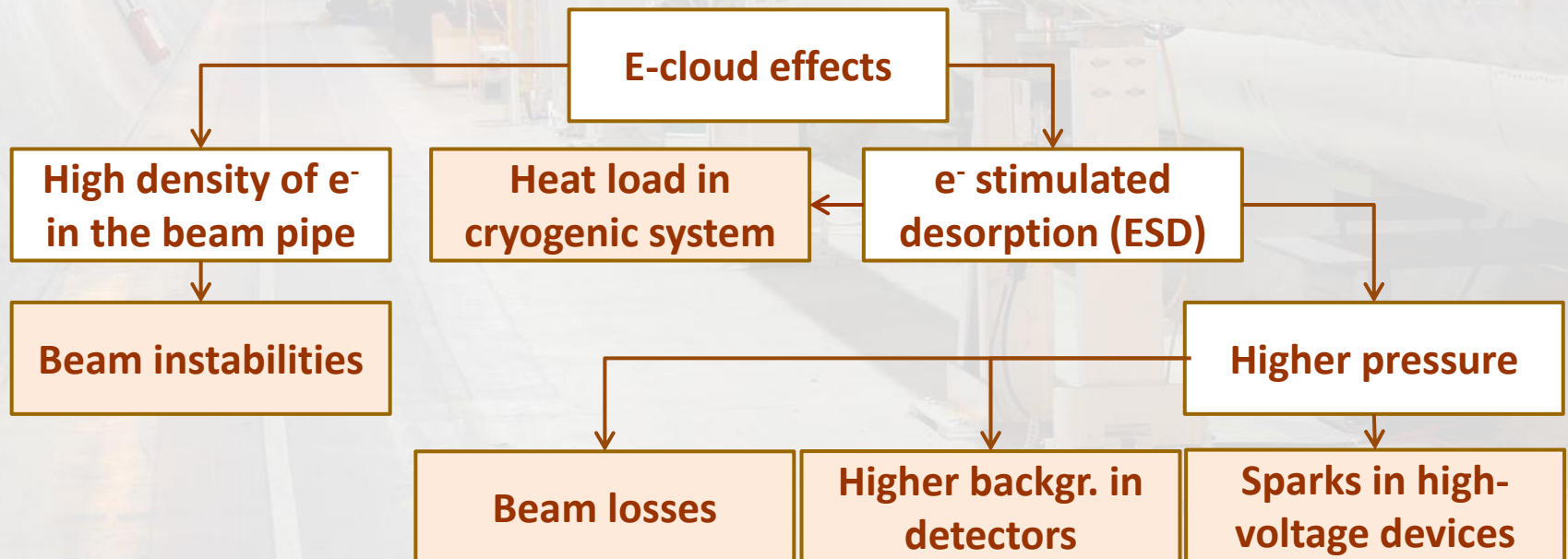
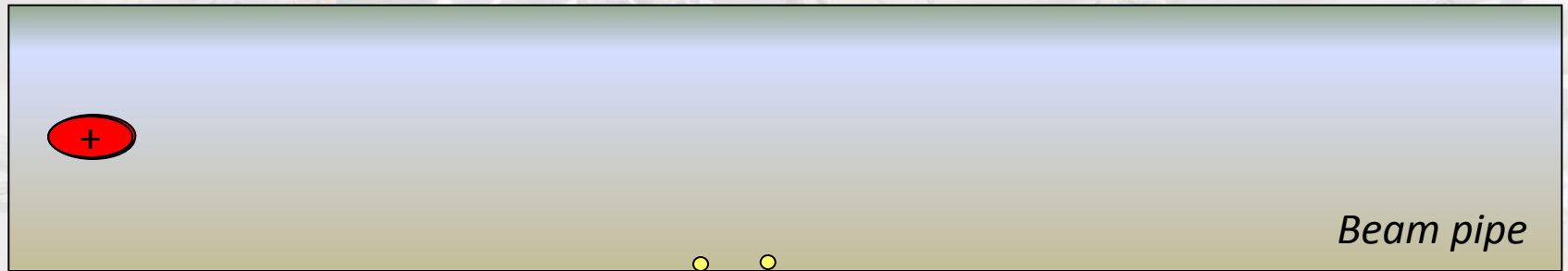
Electron Cloud

Electron clouds in beampipes are generated by **electron multipacting** on the wall of the vacuum chamber. The electrons are accelerated by the electric field of the bunches.



Electron Cloud

Electron clouds in beampipes are generated by **electron multipacting** on the wall of the vacuum chamber. The electrons are accelerated by the electric field of the bunches.



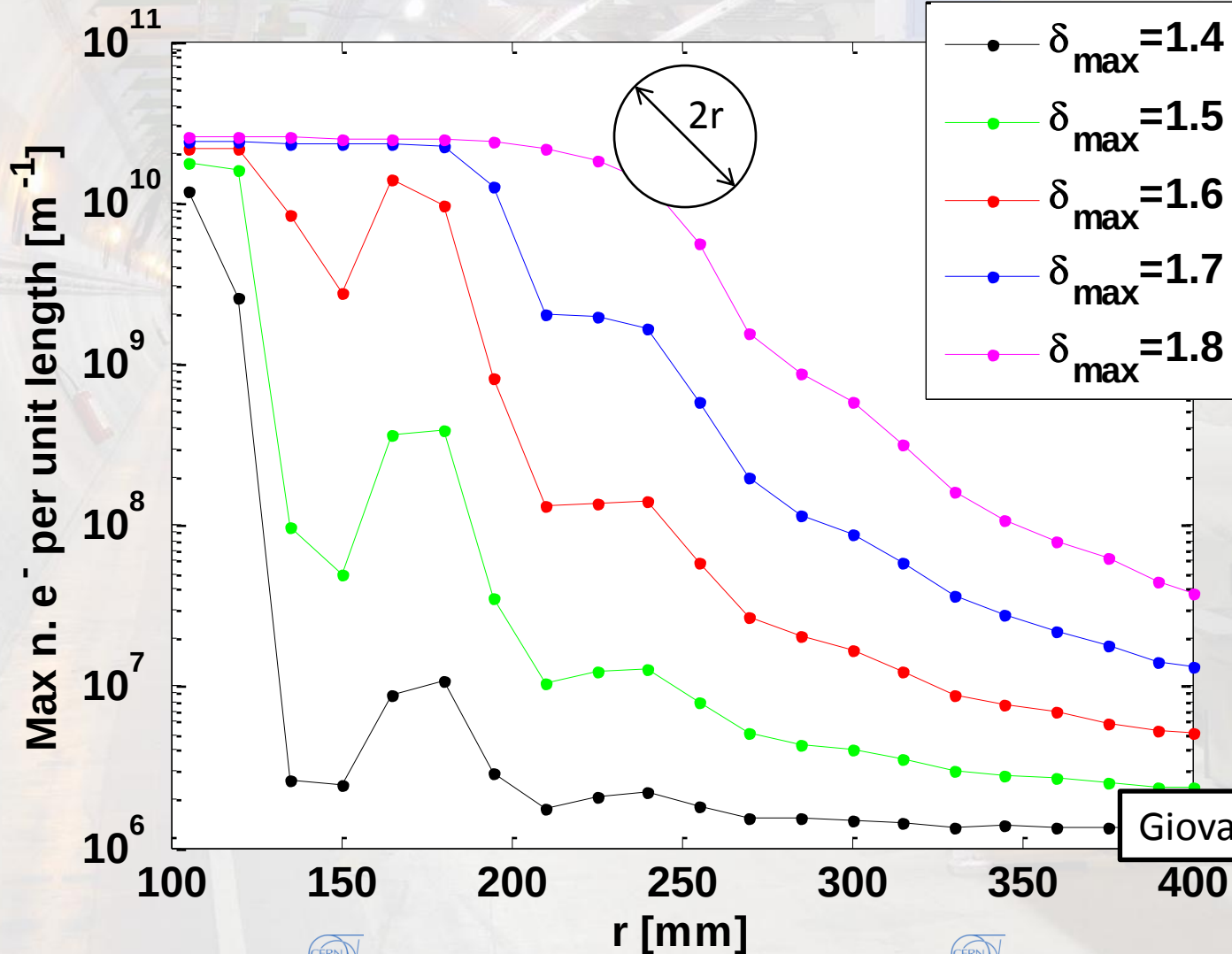
E-Cloud Parameter Dependence

➤ Beam pipe geometry and size

Electron cloud in the taper – 25ns

One 25 ns beam (Intensity $1.1 \cdot 10^{11}$ ppb)

72	8	72	8	72	8	72
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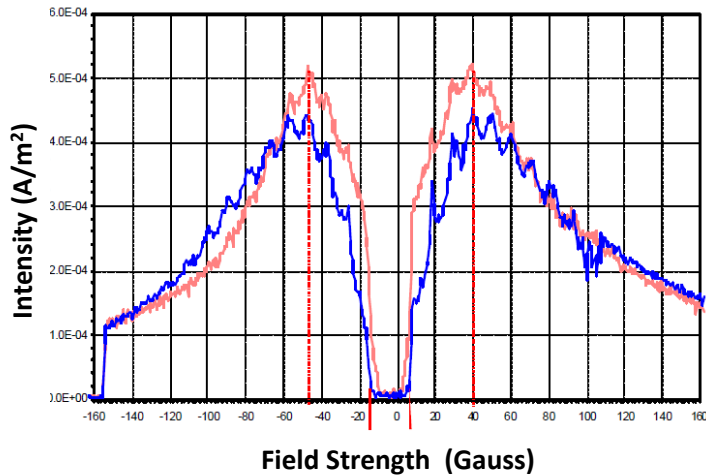
Giovanni Iadarola

E-Cloud Parameter Dependence

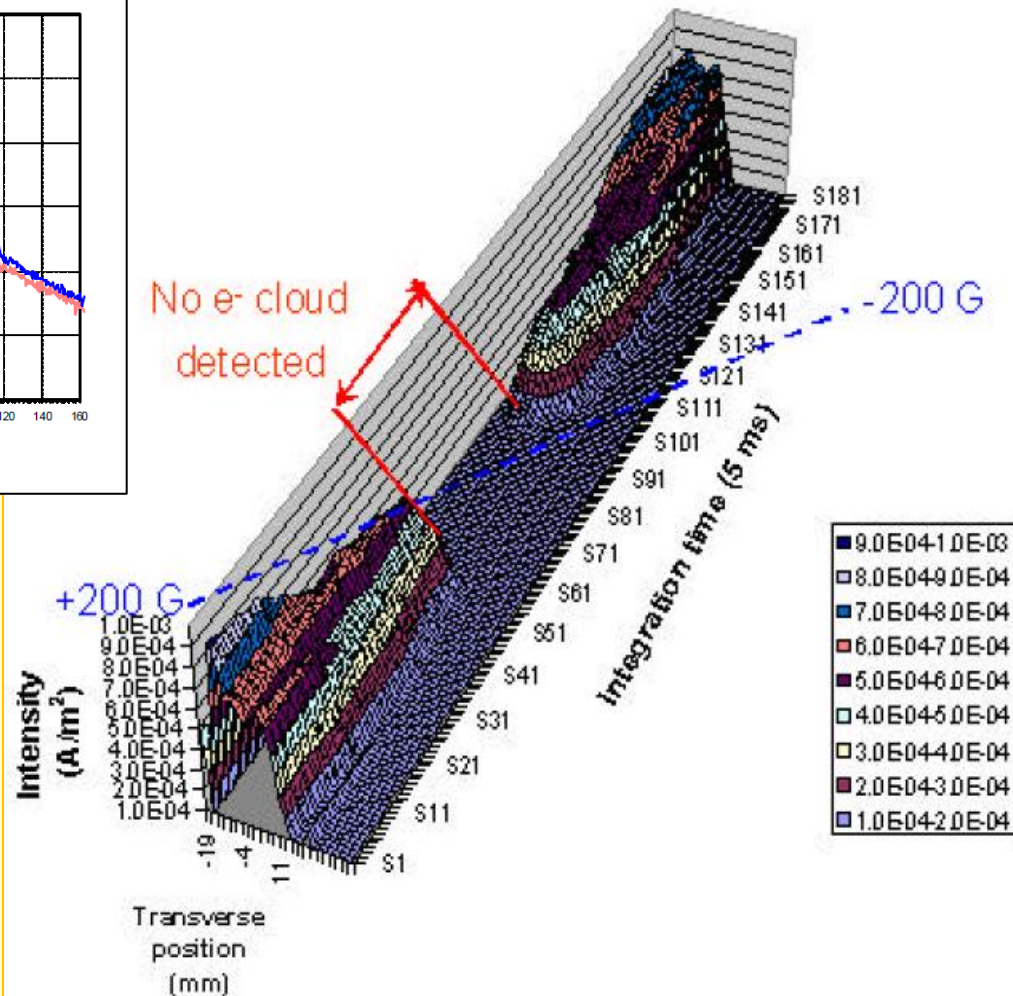
- Beam pipe geometry and size
 - Magnetic field

E-cloud Magnetic Field Dependence

Limit of detection: $4.2 \times 10^{-7} \text{ A/m}^2$



A dipole field of 20 to 30 Gauss was required to trigger the electron cloud



Electron Clouds - Results from SPS and Experiments for 2003
LHC Performance Workshop CHAMONIX XII, Session 10 (2003)

Courtesy J.M. Jimenez

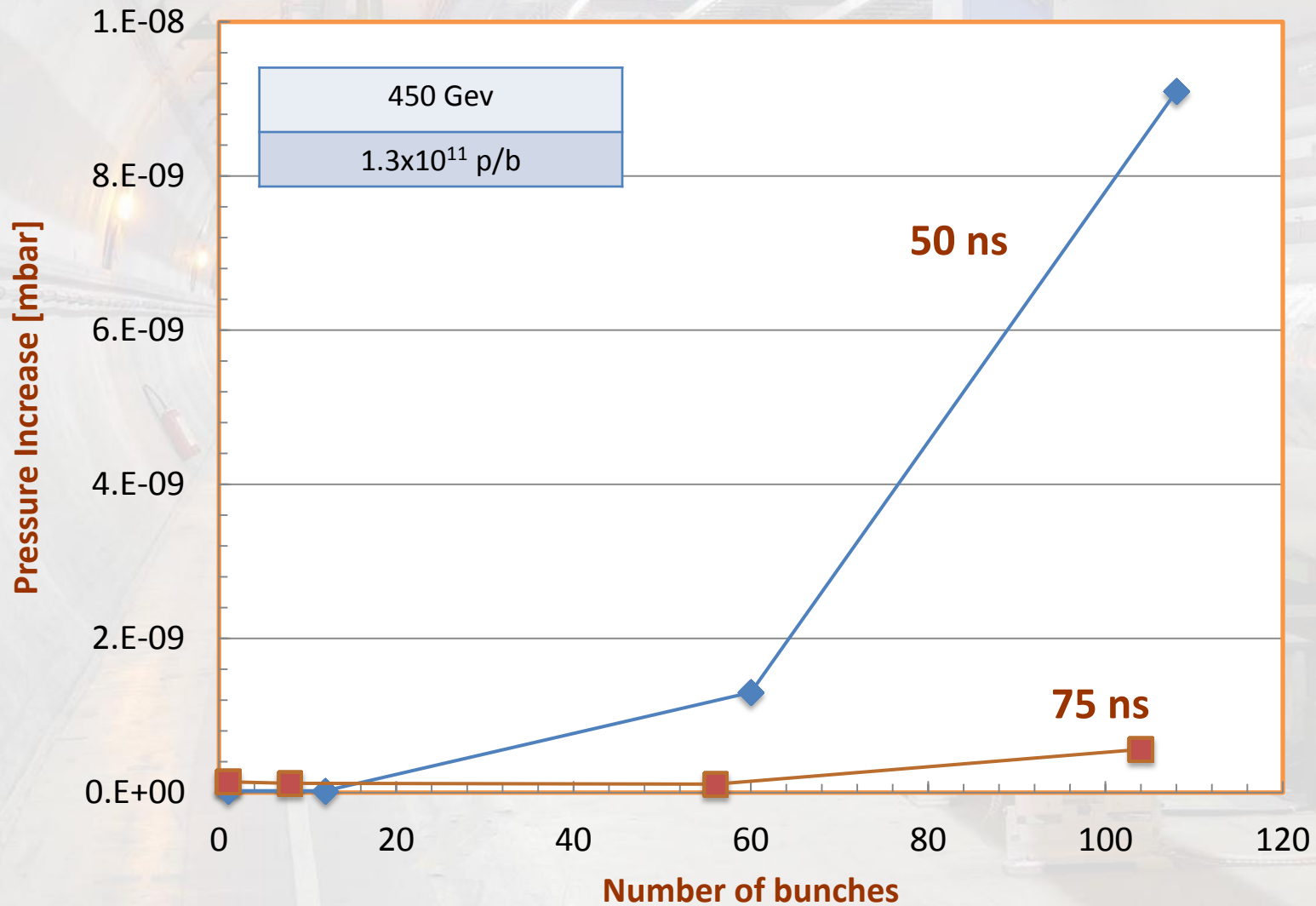
E-Cloud Parameter Dependence

- Beam pipe geometry and size
- Magnetic field
- Beam parameters
 - Bunch spacing
 - Number of bunches
 - Bunch intensity

e-Cloud Effects in LHC Vacuum

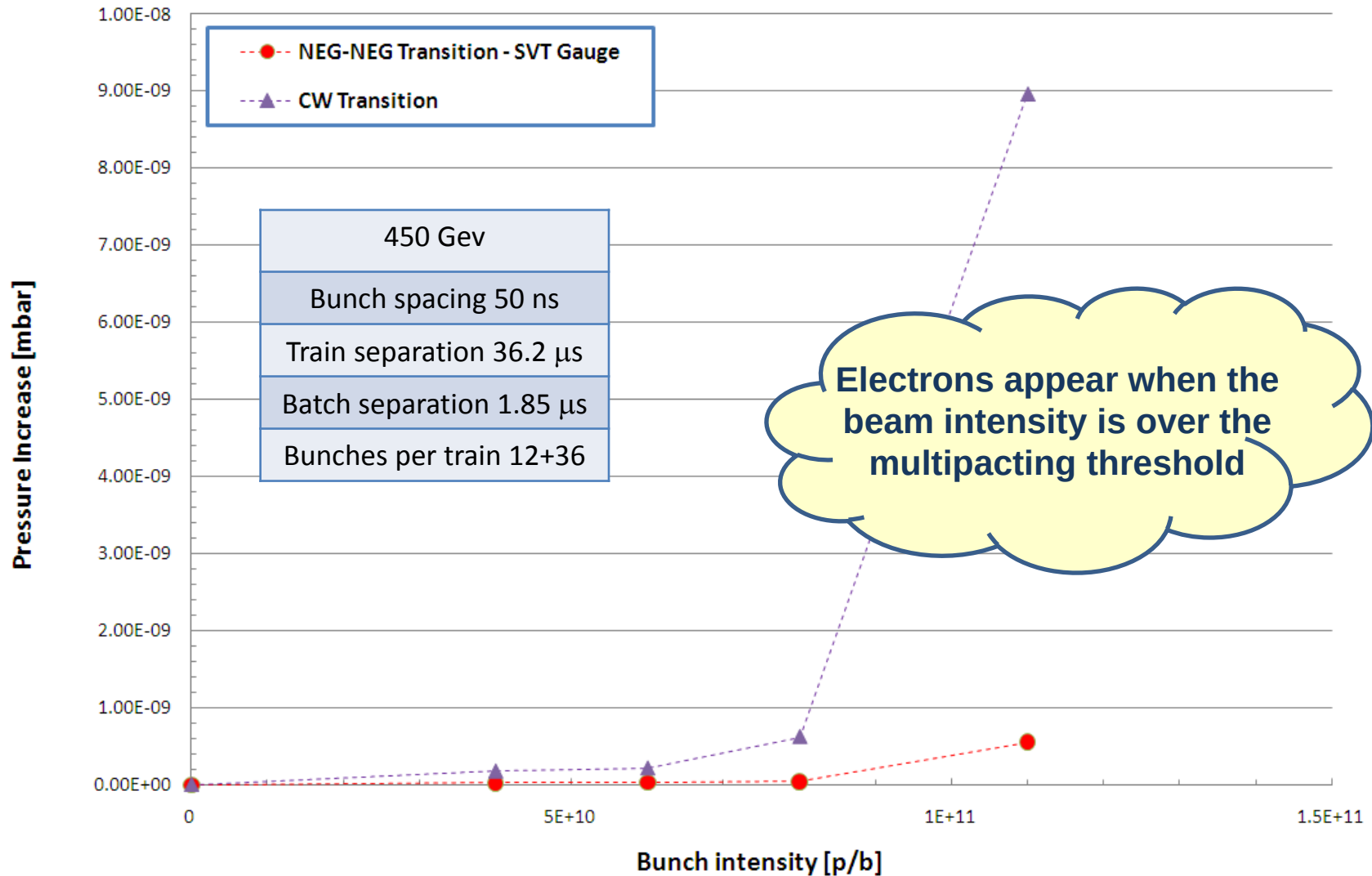
Influence of Bunch Spacing

RT Transition



e-Cloud Effects in LHC Vacuum

Influence of Bunch Population



E-Cloud Parameter Dependence

- Beam pipe geometry and size
- Magnetic field
- Beam parameters
- SEY of the surface material

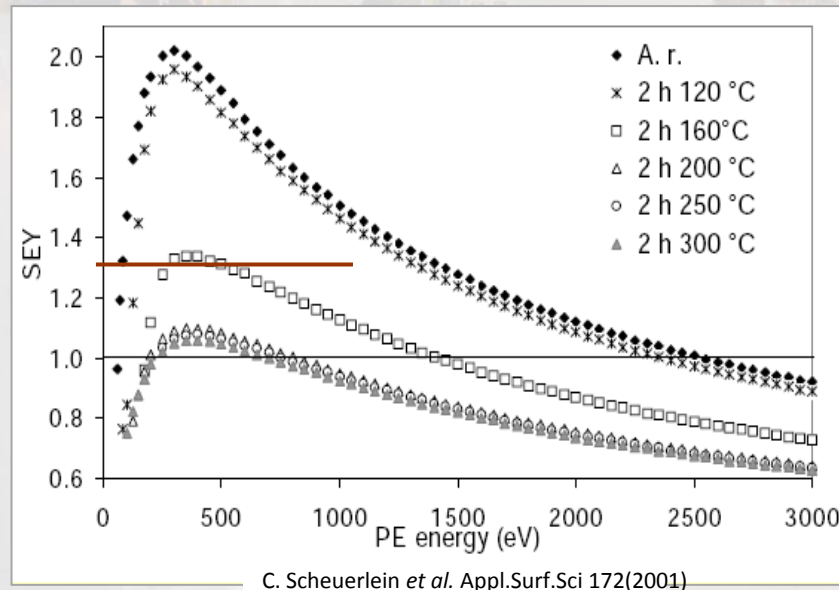
Conditioning

For the LHC: $\delta_{\max} < 1.3$

- Reduction of SEY under electron irradiation
- 1 to 10 mC/mm² is required

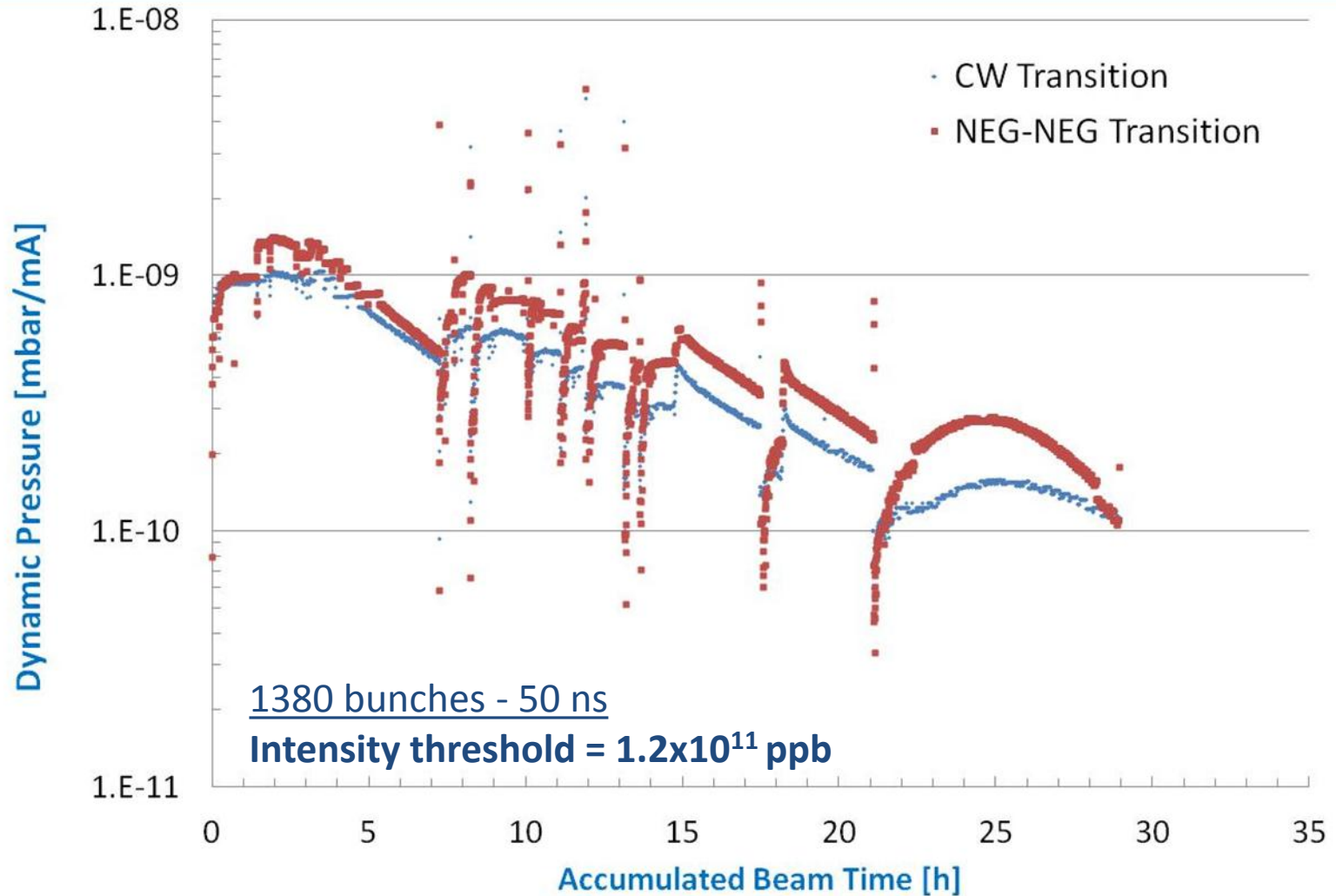
Typical values for LHC vacuum materials:

Material	dmax Surface not conditioned
Stainless steel	2.2
Copper	2.1
TiZrV activated	1.1



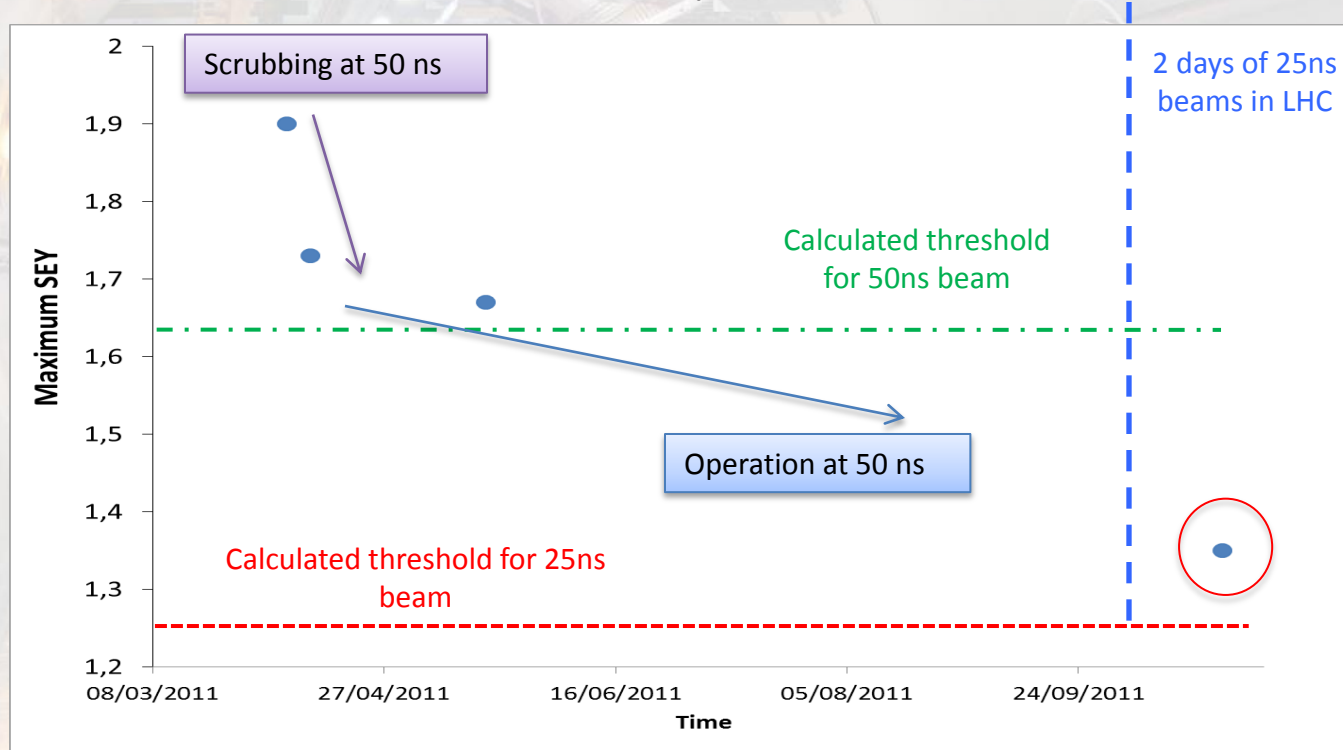
Beam Scrubbing

$$P \approx \frac{\eta_{\text{Electrons}} \cdot \dot{\Gamma}_{\text{Electrons}}}{S}$$



Key Message

- Scrubbing at 50 ns Scrubbing has lowered $\delta_{\max}$ to 1.7.
- During the 2011 operation with 50 ns the $\delta_{\max}$ further decrease.
- Scrubbing with 25ns beam (~40h) has lowered $\delta_{\max}$ to 1.35 !



- 1) No more electron cloud at 50 ns (up to $1.45 \cdot 10^{11}$ ppb at least)
- 2) Requires further scrubbing to operate with 25 ns

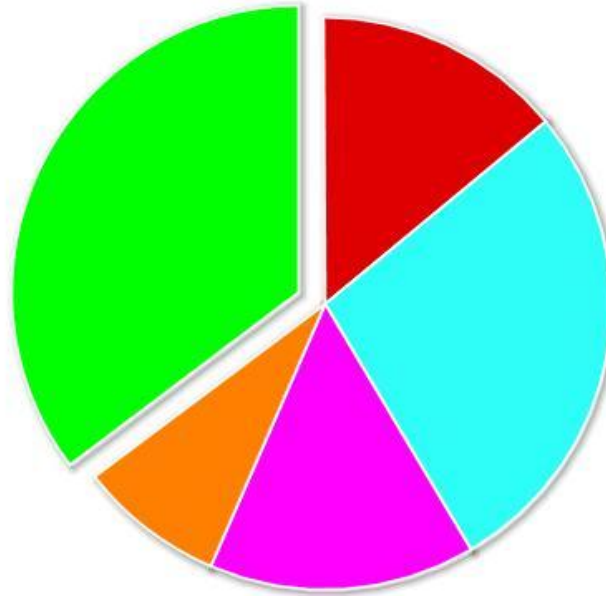
From G.Rumolo, EVIAN 2011



LHC LOCAL INTERVENTIONS

LHC Efficiency and Availability

Mode: Proton Physics
Fills: 2469 – 3191 [592 Fills]
SB Time: 55 days 14 hrs 31 mins



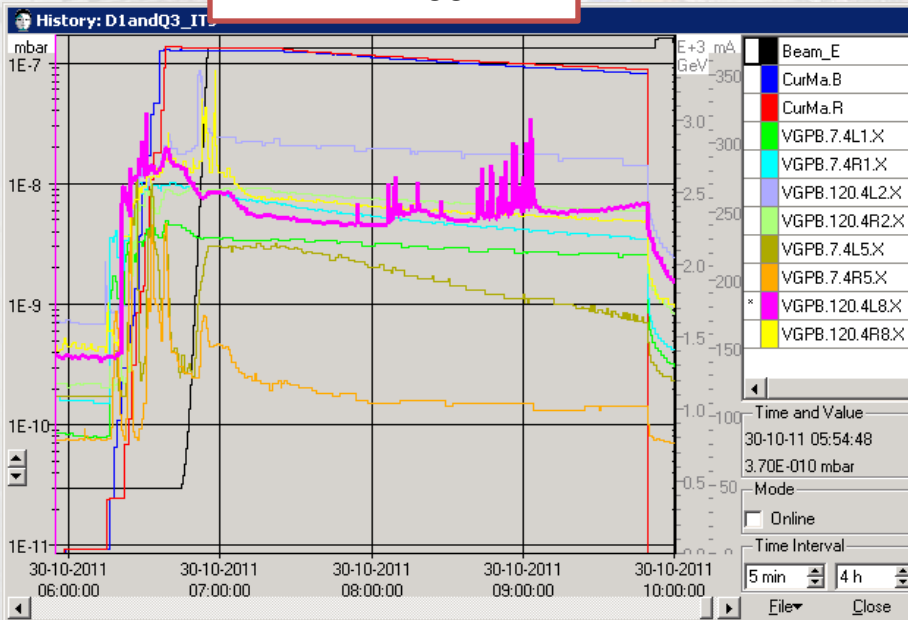
■ Access - No beam : 14.05% ■ Machine setup : 27.43%
■ Beam in : 15.04% ■ Ramp + squeeze : 8.17%
■ Stable beams: 35.31%

Pressure Spikes in LSS2 and LSS8

Frequently, pressure spikes were observed mainly at LSS2 and LSS8

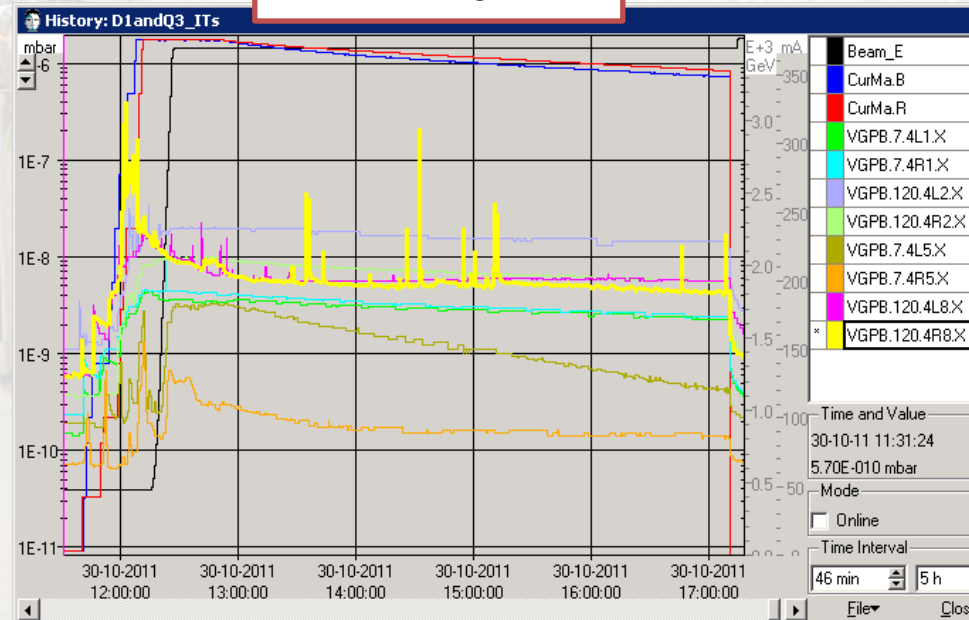
Spikes during **stable beams**
above 10^{-8} mbar

Fill 2266

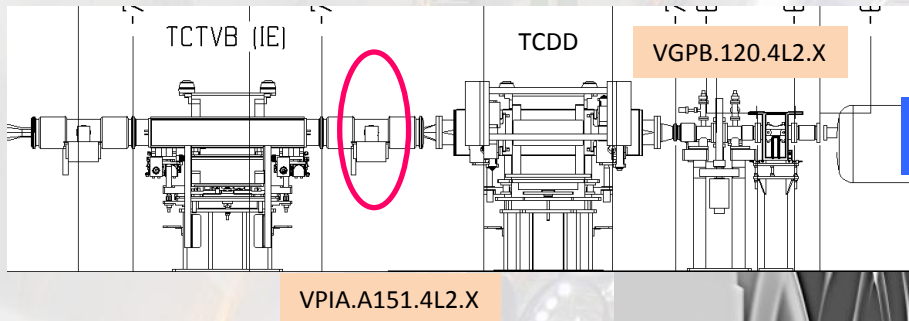


Spikes during **injection and stable beams**
above 10^{-7} mbar

Fill 2267



Typical default in the RF Finger

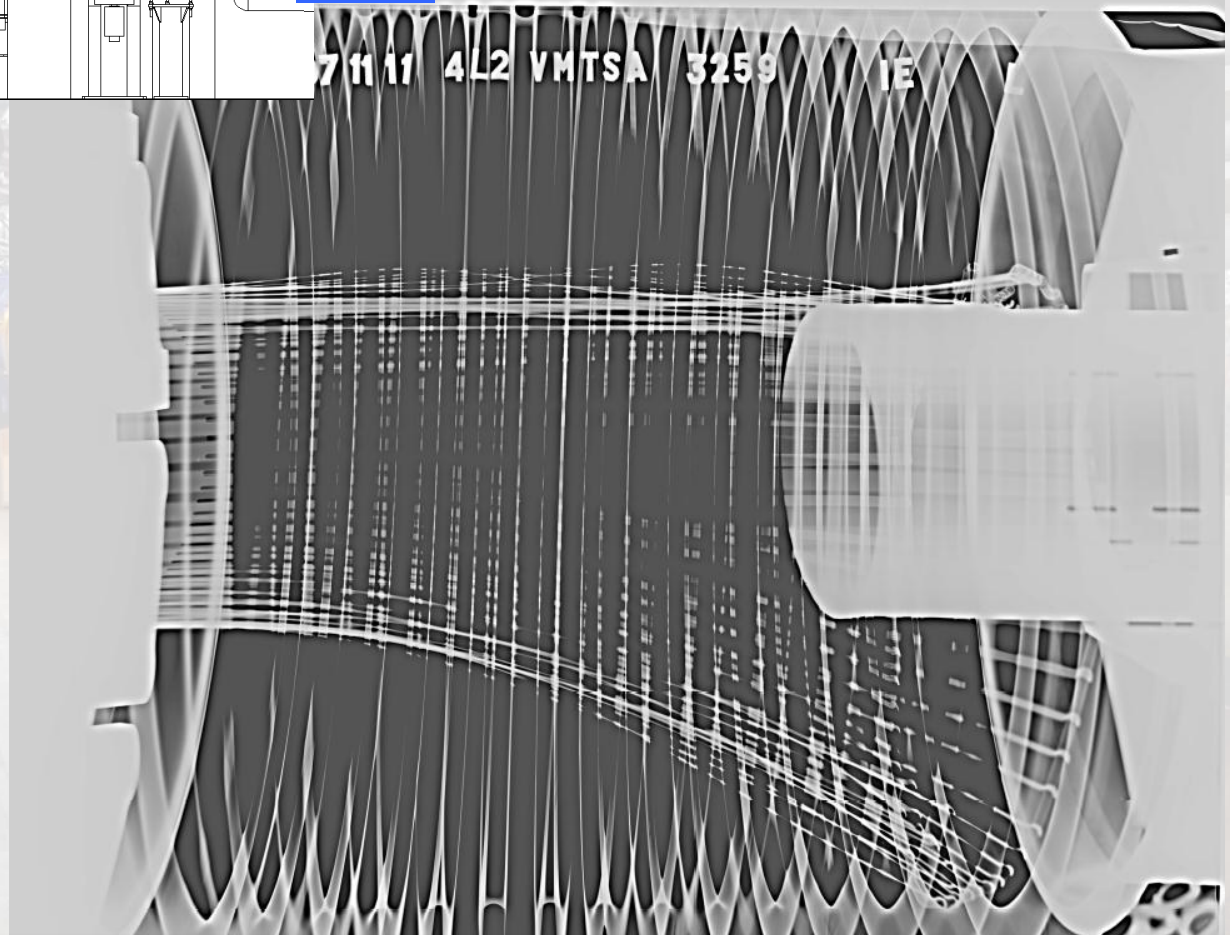


Point 2 Left side: Side view

Heating of RF fingers and spring holding the RF fingers in contact with the slots

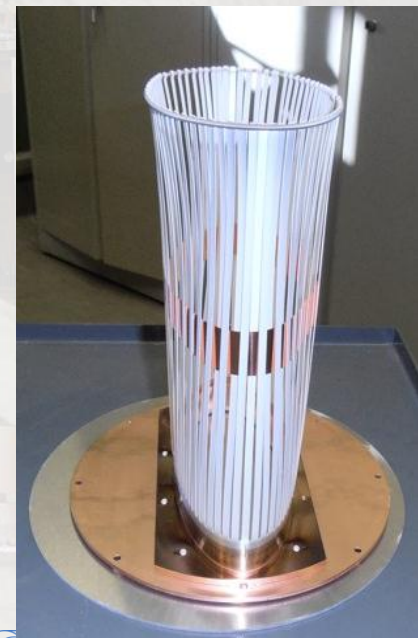
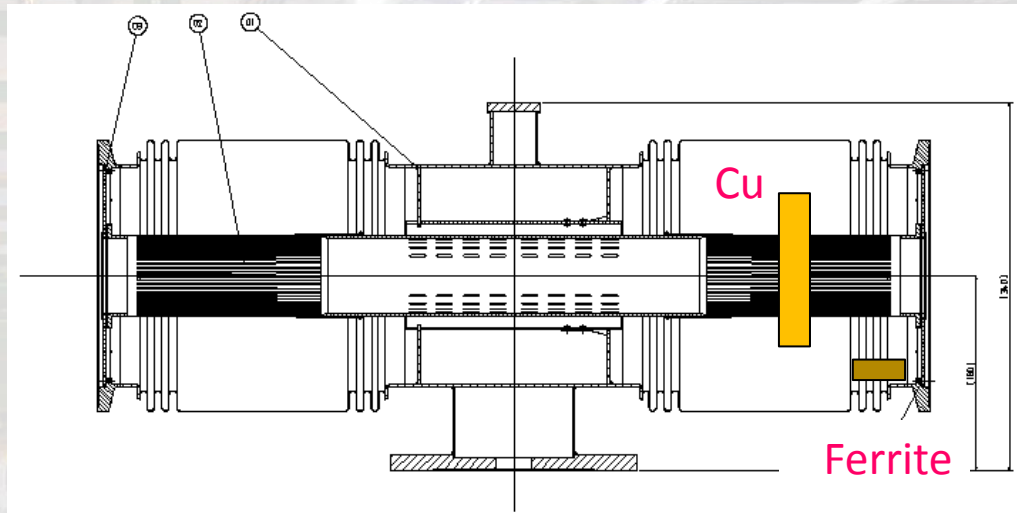
Spring and RF fingers were deformed between May and November 2011

During beam operation possible electric arcs could induce degassing: pressure spikes



Winter Technical Stop 2011-12: The non-conform modules were repaired and consolidated.

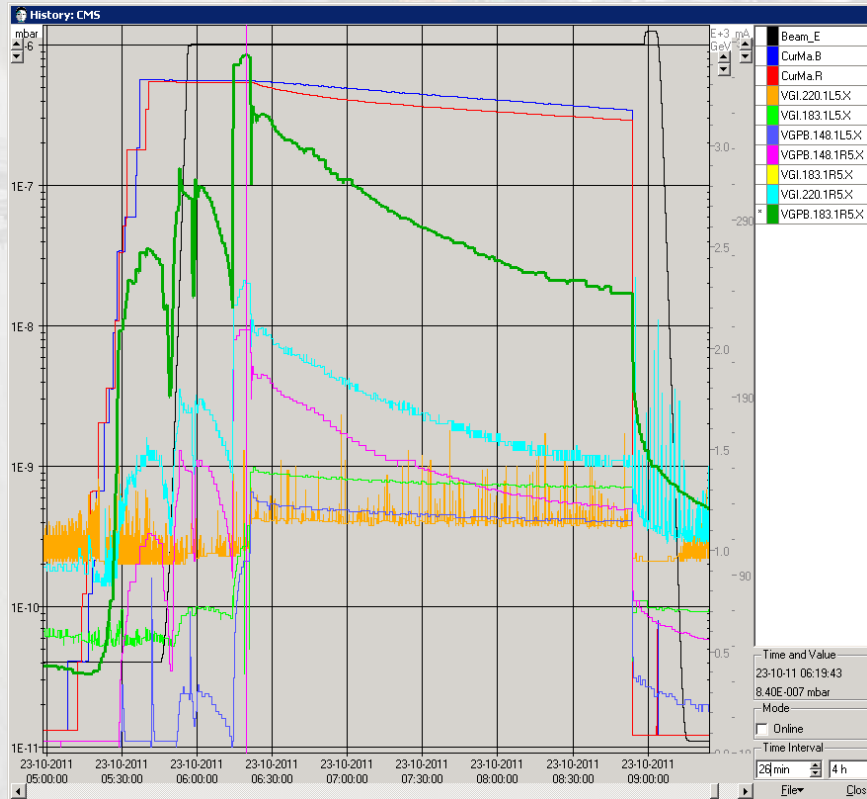
RF Finger consolidation



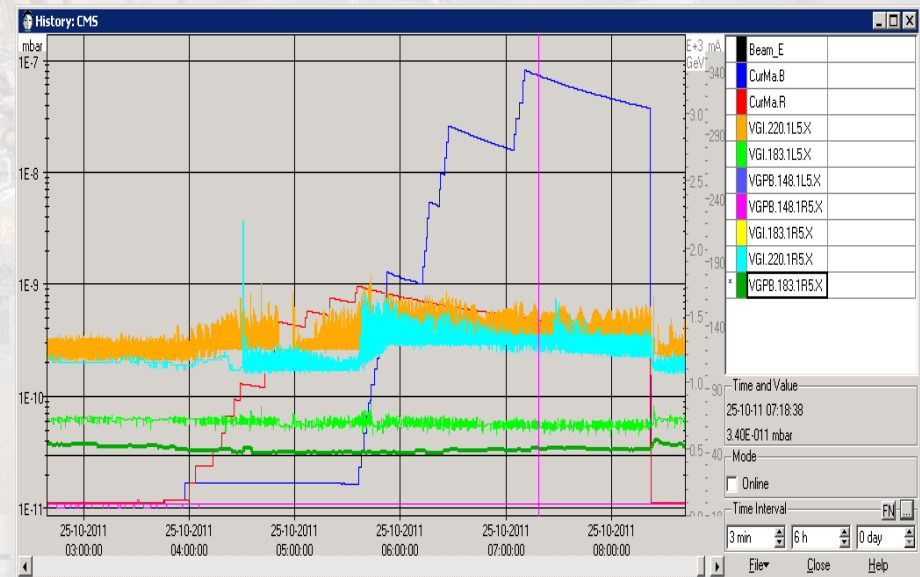
CMS pressure spikes

- CMS background suffers from pressure rise localized around 18 m from the IP
- The CMS magnetic field ensure the multipacting suppression, it's not ecloud!

Fill 2241 at 50 ns bunch spacing



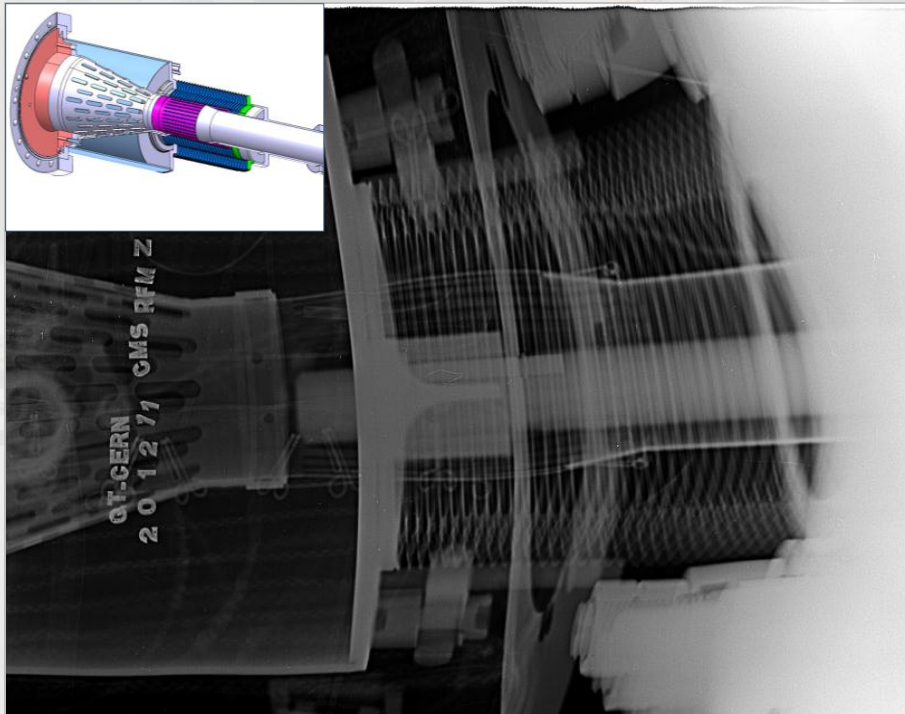
Fill 2251 at 25 ns bunch spacing, small pressure rise were detected



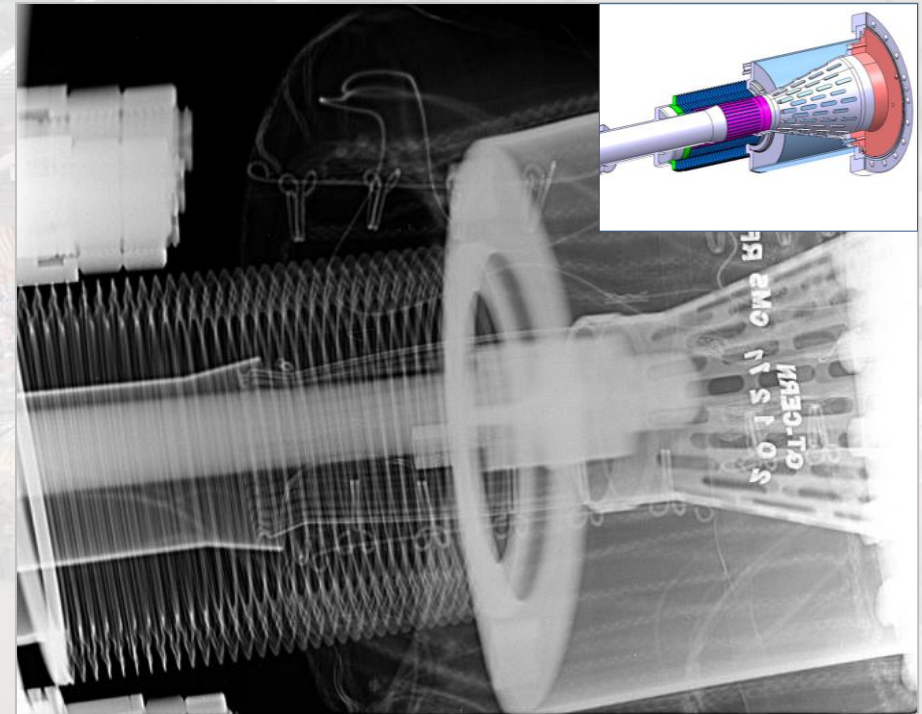
Pressure excursion at 18 m does not seems to be triggered by multipacting

Winter Technical Stop 2011-12 : X-Ray and upgrade of pumping system

RF insert and CMS



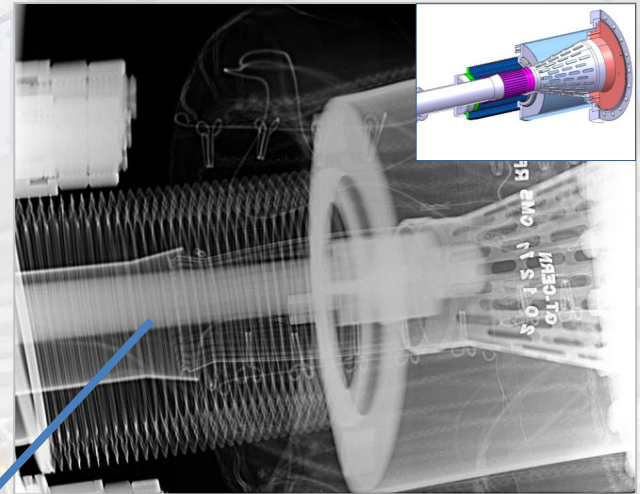
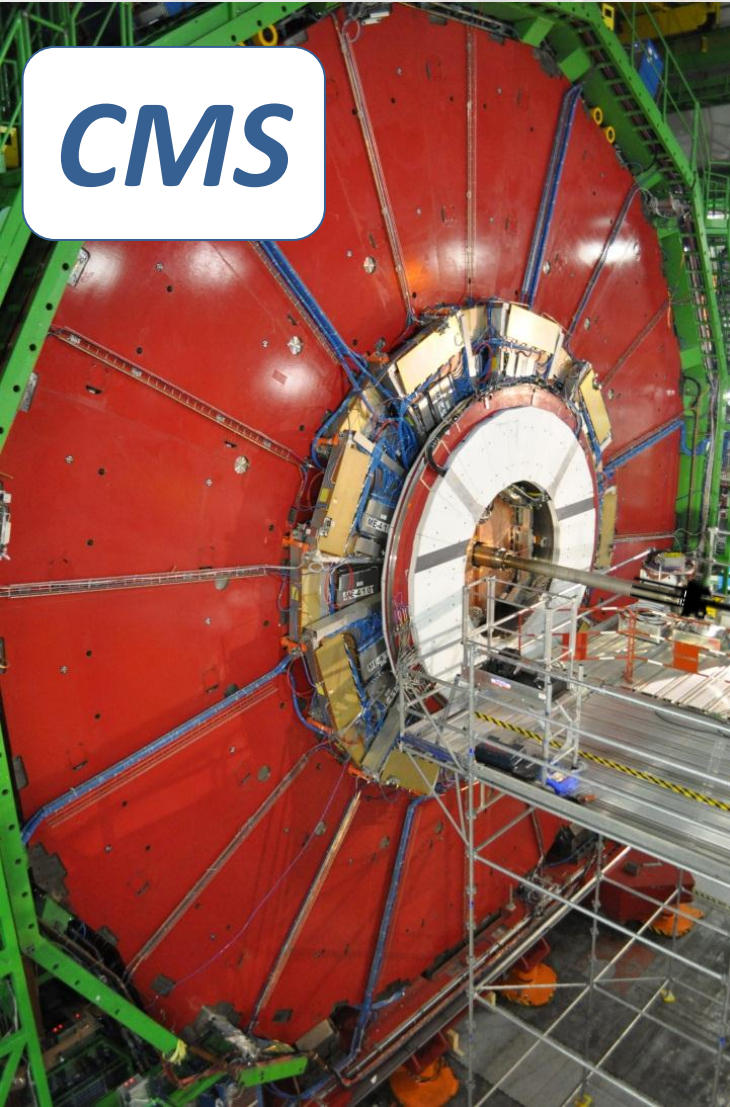
X-ray imaging of the forward module located at 18.3 m from the IP revealed a non conformity of the RF insert



The RF insert fingers overlap was shorter (6 mm) than the standard 13mm and some of the fingers were inside the beam vacuum chamber

CMS

CMS



Forward chamber

CMS

CMS

**16 m & 18 m
flanges were opened
while Ne flushing**

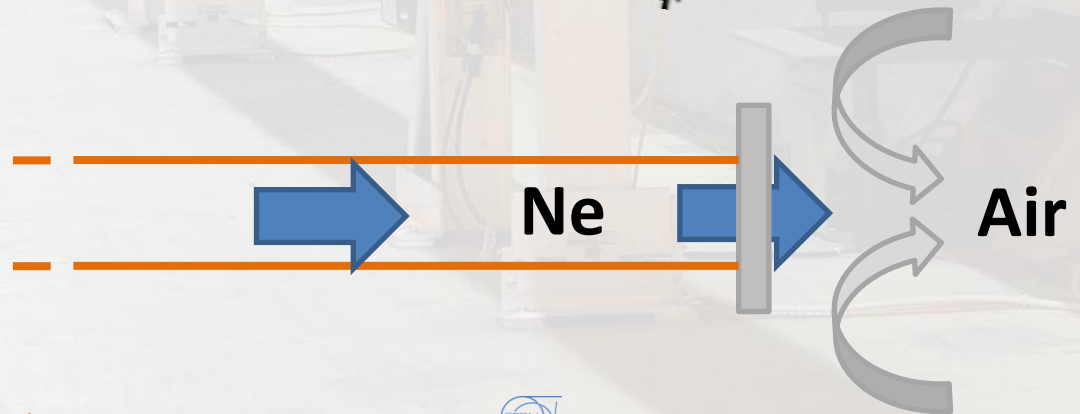
Forward chamber

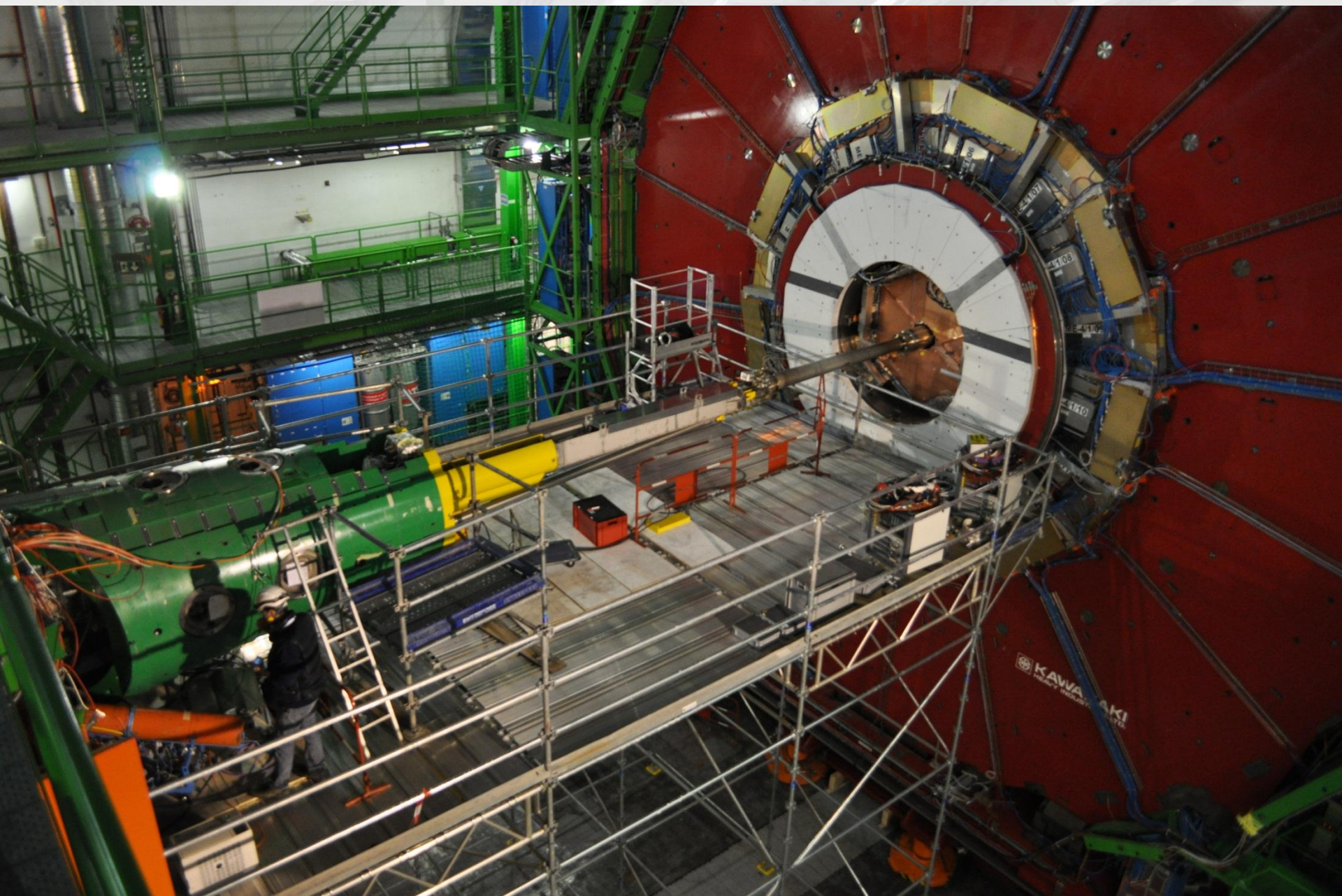
CMS

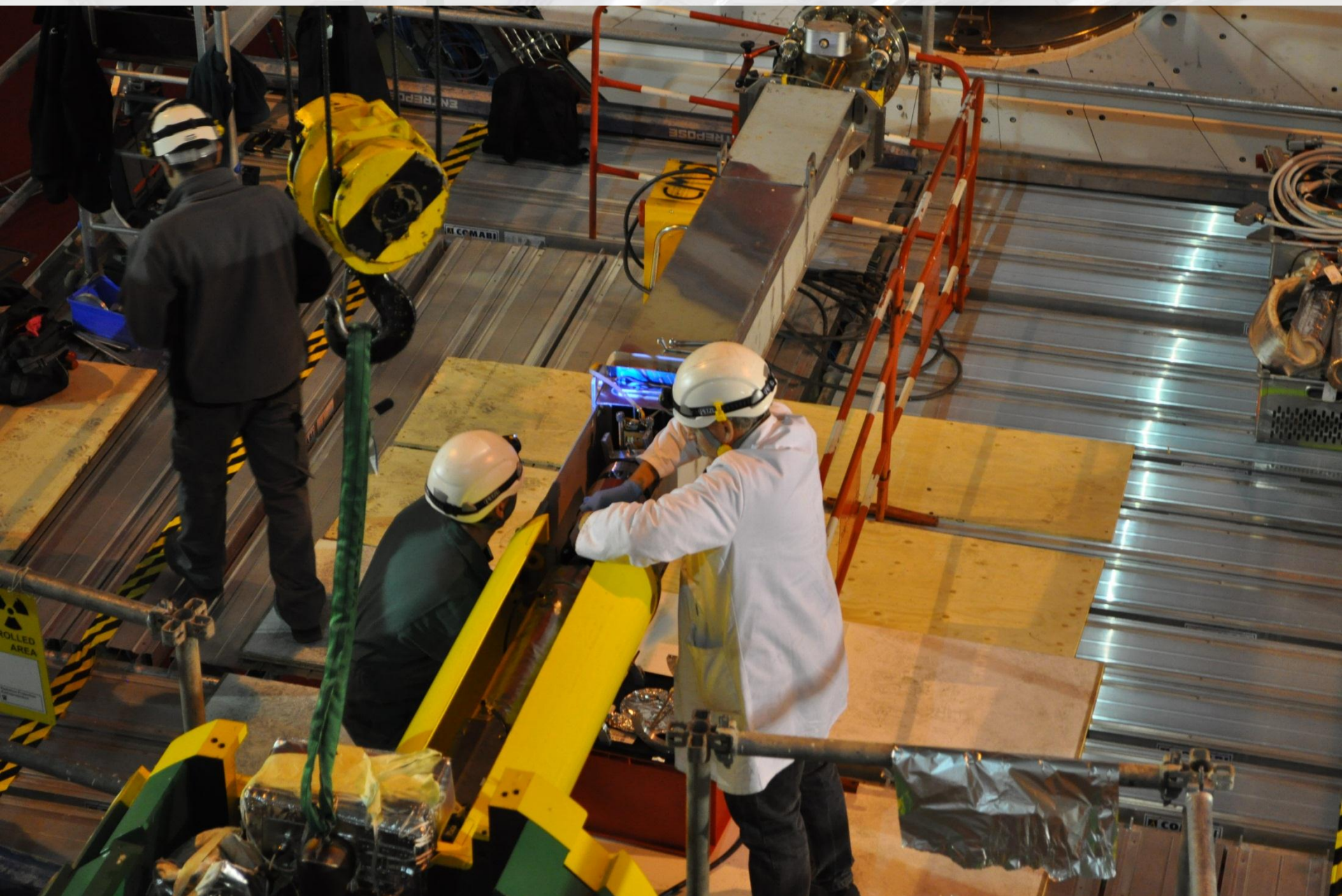
CMS

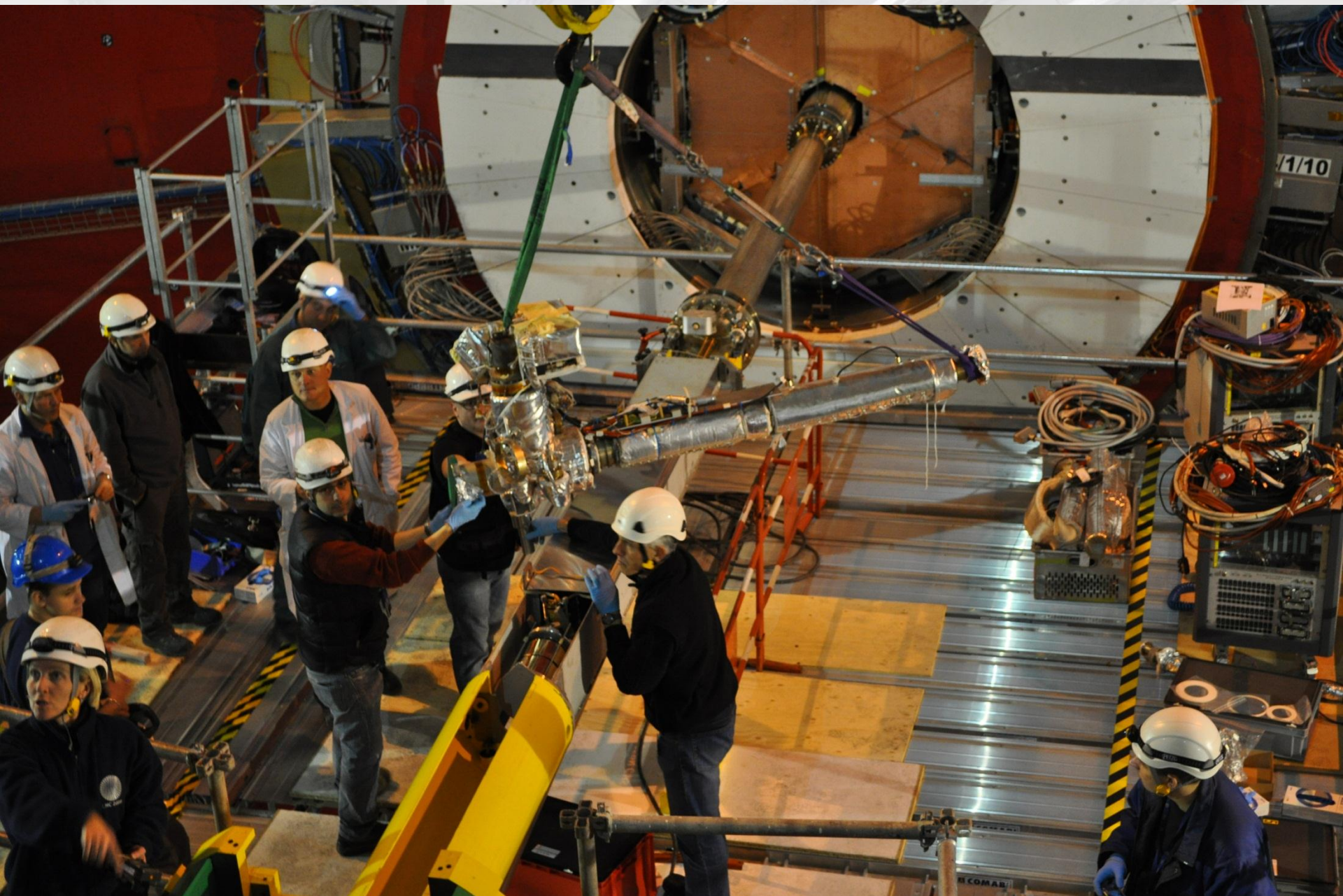
**16 m & 18 m
flanges were opened
while Ne flushing**

Forward chamber









October 18th, 2012



3rd Vacuum Symposium UK



Giulia Lanza





October 18th, 2012

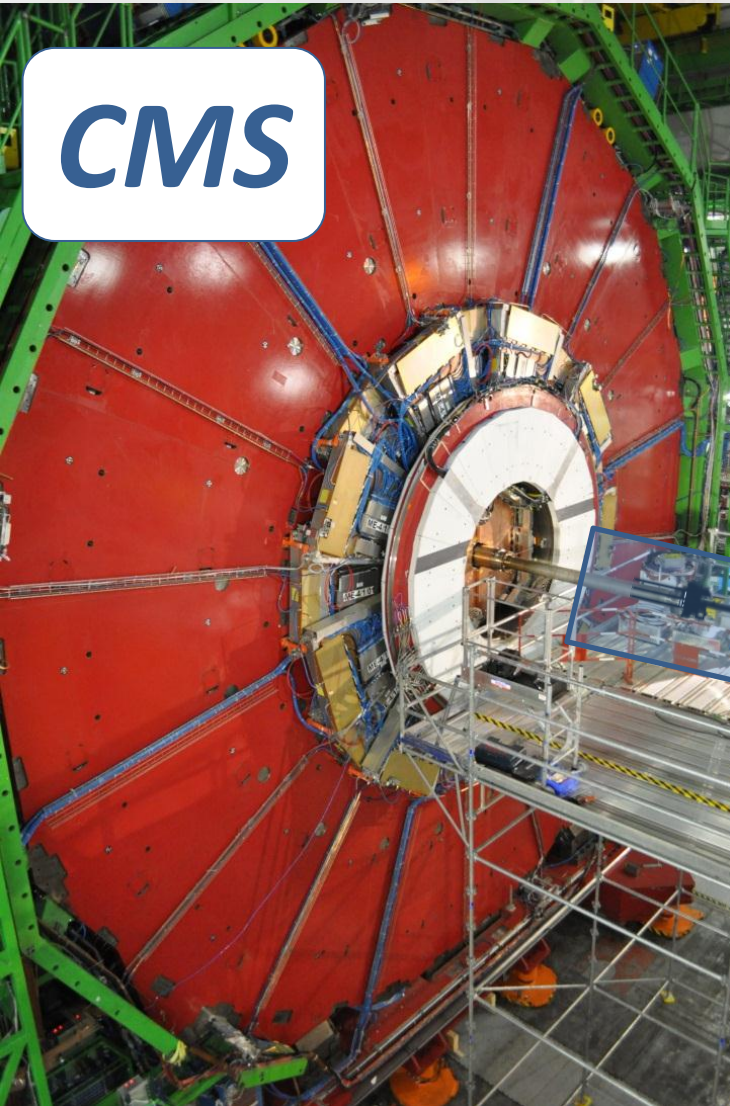


3rd Vacuum Symposium UK



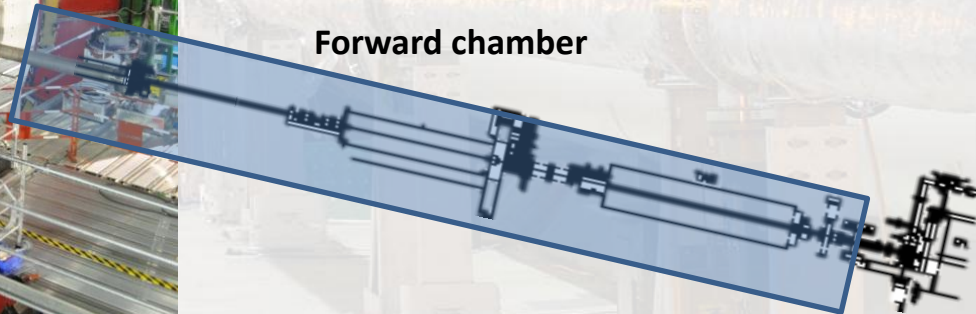
Giulia Lanza

CMS

The CMS logo is displayed in a white rounded rectangle. It features the letters "CMS" in a bold, blue, sans-serif font.

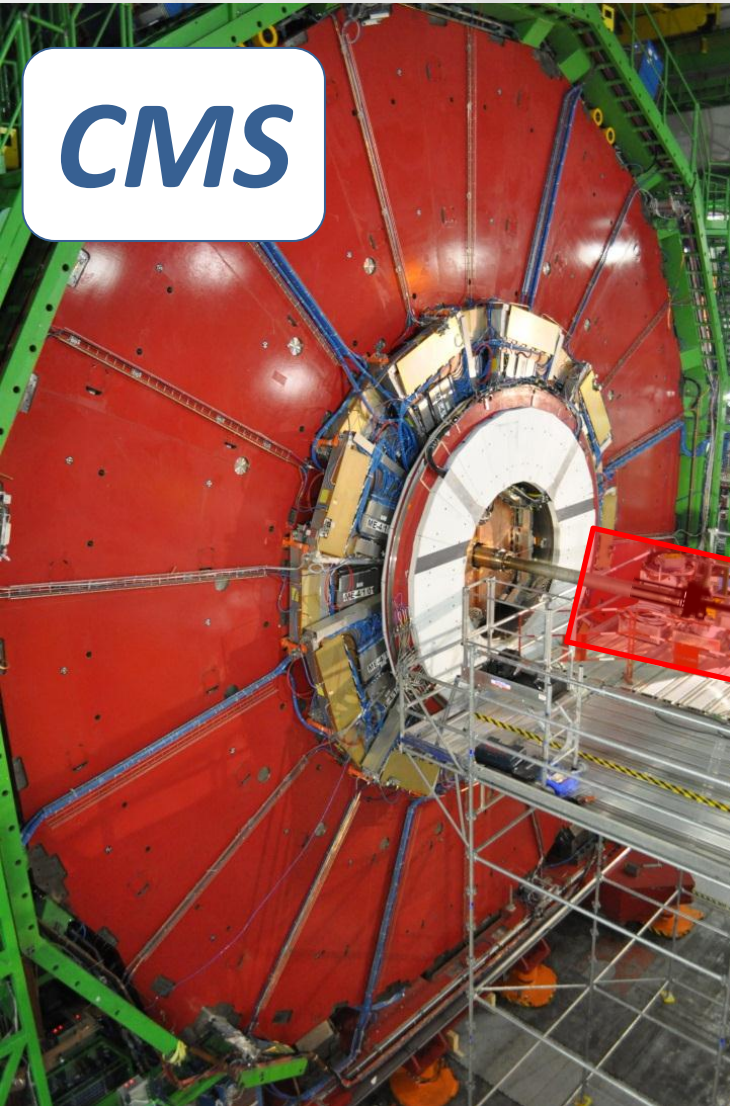
Partial NEG chambers
saturation

Forward chamber



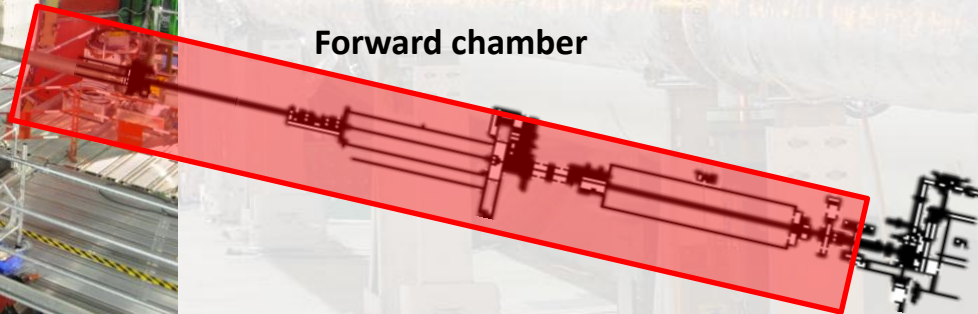
CMS

CMS

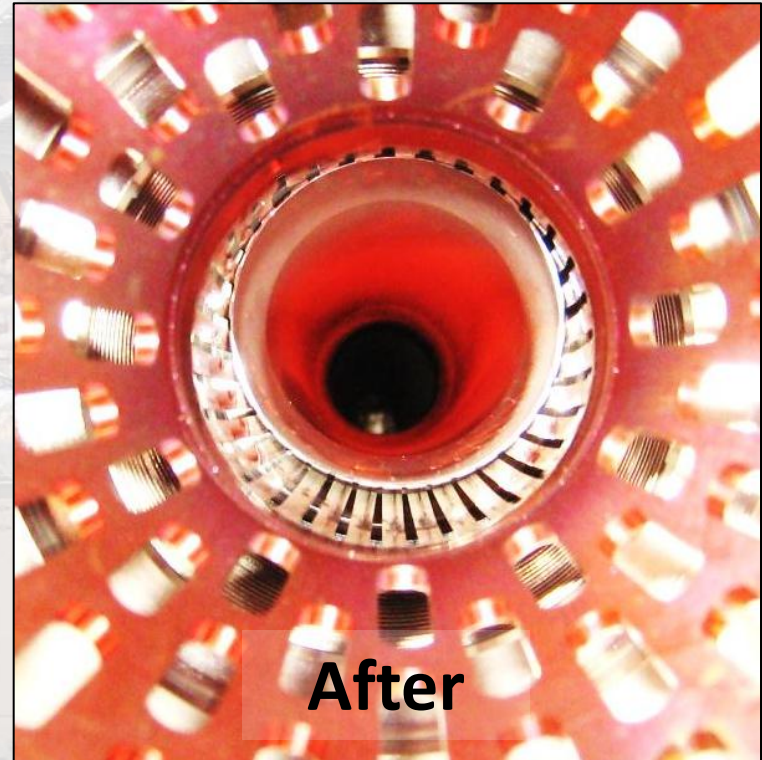
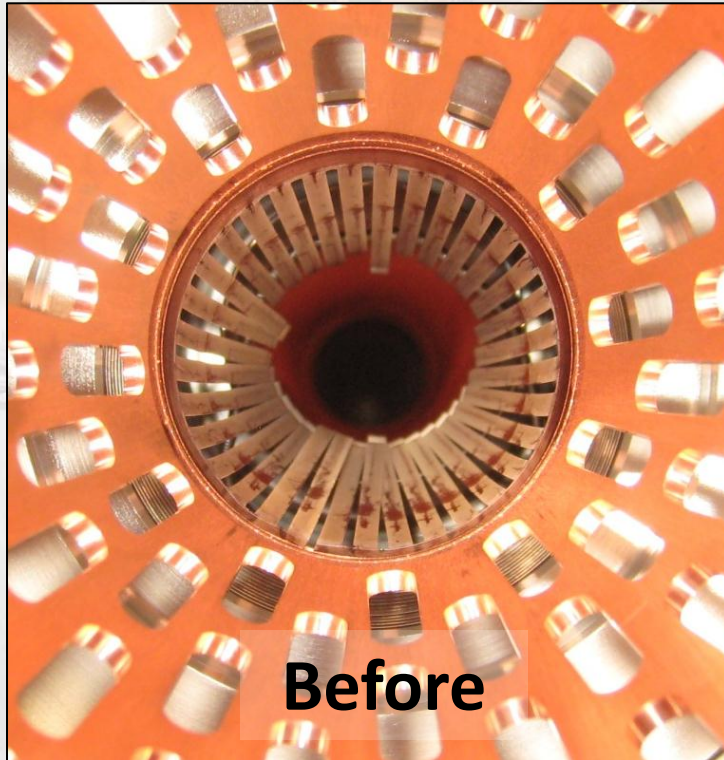


Partial bake out

Forward chamber



RF insert and CMS



The neon injection and flushing helped preserving the NEG properties and avoided the need of a full bake of the CMS beam pipe.'

Neon injection

NEON CHOICE

Amongst the possible noble gas species that can be employed, neon is the choice of preference for the following reasons:

- **helium** is used for leak detection. The small amount that may be left after pump down would reduce the sensitivity of the leak check.
- **Argon** is used as indicator of air leaks during NEG activation, since NEG pumps very efficiently other components like oxygen, nitrogen and carbon dioxide. As for helium, a small amount of argon that may be left after pump down would reduce the sensitivity of the leak monitoring.
- **Krypton** and **xenon** have a too high cross-section for beam-gas interactions, so that even small traces would lead to high background.
- **Neon** has a low mass and does not affect leak detection.



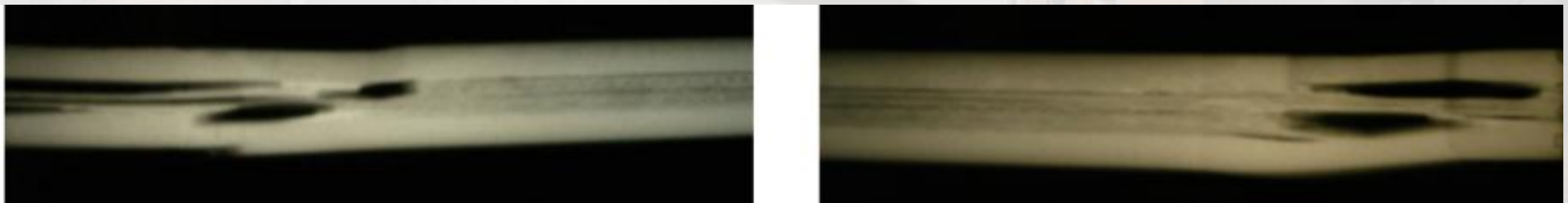
LONG SHUTDOWN 1

Long Shutdown 1: the Magnets splices consolidation

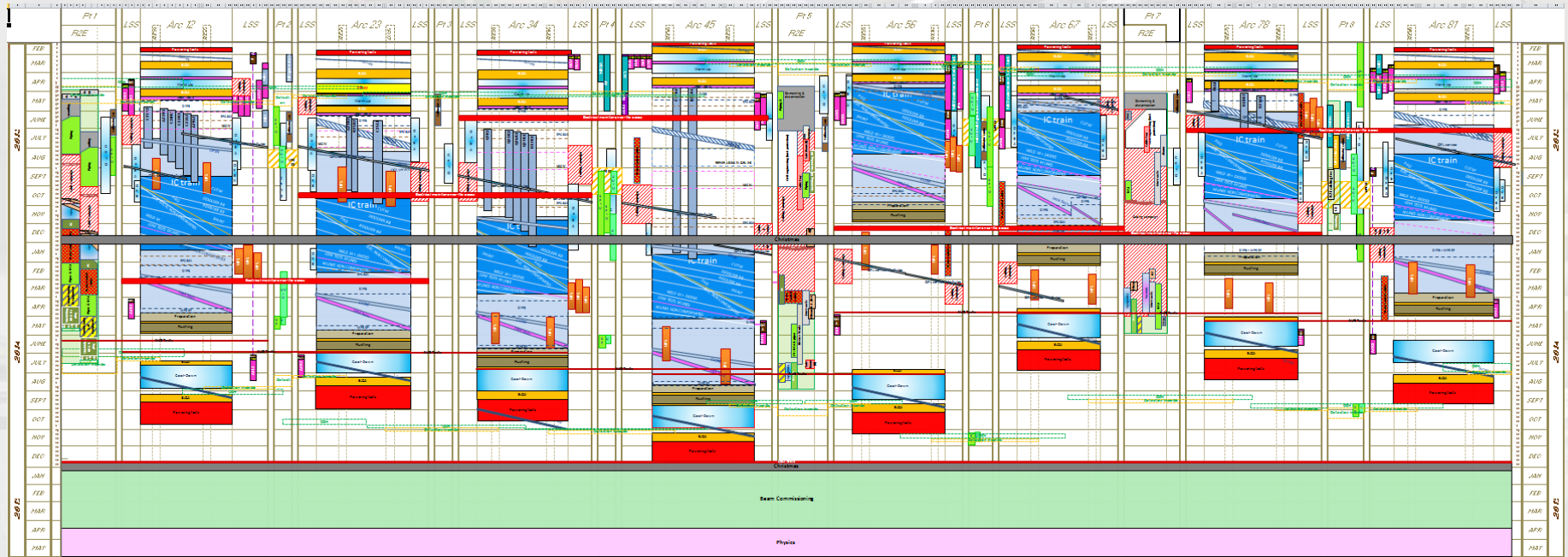
Despite correct splice resistance between SC cables, in case of bad bonding between the SC cable and the copper bus, a 13 kA joint can burn-out when a quench occurs.



Resistance measurements and γ -ray pictures have shown the presence of many of such defective joints with discontinuity in the copper stabilizer in the machine, limiting the safe operating current



Long Shutdown 1

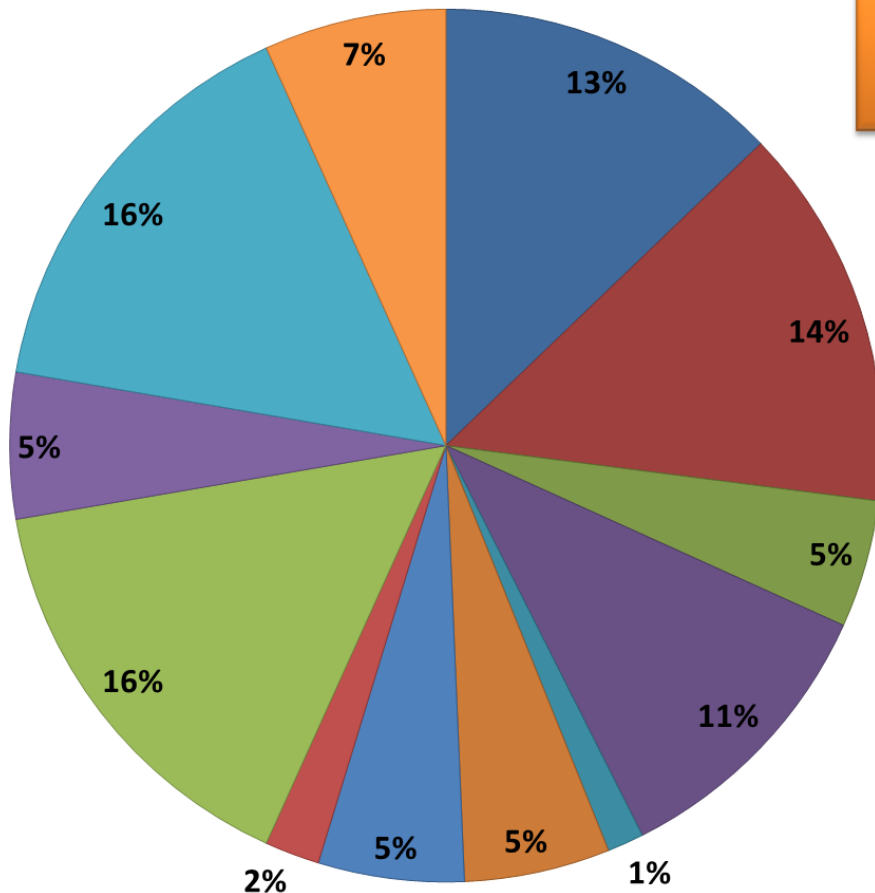


22 months of shutdown

**Warm up of all the
cryogenic sectors**

Long Shutdown 1

148 over 179 vacuum sectors to be baked and NEG activated



- Collimators
- Repair & New BI Equipment
- RF
- ALARA
- TDI Upgrade
- MKI
- NEG & Electron Cloud Pilot Sector
- Experimental Area
- VSC Consolidation & New Layout
- VAX Update
- DFBA Intervention
- Hambourg beam Pipe & TOTEM

Long Shutdown 1: main vacuum activities

- NEG coating inserts
 - Increase the pumping speed
 - Suppress the e-cloud
 - Reduce background pressure level for the Experiments
- NEG cartridge Installation
 - Increase the pumping speed
 - Presence of a fast, easy to re-activate pump to ensure a minimum pumping speed in highly saturated areas
- Long Straight Section opening
 - RF insert exchange
 - Bake out and activation of the opened sectors



After the Long Shutdown 1

2 days

6 days

4 days

- ⇒ Rough time estimate for **first scrubbing run after LS1** (2012)
- ~50h = **2 days** machine time, as was needed in 2011 to get $d_{\max}$ from 2.1 to 1.55
 - An additional 20h net beam time will be needed to get to 1.45
 - At least **4 days** machine time for further scrubbing at 7 TeV with increasing number of bunches
 - **Total of 12 days** with **no machine availability and no contingency**
- ⇒ Scrubbing schedule will foresee a **staged approach**
- First, “ramp down” with 25ns beams (few trains @ injection) to allow a period of operation on cloud free operation with 50ns and intensity ramp up. Then, full scrubbing for 25ns operation

Much to be yet validated with the 2012 scrubbing run + MDs with ramp to 4TeV

Courtesy G. Rumolo

Conclusions

The LHC vacuum performances in 2011 confirmed the sensitivity of the beam vacuum system to the machine parameters

Conclusions

Neon injections were successfully performed during several interventions. It is a fully approved and tested procedure to perform fast intervention without the need of bake out.

Conclusions

Synchrotron Radiation and e-cloud effect challenged the machine as expected.

Beam scrubbing remains the solution for vacuum cleaning and beam pipe conditioning

Conclusions

Further **Machine Development at 25ns** bunch spacing will be run before the long shutdown of 2013-2014 to be ready for the LHC restart with the nominal beam intensity and energy.

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...**THANK YOU FOR
YOUR ATTENTION.**