Dynamic Pressure Related to Electron Cloud during Run 2 Machine Operation in the LHC

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Christina Yin Vallgren

C. Yin Vallgren, P. Ribes Metidieri, G. Bregliozzi, P. Chiggiato
Vacuum, Surfaces and Coatings Group (VSC), TE-department
CERN, CH-1211, Geneva, Switzerland

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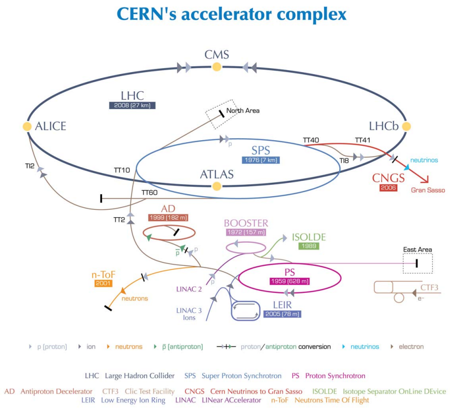
Outline

1. Overview of LHC vacuum system
   - LHC Layout
   - LHC Long Straight Sections
   - LHC ARC
2. Overview of LHC beam parameters in Run 2 (up to mid 2018)
3. LHC pressure evolution during Run 2
   - LHC Long Straight Sections pressure evolution
   - LHC experimental areas dynamic pressure rise
   - LHC ARC pressure evolution
   - Dynamic pressure analysis on some selected gauges
4. LHC vacuum profile simulations v.s measurements
   - LHC vacuum pressure profile simulations
   - LHC vacuum profile simulations v.s measurements

Outline

CERN - Large Hadron Collider (LHC)

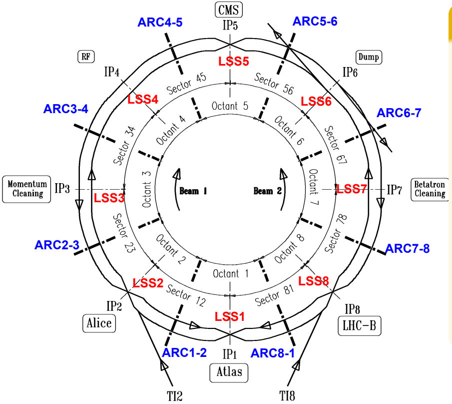


Protons: Linear accelerator(LINAC2) ⇒ Proton Synchrotron Booster(PS Booster) ⇒ Proton Synchrotron(PS) ⇒ Super Proton Synchrotron(SPS) ⇒ LHC.

Few numbers about LHC

- **27** km tunnel located about 100 m underground.
- **1500** niobiumtitanium (NbTi) superconducting magnets.
- cooled down by superfluid helium to **1.9** K.
- **4** experimental areas (ATLAS, CMS ALICE and LHCb).

CERN - Large Hadron Collider (LHC)



LHC vacuum system

- LHC beam vacuum
  - 8 Long Straight Sectors (LSSs):
    - RT beam vacuum chambers (6.5 km).
    - Stand-alone cryogenic magnets: 4.5 K.
  - 8 ARCs (2x2.8 kmx8):
    - 1.9 K cold bores.
    - 5-20 K beam screens.
- LHC insulation vacuum.

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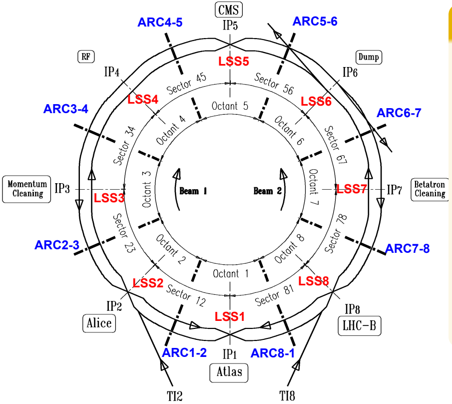

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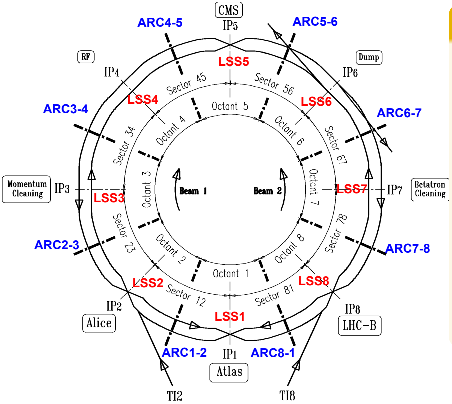

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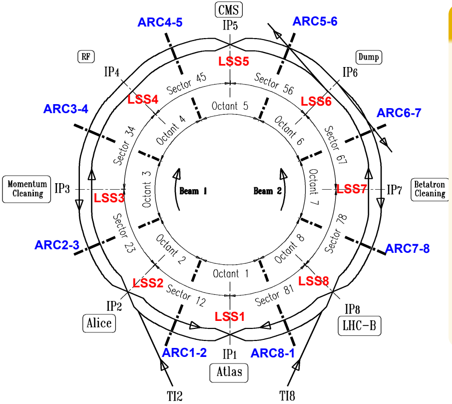

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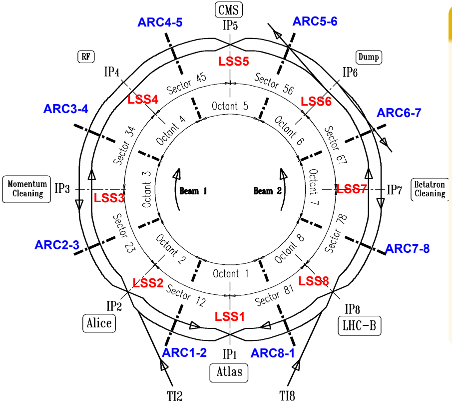

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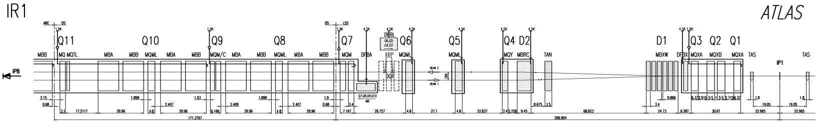
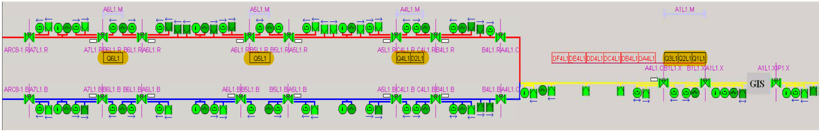
8 Long Straight Sections

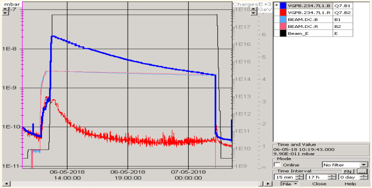
LSS1(ATLAS) Left side:



SCADA application:

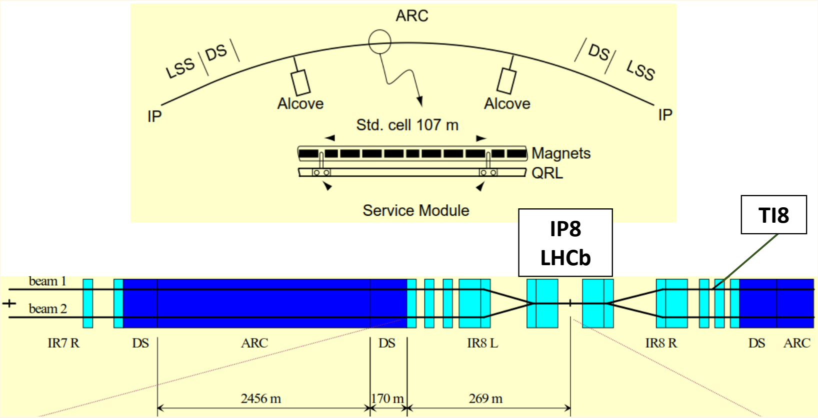


Pressure monitoring:



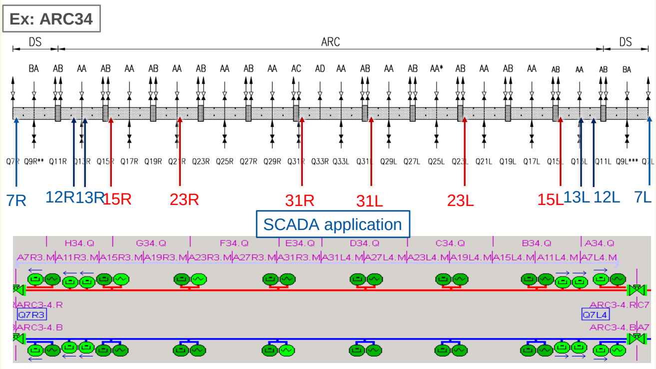
- A typical pressure monitoring with SCADA application.
- Dynamic pressure rise with the beams (EC and SR).
- Beam intensities and energy.

8 ARCs


ARC
LSS
DS
DS
LSS
IP
IP
Alcove
Alcove
Std. cell 107 m
Magnets
QRL
Service Module
IP8
LHCb
TI8
beam 1
beam 2
IR7 R
DS
ARC
DS
IR8 L
IR8 R
DS
ARC
2456 m
170 m
269 m

Cold mass sectorization and vacuum instrumentation

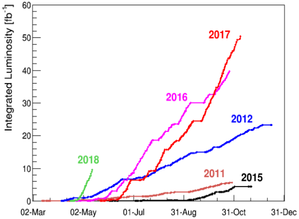
- Q7, 12*, 13*: Passive penning with 500m long cable, TPG300, meas. limit: 10^{-11} mbar.
- The rest: full range penning, pirani gauge, meas. limit: 10^{-9} mbar.
- All the pressure reading are dominated by water vapor pressure in the unbaked part of tubes @ RT, $[10^{-10}, 10^{-9}]$ mbar.



Outline

Overview of LHC beam operation 2015-mid 2018

- 2015: ATLAS 4.24 fb^{-1} and CMS 4.25 fb^{-1}.
- 2016: ATLAS 38.49 fb^{-1} and CMS 40.96 fb^{-1}.
- 2017: ATLAS 50.82 fb^{-1} and CMS 50.58 fb^{-1}.
- 15/5/2018: ATLAS 10.11 fb^{-1} and CMS 9.91 fb^{-1}.

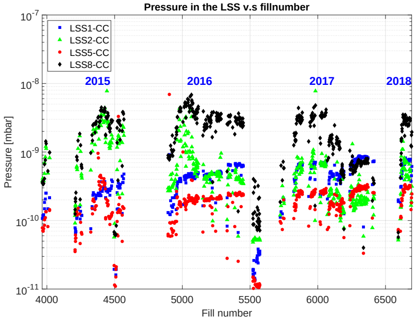


Year	Top achieved beam intensity [b]	Filling scheme bpi	Limitations
2015	2244	trains of 4x36b	Limited to 450b by radiation induced faults in QPS electronic boards until TS2. 144bpi up to 1450b, limited of the available cooling capacity on ARC BS
2016	2220	trains of 96b	Technical issue SPS and LHC dumps
2017	2556	trains of 144b	2556b until early August, stable operation with 1900b of 8b4e due to 16L2.
2018	2556	trains of 144b	-

Outline

LHC Long Straight Section pressure evolution Run 2 (1)

- Average reading of Bayard Alpert gauges $\pm$ 100-120 m from IP in the combination chambers (CC) of each LSS.
- Two beams & NEG coated chambers.
- P $< 1\times10^{-8}$ mbar.



- Normalized maximum dynamic pressure rise in LSS-CC chambers.
- P de-conditioning in-between the operation years, but fast conditioning.
- *Slight increase in P for LSS1 & 5:*

NEG saturation? (come back later)

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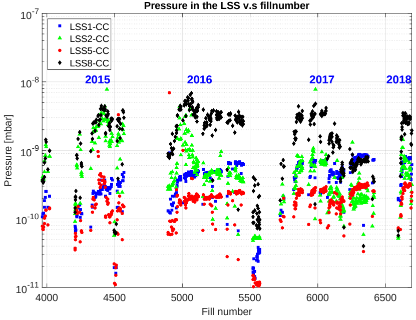

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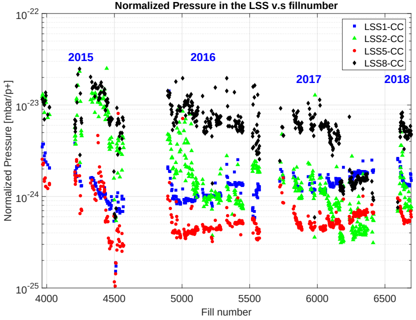

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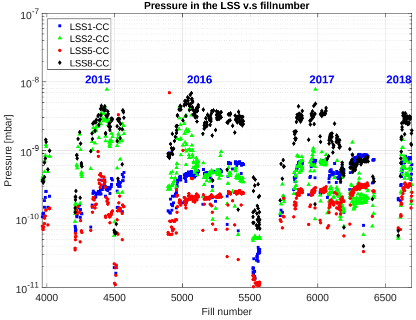

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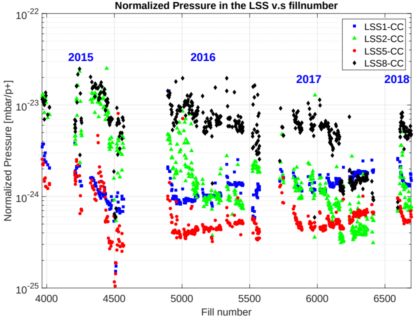
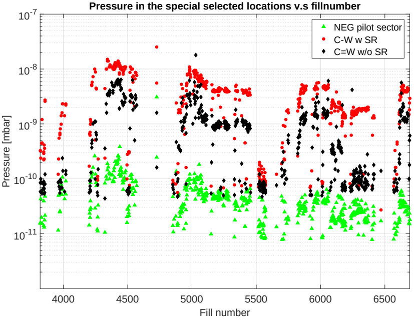
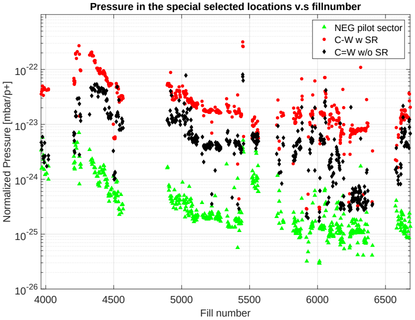


LHC Long Straight Section pressure evolution Run 2 (2)

- NEG pilot sector
  (dedicated NEG coated sectors for studies)
- C-W transition with & without SR.
  (unbaked Cu in LSS;
  C-W with SR: max at end of ramp-up/flattop;
  C-W without SR: max at end of injection)
- $P = [10^{-11}, 10^{-10}]$ in dedicated NEG pilot sector.



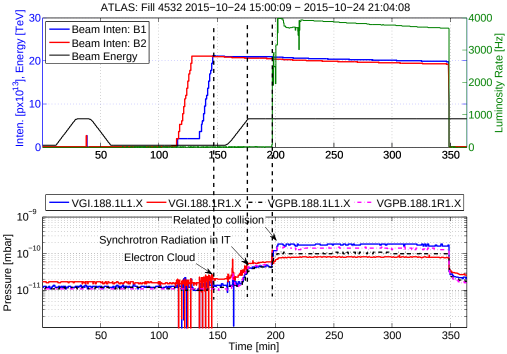
- Normalized dynamic pressure rise in NEG chambers & C-W transitions.
- $P_{C-WwithSR} \approx 2x\ P_{C-WwithoutSR}$.
- Slight pressure increase in-between the operation years.



LHC Experiments dynamic pressure rise (1)

ATLAS pressure as a function of beam parameters

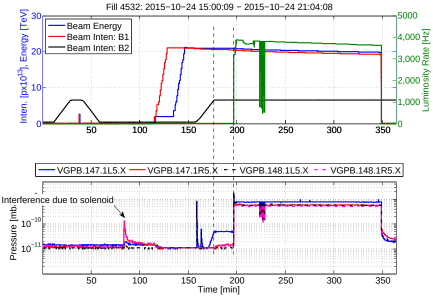
- Typical pressure rise during a physics fill: ATLAS.
- Three main pressure peaks during one typical physics fill.
- Electron Cloud @ injection → Synchrotron Radiation from the inner-triplets @ ramp → related to collision.



LHC Experiments dynamic pressure rise (2)

CMS pressure as a function of beam parameters

- Fill 4532 (left) with solenoid on. ⇒ No pressure rise at injection.
  - However, a huge pressure jump up after the collision.
  - Why: Heavy particles desorbing the gases from the walls or ionization of residual gas in the beam pipes?
- Fill 4536 (right) with solenoid off. ⇒ Electron Cloud @ injection.



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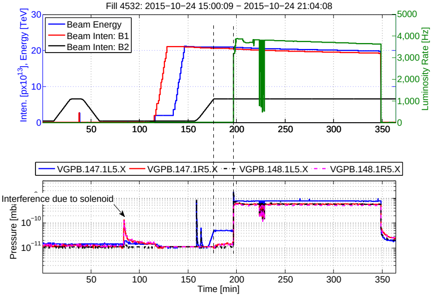

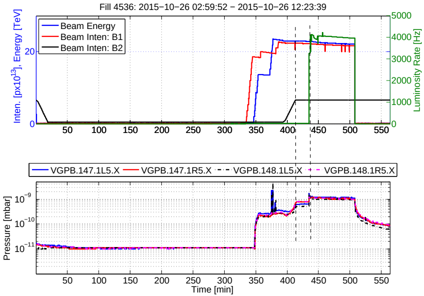

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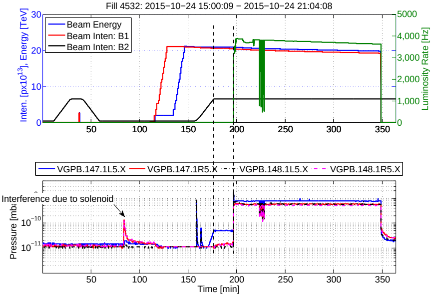

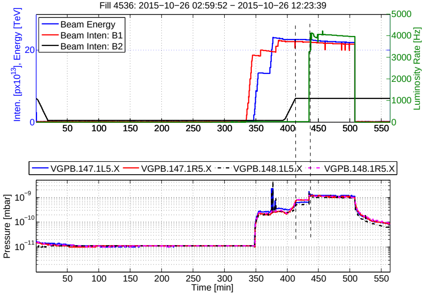

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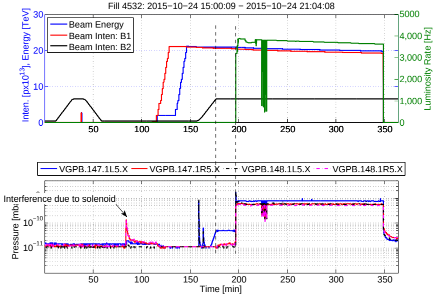
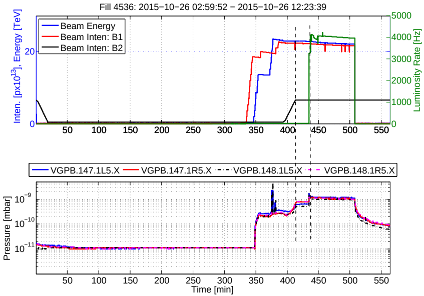
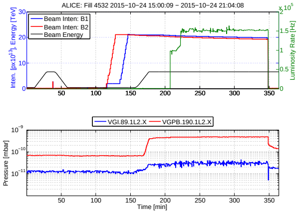




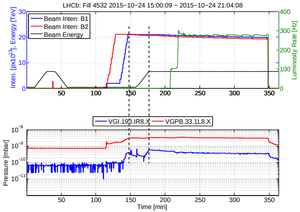
LHC Experiments dynamic pressure rise (3)

Possible NEG saturation explanation in LSS1 & 5

ALICE (LSS2)



LHCb (LSS8).



- Collision rate (ALICE & LHCb) is comparably small, less beam induced outgassing in LSS2 & 8 than in LSS1 & 5.
- No visible pressure rise after the collision.
- Compare to LSS1 &5, no visible NEG saturation.

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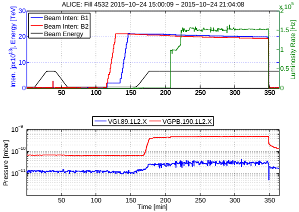

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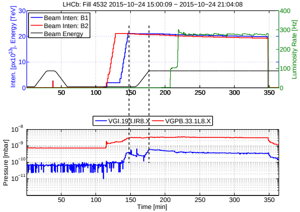

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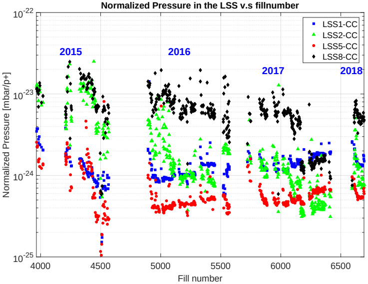
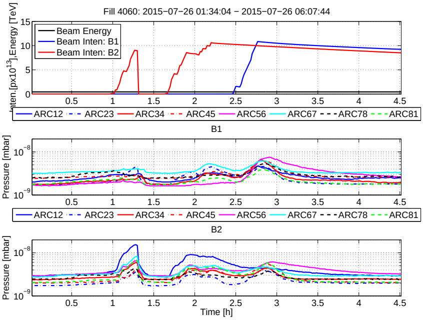


LHC ARC dynamic pressure rise (1)

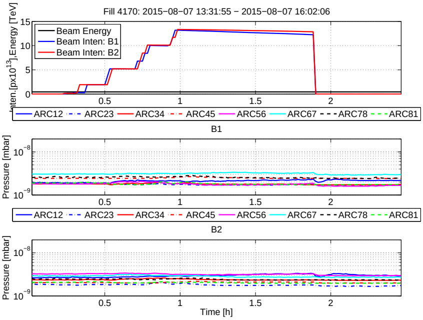
ARC pressure conditioning

- 25 ns scrubbing validation.
- Clear conditioning in pressure with similar beam parameters.

- Before 25 ns scrubbing run.



- After 25 ns scrubbing run.

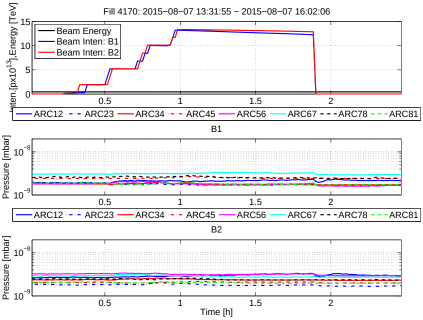


LHC ARC dynamic pressure rise (2)

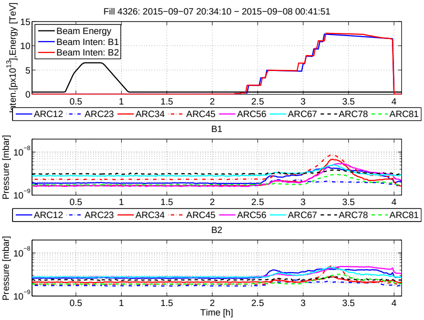
ARC pressure de-conditioning

- After Technical Stop 2 (5 days no beams) in 2015.
- Clear increase in pressure with the same beam parameters.

- After 25 ns scrubbing run.

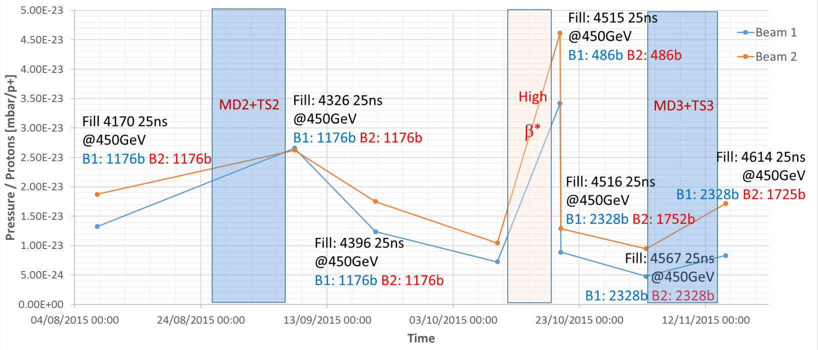


- After TS2.



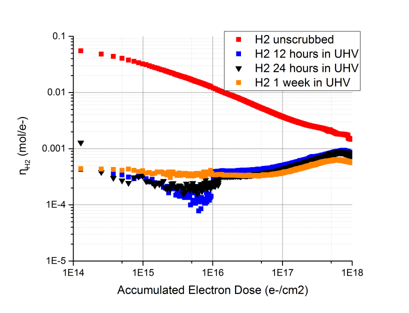
LHC ARC pressure de-conditioning in 2015

Increase of dynamic pressure rise after period without high intensity beams.



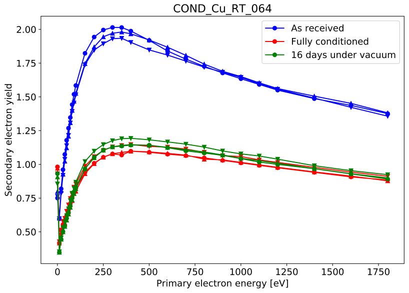
Compare to what happens in the lab (Open question)

Electron Stimulated Desorption (ESD):
Baked Cu fully scrubbed and stored in the UHV.



Thanks to S. Callegari

Secondary Electron Yield (SEY):
Unbaked Cu fully scrubbed and stored in the UHV.



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- No de-conditioning in ESD or SEY observed in the lab.
- Where does the pressure rise come from? Different vacuum in the LHC?

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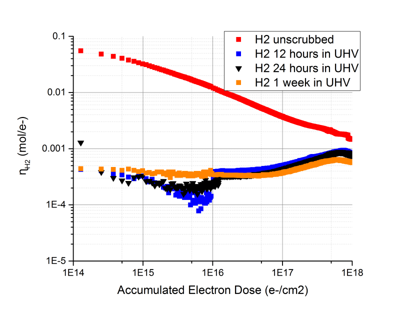

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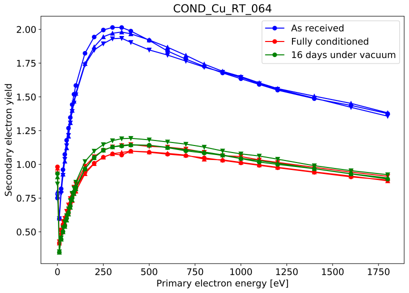

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Selected analyzed pressure gauges (1)

Selected gauges at the extremities of ARCs: to study the beam induced effect on surface in the LHC

- Unbaked Cu.
- Influenced both by EC and SR from the ARCs.
- One side RT vacuum and the other side 1.9 K vacuum.

- VGPB.235.7R1.R:
  B2 $(\mathrm{ARC12} \rightarrow \mathrm{IP1})$ on the right side of LSS1.
- VGPB.229.7R5.B:
  B1 $(\mathrm{ARC56} \rightarrow \mathrm{IP5})$ on the right side of LSS5.
- VGPB.514.7L3.B:
  B1 $(\mathrm{ARC23} \rightarrow \mathrm{IP3})$ on the left side of LSS3.

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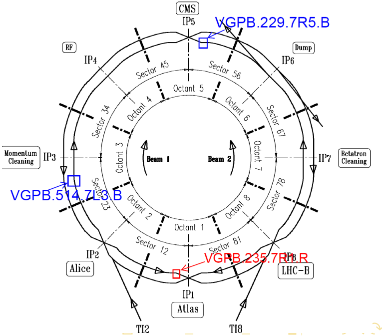
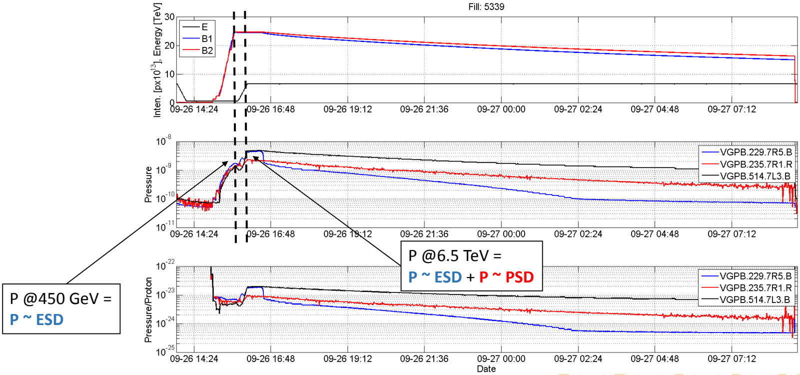
  B1 (ARC56 $\rightarrow$ IP5) on the right side of LSS5.
- VGPB.514.7L3.B:
  B1 (ARC23 $\rightarrow$ IP3) on the left side of LSS3.



Selected analyzed pressure gauges (2)

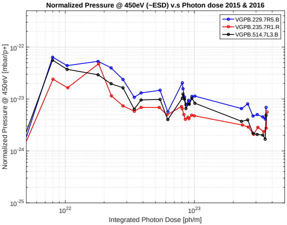
- Dynamic pressure rise = pressure rise due to electron cloud + pressure rise due to synchrotron radiation.
  - Electron Stimulated Desorption (ESD): η_{el}.
  - Photon Stimulated Desorption (PSD): η_{ph}

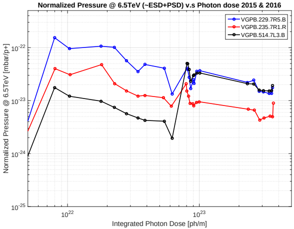


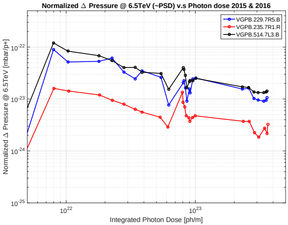
Selected analyzed pressure gauges (3)

Divide the pressure into EC and SR, as a function of integrated photon dose [ph/m].

- Normalized P at 450 GeV: ESD
- Normalized P at 6.5 TeV: ESD+PSD
- Normalized ΔP at 6.5 TeV: PSD

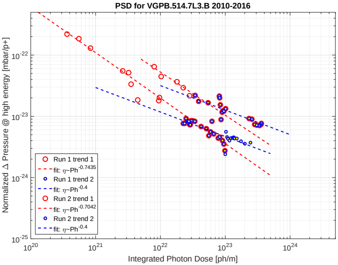




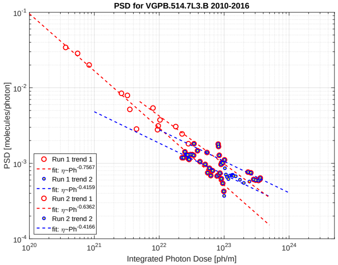


Selected analyzed pressure gauges (4)

- PSD (η_{ph}) as a function of Photon Dose.
  - Beam energy in 2010-2012 (Run 1): 3.5 TeV.
  - Beam energy in 2015-2016 (Run 2): 6.5 TeV (a factor 1.86 for comparison).
  - Assuming de-conditioning of photon desorption, reset photon dose after LS1.
- 2 trends for the curves: $\eta \propto \Gamma^{-\alpha}$ [⊖].
  - Room Temperature ($\alpha = [0.6, 0.8]$).
  - Cryogenic Temperature ($\alpha \approx 0.4$).



Normalized ΔP @ high E [mbar/p+].



PSD [molecules/photon].

⊖: Vincent Baglin, Vacuum 138 (2017) 112-119

Outline

LHC vacuum pressure profile simulations (1)

Simulations for static and dynamic pressure profile

- VASCO (VAcuum Stability COde)⊕ is a code for the simulation of the LHC static and dynamic pressure profiles.
- In order to optimize the performance of code for large geometries, VASCO was rewritten in Python ⇒ PyVASCO

$$\underbrace{V\frac{\partial n}{\partial t}}_{\substack{\text{time variation of}\\ \text{volumic density}\\ \text{in volume V per}\\ \text{unit length}}} = \underbrace{c_{spec}\frac{\partial^2 n}{\partial x^2}}_{\text{diffusion}} + \underbrace{(\eta_i + \eta'_i(\theta'))\underbrace{\sigma_{i-I}\frac{I}{e}n}_{\substack{\text{ions produced}\\ \text{by hadrons}}}}_{\text{ion-induced desorption}} - \underbrace{\sigma_{i-I}\frac{I}{e}n}_{\text{beam pumping}} - \underbrace{S_{wall}(\theta)n}_{\substack{\text{wall distributed}\\ \text{NEG pumping}}} - \underbrace{S_{cryo}(n - n_e(\theta', T))}_{\substack{\text{wall distributed}\\ \text{cryo-pumping and}\\ \text{thermal equilibrium pressure}}}$$
$$+ \underbrace{(\eta_{ph} + \eta'_{ph}(\theta'))\dot{\Gamma}_{ph}}_{\substack{\text{photon stimulated}\\ \text{desorption}}} + \underbrace{(\eta_e + \eta'_e(\theta'))\dot{N}_e}_{\substack{\text{electron stimulated}\\ \text{desorption}}} + \underbrace{a\cdot q}_{\substack{\text{thermal}\\ \text{outgassing}}} \qquad (1)$$

$$\underbrace{a\frac{\partial \theta}{\partial t}}_{\substack{\text{surface density}\\ \text{(on room temperature surfaces)}\\ \text{time variation}\\ \text{in the area A per}\\ \text{unit length}}} = S_{wall}(\theta)n + \underbrace{\sigma_{i-I}\frac{I}{e}n}_{\text{beam pumping}} \qquad (2)$$

$$\underbrace{a\frac{\partial \theta'}{\partial t}}_{\substack{\text{surface density}\\ \text{(on cold surfaces)}\\ \text{time variation}\\ \text{in the area A per}\\ \text{unit length}}} = S_{cryo}(n - n_e(\theta', T)) - \eta'_i(\theta')\sigma_{i-I}\frac{I}{e}n - \eta'_{ph}(\theta')\dot{\Gamma}_{ph} - \eta'_{ph}(\theta)\dot{N}_e \qquad (3)$$

In a room temperature system, the physisorption can be neglected and the equation (1) reads:

$$V\frac{\partial n}{\partial t} = c_{spec}\frac{\partial^2 n}{\partial x^2} + (\eta_i - 1)\sigma_{i-I}\frac{I}{e}n - S_{wall}n - C_{dis}n + \eta_{ph}\dot{\Gamma}_{ph} + \eta_e\dot{N}_e + a\cdot q \qquad (4)$$

⊕: A. Rossi, LHC Project Note 341, CERN

LHC vacuum pressure profile simulations (1)

Simulations for static and dynamic pressure profile

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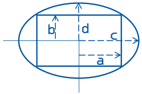
⊕: A. Rossi, LHC Project Note 341, CERN

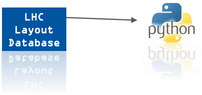
LHC vacuum pressure profile simulations (2)

Simulations for static and dynamic pressure profile

- Based on CERN LHC Layout Database
- Elliptic/rectangular profiles
- 3D model automatically generated in Python ⇒ LHC Geometry



Parameters of rect-elliptic profile



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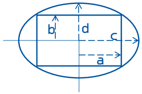

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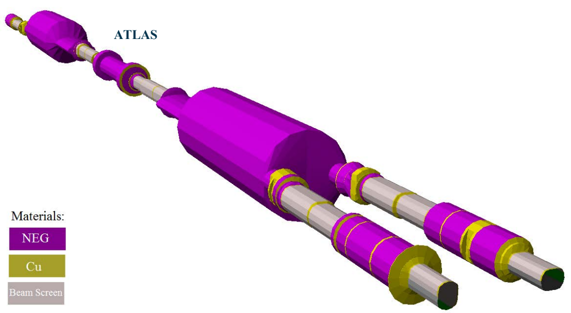
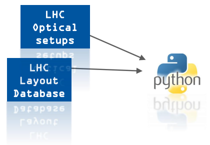


LHC vacuum pressure profile simulations (3)

Simulations for static and dynamic pressure profile

- TWISS table: contains the linear lattice functions for a given element configuration.
- Real position of a particle of the beam and magnet strengths.

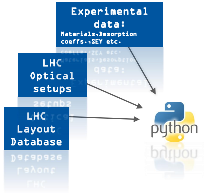


LHC vacuum pressure profile simulations (4)

Simulations for static and dynamic pressure profile

- Create a database for material specifications used as input for simulations
- Outgassing rates measured in the lab
- ESD (Electron Stimulated Desorption), SEY (Secondary Electron Yield) etc measurement data

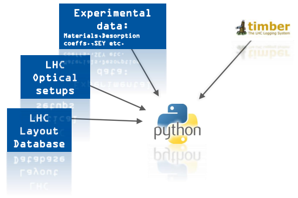
Material		
C	$\longrightarrow$	Carbon coating
S	$\longrightarrow$	Stainless Steel
N	$\longrightarrow$	NEG coating
...		



LHC vacuum pressure profile simulations (5)

Simulations for static and dynamic pressure profile

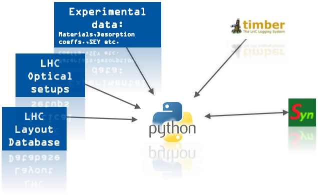
- Using Timber to extract the beam parameters for specific physics fill
- Using Timber to extract the measured pressure in the LHC for specific physics fill



LHC vacuum pressure profile simulations (6)

Simulations for static and dynamic pressure profile

- SynRad+◇: Monte Carlo simulations to calculate flux and power distribution on a surface caused by synchrotron radiation.
- Combine LHC Geometry, Beam parameters and LHC optics.



◇: R. Kersevan and M. Ady https://molflow.web.cern.ch/

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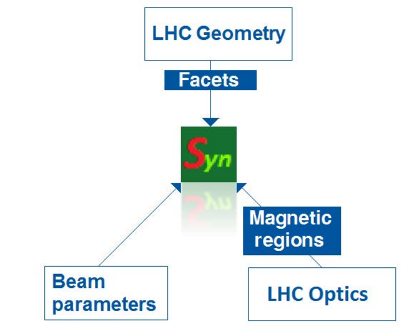
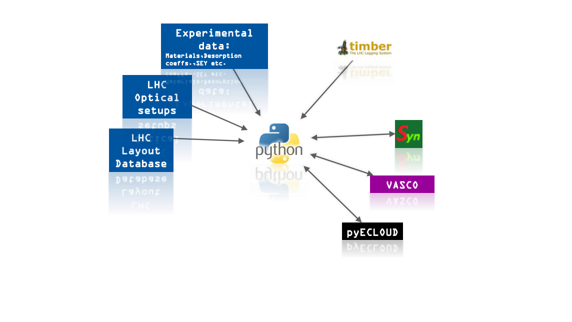


[◇]: R. Kersevan and M. Ady https://molflow.web.cern.ch/

LHC vacuum pressure profile simulations (7)

Simulations for static and dynamic pressure profile

- PyECLOUD*: simulate the electron cloud buid-up.
- Combine LHC Geometry, Experimental SEY data, LHC optics and Beam parameters.



*: G. Iadarola https://github.com/PyCOMPLETE/PyECLOUD

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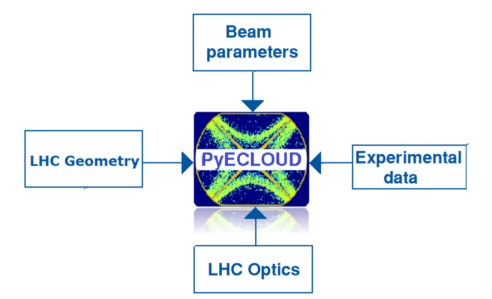
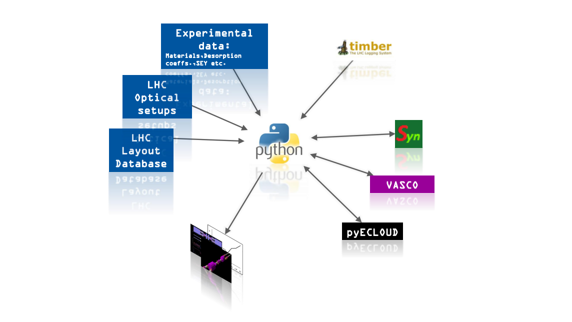


*: G. Iadarola https://github.com/PyCOMPLETE/PyECLOUD

LHC vacuum pressure profile simulations (8)

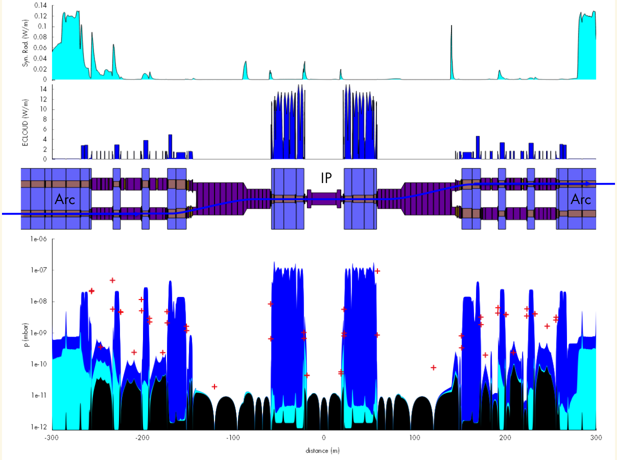
Simulations for static and dynamic pressure profile

- VASCO algorithm implemented in Python ⇒ PyVASCO
- Simulate complete pressure profile in a complex machine
- Static pressure profile, considering the effect of degassing rates and pumping speed.
- Dynamic pressure profile, considering the effect of beams: electron cloud, synchrotron radiation, ion induced desorption etc.



LHC vacuum pressure profile simulations v.s measurements

Example: Dynamic pressure profile for B1 in ATLAS LSS
2244 b, 25 ns, 6.5 TeV at collision



Thanks

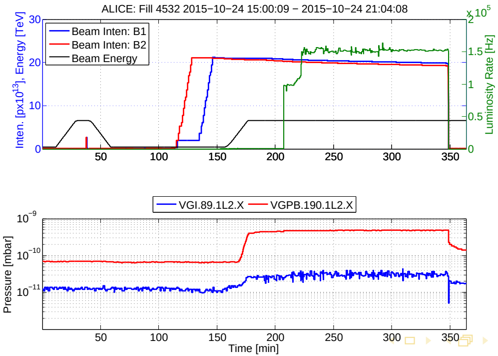
Many thanks to all the members of the TE-VSC group, especially M. Ady, R. Kersevan and J. Sopousek.

Thanks for your attention ! and Questions

Backup Slide (1)

ALICE pressure as a function of beam parameters

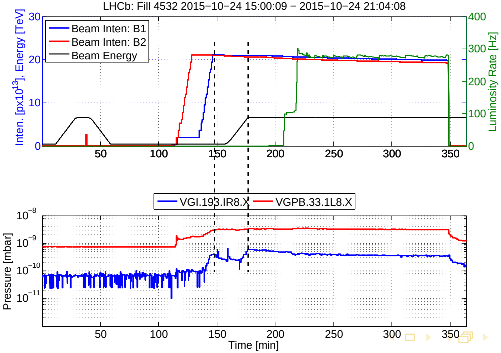
- Typical pressure rise during a physics fill: ALICE.
- Collision rate is comparably small, no visible pressure rise after the collision.
- No visible Electron Cloud @ injection due to solenoid. → Synchrotron Radiation from the inner-triplets @ ramp.



Backup Slide (2)

LHCb pressure as a function of beam parameters

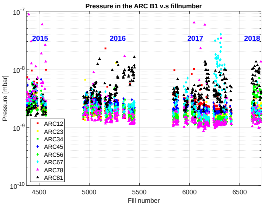
- Typical pressure rise during a physics fill: LHCb.
- Collision rate is comparably small, no visible pressure rise after the collision.
- Electron Cloud @ injection → Synchrotron Radiation from the inner-triplets @ ramp.



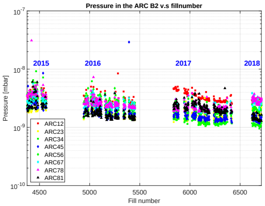
Backup Slide(3)

LHC ARC dynamic pressure rise evolution Run 2

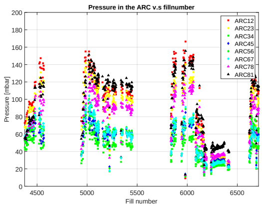
- ARC B1 Pressure.



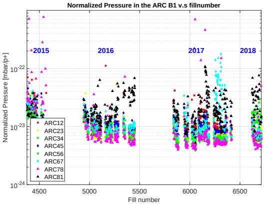
- ARC B2 Pressure.



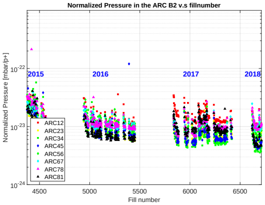
- ARC heat load.



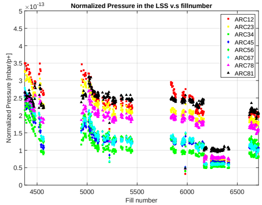
- ARC normalized B1 pressure.



- ARC normalized B2 pressure.



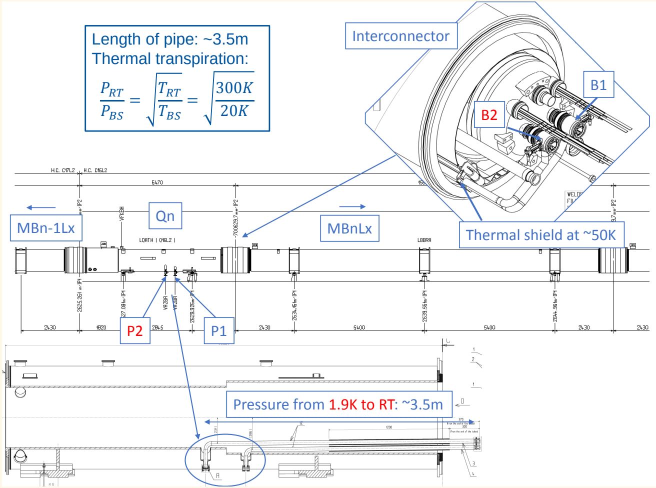
- ARC normalized heat load.



Backup Slide(4)

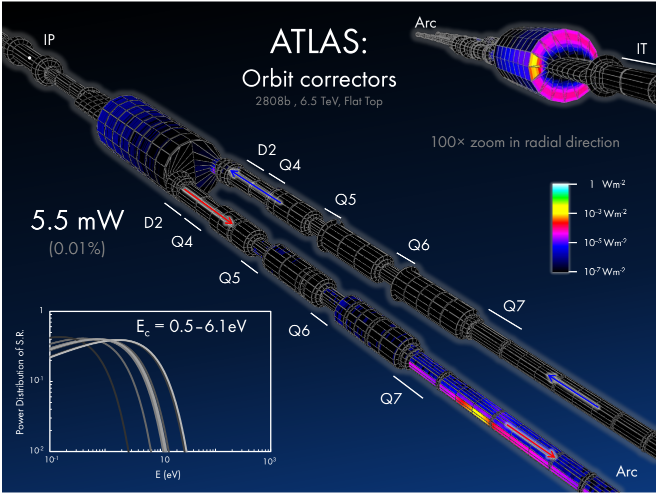
Interconnect Layout

Actual P in the beam screen $\approx$ the measured P at RT/4.



Backup Slide(5)

3D modeling of LSS1 in present of SR



Backup Slide(5)

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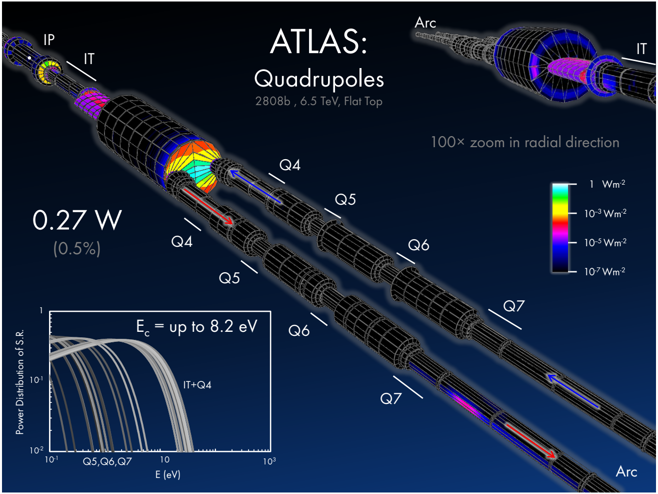

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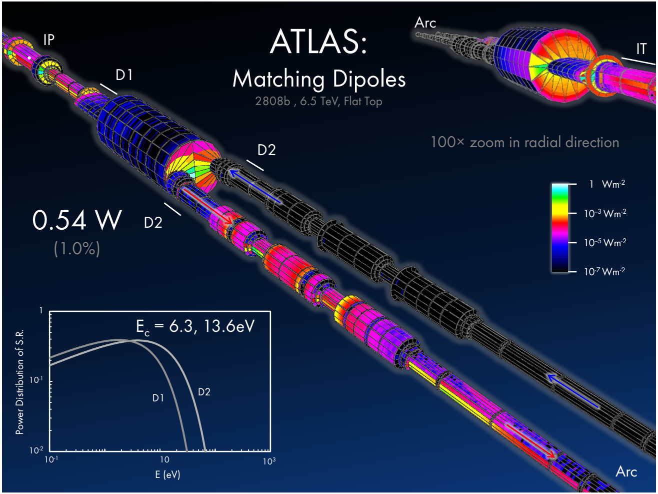

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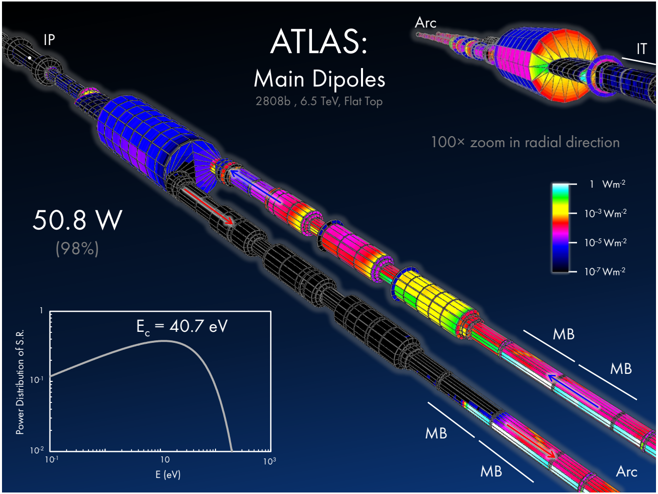

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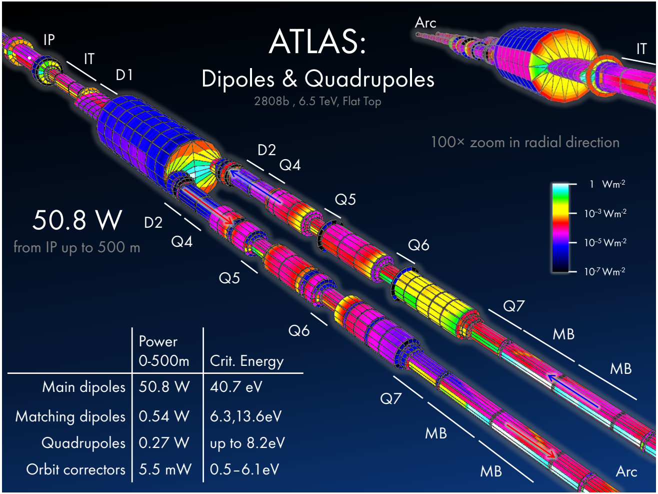

	Power 0-500m	Crit. Energy
Main dipoles	50.8 W	40.7 eV
Matching dipoles	0.54 W	6.3,13.6eV
Quadrupoles	0.27 W	up to 8.2eV
Orbit correctors	5.5 mW	0.5–6.1eV