Vacuum simulations for the High Luminosity LHC

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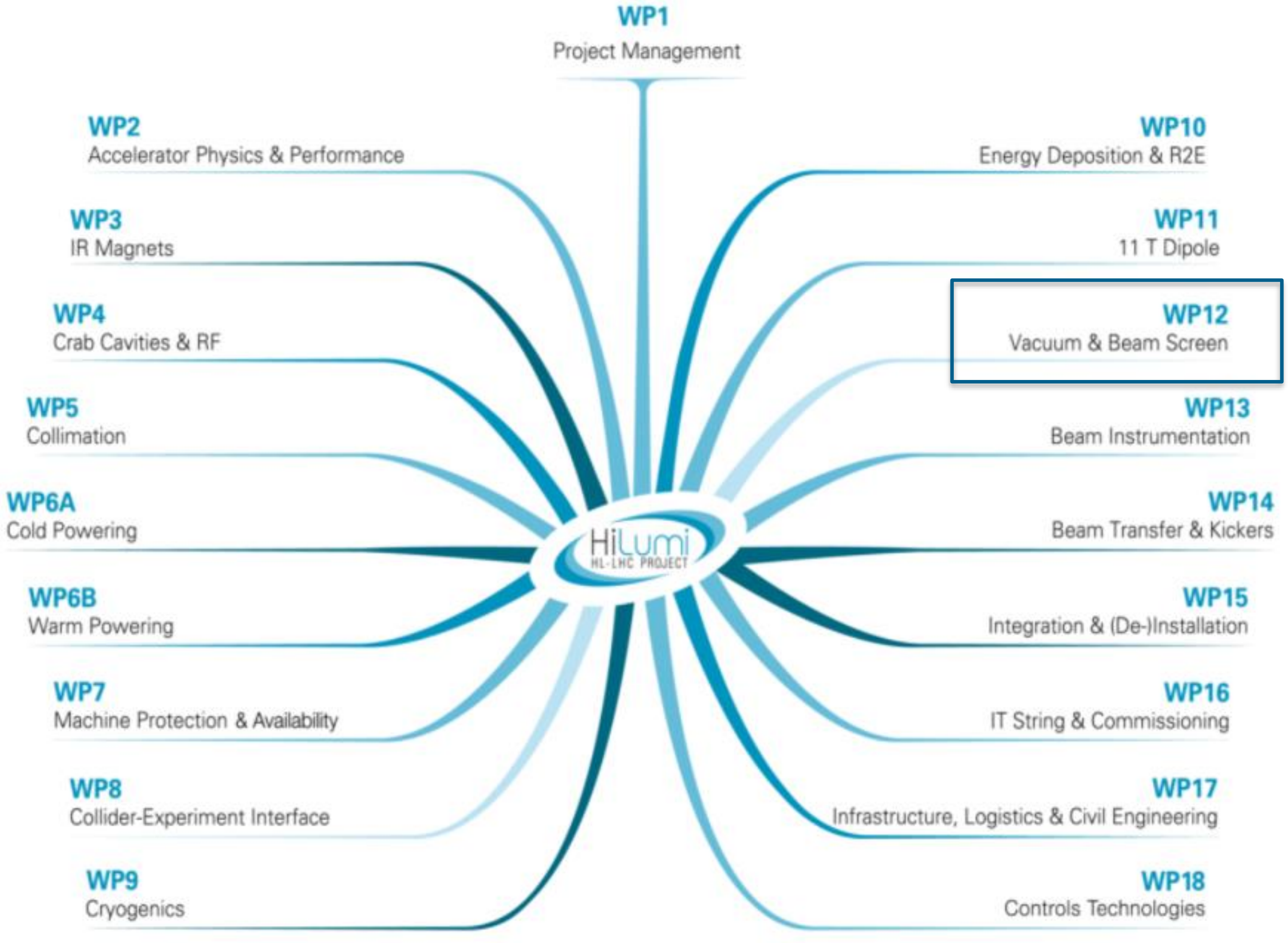
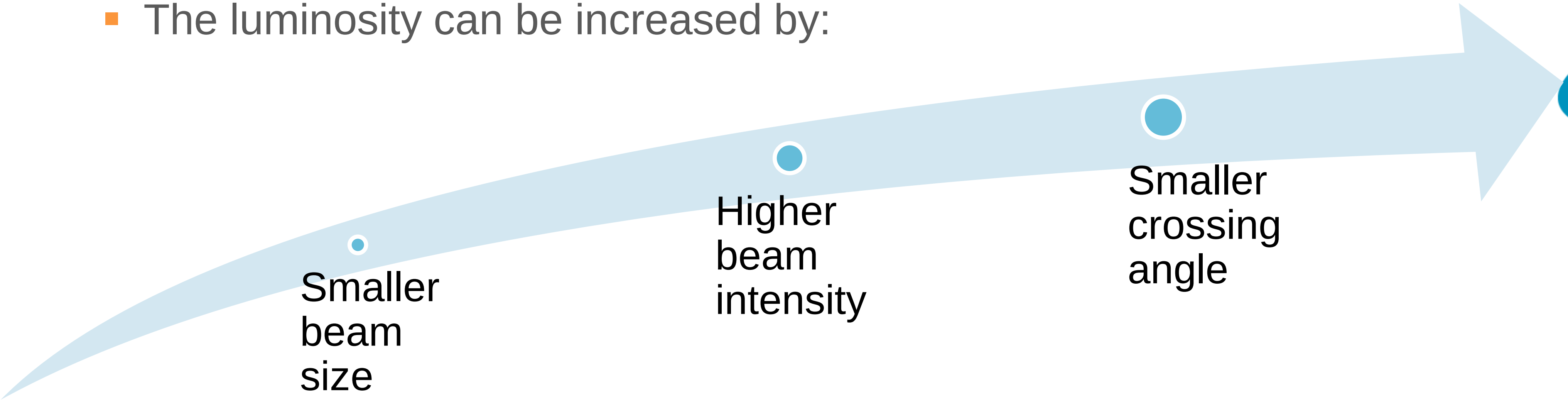
HiLumi HL-LHC PROJECT

HL-LHC project



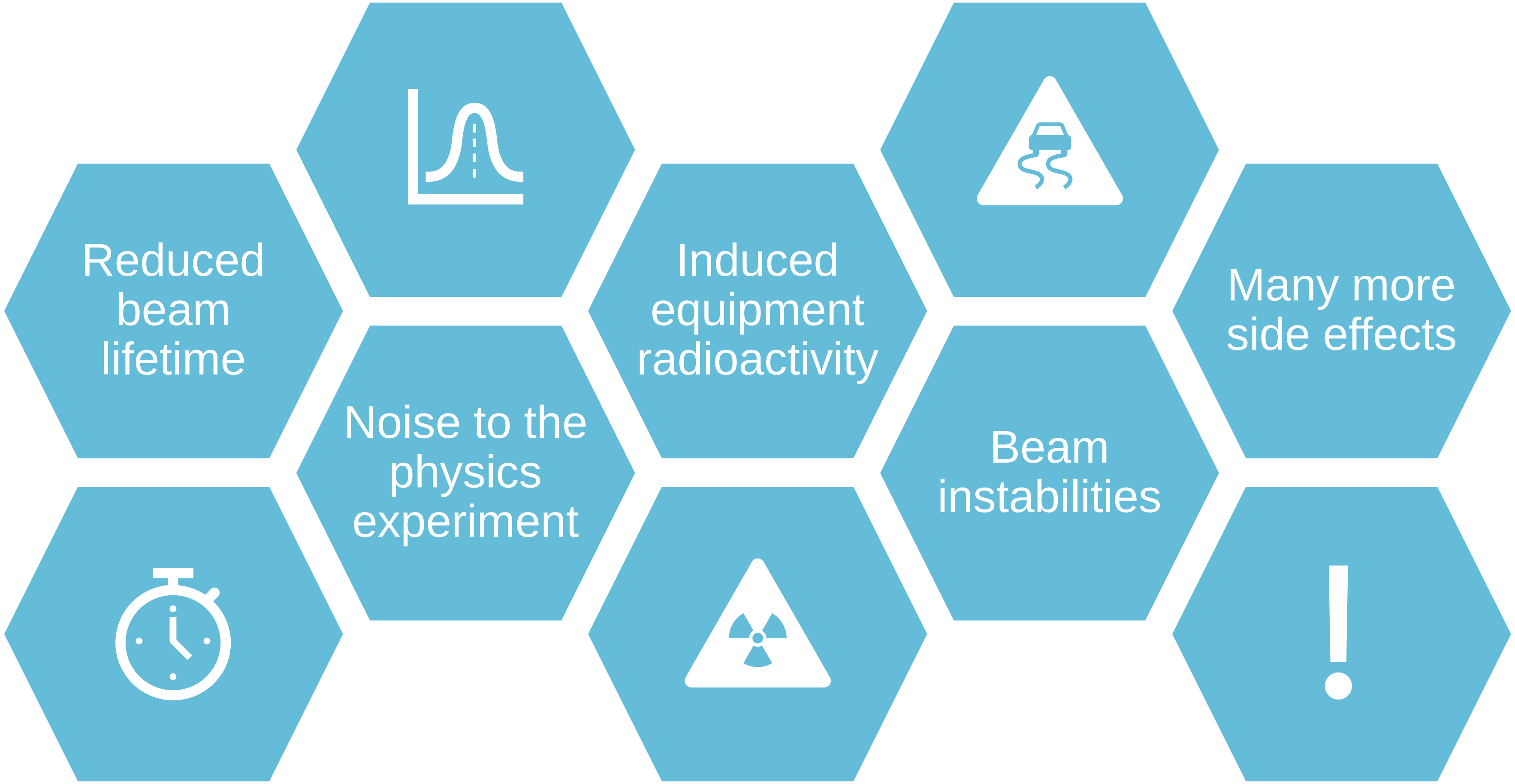
HL-LHC project

- The HL-LHC project aims to increase the luminosity of the current LHC machine
- The luminosity is the number of collision per second that take place in the machine
- More collisions mean more chances to observe very rare phisical phenomena
- The luminosity can be increased by:



Why vacuum in particle accelerators

Vacuum is needed in particle accelerators to avoid **beam-gas interactions**



From where the gas comes from?

- Gas molecules are normally desorbed from surfaces due to thermal outgassing
- In particle accelerators the beam itself is a source of gas

Static Vacuum

Thermal Desorption
- Bakeout
- Cryogenic cooling

Dynamic Vacuum

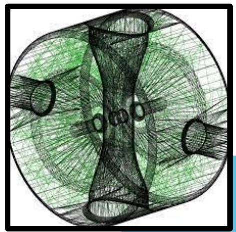
Photon Stimulated Desorption
- Synchrotron radiation

Electron Stimulated Desorption
- Electron cloud

Ion Stimulated Desorption
- Beam-gas interaction
- Beam pumping

How can we simulate

- One can use different codes to simulate vacuum
- The choice has to be made considering the result one wants to obtain and the type of problem that has to be simulated



Molflow+

- TPMC code
- Accurate simulations of 3D components

VASCO

- Analytic code
- 1D simulation of long accelerator structure
- Dynamic vacuum

LTSpice

- Electrical analogy
- Time-dependent non-steady-state simulations

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How can we simulate: The VASCO code

- **VASCO** is a simulation code used to model the dynamic vacuum in particle accelerator
- It was developed at CERN by A. Rossi in 2004

Simulation
- 1-dimensional
- Analytic
- Multi-Gas

Outputs
- Density profile
- Gas composition
- Critical current

LHC Project Note 341

3/23/04

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VASCO (VAcuum Stability COde): multi-gas code to calculate gas density profile in a UHV system

A. Rossi / AT-VAC

Keywords: vacuum calculations, vacuum stability, residual gas pressure, induced desorption

Summary

Calculation of the residual gas pressure in the presence of hadron beam.

1. Introduction

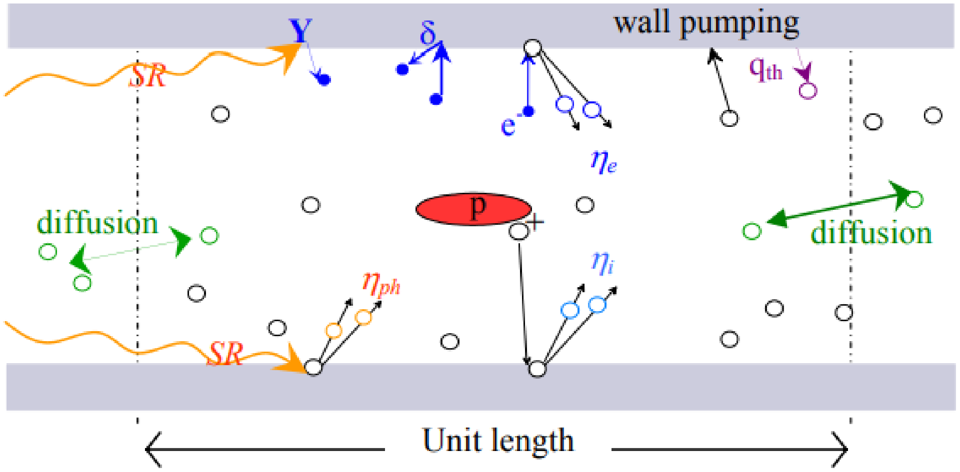
In a particle accelerator the estimation of residual gas density profiles is indispensable to verify the design and confirm vacuum stability [1] and beam lifetime. Moreover, in the experimental insertion regions density profiles are extremely important to estimate machine background effects in the detectors generated by proton or ion-gas scattering.

In a hadron collider, beam induced dynamic effects such as ion, electron and photon-stimulated gas desorption are the main source of residual gas.

In this paper, the VASCO code to estimate vacuum stability and density profiles in steady state conditions is presented. In order to take into account the variation of geometry of the vacuum system, surface materials,

How can we simulate: The VASCO code

- **VASCO** is based on these assumptions:
  - The geometry is a succession of cylinders with the same conductance of the real components
  - The parameters are independent with respect to time
  - The system is in a quasi-steady state



In each segment we solve:

$$\frac{d\boldsymbol{n}}{dx} = -\frac{1}{\boldsymbol{C}_{spec}} \cdot \boldsymbol{Q}$$

$$\frac{d\boldsymbol{Q}}{dx} = \boldsymbol{B} \cdot \boldsymbol{n} + \boldsymbol{C}$$

PSD $\Gamma_{ph}\boldsymbol{\eta}_{PSD}$

ISD $\frac{I}{q_{e^-}}\boldsymbol{\sigma}\boldsymbol{\eta}_{ISD}$

Sticking $\frac{1}{4}A\langle\boldsymbol{v}\rangle\boldsymbol{\alpha}$

ESD $\Gamma_e\boldsymbol{\eta}_{ESD}$

Outgassing $A \cdot \boldsymbol{q}_{th}$

Between segments we impose continuity

$$\boldsymbol{n}_{i+1}^{left} = \boldsymbol{n}_i^{right}$$

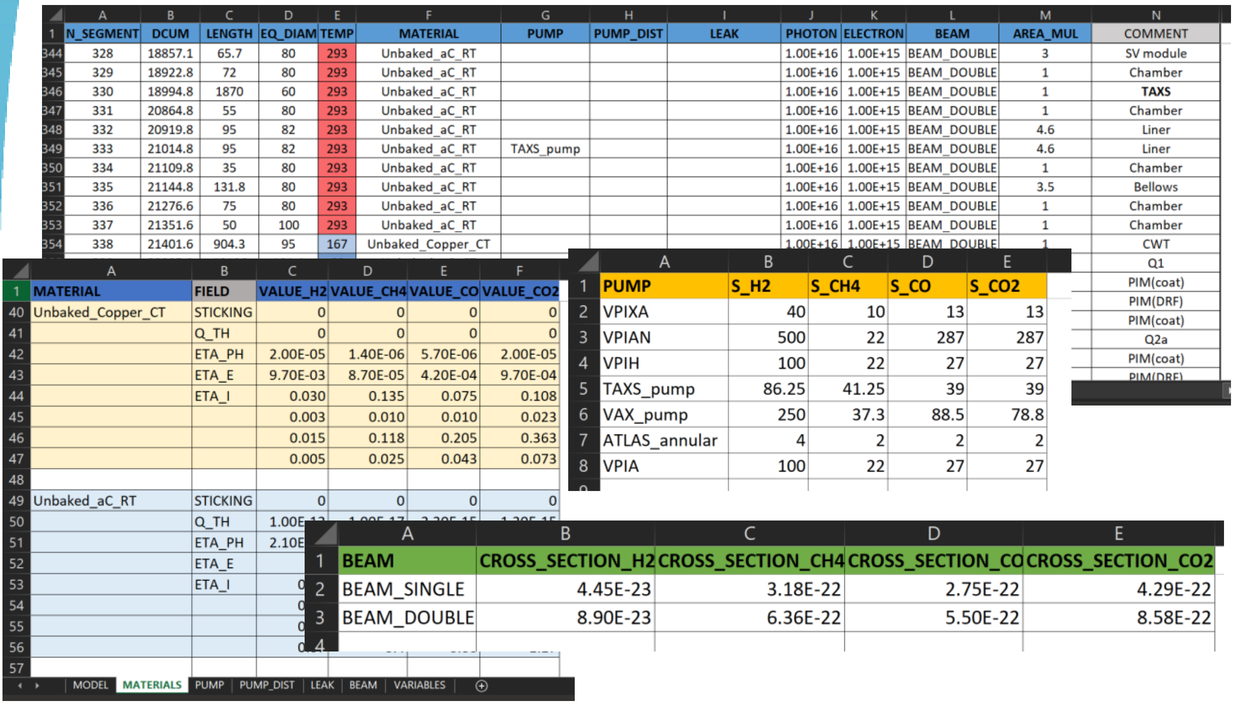
$$\boldsymbol{Q}_{i+1}^{left} - \boldsymbol{Q}_i^{right} = \boldsymbol{g}_{i+1} - \boldsymbol{S}_{i+1} \cdot \boldsymbol{n}_{i+1}^{left}$$

Lumped pumps and gas injection

How can we simulate: Upgrades of VASCO code

New features

- Improved usability
- Result post processing
- Interface with Synrad+
- Conditioning



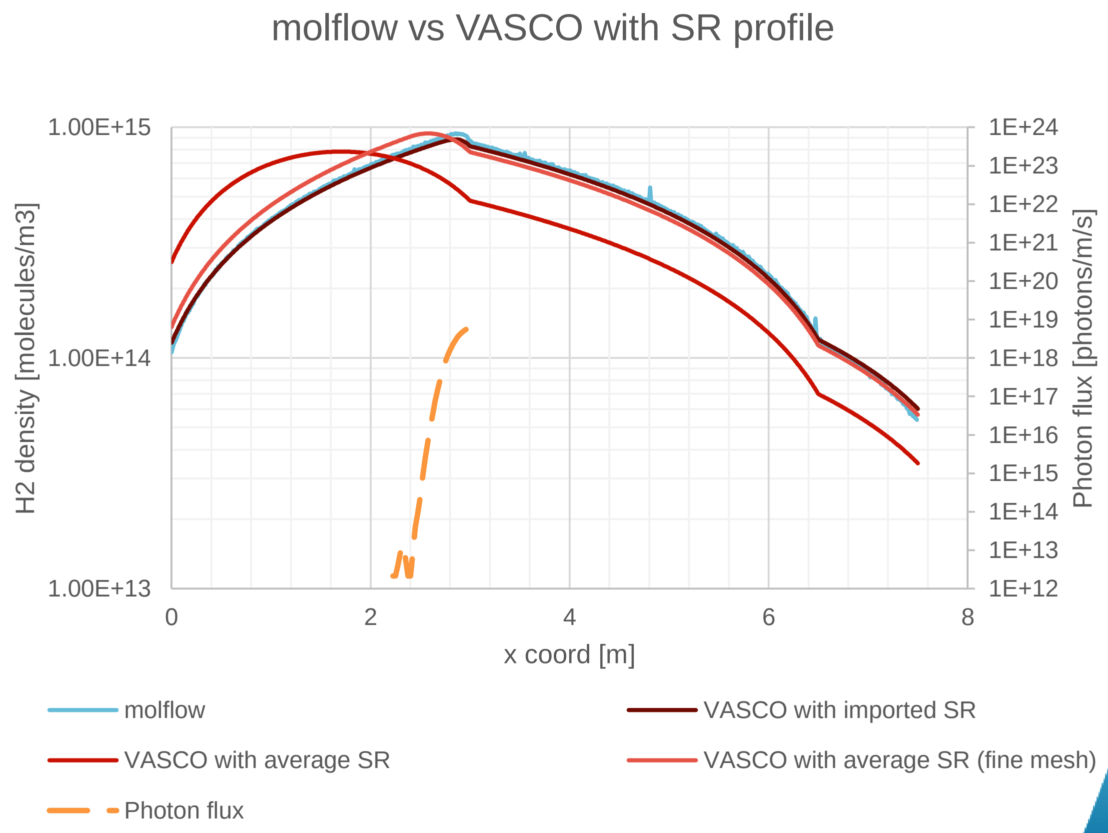
	N_SEGMENT	DCUM	LENGTH	EQ_DIAM	TEMP	MATERIAL	PUMP	PUMP_DIST	LEAK	PHOTON	ELECTRON	BEAM	AREA_MUL	COMMENT
344	328	18857.1	65.7	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	3	SV module
345	329	18922.8	72	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	Chamber
346	330	18994.8	1870	60	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	**TAXS**
347	331	20864.8	55	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	Chamber
348	332	20919.8	95	82	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	4.6	Liner
349	333	21014.8	95	82	293	Unbaked_aC_RT	TAXS_pump			1.00E+16	1.00E+15	BEAM_DOUBLE	4.6	Liner
350	334	21109.8	35	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	Chamber
351	335	21144.8	131.8	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	3.5	Bellows
352	336	21276.6	75	80	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	Chamber
353	337	21351.6	50	100	293	Unbaked_aC_RT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	Chamber
354	338	21401.6	904.3	95	167	Unbaked_Copper_CT				1.00E+16	1.00E+15	BEAM_DOUBLE	1	CWT
														Q1
														PIM(coat)
														PIM(DRF)
														PIM(coat)
														Q2a
														PIM(coat)

	MATERIAL	FIELD	VALUE_H2	VALUE_CH4	VALUE_CO	VALUE_CO2
40	Unbaked_Copper_CT	STICKING	0	0	0	0
41		Q_TH	0	0	0	0
42		ETA_PH	2.00E-05	1.40E-06	5.70E-06	2.00E-05
43		ETA_E	9.70E-03	8.70E-05	4.20E-04	9.70E-04
44		ETA_I	0.030	0.135	0.075	0.108
45			0.003	0.010	0.010	0.023
46			0.015	0.118	0.205	0.363
47			0.005	0.025	0.043	0.073
48						
49	Unbaked_aC_RT	STICKING	0	0	0	0
50		Q_TH	1.00E			
51		ETA_PH	2.10E			
52		ETA_E				
53		ETA_I	0			
54			0			
55			0			
56			0			
57						

MODEL | MATERIALS | PUMP | PUMP_DIST | LEAK | BEAM | VARIABLES

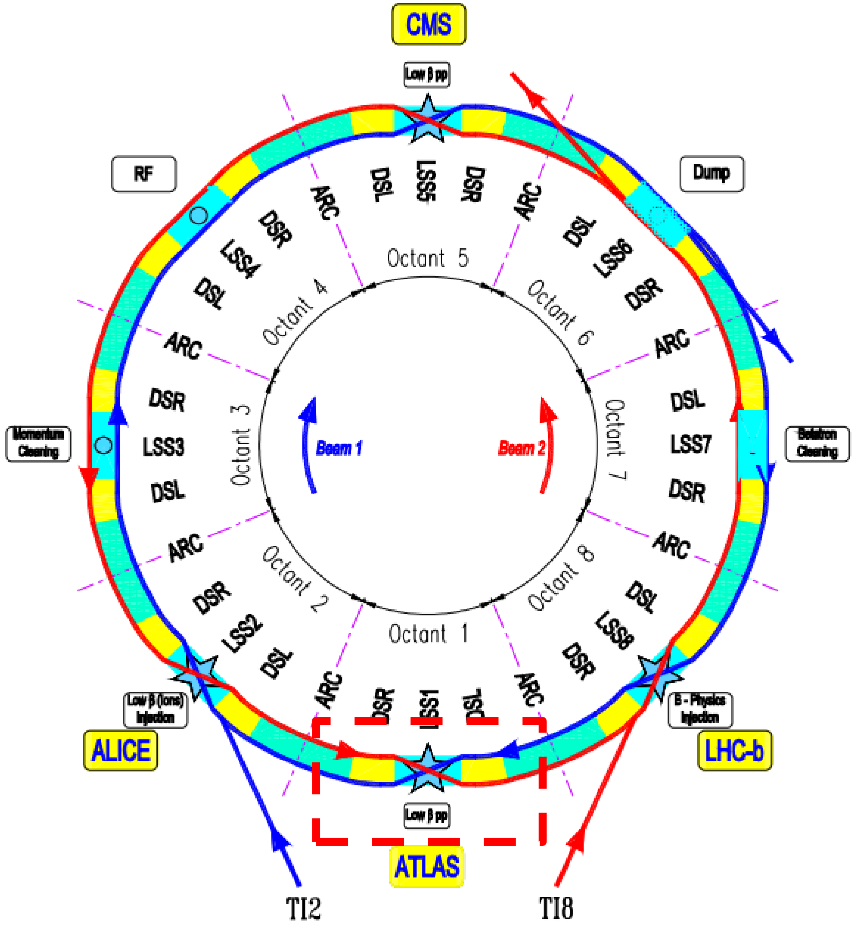
	PUMP	S_H2	S_CH4	S_CO	S_CO2
2	VPIXA	40	10	13	13
3	VPIAN	500	22	287	287
4	VPIH	100	22	27	27
5	TAXS_pump	86.25	41.25	39	39
6	VAX_pump	250	37.3	88.5	78.8
7	ATLAS_annular	4	2	2	2
8	VPIA	100	22	27	27

	BEAM	CROSS_SECTION_H2	CROSS_SECTION_CH4	CROSS_SECTION_CO	CROSS_SECTION_CO2
2	BEAM_SINGLE	4.45E-23	3.18E-22	2.75E-22	4.29E-22
3	BEAM_DOUBLE	8.90E-23	6.36E-22	5.50E-22	8.58E-22



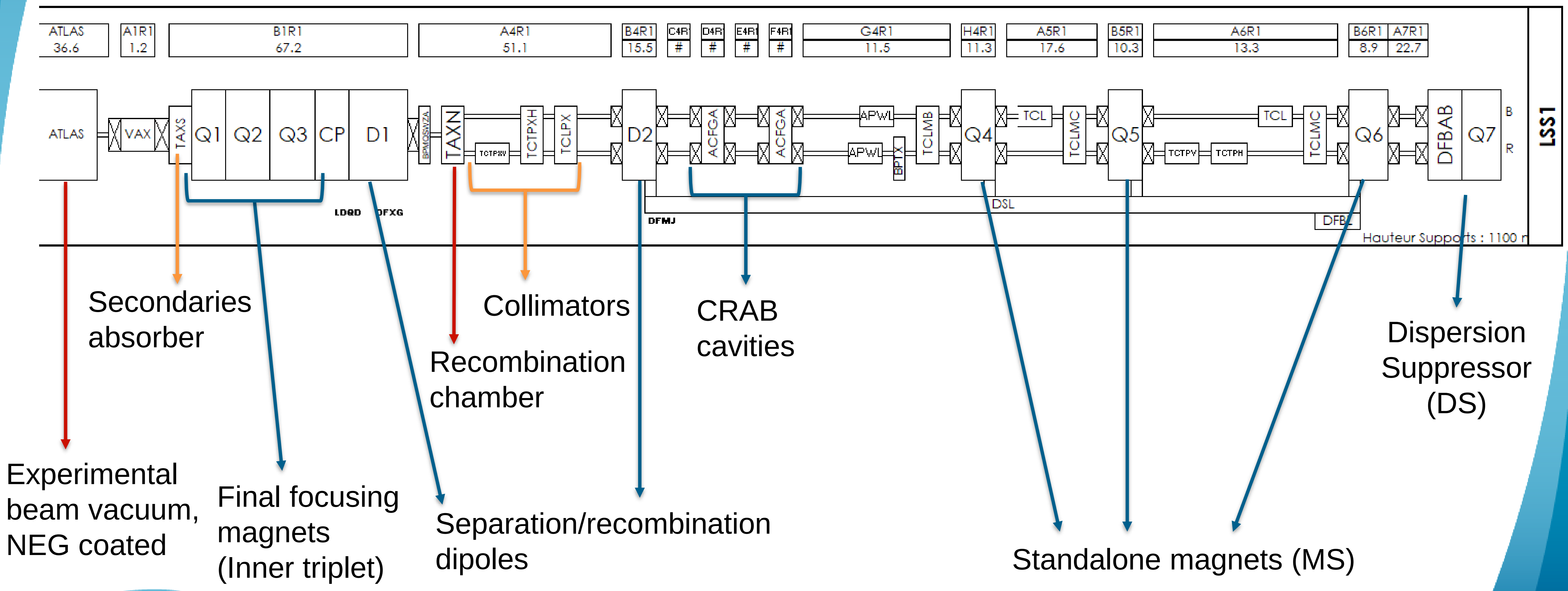
LSS1 pressure profile simulation: The LHC layout

- The Large Hadron Collider is composed of eigth octants
- Each octant contain a «**Long Straight Section**»
  - **LSS1** and **LSS5** are the high luminosity insertions, in which the experiments ATLAS and CMS are inserted
  - In **LSS2** and **LSS8** are the injection points, in which the beams are transferred from the SPS. They also accomodate the experiments ALICE and LHCb
  - In **LSS3** and **LSS7** are situated the main collimators for momentum and betatron cleaning
  - **LSS4** hosts the accelerating RF cavities
  - The beams are dumped through **LSS6**



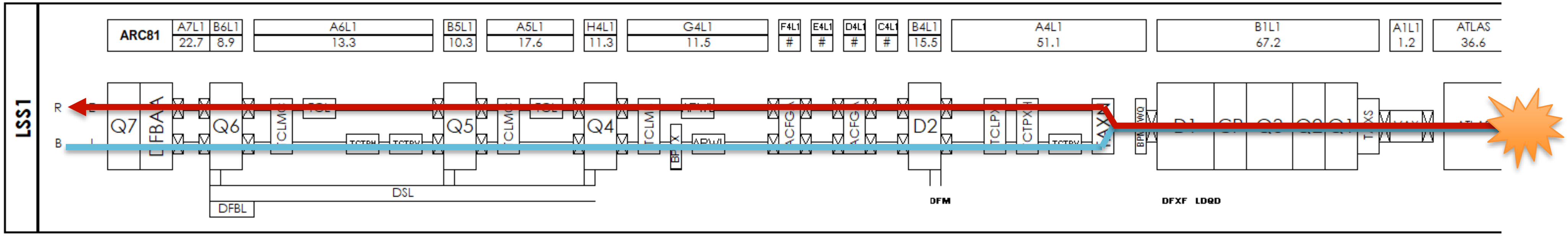
LSS1 pressure profile simulation: Layout of LSS1

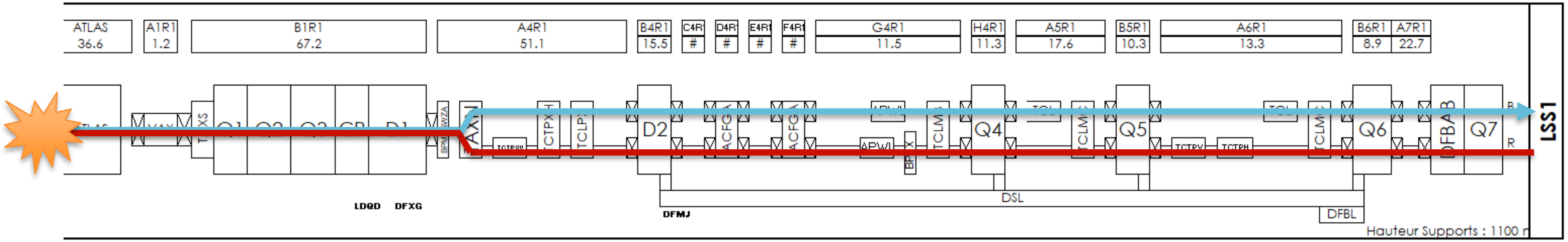
- The LSS1 is symmetric with respect to the IP



LSS1 pressure profile simulation: Layout of LSS1

- In LSS1 the two beams are collided (almost) head on inside the ATLAS detector
- The simulations will follow the pressure profile of Beam 1





LSS1 pressure profile simulation: Input parameters

- The VASCO model is composed by **segments**, each of one has a geometry and a set of parameters
- A segment is has a **lenght** and an **equivalent diameter**
- The other **parameters** are found from the literature and the manufacturing spec of the components
- **Syncrotron radiation** is computed with Synrad, while an educated guess is made for the **electron flux** due to EC

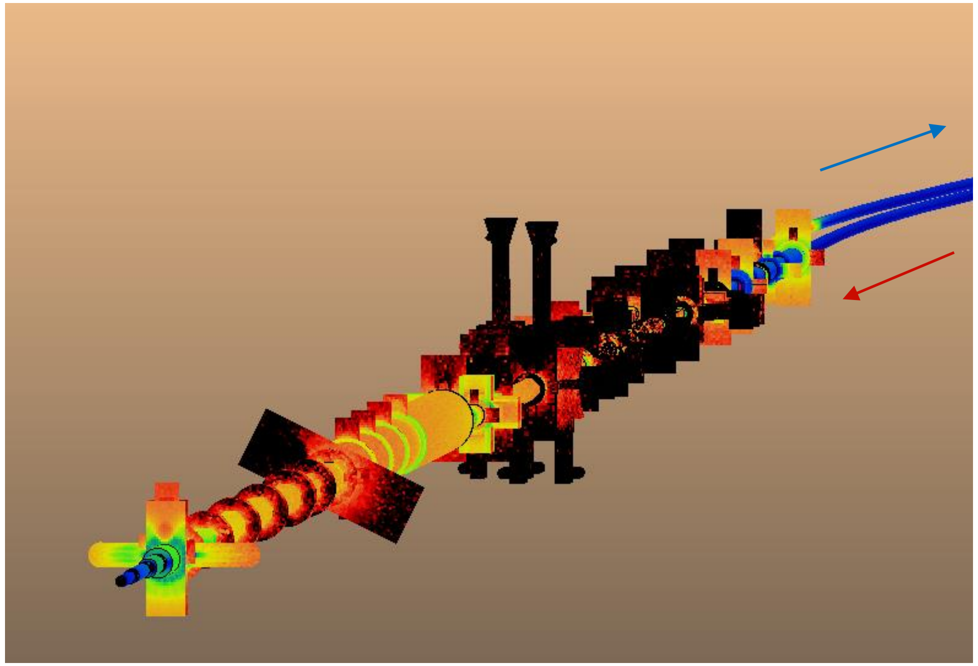
Input parameters

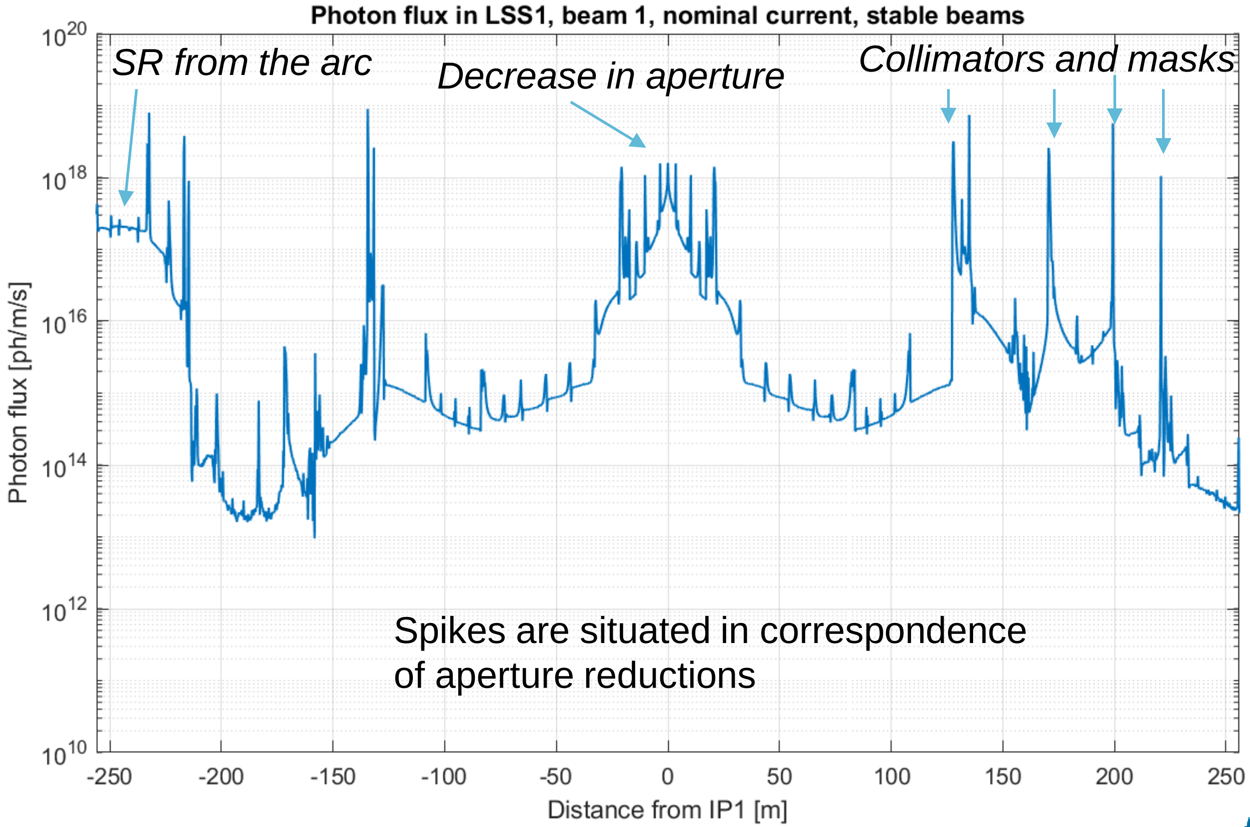
- Geometry
- Thermal outgassing
- Pumping speeds
- Yield data for PSD, ESD and ISD
- Photon and electron fluxes

EDMS 2694563

LSS1 pressure profile simulation: Synchrotron light simulations

- Photon flux in the LSS is evaluated using Synrad+
- The simulation comprehends the LSS and 2 half cells of the arc, and it exploits the symmetry to reduce the calculation effort
- HLLHC-V1.5 optics were used, ultimate energy, nominal intensity, collision mode





LSS1 pressure profile simulation: Machine operation scenarios

- The pressure profile will change with time during operation due to different current and surface conditioning
- 4 scenarios have been simulated:

At startup

Injection energy – 450 GeV

EC present

ESD is the main gas load

SR is negligible

No PSD in the calculations

Beam current ≈590mA

(2748 bunches, 1.2×10^{11}ppb)

After scrubbing

Nominal energy – 7 TeV

EC still present

ESD yields conditioned

SR present

PSD is the main gas load

Beam current ≈590mA

(2748 bunches, 1.2×10^{11}ppb)

Intensity ramp-up

Nominal energy – 7 TeV

EC still present

ESD yields conditioned

SR present

PSD is the main gas load

Beam current ≈1.10A

(2748 bunches, 2.2×10^{11}ppb)

Full conditioning

Nominal energy – 7 TeV

EC is suppressed

No ESD in the calculations

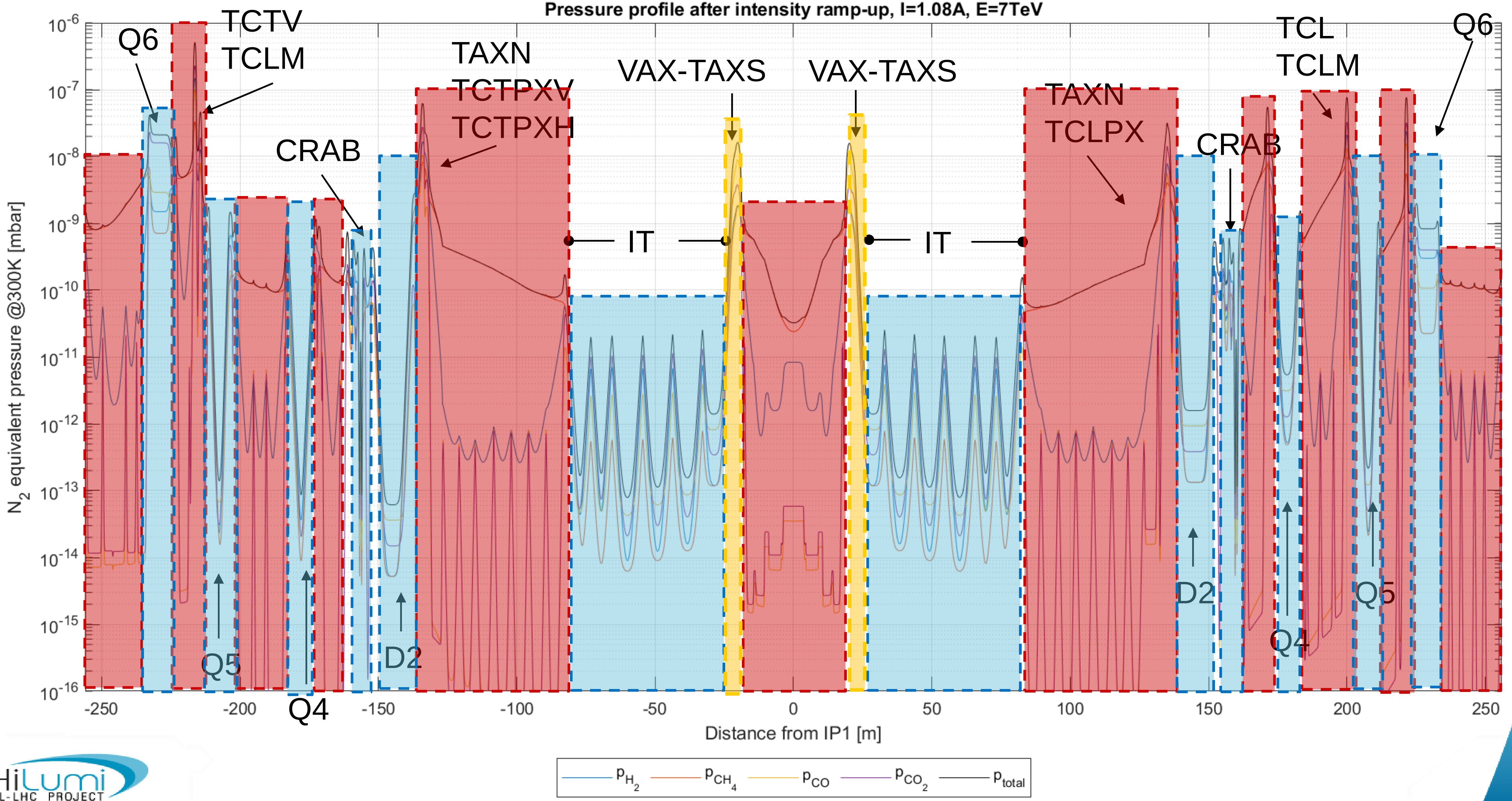
SR present

PSD yields are conditioned

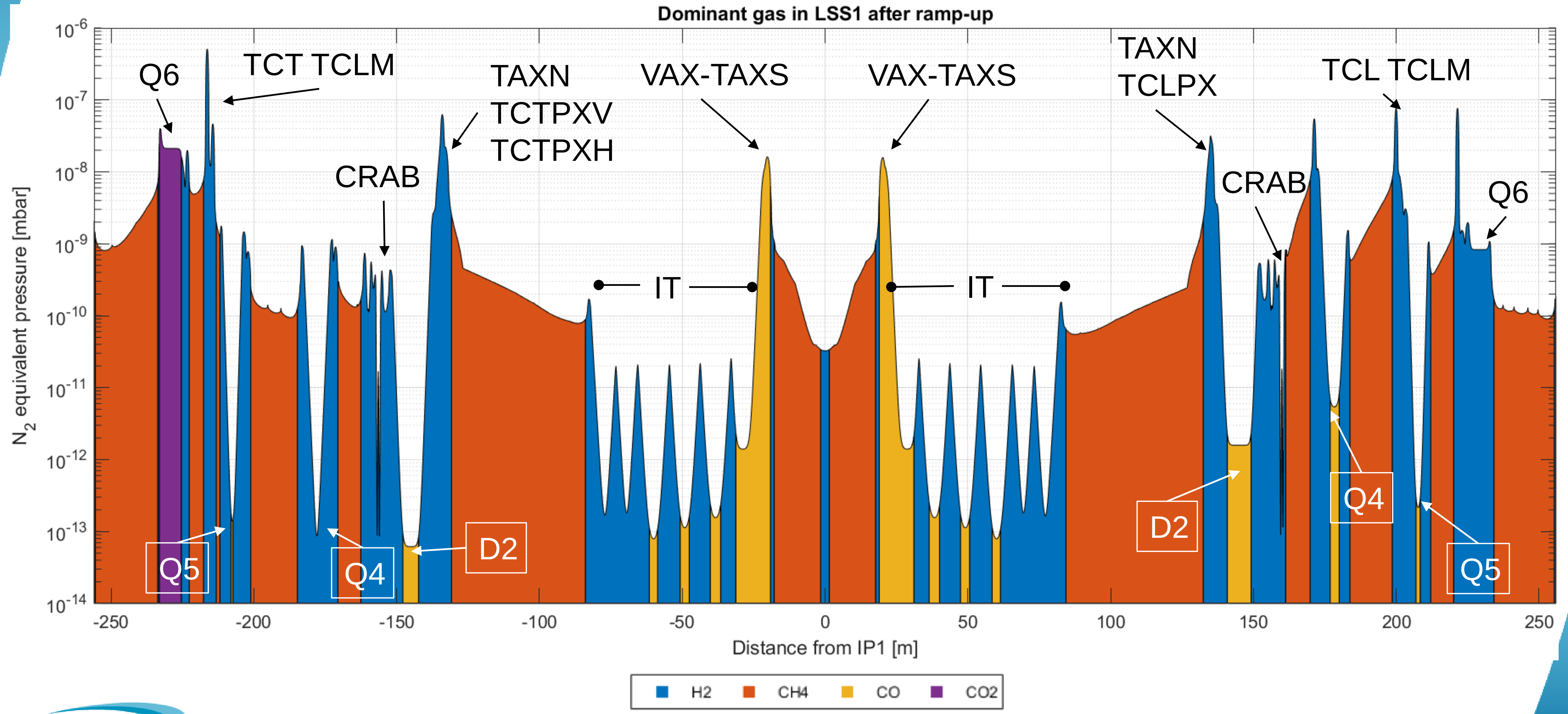
Beam current ≈1.10A

(2748 bunches, 2.2×10^{11}ppb)

LSS1 pressure profile simulation: Pressure profile

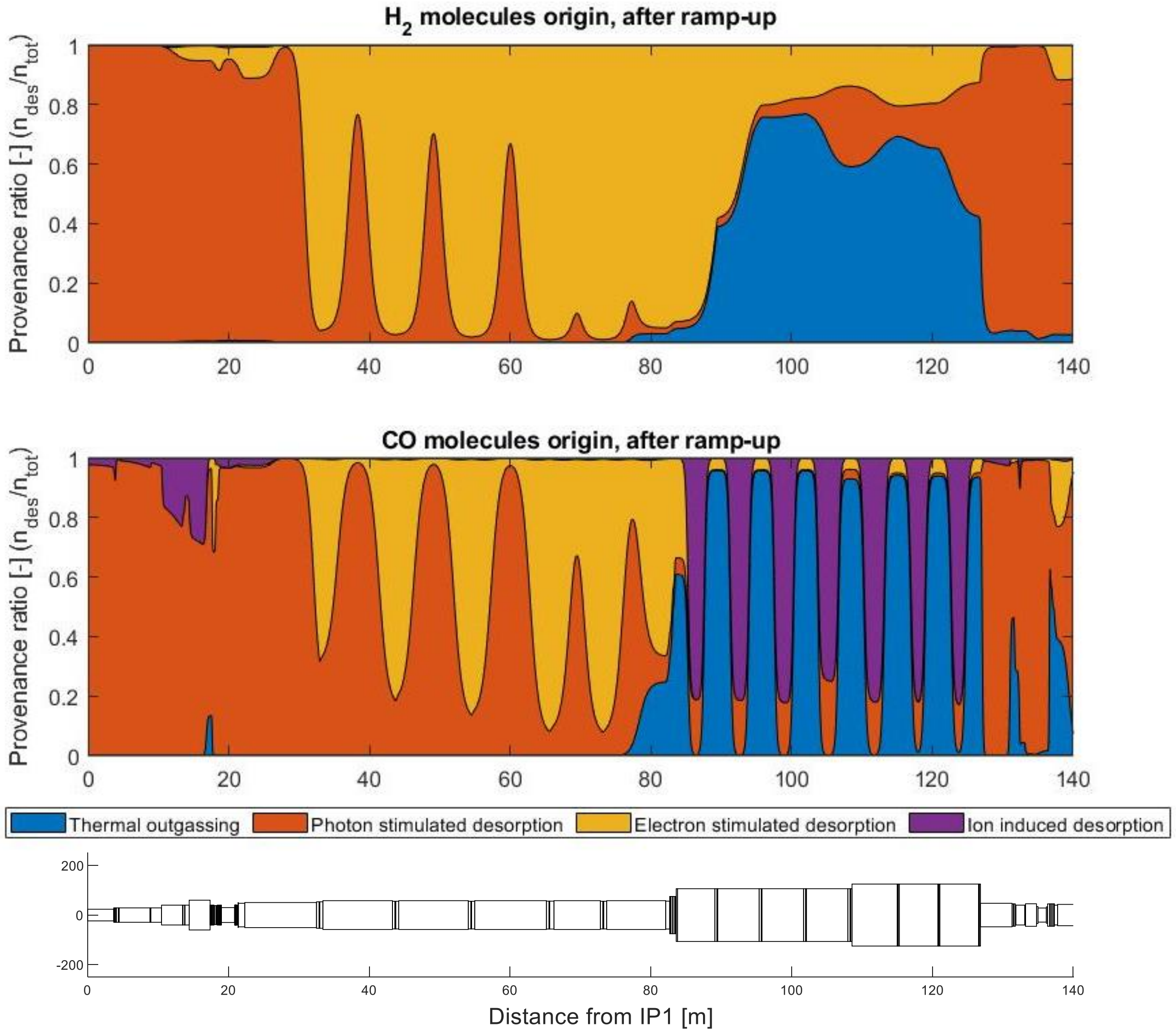


LSS1 pressure profile simulation: Dominant gas



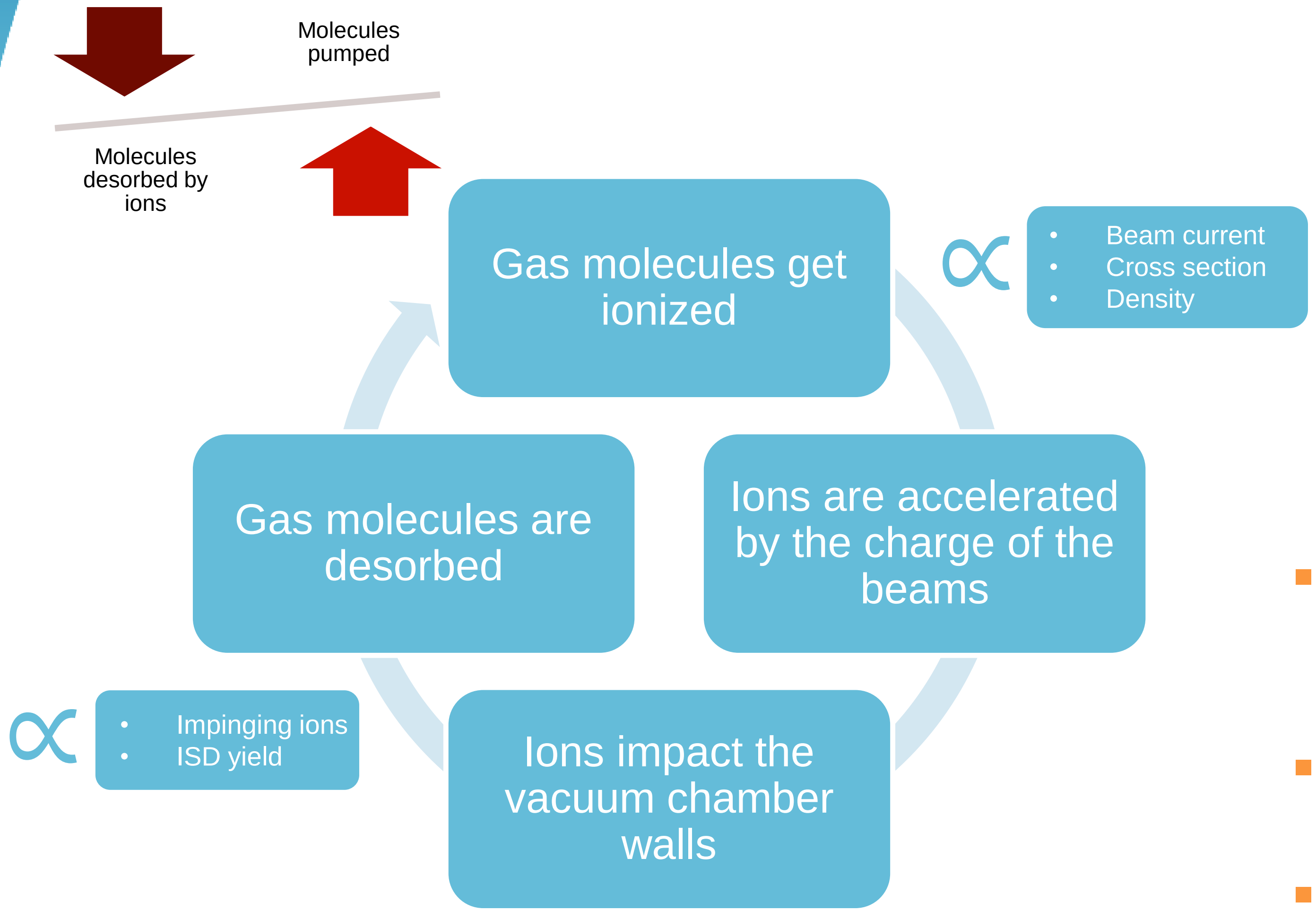
*Based on density, not N_2 equivalent pressure

LSS1 pressure profile simulation: Gas composition survey



- By computing the pressure profile with just **one source of gas at a time**, an analysis of the gas provenance is possible
- These color maps can give a lot of information on **how to optimize** the machine layout and **how to intervene** to reduce the pressure

LSS1 pressure profile simulation: Critical current

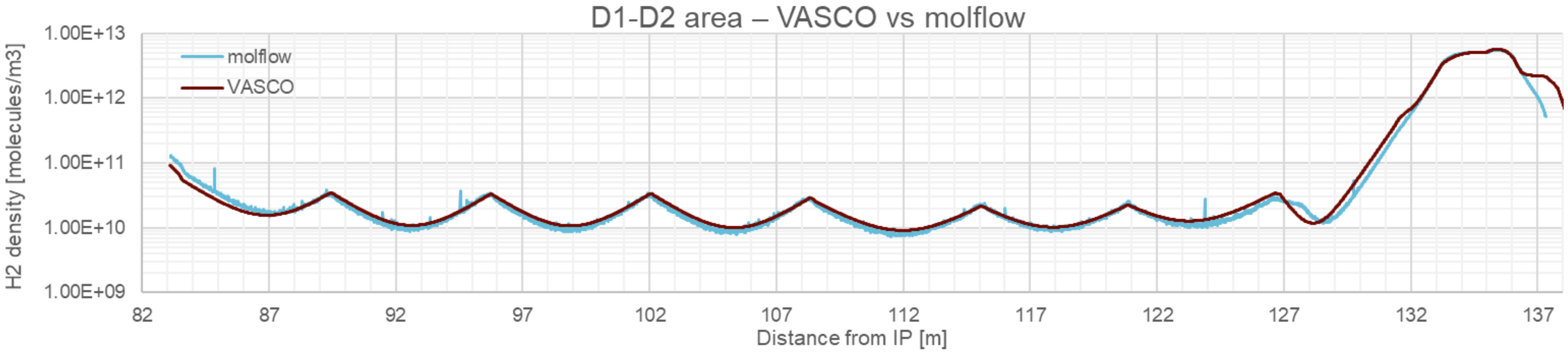


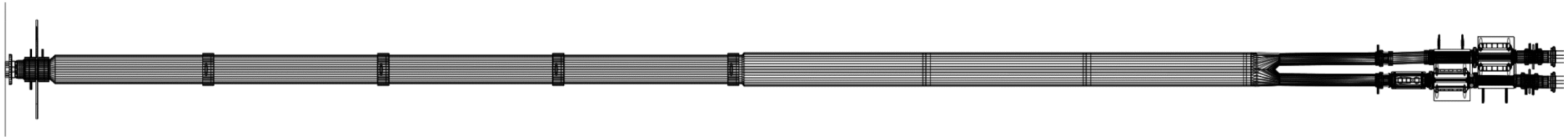
The **critical current** is the beam current at which the amount of desorbed gas is not pumped fast enough from the system and, **given sufficient time**, the pressure **runs away**

- For the **start-up** of the machine a critical current of **5.6A per beam** is foreseen
- The nominal current of the machine is **1.08A per beam**
- After the machine is conditioned, the vacuum will be unconditionally stable

LSS1 pressure profile simulation: Comparison with Molflow

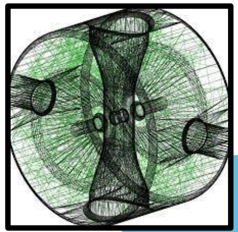
- Finally, it is important to check the performance of the model
- As any analytical code, VASCO can suffer some inaccuracies in certain cases (beaming)
- Comparisons can be made between Molflow and VASCO to evaluate the quality of the model





How can we simulate

- One can use different codes to simulate vacuum
- The choice has to be made considering the result one wants to obtain and the type of problem that has to be simulated



Molflow+

- TPMC code
- Accurate simulations of 3D components

VASCO

- Analytic code
- 1D simulation of long accelerator structure
- Dynamic vacuum

LTSpice

- Electrical analogy
- Time-dependent non-steady-state simulations

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Inner Triplet pumpdown: the vacuum electrical analogy

- The equations that govern molecular flow are very similar to the ones concerning electrical circuit

Vacuum

- Pressure
- Throughput
- Conductance
- Volume

$$Q = S \cdot p \qquad Q = C(p_2 - p_1) \qquad Q = V\frac{dp}{dt}$$

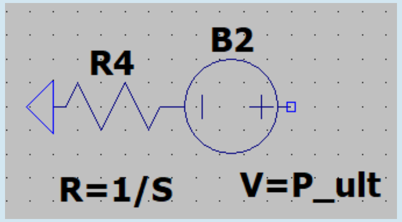
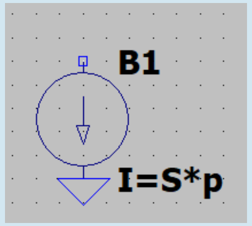
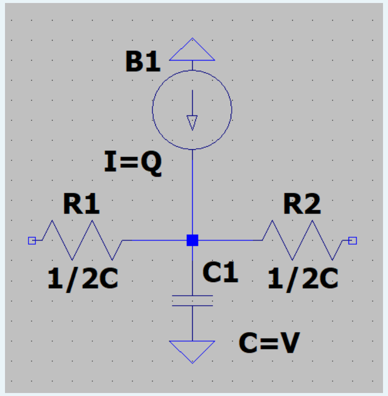
Electrical

- Voltage
- Current
- Resistance^{-1}
- Capacitance

$$I = \frac{1}{R}V \qquad I = \frac{1}{R}(V_2 - V_1) \qquad I = C\frac{dV}{dt}$$

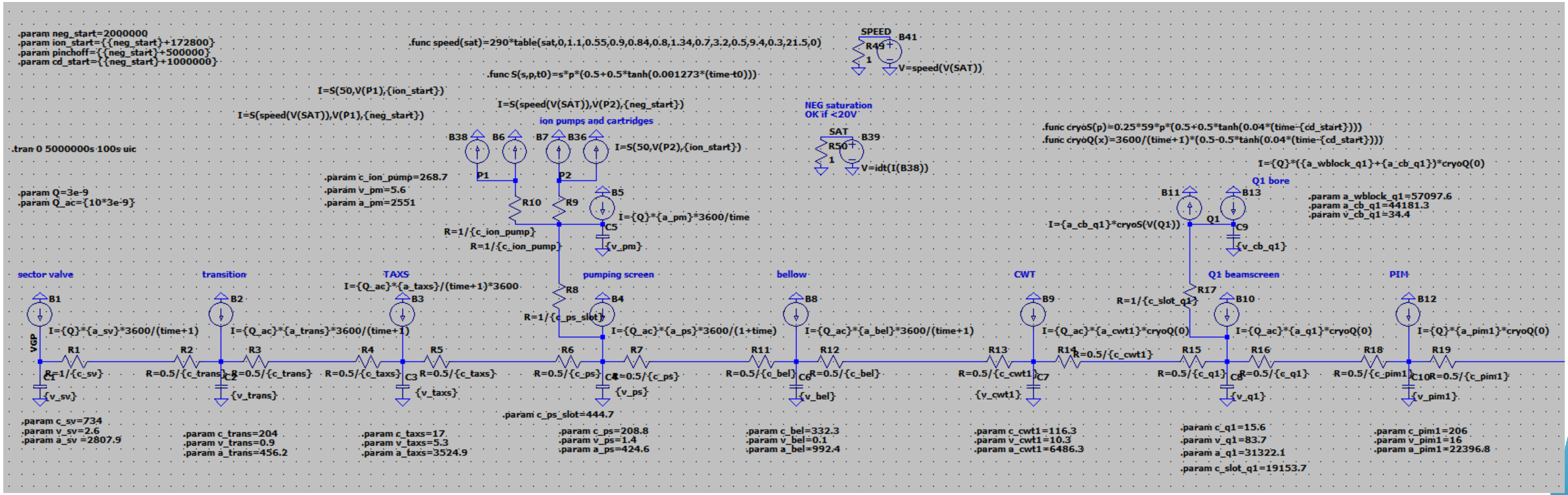
Inner Triplet pumpdown: the vacuum electrical analogy

- For each component of the vacuum system, one can build its electrical analogue

Vacuum	Electrical
Pump	 
Chamber	

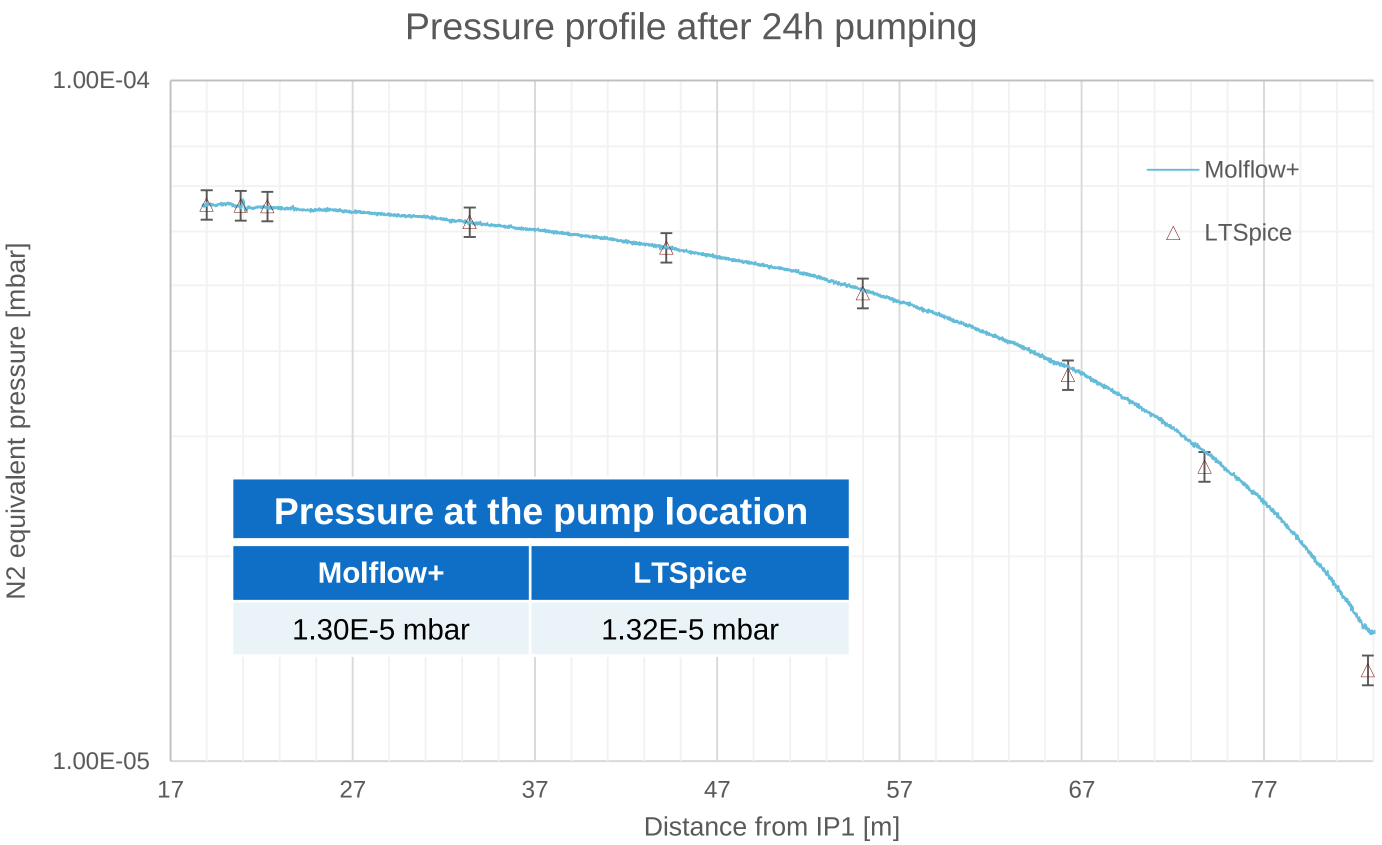
Inner Triplet pumpdown: IT model

- Following the analogy the model can be built as a succession of chambers and pumps
- It is possible to include time dependent outgassing and variable pumping speed
- The model is single gas and it concerns water (unbaked system)



Inner Triplet pumpdown: Model comparison

- Conductance of the segments is computed with molflow
- LTSpice does not give the pressure profile as an output, but the **time evolution** of the pressure in **certain points**
- The model works well and the results are in accordance with molflow+ model



Pressure at the pump location	
Molflow+	**LTSpice**
1.30E-5 mbar	1.32E-5 mbar

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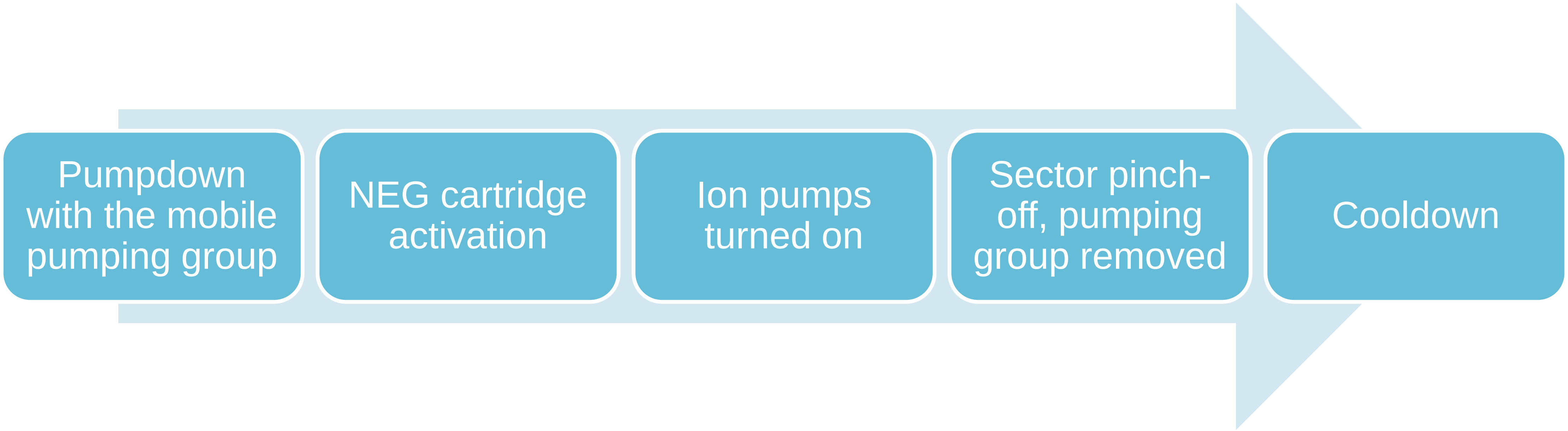
Inner Triplet pumpdown: Pumpdown procedure

Pumpdown and cooldown procedure



- What are the requirements for a good pumpdown:
  - Pressure low enough before the cooldown to avoid cryocondensation on the beamscreen
  - Avoid saturation of the NEG cartridge

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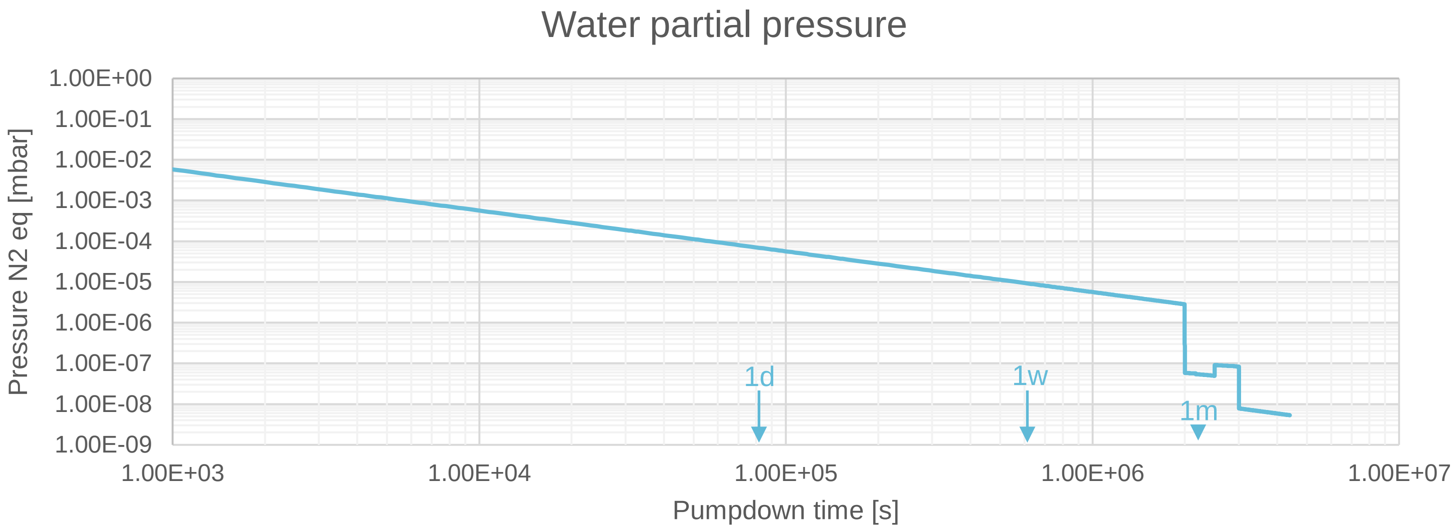
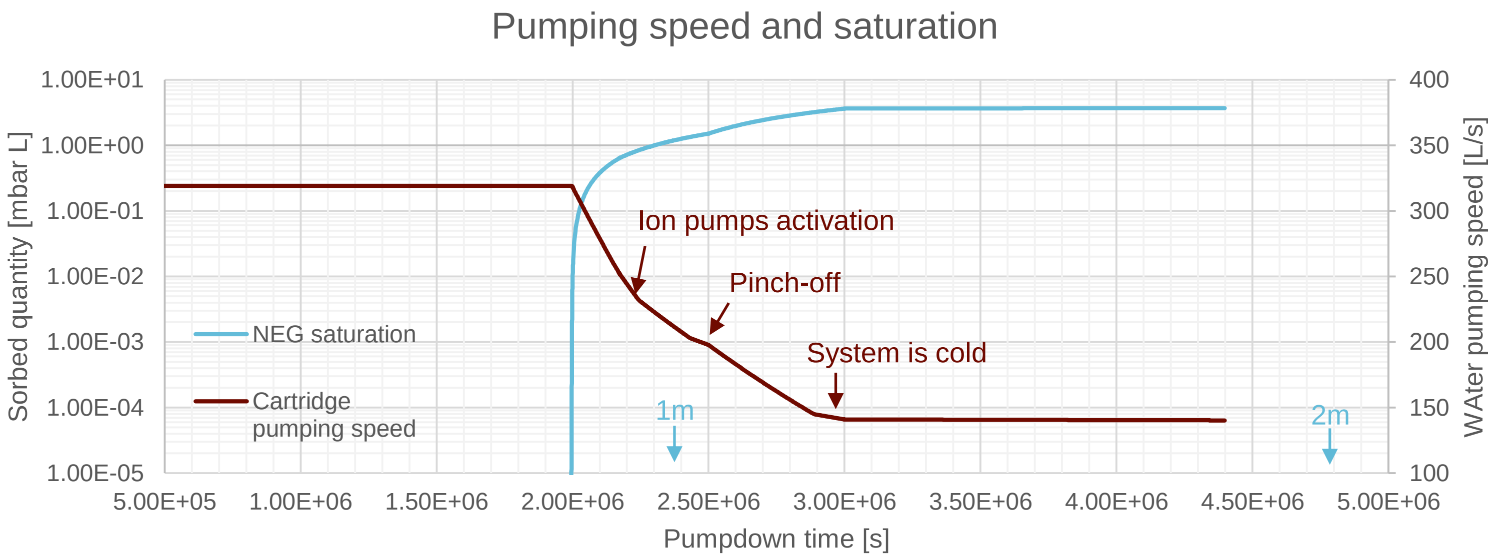
Inner Triplet pumpdown: Results

- Given the outgassing of the carbon coating and the timing of the procedure the model can output:
  - The pumpdown curve
  - The final pumping speed of the cartridge
  - The quantity of gas sorbed by the cartridge
- It is also possible to estimate the time needed to complete the operation





Conclusions and outlooks

- Simulations are a very important tool for both design and operation of large and complex vacuum systems
- Each software is specific for solving a certain type of problem
- They can provide very accurate results as far as the assumptions and the input parameters are of good quality

- The new layout of LSS1 is now finalized and work is ongoing on the LSS5

- Future work will be focused on the same type of simulations for the current LHC for troubleshooting during Run 3
- Also the upgrade of the VASCO code will be continued

Thank you for your attention
Merci pour votre attention

Thanks to Giuseppe Bregliozzi, Jose Antonio Ferreira Somoza and Marton Ady for the constant discussion and support