Beam screen design of the triplet magnets

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AGENDA(*)

1. Vacuum Requirements
2. Triplet Region Lay-out, Lattice and Vacuum Model
3. Conductance Calculations
4. Static Pressure
5. Synchrotron Radiation Fans
6. SR-Induced Pressure Rise
7. Engineering/Integration Issues
8. Conclusions
9. References

(*) Adapted with modifications from presentation made at HiLumi WP3 meeting of 4/9/12.

1. Vacuum Requirements

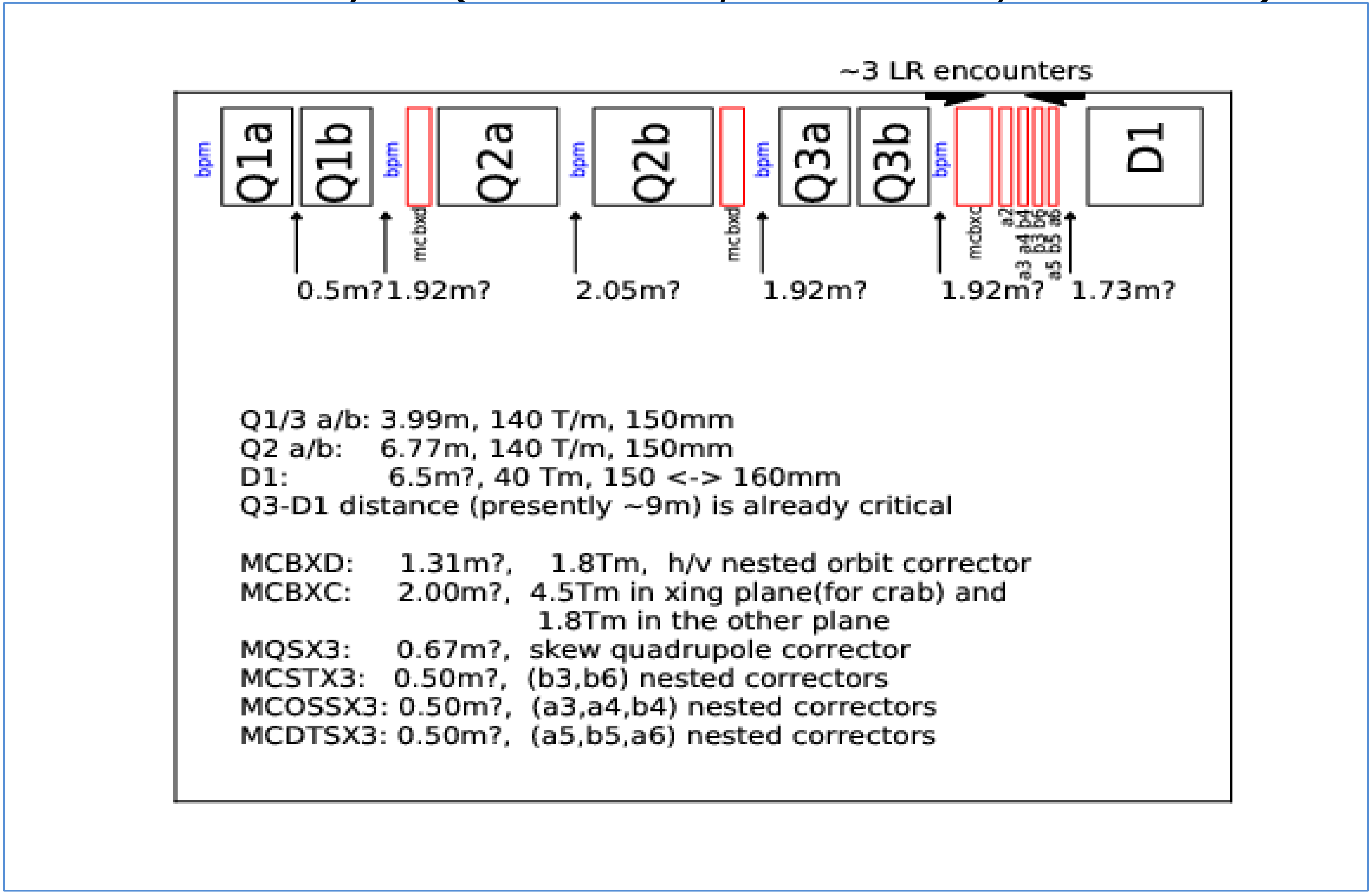
a) Assure a gas pressure better than **6.710^{-8} Pa** i.e. better than **$9.8 \cdot 10^{14}$ molecules/m^3** (H_2**-equiv.) @ 5 °K**, in order to guarantee a **>100 hrs** beam lifetime (nuclear scattering from residual gas, as per *LHC Design Report*)

b) Absorb any **synchrotron radiation-** and **e-cloud-induced** power on a beam-screen at a temperature higher than the 1.9 K of the cold bore

c) Maintain the pressure below the **critical pressure** limit, where runaway pressure rise may start due to **resonant e-cloud** (to be assessed)

2. Triplet Region Lay-out, Lattice and Vacuum Model

Tentative layout (R. De Maria, S. Fartoukh, 26/7/2012)



Q1/3 a/b: 3.99m, 140 T/m, 150mm
Q2 a/b: 6.77m, 140 T/m, 150mm
D1: 6.5m?, 40 Tm, 150 <-> 160mm
Q3-D1 distance (presently ~9m) is already critical

MCBXD: 1.31m?, 1.8Tm, h/v nested orbit corrector
MCBXC: 2.00m?, 4.5Tm in xing plane(for crab) and 1.8Tm in the other plane
MQSX3: 0.67m?, skew quadrupole corrector
MCSTX3: 0.50m?, (b3,b6) nested correctors
MCOSSX3: 0.50m?, (a3,a4,b4) nested correctors
MCDTSX3: 0.50m?, (a5,b5,a6) nested correctors

2. Triplet Region Lay-out, Lattice and Vacuum Model

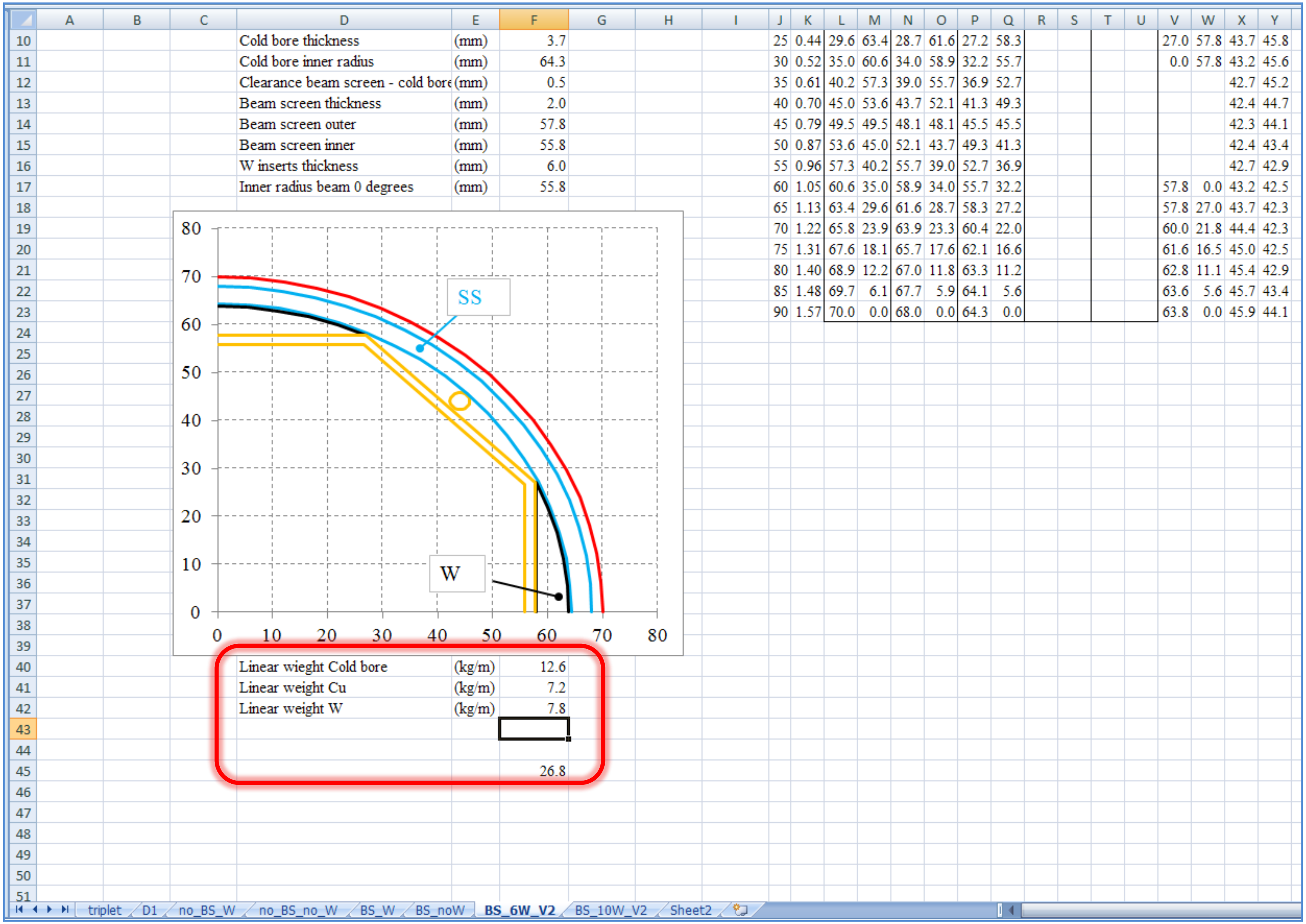
- The area between Q1 and D1 has been modeled using two Montecarlo codes (R. Kersevan, M. Szakacs) :

  a) **SYNRAD+** , ray-tracing MC code
  b) **Molflow+**, Test-Particle MC code

- A 3D model has been made, taking the 2D cross-section of the cold-bore (140 mm ID) as per Excel file of E. Todesco (private comm. 10/7/12) and adding the proper number of pumping slots and pumping slot shields as installed on the LHC arc dipole beam-screens.

2. Triplet Region Lay-out, Lattice and Vacuum Model

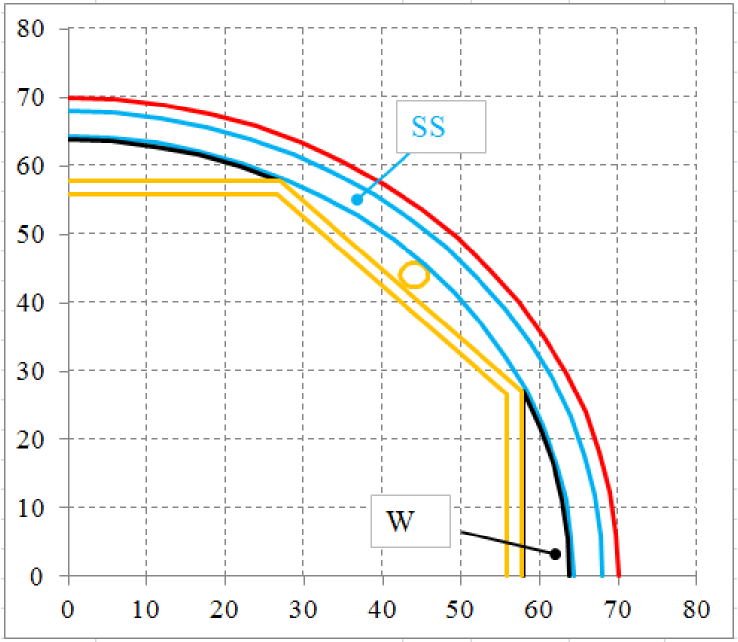
2D model showing the cross-section of the cold-bore (140 mm ID) (E. Todesco, private comm. 10/7/12)



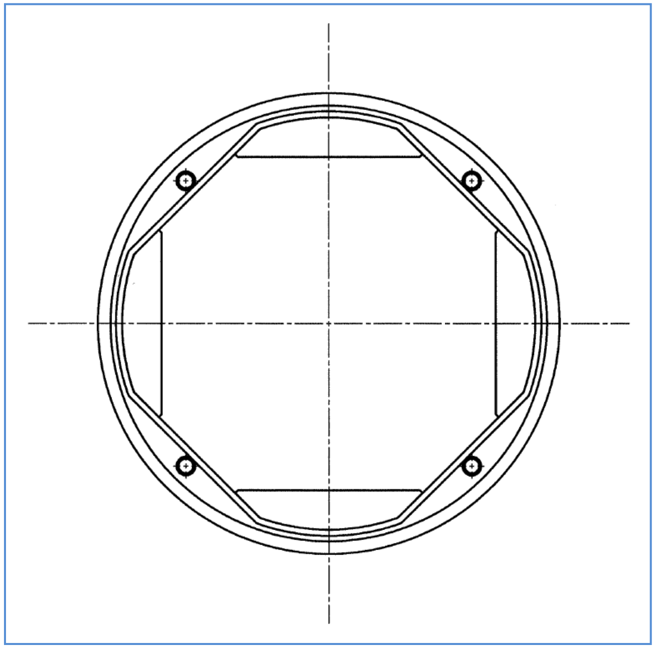
	D	E	F
10	Cold bore thickness	(mm)	3.7
11	Cold bore inner radius	(mm)	64.3
12	Clearance beam screen - cold bore	(mm)	0.5
13	Beam screen thickness	(mm)	2.0
14	Beam screen outer	(mm)	57.8
15	Beam screen inner	(mm)	55.8
16	W inserts thickness	(mm)	6.0
17	Inner radius beam 0 degrees	(mm)	55.8
40	Linear wieght Cold bore	(kg/m)	12.6
41	Linear weight Cu	(kg/m)	7.2
42	Linear weight W	(kg/m)	7.8
43			
44			
45			26.8

	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
10	25	0.44	29.6	63.4	28.7	61.6	27.2	58.3					27.0	57.8	43.7	45.8
11	30	0.52	35.0	60.6	34.0	58.9	32.2	55.7					0.0	57.8	43.2	45.6
12	35	0.61	40.2	57.3	39.0	55.7	36.9	52.7							42.7	45.2
13	40	0.70	45.0	53.6	43.7	52.1	41.3	49.3							42.4	44.7
14	45	0.79	49.5	49.5	48.1	48.1	45.5	45.5							42.3	44.1
15	50	0.87	53.6	45.0	52.1	43.7	49.3	41.3							42.4	43.4
16	55	0.96	57.3	40.2	55.7	39.0	52.7	36.9							42.7	42.9
17	60	1.05	60.6	35.0	58.9	34.0	55.7	32.2					57.8	0.0	43.2	42.5
18	65	1.13	63.4	29.6	61.6	28.7	58.3	27.2					57.8	27.0	43.7	42.3
19	70	1.22	65.8	23.9	63.9	23.3	60.4	22.0					60.0	21.8	44.4	42.3
20	75	1.31	67.6	18.1	65.7	17.6	62.1	16.6					61.6	16.5	45.0	42.5
21	80	1.40	68.9	12.2	67.0	11.8	63.3	11.2					62.8	11.1	45.4	42.9
22	85	1.48	69.7	6.1	67.7	5.9	64.1	5.6					63.6	5.6	45.7	43.4
23	90	1.57	70.0	0.0	68.0	0.0	64.3	0.0					63.8	0.0	45.9	44.1

2. Triplet Region Lay-out, Lattice and Vacuum Model



1/4th of 2D model showing the cross-section of the 140 mm ID cold-bore
(E. Todesco, private comm. 10/7/12)

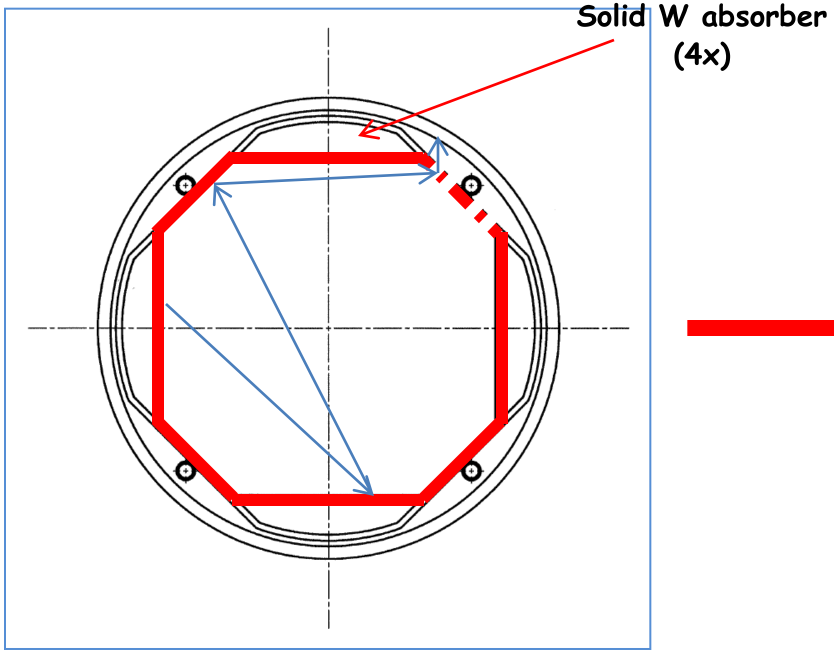


Starting point: drawing LHCVSSX_0004
6/10/2009, "Phase 1 Upgrade"
(re-scaled to 140 mm cold-bore ID, and 6mm W shielding)

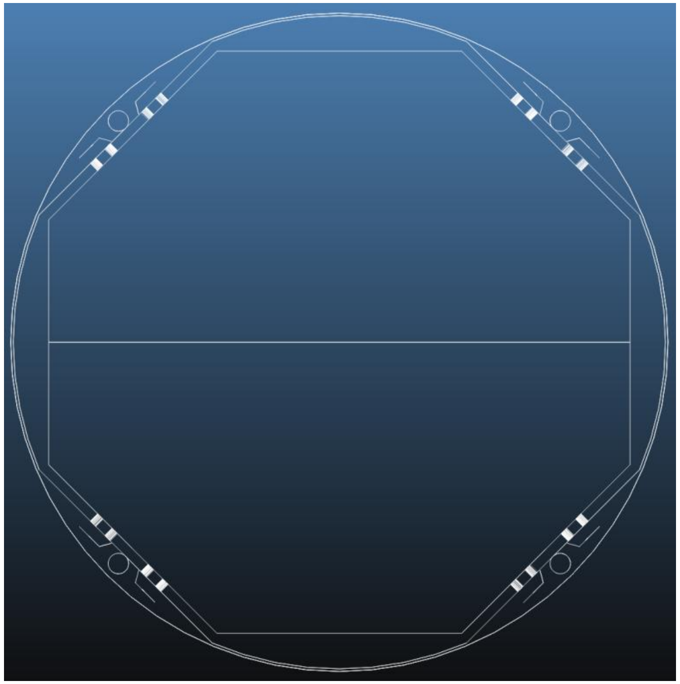
Conceptual 3D Model of 140 mm ID (cold bore, CD) Beam Screen (BS):

- W radiation shield is placed EXTERNALLY to the BS (see next slide)
- 4x4 Pumping Slots, racetrack-shaped like in the LHC arcs' BS have been added (see below), with a longitudinal spacing of 16 mm.

3. Conductance calculations



Drawing LHCVSSX_0004
6/10/2009, "Phase 1 Upgrade"
(not to scale) with superposed octagonal BS
(BS shields not shown)

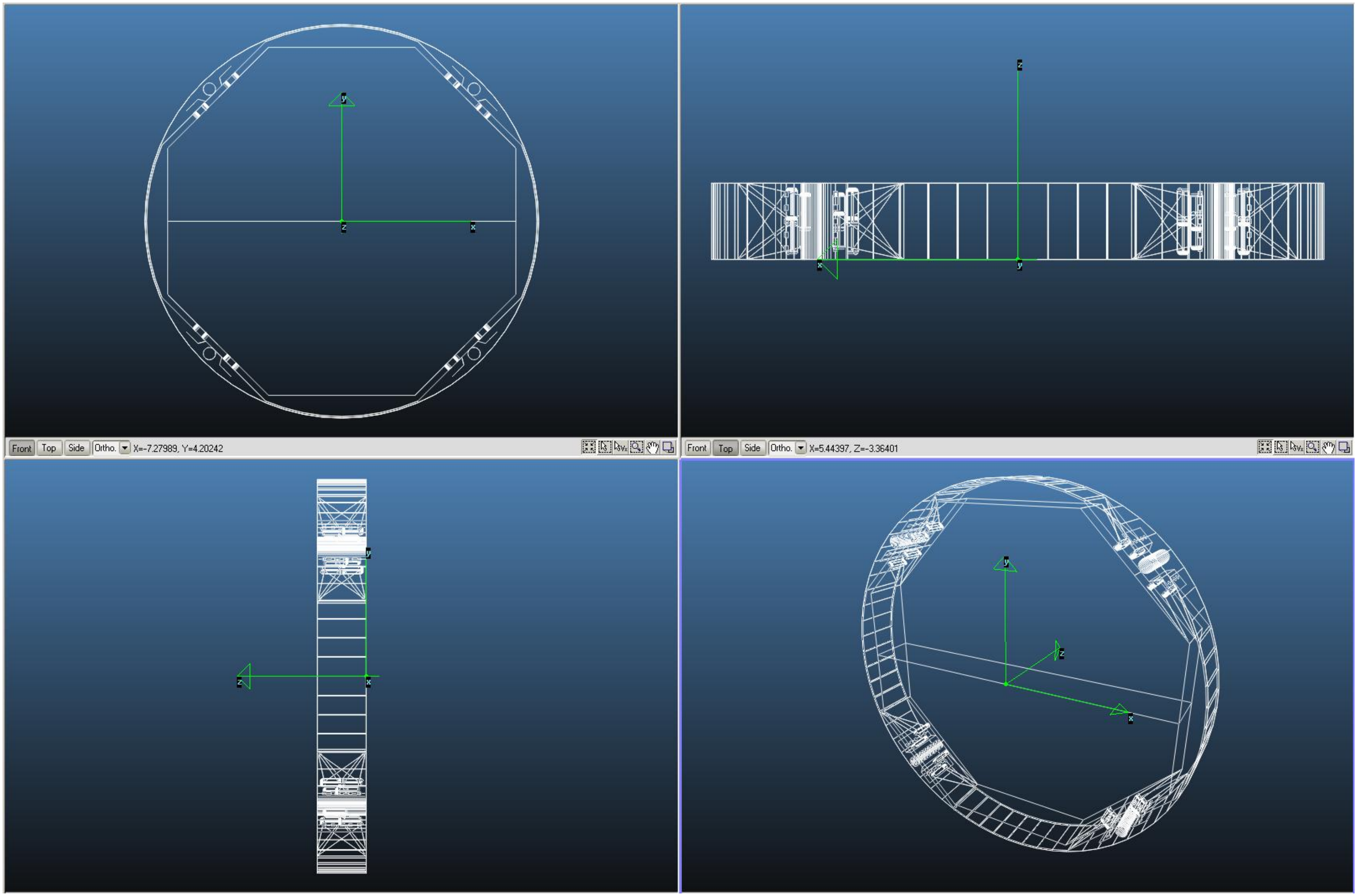


Front-view of 140 mm ID CB BS, with racetrack-shaped pumping slots and 4x pumping slots shields (as per LHC's arc BS): Molflow+ model

Conceptual 3D Model of 140 mm ID (cold bore, CD) Beam Screen (BS):

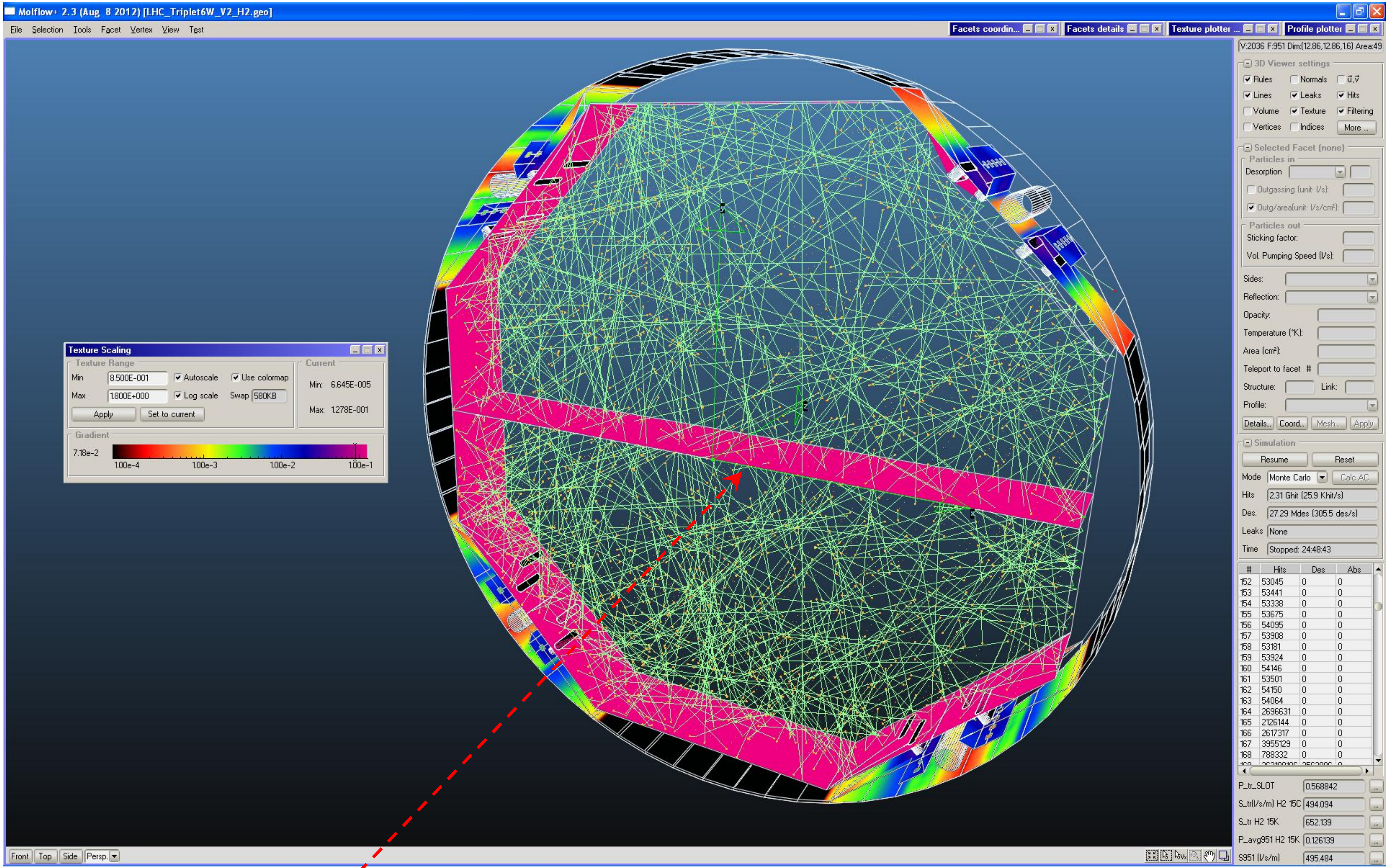
- 2 mm-thick BS is kept at between 5 and 20 °K by means of 4x 3/16" OD stainless steel pipes. Inside surface **must** be copper coated or **SS/Cu co-laminated**
- W radiation shield is fixed EXTERNALLY to the BS (see next slide)
- 4x4 Pumping Slots, racetrack-shaped like in the LHC arcs' BS have been added (see below)
- Molecules are cryopumped on the cold-bore

3. Conductance calculations



Molflow+ screen shot of 1.6 cm long periodic boundary condition slice
The model has 2036 vertices and 951 facets

3. Conductance calculations



Molflow+ 2.3 (Aug 8 2012) [LHC_Triplet6W_V2_H2.geo]

Texture Scaling

Texture Range

Min 8.500E-001 ☑ Autoscale ☑ Use colormap

Max 1.800E+000 ☑ Log scale Swap 580KB

Current

Min: 6.645E-005

Max: 1.278E-001

Gradient

7.18e-2

1.00e-4 1.00e-3 1.00e-2 1.00e-1

V:2036 F:951 Dim:(12.86,12.86,1.6) Area:49

3D Viewer settings

☑ Rules ☐ Normals ☐ $\vec{u},\vec{v}$

☑ Lines ☑ Leaks ☑ Hits

☐ Volume ☑ Texture ☑ Filtering

☐ Vertices ☐ Indices

Selected Facet (none)

Particles in

Desorption

☐ Outgassing (unit: l/s):

☑ Outg/area(unit: l/s/cm²):

Particles out

Sticking factor:

Vol. Pumping Speed (l/s):

Sides:

Reflection:

Opacity:

Temperature (°K):

Area (cm²):

Teleport to facet #

Structure: Link:

Profile:

Simulation

Mode Monte Carlo

Hits 2.31 Ghit (25.9 Khit/s)

Des. 27.29 Mdes (305.5 des/s)

Leaks None

Time Stopped: 24:48:43

#	Hits	Des	Abs
152	53045	0	0
153	53441	0	0
154	53338	0	0
155	53675	0	0
156	54095	0	0
157	53908	0	0
158	53181	0	0
159	53924	0	0
160	54146	0	0
161	53501	0	0
162	54150	0	0
163	54064	0	0
164	2696631	0	0
165	2126144	0	0
166	2617317	0	0
167	3955129	0	0
168	788332	0	0

P_tr_SLOT 0.568842

S_tr(l/s/m) H2 15C 494.094

S_tr H2 15K 652.139

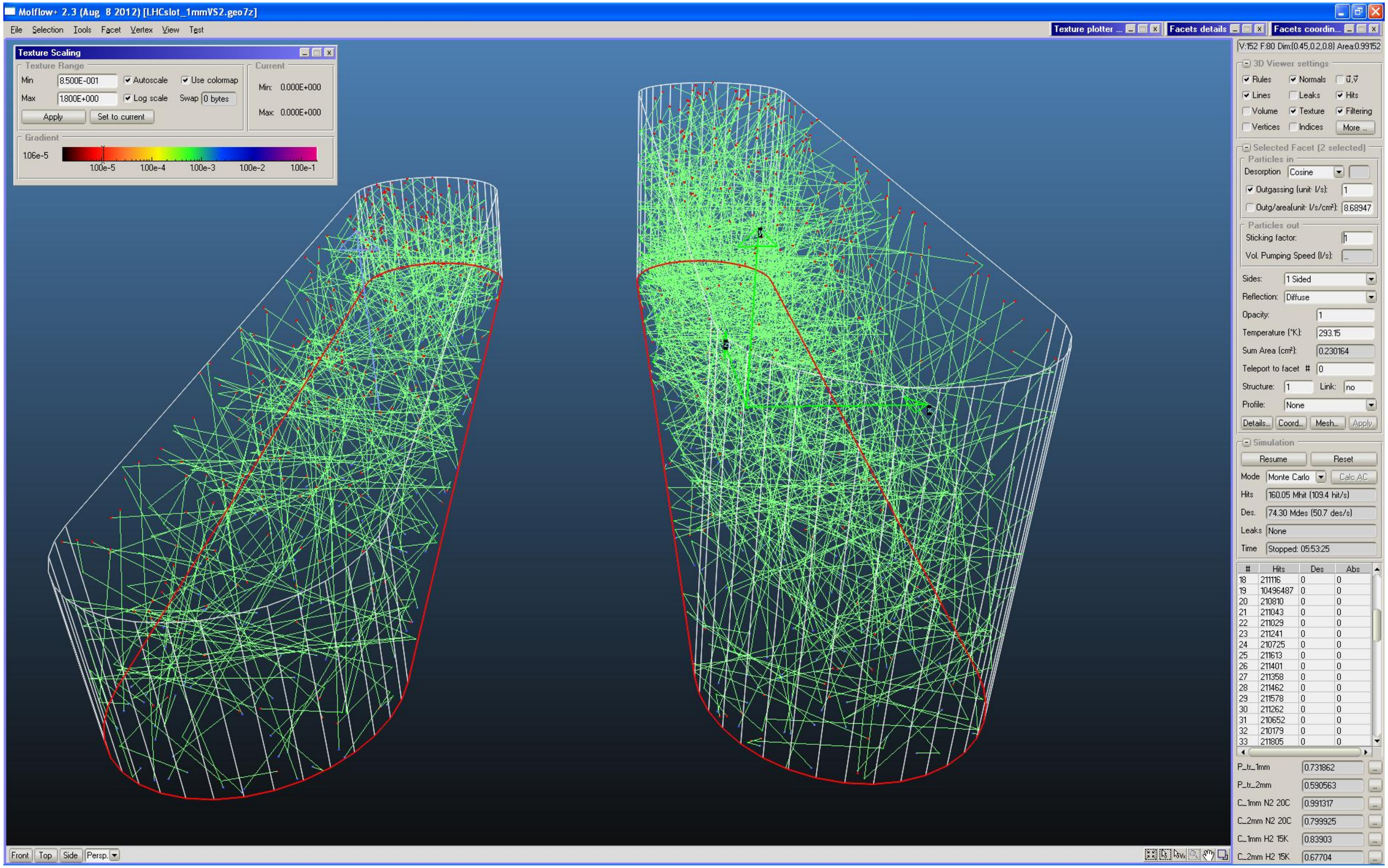
P_avg951 H2 15K 0.126139

S951 (l/s/m) 495.484

- **The conductance of the 4x4 pumping slots is calculated by computing the <u>trasmission probability</u> for molecules to go from inside the BS to outside**
- **The effective pumping speed for H_2 is calculated by taking the reciprocal of the average pressure along the virtual facet <u>inside the BS</u>**

3. Conductance calculations

The conductance of each single slot is obtained here: for the 1 mm-thick slot (left) of the LHC arc dipole BS it is <u>0.99 l/s</u> (N_2 at 20°C), while for the 2 mm-thick proposed for the Triplet BS it is <u>0.80 l/s</u> , 20% less, but there are now 2x as many slots per unit axial length (16 vs 8)



Molflow+ 2.3 (Aug 8 2012) [LHCslot_1mmVS2.geo7z]

Texture Scaling

Texture Range
Min 8.500E-001 ☑ Autoscale ☑ Use colormap
Max 1.800E+000 ☑ Log scale Swap 0 bytes

Current
Min: 0.000E+000
Max: 0.000E+000

V:152 F:80 Dim:(0.45,0.2,0.8) Area:0.99152

3D Viewer settings
☑ Rules ☑ Normals ☐ u,v
☑ Lines ☐ Leaks ☑ Hits
☐ Volume ☑ Texture ☑ Filtering
☐ Vertices ☐ Indices

Selected Facet (2 selected)
Desorption: Cosine
☑ Outgassing (unit· l/s): 1
☐ Outg/area(unit· l/s/cm²): 8.68947
Sticking factor: 1
Vol. Pumping Speed (l/s): ...
Sides: 1 Sided
Reflection: Diffuse
Opacity: 1
Temperature (°K): 293.15
Sum Area (cm²): 0.230164
Teleport to facet #: 0
Structure: 1 Link: no
Profile: None

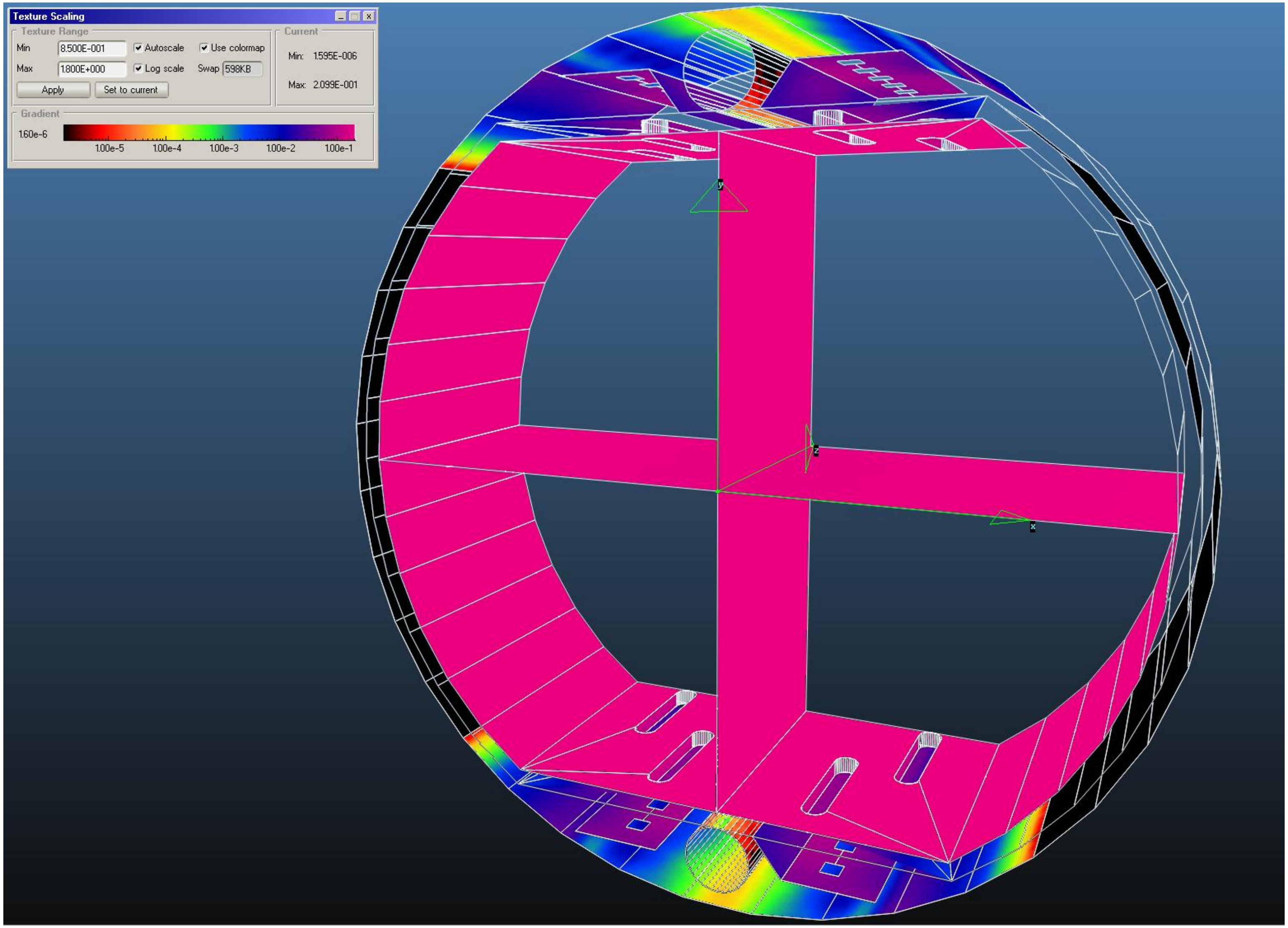
Simulation
Mode: Monte Carlo
Hits: 160.05 Mhit (109.4 hit/s)
Des.: 74.30 Mdes (50.7 des/s)
Leaks: None
Time: Stopped: 05:53:25

#	Hits	Des	Abs
18	211116	0	0
19	10496487	0	0
20	210810	0	0
21	211043	0	0
22	211029	0	0
23	211241	0	0
24	210725	0	0
25	211613	0	0
26	211401	0	0
27	211358	0	0
28	211462	0	0
29	211578	0	0
30	211262	0	0
31	210652	0	0
32	210179	0	0
33	211805	0	0

P_tr_1mm 0.731862
P_tr_2mm 0.590563
C_1mm N2 20C 0.991317
C_2mm N2 20C 0.799925
C_1mm H2 15K 0.83903
C_2mm H2 15K 0.67704

3. Conductance calculations

LHC arc dipole 1.6 cm-long slice, with 1 mm-thick BS and two perpendicular virtual facets showing that pressure/gas density is ~ uniform inside the BS



Texture Scaling

Texture Range

Min 8.500E-001 ☑ Autoscale ☑ Use colormap

Max 1.800E+000 ☑ Log scale Swap 598KB

Current

Min: 1.595E-006

Max: 2.099E-001

3. Conductance calculations

- **After doing some normalization to account for the gas mass and the temperature of the BS, we can summarize the pumping slot calculations by saying that the Triplet/D1 octagonal BS (at an average temperature of 15°K) has a specific pumping speed for H_2 of 677 l/s/m, vs a speed of 419.5 l/s/m for the LHC arc dipole BS.**

- **Since we are interested into calculating pressure profiles ALONG the beam path, we need also to compute the longitudinal conductance (called specific conductance, units are l·m/s) of the proposed Triplet/D1 BS.**

- **In general terms, other than for a shape-factor k ($0<k\leq1$) taking into account how far from circular the cross-section is, the specific conductance is proportional to the cross-sectional area and inversely proportional to the square of the chamber perimeter.**

- **The shape-factor k is not in general analytically computable, that's where MC simulations come to the rescue.**

3. Conductance calculations

- The specific conductance of the two BS (LHC arc dipole and Triplet/D1) are calculated by means of the transmission probability and, as a confirmation, by fitting the MC-simulated pressure profile to an analytical model of parabolic pressure for uniform longitudinal outgassing yield:

$$P(z) = \frac{A}{2c}(Lz - z^2) + \frac{Q}{S}$$

- Where c is the specific conductance, A the specific outgassing yield (i.e. mbar·l/s/m), L the length of the BS profile (5m here, to reduce end effects), Q the gas load (=A·L), and S the pumping speed at the tube's ends

- The two values are (N_2 at 20°C):

  a) LHC arc dipole BS: 10.43 l·m/s
  b) Triplet BS: 186.90 l·m/s

4. Static Pressure

- According the the lattice discussed in sec.2, a 3D model has been made of the internal geometry of the Triplet/D1 area BS

- To speed-up the calculation, the 16x62.5 =1000 slots per meter of axial length are simulated by long rectangular strips having an *equivalent* sticking coefficient s_{equiv} which takes into account the transmission probability of the real slots: $s_{equiv}=0.27284$

- There are 5 independent BSs, one for each of the Q1a-Q1b, Q2a, Q2b, Q3a-Q3b and D1 (including 5 correctors(*)), connected by 100 mm ID circular pipes with tapered conical transitions (see below)

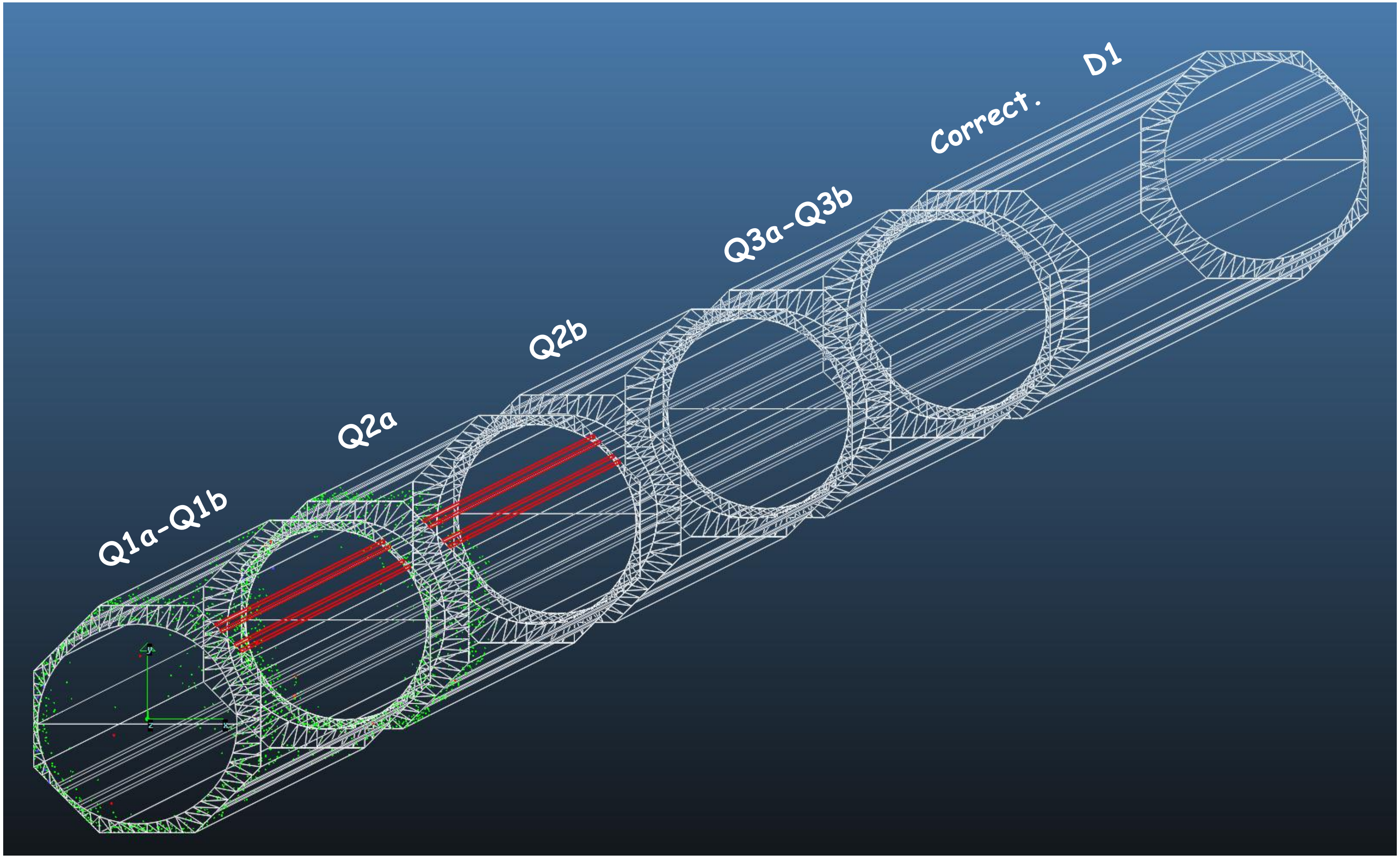
- Uniform thermal outgassing is supposed to take place on all non-pumping surfaces. Octagonal-to-round conical transitions of 0.5 m axial length are placed at either end of each cryostat

- Pumping of some sort is simulated at both ends (50% sticking probability). No pumping in the interconnects (NO BS, BPMs, sliding bellows: possibility of “floating” temperature NOT modeled)

(*) The 5 correctors have NOT been modeled as a stand-alone cryostat

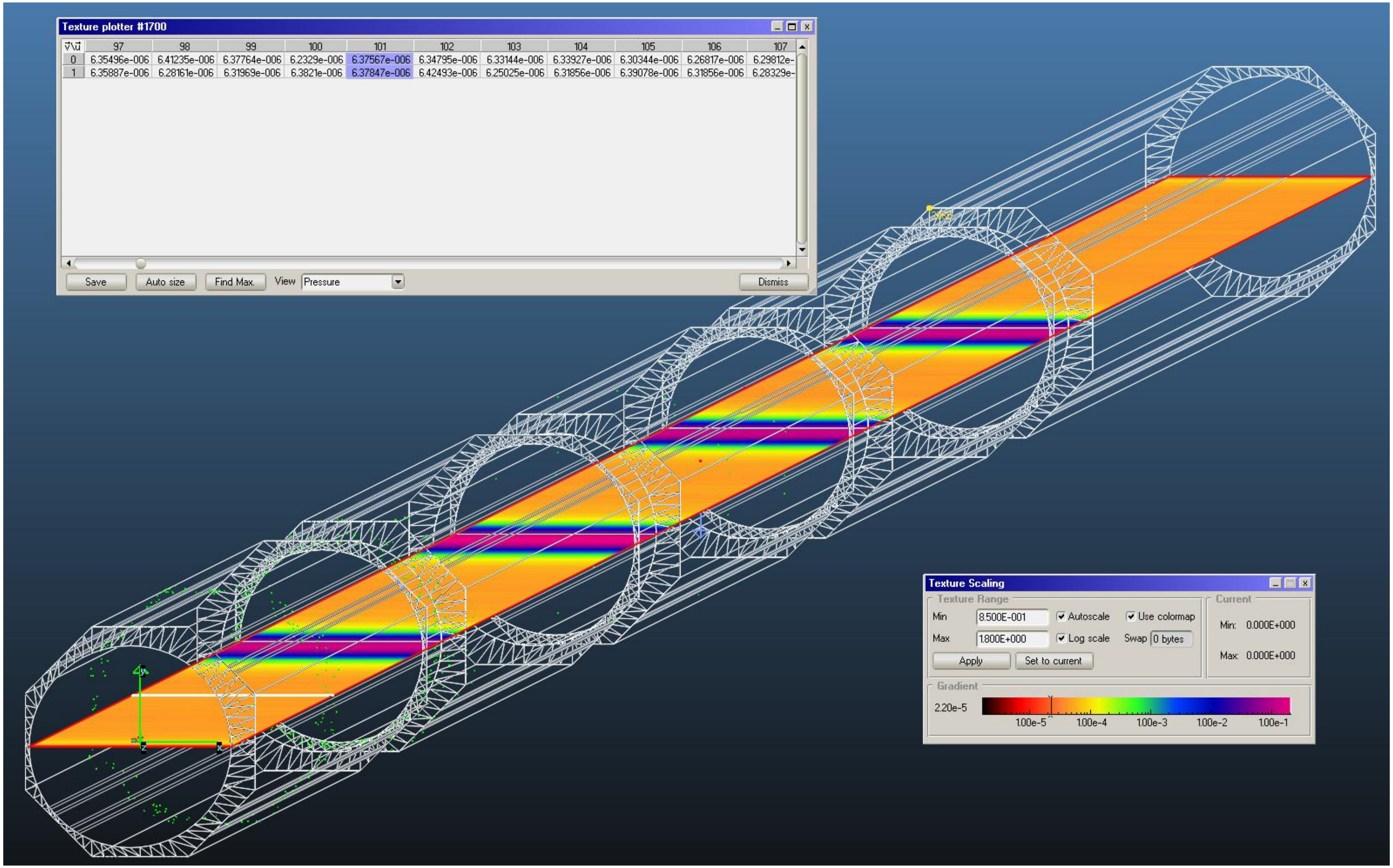
4. Static Pressure

The model looks like this. Highlighted in red are 8 of the equivalent pumping slot areas, 4 on each of the leftmost 2 cryostats



4. Static Pressure

The pressure can be visualized by using a colored texture along a virtual facet placed along the axis of the chamber



Texture plotter #1700

v\u	97	98	99	100	101	102	103	104	105	106	107
0	6.35496e-006	6.41235e-006	6.37764e-006	6.2329e-006	6.37567e-006	6.34795e-006	6.33144e-006	6.33927e-006	6.30344e-006	6.26817e-006	6.29812e-
1	6.35887e-006	6.28161e-006	6.31969e-006	6.3821e-006	6.37847e-006	6.42493e-006	6.25025e-006	6.31856e-006	6.39078e-006	6.31856e-006	6.28329e-

View: Pressure

Texture Scaling

Texture Range

Min 8.500E-001 ☑ Autoscale ☑ Use colormap

Max 1.800E+000 ☑ Log scale Swap 0 bytes

Current

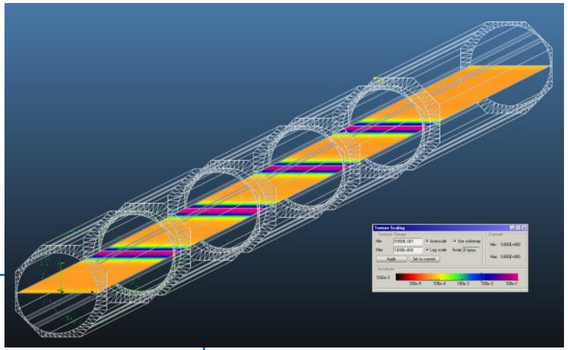
Min: 0.000E+000

Max: 0.000E+000

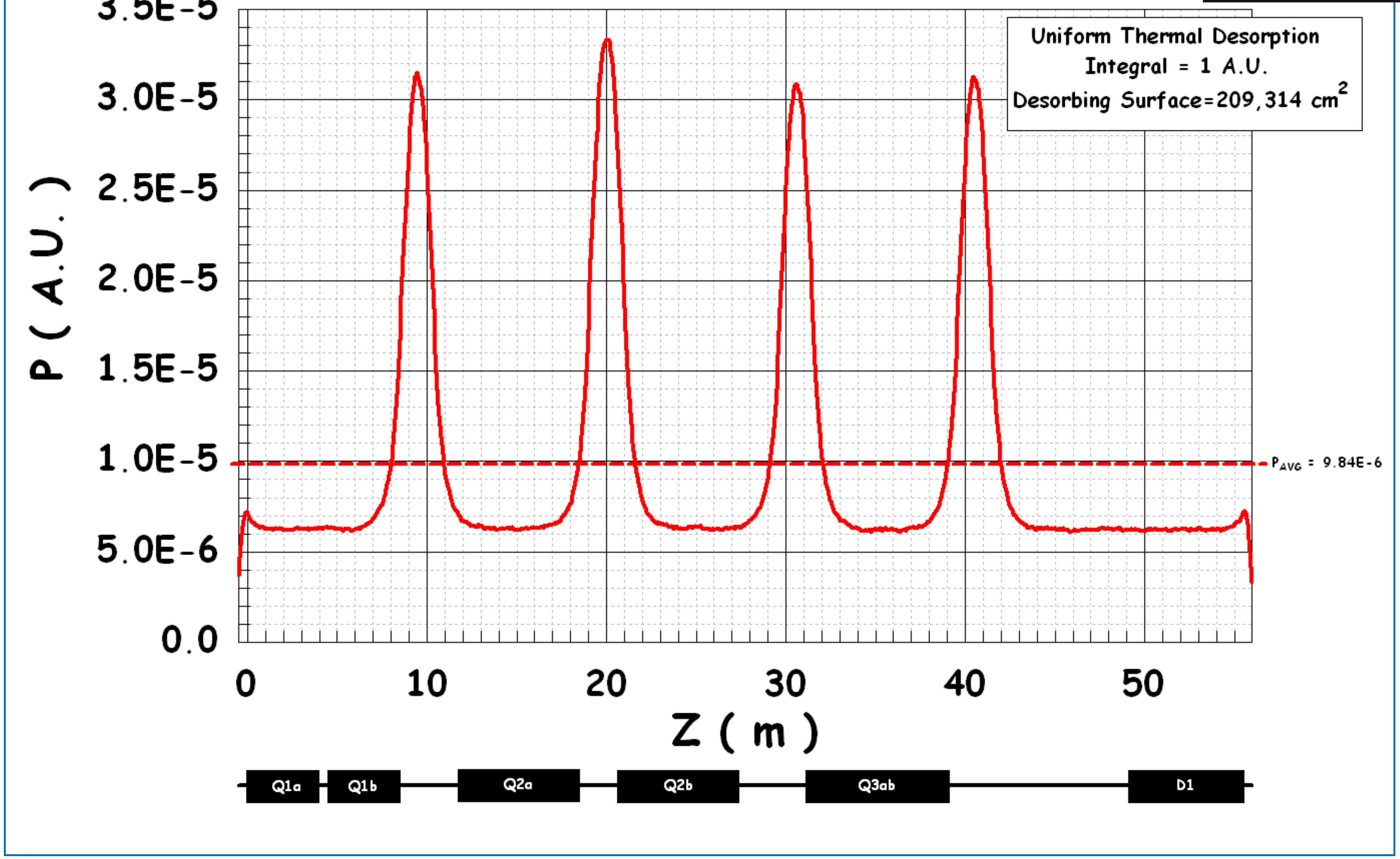
Gradient

4. Static Pressure

The longitudinal pressure profile, averaged across the 5 cm width, is the following

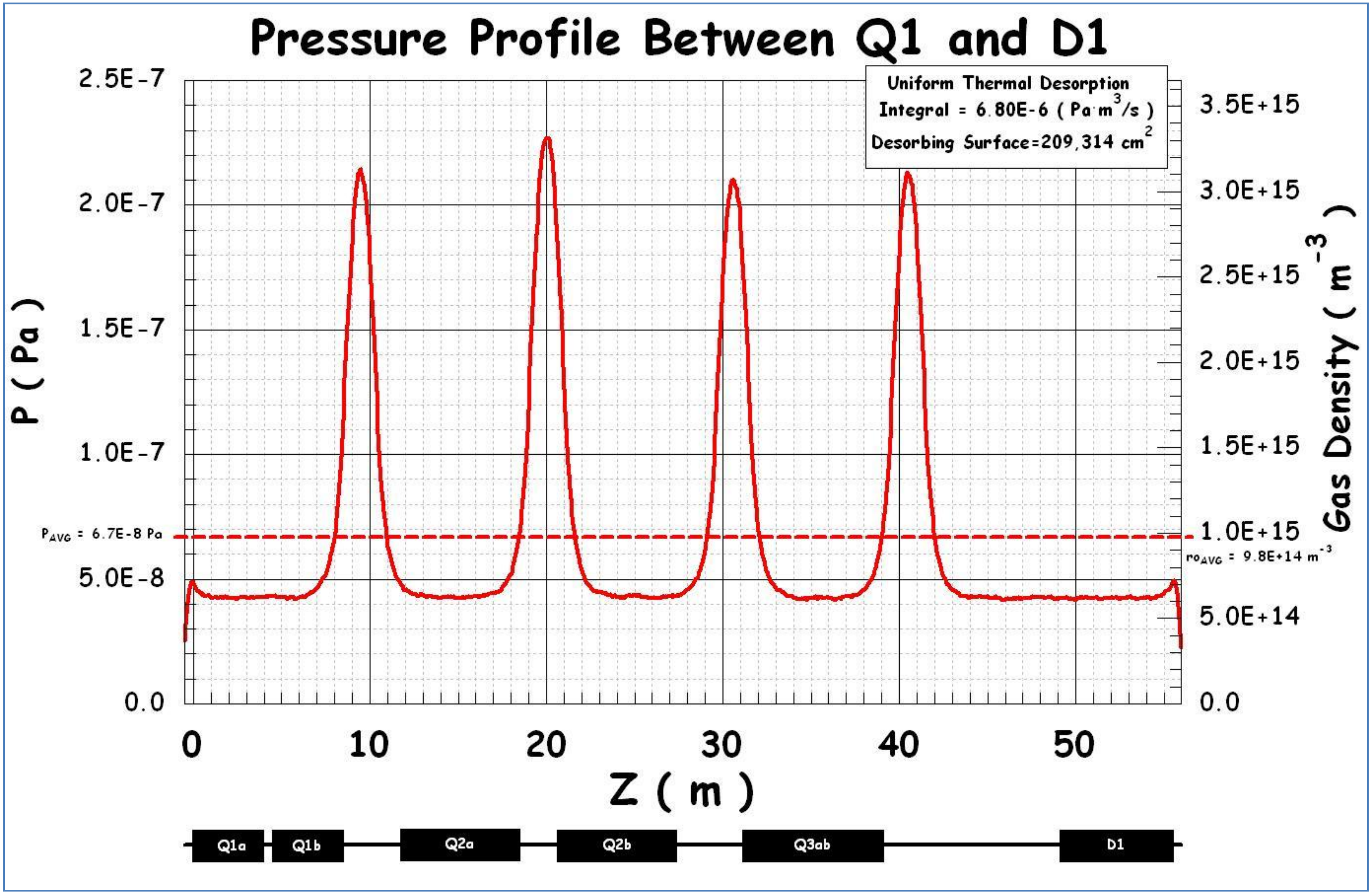


Pressure Profile Between Q1 and D1



4. Static Pressure

Normalizing the average pressure, and gas density, to the H_2 100 hrs lifetime (6.71E-8 Pa and 9.81E+14/m^3), we obtain the equivalent thermal outgassing load desorption rate: 3.25E-10 mbar·l/s/cm^2, easily obtainable.



5. SR Fans

- The ray-tracing MC code SYNRAD+ has been used. It calculates the orbit of the reference lattice (7 TeV, incoming beam) and traces the SR rays
- Two cases, with an average reflectivity of 0 and 50% have been computed
- The 5.2 T, 40 T·m D1 magnet has been assumed as the source of SR
- The critical energy of D1 SR is $E_{crit} = 27.4$ eV
- Only photons in the (4-400) eV interval are generated. According to well known formulae, only 38% of the D1 photon flux and 93% of the photon power fall within this range
- The integrated D1 flux along the ~ 7692 mm-long orbit is F=2.84E+17 ph/s, and the integrated power is P=0.88 W (for the nominal HiLumi current of 860 mA). Critical energy is 27.4 eV, and the fraction of photons above 4 eVcut-off for gas desorption is 0.393.
- The flux F can be converted into a SR-induced outgassing load Q_{SR} by means of the formula

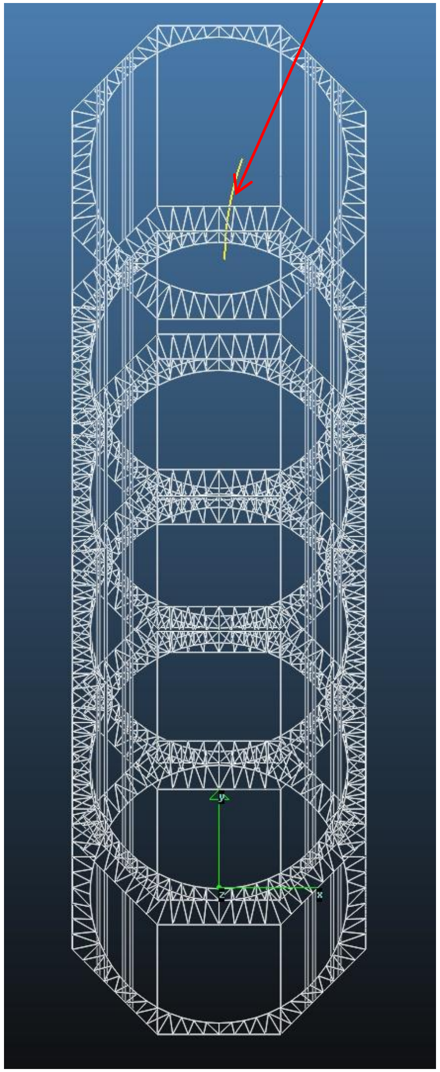
$$Q_{SR} = F \cdot \eta \cdot k$$

where η is the SR-induced outgassing coefficient (molecules/ph), subject to beam conditioning effects, and k is a conversion factor k=4.047E-20 (mbar·l/molec.)

- Assuming a rather high final value of η=1.0E-4 (molec./ph), we get Q_{SR} = 1.15E-6 (mbar·l/s)… a rather small lumped gas load. Smaller additional gas loads can be assumed as the result of SR coming from the triplet magnets (lower E_{crit}), and are therefore neglected here.

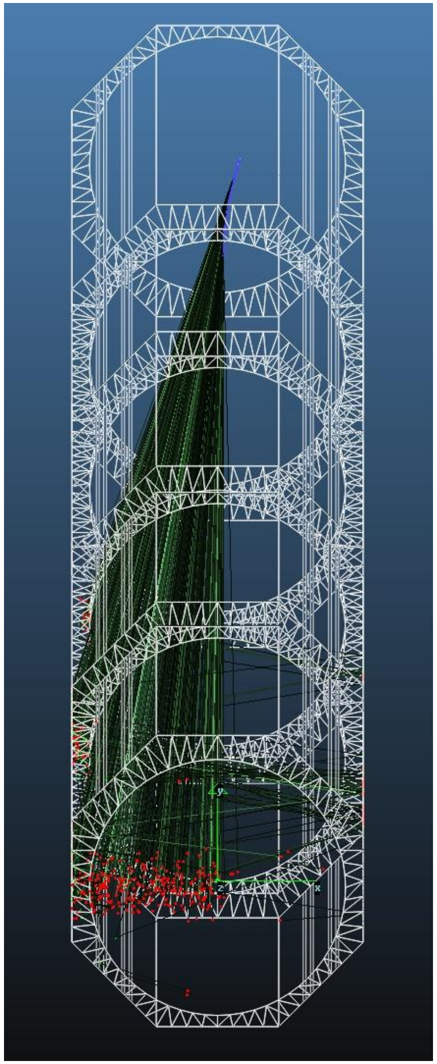
5. SR Fans

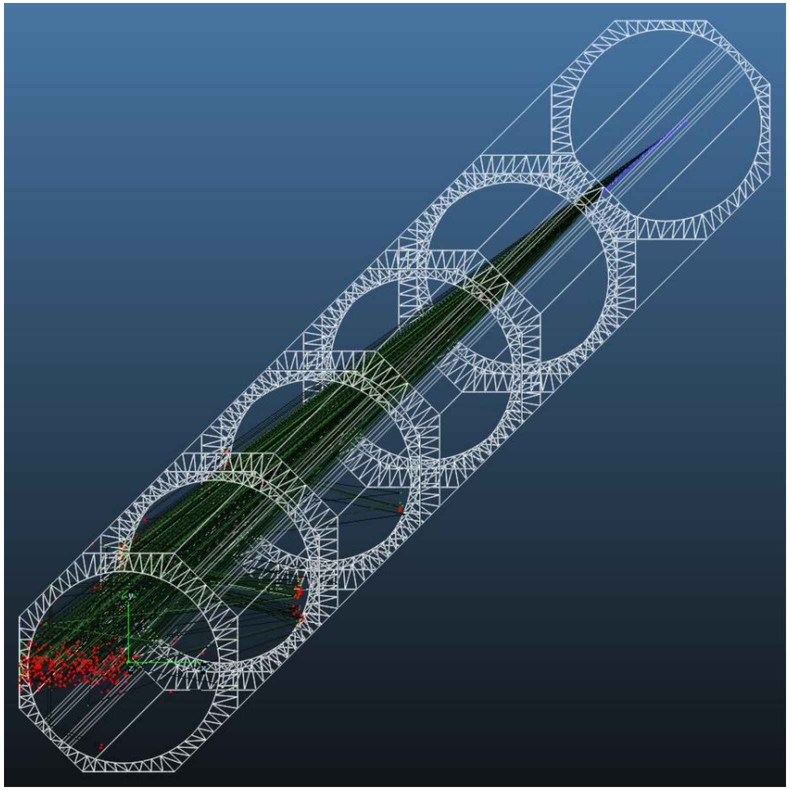
SYNRAD+ uses the same 3D geometrical model of Molflow+ (planar facets)



Orbit: photons are generated every 0.01 mm

Ray-tracing with scattered photon (50% reflectivity)

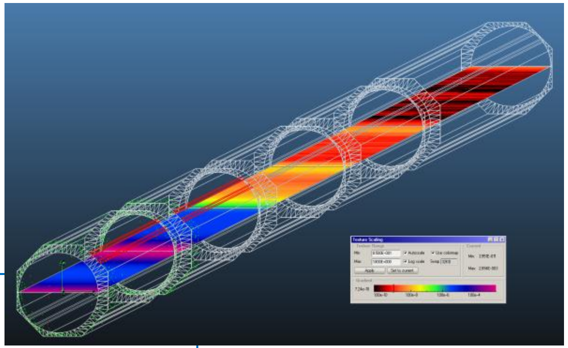




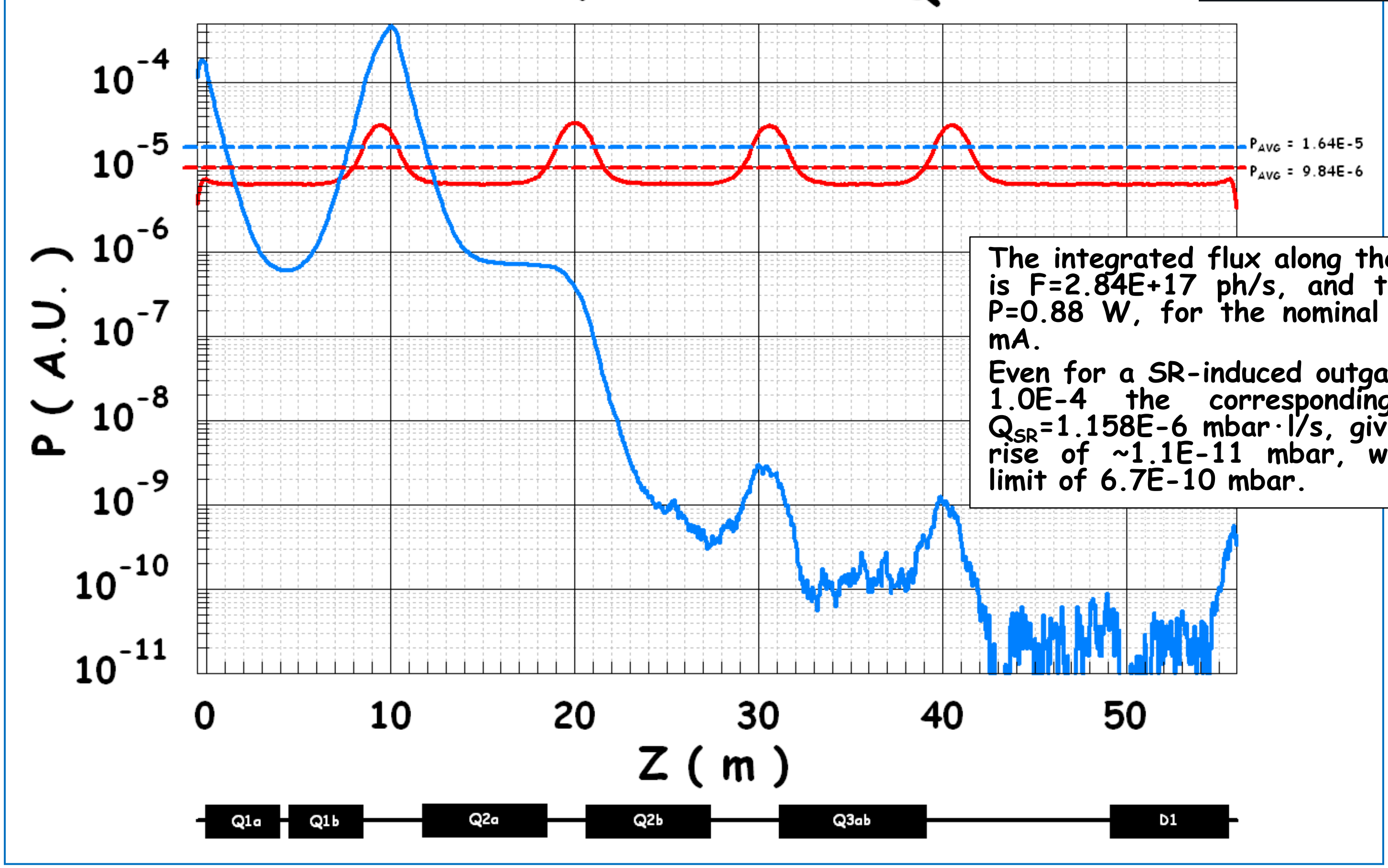
The SR-induced gas load is proportional to the photon flux absorbed on the facets

6. SR-Induced Pressure Rise

The longitudinal pressure profile is shown <u>in blue</u> after having been normalized to the same Q=1 (A.U.)



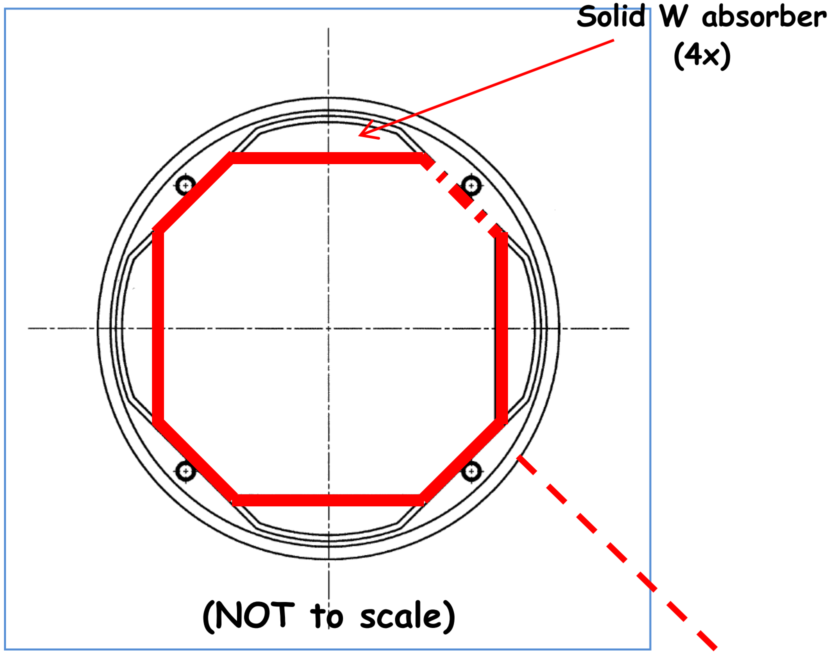
Pressure Profile Between Q1 and D1



The integrated flux along the ~ 7700 mm-long orbit is F=2.84E+17 ph/s, and the integrated power is P=0.88 W, for the nominal HiLumi current of 860 mA.

Even for a SR-induced outgassing yield η(molec/ph)= 1.0E-4 the corresponding gas load Q_{SR} is Q_{SR}=1.158E-6 mbar·l/s, giving an average pressure rise of ~1.1E-11 mbar, well below the pressure limit of 6.7E-10 mbar.

7. Engineering/Integration Issues



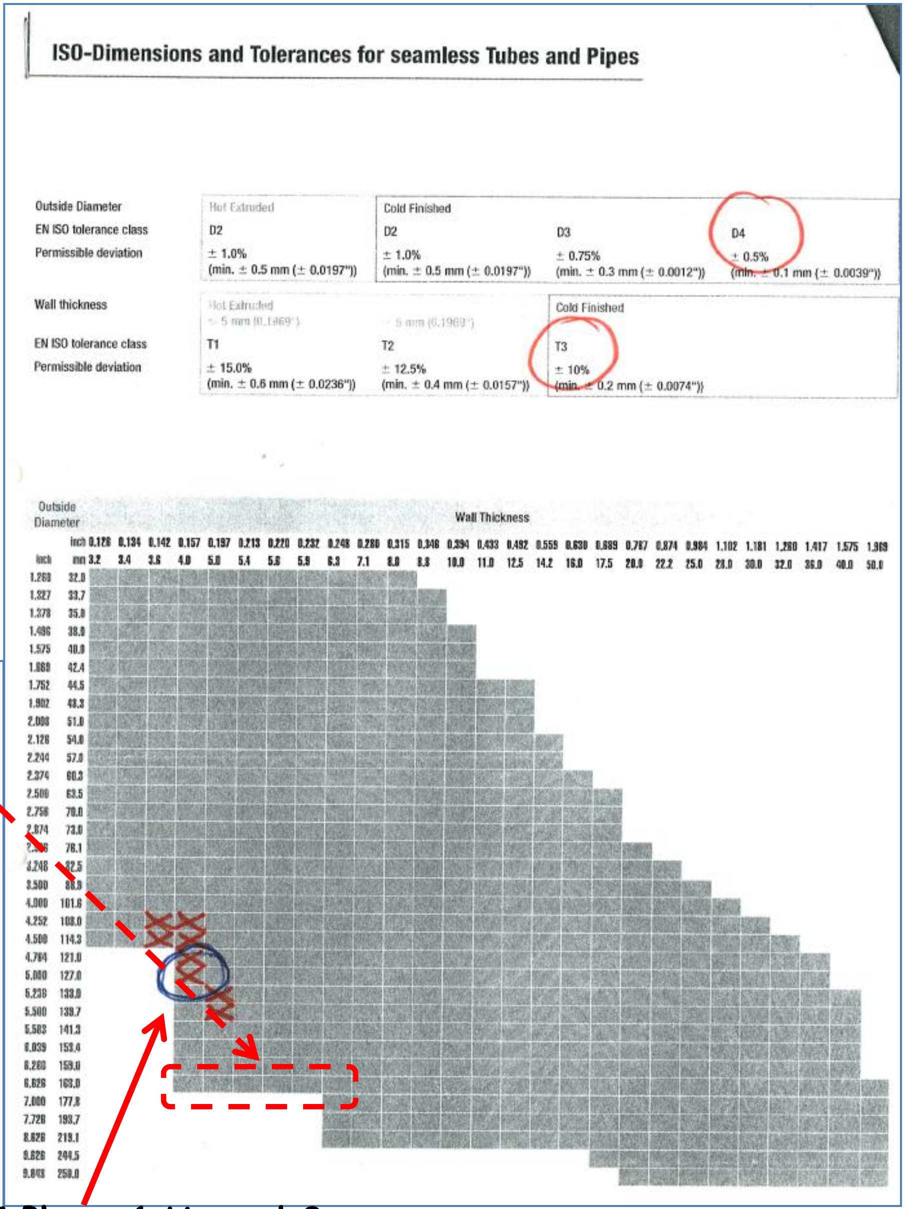
ISO standard for seamless tubing for the CB dictates fabrication tolerances:

- +/- 0.5% on OD
- +/-10% on thickness

For the case of an **8.8 mm-thick 160 mm OD** tube the combined tolerances on the OD of the cold bore are

+/- 0.889 +/- 0.88 => +/- 1.77 mm

<u>ISSUE #1: Is this compatible with the design of the Q1, Q2, Q3 and D1 cold masses and coils?</u>



ISO-Dimensions and Tolerances for seamless Tubes and Pipes

	Hot Extruded	Cold Finished		
Outside Diameter				
EN ISO tolerance class	D2	D2	D3	D4
Permissible deviation	± 1.0% (min. ± 0.5 mm (± 0.0197"))	± 1.0% (min. ± 0.5 mm (± 0.0197"))	± 0.75% (min. ± 0.3 mm (± 0.0012"))	± 0.5% (min. ± 0.1 mm (± 0.0039"))

	Hot Extruded		Cold Finished
Wall thickness	≤ 5 mm (0.1969")	> 5 mm (0.1969")	
EN ISO tolerance class	T1	T2	T3
Permissible deviation	± 15.0% (min. ± 0.6 mm (± 0.0236"))	± 12.5% (min. ± 0.4 mm (± 0.0157"))	± 10% (min. ± 0.2 mm (± 0.0074"))

Wall Thickness

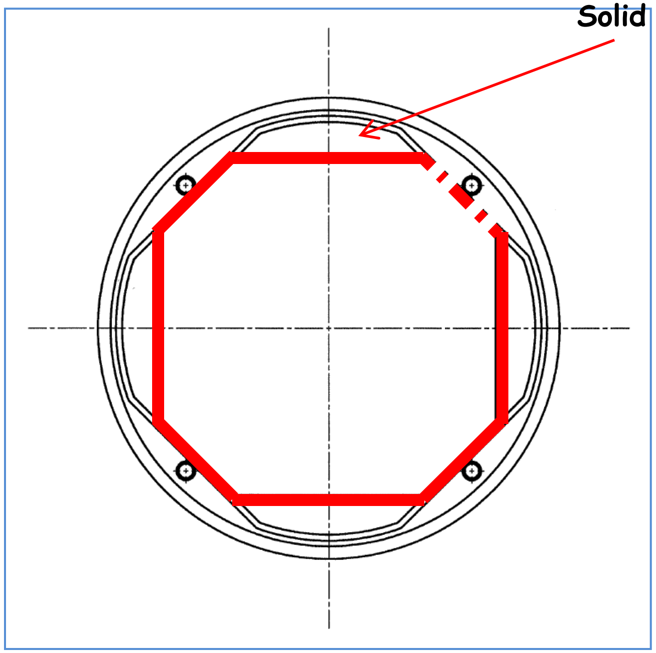
inch	0.126	0.134	0.142	0.157	0.197	0.213	0.220	0.232	0.248	0.280	0.315	0.346	0.394	0.433	0.492	0.559	0.630	0.689	0.787	0.874	0.984	1.102	1.181	1.260	1.417	1.575	1.969
mm	3.2	3.4	3.6	4.0	5.0	5.4	5.6	5.9	6.3	7.1	8.0	8.8	10.0	11.0	12.5	14.2	16.0	17.5	20.0	22.2	25.0	28.0	30.0	32.0	36.0	40.0	50.0

Outside Diameter

inch	mm
1.260	32.0
1.327	33.7
1.378	35.0
1.496	38.0
1.575	40.0
1.669	42.4
1.752	44.5
1.902	48.3
2.008	51.0
2.126	54.0
2.244	57.0
2.374	60.3
2.500	63.5
2.756	70.0
2.874	73.0
[illegible]	76.1
3.248	82.5
3.500	88.9
4.000	101.6
4.252	108.0
4.500	114.3
4.764	121.0
5.000	127.0
5.236	133.0
5.500	139.7
5.563	141.3
6.039	153.4
6.260	159.0
6.626	168.3
7.000	177.8
7.728	193.7
8.626	219.1
9.626	244.5
9.843	250.0

@ LHC Phase 1 Upgrade?

7. Engineering/Integration Issues



- The BS of the LHC arc dipoles, 1 mm-thick with no W shielding, is relatively easy to insert, being rather flexible and weighing about ~1.2 kg/m (sliding on ~50 cm/spaced stainless/bronze rings)

ISSUE #2: since similar tolerances apply also to the INSIDE of the cold bore, are the Horiz and Vert size of the BS big enough to accommodate the two beams and their halos?

ISSUE #3: How is a ~16 kg/m and stiff shielded beam-screen going to be inserted along the cold bores, some of them being 8~9 m-long?

8. Conclusions

- **A proposal for the beam-screen shape for the Triplet/D1 area of HiLumi LHC has been made**
- **It is a re-scaled version of the "Phase 1" LHC upgrade proposal**
- **It has 4x 6mm tungsten shielding fixed on the outside face of an octagonal, 2mm-thick BS, which is either copper coated SS or co-laminated Cu/SS, with 4 GHe cooling tubes and rows of 16 pumping slots, similar to LHC arc dipoles' design**
- **The pumping speed of the slots has been assessed, and found sufficient**
- **The SR fans generated by D1 have been calculated, and potential SR-induced gas load estimated**
- **The longitudinal pressure profile for the two cases of uniform thermal desorption and SR-induced desorption have been calculated. There should be no major problems to obtain an average pressure avoiding any beam-lifetime issues**
- **Three fabrication/engineering issues have been identified, which could affect not only the design of the BS, but also the design of the lattice, and of the Triplet and D1 magnets coils**

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