Synchrotron Radiation with SYNRAD+

R. Kersevan, M. Ady, CERN-TE-VSC-VSM

FCC-ee MDI workshop

16 Jan 2017, 09:00 → 27 Jan 2017, 13:00 Europe/Zurich

37-R-022 (CERN)

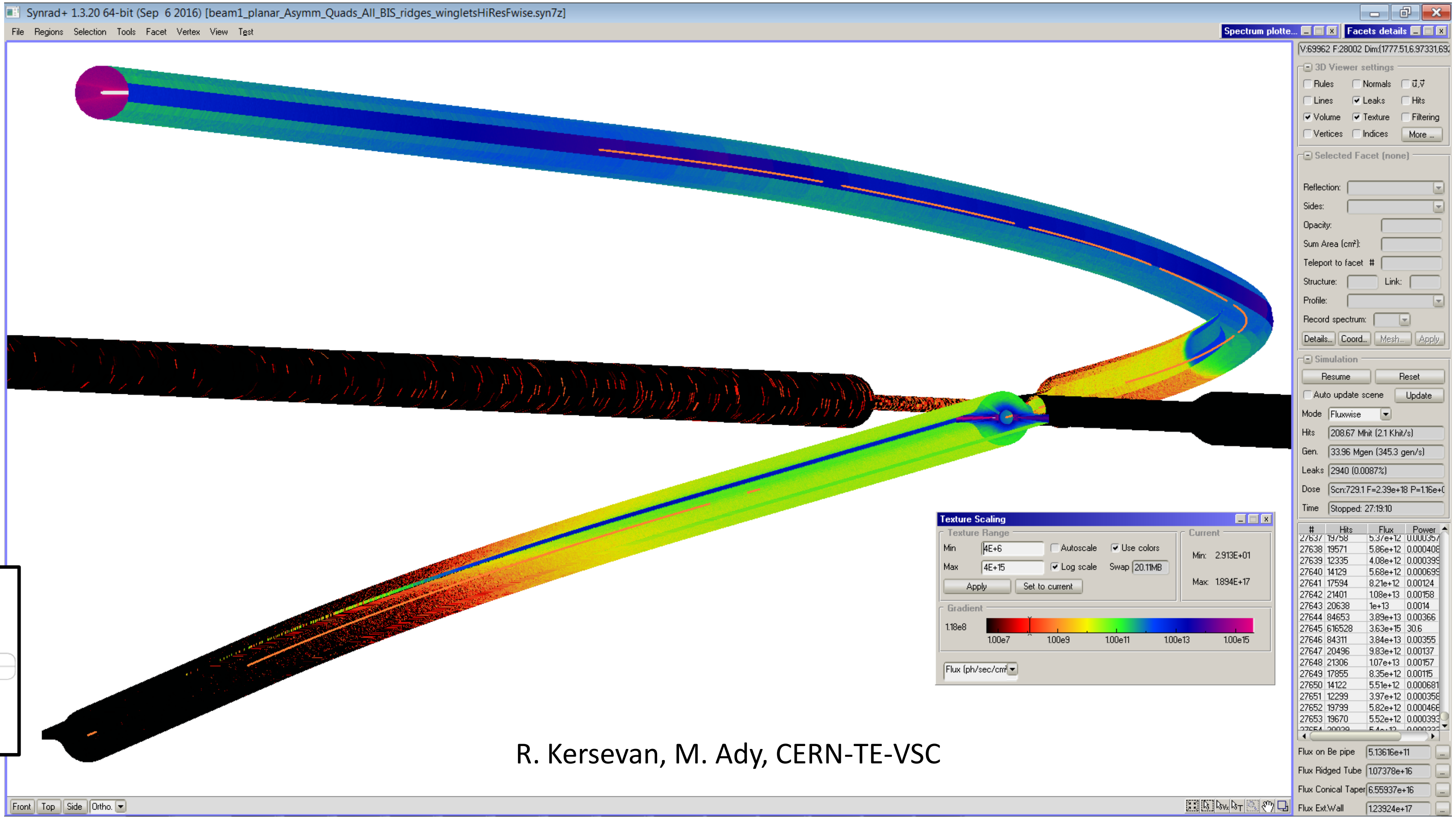
Ray Tracing with SYNRAD+ in FCC-ee IR

R. Kersevan, M. Ady, CERN-TE-VSC-VSM

- The geometry for the ~680 m around the IP for the latest T-pole lattice (as per K. Oide's file on AFS) has been created;
- One beam only has been modelled (assuming the other one is symmetric): it includes 9 dipoles and 9 quadrupoles;
- Two version of the geometry have been created: one with a symmetric opening of the IP quadrupole focusing doublets (20 mm ID) and one with an "exit" doublet chamber twice as big in radius (40 mm ID), following the prescription to let the trapped HOM in the IP "escape" and dissipate their power elsewhere (see previous meetings, this series);
- A third variant of the geometry has included a "winged" geometry, i.e. a chamber cross-section "à-la-SUPERKEKB" which allow the positioning of short localized absorber (to reduce the photon scattering and improve the shielding of high-energy photons, see end of my presentation at FCC Week in Rome);
- → Neither the photon absorbers nor the bellows/contact fingers have been included yet;←
- → This work does NOT aim to take the place of the analysis already done via GEANT4 and/or other calculations (H. Burkhardt et al., M. Sullivan et al.) but simply wants to show the potential of a different code, SYNRAD+, as far as the calculation of photon flux and power on sensitive equipment is concerned (like the Be pipe at the IP);
- The main purpose of this analysis is to prepare a geometry for simulating the pressure profiles (aiming at presenting this as a poster at FCC Week in Berlin, if accepted).

Source: R. Kersevan, FCC-ee MDI meeting #8, 12/12/2016

SYNRAD+: SR flux along one ~680 m-long arm of the interaction region of FCC-ee (175 GeV T-pole machine; 6.632 mA; Z-pole study to be done)



V:69962 F:28002 Dim:(1777.51,6.97331,69

3D Viewer settings

☐ Rules ☐ Normals ☐ u⃗,v⃗
☐ Lines ☑ Leaks ☐ Hits
☑ Volume ☑ Texture ☐ Filtering
☐ Vertices ☐ Indices More ...

Selected Facet (none)

Reflection:
Sides:
Opacity:
Sum Area (cm²):
Teleport to facet #
Structure: Link:
Profile:
Record spectrum:

Details... Coord... Mesh... Apply

Simulation

Resume Reset

☐ Auto update scene Update

Mode: Fluxwise
Hits: 208.67 Mhit (2.1 Khit/s)
Gen.: 33.96 Mgen (345.3 gen/s)
Leaks: 2940 (0.0087%)
Dose: Scn:729.1 F=2.39e+18 P=1.16e+0
Time: Stopped: 27:19:10

#	Hits	Flux	Power
27637	19758	5.37e+12	0.000357
27638	19571	5.86e+12	0.000408
27639	12335	4.08e+12	0.000399
27640	14129	5.68e+12	0.000699
27641	17594	8.21e+12	0.00124
27642	21401	1.08e+13	0.00158
27643	20638	1e+13	0.0014
27644	84653	3.89e+13	0.00366
27645	616528	3.63e+15	30.6
27646	84311	3.84e+13	0.00355
27647	20496	9.83e+12	0.00137
27648	21306	1.07e+13	0.00157
27649	17855	8.35e+12	0.00115
27650	14122	5.51e+12	0.000681
27651	12299	3.97e+12	0.000358
27652	19799	5.82e+12	0.000466
27653	19670	5.52e+12	0.000393

Flux on Be pipe: 5.13616e+11
Flux Ridged Tube: 1.07378e+16
Flux Conical Taper: 6.55937e+16
Flux Ext.Wall: 1.23924e+17

Texture Range

Min: 4E+6 ☐ Autoscale ☑ Use colors
Max: 4E+15 ☑ Log scale Swap: 20.11MB

Apply Set to current

Current

Min: 2.913E+01
Max: 1.894E+17

Gradient: 1.18e8

Flux (ph/sec/cm²)

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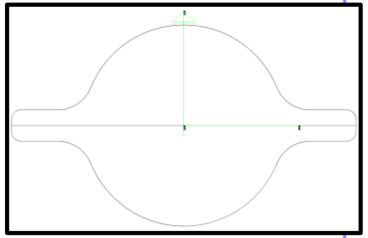
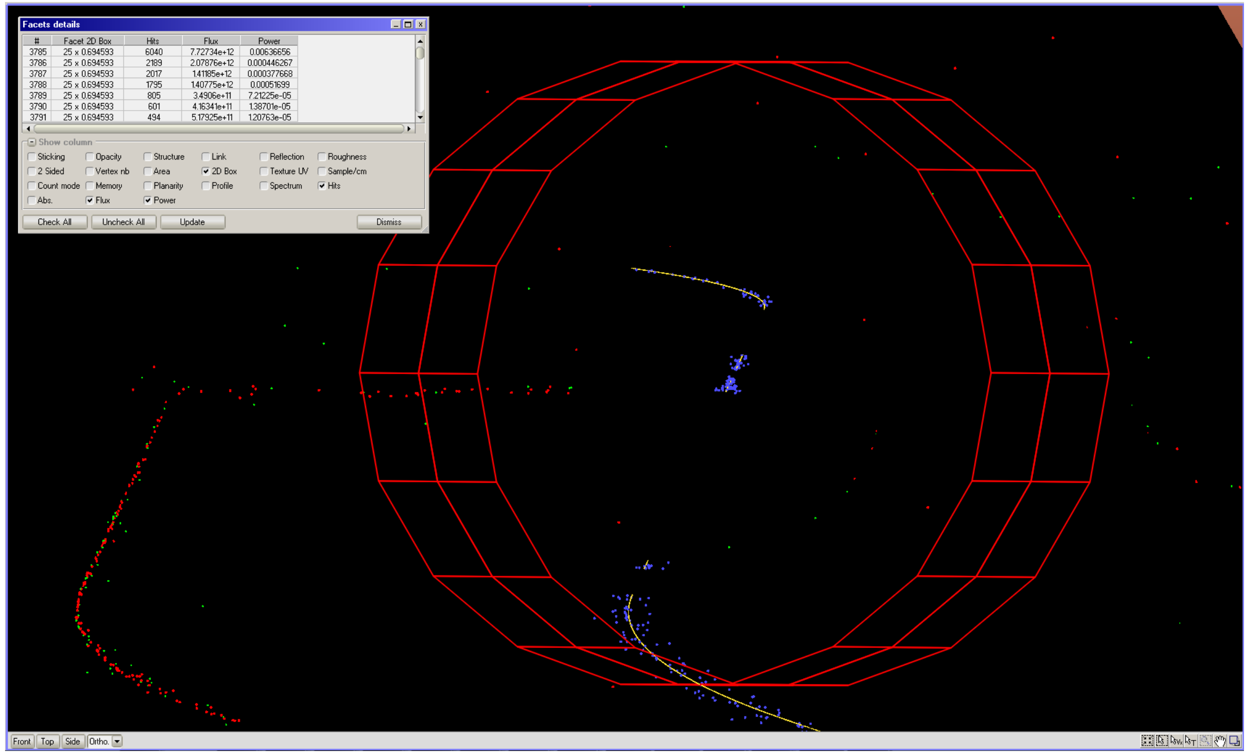


One arm of the IP chambers: ~ -347 m to ~ +337 m;

Round pipe (70 mm ID) everywhere except along the incoming beam, which has winglets;

→ NO BEAM HALOS!... to be done... ←

SYNRAD+: SR flux along one ~640 m-long arm of the interaction region of FCC-ee (175 GeV T-pole machine; 6.632 mA)



Facets details

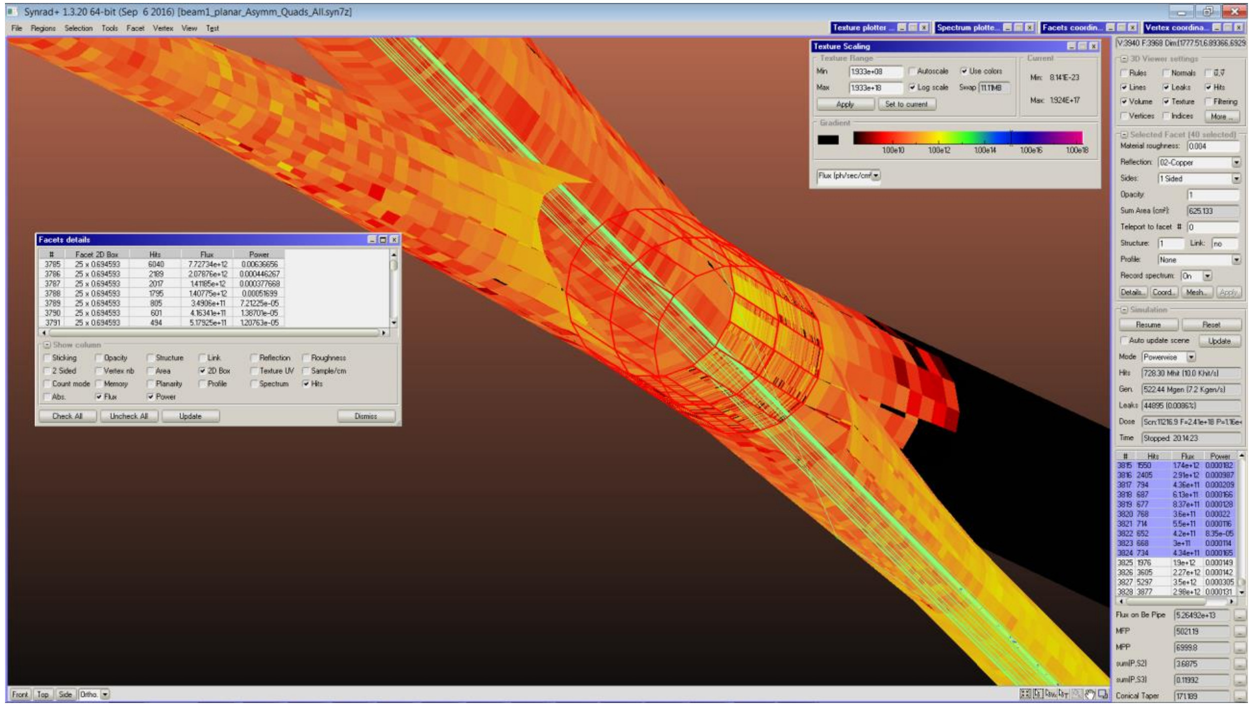
#	Facet 2D Box	Hits	Flux	Power
3785	25 x 0.694593	6040	7.72734e+12	0.00636656
3786	25 x 0.694593	2189	2.07876e+12	0.000446267
3787	25 x 0.694593	2017	1.41185e+12	0.000377668
3788	25 x 0.694593	1795	1.40775e+12	0.00051699
3789	25 x 0.694593	805	3.4906e+11	7.21225e-05
3790	25 x 0.694593	601	4.16341e+11	1.38701e-05
3791	25 x 0.694593	494	5.17925e+11	1.20763e-05

Show column

☐ Sticking ☐ Opacity ☐ Structure ☐ Link ☐ Reflection ☐ Roughness
☐ 2 Sided ☐ Vertex nb ☐ Area ☑ 2D Box ☐ Texture UV ☐ Sample/cm
☐ Count mode ☐ Memory ☐ Planarity ☐ Profile ☐ Spectrum ☑ Hits
☐ Abs. ☑ Flux ☑ Power

View of the source points (blue) and centroid trajectory (yellow); Red and Green points are locations of absorbed/reflected photons;

Red lines represent the 50 cm-long Be pipe



Synrad+ 1.3.20 64-bit (Sep 6 2016) [beam1_planar_Asymm_Quads_All.syn7z]

Texture Scaling

Texture Range
Min: 1.933e+08 ☐ Autoscale ☑ Use colors
Max: 1.933e+18 ☑ Log scale Swap: 11.1MB

Current
Min: 8.141E-23
Max: 1.924E+17

Flux (ph/sec/cm²)

Facets details

#	Facet 2D Box	Hits	Flux	Power
3785	25 x 0.694593	6040	7.72734e+12	0.00636656
3786	25 x 0.694593	2189	2.07876e+12	0.000446267
3787	25 x 0.694593	2017	1.41185e+12	0.000377668
3788	25 x 0.694593	1795	1.40775e+12	0.00051699
3789	25 x 0.694593	805	3.4906e+11	7.21225e-05
3790	25 x 0.694593	601	4.16341e+11	1.38701e-05
3791	25 x 0.694593	494	5.17925e+11	1.20763e-05

V:3940 F:3968 Dim:(1777.51,6.89366,6.6929

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

Selected Facet (40 selected)
Material roughness: 0.004
Reflection: 02-Copper
Sides: 1 Sided
Opacity: 1
Sum Area (cm²): 625.133
Teleport to facet #: 0
Structure: 1 Link: no
Profile: None
Record spectrum: On

Simulation
☐ Auto update scene
Mode: Powerwise
Hits: 728.30 Mhit (10.0 Khit/s)
Gen: 522.44 Mgen (7.2 Kgen/s)
Leaks: 44895 (0.0086%)
Dose: Scn:11216.9 F=2.41e+18 P=1.16e
Time: Stopped: 20:14:23

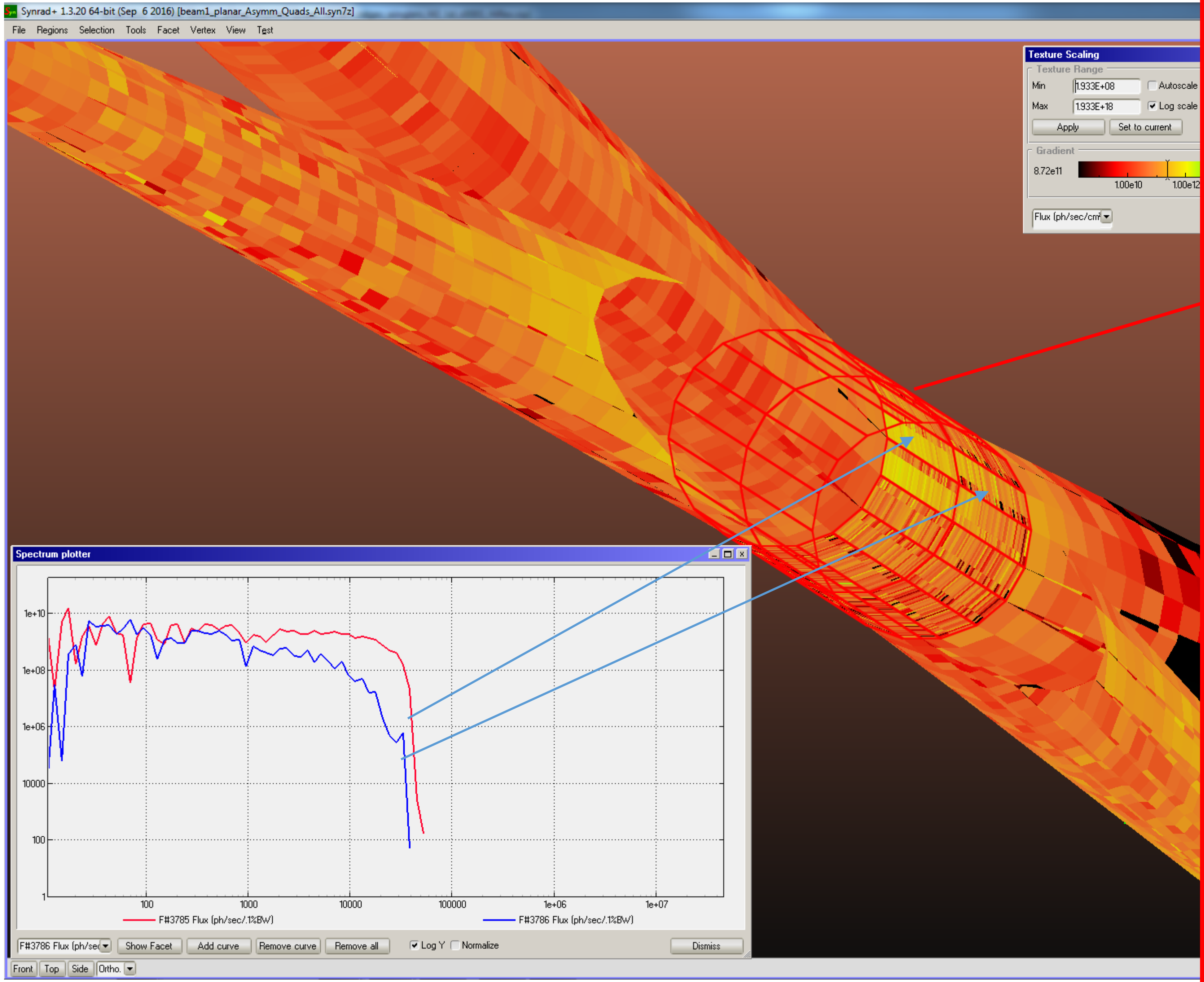
#	Hits	Flux	Power
3815	1550	1.74e+12	0.000182
3816	2405	2.91e+12	0.000987
3817	794	4.36e+11	0.000209
3818	687	6.13e+11	0.000166
3819	677	8.37e+11	0.000128
3820	768	3.6e+11	0.00022
3821	714	5.5e+11	0.000116
3822	652	4.2e+11	8.35e-05
3823	668	3e+11	0.000114
3824	734	4.34e+11	0.000165
3825	1976	1.9e+12	0.000149
3826	3605	2.27e+12	0.000142
3827	5297	3.5e+12	0.000305
3828	3877	2.98e+12	0.000131

Flux on Be Pipe: 5.26492e+13
MFP: 5021.19
MPP: 6999.8
sum(P.S2): 3.6875
sum(P.S3): 0.11992
Conical Taper: 171.189

Zoom into the IP region: 50 cm-long Be pipe and local photon flux density distribution;

A total of 5.26E+13 ph/s hit the Be pipe;

Photon flux spectrum on the two highest-flux facets of the Be pipe



Synrad+ 1.3.20 64-bit (Sep 6 2016) [beam1_planar_Asymm_Quads_All.syn7z]

Texture Scaling

Texture Range

Min 1.933E+08 ☐ Autoscale

Max 1.933E+18 ☑ Log scale

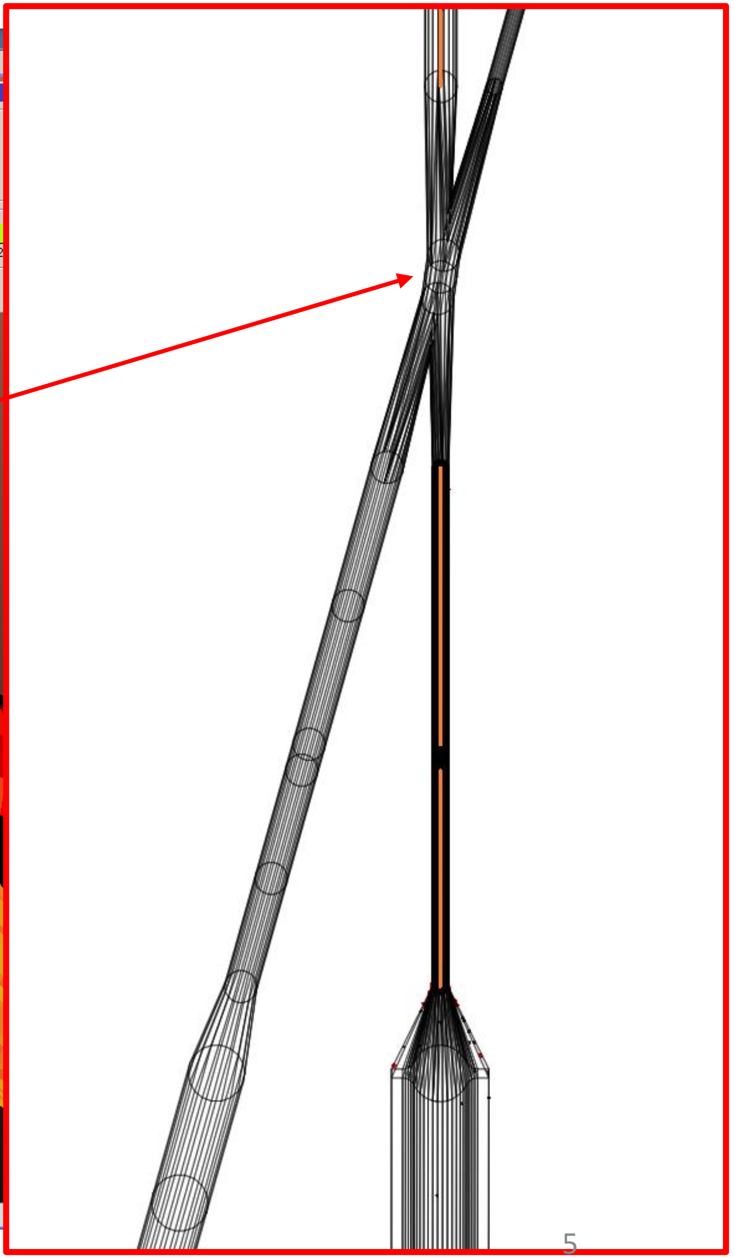
Gradient

8.72e11

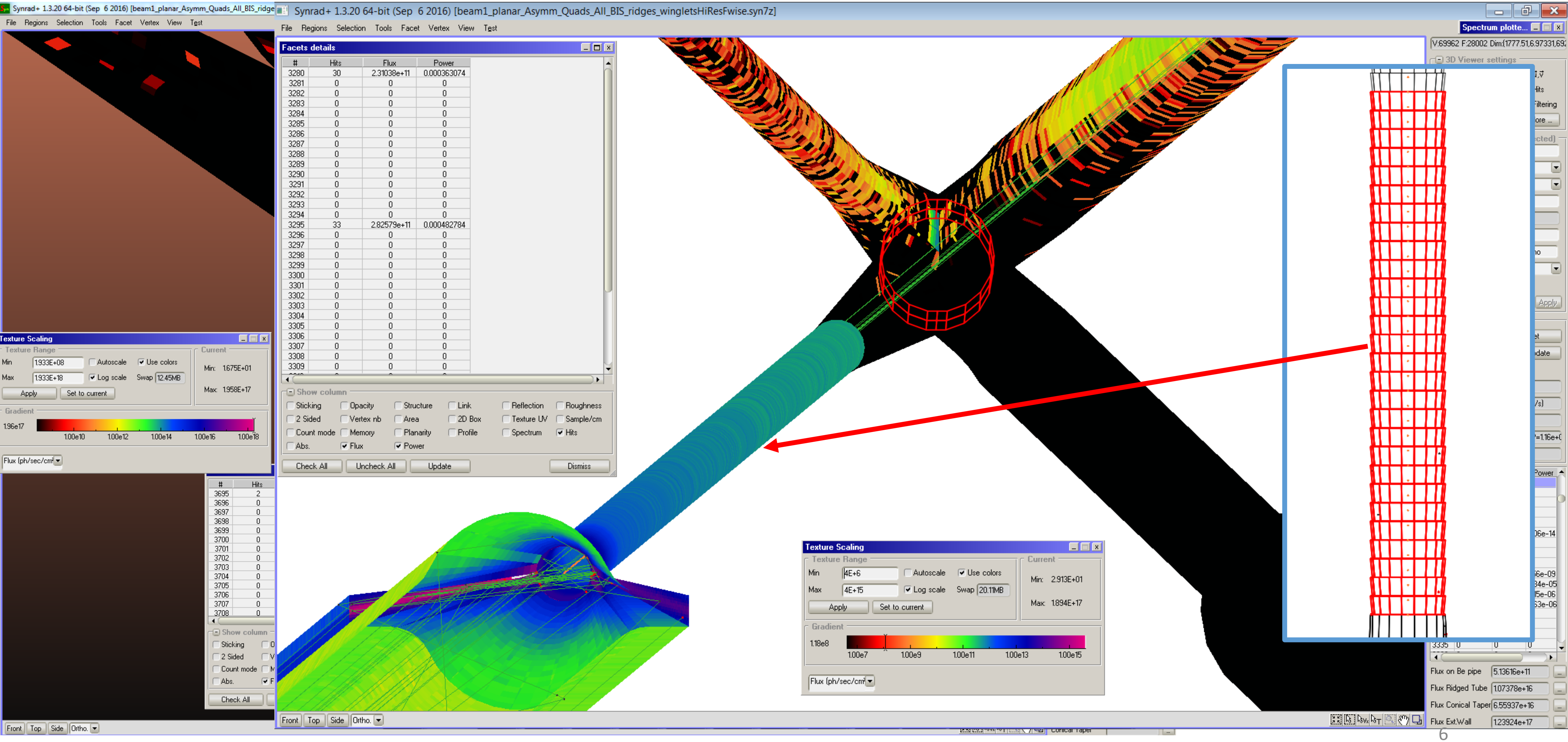
Flux (ph/sec/cm²)

Spectrum plotter

F#3786 Flux (ph/sec ☑ Log Y ☐ Normalize



Adding a “ridged” (sawtooth) profile to the 20 mm ID doublet quad pipe: reduces the flux onto Be pipe to virtually zero; (ridge/sawtooth: 0.5 mm radial, 5 mm step)



Facets details

#	Hits	Flux	Power
3280	30	2.31038e+11	0.000363074
3281	0	0	0
3282	0	0	0
3283	0	0	0
3284	0	0	0
3285	0	0	0
3286	0	0	0
3287	0	0	0
3288	0	0	0
3289	0	0	0
3290	0	0	0
3291	0	0	0
3292	0	0	0
3293	0	0	0
3294	0	0	0
3295	33	2.82579e+11	0.000482784
3296	0	0	0
3297	0	0	0
3298	0	0	0
3299	0	0	0
3300	0	0	0
3301	0	0	0
3302	0	0	0
3303	0	0	0
3304	0	0	0
3305	0	0	0
3306	0	0	0
3307	0	0	0
3308	0	0	0
3309	0	0	0

Show column
☐ Sticking ☐ Opacity ☐ Structure ☐ Link ☐ Reflection ☐ Roughness
☐ 2 Sided ☐ Vertex nb ☐ Area ☐ 2D Box ☐ Texture UV ☐ Sample/cm
☐ Count mode ☐ Memory ☐ Planarity ☐ Profile ☐ Spectrum ☑ Hits
☐ Abs. ☑ Flux ☑ Power

Check All | Uncheck All | Update | Dismiss

Texture Scaling

Texture Range
Min 1.933E+08 ☐ Autoscale ☑ Use colors
Max 1.933E+18 ☑ Log scale Swap 12.45MB
Apply | Set to current
Current
Min: 1.675E+01
Max: 1.958E+17
Gradient
1.96e17
1.00e10 1.00e12 1.00e14 1.00e16 1.00e18
Flux (ph/sec/cm²)

#	Hits
3695	2
3696	0
3697	0
3698	0
3699	0
3700	0
3701	0
3702	0
3703	0
3704	0
3705	0
3706	0
3707	0
3708	0

Show column
☐ Sticking
☐ 2 Sided
☐ Count mode
☐ Abs. ☑ F
Check All

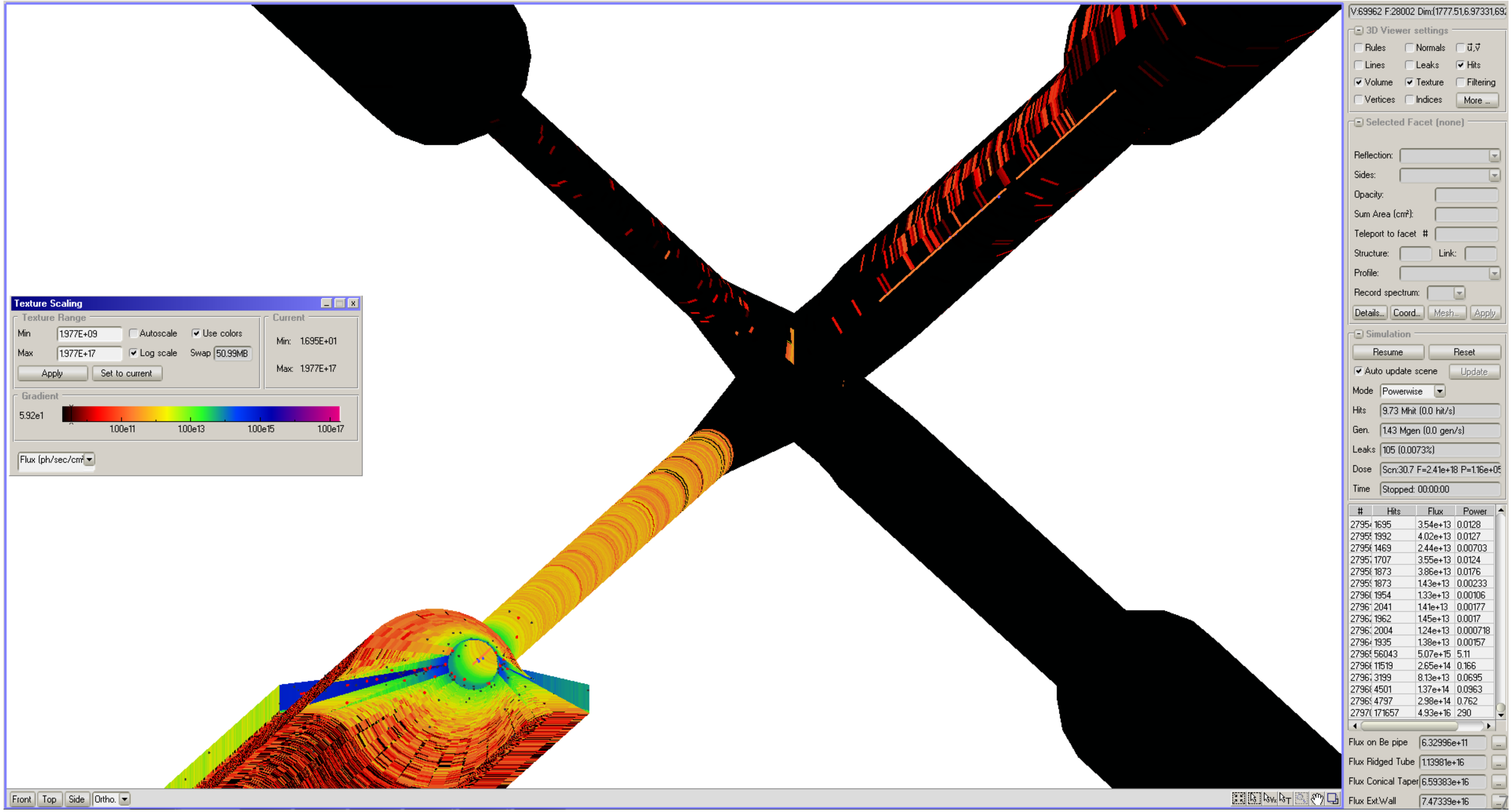
Texture Scaling

Texture Range
Min 4E+6 ☐ Autoscale ☑ Use colors
Max 4E+15 ☑ Log scale Swap 20.11MB
Apply | Set to current
Current
Min: 2.913E+01
Max: 1.894E+17
Gradient
1.18e8
1.00e7 1.00e9 1.00e11 1.00e13 1.00e15
Flux (ph/sec/cm²)

3335	0	0	0

Flux on Be pipe 5.13616e+11
Flux Ridged Tube 1.07378e+16
Flux Conical Taper 6.55937e+16
Flux Ext.Wall 1.23924e+17

Adding a “ridged” (sawtooth) profile to the 20 mm ID doublet quad pipe: reduces the flux onto Be pipe to virtually zero; (ridge/sawtooth: 0.5 mm radial, 5 mm step)



V:69962 F:28002 Dim:(1777.51,6.97331,69

3D Viewer settings

☐ Rules ☐ Normals ☐ $\vec{u},\vec{v}$

☐ Lines ☐ Leaks ☑ Hits

☑ Volume ☑ Texture ☐ Filtering

☐ Vertices ☐ Indices

Selected Facet (none)

Simulation

☑ Auto update scene

Mode: Powerwise

Hits: 9.73 Mhit (0.0 hit/s)

Gen.: 1.43 Mgen (0.0 gen/s)

Leaks: 105 (0.0073%)

Dose: Scn:30.7 F=2.41e+18 P=1.16e+05

Time: Stopped: 00:00:00

#	Hits	Flux	Power
2795	1695	3.54e+13	0.0128
2795	1992	4.02e+13	0.0127
2795	1469	2.44e+13	0.00703
2795	1707	3.55e+13	0.0124
2795	1873	3.86e+13	0.0176
2795	1873	1.43e+13	0.00233
2796	1954	1.33e+13	0.00106
2796	2041	1.41e+13	0.00177
2796	1962	1.45e+13	0.0017
2796	2004	1.24e+13	0.000718
2796	1935	1.38e+13	0.00157
2796	56043	5.07e+15	5.11
2796	11519	2.65e+14	0.166
2796	3199	8.13e+13	0.0695
2796	4501	1.37e+14	0.0963
2796	4797	2.98e+14	0.762
2797	171657	4.93e+16	290

Flux on Be pipe: 6.32996e+11

Flux Ridged Tube: 1.13981e+16

Flux Conical Taper: 6.59383e+16

Flux Ext.Wall: 7.47339e+16

Texture Scaling

Texture Range

Min: 1.977E+09

Max: 1.977E+17

☐ Autoscale ☑ Use colors

☑ Log scale Swap: 50.99MB

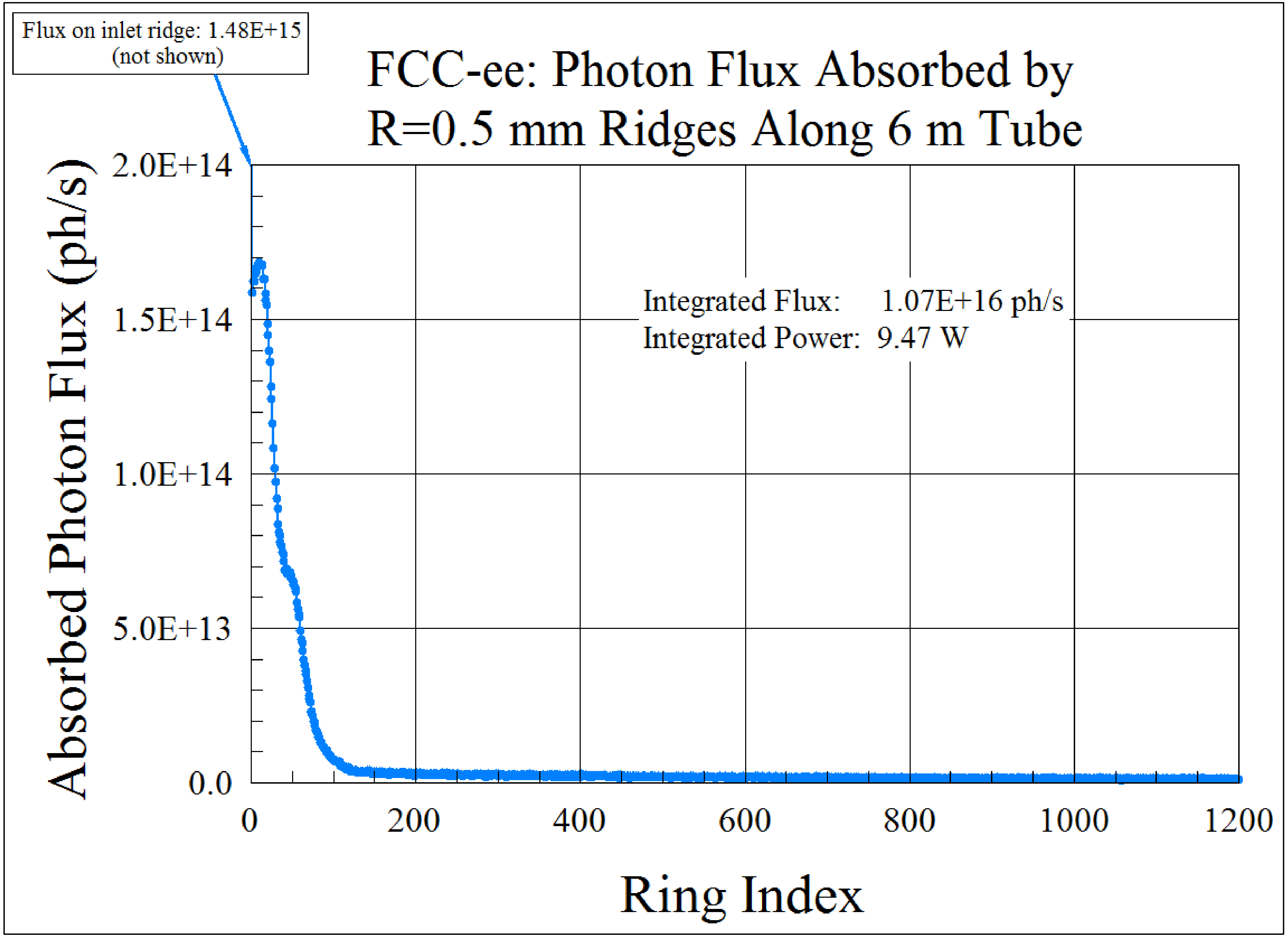
Current

Min: 1.695E+01

Max: 1.977E+17

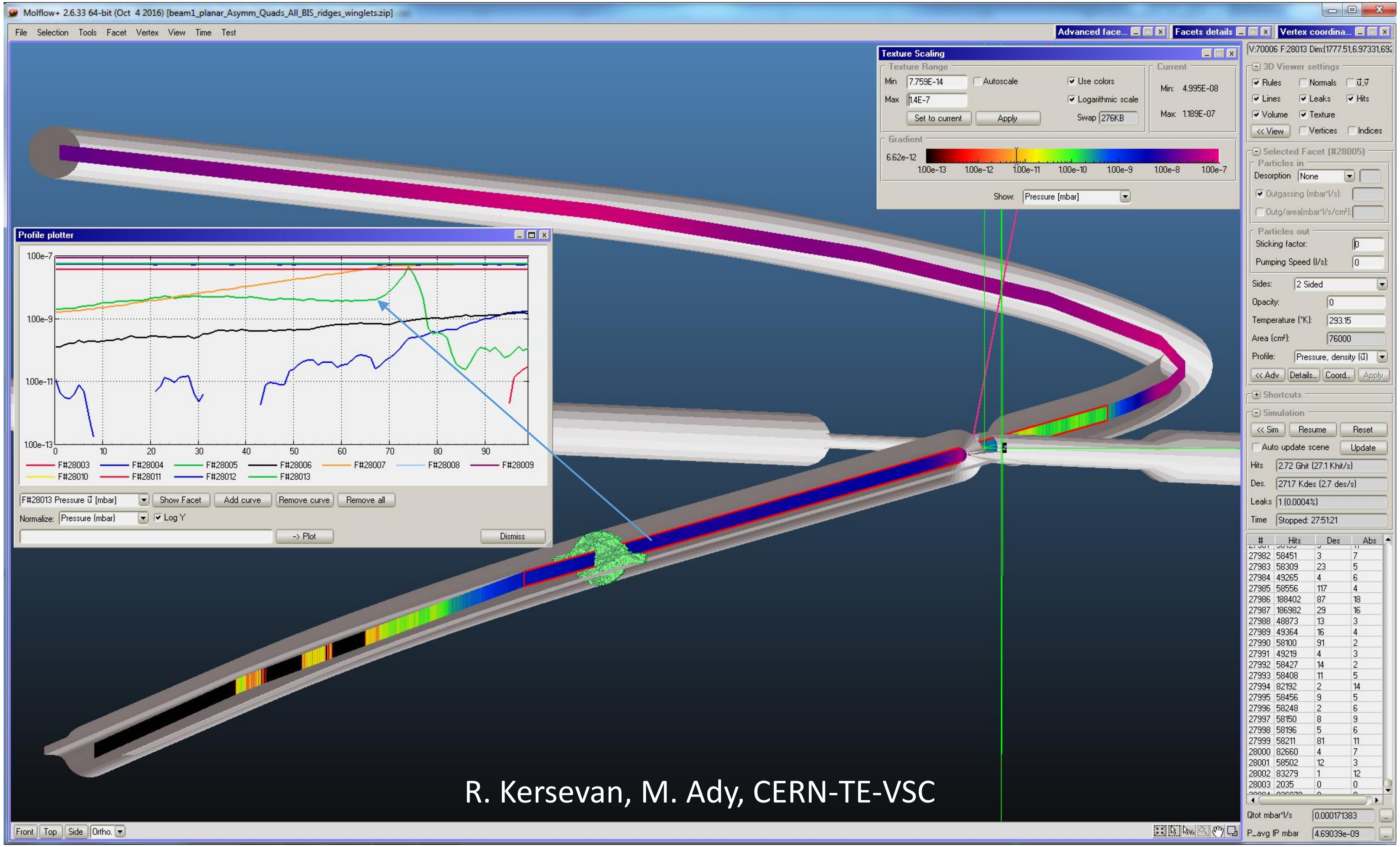
Flux (ph/sec/cm²)

FCC-ee: Photon Flux Absorbed by R=0.5 mm Ridges Along 6 m Tube


Flux on inlet ridge: 1.48E+15
(not shown)

Integrated Flux: 1.07E+16 ph/s
Integrated Power: 9.47 W

Molflow+: Pressure profile along one ~680 m-long arm of the interaction region of FCC-ee (175 GeV T-pole machine; 6.632 mA)



Molflow+ 2.6.33 64-bit (Oct 4 2016) [beam1_planar_Asymm_Quads_All_BIS_ridges_winglets.zip]

Profile plotter

F#28013 Pressure $\vec{u}$ [mbar]

Normalize: Pressure [mbar]

☑ Log Y

Texture Scaling

Texture Range

Min 7.759E-14 ☐ Autoscale ☑ Use colors

Max 1.4E-7 ☑ Logarithmic scale

Swap 276KB

Current

Min: 4.995E-08

Max: 1.189E-07

Show: Pressure [mbar]

V:70006 F:28013 Dim:(1777.51,6.97331,692

3D Viewer settings

☑ Rules ☐ Normals ☐ $\vec{u},\vec{v}$

☑ Lines ☑ Leaks ☑ Hits

☑ Volume ☑ Texture

☐ Vertices ☐ Indices

Selected Facet (#28005)

Particles in

Desorption: None

☑ Outgassing (mbar*l/s):

☐ Outg/area(mbar*l/s/cm²):

Particles out

Sticking factor: 0

Pumping Speed (l/s): 0

Sides: 2 Sided

Opacity: 0

Temperature (°K): 293.15

Area (cm²): 76000

Profile: Pressure, density ($\vec{u}$)

Simulation

☐ Auto update scene

Hits 2.72 Ghit (27.1 Khit/s)

Des. 271.7 Kdes (2.7 des/s)

Leaks 1 (0.0004%)

Time Stopped: 27:51:21

#	Hits	Des	Abs
27982	58451	3	7
27983	58309	23	5
27984	49265	4	6
27985	58556	117	4
27986	188402	87	18
27987	186982	29	16
27988	48873	13	3
27989	49364	16	4
27990	58100	91	2
27991	49219	4	3
27992	58427	14	2
27993	58408	11	5
27994	82192	2	14
27995	58456	9	5
27996	58248	2	6
27997	58150	8	9
27998	58196	5	6
27999	58211	81	11
28000	82660	4	7
28001	58502	12	3
28002	83279	1	12
28003	2035	0	0

Qtot mbar*l/s 0.000171383

P_avg IP mbar 4.69039e-09

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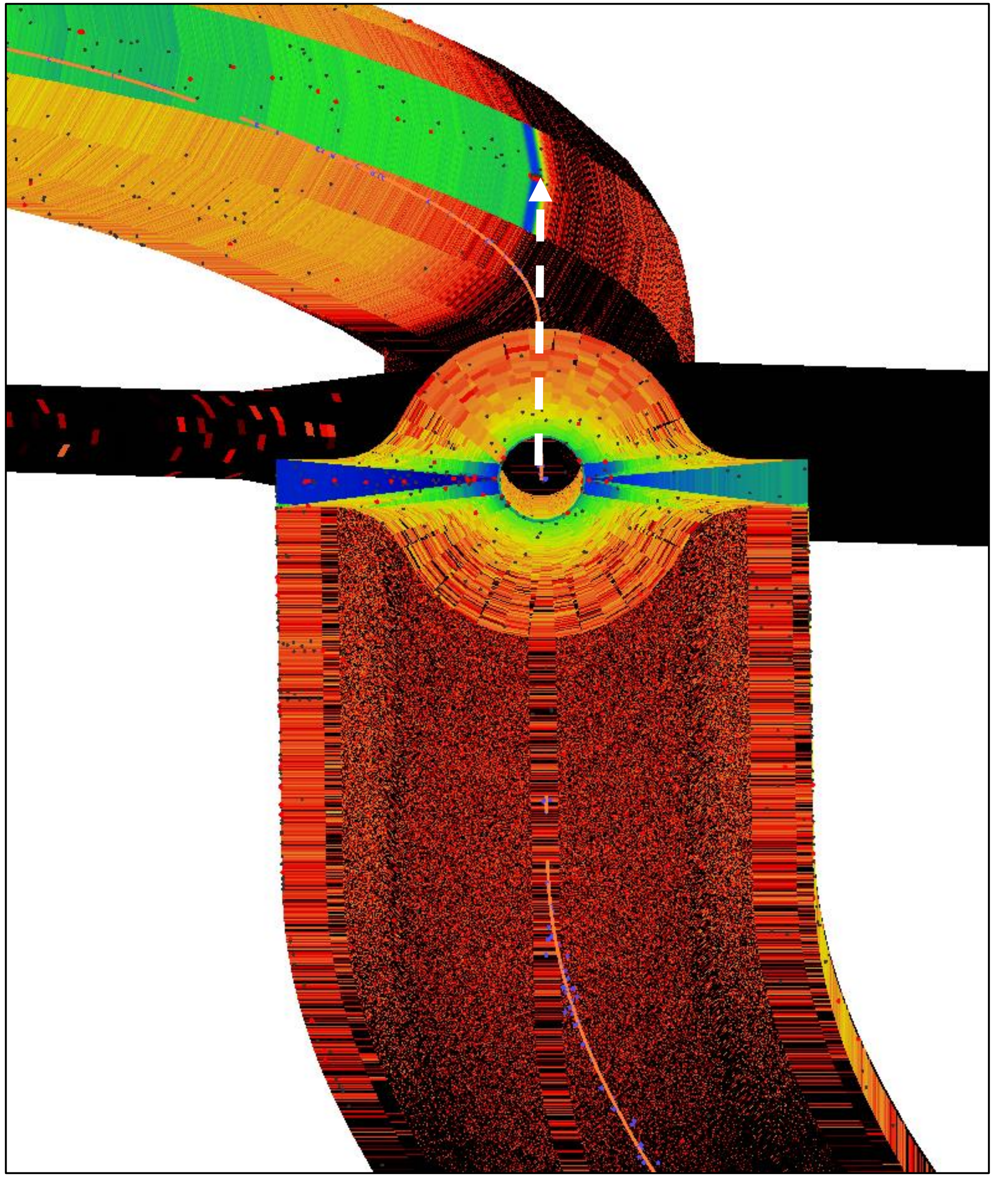
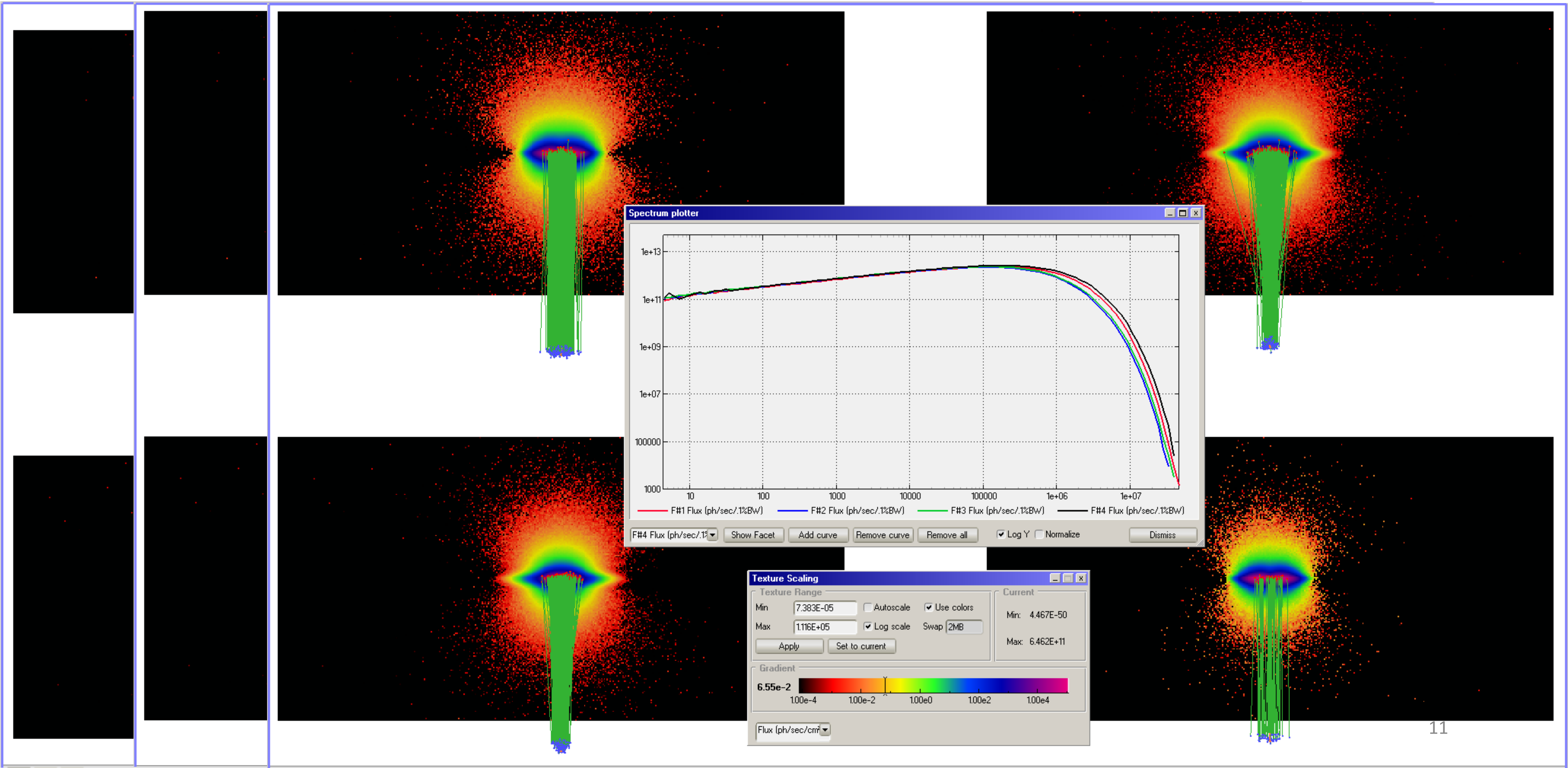


Average distance travelled by SR photons generated in the 2 doublets is ~ 63 m

Synrad+: angular distribution of the SR generated along the 4 SC doublet magnets, viewed on a flat perpendicular screens (4x2 cm^2) placed at 63 m



F#4 Flux (ph/sec/.1%
☑ Log Y ☐ Normalize

Texture Range
Min 7.383E-05 ☐ Autoscale ☑ Use colors
Max 1.116E+05 ☑ Log scale Swap 2MB

Current
Min: 4.467E-50
Max: 6.462E+11

Gradient
6.55e-2

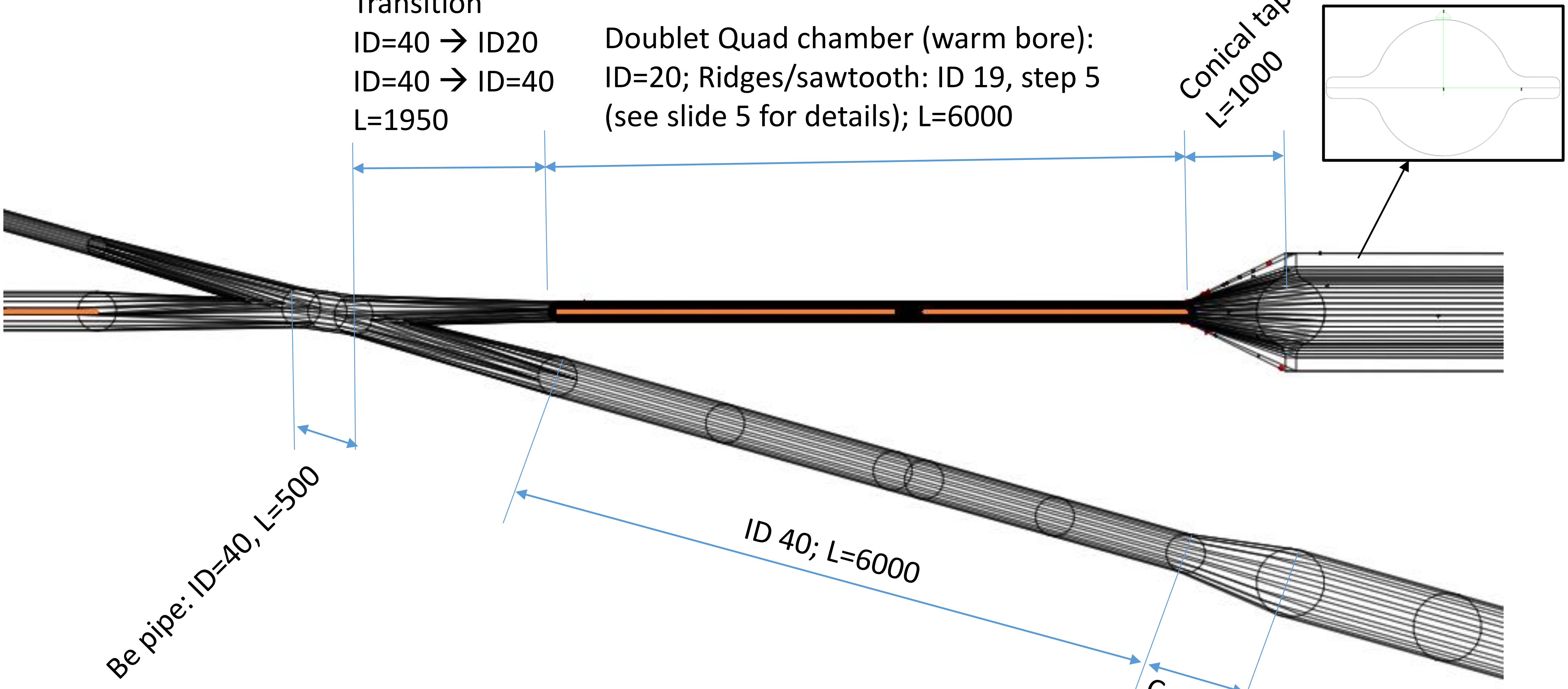
Flux (ph/sec/cm²)

Preliminary conclusions:

- The ray-tracing montecarlo code SYNRAD+ has been applied to the FCC-ee IP region;
- A model of approximately 680 m length around the IP has been made: for the time being it doesn't have details about many important vacuum components, which could change the way low-energy photons are scattered (low-energy='those photons with energies below the Compton threshold', ~100 keV);
- It is evident that without a proper masking of the Be pipe, the pipe will get a non-negligible photon flux with photons up to several 10's keV: is this a problem for the detector's hardware and electronics?
- It is also evident that a rather simple to implement ridged (sawtooth-ed) geometry somehow machined on the internal part of the cold bore focusing doublet helps in reducing a lot (virtually to zero) the photon flux on the Be pipe; it needs to be coupled to a larger-bore 'exit' tube (which would also be beneficial for avoiding trapped modes in the Be pipe area (see E. Belli's presentation);
- The 4 quadrupole magnets of the doublet generate a rather large and extremely hard photon flux, with photons reaching the energy range of several TENS MeV: they mostly land on a small spot on the exit side of the beam, about ~63 m downstream, past the detector: careful shielding of that area must be envisaged;

Bonus slides (following yesterday's discussions):

Shape and dimensions (in mm) of IP chambers:



Transition
ID=40 → ID20
ID=40 → ID=40
L=1950

Doublet Quad chamber (warm bore):
ID=20; Ridges/sawtooth: ID 19, step 5
(see slide 5 for details); L=6000

Conical taper:
L=1000

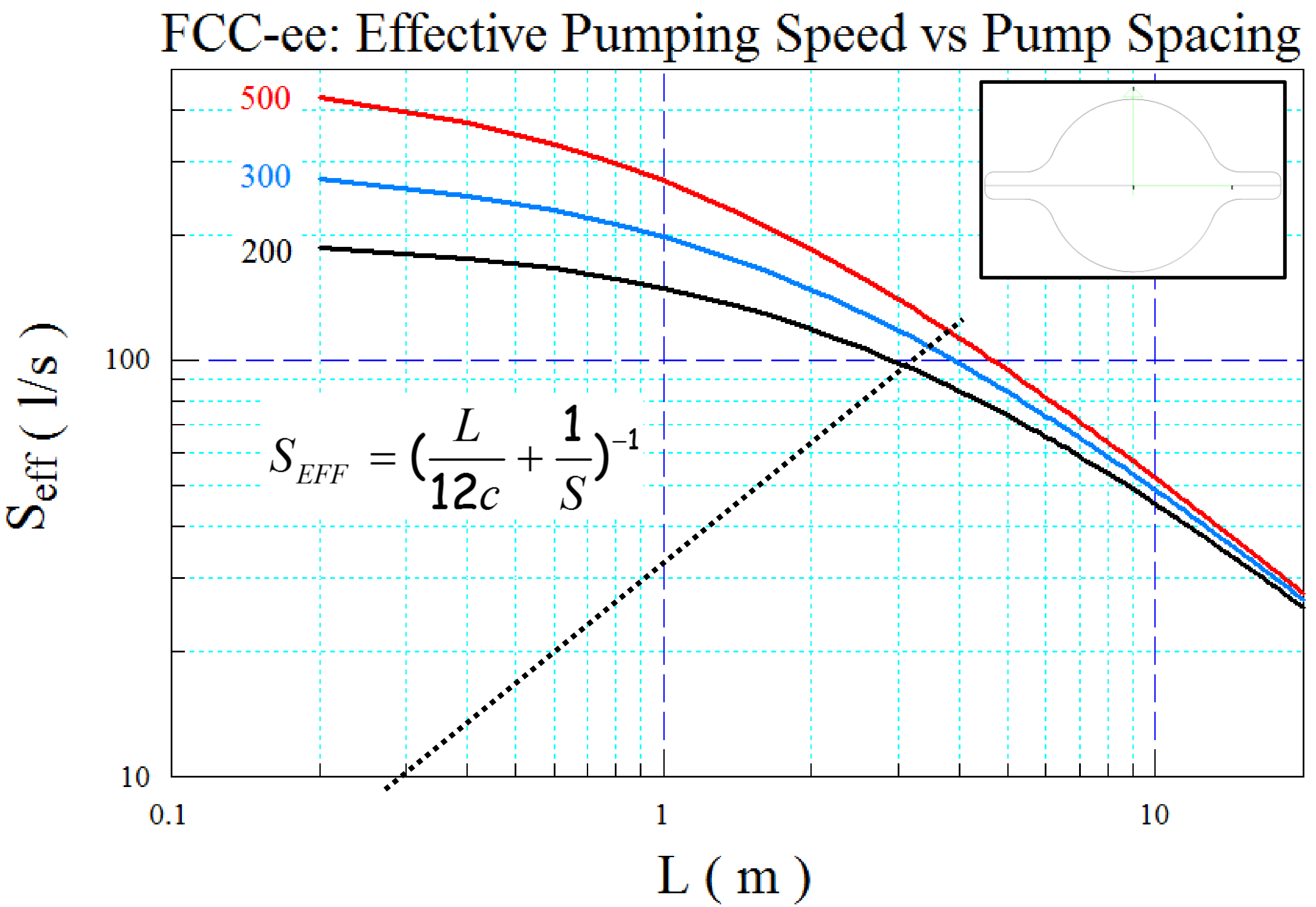
Be pipe: ID=40, L=500

ID 40; L=6000

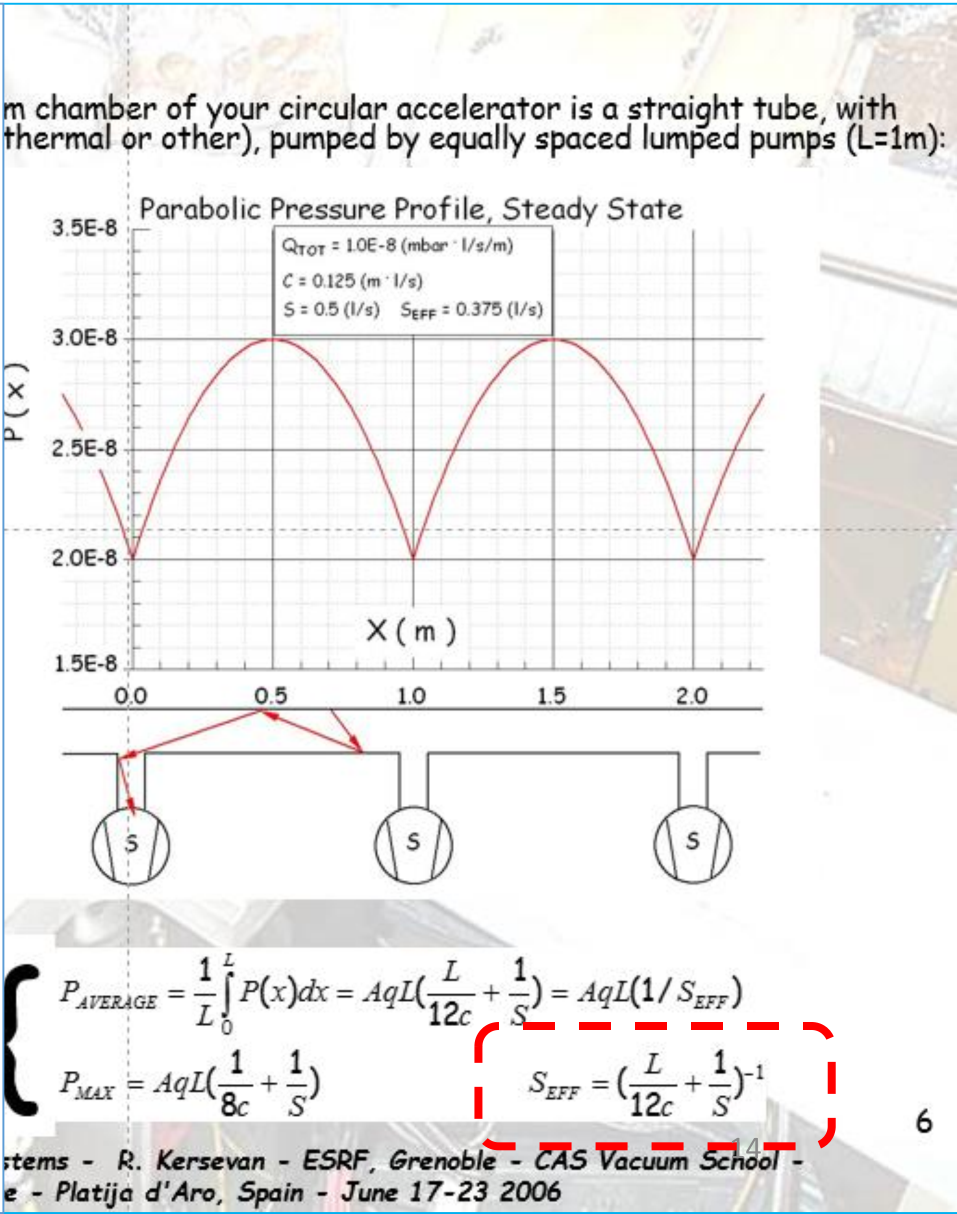
Conical taper:
L=1000
ID40 → ID70

Conductance limitation severely affects the effective pumping speed, and therefore the final pressure

Specific conductance of 70 mm ID, winged (SUPERKEK) cross-section: 48.65 l*m/s


FCC-ee: Effective Pumping Speed vs Pump Spacing

$$S_{EFF} = \left(\frac{L}{12c} + \frac{1}{S}\right)^{-1}$$


m chamber of your circular accelerator is a straight tube, with
thermal or other), pumped by equally spaced lumped pumps (L=1m):

Parabolic Pressure Profile, Steady State

Q_{TOT} = 1.0E-8 (mbar · l/s/m)
C = 0.125 (m · l/s)
S = 0.5 (l/s) S_{EFF} = 0.375 (l/s)

$$\begin{cases} P_{AVERAGE} = \frac{1}{L}\int_0^L P(x)dx = AqL\left(\frac{L}{12c} + \frac{1}{S}\right) = AqL(1/S_{EFF}) \\ P_{MAX} = AqL\left(\frac{1}{8c} + \frac{1}{S}\right) \end{cases}$$

$$S_{EFF} = \left(\frac{L}{12c} + \frac{1}{S}\right)^{-1}$$

6

stems - R. Kersevan - ESRF, Grenoble - CAS Vacuum School -
e - Platija d'Aro, Spain - June 17-23 2006

Example: What average effective pumping speed would be necessary for the Z-pole machine in order to have an average pressure lower than 1.0E-9 mbar?

Photon flux: F (ph/s) = 8.08E+17 · E (GeV) · I (mA) = 5.34E+22 (ph/s)

If k=2.47E+19 (mol/mbar/liter), then the gas load Q is:

Q (mbar·l/s) = F (ph/s) / k(mol/mbar/l) · η(mol/ph)

with η= photodesorption yield.

→ Typically a machine is considered *vacuum conditioned* when η < 1.0E-6 (mol/ph):

Q' (mbar·l/s/m) = Q/ 2πρ = 3.44E-8 (mbar·l/s/m) (in the arcs, ρ ~10 km)

P_{avg} (mbar) = Q' (mbar·l/s/m) / S_{eff} (l/s) · L(m)

Explicitating for S_{eff}, one gets: S_{eff} (l/s) = 34.42 · L(m) (dotted line at 45 deg on previous plot)

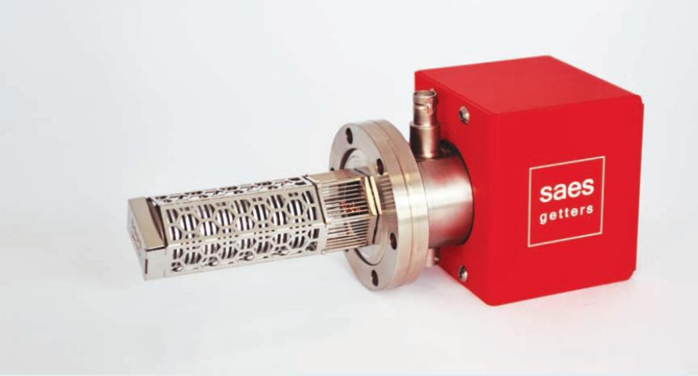
- This means that the Z-pole machine, due to its huge photon flux, would condition to P_{avg}<1.0E-9 only if 200 ÷ 500 l/s pumps are placed at a distance < 3 ÷ 4 m from each other;
- This, in turn, would mean that in the arcs one would need 19000 ÷ 25000 pumps/beam;
- Each lumped pump would in turn need pumping slots machined on the vacuum chamber: impedance budget?... and compare this to impedance generated by NEG-coating.

NEG pumps: the NEXTorr family (SAES Getters, Milan, Italy)

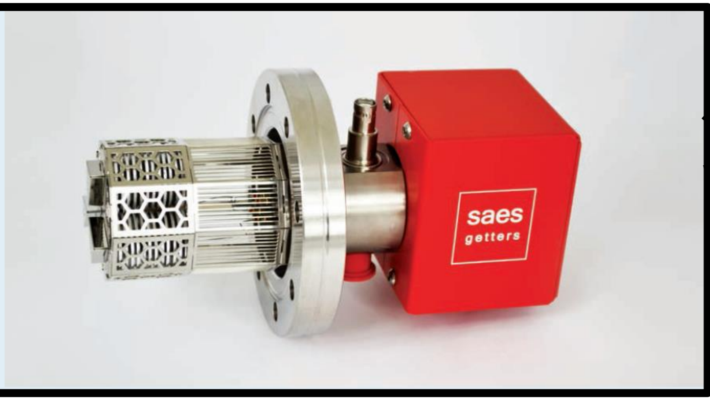
Integrated NEG pump with “small” noble ion-pump (~10 l/s)

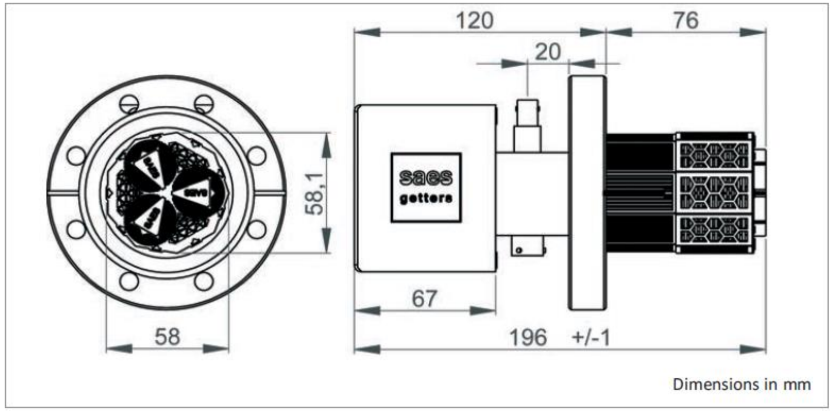
NEXTorr® D 100-5

NEXTorr® D 200-5



NEXTorr® D 300-5

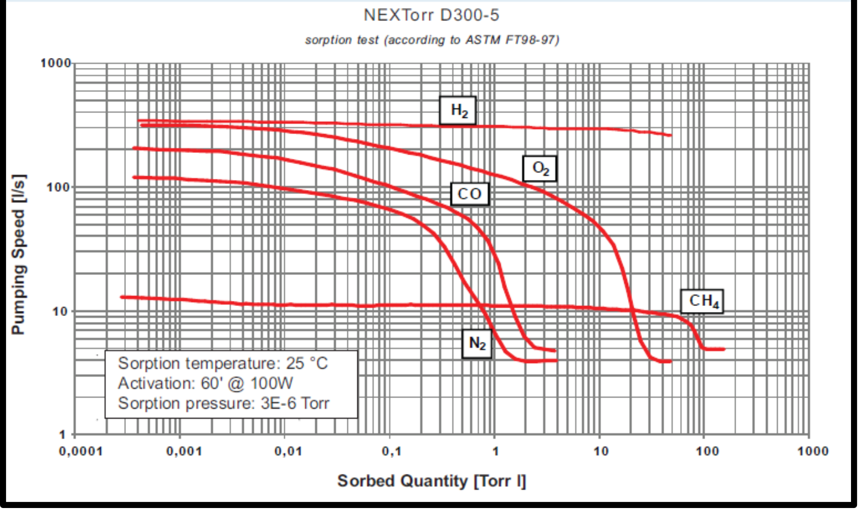




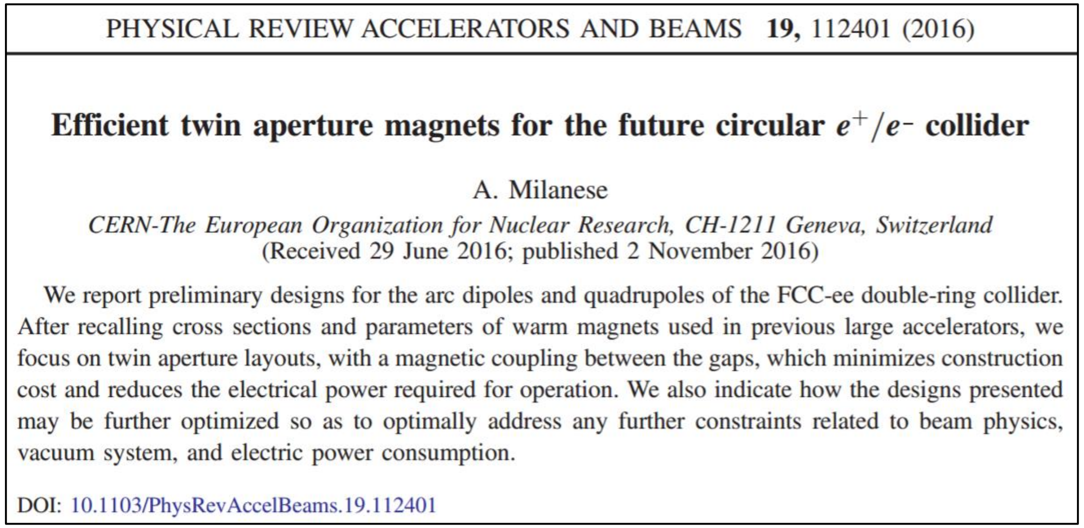
Dimensions in mm

Total pump weight (magnets included)	3.1 kg
Total pump volume	0.6 litre
Type of ion pump	Diode
Operation Voltage Ion Element	5.0 kVdc
Operation Voltage NEG Element	20 Vdc

Pumping speed curves for various gases



Twin-aperture magnets for FCC-ee and ante-chamber design compatibity:


PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 112401 (2016)

Efficient twin aperture magnets for the future circular e^+/e^- collider

A. Milanese
CERN-The European Organization for Nuclear Research, CH-1211 Geneva, Switzerland
(Received 29 June 2016; published 2 November 2016)

We report preliminary designs for the arc dipoles and quadrupoles of the FCC-ee double-ring collider. After recalling cross sections and parameters of warm magnets used in previous large accelerators, we focus on twin aperture layouts, with a magnetic coupling between the gaps, which minimizes construction cost and reduces the electrical power required for operation. We also indicate how the designs presented may be further optimized so as to optimally address any further constraints related to beam physics, vacuum system, and electric power consumption.

DOI: 10.1103/PhysRevAccelBeams.19.112401

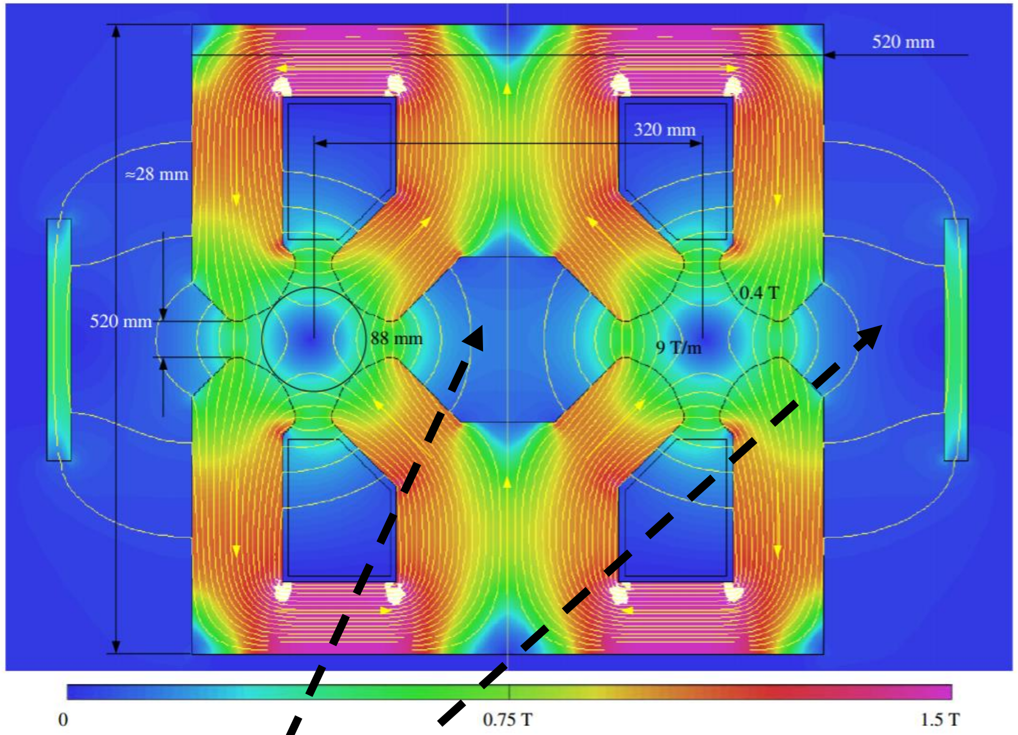


FIG. 7. First cross section of FCC-ee twin quadrupoles; the geometry is to scale with the twin dipole of Fig. 6 (field levels for 175 GeV).

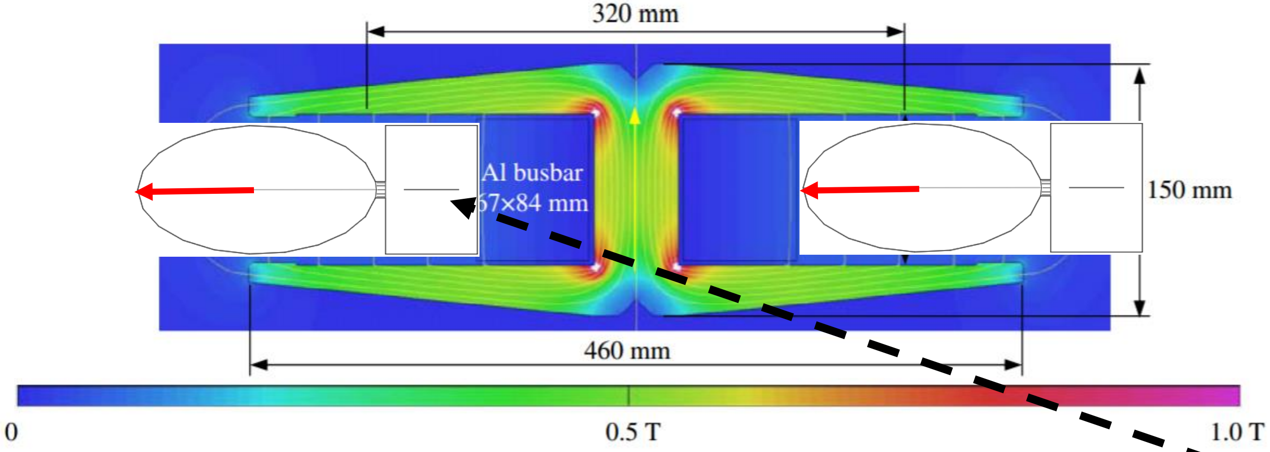


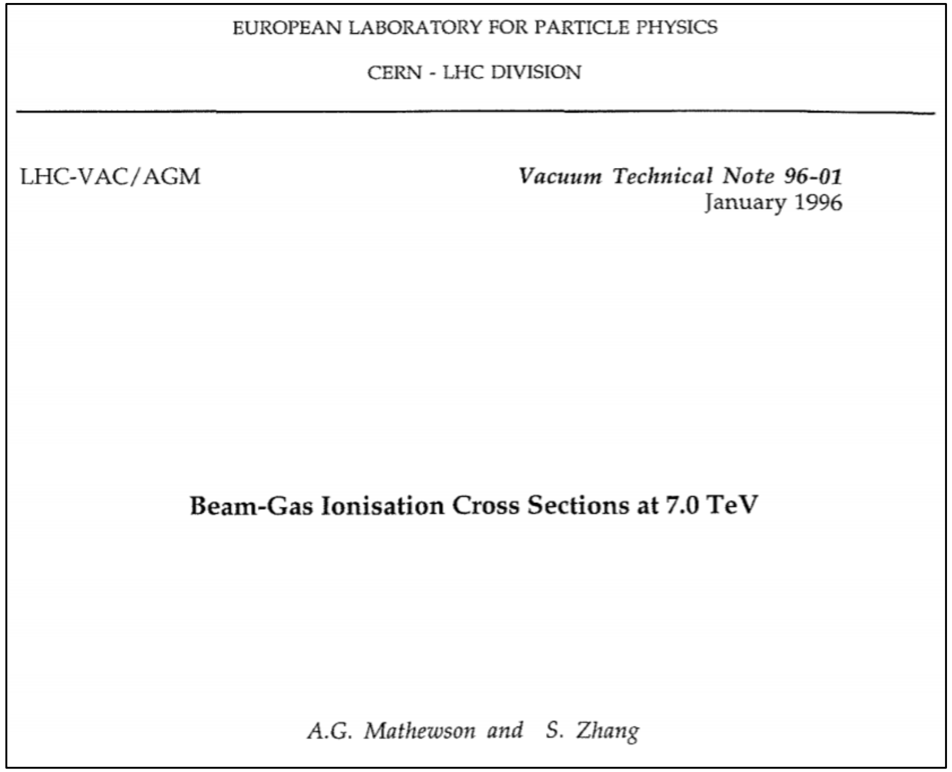
FIG. 6. First cross section of FCC-ee bending magnets with an I layout (field levels for 175 GeV).

Space for antechamber????

<u>Yes</u> for the quads…

… <u>difficult</u> for one of the dipoles!

Beam ionization and its electron density
(follow up to E. Belli’s presentation)



EUROPEAN LABORATORY FOR PARTICLE PHYSICS

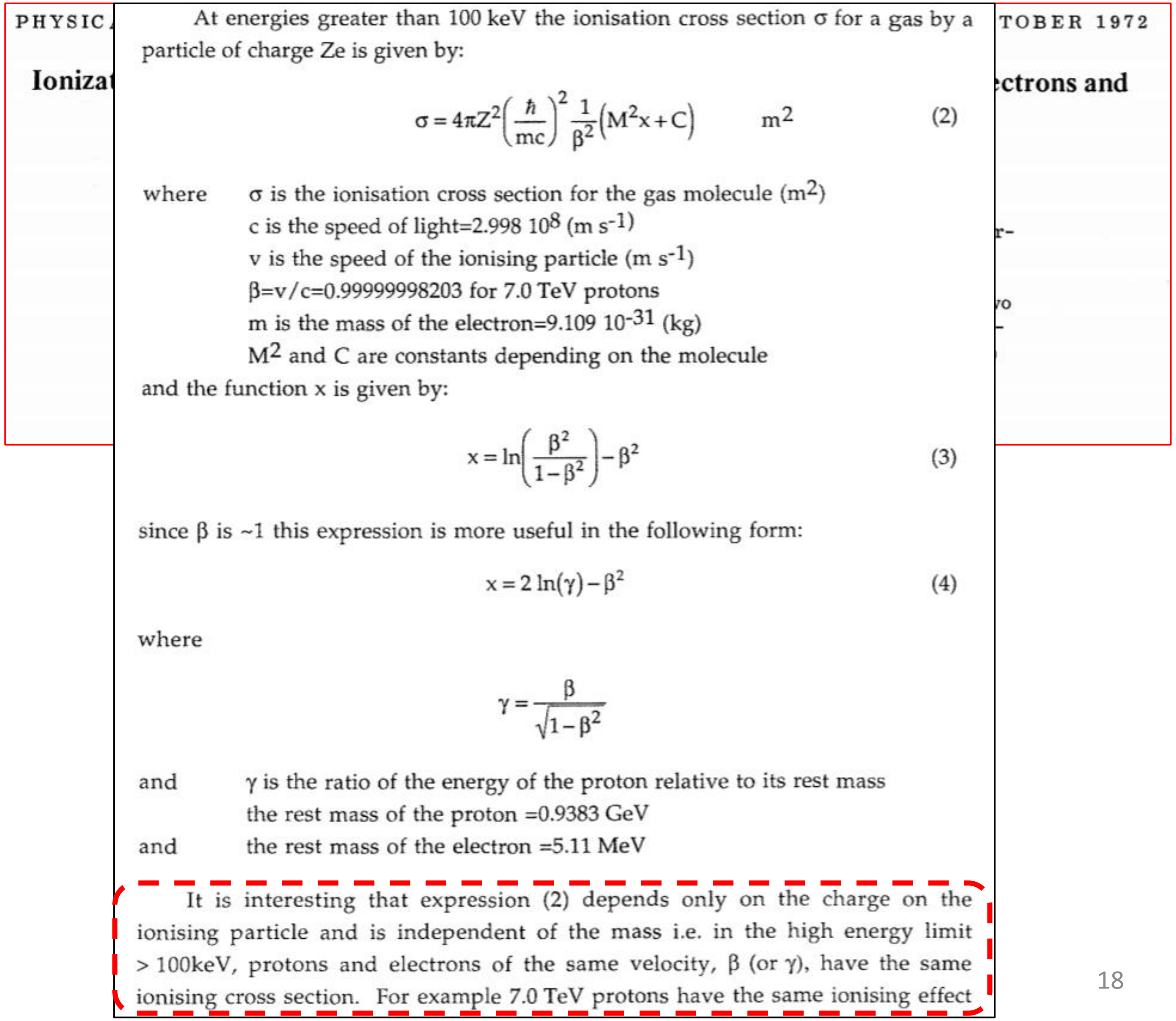
CERN - LHC DIVISION

LHC-VAC/AGM

Vacuum Technical Note 96-01
January 1996

Beam-Gas Ionisation Cross Sections at 7.0 TeV

A.G. Mathewson and S. Zhang



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ctrons and

At energies greater than 100 keV the ionisation cross section σ for a gas by a particle of charge Ze is given by:

$$\sigma = 4\pi Z^2\left(\frac{\hbar}{mc}\right)^2 \frac{1}{\beta^2}\left(M^2 x + C\right) \qquad m^2 \qquad (2)$$

where σ is the ionisation cross section for the gas molecule (m^2)

c is the speed of light=2.998 10^8 (m s^{-1})

v is the speed of the ionising particle (m s^{-1})

$\beta = v/c = 0.99999998203$ for 7.0 TeV protons

m is the mass of the electron=9.109 10^{-31} (kg)

M^2 and C are constants depending on the molecule

and the function x is given by:

$$x = \ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2 \qquad (3)$$

since β is ~1 this expression is more useful in the following form:

$$x = 2\ln(\gamma) - \beta^2 \qquad (4)$$

where

$$\gamma = \frac{\beta}{\sqrt{1-\beta^2}}$$

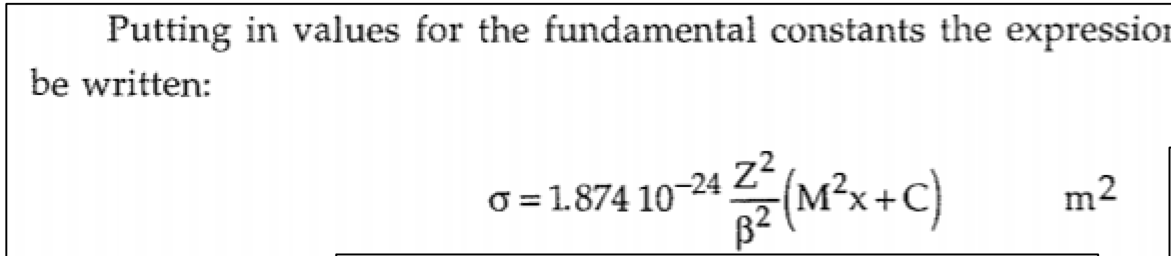
and γ is the ratio of the energy of the proton relative to its rest mass

the rest mass of the proton =0.9383 GeV

and the rest mass of the electron =5.11 MeV

It is interesting that expression (2) depends only on the charge on the ionising particle and is independent of the mass i.e. in the high energy limit > 100keV, protons and electrons of the same velocity, β (or γ), have the same ionising cross section. For example 7.0 TeV protons have the same ionising effect

Beam ionization and its electron density



Putting in values for the fundamental constants the expression (2) for σ can be written:

$$\sigma = 1.874\,10^{-24}\,\frac{Z^2}{\beta^2}\left(M^2 x + C\right) \qquad m^2$$

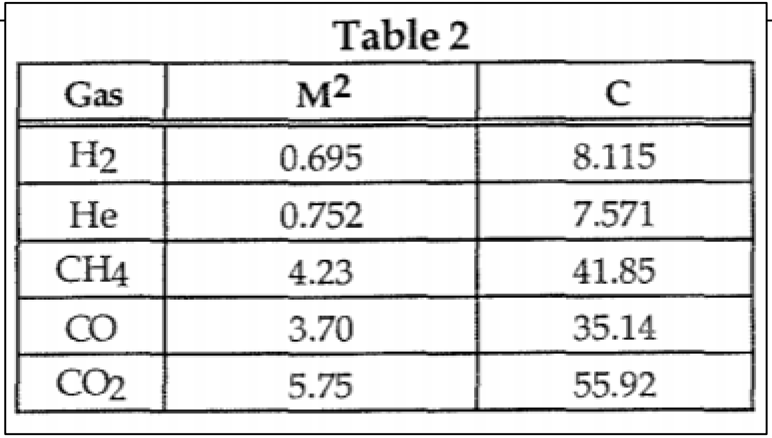
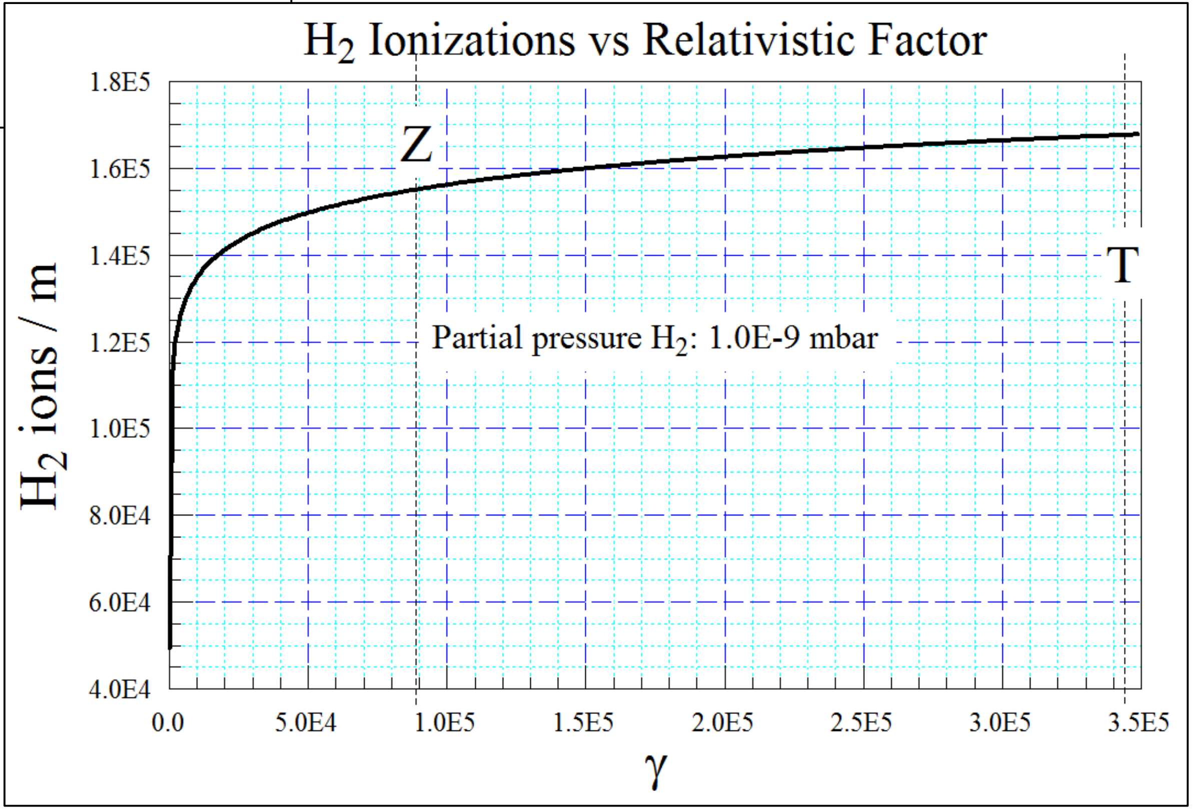


Table 2

Gas	M^2	C
H_2	0.695	8.115
He	0.752	7.571
CH_4	4.23	41.85
CO	3.70	35.14
CO_2	5.75	55.92



Example: H_2, 1.0E-9 mbar

1.0E-9 mbar → ρ= 2.47E+13 mol/m^3

If the primary electrons traverse a path L in a gas of concentration ρ then the average number of primary ionizations z per primary electron is: $z = \sigma \cdot L \cdot \rho$

Substituting for $n_{e-}(Z_{1450\,mA})$=9.05E+13/m → the average number of ionizations per meter length: ~ 1.55E+5 vs the 1.0E+8 assumed by E. Belli. ???? ← Negligible!