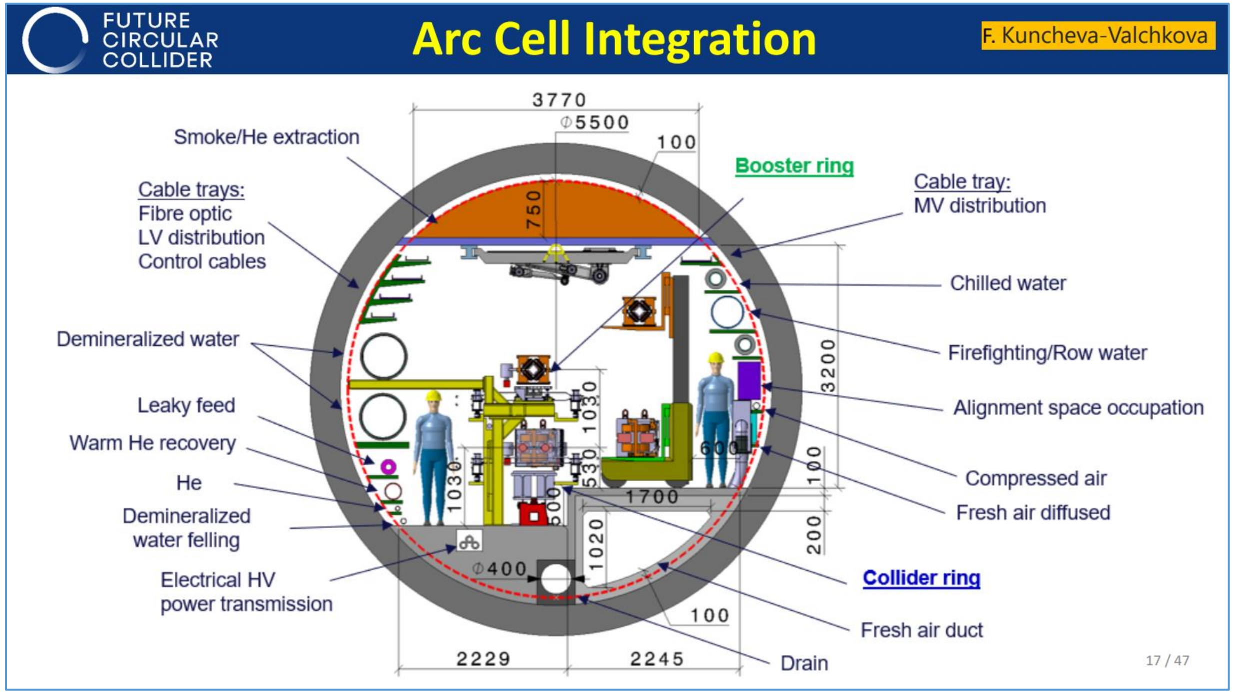
Vacuum system and photoelectron distributions in the booster

R. Kersevan, FCCIS 2023 WP2 Workshop

Angelicum Centro Congressi, Rome, Nov 13-15, 2023

- The tunnel along the arcs has a typical cross-section as shown below (left)



FUTURE CIRCULAR COLLIDER

Arc Cell Integration

F. Kuncheva-Valchkova

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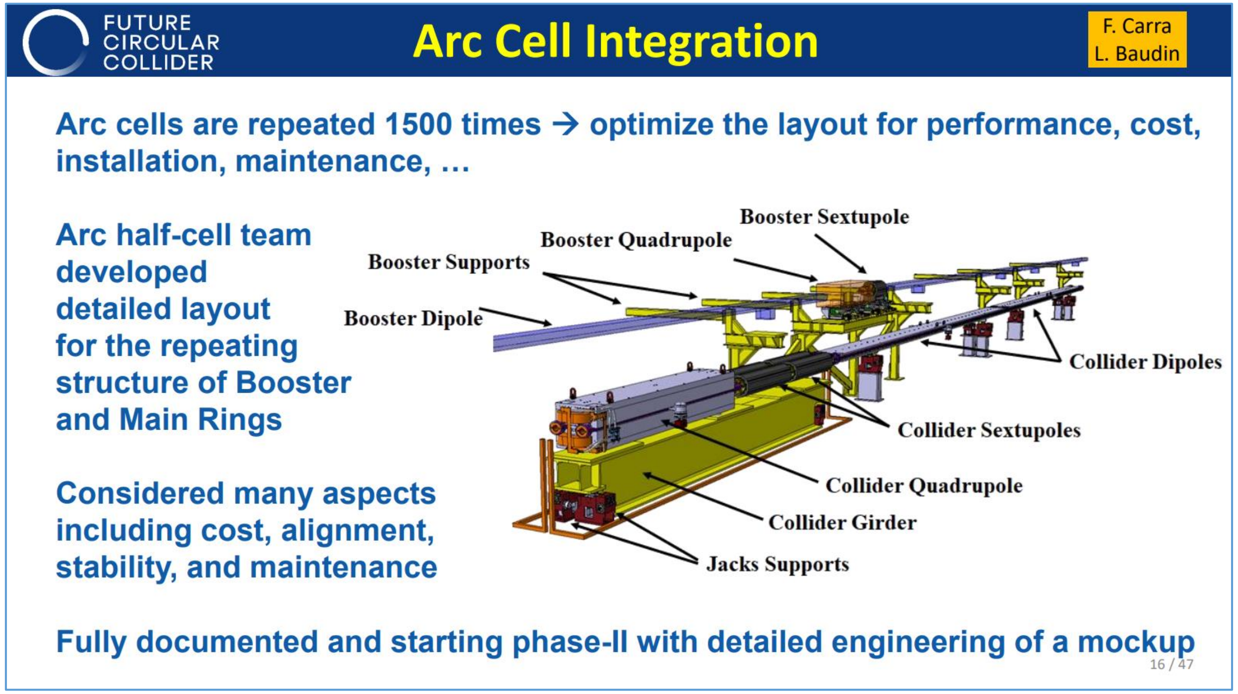

FUTURE CIRCULAR COLLIDER

Arc Cell Integration

F. Carra
L. Baudin

Arc cells are repeated 1500 times → optimize the layout for performance, cost, installation, maintenance, …

Arc half-cell team developed detailed layout for the repeating structure of Booster and Main Rings

Considered many aspects including cost, alignment, stability, and maintenance

Fully documented and starting phase-II with detailed engineering of a mockup

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- There are TWO counter-rotating beams (e- and e+) guided by dipole, quadrupole, and sextupole magnets (above, right)
- Above the two rings of the collider, there is a THIRD ring, the full-energy injection BOOSTER, which injects both e- and e+ (in opposite directions) whenever necessary
- There are, therefore, about 3x 91 km ring vacuum system, plus additional (many) km of TRANSFER LINES (TLs) from booster to collider rings, and also other TLs from other accelerators in the chain (pre-booster chain has different options under study)

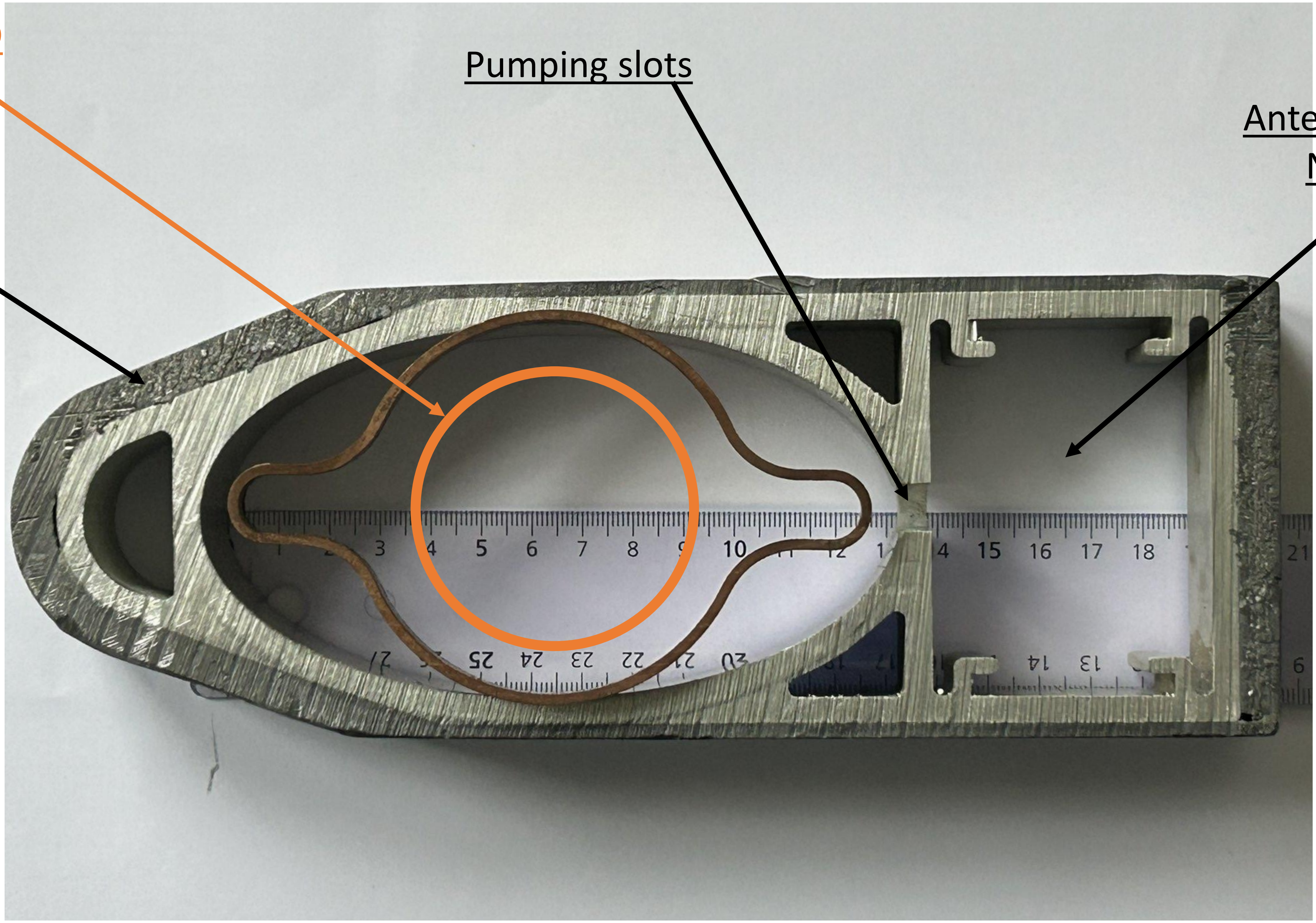
General Consideration (all this is the result of the Cost Review exercise)

1. The vacuum chamber cross section in the booster is NOW 50 mm circular (ID): The specific conductance of a 50 mm ID circular tube is only ~41 l·m/s → LOWER CONDUCTANCE
2. Material is stainless steel (probably 316L or LN) with NO welding seam (extruded, not bent and welded like the LHC beam-screen)
3. NO copper coating → RW IMPEDANCE???
4. NO NEG-coating → HIGH PRESSURE
5. NO bakeout system → HIGHER MASS SPECIES (ineffective water vapour removal)
6. NO RF fingers in the bellows → GEOMETRIC IMPEDANCE/HOMs???
7. No SR Absorbers possible (the booster accelerates both beams in opposite directions) → SLOWER CONDIT.
8. It is a rather “conventional” design (other than its size) as implemented for decades in e.g. light sources worldwide
9. Same sectoring as for the 2 storage rings (i.e. 400 m between adjacent gate valves)

If you put together some of these points then it is clear, even before doing any calculation, that the pressure along the booster won’t be very low very quickly, as it is expected to be in the storage rings.

Also the booster will be prone to several instabilities due to high(er) pressure, high(er) gas ionization (ion-trapping) and high(er) photoelectron yield and SEY, and e-cloud effects

Comparison of LEP extruded cross-section (dipole chambers) with FCC-ee’s



BOOSTER 50 mm ID

Pumping slots

Antechamber for NEG strip

Lead shielding

LEP:
ellipse 131x70 mm^2

FCC-ee:
115 mm wide, 70 mm ID

The specific conductance of FCC-ee is ~1/2 that of LEP, ~100:50 l·m/s
The proposed 60 mm ID version for FCC-ee would have a 37% conductance decrease, i.e. only ~1/7 that of LEP; BOOSTER: 13.7 l·m/s

FCC-ee Booster Parameters

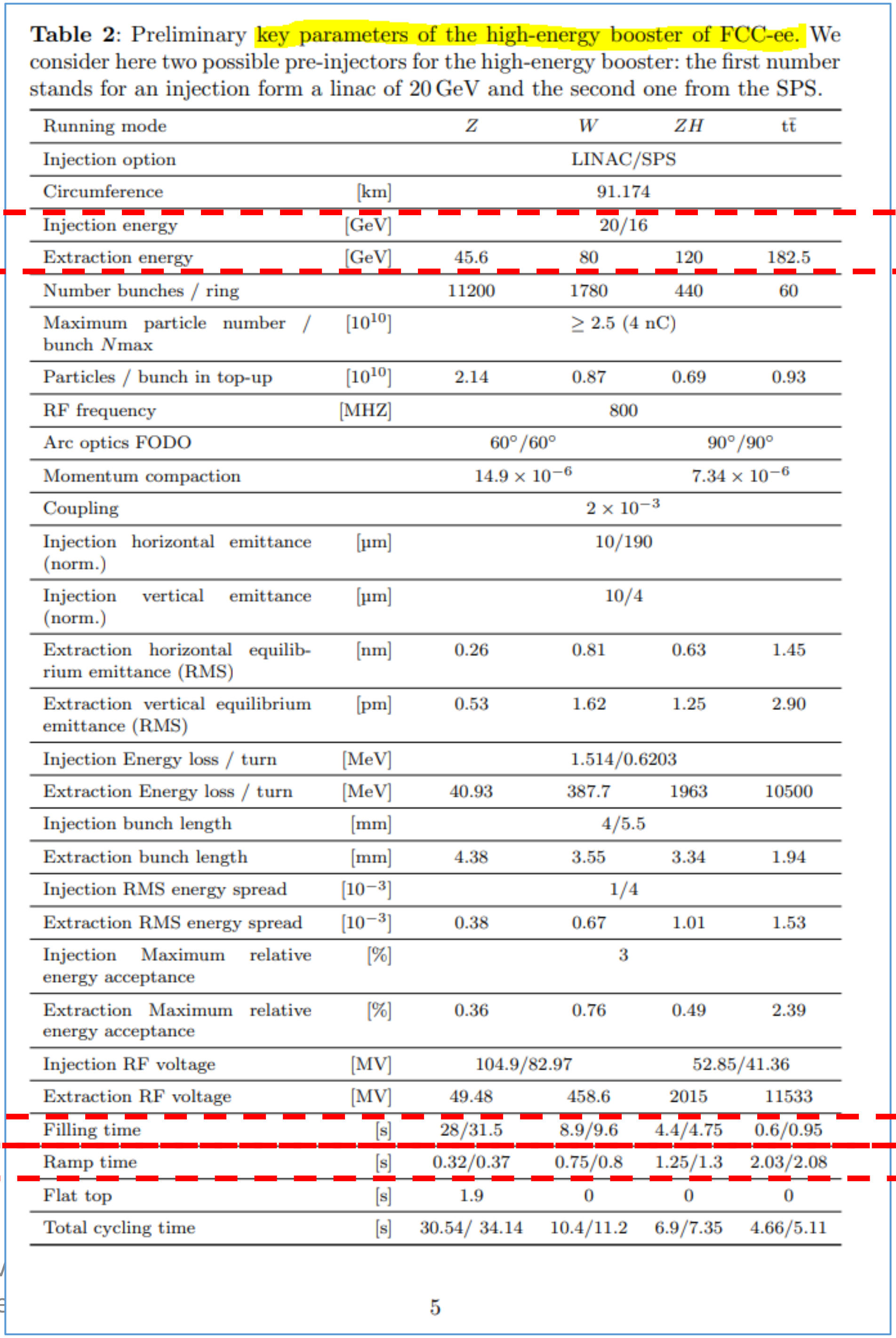


Table 2: Preliminary key parameters of the high-energy booster of FCC-ee. We consider here two possible pre-injectors for the high-energy booster: the first number stands for an injection form a linac of 20 GeV and the second one from the SPS.

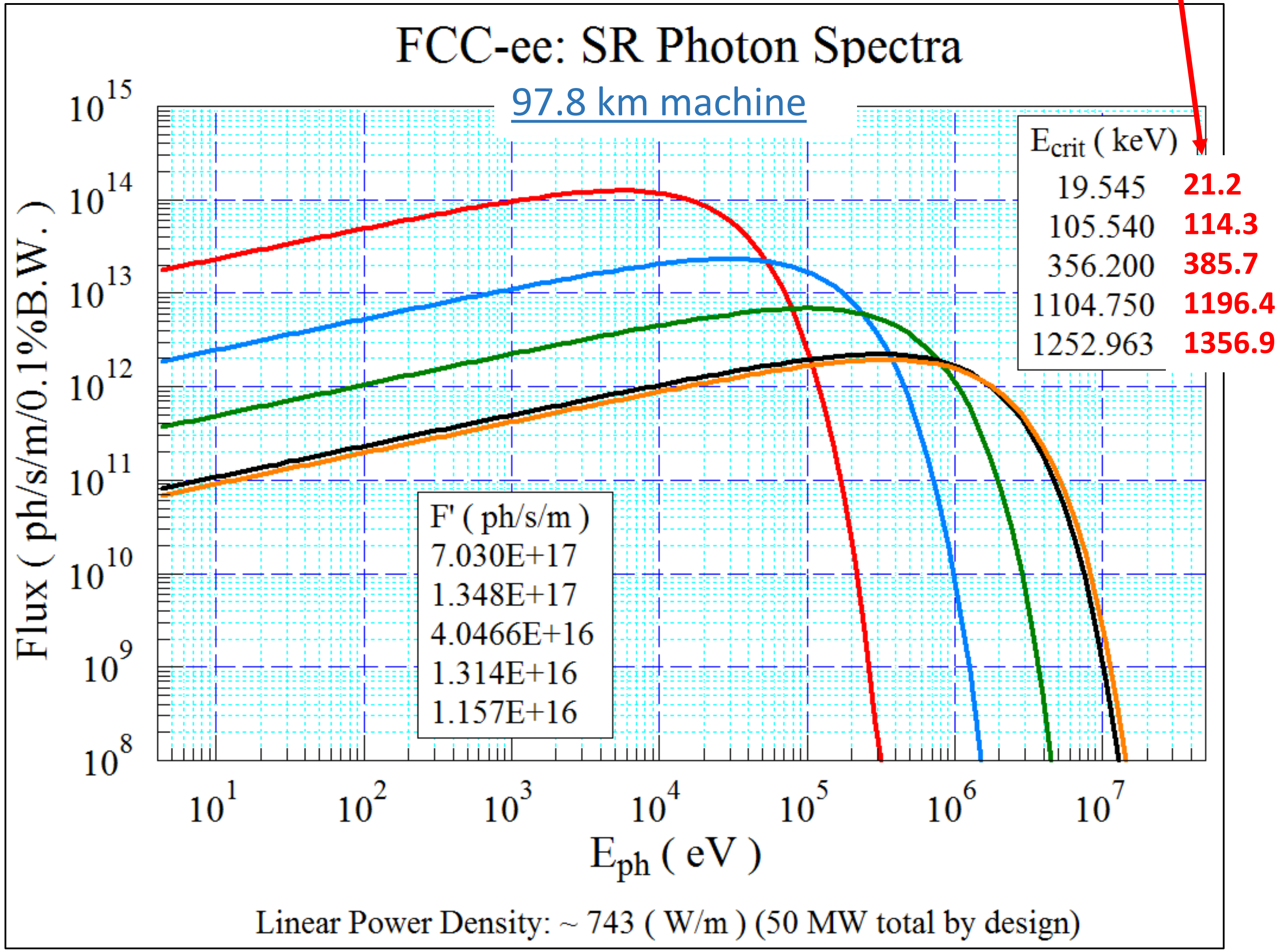
Running mode		Z	W	ZH	$t\bar{t}$
Injection option		LINAC/SPS			
Circumference	[km]	91.174			
Injection energy	[GeV]	20/16			
Extraction energy	[GeV]	45.6	80	120	182.5
Number bunches / ring		11200	1780	440	60
Maximum particle number / bunch Nmax	$[10^{10}]$	≥ 2.5 (4 nC)			
Particles / bunch in top-up	$[10^{10}]$	2.14	0.87	0.69	0.93
RF frequency	[MHZ]	800			
Arc optics FODO		60°/60°		90°/90°	
Momentum compaction		14.9×10^{-6}		7.34×10^{-6}	
Coupling		2×10^{-3}			
Injection horizontal emittance (norm.)	[µm]	10/190			
Injection vertical emittance (norm.)	[µm]	10/4			
Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26	0.81	0.63	1.45
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53	1.62	1.25	2.90
Injection Energy loss / turn	[MeV]	1.514/0.6203			
Extraction Energy loss / turn	[MeV]	40.93	387.7	1963	10500
Injection bunch length	[mm]	4/5.5			
Extraction bunch length	[mm]	4.38	3.55	3.34	1.94
Injection RMS energy spread	$[10^{-3}]$	1/4			
Extraction RMS energy spread	$[10^{-3}]$	0.38	0.67	1.01	1.53
Injection Maximum relative energy acceptance	[%]	3			
Extraction Maximum relative energy acceptance	[%]	0.36	0.76	0.49	2.39
Injection RF voltage	[MV]	104.9/82.97		52.85/41.36	
Extraction RF voltage	[MV]	49.48	458.6	2015	11533
Filling time	[s]	28/31.5	8.9/9.6	4.4/4.75	0.6/0.95
Ramp time	[s]	0.32/0.37	0.75/0.8	1.25/1.3	2.03/2.08
Flat top	[s]	1.9	0	0	0
Total cycling time	[s]	30.54/ 34.14	10.4/11.2	6.9/7.35	4.66/5.11

Synchrotron Radiation Spectra (SIMILAR ARGUMENTS)

- **Z-Pole: very high photon flux (→ large outgassing load);**
- **Z-pole: compliance with scheduled operation (~~integrated luminosity first 2 years~~), requires quick commissioning to I_{NOM}=~~1.390 A~~ 1270 mA;**
- **T-pole (182.5): extremely large and penetrating radiation, critical energy ~~1.25 MeV~~ 1.36 MeV;**
- **T-pole (and also W and H): need design which minimizes activation of tunnel and machine components (→ FLUKA);**
- **W, H-pole: intermediate between Z and T; still E_{crit} > Compton edge (~100 keV (Al), ~200 keV (Cu))**

90.7 km machine

Critical energy: $\varepsilon_c = 2218 \cdot E^3$ (GeV) / ρ(m)



E_{crit} (keV)	
19.545	21.2
105.540	114.3
356.200	385.7
1104.750	1196.4
1252.963	1356.9

F' (ph/s/m)
7.030E+17
1.348E+17
4.0466E+16
1.314E+16
1.157E+16

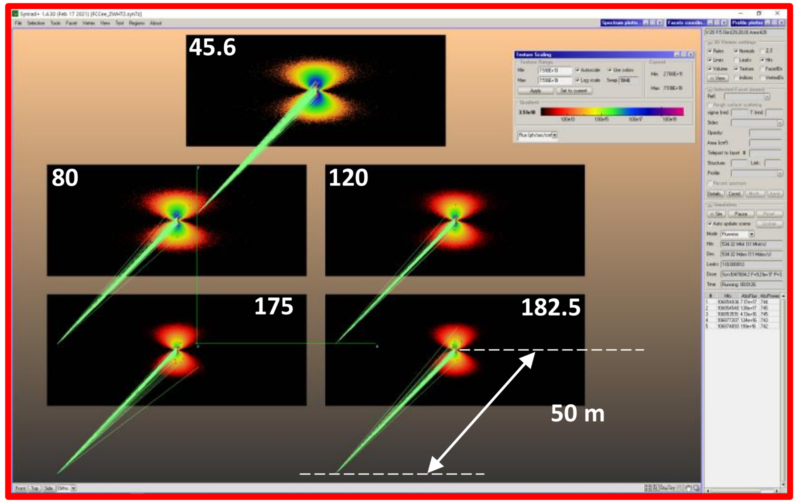
Linear Power Density: ~ 743 (W/m) (50 MW total by design)

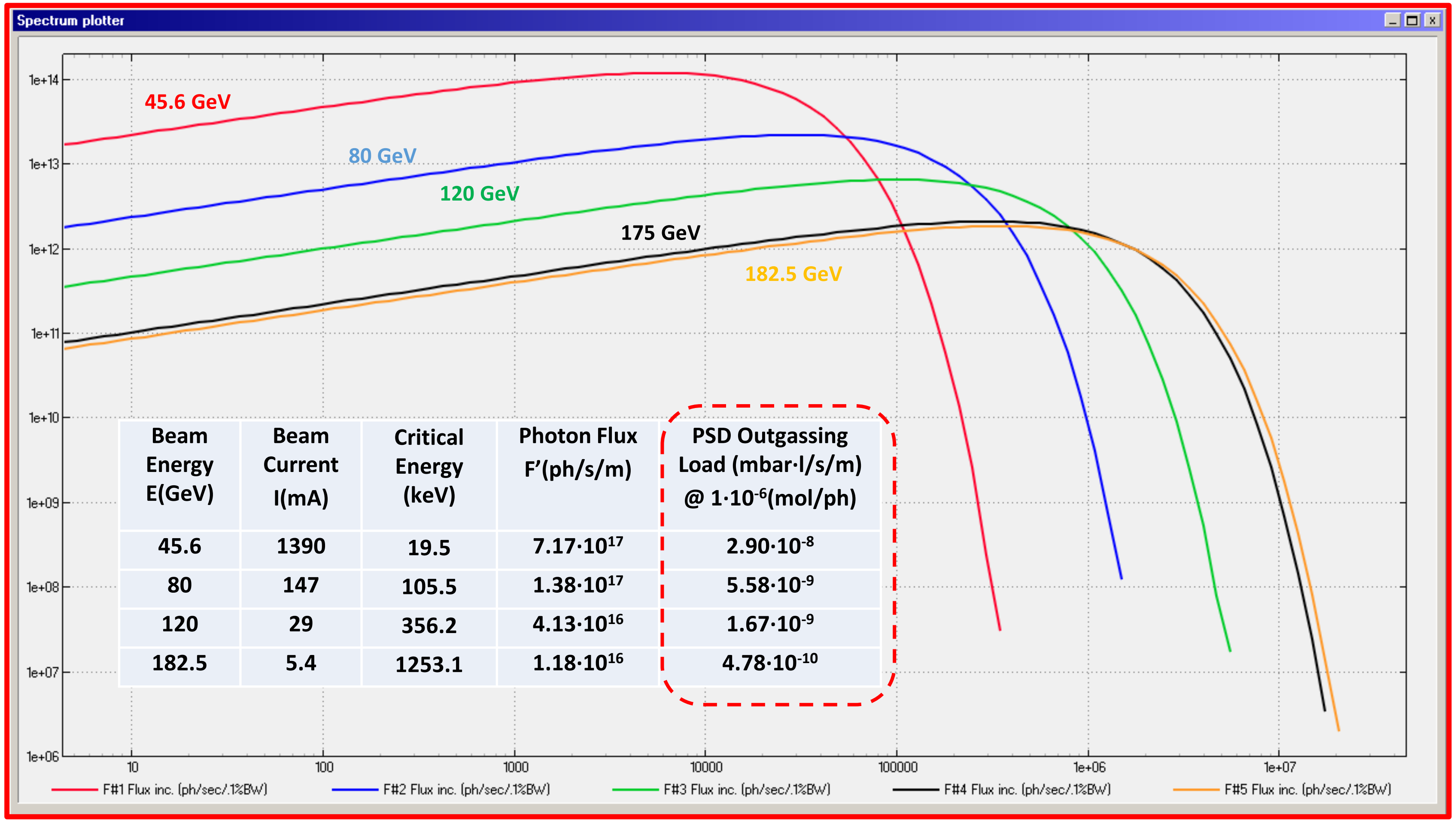
Synchrotron radiation spectrum, flux, power (SIMILAR ARGUMENTS)

Typical vertical opening angle SR: 1/γ; γ(ttbar)=357,143; 1/γ=2.8 μrad → @50 m = 0.14 mm

SR Spectra computed with SYNRAD+

- Radiation projected onto five 14x6 cm^2 screens;
- 1 cm-long dipole arc trajectories;
- Flux distribution shown here,
- Logarithmic scale for textures,
- 6 orders of magnitude displayed;





Beam Energy E(GeV)	Beam Current I(mA)	Critical Energy (keV)	Photon Flux F'(ph/s/m)	PSD Outgassing Load (mbar·l/s/m) @ $1\cdot10^{-6}$(mol/ph)
45.6	1390	19.5	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
80	147	105.5	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
120	29	356.2	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
182.5	5.4	1253.1	$1.18\cdot10^{16}$	$4.78\cdot10^{-10}$

Units: Vertical: photons/s/(0.1% bandwidth)/m; Range [10^6 - $2\cdot10^{14}$]

Horizontal eV; Range [4 - $5\cdot10^7$]

- **Gas Load for W-, H-, T-poles will have a significant contribution proportional to SR power, due to <u>Compton photons</u> (as per LEP operation, ref. “*The pressure and gas composition evolution during the operation of the LEP accelerator at 100 GeV*”, M. J. Jimenez et al., Vacuum 60 (2001) p183-189);**

<u>F (FCC-ee)>100 keV (%)</u>	
Z	**0.0639**
W	**9.220**
H	**28.852**
T(175)	**47.810**
T(182.5)	**49.717**

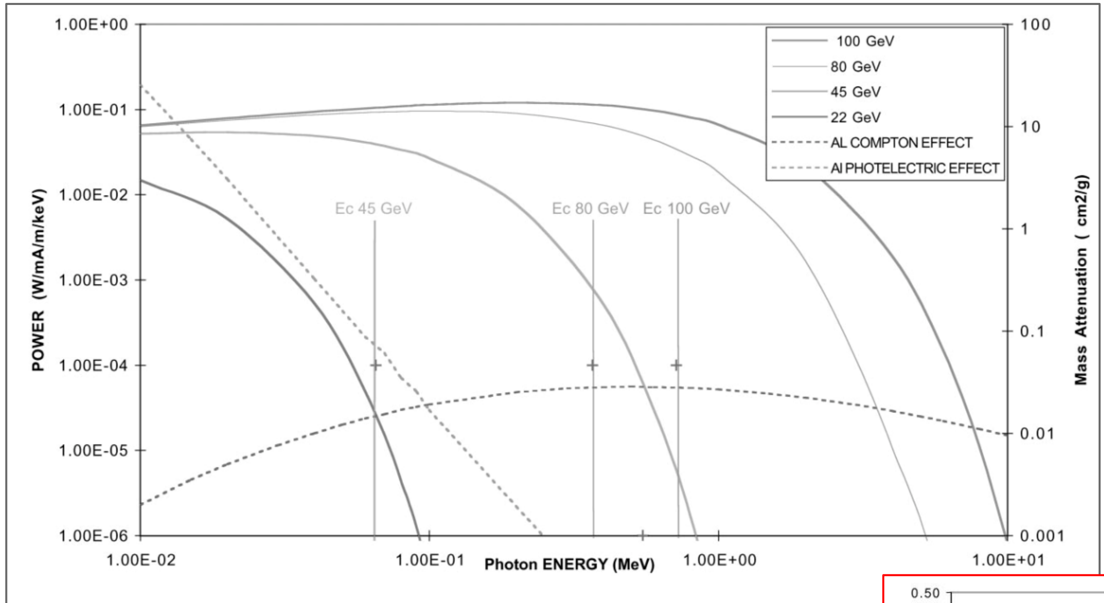


Fig. 2. The LEP synchrotron radiation spectrum.

A.S. Wilhelm and I. Jovanovic

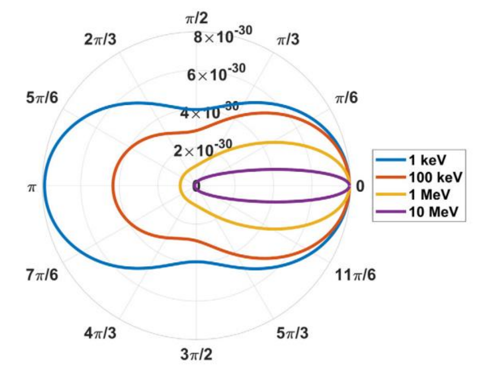


Fig. 1. The Klein–Nishina differential cross-section shapes for photons of various energies scattered off a hydrogen atom. The photon is incident at $\theta = 0$ and cross-section is measured in m^2. For heavier atoms, the magnitude of the KNDCS changes, but the shape is invariant for a given photon energy. Higher energy photons are much less likely to undergo a high-angle scattering than lower energy photons.

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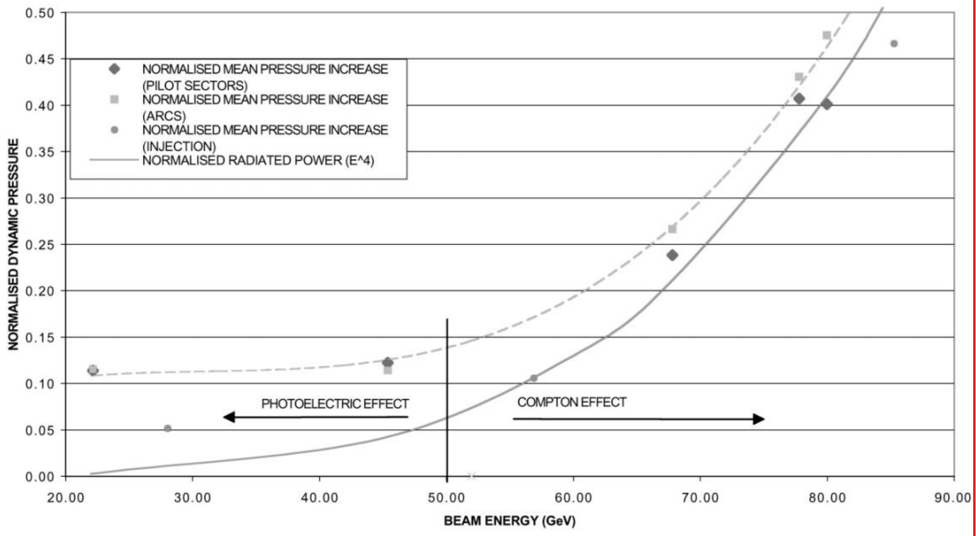


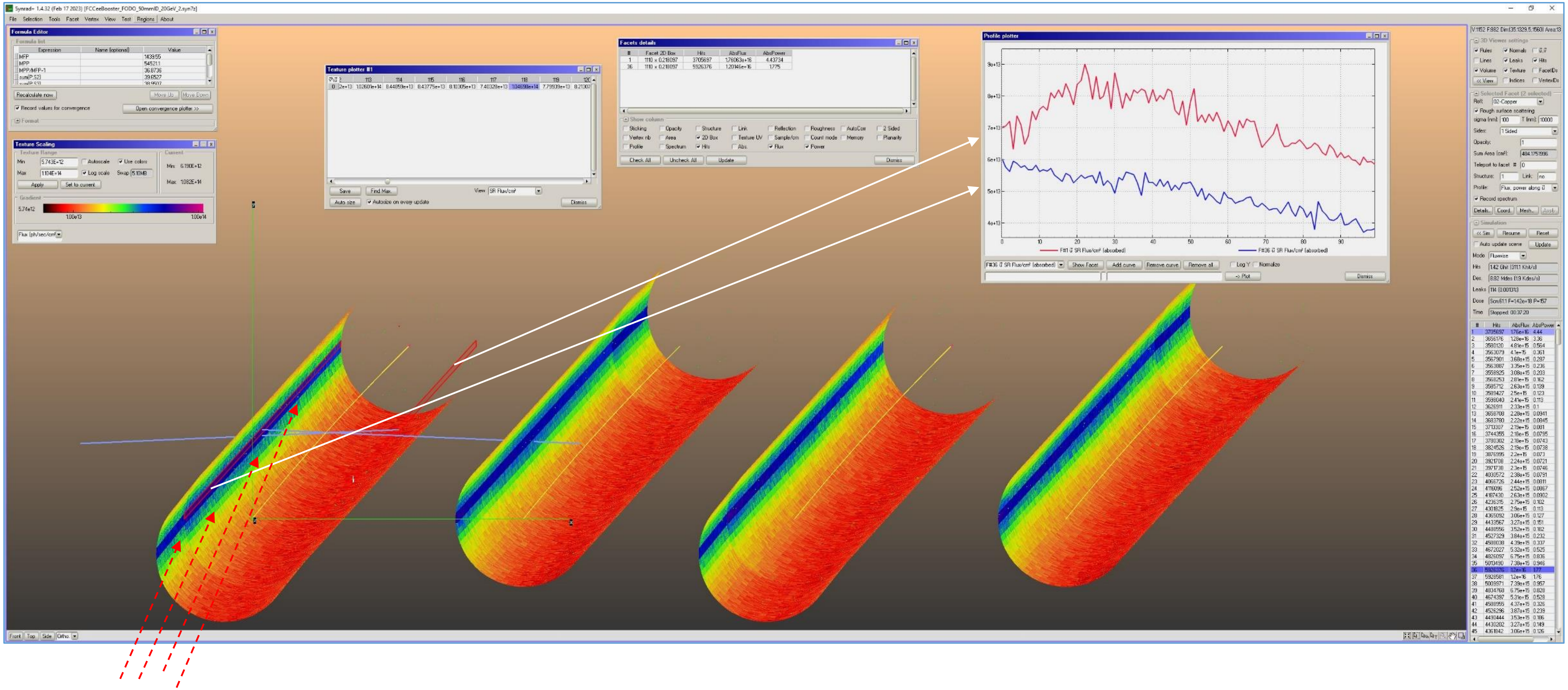
Fig. 5. Normalised pressure increase (low beam energy, measured in LEP arcs, 1999).

- **If copper alloy is chosen as the material for the vacuum chamber, then a smaller fraction goes into Compton, and shielding improves;**
- **In addition, copper has a lower photon-stimulated desorption yield;**

(SIMILAR ARGUMENTS: SHIELDING REQUIREMENTS??)

FCC-ee Booster: SR photon FLUX absorption mapping along the wall (20 GeV case)

- One unitary cell of the BOOSTER, 4 dipoles
- 53.4 m long model, split into 4 sections connected by “teleporting” (SYNRAD+); 4x50 l/s pumps (avg. spacing ~13.5 m)



Expression	Name (optional)	Value
MFP		1439.55
MPP		54521.1
MPP/MFP-1		36.8736
sum(P,S2)		39.6527
sum(P,S3)		38.9607

☑ Record values for convergence

Min 5.743E+12 ☐ Autoscale ☑ Use colors
Max 1.104E+14 ☑ Log scale Swap 5.10MB
Current: Min: 6.190E+12 Max: 1.082E+14
Flux (ph/sec/cm²)

▽\U	…2	113	114	115	116	117	118	119	120…
0	…2e+13	1.02601e+14	8.44859e+13	8.43775e+13	8.10305e+13	7.40328e+13	1.04698e+14	7.79939e+13	8.21307…

☑ Autosize on every update
View: SR Flux/cm²

#	Facet 2D Box	Hits	AbsFlux	AbsPower
1	1110 x 0.218097	3705697	1.76063e+16	4.43734
36	1110 x 0.218097	5926376	1.20146e+16	17.75

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

F#36 ū SR Flux/cm² (absorbed) ☐ Log Y ☐ Normalize

V:1152 F:882 Dim:(35.1329.5.1560) Area:13

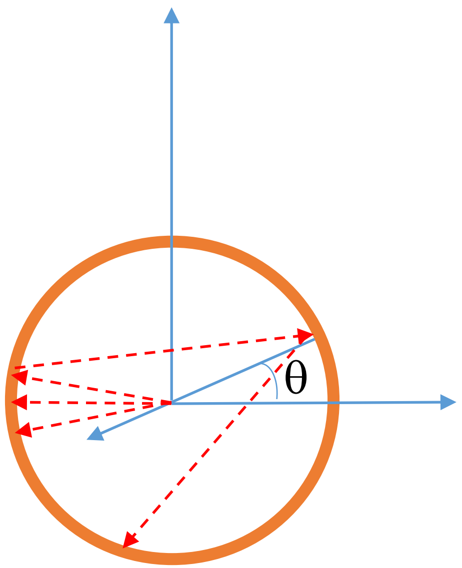
☑ Rules ☑ Normals ☐ ū,v̄
☐ Lines ☑ Leaks ☑ Hits
☑ Volume ☑ Texture ☐ FacetIDs
☐ Indices ☐ VertexIDs

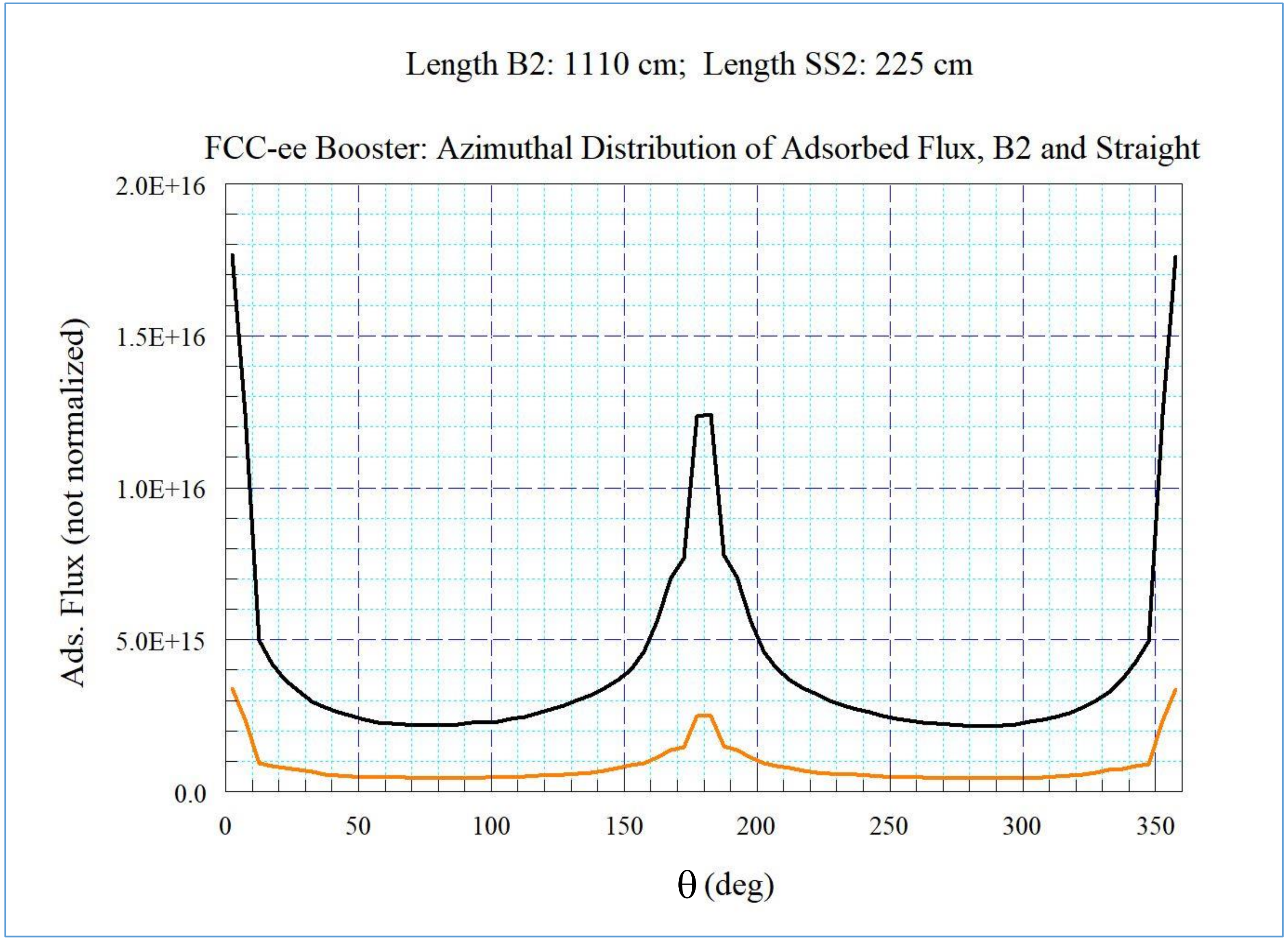
Refl: 02-Copper
☑ Rough surface scattering
sigma (nm): 100 T (nm): 10000
Sides: 1 Sided
Opacity: 1
Sum Area (cm²): 484.1751996
Teleport to facet #: 0
Structure: 1 Link: no
Profile: Flux, power along ū
☑ Record spectrum

☐ Auto update scene
Mode: Fluxwise
Hits: 1.42 Ghit (311.1 Khit/s)
Des.: 8.82 Mdes (1.9 Kdes/s)
Leaks: 114 (0.0013%)
Dose: Scn:61.1 F=1.42e+18 P=157
Time: Stopped: 00:37:20

#	Hits	AbsFlux	AbsPower
1	3705697	1.76e+16	4.44
2	3656176	1.28e+16	3.36
3	3580120	4.81e+15	0.564
4	3563079	4.1e+15	0.361
5	3567901	3.68e+15	0.287
6	3563887	3.35e+15	0.236
7	3558925	3.08e+15	0.203
8	3568253	2.81e+15	0.162
9	3585712	2.63e+15	0.139
10	3589427	2.5e+15	0.123
11	3598040	2.41e+15	0.113
12	3626911	2.33e+15	0.1
13	3658708	2.28e+15	0.0941
14	3683780	2.22e+15	0.0845
15	3713307	2.19e+15	0.081
16	3744355	2.18e+15	0.0795
17	3780302	2.18e+15	0.0743
18	3824526	2.19e+15	0.0738
19	3876995	2.2e+15	0.073
20	3921708	2.24e+15	0.0721
21	3971738	2.3e+15	0.0746
22	4030572	2.38e+15	0.0791
23	4066726	2.44e+15	0.0811
24	4116096	2.52e+15	0.0867
25	4187430	2.63e+15	0.0902
26	4236315	2.75e+15	0.102
27	4301825	2.9e+15	0.113
28	4365092	3.06e+15	0.127
29	4433567	3.27e+15	0.151
30	4488556	3.52e+15	0.182
31	4527329	3.84e+15	0.232
32	4588038	4.39e+15	0.337
33	4672027	5.32e+15	0.525
34	4826097	6.75e+15	0.836
35	5013490	7.38e+15	0.946
36	5926376	1.2e+16	1.77
37	5928581	1.2e+16	1.76
38	5009971	7.39e+15	0.957
39	4834768	6.75e+15	0.828
40	4674397	5.31e+15	0.528
41	4588955	4.37e+15	0.326
42	4526296	3.87e+15	0.239
43	4490444	3.53e+15	0.186
44	4430202	3.27e+15	0.149
45	4361842	3.06e+15	0.126

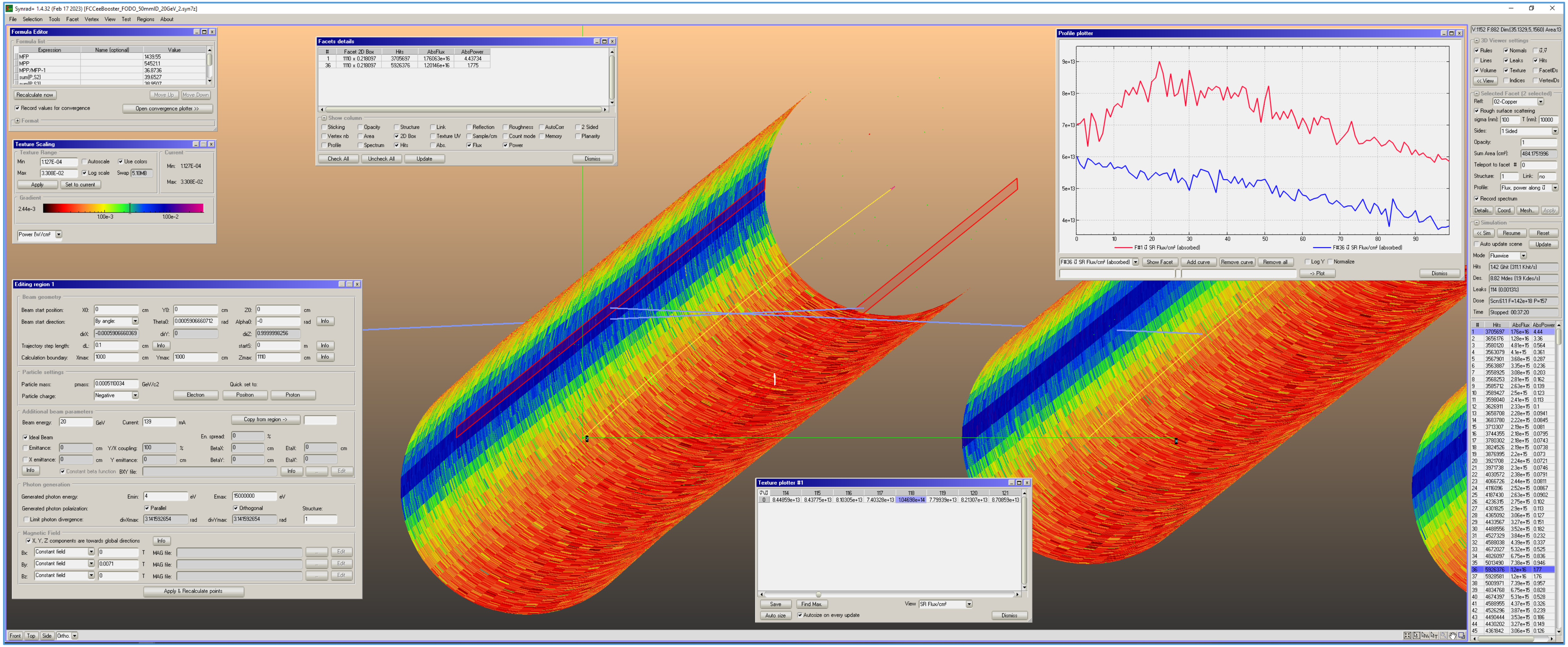
FCC-ee Booster: azimuthal distribution of SR photon FLUX absorbed along the wall (20 GeV case)





FCC-ee Booster: azimuthal distribution of SR photon FLUX absorbed along the wall (20 GeV case)

Beam current: 139 mA



Formula Editor

Expression	Name (optional)	Value
MFP		1439.55
MPP		545211
MPP/MFP-1		36.8736
sum(P,S2)		39.6527
sum(P,S3)		38.9507

☑ Record values for convergence

Texture Scaling

Texture Range: Min 1.127E-04; Max 3.308E-02; ☐ Autoscale; ☑ Use colors; ☑ Log scale; Swap 5.10MB

Current: Min: 1.127E-04; Max: 3.308E-02

Gradient: 2.44e-3

Facets details

#	Facet 2D Box	Hits	AbsFlux	AbsPower
1	1110 x 0.218097	3705697	1.76063e+16	4.43734
36	1110 x 0.218097	5926376	1.20146e+16	1.775

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

Editing region 1

Beam geometry

Beam start position: X0: 0 cm Y0: 0 cm Z0: 0 cm

Beam start direction: By angle: Theta0: 0.0005906660712 rad Alpha0: -0 rad

dirX: -0.0005906660369 dirY: 0 dirZ: 0.9999998256

Trajectory step length: dL: 0.1 cm startS: 0 m

Calculation boundary: Xmax: 1000 cm Ymax: 1000 cm Zmax: 1110 cm

Particle settings

Particle mass: pmass: 0.0005110034 GeV/c2

Particle charge: Negative

Quick set to: Electron Positron Proton

Additional beam parameters

Beam energy: 20 GeV Current: 139 mA

☑ Ideal Beam En. spread: 0 %

☐ Emittance: 0 cm Y/X coupling: 100 % BetaX: 0 cm EtaX: 0 cm

☐ X emittance: 0 cm Y emittance: 0 cm BetaY: 0 cm EtaX': 0

☑ Constant beta function BXY file:

Photon generation

Generated photon energy: Emin: 4 eV Emax: 15000000 eV

Generated photon polarization: ☑ Parallel ☑ Orthogonal Structure: 1

☐ Limit photon divergence: divXmax: 3.141592654 rad divYmax: 3.141592654 rad

Magnetic Field

☑ X, Y, Z components are towards global directions

Bx: Constant field 0 T MAG file:

By: Constant field 0.0071 T MAG file:

Bz: Constant field 0 T MAG file:

Profile plotter

Texture plotter #1

v⃗\u⃗	114	115	116	117	118	119	120	121
0	8.44859e+13	8.43775e+13	8.10305e+13	7.40328e+13	1.04698e+14	7.79939e+13	8.21307e+13	8.70859e+13

View: SR Flux/cm²

☑ Autosize on every update

V:1152 F:882 Dim:(35.1329,5,1560) Area:13

3D Viewer settings: ☑ Rules ☑ Normals ☐ ū,v⃗ ☐ Lines ☑ Leaks ☑ Hits ☑ Volume ☑ Texture ☐ FacetIDs ☐ Indices ☐ VertexIDs

Selected Facet (2 selected)

Refl: 02-Copper

☑ Rough surface scattering

sigma (nm): 100 T (nm): 10000

Sides: 1 Sided

Opacity: 1

Sum Area (cm²): 484.1751996

Teleport to facet # 0

Structure: 1 Link: no

Profile: Flux, power along ū

☑ Record spectrum

☐ Auto update scene

Mode: Fluxwise

Hits: 1.42 Ghit (311.1 Khit/s)

Des.: 8.82 Mdes (1.9 Kdes/s)

Leaks: 114 (0.0013%)

Dose: Scn:61.1 F=1.42e+18 P=157

Time: Stopped: 00:37:20

#	Hits	AbsFlux	AbsPower
1	3705697	1.76e+16	4.44
2	3656176	1.28e+16	3.36
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4	3563079	4.1e+15	0.361
5	3567901	3.68e+15	0.287
6	3563887	3.35e+15	0.236
7	3558925	3.08e+15	0.203
8	3568253	2.81e+15	0.162
9	3585712	2.63e+15	0.139
10	3589427	2.5e+15	0.123
11	3598040	2.41e+15	0.113
12	3626911	2.33e+15	0.1
13	3658708	2.28e+15	0.0941
14	3683780	2.22e+15	0.0845
15	3713307	2.19e+15	0.081
16	3744355	2.18e+15	0.0795
17	3780302	2.18e+15	0.0743
18	3824526	2.19e+15	0.0738
19	3876995	2.2e+15	0.073
20	3921708	2.24e+15	0.0721
21	3971738	2.3e+15	0.0746
22	4030572	2.38e+15	0.0791
23	4066726	2.44e+15	0.0811
24	4116096	2.52e+15	0.0867
25	4187430	2.63e+15	0.0902
26	4236315	2.75e+15	0.102
27	4301825	2.9e+15	0.113
28	4365092	3.06e+15	0.127
29	4433567	3.27e+15	0.151
30	4488556	3.52e+15	0.182
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36	5926376	1.2e+16	1.77
37	5928581	1.2e+16	1.76
38	5009971	7.39e+15	0.957
39	4834768	6.75e+15	0.828
40	4674397	5.31e+15	0.528
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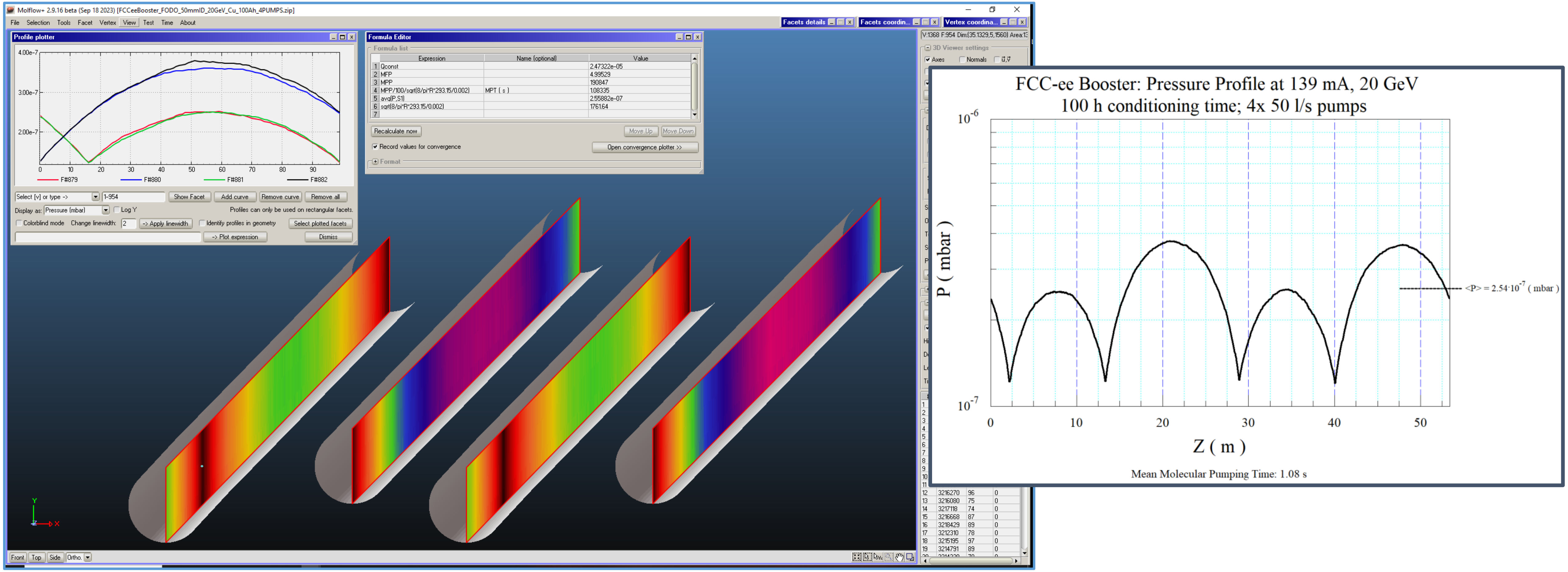
42	4526296	3.87e+15	0.239
43	4490444	3.53e+15	0.186
44	4430202	3.27e+15	0.149
45	4361842	3.06e+15	0.126

Pressure profiles (for 50 mm ID chamber)

- We have used Molflow+ to calculate the PSD pressure rise at different beam doses, using the photon irradiation maps calculated by SYNRAD+
- Pressure with 139 mA at 20 GeV after 100 h conditioning (13.9 A·h beam dose): average pressure is $2.54 \cdot 10^{-7}$ mbar



	Expression	Name (optional)	Value
1	Qconst		2.47322e-05
2	MFP		4.99529
3	MPP		190847
4	MPP/100/sqrt(8/pi*R*293.15/0.002)	MPT (s)	1.08335
5	avg(P,S1)		2.55882e-07
6	sqrt(8/pi*R*293.15/0.002)		1761.64
7			

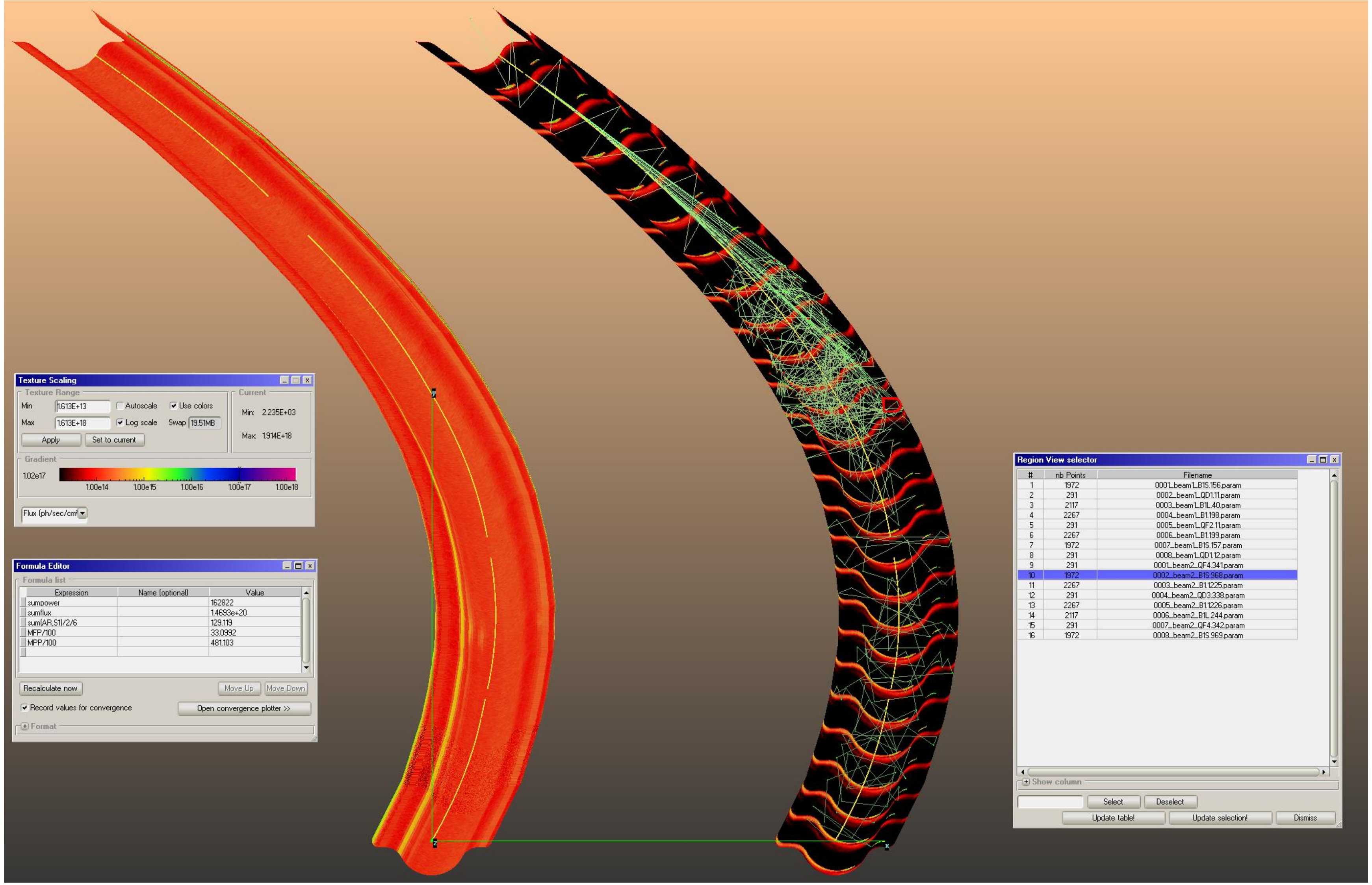
V:1368 F:954 Dim:(35.1329,5,1560) Area:13

12	3216270	96	0
13	3216080	75	0
14	3217118	74	0
15	3216668	87	0
16	3218429	89	0
17	3212310	78	0
18	3215195	97	0
19	3214791	89	0

4x50 (l/s) lumped pumps/beam, and no NEG-coating

Total Outgassing: $2.473 \cdot 10^{-5}$ mbar·l/s → S_{eff} = ~97 l/s (out of 200 l/s installed)

FCC-ee Z: SR photon irradiation maps



Texture Scaling

Texture Range

Min: 1.613E+13
Max: 1.613E+18
☐ Autoscale
☑ Use colors
☑ Log scale
Swap: 19.51MB

Current

Min: 2.235E+03
Max: 1.914E+18

Gradient

1.02e17

Flux (ph/sec/cm²)

Formula Editor

Formula list

Expression	Name (optional)	Value
sumpower		162822
sumflux		1.4693e+20
sum(AR,S1)/2/6		129.119
MFP/100		33.0992
MPP/100		481.103

☑ Record values for convergence

Region View selector

#	nb Points	Filename
1	1972	0001_beam1_B1S.156.param
2	291	0002_beam1_QD1.11.param
3	2117	0003_beam1_B1L.40.param
4	2267	0004_beam1_B1.198.param
5	291	0005_beam1_QF2.11.param
6	2267	0006_beam1_B1.199.param
7	1972	0007_beam1_B1S.157.param
8	291	0008_beam1_QD1.12.param
9	291	0001_beam2_QF4.341.param
10	1972	0002_beam2_B1S.968.param
11	2267	0003_beam2_B1.1225.param
12	291	0004_beam2_QD3.338.param
13	2267	0005_beam2_B1.1226.param
14	2117	0006_beam2_B1L.244.param
15	291	0007_beam2_QF4.342.param
16	1972	0008_beam2_B1S.969.param

Conclusions and future work

- The FCC-ee booster vacuum system has been greatly "simplified" by the Cost Review exercise
- It is now a "old school" with no bake-out (BO), with no NEG-coating, no RF contact fingers, no SR absorbers: as such its vacuum conditioning will be slow
- The pressures will be rather high and water vapour will be the initial dominant gas specie, unless long pump-down times with no beam are foreseen
- E-cloud and ion-trapping will be possible → FEEDBACK/MITIGATION REQUIREMENTS
- 4 pumps per each ~54 m-long arc section means ~6700 pumps, i.e. lots of cabling and need to carefully protect them from the high fluences in the tunnel → SHIELDING REQUIREMENTS
- The SR photon fluxes absorbed along the walls of the 50 mm ID pipes are rather uniform with two narrow strips in the plane of the orbit (o and 180 deg) → PHOTOELECTRON AND SEY CALCULATIONS NEEDED
- More detailed models of the vacuum chamber geometry, including shape/size of the bellows (with no BO needed) they will be rather short… see other "booster"talks this workshop)

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