Synchrotron Radiation in FCC-ee: Simulation, Absorption, and Related Issues

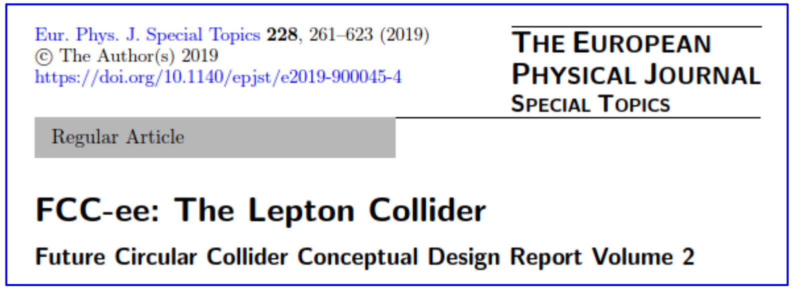
R. Kersevan, reporting for TE-VSC

TE FCC-ee workshop, CERN, 16 May 2024

OUTLINE

- FCC study program (2013-today)
- FCC-ee: relevant machine and vacuum parameters
- Vacuum chamber cross section
- Synchrotron radiation spectra
- SR absorbers: yes or no?
- Pumping solutions
- Pressure profiles
- The MDI region
- Synchrotron radiation ray-tracing
- Pressure profiles
- Conclusions and future work
- Acknowledgments

FCC study program; Relevant machine and vacuum parameters (pre-2019)



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Regular Article

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

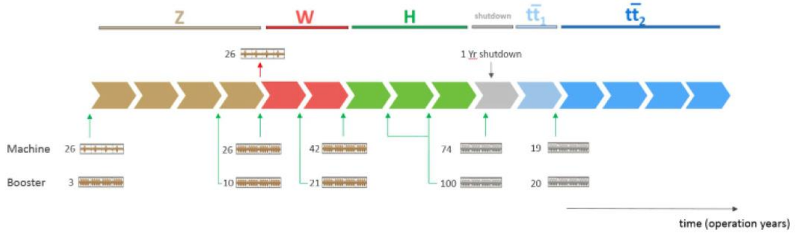

Fig. 4. FCC-ee operation time line. The bottom part indicates the number of cryomodules to be installed in the collider and booster, respectively, during the various winter shutdown periods; also see [22].

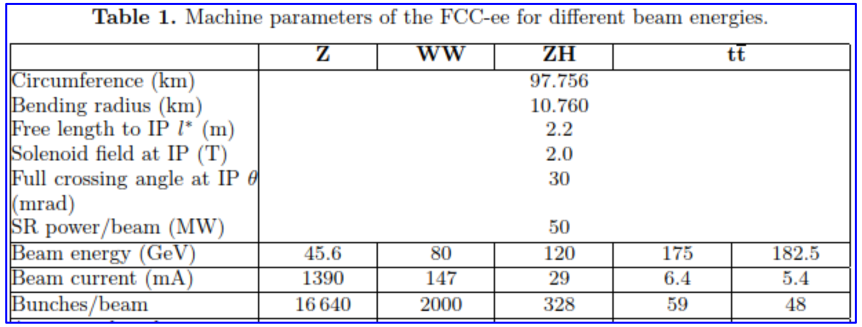

Table 1. Machine parameters of the FCC-ee for different beam energies.

	Z	**WW**	**ZH**	$\mathbf{t\bar{t}}$	
Circumference (km)	97.756				
Bending radius (km)	10.760				
Free length to IP l^* (m)	2.2				
Solenoid field at IP (T)	2.0				
Full crossing angle at IP θ (mrad)	30				
SR power/beam (MW)	50				
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches/beam	16 640	2000	328	59	48

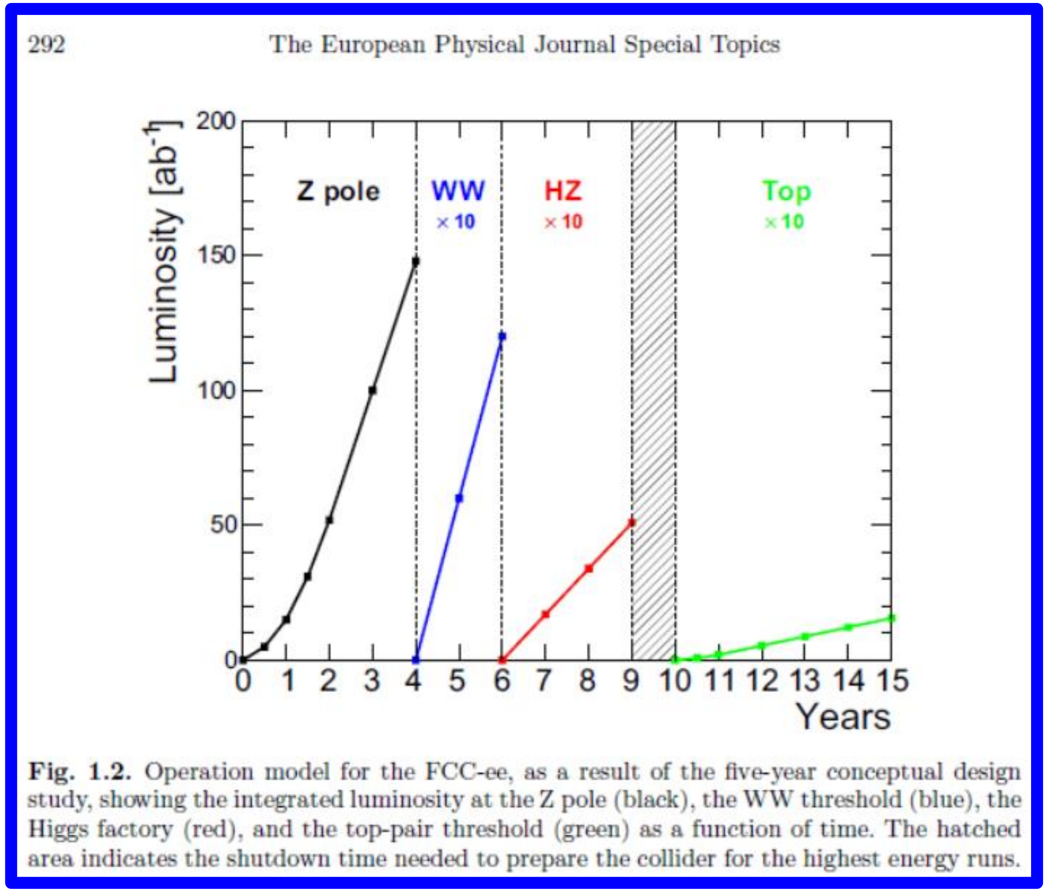

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Fig. 1.2. Operation model for the FCC-ee, as a result of the five-year conceptual design study, showing the integrated luminosity at the Z pole (black), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. The hatched area indicates the shutdown time needed to prepare the collider for the highest energy runs.

Big variation of nominal current vs beam energy, since all machine versions are limited to 50 MW of synchrotron radiation per beam

$$P\,(W) = 88.46 \cdot E^4(GeV) \cdot I(mA) / \rho(m)$$

$$F\,(ph/s) = 8.08 \cdot 10^{17} \cdot E(GeV) \cdot I(mA)$$

- **We aim at an average pressure giving a beam-gas scattering lifetime large enough not to be detrimental to the integrated luminosity, say in the low 10^{-9} mbar range, or better, with a gas composition of 80~90% hydrogen, and no molecular masses above 44 (CO_2).**
- **We also aim at reducing/eliminating the e-cloud and ion-trapping effects and related beam instabilities and losses**
- **Typically, we assume a residual gas composition of 80~90% H_2, 10~20% CO+CO_2, traces of CH_4**

New parameter table (90.7 km rings)

Consequence of 50 MW/beam MAX

$$P\,(\mathrm{W}) = 88.46 \cdot E^4(\mathrm{GeV}) \cdot I(\mathrm{mA}) \,/\, \rho(\mathrm{m})$$

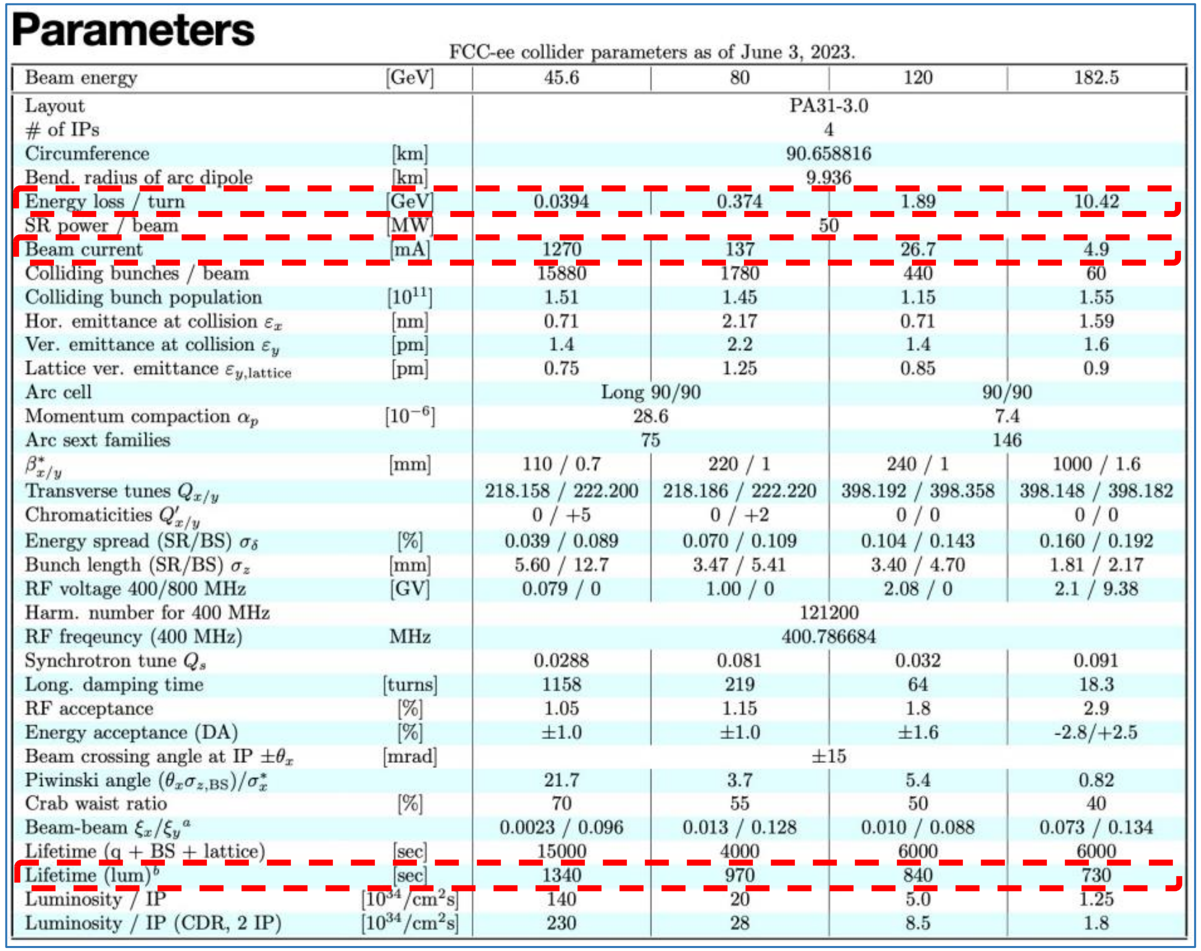
$$F\,(\mathrm{ph/s}) = 8.08 \cdot 10^{17} \cdot E(\mathrm{GeV}) \cdot I(\mathrm{mA})$$

The beam currents at the various energies scale as the reciprocal of the 4th power of the beam energy:

The beam current at ttbar is only $(45.6/182.5)^4$ = $1/4^4$=1/256 that of the Z-pole

- **High current (B-factory level) for Z energy**
- **The beam currents at the various energies scale as the reciprocal of the 4th power of the beam energy**
- **The beam current at ttbar is only $(45.6/182.5)^4$ = $1/4^4$=1/256 that of the Z-pole**

- **Starting the machine not at the Z energy prevents having a fast vacuum conditioning**

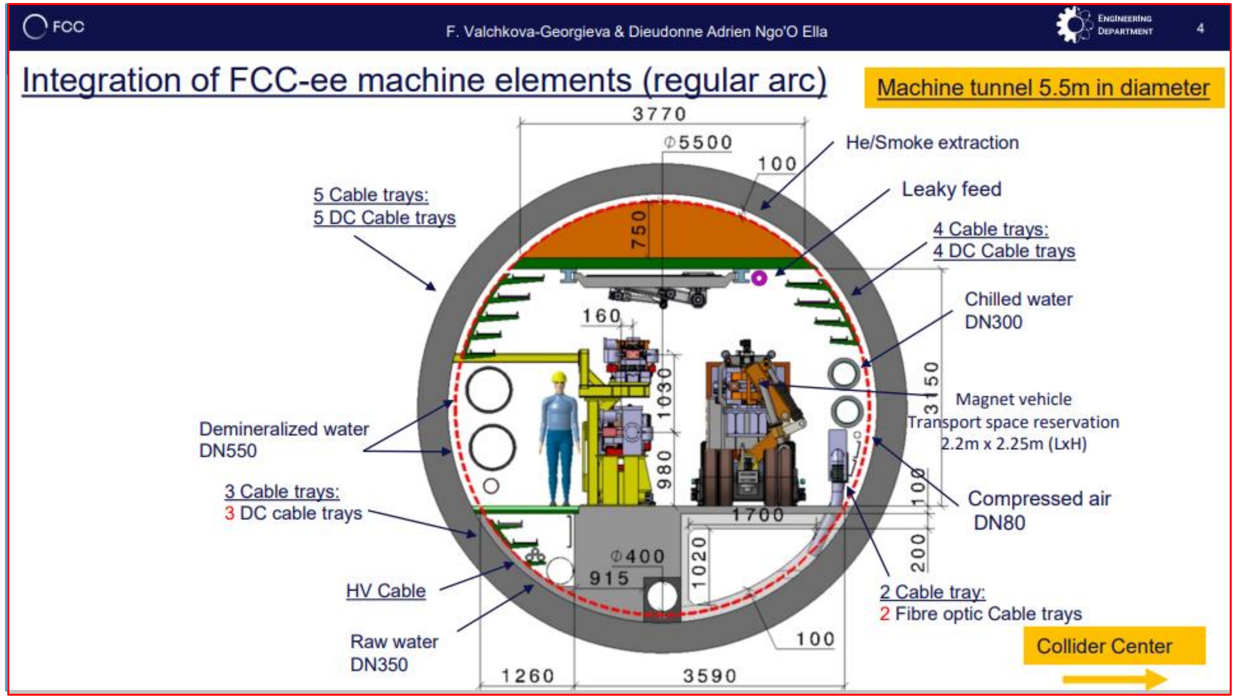


Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma_x^*$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)[b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

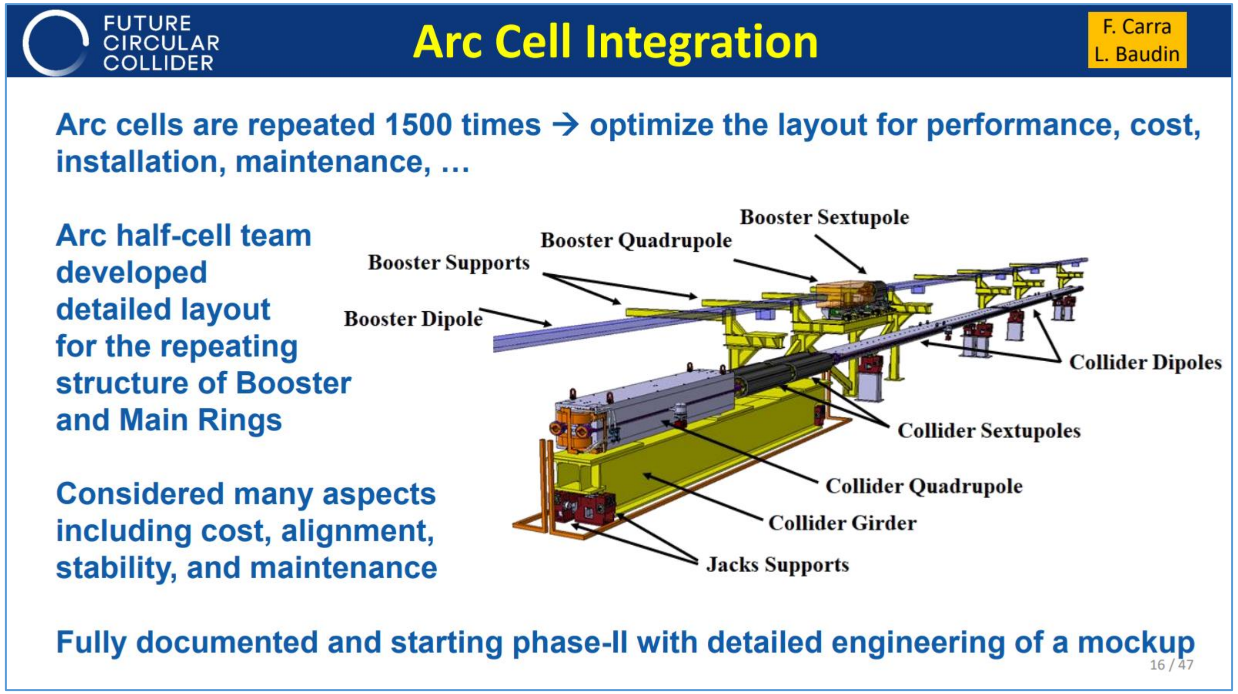
- The tunnel along the arcs has a typical cross-section as shown below (left)



FCC F. Valchkova-Georgieva & Dieudonne Adrien Ngo'O Ella 4

Integration of FCC-ee machine elements (regular arc)

Machine tunnel 5.5m in diameter



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 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)
- Standardization and easy-to-transfer to industry design and technology must be implemented

Synchrotron Radiation Spectra

- **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}=1270 mA;**
- **T-pole (182.5): extremely large and penetrating radiation, critical energy 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))**

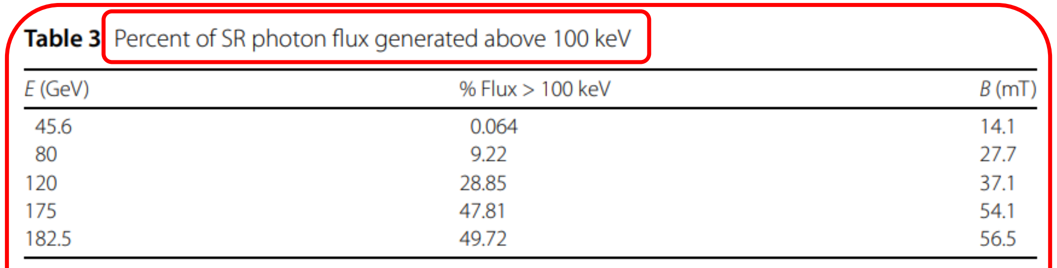


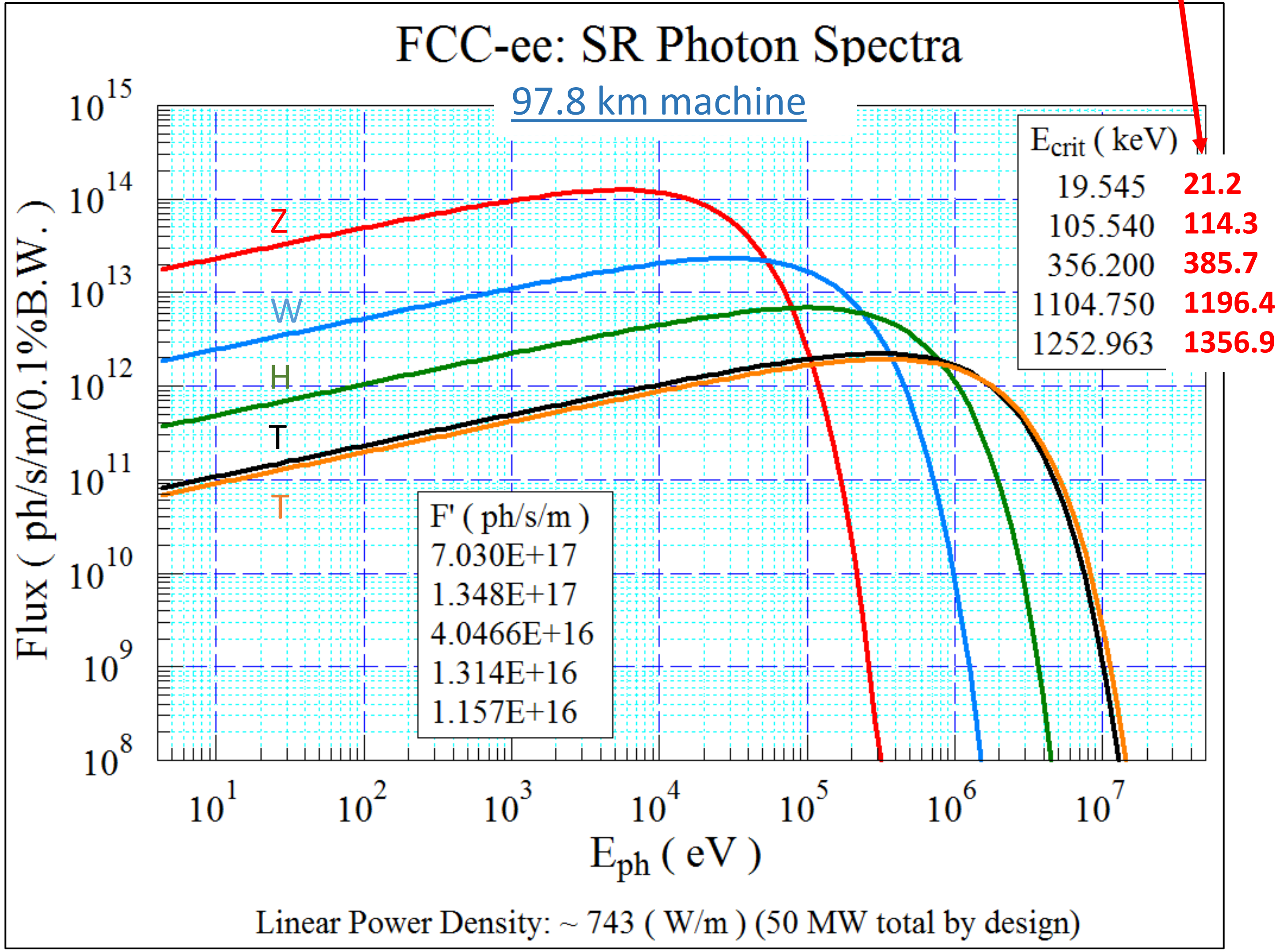
Table 3 Percent of SR photon flux generated above 100 keV

E (GeV)	% Flux > 100 keV	B (mT)
45.6	0.064	14.1
80	9.22	27.7
120	28.85	37.1
175	47.81	54.1
182.5	49.72	56.5

https://doi.org/10.1140/epjti/s40485-022-00087-w

Critical energy: ε_c = 2218·E^3 (GeV) / ρ(m)

90.7 km machine



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

Synchrotron Radiation-Induced Desorption

- When photons with energy above the work function of the vacuum chamber (VC) material hit the surface they can generate PSD molecular outgassing, mediated by PE emission
- The PSD yield η (molecules/photon) is characterized by a conditioning curve which, in a log-log scale vs accumulated photon dose D (photons/m) resembles a power law $\eta=\eta_o \cdot D^{-\alpha}$, with $0.3<\alpha<1$

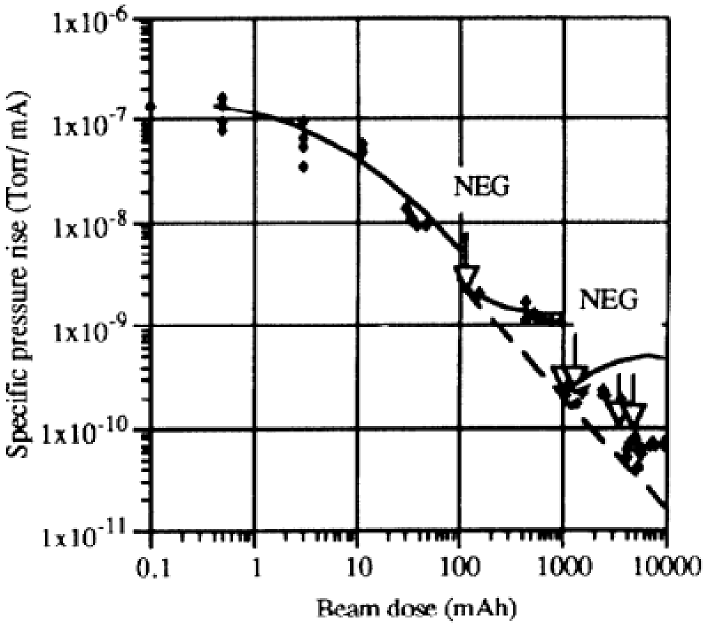


Figure 1. Specific pressure rise predicted for LEP on the basis of synchrotron radiation desorption data from the DCI test beam line compared with measurements in LEP. NEG reconditioning are marked by arrows. The dashed line extrapolates the specific pressure rise for maximum NEG pumping speed.

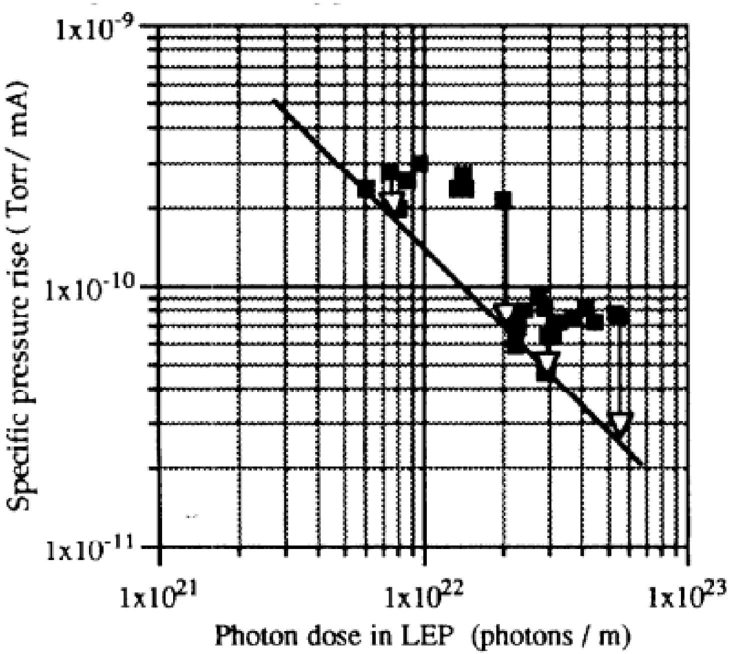


Figure 2, Specific pressure rise in LEP at 46 GeV beam energy during 1990 and 1991 as a function of the integrated photon dose. Arrows indicate NEG reconditioning.

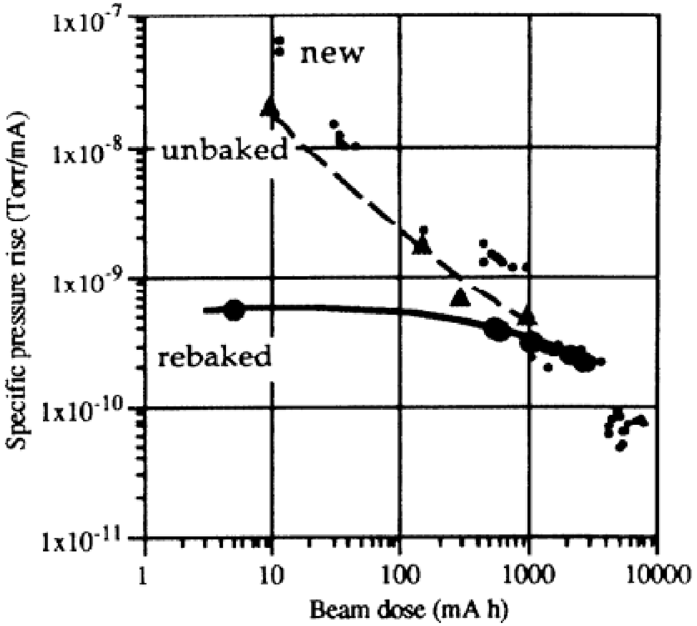


Figure 5. Comparison between a new sector and sectors re-exposed to atmosphere, with and without rebaking.

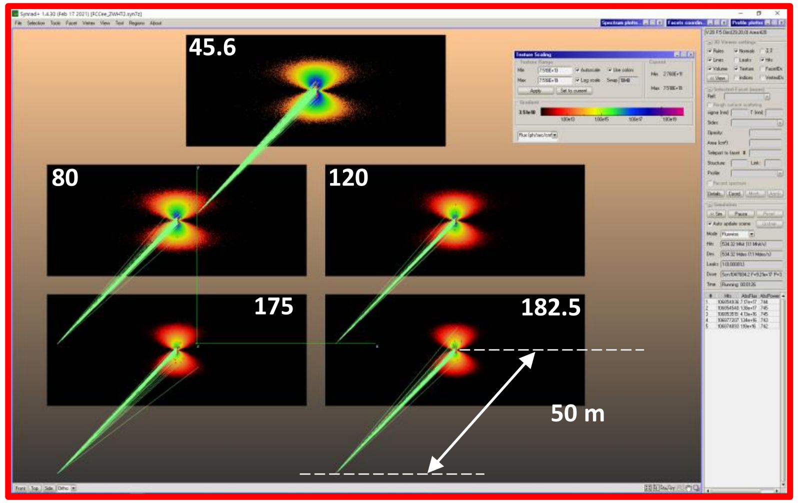
"Experience with the Operation of the LEP Vacuum System and its Performance for LEP200", O. Gröbner et al., EPAC'92

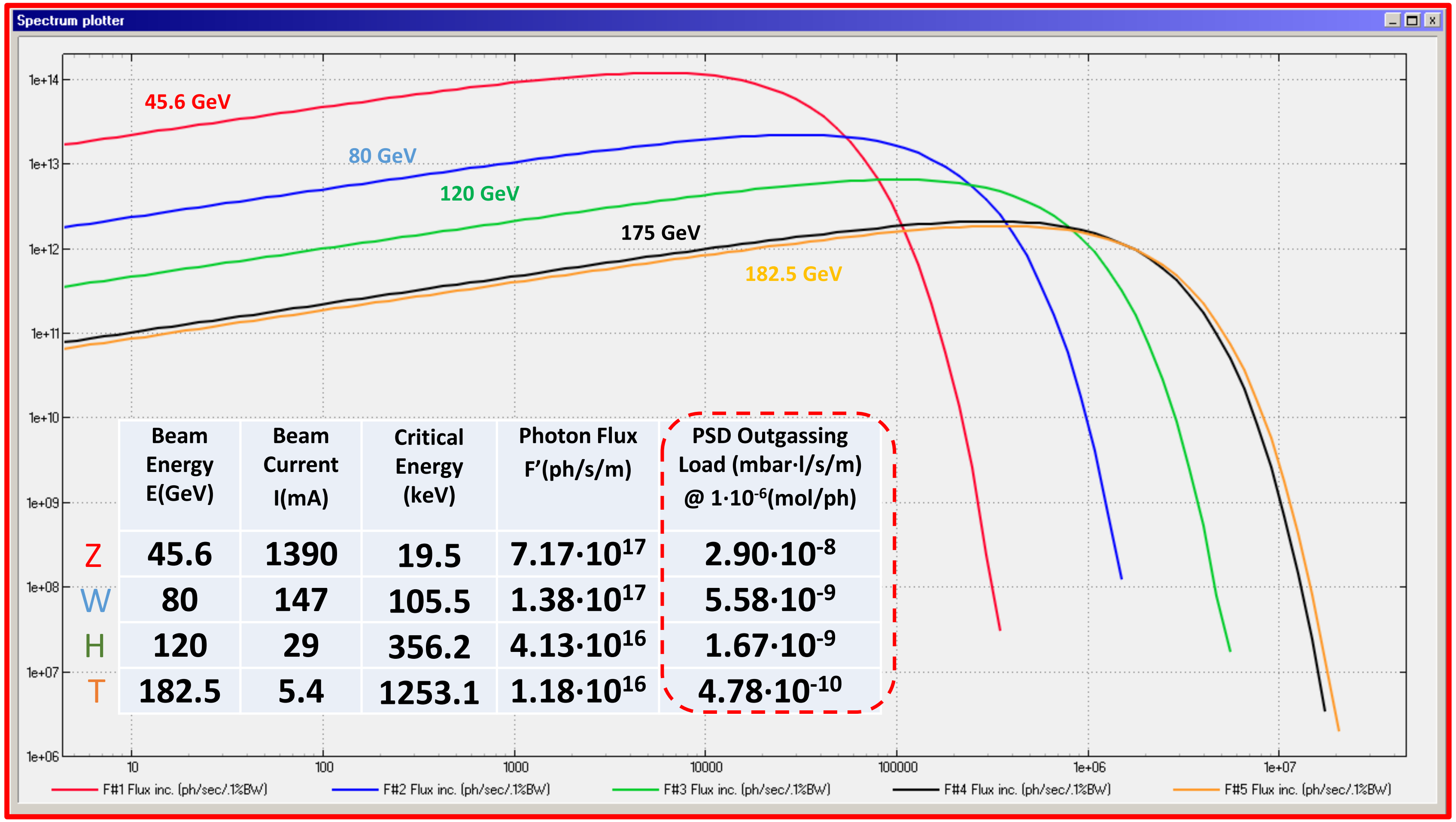
Synchrotron radiation spectrum, flux, power

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;





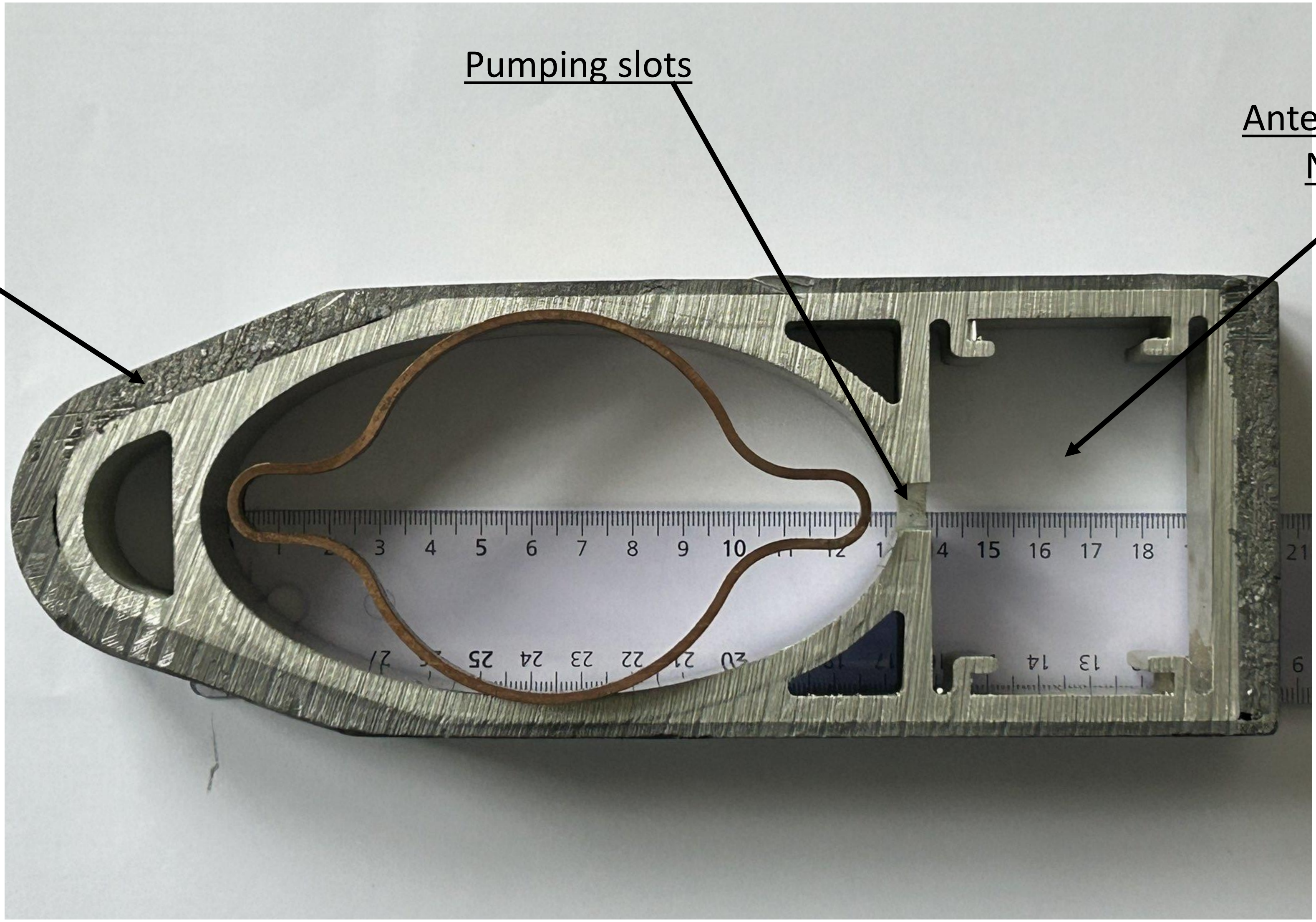
	Beam Energy E(GeV)	Beam Current I(mA)	Critical Energy (keV)	Photon Flux F'(ph/s/m)	PSD Outgassing Load (mbar·l/s/m) @ $1\cdot10^{-6}$(mol/ph)
Z	45.6	1390	19.5	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
W	80	147	105.5	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
H	120	29	356.2	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
T	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 - $5\cdot10^7$]

Comparison of LEP extruded cross-section (dipole chambers) with FCC-ee's (70 mm ID version)

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, i.e. ~50 l·m/s

The *new baseline 60 mm ID version* for FCC-ee would have a 37% additional conductance decrease, i.e. only ~1/3 that of LEP

We therefore have (Machine/Optics design and desiderata):

- High SR photon flux generating **high photon-stimulated desorption** (PSD) gas load
- Rather **low specific conductance** of the vacuum chamber (dictated by the size of the quadrupole/sext opening)
- Requirement of a **fast vacuum conditioning** so that a large integrated luminosity can be achieved
- Need for a vacuum system which **minimizes e-cloud** (e+ beam) and **ion-trapping** (e- beam) (to preserve the quality of the beam)

This leads to (Requirements):

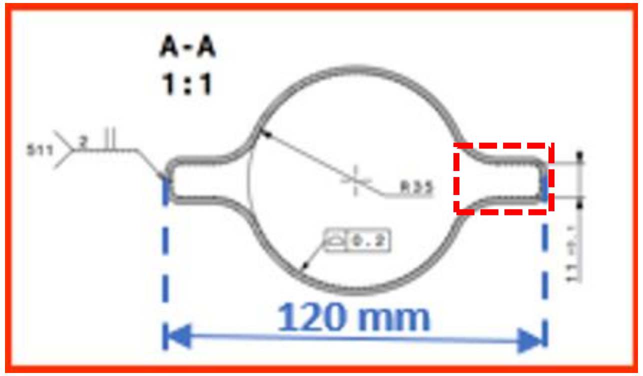
- Efficient **removal of the 50 MW/beam** SR power load
- Vacuum surfaces (materials, thin-films, treatments) having a low PSD yield, **minimizing gas-beam interactions**
- **Efficient pumping**, both in cost and in performance
- **Minimization of the high-energy component of the Compton-scattered primary SR fan** (for energies W, H, T), as per FLUKA simulations/results

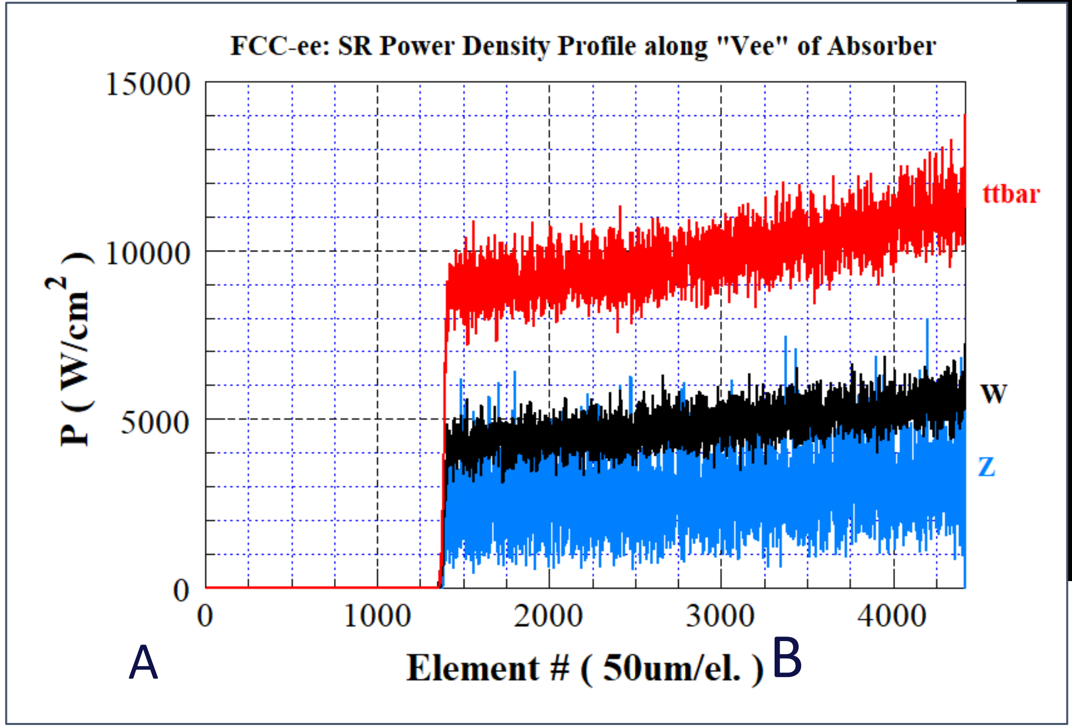
We can satisfy these requirement if we design a vacuum system based on:

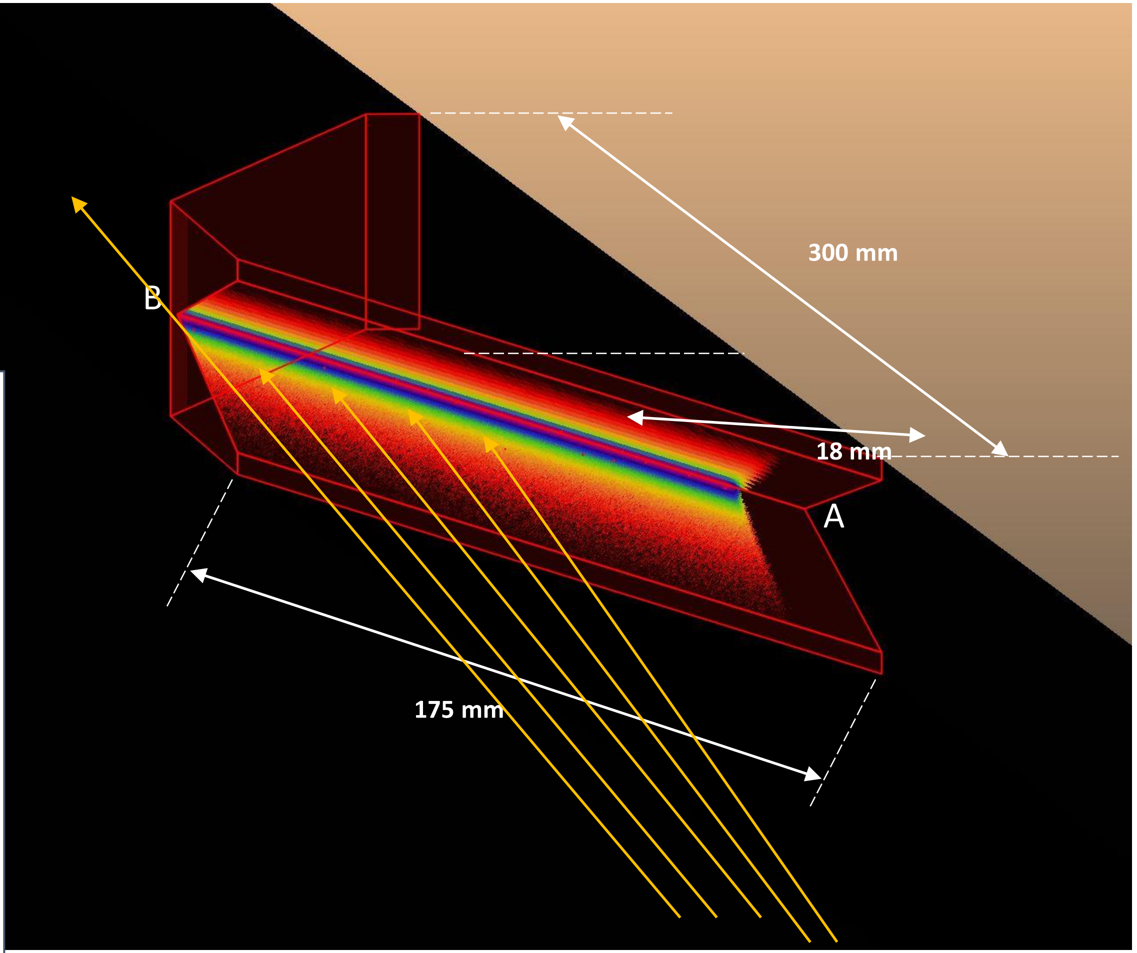
- **NEG-coating** (thin, ~200 nm, to reduce resistive-wall impedance contribution)
- Primary SR fans intercepted by **localized SR absorbers**, rather than a LEP-like configuration where the SR fans are distributed more or less uniformly along the external side of the vacuum chamber

The next slides will summarize the modelling exercise showing that ***a NEG-coated, localized SR absorber configuration meets the requirements***

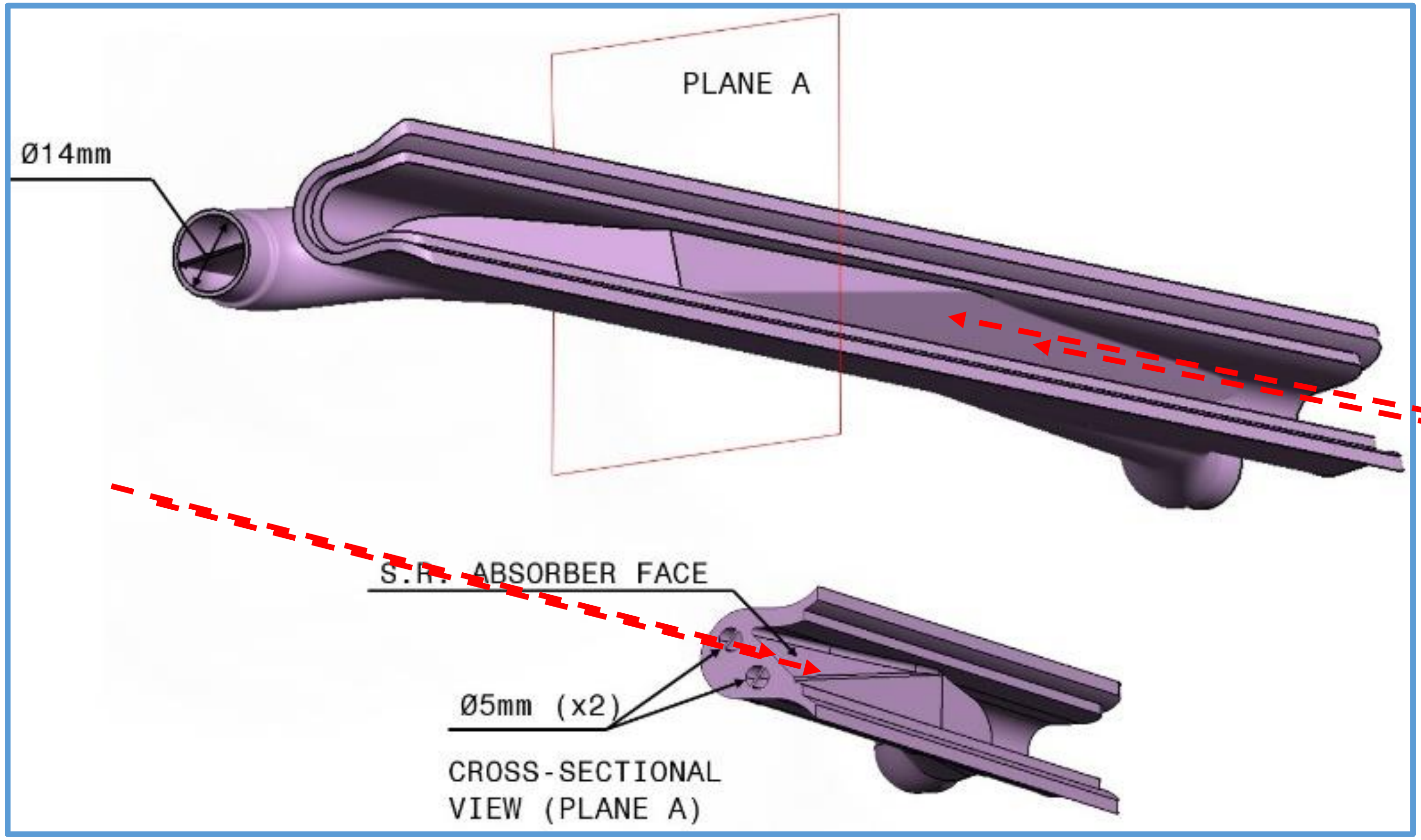
Initial geometry of the SR photon absorber, now superseded by 3D-printed one (next slide)

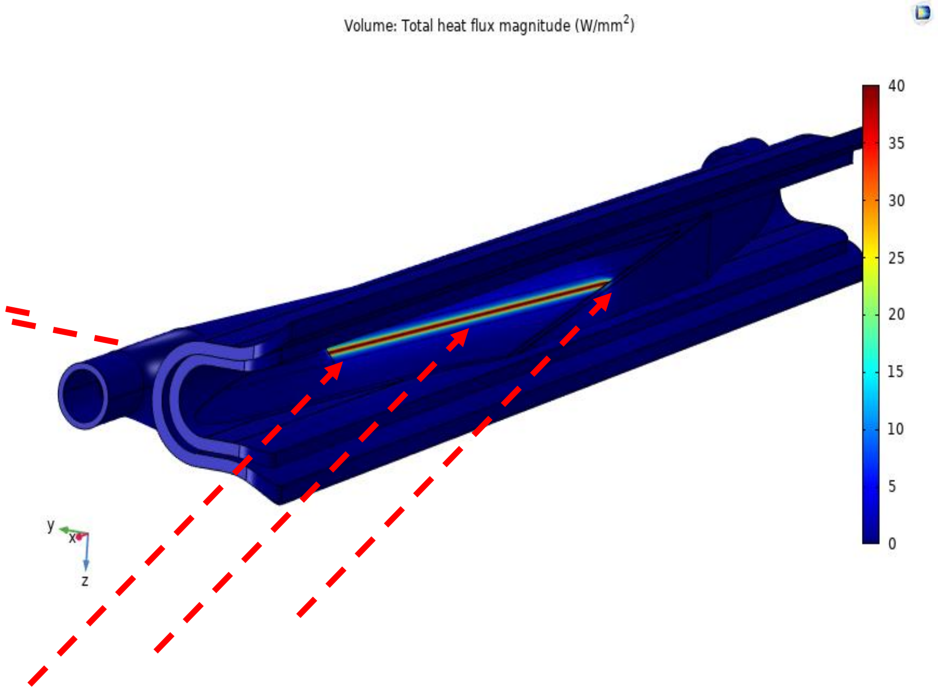


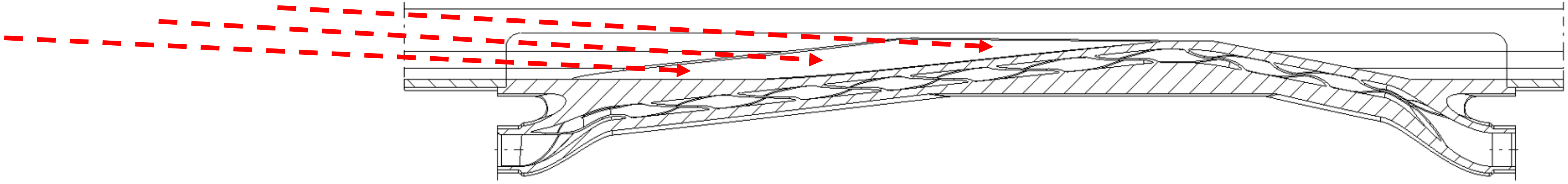




Current design: 3D-PRINTED SR ABSORBER, with INTEGRATED COOLING CIRCUIT AND SWIRL TAPE TO IMPROVE HEAT EXCHANGE

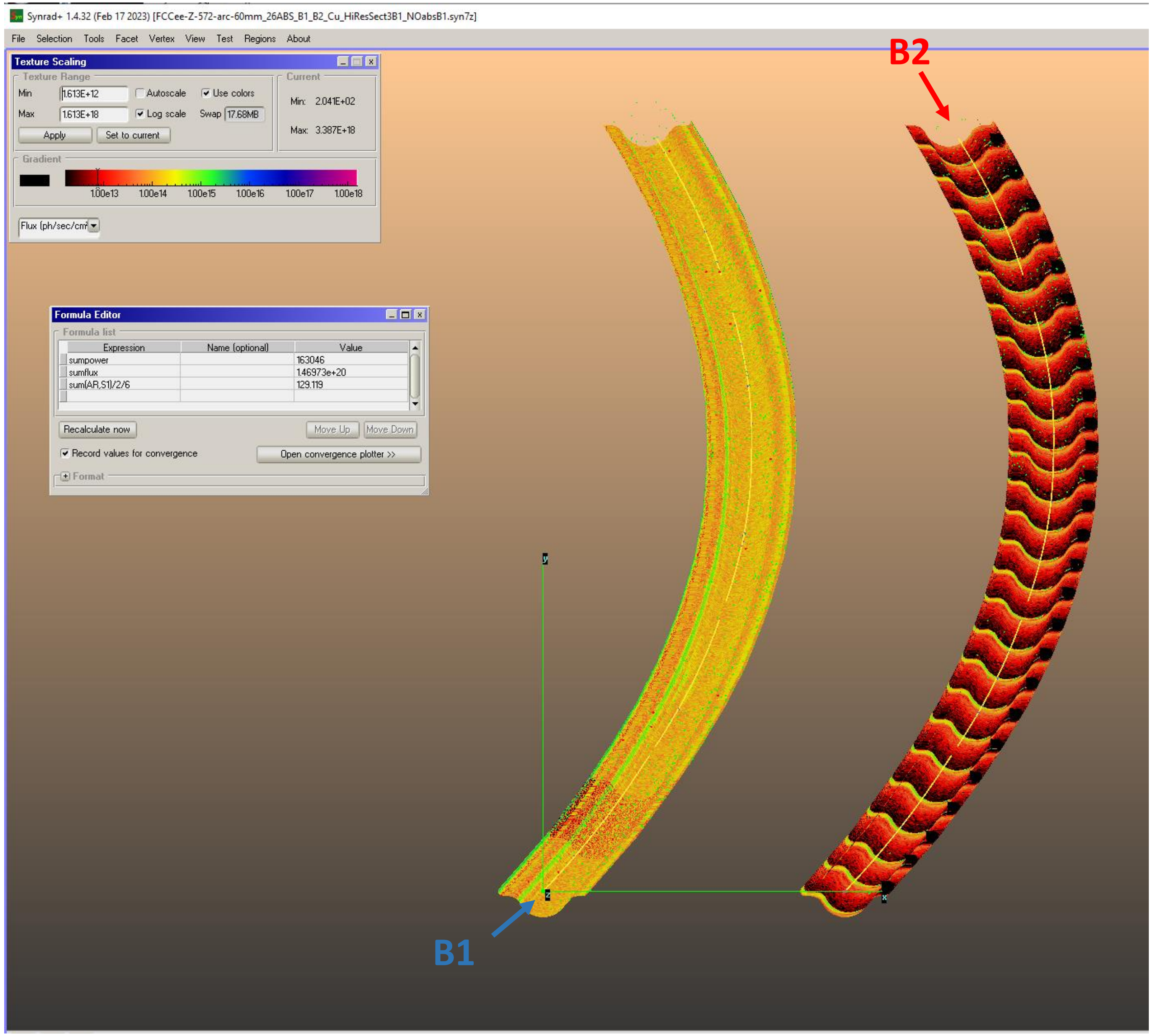






Pumping solutions (new baseline 60 mm ID chamber)

- These 2 models represent a section of the arcs (132.4 m long)
- We have used Molflow+ to calculate the PSD pressure rise at different beam doses, using the photon irradiation maps calculated by SYNRAD+
- A sample 132.4 m-long section of an arc has been considered, with the two beams side by side: 4 dipoles and 4 quadrupoles as sources of SR
- The orbits along 4 dipoles interleaved with 4 quadrupoles are simulated, importing the lattice files from MADX into SYNRAD+
- The 3D model for B2 has 26 absorbers placed at ~ 5.0 m average spacing (avoiding quadrupoles and sextupoles which have tight coils), while B1 has no absorbers, and the SR fan is let impinge onto the bottom of the external winglet
- The MDI region adopts the same philosophy: **lumped absorbers covering ~100%[†] of the primary SR photon fans**
- **~12% MORE ABSORBERS as compared to the 70 mm ID chamber and different lattice!**



Synrad+ 1.4.32 (Feb 17 2023) [FCCee-Z-572-arc-60mm_26ABS_B1_B2_Cu_HiResSect3B1_NOabsB1.syn7z]

Texture Scaling

Texture Range

Min 1.613E+12 ☐ Autoscale ☑ Use colors

Max 1.613E+18 ☑ Log scale Swap 17.68MB

Current

Min: 2.041E+02

Max: 3.387E+18

Flux (ph/sec/cm²)

Formula Editor

Formula list

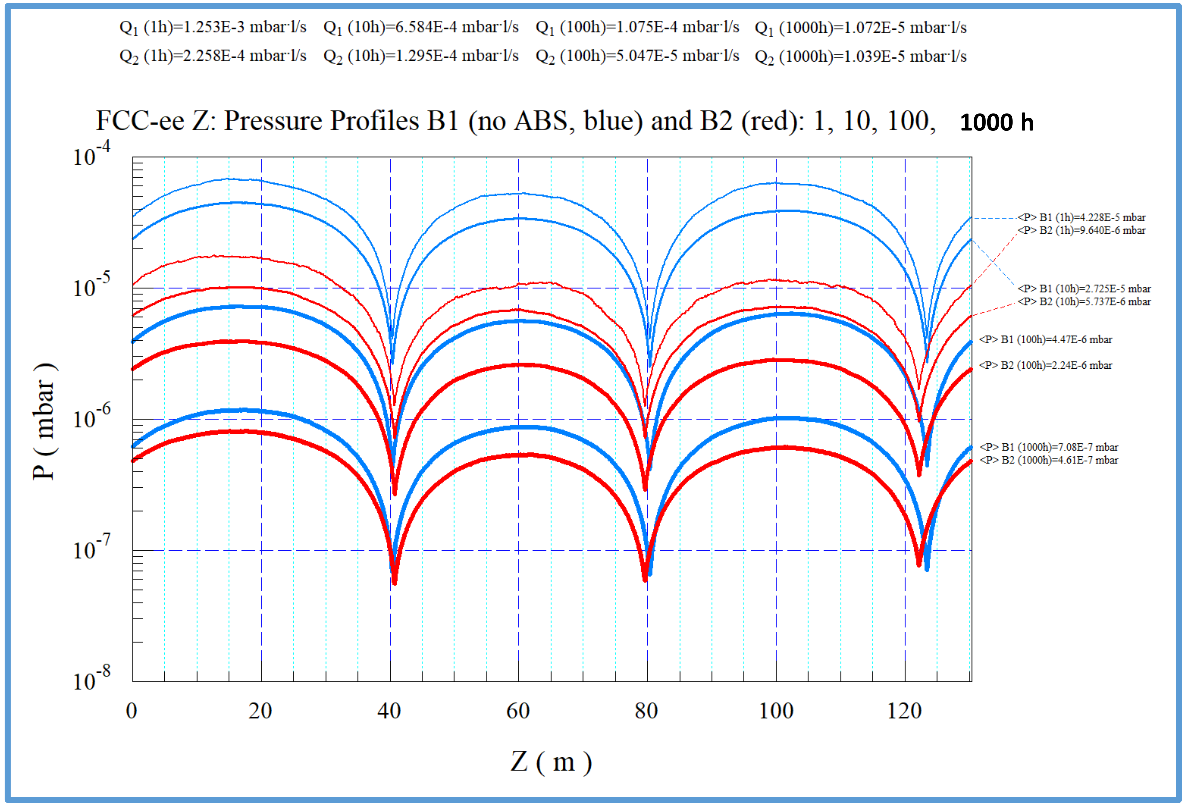
Expression	Name (optional)	Value
sumpower		163046
sumflux		1.46973e+20
sum(AR,S1)/2/6		129.119

☑ Record values for convergence

[†] To be precise, ~0.6% of the generated photons miss the absorbers, being generated at a large vertical angle. Average distance for first hit is 33.8 m

Pressure profiles

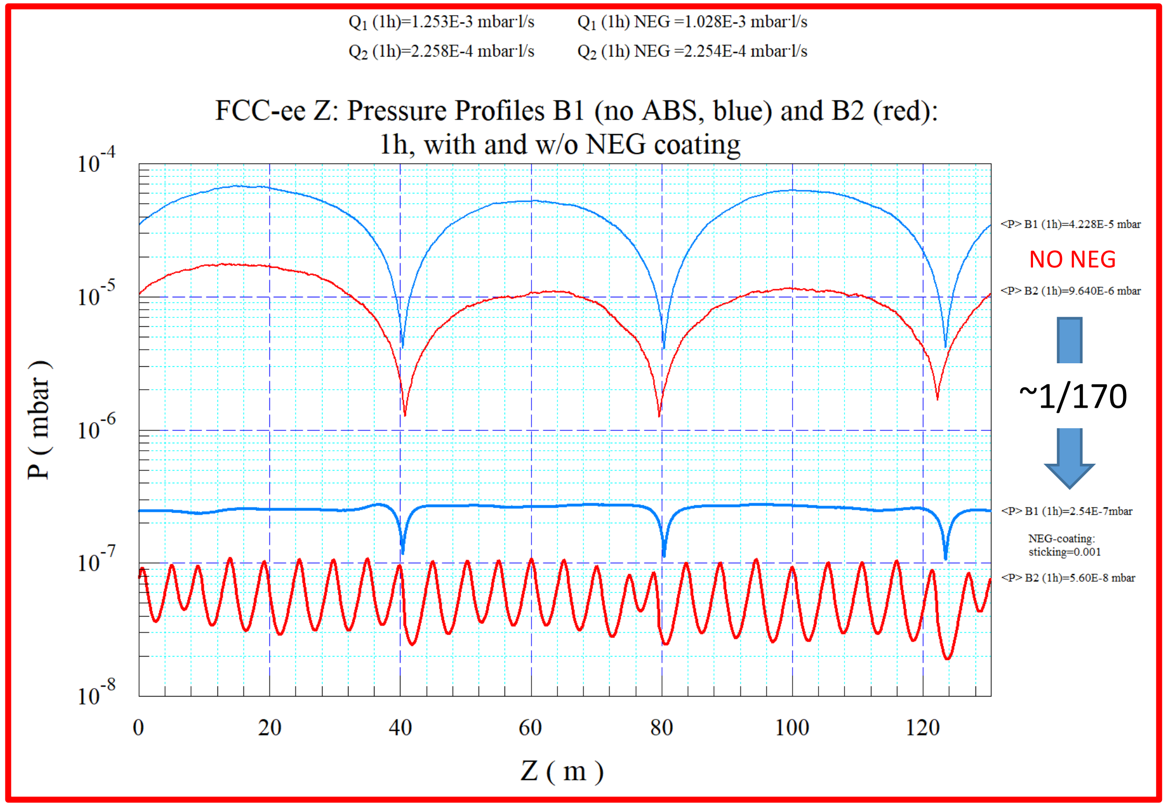
- We have calculated the PSD pressure profiles for 4 different beam doses, corresponding to times of 1 h, 10 h, 100 h, 1000 h at nominal current (1270 mA); Simulated gas: CO
- On the left the case with 3x 100 (l/s) lumped pumps/beam, and <u>no NEG-coating</u>
- On the right, the case <u>with NEG-coating</u> with some residual sticking (*s*=0.001) for 1h case



Q_1 (1h)=1.253E-3 mbar·l/s Q_1 (10h)=6.584E-4 mbar·l/s Q_1 (100h)=1.075E-4 mbar·l/s Q_1 (1000h)=1.072E-5 mbar·l/s

Q_2 (1h)=2.258E-4 mbar·l/s Q_2 (10h)=1.295E-4 mbar·l/s Q_2 (100h)=5.047E-5 mbar·l/s Q_2 (1000h)=1.039E-5 mbar·l/s

FCC-ee Z: Pressure Profiles B1 (no ABS, blue) and B2 (red): 1, 10, 100, **1000 h**



Q_1 (1h)=1.253E-3 mbar·l/s Q_1 (1h) NEG =1.028E-3 mbar·l/s

Q_2 (1h)=2.258E-4 mbar·l/s Q_2 (1h) NEG =2.254E-4 mbar·l/s

FCC-ee Z: Pressure Profiles B1 (no ABS, blue) and B2 (red): 1h, with and w/o NEG coating

Conclusions and open issues

1. The synchrotron radiation flux in the FCC-ee is particularly large for the Z energy, creating the largest SR-induced gas load
2. The higher energies are characterized by much lower beam currents but there is an additional contribution to the SR-induced gas load coming from the back-scattered Compton showers, with increasing intensity as the beam energy increases
3. The advantage of both having SRAs and distributed NEG-coating are clear: we should pursue these two technologies in order to speed up the vacuum conditioning of the machine, especially if the FCC-ee is not started at the Z energy
4. The design of the SR photon absorbers (SRAs) has been optimized, prototypes have been ordered and received; TO DO: define the welding parameters
5. TO DO: try to minimize the fraction of primary SR photons reflected by the SRAs, tentatively introducing a sawtooth profile on the photon intercepting facet of the SRAs
6. Not shown here: some work has been carried out on the MDI region too, and the full-energy booster as well; TO DO: make detailed design of vacuum components, for both MDI and booster
7. BOOSTER: our original proposal was to have a fully bakeable ring with NEG-coating: the cost review team has asked us to backtrack to a simpler and less expensive version with NO bake out, NO NEG-coating, and NO RF contact fingers
8. A booster as defined above, would need a very long time to be vacuum conditioned to the low 10^{-9} mbar level: TO DO, a re-appraisal of this issue
9. Comments: 1. Collaboration with other groups/departments is functioning rather well: machine physics, radiation losses and R2E, tunnel integration, project costing, etc…; 2. If we want to go to a deeper level of details, human/financial resources are needed