Conceptual Design of the Vacuum System for the FCC-ee Main Rings

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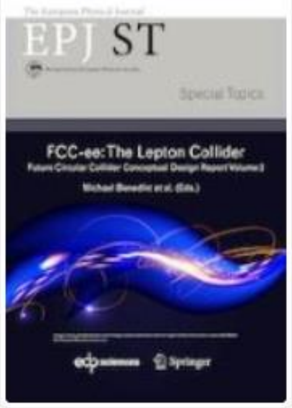
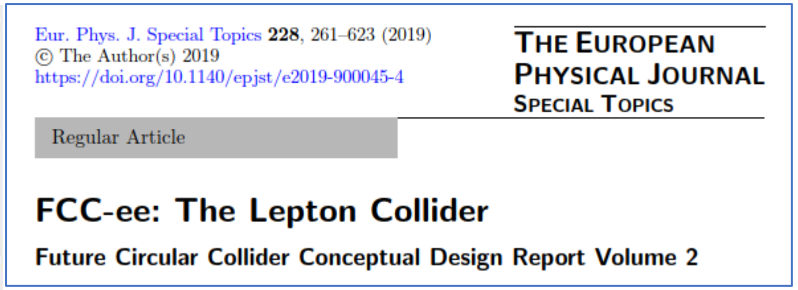
Reporting for the Vacuum Surfaces and Coatings Group

photo: J. Wenninger, CERN

FCCIS: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

http://cern.ch/fcc

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The European Physical Journal Special Topics

Regular Article

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

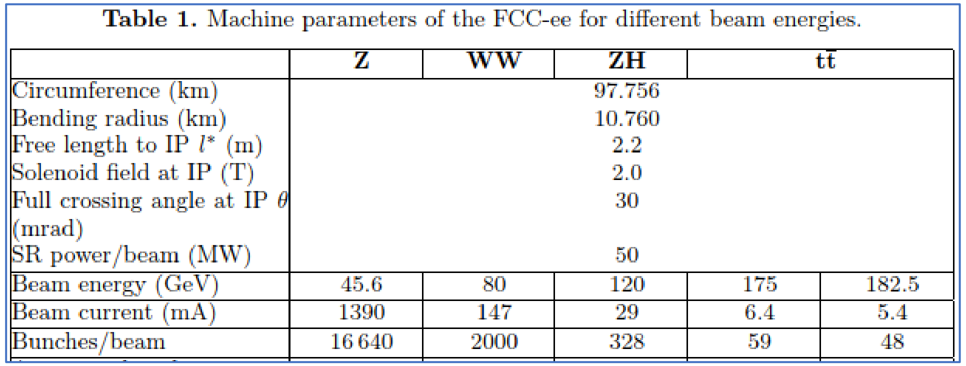

Table 1. Machine parameters of the FCC-ee for different beam energies.

	Z	WW	ZH	$t\bar{t}$	
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

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

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

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

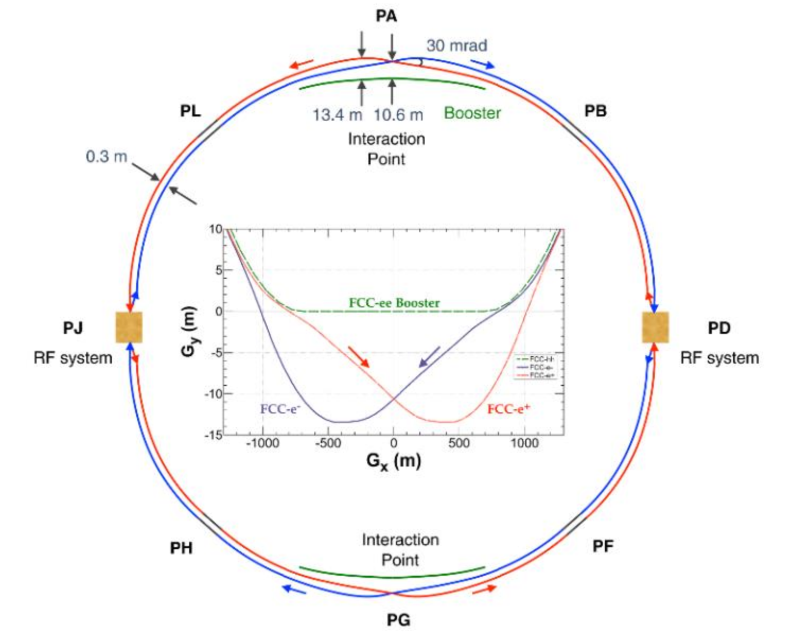

Fig. 1. Overall layout of the FCC-ee with a zoomed view of the trajectories across interaction point G. The FCC-ee rings are placed 1 m outside the FCC-hh footprint (used for the booster and indicated in green colour in the figure) in the arc. In the arc the e^+ and e^- rings are horizontally separated by 30 cm. The main booster follows the footprint of the FCC-hh collider ring. The interaction points are shifted by 10.6 m towards the outside of FCC-hh. The beam trajectories toward the IP are straighter than the outgoing ones in order to reduce the synchrotron radiation at the IP.

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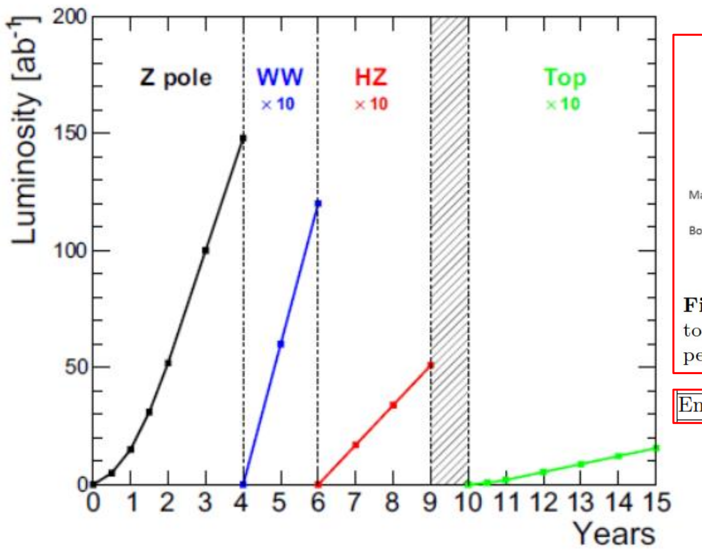


Fig. 1.2. Operation model for the FCC-ee, as a result of the five-year conceptual design study, showing the integrated luminosity at the Z pole (black), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. The hatched area indicates the shutdown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

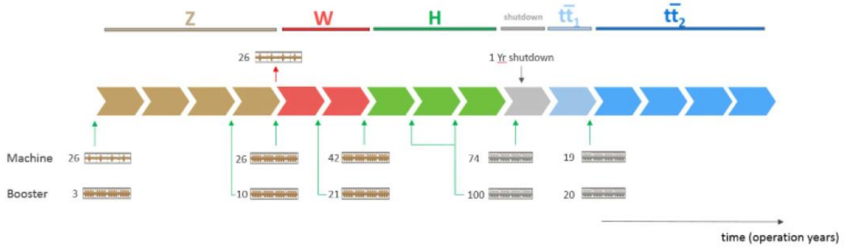
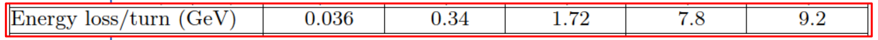


Fig. 4. FCC-ee operation time line. The bottom part indicates the number of cryomodules to be installed in the collider and booster, respectively, during the various winter shutdown periods; also see [22].



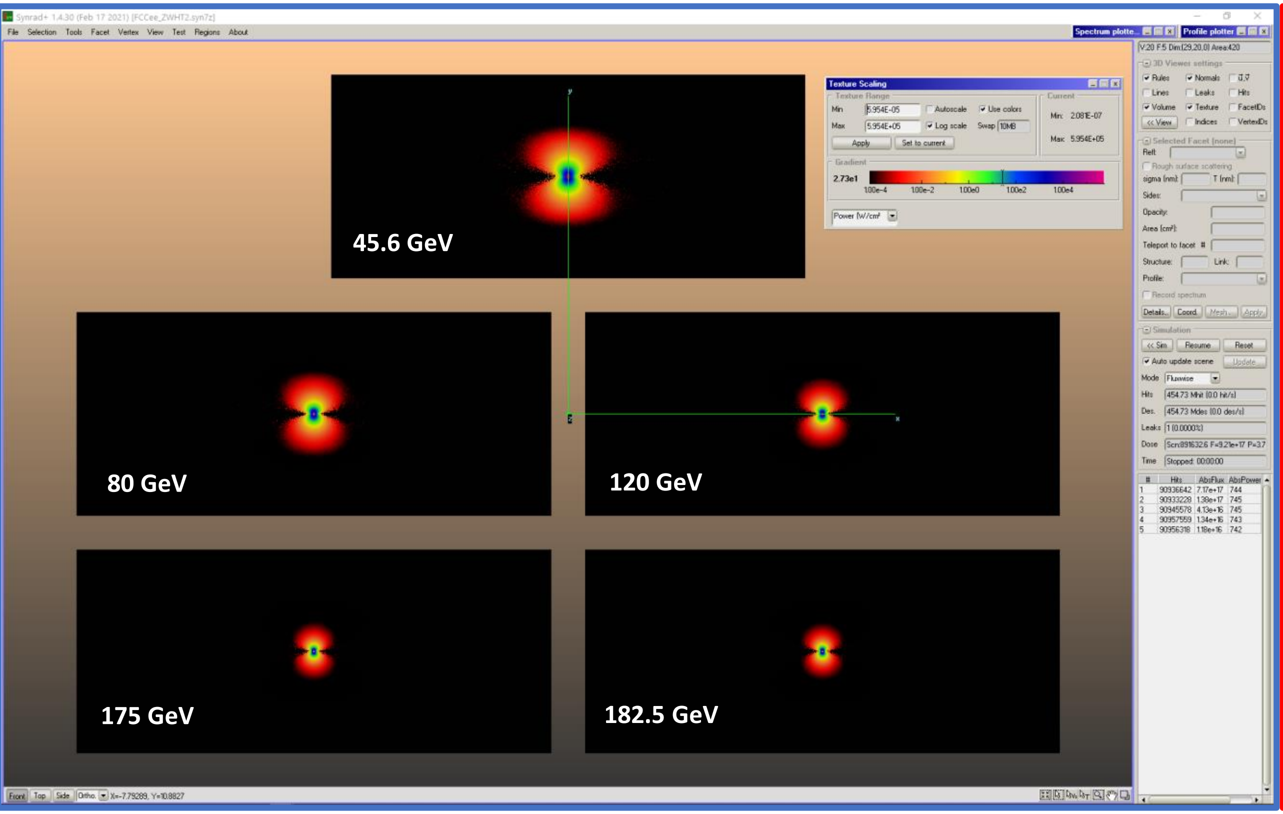
Energy loss/turn (GeV)	0.036	0.34	1.72	7.8	9.2

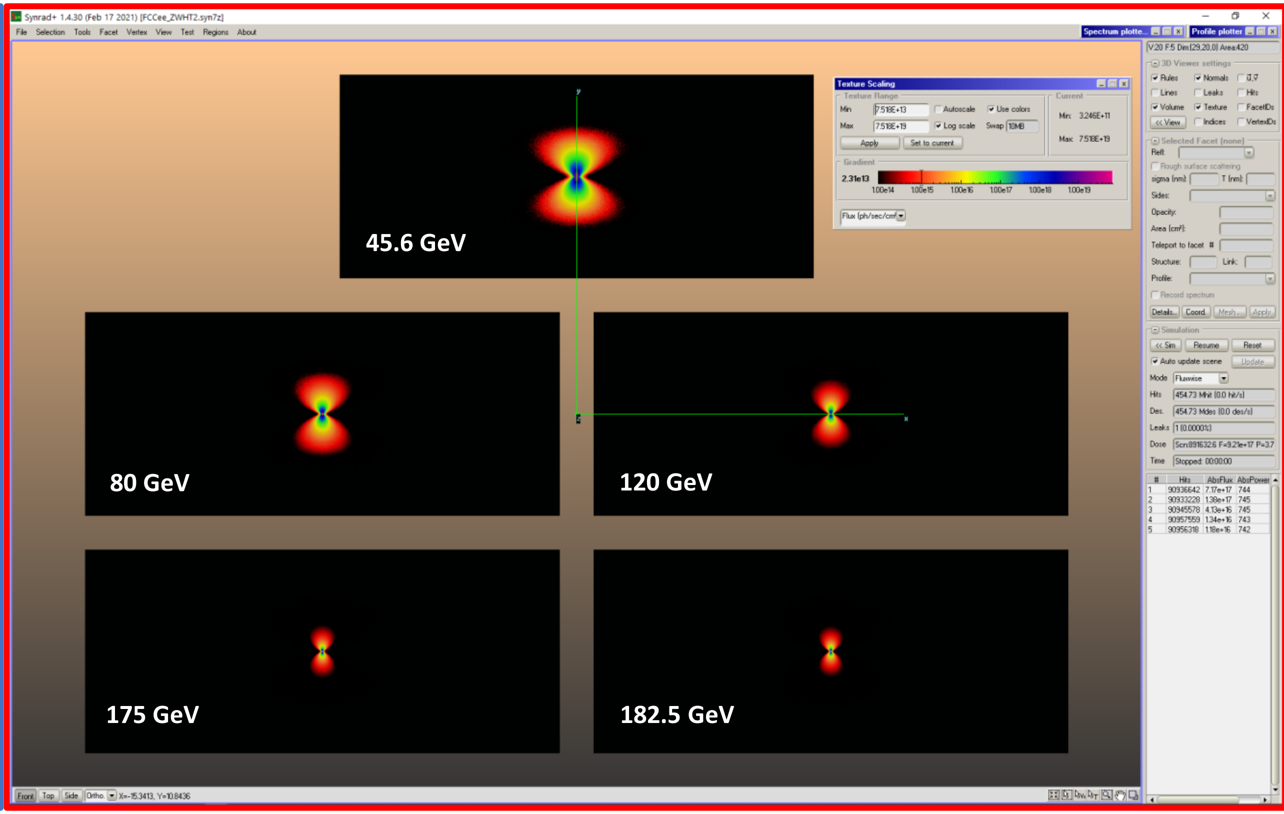
Large use of montecarlo raytracing techniques

Two codes used: *SYNRAD+* (SR) and *Molflow+* (molecular flow)

SYNRAD+ simulations: SR power and flux for the 5 beam energies and currents

SR fans are projected on 14x6 cm^2 (HxV) screens, placed 50 m away from a 1 cm arc length
i.e. +/- 1.4 mrad H and +/- 0.6 mrad V

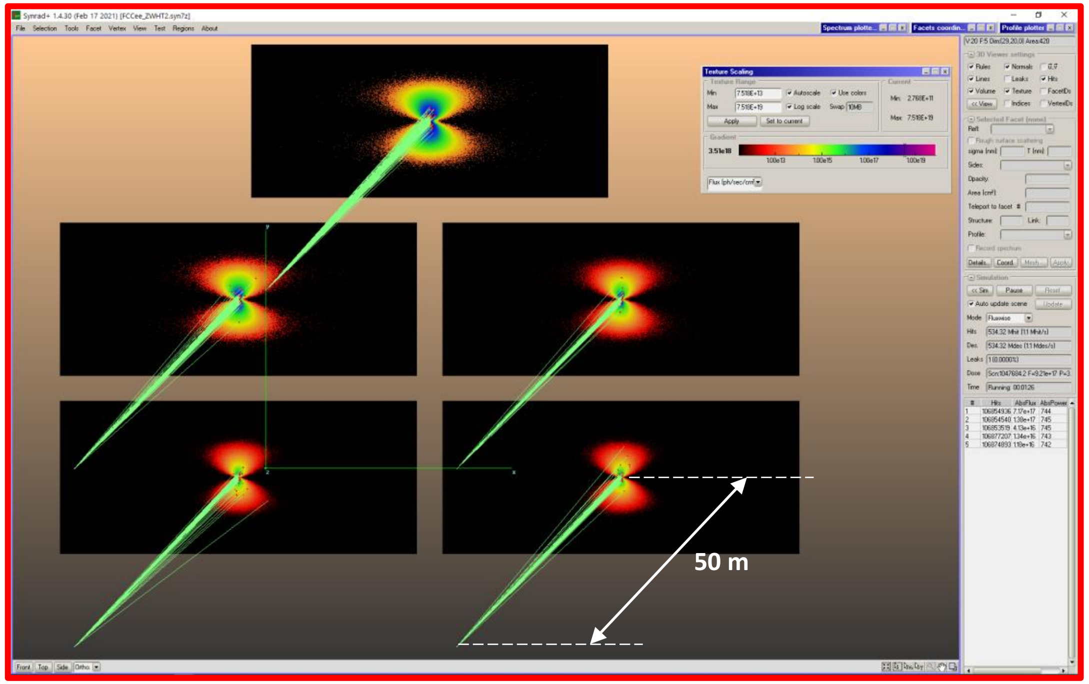


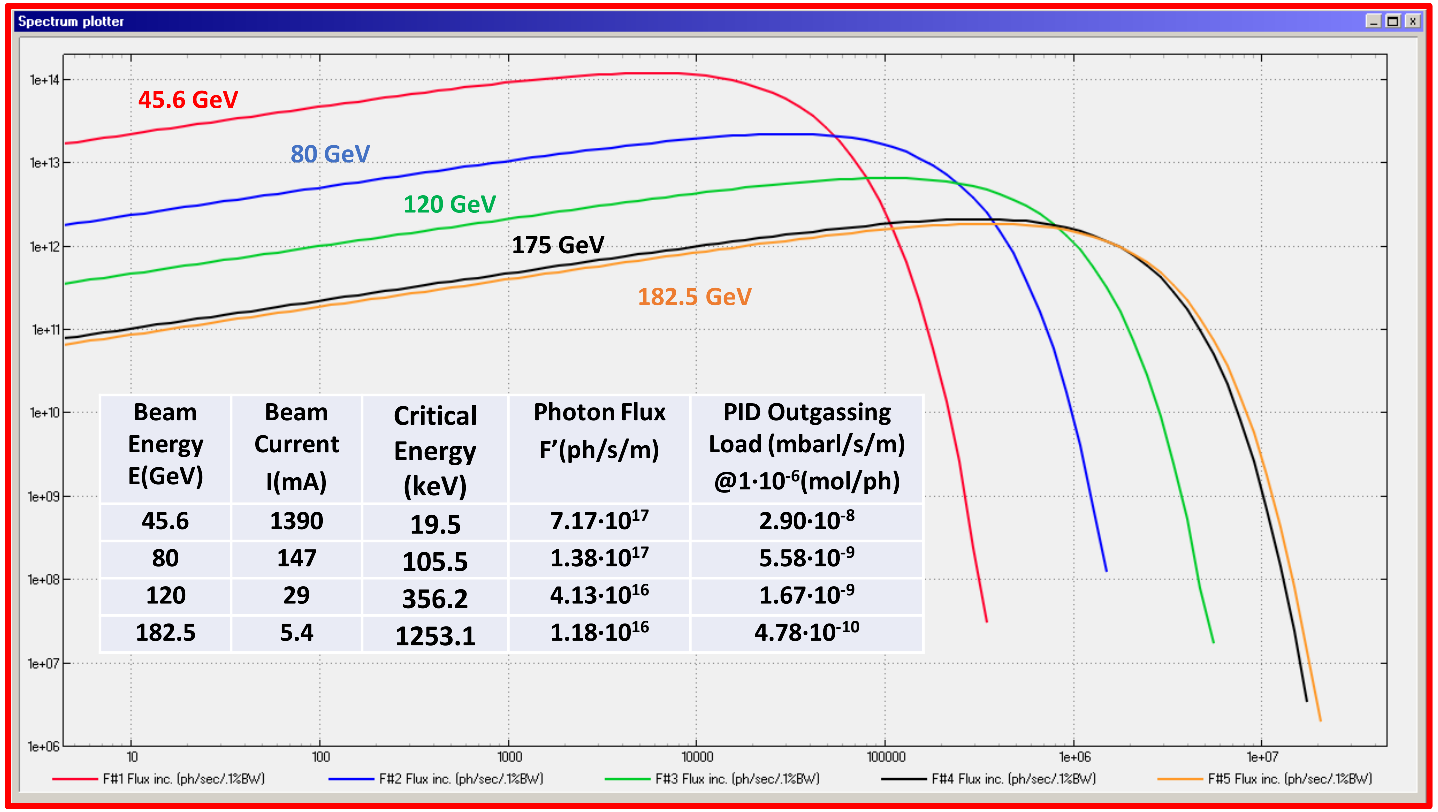


SR power density (W/cm^2) generated by 1m of dipole arc for the 5 beam energies; Total linear power is 744 W/m

SR flux density (ph/s/cm^2) generated by 1m of dipole arc for the 5 beam energies; Total linear flux varies with each machine

SYNRAD+: SR Flux Spectra





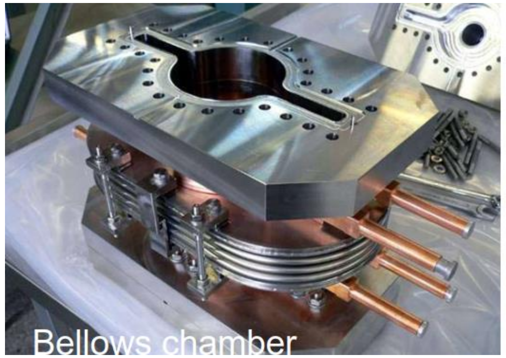
Beam Energy E(GeV)	Beam Current I(mA)	Critical Energy (keV)	Photon Flux F'(ph/s/m)	PID Outgassing Load (mbarl/s/m) @$1\cdot10^{-6}$(mol/ph)
45.6	1390	19.5	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
80	147	105.5	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
120	29	356.2	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
182.5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

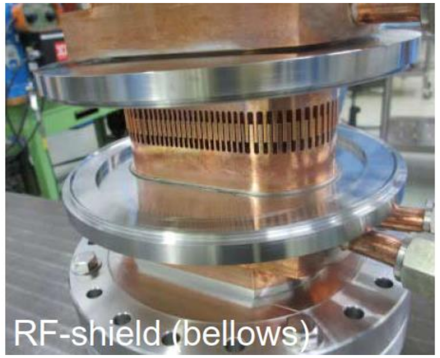
Units: **Vertical:** **photons/s/(0.1% bandwidth)/m ; Range [10^6 - $2\cdot10^{14}$]**
Horizontal: **eV ; Range [4 - $5\cdot10^6$]**

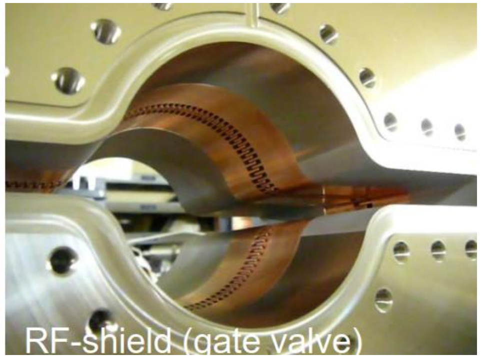
SuperKEKB e-e+ Collider

Vacuum components and chamber cross-section good inspiration to us…

- Low-loss, water-cooled, “comb-type” contact fingers
- (KEK concept, to be adapted to our dimensions)
- Good for impedance reasons (few tapers)

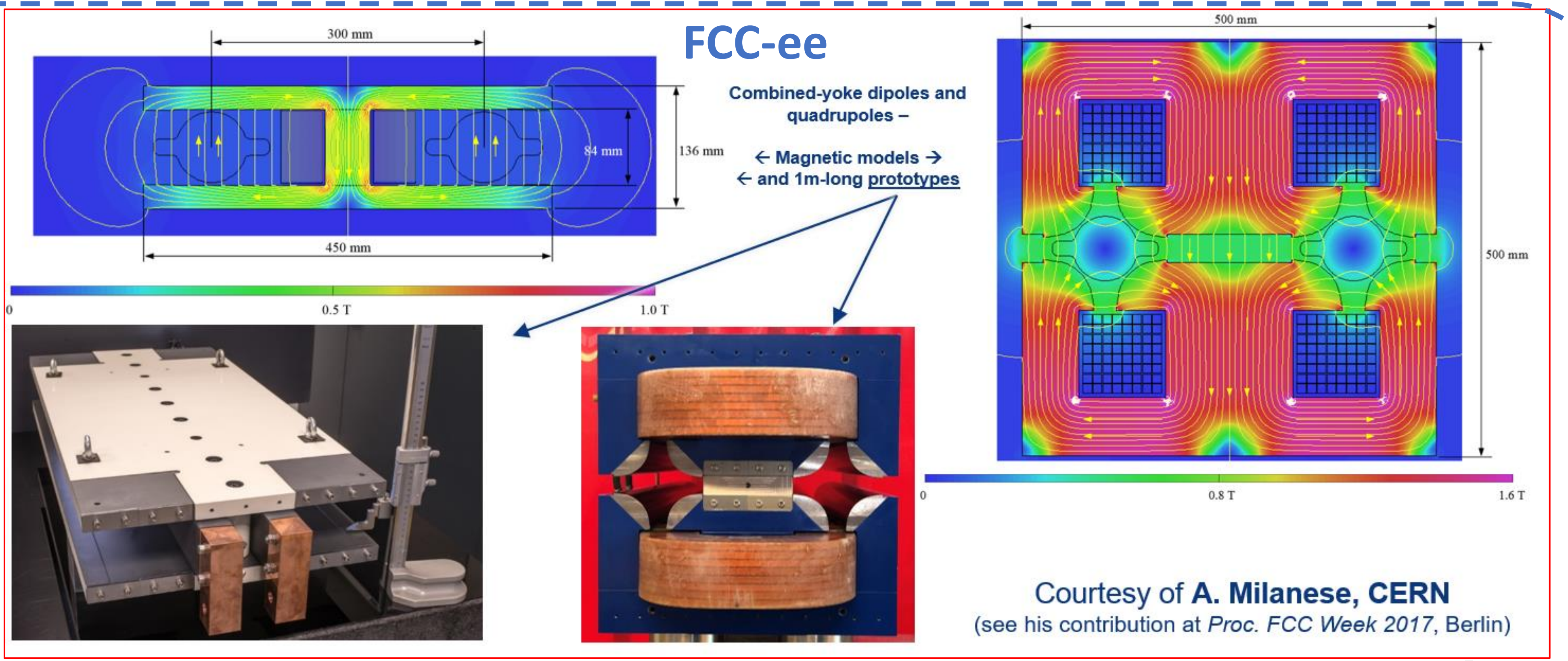

Bellows chamber


RF-shield (bellows)


RF-shield (gate valve)

Our two-in-one magnet design for the dipoles and the quadrupoles could profit from a vacuum chamber cross section like that of SuperKEKB:

- ➢ Winglets (to place SR absorbers)
- ➢ No need for tapers
- ➢ Low-loss components field-tested



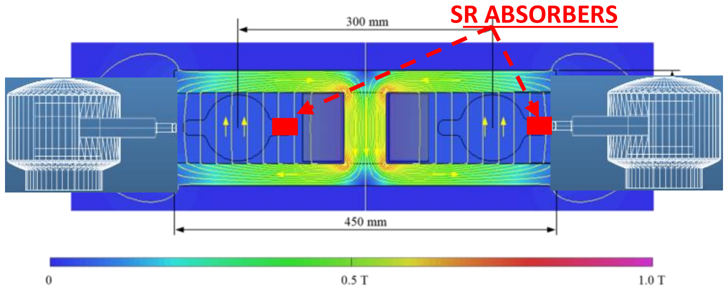
FCC-ee

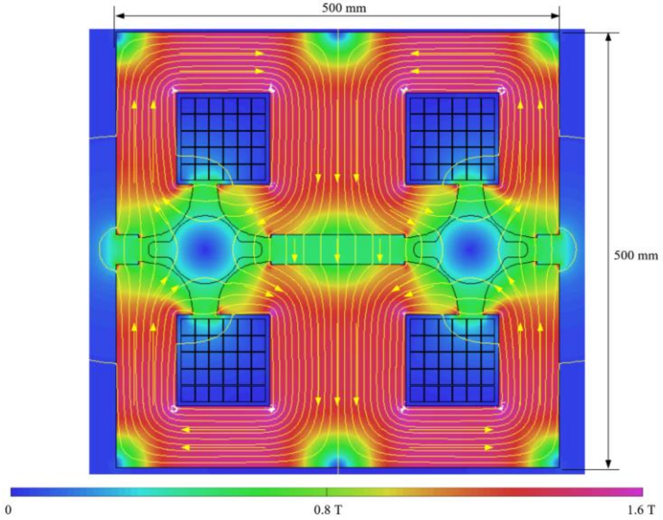
Combined-yoke dipoles and quadrupoles –

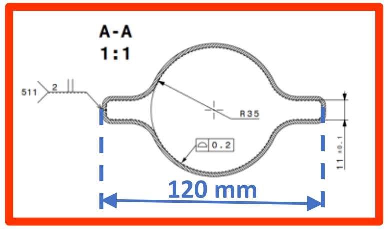
← Magnetic models →
← and 1m-long prototypes

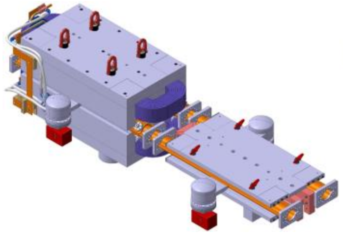
Courtesy of **A. Milanese, CERN**
(see his contribution at *Proc. FCC Week 2017*, Berlin)

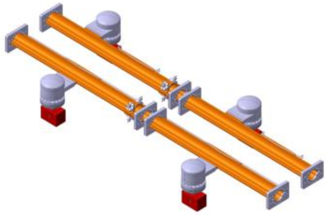
FCC-ee CAD Models



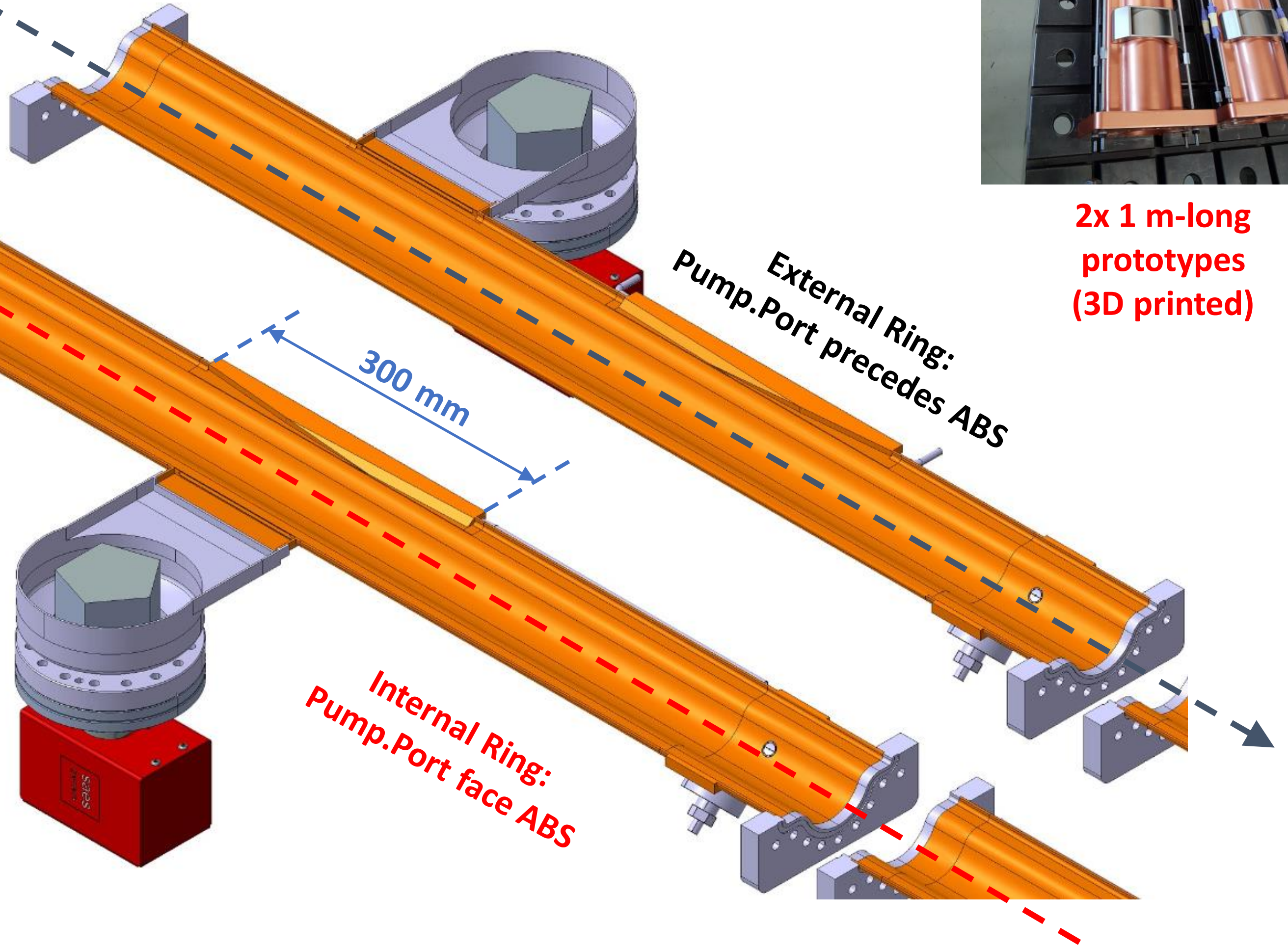






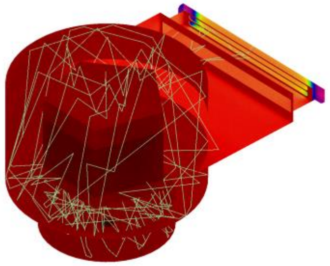


2x 1 m-long prototypes (3D printed)



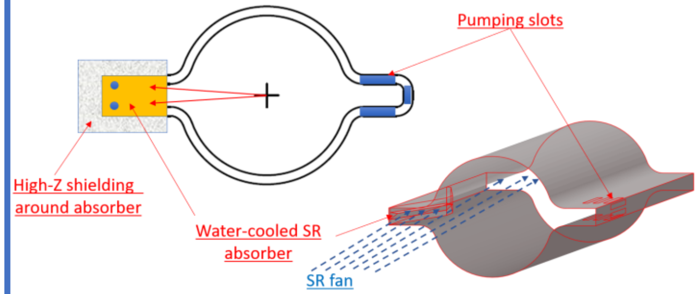
External Ring: Pump.Port precedes ABS

Internal Ring: Pump.Port face ABS



Pumping dome optimized via Molflow+ simulation: NEXTorr 1000

Material: OFC copper;
Specific Cond.: ~47 l·m/s (CO, 20 ºC)



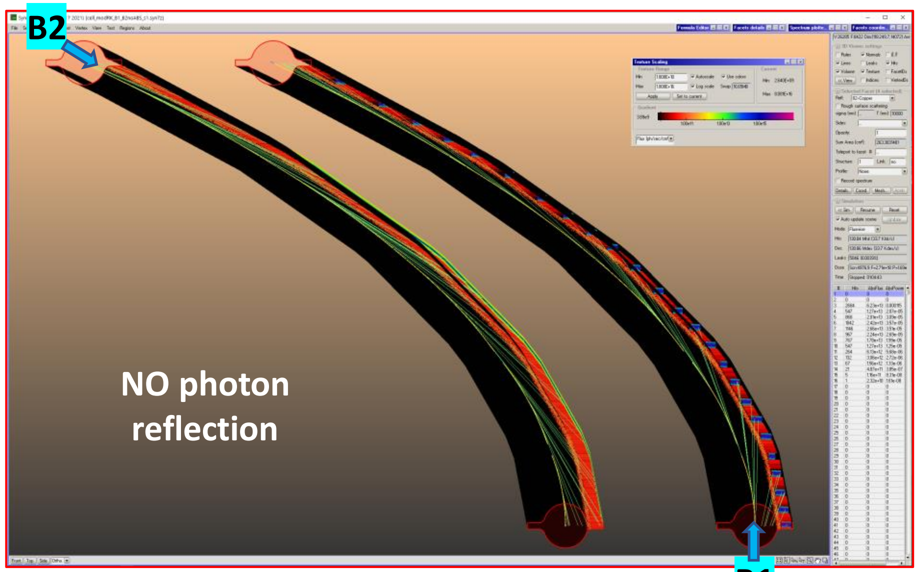
Schematics of SR absorbers and pumping slots (internal beam)

Molflow+: Molecular Flow Simulations

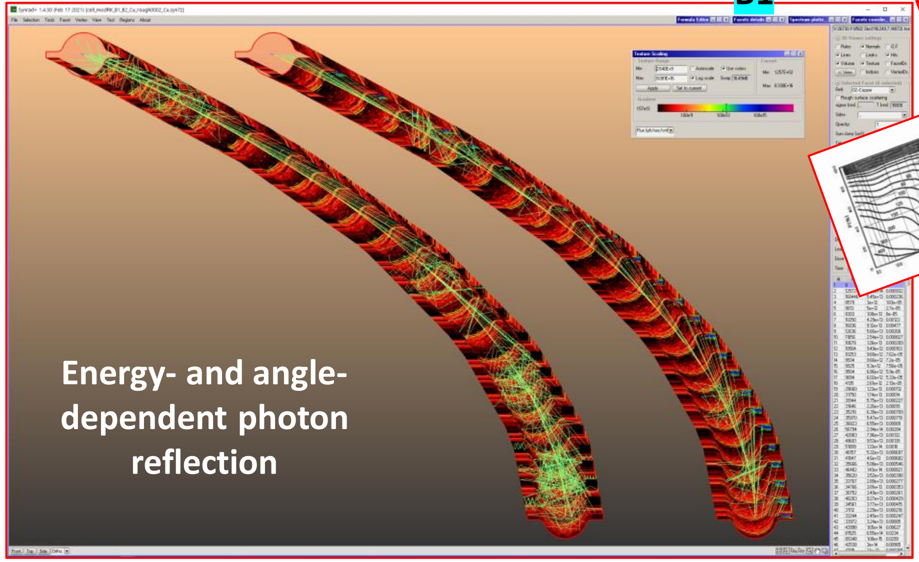
1. **The distribution of SR photons absorbed along the walls of the vacuum system are transformed into corresponding photon-induced desorption (PID) outgassing profiles**
2. **The instantaneous SR flux density (ph/s/cm^2) calculated on "textured" surfaces of the 3D model by *SYNRAD+* are multiplied by the time since start of commissioning of the machine and then each photon dose (ph/cm^2) is converted into a local outgassing yield Q_{PID}(mbar·l/s), using experimental data for the material-dependent outgassing yield η_{PID}(mol/ph). This is done within *Molflow+*.**
3. **The newly obtained *Molflow+* file now has desorption surfaces which mimic the PID yield. *Molflow+* is then used to simulate the random walk of the molecules. Pumping surfaces are defined, and relevant facets over which pressure, density, impingement rate, and other quantities of interest to the vacuum engineer are calculated.**
4. **Repeating the steps from 2 onward for different times during commissioning, we can obtain the pressure profiles at different moments.**
5. **In particular we can check whether the modelled pumping speeds are sufficient to meet the targeted pressure specifications: an accelerator like FCC-ee aims at having an average pressure along the beam path in the low 10^{-9} mbar range (e.g. $2.0 \cdot 10^{-9}$ mbar).**

Molflow+: Molecular Flow Simulations

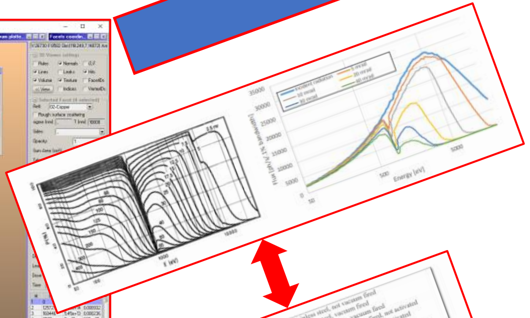
140 m-long typical section of one arc (5 dipoles and 5 quadrupoles/sextupoles, interleaved)

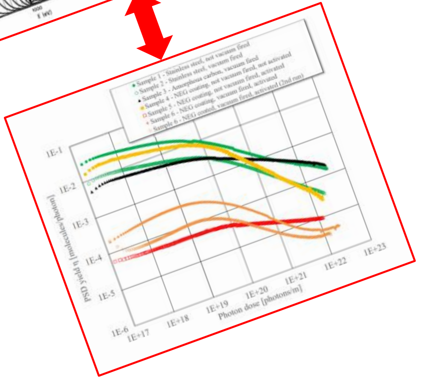


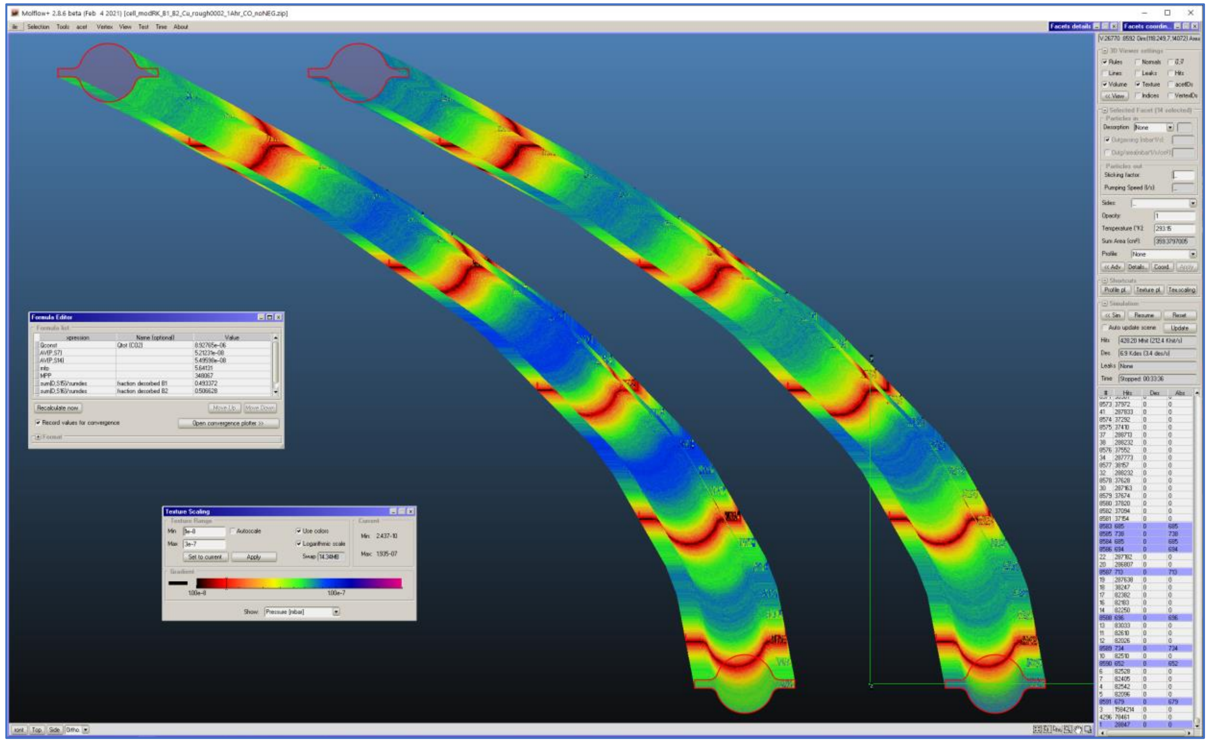
NO photon reflection



Energy- and angle-dependent photon reflection







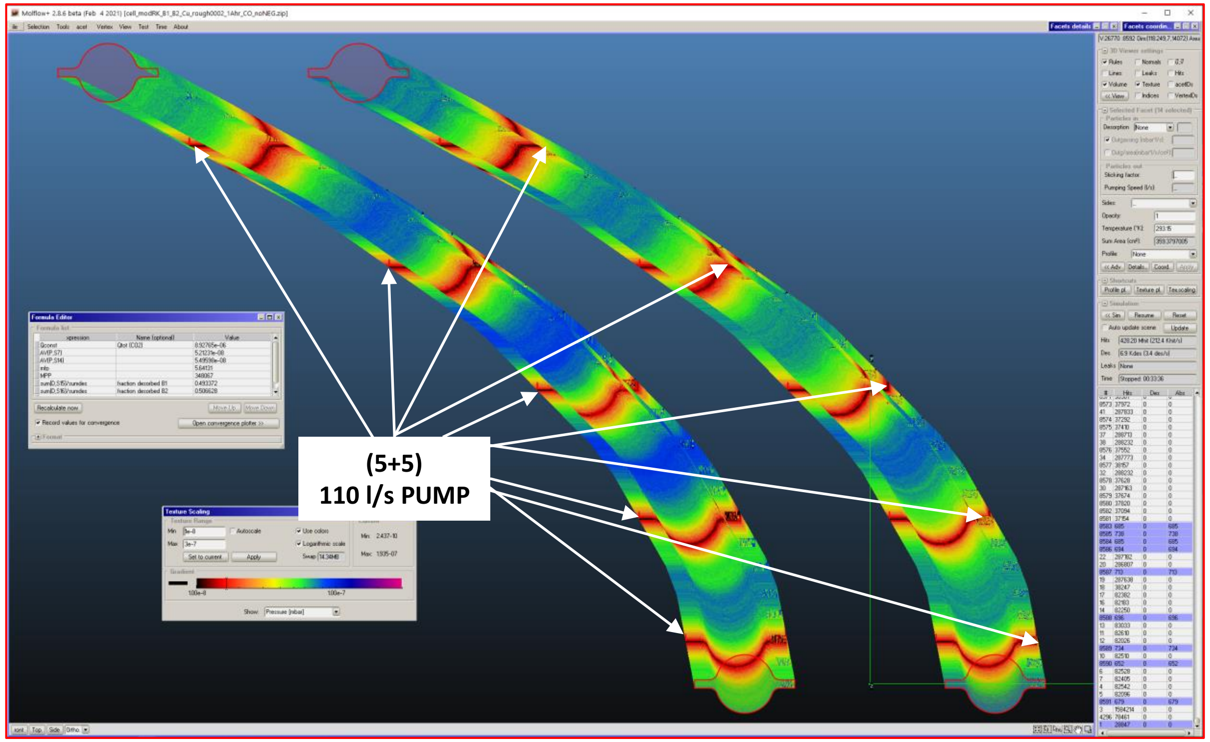
One example of Molflow+ calculation:

- Pressure distribution after 1 h of conditioning at nominal current, 45.6 GeV, 1390 mA;
- Chamber and absorber material is copper; No NEG-coating
- 5x 110 l/s pumps on each beam;
- Simulated gas: CO (20 ºC);

Average Pressure: ~$5.3 \cdot 10^{-8}$ mbar (~25x too high)

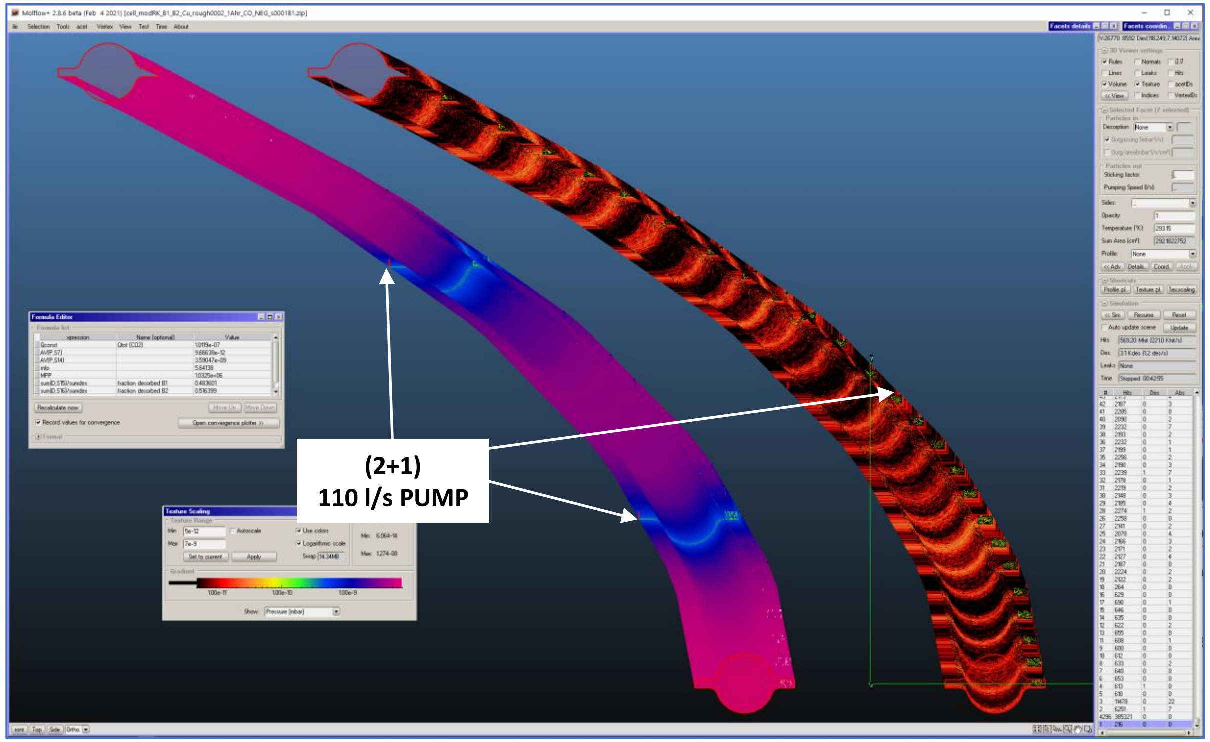
NEG-coating: yes or no?

Much faster machine commissioning with NEG-coating



- Pressure distribution after 1 h of conditioning at nominal current, 45.6 GeV, 1390 mA; Total PID gas load (2 beams): 8.93·10^{-6} mbar·l/s
- Chamber and absorber material is copper; NO NEG-coating
- 5x 110 l/s pumps on each beam;
- Simulated gas: CO (20 ºC);

Average Pressure: 5.2 x10^{-8} mbar (B1)
5.5 x10^{-8} mbar (B2)



- Pressure distribution after 1 h of conditioning at nominal current, 45.6 GeV, 1390 mA; Total PID gas load (2 beams): 1.02·10^{-7} mbar·l/s
- Chamber and absorber material is copper; NEG-coating
- 2x 110 l/s pumps on B2, 1x on B1;
- Simulated gas: CO (20 ºC);

Average Pressure: 9.7 x10^{-12} mbar (B1)
3.6 x10^{-09} mbar (B2)

NEG-coating on B1 has sticking coeff.= 0.001: HUGE effect!

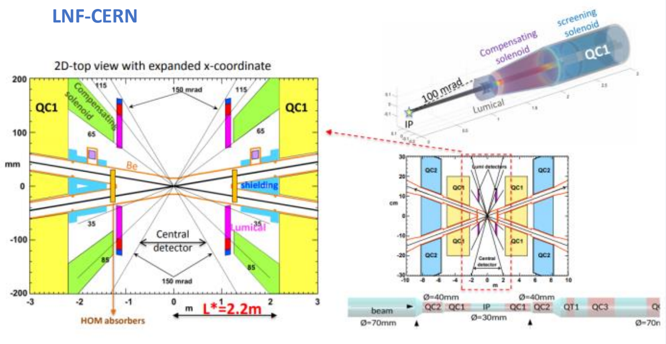
Machine Detector Interface (MDI) area

- Modelling work has also been carried out for the MDI areas of FCC-ee, see relevant MDI meeting, study group, and workshop pages on indico
- A 3D model of the vacuum chamber geometry ~660 m upstream of the IP has been created; it implements the winglet cross-section with lumped absorbers and NEG pumps already described for the arc chambers
- SYNRAD+ and Molflow+ have been run, coupled for the high-current Z-pole machine and ttbar as well
- The figure on the right shows the model with the colour-coded pressure along the beam path and the absorbers in red
- Some absorbers need to be placed on the opposite side of the chamber due to the anti-bend configuration near the IP

See companion paper M. Boscolo et al., this conf.

Credit: M. Boscolo, LNF-CERN

Interaction Region Layout

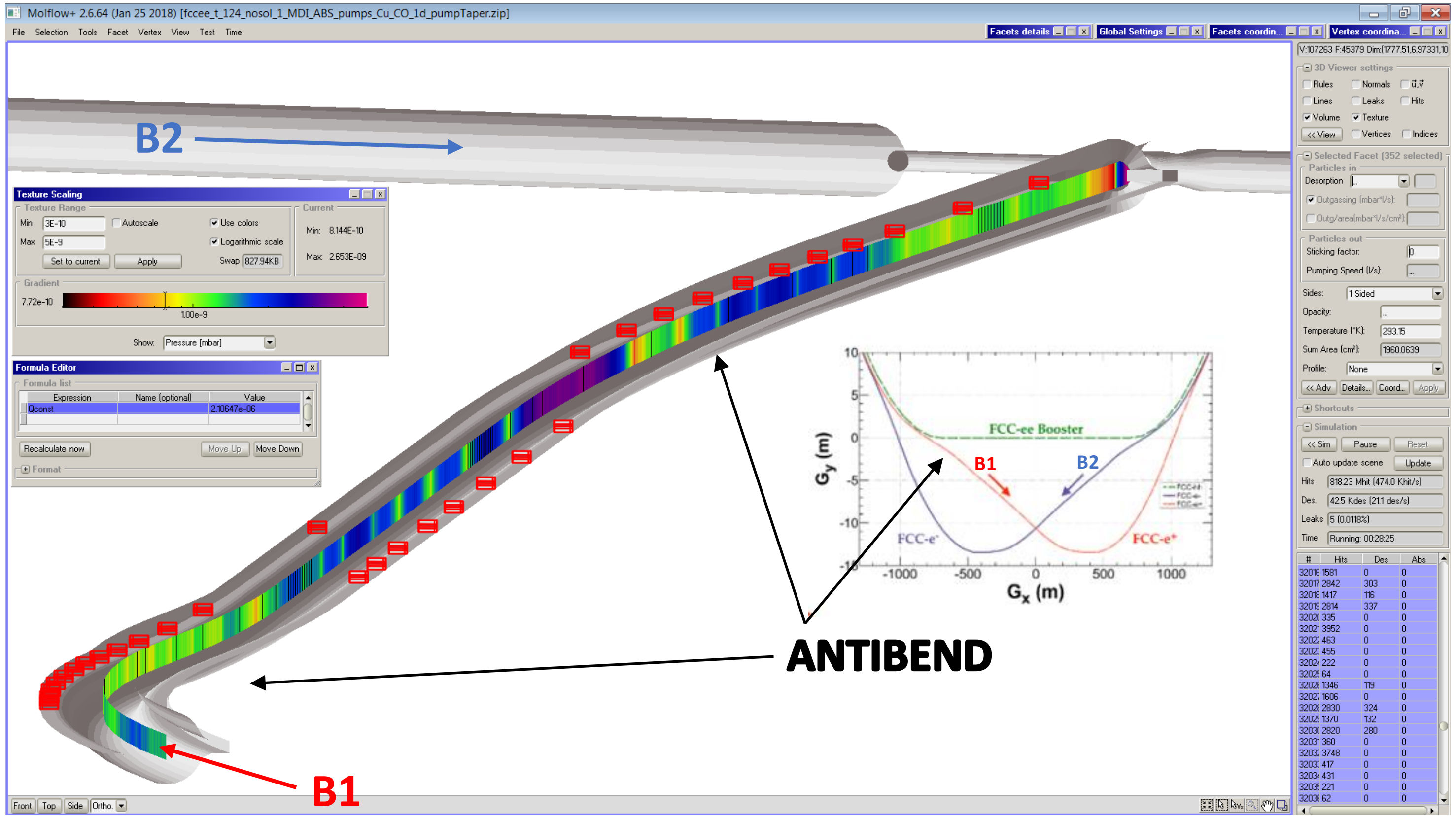


1.5 cm radius z ± 12.5 cm

L* = 2.2 m distance from IP to first quadrupole

2 T detector

smaller central pipe: 1.0 cm for z ± 9 cm
(with taper starting at z ± 40 cm from IP)



Molflow+ 2.6.64 (Jan 25 2018) [fcceе_t_124_nosol_1_MDI_ABS_pumps_Cu_CO_1d_pumpTaper.zip]

Texture Scaling

Texture Range
Min 3E-10 ☐ Autoscale ☑ Use colors
Max 5E-9 ☑ Logarithmic scale
Swap 827.94KB

Current
Min: 8.144E-10
Max: 2.653E-09

Gradient
7.72e-10
1.00e-9

Show: Pressure [mbar]

Formula Editor

Formula list

Expression	Name (optional)	Value
Qconst		2.10647e-06

V:107263 F:45379 Dim:(1777.51,6.97331,10

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

Selected Facet (352 selected)
Particles in
Desorption: ...
☑ Outgassing (mbar*l/s):
☐ Outg/area(mbar*l/s/cm²):
Particles out
Sticking factor: 0
Pumping Speed (l/s): ...
Sides: 1 Sided
Opacity: ...
Temperature (°K): 293.15
Sum Area (cm²): 1960.0639
Profile: None

Shortcuts

Simulation
☐ Auto update scene
Hits: 818.23 Mhit (474.0 Khit/s)
Des.: 42.5 Kdes (21.1 des/s)
Leaks: 5 (0.0118%)
Time: Running: 00:28:25

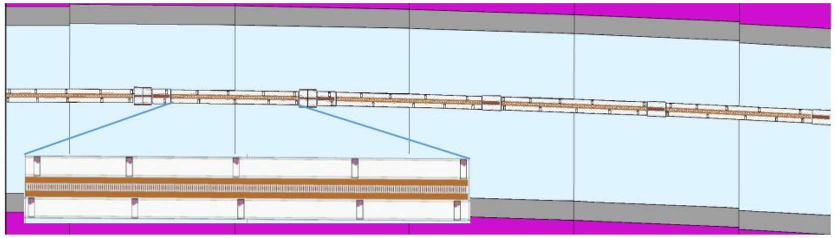
#	Hits	Des	Abs
32016	1581	0	0
32017	2842	303	0
32018	1417	116	0
32019	2814	337	0
32020	335	0	0
32021	3952	0	0
32022	463	0	0
32023	455	0	0
32024	222	0	0
32025	64	0	0
32026	1346	119	0
32027	1606	0	0
32028	2830	324	0
32029	1370	132	0
32030	2820	280	0
32031	360	0	0
32032	3748	0	0
32033	417	0	0
32034	431	0	0
32035	221	0	0
32036	62	0	0

Tunnel and Machine Component Irradiation Due to High-Energy SR Photons
(in combination with FLUKA team)

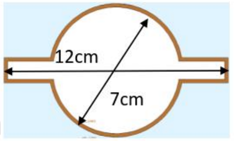
- **We have also worked in conjunction with our FLUKA team (B. Humann, F. Cerutti) on the study of the effects of the proposed vacuum system design in terms of radiation deposition on different tunnel areas and components, for the ttbar 182.5 GeV version of the machine, which is characterized by extremely high SR critical energy (1.25 MeV).**
- **“VC”=Vacuum Chamber**

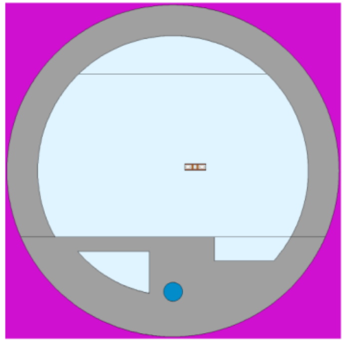
Geometry – periodic cell

- Periodic cell of the arc
  - 140m
  - 5 dipoles (3 long, 2 short)
  - 5 quadrupoles
  - 4 sextupoles

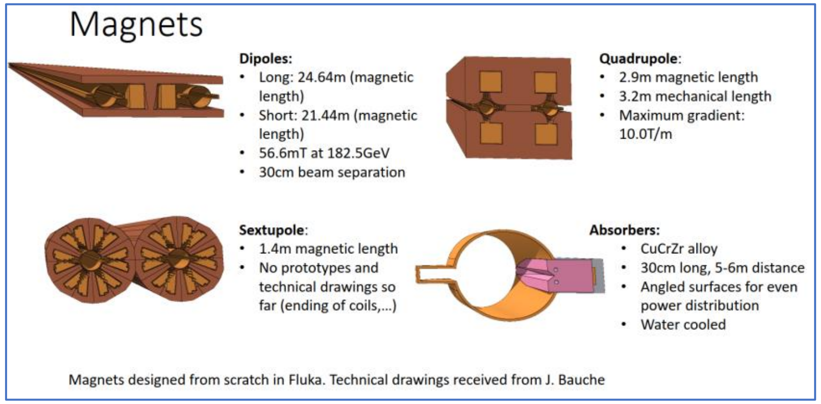


- 25 SR absorbers per beam. Design and initial placement by R. Kersevan
- Cu vacuum chamber with winglets
- 182.5GeV (ttbar); electrons & positron





Tunnel layout by F. Valchkova-Georgieva (IOWG, 16.10.2019)



Magnets

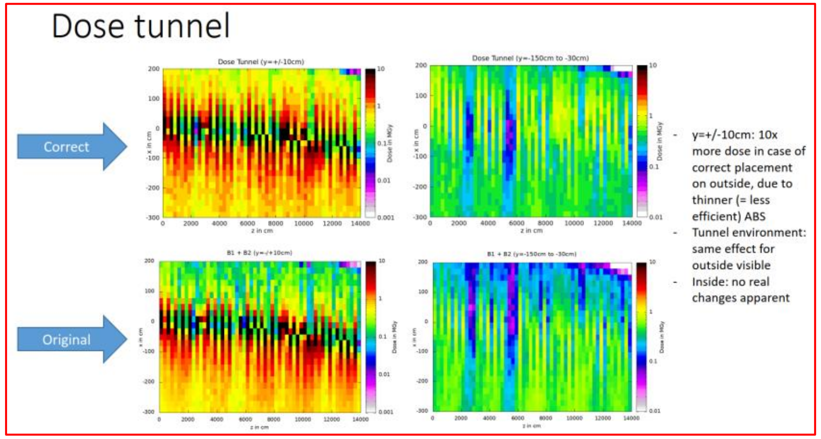
Dipoles:
- Long: 24.64m (magnetic length)
- Short: 21.44m (magnetic length)
- 56.6mT at 182.5GeV
- 30cm beam separation

Quadrupole:
- 2.9m magnetic length
- 3.2m mechanical length
- Maximum gradient: 10.0T/m

Sextupole:
- 1.4m magnetic length
- No prototypes and technical drawings so far (ending of coils,…)

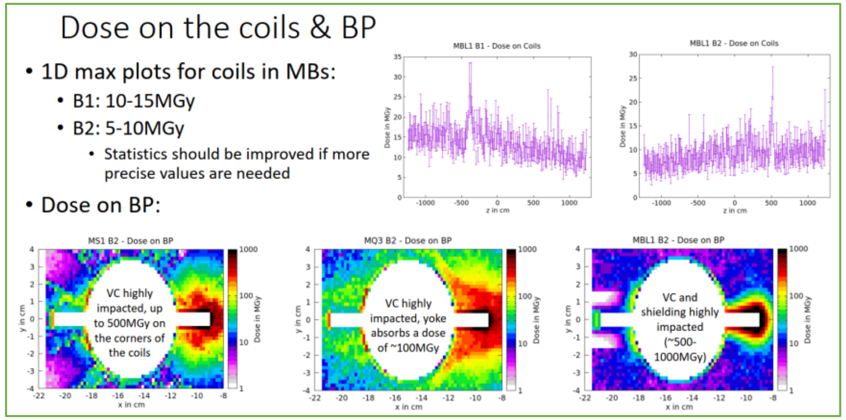
Absorbers:
- CuCrZr alloy
- 30cm long, 5-6m distance
- Angled surfaces for even power distribution
- Water cooled

Magnets designed from scratch in Fluka. Technical drawings received from J. Bauche



Dose tunnel

- y=+/-10cm: 10x more dose in case of correct placement on outside, due to thinner (= less efficient) ABS
- Tunnel environment: same effect for outside visible
- Inside: no real changes apparent



Dose on the coils & BP

- 1D max plots for coils in MBs:
  - B1: 10-15MGy
  - B2: 5-10MGy
    - Statistics should be improved if more precise values are needed
- Dose on BP:

VC highly impacted, up to 500MGy on the corners of the coils

VC highly impacted, yoke absorbs a dose of ~100MGy

VC and shielding highly impacted (~500-1000MGy)

Conclusions and Future Work, R&D, Prototyping

- **The conceptual design of the vacuum system of the FCC-ee collider rings has been obtained via extensive montecarlo modelling techniques**
- **As a starting point, we have taken and adapted some of the successful concepts applied on the SuperKEKB e-e+ collider**
- **We have determined that without NEG-coating, and it's well documented low PID yields, the commissioning of the machine at low-energy and high-current would take a long time, making it difficult to integrate the required luminosity at the experiments**
- **We plan, during the second phase of the Horizon 2020 funding, the FCCIS program(*), to design, fabricate and test one full-scale prototype of one arc half-cell (25 m or so), and of all vacuum components, such as RF bellows with low-loss RF contact fingers, SR absorbers, long vacuum chambers with integrated absorbers (study also the welding/brazing/… techniques), pumping domes**
- **We also have a part in the design of the vacuum system for the Machine Detector Interface area (see companion paper by M. Boscolo et al., this conf.)**
- **We will contribute to the integration of the vacuum system and components into the tunnel layout, in particular towards the integration of the full-energy booster machine**

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