CERN

Comparison of Two Accelerators at the Opposite End of the Spectrum

(The characteristics and specifications of the vacuum systems of the 100 keV antiproton decelerator ELENA vs that of the (50+50) TeV pp-collider FCC-hh)

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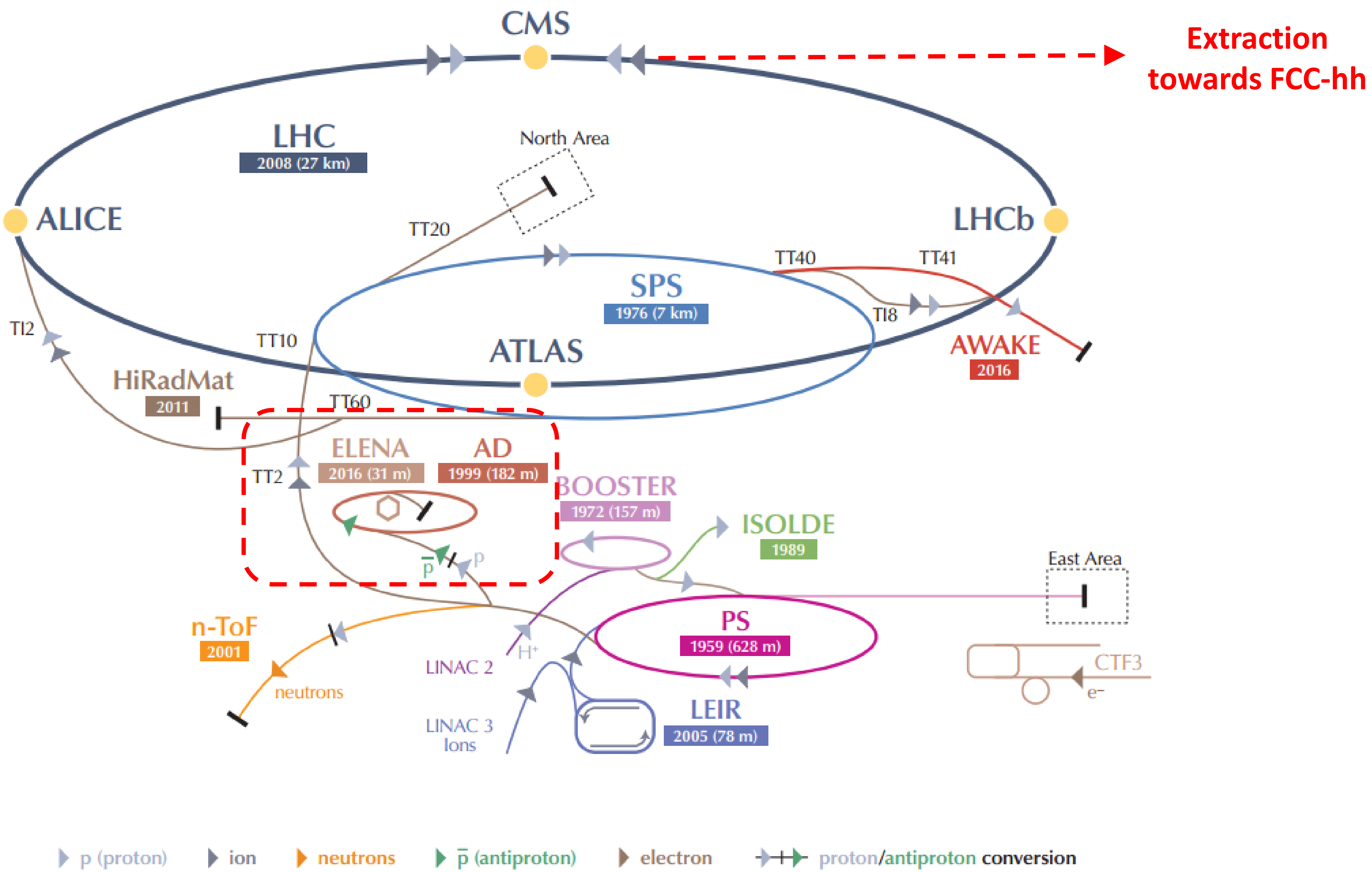
Starting point: the network of accelerators at CERN



Face to Face: ELENA FC vs C-hh

ELENA: Extra-Low ENergy Antiproton Decelerator Ring:

- Particles: **anti-protons or pbars** (extracted from **AD**, Antiproton Decelerator)
- Circumference: 30.4 m
- Beam energy: 5.3 MeV → 100 keV (decelerator!)
- Vacuum system: **room temperature**; pumping: mainly non-evaporable getters (NEG), coatings and pumps
- Vacuum spec.: **< $4x10^{-12}$ mbar** (<$9.9x10^{10}$ mol/m^3 (*))
- Requirement: due to the extremely low energy at extraction, it needs very low permeability materials for its vacuum chambers
- Duration of a deceleration cycle: ~20 seconds (see below)
- Start date: **2016/2017** (ring/experimental transfer lines)

(*) Density of a gas at 1 standard atmosphere at 20 °C: 2. $7x10^{25}$ mol/m^3

FCC-hh:

- Particles: **protons**
- Circumference: ~ 100 km (3.75x LHC)
- Beam energy: 3.3 → 50 TeV (ramped machine)
- Vacuum system: **cryogenic** (~ 80 km); **room temperature** (~20 km) (pumping: NEG coating + ion pumps)
- Vacuum spec.: **< $2x10^{14}$ H_2/m^3** (equivalent to 100 hrs nuclear beam-gas scattering lifetime, LHC **< $1x10^{15}$ H_2/m^3**)
- Beware: having a mix of cryogenic and room-temperature vacuum chambers the equation **PV=nRT** cannot be applied directly; the vacuum specification is given in **H_2-equivalent density**
- Duration of a filling/acceleration cycle: ~ 1-2 hours
- Start: **> 2030~2040** (after the end of the HL-LHC experimental program)

Face to Face: ELENA vs FCC-hh

ELENA:

- Main Vacuum Issues:

1. The small size and compactness of the ring does not leave much space for the installation of conventional pumps
2. It has therefore been decided to apply the ***non-evaporable thin-film technology*** ("**NEG-coating**", CERN patent)
3. The main equation of vacuum technology for particle accelerators is: **P = Q /S** (P=pressure; Q=outgassing rate; S=effective pumping speed)
4. From this equation one can derive the conclusion that, for S limited by the space available to pumps, the only way to decrease P is to minimize Q, i.e. the number of molecules desorbed by the walls of the vacuum chamber, and also that of any components placed inside of it
5. An efficient way of reducing Q is to use a high-temperature "vacuum firing" (650~1100 C), in a dedicated oven which is available on the Meyrin site of CERN
6. A particular kind of austenitic stainless steel has been therefore selected: **316 LN** (in addition to better mechanical properties it also has a lower magnetic permeability)

FCC-hh:

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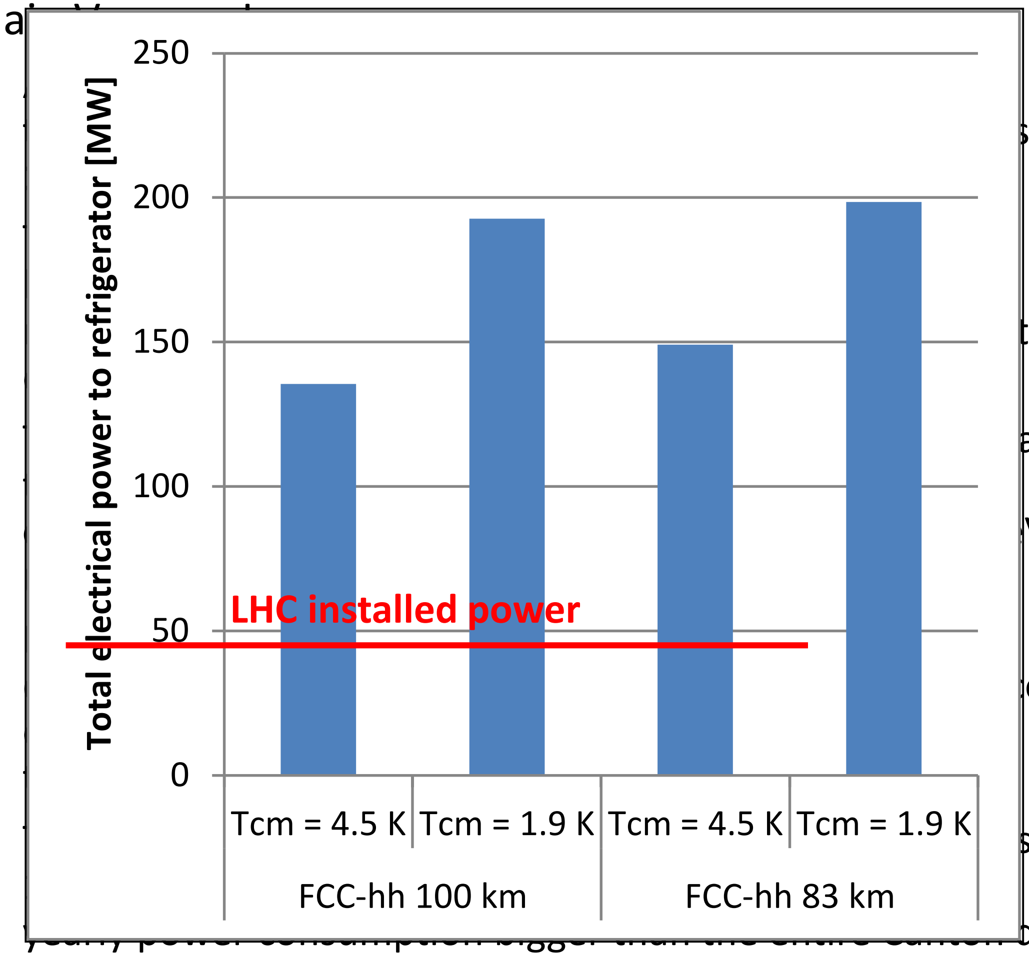


Geneve (1.2 TWh/anno), see plot (credit: L. Tavian, CERN, FCC Week, Washington DC, 2015)

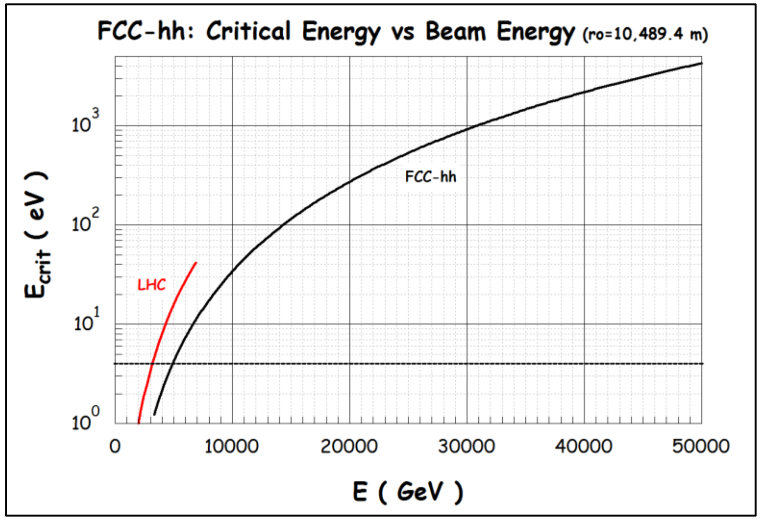
(*) **SR critical energy**: median energy of the generated photons: ½ of the power is generated above it, ½ below.

Face to Face: ELENA vs FCC-hh

ELENA:

- Main Vacuum Issues (cont.):

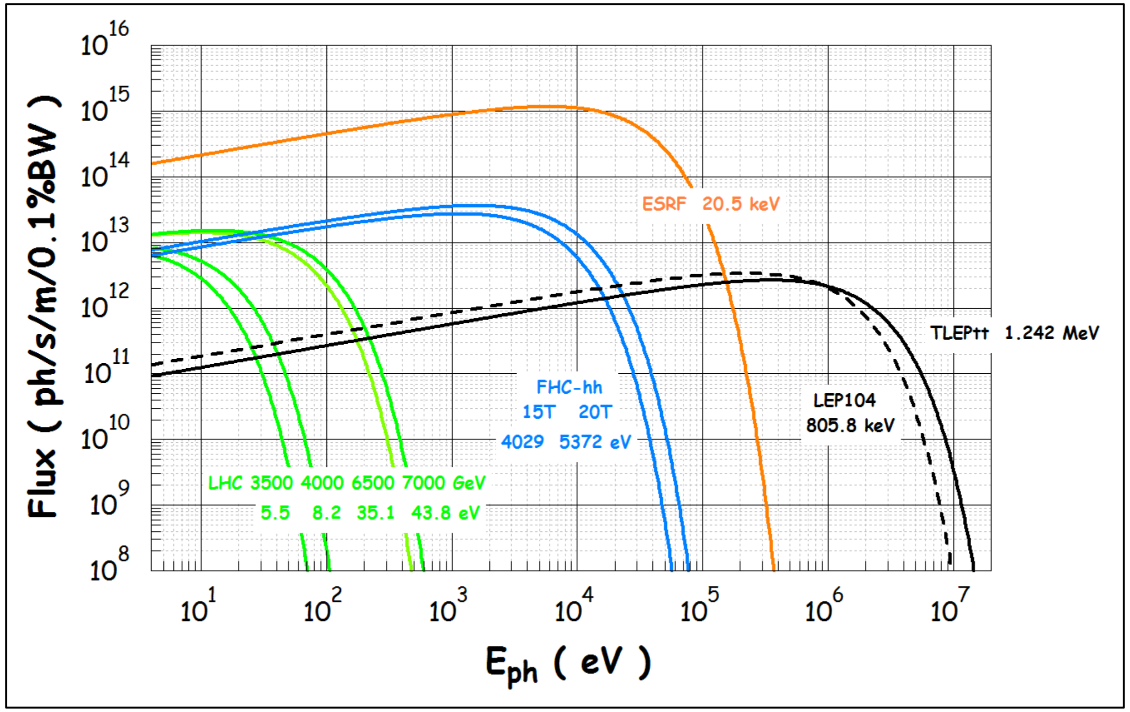
7. The main source of gas load in ELENA is **thermal outgassing**
8. NEG-coating needs to be activated at temperatures above 180 °C in order to develop a pumping speed (sticking coeff ~ 0.008 for H_2)
9. Before activating the NEG, it is mandatory to remove all of the water vapour which is present on the walls of the vacuum system, the so-called "**bake-out**" (> 120 C)
10. The ELENA vacuum system must therefore be bakeable"**in situ**" without damaging any components placed near it (like windings of magnets, cables, delicate feed-throughs, etc…)



FCC-hh:

- Main Vacuum Issues (cont.):

6. The SR photon flux in FCC-hh is so large that it can generate the so-called **"electron cloud"**, a very detrimental effect which could make the accelerator very difficult to run (heat deposition on the cryogenic system and beam detuning, among other things)
7. The **spectral flux distribution** of FCC-hh vs LHC is shown here, together with that of an electron light source (ESRF, Grenoble), the LEP at 104 GeV and a version of FCC-ee at 175 GeV (ttbar channel)

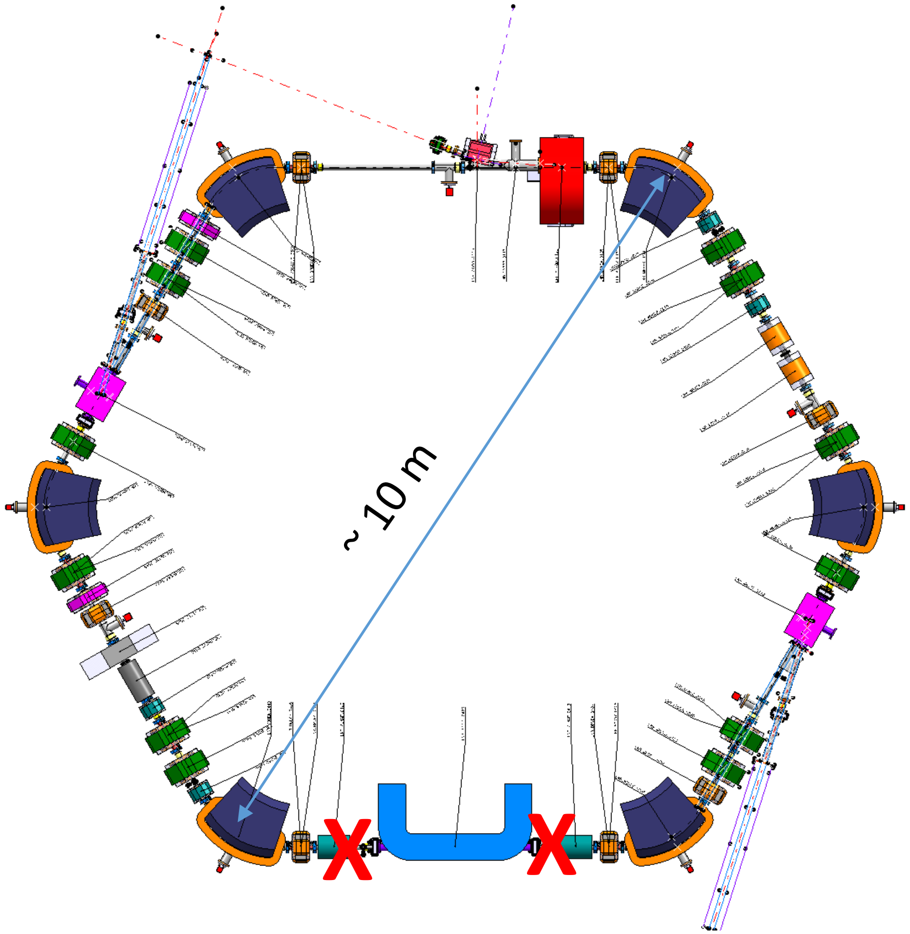


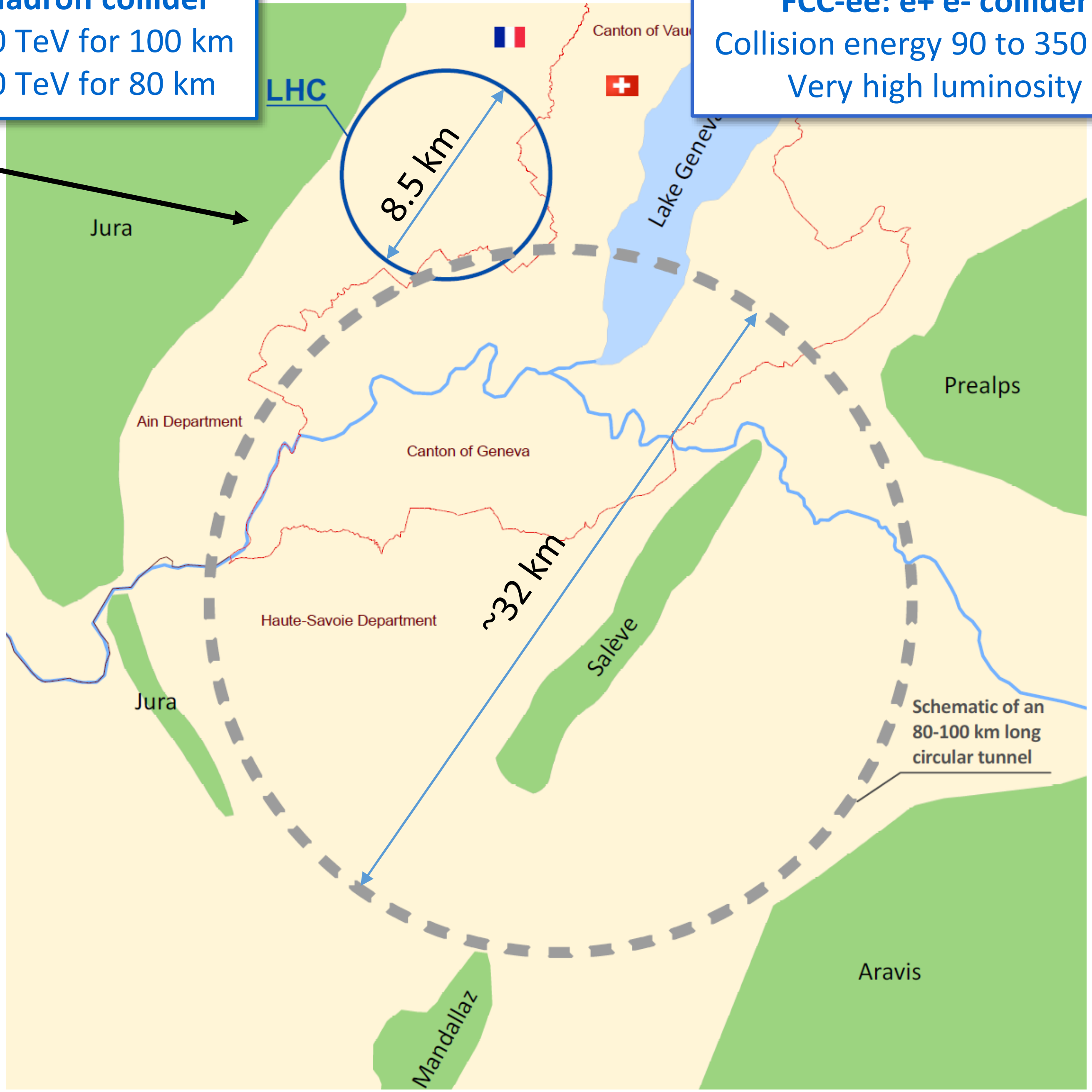
Fcc-hh: Hadron collider
16 T ⟹ 100 TeV for 100 km
20 T ⟹ 100 TeV for 80 km

FCC-ee: e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity

At this scale.

The tiny **ELENA ring** (below), with its 10m ***equivalent diameter***, is smaller than the dot at the end of this sentence.

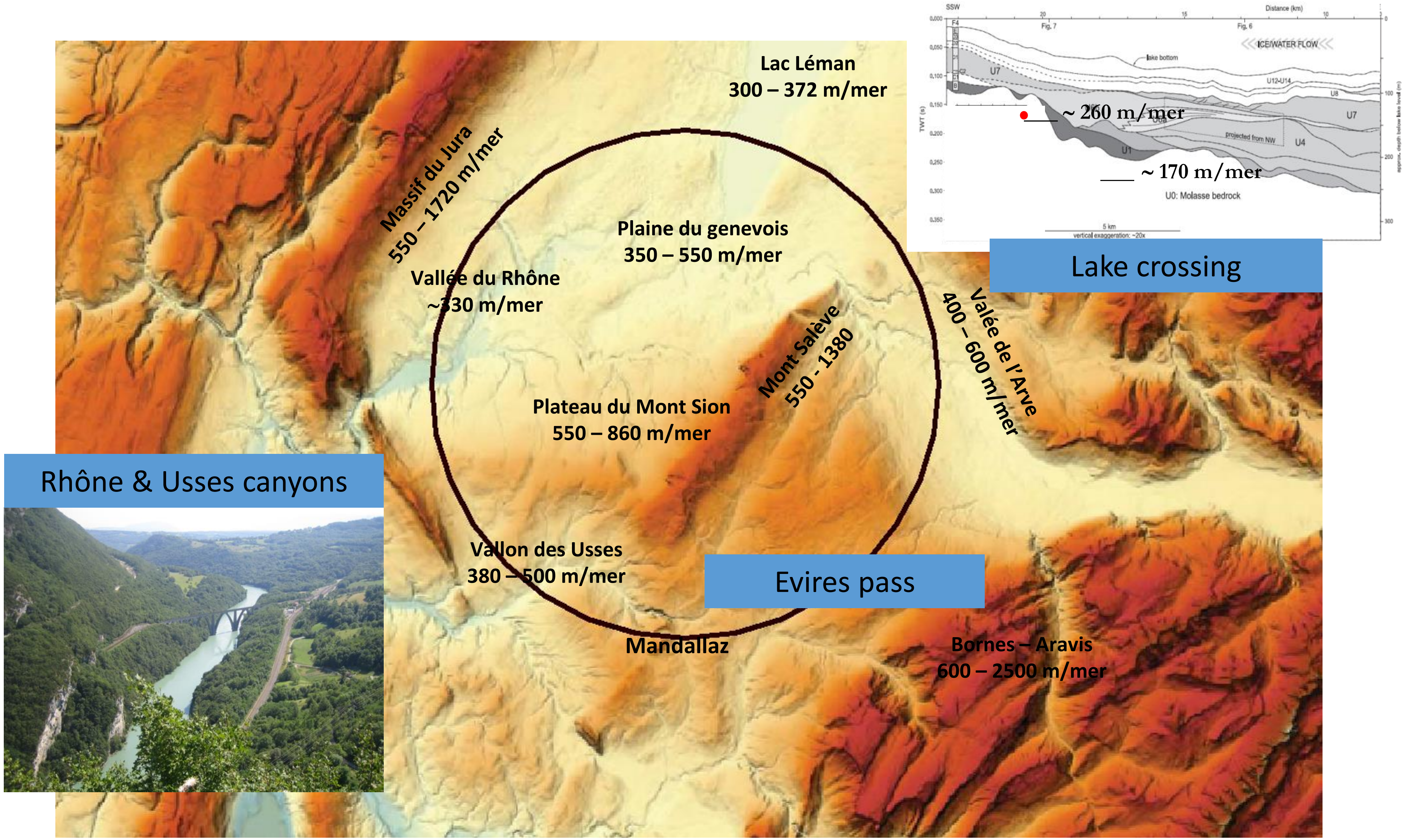




Credit: Ph. Lebrun, CERN, FCC Week 2015 - Washington, DC

FCC-hh:

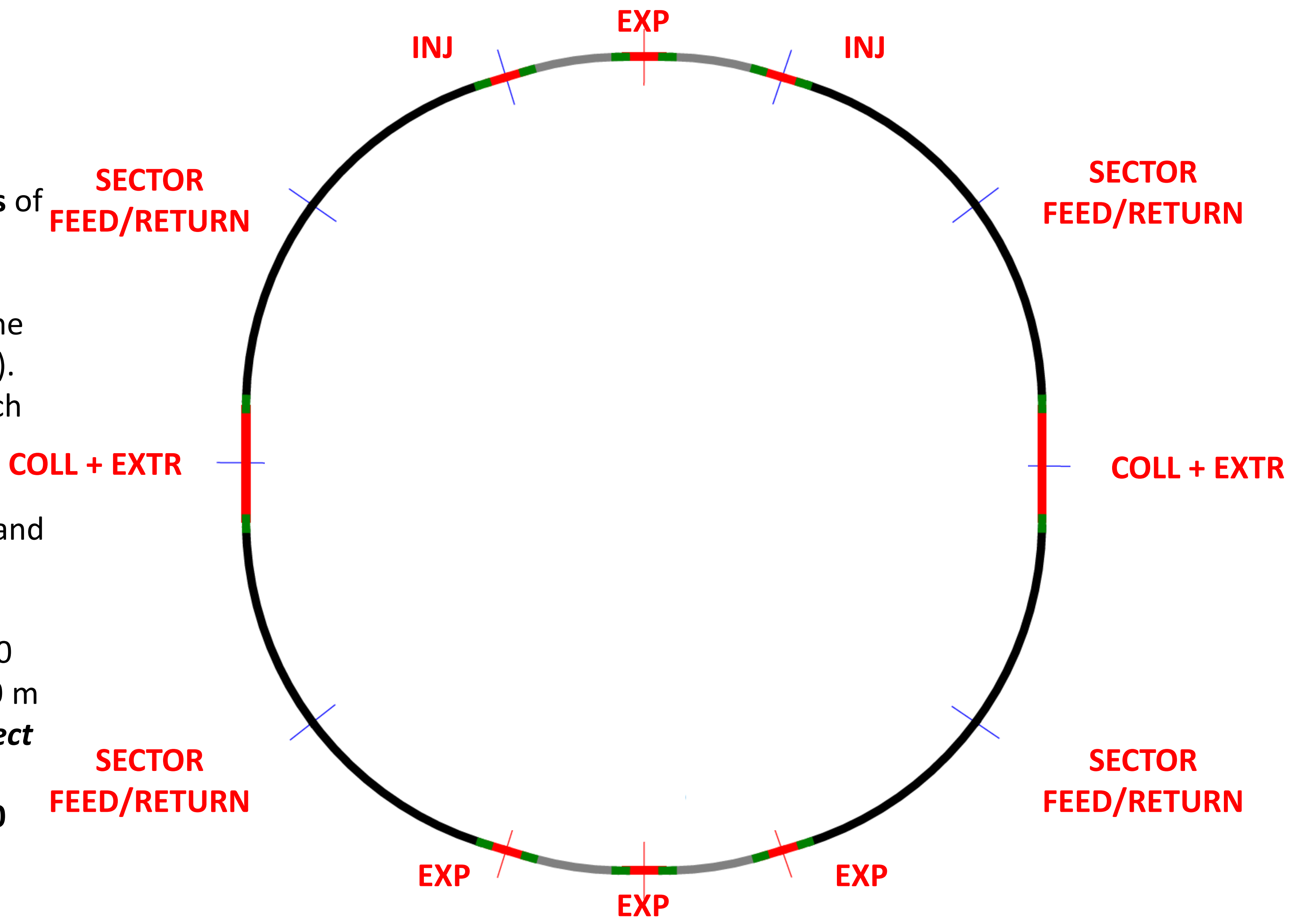
- Feasibility studies aiming at identifying the best location/orientation of the ring vis a vis the composition of rocks along the path of the ring have already;
- The ring must be place so as to avoid vertical shafts too deep (<500 m)



Credit: Ph. Lebrun, CERN, FCC Week 2015 - Washington, DC

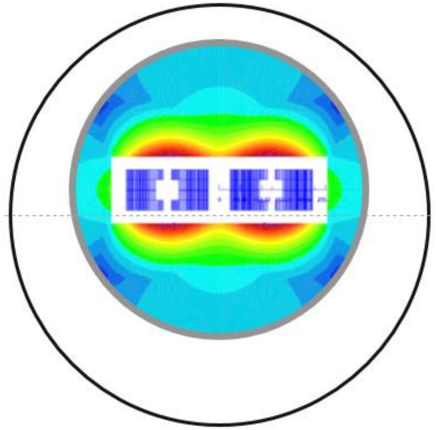
FCC-hh: RING LAYOUT:

- Like for the LHC, the FCC-hh ring is split in several sections, called arcs and long straight sections (LSS).
- The **arcs** are mainly a repetition of hundreds of base "**cells**", approximately 200 m-long each, which contain the main dipoles, quadrupoles, correctors that define the ***lattice*** and the **optics** of the machine.
- The lattice defines the quality of the beam (emittance, beam size) and the **luminosity** of the collisions at the experimental locations ("EXP")).
- There are 2 **injection zones** ("INJ"), one per each counter-rotating beam.
- The high energy beams must be "**collimated**" (zone "COLL+EXTR"): the collimators intercept and remove from the machine in a controlled and "safe" way any stray protons.
- The kinetic energy (KE) stored in the beam at 50 TeV is huge, capable of penetrating across ~340 m of copper via the ***hydrodynamic tunnelling effect*** (LHC ~ 38 m).
- The KE totals **8.5 GJ**, i.e. the equivalent of **a 500 ton Airbus A380 at 660 km/h**.



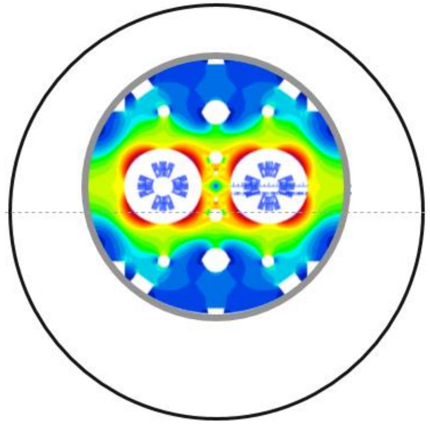
Credit: Ph. Lebrun, CERN, FCC Week 2015 - Washington, DC

- One possible layout of the **FCC-hh** tunnel in the **arcs** (right)
- See the location of the superconducting magnets in the **lower left side of the tunnel** (1200 mm maximum cryostat diameter), and here below some of the possible coil designs for the dipoles and quadrupoles



Dipole

(bends the beam)
Magnetic field 16 T

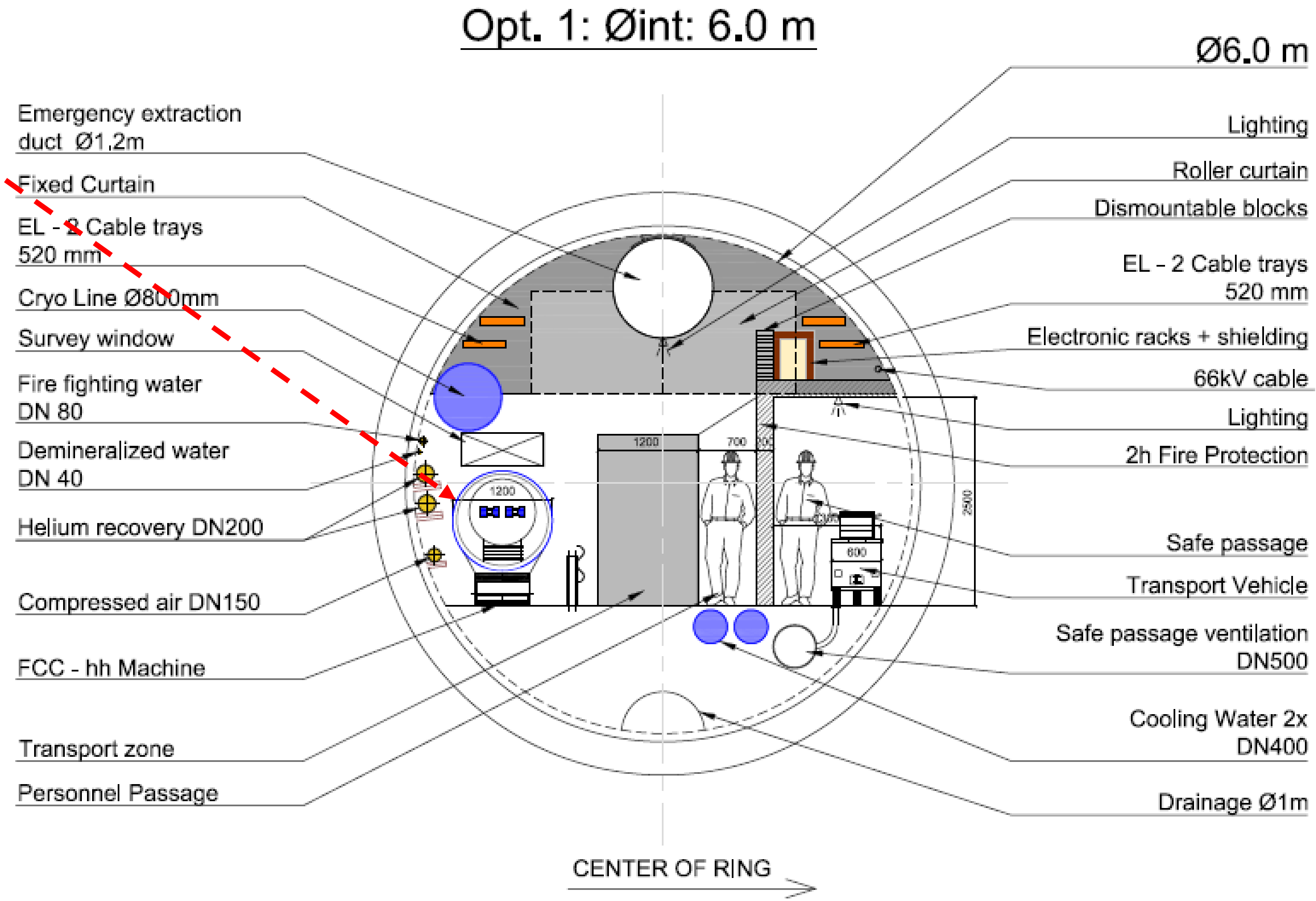


Quadrupole

(focusing)
Mag. gradient ~380 T/m

(courtesy E. Todesco, CERN)

Coil ID: 50 mm →



Credit: Ph. Lebrun, CERN, FCC Week 2015 - Washington, DC

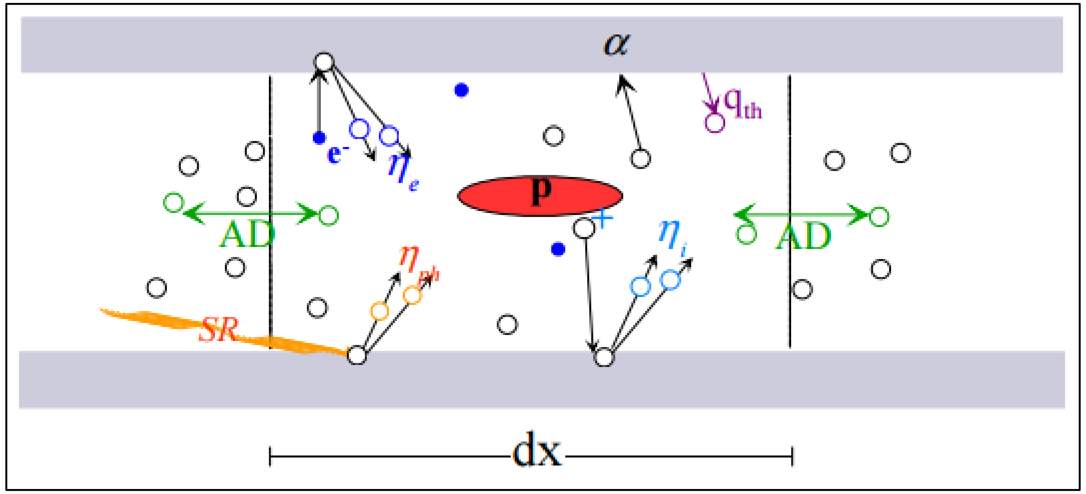
The tiny coil ID (50 mm) represents a real challenge for the cryogenic and vacuum groups, as the space to intercept and dispose of the large SR power (and any other power sources) and provide pumping is very small!

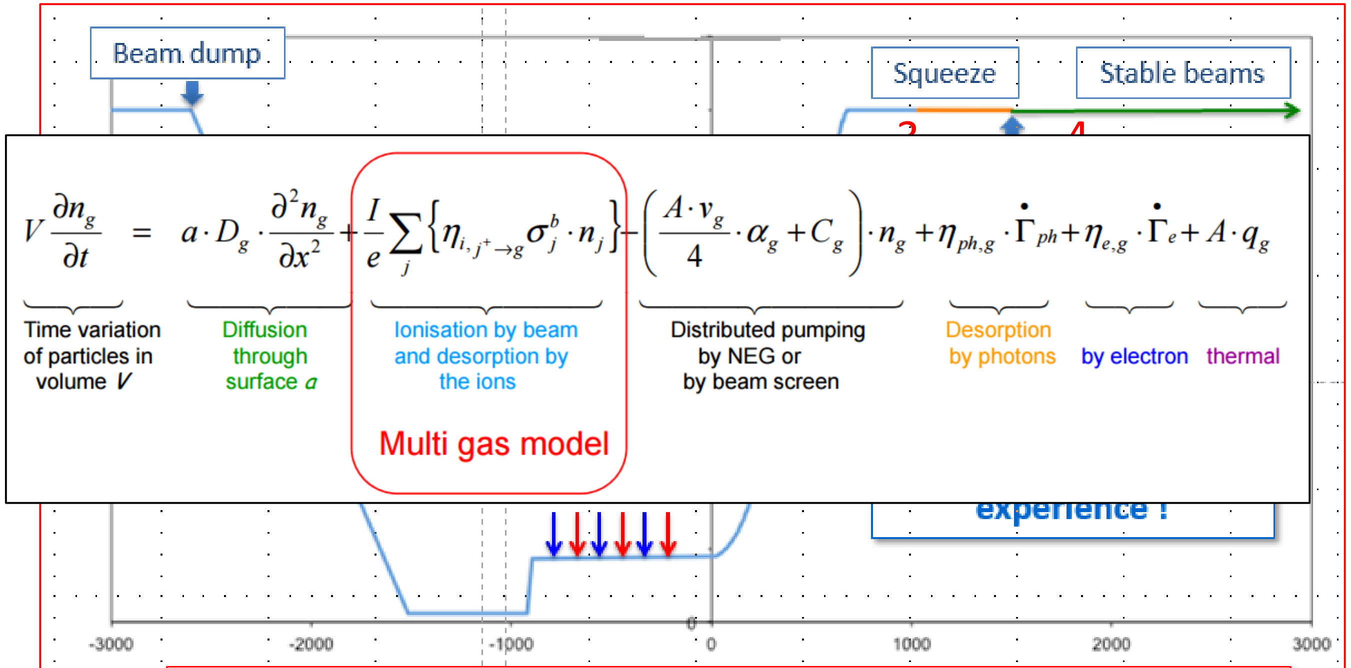
FCC-hh:

Face to Face: ELENA vs FCC-hh

- **Vacuum working scheme (arcs):**

1. **Same as that of the LHC**: **1)** Injection and storage at low-energy (3.3TeV); **2)** Energy ramp-up to 50 TeV; **3)** Collimation and beam-“squeeze” to collision conditions; **4)** start collision phase; Time scale, extrapolating from several years of experience on the LHC: 1000~2000 seconds, followed by 4~6 hours of collisions (limited by ***luminosity burn-out***).
2. During these 2 phases the SR spectrum, the **photon flux**, and the **SR-induced outgassing**, span several orders of magnitude, and **different physical phenomena take place**: **1)** electron cloud; **2)** ***re-cycling*** by SR of physisorbed molecules; **3)** residual gas ionization (by the proton beams) and consequent generation of more gas species via **ion-bombardment**; **4)** **beam-screen** heating due to SR and other effects (impedance), which entails a change of the **equilibrium pressures** of the various gas species.
3. These processes can be modelled via a **multi-gas model,** which can be described by a set of differential equations (1 for each gas specie):





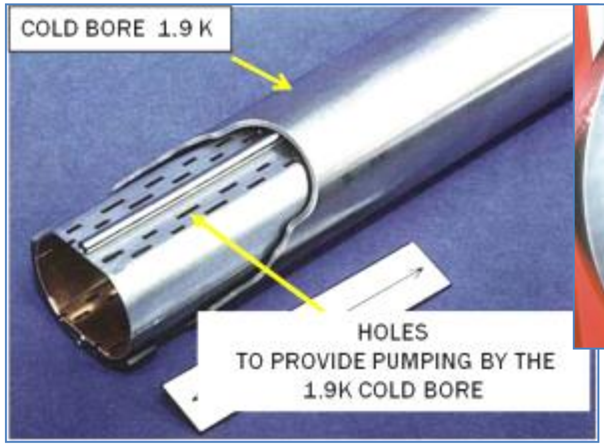
Credit: Ph. Gayet, “Control concepts for future circular accelerators: why it is not too early to speak about them”, FCC Week, Washington DC, 2015

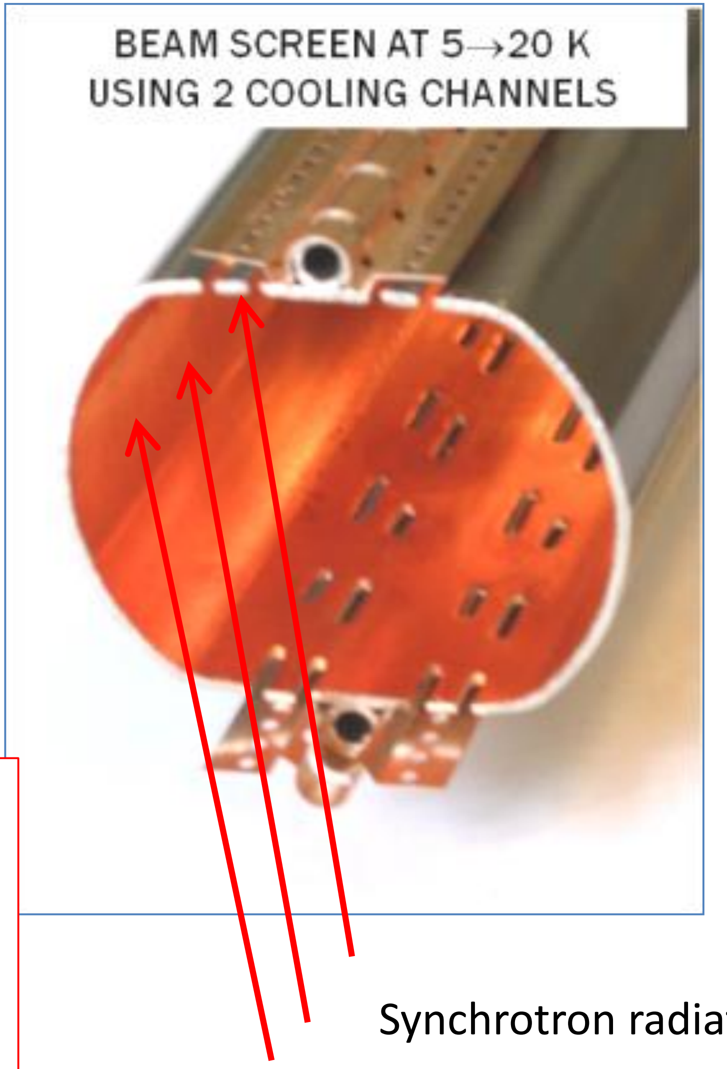
4. All these contributions must be quantified precisely and practical **engineering solutions** implemented. Some of them are still “***terra incognita***”, as they have never been experienced before at the levels attained by FCC-hh.

LHC arcs pumping scheme: perforated “**beam screen**” (BS) kept at 5~20 K (supercritical He) inside the 1.9 K **cold-bore** cooled by superfluid He

LHC beam screen:

Linear SR power density: 14 mW/m @ 3.5 TeV
222 mW/m @ 7.0 TeV





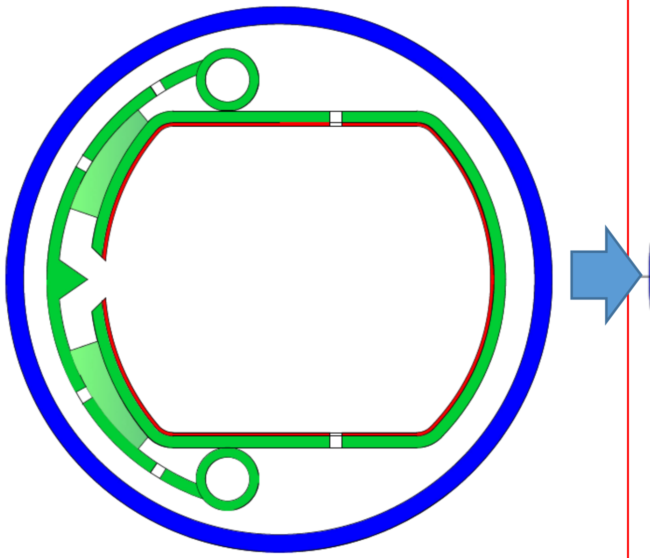
Synchrotron radiation fan

1) SR desorbs H_2, CO, CO_2, CH_4 molecules from the BS walls;
2) The molecules move randomly until they go through one of the many perforated slots (***molecular regime***);
3) Once they hit the 1.9 K CB they are permanently pumped

- Unfortunately the pumping scheme (BS geometry) of the LHC **can not** be copied to the FCC-hh, due to the large difference in power density to absorb, transport and dissipate (~ 30 W/m vs 0.18 W/m in the LHC):
  - An immediate consequence of this is that the FCC-hh BS temperature must be **increased** in the range **40 ~ 60 K**, as compared to the **5 ~ 20 K** of the LHC;
  - This conclusion could have large repercussions on the vacuum (***equilibrium vapour pressure*** and related instabilities); We are still looking at how to test this and validate the design;
- Moreover, the SR photon flux in FCC-hh at 50 TeV is **much bigger** than that of LHC at 7 TeV (**~3.6x bigger**), and therefore **the amount of gas to be pumped is correspondingly bigger**. Another compounding effect is that the peak residual "**H_2-equivalent**" gas density must be kept **~5x lower** inside of the BS of FCC-hh as compared to LHC's (to balance the ~5x increased nuclear scattering cross-section).
- The required molecular density improvement factor is **~ 20x better (lower)**:
  - **Consequence:** we must **improve pumping and/or decrease the SR-induced outgassing rate**; This leads us to the need to study in detail and find solutions for obtaining surface treatments with lower outgassing yields;
- A **EuroCircol** R&D program, a collaboration between CERN and 5 other research institutes is underway; it aims at developing a conceptual BS design, and testing it with SR fans at the ANKA light source;
- The program also aims at testing surface treatments capable of avoiding the e-cloud effect: **Laser Engineered Surface Structures** (**LESS**) technology (ASTeC) and **amorphous-carbon coatings** (CERN), among other possibilities.

Genesis of the design of the beam screen for FCC-hh

→ Total SR power generated in **LHC at 7 TeV**: **3.3 kW** ; Total SR power generated in **FCC-hh at 50 TeV**: **2.32 MW ~ 700x higher** ←

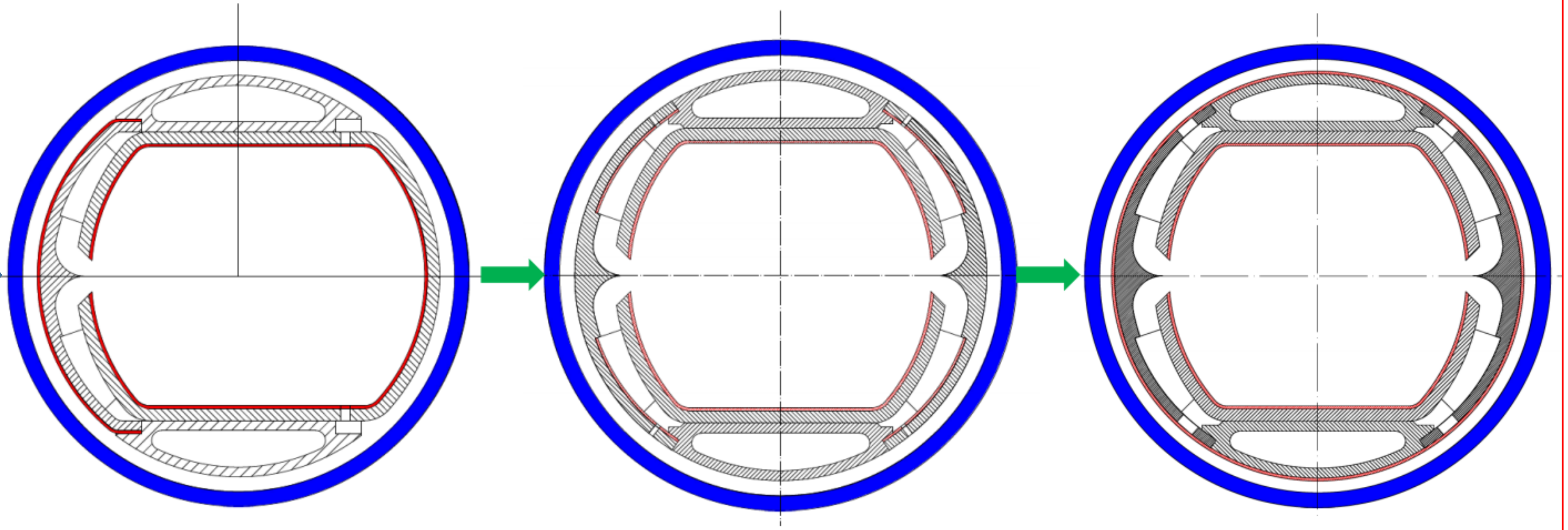


Original proposal at “FCC Week Conference”, Washington D.C., May 2015;

One-slot BS with reduced number of pumping slots (source of impedance)

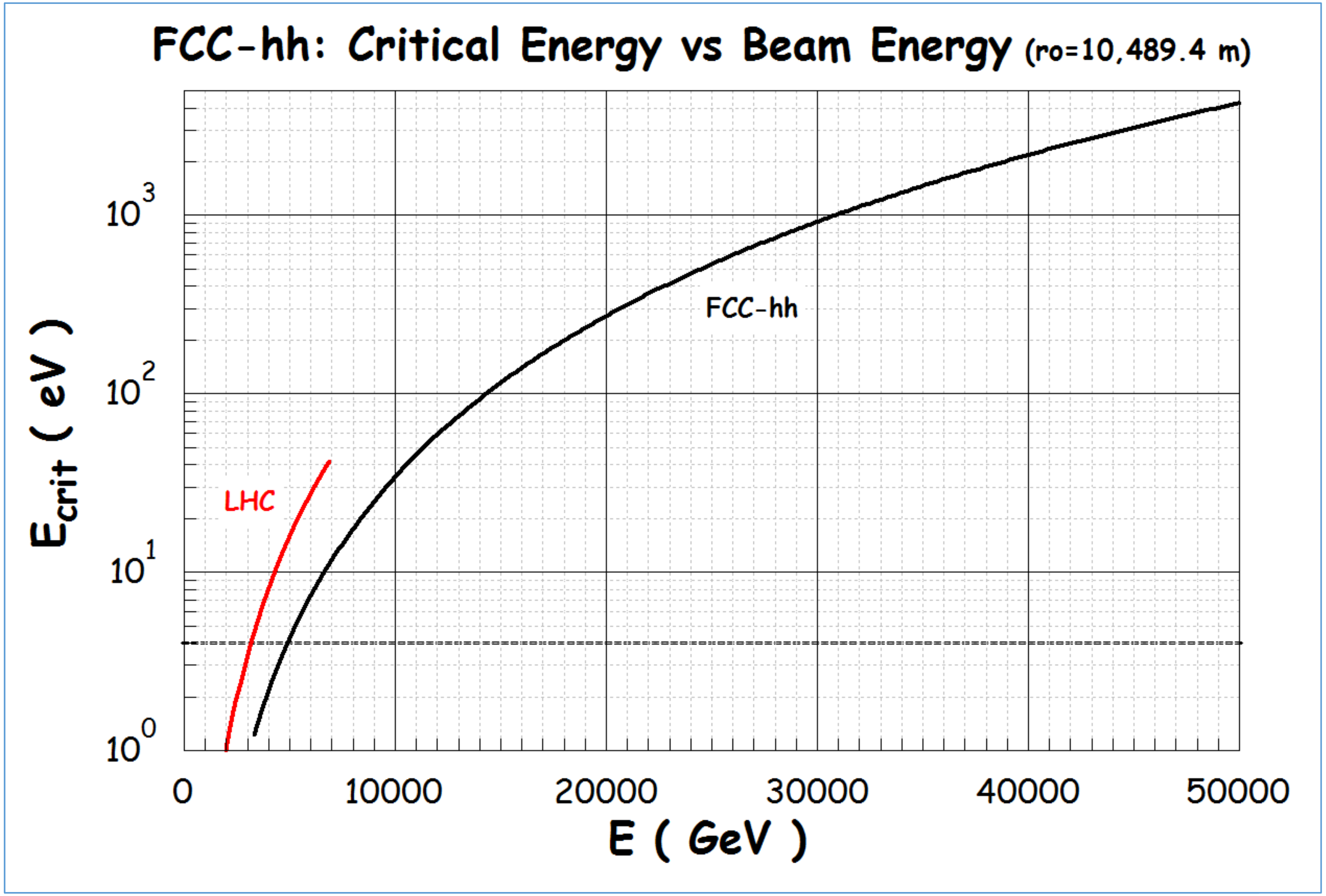
EuroCirCol
A key to New Physics

Design Updates



- Symmetrical design
  - → Better impedance
  - → Pumping holes hidden by the screen
- Thermal copper coating on the outer side
- Bigger pumping holes – no constraint for the distribution

Critical energy E_{crit} of the SR photon spectrum for FCC-hh vs beam energy: it is shown that up to about 5 TeV E_{crit} stays below **4 eV** (i.e. it cannot generate neither **photo-electrons** (**direct seed of e-cloud**) nor **photon-induced gas desorption** (**indirect seed of e-cloud via gas ionization**), as there is a threshold due to the work function of the metallic walls of the vacuum chamber)

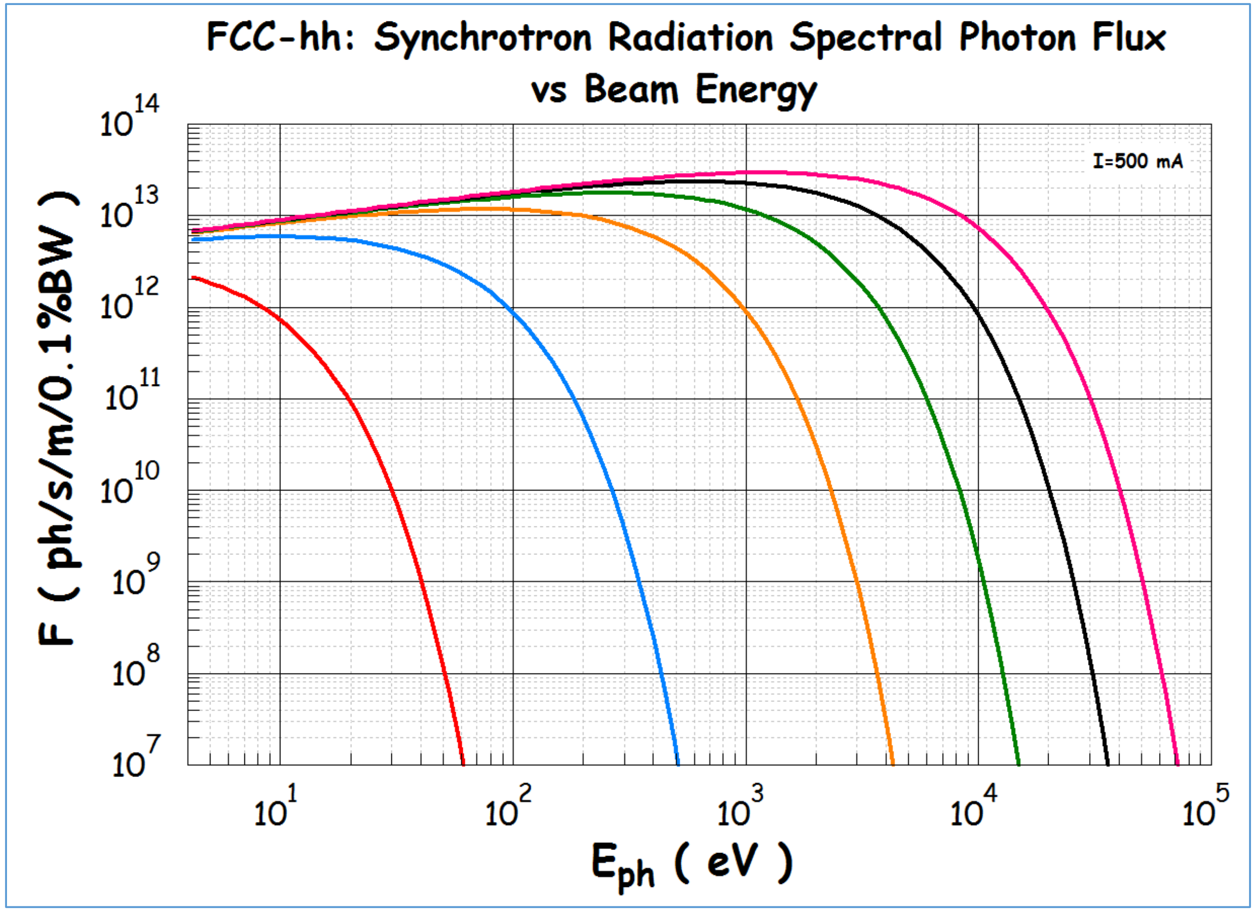


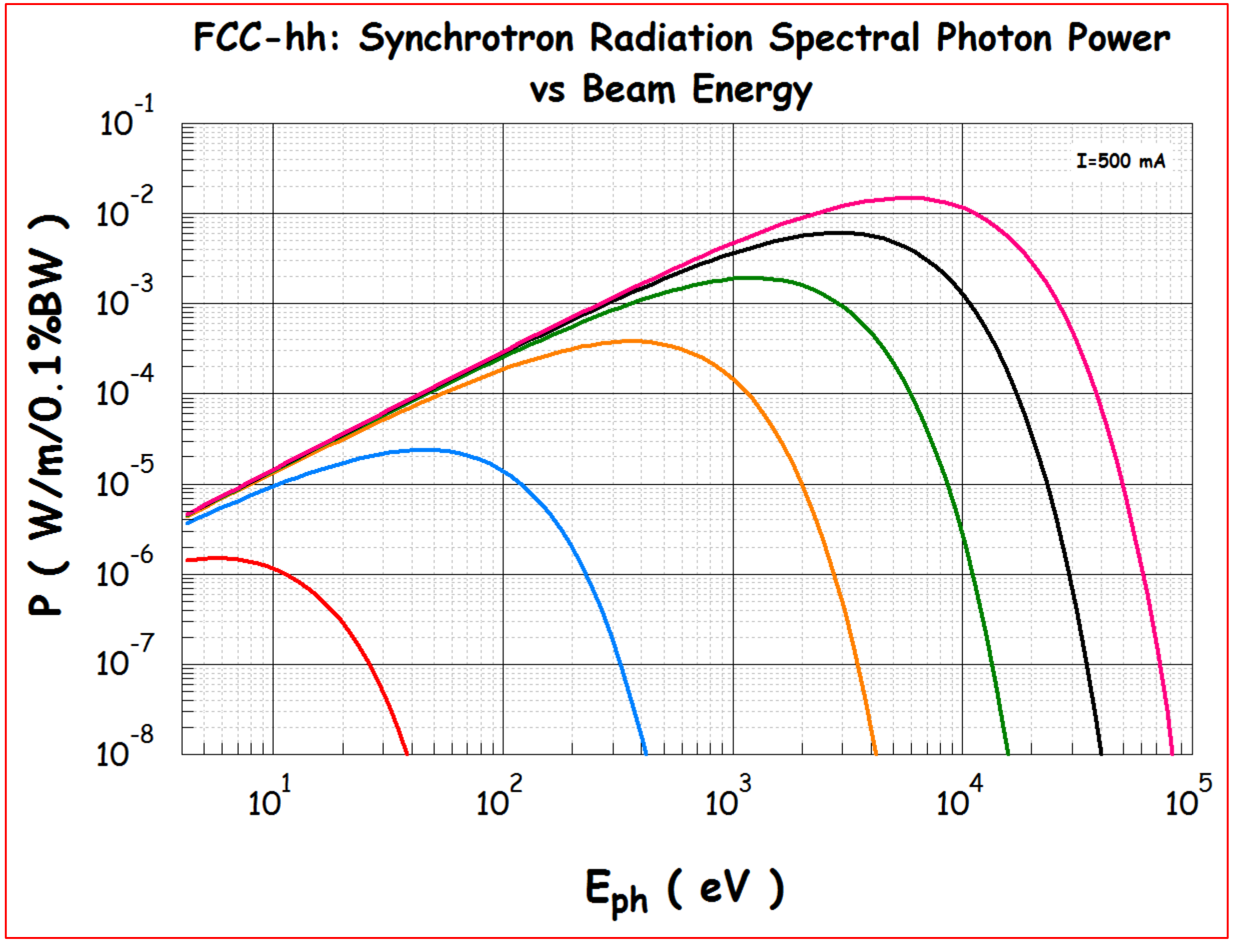
E (TeV)	F (ph/s/m)	P (W/m)
3.3	5.6848e+13	0.0000
5	1.5818e+15	0.0018
7.5	7.2822e+15	0.0153
10	1.4609e+16	0.0535
15	3.0563e+16	0.2820
20	4.7361e+16	0.8979
25	6.3581e+16	2.1966
30	8.0213e+16	4.5582
40	1.1355e+17	14.4130
50	1.4693e+17	35.1923

LHC: Critical energy **E_{crit} = 43.8 eV** (@7 TeV);
Flux = 4.2e+16 ph/s/m (@500 mA)
Power = 0.183 W/m " "

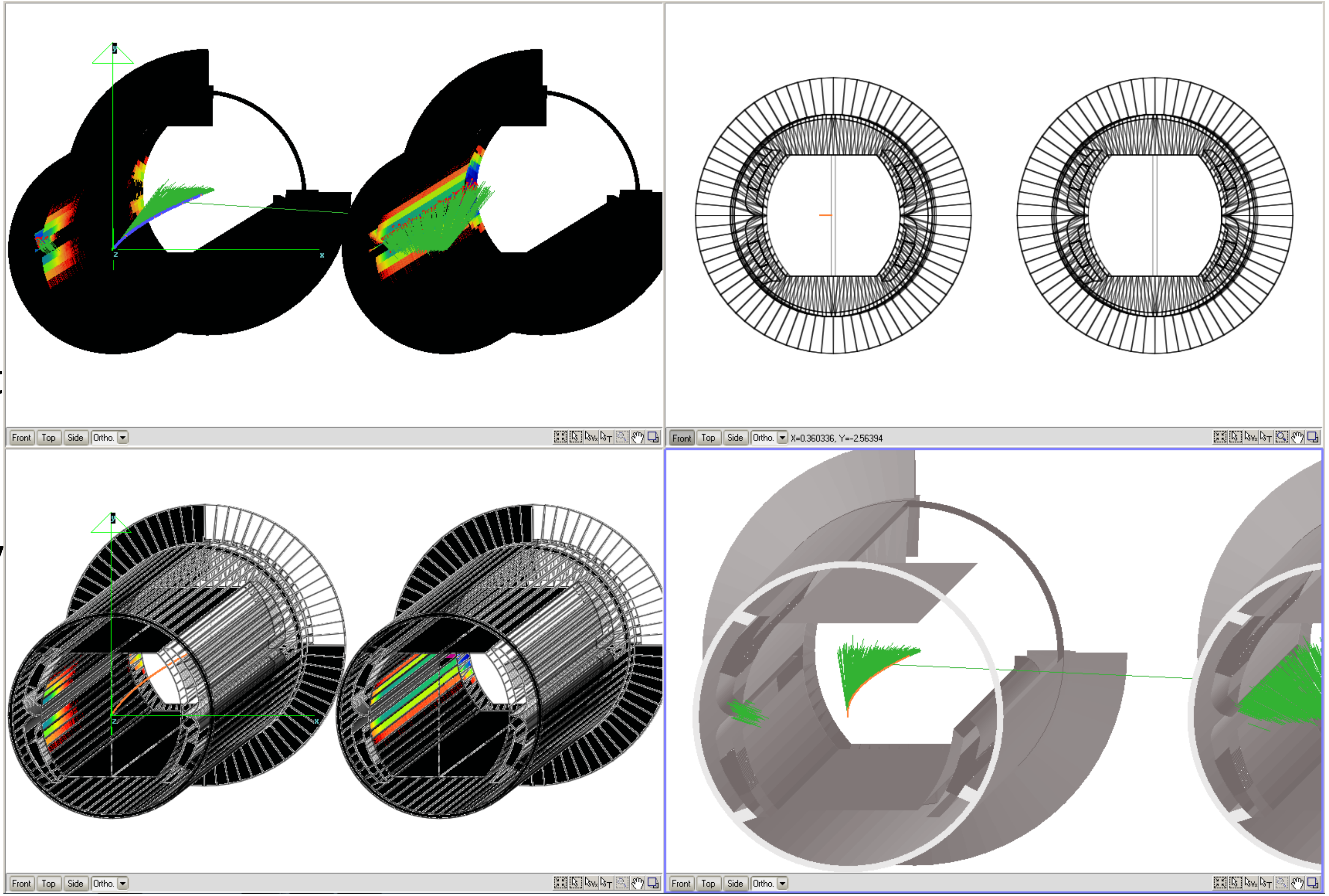
FCC-hh: SR flux and power spectra vs proton beam energy

1. **Left:** SR **flux** spectra for FCC-hh vs beam energy (for 5, 10, 20, 30, 40, 50 TeV) for a 1 m-long arc of dipole trajectory
2. **Right:** Same for the SR **power** spectra;





- **Detailed Montecarlo simulations** of the SR fans are also mandatory (here 2x 14.3 m long connected dipoles, with quadrupole section are shown side-by-side, for clarity): **E=20 TeV;**
- The SR photon fans going out from the dipole on the left are transported to the entrance of the dipole on the right;
- The curvature of the orbit inside of the **cold-bore** is visible (**Length=14.3 m**), same as for the LHC;
- Total power ~500 W/dipole at 50 TeV, 12.8 W/dipole at 20 TeV (LHC: 2.6 W/dipole at 7 TeV);
- Photons are generated only along the orbit of the first dipole, for clarity.



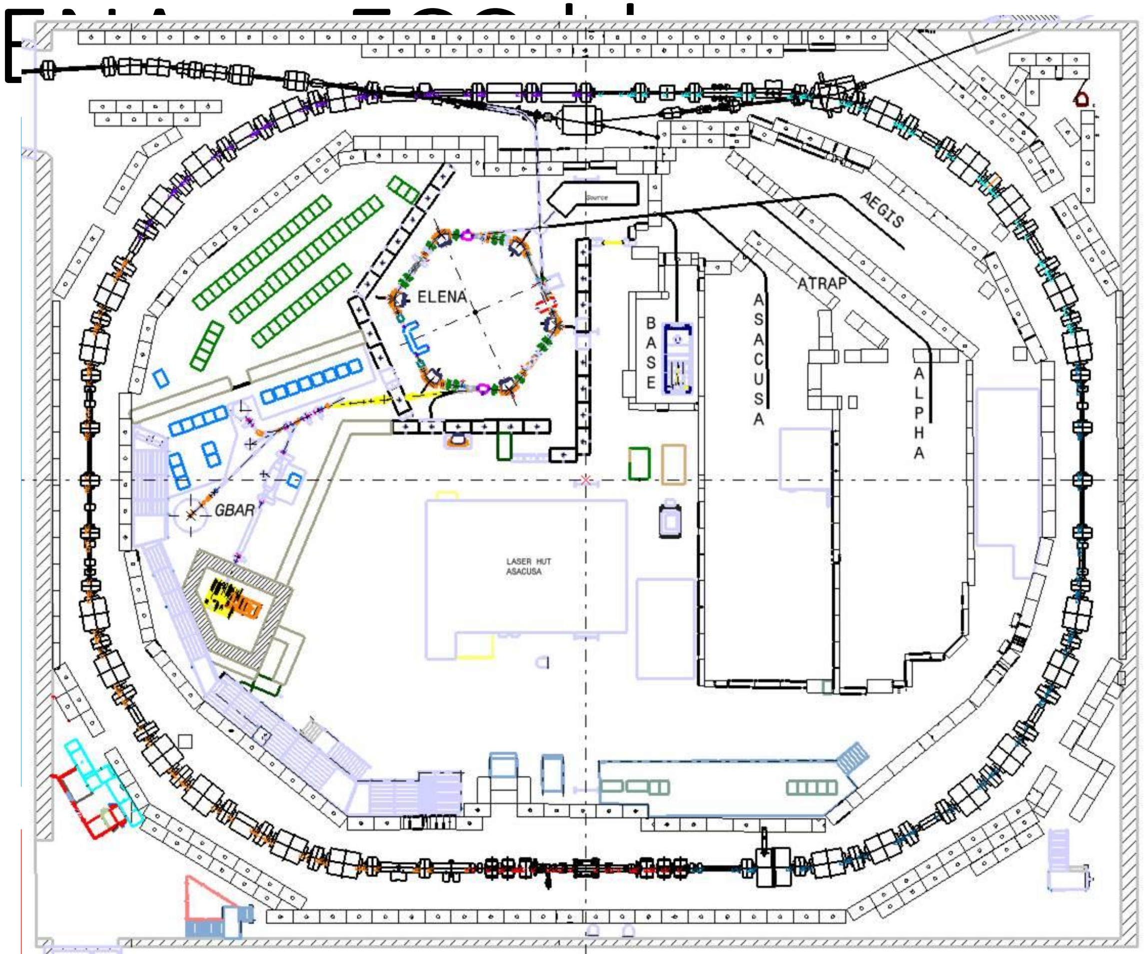
Code used: SYNRAD+

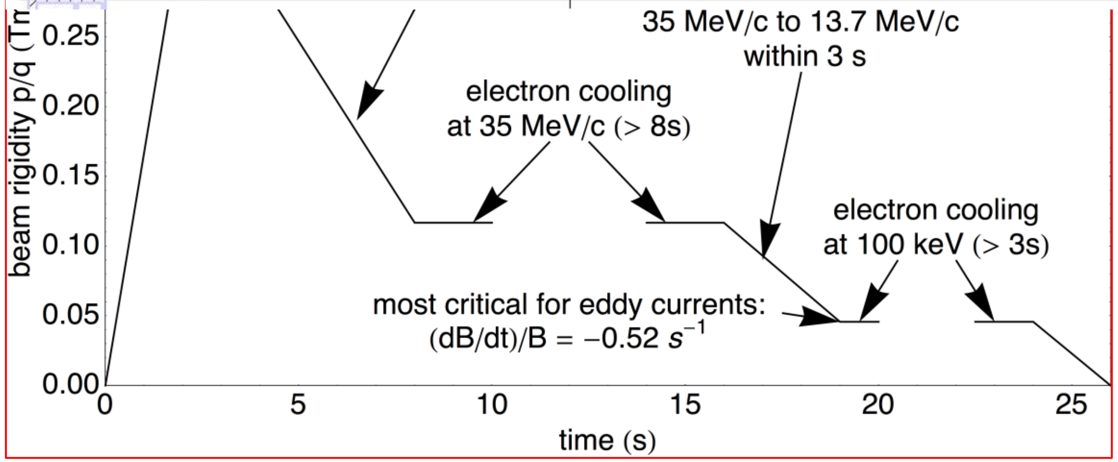
Face to Face: ELE

ELENA:

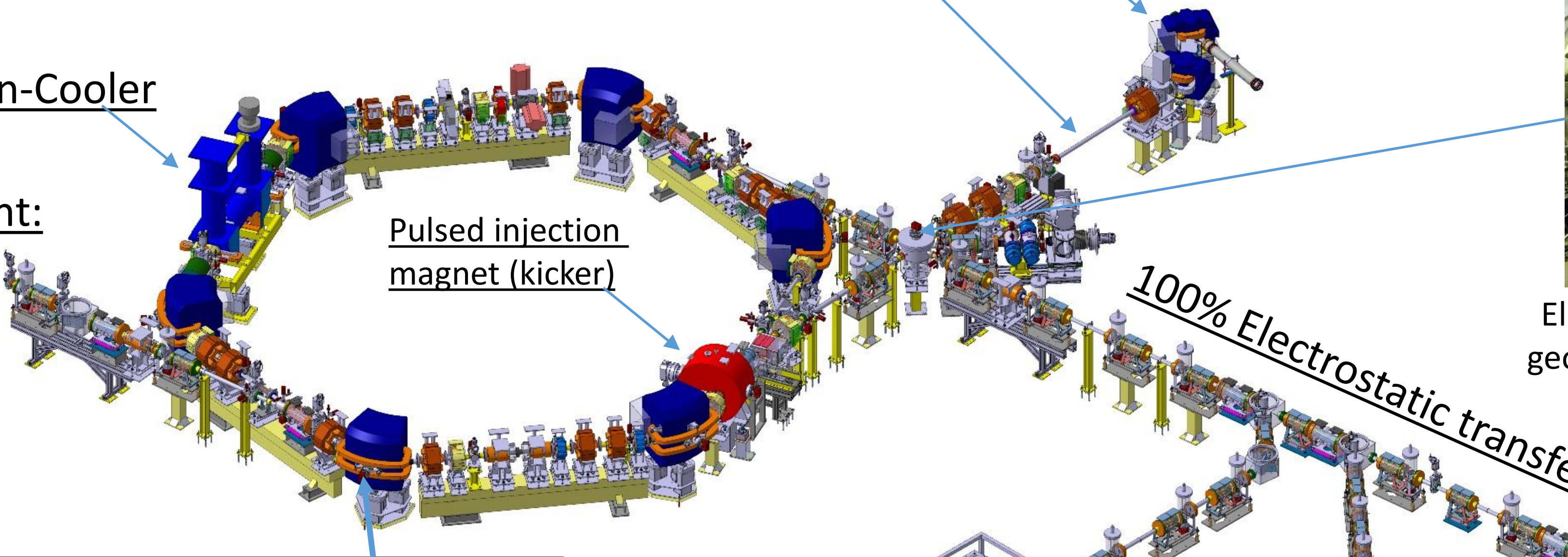
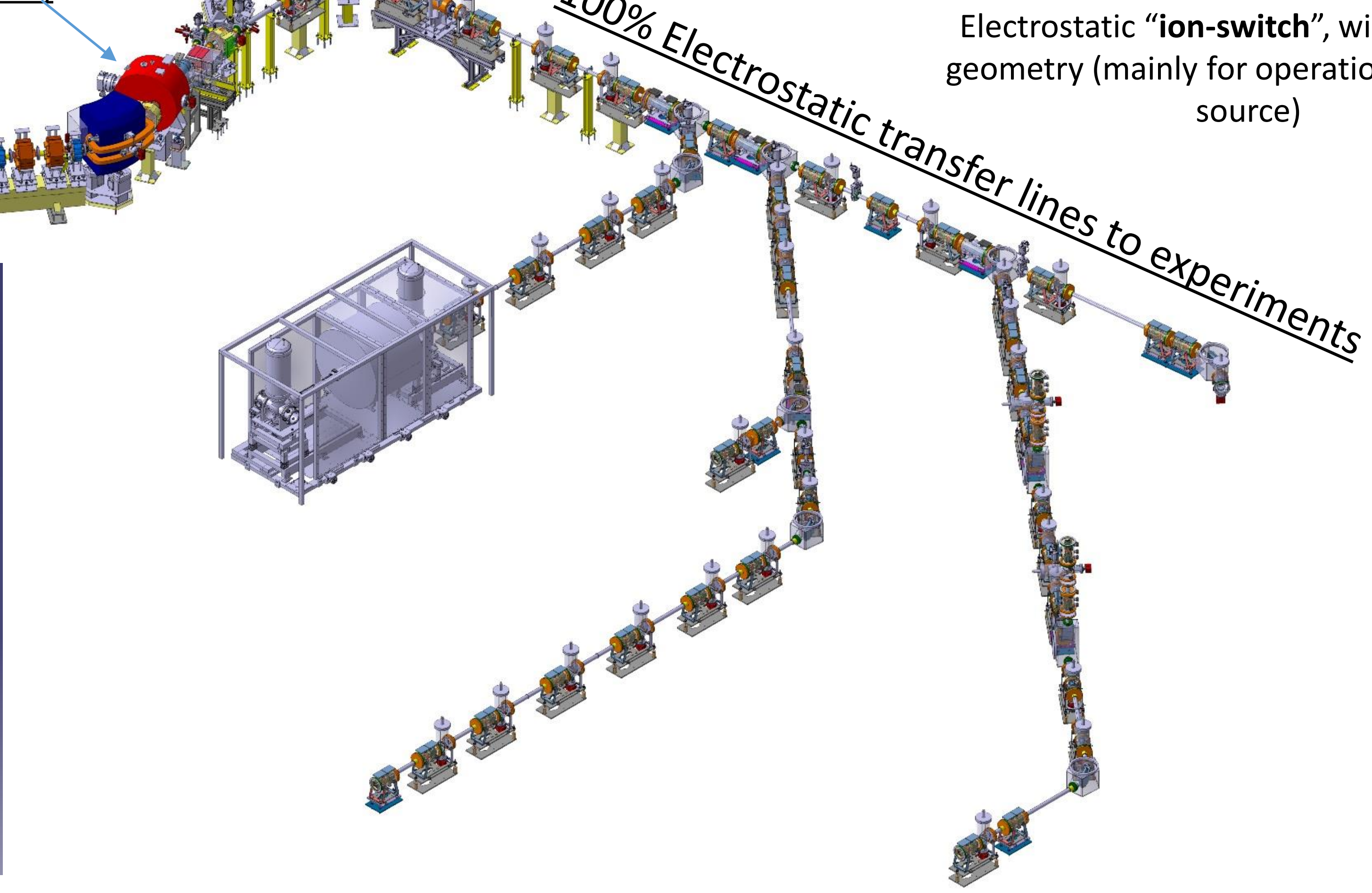
- **Working principle:** **(circumference ELENA = 1/6x AD's)**

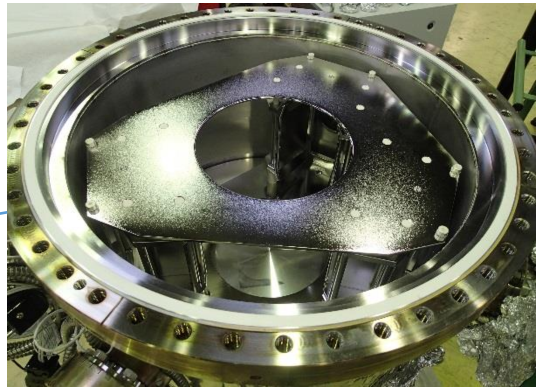
1. An antiproton beam (**pbar**) is generated via collisions of the protons coming from the **PS** and colliding with a fixed target; they are then **focused and captured** in the **AD** ring →
2. After a series of decelerations, focusing, transverse momentum cooling (**e-cooler**), the pbars are extracted from AD and sent to the experimental lines (**ATRAP, BASE, ASACUSA, AEgIS, ACE, ALPHA**), but only a small fraction of them actually reaches the experiments (**<0.1% due to degrader foils**). **If is for this reason that ELENA has been designed: to improve the capture and transport efficiency of the pbar bunches delivered to the experiments** →
3. The 0.1 GeV/c pbars will then be **extracted from AD and injected into ELENA**: here they will go through a series of decelerations, cooling and focusing , lasting about **25 seconds**. At the end of the cycle, at an energy of **100 keV**, the pbars will be extracted using fast electrostatic deflectors and sent to the experiments →
4. **Bunches of pbars at an energy of only 100 keV are a novelty at CERN: it is the first time something like this is done;**
5. The pbars, due to their low energy and long time of residence in ELENA, are **extremely sensitive** to any interactions with the residual gas (**elastic scattering**) **and thefore a vacuum specification of 4.0x10^{-12} mbar (corresponding to an average density ~ 9.9·10^{10} H_2/m^3) is being implemented.**
6. **This has an important impact on the design of the ELENA vacuum system: NEG coating of as much of the vacuum surfaces and components as possible is MANDATORY.**



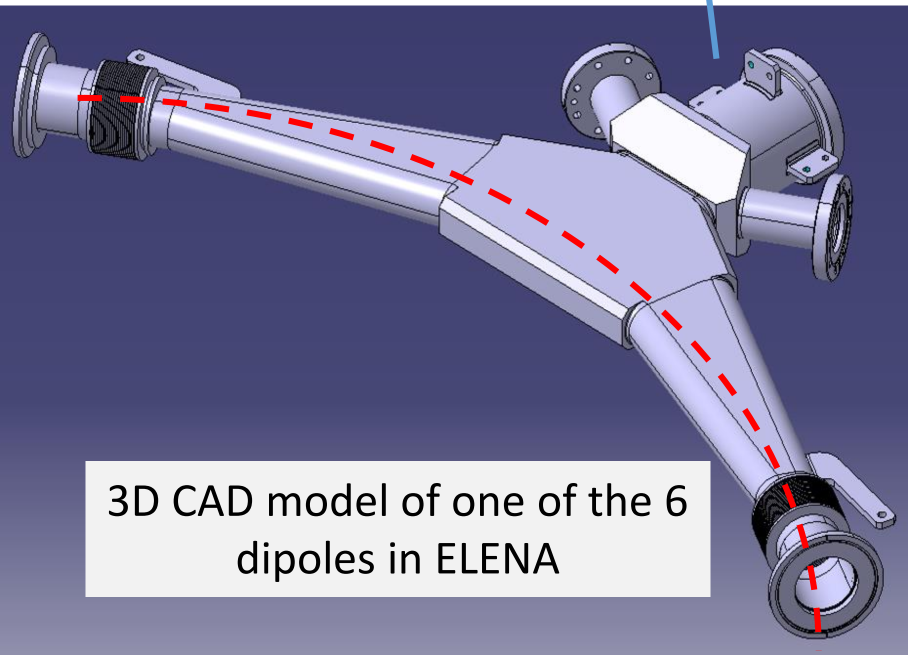


Layout of the ELENA Ring and its Electrostatic Transfer Lines (> 100 m long)

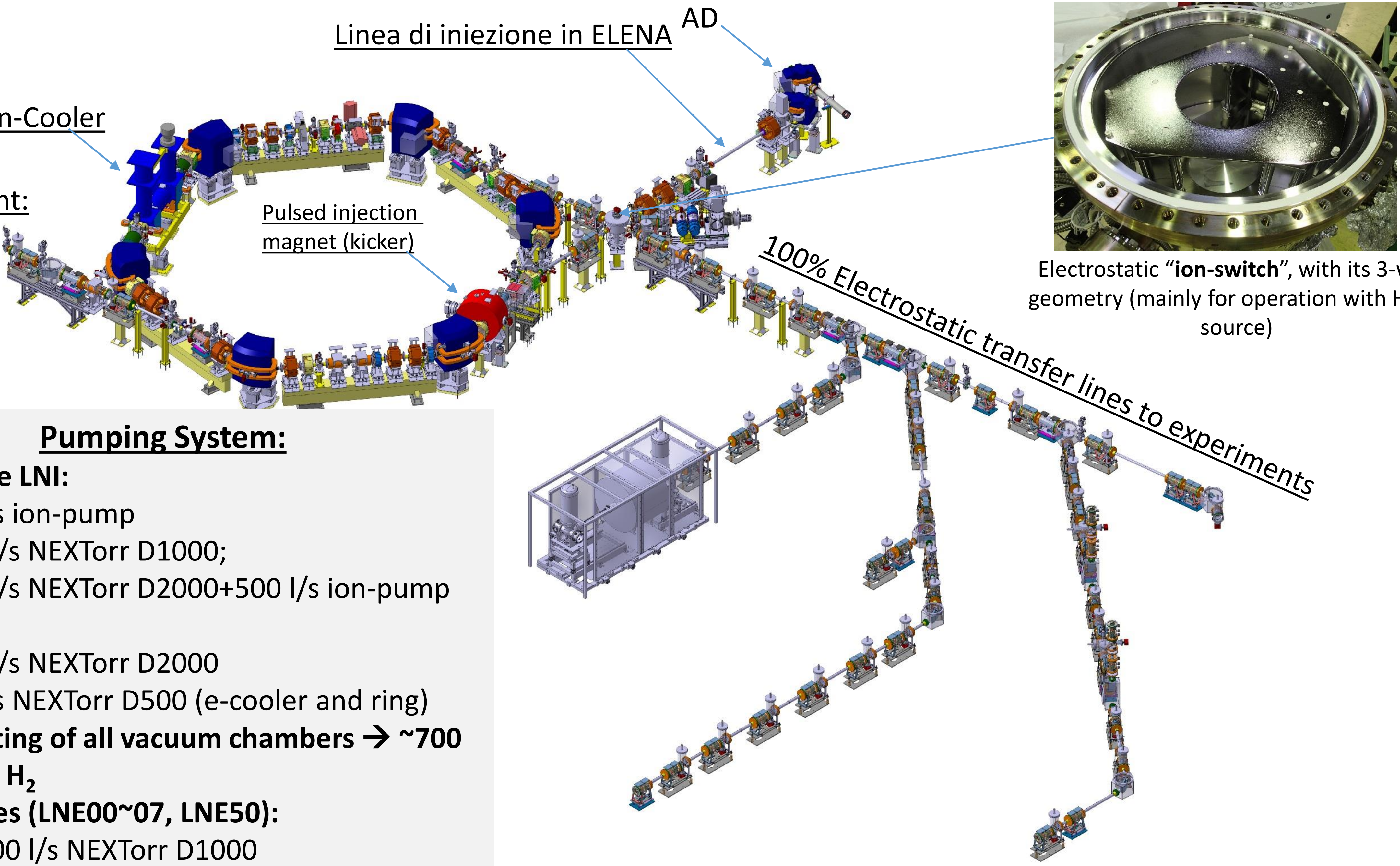


Electrostatic “**ion-switch**”, with its 3-way geometry (mainly for operation with H^-/H^+ source)



3D CAD model of one of the 6 dipoles in ELENA

Layout of the ELENA Ring and its Electrostatic Transfer Lines (> 100 m long)



Electrostatic "**ion-switch**", with its 3-way geometry (mainly for operation with H^-/H^+ source)

Pumping System:

Injection line LNI:

- 1x 250 l/s ion-pump
- 3x 1000 l/s NEXTorr D1000;
- 1x 2000 l/s NEXTorr D2000+500 l/s ion-pump

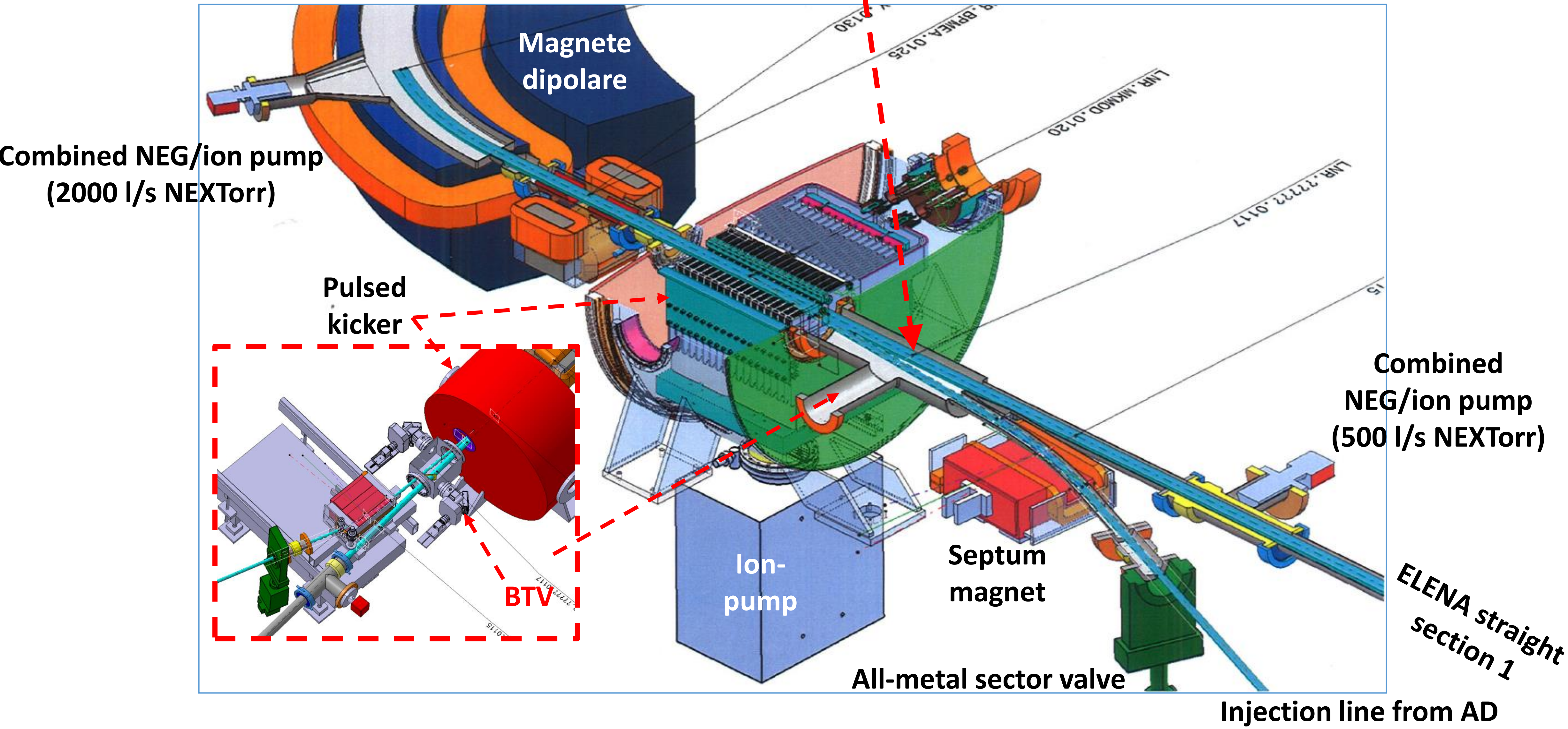
Ring:

- 6x 2000 l/s NEXTorr D2000
- 6x 500 l/s NEXTorr D500 (e-cooler and ring)
- **NEG-coating of all vacuum chambers → ~700 l/s/m for H_2**

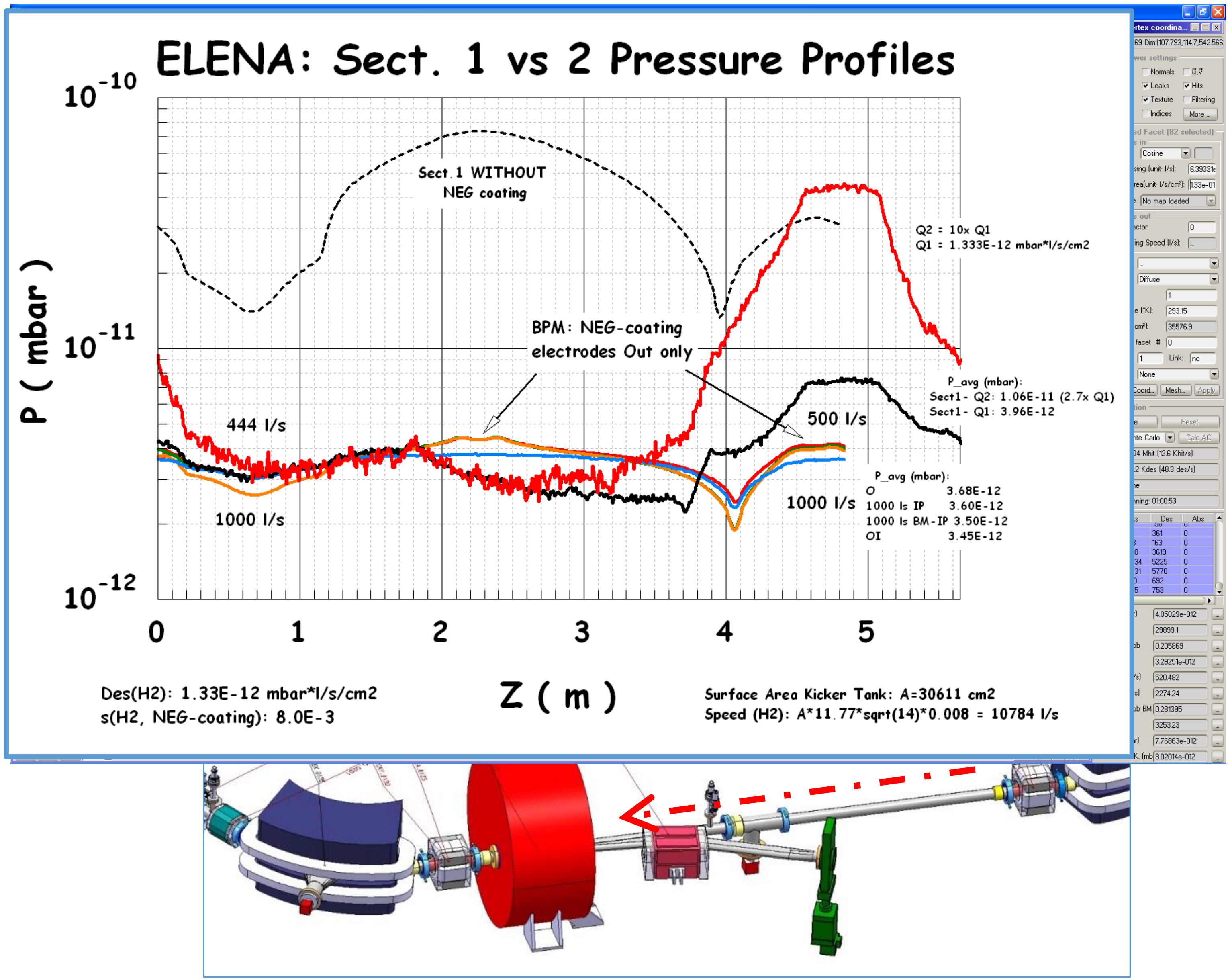
Transfer Lines (LNE00~07, LNE50):

- ~ 45x 1000 l/s NEXTorr D1000

- **ELENA: Horizontal plane cut showing the injection straight section with the pulsed kicker, preceded by the static septum magnet.**
- **Between the two a fluorescent screen diagnostic system capable of measuring the position and shape of the injected and stored beam separately is installed ("BTV")**

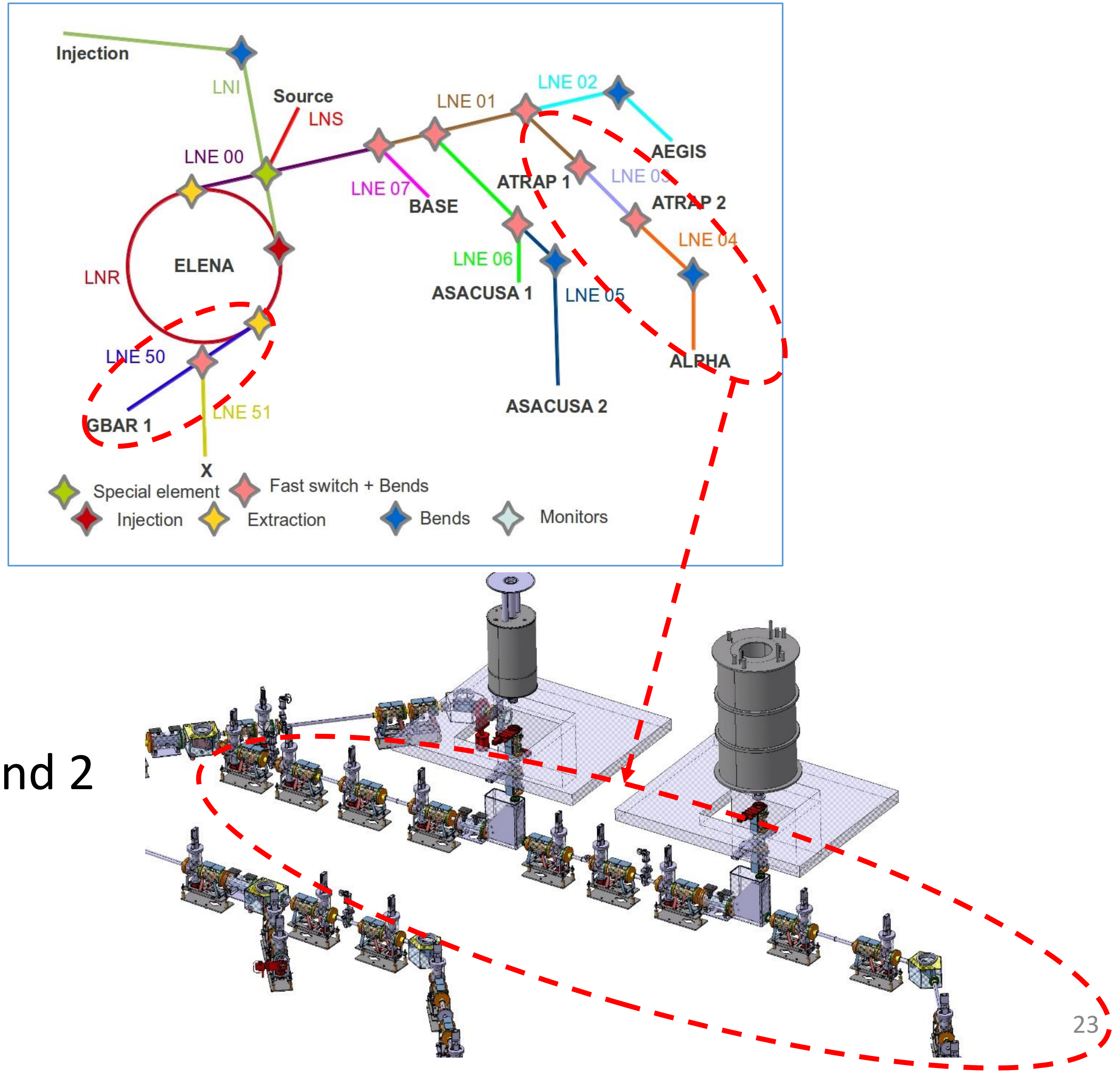


3D modelling of the pressure profile along one section of ELENA (Molflow+ code)



- The Test-Particle Monte Carlo method(TPMC) allows a precise modelling of all details of the vacuum system (geometry imported in STL format from CAD software)
- The laminations of the in-vacuum kicker magnets generate a pressure bump
- Molflow+ allows the user to rapidly change some of the parameters (e.g. local or global gas load, simulating leaks, changing the pumping speed of pumps or NEG-coating,etc…) and determine which vacuum configuration is the most suited one

- **Another example: how to protect the ELENA ring from a vacuum accident along one of the experimental beamlines (loss of vacuum accident, LOVA)**
- **Aim: determine le position where fast-closing valves (FVs, closing time < 10 ms) could be installed in order to minimize the contamination of the system, and preserve good vacuum conditions as much as possible;**

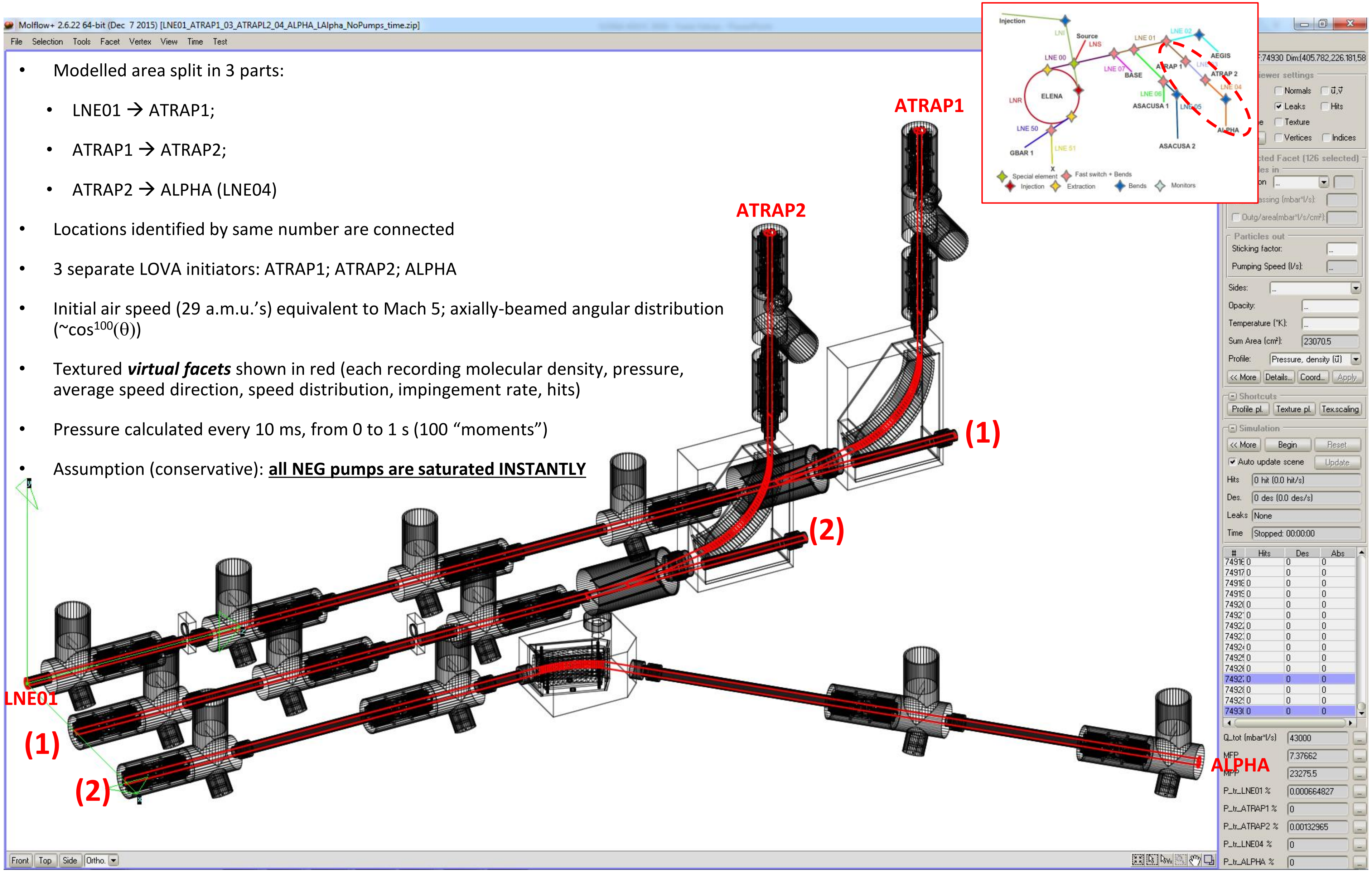


- LNE50: Gbar
- LNE03-04: ATRAP 1 and 2 and ALPHA

- **(loss of vacuum accident, LOVA)**

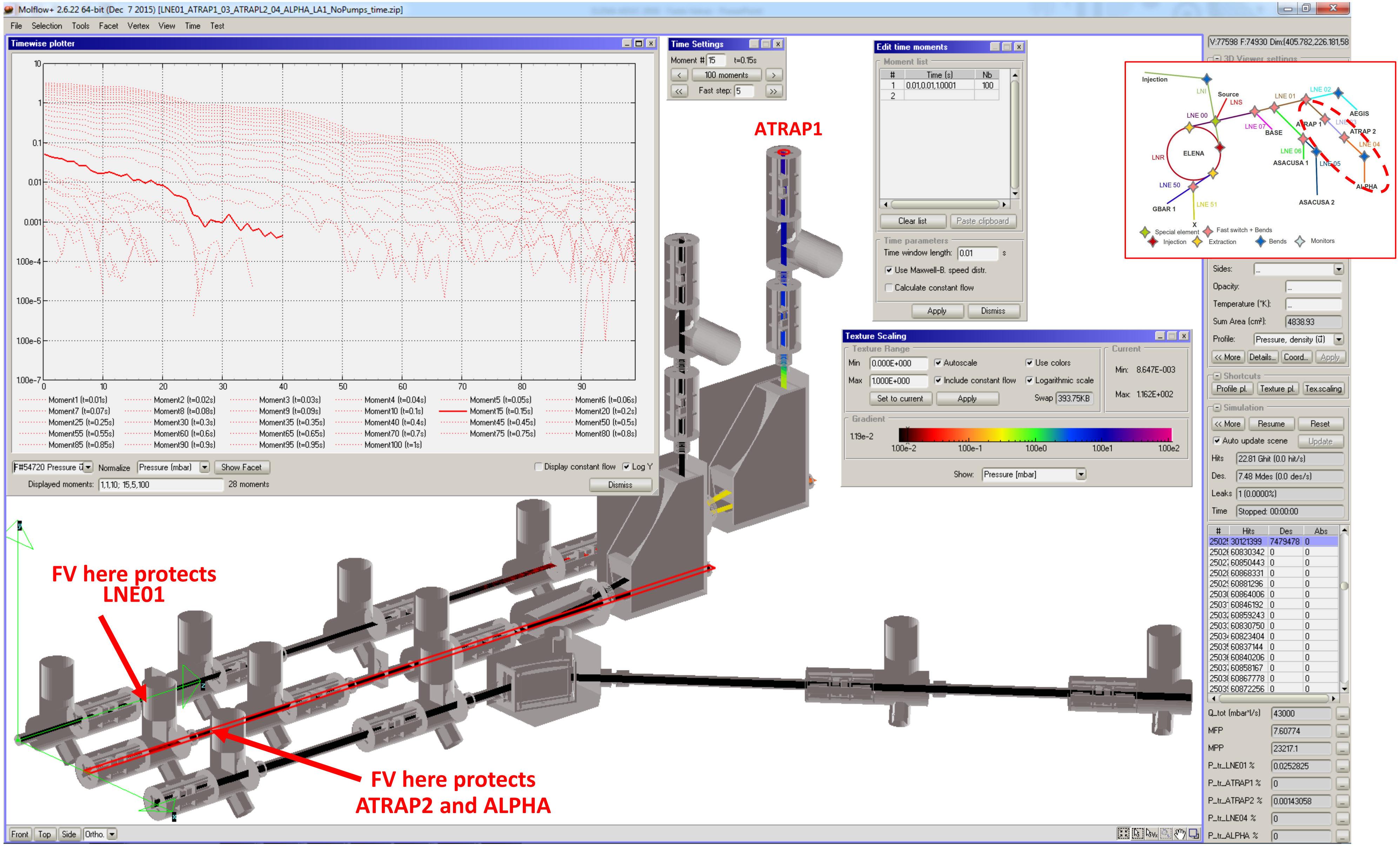
Time-dependent TPMC simulations: The 3D Model

- Modelled area split in 3 parts:
  - LNE01 → ATRAP1;
  - ATRAP1 → ATRAP2;
  - ATRAP2 → ALPHA (LNE04)
- Locations identified by same number are connected
- 3 separate LOVA initiators: ATRAP1; ATRAP2; ALPHA
- Initial air speed (29 a.m.u.'s) equivalent to Mach 5; axially-beamed angular distribution (~$\cos^{100}(\theta)$)
- Textured ***virtual facets*** shown in red (each recording molecular density, pressure, average speed direction, speed distribution, impingement rate, hits)
- Pressure calculated every 10 ms, from 0 to 1 s (100 "moments")
- Assumption (conservative): **<u>all NEG pumps are saturated INSTANTLY</u>**



- **(loss of vacuum accident, LOVA)**

Time-dependent TPMC simulations: LOVA at **ATRAP1**



Remarks and conclusions:

- We have seen how two machines so different from one another can share the common requirement of an **extremely low residual gas density**;
- For **ELENA** the chosen technology is that of **non-evaporable getters** (NEGs), either as **thin-films** deposited on the walls of the chambers, or **lumped NEG pumps** wherever a high pumping speed is needed to match a local source of outgassing; This will allow us to reach the better than $\mathbf{4 \cdot 10^{-12}}$ mbar average pressure necessary for the operation;
- **ELENA** experimental beamlines need to be protected against **loss-of-vacuum-accidents** happening in any experiment and propagating towards the other experiments or, even worse, towards the ELENA ring; detailed time-dependent montecarlo simulations allow us to define the location of **fast-closing valves** which perform the task;
- For **FCC-hh**, like done for the present LHC, the choice of a **mixed room-temperature/cryogenic system** is the natural and obvious choice; The long-straight-sections at RT will be pumped by **NEG-coatings and ion-pumps**; The exact temperature of the cold-bore of the SC magnet in the arcs is not defined yet, will depend mainly from the technology implemented for the 16-20 T magnets, and this will have repercussions on the way the arcs are pumped, and the gas density levels attainable in them; **The challenge for vacuum is to keep the average density in the arcs below the** $\mathbf{2 \cdot 10^{14}\ H_2/m^3}$;
- Concerning vacuum issues in **FCC-hh**, how to deal exactly with the extremely high levels of SR power, photon flux, and related photon-induced desorption of the FCC-hh dipoles is still to be defined by an **aggressive R&D program (EuroCirCol)**;
- **FCC-hh** is only at the level of **design study**, aiming at presenting a **Conceptual Design Report** to the funding agencies by 2018; It should be added that there is a companion machine, supposedly hosted in the same tunnel, which should precede the installation of the FCC-hh; It is an **electron-positron collider**, codename **FCC-ee** or "**TLEP**", which would employ relatively cheap **normal-conducting magnets**, like **LEP** did before the **LHC**;
- It should also be noted that both FCC-hh and FCC-ee have "competing" conceptual design **projects in China**, where they aim to build such machines on a much shorter time horizon as compared to our FCC-hh and FCC-ee;

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