



IAS PROGRAM

Fundamental Physics

LEP3: Accelerator design choices

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LEP3

- LEP3 is a low-cost Higgs factory in a re-purposed LHC tunnel
- It offers \sim one third of the performance of FCC but only at \sim one third of the cost.
- Talk by T. Camporesi in this conference (Wednesday)
- Here I will concentrate on technical choices for the accelerator and especially on progress since the ESPP Venice Meeting (in June 25 2025)

Strategic choices of LEP3

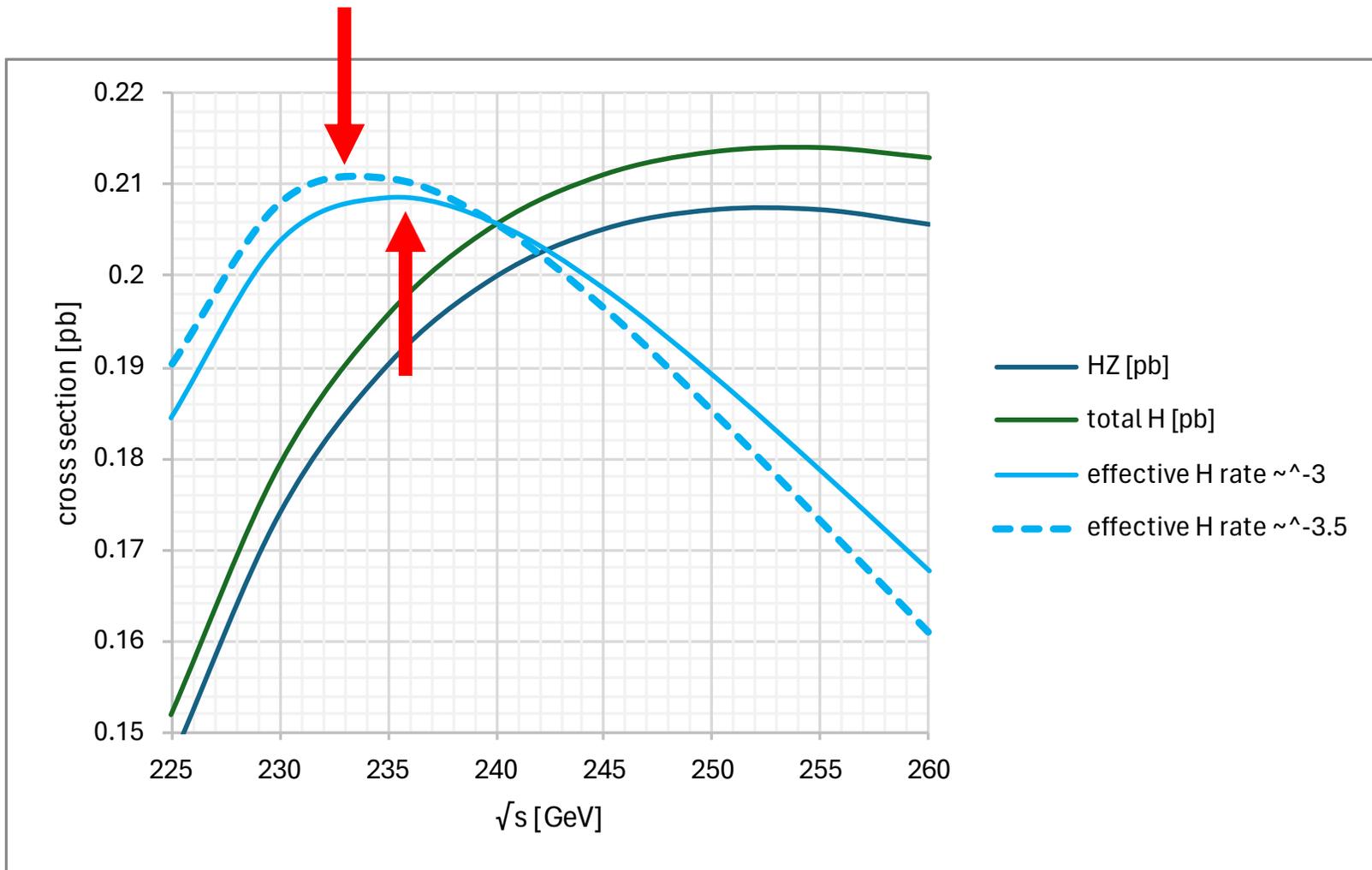
- Reuse the LHC tunnel
- Utilize most of the FCC-ee work done so far
- Have two experiments, could use repurposed ATLAS and CMS
- Reduce the ZH energy to 115GeV per beam
- Give up running at the $t\bar{t}$ threshold
- Use a single RF frequency (800MHz) for a simpler system
- Reduce the beampipe diameter from 60 to 30mm

HIGGS RATE

ZH energy

- FCC runs at 120GeV (slightly above the maximum Higgs rate)
- Energy lost per turn is proportional to E^4
- Luminosity is proportional to E^{-3} (to first order)
- by running at 115 GeV we gain 1GV or **18.5%** of RF voltage (and cost), which is a lot!
- We also gain **13.6%** of luminosity
- Unfortunately, we also lose **14.4%** of total Higgs xsection. The effect of background needs to be evaluated

Higgs effective rate



In a circular collider, the maximum Higgs rate is not at maximum cross section!

To first order, we expect a power law of E_{beam}^{-3} .

If we do the best fit to FCC luminosities over the range 45-182.5 GeV, we get a power law of $E_{\text{beam}}^{-3.6}$ to $E_{\text{beam}}^{-3.2}$

- Power law of -3: maximum at 236 GeV. At 230 GeV we are 2.2% lower than max
- Power law -3.5: maximum rate at 233 GeV. At 230 GeV we are 1.4% lower than max

Above is without taking into account ISR – after taking ISR into account, the 230 GeV rate is **2.3%** lower compared to 240 GeV

Choose beam energy of 115 GeV

LUMINOSITY

Luminosity of circular colliders

The usual luminosity formula is this:

$$\mathcal{L} = \frac{f_{rev} n_b N_b^2}{4\pi\sigma_x\sigma_y} R_{hg}$$

$$\xi_y = \frac{N_b r_e \beta_y^*}{2\pi\gamma\sigma_x\sigma_y}$$

$$P_{tot} = \frac{4\pi}{3} \frac{r_e}{m_e^3} E^4 \frac{f_{rev} n_b N_b}{\rho}$$

This is not very informative as to what luminosities might be achievable. But if we express the above formula in terms of 1/total synchrotron radiation power and 2/vertical beam-beam parameter we get:

$$\mathcal{L} = const \times P_{tot} \frac{\rho}{E_0^3} \xi_y \frac{R_{hg}}{\beta_y^*}$$

The vertical beam-beam parameter (or tune shift) is a measure of disruption of the colliding beams. At LEP (4 IPs) it reached a value of 0.1. FCC-ee ZH (also 4 IPs) runs at 0.134. Colliders with two IPs (line LEP3) can run with higher tune shifts than colliders with 4 IPs

Luminosity of circular colliders (2)

In natural units, the achievable luminosity (for FCC) is:

$$\mathcal{L} = 6.0 \times 10^{34} \left(\frac{P_{tot}}{50MW} \right) \left(\frac{\rho}{10km} \right) \left(\frac{120GeV}{E_0} \right)^3 \left(\frac{\xi_y}{0.1} \right) \left(\frac{R_{hg}}{0.84} \right) \left(\frac{1mm}{\beta_y^*} \right) cm^{-2}s^{-1}$$

And for LEP3 is:

$$\mathcal{L} = 2.0 \times 10^{34} \left(\frac{P_{tot}}{50MW} \right) \left(\frac{\rho}{3km} \right) \left(\frac{115GeV}{E_0} \right)^3 \left(\frac{\xi_y}{0.1} \right) \left(\frac{R_{hg}}{0.84} \right) \left(\frac{1mm}{\beta_y^*} \right) cm^{-2}s^{-1}$$

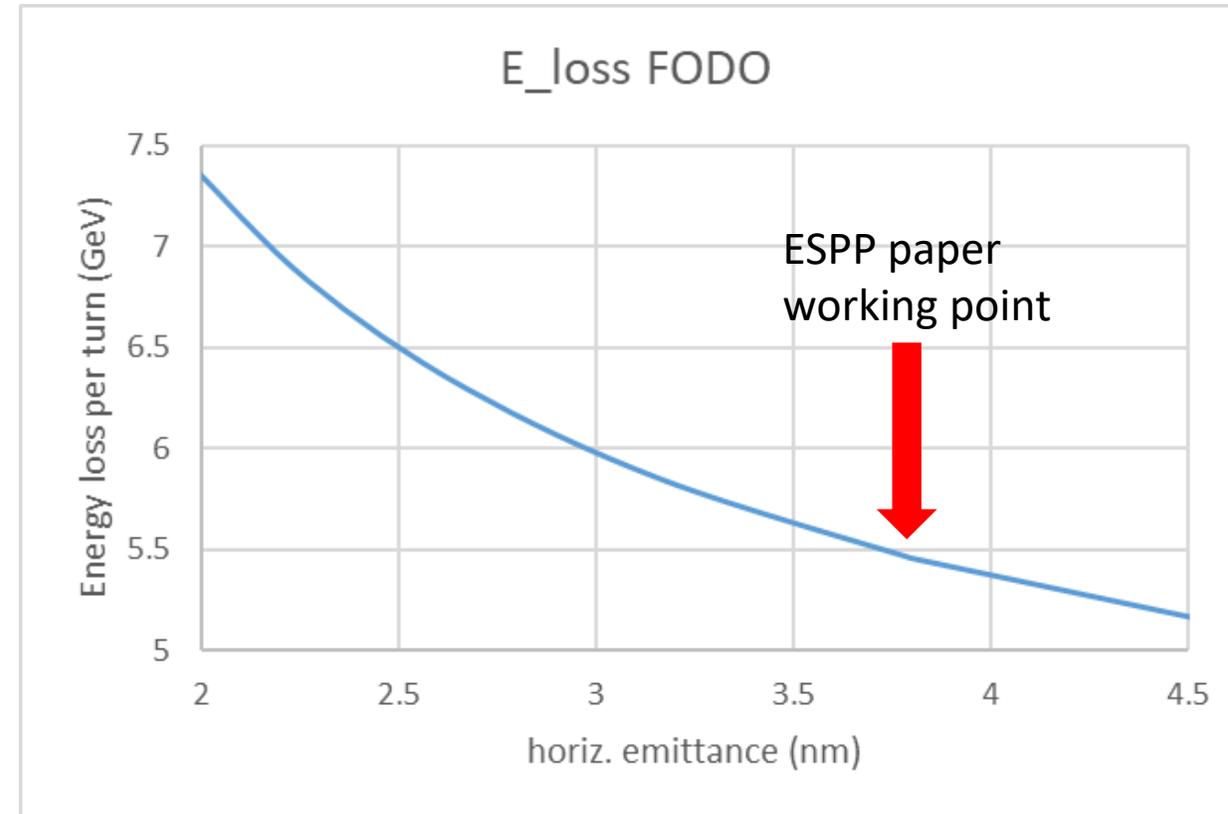
Note that the above formula does not tell you how to design your collider; simply gives you the maximum performance. You need to design the optics so that your beam lifetimes are sufficient.

To increase luminosity at a fixed power, bending radius and beam energy one needs to

- Use the smallest possible β_y^*
- Run at the highest possible vertical beam-beam parameter

The FODO lattice

- The first LEP3 lattice was derived from the FCC FODO one. It delivered a horizontal emittance of **3.8nm** for an energy loss of **5.5GeV**.
- Emittance grows as the third power of the FODO length
- Strength of Quads grows inversely with FODO length; Quads become longer and therefore the dipoles need to grow stronger; this results in smaller bending radius and therefore larger Energy loss per turn



This lattice was used for the parameter set already published for LEP3

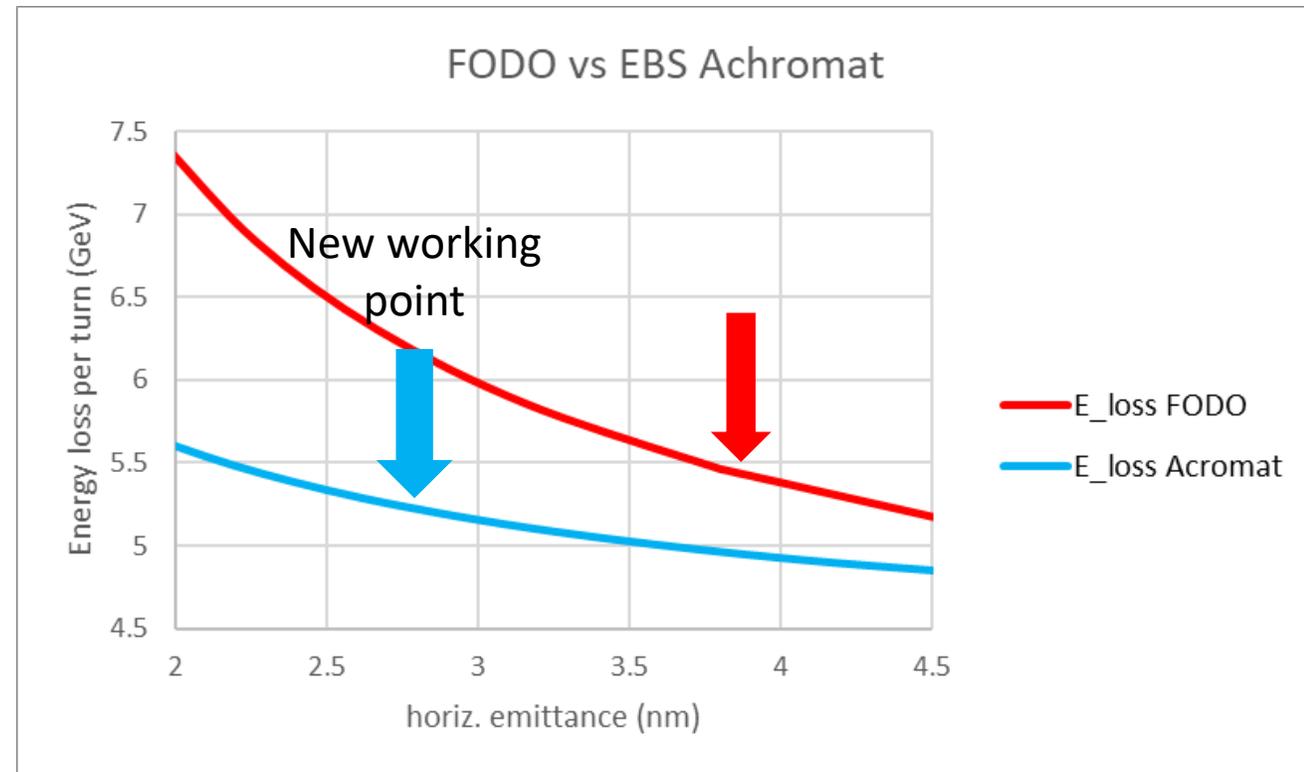
Low-emittance lattice – EBS achromat

- ...Is able to deliver lower emittance for the same energy loss compared to FODO

Lower horizontal emittance means:

- Lower vertical emittance
- Smaller beam sizes
- For the same magnet aperture, smaller β^*_y is possible
- This translates into higher luminosity

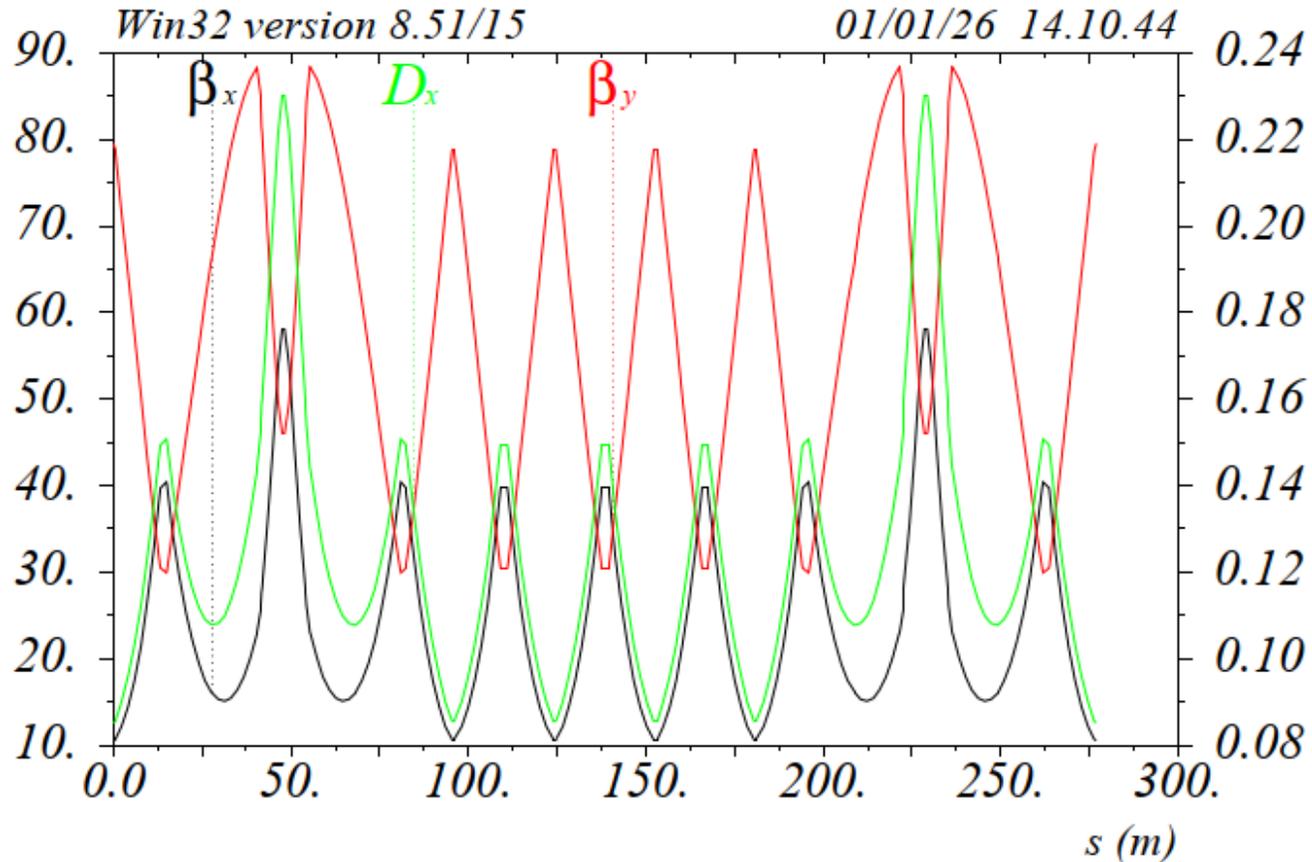
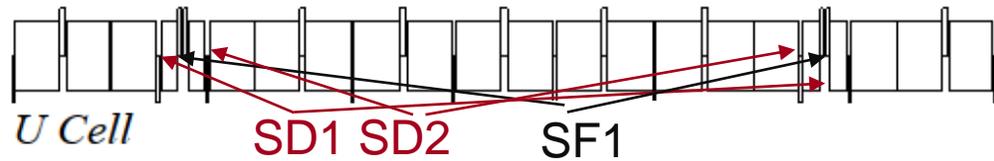
Pioneered by Pantaleo Raimondi



LEP3 Optics

EBS Achromat cell adapted for LEP3

Z/W/ZH modes



Sextupoles are grouped in a high beta/dispersion region

Phase advance between the sextupoles:

$$dmux \sim 3\pi$$

$$dmuy \sim \pi$$

Given the phase relations, all the detunings are intrinsically small, effective $dmux$ and $dmuy$ are slightly adjusted (few %) to compensate for the interleaved sextupole scheme.

Betas and dispersion at sextupoles and dispersion are optimized for best performance

Pantaleo Raimondi

ARC lattice layout

Cell length: 276.88m

Each cell consists of:

- 18 dipoles ~ 12.618m long with defocusing gradient
~0.51T/m @115GeV
- 4 dipoles ~ 4.5m long
- 20 quadrupoles with gradients ~ 21T/m @115GeV and more precisely:
7 QFs ~ 1.85m, 4 QFs ~ 1.10m, 9 QDs ~ 0.85m
- 6 sextupoles with gradients ~ 740T/m² @115GeV, more precisely:
2 SFs ~ 0.54m long, 4 SDs ~ 0.34m long

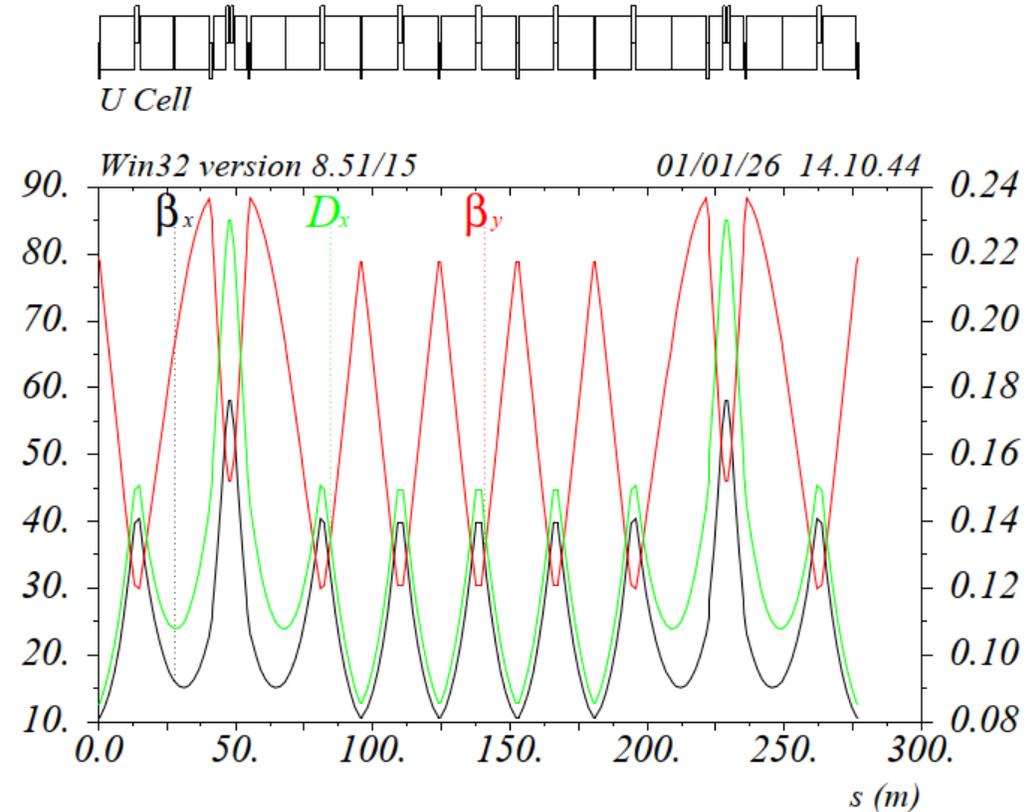
80 Cells make a 22151m circumference

To this we need to add:

- 6 Straight sections (for RF, injection, collimation...)
- 2 Interaction Regions (for the two experiments)

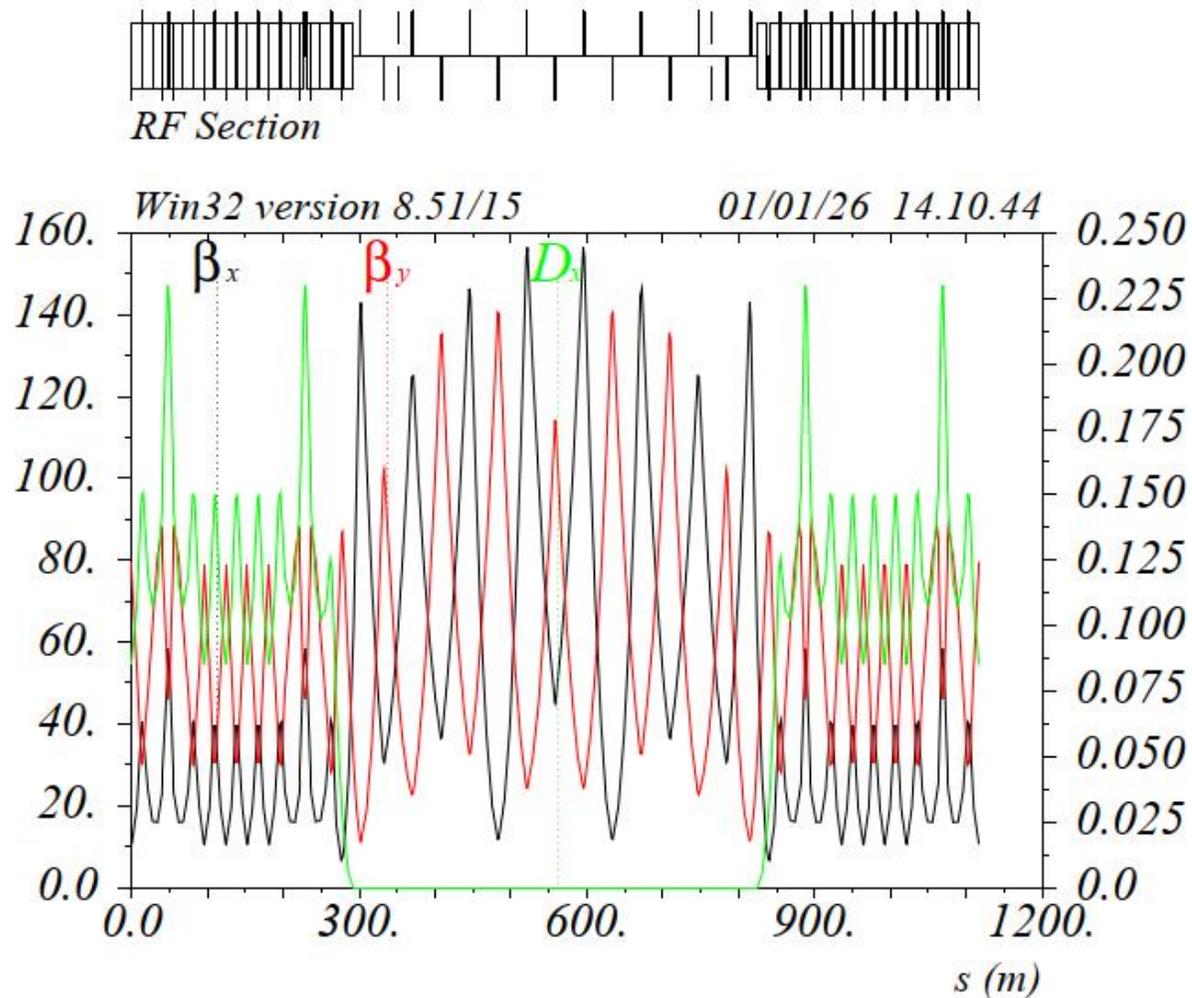
the 8 octants will be divided in:

- 4 octants consisting of **10 cells**
- 4 octants facing the 2 interaction regions consisting of **9 cells**
(to be explained in the Final Focus section)



Pantaleo Raimondi

Straight Section insertion



Straight Sections (SSs) are included with the Transparency Conditions criteria (TCs)

SSs are 563.5 m long, however two extra dipoles are needed in the Dispersion Suppressor and they sit in the SSs, reducing the available SSs length to about **535m**

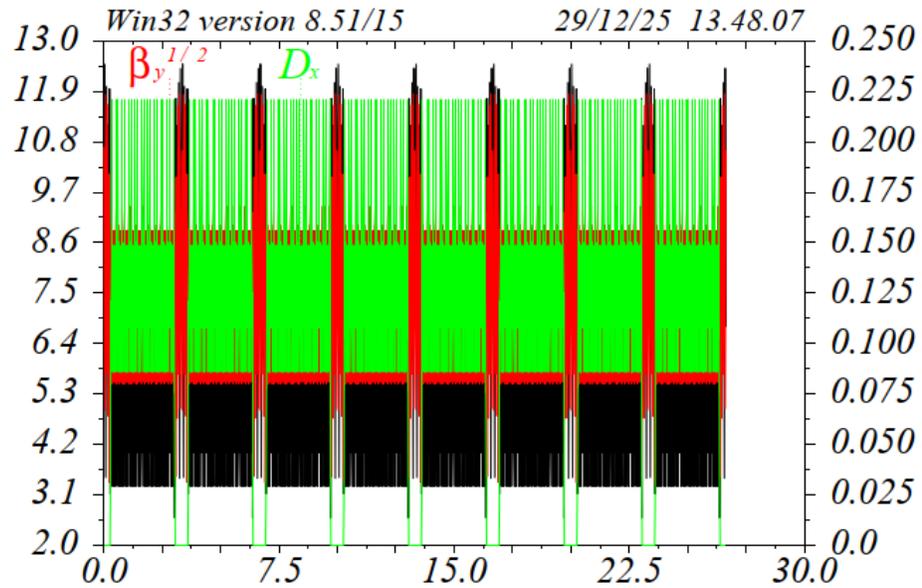
In fact the 4*2 last dipoles facing the SSs are 25% weaker wrt the ARC dipoles.

The TCs make so that the breaking of the ring periodicity is minimal, and no ARC sextupole families are needed when the SSs are included in the lattice.

Presently all the SSs are the same and they are very close to what will be the “Standard” RF section.

Pantaleo Raimondi

Straight Section insertion



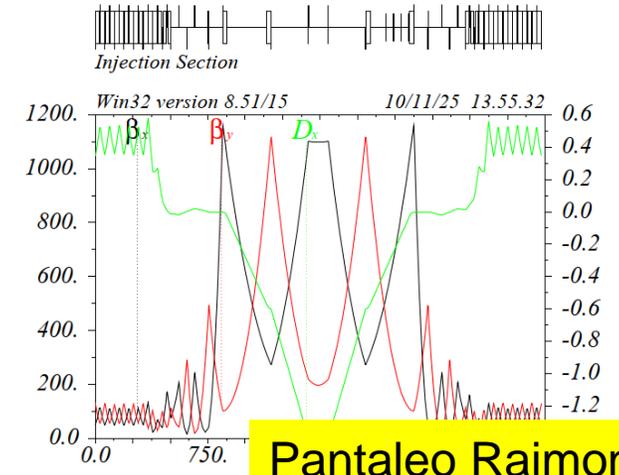
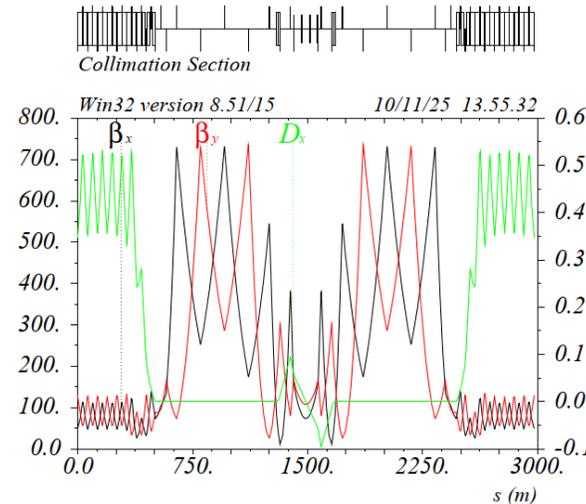
Full ring, consisting of 8 octants and 8 identical Straight Sections. Because of the TCs, the chromatic functions in the octants remains periodic.

The ring is 26659mt long.

Specialized SSs (injection and collimation) can be included as well, they can be a shorter version of the FCCee ones

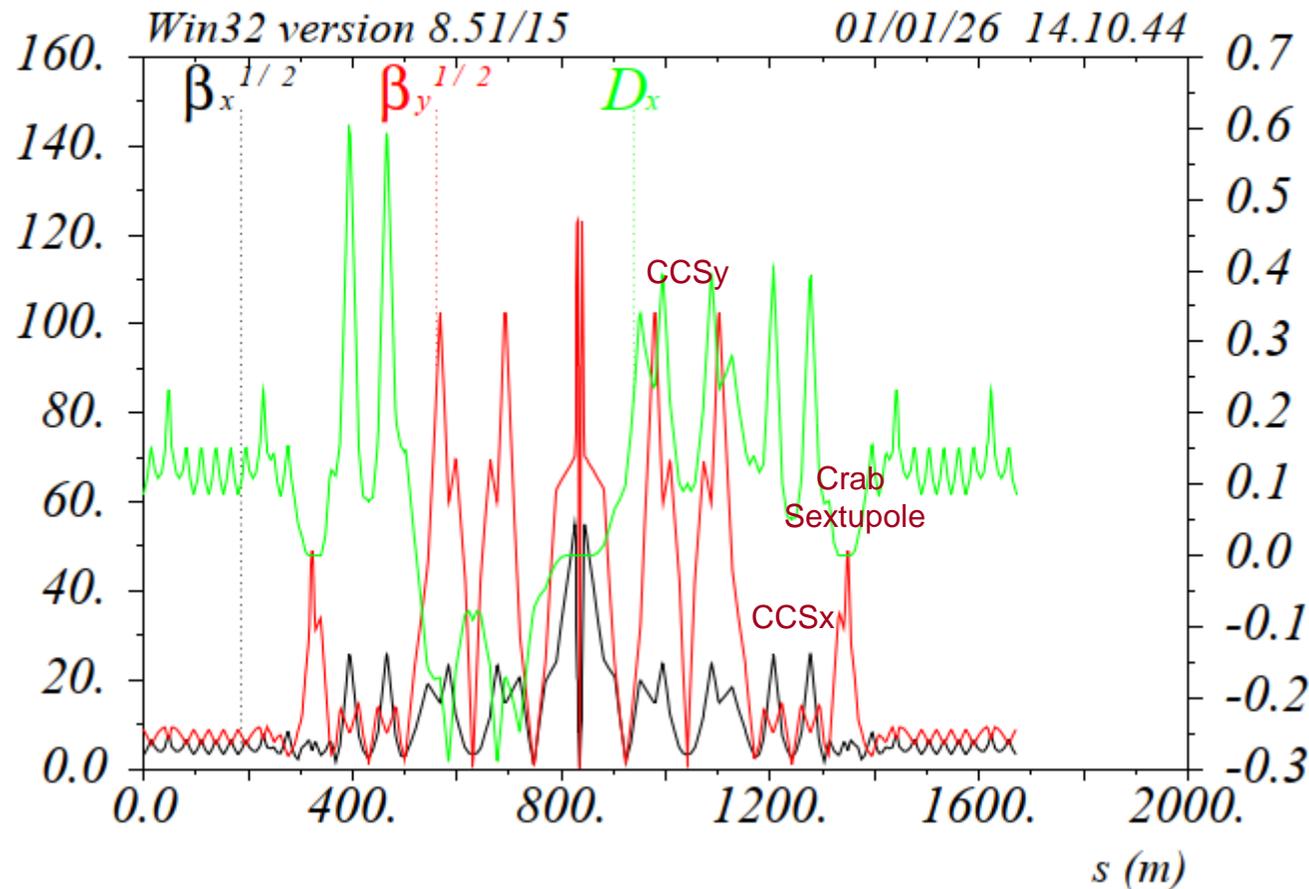
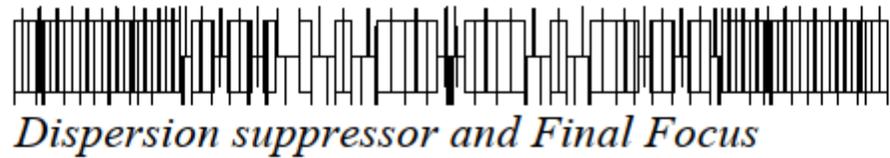


$dD/d\delta$ (m)



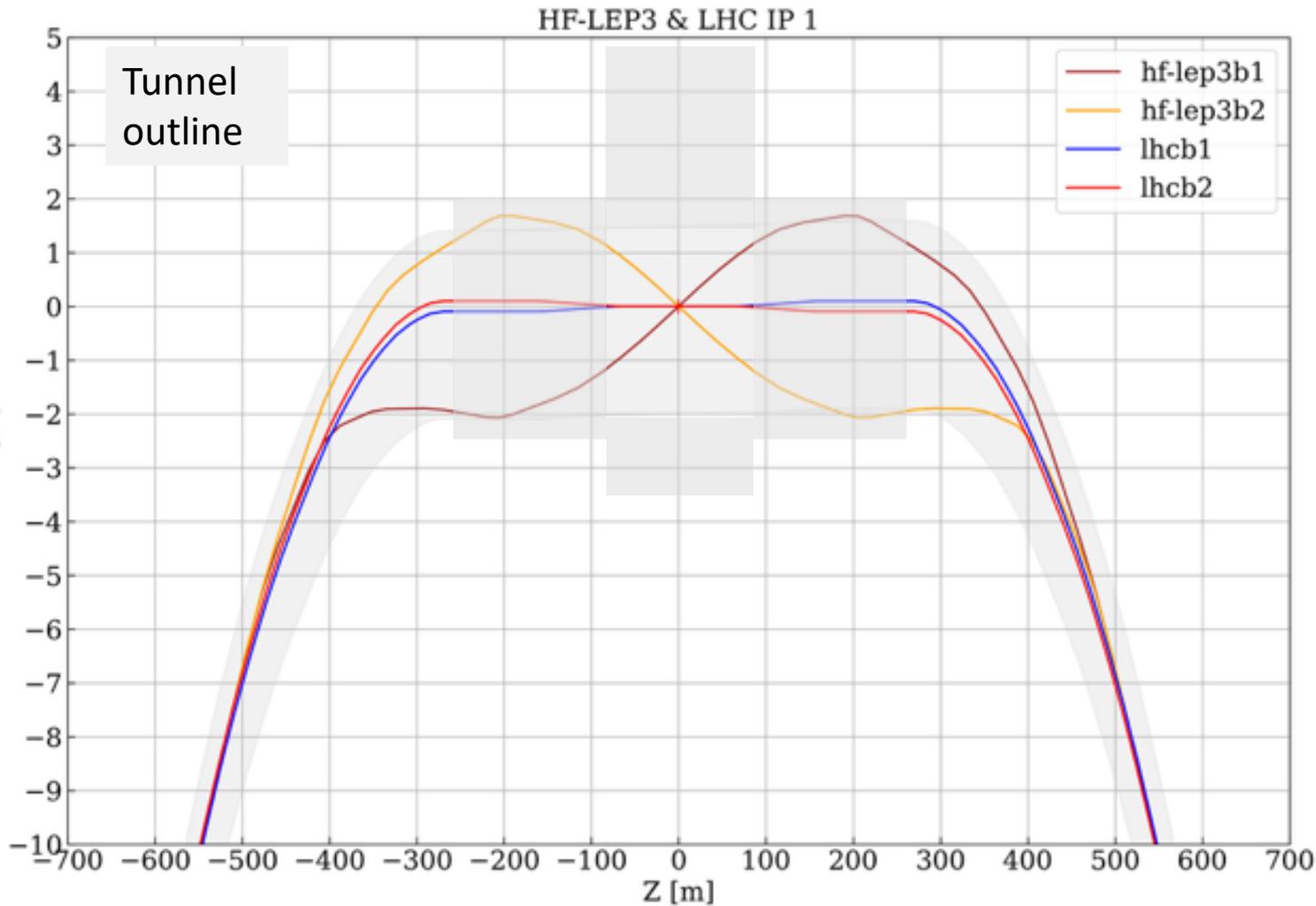
Pantaleo Raimondi

Final Focus system



- LEP3 FF has been developed starting from a rescaling of the FCCee LCC-FF design.
- **All the layout constraints are met, in particular:**
 - Ring length
 - IP positions
 - IP crossing angle (30mrad)
- The FF is **1025.9m long** and has a net bend angle of 0.1347rad.
- The last ARC octant cell (per side) has been replaced by the FF-Dispersion Suppressor and the FF itself.
- The FF is a 5th order achromat in both planes.
- The dipoles have been optimized for best dispersion and optical functions across the Chromatic Correction Sections (CCSx/y)
- The dipoles in the incoming CCSy have opposite sign wrt to other dipoles, thus generating a dogleg that matches the layout constraints.
- The FF Left and Right magnets and drift lengths are identical and optics nearly identical as well, thus ensuring a high degree of symmetry
- FF has been inserted in the lattice with the TCs

How it fits in the LHC tunnel



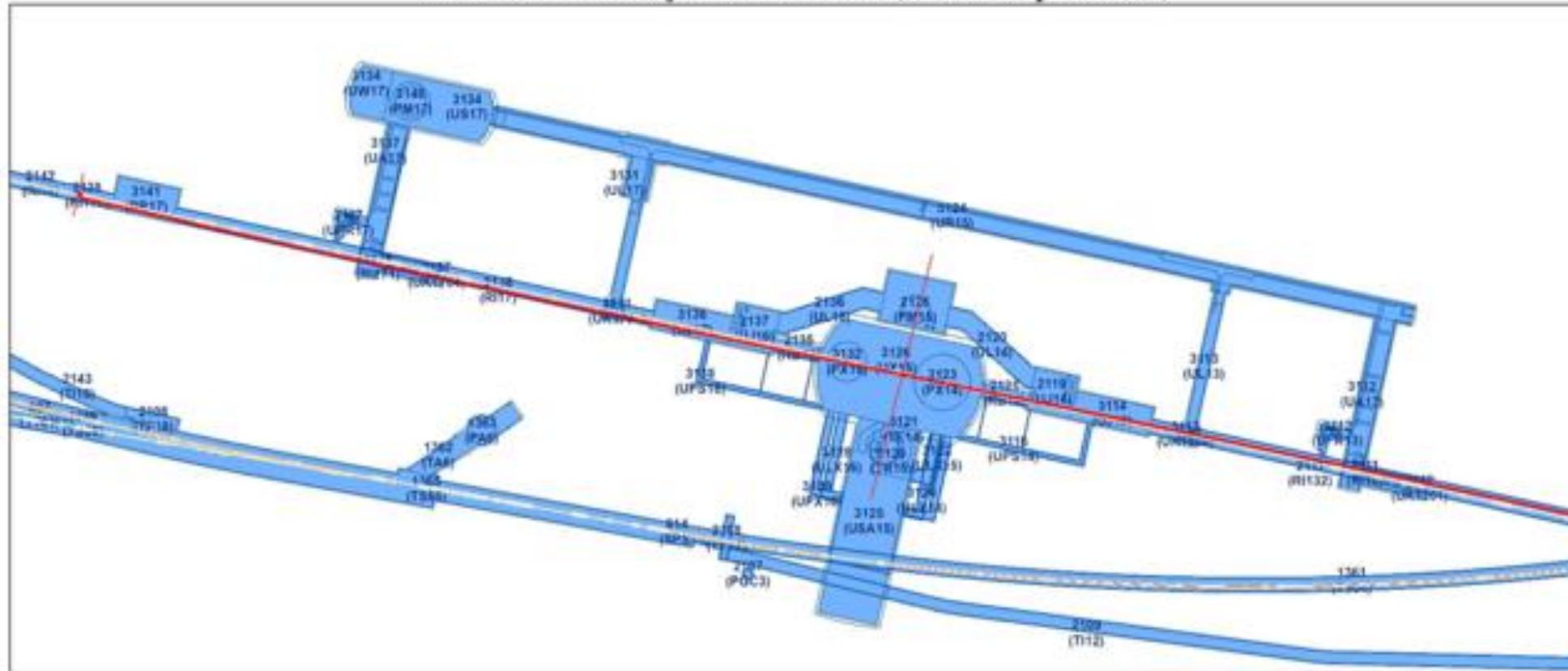
- LSS half length is 282.75m
- IP1: tunnel diameter 4.4m
- **IP5: tunnel diameter 3.8m**
- **Beam separation begins at ~500m from the IP**
- **Maximum distance of the two beams 3.8m** (at 200m from the IP) tunnel diameter at 200m is 4.4m
- At 282m, where the tunnel diameter changes to 3.8m, beam separation is ~2.9m

- We should be able to fit the two beams in the existing tunnel with minimum civil engineering intervention.
- **The booster ring would need an experiment bypass**

Ilias Efthymiopoulos

Fit around Point 1

HFLEP3 - beam layout around IP1 (ATLAS exp. cavern)



- Scraping the sides of the tunnel
- Beams collide at ATLAS center

Ilias Efthymiopoulos

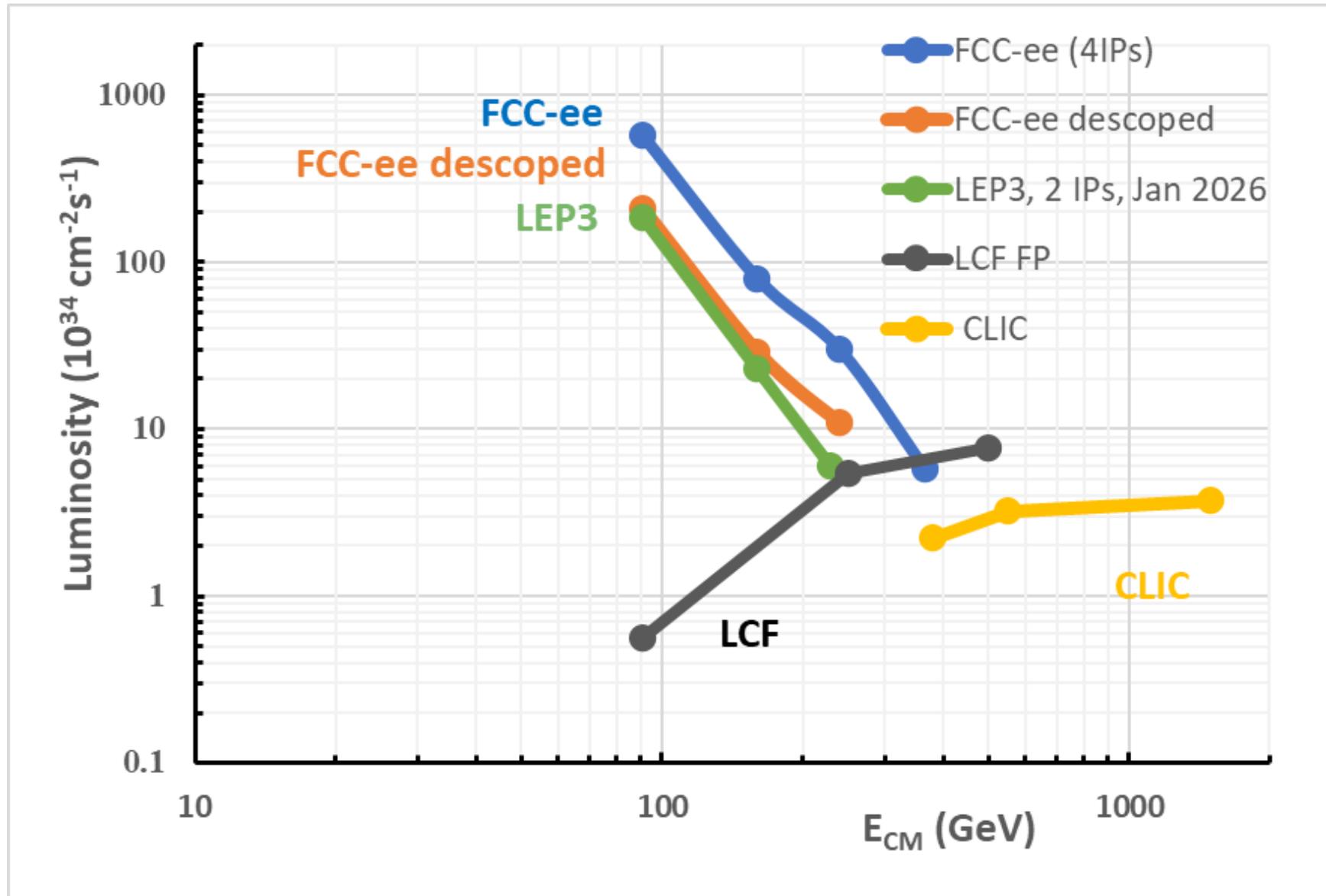
Parameter	LEP3 (ZH)	LEP3 (WW)	LEP3 (Z)
beam energy [GeV]	115	80	45.6
number of experiments/crossing angle at the IP [mrad]	2/30	2/30	2/30
Circumference [m]	26659	26659	26659
Bending radius [m]	3080	3080	3080
SR power per beam [MW]	50	50	50
beam current [mA]	10	41	387
number bunches/beam	12	80	1600
bunch intensity [10^{11}]	4.4	2.8	1.3
SR energy loss / turn [GeV]	5.2	1.2	0.13
total RF voltage [GV]	6.0	1.5	0.30
RF frequency [MHz]	800	800	800
longitudinal damping time [turns]	22	65	353
horizontal beta* [m]	0.2	0.15	0.1
vertical beta* [mm]	1.0	0.7	0.5
horizontal emittance [nm]	2.7	1.3	0.4
vertical emittance [pm]	5.5	2.6	0.9
horizontal rms IP spot size [μm]	23	14	7
vertical rms IP spot size [nm]	74	43	21
horiz. beam-beam parameter	0.03	0.01	0.00
vert. beam-beam parameter	0.16	0.14	0.14
rms bunch length SR only [mm]	3.1	3.4	2.6
rms bunch length with SR + BS [mm]	4.6	6.2	8.0
beam lifetime rad Bhabha + BS [min]	6	11	13
luminosity per IP [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	3.0	11.4	92
integrated luminosity/year [ab-1]	0.7	2.7	22.1
years of operation	6	3	5
total integrated luminosity[ab-1]	4.3	8.2	110.3

LEP3
Updated
parameter
set

Improvements since the ESPP meeting

- Compared to LEP3 of May 2025, we have reduced emittances, increased bending radius, increased vertical beam-beam parameter. Result is 85% higher luminosity at the ZH and 120% at the Z
- Compared to LEP3 of May 2025, sextupole power requirements have decreased dramatically.
- Compared to FCC:
 - For ZH: higher vertical beam-beam parameter, but with half the number of IPs – luminosity is a factor 2.5 lower
 - For Z: LEP3 has smaller emittances (LEP3 does not change the lattice at the Z, but FCC does), so comes to within 25% of the FCC luminosity. This leaves the option open to decrease the SR power at the Z while keeping reasonable performance
- Compared to LCF:
 - LCF for the full power program has 0.5 ab^{-1} per year (>99% sqrt(s)) and LEP3 has 0.7 ab^{-1} (+40%)

Luminosity of projects considered in the ESPP



BEAM PIPE DIAMETER

Beam pipe diameter

- Another area of improvement, which can decrease the cost of the project considerably, is reducing the size of the beam pipe.
- The beam pipe diameter is chosen so that beam instabilities are avoided. These instabilities are proportional to the resistive wall impedance of the beam pipe, which grows:
 - linearly with the total arc length of the collider (~factor 4 wrt FCC)
 - Linearly with the beta functions (~factor 2 wrt FCC)
 - Linearly with the beam current (~factor 3 wrt FCC)
 - inversely with the third power of the beampipe diameter;
- Therefore, if we decrease the inner diameter of LEP3 by 2 (from 60 to **30mm**) the impedance would still be reduced by a factor: $\sim 4 * 2 * 3 / 8 = 3$.
- The cost of the magnets goes with the square of the beam pipe inner diameter of the diameter, so cost savings will be substantial.

SYNCHROTRON RADIATION ABSORBER

FCC-ee: discreet absorber option

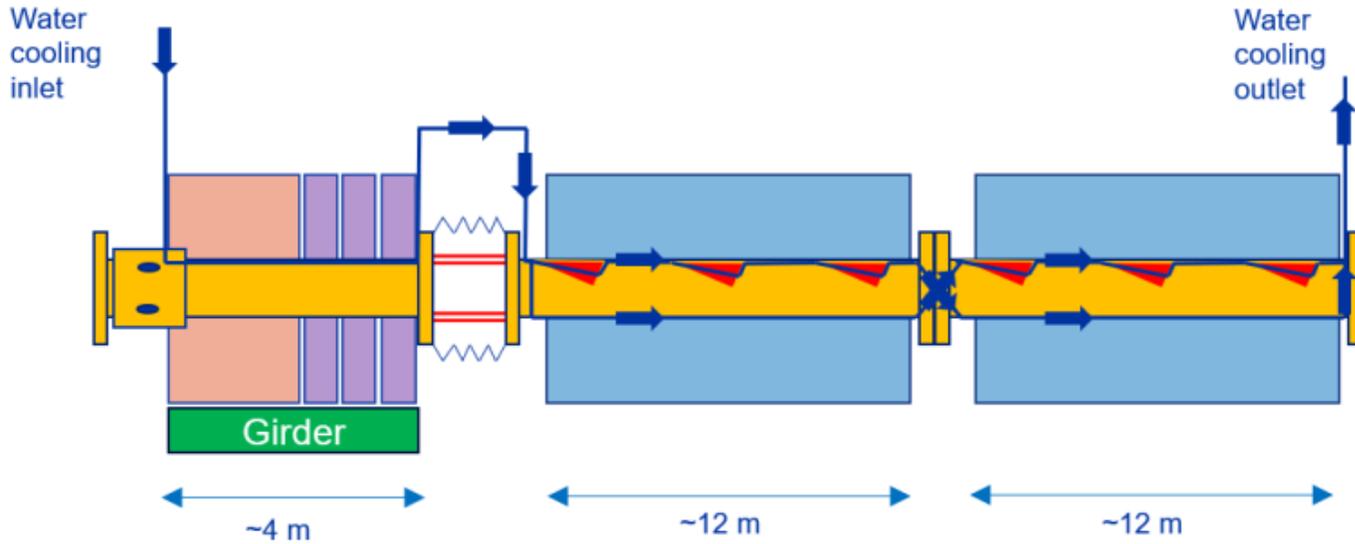


Fig. 3.19: The vacuum chamber cooling layout for the arc half cell.

A discrete SR absorber of 0.4m length every ~4m

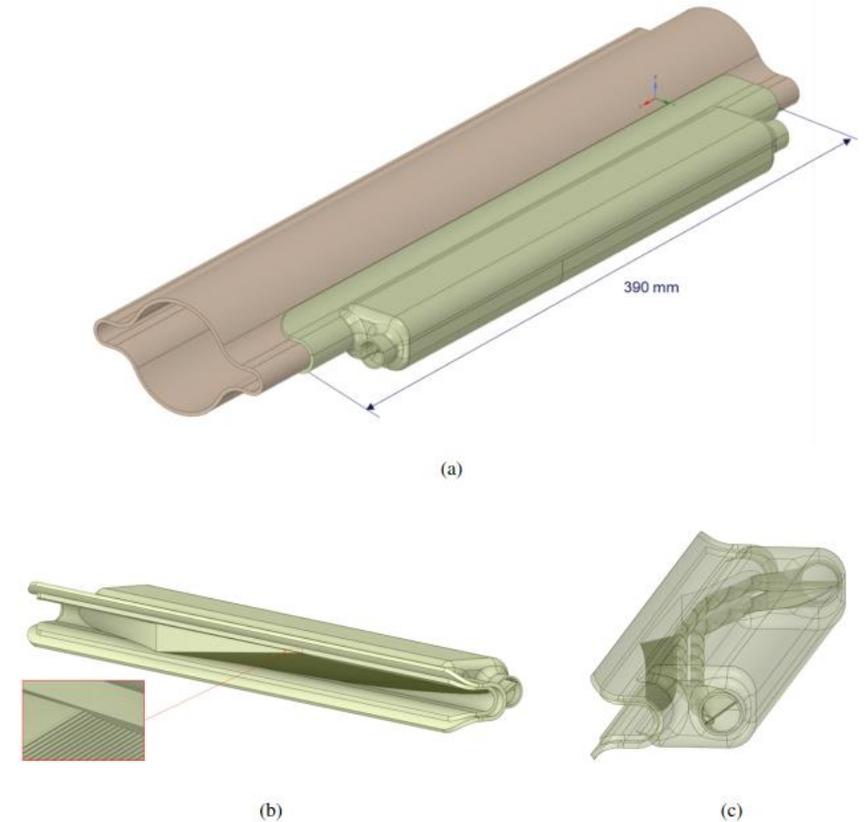


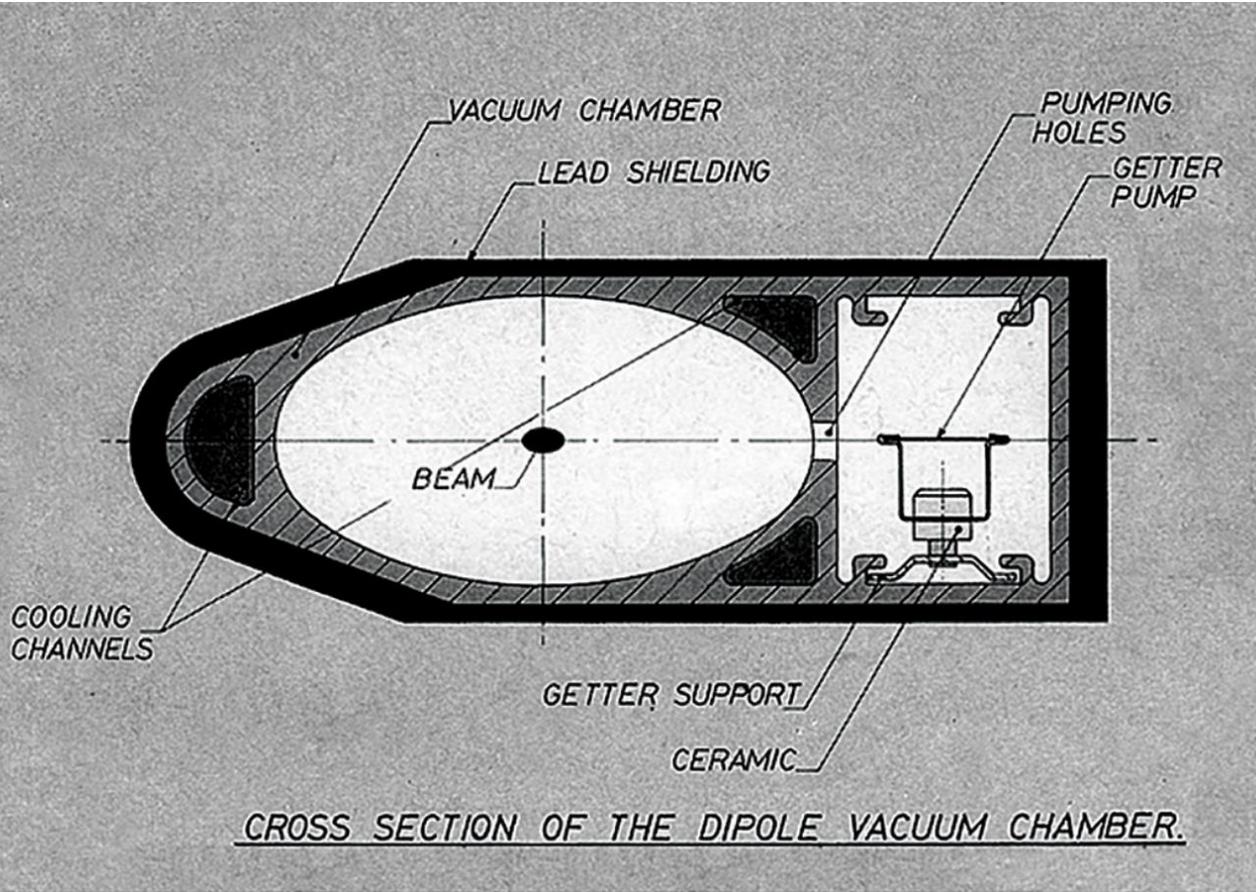
Fig. 3.9: (a) Synchrotron radiation absorber integrated in the vacuum chamber, (b) sawtooth profile highlighted, and (c) cooling channels with twisted tape.

Synchrotron radiation absorber

- If we keep the discrete absorber solution of FCC-ee, our discrete absorbers (for the same power) would be $\sim 1.5\text{m}$ from each other
- We should investigate if a continuous system works better for LEP3
- SR power per meter at LEP3: 2.5kW

From LEP2 to LEP3

LEP2 vacuum chamber – extruded Aluminium



- Oval shape is bad for impedance
- Beam sizes were larger at LEP2
- Artist's impression of LEP3 beam pipe:

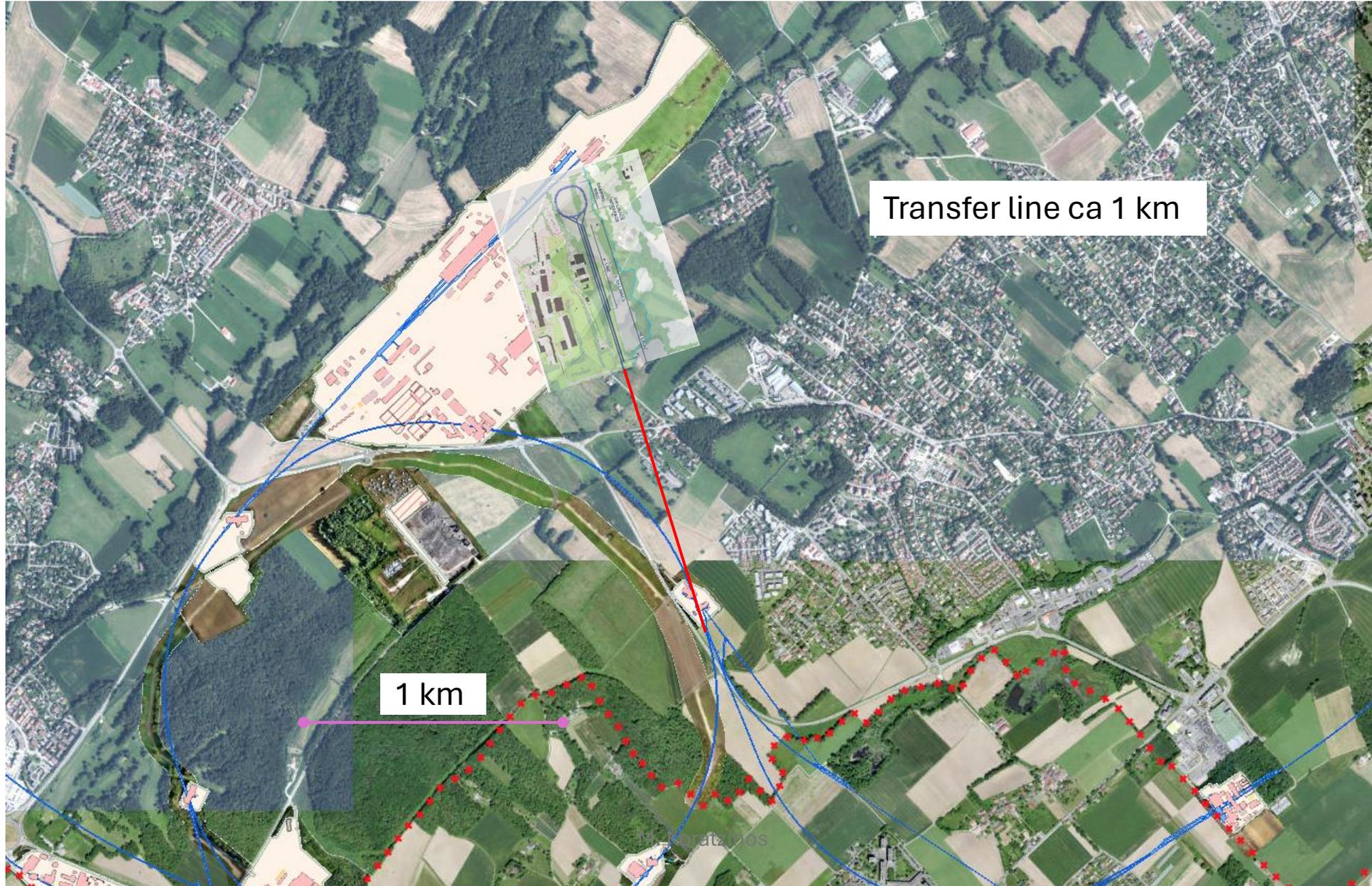


Injector complex

LEP3 injector

- The energy of the injector is determined by the minimum field of the booster magnets and the energy swing
- For FCC, injector energy is 20GeV.
- LEP3 has magnets that are a factor 3.4 stronger
- We can safely reduce the energy to 10GeV – maybe more?
- This makes the injector shorter and cheaper
- This in turn possibly allows a different placement, **fully on CERN land**, resulting in a much shorter transfer line

Injector placement



RF

RF strategy

- Together with the RF group, we have come up with an RF design that respects all our requirements (Ivan Karpov)
- We have opted for a pure 800MHz system (cheaper to build and operate than a hybrid 400-800MHz system)
- For the Z running: single cell; for the WW and ZH collider: 4-cell for the booster: 6-cell
- We use a single RF system at the ZH and a double at the Z (and currently a double system at the WW)
- We have four LSS to fit the RF for the collider and the booster, each 563.5m long

RF parameters

800 MHz system only

Running	Z	WW*	ZH	Booster ZH
Common RF for two beams	No	No	Yes	No
Total Required RF Voltage (MV)	500	1500	6000	6000
No. of Cryomodules	104	104	104	66
Frequency (MHz)	800	800	800	800
Cells/Cavity	1	4	4	6
Voltage/Cavity (MV)	2.4	14.4	14.4	22.7
Accelerating gradient (MV/m)	12.9	19.3	19.3	20.3
Power/cavity (kW)	240.4	240.4	240.4	20.1
Beam current (mA)	371	39	9	0.9
Total Power (MW)	100	100	100	5.3
Total Voltage (MV)	1000	3000	6000	6000

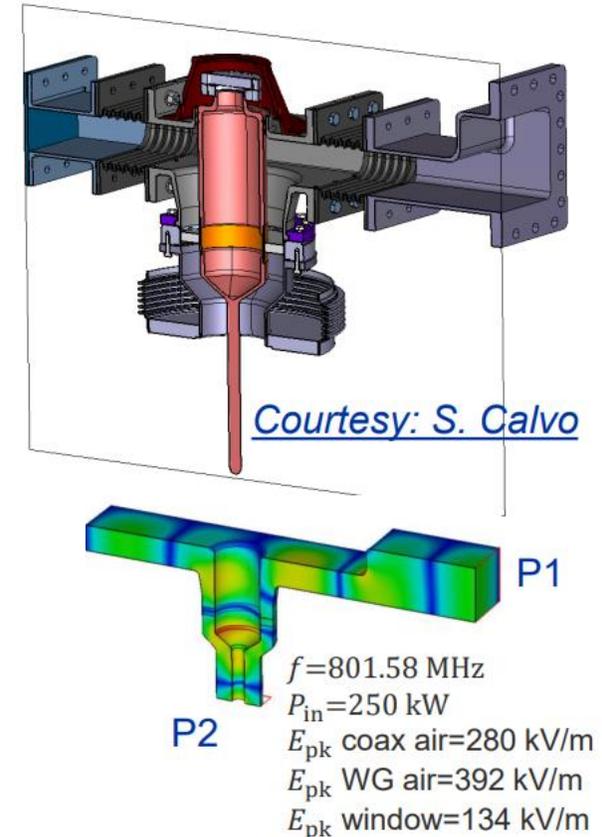
*Reverse Phase Operation allows to avoid fundamental power coupler modification between WW and ZH modes

Total cost of 1.4 BCHF

- 800 MHz option seems to be more feasible in terms of integration, performance margins, and cost
- Additional R&D can help in reducing the RF system cost (e.g., more powerful FPCs)

Fundamental power couplers

- At LEP3 we are not limited by the achievable gradient, but by the amount of power we can put in the cavities (the Fundamental Power Couplers)
- Current state of the art of these couplers is 250kW for 800MHz
- If we were able to get **22% more power** from these couplers, then 6-cell cavities (which are more space efficient) would fit, and the collider would not need 4-cell cavities
- This would make the system cheaper (less cryomodules) and shorter
- Some R&D on this topic would be very beneficial for LEP3

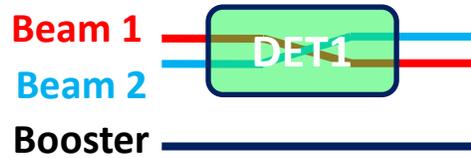


Does the RF fit in the LEP3 tunnel?

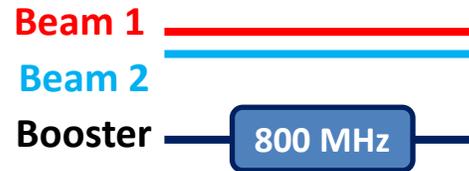
- LEP3 has 8 LSS, each 563.5m long (4360m total)
- Two will be used by the experiments (plus polarimeters, plus depolarizers?)
- Two are difficult to access
- We are planning to fit the collider RF in two LSSs and the booster RF in two other LSSs
- LEP3 at ZH: SR loss: 5.2GeV; **installed RF: 6.0GV**
- (the LEP3 RF system is **52%** of the FCC one)
- We have fitted the RF system in the 563.5m available using 4 LSSs

LEP3 RF configuration -Z

Point 1



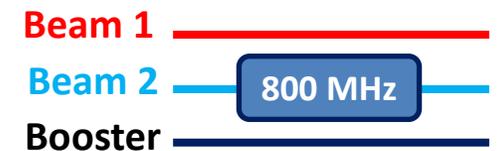
Point 2



Point 3



Point 4

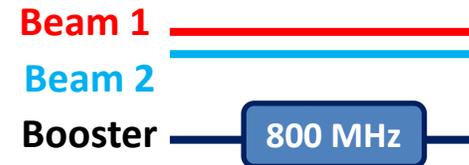


Z (45GeV)
800 bunches

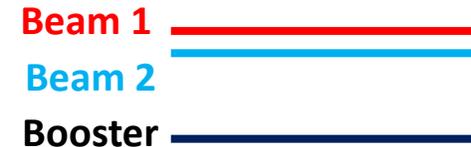
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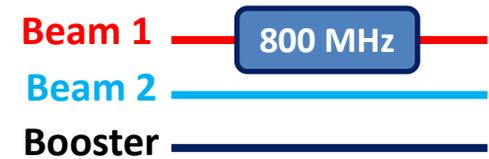
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Point 7



Point 8

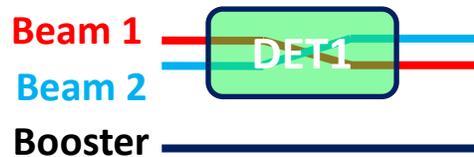


LEP3 RF configuration -ZH

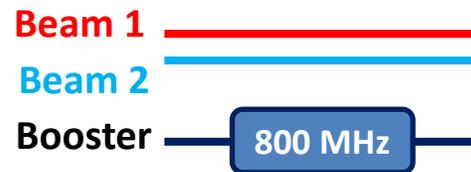
H (115GeV)

20 bunches

Point 1



Point 2



Point 3



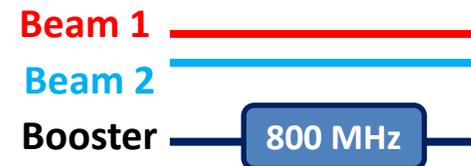
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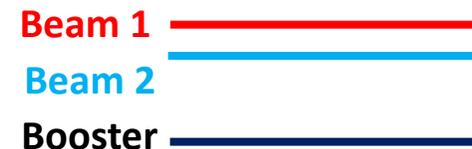
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Point 6



Point 7



Point 8



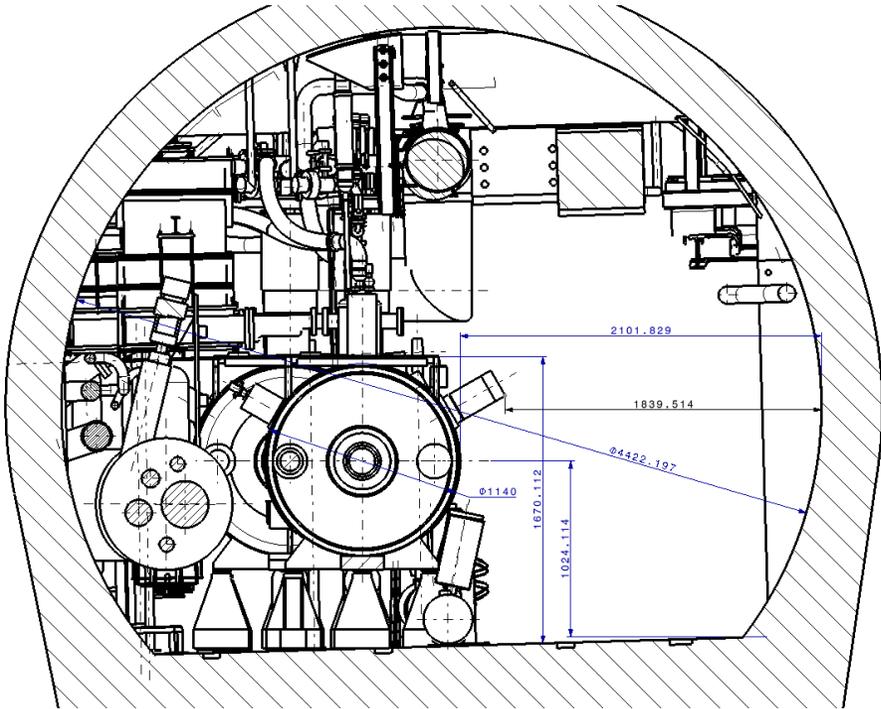
This arrangement needs electrostatic separators which will have to be designed and should fit in the tunnel

RF integration

- Space is more tight in LEP3 than FCC with the exception of height:
 - LEP3: diameter: 4.4m height: 3.6m
 - FCC: diameter: 5.5m height: 3.2m
- Integration will be difficult because we have (in the Z running mode) three beampipes. Two need to bypass the cryomodules
- LEP3 plans to use 800MHz modules that are more compact than 400MHz
- R&D on compact cryomodules would be appreciated!

Compare tunnel sizes @RF areas

LHC 400MHz



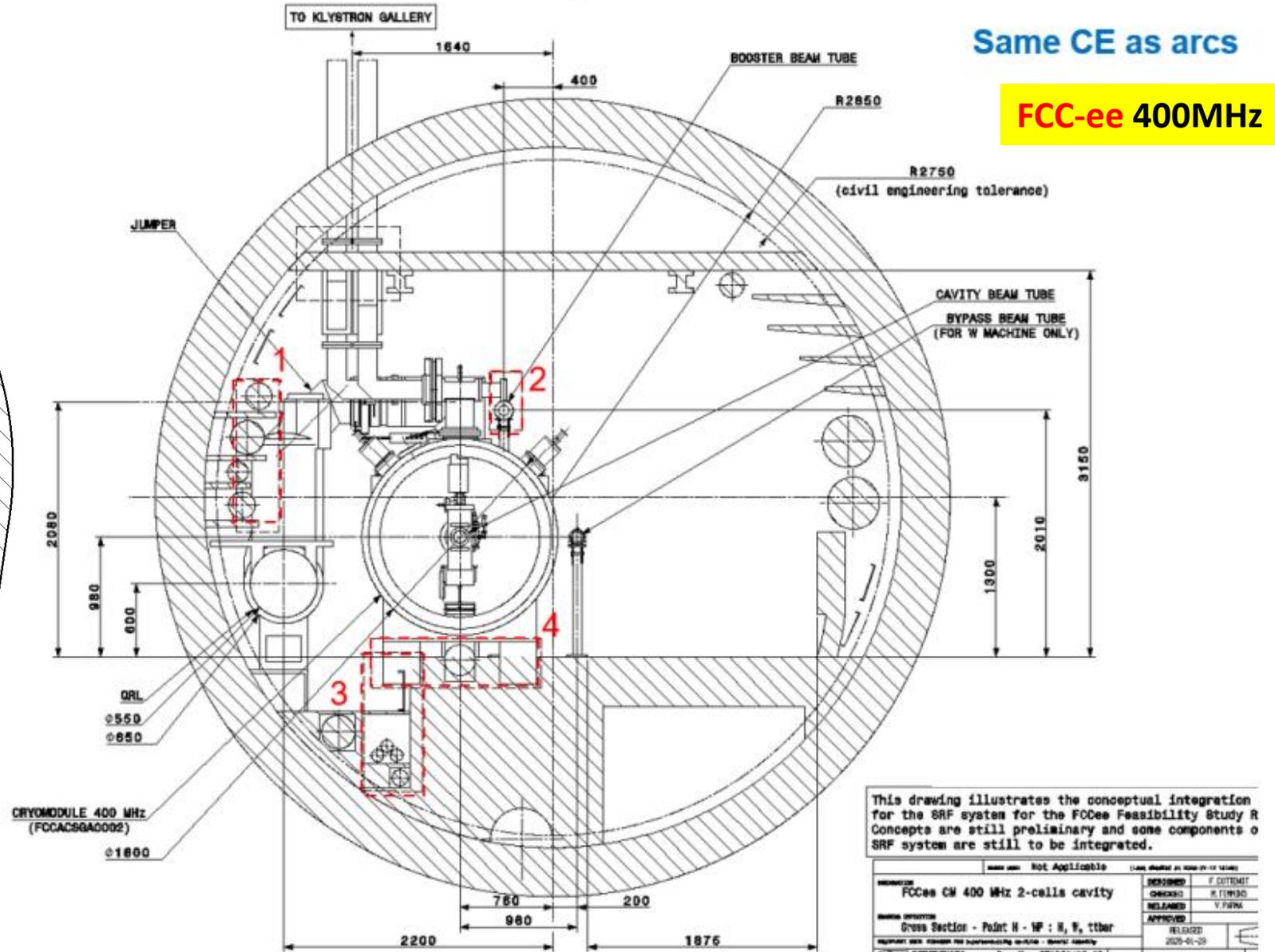
LEP3 has more headroom!

LEP3 3.6m

FCC 3.2m

Same CE as arcs

FCC-ee 400MHz



M. Koratzinos

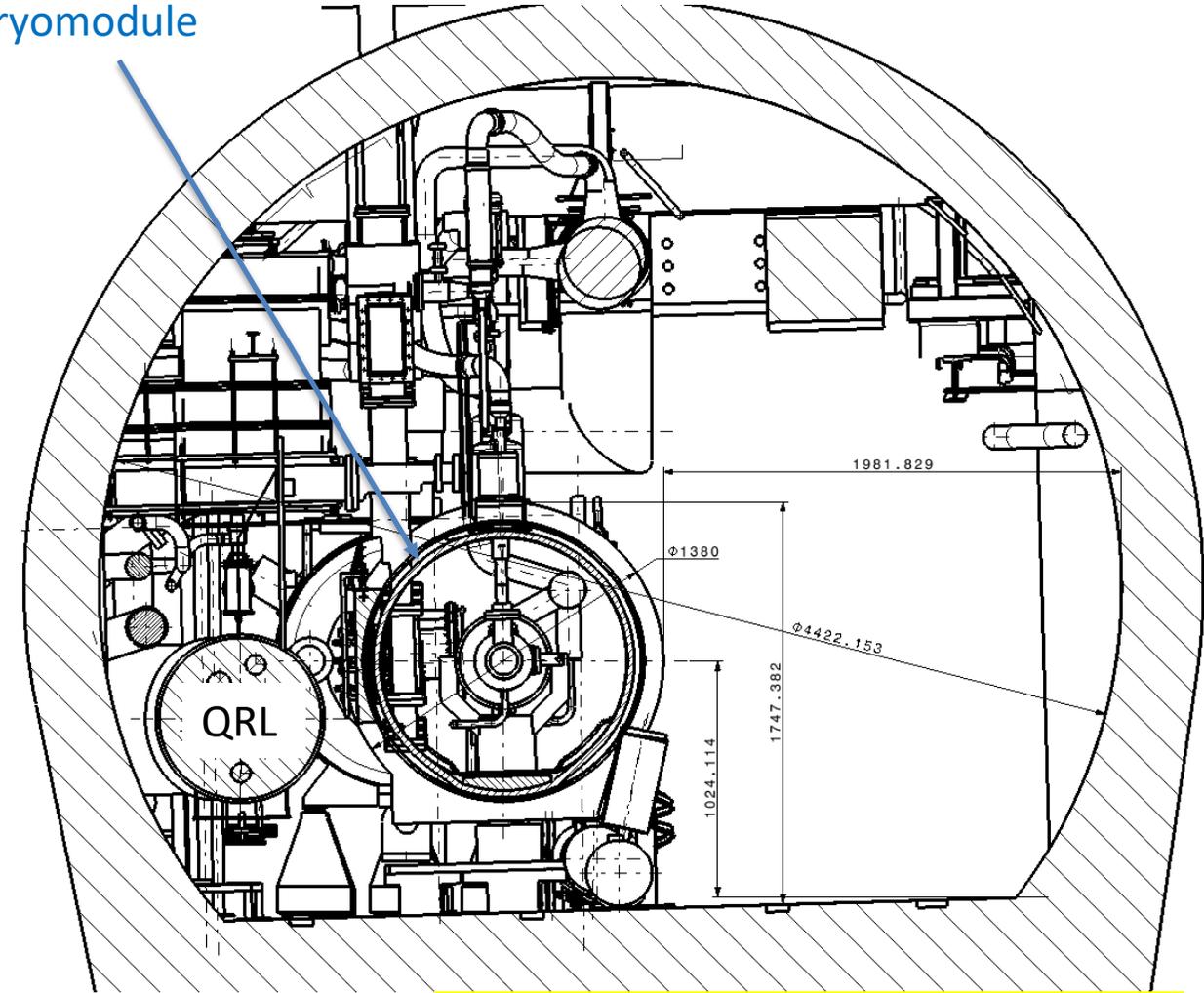
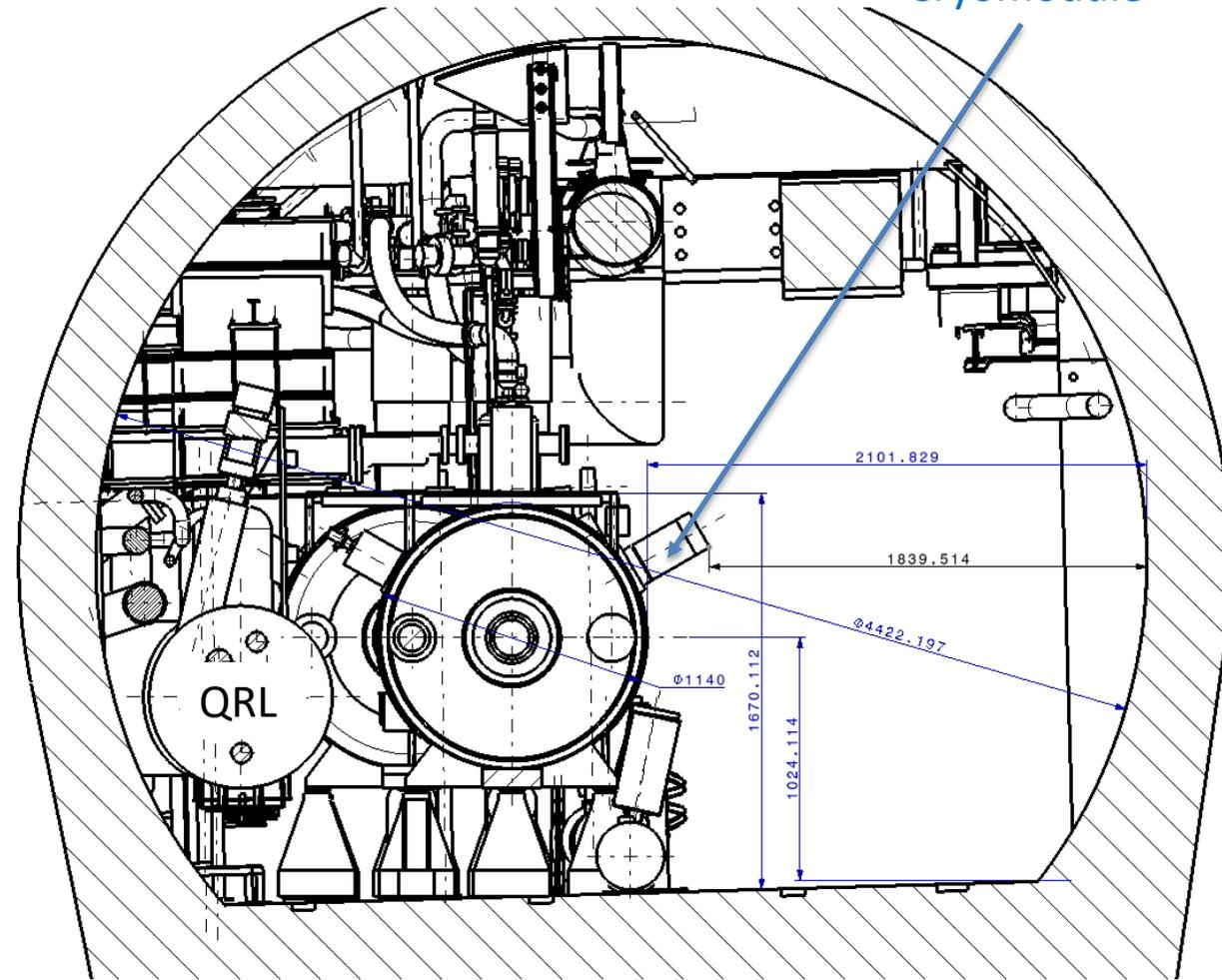
First LEP3 integration studies

LHC 400 MHz CM integration Pt 4

LHC 400 MHz
Cryomodule

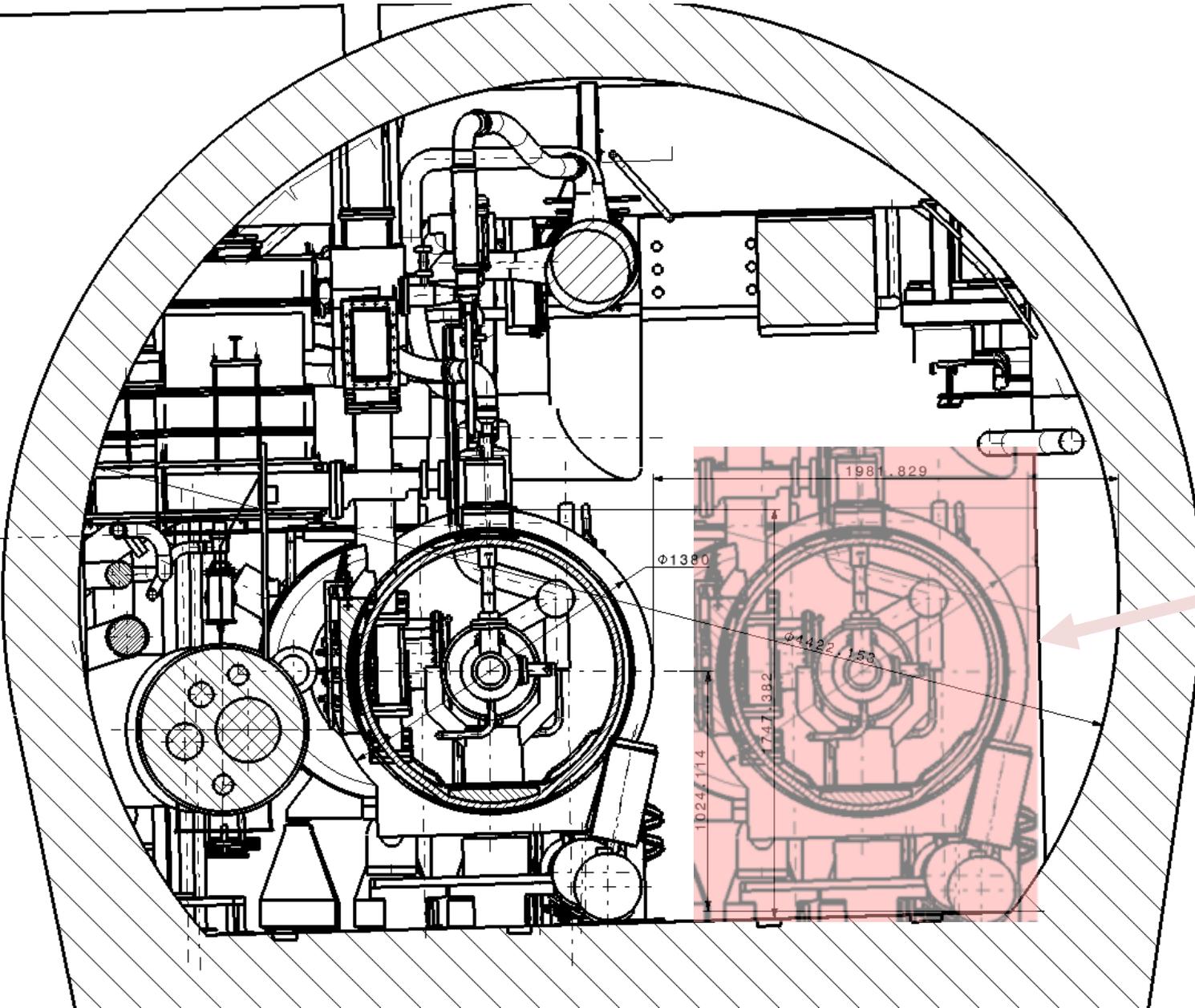
FCc_{ee} 800 MHz
Cryomodule

FCc_{ee} 800 MHz CM integration Pt 4



The two beam pipes bypassing the system are not shown!

New integration drawings



What is not shown are the other two beam lines, the second collider line and the booster line. More integration work needed

Overtaking unit

Power consumption

Collider magnet power consumption

- Compared to FCC, LEP3 is:
 - Factor 3 smaller
 - Factor 3 higher dipole field
 - Factor 2 smaller aperture (leading to a factor 4 less power)
 - Dipoles: aperture 74 strength 61mT (at 182.5GeV)
 - Quads: FCCee (feasibility study) total length: 8410m max strength: 12T/m, aperture 74mm; LEP3 1900m; 21T/m; 44mm
 - Sextupoles: aperture 66mm, strength 880T/m²; length 6074m; LEP3 **only** 185m 740T/m²; 44mm
- The new lattice design has a much lower number of sextupoles, so a normal-conducting solution is feasible
- We will keep the superconducting option as an option for increased performance/lower consumption

Collider magnet power consumption

- Use FCC lattice V24.3 GHC as basis

Table 3.1: Magnet requirements for the FODO lattice V24.3 GHC.

	Dipole	Quadrupole	Sextupole
Total number in lattice. . .	6128	3324	4672
. . . of which in the arcs	5680	2836	4672
Bore aperture	74 mm	74 mm	66 mm
Magnetic length	9.7 - 11.2 m	2.9 m	1.3 m
Max strength [†] , arc ($\bar{t}\bar{t}$, 182.5 GeV)	61.0 mT	11.9 T m ⁻¹	880 T m ⁻²

[†] Sextupole strength given as B'' ($B'' = 2S$)

Power demand (next page) includes conversion (10%) and distribution (5%) losses, so total power consumption (this page) needs to be multiplied by 1.17 to get the power demand

Apertures of LEP3 quads and sextupoles are under discussion and might change by small amounts – overall pictures remains.

	length	strength mT	aperture mm	length factor	strength factor	aperture factor	Power factor	power Z (MW)	power W (MW)	power H (MW)
FCC dipoles	62964	38.40	74	1.00	1.00	1.00	1.00	0.80	2.60	5.80
LEP3 dipoles	19352	125.00	38	0.31	10.60	0.26	0.86	0.69	2.23	4.98
FCC quads	8410	12.00	74	1.00	1.00	1.00	1.00	1.40	4.30	9.80
LEP3 quads	1900	21.00	44	0.23	3.06	0.35	0.24	0.34	1.05	2.40
FCC sexts	6074	880.00	66	1.00	1.00	1.00	1.00	1.30	3.90	8.90
LEP3 sexts	185	740.00	44	0.03	0.71	0.44	0.01	0.01	0.04	0.09
FCC cables	62964						1.00	1.2	3.80	8.60
LEP3 cables	19352						0.31	0.37	1.17	2.64
FCC total								4.70	14.60	33.10
LEP3 total								1.41	4.49	10.11

LEP3 power consumption – FCC as basis

FCC		Z	LEP3-Z	W	LEP3-W	H	LEP3-H	TT
Beam energy (GeV)		45.6	45.6	80	80	120	115	182.5
PRF EL (MW)	Collider	146	146	146	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2	2	2	2
Pcryo (MW)	Collider	1.2	10	11.5	21	11.5	21	27.6
Pcryo (MW)	Booster	0.35	1.3	0.80	2.5	1.50	4.9	7.40
Pcv (MW)	all	25	9	26	9	28	10	33
PEL magnets (MW)	Collider	6	2	17	5	39	12	89
PEL magnets (MW)	Booster	1	.3	3	1	5	1.5	11
Experiments (MW)	Pt A & G	10	5	10	5	10	5	10
Data centers (MW)	Pt A & G	4	2	4	2	4	2	4
General services (MW)		26	7	26	7	26	7	26
Power during beam operation (MW)		222	185	247	201	273	211	357
Average power / year (MW)		122		138		152		202

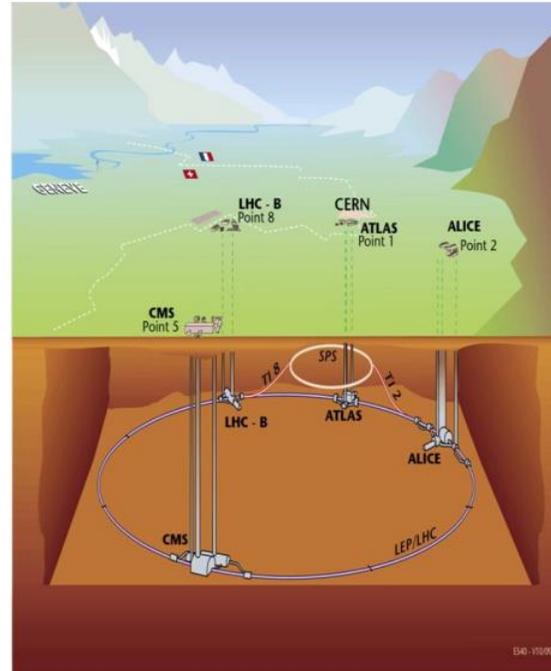
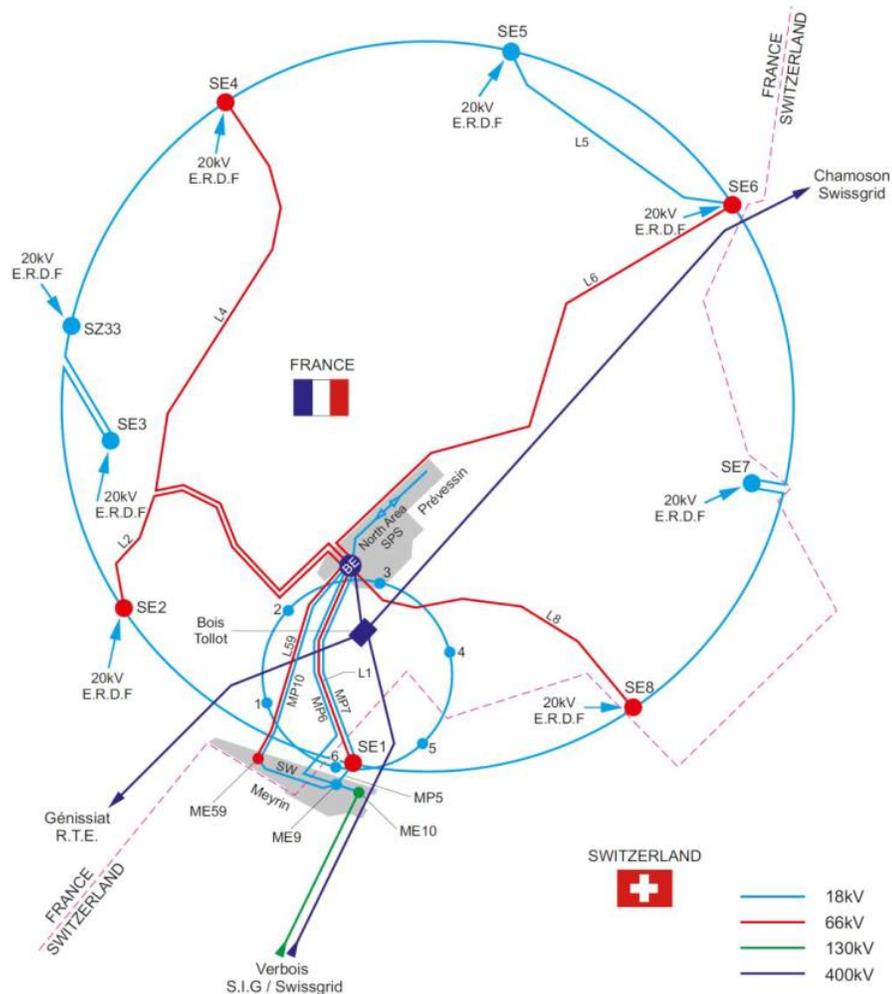
Highlighted: new numbers

Cooling and ventilation: about 1/3 of FCC, due to tunnel lengths

Cryo: LEP3 calculation is slightly higher than FCC – to be checked.

Installed capacity

Electrical network: geographical extension



Voltage levels:

- 400 kV main incomer
- 66 kV transmission
- 18 kV distribution
- 3.3 kV motors
- 0.4 kV users

- More than **700MVA** installed in the 400kV line, so no modification needed
- **400MVA** installed on the 66kV lines

Point 2: two 38MVA transformers; would need to install a third or replace the 38MVA with a 70MVA

Point 6: only one 38MVA transformer; would need to install a second 70MVA transformer

Power lines to points 2 and 6 would need upgrading

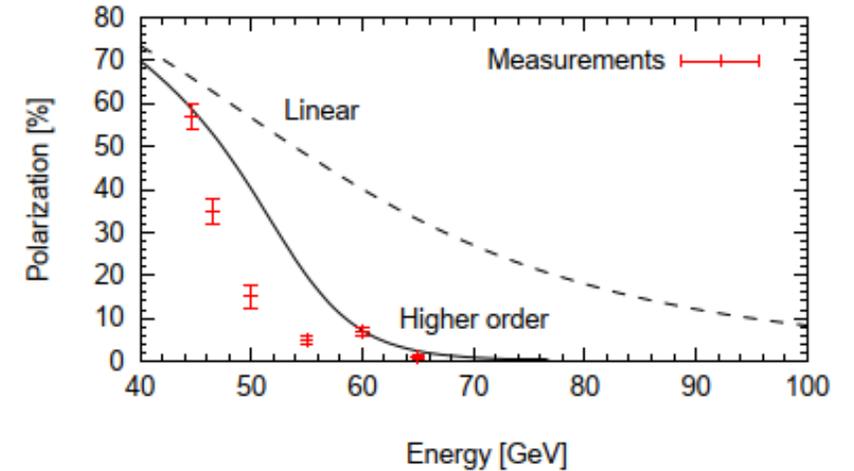
polarization

Polarization

- When we talk about polarization for LEP3 (and FCC) we refer to transverse polarization which can be used as an accurate means of measuring the beam energy using the **resonant depolarization method (RDP)**:
 1. Built up 5% or more transverse polarization (or inject polarized bunches)
 2. Measure and monitor the polarization levels
 3. Use a resonator to find the ‘spin tune’ by destroying polarization for a specific bunch
 4. Spin tune is proportional to energy
- A second method is also considered: **free spin precession (FSP)**, relying on injecting polarized bunches. If it could be made to work, it has many advantages over the RDP method

Polarization at the Z and WW

- LEP only saw polarization up to 60GeV
- Problem is that energy spread increases with energy squared and decreases with the square root of the bending radius
- If the energy spread is larger than $\sim 52\text{MeV}$ in the case of LEP, the distribution hits half integer spin tune resonance bands and the bunch quickly depolarizes
- In the case of FCC, due to the large bending radius, polarization is expected at the Z and WW energies
- LEP3 can get polarization at the Z, but will be difficult for the WW running



$$\sigma_E \propto \frac{E^2}{\sqrt{\rho}}$$

Energy determination

- LEP achieved an energy uncertainty for the Z mass of $\sim 2\text{MeV}$
- FCC is expected to achieve a systematic error of 100keV or lower. This is achieved by performing $\sim 10,000$ depolarization measurements instead of ~ 30 (and a lot of hard work on the systematics)
- LEP3 can achieve similar systematic error on the Z
- On the W, FCC is hoping to achieve $\sim 160\text{keV}$ using RDP.
- Work is needed to determine if LEP3 can make the RDP or FSP methods work (maybe not routinely, but with special optics)

WW running: can LEP3 measure the energy?

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

THE REGIMES OF POLARIZATION IN A HIGH ENERGY e^+e^- STORAGE RING

R.W. Assmann, CERN, SL Division, Geneva, Switzerland

The prediction is that for very high synchrotron tune values, detectable levels of polarization might be possible

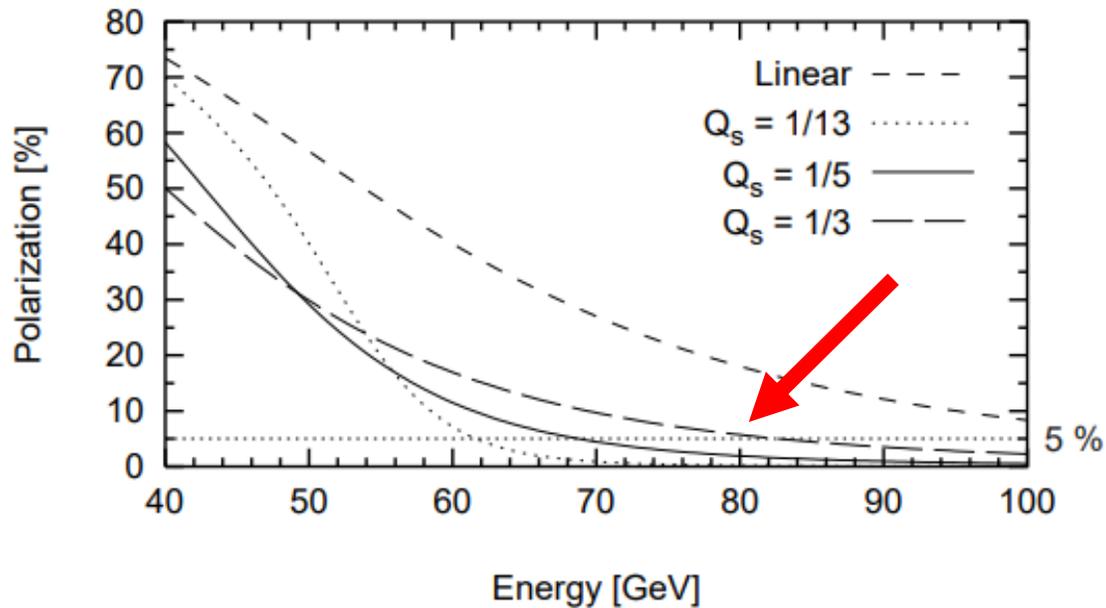


Figure 4: Predicted transverse spin polarization in LEP as a function of beam energy for different values of Q_s .

I. Korat

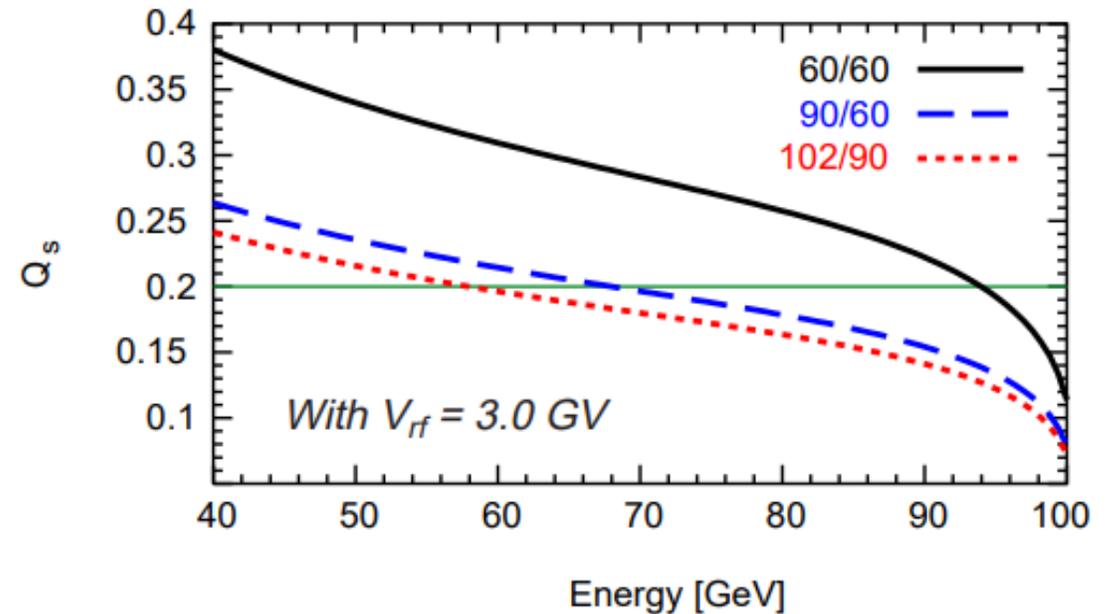
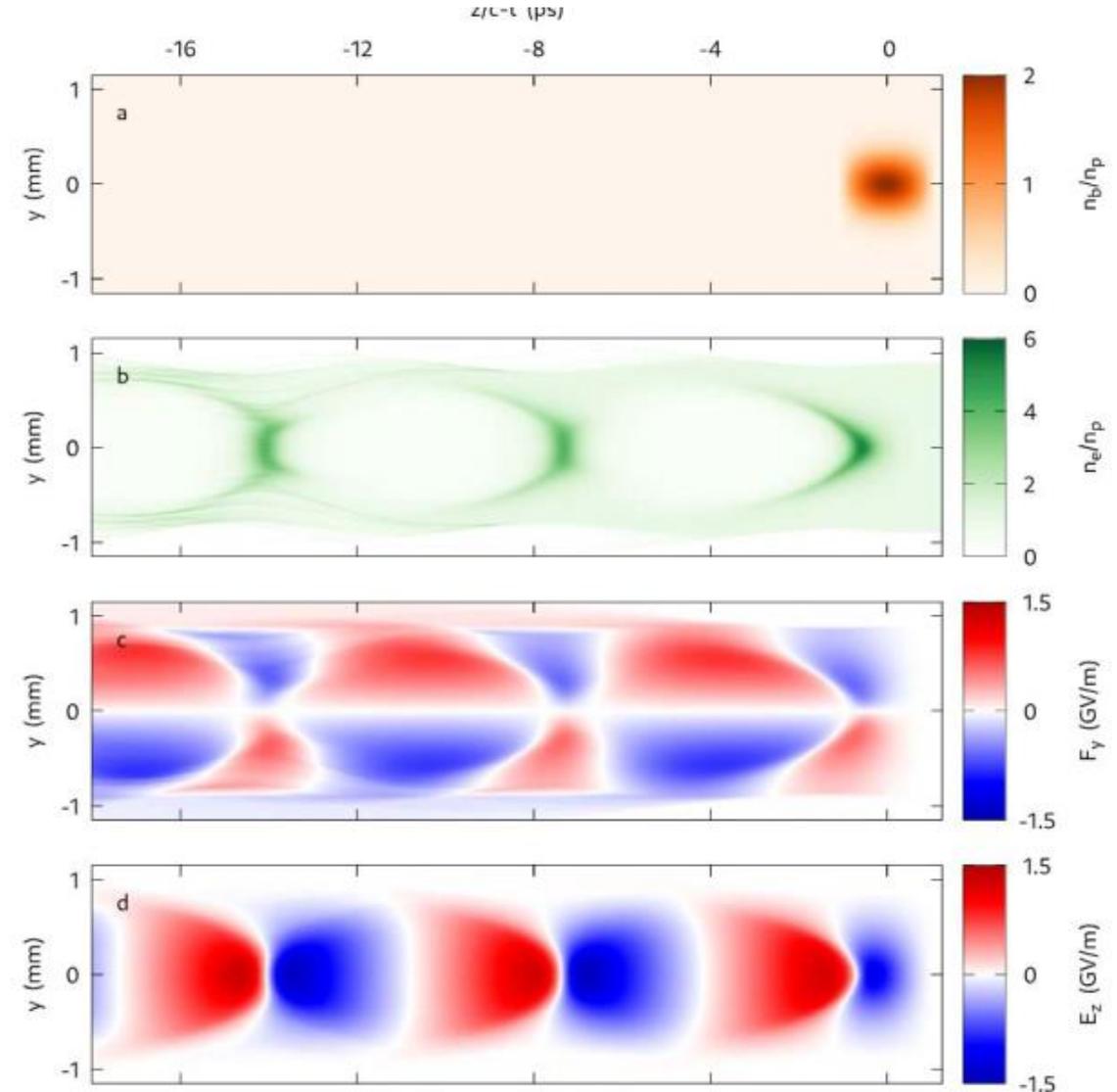


Figure 2: Maximum achievable Q_s as a function of energy and for different optics (with 3 GV RF voltage).

Upgrades

LEP3 cannot reach the $t\bar{t}$ threshold

- ...not so fast!
- Please follow Allen Caldwell's presentation on Thursday on LEP3 ALiVE (WORK BY (Tom Wilson and John Farmer Max))
- → Reach the $t\bar{t}$ threshold by colliding 115GeV positrons with 290GeV electrons from a **proton-driven plasma accelerator** of size 300-500m
- Possible luminosity: $0.2E34$
- Protons can be had by a super SPS with 14-16T magnets
- A long shot, but it is nice that people are thinking about these things and coming to innovative solutions



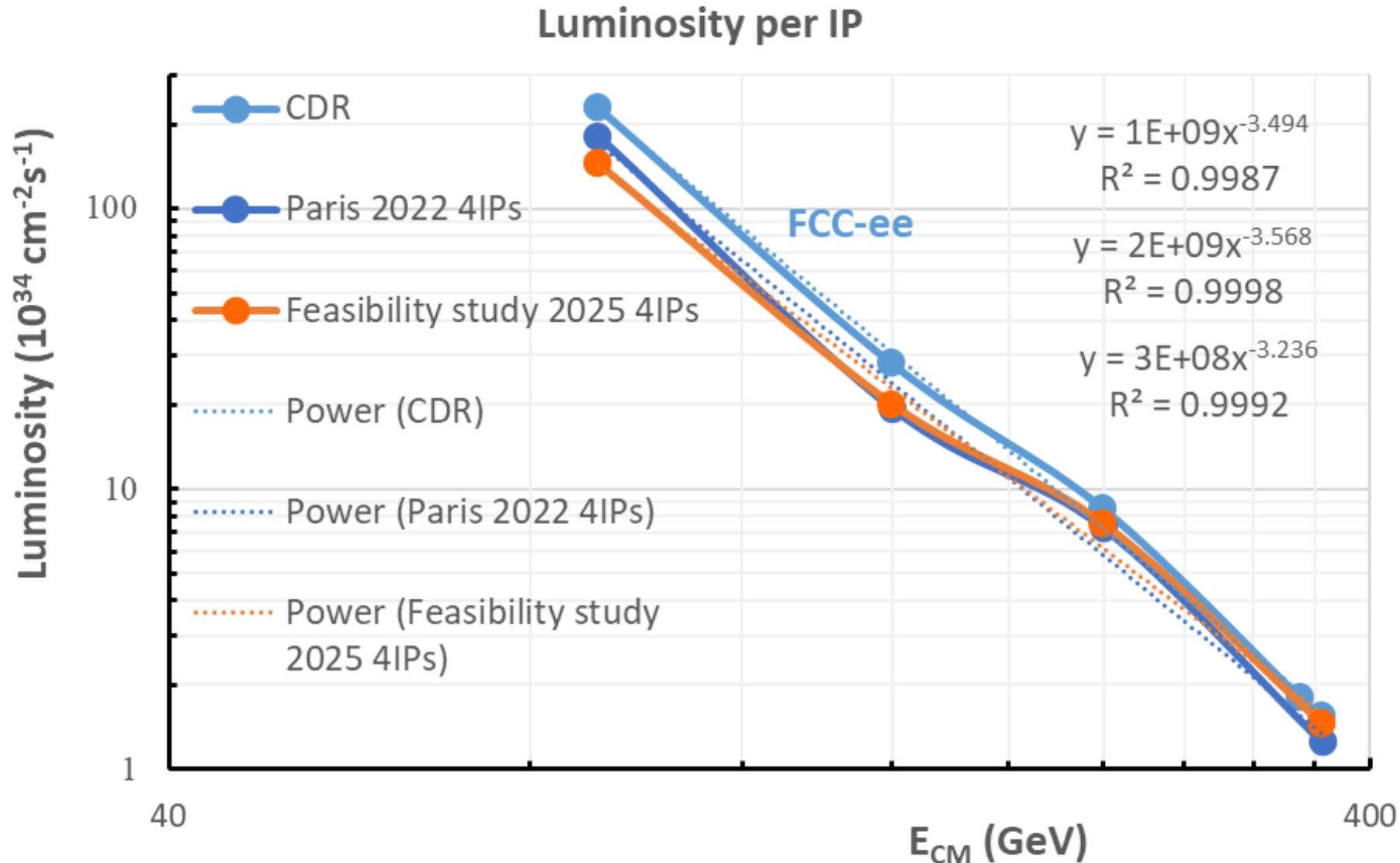
Conclusions

- We have started addressing the points where we were given poor marks by the ESPP
- Recent work on optics of LEP3 gives excellent results
- Luminosity is greatly improved over the ESPP version
- Vacuum chamber diameter can be reduced from the ESPP version
- Power demand is reduced
- If this is to be a viable option, more work on verifying all aspects of the design is needed.

THANK YOU

EXTRA SLIDES

What is the power law of FCC luminosities?



Power law varies between -3.6 and -3.2. Latest is -3.2

Empirical formula from FCC suggests that luminosity drops a bit more steeply than the expected E_{beam}^{-3}

LEP3 lattice development

January 7th, 2026

Pantaleo Raimondi
Fermilab/CERN

Outline

- Strategy recap
- ARC lattice
- Straight sections
- Final Focus system
- Hardware requirements
- Performances
- Conclusions

LEP3 vs FCC Superfactory

- LEP3/FCC length ratio ARC about 0.30 =>
 - 3 times lower current (constant SR/RF power)
 - @Z <3% of the RF buckets are used
 - 2 vs 4 IPs
- LEP3 potential should assume:
 - ARC lattice that delivers same FCC emittance
 - FF that delivers same betas*
 - sqrt(2) larger vertical tune shift (because 2 IPs)
- Luminosity could be around 50% wrt FCC (per IP)

If the y-tuneshift is only limited by the half-integer (FCC assumption @Z), the luminosity could be around 70% wrt FCC @Z.

Since at ZH the half-integer is crossed for FCC, L@LEP3 can't easily exceed 50% of the L@FCC

LEP3 challenges

- Not a green field:
 - Cons: Limits to performances and options
 - Pros: Reuse existing infrastructure
- Conceive an ARC lattice that delivers an FCC-like horizontal emittance
- Conceive a Final-Focus system with FCC characteristics that can be
 - Scaling from other machines and scaling laws might mislead us
 - Specificity of the requirements should drive the choice of technical solutions
- Optimize parameters for optimal performances specific to LEP3
- Optimize hardware for cost and power consumption

LEP3 ARC vacuum chamber diameter

- Chamber diameter is crucial
 - Daphne has about 90mm: 0.5GeV 2.0amps colliding
 - EBS has about 20mm 6.0GeV 0.2amps circulating (10mAmps single bunch)
 - MAX4 has about 20mm 3.0GeV 0.5Amps circulating

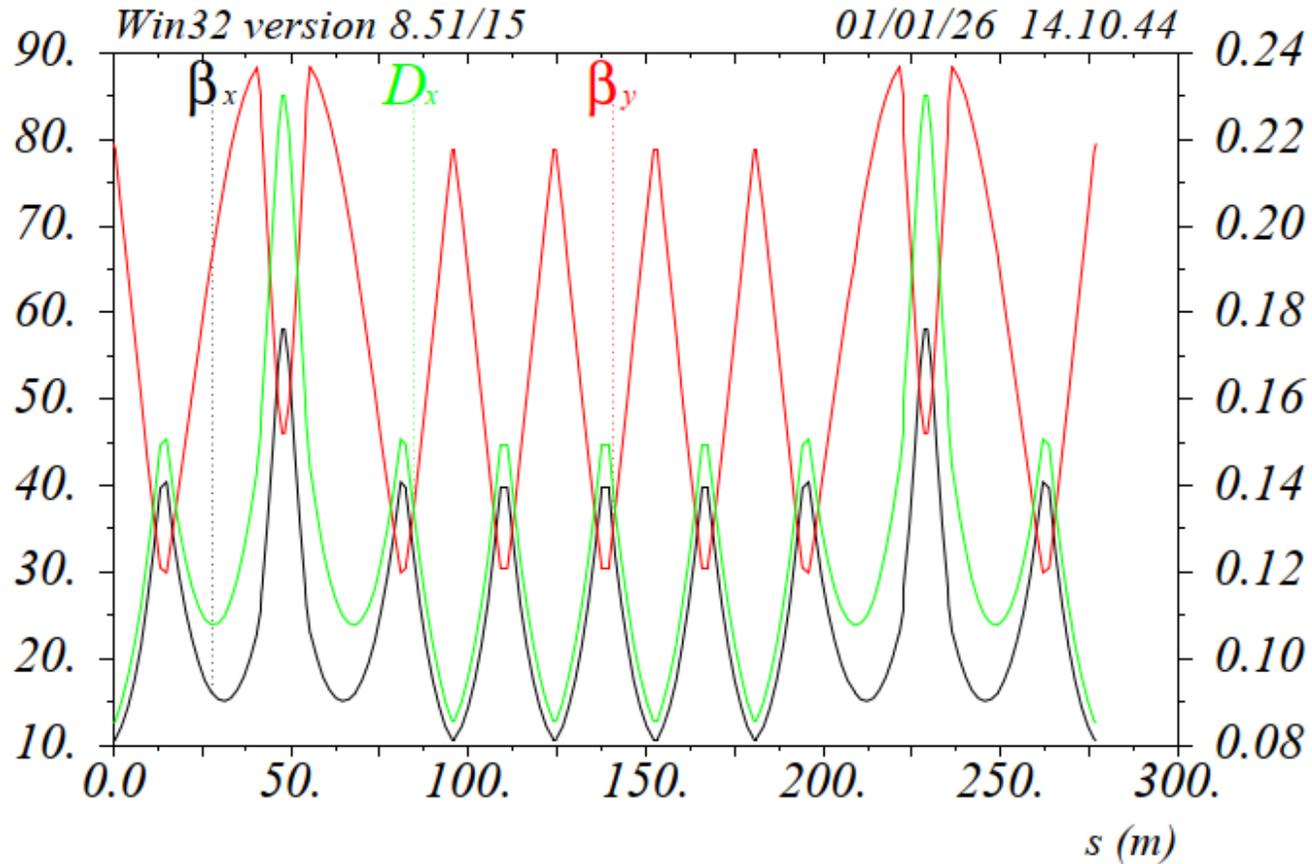
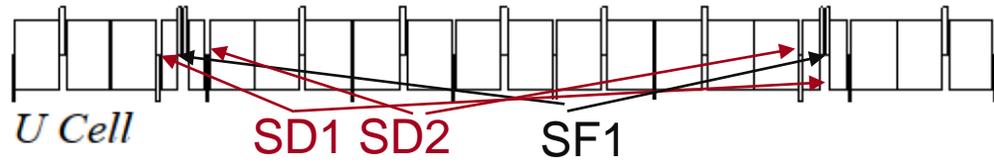
 - LEP3 will operate in the 45/120GeV range with ~0.01-0.3Amps colliding beams, most likely up to 30% of the FCC current

 - Impedance is a strong parameter that limits the minimum chamber dia, for the transverse part we should consider that (ARC only part):
 - impedance effect decreases linearly with total ARC length => factor 4 wrt FCCee
 - impedance effect decreases linearly with betas => factor 2 wrt FCCee
 - impedance effect decreases linearly(?) with current => factor 3 wrt FCCee
 - impedance is affected by bunchlength
 - impedance increases with $1/\text{dia}^3$
 - same overall impedance effect is achieved by decreasing the dia by $24^{1/3}$ => factor 2.9
- FCCee has dia= 60mm => LEP3 can adopt dia=30mm and still have more stable beams

LEP3 inner chamber diameter can be very comfortably set to 30mm
Magnets gaps (opposite poles) should be around 38mm

EBS Achromat cell adapted for LEP3

Z/W/ZH modes



Sextupoles are grouped in an high beta/dispersion region

Phase advance between the sextupoles:

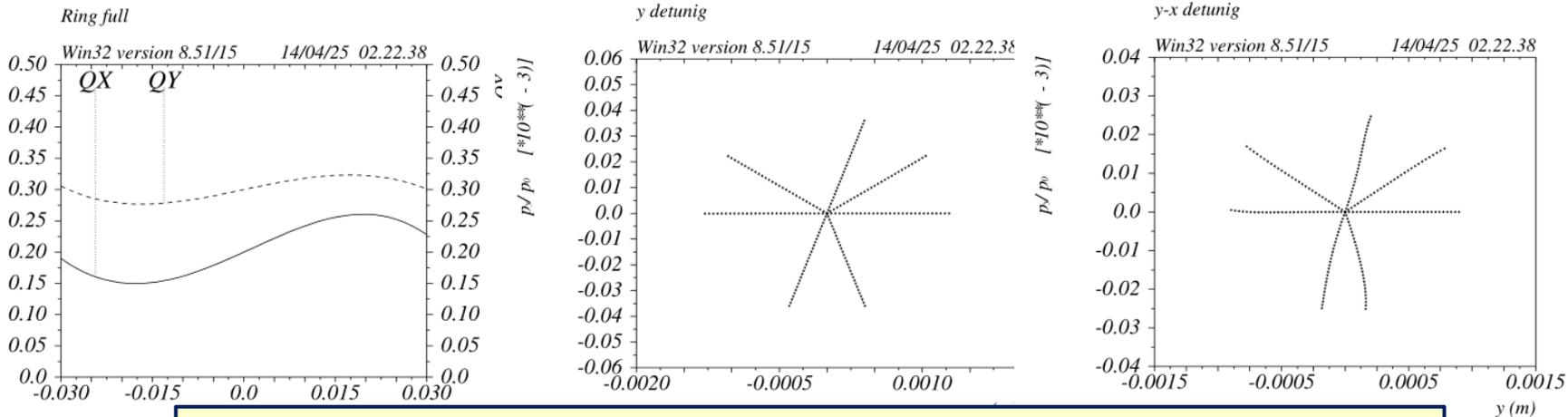
$$dmux \sim 3\pi$$

$$dmuy \sim \pi$$

Given the phase relations all the detunings are intrinsically small, effective $dmux$ and $dmuy$ are slightly adjusted (few %) to compensate for the interleaved sextupoles scheme.

Betas and dispersion at sextupoles and dispersion are optimized for best performance

Chromatic and DA properties HFD

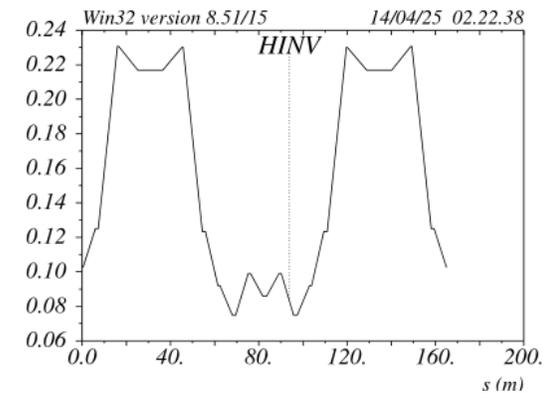
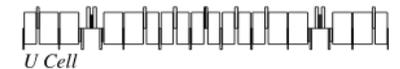
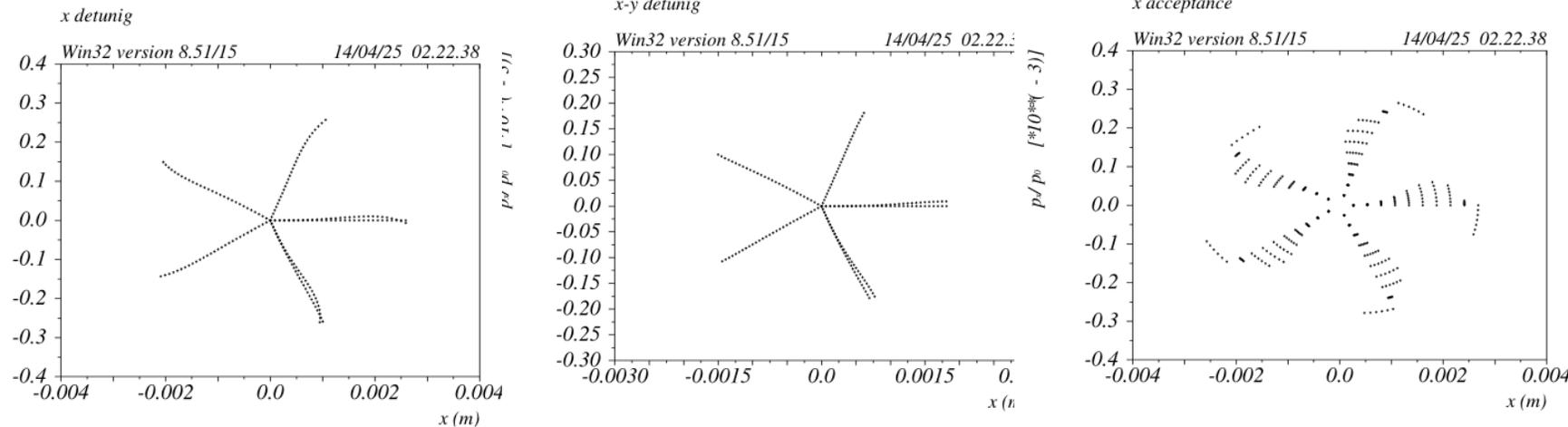


High order chromaticities are small, $MA > +/- 3\%$

No visible high order x detuning

Energy dependent detuning is very small as well (not shown)

(Repeat) All the studies are based on cell designs with vanishing RDTs up to the second order



ARC lattice layout

Cell length: 2768.88mt

Each cell consists of:

- 18 dipoles ~ 12.618mt long with defocusing gradient
~0.51T/m @115GeV
- 4 dipoles ~ 4.5mt
- 20 quadrupoles with gradients ~ 21T/m @115GeV
7 QFs ~ 1.85mt, 4 QFs ~ 1.10mt, 9 QDs ~ 0.85mt
- 6 sextupoles with gradients ~ 740T/m² @115GeV
2 SFs ~ 0.54mt long, 4 SDs ~ 0.34mt long

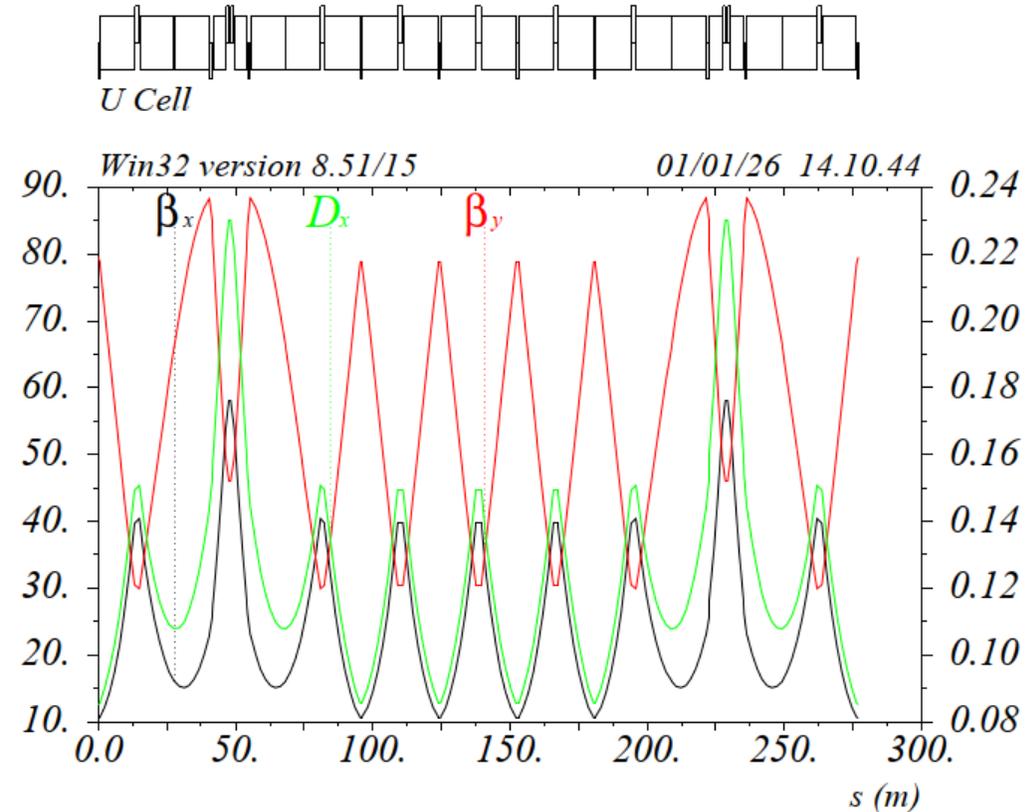
80 Cells make a 22151mt circumference

In facts including:

- 6 Straight sections
- 2 Interaction Regions (IR)

the 8 octants will be divided in:

- 4 octants consisting of **10 cells**
- 4 octants facing the 2 interaction regions consisting of **9 cells**
(to be explained in the Final Focus section)



LEP3 quadrupoles and sextupoles requirements wrt FCC @115GeV

FCC-LCC Ring-ARC needs:

2240 quads/beam

QFs about 2.9mt long

QDs about 2.1mt long

Gradients about 7.5 T/m

Total magnet length for the 2 rings (QFs + QDs) = $1120 \times (2.9 + 2.1) = 5600\text{mt}$ @7.5T/m

LEP3 Ring-ARC needs:

1520 quads/beam

QFs about 1.0-1.8mt long

QDs about 0.85mt long

Gradients about 21T/m

Total quadrupole length for the LEP3 ARC (QFs+QDs) = $76 \times 25.0 = 1900\text{mt}$ @21T/m

Quadrupole length ratio: for LEP3 about 34% of the FCCee quads are needed

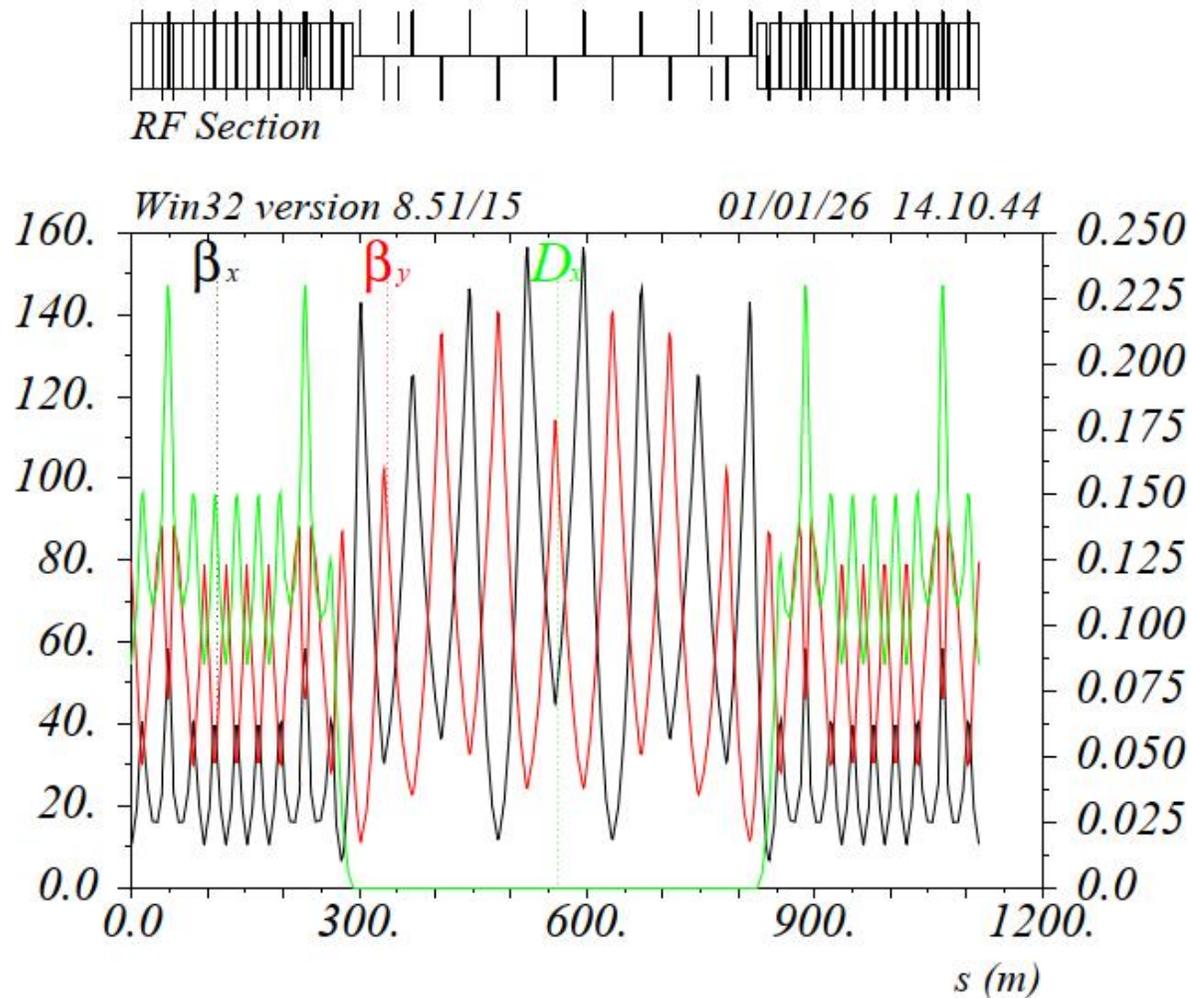
Power consumption scaling (LEP3/FCC) @115GeV:

Power goes with $L_{\text{mag}} \cdot G^2 \cdot \text{gap}^2$

Power ratio LEP3/FCCee @115GeV = $1900/5600 \times (21/7.5)^2 \times (1/2)^2 = 0.67$ (the $1/2^2$ is due to the ratio of Lep3 vs FCC magnet gaps)

Total sextupole length is about 185mt, whereas FCC-LCC needs about 730mt

Straight Section insertion



Straight Sections (SSs) are included with the Transparency Conditions criteria (TCs)

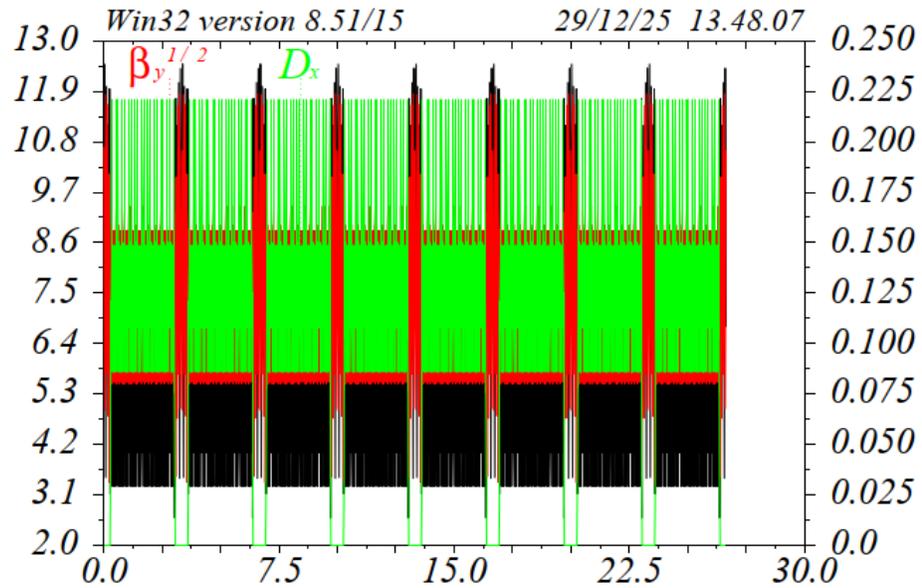
SSs are 563.5 mt long, however two extra dipoles are needed in the Dispersion Suppressor and they sit in the SSs, reducing the available SSs length to about 535mt

In fact the 4*2 last dipoles facing the SSs are 25% weaker wrt the ARC dipoles.

The TCs make so that the breaking of the ring periodicity is minimal, and no ARC sextupole families are needed when the SSs are included in the lattice.

Presently all the SSs are the same and they are very close to what will be the "Standard" RF section.

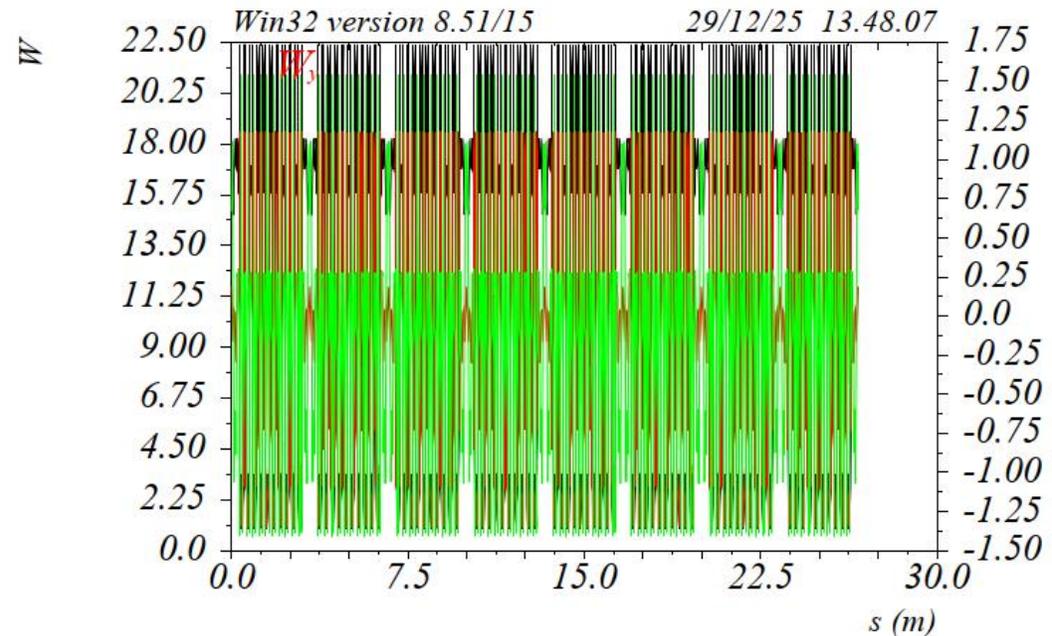
Straight Section insertion



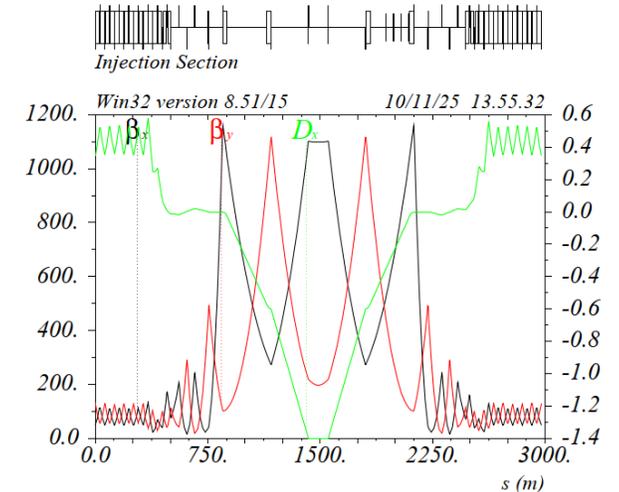
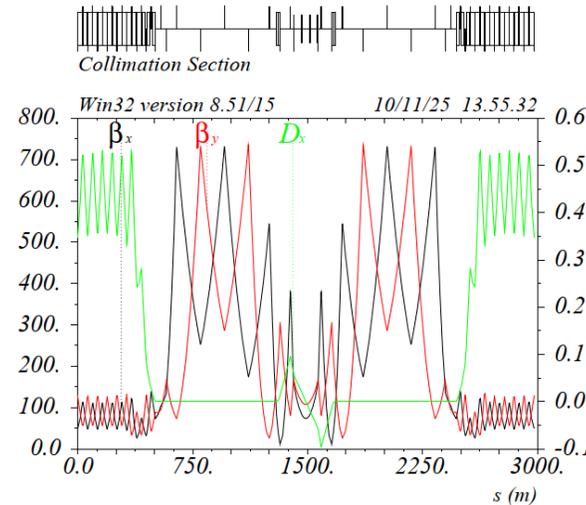
Full ring, consisting of 8 octants and 8 identical Straight Sections. Because of the TCs, the chromatic functions in the octants remains periodic.

The ring is 26659mt long.

Specialized SSs (injection and collimation) can be included as well, they can be a shorter version of the FCCee ones



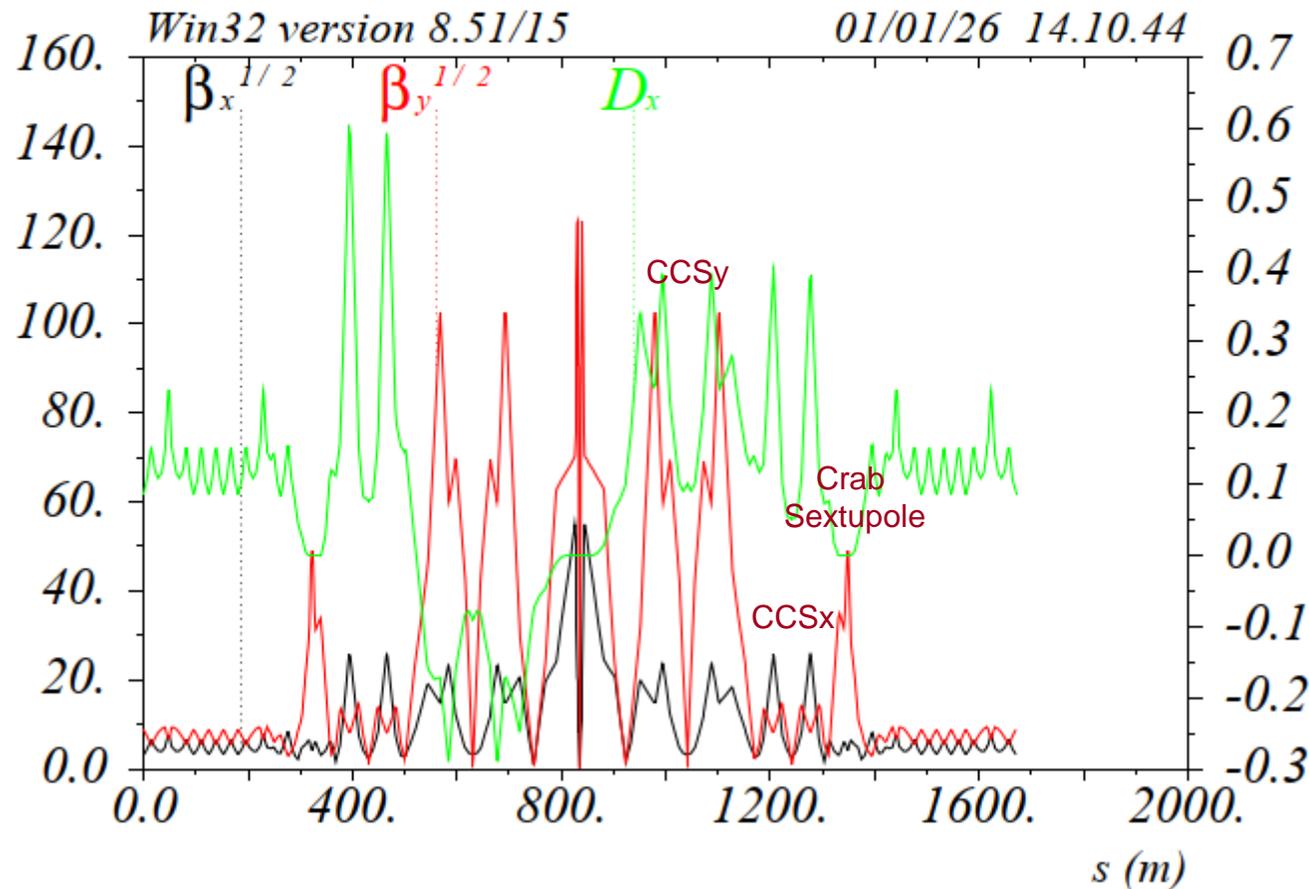
$dD/d\delta$ (m)



Final Focus system



Dispersion suppressor and Final Focus



- LEP3 FF has been developed starting from a rescaling of the FCCee LCC-FF design.
- All the layout constraints are met, in particular:
 - Ring length
 - IP positions
 - IP crossing angle (30mrad)
- The FF is 1025.9mt long and has a net bend angle of 0.1347rad.
- In fact the last ARC octant cell (per side) has been replaced by the FF-Dispersion Suppressor and the FF itself.
- FF is a 5th order achromat in both planes.
- The dipoles have been optimized for best dispersion and optical functions across the Chromatic Correction Sections (CCSx/y)
- The dipoles in the incoming CCSy have opposite sign wrt to other dipoles, thus generating a dogleg that matches the layout constraints.
- The FF Left and Right magnets and drifts lengths are identical and optics nearly identical as well, thus ensuring a high degree of symmetry
- FF has been inserted in the lattice with the TCs

Final Focus system

- Chromaticities due to the low-betas IP are compensated in the FF, ARC sextupoles remain unchanged.
- FF dipoles presently generate about 20% emittance growth.

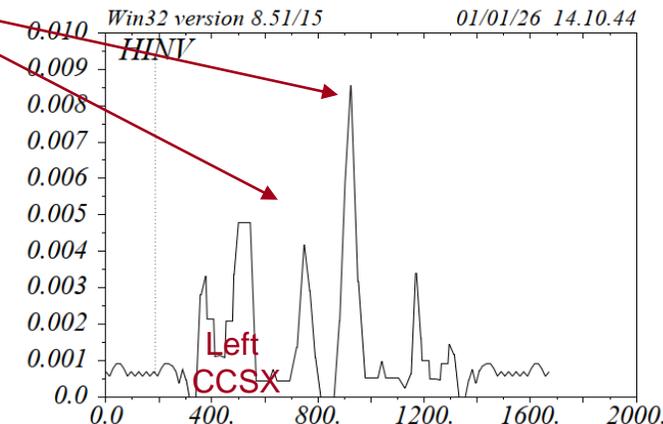
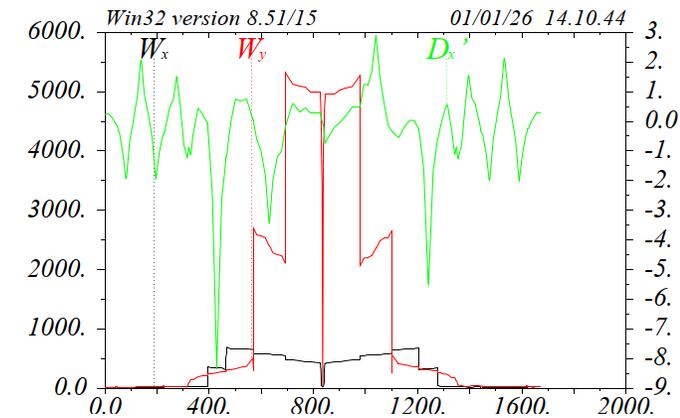
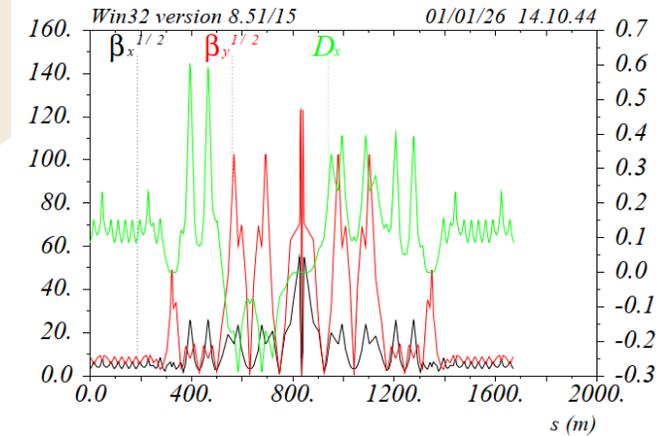
The larger contribution comes from the Left_CCSx that has the stronger dipoles and a correspond larger Curl-H.

These dipoles also increase the total E_Loss/turn by about 4%.

Further optimizations should mitigate these drawbacks

- The Curl-H spikes just on the side of the IP do not correspond to significant emittance growth, since the dipoles in these region are extremely weak to meet the SR requirements in the Interaction Region.

Dispersion suppressor and Final Focus



Draft parameters comparisons

	P_{SR}	Energy	#bunches	β_x	β_y	ϵ_x	ϵ_y	α_c	f_{RF}	V_{RF} (GV)	E_{loss}	N_b	I_{tot} (A)	σ_x	σ_y	ξ_x	ξ_y	\mathcal{L}
LEP1	0.315	45.5	8	1.25	5.00E-02	1.50E-08	6.50E-10	5.00E-06	3.52E+08	0.15	0.125	1.74E+11	2.51E-03	1.37E-04	5.70E-06	0.056	0.054	2.79E+31
LEP2 (Not ultimate performances)	9.06	104.5	4	1.5	5.00E-02	4.80E-08	1.40E-10	1.85E-04	3.52E+08	3.60	3.491	3.60E+11	2.60E-03	2.68E-04	2.65E-06	0.016	0.055	6.43E+31
FS final April 2025																		
FCC-ee-Z	50	45.6	11200	0.11	7.00E-04	7.10E-10	2.10E-12	2.87E-05	4.01E+08	0.08	0.039	2.18E+11	1.29E+00	8.84E-06	3.83E-08	0.002	0.085	1.14E+36
FCC-ee-W	50	80	1856	0.22	1.00E-03	2.17E-09	2.20E-12	2.87E-05	4.01E+08	1.00	0.362	1.41E+11	1.38E-01	2.18E-05	4.69E-08	0.014	0.108	1.88E+35
FCC-ee-H	50	120	300	0.24	1.00E-03	6.70E-10	1.00E-12	7.40E-06	4.01E+08	2.10	1.833	1.72E+11	2.73E-02	1.27E-05	3.16E-08	0.013	0.134	7.72E+34
LEP3 ultimate (LCC optics, FCC total tune shift + beta*y reduction)																		
LEP3-Z	50	45.6	1600	0.1	5.00E-04	4.30E-10	8.60E-13	2.74E-05	8.00E+08	0.30	0.128	1.35E+11	3.89E-01	6.56E-06	2.07E-08	0.005	0.136	9.26E+35
LEP3-W	50	80	80	0.15	7.00E-04	1.32E-09	2.64E-12	2.74E-05	8.00E+08	1.60	1.217	2.85E+11	4.11E-02	1.41E-05	4.30E-08	0.015	0.148	1.21E+35
LEP3-H	50	115	12	0.2	1.00E-03	2.74E-09	5.48E-12	2.74E-05	8.00E+08	6.00	5.196	4.45E+11	9.62E-03	2.34E-05	7.40E-08	0.033	0.163	3.06E+34

M Koratzinos

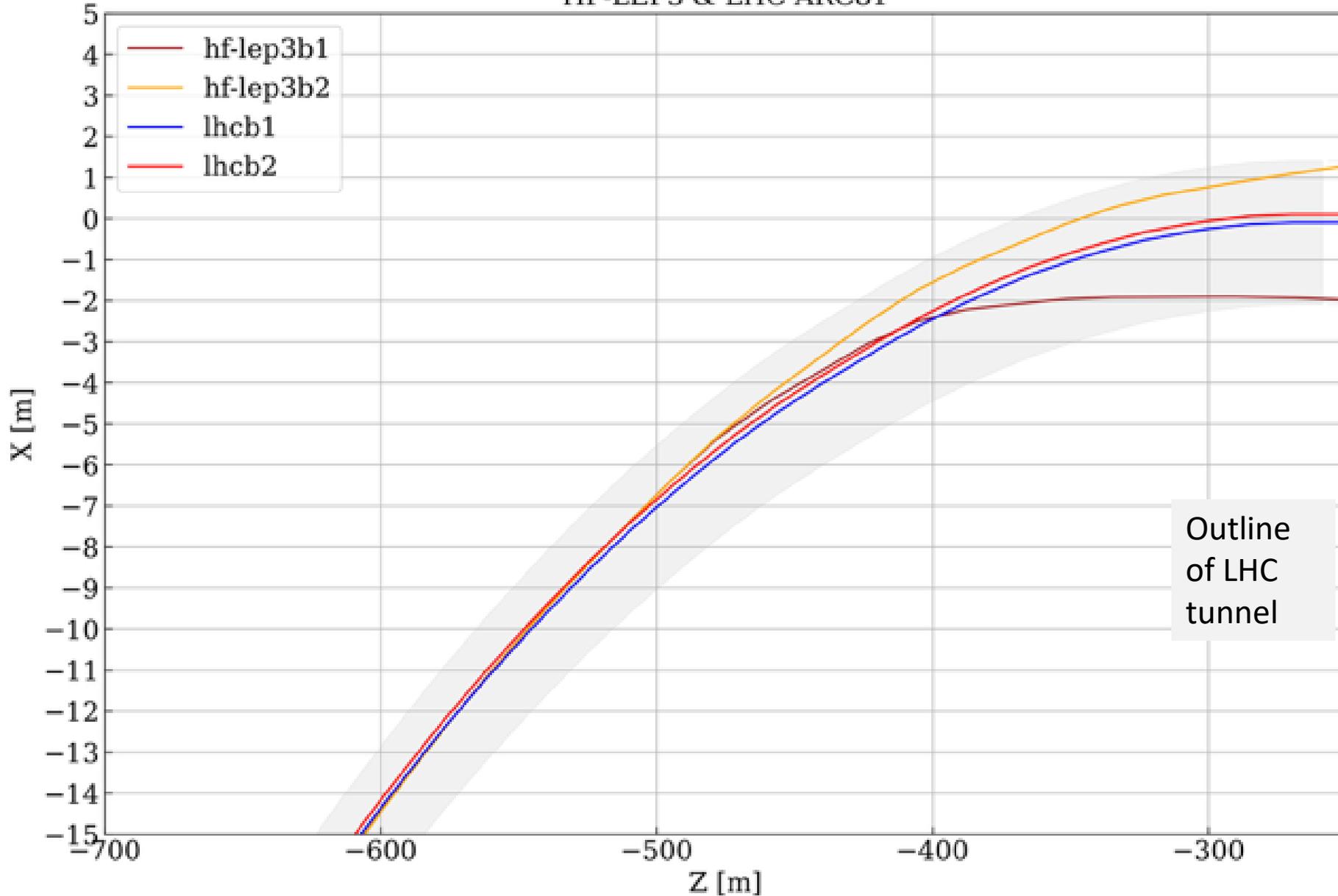
- LEP3 parameters dimensioned considering:
 - 50MW SR per beam
 - Best “reasonable” vertical tune_shift
 - Beam parameters consistency and most consistent with FCC ones
- Arc optic identical for all modes => Favors Z-mode, that approaches the FCC performances
- LEP2 vs LEP3-H shows the effective gain from LPA&CW scheme (~35)

Conclusions

- An optic optimized for LEP3 has been realized with the same strategy and techniques developed for FCCee
- The resulting lattice can be used for easy performance comparison, considering that the IP parameters are similar to the FCC
- **Layout compatibility with LHC tunnel, while ensuring optimal performances and hardware constraints is confirmed**
- First look at hardware requirements/solutions/options (magnets, vacuum chamber etc) can be performed
- Beam Dynamics and Beam-Beam studies have yet to be performed, keeping in mind that there is a high degree of similarities with the work done for FCCee
- Lattice will evolve in order to improve performances and relax hardware requirements
- ARC lattice presents intriguing aspects that might be studied for possible FCCee implementation
- FF lattice presents intriguing aspects that might be studied for possible FCCee implementation as well

Fit at the beginning of the arcs

HF-LEP3 & LHC ARC81



Beams start deviating already at the arcs (but of course deviation in the beginning is small)

Outline of LHC tunnel

Installed power

Type and quantity of equipment

Equipment type	Quantity
Power transformers (400 kV and 66 kV)	6 + 8 (Installed power 710 + 400 MVA)
Distribution transformers (18/0.4 kV)	~750 (oil and dry-type)
High voltage switchgears (18 kV & 3.3 kV)	~1 000
Low voltage feeders	~30 000
UPS	~300
48 Vdc battery systems	~100
Network protection relays	~1 000
Gensets	17 (Installed power 22 MVA)
Water cooled cables	1 500 (length 3 to 250 m)
SCADA	23 000 devices / 250 000 data-points

- More than **700MVA** installed in the 400kV line, so no modification needed
- 400MVA installed on the 66kV lines
- There are dedicated lines going to the even IP points

Point 2: two 38MVA transformers; would need to install a third or replace the 38MVA with a 70MVA

Point 6: only one 38MVA transformer; would need to install a second 70MVA transformer

Power lines to P2 and P6

- From the LEP technical design report vol. 2

Table 13.5

Technical features of the 66 kV lines

Characteristics	Link to:			
	SE2		SE6	
Length (m)	4400		7200	
Cross-section of single-core Al cable (mm ²)	500		400	
Core temperature (°C)	65	90	65	90
Maximum link capacity at 63 GeV (A)	516	560	428	494
(MVA)	56	61	47	54
Expected load – Phase 1 (MVA)	29		23	
– final phase (MVA)	48.2		30	

The installed copper (aluminium) conductor is 4.4+7.2kms long and is able to carry 50-60MVA. These conductors would need upgrading

Upgrade of P5

For the upgrade of the transmission network, various solutions were studied, of which the reinforcement of the current 18 kV cable between P5 and P6 and the installation of a new 66 kV line coming from the existing 66 kV substation of Prévessin (SEH9) to P5 were shortlisted. After considering both the technical and financial aspects of the shortlisted solutions, it was decided to opt for the supply of P5 through the installation of a new 66 kV line from P6.

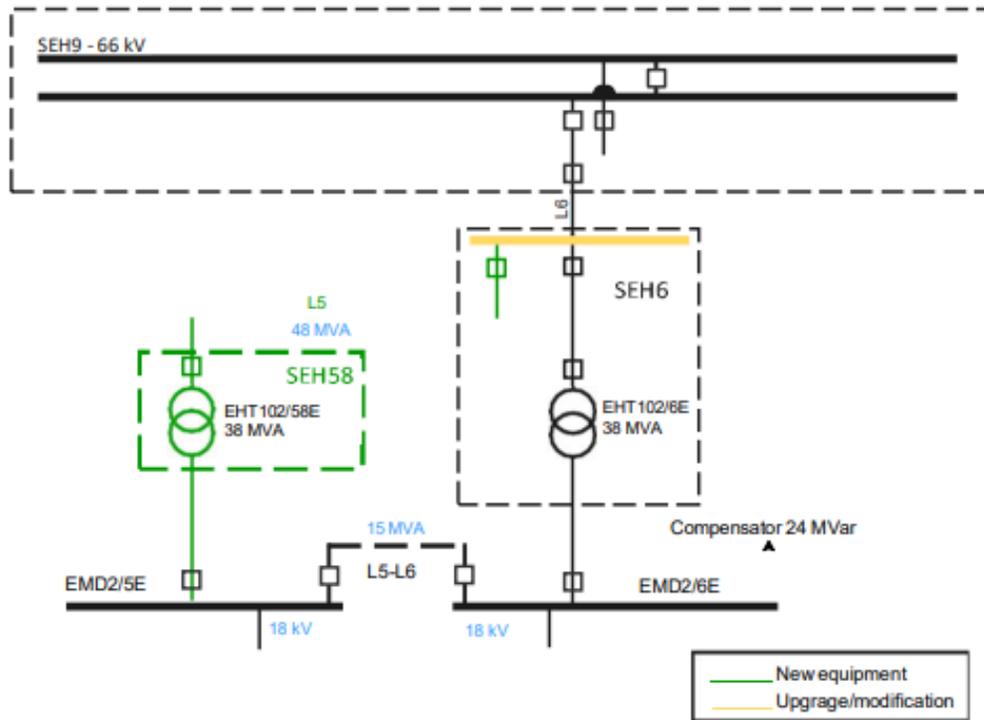


Figure 1: New P5 transmission layout.

UPGRADE OF LHC POINT 5 ELECTRICAL INFRASTRUCTURE

S. Bertolasi ^{*}, N. Dos Santos [†], and P. Valdes Lucas [‡], CERN, Geneva, Switzerland

- Recently, an upgrade of the capacity of P5 has been performed, through the supply of a new 66kV line from P6.
- We can use this upgrade to get an idea of the cost of upgrading for LEP3

CERN electrical consumption

Electrical consumption: typical figure

GWh (annual consumption)

- 1'200 GWh (normal operation year)
- 350 GWh (shutdown year)

MW (max active power)

- 190 MW (daily average)
- 210 MW (10-min average)
- 320 MW (instantaneous)

- Long shutdown: 40MW
- YETS: 60MW
- Full LHC operation: 200MW
- LHC+injector chain: 140MW



Courtesy B. Mouche / EN-EL

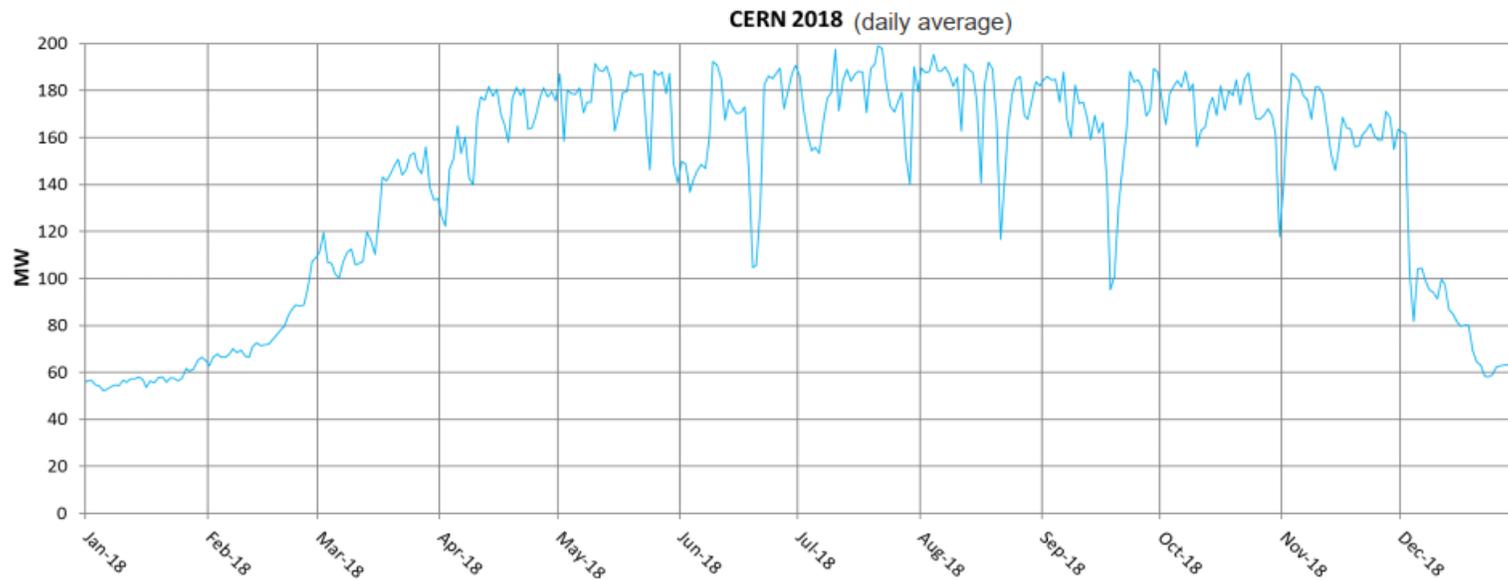
Consumption 2018

Electrical consumption: 2018 figures



- 199 MW (daily average)
- 215 MW (10-min average)
- 320 MW (instantaneous)

- 10-min average maximum: 215MW

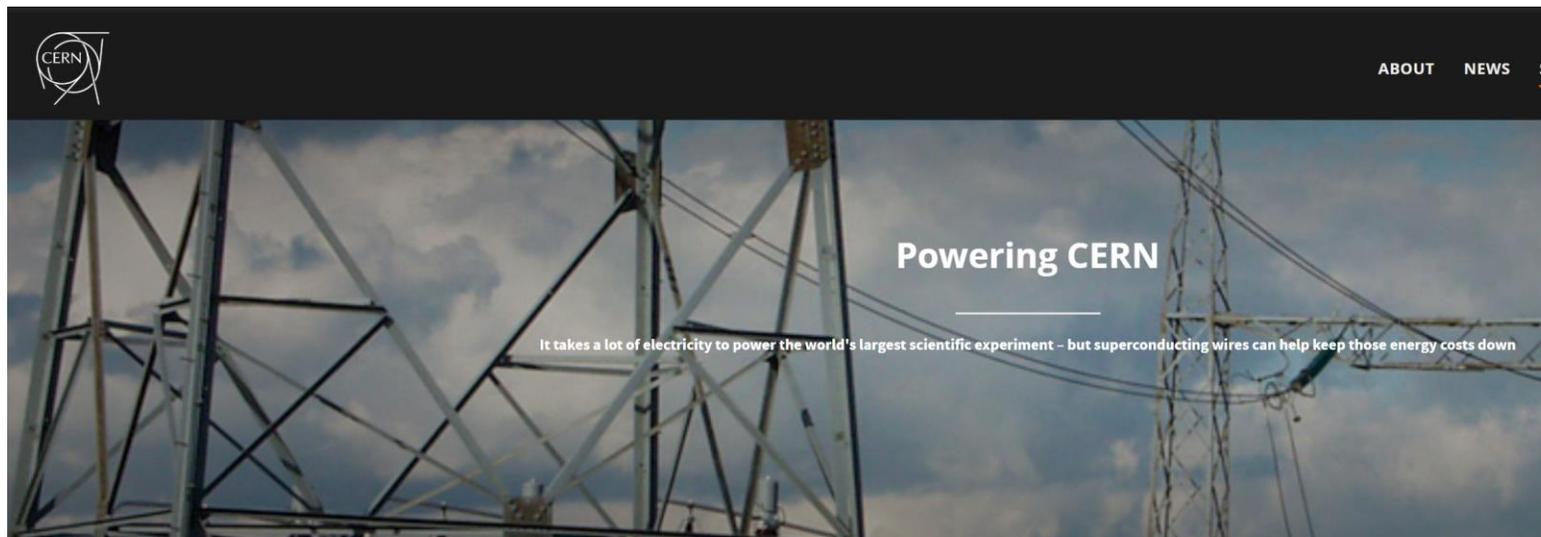


Courtesy B. Mouche / EN-EL

From power consumption to energy per year

- FCC-ee, ttbar operation, new numbers: **357MW, 1.8TWh**
- LEP3, ZH at 230GeV operation, **250MW, 1.3TWh**

From the CERN web pages:



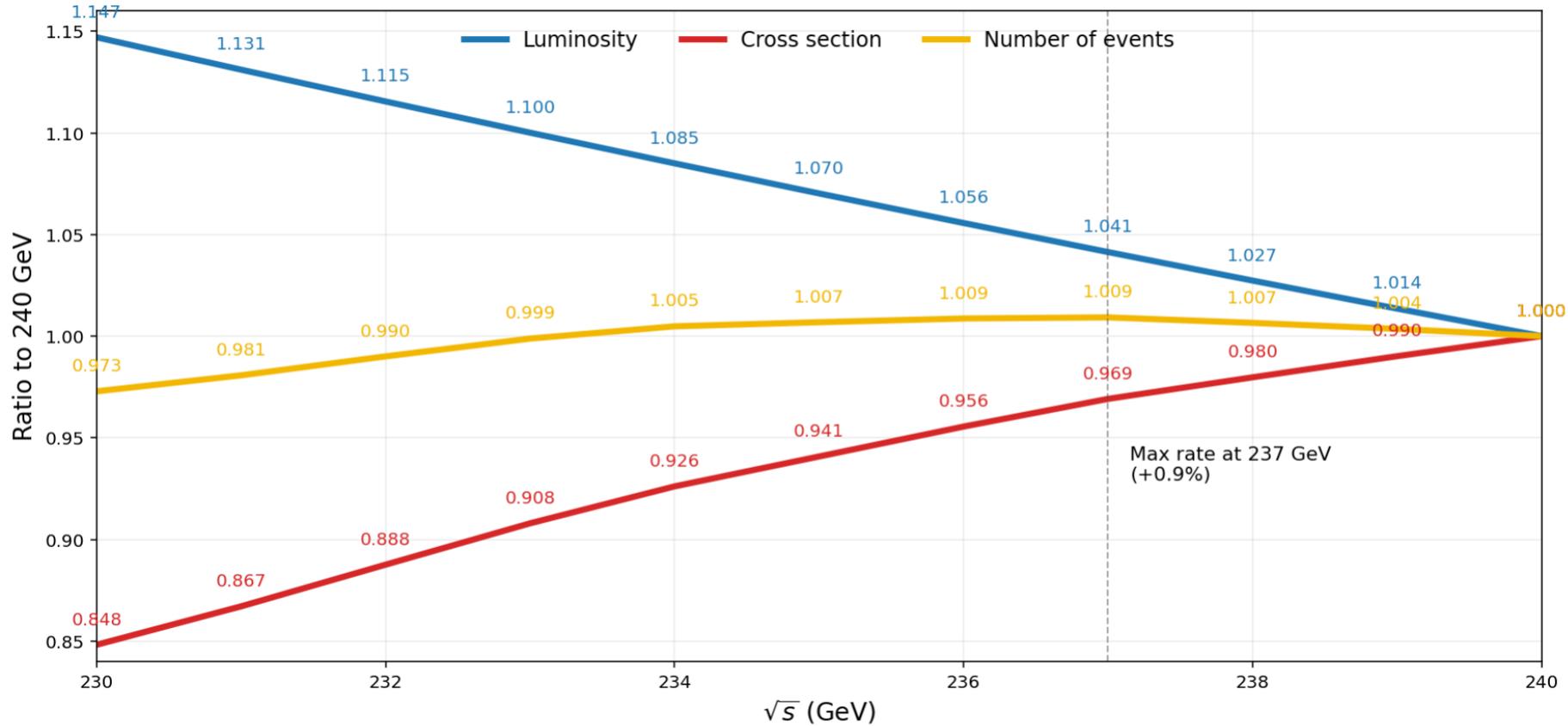
As CERN's [physics programme](#) has evolved and expanded, physicists at the laboratory have used more powerful [accelerators](#) and [detectors](#) to study the fundamental particles. The laboratory has had to innovate to keep up with electrical demands. CERN uses 1.3 terawatt hours of electricity annually. That's enough power to fuel 300,000 homes for a year in the United Kingdom. But the energy needed changes from month to month, as the seasons shift and the

CERN uses 1.3 terawatt hours of electricity annually.

Higgs rate when including ISR

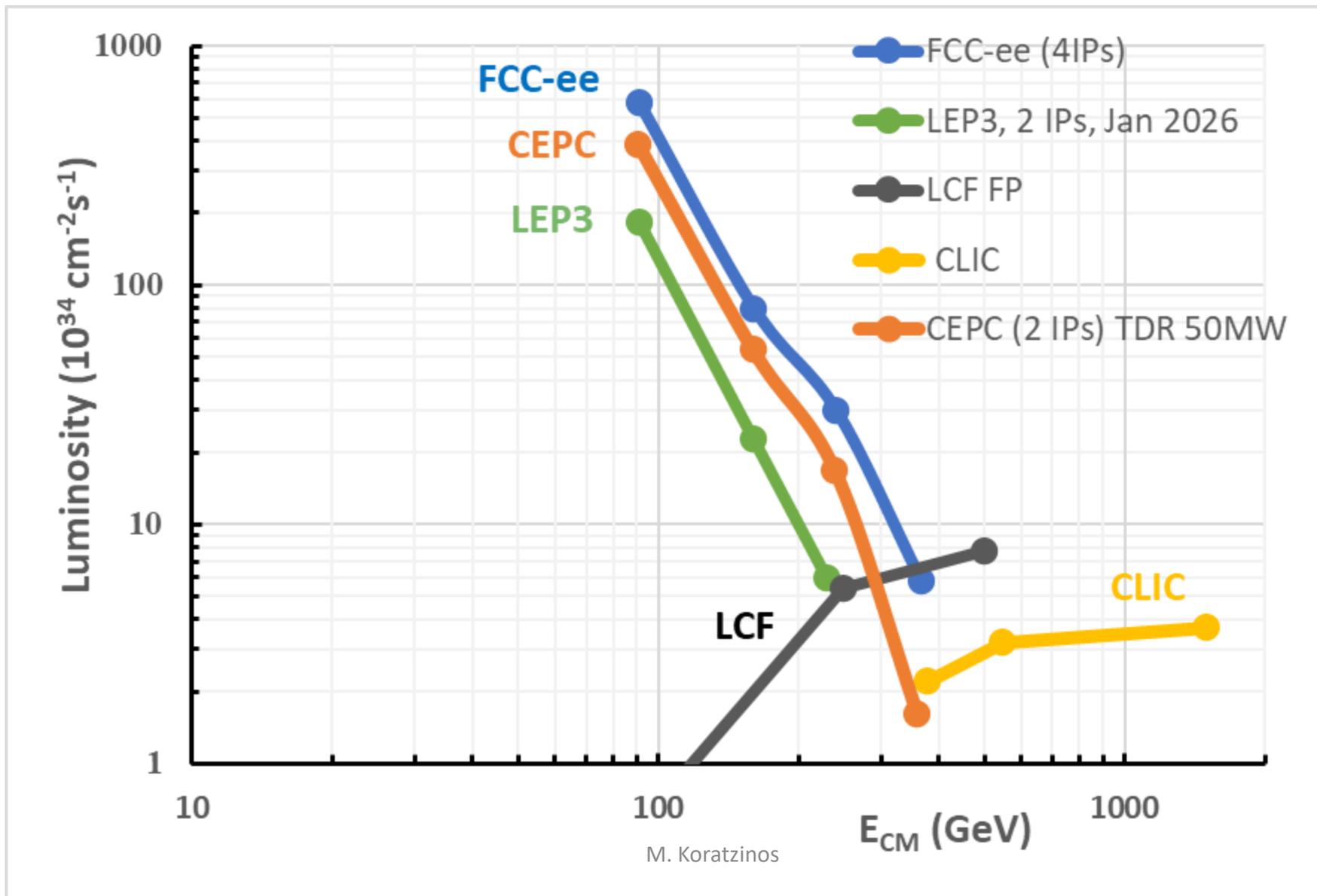
Oliver Buchmuller

Luminosity, ZH cross section, ZH event rate (wrt 240 GeV)
ZH production: At 230 GeV, larger luminosity, smaller cross section, similar rate



difference of rates at 240GeV to 230GeV: 2.7%

Luminosity of world projects



Polarization times: FCC and LEP3

machine	Circumf (m)	Radius (m)	energy	tau_pol (hours)	pol to 5% (mins)
FCC - 45	90658	10021	45	215.9	650
FCC - 80	90658	10021	80	12.2	37
LEP3 - 45	26660	2958	45	5	15
LEP3 - 80	26660	2958	80	0.3	1

FCC-ee at the Z needs polarization wigglers.
LEP3 at the Z (or W) needs no polarization wigglers