DE LA RECHERCHE À L'INDUSTRIE

FCC-hh Lattice Design

Antoine CHANCE
on behalf of FCC-hh machine team

CEA/DRF/IRFU/DACM

International Workshop on the High Energy Circular Electron Positron Collider
26-28 October 2020

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EuroCirCol
A key to New Physics

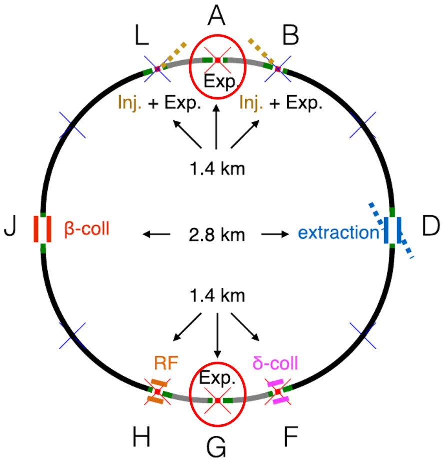
Irfu

Collider parameters

		LHC	HL-LHC	FCC-hh	
				Initial	Baseline
Energy c.m.	TeV	14		100	
Injection energy	TeV	0.45		3.3	
Circumference	km	26.7		97.75	
Peak luminosity	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.0	5.0	5.0	<30
Integrated luminosity/day	fb^{-1}	0.47	2.8	2.2	8
Assumed Turnaround time	h			5	4
Number of bunches	-	2808		10400	
Bunch spacing Δt	ns	25		25	
Bunch charge N	10^{11}	1.15	2.2	1.0	
Normalized emittance	µm	3.75	2.5	2.2	
Maximum ξ with 2 IPs	-	0.01	0.015	0.011	0.03
RMS bunch length	cm	7.55		8	
β at IP	m	0.55	0.15	1.1	0.3
Beam size at IP	µm	16.7	7.1	6.8	3.5
Full crossing angle	µrad	285	590	104	200
Stored energy per beam	GJ	0.392	0.694	8.3	
SR power per ring	MW	0.0036	0.0073	2.4	
Dipole coil aperture	mm	56		50	
RF voltage (400.79 MHz)	MV	16		48	

Collider layout

- 2 interaction regions with high luminosity (low β): A and G.
- 2 interaction regions with lower luminosity hosting also the injection: B and L.
- 1 insertion dedicated to extraction: D.
- 2 insertions for the collimation (betatron and energy): F et J.
- 1 insertion hosting RF cavities: H.
- 4 long arcs of 16 km and 4 short arcs of 3.4 km.



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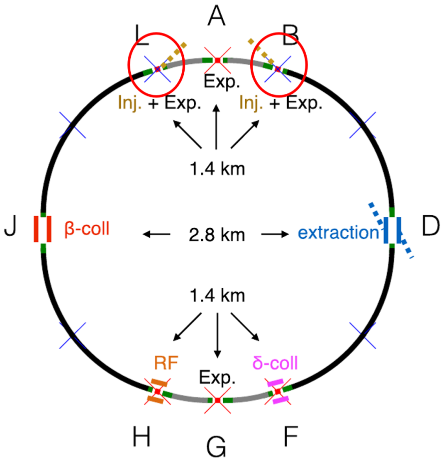

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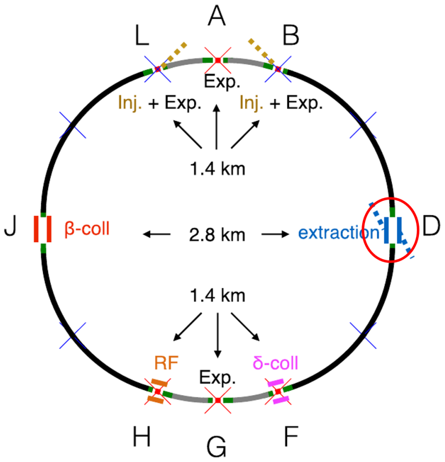

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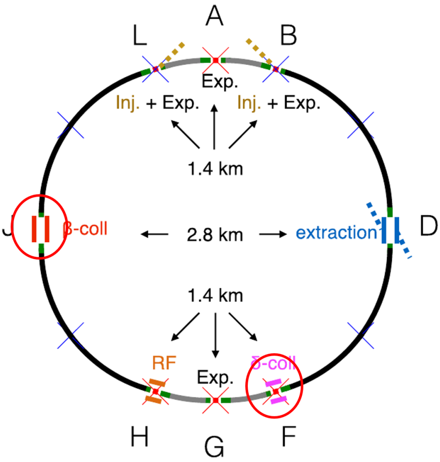

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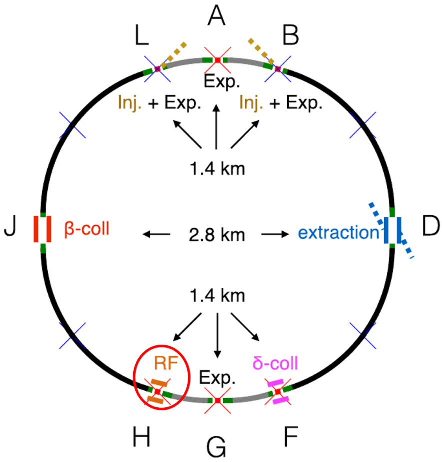

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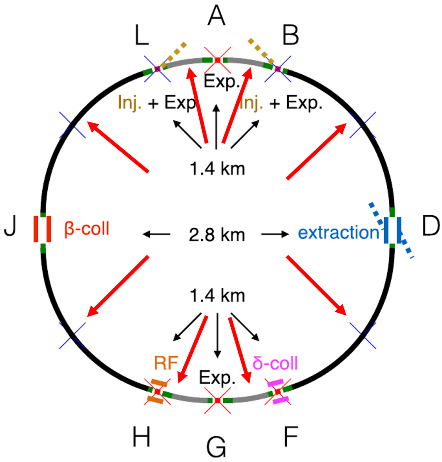
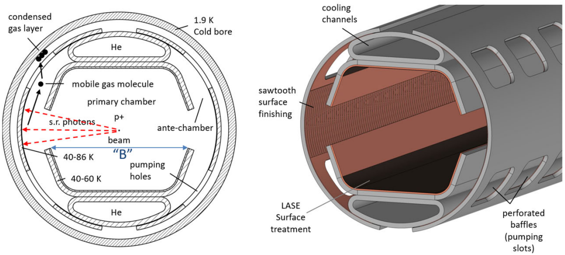


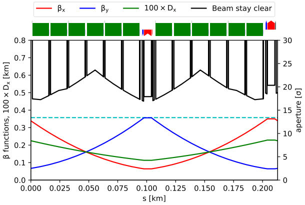
Arc specificities vs LHC

- Contrary to LHC, the dipoles are assumed to be straight.
  - Margin of 1.2 mm added to the horizontal tolerance due to the sagitta.
  - Reduction of the beam-stay clear by 1.5σ because of the sagitta.
- Intra-beam distance: 250 mm: Cross-talk between both apertures.
  - $\Rightarrow$ $b_2 = 0$ at collision and $b_2 = 6$ units at injection.
- New beam pipe to handle synchrotron radiation, electron cloud, impedance, ...

Courtesy: I. Bellafont *et al.*
Courtesy: R. Martin

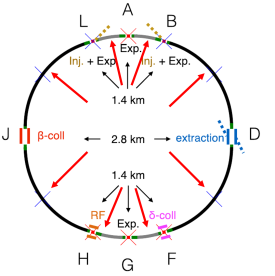


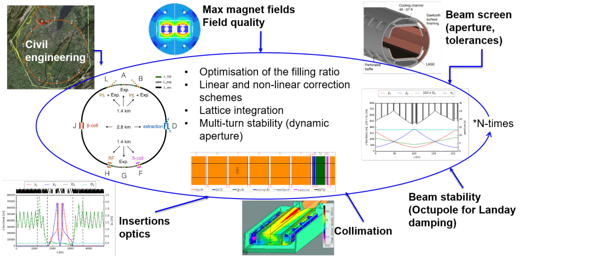
Arc AB: $b_2 = +6$



$n_{1,\text{min}} = 16.9$

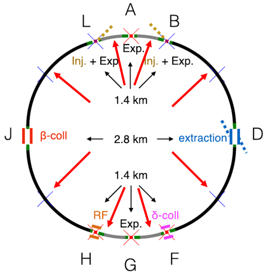
- **Target: 13.4σ at injection and 15.5σ at collision.**

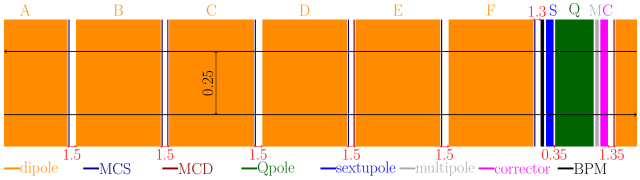




- Python scripts to:
  - **optimize** and **generate** the arcs.
  - generate the dispersion suppressors.
  - generate the matching procedures.
  - **integrate** the insertion optics.
- **Phase advance of** 90° in the short arcs and 90°+ϵ in the long arcs (to adjust the global tune and phase advance between the insertions).

- Each arc cell contains:
  - 12 dipoles (14.19 m/15.81 T),
  - 12 b_3 correctors,
  - 6 b_5 correctors,
  - 2 quadrupoles (6.4 m/358 T m^{-1}),
  - 2 sextupoles (1.2 m/7000 T m^{-2}),
  - 2 BPMs,
  - 2 dipole correctors,
  - 2 correctors (quadrupole, skew quadrupole or octupole).
- Collider tune: 109.31/107.32





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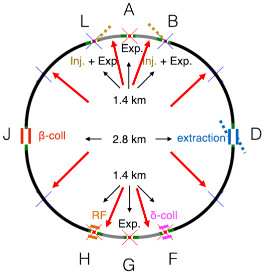

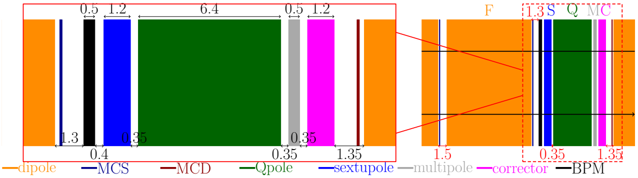

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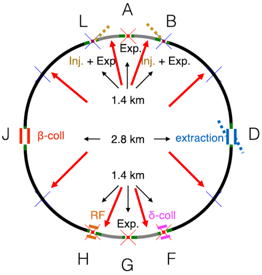
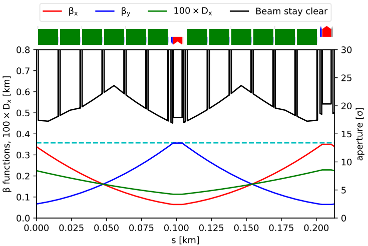
Arcs



Apertures @3.3 TeV, phase advance of 90°



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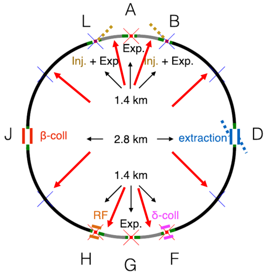
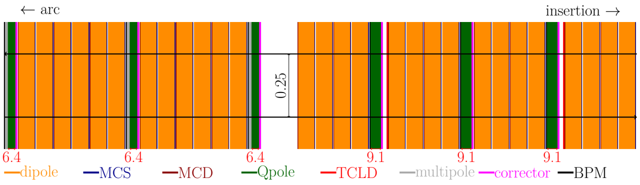
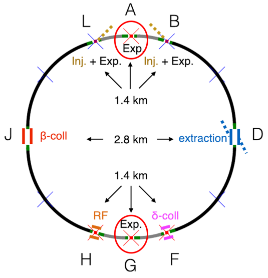
Dispersion suppressors

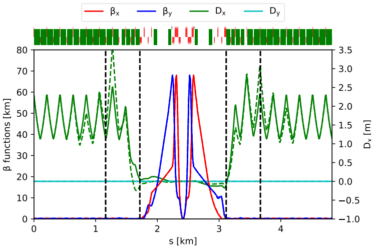




- Goal: **matching the optical functions from the arc to the insertions**.
- **Similar to LHC**: best compromise between flexibility and compactness.
- Insertion of **two collimators** (TCLD) of one meter to clean the beam before entering the arcs (like HL-LHC).
- The **dispersion and β** peaks are located in this section.
- Strong constraints to keep the optical functions below the aperture requirements.



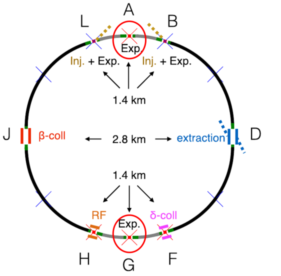
Collision optics LSS-PA-EXP $\beta^* = 0.3\,\text{m}$. Courtesy: R. Martin



- Collision: $\beta^* = 0.3\,\text{m}$ and $L^* = 40\,\text{m}$.
- Going up to $\beta^* = 0.2\,\text{m}$ is possible (margins on the normalized aperture).
- **Optimised interaction triplet** (aperture and length) to manage the peak doses near the interaction point.
- Q7 still to be optimised (critical dose: collimators to optimise).

- Injection: $\beta^* = 4.6\,\text{m}$.
- **Local non-linear correctors** (sextupoles and octupoles) **required** to enlarge the dynamic aperture at low β^*.
- **Alternative optics** to use the **same quadrupole family** for the triplet.
- **Asymmetric optics** exists ($\beta_x^* = 1.2\,\text{m}/\beta_y^* = 0.15\,\text{m}$): alternative to crab cavities.

Insertions high $\mathscr{L}$



Collision optics LSS-PG-EXP $\beta^* = 0.3\,\text{m}$.

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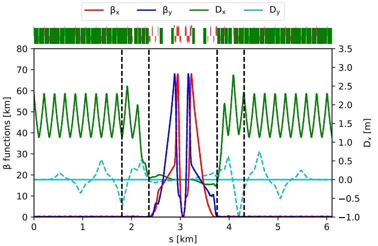

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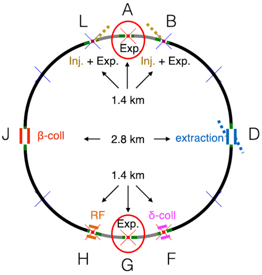

Injection optics LSS-PA-EXP $\beta^* = 4.6\,\mathrm{m}$

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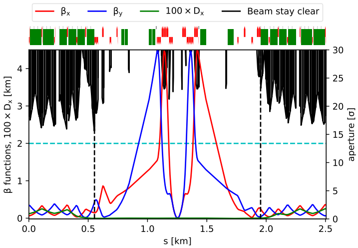

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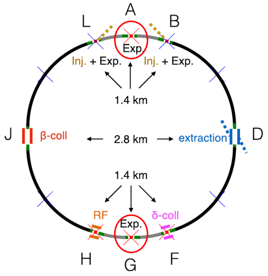
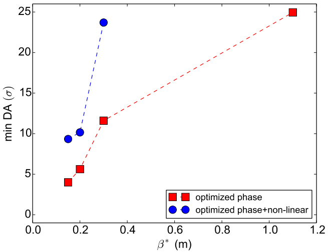


Courtesy: E. Cruz-Alaniz



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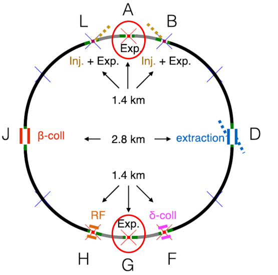
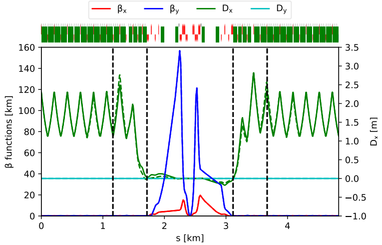


Alternative: $\beta_x^* = 1.2\,\text{m}/\beta_y^* = 0.15\,\text{m}$

Courtesy: L. van Riesen-Haupt



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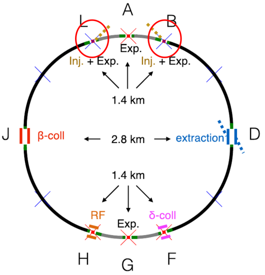
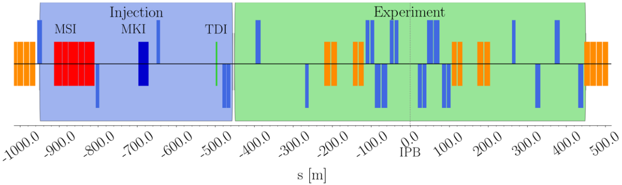


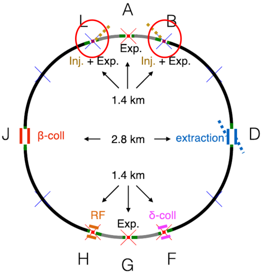
Courtesy: M. Hofer



- Two uses:
  - **Injection** with an injection septum MSI, kickers (MKI) and a beam dump (TDI)
  - **Experiments at low luminosity**: 500 fb^{-1} integrated. $L^* = 25\,\text{m}$

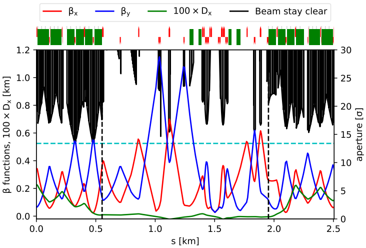
- Injection: $\beta^* = 27\,\text{m}$.
  - Phase advance between MKI and TDI near 90°.
  - Large beam size at TDI to reduce the energy density on the absorber.
- Collision: $\beta^* = 3\,\text{m}$.

Insertions Low $\mathscr{L}$ + injection



Injection optics LSS-PB-EXP $\beta^* = 27\,\text{m}$

Courtesy: M. Hofer



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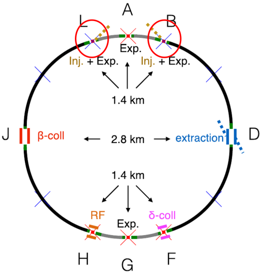
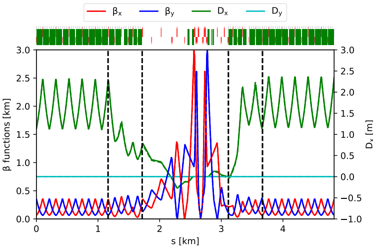


Collision optics LSS-PB-EXP $\beta^* = 3.0\,\mathrm{m}$ Courtesy: M. Hofer



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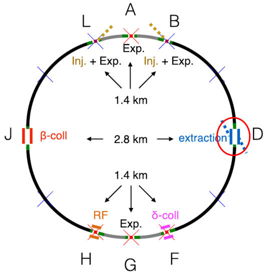
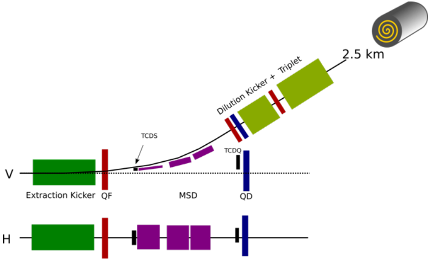
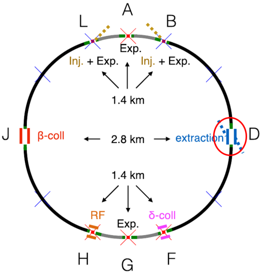




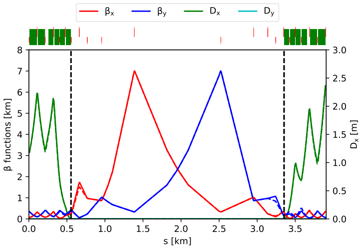
- Extraction based on **innovative extraction septa** SuShi (3.2 T) or truncated CosTheta (4 T).
- Extraction optics optimised for the **machine safety**.
- **Highly segmented kickers (150)** to reduce the error probabilities.
  - Error tolerance: up to 4 misfiring kickers are manageable.
  - Depends on the phase advances in the machine.

Extraction



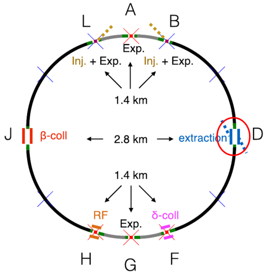
Optics ESS-PD-EXT

Courtesy: W. Bartmann



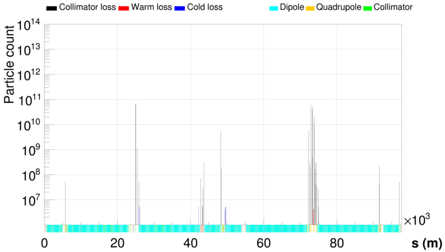
- Extraction based on **innovative extraction septa** SuShi (3.2 T) or truncated CosTheta (4 T).
- Extraction optics optimised for the **machine safety**.
- **Highly segmented kickers (150)** to reduce the error probabilities.
  - Error tolerance: up to 4 misfiring kickers are manageable.
  - Depends on the phase advances in the machine.

Extraction



Case of 4 misfiring kickers. Allowed loss: 10^{11}

Courtesy: J. Molson



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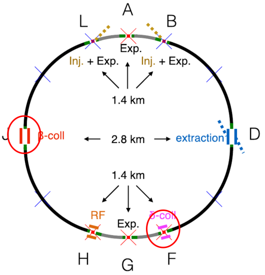
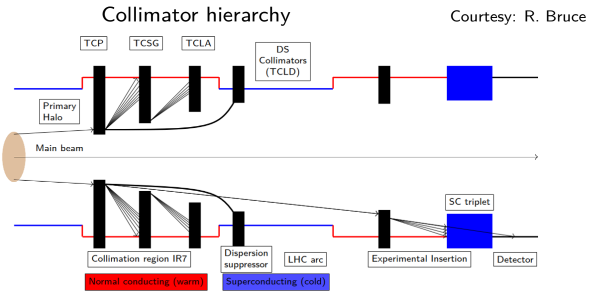
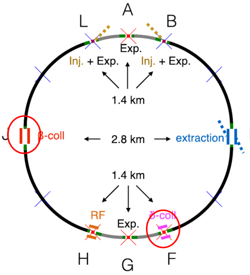


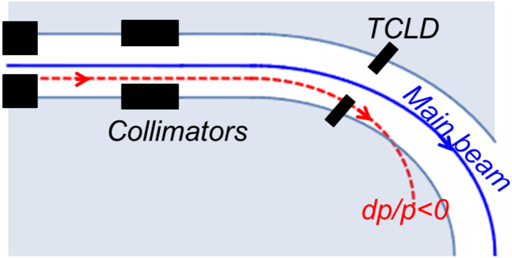


- **Multi-stage collimation** (like LHC) to distribute the losses.
- **Insertions of collimators (TCLDs) into the dispersion suppressors** to absorb the off-momentum particles (like HL-LHC).
- Optics of the β collimation section **similar to LHC**.
- Optics of the energy collimation section also scaled from LHC.
- **The protection system works well** and the **absorbers should manage** the lost beam power (11.6 MW).
- **Next steps**: primary skew absorbers, crystal collimation, hollow electron lenses for an active halo control, new materials, more compact optics...

Collimation



Insertions of collimators at the arc entrance



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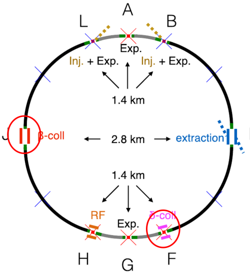
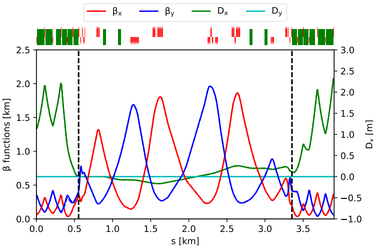


Collimation optics β ESS-PJ-COL



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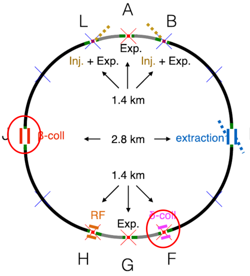

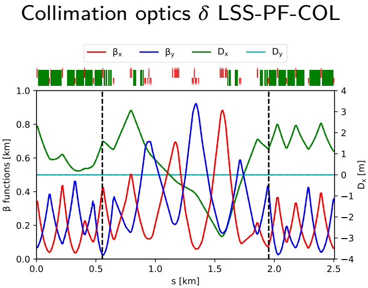

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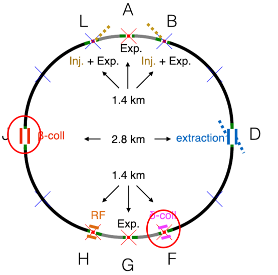

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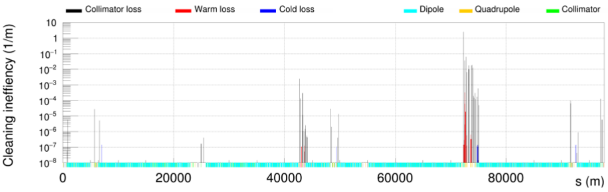

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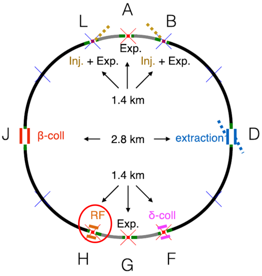
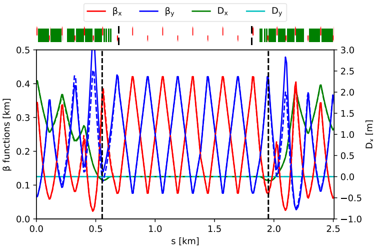
RF system

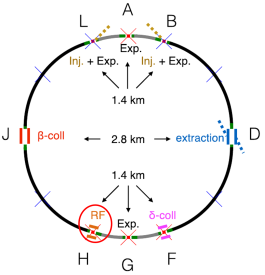


Optics of the RF section LSS-PH-RFS



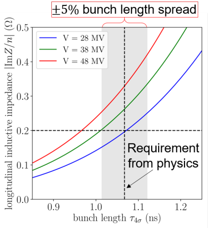
- Optics made of FODO cells.
- The required RF power is deduced from the **constraints on longitudinal stability**.
  - At the beginning $\tau_{4\sigma} = 1.35\,\text{ns}$.
  - At the end $V_{RF} = 38\,\text{MV}$.
  - Longitudinal emittance growth $\propto \sqrt{E}$.
- RF power calculated for different compensation modes of transient beam-loading.
  - The **full compensation** requires a peak power of 600 kW against 400 kW without any compensation.

RF system

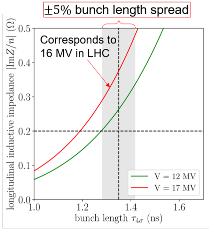


Stability thresholds

Courtesy: I. Karpov



Thresholds at 50 TeV



Thresholds at 3.3 TeV

- Optics made of FODO cells.
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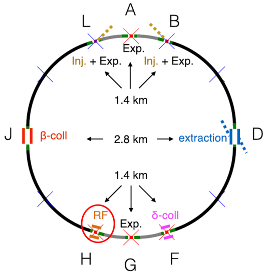
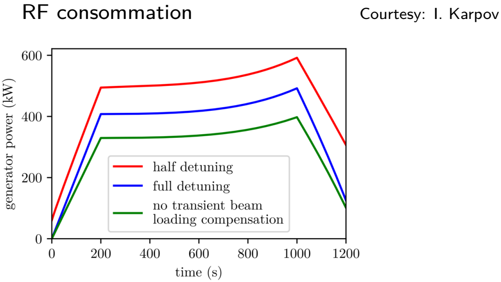
RF system





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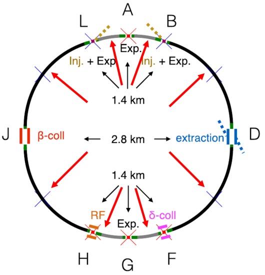
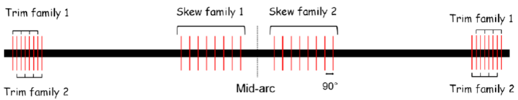
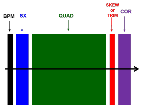


Corrector distribution in the arcs

Courtesy: D. Boutin

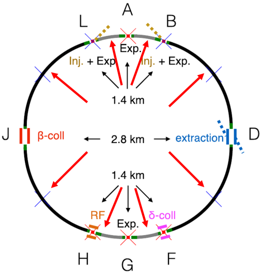




- The linear correction addresses:
  1. Correction of the linear coupling (with skew quadrupoles).
  2. Global correction of the orbit.
  3. Tune correction.
  4. If necessary, steps 2 et 3 are reiterated.
- **Acceptable residual errors**.
- The β and dispersion beatings are not corrected yet.

- Correction of the spurious dispersion (due to a non-zero orbit on the interaction triplet):
  - HL-LHC: Non-zero orbit in the sextupoles. Non acceptable for FCC-hh: amplitudes of 9 mm!
  - SSC: family of 4 quadrupoles (normal or skew) in a dispersive area. **Adopted solution**.

Linear correction



Residual values (90% quartile)

Courtesy: D. Boutin

Observable	Injection	Collision
Hori. orbit Vert. orbit	0.80 mm 0.73 mm	0.79 mm 0.73 mm
Hori. angle Vert. angle	26 μrad 25 μrad	26 μrad 27 μrad
Hori. beta-beating Vert. beta-beating	22 % 24 %	34 % 42 %
Hori. disp. beating Vert. disp. beating	$0.023 \frac{1}{\sqrt{m}}$ $0.028 \frac{1}{\sqrt{m}}$	$0.036 \frac{1}{\sqrt{m}}$ $0.027 \frac{1}{\sqrt{m}}$
Hori. orbit corr. str. Vert. orbit corr. str.	0.31 Tm 0.28 Tm	4.7 Tm 4.2 Tm
Skew quad. str. Trim quad. str.	8.57 T/m 3.68 T/m	148 T/m 140 T/m

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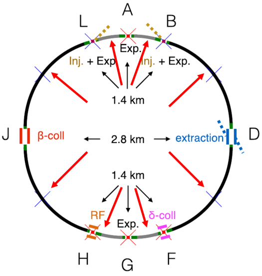
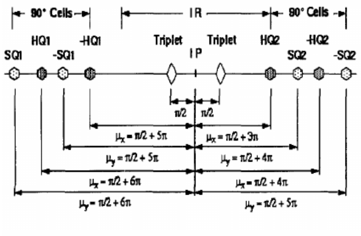


Correction of the spurious dispersion (SSC-like)



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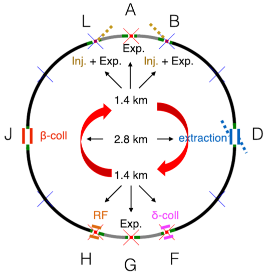
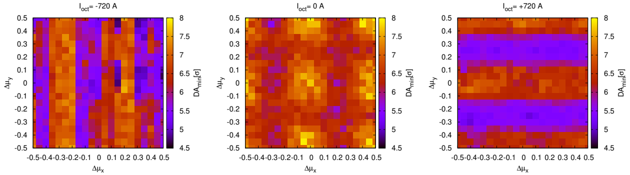
Dynamic aperture (multi-turn stability)



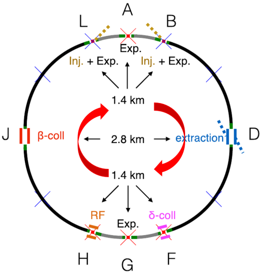
DA interaction beam-beam + octupoles

Courtesy: E. Cruz-Alaniz



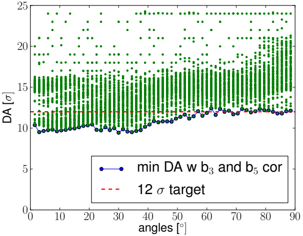
- **The dynamic aperture (DA) strongly depends** on the **phase advance** between IPs A and G at the collision.
- **Phase advance** optimized for the collision.
- DA$>5\sigma$ with multipole errors + beam-beam + $\beta^* = 0.3\,\mathrm{m}$.

- At injection, the DA is **driven** by the **dipole multipole errors**.
- The DA is below the target value when octupoles on.
- **Value above the threshold** for the collimation (like LHC).



DA at injection + errors + octupoles

Courtesy: B. Dalena



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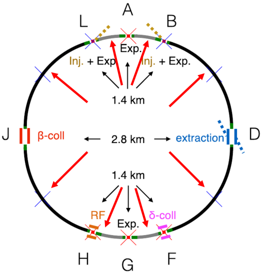
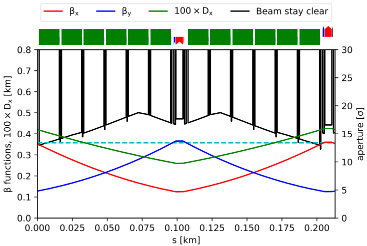


Apertures @3.3 TeV, phase advance 60°



- Alternative with a **phase advance** per cell of 60° against 90°.
- Integrated gradient of the quadrupole multiplied by $\frac{\sin 30°}{\sin 45°} \approx 0.7$.
- ☺ Shorter quadrupole: 6.4 m → 4.5 m.
- Longer dipoles: 14.19 m → 14.52 m.
- ☺ **Lower dipole field:** 15.81 T → 15.44 T.
- ☹ Twice larger dispersion: smaller beam-stay clear.

- ☺ **Chromaticity correction twice more efficient** (larger D_x).
- ☹ Correction scheme to be modified.
  - FCC-ee works with phase advances of 60° or 90° depending on working energy .

- **Integrated and consolidated optics** of the collider FCC-hh has been delivered.
- It **fills a large part of the requirements**:
  - Magnet fields within the requirements.
  - Reached performances at the interaction point.
  - Beam-stay clear within the specifications.
  - Efficient machine protection (collimation).
  - Correction schemes.
- The whole study is published in the **Conceptual Report** (volume 3): `https://fcc-cdr.web.cern.ch`
- **Alternative optics** also developed.
- **No show-stopper clearly identified**.
- But still room to improve the machine.

Thank you for your attention

Thank you to the FCC-hh machine team for the great job!