Consolidated Lattice of the FCC-hh

Antoine CHANCE
on behalf of FCC-hh machine team

CEA/DRF/IRFU/DACM

FCC-France workshop
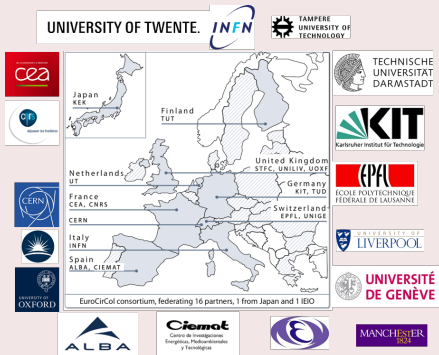14 November 2019

EuroCirCol: 2015-2019

EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

- Participation of CEA and CNRS to **Arc optics**, **collimation** and **magnets**.
- Input data for the European Strategy of Particle Physics.

- 15 partners
- Key points:
  - Feasibility of the optics (arcs and interaction regions).
  - Optimization of the beam pipe (impedance, surface treatment, electron cloud, vacuum, cryogenic, ...).
  - Dipoles of 16 T
  - → **see H. Felice "Magnet R&D effort toward FCC-hh"**
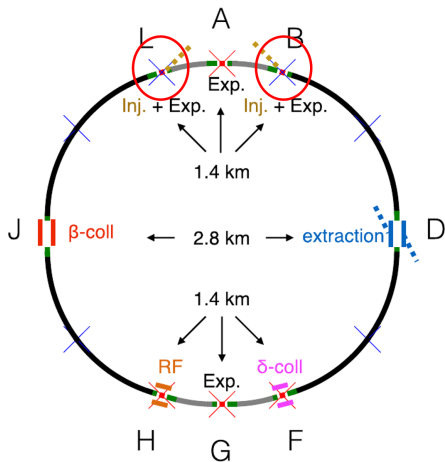 - Cost model.
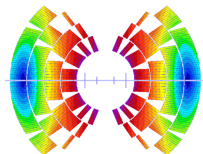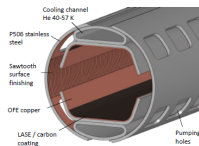
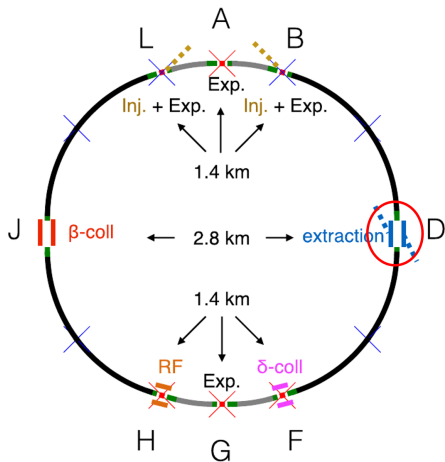|		LHC	HL-LHC	FCC-hh Initial	FCC-hh Baseline
Energy c.m.	TeV	14		100	
Injection energy	TeV	0.45		3.3	
Peak luminosity	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.0	5.0	5.0	<30
Integrated luminosity/day	fb^{-1}	0.47	2.8	2.2	8
Bunch spacing Δt	ns	25		25	
Bunch charge N	10^{11}	1.15	2.2	1	
Number of bunches	-	2808		10400	
Normalized emittance	µm	3.75	2.5	2.2	
Maximum ξ with 2 interaction points (IPs)	-	0.01	0.015	0.01 (0.02)	0.03
β at IP	m	0.55	0.15	1.1	0.3
Beam size at IP	µm	≈16	≈7	6.8	3.5
RMS bunch length	cm	7.55		8	
Turnaround time	h			5	4
Stored energy per beam	GJ	0.392	0.694	8.3	
Synchrotron radiated power per beam	MW	0.0036	0.0073	2.4	

- ▶ 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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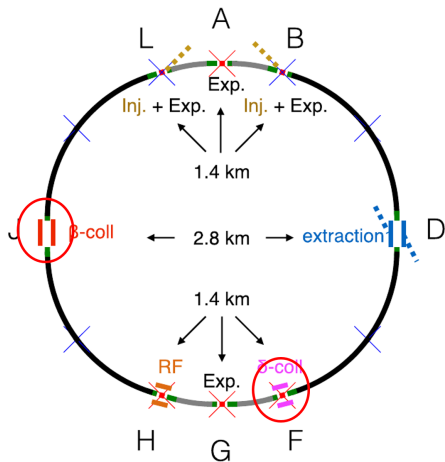- ▶ 4 long arcs of 16 km and 4 short arcs of 3.4 km.

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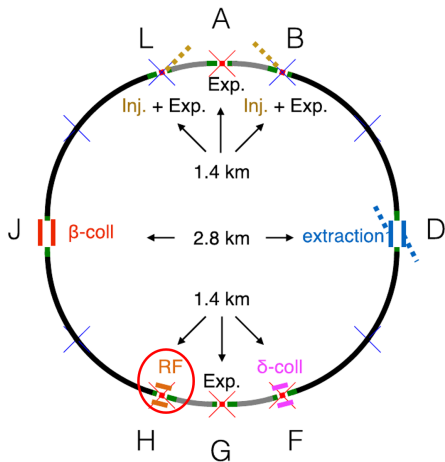- ▶ 4 long arcs of 16 km and 4 short arcs of 3.4 km.

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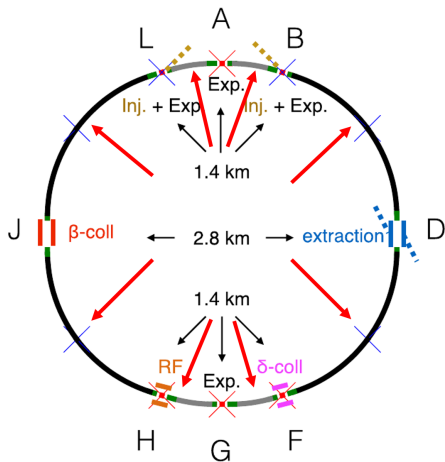- ▶ 4 long arcs of 16 km and 4 short arcs of 3.4 km.

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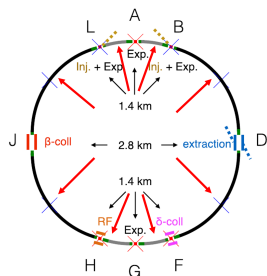- ▶ 4 long arcs of 16 km and 4 short arcs of 3.4 km.

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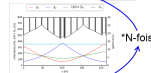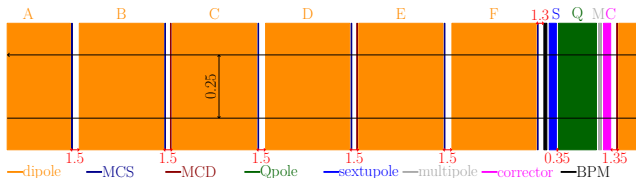- 4 long arcs of 16 km and 4 short arcs of 3.4 km.

- ▶ 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,
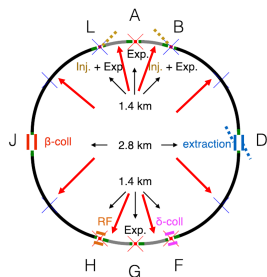 - ▶ 2 correctors (quadrupole, skew quadrupole or octupole).

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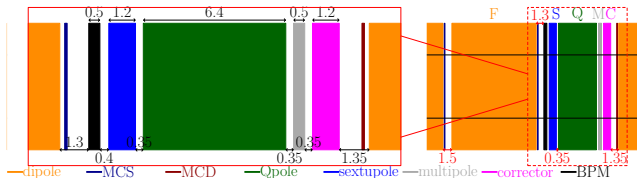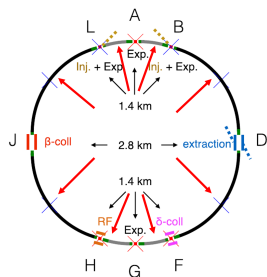
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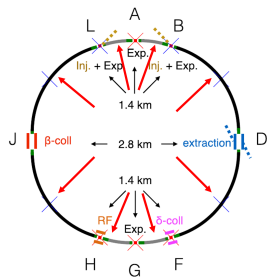
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Arcs
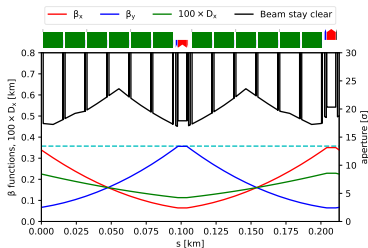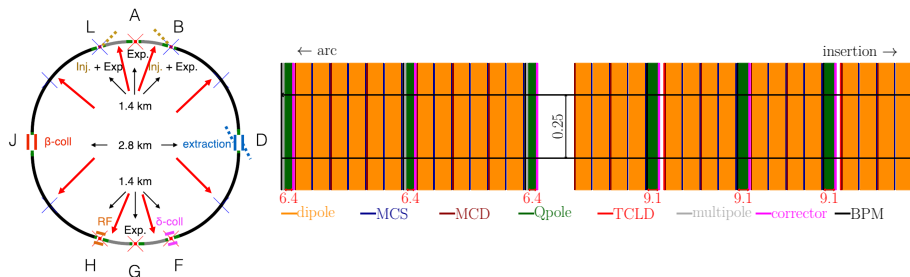
Apertures @3.3 TeV, phase advance of 90°

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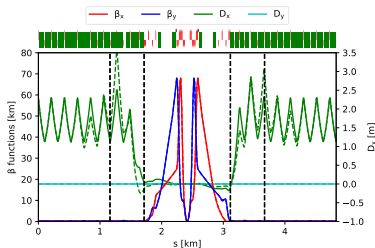
Dispersion suppressors

- ▶ 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.
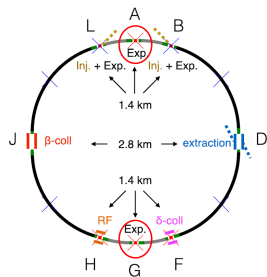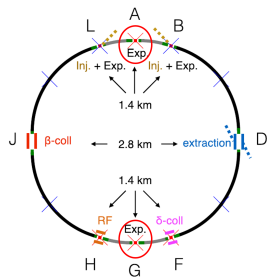
Collision optics LSS–PA–EXP $\beta^* = 0.3$ m. *Courtesy: R. Martin*

- ▶ Collision: $\beta^* = 0.3$ m and $L^* = 40$ m.
- ▶ Going up to $\beta^* = 0.2$ 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: $\beta^* = 4.6$ 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 ($\beta_x^* = 1.2$ m/$\beta_y^* = 0.15$ m): alternative to crab cavities.

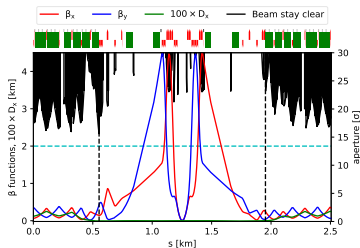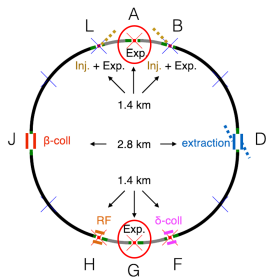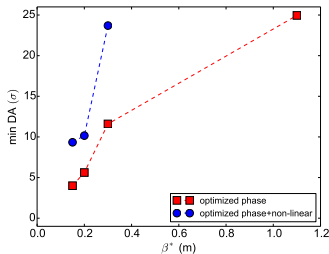Injection optics LSS-PA-EXP $\beta^* = 4.6\,\text{m}$ Courtesy: R. Martin

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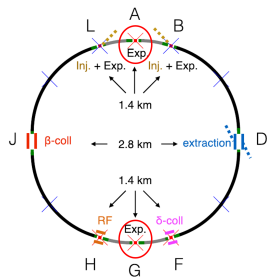
Courtesy: E. Cruz-Alaniz

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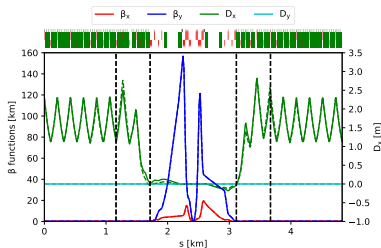- ▶ Q7 still to be optimised (critical dose: collimators to optimise).

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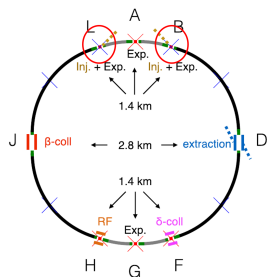
Alternative: $\beta_x^* = 1.2\,\mathrm{m}/\beta_y^* = 0.15\,\mathrm{m}$ Courtesy: L. van Riesen-Haupt

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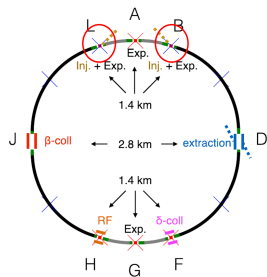
Courtesy: M. Hofer
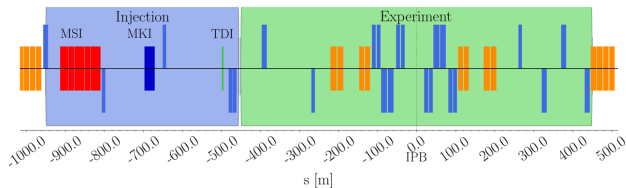
- Two uses:
  - **Injection** with an injection septum MSI, kickers (MKI) and a beam dump (TDI)
  - **Experiments at low luminosity**: 500 fb^{-1} integrated. $L^* = 25$ m

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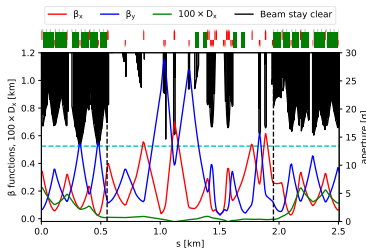 - Phase advance between MKI and TDI near 90°
  - Large beam size at TDI to reduce the energy density on the absorber
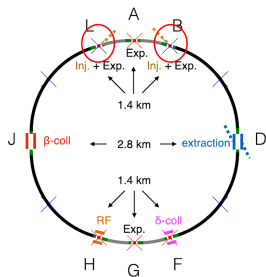
- Collision: $\beta^* = 3$ m.

Injection optics LSS-PB-EXP $\beta^* = 27\,\text{m}$ Courtesy: M. Hofer

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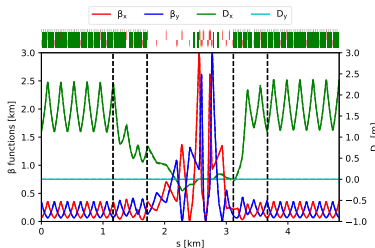Collision optics LSS-PB-EXP $\beta^* = 3.0\,\mathrm{m}$ Courtesy: M. Hofer

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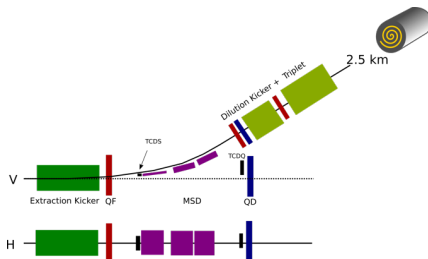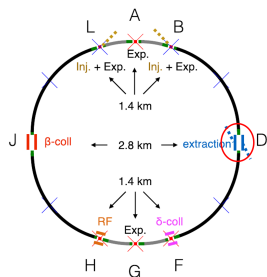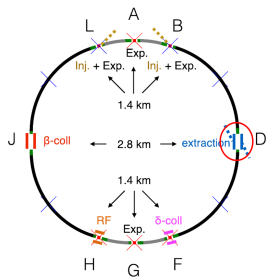
- ▶ Collision: $\beta^* = 3\,\mathrm{m}$.

- 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.

Optics ESS-PD-EXT

Courtesy: W. Bartmann

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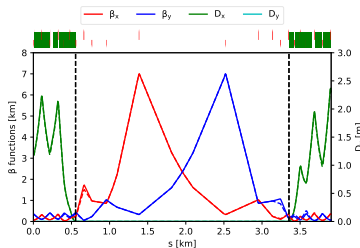- ▶ Highly segmented kickers (150) to reduce the error probabilities.
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Case of 4 misfiring kickers. Allowed loss: 10^{11}
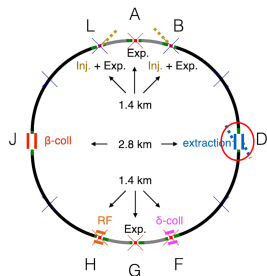
Courtesy: J. Molson

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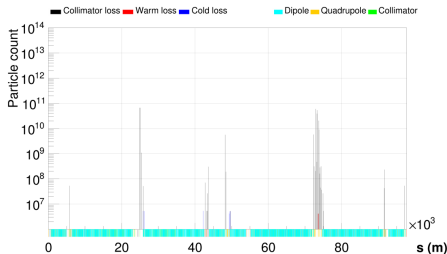- ▶ Extraction optics optimised for the **machine safety**.

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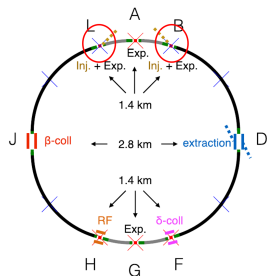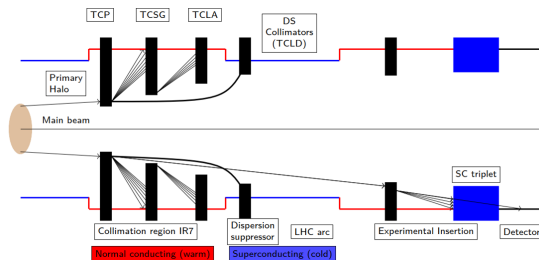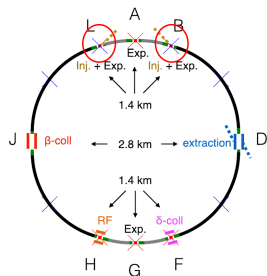 - ▶ Depends on the phase advances in the machine.

Collimator hierarchy

Courtesy: R. Bruce

- ▶ **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...
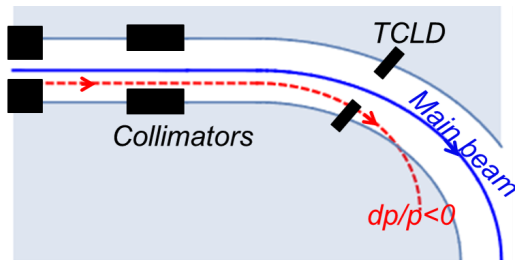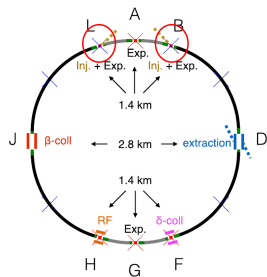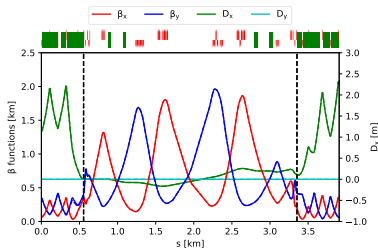
Insertions of collimators at the arc entrance

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Collimation

Collimation optics β ESS-PJ-COL

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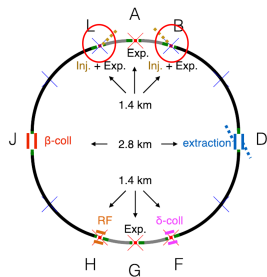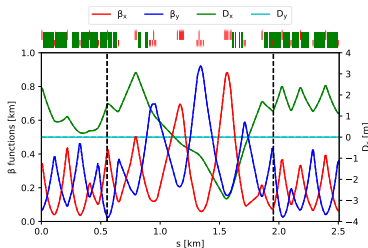
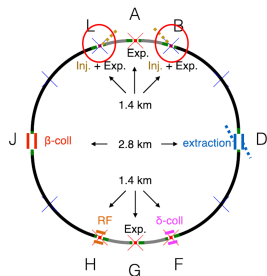# Collimation

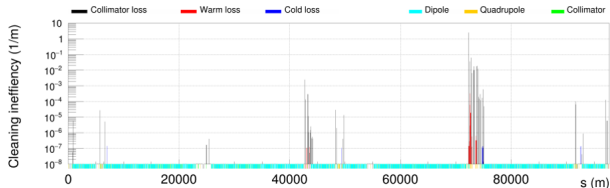Collimation optics δ LSS-PF-COL

- ▶ **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.

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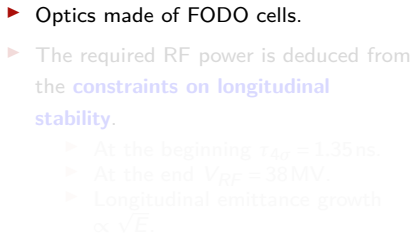
Courtesy: J. Molson

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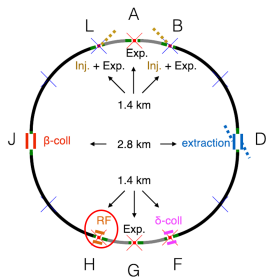
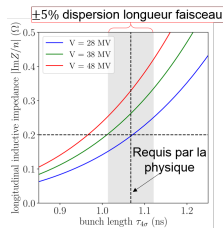### Optics of the RF section LSS-PH-RFS

▶ 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.
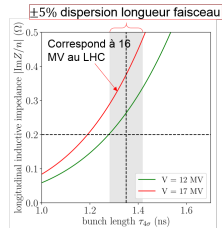
Stability thresholds

Courtesy: I. Karpov

Seuils à 50 TeV

Seuils à 3.3 TeV

- Optics made of FODO cells.

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RF consommation

Courtesy: I. Karpov
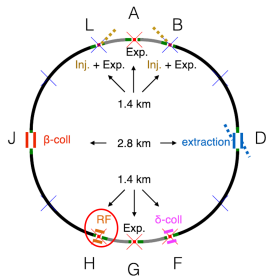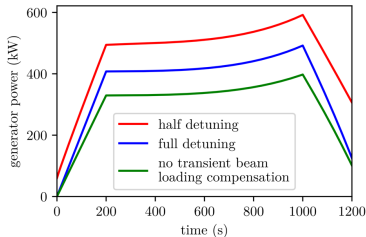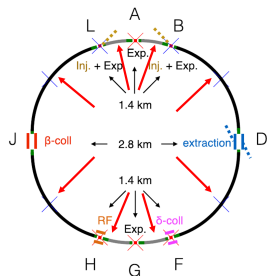
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Corrector distribution in the arcs   Courtesy: D. Boutin
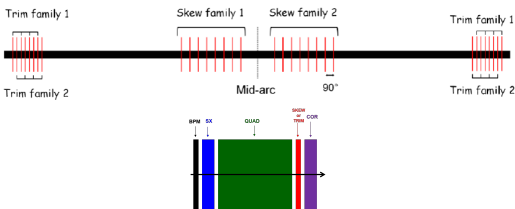
- ▶ The linear correction addresses:
  1. Correction of the linear coupling (with skew quadrupoles).
  2. Global correction of the orbit.
  3. Tune correction.
  4. If necessary, steps 2 et 3 are reiterated.
  - ▶ Acceptable residual errors.
  - ▶ The β and dispersion beatings are not corrected yet.

- ▶ 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
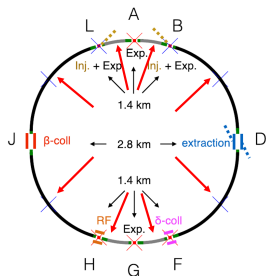
Residual values (90% quartile)   Courtesy: D. Boutin

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

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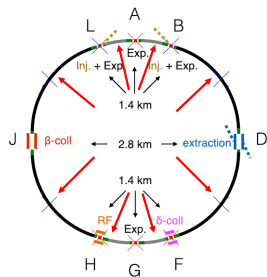
Correction of the spurious dispersion (SSC-like)
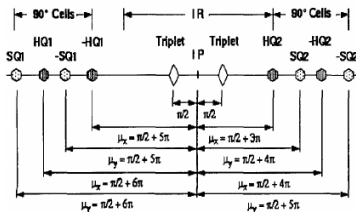
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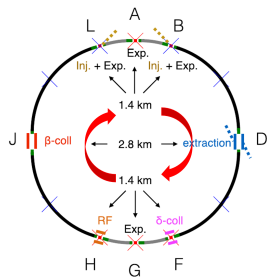
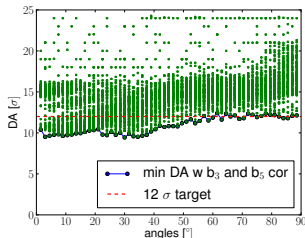DA interaction beam-beam + octupoles $\qquad$ Courtesy: E. Cruz-Alaniz
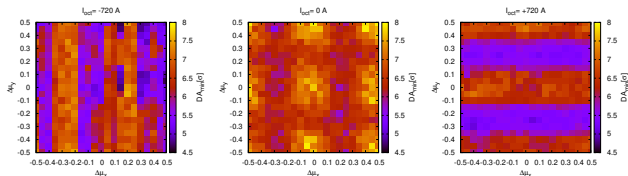
- **The dynamic aperture (DA) strongly depends** on the **phase advance** between IPs A and G at the collision.

- **Phase advance** optimized for the collision.

- DA>5σ 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).
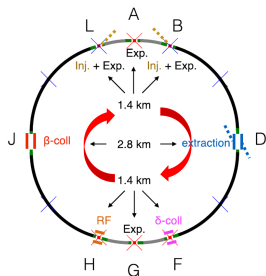
DA at injection + errors + octupoles

Courtesy: B. Dalena

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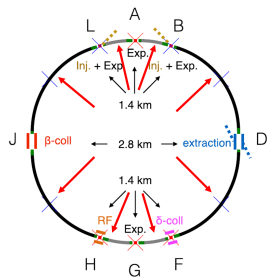
Apertures @3.3 TeV, phase advance 60°
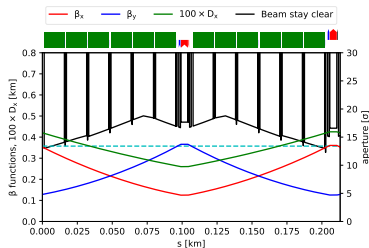
- ▶ Alternative with a **phase advance** per cell of 60° against 90°.

- ▶ 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!