DE LA RECHERCHE À L'INDUSTRIE

Summary FCC-hh machine design

Antoine CHANCE

CEA/DRF/Irfu/DACM

on behalf of FCC-hh machine team
FCC week 2017

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FCC-hh machine sessions - Tuesday

08:30 - 10:00	FCC-hh machine design: Review: design (1), chair: Roy Aleksan	
08:30 - 08:45	Daniel Schulte	Parameters and layout
08:45 - 09:10	Antoine Chance	Arc design and lattice integration
09:10 - 09:35	Andrei Seryi	Experimental insertions
09:35 - 10:00	Florian Burkart	Injections and extraction insertions and dump lines
10:30 - 12:00	FCC-hh machine design: Review: design (2), chair: Francesco Cerutti	
10:30 - 10:52	Andy Sven Langner	Betatron collimation system insertions
10:52 - 11:14	Angeles Faus-Golfe	Energy collimation system insertions
11:14 - 11:36	Elena Shaposhnikova	Longitudinal dynamics and RF requirements
11:36 - 11:58	Michaela Schaumann	Ion considerations
13:30 - 15:00	FCC-hh machine design: Review: Beam performance and specifications, chair: Mauro Migliorati	
13:30 - 13:55	Barbara Dalena	Dynamic aperture and alignment
13:55 - 14:15	Oliver Boine-Frankenheim	Impedances and electron cloud
14:15 - 14:35	Tatiana Pieloni	Beam-beam effects
14:35 - 14:55	Laurette Ponce	Instrumentation overview and challenges
15:30 - 17:00	FCC-hh machine design: Review: Injectors, chair: Peter-Jurgen Spiller	
15:30 - 15:55	Wolfgang Bartmann	LHC as 3.3 TeV HEB
15:55 - 16:15	Florian Burkart	scSPS as 1.3 TeV HEB
16:15 - 16:35	Michael Hofer	3.3 TeV beam injection into combined experimental and injection FCC machine insertions
16:35 - 16:55	Antoine Chance	Impact of injection energy on collider design

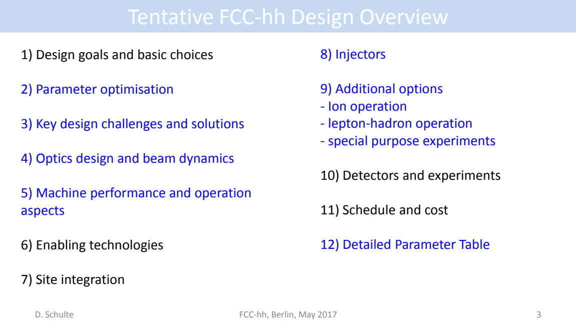
FCC-hh machine sessions - Wednesday

08:30 - 10:00	FCC-hh machine design: SppC and selected topics, chair: Angeles Faus-Golfe	
08:30 - 08:55	Jingyu Tang	SppC study progress
08:55 - 09:15	Jianquan Yang	SppC collimation study
09:15 - 09:35	Vladimir Shiltsev	Use of electron lenses in FCC-hh
09:35 - 09:55	Elena Shaposhnikova	Implications of 5 ns bunch spacing for the injector chain
10:30 - 12:00	FCC-hh machine design: Selected topics, chair: Oliver Boine-Frankenheim	
10:30 - 10:40	Emilia Cruz Alaniz	Correction schemes for the interaction region of FCC-hh
10:40 - 10:50	Leon Van Riesen-Haupt	Exploring the triplet parameter space to optimise the final focus of the FCC
10:50 - 11:00	Haroon Rafique	Cross-talk simulations between FCC-hh experimental interaction regions
11:00 - 11:10	Alexei Sytov	Simulation of the FCC-hh double crystal-based collimation system
11:10 - 11:20	Alexander Krainer	Dispersion suppressor protection
11:20 - 11:30	David Boutin	Alignment and beam-based correction
11:30 - 11:40	Sergey Arsenyev	Importance of the surface resistivity for the impedance model
11:40 - 11:50	Vladimir Kornilov	Landau damping of intra-bunch oscillations
11:50 - 12:00	Lotta Mether	FCC-hh electron cloud

6 sessions, 29 talks

Tentative plan for FCC-hh CDR

D. Schulte



Tentative FCC-hh Design Overview

1) Design goals and basic choices

2) Parameter optimisation

3) Key design challenges and solutions

4) Optics design and beam dynamics

5) Machine performance and operation aspects

6) Enabling technologies

7) Site integration

8) Injectors

9) Additional options
- Ion operation
- lepton-hadron operation
- special purpose experiments

10) Detectors and experiments

11) Schedule and cost

12) Detailed Parameter Table

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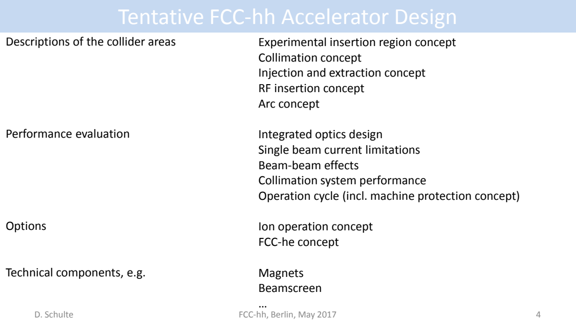

Tentative FCC-hh Accelerator Design

Descriptions of the collider areas	Experimental insertion region concept Collimation concept Injection and extraction concept RF insertion concept Arc concept
Performance evaluation	Integrated optics design Single beam current limitations Beam-beam effects Collimation system performance Operation cycle (incl. machine protection concept)
Options	Ion operation concept FCC-he concept
Technical components, e.g.	Magnets Beamscreen ...

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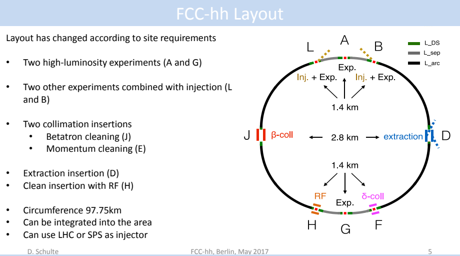
Outline

Tentative plan for FCC-hh CDR

D. Schulte



FCC-hh Layout

Layout has changed according to site requirements

- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector

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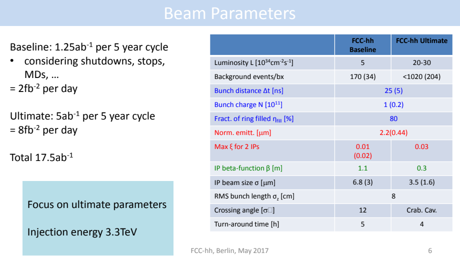

Beam Parameters

Baseline: 1.25ab^{-1} per 5 year cycle

- considering shutdowns, stops, MDs, …

= 2fb^{-2} per day

Ultimate: 5ab^{-1} per 5 year cycle

= 8fb^{-2} per day

Total 17.5ab^{-1}

Focus on ultimate parameters

Injection energy 3.3TeV

	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

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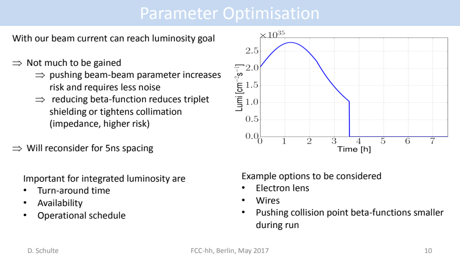

Parameter Optimisation

With our beam current can reach luminosity goal

⇒ Not much to be gained

⇒ pushing beam-beam parameter increases risk and requires less noise

⇒ reducing beta-function reduces triplet shielding or tightens collimation (impedance, higher risk)

⇒ Will reconsider for 5ns spacing

Important for integrated luminosity are

- Turn-around time
- Availability
- Operational schedule

Example options to be considered

- Electron lens
- Wires
- Pushing collision point beta-functions smaller during run

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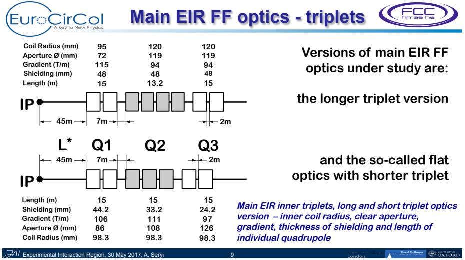
Outline

1. Parameters
2. Optics design
3. Machine performance
4. Injectors
5. Options
6. SppC
7. Summary

Experimental Interaction Region

A. Seryi, M. Hofer, E. Cruz, L. Van Riesen-Haupt, *et al.*



Main EIR FF optics - triplets

Coil Radius (mm)	95	120	120
Aperture Ø (mm)	72	119	119
Gradient (T/m)	115	94	94
Shielding (mm)	48	48	48
Length (m)	15	13.2	15

Length (m)	15	15	15
Shielding (mm)	44.2	33.2	24.2
Gradient (T/m)	106	111	97
Aperture Ø (mm)	86	108	126
Coil Radius (mm)	98.3	98.3	98.3

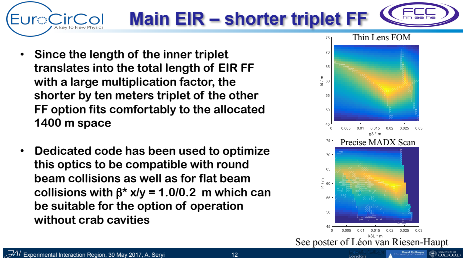
Versions of main EIR FF optics under study are:

the longer triplet version

and the so-called flat optics with shorter triplet

Main EIR inner triplets, long and short triplet optics version – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

Experimental Interaction Region, 30 May 2017, A. Seryi 9



Main EIR – shorter triplet FF

- Since the length of the inner triplet translates into the total length of EIR FF with a large multiplication factor, the shorter by ten meters triplet of the other FF option fits comfortably to the allocated 1400 m space
- Dedicated code has been used to optimize this optics to be compatible with round beam collisions as well as for flat beam collisions with β^* x/y = 1.0/0.2 m which can be suitable for the option of operation without crab cavities

See poster of Léon van Riesen-Haupt

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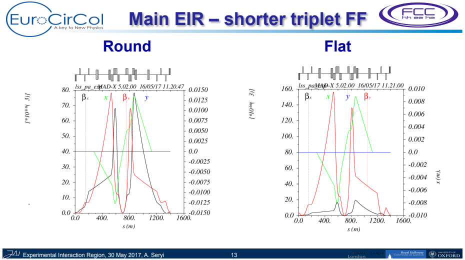

Main EIR – shorter triplet FF

Round **Flat**

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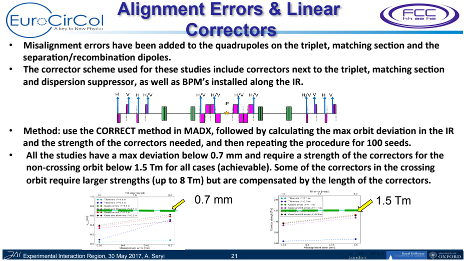

Alignment Errors & Linear Correctors

- **Misalignment errors have been added to the quadrupoles on the triplet, matching section and the separation/recombination dipoles.**
- **The corrector scheme used for these studies include correctors next to the triplet, matching section and dispersion suppressor, as well as BPM's installed along the IR.**

- **Method: use the CORRECT method in MADX, followed by calculating the max orbit deviation in the IR and the strength of the correctors needed, and then repeating the procedure for 100 seeds.**
- **All the studies have a max deviation below 0.7 mm and require a strength of the correctors for the non-crossing orbit below 1.5 Tm for all cases (achievable). Some of the correctors in the crossing orbit require larger strengths (up to 8 Tm) but are compensated by the length of the correctors.**

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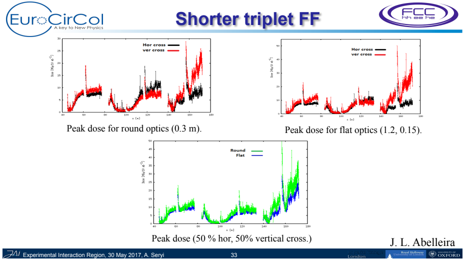
Experimental Interaction Region Protection

A. Seryi, H. Rafique, *et al.*



Shorter triplet FF

Peak dose for round optics (0.3 m).

Peak dose for flat optics (1.2, 0.15).

Peak dose (50 % hor, 50% vertical cross.)

J. L. Abelleira

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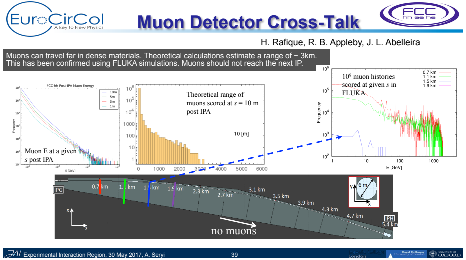

Muon Detector Cross-Talk

H. Rafique, R. B. Appleby, J. L. Abelleira

Muons can travel far in dense materials. Theoretical calculations estimate a range of ~ 3km. This has been confirmed using FLUKA simulations. Muons should not reach the next IP.

Muon E at a given *s* post IPA

Theoretical range of muons scored at *s* = 10 m post IPA

10^9 muon histories scored at given *s* in FLUKA

no muons

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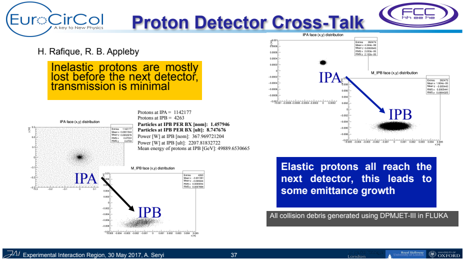

Proton Detector Cross-Talk

H. Rafique, R. B. Appleby

Inelastic protons are mostly lost before the next detector, transmission is minimal

Protons at IPA = 1142177
Protons at IPB = 4263
Particles at IPB PER BX [nom]: 1.457946
Particles at IPB PER BX [ult]: 8.747676
Power [W] at IPB [nom]: 367.969721204
Power [W] at IPB [ult]: 2207.81832722
Mean energy of protons at IPB [GeV]: 49889.6530665

Elastic protons all reach the next detector, this leads to some emittance growth

All collision debris generated using DPMJET-III in FLUKA

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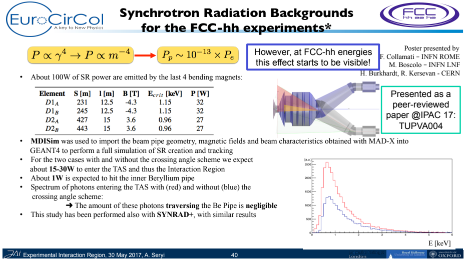


Synchrotron Radiation Backgrounds for the FCC-hh experiments*

$P \propto \gamma^4 \rightarrow P \propto m^{-4}$ → $P_p \sim 10^{-13} \times P_e$

However, at FCC-hh energies this effect starts to be visible!

Poster presented by
F. Collamati – INFN ROME
M. Boscolo – INFN LNF
H. Burkhardt, R. Kersevan - CERN

- About 100W of SR power are emitted by the last 4 bending magnets:

Element	S [m]	l [m]	B [T]	E_{crit} [keV]	P [W]
$D1_A$	231	12.5	-4.3	1.15	32
$D1_B$	245	12.5	-4.3	1.15	32
$D2_A$	427	15	3.6	0.96	27
$D2_B$	443	15	3.6	0.96	27

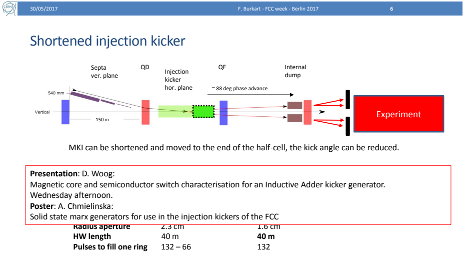
Presented as a peer-reviewed paper @IPAC 17: TUPVA004

- **MDISim** was used to import the beam pipe geometry, magnetic fields and beam characteristics obtained with MAD-X into GEANT4 to perform a full simulation of SR creation and tracking
- For the two cases with and without the crossing angle scheme we expect about **15-30W** to enter the TAS and thus the Interaction Region
- About **1W** is expected to hit the inner Beryllium pipe
- Spectrum of photons entering the TAS with (red) and without (blue) the crossing angle scheme:
  ➔ The amount of these photons **traversing** the Be Pipe is **negligible**
- This study has been performed also with **SYNRAD+**, with similar results

Experimental Interaction Region, 30 May 2017, A. Seryi 40

Injection and extraction insertions

F. Burkart, M. Hofer, *et al.*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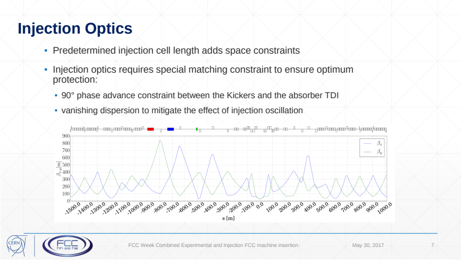
Shortened injection kicker

MKI can be shortened and moved to the end of the half-cell, the kick angle can be reduced.

Presentation: D. Woog:
Magnetic core and semiconductor switch characterisation for an Inductive Adder kicker generator.
Wednesday afternoon.
Poster: A. Chmielinska:
Solid state marx generators for use in the injection kickers of the FCC

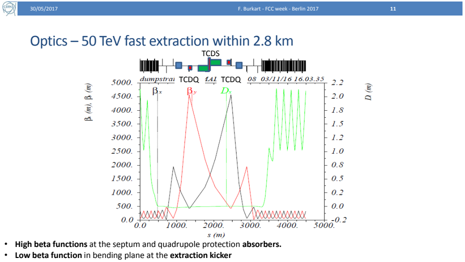
Radius aperture	2.3 cm	1.6 cm
HW length	40 m	**40 m**
Pulses to fill one ring	132 – 66	132



Injection Optics

- Predetermined injection cell length adds space constraints
- Injection optics requires special matching constraint to ensure optimum protection:
  - 90° phase advance constraint between the Kickers and the absorber TDI
  - vanishing dispersion to mitigate the effect of injection oscillation

FCC Week Combined Experimental and Injection FCC machine insertion May 30, 2017 7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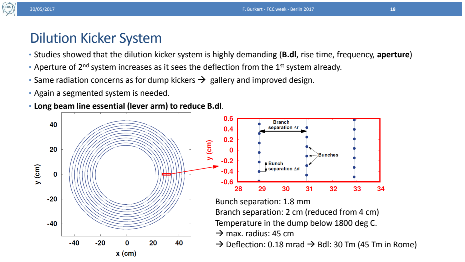
Optics – 50 TeV fast extraction within 2.8 km

- **High beta functions** at the septum and quadrupole protection **absorbers.**
- **Low beta function** in bending plane at the **extraction kicker**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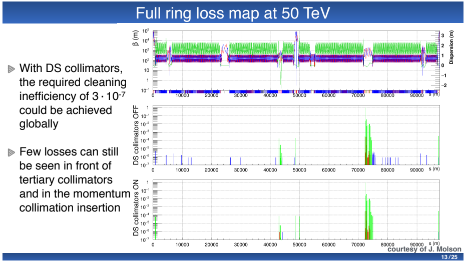
Dilution Kicker System

- Studies showed that the dilution kicker system is highly demanding (**B.dl**, rise time, frequency, **aperture**)
- Aperture of 2nd system increases as it sees the deflection from the 1st system already.
- Same radiation concerns as for dump kickers → gallery and improved design.
- Again a segmented system is needed.
- **Long beam line essential (lever arm) to reduce B.dl**.

Bunch separation: 1.8 mm
Branch separation: 2 cm (reduced from 4 cm)
Temperature in the dump below 1800 deg C.
→ max. radius: 45 cm
→ Deflection: 0.18 mrad → Bdl: 30 Tm (45 Tm in Rome)

β and δ cleaning sections

A. Langner, A. Faus-Golfe, A. Krainer, *et al.*



Full ring loss map at 50 TeV

- With DS collimators, the required cleaning inefficiency of $3 \cdot 10^{-7}$ could be achieved globally
- Few losses can still be seen in front of tertiary collimators and in the momentum collimation insertion

courtesy of J. Molson

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Power on Collimator Jaws

Primaries

Collimator	[kW]
TPC_D6L	0.02
TPC_C6L	23.1
TPC_B6L	209.0

Secondaries

Collimator Jaws	[kW]
TCSG_A6L	233.6
TCSG_B5L	8.2
TCSG_A5L	35.7
TCSG_D4L	27.6
TCSG_B4L	7.1
TCSG_A4L	13.1
TCSG_A4R	15.9
TCSG_B5R	4.9
TCSG_D5R	9.0
TCSG_E5R	15.7
TCSG_6R	3.5

About a factor 15 higher wrt to LHC (6.5 TeV, 500 kW power losses)

A factor of 2-2.5 higher than LHC

Active absorbers

Collimator	[kW]
TCLA_A6R	74.5
TCLA_B6R	13.5
TCLA_C6R	2.0
TCLA_D6R	2.6

A factor of 35 higher than LHC

Passive absorbers

Collimator	[kW]
TCAPA.6L	560.7
TCAPB.6L	93.4
TCAPC.6L	359.9

courtesy of I. Besana

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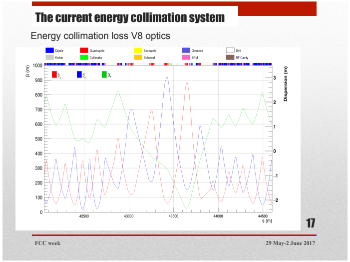

The current energy collimation system

Energy collimation loss V8 optics

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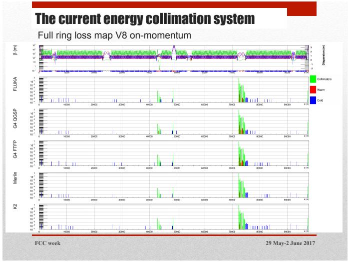
FCC week

29 May-2 June 2017



The current energy collimation system

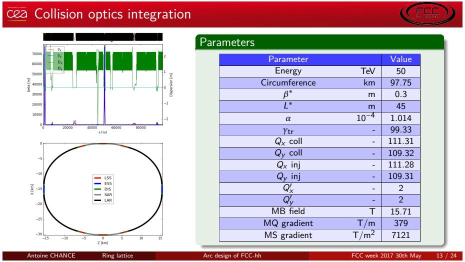
Full ring loss map V8 on-momentum

FCC week

29 May-2 June 2017

Arcs and lattice integration

A. Chance, A. Langner, *et al.*

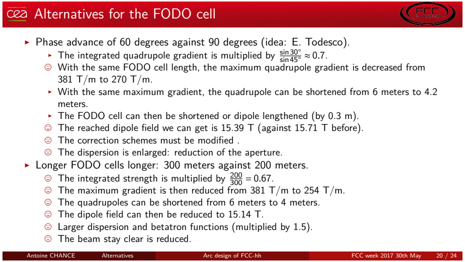


Collision optics integration

Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	45
α	10^{-4}	1.014
γ_{tr}	-	99.33
Q_x coll	-	111.31
Q_y coll	-	109.32
Q_x inj	-	111.28
Q_y inj	-	109.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.71
MQ gradient	T/m	379
MS gradient	T/m^2	7121

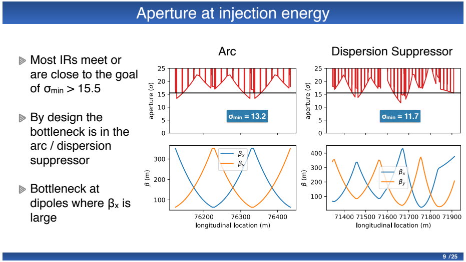
Antoine CHANCE Ring lattice Arc design of FCC-hh FCC week 2017 30th May 13 / 24



Alternatives for the FODO cell

- Phase advance of 60 degrees against 90 degrees (idea: E. Todesco).
  - The integrated quadrupole gradient is multiplied by $\frac{\sin 30°}{\sin 45°} \approx 0.7$.
  - ☹ With the same FODO cell length, the maximum quadrupole gradient is decreased from 381 T/m to 270 T/m.
  - With the same maximum gradient, the quadrupole can be shortened from 6 meters to 4.2 meters.
  - The FODO cell can then be shortened or dipole lengthened (by 0.3 m).
  - ☹ The reached dipole field we can get is 15.39 T (against 15.71 T before).
  - ☹ The correction schemes must be modified .
  - ☹ The dispersion is enlarged: reduction of the aperture.
- Longer FODO cells longer: 300 meters against 200 meters.
  - ☺ The integrated strength is multiplied by $\frac{200}{300} = 0.67$.
  - ☺ The maximum gradient is then reduced from 381 T/m to 254 T/m.
  - ☺ The quadrupoles can be shortened from 6 meters to 4 meters.
  - ☺ The dipole field can then be reduced to 15.14 T.
  - ☹ Larger dispersion and betatron functions (multiplied by 1.5).
  - ☹ The beam stay clear is reduced.

Antoine CHANCE Alternatives Arc design of FCC-hh FCC week 2017 30th May 20 / 24



Aperture at injection energy

- Most IRs meet or are close to the goal of $\sigma_{min} > 15.5$
- By design the bottleneck is in the arc / dispersion suppressor
- Bottleneck at dipoles where β_x is large

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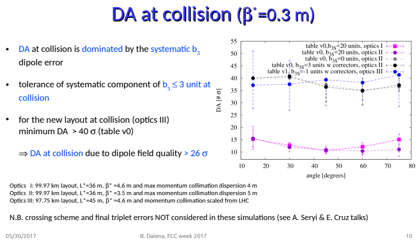
Outline

1. Parameters
2. Optics design
3. **Machine performance**
4. Injectors
5. Options
6. SppC
7. Summary

Dynamic aperture and beam correction

B. Dalena, D. Boutin, E. Cruz, *et al.*



DA at collision (β^*=0.3 m)

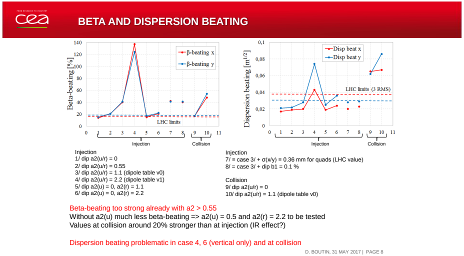
- DA at collision is dominated by the systematic b_3 dipole error
- tolerance of systematic component of $b_3 \leq 3$ unit at collision
- for the new layout at collision (optics III) minimum DA > 40 σ (table v0)

  ⇒ DA at collision due to dipole field quality > 26 σ

Optics I: 99.97 km layout, L^*=36 m, β^* =4.6 m and max momentum collimation dispersion 4 m
Optics II: 99.97 km layout, L^*=36 m, β^* =3.5 m and max momentum collimation dispersion 5 m
Optics III: 97.75 km layout, L^*=45 m, β^* =4.6 m and momentum collimation scaled from LHC

N.B. crossing scheme and final triplet errors NOT considered in these simulations (see A. Seryi & E. Cruz talks)

05/30/2017 B. Dalena, FCC week 2017 10



BETA AND DISPERSION BEATING

Injection
1/ dip a2(u/r) = 0
2/ dip a2(u/r) = 0.55
3/ dip a2(u/r) = 1.1 (dipole table v0)
4/ dip a2(u/r) = 2.2 (dipole table v1)
5/ dip a2(u) = 0, a2(r) = 1.1
6/ dip a2(u) = 0, a2(r) = 2.2

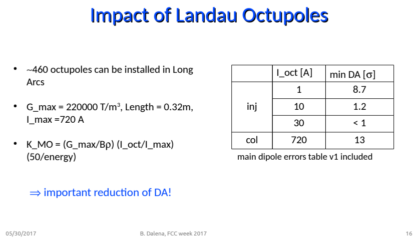
Injection
7/ = case 3/ + σ(x/y) = 0.36 mm for quads (LHC value)
8/ = case 3/ + dip b1 = 0.1 %

Collision
9/ dip a2(u/r) = 0
10/ dip a2(u/r) = 1.1 (dipole table v0)

Beta-beating too strong already with a2 > 0.55
Without a2(u) much less beta-beating => a2(u) = 0.5 and a2(r) = 2.2 to be tested
Values at collision around 20% stronger than at injection (IR effect?)

Dispersion beating problematic in case 4, 6 (vertical only) and at collision

D. BOUTIN, 31 MAY 2017 | PAGE 8



Impact of Landau Octupoles

- ~460 octupoles can be installed in Long Arcs
- G_max = 220000 T/m³, Length = 0.32m, I_max =720 A
- K_MO = (G_max/Bρ) (I_oct/I_max) (50/energy)

⇒ important reduction of DA!

	I_oct [A]	min DA [σ]
inj	1	8.7
	10	1.2
	30	< 1
col	720	13

main dipole errors table v1 included

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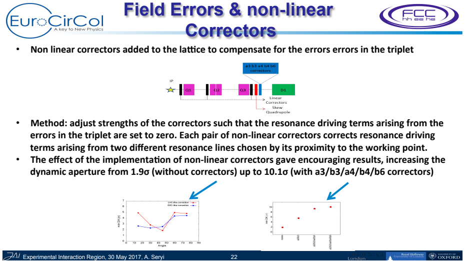


Field Errors & non-linear Correctors

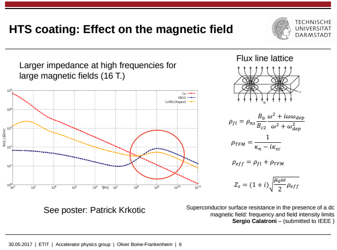
- **Non linear correctors added to the lattice to compensate for the errors errors in the triplet**

- **Method: adjust strengths of the correctors such that the resonance driving terms arising from the errors in the triplet are set to zero. Each pair of non-linear correctors corrects resonance driving terms arising from two different resonance lines chosen by its proximity to the working point.**
- **The effect of the implementation of non-linear correctors gave encouraging results, increasing the dynamic aperture from 1.9σ (without correctors) up to 10.1σ (with a3/b3/a4/b4/b6 correctors)**

Experimental Interaction Region, 30 May 2017, A. Seryi 22

Single beam current limitations (1)

O. Boine-Frankenheim, V. Kornilov, S. Arsenyev, A. Langner, *et al.*



HTS coating: Effect on the magnetic field

TECHNISCHE UNIVERSITÄT DARMSTADT

Larger impedance at high frequencies for large magnetic fields (16 T.)

Flux line lattice

$$\rho_{fl} = \rho_{ns}\frac{B_0}{B_{c2}}\frac{\omega^2 + i\omega\omega_{dep}}{\omega^2 + \omega_{dep}^2}$$

$$\rho_{TFM} = \frac{1}{\kappa_n - i\kappa_{sc}}$$

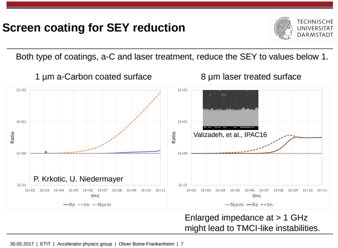
$$\rho_{eff} = \rho_{fl} + \rho_{TFM}$$

$$Z_s = (1+i)\sqrt{\frac{\mu_0\omega}{2}\rho_{eff}}$$

See poster: Patrick Krkotic

Superconductor surface resistance in the presence of a dc magnetic field: frequency and field intensity limits
Sergio Calatroni – (submitted to IEEE)

30.05.2017 | ETIT | Accelerator physics group | Oliver Boine-Frankenheim | 6



Screen coating for SEY reduction

TECHNISCHE UNIVERSITÄT DARMSTADT

Both type of coatings, a-C and laser treatment, reduce the SEY to values below 1.

1 µm a-Carbon coated surface

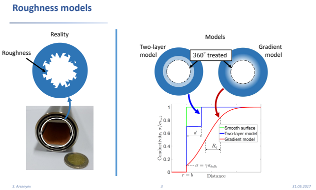
8 µm laser treated surface

P. Krkotic, U. Niedermayer

Valizadeh, et al., IPAC16

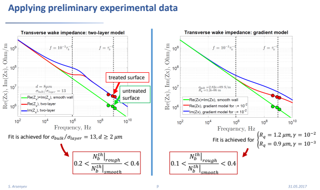
Enlarged impedance at > 1 GHz might lead to TMCI-like instabilities.

30.05.2017 | ETIT | Accelerator physics group | Oliver Boine-Frankenheim | 7



Roughness models

S. Arsenyev 3 31.05.2017



Applying preliminary experimental data

Fit is achieved for $\sigma_{bulk}/\sigma_{layer} = 13, d \geq 2\ \mu m$

$$0.2 < \frac{N_b^{th}|_{rough}}{N_b^{th}|_{smooth}} < 0.4$$

Fit is achieved for $\begin{cases} R_q = 1.2\ \mu m, \gamma = 10^{-2} \\ R_q = 0.9\ \mu m, \gamma = 10^{-3} \end{cases}$

$$0.1 < \frac{N_b^{th}|_{rough}}{N_b^{th}|_{smooth}} < 0.4$$

S. Arsenyev 9 31.05.2017

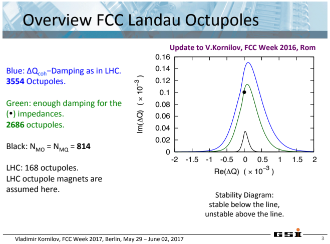
Energy deposition

- Previous plots show cleaning inefficiency in terms of simulated proton losses on the aperture
- For detailed assessment of performance, need to simulate energy deposition in all elements (collimators + magnets)
  - assess quenches and robustness of elements during high losses
  - assess long-term radiation damage effects
- As for HL-LHC, using FLUKA,
  - Starting conditions: output from the tracking studies (M. Fiascaris)
  - Need to build detailed 3D geometry in FLUKA of the collimation insertion

15/25

Single beam current limitations (2)

V. Kornilov, L. Mether, *et al.*



Overview FCC Landau Octupoles

Update to V.Kornilov, FCC Week 2016, Rom

Blue: ΔQ_{coh}–Damping as in LHC. **3554** Octupoles.

Green: enough damping for the (•) impedances. **2686** octupoles.

Black: $N_{MO} = N_{MQ} =$ **814**

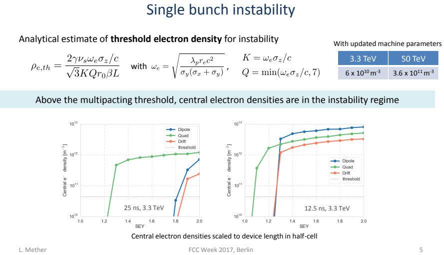
LHC: 168 octupoles. LHC octupole magnets are assumed here.

Stability Diagram: stable below the line, unstable above the line.

Vladimir Kornilov, FCC Week 2017, Berlin, May 29 – June 02, 2017

GSI

3



Single bunch instability

Analytical estimate of **threshold electron density** for instability

$$\rho_{e,th} = \frac{2\gamma\nu_s\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L} \quad \text{with} \quad \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x+\sigma_y)}}, \quad K = \omega_e\sigma_z/c, \quad Q = \min(\omega_e\sigma_z/c, 7)$$

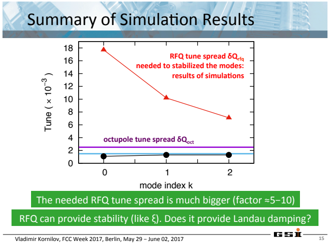
With updated machine parameters

3.3 TeV	50 TeV
6 x 10^{10} m^{-3}	3.6 x 10^{11} m^{-3}

Above the multipacting threshold, central electron densities are in the instability regime

Central electron densities scaled to device length in half-cell

L. Mether FCC Week 2017, Berlin 5



Summary of Simulation Results

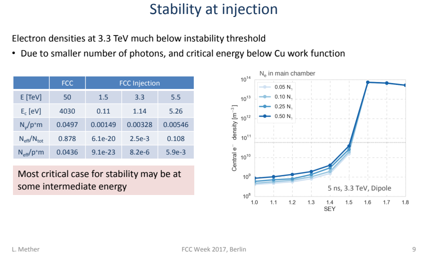
The needed RFQ tune spread is much bigger (factor ≈5–10)

RFQ can provide stability (like ξ). Does it provide Landau damping?

Vladimir Kornilov, FCC Week 2017, Berlin, May 29 – June 02, 2017

GSI

15



Stability at injection

Electron densities at 3.3 TeV much below instability threshold

- Due to smaller number of photons, and critical energy below Cu work function

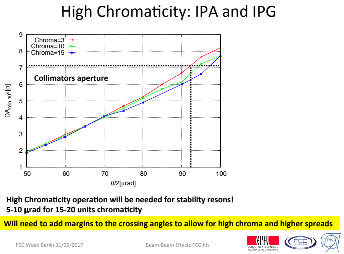
	FCC	FCC Injection		
E [TeV]	50	1.5	3.3	5.5
E_c [eV]	4030	0.11	1.14	5.26
N_γ/p^+m	0.0497	0.00149	0.00328	0.00546
N_{eff}/N_{tot}	0.878	6.1e-20	2.5e-3	0.108
N_{eff}/p^+m	0.0436	9.1e-23	8.2e-6	5.9e-3

Most critical case for stability may be at some intermediate energy

L. Mether FCC Week 2017, Berlin 9

Beam-beam effects

T. Pieloni

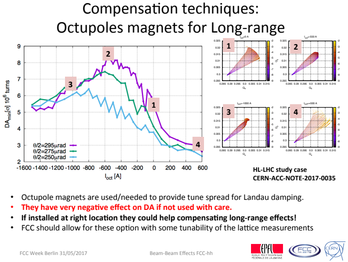


High Chromaticity: IPA and IPG

High Chromaticity operation will be needed for stability resons!
5-10 μrad for 15-20 units chromaticity

Will need to add margins to the crossing angles to allow for high chroma and higher spreads

FCC Week Berlin 31/05/2017 Beam-Beam Effects FCC-hh

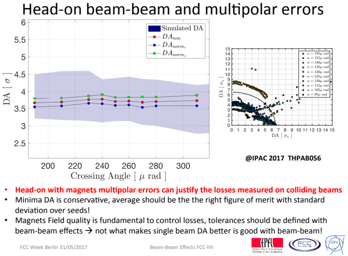


Compensation techniques: Octupoles magnets for Long-range

HL-LHC study case
CERN-ACC-NOTE-2017-0035

- Octupole magnets are used/needed to provide tune spread for Landau damping.
- They have very negative effect on DA if not used with care.
- **If installed at right location they could help compensating long-range effects!**
- FCC should allow for these option with some tunability of the lattice measurements

FCC Week Berlin 31/05/2017 Beam-Beam Effects FCC-hh

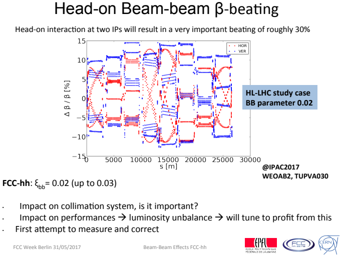


Head-on beam-beam and multipolar errors

@IPAC 2017 THPAB056

- Head-on with magnets multipolar errors can justify the losses measured on colliding beams
- Minima DA is conservative, average should be the the right figure of merit with standard deviation over seeds!
- Magnets Field quality is fundamental to control losses, tolerances should be defined with beam-beam effects → not what makes single beam DA better is good with beam-beam!

FCC Week Berlin 31/05/2017 Beam-Beam Effects FCC-hh



Head-on Beam-beam β-beating

Head-on interaction at two IPs will result in a very important beating of roughly 30%

HL-LHC study case
BB parameter 0.02

@IPAC2017
WEOAB2, TUPVA030

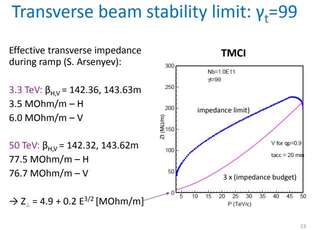
FCC-hh: ξ_{bb}= 0.02 (up to 0.03)

- Impact on collimation system, is it important?
- Impact on performances → luminosity unbalance → will tune to profit from this
- First attempt to measure and correct

FCC Week Berlin 31/05/2017 Beam-Beam Effects FCC-hh

Longitudinal dynamics

E. Shaposhnikova



Transverse beam stability limit: γ_t=99

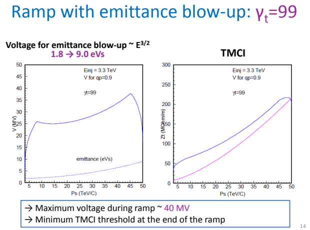
Effective transverse impedance during ramp (S. Arsenyev):

3.3 TeV: $\beta_{H,V}$ = 142.36, 143.63m
3.5 MOhm/m – H
6.0 MOhm/m – V

50 TeV: $\beta_{H,V}$ = 142.32, 143.62m
77.5 MOhm/m – H
76.7 MOhm/m – V

→ $Z_\perp$ = 4.9 + 0.2 $E^{3/2}$ [MOhm/m]

13

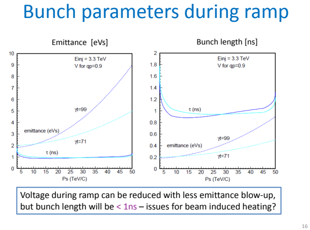


Ramp with emittance blow-up: γ_t=99

Voltage for emittance blow-up ~ $E^{3/2}$
1.8 → 9.0 eVs

→ Maximum voltage during ramp ~ 40 MV
→ Minimum TMCI threshold at the end of the ramp

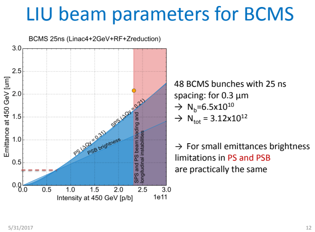
14



Bunch parameters during ramp

Voltage during ramp can be reduced with less emittance blow-up, but bunch length will be < 1ns – issues for beam induced heating?

16



LIU beam parameters for BCMS

48 BCMS bunches with 25 ns spacing: for 0.3 µm
→ N_b=6.5x10^{10}
→ N_{tot} = 3.12x10^{12}

→ For small emittances brightness limitations in PS and PSB are practically the same

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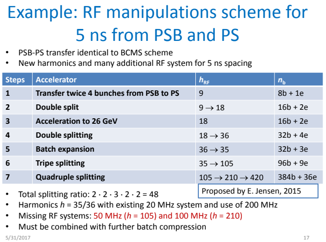

Example: RF manipulations scheme for 5 ns from PSB and PS

- PSB-PS transfer identical to BCMS scheme
- New harmonics and many additional RF system for 5 ns spacing

Steps	Accelerator	h_{RF}	n_b
1	**Transfer twice 4 bunches from PSB to PS**	9	8b + 1e
2	**Double split**	9 → 18	16b + 2e
3	**Acceleration to 26 GeV**	18	16b + 2e
4	**Double splitting**	18 → 36	32b + 4e
5	**Batch expansion**	36 → 35	32b + 3e
6	**Tripe splitting**	35 → 105	96b + 9e
7	**Quadruple splitting**	105 → 210 → 420	384b + 36e

Proposed by E. Jensen, 2015

- Total splitting ratio: 2 · 2 · 3 · 2 · 2 = 48
- Harmonics *h* = 35/36 with existing 20 MHz system and use of 200 MHz
- Missing RF systems: 50 MHz (*h* = 105) and 100 MHz (*h* = 210)
- Must be combined with further batch compression

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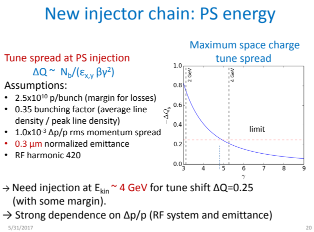

New injector chain: PS energy

Tune spread at PS injection
$\Delta Q \sim N_b/(\varepsilon_{x,y}\, \beta\gamma^2)$

Assumptions:

- 2.5x10^{10} p/bunch (margin for losses)
- 0.35 bunching factor (average line density / peak line density)
- 1.0x10^{-3} Δp/p rms momentum spread
- 0.3 µm normalized emittance
- RF harmonic 420

Maximum space charge tune spread

→ Need injection at E_{kin} ~ 4 GeV for tune shift ΔQ=0.25 (with some margin).
→ Strong dependence on Δp/p (RF system and emittance)

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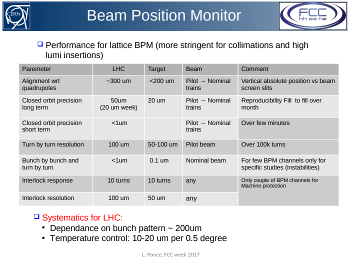
Beam instrumentation

L. Ponce



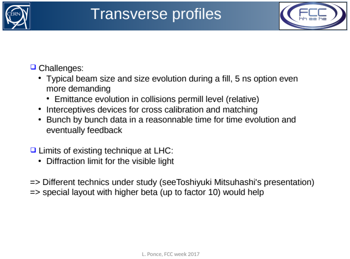
Beam Position Monitor

- Performance for lattice BPM (more stringent for collimations and high lumi insertions)

Paremeter	LHC	Target	Beam	Comment
Alignment wrt quadrupoles	~300 um	<200 um	Pilot → Nominal trains	Vertical absolute position vs beam screen slits
Closed orbit precision long term	50um (20 um week)	20 um	Pilot → Nominal trains	Reproducibility Fill to fill over month
Closed orbit precision short term	<1um		Pilot → Nominal trains	Over few minutes
Turn by turn resolution	100 um	50-100 um	Pilot beam	Over 100k turns
Bunch by bunch and turn by turn	<1um	0.1 um	Nominal beam	For few BPM channels only for specific studies (instabilities)
Interlock response	10 turns	10 turns	any	Only couple of BPM channels for Machine protection
Interlock resolution	100 um	50 um	any	

- Systematics for LHC:
  - Dependance on bunch pattern ~ 200um
  - Temperature control: 10-20 um per 0.5 degree

L. Ponce, FCC week 2017

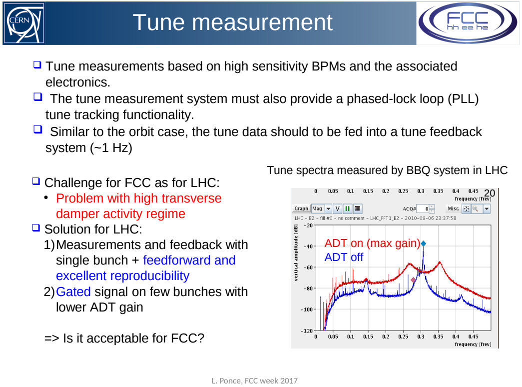


Transverse profiles

- Challenges:
  - Typical beam size and size evolution during a fill, 5 ns option even more demanding
    - Emittance evolution in collisions permill level (relative)
  - Interceptives devices for cross calibration and matching
  - Bunch by bunch data in a reasonnable time for time evolution and eventually feedback
- Limits of existing technique at LHC:
  - Diffraction limit for the visible light

=> Different technics under study (seeToshiyuki Mitsuhashi's presentation)
=> special layout with higher beta (up to factor 10) would help

L. Ponce, FCC week 2017



Tune measurement

- Tune measurements based on high sensitivity BPMs and the associated electronics.
- The tune measurement system must also provide a phased-lock loop (PLL) tune tracking functionality.
- Similar to the orbit case, the tune data should to be fed into a tune feedback system (~1 Hz)

- Challenge for FCC as for LHC:
  - Problem with high transverse damper activity regime
- Solution for LHC:
  1) Measurements and feedback with single bunch + feedforward and excellent reproducibility
  2) Gated signal on few bunches with lower ADT gain

=> Is it acceptable for FCC?

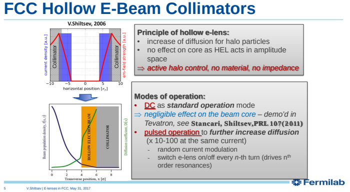
Tune spectra measured by BBQ system in LHC

LHC – B2 – fill #0 – no comment – LHC_FFT1_B2 – 2010-09-06 23:37:58

L. Ponce, FCC week 2017

Alternatives for collimation

V. Shiltsev, A. Sytov



FCC Hollow E-Beam Collimators

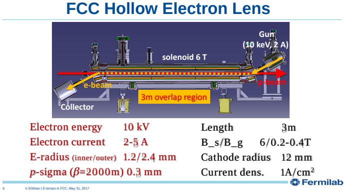
Principle of hollow e-lens:
- increase of diffusion for halo particles
- no effect on core as HEL acts in amplitude space

⇒ *active halo control, no material, no impedance*

Modes of operation:
- DC as ***standard operation*** mode

⇒ *negligible effect on the beam core – demo'd in Tevatron, see* **Stancari, Shiltsev,PRL 107(2011)**
- pulsed operation to ***further increase diffusion*** (x 10-100 at the same current)
  - random current modulation
  - switch e-lens on/off every *n*-th turn (drives nth order resonances)

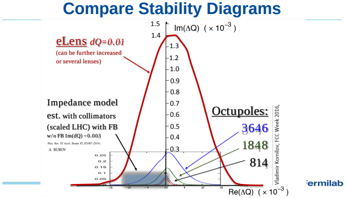
5 V.Shiltsev | E-lenses in FCC, May 31, 2017 Fermilab



FCC Hollow Electron Lens

Electron energy	10 kV	Length	3m
Electron current	2-5 A	B_s/B_g	6/0.2-0.4T
E-radius (inner/outer)	1.2/2.4 mm	Cathode radius	12 mm
p-sigma (β=2000m)	0.3 mm	Current dens.	1A/cm^2

6 V.Shiltsev | E-lenses in FCC, May 31, 2017 Fermilab



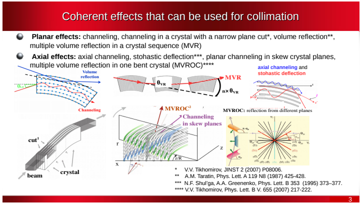
Compare Stability Diagrams

eLens *dQ=0.01*
(can be further increased or several lenses)

Impedance model est. with collimators (scaled LHC) with FB
w/o FB Im(dQ) ~0.003
Phys. Rev. ST Accel. Beams 17, 021007 (2014)
A. BUROV

Octupoles:
3646
1848
814

Fermilab



Coherent effects that can be used for collimation

- **Planar effects:** channeling, channeling in a crystal with a narrow plane cut*, volume reflection**, multiple volume reflection in a crystal sequence (MVR)
- **Axial effects:** axial channeling, stohastic deflection***, planar channeling in skew crystal planes, multiple volume reflection in one bent crystal (MVROC)****

* V.V. Tikhomirov, JINST 2 (2007) P08006.
** A.M. Taratin, Phys. Lett. A 119 N8 (1987) 425-428.
*** N.F. Shul'ga, A.A. Greenenko, Phys. Lett. B 353 (1995) 373–377.
**** V.V. Tikhomirov, Phys. Lett. B V. 655 (2007) 217-222.

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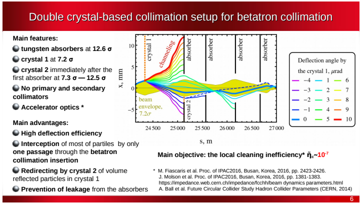


Double crystal-based collimation setup for betatron collimation

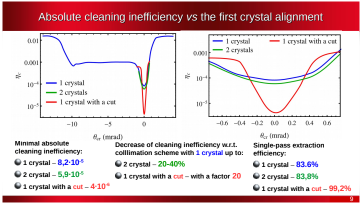
Main features:
- **tungsten absorbers** at **12.6 σ**
- **crystal 1** at **7.2 σ**
- **crystal 2** immediately after the first absorber at **7.3 σ — 12.5 σ**
- **No primary and secondary collimators**
- **Accelerator optics ***

Main advantages:
- **High deflection efficiency**
- **Interception** of most of partiles by only **one passage** through the **betatron collimation insertion**
- **Redirecting by crystal 2** of volume reflected particles in crystal 1
- **Prevention of leakage** from the absorbers

Main objective: the local cleaning inefficiency* $\tilde{\eta}_c$~10^{-7}

* M. Fiascaris et al. Proc. of IPAC2016, Busan, Korea, 2016, pp. 2423-2426.
J. Molson et al. Proc. of IPAC2016, Busan, Korea, 2016, pp. 1381-1383.
https://impedance.web.cern.ch/impedance/fcchh/beam dynamics parameters.html
A. Ball et al. Future Circular Collider Study Hadron Collider Parameters (CERN, 2014)

6



Absolute cleaning inefficiency *vs* the first crystal alignment

Minimal absolute cleaning inefficiency:
- **1 crystal** – $8{,}2\cdot10^{-5}$
- **2 crystal** – $5{,}9\cdot10^{-5}$
- **1 crystal with a cut** – $4\cdot10^{-6}$

Decrease of cleaning inefficiency w.r.t. colllimation scheme with 1 crystal up to:
- **2 crystal** – **20-40%**
- **1 crystal with a cut – with a factor 20**

Single-pass extraction efficiency:
- **1 crystal** – **83.6%**
- **2 crystal** – **83,8%**
- **1 crystal with a cut** – **99,2%**

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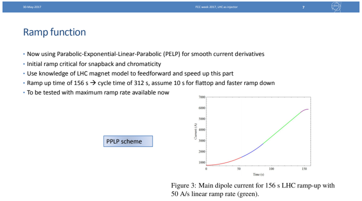
Outline

1. Parameters
2. Optics design
3. Machine performance
4. **Injectors**
5. Options
6. SppC
7. Summary

LHC or ScSPS as the FCC-hh injector

F. Burkart, W. Bartmann, *et al.*



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Ramp function

- Now using Parabolic-Exponential-Linear-Parabolic (PELP) for smooth current derivatives
- Initial ramp critical for snapback and chromaticity
- Use knowledge of LHC magnet model to feedforward and speed up this part
- Ramp up time of 156 s → cycle time of 312 s, assume 10 s for flattop and faster ramp down
- To be tested with maximum ramp rate available now

PPLP scheme

Figure 3: Main dipole current for 156 s LHC ramp-up with 50 A/s linear ramp rate (green).

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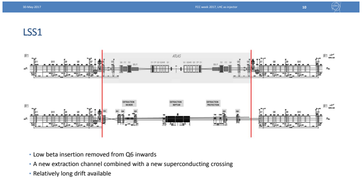

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LSS1

- Low beta insertion removed from Q6 inwards
- A new extraction channel combined with a new superconducting crossing
- Relatively long drift available

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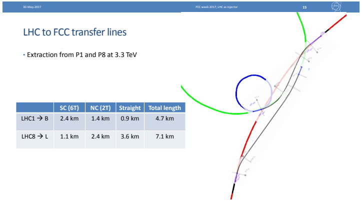

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LHC to FCC transfer lines

- Extraction from P1 and P8 at 3.3 TeV

	SC (6T)	NC (2T)	Straight	Total length
LHC1 → B	2.4 km	1.4 km	0.9 km	4.7 km
LHC8 → L	1.1 km	2.4 km	3.6 km	7.1 km

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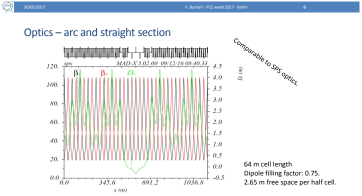

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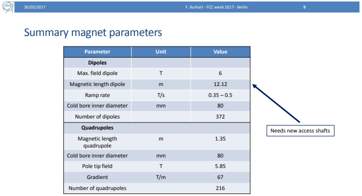
Optics – arc and straight section

Comparable to SPS optics.

64 m cell length
Dipole filling factor: 0.75.
2.65 m free space per half cell.



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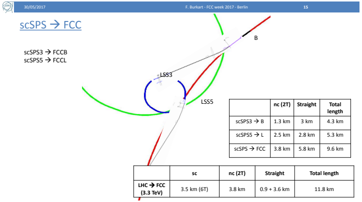
Summary magnet parameters

Parameter	Unit	Value
Dipoles		
Max. field dipole	T	6
Magnetic length dipole	m	12.12
Ramp rate	T/s	0.35 – 0.5
Cold bore inner diameter	mm	80
Number of dipoles		372
Quadrupoles		
Magnetic length quadrupole	m	1.35
Cold bore inner diameter	mm	80
Pole tip field	T	5.85
Gradient	T/m	67
Number of quadrupoles		216

Needs new access shafts



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scSPS → FCC

scSPS3 → FCCB
scSPS5 → FCCL

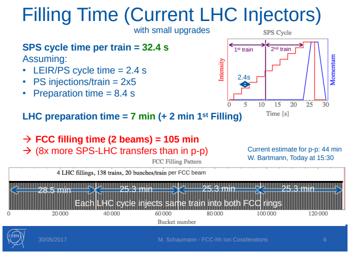
	nc (2T)	Straight	Total length
scSPS3 → B	1.3 km	3 km	4.3 km
scSPS5 → L	2.5 km	2.8 km	5.3 km
scSPS → FCC	3.8 km	5.8 km	9.6 km

	sc	nc (2T)	Straight	Total length
LHC → FCC (3.3 TeV)	3.5 km (6T)	3.8 km	0.9 + 3.6 km	11.8 km

Outline

Ion operation

M. Schaumann



Filling Time (Current LHC Injectors)

with small upgrades

SPS cycle time per train = 32.4 s
Assuming:

- LEIR/PS cycle time = 2.4 s
- PS injections/train = 2x5
- Preparation time = 8.4 s

LHC preparation time = 7 min (+ 2 min 1st Filling)

→ **FCC filling time (2 beams) = 105 min**
→ (8x more SPS-LHC transfers than in p-p)

Current estimate for p-p: 44 min
W. Bartmann, Today at 15:30

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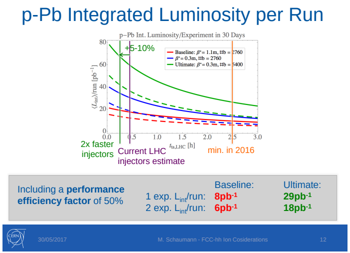

p-Pb Integrated Luminosity per Run

Including a **performance efficiency factor** of 50%		Baseline:	Ultimate:
	1 exp. L_{int}/run:	**8pb^{-1}**	**29pb^{-1}**
	2 exp. L_{int}/run:	**6pb^{-1}**	**18pb^{-1}**

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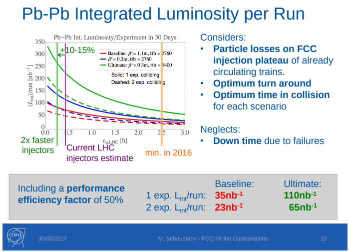

Pb-Pb Integrated Luminosity per Run

Considers:

- **Particle losses on FCC injection plateau** of already circulating trains.
- **Optimum turn around**
- **Optimum time in collision** for each scenario

Neglects:

- **Down time** due to failures

Including a **performance efficiency factor** of 50%		Baseline:	Ultimate:
	1 exp. L_{int}/run:	**35nb^{-1}**	**110nb^{-1}**
	2 exp. L_{int}/run:	**23nb^{-1}**	**65nb^{-1}**

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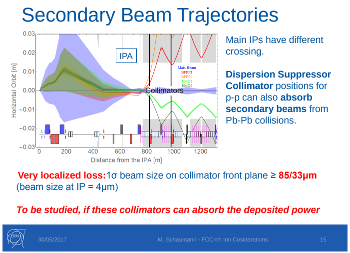

Secondary Beam Trajectories

Main IPs have different crossing.

Dispersion Suppressor Collimator positions for p-p can also **absorb secondary beams** from Pb-Pb collisions.

Very localized loss: 1σ beam size on collimator front plane ≥ **85/33μm**
(beam size at IP = 4μm)

To be studied, if these collimators can absorb the deposited power

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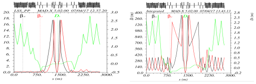
SppC status

J. Tang, J. Yang

Lattice design

- Different lattice designs
  - Different schemes (100 TeV and 75 TeV @100 km)
  - Lattice at injection
  - Compatibility between CEPC and SPPC
  - Arc cells, Dispersion suppressors, insertions

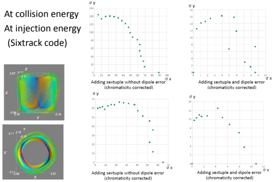


IP: at collision

IP: at injection

Dynamic aperture study

- At collision energy
- At injection energy
  (Sixtrack code)



Adding sextuple without dipole error (chromaticity corrected)

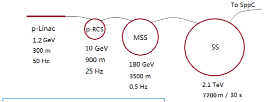
Adding sextuple and dipole error (chromaticity corrected)

Adding sextuple without dipole error (chromaticity corrected)

Adding sextuple and dipole error (chromaticity corrected)

Injector chain

(for proton beam)



p-Linac: proton superconducting linac

p-RCS: proton rapid cycling synchrotron

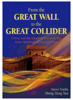
MSS: Medium-Stage Synchrotron

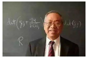
SS: Super Synchrotron

Ion beams have dedicated linac (I-Linac) and RCS (I-RCS)

Project status

- CEPC is now the key project at IHEP
  - SPPC modestly behind CEPC, as a long-term plan
- Modest budget is coming from: MOST (2016, 2018, national key research program) , Beijing Municipal Government (advanced accelerator technology development platform, shared with HEPS), CAS (pioneering projects) and NSFC (research centers, may need to wait for longer time)
- Study team steadily building-up
- International workshop on CEPC on November 6-8
- Very interesting: national debate (also with international players) on if China should build super colliders since last year, triggered by Nobel Laureate C.N. Yang's opposition on CEPC-SPPC





S.T. Yau
C.N. Yang
Y.F. Wang

motivations

The novel collimation method

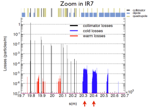
- Single diffractive scattering

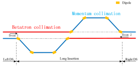
$$P_1 = P_0 \cdot \frac{\sqrt{E_1}\cdot\ln(0.3\cdot E_1)}{\sqrt{E_0}\cdot\ln(0.3\cdot E_0)} \quad \text{With } E_1 > E_0$$

Loss from 7 TeV to 37.5 TeV factor 7

- The particles experiencing single diffractive interactions in the primary collimators will loss in the cold magnets of DS
- In order to deal with these particle losses, we can arrange the transverse and momentum collimation in the same cleaning insertion

From M. Fiascaris

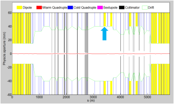


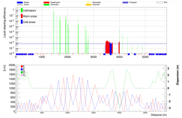


Simulation results

Solution I

- enlarge the aperture of cold dipoles in the momentum collimation, making beam halo through this cold region to impinge on the primary momentum collimators
- Less particle losses in cold dipoles





Outline

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Where we are (1)

- The layout is now 97.75 km long with a new distribution of the functional parts.
- The current design of Experimental Insertion Region (EIR) is consistent with the overall FCC-hh design and its performance goals.
  - The main EIR length is 1500 m against 1400 m. Shorter EIR significantly decreases the operational margins and flexibility.
  - The inner triplet was modified to respect the manufacturing and installation requirements.
  - Preliminary designs of the low luminosity EIR (combined with injection) have been made.
  - Alternative optics with flat beams to operate without crab cavities was provided.
  - The proton and muon cross-talks are not an issue. The power deposited by synchrotron radiation in the experimental beam pipe is negligible.
  - **Reducing L^* even by 10% will have great benefits in terms of field quality tolerances, operational margins and triplet lifetime.**
  - This global dependency will need to be addressed so that the overall performance/cost of the FCC-hh design will be further optimized. The value of L^* is kept at 45 m for the CDR because of the timeline but should be minimized accordingly with detector people.

Where we are (2)

- The injection upstream to the experiment seems to be possible.
- Design of the extraction line: feasible with a 2.5-km-long dump line. The dilution of the beam on the dump was addressed.
- The current design of Experimental Insertion Region (EIR) is consistent with the overall FCC-hh design and its performance goals.
- The collimation studies have well advanced:
  - The aperture model has been refined for FCC-hh. Minor changes need to be addressed again.
  - Major work in benchmarking codes: result discrepancy was enlightened.
  - Some collimators to insert in the dispersion suppressor have been designed.
  - Adding collimators in the DIS reduces the losses: the target inefficiency could be reached.
  - Still work to solve too large power deposition in few collimators
  - First results on off momentum protons were shown.
  - Alternatives like electron lenses or crystal channeling seem promising.
- Arcs were optimized and strong collaboration with magnet group occurs to confirm their feasibility.
  - Alternatives to the arc cells were shown.

Where we are (3)

- Dynamic apertures have gone on
  - Impact of linear imperfections seems small.
  - Impact of Landau octupole important
  - The field quality of the final focusing triplets strongly affects the achievable DA and requires accurate corrections with dedicated coils.
  - Strong reduction of DA with beam-beam effects (but no more zero)
- Single bunch instabilities studies have gone on.
  - Impact of coating on impedance has been evaluated.
  - **Experimental data would be a big asset.**
  - Progress on Landau octupoles.
  - RF quadrupole still under investigation.
  - Electron cloud studies have gone on: 12.5 ns spacing is even worse than 5 ns or 25 ns spacing.

Where we are (4)

- Beam-beam effects were investigated for the different collision schemes.
    - Flat op;cs requires larger beam to beam separation
    - Magnets field quality tolerances should be defined with Beam-beam at design stage to ensure large DA with BB head-on more than with single beam
    - Compensation techniques (octupoles or e- lenses) should be investigated.
- RF ramp and voltage were investigated for nominal and alternative optics.
- 5 ns spacing is challenging with the current injection chain.
- First considerations for the beam instrumentation were presented.
- LHC or scSPS as an injector were investigated further with pros and cons for each solution. Needs on the transfer lines and on magnets were shown.
- Ion operation was addressed.
    - Injection chain should see the ion availability.
    - The major concern is collimation efficiency.
    - Experimental data of interaction of Pb with material would be an advantage.
- SppC status was shown with a new scheme for the collimation with a combined $\beta+\delta$ section.

Did we answer to last year recommendations?

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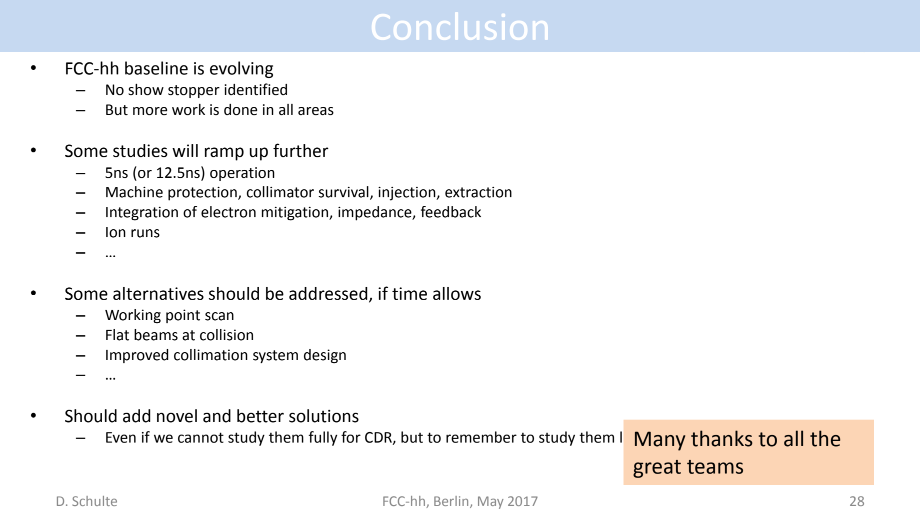
For Next Year…

- Continue with the list…
  - everything is still growing in effort, and must continue — nothing is yet “good enough”
- Begin specification of beam instrumentation and diagnostics systems, especially any optics implications
- Begin studying heavy ion implications
- Address specific questions, such as:
  - how much loss (p/sec/meter) can we tolerate?

MS/DS 15 Apr 16 Northern Illinois University

Conclusion



Conclusion

- FCC-hh baseline is evolving
  - No show stopper identified
  - But more work is done in all areas

- Some studies will ramp up further
  - 5ns (or 12.5ns) operation
  - Machine protection, collimator survival, injection, extraction
  - Integration of electron mitigation, impedance, feedback
  - Ion runs
  - …

- Some alternatives should be addressed, if time allows
  - Working point scan
  - Flat beams at collision
  - Improved collimation system design
  - …

- Should add novel and better solutions
  - Even if we cannot study them fully for CDR, but to remember to study them l

Many thanks to all the great teams

D. Schulte FCC-hh, Berlin, May 2017 28

Thank you for your attention and to all the team for the great work!