DE LA RECHERCHE À L'INDUSTRIE

FCC-hh machine summary

Antoine CHANCE
on behalf of the FCC-hh machine team

CEA/DRF/IRFU/DACM

FCC week 2019
28th June 2019

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

EuroCirCol
A key to New Physics

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FCC-hh machine programme

Tuesday morning

	Lattice integration	Dr Antoine Chance	Ground floor	08:30 - 08:48
09:00	Correction schemes	David Boutin	Ground floor	08:48 - 09:06
	Field Quality at injection for FCC-hh	Barbara Dalena	Ground floor	09:06 - 09:24
	FCC-hh single beam intensity limitations and cures	Oliver Boine-Frankenheim	Ground floor	09:24 - 09:42
	Impedance budget and stability	Sergey Arsenyev	Ground floor	09:42 - 10:00
10:00	Coffee break		Crowne Plaza Brussels Le Palace	10:00 - 10:30
	FCC-hh: Longitudinal beam dynamics and RF requirements	Dr Ivan Karpov	Ground floor	10:30 - 10:45
	Electron cloud	Lotta Mether	Ground floor	10:45 - 11:00
11:00	Status of FCC-hh collimation studies	Roderik Bruce	Ground floor	11:00 - 11:15
	Collimation inefficiency	James Molson	Ground floor	11:15 - 11:30
	Cold losses and deposited power density	Mohammad VARASTEH	Ground floor	11:30 - 11:40
	Thermo-mechanical studies of collimator robustness	Giorgia Gobbi	Ground floor	11:40 - 11:55

Tuesday afternoon

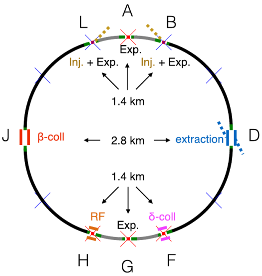
	Optics	Roman Martin	Ground floor	13:30 - 13:48
14:00	Alternative optics	Leon Van Riesen-Haupt	Ground floor	13:48 - 14:06
	Beam-Beam effects	Tatiana Pieloni	Ground floor	14:06 - 14:24
	Dynamic aperture Studies	Emilia Cruz Alaniz	Ground floor	14:24 - 14:42
	Energy deposition in the FCC-hh EIR	Barbara Humann	Ground floor	14:42 - 15:00
	Synchrotron radiation backgrounds in the experimental insertion region of the FCC-hh	Manuela Boscolo	Ground floor	16:30 - 16:45
	Low luminosity interaction regions	Michael Hofer	Ground floor	16:45 - 17:00
17:00	Injector Design	Jan Borburgh	Ground floor	17:00 - 17:15
	Injection and extraction insertions	Agnieszka Chmielinska	Ground floor	17:15 - 17:30
	Ion option for FCC-hh	Michaela Schaumann	Ground floor	17:30 - 17:45
	FCC-hh heavy-ion collimation	Andrey Abramov	Ground floor	17:45 - 17:55

Wednesday morning

	Study on the beam induced vacuum effects in the FCC-hh beam vacuum chamber	Ignasi Bellafont	Ground floor	08:30 - 08:50
09:00	Material properties of relevance to cryogenic vacuum systems	Luisa Spallino	Ground floor	08:50 - 09:10
	R and PY from candidate materials for the FCC-hh Vacuum system.	Roberto Cimino	Ground floor	09:10 - 09:30
	Photo desorption studies at the WINDY set-up at LNF	Marco Angelucci	Ground floor	09:30 - 09:50
10:00	Coffee break		Crowne Plaza Brussels Le Palace	10:00 - 10:30
	Evaluation of LASER ablated surface engineering of copper and stainless steel for particle accelerators	Reza Valizadeh		
11:00	Recent Results on NEG Coating Characterisation	Ruta Sirvinskaite	Ground floor	10:50 - 11:10
	Photodesorption Studies on FCC-hh Beam Screen Prototypes at KARA	Luis Antonio Gonzalez Gomez	Ground floor	11:10 - 11:30
	Update of the design and thermal mechanical study of the FCC-hh beam screen	Marco Morrone	Ground floor	11:30 - 11:50

30 talks.

Layout and parameters

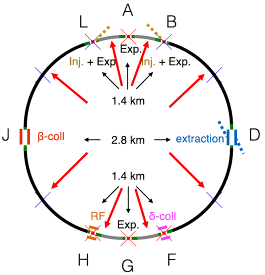


Beam parameters

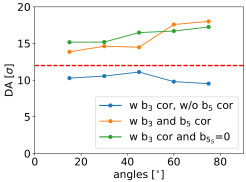
D. Schulte et al.

	LHC	HL-LHC	FCC-hh Initial	FCC-hh Nominal
C.M. Energy [TeV]	14		100	
Injection Energy [TeV]	0.45		3.3	
Peak Luminosity [$10^{34}cm^{-2}s^{-1}$]	1.0	5.0	5	<30
Integrated Luminosity/day [fb^{-1}]	0.47	2.8	2.2	8
Bunch distance Δt [ns]	25		25	
Bunch charge N [10^{11}]	1.15	2.2	1	
Number of bunches	2808		10400	
Norm. emitt. [mm]	3.75	2.5	2.2	
Max ξ for 2 IPs	0.01	0.015	0.01 (0.02)	0.03
IP beta-function β [m]	0.55	0.15	1.1	0.3
IP beam size σ [μm]	~16	~7	6.8	3.5
RMS bunch length σ_z [cm]	7.55		8	
Assumed Turn-around time [h]			5	4
Stored Energy per beam [GJ]	0.392	0.694	8.3	
SR power per ring [MW]	0.0036	0.0073	2.4	

Courtesy: **Dalena**



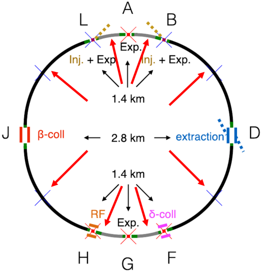
DA results at injection

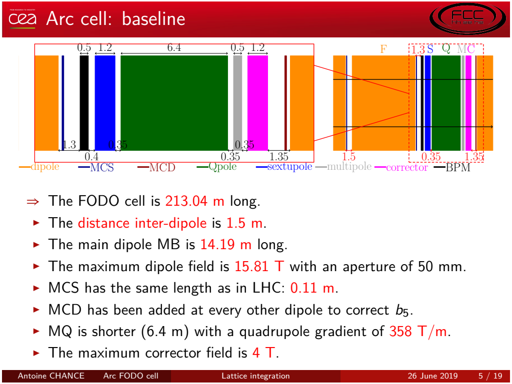


- Sextupole and decapole corrections required to have minimum DA above the target of 12 σ
- Negligible impact of Experimental Insertion Regions (EIR) on DA
- Minimum DA ~ 8.3 σ at injection energy of 1.3 TeV

17/10/2018 B. Dalena, 4th EuroCirCol meeting 9

- Integrated MCD in lattice to correct b_5.
- Larger intra-beam distance: 250 mm.
  - Shorter MQ (smaller b_2 in MB), longer and weaker MB
  - Updated arc lattice.
- Consolidated correction scheme.
- Most of residual errors acceptable.
  - β-beating and dispersion beating are too large but uncorrected.
- Alternative FODO arc cells with 60°.





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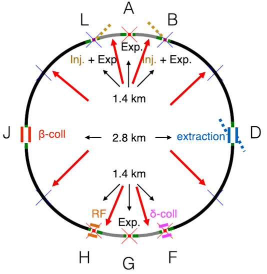
Courtesy: **Boutin**



OVERVIEW OF THE RESULTS

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

- Results satisfactory except for beta-beating
- Some DIS and all insertion correctors are not included into the results
- Beta-beating and dispersion beating need further investigation

D. BOUTIN, CORRECTION SCHEMES, 25 JUNE 2019 | PAGE 14

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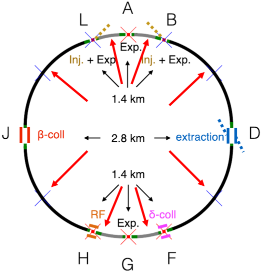
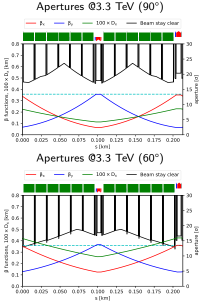


Phase advance of 60 degrees



$n_1 = 16.9 \rightarrow n_1 = 12.9$ below the target!

Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	97.75
β^*	m	0.3
L^*	m	40
α	10^{-4}	2.068
γ_{tr}	-	69.54
Q_x coll	-	78.31
Q_y coll	-	75.32
Q_x inj	-	78.28
Q_y inj	-	75.31
Q'_x	-	2
Q'_y	-	2
MB field	T	15.44
MQ gradient	T/m	360
MS gradient	T/m^2	3215

Antoine CHANCE Alternatives Lattice integration 26 June 2019 18 / 19

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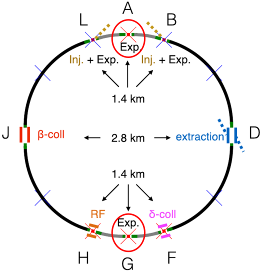
Courtesy: **Martin**



Main IR Optics: Energy deposition in triplet

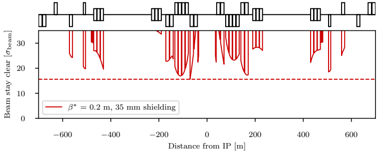
- Triplet magnets are exposed to high levels of radiation from **collision debris**
- Large apertures necessary to house thick shielding inside

See talk by B. Humann, this session

Thick shielding option now default:

- 35 mm of INERMET180 (Tungsten)
- Aperture large enought to accomodate $\beta^* = 0.2$ m

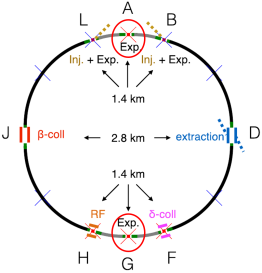
Can reach β^* beyond Ultimate / have comfortable margins

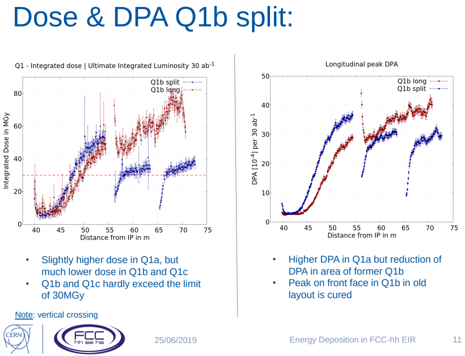


R. Martin | FCC-hh interaction region optics | 10 / 1

- Updated optics.
- Margins on beam-stay clear (up to $\beta^* = 0.2$ m.
- Proposal to split Q1b to reduce peak energy deposition.
- Critical deposition in Q7: collimator to optimize.
- SR radiation is negligible.
- Linear correction scheme updated.
- Non linear correctors are mandatory for DA.
- Alternative triplet exists (same Qpoles).
- Flat optics (no crab cavities).

Courtesy: **Humann**





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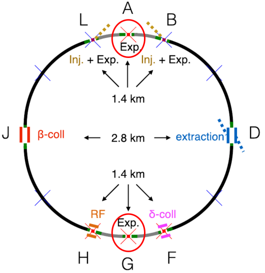
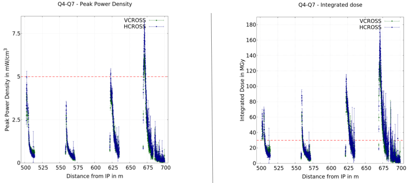


Peak Power Density & Integrated Dose



- Peak power density mostly below 5mW/cm³, except in Q7a (not higher than 8mW/cm³)
- Peak always at front face of the magnets

- Limit of 30MGy always exceeded
- Shift of critical value, due to change of insulator material?
- Further split of Q7 to reduce integrated dose? Shieling in Q7?

Critical situation in Q7: change half gap or position of collimator

25/06/2019 Energy Deposition in FCC-hh EIR 16

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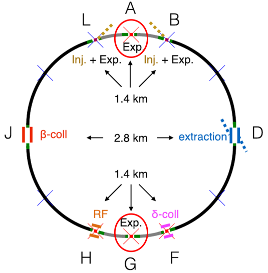
Courtesy: **Boscolo**



SR that reaches the experimental area

- MDISim used to produce geometry and magnetic field description
- SR simulation with GEANT4 from -700 m from IP, Gaussian proton beam

Lattice v9	half crossing angle	Power (TAS) [W]	Power(Be) [W]	Nγ(Be) [10^9]	Em(Be) [keV]
Initial	No	9	1	1	0.2
	yes, 52μrad	27	1.2	2	0.2
Nominal	No	9	1	1	0.2
	yes, 100μrad	47	13	16	0.2

- Slight increase of SR with the nominal crossing angle, due to the magnets that are switched on to produce it.

EuroCirCol M. Boscolo, FCCWEEK2019, 25 June 2019

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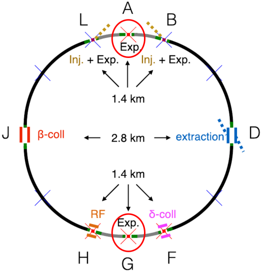
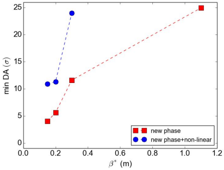
Courtesy: **Cruz**



Results - Different β*

- Explore different options of β* for the baseline design (β*=0.15, 0.2, 0.3, 1.1 m)
  R. Martin/Overview of the IR



- β*=1.1 m ok even w/o non-linear corr
- Increase of 5-10σ for other cases
- Non-linear correctors crucial for acceptable DA for cases β*=0.15 and 0.2.
- Final results w/non-linear correctors:
  - **DA > 20σ** for β*=0.3 and 1.1 m
  - **DA > 10σ** for β*=0.15 and 0.2m

E. Cruz-Alaniz FCC Week 2019 35

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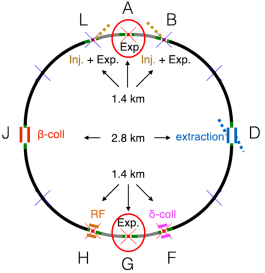
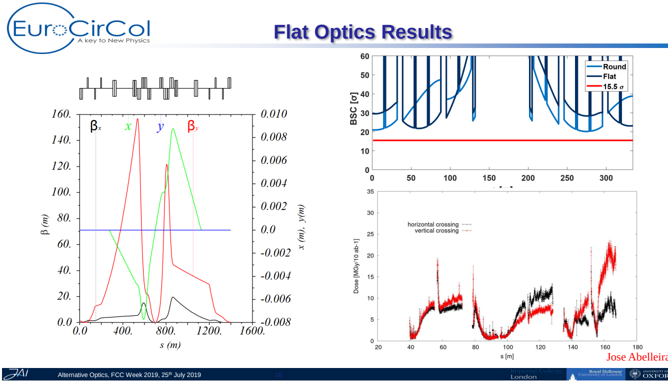
High $\mathscr{L}$ Experimental insertion

Courtesy: **van Riesen-Haupt**





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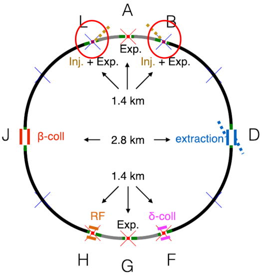
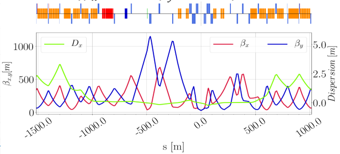
Courtesy: **Hofer**



Injection optics

- For optimal machine protection, some constraints on injection optics apply
  - Phase advance between kicker and TDI close to 90 degree, such that miskick translates into additional orbit offset at TDI
  - Small dispersion to reduce kicker aperture and ease of protection device setup
  - Large beam size at the TDI to limit peak energy density on the absorber [1]
- Currently very flat beam at TDI ($\beta_x = 37\ m$, $\beta_y = 932\ m$)
  - Possible issues with collimator alignment [2]
  - Alternative concepts to be looked into in the future



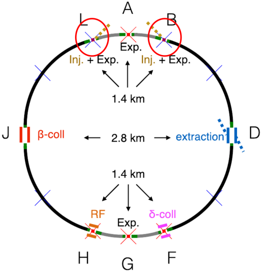
[1] A. Lechner, "FCC-hh protection absorbers and dumps", FCC-Week 2018
[2] E. Renner, "FCC–hh: Transferlines and Injection Insertion", FCC-Week 2018

4

- Updated optics.
- Energy depositions is handled (500 fb^{-1}).
- New shielding design of MKI to reduce impedance.
  - Some solutions to mitigate impedance.
- New generator technologies required and studied
- Loss studies for injection failures are ongoing.

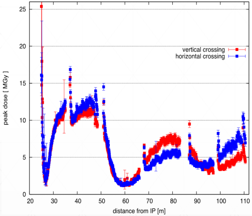
Low $\mathscr{L}$ + injection insertion

Courtesy: **Hofer**



Integrated Dose

- With current baseline radiation limits of 30 MGy, 500 fb^{-1} seem feasible
- Options could be explored to increase triplet lifetime
  - Switch in crossing plane
  - Swap of triplet magnet in a long shutdown



Peak dose for 500 fb^{-1}

FCC Week 19 | Low Luminosity Experimental insertions June 25, 2019 9

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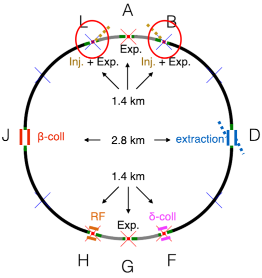
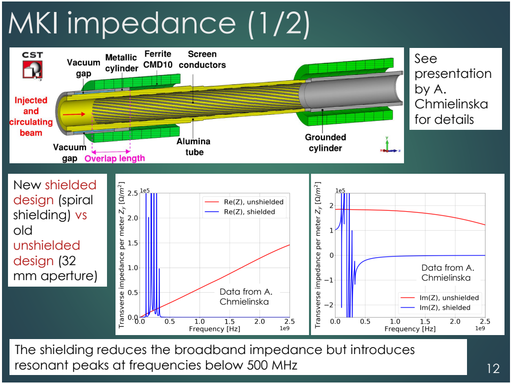
Courtesy: **Arsenyev**





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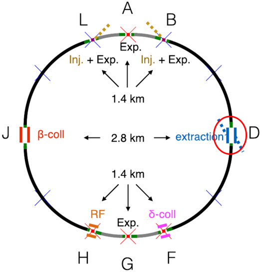
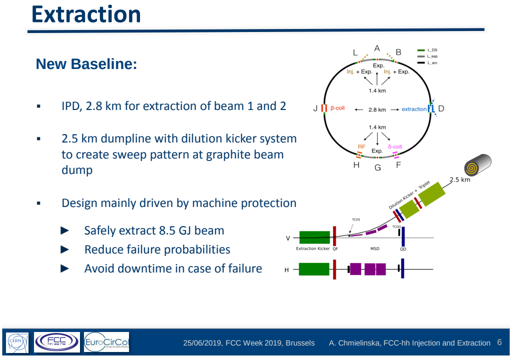
Extraction insertion

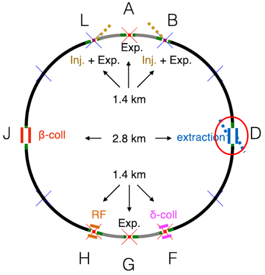
Courtesy: **Chmielinska**

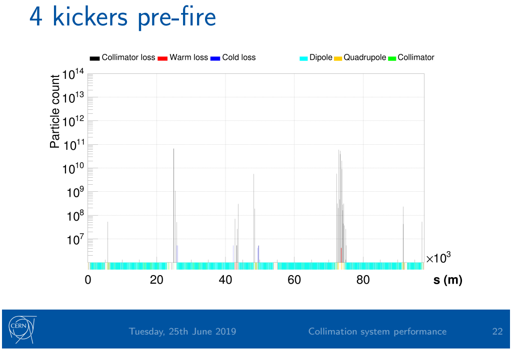




- New proposed baseline.
  - reduced system length, pot. less kick strength required
- Highly segmented extraction kicker system (150 modules).
- Up to 4 kickers can safely pre-fi re without damage to the machine.
- Impact of 1.5 sigma oscillation in case of single erratic acceptable.
- System designed to run with min. 10% less dilution/kick strength
- 4 abort gaps with 1.5 us proposed to reduce machine impact in case of failure

Courtesy: **Molson**





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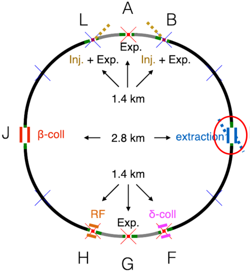

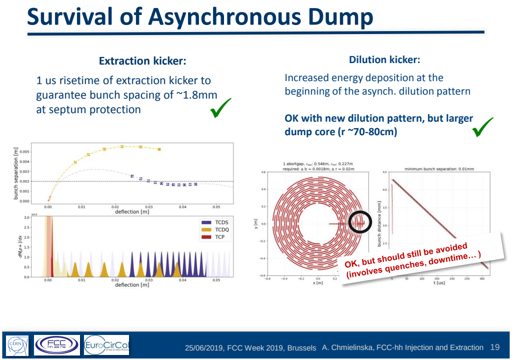

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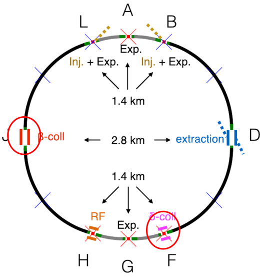
Courtesy: **Bruce**



Present baseline collimation system

- Most loaded collimators (primaries and first secondary) in CFC (carbon-fibre composite) for robustness, other secondaries in molybdenum-graphite with Mo coating for better impedance (taking over the HL-LHC design)

Group	Type	Collimator	Material	Number	Injection ($n\sigma$)	Collision ($n\sigma$)
Betatron cleaning	primary	β TCP	CFC	2	7.6	7.6
	secondary	β TCSG	CFC/MoGr	11	8.8	8.8
	absorber	β TCLA	W	5	12.6	12.6
	dispersion suppressor	β TCLD	W	3	21.0	35.1
Momentum cleaning	primary	δ TCP	CFC	1	10.8	18.7
	secondary	δ TCSG	MoGr	4	13.0	21.7
	absorber	δ TCLA	W	5	14.4	24.1
	dispersion suppressor	δ TCLD	W	4	21.0	35.1
Experiments	tertiary	TCT	W	12	14.0	10.5
	dispersion suppressor	experimental TCLD	W	8	21.0	35.1
Extraction	dump protection (ABT)	TCDQ	CFC	1	9.8	9.8
	absorber	extraction TCLA	W	2	11.8	11.8
	dispersion suppressor	extraction TCLD	W	1	21.0	35.1

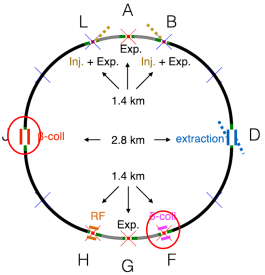
Still to be added in lattice: active physics debris absorbers

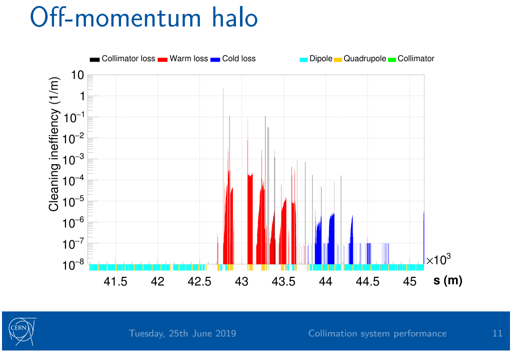
For 2.2 μm emittance

R. Bruce, 2019.06.25 10

- Updated optics of momentum collimation insertion (larger dispersion) and DIS (reduction of peaks).
- Updated collimator lists.
- Cleaning at injection is acceptable (also in energy collimation section).
- May need skew collimator.
- Extended studies in cold parts.
  - TCLD is a must do have in DIS.
- Extended thermo-mechanical studies.
  - Collimation system survives.
  - ⚠ Outgassing from collimators, power loads on warm magnets passive absorbers, material of cooling pipes.

Courtesy: **Molson**





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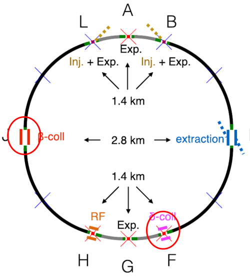
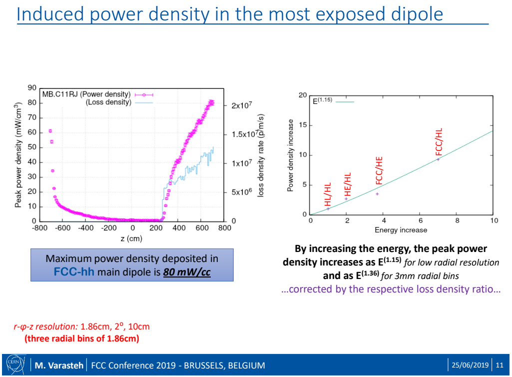
Collimation

Courtesy: **Varasteh**





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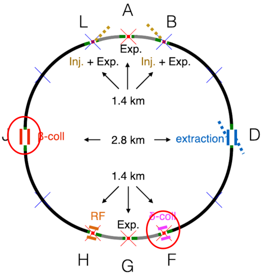
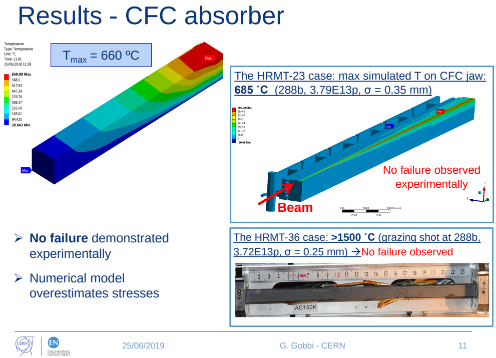
Courtesy: **Gobbi**





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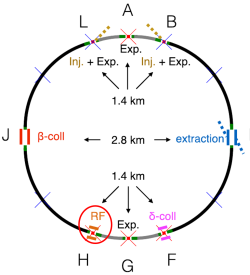
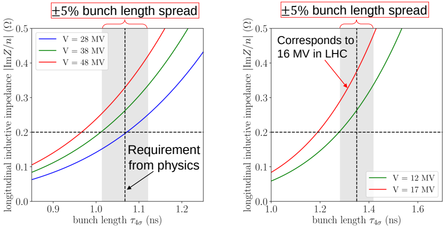
RF system + insertion

Courtesy: **Karpov**



RF voltage at 50 TeV and 3.3 TeV



Thresholds at 50 TeV — Thresholds at 3.3 TeV

→ RF voltage of 38 MV provides stability for average $\tau_{4\sigma} = 1.07$ ns with ±5% bunch length spread at 50 TeV

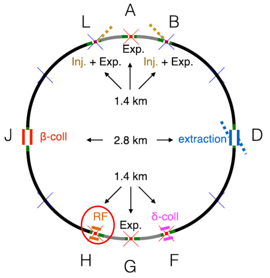
→ For $V_{\mathrm{RF}} = 12$ MV at 3.3 TeV, 1.35 ns bunch length is required for stability

6

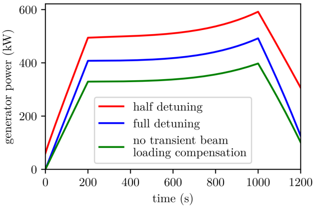
- Updated optics.
- RF power, single-bunch stability and coupled-bunch stability gave an updated of beam and RF parameters.
  - At flat top $V_RF = 38$ MV.
  - At flat bottom $\tau_{4\sigma} = 1.35$ ns.
  - Long. emittance blowup $\propto \sqrt{E}$.
- RF power consumption was calculated for different transient beam loading compensation schemes.
  - Full compensation requires 600 kW peak power during acceleration (against 400 kW without compensation).

RF system + insertion

Courtesy: **Karpov**



Power consumption during cycle*



→ Keeping constant amplitude and phase of the cavity voltage during the FCC-hh cycle would require about 600 kW peak power (half-detuning scheme).
→ The full-detuning scheme, requires about 25% more power compared with the case without transient beam loading compensation.

*I. Karpov, P. Baudrenghien, submitted to PRAB

12

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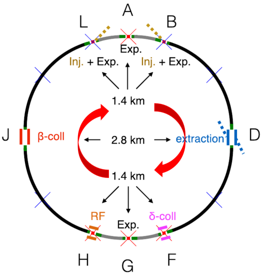
Dynamic aperture + beam-beam

Courtesy: **Tambasco**



Global compensation of long range interactions

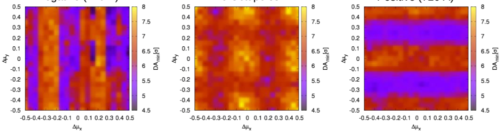
See talks A. Chance, E. Cruz

We choose to have Landau Octupoles powered such that they compensate the BB long-range effects:

- provides larger stability for single beam (see beam stability studies)
- allows for larger Dynamic aperture → beam lifetimes

Full integration in the lattice design (J. Shi et al., CERN-ACC-NOTE-2017-036)

Dynamic Aperture with head-on + Long range interactions

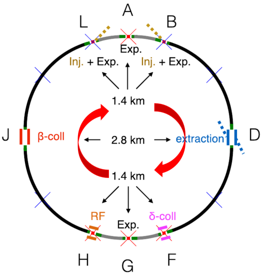


Lattice and Beam-Beam optimized together to enhance at a design stage the natural compensation between effects and allow these flexibility.

11

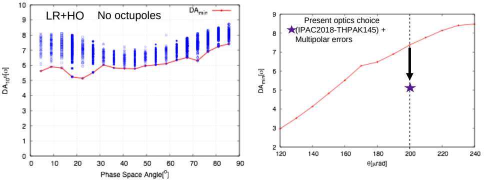
- Negative polarity for octupoles.
- Phase advance PA/PG compatible DA and beam-beam at collision.
- DA>5σ with multipolar errors + beam-beam (Ultimate).
  - Challenging. Needs for new DA optimization paths.
- Large β-beating due to beam-beam.
- Updated DA with new lattice and error table of dipoles.
  - DA below target value when octupoles are used at injection.
  - Still above collimation settings.
  - DA reduced also by RF bucket.

Courtesy: **Tambasco**



DA with multipolar errors

FCC New Lattice L* 40 m 200 μrad at IPA and IPG



- 60 seeds simulation → 60 different machines
- Minimum of DA 5 σ reached ➞ Reduction of 2 σ w.r.t. the case without errors
- **Challenging set-up that needs further studies and newer ways to look at DA because of the very large parameter space → Machine Learning project on-going to automatize the optimization of DA-lifetimes and feedback to design**

9

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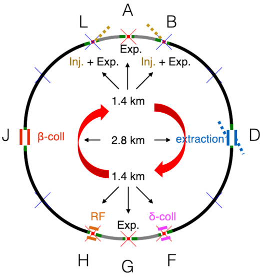
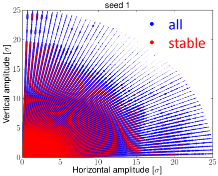
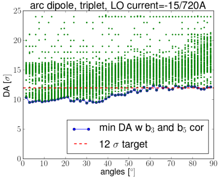
Courtesy: **Dalena**



Effect of Landau Damping octupoles at injection

- Minimum DA below target with LO (like for LHC)
- Minimum above the collimation settings ⇒ is not considered a big issue
- DA is dominated by multipoles random components with sextupole and decapole correction
- DA seeds distribution is non Gaussian





17/10/2018 B. Dalena, 4th EuroCirCol meeting 10

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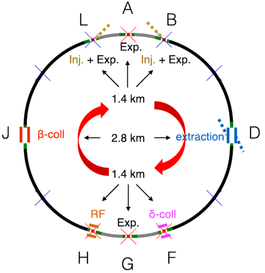
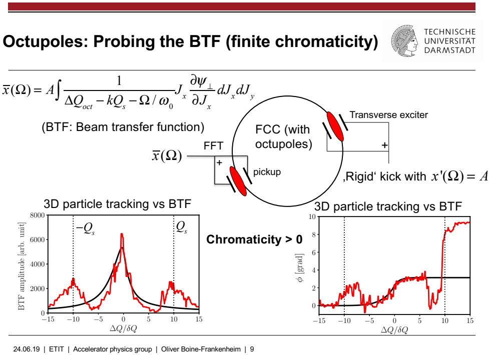
Single and two beam stability

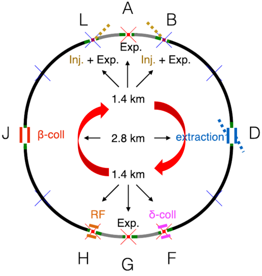
Courtesy:
Boine-Frankenheim





- Landau damping has been addressed:
  - Octupoles, energy scaling and damping of "non-rigid" bunch modes
  - Electron lenses and combinations.
  - Beam Transfer Function simulation of stable beams and time evolution of unstable beams
- Energy scaling of electron cloud induced effects: induced tune shift negligible for FCC-hh
- Fully squeezed optics does not allow margins at end of squeeze.
  - Initial collisions at larger β^*.
  - Collide and Squeeze.

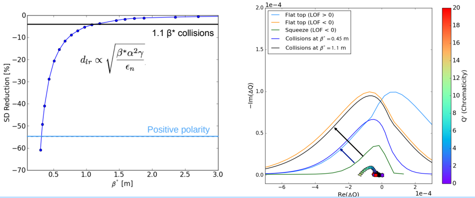
Courtesy: **Tambasco**



Two beam stability: Collide & Squeeze

In order to avoid stability reduction during the squeeze, collisions at larger β* are foreseen (as for the HL-LHC)

Beam-beam wise we cancel long-range beam-beam effects and have only head-on → go to reduced separations when beams transverse emittances have been reduced due to damping



- Stability reduction evaluated w.r.t. the flat top SD with negative octupole polarity (relative difference of the negative real part at the half-height)
- **β*= 1.1 m:** reduction of stability of few percent → **negligible effect**

19

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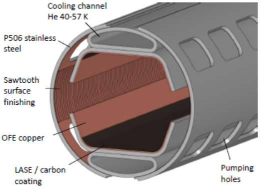
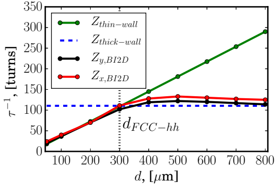
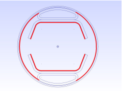


FCC beam screen: copper coating

TECHNISCHE UNIVERSITÄT DARMSTADT





„Optimum“ thickness of the copper layer: 300 μm

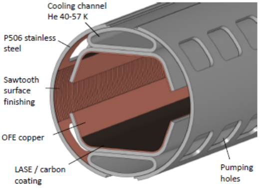
D. Astapovych

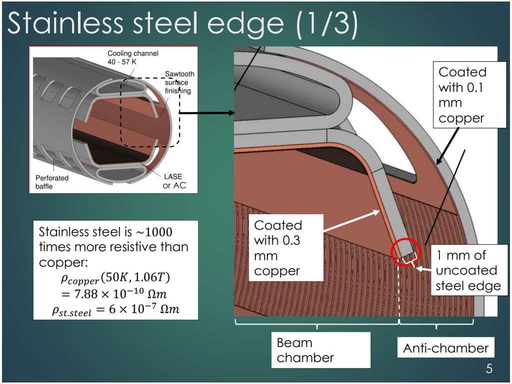
24.06.19 | ETIT | Accelerator physics group | Oliver Boine-Frankenheim | 3

- Mechanical design updated and validated by impedance team.
- Resistive wall impedance to reduce:
  - Cu coating thickness: 0.3 mm.
  - Stainless edge increases impedance.
  - Mitigation proposals: coating the edge or bending, sharp cuts.
- Reduction of SEY (Electron cloud).
  - a-C coating (baseline).
  - Alternatives need other treatments like LASE coating.
- Reduction of photoelectron yield.
  - Saw-tooth sufficiently efficient.
  - Radiation absorbers may be an issue if separation of 5 ns.

Beam screen

Courtesy: **Arsenyev**





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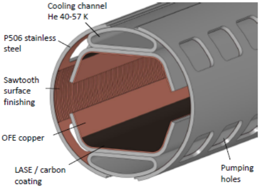
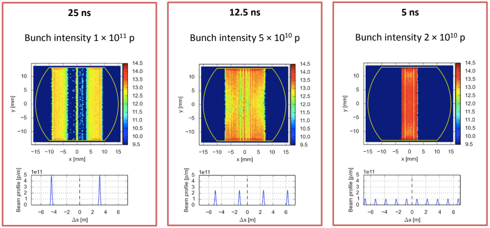
Beam screen

Courtesy: **Mether**

Mitigation scenario for alternative beams

- LASE surface treatments an option for decreasing the SEY beyond a-C
  - Within constraints imposed by the impedance
- Coating or other mitigation scheme to be considered also in drifts





7

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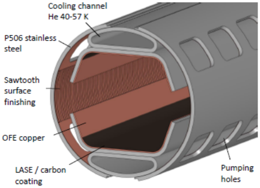

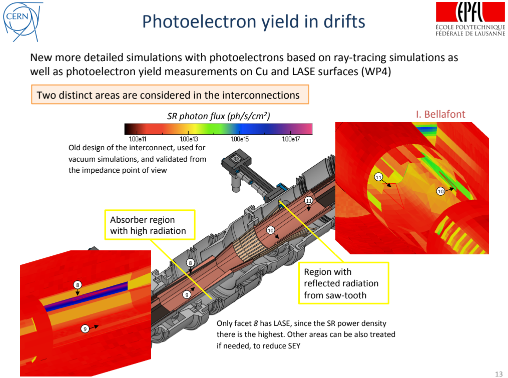

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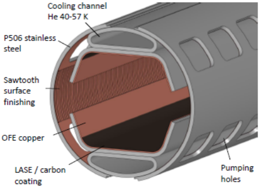
Beam screen: experiments

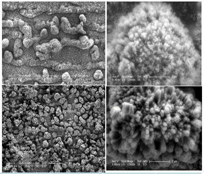
Courtesy: **Valizadeh**

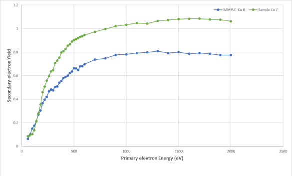


Science & Technology Facilities Council

SEY AND SURFACE RESISTANCE OF LASE TREATED COPPER

Sample	Material	λ (nm)	Average Power (W)	Pulse length (ns)	Frequency (KHz)	Pitch (μm)	Beam size (μm)	Power per pulse (μJ)	Fluence per pulse (Jcm^{-2})	Speed (mms-1)
7	Cu	1063	30	0.15	600	10	15	50	28	40
8	Cu	1063	30	0.15	600	5	15	50	28	40





	Condition 1	Condition 2	Untreated
$R_{S_{RT}}$ [mΩ]	28.516	39.431	25.175
$R_{S_{77K}}$ [mΩ]	14.091	25.335	10.913

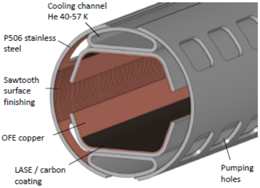
•An increase of 14% for SEY of 1.1 and 60% for SEY of 0.8

24 - 28 June 2019 FCC WEEK 2019 Brussel 21

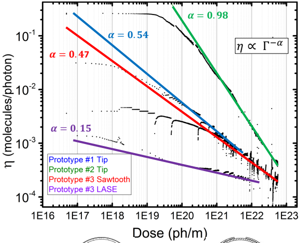
- LASE surface enables small SEY but impact on impedance not very well known. Needs for experiments.
  - Promising results: SEY of 1.1/0.8 with a surface resistance increase by 14%/60%..
  - To be continued.

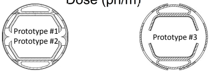
- Photodesorptions measured at KARA.
  - Validation of saw tooth strategy.
  - LASE treatment has a dramatic effect.
  - Experiments at DAFNE very soon
- Discrepancy between SEY models.
  - Needs for validation experiments.

Courtesy: **Gonzalez**



PSD Results





SS			Cu		
α	Surface	[ref]	α	Surface	[ref]
0.99	Unbaked/RT Ec=3.75 KeV	[4]	0.88	Baked/RT Ec=26.3 KeV	[1]
0.54	Baked/RT Ec=4 KeV	[5]	0.61	Unbaked/RT Ec=486 eV	
			0.32	Unbaked/77K Ec=50 eV	
			0.88	Baked/RT Ec=3.75 KeV	

η of Prototype #1 decreases with the same rate as SS at similar Ec under the same surface conditions

η of Prototype #3 (sawtooth) decreases with a rate much lower tha for Cu at the same surface conditions and similar Ec. Closer to Cu at 77K and Ec = 50eV

η of Prototype #3 (LASE) decreases with an extremely low rate.

Photodesorption studies on FCC-hh Beam Screen Prototypes at KARA
FCC Week 2019 June 26th
16
Luis Gonzalez
CERN TE-VSC

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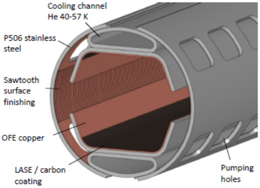
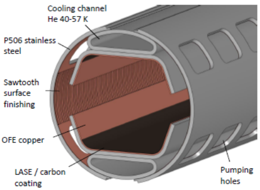
Courtesy: **Angelucci**



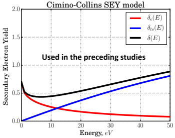
- LASE surface enables small SEY but impact on impedance not very well known. Needs for experiments.
  - Promising results: SEY of 1.1/0.8 with a surface resistance increase by 14%/60%..
  - To be continued.
- Photodesorptions measured at KARA.
  - Validation of saw tooth strategy.
  - LASE treatment has a dramatic effect.
  - Experiments at DAFNE very soon
- Discrepancy between SEY models.
  - Needs for validation experiments.

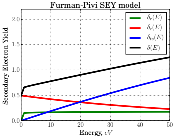
Courtesy: **Mether**



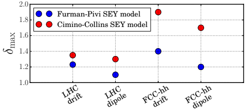
Secondary emission yield model

A comparison of two different SEY models for Cu surfaces was presented in Amsterdam





Work by D. Astapovych, using openECLOUD code



Significant differences in the multipacting thresholds with the two models were found

Possible causes:
- Shape of total SEY curve for given δ_{max}
- Energy spectrum of emitted electrons for rediffused component
- Numerical details e.g. representation of emitted electrons

18

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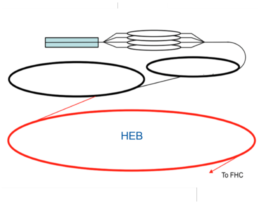
Courtesy: **Borburgh**

Overall performance comparison

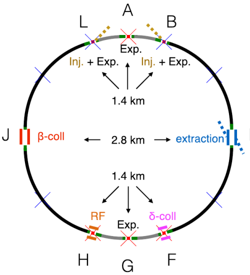


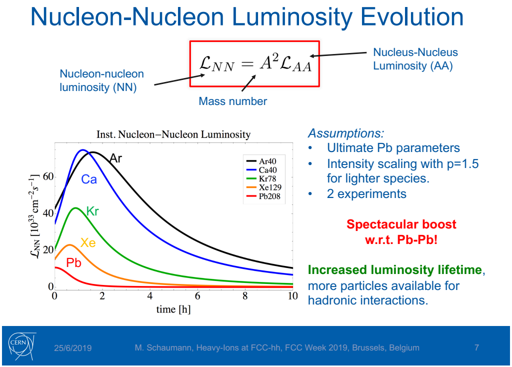
Parameter	Unit	6 T scSPS	reuse LHC	new 4 T LHC	1 T 100 km
Circumference	km	6.9	26.7	26.7	100
Apertures		1	2	1	2
Injection energy	GeV	26	450	450	450
Extraction energy	TeV	1.3	3.3	3.3	3.3
Injection field	T	0.12	0.6	0.6	0.14
Maximum field	T	6	4	4	1.1
Energy/field swing factor		50	7	7	7
Individual dipole length	m	12	14.3	14.3	8
Overall dipole filling factor		0.65	0.66	0.66	0.63
Number of dipoles		372	1232	1232	7856
Number of quads		216	480	480	1250
Total HEB bunches		640	2600	2'600	11'000
Stored HEB energy per beam	MJ	15	167	167	670
HEB filling time	min	0.5	7.5	3.8	30.1
HEB ramp rate	T/s	0.4	0.026	0.08*	0.011*
Total HEB cycle length	minutes	1.1	12	4.9	32
HEB cycles per FCC fill		34	4	8	2
FCC filling time (25 ns)	minutes	37	46	39	32

25 June 2018 FCC Week Brussels 18

- scSPS option (@1.3 TeV) excluded because of dynamic aperture. Large energy swing may be an issue.
- Existing LHC with 5x faster ramp.
  - 3.3 TeV beam (baseline),
  - Longer filling time than desired.
  - High operating cost and complexity, availability concerns.
- 4 T, 27 km, purposed built single aperture HEB alternative:
  - Less complex machine.
  - Slightly faster filling time (39 minutes).
- Costing is needed for real comparison of both options.

Courtesy: **Schaumann**



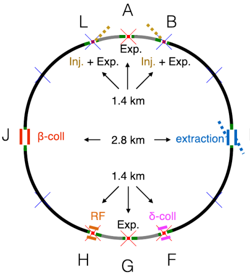


- FCC-hh could be a very high performance heavy-ion collider.
- Lead but also lighter ions are considered.
  - Operationally less challenging
  - potential for higher performance compared to baseline Pb.

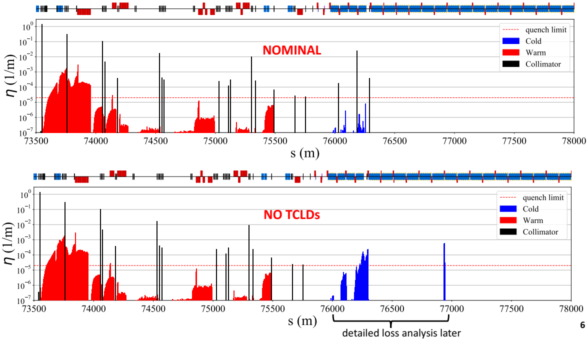
- Collimation system has a good cleaning performance.
- As for FCC-pp, the TCLD is a must do have.

Ion operation

Courtesy: **Abramov**



Betatron cleaning at collision – B1H IRJ



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Summary^2

- A lot of different aspects have been covered: optics, collimation, dynamic aperture, collimation, machine protection, single and two beam stability, beam-beam, experimental set-up ...
- All results are compiled in the long CDR.
- FCC-hh machine design is in good shape.
- Selected outlook:
  - Development of IA algorithms to predict DA.
  - To split inner triplet quadrupole to reduce peak dose.
  - New materials or system design for collimation.
  - Electron lenses or RF quads.
  - Experimental data for surface properties (SEY, impact of LASE treatment on impedance,...).
  - and many other topics.

FCC WEEK 2019

BRUSSELS, BELGIUM
24 - 28 JUNE 2019
Crowne Plaza Brussels
Le Palace

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

WRITING the FUTURE

http://fccweek2019.web.cern.ch/

FCC-hh TDR