FCC-hh Machine Layout and Optics

Daniel Schulte for the FCC-hh team

Rome, April 2016

Unfortunately, Antoine Chance cannot give this presentation

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EuroCirCol

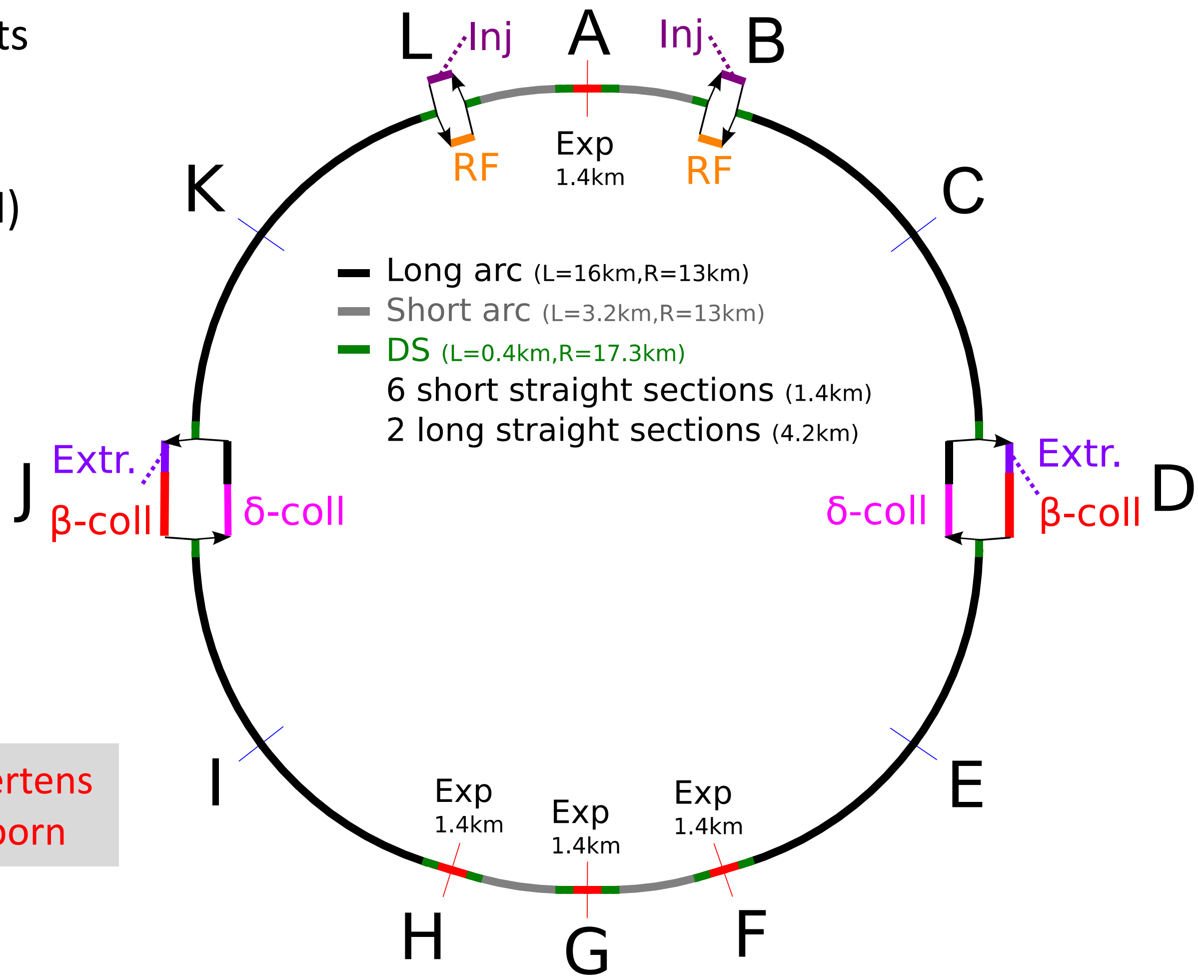
A key to New Physics

FCC-hh Layout

- Two high-luminosity experiments (A and G)
- Two other experiments (F and H)
- Two collimation and extraction insertions
    - Different options
- Two injection insertions with RF

⇒ V. Mertens
⇒ J. Osborn

- Circumference 100km
- Can be integrated into the area
- Can use LHC or SPS as injector
- Managed to defend against kinks
- Has been reviewed successfully



Technology covered by M. Jimenez et al.

Initial Beam Parameters

Baseline parameter document delivered to EU

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

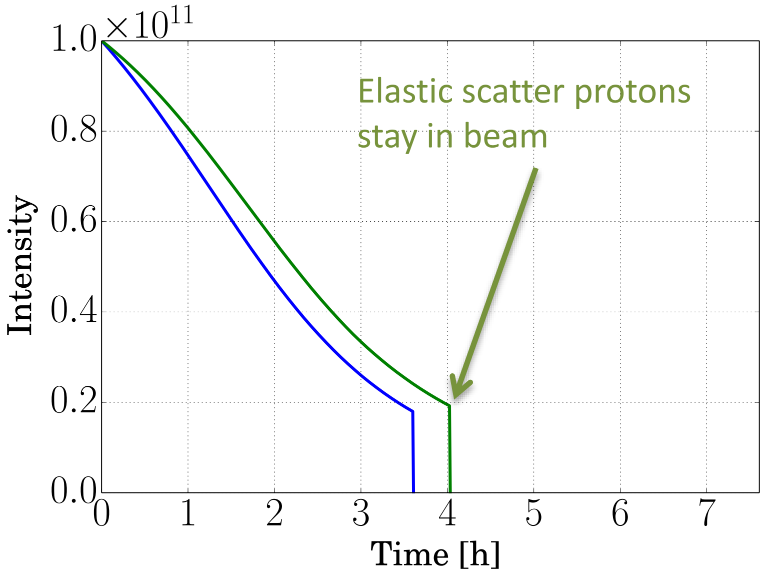
Total $17.5ab^{-1}$

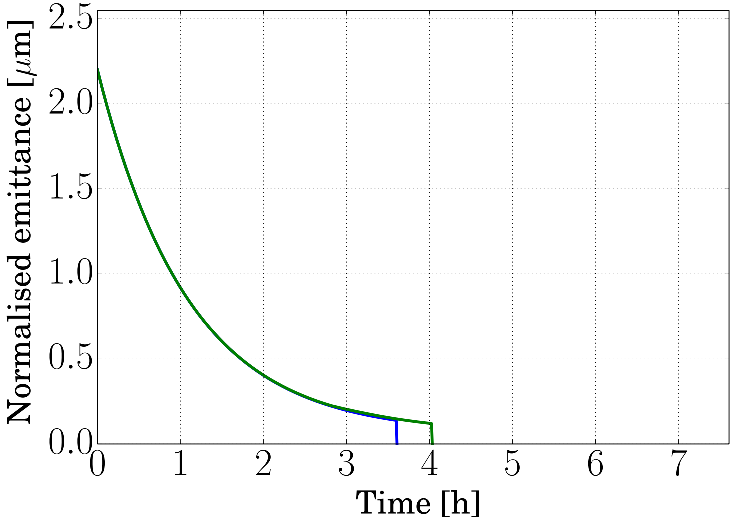
Focus on ultimate parameters

Injection energy 3.3TeV

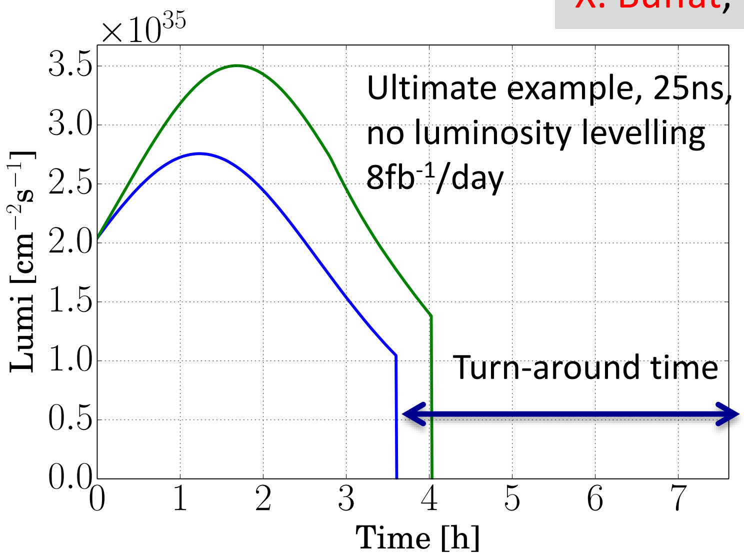
	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function 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

Luminosity Run Example





X. Buffat, D.S..



Example with ultimate parameters shown
⇒ Turn-around time is important

Most elastic scattered protons stay in beam
⇒ Detailed calculations to confirm

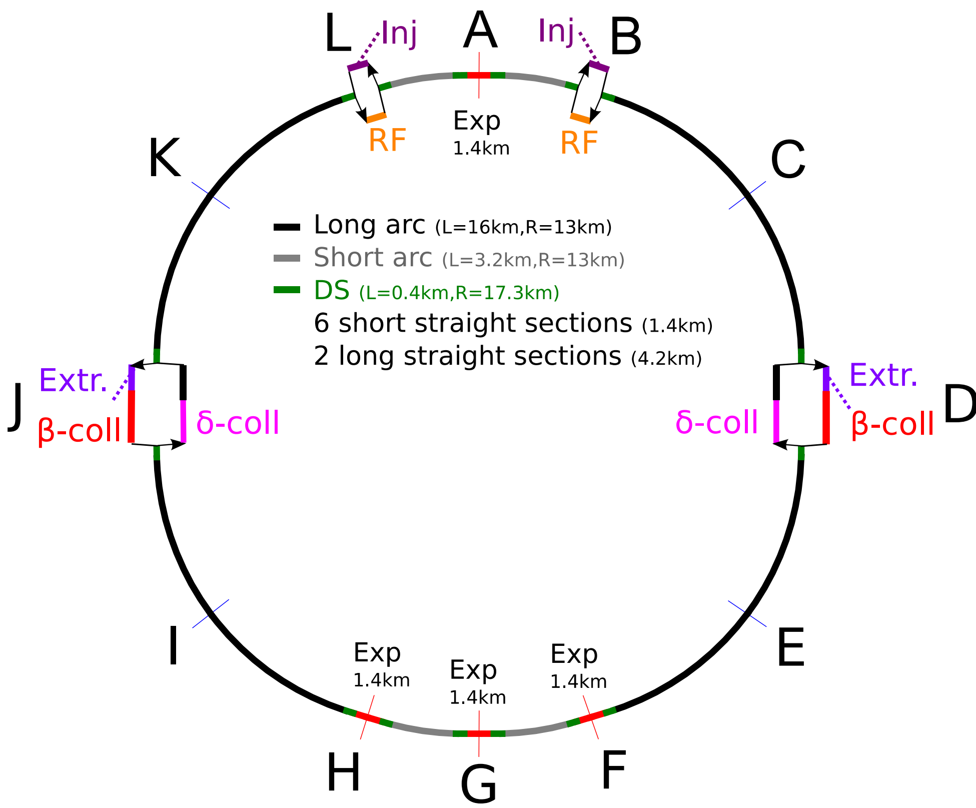
⇒ Different scenarios can be considered
⇒ E.g. are shorter bunch lengths acceptable?

Integrated Lattice

Full integrated lattice exists

- small length issue in A and G
- H and F are simple transport

A. Chance, B. Dalena et al.



Integration required lots of work

- Knobs to set global tune
- Correction of chromaticity
- Mini straights in technical sections
- Correction of spurious dispersion due to crossing in experiments
- …

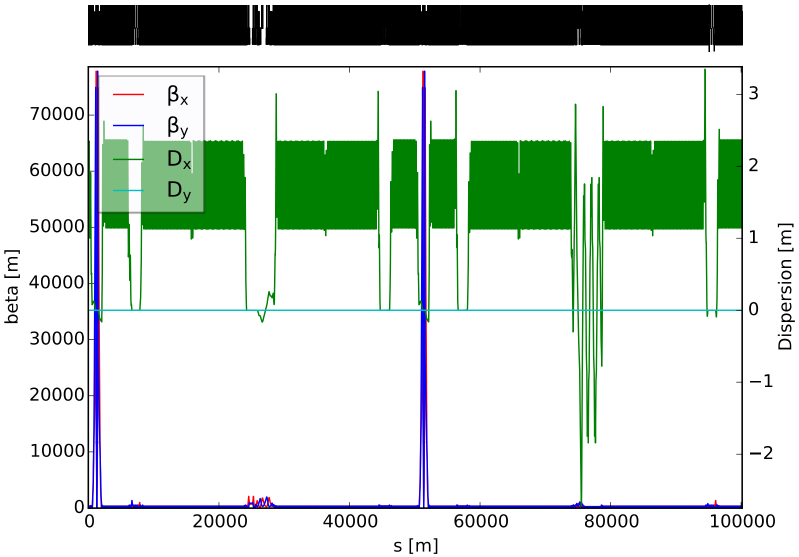
Lattice allows to identify the short-comings and potential for improvement

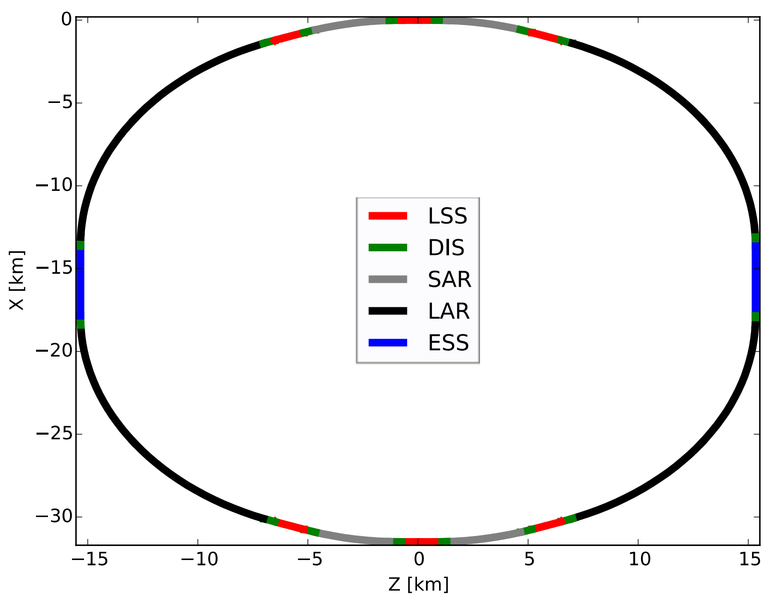
The baseline has started to serve for more detailed studies

- e.g. collimation, dynamic aperture

Integrated Design

A. Chance et al.





Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	100.171
β^*	m	0.3
L^*	m	45
α	10^{-4}	1.008
γ_{tr}	-	99.580
Q_x	-	111.31
Q_y	-	108.32
Q'_x	-	2
Q'_y	-	2
# dipoles MB	-	4616
MB field	T	15.93
# quadrupoles MQ	-	846
Max grad MQ	T/m	370 [a]
# sextupoles MS	-	710
Max grad MS	T/m^2	18670

a. in the arcs

Arc Beam Screen Design

Great progress on beam screen

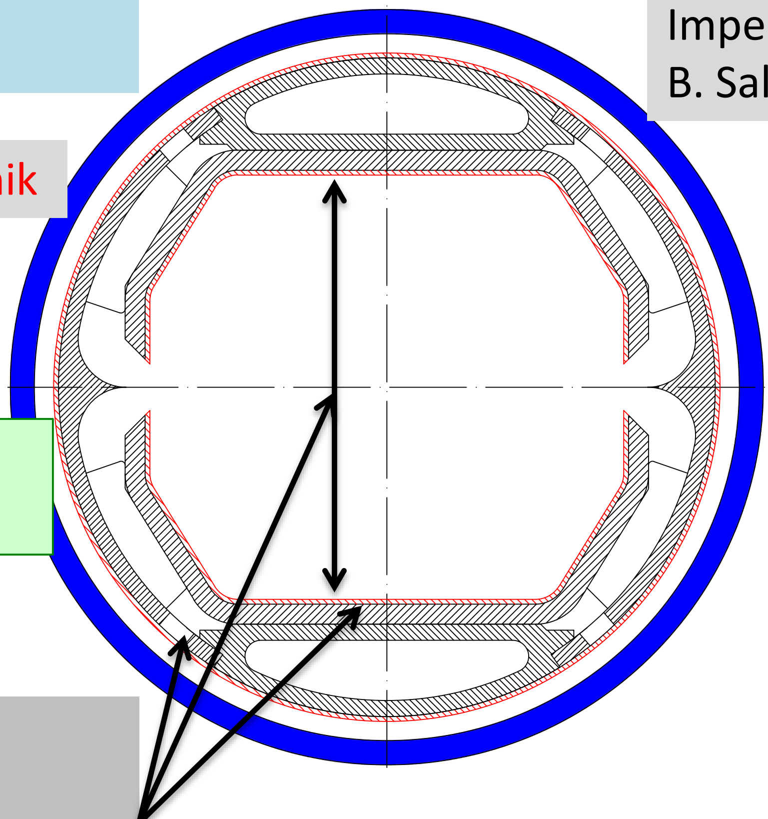
- Essential for arc design
- Specifications from beam physics
- Tests foreseen

F. Perez, C. Garion, R. Kersevan, P Ciggiato et al.

Impedance: O. Boine-Frankenheim, B. Salvant, X. Buffat et al.

Cooling: L. Tavian, C. Kotnik

Feedback: W. Höfle et al.



Octupoles: V. Kornilov et al.

Magnet aperture 50mm
Had been 40mm before

Electron cloud: L. Mether, G. Rumolo, K. Ohmi

Impedance:
Aperture > 26mm
0.3mm copper coating
Pumping holes invisible to beam

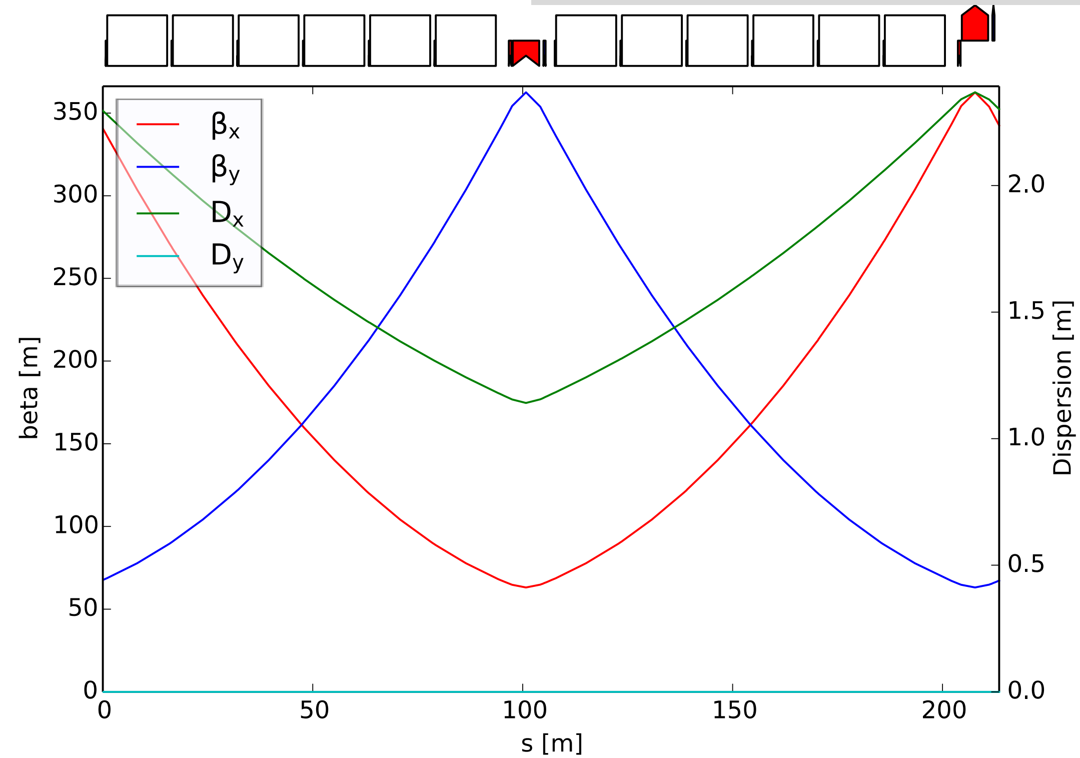
Verify impedance of slit

Alignment of beam to slit has to be studied

Arc Layout

90° FODO cells, L_{cell}=213.89m
- 12 dipoles a 14.3m
- Quadrupoles, sextulpoles, spool pieces, correctors, …
- Dipole field (16-ε) T

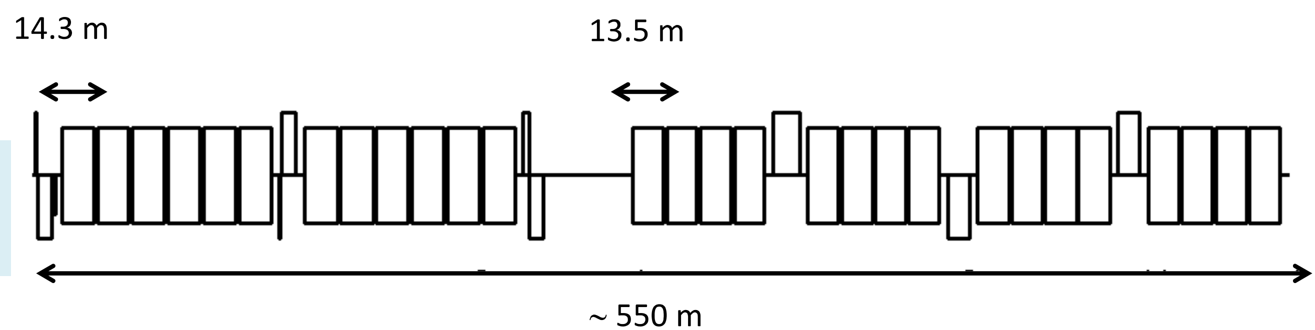
A. Chance, B. Dalena, J. Payet



Iterating with magnet team
- Improved length estimates
- Found sextupoles quite strong due to beam delivery system

⇒ Integrated optics is useful

Dispersion suppressors (end of the arcs) are LHC-style

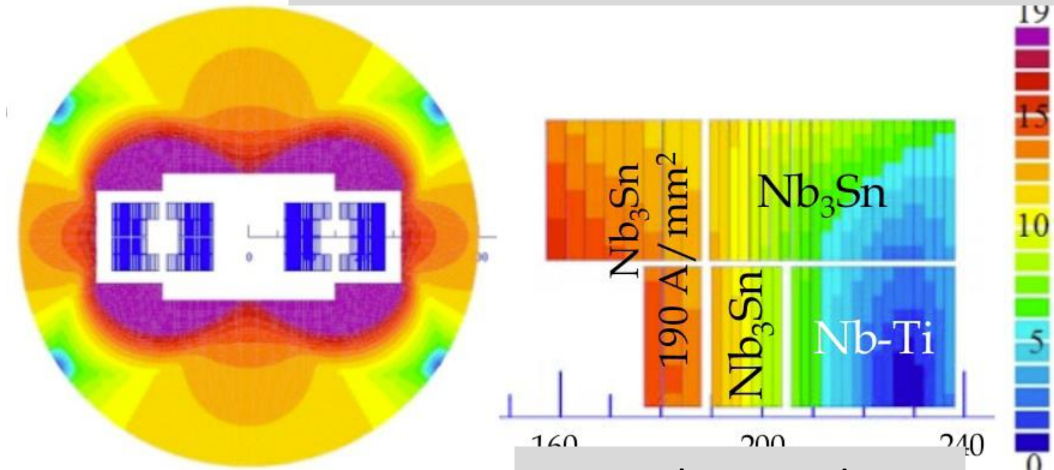


Dynamic Aperture Studies

L. Bottura, D. Tommasini, E. Todesco et al.

Magnet field errors are critical at injection and collision energy

- Systematic errors
- Random errors



Design by E. Todesco

Dynamic aperture studies started

- Needed to solve many code issues
- Closed loop between magnet and beam teams established

Important feedback for magnet design

- E.g. modify magnet for less sextupole error at top energy

D. Boutin

Modelling of misalignments and correction techniques started

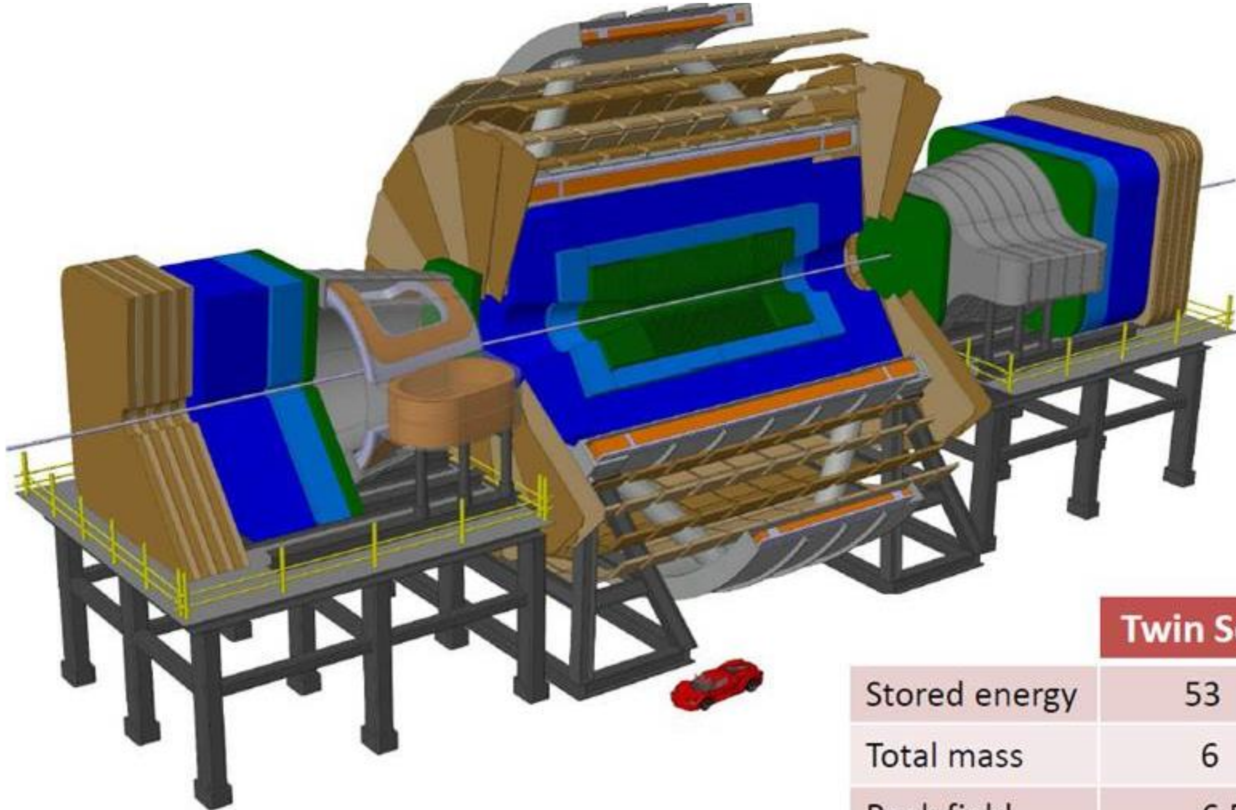
Orbit corrector strength about 2xLHC

Beam: B. Dalena et al.
Magnets: E. Todesco et al.

Current FCC Detector Model

Matthias Mentink, Alexey Dudarev, Helder Filipe Pais Da Silva, Christophe Paul Berriaud, Gabriella Rolando, Rosalinde Pots, Benoit Cure, Andrea Gaddi, Vyacheslav Klyukhin, Hubert Gerwig, Udo Wagner, and Herman ten Kate

H. Ten Kate,
W. Riegler et al.



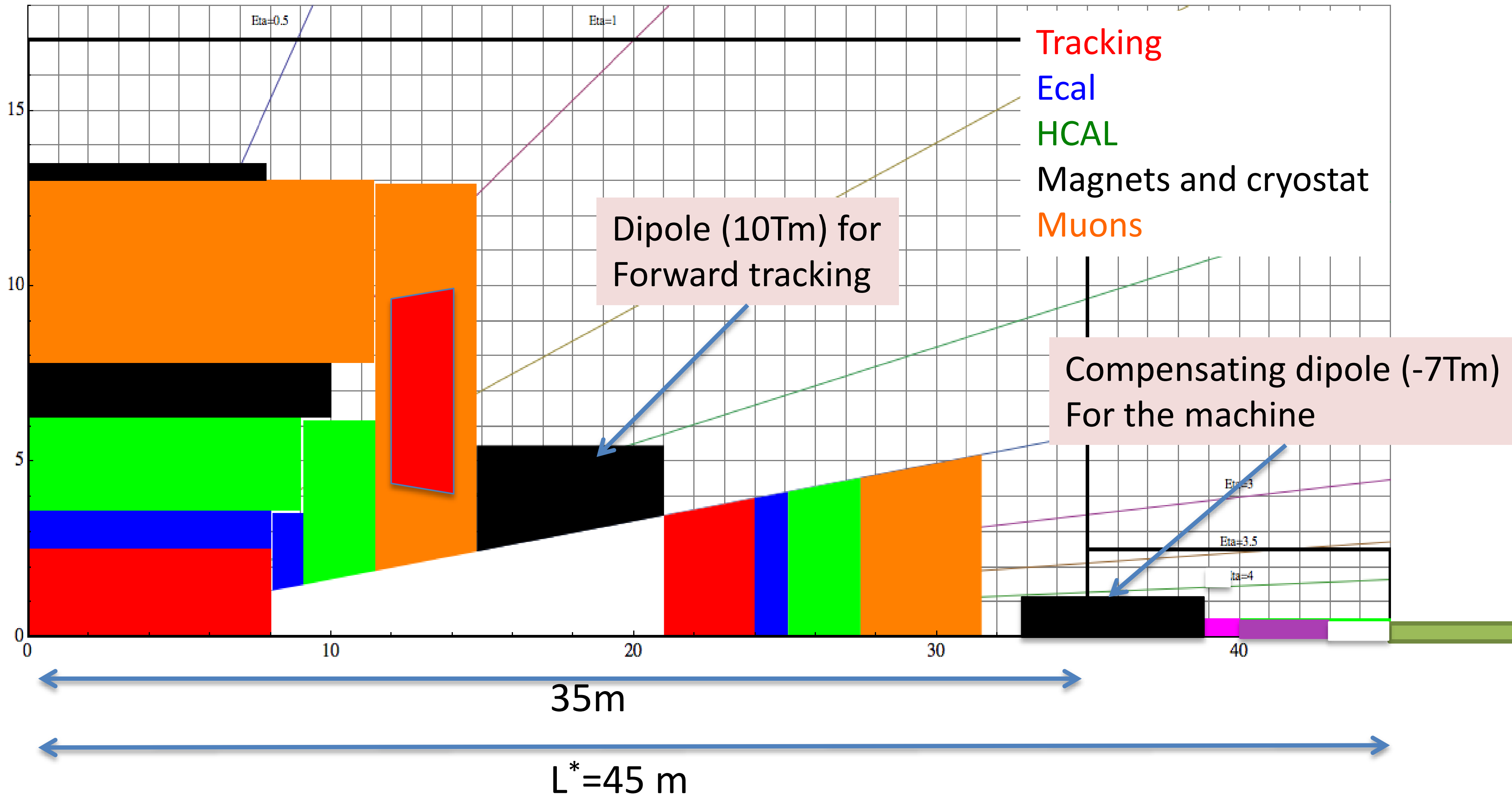
	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

FCC Air core Twin solenoid and Dipoles

State of the art high stress / low mass design.

MDI Layout

⇒ MDI session
A. Seryi, W. Riedler, R . Tomas et al.

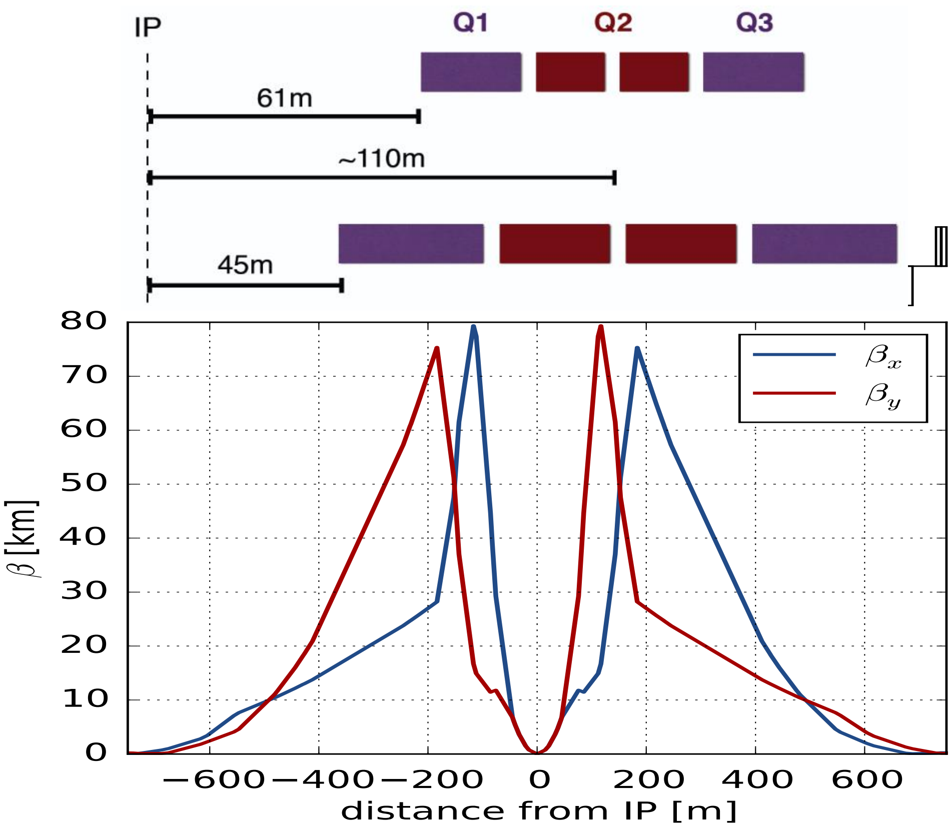


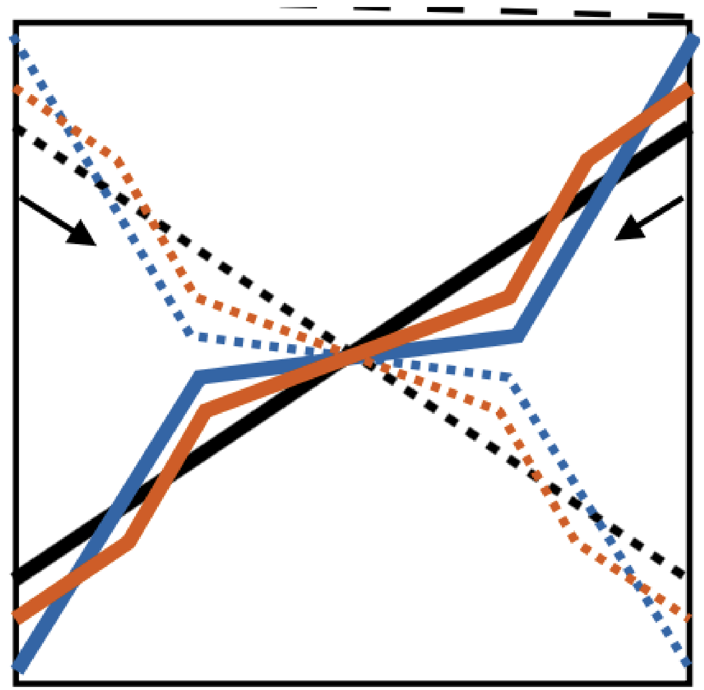
High-luminosity Insertions

New L*=45m and long triplets
Increased aperture from 140mm to 240mm
- can allow more shielding
- or smaller betafunction
- or simplify collimation
- …

A. Seryi, R. Tomas, R. Martin, A. Langner et al.

Detector and machine dipoles change beam separation
- Mixed blessing
- Impacts beam-beam effects
- Larger beam offset in triplets (debris)



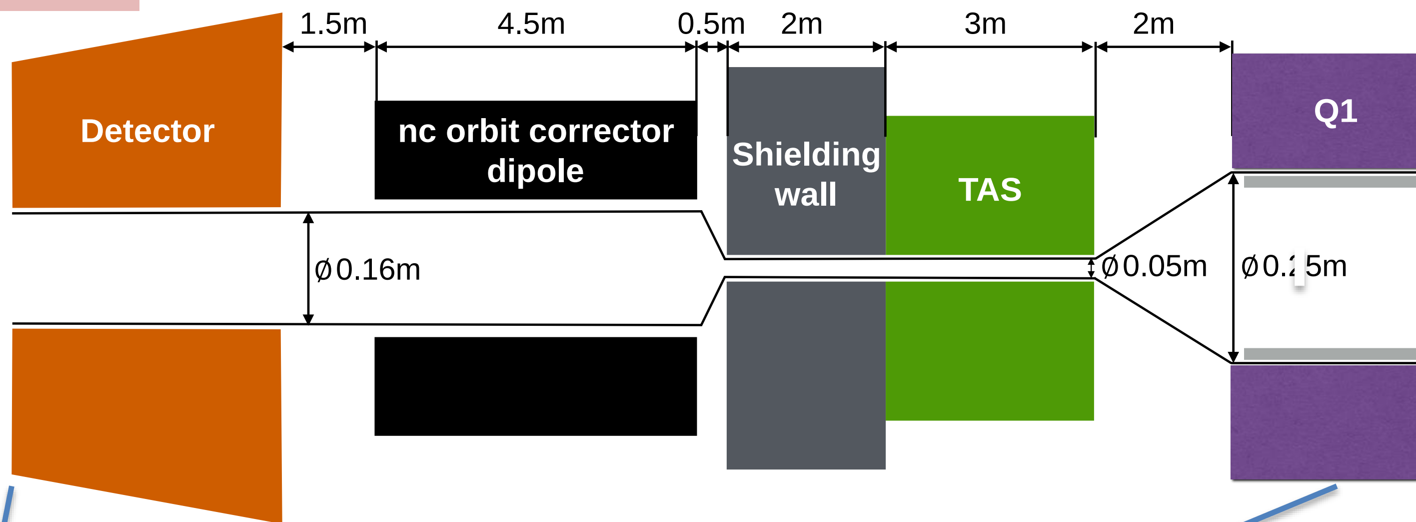


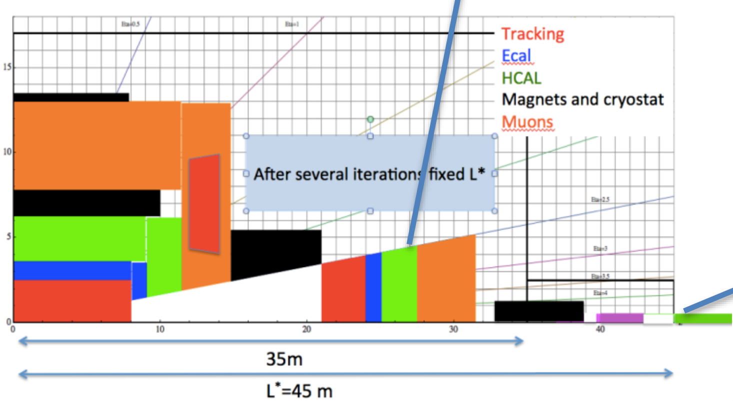
Collision Debris

Power of collision debris 100-500kW per experiment

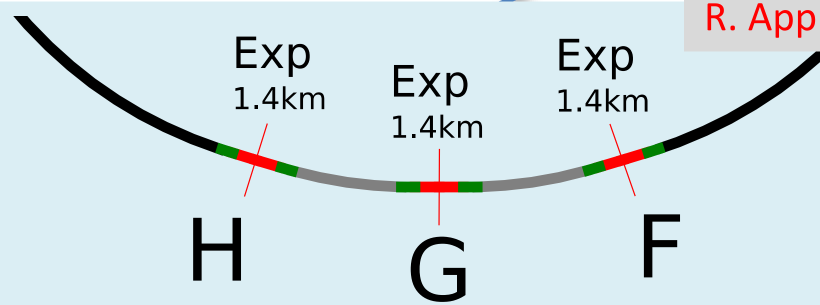
MDI team

Designed to protect detector and magnets





R. Appleby



Studies of impact on next experiment started

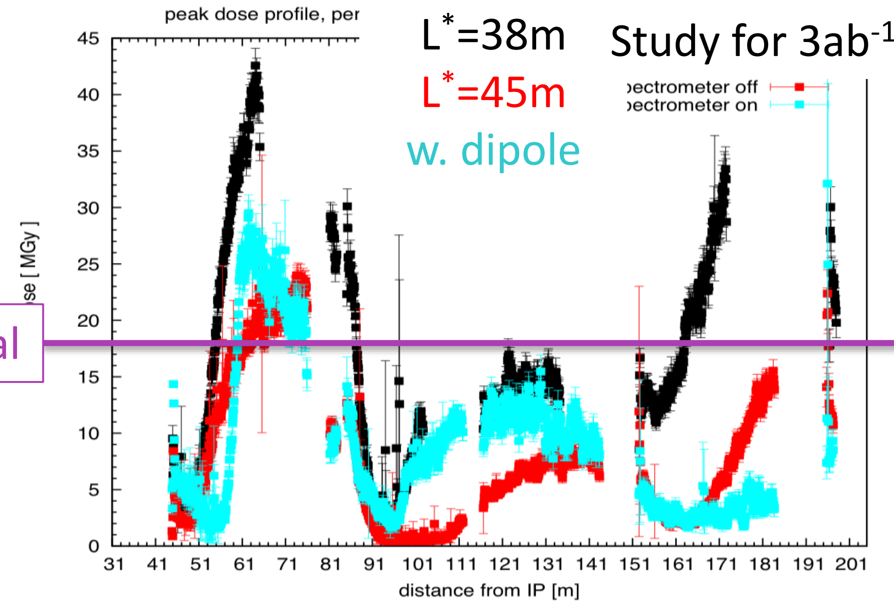
$\Rightarrow$ Careful design needed to avoid losses

Debris in Triplet

Minimum goal: survive 5ab^{-1} (<30MGy)

- Gain almost factor 2 with new design
- Vary crossing scheme to distribute damage helps (S. Fartoukh)
- Meet target w/o dipoles
- Checking with dipoles (jobs running)

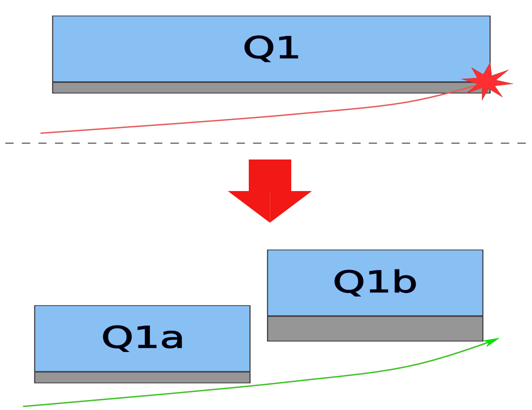
Current goal

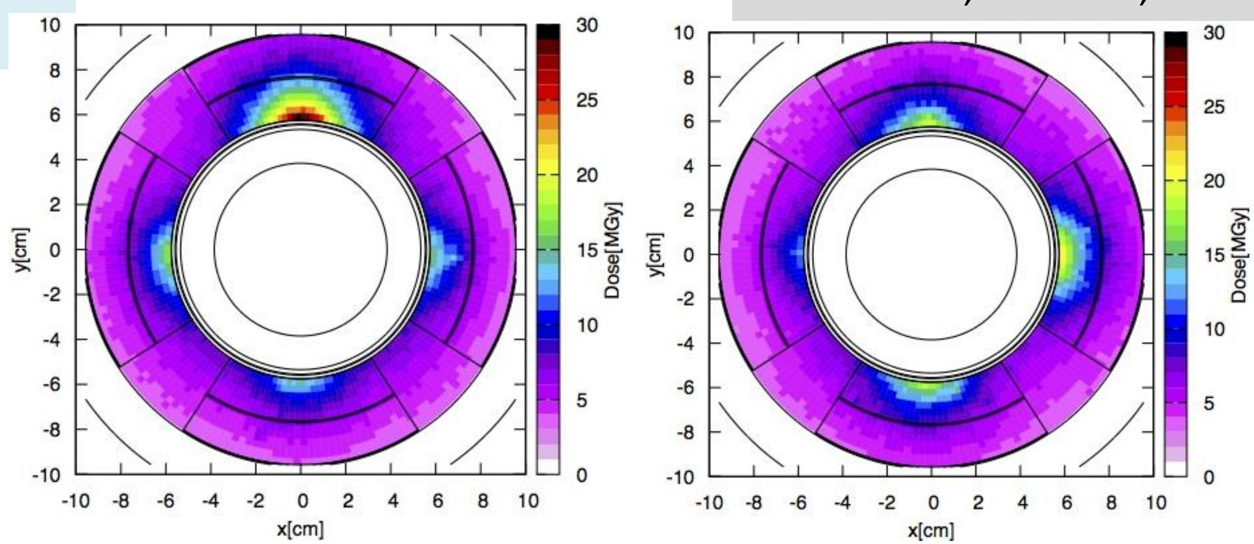


M. I. Besana, F. Cerutti, et al.

Need to (re-)explore

- More shielding
- Improved radiation hardness
- Split magnets





Beam-beam Effects

One experiment should have vertical one horizontal crossing

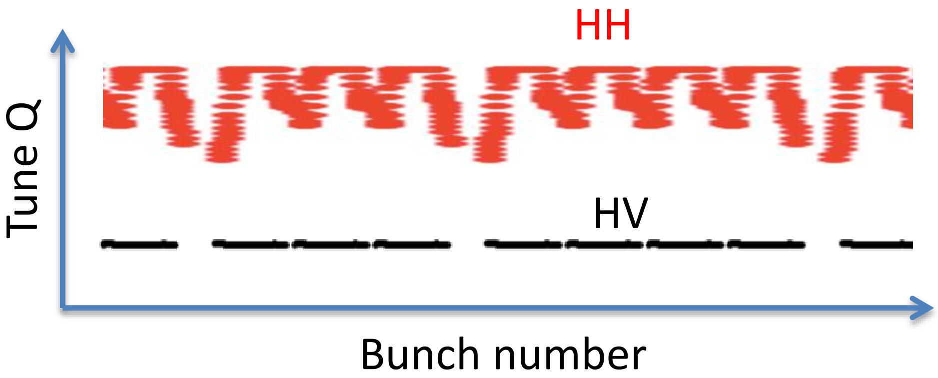
- Minimises spread in beam-beam tuneshift (PACMAN bunches)

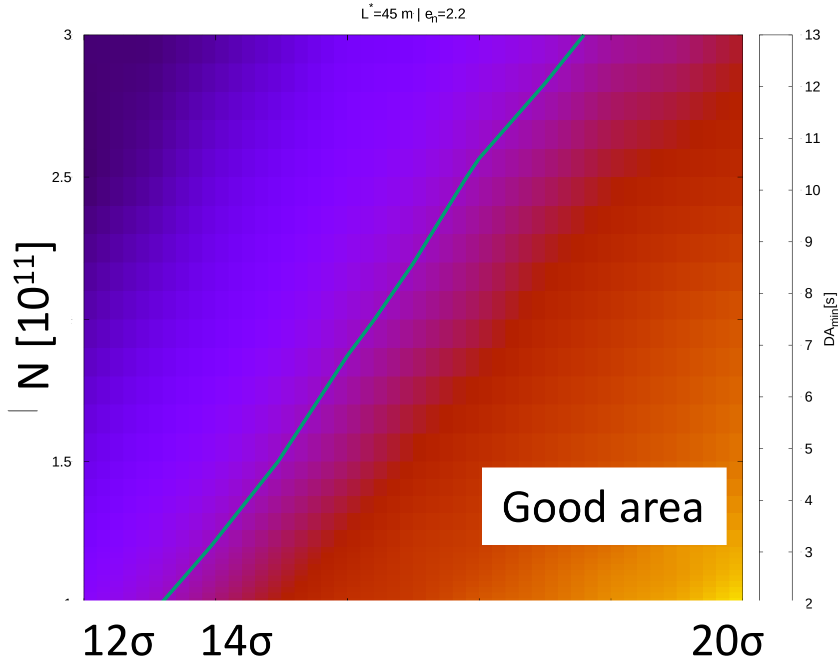
Prefer same configuration in both IPs

- I.e. also a dipole, rotated by 90°

Other options require detailed study

T. Pieloni, J. Barranco Garcia, X. Buffat





Beam-beam simulations for new BDS started

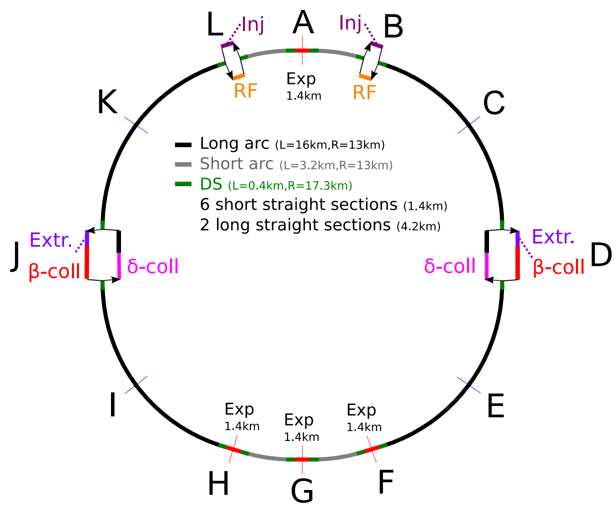
- Dynamic aperture seems OK
- Alternative scenarios, e.g. flat beams …

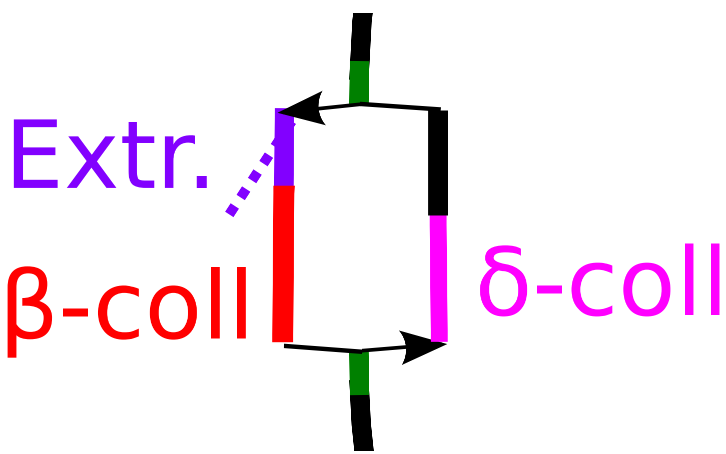
Emittance growth needs to be studied

- Interplay with noise critical

Extended Straight Sections

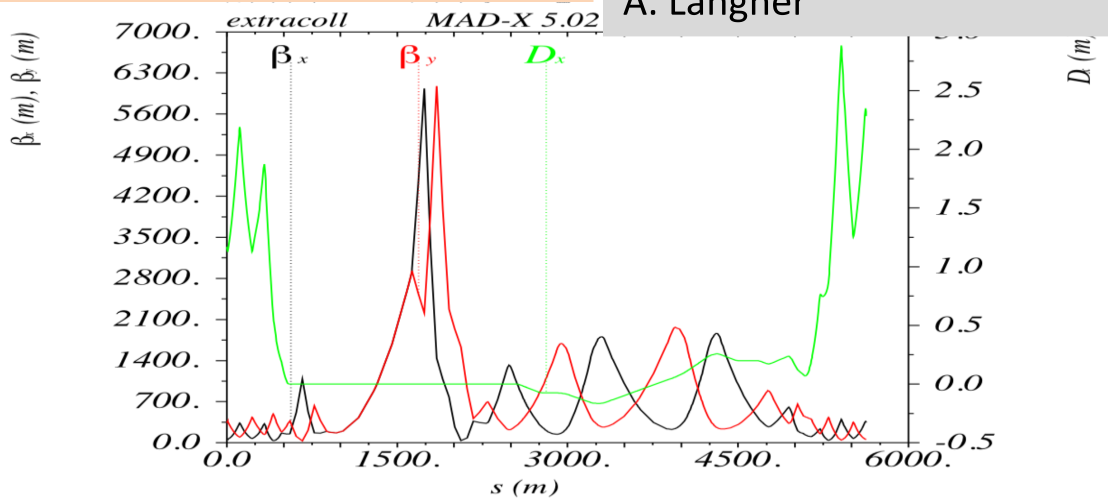
First optics designs exist for collimation and extraction





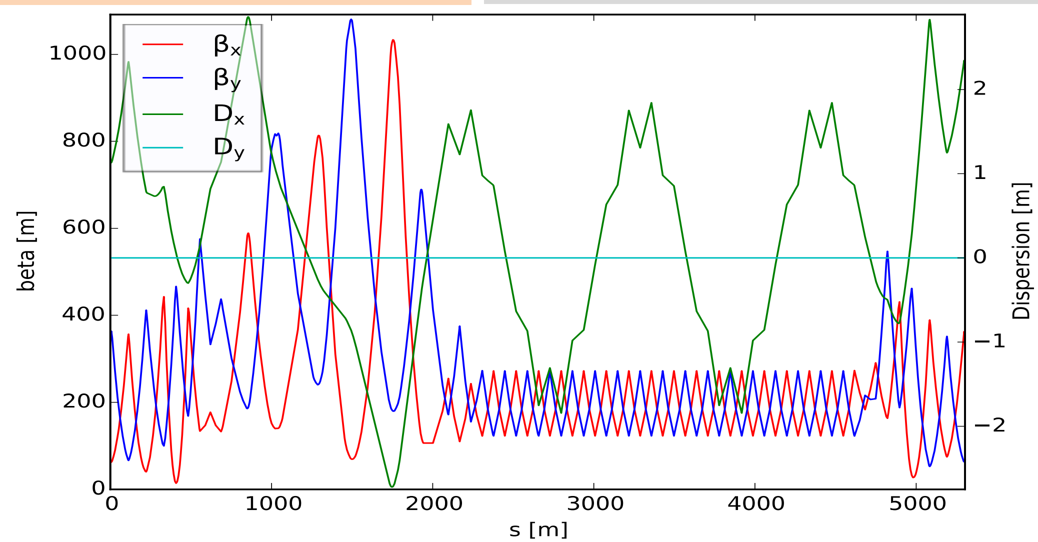
Betatron collimation/extraction

R. Tomas, F. Burkart et al., A. Langner



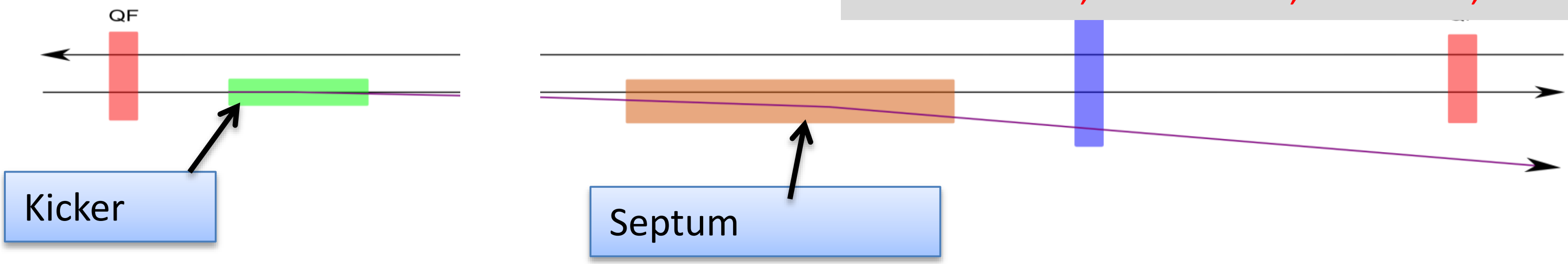
Momentum collimation

J. Molson, B. Dalena, A. Chance



Extraction

W. Bartmann, B. Goddard, F. Burkart, A. Lechner, …



Th. Kramer, M. Barnes et al.

M Atanasov, D. Barna, E. Fisher et al.

Normally fire kickers in the abort gap of the beam

But kicker can fire on its own

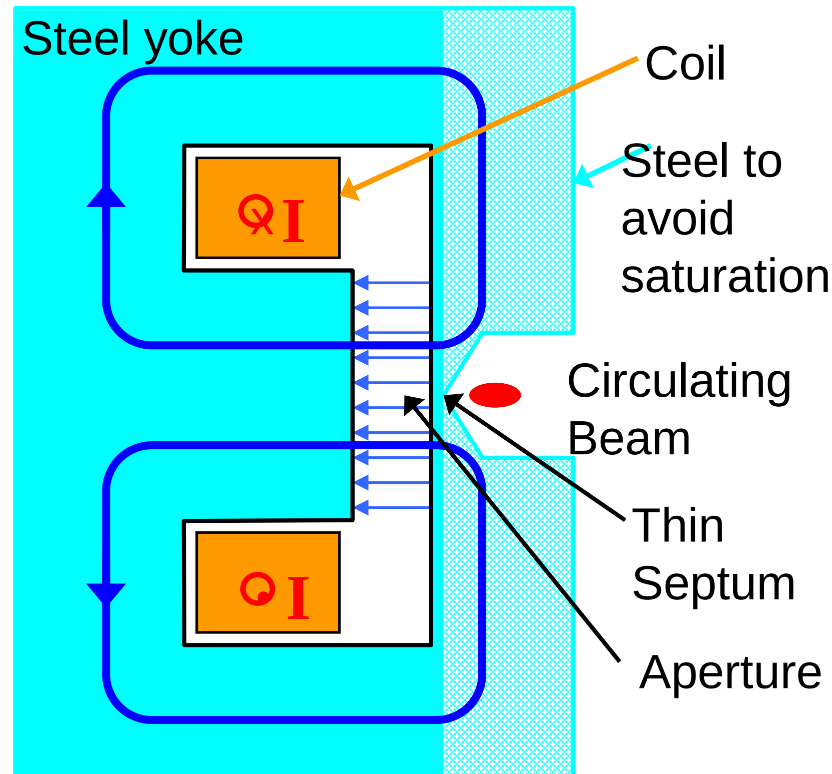
⇒ In LHC fire all and sweep beam out

⇒ Does the extraction line survive?

⇒ Can we segment kicker such that we can leave beam circulating until abort gap?

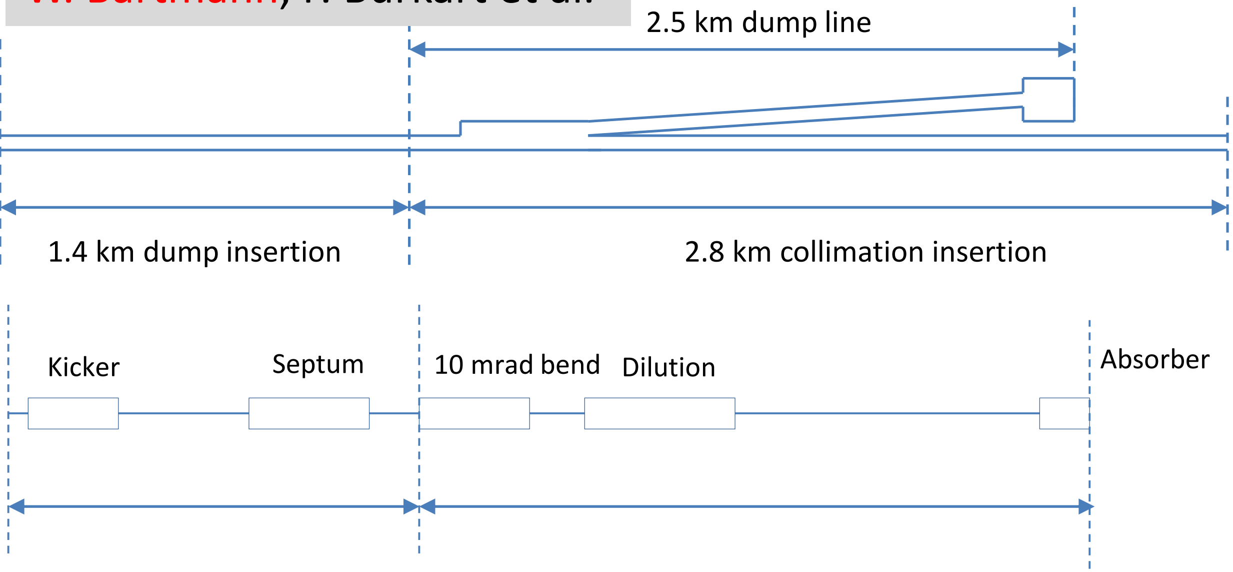
⇒ Is this safe?

B. Goddard

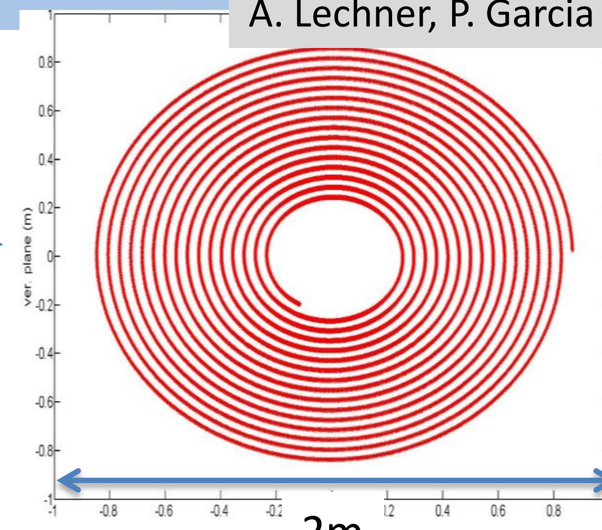


Beam Dump

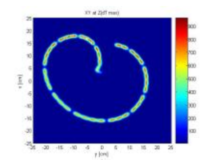
W. Bartmann, F. Burkart et al.



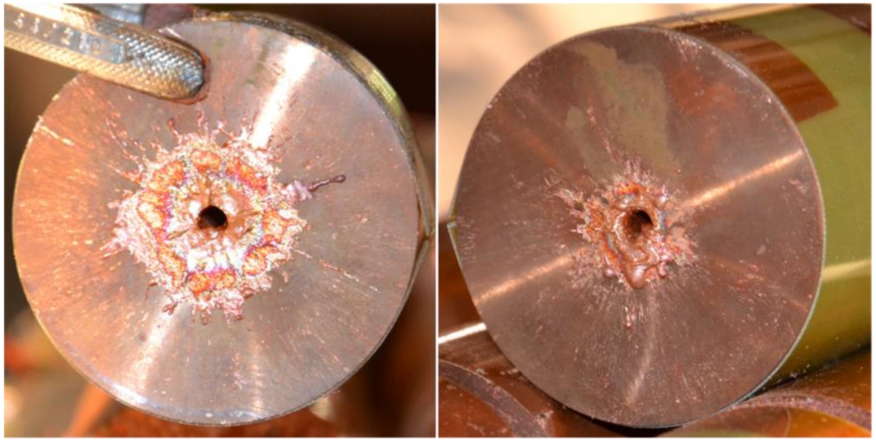
A. Lechner, P. Garcia



LHC pattern
(same scale)



N. Tahir, R. Schmidt



8GJ kinetic energy per beam

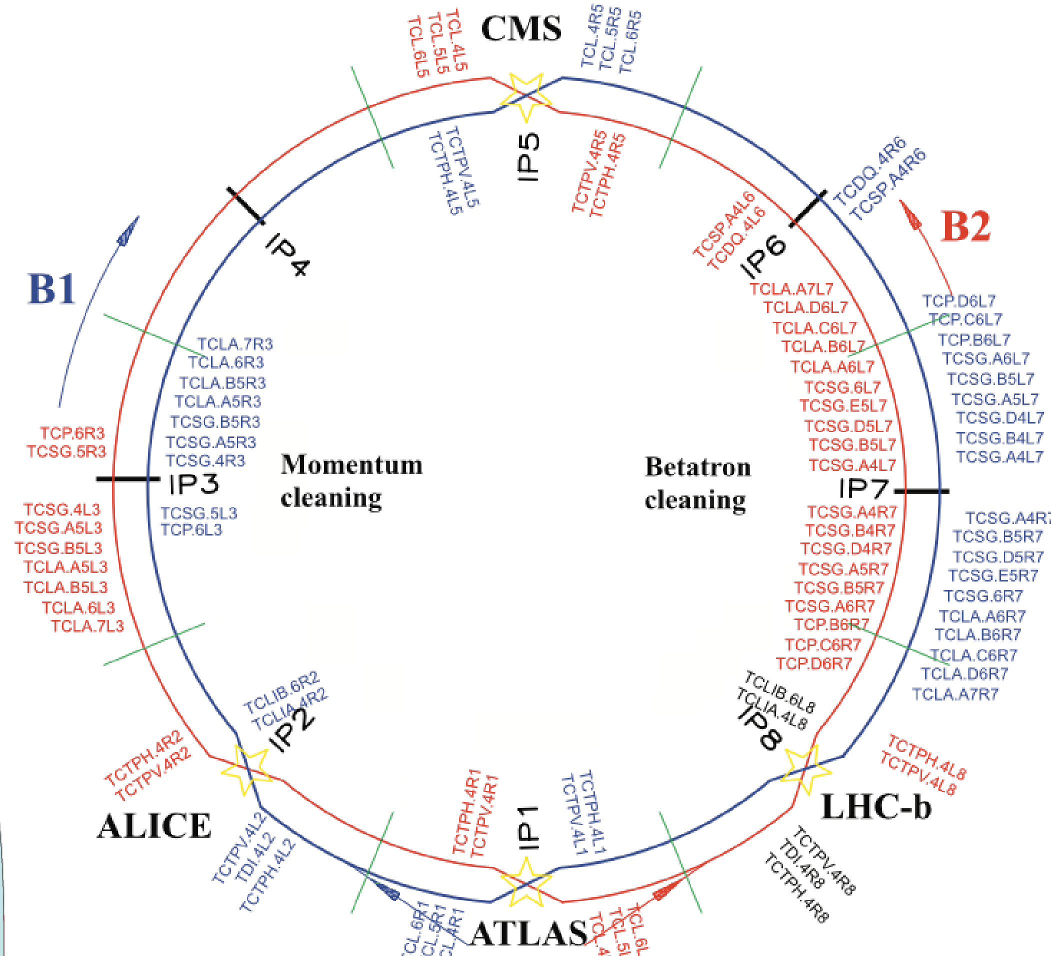
- Airbus A380 at 720km/h
- 2000kg TNT
- 400kg of chocolate
  - Run 25,000km to spent calories
- O(20) times LHC

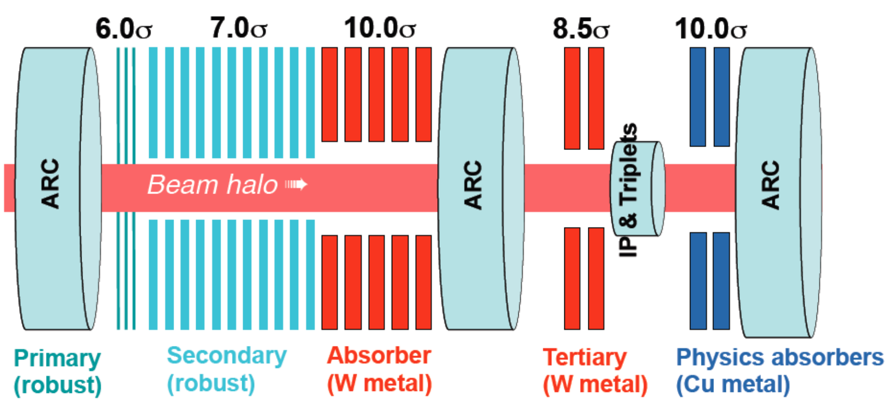
Collimation

Removes particles that enter the tails

First integrated aperture model based on

- Element sizes
- Tolerances
- Beam sizes
- …
- Some parts to be added (e.g. extraction)





M. Fiascaris, J. Molson, A. Lachaize, M. Syphers, S. Redaelli, A. Fauss-Golfe, Ph. Bambade,

First Collimation Results

Collimation must sustain high loss
Tentative specification:
Full beam lost in 12 minutes

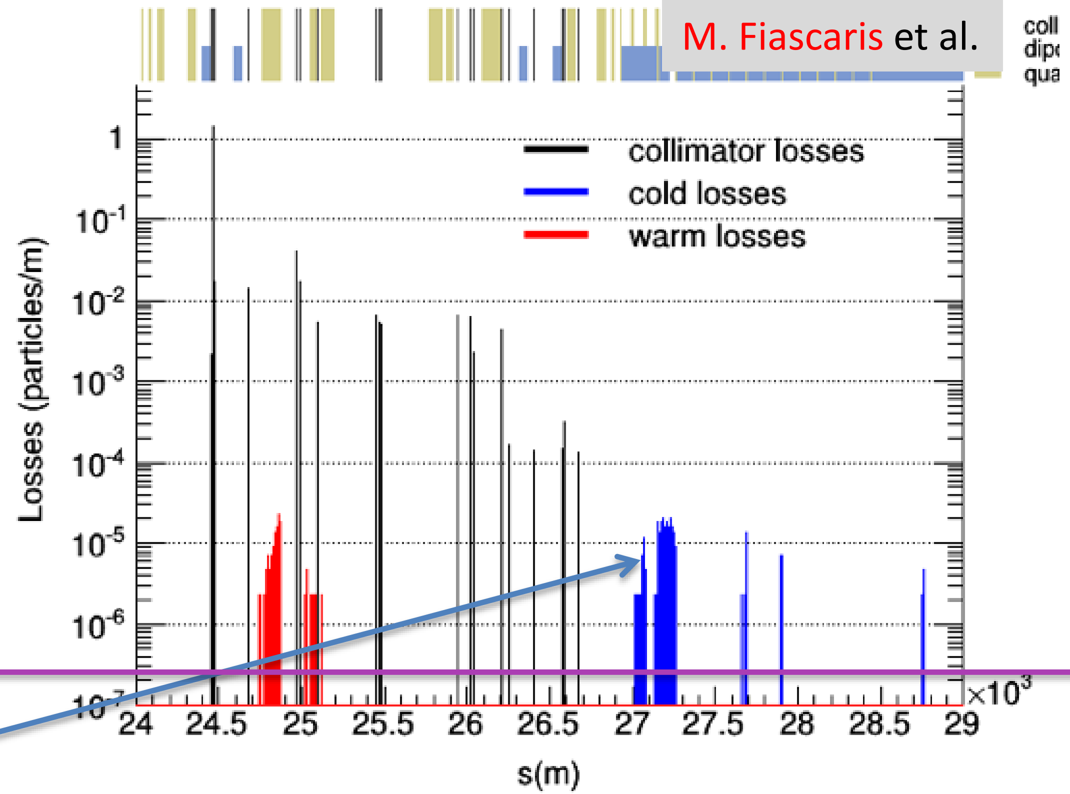
Tentative loss limit (agreed with magnet and FLUKA teams)

- LHC limit 7.8×10^6 p/m/s
- FCC-hh limit 0.5×10^6 p/s/m

Based on

- Same power limit in FCC as in LHC
- Scaled energy density with proton energy from LHC Note 44

Detailed study required



Tentative goal 3×10^{-7}
No DIS collimation 2×10^{-5}
$\Rightarrow$ Loss rate about O(70) times too large

$\Rightarrow$ Need DIS collimation

Tentative results with DIS collimation $O(10^{-6})$
Significant uncertainty
Still high
Showers are a concern

$\Rightarrow$ Likely need special optics design

Injection Insertion

Contains the injection and the RF

RF with 400MHz

E. Shaposhnikova, Ph. Baudrenghien

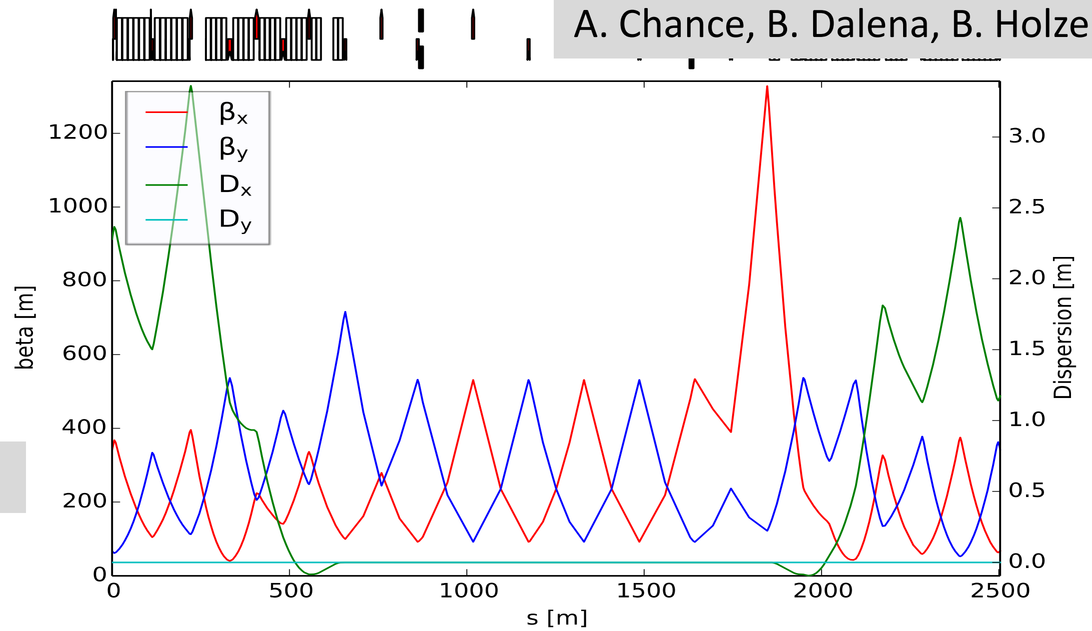
Have to limit injected batch

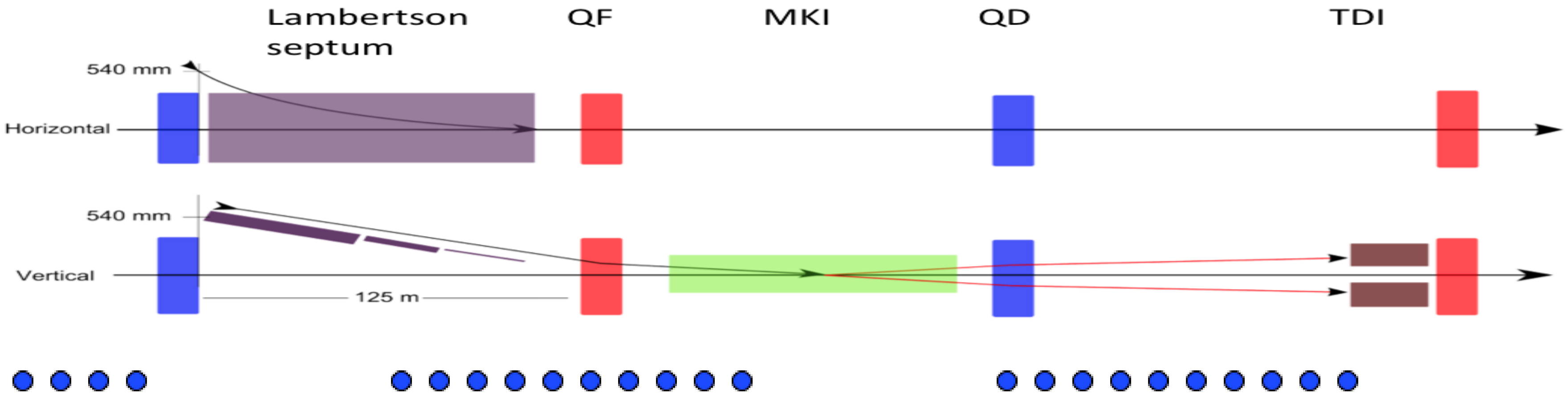
⇒ With LHC limits can inject O(100) bunches

Th. Kramer, M. Barnes et al.

⇒ Very fast kicker (O(300ns)) for beam filling factor of 80%

A. Chance, B. Dalena, B. Holzer,





W. Bartmann, B. Goddard, F. Burkart, …

Injectors

Layout and geology allow to inject from
LHC
SPS
or FCC tunnel

Injection energy (energy swing) is a challenge and strongly impacts collider design

- Magnet quality
- Apertures
- Impedances
- Electron cloud
- …

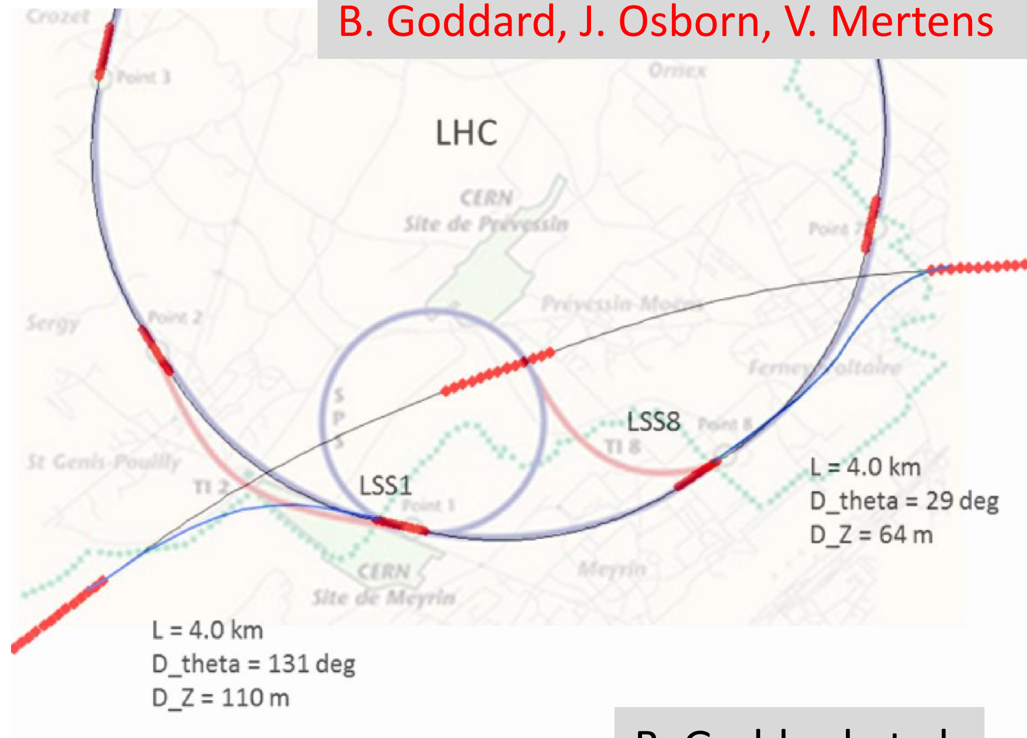
Baseline for injection is 3.3TeV

- Has been review by committee

Other options will be further explored

- From 0.45TeV to 6TeV

B. Goddard, J. Osborn, V. Mertens



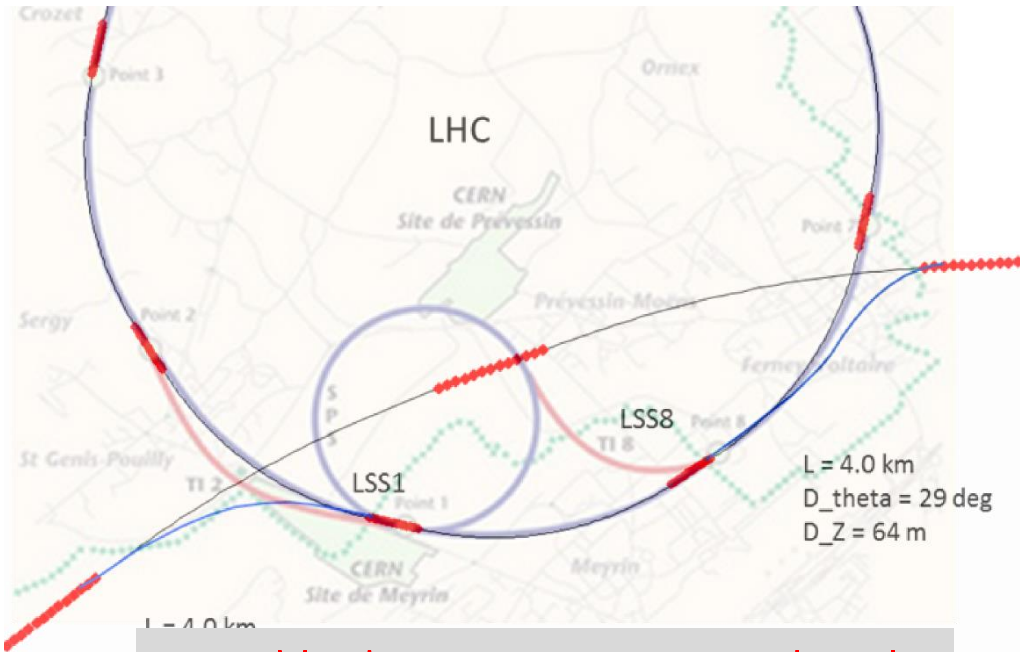
B. Goddard et al.

Will try to reduce beam energy in LHC to demonstrate larger energy swing

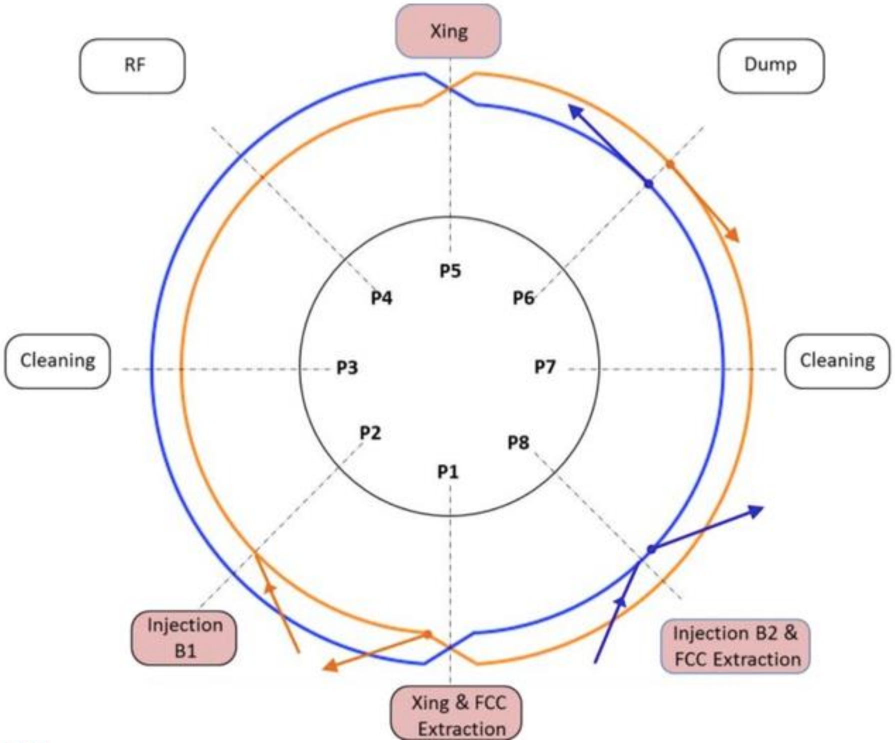
Summary of review by O. Bruning

Injectors

- Limited modifications to 3/4 LHC insertions
- Use ATLAS and LHC for extraction
- Up to 5.8TeV is possible with better kickers
- Superconducting transfer lines
- Slope of transfer lines is a bit high (8%)



B. Goddard, W. Bartman, L. Stoel et al.



A. Milanese

Ramping time in LHC is most critical

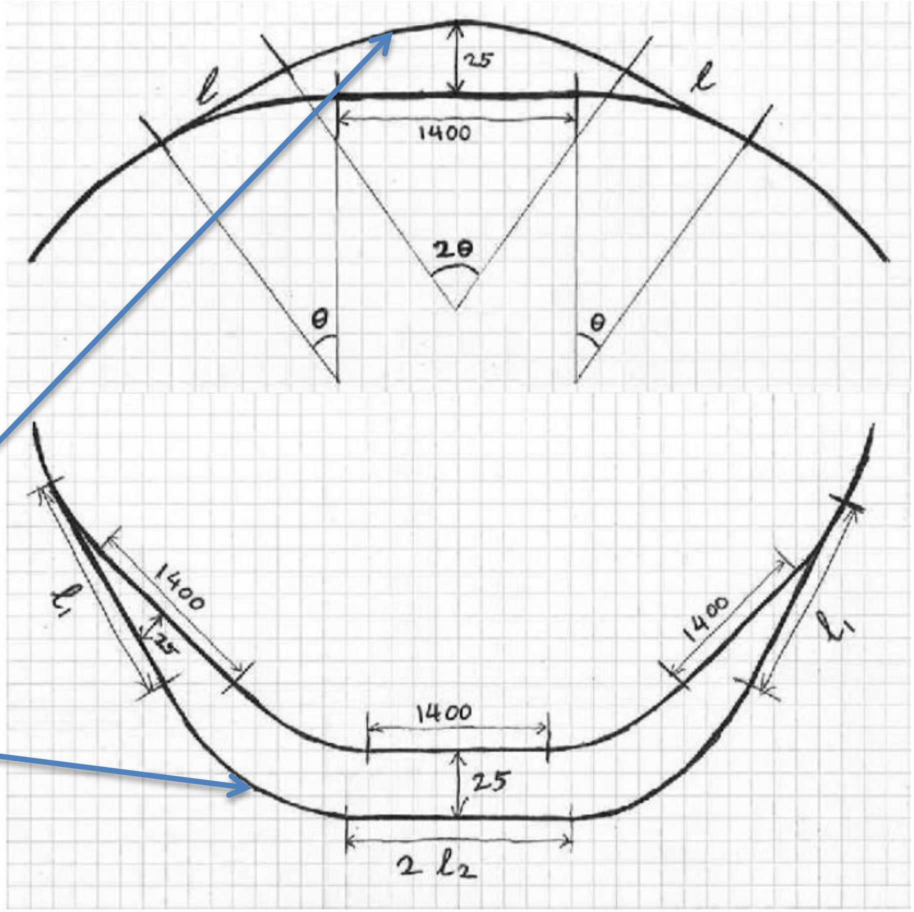
- Reduction from 20 minutes to 4 could be possible
- I.e. 20+16 minutes to fill FCC

Other Options

SPS:
- Up to 1.5TeV (w. 7T magnets)
- Upgrade of PS required to 45GeV
- Can be faster than LHC
- Transfer could be normal conducting
- Slope of transfer lines is a bit high (8%)

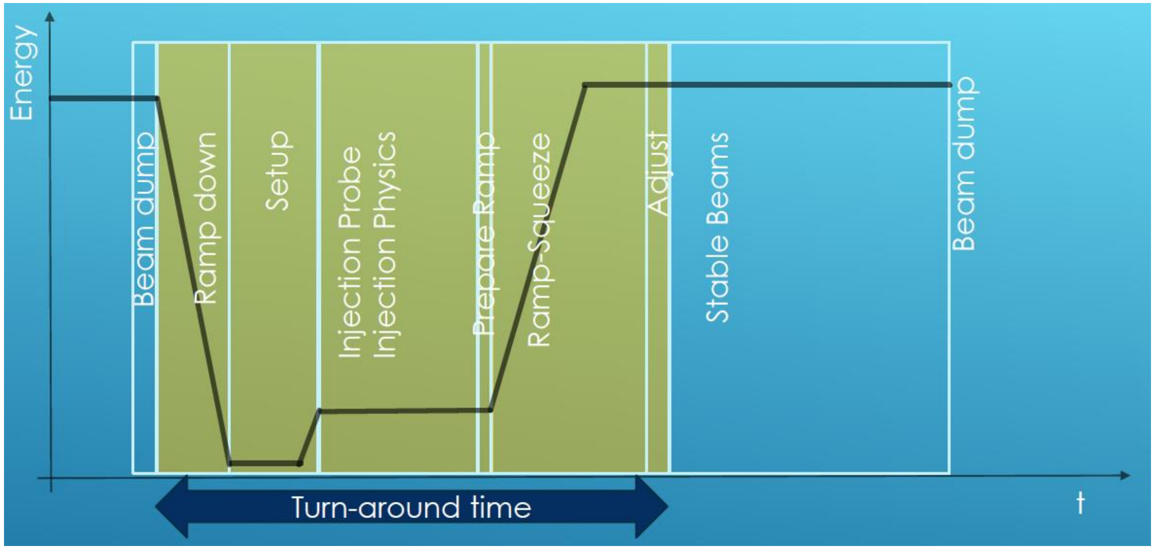
- Even consider staying at 450GeV

FCC:
- Can use normal conducting magnets
- Can be faster than LHC
- Have to bypass experiments
- Transfer in the same tunnel



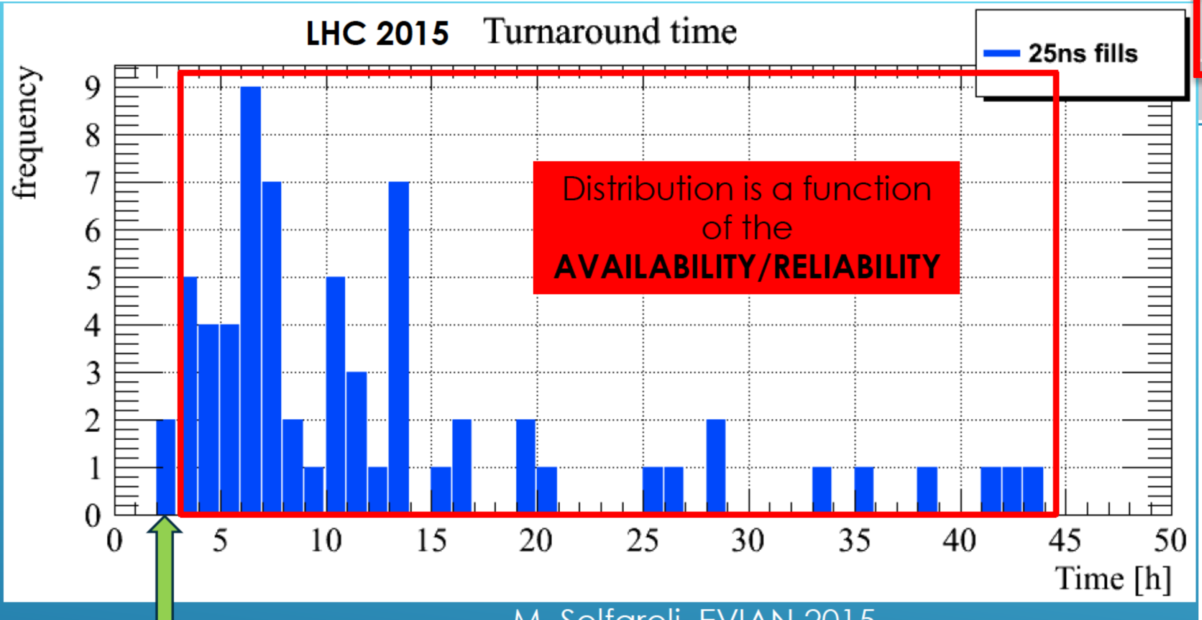
B. Goddard, W. Bartman, L. Stoel et al.

Turn-around Time



R. Alemany Fernandez et al.

Mode	Time (min)
PRE-INJECTION TO INJECTION	10
INJECTION	36
PREPARE RAMP	5
RAMP-SQUEEZE-FLAT TOP	20+5
ADJUST	10
RAMP DOWN	20
TOTAL	106 (1.8 hours)



M. Solfaroli, EVIAN 2015

Better than 4h theoretically possible

Availability / reliability to be established

A. Apollonio et al.

Future Work

Many hardware activities were instrumental for the design progress

- Beamscreen and magnets are prime examples
- More will be covered in the following talks

⇒ M. Jimenez
⇒ G. De Rijk
⇒ F. Perez
⇒ E. Jensen

We need to continue and extend this

- Connections between beamscreens, extraction septum design, protection devices, …

Develop functional specifications together with the hardware teams

Optimisation of existing design

- Tradeoff between lattices, optimisation of each section
- Triplet shielding, arc magnets, special magnets, …

Alternatives also important

- Different injection energy
- HTS coating for beamscreen
- Layout of extended straight sections
- Flat beams
- Collimation with electron beams
- …

Conclusion

- FCC-hh baseline exists
  - Great basis to evaluate and improve
- Next steps (in part already ongoing)
  - Develop functional specifications with hardware teams
    - Some loops are required
  - Tradeoffs need to be made between systems
    - More integrated studies and modelling
  - Local optimisation of systems
  - Study alternatives (e.g. extended straight sections, injection energy)
- Goal is to arrive at better baseline
  - We want something good for the CDR
  - We know it will be even better in the real machine
- Your contributions are most welcome

Many thanks to all the great teams

Reserve Slides

Filling Time

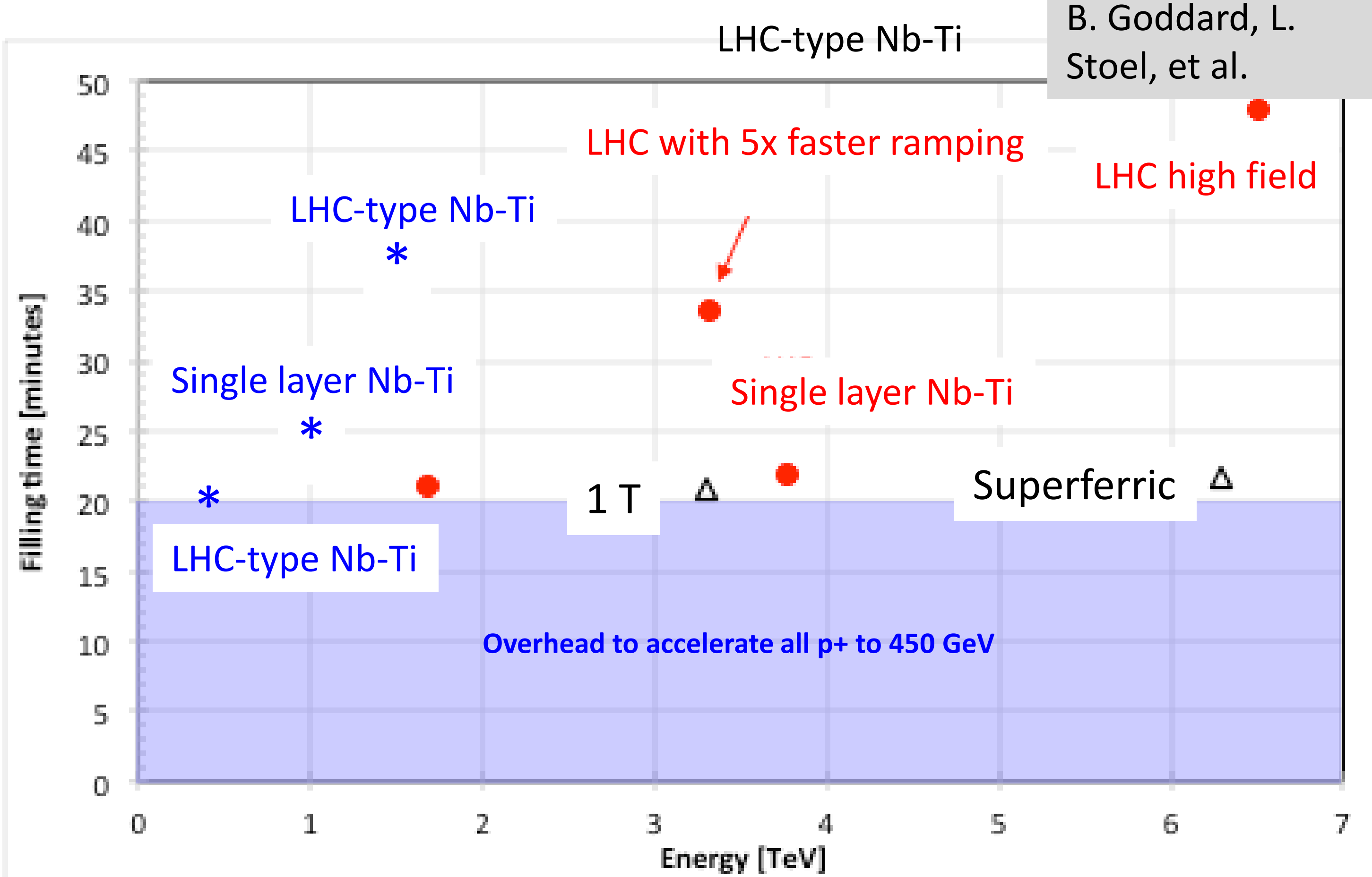
SPS -> FCC

Higher fields lead to long ramp times

SPS -> LHC -> FCC

SPS -> FCC booster -> FCC

B. Goddard, L. Stoel, et al.



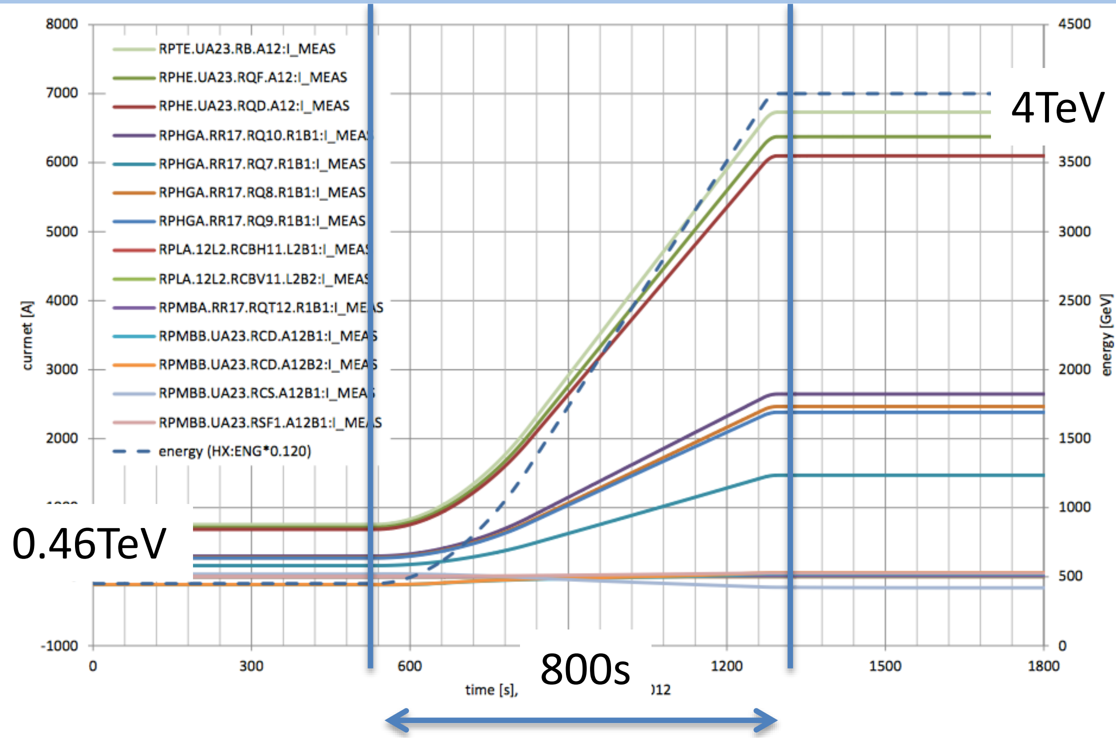
LHC would work as injector

Will study other options in more detail

Study effects of lower energy in collider ring

LHC as Injector

The LHC is basically suited as injector
- Some modifications required



Faster ramping of magnets is required
- Need four fillings into FCC
- In total roughly 1.5h ramping up and down
- Realistic goal seems a factor 5 improvement
  - Better ramp shape
  - Upgrade of power converters

Many studies to come
- 5ns bunch spacing
- Injection into LHC
- …
- Develop the other options

B. Goddard, A. Milanese et al.

LHC Experiments

Field error depends on injection energy

Uncertain about reproducibility and stability at low fields

Experiment is important

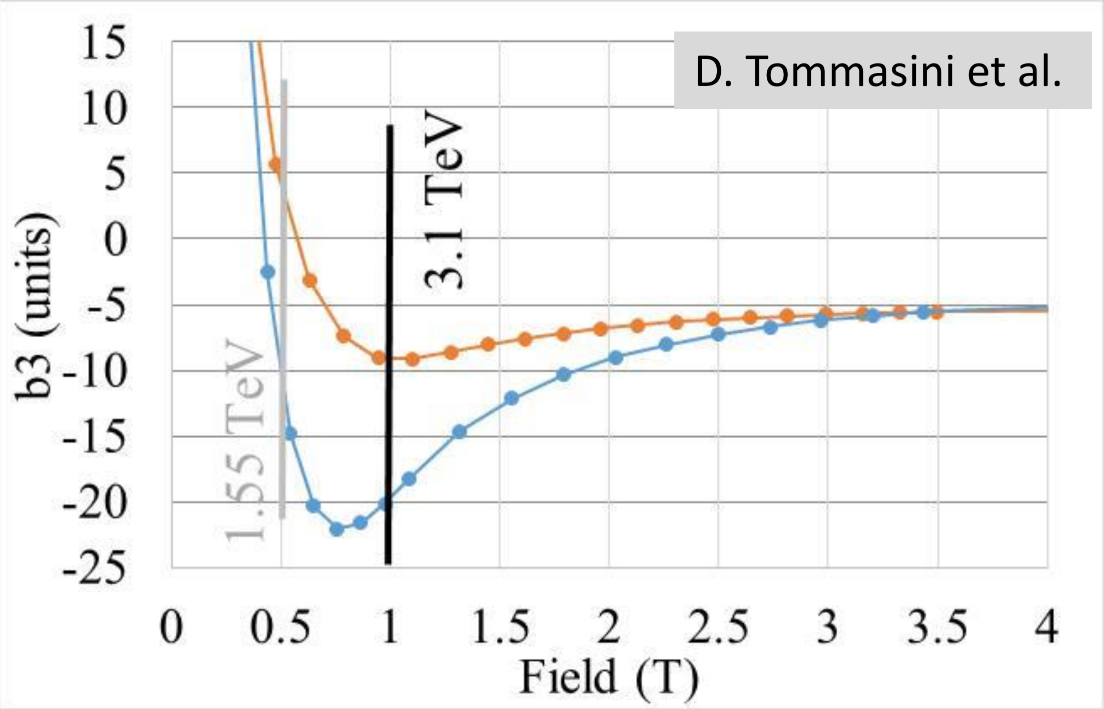
Inject beam into LHC at 225GeV

- Or decelerate injected beam to 225GeV

Many changes are required and need to be undone

⇒ Best at the end of a run

http://indico.cern.ch/event/469656/
B. Goddard et al.



Important for FCC as well:

- Faster ramping

Profit from LHC and HL-LHC MDs

- Impedances
- Beam-beam
- …

Example for Loss Mechanism

F. Cerutti, I. Besana

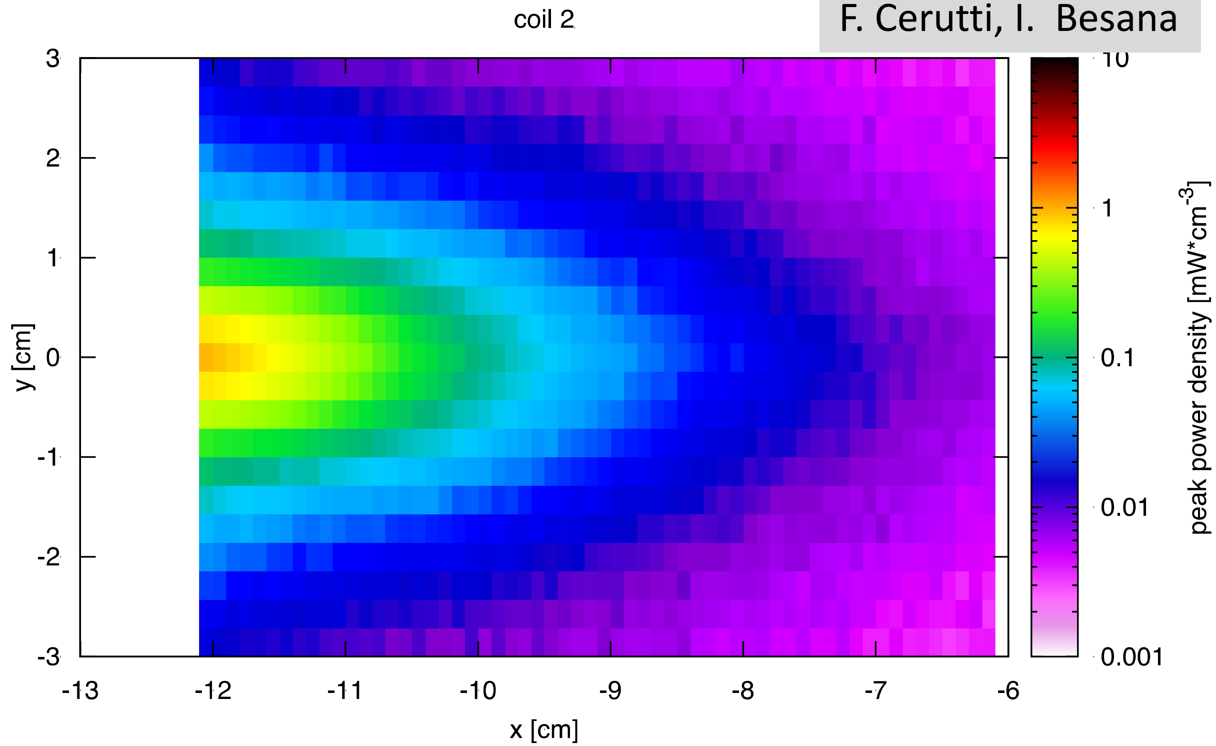
Beam-gas scattering goal >100h beam lifetime

⇒ <O($10^{15}m^{-3}$) H_2 (σ≈100mb)

⇒ 45kW proton losses

⇒ power for cooling

- @2K ~30MW
- @4K ~15MW
- some part is lost in collimation system



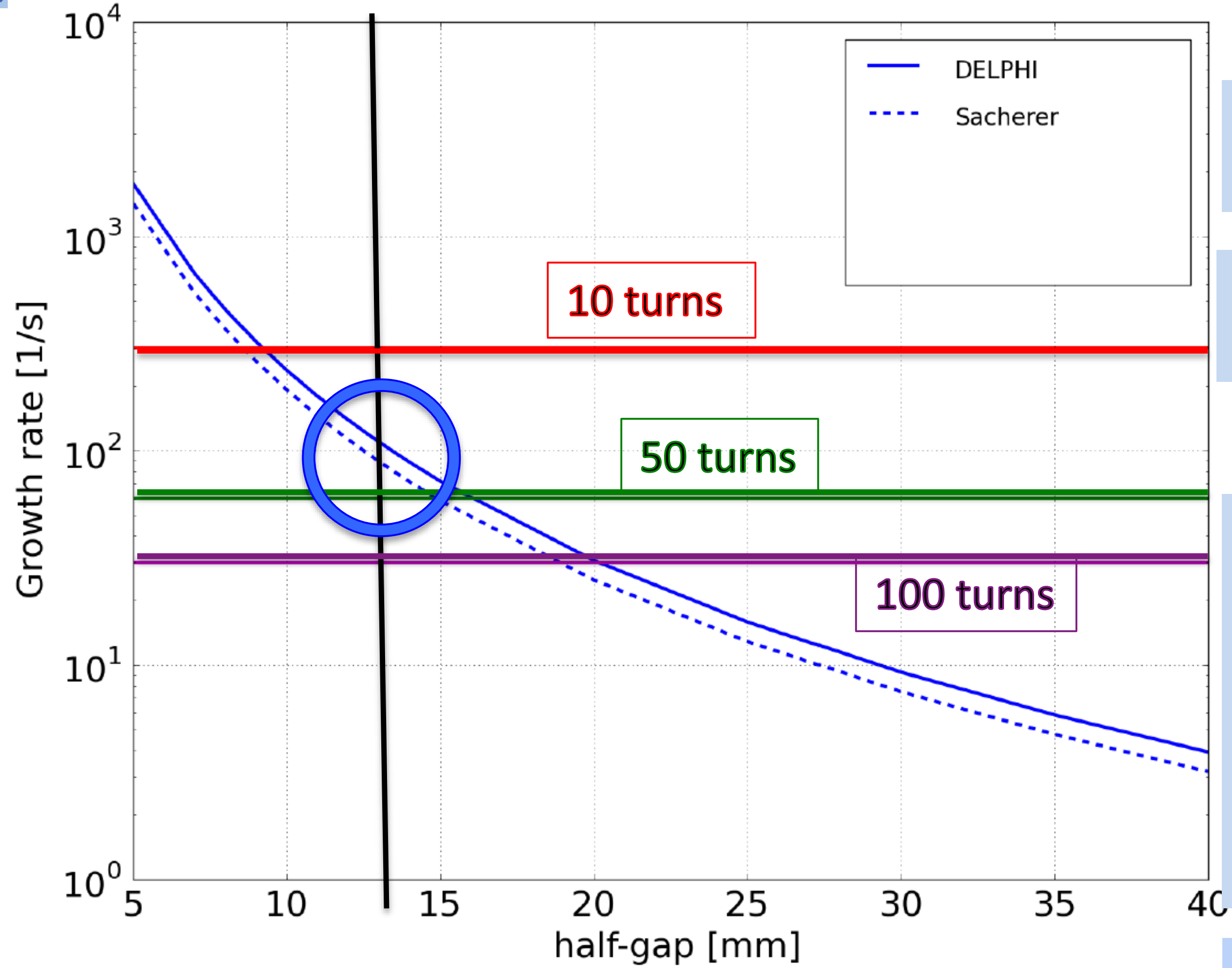
First studies indicate peak power density O(1mW/cm^{-3}) and 3.5W/beam/dipole in cold

Seems very acceptable but need to define margin

Work in progress

Estimates of Beamipe Impedance Effects

N. Mounet, G. Rumolo



Multi-bunch effect at 50K and injection (worst case)
Only resistive wall (infinite copper layer assumed)

Growth rate of multi-bunch instability

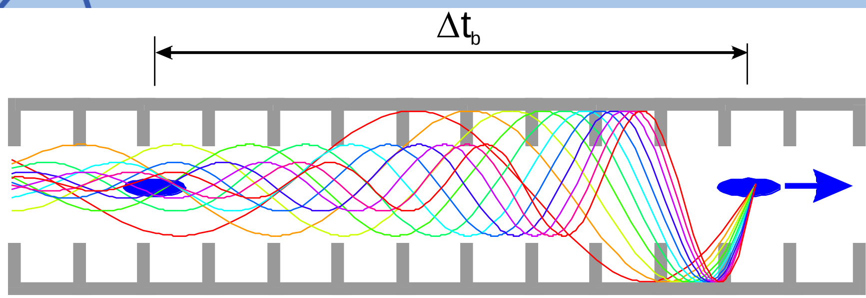
Noise growths every 20-30 turns by factor e

Need feedback within 10 turns

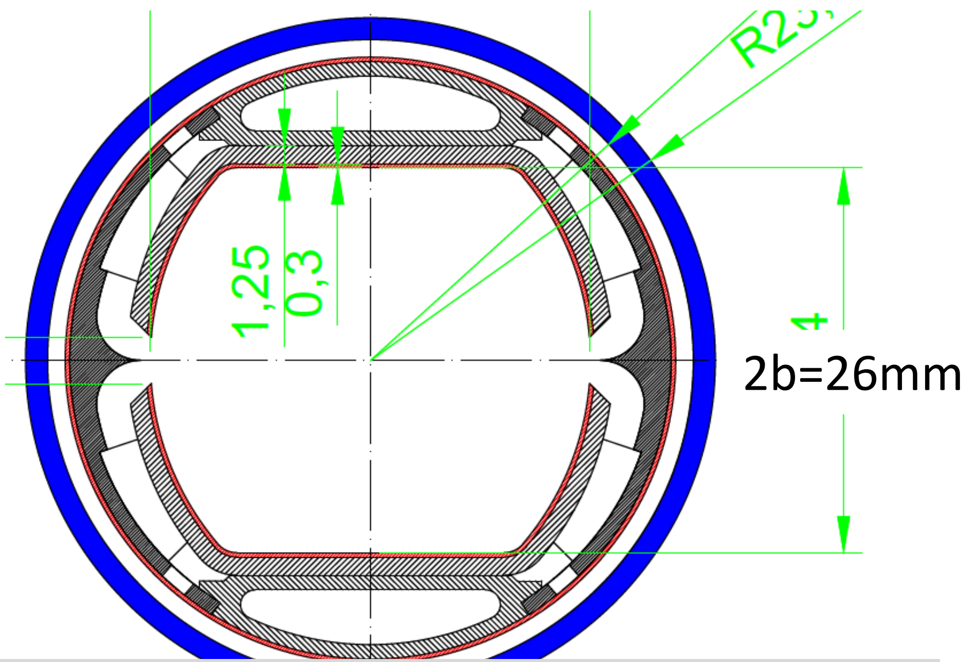
- Challenge for RF and instrumentation
- Or increase the beam screen radius
- Or decrease beam current

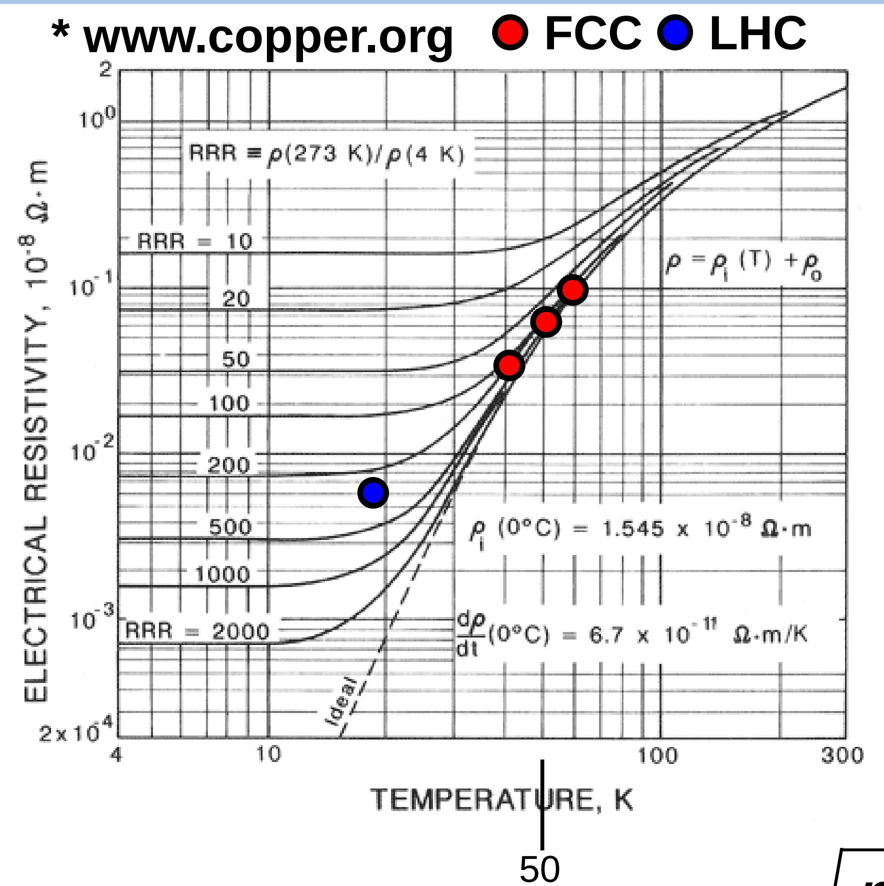
Many more impedance studies required

Low Frequency Impedances



At injection multi-bunch instability is driven by resistivity of arc beam screen





Strong dependence on radius

$$Z_{\perp} \propto \frac{\sqrt{r}}{b^3}$$

Defines minimum b

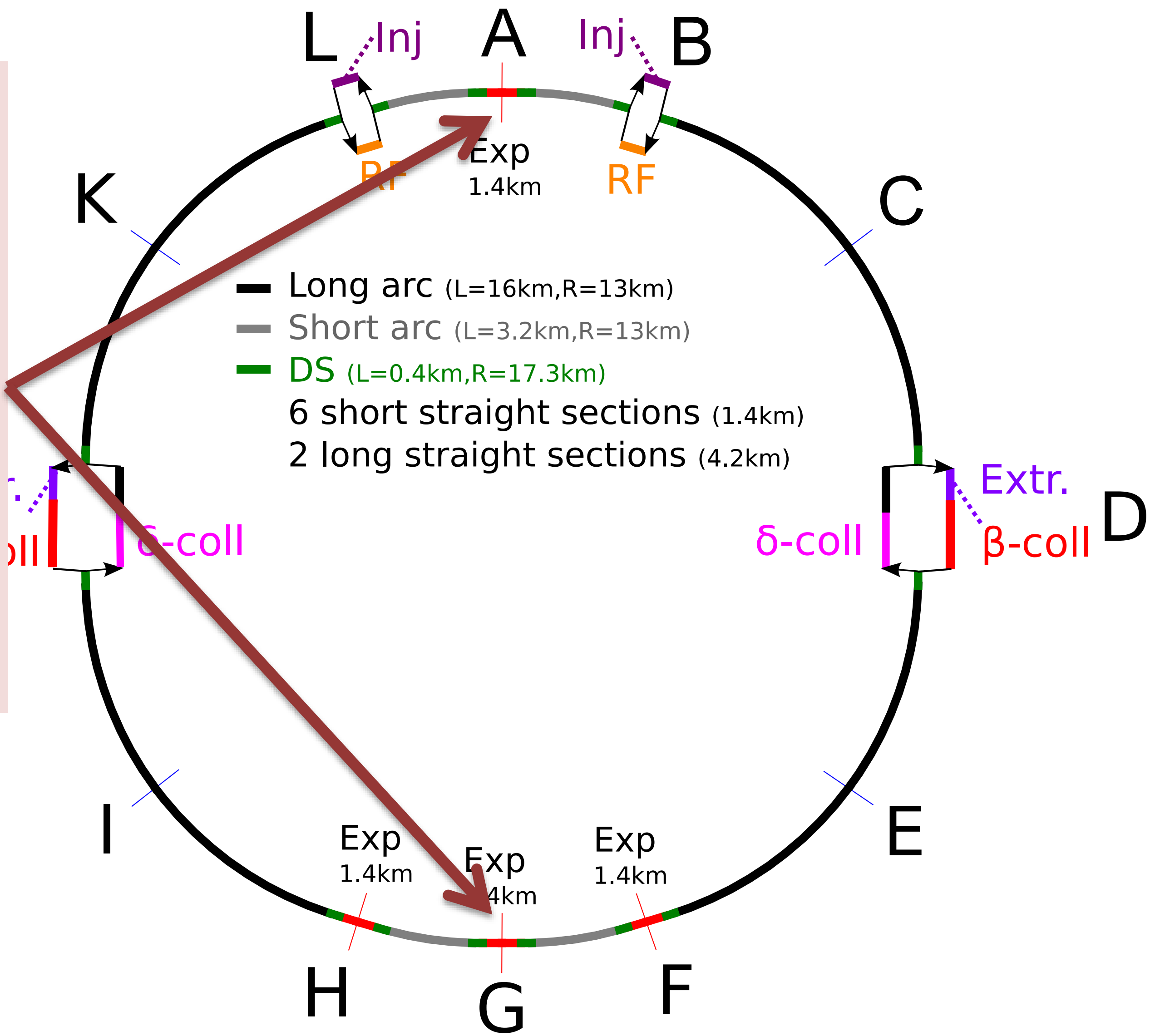
Multi-bunch instability O(10) worse than in LHC

N. Mounet, G: Rumolo, O. Boine-Frankeheim, U. Niedermayer, F. Petrov, B. Salvant, X. Buffat, D.S.

FCC-hh Layout

Two main experiments on opposite sides of the collider

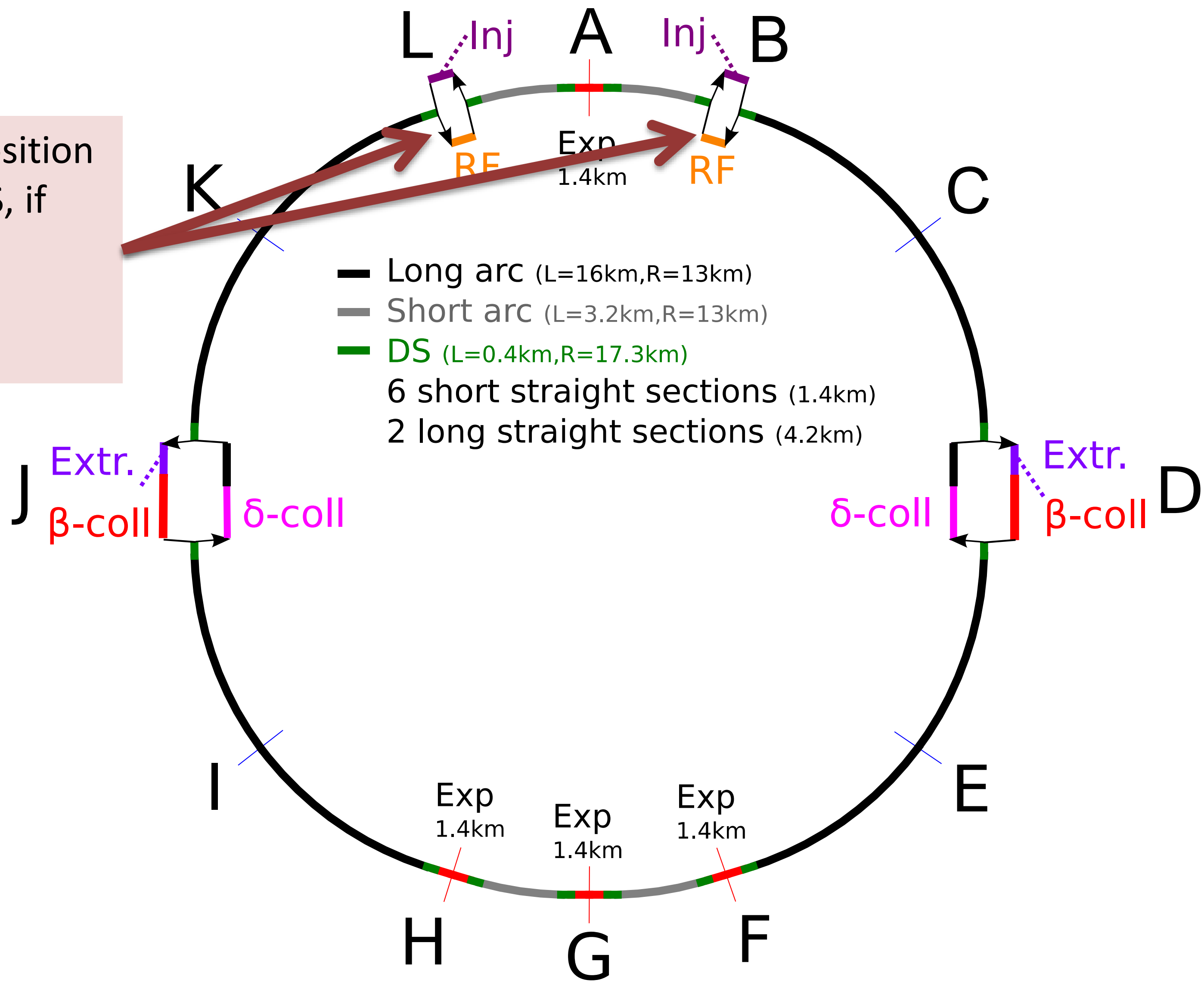
- All bunches collide in main experiments
  - independent of filling pattern
  - Highest luminosity
- Each bunch collides with the same bunch in both experiments
  - Compensation of beam-beam effects



FCC-hh Layout

The injection insertion position is determined by LHC/SPS, if used as injector

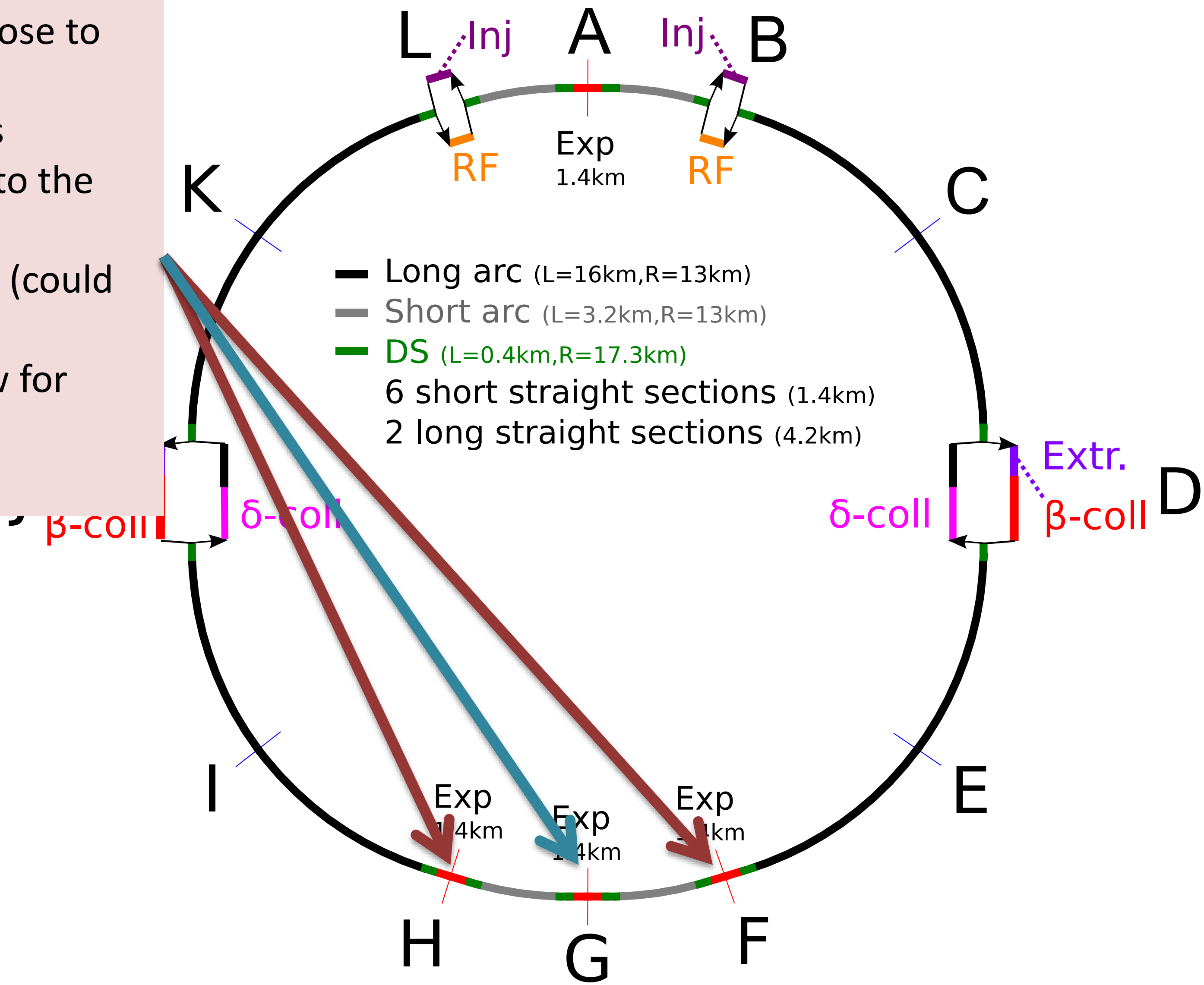
Best place for RF



FCC-hh Layout

Additional experiments close to one main experiment

- Separation to suppress background from one to the next
- Symmetric to injection (could be changed)
- Short arcs should allow for enough tuning



FCC-hh Layout

Foresee two collimation and extraction insertions

- Insertions with largest risk
- Scheme provides flexibility

Current baseline

- betatron-collimation after extract to protect machine
- Energy collimation