# FCC-hh Conceptual Machine Design

Daniel Schulte for the FCC-hh team
CERN, March 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

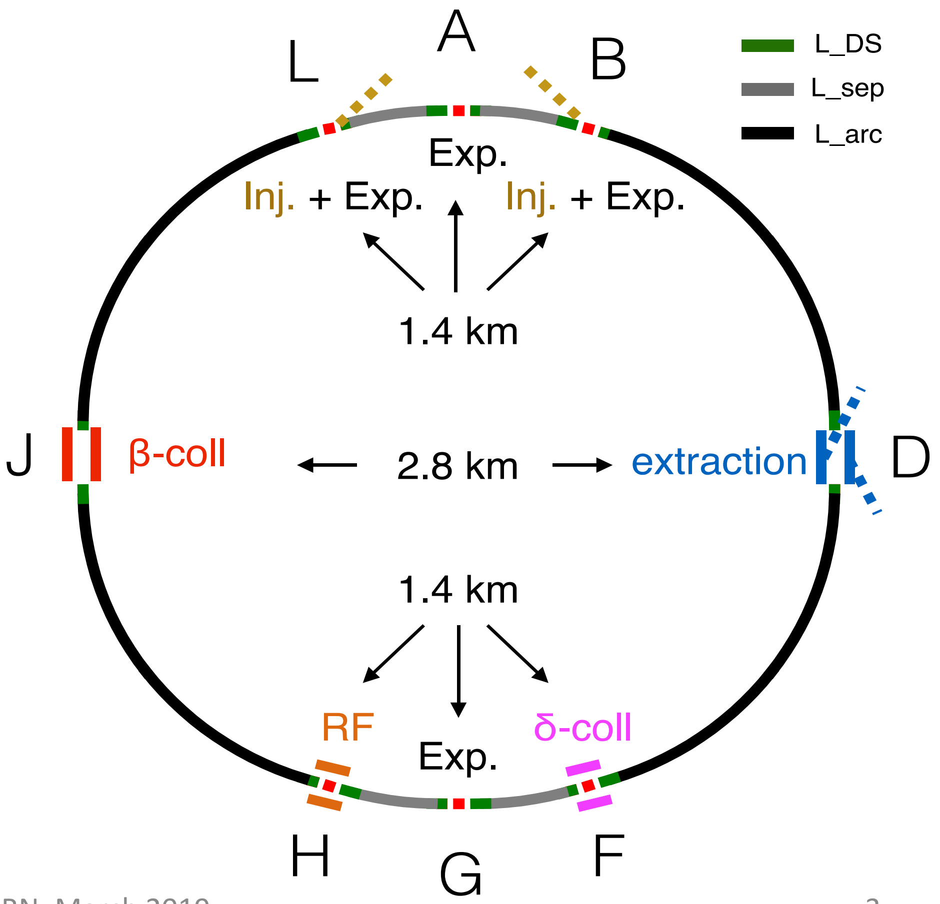
# Hadron Collider Parameters

| | LHC / HL-LHC | HE-LHC (tentative) | FCC-hh Initial | FCC-hh Ultimate |
|---|---|---|---|---|
| Cms energy [TeV] | 14 | 27 | 100 | 100 |
| Luminosity [$10^{34}cm^{-2}s^{-1}$] | 1 / 5 | 28 | 5 | 20-30 |
| Machine circumference | 27 | 27 | 97.75 | 97.75 |
| Arc dipole field [T] | 8 | 16 | 16 | 16 |
| Bunch charge | 1.15 / 2.2 | 2.2 | 1 | 1 |
| Bunch distance [ns] | 25 | 25 | 25 | 25 |
| Background events/bx | 27 / 135 | 800 | 170 | <1020 |
| Bunch length [cm] | 7.5 | 7.5 | 8 | 8 |

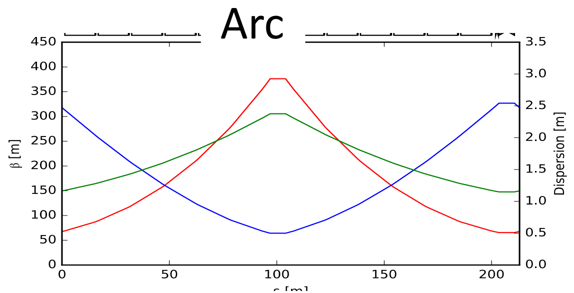
# FCC-hh Layout

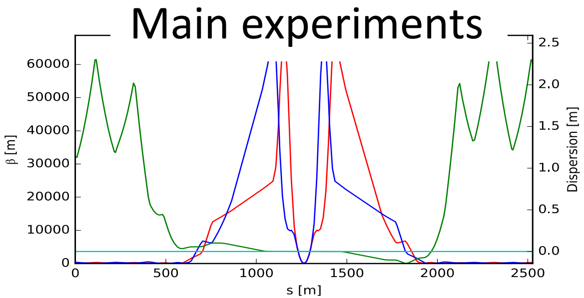
Layout for CERN site

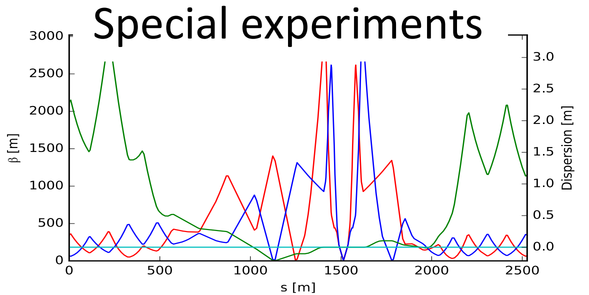
- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection at 3.3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector

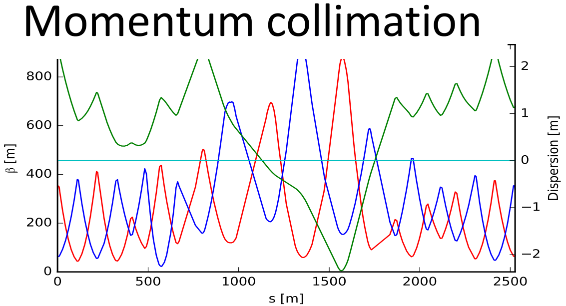


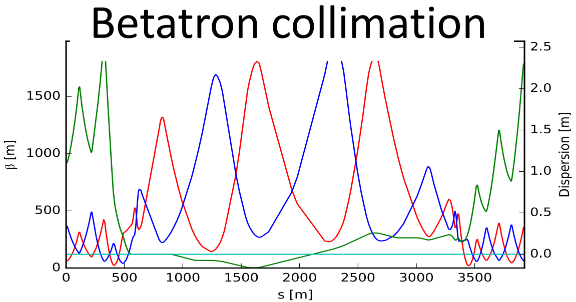
# Integrated Lattice

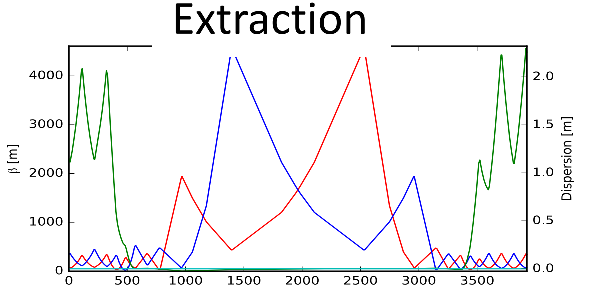


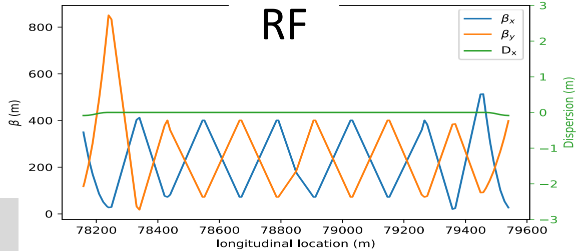




Full integrated lattice exists

- large amount of work (system designs, code, matching, tuning, …)
- always room for even further improvement

A. Chance et al.

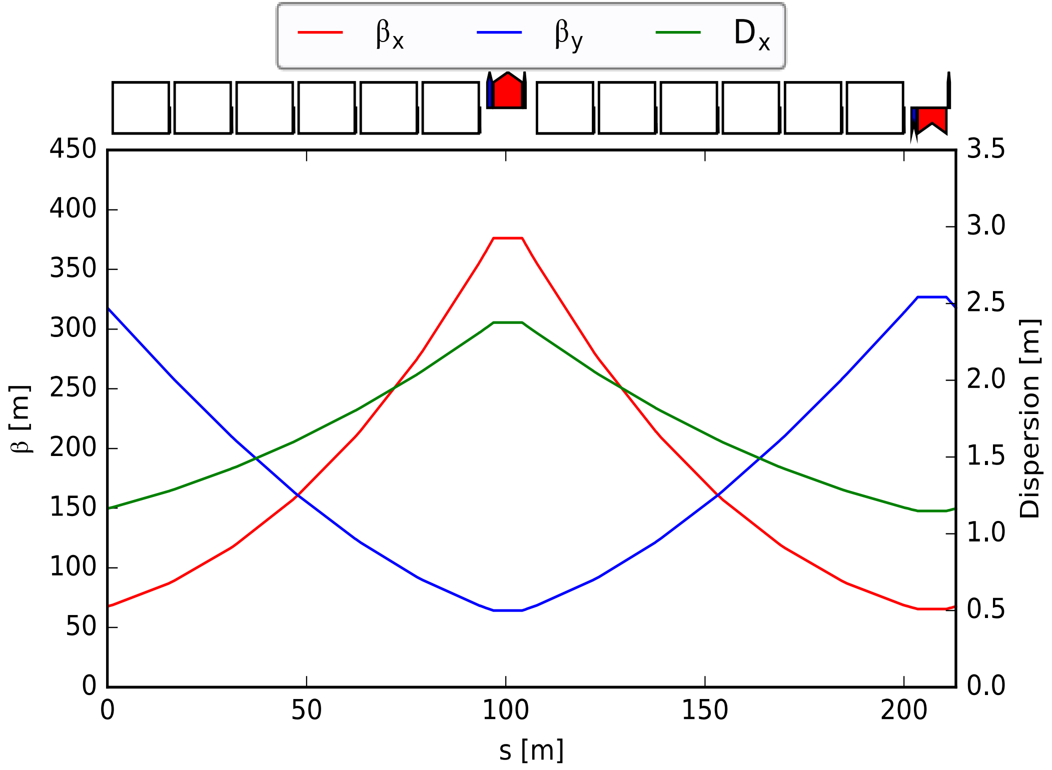
# Arc Layout

A. Chance, B. Dalena, J. Payet

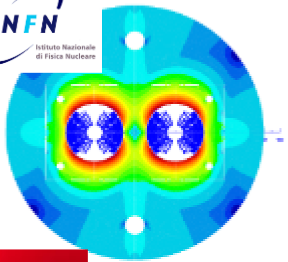
Arc cell length is 213.04 m

- 90° FODO cells
- Contains 12 dipoles
  - Each 14.07 m long
- Also quadrupoles, sextupoles, spool pieces, correctors, …

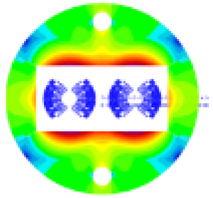
- Needed dipole field is 15.96 T

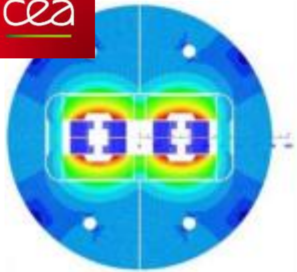


# Magnet Development

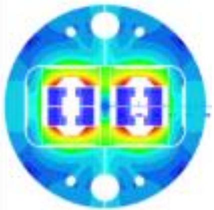


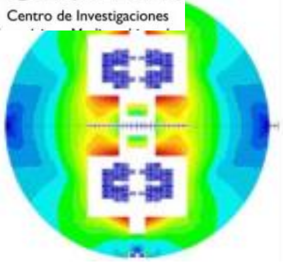
Cosine theta



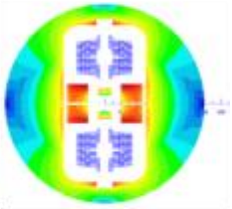


Block design

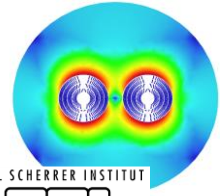




Common coils



Canted coils



Need 16 T to reach 50 TeV /beam

⇒ Move from NbTi (LHC technology) to $Nb_3Sn$

14.3 m long dipoles

Magnet is key cost driver

- Improve cable performance
- Reduce cable cost
- Improve fabrication of magnet
- Minimise amount of cables
- Push lattice filling factor

Safety margin from 18% to 14%
Reduced inter-beam distance from 250 to 204 mm
Stray field up to 0.1 T
⇒ Total conductor (incl. copper) from O(10 kt) to 7.6 kt

Short models in 2018 – 2023
Prototypes 2026 -- 2032

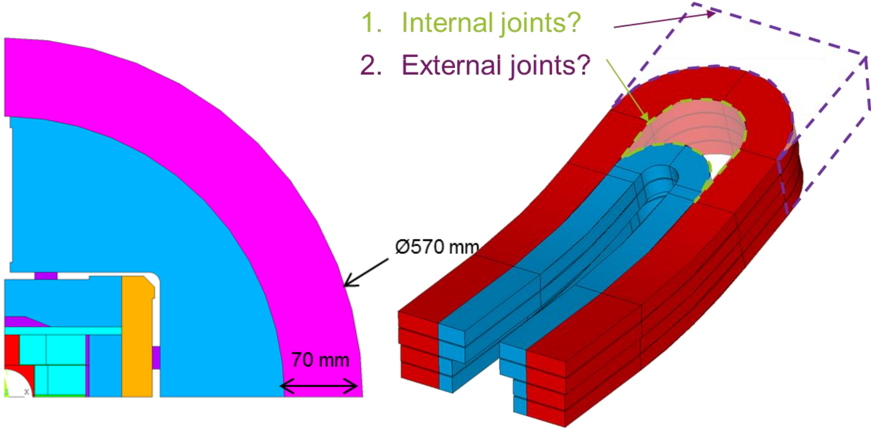
D. Tommasini et al.

# Magnet Models

With today's state of the art conductors:

- 15 T achievable at 14 % margin
- 17 T at short sample

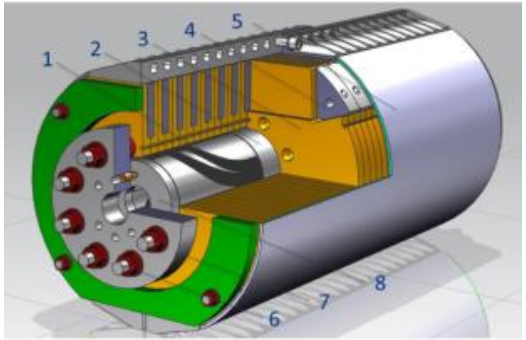
- Cos-theta and common-coil model magnet programs are under preparation

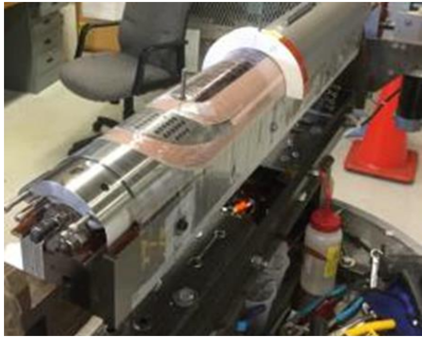



U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab
50 Years of Discovery

15 T dipole demonstrator
60-mm aperture
4-layer graded coil
Test foreseen in 2018



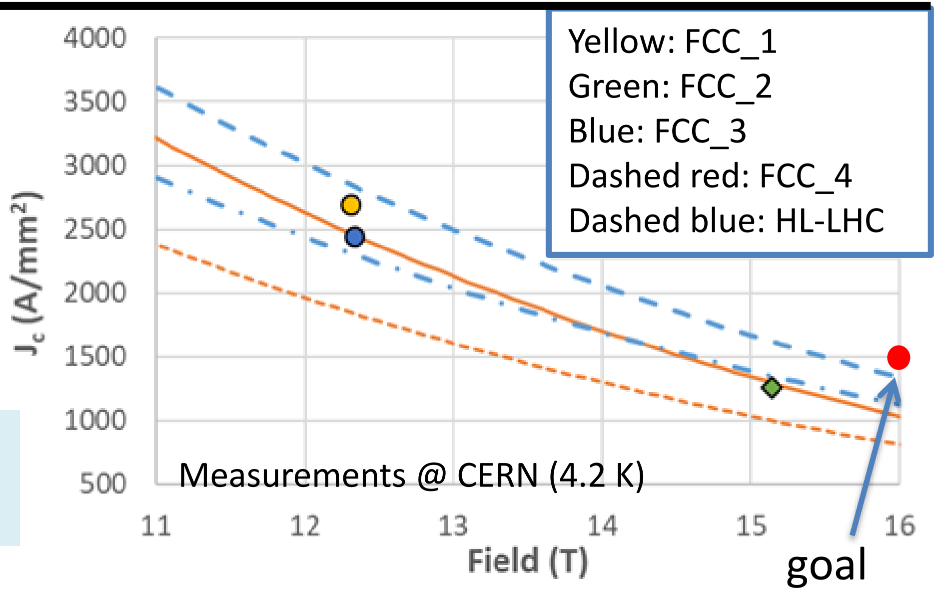



D. Tommasini et al.

# Conductor

New activity with many collaborators started in 2017 with ambitious targets


| | | |
|---|---|---|
| Wire diameter | mm | ~ 1 |
| Non-Cu Jc (16 T, 4.2 K)* | A/mm² | ≥ 1500 |
| Unit length | km | ≥ 5 |
| Cost | €/kA m** | ≤ 5 |




D. Tommasini et al.

First wires almost reached HL-LHC requirements

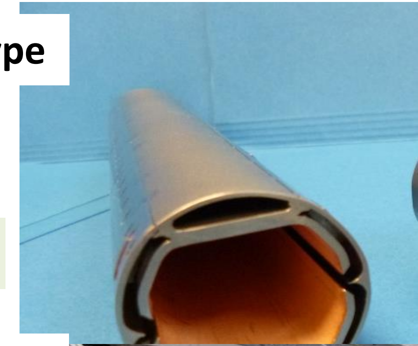
# Beamscreen Design

30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

EuroCirCol
A key to New Physics

**Prototype**

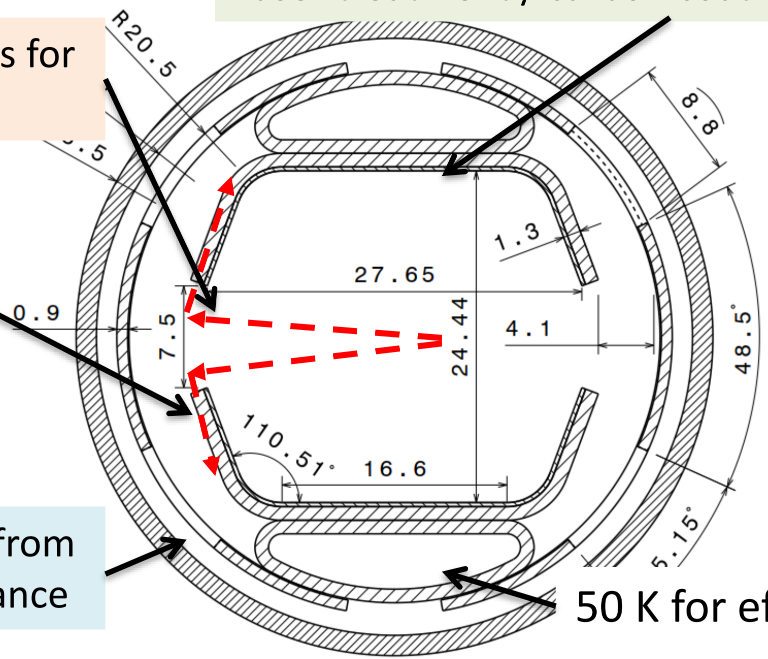


Laser treatment / carbon coating against ecloud

Extract photons for great vacuum

Strong to withstand quench

Hide pumping holes from beam for low impedance




50 K for efficiency

**Test station in ANKA**

P. Chiggiato et al. et al.

# Beam Parameters and Luminosity

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Beam physics

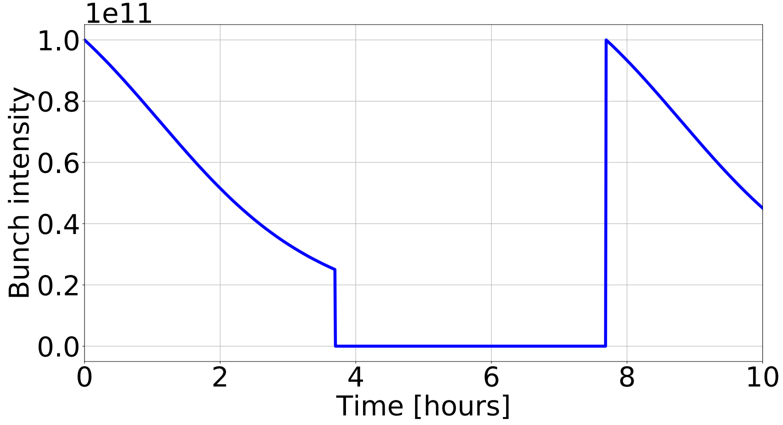
Interaction region design

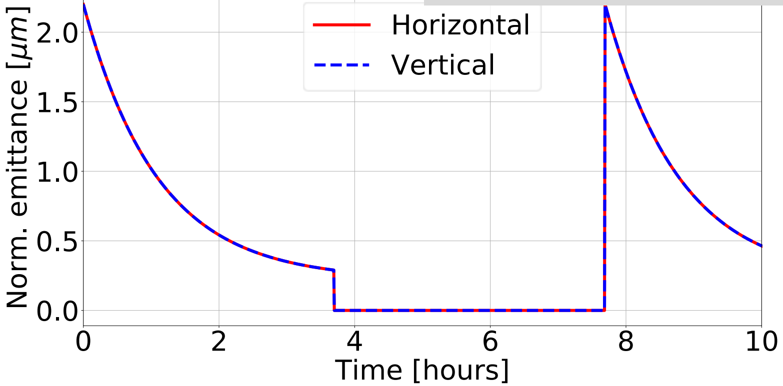
Power consumption
Beam stability
Damage potential

| | Initial | Nominal |
|---|---|---|
| Luminosity L [$10^{34}$cm$^{-2}$s$^{-1}$] | 5 | 20-30 |
| Background events/bx | 170 | <1020 |
| Bunch distance Δt [ns] | 25 | |
| Bunch charge N [$10^{11}$] | 1 | |
| Fract. of ring filled $\eta_{fill}$ [%] | 80 | |
| Norm. emitt. [μm] | 2.2 | |
| 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 | 3.5 |
| RMS bunch length $\sigma_z$ [cm] | 8 | |
| Crossing angle [σ□] | 12 | Crab. Cav. |
| Turn-around time [h] | 5 | 4 |

# Integrated Luminosity

X. Buffat, S. Arsenjev, D.S..



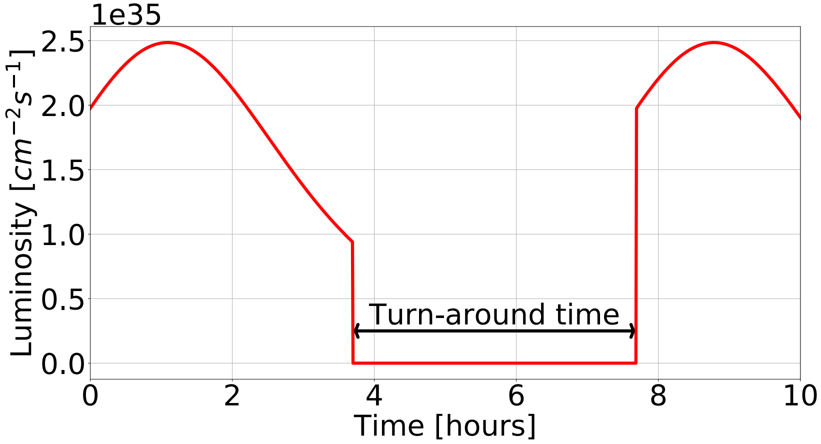




Luminosity changes during a run

- Damping, burn-off, …
- Use full model (here nominal)

⇒ Reach 8 $fb^{-1}$/day with ultimate for 25ns spacing

⇒ Include 70% availability in integrated luminosity prediction



# Turn-around Time

| Phase | FCC target | LHC theoretical | LHC min 2017 | LHC mean 2017 |
|---|---|---|---|---|
| Setup | 10 | 10 | - | - |
| Injection | 40 | 16[a] | 28.0 | 77.1 |
| Prepare ramp | 5 | - | 2.3 | 5.0 |
| Ramp-Squeeze-Flat top | 20+ 5+3 | 20 | 20.2+13.4+2.8 | 20.5+18.1+4.5 |
| Adjust | 5 | - | 3.3 | 7.9 |
| Ramp down | 20 | 20 | 36 | 153.2[b] |
| Total | 108 (1.8 h) | ≈ 70 (1.2 h) | 106.0 (1.8 h) | 150 (2.5 h) |

FCC goal/working assumption is 4 h
on average, factor 2.2 margin

Factor 2.1

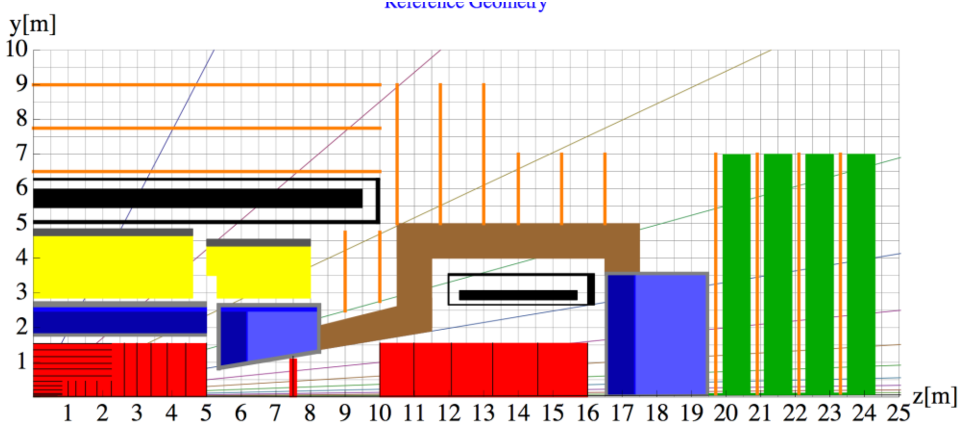
Largest difference between theory and practice in setup time
But this contains time to recover from failures
So should be counted in **different** budget

D. Nisbet, K. Fuchsberger,
R. Fernandez et al.

# FCC Machine Detector Interface

W. Riegler at al.

Decided to use $L^* = 40$ m
⇒ Experimental insertion fits in allocated space
⇒ Have some reserve in beta-function




Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Add. protection
TAS
Triplet

Hall half length: 33m

$L^*$=40 m

Detector half length 24m

# High-luminosity Insertions

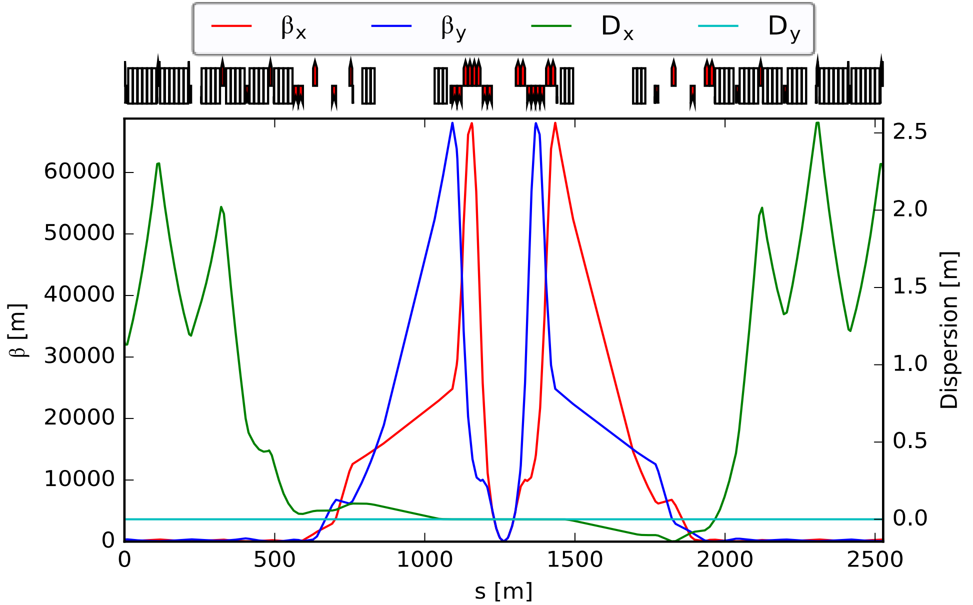
Challenging design:

Small beam size at IP leads to large beam in focusing magnets
⇒ Require large aperture

Need to protect magnet
⇒ Need even more aperture

Larger aperture makes magnet weak
⇒ Makes triplet and insertion long
⇒ Difficult to fit system in 1400 m long insertion

Magnetic field quality is important
⇒ Add correction of bad fields




Goal is $\beta^* = 0.3$ m
Achieve $\beta^* = 0.2$ m
⇒ Some margin for robustness

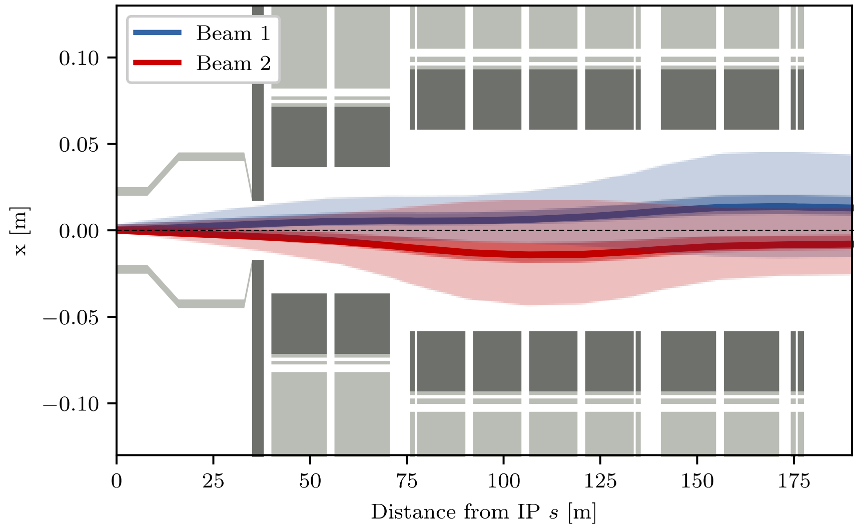
R. Tomas, R. Martin, E. Cruz et al.

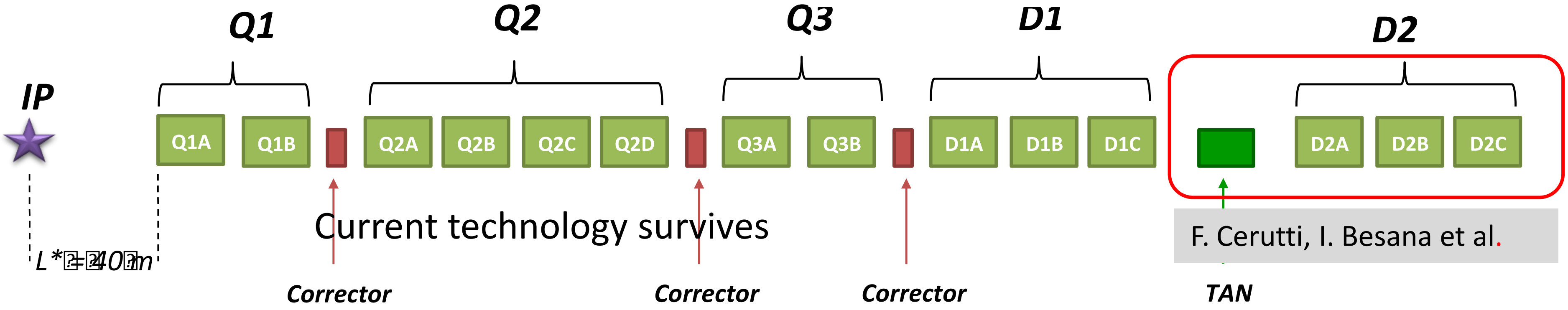
# Collision Debris

500 kW debris per experiment (HL-LHC x 42)

Pions enter magnet aperture and can be lost

Protect magnets by TAS
And internal shielding (35 mm tungsten)



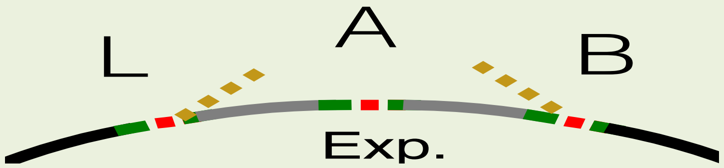
# Collision Debris

Current triplet technology reaches radiation limit after 15-22.5 $fb^{-1}$

Expect to improve hardness by a factor

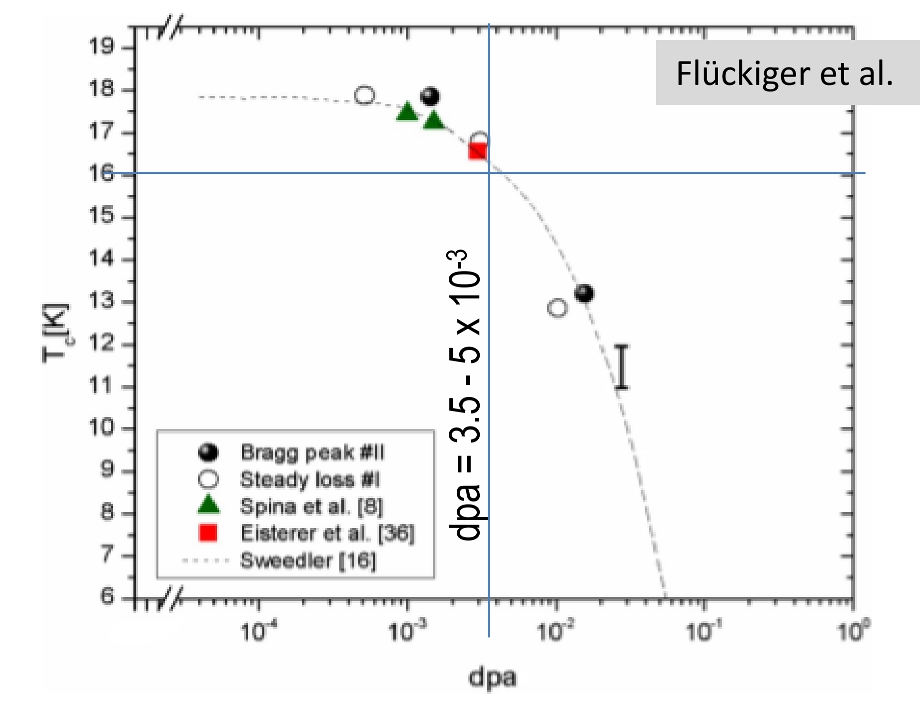
Heat load is below 4.5 $mW/cm^3$
Below the safe limit of 5 $mW/cm^3$

Protection of the arcs by collimators seems OK




Studies show no muon background from A into B and L

H. Rafique et al.




Dislocation of atoms changes superconductor
Small difference with shielding thickness (40%)
Seems to be still OK but measurements would be useful

# Special Experiment Insertions

Takes half of the insertion
Beam is injected in direction of the detector

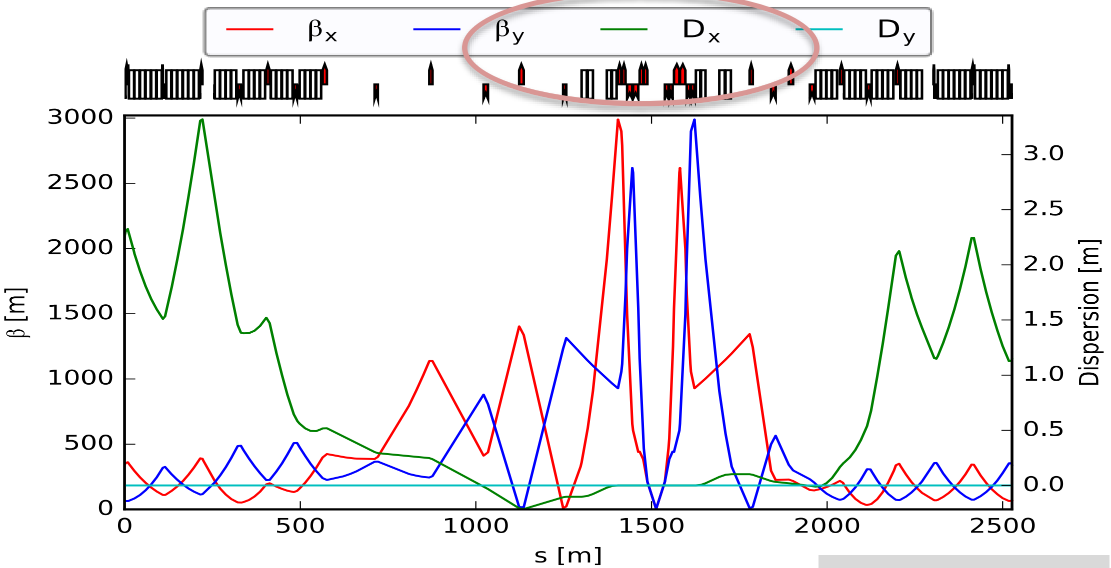
Preliminary design exists

- achieves $\beta^*$=3m
- up to L=O($2x10^{34}cm^{-2}s^{-1}$)
- Enough beam stay clear
- Room for shielding
- Injection optics to be refined
- Dynamic aperture to be checked

Total lifetime of triplet O($0.5ab^{-1}$)

Several improvements in past months

- E.g. magnet adjusted to model from magnet group




M. Hofer et al.

This is an example of what can be done

- Physics community will have to make some input
- Tradeoff with general purpose experiments
- How much integrated luminosity reduction in main experiments is acceptable?

# Injection Insertions

Same as special experiments

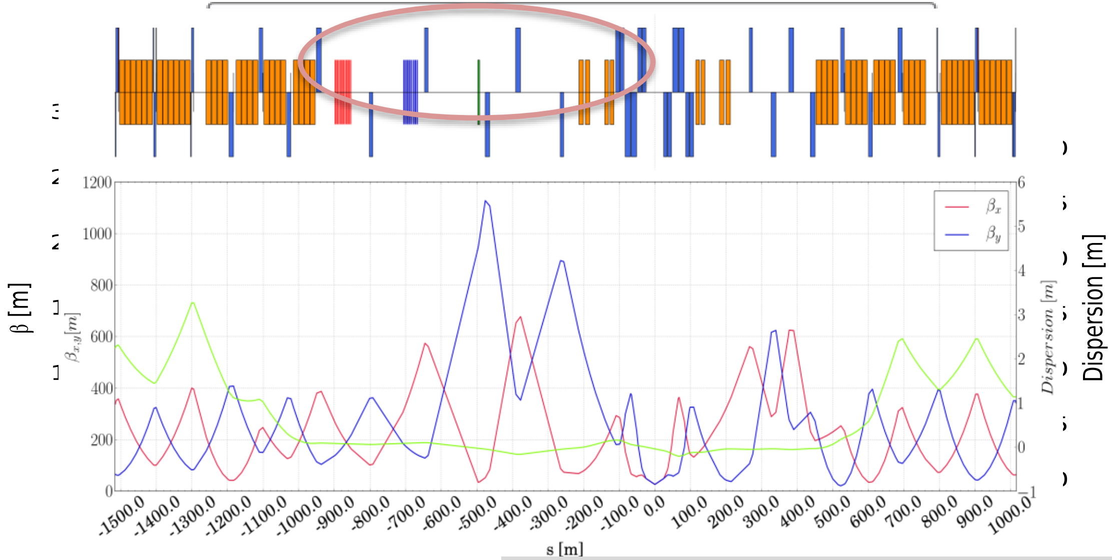
Have to inject before the experiment

- Otherwise beam could not pass

Main risk is beam loss at injection (misfired kicker)

- Inductive adder powering has different failures than LHC system, reduced risk

80 bunches avoids absorber damage




W. Bartmann, B. Goddard, E. Renner, M. Hofer, F. Burkart et al.

Studies of injection failures started
Local protection is OK
Novel ideas consider: e.g. massless septum

Global protection study ongoing with collimation team
Impedance of injection kicker needs to be worked on
(faster kick could imply higher impedance)

# Beam Losses

8 GJ kinetic energy per beam

- Boing 747 at cruising speed
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC
- Can drill 300 m deep hole

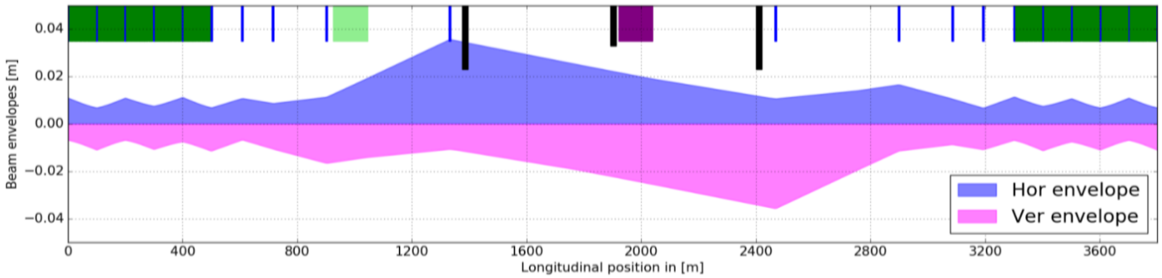
Machine protection strategy

- Make failures slow enough so that we can detect them and extract the beam
- Fast and robust extraction
- Proper injection design
- Collimation

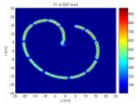
R. Schmidt et al.

# Extraction Insertion and Beam Dump

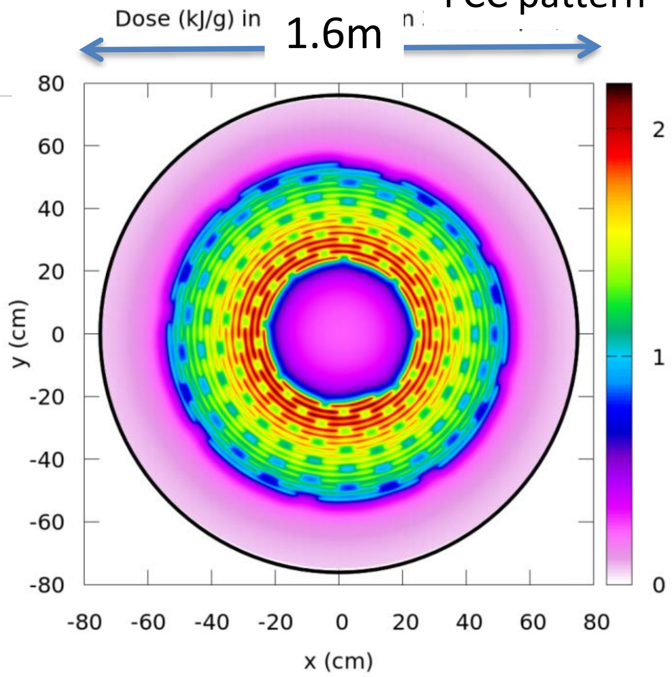
W. Bartmann, F. Burkart E. Renner, A. Lechner et al.




LHC pattern



FCC pattern




Main challenges
- Dilute beam on dump block
- Ensure asynchronous dump is handled

Insertion based on novel superconducting septa (SUSHI, CosTheta)
- Single kicker failure causes only 1.5 σ beam oscillation, consider leaving beam circulating and dump synchronously

# Collimation

Designs exist for collimation insertions, focused on betatron system (most challenging)

- Apertures defined and studied around the ring, about OK
- Main issues to sustain beam lifetime of 12 minutes (12 MW losses, very stringent specification)

Some momentum collimation work done in LAL and at FNAL

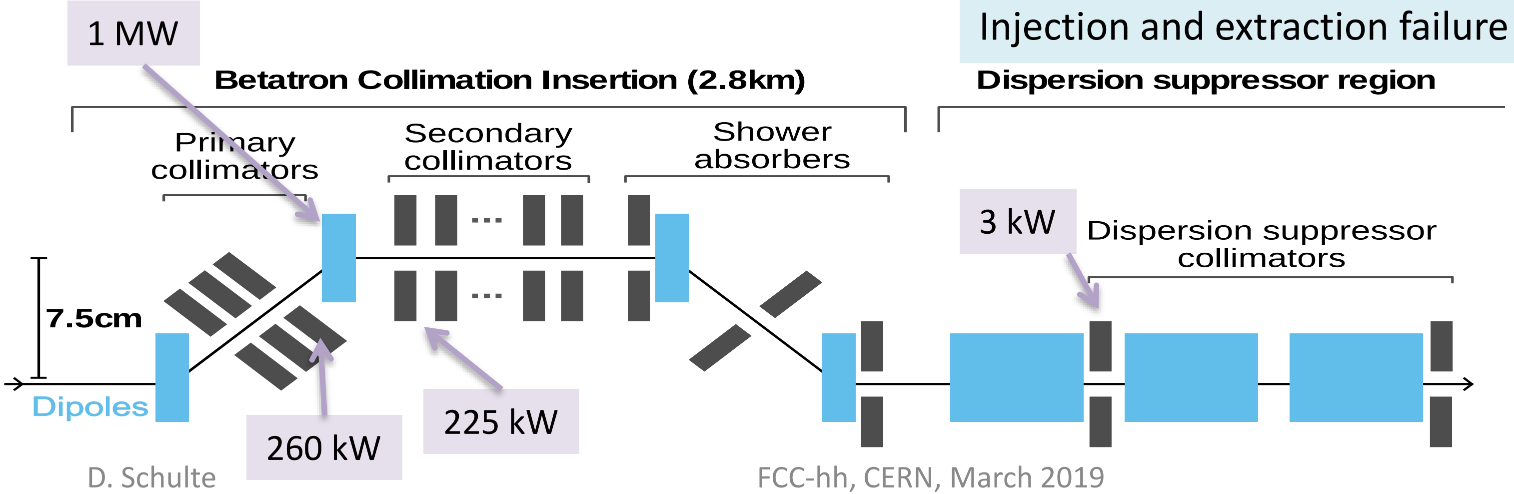
FLUKA simulations highlighted four critical points

- Evaluated strategies to resolve them

Choice of individual collimator material for acceptable impedance

- MoC with Mo coating, except for primaries and first secondary

Injection and extraction failure studies started



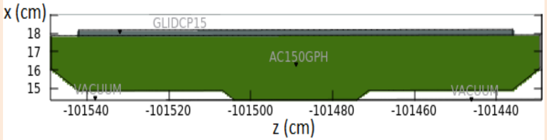

R. Bruce, F. Cerutti, J. Molson et al.

# Problems Solved

**Primary Collimators**

- Active length halved
- Skew removed

⇒ Max. power from 260 kW to 80 kW



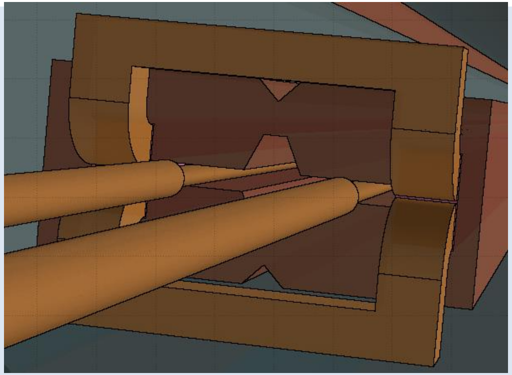

M. Varasteh et al.

50-100 kW acceptable
⇒ Consider system robust enough

**Dipole Losses**

Bend return coil away from beam

Place protection



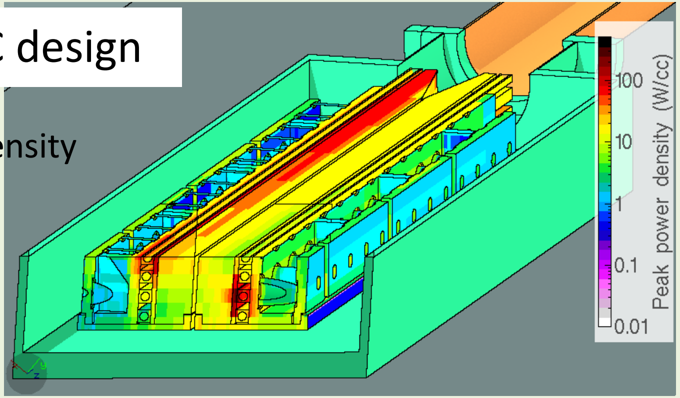
A. Krainer et al.

**Arc protection**

Protection design offers sufficient margin

**1st Secondary Collimator**

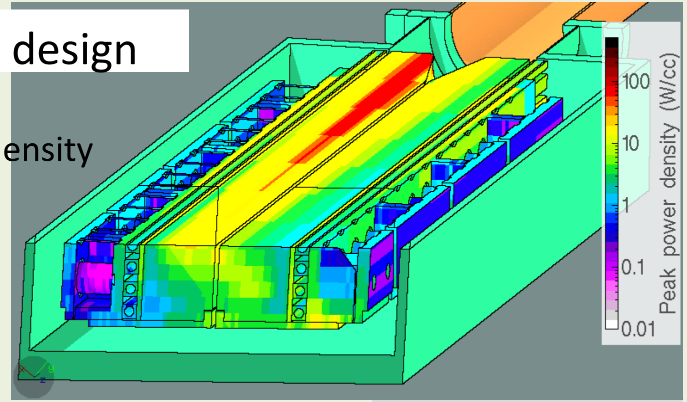
LHC design




max power density
800 $Wcm^{-3}$

total power
**225 kW**

New design



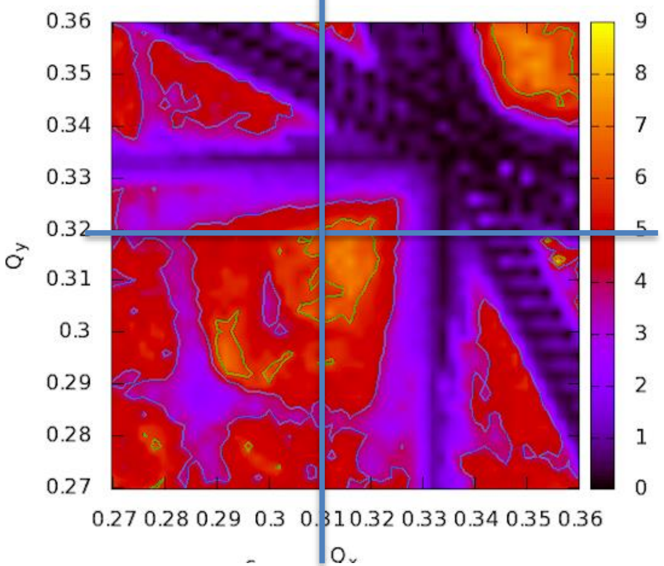

max power density
115 $Wcm^{-3}$

total power
**92 kW**

M. Varasteh et al.

# Beam Dynamics

Beam-beam studies



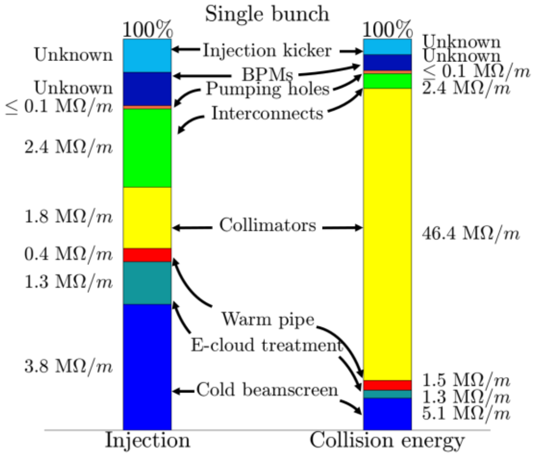

Lattice design, integration of octupoles for stability etc. corrector design, dynamic aperture studies, …

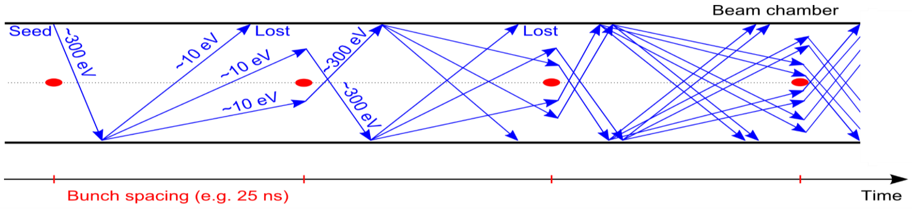
Beam dynamics studies validate the design

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Instabilities:
Impedances, octupoles, electron lens, feedback, ..
Electron cloud, coatings, …

Beam handling:
Collimation, injection, extraction, …



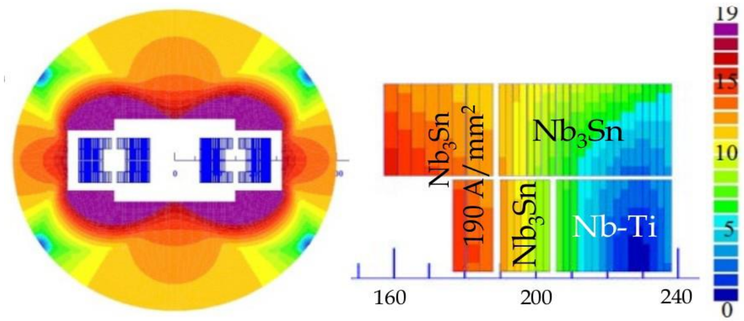



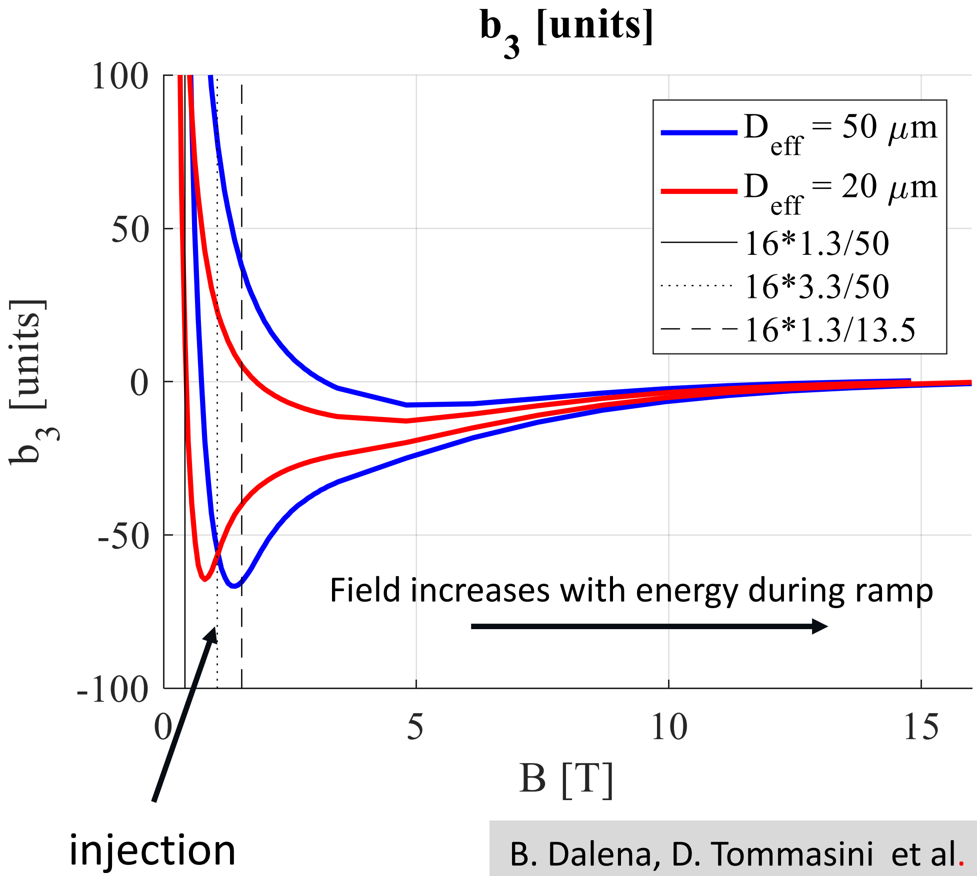
# Magnet Field Quality

Random and systematic field errors limit dynamic aperture at injection
⇒ Particles can be lost

Can correct with spool pieces (corrector magnets)
But need good alignment and loose length

Seem to have found a good solution but experimental verification is needed



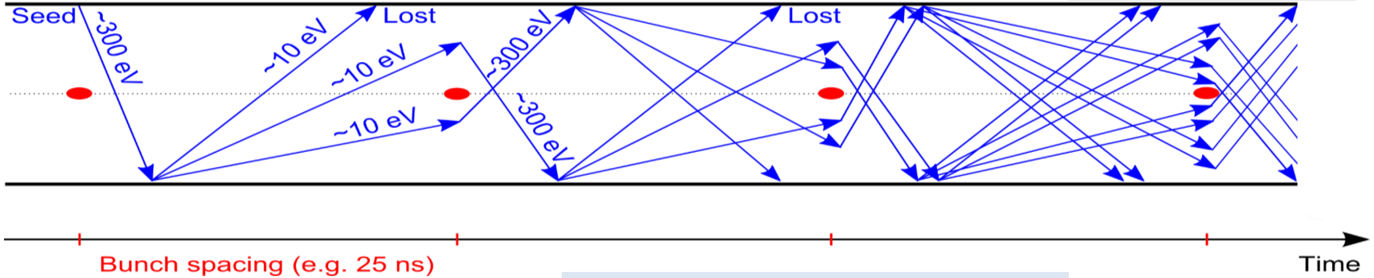

B. Dalena, D. Tommasini et al.

# Electron Cloud

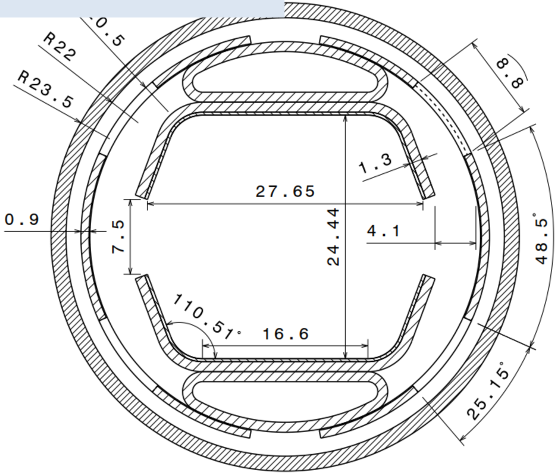
Important nuisance in LHC
- More critical in FCC-hh

Detailed studies of
- Seeding
- Build-up
- Beam stability

L. Mether et al.




Beamscreen design reduces photoproduction




Will treat surface to suppress electron cloud
- Either amorphous carbon
- or laser treatment

EuroCirCol WP4

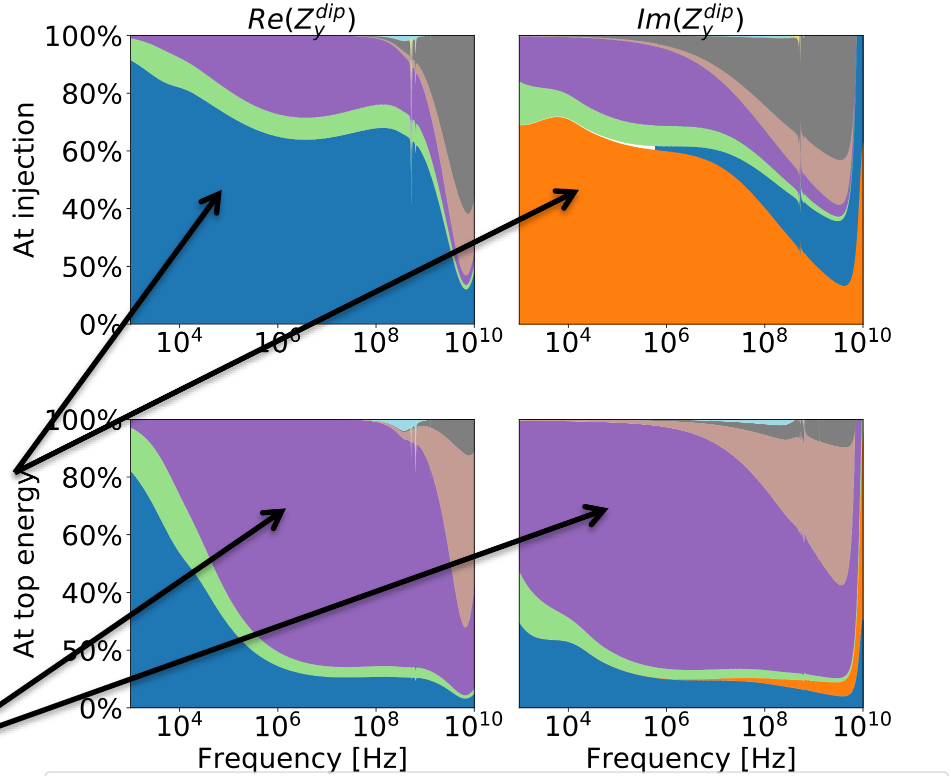

O. Malychev, S. Arsenyev, S. Calatroni et al.

# Impedance

One of the main current limitations
Critical for integrated luminosity

Beamscreen largest impedance at injection
- We have chosen its size accordingly
- Impedance of LASE surface treatment unknown
- Carbon coating is OK
- Edge coating should be applied

Collimation largest impedance at collision
- Bottleneck is final triplet
- Large enough so that impedance is just OK




O. Boine-Frankenheim, S. Arsenjev et al.

# RF and RF Insertion

E. Shaposhnikova

RF will be similar to LHC 400MHz
48 MV installed (3 x LHC)

Consider adding 800MHz for operational stability

Feedback to stabilise beam
- Change compared to LHC:
  - Operate in collision
  - Not foreseen in LHC design
  - But works
  - Required in FCC-hh

W. Hofle,
J. Komppulla

Space for electron lens or RF quadrupoles foreseen

T. Pieloni et al.

400 MHz(Nb-Cu)

# Injector Options

| | Energy range | Magnet design | Filling time | # of ramps | Bunches per cycle |
|---|---|---|---|---|---|
| scSPS | 26 GeV - 1.3 TeV | Sc NbTi/ s.apert. | 37 min | 35 | 4x160 |
| HEB@LHC | 450 GeV – 3.3 (6.5) TeV | Sc NbTi/ d.apert. | 44 min | 4 | 33x80 per ring |
| HEB@FCC | 450 GeV - 3.3 TeV | Superferric/s.apert. | 29 min | 2 | 130x80 |

B. Goddard, W. Bartmann, F. Burkard et al.

The baseline is 3.3 TeV from LHC

- Injection of about 40 minutes possible with faster ramping in LHC

The main alternative is 1.3 TeV from a superconducting SPS

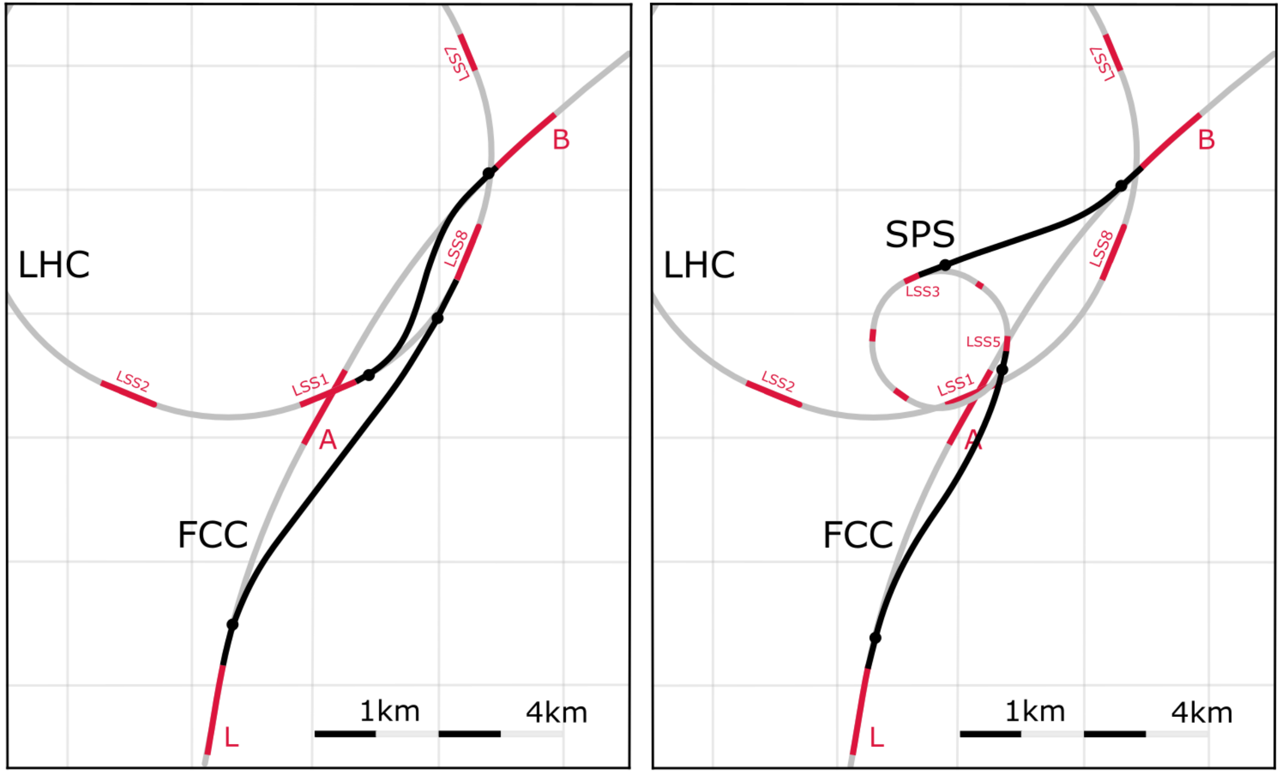
- Similar injection time
- But more work to make sure dynamic aperture is large enough
- Also beam stability will be reduced

# Transfer Lines

LHC and SPS can be connected to FCC-hh

Total of O(5.5 km) superconducting bends in transferlines from LHC, at 7.2 T

O(6.5 km) normal-conducting bends from SPS, at 1.8 T




E. Renner et al.

# Heavy Ion Operation

M. Schaumann, J. Jowett et al.

Estimates for ion operation assume LHC as injector.

Luminosity per experiment for 2 active experiments in a 1-month run:

| Beam scenario | Pb-Pb | p-Pb |
|---|---|---|
| Initial | 23 $nb^{-1}$ | 6 $pb^{-1}$ |
| Nominal | 62 $nb^{-1}$ | 18 $pb^{-1}$ |

Most critical issues that have been addressed:

- Collisions produce secondary ions with changed rigidities that will be lost in small spots in the dispersion suppressor around the experiments, seems OK with protection from protons
- Reduced collimation cleaning efficiency for ions is OK for collimation system
- Additional arc protection is required (needs integration with protection for protons)

More work to be done to integrate with proton design and to further push performance

- E.g. injector complex

# Note: Other Bunch Spacings

Identified three main alternative scenarios, but need to study them

| | | | Opt 1 | Opt 2 | Opt 3 |
|---|---|---|---|---|---|
| Bunch spa | | | 12.5 | 5 | 5 |
| Protons pe | | | 0.5 | 0.2 | 0.2 |
| Init. hor. t | | | 1.1 | 1.1 | 0.44 |
| Init. vert. t | | | .1 | 1.1 | 0.44 |
| Final hor. | | | .25 | 0.22 | 0.22 |
| Final vert. transv. e | | | .2 | 0.17 | 0.17 |
| Max. total beam-be | | | .03 | 0.03 | 0.03 |
| IP beta-function [m] | | | | | 0.3 |
| Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$] | 5.0 | | | | 20.1 |
| Max. number events per crossing | 17 | | | | 137 |
| Optimum integrated luminosity / day [fb$^{-1}$] | 2.2 | | | | 6.2 |

Important improvements of injector system

Higher risk in beam transfer

Electron ... tor

Much more study is required before we can conclude

Higher risk in beam transfer

Electron cloud more severe

# Conclusion

- Have FCC-hh conceptual design
  - Many key issues addressed
  - Further R&D required to improve robustness of design
  - But expect no insurmountable obstacle
  - Concise FCC-hh CDR is available
  - More extended CDR is being written

Many thanks to all the great teams

- Further opportunities exist to optimise the design
  - Overall design, e.g. layout, optics, tuning procedures
  - A number of important R&D items, e.g. magnet field quality, beamscreen laser treatment, …

# Key R&D

Important needs for magnets:

- 16 T magnets and $Nb_3Sn$ wire
- If FCC-hh is second stage: higher fields and HTS

Beam transfer

- Superconducting septum magnet
- Solid state generators

Efficiency and cost

- Efficient and cost effect cryogenics refrigeration and distribution
- Energy storage and release to reduce energy consumption
- Efficient power distribution