FCC-hh Conceptual Machine Design
CDR Status

Daniel Schulte for the FCC-hh team
Amsterdam, April 2018

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

Overview and Beam Parameters

Draft of the concise CDR is available

- Some improvements are required
- Some finalisation of choices
- People are still happy to improve the design …

Maybe should modify wording

- "Baseline" to "initial" beam parameters
  - Baseline can now be confusing
- "Ultimate" beam parameters remain

Focus is on ultimate parameters

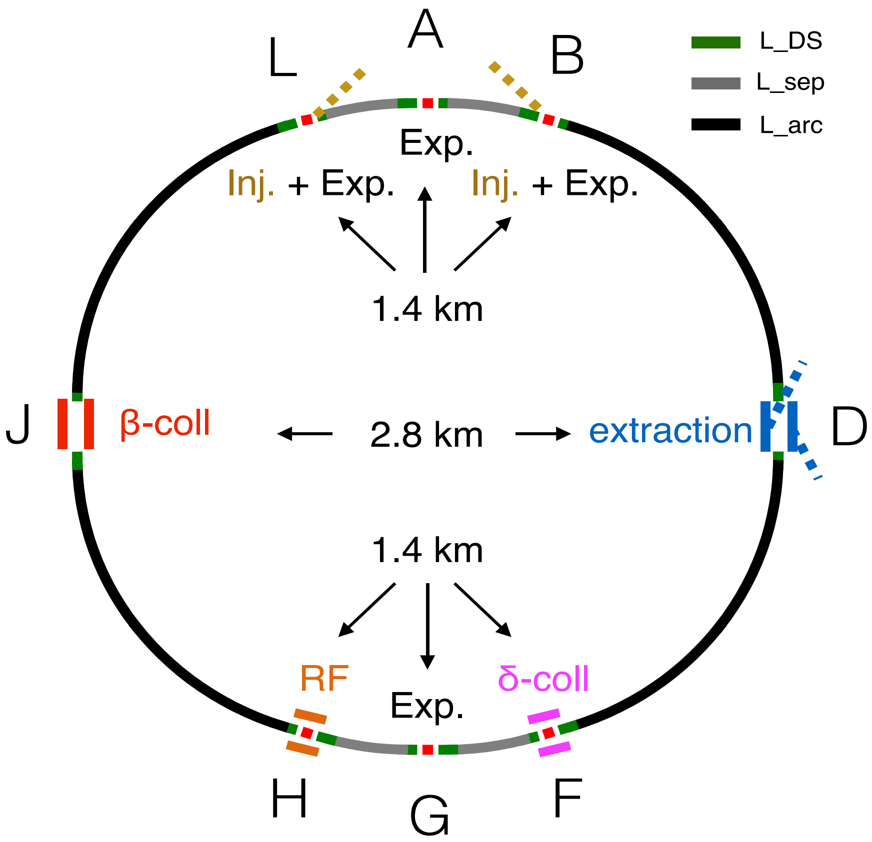
Comprehensive CDR has started

	FCC-hh Initial	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

FCC-hh Layout

Layout has changed according to site requirements
Some further change in the future expected

- 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 use LHC or SPS as injector



Luminosity During a Run

Developed model including most relevant effects

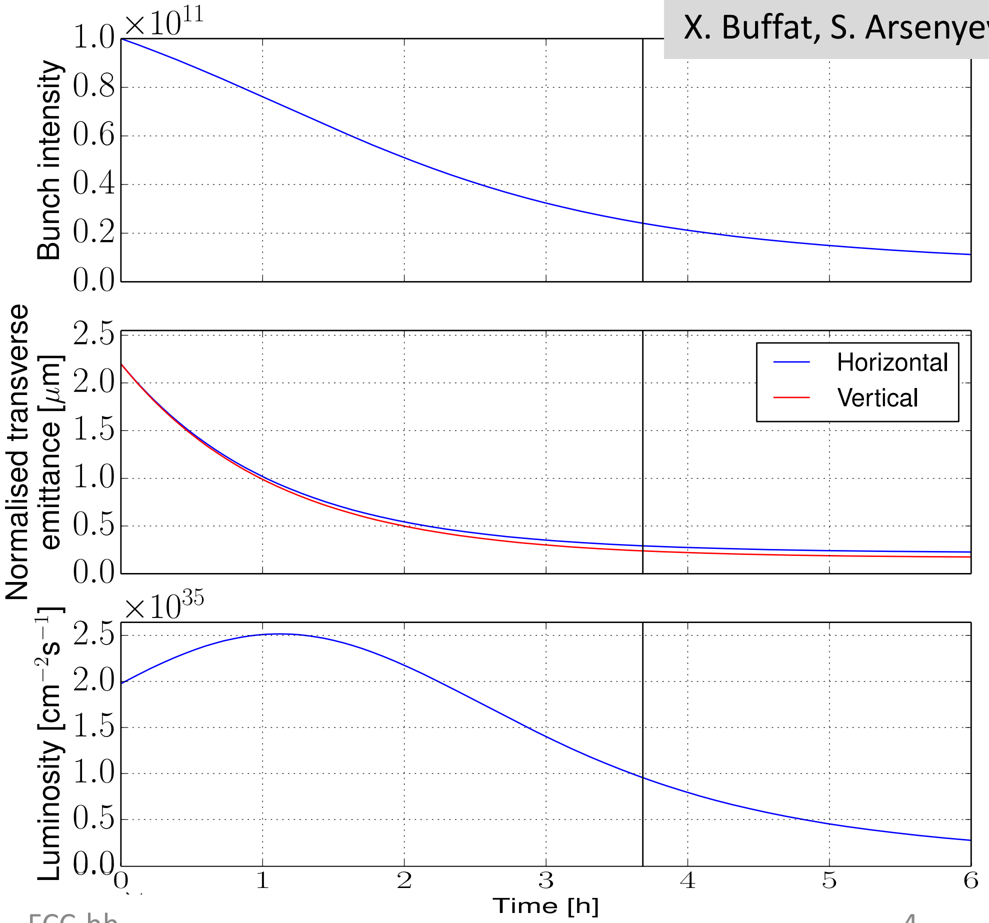
- Radiation damping and heating
- Beam burn-off
- Emittance growth due to beam-beam is included
    - Based on LHC experience
    - Same power supply ripples assumed

⇒ Beam is burned quickly

⇒ A reason to have enough charge stored

⇒ Expect to reach integrated luminosity target

X. Buffat, S. Arsenyev



Arc Layout

90° FODO cells, L_{cell}=213.03 m

- 12 dipoles a 14.069 m
- Quadrupoles, sextupoles, spool pieces, correctors, …
- Dipole field 15.96 T

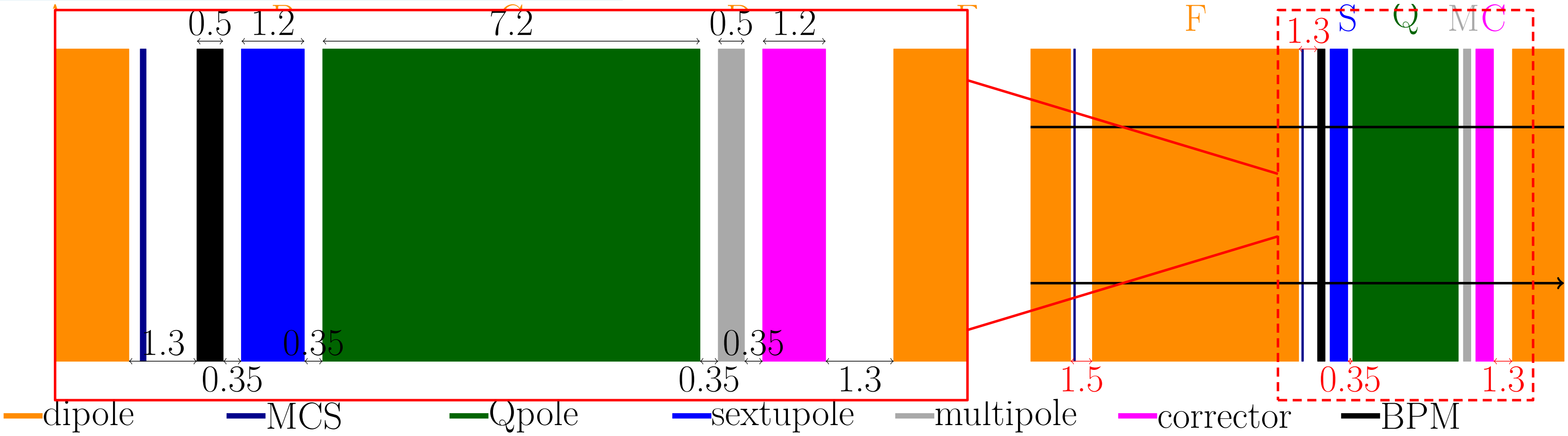
Dispersion suppressors (end of the arcs) are LHC-style

Iterated with magnet team

- Improved length estimates
- Integration of octupoles

Strategy if more space is required for correctors or quadrupole: shorten dipoles to preserve cell length

A. Chance, B. Dalena, J. Payet

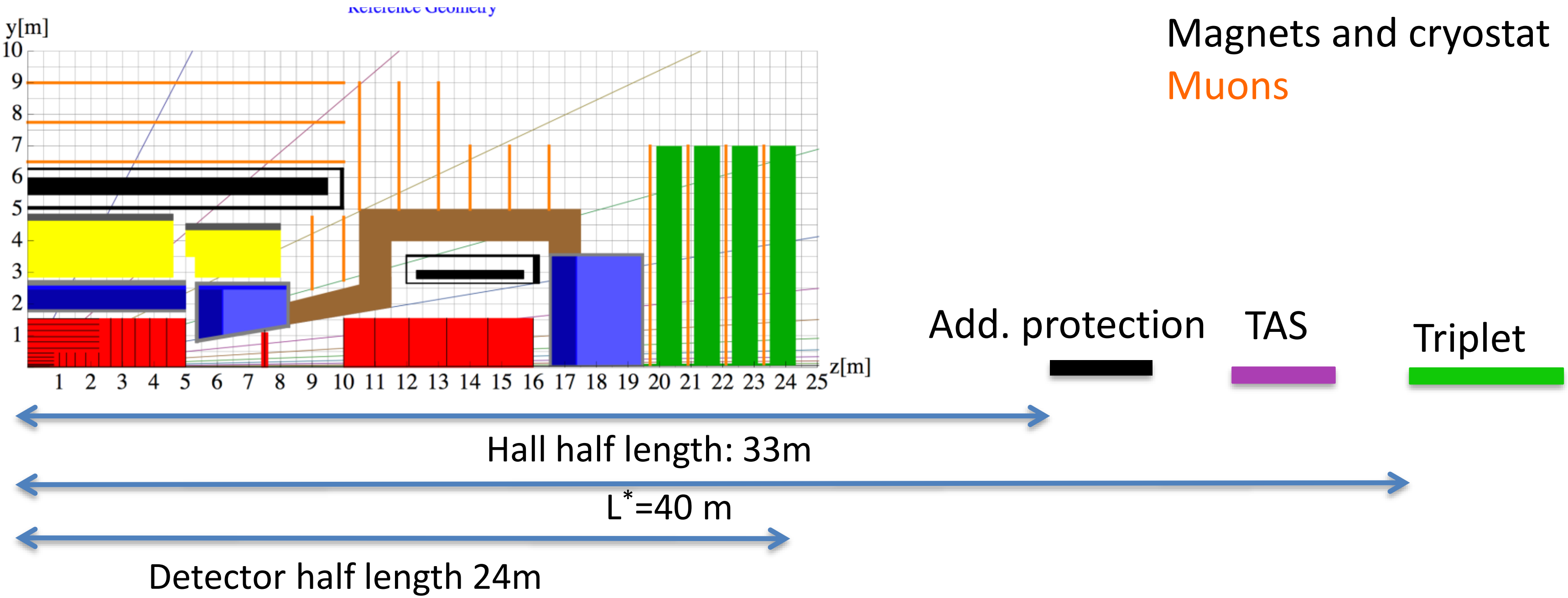


FCC Machine Detector Interface

W. Riegler at al.

Experiments prefer L^* = 45 m to allow for different detector solutions
But difficult for focusing system, system 100 m too long
Decided to use L^* = 40 m, system now fits

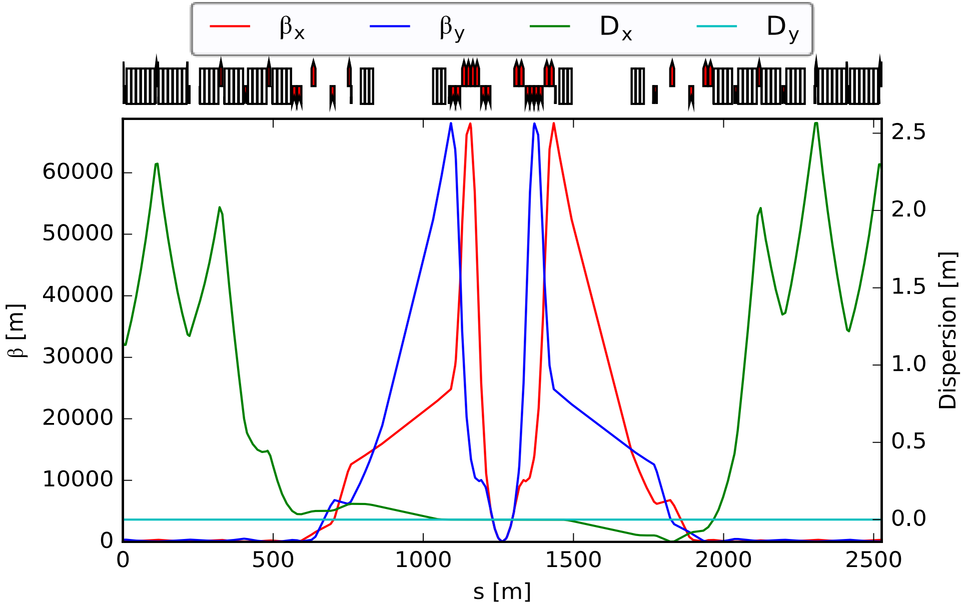
Tracking
Ecal
HCAL
Magnets and cryostat
Muons



High-luminosity Insertions

New L^* = 40 m to shorten the insertion to 1400 m

Room for shielding of triplets somewhat reduced



Important effort to achieve dynamic aperture with triplet magnetic field errors

- Significant improvements in correction techniques
- On a good path but no quite there

Many issues are being addressed

- Aperture of separation dipoles
- Technology choice for dipoles
- Crab cavity integration
- …

Alternative optics with flat beams is also being studied

R. Martin, E. Cruz et al.

Collision Debris

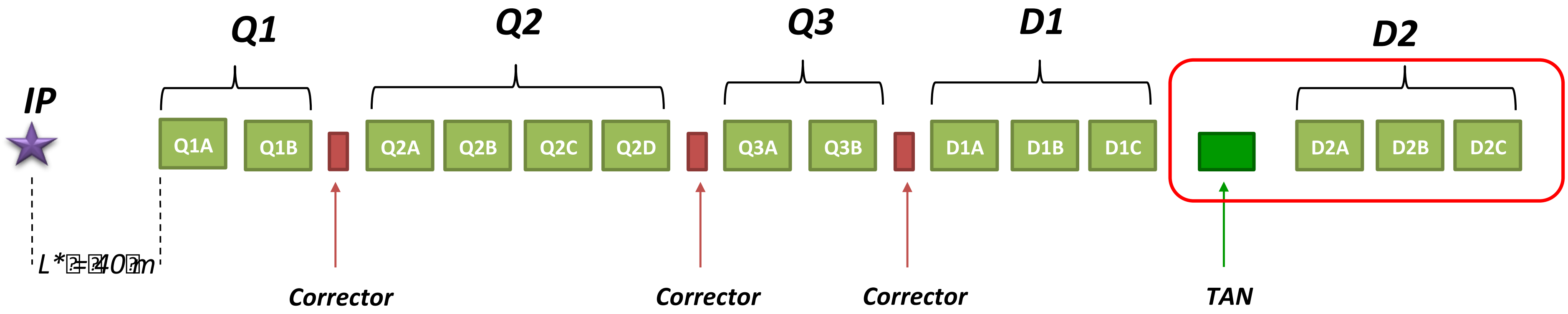
F. Cerrutti et al.

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

- Repeated triplet studies for new design
- First study of losses in dipoles

Triplets are protected by shielding
35 mm on the inside (before 55 mm)

	Max. dose	Comment
Radiation Triplet	70 (40) Mgy int. L = 30 ab^{-1}	Today's limit 30 MGy Hope to improve limit
Heat load Triplet	4.5 mW/cm^3 L = 3 x 10^{35} $cm^{-2}s^{-1}$	Expected limit (with safety marging) 5 mW/cm^3
Radiation dipole	90 MGy	Today's limit 30 MGy Hope to improve limit Better protection possible



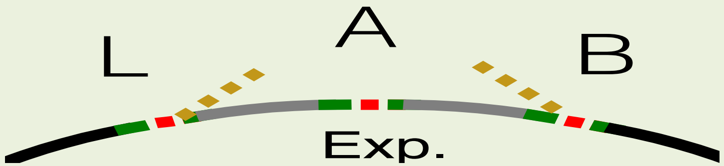
Collision Debris

Background in into the arcs and into other experiments has been studied in the past

Choice of short arc minimum length for this purpose

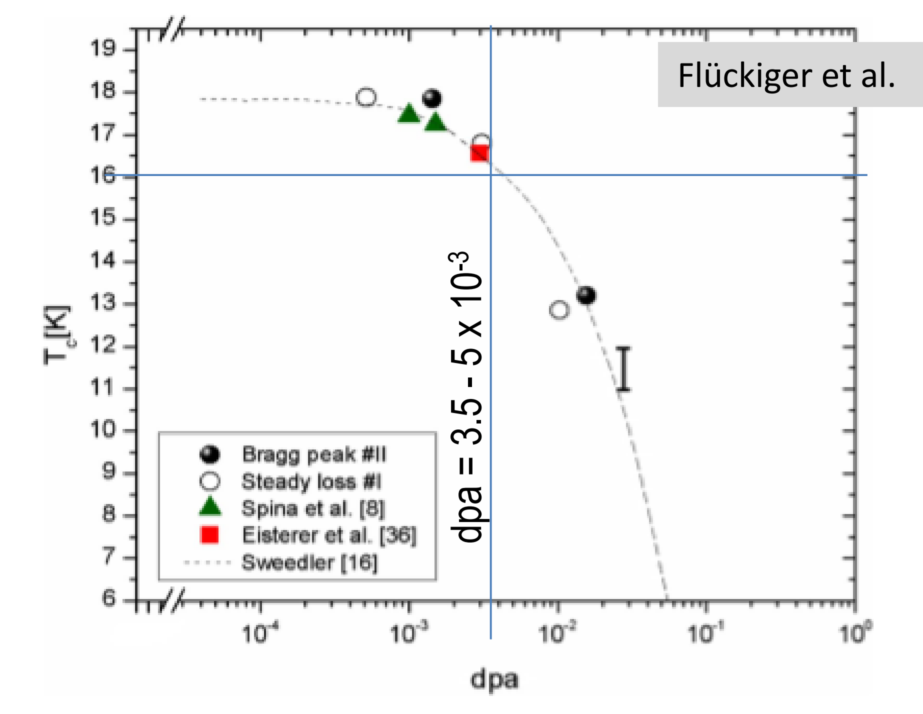
Protection of the arcs by collimators seems OK

A. Krainer et al.



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

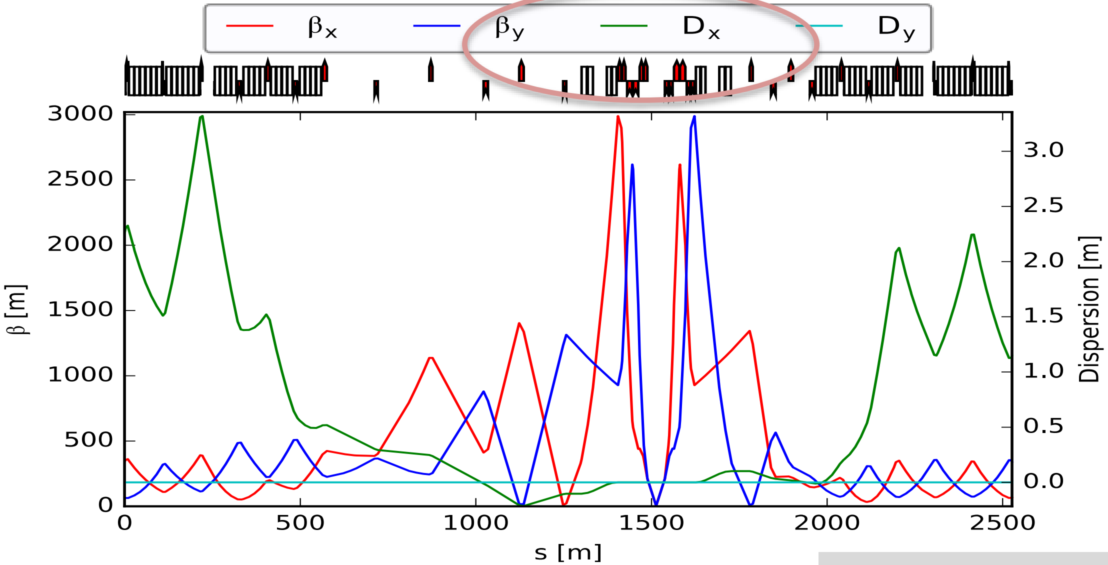
Special Experiment Insertions

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

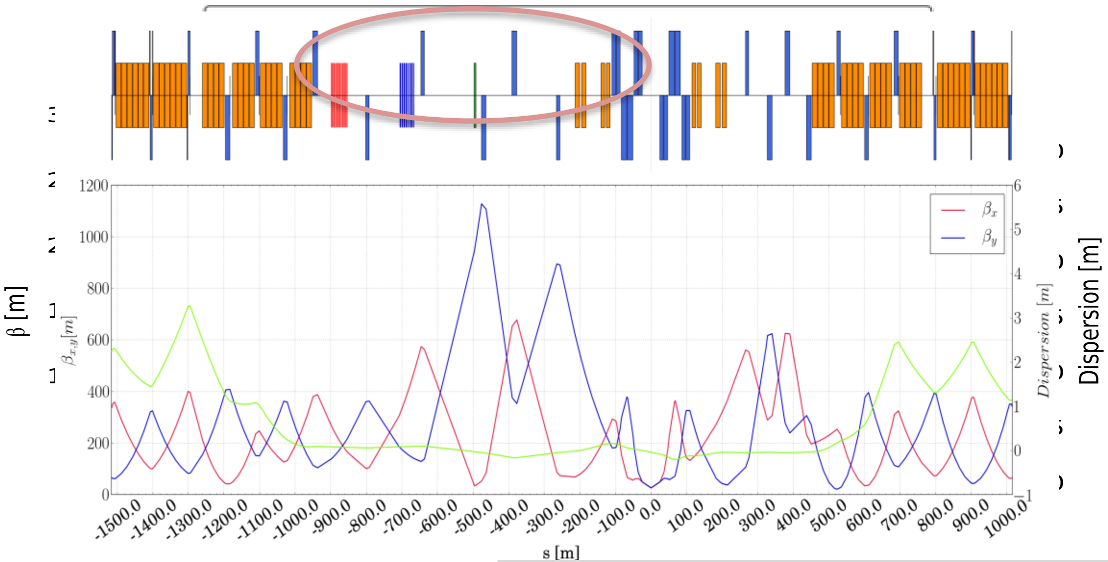
Have to inject before the experiment

- 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)

RF and RF Insertion

RF will be similar to LHC 400MHz

E. Shaposhnikova

Consider adding 800MHz for operational stability

Installed voltage of 48 MV (40 MV might be enough)

- Bucket forming voltage 12 MV at injection
- 32 MV at collision
- Synchrotron tune and energy spread smaller than in LHC

Space for feedback foreseen

W. Hofle, J. Komppulla

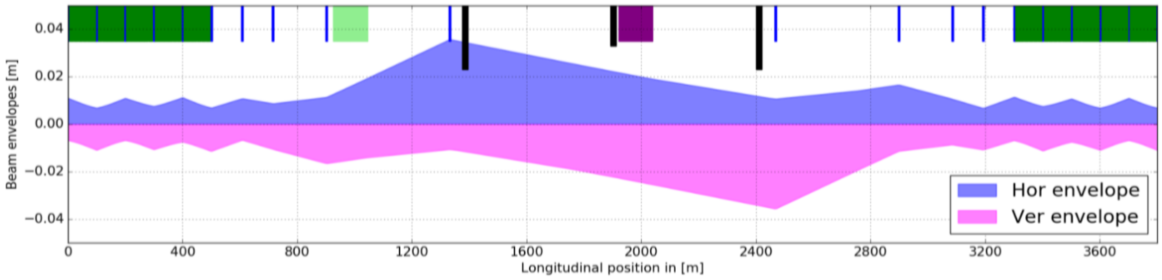
Design is being optimised

- Damping time of 20 turns at injection
- 220 turns at collision energy
- Provides safety margin of factor 3

Space for electron lens or RF quadrupoles foreseen

400 MHz(Nb-Cu)

Extraction Insertion and Beam Dump

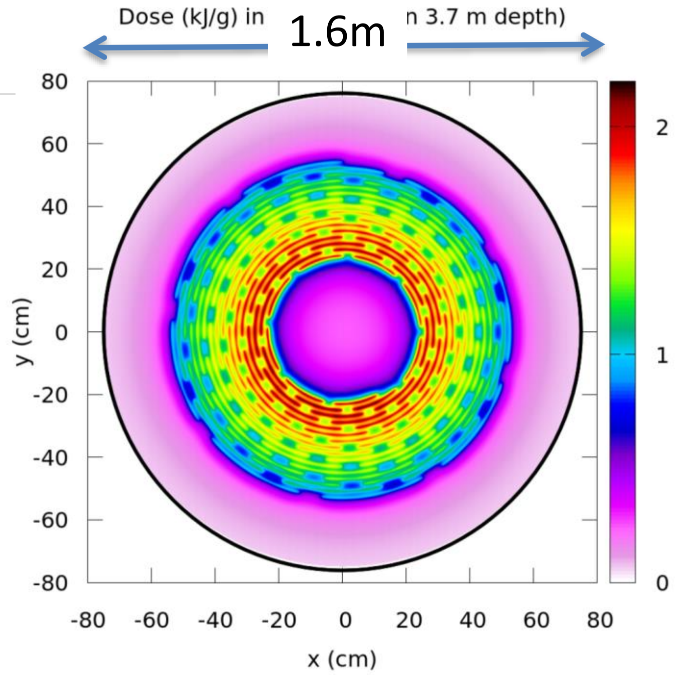


W. Bartmann, F. Burkart E. Renner, A. Lechner et al.

Recently new insertion design has been proposed

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

Global protection study is ongoing with collimation team



Dilution pattern to distribute beam power based on FLUKA studies

Issue of dilution in case of asynchronous beam dump is solved

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

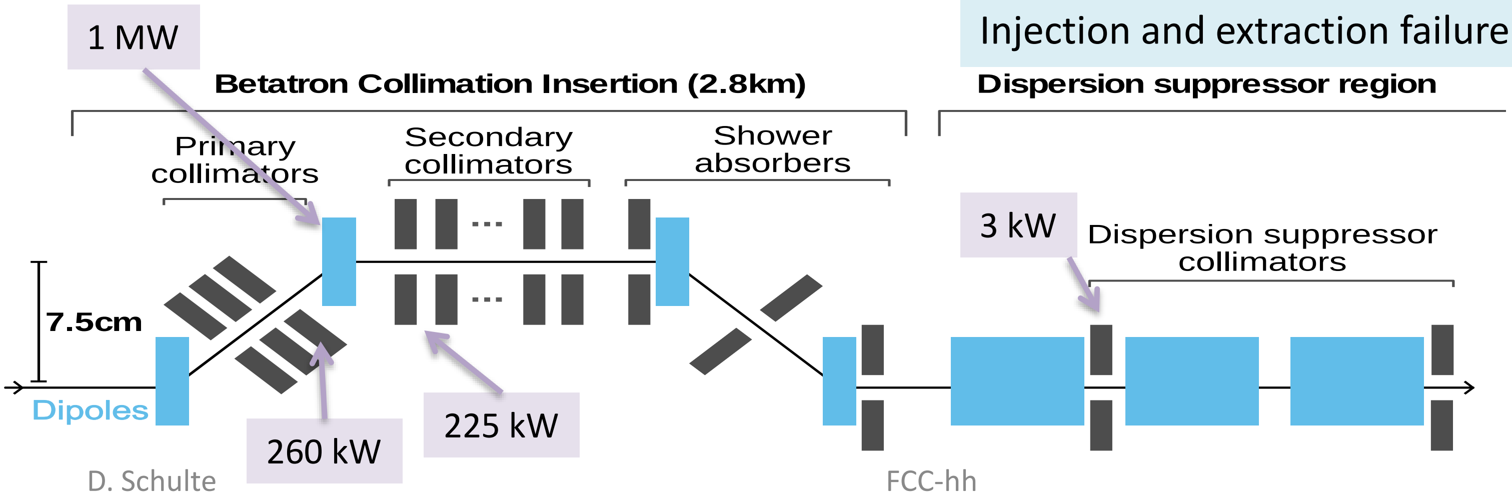
FLUKA simulations highlighted four critical points

- 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

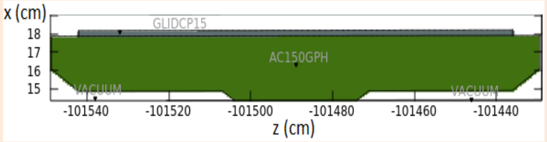


R. Bruce, F. Cerutti, J. Molson et al.

Save the Collimators

Primary Collimators
- Active length halved
- Skew removed

⇒ Max. power from 260 kW to 80 kW



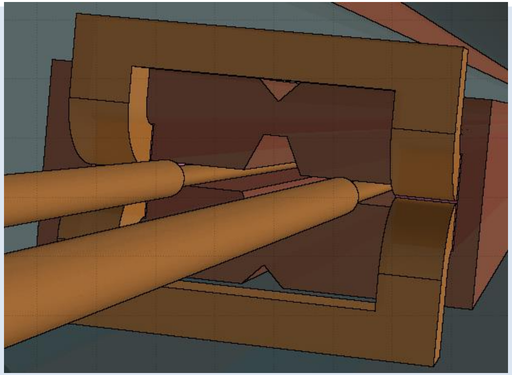
50-100 kW acceptable

⇒ Consider system robust enough

M. Varasteh et al.

Dipole Losses
Bend return coil away from beam

Place protection



A. Krainer et al.

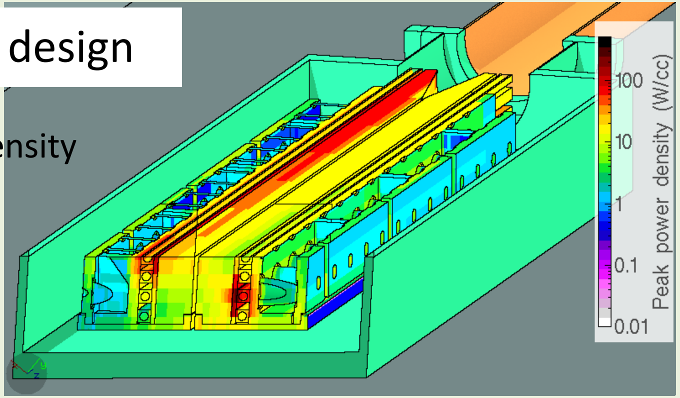
Arc protection
Protection design offers sufficient margin

1st Secondary Collimator

Old design

max power density 800 Wcm^{-3}

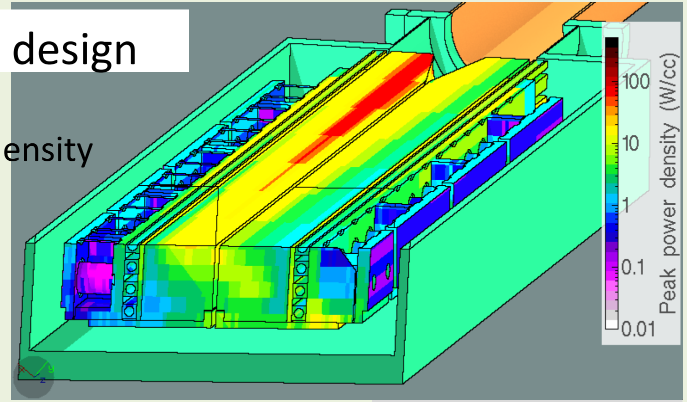
total power **225 kW**



New design

max power density 115 Wcm^{-3}

total power **92 kW**



M. Varasteh et al.

More Collimation

Aperture studies show: basically OK, a few tight points (e.g. dispersion suppressor)

- Confident to solve this

R. Martin et al.

Momentum collimation must collimate 1% loss over 10 s at start of ramp (560 kW)
A new momentum collimation system proposed by FNAL team
Studies of efficiency and losses will start

Mokhov, Alexahin, Gianfelice, Tropin), NIU (Narayanan, Syphers)

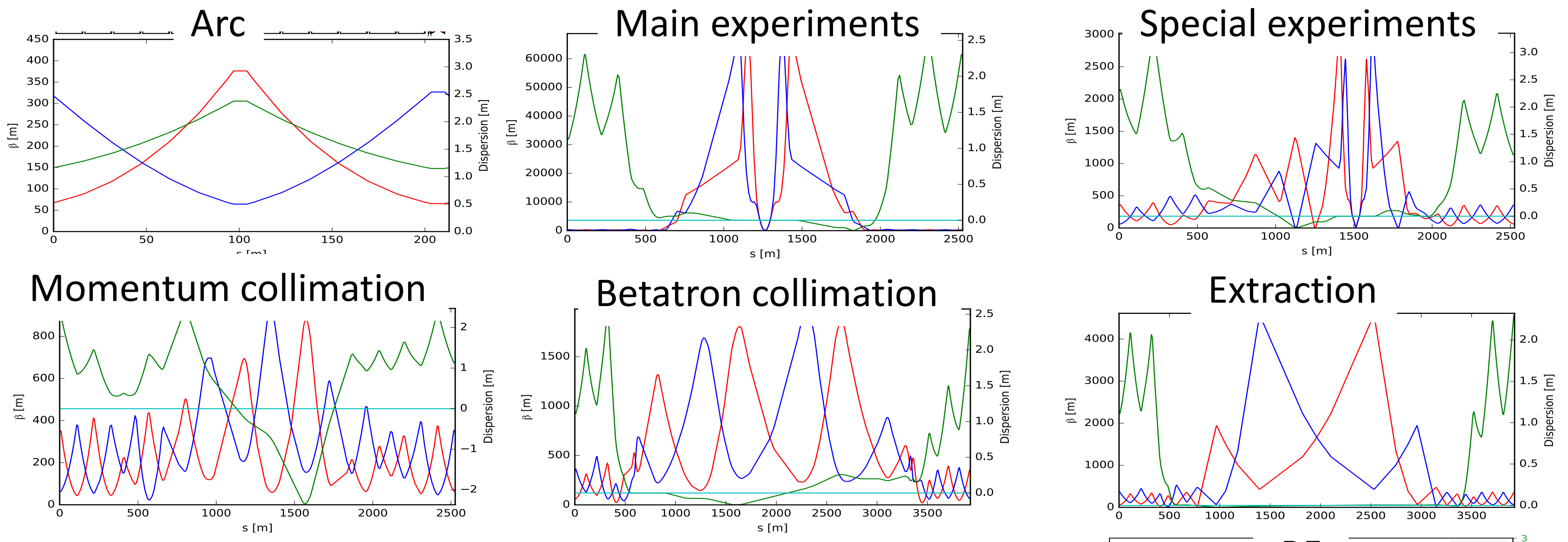
MARS - MAD-X/PTC recently completed, will simplify benchmarking

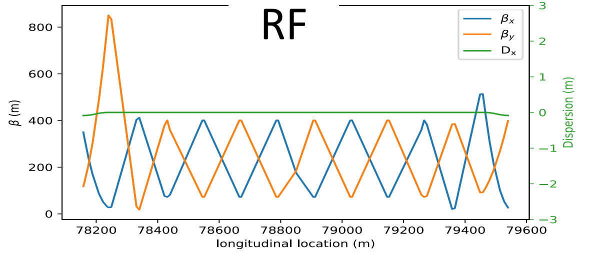
Failure studies started for extraction kickers (for old extraction system)

- 3 misfiring kickers (of 300) do not lead to damage on collimators or other components

J. Molson, E. Renner, Y. Nie

Integrated Lattice





Full integrated lattice exists

- large amount of work (code, matching, tuning, …)
- some small issues remain to be solved
- specifications for magnets are almost complete
- beam separation changed recently to 204mm

A. Chance et al.

Lattice Imperfection Studies

Dynamic aperture limitation due to field errors

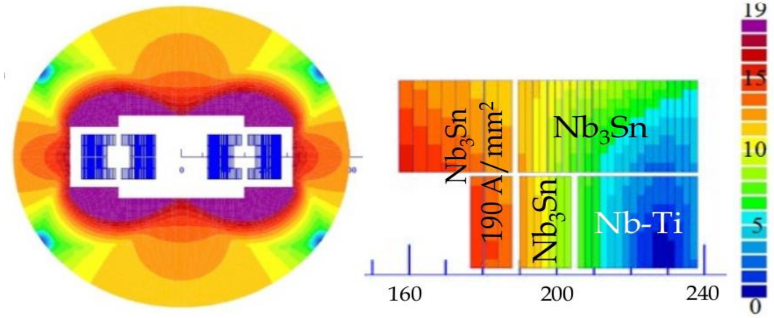
Important feedback to the magnets before Berlin
Systematic field errors increase strongly for **b2** and **b3**

Need to compensate b3 with spool pieces
- Alignment of spool pieces needs to be 5 times better than in LHC (0.1 vs. 0.5 mm)
- Or reduce b3 in the magnets

Larger b2 leads to beta-beating
- Mainly a result of the reduced beam distance
- Can be controlled with the regular lattice

Require improvement of magnet design
- Could be important factor in choice of magnet baseline design

B. Dalena et al.



Alignment tolerances and corrector specification
- Modeling available
- Improved solutions since Berlin

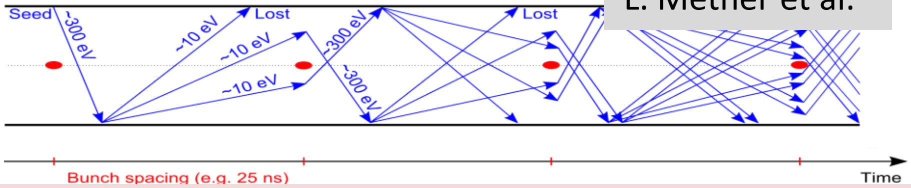
- Most tolerances similar to LHC
  - BPM read error has to be tighter with 0.2 mm vs. 0.5 mm in LHC

D. Boutin, B. Dalena et al.

Electron Cloud

Secondary emission yield requirements:
For 25 ns: below 1.2
For 12.5 ns: below 1.0

L. Mether et al.

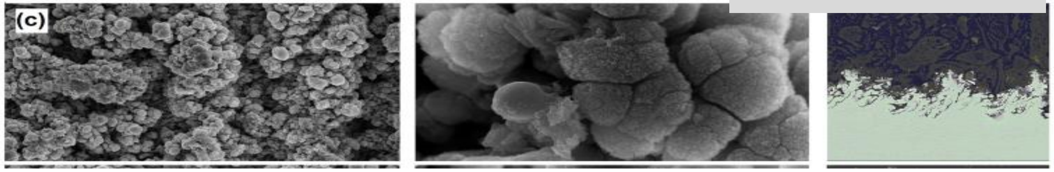


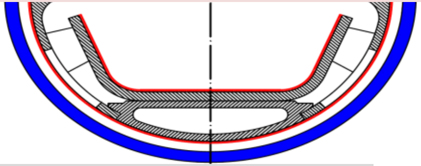
Arc element	25 ns injection / top energy	12.5 ns injection / top energy	5 ns injection / top energy
Dipole	1.6 / 1.6	1.2 / 1.2	1.5 / 1.4
Quadrupoles	1.2 / 1.3	1.0 / 1.1	1.1 / 1.1
Drift	1.8 / 1.8	1.2 / 1.2	1.5 / 1.4

Mitigation techniques are laser treatment or carbon coating
OK for 25 ns
Somewhat marginal for 12.5 ns

Impedance of laser treatment might be high
- Experiment will allow to optimise
- Or amorphous carbon

EuroCirCol WP4





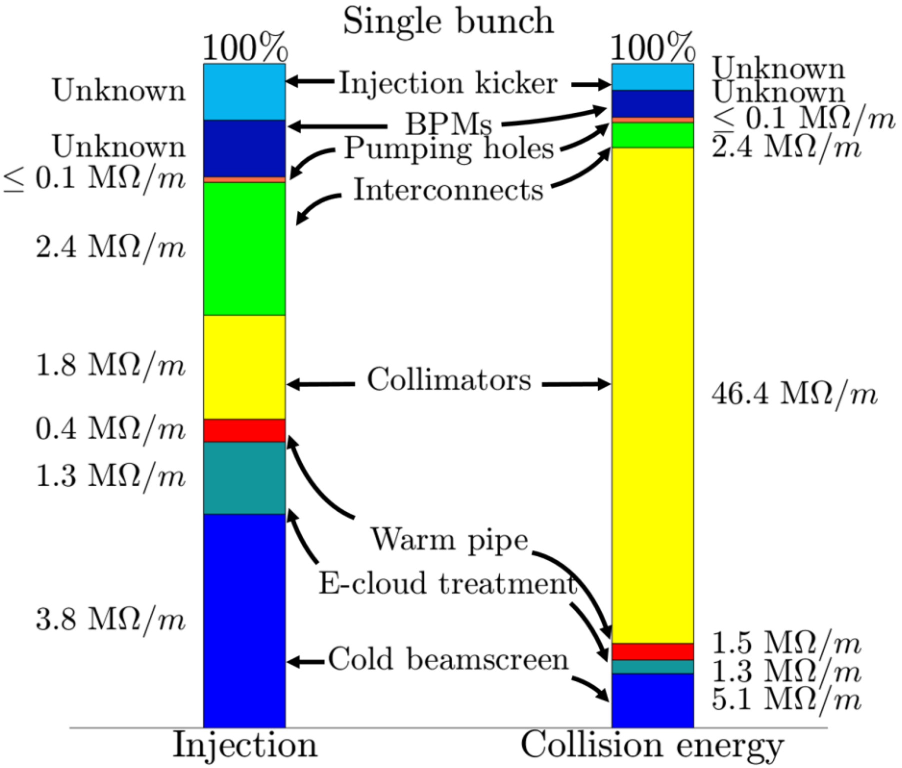
O. Malychev, S. Arsenyev, S. Calatroni et al.

Impedances

Impedance estimated significantly improved

- Resistive impedance of the cold beamscreen: OK
- Impedance of the pumping holes estimated: OK
- Impedance of the laser treatment against electron cloud: measurements needed might be high
  - Alternative carbon coating: OK
- Interconnect between dipoles: OK
- Choice of collimators for acceptable trade-off robustness vs. impedance: OK
- Impedance of warm beam pipe of the machine: OK

Mitigation is use of feedback for rigid bunch modes
Octupoles / electron lens (0.6 A) / RF quadrupoles / intra-bunch feedback for other modes



O. Boine-Frankenheim, S. Arsenyev, B. Riemann, C. Tambasco, T. Pieloni et al.

Beam-beam Effects

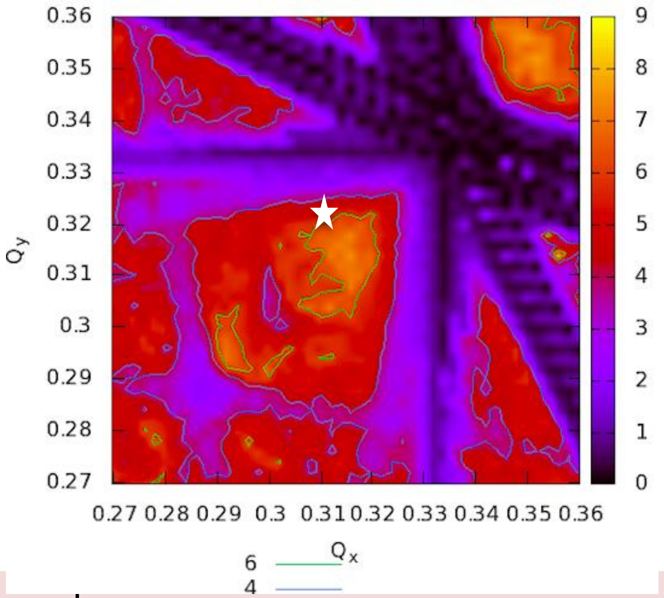
Dynamic aperture of 7.2 σ with beam-beam effects
⇒ The same as the collimation aperture
⇒ No contribution to particle loss
⇒ Reserve for octupoles, chromaticity etc.

Long-range effects can cause beam-beam offsets in the 0.2 σ - 0.3 σ range
⇒ Luminosity loss of <1%

For ultimate parameters need to operate additional experiments with beam offsets to limit tuneshift

Noise budget for beam-beam effects leads to 0.15 μm/h emittance growth
Based on scaling from LHC

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



More work
- Operation scenario with four experiments
- Interaction of noise with instabilities
- …

Machine Protection

8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- O(20) times LHC

Beam loss		Comment	
Loss at IP	3.2h lifetime	0.5 MW collision debris => shielding	Basically OK
Distributed losses (beam-gas)	Lifetime 100h Lifetime 20h	20-30 MW of additional cooling power Still below quench limit for magnets	Studied FLUKA team
Operation limit	Beam loss rate is 1/720s in β coll. syst.	Collimation system must protect machine loss	Seems basically OK
(Very) fast beam loss	Several to many turns	Detect equipment failure quickly enou E.g. sets limits on magnet failure spee	Being studied Y. Nie, R. Schmidt et al.
Single turn	Will not make turn	E.g. Injection/extraction failure Use active/passive protection	Studies are ongoing

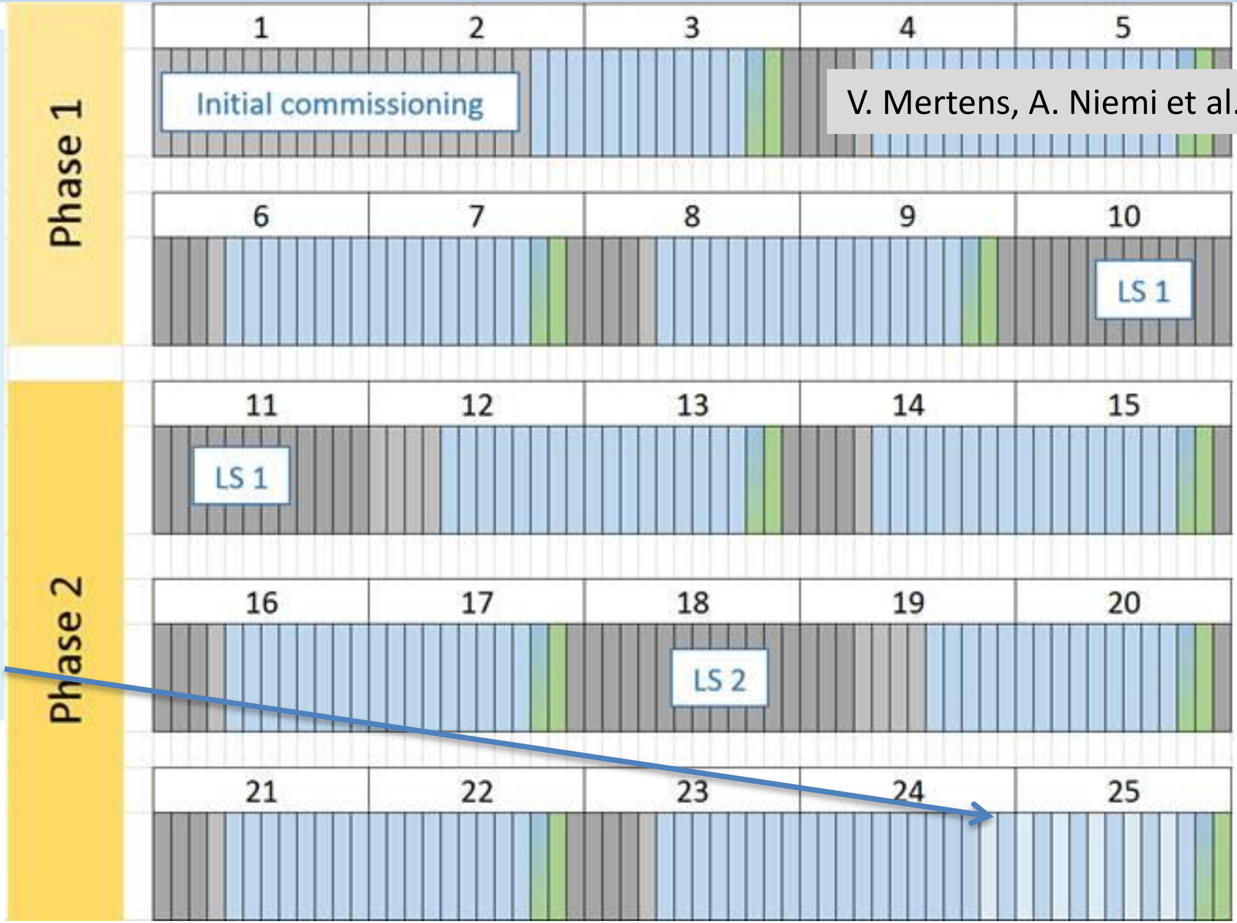
Operational Scenario/Availability

From 5 year to 9 year cycles

For 5 year cycles:
18 m shutdown
9 m stops and commissioning
33 m physics (~1000 days)

- 70% availability leads to goal of 5ab^{-1} per ultimate run
- For ions 3x30 days, i.e. 10% of integrated luminosity?

Now 184 months of physics until here



V. Mertens, A. Niemi et al.

Availability studies started
⇒ Volker Mertens

A. Apollonio et al.

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)	286.3 (4.8 h)

FCC goal is 4h on average
Updated with 2017 LHC data

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.

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

Issues are:

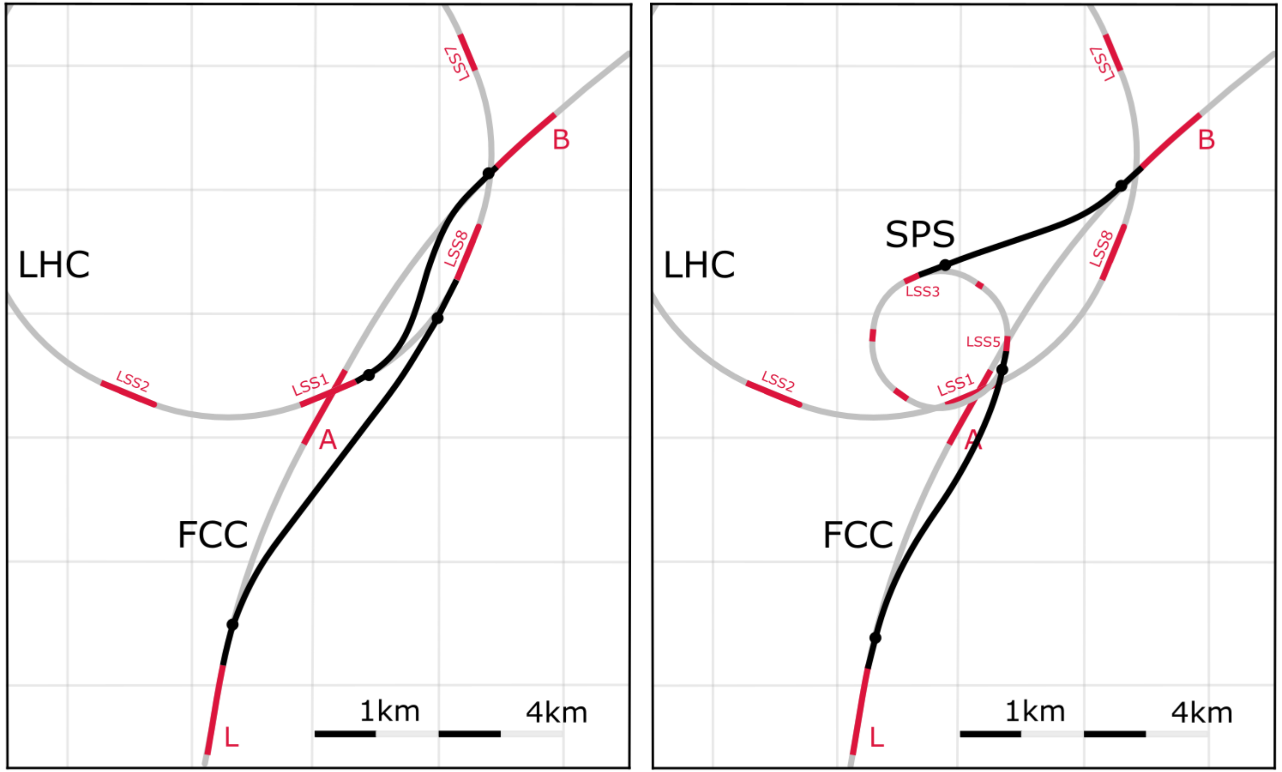
- Normalised aperture at injection reduced to 60%, i.e. 4.5σ for primaries
- Impedance effects increase by factor 2.5
- Field quality at lower injection field, the values are being investigated

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

Estimates for ion operation assume LHC as injector.

M. Schaumann et al.

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}
Ultimate	65 nb^{-1}	18 pb^{-1}

Most critical issues:

- Collisions produce secondary ions with changed rigidities that will be lost in small spots in the dispersion suppressor around the experiments → *A protection system has to be designed*
- Reduced collimation cleaning efficiency for ions → *More studies of collimation for ions needed*

Issues that will be followed:

- Inclusion of heavy ions in injector chain design
- Vacuum requirements, RF requirements etc.

Different Bunch Spacing

Experiments would like us to keep exploring smaller bunch spacings

- Less background per crossing

Identified three main alternative scenarios, but need to study them

E. Shaposhnikova et al.

S. Arsenyev, X. Buffat, A. Langner

			Opt 1	Opt 2	Opt 3
Bunch			12.5	5	5
Proton			0.5	0.2	0.2
Init. h			1.1	1.1	0.44
Init. v			1.1	1.1	0.44
Final hor. transv. emittance [µm]	1.28	0.29	0.25	0.22	0.22
Final vert. transv. emittance [µm]	1.28	0.24	0.2	0.17	0.17
Max. total beam-beam tuneshift	0.01				0.03
IP beta-function [m]	1.1				0.3
Peak luminosity [10^{34} $cm^{-2} s^{-1}$]	5.01				20.1
Max events per crossing	170				137
Optimum integrated lumi / day [fb^{-1}]	2.2				6.2

Important improvements of injector system

Higher risk in beam transfer

Electron cloud more severe

SPL-type of injector

Higher risk in beam transfer

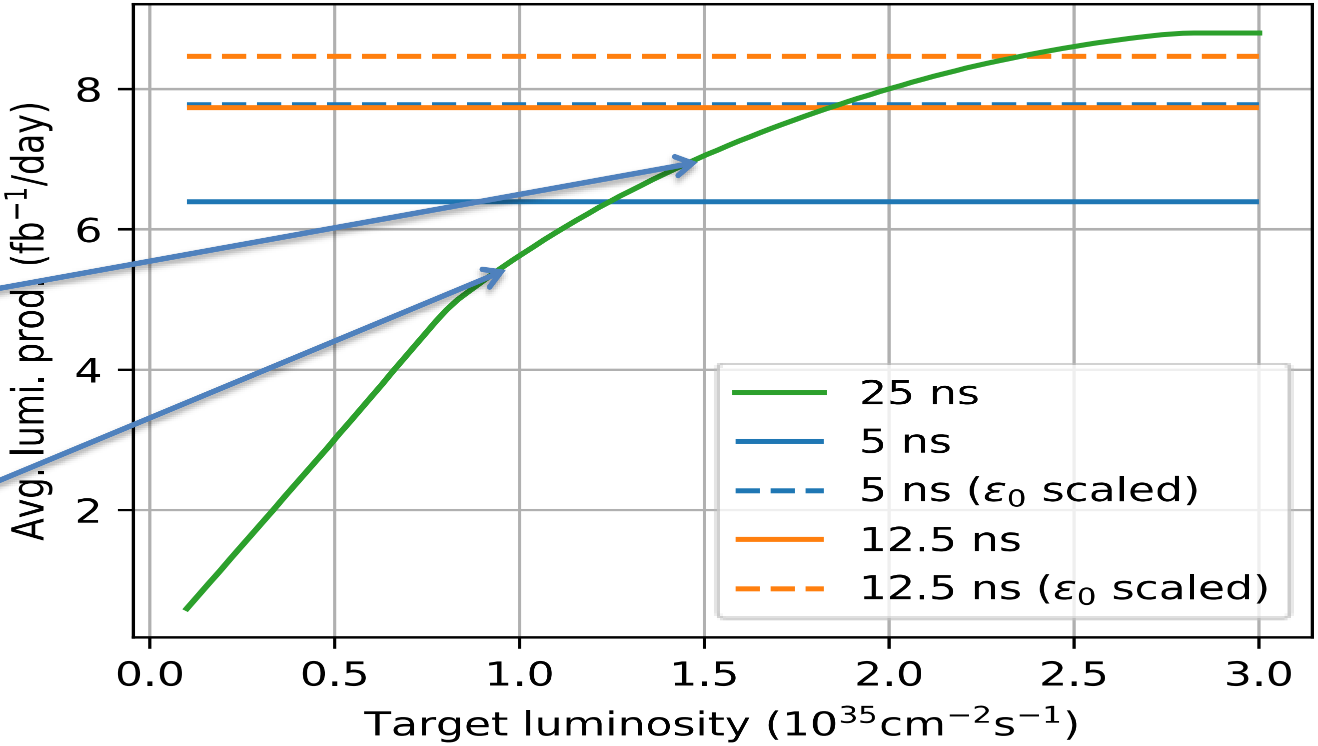
Electron cloud more severe

Alternative: Luminosity Leveling

Luminosity leveling with 25ns beam is an option

Limited luminosity loss for 500 events per bunch crossing

Maybe still acceptable at 330 events



Conclusion

- FCC-hh baseline has improved
  - No show stopper identified
  - Solved several outstanding issues
    - E.g. solution for collimation system looks robust
  - Some points to be finalised
    - E.g. new beamscreen design, extraction insertion design, …
  - Coherent design that allows to understand trade-offs
  - Draft of FCC-hh CDR is available

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, …

Reserve

Other Key Hardware

Main instrumentation specifications have been produced, included 5ns bunch spacing

L. Ponce, H. Schmickler et al.

- No mayor obstacle found, some improvements compared to LHC operation considered
- Some iteration required on feedback BPMs when we understand feedback performance better

RF quadrupoles are being considered to stabilise beam as alternative to octupoles, would save

A.Grudiev, K. Lee et al.
-> V.Kornilov

- Seems sofar to be OK in simulations, some more work to be done

Feedback development is ongoing

W. Hofle et al.

- Turn-by-turn, bunch-by-bunch and intra-bunch
- Bunch-to-bunch feedback creates robustness against ground motion, low frequency impedance modes etc.
- An interesting option for beam stability even in collision, if low noise
- Intra-bunch feedback has potential to improve robustness against impedance and electron cloud
- Hoping for performance predictions soon

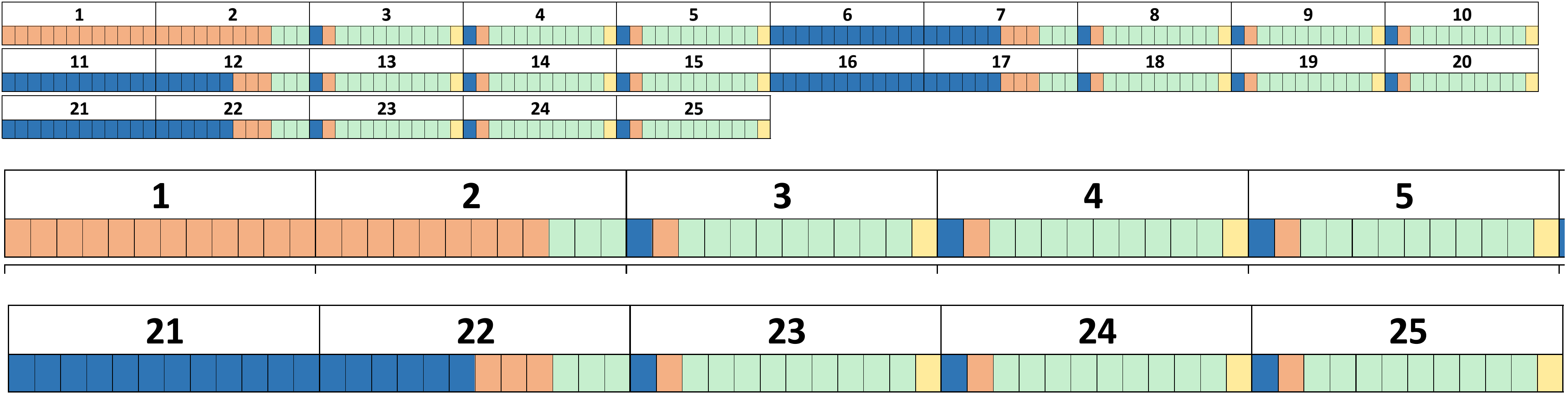
Alternative hardware will be considered

- Electron lens to compensate beam-beam
- Electron lens to stabilise beam
- Hollow electron lens for collimation
- …

V. Shiltsev

Operational Scenario

V. Mertens, A. Niemi et al.



Per cycle about 1000 days for physics

- 70% availability leads to goal of $5ab^{-1}$ per ultimate run
- For ions 3x30 days, i.e. 10% of integrated luminosity?

New 6 year cycle planned