FCC-hh Optics Challenges

Daniel Schulte for the FCC-hh team
CERN, February 2015

European Strategy

Approved by CERN council, ESFRI roadmap

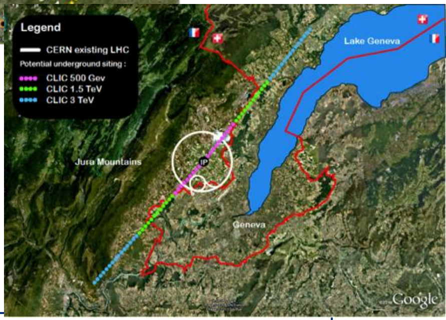
Identified four highest priorities:

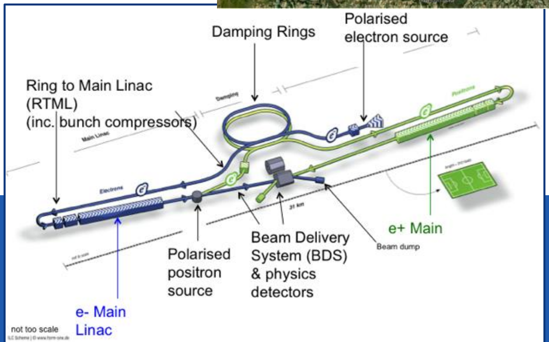
- Highest priority is exploitation of the LHC including luminosity upgrades

- Europe should be able to propose an ambitious project at CERN after the LHC
  - Either high energy proton collider (**FCC-hh**)
  - Or high energy linear collider (**CLIC**)

- Europe welcomes Japan to make a proposal to host **ILC**

- Long baseline neutrino facility





FCC Accelerator Study Goals

• The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new tunnel of 80 - 100 km circumference for the purposes of studying physics at the highest energies.

• The conceptual design study shall also include a lepton collider and its detectors, as a potential intermediate step towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered.

• Options for e-p scenarios and their impact on the infrastructure shall be examined at conceptual level.

• The study shall include cost and energy optimisation, industrialisation aspects and provide implementation scenarios, including schedule and cost profiles

Target Beam Parameters

	LHC	HL-LHC	Baseline	Ultimate
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	20
Bunch distance [ns]	25	25	25 (5)	25 (5)
Background events/bx	27	135	170 (34)	680 (136)
Bunch charge [10^{11}]	1.15	2.2	1 (0.2)	1 (0.2)
Norm. emitt. [μm]	3.75	2.5	2.2(0.44)	2.2(0.44)
IP beta-function [m]	0.55	0.15	1.1	0.3
IP beam size [μm]	16.7	7.1	6.8 (3)	3.5 (1.6)
RMS bunch length [cm]	7.55	7.55	8	8
Turn-around time [h]			5	4
Crossing angle [σ□]			12	Crab. Cav.

- Find baseline at : http://indico.cern.ch/event/282344/material/3/
- Values in brackets for 5ns spacing, would be good for background
- Beam-beam tuneshift for two IPs <0.01 for baseline and <0.03 for ultimate

Preliminary Layout

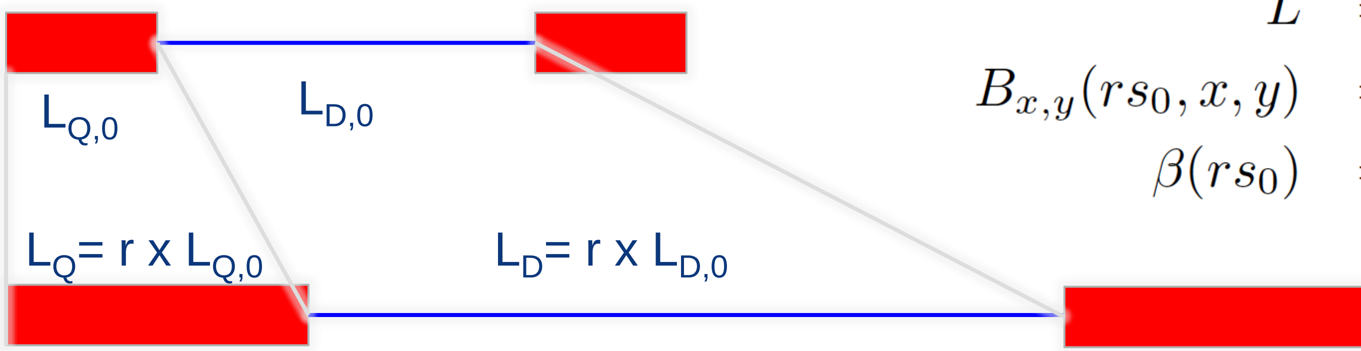
First layout developed (different sizes under investigation)

- To serve two high-luminosity experiments (3 and 4)
- And two other experiments
- Two collimation lines
- Two injection and two extraction lines
- Insertion lengths are based on first order estimates

Note: Natural Optics Scaling and Insertion Lengths

For use of same technology (e.g. magnets with same aperture and field) can scale as

$$
\begin{aligned}
r &= \sqrt{\frac{\gamma}{\gamma_0}} \\
L &= r L_0 \\
B_{x,y}(r s_0, x, y) &= B_{x,y,0}(s_0, x, y) \\
\beta(r s_0) &= r \beta_0(s_0)
\end{aligned}
$$



Orbit will scale as

$$
\begin{aligned}
x(r s_0) &= x_0(s_0) \\
x'(r s_s) &= r^{-1} x'(s_0)
\end{aligned}
$$

Normalised aperture and separation scale as

$$
\begin{aligned}
\frac{a}{\sigma(\gamma)} &\propto \gamma^{\frac{1}{4}} \\
\frac{\alpha(\gamma)}{\sigma'(\gamma)} &\propto \gamma^{\frac{1}{4}}
\end{aligned}
$$

Obtained insertion lengths of 1400m by scaling from LHC with ~500m
Currently larger length for collimation system (2800m)

Key Optics Challenges

- Energy
  - The site length is limited
  - The dipole field is limited
  - ⇒ Minimise space used for insertions
  - ⇒ Maximise dipole filling factor of arcs

- Luminosity
  - ⇒ Minimise beta-function at IP
  - ⇒ Maximise beam current
    - ⇒ collective effects
    - ⇒ machine protection and collimation
  - ⇒ Maximise beam-beam tune-shift

$$\mathcal{L} \propto \xi \frac{1}{\beta_y} N n_b f_r$$

- Cost and power
  - ⇒ Will put pressure on many systems

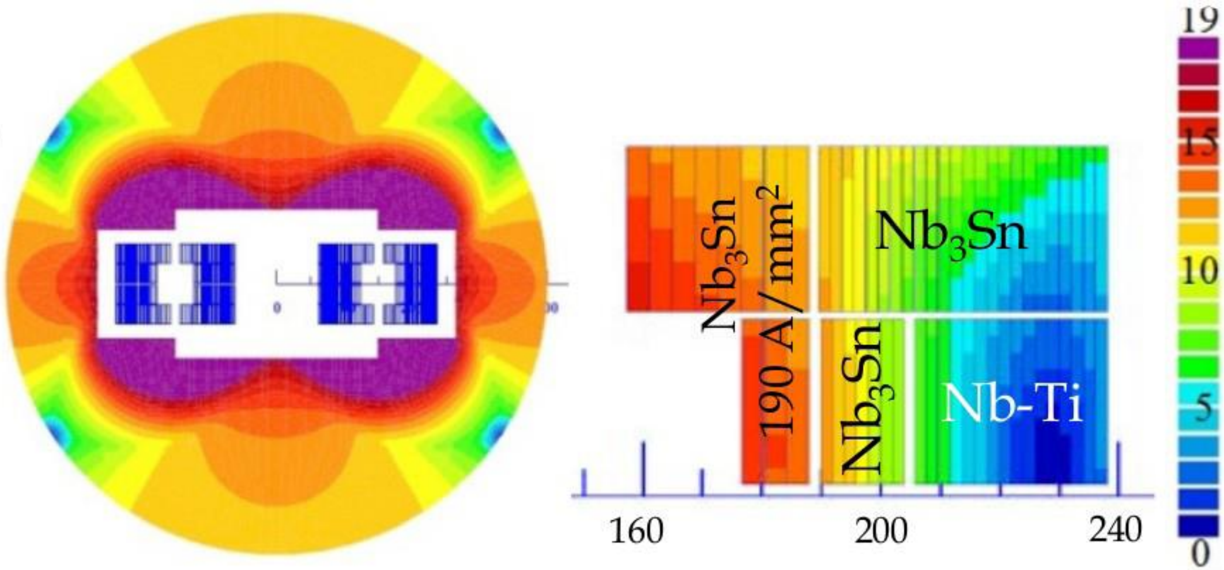
- Most challenging lattices: arcs with dispersion suppressors, experimental insertions, collimation, injection and extraction and their interplay

FCC-hh Challenges: Magnets

Arc dipoles are the main cost and parameter driver

Baseline is Nb_3Sn at 16T

HTS at 20T also to be studied as alternative



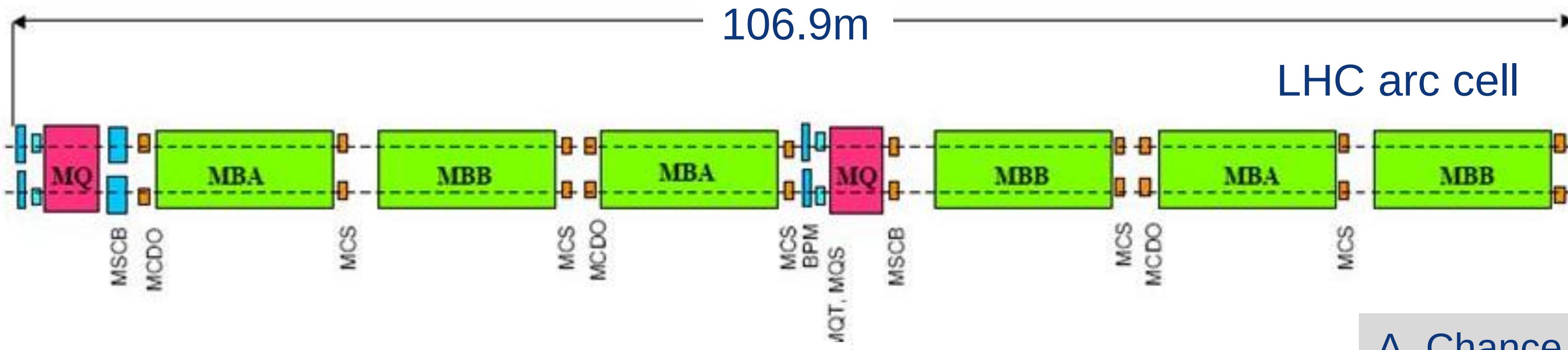
Coil sketch of a 15 T magnet with grading, E. Todesco

Field level is a challenge but many additional questions:

- Aperture (the smaller the cheaper => optics work)
- Field quality (might be worse than in LHC => optics and tolerances)
- Length and weight

Goal is to develop prototypes in all regions

Arc Cell Layout



A. Chance et al.

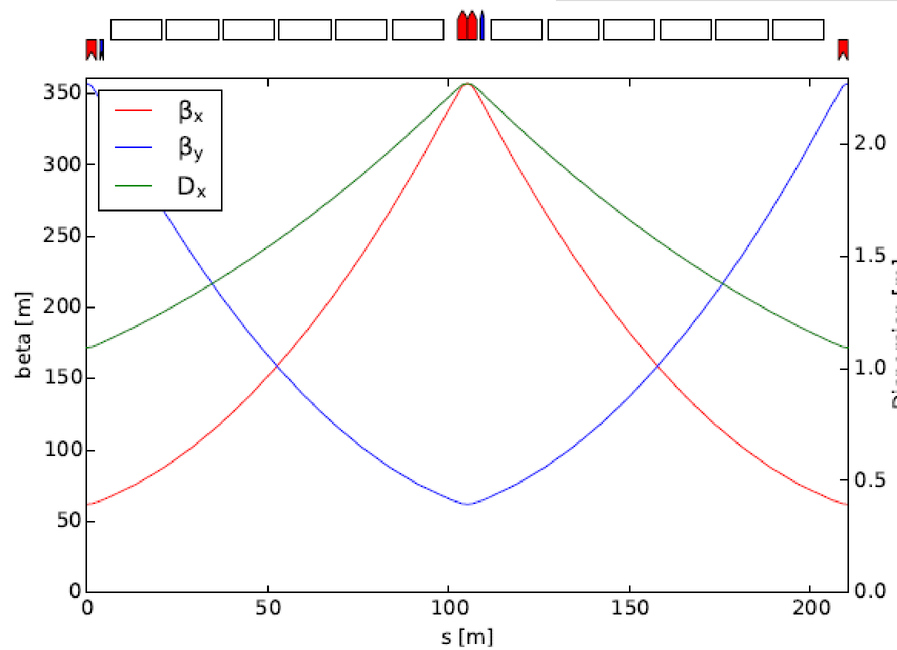
Long cell => good dipole filling factor (fewer and shorter quadrupoles)

Short cells => more stable beam (growth rate proportional to beta-function)

Scale from LHC

- Natural scaling for same technology 286m
- Stronger magnets, smaller aperture => ~200m

Maximise filling factor (including dispersion suppressors) and deal with field errors



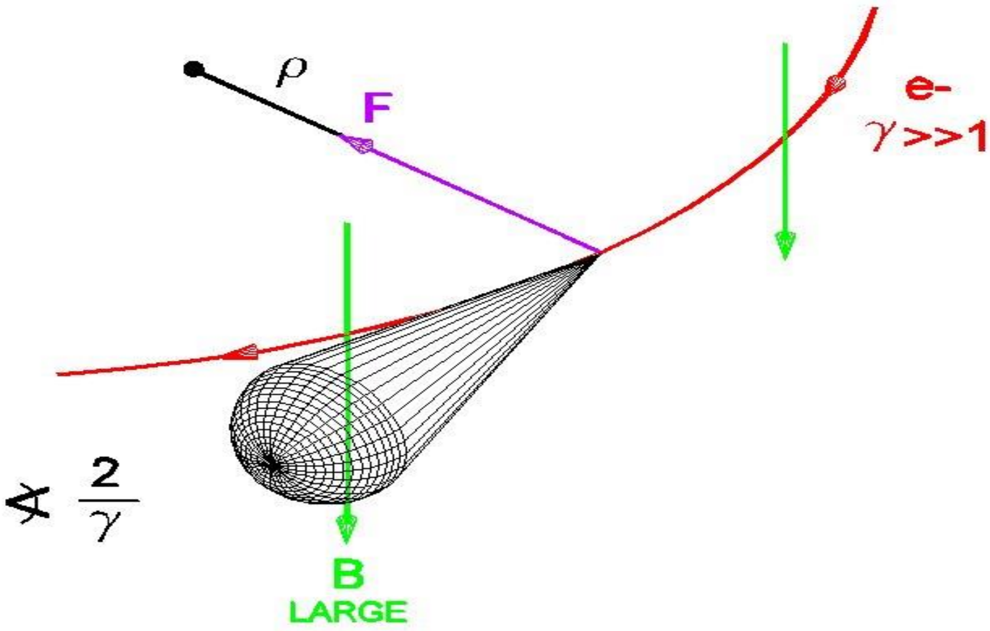
Synchrotron Radiation

At 50 TeV even protons radiate significantly

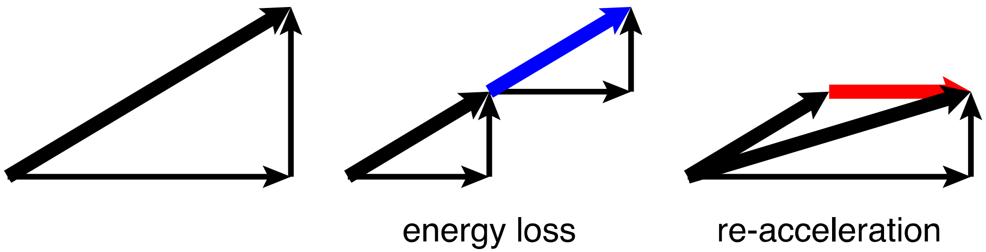
Total power of 5 MW (LHC 7kW)
⇒ Needs to be cooled away

Equivalent to 30W/m /beam in the arcs (16T magnets)

- LHC <0.2W/m, total heat load 1W/m



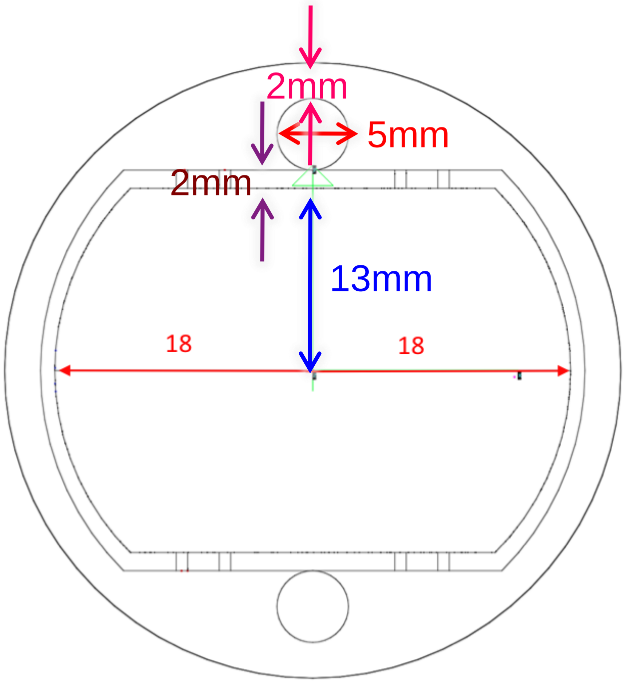
Critical energy 4.3keV, close to B-factory



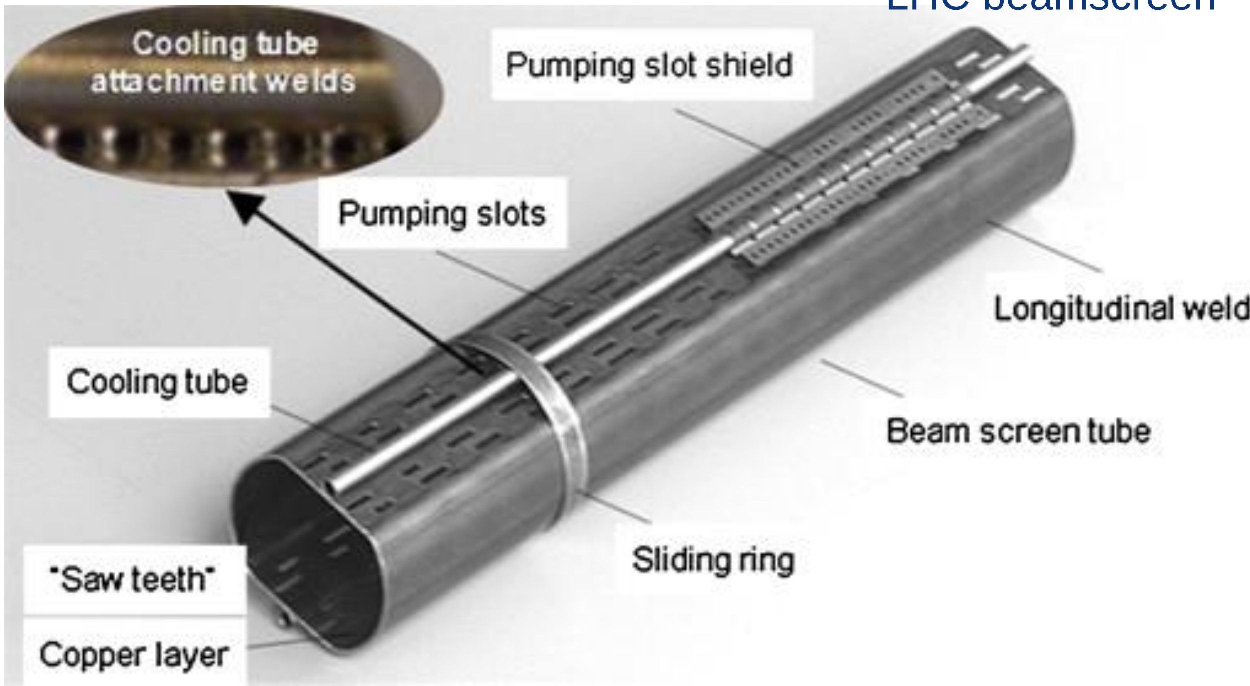
Protons lose energy
⇒ They are damped
⇒ Emittance improves with time

- Typical transverse damping time 1 hour

Baseline Beam Screen Design



LHC beamscreen



Current ambitious goal
beam aperture: 2x13mm
magnet aperture: 2x25mm
(initial target was 40mm)

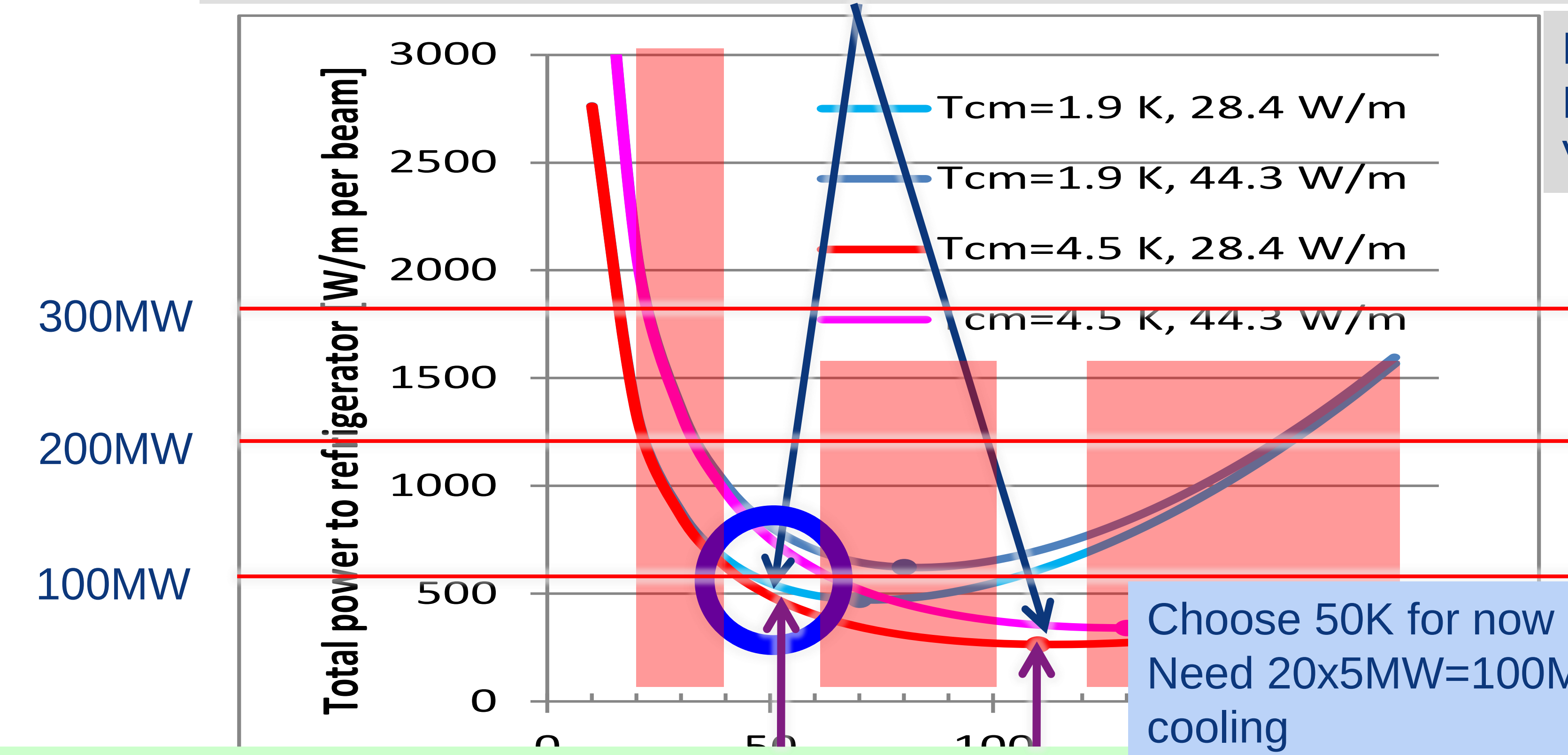
Most of the power will be cooled at the beam screen, i.e. at its temperature

A part is going into the magnets, i.e. cooled at 2-4K

Power for Cooling

Better use only some temperatures in order to maintain good vacuum
<20, 40K-60K, 100K-120K, >190K

Ph. Lebrun
L. Tavian
V. Baglin



Multi-bunch instability growth time: 25 turns 9 turns
($\Delta Q=0.5$)

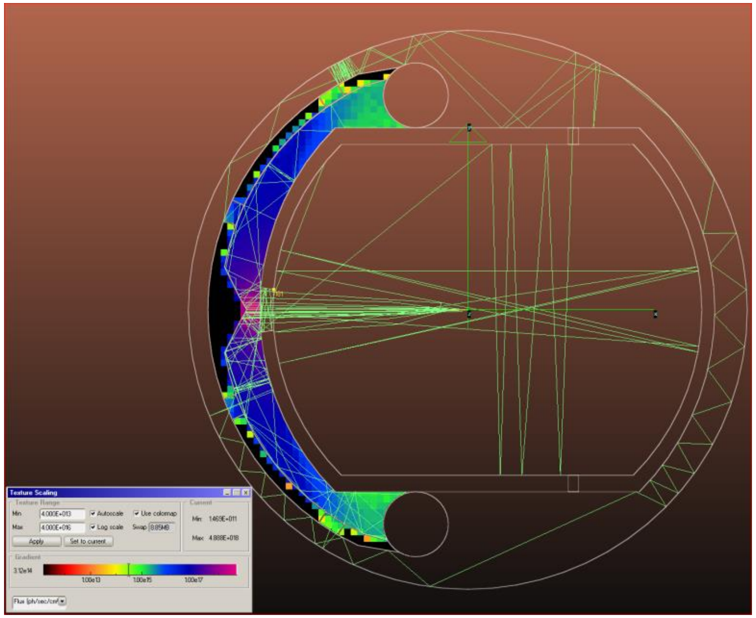
Choose 50K for now
Need 20x5MW=100MW for cooling

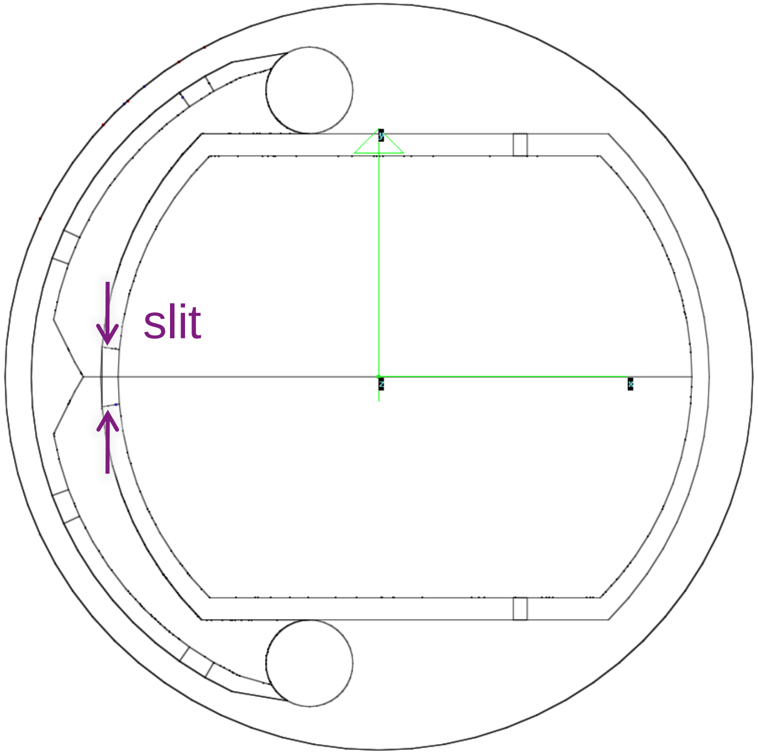
Photon stops? Open midplane?

Alternative Beam Screen Design

Attempt to improve vacuum by adding mini antechamber

Mechanically challenging
Requires excellent orbit control
Shift magnetic centre away from aperture centre





R. Kersevan

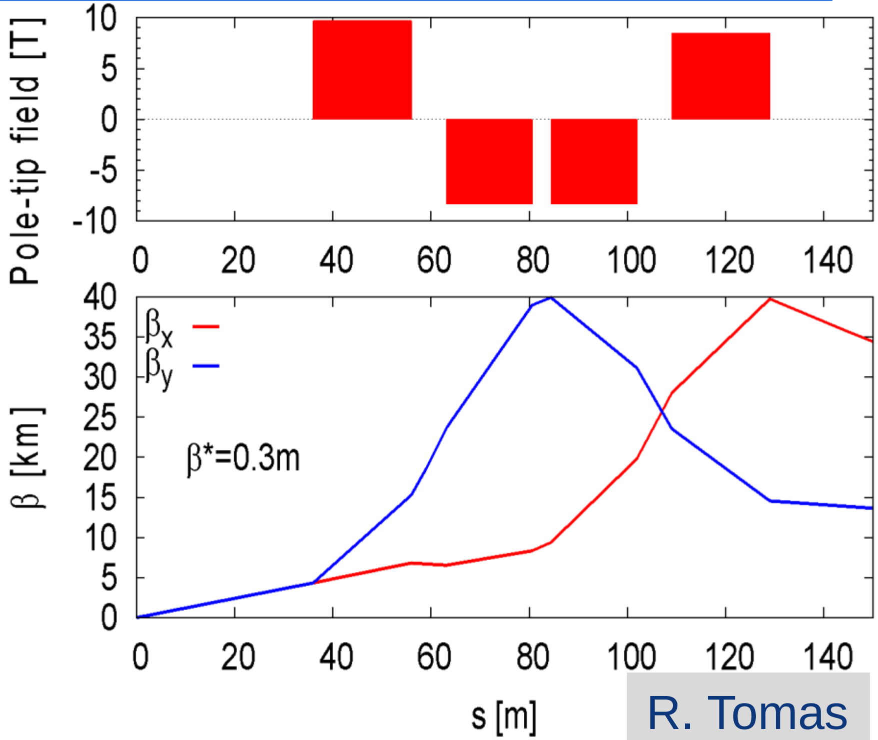
Interaction Region and Final Focus Design

Required L^* expected in [25m..40m],

Currently study L^*=36m

Baseline β^*=1.1m scaled from LHC optics with β^*=0.4m (natural scaling)

Ultimate β^*=0.3m based on lattice studies, more ambitious than HL-LHC (0.15m in LHC corresponding to 0.4m in FCC)

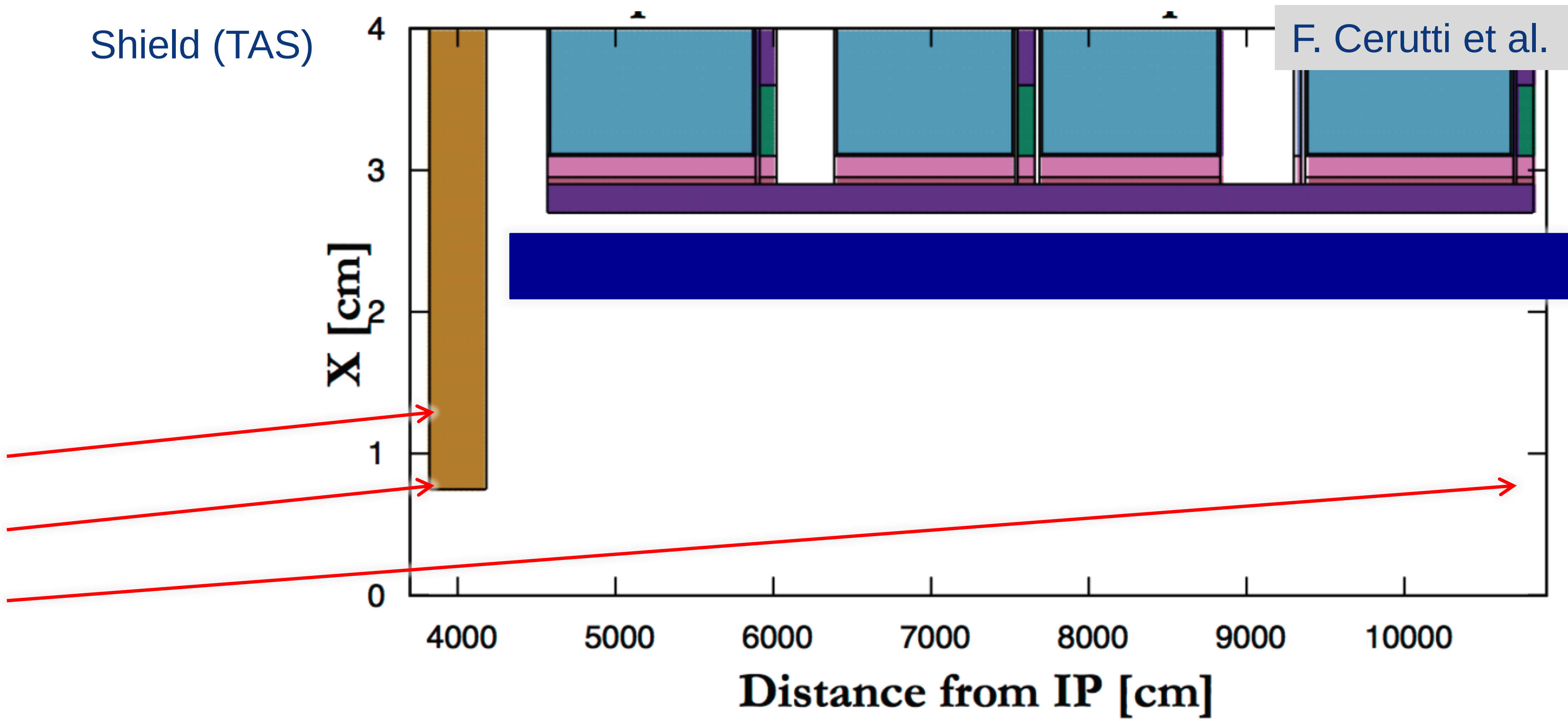


R. Tomas
R. Martin

Many issues need to be addressed

- Aperture
- Magnet performance and tolerances
- Radiation effects
- Space constraints from experiments
- Beam-beam effects and mitigation
- …

Final Triplet



- Total power of background events: 100kW per experiment (a car engine)
- Already a problem in LHC and HL-LHC (heating, lifetime)

⇒ Improved shielding required

Final Triplet II

F. Cerutti, et al.

With 15-20mm liner survive O(3000fb^{-1})

Integrated luminosity per run:

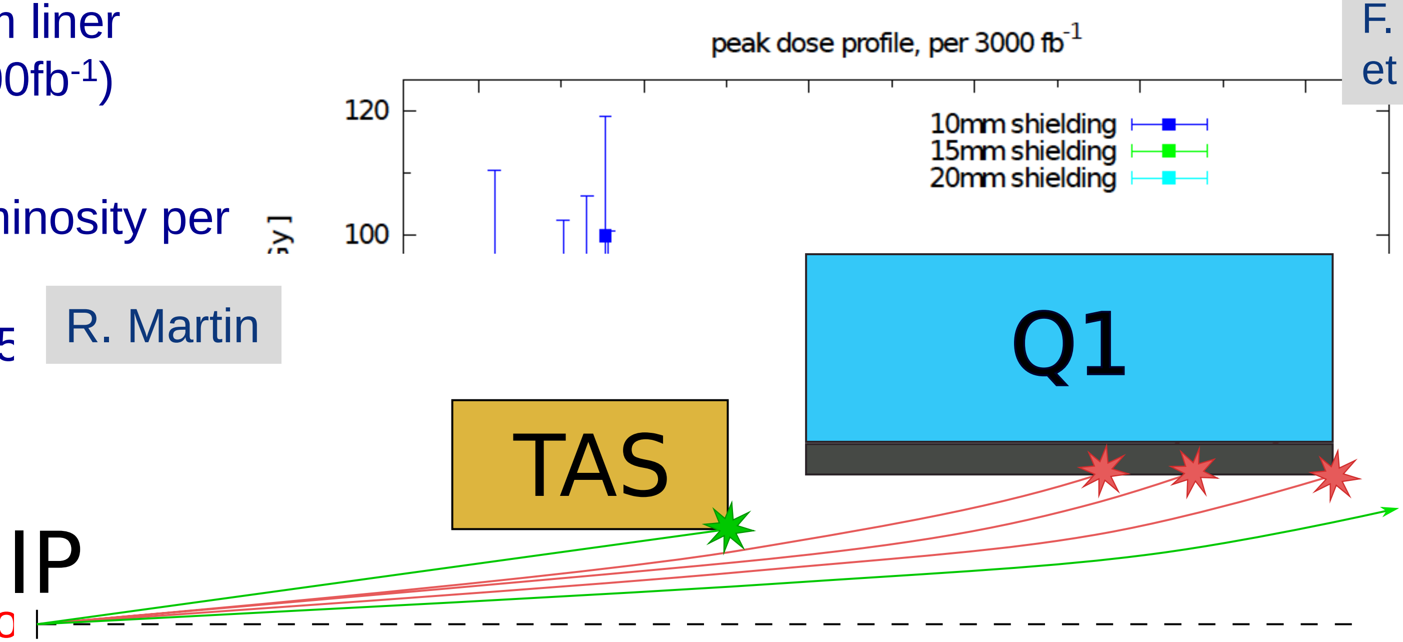
- Baseline: 125

R. Martin

- Ultimate run:

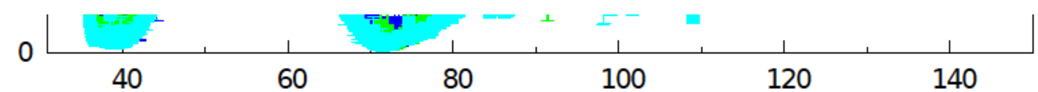
Need to

- Further impro
shielding
- Improved radiation hardness of magnets
- Think about replacement of triplets
- …



Will look into new approach:

Optimise already the optics design to minimise losses of pions

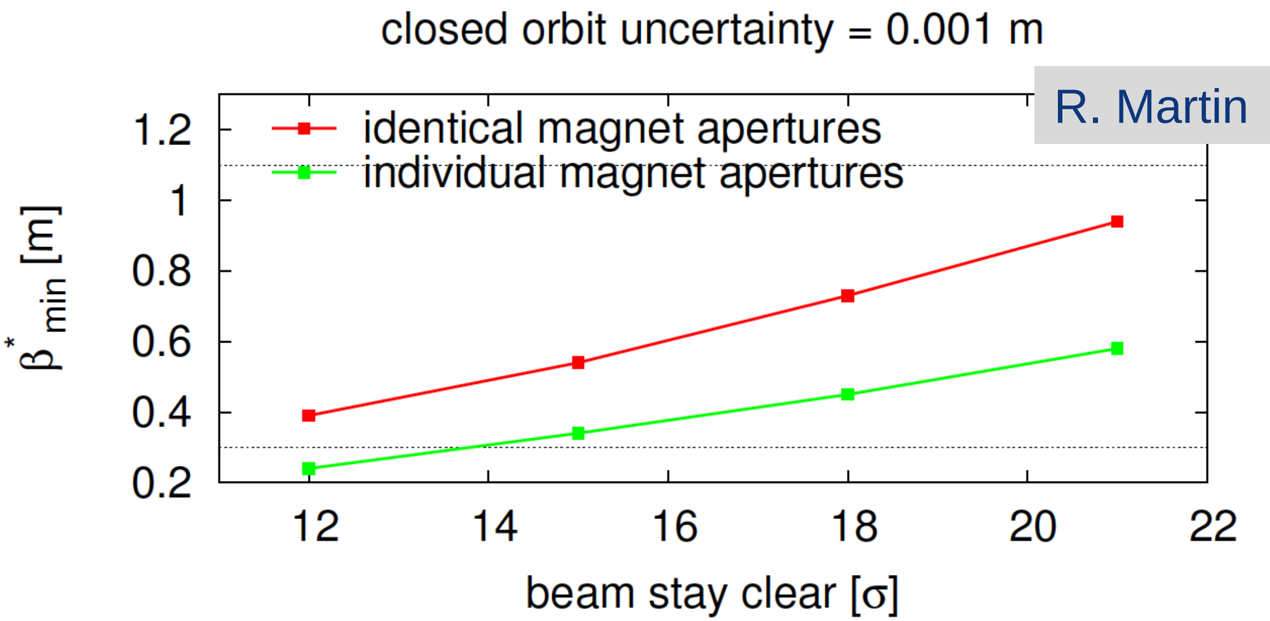


Aperture and Beta-function at IP

20 and 15mm shielding assumed, reduces aperture

Closed orbit uncertainty smaller than in LHC

More studies to be done
- dispersion
- magnet misalignment
- iteration on imperfections



⇒ Win using different magnet apertures in the final triplet, but cost to be considered

⇒ Can we win even more by varying also the lengths?

⇒ Beam stay clear >21 sigma for baseline (1.5 times as many as in LHC required to reach LHC-size gaps in collimation, 6σ in LHC collimation is 9σ in FCC)

⇒ Beam stay clear >12 sigma for ultimate (appears too little)

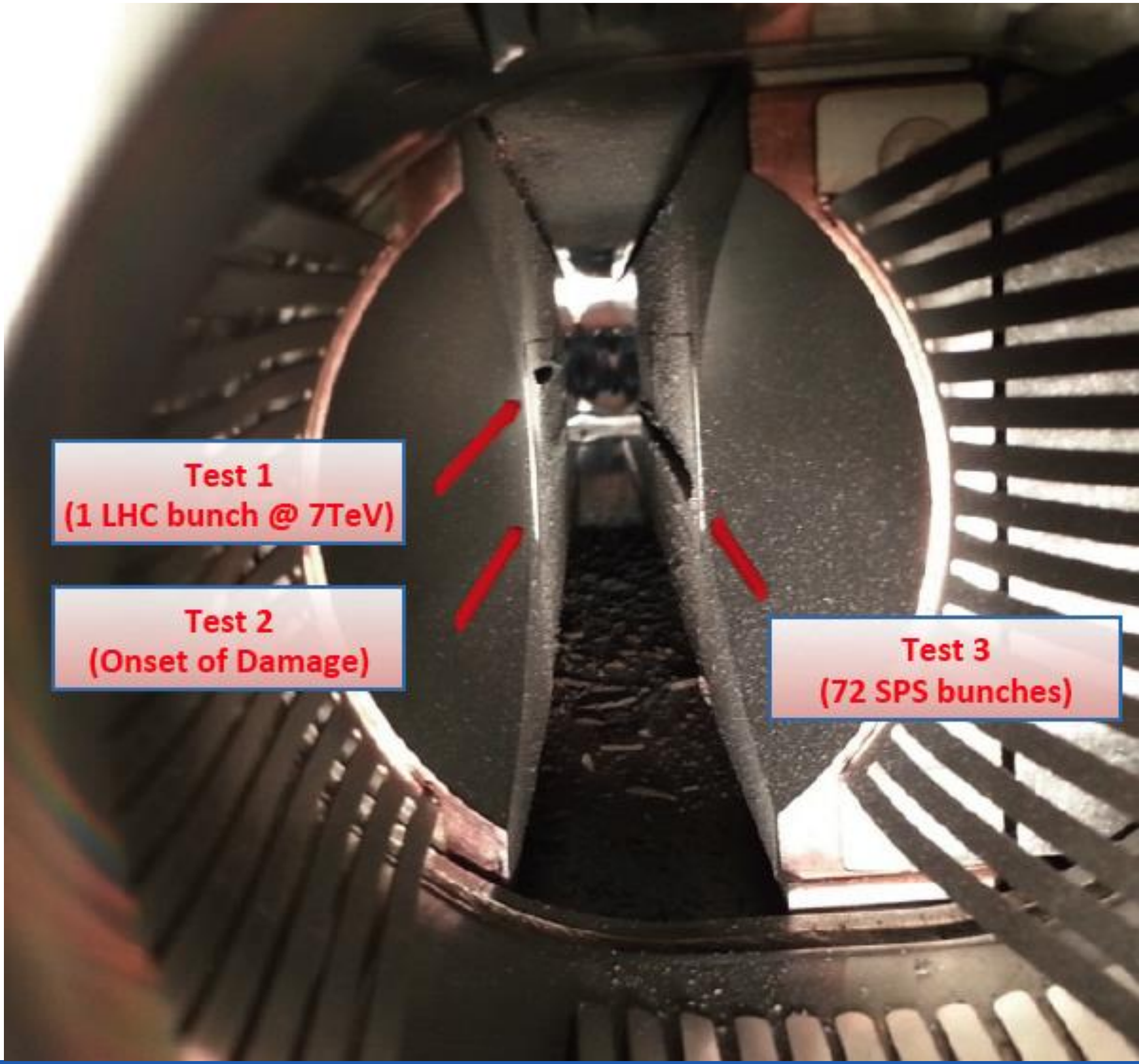
Further questions:

⇒Which role does L* play?

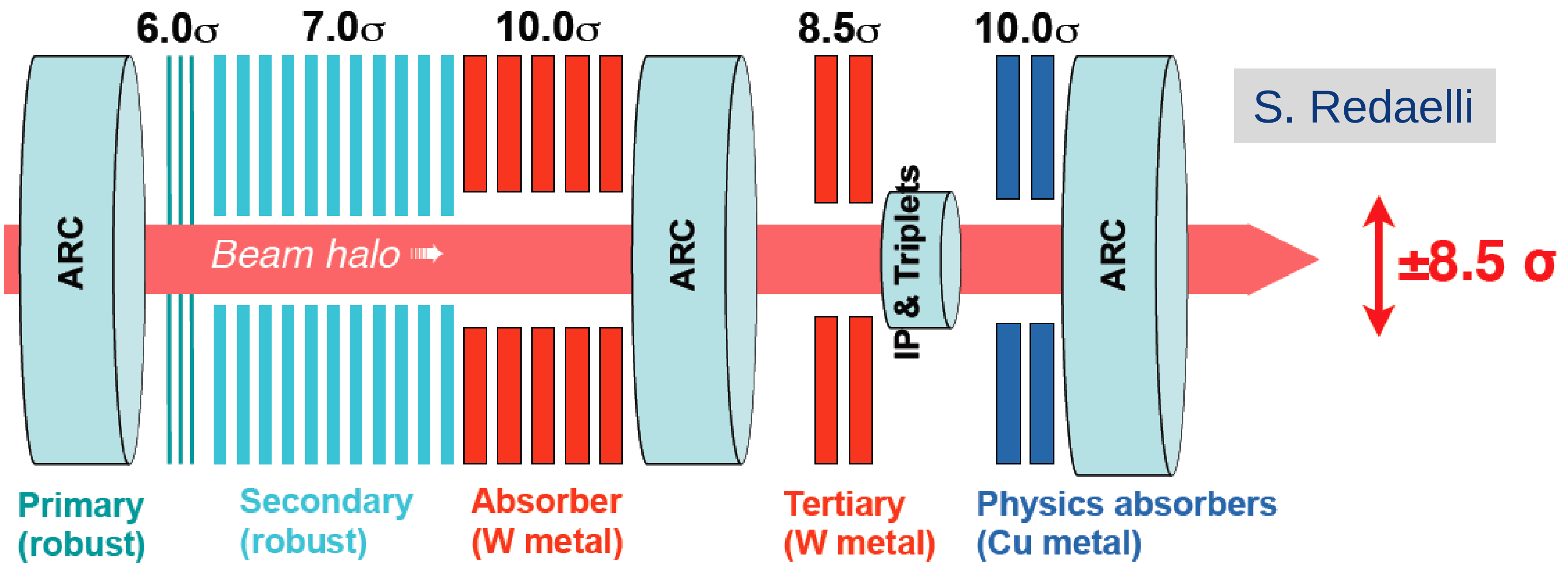
⇒ What is the interplay with the collision debris losses?

Machine Protection and Friends

- >8GJ kinetic energy per beam
  - Airbus A380 at 720km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ Machine protection
- Also small loss is important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ Collimation system



Collimation Optics Challenges

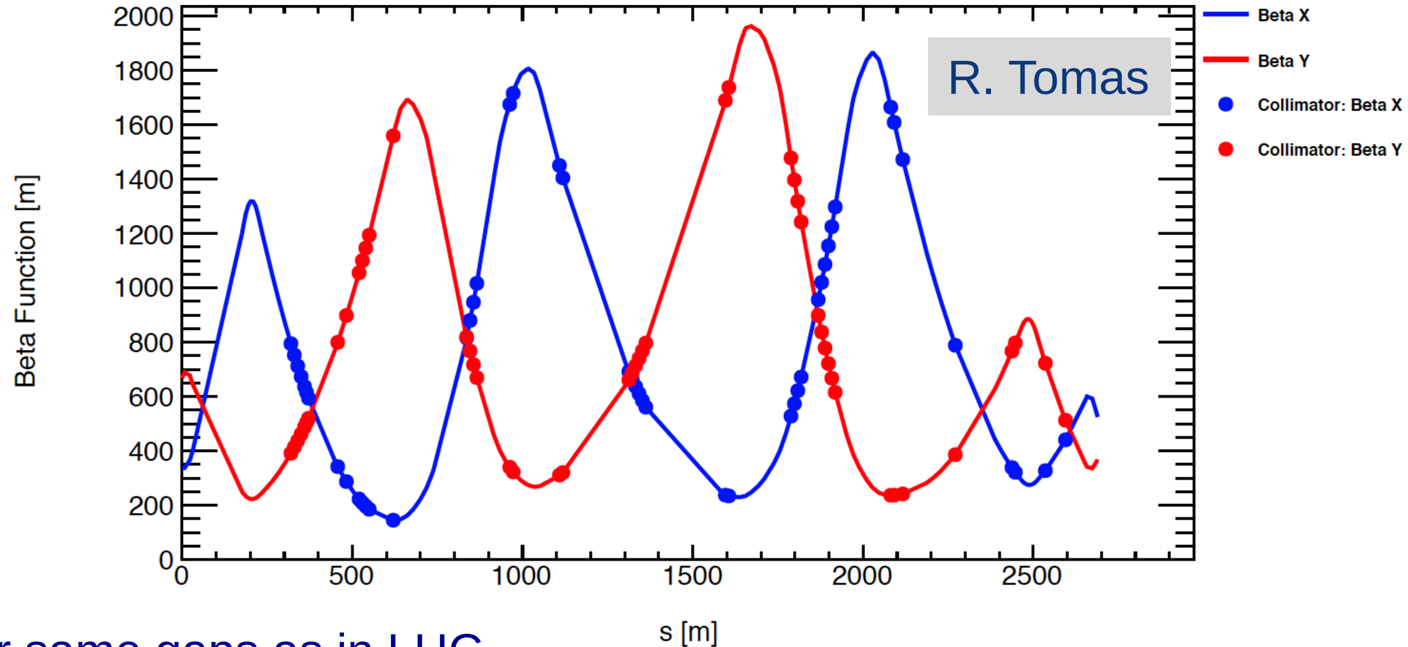


- The system protects the machine (8GJ per beam)
- Limits losses from tails and collision debris into cold magnets to avoid quench
- Limits and concentrates radiation doses

- At collision experimental insertions provide the smallest aperture
  $\Rightarrow$ trade-off between the two systems

Collimation Optics

- First betatron collimation system is based on scaled LHC system ($r_C = 5$)
- But we know that LHC system has weaknesses, e.g. losses in dispersion suppressor



Scaling should allow for same gaps as in LHC collimation:

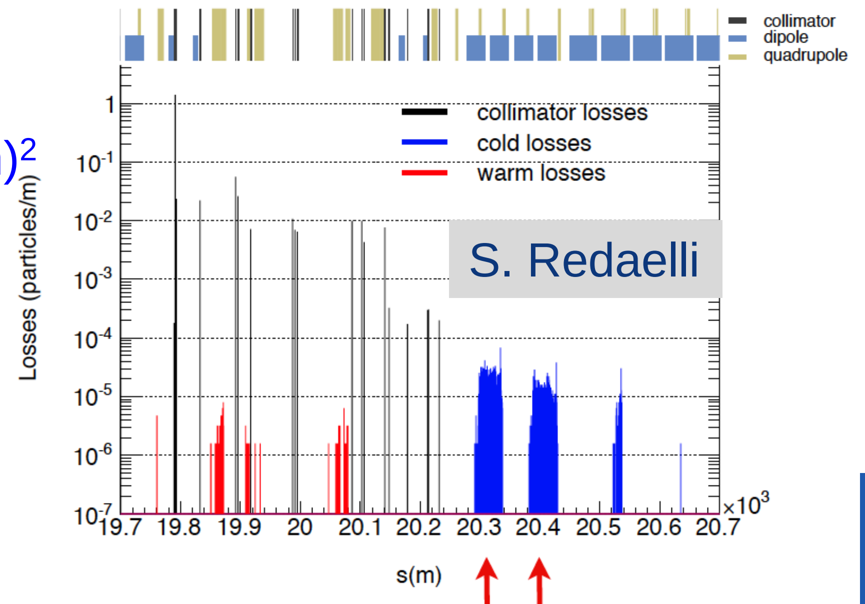
$$r_C = (50\,\mathrm{TeV}/7\,\mathrm{TeV})^{1/2} \times 0.4\,\mathrm{m}/0.3\,\mathrm{m} \times (59\,\mathrm{mm}/49\,\mathrm{mm})^2$$

$$r_C \sim 5$$

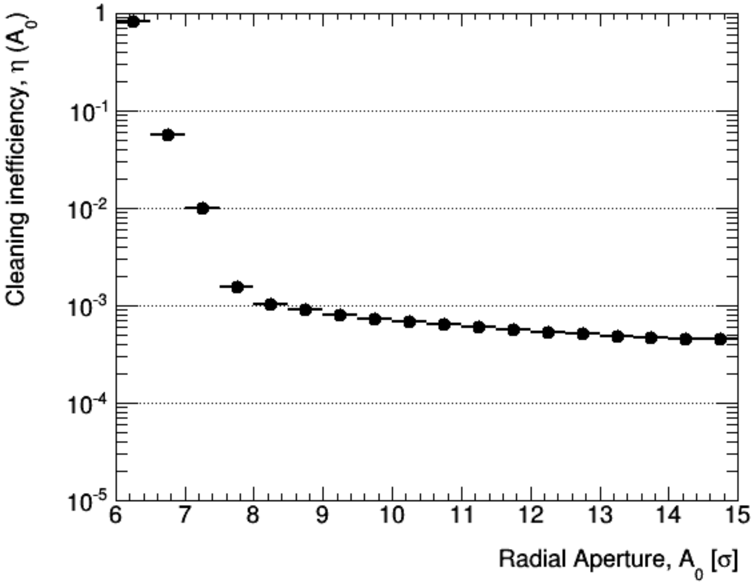
Normal scaling

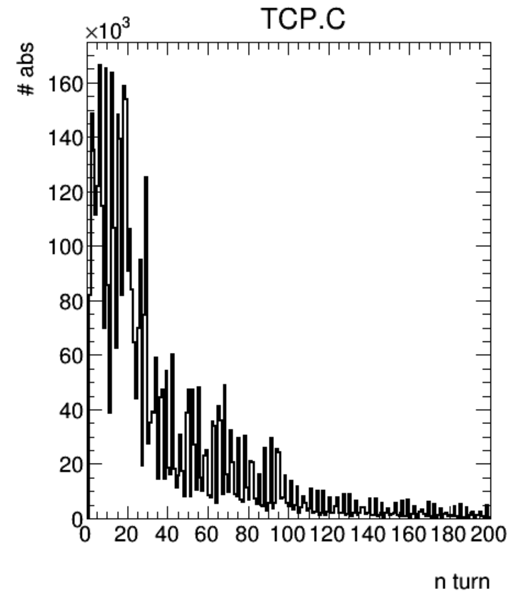
IP beta-function

Aperture reduction due to shielding



Collimation Studies





M. Fiascari,
S. Redaelli

Collimation efficiency studies started

⇒ First results look promising

⇒ Need to understand the impact of different length scalings on inefficiency
  - More sigma distances, smaller normalised scattering angle

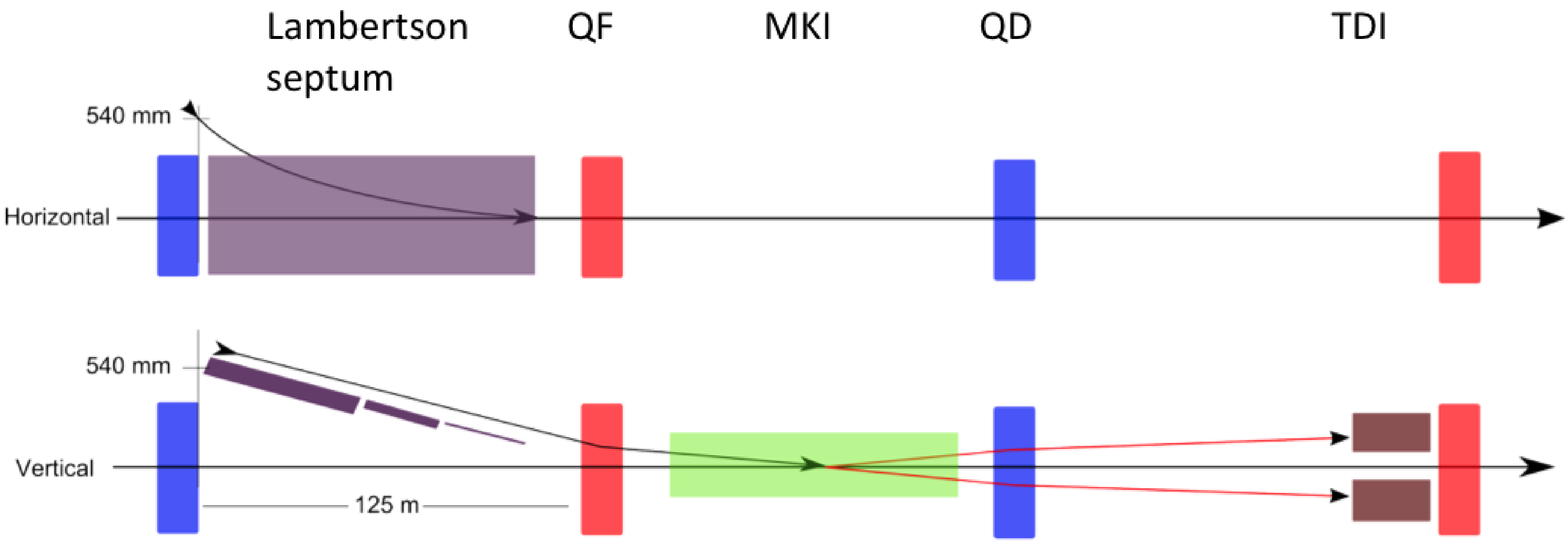
⇒ Need to address losses in dispersion suppressors

⇒ Integration of collimation into overall design should be revisited

⇒ System optimisation

⇒ Impedance studies

Injection Challenge



- About 5MJ can be injected into HL-LHC
- Each FCC-hh bunch contains about 53kJ (3.3TeV)

⇒ Can inject O(100) bunches

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

⇒ What is the impedance of such a design?

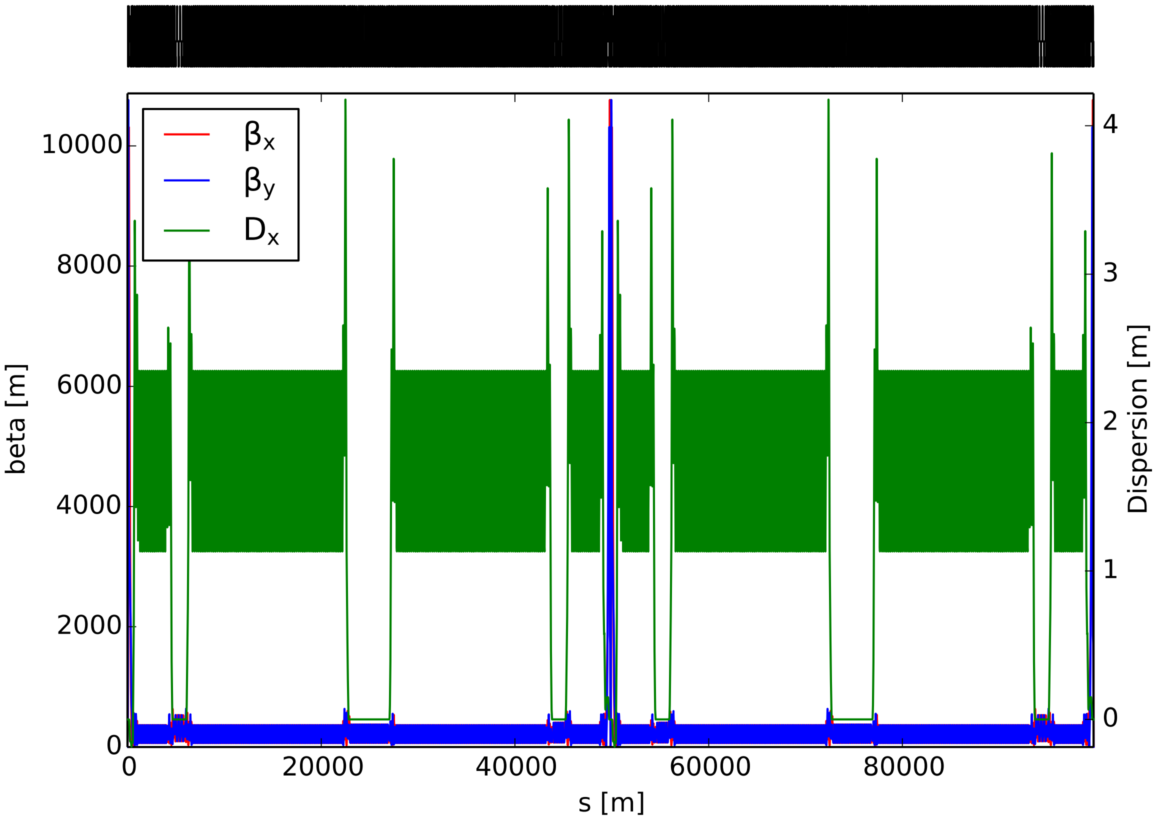
⇒ Can we design an optics with a safely more distributed loss pattern?

	LHC	FCC-hh
Kick angle [mradian]	0.85	0.29
Integrated field [Tm]	1.3	3.2
MKI length [m]	10.6	<120
Rise time [ns]	900	280

Integrated Lattice and Issues

First lattice integration started

A. Chance et al.



Many issues to be addressed

- Dispersion suppressor choice and matching
- Lattice optimisation and trade-offs
- Overall layout and civil engineering
- Working point
- Dynamic aperture
- Tolerances
- Orbit stability
- Collective effects and mitigation, e.g. crab cavities
- operation, e.g. changing crossing angle
- …
- Many iterations to integrate study results

Site Study (93km example)

PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option: 93km quasi-circular

Tunnel depth at centre: 286mASL

Gradient Parameters

- Azimuth (°): -15
- Slope Angle x-x(%): .3
- Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2498923 Y: 1106695

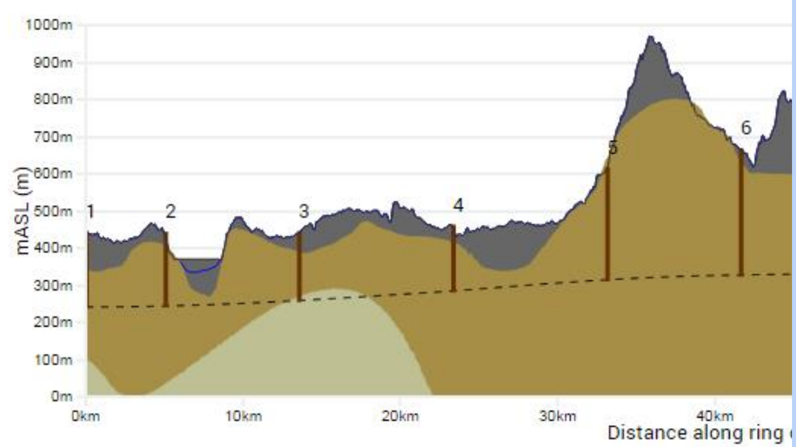
LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0

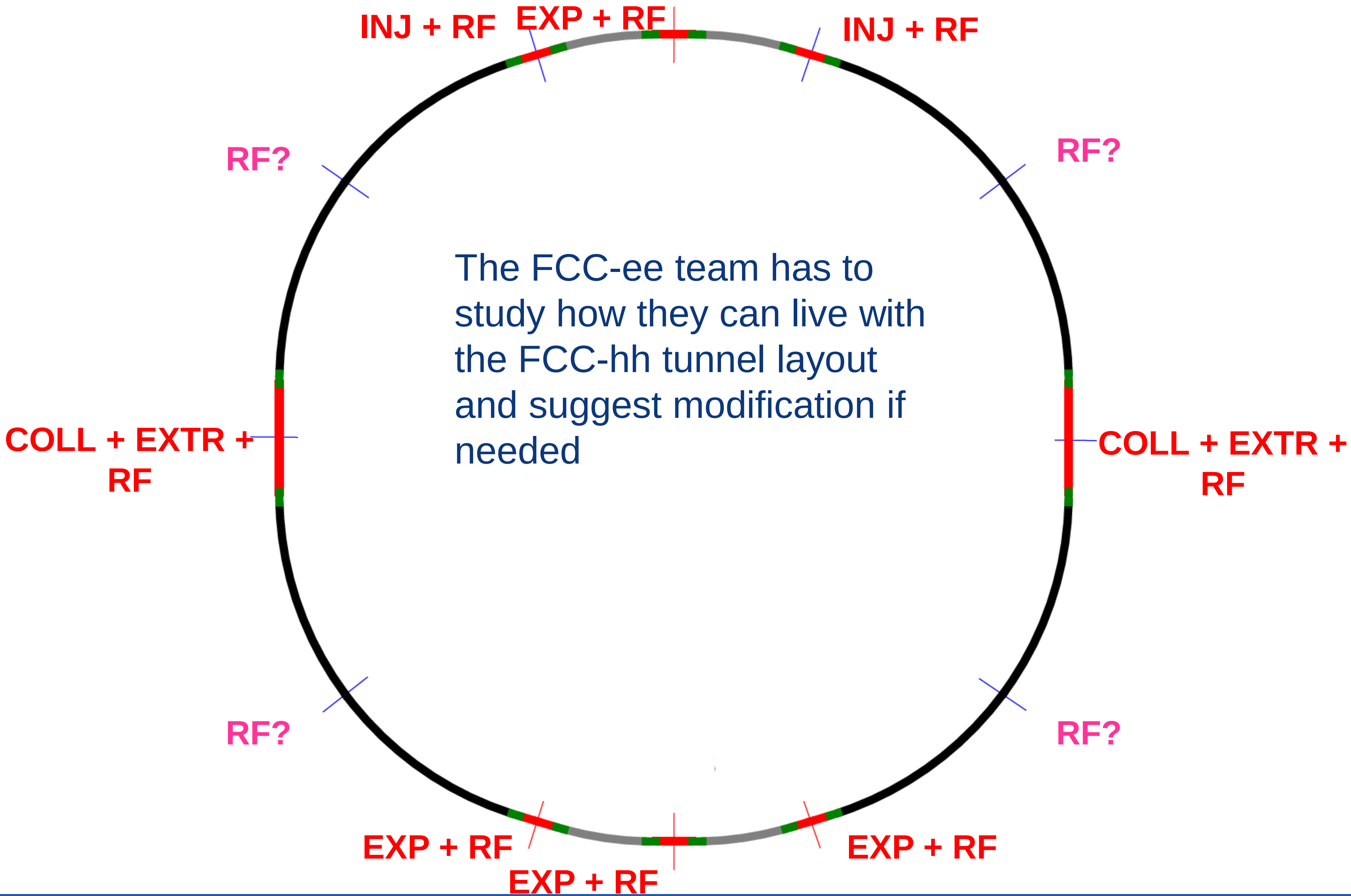
Alignment Profile



Preliminary conclusions:

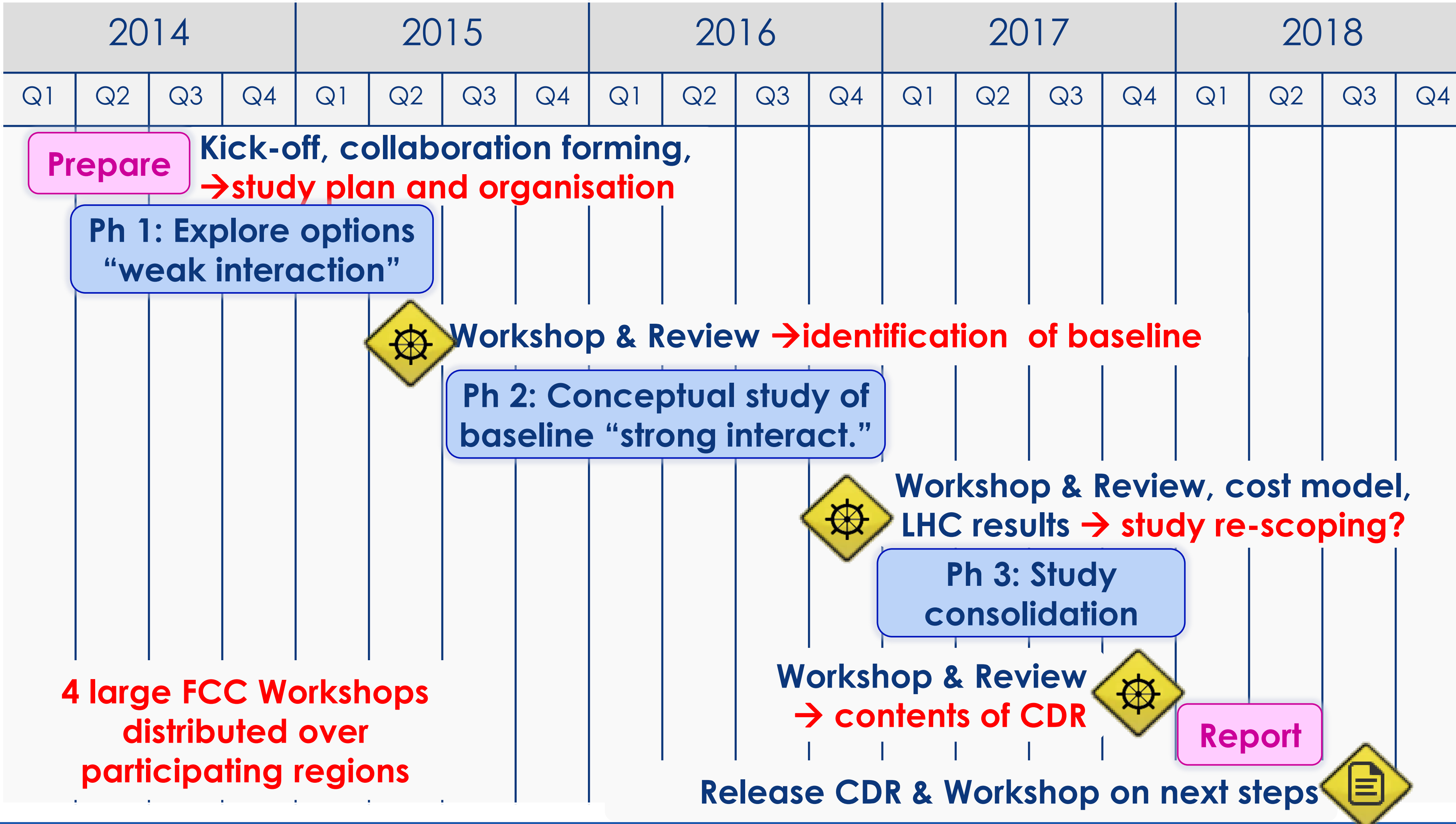
- 93km seems to fit the site really well, likely better than smaller ring
- 100km tunnel appears possible
- The LHC could be used as an injector

Integration of FCC-ee



The FCC-ee team has to study how they can live with the FCC-hh tunnel layout and suggest modification if needed

Proposed FCC Timeline



If You Want To Contribute

Work/meeting structures established based on INDICO, see:

- **FCC Study: https://indico.cern.ch/category/5153/**

In particular:

- **FCC-hh Hadron Collider VIDYO meetings**
  - **https://indico.cern.ch/category/5263/**
  - **Contacts: daniel.schulte@cern.ch**

- **FCC-hadron injector meetings**
  - **https://indico.cern.ch/category/5262/**
  - **Contacts: brennan.goddard@cern.ch**

Conclusion

- FCC study is working towards a CDR in 2018
  - The lattice will be the basis of this report

- Have many important and interesting optics challenges
  - Effective arc design
  - Small beta-function at IP
  - Collimation and machine protection
  - Injection and extraction
  - And their interplay
  - Can use the vast experience and technology from LHC
  - But need to meet challenges due to high beam energy and luminosity

- You are most welcome to help

- Let us hope that the LHC will find exciting new physics and guide our choice between the two machines

- Many thanks to the FCC-hh team from whom I stole slides and who provided the input

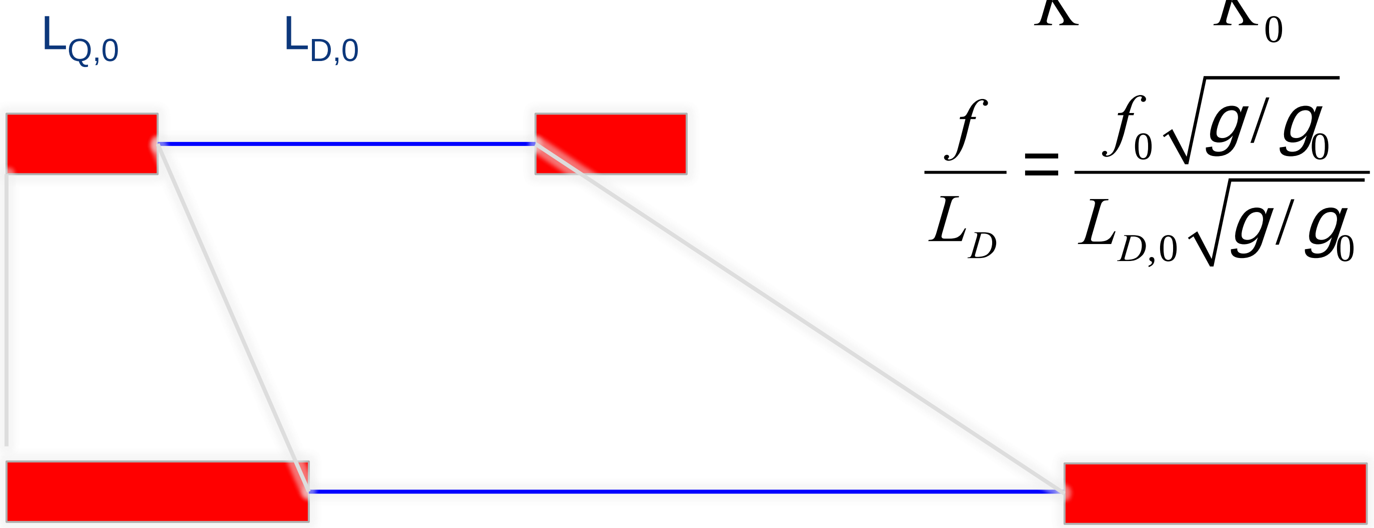
Reserve

Scaling

$$K = \frac{K_0}{g/g_0}\sqrt{g/g_0} = \frac{K_0}{\sqrt{g/g_0}}$$

$$f = \frac{1}{K} = \frac{\sqrt{g/g_0}}{K_0} = f_0\sqrt{g/g_0}$$

$$\frac{f}{L_D} = \frac{f_0\sqrt{g/g_0}}{L_{D,0}\sqrt{g/g_0}} = \frac{f_0}{L_{D,0}}$$



$L_Q = r \times L_{Q,0}$ $L_D = r \times L_{D,0}$

Scaling II

Normalised wakefield kick is given by $$wL_0 \frac{b_0}{g_0}$$

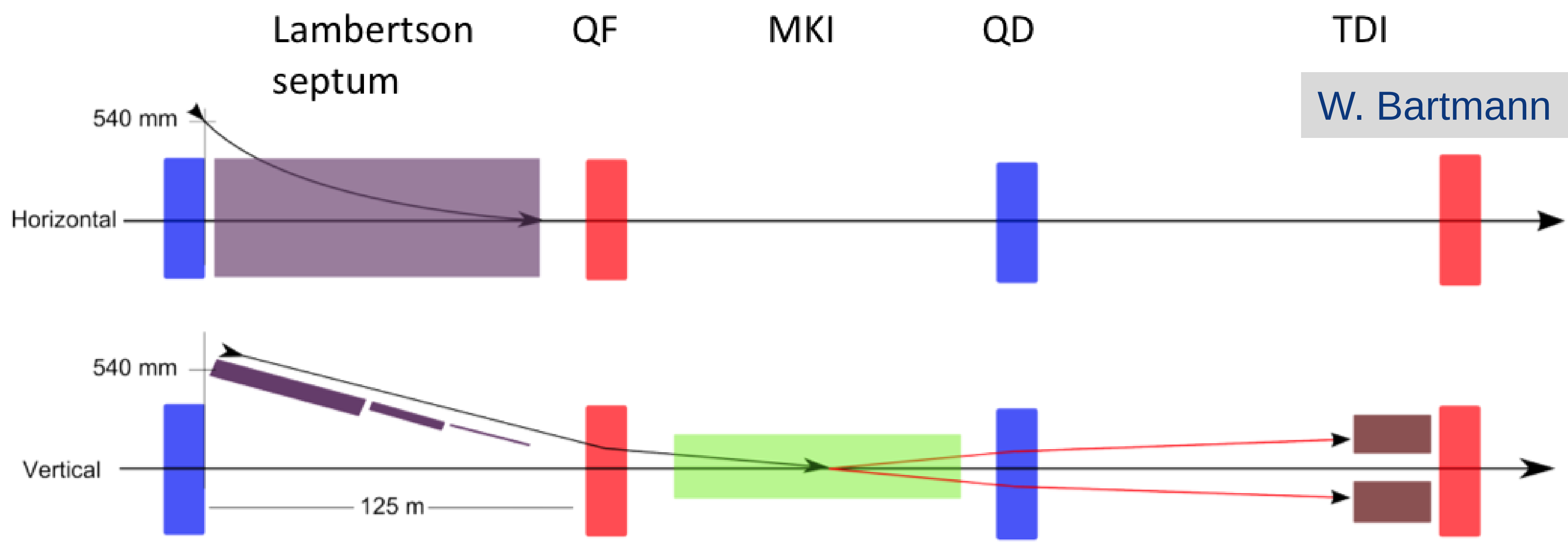
In scaled design, normalised wakefield kick is given by

$$wL\frac{b}{g} = w\sqrt{\frac{g}{g_0}}L_0\frac{\sqrt{\frac{g}{g_0}}b_0}{g} = wL_0\frac{b_0}{g_0}$$

Wakefield effect per turn is the same in scaled design

Difference can exist for very low frequency impedances
Note: the scaling does not apply to the arcs, because the cell number increases with factor r

Preliminary Injection Layout

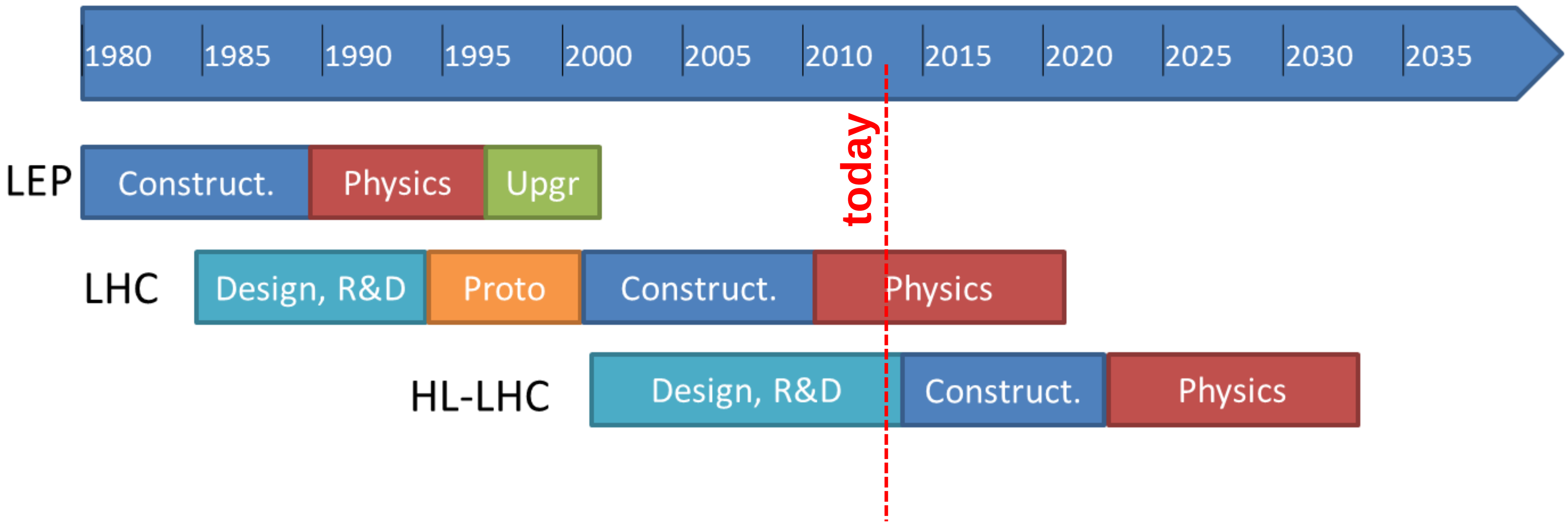


- 500 m quad half width → clearance of 540 mm
- Rms beam size at inj of 0.6 mm, +/-10 sig, +/- 3 mm orbit → beam clear 18 mm
- Beam offset in quad is 18 mm, required quad diameter inside chamber 36 mm
- First septum blade 6 mm, requires beam separation of 24 mm at septum entrance

	LHC	FCC-hh
Kick angle [mradian]	0.85	0.29
Integrated field [Tm]	1.3	3.2
MKI length [m]	10.6	<120
Rise time [ns]	900	280

LHC and HL-LHC

c) … *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. …*



General Luminosity Considerations

- Luminosity depends on the number of circulating particles
- And on how much luminosity one obtains per particle
- Use a round beam $\sigma_x = \sigma_y$

$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\sigma^2 \propto \beta\epsilon$$

Beam brightness (beam-beam tuneshift, IBS)
Collision point beta-function
Beam current

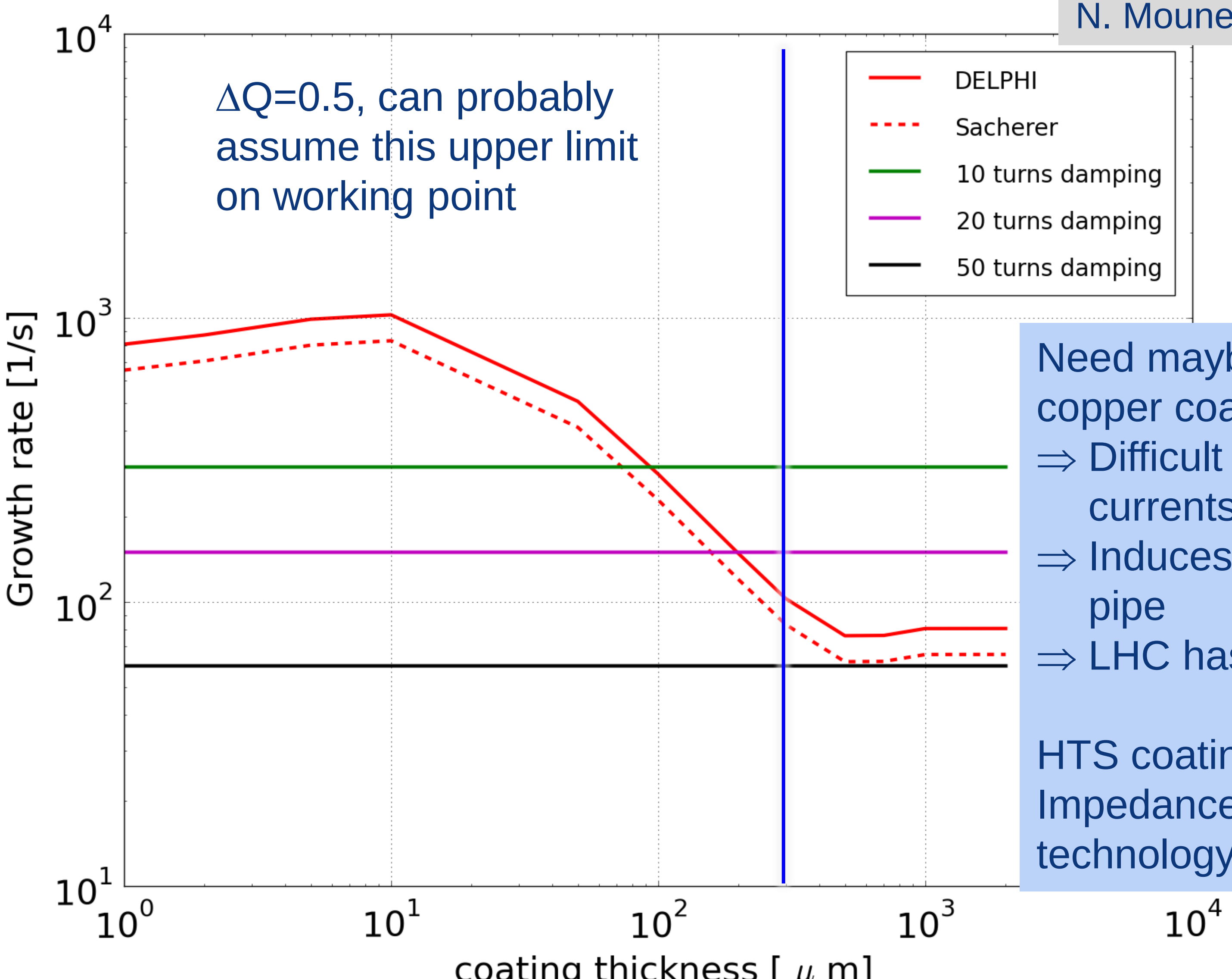
$$\mathcal{L} \propto \frac{N}{\epsilon}\frac{1}{\beta_y} N n_b f_r$$

$$\mathcal{L} \propto \xi \frac{1}{\beta_y} N n_b f_r$$

- Need to push beta-function, beam-beam tuneshift, injector brightness, turn-around time to either reduce beam current or increase luminosity
- Flat beams also to be considered

Copper Coating

N. Mounet



Need maybe 300μm of copper coating

⇒ Difficult because of eddy currents in quench

⇒ Induces stress on beam pipe

⇒ LHC has 50μm

HTS coating? Lots of work Impedance, coating technology, ecloud, …

RF Design Considerations

400.8 MHz seems a good baseline

- 16MV minimum with no margin
- 32MV seems fine

200MHz appear somewhat low

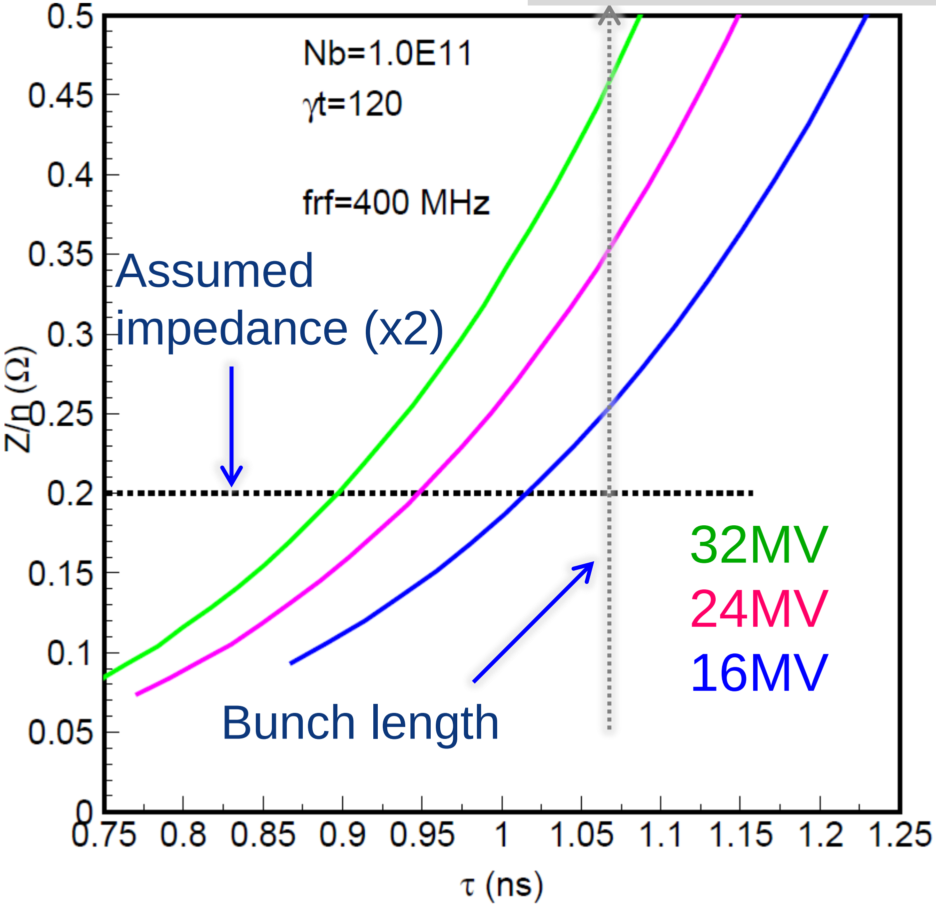
- Needs higher voltage (>100MV)
- Or longer bunches (12cm)

800MHz appears too high

Combination of 200 and 400MHz?

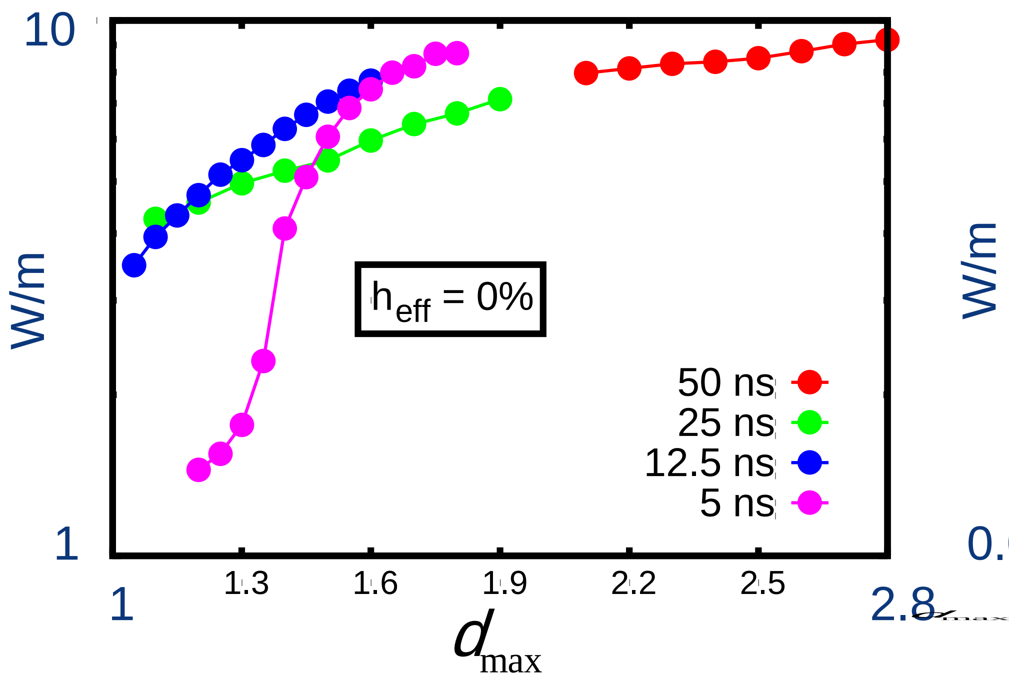
Feedback design is critical
Emittance control also

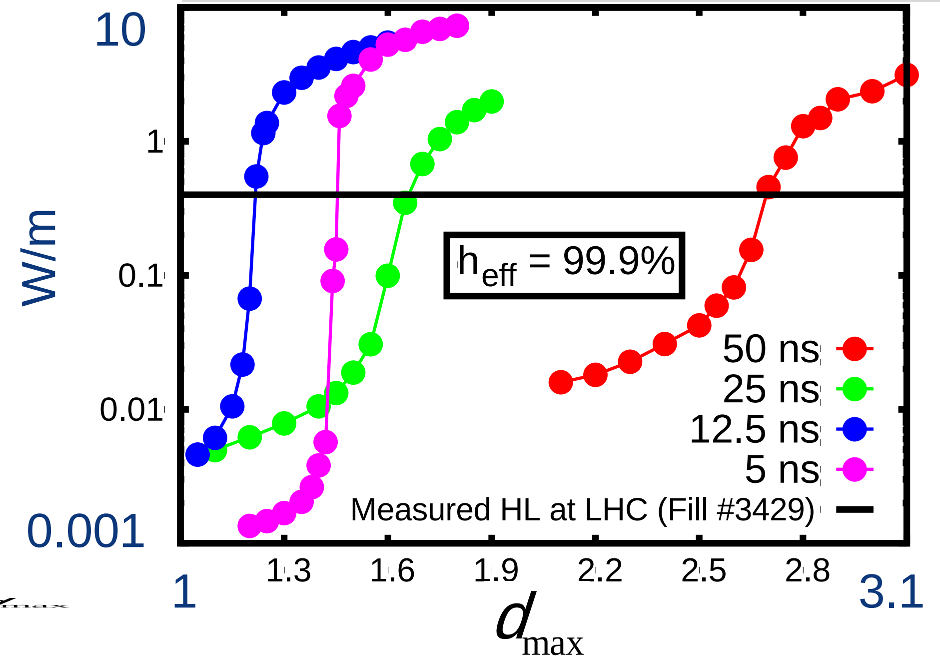
E. Shaposhnikova



Electron Cloud

O. Domingues Sanches De La Blanca





Need to quantitatively asses physics parameters

- Flux of photons increases with B, $1.3x10^{17}m^{-1}s^{-1}$, i.e. twice LHC
- Critical energy 4.3keV, i.e. 100 times LHC, similar to KEKB, photoemission yield?
- Photon capture efficiency?

Likely need mitigation techniques

Need hardware studies, simulation studies and beam experiments