Hadron-hadron Future Circular Collider

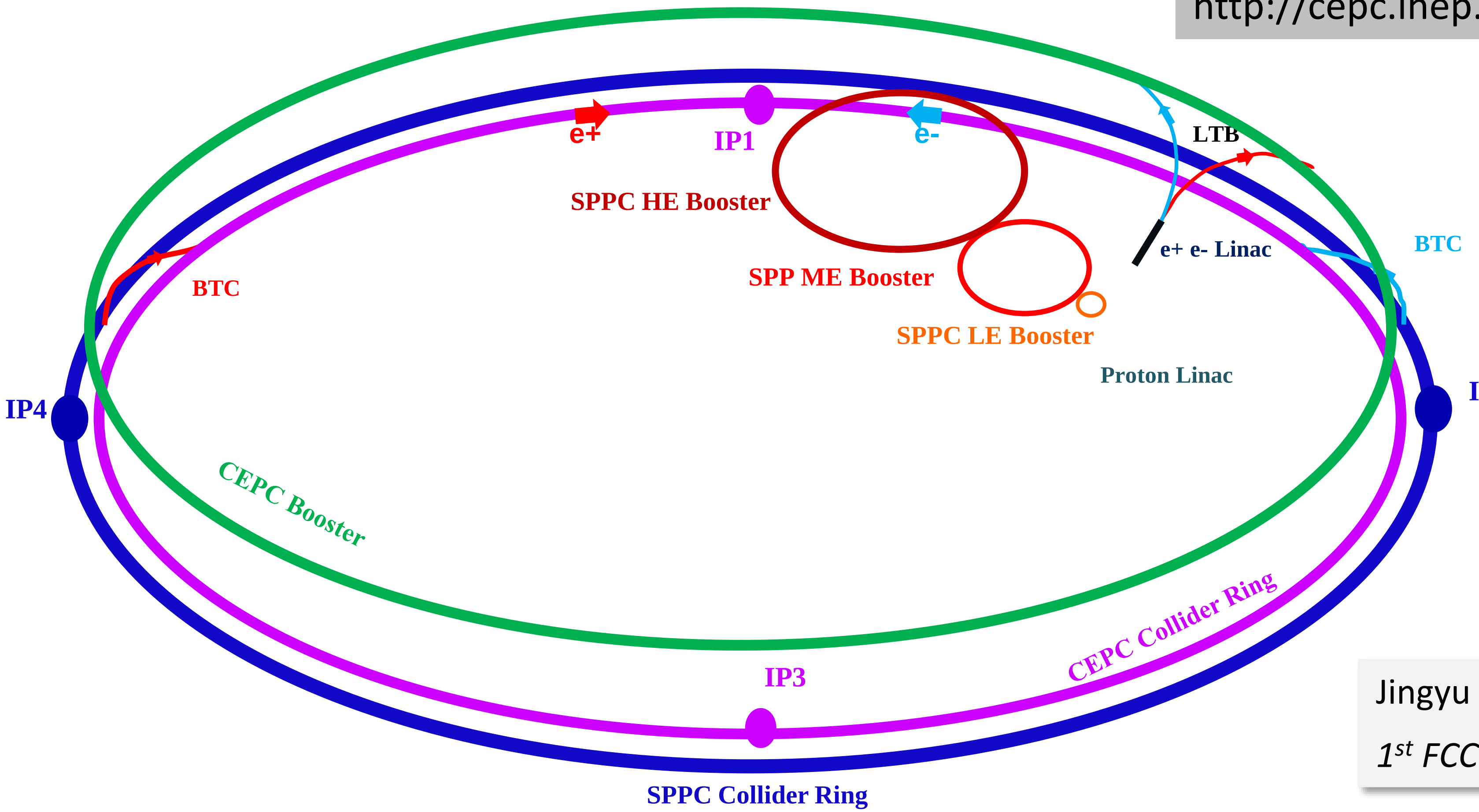
Daniel Schulte

Aspen, January 2016

CEPC and SppC

CEPC is a 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider SPPC, to study the new physics beyond the Standard Model.

http://cepc.ihep.ac.cn

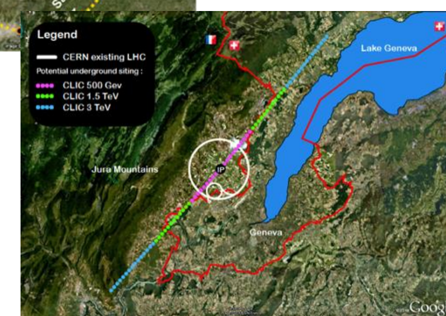


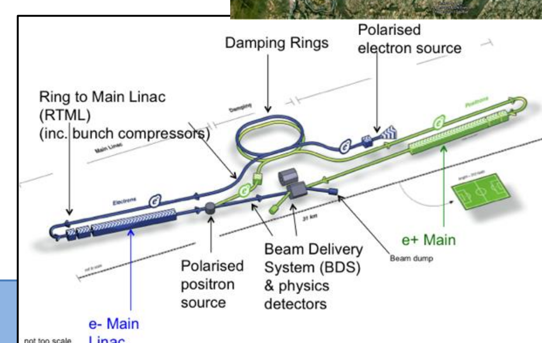
Jingyu Tang

1st FCC Week

European Strategy

- Highest priority is exploitation of the LHC including luminosity upgrades
- Europe should be able to propose an ambitious project 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 Scope

Develop CDR until 2018

FCC-hh

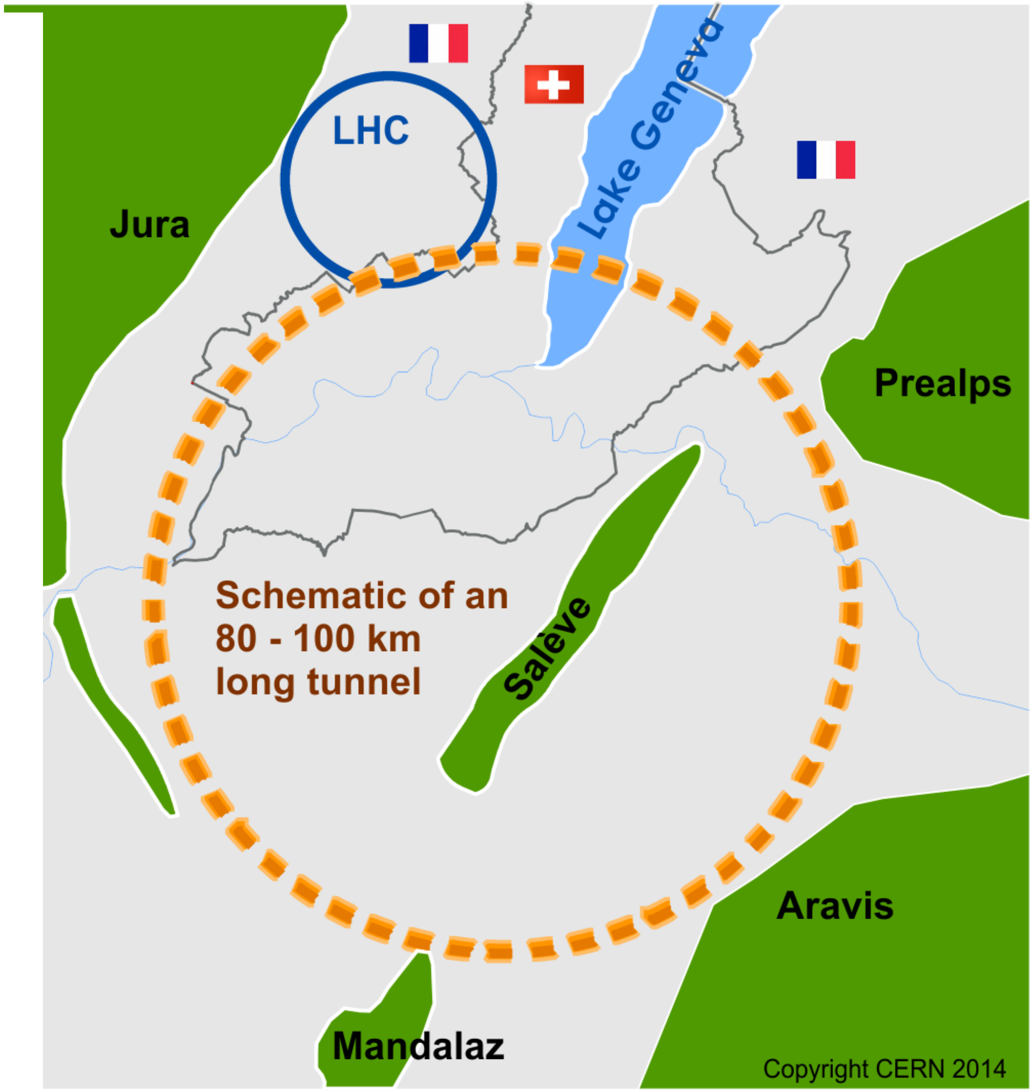
- pp collider (ion option)
- 100TeV cms energy
  - ⇒ defines infrastructure requirements

FCC-ee

- e^+e^- collider
- potential intermediate step

FCC-he

- additional option



https://fcc.web.cern.ch

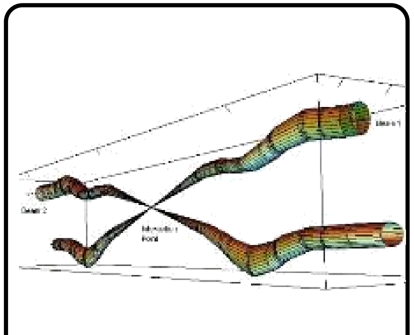
FCC Collaboration

- 70 institutes
- 26 countries + EC

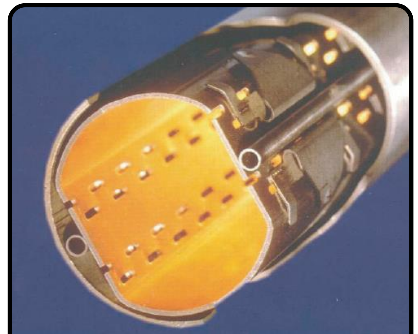
Status: November, 2015

EuroCirCol

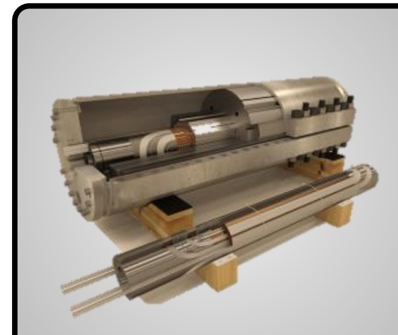
Arc Design



EIR Design



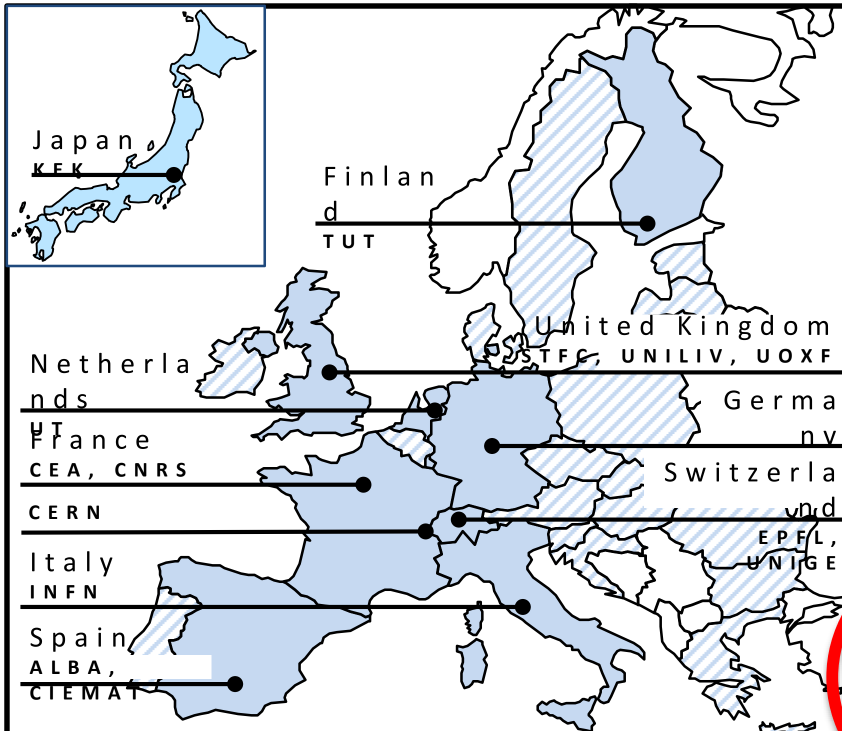
Cryo Beam Vacuum



High Field Magnet

EU co-funded design study for FCC-hh, focus on core activities

Accepted in 2015



CERN	IEIO
TUT	Finland
CEA	France
CNRS	France
KIT	Germany
TUD	Germany
INFN	Italy
UT	Netherlands
ALBA	Spain
CIEMAT	Spain
STFC	United Kingdom
UNILIV	United Kingdom
UOXF	United Kingdom
KEK	Japan
EPFL	Switzerland
UNIGE	Switzerland
NHFML-FSU	USA
BNL	USA
FNAL	USA
LBNL	USA

Luminosity and Operation

FCC (100TeV)	SppC (70TeV)
5 year long operation cycles (1.5 year shutdown, 1 year MD and stops, 2.5 years luminosity)	
2 cycles at baseline parameters Peak luminosity $5x10^{34}cm^{-2}s^{-1}$ Total of $2.5ab^{-1}$ (per detector) 3 cycles of ultimate parameters Peak luminosity $<=30x10^{34}cm^{-2}s^{-1}$ Total of $15ab^{-2}$	Run for 10 years Peak luminosity $<=12x10^{34}cm^{-2}s^{-1}$
$17.5ab^{-1}$[1] per experiment Detectors must be able sustain a total of $30ab^{-1}$[1]	$30fb^{-1}$ assuming two detectors

This and all SppC from arXiv: 1507.03224v1

Future Hadron Colliders

	LHC	HL-LHC	FCC-hh Baseline	FCC-hh Ultimate	SPPC
Cms energy [TeV]	14	14	100	100	71
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	20	12
Machine circumference	27	27	100	100	54
Arc dipole field [T]	8	8	16	16	20
Bunch distance [ns]	25	25	25	25 (5)	25 (10/5)
Background events/bx	27	135	170	680 (136)	490 (196/98)
Bunch length [cm]	7.5	7.5	8	8	7.55

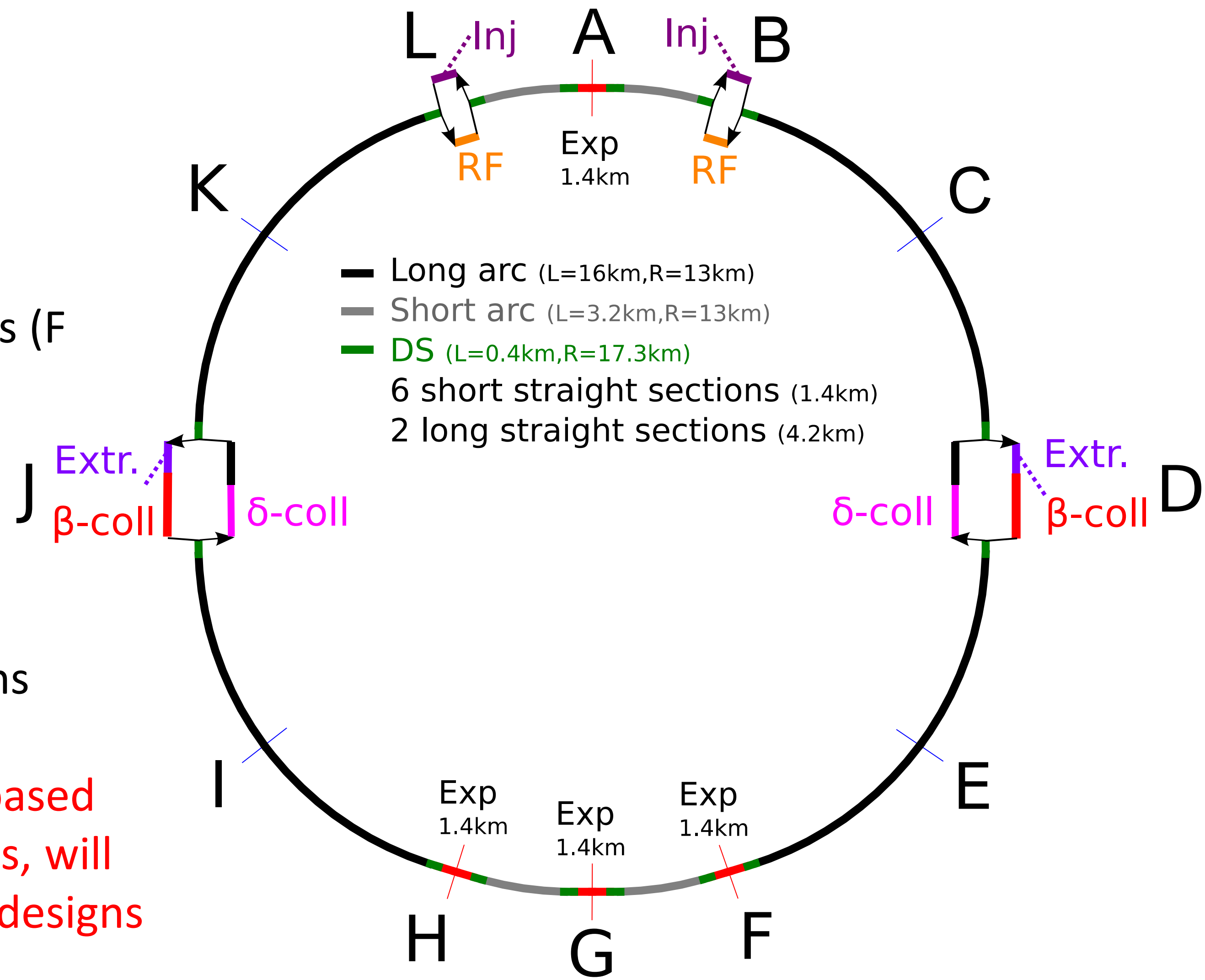
For FCC-hh baseline currently consider 25ns bunch spacing, for ultimate consider small bunch spacing to reduce background per crossing

Question: Is it acceptable for the detector to run at different bunch spacings?

FCC-hh Layout

First layout developed

- Two high-luminosity experiments (A and G)
- Two other experiments (F and H)
- Two collimation and extraction insertions
- Two injection insertions
- Insertion lengths are based on first order estimates, will be reviewed as optics designs are optimised

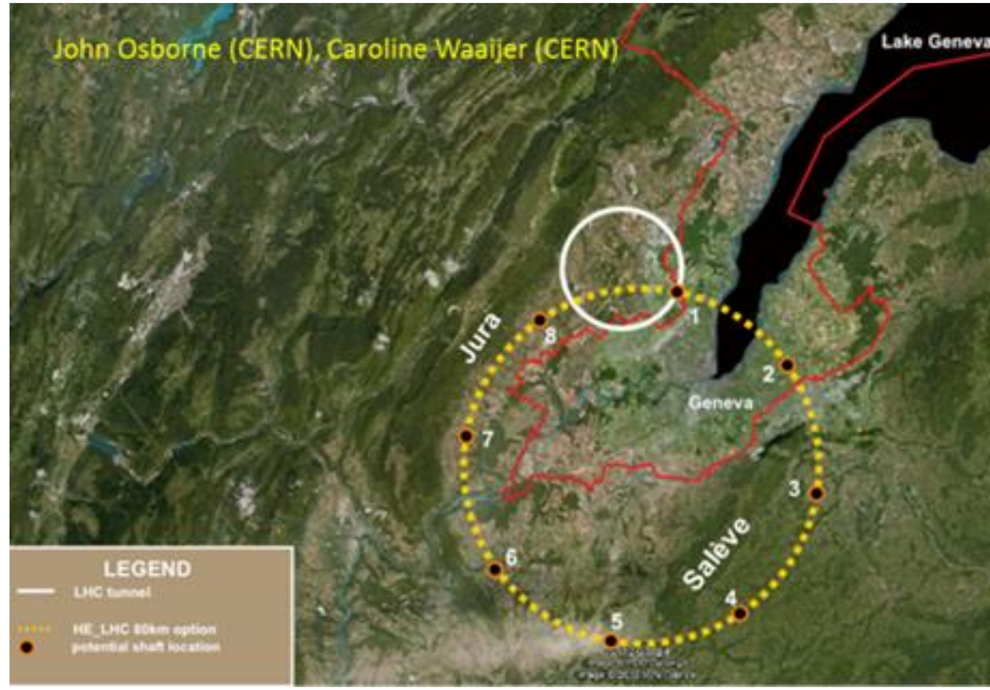


FCC Injection and Site Study

Detailed site studies are ongoing

- Geology
- Surface buildings
- …

⇒ 100km ring fits well into the Geneva area

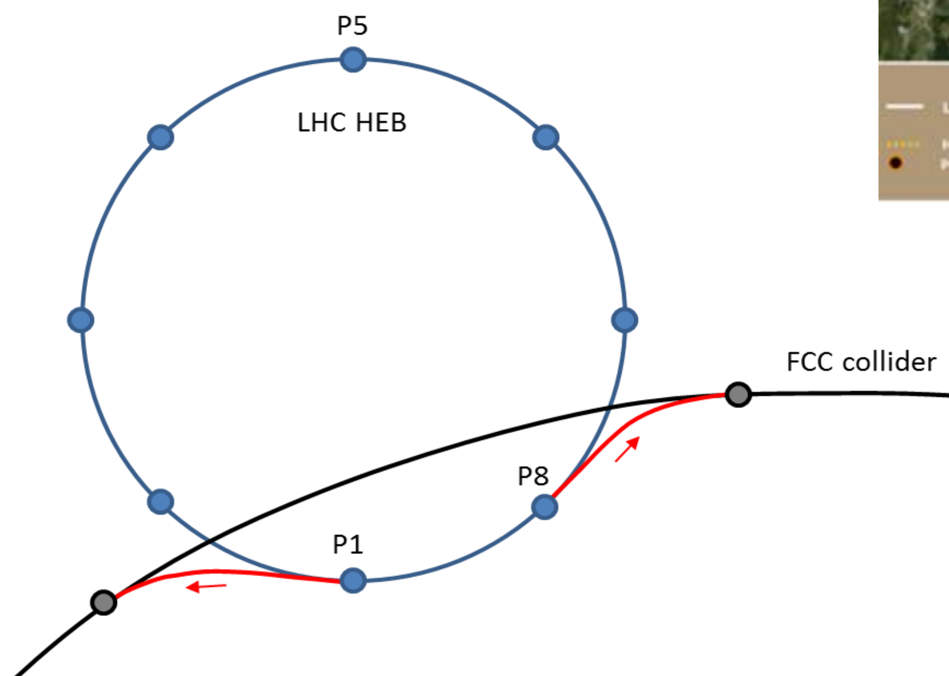


LHC can be used as injector

- Small changes on LHC
- The two tunnels would match nicely
- Energy and beam quality are sufficient

Also consider SPS and FCC tunnel for injector

- SPS located at the right place



SppC Layout and Injector Chain

Two ee-experiments in LSS1+5

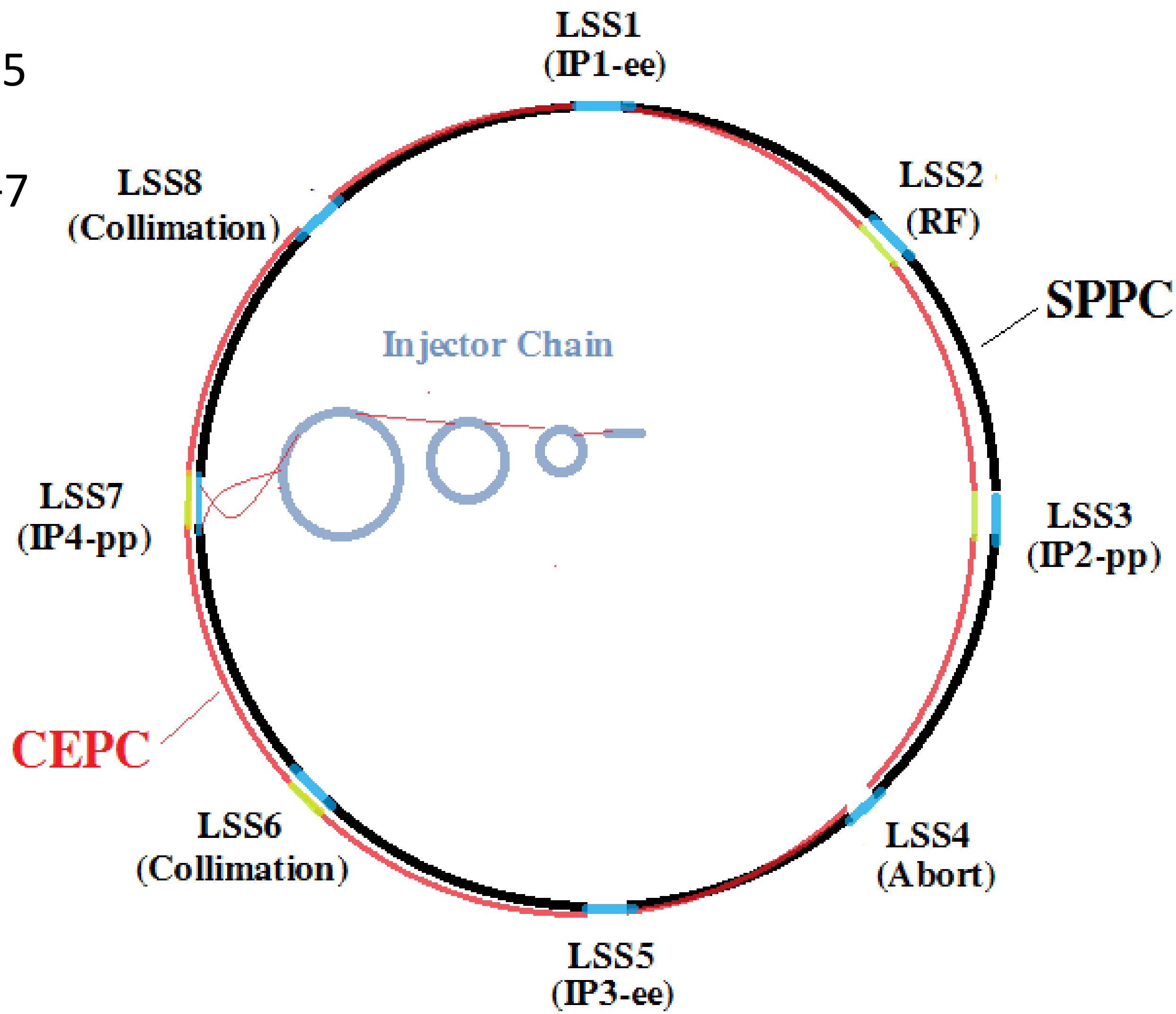
Two pp-experiments in LSS3+7

Two collimation insertions

One RF insertion

Injector chain needs to be built

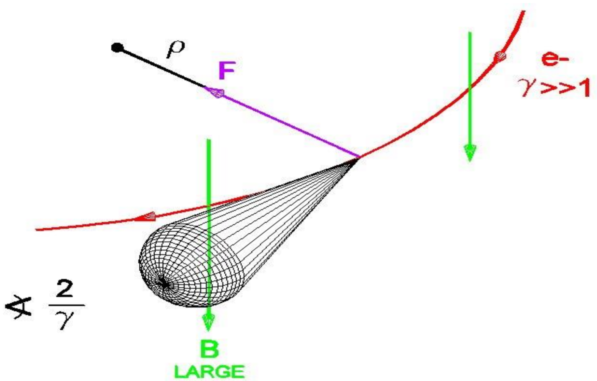
- final energy 2.1TeV



Initial Beam Parameters

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

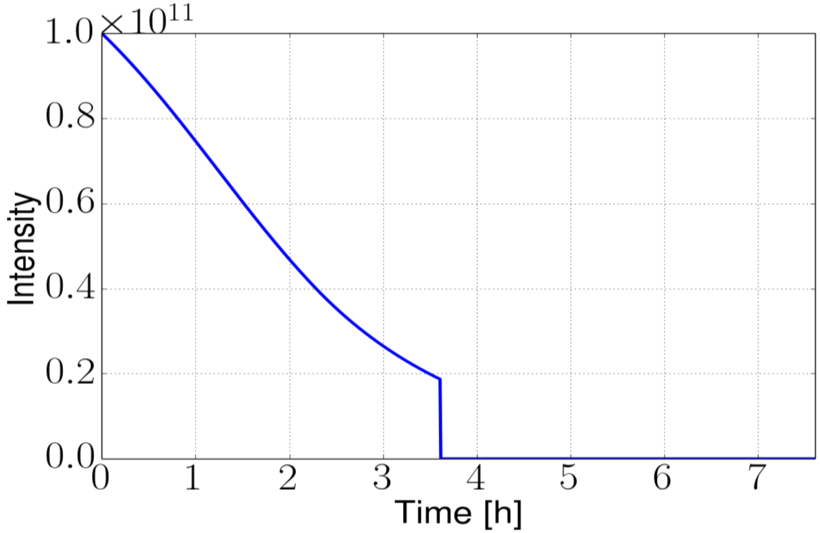
$$\mathcal{L} = \xi\frac{1}{\beta}\frac{N}{\Delta t}\eta_{fill}$$

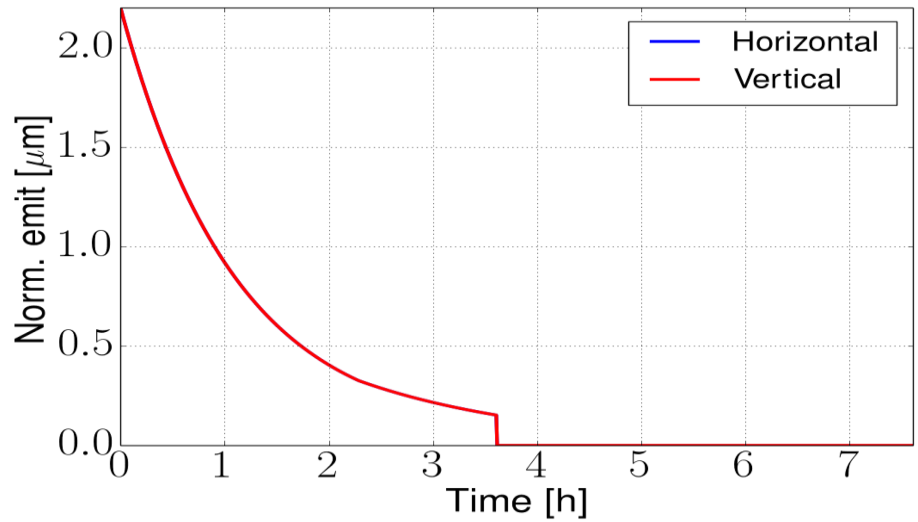


~5MW in both projects
Damps the beam

	FCC-hh Baseline	FCC-hh Ultimate	SPPC
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20	12
Background events/bx	170 (34)	680 (136)	
Bunch distance Δt [ns]	25 (5)		25
Bunch charge N [10^{11}]	1 (0.2)		2
Fract. of ring filled η_{fill} [%]	80		
Norm. emitt. [μm]	2.2(0.44)		4.1
Max ξ for 2 IPs	0.01 (0.02)	0.03	0.03
IP beta-function β [m]	1.1	0.3	0.75
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)	9
RMS bunch length σ_z [cm]	8		7.55
Crossing angle [σ□]	12	Crab. Cav.	12
Turn-around time [h]	5	4	3

Integrated Luminosity (FCC)





Developing model including all relevant effects

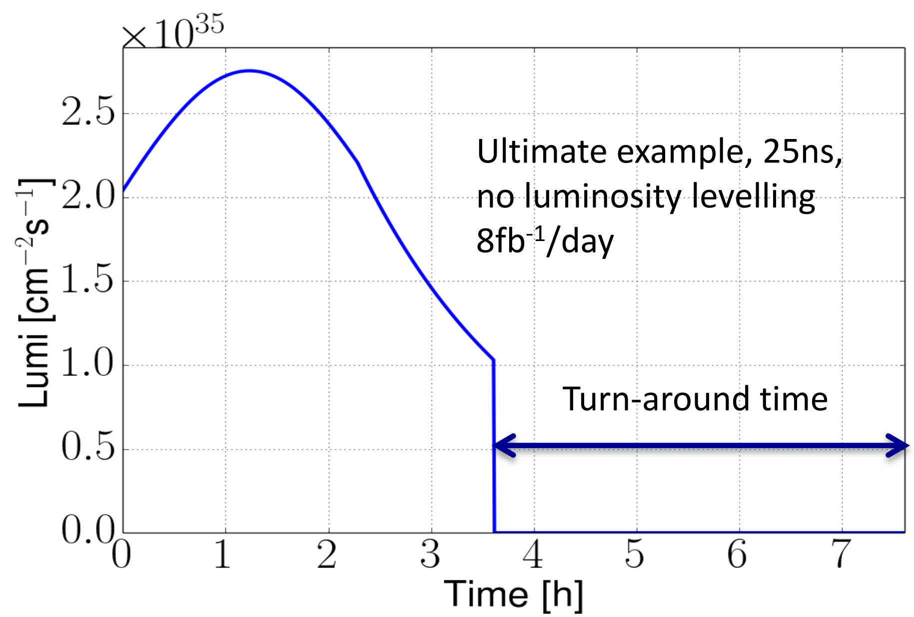
- Iterations required

⇒ Can reach >8fb^{-1}/day with ultimate for ξ=0.03

  ⇒ 5000fb^{-1} per 5 year run

⇒ Beam is burned quickly

  ⇒ Another reason to have enough charge stored



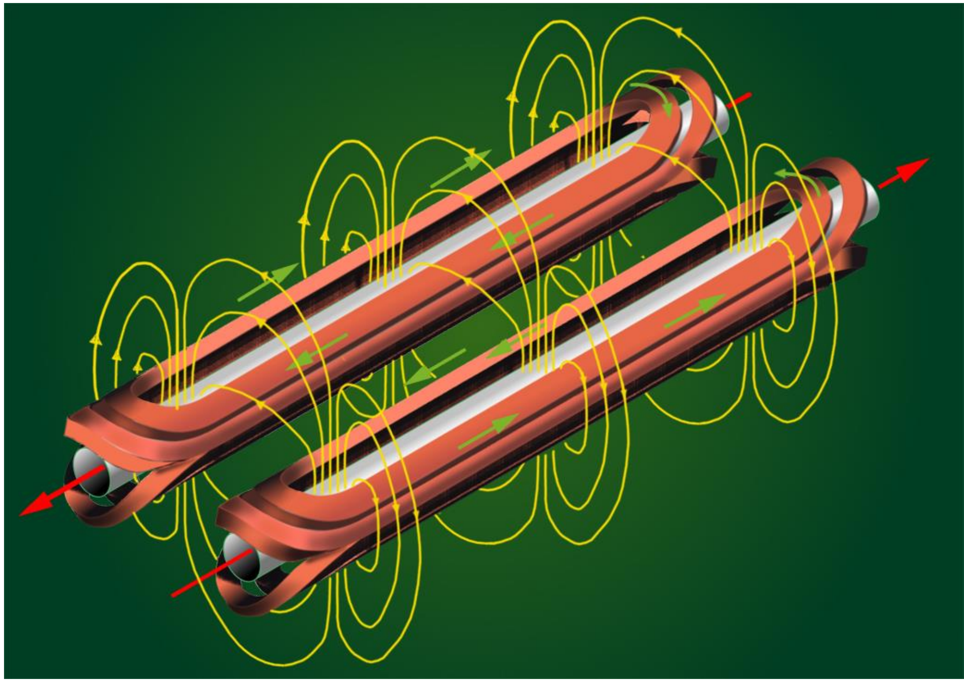
Magnets

FCC goal is 16T operating field

- Requires to use Nb_3Sn technology
- At lower field levels used for HL-LHC

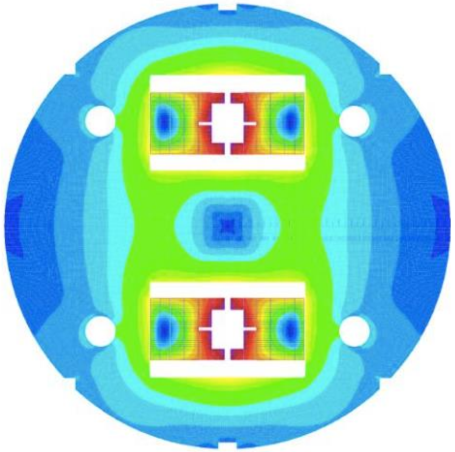
Also potential for 20T is being explored

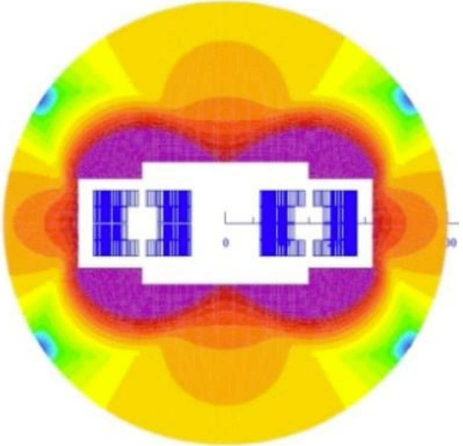
- Requires use of HTS



SppC goal is 20T

SppC (left)and FCC (right) examples





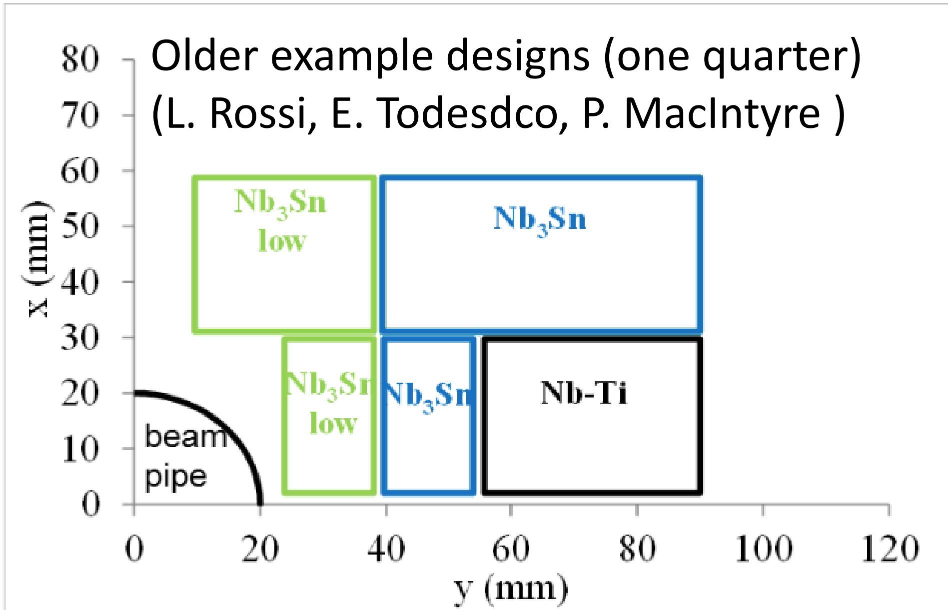
Also field quality is important

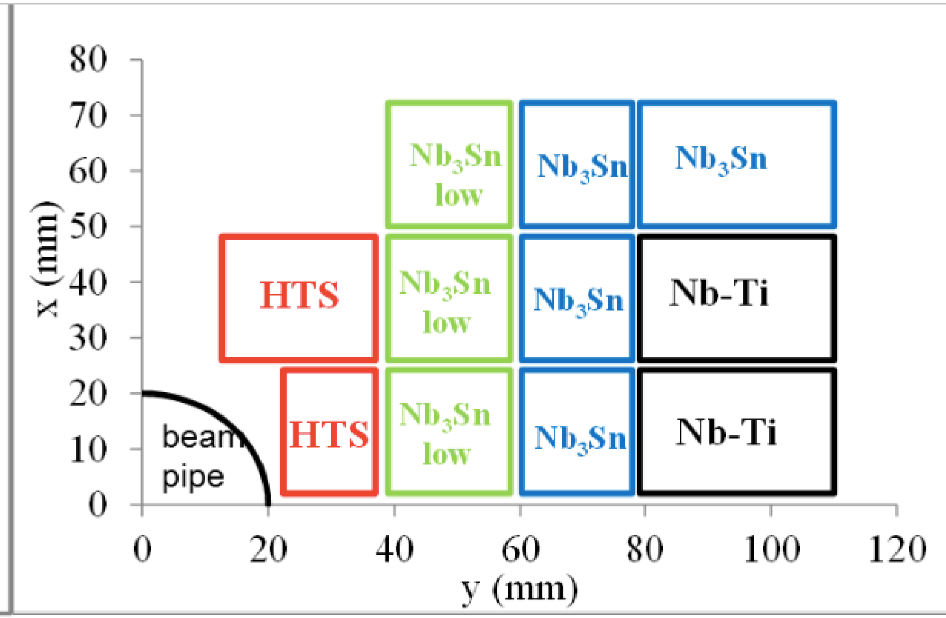
- at injection energy
- At top energy

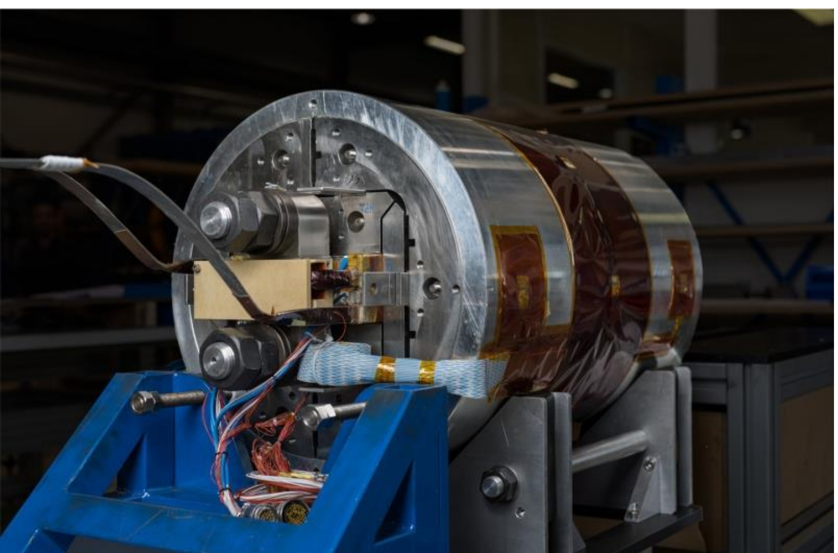
Important parameter is the required aperture of the coils

- Larger is more expensive

Magnets







Combination of materials used to reduce cost

Different designs are being explored for FCC

A recent test AT CERN has achieved world record of 16.2T

- But a short racetrack magnet

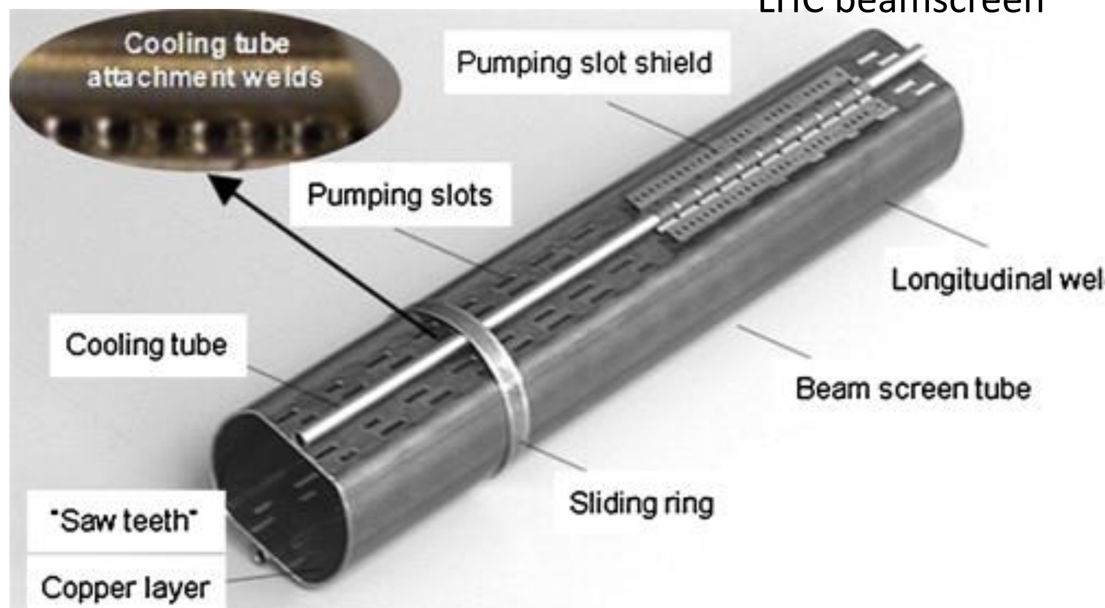
Synchrotron Radiation and Beamscreen

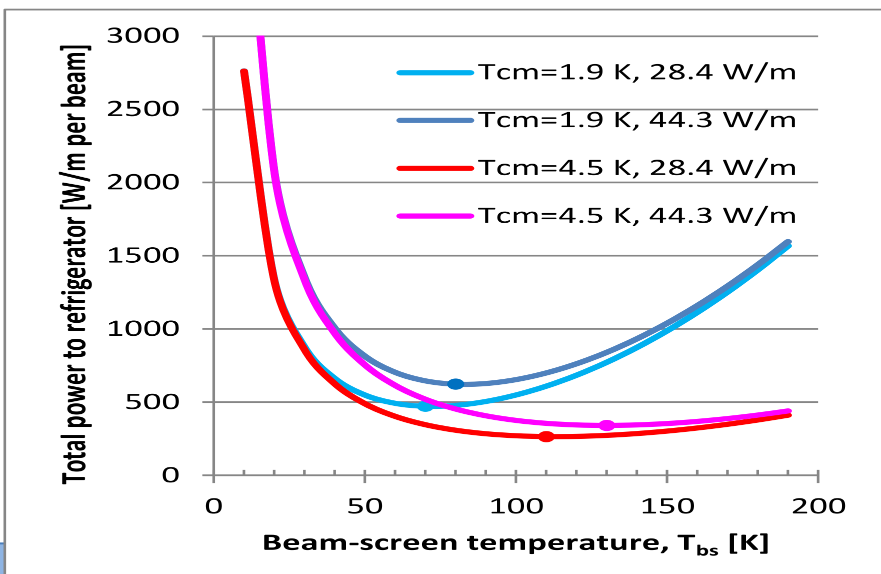
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

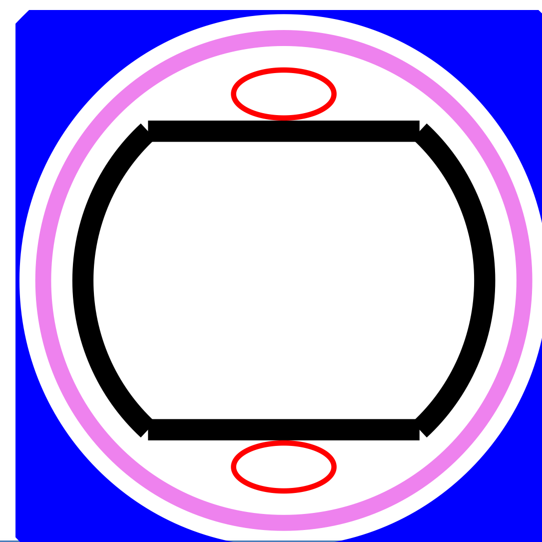
5MW synchrotron radiation
3,500 MW cooling power at 2K

Beamscreen at 50K
100MW power for cooling

LHC beamscreen



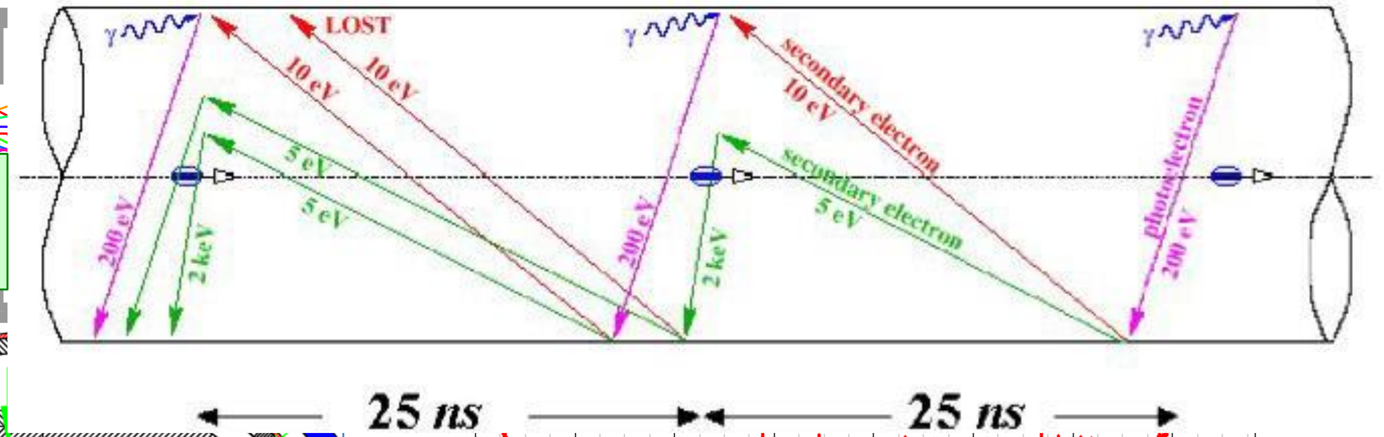


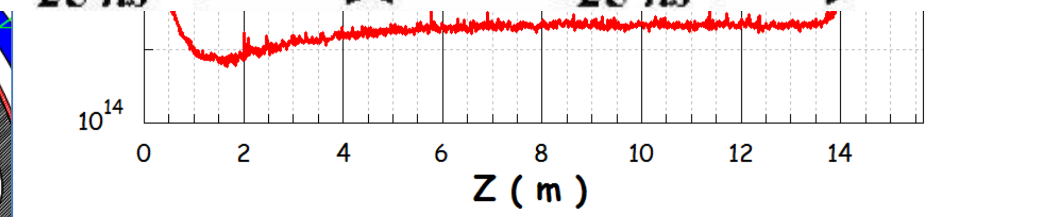


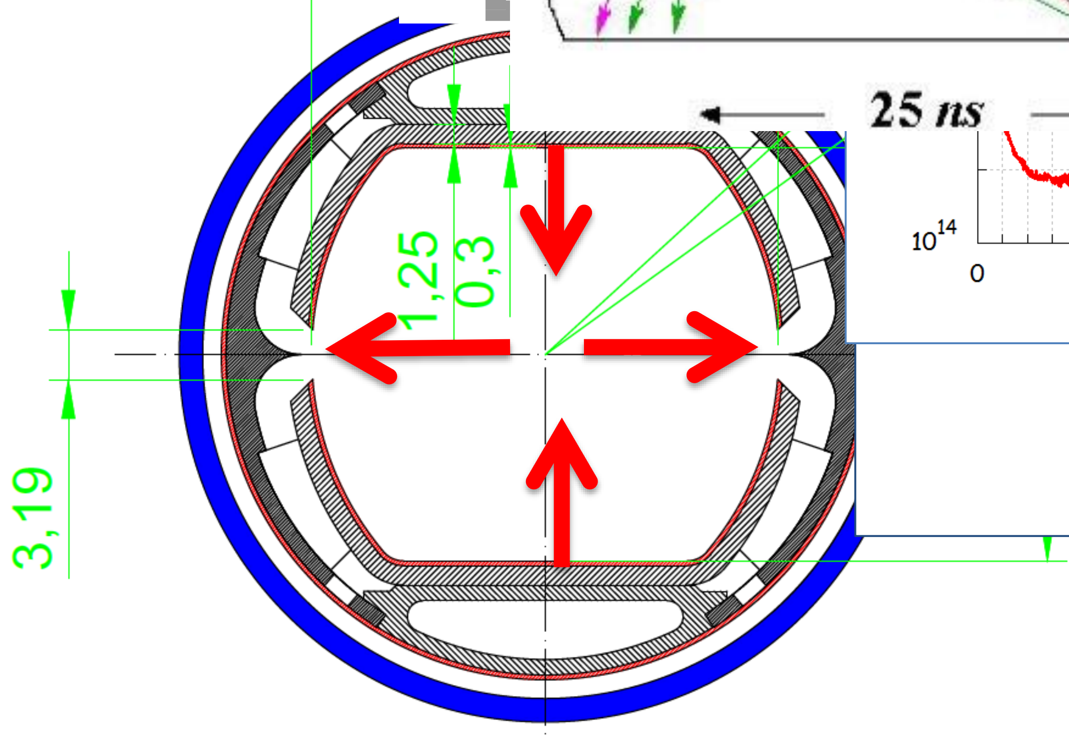
FCC Beam Screen Design

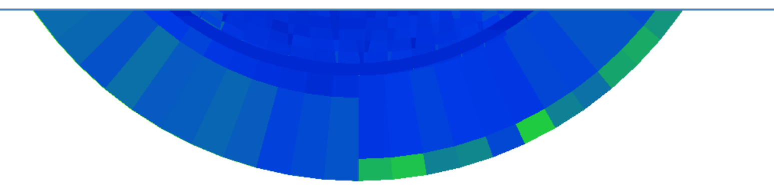
$$\mathcal{L} = \xi \frac{1}{\beta^*} \frac{N}{\Delta t} \eta_{fill}$$

Total magnet aperture 50mm









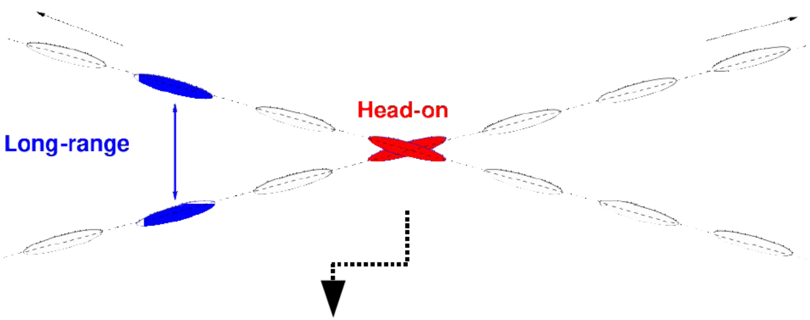
Avoid build-up of electron cloud

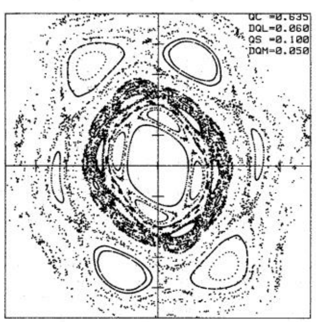
Beam to screen alignment

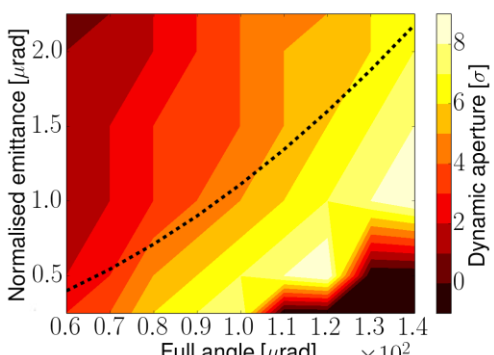
FCC Beam Physics Studies

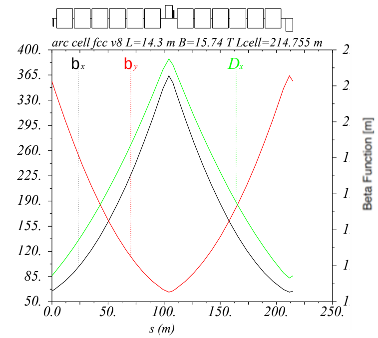
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

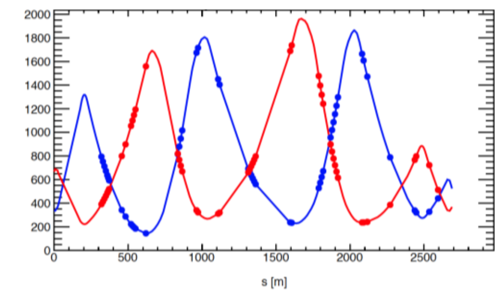
Beam-beam studies ongoing, promising results











First lattice complete except for some details

First dynamic aperture studies have been performed

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

Impedances

Electron cloud

Collimation

Injection

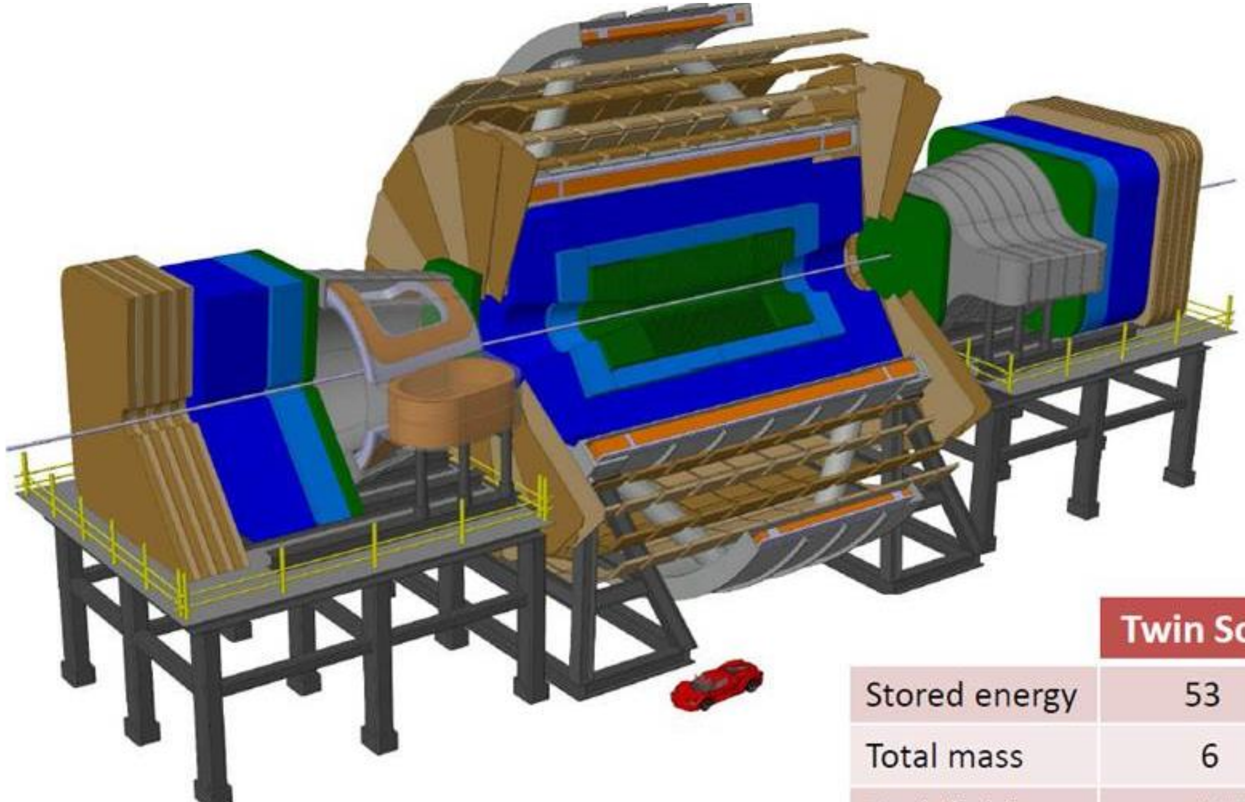
Extraction

…

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

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

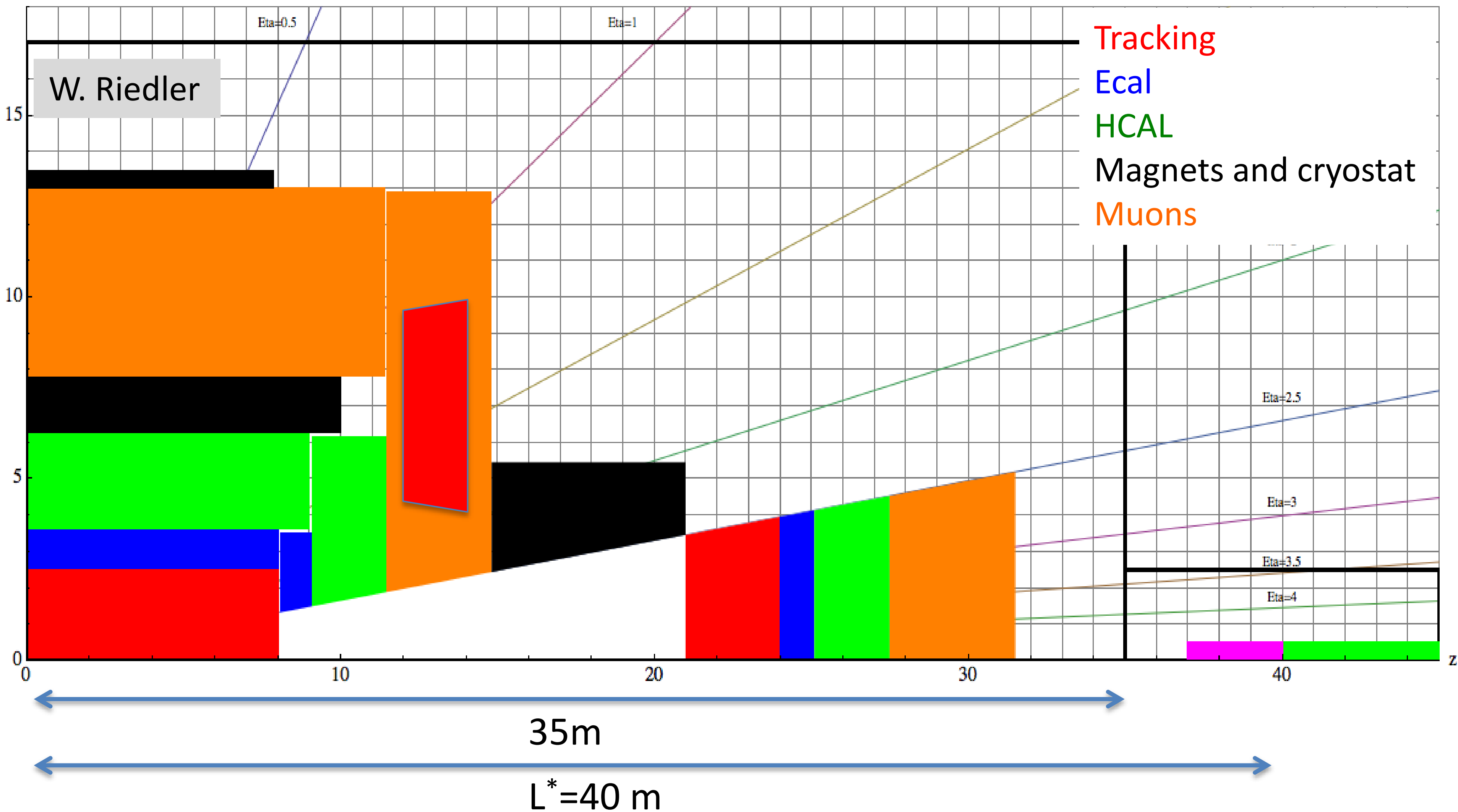


	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

FCC Air core Twin solenoid and Dipoles

State of the art high stress / low mass design.

Space for FCC Detector



Probably need a bit larger L*

FCC Final Focus Design

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

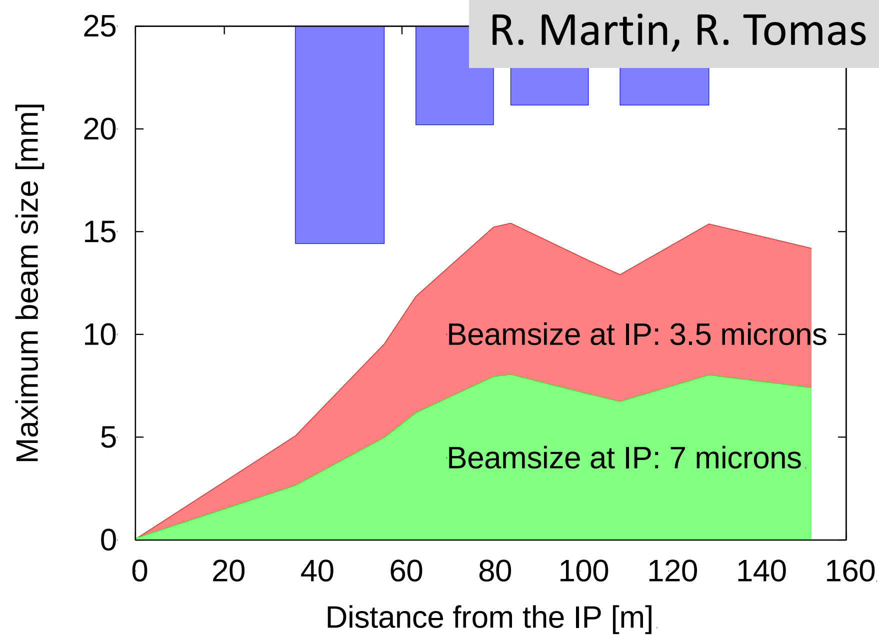
Small beam in interaction point leads to large beam in triplets

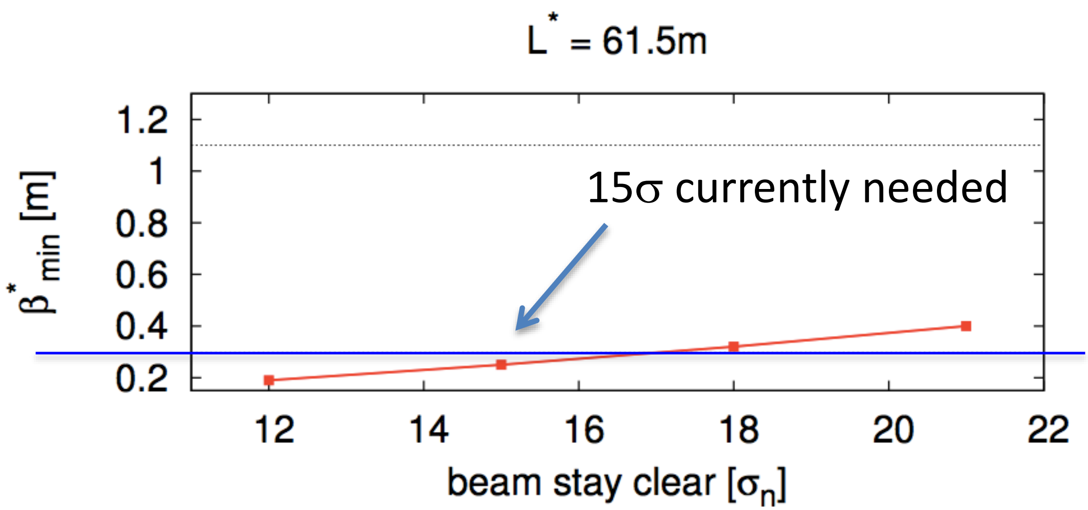
The maximum quadrupole field limits the beta-function/beam size at the IP

Have a good solutions with L^*=36m and 61.5m

Will optimise this further

R. Martin, R. Tomas





Radiation from Beam-beam (FCC)

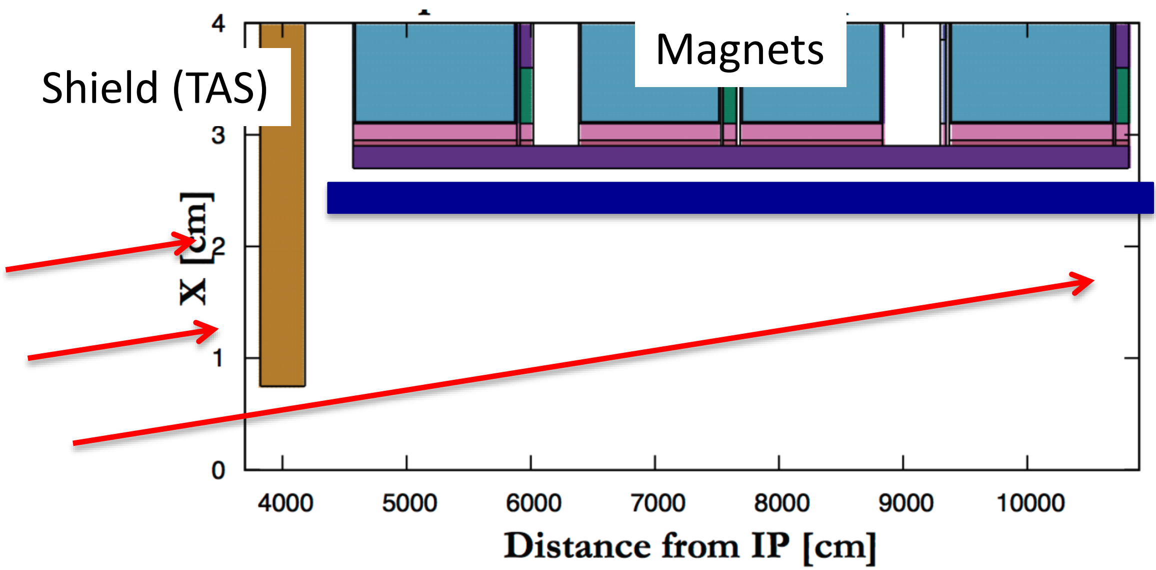
Total power of background events 100-500kW per experiment

- Car or truck engine

Already limit in LHC and HL-LHC

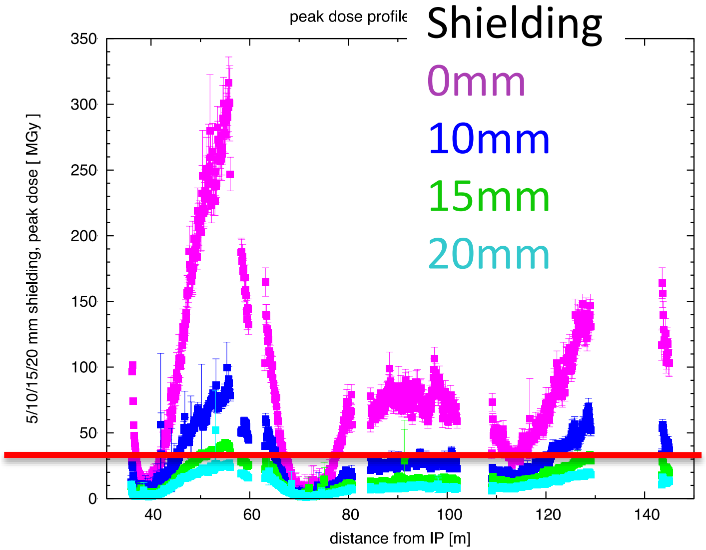
- Magnet lifetime, heat load

Study of 3000fb^{-1} in older FCC-hh detector design



Dose for 3000fb^{-1}

30MGy= Current limit



Split magnets?

Better glue, but copper is next issue?

Switching from horizontal to vertical crossing after some time? OK for the experiment?

Machine Protection and Friends (FCC)

8GJ kinetic energy per beam

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

⇒ Machine protection

High risk at injection and extraction

Instrumentation to detect failures

Interlock system

Passive protection and collimation system

Machine protection strategy

O(160GJ) in magnets
O(20) times LHC

⇒ Serious protection issue
⇒ Similar for SppC

LHC has O(100) collimators

- Distributed around the machine
- Protects the machine and experiments

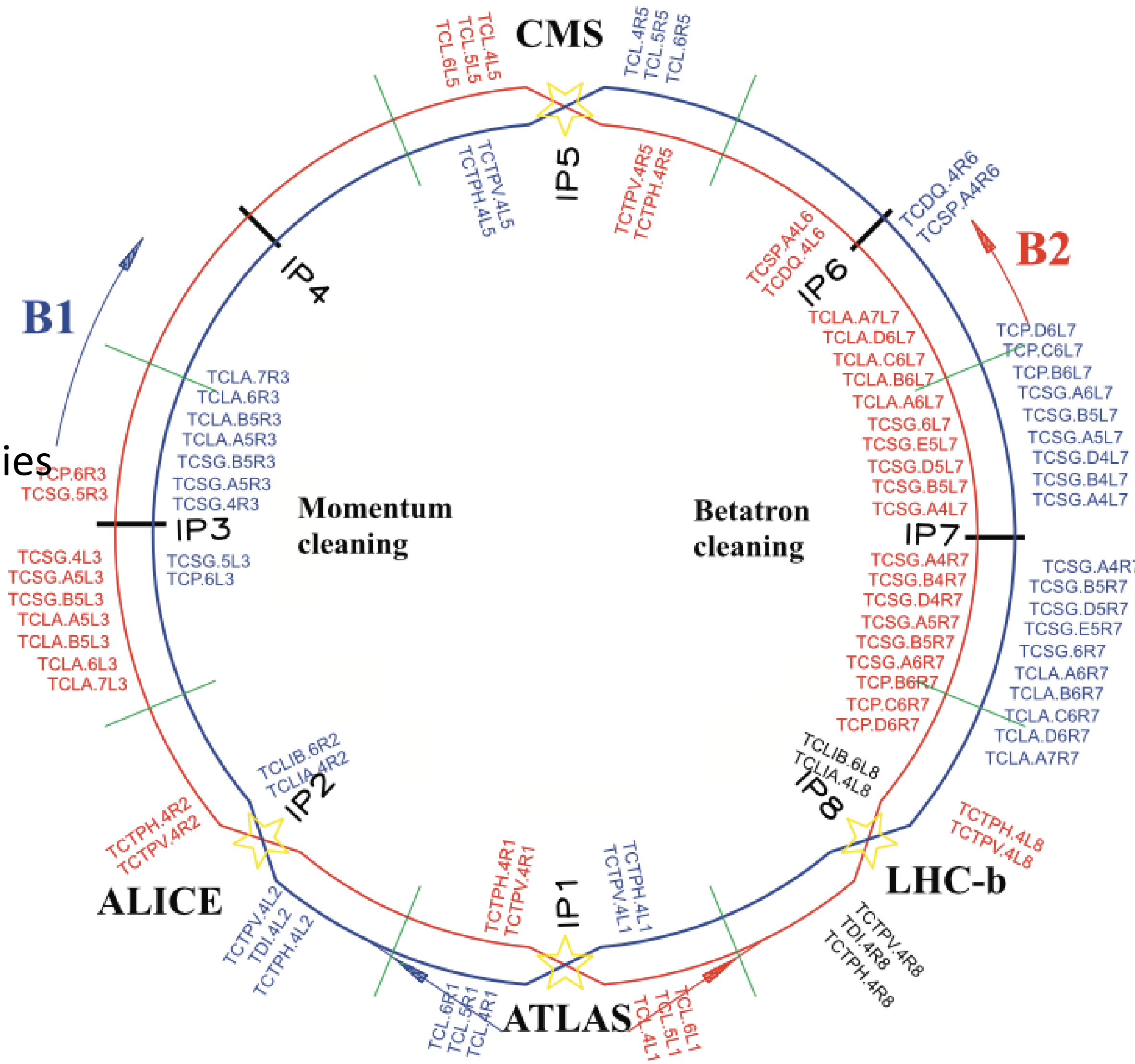
First designs of FCC collimation system lattices exist

Have to review FLUKA at FCC energies

Performance studies are ongoing

- Collimation efficiency
- Power losses

A complex long-term optimisation



Conclusion

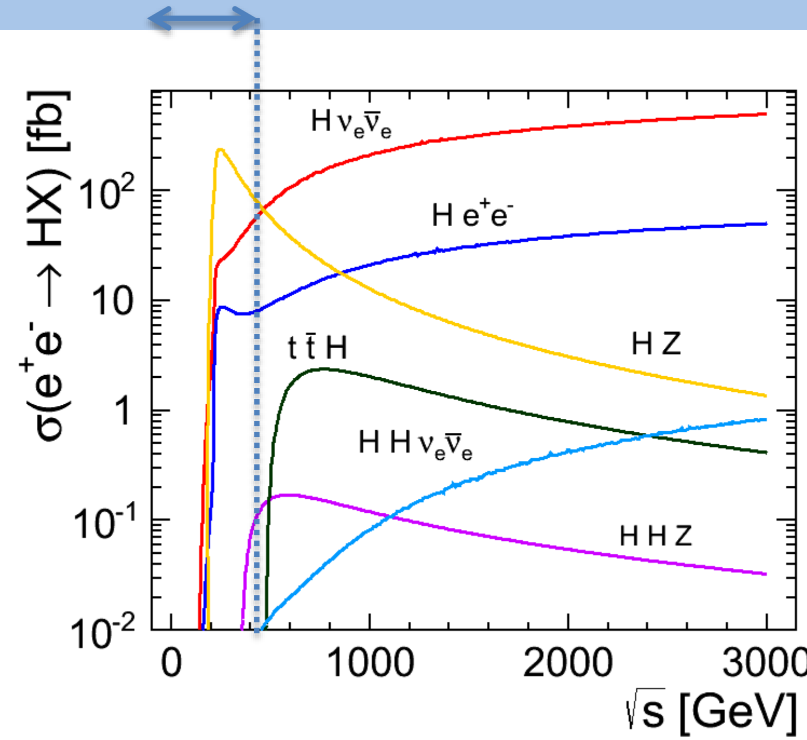
- In China SPPC is considered as upgrade to potential CEPC
- FCC developed as option for future flagship project at CERN
  - FCC-hh, with possibly FCC-ee as intermediate step (also FCC-he option)
  - Goal is to have CDR ready for European strategy update (2018)
  - https://indico.cern.ch/category/5153/
  - Workshop in Rome April 11-15, 2016
- First baseline exists
- More work to be done
  - Exciting technological challenges
  - Exciting beam physics
  - Exciting physics
- Your contributions are most welcome

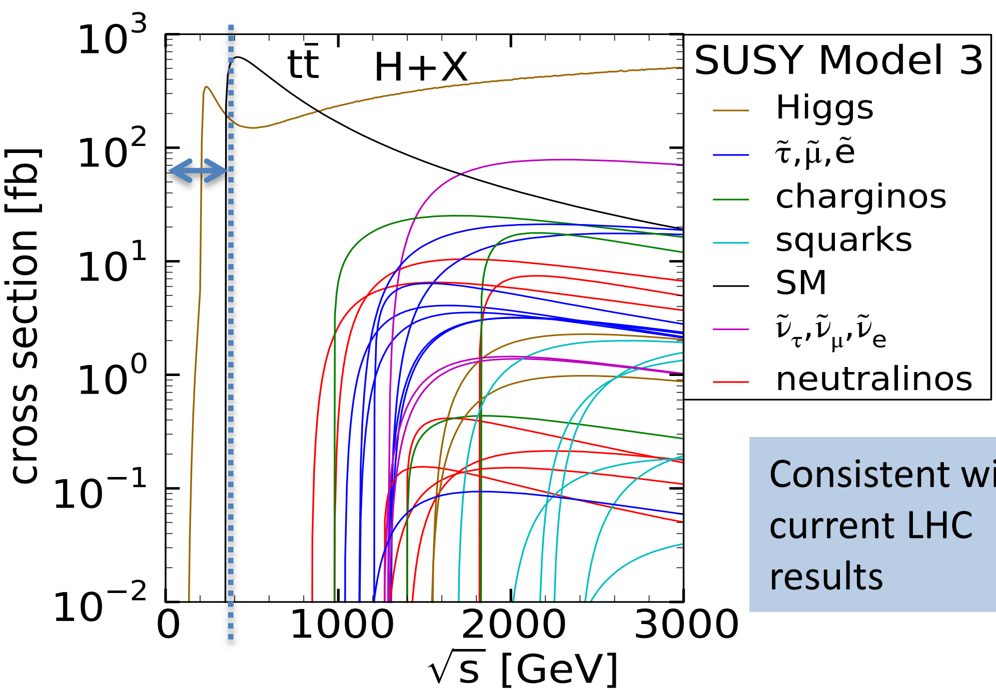
Reserve Slides

FCC-ee Rational

- Can use FCC-hh tunnel
  - Tunnel cost has to be paid only once

- Can operate at
  - 90 GeV (“Tera-Z”)
  - 160GeV (W pairs)
  - 240GeV (Higgs via Zh)
  - 350GeV (top threshold, higgs via Zh and WW)





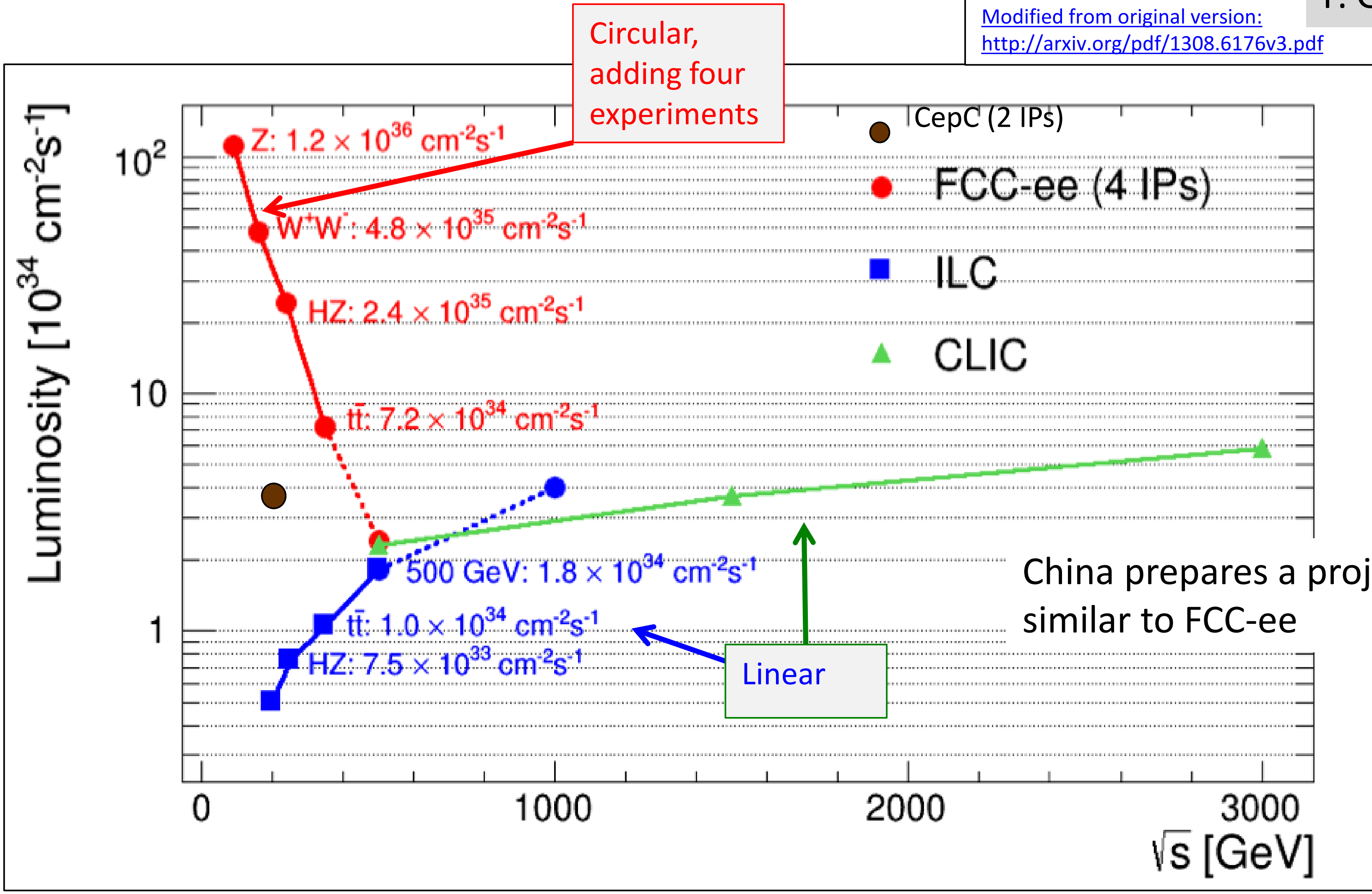
Consistent with current LHC results

- Limited energy reach
- But proton collider takes care of high energies

FCC-ee vs. Linear Colliders

F. Gianotti

Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf



The Key Challenges

- Energy
  - Limited by the machine size and the strength of the bending dipoles

  ⇒ Have to maximise the magnet strength

- Luminosity

  ⇒ Need to maximise the use of the beam for luminosity production

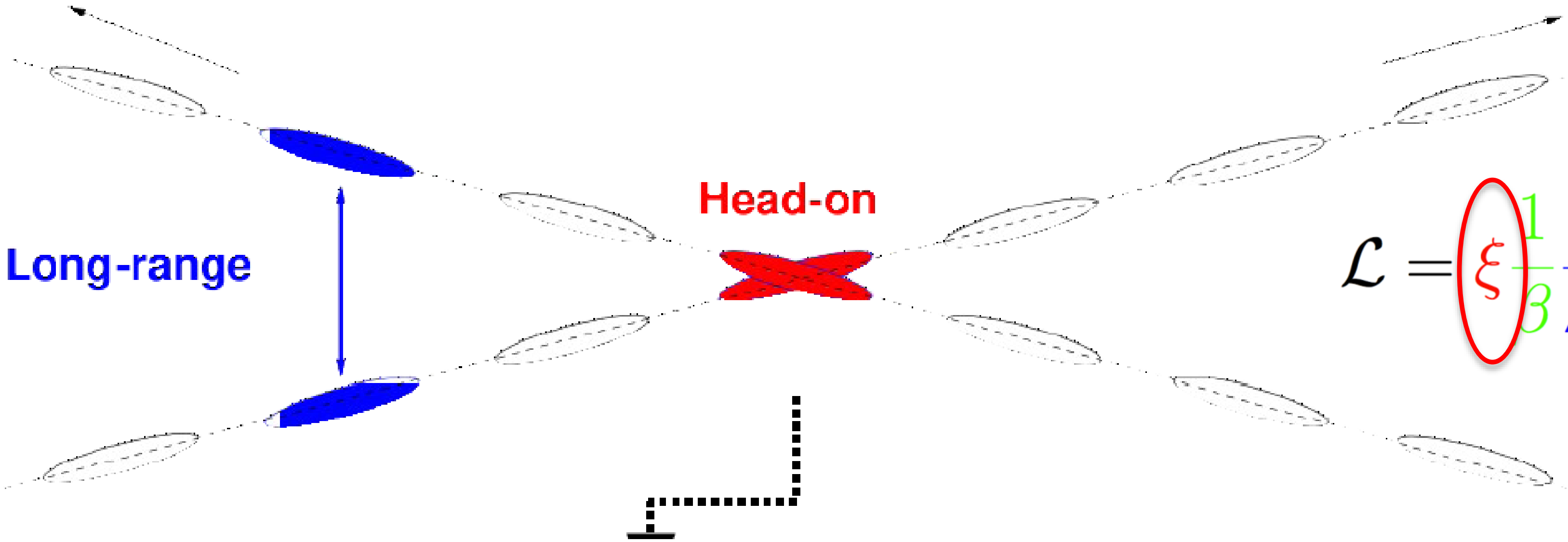
- Beam power handling
  - The beam can damage the machine
  - Quench the magnets
  - Create background in the experiments

  ⇒ Need a concept to deal with the beam power

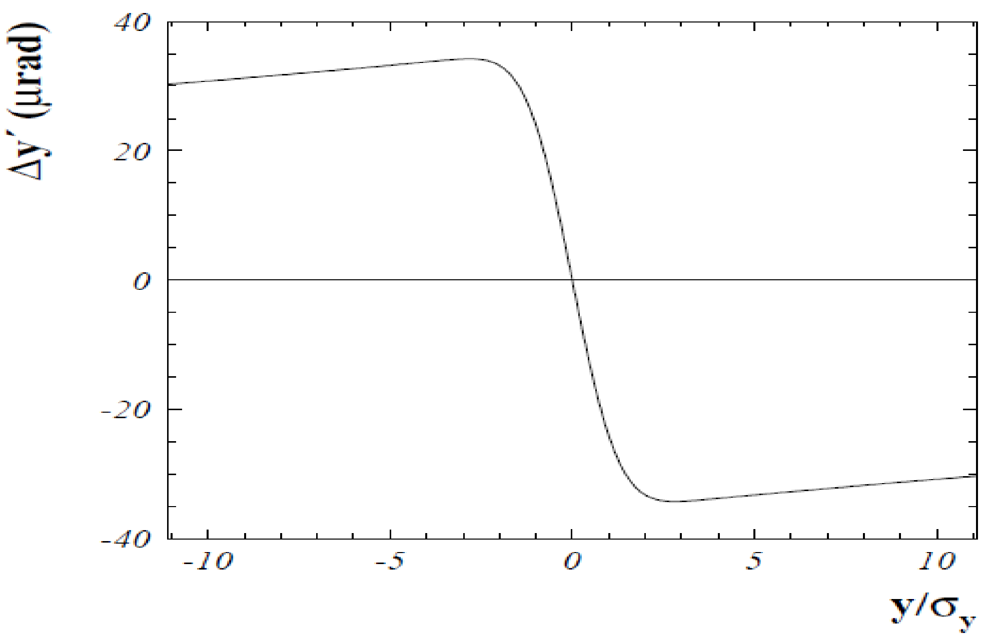
- Cost
  - The total cost is a concern, so we have to push everything to the limit to reduce cost

  ⇒ Most things will become difficult

Beam-beam Effects



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



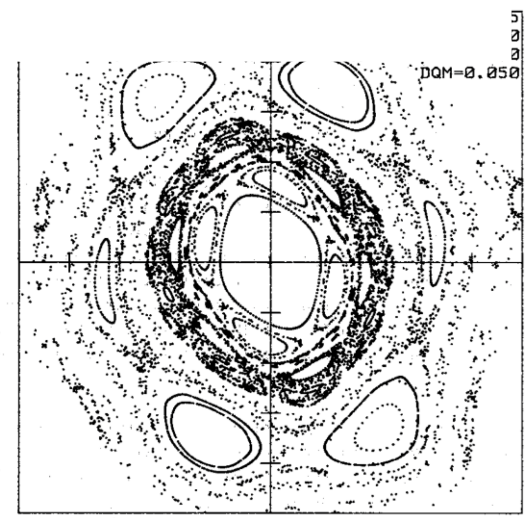
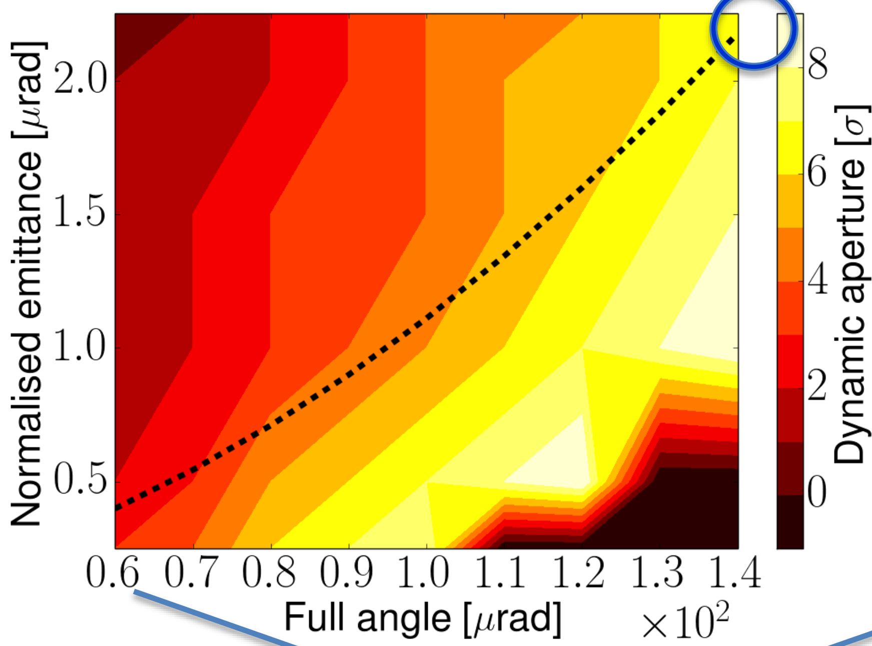


Plate 3b

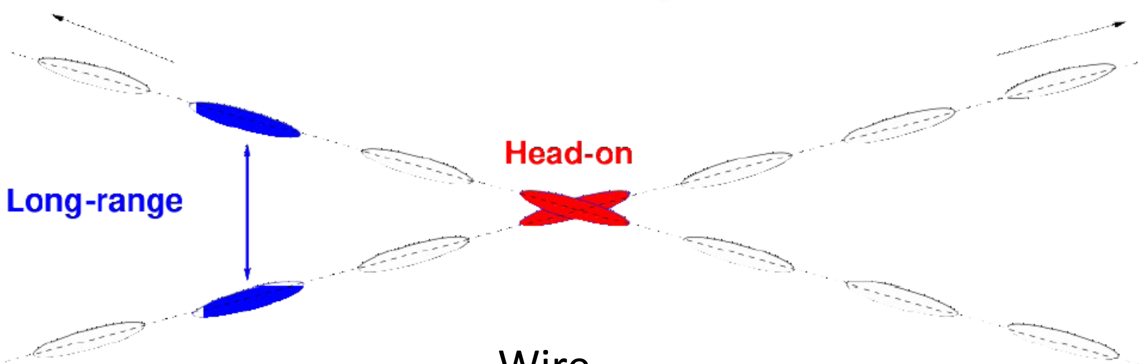
- ⇒ About ξ=0.03 is acceptable
- ⇒ More study needed



Effect is about OK

But would like to have margin and to push further

Some mitigation techniques are possible:

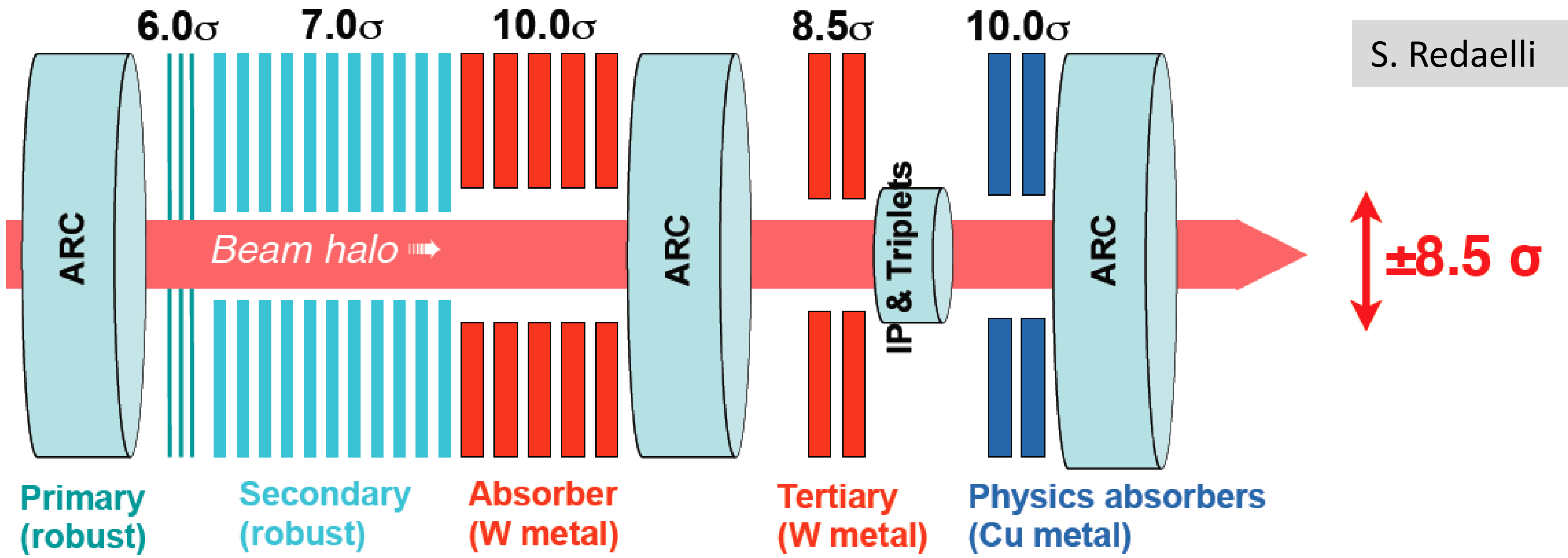


Wire

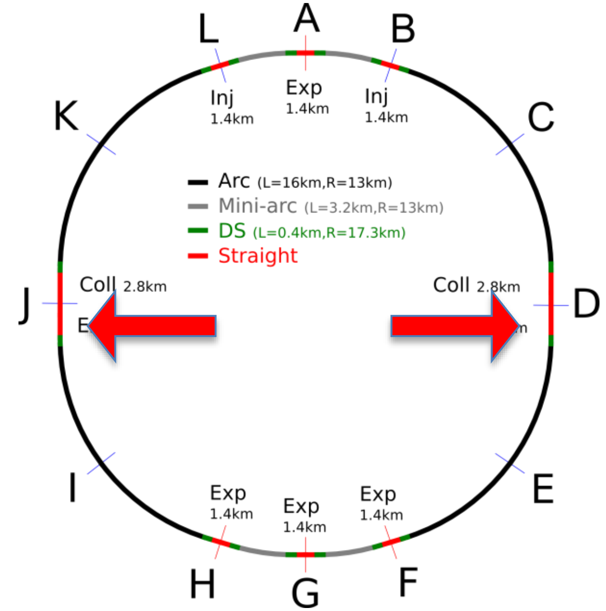
Head-on:
Electron lens

Long-range:
Larger crossing angle (and crab crossing)
Compensating wire (to be tested for HL-LHC)

Collimation System



- Efficiency is important
- Robustness in case of fast beam loss (in a few minutes)
  ⇒ Materials, …
- Main impedance at collision energy
  => Optics, materials, …

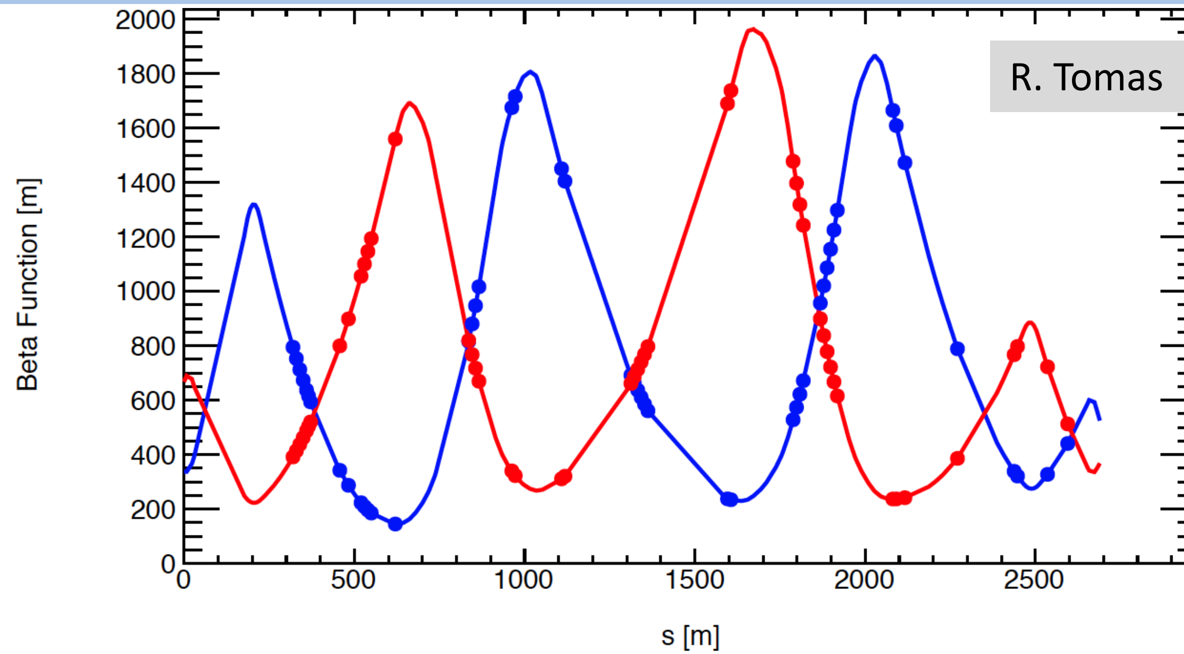


First Collimation Studies

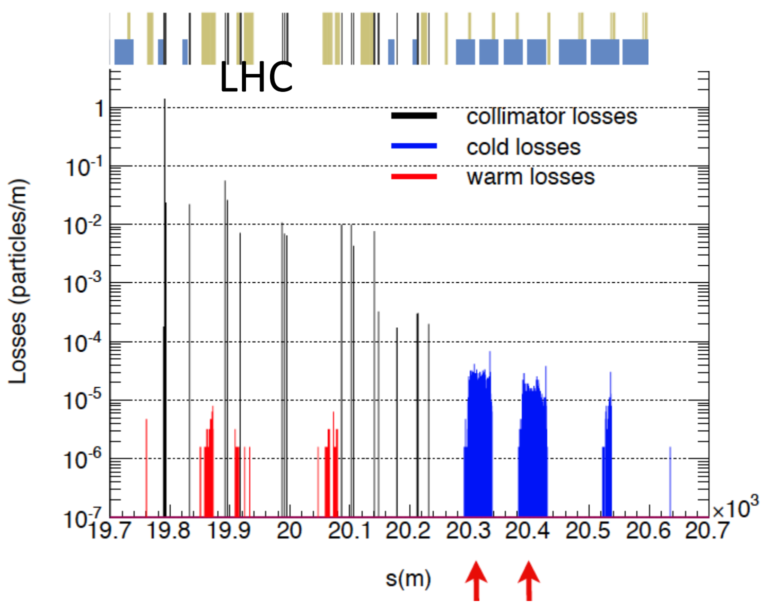
First betatron collimation system scaled from LHC
- Gaps as in HL-LHC
- But 2.7km long

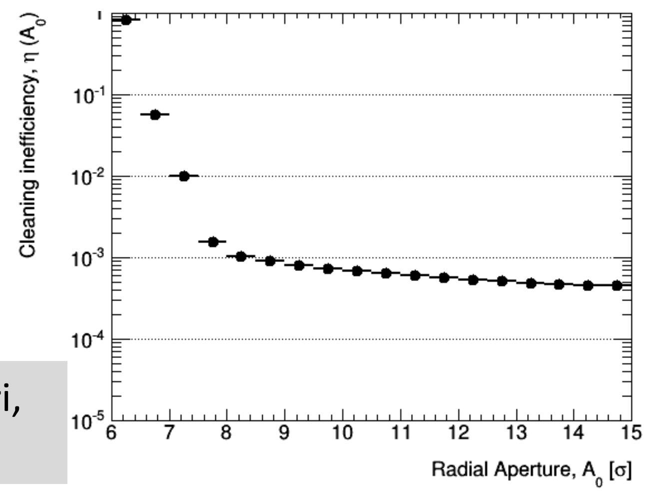
⇒ Starting point for exploration

⇒ Fix issues from LHC design



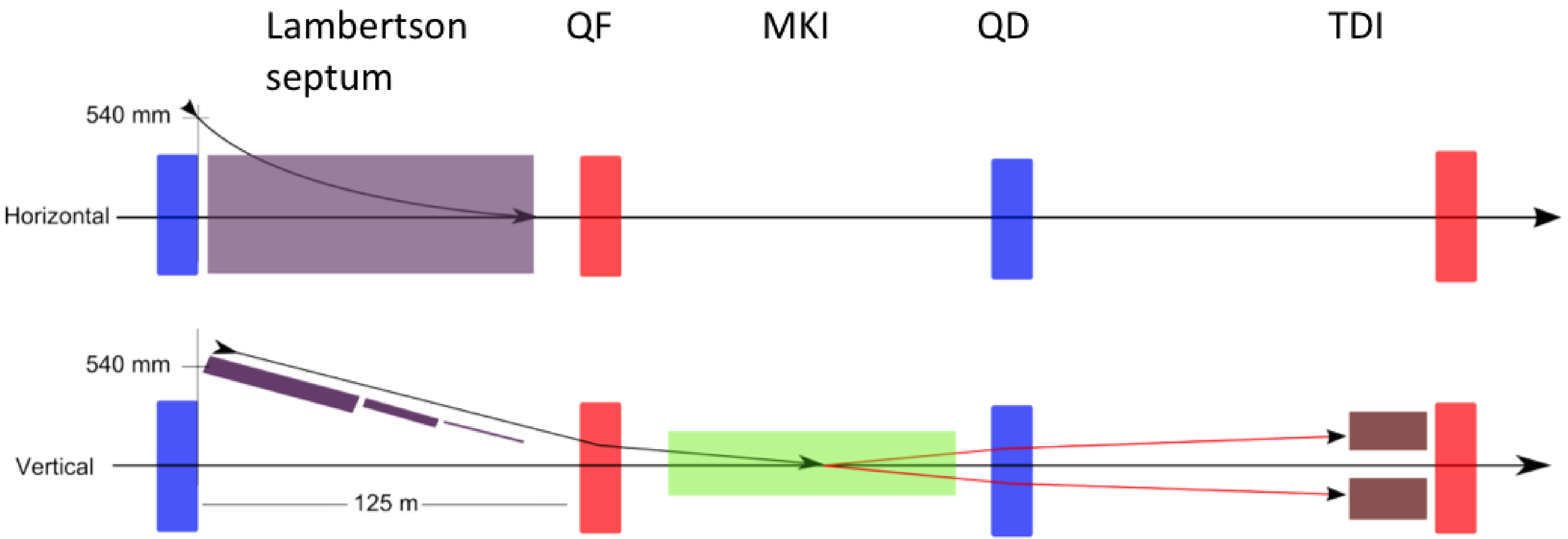
R. Tomas





M. Fiascari, S. Redaelli

Injection/Extraction Challenge



- Total energy in beam batch injected needs to be limited
- With LHC limit can inject O(100) bunches

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

⇒ Design improvements? Massless septum?

- Miss-firing of extraction kicker can lead to losses

⇒ Which strategy?

Arc Cell Layout

Longer cell

⇒ better dipole filling factor

Shorter cells

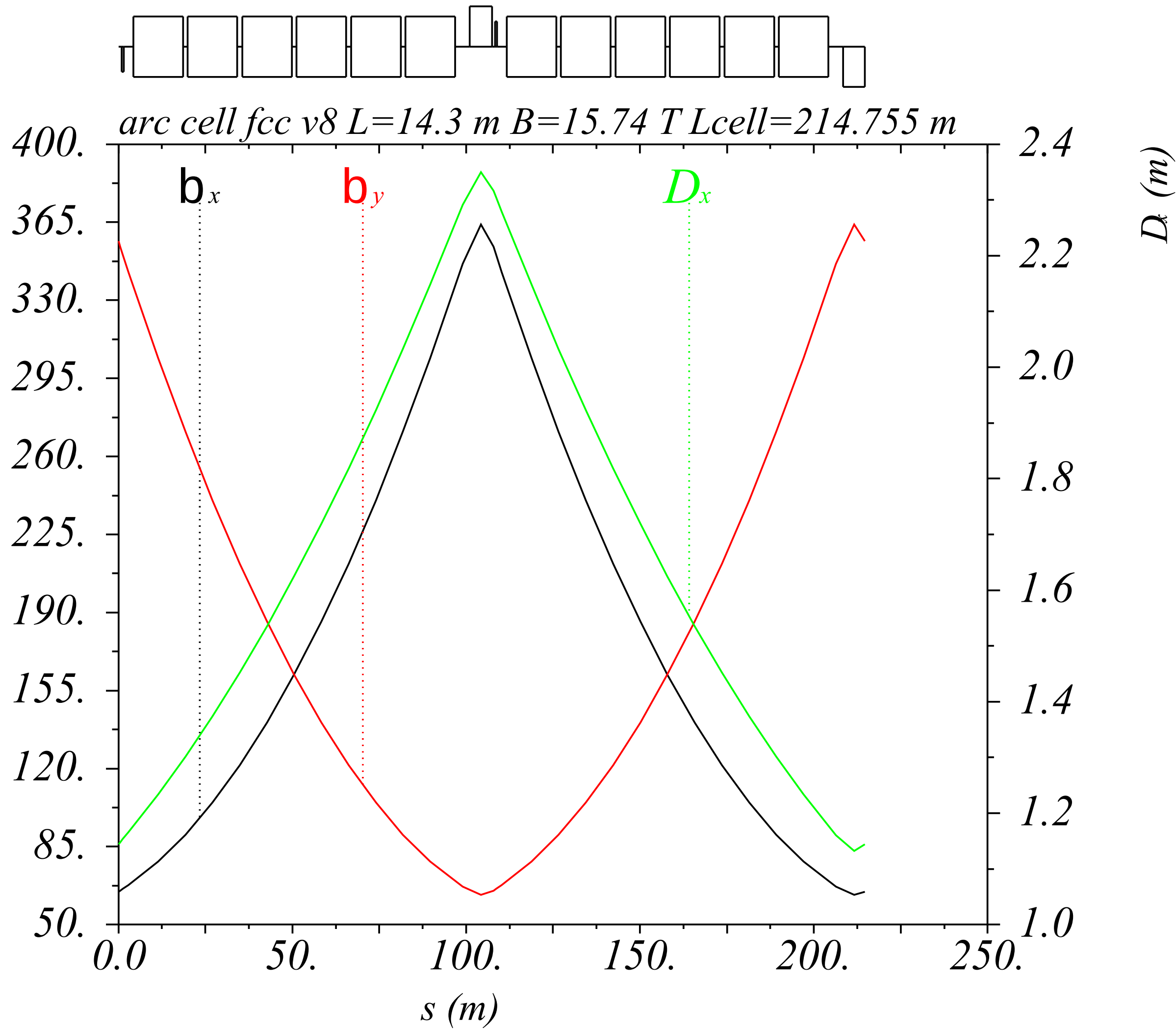
⇒ more stable beam

12 dipoles with L=14.3m

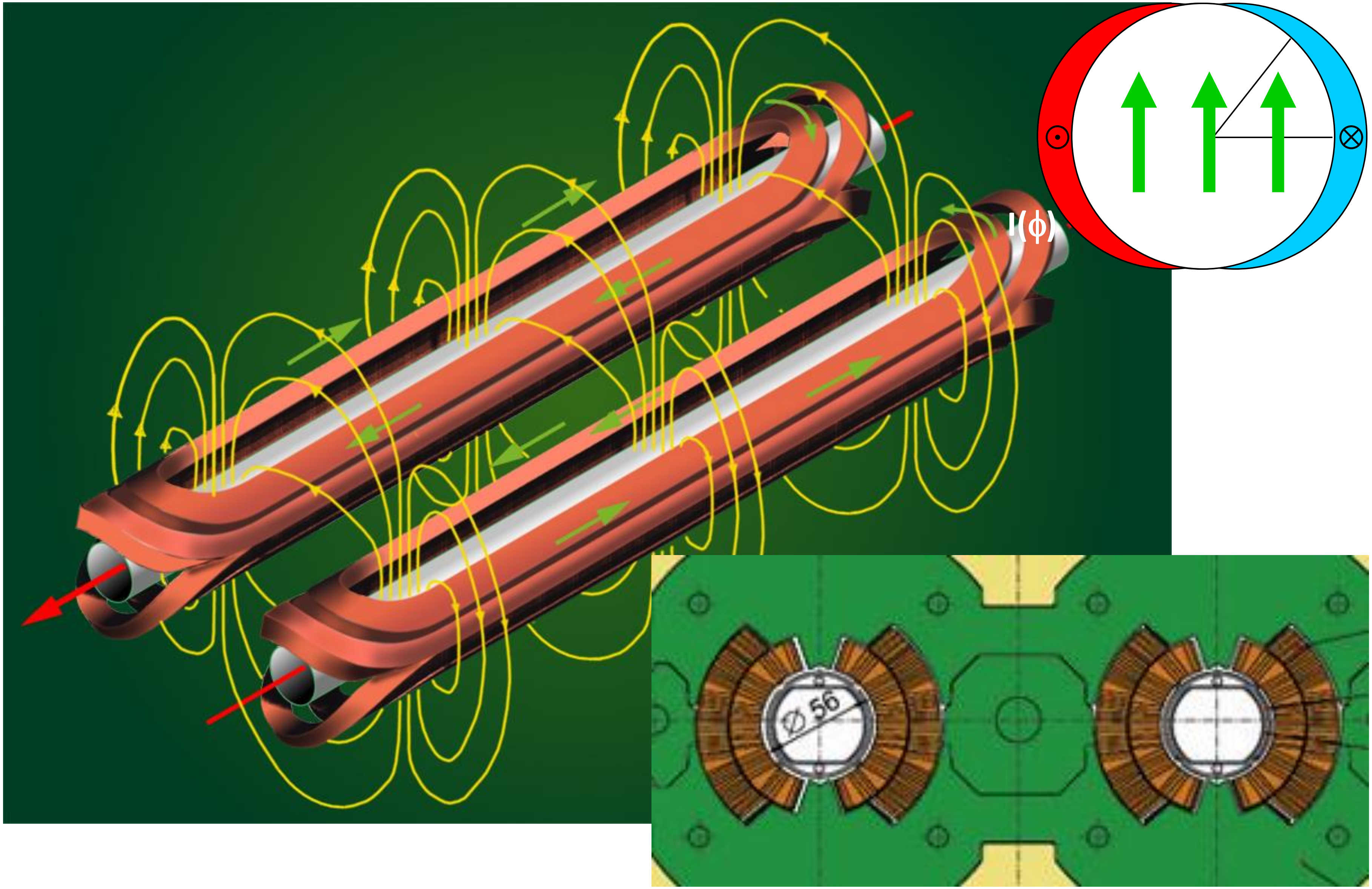
L_{cell}=214.755m

Fill factor about 80%

Field (100km ring): (16-ε)T

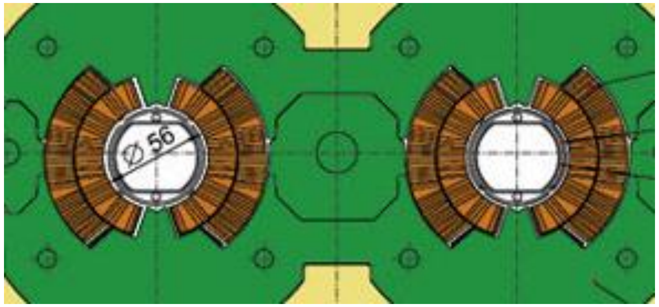


Dipole Basic Concept ("Cosine Theta")



Magnet Design Issues

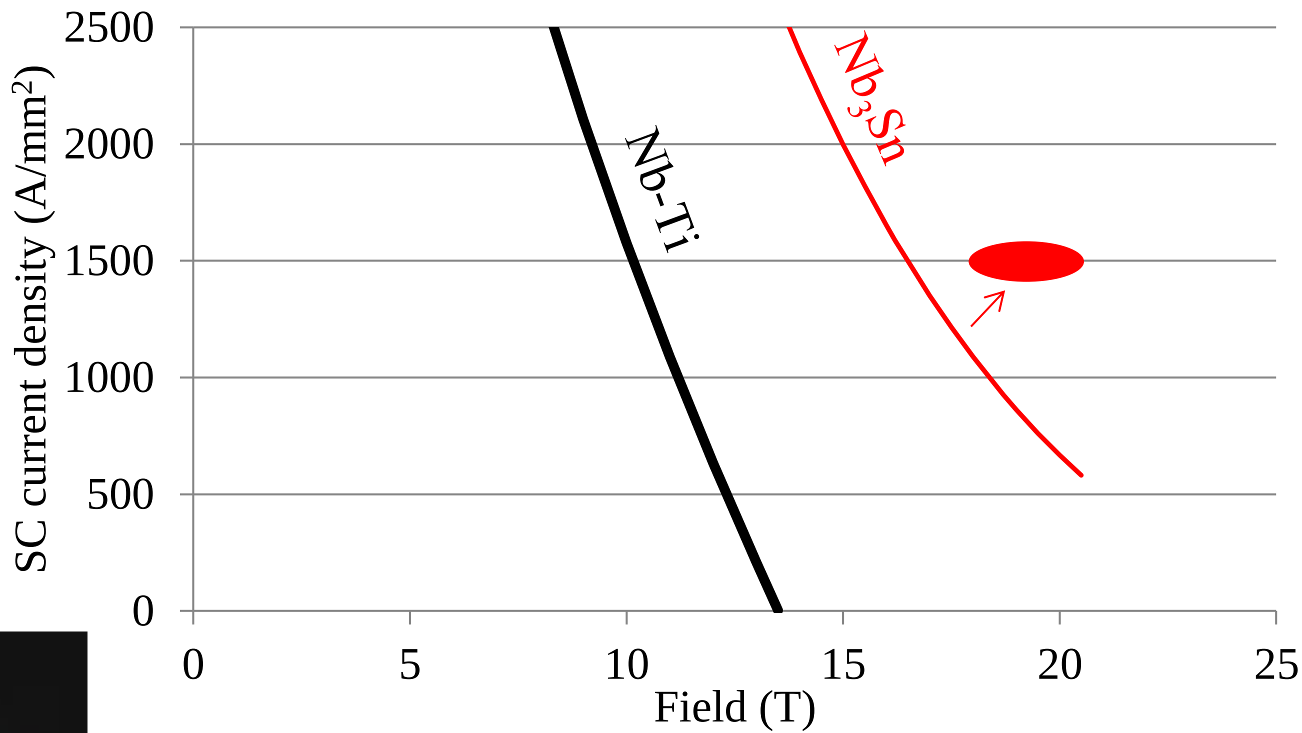
- Field level
  - Higher field level allows to use a smaller ring
  - But is technically challenging
- Aperture
  - A larger aperture means more volume with the magnetic field
  - Larger stored energy and larger forces
  - Higher cost
- The field quality
  - Unwanted non-linear field components
  - Especially at injection (low field)
  - Can make particles move chaotic and be lost
- The cost
  - The most costly component in the machine



Limits for the Field

The cable can quench (superconductivity breaks down)

- if the current is too high
- If the magnetic field is too high

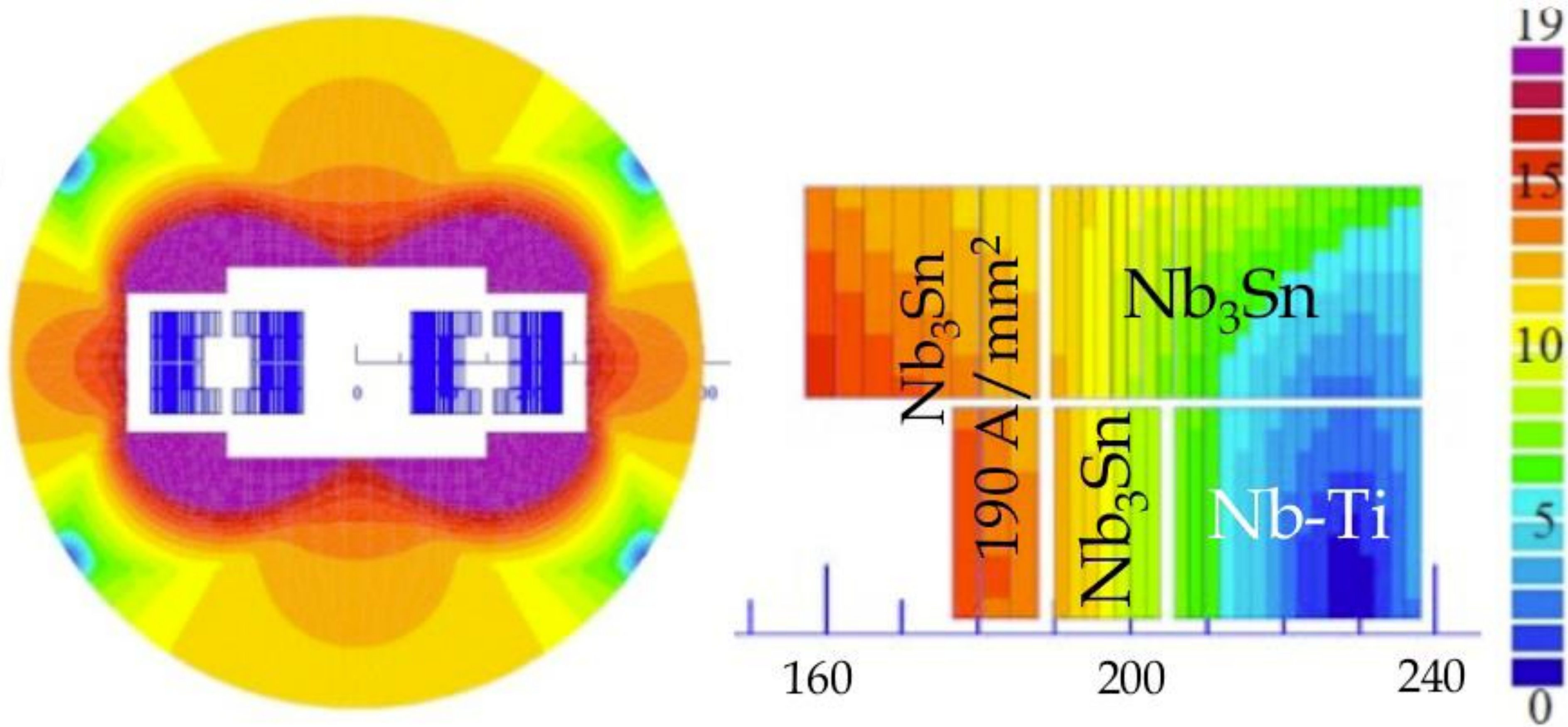


- This limits the achievable field
  - In theory
  - Even lower limit in practice (shown)
- Can use different materials
  - Nb-Ti is used for LHC
  - Nb_3Sn is used for high luminosity upgrade

Cost Effective Magnet Design

Nb_3Sn is much more costly than Nb-Ti

⇒Use both materials

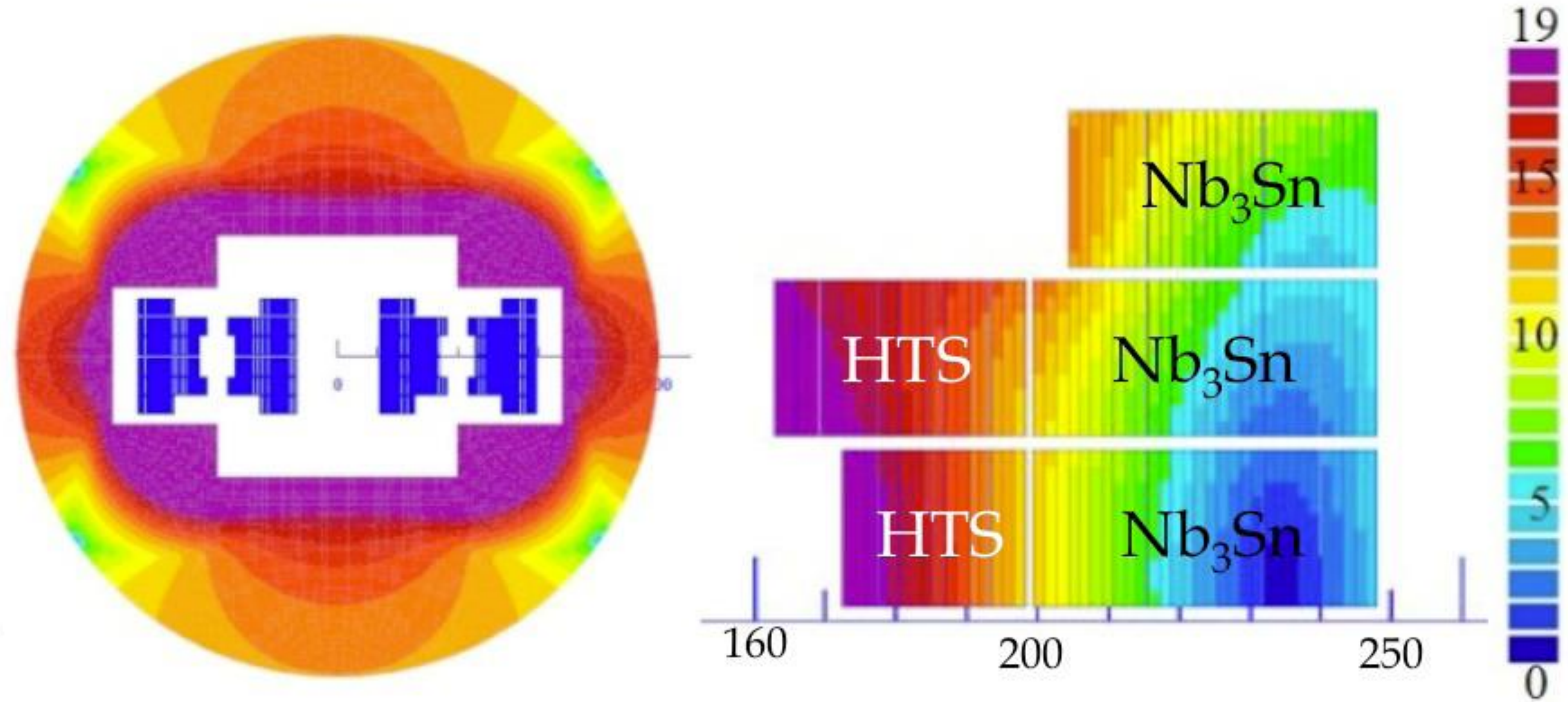


Coil sketch of a 15 T magnet with grading, E. Todesco

Cost Effective Magnet Design II

HTS is even more expensive than Nb_3Sn

$\Rightarrow$ Even more complex design



Coil sketch of a 20 T magnet with grading, E. Todesco

Beam Screen Design

Space for support: O(1mm)

Total coil aperture 50mm

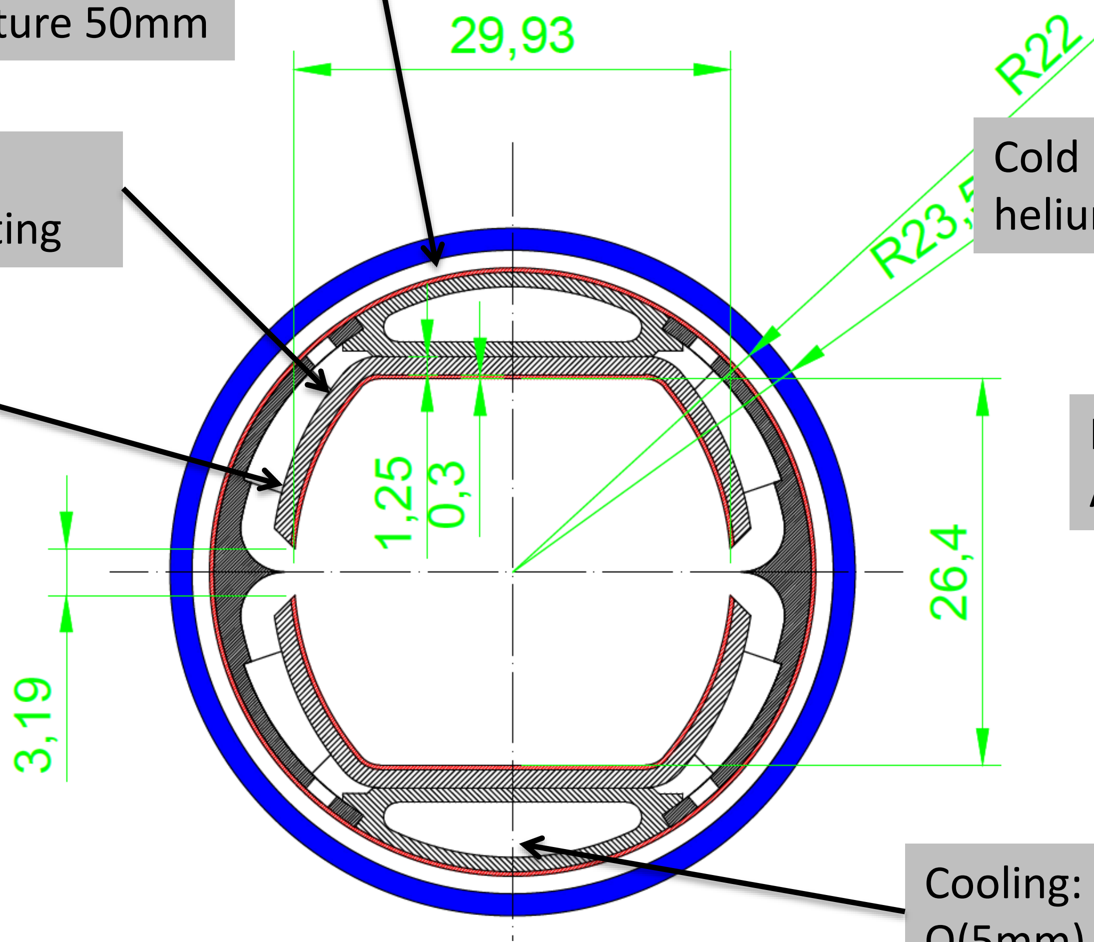
Magnet coil aperture 50mm

Impedance: 0.3mm copper coating

Cold bore + space for helium 1.5mm+1.5mm

Stress in quench: 1.25mm steel

Impedance: Aperture >26mm



Cooling: O(5mm) outer diameter