Future High-Energy Collider Projects II

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FCC and CEPC/SppC

FCC (Future Circular Collider):
Proposal for project at CERN

- CDR for EU strategy end 2018

FCC-hh

- pp collider with 100 TeV cms
- Ion option
- Defines infrastructure

FCC-ee

- Potential e^+e^- first stage

FCC-eh

- additional option

HE-LHC

- LHC with high field magnets

CEPC / SppC (Circular Electron Positron Collider, Super proton-proton Collider)
Proposal for project in China

- CDRs exist but changes since

CEPC

- e^+e^- collider 90-240 GeV
- focus on higgs

SppC

- Hadron collider to later be installed in the same tunne
- 75 to O(150) TeV

Focus on proton colliders

FCC-hh

Future Hadron Collider Parameters

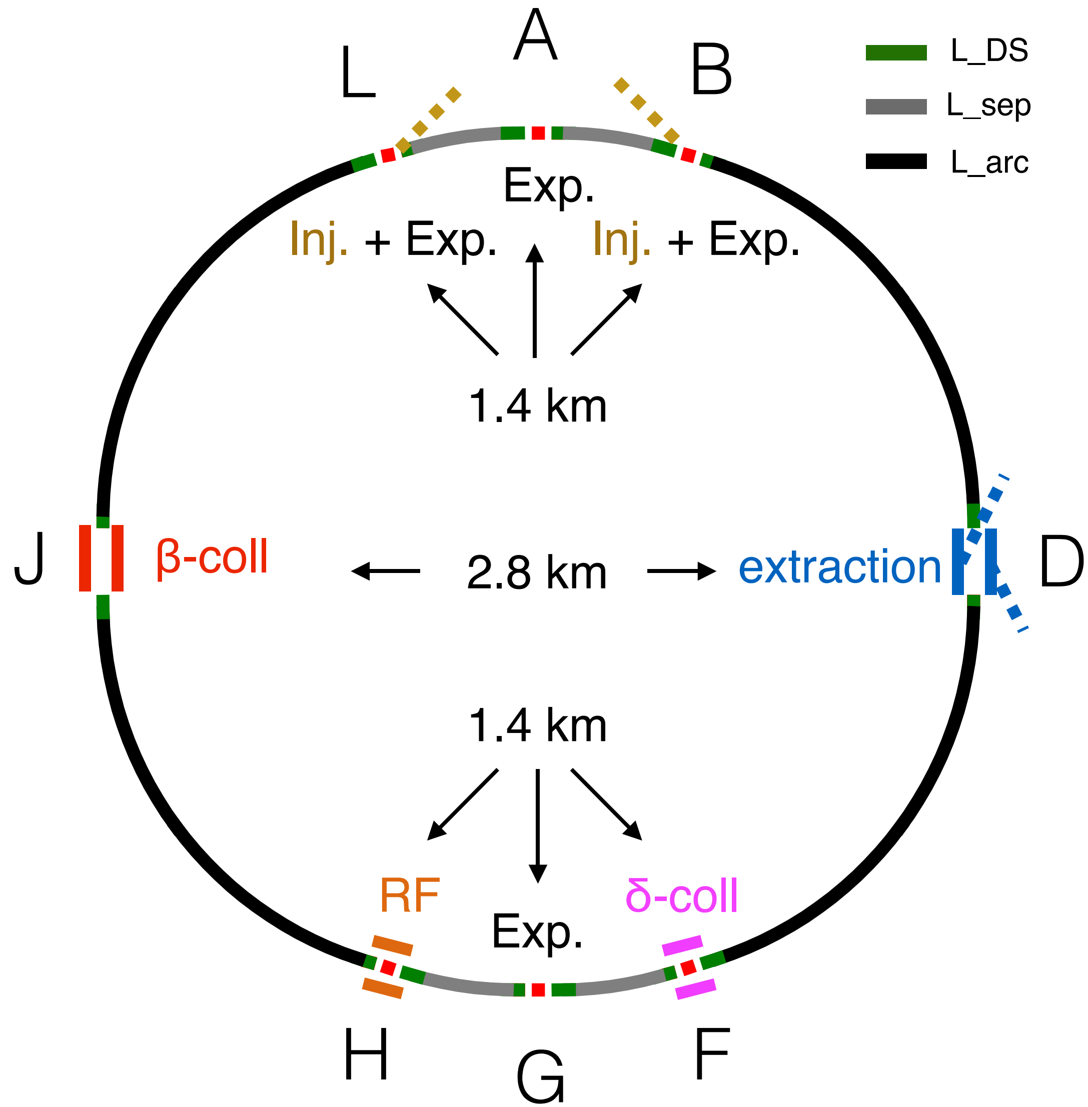
	LHC (HL-LHC)	HE-LHC (tentative)	FCC-hh Baseline	FCC-hh Ultimate	SppC	SppC ultimate
Cms energy [TeV]	14	27	100	100	75	150
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1 (5)	25	5	< 30	10	?
Machine circumference	27	27	97.75	97.75	100	100
Arc dipole field [T]	8	16	16	16	12	24
Bunch distance [ns]	25	25 (5)	25	25 (5)	25 (10/5)	?
Background events/bx	27 (135)	800 (160)	170	< 1020 (< 202)	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:
Can the detector cope with the background?

FCC-hh Layout

- Two high-luminosity experiments (A and G)
- Two other experiments (B and L), combined with injection
- Two collimation insertions
- One extraction insertion
- Insertions are 1.4/2.8 km long
- Total length is 97.75 km
- 83 km for arcs

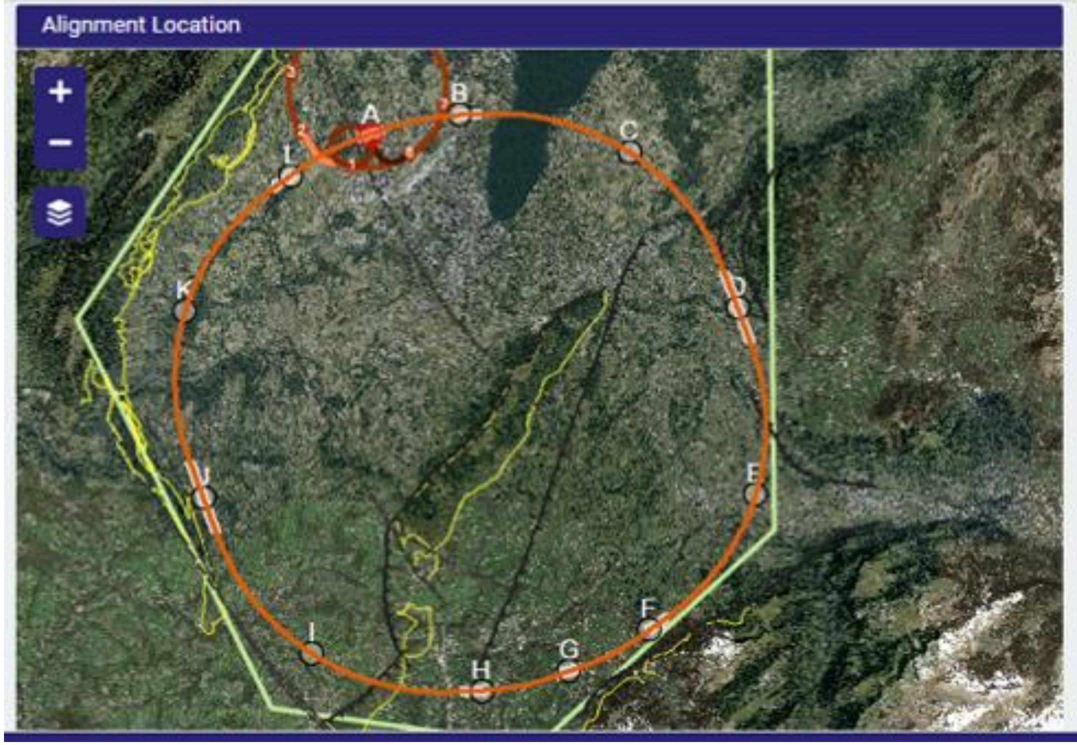


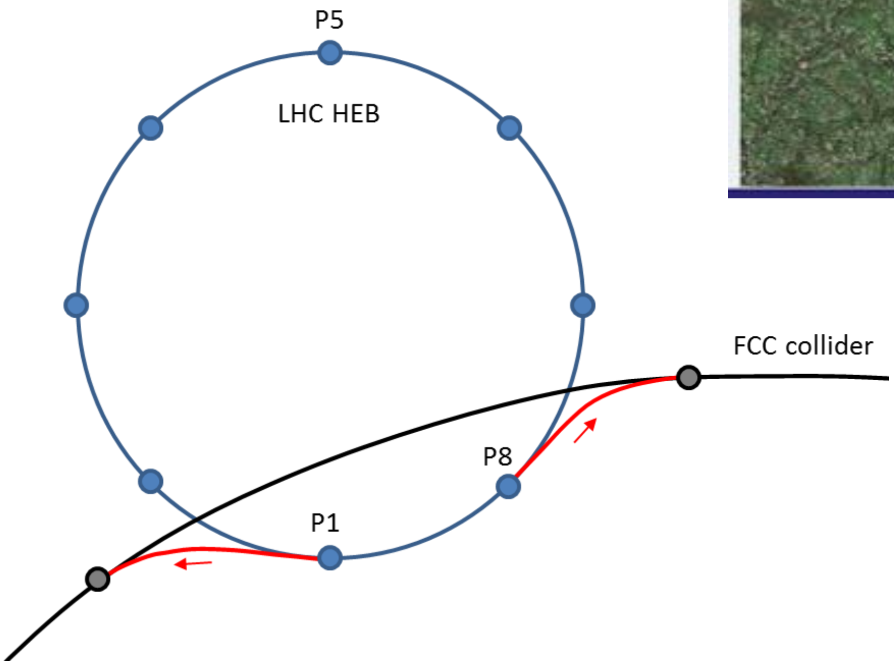
Site Studies

First site studies of

- Geology
- Surface buildings
- …

⇒ 97.75 km ring fits well into the Geneva area





Can LHC be used as injector?

- Machine is OK
- The two tunnels would match nicely

Also consider SPS and FCC tunnel for injector

Arc Cell Layout

Longer cell

⇒ better dipole filling factor

Shorter cells

⇒ more stable beam

12 dipoles with L=14.3m

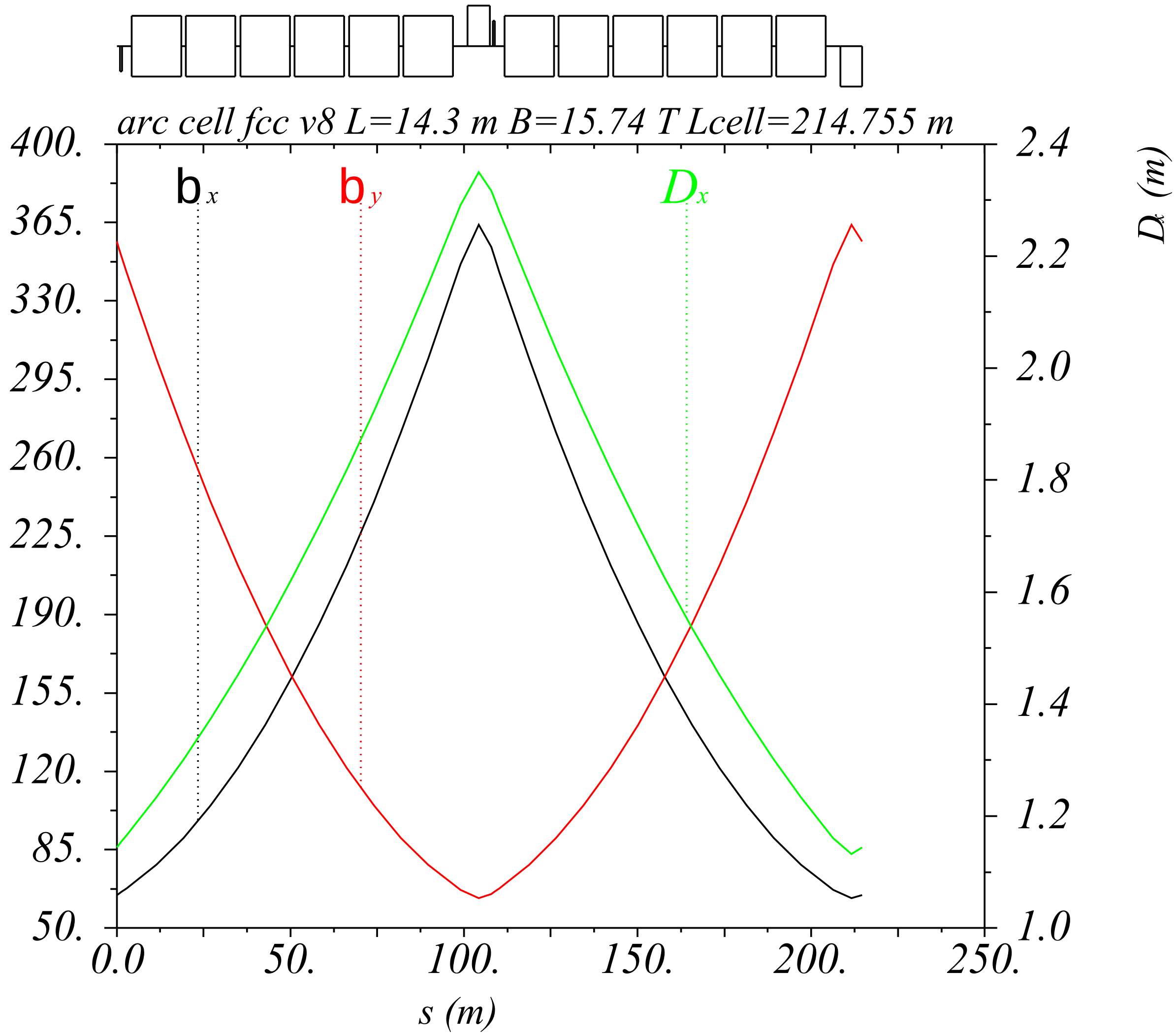
L_{cell}=214.755m

Fill factor about 80% (as in LHC)

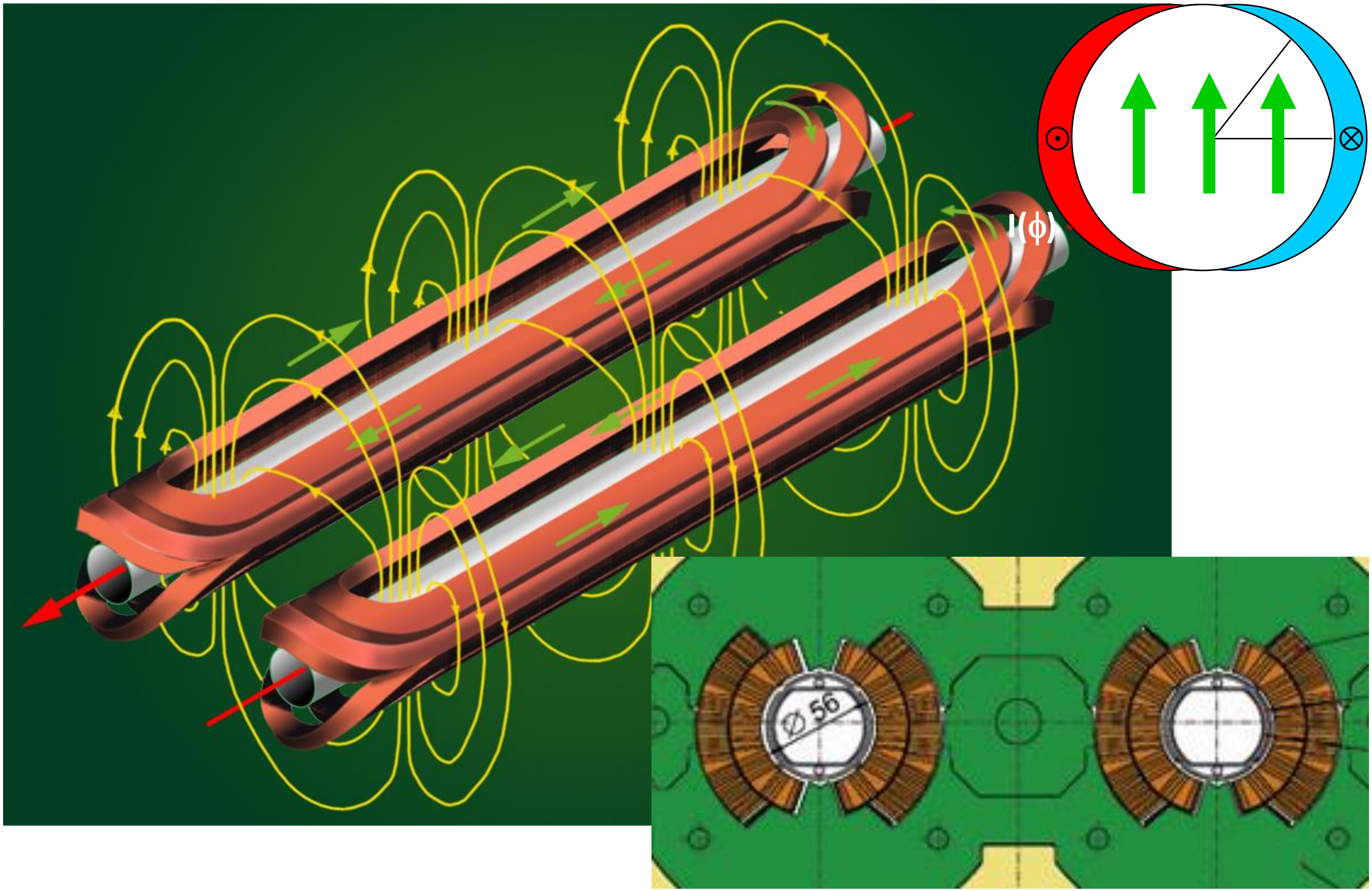
Bending radius in magnets ρ=10.5km

$$r = \frac{T}{0.3GeV}\frac{E}{B}$$

⇒ Field: (16-ε)T



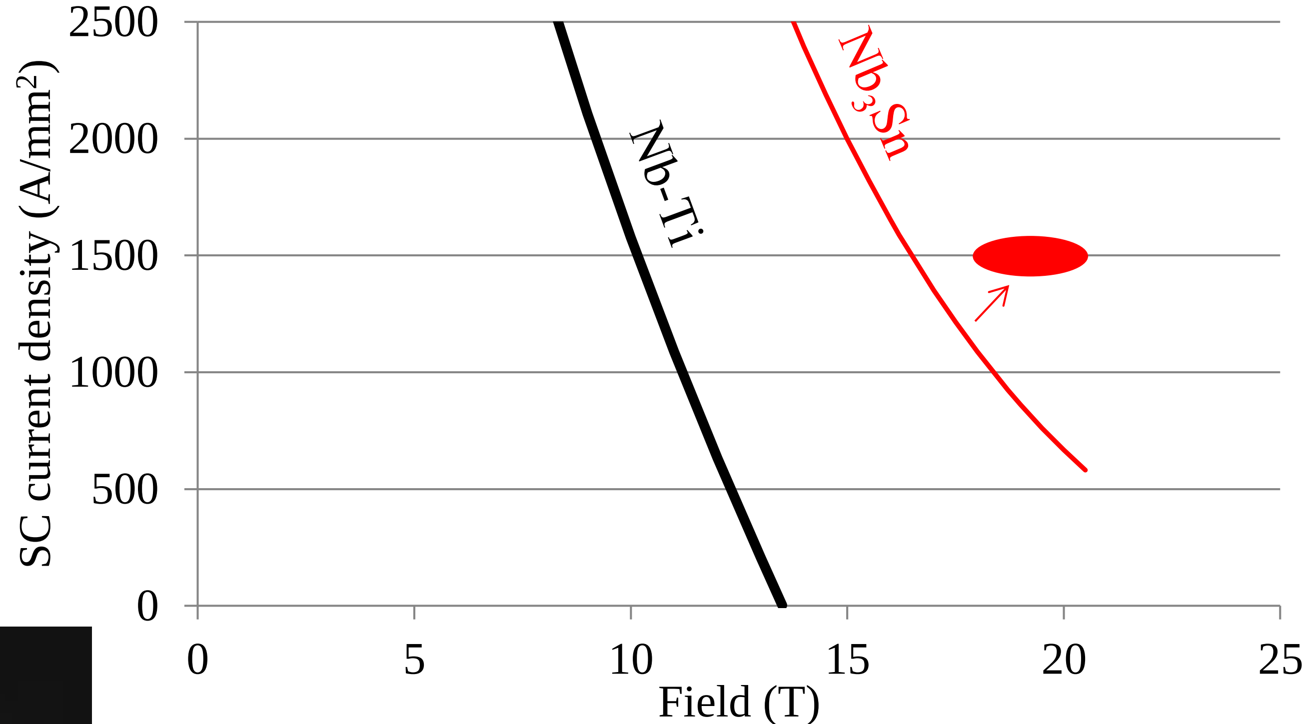
Dipole Basic Concept ("Cosine Theta")



Limits for the Field

The cable can quench (superconductivity breaks down)

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

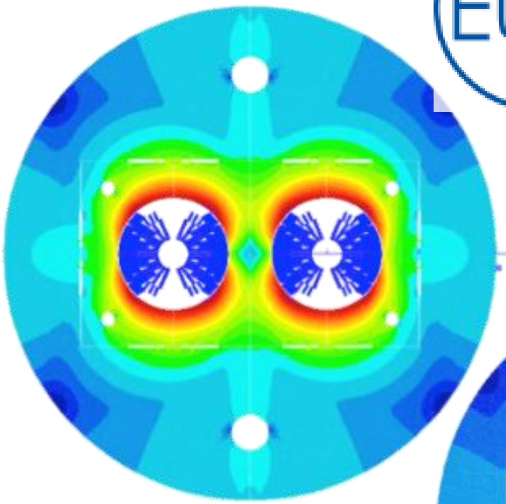


- This limits the achievable field
  - In theory
  - Even lower limit in practice (shown)
- Can use different materials
  - Nb-Ti is used for LHC
  - Nb_3Sn is used for high luminosity upgrade

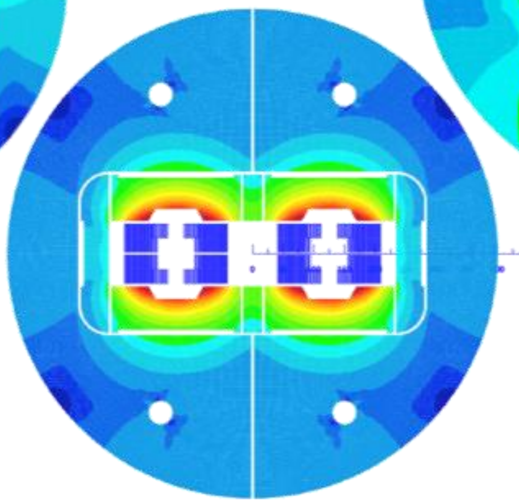
Magnet Designs

EuroCirCol
A key to New Physics

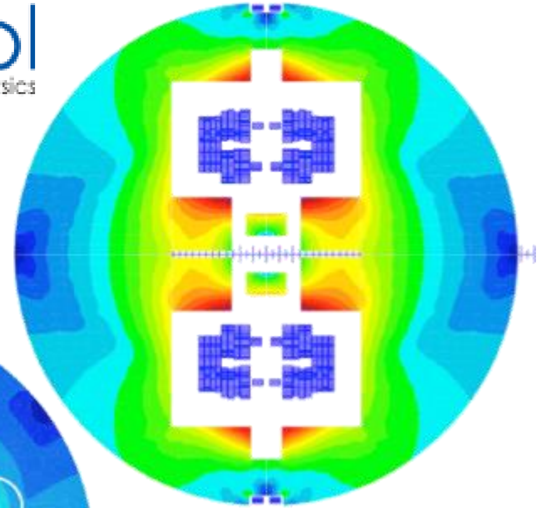
Cos-theta



Blocks

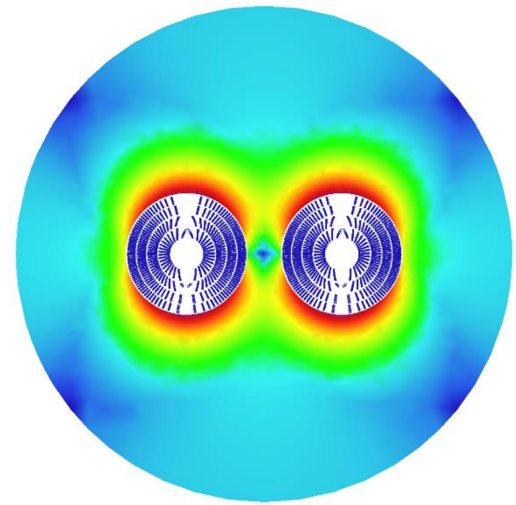


Common coils



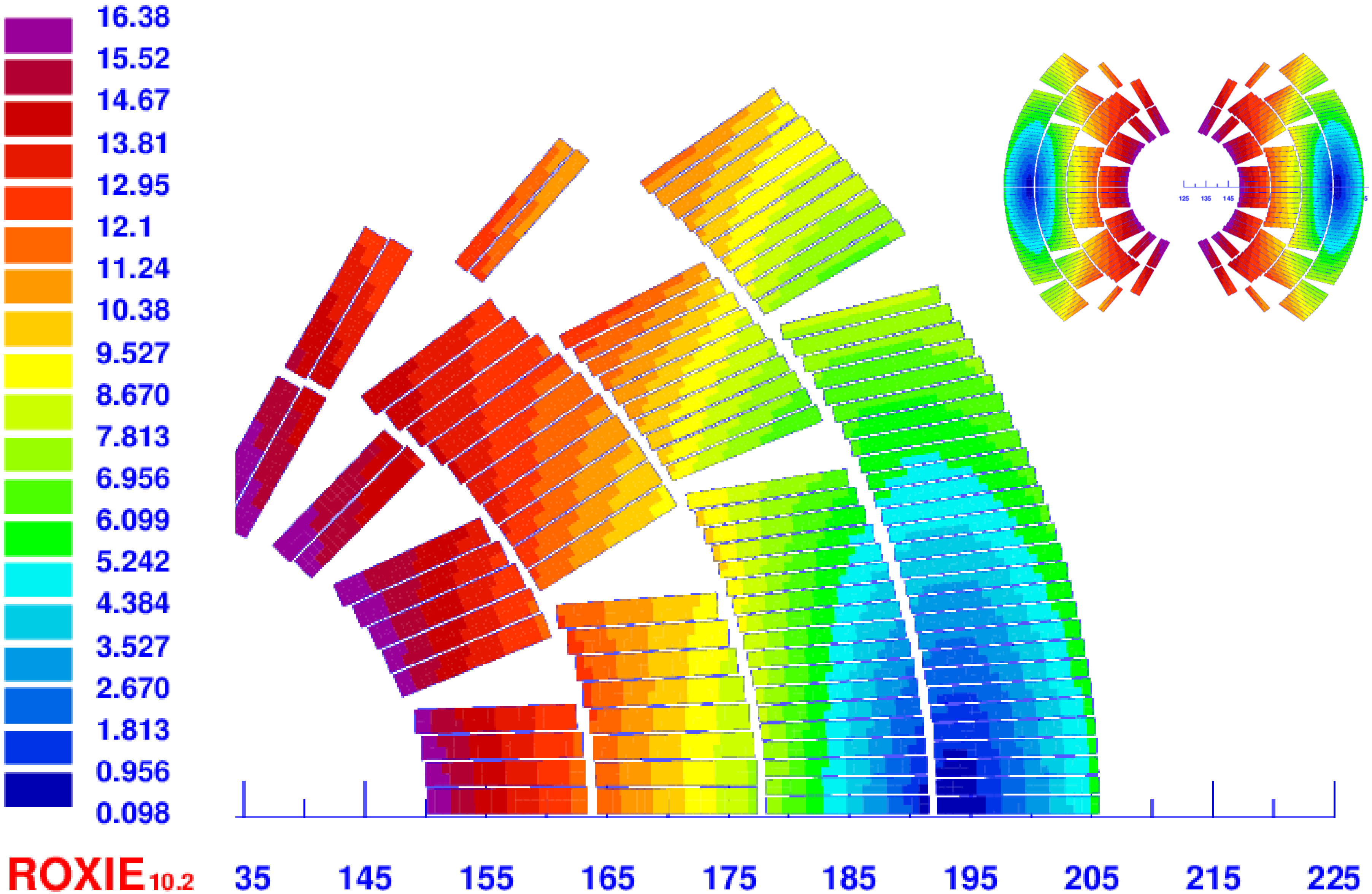
Swiss contribution
via PSI

Canted
Cos-theta



- Tentative baseline design choice: Cos-theta
- Model production 2018 - 2022
- Prototype production 2023 – 2025

Cost Effective Magnet Design



Parameters and Luminosity Target

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

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

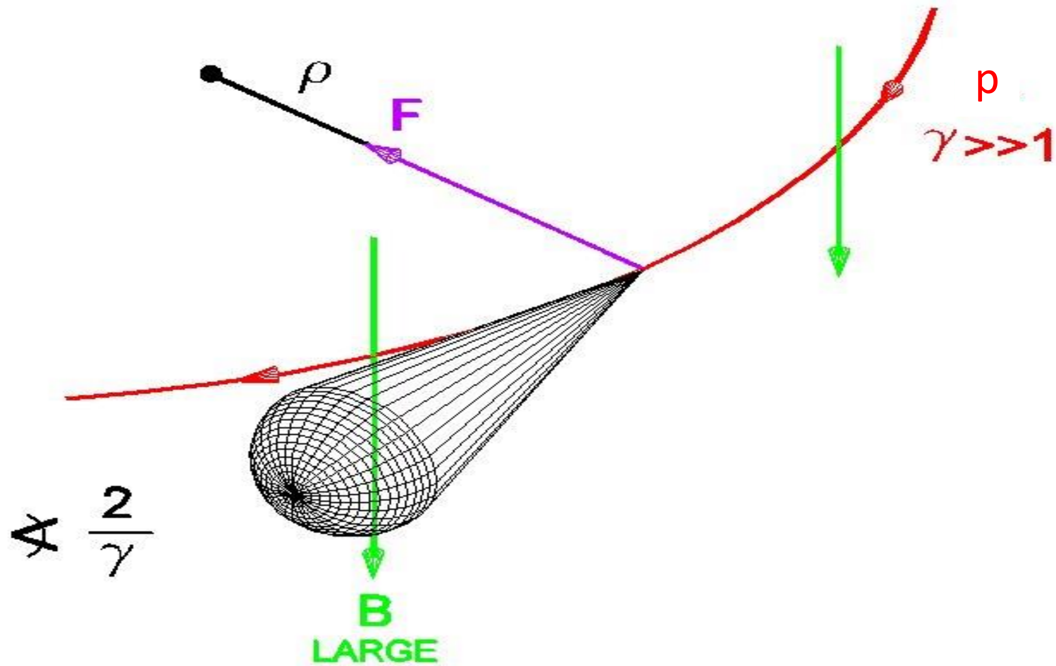
$$\mathcal{L} \propto \frac{N}{\epsilon}\frac{1}{\beta} N n_b f_r$$

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

	Baseline	Ultimate
Luminosity L [$10^{34} cm^{-2}s^{-1}$]	5	20
Background events/bx	170 (34)	680 (136)
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

Synchrotron Radiation

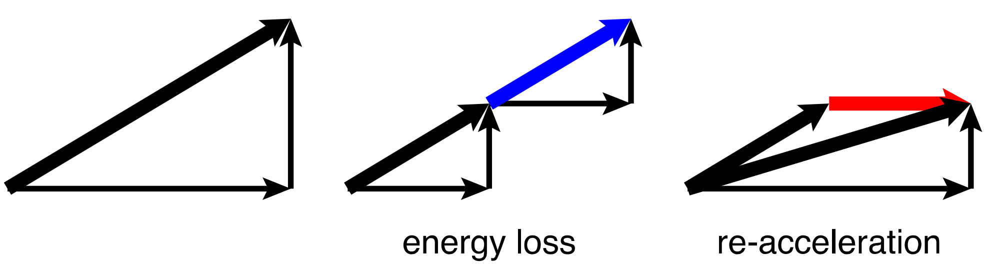
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



At 100 TeV even protons radiate significantly

Total power of 5 MW
⇒ Needs to be cooled away

Equivalent to 30 W/m/beam in the arcs



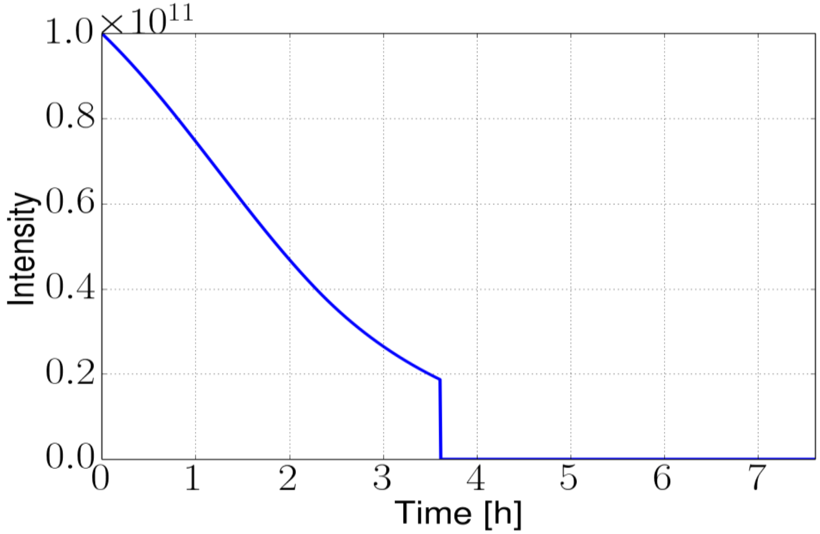
Protons loose energy

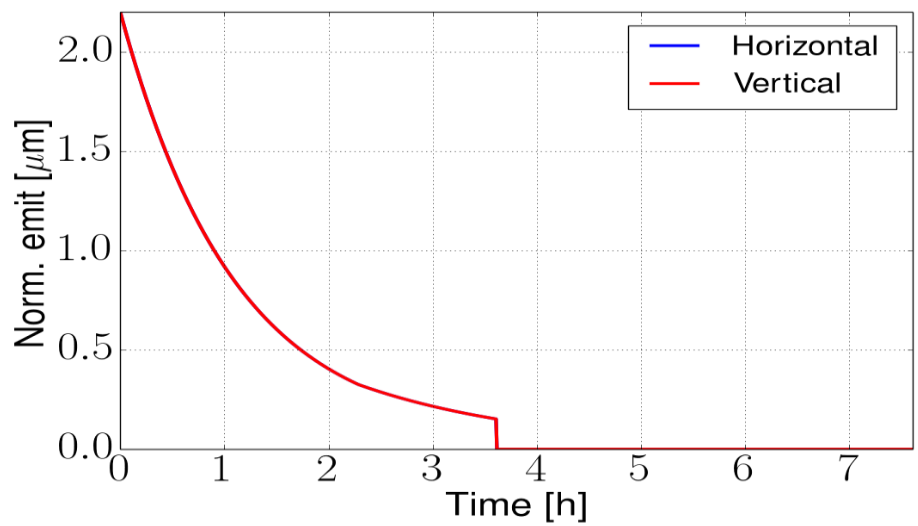
⇒ They are damped

⇒ Emittance improves with time

- Typical damping time 1 hour

Luminosity During the Run





Main loss mechanism is luminosity

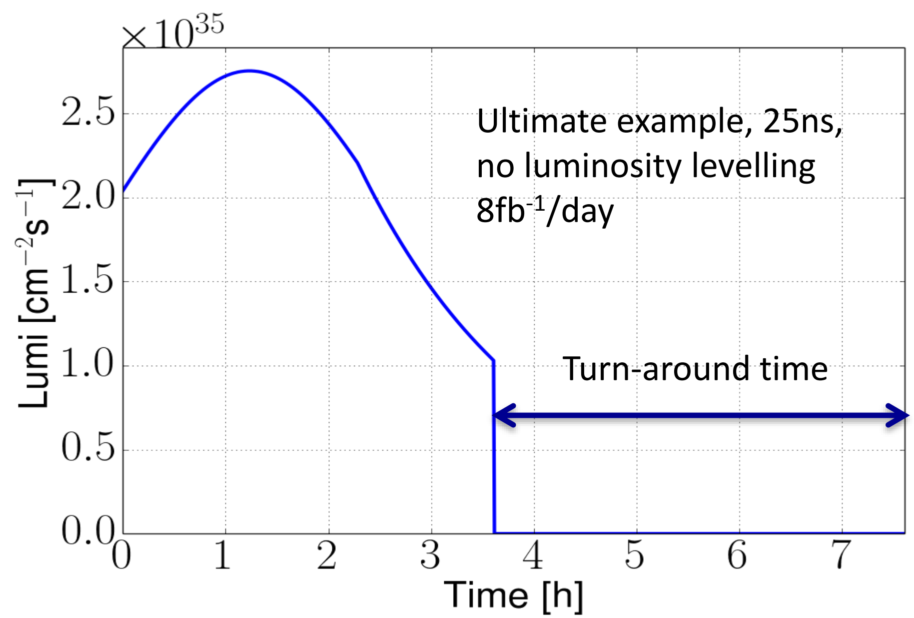
$\Rightarrow$ This is what we want

$\Rightarrow$ Can reach >8fb^{-1} with ultimate for ξ=0.03

$\Rightarrow$ 5000fb^{-1} per 5 year run

$\Rightarrow$ Beam is burned quickly

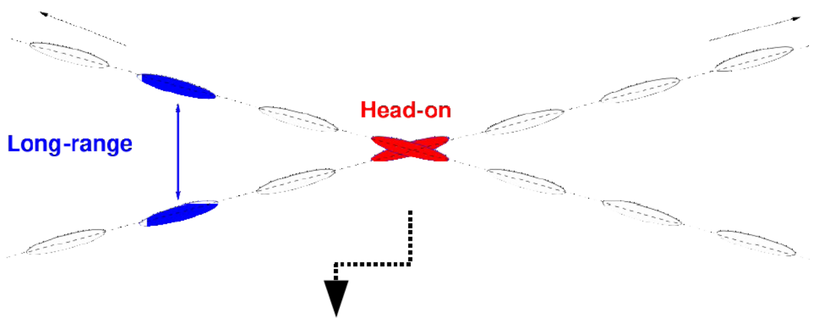
$\Rightarrow$ Another reason to have enough charge stored

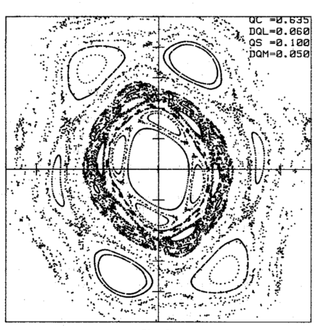


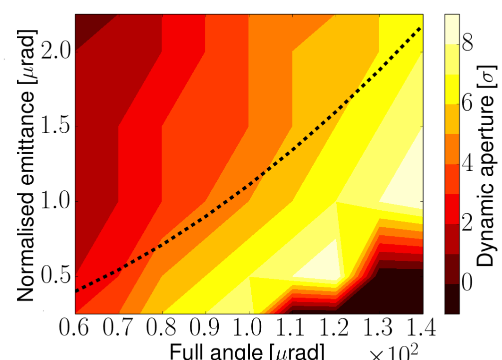
Beam Physics Studies

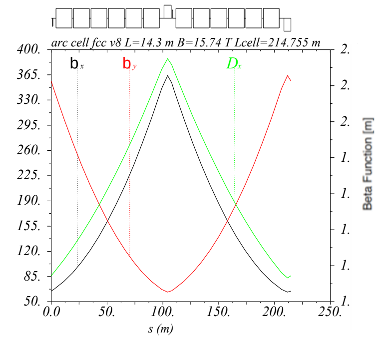
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

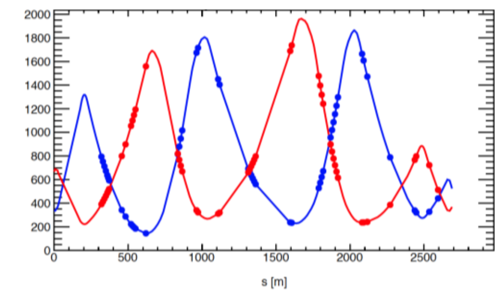
Beam-beam studies ongoing, promising results











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

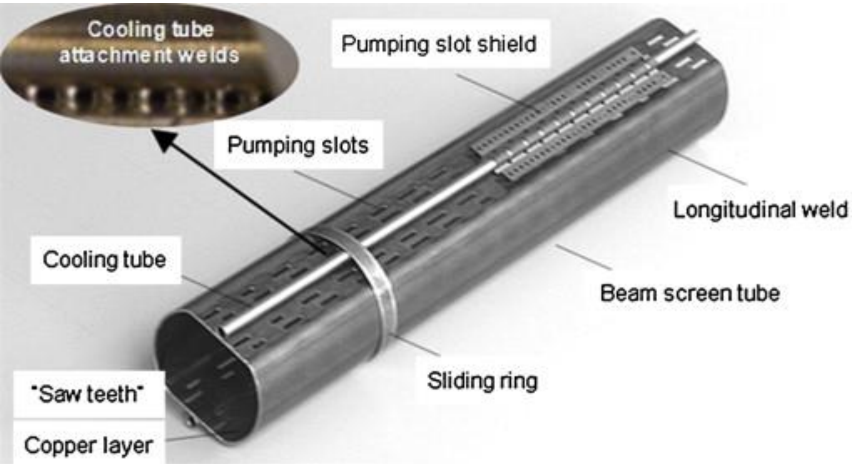
Injection

Extraction

...

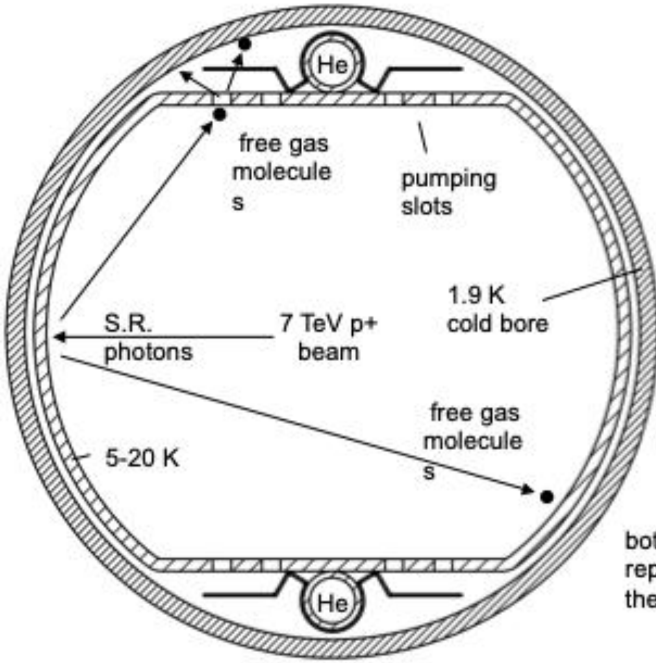
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

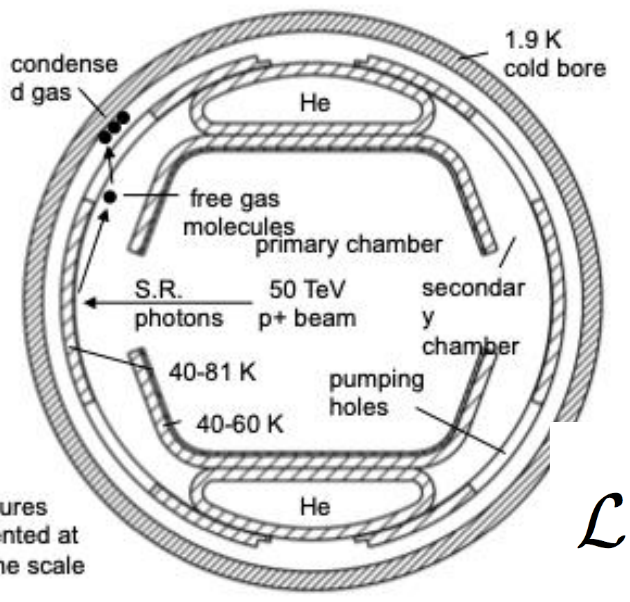
Beamscreen Design



LHC beamscreen

FCC-hh beamscreen

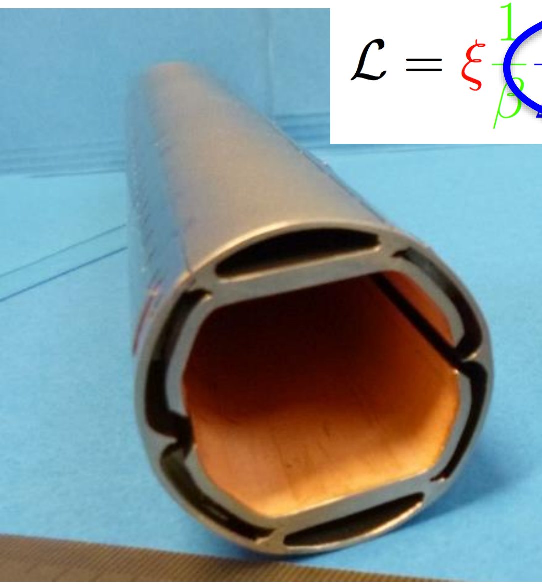




both figures represented at the same scale

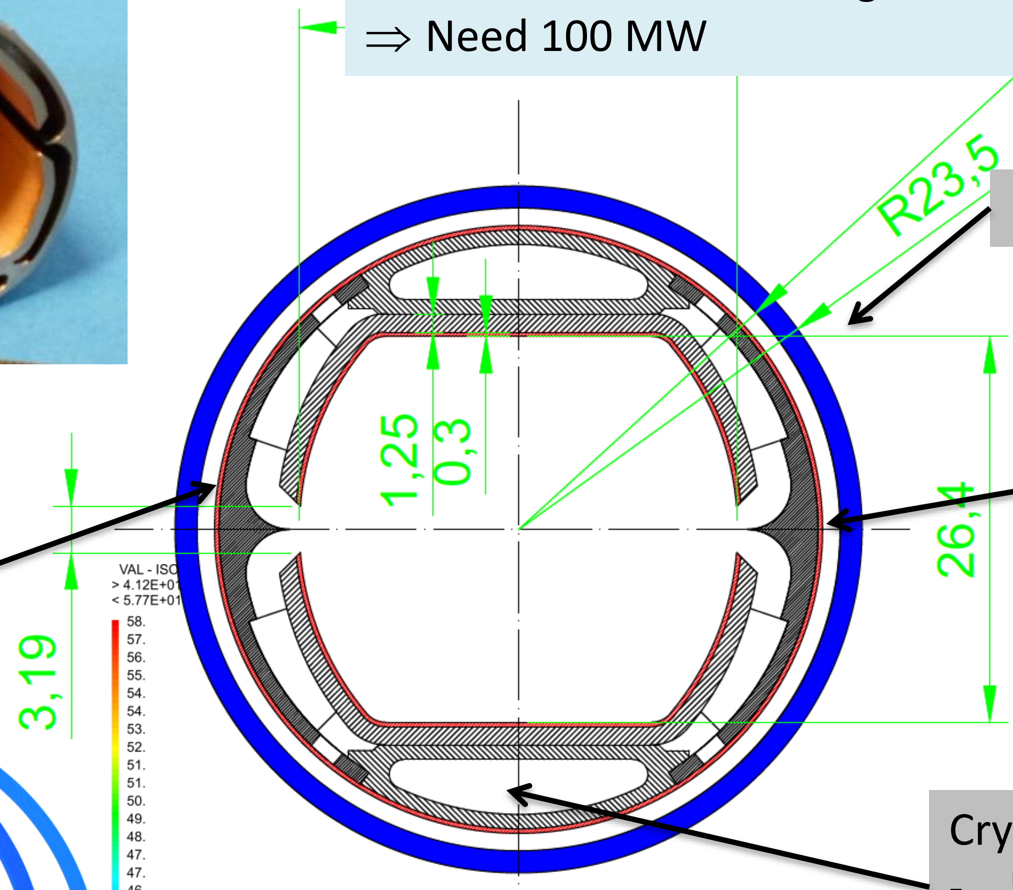
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Example: Beam Screen Design



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

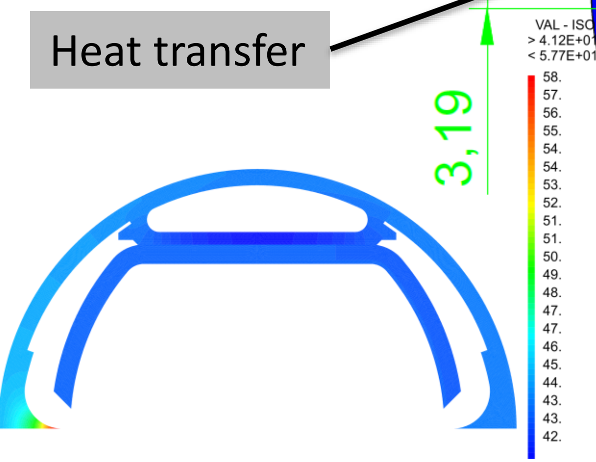
5 MW synchrotron radiation
3,500 MW cooling power at 2K
$\Rightarrow$ Need to shield the magnet with beamscreen at 50K
$\Rightarrow$ Need 100 MW



Magnets at 2K

Vacuum insulates

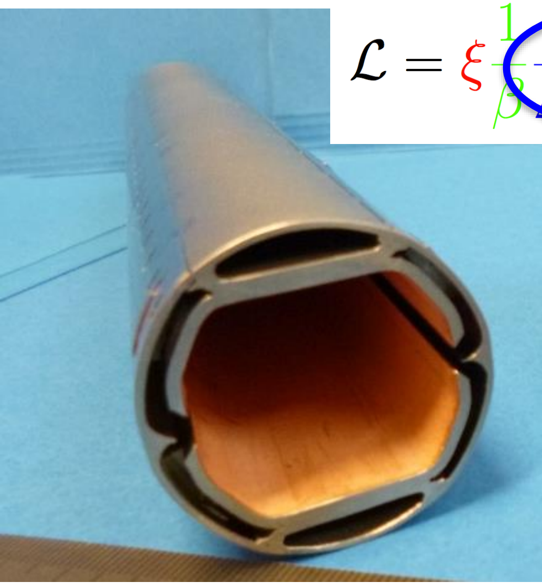
Heat transfer

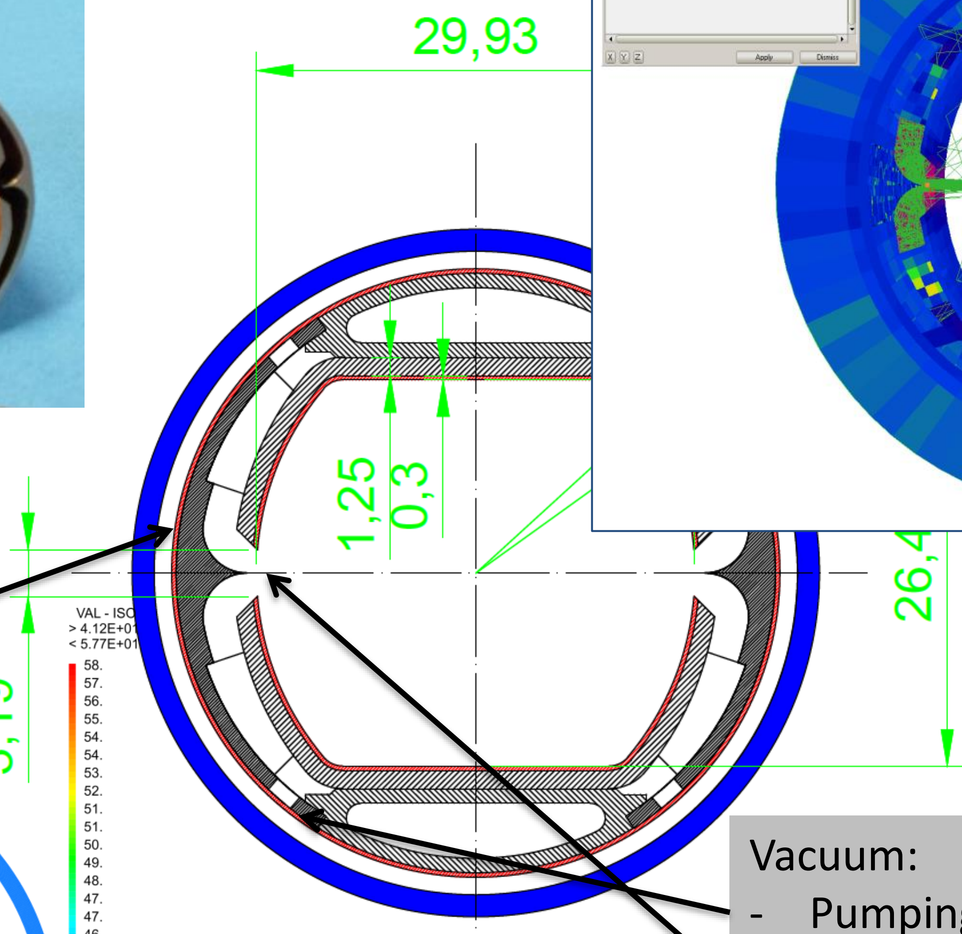


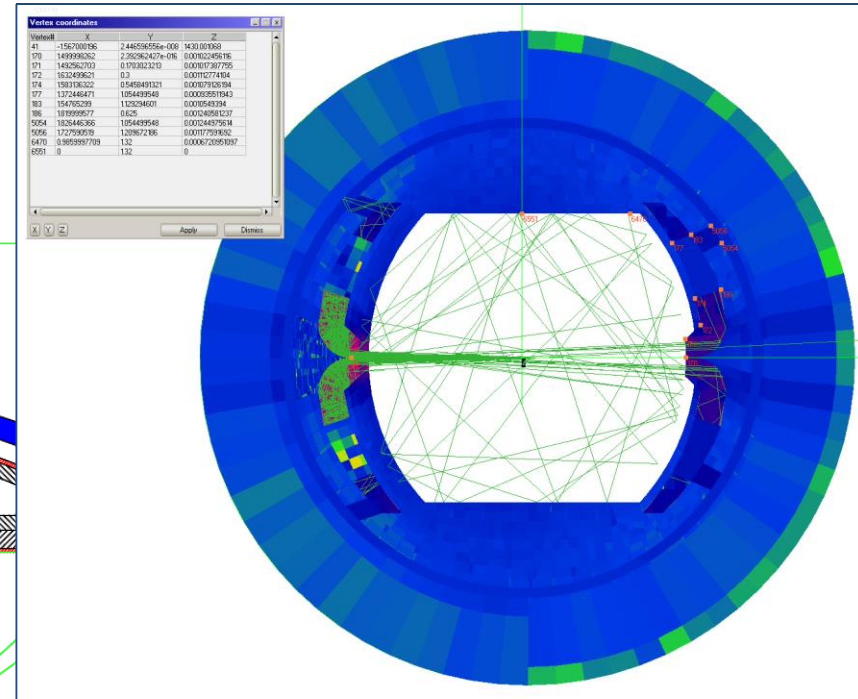
Cryogenics:
- 50K
- Space for helium flow

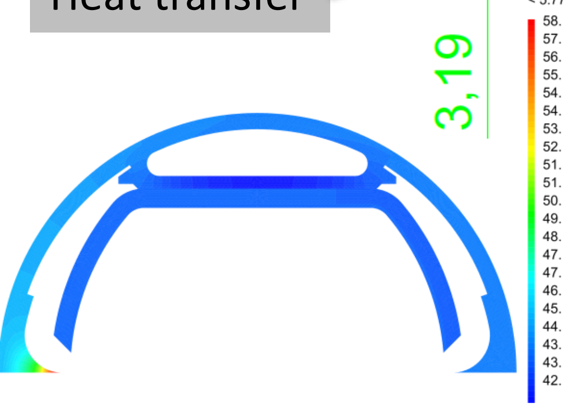
Example: Beam Screen Design

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





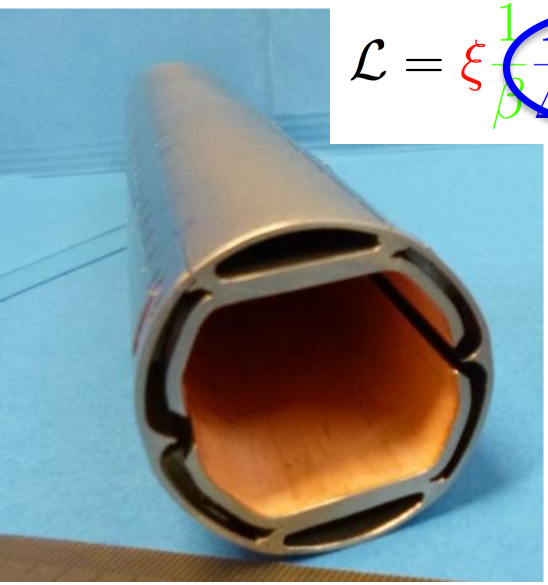




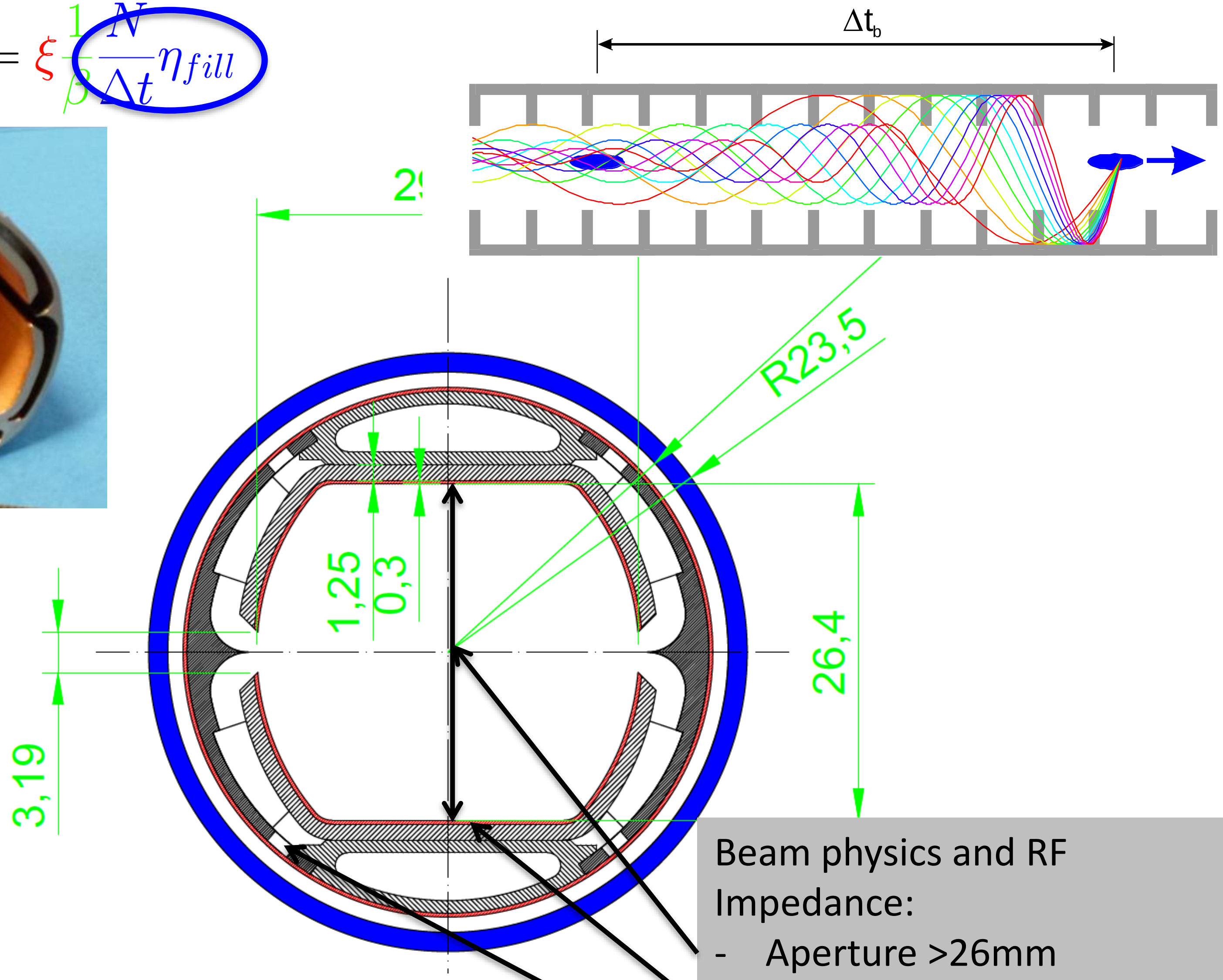
Heat transfer

Vacuum:
- Pumping holes
- Localisation of synchrotron radiation

Example: Beam Screen Design



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

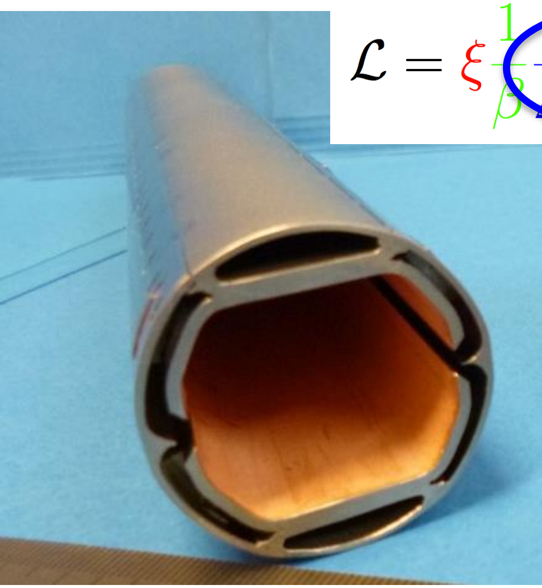


Beam physics and RF

Impedance:

- Aperture >26mm
- 0.3mm copper coating
- Pumping holes shielded by slit

Example: Beam Screen Design



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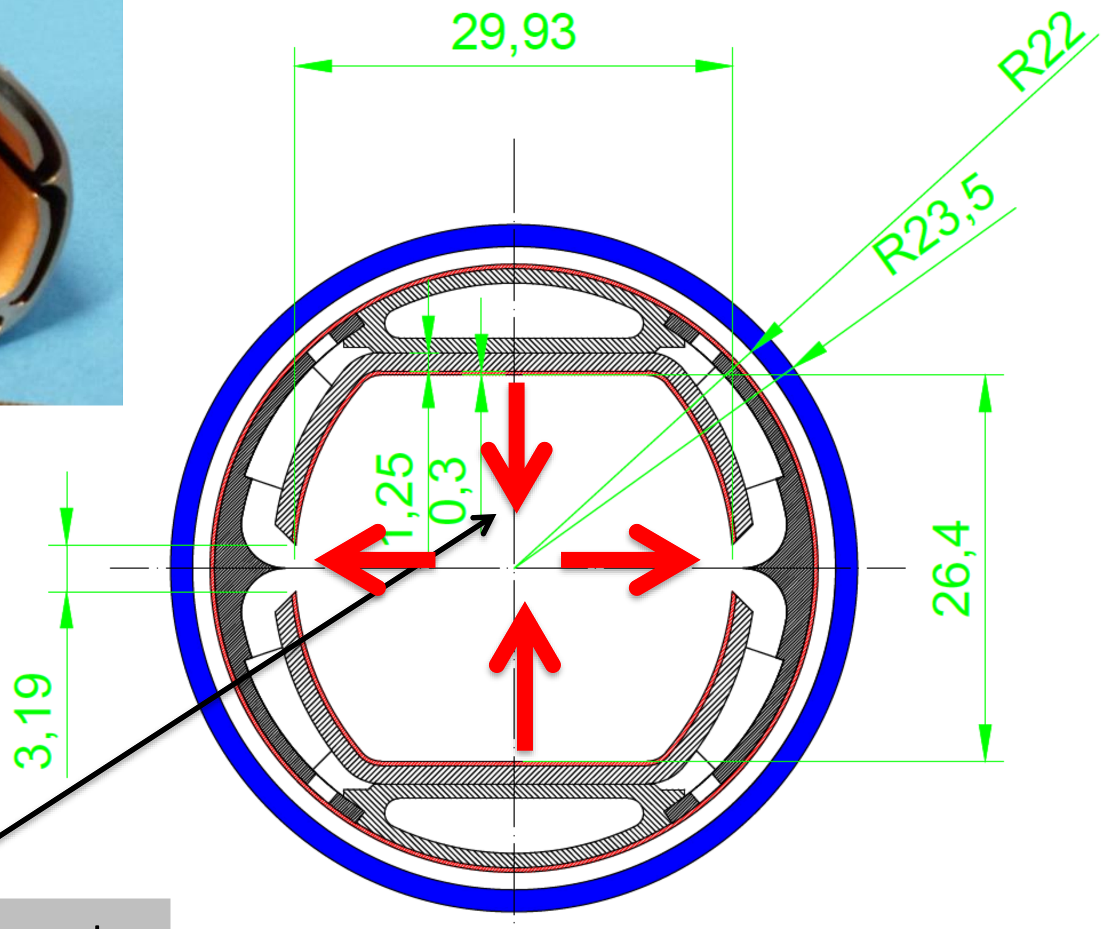
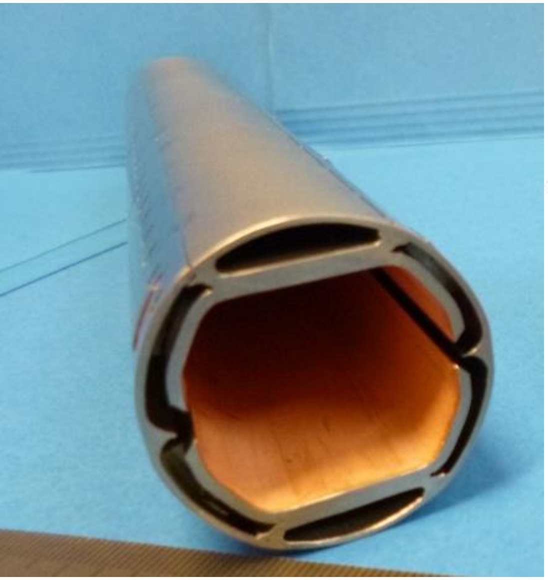
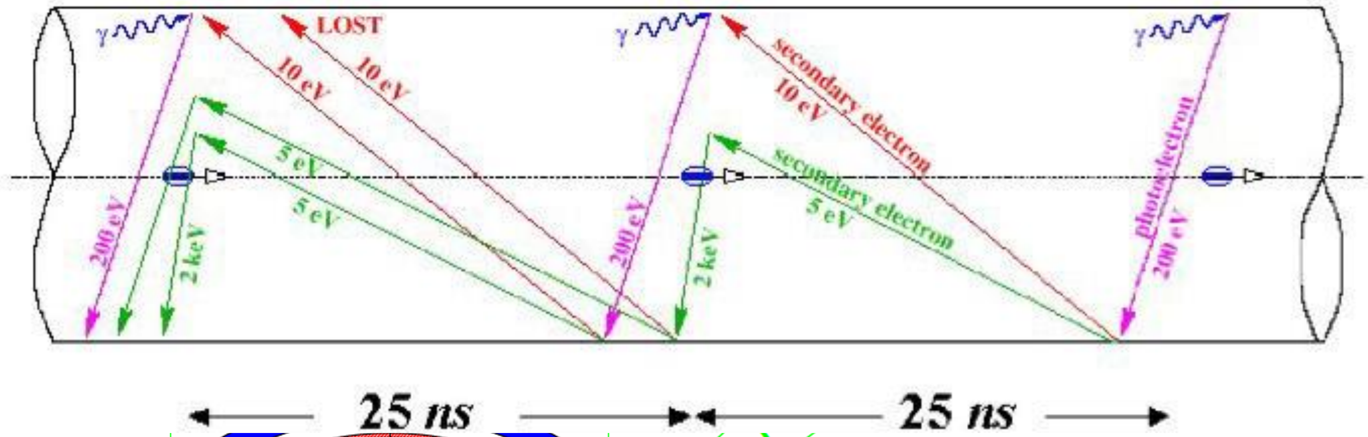


Strong forces if magnet quenches

Example: Beam Screen Design





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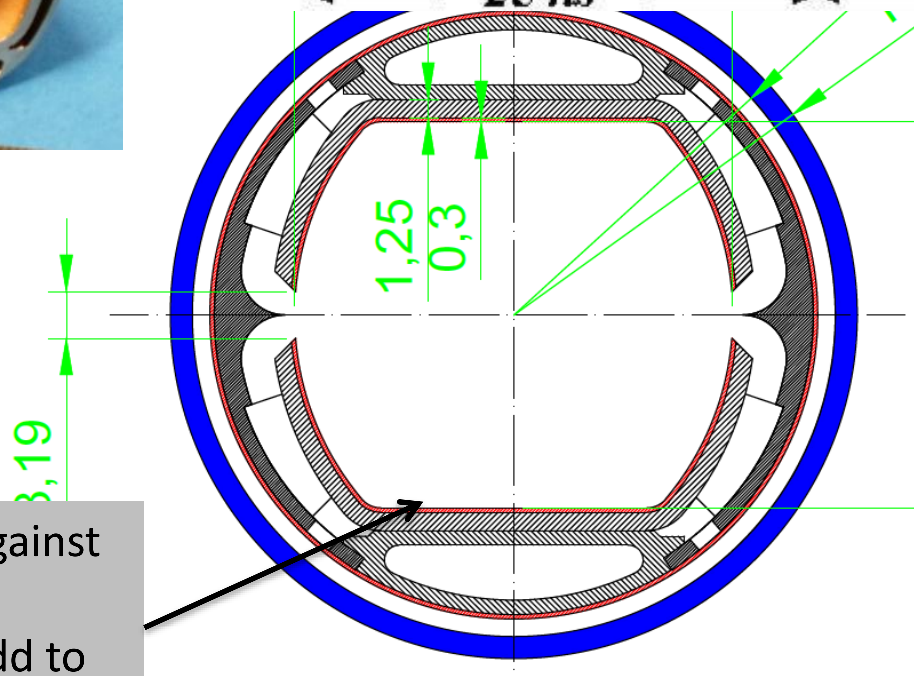
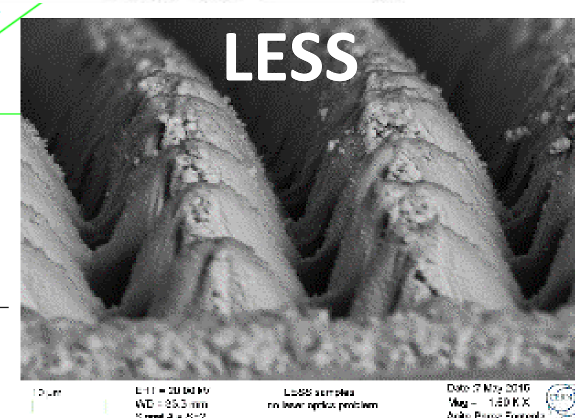
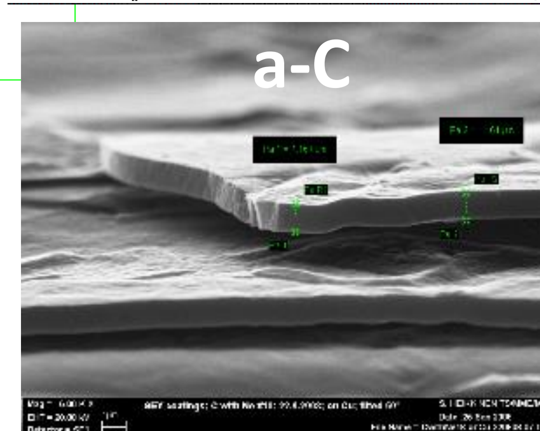
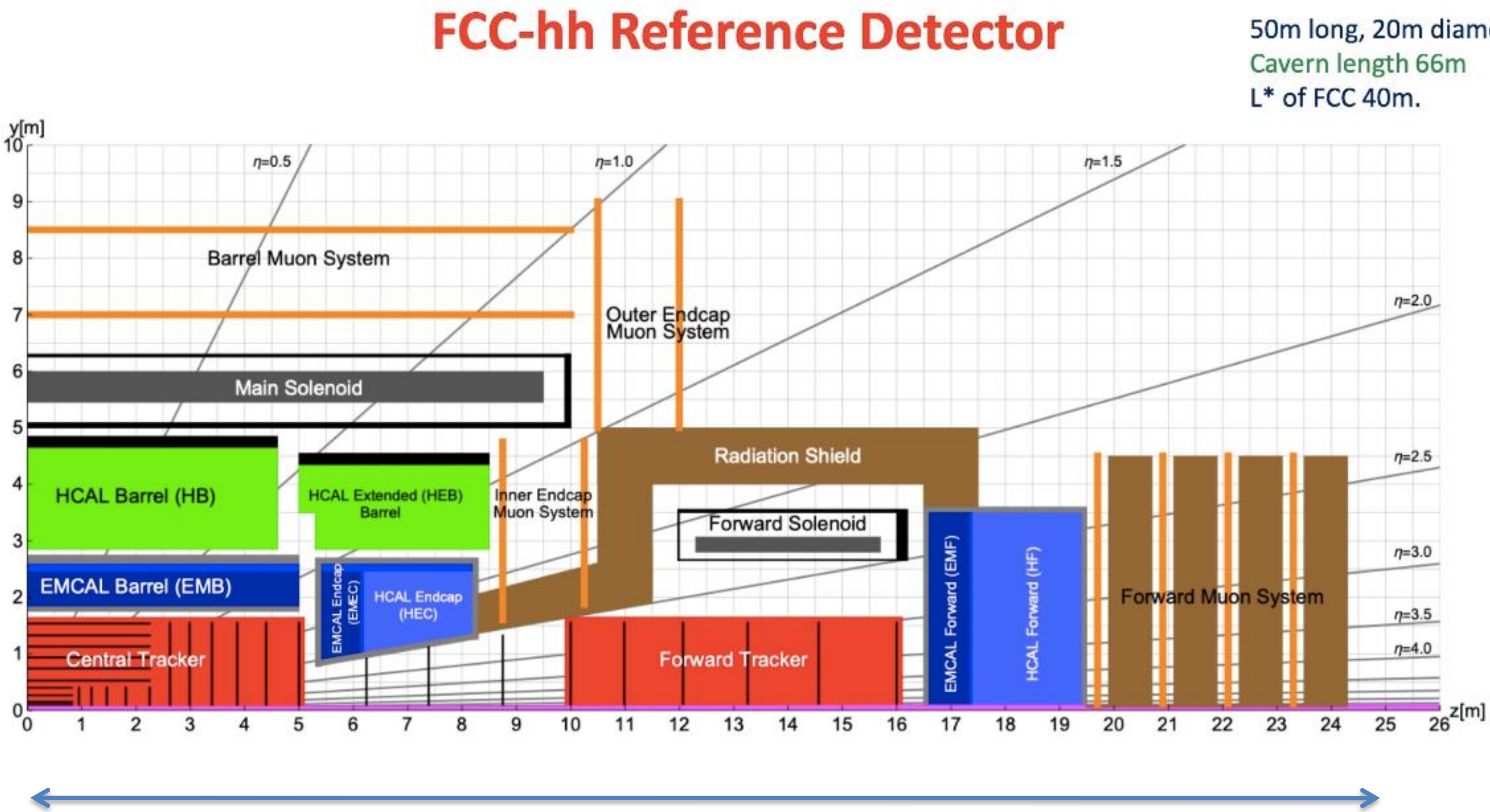






Surface treatment against electron cloud
How much does it add to the impedance?

Current FCC Detector Model



50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.

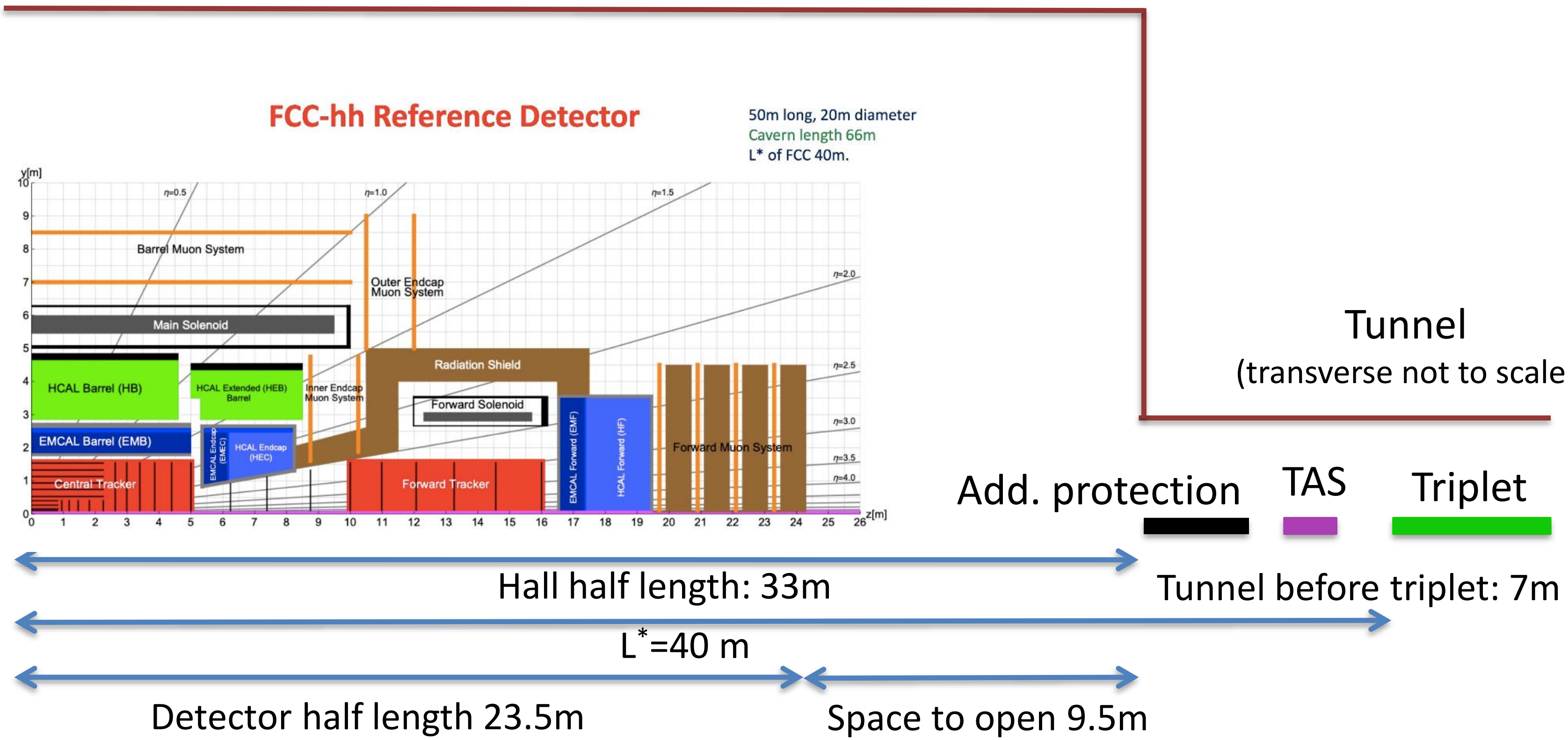
Hall half length: 25m

MDI Layout

Uses forward solenoid

Alternative option with forward dipole considered

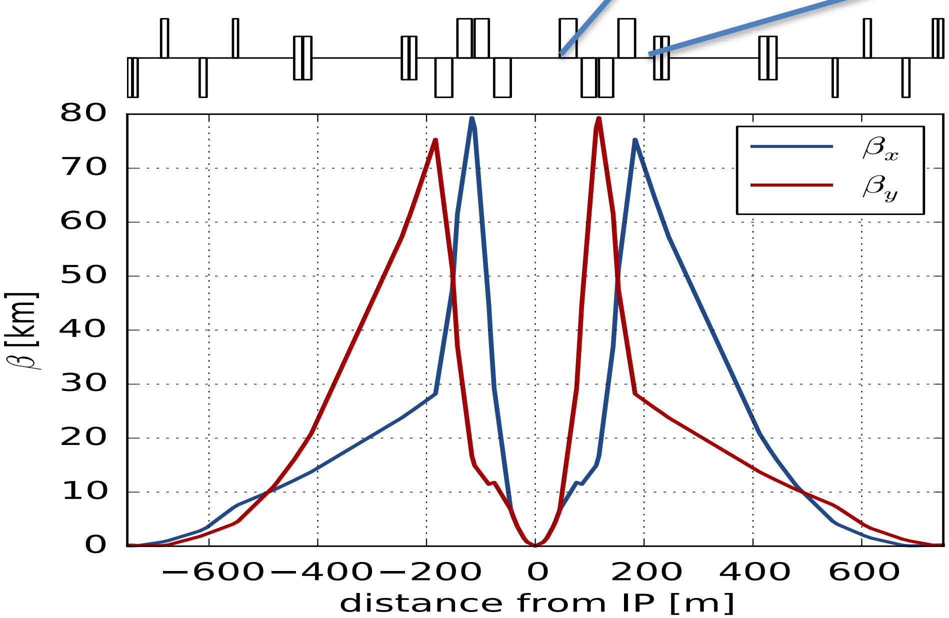
Detector hall
(transverse not to scale)

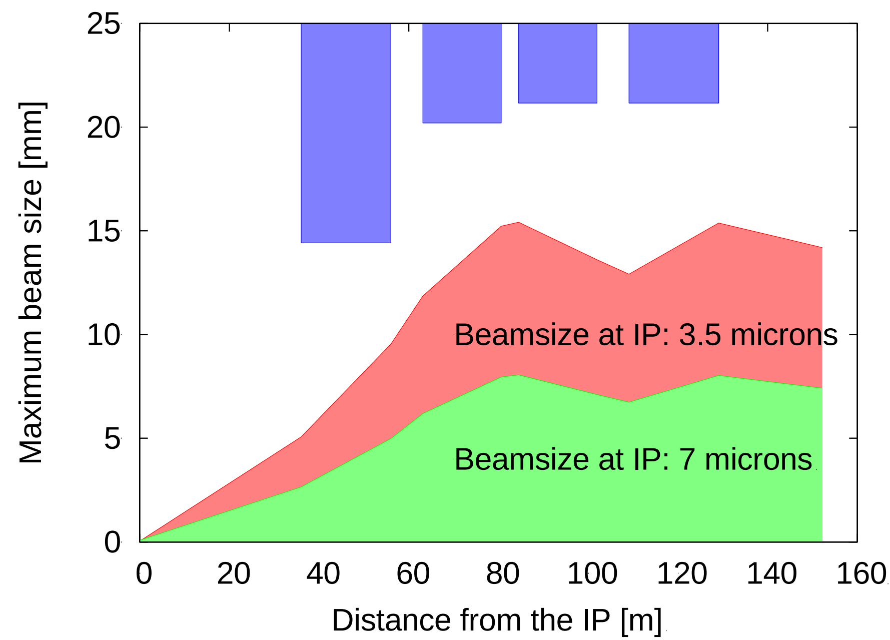


Interaction Region and Final Focus Design

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

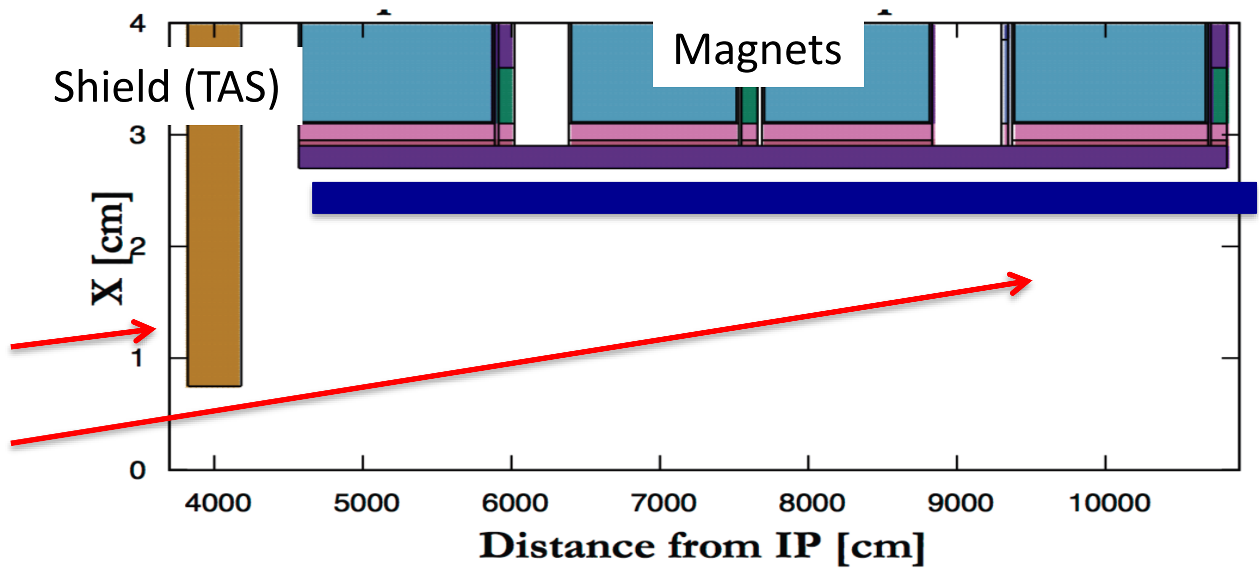
Beam size is limited by aperture in the magnets





Radiation from Beam-beam (FCC)

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

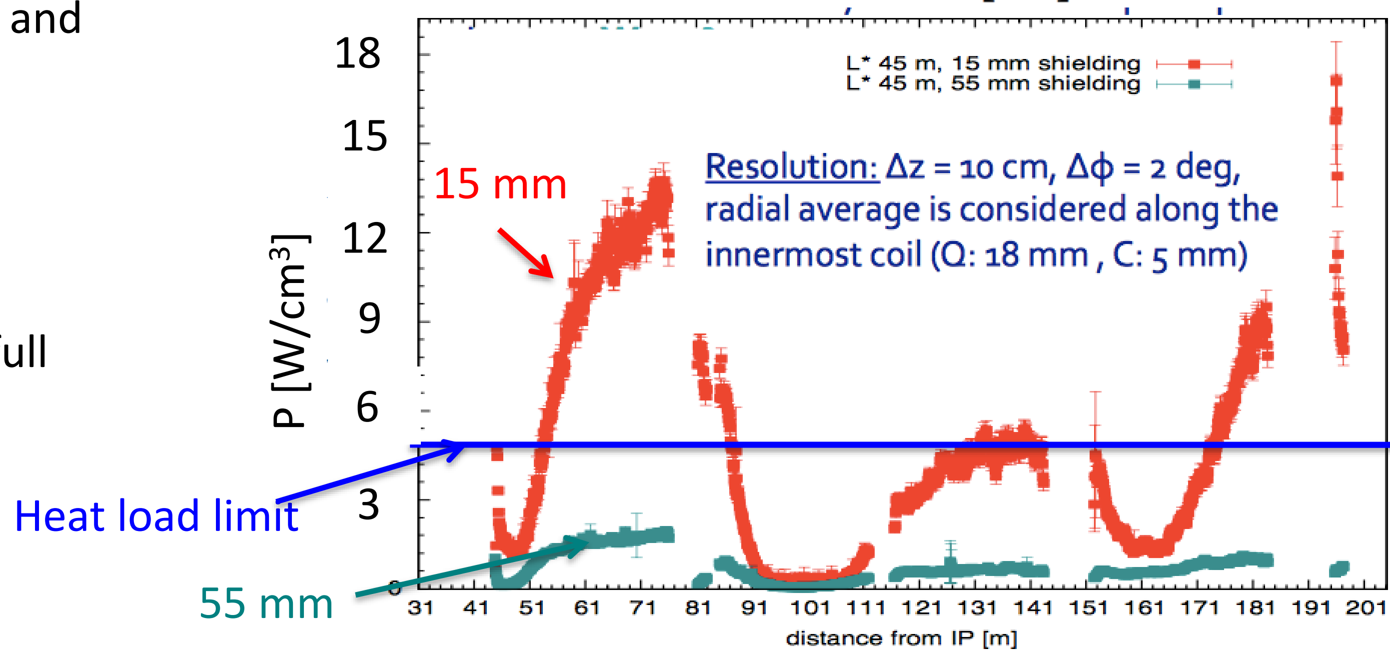


Total collision debris is up to 500 kW per experiment

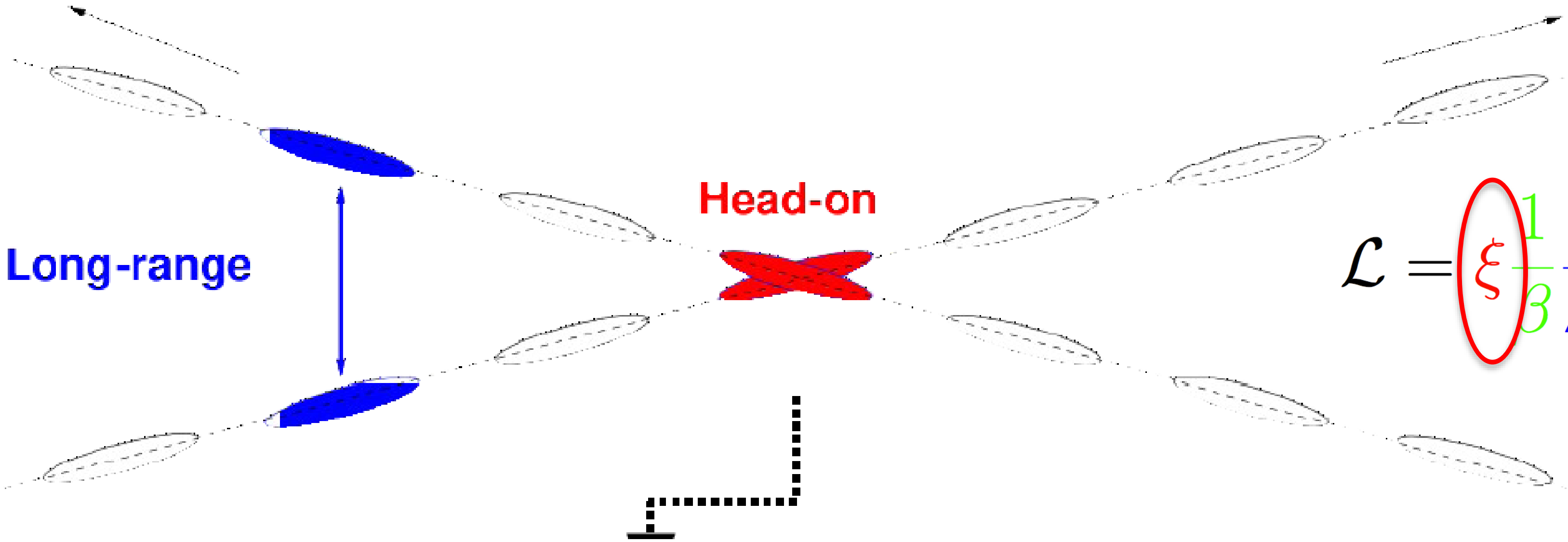
Issue for magnet lifetime and heat load

Require thick shielding

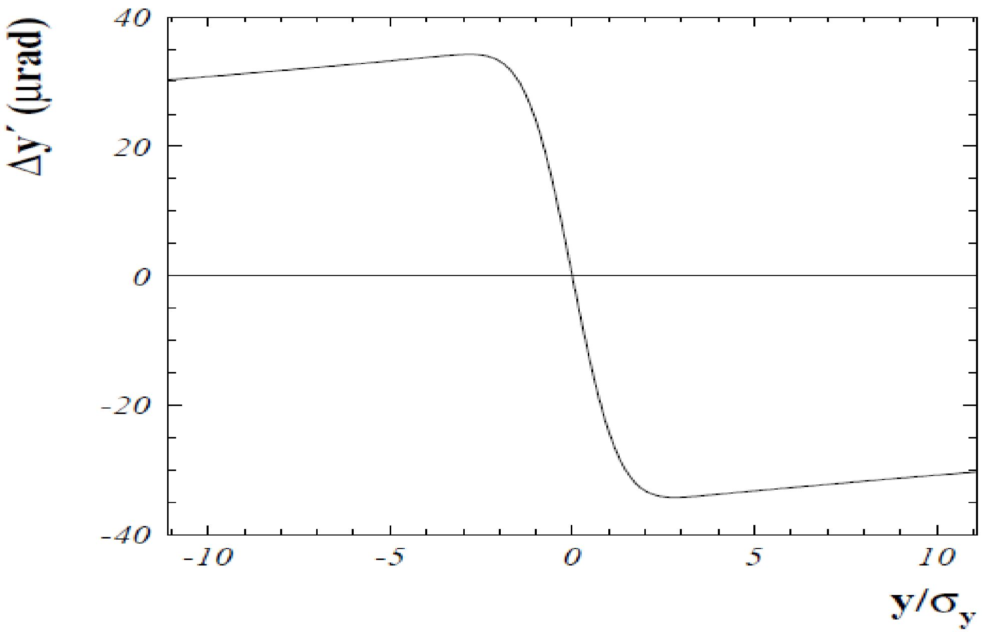
Magnet will just survive full project duration



Beam-beam Effects



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



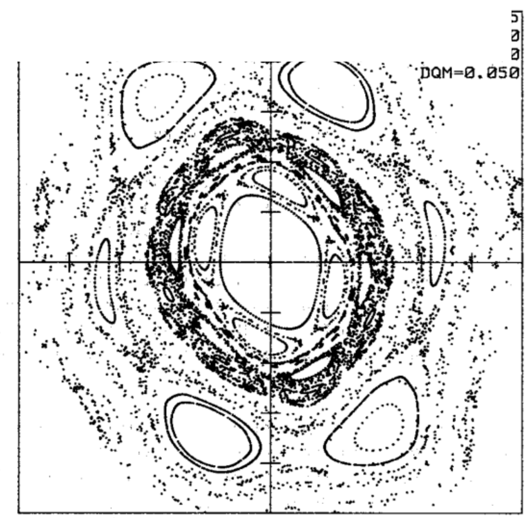


Plate 3b

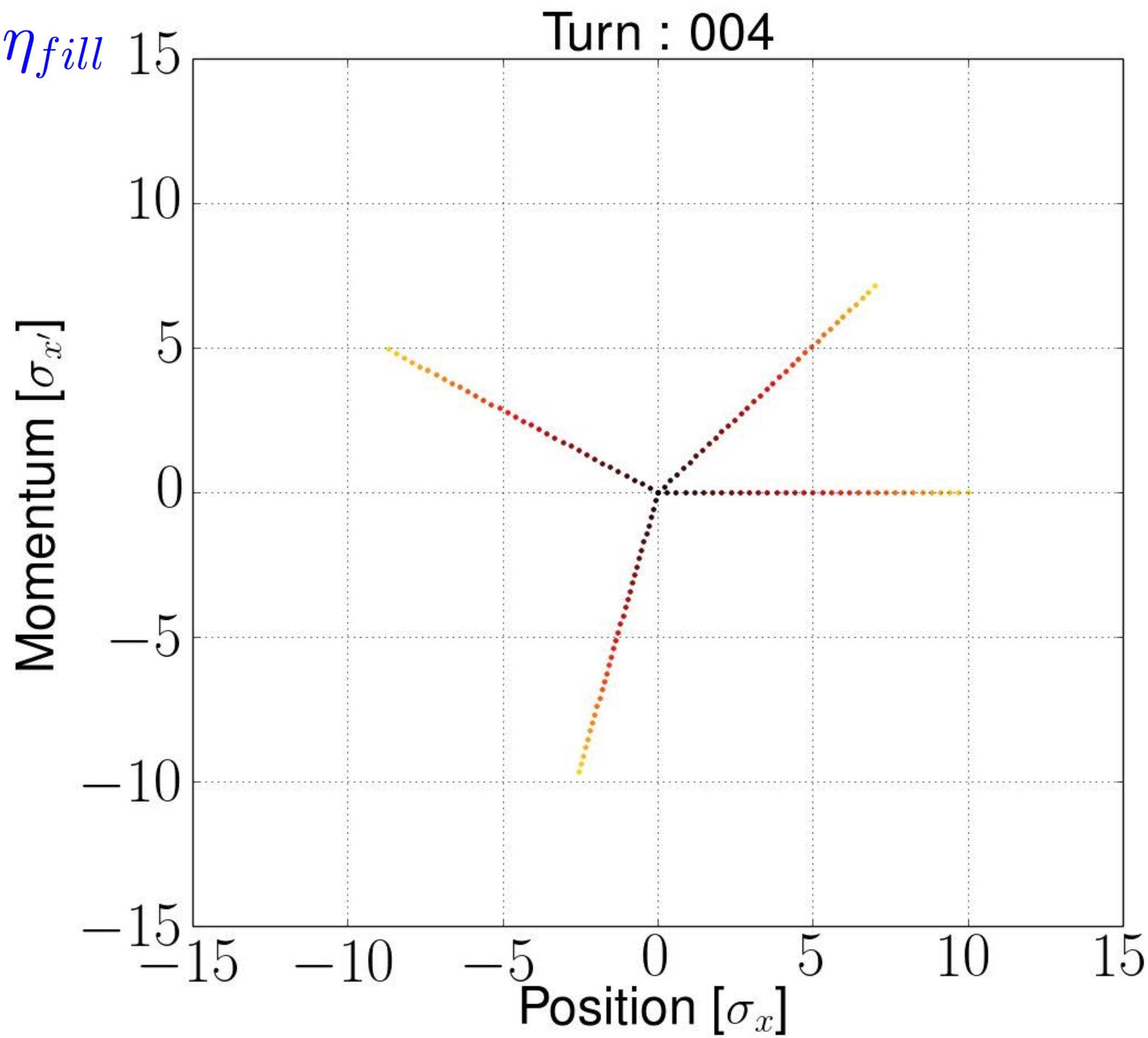
⇒ About ξ=0.03 is acceptable

⇒ More study needed

Beam-beam Effects

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

X. Buffat



Beam-beam Effects

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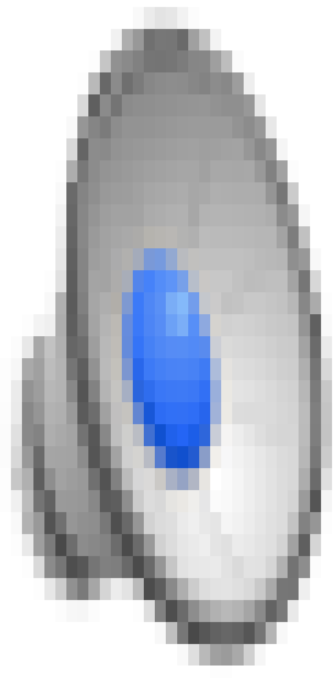
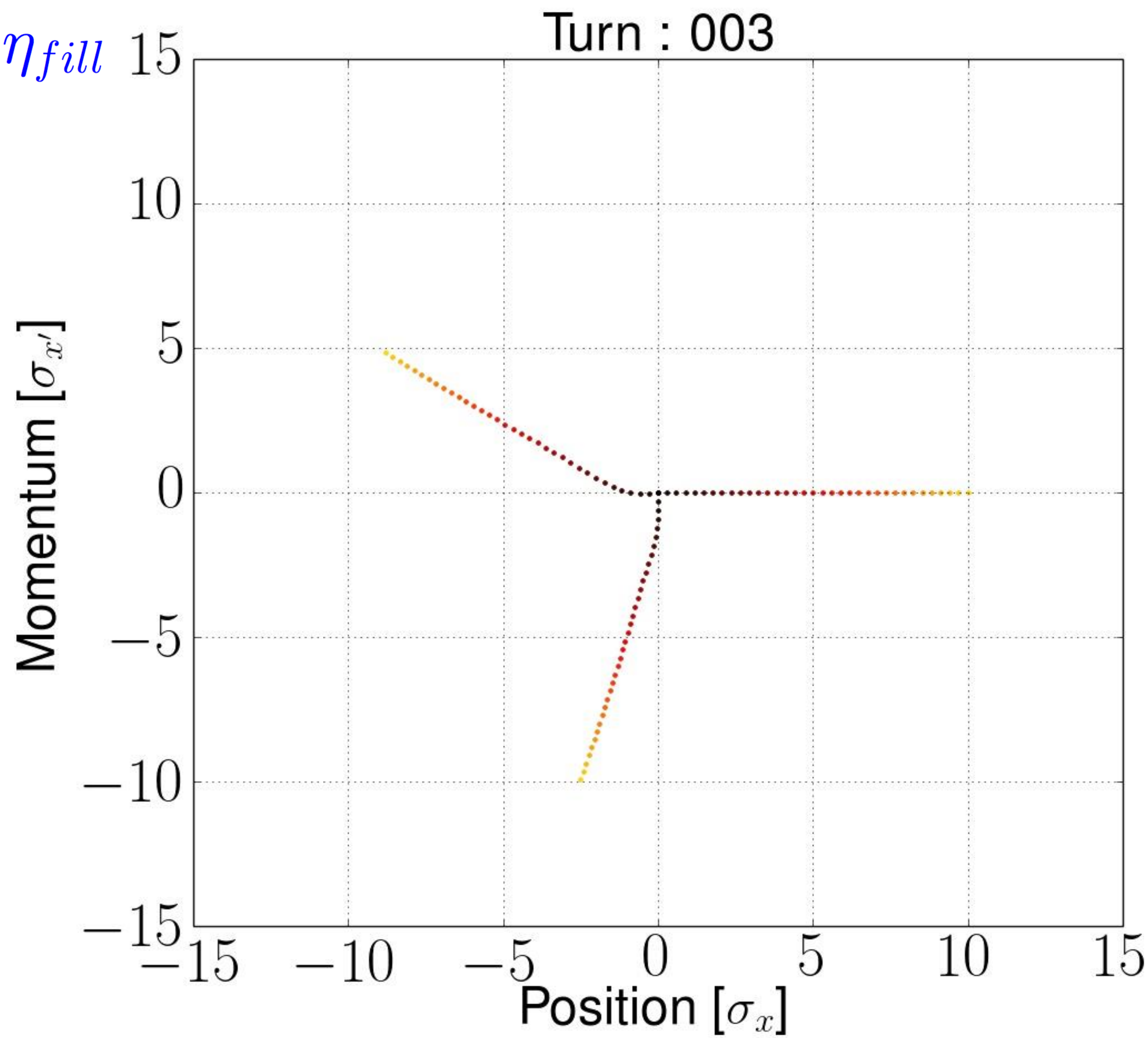
X. Buffat



Beam-beam Effects

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

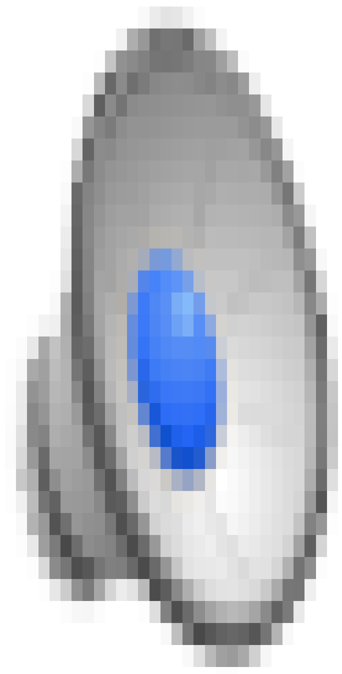
X. Buffat



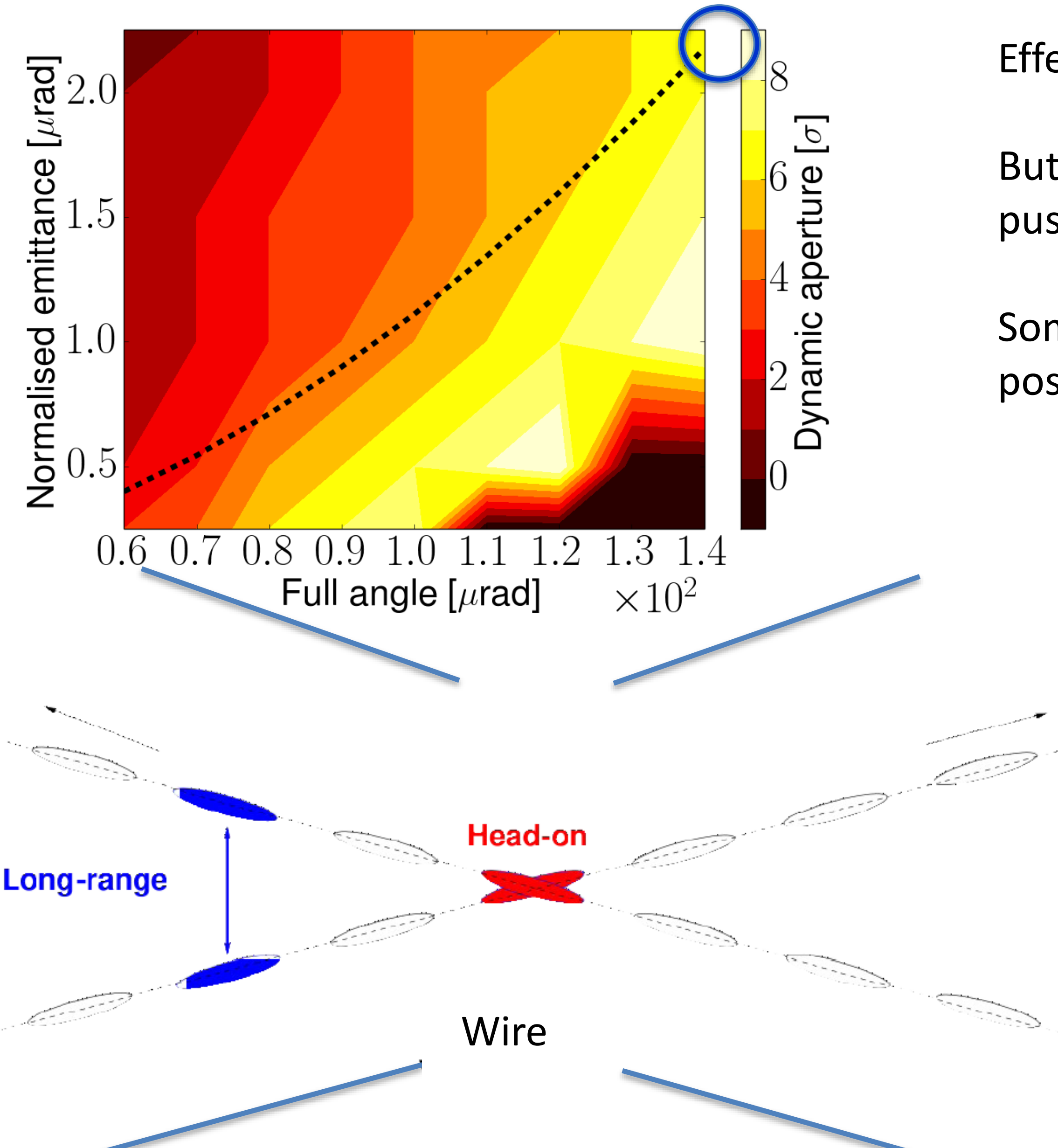
Beam-beam Effects

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

X. Buffat



Beam-beam Effect Mitigation



Effect is about OK

But would like to have margin and to push further

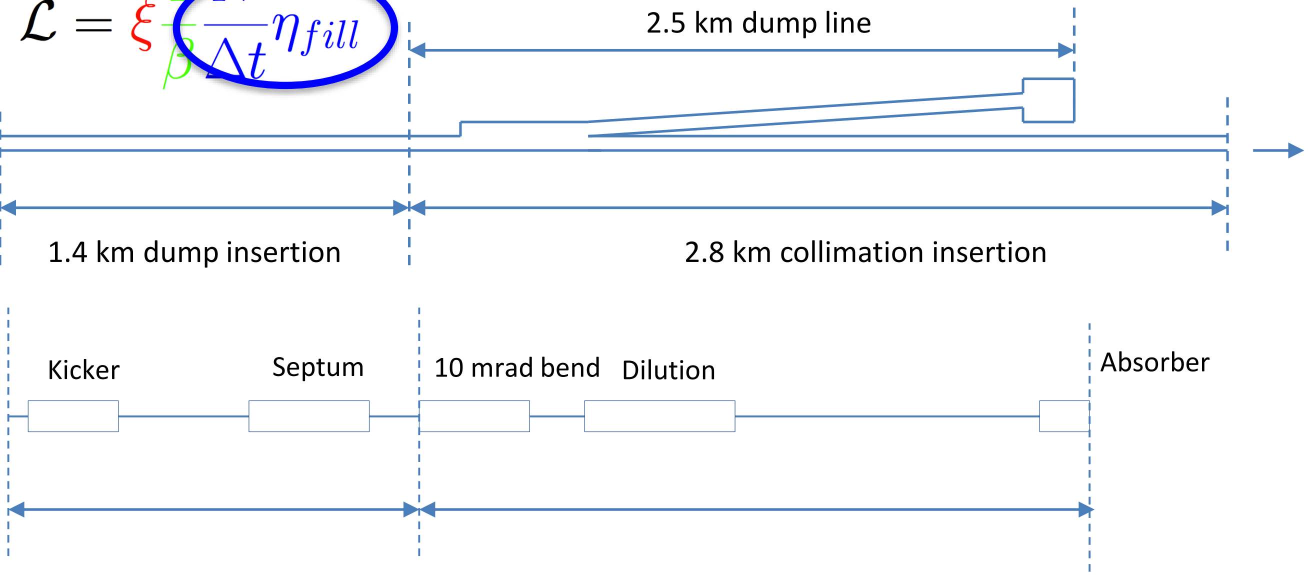
Some mitigation techniques are possible:

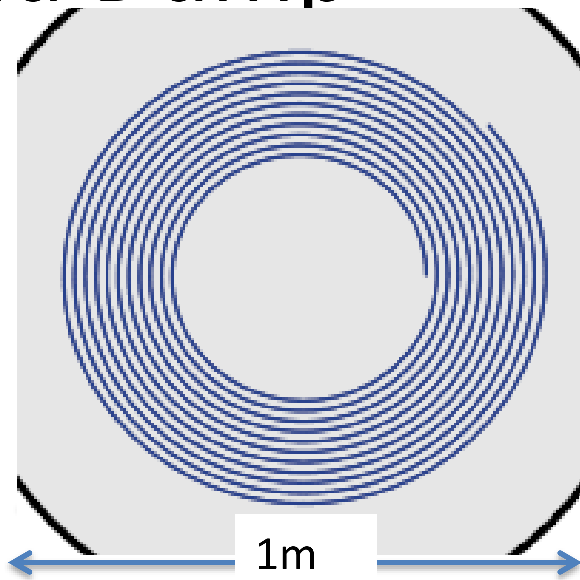
Head-on:
Electron lens

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

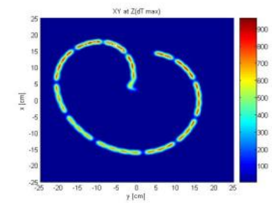
Example: Beam Energy and Dump

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





LHC pattern
(same scale)



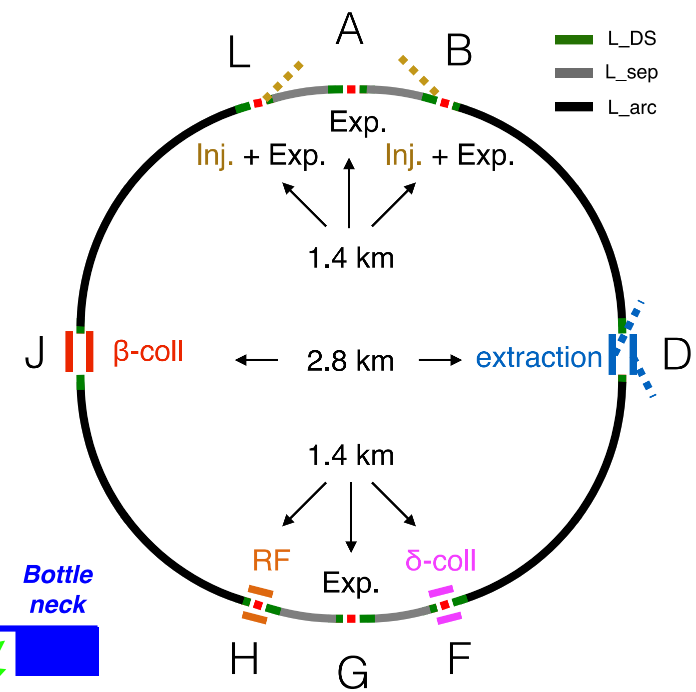
8GJ kinetic energy per beam

- Airbus A380 at 720km/h
- 2000kg TNT
- 400kg of chocolate
  - Run 25,000km to spent calories
- O(20) times LHC
- Can drill 300m long hole in copper

Collimation System

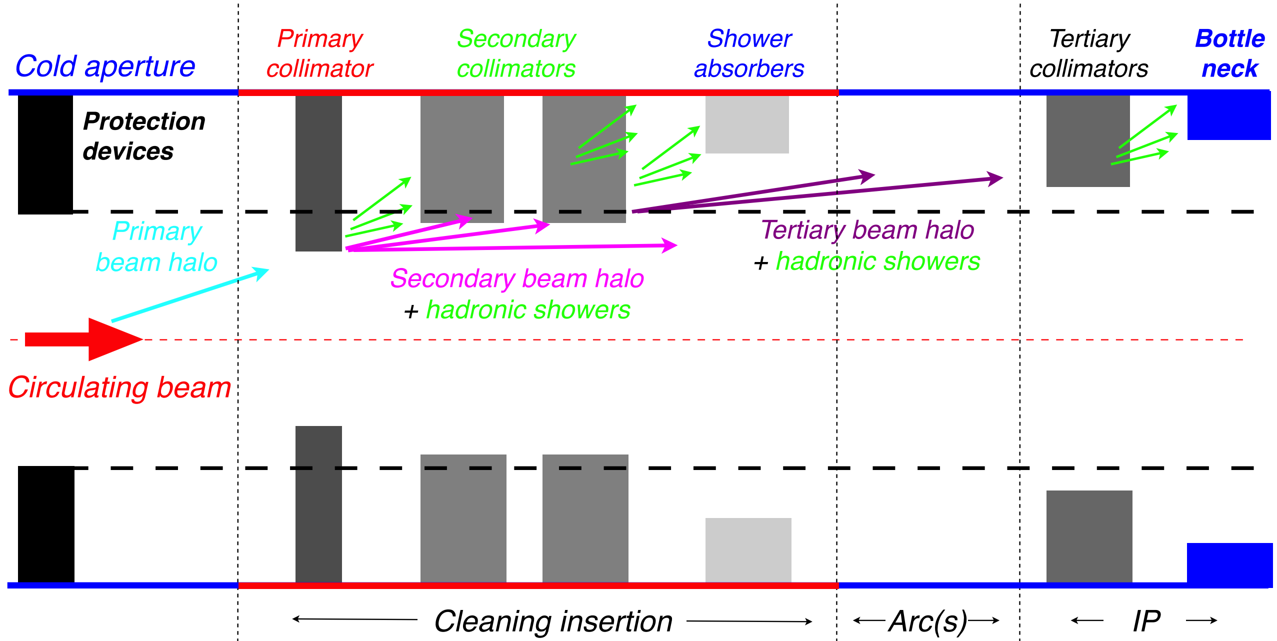
Three main goals:

- Protect from injection failure
- Protect from asynchronous beam dump
- Removes particles that enter the tails



Much more challenging in FCC than in LHC due to much higher beam power

Should withstand up to 11 MW losses



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

HE-LHC

HE-LHC

Basic idea is to reuse LHC tunnel with stronger magnets

- Can go from 14 TeV to 27 TeV
- Can increase luminosity by about factor 3-4

But many challenges

- Only limited improvement for physics
- Project cost O(7 GCHF)
- Existing tunnel geometry requires compromises

$\Rightarrow$ Probably not a good option

FCC-ee

FCC-ee Baseline Parameters

Parameter	Z	W	H	t	LEP2
Cms E [GeV]	91.2	160	240	350	208
I [mA]	1390	147	29	6.4	4
L [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.8	0.012
Years op.	4	2	3	5	
Int L / IP [ab^{-1}]	75	5	2.5	1.5	

Using flat beams

Significant luminosity increase compared to LEP:
Smaller emittances, beta-functions, larger power consumption

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

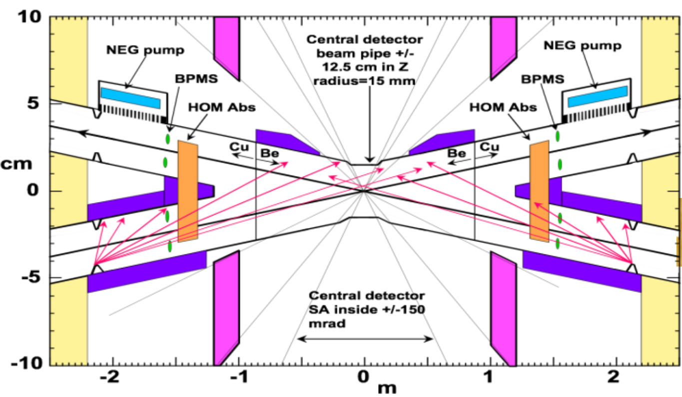
Current limit 100MW of synchrotron radiation (both beams)

Layout

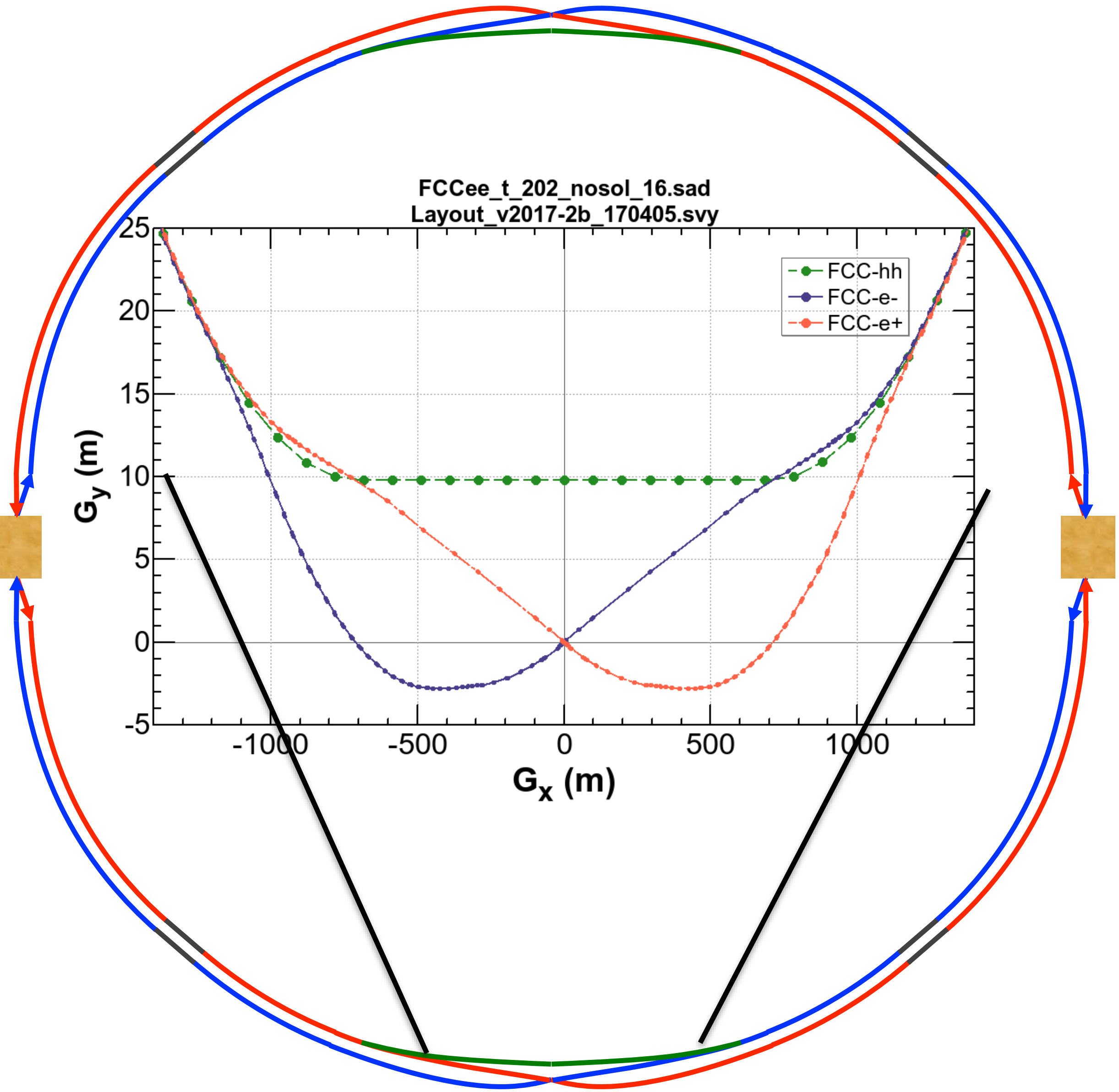
Need a crossing angle at IP

Cannot bend beams close to IP

Requires additional tunnel



Very short beam lifetime requires top-up injection, i.e. booster ring

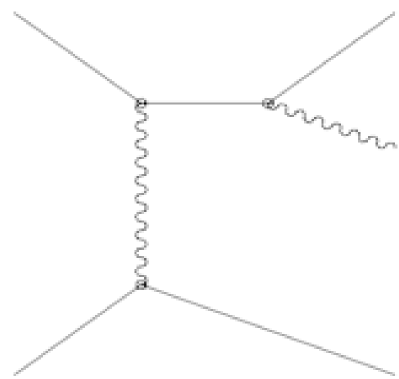


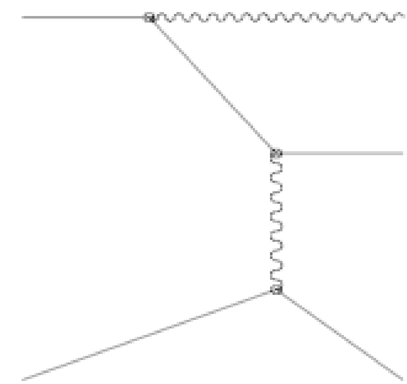
Top-up Injection

Beam lifetime is short (18-200 minutes)

- Bremsstrahlung
- Beamstrahlung
- …

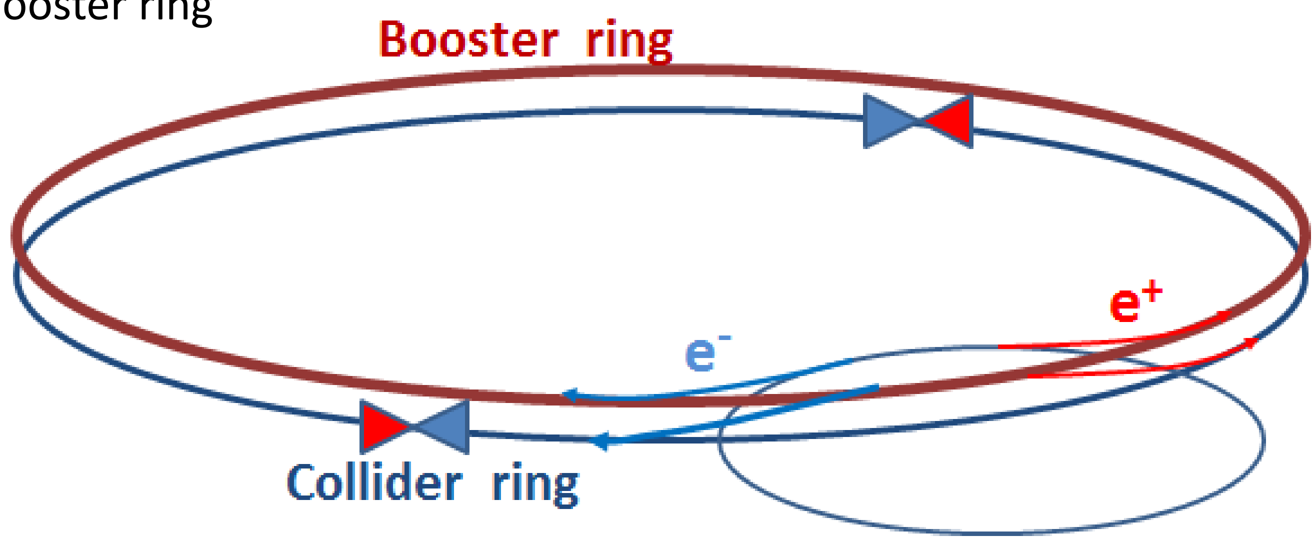
$$\tau_{ee} \propto \frac{I}{L\,\sigma_{ee}\,n_{ip}}$$





Have to refill beam permantently

$\Rightarrow$ top-up injection with booster ring

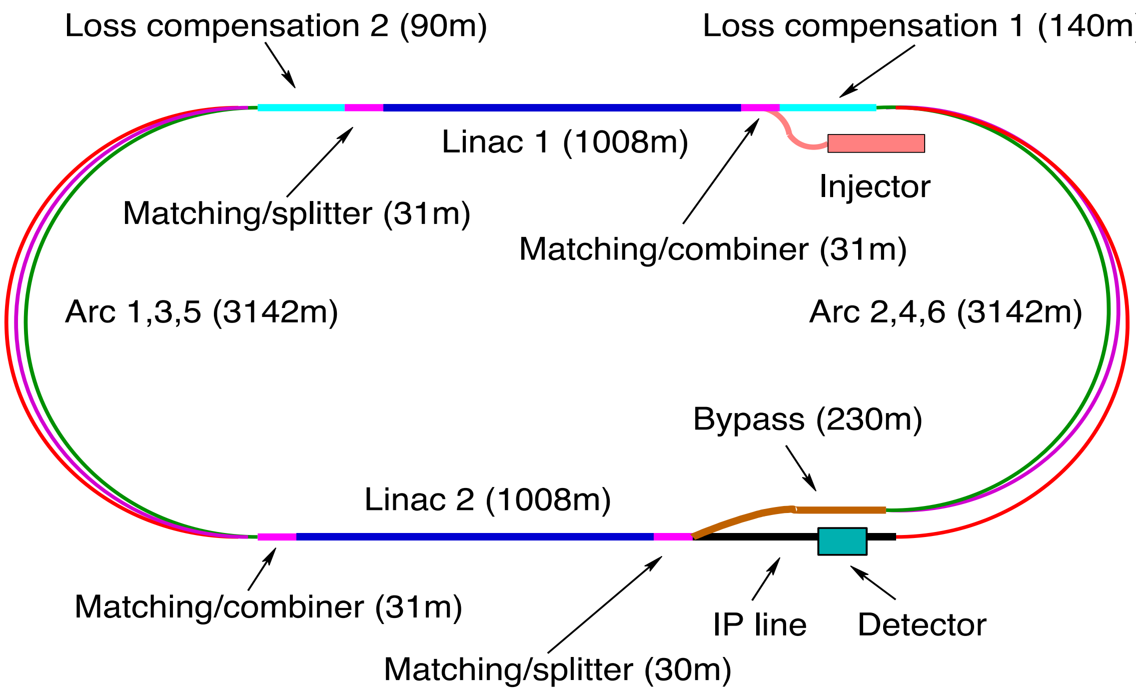


FCC-he/LHeC

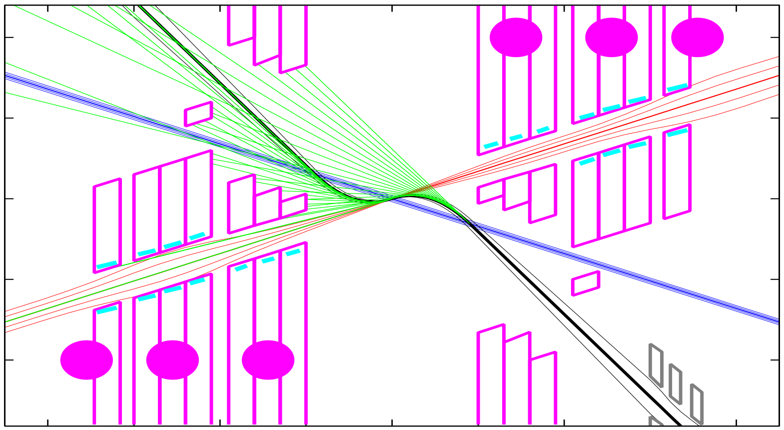
LHeC / FCC-he

Recirculating linac allows to recover beam energy

800 MW beam power for 100 MW power consumption

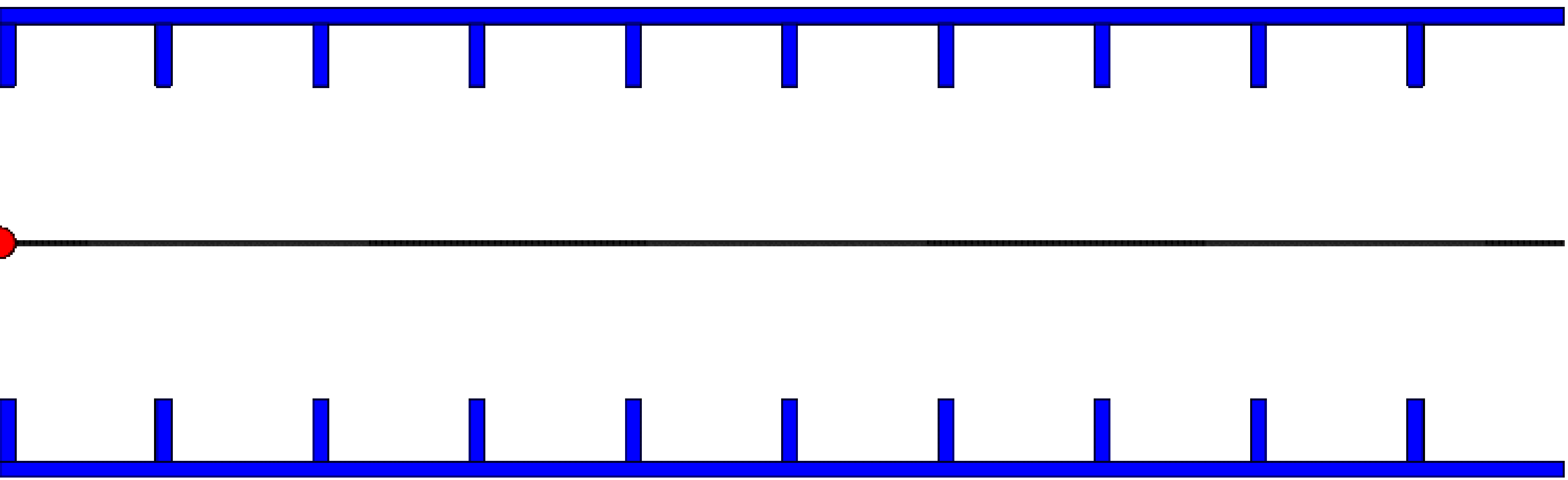


	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
L [10^{33} $cm^{-2}s^{-1}$]	1	8	12	15

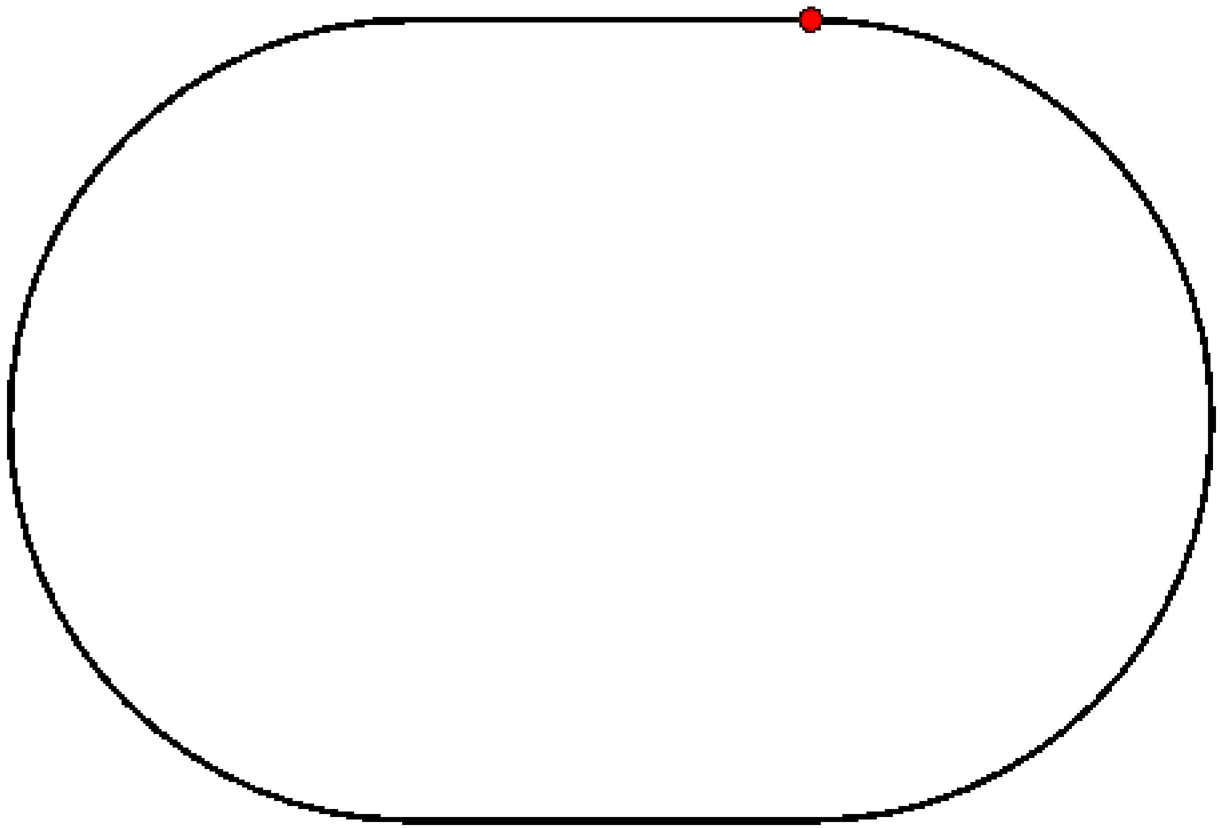


LHeC CDR: http://arxiv.org/abs/1206.2913

Energy Recovery Principle



LHeC Linac-ring Option

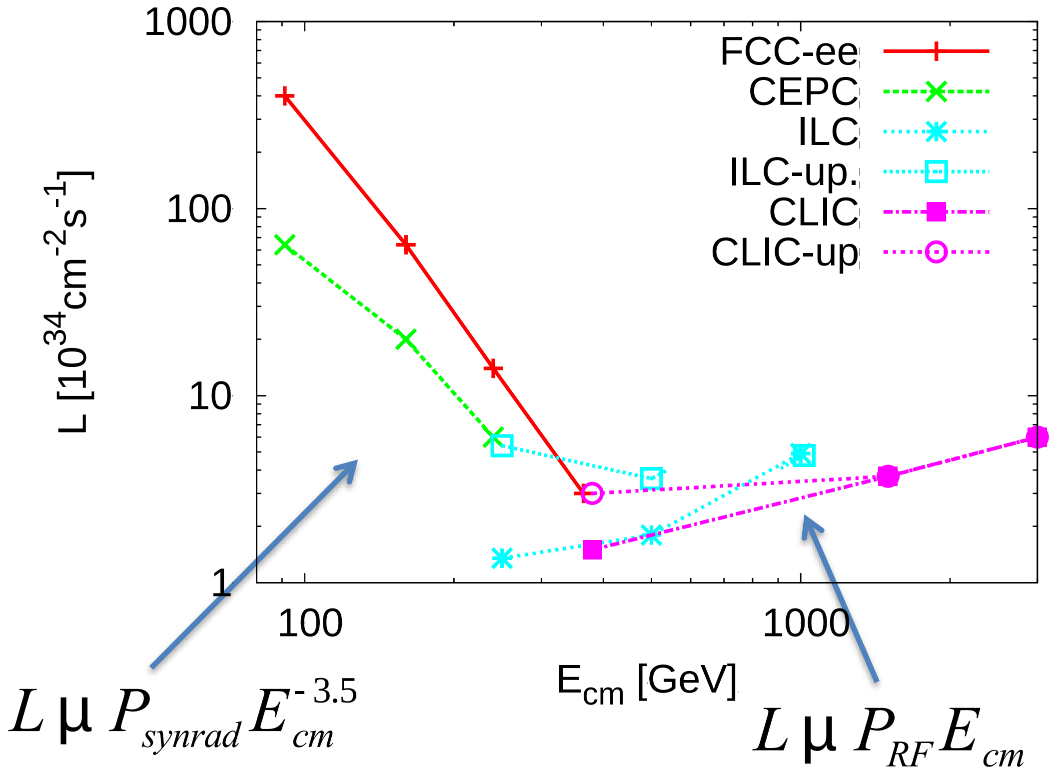


Principle has been tested at CEBAF (JLAB), but with small current/little beam-loading

Note: Muon Collider

Proposed Lepton Colliders

Luminosity per facility



CLIC can reach 3 TeV

- Cost estimate 18 GCHF
  - Largely main linac, i.e. energy
- Power 580 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy but is it affordable?

R&D required towards higher energies (or improvement of 3 TeV)
- Reduction of cost per GeV (improved NC acceleration, novel acceleration technologies)
- Improved power consumption (higher RF to beam efficiency, higher beam quality)

Muon Collider Concept

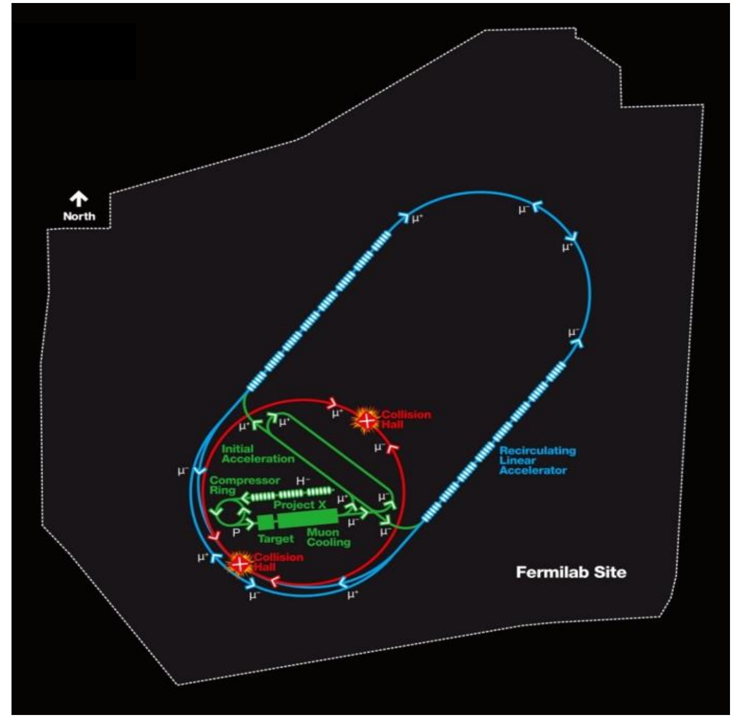
Muon are heavy so they emit little synchrotron radiation

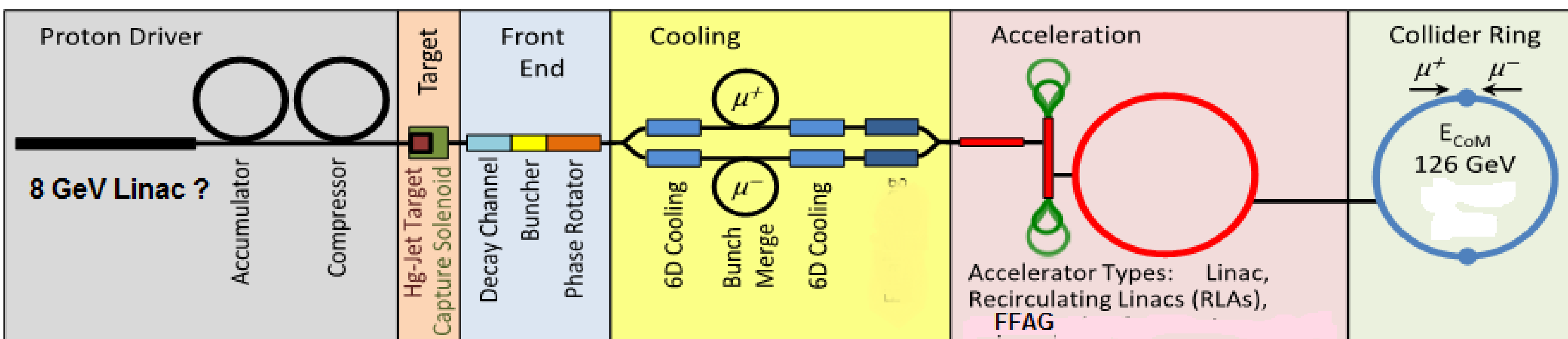
$$m_\mu \approx 106\, MeV/c^2 \approx 207\, m_e$$

But they do not live very long

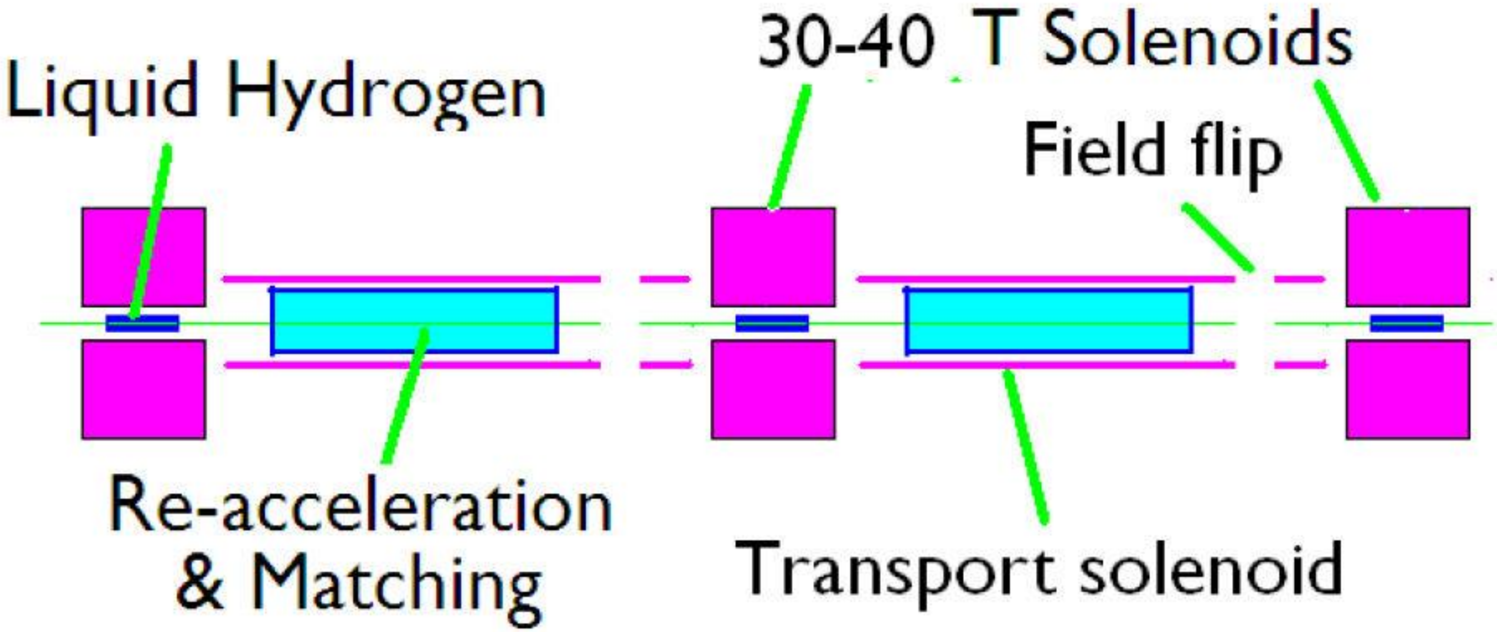
$$\tau_\mu \approx 2.2\, \mu s \times \gamma$$

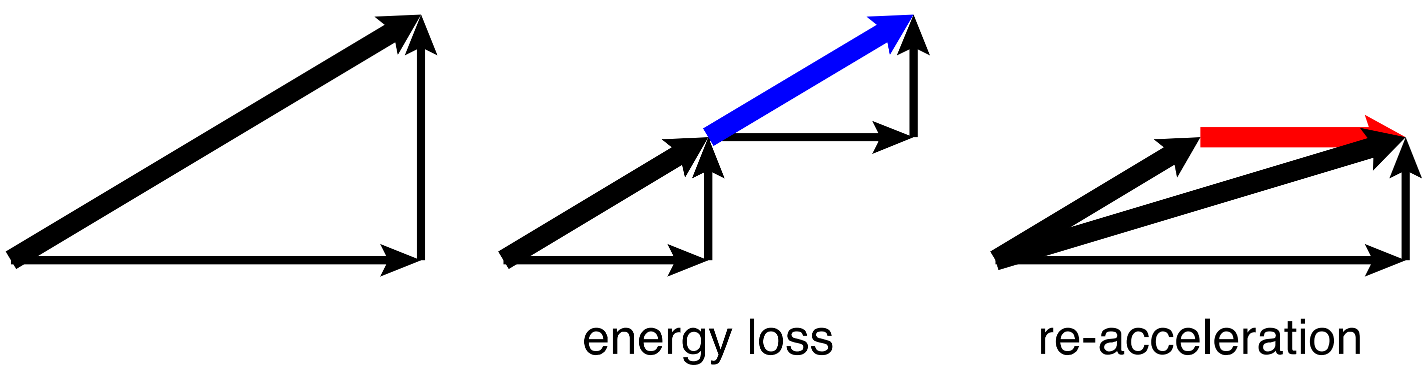
Produce them, cool them quickly and let them collide in a small ring



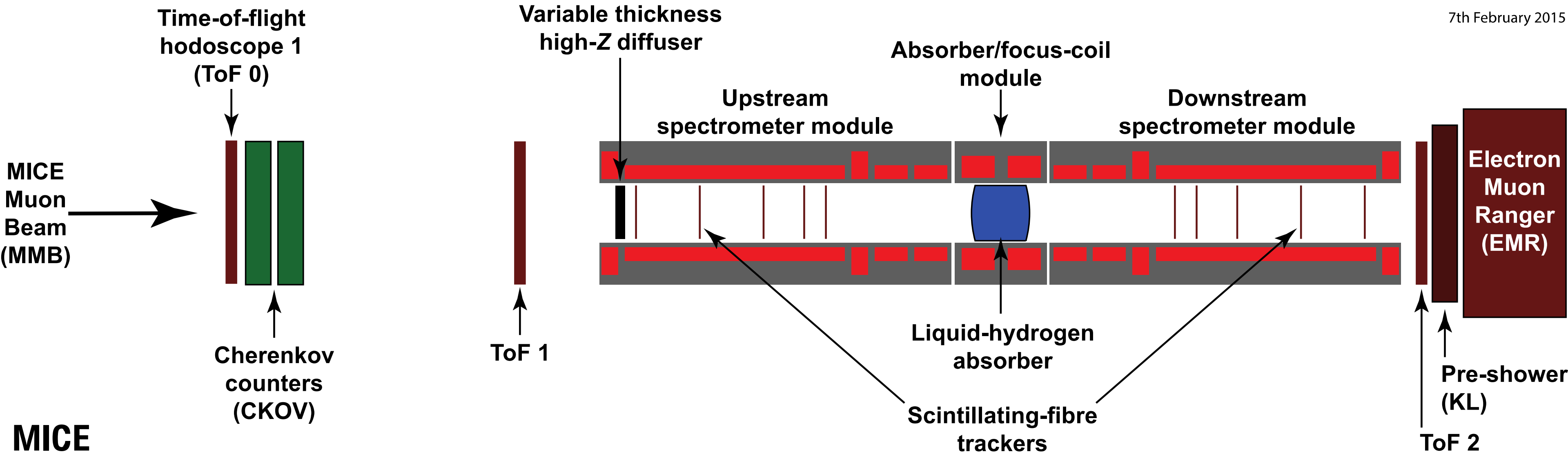


Final Transverse Cooling System



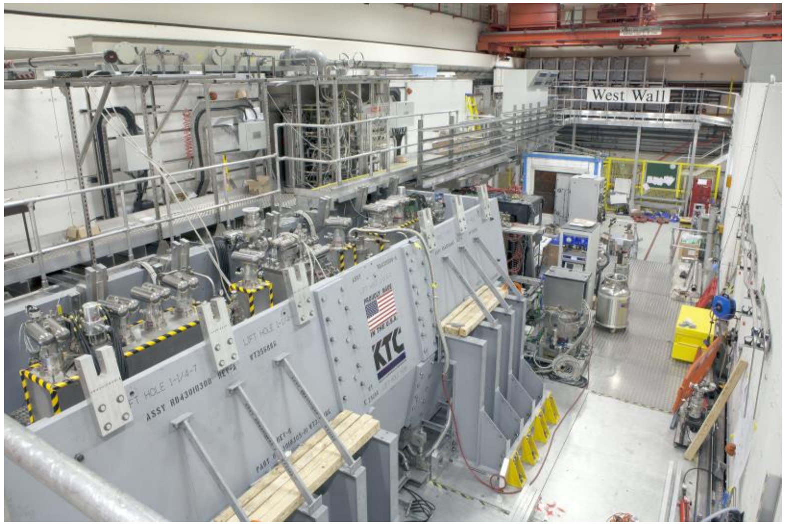


Cooling and MICE



$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

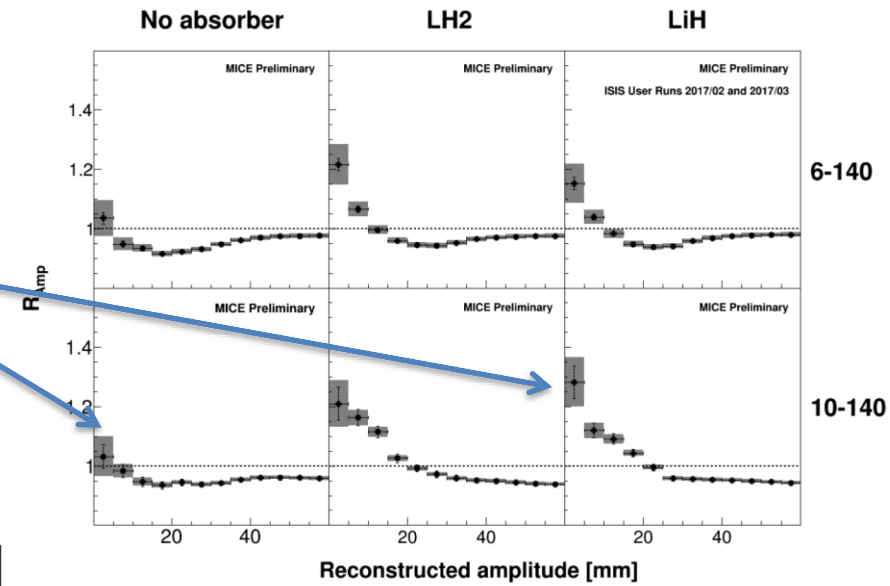
MICE allowed to address 4D cooling
with low muon flux rate



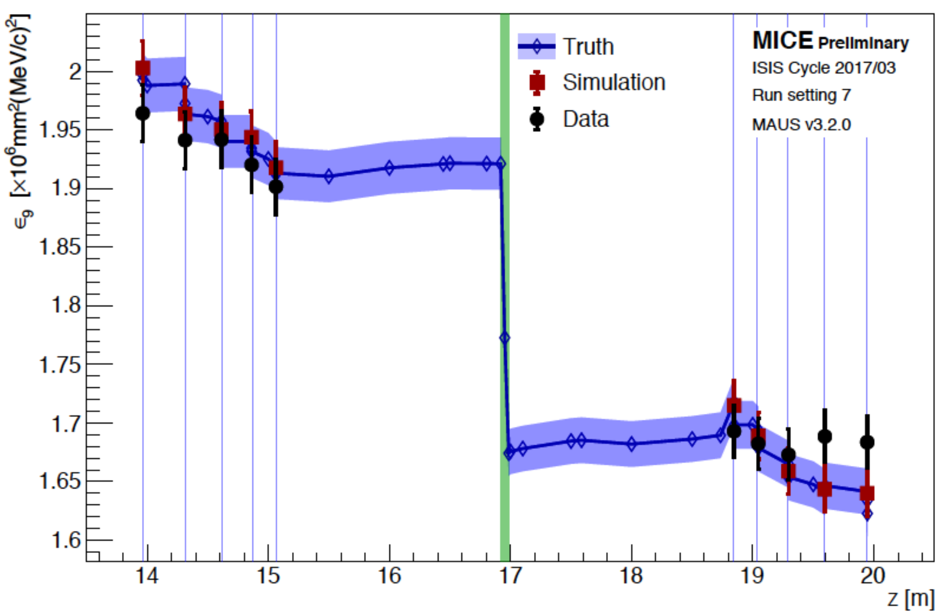
MICE Results

The absorber reduces the number of particle with large amplitude

They appear with smaller amplitude



Noticeable reduction of 9% emittance

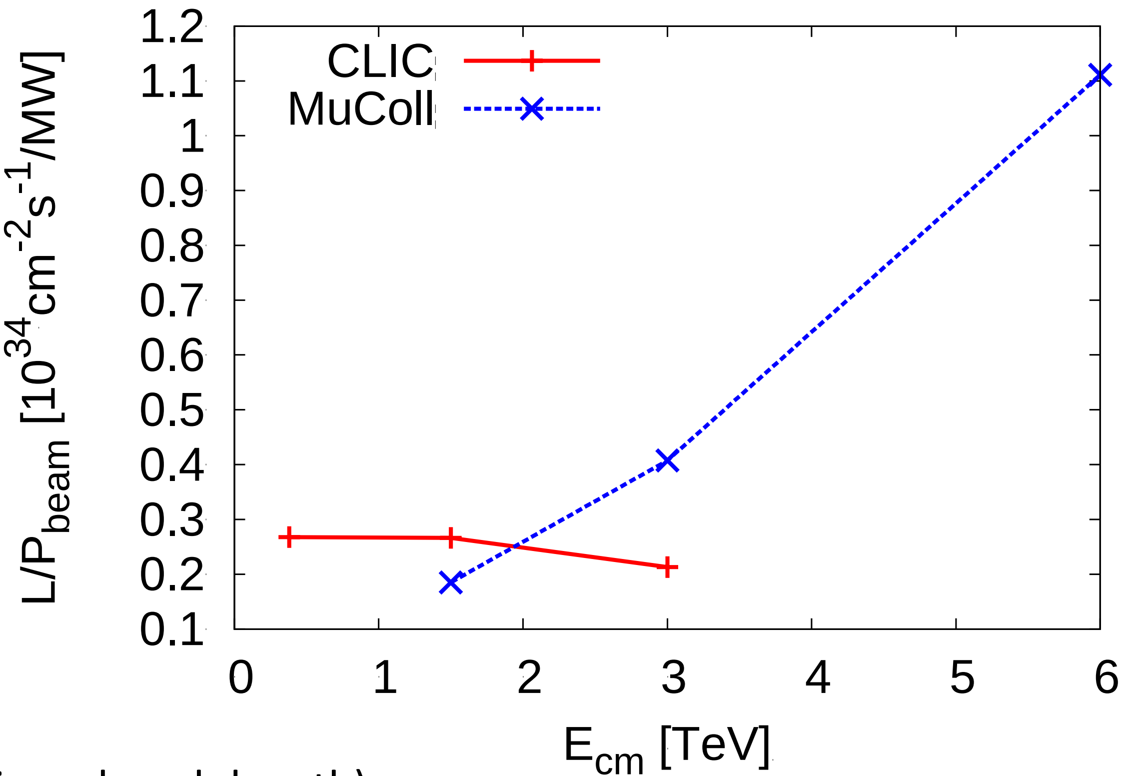


But still some way to go
- 6D cooling
- Stages
- Small emittances

Luminosity Comparison

The luminosity per beam power is about constant in linear colliders

It can increase in muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

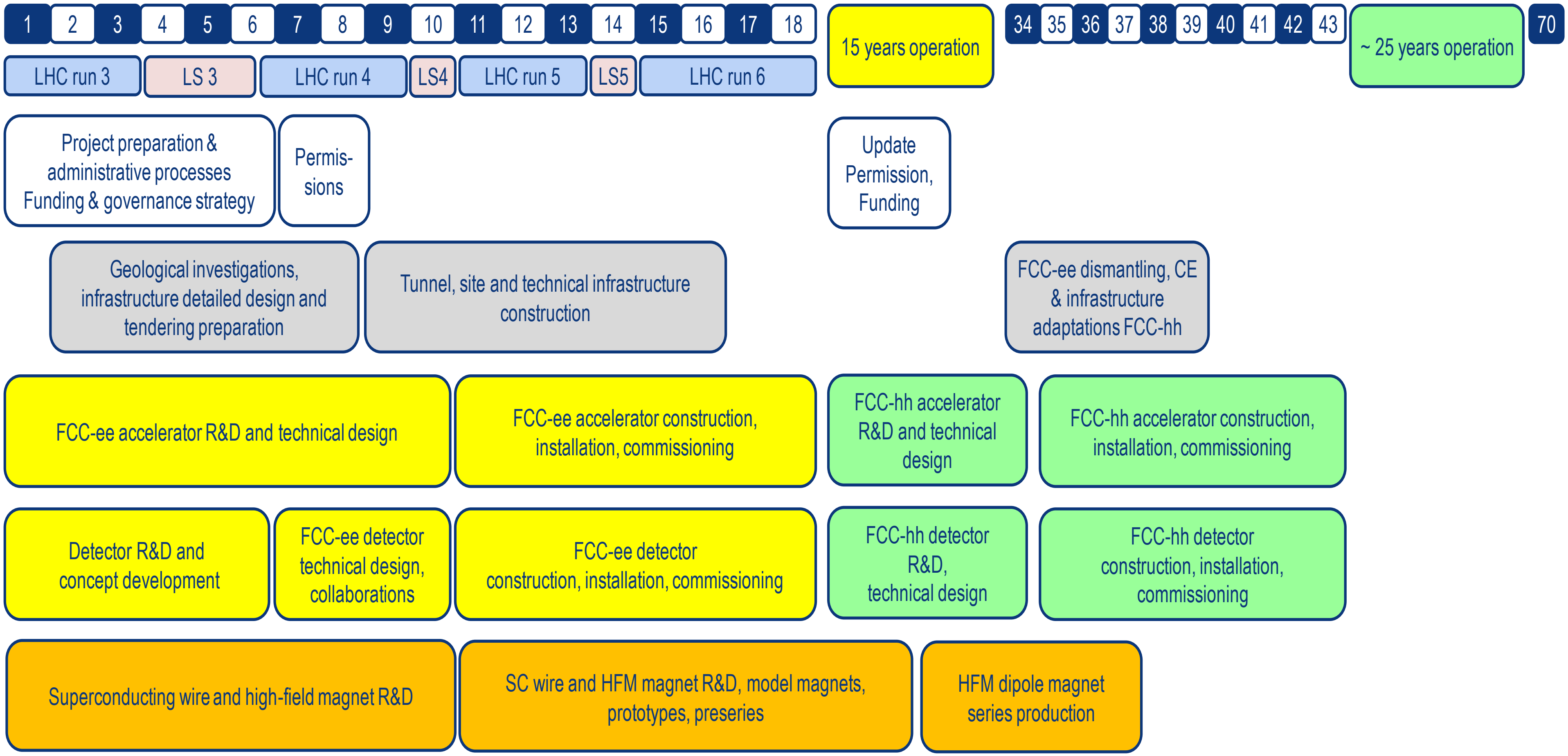
Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)

Summary

- CLIC
  - Given high priority by European strategy
  - Conceptual design and project implementation plan exist
- FCC (FCC-ee then FCC-hh, maybe FCC-he)
  - Given high priority by European strategy
  - Conceptual design exists
- ILC
  - Japan might offer to be the host (decision process is ongoing since several years)
- CEPC/SppC
  - China will decide

- Other work
  - Muon collider
    - For the next-to-next project
  - LHeC
    - As upgrade of HL-LHC
  - Plasma acceleration
    - Novel technology, e.g. for linear collider upgrades

FCC Schedule



- **FCC integrated project plan is fully integrated with HL-LHC exploitation**
- **provides for seamless further continuation of HEP in Europe.**

Thanks

- Thanks for your patience

- Thanks to all the people who helped or from whom I stole figures
  - S. Stapnes, L. Rossi, Ralph Assmann, Jean-Pierre Delahaye, Lucie Linssen, Steffen Doebert, Alexej Grudiev, Frank Tecker, Walter Wuensch, Stephane Poss, Jan Strube, Joerg Wenninger, M. Benedikt, Frank Zimmermann, Bernhard Holzer, Roberto Kersevan, Ph. Lebrun, …

If you can look into the seeds of time, And say which
(Shakespeare)

Reserve

Muon Collider

Muon Collider Parameters

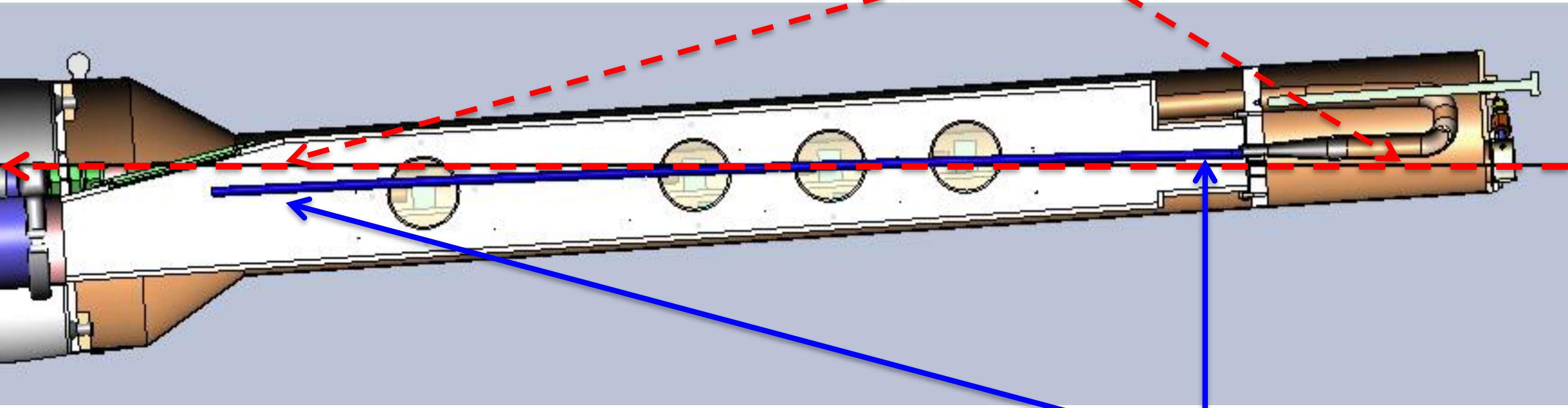
M. Palmer

Muon Collider Parameters						
		Higgs	**Multi-TeV**			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Muon Production: MERIT Experiment

Protons → Target → Pions → Muons

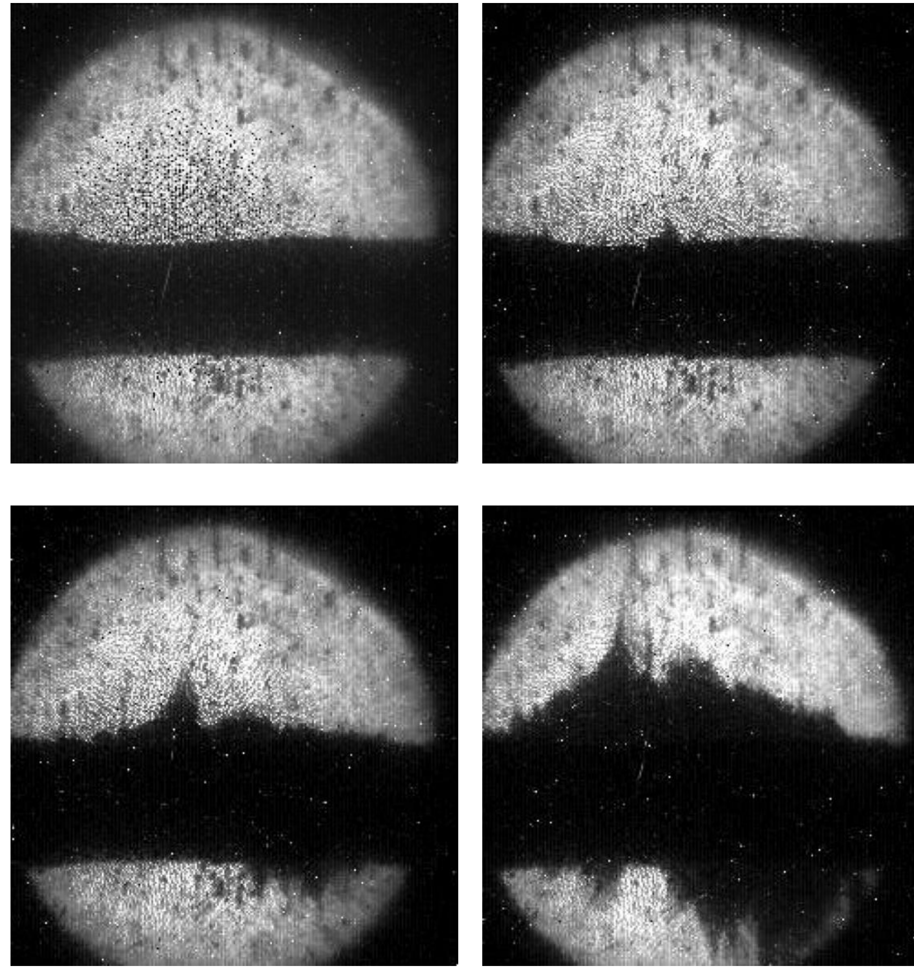
Proton beam



MERIT experiment at CERN

Liquid mercury target to avoid destruction

MERIT

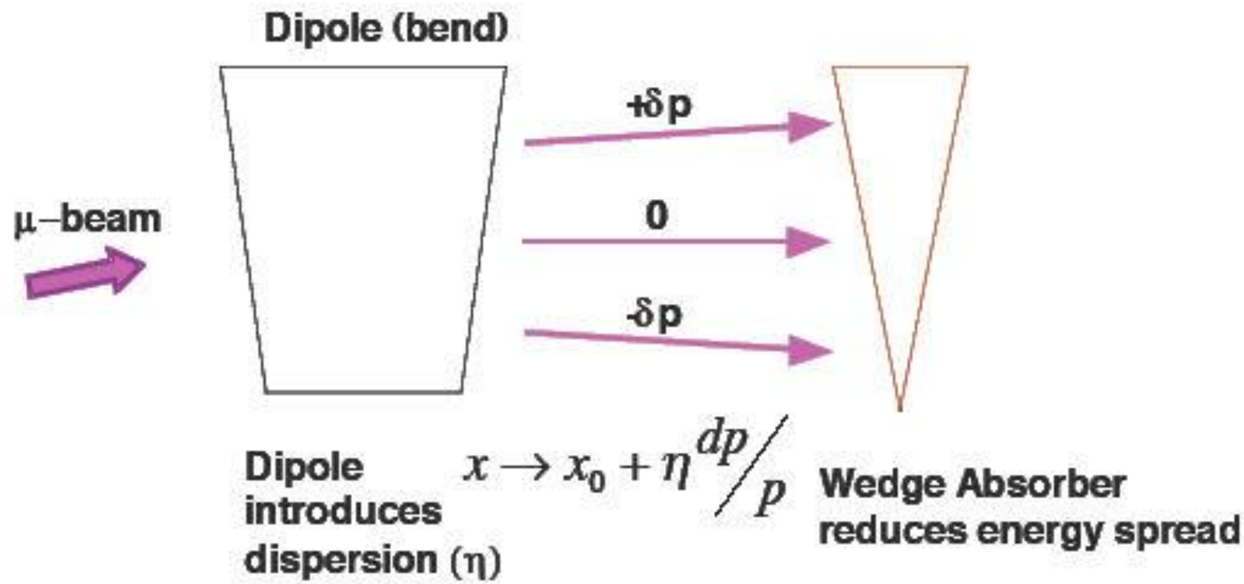


The jet explodes **after** the beam is generated
-> success

Longitudinal Cooling/Emittance Exchange

Used together with transverse cooling at the beginning

Several options under study



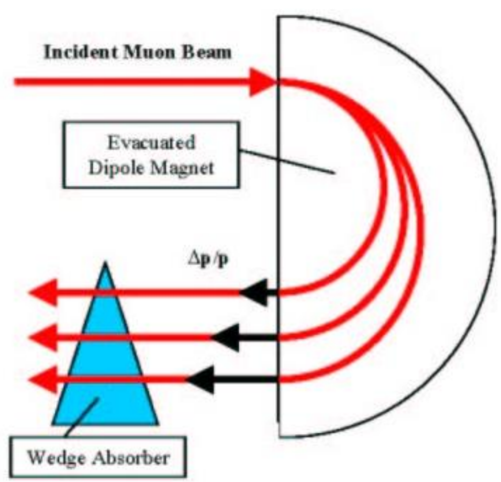


Figure 1. Use of a Wedge Absorber for Emittance Exchange

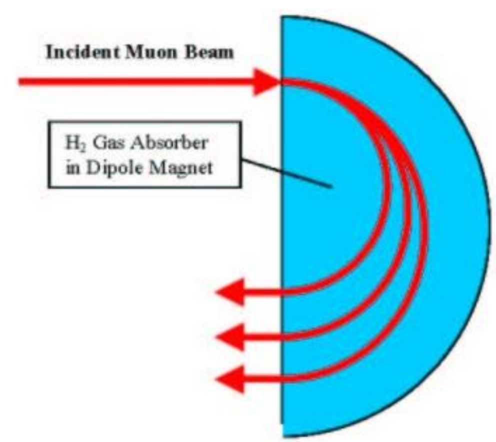
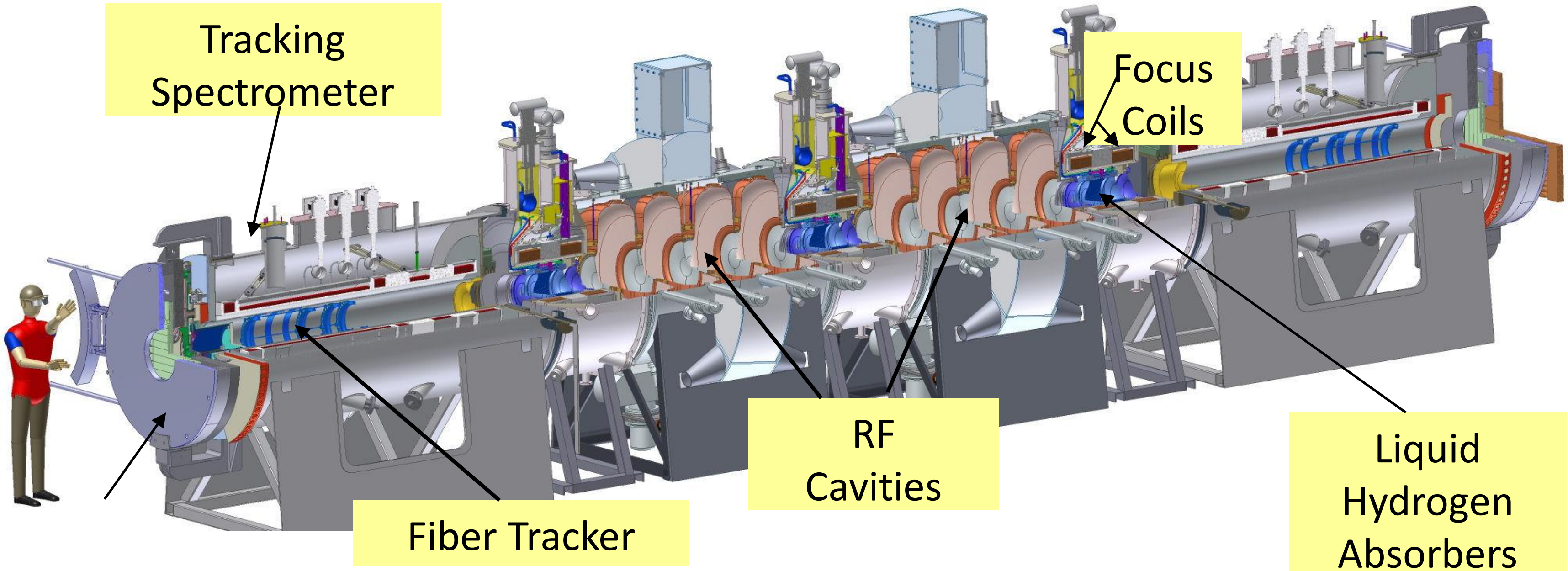


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

MICE



Under construction

Linda Coney, UCR

Will test 10% 4D emittance reduction (0.1% accuracy)

http://www.mice.iit.edu/

Single particle experiment

LHeC

road map to 10^{33} cm^{-2}s^{-1}

luminosity of LR collider:

(round beams)

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg}$$

highest proton beam brightness "permitted" (ultimate LHC values)

$\gamma\varepsilon$=3.75 μm

N_b=1.7x10^{11}

bunch spacing 25 or 50 ns

smallest conceivable proton β* function:

- **reduced *l** (23 m → 10 m)**
- **squeeze only one *p* beam**
- **new magnet technology *Nb_3Sn***

β*=0.1 m

average e$^-$ current !

maximize geometric overlap factor

- **head-on collision**
- **small e- emittance**

***θ_c*=0**

***H_{hg}*≥0.9**

ERL electrical site power

cryo power for two 10-GeV SC linacs: 28.9 MW

MV/m cavity gradient, 37 W/m heat at 1.8 K

700 "W per W" cryo efficiency

RF power to control microphonics: 22.2 MW

10 kW/m (eRHIC), 50% RF efficiency

RF for SR energy loss compensation: 24.1 MW

energy loss from SR 13.2 MW, 50% RF efficiency

cryo power for compensating RF: 2.1 MW

1.44 GeV linacs

microphonics control for compensating RF: 1.6 MW

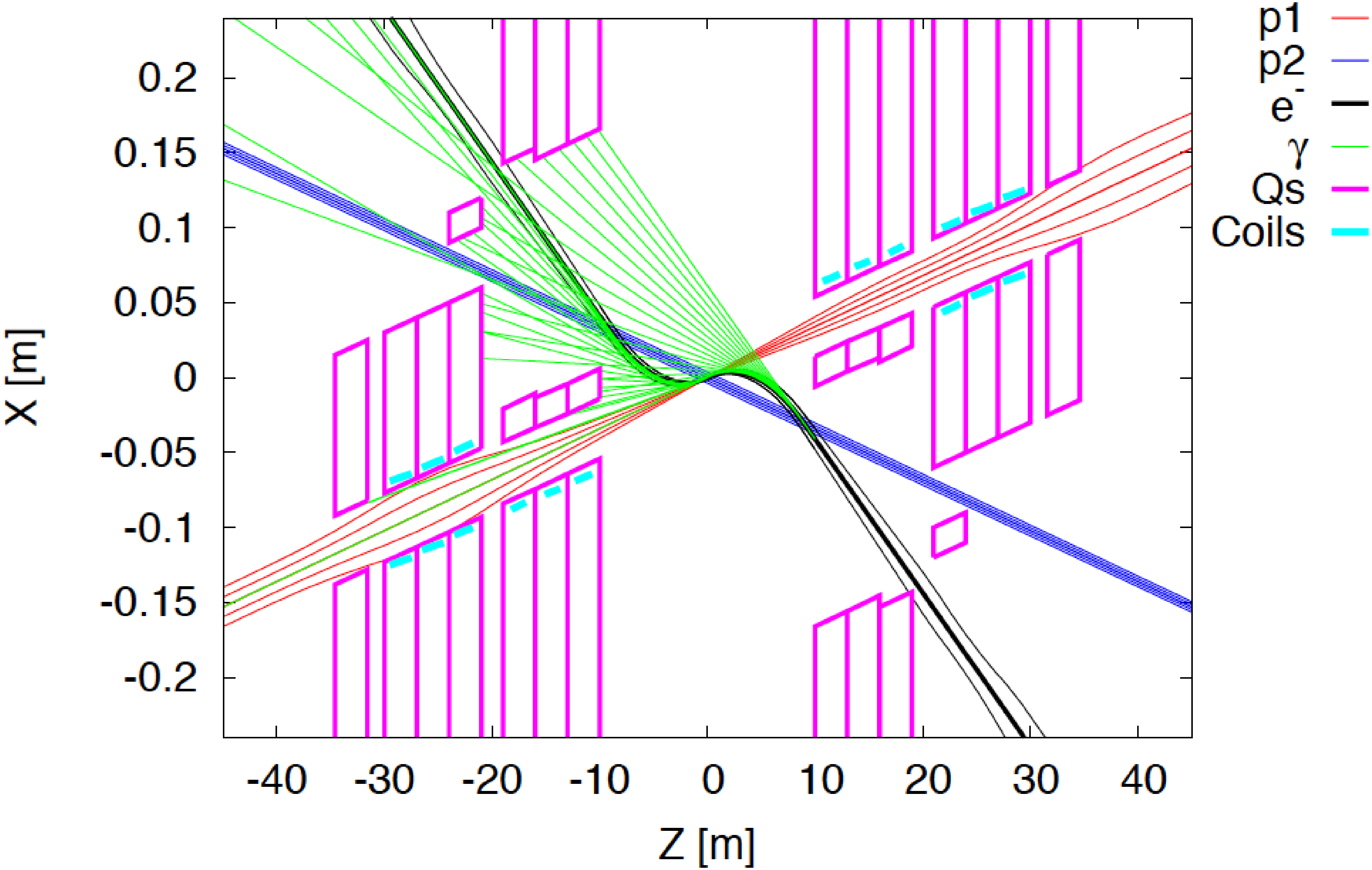
injector RF: 6.4 MW

500 MeV, 6.4 mA, 50% RF efficiency

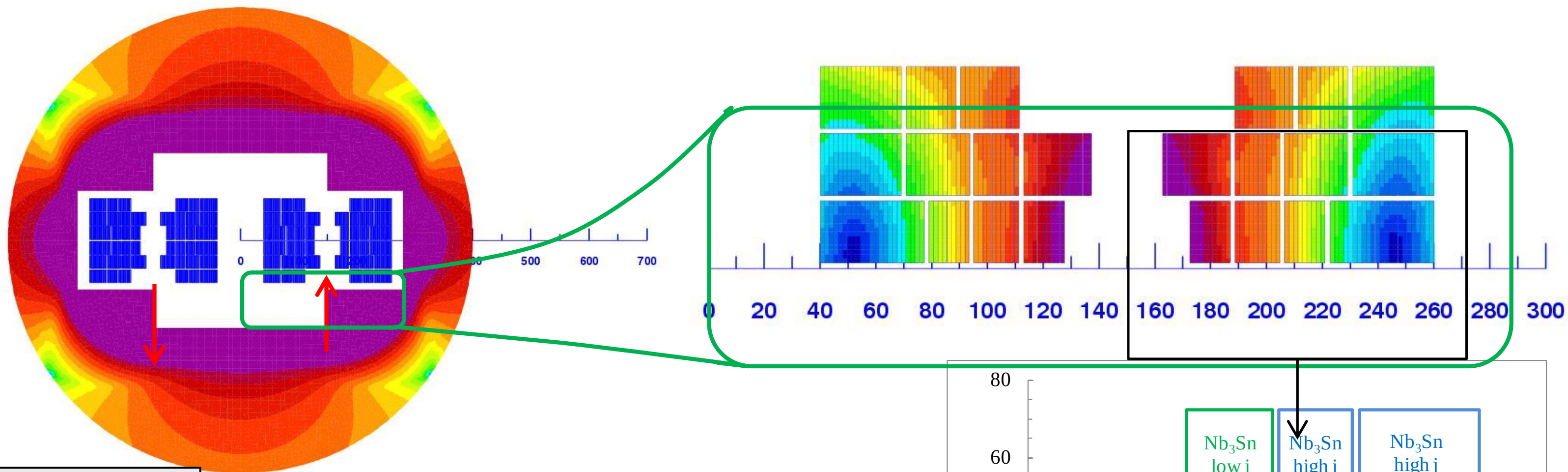
magnets: 3 MW

grand total = 88.3 MW

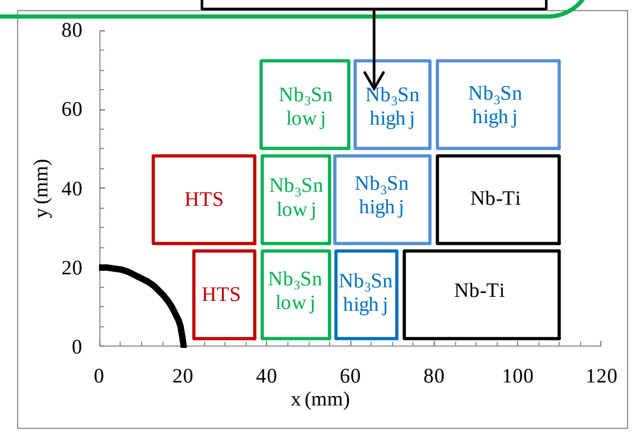
Interaction Region



Example Magnet Design



L. Rossi and E. Todesco

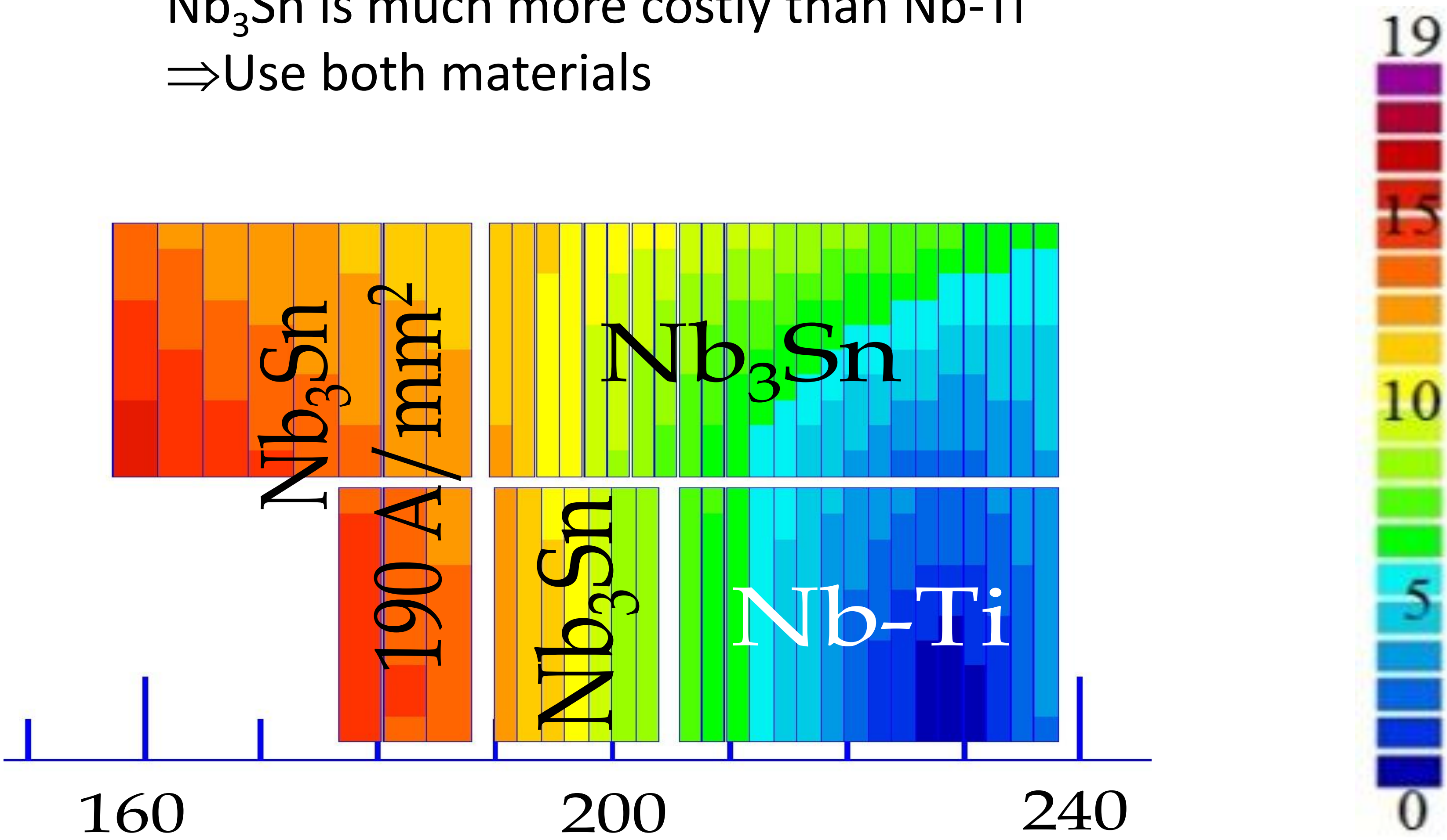


Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Very challenging but feasable: 300 mm inter-beam; **anticoils to reduce flux**
Approximately 2.5 times more SC than LHC: 3000 tonnes!
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Certainly only a first attempt: cosϑ and other shapes will be also investigated

Cost Effective Magnet Design

Nb_3Sn is much more costly than Nb-Ti
⇒Use both materials

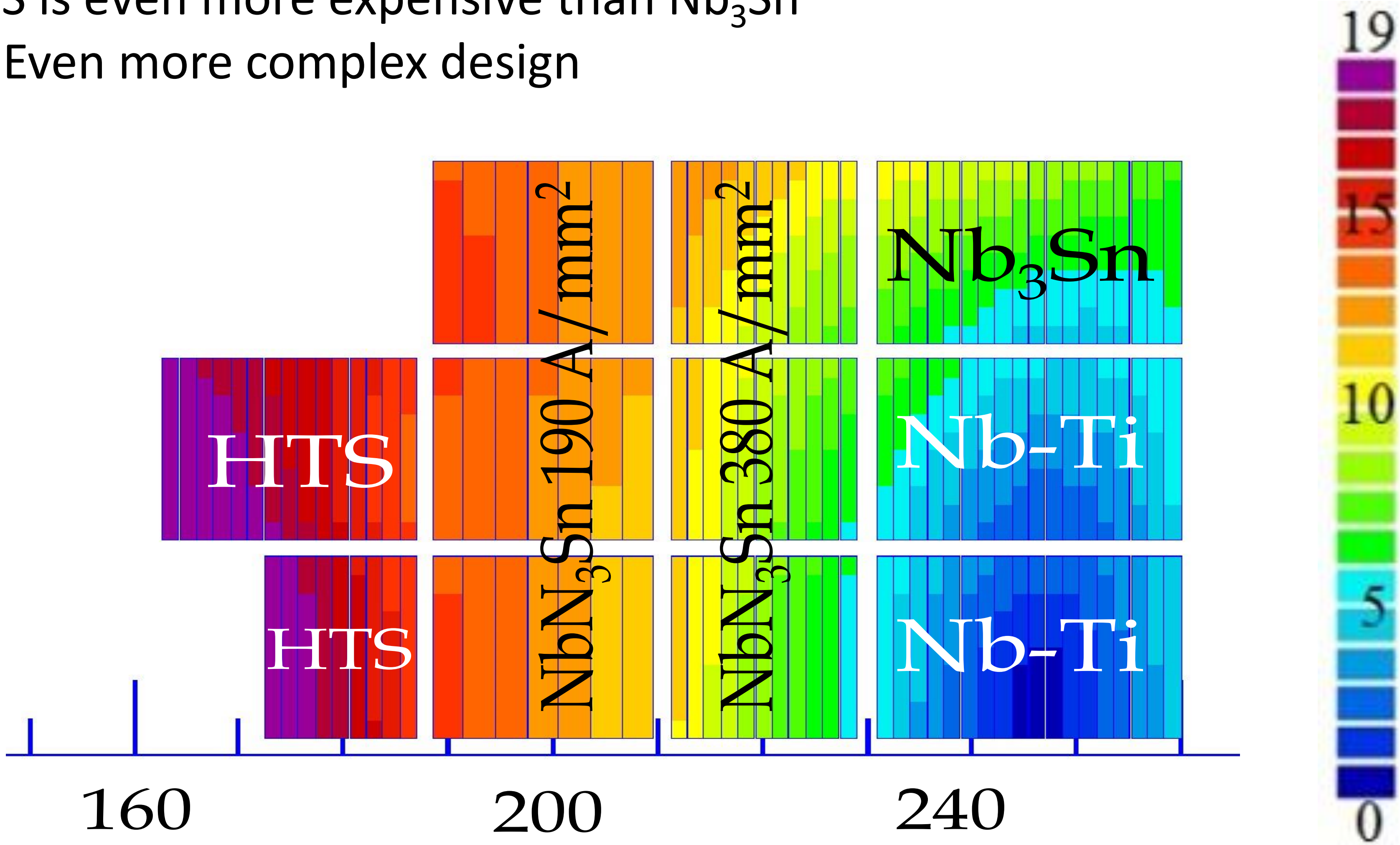


Coil sketch of a 15 T magnet with grading, E. Todesco

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 Intensity During Run

Non-linear fields
- Particles can go on unstable points in phase space
- Drift to large amplitudes

$\Rightarrow$ Reduce the probability

Collimation should remove these particles

Beam-gas scattering
- Showers into magnets are a problem

$\Rightarrow$ Very good vacuum

Collimation removes some of these particles
Magnets have to take the rest

Luminosity
- Particles are destroyed in collision

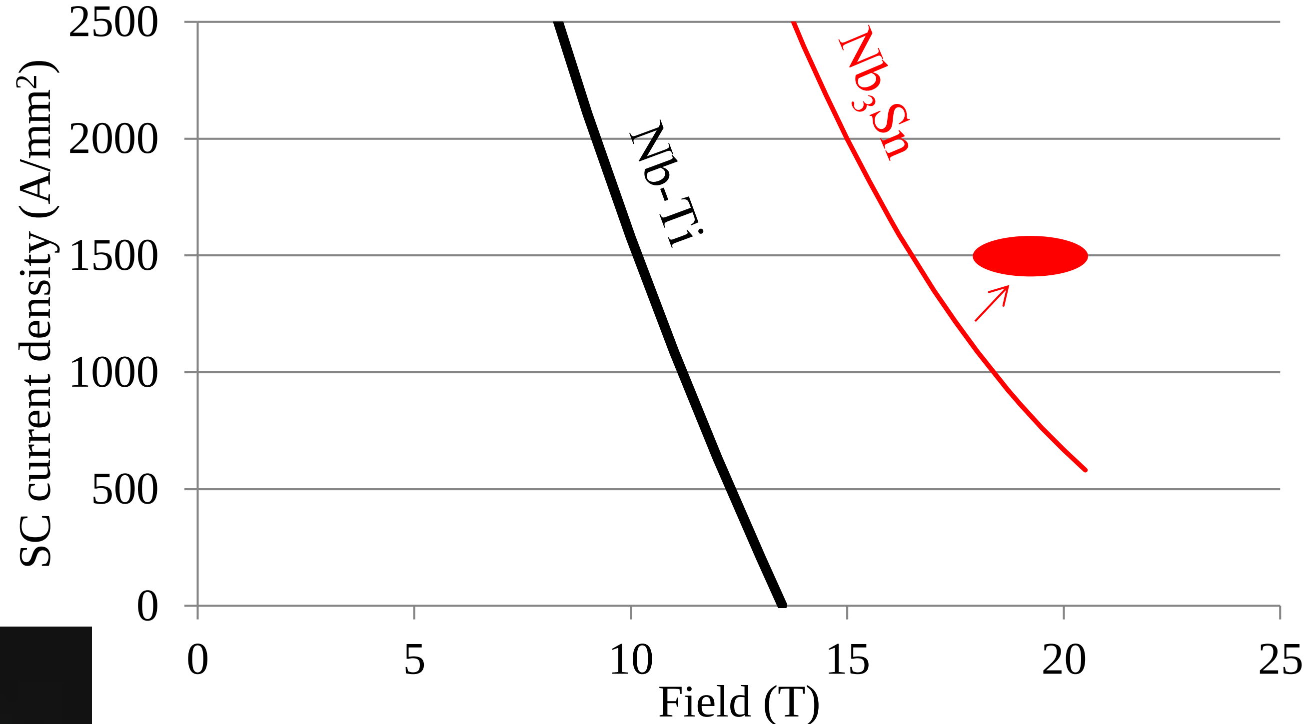
$\Rightarrow$ Proportional to luminosity

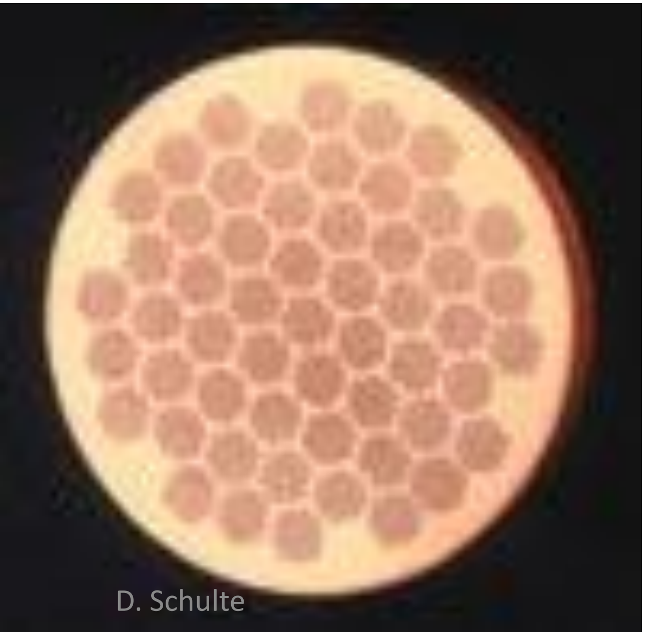
Main effect of intensity loss
100-500kW per experiment
Important shielding problem

Limits for the Field

The cable can quench (superconductivity breaks down)

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

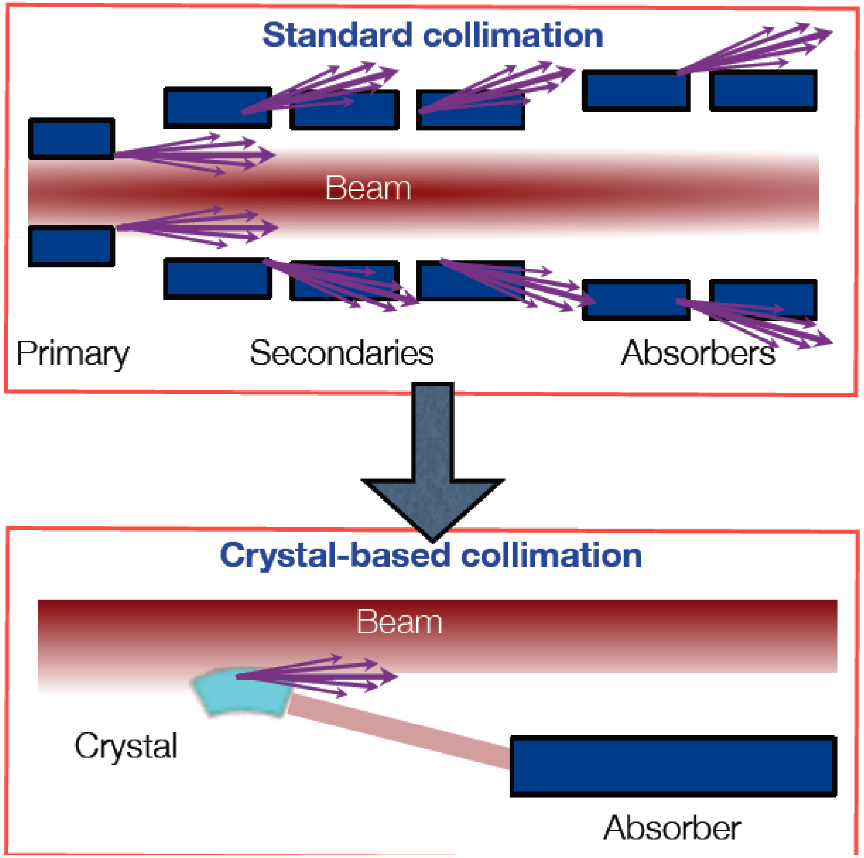




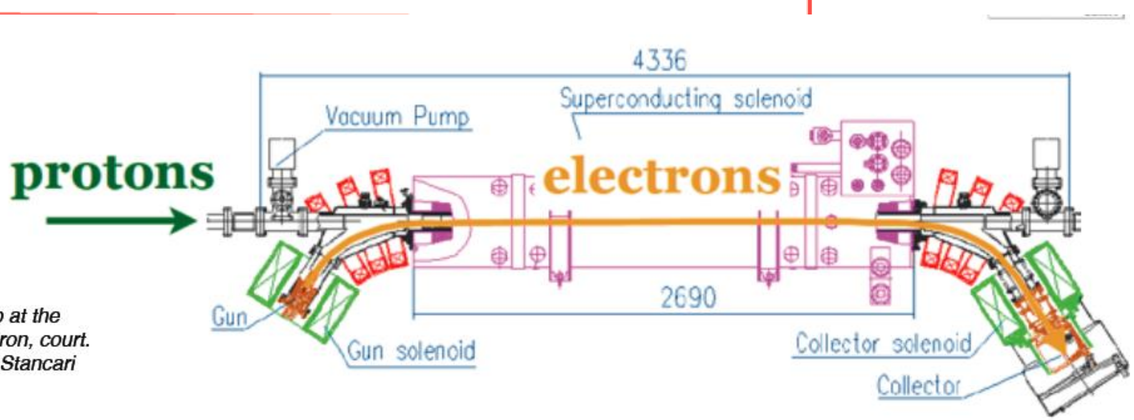
- This limits the achievable field
  - In theory
  - Even lower limit in practice

- Can use different materials
  - Nb-Ti is used for LHC
  - Nb_3Sn is used for high luminosity upgrade

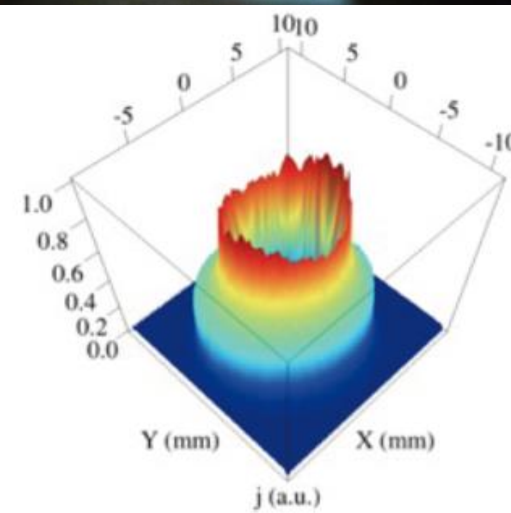
Collimation System Issues



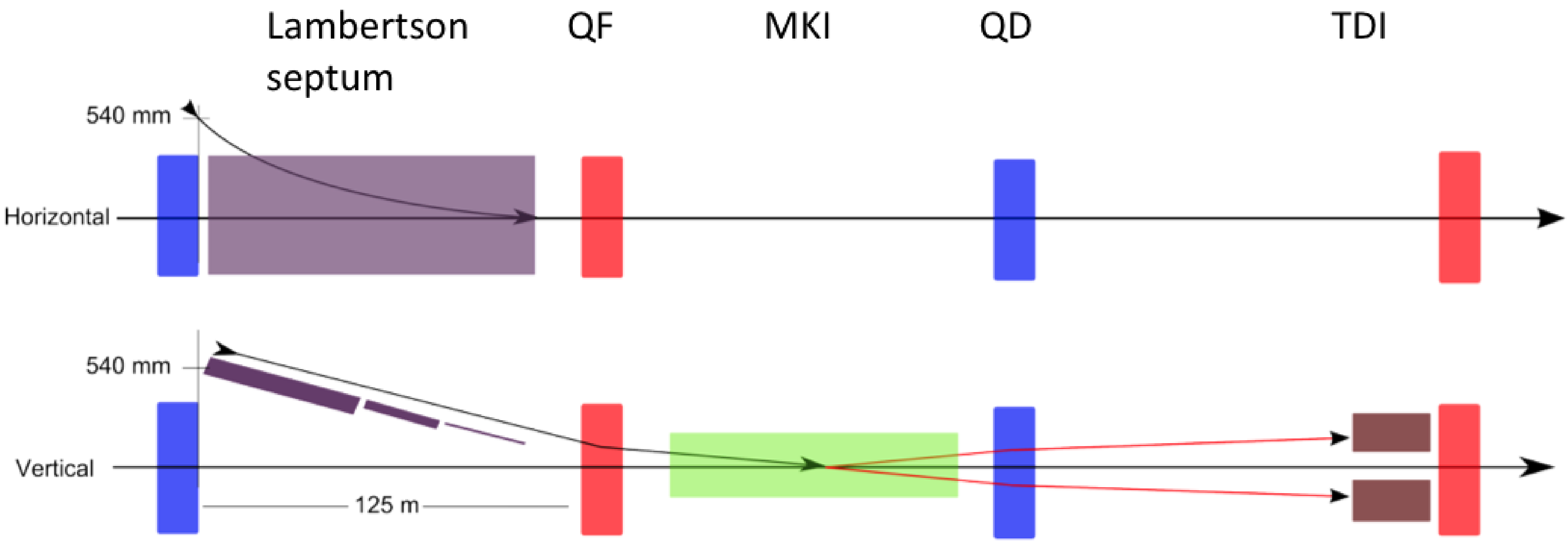
Other solutions are being investigated
- hollow beams
- crystals
- renewable collimators



Setup at the Tevatron, court. of G. Stancari



Injection/Extraction Challenge



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

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

$\Rightarrow$ Design improvements? Massless septum?

- Miss-firing of extraction kicker can lead to losses

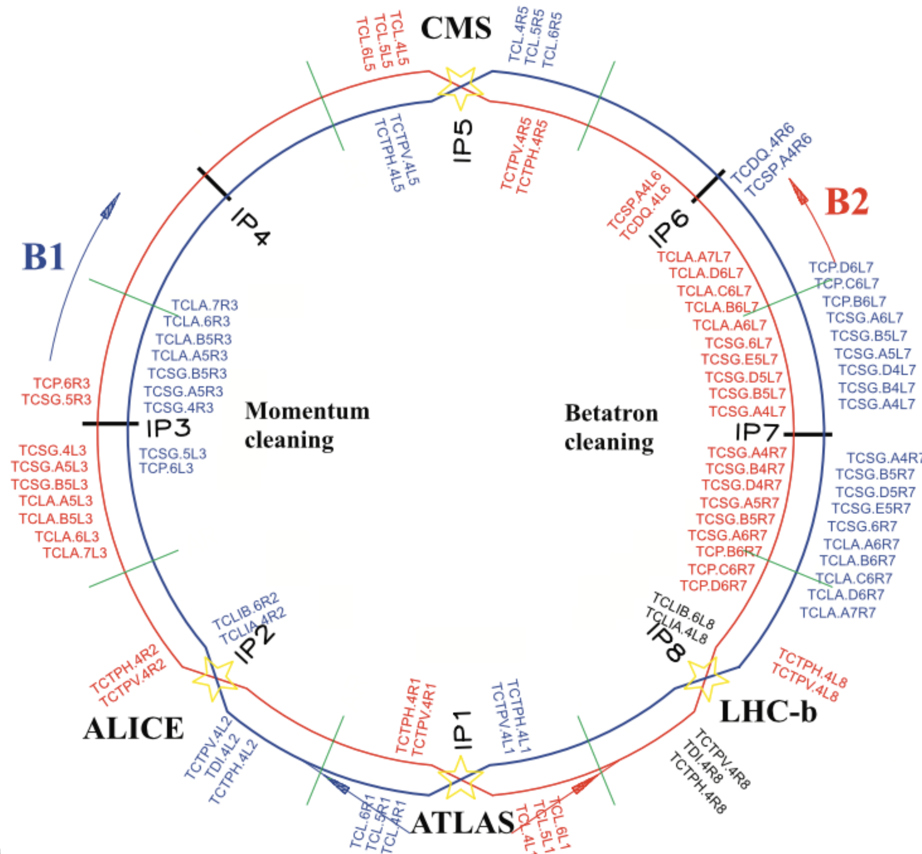
$\Rightarrow$ Which strategy?

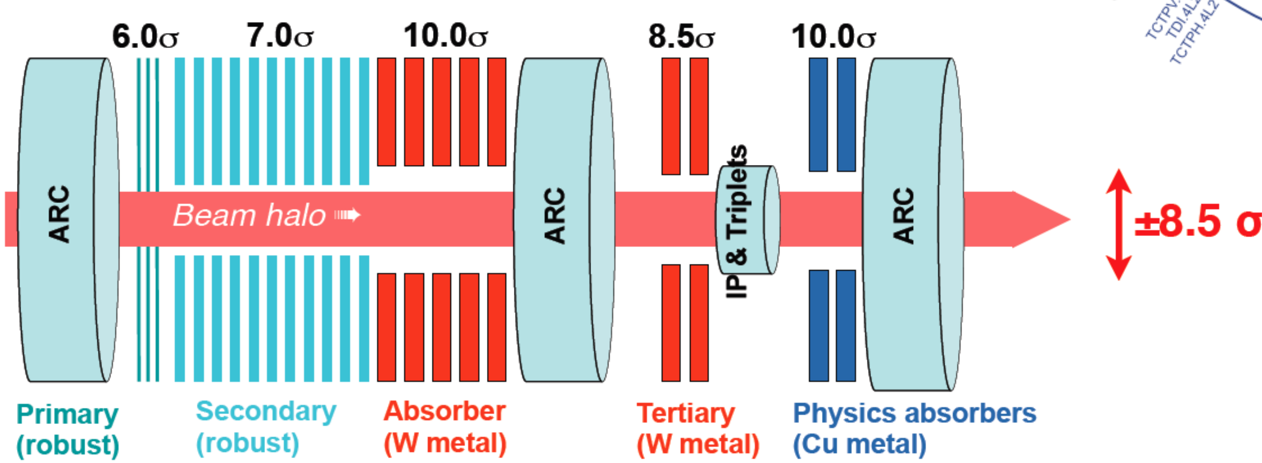
Collimation

Removes particles that enter the tails

First integrated aperture model based on

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





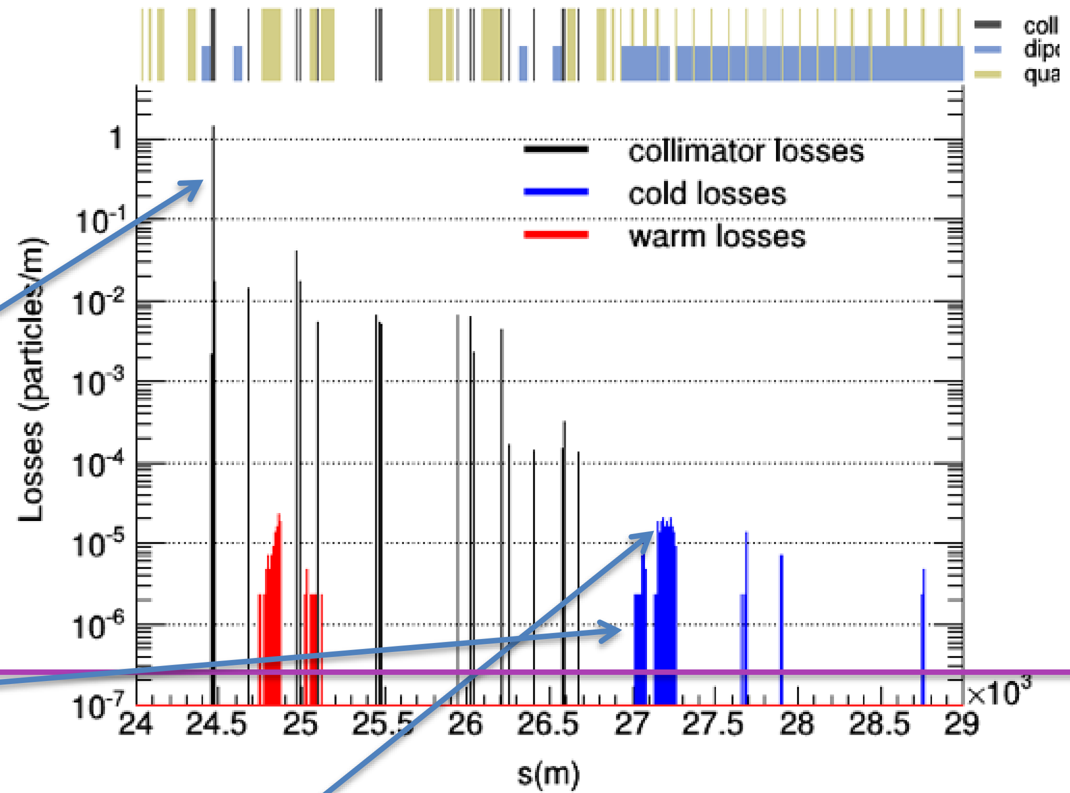
Example Collimation Issue

Collimation must protect machine if beam lifetime is short (12 minutes)
Otherwise would have to dump beam

Primary collimators

Losses in the next arc can quench superconducting dipole

Proton can lose energy in primary and will then be lost in arc
Goal: $<3\times10^{-7}\ m^{-1}$ in arc per collimated proton



No DIS collimation $2\times10^{-5}\ m^{-1}$
⇒ Loss rate about O(70) times too large
⇒ Have to place absorbers in DIS

Absorbers will generate showers
⇒ Have to study them
⇒ Design the system to safely protect magnets
⇒ Optics, absorber hardware, special magnets, …