Summary from Rome: FCC Week 2016 — Hadron Collider

Mike Syphers, NIU/Fermilab

APC Seminar *23 June 2016*

The Future Circular Collider Study

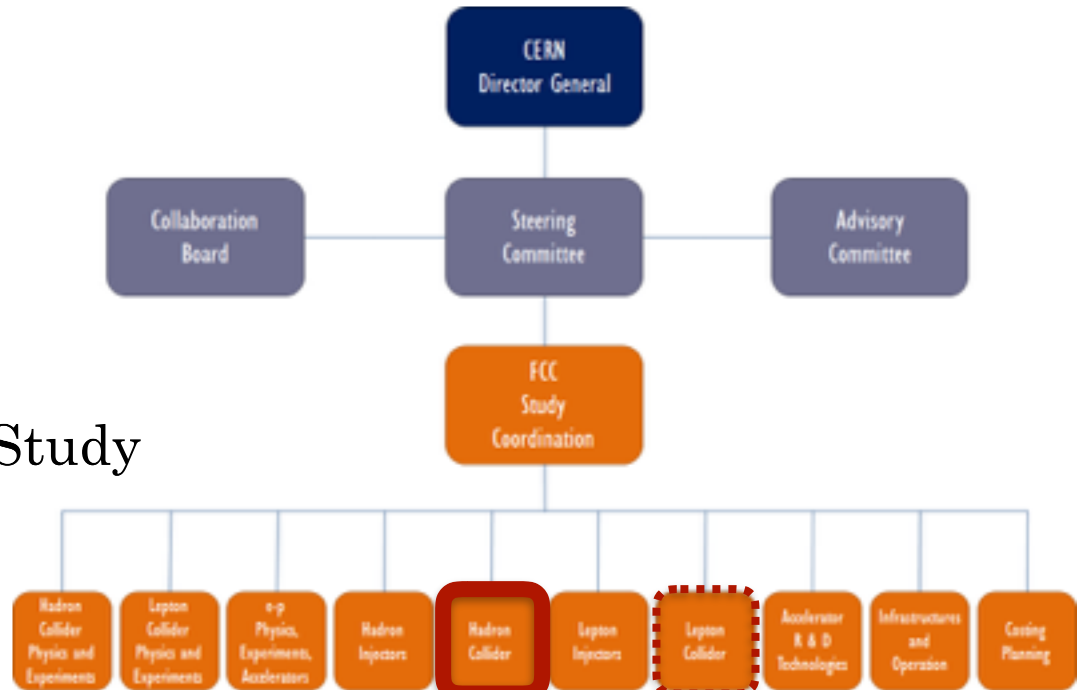
- On the heals of the LHC success, looking into the next steps toward higher-energy accelerators for fundamental physics research

View from France into Switzerland, showing existing LHC complex (orange) and a possible 100 TeV collider ring (yellow).

Photo courtesy J. Wenninger (CERN)

The Future Circular Collider Study
Collaboration and Organization

http://fcc.web.cern.ch



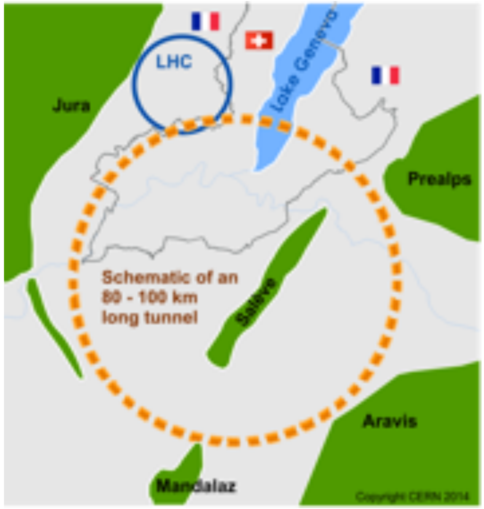
- Organization of the FCC Study
  - FCC-ee
  - FCC-hh **<— driver**
  - FCC-he

FCC-hh Design Issues

- magnets
- beam screen and vacuum
- luminosity evolution
- synchrotron radiation
- energy deposition
- general machine parameters

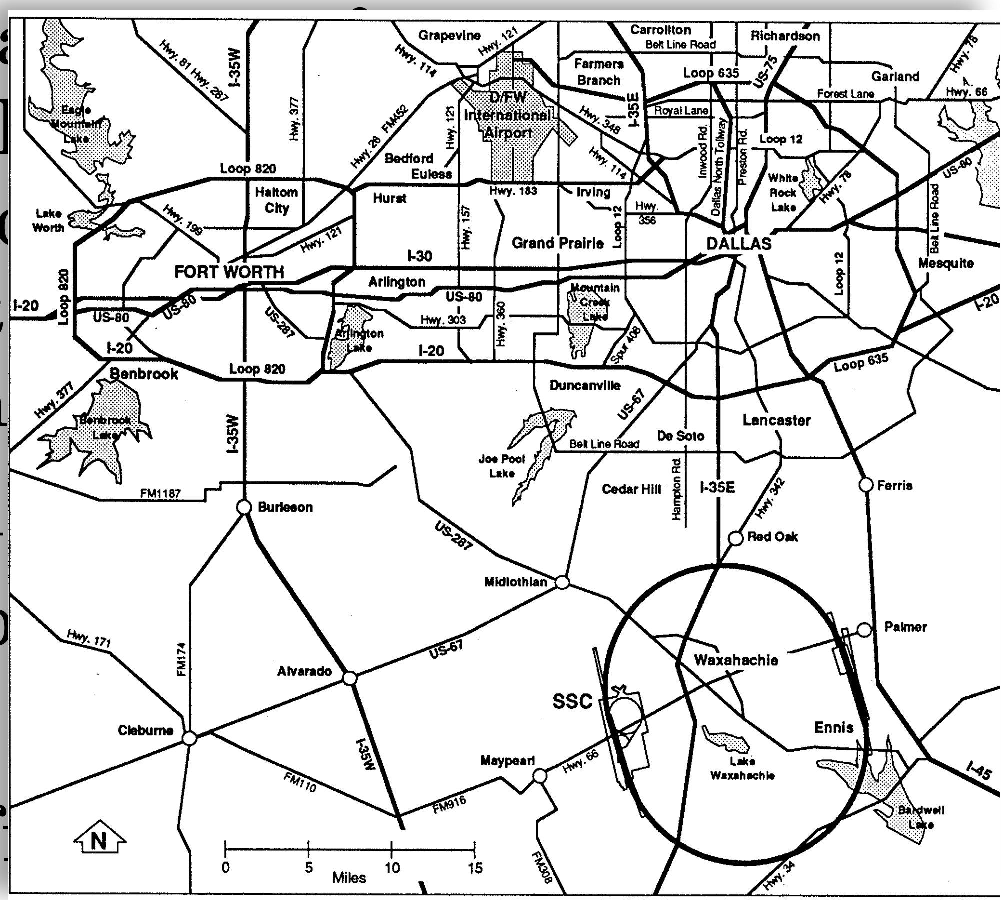
High-Level Parameters for FCC-hh Studies

- A wider range of parameters often occupies discussion, however to make progress present studies are being geared around a certain coherent set of geometrical and technical parameters:
  - Circumference = 100 km
  - Energy = 50 TeV per beam
  - Bend Field = 16 T
  - Geometry: "modified racetrack"



High-Level Parameters for FCC-hh Studies

- A wider range of para
  occupies discussion, l
  progress present stu
  geared around a cert
  geometrical and tech
  - Circumference = 1
  - Energy = 50 TeV p
  - Bend Field = 16 T
  - Geometry: "modif



High-Level Parameters Development

	LHC	HL-LHC	FCC-hh
CM energy [TeV]	14	14	100
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5
Bunch separation [ns]	25	25	25
Background events/bx	27	135	170
Bunch length [cm]	7.5	7.5	8

- Two main experiments sharing the beam-beam tune shift
- Two reserve experimental areas not contributing to tune shift
- 80% of circumference filled with bunches

In Round Numbers…

$(5\ 10^4)(0.005)$ / $[(1.5\ 10^{-16}\ \text{cm})(100\ \text{cm})(25\ 10^{-9}\ \text{s})]$ * 10^{11} * $(9/10)$

$\sim 5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

$$\xi = \frac{r_0 N}{4\epsilon_n}$$ *(beam-beam "tune shift" parameter)*

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma^2} \longrightarrow \frac{\gamma\xi}{r_0\beta^* t_b}\ N\ \mathcal{F}(\alpha)$$

$$\mathcal{F}(\alpha) \approx \frac{1}{\sqrt{1+(\alpha/2)^2(\sigma_s/\sigma_x)^2}}$$

- Adjustment of parameters, realistic bunch patterns, effects of synchrotron radiation damping, etc., come into play
- Can also, for example, adjust β^* or form factor with time to level out the instantaneous luminosity

Beam Parameters

$$\mathcal{L} \approx \frac{\gamma\xi}{r_0\beta^* t_b} N\, \mathcal{F}(\alpha)$$

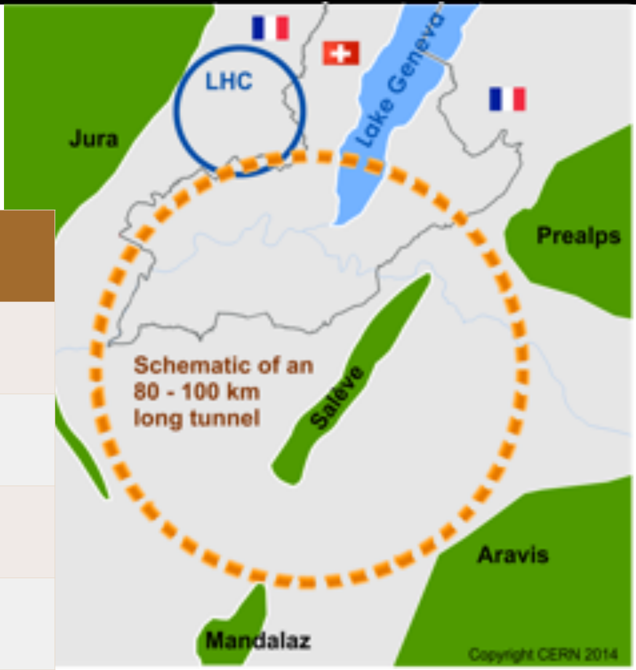
- Same values for 16 T and 20 T field
- Values in brackets for 5 ns spacing

	LHC	HL-LHC	FCC-hh
Bunch charge [10^{11}]	*1.15*	*2.2*	*1 (0.2)*
Norm. emitt. [μm]	*3.75*	*2.5*	*2.2 (0.44)*
IP beta-function [m]	*0.55*	*0.15*	*1.1*
IP beam size [μm]	*16.7*	*7.1*	*6.8 (3)*
RMS bunch length [cm]	*7.55*	*7.55*	*8*

- Assume beam-beam tune shift for two IPs: 0.01
- Here, beta-function at IP has been scaled with $E^{1/2}$ from existing LHC insertion design

FCC-hh "Baseline"

parameter	FCC-hh	LHC
energy	**100 TeV c.m.**	14 TeV c.m.
dipole field	**16 T**	8.33 T
# IP	2 main, +2	4
normalized emittance	2.2 μm	3.75 μm
bunch charge	10^{11} (2×10^{10})	1.15×10^{11}
luminosity/IP_{main}	**5×10^{34}** $cm^{-2}s^{-1}$	1×10^{34} $cm^{-2}s^{-1}$
energy/beam	**8.4 GJ**	0.39 GJ
synchr. rad.	**28.4 W/m/apert.**	0.17 W/m/apert.
bunch spacing	25 ns (5 ns)	25 ns

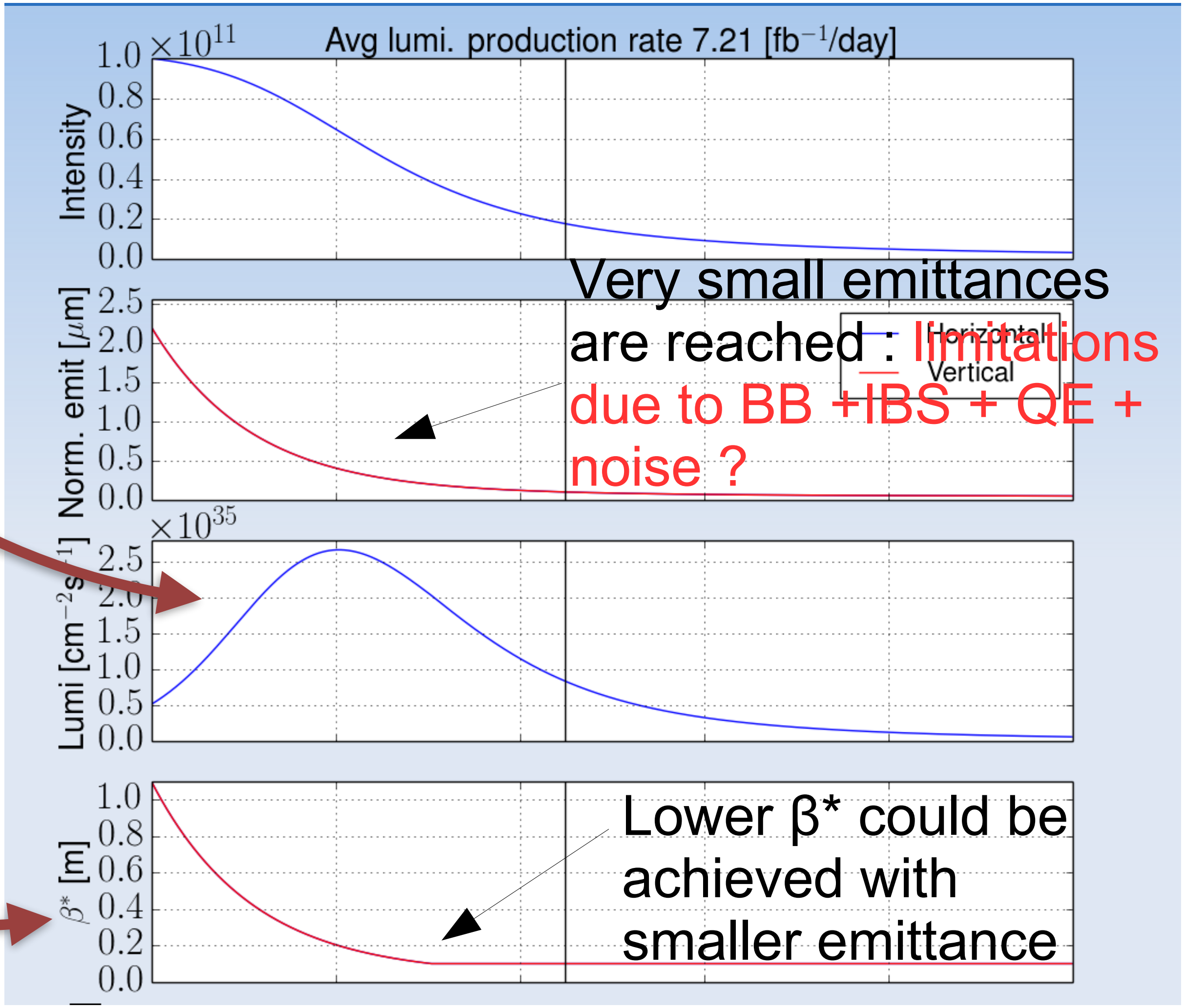


Preliminary; continues to evolve

Beam Parameter Evolution — an Example

luminosity rises, falls as in the SSC

actively vary the final focus optics to mitigate beam-beam interaction effects



X. Buffat

FCC Performance Parameters Assumptions

- $\beta^* = 1.1$ m
- beam-beam tune shift limit = 0.01 (for 2 experiments)
- Injected Beam parameters (see FCC Baseline Doc.)
  - focus has been on 25 ns spacing
- Peak Luminosity: 5×10^{34} cm^{-1}s^{-1} (= final LHC-HL)
- Averaged Luminosity: 2.5×10^{34} cm^{-1}s^{-1}
  - includes 5 h turnaround time
- Integral Luminosity: 250 fb^{-1}/year
  - ~125 days effective operation/year
- Total Integrated Luminosity: ~2500 fb^{-1} (10 years)

FCC Ultimate Performance Assumptions

- $\beta^* = 0.3$ m
- beam-beam tune shift limit = 0.03 (for 2 experiments)
- Injected Beam parameters (see FCC Baseline Doc.)
  - 25 ns and 5 ns spacing
- Peak Luminosity: $2.5\text{x}10^{35}$ $cm^{-1}s^{-1}$
- Averaged Luminosity: $1.1\text{x}10^{35}$ $cm^{-1}s^{-1}$
  - includes 4 h turnaround time
- Integral Luminosity: 1000 fb^{-1}/year
  - ~125 days effective operation/year
- Total Integrated Luminosity: ~15000 fb^{-1} (15 years)

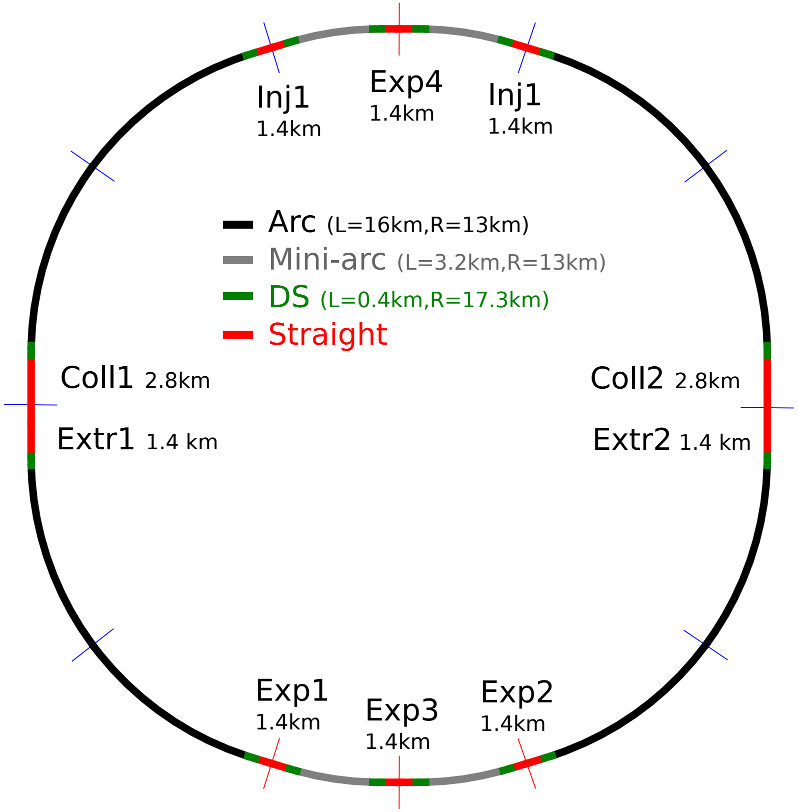
Availability Assumptions

- Three year operating cycles
  - Two years of operation
  - One year of shut-down
    - i.e., run 720 days in three years
- One quarter used for commissioning, Machine Development, …
- 540 days of scheduled luminosity operation
  - 70% of actual luminosity operation
- 378 days of effective operation
  - i.e. 126 per year = 1.08864×10^{7} s/year

- $L_0 = 5 \times 10^{34} cm^{-2} s^{-1}$, $\langle L \rangle / L_0 = 0.46$ leads to 250 fb^{-1} per year

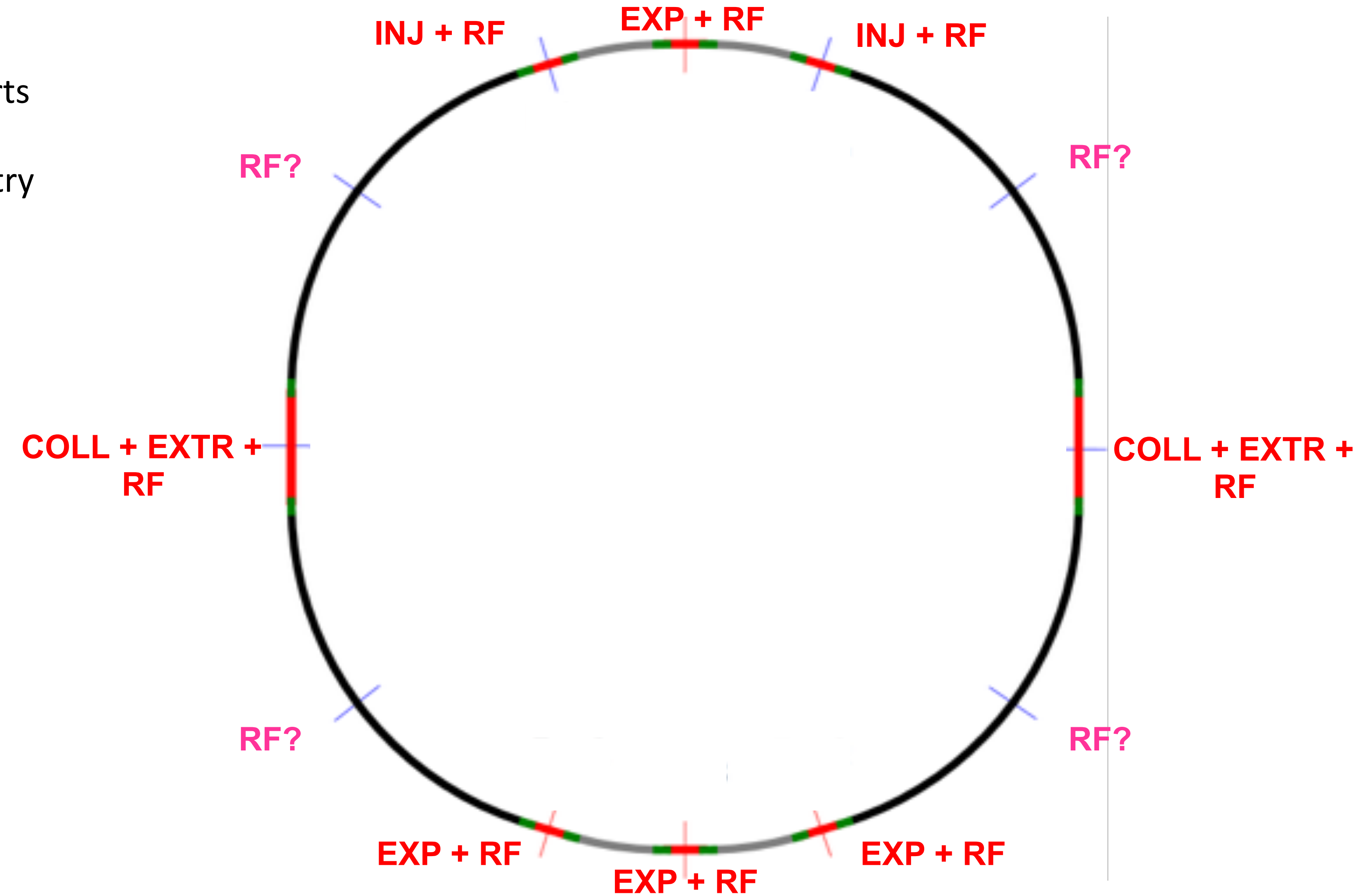
Preliminary Layout

- A first layout has been developed, to be a guide for…
  - Collider ring design (lattice/hardware)
  - Site studies (geology)
  - Injector studies
  - Machine detector interface
  - Overlap with lepton option
- Iterations will continue…



Layout of FCC-ee

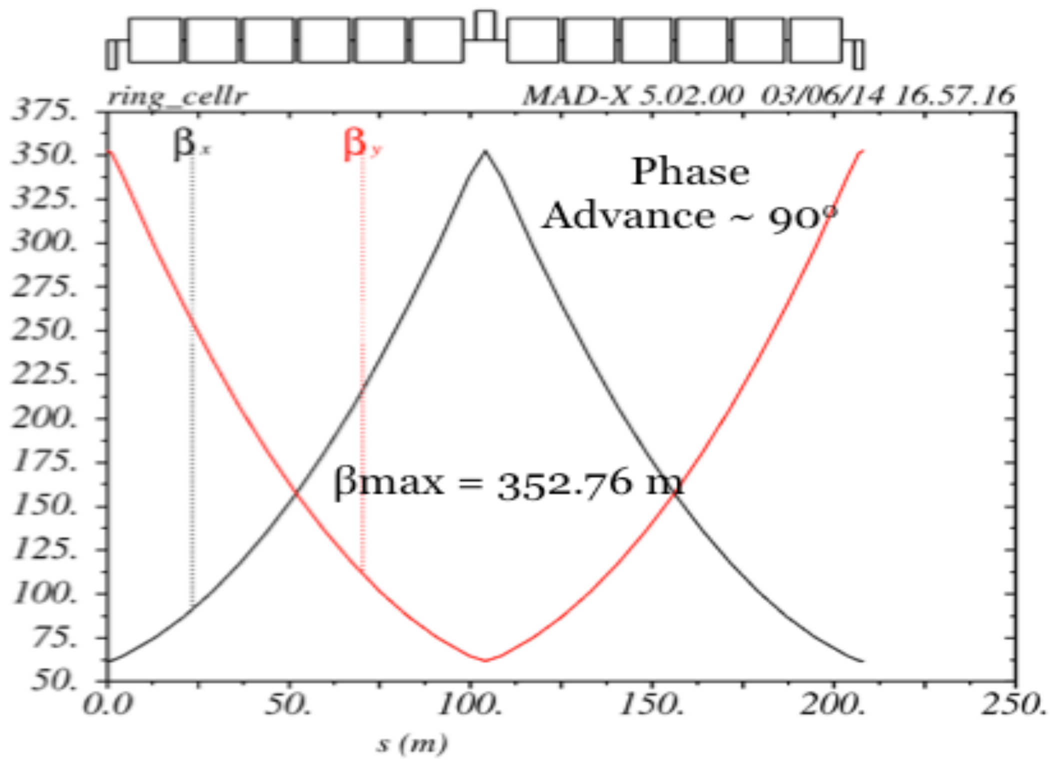
Both ee/hh efforts dealing with identical geometry



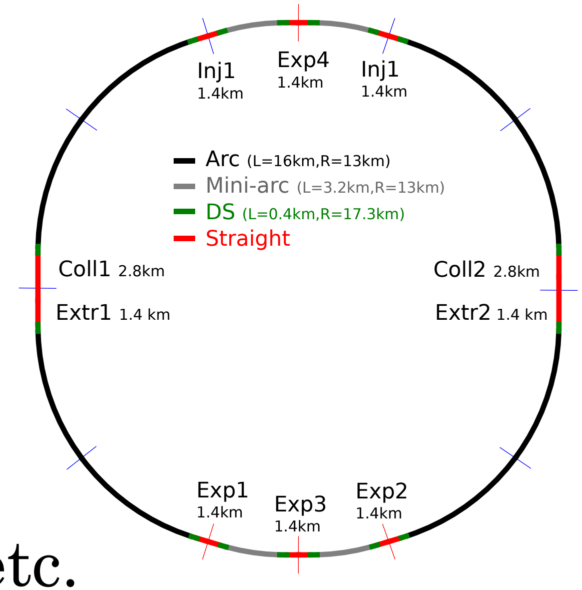
Example Arc Cell Layout for FCC-hh

- Long cells => good dipole filling factor
  - fewer and shorter quadrupoles
- Short cells => more stable beam
  - smaller beta-function
- Figure on Right: scaled from LHC
- For same technology as LHC, natural spacing would scale: 107 m spacing in LHC => ~300 m spacing for FCC
- For FCC magnet technology choose => 200 m
- Dipole length should be similar to LHC (truck transport)

example FCC basic cell



Straight Sections

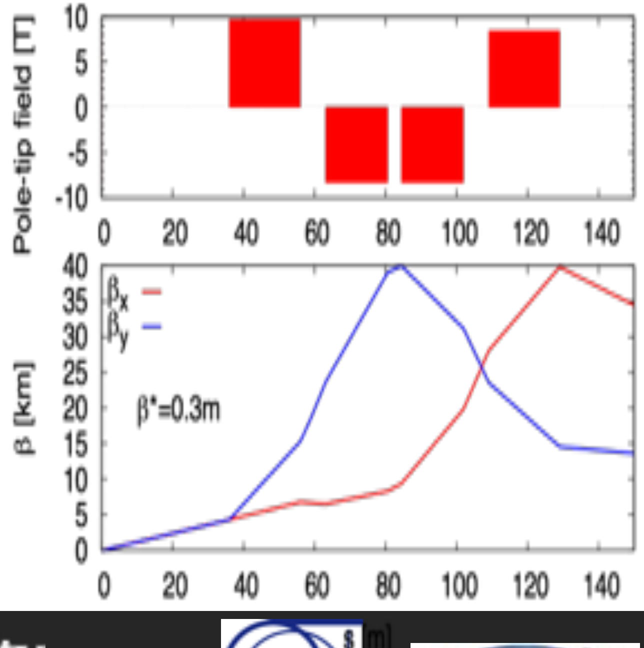


- Interaction Regions
- Injection / Extraction of beam
- RF accelerating stations
- Machine Protection
  - injection points, beam abort, IR, etc.
- Beam Collimation (magnet protection in arcs)
- Beam Cleaning (collimation outside of arcs)
  - cleaning of beam halo, both transverse/ longitudinal
- Shorter spaces: instrumentation, diagnostics, kickers, correctors, …

IR Layout and Optics

- L* options (present assumptions)
  - Short L* = 25 m; Long L* = 40 m
- Easier to obtain small beta-functions with shorter L*
  - tendency is to reduce L*

example (here, L* was 36 m)



- Many issues need to be addressed
  - Magnet performance
  - Radiation effects
  - Space constraints from experiments
  - Beam-beam effects and mitigation
  - …

Reminder: The SSC “Diamond Bypass”

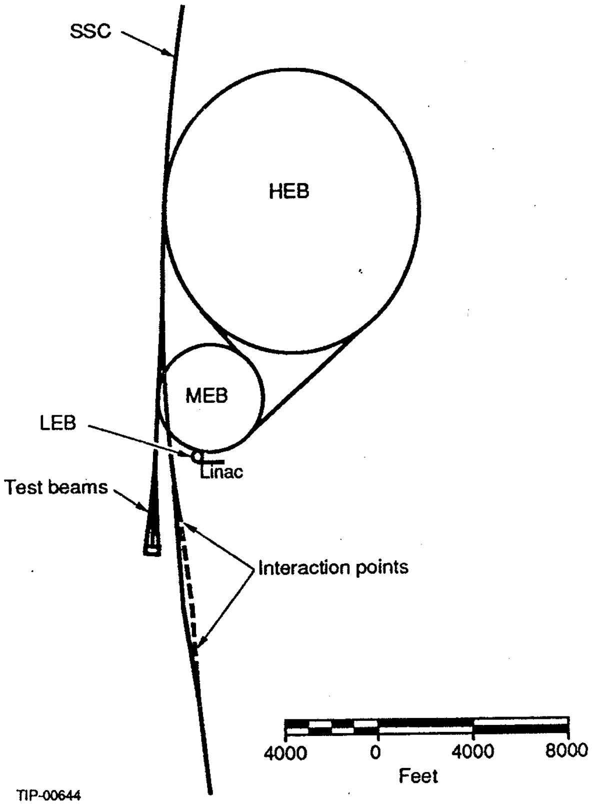


Figure 4.1.1.1-2. Layout of west campus region.

from SSC SCDR

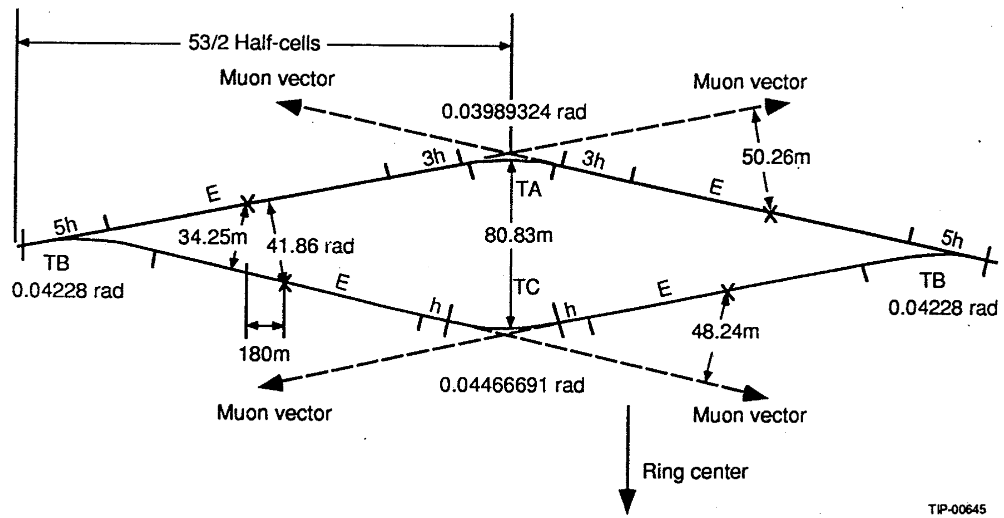


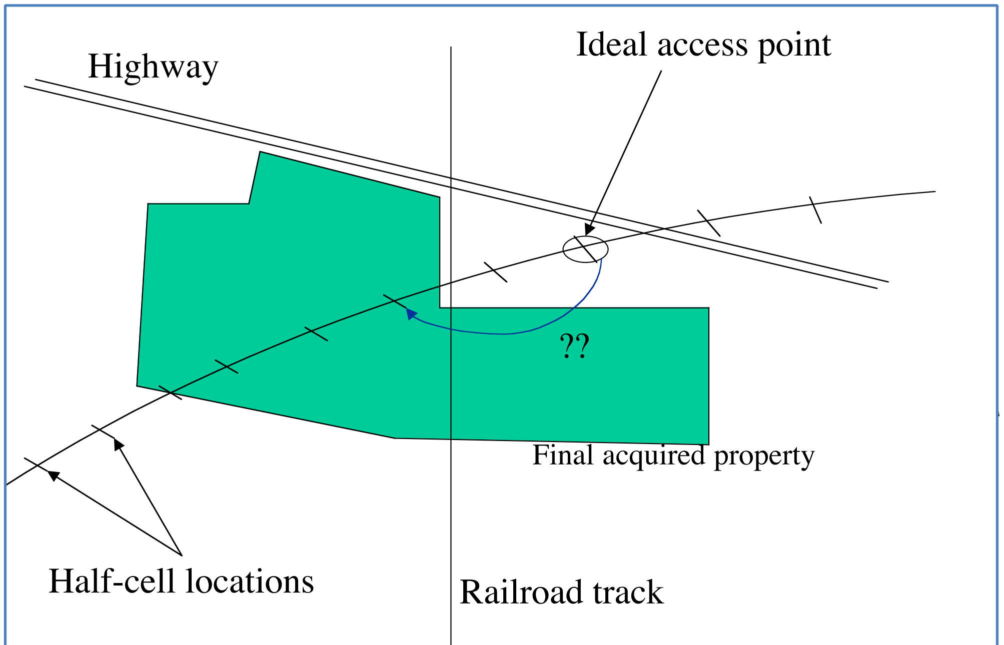
Figure 5.2.1 The diamond bypass arrangement. In the initial configuration, the outer legs (farther from ring center) will be instrumented.

Modularity and the Need for "Space"

The SSC "10F" Lattice

i.e., Version 10, sub-version F (1993)

modularity in the final layout



- "free space" created in arcs
  - "missing" dipoles in cells

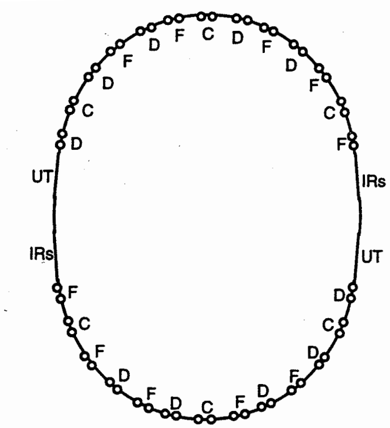
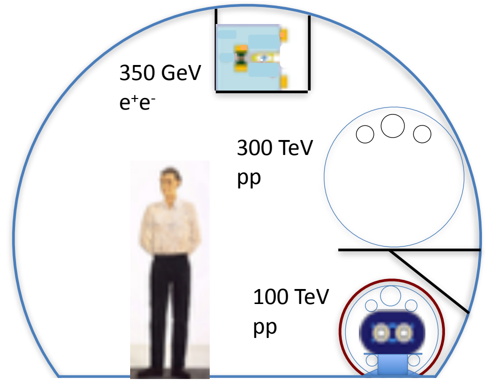


Figure 7-1. Schematic Layout of the Free Space in the Collider.

Lessons from SSC and VLHC 1

High Field *vs.* Low Field

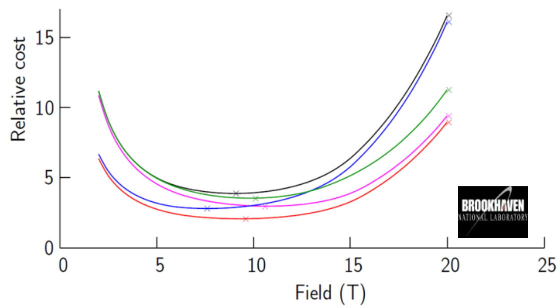
- Total costs of collider could be less, and leaves path for further upgrades



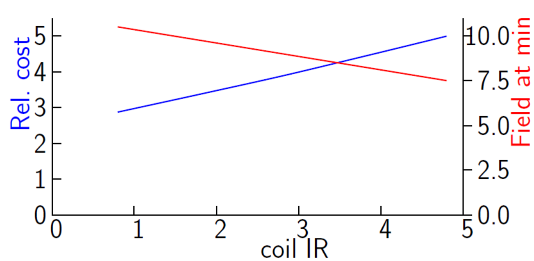
B. Palmer et al., "Accelerator Optimization issues of a 100 TeV collider", ARD panel meeting, BNL

Updating/refining VLHC models

Sensitivity to different assumptions



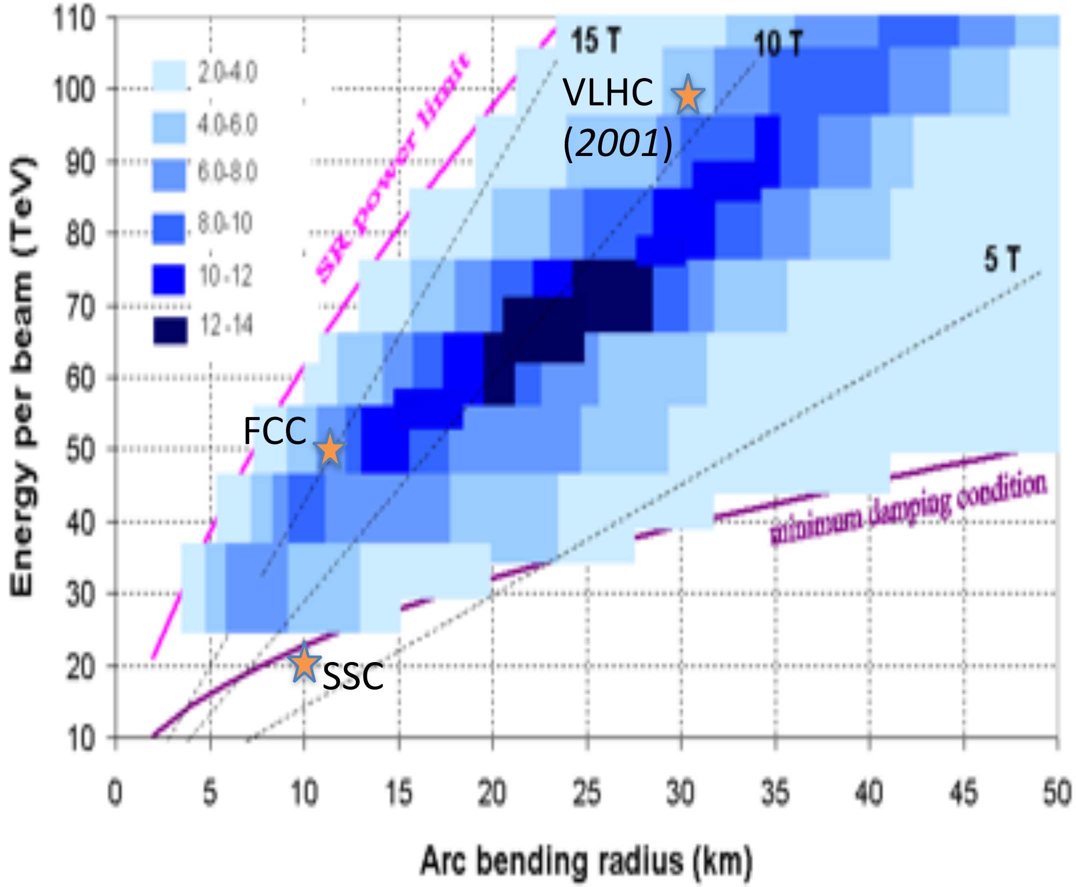
Dependence on aperture



P. McIntyre

VLHC Optimum Field (revisited)

P_{SR}<10 W/m/beam peak **$t_L > 2\ t_{sr}$** **Int/cross < 60** **L units 10^{34} $cm^{-2}s^{-1}$**



currently, radius of FCC is being constrained by CERN site and the Alps…

P. Bauer, *et al.*

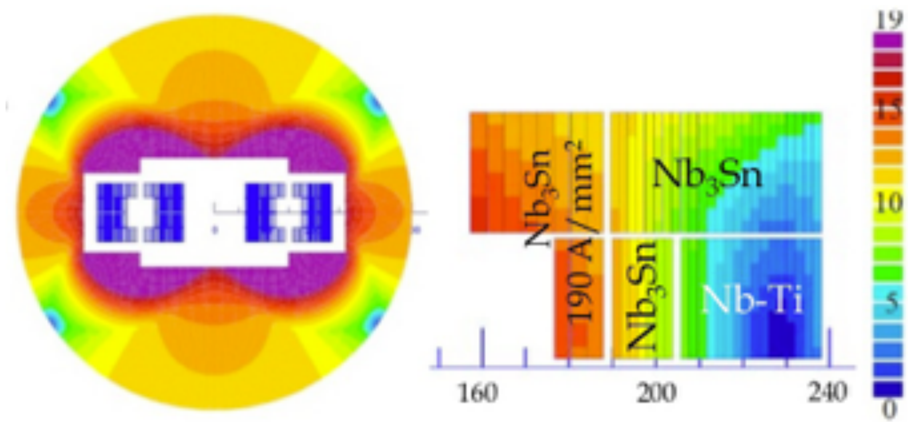
Technical Challenges for FCC

- Magnetic Field Strength!
- Optics and beam dynamics
  - IR design, dynamic aperture studies, SC magnet field quality, beam-beam, e-cloud, resistive wall, feedback systems design, luminosity levelling, emittance control, …
- High synchrotron radiation load on beam pipe
  - Up to 30 W/m/aperture in arcs, total of ~5 MW
- Machine protection, collimation, beam extraction/abort, etc.
  - > 8 GJ stored in each beam (24x LHC at 14 TeV)
  - Collimation against background and arc magnet quench
  - 100kW of hadrons produced in each IP
  - Stored energy in magnets will be huge (O(180GJ))
- Injection system

FCC Magnets

- Arc dipoles are the main cost and parameter driver
  - Baseline is Nb_3Sn at 16 T
  - HTS at 20 T also to be studied as alternative
- Field level is a challenge but many additional questions:
  - Aperture
  - Field quality

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

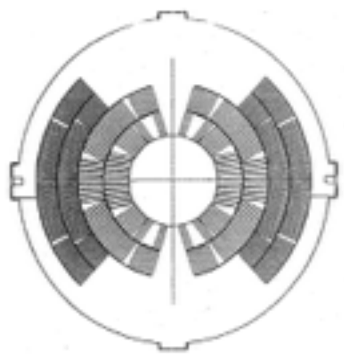


- Different design choices (e.g. slanted solenoids) should be explored
- Goal is to develop prototypes in all regions; US has world-leading expertise

State of the Art

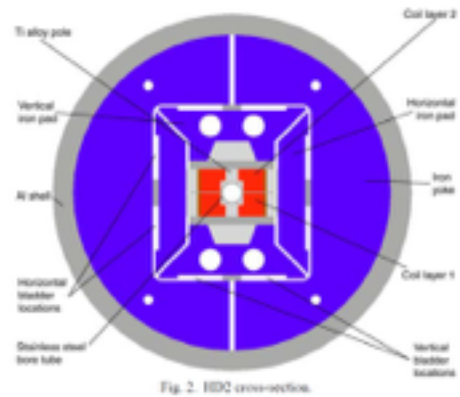
Courtesy Daniel Schoerling (CERN)

Cos-θ (D20, achieved bore field 13.5 T at 1.9 K)



D. Dell'Orco et al., IEEE Trans. Appl. Supercond., Vol. 3, No.1, 1993

Block (HD2c, achieved bore field 13.8 T at 4.3 K)



P. Ferracin et al., IEEE Trans. Appl. Supercond., Vol. 19, No.3, 2009

Common coil (Rd3d, achieved bore field ~11 T)

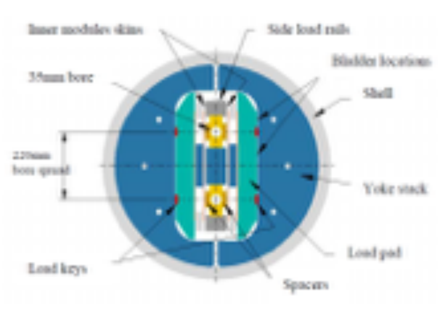
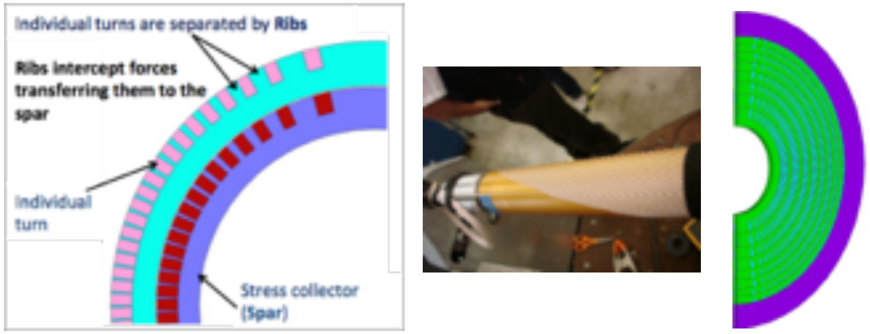


Figure 1: The magnet cross-section for RD3c.

A.F. Lietzke, IEEE Trans. Appl. Supercond., Vol. 13, No.2, 2003

Canted-Cos- θ (concepts)

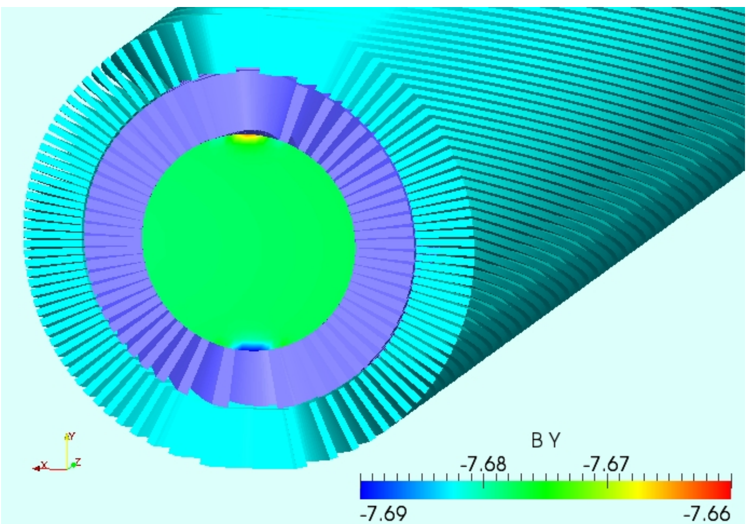


S. Caspi, FCC kick-off meeting, SC Magnet Development Toward 16 T Nb3Sn Dipoles

L. Brouwer, IEEE Trans. Appl. Supercond., Vol. 25, No. 3, 2015

Toward Higher-Field Magnets

- Recent renewed interested in an older magnet concept



Nucl. Instr. & Meth., **80**, pp. 339-341, 1970

A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

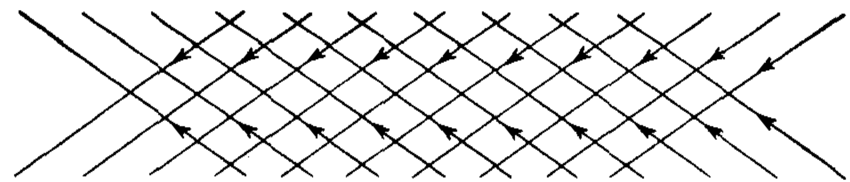


Fig. 2. Two superimposed coils with opposite skew.

Stabilization of high pressures between conductors generated by the magnetic field

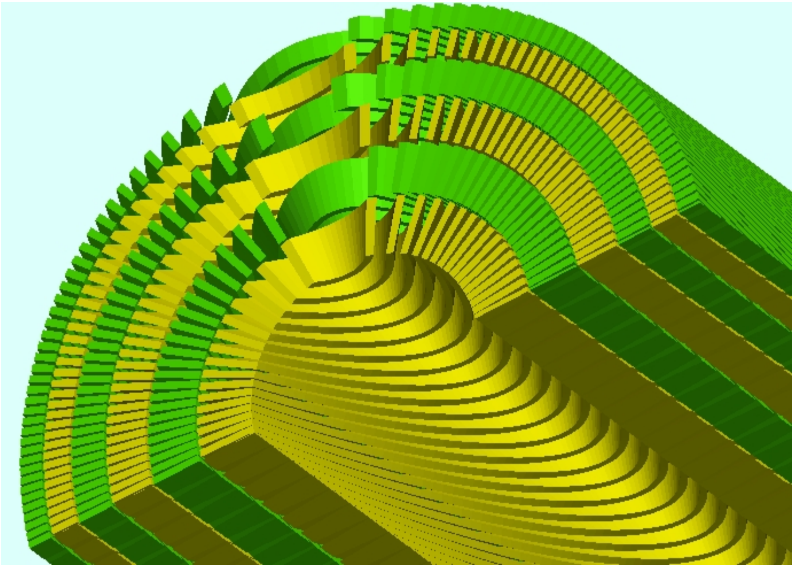
$$P = B^2/2\mu_0$$

1 T	*4 Atm*
5 T	*100 Atm*
10 T	*400 Atm*
20 T	*1600 Atm*

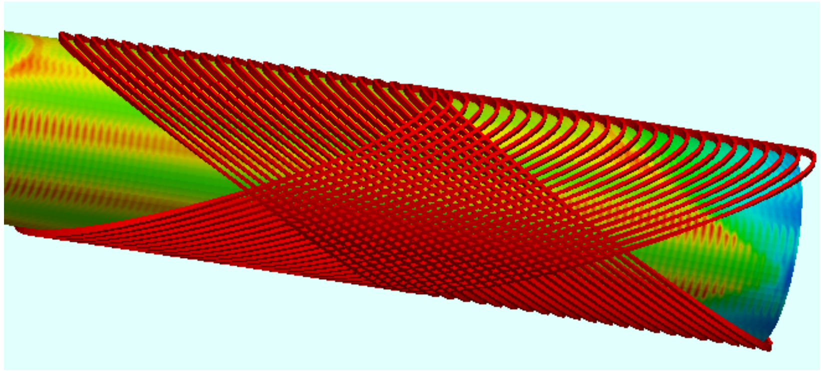
Canted Cosine-Theta Magnet

- LBNL Superconducting Magnet Program

Example – 6 layers 18T dipole, 56mm bore



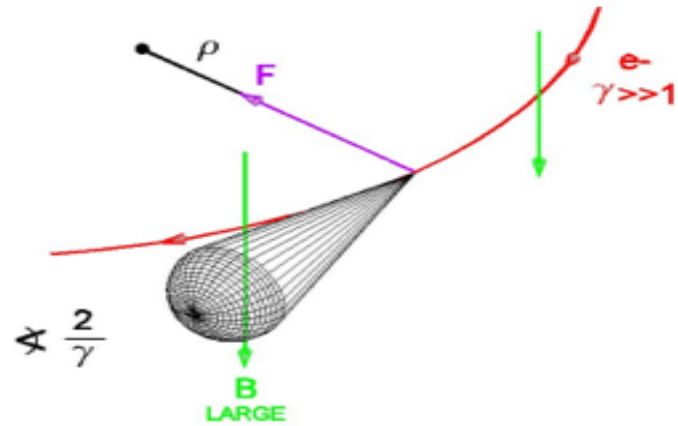
So far only calculations and small-scale models; compact, high-quality high fields appear feasible

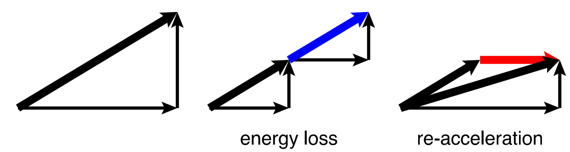


LBNL, ATAP Division, SC Magnet Program

Synchrotron Radiation

- At 50 TeV even protons radiate significantly
- Total radiated power of 5 MW
  - LHC is 7 kW
- Needs to be cooled away
- Equivalent to 30 W/m /beam in the arcs
  - LHC < 0.2 W/m, total heat load of magnet system is ~1W/m
- Critical photon energy 4.3 keV
  - electron emission from pipe





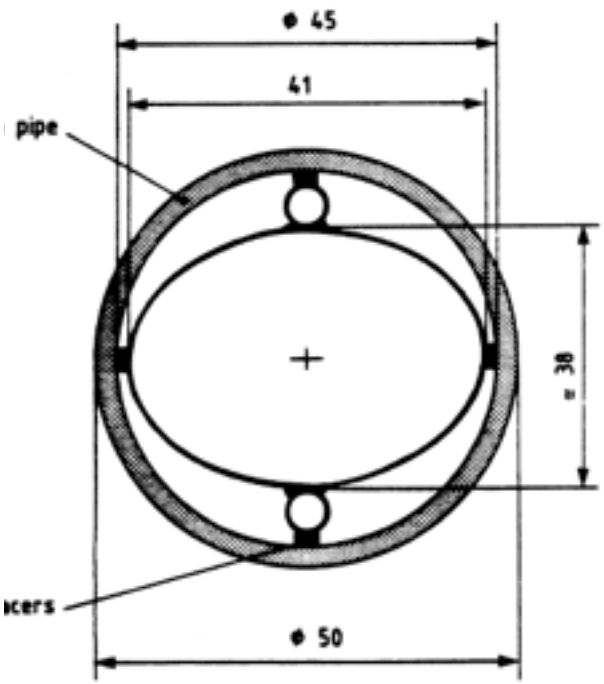
Protons loose energy
⇒ They are damped
⇒ Emittance improves with time

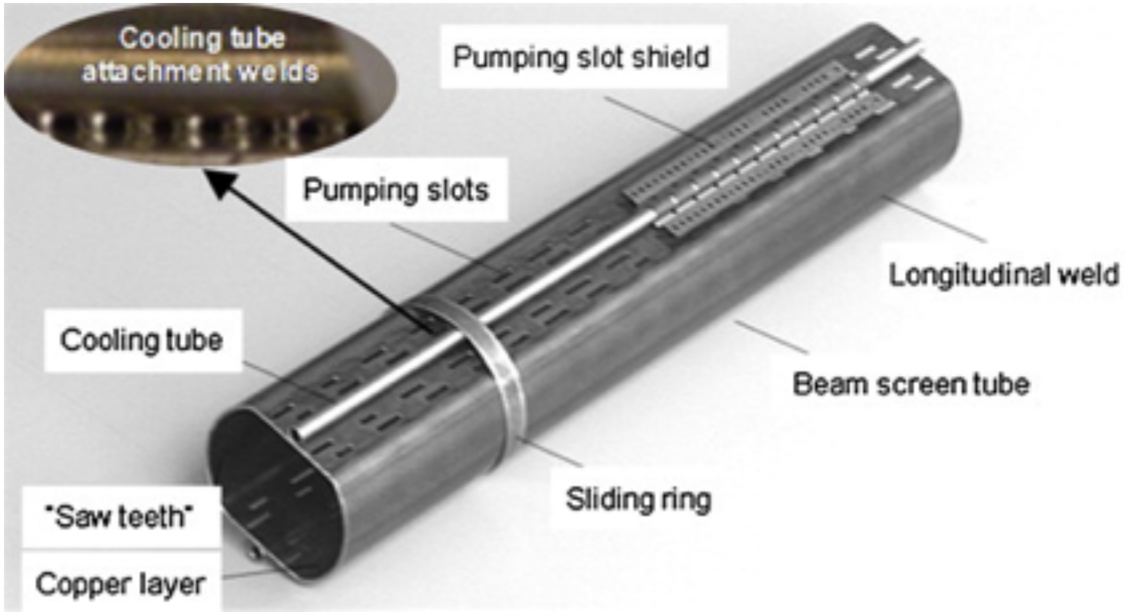
Typical transverse damping time:
~ 1 hour

Vacuum Issues

- Will mainly come from extremely large SR power load and photon flux: comparable to that of a modern SR light source!
- Vacuum: Outgassing and e-cloud are proportional (to some extent) to the photon flux
- Cryogenics: Load is proportional to SR Power/m
  - and, via e-cloud, to the photon flux.
  - vacuum chamber/beam screen (BS) geometry may add a resistive impedance contribution

LHC Beam Pipe Design



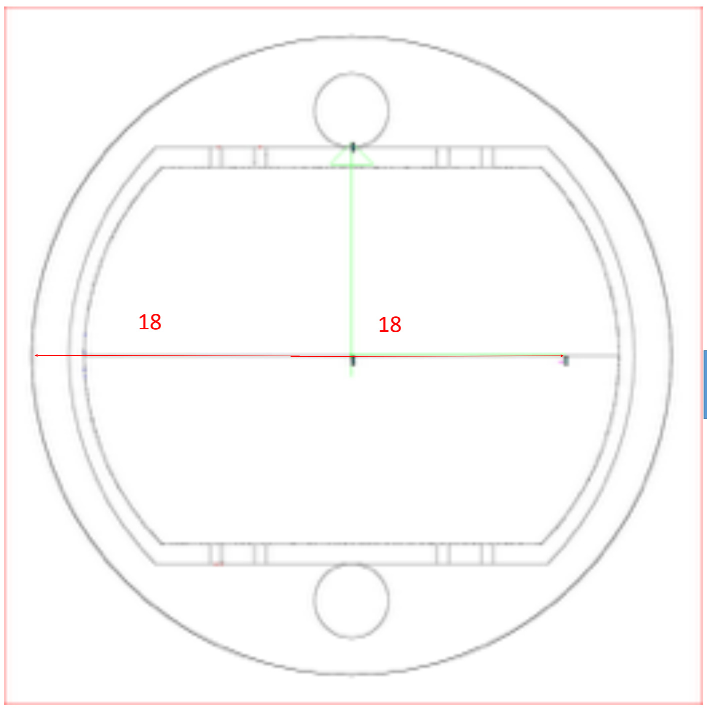


Vacuum Issues

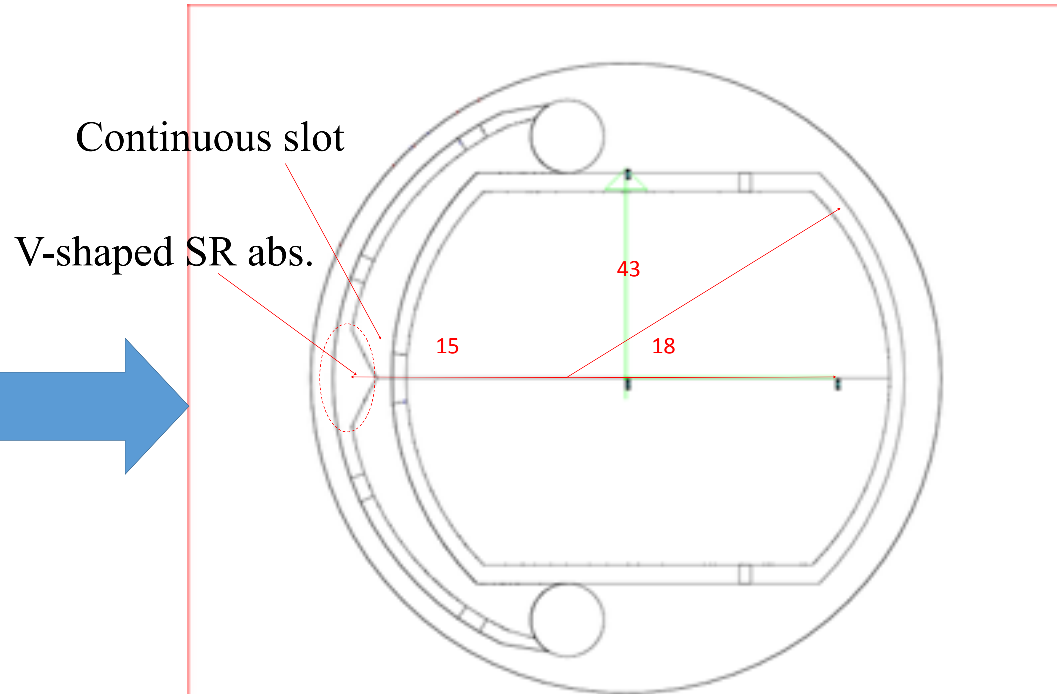
R. Kersevan

Configuration:

A combined BS, made up of a LHC-like BS with a continuous slot and an "external" SR power absorber is proposed here.



LHC-like BS solution



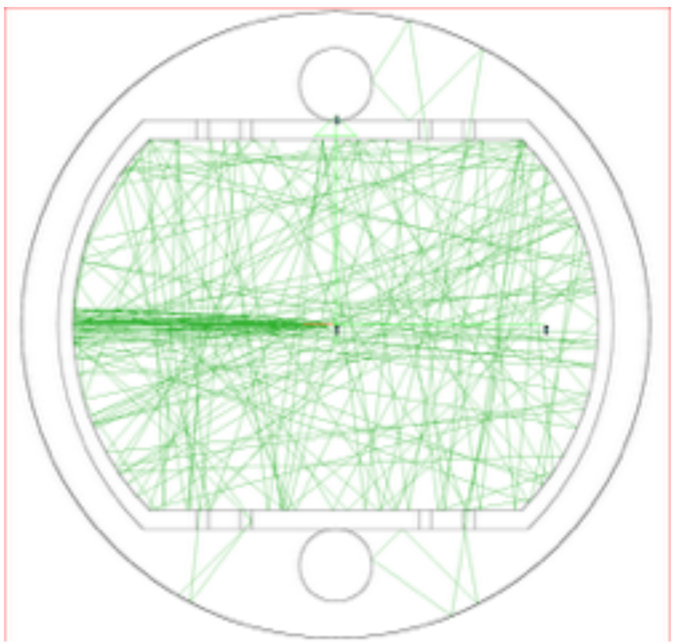
Slotted BS solution asymmetric

Initial FCC Beam Screen Studies

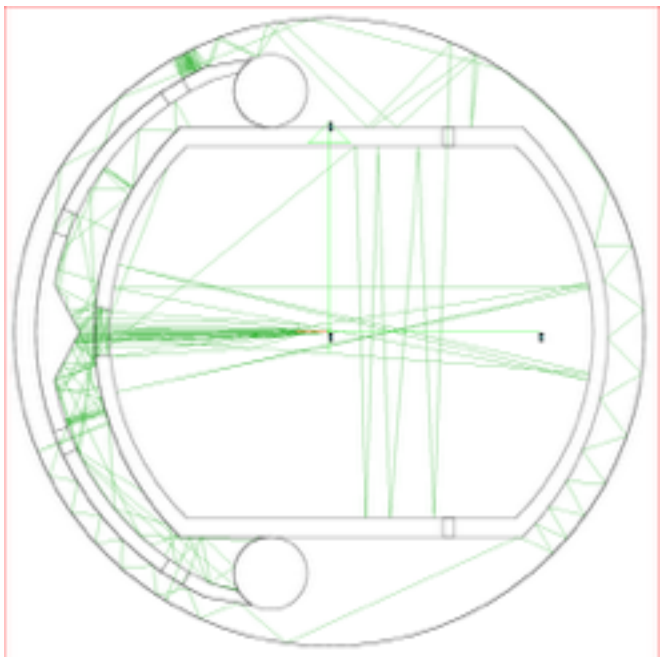
R. Kersevan

SR Ray-Tracing (Synrad+):

The high-energy small vertical angle opening of the primary SR fan passes almost unscathed inside of the 2x 1.57 mm-high continuous slot



All SR-induced gas load may interact with the beam



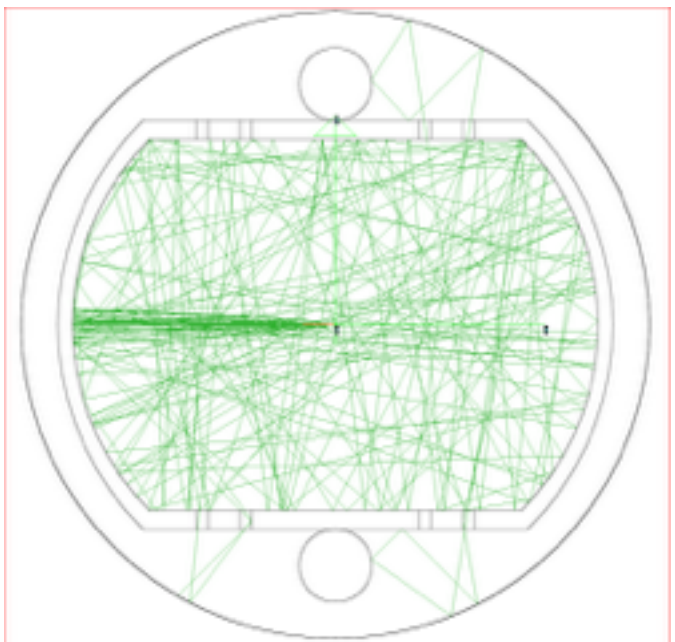
Only a fraction of the SR-induced gas load may interact with the beam

Initial FCC Beam Screen Studies

R. Kersevan

SR Ray-Tracing (Synrad+):

The high-energy small vertical angle opening of the primary SR fan passes almost unscathed inside of the 2x 1.57 mm-high continuous slot



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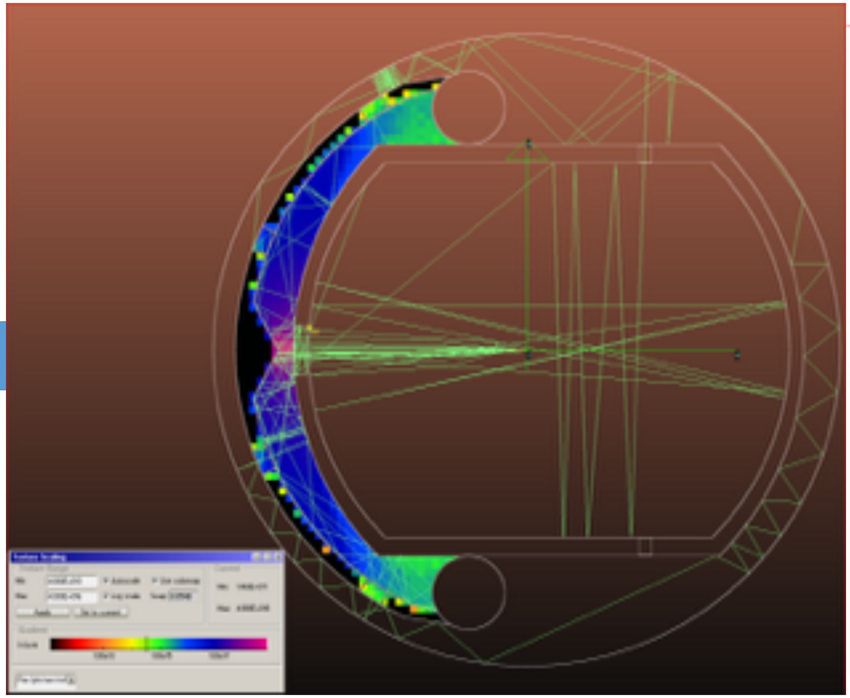
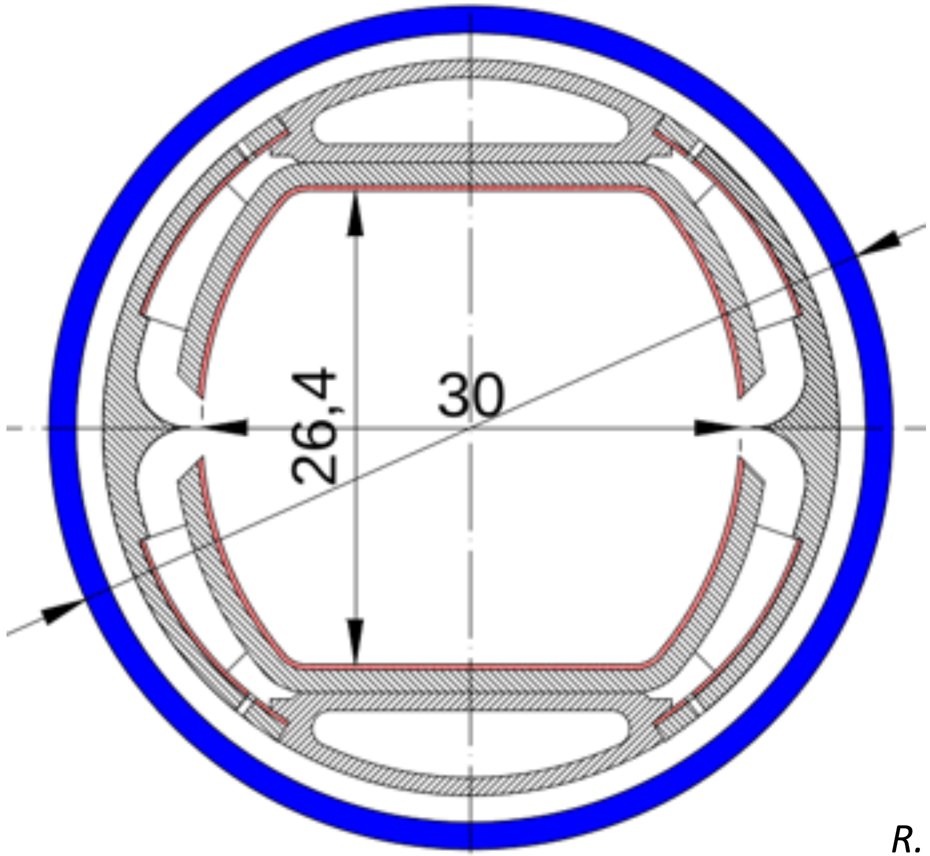


Only a fraction of the SR-induced gas load may interact with the beam

Beam Screen

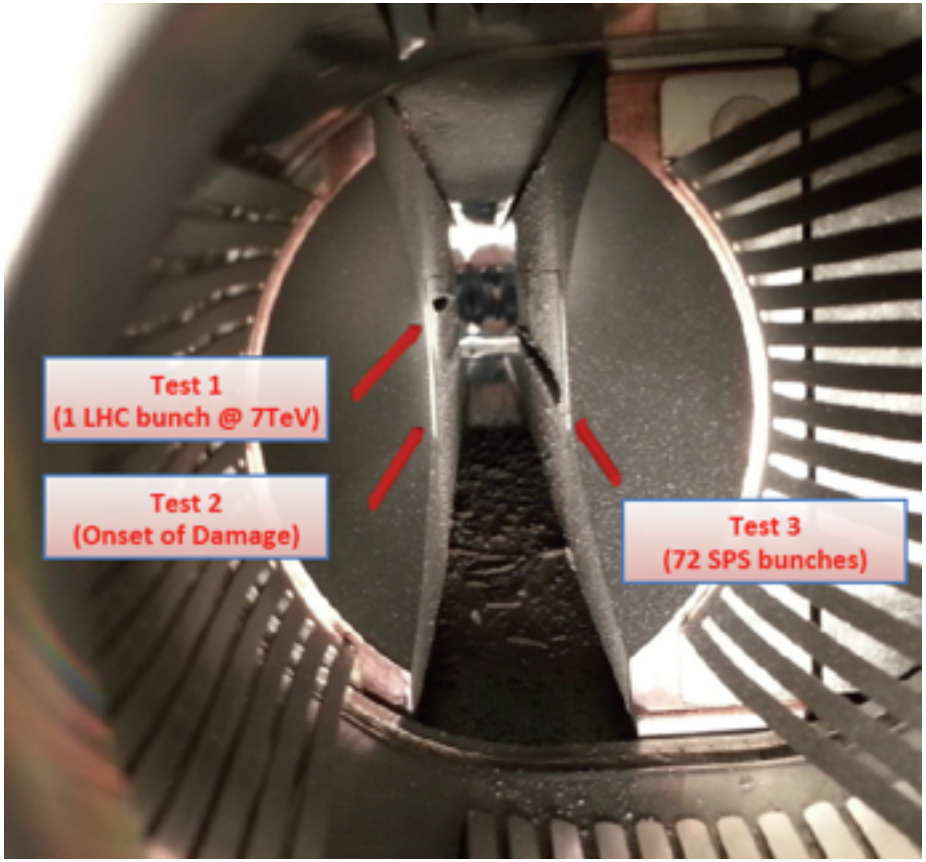
- Is now evolving into a more symmetrical design…



R. Kersevan, C. Kotnig, et al.

Machine Protection

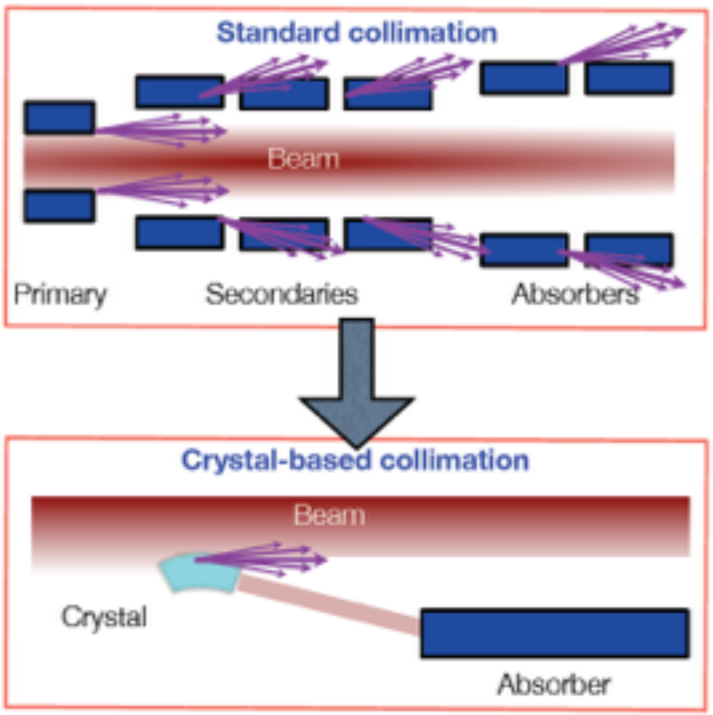
- > 8 GJ kinetic energy per beam
  - Airbus A380 at 720km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12 tons of copper
  - Or drill a 300m long hole
  - ⇒ Machine protection
- Also small loss is important
  - e.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background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

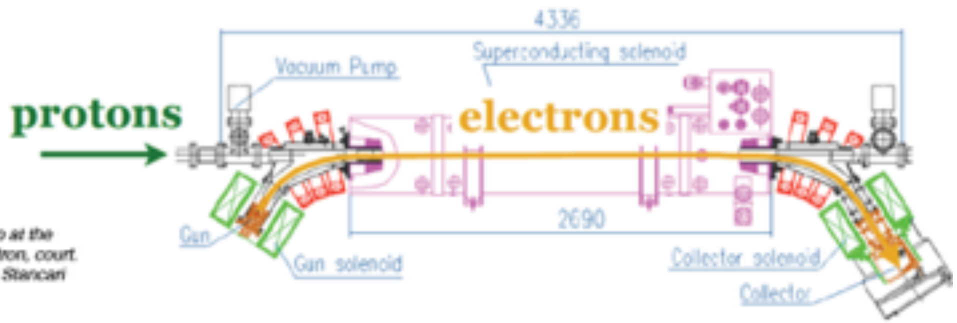


Beam Collimation

Can make an LHC-type solution, but other solutions should be investigated

- hollow beam as collimator
- crystals to guide particles
- renewable collimators



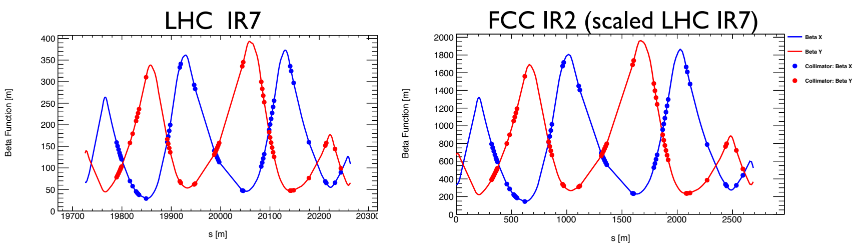


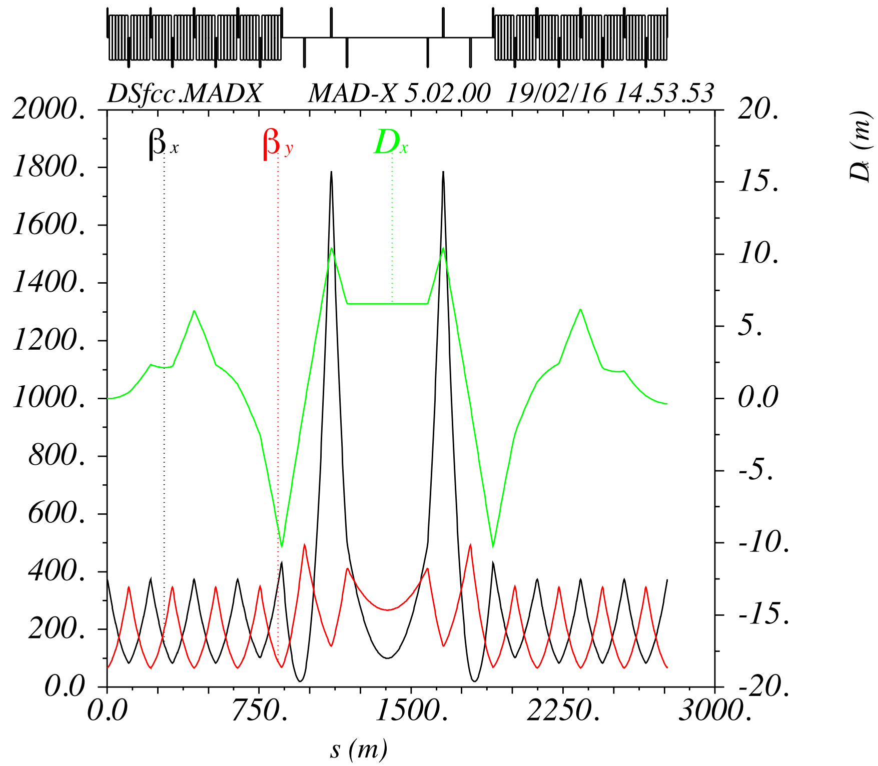
Setup at the Tevatron, court. of G. Stancari

Lattice Design Investigations

- Looking at optical design options to enhance collimation and protection systems

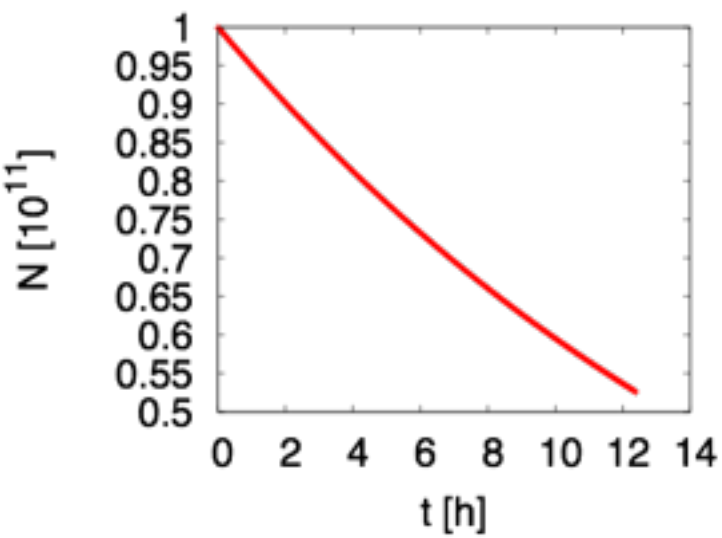
FCC betatron cleaning

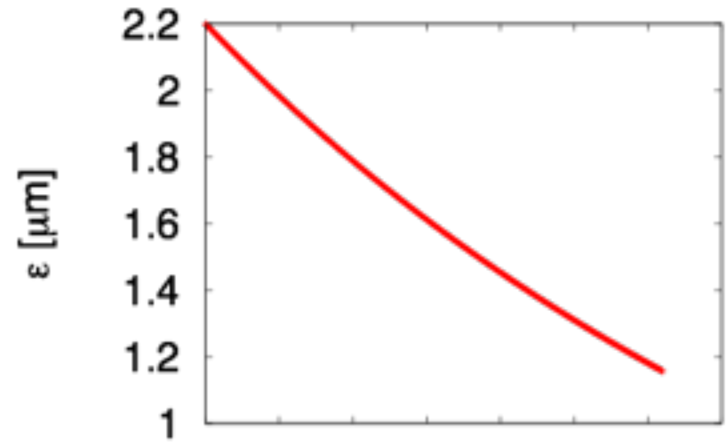




- Betatron cleaning scales well; can improve momentum cleaning through optical design

Simplified Example Luminosity Evolution

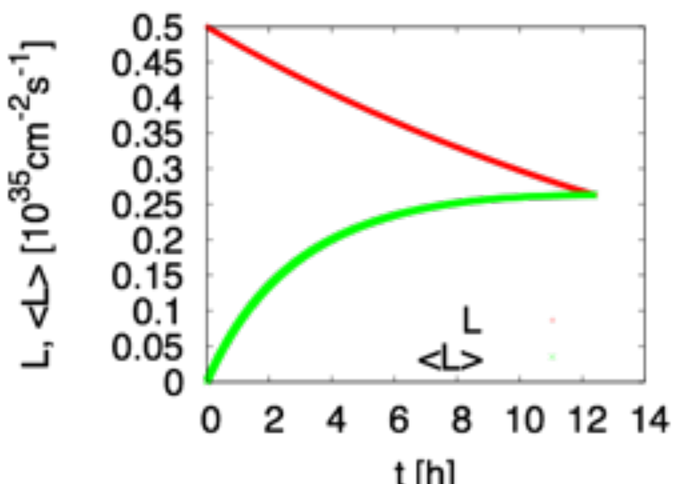




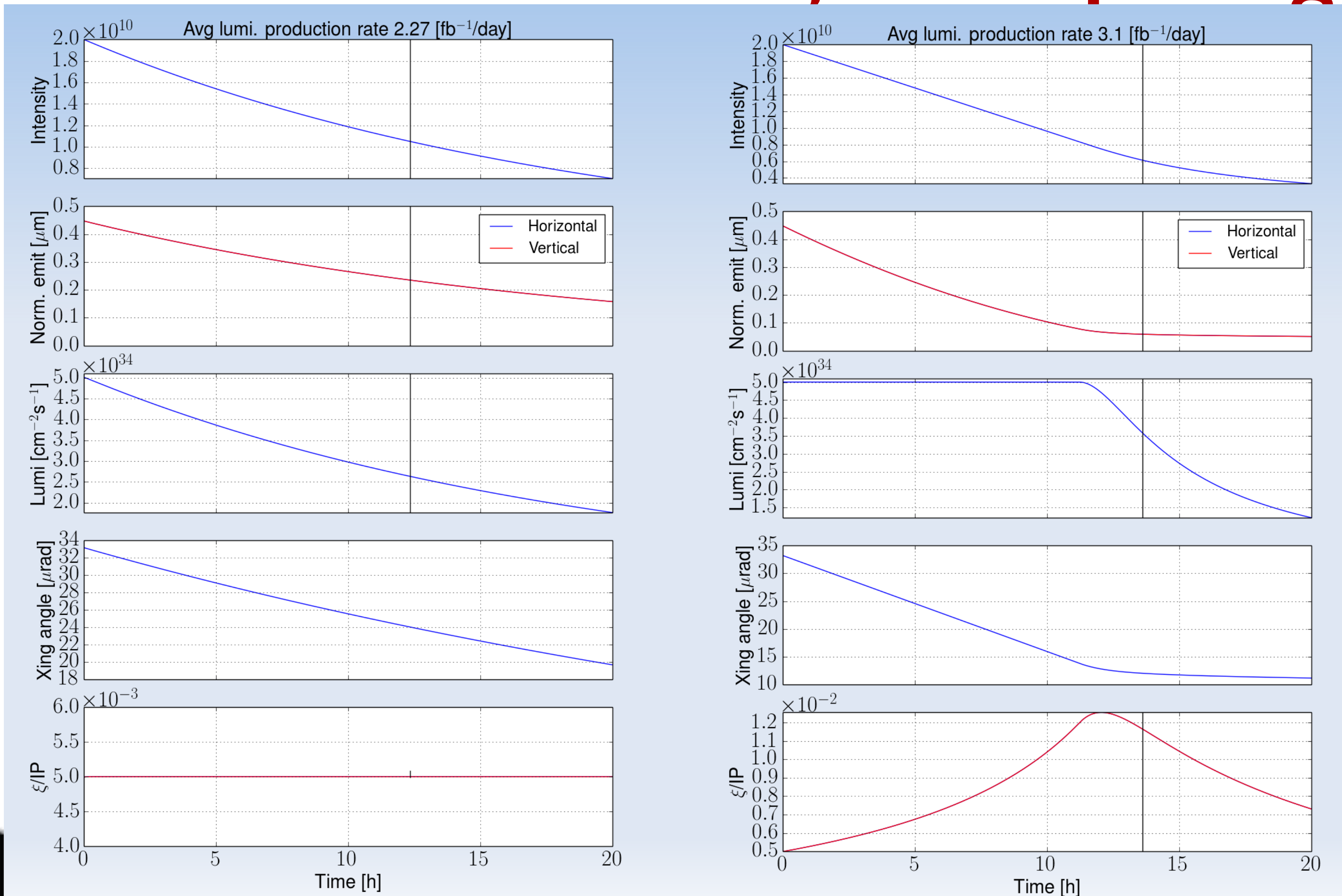
Keep beam-beam tune shift constant
Control emittance as $\varepsilon \sim L$

Luminosity decays exponentially
Optimum run time 12.1h for 5h turn-around

Relation $T_B/T_{turn\text{-}around}=a/(1-a+a\ln(a))$
$a=\langle L\rangle/L_0$



Nominal Parameters, 5 ns Spacing

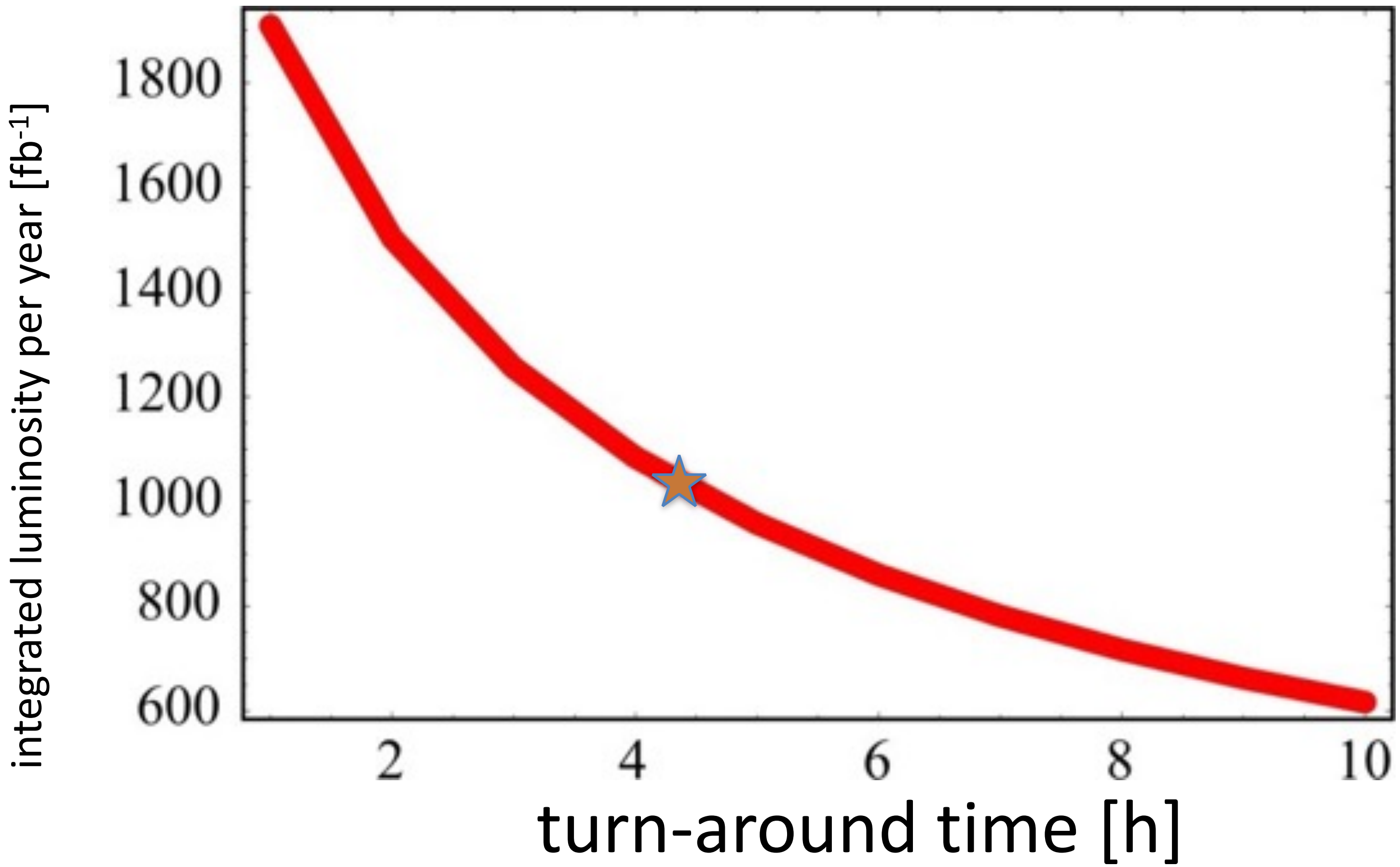


per IP:

$$\xi = \frac{r_0 N}{4\epsilon_n}$$

Integrated Luminosity *vs.* Turn-around Time

high luminosity scenario



FCC Week 2016

http://fccw2016.web.cern.ch/fccw2016/

FCC Week 2016, Rome

12-16 April 2016

- Second annual FCC Week meeting
  - 1st: Washington, D.C., 23-27 March 2015

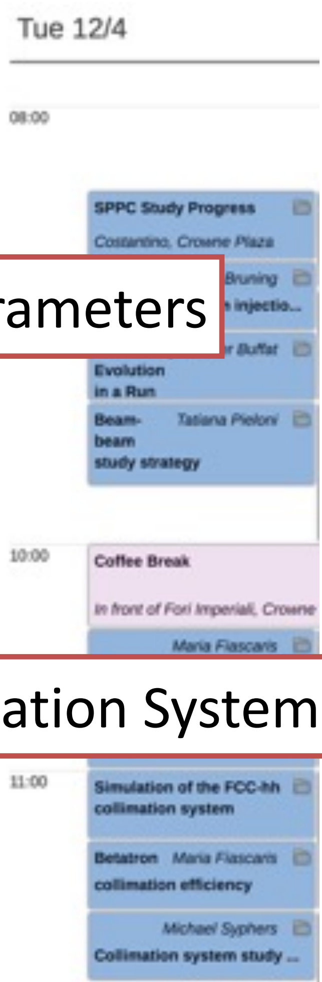
Version: 0.12 Date: 12.02.2016

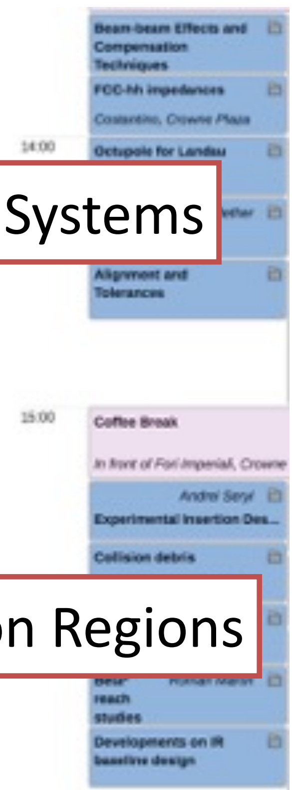
Preliminary FCC Week 2016 Program

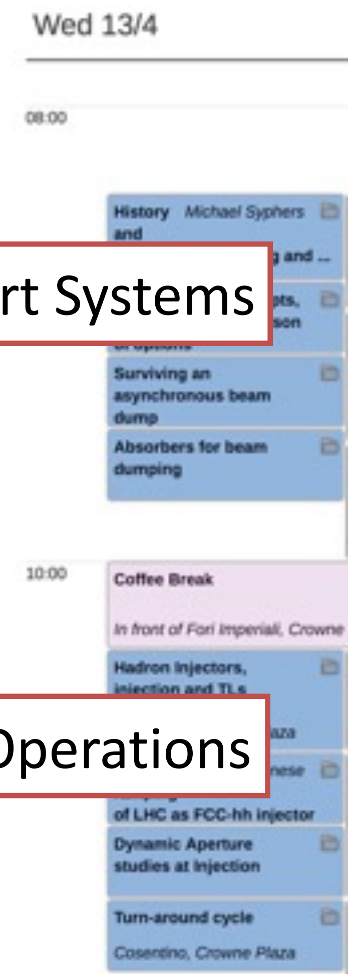
Time	Sunday	Monday (11.4)			Tuesday (12.4)				Wednesday (13.4)				Thursday (14.4)				Friday (15.4)
08:30-09:00		Registration	Welcome		FCC-hh Overall Design	Conductor Development - Overview	Physics at 100TeV (SM, Higgs, BSM)	RF concepts and directions for R&D	Injection, Extraction, Transfer Lines	16T dipole development - Overview	FCC-ee Machine Detector Interface	FCC-ee Beam-Beam & Luminosity	Technologies R&D: Beam vacuum & cryogenics	FCC-ee Lattice corrections & performance	Other Magnets	Common experiment software	Summary FCC-hh
09:00-09:30			Study Status & Parameter Update														Summary FCC-ee
09:30-10:00		KEYNOTE: FCC and the Physics Landscape															Summary infrastructures / technologies
10:00-10:30					Coffee Break				Coffee Break				Coffee Break				Summary Magnets / RF
10:30-11:00		Coffee Break			FCC-hh Collimation System	Conductor Development - Contributed talks	Physics of FCC-eh, and of HI collisions at FCC-hh	Recent designs and progress	FCC-hh Beam dump concepts	16T dipole development - EuroCirCol	FCC-hh Experiments and Detectors I	Communication	Cryogenics	FCC-ee Energy calibration & polarization	Beam induced effects	Comon detector technologies	Coffee Break
11:00-11:30		Accelerators and Infrastructure Plenary Session	FCC-hh machine layout and optics														Summary physics & phenomenology
11:30-12:00			FCC-ee overview	FCC-ee layout and IR optimisation													Summary experiments hh, ee, he
12:00-12:30		Chairperson tbd	I&O Overview	Geology studies and implementation/layout optimization	Lunch				Lunch				Lunch				
12:30-13:00		Lunch															Closing remarks
13:00-13:30																	
13:30-14:00					Beam dynamics	Conductor Development - Industry contribution I	Physics of FCC-ee	Material, cavities and cryomodules R&D	Technologies R&D: Beam transfer, Magnets & Instrumentation	16T dipole development - Protection	FCC-hh Experiments and Detectors II	FCC-ee Single-beam collective effects	Implementation, Electricity, CV	FCC-ee Injector	FCC-eh: Accelerator/Detector	FCC-ee experiments	
14:00-14:30		Technologies Plenary Session	RF R&D Overview	Towards very efficient RF power production													
14:30-15:00			16T Overview ?	The steps towards 16 T FCC magnets													
15:00-15:30		Chairperson tbd	STP Overview	Design, Prototyping and Tests of the FCC Vacuum Beam	Coffee Break				Coffee Break				Coffee Break				
15:30-16:00		Coffee Break			FCC-hh Machine Detector Interface	Conductor Development - Industry contribution II	Selected contributions from the submitted abstracts	RF efficiency optimization	Beam energy deposition & machine protect.	Manufacturing & Test Infrastructures	FCC-hh Experiments and Detectors III	FCC-ee optics	Safety, availability, survey	Cost Model	FCC-eh: Physics	FCC-ee experiments	
16:00-16:30	Registration	Experiments Plenary Session	Design studies for experiment magnets														
16:30-17:00			Progress on physics and experiment studies														

FCC-hh Parallel Sessions

27 talks in 6 sessions







FCC Parameters

Correction Systems

Beam Abort Systems

Collimation System

Interaction Regions

Injectors, Operations

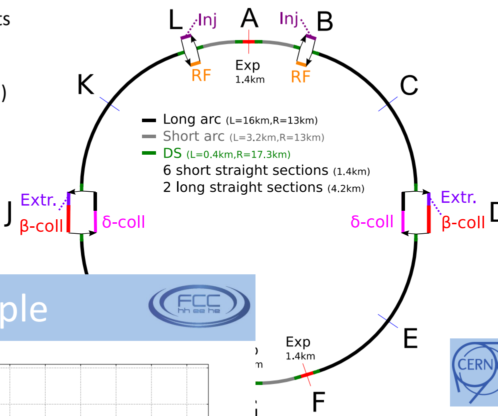
FCC-hh Parallel Sessions Topics

- Introductory material:
  - Plenary
    - Overview, magnets, beam screen
  - Status of SPPC studies in China

Overview - D. Schulte

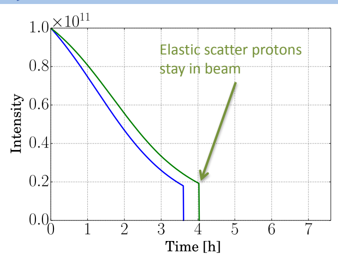
FCC-hh Layout

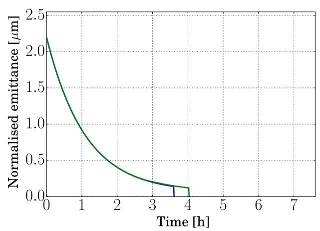
- Two high-luminosity experiments (A and G)
- Two other experiments (F and H)
- Two collimation and extraction insertions
  - Different options
- Two injection insertions with RF



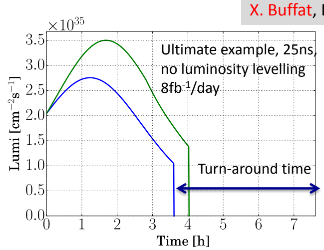
overed by M. Jimenez e

Luminosity Run Example





X. Buffat, D.S..



Example with ultimate parameters shown
⇒ Turn-around time is important

Most elastic scattered protons stay in beam
⇒ Detailed calculations to confirm

⇒ Different scenarios can be considered
⇒ E.g. are shorter bunch lengths acceptable?

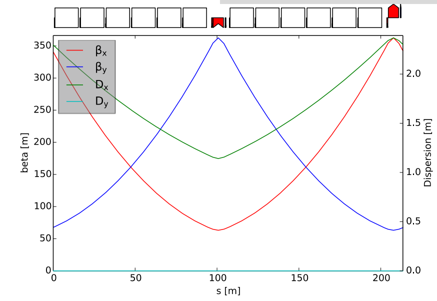
Arc Layout

A. Chance, B. Dalena, J. Payet

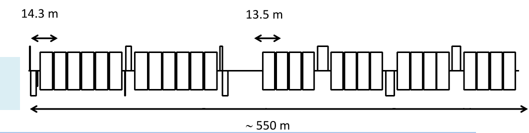
90° FODO cells, L_{cell}=213.89m
- 12 dipoles a 14.3m
- Quadrupoles, sextulpoles, spool pieces, correctors, ...
- Dipole field (16-ε) T

Iterating with magnet team
- Improved length estimates
- Found sextupoles quite strong due to beam delivery system

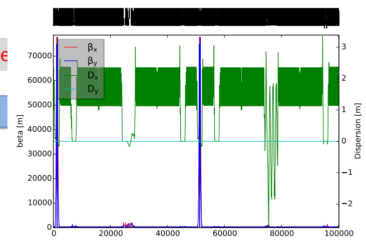
⇒ Integrated optics is useful

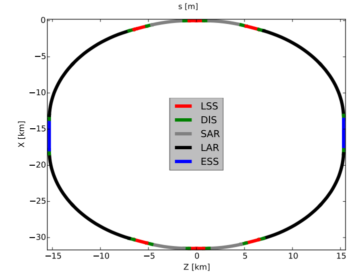


Dispersion suppressors (end of the arcs) are LHC-style



Integrated Design





A. Chance et al.

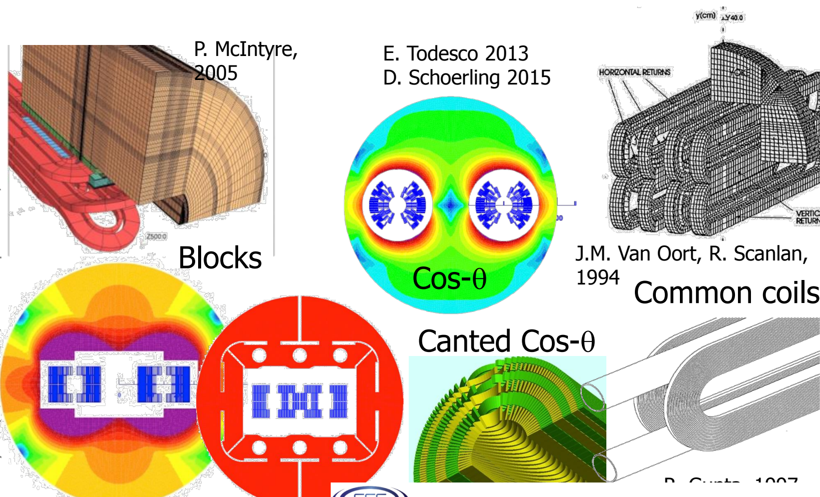
Parameters

Parameter		Value
Energy	TeV	50
Circumference	km	100.171
β^*	m	0.3
L^*	m	45
α	10^{-4}	1.008
γ_{tr}	-	99.580
Q_x	-	111.31
Q_y	-	108.32
Q'_x	-	2
Q'_y	-	2
# dipoles MB	-	4616
MB field	T	15.93
# quadrupoles MQ	-	846
Max grad MQ	T/m	370 [a]
# sextupoles MS	-	710
Max grad MS	T/m^2	18670

a. in the arcs

Magnets - G. de Rijk

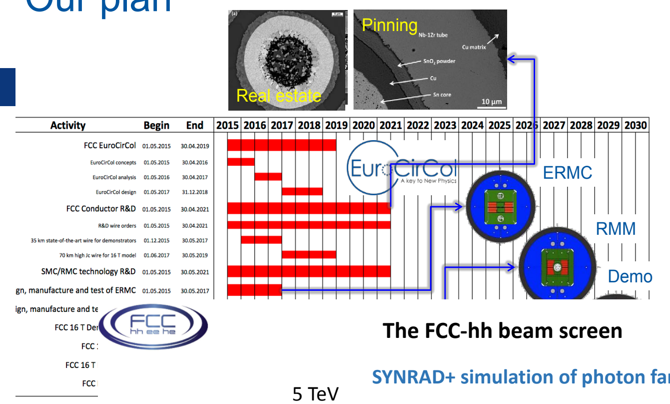
FCC: Magnet design for 16 T dipoles, LTS Nb_3Sn



16T and beyond, FCC Rome, 11-15 April 2016, GdR

program for FCC 16 T

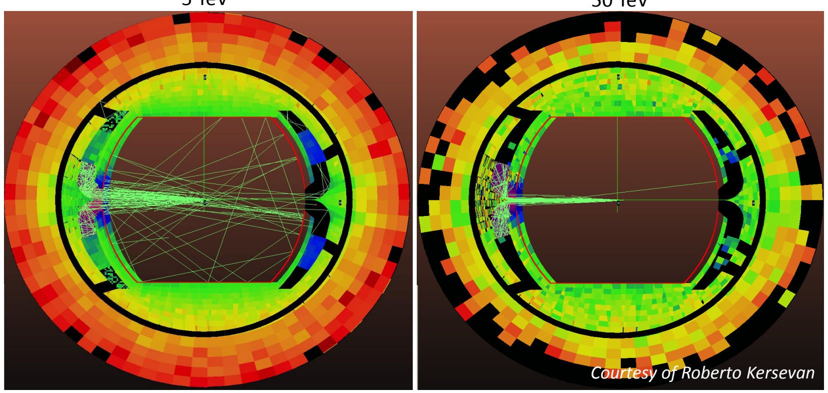
Our plan



The FCC-hh beam screen

EuroCirCol WP4

SYNRAD+ simulation of photon fans



Gas density simulation by MolFlow+: strongly dependent on accumulated photon dose. Vacuum requirement attained after about 10 days at full current. Work in progress…

11/04/2016 Francis Perez & Paolo Chiggiato: Design, Prototyping and Tests of the FCC-hh Vacuum Beam Screen 11

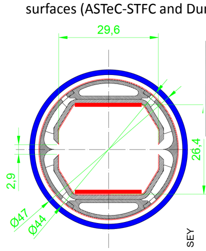
Ecloud mitigation integrated in the design

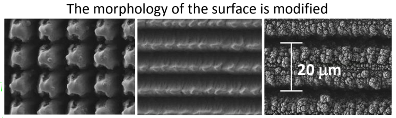
EuroCirCol WP4

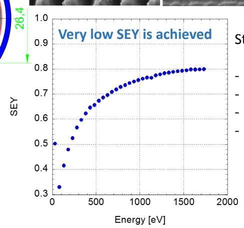
Present baseline

Laser treatment, just above the ablation threshold, of the top and bottom beam screen surfaces (ASTeC-STFC and Dundee University).

The morphology of the surface is modified







Very efficient to reduce photon reflectivity

Studies in progress:

- Morphology optimisation
- Impedance
- Dust generation
- Effect of magnetic field

See **Reza Valizadeh** contribution. **Wednesday PM – Poster section**

11/04/2016 12

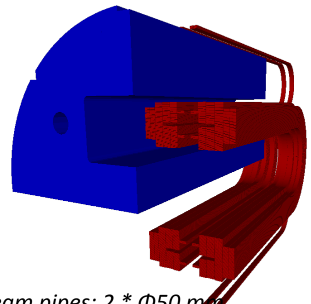
Beam Screen - F. Perez,

SPPC Progress — J. Tang

Technical challenges and R&D requirements

-High field SC magnets

- SC dipoles of 20 T are key both in technical challenges and machine cost
  - 2/3 ring circumference
  - Nb_3Sn (15T) +HTS (5T) or pure HTS
  - Twin-aperture: save space and cost
  - Common coils or Cosine-theta type
  - Open mid-plane structure to solve SR problem?
  - SC quads: less number but also difficult
- Domestic and intern. collaboration very important



*Beam pipes: 2 * Φ50 mm*
Load line ratio: ~80% @ 1.9 K
Yoke diameter: 800 mm

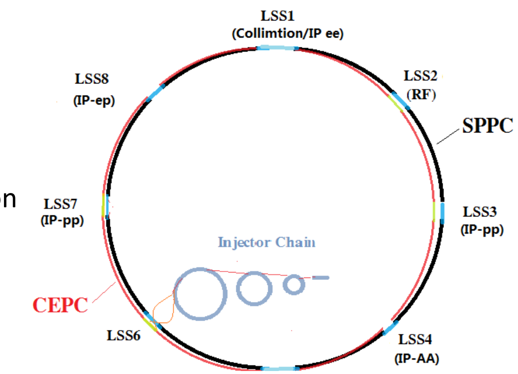
Q.J. Xu's talk on Wed.

18

General layout

SPPC rings:

- 8 arcs (5.9 km) and long straight sections
- 1 longer LSS collimation (ee detector)
- 1 longer LSS for extraction (ee detector)
- 2 LSSs for pp detectors
- 2 LSSs for AA or ep detector



SPPC main parameters

Parameter	Value	Unit
Circumference	54.36	km
C.M. energy	70.6	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56.9	W/m

(80-100 km tunnel, 100 TeV is also under study)

5

Topics [2]

- FCC Parameters
  - Beam parameter evolution through a store
  - Beam-beam strategy
  - Injection Energy Review

Parameter Evolution Buffat, Schulte

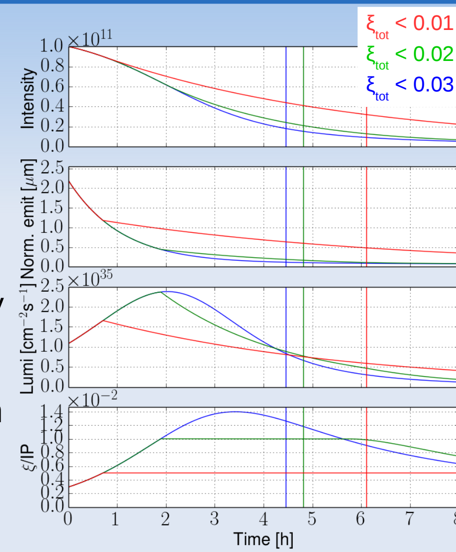
Model

$$
\begin{cases}
\frac{\partial I}{\partial t}(t) = -\frac{I(t)}{\tau_l} - \sum_{IP} \mathcal{L}_{IP}(t) \frac{1}{n_b} \sigma_{tot} \\
\frac{\partial \epsilon_x}{\partial t}(t) = \frac{\epsilon_x(t)}{\tau_{\epsilon_x}} - \frac{\epsilon_x(t)}{\tau_{rad}} + \sqrt{\frac{2\epsilon_{x,equ}}{\tau_{rad}}} \\
\quad + \frac{1}{\tau_{IBS}} \frac{I(t)}{I_0} \frac{\epsilon_{x,0}\epsilon_{y,0}\epsilon_{s,0}}{\epsilon_x(t)\epsilon_y(t)\epsilon_s(t)} \\
\frac{\partial \epsilon_y}{\partial t}(t) = \frac{\epsilon_y(t)}{\tau_{\epsilon_y}} - \frac{\epsilon_y(t)}{\tau_{rad}} \\
\epsilon_s(t) = \left(\frac{I(t)}{I_0}\right)^{\frac{2}{5}} \epsilon_{s,0} \\
\mathcal{L}_{IP}(t) = \frac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^*(t)\sqrt{\epsilon_x(t)\epsilon_y(t)}} \frac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma_t(t)^2} tan\left(\frac{\phi(t)}{2}\right)^2}} \\
\phi(t) = \sqrt{\frac{\epsilon_x(t)}{\beta^*(t)\gamma_r}} S_{drift}
\end{cases}
$$

- $\xi_{tot} < 0.01$

Performance
25 ns

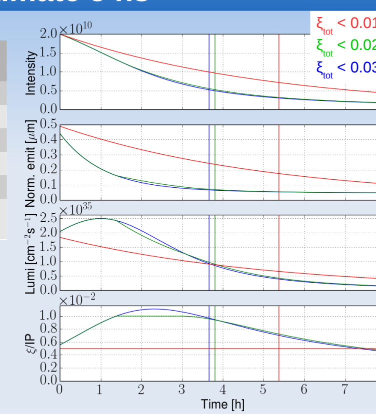
- The optimal time in luminosity production is comparable to the turn around time
- Baseline performance : 2.3 fb^{-1}/day
  - With β* =0.3 [m]: 5.1 fb^{-1}/day
  - With $\xi_{tot} < 0.03$: 7.2 fb^{-1}/day
- The bunch length varies from 8 to 5 cm
- The crossing angle is adjusted from 140 to 30 µrad



Short bunch spacing
Ultimate 5 ns

Configuration	Performance [fb^{-1}/day]	
	25 ns	5 ns
Baseline	2.3	2.3
+ β* = 0.3	5.2	5.1
+ xi < 0.03	7.2	6.0
+ Crab cavity	7.9	7.1
- 1h turn around time (→ Ultimate)	8.9	8.0

- Similar performance as for the 25 ns configurations
  - Ultimate configurations seems at the edge of the required performance



Beam-Beam Strategy
T. Pieloni

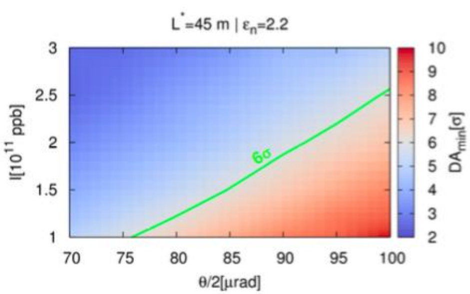
Crossing angle set-up

Dynamic Aperture studies for round optics

Results. Baseline L^{*}=45 m

For the baseline parameters a 6σ DA is ensured with a θ/2~76 μrad, i.e. d_{sep}= 12.8σ.

This is consistent with previous studies done with a toy lattice.



Study On-going

Talk J. Barranco (EPFL)

- Parameter space
- Spectr
- Rounc
- Crab C
- Magn
- Possib (octup
- Active elens,
- …..

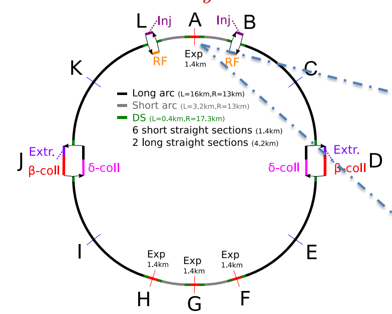
Beam-Beam Interactions

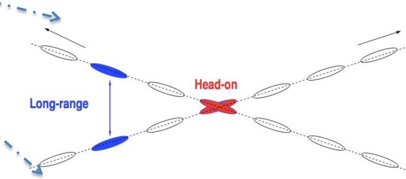
Luminosity

$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

Beam-Beam Force

$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$





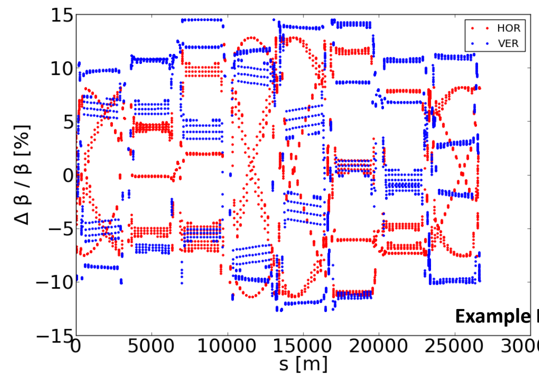
FCC collider: bunches
2 Experiments with Head-On collision

Separation is typically 12-14 σ
Scaled from LHC

10600 bunches…
25 ns bunch spacing → beams will meet every 3.75 m
For L*45m 60 beam-beam Long Range encounters per experiment

$\xi_{bb} = 0.02$ interactions
sing angle)

Optics distortions and implications



Example HL-LHC lattice

Synergy with optics group

Experimental test of local correction in the LHC (R.Tomas et al.)

P. Jorge (EPFL student) implications of BB beating, optics dependency, phase advance and impact on collimation and performances

Study On-going

Injection Energy Review
O. Brüning

Review Goals

- **Determine the minimum reasonable injection energy and impact on collider design**
- **Determine the maximum useful injection energy and impact on collider design**
- **Confirm/define injector/collider scenarios** (taking into account existing infrastructure) **to be studied in detail**

Review Members:

Ralph Assmann, Oliver Brüning, Yunhai Cai,

Antoine Daël, Lyn Evans, Wolfram Fischer (Chair),

Valeri Lebedev, Akira Yamamoto

➔ 9 technical presentations in one day meeting

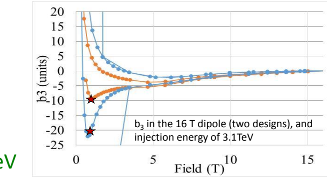
Indico: https://indico.cern.ch/event/449449/other-view?view=standard

FCC Week in Rome12. April 2016 O. Brüning; CERN 3

Field Quality and Q'

- Two designs of 16 T, 50 micron filament, if we inject at 1 T we are at penetration field ☺
- From 10 to 20 units of persistent current
  - Chroma swing of 800 to 1600 units, but stable working point for injection
  - Compensation schemes or smaller filament or design can reduce this

[D. Tommasini @ Review]



➔Injection energy of 1.5TeV might be feasible!

Review Conclusions: Charge replies

- **Maintain 3.3 TeV as the baseline injection energy.**
  - **The dynamic energy range in FCC-hh is 15x (Tev: 7, HERAp: 23, RHIC: 10, LHC = 16).**
  - **The LHC is usable as injector.**
  - **Transfer is possible.**
  - **A design for a beam screen exists with acceptable impedance.**
  - **Instabilities at FCC-hh injection can be controlled with a damper.**
  - **The dynamic aperture is probably sufficient (limited knowledge of field errors).**
- **Determine the minimum reasonable injection energy and its impact on collider design:** The minimum injection energy considered should be 450 GeV, allowing injection directly from the SPS.
- **Determine the maximum useful injection energy and its impact on collider design:** The maximum useful injection energy is approximately 6.5 TeV, allowing injection from the existing LHC.

FCC Week in Rome12. April 2016 O. Brüning; CERN 14

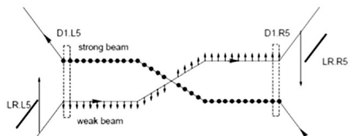
Topics [3]

- Correction Systems
  - beam-beam (separation in triplets)
  - impedances/instabilities
  - Landau damping octupole correction
  - electron cloud
  - alignment requirements

Correction Systems
Barranco, Boine-Frankenheim
Boutin, Kornilov, Mether

LR compensation: Wires,e-lens

- It is possible to compensate locally the kick by the long range interactions using an electrostatic wire[1].



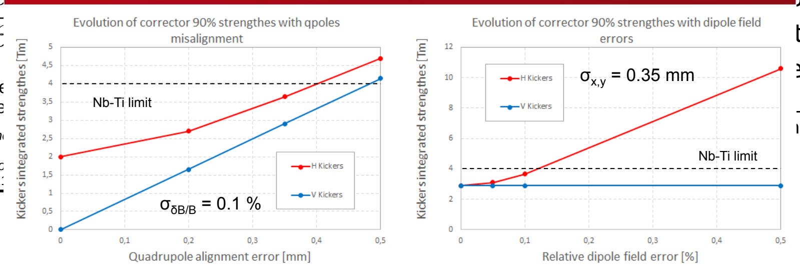
- These devices has been tested in several beam experiments. However its location, current settings, distance to the circulating where always an iterative
- In [2] a new semi analytic approach was developed showing that the compensation is maximized for a given

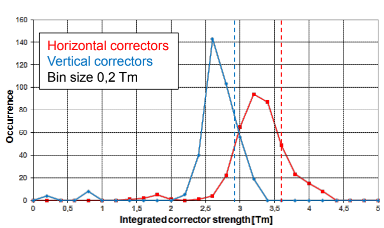
$r_w \equiv$

- Test of wire
experience

[1]J. P. Koutchouk, *"Prin*
Note 223, April 2000.
[2]S. Fartoukh *et al.*, *"C*
LHC", PRSTAB 18, 12

CORRECTOR STRENGTHS





Histogram of the maximum value of the integrated correctors strengths

D. BOUTIN, FCC WEEK, 12 APRIL 2016 | PAGE 9

Overview FCC Landau Octupoles

Blue: ΔQ_{coh}–Damping as in LHC. **3646** Octupoles.

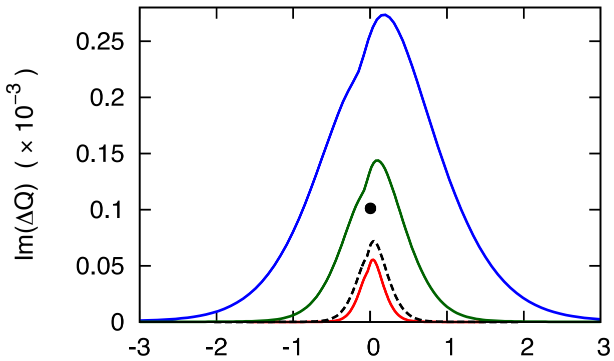
Green: enough damping for the (•) studied impedances (no collimators). **1828** octupoles.

Black Dashed: $N_{MO} = N_{MQ}$ = **814** (figures above)

Red: N_{MO} per length as in LHC
627 octupoles.

58 octupo
tupole m
ed here.

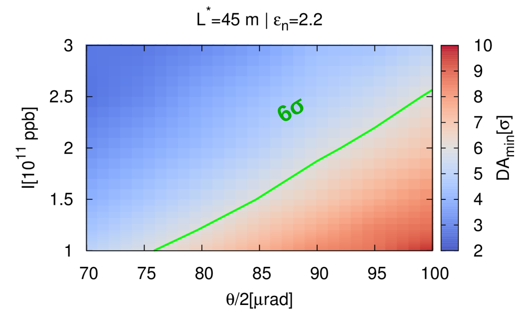
ir Kornilov, F



Results. Baseline L*=45 m

- For the baseline parameters (I=10[11] ppb, see table before) a 6σ DA is ensured with a θ/2~76μrad, i.e. d_{sep}= **12.95σ**.
- Large parameter space for more challenging scenarios.
- This is consistent with previous studies done with a FCC toy lattice (Xavier's presentation in Washington 2015) taking into account the differences in the IR region design.

21

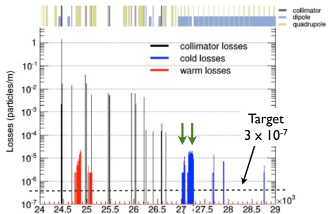


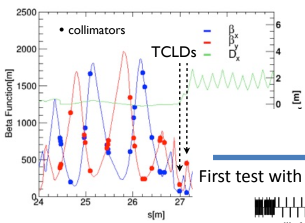
Topics [4]

- Collimation System
  - layout/overview
  - optics, simulations
- Beam Abort System
  - beam dump concepts, optics
  - surviving asynchronous aborts
  - beam absorbers for abort system

Collimation System
Fiascaris, Lachaise, Molson, Syphers, *et al.*

Loss maps - Zoom in IRD





Maria Fiascaris

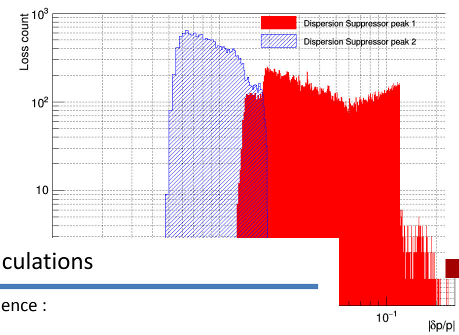
Cold losses in the dispersion s
the dispersion starts to rise.

Due to single diffractive events fr
with primary collimators

Losses concentrated in 2 clusters
with characteristic Δp/p distribu

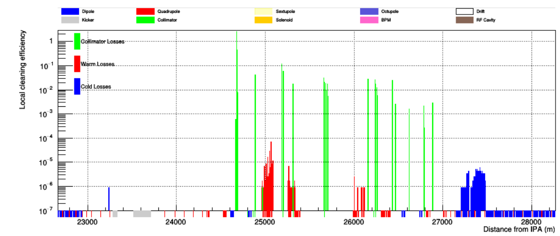
- **1st cluster:**
  - peak loss (± stat.)= (1.2 ±
  - Δp/p < −0.02
- **2nd cluster:**
  - peak loss (± stat.)= (2.2 ±
  - −0.02 < Δp/p < −0.005

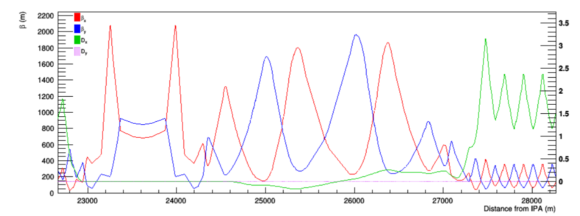
Dispersion suppressor losses



tem April 12, 2016 33 / 34

Betatron collimation region

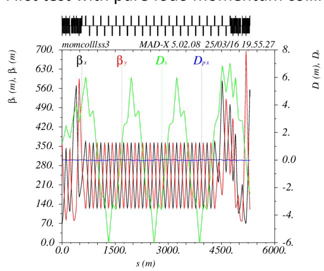




J. Molson et al (LAL) Simulation of the FCC-hh collimation system April 12, 2016 26 / 34

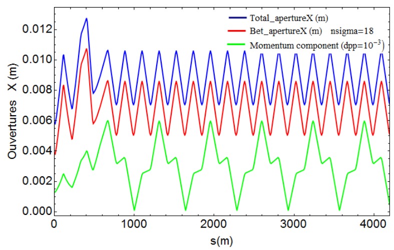
First aperture calculations

First test with pure fodo momentum collimation sequence :



Optical functions of the section

Horizontal beam size for n = 18 sigma et dp/= 10^{-3}



Maximum aperture includin
2mm for chamber thickness
12.7mm

12/04/2016 FCC week 2016 - Rome 19

Off-momentum cleaning (I)

Main purpose

Intercept primary off momentum losses

Capture losses, synchrotron radiation losses, …

Important for failures: RF off, wrong frequency settings

Provide adequate cleaning for design loss scenarios

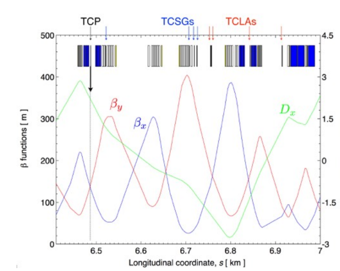
LHC solution

Dedicated cleaning insertion

Three stage cleaning

(TCP/TCS/TCLA)

Maximised normalized D_x



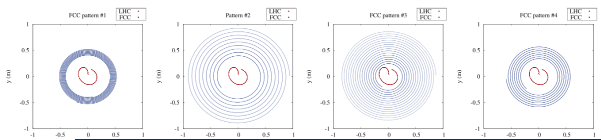
Maria Fiascaris 10 FCC week 12/04/2016

Abort System
Bartmann, Goddard, Lechner, Syphers, *et al.*

Energy deposition studies on the dump absorb

	MKB frequency modulation	Frequency	B·dl[a)]	Distance between neighbouring bunches	Distance between neighbouring branches
#1[b)]	No	32.8 kHz	34 Tm	2.00–2.64 mm	1.6 cm
#2	No	32.8 kHz	56 Tm	1.87–4.70 mm	6.5 cm
#3[c)]	No	50.9 kHz	53 Tm	1.83–6.95 mm	4.0 cm
#4[c)]	Yes	20–43 kHz	39 Tm	1.90 mm	3.7 cm

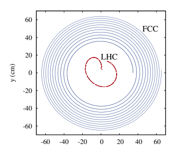
[a)] For a dump line length of 2.5 km. [b)] See F. Burkart, FCC Dump Meeting, 02/07/2015. [c)] See F. Burkart, FCC Dump Meeting 02/12/2015.

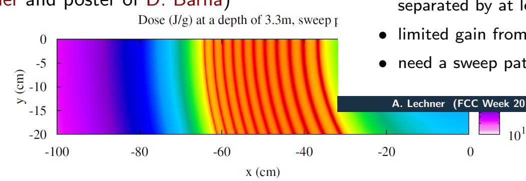


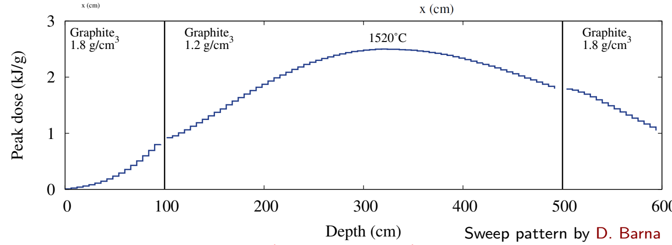
- Assu
- Beam
- Need
- (Antc
- Have

Spiral sweep pattern: optimized pattern

Optimized pattern under consideration of achievable kicker
(see talk of T. Kramer and poster of D. Barna)



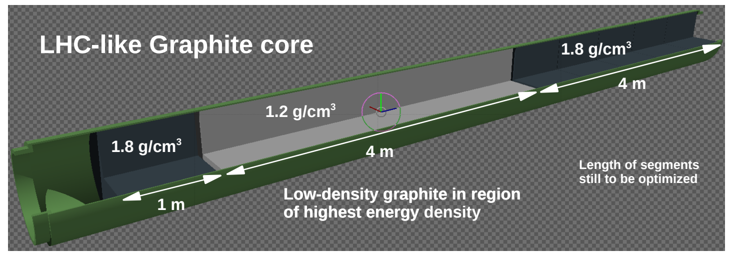




Sweep pattern by D. Barna

→ need a large dump cross section (diameter of 1.5m!)

Considerations about the dump block

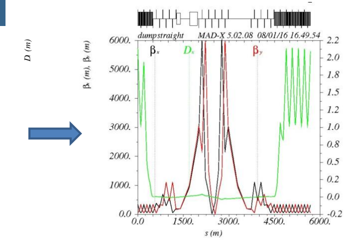


Overlap of transverse shower tails:

- bunches need to be swept over dump front face in order to keep temperatures in core within reasonable limits (say below 1500°C)
- considering β-functions of a few km, neighbouring bunches separated by at least d_{min} =1.6-1.8 mm (A. Lechner, FCC W
- limited gain from larger β-functions (e.g. d_{min} =1.2-1.5 mm
- need a sweep path length of more than 20 meters! (LHC: 1

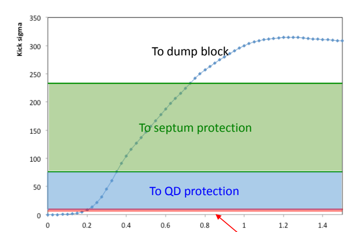
Extraction insertion optics - alternative

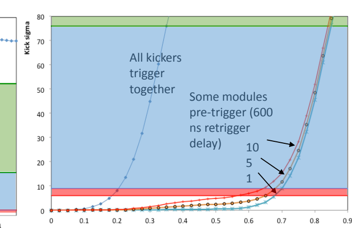
- **High beta functions** at the septum and quadrupole protection **absorbers** (min of 800 m)
- **Low beta function** in bending plane at the **extraction kicker** opens the possibility not to retrigger the full system in case one of the 300 units is pre-firing and thus **significantly reduce the probability of an asynchronous beam dump** (see B. Goddard's talk)
- Consider further increasing beta function at absorbers – envisage **ramping optics** …eam size, less critical for absorbers) and flattop …absorbers)



Sweep form

- Depends strongly at low amplitudes on whether single kicker has pre-fired, or all kickers together
- Pretrigger produces highest densities close to beam core
- Faster rise time (and faster retriggering) means less beam swept across downstream aperture
  - Aiming for 1 µs for FCC (to compare with 3 µs for LHC)





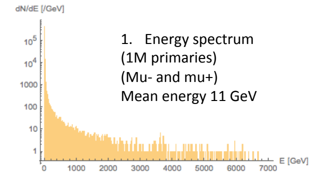
Topics [5]

- Interaction Region Design/Developments
  - collision debris — IR and into the arcs
  - β^* reach
  - baseline L* progress

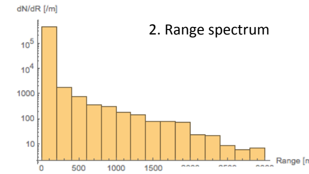
Interaction Regions
Appleby, Besana, Cerutti, Langner, Martin, Seryi, *et al.*

Muon range through rock (prompt+decay)

The Cockcroft Institute of Accelerator Science and Technology



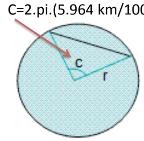
1. Energy spectrum (1M primaries) (Mu- and mu+) Mean energy 11 GeV



2. Range spectrum

3. Chord through FCC-hh ring

circum=100 km. r=15.9 km.
C=2.pi.(5.964 km/100 km) = 0.37 rad



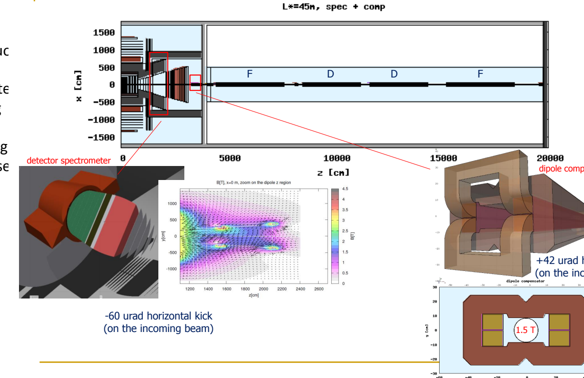
Chord=2.r.Sin(c/2) = 5.92 km

Max energy is 22 TeV
Max range is ~3 km

So do not expect many muc

Needs checking with Monte fluctuations and straggling -> FLUKA
And check muons bouncing along with local losses close

L*=45m LAYOUT WITH SPECTROMETER

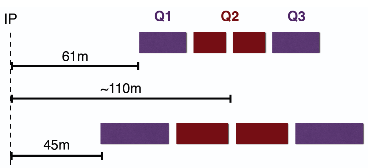


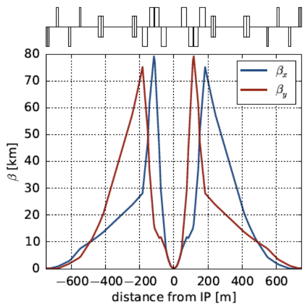
2016 April 12th F. Cerutti FCC-hh MDI FCC week, Rome

Latest optics with L* of 45m

EuroCirCol A key to New Physics

- **L* 61m => 45m**
  - Following the selected strategy increase triplet length by ~50%





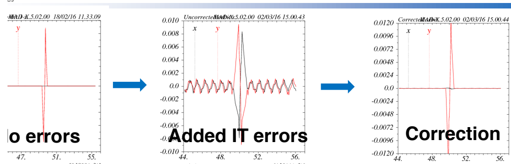
Optics for $\beta^* = 0.3\,\mathrm{m}$

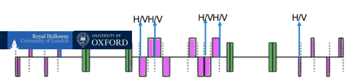
- **Further optics optimization needed (system length longer by 50m per side and per IP then desired)**

More details in the talk of Roman Martin

Experimental Interaction Region, 12 April 2016, A. Seryi

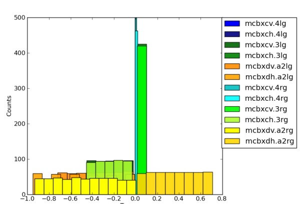
IR optics – orbit corrections





Max misalignment errors in the inner triplet of 0.5 mm

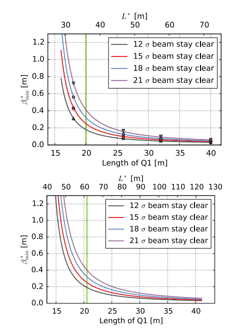
Result: successful correction and all correctors in the achievable range of -1, 1 TM



Emilia Cruz Alaniz

Experimental Interaction Region, 12 April 2016, A. Seryi

L^* range and aperture



- Longitudinal scaling (**of both** L^* **and triplet**) used to explore L^* range
- At reference points ($L^* = 36\,\mathrm{m}$ and $L^* = 61\,\mathrm{m}$, triplet lengths are approximately same
- **Difference in both lattices:** ratio of triplet magnet length to L^*
- **Conclusion 1:** aperture limitation on β^* is lower for longer L^* and longer triplet
- **Conclusion 2:** triplet length seems to have a larger impact

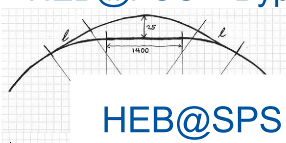
R. Martin β^* reach studies 4 / 1

Topics [6]

- Injector, Operations
  - injectors, transfer lines
  - fast ramping LHC
  - dynamic aperture at injection
  - turn-around time

Injectors, Operation
Apollonio, Dalena, Milanese, Stoel, *et al.*

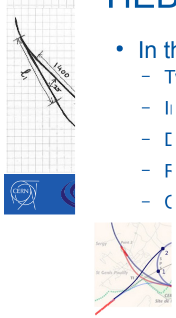
HEB@FCC – Bypasses



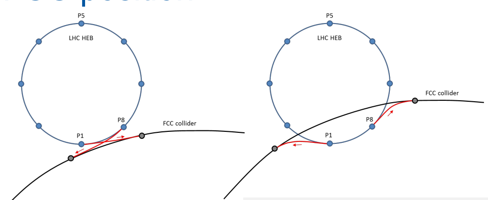
• Initial design with the same bending

HEB@SPS – Changes

- In the straights we need:
  - Two high energy extractions
  - I
  - D
  - F
  - C



FCC position



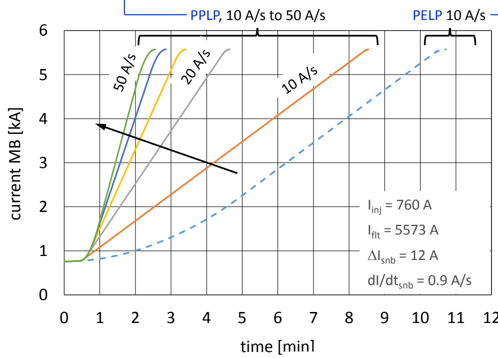
2 layouts, focus on "inte
but non-intersecting is a
(Talk by C. Cook, Thu 1

4/13/16

These are several options for faster ramps up to 3.3 TeV

Parabolic-Parabolic-Linear-Parabolic instead of Parabolic-Exponential-Linear-Parabolic

not effective - the initial part is very slow
(the exponential is there for historical eddy currents reasons)



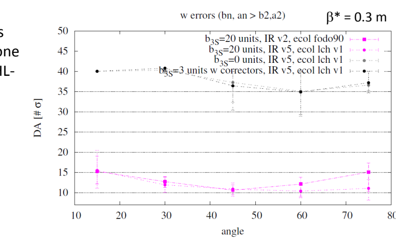
ramp	time [s]	dI/dt_{avg} [A/s]
PELP, 10 A/s	643	7.5
PPLP, 10 A/s	513	9.4
PPLP, 20 A/s	279	17.3
PPLP, 30 A/s	205	23.5
PPLP, 40 A/s	171	28.1
PtLP, 50 A/s	154	31.3

the gain is not linear

13 Apr. 2016

b3 correctors: collision

Average b_{3s} for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (same scheme of HL-LHC by S. Fartoukh).



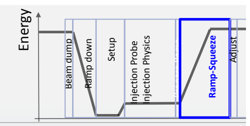
MS integrated strength	$b_3 = 0$	b_{3S} = 20 error table	b_{3S} = 3 + correctors
KSF [10^{-2} m^{-2}]	2.4	**-5.8**	2.4
KSD[10^{-2} m^{-2}]	-4.8	**-17.9**	-4.8

⇒ **~81% of 2 times the strength of LHC MCS fully correct b_{3S}=3 units** (minimum DA ~28 σ)

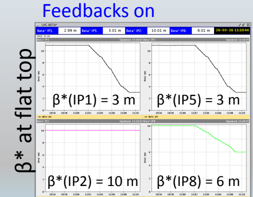
If 3 times stronger MCS are feasible and correct up to 6 units of b_3 at 50 TeV (see E. Todesco talk)
⇒ **possibility to reduce the number of MCS ?**

13/04/2016 B. Dalena, FCC week 2016 9

Ramp-Squeeze



Ramp-squeeze in LHC:
- Function playing (automatic procedure)
- Q, Orbit and Transverse Feedbacks on



- **RAMP TIME in FCC**:
  20 min ➔ Ref: "Concepts for ma powering and protection", M. Prioli, FC 2016
- **SQUEEZE TIME in FCC**:
  - LHC squeeze from 11 m to 0.8 m (l minutes
  - FCC-hh baseline squeeze from 5 m half of the LHC squeeze ➔ **6 min**
  - Since combined with the ramp, pa the shadow ➔ **3 min**
- **FLAT TOP in FCC**: operator sequential

13/4/2016 FCC WEEK 2016 8

Recent Major Accomplishments

- Detailed design of the standard arc cell
  - dynamic aperture studies produced improved specifications to the field quality requirements — in particular, b_3
  - example of close collaboration with magnet group
- Lattice integration among various functions and systems
- An improved extraction system design

Recent Major Accomplishments

- Agreed on layout with detectors
  - $L^* = 45$ m, dipole + compensating dipole within the detector volume
  - IR optics with large apertures, allowing collision debris effects at acceptable levels
- First design of betatron and energy collimation schemes
  - early studies of inefficiencies

Recent Major Accomplishments

- Operating scenarios and parameter evolution
  - started to explore options to max. luminosity
  - octupoles to improve beam stability
- Estimates and modeling of turn-around times, with impact on integrated luminosity
- Concept of fast-ramping of LHC, to be used as injector, has been explored
- Injection energy of the FCC has been reviewed and baseline confirmed, with alternatives to be explored

Recent Major Accomplishments

- First aperture model of complete machine has been achieved, providing means to study bottlenecks
- First inefficiency studies were performed, identifying the scale of the problem in the dispersion suppressor regions that now can be addressed
- Abort system and beam dump studies have begun in earnest
  - most likely fault — asynchronous abort — can be accommodated in a passive way

Recent Major Accomplishments

- Collision debris
  - bending region between IR's helps protect the next experiment as intended
  - now, how to handle the losses within the short arc between two IRs!!
    - will now work toward a loss-robust Dispersion Suppressor design

Let's see where we are from last year

A Short List of Key Issues for Further Study

- Optics and Layout √
  - Optics "module" development √
  - IR design; flat beam optics ~ options; MDI issues √
- Parameter interdependencies and optimization √
  - Overall parameter optimization √ **document exists**
  - Luminosity leveling procedures, algorithms √
  - Collimation system strategies ~
  - Corrector/adjustment system strategies ~√ **incl. octupole correctors**
  - Injection/extraction design √
  - Requirements pertinent to heavy ion operation **X**

A *Short* List of Key Issues for Further Study [2]

- Field quality, error analyses, adjustment systems **~√**
- Beam/environment interactions (beam screen, **√** vacuum, impedances, etc.)
  need more input, detail for impedances — ready for next level of detail
- Energy deposition and loss control/mitigation
  - Noise, emittance growth, lifetime and loss rates **~√**
  - Losses, energy deposition, protection **~√**
  - Cleaning inefficiency; full system optimization **~√**
  - Sacrificial protection for injection/extraction? **??**
  - True beam-beam limit **~√**
- Feedback systems and algorithms

see summary from RF session

A *Short* List of Key Issues for Further Study [3]

- Beam instrumentation and diagnostics **X**
- RF requirements **~√**
- Availability issues; turn-around time **~√**
- Sorting strategies, acceptance strategies
- … **need more work on EnDep codes, collimation, shower studies, IR protection, dispersion suppressor losses, IR cross-talk, etc..**

- General Tool Development
  - particle tracking, dynamic aperture, etc. **√**
  - optimization algorithms; design codes, … **√**
  - scripts, integrated models, visualization tools, … **√**

continue to improve visualization tools

A *Short* List of Key Issues for Further Study [4]

- Possible beam experiments **low-energy injection tests into the LHC**
  - modeling code/calculation verifications, etc.

possible parasitic profiting from HI-Lumi: flat optics, bb compensation, etc.

- Note: Collider design requires close interplay and feedback between hardware R&D and beam physics studies **very close interactions between magnet group and AP group, as well as with beam screen design group**
- Note: Strongly encourage junior colleague participation in all AP studies **√√**
  - it will be *their* collider **!!**

Concluding Remarks

- With a consistent “baseline” layout, optics, and parameter set now in hand, sensitivities and alternatives to various systems and parameters can be explored for possible improvements and further optimization
- Continue to further expand interactions with all the various hardware groups

For Next Year…

- Continue with the list…
  - everything is still growing in effort, and must continue — nothing is yet "good enough"
- Begin specification of beam instrumentation and diagnostics systems, especially any optics implications
- Begin studying heavy ion implications
- Address specific questions, such as:
  - how much loss (p/sec/meter) can we tolerate?

Conclusion

re-iterate:

- FCC-hh baseline exists
  - Great basis to evaluate and improve
- Next steps (in part already ongoing)
  - Develop functional specifications with hardware teams
    - Some loops are required
  - Tradeoffs need to be made between systems
    - More integrated studies and modelling
  - Local optimisation of systems
  - Study alternatives (e.g. extended straight sections, injection energy)
- Goal is to arrive at better baseline
  - We want something good for the CDR
  - We know it will be even better in the real machine
- Your contributions are most welcome

Many thanks to all the great teams