MICHIGAN STATE UNIVERSITY

Very Large Hadron Collider

FCC-hh Summary

Mike Syphers

Special thanks:

- D. Schulte, U. Wienands, S. Peggs
- M. Benedikt, F. Zimmermann
- ***All* presenters**
- B. Strauss; S. Nagaitsev

NSCL | CERN | FCC hh ee he | U.S. DEPARTMENT OF ENERGY | Office of Science

FCC Week
27 March 2015

FCC-hh Presentations

Lessons from SSC and VLHC	*Michael SYPHERS*	
ROOM A, Marriott Georgetown Hotel		08:30 - 08:50
SPPC	*Jingyu TANG*	
ROOM A, Marriott Georgetown Hotel		08:50 - 09:10
LHC experience	*Oliver BRUNING*	
ROOM A, Marriott Georgetown Hotel		09:10 - 09:30
Layout and arc lattice design	*Barbara DALENA*	
ROOM A, Marriott Georgetown Hotel		09:30 - 09:50

Arc vacuum considerations and design	*Cedric GARION*	
ROOM A, Marriott Georgetown Hotel		13:30 - 13:50
Single beam collective effects	*Uwe NIEDERMAYER*	
ROOM A, Marriott Georgetown Hotel		13:50 - 14:10
RF system and feedback		
ROOM A, Marriott Georgetown Hotel		14:10 - 14:30
Electron cloud effects and mititgation	*kazuhito OHMI*	
ROOM A, Marriott Georgetown Hotel		14:30 - 14:50

FCC-hh Presentations [2]

MDI Overview	*Werner RIEGLER*	
ROOM A, Marriott Georgetown Hotel	15:30 - 15:50	
Interaction region design	*Andrei SERYI*	
ROOM A, Marriott Georgetown Hotel	15:50 - 16:10	
Parameters and luminosity performance	*Xavier BUFFAT*	
ROOM A, Marriott Georgetown Hotel	16:10 - 16:30	
FCC-hh as a heavy-ion collider	*John JOWETT*	
ROOM A, Marriott Georgetown Hotel	16:30 - 16:50	

Wednesday

Beam-beam effects	*Vladimir SHILTSEV*
ROOM A, Marriott Georgetown Hotel	10:30 - 10:50
Collimation system design	*Maria FIASCARIS*
ROOM A, Marriott Georgetown Hotel	10:50 - 11:10
Injection and extraction	*Wolfgang BARTMANN*
ROOM A, Marriott Georgetown Hotel	11:10 - 11:30
Injector considerations	*Brennan GODDARD*
ROOM A, Marriott Georgetown Hotel	11:30 - 11:50

FCC-hh Contributed Talks

Wednesday

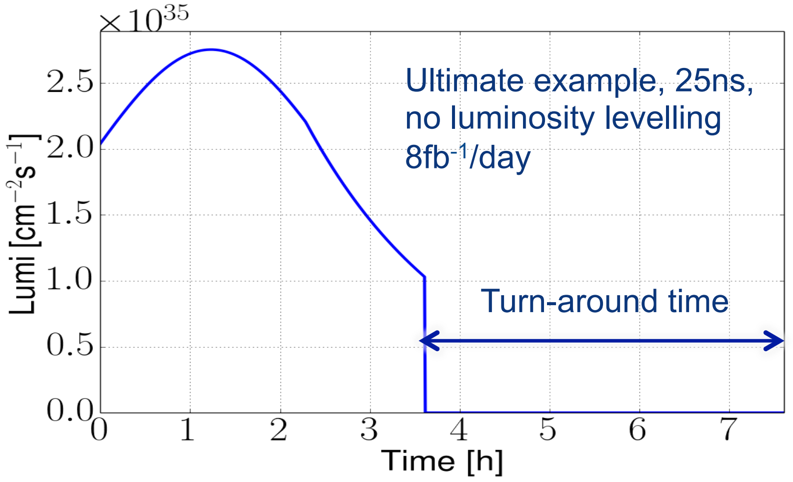
Concept of a Collimation System with Enhanced Operational Stability and Performance	*Ralph Wolfgang ASSMANN*
Design issues of the LHC as injector	*Werner HERR*
ROOM A, Marriott Georgetown Hotel	13:50 - 14:05
Focusing and Space Charge Compensation of Beams with Electron Columns	*Kathrin SCHULTE*
ROOM A, Marriott Georgetown Hotel	14:05 - 14:20
Emittance evolution in hadron colliders	*Valeri LEBEDEV*
ROOM A, Marriott Georgetown Hotel	14:20 - 14:35
Scaling behavior of circular colliders	*Richard TALMAN*
ROOM A, Marriott Georgetown Hotel	14:35 - 14:50

Thursday

Trigger and data acquisition challenges and possible technology evolution over the next two decades	*Wesley SMITH*
ROOM C, Marriott Georgetown Hotel	15:30 - 16:00
Performance requirements for Hadron Calorimeters	*Sergei CHEKANOV*
ROOM C, Marriott Georgetown Hotel	16:00 - 16:20
Beam losses and collision debris studies in Europe	*Maria Ilaria BESANA*
ROOM C, Marriott Georgetown Hotel	16:20 - 16:40
FCC-hh beam losses and radiation	*Nikolai MOKHOV*
ROOM C, Marriott Georgetown Hotel	16:40 - 17:00

Highlights from Presentations Include…

- Sharing of Experience — VLHC, SSC, LHC, Tev, …
- Lattice and optics; scaling laws
- Energy deposition, beam loss, collimation/protection
- IR design and MDI requirement development
- Many recent computational tool developments
- Beam-beam limits and luminosity optimization
- Injection/extraction issues; injector
- Beam screen development
- FCC-he investigations
- Many other topics…



Parameters and Preliminary Layout

Two main experiments
Baseline also two other experiments

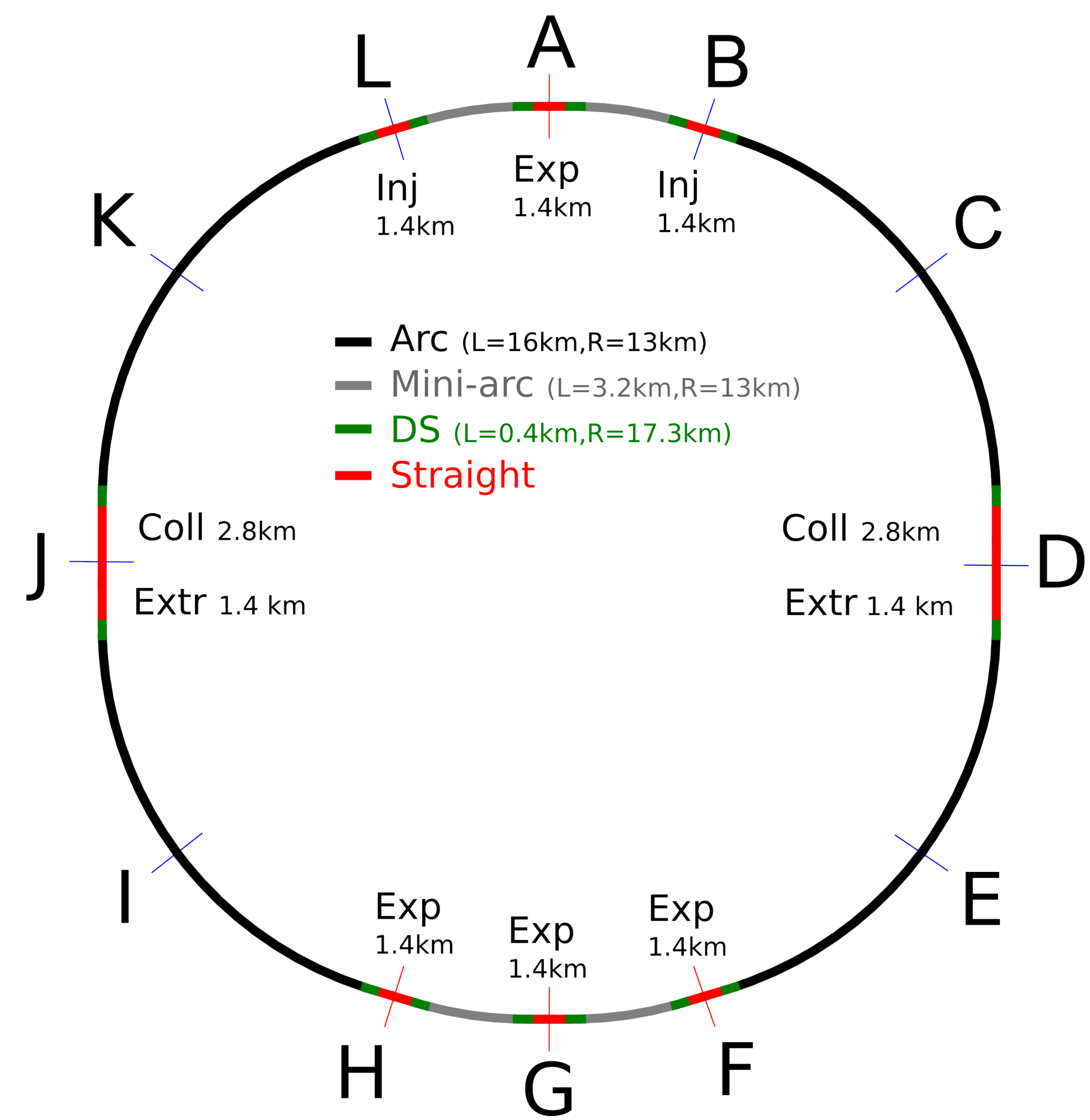
Baseline
- Promise
- Goal 250fb^{-1} per year
    - 2fb^{-1} per day
- focus on 25ns spacing

Ultimate
- reasonable hope
- goal 1000fb^{-1} per year
- more emphasis on 5ns

Assume 5 year operation cycles
- 3.5 year run
- 0.75-1.0 year for stops, MDs etc.
- 70% efficiency
- 625-700 effective days per year

	Baseline	Ultimate
Luminosity [10^{34}cm^{-2}s^{-1}]	5	20
Bunch distance [ns]	25 (5)	
Background events/bx	170 (34)	680 (136)
Bunch charge [10^{11}]	1 (0.2)	
Norm. emitt. [μm]	2.2(0.44)	
RMS bunch length [cm]	8	
IP beta-function [m]	1.1	0.3
IP beam size [μm]	6.8 (3)	3.5 (1.6)
Max ξ for 2 IPs	0.01 (0.02)	0.03
Crossing angle [σ']	12	Crab. Cav.
Turn-around time [h]	5	4

iminary Layout



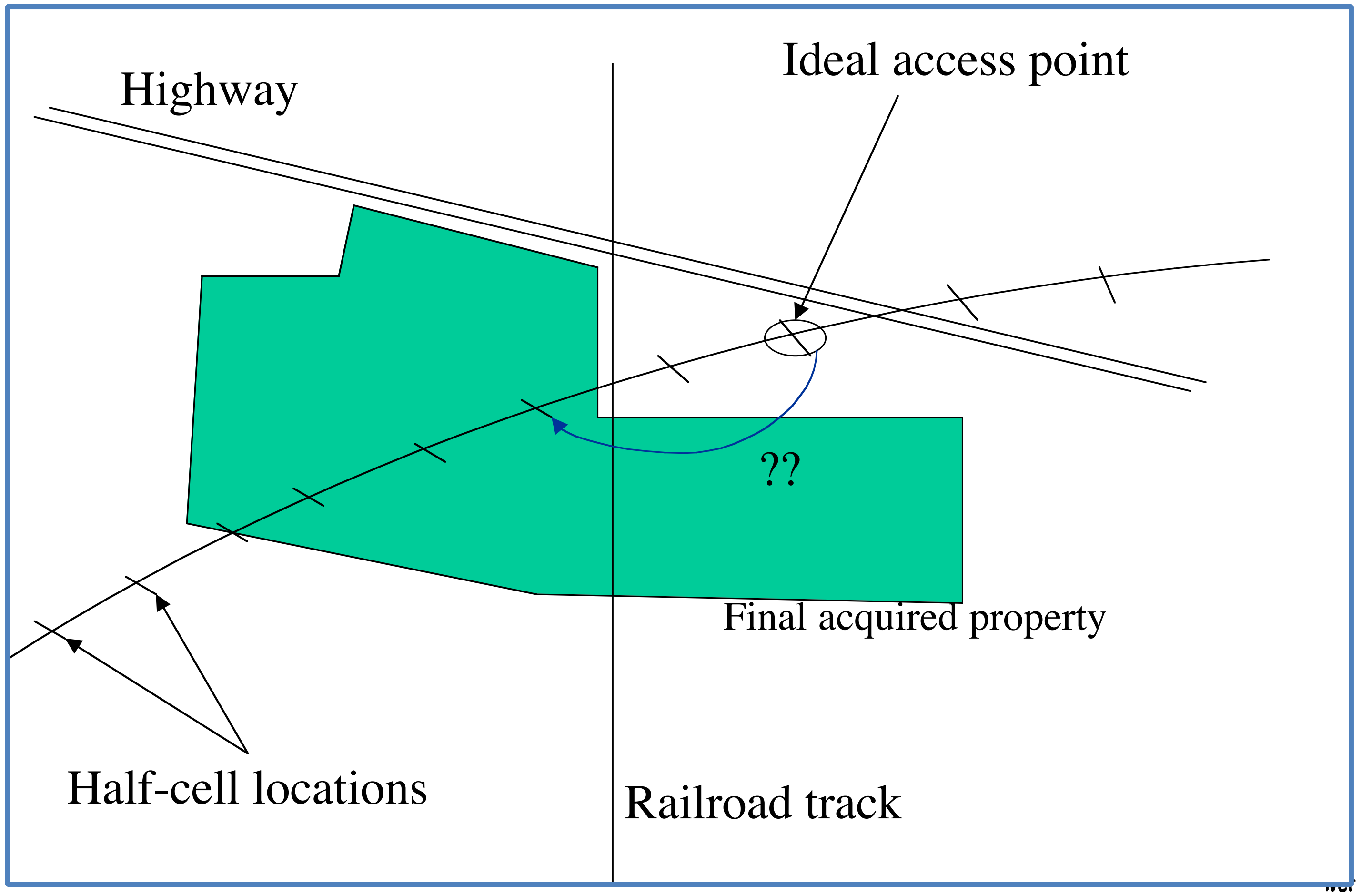
- Insertion lengths are based on first order estimates, will be reviewed as optics designs are made

Modularity and the Need for "Space"

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

modularity in the final layout

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



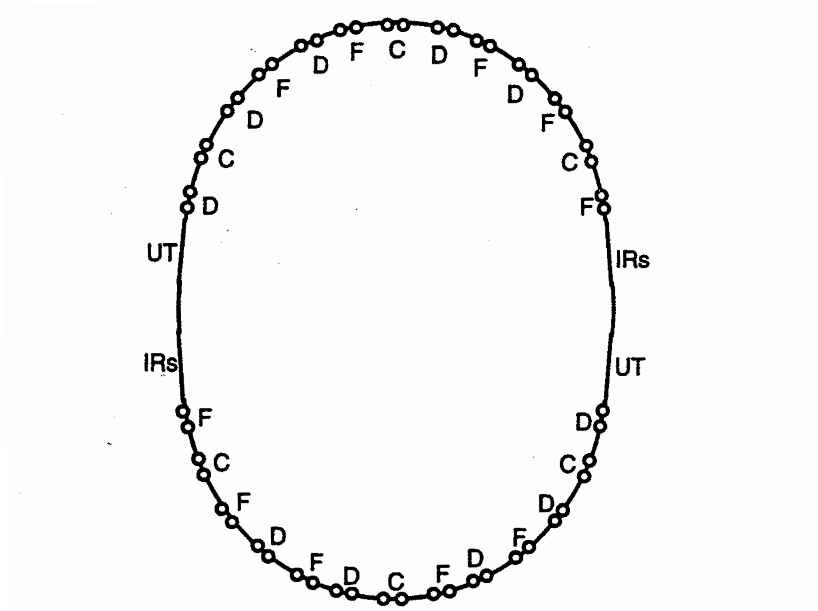


Figure 7-1. Schematic Layout of the Free Space in the Collider.

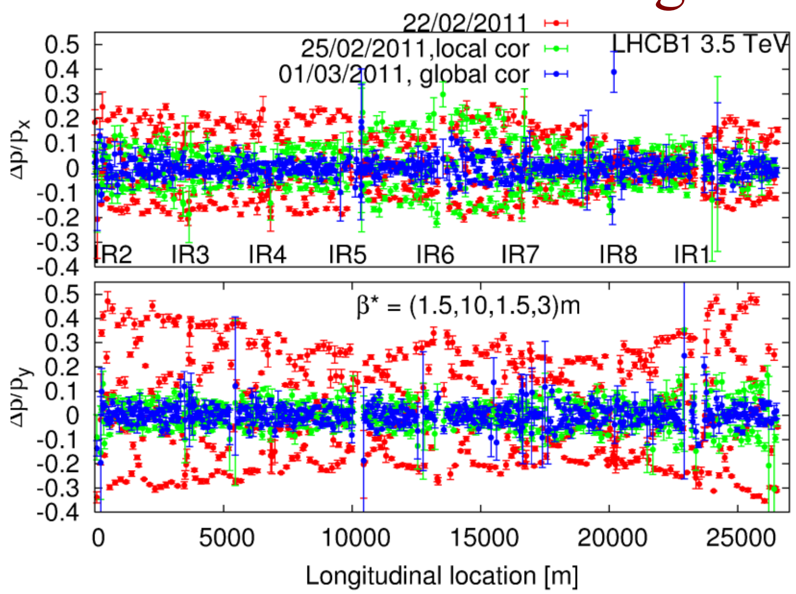
M. Syphers

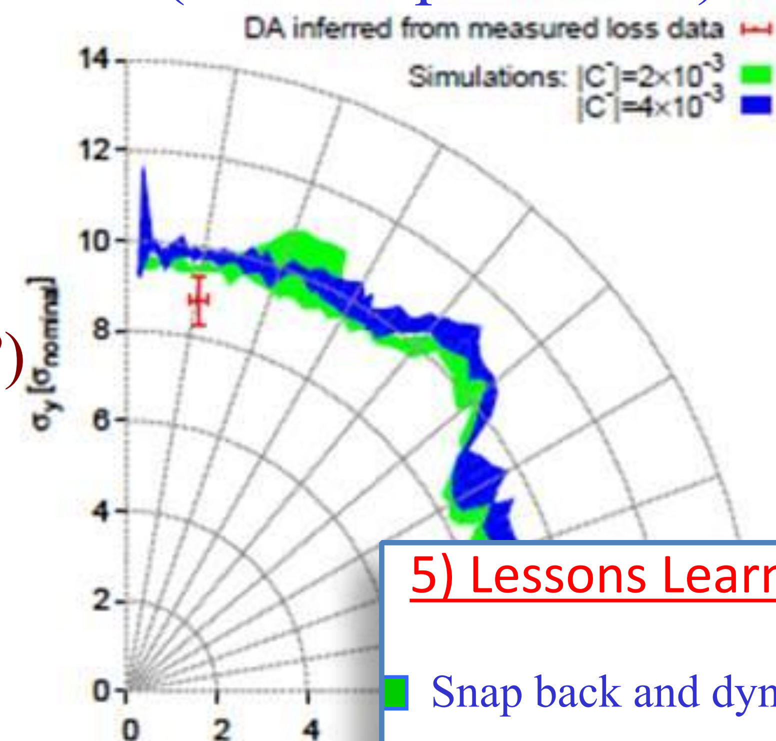
Lessons from SSC and VLHC

LHC Experience

O. Bruning

- Field Quality and Dynamic Aperture (factor 2 prediction)
  - ➔ Excellent DA thanks to sorting and manet quality!
  - ➔ Excellent Agreement for LHC (No noise from PC and RF? Excellent knowledge of optic?)





5) Lessons Learned from Commissioning & Run I

- Snap back and dynamic effects under control thanks to detailed magnet measurements (no need for reference magnets)
  - ➔ LHC achieved very good machine reproducibility and stability!
- Machine reproducibility is key for high efficiency of the cleaning insertions and for Machine Protection
- Losses in the Dispersion Suppressor:
  - ➔ Integrate already @ design stage collimators into the dispersion suppressor

Report on SPPC

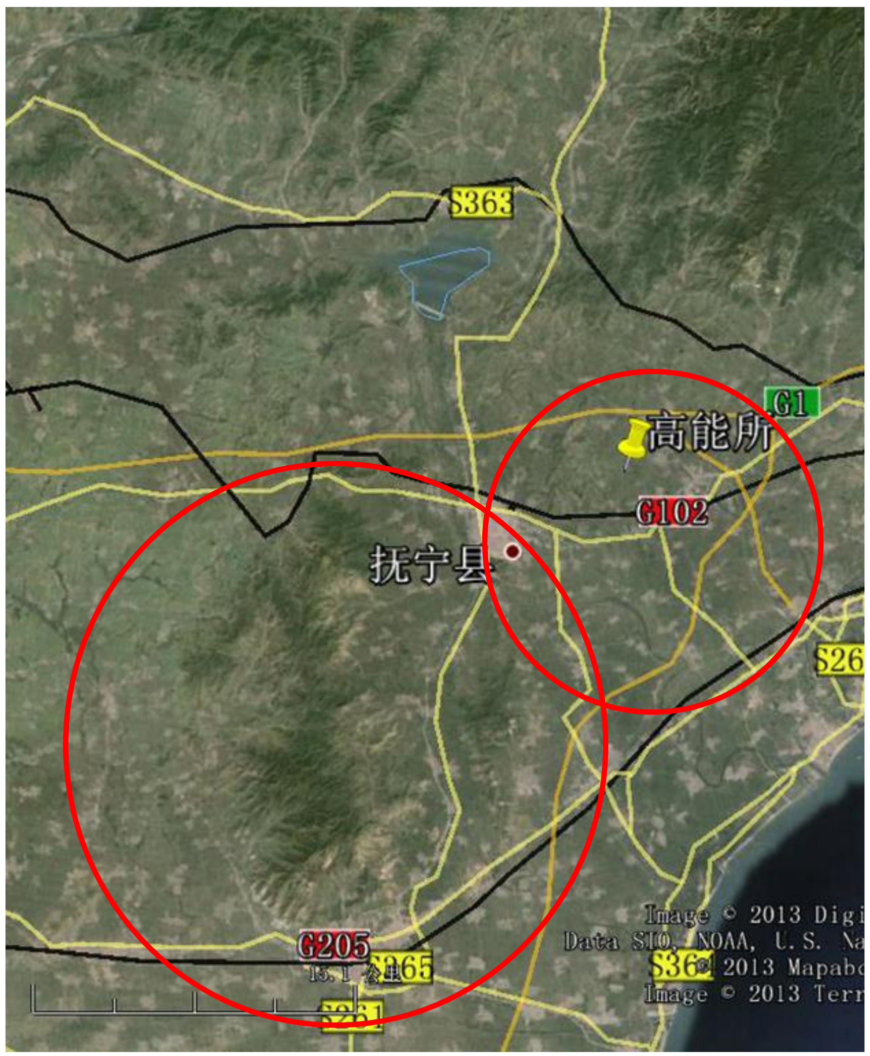
J. Tang

CEPC –SPPC Site Selection

A candidate is QinHuangDao (秦皇岛)

3 ho

300 km from Beijing

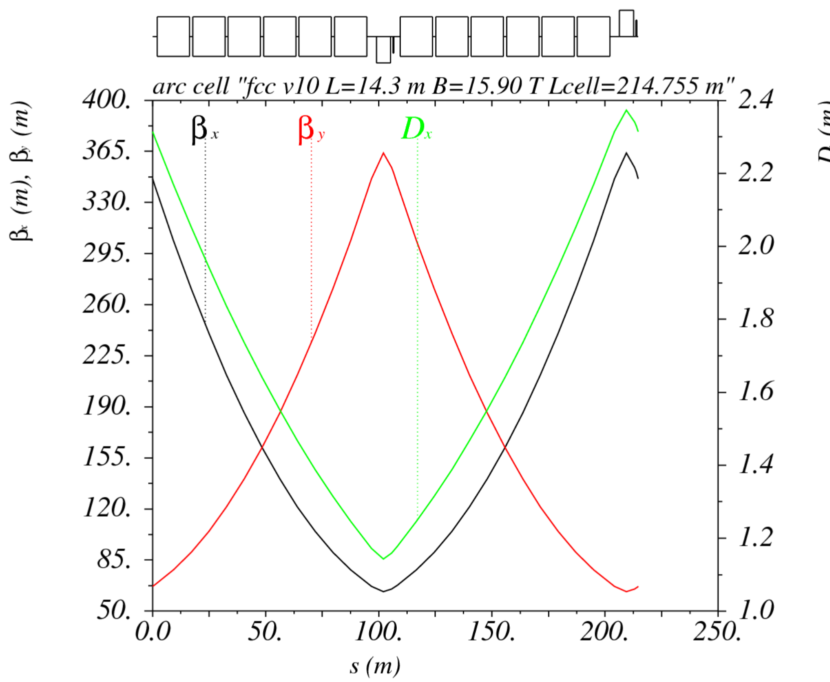


SPPC main parameters

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 (4)	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56.9	W/m

FCC-hh Lattice Design

B. Dalena



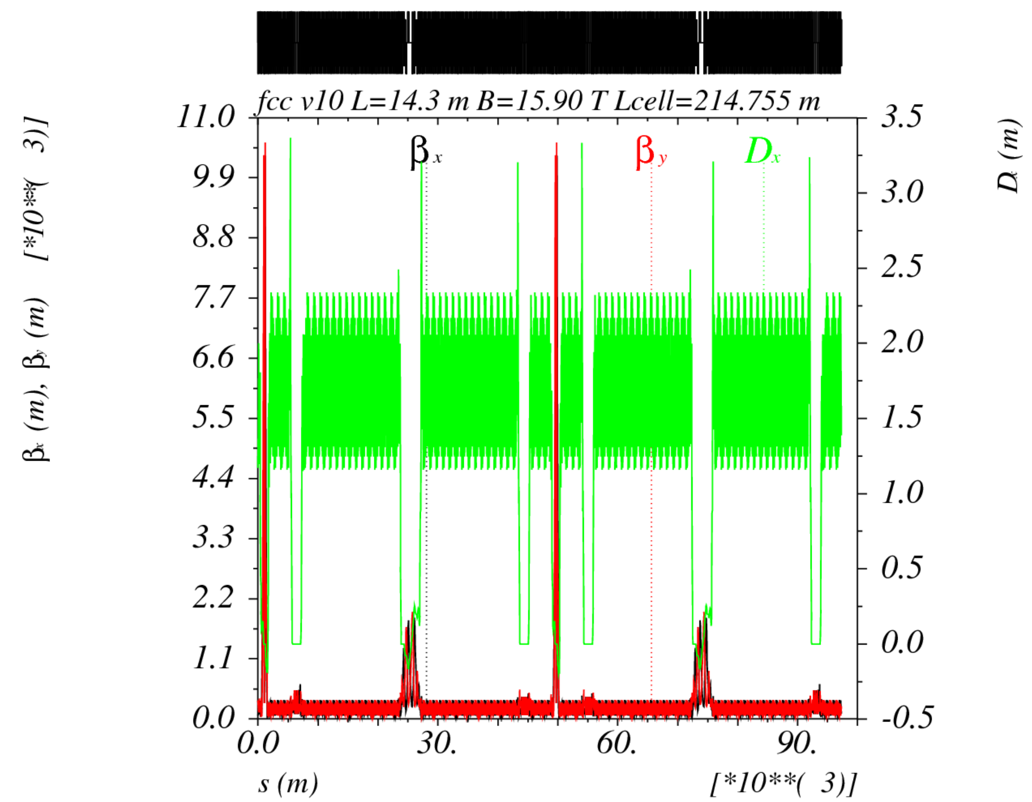
# dipoles	B max [T]	Length [m]
4368	15.90	14.3

# quadrupoles	G max/min [T/m]	Length [m]
812*	356/-356.26	6.29

# sextupoles	G max/min [T/m²]	Length [m]
700	-7144.37/ 3551.32	0.5 (fixed)

Some Lattice parameters

Parameter	value
Bρ [T m]	166667
γ	53289
$\gamma_{transition}$	97
α	0.0001
β* [m]	1.1
Natural chromaticity x/y	-196./-197.
Equilibrium emittance* [m rad]	1e-12
$\varepsilon_{norm}/\beta\gamma$ [m rad]	4.1e-11
Transverse/Longitudinal Damping time** [h]	2/1



* $\varepsilon_{eq} = \frac{C_q \gamma^2 I_5}{I_2\left(1-\frac{I_4}{I_2}\right)}$

** $\tau_t = \frac{2E_0 T_0}{U_0}$ $\tau_l = \frac{2E_0 T_0}{U_0\left(2+\frac{I_4}{I_2}\right)}$

B. Dalena, FCC week 2015 10

Scaling of Optics Design

R. Talman

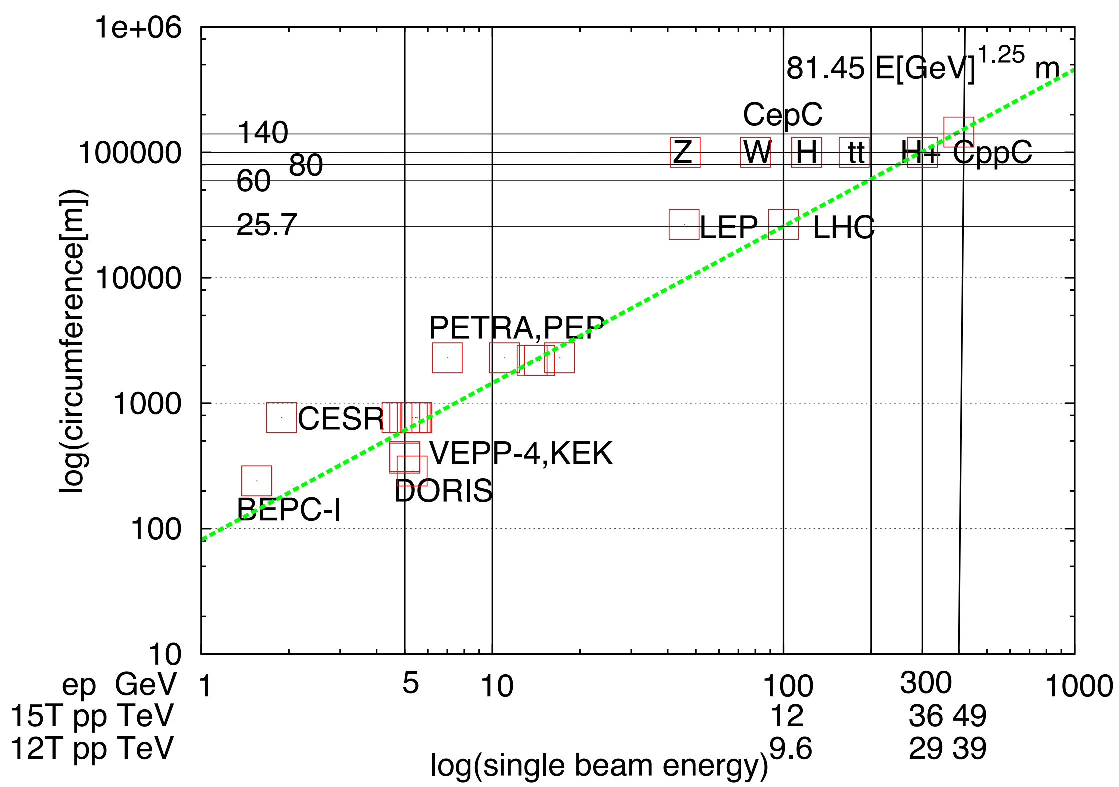


Figure: Dependence of circumference on beam energy, both for GeV-scale electron colliders, and for TeV-scale proton colliders of magnetic field 12T or 15T.

Parameter	Symbol	Proportionality	Scaling
phase advance per cell	μ		1
collider cell length	L_c		$R^{1/2}$
bend angle per cell	ϕ	$= L_c/R$	$R^{-1/2}$
quad strength $(1/f)$	q	$1/L_c$	$R^{-1/2}$
dispersion	D	ϕL_c	1
beta	β	L_c	$R^{1/2}$
tunes	Q_x, Q_y	R/β	$R^{1/2}$
Sands's "curly H"	$\mathcal{H}$	$= D^2/\beta$	$R^{-1/2}$
partition numbers	$J_x/J_y/J_\epsilon$	$= 1/1/2$	1
horizontal emittance	ϵ_x	$\mathcal{H}/(J_x R)$	$R^{-3/2}$
fract. momentum spread	σ_δ	$\sqrt{B}$	$R^{-1/2}$
arc beam width-betatron	$\sigma_{x,\beta}$	$\sqrt{\beta\epsilon_x}$	$R^{-1/2}$
-synchrotron	$\sigma_{x,synch.}$	$D\sigma_\delta$	$R^{-1/2}$
sextupole strength	S	q/D	$R^{-1/2}$
dynamic aperture	$x^{\max}$	q/S	1
relative dyn. aperture	$x^{\max}/\sigma_x$		$R^{1/2}$
pretzel amplitude	x_p	σ_x	$R^{-1/2}$

Table: *Constant dispersion* scaling is the result of choosing cell length $L \propto R^{1/2}$. The entry "1" in the last column of the shaded "dispersion" row, indicates that the dispersion is independent of R when the cell length L_c varies proportional to $\sqrt{R}$ with the phase advance per cell μ held constant.

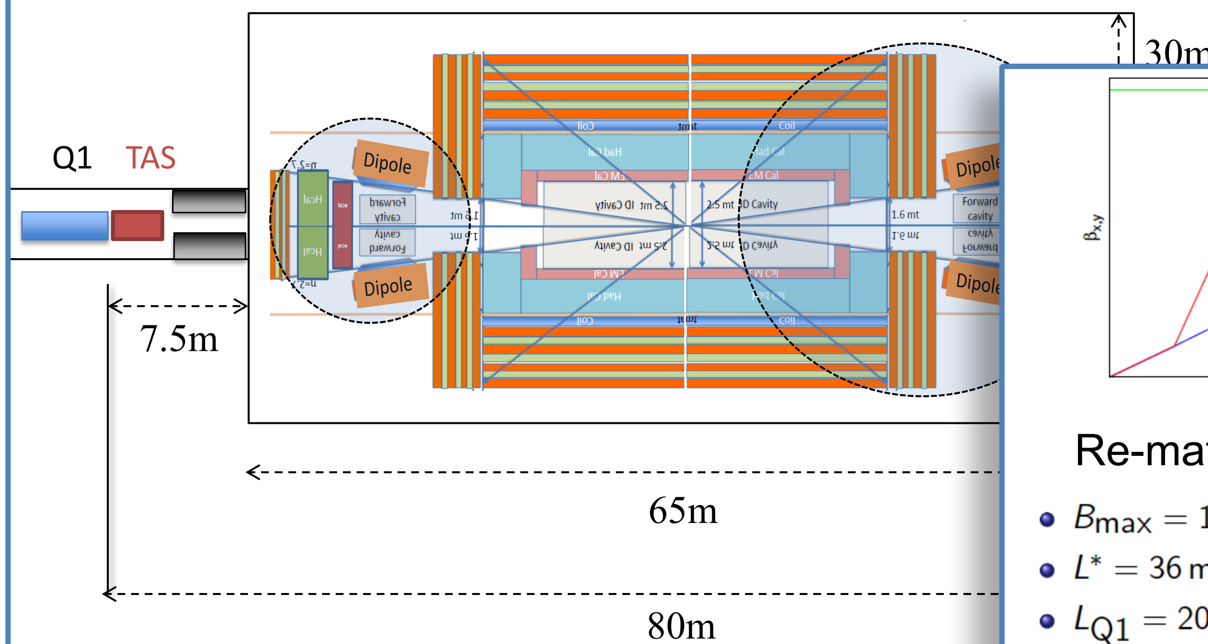
FCC-hh cell parameters, etc., … "about right"

IR Design Studies and Machine-Detector Interface

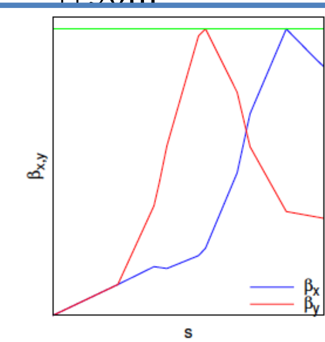
L* > 40m

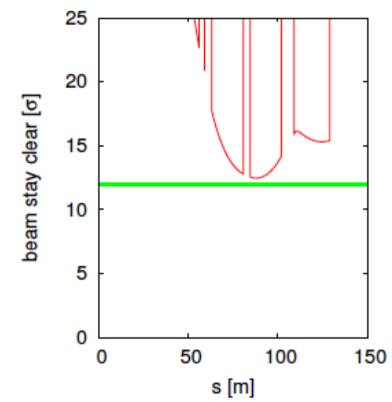
L* >40m allows the the triplet (Q1-Q3) and the triplet shielding (TAS) to be 'hidden' in the tunnel

→ very comfortable situation for cavern infrastructure and ALARA related items.



A. Seryi





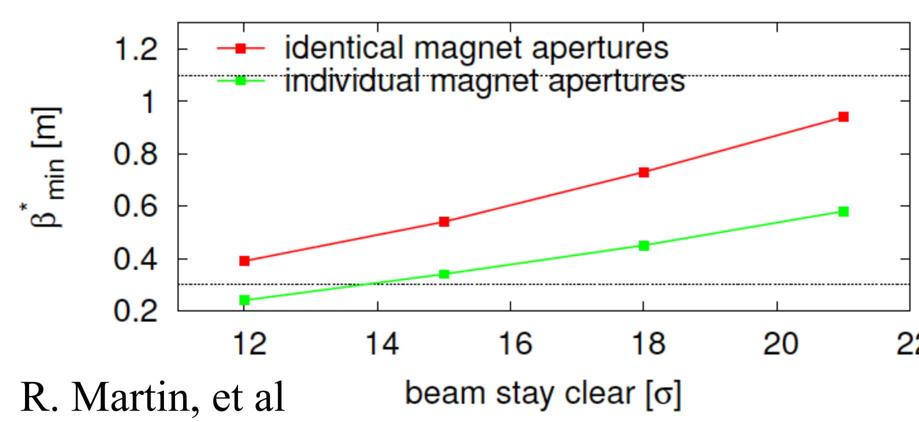
Checking beam stay clear

Re-matched triplet

- $B_{max} = 11$ T
- $L^* = 36$ m
- $L_{Q1} = 20$ m
- Beam stay clear $= 12\,\sigma$
- Beam separation $= 12\,\sigma$
- Shielding = 15 mm
- Further layers:
  - Cold bore: 2.0 mm
  - Kapton insulator: 0.5 mm
  - LHe: 1.5 mm
  - Beam screen: 2.05 mm
  - Beam screen insulator: 2.0 mm

Initial results for stay clear vs beta*

closed orbit uncertainty = 0.001 m

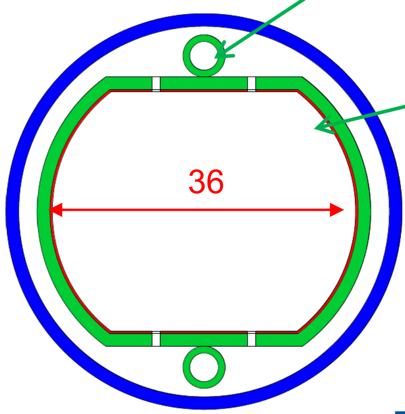


R. Martin, et al

Beam Screen and Photon Absorber

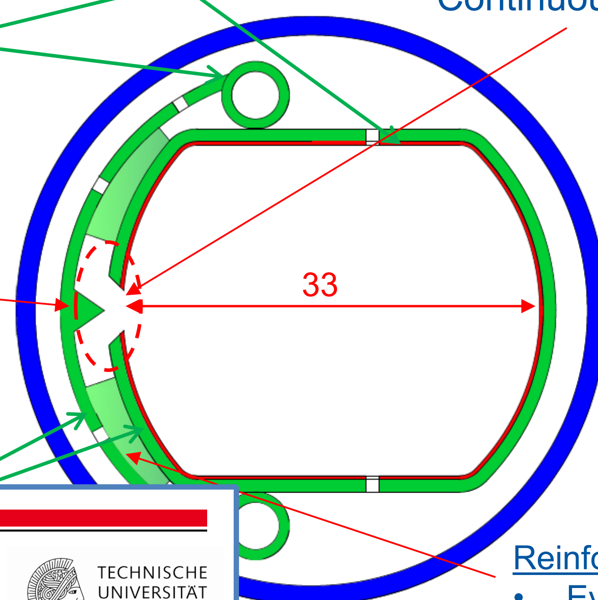
Cooling tube:
- Heat transfer coefficient: 150 W/(K.m^2)
- Refrigerant temperature: 40 K

Copper layer:
- 0.3mm,
- k ~ 700 W/(m.K),
- σ_y = 70 MPa



LHC-like BS solution

V-shaped SR abs.



Continuous slot

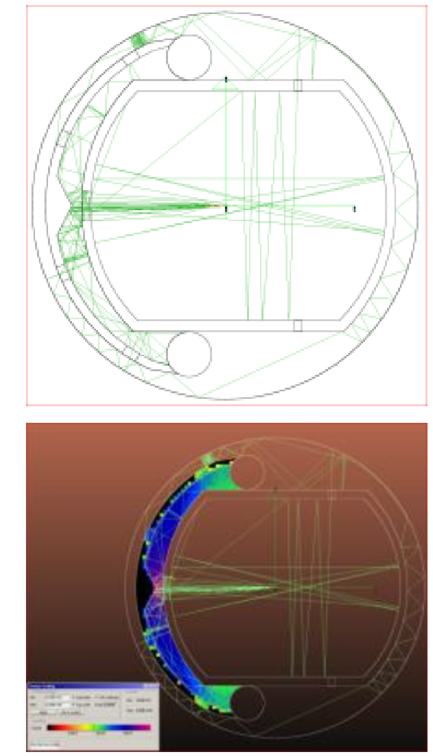
P506:
- 1 mm

Reinforcement
- Every 200m

BS solution asymmetric

C. Garion

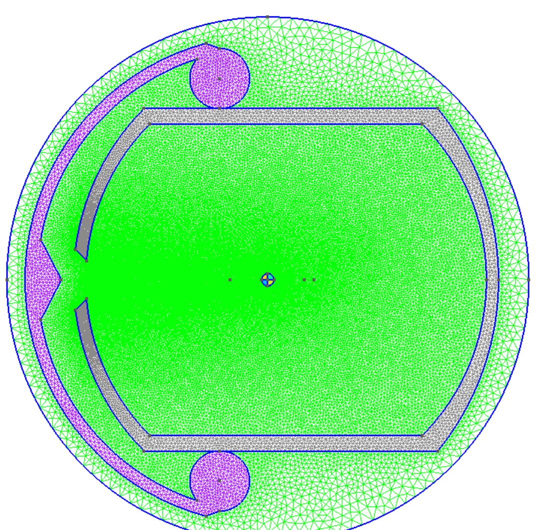
C. Garion,
U. Niedermayer,
et al.



Monte Carlo simulations of photon distribution

Discretization

TECHNISCHE UNIVERSITÄT DARMSTADT



GMSH (Geuzaine et al.) triangular mesh

Meshing the whole structure is required only for extremely low frequency!

Otherwise: **S**urface **I**mpedance **B**oundary **C**ondition (SIBC)

Thilo Egenolf, TU Darmstadt

24 March 2015 | TU Darmstadt | Fachbereich 18 | Institut Theorie Elektromagnetischer Felder | Uwe Niedermayer | 4

2D Simulations in the Frequency Domain

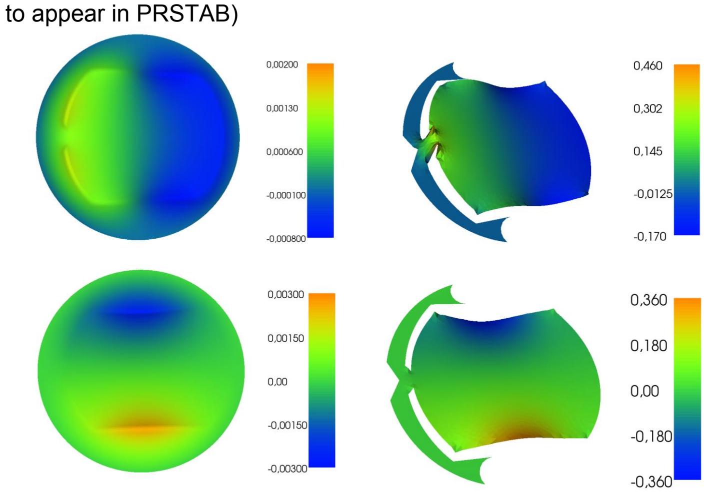
TECHNISCHE UNIVERSITÄT DARMSTADT

- BeamImpedance2D, PYTHON code using FEniCS finite element toolbox (U. Niedermayer et al., to appear in PRSTAB)

$\mathrm{Re}\{E_z\}$

Horizontal

Vertical



f=100Hz　　f=1MHz

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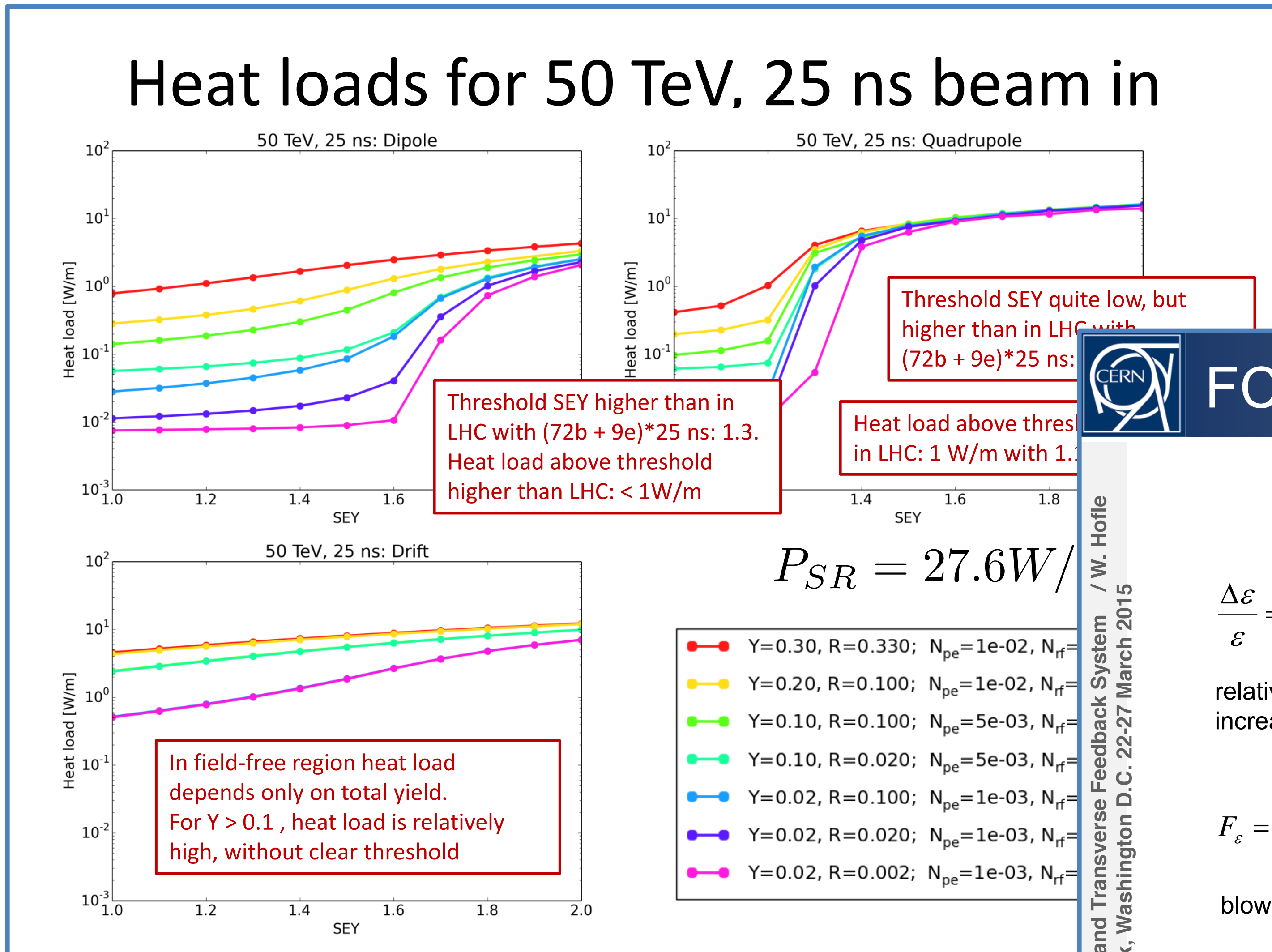
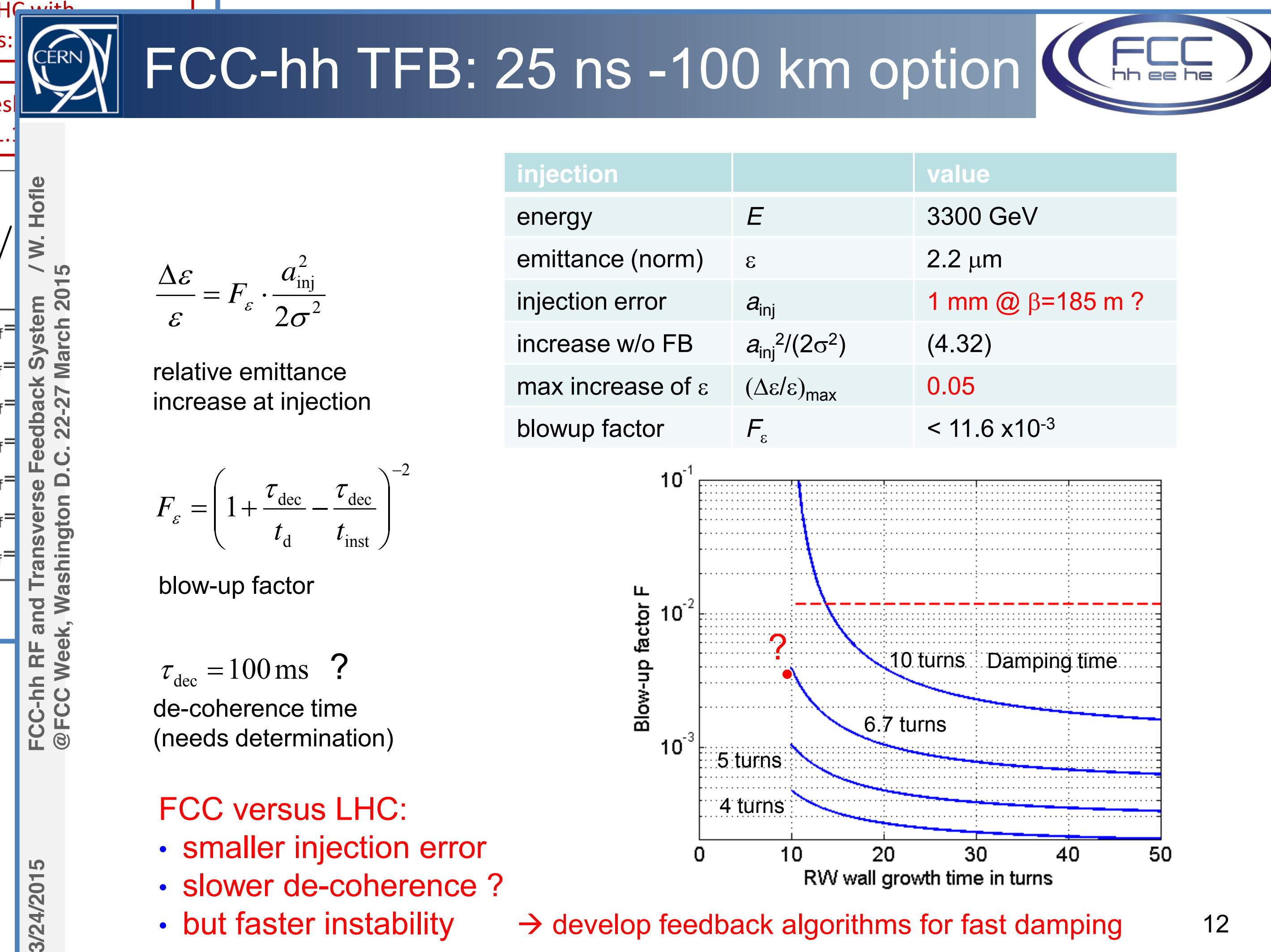
Heat Loads & Beam Instabilities



K. Ohmi

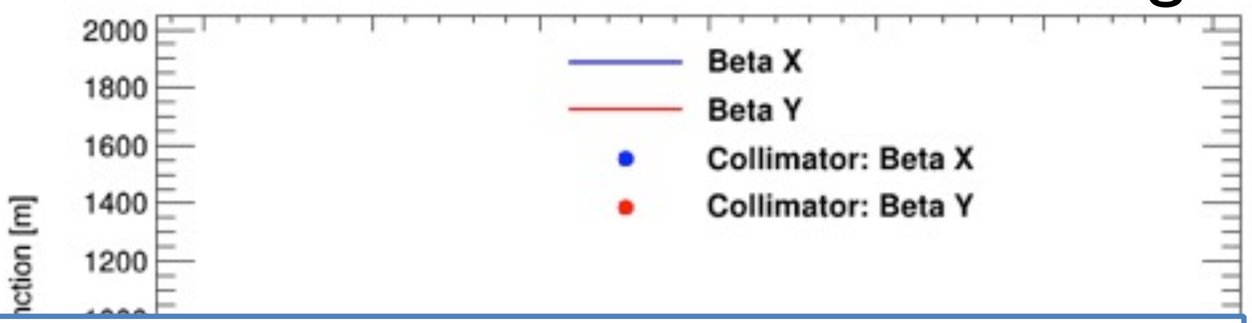
W. Hofle



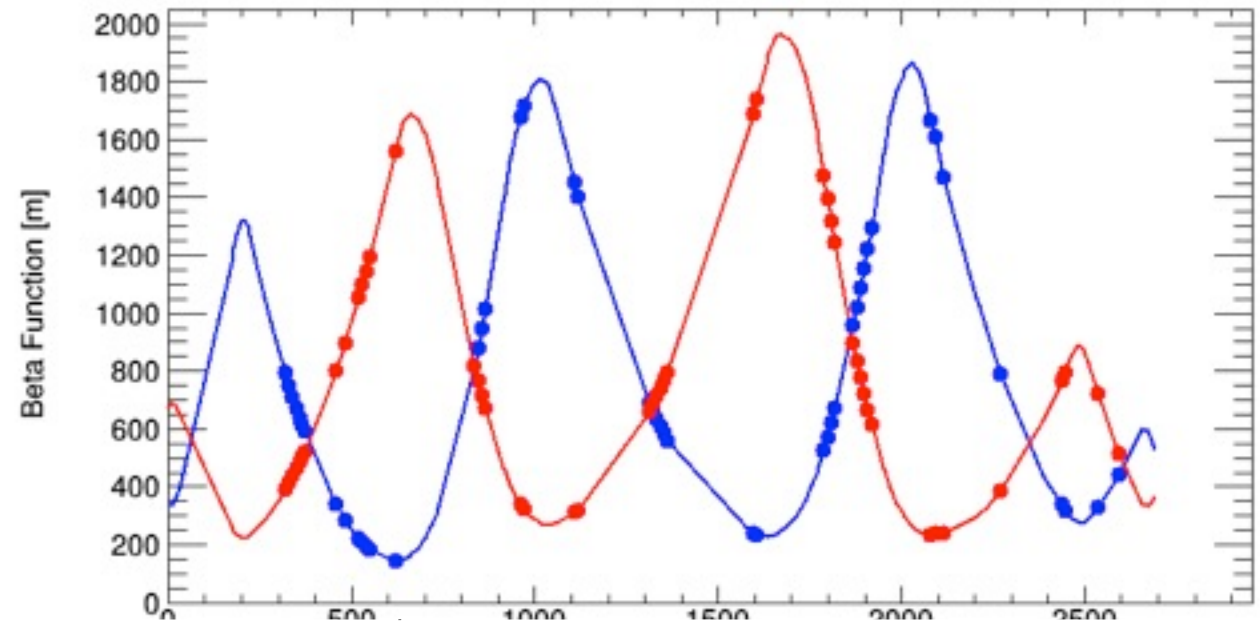
FCC Collimation — Scaling from LHC

M. Fiascaris

LHC IR7 - betatron cleaning

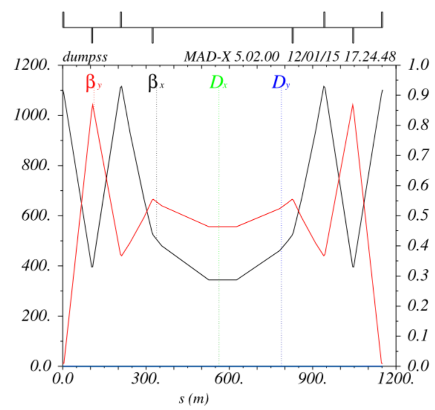


FCC IR2 - betatron cleaning

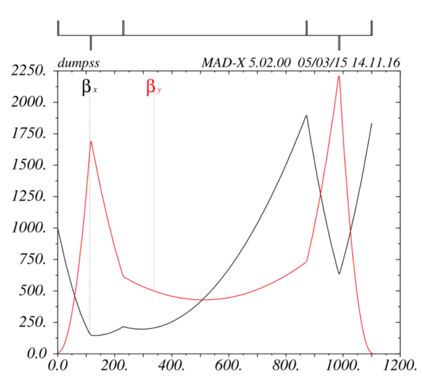


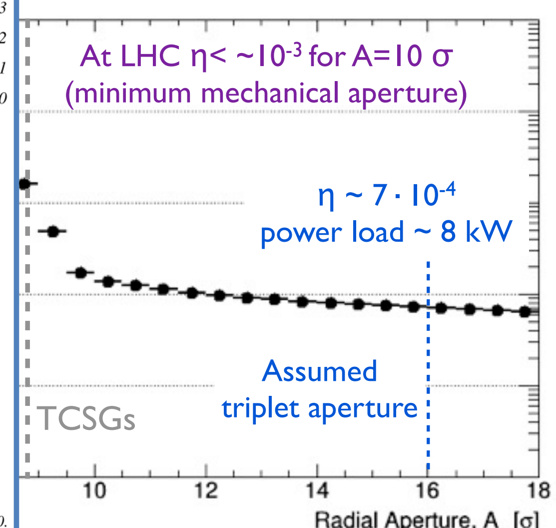
Dump insertion alternatives

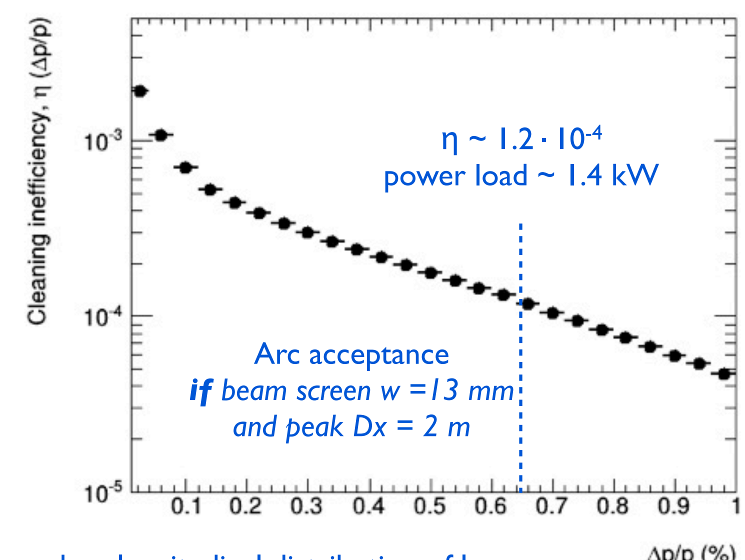
SSC like
- Septum is part of extraction bump
- Use field free channel of septum to extract
- Need strong, good field quality septum



- Asymmetric insertion optics
  - Avoid asynchronous dumps by accepting single kicker erratic
  - High segmentation of kicker system (200-300 modules)
  - Asymmetric optics
    - to reduce oscillation from single kicker failure (small hor beta)
    - to reduce kicker strength and dilute beam at absorbers (high betas at septum)





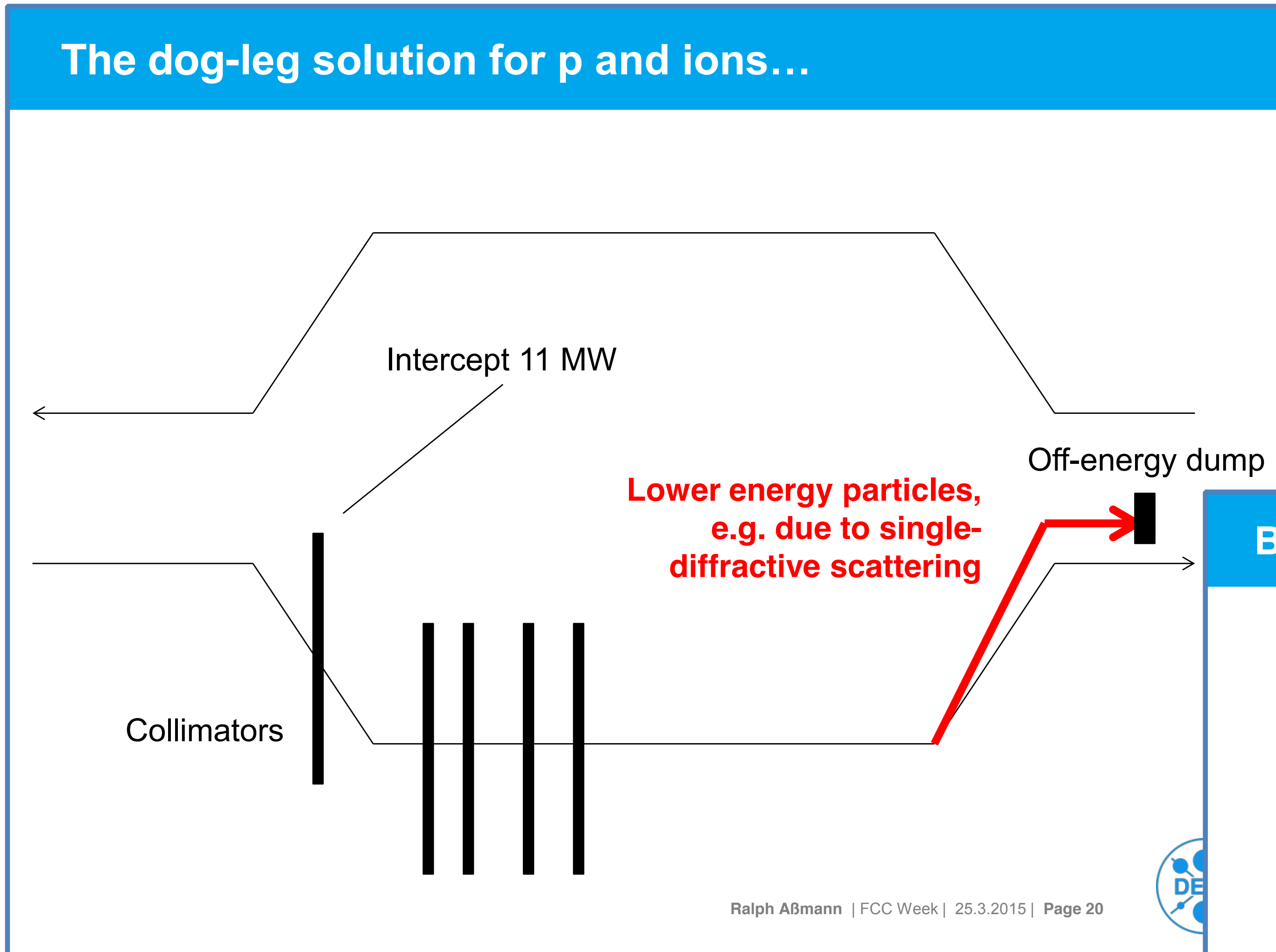


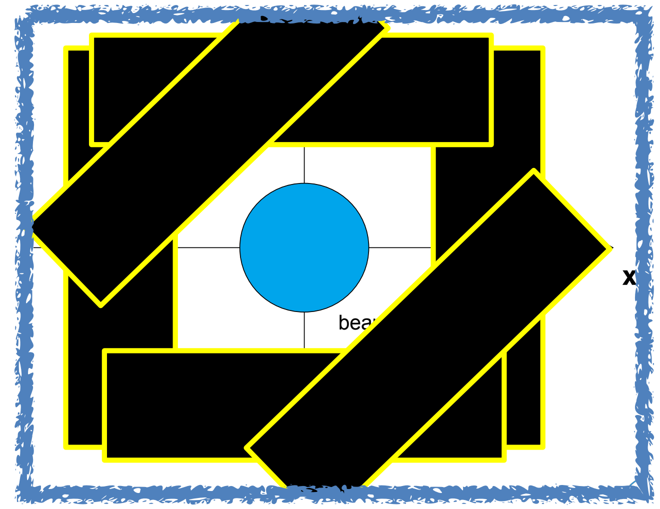
Power loads on cold elements will depend on longitudinal distribution of losses

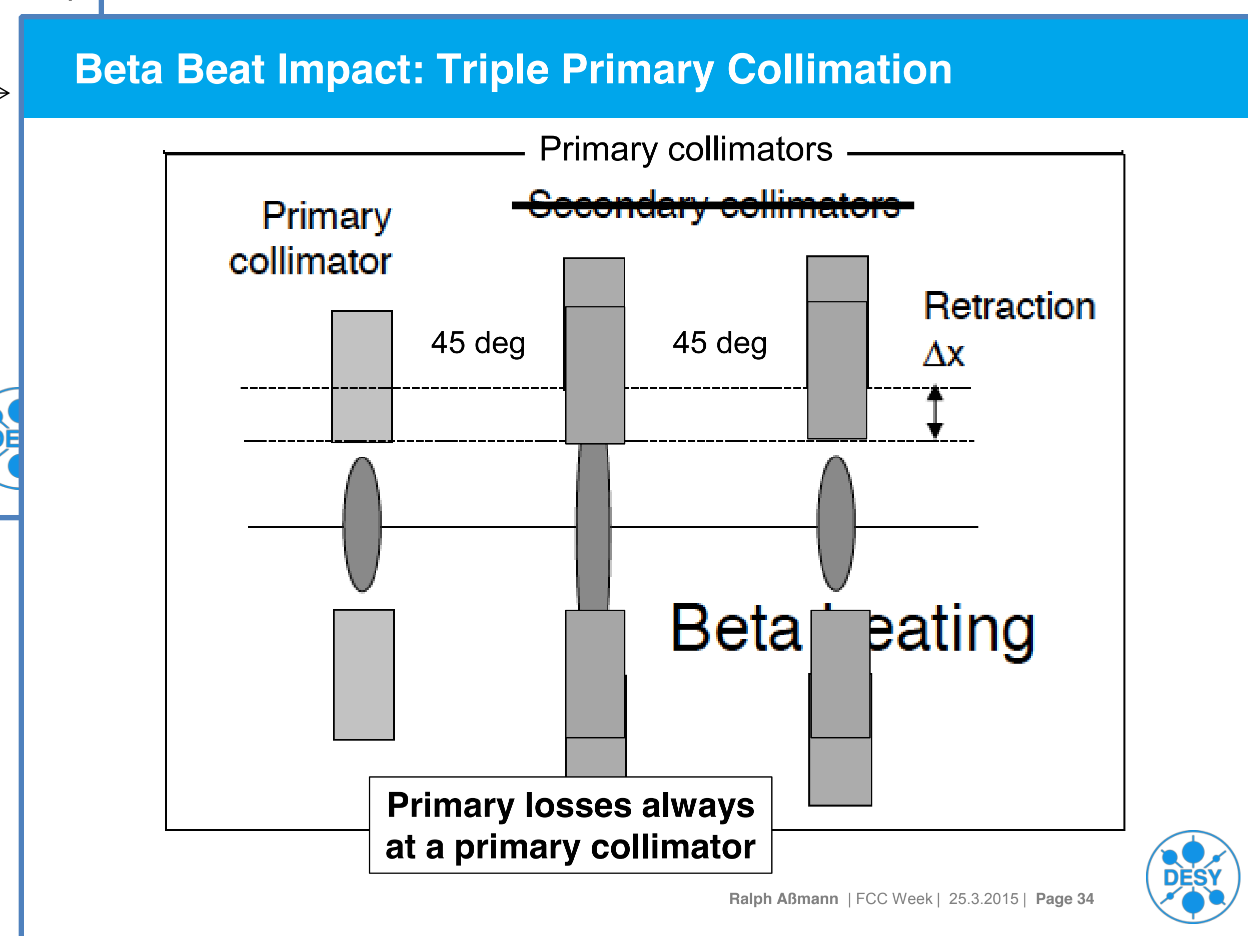
Maria Fiascaris 17 FCC week 24/03/2015

Beam Collimation Systems

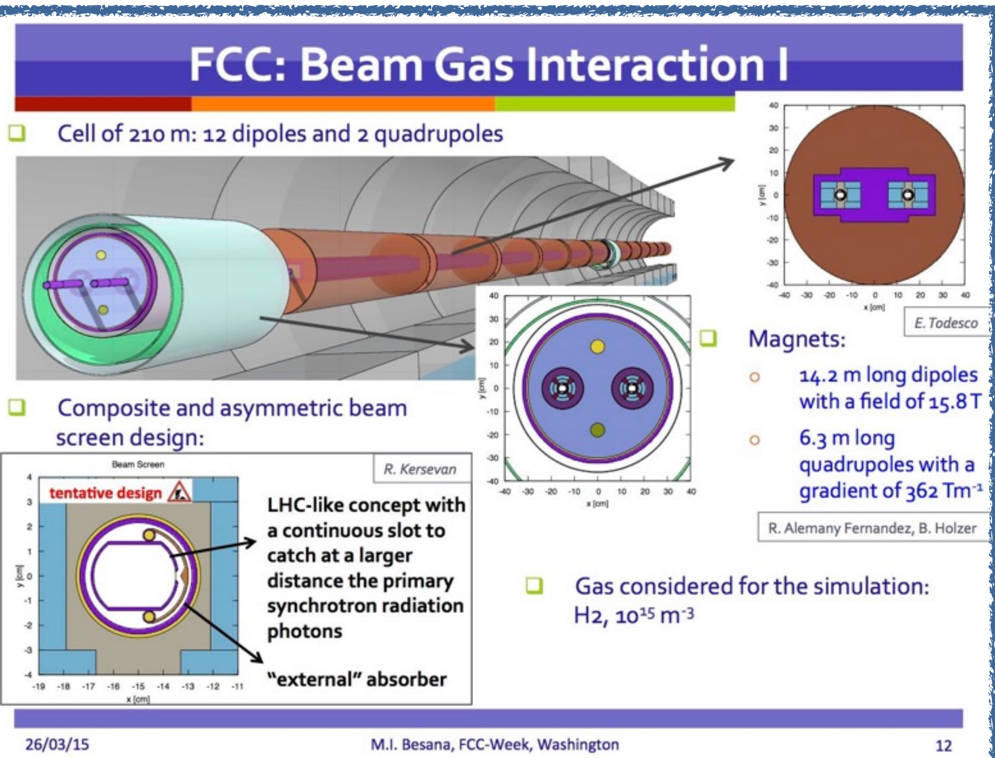
R. Assmann



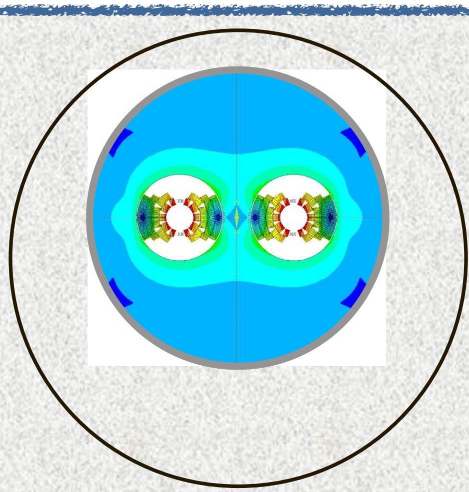




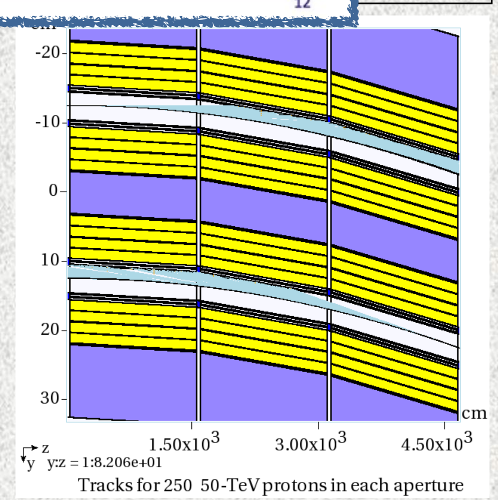
Energy Deposition Modeling



M. Besana



16-T dual-aperture Nb_3Sn dipole with Ti-collar, in 1-m diameter cryostat envelope (A. Zlobin)



MARS15-modelled synchrotron photon emission: ~30 W/m/aperture deposited by keV electrons in dipole beam-pipe (slits in dipoles and photon absorbers in interconnect regions, see my talk at the magnet session)

FCC Week, Washington, DC, March 23-27, 2015 FCC-hh: Beam Loss, IP Debris & MDI - N.V. Mokhov 7

Summary

- **IP collision debris**: dominant at multi-TeV pp colliders; hard to deal with but manageable up to HL-LHC. Challenging at FCC-hh – especially in its Phase II - for inner triplet, neutral beam dump and beyond. The FCC-hh inner triplet based on large-aperture cos-theta Nb_3Sn quads with a room for thick tungsten inserts is a solution with R&D on rad-hard insulation! 20-T HTS schemes also deserve consideration for IT quads

  Machine-induced backgrounds: manageable for multi-TeV proton beams with appropriate multi-component collimation systems far from IP and in the IP vicinity

  Full simulations for FCC-hh are needed in iterations with detector, IR lattice and magnet designers

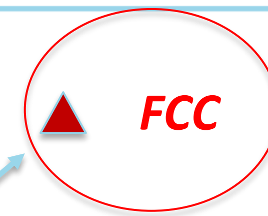
FCC Week, Washington, DC, March 23-27, 2015 FCC-hh: Beam Loss, IP Debris & MDI - N.V. Mokhov 23

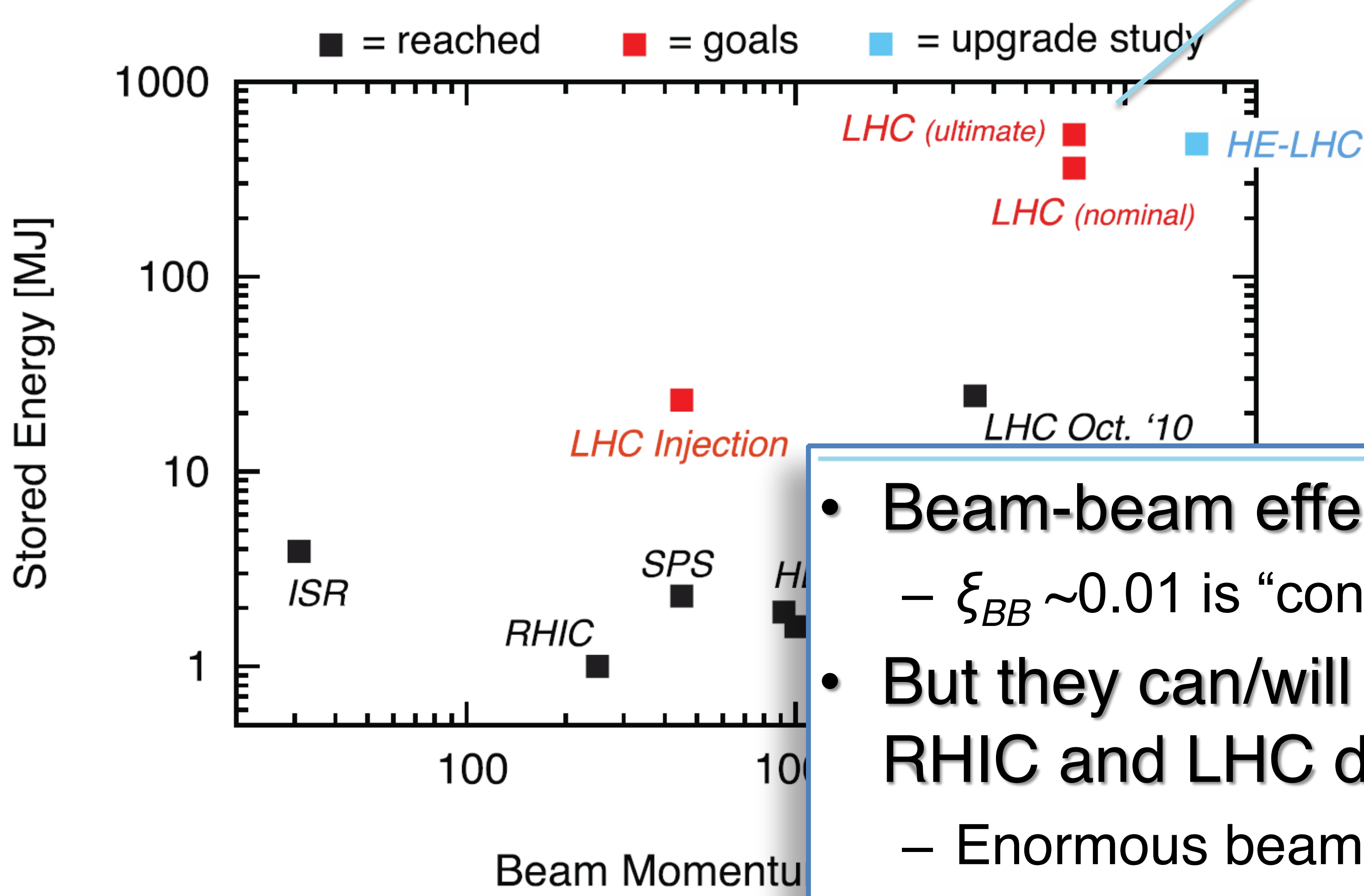
N. Mokhov

Setting the Beam-Beam "Limit"

V. Shiltsev

8.4 GJ of stored beam energy (x20 LHC)



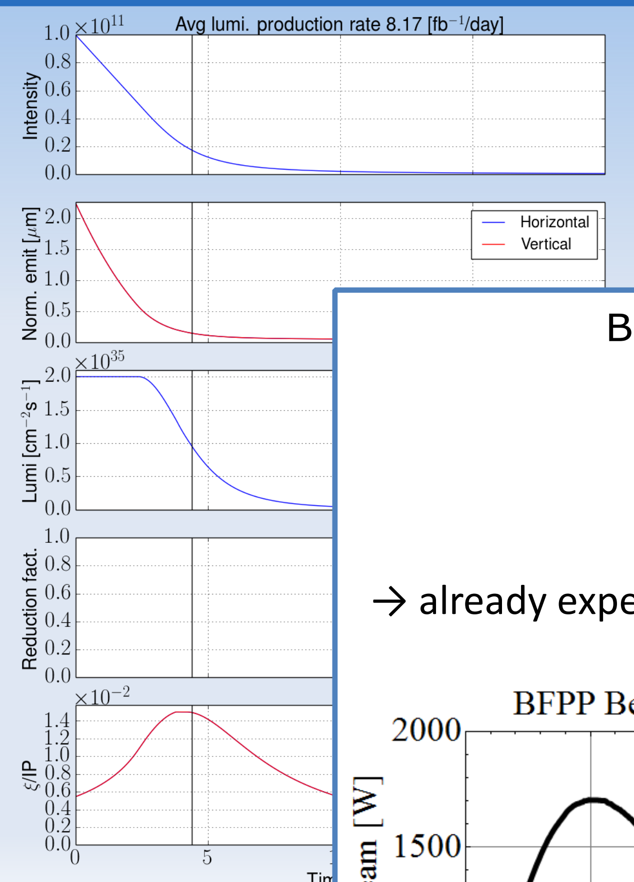


- Beam-beam effects might appear "not bad" in FCC:
  - ξ_{BB} ~0.01 is "conservative"… visible SR damping…
- But they can/will be worse than in the Tevatron, RHIC and LHC due to:
  - Enormous beam power → very low loss tolerances
  - Lower betatron frequencies → larger noises
  - Longer IRs and L* → more long-range beam-beam

Luminosity Evolution; Heavy Ions

Ultimate configuration

Parameter	Nominal	Ultimate
Energy [TeV]	50	
Length [km]	100	
Bunch intensity [p]	10^{11}	
Normalised emittance [μm]	2.2	
Nb. bunches	10'600	
Target luminosity [$cm^{-2}s^{-1}$]	$5\cdot10^{34}$	$2\cdot10^{35}$
Bunch length [cm]	8	
ξ_{tot}	0.01	0.03
Turn around [h]	5	4
Number of IPs	2	
β* [m]	1.1	0.3
Long-range beam-beam separation [σ]	12	Crab Cavity



X. Buffat

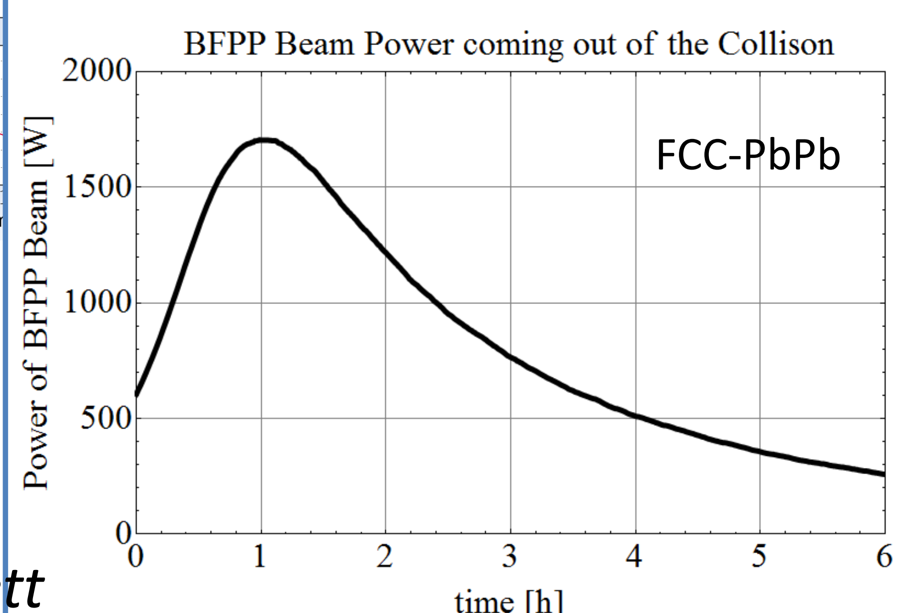
FCC-eh

BFPP1 Beam power: $P = \sigma_c \; L \quad E \quad \approx 1.7$ kW (peak)

4.1 PeV

nominal LHC: *P* ≈ 26W

→ already expected to cause operational problems and poaaible long-term damage



Countermeasures (e.g., DS collimators) have to be considered in initial lattice & hardware design.

J. Jowett

Overall Parameter Optimization

P_{SR}<10 W/m/beam peak

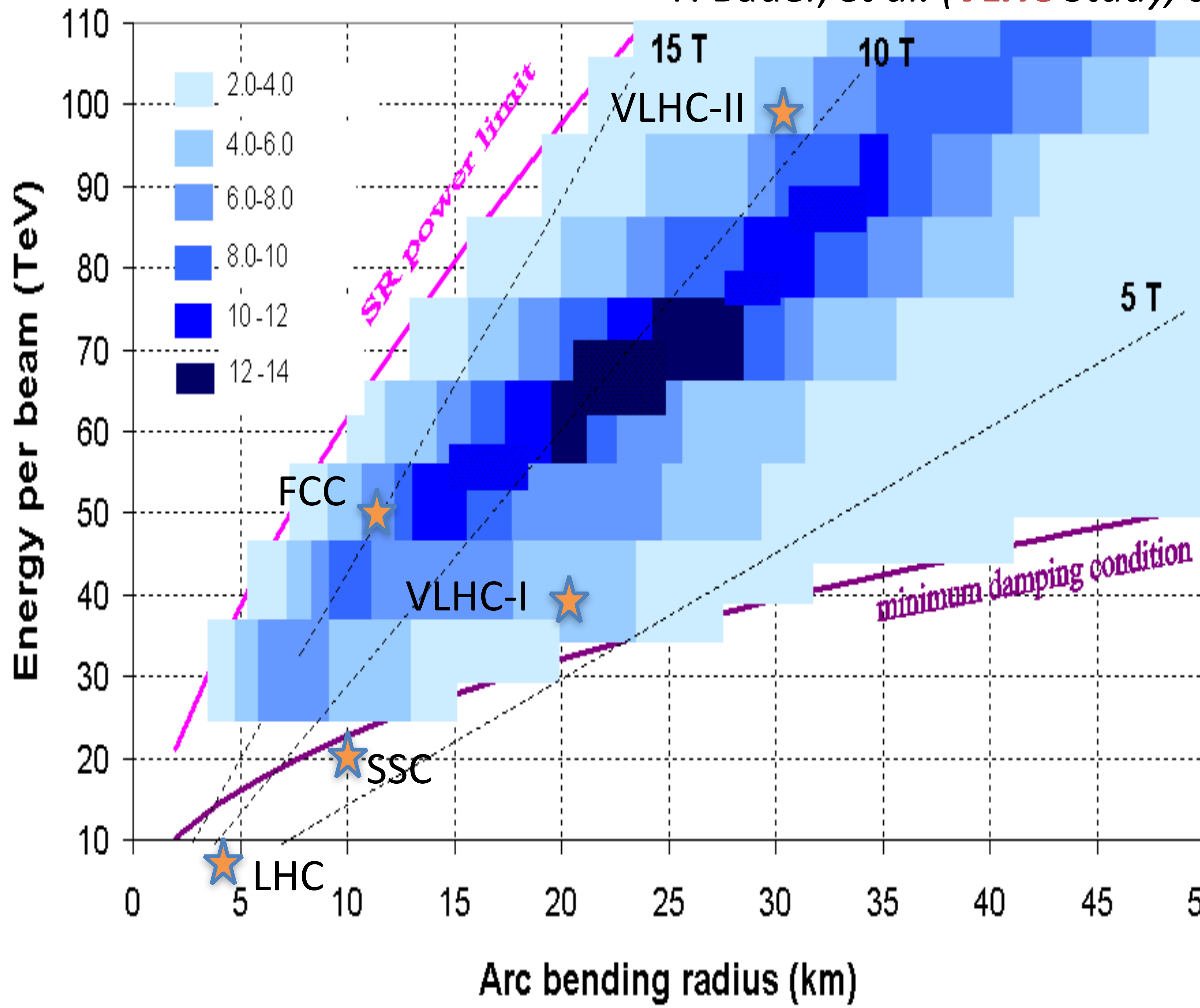
$t_L > 2\ t_{sr}$

Int/cross < 60

L units $10^{34}\ cm^{-2}s^{-1}$

Would be useful to repeat similar studies, now almost 15 years later, with today's "constraints"

P. Bauer, *et al.* (*VLHC Study, c. 2003)*



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
  - Luminosity leveling procedures, algorithms
  - Collimation system strategies
  - Corrector/adjustment system strategies
  - Injection/extraction design
  - Requirements pertinent to heavy ion operation

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

- Field quality, error analyses, adjustment systems
- Beam/environment interactions (beam screen, vacuum, impedances, etc.)
- 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

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

- Beam instrumentation and diagnostics
- RF requirements
- Availability issues; turn-around time
- Sorting strategies, acceptance strategies
- …

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

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

- Possible beam experiments
  - modeling code/calculation verifications, etc.

- Note: Collider design requires close interplay and feedback between hardware R&D and beam physics studies

- Note: Strongly encourage junior colleague participation in all AP studies
  - it will be *their* collider

Going Forward

- The U.S. has much to convey to the FCC studies, including accelerator physics and design optimization
  - 25 years of 2-TeV collider operation (Tevatron)
  - 10 years studying, designing, and (partially) constructing a ~90 km, 40 TeV collider project (SSC)
  - >5 - year study of a 40-200 TeV-scale collider (VLHC)
  - 10-15 years with LHC (LARP, in the least)

- Technology challenges should be the main thrust in the U.S., as well as Accelerator Physics efforts that will help to guide these future activities of the FCC

Very Large Hadron Collider

Thank you for your participation!

NSCL