LHC Upgrades and Future Circular Colliders

M. Benedikt

gratefully acknowledging input from HL-LHC project team, FCC coordination group global design study team and many other contributors.

HL-LHC SPS PS FCC

Particular thanks to O. Bruning and F. Zimmermann for providing some read-to-use slides.

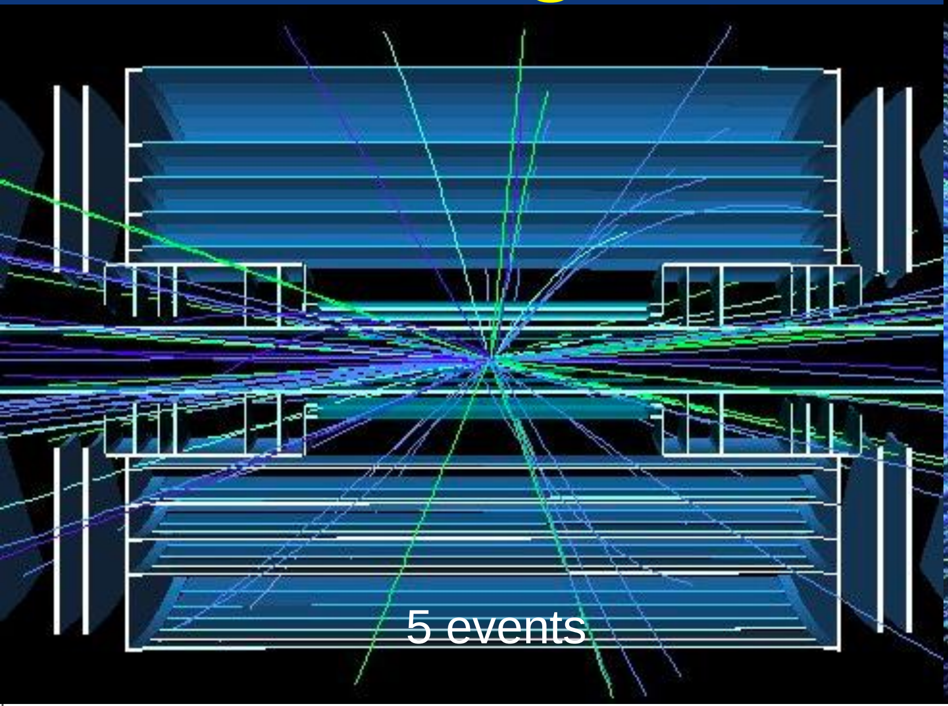
http://cern.ch/fcc

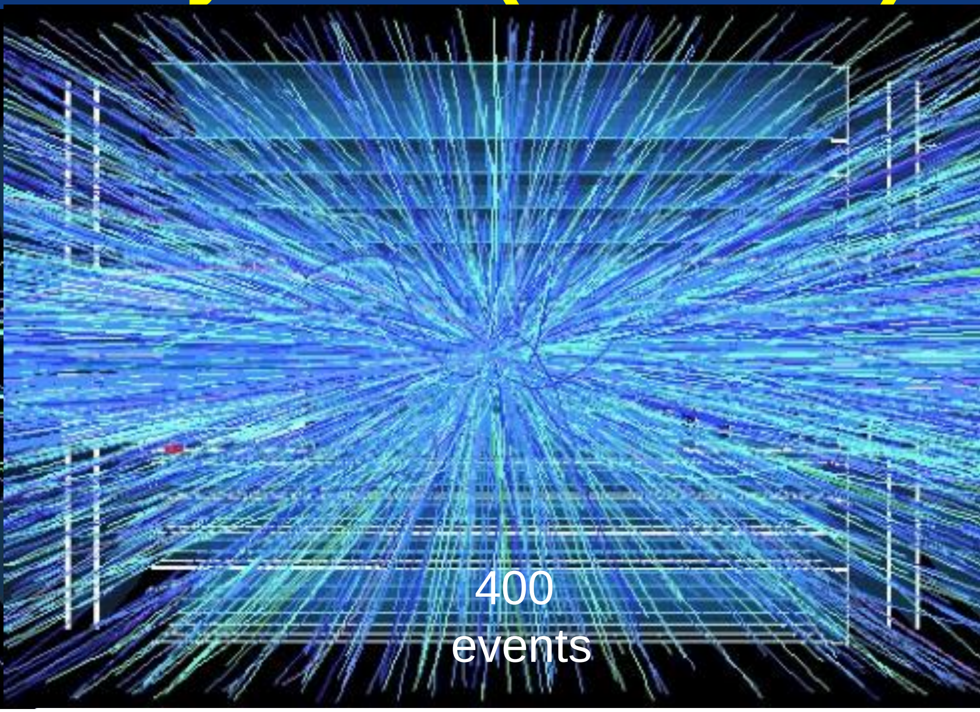
*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

Outline

- HL-LHC motivation and goals
- HL-LHC building blocks
- FCC motivation and scope
  - Parameters
  - Design Status
  - Technologies

Goal of High Luminosity LHC (HL-LHC)





implying an integrated luminosity of **250 fb^{-1} per year**,

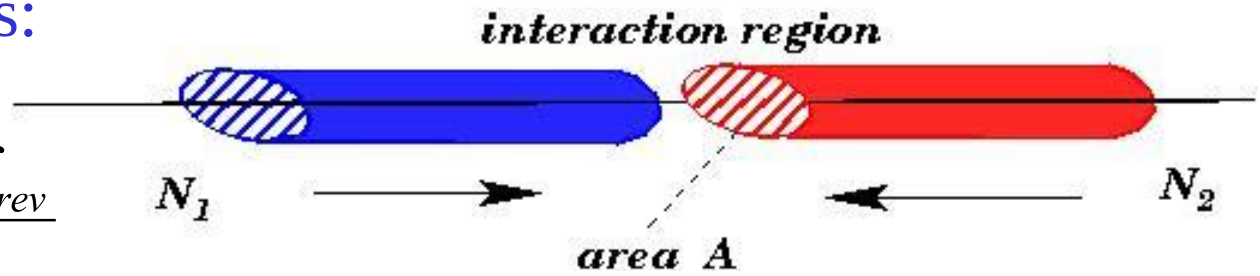
design oper. for $\mu = $ **140** (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity! (beta*, crossing angle & crab cavity)

➔10x the luminosity reach of first 10 years of LHC operation!!

Recap: Luminosity

colliding bunches:



$$L = \frac{n_b \times N_1 \times N_2 \times f_{rev}}{A}$$

$A = 4\pi \times \sigma_x \times \sigma_y$ with: $\sigma = \sqrt{\beta \times \epsilon}$

β is determined by the magnet arrangement & powering

$\epsilon = \epsilon_n / \gamma$ ε_n is determined by the injector chain

goal: → high bunch intensity and many bunches

L_{peak} >2 x 10^{35} $cm^{-2}s^{-1}$ small β at IP and high collision energy

LHC upgrade goals: performance optimization

- Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

➔ maximize bunch intensities (1.1 → $2.2x10^{11}$) ➔ Injector complex

➔ minimize the beam emittance (3.75→ 2.5 μm) Upgrade LIU

➔ minimize beam size (β∗ 0.55 → 0.15 m); ➔ New triplets

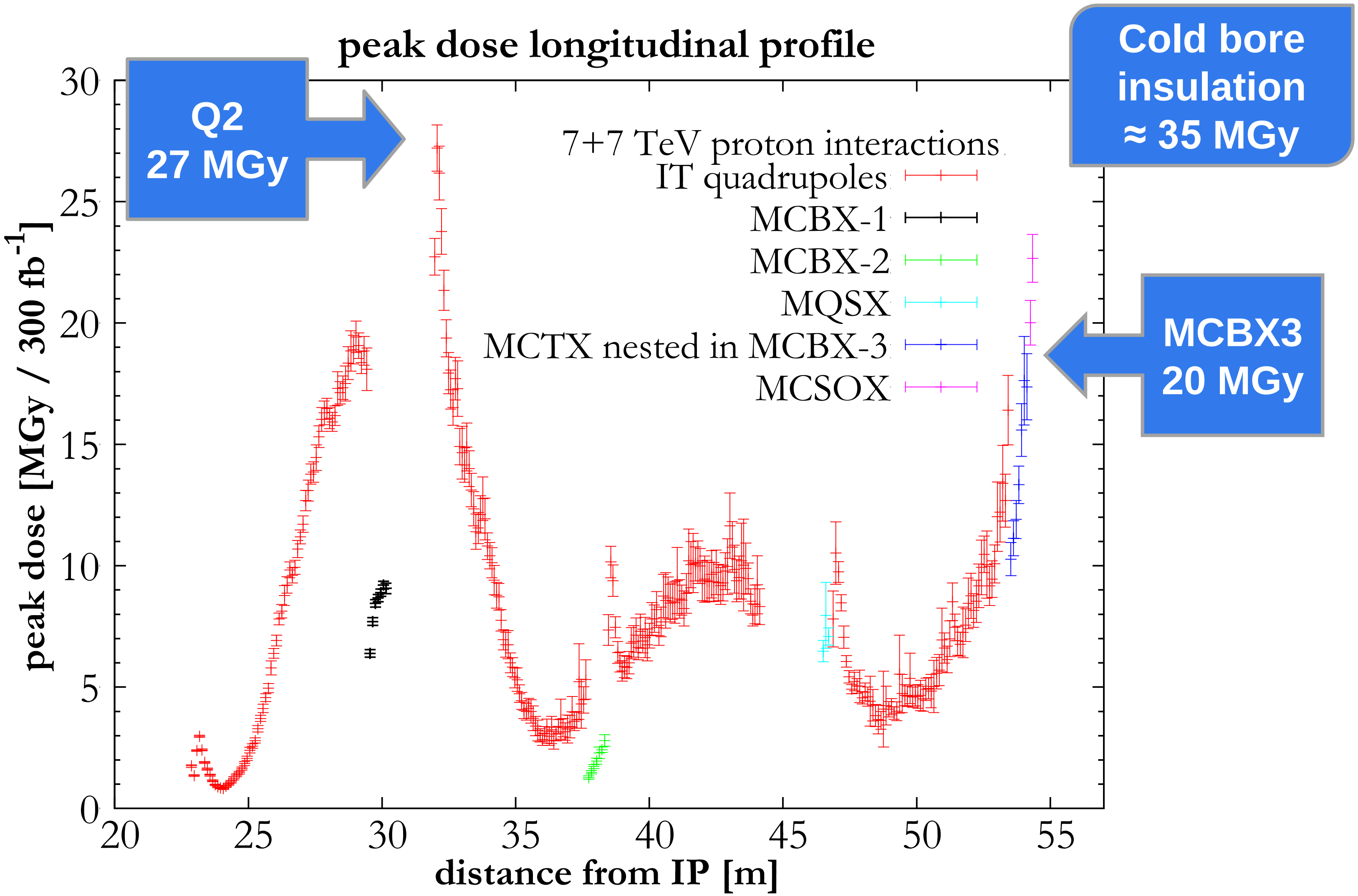
➔compensate for ʻF' geometry crossing; ➔ Crab Cavities

➔ improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

LHC Limitations and HL-LHC challenges

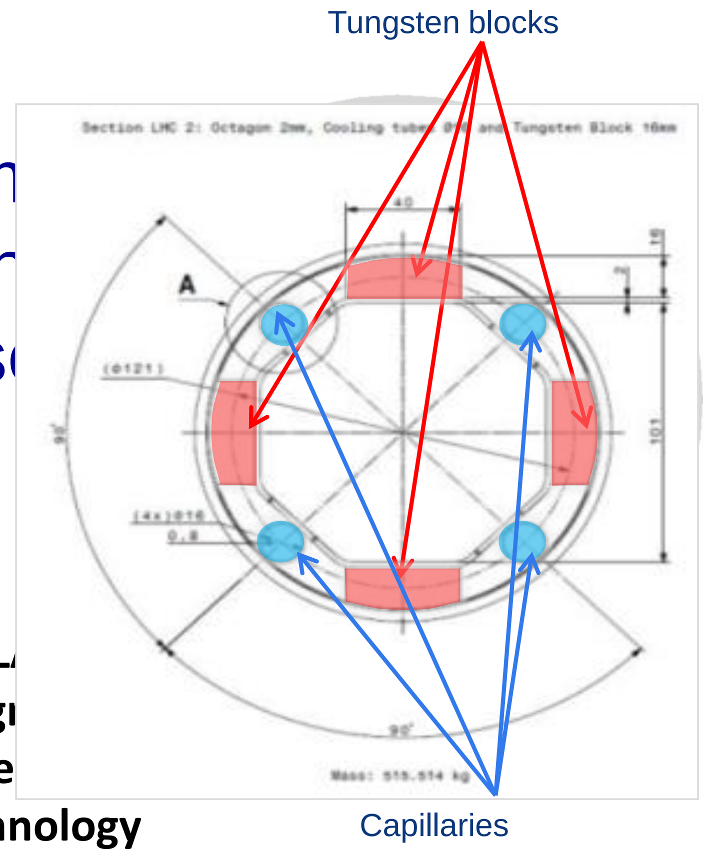
- **Insertion quadrupole magnets lifetime and aperture:**
  ➔ New insertion magnets and low-β with increased aperture
- **Geometric Reduction Factor:** ➔ SC Crab Cavities
  ➔ New technology and first time for a hadron storage ring!
- **Performance Optimization: Pileup density** ➔ Lumi levelling
  ➔ requires virtual luminosity >> target levelled luminosity
- **Beam power & losses** ➔ addt'l collimators in dispersion suppressors
- **Machine effciency and availability:**
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface), etc
- **Technical bottle necks (e.g. cryogenics)**
- **Civil Engineering (underground)**

LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb-1



HL-LHC technical bottleneck: Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magn coils receive a similar radiation dose @ 10 times higher integrated luminosity 3000 fb^{-1}! ➔ Shielding!



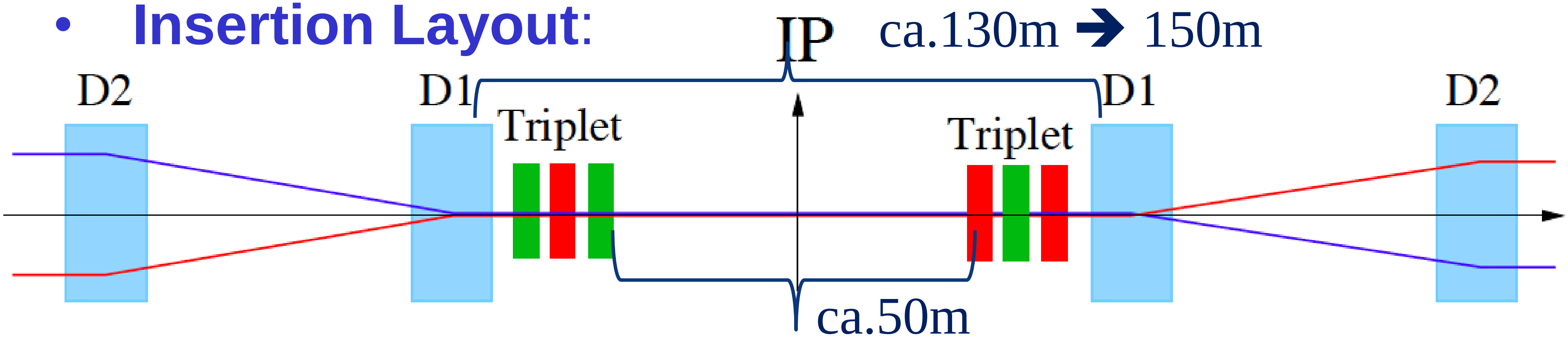
- ➔ Requires larger aperture!
- ➔ New magnet technology

US-L
magn
Base
technology

- ➔ LHC: 70mm at 210 T/m ➔HL@ 150mm diameter 140 T/m
- ➔ LHC: 8T peak field at coils ➔ HL> 12T field at coils (Nb_3Sn)!

HL-LHC Challenges: Crossing Angle

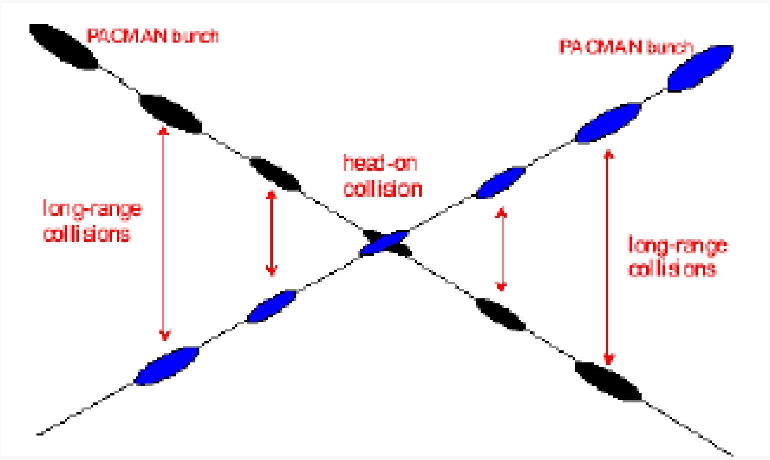
- **Insertion Layout:**



- **Parasitic bunch encounters:**

Operation with ca. 2800 bunches @ 25ns spacing
➔ approximately 30 unwanted collisions per Interaction Region (IR).

Operation requires crossing angle prop. $1/\sqrt{\beta^*}$.
➔ Factor 2 increase, 2 x 150 to 2 x 300 μrad)



- **Perturbations from long-range beam-beam interaction:**

efficient operation requires large beam separation at unwanted collision points
➔ Separation of 10 -12 σ ➔ **larger triplet apertures for HL-LHC!**

HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

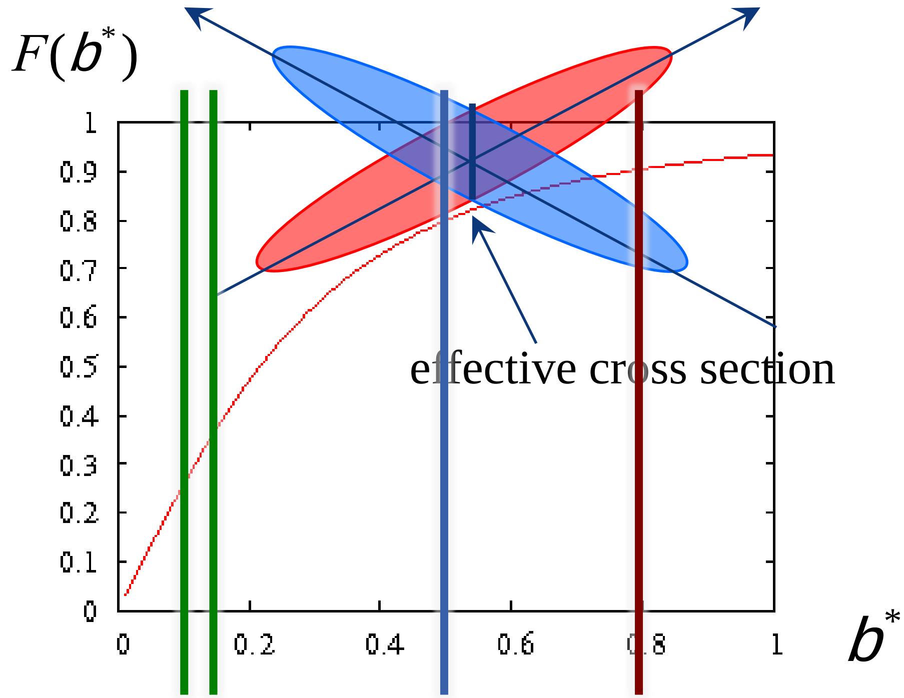
Crab Cavities:

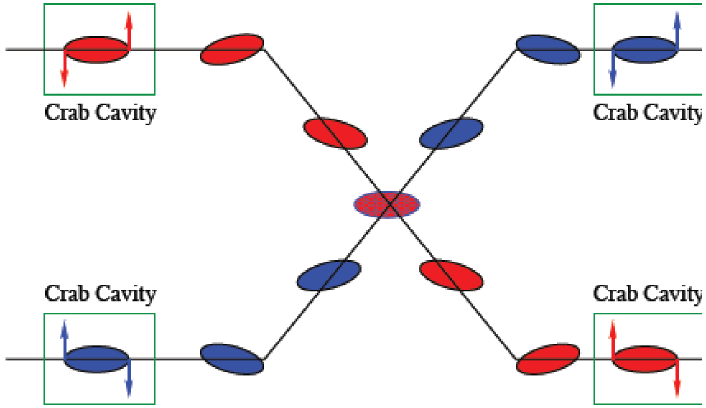
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

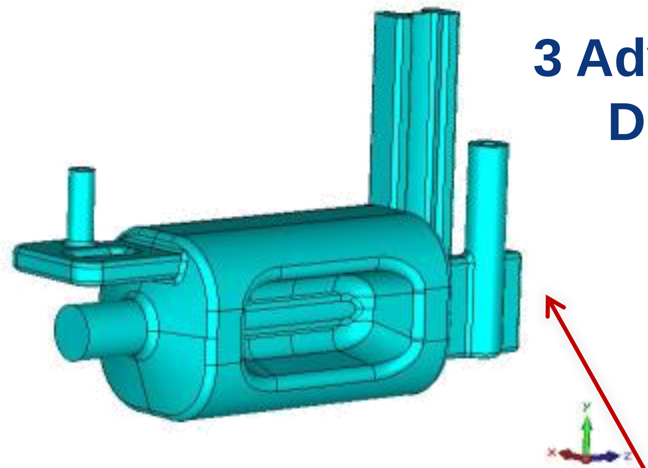
- Challenging space constraints:

  ➔ requires novel compact cavity design

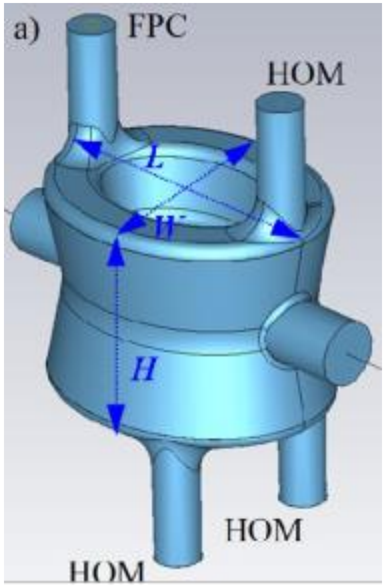




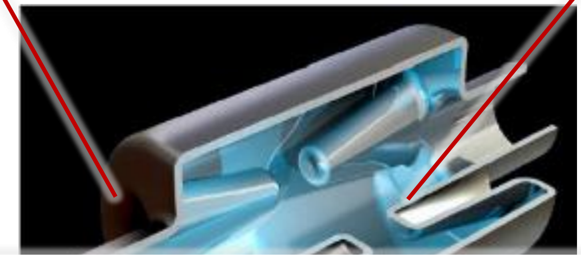
HL-LHC crab cavity designs



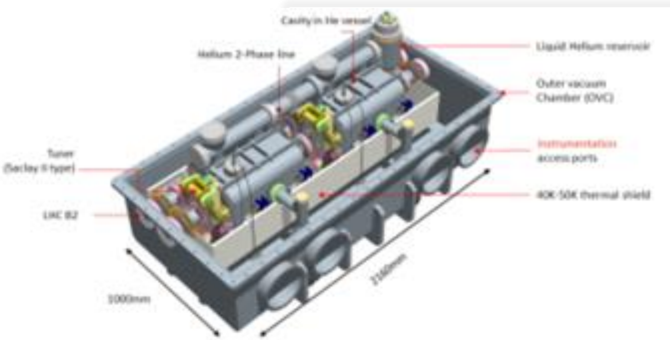
3 Advanced Design Studies with Different Coupler concepts



RF Dipole: Waveguide or waveguide-coax couplers



Double ¼-wave: Coaxial couplers with hook-type antenna



ave installed in SPS
hutdown 2017/2018

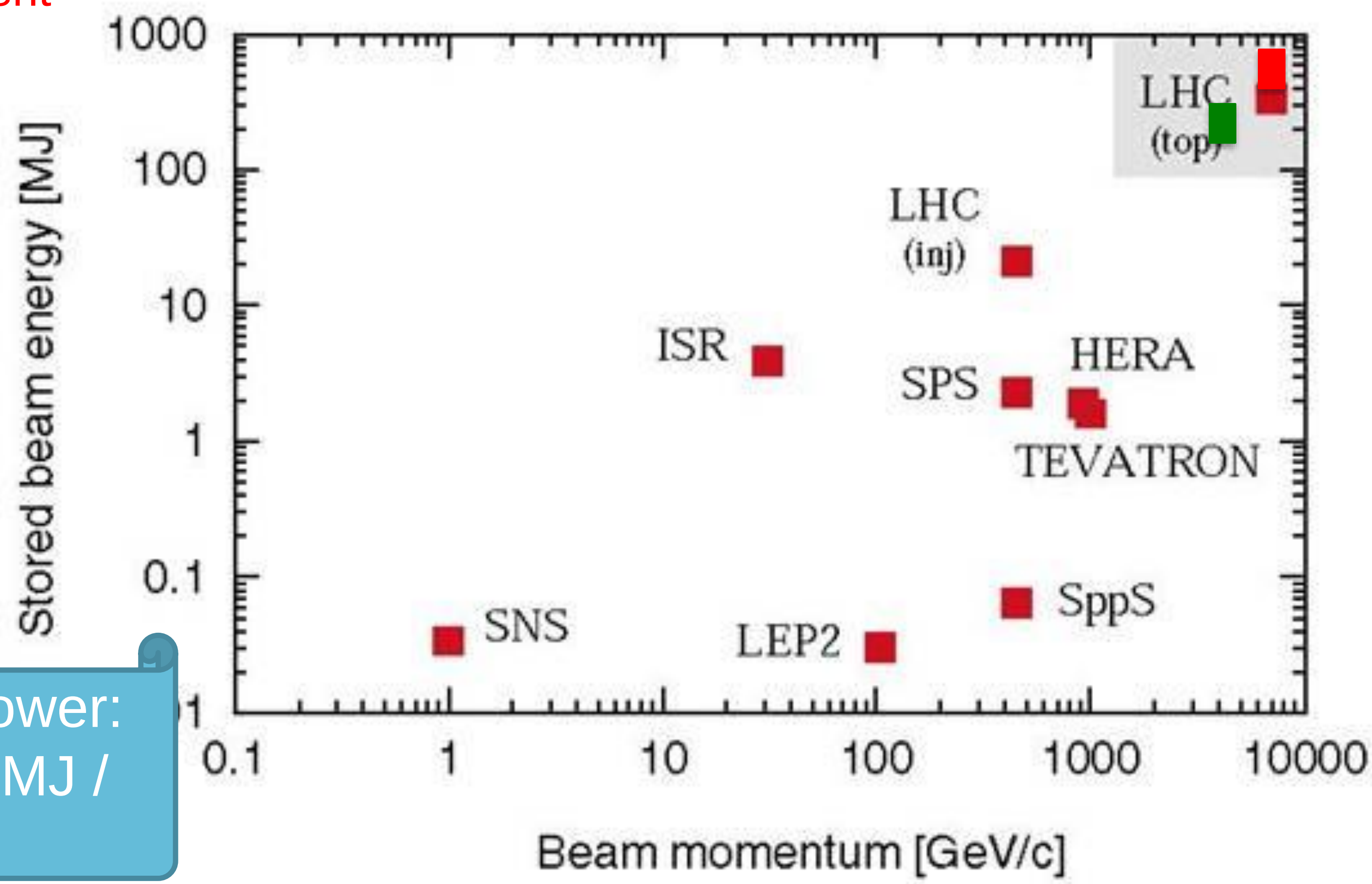
4-rod: (
differen

Present baseline: 4 cavity/cryomod
Succesful tests in SPS

LHC Challenges: Beam Power

Unprecedented beam power:

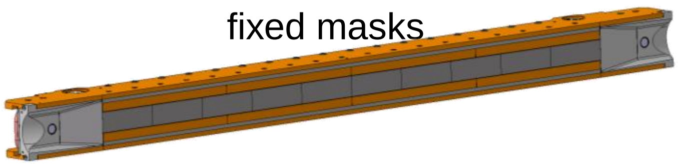
- ➔ potential equipment damage in case of failures during operation
- ➔ In case of failure the beam must never reach sensitive equipment!



Stored Beam power: HL-LHC > 500 MJ / beam

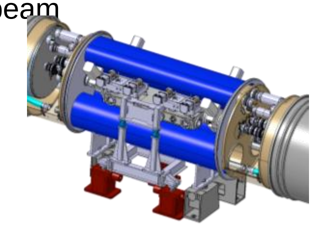
Collimation system upgrades

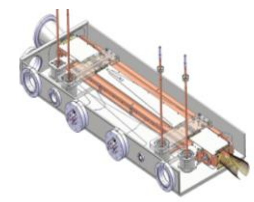
Completely new layouts
Novel materials.
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks



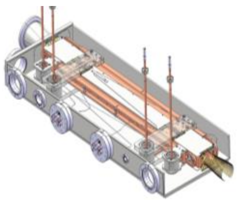
40 new collimators to be produced by LS3 in the present baseline!

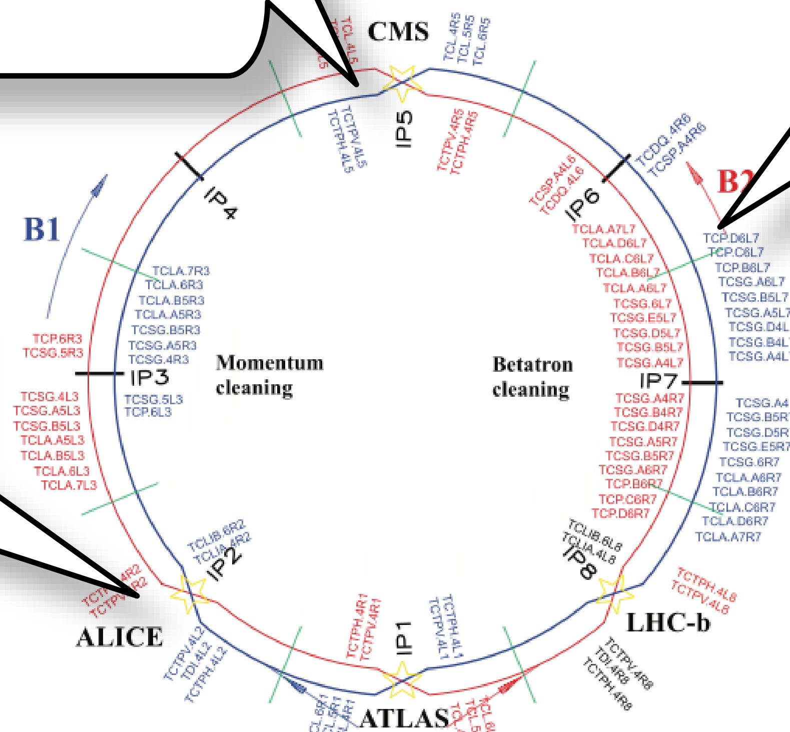
Cleaning: DS coll. + 11T dipoles, 2 units per beam



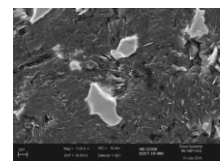


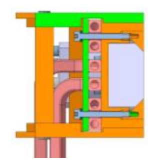
Ion physics debris: DS collimation

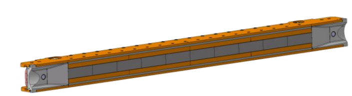




Low-impedance, high robustness secondary collimators

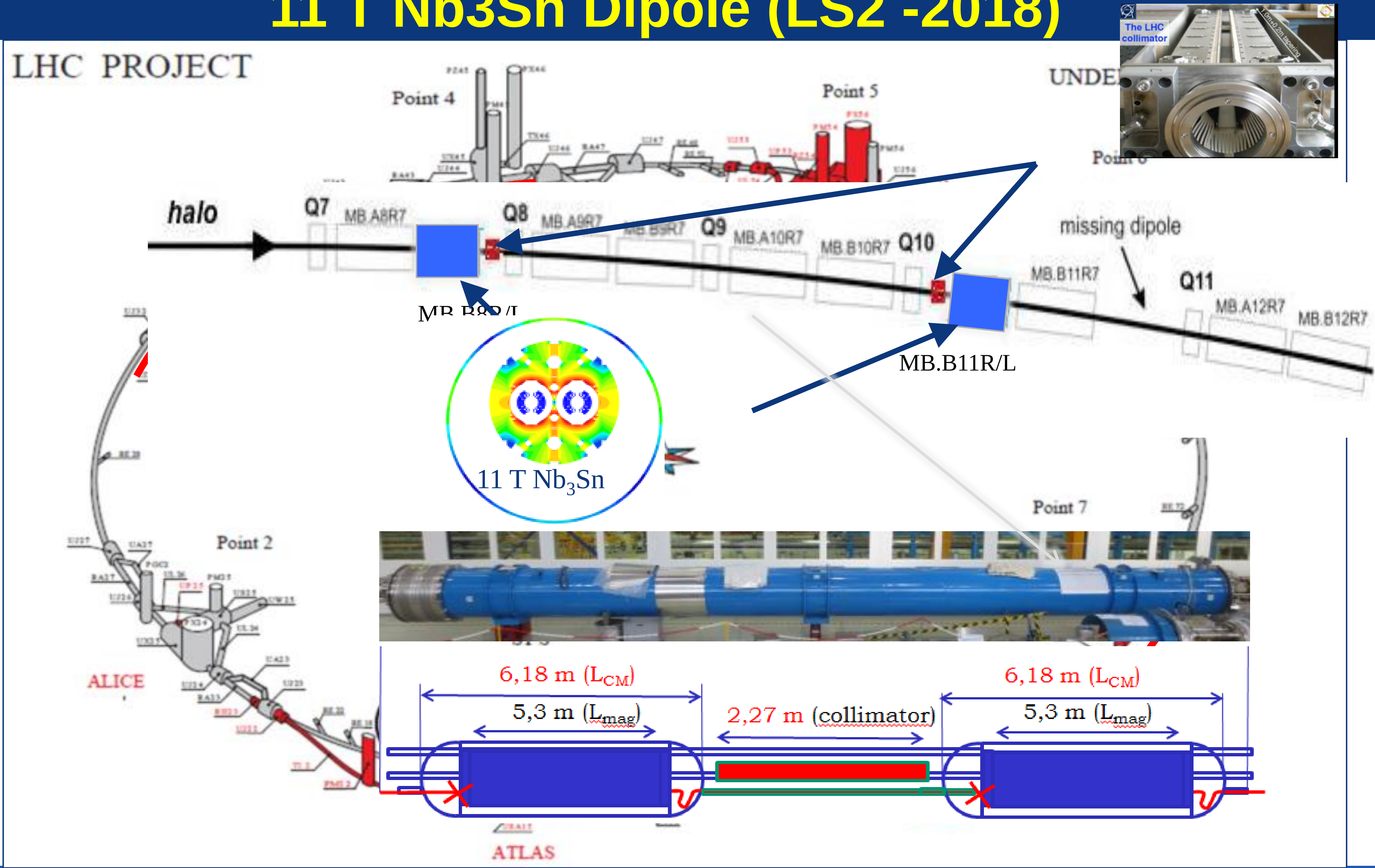




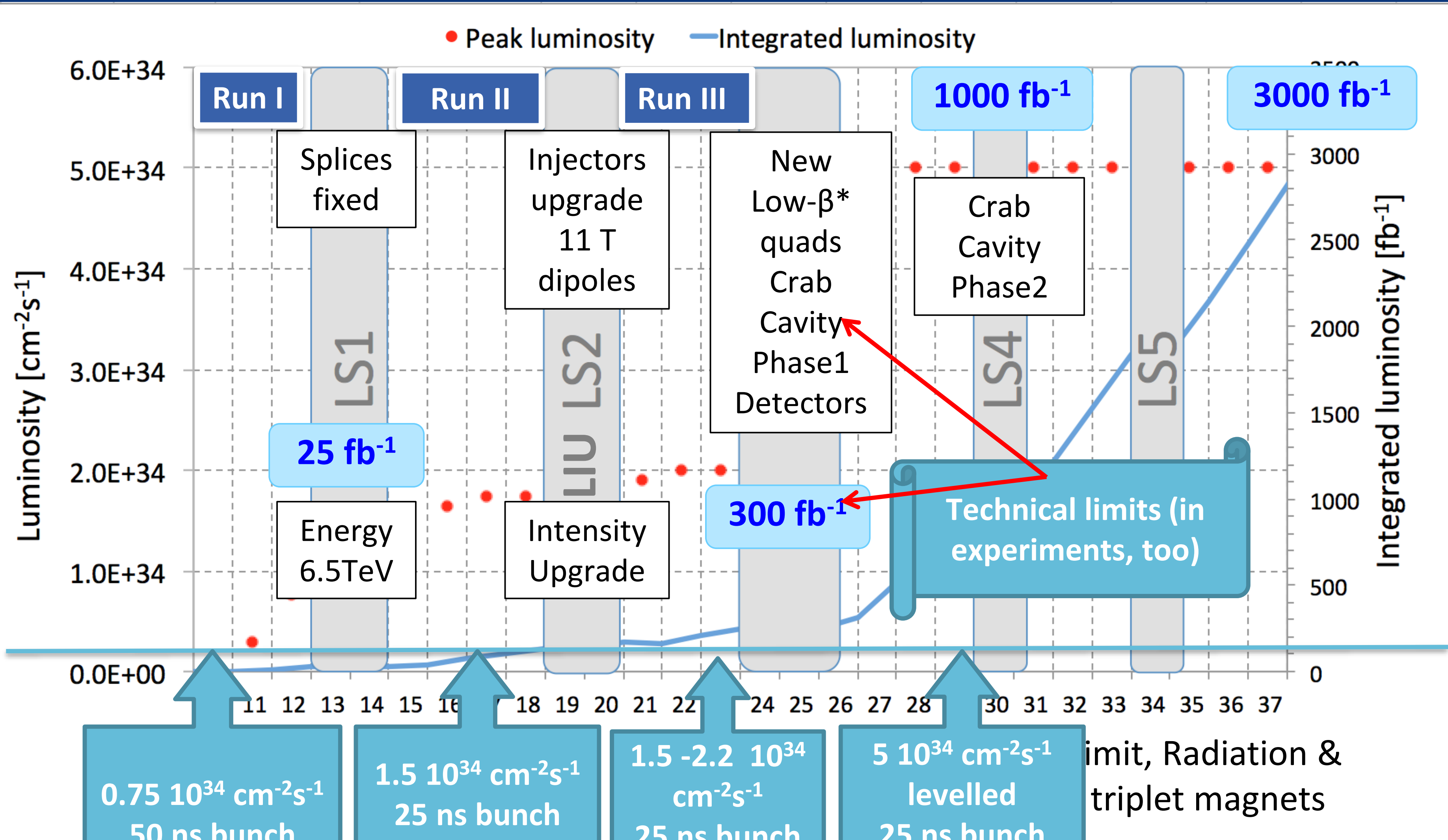


S. Redaelli,
Chamonix 2016, 28-01-2016

Dispersion Suppressor collimators – 11 T Nb3Sn Dipole (LS2 -2018)



Implementation & Performance Projection:



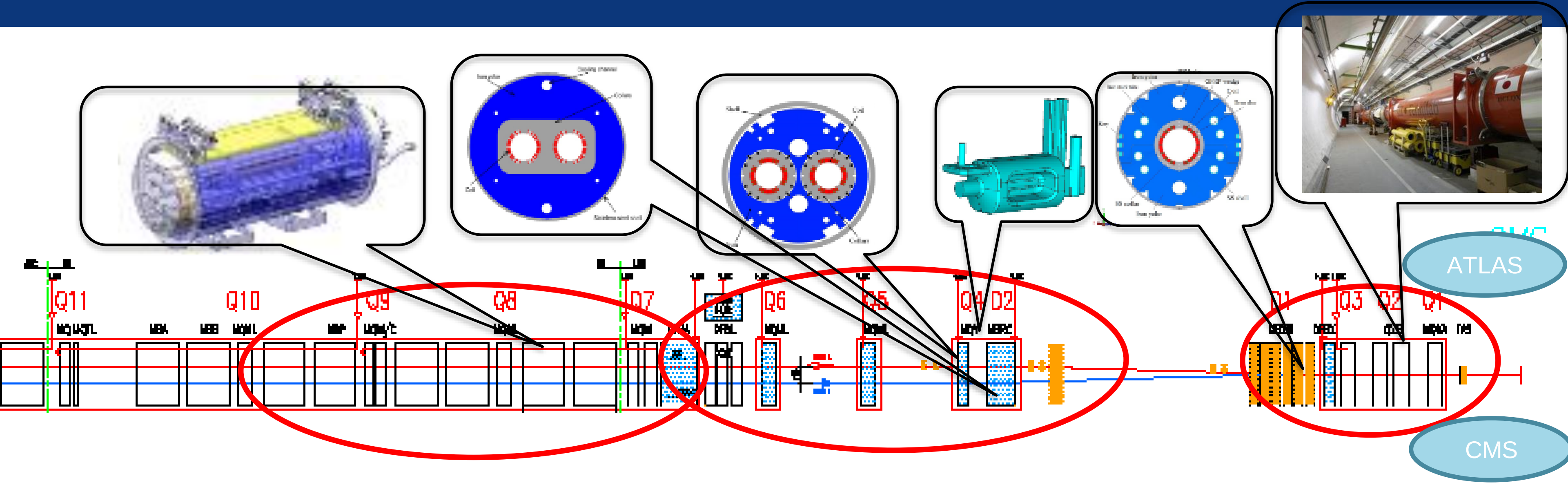
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
high pile up ~40

1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
high pile up ~40

1.5 -2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
very high pile up > 60

5 10^{34} $cm^{-2}s^{-1}$ levelled
25 ns bunch
very high pile up ~140

The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb_3Sn dipole

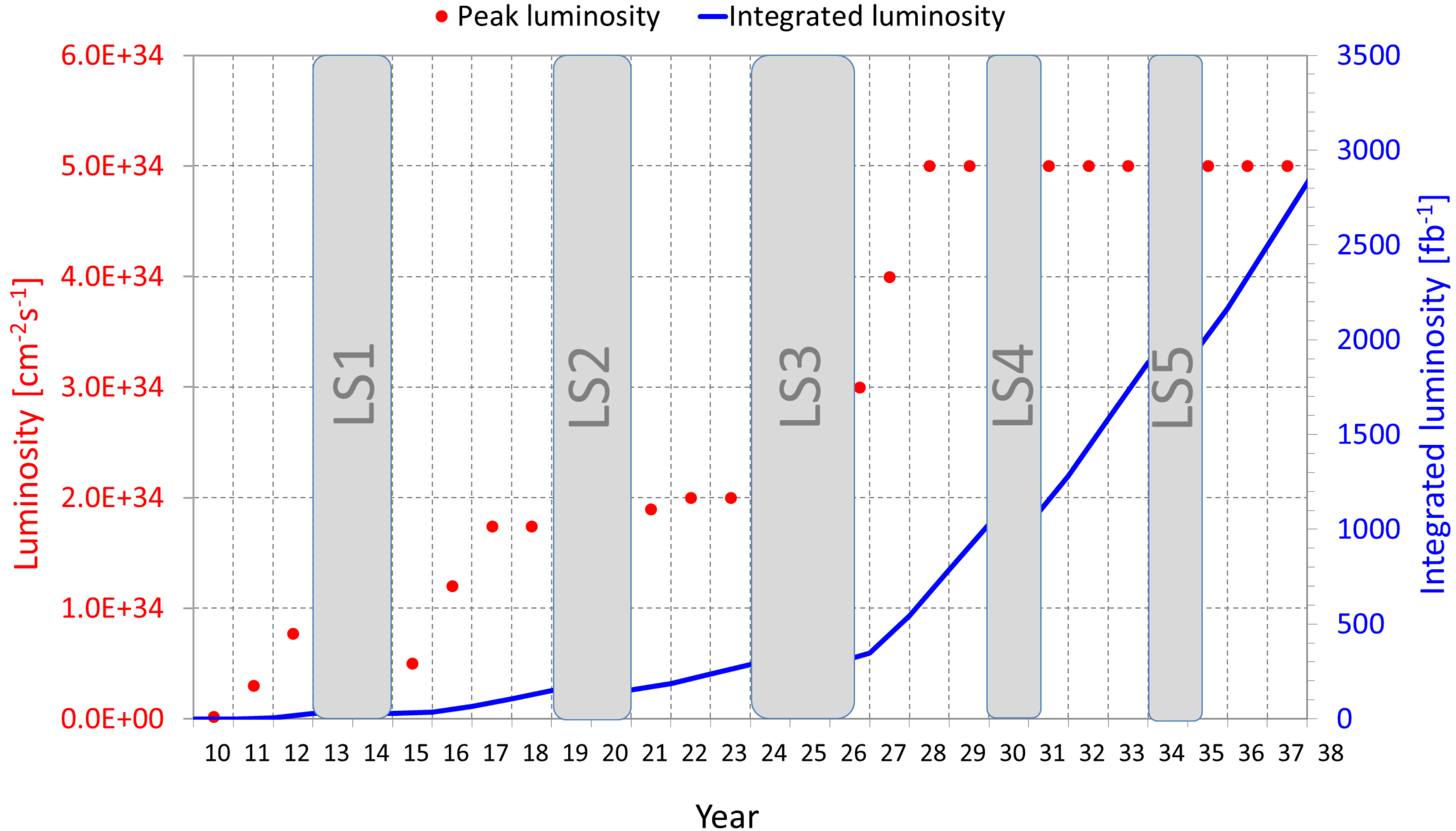
2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

1. New triplet Nb_3Sn required due to:
-Radiation damage
-Need for more aperture

Changing the triplet region is not enough for reaching the HL-LHC goal!

➔ More than 1.2 km of LHC !!
➔ Plus technical infrastructure (e.g. Cryo and Powering)!!

Luminosity profile : NOMINAL HL-LHC



After LS4, proton physics days increase from standard 160 days to 200 and after LS5 to 220

Energy frontier in the 21st century

- **Very large circular hadron collider - only feasible approach to reach 100 TeV c.m. collision energy in coming decades**
- **Access to new particles (direct production) in few-TeV to 30 TeV mass range, far beyond LHC reach**
- **Much-increased rates for phenomena in sub-TeV mass range → much increased precision w.r.t. LHC**

M. Mangano

Hadron collider energy reach

$$E \propto B_{dipole} \times \rho_{bending}$$

FCC-hh aims at O(10) higher performance (E, L) than LHC

LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

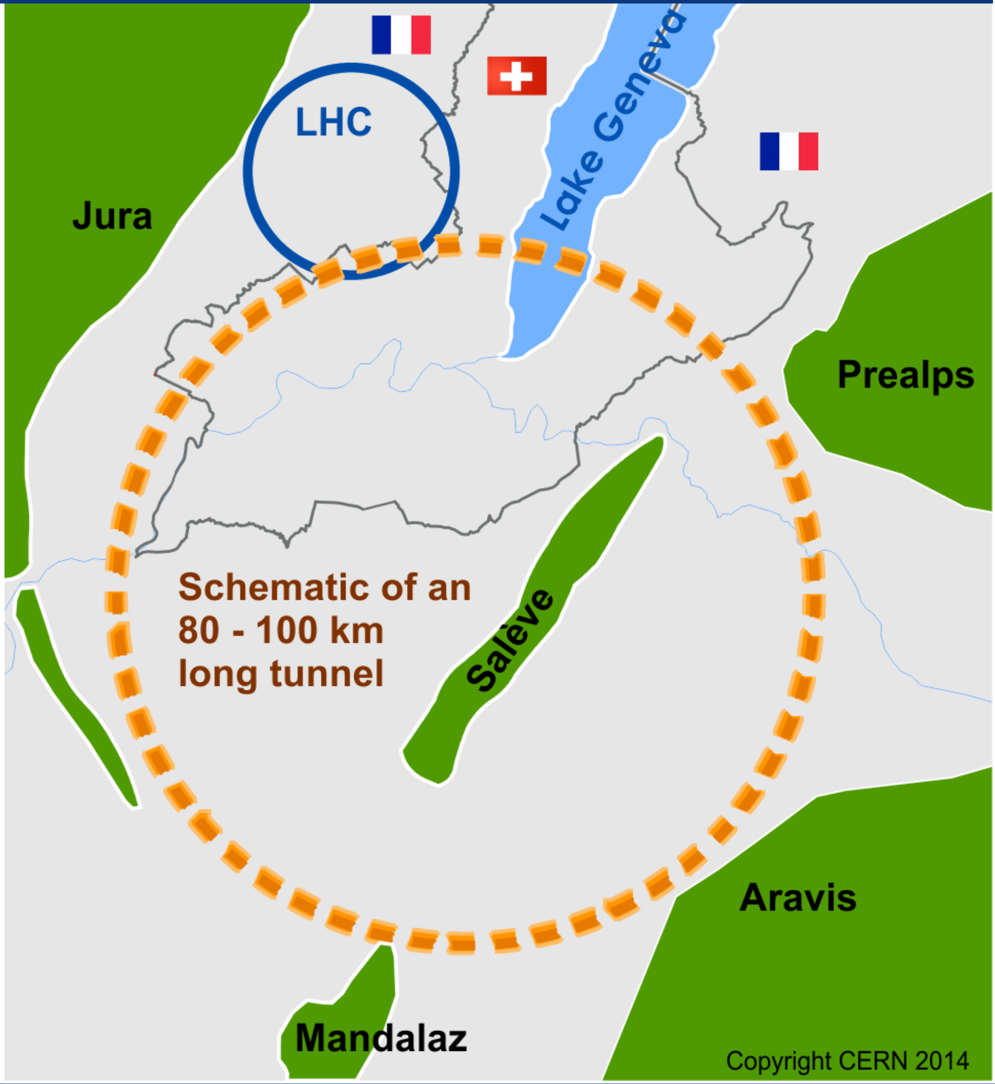
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



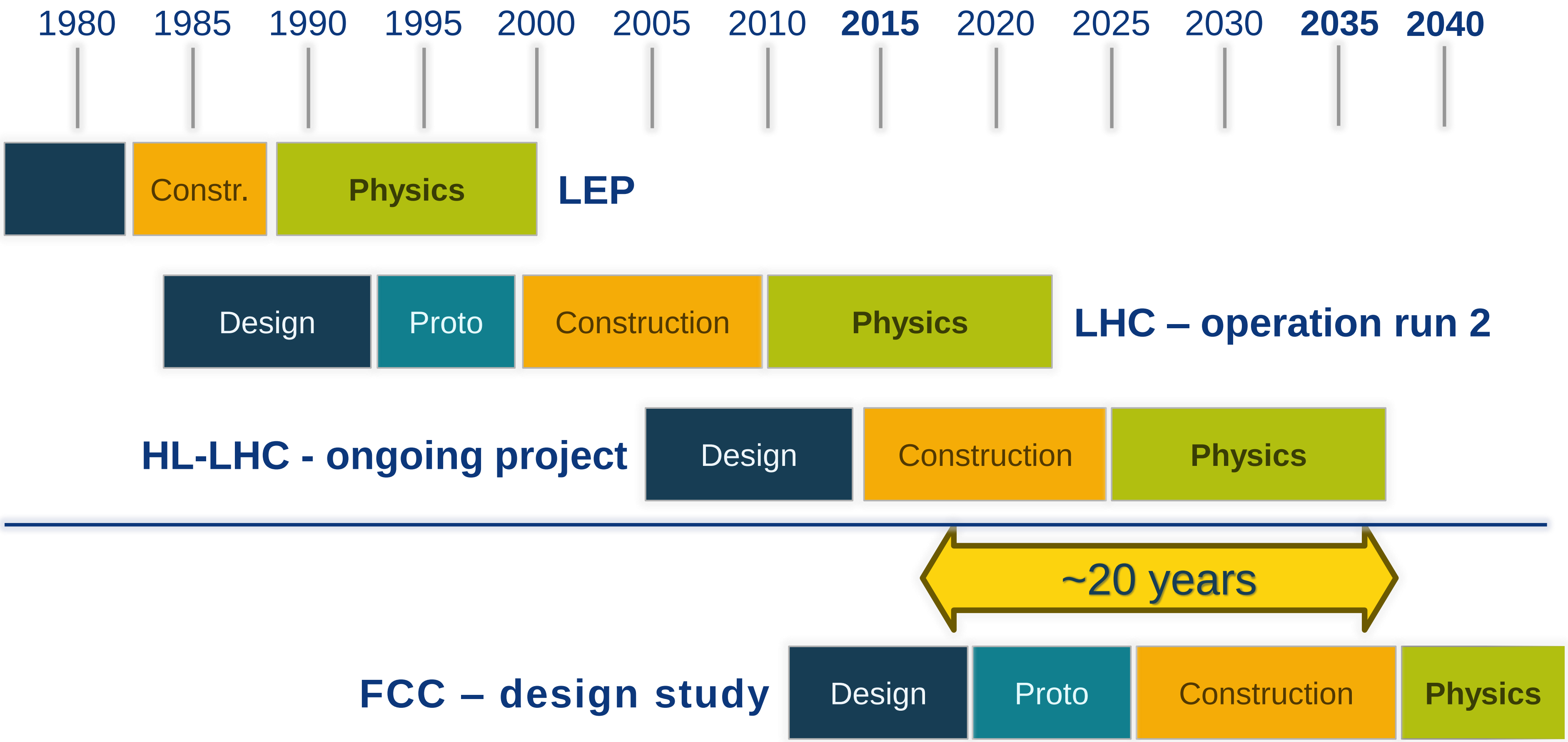
CepC/SppC study (CAS-IHEP) 100 km (new baseline!) , e^+e^- collisions ~2028; *pp* collisions ~2042

easy access
300 km east
from Beijing
3 h by car
1 h by train

Yifang Wang

"Chinese Toscana"

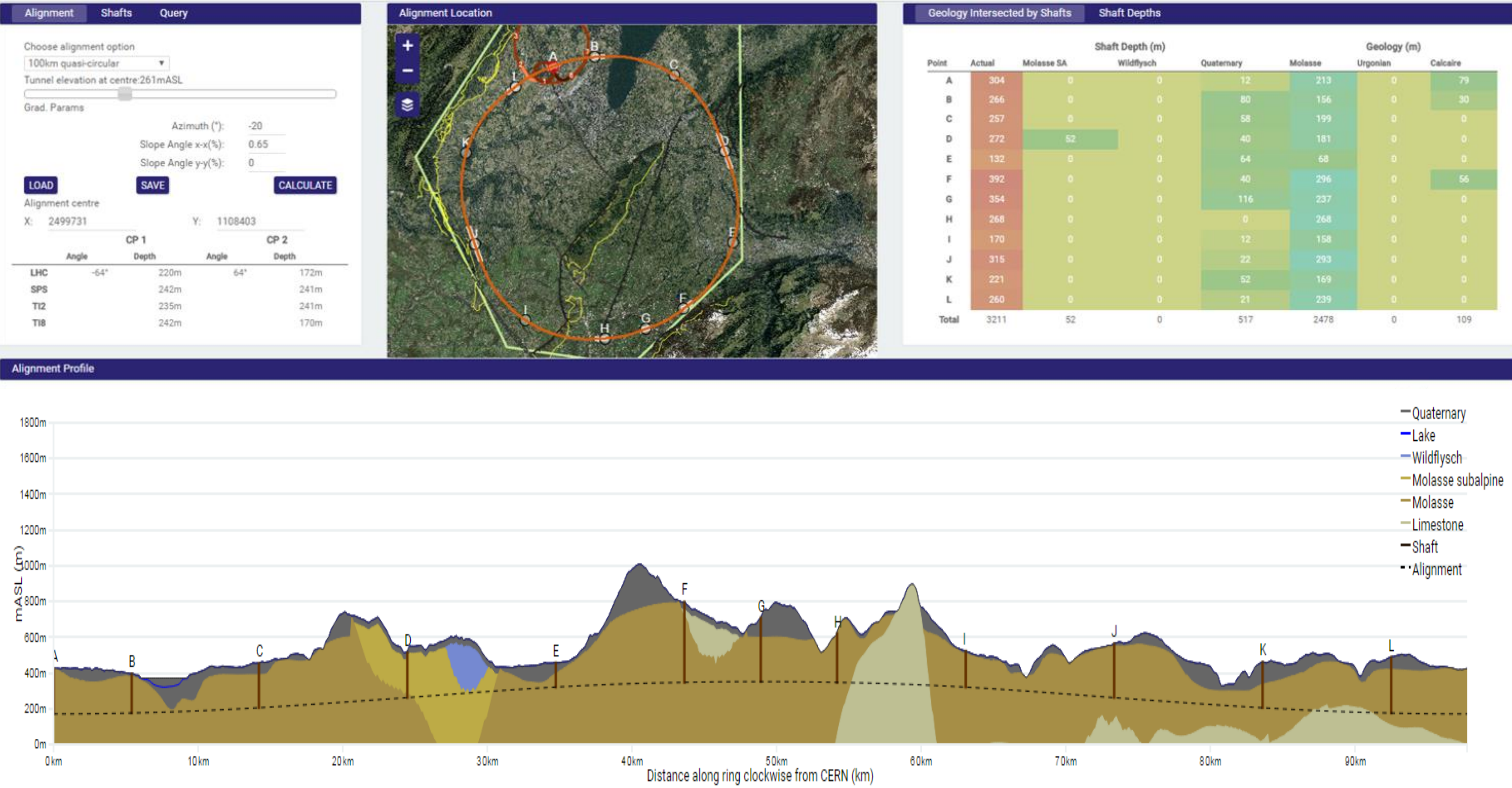
CERN Circular Colliders & FCC



Must advance fast now to be ready for the period 2035 – 2040

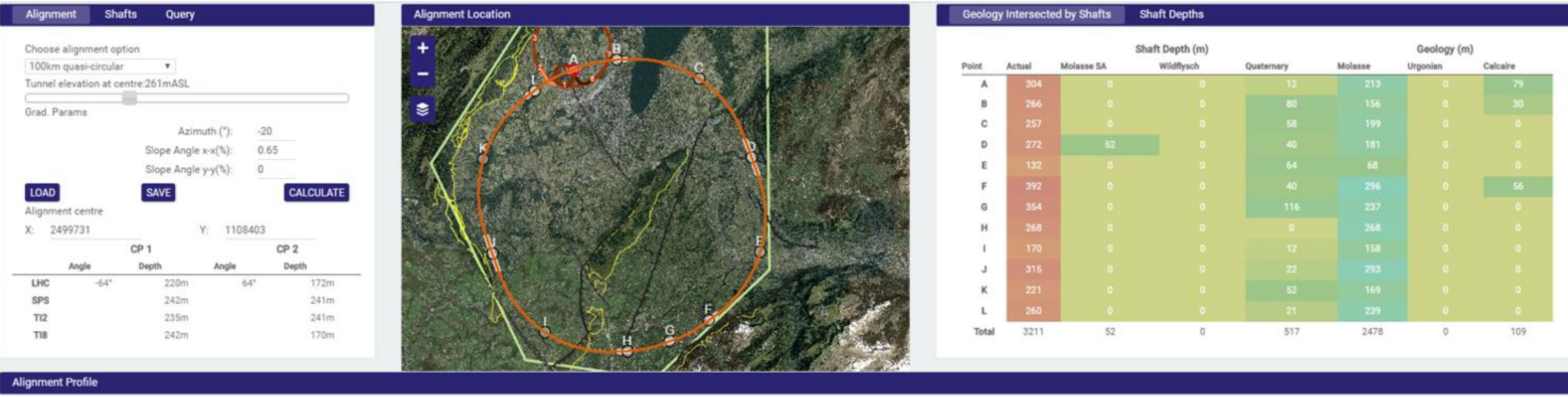
Results phase 1: CDR published end 2018 for update European Strategy

Progress on site investigations



Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
	Shaft Depth (m)				Geology (m)		
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

Progress on site investigations



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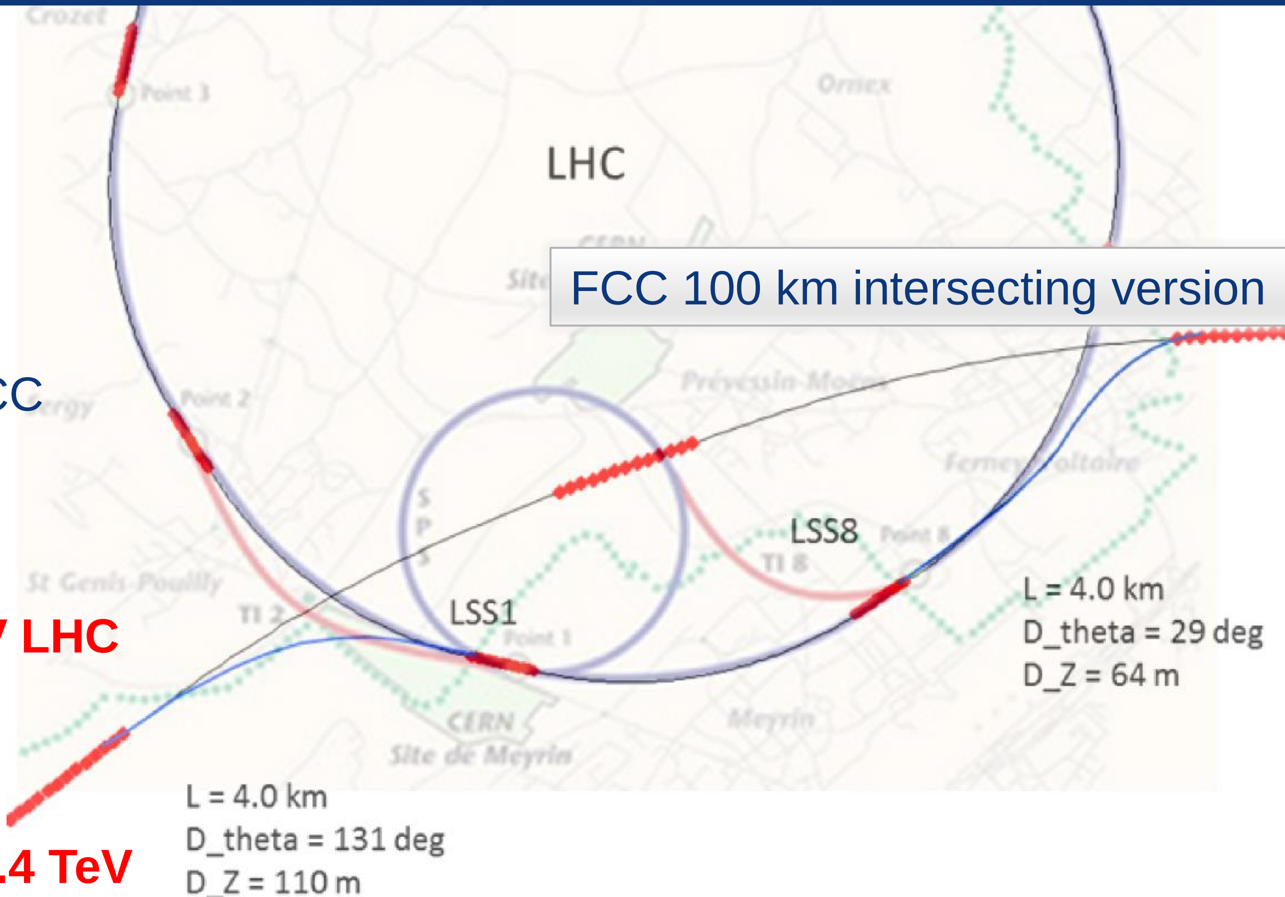
- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 97.75 km version, intersecting LHC, is now being studied in more detail

FCC-hh injector studies

Injector options:

- **SPS → LHC → FCC**
- SPS/**SPS$_{upgrade}$ → FCC**
- SPS -> FCC booster → FCC



Current baseline:

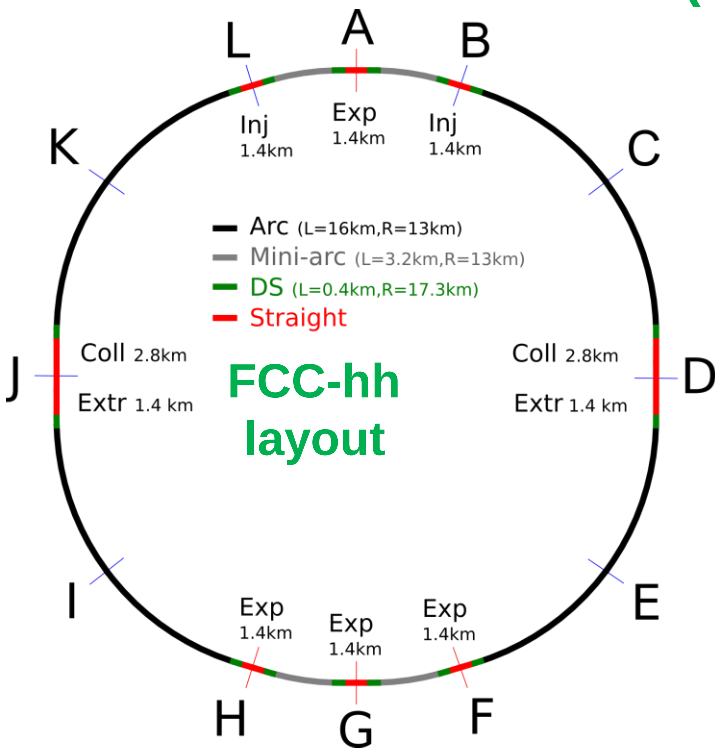
- **injection energy 3.3 TeV LHC**

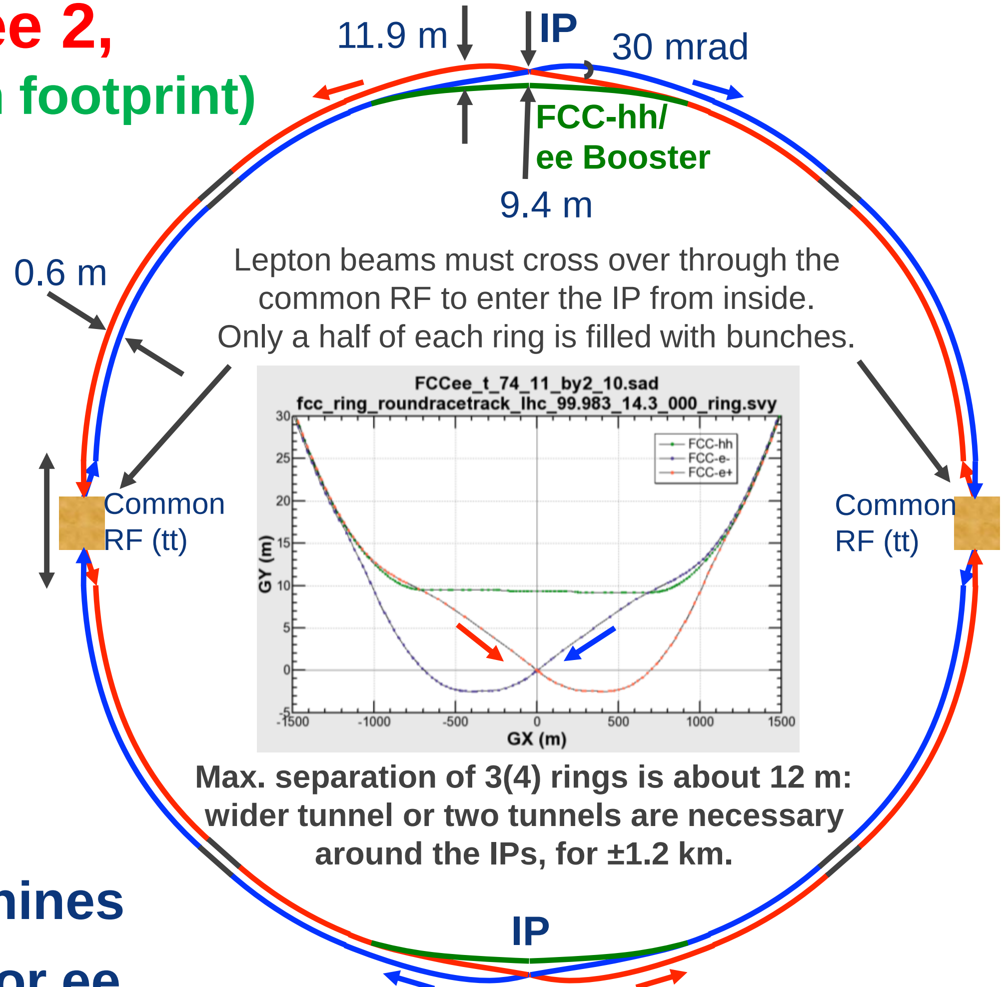
Alternative options:

- **Injection around 1.3 – 1.4 TeV**
- **compatible with: SPS$_{upgrade}$, LHC, FCC booster**
- **SPS$_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp**
  - **SC Magnet R&D program being launched (similar to SIS 300 parameters)**

Common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)



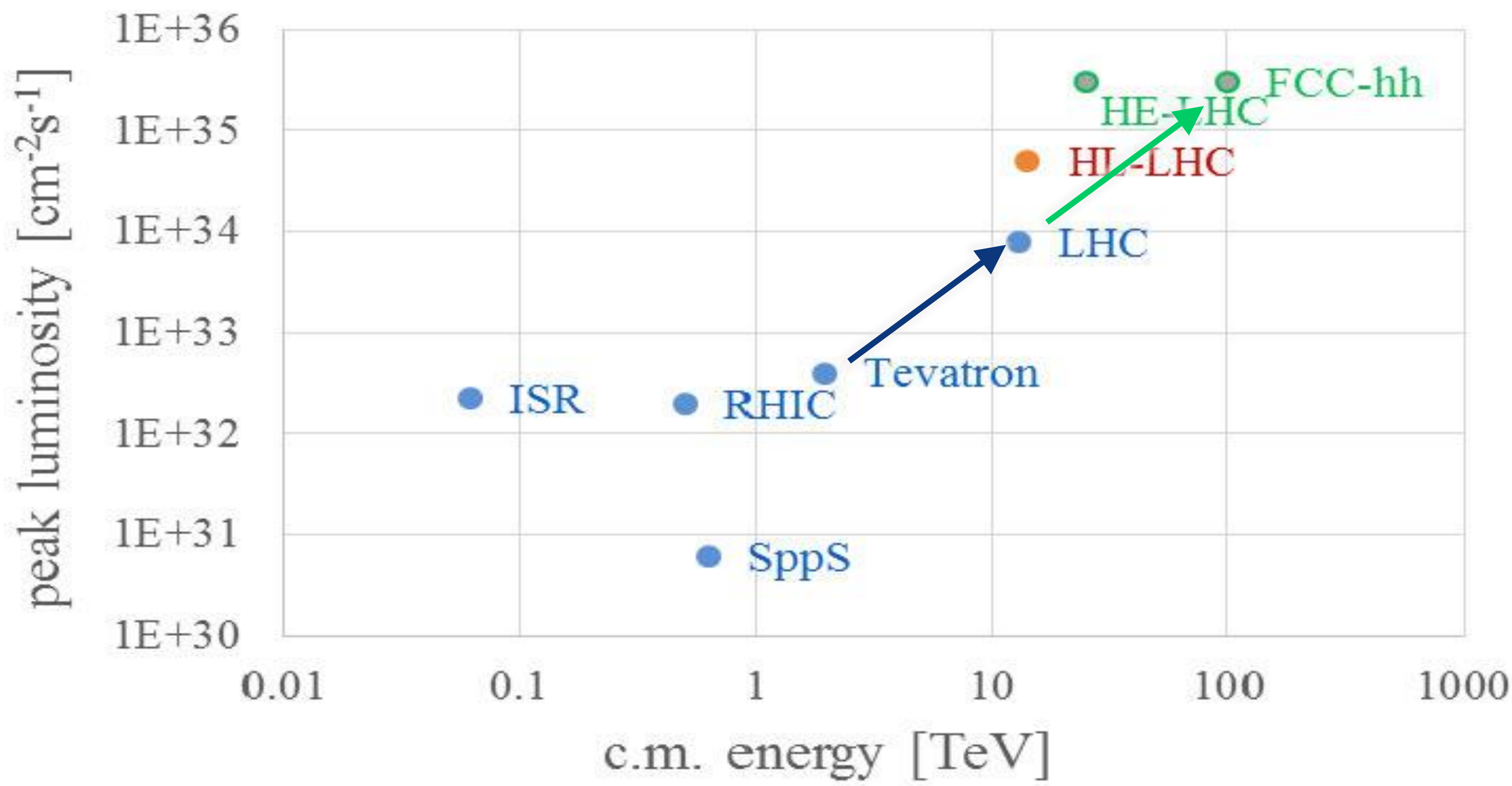


- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

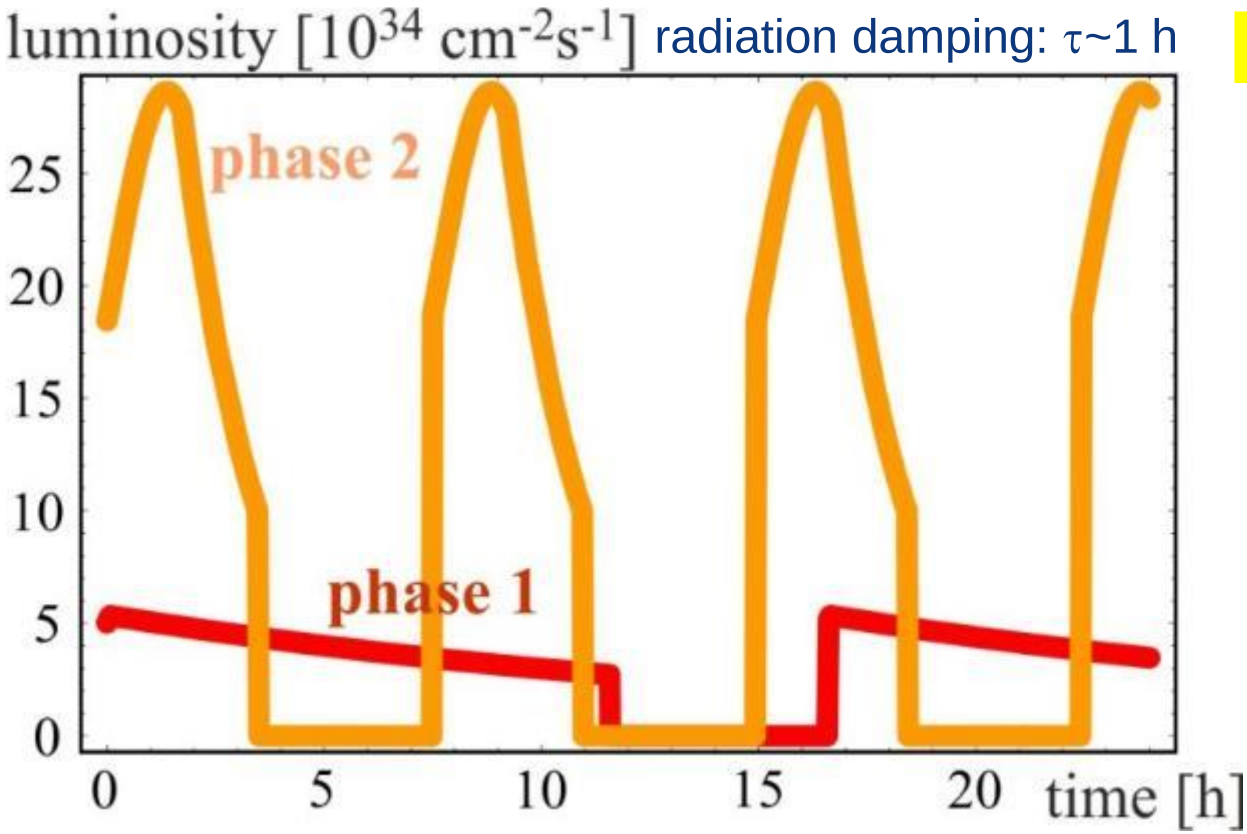
hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	**100**		**27**	14
dipole field [T]	**16**		**16**	8.3
circumference [km]	**100**		**27**	27
# IP	**2 main & 2**		**2 & 2**	2 & 2
beam current [A]	**0.5**		**1.27**	(1.12) 0.58
bunch intensity [10^{11}]	**1 (0.2)**	**1 (0.2)**	**2.5**	(2.2) 1.15
bunch spacing [ns]	**25 (5)**	**25 (5)**	**25 (5)**	25
IP $\beta^*_{x,y}$ [m]	**1.1**	**0.3**	**0.45**	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	**30**	**16**	(5) 1
peak #events/bunch crossing	170	**1020** (204)	**460** (92)	(135) 27
stored energy/beam [GJ]	**8.4**		**1.4**	(0.7) 0.36
synchrotron rad. [W/m/beam]	**30**		**4.1**	(0.35) 0.18

pp/p-pbar in the *L-E* plane



luminosity evolution over 24 h



PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

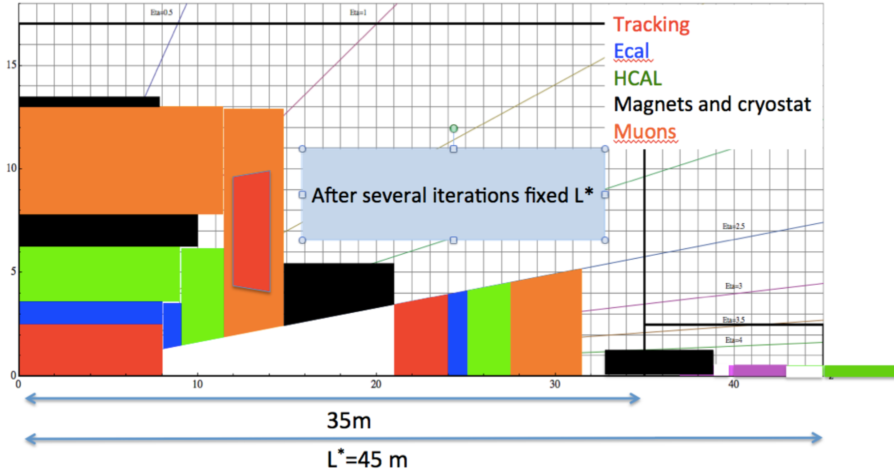
phase 1: β^*=1.1 m, ξ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

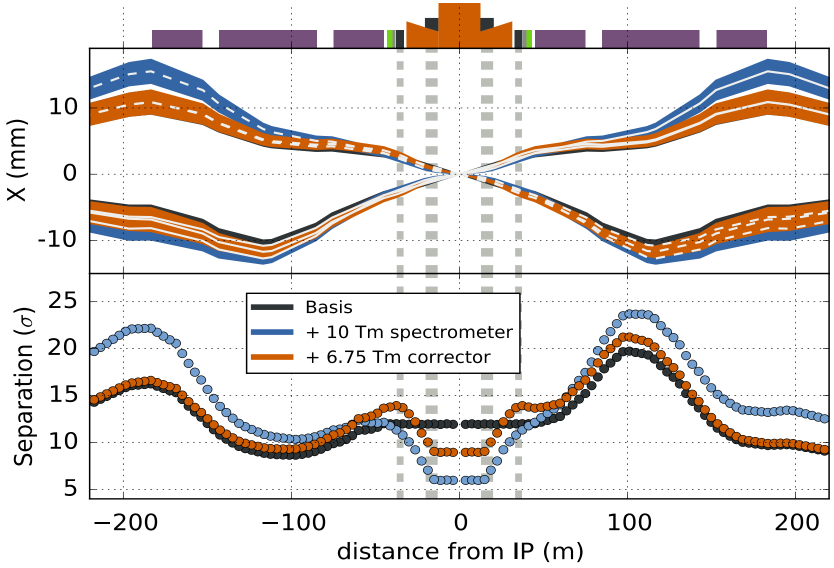
phase 2: β^*=0.3 m, ξ_{tot}=0.03, t_{ta}=4 h, 1000 fb^{-1} / year

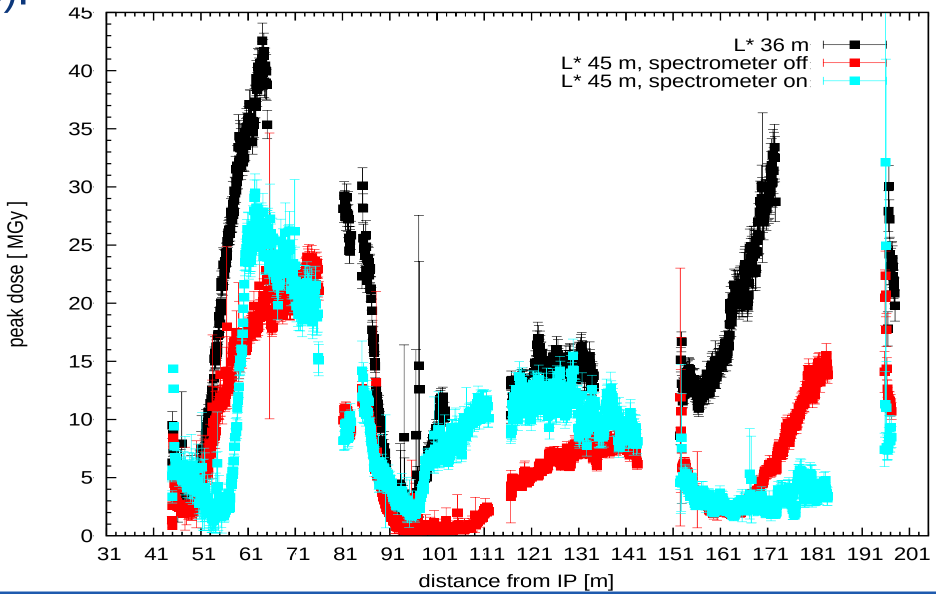
FCC-hh MDI status

Design of interaction region

- Distance from IP to first machine quadrupole L^*=45 m.
- Allows integrated spectrometers and compensation dipoles (or fwd solenoids)
- **Optics and magnet optimization for beam stay clear and collision debris.**
  - ✓ Magnet (triplet) lifetime should be collider lifetime (from radiation damage).







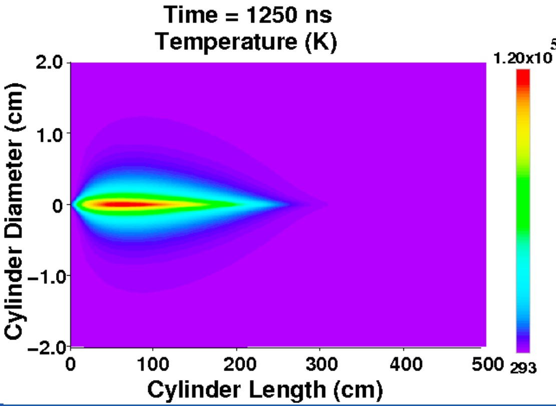
Beam power & machine protection

Stored energy 8.4 GJ per beam

– Factor 25 higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h). Can melt 12t of copper.

Damage of a beam with an energy of 2 MJ

Hydrodynamic tunneling:
beam penetrates ~**300 m** in Cu



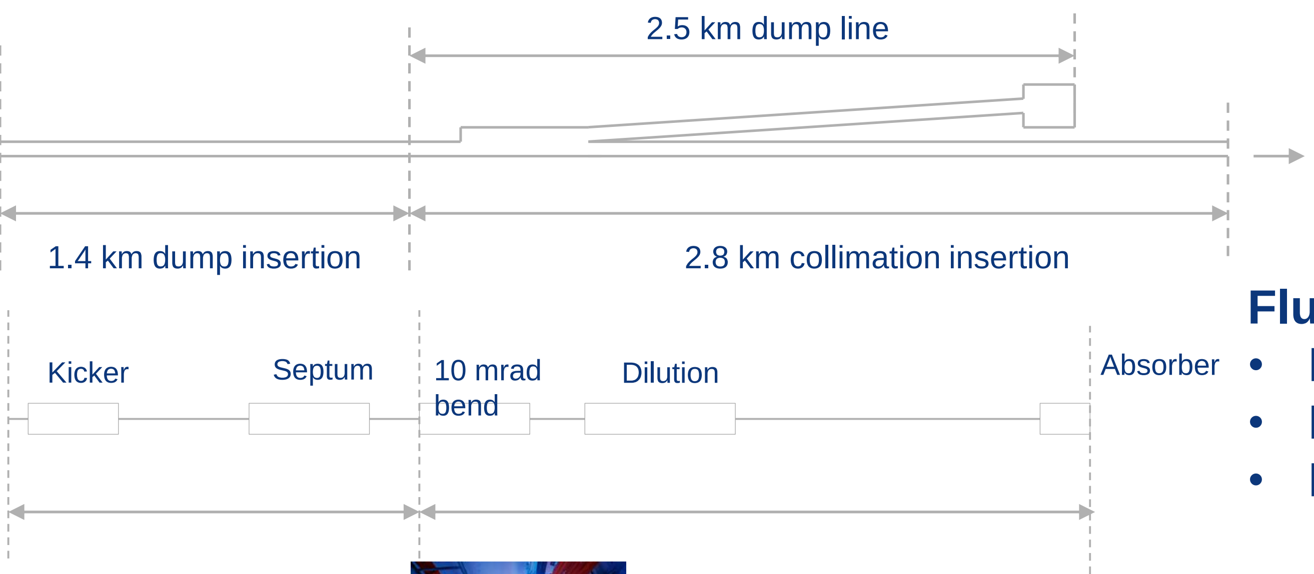
– **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**

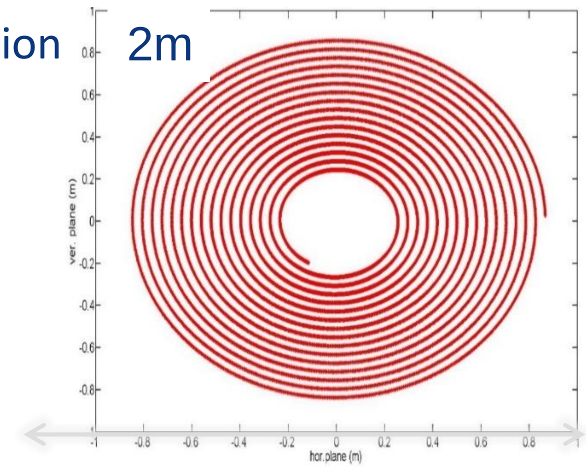
– **Injection, beam transfer and beam dump all critical.**

Machine protection issues to be addressed early on!

FCC-hh beam dilution system

Huge energy to be extracted and dumped => need large dump section
Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!

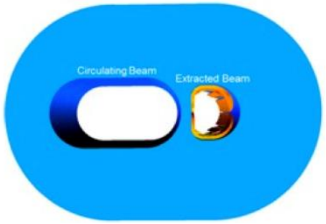




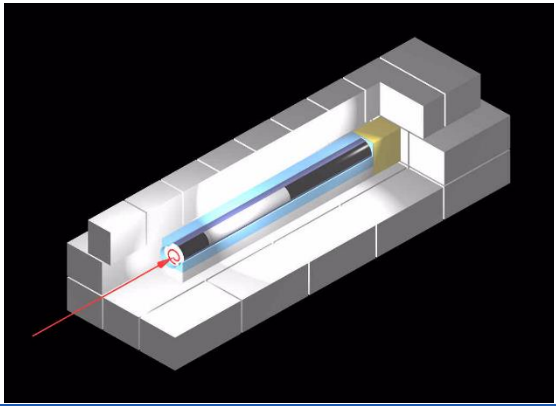
Fluka studies:

- Bunch separation >1.8 mm
- Branch separation: 4 cm
- Keeps T<1500°C

Very reliable kickers, high segementation, new methods for triggering (laser)

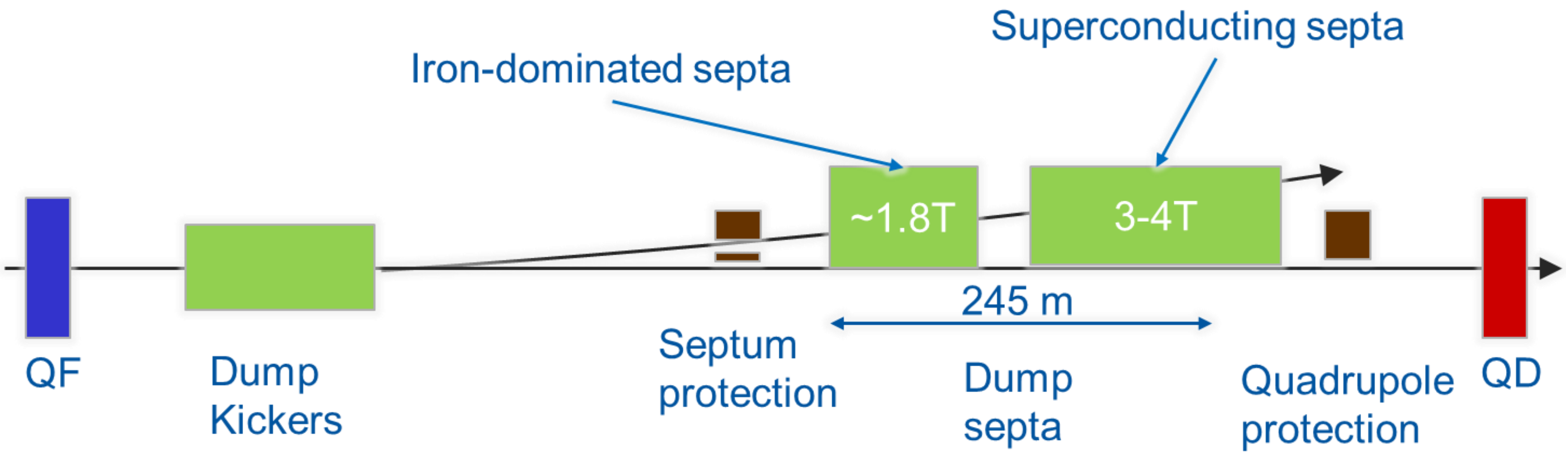


SC septum

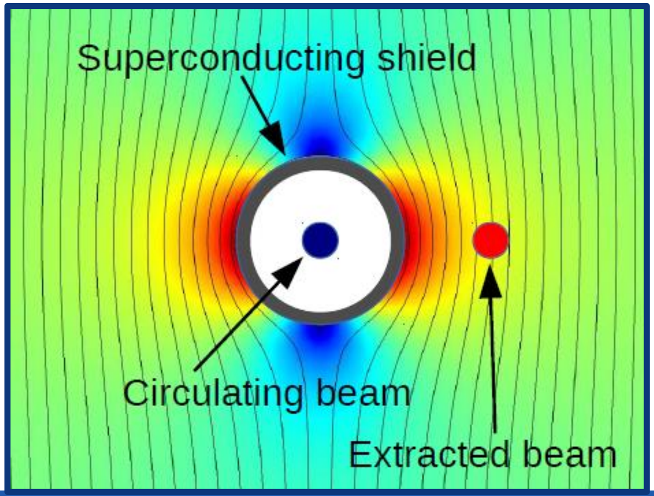


R&D on Superconducting Septa

Need an extraction system for safely removing the beam from the collider hybrid system: short overall length with high robustness & availability

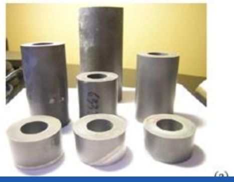


SuShi concept: SC shield creates field-free region inside strong dipole field



3 candidate technologies:

(1) NbTi/Nb/Cu multilayer sheet
(2) HTS tape/coating
(3) Bulk MgB_2



Synchrotron radiation beam screen prototype

High synchrotron radiation load of proton beams @ 50 TeV:

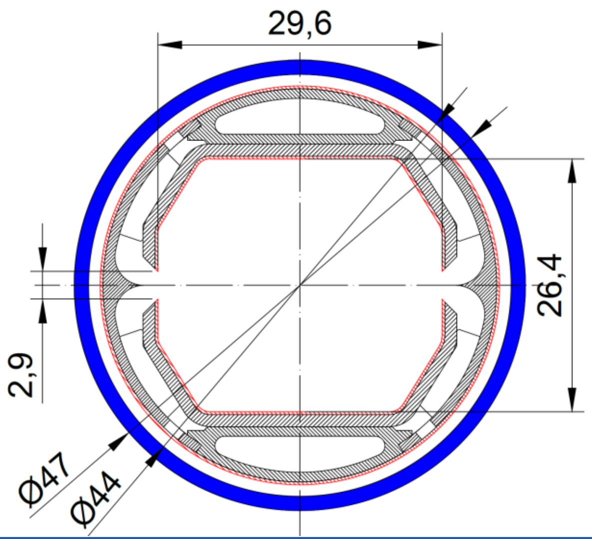
- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

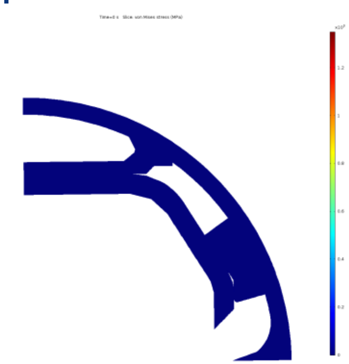
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of cryo power

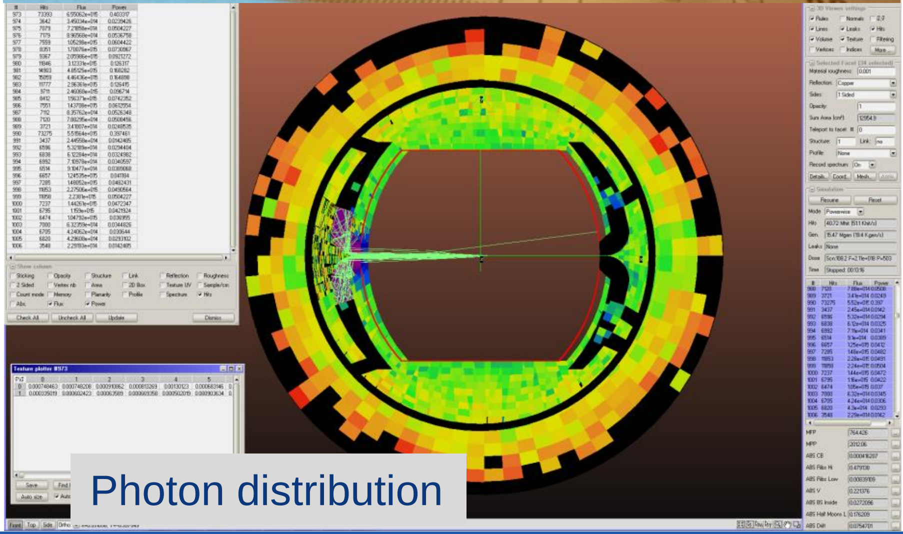
FCC-hh beam screen prototypes

Ready for Testing 2017 in ANKA within EuroCirCol study





Simulation of quench behaviour

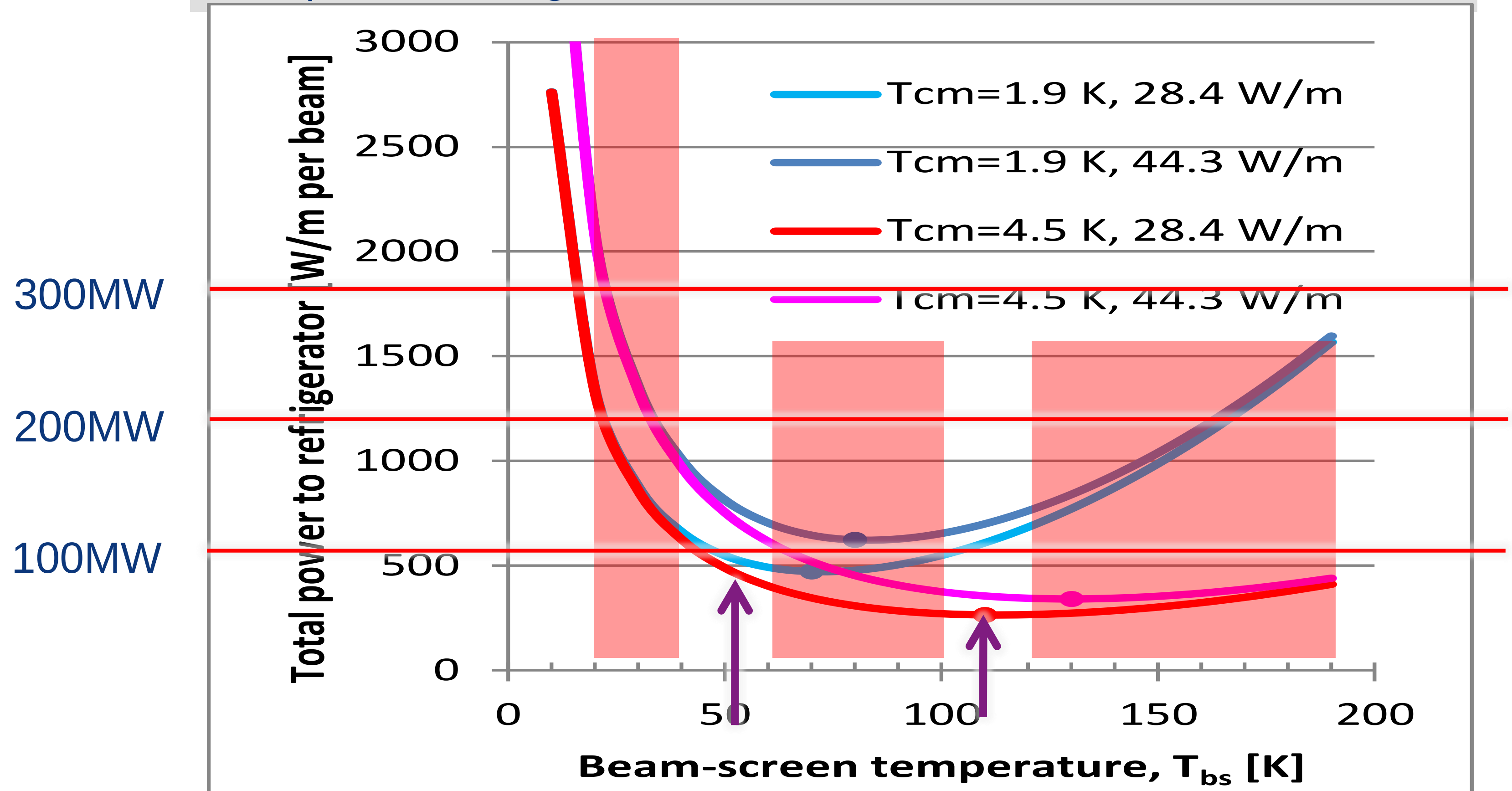


Photon distribution

Cryo power for cooling of SR heat

Overall optimisation of cryo-power, vacuum and impedance

Termperature ranges: <20, 40K-60K, 100K-120K



Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)

Main SC Magnet system FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm

Dipoles: $4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl \sim 1\ MTm$

$\text{Stored energy} \sim 200\ \text{GJ (GigaJoule)} \sim 44\ \text{MJ/unit}$

Quads: $762\ magnets,\ \ 6.6\ m\ long, 375\ T/m$

LHC

Bore diameter: 56 mm

Dipoles: $1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl \sim 0.15\ MTm$

$\text{Stored energy} \sim 9\ \text{GJ (GigaJoule)} \sim 7\ \text{MJ/unit}$

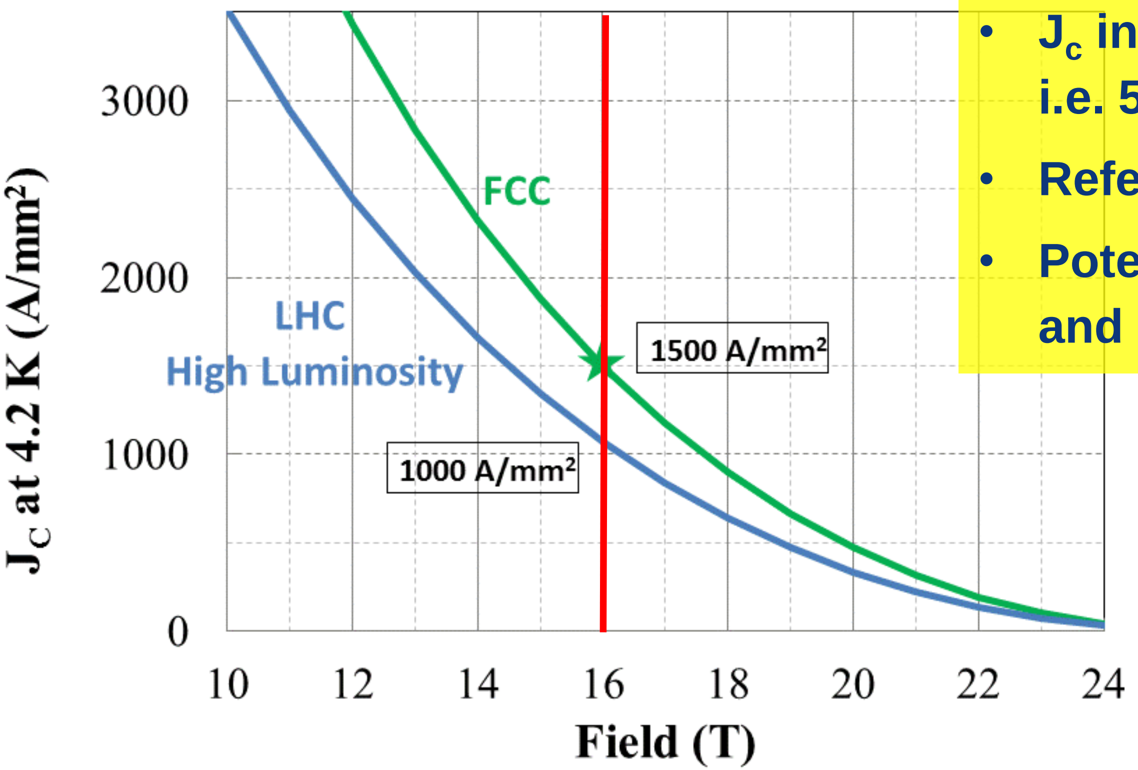
Quads: $392\ units,\ 3.15\ m\ long, 233\ T/m$

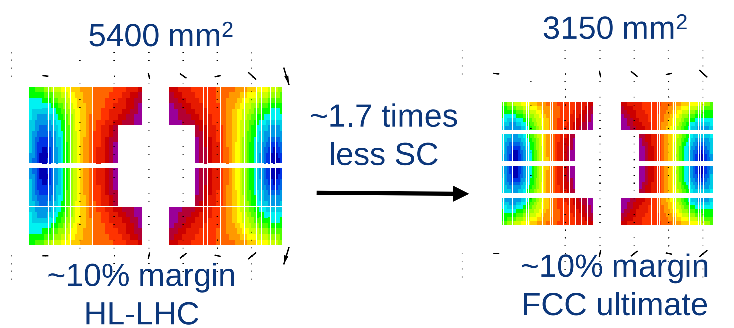
Nb_3Sn conductor program

Nb_3Sn is one of the major cost & performance factors for FCC-hh and is given highest attention

Main development goals until 2020:

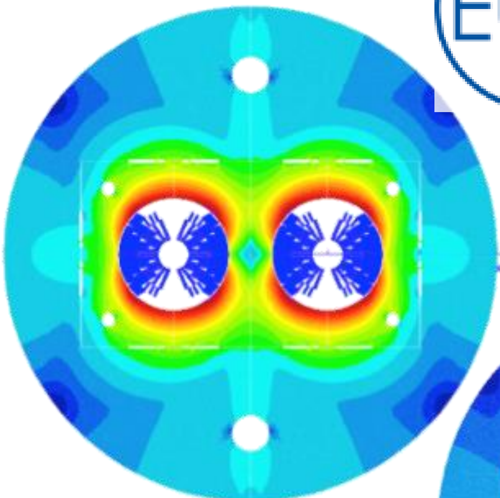
- **J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire**
- **Reference wire diameter 1 mm**
- **Potentials for large scale production and cost reduction**





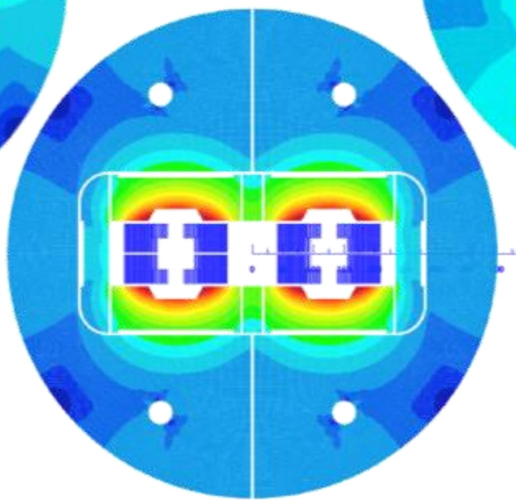
16 T dipole options and plans

Cos-theta

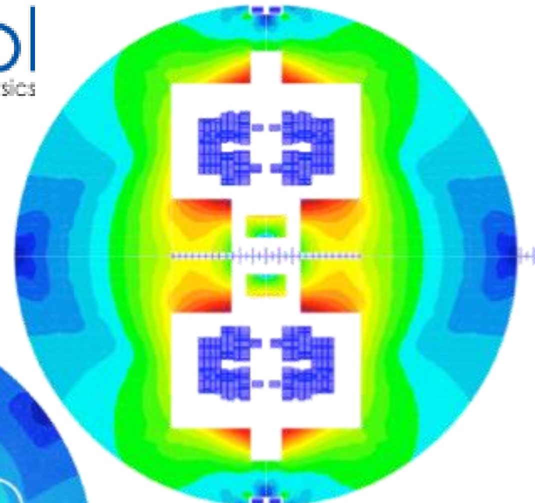


EuroCirCol
A key to New Physics

Blocks

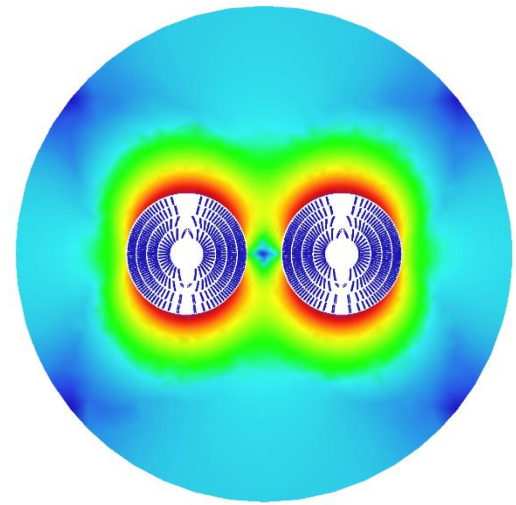


Common coils



Swiss contribution
via PSI

Canted
Cos-theta



- **Model production 2018 – 2022,**
- **Prototype production 2023 - 2025**

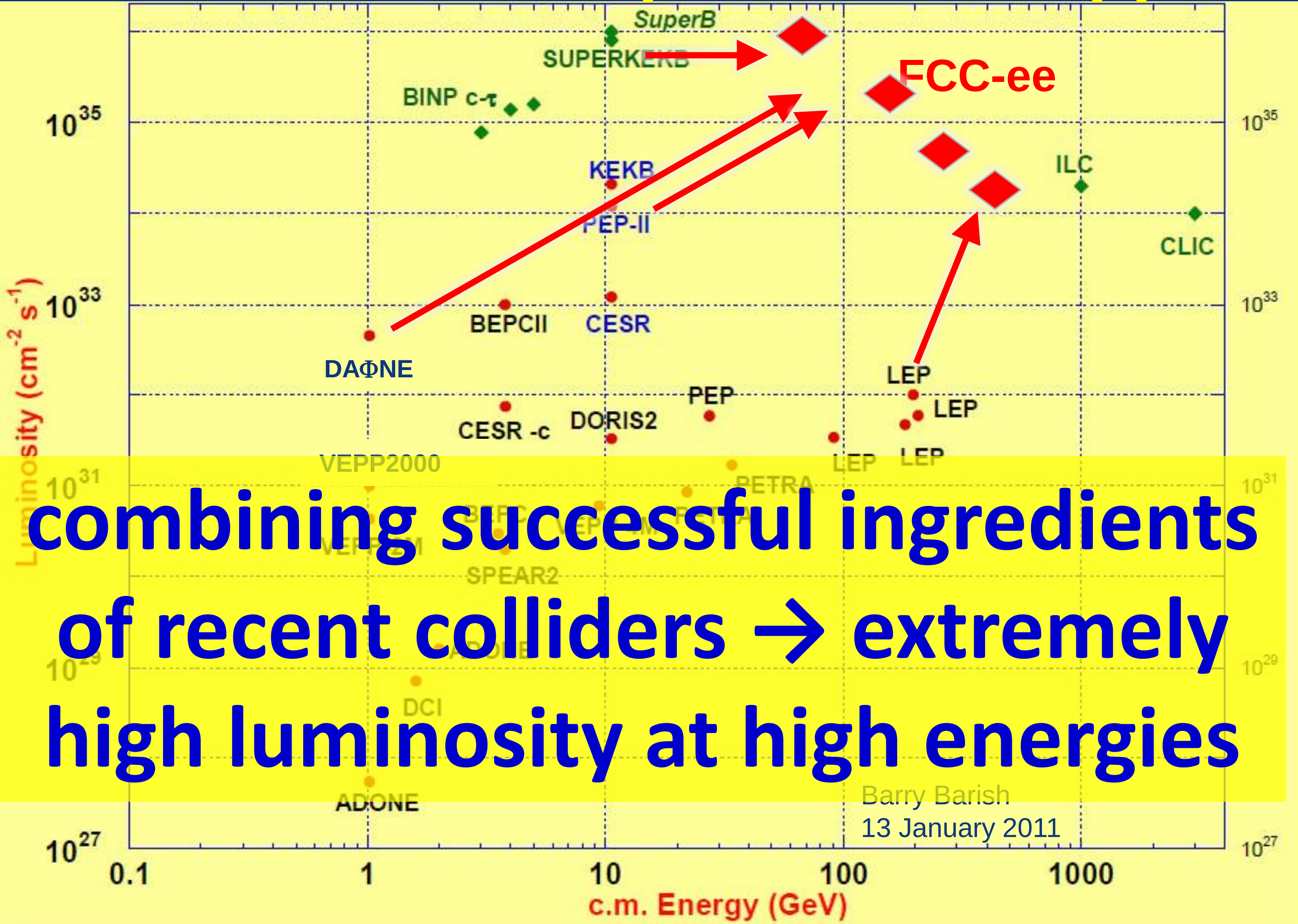
lepton collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

FCC-ee exploits lessons & recipes from past e^+e^- and *pp* colliders



combining successful ingredients of recent colliders → extremely high luminosity at high energies

LEP:
high energy
SR effects

B-factories:
KEKB & PEP-II:
high beam currents
top-up injection
DAFNE: crab waist

Super B-factories
S-KEKB: low β_y*

KEKB: e^+ source

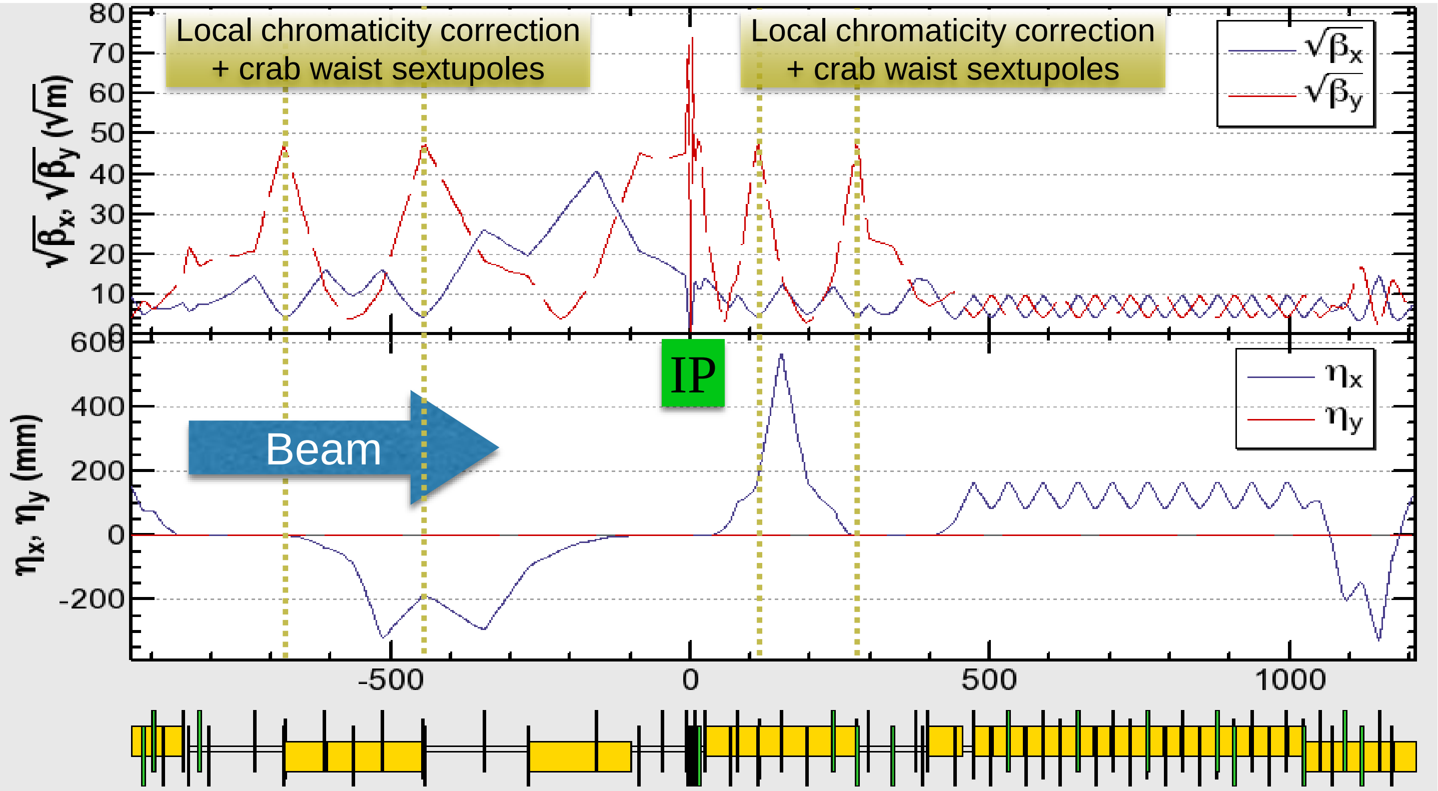
HERA, LEP, RHIC:
spin gymnastics

FCC-ee optics design

Optics design for all working points achieving baseline performance

Interaction region: asymmetric optics design

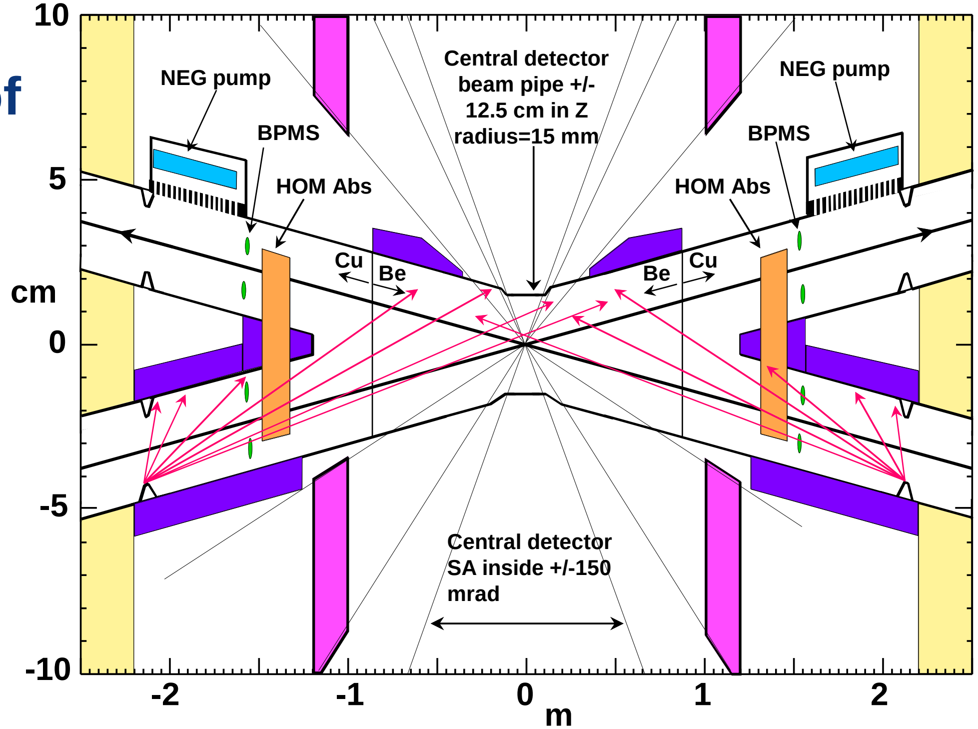
- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs

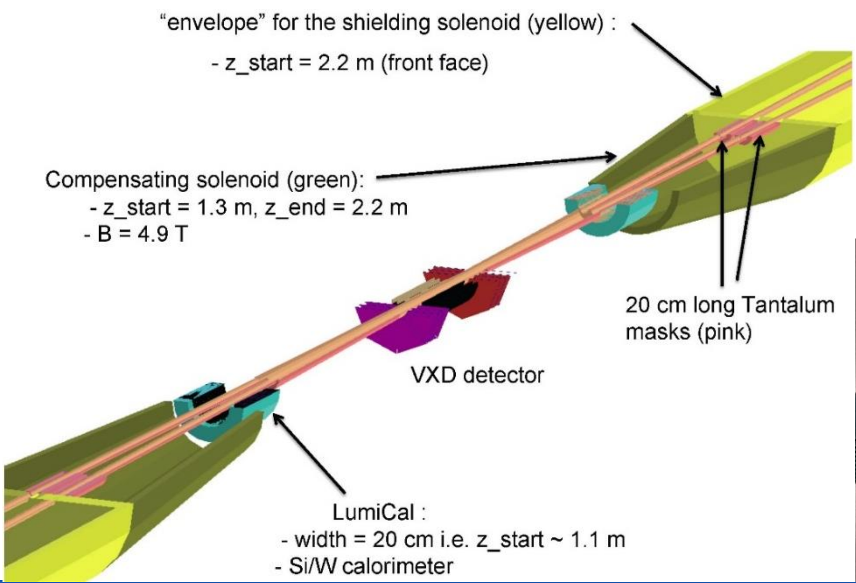


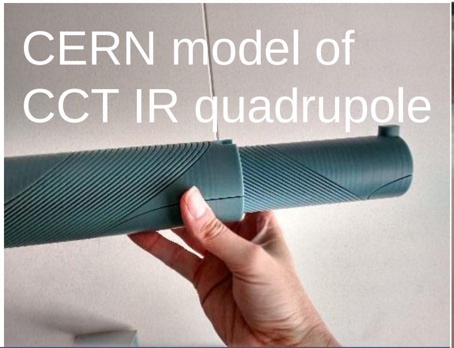
FCC-ee MDI optimisation

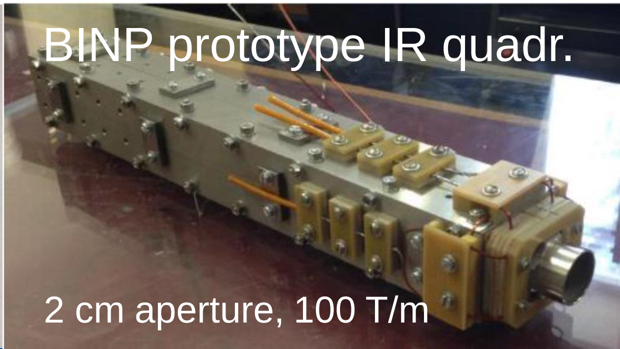
MDI work focused on optimization of

- *l**, IR quadrupole design
- Detector, compensation solenoid
- SR masking and chamber layout

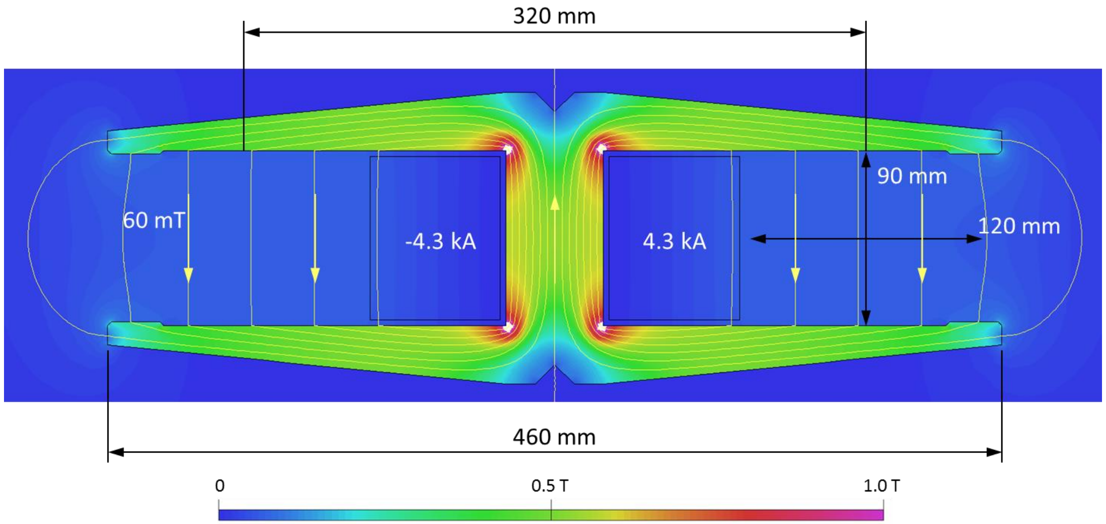






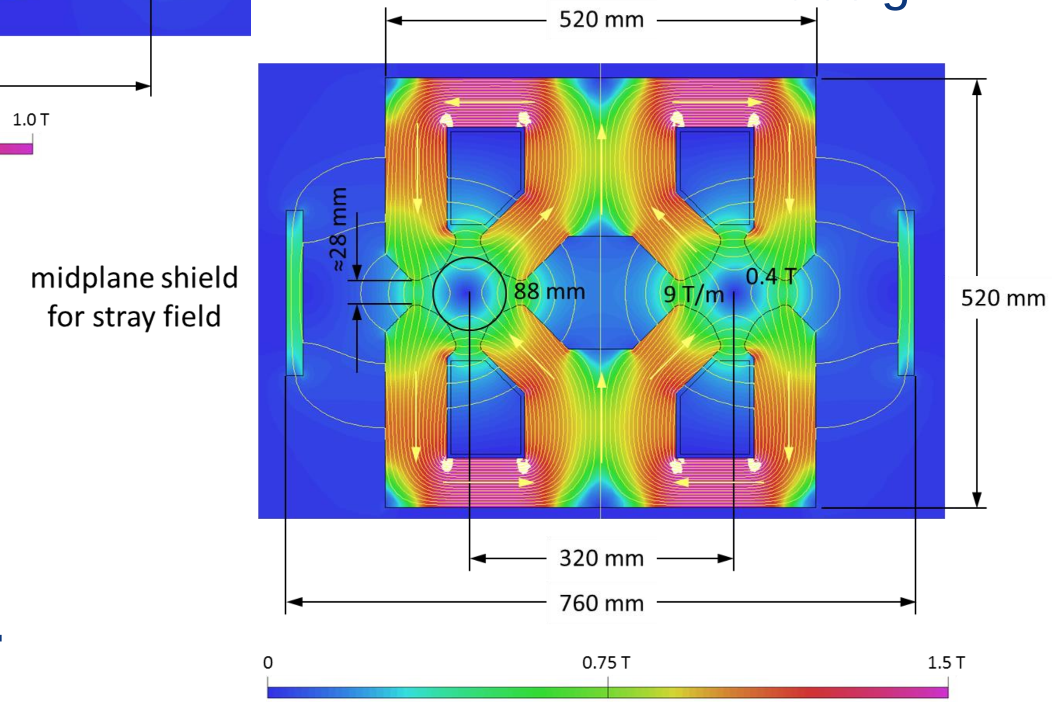


Efficient 2-in-1 FCC-ee arc magnets



Dipole:
twin aperture yoke
single busbars as coils

Quadrupole:
twin 2-in-1 design



- **Novel arrangements allow for considerable savings in Ampere-turns and power consumption**
- **Less units to manufacture, transport, install, align, remove,…**

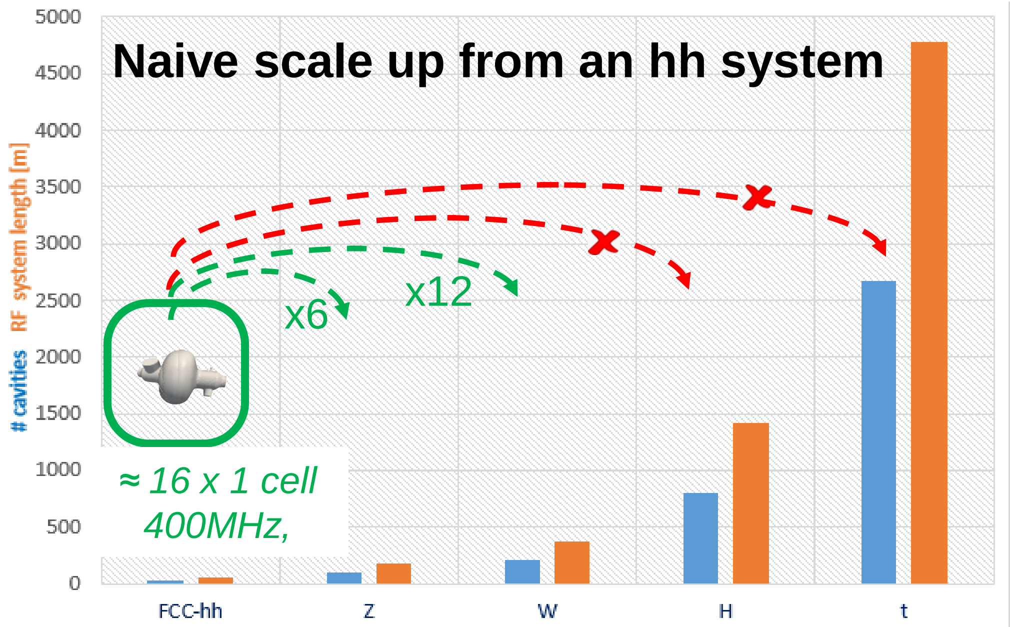
RF system requirements

Very large range of operation parameters

"Ampere-class" machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		**500**	
Z	0.4/0.2	30000/90000	**1450**	0.034
W	0.8	5162	152	0.33
H	**5.5**	770	30	1.67
t	**10**	78	6.6	7.55

"high gradient" machines

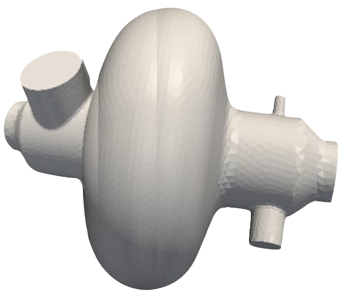


- **Voltage and beam current ranges span more than factor > 10^2**
- **No well-adapted single RF system solution satisfying requirements**

RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)



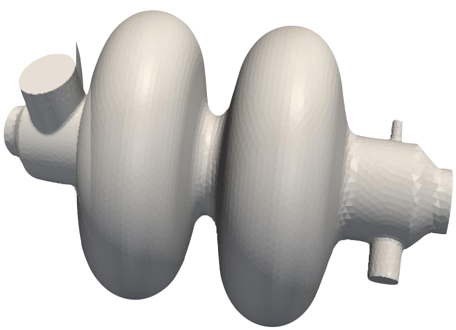
hh ≈ 16 cells per beam

Z ≈ 100 per beam (+ 100 for booster ring)

W ≈ 210 per beam (+ 210 for booster ring)

400 or 800 MHz multi-cell cavities preferred for ee-ZH, ee-tt and ee-WW

- Baseline options 400 MHz Nb/Cu @4.5 K, ◄▬► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn like components



W ≈ 200 per beam (+ 200 for booster)

H ≈ 800 per beam (+ 800 for booster)

t ≈ common 2600 cells for both beams (+ 2600 for booster)

Summary

- The HL-LHC upgrade project is in full swing with first installations in LS2.
- The FCC study phase 1 is completed with Design Reports.
- Clearly HL-LHC is a necessary first step in the development of technologies for future HE accelerators, in particular the FCC.
- Superconductivity is the key enabling technology for LHC, HL-LHC, HE LHC and FCC.
- The Nb3Sn program for HL-LHC triplets and 11 T dipoles is of prime importance towards development fo 16 T model magnets.
- SC crab cavities are a major ingredient for HL-LHC and the development of high efficiency SRF systems is critical for FCC-ee.
- Both HL-LHC project and FCC study show the importance of international collaboration in our field, to advance on all challenging subjects and to assure a long-term future!
- **In this sense we rely on your future contributions!**