# 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.**


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

FCC hh ee he

EuroCirCol

http://cern.ch/fcc

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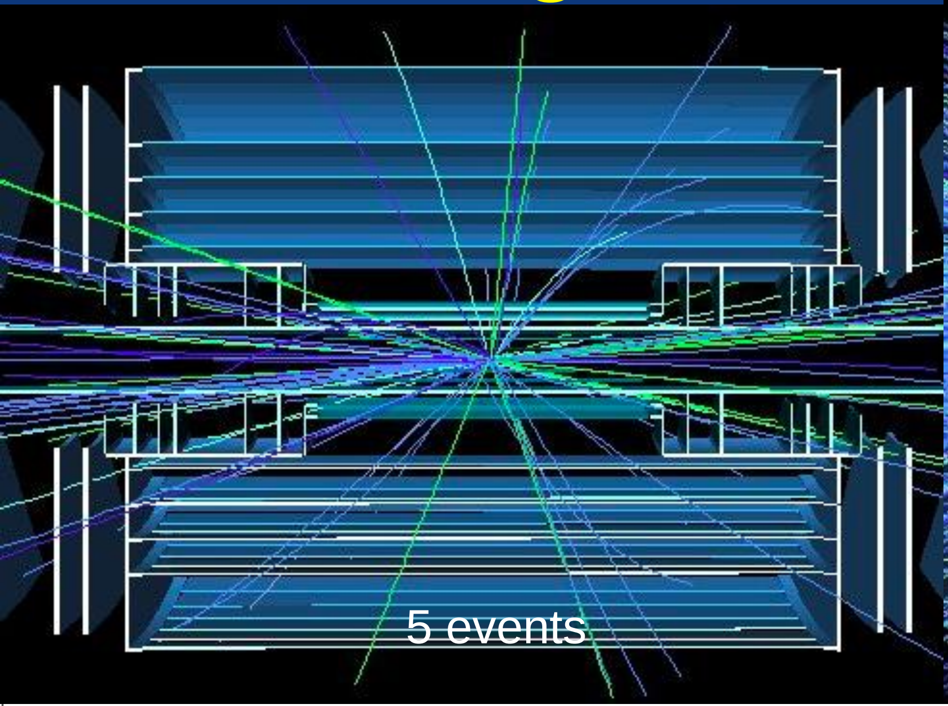
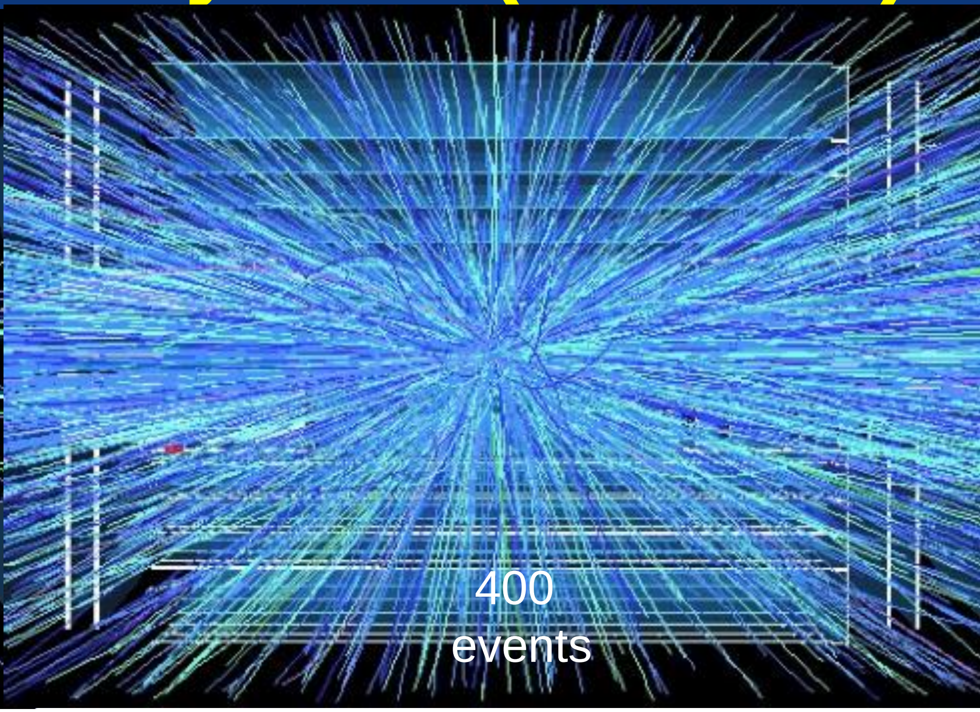
# Outline

- 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**,

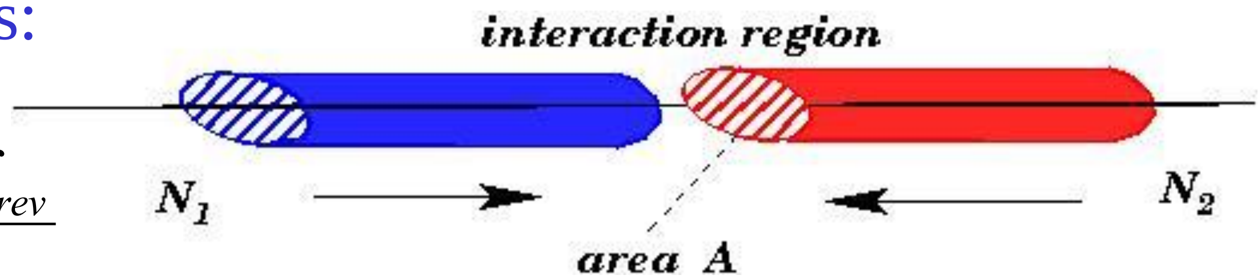
# design oper. for $\mu = $ **140** (➔ peak luminosity **5 10$^{34}$ cm$^{-2}$ s$^{-1}$**)

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

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

# Recap: Luminosity

colliding bunches:




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

$$A = 4\pi \cdot \sigma_x \cdot \sigma_y$$ with: $$\sigma = \sqrt{\beta \cdot \varepsilon}$$

$\beta$ is determined by the magnet arrangement & powering

$\varepsilon = \varepsilon_n / \gamma$ $\varepsilon_n$ 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):

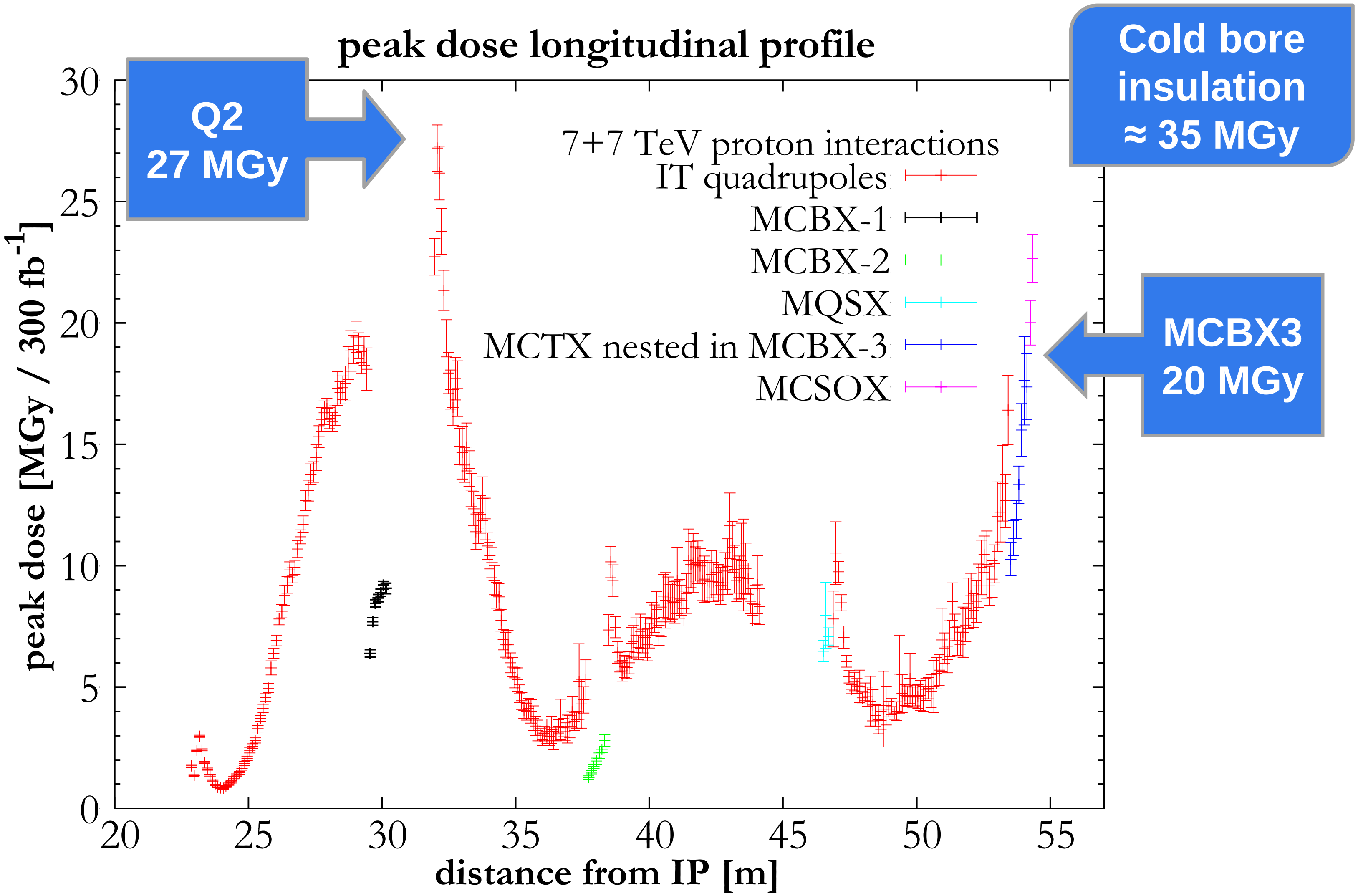
$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

| | |
|---|---|
| → maximize bunch intensities (1.1 → 2.2x$10^{11}$ ) | → Injector complex Upgrade LIU |
| → minimize the beam emittance (3.75→ 2.5 μm) | |
| → minimize beam size (β* 0.55 → 0.15 m); | → New triplets |
| →compensate for 'F' geometry crossing; | → Crab Cavities |
| → improve machine 'Efficiency' | → minimize number of unscheduled beam aborts |

# LHC Limitations and HL-LHC challenges

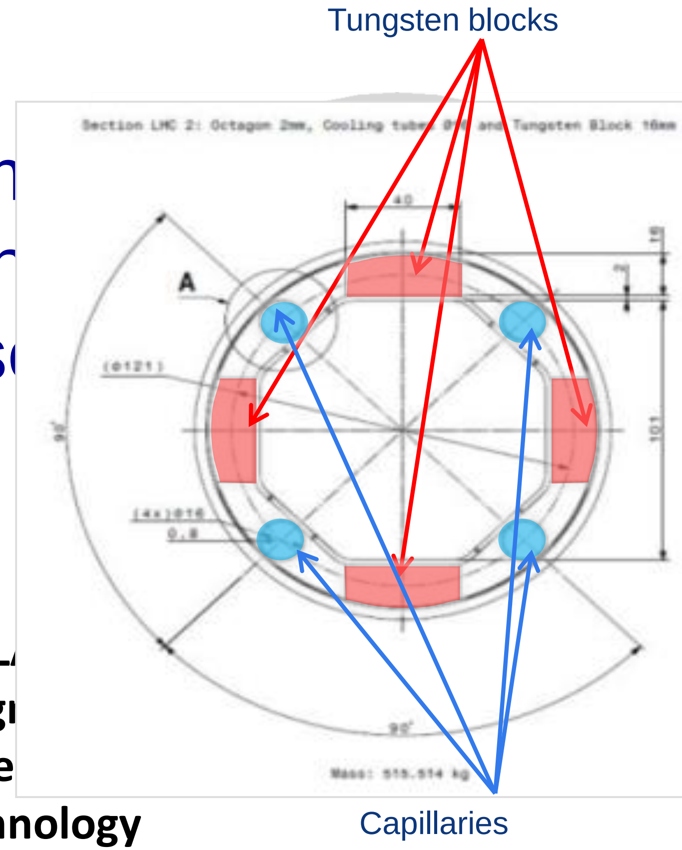
- **Insertion quadrupole magnets lifetime and aperture:**
  - ➔ New insertion magnets and low-β with increased aperture
- **Geometric Reduction Factor:** ➔ SC Crab Cavities
  - ➔ New technology and first time for a hadron storage ring!
- **Performance Optimization: Pileup density** ➔ Lumi levelling
  - ➔ 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 dos @ 10 times higher integrated luminosity 3000 fb$^{-1}$! ➔ Shielding!

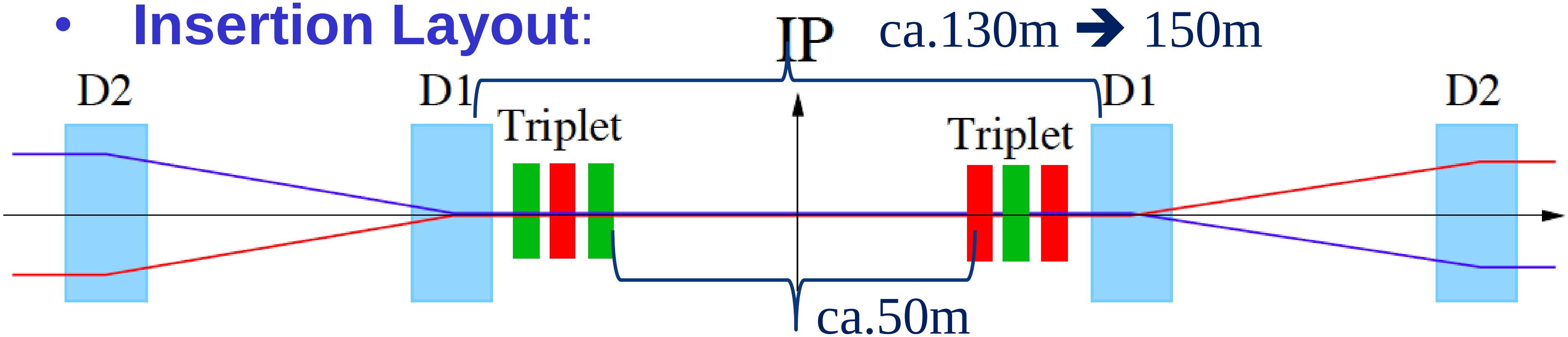



US-L
magı
Base
technology

- ➔ Requires larger aperture!
- ➔ New magnet 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

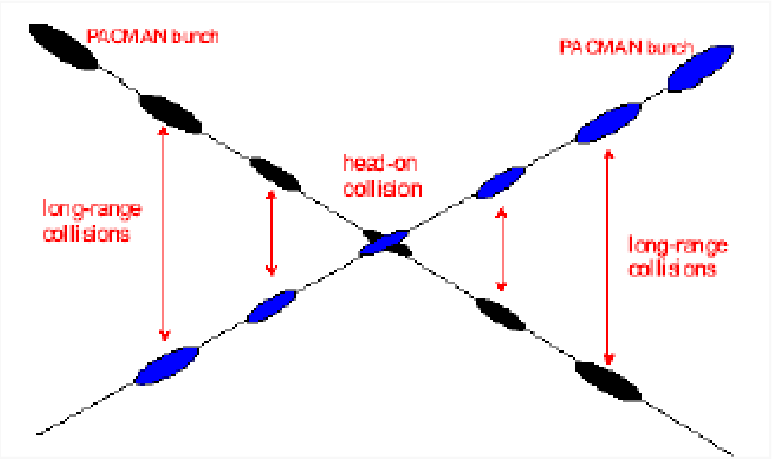
- **Insertion Layout:**




- **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:

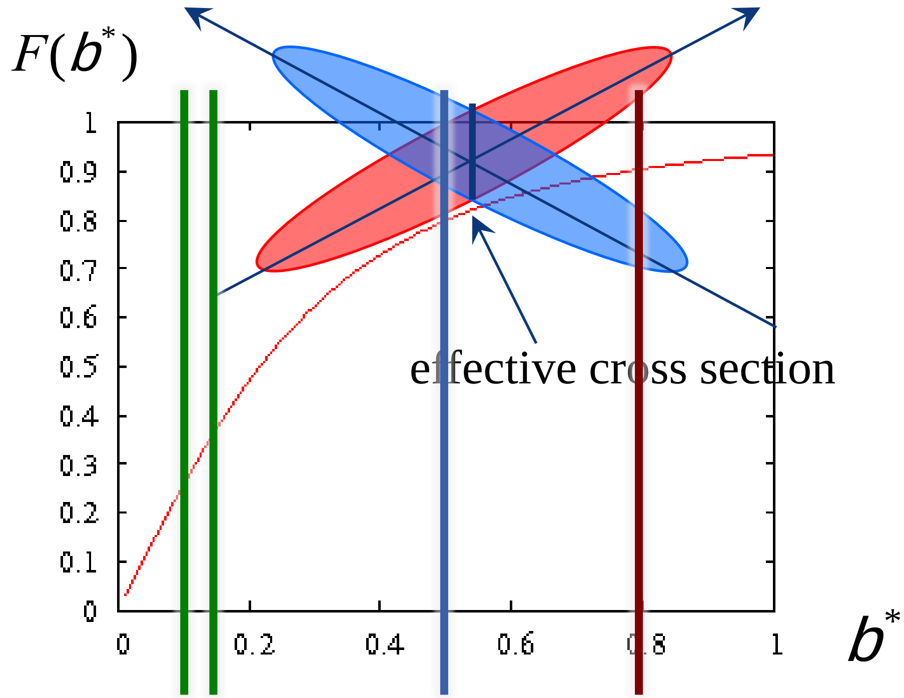
Crab Cavities:

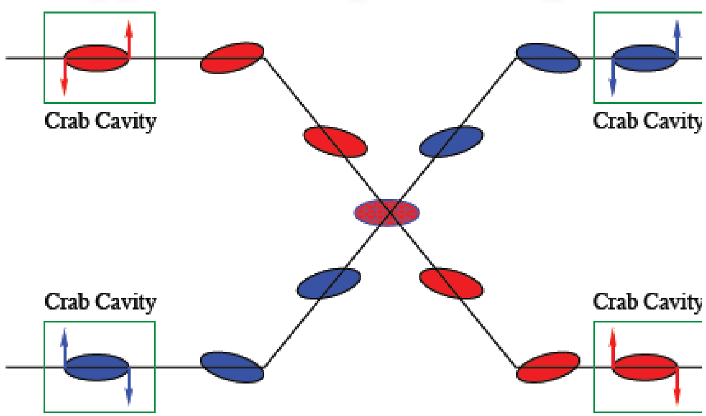
- Reduces the effect of geometrical reduction factor
- Independent for each IP

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

- Challenging space constraints:

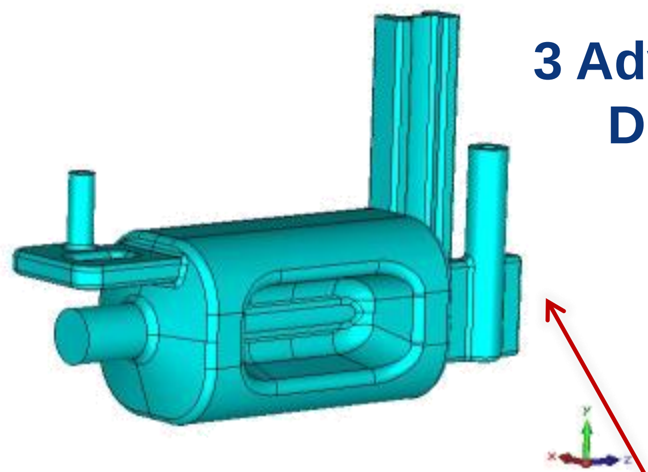
  ➔ requires novel compact cavity design



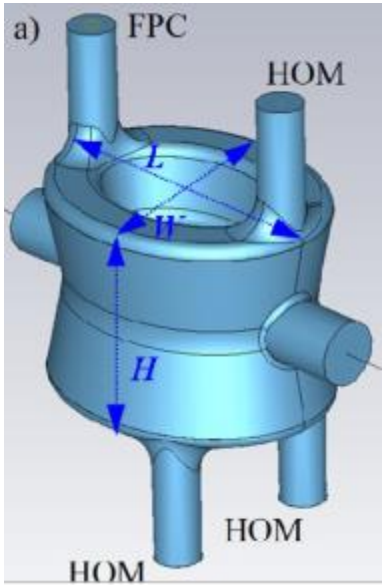



# HL-LHC crab cavity designs

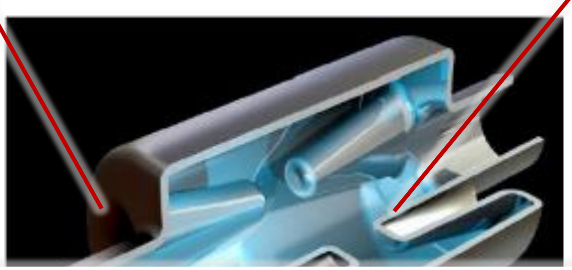
## 3 Advanced Design Studies with Different Coupler concepts

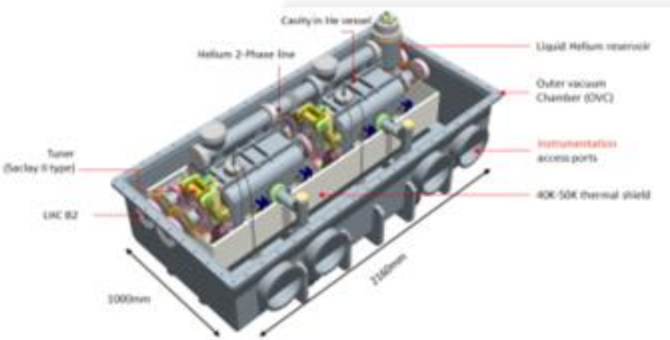


RF Dipole: Waveguide or waveguide-coax couplers




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





ave installed in SPS
hutdown 2017/2018

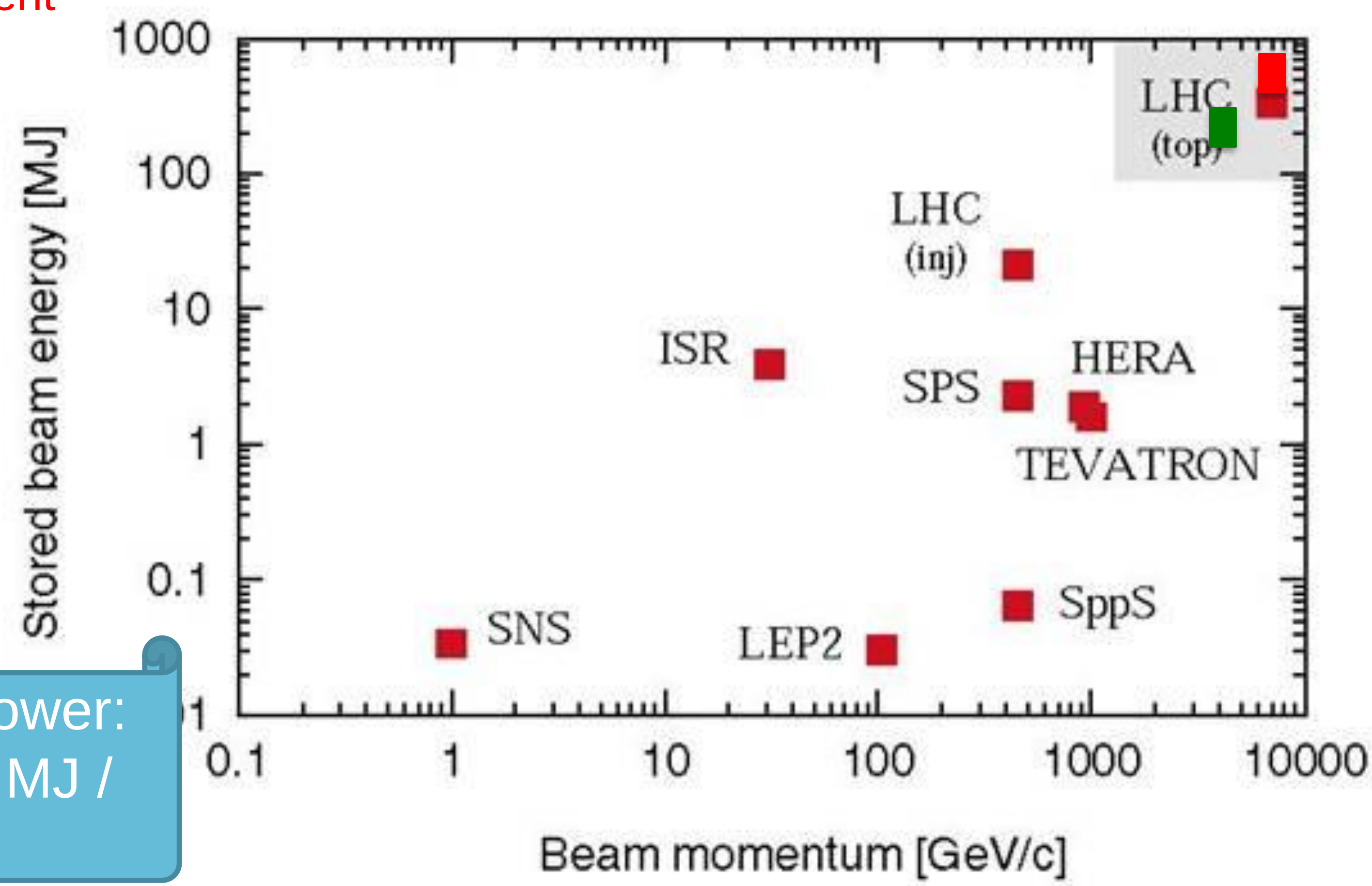
4-rod: (
differen

**Present baseline: 4 cavity/cryomod**
**TEST presently ongoing in SPS**

# LHC Challenges: Beam Power

## Unprecedented beam power:

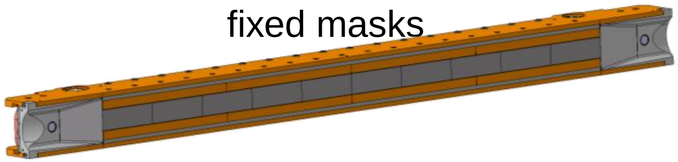
- ➔ potential equipment damage in case of failures during operation
- ➔ In case of failure the beam must never reach sensitive equipment!




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

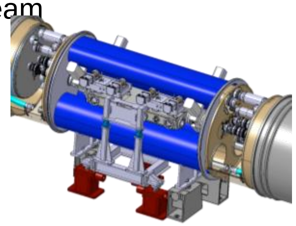
# Collimation system upgrades

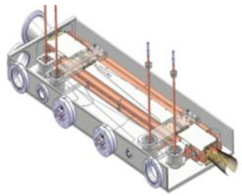
**Completely new layouts**
**Novel materials.**
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

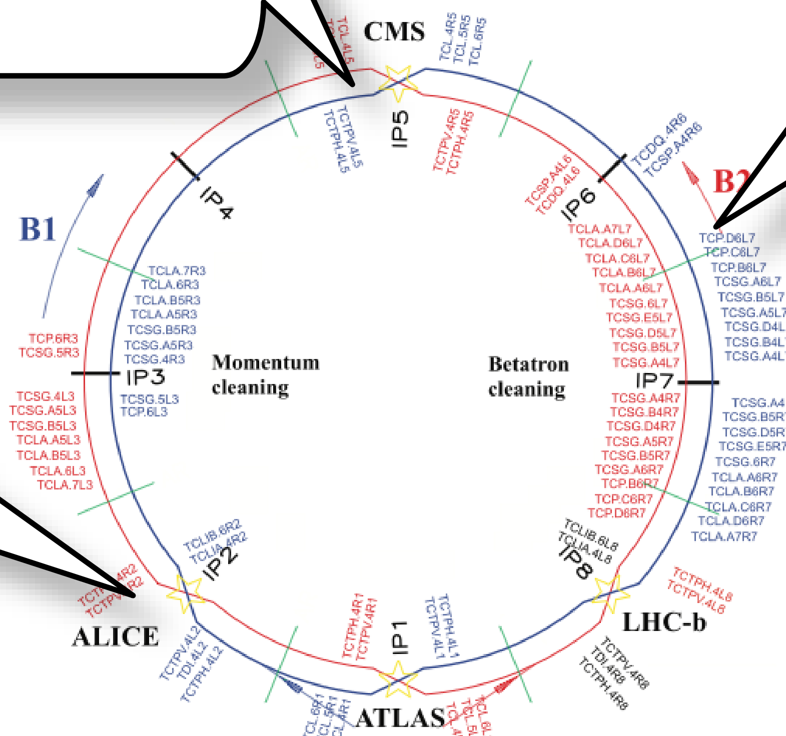


*40 new collimators to be produced by LS3 in the present baseline!*

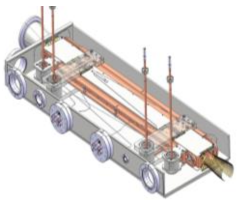
Cleaning: DS coll. + 11T dipoles, 2 units per beam



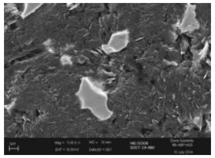


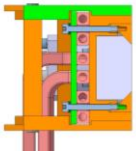


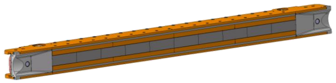

Ion physics debris:
DS collimation



Low-impedance, high robustness secondary collimators

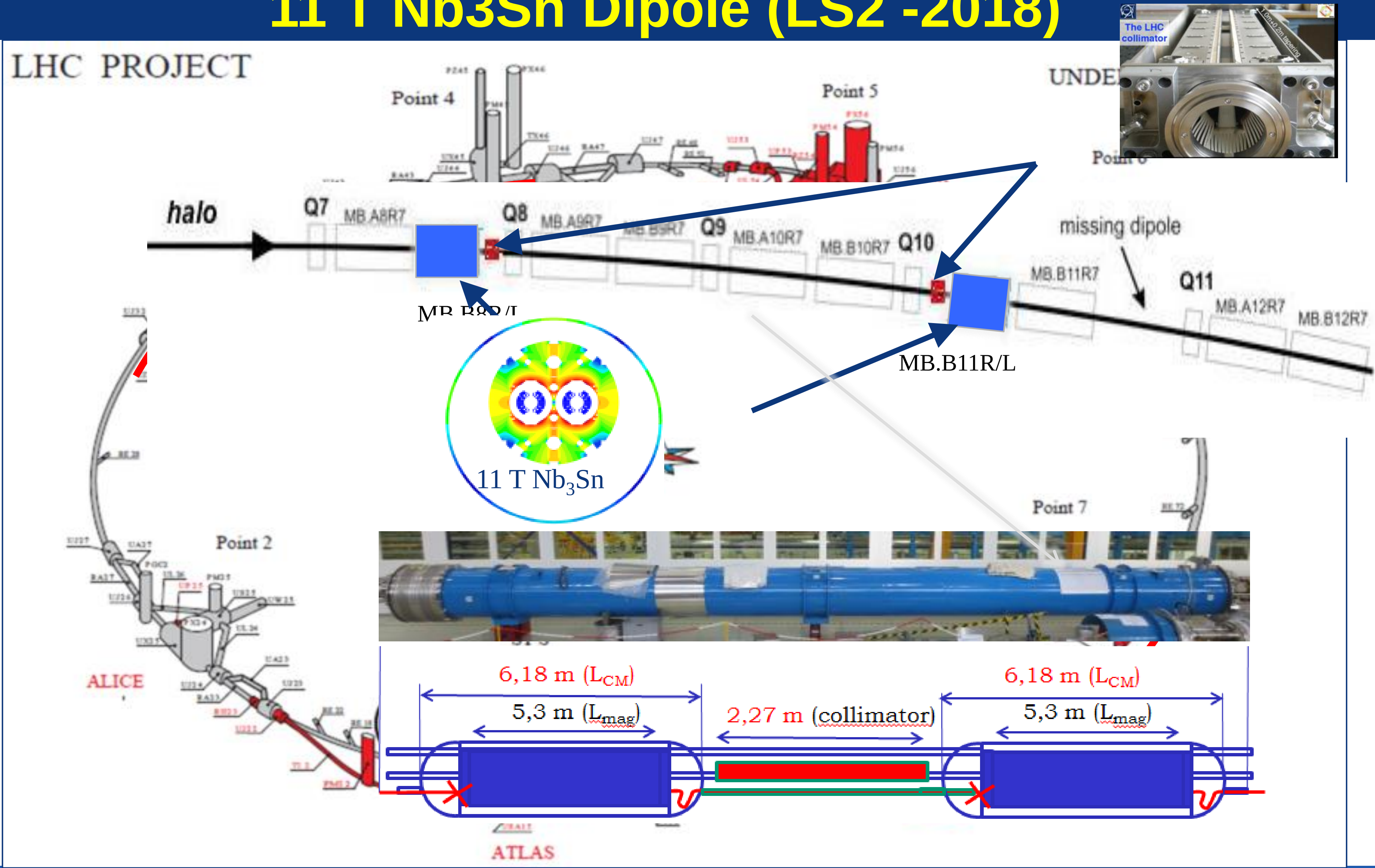




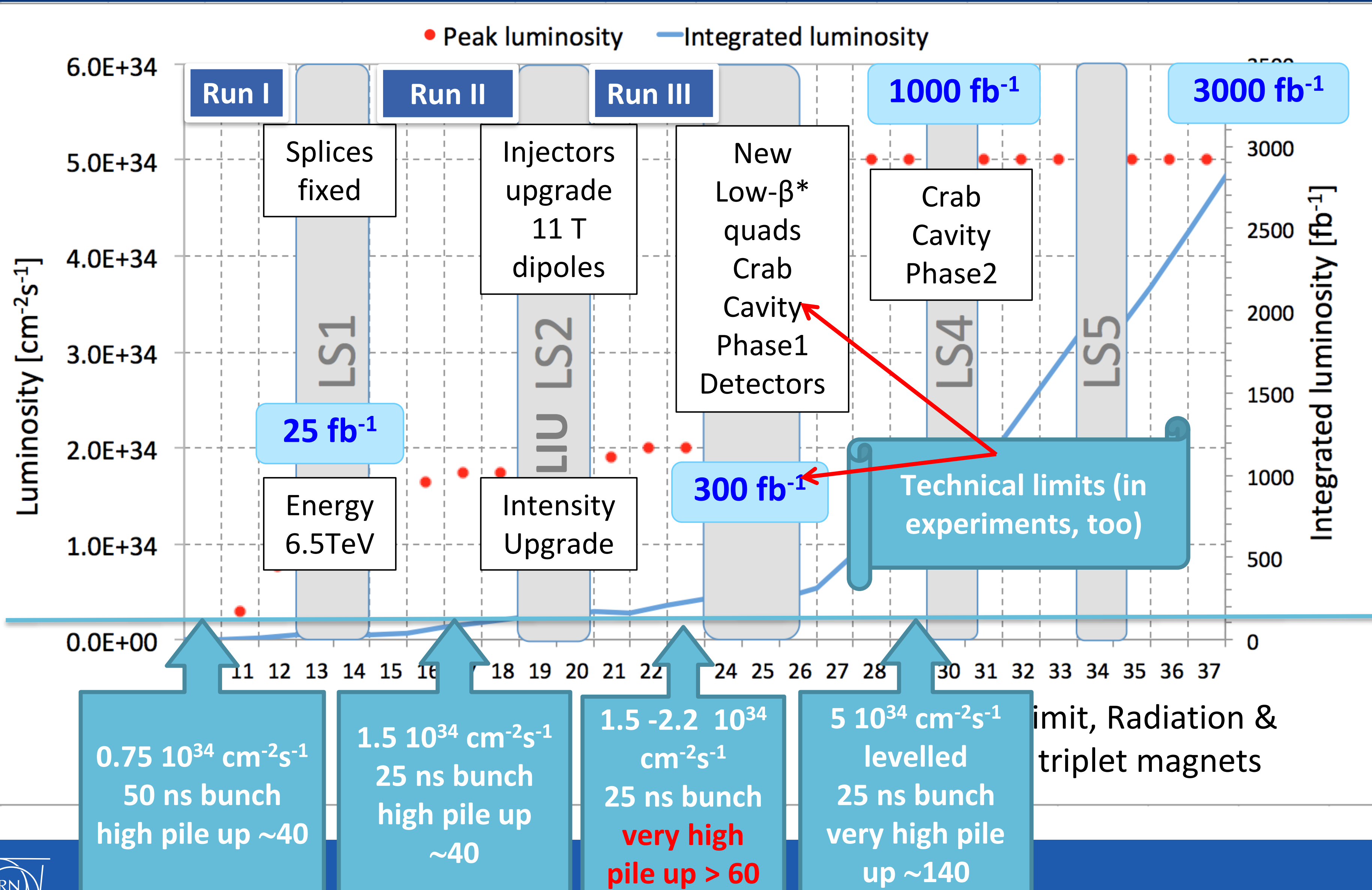


S. Redaelli,
Chamonix 2016, 28-01-2016

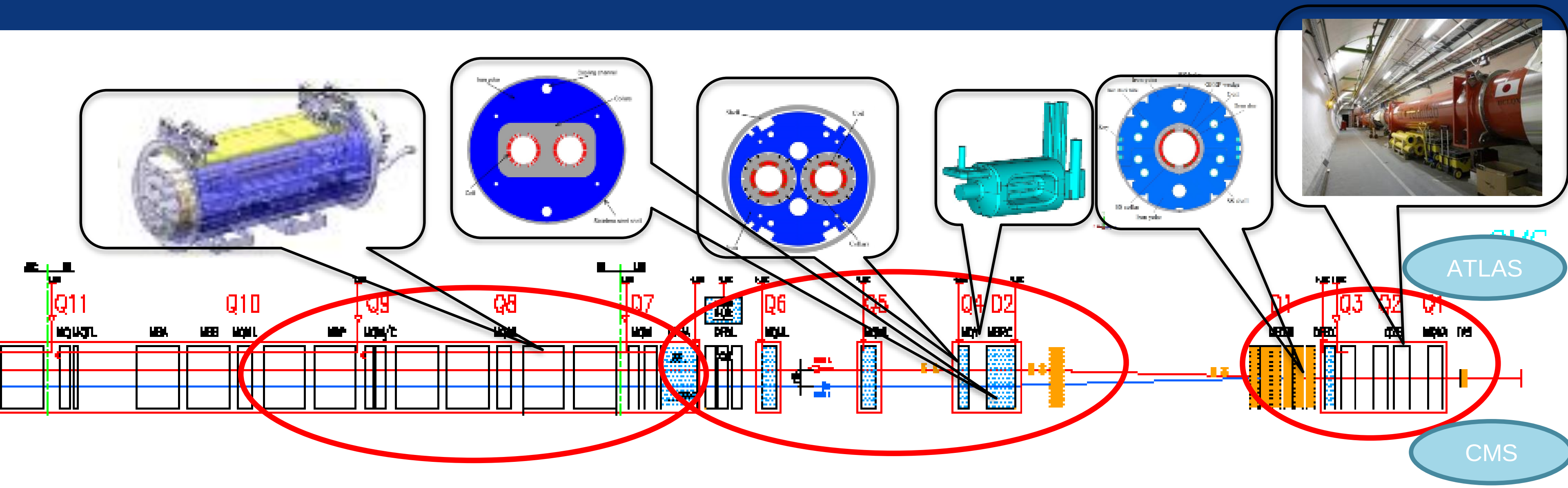
# Dispersion Suppressor collimators – 11 T Nb3Sn Dipole (LS2 -2018)



# Implementation & Performance Projection:



# 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

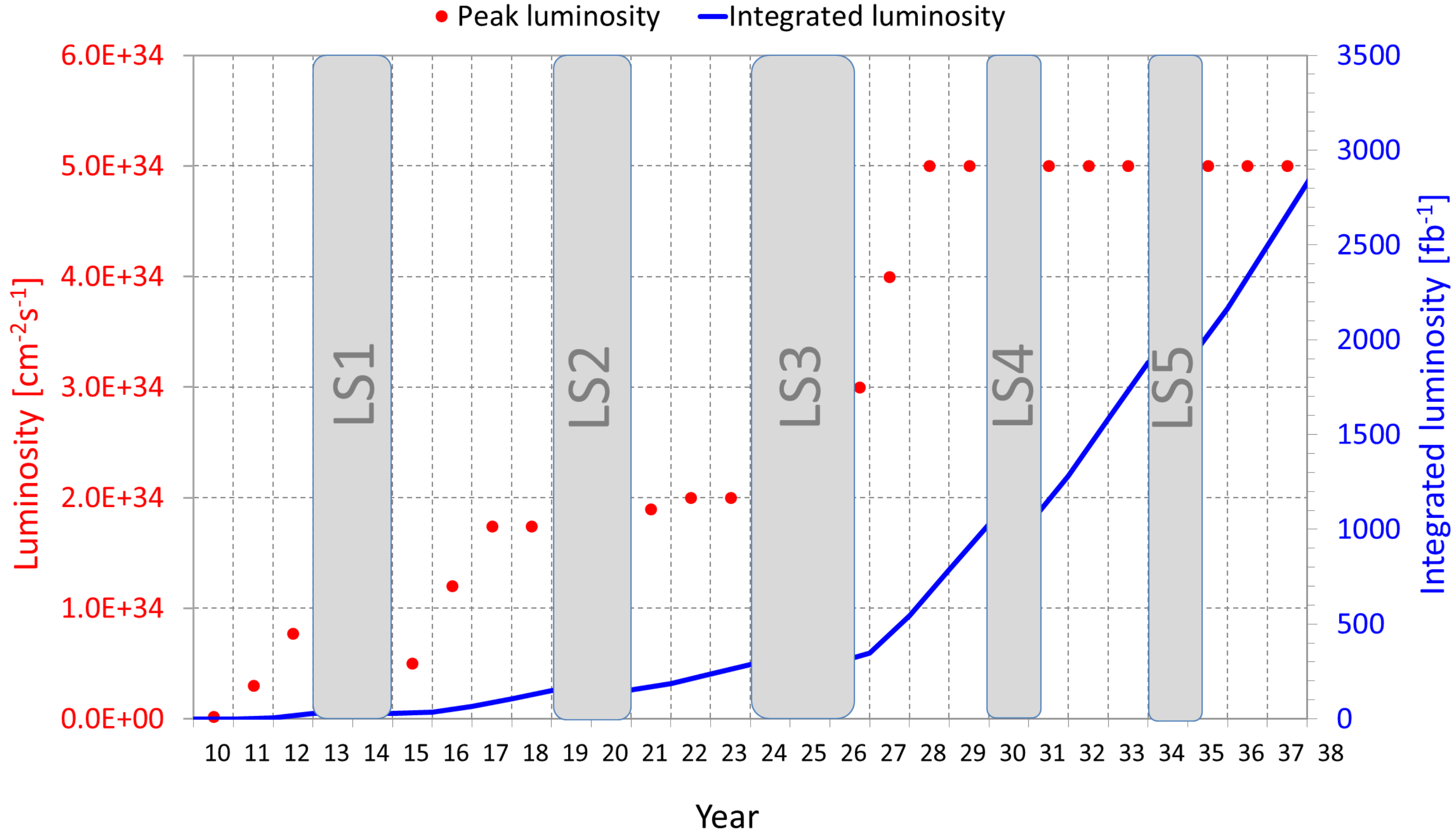
2. We also need to modify a large part of the matching section
e.g. Crab Cavities & D1, D2, Q4 & corrector

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 $E_{cms}$**

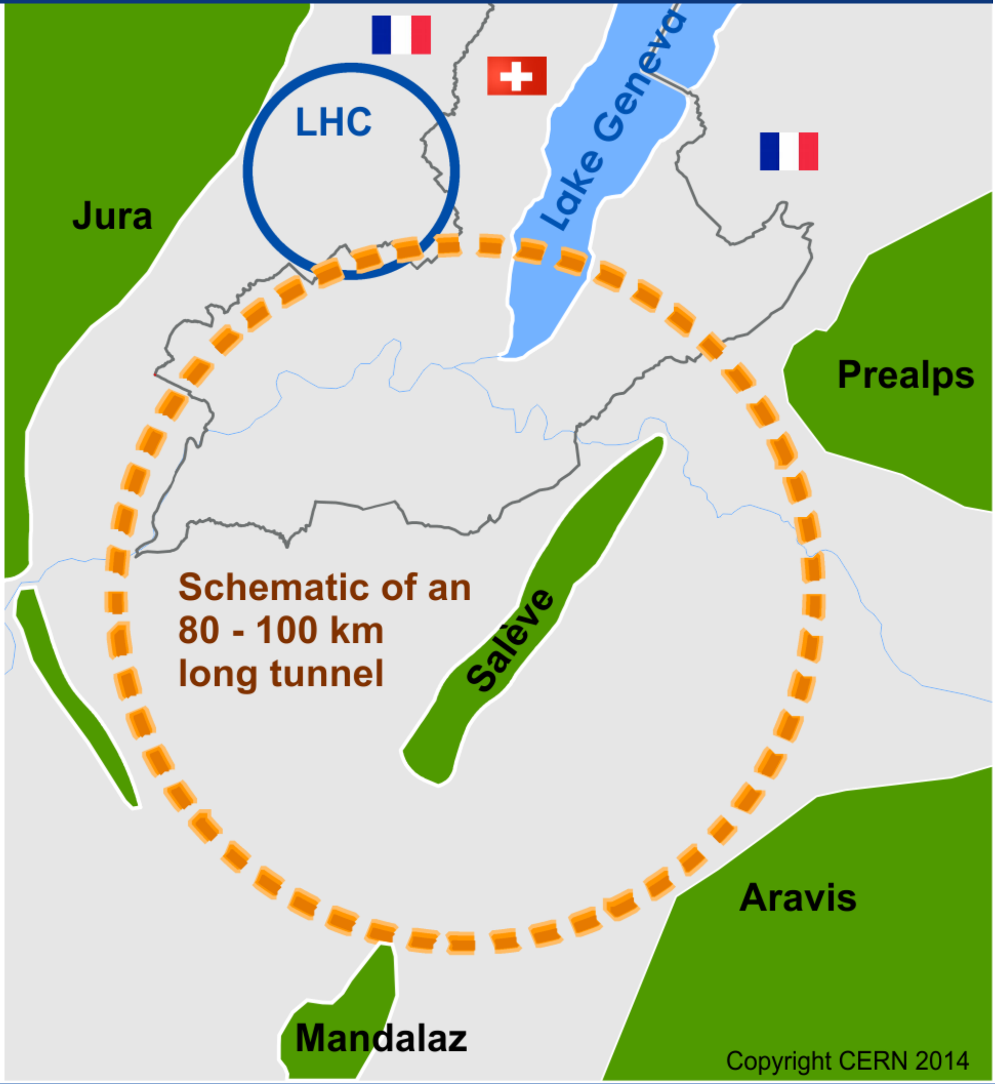
# Future Circular Collider Study
## Goal: CDR for European Strategy Update 2018/19

**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



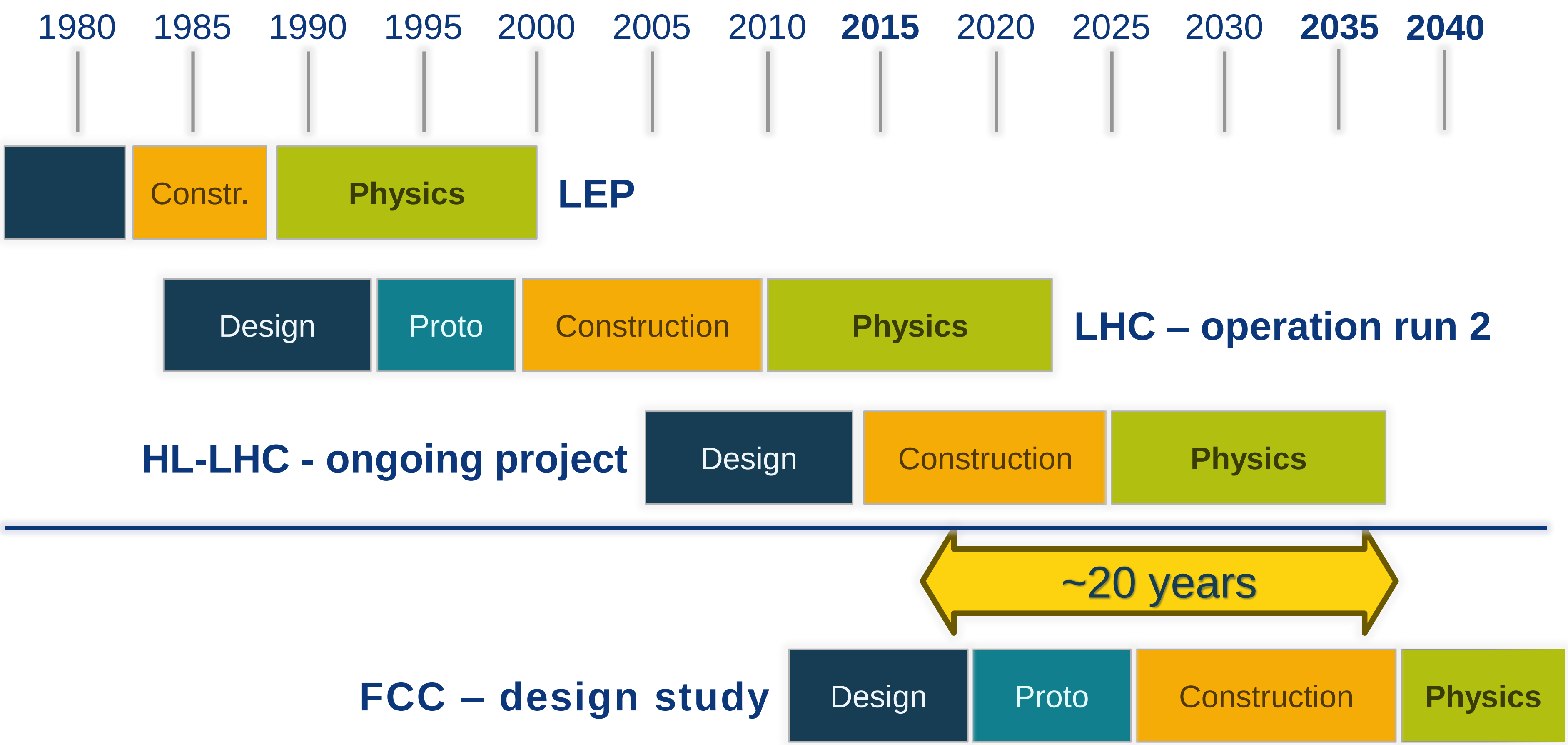
# CepC/SppC study (CAS-IHEP) 100 km (new baseline!) , $e^+e^-$ collisions ~2028; *pp* collisions ~2042


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**

**Goal of phase 1: CDR by end 2018 for next update of European Strategy**

# Progress on site investigations

Alignment | Shafts | Query

Choose alignment option

100km quasi-circular

Tunnel elevation at centre:261mASL

Grad. Params

Azimuth (°): -20

Slope Angle x-x(%): 0.65

Slope Angle y-y(%): 0

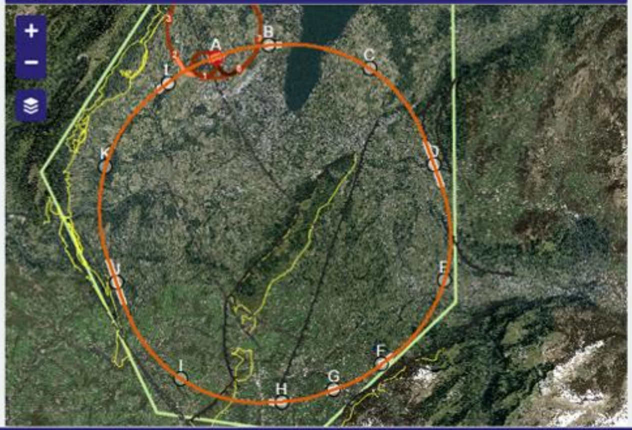
LOAD | SAVE | CALCULATE

Alignment centre

X: 2499731 Y: 1108403

| | CP 1 | | CP 2 | |
|---|---|---|---|---|
| | Angle | Depth | Angle | Depth |
| LHC | -64° | 220m | 64° | 172m |
| SPS | | 242m | | 241m |
| TI2 | | 235m | | 241m |
| TI8 | | 242m | | 170m |

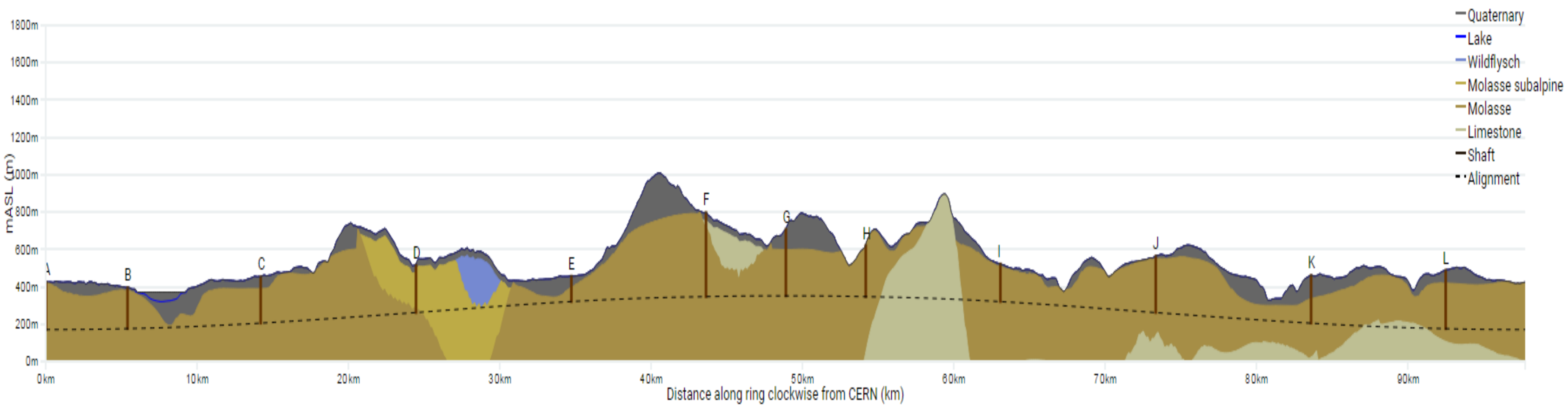
Alignment Location



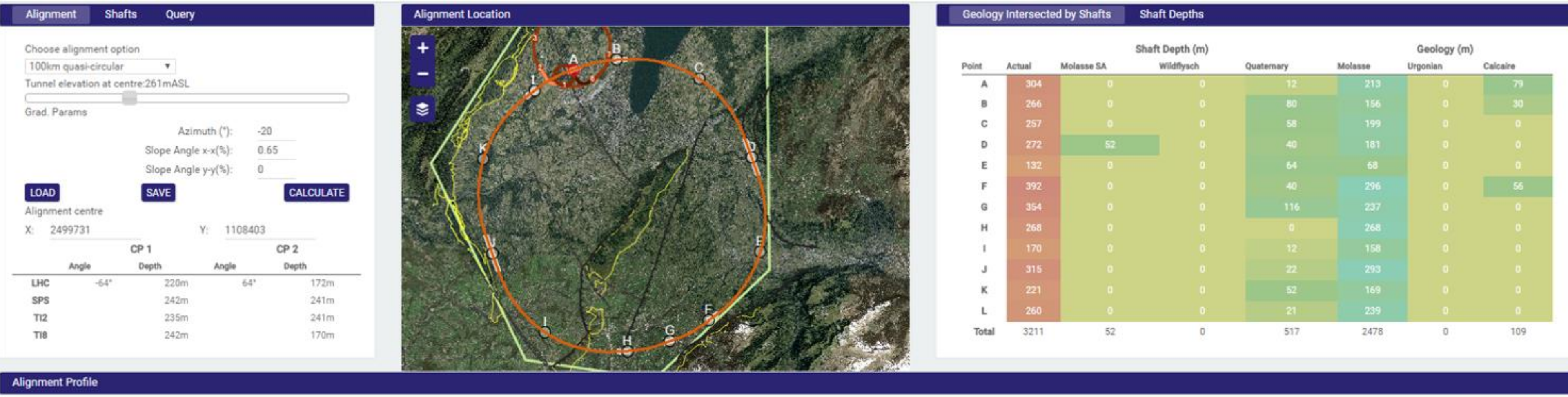

Geology Intersected by Shafts | Shaft Depths

| | Shaft Depth (m) | | | | Geology (m) | | |
|---|---|---|---|---|---|---|---|
| Point | Actual | Molasse SA | Wildflysch | Quaternary | Molasse | Urgonian | Calcaire |
| 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 |

Alignment Profile



# Progress on site investigations




| | Shaft Depth (m) | | | Geology (m) | | | |
|---|---|---|---|---|---|---|---|
| Point | Actual | Molasse SA | Wildflysch | Quaternary | Molasse | Urgonian | Calcaire |
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| E | 132 | 0 | 0 | 64 | 68 | 0 | 0 |
| F | 392 | 0 | 0 | 40 | 296 | 0 | 56 |
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| I | 170 | 0 | 0 | 12 | 158 | 0 | 0 |
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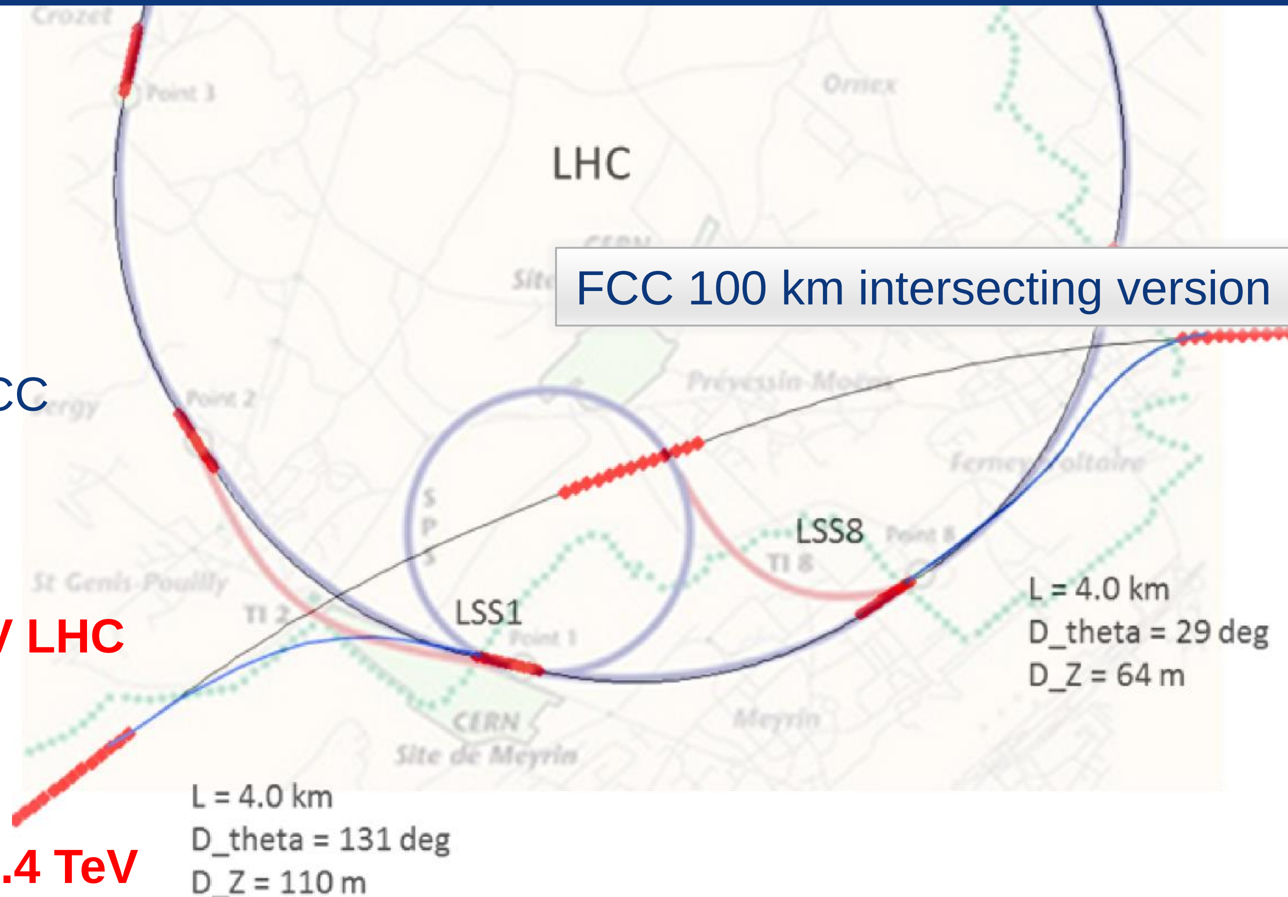
| K | 221 | 0 | 0 | 52 | 169 | 0 | 0 |
| L | 260 | 0 | 0 | 21 | 239 | 0 | 0 |
| Total | 3211 | 52 | 0 | 517 | 2478 | 0 | 109 |

- 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:**

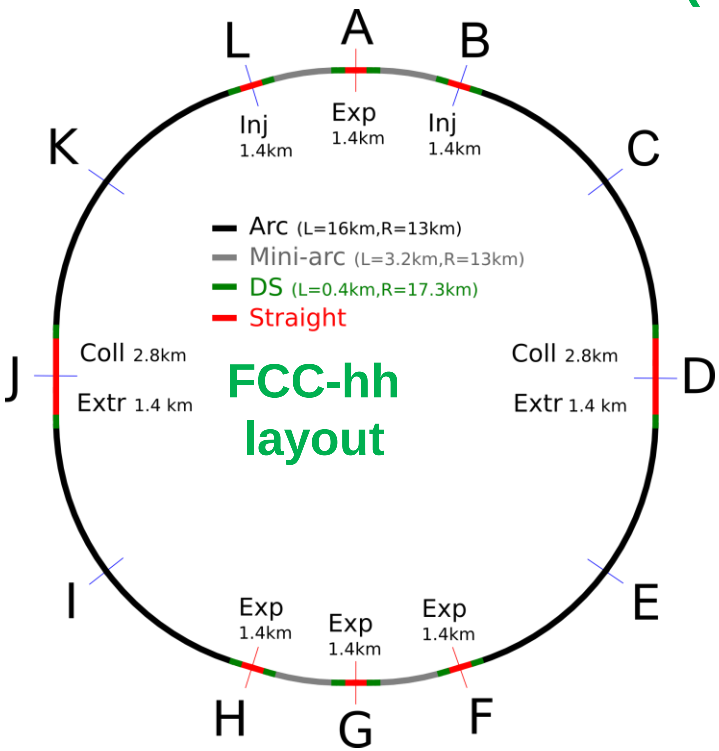
- **injection energy 3.3 TeV LHC**

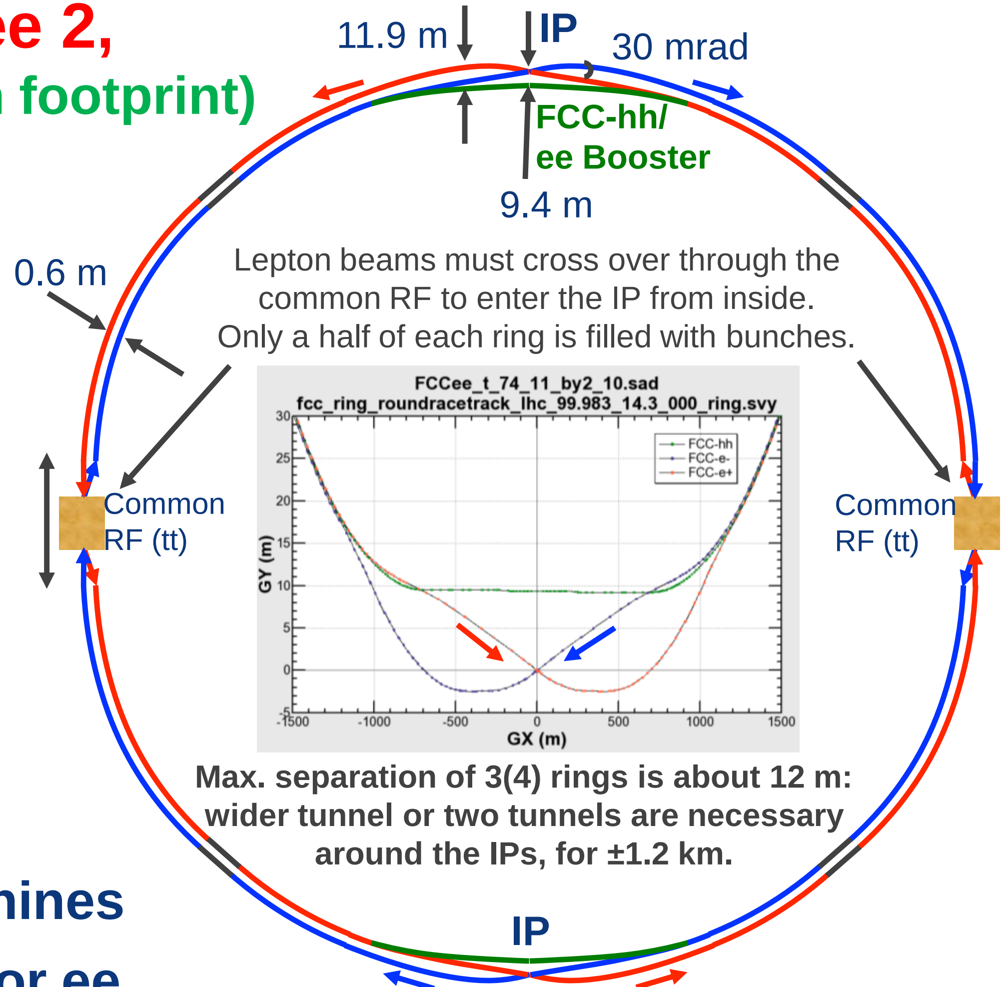
**Alternative options:**

- **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)



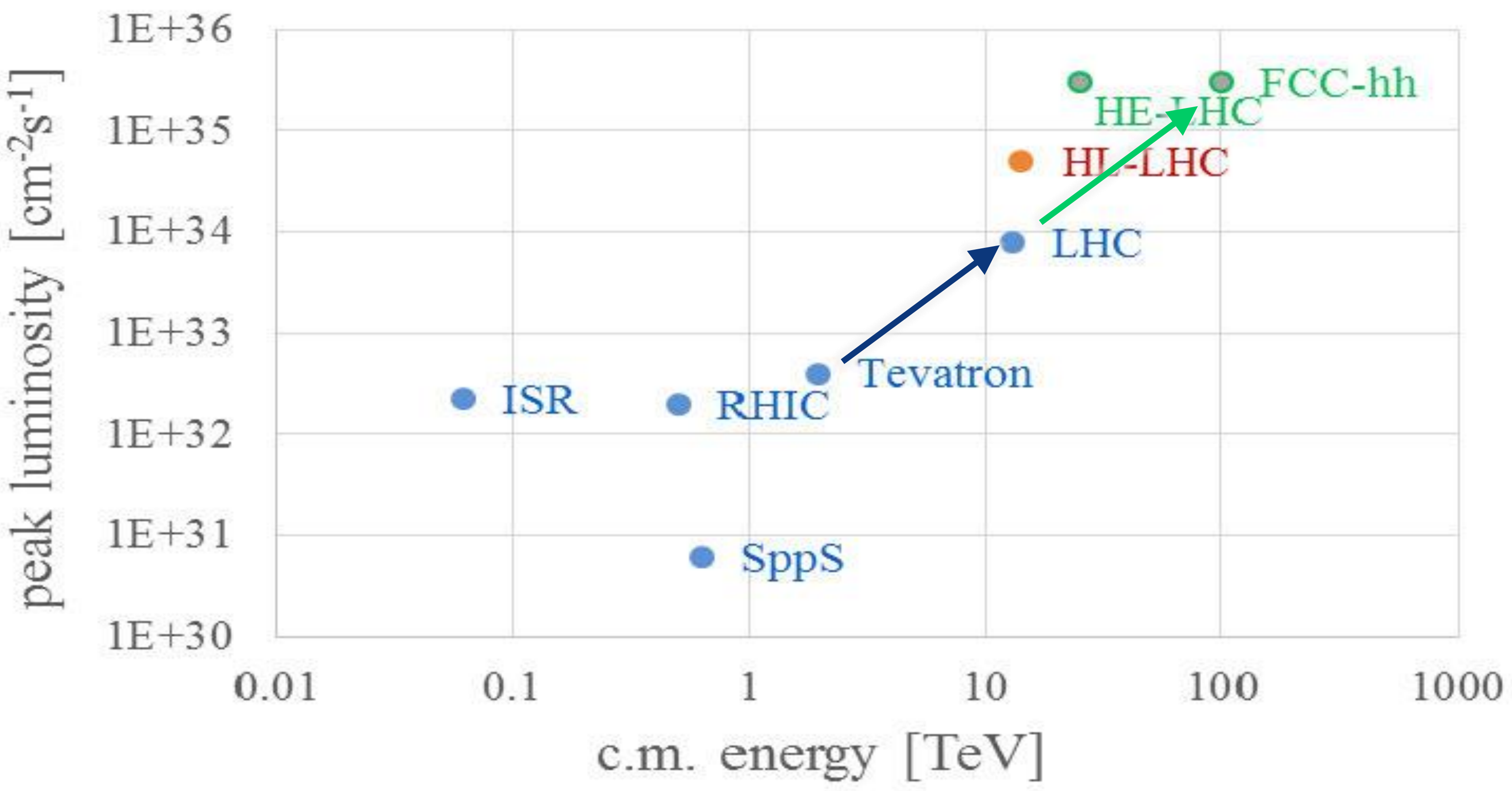




- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**

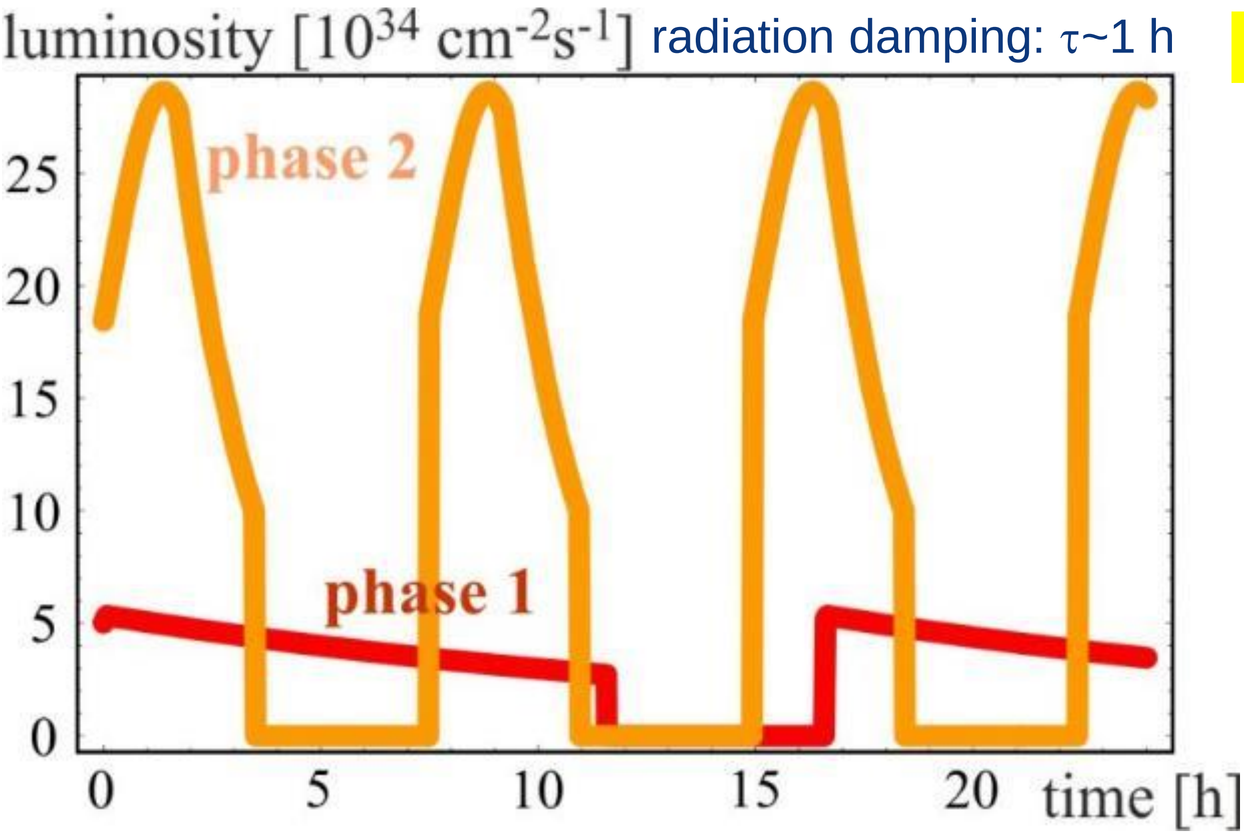
# hadron collider parameters (*pp*)

| 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.

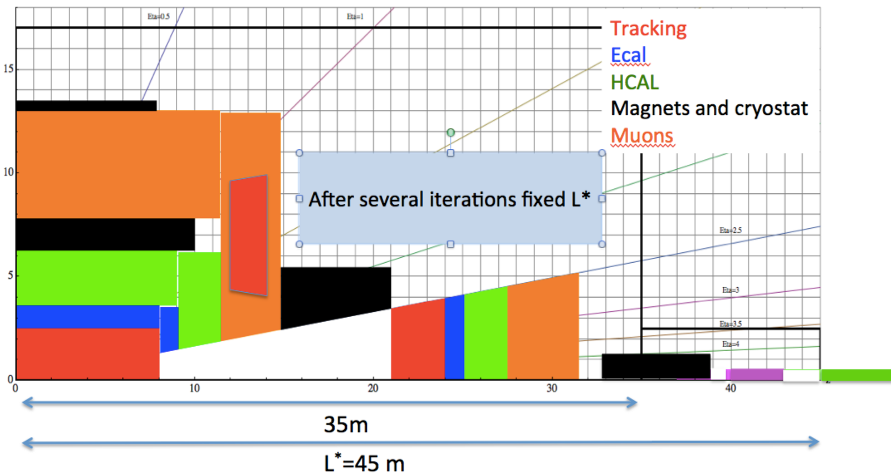
**phase 1: $\beta^*$=1.1 m, $\xi_{tot}$=0.01, $t_{ta}$=5 h, 250 fb$^{-1}$ / year**

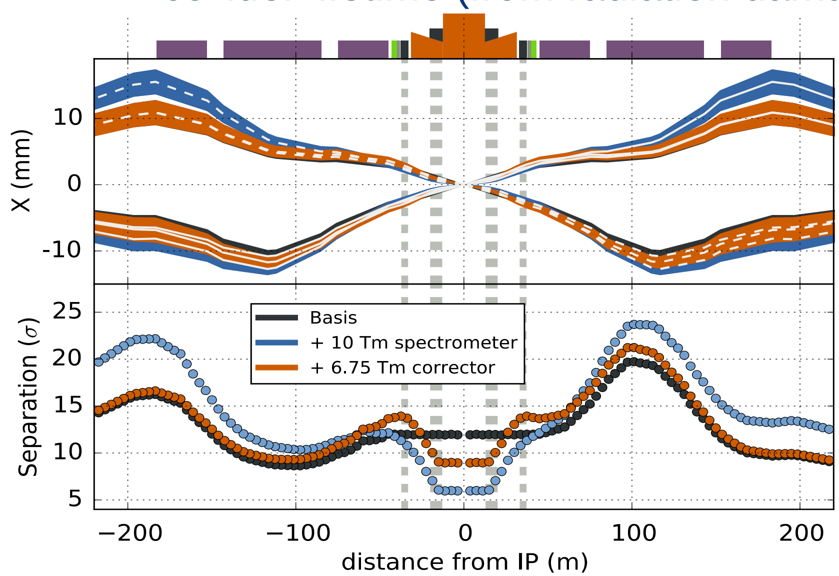
**phase 2: $\beta^*$=0.3 m, $\xi_{tot}$=0.03, $t_{ta}$=4 h, 1000 fb$^{-1}$ / year**

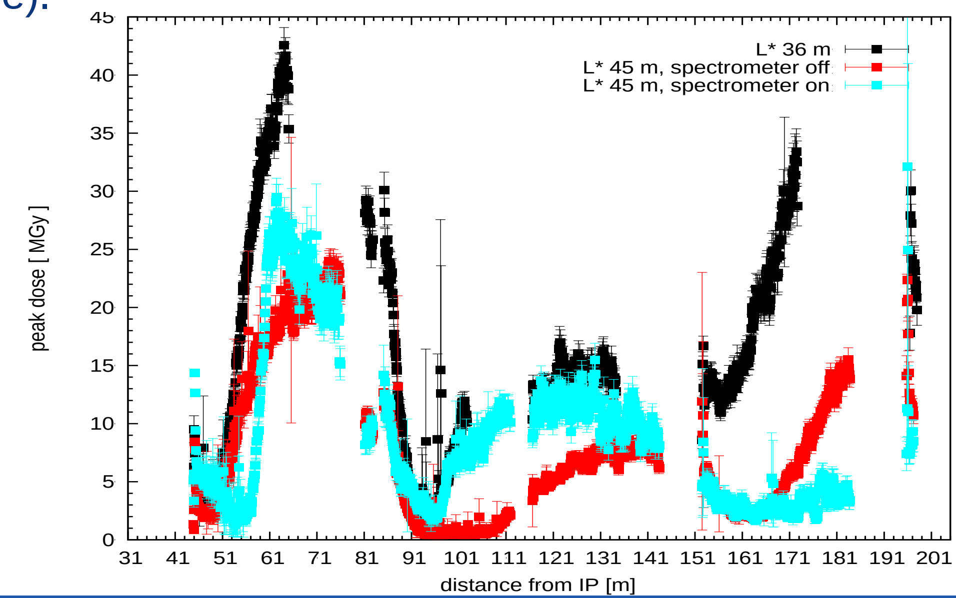
# FCC-hh MDI status

## 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).



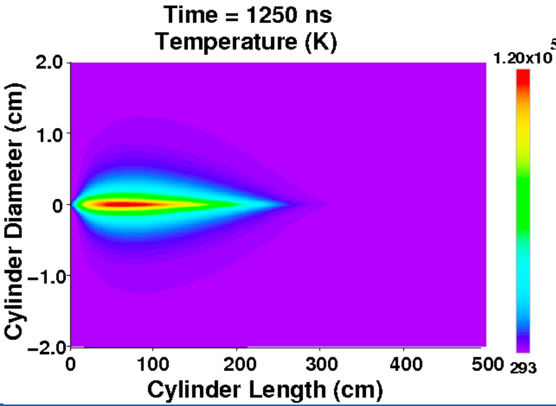
# Beam power & machine protection

**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

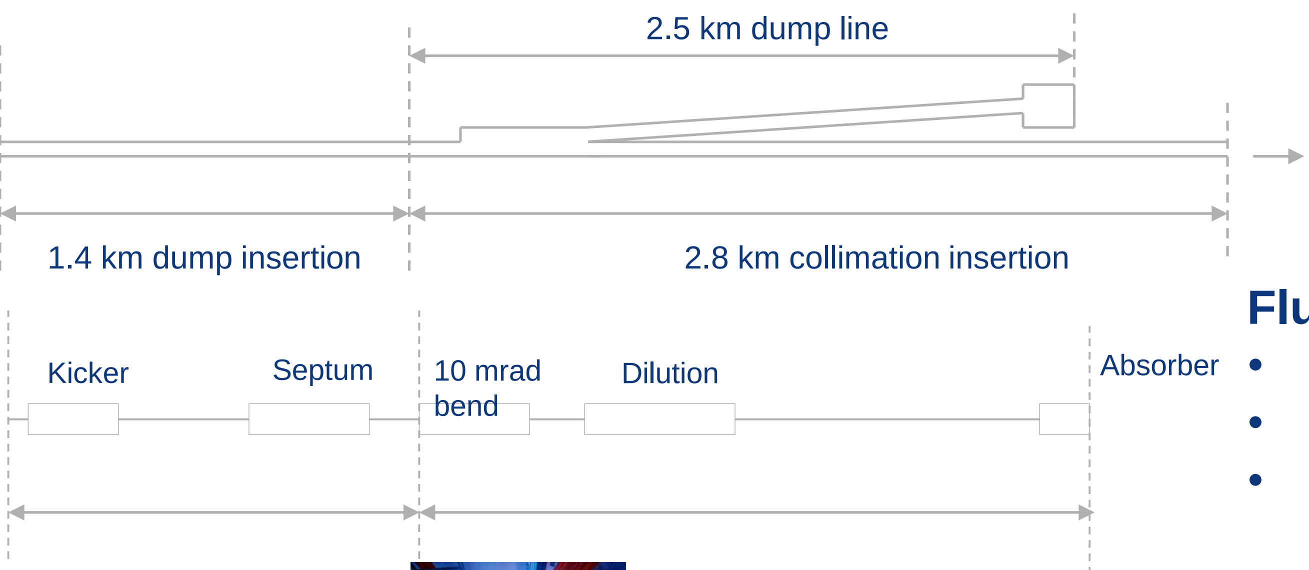


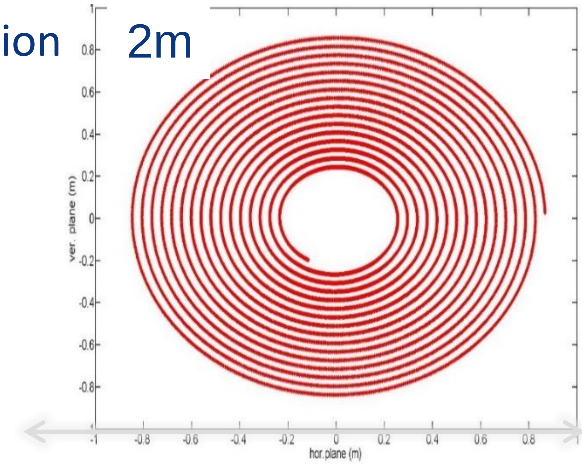

- **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**
- **Injection, beam transfer and beam dump all critical.**

**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!

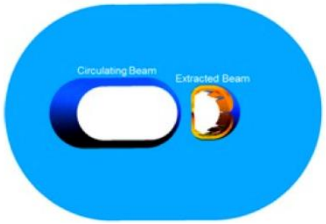


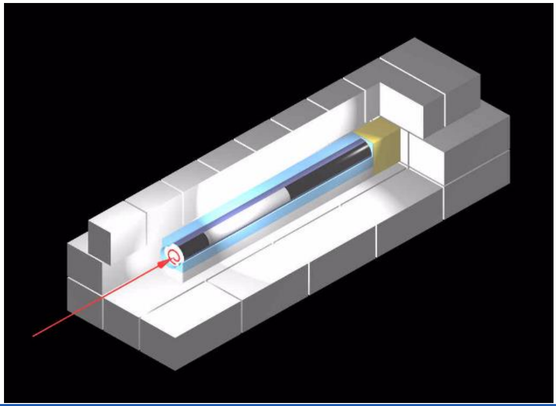

**Fluka studies:**

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

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

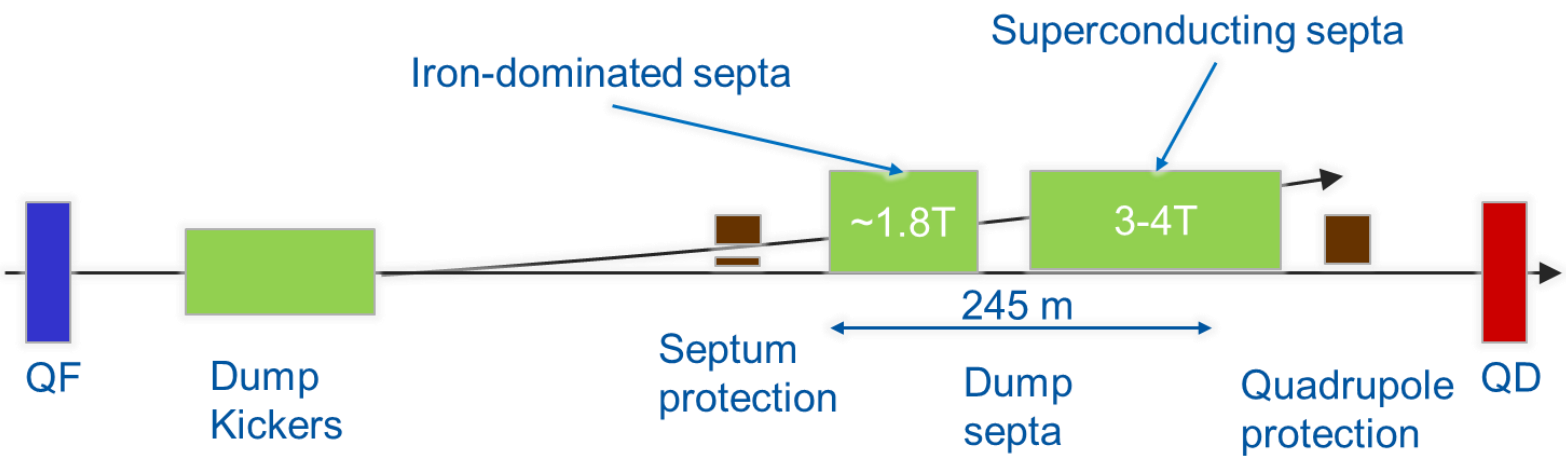



SC septum

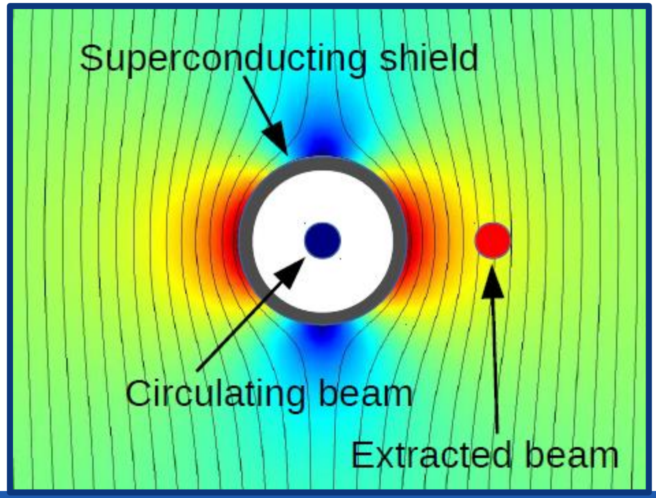


# R&D on Superconducting Septa

**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:

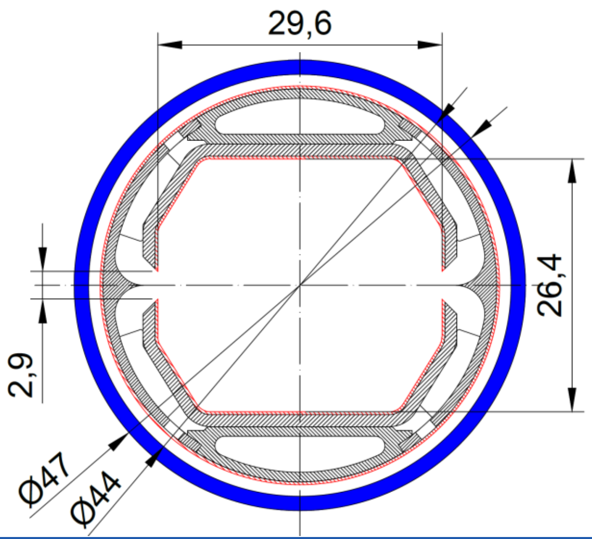
- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

## New Beam screen with ante-chamber

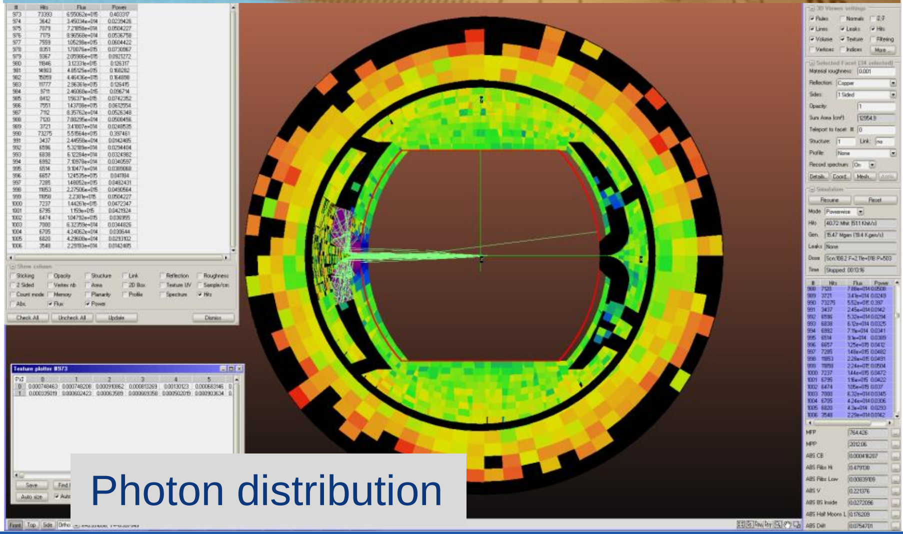
- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of cryo power

**FCC-hh beam screen prototypes**

**Ready for Testing 2017 in ANKA within EuroCirCol study**




**Simulation of quench behaviour**

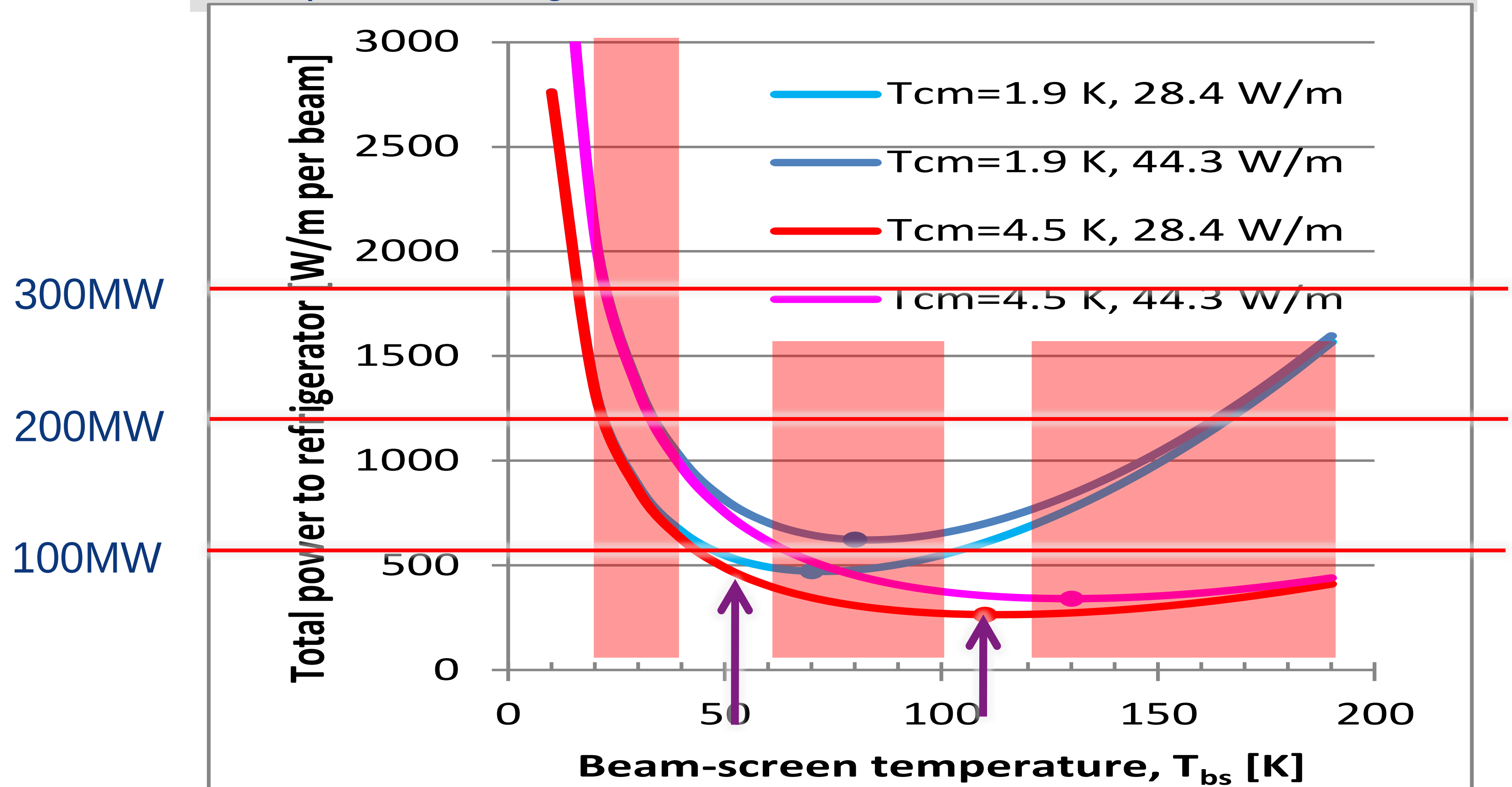


Photon distribution

# 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:** $\mathbf{4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl{\sim}1\ MTm}$

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

**Quads:** $\mathbf{762\ magnets,\ \ 6.6\ m\ long, 375\ T/m}$

## LHC

**Bore diameter: 56 mm**

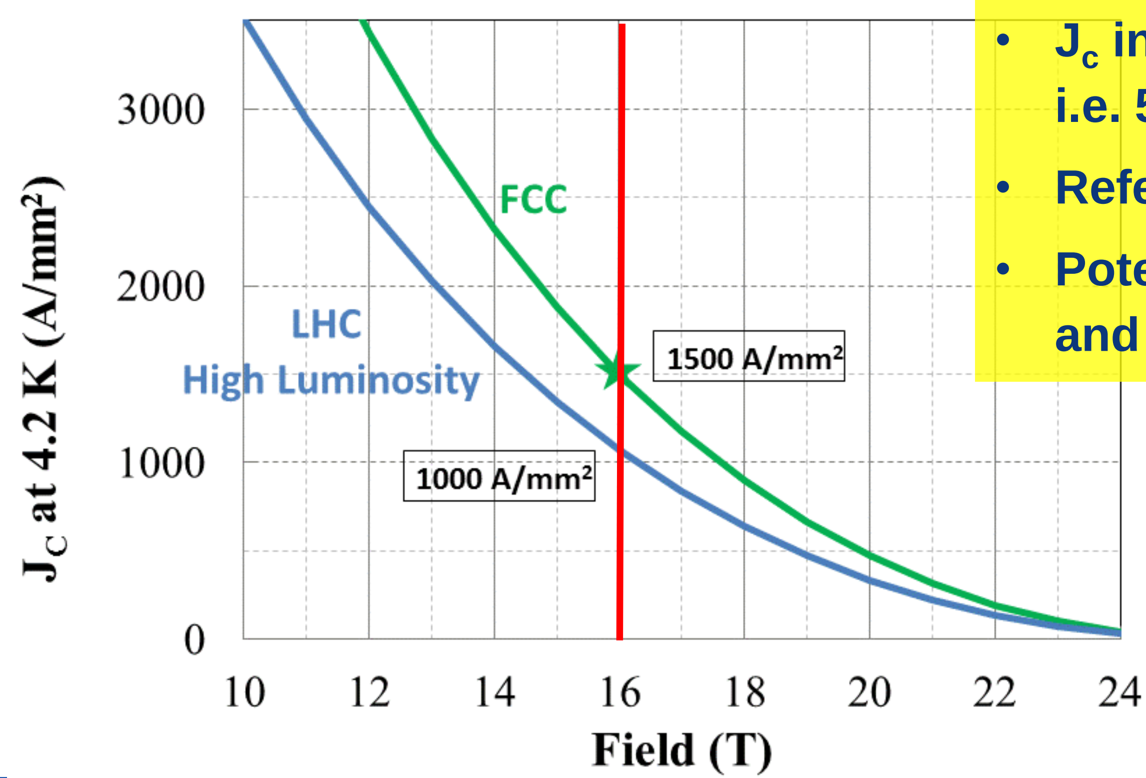
**Dipoles:** $\mathbf{1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl{\sim}0.15\ MTm}$

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

**Quads:** $\mathbf{392\ units,\ \ 3.15\ m\ long, 233\ T/m}$

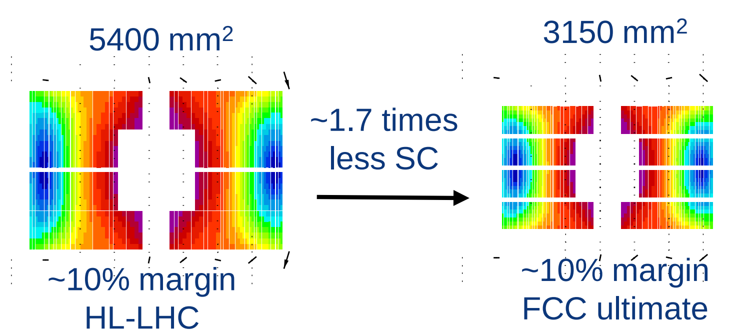
# $Nb_3Sn$ conductor program

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



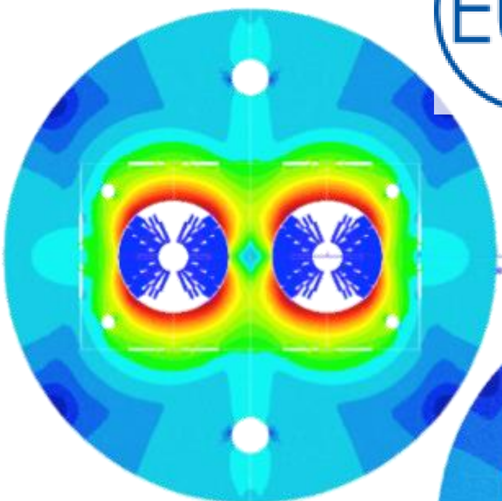

**Main development goals until 2020:**

- $J_c$ increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large scale production and cost reduction

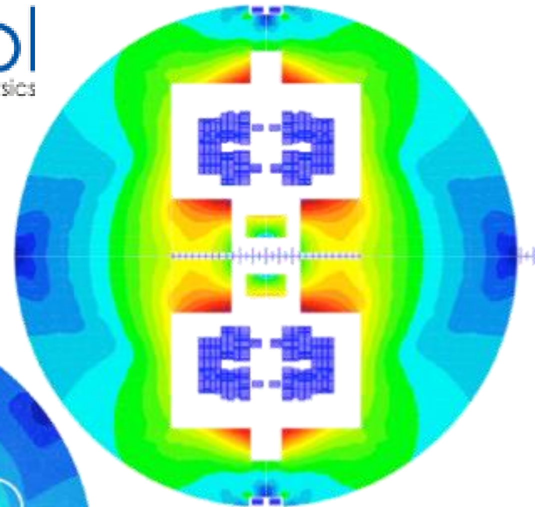


# 16 T dipole options and plans

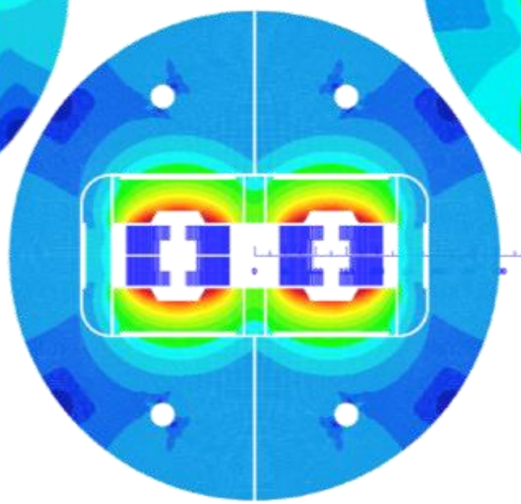
Cos-theta



Common coils



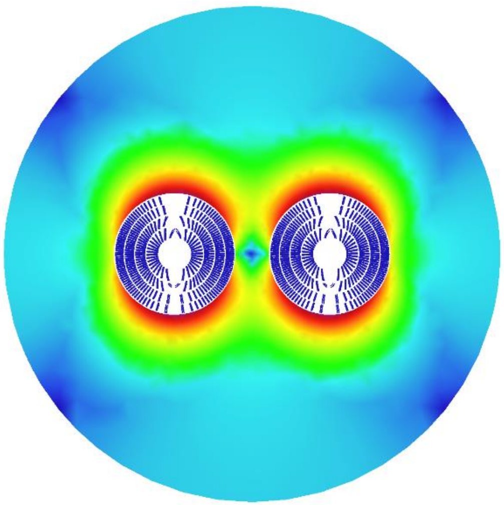
Blocks



**Swiss contribution**

via PSI

Canted Cos-theta



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

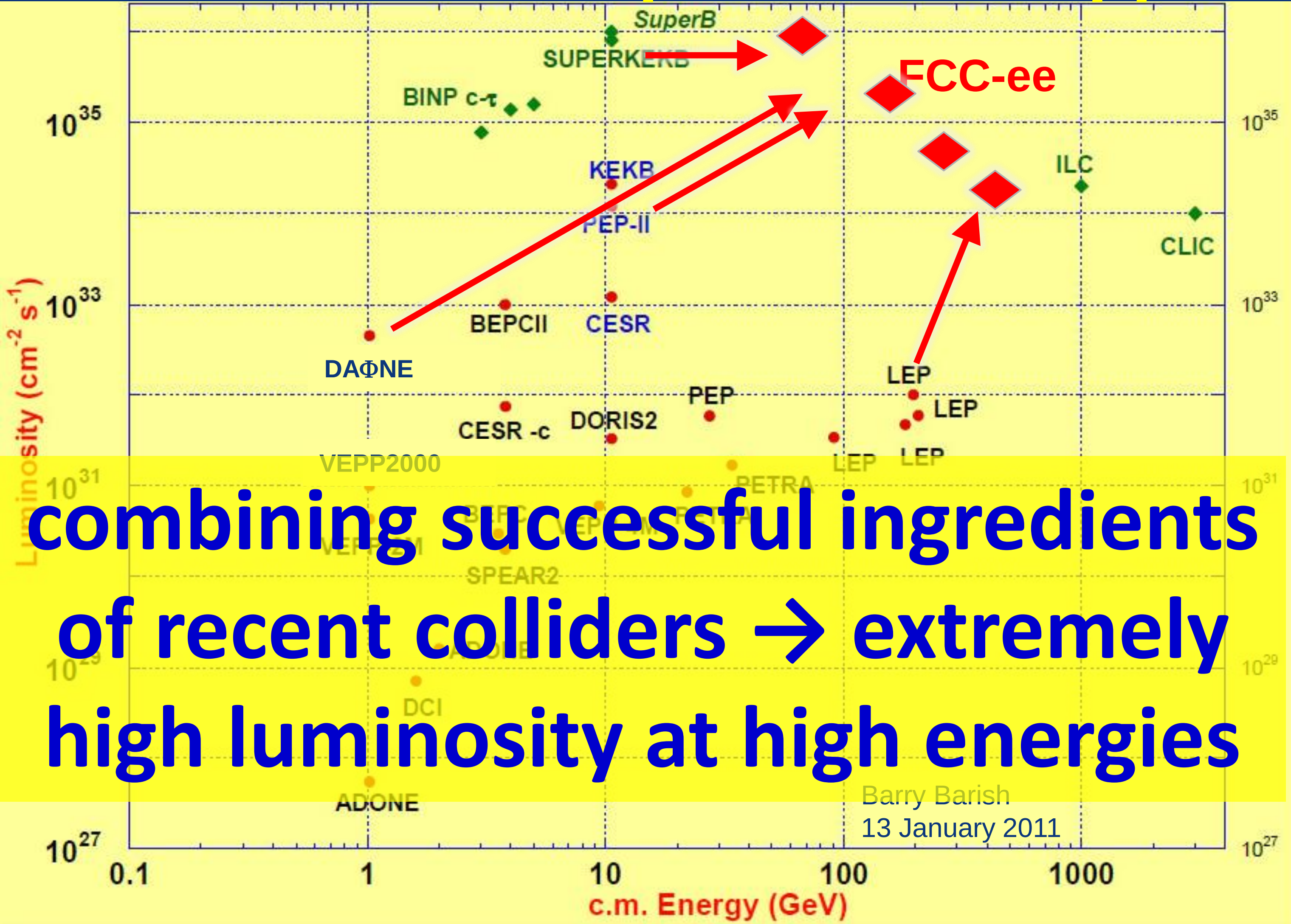
# lepton collider parameters

| 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 $\beta_y^*$

**KEKB:** $e^+$ source

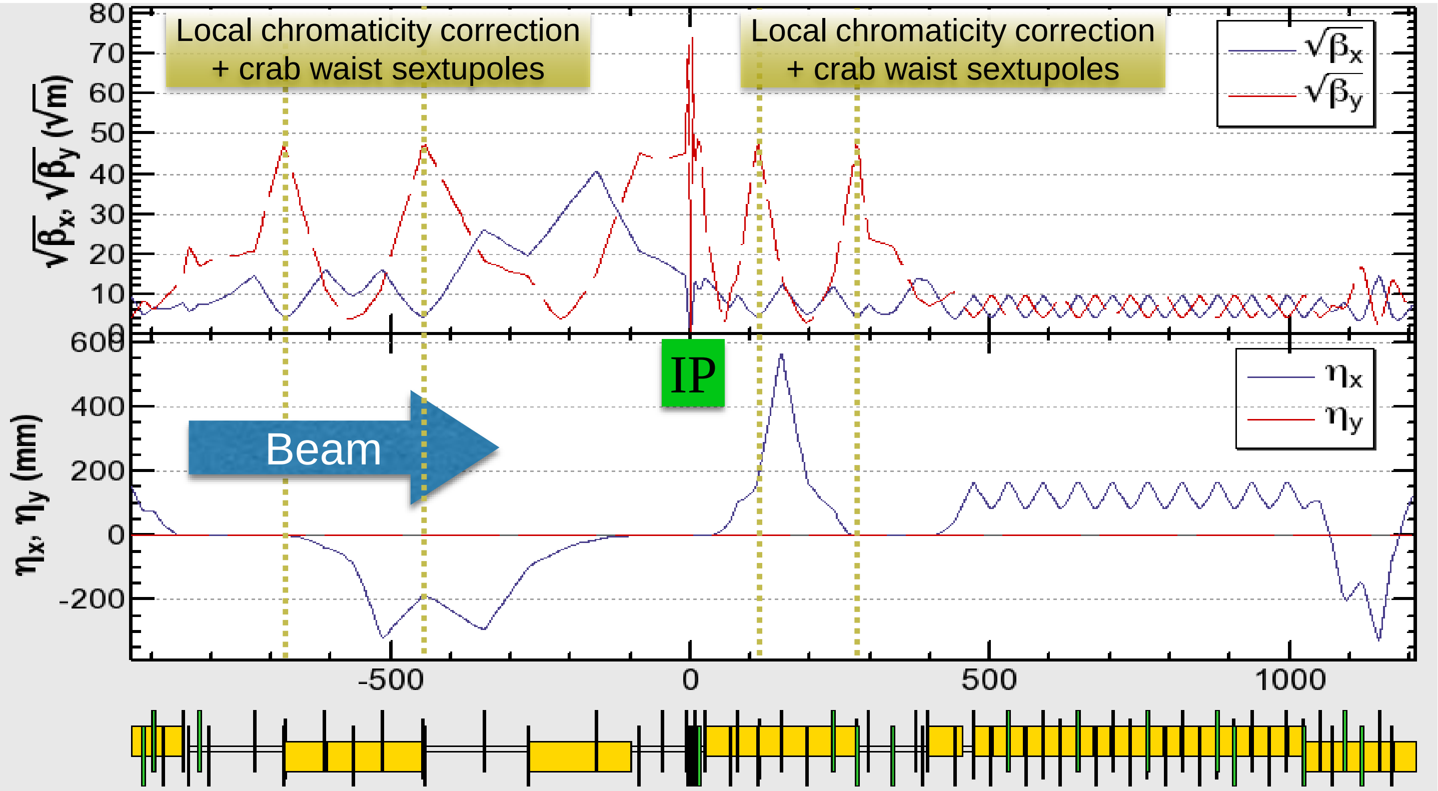
**HERA, LEP, RHIC:**
spin gymnastics

# FCC-ee optics design

**Optics design for all working points achieving baseline performance**

**Interaction region: asymmetric optics design**

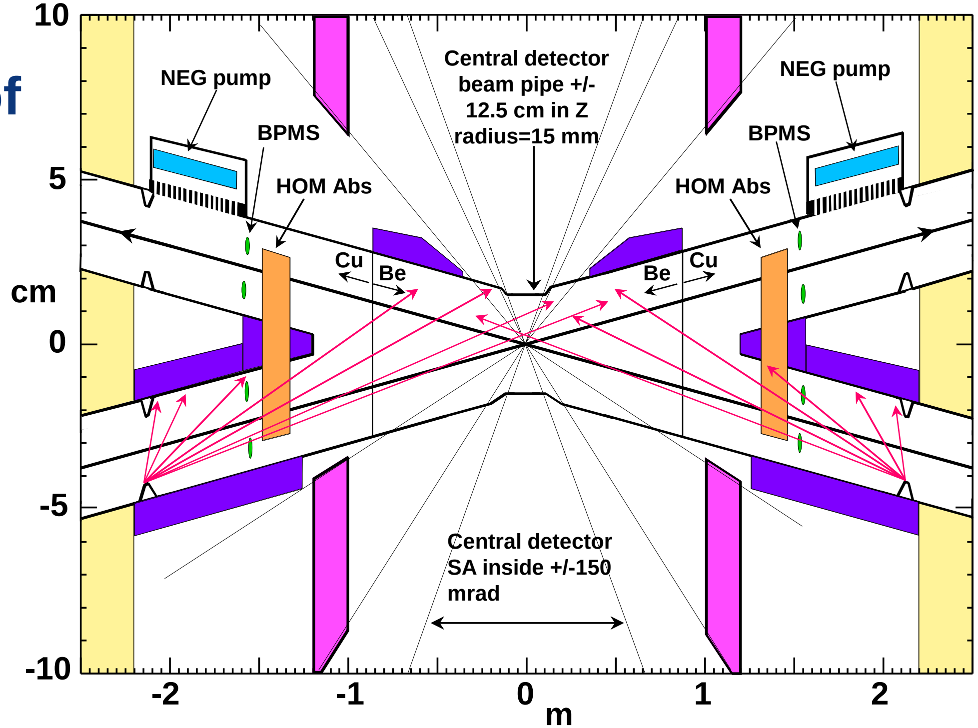
- Synchrotron radiation from upstream dipoles <100 keV up to 450 m from IP
- Dynamic aperture & momentum acceptance requirements fulfilled at all WPs

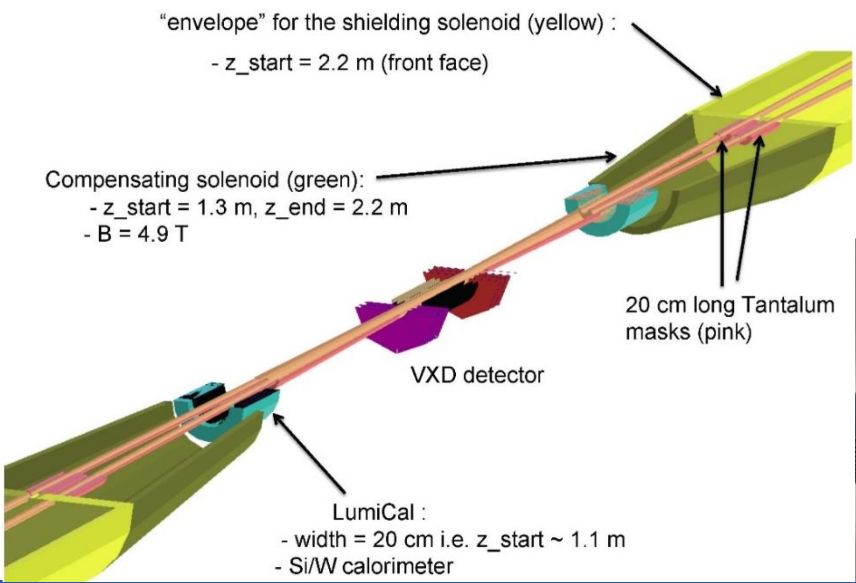


# FCC-ee MDI optimisation

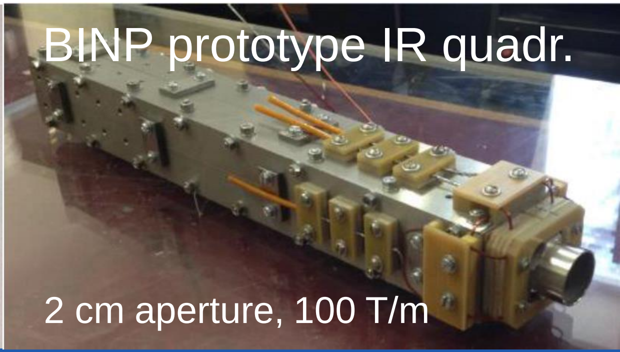
**MDI work focused on optimization of**

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

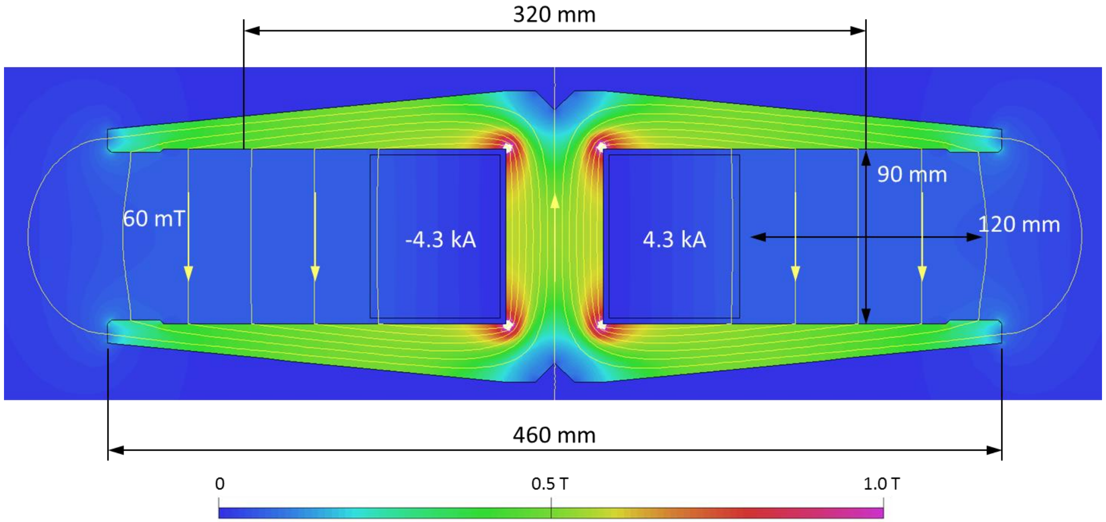




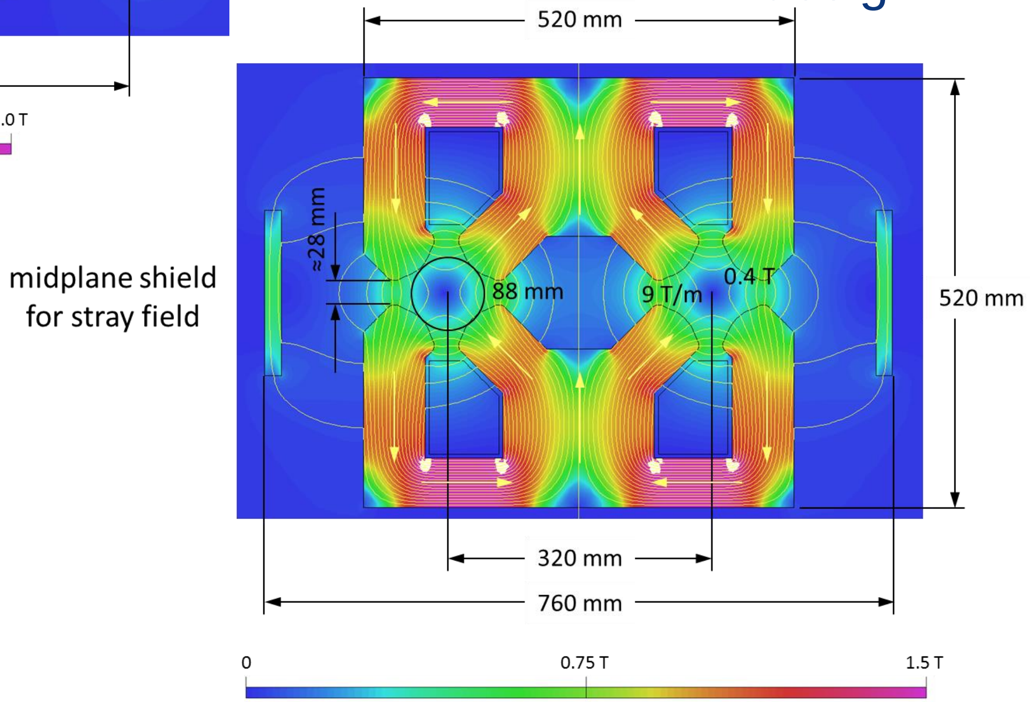


# Efficient 2-in-1 FCC-ee arc magnets




**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,…**

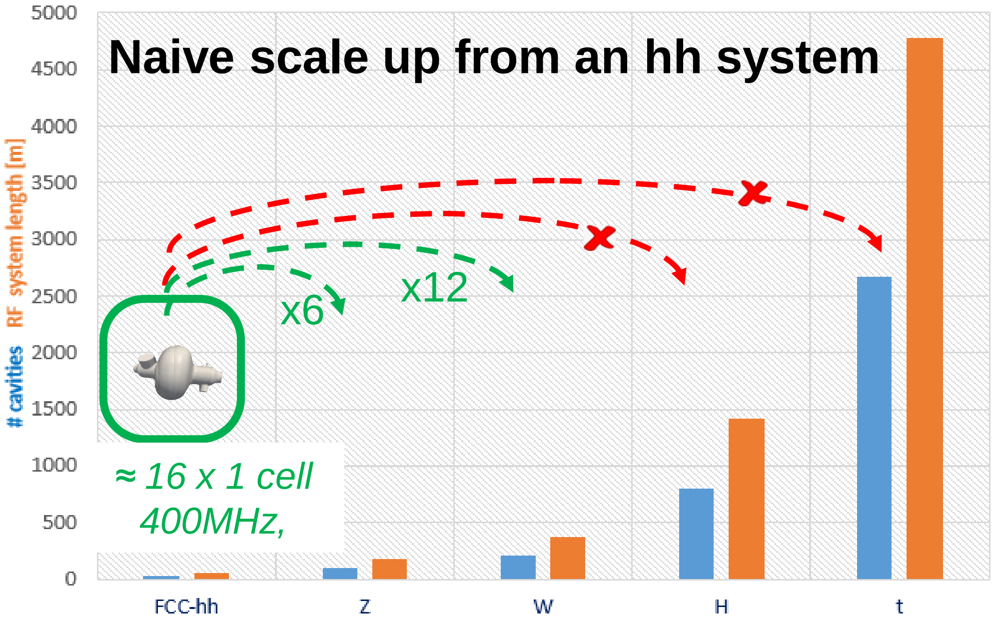
# RF system requirements

## 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

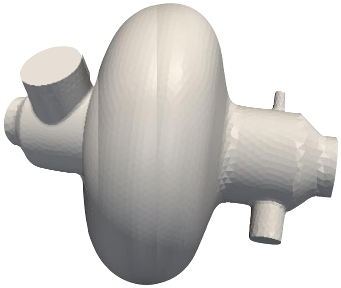



- Voltage and beam current ranges span more than factor > $10^2$
- No well-adapted single RF system solution satisfying requirements

# 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)



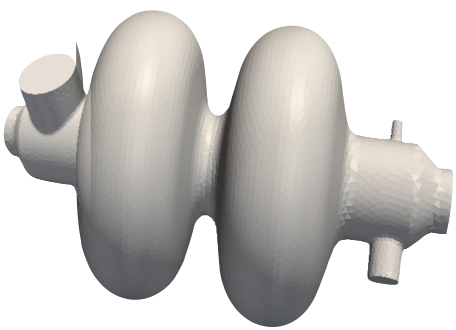
**hh**
≈ 16 cells per beam

**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 and progressing towards first major installations in LS2.
- The FCC study is advancing well towards the Design Report for end 2018
- 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 fully rely on your future contributions!**