# High-Energy LHC Machine

Michael Benedikt, Frank Zimmermann
for the FCC collaboration

HL-LHC/HE-LHC Physics Workshop
CERN, 30 October 2017

http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 projects EuroCirCol, grant agreement 654305, and ARIES, grant agreement 730871.*

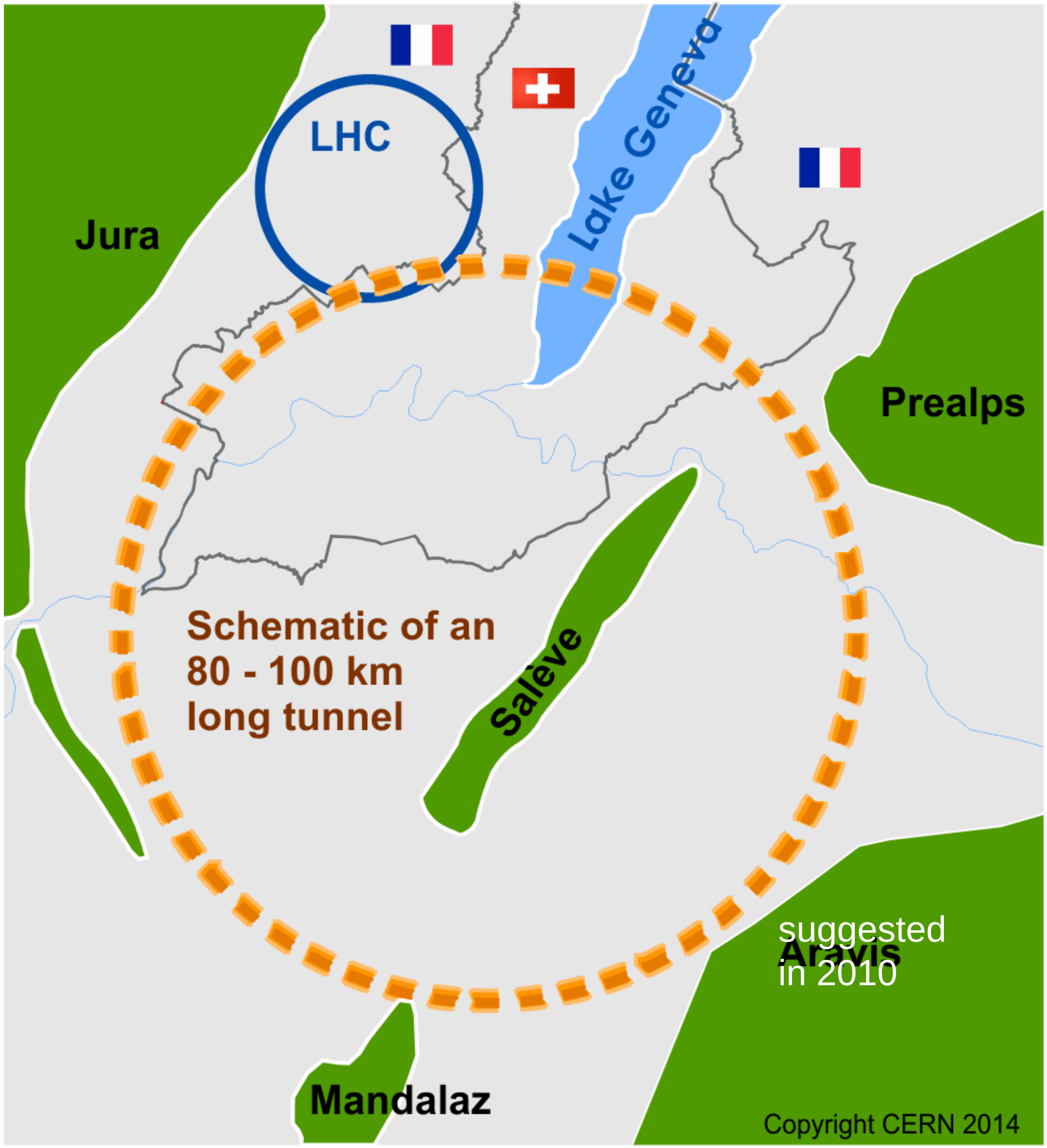
# Future Circular Collider Study
## CDR for European Strategy Update 2019/20

**international FCC collaboration (CERN as host lab) to design:**

- ***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 a possible first step
- ***p-e* (*FCC-he*) option,** one IP, FCC-hh & ERL
- **HE-LHC** w *FCC-hh* technology



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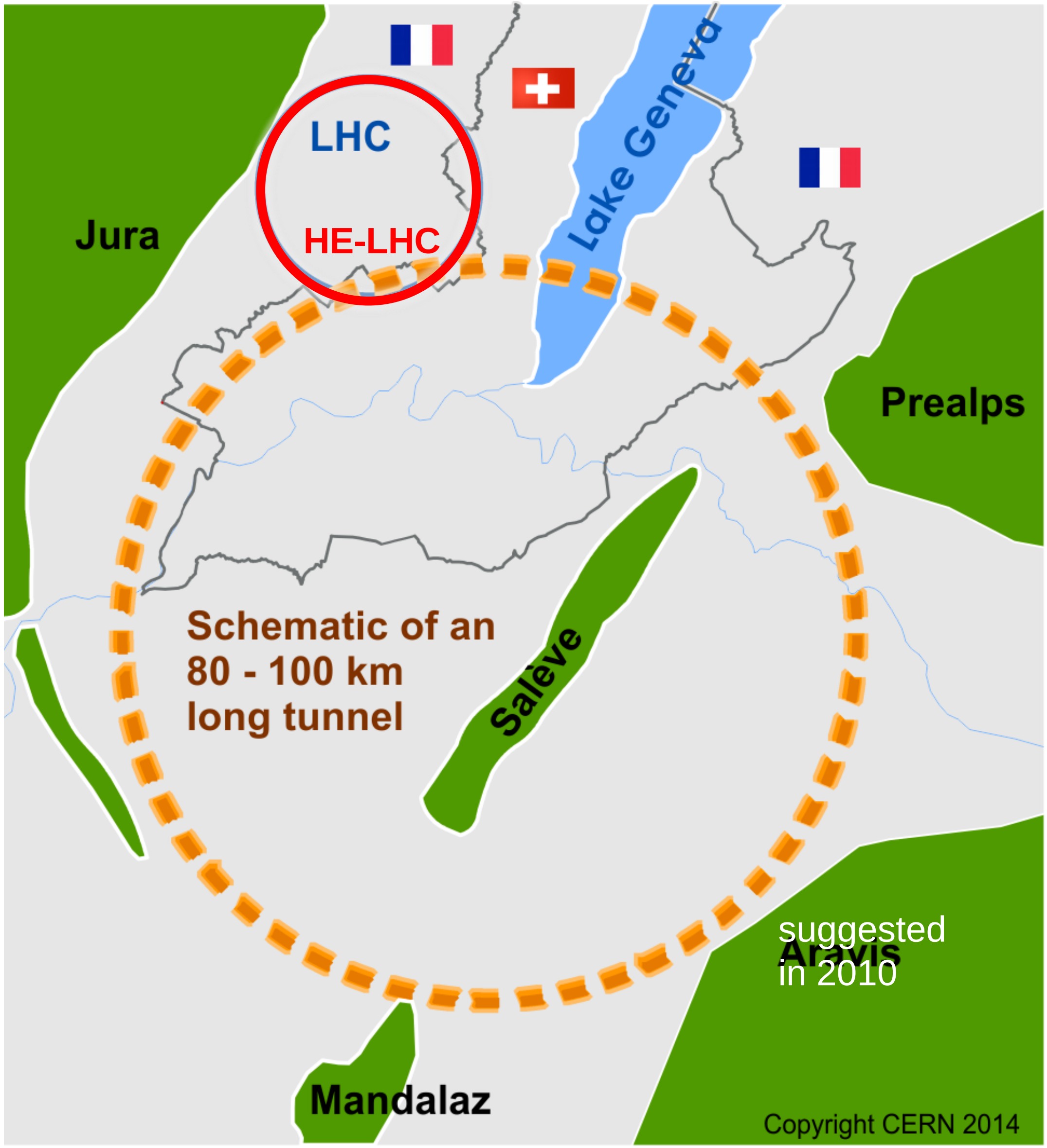


# HE-LHC design goals & basic choices

**physics goals:**

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
- target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$)

**key technologies:**

- FCC-hh magnets & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

**beam:**

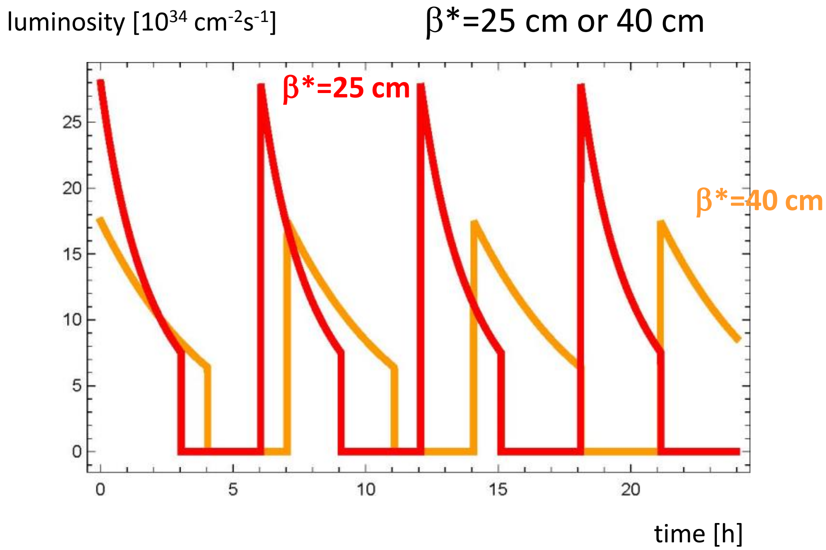
- HL-LHC/LIU parameters (25 ns baseline, 12.5 ns option)

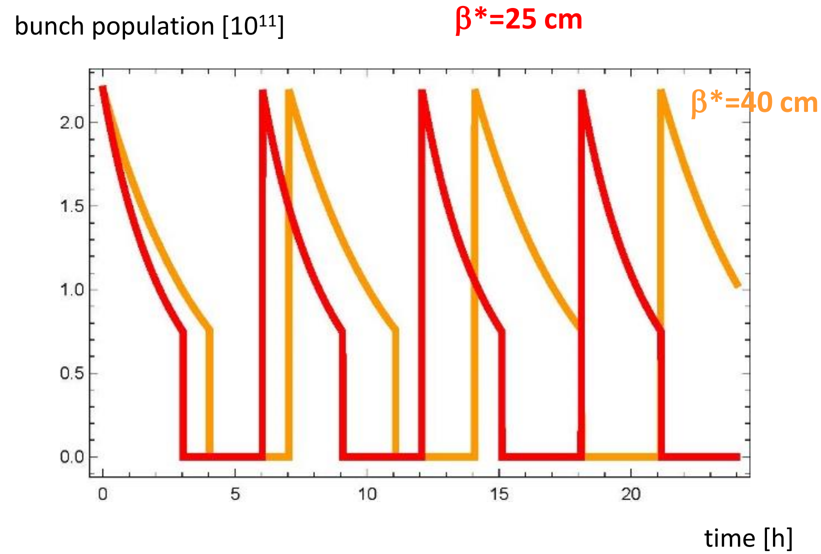
# hadron collider parameters (*pp*)

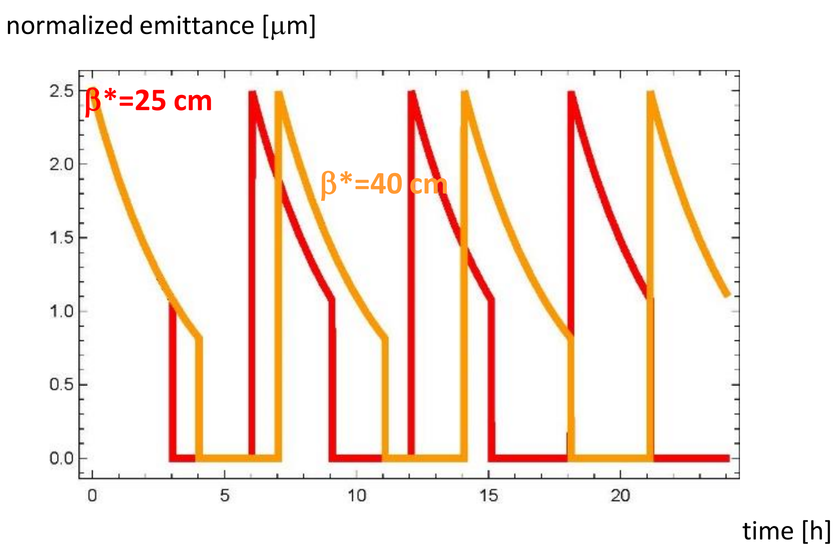
| parameter | FCC-hh | | HE-LHC | (HL) LHC |
|---|---|---|---|---|
| collision energy cms [TeV] | 100 | | **27** | 14 |
| dipole field [T] | 16 | | **16** | 8.3 |
| circumference [km] | 100 | | **27** | 27 |
| beam current [A] | 0.5 | | **1.12** | (1.12) 0.58 |
| bunch intensity [$10^{11}$] | 1 (0.5) | | **2.2** | (2.2) 1.15 |
| bunch spacing [ns] | 25 (12.5) | | **25 (12.5)** | 25 |
| norm. emittance $\gamma\varepsilon_{x,y}$ [μm] | 2.2 (2.2) | | **2.5 (1.25)** | (2.5) 3.75 |
| IP $\beta^*_{x,y}$ [m] | 1.1 | 0.3 | **0.25** | (0.15) 0.55 |
| luminosity/IP [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | **25** | (5) 1 |
| peak #events / bunch Xing | 170 | 1000 (500) | **800** (400) | (135) 27 |
| stored energy / beam [GJ] | 8.4 | | **1.4** | (0.7) 0.36 |
| SR power / beam [kW] | 2400 | | **100** | (7.3) 3.6 |
| transv. emit. damping time [h] | 1.1 | | **3.6** | 25.8 |
| initial proton burn off time [h] | 17.0 | 3.4 | **3.0** | (15) 40 |

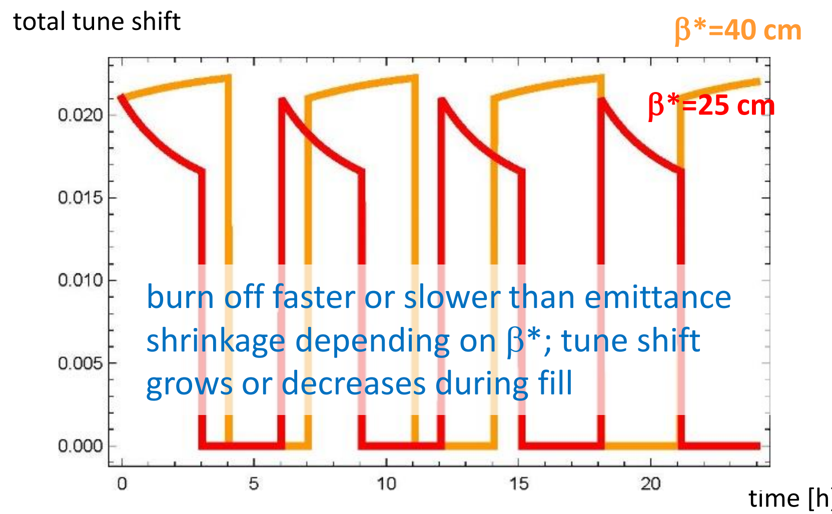
# "typical day" at the HE-LHC

β*=25 cm or 40 cm

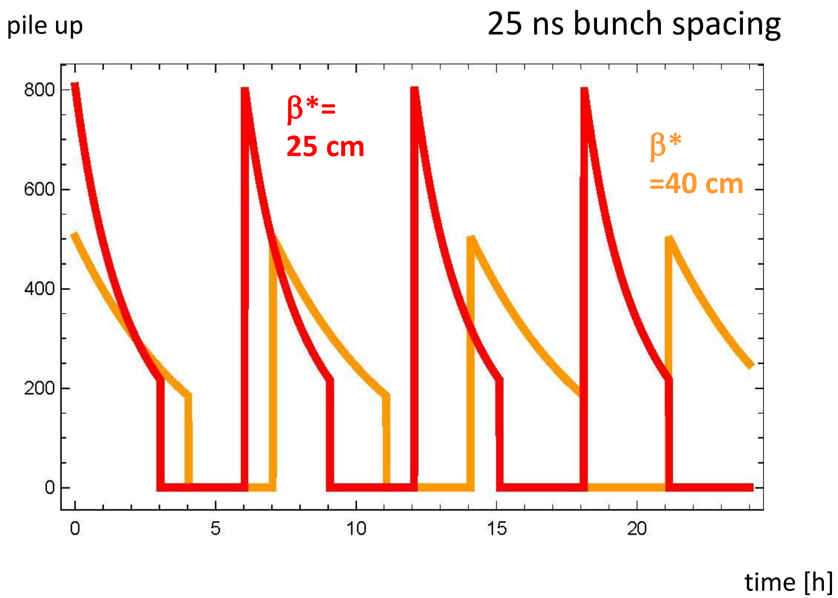


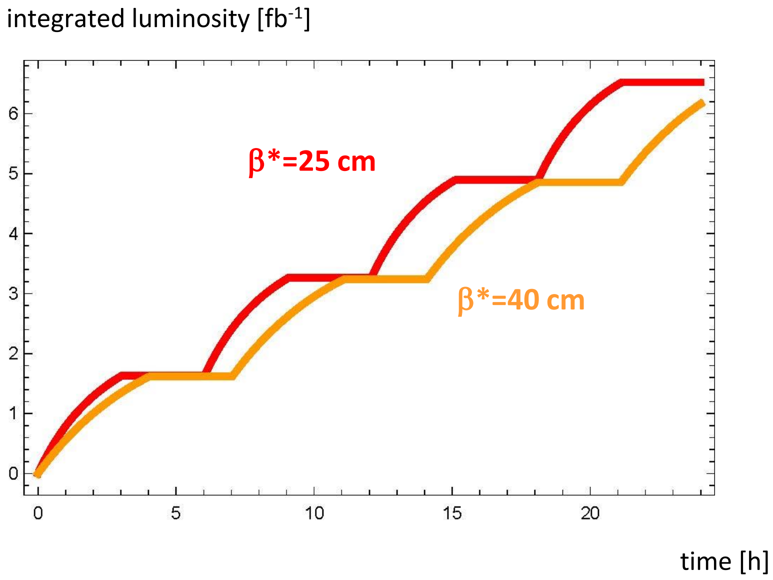



# HE-LHC pile up & performance




with 160 days of physics, 70% availability, 3 h turnaround time

$\beta^*$=25 cm: 820 $fb^{-1}$/year

$\beta^*$=40 cm: 700 $fb^{-1}$/year

not quite 4x HL-LHC, but close

~15% reduction with 2x lower peak pile up

# topics requiring special attention

many aspects extrapolated/copied from HL-LHC or FCC-hh

exceptions:

## tunnel integration and magnet technology

- push for **compact 16 T** magnets (magnetic cryostat, shielding)
- **HE-LHC *$Nb_3Sn$* magnets must be bent** - 5 mm horizontal orbit shift over 14 m

## arc optics

- high dipole filling factor to reach energy target → different arc optics
- relaxed strength of quadrupoles and sextupoles → different arc optics

## straights

- low-beta insertions, longer triplet than HL-LHC, $\beta^*$ reach
- collimation straights, FCC-hh scaling not applicable,
  warm dipole length increases w.r.t. to LHC; new approach?!
- extraction straights – length of kicker & septum sections

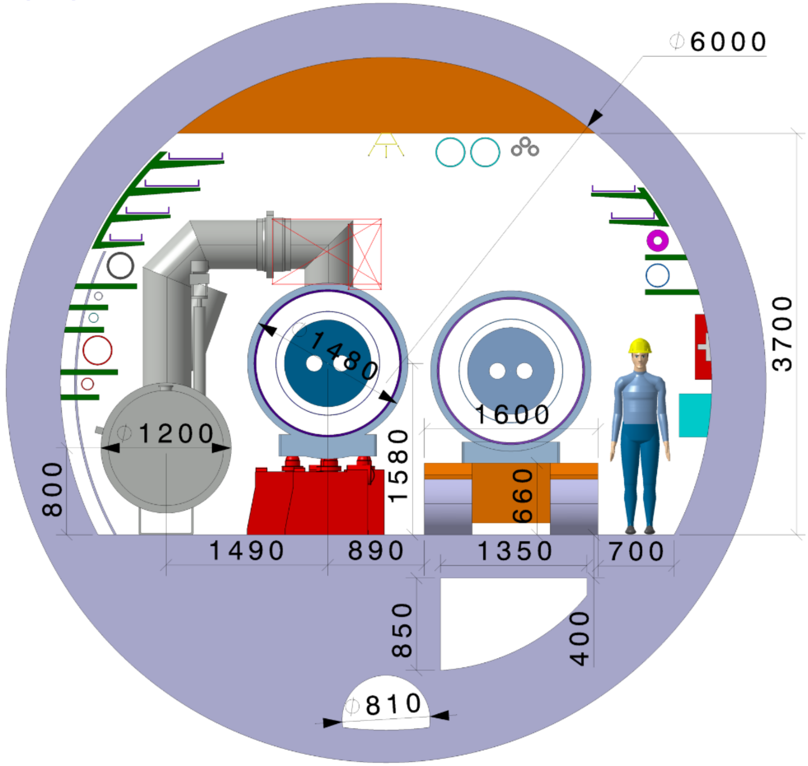
## injector

- determined by extraction system, physical & dynamic aperture, impedance…

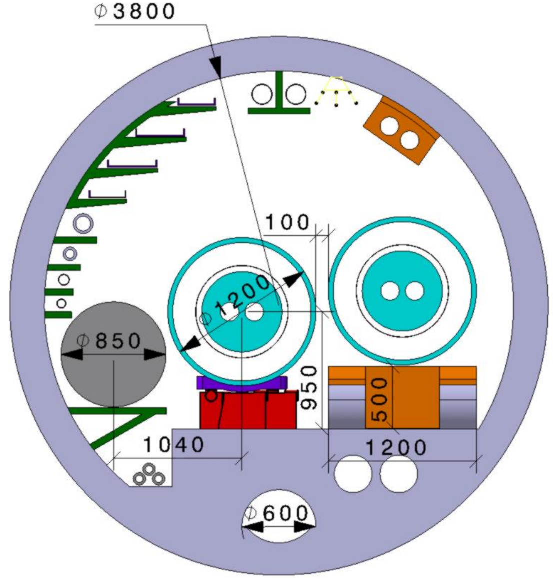
# tunnel integration

V. Mertens et al.

## FCC-hh




## HE-LHC




**6 m inner tunnel diameter**

main space allocation:

- 1200 mm cryo distribution line (QRL)
- 1500 mm installed cryomagnet
- 1600 cryomagnet magnet transport
- >700 mm free passage.

**3.8 m inner tunnel diameter**

main space allocation:

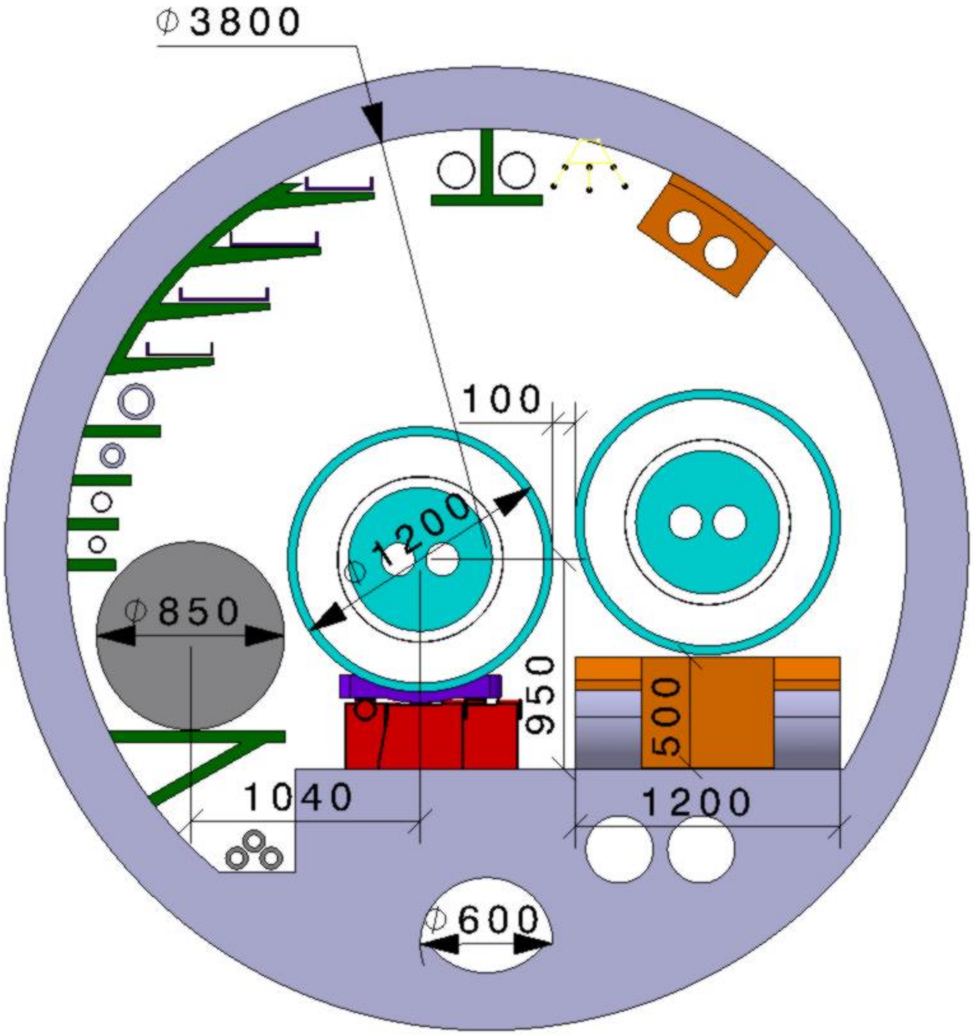
- 850 mm cryo distribution line (QRL)
- 1200 mm installed cryomagnet
- 1200 cryomagnet magnet transport

*challenging*

# HE-LHC tunnel integration

**requirement: no major CE tunnel modifications**

- challenges for tunnel integration
- **maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**



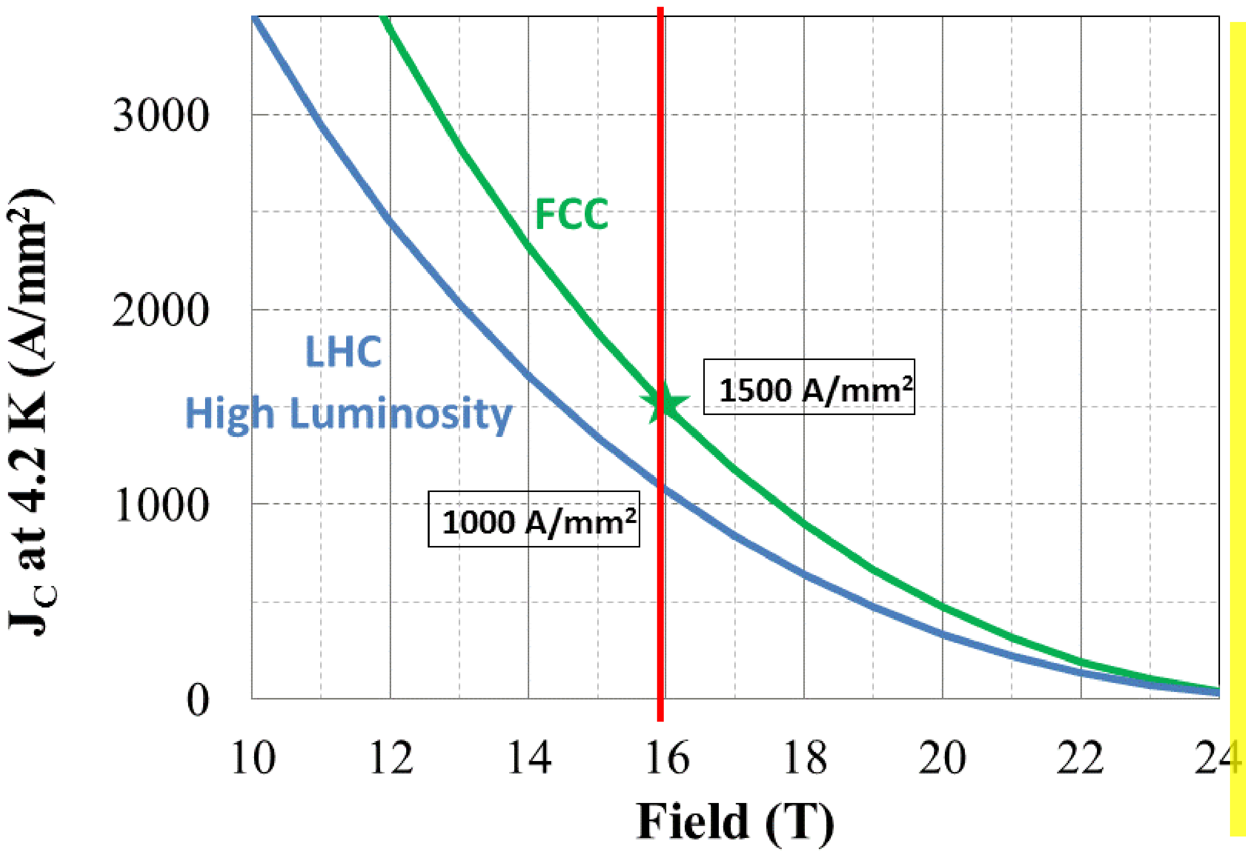

**strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:**

- options und consideration:
  - **allow stray-field and/or cryostat as return-yoke**
  - active compensation with (simple) shielding coils
  - **optimization of inter-beam distance (compactness)**
  - *(QRL integrated in magnets, → reduced integral field because of longitudinal space required for service module (5%))*

**→ smaller diameter, also relevant for FCC-hh cost optimization**

# FCC/HE-LHC *$Nb_3Sn$* conductor R&D

## *$Nb_3Sn$* is one of the major cost & performance factors for FCC-hh/HE-LHC




**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**

# collaborations FCC $Nb_3Sn$ program

procurement of state-of-the-art conductor for protoyping:

- **Bruker/OST**– **European/US**

stimulation of conductor development with regional industry:

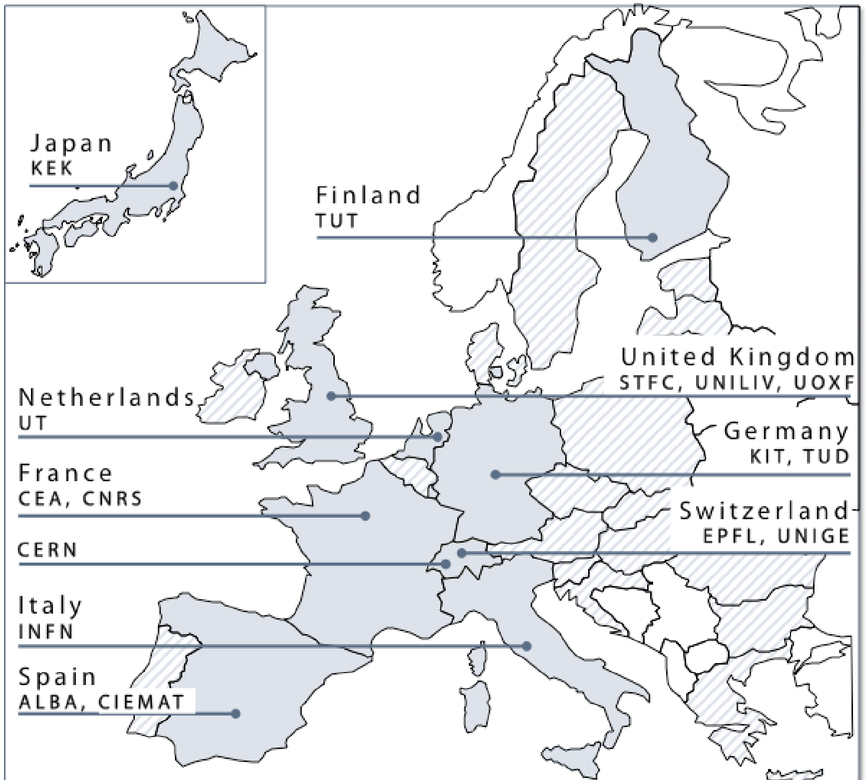
- **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
- **CERN/Bochvar High-technology Research Inst.** – **Russian** contribution. Russian **industry** (TVEL) and laboratories
- **CERN/KAT** – **Korean** **industrial** contribution
- **CERN/Bruker**– **European** **industrial** contribution

characterization of conductor & research with universities:

- **Europe: Technical Univ. Vienna, Geneva University, University of Twente**
- **Applied Superconductivity Centre** at Florida State University

**new US DOE MDP effort** – **US** activity with **industry** (OST) and labs

# EU H2020 DS 'EuroCirCol' on 16 T dipole & vacuum system design




EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

**European Union Horizon 2020 program**

- **Support for FCC**
- **3 MEURO co-funding**

**Scope: FCC-hh (&HE-LHC) collider**

- **Optics Design**
- **Cryo vacuum system design**
- **16 T dipole design, construction folder for demonstrator magnets**

# EASITrain Marie Curie Training Network

**European Advanced Superconductivity Innovation & Training Network**

➢ **selected for funding by EC in May 2017, start 1 October 2017**

- SC wires at low temperatures for magnets ($Nb_3Sn$, $MgB_2$, HTS)
- Superconducting thin films for RF and beam screen ($Nb_3Sn$, Tl)
- Turbocompressor for Nelium refrigeration
- Magnet cooling architectures

## 13 Beneficiaries

BRUKER
cea
Columbus Superconductors
HZB Helmholtz Zentrum Berlin
SPIN
Universität Stuttgart
INFN
TECHNISCHE UNIVERSITÄT DRESDEN
TU WIEN TECHNISCHE UNIVERSITÄT WIEN
UNIVERSITÄT SIEGEN
WU
I-CUBE
CERN

## 12 Partners

Bmax power to shape
ASG Superconductors
BILFINGER Babcock Noell GmbH
CemeCon The Tool Coating
IEEE Advancing Technology for Humanity
Criotec IMPIANTI S.r.l.
MAN Diesel & Turbo
Terra Mater Factual Studios
Red Bull MEDIA HOUSE
research instruments
SIGMAPHI
UNIVERSITÀ DEGLI STUDI DI GENOVA
AIR LIQUIDE

# FCC 16 T dipole design activities & options

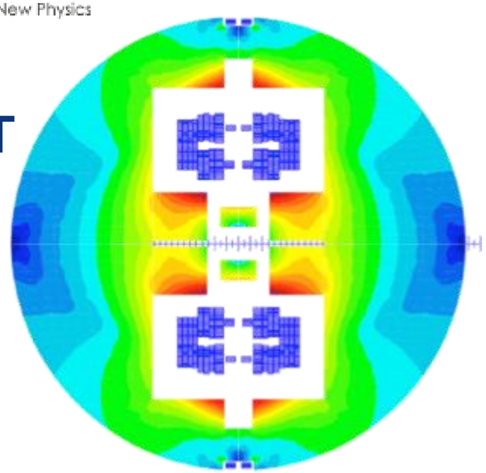
H2020

Common coils

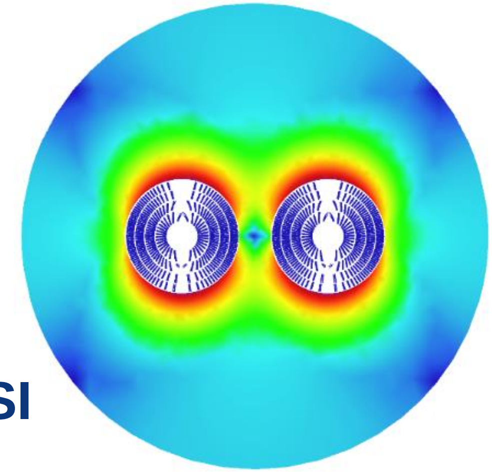
Swiss contribution

Cos-theta

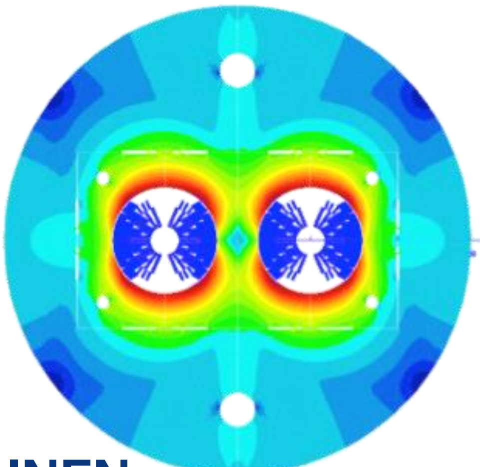
CIEMAT



Canted Cos-theta

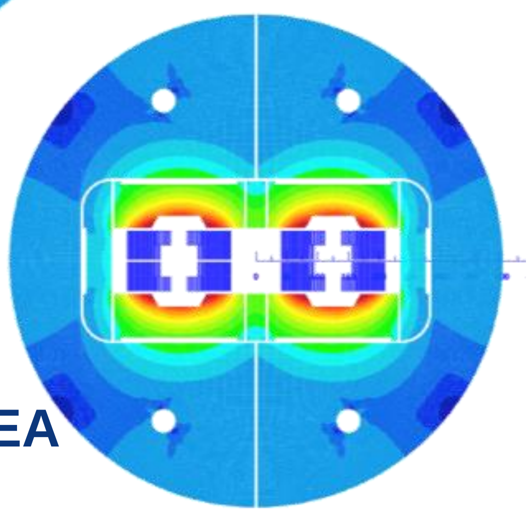


PSI

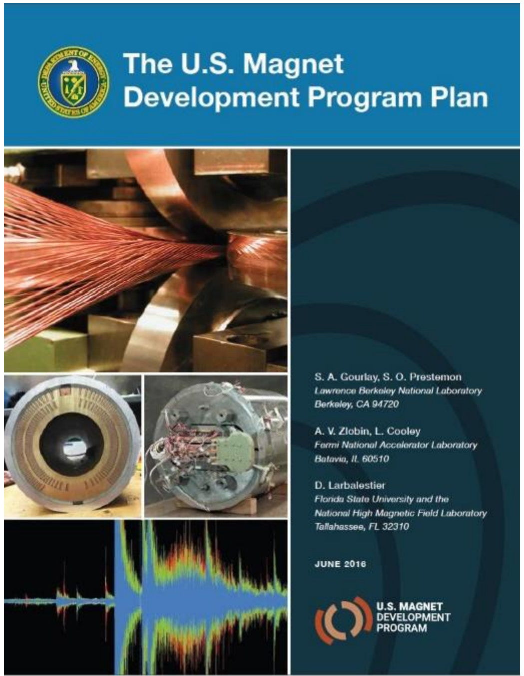


INFN

Blocks



CEA


The U.S. Magnet Development Program Plan

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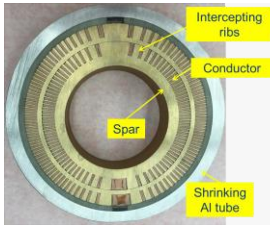
JUNE 2016

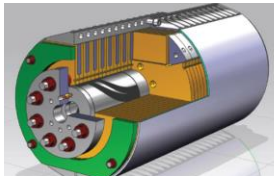
U.S. MAGNET DEVELOPMENT PROGRAM

**short model magnets (1.5 m lengths) will be built from 2018 - 2023**

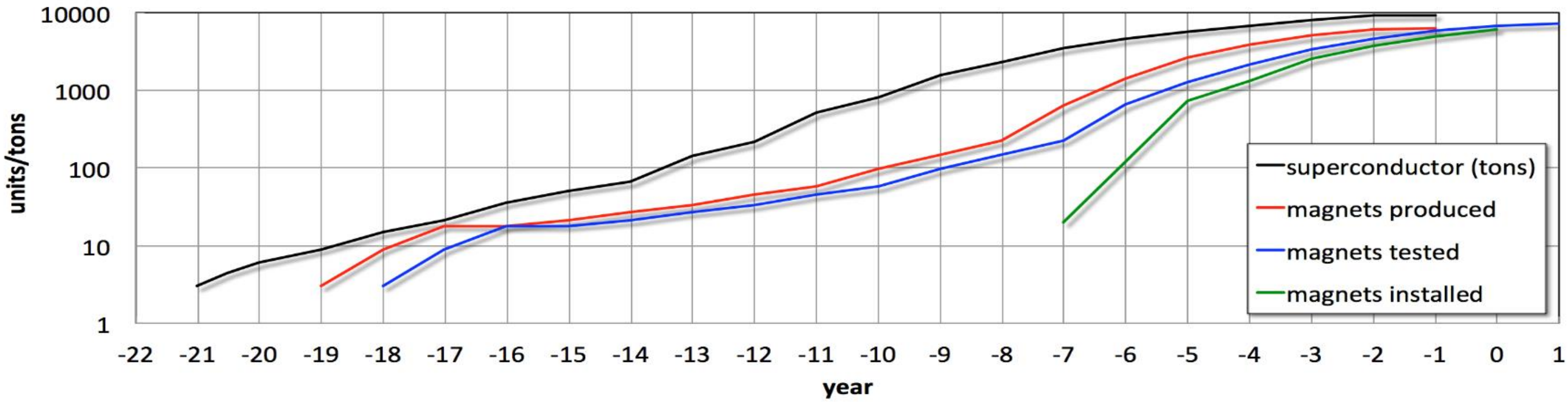
LBNL

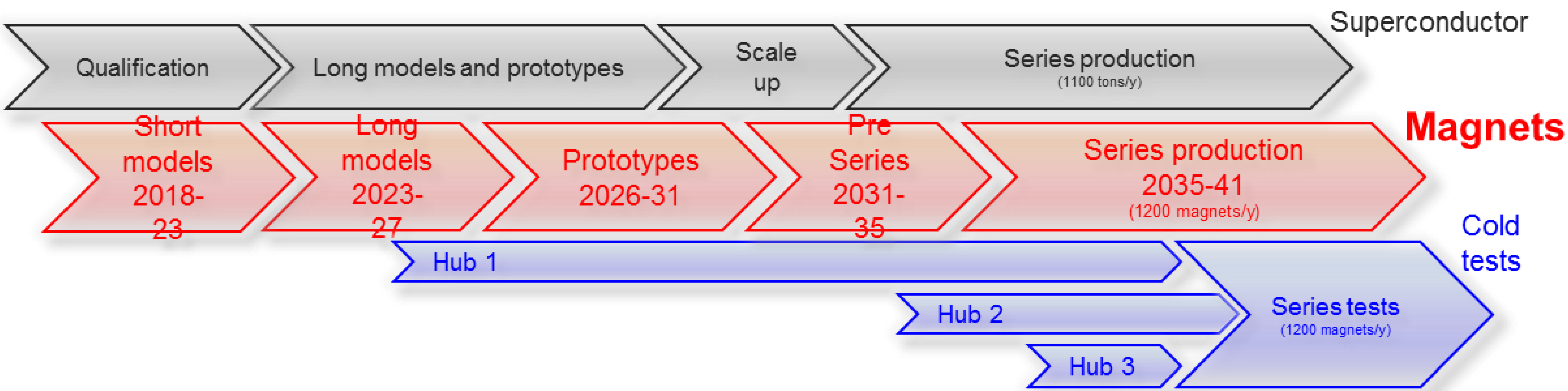



FNAL



# FCC 16 T magnet R&D schedule

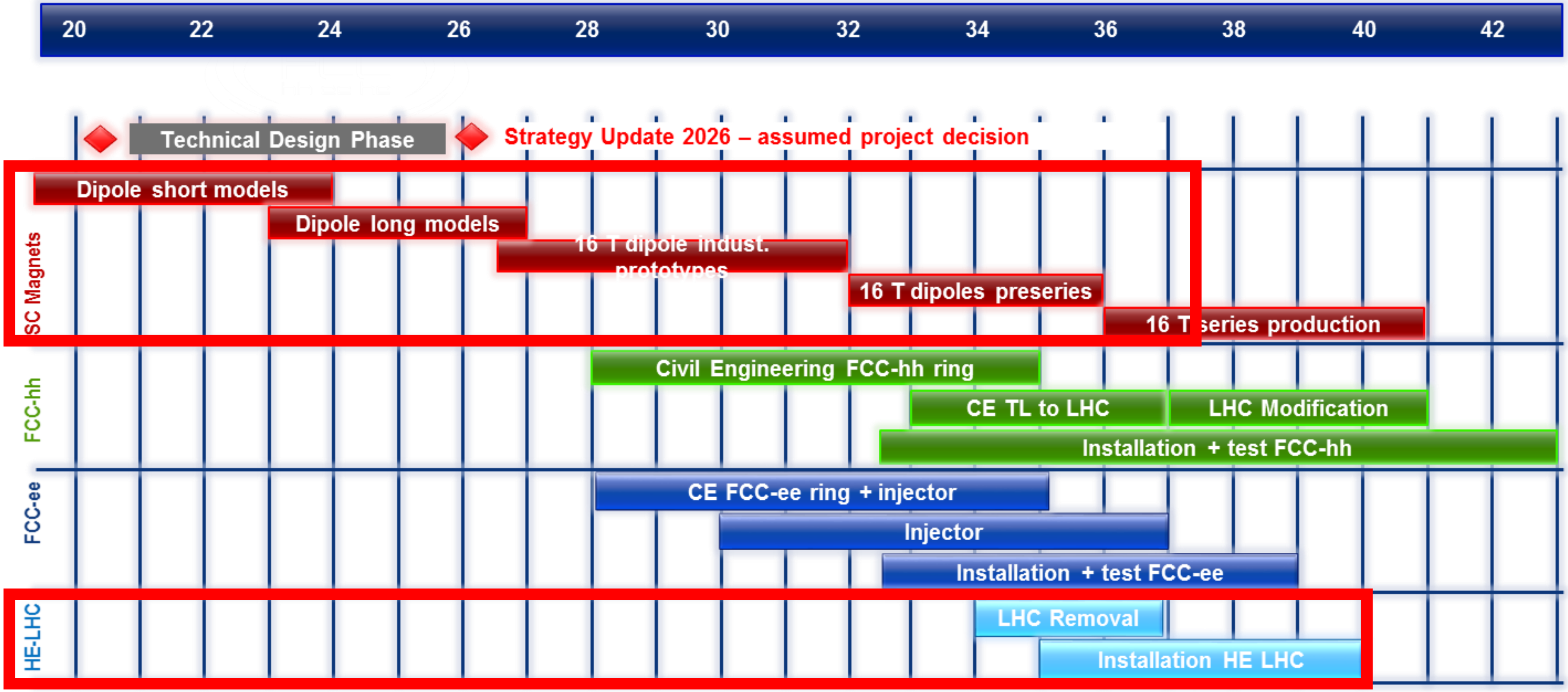



**total duration of magnet program: ~20 years**

**would follow HL-LHC *$Nb_3Sn$* program with long models w industry from 2023/24**

# Fastest Possible Technical Schedules




technical schedule defined by magnets program and by CE
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

**HE-LHC**
**design & construction**

M. Benedikt

# HE-LHC magnet challenge 1: field errors

original 16 T magnet (Ø=1500 mm)

| Normal | Injection | High Field | Uncertainty Injection | Uncertainty High Field | Random Injection | Random High Field |
|---|---|---|---|---|---|---|
| 2 | 0.000 | 0.000 | 0.484 | 0.484 | 0.484 | 0.484 |
| 3 | -5.000 | 20.000 | 0.781 | 0.781 | 0.781 | 0.781 |
| 4 | 0.000 | 0.000 | 0.065 | 0.065 | 0.065 | 0.065 |
| 5 | -1.000 | -1.500 | 0.074 | 0.074 | 0.074 | 0.074 |
| 6 | 0.000 | 0.000 | 0.009 | 0.009 | 0.009 | 0.009 |
| 7 | -0.500 | 1.300 | 0.016 | 0.016 | 0.016 | 0.016 |
| 8 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 9 | -0.100 | 0.050 | 0.002 | 0.002 | 0.002 | 0.002 |
| 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Skew | | | | | | |
| 2 | 0.000 | 0.000 | 1.108 | 1.108 | 1.108 | 1.108 |
| 3 | 0.000 | 0.000 | 0.256 | 0.256 | 0.256 | 0.256 |
| 4 | 0.000 | 0.000 | 0.252 | 0.252 | 0.252 | 0.252 |
| 5 | 0.000 | 0.000 | 0.050 | 0.050 | 0.050 | 0.050 |
| 6 | 0.000 | 0.000 | 0.040 | 0.040 | 0.040 | 0.040 |
| 7 | 0.000 | 0.000 | 0.007 | 0.007 | 0.007 | 0.007 |
| 8 | 0.000 | 0.000 | 0.007 | 0.007 | 0.007 | 0.007 |
| 9 | 0.000 | 0.000 | 0.002 | 0.002 | 0.002 | 0.002 |
| 10 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 |
| 11 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

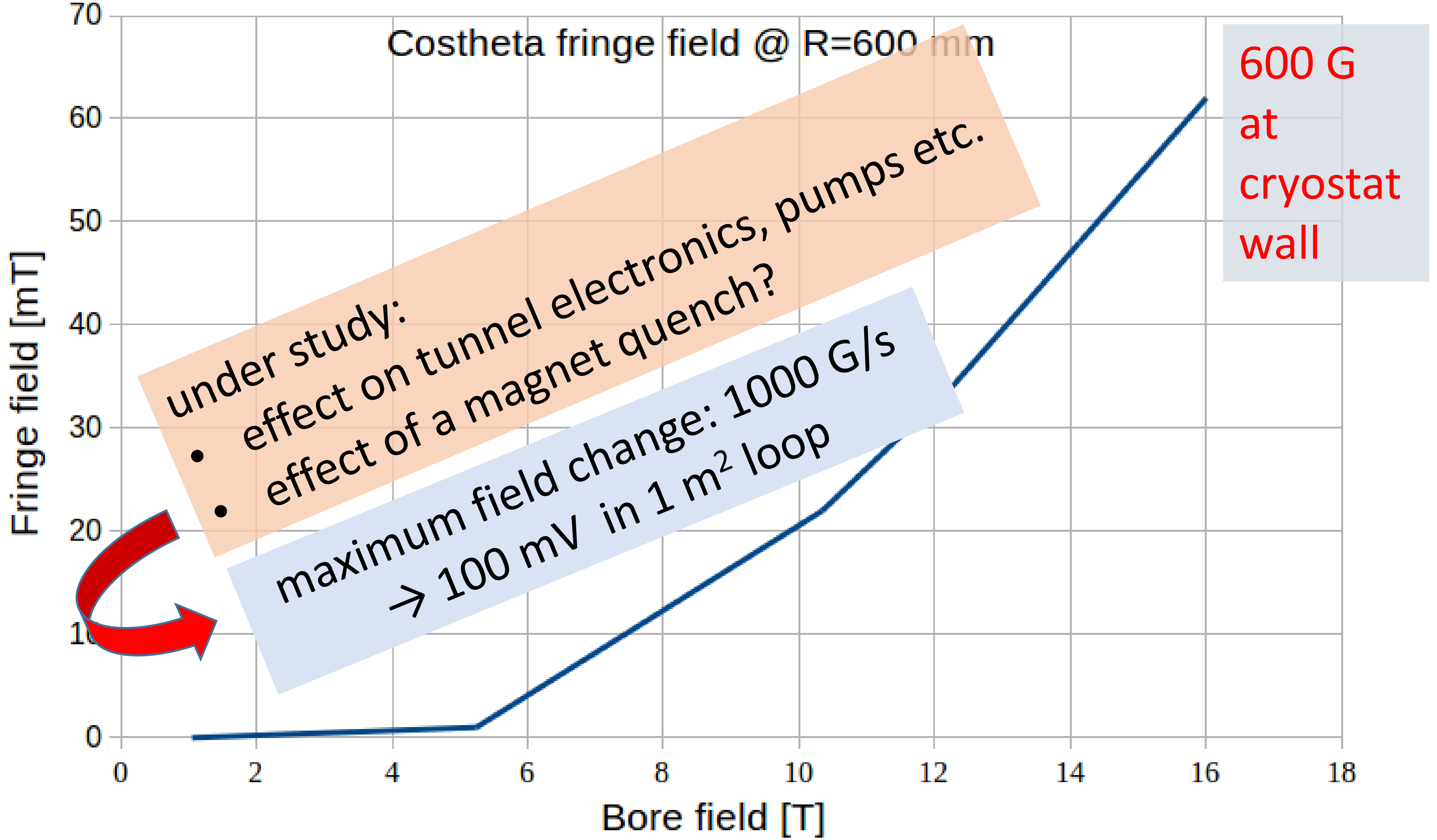
compact 16 T magnet (Ø=1200 mm)

*FCC Dipole field quality version 2 - 3 Oct 2017 - $R_{ref}$=16.7 mm. 3.3 TeV Injection*

| Normal | Systematic Geometric | Systematic Saturation | Systematic Persistent | Systematic Injection | Systematic High Field | Uncertainty Injection | Uncertainty High Field | Random Injection | Random High Field |
|---|---|---|---|---|---|---|---|---|---|
| 2 | -2.230 | -44.610 | 0.000 | -2.230 | -46.840 | 0.922 | 0.922 | 0.922 | 0.922 |
| 3 | -18.140 | 17.000 | -38.560 | -56.700 | -1.140 | 3.000 | 1.351 | 3.000 | 1.351 |
| 4 | -0.100 | -0.930 | 0.100 | 0.000 | -1.030 | 0.449 | 0.449 | 0.449 | 0.449 |
| 5 | -0.690 | -0.340 | 13.660 | 12.970 | -1.030 | 2.000 | 0.541 | 2.000 | 0.541 |
| 6 | 0.000 | -0.010 | 0.000 | 0.000 | -0.010 | 0.176 | 0.176 | 0.176 | 0.176 |
| 7 | 1.610 | 0.140 | -1.920 | -0.310 | 1.750 | 0.250 | 0.211 | 0.250 | 0.211 |
| 8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.071 | 0.071 | 0.071 | 0.071 |
| 9 | 1.310 | 0.120 | 3.970 | 5.280 | 1.430 | 1.000 | 0.092 | 1.000 | 0.092 |
| 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.027 | 0.027 | 0.027 | 0.027 |
| 11 | 0.960 | 0.090 | -0.100 | 0.860 | 1.050 | 0.200 | 0.028 | 0.200 | 0.028 |
| 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.009 | 0.000 | 0.009 | 0.009 |
| 13 | -0.170 | -0.020 | 0.170 | 0.000 | -0.190 | 0.011 | 0.000 | 0.011 | 0.011 |
| 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.000 | 0.003 | 0.003 |
| 15 | 0.010 | 0.000 | -0.010 | 0.000 | 0.010 | 0.004 | 0.000 | 0.004 | 0.004 |
| Skew | | | | | | | | | |
| 2 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.040 | 1.040 | 1.040 | 1.040 |
| 3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.678 | 0.678 | 0.678 | 0.678 |
| 4 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.450 | 0.450 | 0.450 | 0.450 |
| 5 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.317 | 0.317 | 0.317 | 0.317 |
| 6 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.205 | 0.205 | 0.205 | 0.205 |
| 7 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.116 | 0.116 | 0.116 | 0.116 |
| 8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.071 | 0.071 | 0.071 | 0.071 |
| 9 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.041 | 0.041 | 0.041 | 0.041 |
| 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.025 | 0.025 | 0.025 | 0.025 |
| 11 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.016 | 0.016 | 0.016 | 0.016 |
| 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.009 | 0.009 |
| 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.005 | 0.005 |
| 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.003 |
| 15 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 | 0.002 |

FCC-hh dynamic aperture at injection reduced 5x!

# HE-LHC magnet challenge 2: stray field



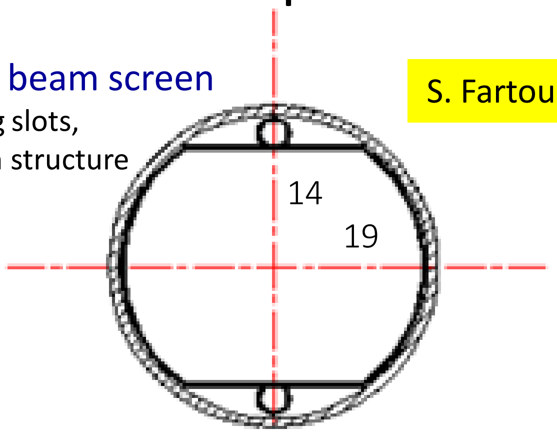
# "n1" beam stay clear

## 16-Tesla magnet bore: 50 mm
(LHC: 56 mm)

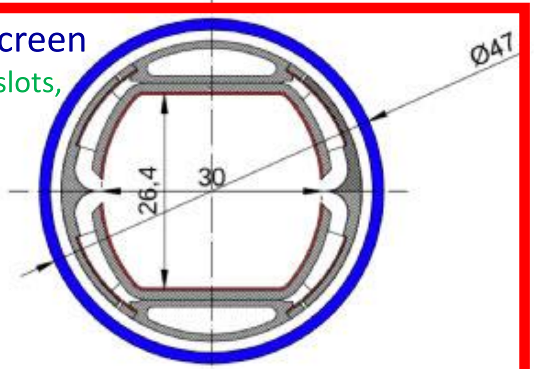
## arc beam-screen options for HE

scaled LHC beam screen
with pumping slots,
and sawtooth structure

S. Fartoukh




FCC-hh beam screen
shielded pumping slots,
less electron cloud




✓ choice for cooling & vacuum

## "n1" concept for beam stay clear

$L_x$=15 mm, $t_x$=(2+1) mm, $f_{arc}$=0.14, $\delta_p$=8.6*10$^{-4}$, $\varepsilon_x$=2.5 µm, $k_\beta$=1.05

$$n1_x = \frac{L_x - t_x - (1 + f_{\mathrm{arc}}) D_x \delta_p}{k_\beta \sigma_x}$$

$$\sigma_x = \sqrt{\beta_x \epsilon_x}$$

B. Jeanneret

## assume HL-LHC tolerances for optics orbit, and alignment

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2016-0328

**Parameters for aperture calculations at injection for HL-LHC***

**R. Bruce, C. Bracco, R. De Maria, M. Giovannozzi, S. Redaelli, R. Tomás, F. Velotti, J. Wenninger**

**Abstract**

Accurate evaluations of the margins of available aperture in the LHC and HL-LHC are very important, in order to judge if proposed optics and hardware are adequate, and to push the machine performance. A 2D calculation model was used during the design stage to study the aperture margins, however, the parameters of the model can now be refined based on LHC measurements and operational experience. This has already been carried out for the triplet aperture in the experimental insertions during physics operation [1]. In this report, we study instead the parameter sets for aperture calculations at injection for HL-LHC, and provide an updated set of tolerances as well as a criterion for the allowed aperture.

Geneva, Switzerland
5 February 2016

Table 1: The new proposed parameters to be used in the $n_1$ model for HL-LHC studies at injection (in bold) together with the parameter set that was used during the LHC design phase.

| Parameter set | LHC design | **HL-LHC design** |
|---|---|---|
| Primary halo extension | 6 $\sigma$ | **6 $\sigma$** |
| Secondary halo, hor./ver. | 7.3 $\sigma$ | **6 $\sigma$** |
| Secondary halo, radial | 8.3 $\sigma$ | **6 $\sigma$** |
| Normalized emittance $\epsilon_n$ | 3.75 $\mu$m | **2.5 $\mu$m** |
| Radial closed orbit excursion $x_{co}$ | 4 mm | **2 mm**[1] |
| Momentum offset $\delta_p$ | $1.5 \times 10^{-3}$ | **$8.6 \times 10^{-4}$** |
| $\beta$-beating fractional beam size change $k_\beta$ | 1.1 | **1.05** |
| Relative parasitic dispersion $f_{arc}$ | 0.27 | **0.14** |
| Mechanical alignment | ~2 mm | 1 mm? |

M. Giovannozzi, D. Zhou, F. Zimmermann

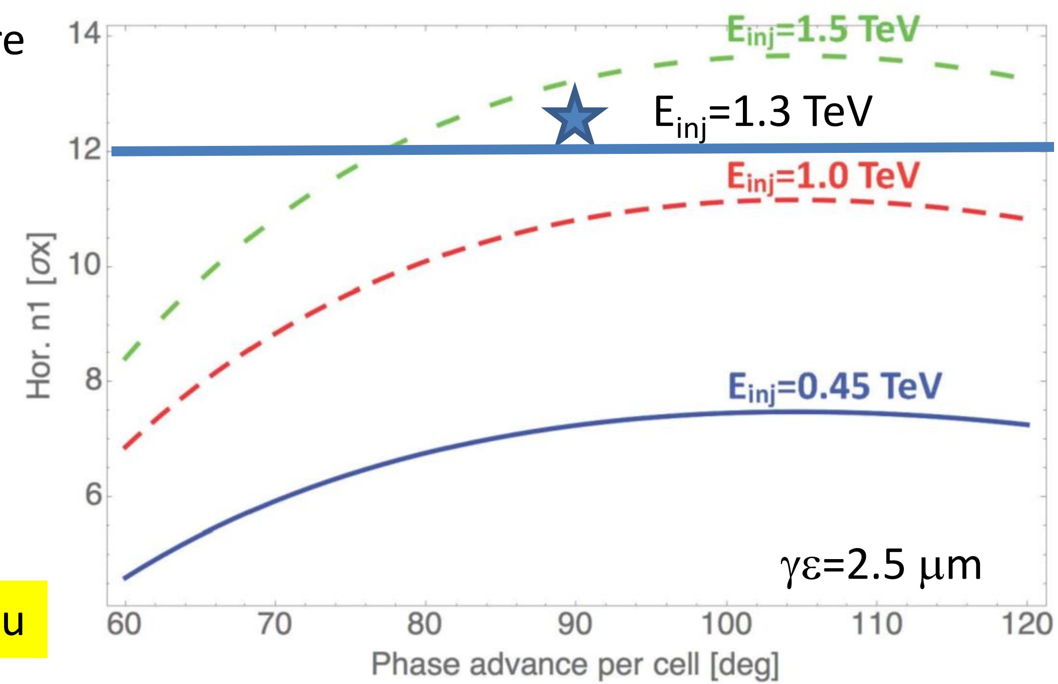
# $1^{st}$ HE-LHC optics release V0.1

**main features:**

- 18 cells / arc (cf LHC: 23)
- 90 degree phase advance / arc cell as in LHC
- 8 dipoles per cell (LHC: 6)
- ring separation: 204 mm (LHC: 194 mm)
- IR1 and IR5 optimized with longer triplet and shielding
- IR4 optimized with more RF and limited dipole strength
- global matching and chromaticity correction


D. Zhou, KEK
Y. Nosochkov, SLAC
T. Risselada, CERN (ret.)
M. Hofer, TU Vienna,
L. van Riesen-Haupt,
J. Abelleira, Oxford JAI,
M. Crouch (CERN)


aperture in units of σ




D. Zhou

| accelerator | 450 GeV | 1.3 TeV |
|---|---|---|
| HL-LHC | 13.5 | - |
| HE-LHC 18x90 degree | 7.1 | 12.5 |

# HE-LHC experimental IR

**triplet lengths:**

**HE-LHC: 56 m** (13.5 TeV)

HL-LHC: 41. 8m

**present**

**LHC: 30.4 m**

ca. 11 m space

for crab cavities

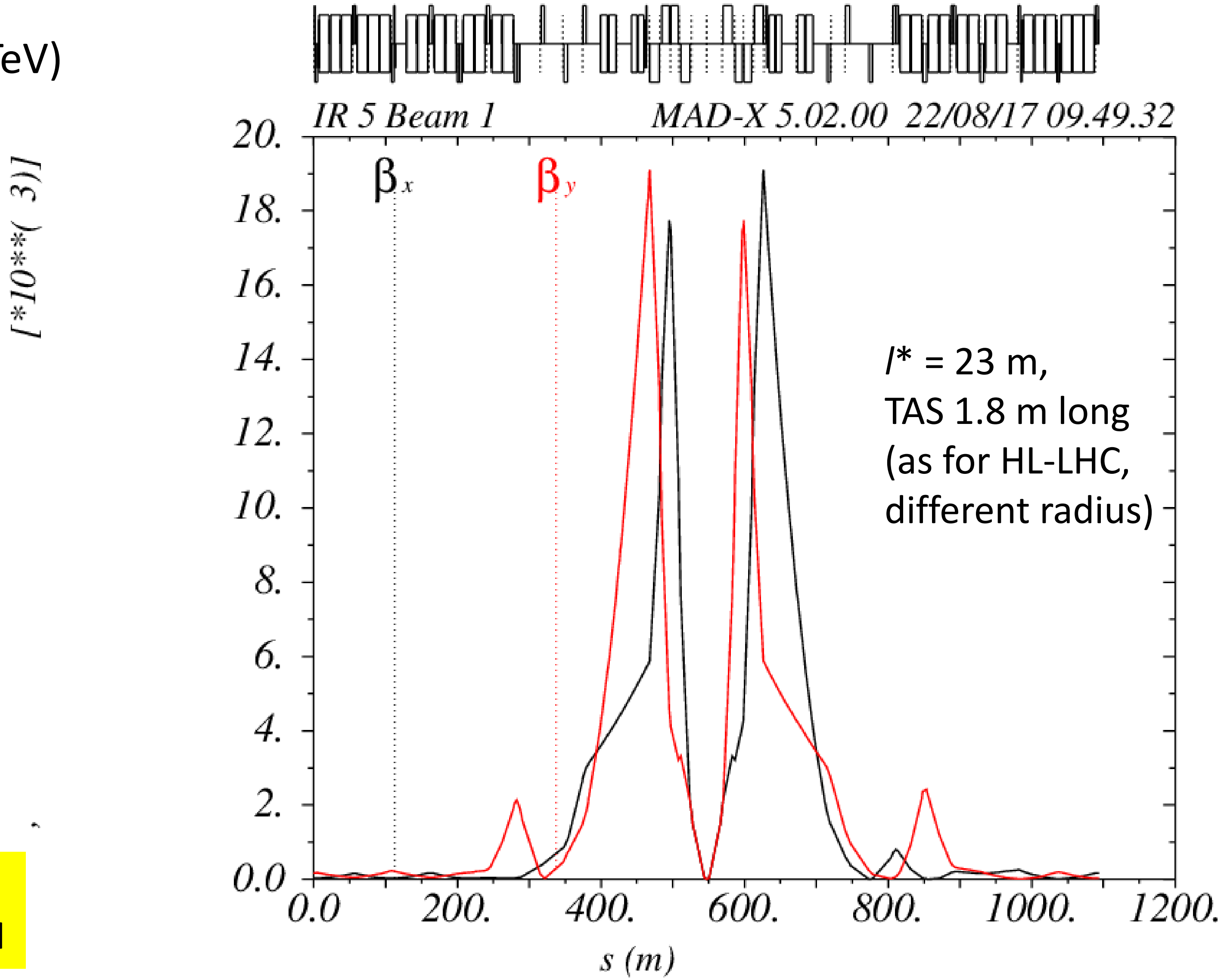
injection optics

with $\beta^*$=11 m

(n1 >12 $\sigma$ )


L. van Riesen-Haupt,
J. Abelleira, Oxford JAI


collision optics with $\beta^*$=0.25 m

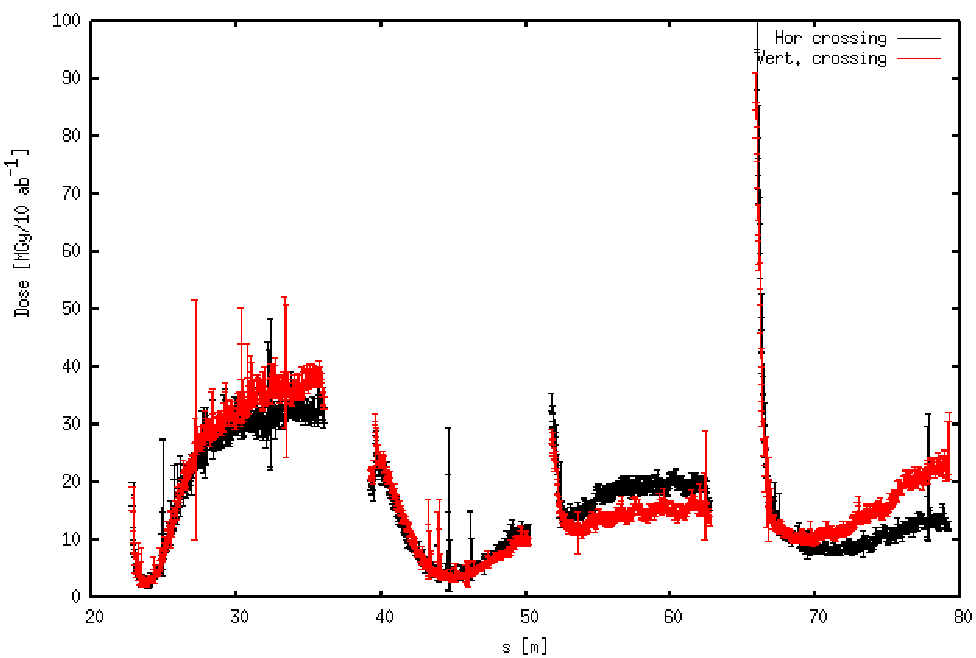


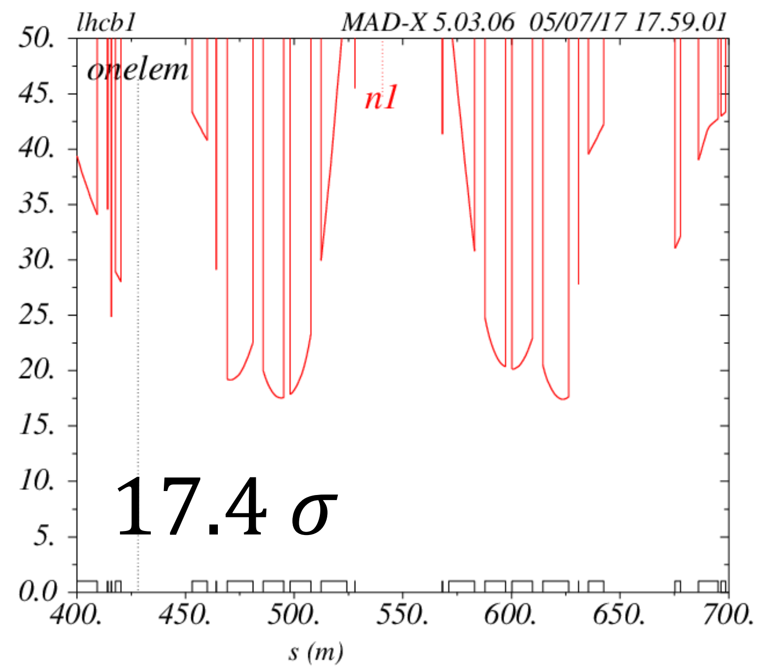

*l** = 23 m,
TAS 1.8 m long
(as for HL-LHC,
different radius)

# final triplet shielding & aperture

- **triplet quadrupoles with 2 cm inside W shielding**
- $\boldsymbol{\beta^* = 25\ \mathrm{cm}}$
- $\boldsymbol{> 12.5\ \sigma}$ **stay clear with crossing angle**
- **for** $\boldsymbol{10\ \mathrm{ab}^{-1}}$ **total luminosity:** $\boldsymbol{30 - 50\ \mathrm{MGy}}$ **peak radiation**

**(peak at Q3 can be reduced with shield in frnot)**




L. van Riesen-Haupt, J. Abelleira, Oxford JAI

# HE-LHC collimation challenge

- must fit into existing straights (0.5 km)

→ scaling solution used for FCC-hh (0.5→2.8 km) not applicable

→ reduced collimator gaps and(/or) **hollow e-lenses** (under study for HL-LHC)

- dogleg separation with NC magnets gets longer

→ **shielded SC dipoles and/or quadrupoles**

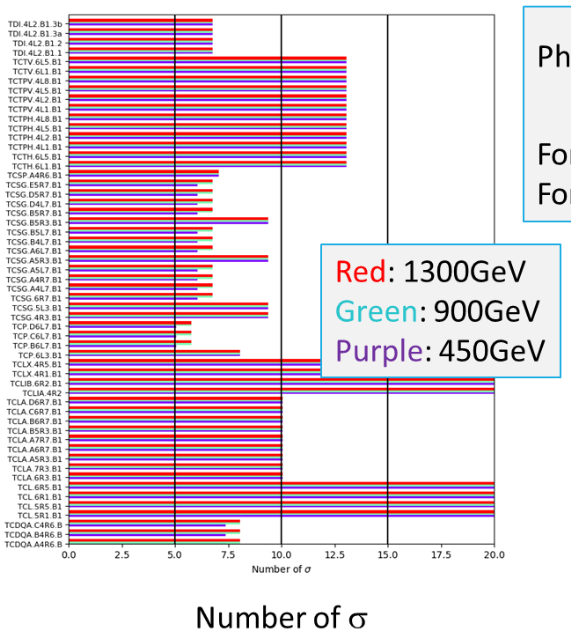
M. Crouch, M. Giovannozzi, S. Redaelli, Thys Risselada et al.

# HE-LHC collimator settings

tighter gaps than LHC/HL-LHC

scaling from HL-LHC

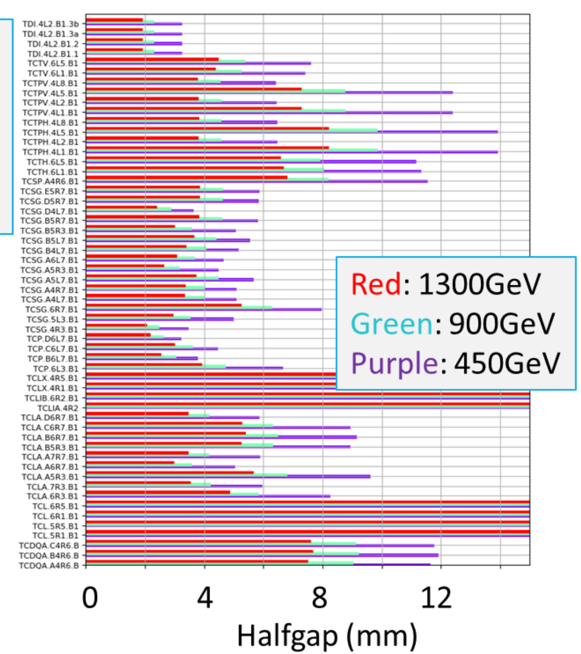
| | 450 GeV | 900 GeV | 1.3 TeV |
|---|---|---|---|
| reference emittance | 2.5 um | 2.5 um | 2.5 um |
| primary colls | **5 σ** | 5.7 σ | 5.7 σ |
| secondary colls | 6 σ | 6.7 σ | 6.7 σ |
| TCDQA | 7.3 σ | 8.3 σ | 8.3 σ |
| machine aperture | **~ 8 σ** | > 10.6 σ | > 10.6 σ |
| Comments | **very tight, not compatible with aperture** | | |




Physical gaps scale as $\sqrt{\frac{\varepsilon_n}{E}}$

For HL-LHC, $\varepsilon_n = 3.5\mu m$

For HE-LHC, $\varepsilon_n = 2.5\mu m$

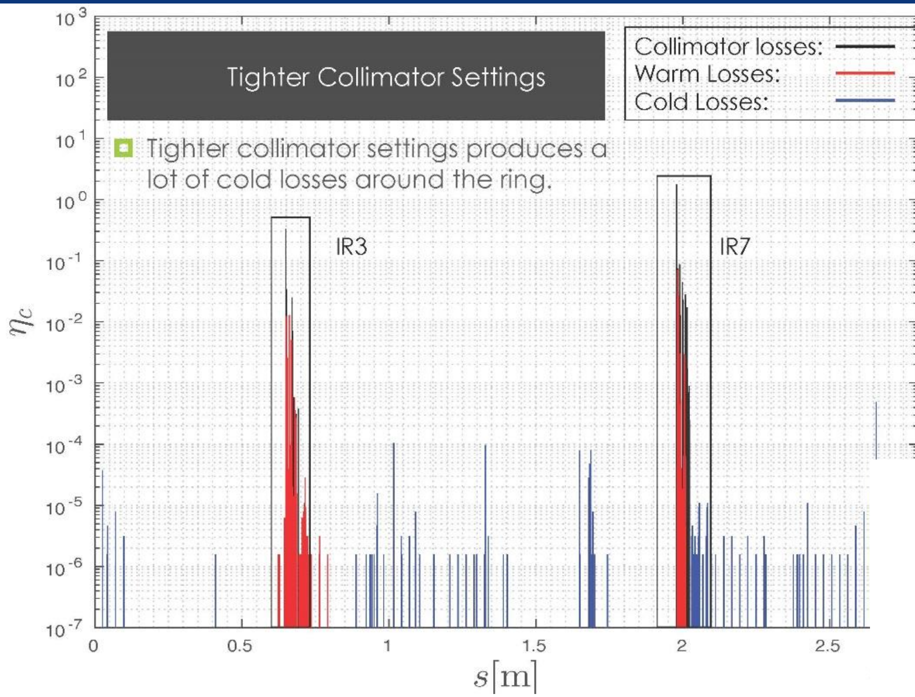




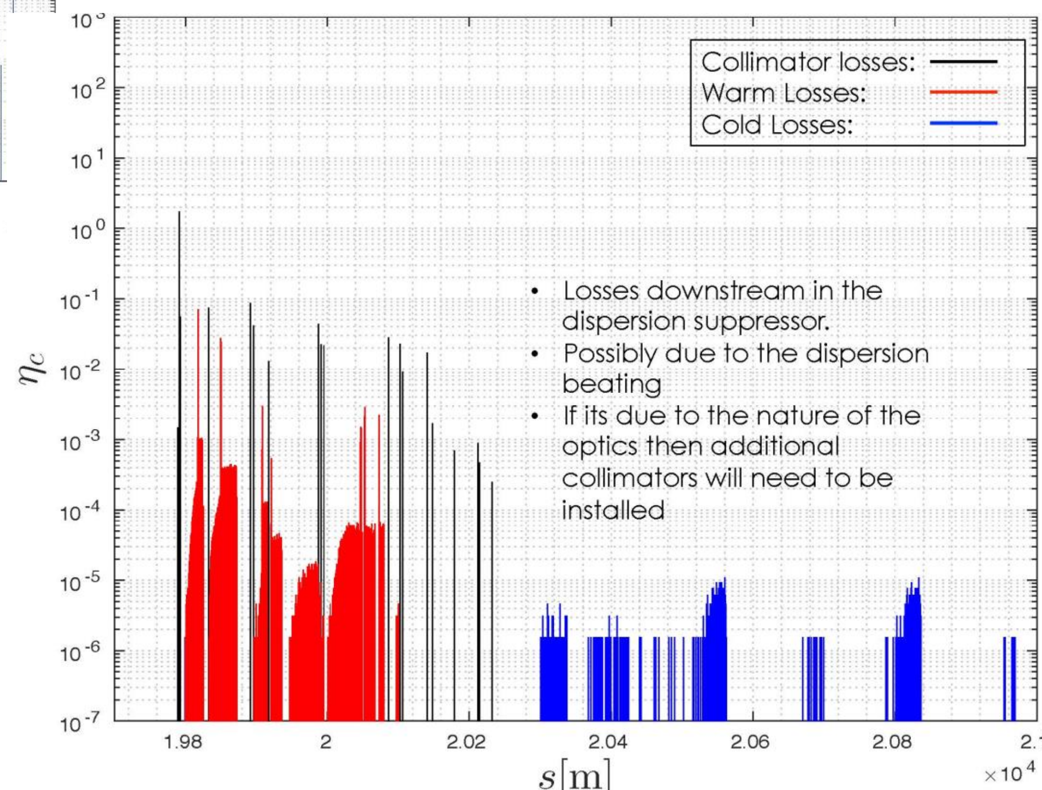
D. Amorim,
S. Antipov,
S. Arsenyev,
R. Bruce,
M. Crouch,
S. Redaelli,
F. Zimmermann

# collimation loss maps

M. Crouch




tight settings at 450 GeV

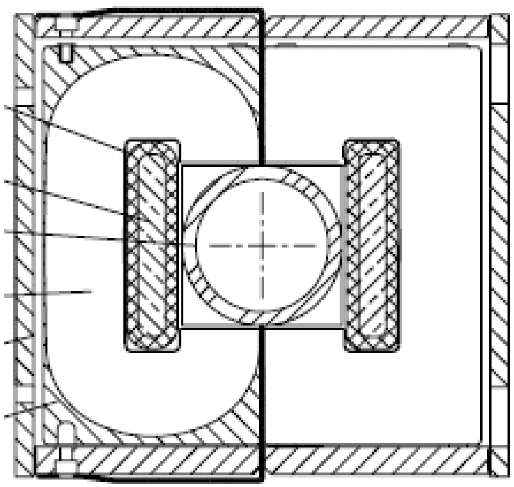


# HE-LHC beam extraction

doubling length of extraction kicker & septa challenging (space constraints)

preferred: new kicker with reduced vertical opening & increased rise time

- scaling kicker opening to √(450/1000): 62 → 42 mm
- kicker magnetic gap 72 → 52 mm (vacuum chamber)



| | | LHC Nominal | HE Nominal |
|---|---|---|---|
| MKD V gap | mm | 72 | 52 |
| MKD rise time | us | 3.00 | 4.30 |
| MKD angle | mrad | 0.27 | 0.27 |
| MKD B.dl | Tm | 6.3 | 12.6 |
| MKD field | T | 0.30 | 0.60 |
| MKD peak field | T | 0.41 | 0.80 |
| MKD dI/dT | kA/us | 6.17 | 6.21 |
| MKD I | kA | 18.5 | 26.7 |
| MKD length | m | 21.0 | 21.2 |
| MKD Filling factor | | 0.761 | 0.761 |
| MKD Required length | m | 27.6 | 27.8 |
| MKD magnets | | 15.0 | 15.1 |

- 15 magnets, 0.8 T and 26.7 kA: gives 4.3 μs rise time

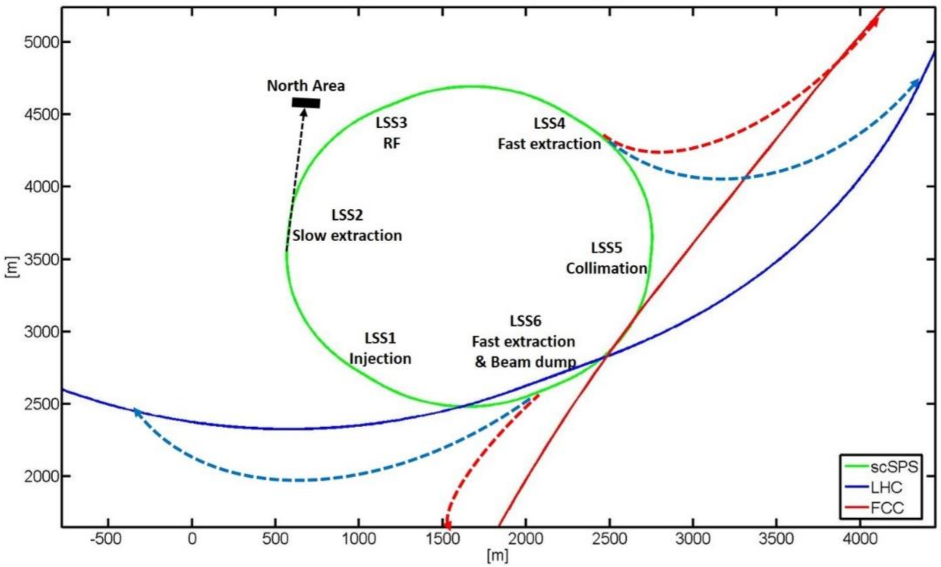
beam extraction system for 13.5 TeV beam in existing LHC straight → preference for injection energy > 1 TeV

B. Goddard

# scSPS as HE-LHC injector

- keep SPS geometry (6 LSS)
- replace SPS by new superconducting single aperture machine
- peak **magnetic field 6 T → extract at 1.3 TeV** - **fast ramping**
- scSPS energy swing ~50
- scSPS design as injector option for FCC-hh

scSPS helps for HE-LHC optics, physical & dynamic aperture, impedance effects & extraction, …

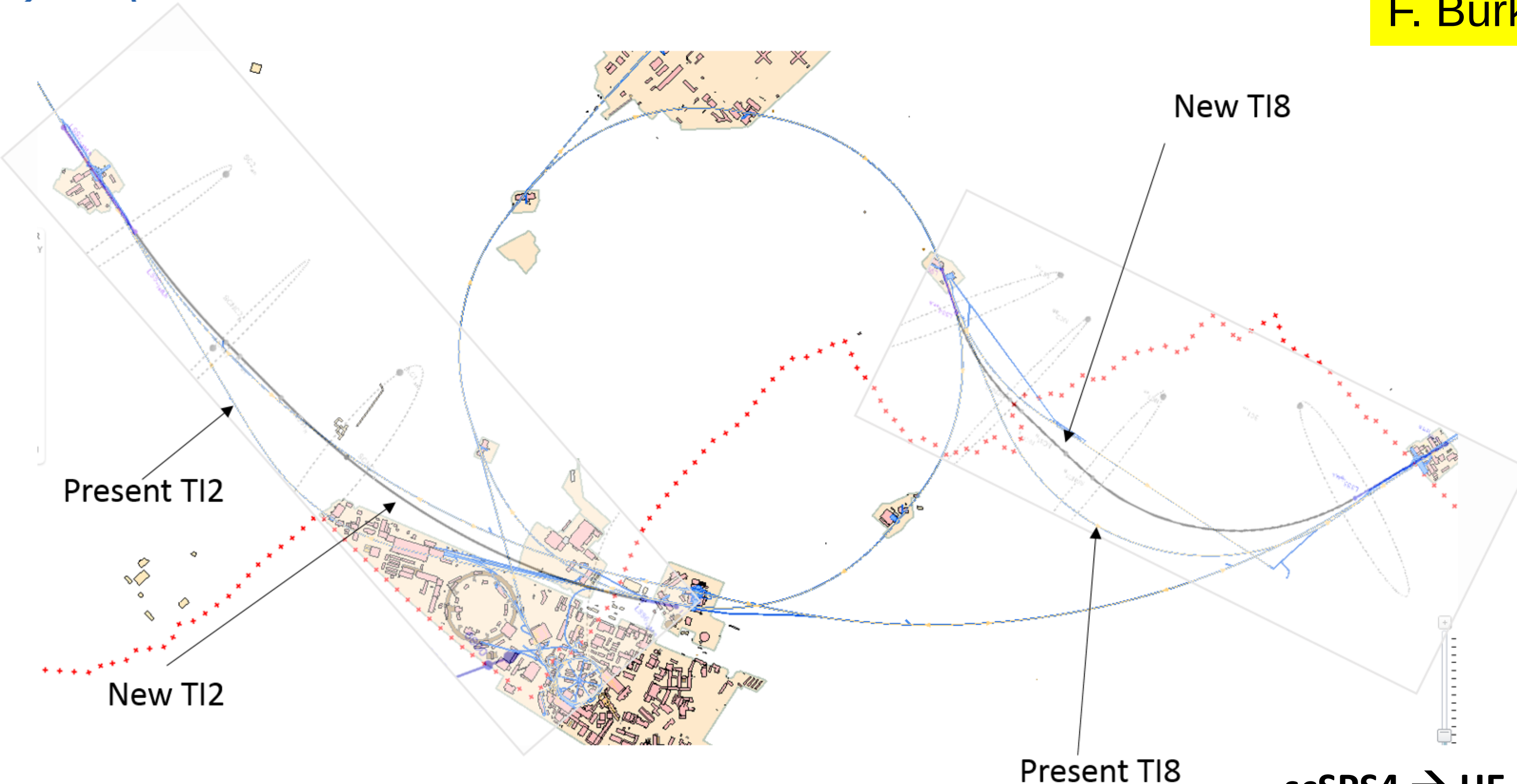



| Parameter | Unit | Value |
|---|---|---|
| Injection energy | GeV | 26 |
| Extraction energy | GeV | 1300 |
| Maximum dipole field | T | 6 |
| Dipole field at injection | T | 0.12 |
| Number of dipoles | | 372 |
| Number of quadrupoles | | 216 |
| Ramp rate | T/s | 0.35 - 0.5 |
| Cycle length | min | 1 |
| Number of bunches per cycle | | 640 |
| Number of injections into scSPS | | 8 (80b) |
| Number of protons per bunches | | $\leq 2.5\times10^{11}$ |
| Number of extraction per cycle | | 2 (2x320 b) |
| Number of cycles per FCC filling | | 34 |
| FCC filling time | min | 34 - 40 |
| Max stored beam energy | MJ | 33 |

F. Burkart

# scSPS → HE-LHC: new transfer lines

F. Burkart




**scSPS6 → HE-LHC2:**

nc (2T): 2187 m
straight: 446 m
nc (2T): 72 m
sc (6T): 136 m

filling factor: 70%, slopes for sc below 3%.

**scSPS4 → HE-LHC8:**

sc(6T): 1300 m
nc (2T): 166 m
straight: 280 m
nc(2T): 76 m
sc(6T): 468 m

# HE-LHeC ep collisions

| parameter [unit] | LHeC CDR | ep at HL-LHC | ep at HE-LHC | FCC-he |
|---|---|---|---|---|
| $E_p$ [TeV] | 7 | 7 | 12.5 | 50 |
| $E_e$ [GeV] | 60 | 60 | 60 | 60 |
| $\sqrt{s}$ [TeV] | 1.3 | 1.3 | 1.7 | 3.5 |
| bunch spacing [ns] | 25 | 25 | 25 | 25 |
| protons per bunch [$10^{11}$] | 1.7 | 2.2 | 2.5 | 1 |
| $\gamma\epsilon_p$ [$\mu$m] | 3.7 | 2 | 2.5 | 2.2 |
| electrons per bunch [$10^9$] | 1 | 2.3 | 3.0 | 3.0 |
| electron current [mA] | 6.4 | 15 | 20 | 20 |
| IP beta function $\beta_p^*$ [cm] | 10 | 7 | 10 | 15 |
| hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 | 0.9 |
| pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 | 1.3 |
| proton filling $H_{coll}$ | 0.8 | 0.8 | 0.8 | 0.8 |
| luminosity [$10^{33}$cm$^{-2}$s$^{-1}$] | 1 | 8 | 12 | 15 |

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
April $6^{th}$, 2017

# HE-LHC summary

**HE-LHC physics parameters**

27 TeV c.m. energy in *pp* collisions

>10 $ab^{-1}$ over 20 years

pile up of up to ~800 at 25 ns spacing (~400 w 12.5 ns or w leveling)

excellent prospects for lepton-hadron & heavy-ion collisions

earliest technically possible **start of physics: 2040**

- *this would require HL-LHC stop at LS5*

**HE-LHC main challenges**

bent, compact 16 T $Nb_3Sn$ dipole magnets

- *more constrained & more difficult than FCC-hh magnets*

collimation and extraction in given length of straight section

new superconducting SPS as 1.3 TeV injector, new transfer lines

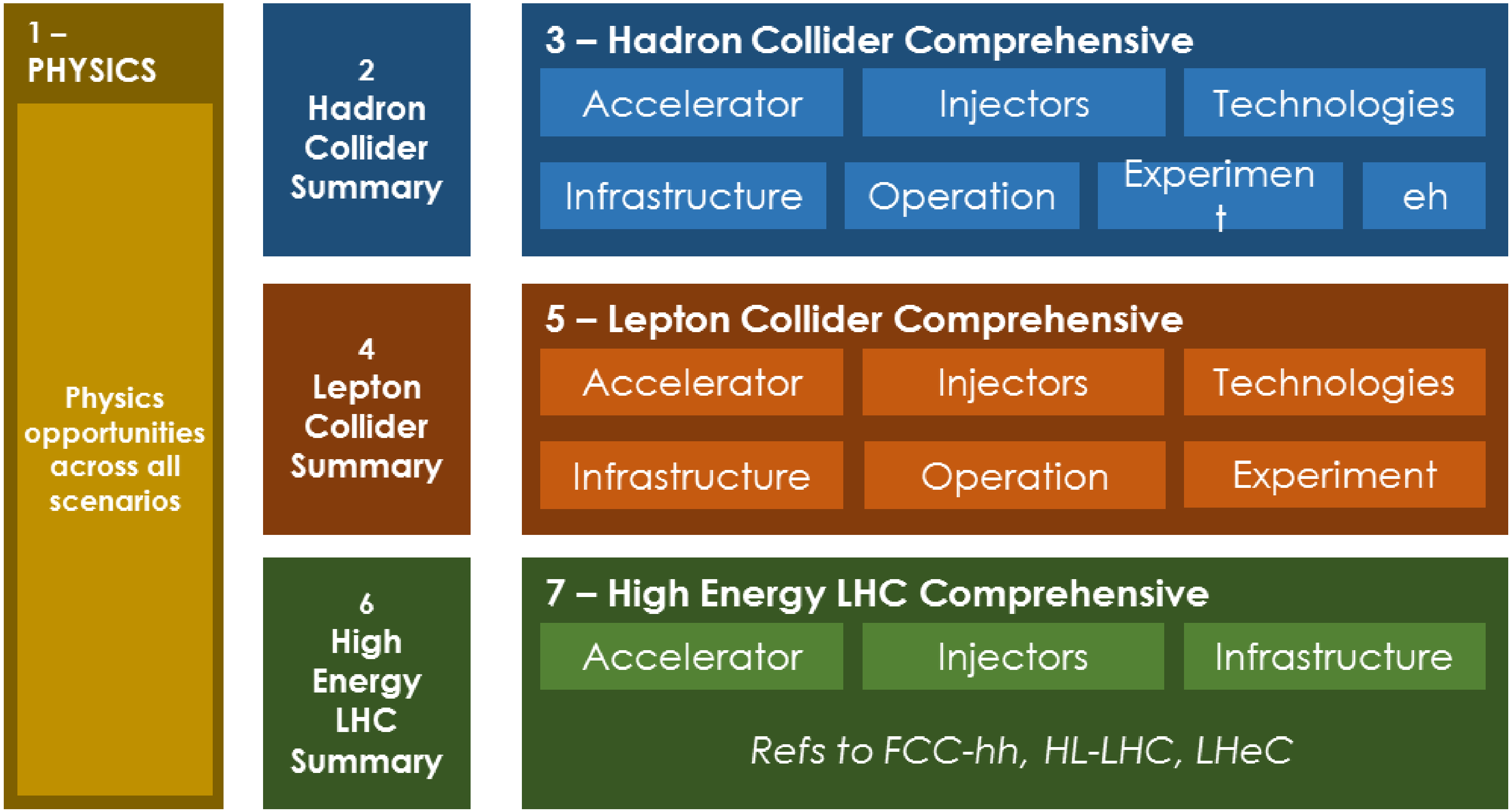
synchrotron radiation and $Nb_3Sn$ AC losses during current ramp

# FCC/HE-LHC Advisory Committee

- **IAC composition covering all study areas, 17 members**
- **important role as expert review committee for study and CDR preparation**

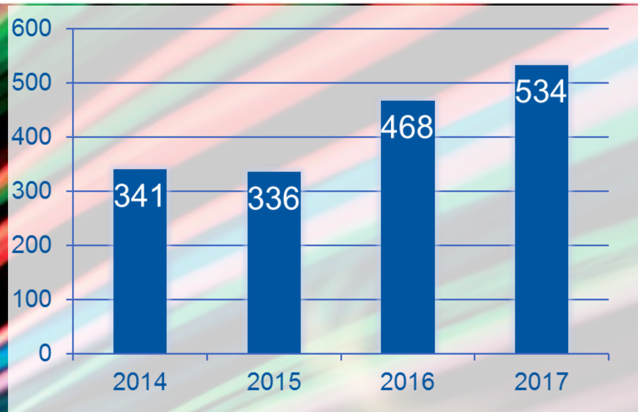
| | **FCC International Advisory Committee** | | | |
|---|---|---|---|---|
| **Chair** | **Dissertori** | Guenther | ETHZ | CH |
| **Physics Experiments** | **Diemoz** | Marcella | INFN | IT |
| | **Egorychev** | Victor | ITEP | RU |
| | **Herten** | Gregor | U. Freiburg | GE |
| | **Quigg** | Chris | FNAL | US |
| | **Parker** | Andrew | U. Cambridge | UK |
| **Accelerator Design** | **Assmann** | Ralph | DESY | GE |
| | **Biscari** | Caterina | ALBA-CELLS | ES |
| | **Fischer** | Wolfram | BNL | US |
| | **Shiltsev** | Vladimir | FNAL | US |
| **Technology and Infrastructure** | **Lebrun** | Philippe | JUAS | FR |
| | **Minervini** | Joe | MIT | US |
| | **Mosnier** | Alban | CEA | FR |
| | **Ross** | Marc | SLAC | US |
| | **Seidel** | Mike | PSI | CH |
| | **Watson** | Tim | ITER | ITER |

# Conceptual Design Report




- **required for end 2018, as input for European Strategy Update**
- **common physics summary volume**
- **three detailed volumes FCC-hh, FCC-ee, HE-LHC**
- **three summary volumes  FCC-hh, FCC-ee, HE-LHC**

# FCC Collaboration - Status July 2017




> 500 participants
147 institutes
a lot of young people
(>35% younger than 35)

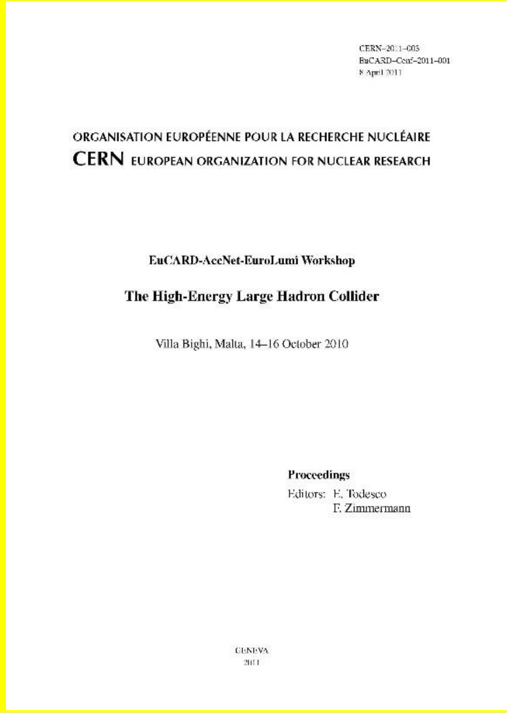

FCCWEEK2018
Future Circular Collider Conference
AMSTERDAM, Netherlands
9 - 13 APRIL
fccw2018.web.cern.ch
IEEE CSC
DPG
DESY
CERN
see you in Amsterdam!
also 2018 FCC Physics Workshop, 15-19 January 2018, CERN

*spare slides*

# High-Energy LHC

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1



CERN–2011–003
EuCARD–Conf–2011–001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments

# options for HE-LHC arc optics

| | LHC-like | 18x60⁰ | 18x80⁰ | 18x90⁰ | 20x90⁰ |
|---|---|---|---|---|---|
| Arc cell phase advance [deg] | 90/90 | 60/60 | 80/80 | 90/90 | 90/90 |
| Arc cell length [m] | 106.958 | | 137.233 | | 124.8 |
| K1 [$m^{-1}$] | 0.027 | 0.0148 | 0.019 | 0.021 | 0.023 |
| $\beta_{max/min}$ [m] | 181.3/31.5 | 236.7/79.5 | 227.7/50.0 | 233.0/40.4 | 211.7/36.8 |
| $\eta_{max/min}$ [m] | 2.2/1.1 | 6.7/4.1 | 4.3/2.2 | 3.6/1.8 | 3.0/1.5 |
| Dipole length [m] | 14.3 [x6] | | 14.18 [x8] | | 12.625 [x8] |
| Dipole field [T] @13.5TeV | 16.06 | | 15.59 | | 15.92 |
| Quad. gradient [T/m] @13.5TeV | 391.7 | 214.8 | 276.2 | 303.9 | 334.7 |
| Sext. gradient [$T/m^2$] @13.5TeV | 4883 | 866 | 1824 | ? | 2940 |
| Filling factor | 0.802 | | 0.827 | | 0.809 |

longer arc cells!

60 deg / cell would allow Nb-Ti quadrupoles and sextupoles

D. Zhou, KEK; Y. Nosochkov, SLAC; T. Risselada, E. Todesco, CERN