JAI students' design project 2017/2018

HE-LHC

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JAI

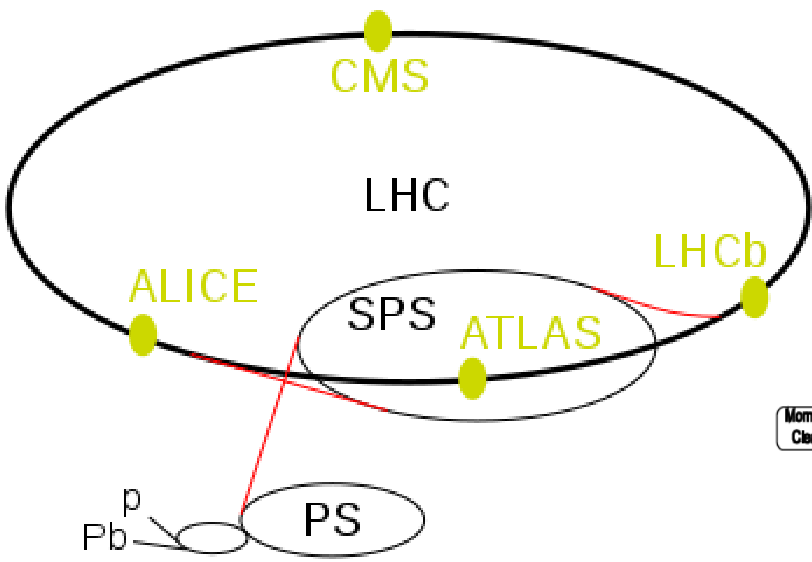
30 November 2017

With thanks to many colleagues for slides used in this intro

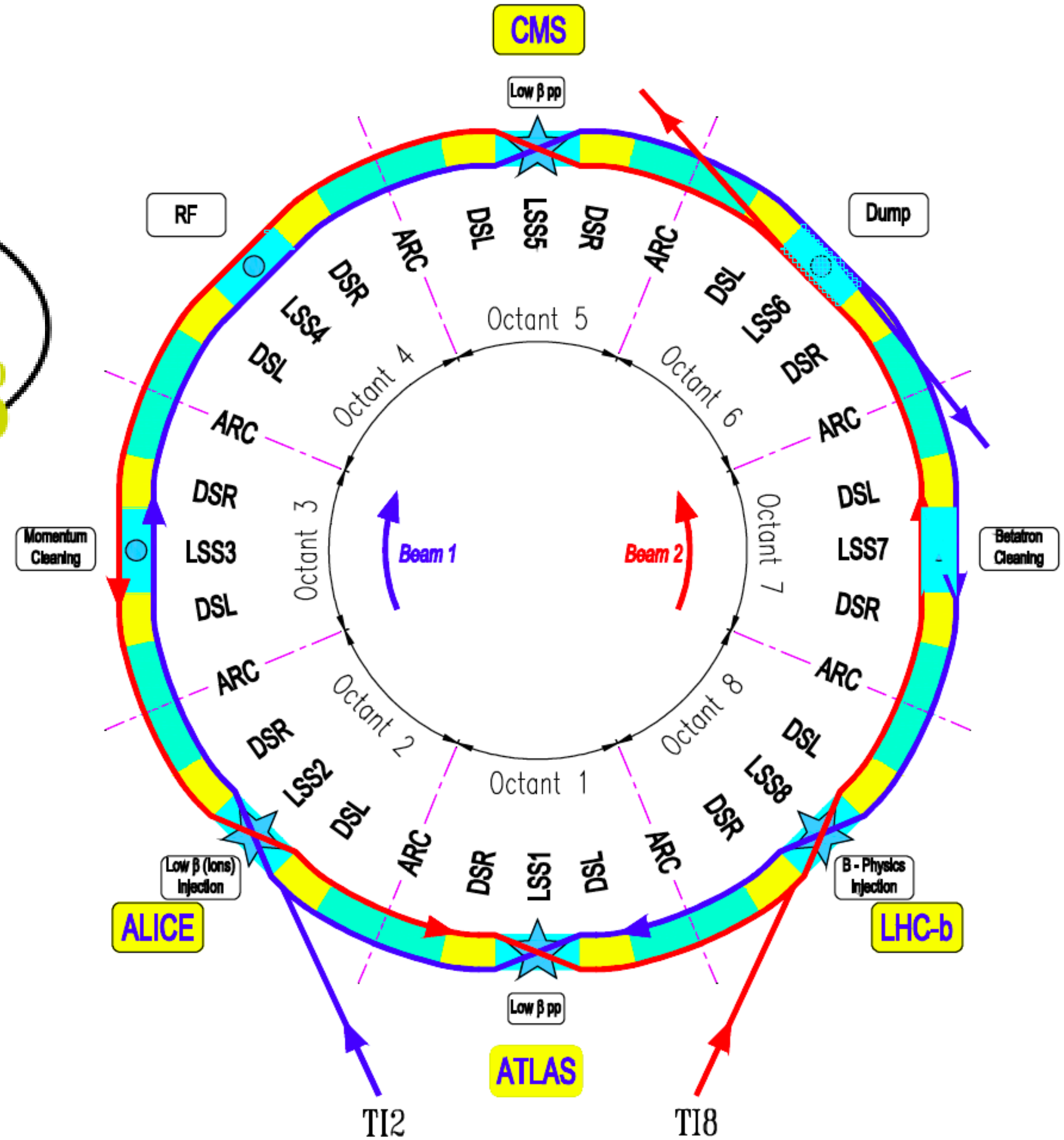
Contents

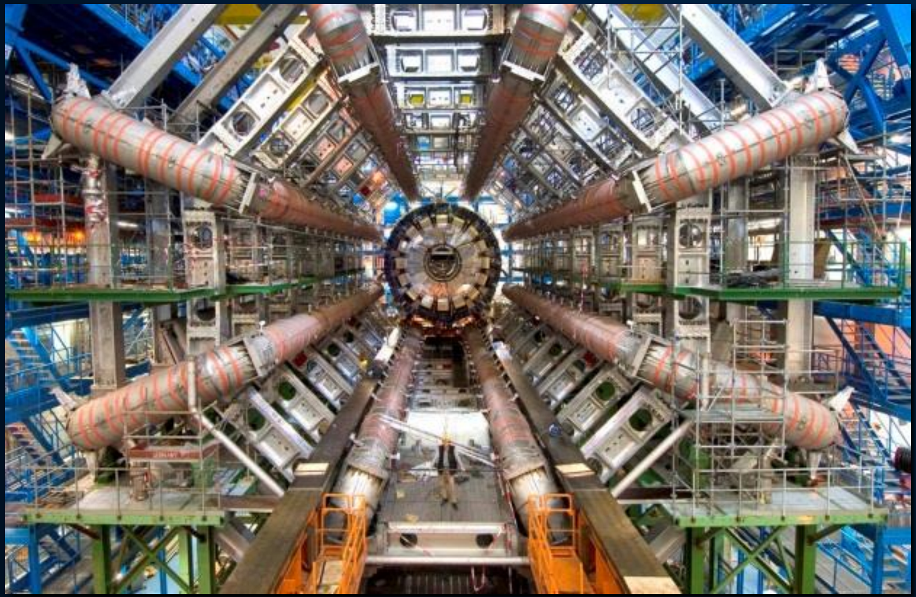
- **First – briefly remind about**
  - **LHC**
  - **HL-LHC (High Lumi LHC)**
- **Then**
  - **FCC (Future Circular Collider)**
- **And then**
  - **Describe HE-LHC (High Energy LHC)**
- **And after that describe**
  - **Topics of possible contribution**

Large Hadron Collider



27 km circumference,
up to 14 TeV CM,
8.33 T magnets





Large Hadron Collider
LHC

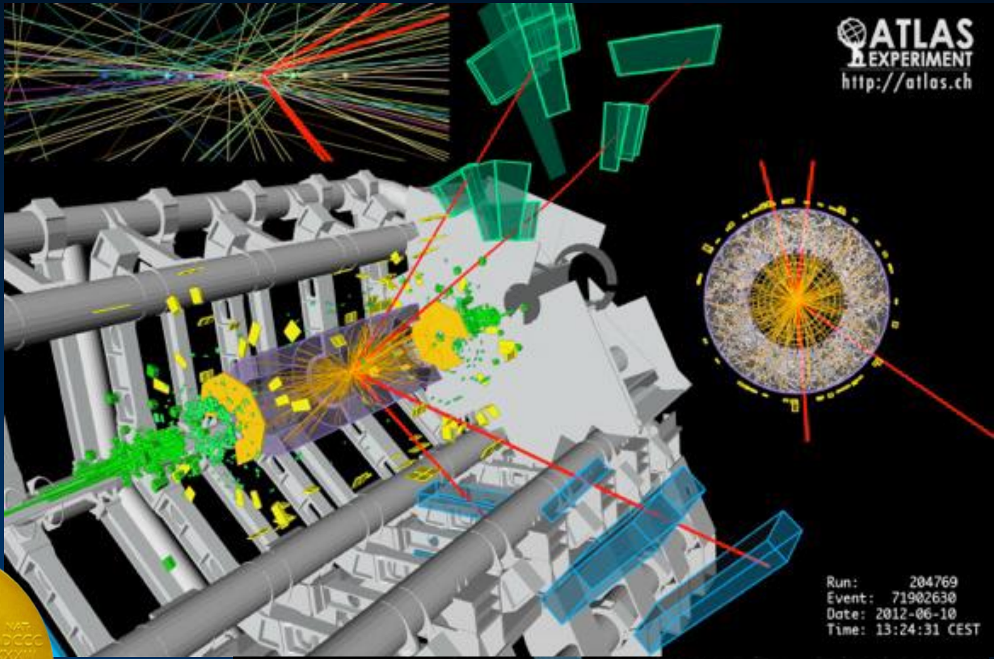
Theory: 1964

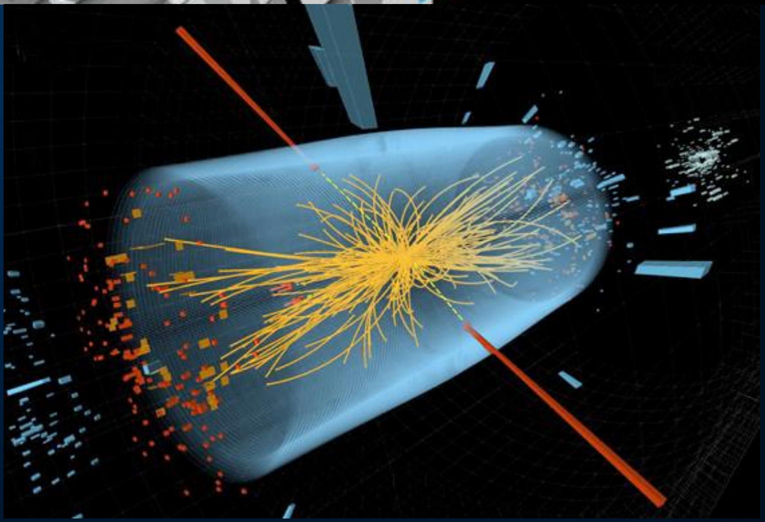
Discovery of Higgs boson

Experimental project: 1984

Construction of collider and detectors: 1998

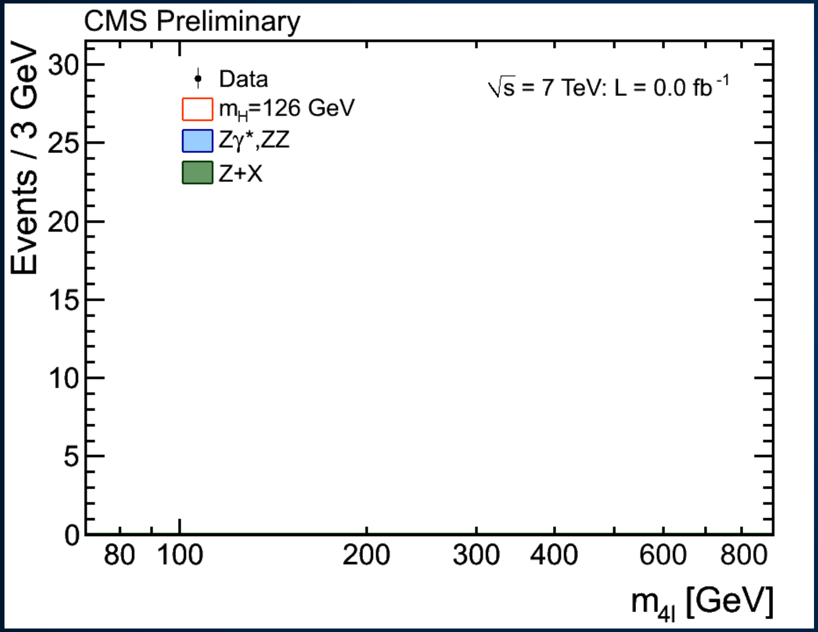
Discovery: 2012

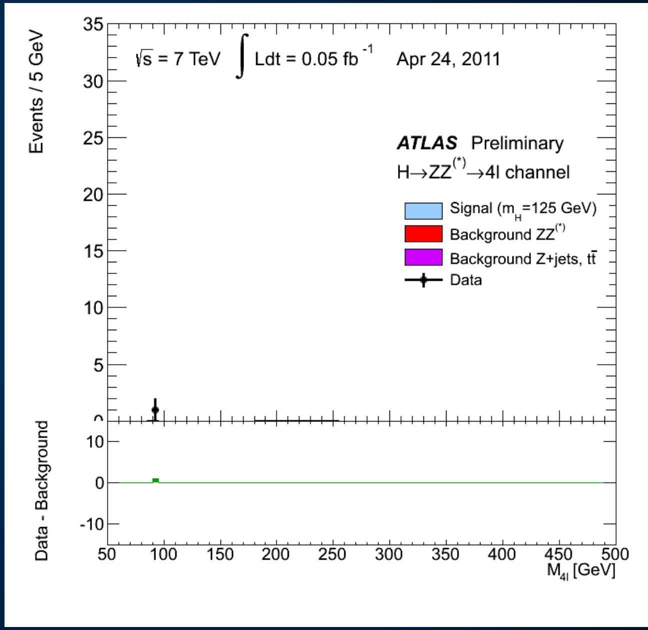




The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Higgs – storing the data





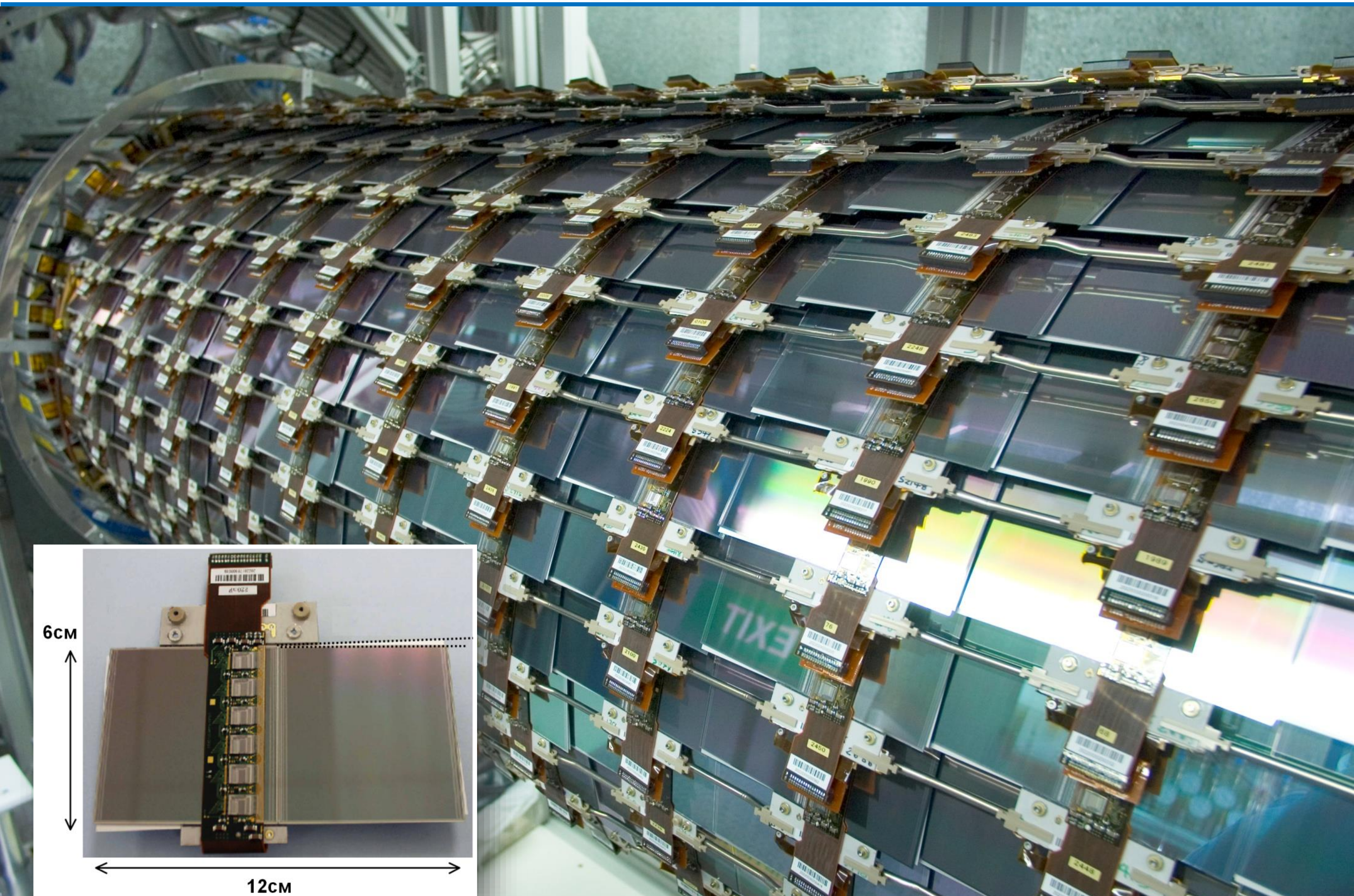
$m_H = 125.8 \pm 0.5 \pm 0.3$ GeV

$\mu = 0.91^{+0.30}_{-0.24}$

$m_H = 124.3 \pm 0.6 \pm 0.4$ GeV

$\mu = 1.5 \pm 0.4$ (at 125.5 GeV)

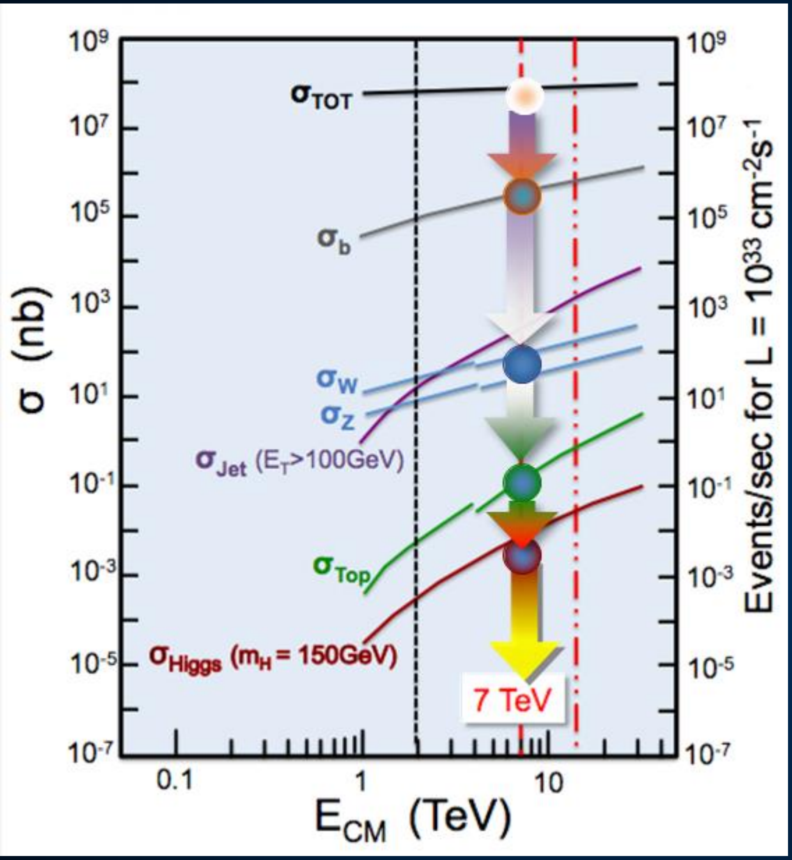
Central part of silicon detector ATLAS - made in Oxford



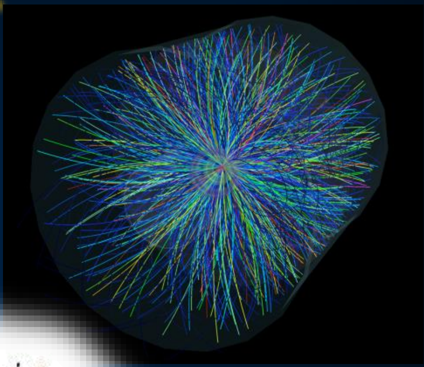
New physics

Higgs and Standard model do not explain everything
There must be new physics out there
Supersymmetry – one of possibilities

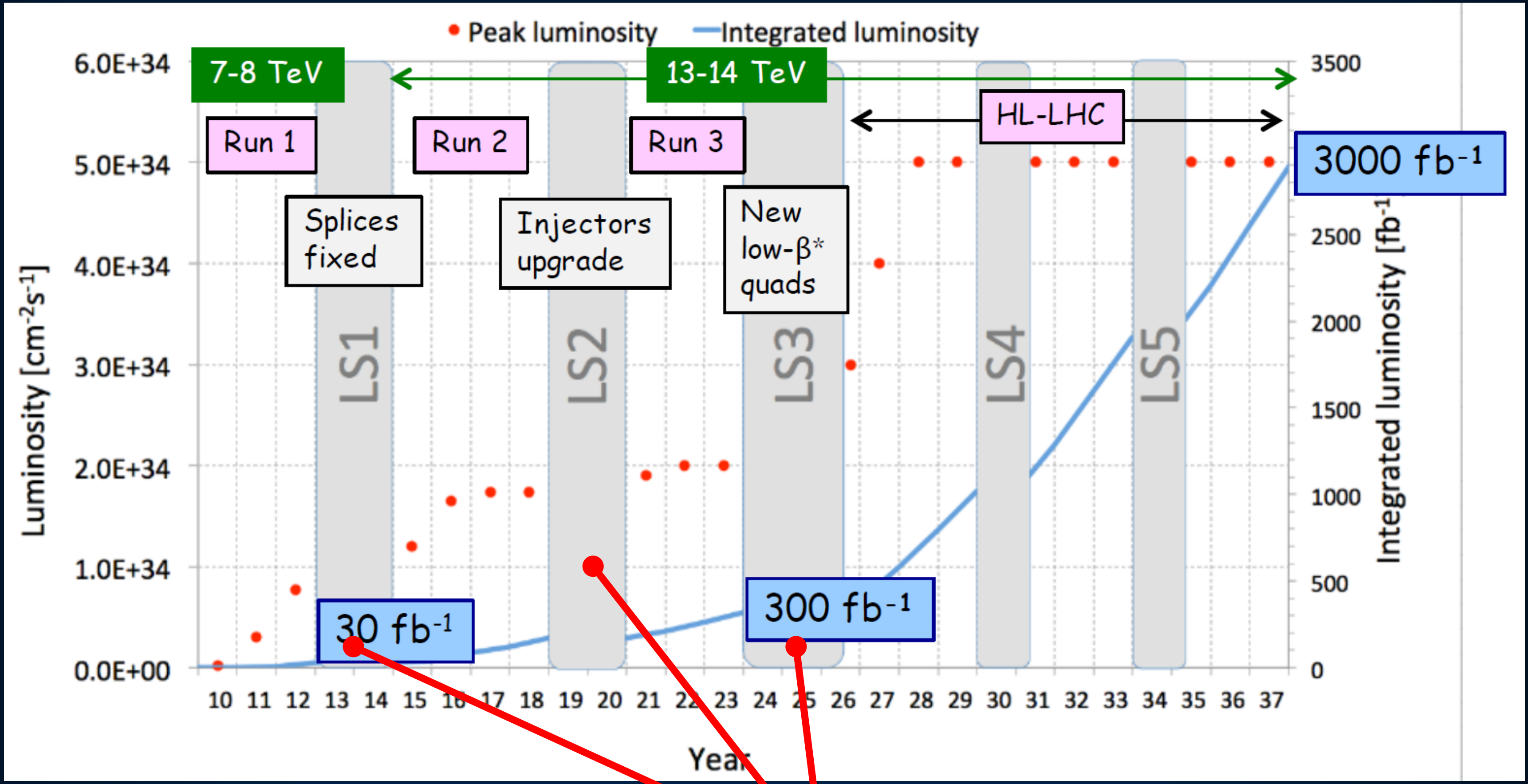
A needle in a haystack



10^{10}



LHC – next steps



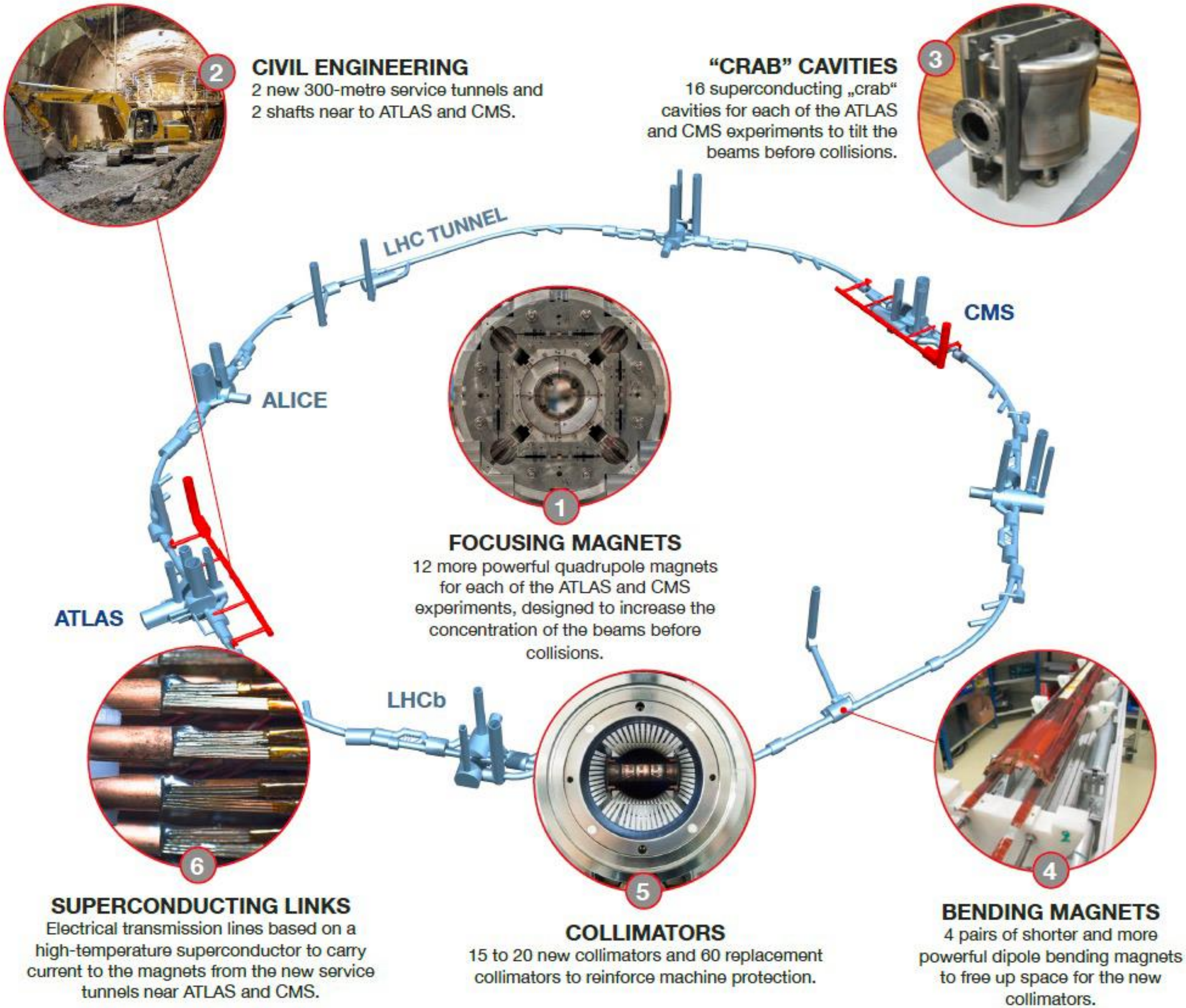
Storing the data

High Luminosity upgrade project

Much more data:

100 times more data in 2037!

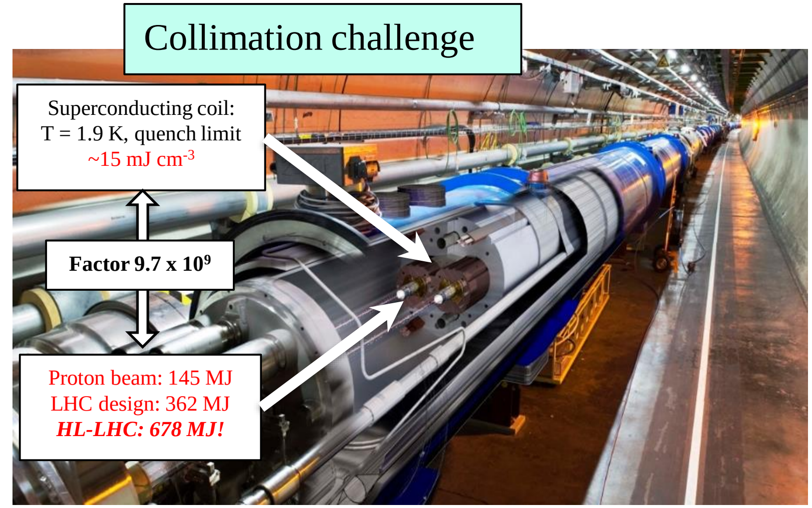
High Luminosity LHC project

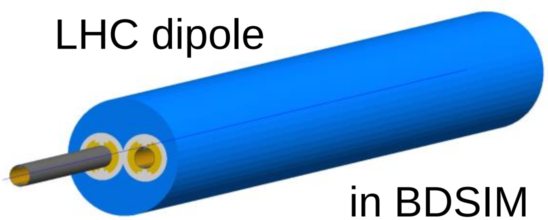


JAI contribution to High Luminosity LHC

Collimation challenge:

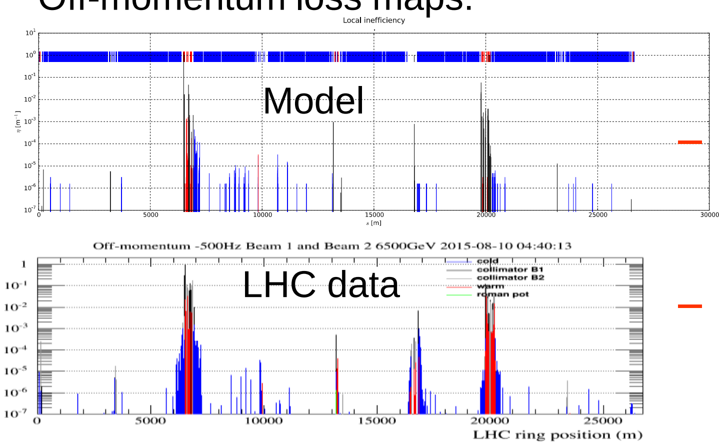
- **to efficiently clean the LHC beam, while…**
- **protecting cryogenic magnets from huge stored beam energy (doubles at HL-LHC!)**
- **mitigating beam backgrounds that reach the experiments!**

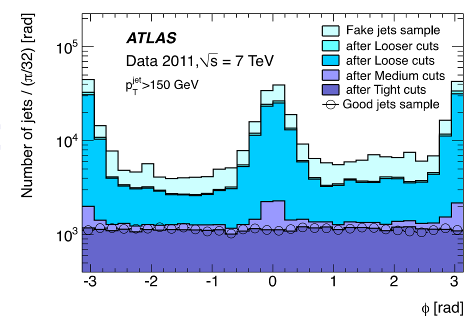


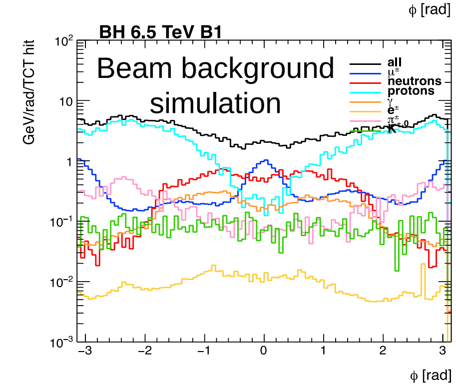


- JAI-RHUL experts already integrated in team at CERN. Main contributions:
  - **Off-momentum loss maps**: new model recently validated with energy deposition measurements at LHC.
  - **Advanced simulations of beam dynamics** to design the new triplet layout for HL-LHC.
  - RHUL-developed tool (BDSIM) to model **LHC beam backgrounds measured at ATLAS**.

Off-momentum loss maps:



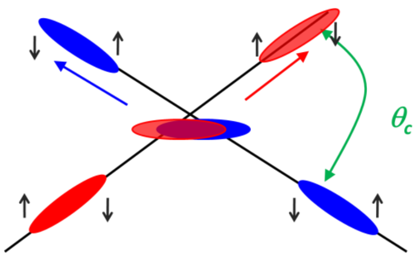


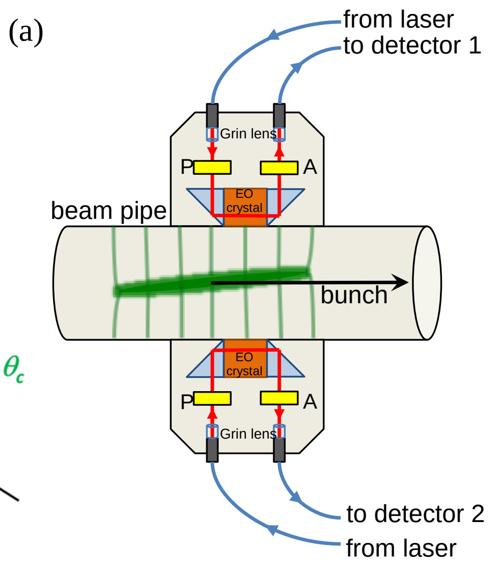


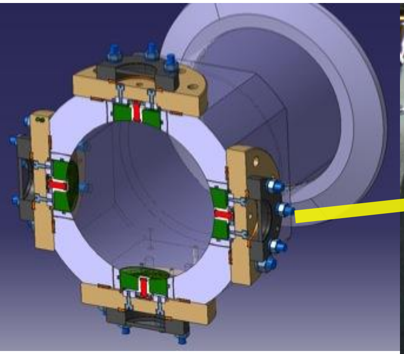
JAI for High Luminosity LHC

Diagnostics: Electro-optic Beam Position Monitors

- **HL-LHC crab cavities require new instrumentation to monitor bunch rotation and optimize performance.**
- **High bandwidth electro-optical pick-ups enable intra-bunch measurements of transverse position.**
- **JAI built prototype installed in 2016 at CERN SPS for proof of principle tests, in collaboration with CERN BI group.**

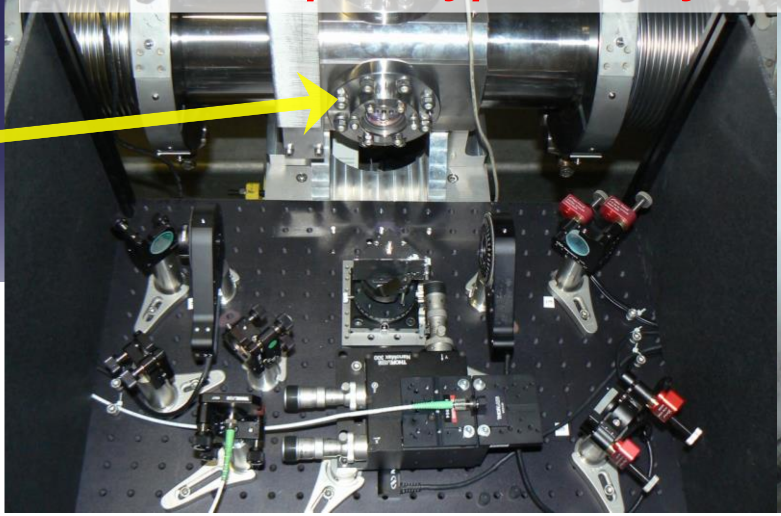


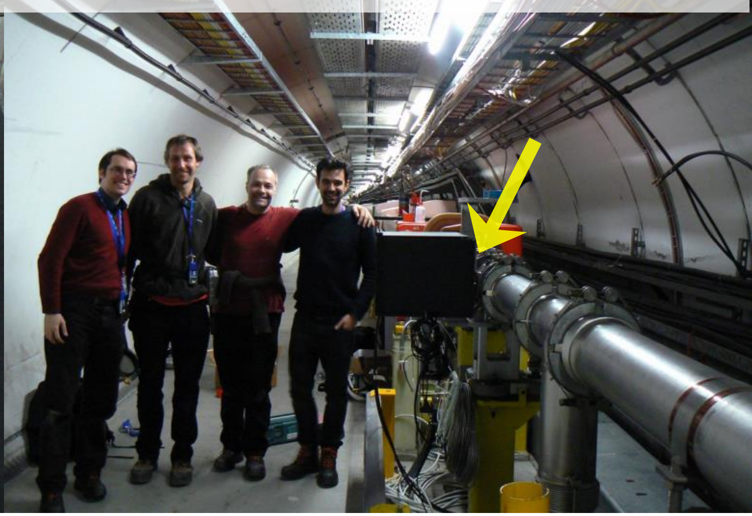




Second prototype planned for LHC, before deployment at HL-LHC

JAI built prototype already installed for tests at CERN SPS



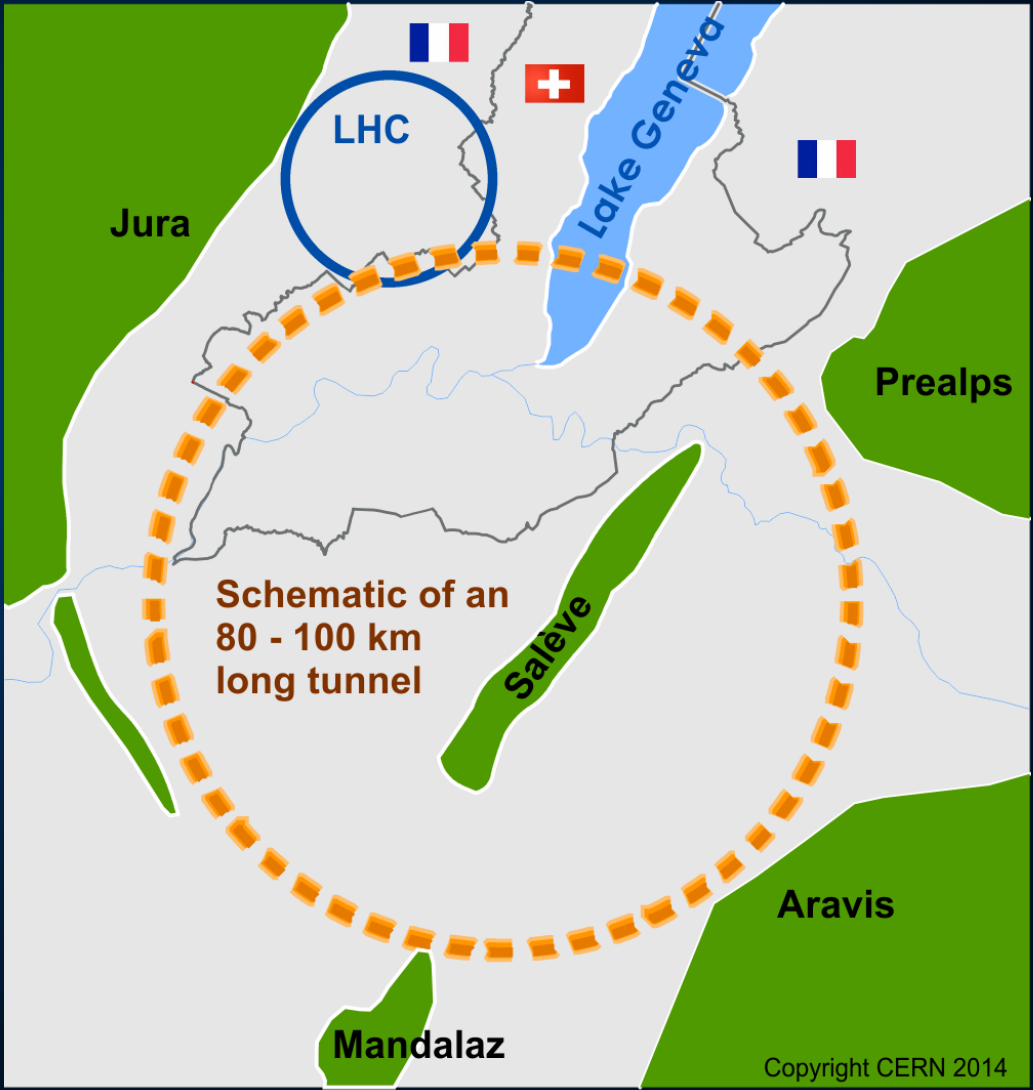


Circular Collider after LHC – FCC (CERN)

FCC = Future Circular Collider

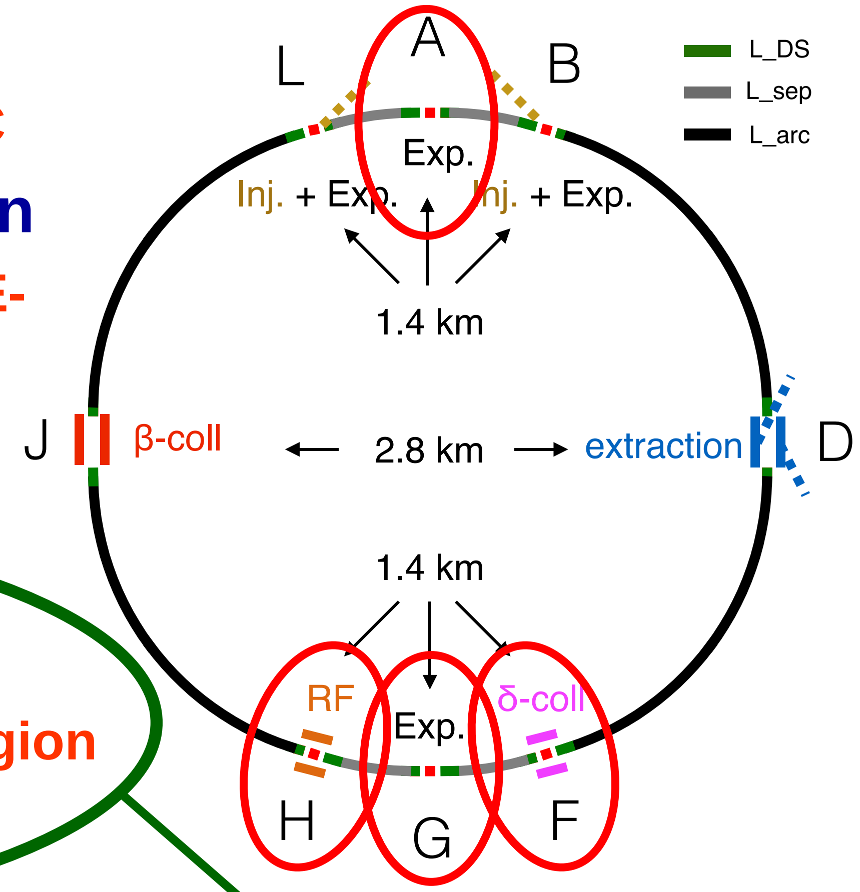
100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements *with possibility of e+-e- and p-e*

Preliminary parameters (FCC-hh):	
CM energy	100 TeV
Circumference	100 km
Dipole field	16 Tesla
Peak Lumi	5E34 $cm^{-2}s^{-1}$



WP4.3: FCC-hh and MDI

- **Future Circular Collider**
  - **Possible 100km successor of HLC**
- **Experimental Interaction Region**
  - **Critical areas defining FCC-hh (HE-LHC) performance**
- **Design tasks of EuroCirCol IR Work Package**
  - **Coordination**
    - **JAI/Oxford (lead), CERN, task 3.1**
  - **Development of the interaction region lattice**
    - **JAI/Oxford (lead), CERN, task 3.2**
  - **Design of machine detector interface**
    - **CI/Manchester (lead), INFN, CERN, task 3.3**
  - **Study of beam-beam interaction**
    - **EPFL (lead), CERN, task 3.4**

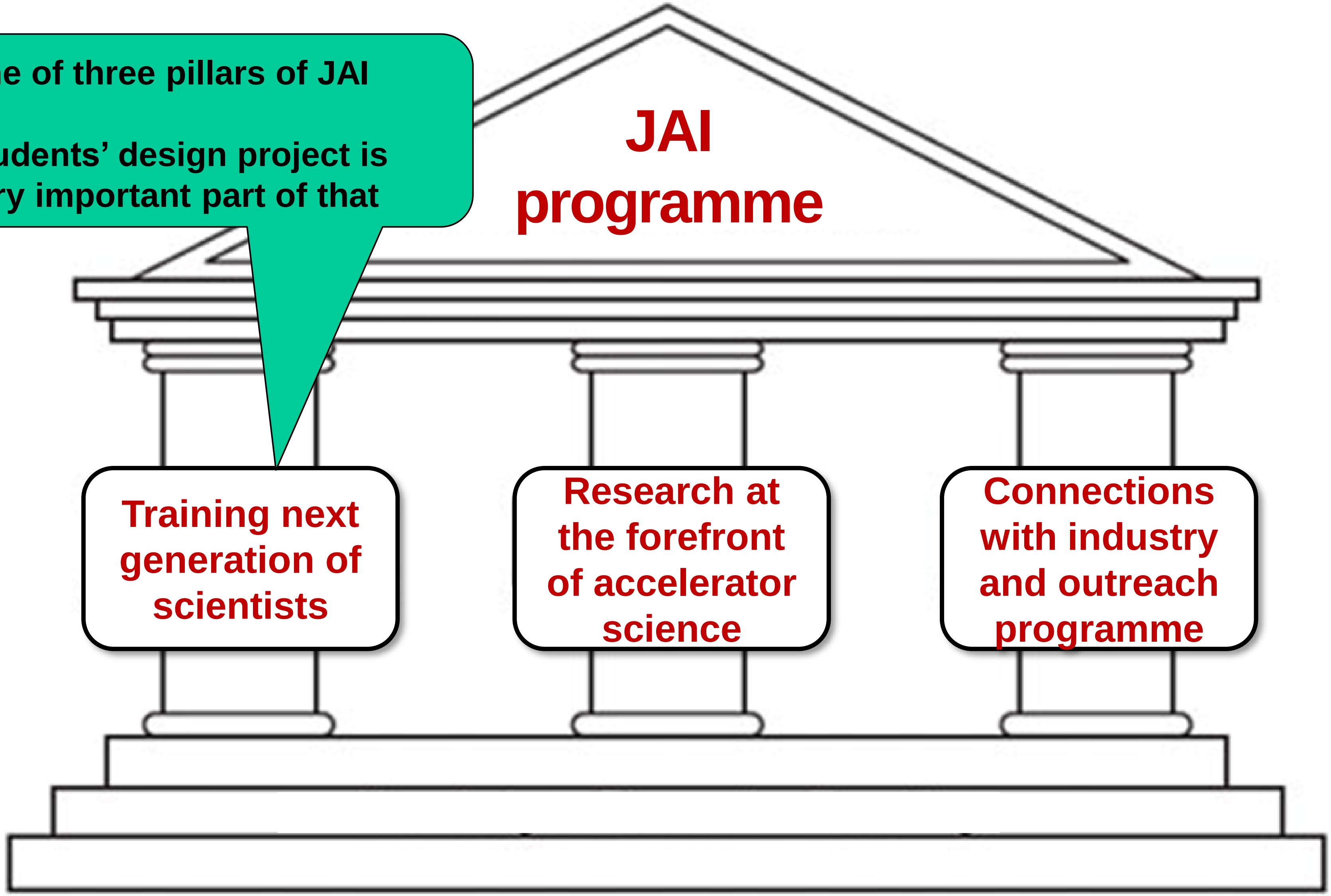


Responsibility of JAI

Foundation of JAI programme

One of three pillars of JAI

Students' design project is very important part of that



Research directions

We have different topics for design projects every year. E.g., last year we worked on compact ring laser-plasma light source and before that on FCC e+e-

2017 -2021

FEL and novel light sources

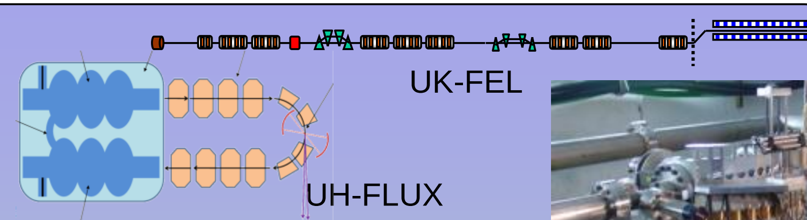
Plasma acceleration

Future colliders and particle physics facilities

Intense hadron beams

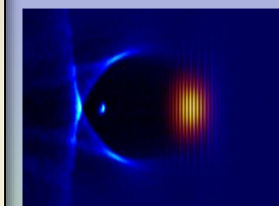
Training

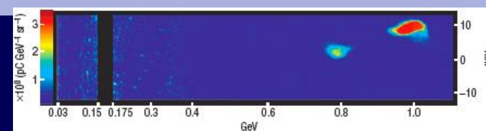
Diamond upgrade



UK-FEL

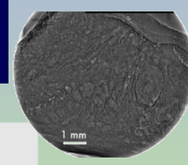
UH-FLUX

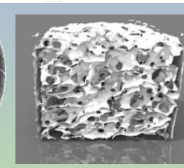


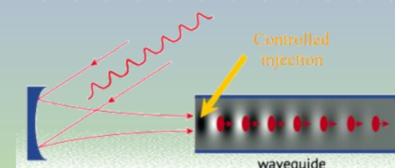


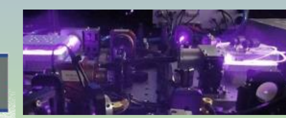
MP LWFA

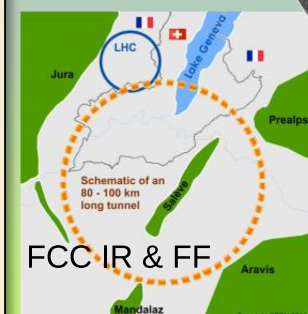
Beam diagnostics



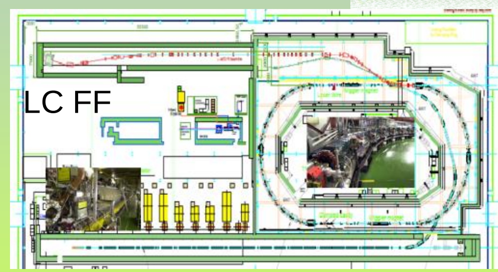




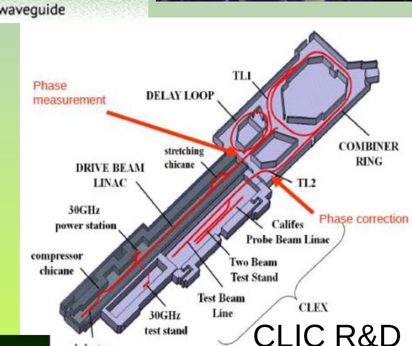




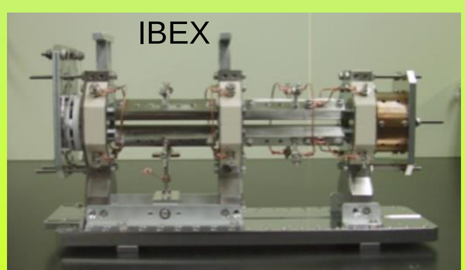
FCC IR & FF



LC FF



CLIC R&D



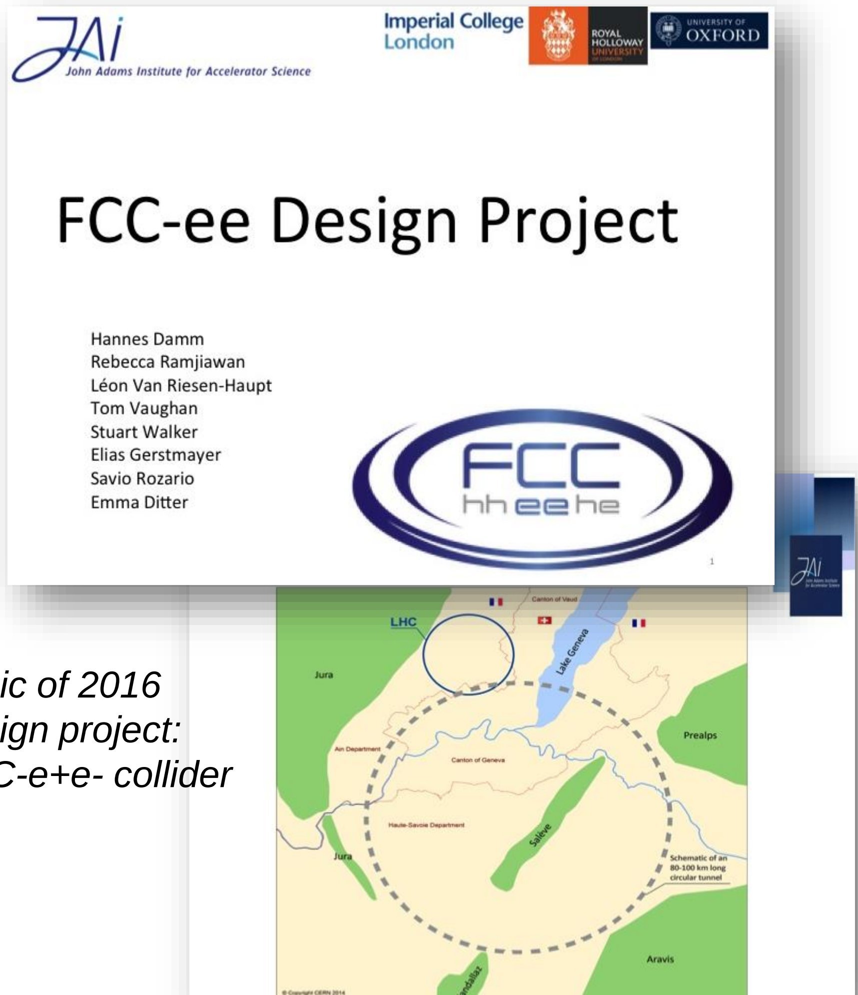
IBEX

AWAKE

Students' project steps (based on 2016 example)

1: work on design project (be inventive, suggest and implement some good ideas), write a report

2: present results to JAI staff
3: present to JAI Advisory Board
4: then to CERN colleagues



Topic of 2016 design project: FCC-e+e- collider

Presentation at CERN Council Chamber May 2016

Group Photo at CERN May 2016

HE-LHC

With thanks for slides to Michael Benedikt and Frank Zimmermann

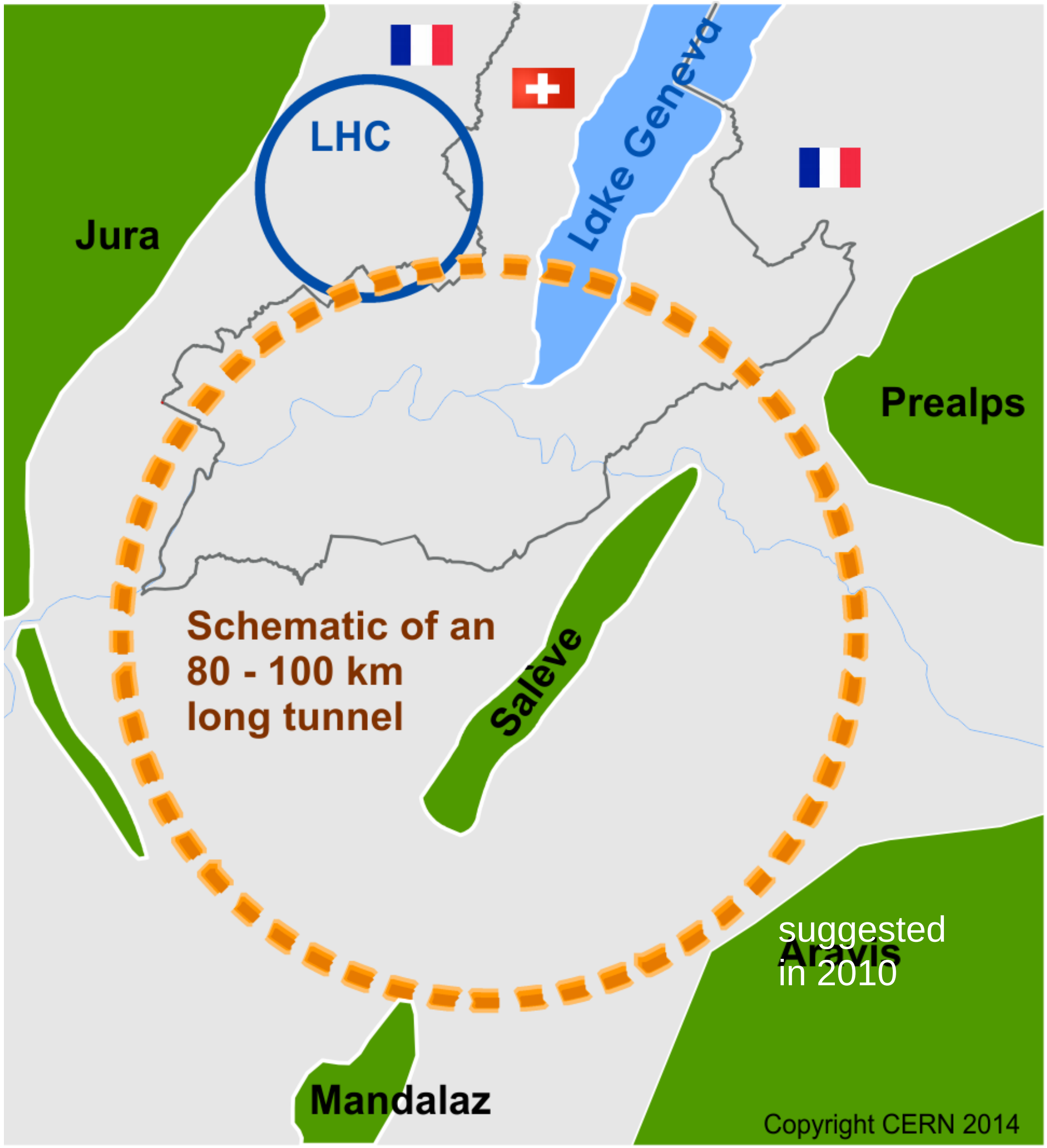
Future Circular Collider Study
CDR for European Strategy Update 2019/20

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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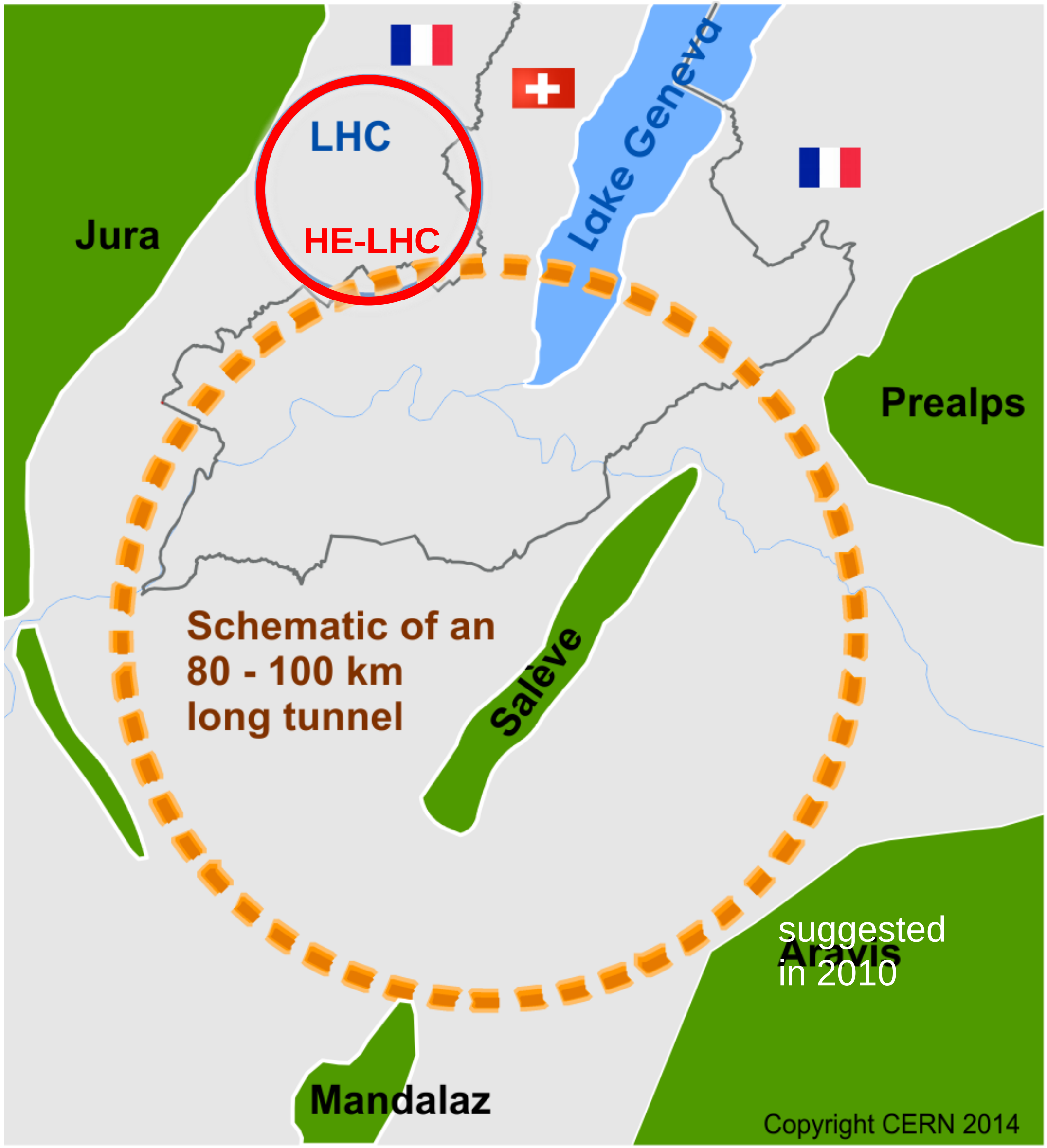


HE-LHC design goals & basic choices

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 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

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, β^* 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

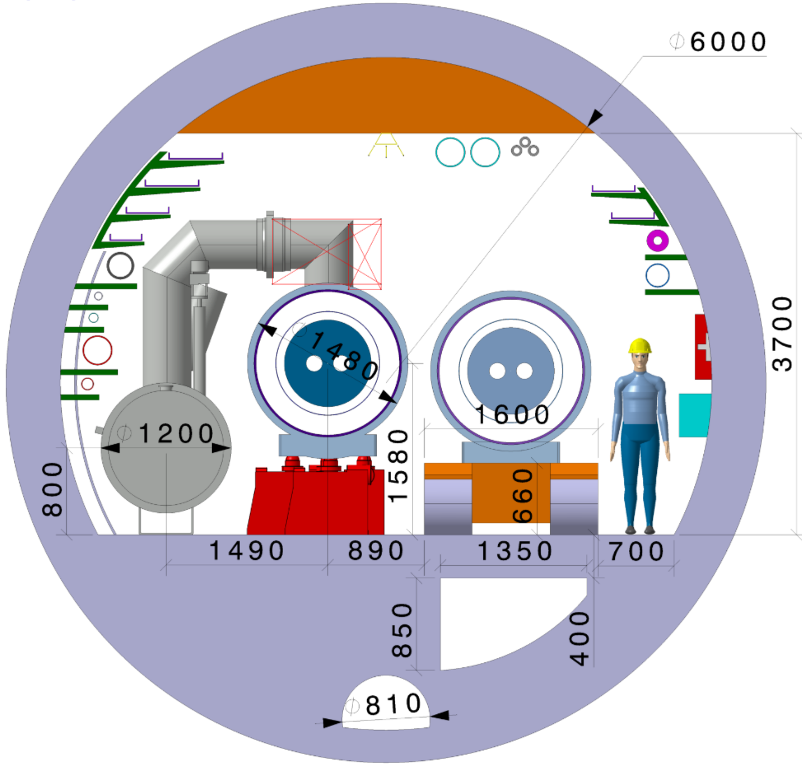
injector

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

tunnel integration

V. Mertens et al.

FCC-hh

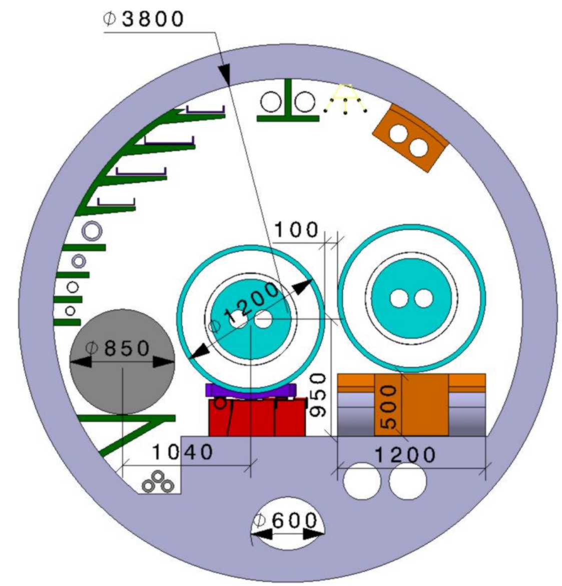


6 m inner tunnel diameter

main space allocation:

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

HE-LHC



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

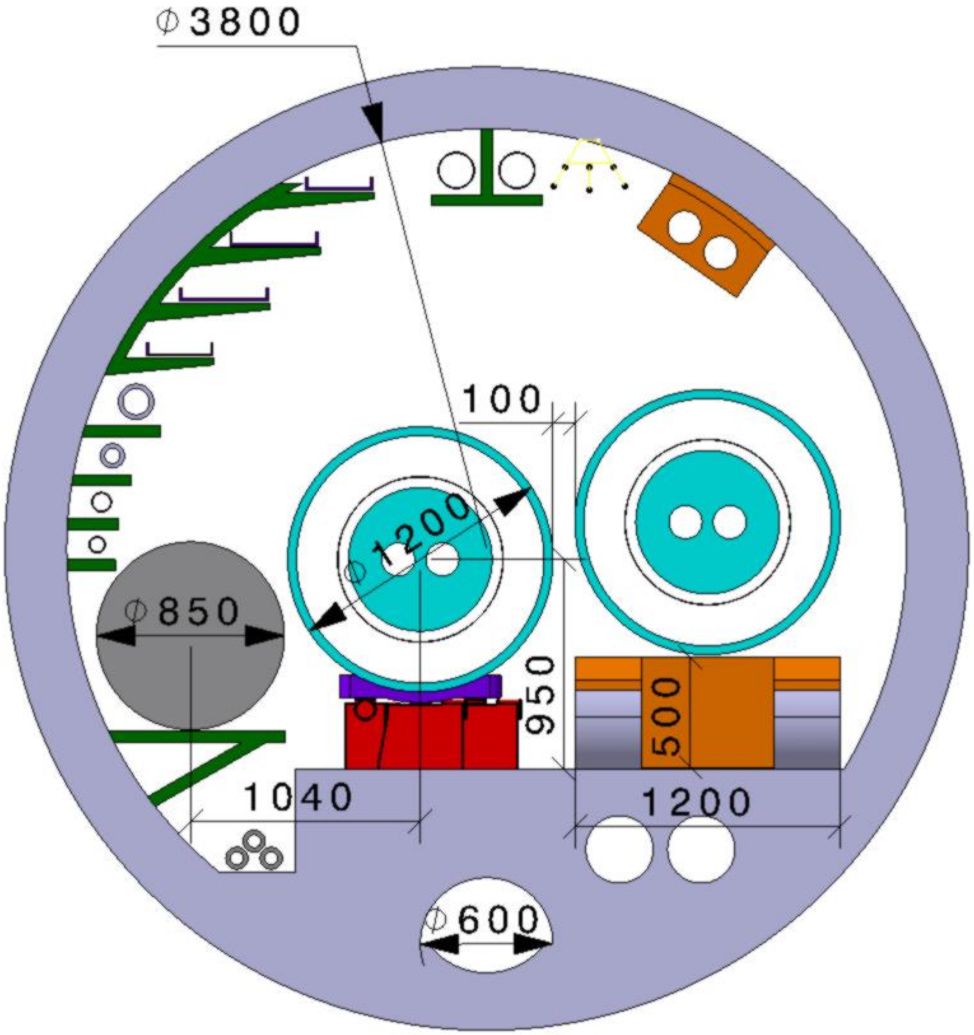
requirement: no major CE tunnel modifications

- 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 under 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



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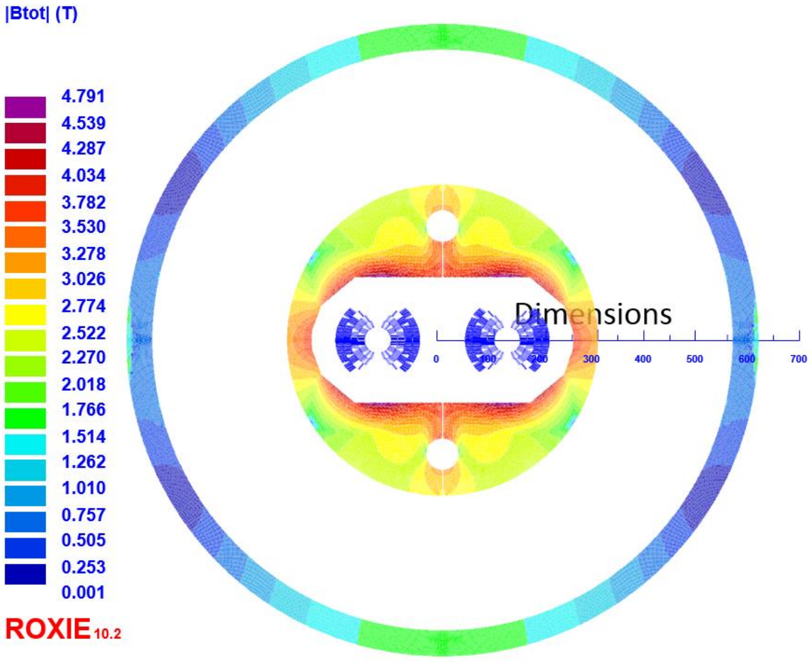
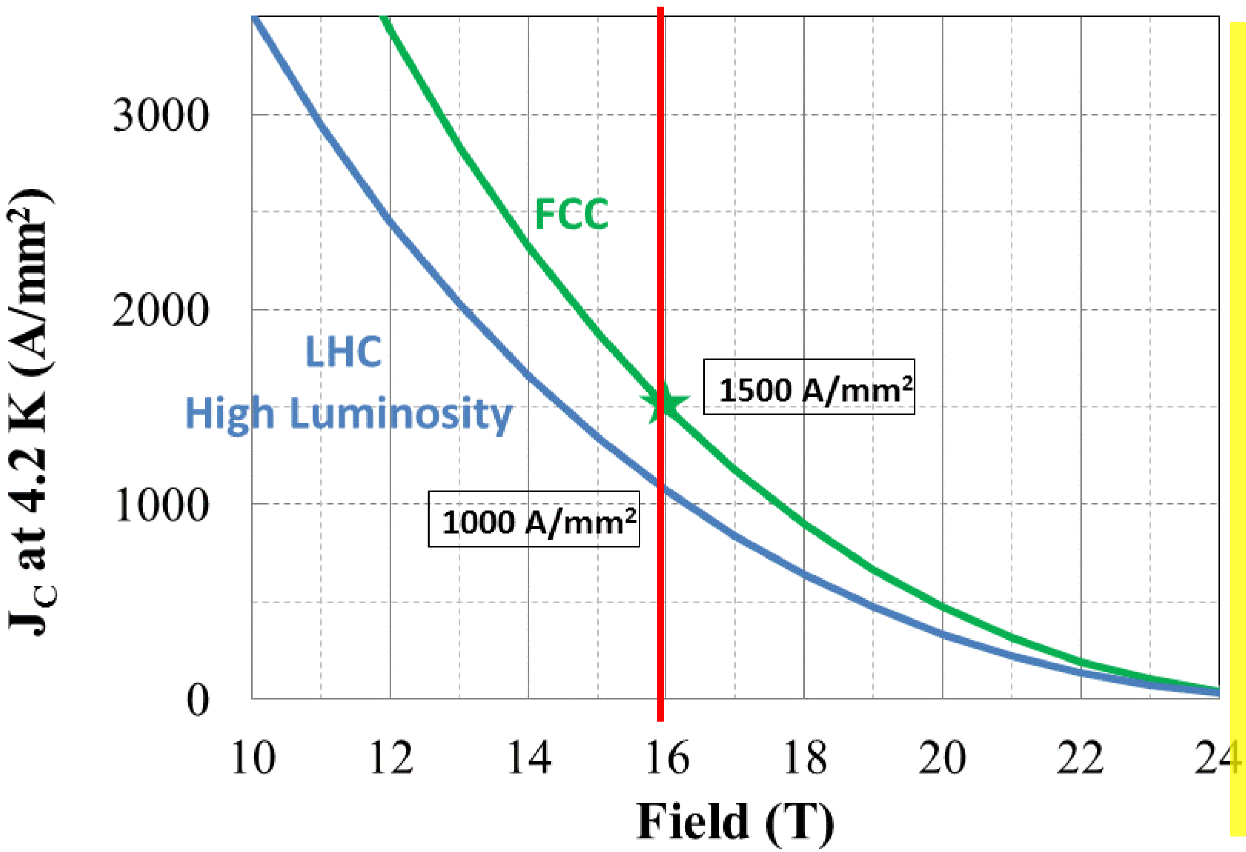
Example magnetic cryostat coldmass 40t, total mass 62t



Only magnetic elements shown

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**

FCC 16 T dipole design activities & options

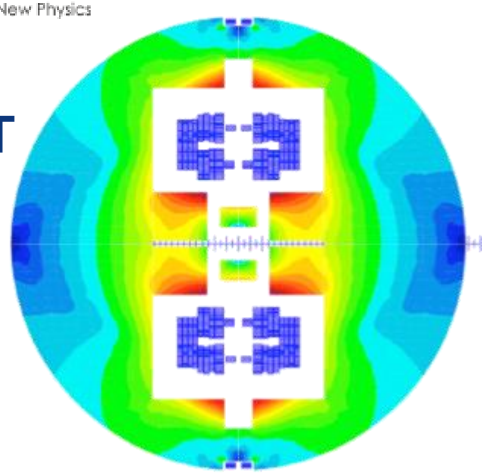
H2020 EuroCirCol

Common coils

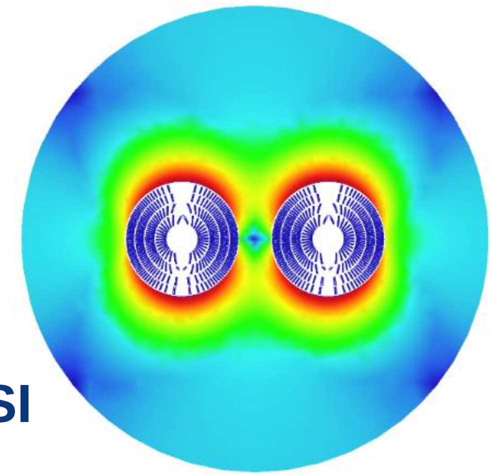
Swiss contribution

Cos-theta

CIEMAT



Canted Cos-theta



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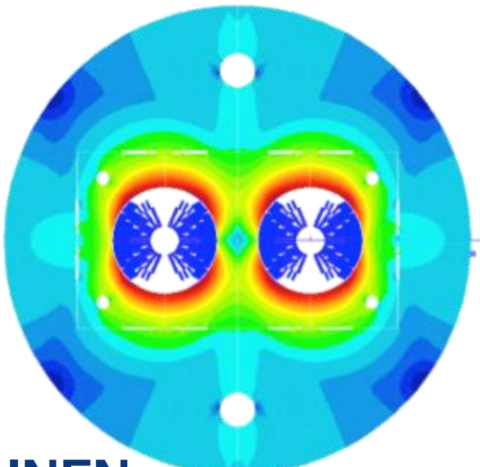
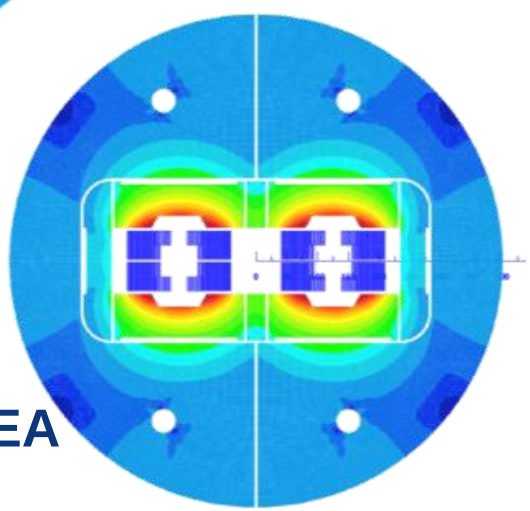
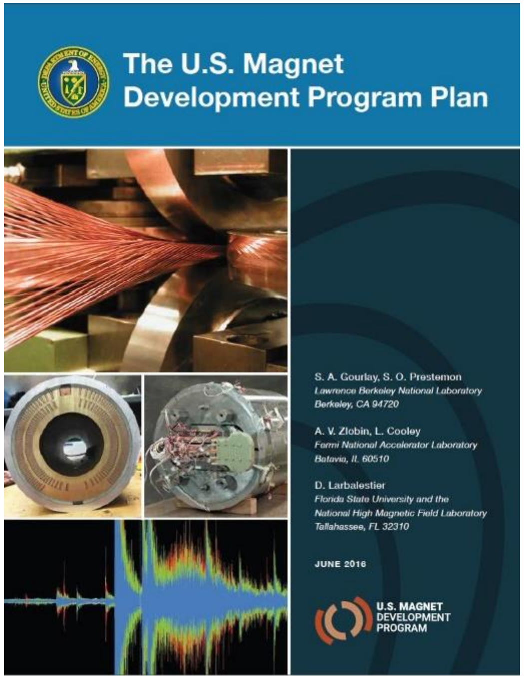


INFN

Blocks



CEA



The U.S. Magnet Development Program Plan

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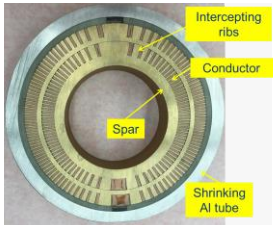
JUNE 2016

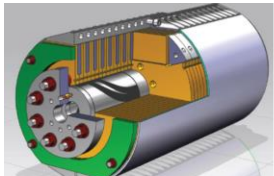
U.S. MAGNET DEVELOPMENT PROGRAM

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

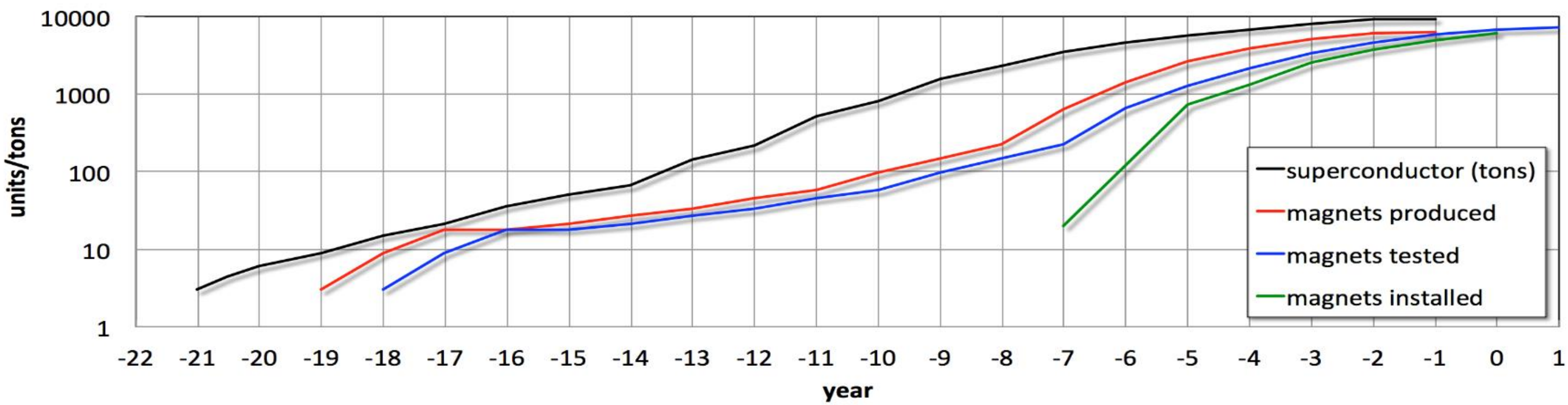
LBNL

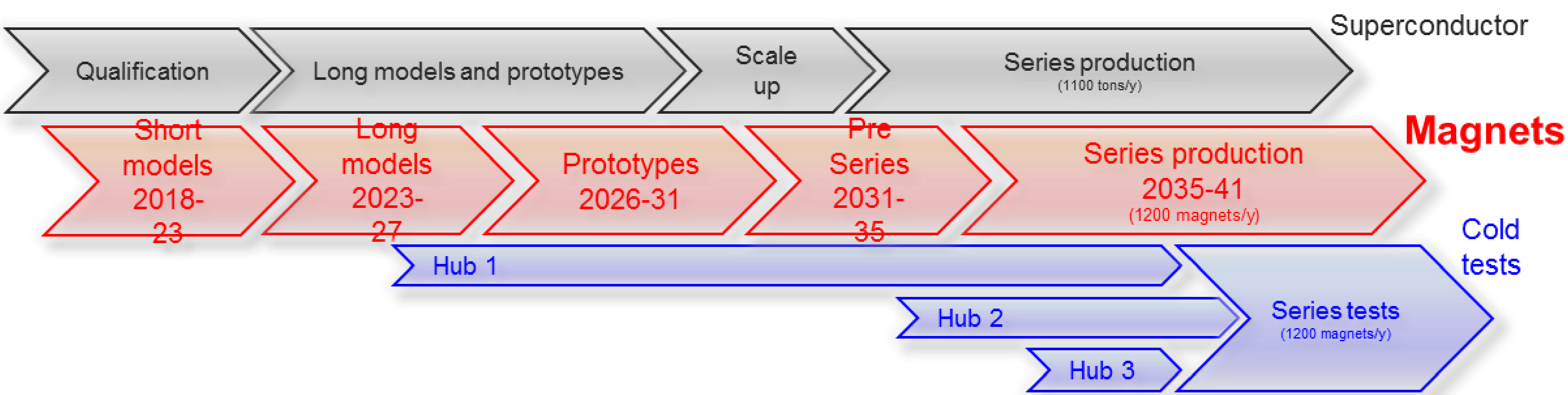


FNAL



FCC 16 T magnet R&D schedule

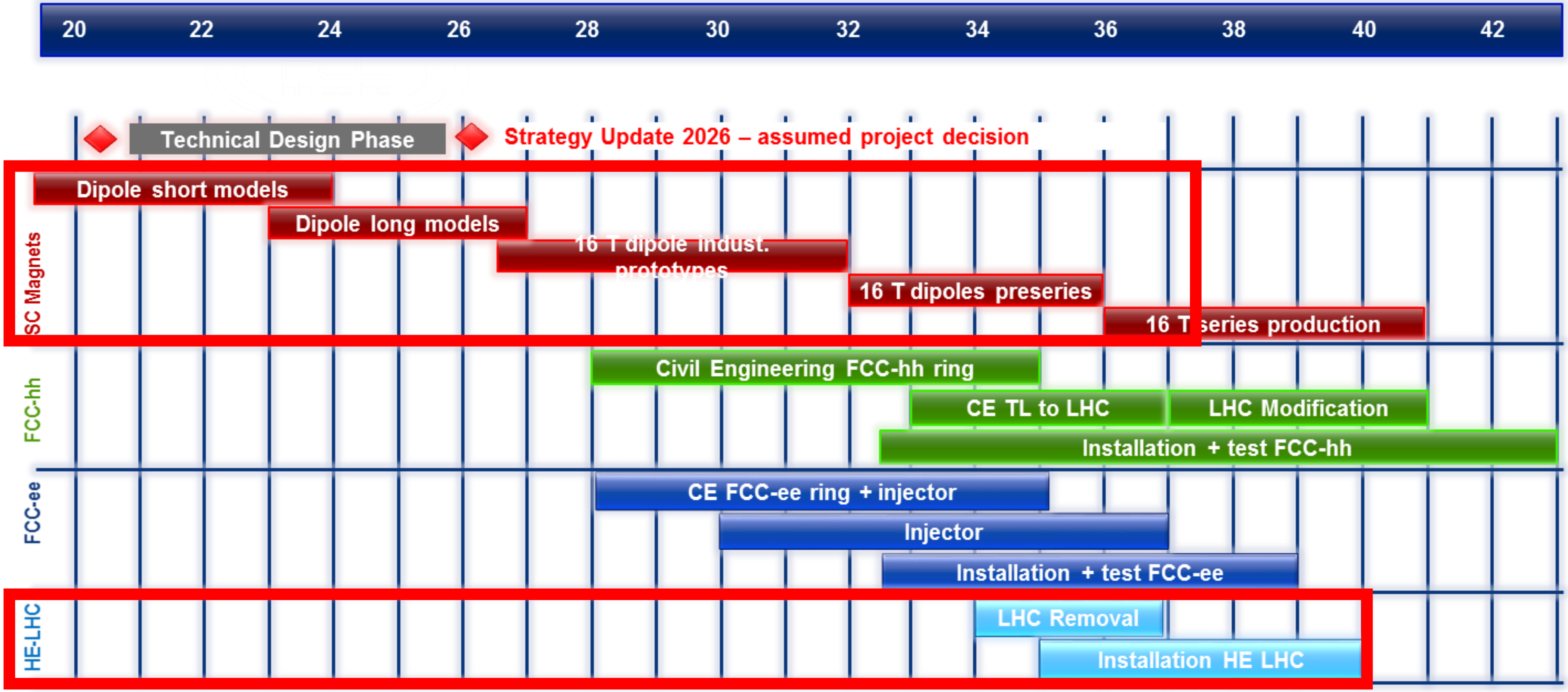




total duration of magnet program: ~20 years

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 (=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

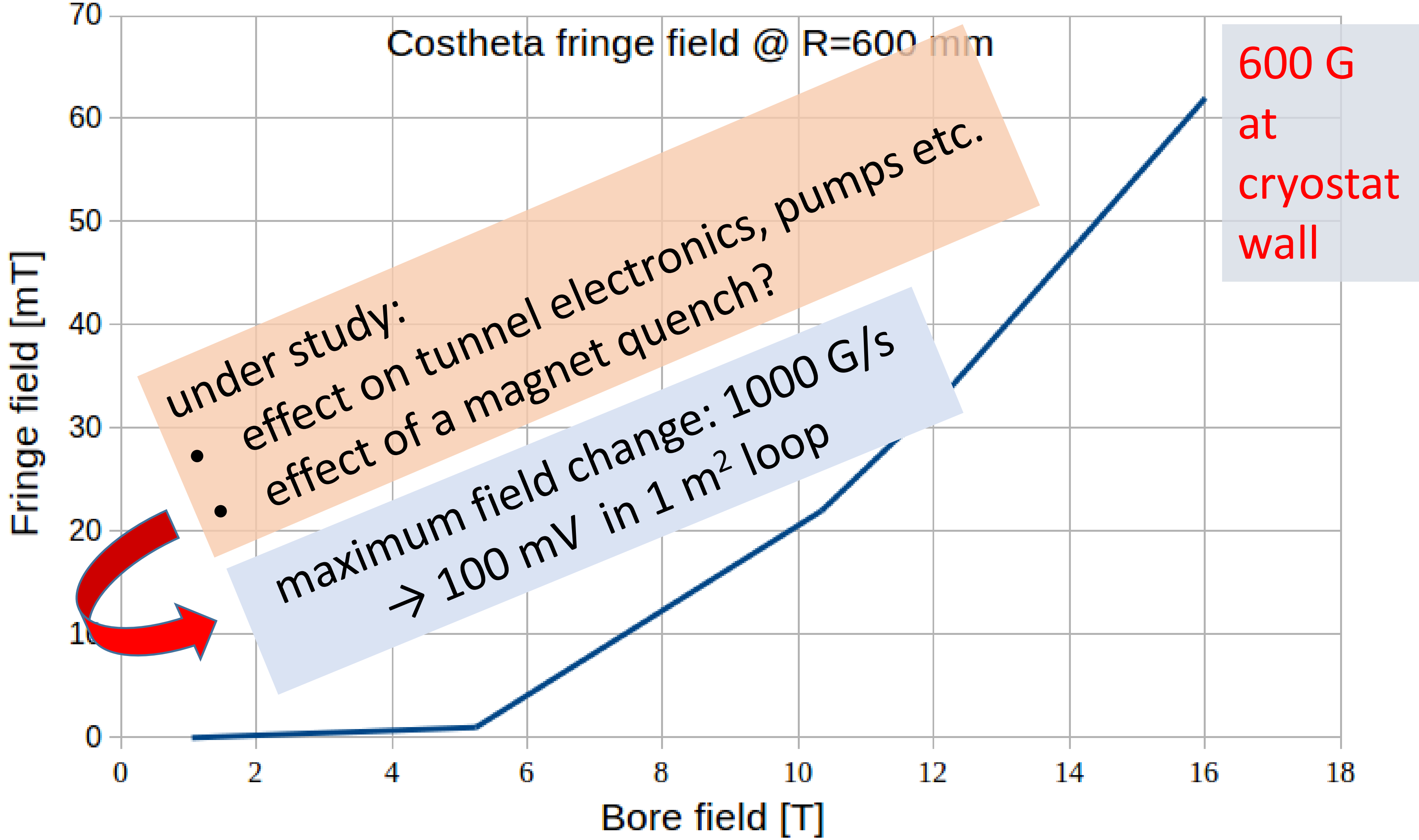
compact 16 T magnet (=1200 mm)

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

	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	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



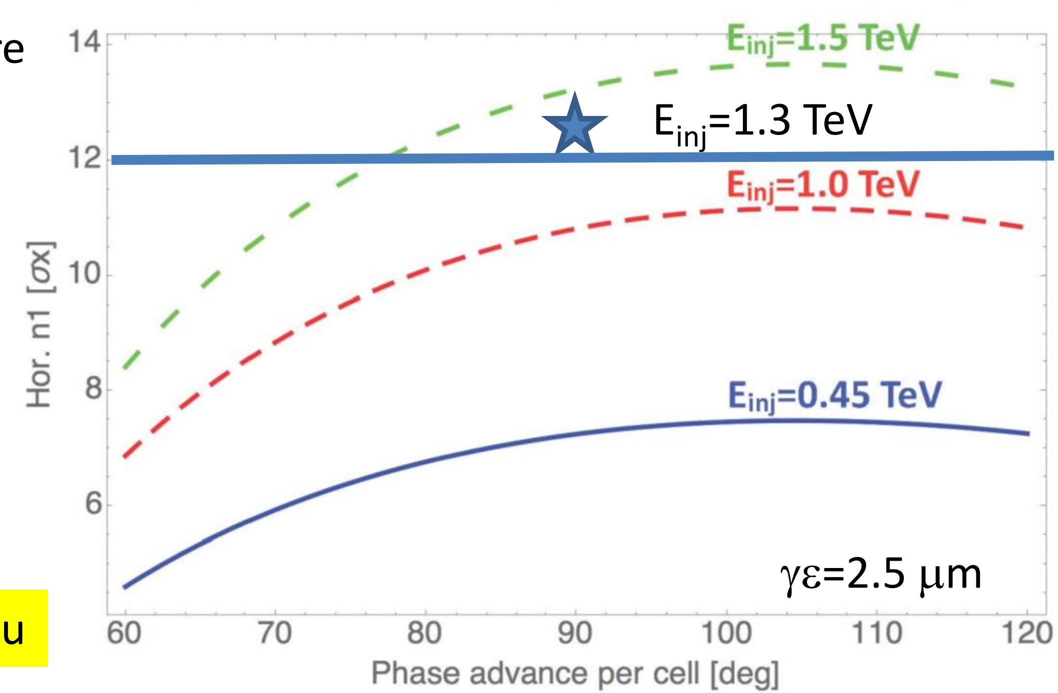
1st HE-LHC optics release V0.1

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

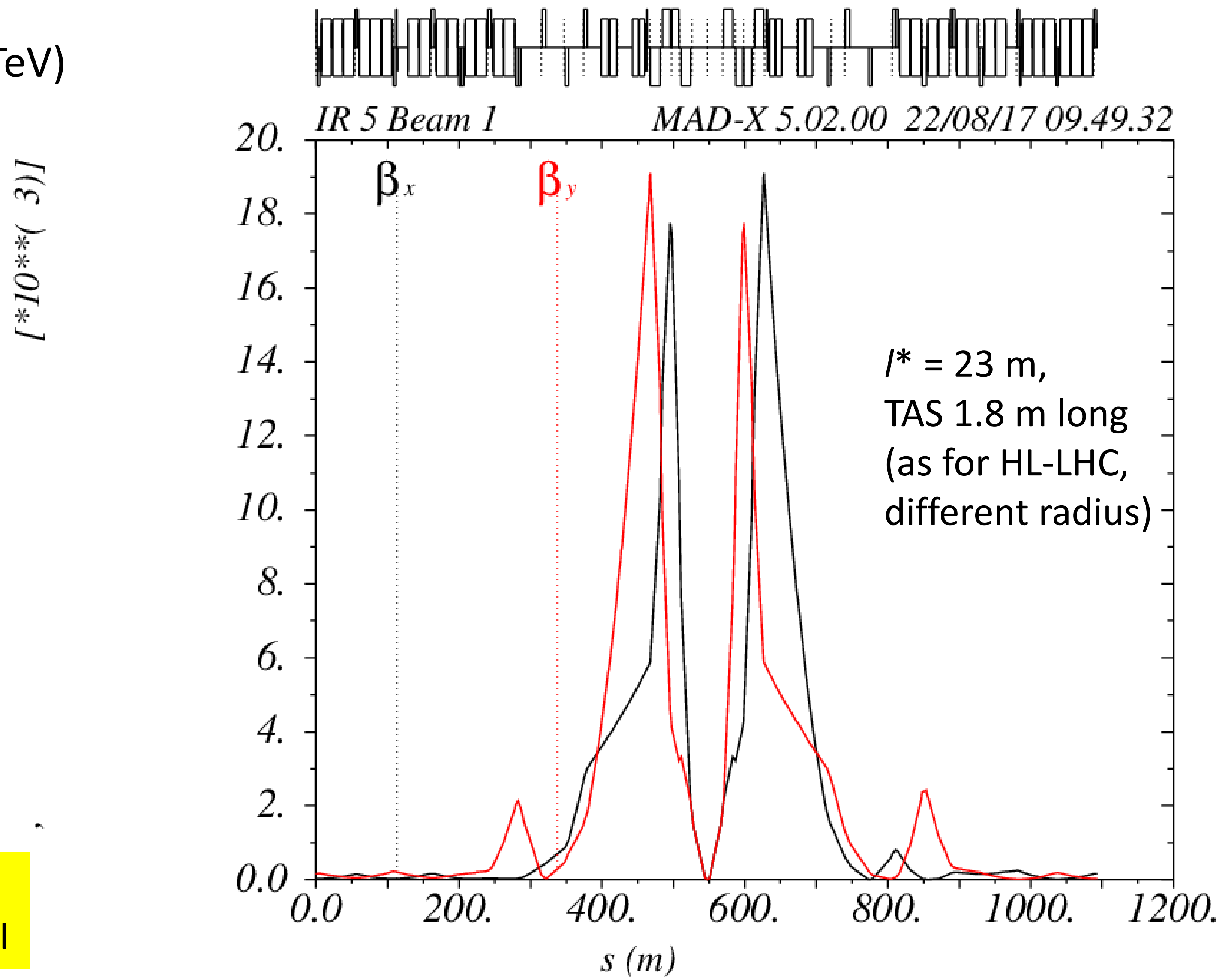
LHC: 30.4 m

ca. 11 m space
for crab cavities

injection optics
with β*=11 m
(n1 >12 σ)

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

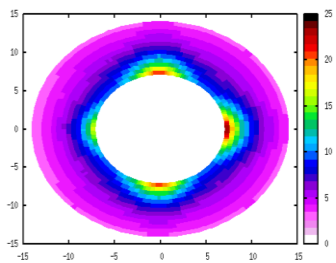
collision optics with β*=0.25 m

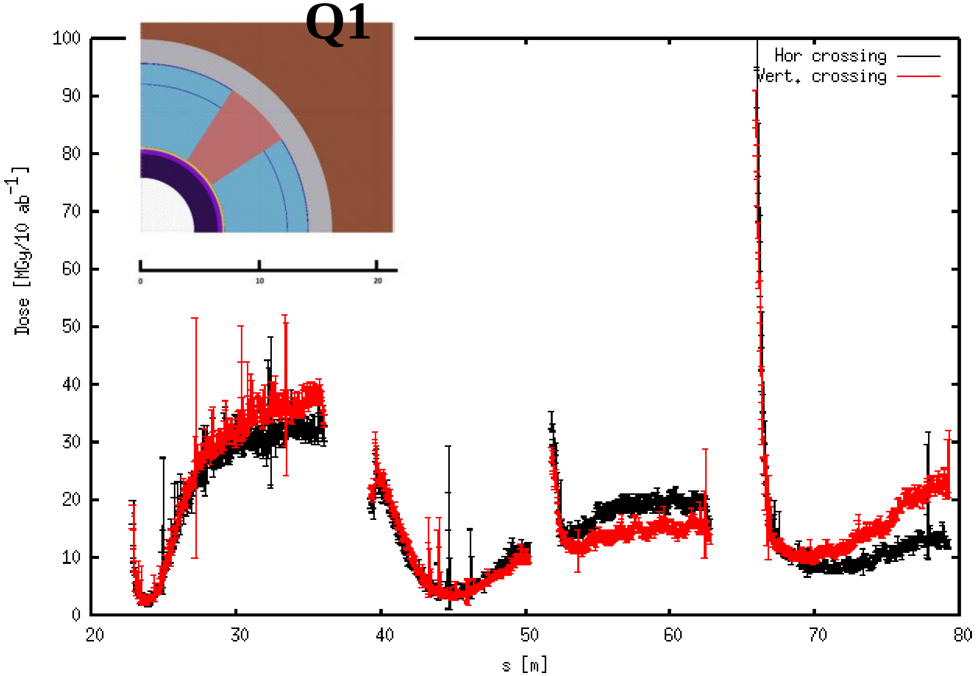


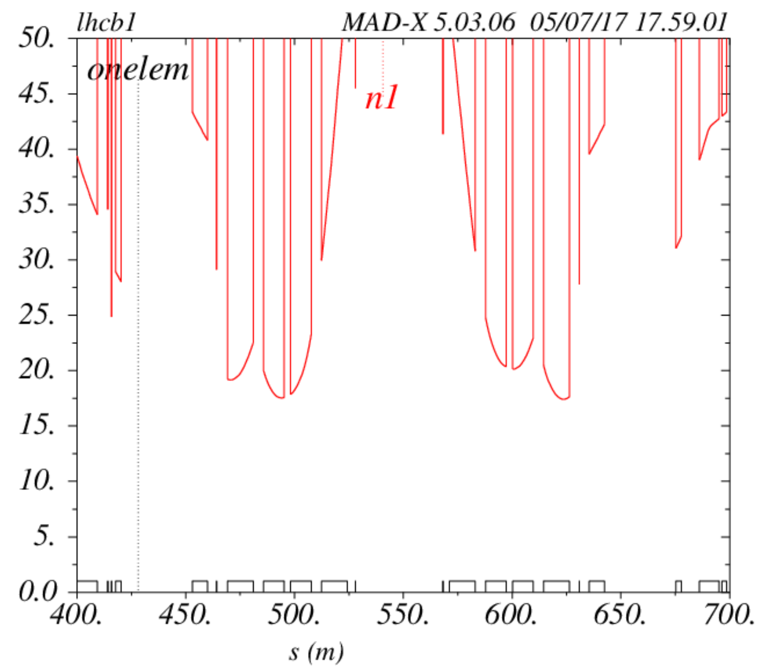
final triplet shielding & aperture

- triplet quadrupoles with 2 cm inside W shielding
- β* = 25 cm
- > 12.5σ stay clear with crossing angle (140μrad)
- for 10ab-1 total luminosity: 30-50 MGy peak radiation

(peak at Q3 can be reduced with shield in front)

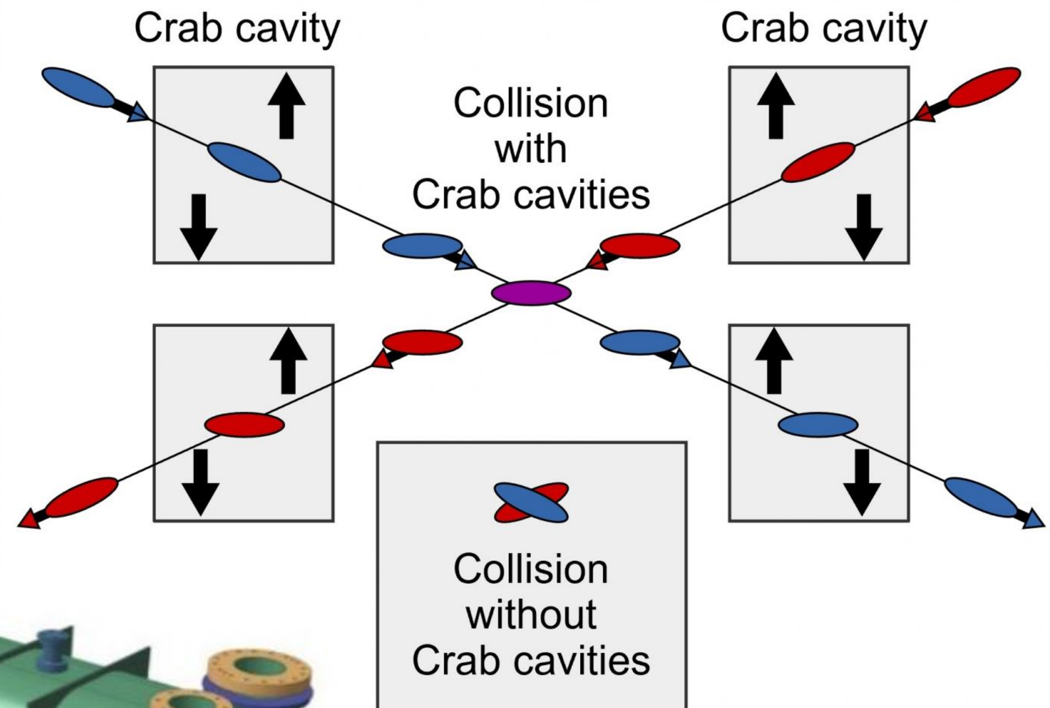






L. van Riesen-Haupt, J. Abelleira, Oxford JAI

Crab cavities (HL-LHC)



Double Quarter Wave (DQW) and RF Dipole (RFD) cavities built for test at SPS

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

HE-LHC students' project plan

- **Optics studies**
  - Work on various IRs or integration or study various arc options
- **Magnet design**
  - Very large stray fields at the moment – optimize this
  - Could also look into HTS instead of Nb3Sn
- **Energy deposition studies**
  - In IR or collimation areas
  - Simulations with FLUKA code
- **RF system or crab Cavities**
  - Design RF system
  - Or design cavities that fit in the space and produce the right kick

Conceptual Design Report

1 – PHYSICS

Physics opportunities across all scenarios

2 Hadron Collider Summary

3 – Hadron Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experimen t
- eh

4 Lepton Collider Summary

5 – Lepton Collider Comprehensive
- Accelerator
- Injectors
- Technologies
- Infrastructure
- Operation
- Experiment

6 High Energy LHC Summary

7 – High Energy LHC Comprehensive
- Accelerator
- Injectors
- Infrastructure

Refs to FCC-hh, HL-LHC, LHeC

CDR is required for end 2018, as input for European Strategy Update

HE-LHC students' design project is not only of academic interest but is being viewed as some contribution and input to the HE-LHC Conceptual Design Report to be completed in 2018

Results of HE-LHC students' design project may be submitted as a poster to FCC-Week conference