HiLumi
HL-LHC PROJECT

UPPSALA
UNIVERSITET

FREIA

High Luminosity Large Hadron Collider

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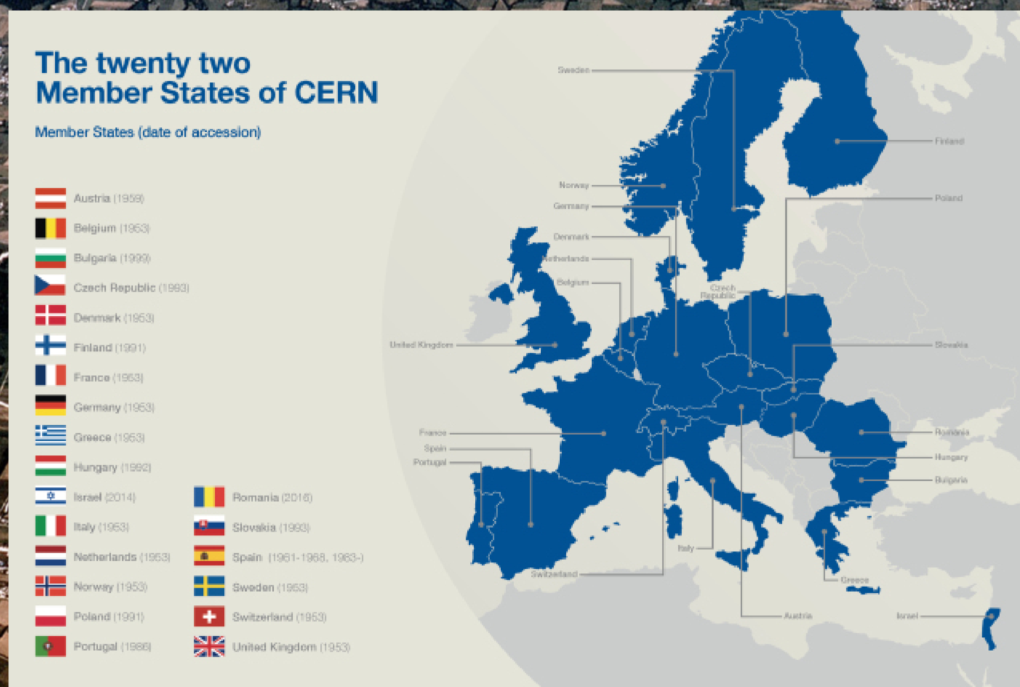
FREIA Project Meeting - 26 September 2016

CERN

European Organization for Nuclear Research

- Founded in 1954, today 22 Member States
- About 11’000 users from all over the world
- ~ 1100 MCHF annual budget
- 2250 staff members + 1000 associates + 1000 external services



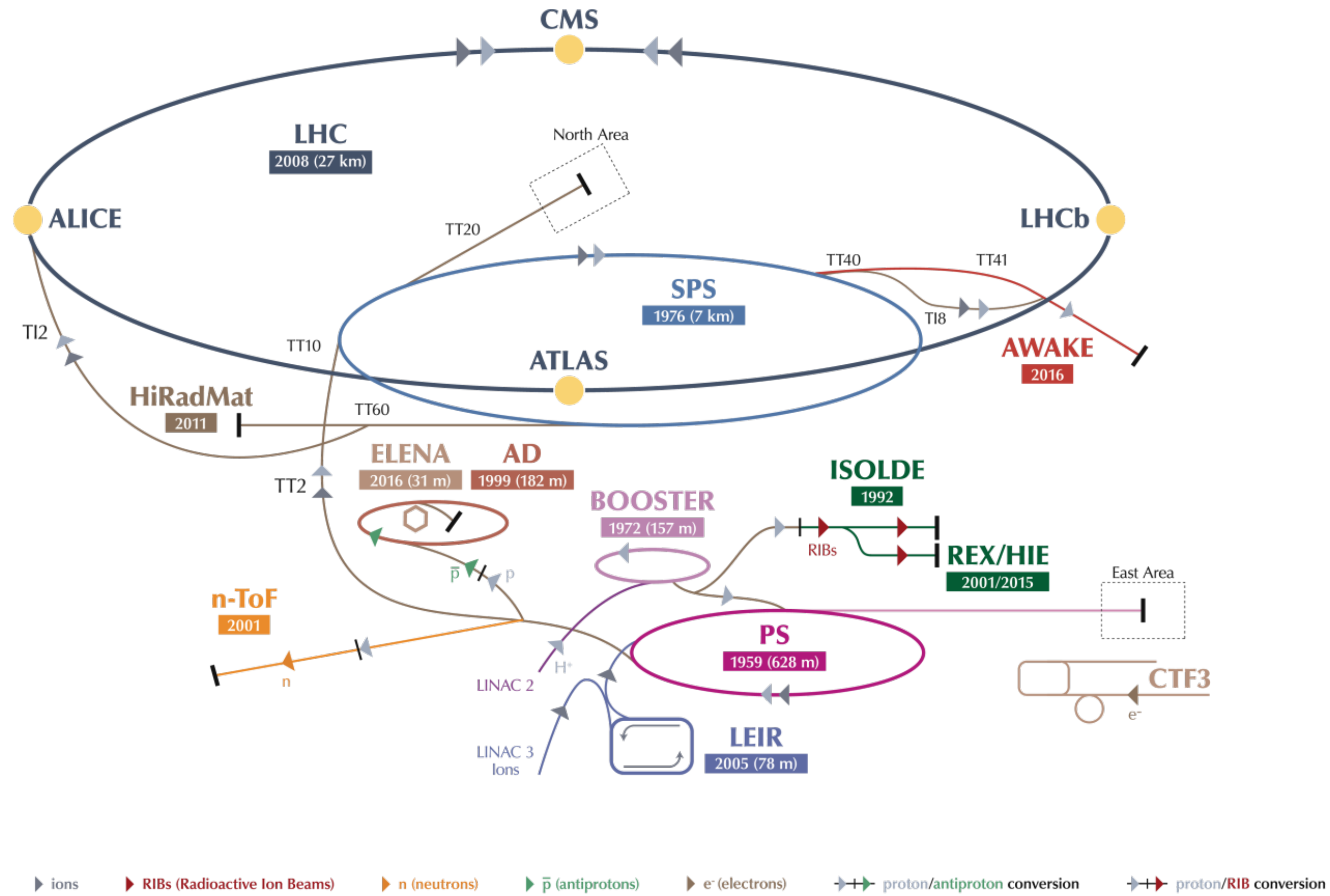
CERN's Mission

- Research & Discovery
  - to push forward the frontiers of knowledge
  - E.g. the secrets of the Big Bang … what was the matter like within the first moments of the Universe's existence?
- Technology
  - R&D, application and transfer
  - E.g. new technologies for accelerators and detectors; Information technology - the Web and the GRID; Medicine - diagnosis and therapy
- Training
  - scientists and engineers of tomorrow
- Collaborating
  - Unite people from different countries and cultures

CERN Physics Research Program

- ISOLDE and REX-HIE: 'Online' separation of isotopes
  - to study special radioactive nuclei; possible to post-accelerate
- AD: antiproton decelerator
  - provide 'cold' antiprotons to make and trap anti-hydrogen; then do spectroscopy
- n-TOF: low energy 'spallation' neutrons
  - dump high intensity proton beam in lead target and use low energy 'spallation' neutrons (kinetic energy measured by 'time of flight') for high precision measurements of nuclear reactions
- Extracted PS beam:
  - also used for other 'fixed target' experiment measuring the lifetime of $\pi^+\pi^-$ 'atoms'
- Extracted SPS beam:
  - used to create polarized μ beam for deep inelastic scattering experiment (COMPASS)
- LHC: high energy proton-proton and proton-ion collissions
  - to study elementary particles, fields and their interactions; experimental exploration of the Terascale

CERN Accelerator Complex

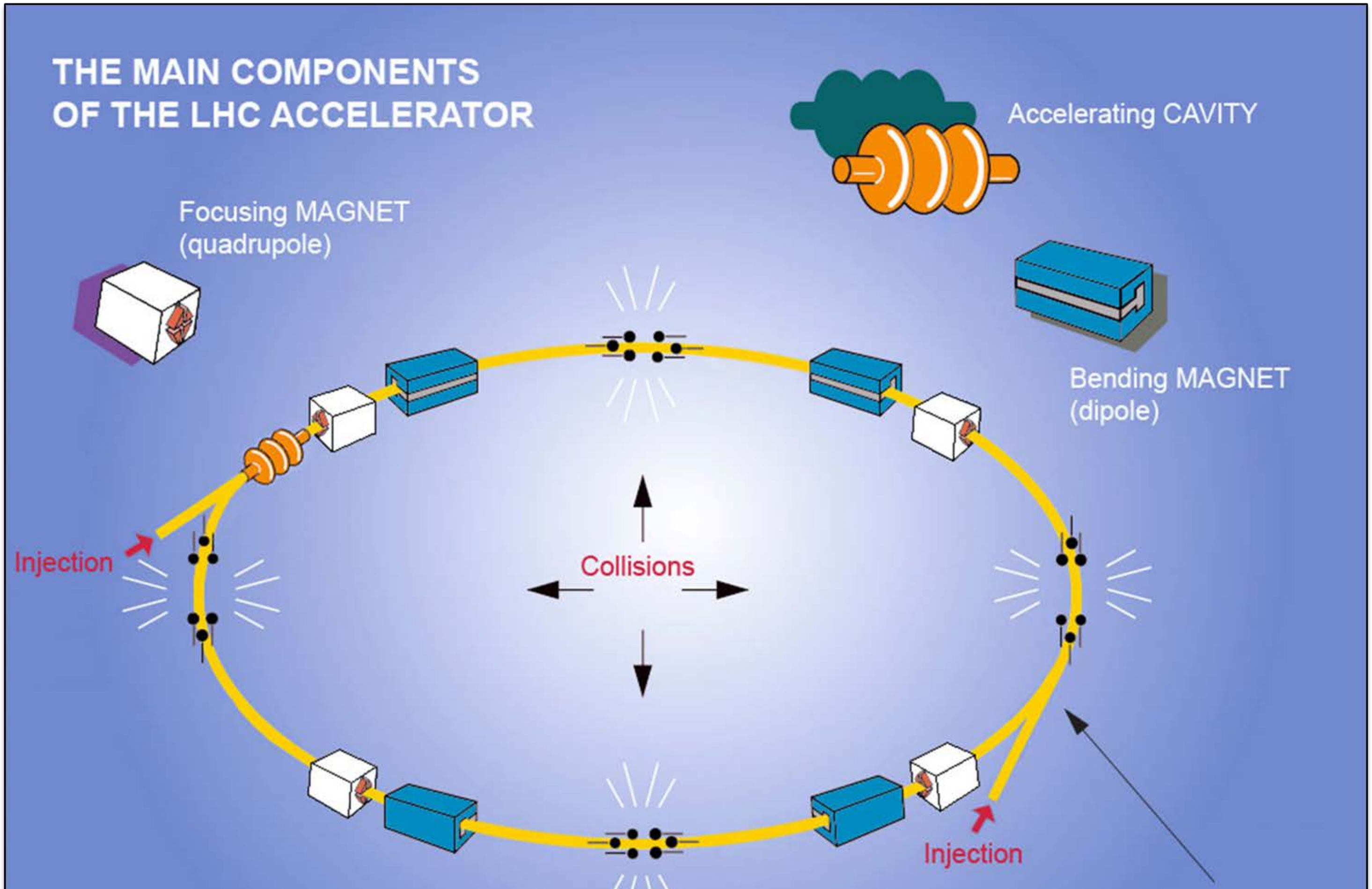


LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

Large Hadron Collider



- 27 km, p-p at 7+7 TeV
  - 3.5+3.5 in 2008, 4+4 in 2012, 6.5+6.5 TeV in 2015

LHC Dipoles

Twin Superconducting Dipoles

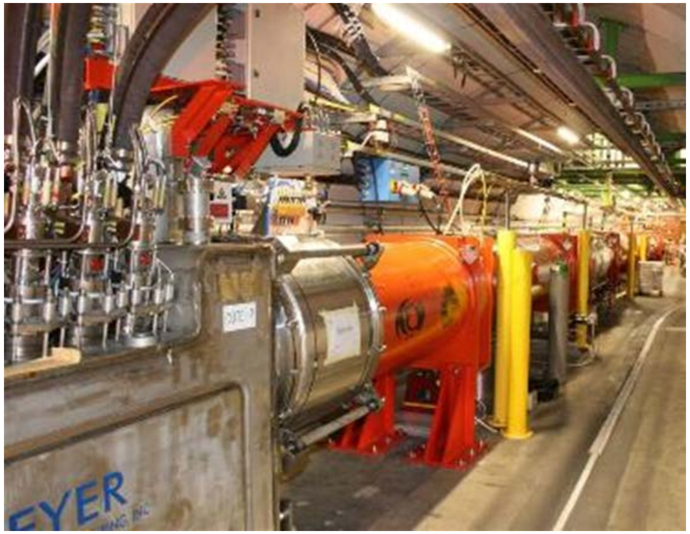
- 1232 x 15 m Twin Dipoles
- Operational field 8.3 T @11.85 kA (9 T design)
- HEII cooling at 1.9 K
  - 3 km circuits
  - 130 tonnes He inventory
- Field homogeneity of 10-4
  - bending strength uniformity better then 10-3.
  - field quality control (geometric and SC effects) at 10-5.

Dipole line in the ring

Quadrupole And Other Magnets

- 392 Main Quads
  - Two-In-One rated for a peak field of 7 T.
- About 100 other Two-in-One MQs
- 32 MQX (low-β) single bore
  - for luminosity design $L=1\cdot10^{34}\ cm^{-2}s^{-1}$,
  - 70 mm apertures, about 8 T peak field
- A «zoo» of 7600 «small» Sc magnets
  - correctors and higher order magnets

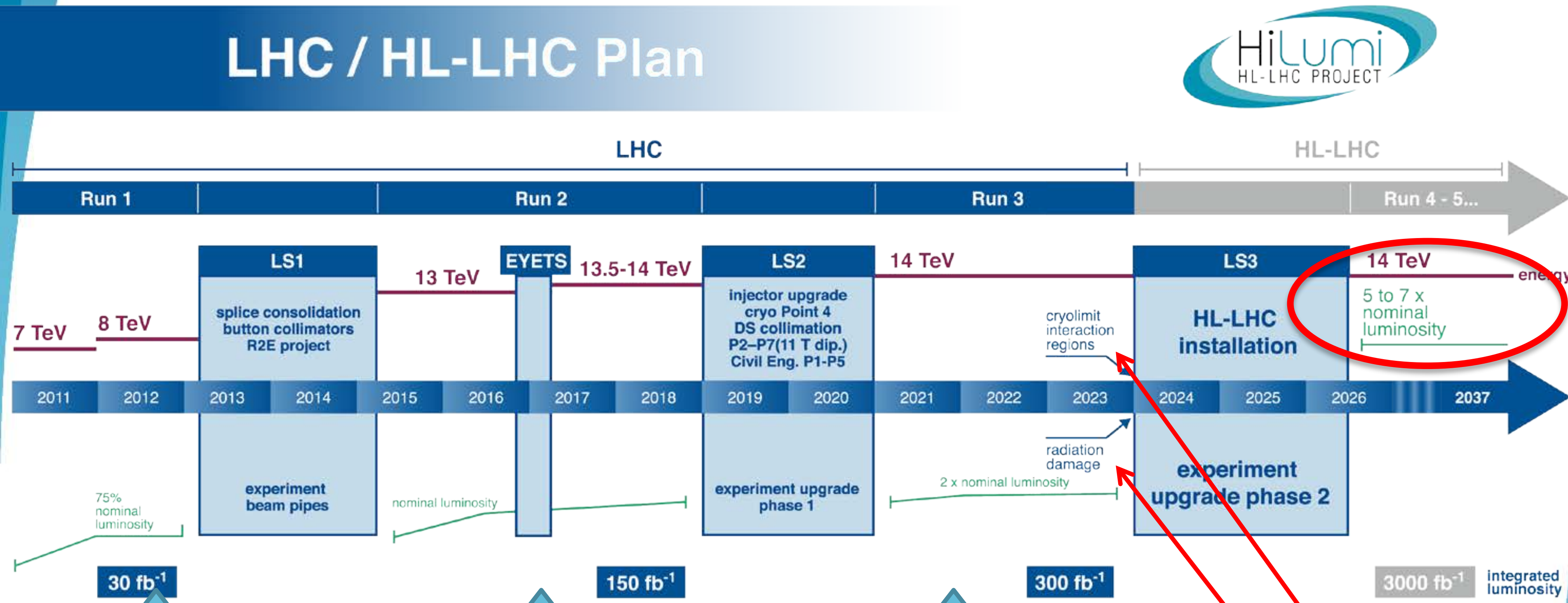
- Large detector magnets
  - ATLAS toroid – 25 m long (1.2 GJ)
  - CMS solenoid – 12 m long (2.5 GJ)



Radio Frequency Acceleration

- 400 MHz standing wave RF
- Nominal gradient 5.5 MV/m
  - nominal 2MV per cavity
  - up to 3 MV at 8 MV/m
- Single cell cavities
  - 16 cavities total,
  - 4 cavities per cryomodule,
  - 2 cryomodules per beam.
- Sputtered niobium design (like LEP)

Why Upgrading LHC



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

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

1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pile up ~60

Technical limits to lumi increase (Machine & Experiments)

50 ⇒ 25 ns

HiLumi HL-LHC PROJECT FREIA

High Luminosity LHC Project

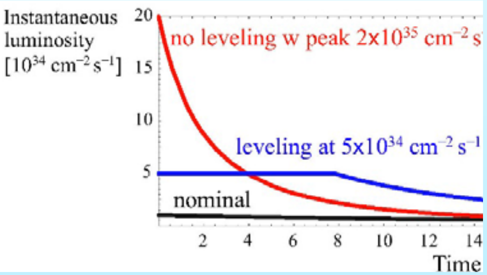
- Started in 2010 as EC-FP7 design study

From FP7 **HiLumi LHC** Design Study application

The HiLumi LHC Design Study (a sub-system of HL-LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:



An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than **ten times** the luminosity reach of the first 10 years of the LHC lifetime.

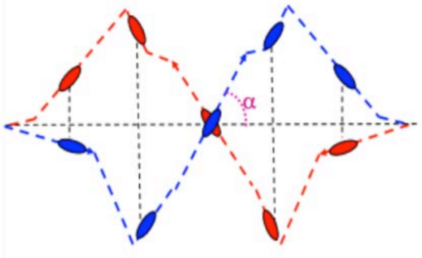
Common Terms

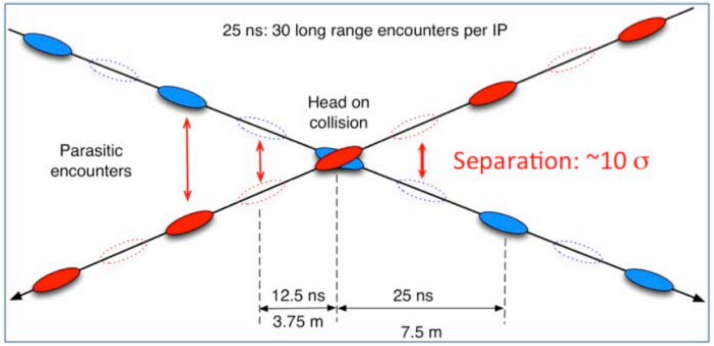
- Luminosity, interaction rate per unit cross section
  - $\mathcal{L} = \mathrm{f}\frac{N^2}{4\pi\sigma^2}$
  - integrated $\mathcal{L}$ [fb^{-1}]: integrated over time in units of relevant X-section

- Phase space beam size
  - $\sigma^2 = \varepsilon\beta$
  - betatron-function β ; β* is its value in the interaction point (IP)
  - emittance $\varepsilon \propto {}^{1}/_{p}$
- Beta-function
  - $\beta(L) = \beta^* + L^2/\beta^*$
  - beam size squared grows quadratically as we move away (distance L) from the waist
  - **Note**: the smaller beam we want at the waist, the faster it gets large as we move away from the waist.

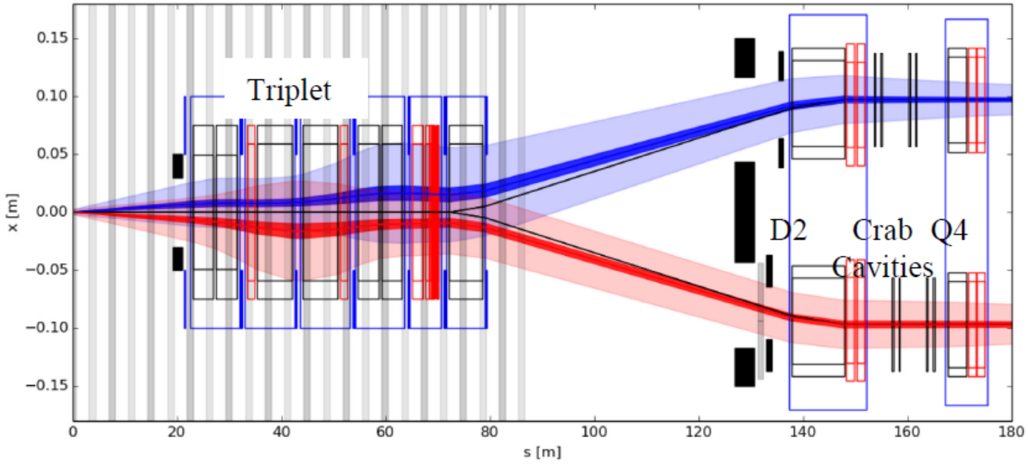
HL-LHC Main Upgrade Idea

- Want to
  - increase the beam brightness
    - classic solution is to reduce β*





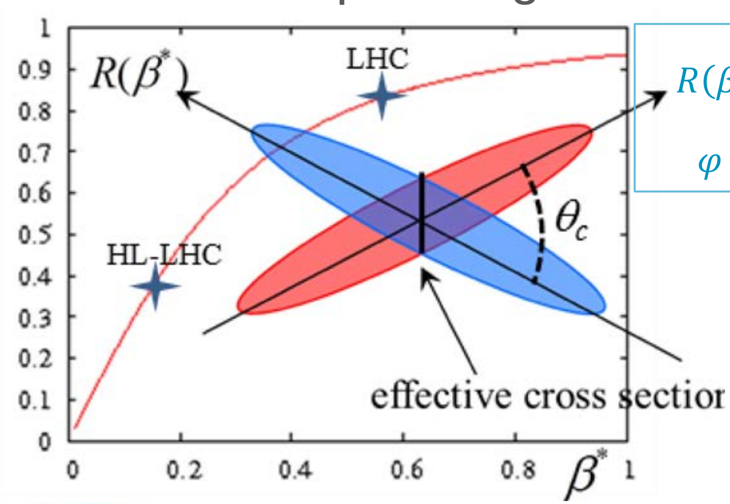
- Beam envelop
  - dark = 2σ; light = 12σ,
  - emittance = 3.5 μm
- Collimators
  - for charged (TAS)
  - neutral particles (TAN)
  - protect SC magnets from collision debris
  - reduction of background to experiments



Crabbing

Drawback of small β* is a large crossing angle

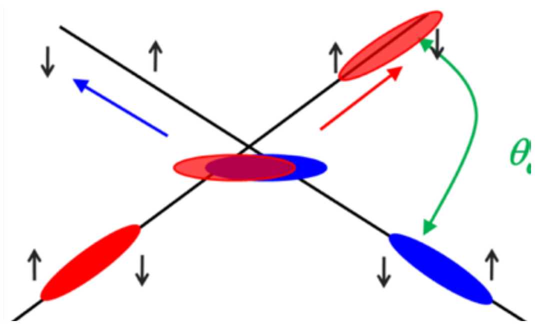
- because beam overlap must be minimized until real IP
- causes a reduction of the $R(\beta)$ geometrical luminosity factor
- requires larger aperture size in the inner triplet magnets

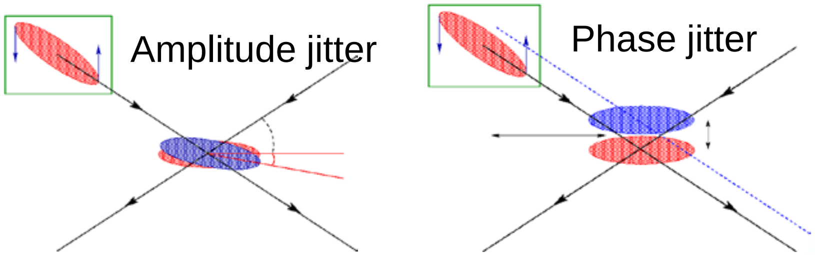


$$R(\beta) = \frac{1}{\sqrt{1+\varphi^2}}$$
$$\varphi = \theta_c \sigma_z / 2\sigma_x$$

Compensate with crab cavity

- and replace inner triplet magnets to increase the aperture





HL-LHC Parameters

CERN-2015-005, Table 1-1

Parameter		LHC	HL-LHC 25 ns	HL-LHC 50 ns
Beam energy	[TeV]	7	7	
N_b		1.5×10^{11}	2.2×10^{11}	3.5×10^{11}
N_b		2808	2748	1404
N_{total}		3.2×10^{14}	6×10^{14}	4.9×10^{14}
Beam current	[A]	0.58	1.09	0.89
Crossing angle	[μrad]	285	590	590
β*	[m]	0.55	0.15	0.15
ε_n	[μm]	3.75	2.50	3
Peak luminosity w/o crab	[$cm^{-2}s^{-1}$]	1.0×10^{34}	7.2×10^{34}	8.4×10^{34}
Virtual luminosity w/ crab	[$cm^{-2}s^{-1}$]	(1.2×10^{34})	19.5×10^{34}	21.4×10^{34}
Levelled luminosity	[$cm^{-2}s^{-1}$]	-	5.0×10^{34}	2.5×10^{34}
Events/crossing		27	138	135
Levelling time	[h]	-	8	18

FP7-HiLumi classified as «success story» by EC

High Luminosity LHC

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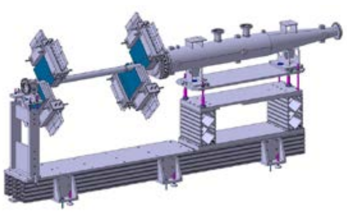
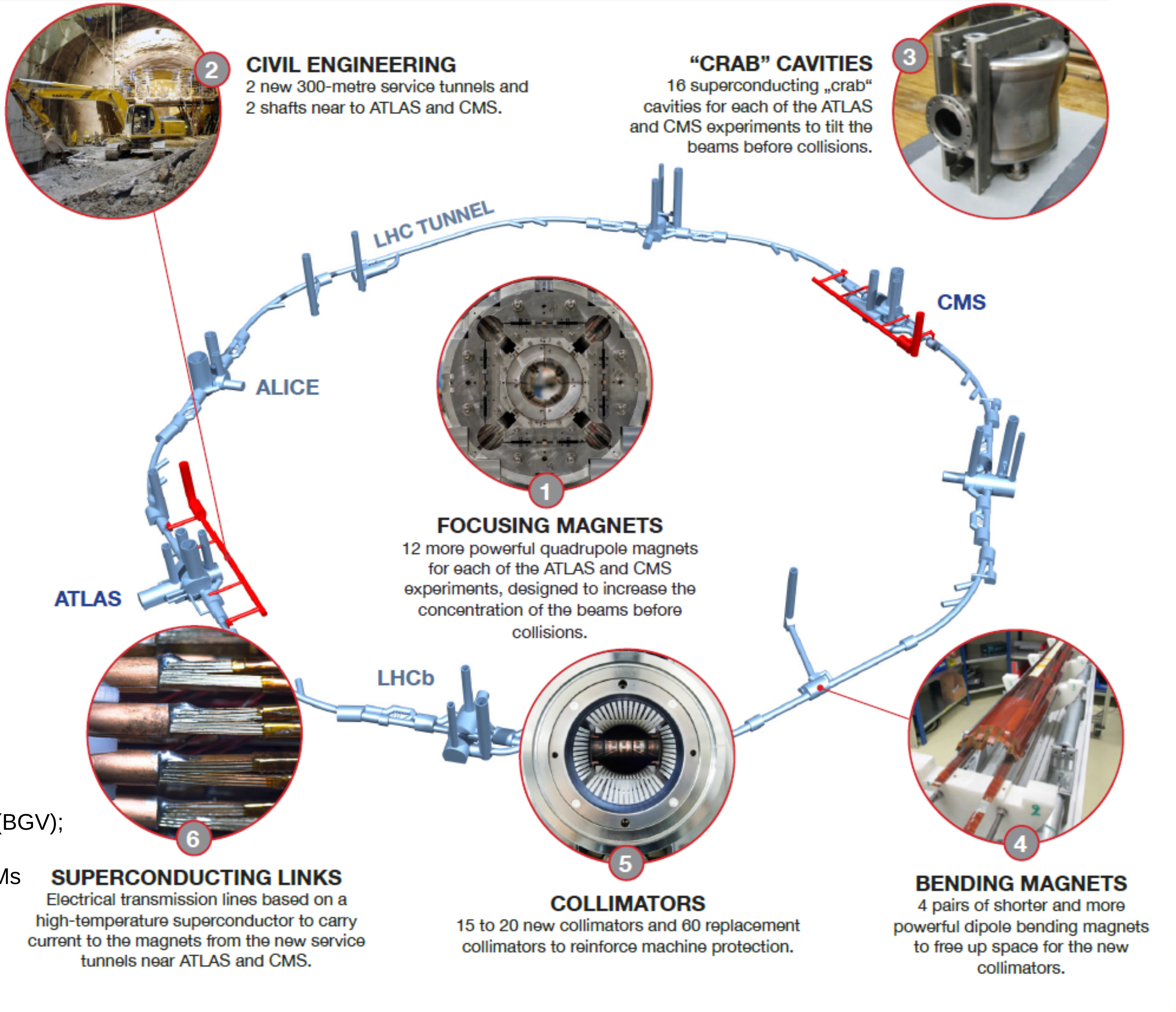
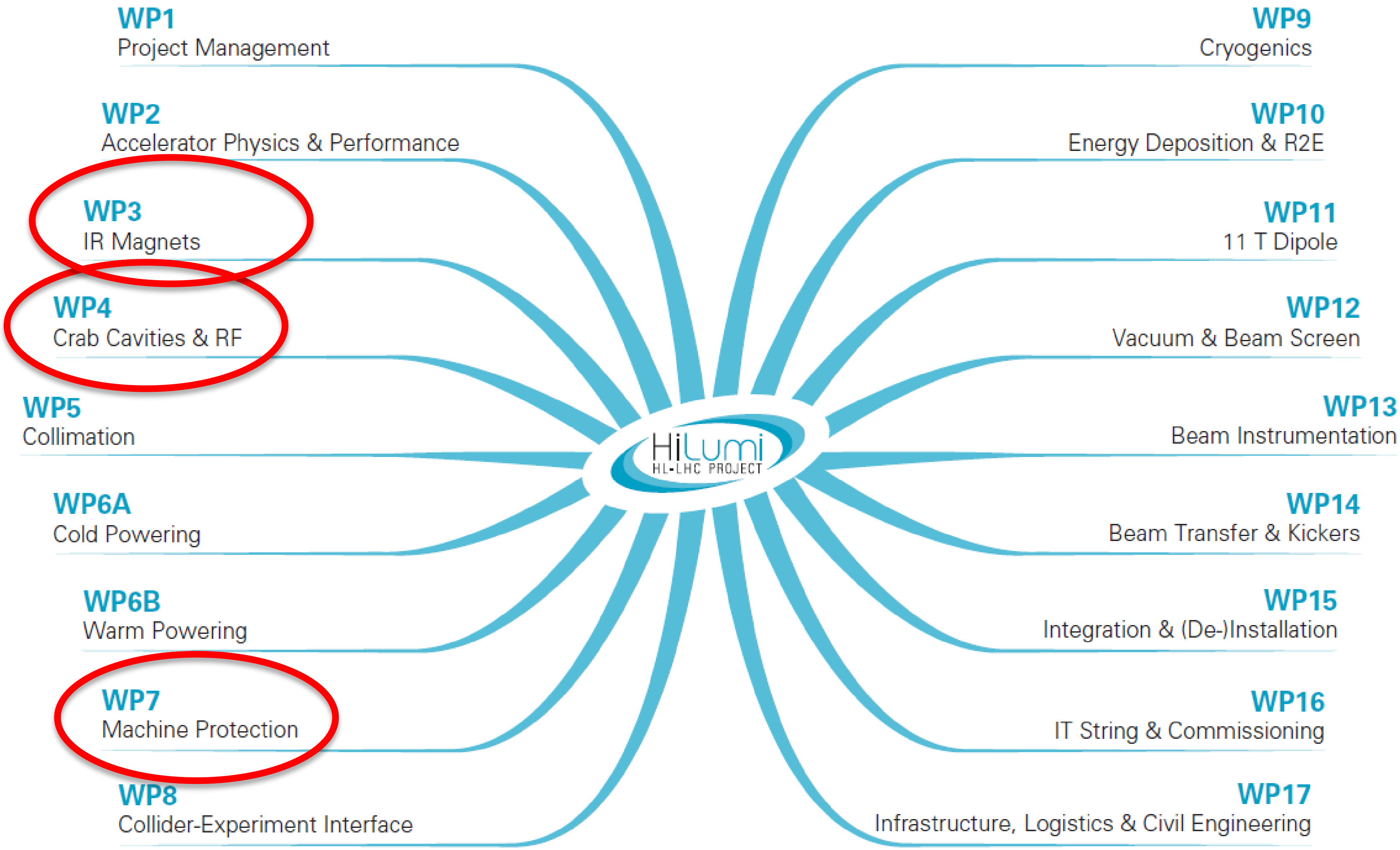
Cryogenics
Upgrade at P1/4/5



Beam Instrumentation
Beam Gas Vertex profile monitor (BGV);
cryogenic beam loss monitor;
new stripline & electro-optical BPMs

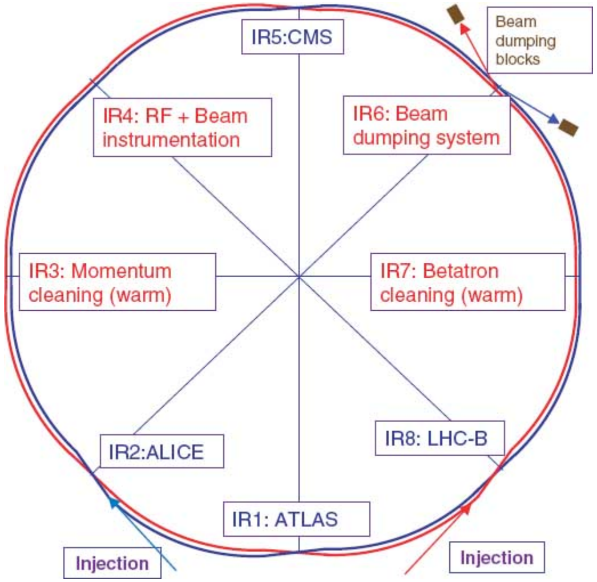


HL-LHC project breakdown structure

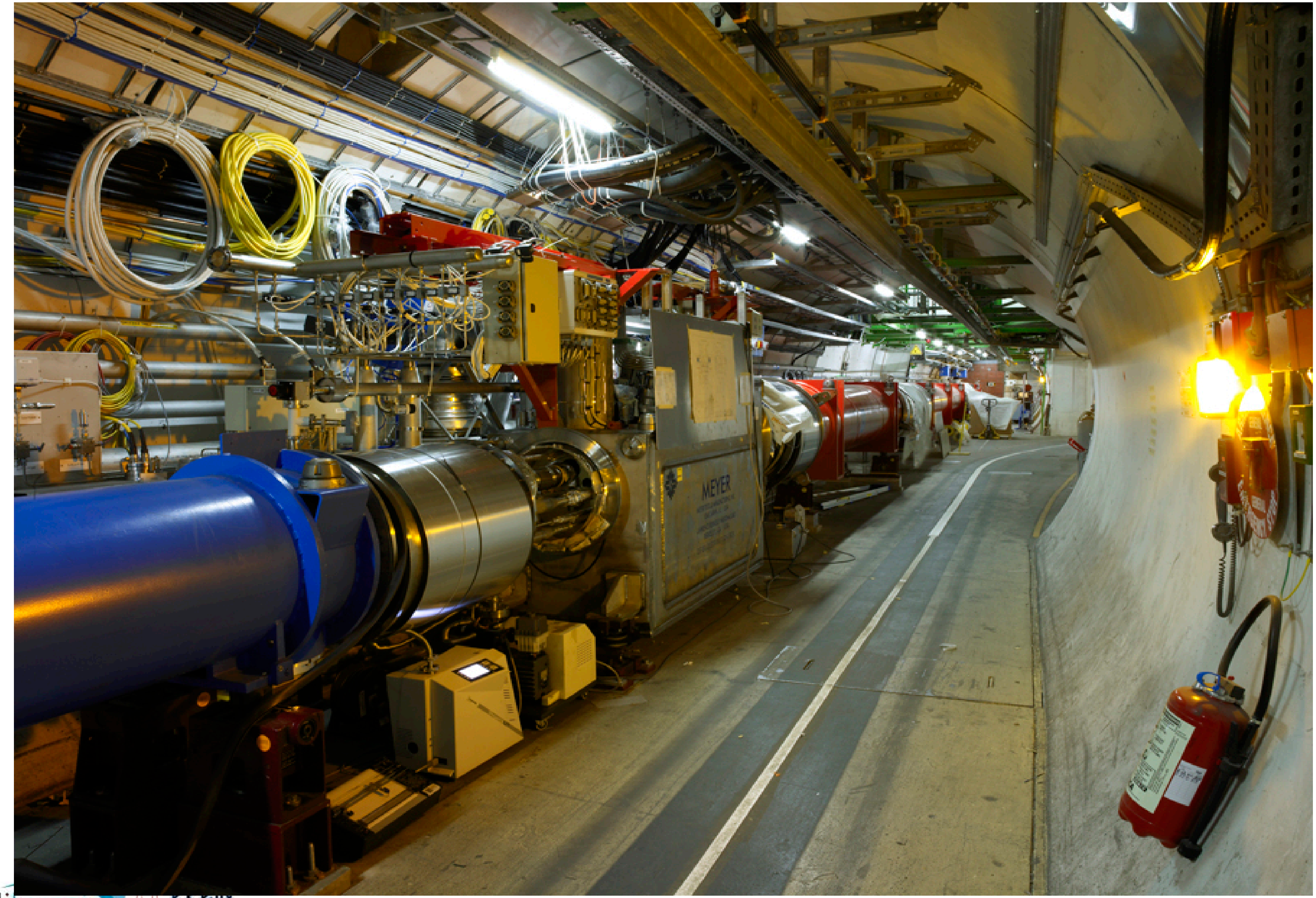


HL-LHC Interaction Region

- Four interaction regions for experiments
  - two (IR1/5) to be upgraded
- Purpose
  - separate the two counter-rotating beams transversely
  - mitigate parasitic crossings
- Experiment IR equals (one side)
  - 60 m focusing channel
  - 21 m drift space
  - 20 m dipole channel



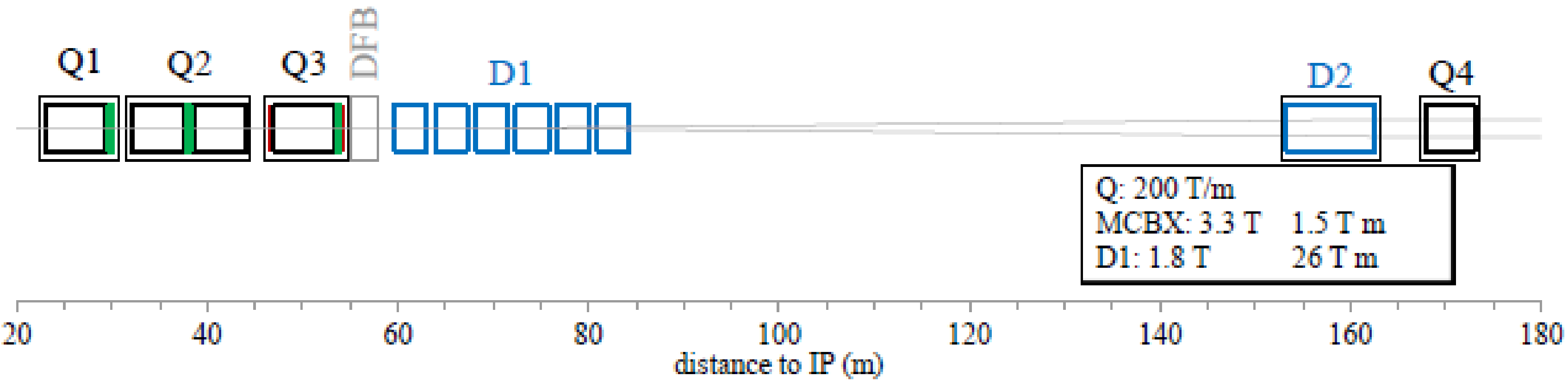
Looking Towards The Collision Point



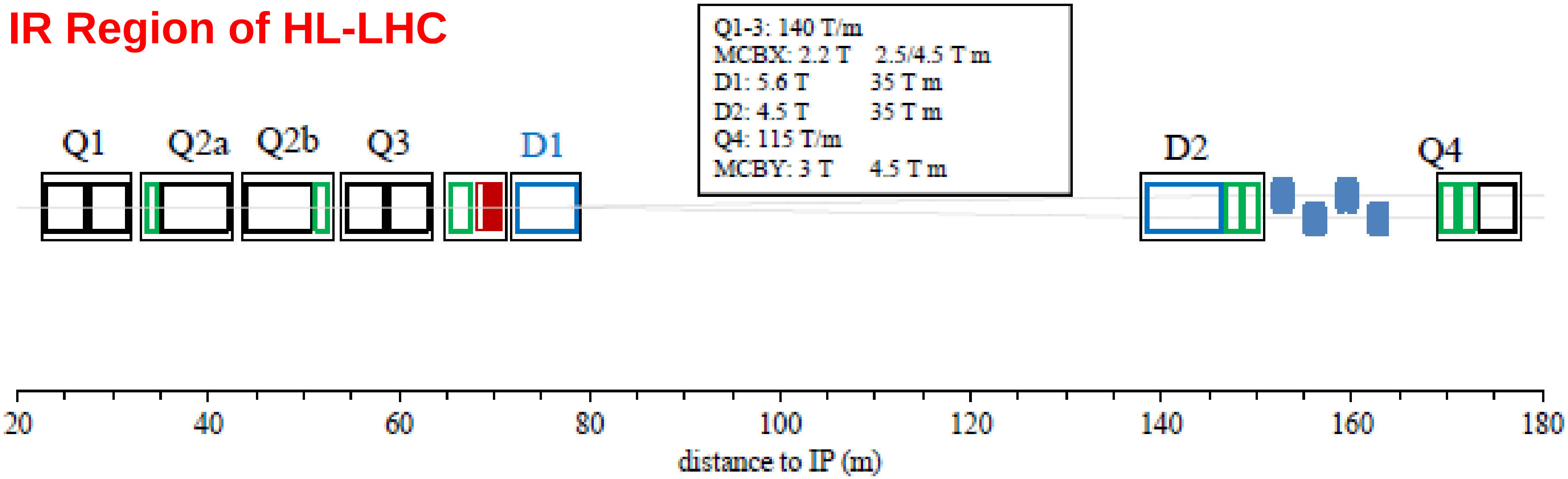
Looking Over The Shoulder

Conceptual Layout IR Region

IR Region of LHC

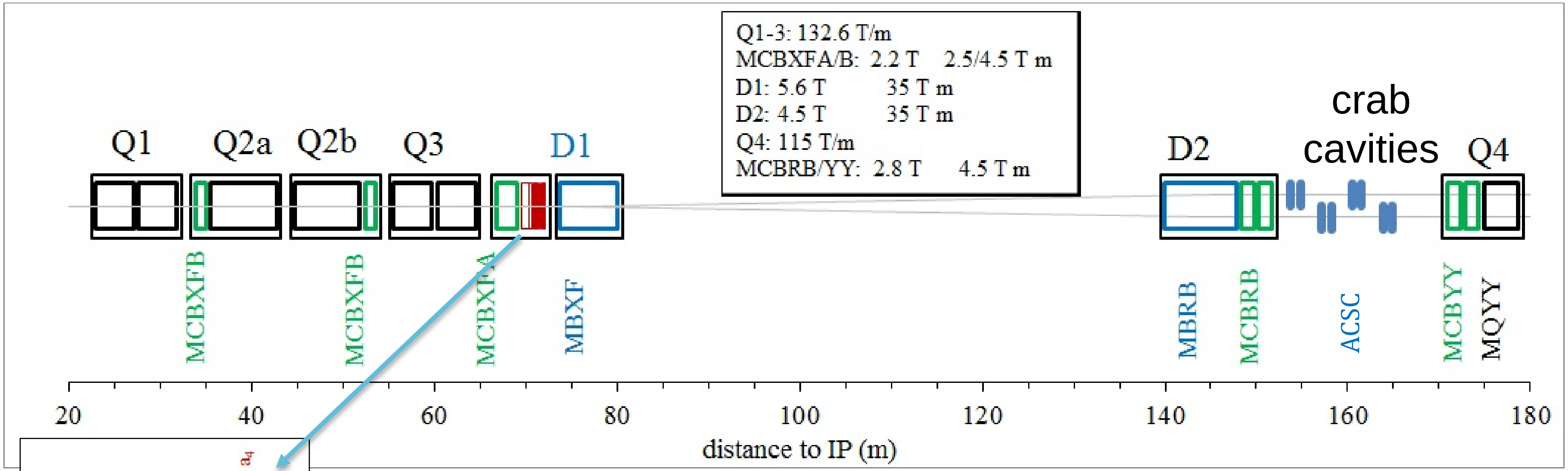


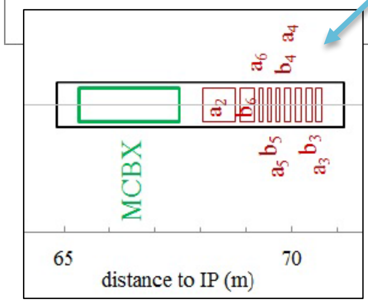
IR Region of HL-LHC



HL-LHC Lay-out of the IR

- IR zone has in different strategic points corrector magnets of dipolar field, giving corrections on the horizontal or on the vertical plane.



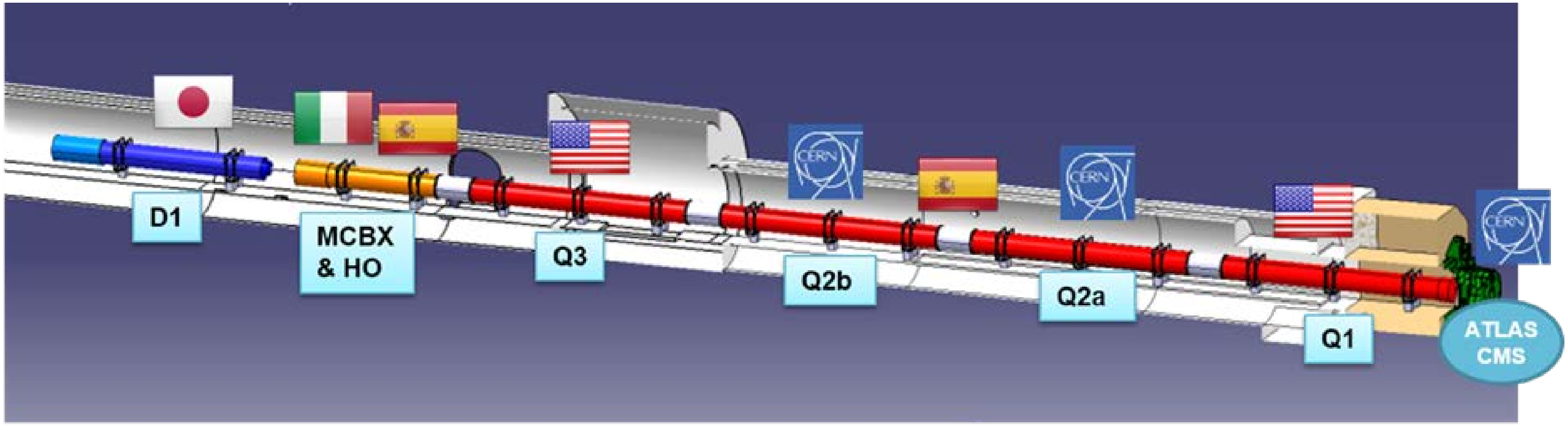


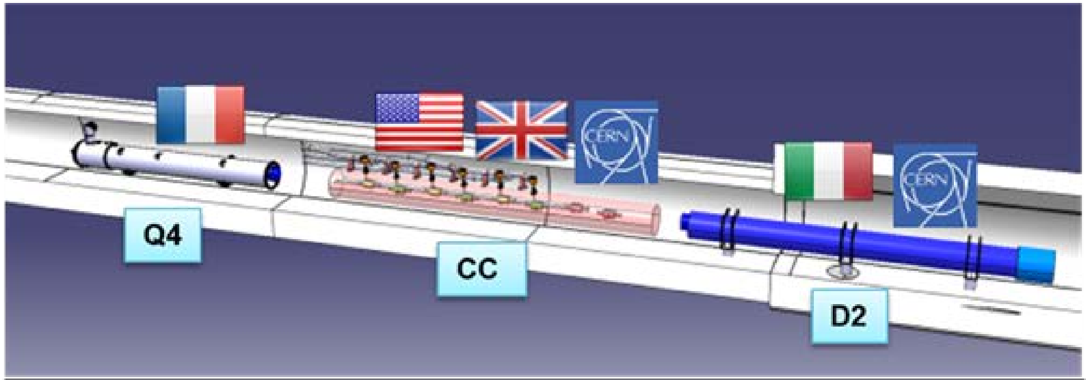
MCB corrector magnets (in "green")

ACSC crab cavities (in "blue")

proposed to be tested at FREIA.

WP3: Interaction Region Magnets
Inner Triplet at ATLAS & CMS





CC : R&D, Design and in-kind **USA & UK**

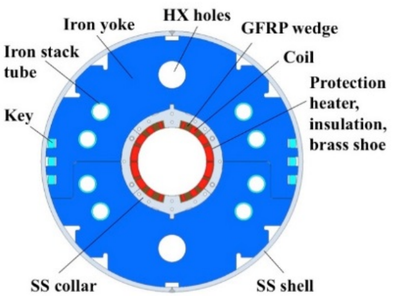
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
D2 Design **IT**
Q4 : Design and Prototype **FR**

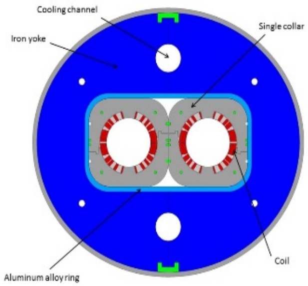
What Is Special

- Magnet apertures of triplet, D1, correctors are large
  - Larger forces
  - At the limit of what is reasonable with the given cryostat (and tunnel) size
- Triplet quadrupoles:
  - Nb_3Sn cable: Power-in-Tube (PIT), Restack Rod Process (RRP)
  - US design split in two 4.2 m long magnets,
  - CERN opted for making a 7.15 long magnet
- Nested correctors:
  - even though the field is only 2 T in each plane, the magnet is not trivial
  - mechanics and double collaring is the challenge

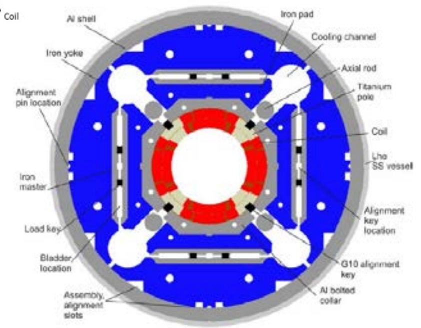
Dipoles & Quadrupoles

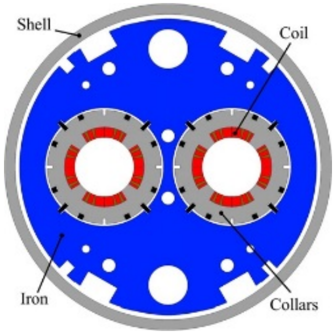
- D1 separation dipole, by KEK (JP)
  - 5.6 T, 150 mm aperture (6.6 T peak field)
  - short model prototype reached 300 A less than nominal after 9 quenches at 1.9 K
- D2 recombination dipole, by INFN (IT)
  - 4.5 T, 105 mm aperture (5.1 T peak field)
  - short model prototype test in 2017





- Q1/Q2/Q3 triplet quadrupole
  - 140 T/m, 150 mm aperture (12.1 T peak field)
  - based on Nb_3Sn cable
- Q4 quadrupole, by CEA Saclay (FR)
  - 115 T/m, 90 mm aperture (6.3 T peak field)
  - short model prototype test end 2017





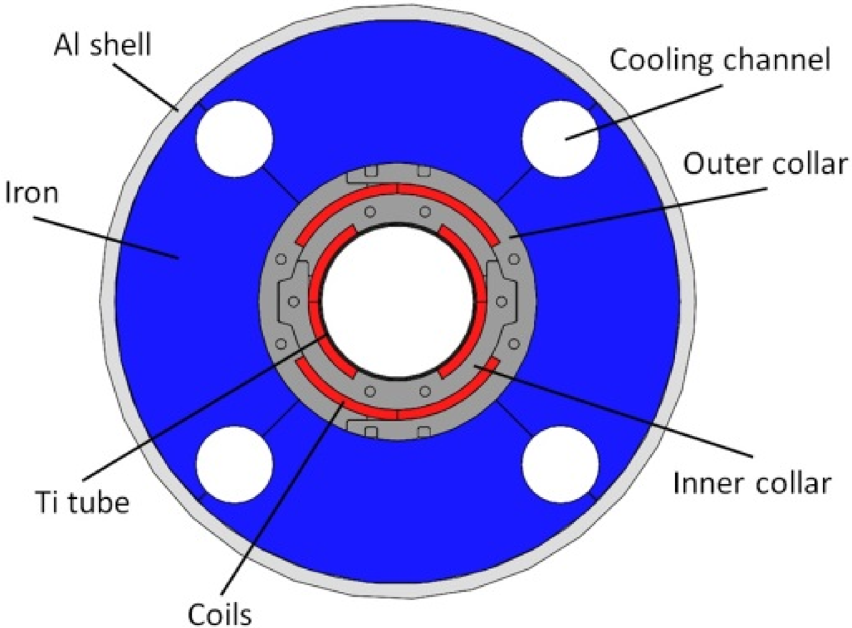
Q1-Q2-Q3 ORBIT CORRECTORS
MCBXFA, MCBXFB

Possible test at FREIA

- Nested orbit corrector , by CIEMAT (ES)
  - 2.1 T, 150 mm aperture (4.2 T peak field)
  - prototype test 2018 (~1 year delay in design)

MAGNET CHARACTERISTICS

Integrated into	Q2a, Q2b	CP
Magnet name	**MCBXFB**	**MCBXFA**
I nom (kA)	1,6	
I max (2*I nom)	3,2	
Max Diameter(mm)	630,0	
Max Length (mm)	1500	2100
Max Energy magnet (kJ/m)	160,0	
Inductance (mH/m)	46,0/99	
Dump (Ohm)	0,3	
Protection Heater	Maybe	
nr of magnets	10	5



OPERATION TEMPERATURE : 1.9 K
Inner an Outer magnets are powered INDIVIDUALLY

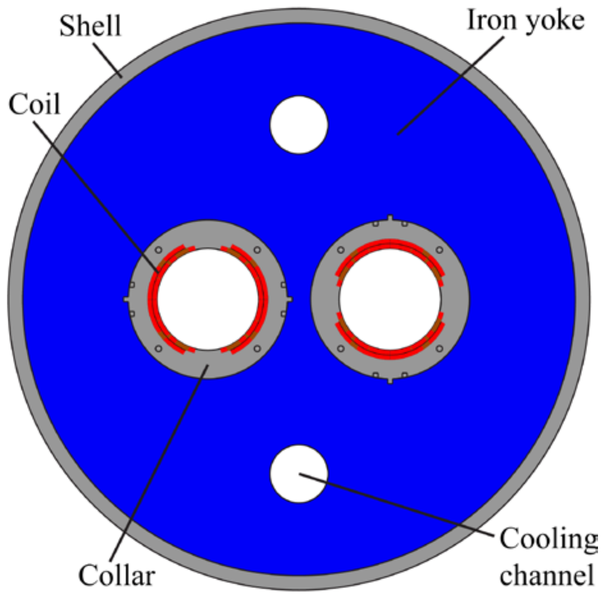
Q4-D2 ORBIT CORRECTORS
MCBRD, MCBRYY

Possible test at FREIA

- Double aperture orbit corrector, by CERN
  - 3.0 T, 100 mm aperture (3.8 T peak field)
  - prototype by 2017

MAGNET CHARACTERISTICS

Integrated into	D2	Q4
Magnet name	**MCBRD**	**MCBYY**
I nom (kA)	1,7	
I max (2*I nom)	3,4	
Max Diameter(mm)	630,0	
Max Length (mm)	1600	
Max Energy magnet (kJ/m)	78,0	
Inductance (mH/m)	29	
Dump (Ohm)	TBC	
Protection Heater	Maybe	
nr of magnets	10	10



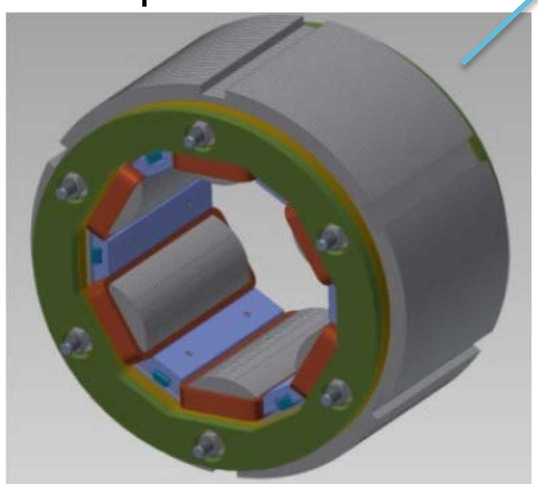
OPERATION TEMPERATURE : 1.9 K

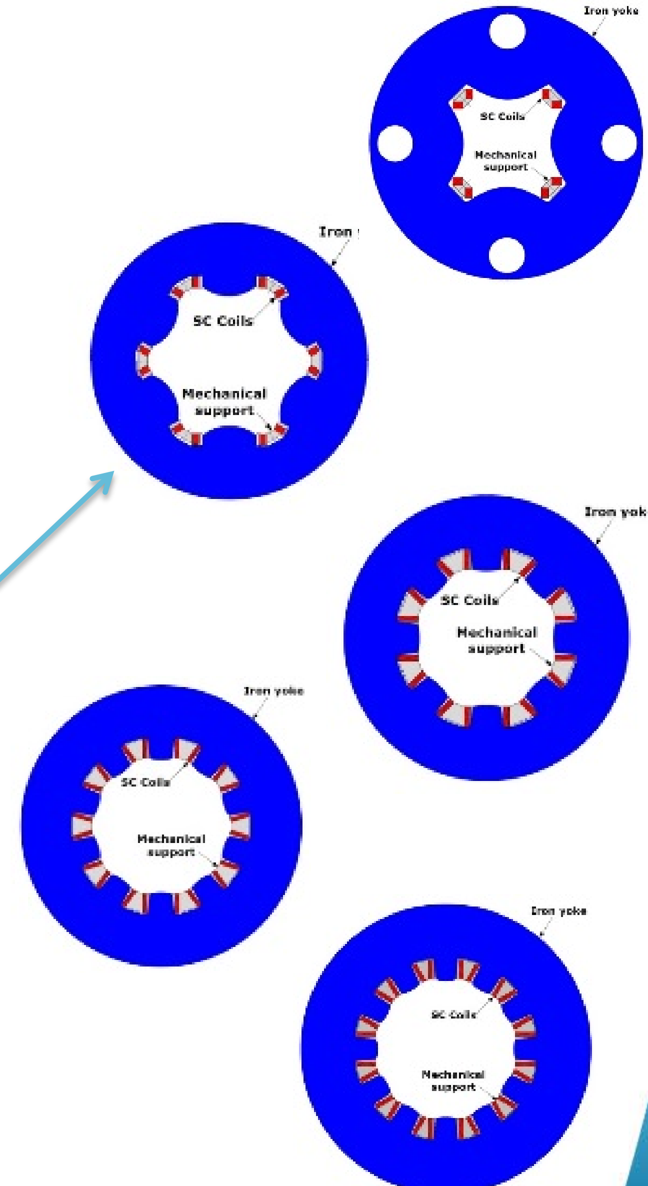
The two apertures are powered INDIVIDUALLY

Zoo of Higher Order Correctors

- Superferric design, by INFN (IT)
  - NbTi racetrack coils provide ampere-turns
  - iron yoke provides field shape
  - 2 to 3 T peak field, 150 mm aperture
  - 100 to 850 mm coil length
  - first sextupole tested Feb. 2016

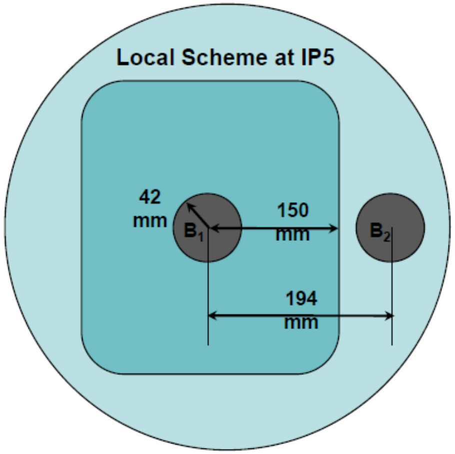
sextupole



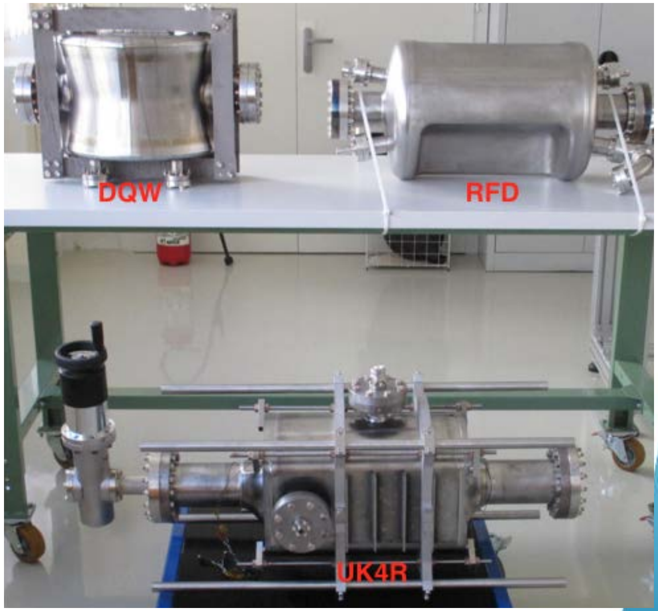


WP4: Crab Cavities & RF

- Boundary conditions
  - aperture size 84 mm
  - max cavity radius ≤ 145 mm
  - nominal deflecting voltage 3.4 MV per cavity
  - resonance frequency 400.79 MHz



- Main design options proposed
  https://indico.cern.ch/event/136807
  - 4 Rod Crab Cavity (4RCC), Lancaster Univ.
  - Double Quarter Wave (DQW), BNL
    - most advanced design
  - Radio Frequency Dipole (RFD), ODU and SLAC
  - Compact Coated Cavity (CCC), CERN and Politecnico di Torino

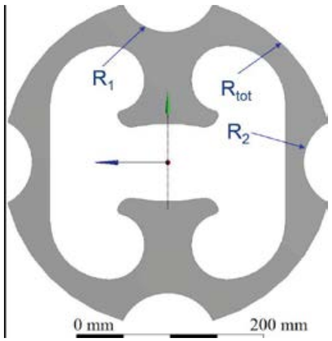


Compact Nb-on-Cu Coating Cavity

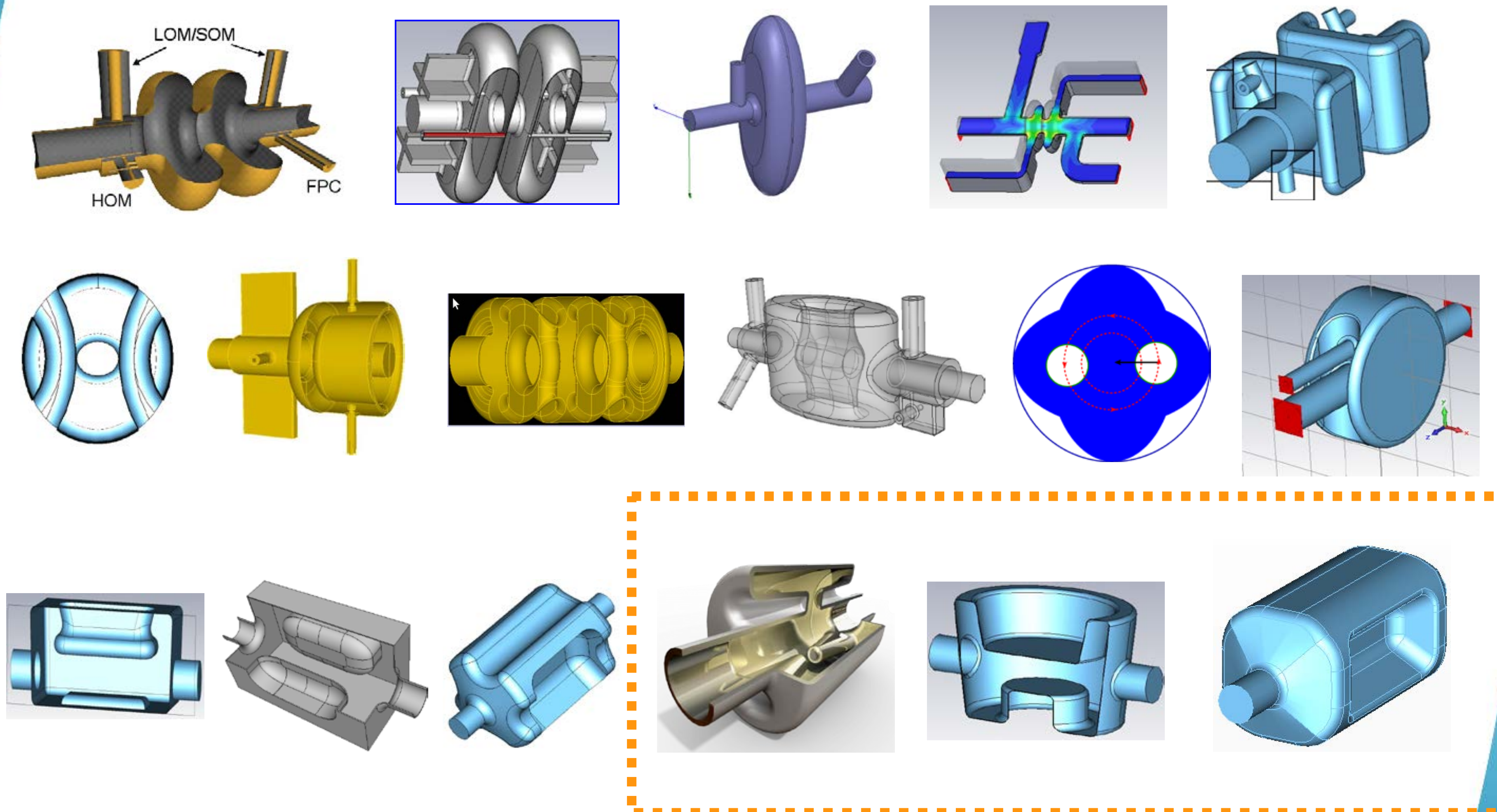
SRF2015-THPB048

- Shape based on ridged waveguide resonator
  - with wide open apertures to provide access to the inner surface of the cavity for coating
  - provides natural damping for HOMs
  - rather low longitudinal and transverse impedances
- Advantage of Nb-on-Cu coating
  - higher surface resistance (RF-loss) but lower quenching probability
  - possibility for more complex and accurate shape by using modern CNC 5-axis milling than solid Nb sheet technology
  - reduced sensitivity for microphonics and Lorenz force detuning

Parameter		
E_{max}	[MV/m]	30
B_{max}	[kA/m]	25
R/Q	[Ohm]	
U_{stored}	[J]	



Crab Cavity Design Evolution (~4yr)

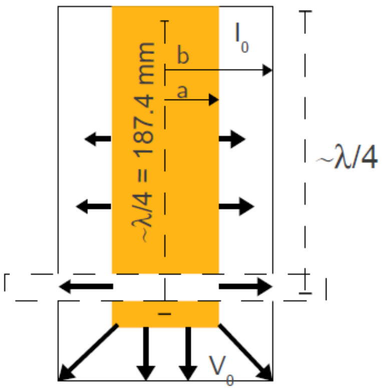


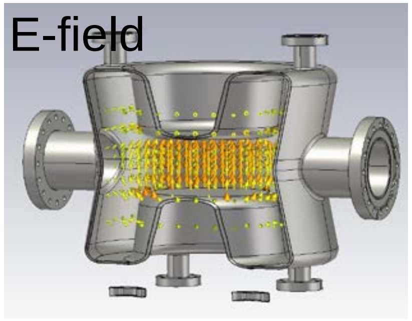
Development of new concepts

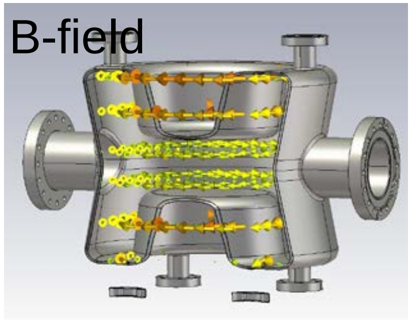
(BNL, CERN, CI-DL-LU, FNAL, KEK, ODU/JLAB, SLAC)

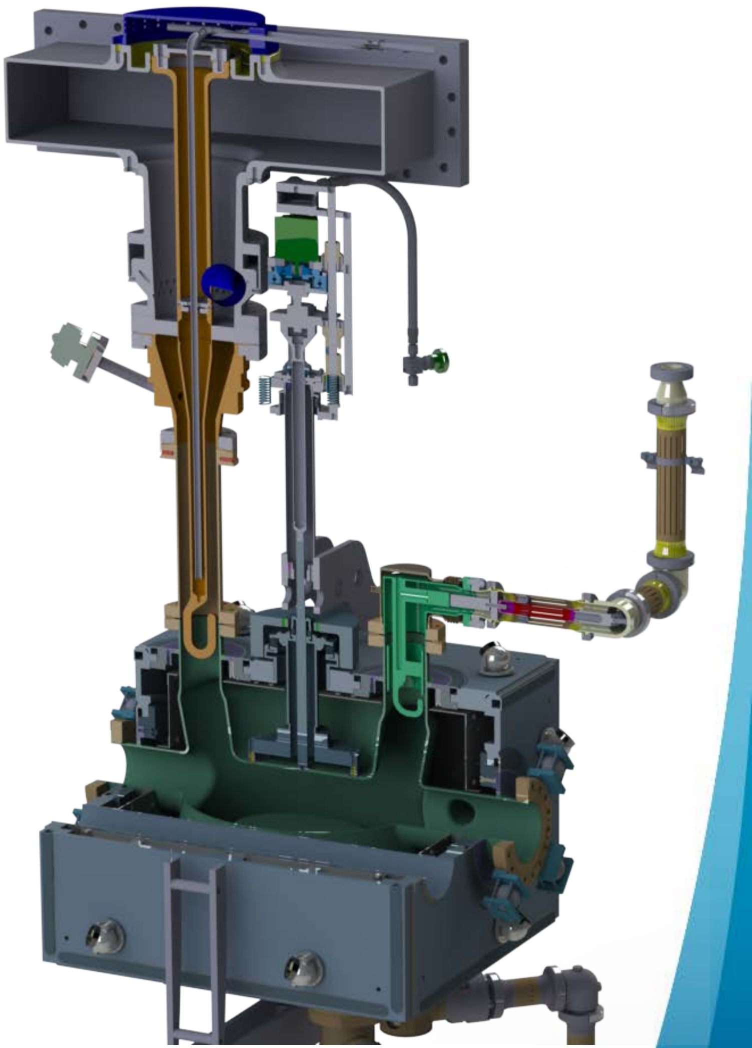
Double Quarter Wave Cavity
λ/4 TEM Resonator

- Design by BNL
- Equipped with
  3 HOM couplers







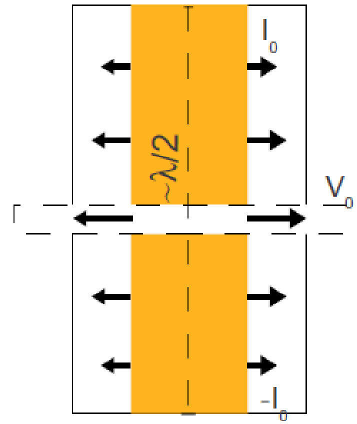


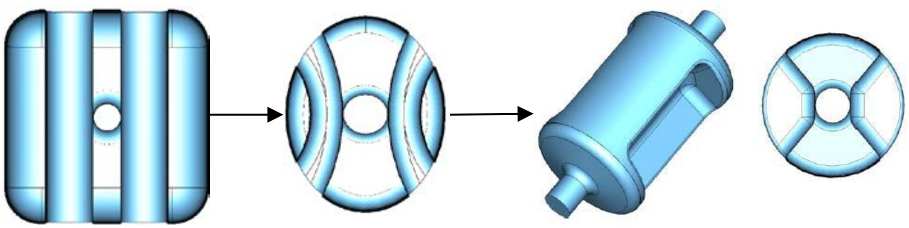
Parameter		
f_{fund}	[MHz]	400
f_{HOM}	[MHz]	579
E_{max}	[MV/m]	44
B_{max}	[mT]	60
R/Q	[Ohm]	400
U_{stored}	[J]	12

Radio Frequency Dipole (RFD)

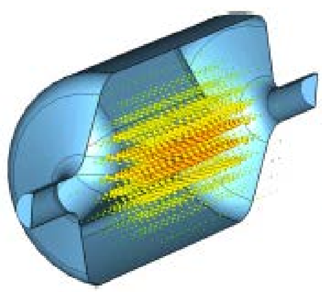
λ/2 TEM Resonator

- Design by ODU and SLAC
- Two λ/4 resonators → λ/2
  - HOM (TE_{11}-like) for deflection
  - bar length ~λ/2

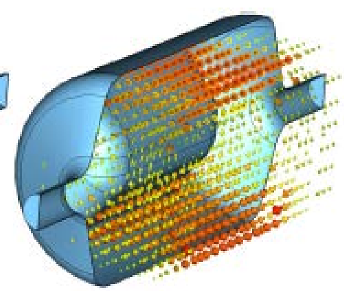




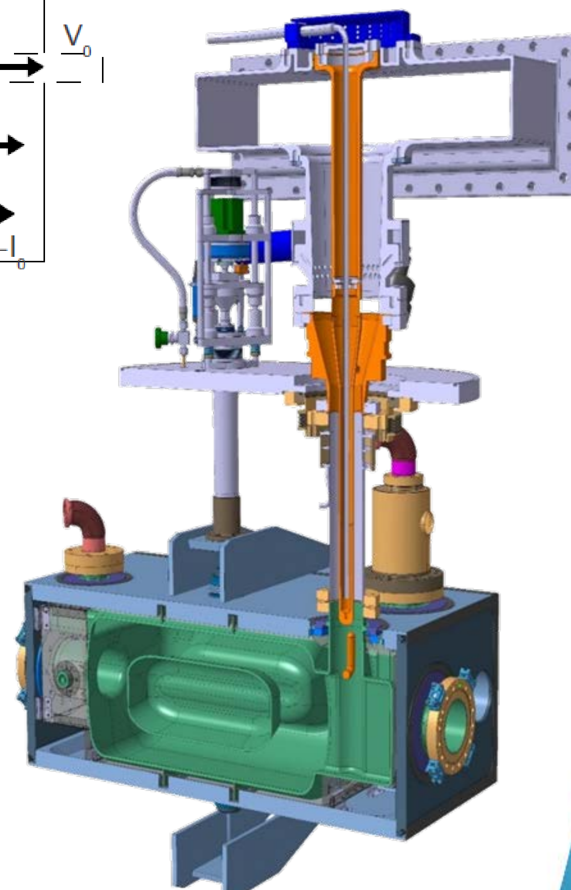
Parameter		
E_{max}	[MV/m]	33
B_{max}	[mT]	65
R/Q	[Ohm]	287
U_{stored}	[J]	



E-field

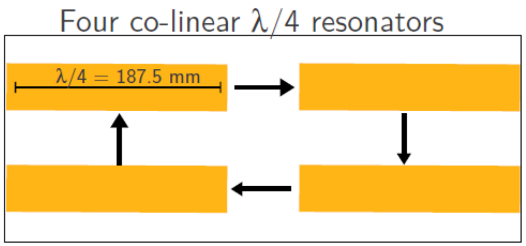


B-field

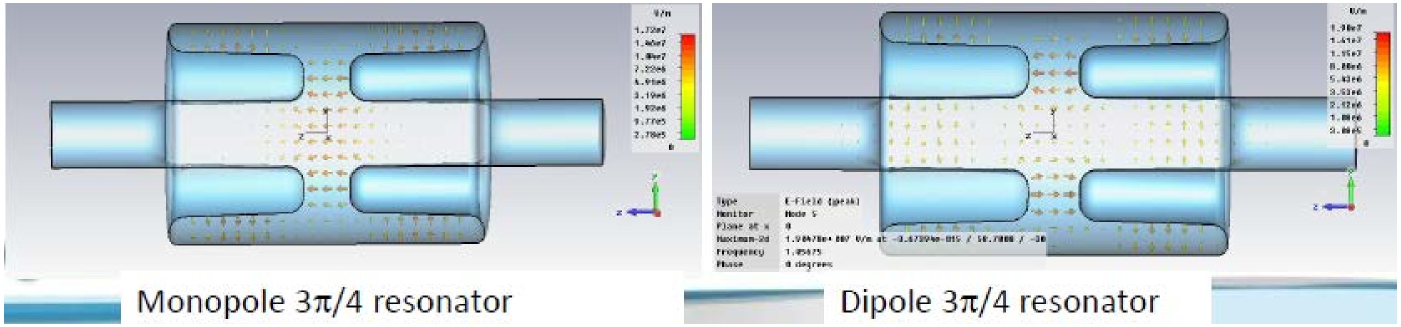


4 Rod Crab Cavity (4RCC)
Four co-linear λ/4 TEM Resonators

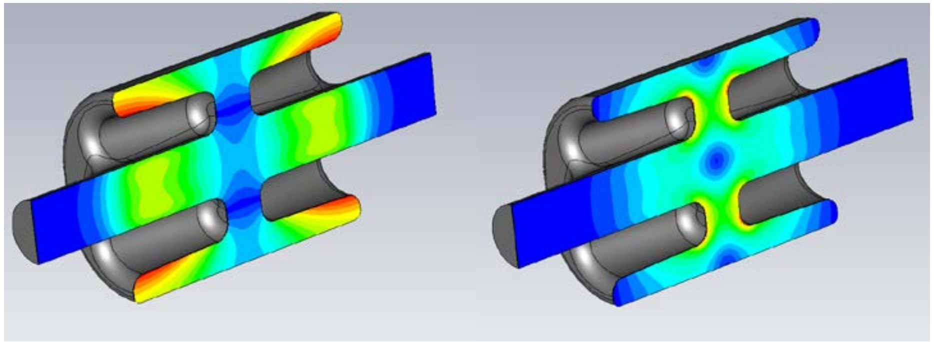
- Design by Lancaster University
- Conical resonators for mechanical stability
- Deflection mode is HOM



4 eigenmodes, mode 2 is our crab mode

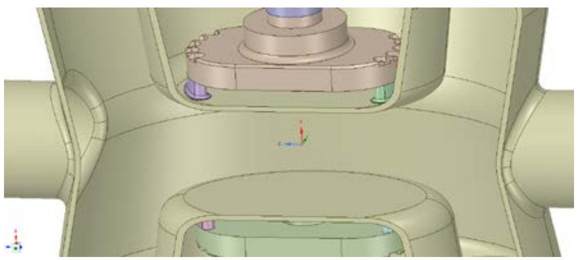


Parameter		
E_{max}	[MV/m]	32
B_{max}	[mT]	60.5
R/Q	[Ohm]	915
U_{stored}	[J]	

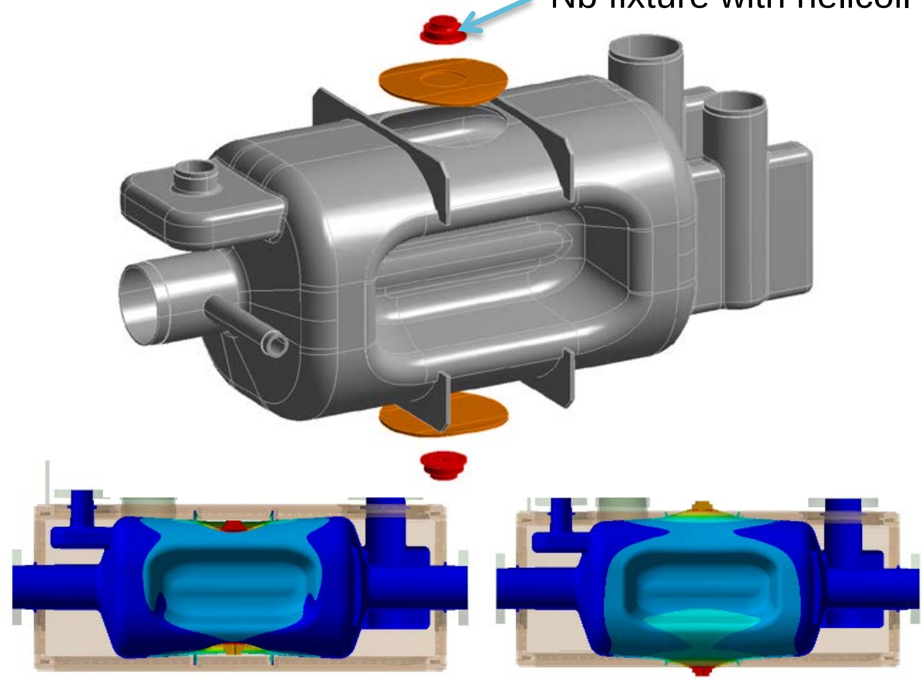


Cavity Tuning

- Warm frequency tuning limited by tuning fixture
- Limiting factor is the strength of NbTi fixture and weld
  - CERN (NbTi), USLARP (Nb with reinforced shape)



DQW Pre-tuning: ≥ 0.3 mm permanent deformation



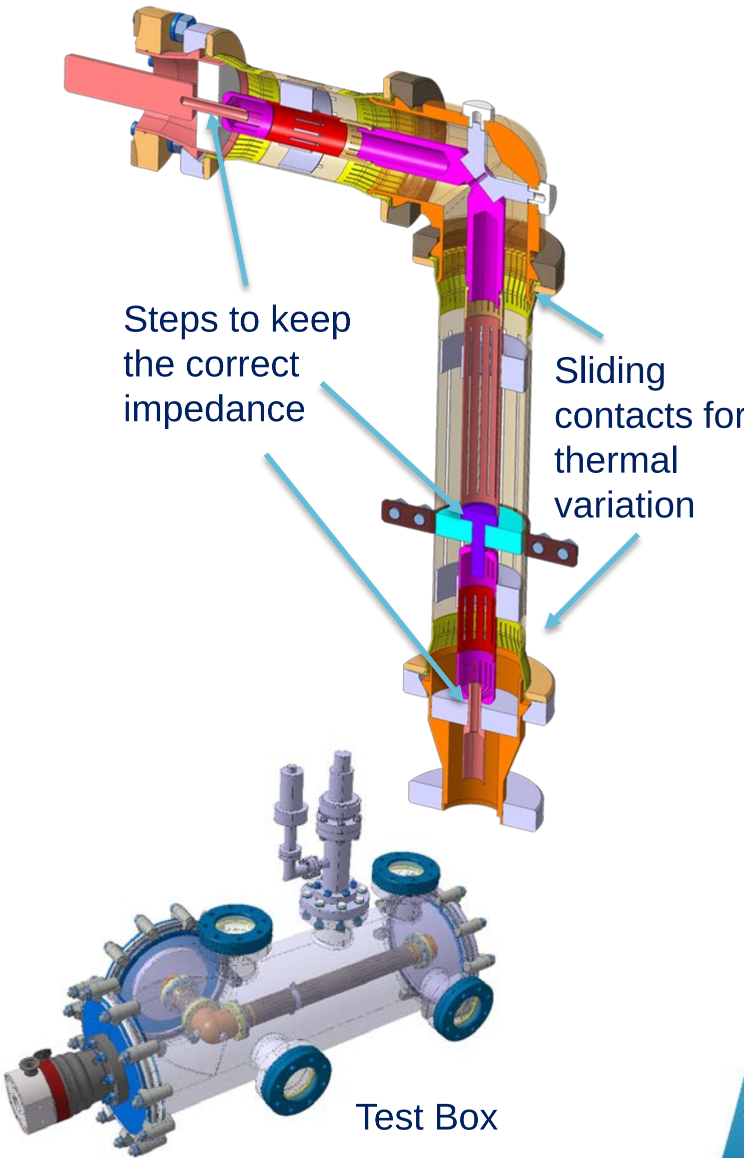
RFD: ~ 1.4 mm (7000 kN elastic limit)

Transmission Lines

- Specific transmission lines are being developed to allow expansion due to thermal cycles

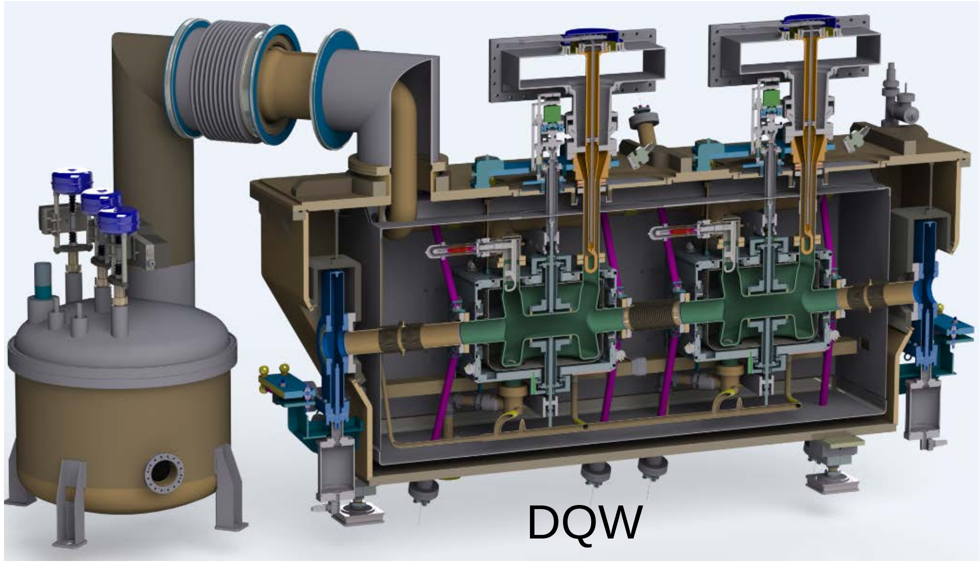
- In case of full reflection at the load, maximum standing wave and voltage along the line will be up to twice the nominal forward voltage
  - Vtotal = Vf + Vr
  - With full reflection
    - Vr = Vf
    - So Vtotal = 2 Vf and Pmaximum = 4 Pf

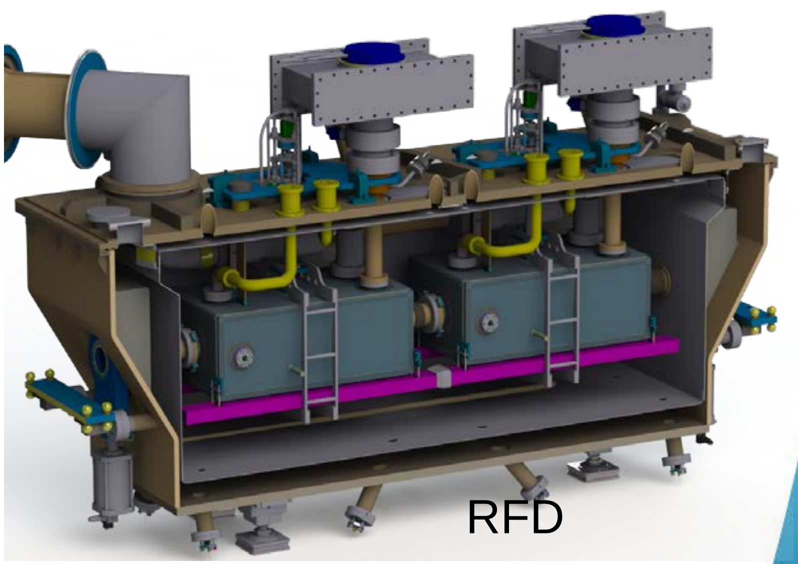
- The source is the HOM, the load is at the air side
- In case of a load failure, there will be full reflection back to the HOM



Cryomodules

- magnetic shield inside cavity helium vessel



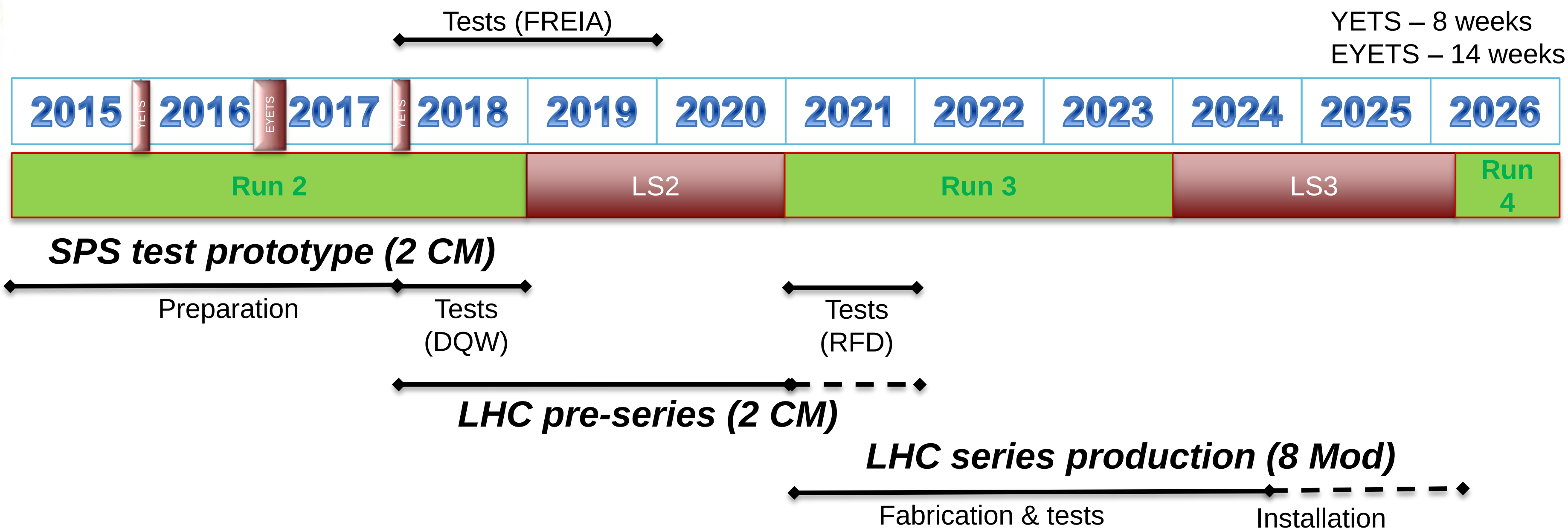


Crab Cavity Tests

Possible test at FREIA

- 2 Cavities in 1 cryomodule in SPS to demonstrate
  - deflection action and verification of cavity control,
  - operation without crab cavity action ("invisibility" to the beam),
    - by counter-phasing two cavities or by de-tuning,
  - non-correlated operation,
    - trigger quench in one without inducing quench in the other,
  - that the crab cavities are a high availability RF system,
  - performance of crab cavities with high intensity beam,
  - effect of crab cavity noise to the beam,
    - may trigger the necessity of a wide-band feedback system including pick-ups and kicker elements,
  - test techniques for beam-based crab cavity qualification in HL-LHC.
- 1 or 2 Cavities in HNOSS to study
  - fast failure (quench) modes including non-correlated operation,
  - prototype tetrode based amplifier system (IOT system is new baseline).

Planning



Tests (FREIA)
YETS – 8 weeks
EYETS – 14 weeks
2015
YETS
2016
EYETS
2017
YETS
2018
2019
2020
2021
2022
2023
2024
2025
2026
Run 2
LS2
Run 3
LS3
Run 4
SPS test prototype (2 CM)
Preparation
Tests (DQW)
Tests (RFD)
LHC pre-series (2 CM)
LHC series production (8 Mod)
Fabrication & tests
Installation

WP4: Additional RF System Upgrades
Under Discussion

- Harmonic RF system
  - 200 MHz sub-harmonic system will improve the luminosity by
    - improved capture efficiency of longer SPS bunches with very high intensity (note: SPS works at 200 MHz)
  - 800 MHz higher harmonic system to reduce beam-induced heating, intra-beam scattering, improve longitudinal beam stability by
    - changing the bunch profile
    - increasing the synchrotron frequency spread

- Transverse damper
  - transverse feedback system to damp beam oscillations originating from injection and/or impedance
  - preserve beam intensity and emittance
  - present system bandwidth 20 MHz, increase might be useful for HL-LHC

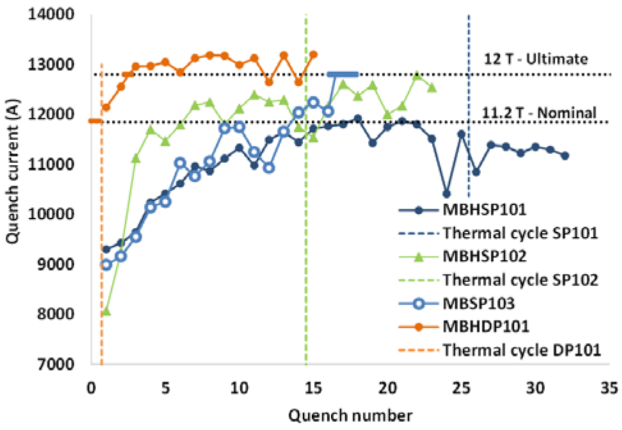
WP7: Machine Protection

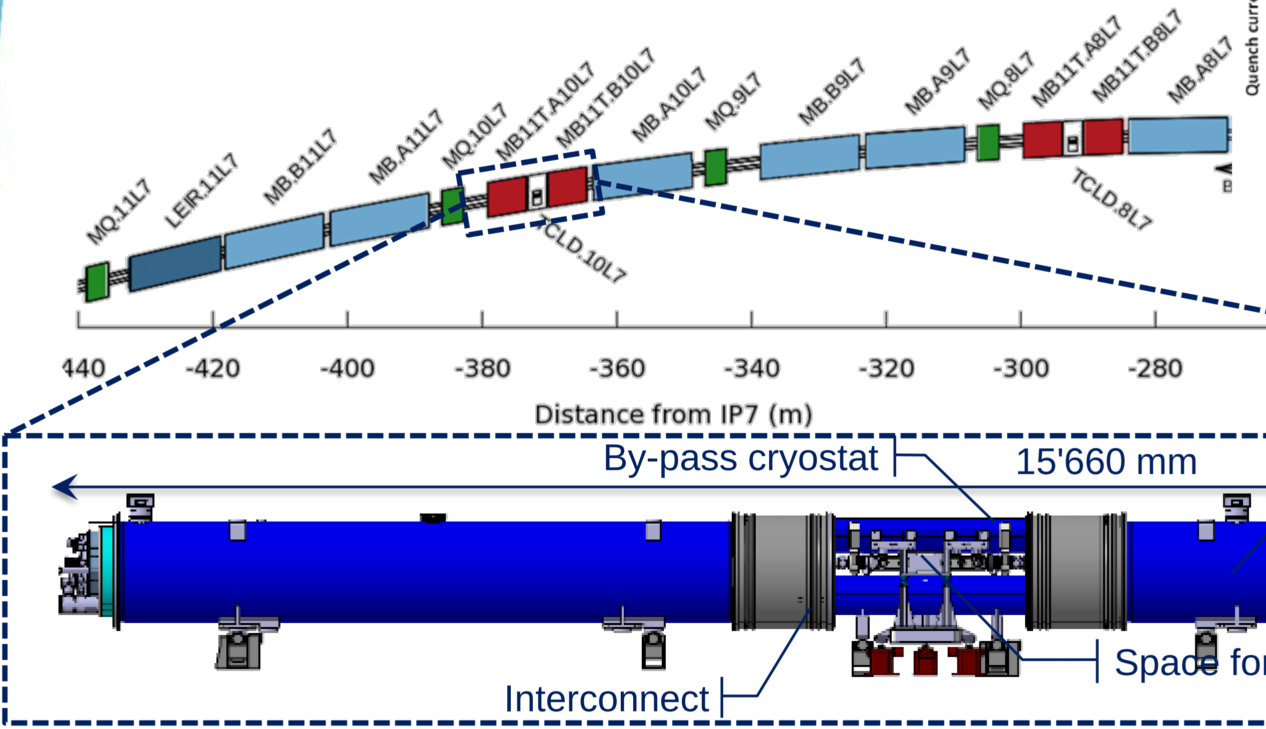
PhD Student at HEP/FREIA

- Stored energy ~700 MJ per beams
  - 2.2×10^{11} p/bunch, 25 ns bunch spacing, 2748 bunches, 7 TeV
  - for LHC it is ~362 MJ per beam
- Uncontrolled beam loss can cause severe damage
  - nominal LHC beam can penetrate 20 m long copper block
  - accident could happen if extraction kickers deflect at incorrect angle
- Necessary to
  - review LHC damage studies with new parameters
  - extend to new failure scenarios related to
    - optics modifications
    - new hardware components: crab cavities, wire scanners

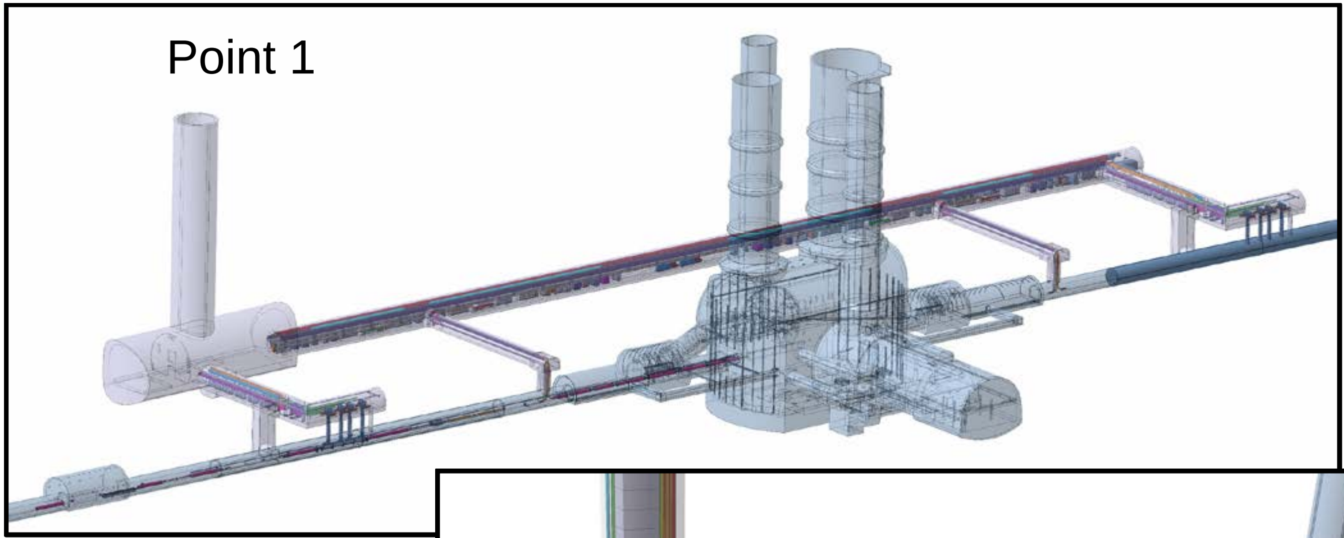
WP11: 11 T Dipole

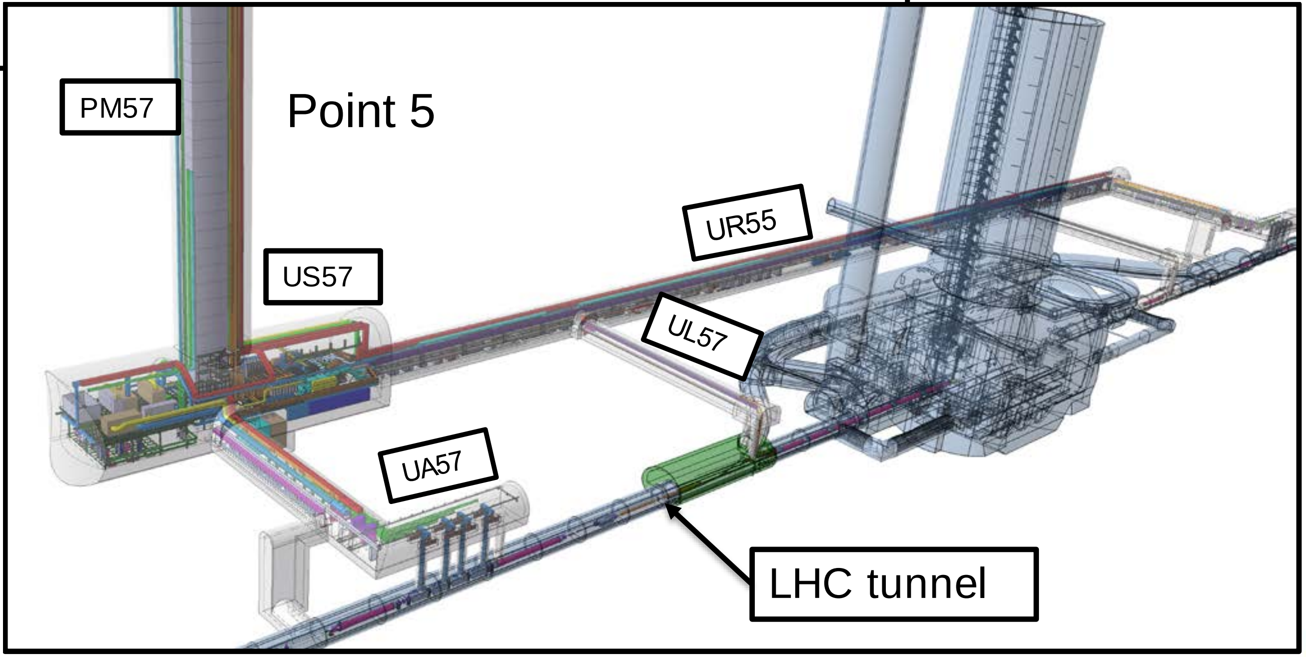
- a pair of 11 T dipoles will replace some 8.3 T main dipoles (MB)
  - space for additional collimators in the dispersion suppressor regions
  - 6.252 m long and straight, Nb_3Sn cable
  - trim coil to correct for field difference with MB below nominal current





WP17: Civil Engineering





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J. Delayen, E. Montesinos

HL-LHC web site: http://hilumilhc.web.cern.ch/

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