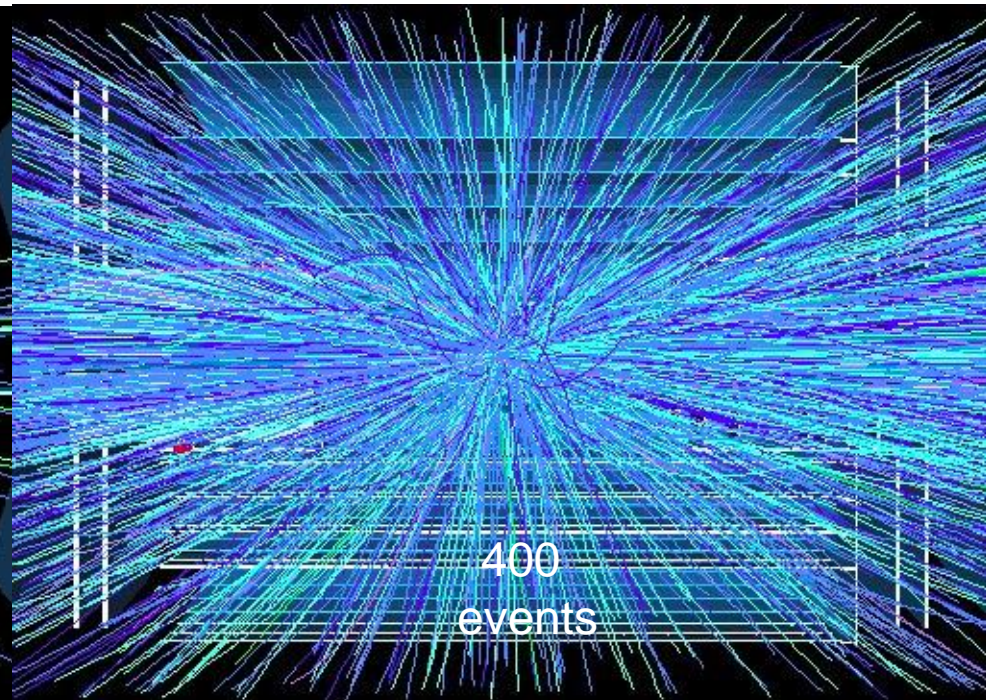
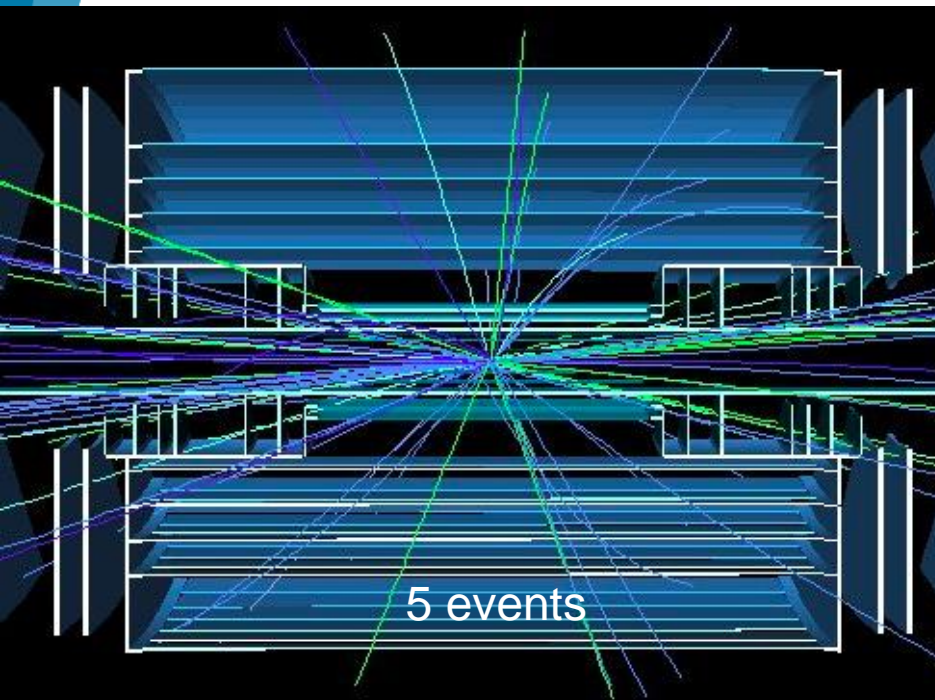


The image shows a perspective view down a long, circular tunnel. In the foreground, a large, blue and silver superconducting magnet is visible, extending into the distance. The tunnel walls are lined with various pipes, cables, and structural elements. The floor is a smooth, light-colored surface. The lighting is bright and even, illuminating the entire scene. The text "HL-LHC Upgrade Plans" is overlaid in red in the upper center of the image.

HL-LHC Upgrade Plans

O. Brüning
CERN, Geneva, Switzerland

Goal of High Luminosity LHC (HL-LHC):



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

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

\rightarrow **Operation with levelled luminosity!**

\rightarrow **Ten times the luminosity reach of first 10 years of LHC operation!!**

LHC Upgrade Goals: Performance optimization

Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4p \times b^* \times e_n} \times F(f, b^*, e, S_s)$$

- 1) maximize bunch intensities
- 2) minimize the beam emittance
- 3) minimize beam size (constant beam power); → triplet aperture
- 4) maximize number of bunches (beam power); → 25ns
- 5) compensate for 'F'; → Crab Cavities
- 6) Improve machine 'Efficiency'; → minimize number of unscheduled beam aborts

LHC Limitations and HL-LHC Challenges:

- Technical bottle necks (e.g. cryogenics) → New addit. Equipment
- Insertion magnet lifetime and aperture:
 - New insertion magnets and low- β with increased aperture
- Geometric Reduction Factor: → SC Crab Cavities
 - New technology and a first for a hadron storage ring!
- Performance Optimization: Pileup density → luminosity levelling
 - devise parameters for virtual luminosity \gg target luminosity
- Beam power & losses → additional DS (cold region) collimators
- Machine efficiency and availability:
 - # R2E → removal of all electronics from tunnel region
 - # e-cloud → beam scrubbing (conditioning of surface)
 - # UFOs → beam scrubbing (conditioning of surface)

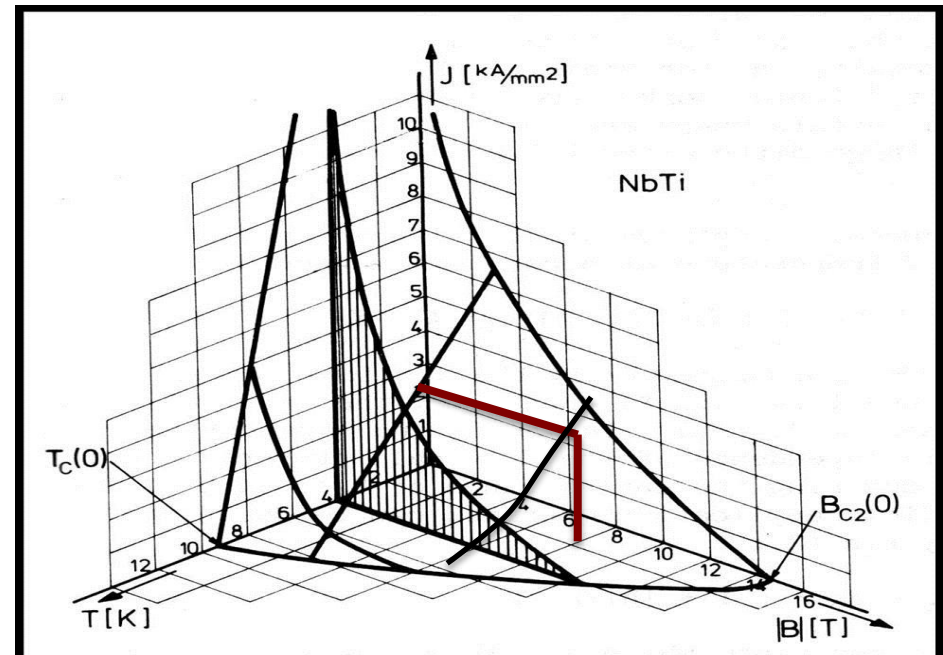
HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
 - ➔ ca. 8 T @ coil
 - ➔ 1.8 K cooling with superfluid He (thermal conductivity)
 - ➔ current density of 2.75 kA / mm²
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm²)!!!

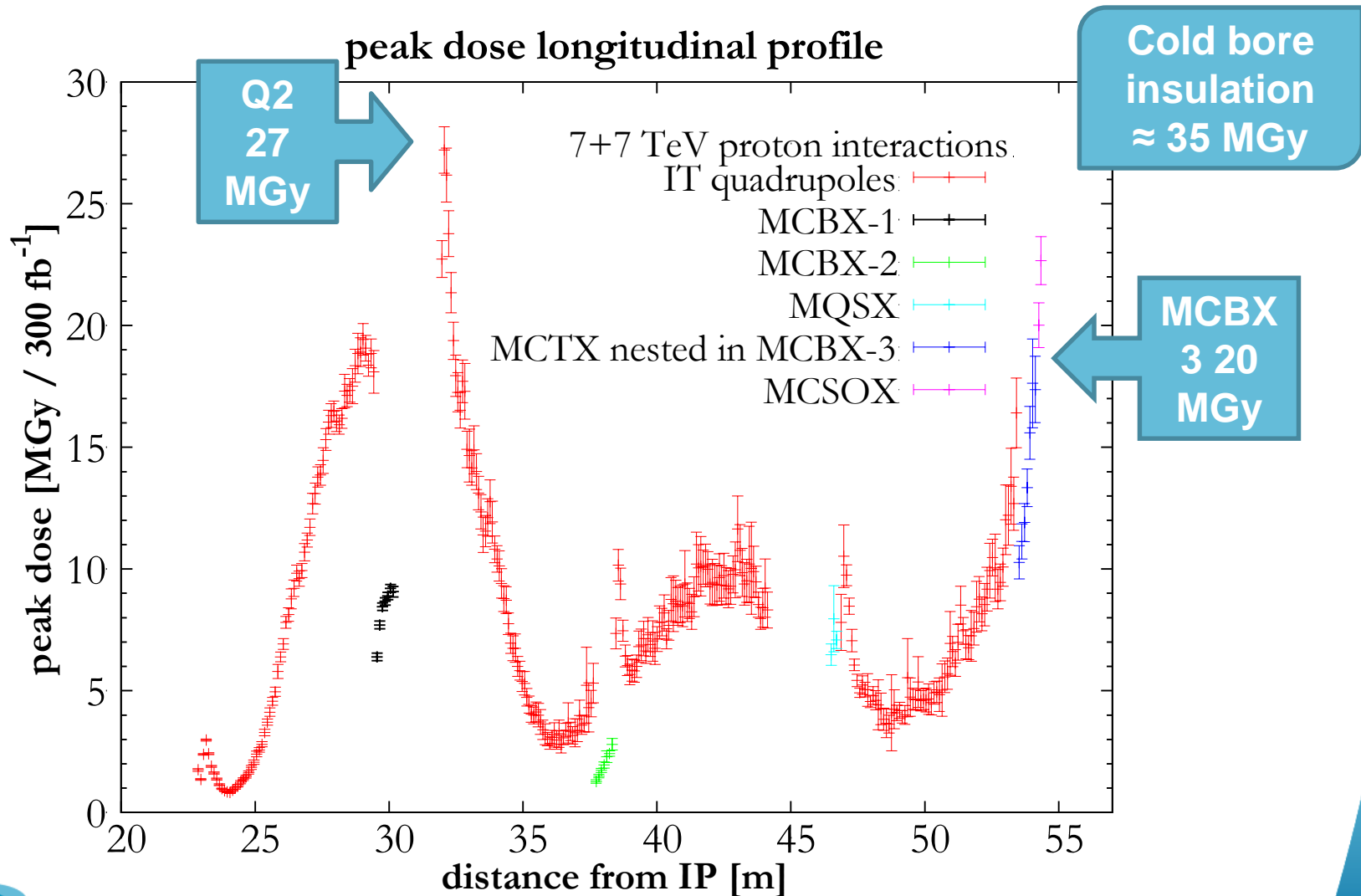
LHC Production in collaboration with USA and KEK



Critical Surface for NbTi

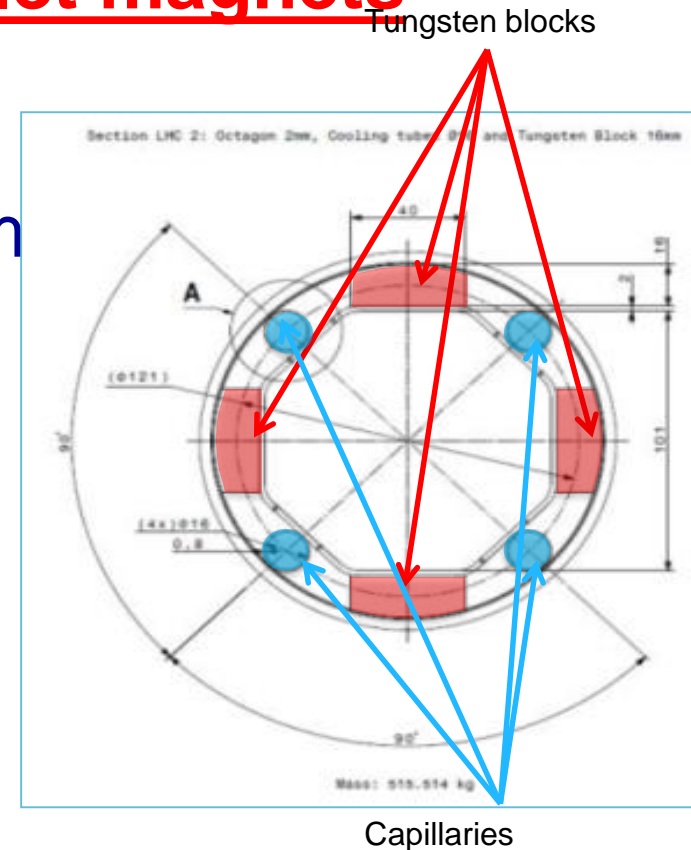


HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb⁻¹



HL-LHC technical bottleneck: Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!



→ Requires larger aperture!

→ 70mm at 210 T/m → 150mm diameter 140 T/m
8T peak field at coils → 12T field at coils!!!

HL-LHC Magnets

LHC triplet:

210 T/m, 70 mm bore aperture

→ 8 T @ coil (limit of NbTi tech.)

HL-LHC triplet:

140 T/m, 150 mm coil aperture

(shielding, β^* and crossing angle)

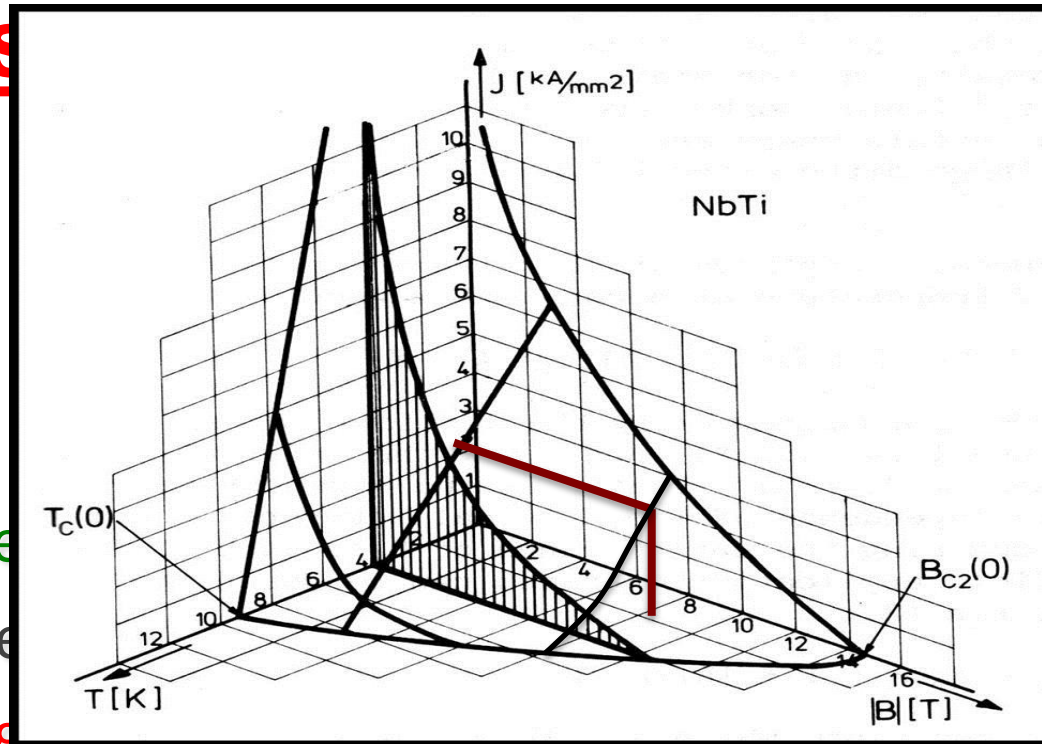
→ ca. 12 T @ coil → 30% longer

- Requires Nb₃Sn technology

→ ceramic type material (fragile)

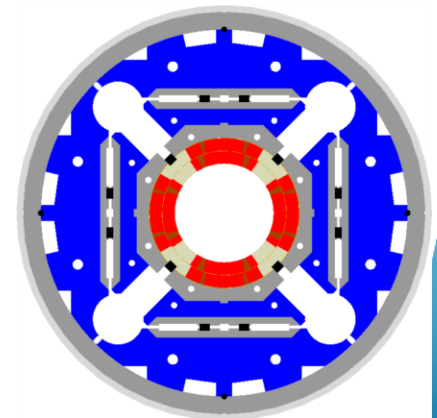
→ ca. 25 year development for this new magnet technology!

- US-LARP – CERN collaboration



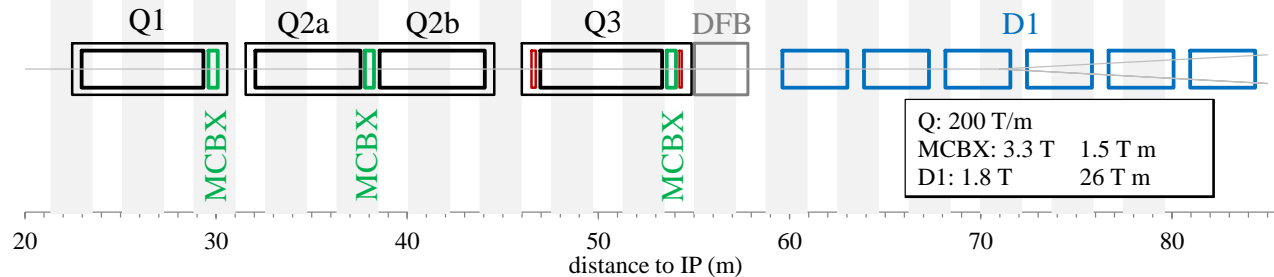
Magnetic field (T)

US-LARP MQXF
magnet design
Based on
Nb₃Sn
technology

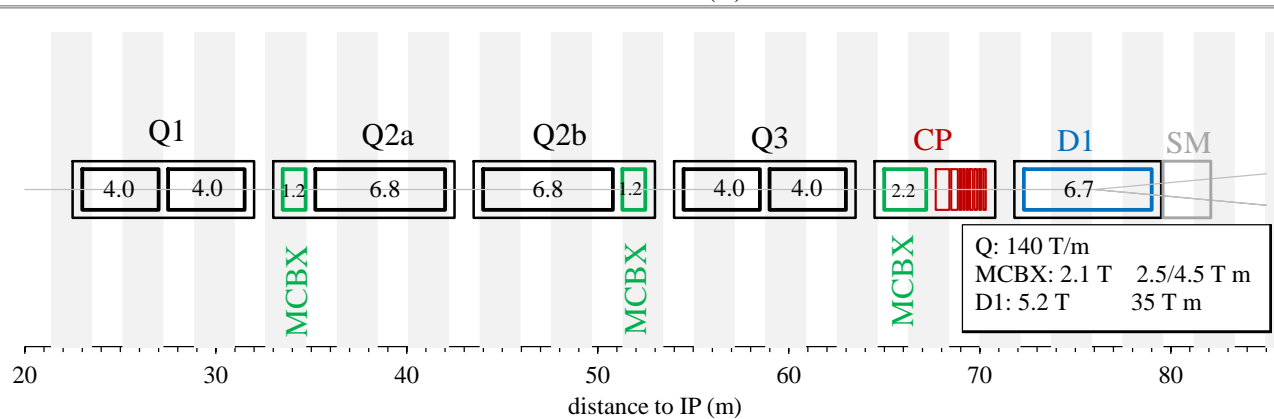


New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)



LHC

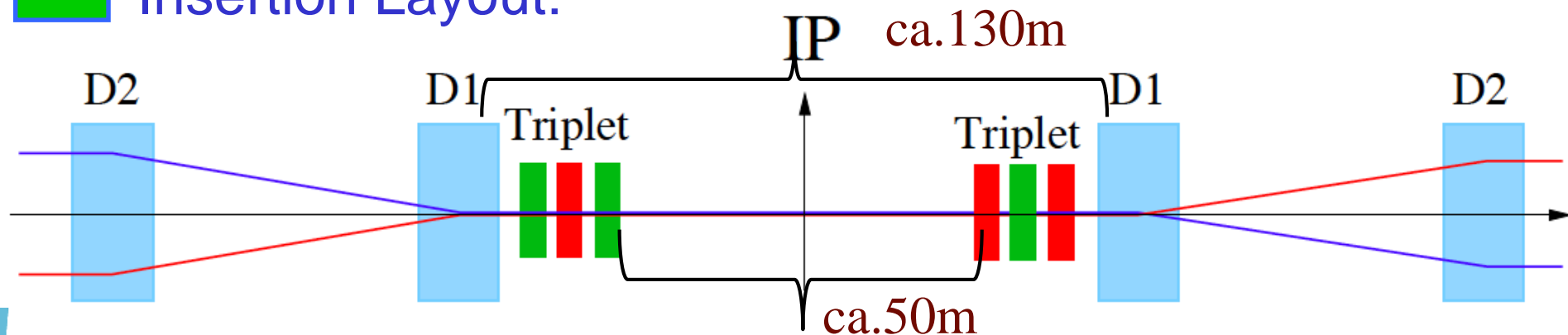


HL LHC

Thick boxes are magnetic lengths -- Thin boxes are cryostats

HL-LHC Challenges: Crossing Angle

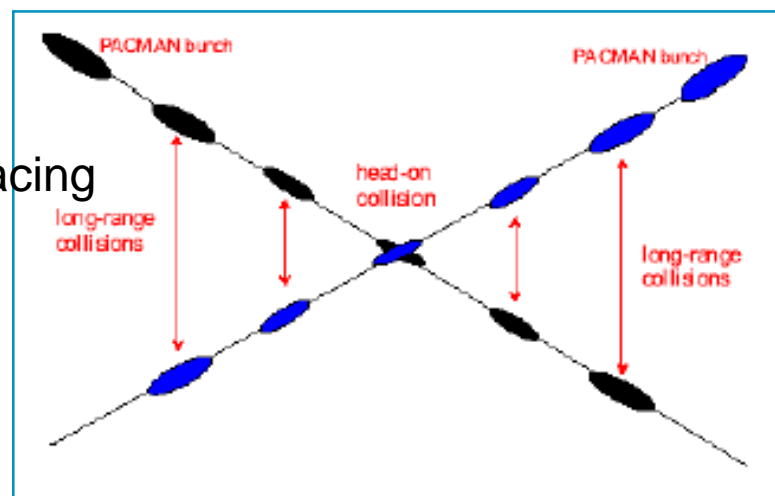
Insertion Layout:



Parasitic bunch encounters:

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

→ Operation requires crossing angle



non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points → Separation of 10 -12 σ

→ large triplet apertures for HL-LHC upgrade!!

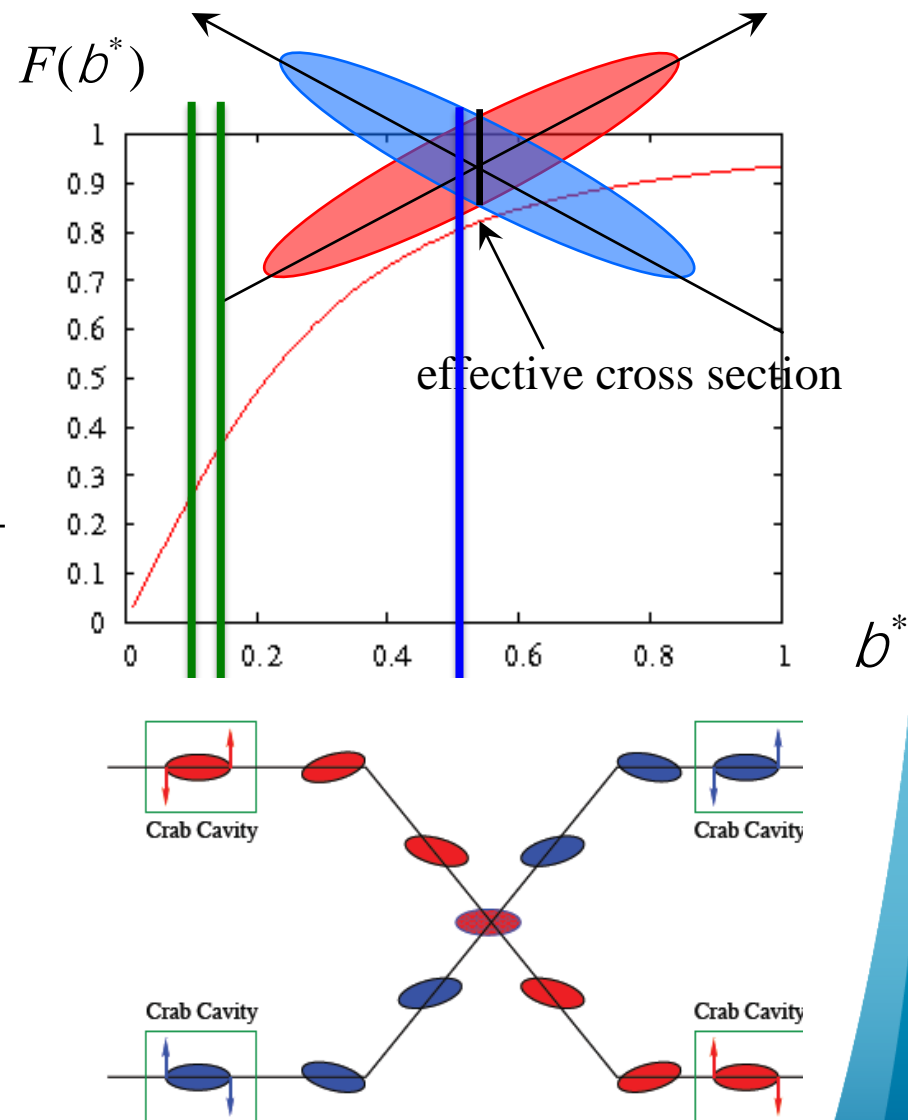
HL-LHC Upgrade Ingredients: Crab Cavities

Crab Cavities

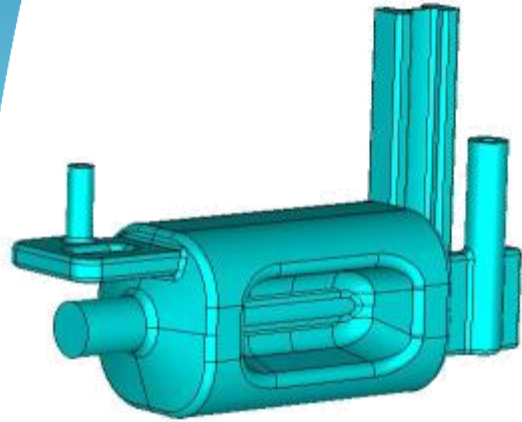
- Reduces the effect of geometrical reduction factor
- Independent for each IP

$$F = \frac{1}{\sqrt{1 + Q^2}}; \quad Q \propto \frac{q_c s_z}{2s_x}$$

- Noise from cavities to beam?!?
- Challenging space constraints:
 - requires novel compact cavity design

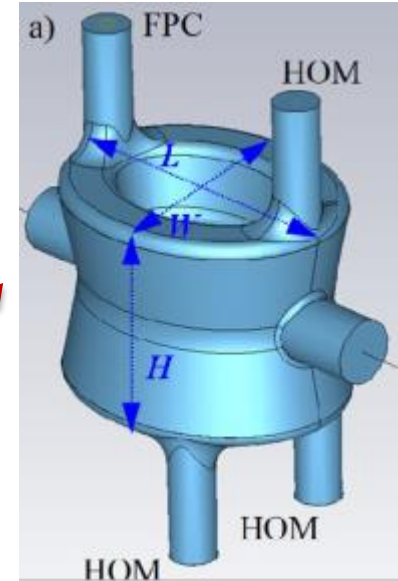
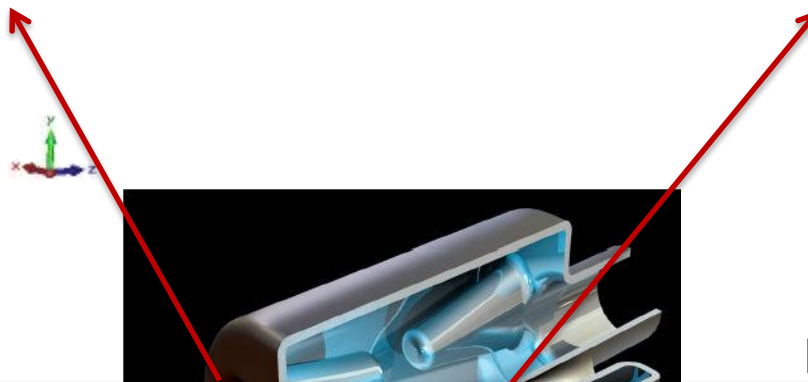


Latest cavity designs toward accelerator



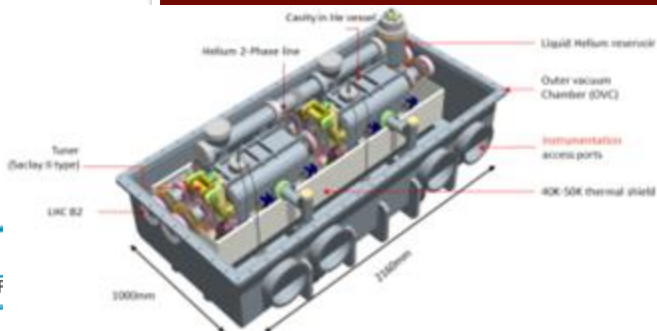
RF Dipole: Waveguide or waveguide-coax couplers

3 Advanced Design Studies with Different Coupler concepts



Double 1/4-wave:

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS



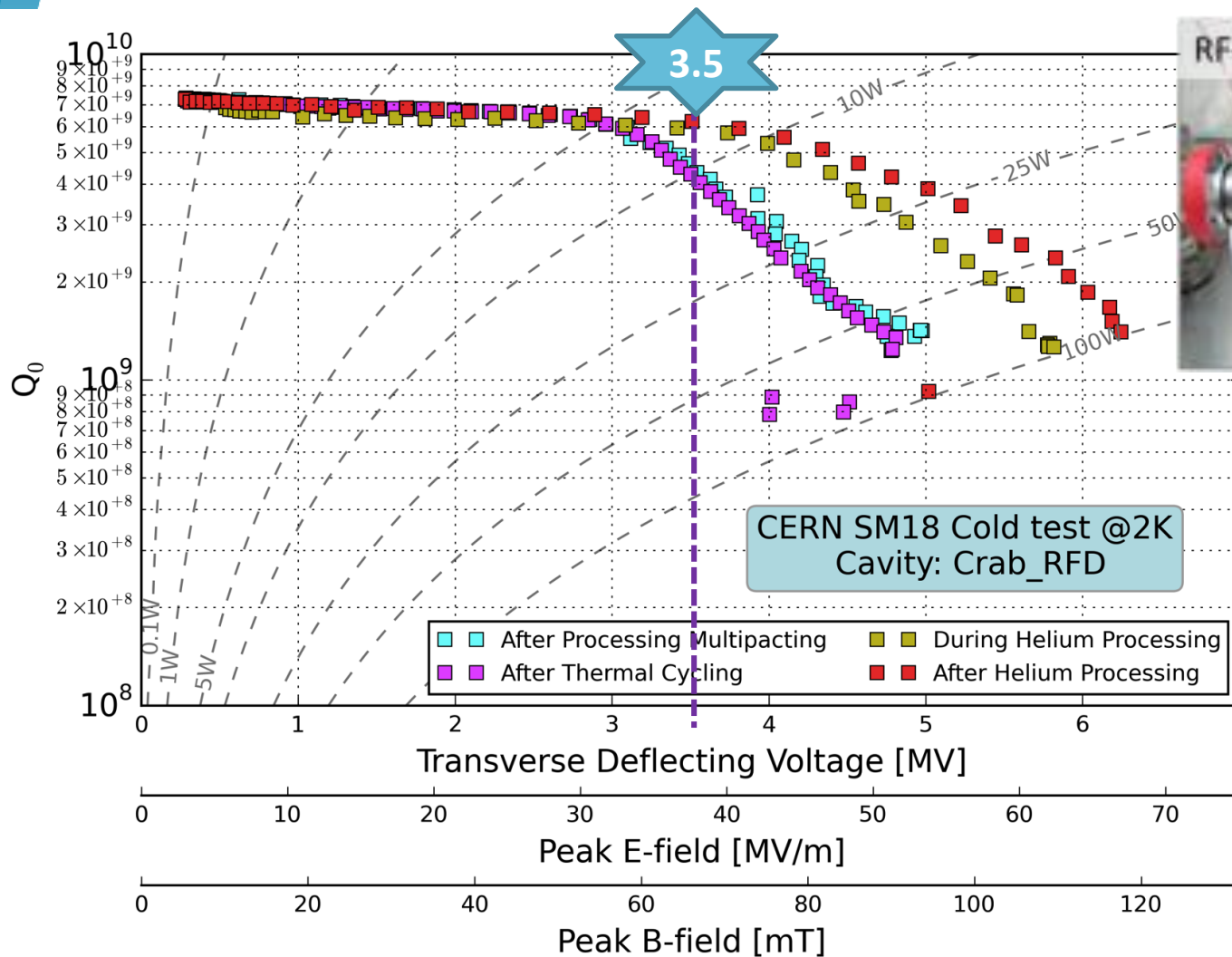
Coaxial couplers with
not all

Present baseline: 4 cavity/cryomod
TEST in SPS under preparation for 2017

Oliver Brüning, CERN

And excellent first results: RF Dipole

Recent results from Measurements @ CERN

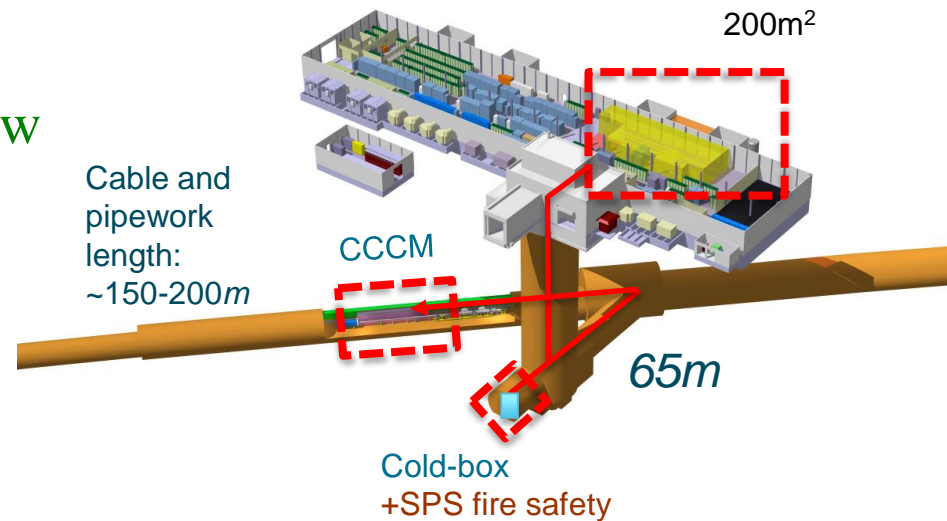
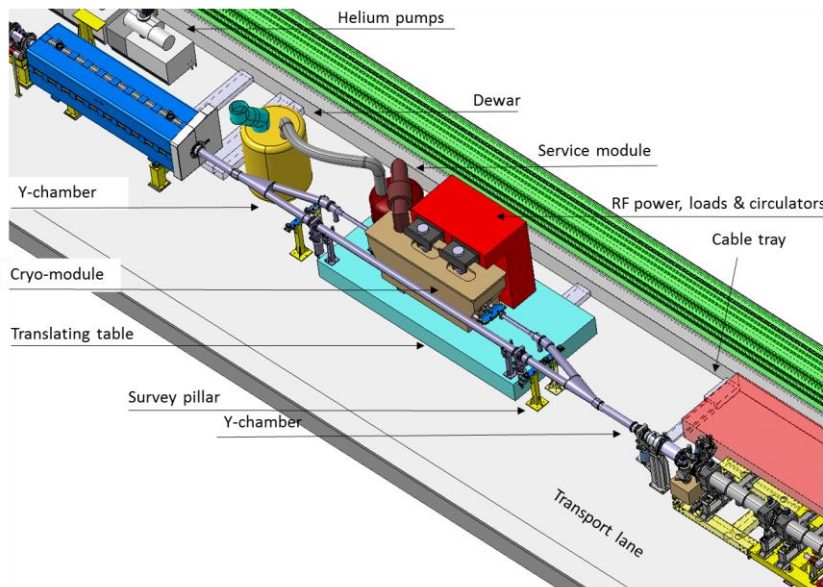


Initial goal was
3.5 MV
however
 $\Delta V > 5-6$ MV
would ease
integration

Testing Crab Cavities with Beams

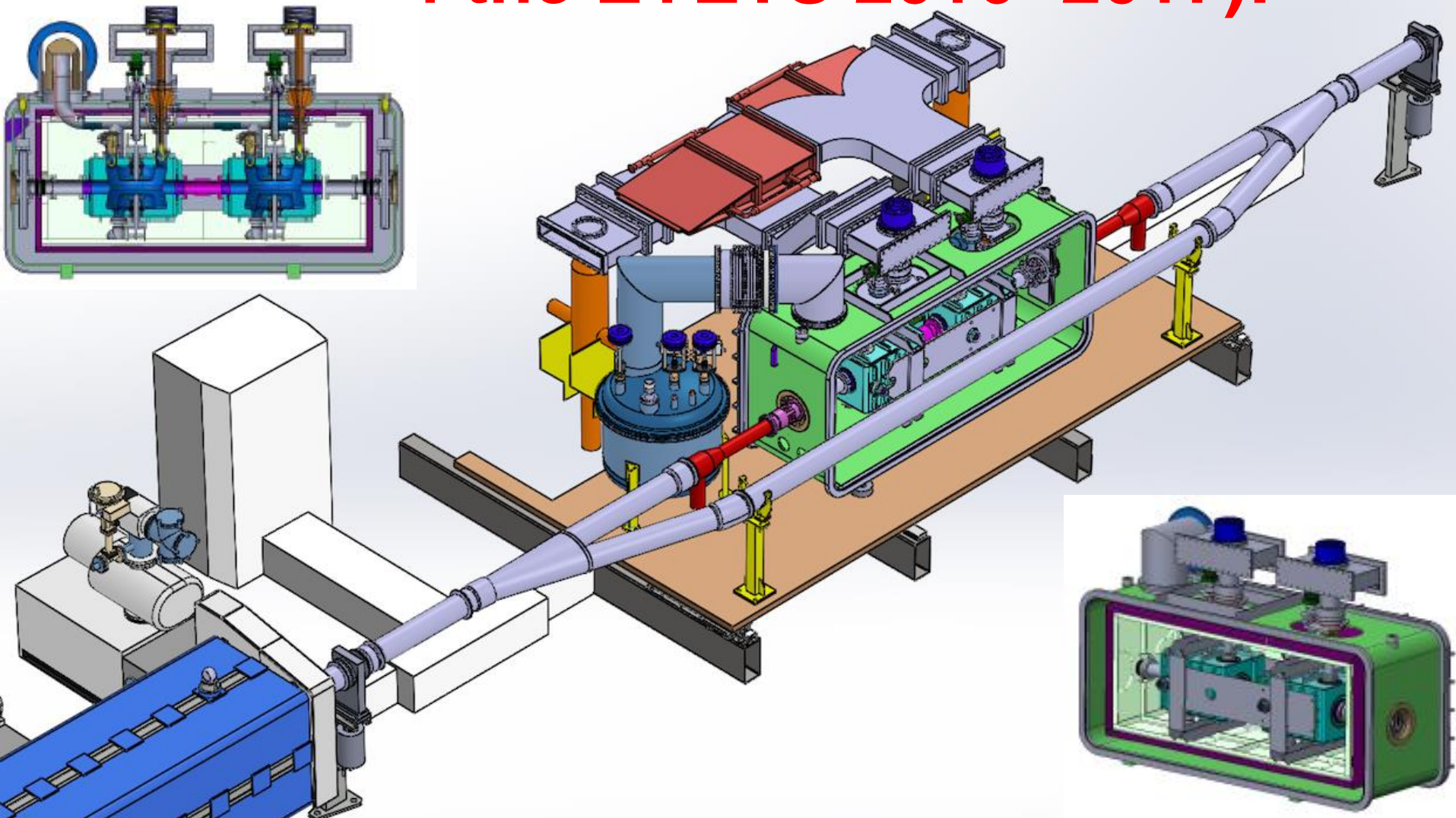
Crab Cavity Test Installation in the SPS:

- Vital to gain feedback from operation with beam before launching of cavity production for HL-LHC → need results before LS2!!!
 - Tight and ambitious schedule but doable!
- Visualization and planning now
→ Preparation in EYETS 16/17
→ Installation YETS 17/18



- vital for project to be able to launch Carb cavity production by LS2!!!
(international partners!!!)

SPS beam test: a critical step for Crab Cavities (profiting of the EYETS 2016- 2017):



LHC Challenges: Beam Power

Unprecedented beam power:

Worry about beam losses:

Failure Scenarios → Local beam Impact

→ Equipment damage

→ Machine Protection

Lifetime & Loss Spikes → Distributed losses

→ Magnet Quench

→ R2E and SEU

→ Machine efficiency

Collimation Upgrade Plans for HL-LHC

Collimation Upgrade Path for the HL-LHC:

- 2015 operation experience:
 - ➔ up to 280MJ beam energy and no quench from beam losses

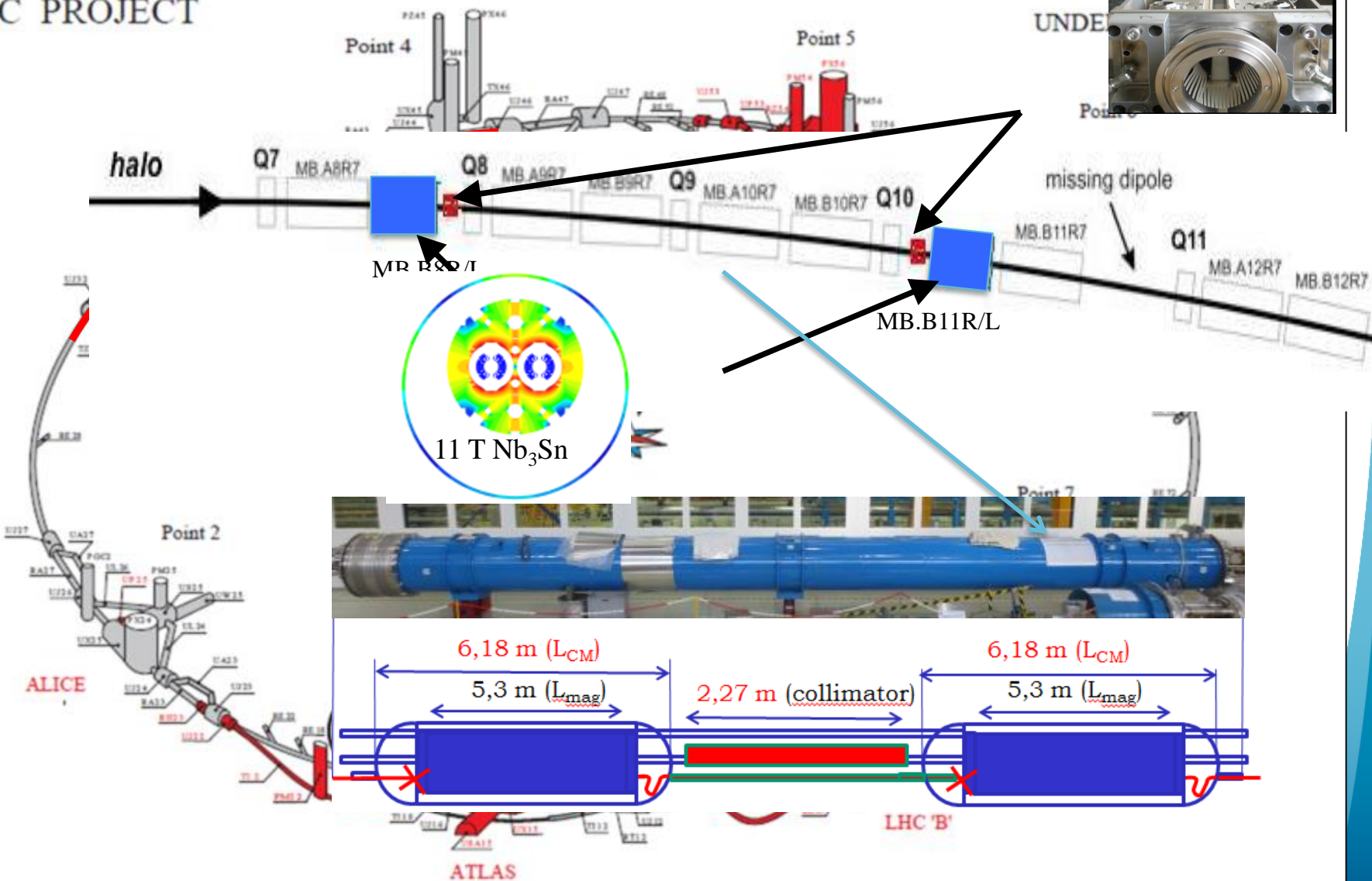
Quench test with beam:

$$E_{b-\max} > 420\text{MJ}, \text{LHC}_{\text{nom}} = 335\text{MJ}, \text{HL-LHC} = 630\text{MJ}$$

- ➔ 11T DS collimators in IR7 (2 per beam ➔ 4 units for LS2),
 - ➔ connection cryostat DS collimators in IR2 (2 units total)
 - ➔ mitigation in DS of IR1 & IR5 via orbit bumps
- Hollow e-lens: interesting for Halo depletion
 - ➔ on path to Baseline

DS collimators – 11 T Dipole (LS2 -2018)

LHC PROJECT



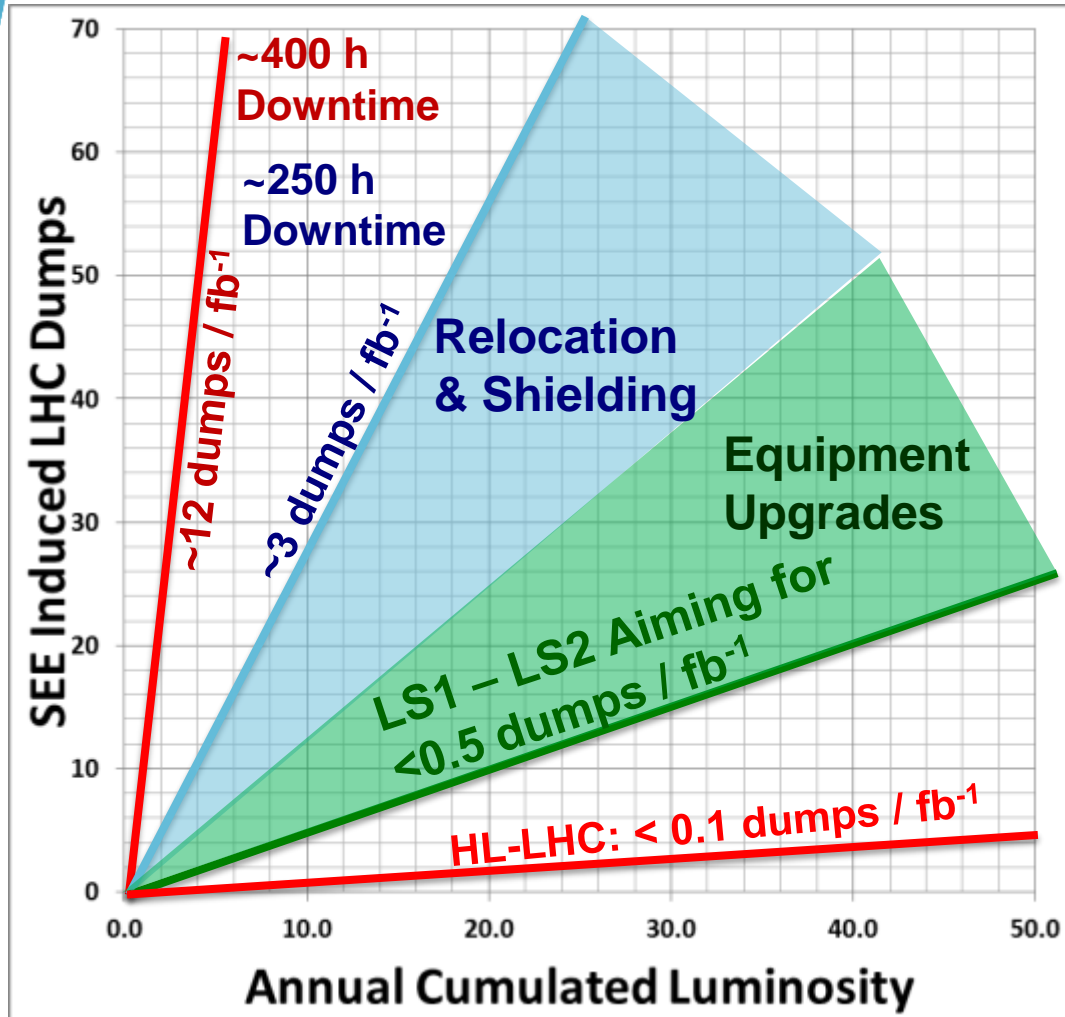
Prototyping of cryogenics bypass @ CERN



Prototyping of the by-pass cryostat (QTC) for the installation of a warm collimator in the cold dispersion

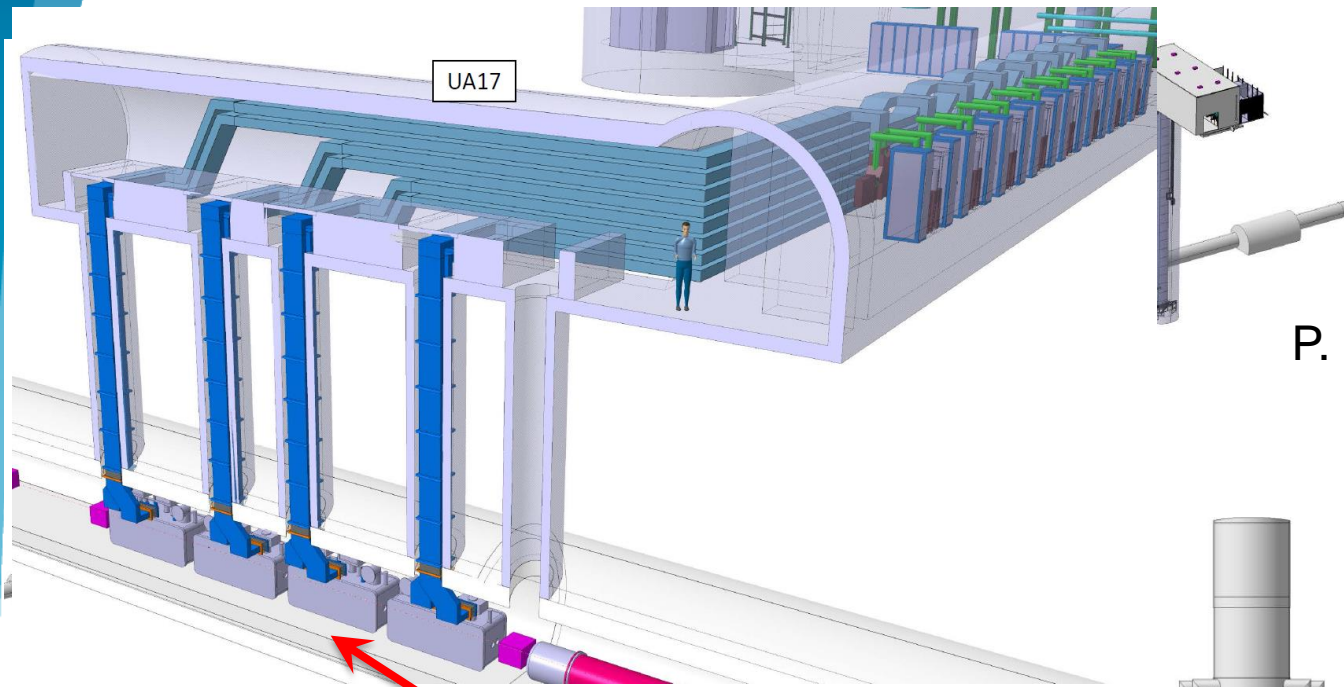
Magnet: prototypes reached 11 T field in March 2013!

R2E SEU Failure Analysis - Actions

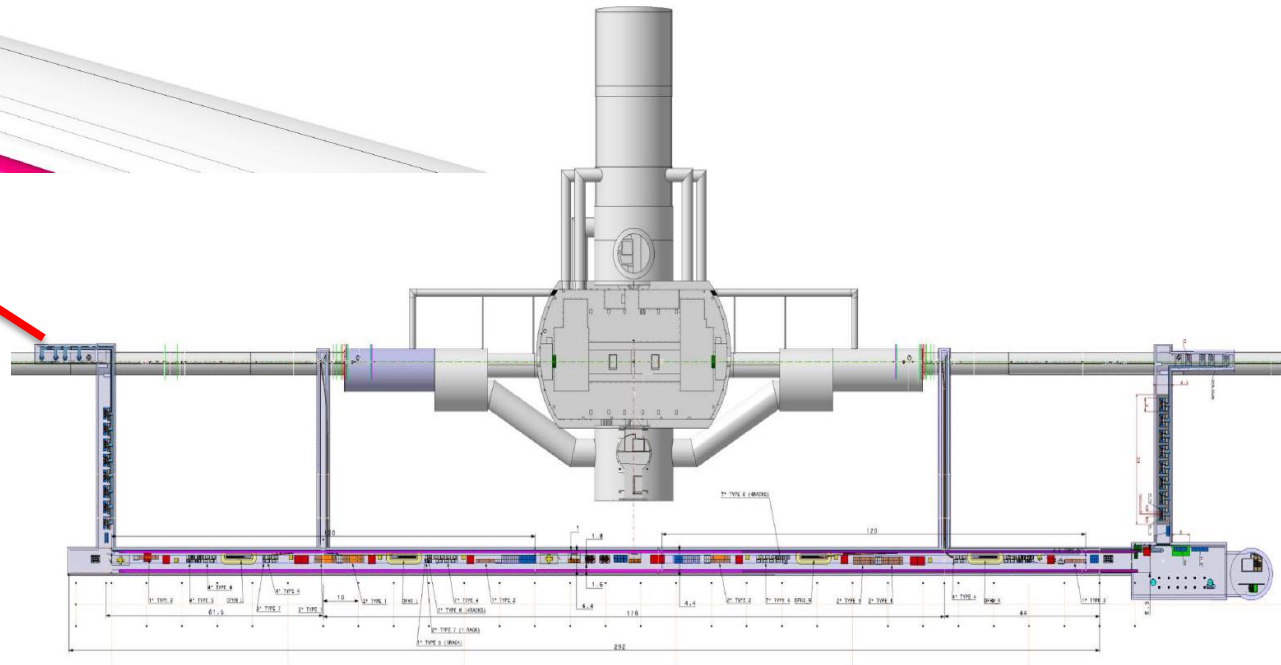


- **2008-2011**
 - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
 - Focus on equipment with long downtimes; provide shielding
- **LS1 (2013/2014)**
 - Relocation of power converters
- **LS1 – LS2:**
 - Equipment Upgrades
- **LS3 -> HL-LHC**
 - Remove all sensitive equipment from underground installations

IR1 & IR5 Underground Civil Engineering:



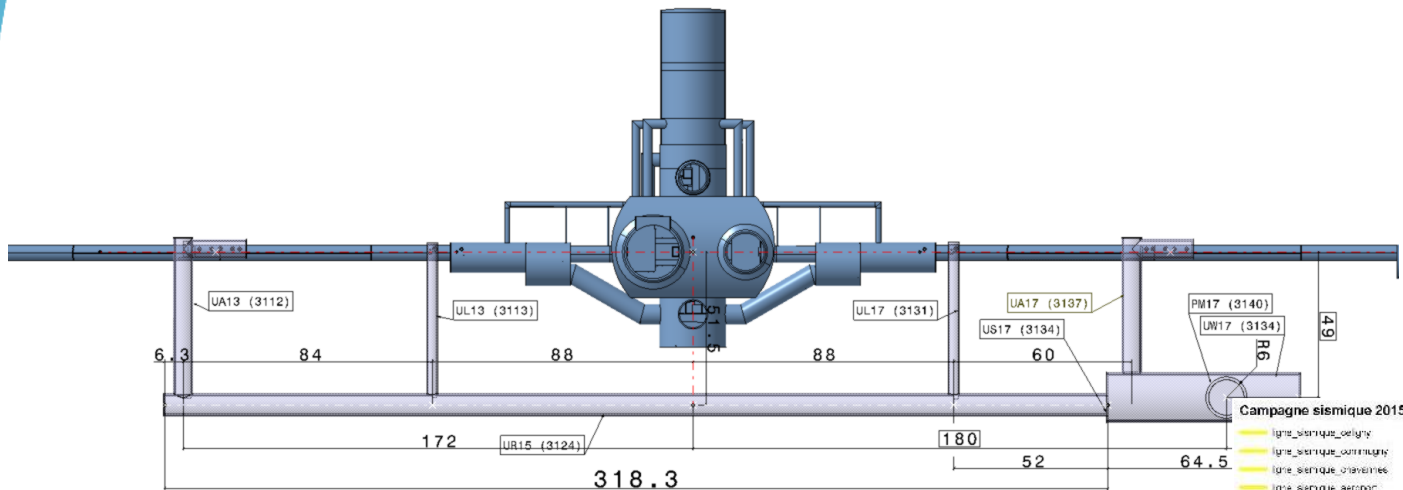
P. Fessia, HL-LHC TDR



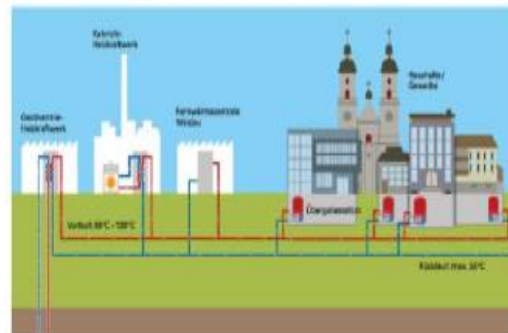
Vibration Tolerances for Operation

Lessons from Civil Engineering Test Drills and Earth Quakes On Vibration Tolerances:

- Driven by worries about vibrations from the HL-LHC civil engineering

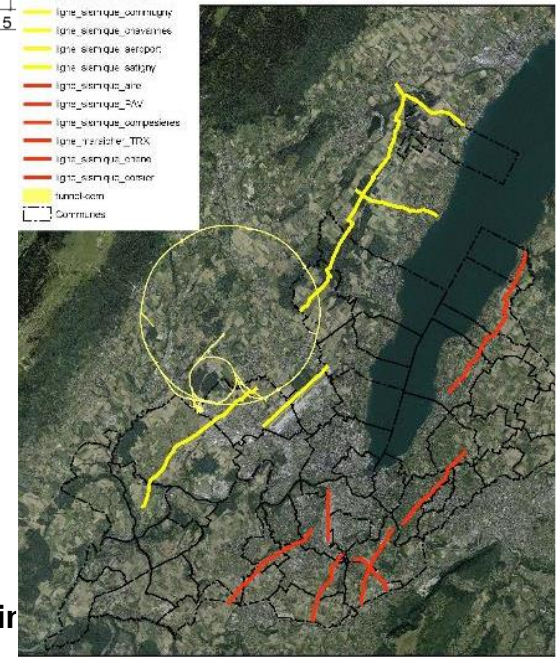


- GEO THERM2020**
a renewable energy
production project by
the Canton of Geneva



Campagne sismique 2015

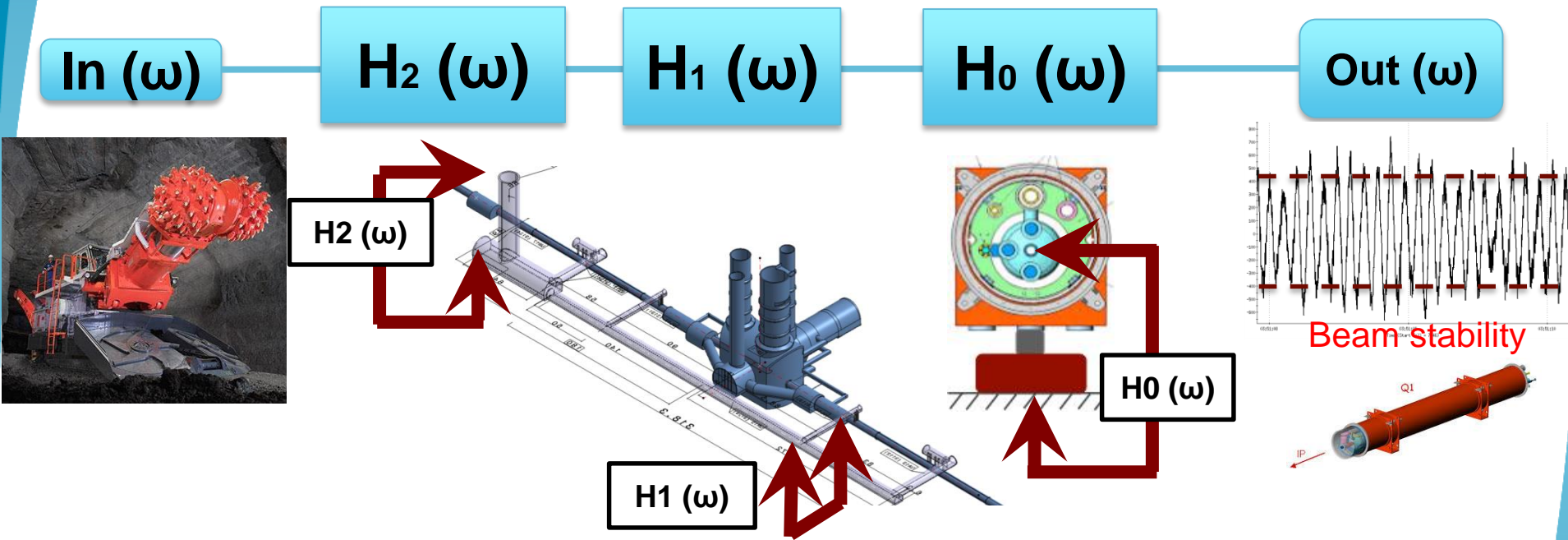
- ligne_sismique_courly
- ligne_sismique_continu
- ligne_sismique_observatoire
- ligne_sismique_serpent
- ligne_sismique_sauvage
- ligne_sismique_ave
- ligne_sismique_20V
- ligne_sismique_compression
- ligne_sismique_TTX
- ligne_sismique_observatoire
- ligne_sismique_observatoire
- tunnel-com
- Continuités



Vibration Tolerances for Operation

Lessons from Civil Engineering Test Drills and Earth Quakes On Vibration Tolerances:

- From Noise to Beam

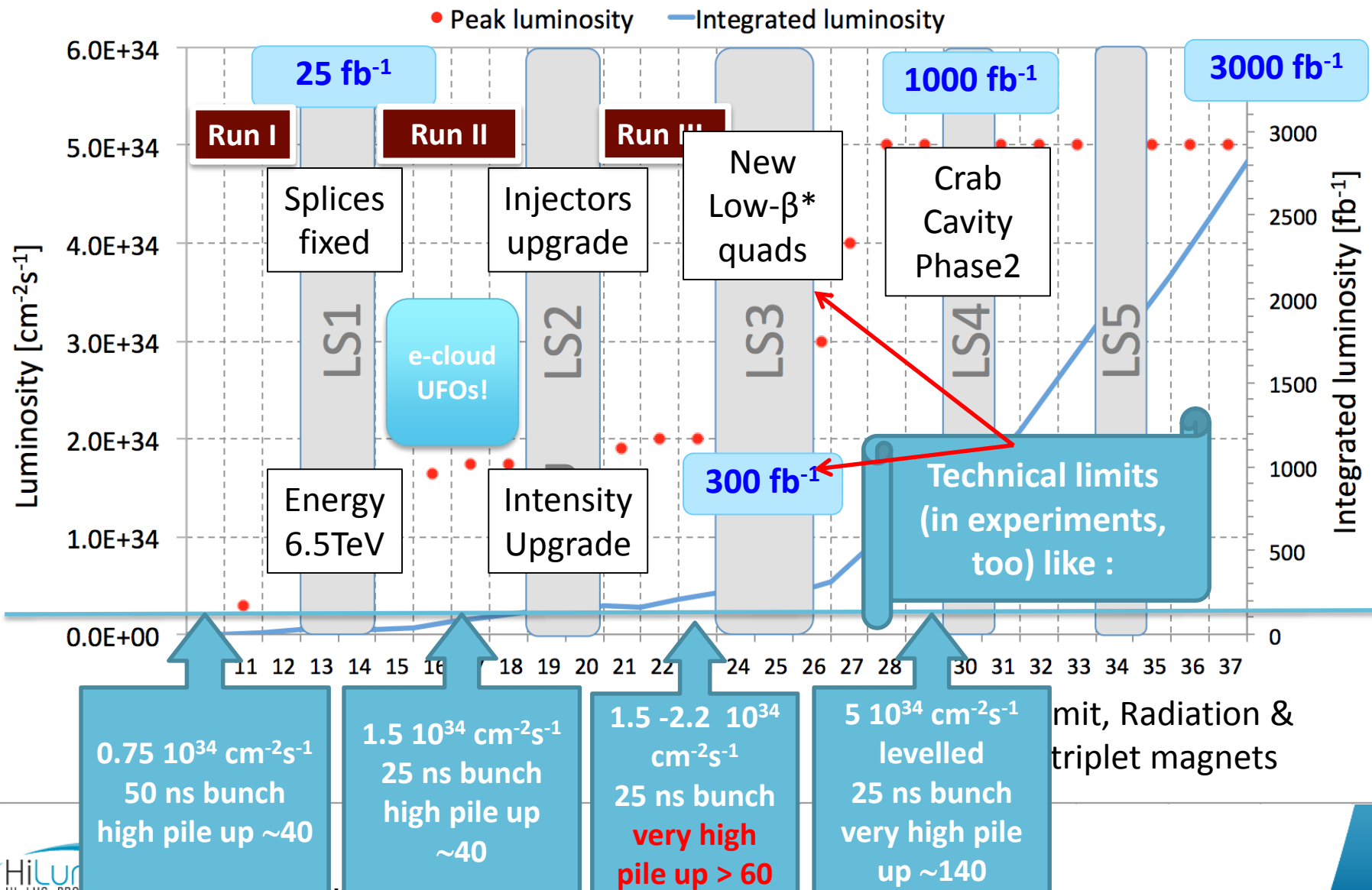


- O(100) amplification to cold-mass for certain modes (H_0)
- O(10-100) attenuation H_1 and H_2
- **order of micrometer tolerance for vibrations!**
- **Schedule that allows CE construction during LS2!!**
- **Hollow electron lens for halo depletion!**

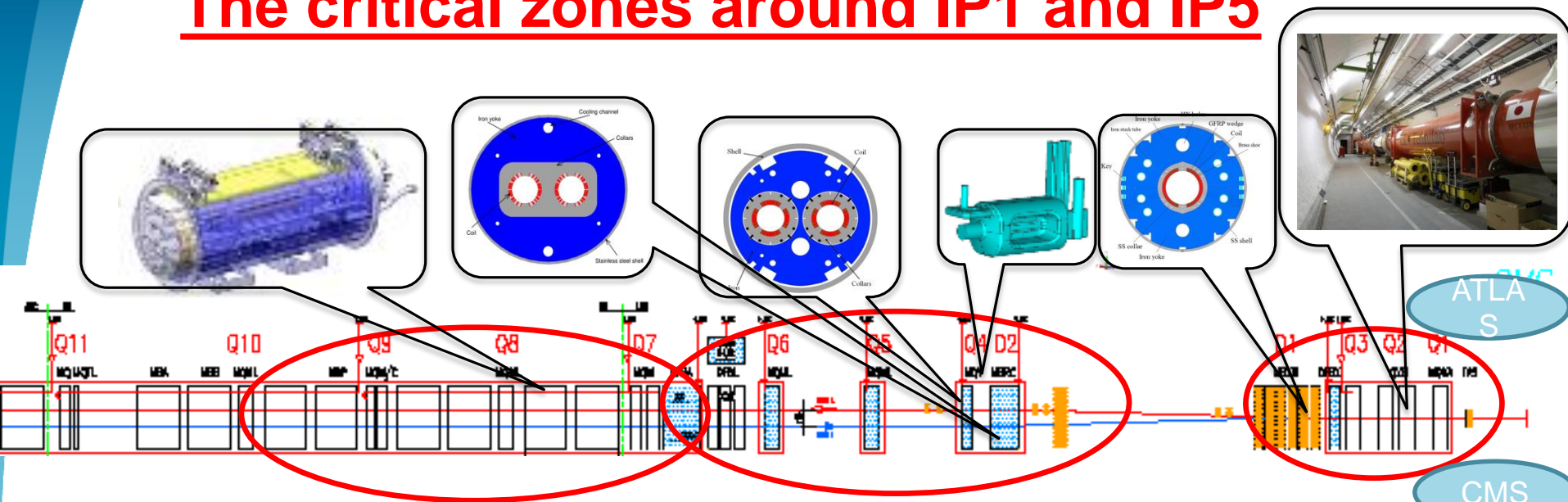
New Schedule: → HL-LHC CE during LS2



Performance Projections up to HL-LHC:



The critical zones around IP1 and IP5



3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb₃Sn dipole

2. We also need to modify a large part of the matching section
e.g. Crab Cavities & D1, D2, Q4, Q5

1. New triplet Nb₃Sn required due to:
-Radiation damage
-Need for more aperture

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

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

HL-LHC Baseline Parameters:

Collision values

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25 ns (BCMS)	HL-LHC 50ns
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E11	3.5E+11
n_b	2808	2748 ¹	2604	1404
Number of collisions at IP1 and IP5	2808	2736	2592	1404
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.9E+14
beam current [A]	0.58	1.09	1.03	0.89
x-ing angle [μrad]	285	590	590	590
beam separation [σ]	9.4	12.5	12.5	11.4
β^* [m]	0.55	0.15	0.15	0.15
ϵ_n [μm]	3.75	2.50	2.50	3
ϵ_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	20.4	16.1
Piwinski angle	0.65	3.14	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	0.305	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.838
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [cm ⁻² s ⁻¹]	1.00E+34	7.18E+34	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: $L_{peak} \cdot R1/R0$ [cm ⁻² s ⁻¹]	(1.18E+34)	19.54E+34	18.52E+34	21.38E+34
Events / crossing without levelling w/o crab-cavity	27	198	198	454
Levelled Luminosity [cm ⁻² s ⁻¹]	-	5.00E+34	5.00E34	2.50E+34
Events / crossing (with levelling and crab-cavities for HL-LHC)	27	138	146	135
Peak line density of pile up event [evt/mm] (max over stable beam)	0.21	1.25	1.31	1.20
Levelling time [h] (assuming no emittance growth)	-	8.3	7.6	18.0

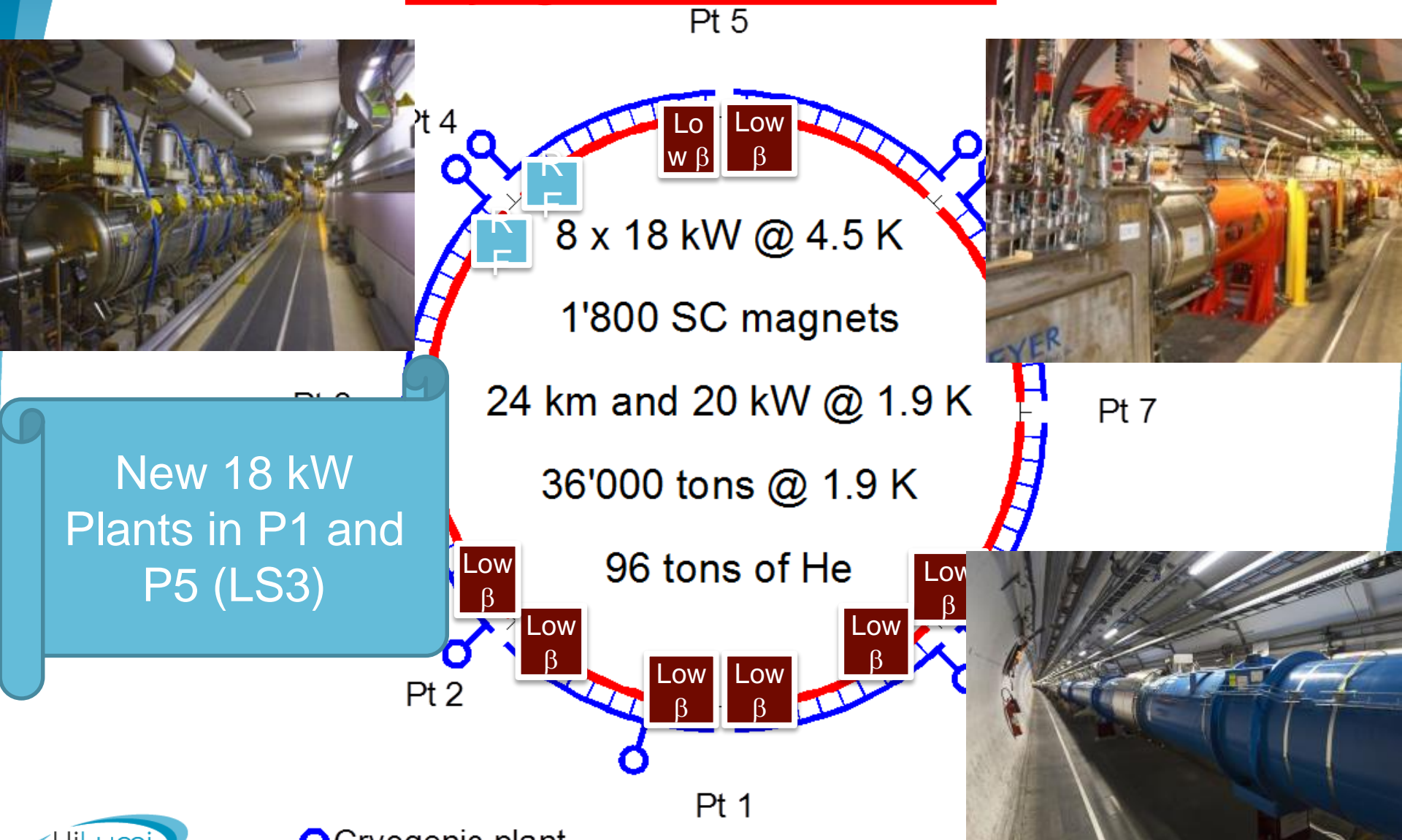
$$L = \gamma \frac{f_{rev} n_b N_b^2}{4\pi \epsilon_n \beta^*} R$$

ATS required

Reserve Transparencies

Eliminating Technical Bottlenecks

Cryogenics P4- P1 –P5



High Luminosity LHC Participants

SLAC
NATIONAL ACCELERATOR LABORATORY



Fermilab

OLD DOMINION UNIVERSITY

BROOKHAVEN
NATIONAL LABORATORY



Science & Technology
Facilities Council



UNIVERSITY OF
LIVERPOOL

LANCASTER UNIVERSITY

MANCHESTER 1824



ROYAL HOLLOWAY
UNIVERSITY OF LONDON

UNIVERSITY OF
Southampton



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

CSIC
Consejo Superior de Investigaciones Científicas

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

INFN
Istituto Nazionale
di Fisica Nucleare

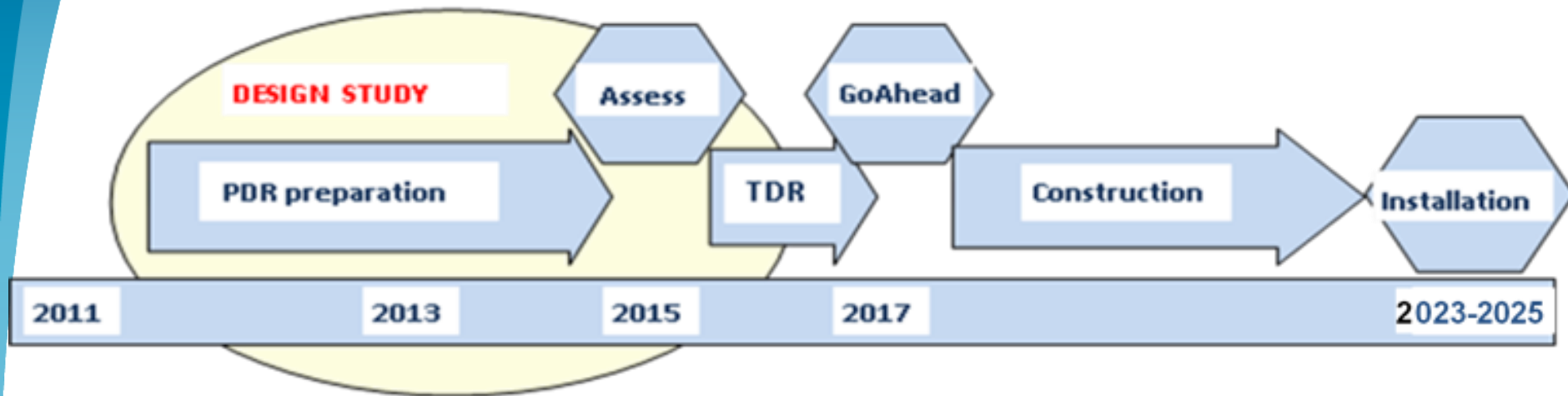


KEK

KEK HIGH ENERGY ACCELERATOR PROGRAM ORGANIZATION



Implementation plan:



- PDR: Oct 2014 ; Ext. Cost & Schedule Review in Jan-Feb 2015;
- TDR: OCT 2015; TDR_v2 : 2017
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Start construction 2018 for IT, CC & other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-25
- Though but – based on LHC experience – feasible

Project approval milestones:

- June 2010: launch of High Luminosity LHC
- November 2010 : HiLumi DS application to FP7
- November 2011: start FP7-HiLumi DS
- May 2013: approval of HL-LHC as 1st priority of EU-HEP strategy by CERN Council in Brussels
- May 2014: US P5 ranks HL-LHC as priority for DOE
- June 2014: CERN Council approves the financial plan of HL-LHC till 2025 (with an overall 10% budget cut)

LHC Challenges: Quench Protection

■ Magnet Quench:

→ beam abort → several hours of recovery

■ HL LHC beam intensity: $I > 1 \text{ A} \Rightarrow > 7 \cdot 10^{14} \text{ p /beam}$

■ Quench level: $N_{\text{lost}} < 7 \cdot 10^8 \text{ m}^{-1} \rightarrow < 10^{-6} N_{\text{beam}}!$

(compared to 20% to 30% in other superconducting rings)

→ requires collimation during all operation stages!

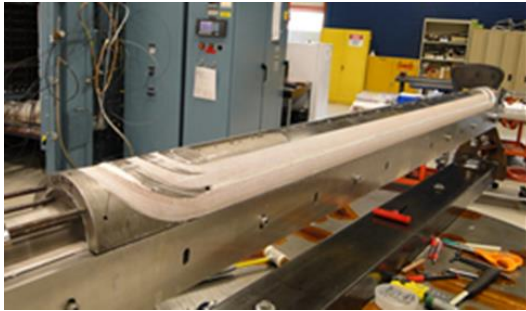
→ requires good optic and orbit control! → Which we have demonstrated during Run1

→ HL-LHC luminosity implies higher leakage from IP & requires additional collimators

FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)



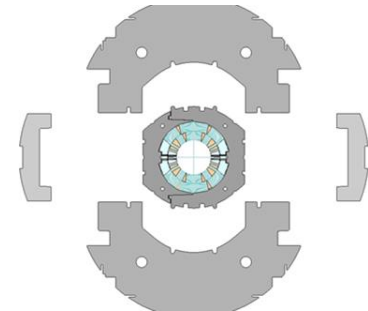
40-strand cable fabricated using FNAL cabling machine



Coil fabrication



Collared coil assembly



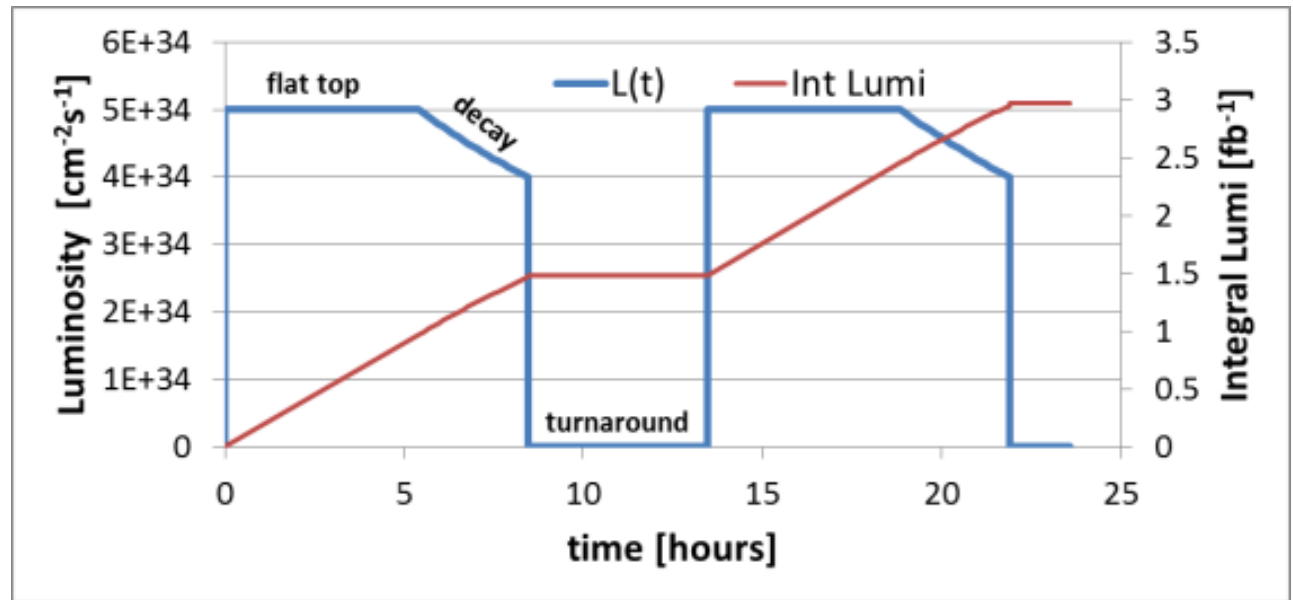
Cold mass assembly



MBHSP02 passed 11 T field during training at 1.9 K
with $I = 12080\text{A}$ on 5th March 2013!

LHC Upgrade Goals: Performance optimization

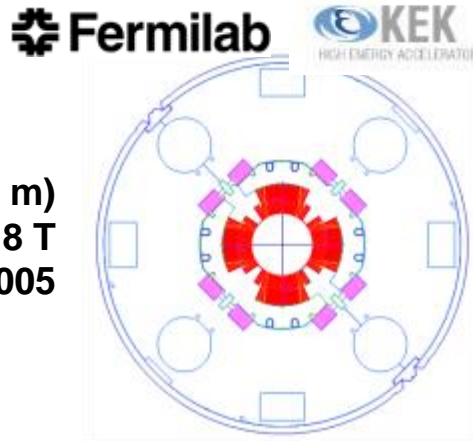
■ Levelling:



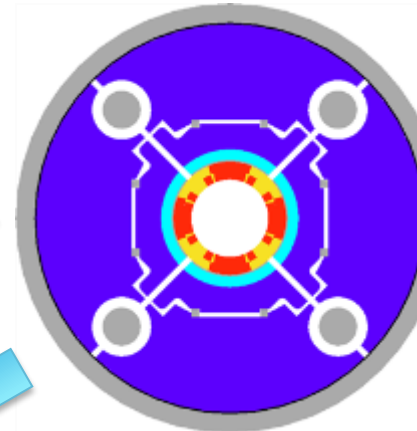
■ Luminosity limitation(s):

- Even Pileup in detectors
- Debris leaving the experiments and impacting in the machine (magnet quench protection)
- Triplet Heat Load

LHC low- β quads: steps in magnet technology from LHC toward HL-LHC

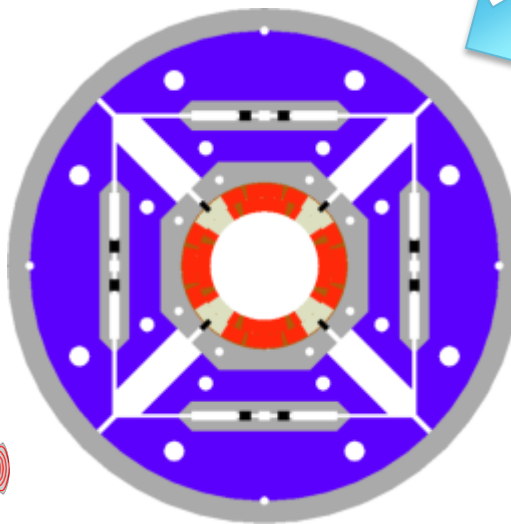


LHC (USA & JP, 5-6 m)
 $\varnothing 70$ mm, $B_{\text{peak}} \sim 8$ T
 1992-2005

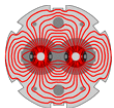


LARP TQS & LQ (4m)
 $\varnothing 90$ mm, $B_{\text{peak}} \sim 11$ T
 2004-2010

New structure
 based on
 bladders and
 keys (LBNL,
 LARP)

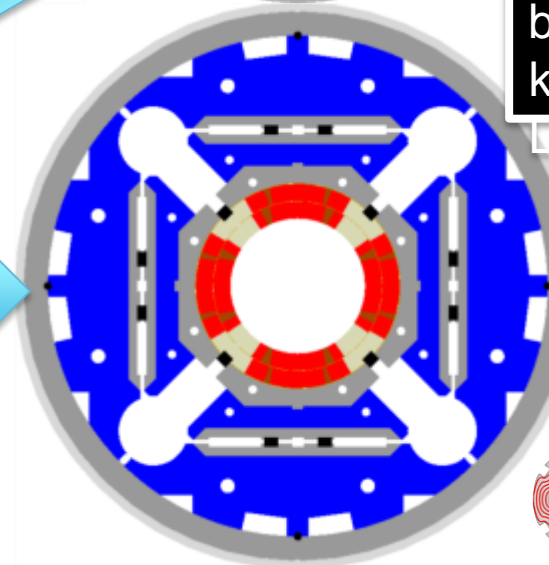


LARP HQ
 $\varnothing 120$ mm,
 $B_{\text{peak}} \sim 12$ T
 2008-2014

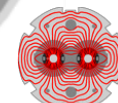


LARP

ACES Workshop March 7th 2016



LARP & CERN
 MQXF
 $\varnothing 150$ mm,
 $B_{\text{peak}} \sim 12.1$ T
 2013-2020



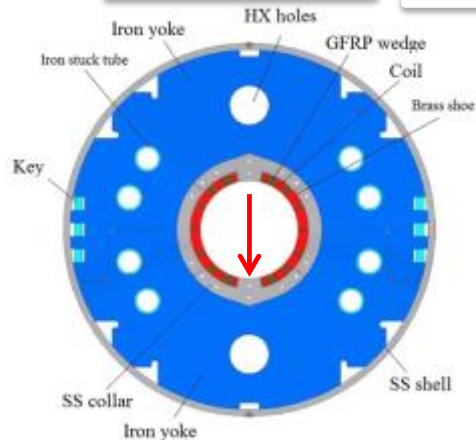
LARP



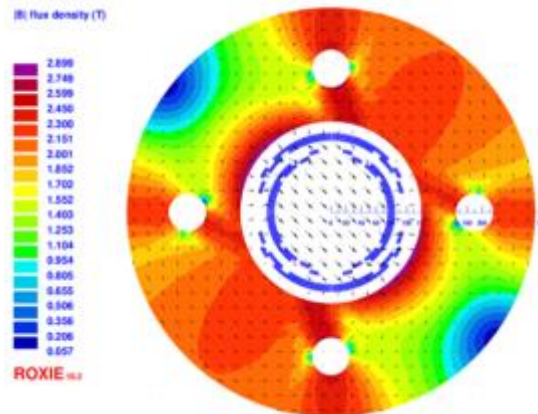
Oliver Brüning, CERN

The HL-LHC Nb-Ti magnet zoo...

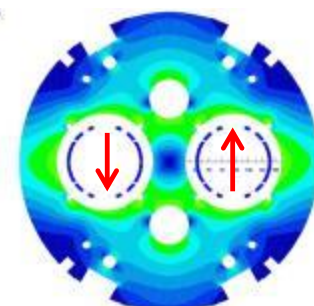
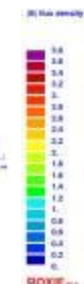
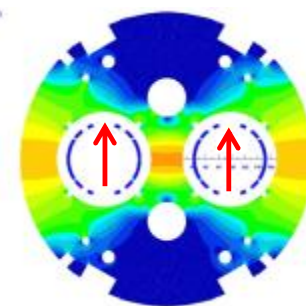
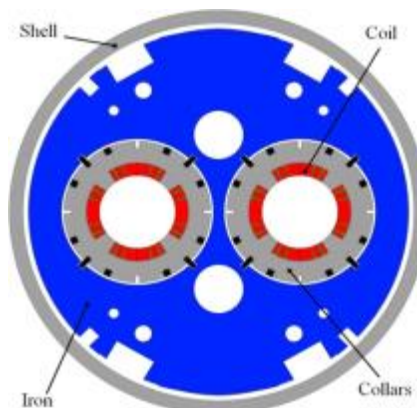
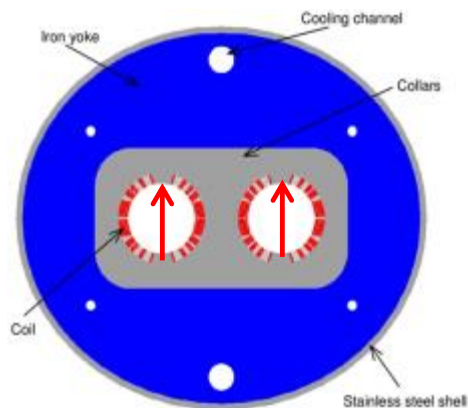
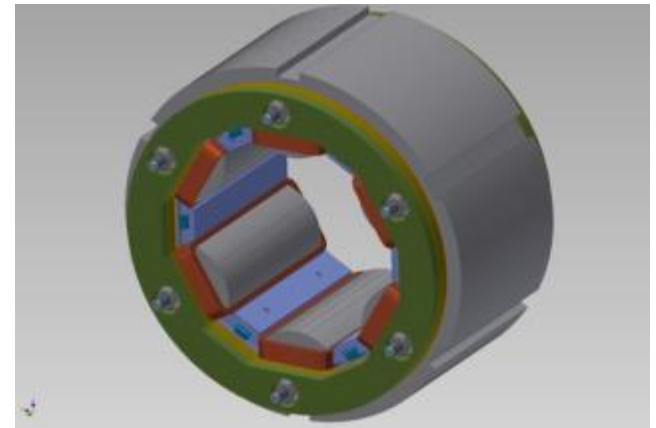
D1 (KEK)



Nested Orbit corrector (CIEMAT)



HO correctors: superferric (INFN)

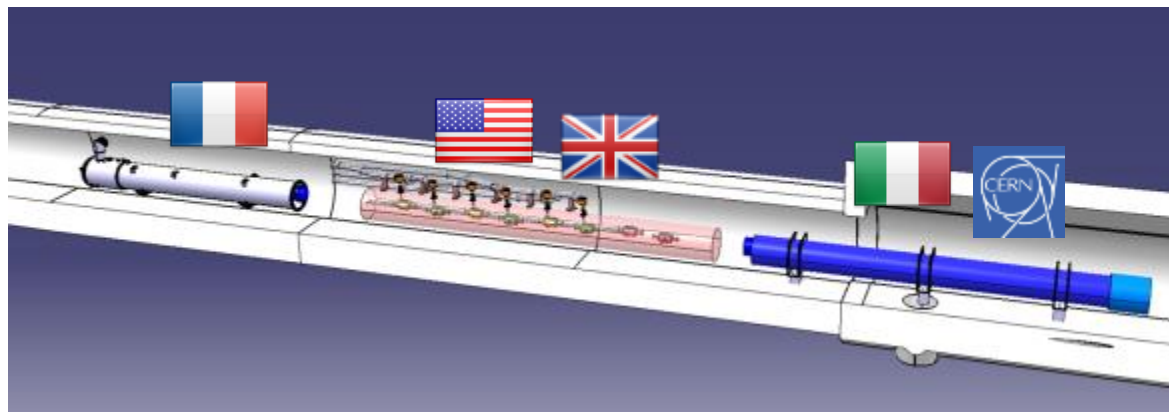
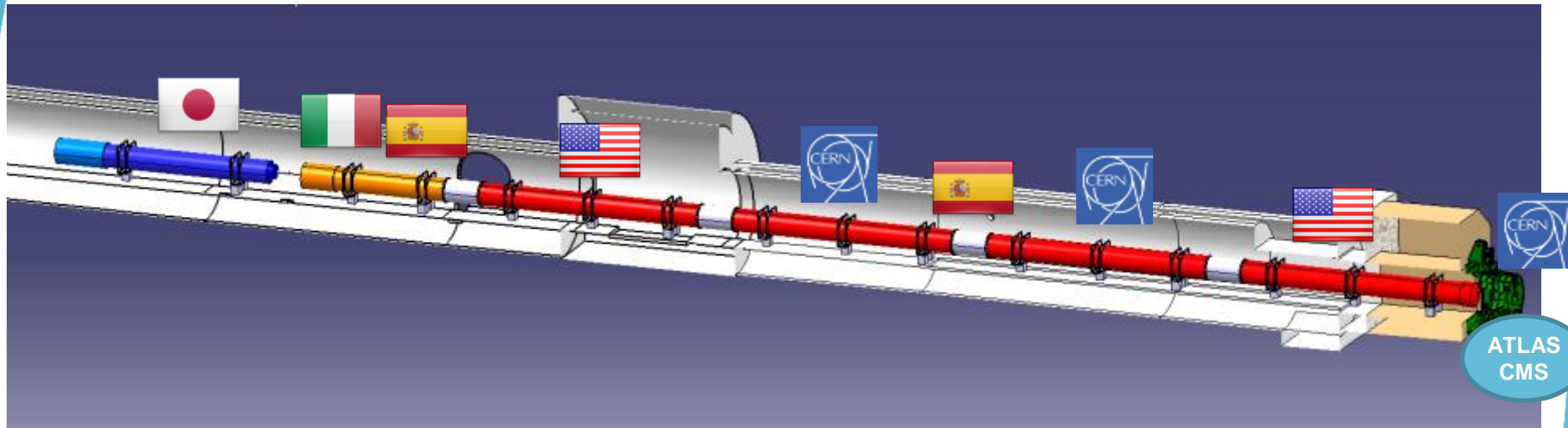


D2 (INFN)

Q4 (CEA)

D2 corr

In-kind contribution and Collaboration for HW design and prototypes



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**

Q4 : Design and Prototype **FR**

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

CC : R&D and Design **UK**

3 Crab Cavity prototypes:

RF-Dipole Nb prototype [ODU-SLAC]



4-rod in SM18 for RF measurements [Lancaster UK]



4-rod prepared for rinsing @ CERN

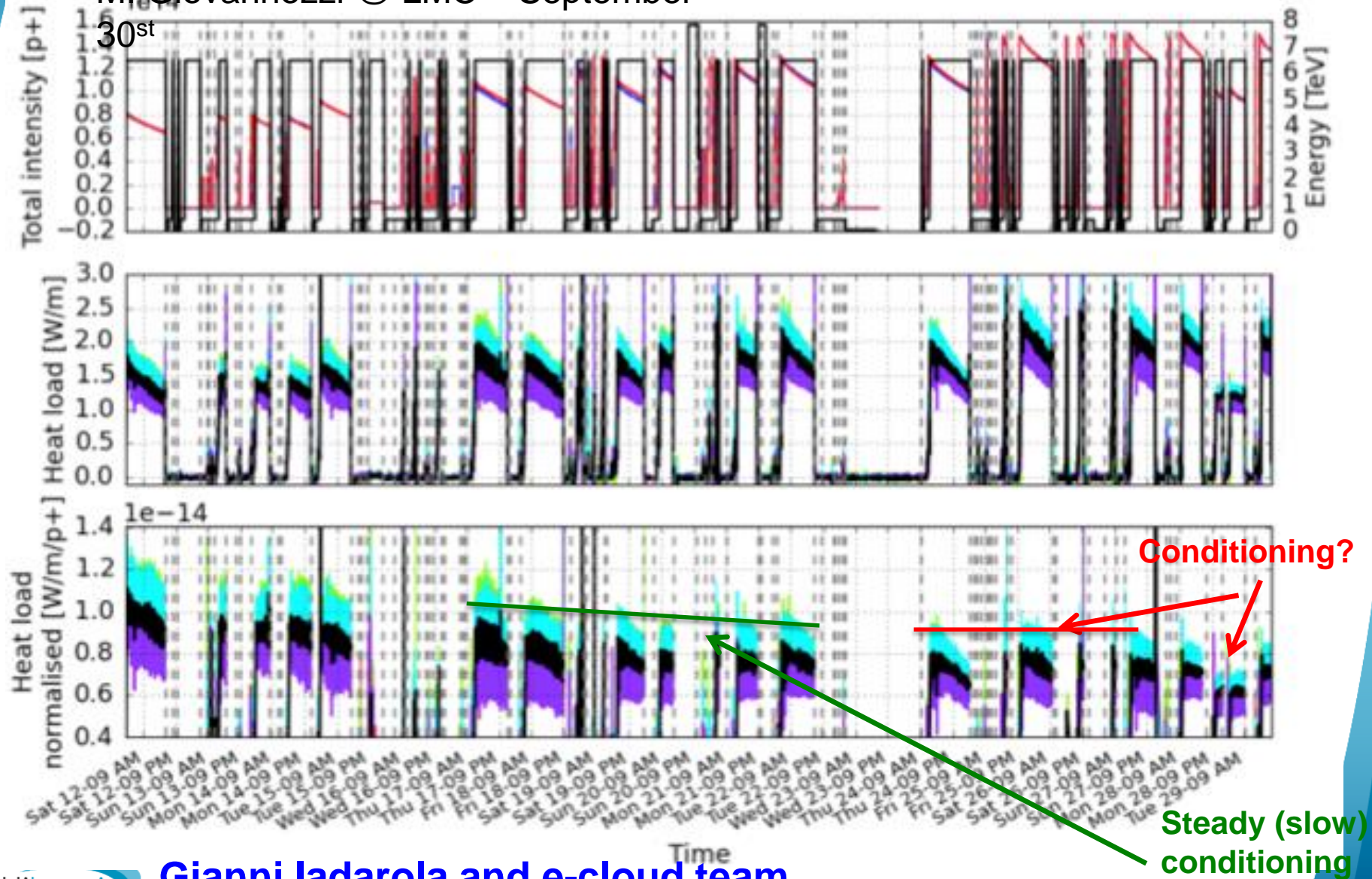


DQWR prototype
(17-Jan-2013) [BNL]



Scrubbing with 25ns: Heat Load Evolution

M. Giovannozzi @ LMC – September



Gianni Iadarola and e-cloud team

ACES Workshop March 7th 2016

Oliver Brüning, CERN