Future of the LHC and particle accelerators

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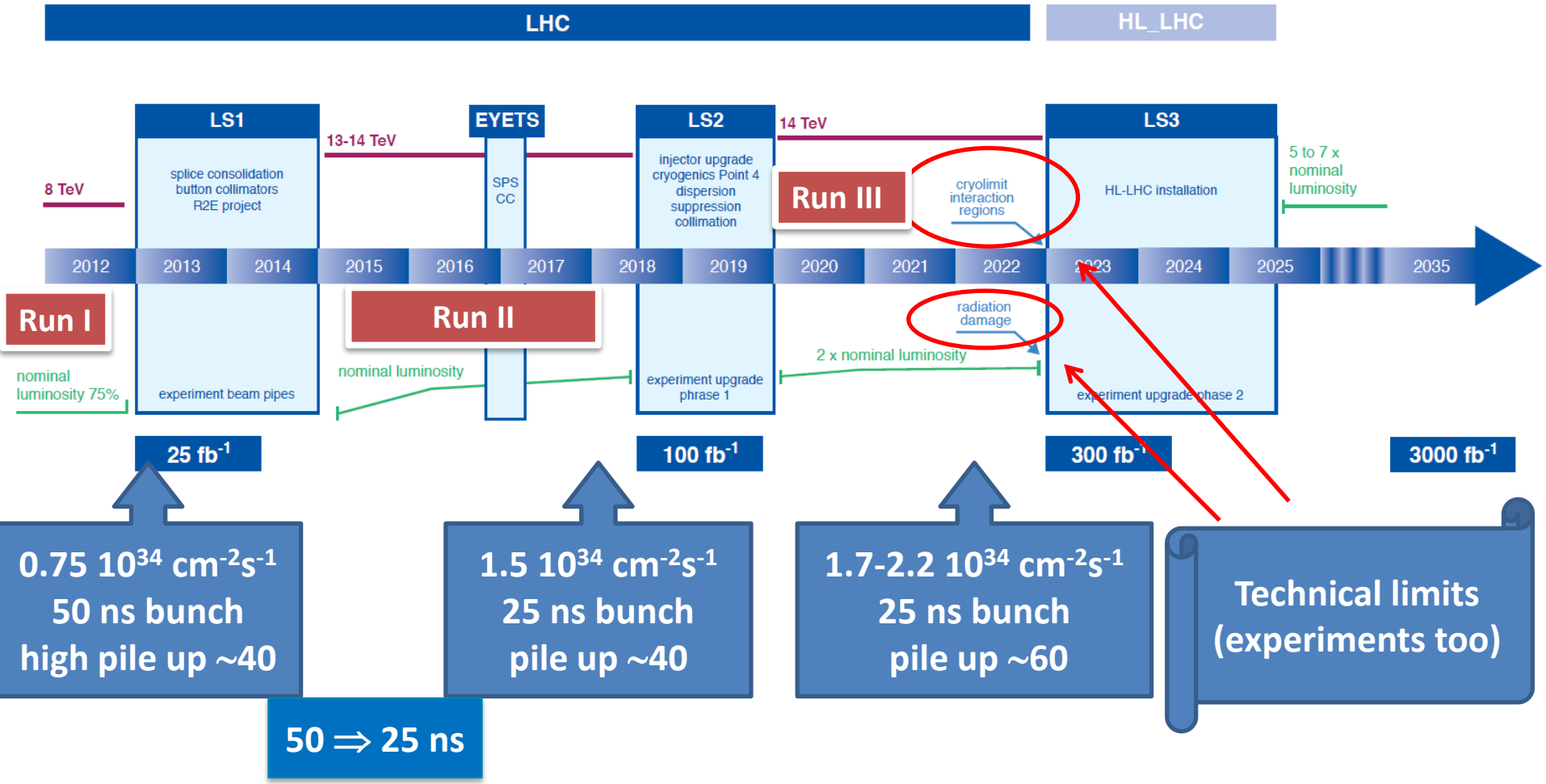
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

New LHC / HL-LHC Plan



Goal of High Luminosity LHC (HL-LHC) as fixed in November 2010

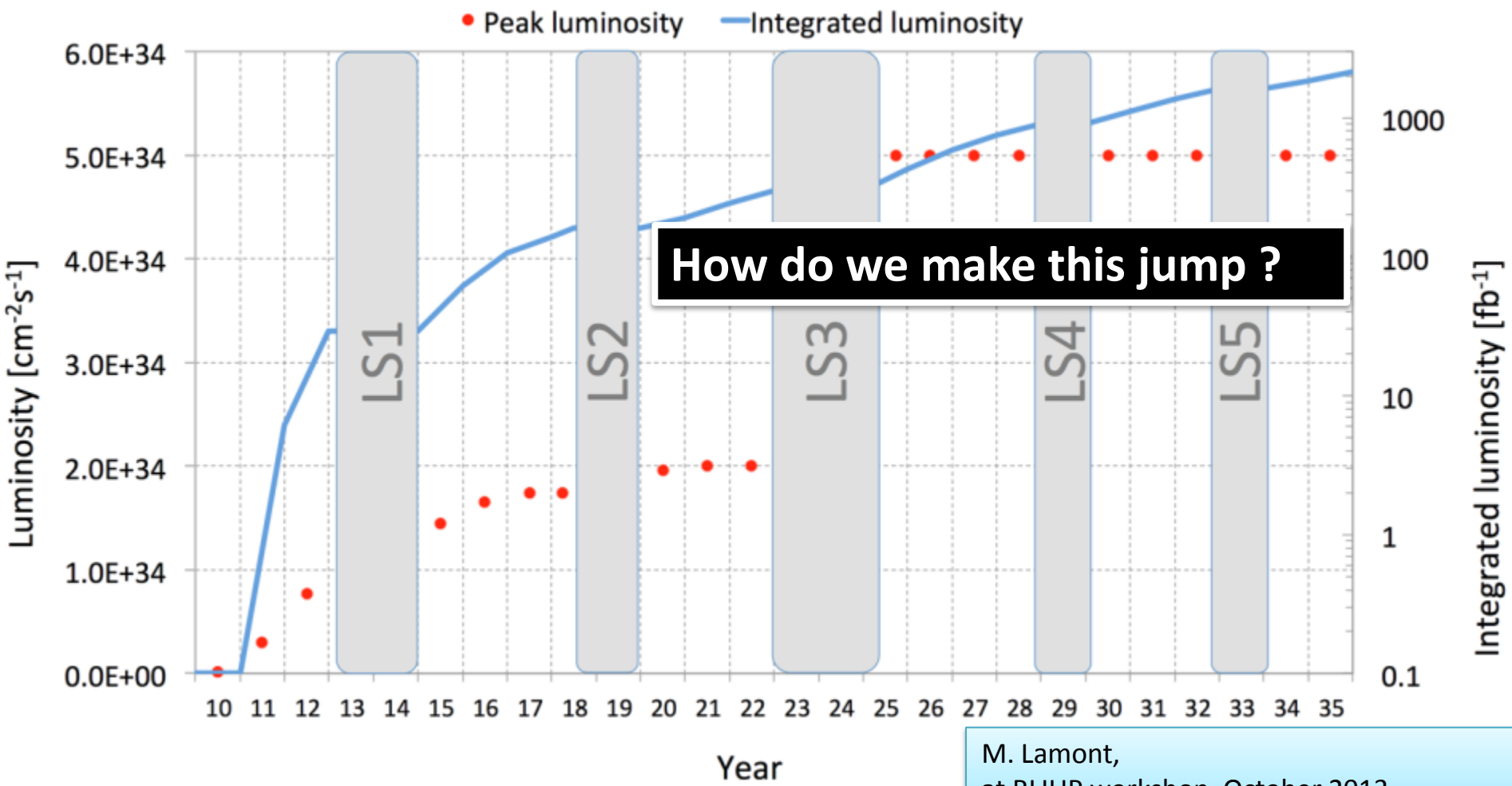
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

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

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **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.

Concept of ultimate performance: under definition:
$L_{peak} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and Int. L ~ 4000 fb^{-1}

This goal would be reached in 2036



How do we make this jump ?

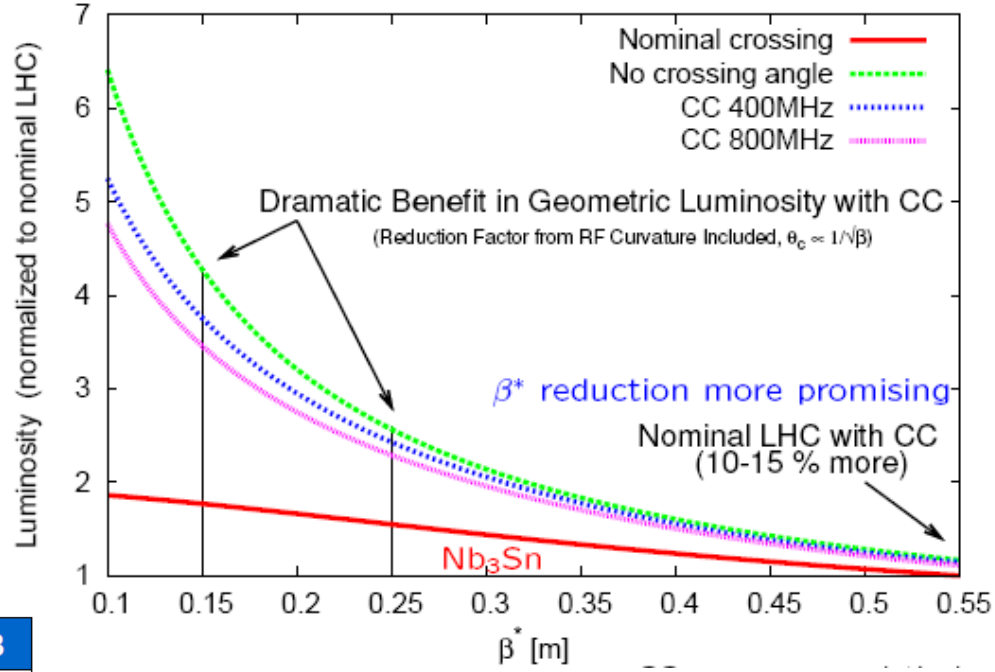
M. Lamont,
at RLIUP workshop, October 2013

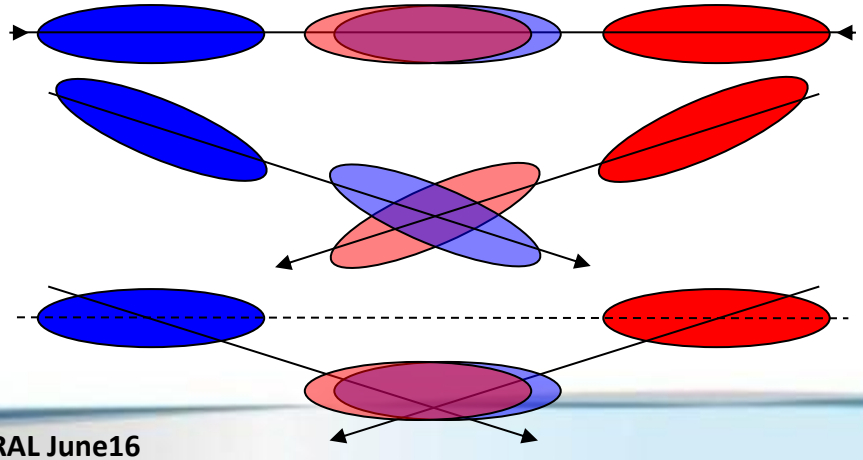
Luminosity increase

- Increasing the crossing angle decreases the long range effect but decreases geometric overlap
- Rotating the bunches with crab cavities before and after collision can reduce this effect

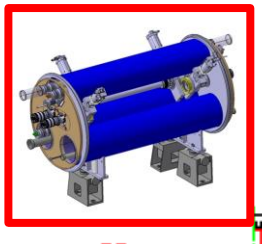
$$L \propto \frac{N_b^{\,2}}{\sigma^2} / R_\Phi F_{RF}$$

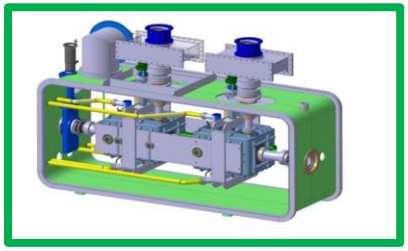
	2011	2012	after LS1	after LS3
Energy	3.5 TeV	4 TeV	7 TeV	7 TeV
β* [cm]	100	60	55	15
2ϕ [μrad]	260	313	247	473
$R_\Phi(\sigma_z = 7.55\text{cm})$	0.94	0.85	0.82	0.37
$R_\Phi(\sigma_z = 10.1\text{cm})$		0.76	0.74	0.28

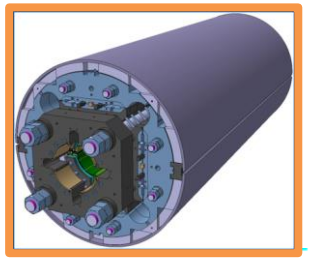


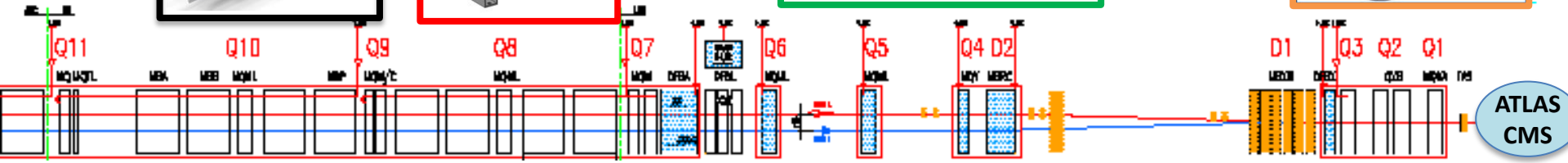


HiLumi: largest HEP accelerator in construction









Dispersion Suppressor (DS)

Matching Section (MS)

Interaction Region (ITR)

Modifications

1. In IP2: new DS collimation in C.Cry.
2. In IP7 new DS collimation with 11 T

+ Cryogenics, Protection, Interface, Vacuum, Diagnostics, Inj/Extr… extension of infrastr.

Complete change and new lay-out in IP1-IP5

1. TAN
2. D2
3. CC
4. Q4
5. All correctors
6. Q5 (Q6 @1.9 K?)
7. New MQ in P6
8. New collimators

Complete change and new lay-out in IP1-IP5

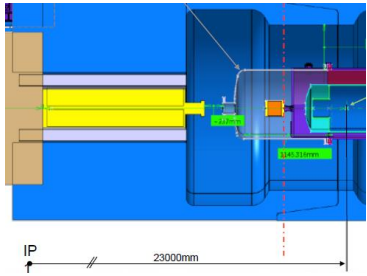
1. TAS
2. Q1-Q2-Q3
3. D1
4. All correctors
5. Heavy shielding (W)

> 1.2 km of LHC !!

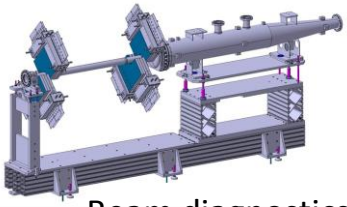
But work is required all around the ring…

Cryo@P4

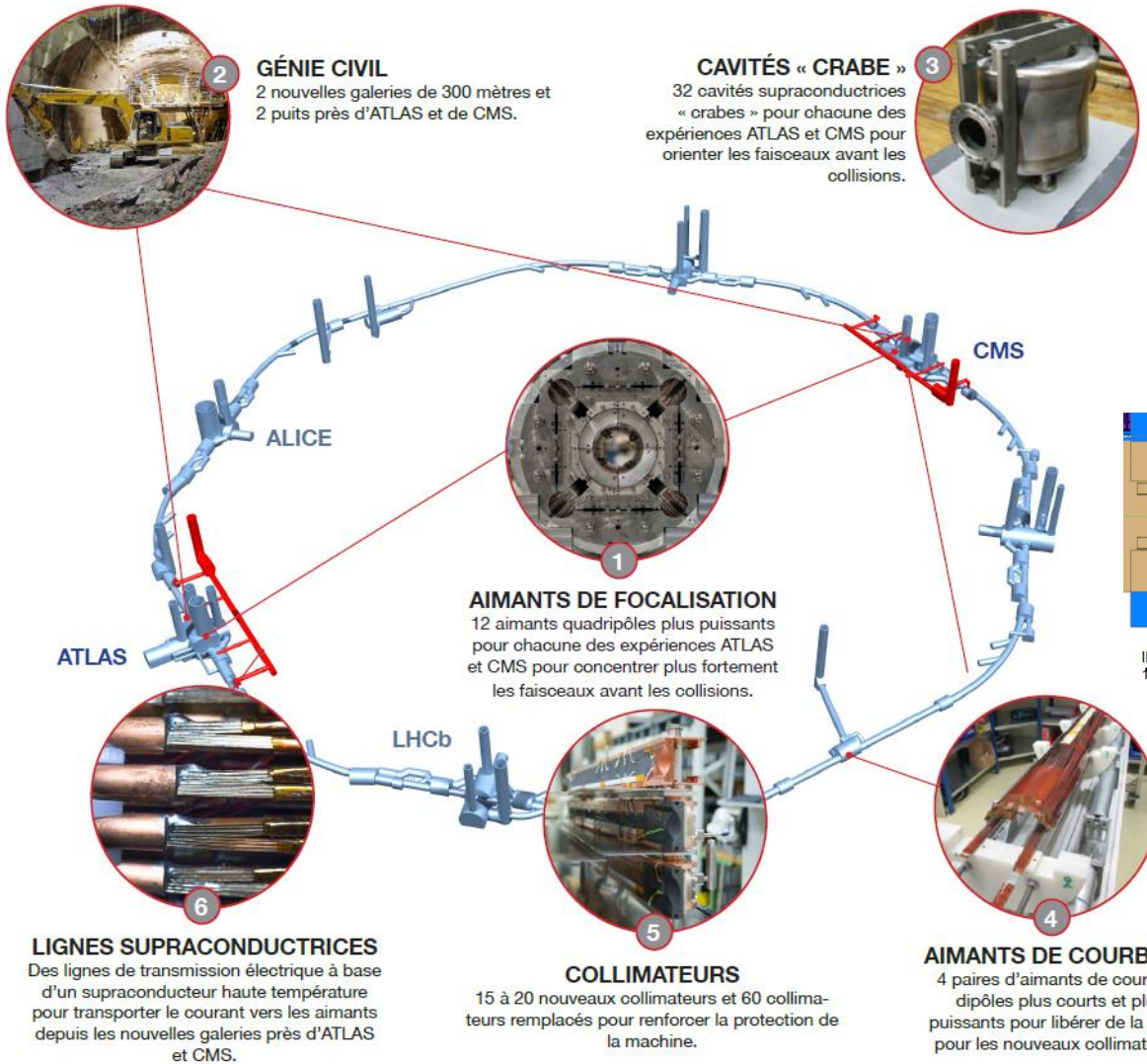
Cryo@P1-P5



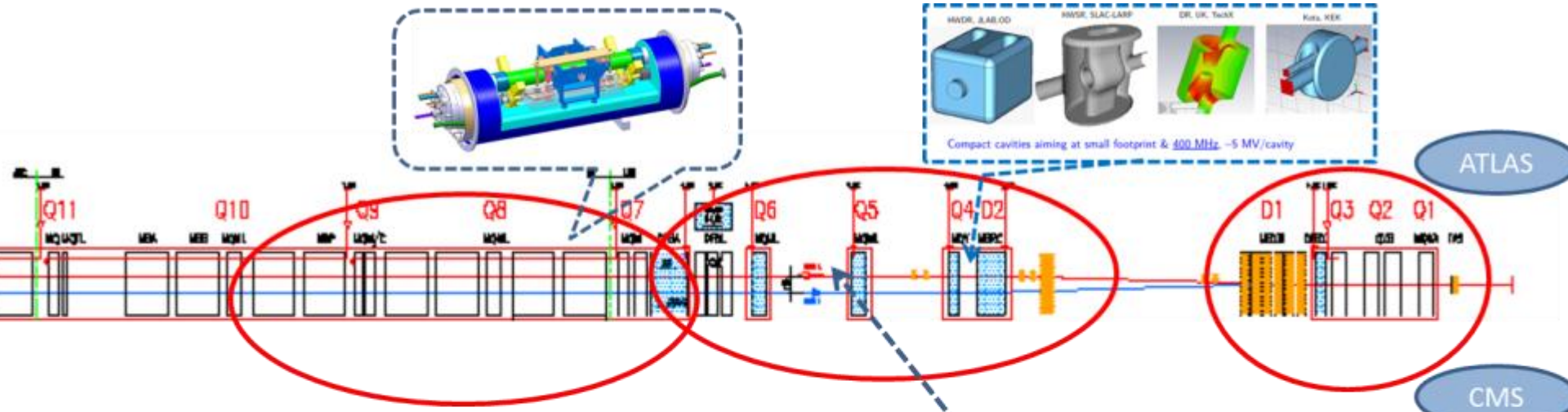
New TAS and VCX



Beam diagnostics BGV



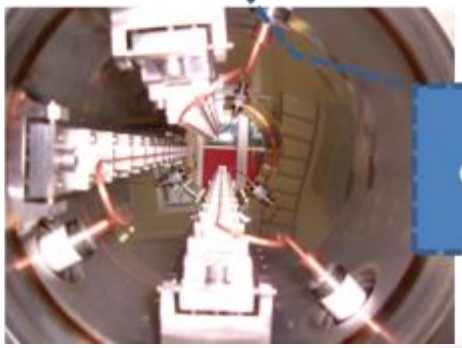
The critical zone around IP1 and IP5



3. For collimation we need to change also this part, DS in the continuous cryostat

2. Deep change also matching section: Magnets, collimators and CC

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

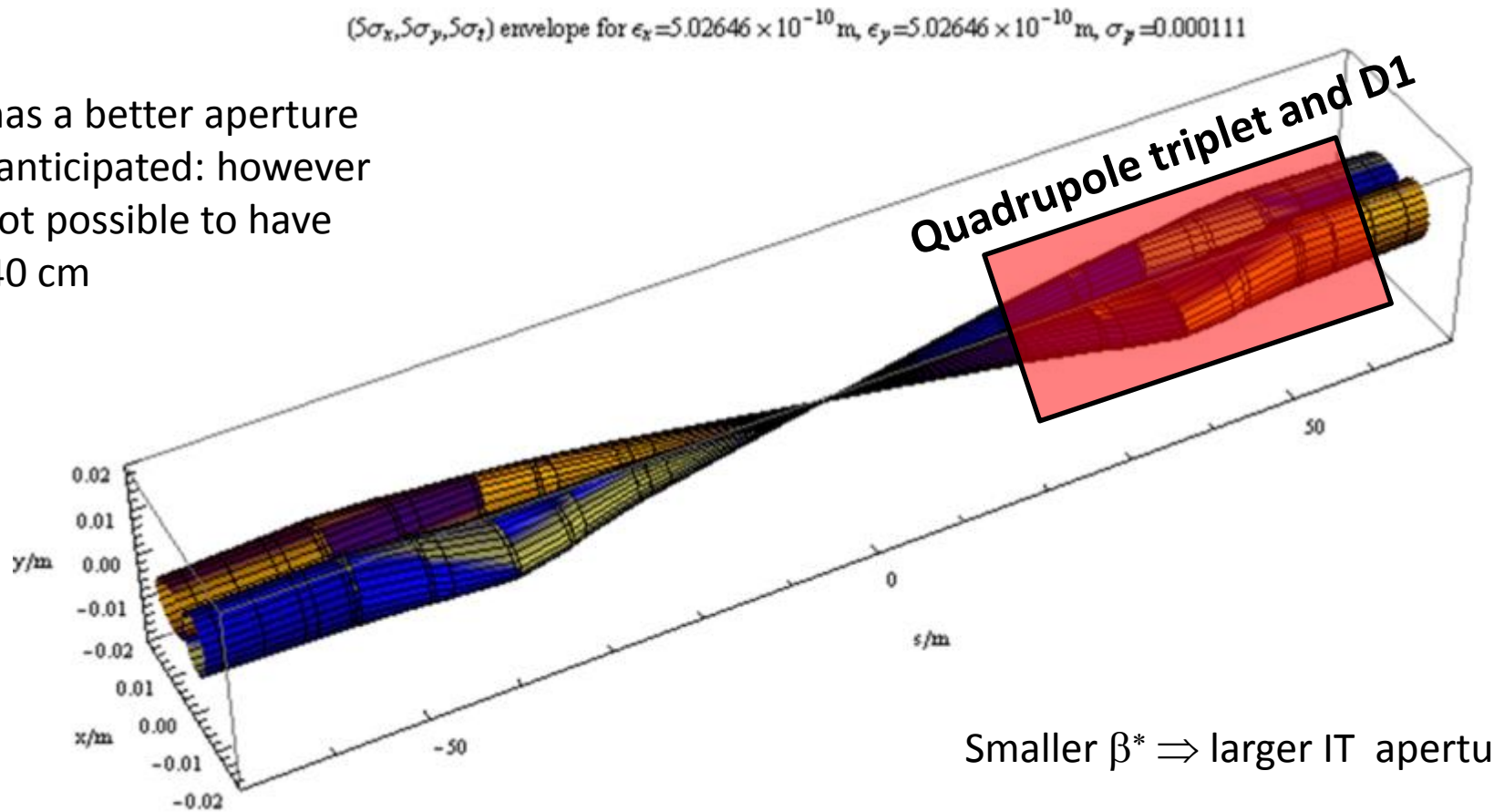


4. LR BB compensation wires

1.2 km of LHC !!

The most straight forward action: reducing beam size with a «local» action

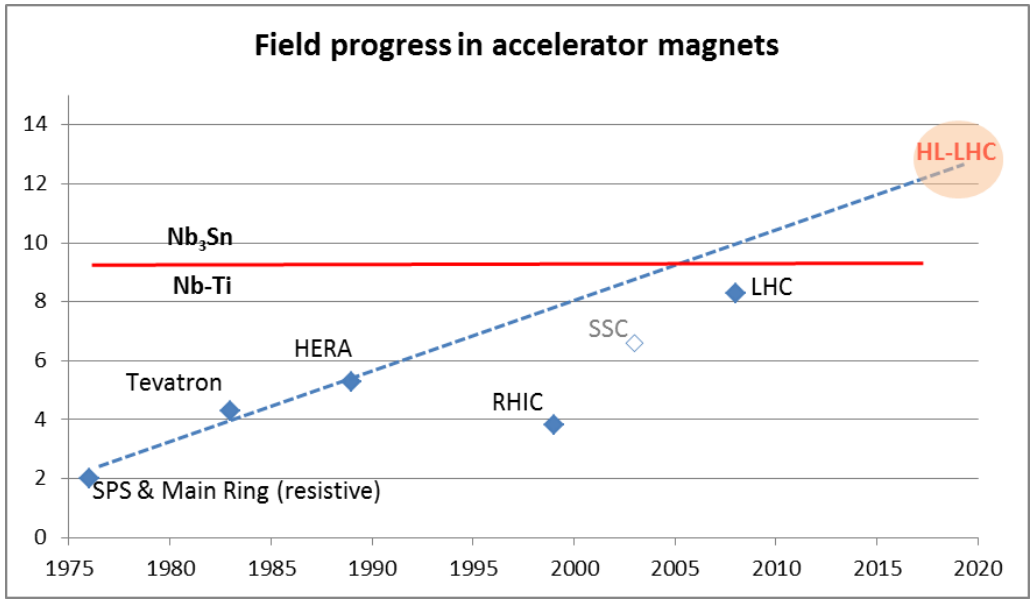
LHC has a better aperture than anticipated: however it is not possible to have $\beta^* < 40$ cm



Smaller $\beta^* \Rightarrow$ larger IT aperture

Magnet progress

- LHC dipoles features 8.3 T in 56 mm (designed for 9.3 peak field)
- LHC IT Quads features 205 T/m in 70 mm with 8 T peak field
- HL-LHC
  - 11 T dipole (designed for 12.3 T peak field, 60 mm)
  - New IT Quads features 140 T/m in 150 mm > 12 T operational field, designed for 13.5 T).



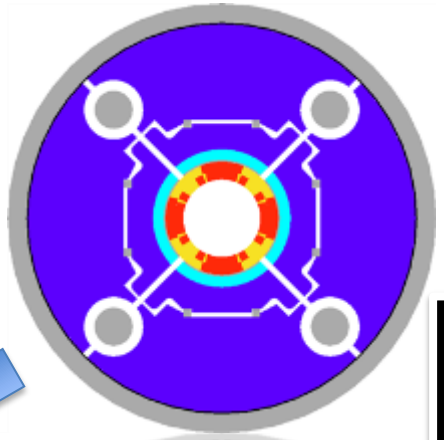
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

Fermilab KEK

LHC (USA & JP, 5-6 m)
∅70 mm, B_{peak}~ 8 T
1992-2005

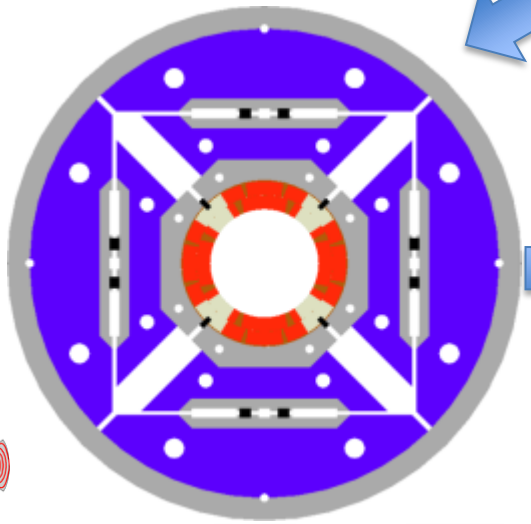
LARP

LARP TQS & LQ (4m)
∅90 mm, B_{peak}~ 11 T
2004-2010

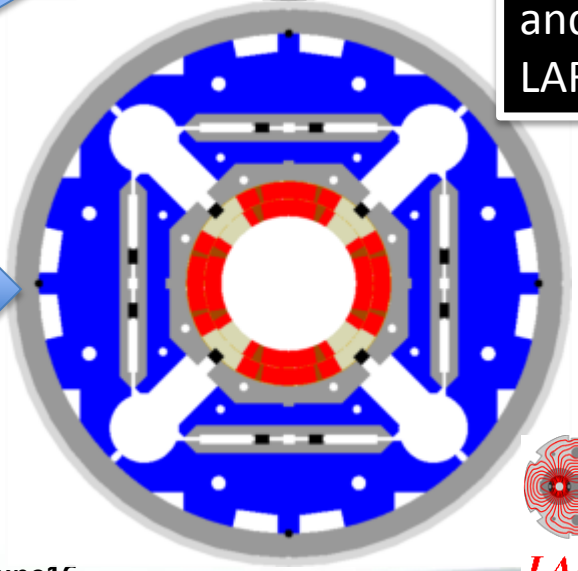


New structure based on bladders and keys (LBNL, LARP)

LARP HQ
∅120 mm,
B_{peak}~ 12 T
2008-2014



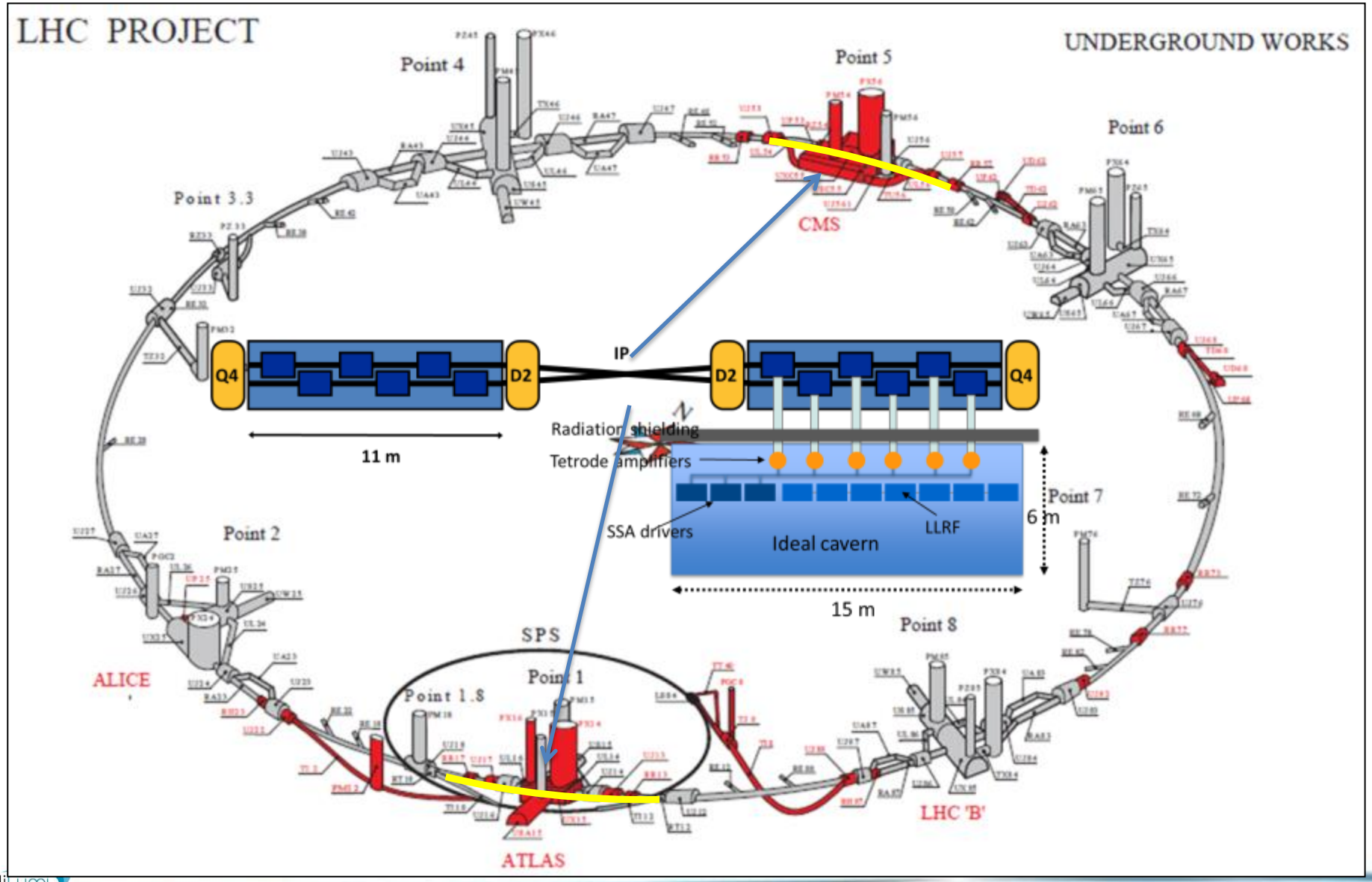
LARP



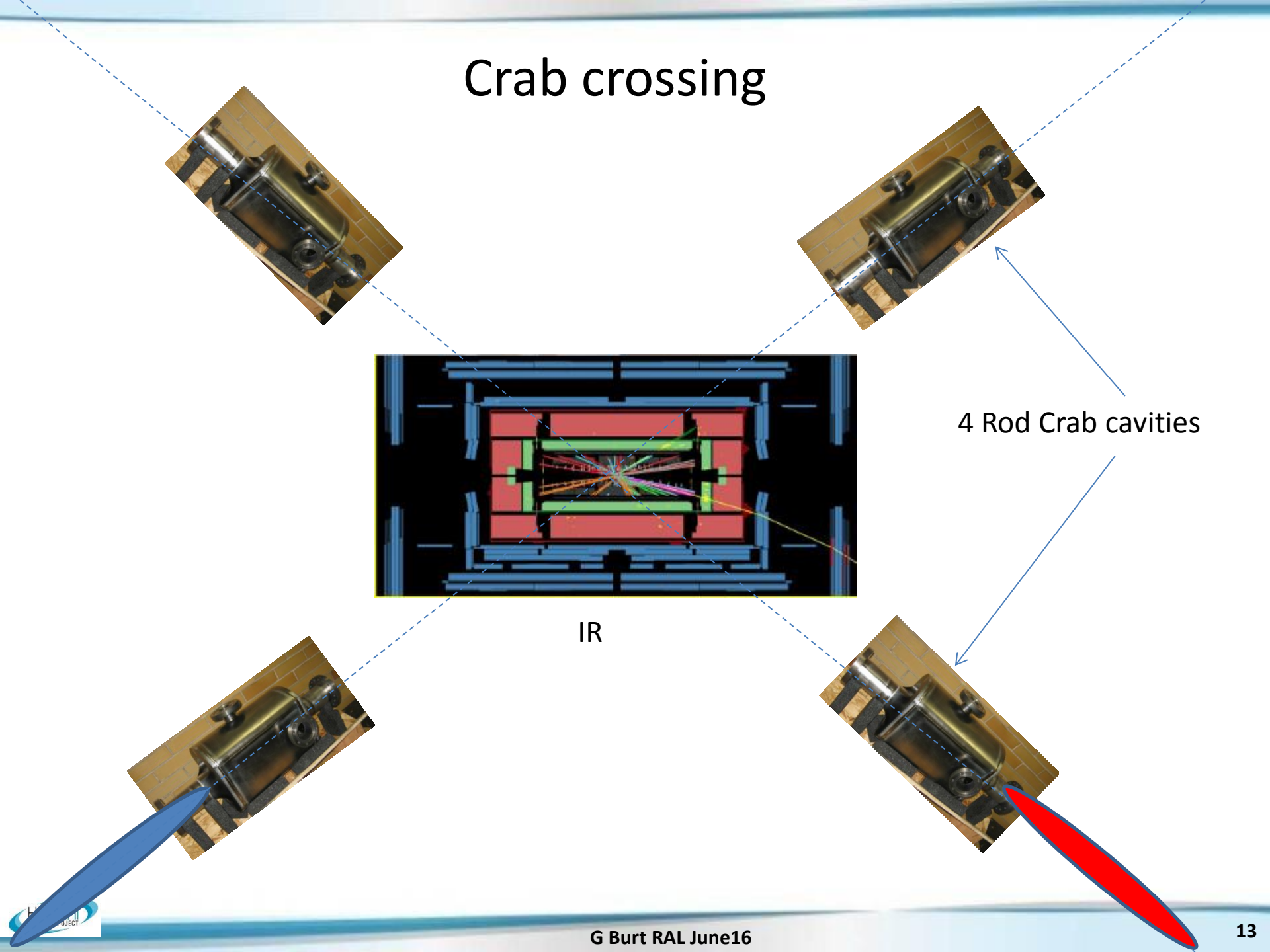
LARP & CERN
MQXF
∅150 mm,
B_{peak}~ 12.1 T
2013-2020

LARP

Crab Cavities for fast beam rotation



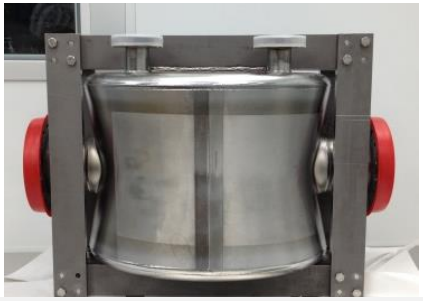
Crab crossing



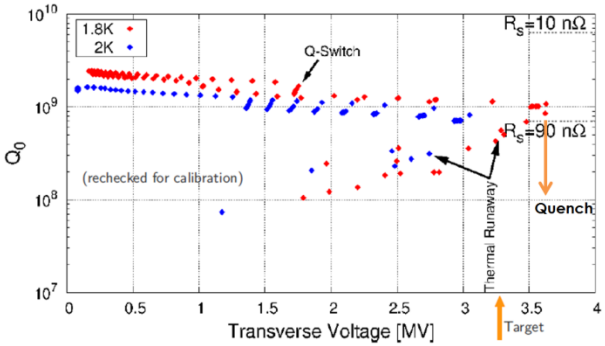
Successful Cold Testings

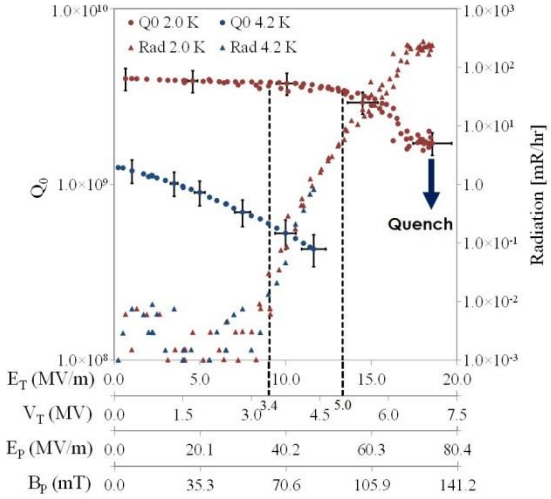
4 Rod

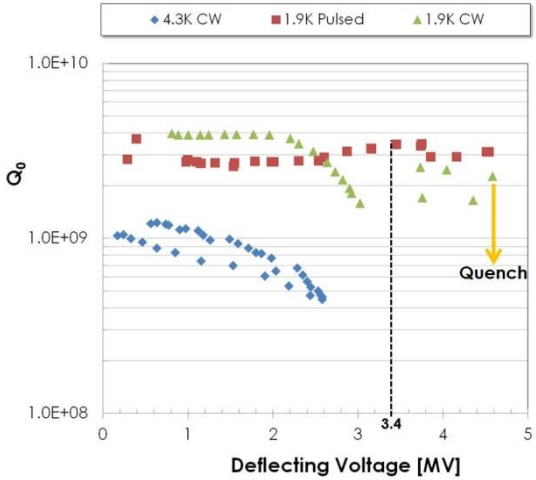
RF Dipole



Double Quarter Wave



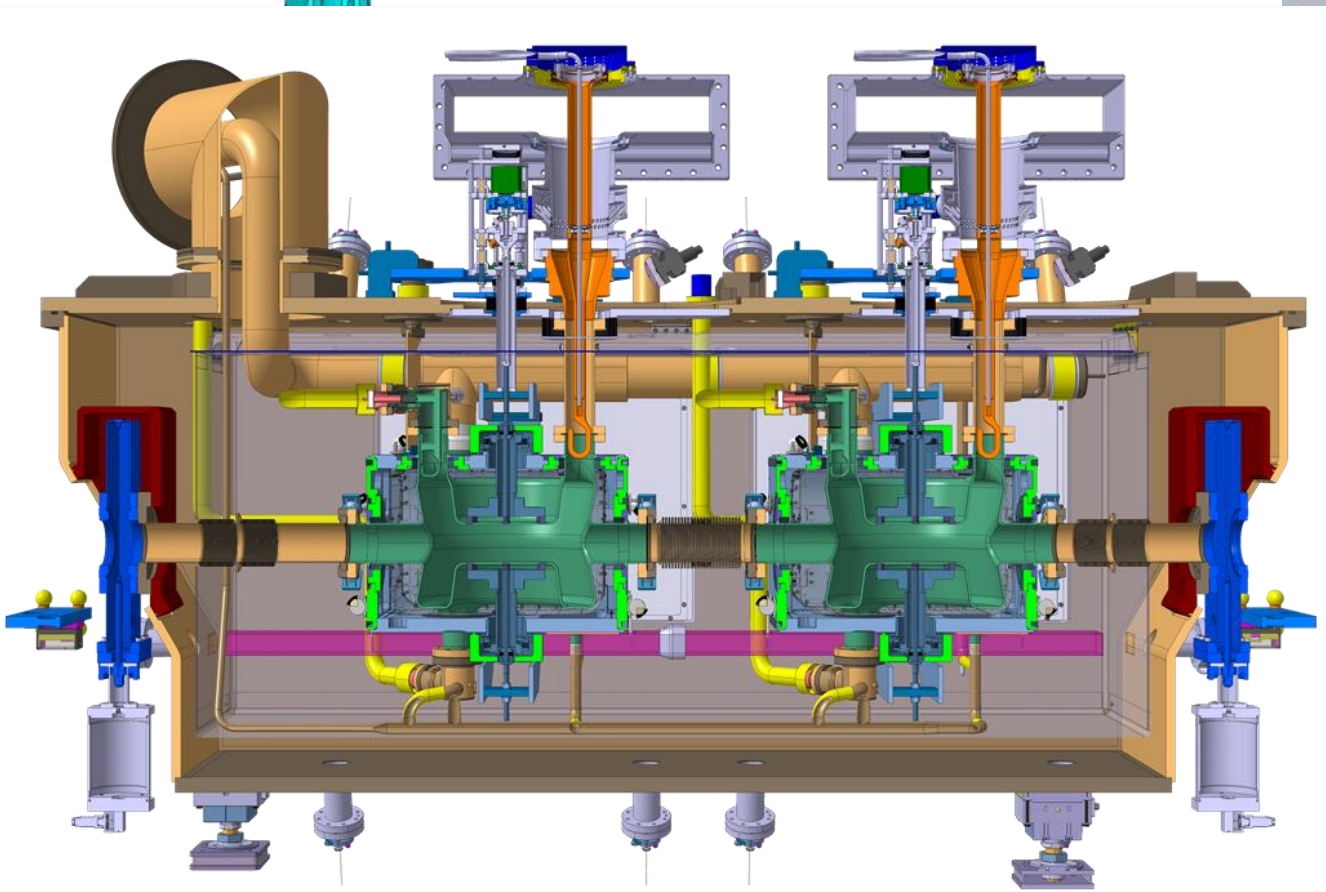


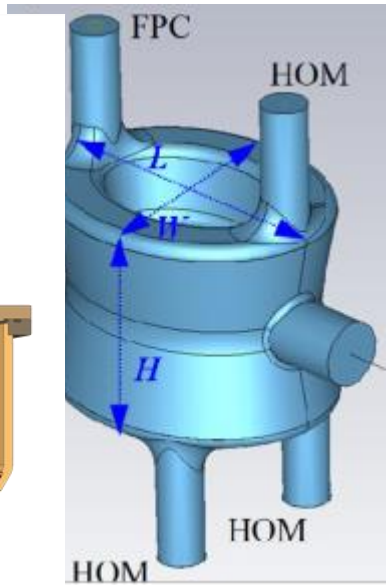


HiLumi-LHC/LARP Crab Cavity System External Review, May 5-6 2014

Latest cavity designs toward accelerator

RF
wa



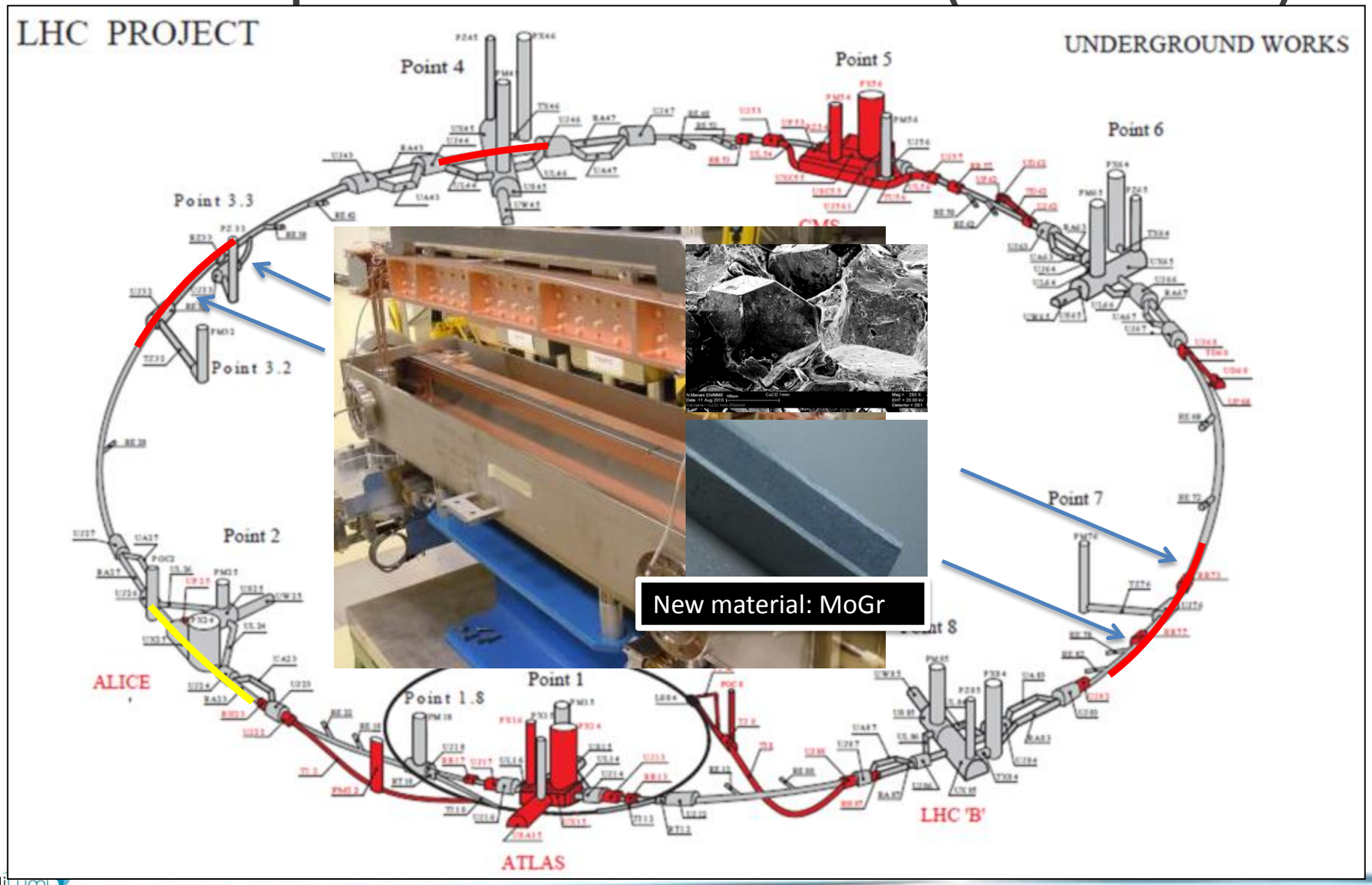


ble ¼-wave:
ial couplers with
-type antenna

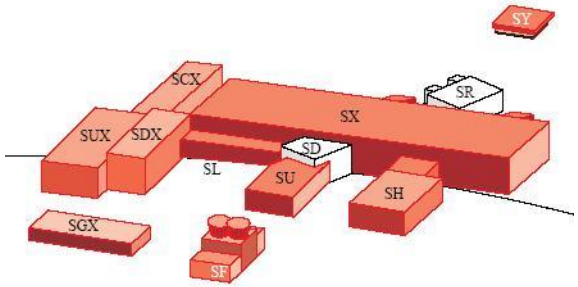
4-rod: Coax
different ar

Present baseline: 3 cavity /cyomodule
4 cavity/cryomod is under study for Crab Kissing
TEST in SPS under preparation

Low impedence collimators(LS2 & LS3)



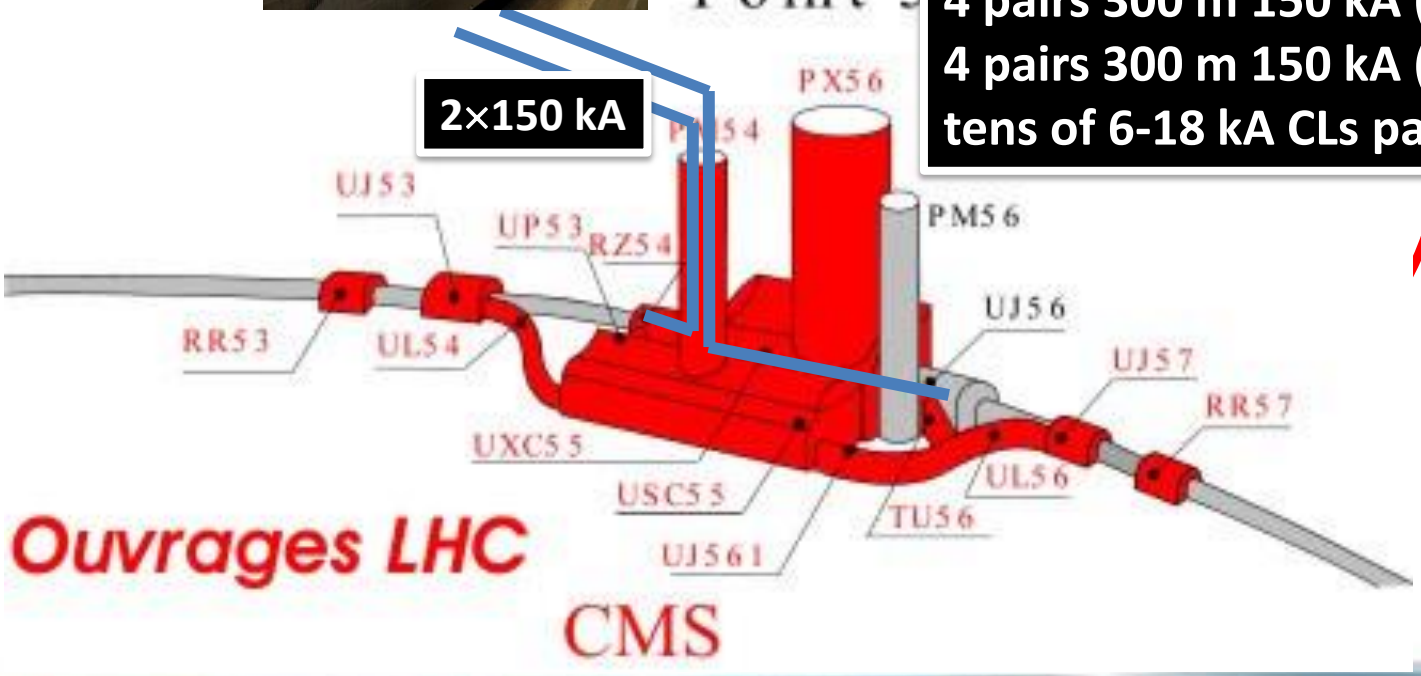
Availability: SC links ⇒removal of EPCs, DFBs from tunnel to surface

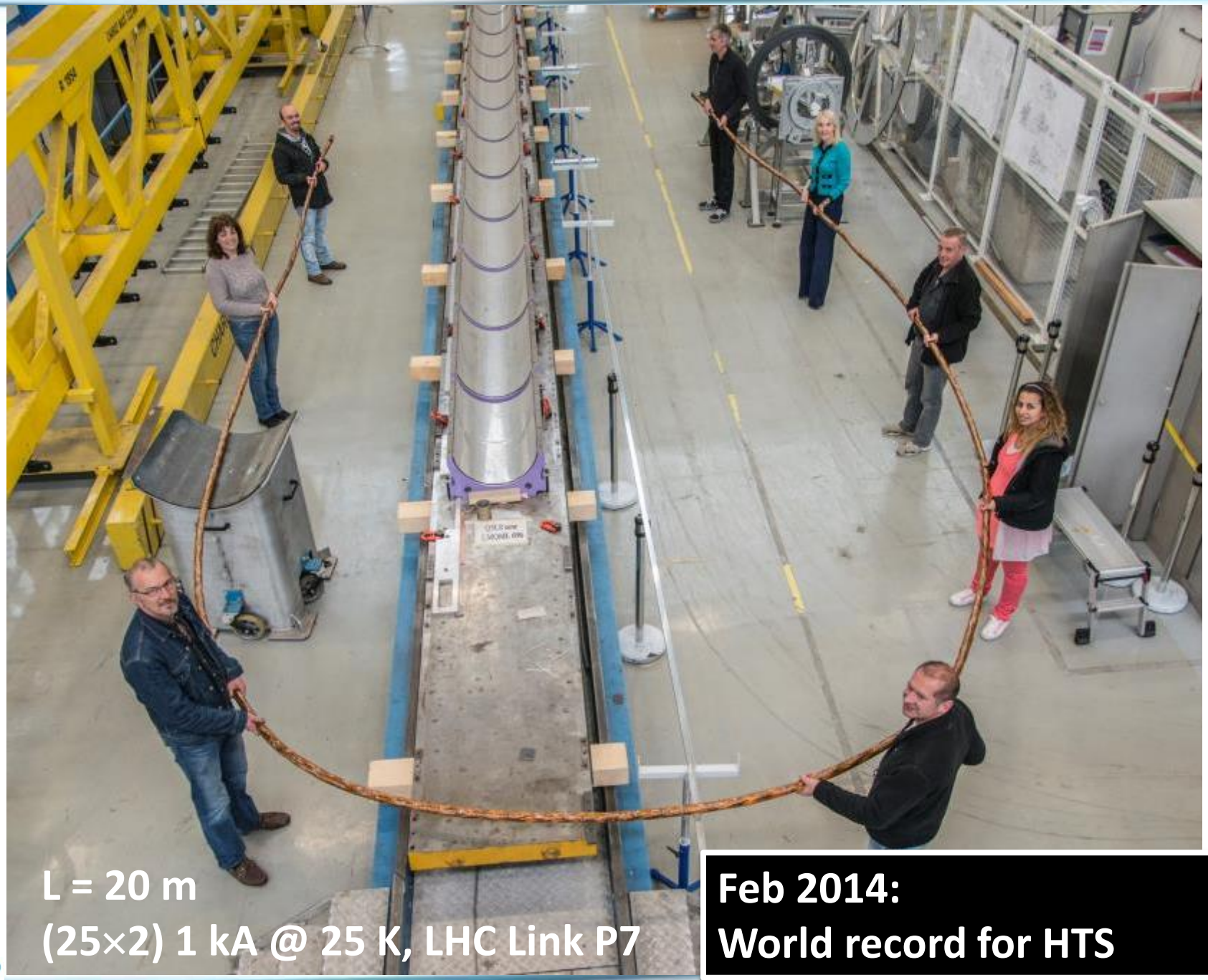


POIN

Point 5

1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS)– LS3
4 pairs 300 m 150 kA (IR) – LS3
tens of 6-18 kA CLs pairs in HTS





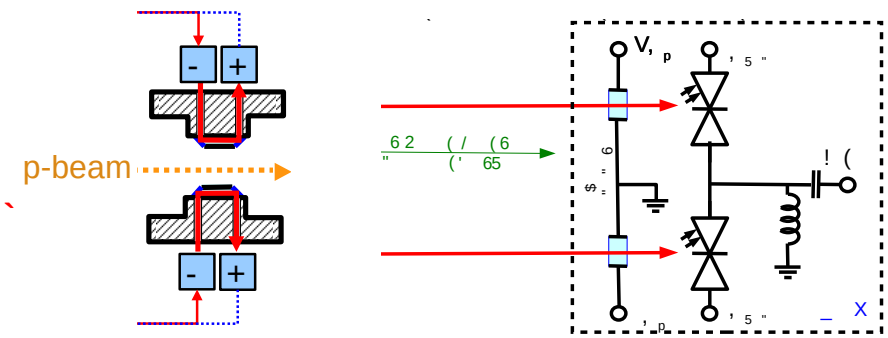
Feb 2014:
World record for HTS

Diagnostics

Precise measurement of beam parameters is essential. The LHC is equipped with an extensive array of beam diagnostics that has played a major role in commissioning, rapid intensity ramp-up and safe and reliable operation of the accelerator. The HL-LHC presents new challenges:

Challenge 1:

- Crab-cavities will rotate the bunches
- *A method to accurately measure the bunch rotation is required.*
- Conventional BPMs have insufficient bandwidth for single pass, intra-bunch measurements.
- *A new technology is needed:*



Electro-optic crystals as the BPM pickup

The electric field of the passing bunch induces a polarization change in the crystal that is readout with <50ps time resolution to derive the transverse position along the bunch.

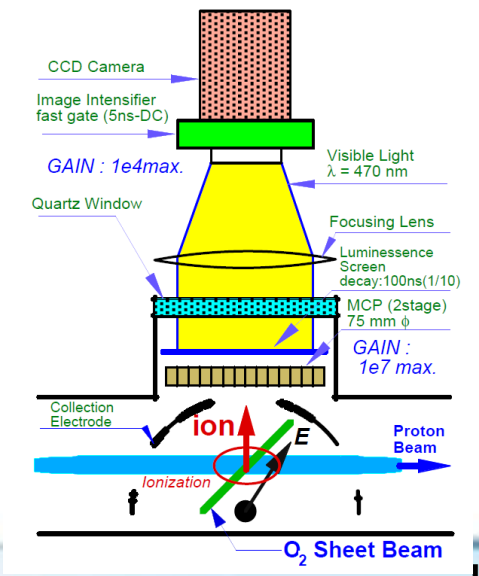
Challenge 2:

- The unprecedented stored beam energy would damage conventional diagnostics and/or disrupt the particle beam.
- *Non-invasive diagnostics are required to measure the beam profile and beam halo.*

Gas-jet based beam profile monitor

A supersonic jet of neutral gas is shaped into a thin sheet and injected with a 45º tilt across the particle beam.

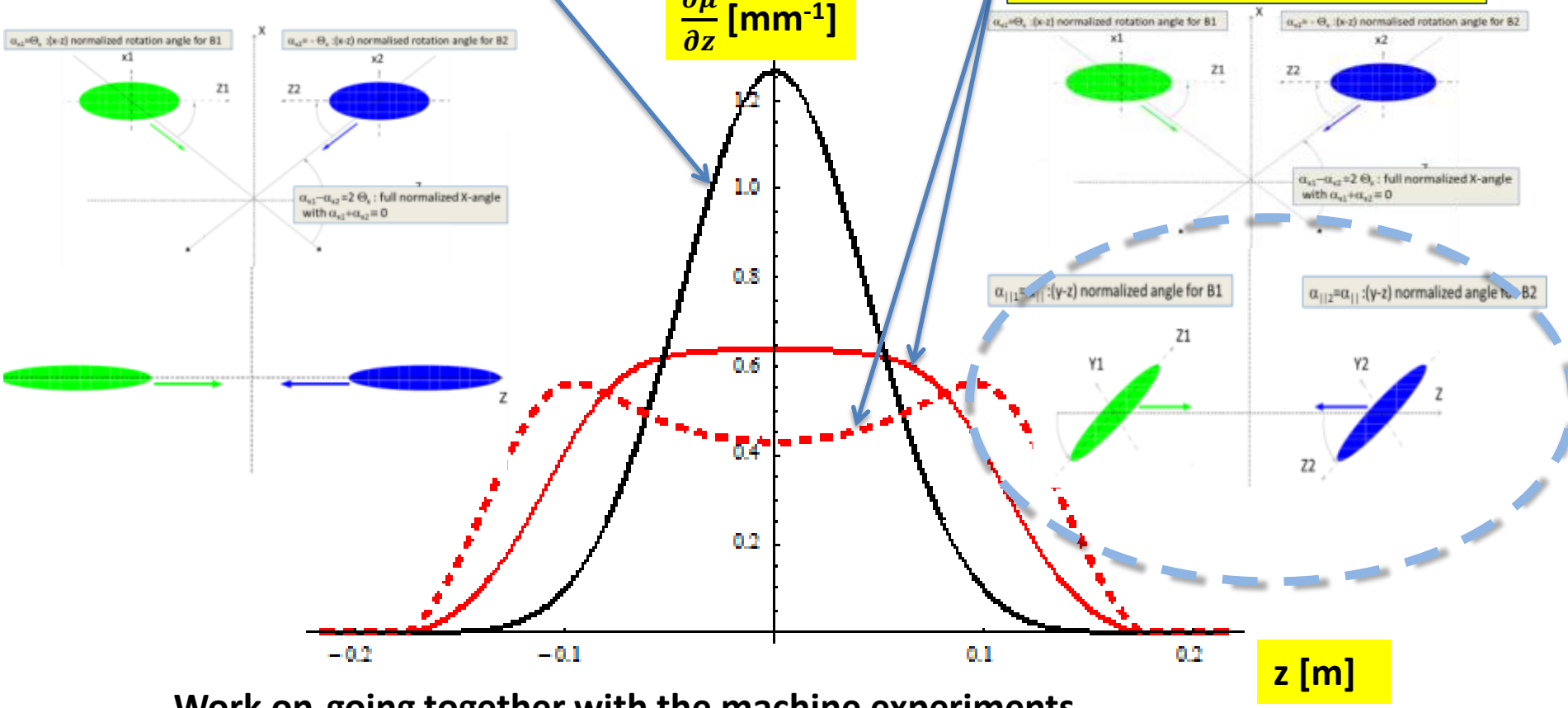
Ions produced accelerate toward a phosphor screen, to monitor profile



The **Crab-kissing** (CK) scheme for **pile-up density** shaping and leveling (S. Fartoukh)

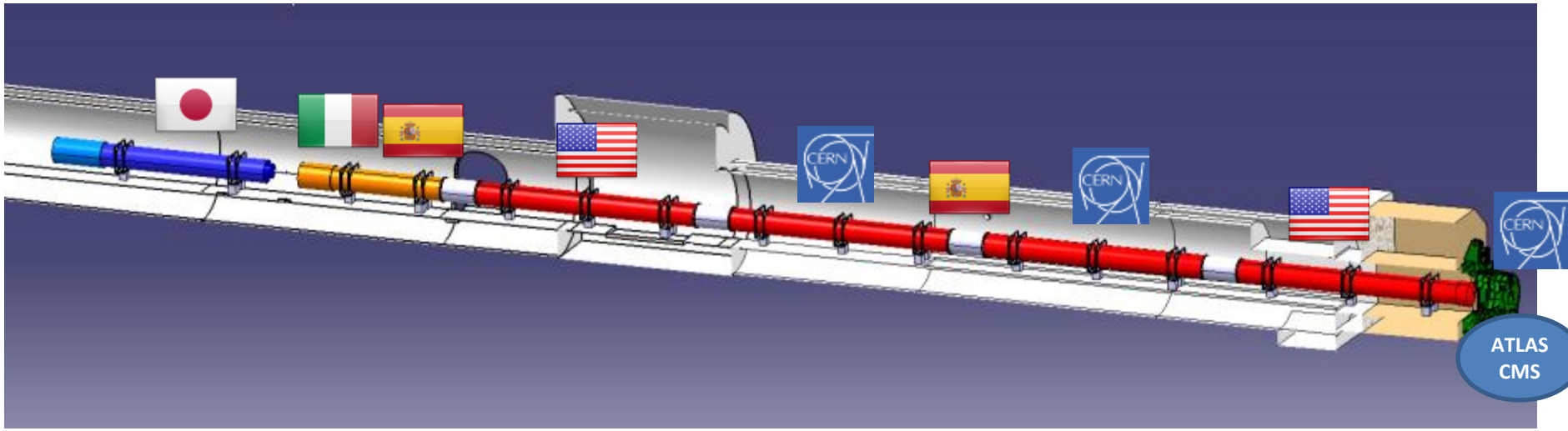
Baseline: CC in X-plane "only"

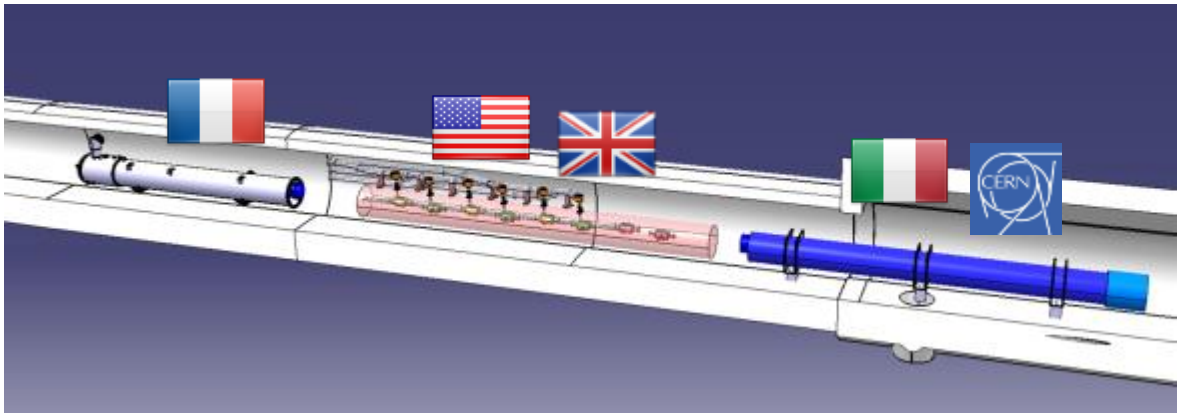
Crab-kissing & variants: CC also in ||-plane



... Work on-going together with the machine experiments (S. Fartoukh, A. Valishev, A. Ball, B. Di Girolamo, *et al.*)

In-kind contribution and Collaboration for HW design and prototypes





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

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

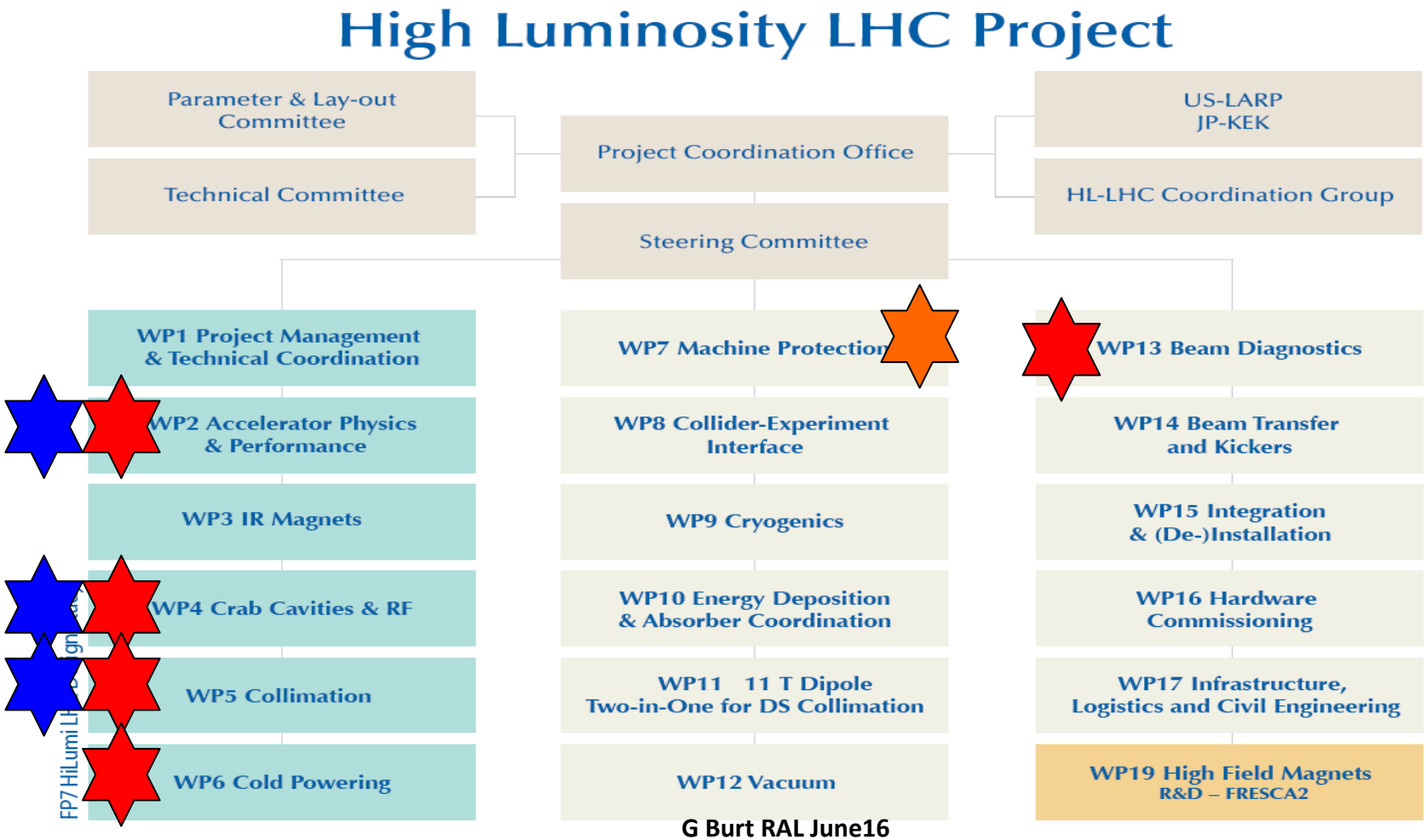
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

Where the UK fits into HL-LHC

HL-LHC-UK Involvement

HiLumi-LHC Leadership

HiLumi-LHC involvement

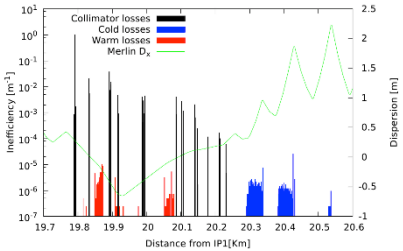


HL-LHC-UK

Manchester
Lancaster
ASTeC

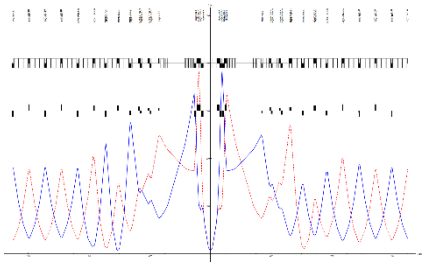
Crab Cavities

Manchester
RHUL



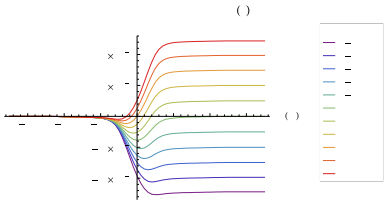
Collimation

Manchester
Liverpool
ASTeC

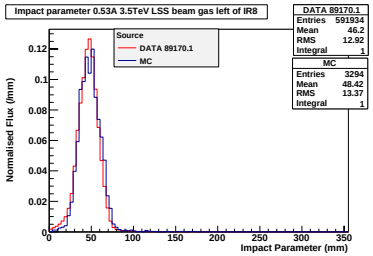


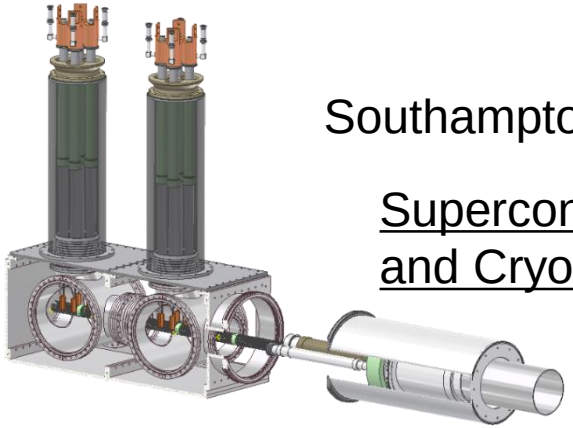
Beam dynamics

Manchester
Liverpool
ASTeC



HiLumi-LHC
UK





Southampton

Superconductivity
and Cryogenics

Liverpool
RHUL

Diagnostics

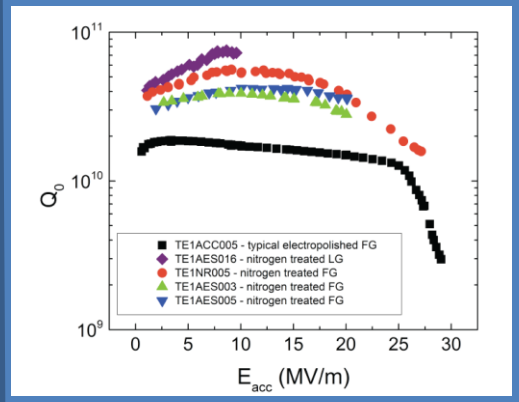
Manchester
Machine-detector interface

What's next?

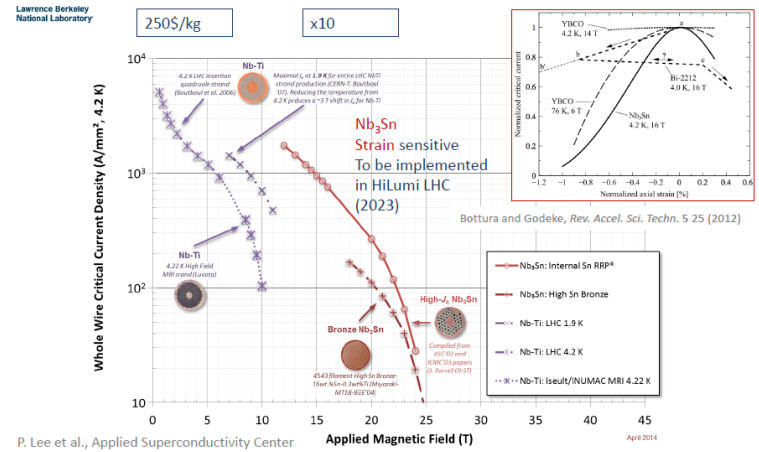
- Energy upgrade of LHC with new Nb_3Sn dipoles?
- A 80/100 km tunnel as a higgs factory and then a 100 TeV pp collider (FCC)? Could CERN afford such a large machine that cannot be staged?
- Chinese Higgs factory or FCC? Could they get the international community to buy in?
- A staged linear collider going to 1 TeV (ILC) or 3 TeV (CLIC)? ILC could be built now, CLIC still has some technical challenges.
- An electron-ion collider (LHeC, ELIC, e-RHIC)? We can do it if the HEP community wants it enough.

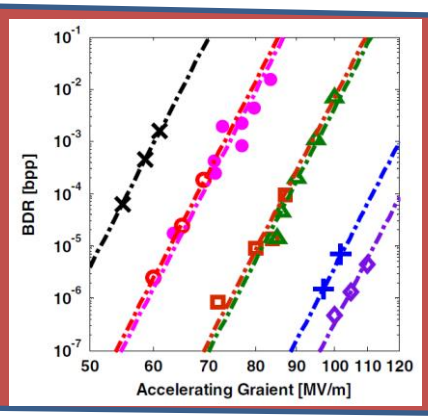
New “Conventional” breakthrough's

- High field dipole magnets allowing projects like FCC.



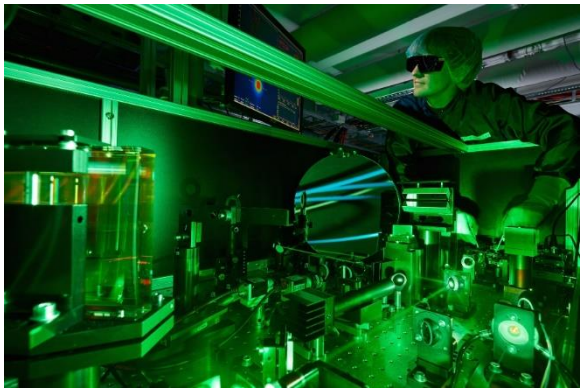
- N-doped, Nb3Sn and Multilayer SRF provides higher Q, higher temperature and higher fields.
- High gradient X-band still going strong and replacing old S-band technology

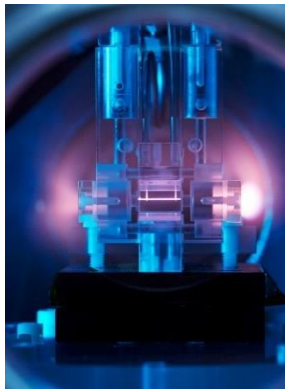




Novel or Advanced Accelerators

- <u>Laser-Plasma-based electron and hadron accelerators:</u>
  - Driven by lasers (for both e- and hadron) e-: Multi-GeV beams have been achieved → beam energy sufficient for applications → applications around the corner???
  - Hadrons: ion beams have been produced and transported at low energies
  - Activities at many centers in Europe (as well as US and Asia)
  - This dominates the novel acceleration arena
  - Excellent future sources of compact accelerators but can they be used for HEP?





Laser Plasma Accelerators Efficiency and rep-rate

- Efficiency is at least one or two order of magnitude less than conventional sources (around 1% if that). For a 1 TeV collider at CERN the required power would dwarf the rest of Geneva (roughly 10 times the entire energy budget of Geneva) and would potentially require several new dedicated power stations.

- Rep-rate is limited by material heating to sub-1Hz, this would limit luminosity.

- Laser efficiency and rep-rate could be increased by
  - OPCPA but would need new pump sources that are also more efficient and can handle higher average powers, currently can demonstrate either high power, high efficiency or high rep-rate but only one at a time.
  - Combining fibre lasers but locking that many lasers is far from realisable at present. Progress has been made on locking tens of lasers (ICAN) together but millions would be required.

Staging of laser plasma

- At present a few GeV beams can be obtained, but higher energies need either
  - Higher power lasers (material heating limits are difficult to overcome)
  - Combining multiple stages.
- The laser stability coupled with the sensitivity to the laser parameters means every shot is different and most have poor beam quality. Typical variation is 1-5% energy, 5-50% charge, 1-3mrad beam pointing.
- The phase space for external injection is very small in both longitudinal (fs synchronisation) and transverse planes. We are far from a point where we can get close to staging and there are few theories on how this could be achieved.
- Also holes in the mirrors for beam injection get burnt by the laser meaning they need replaced or repositioned frequently.
- Even if we could proposals either require very high laser mean powers (GW) or very high rep rates (15 kHz)

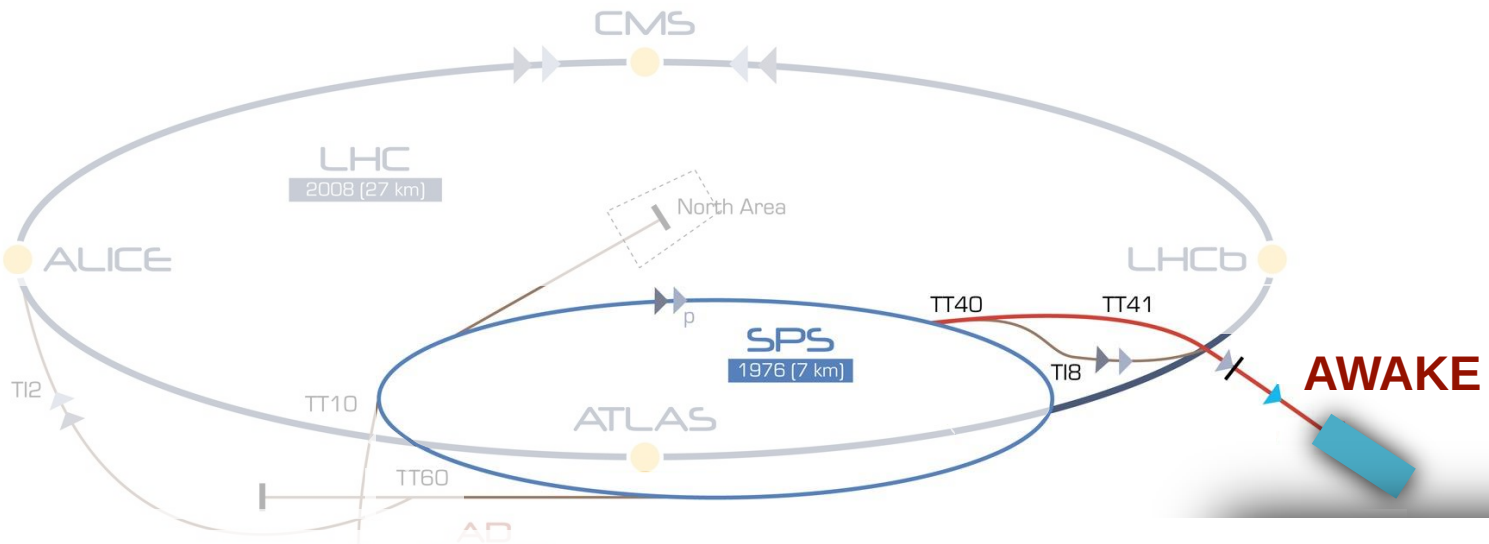
Accelerator size

- The laser travels slower than c in the plasma while electrons travel close to c hence you loose synchronisation after a few mm. The gradient is very high (10's GV/m) but acceleration is limited to synchronisation length
- Several items of equipment would be required around each plasma stage, the laser itself, vacuum pumps, mirrors, beam transport and diagnostics. In a conventional linear accelerator these items can be 20-50% of the accelerators length. For example a plasma FEL would be only half the size of conventional ones.
- The lasers and power supplies are very large so the gradient is often overstated. In conventional sources we have two numbers active length and total length. LPWA have a small active length but the total length is still significant. Still smaller than linacs but not by as much as implied.

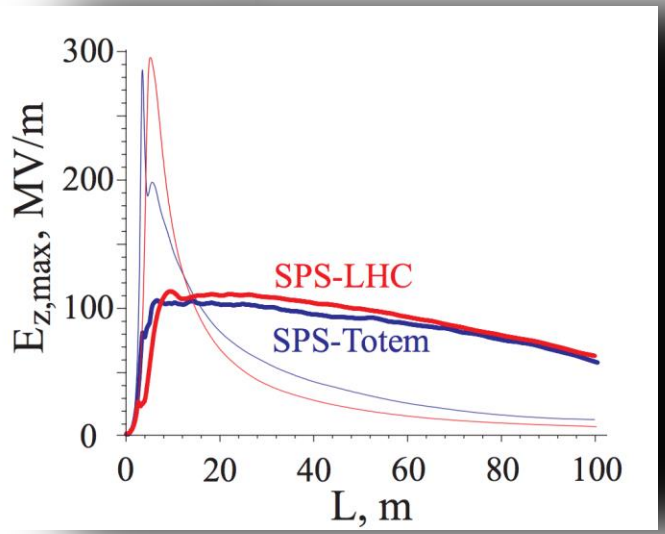
Are there other options or are we stuck with conventional accelerators until we can stage plasma?

- YES!!!!
- Lasers could be used with dielectrics to overcome the stability issues and reach gradients up to 1 GV/m. Using THz lasers/vacuum tubes significantly increases beam quality over shorter wavelength sources in dielectrics. Efficiency still is an issue at present. Good for medical linacs and light source replacements. Good potential for higher efficiency THz vacuum tubes (harmonic gyrotrons, BWO's) or wakefield driven could allow path to TeV colliders.
- You could drive the plasma with a proton or electron beam as opposed to a laser. The drive beam could be a highly efficient high current beam. This would be far more efficient and stable than a laser plasma accelerator. Likely the most viable option for a novel multi-TeV collider other than traditional accelerators. But luminosity is low

AWAKE Project



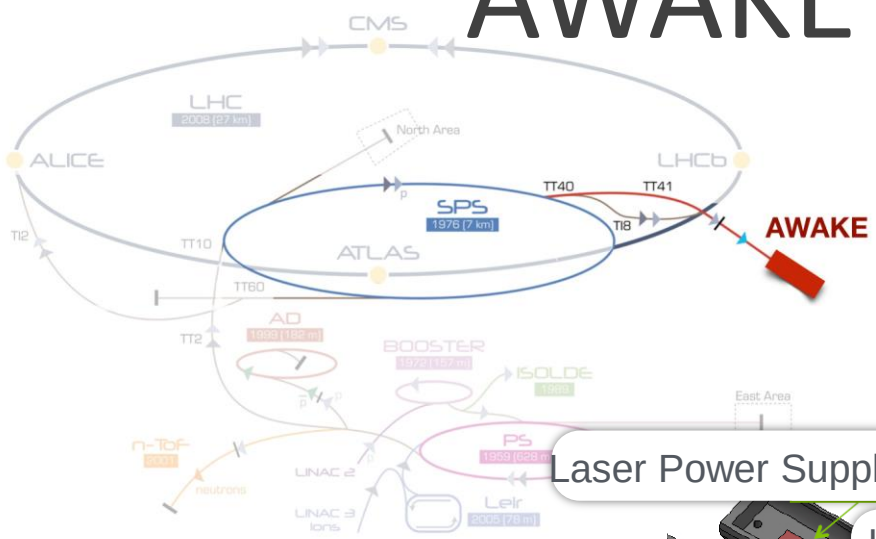
AWAKE project, a proton driven plasma wakefield acceleration (PDPWA) experiment is approved by CERN. The PDPWA scheme consists of a seeding laser, a drive beam and a witness beam to be accelerated. The primary goal of this experiment is to demonstrate acceleration of a 16 MeV single bunch electron beam up to 1 GeV in a 10m of plasma.

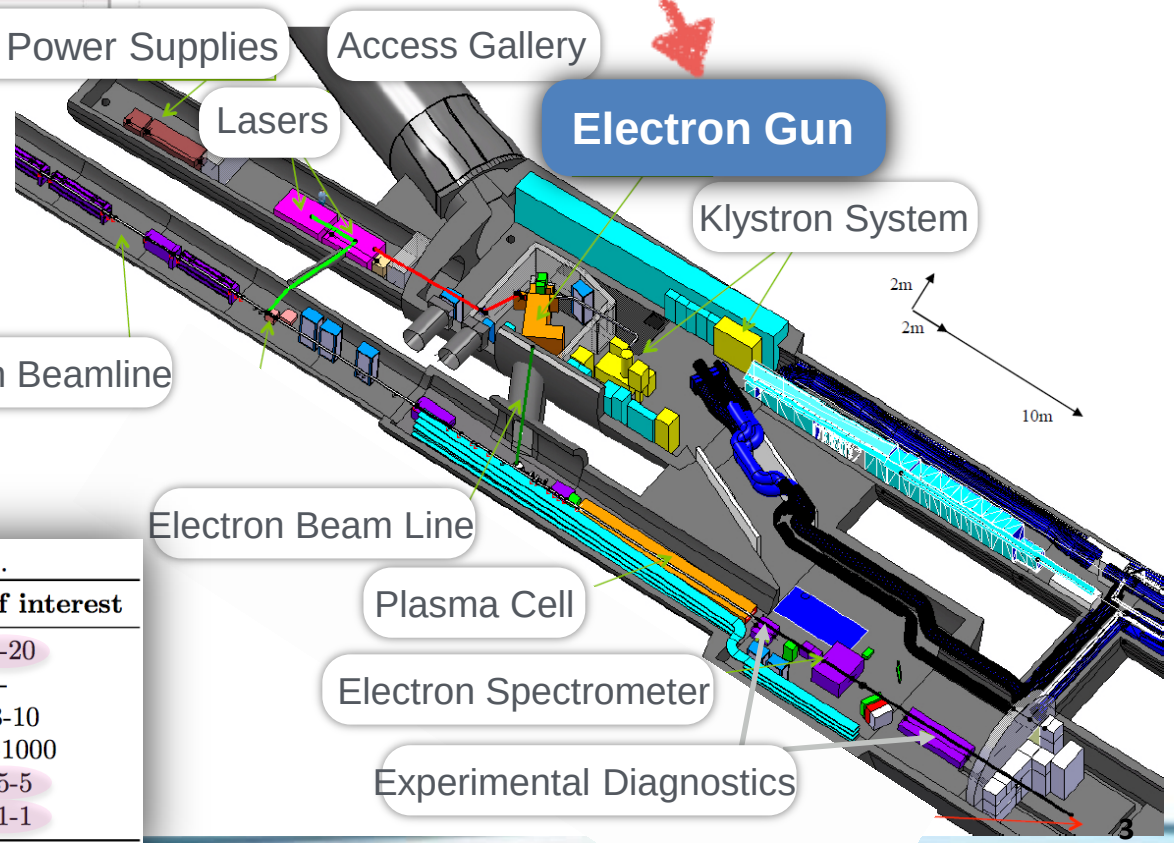


A. Caldwell, K. V. Lotov, PHYSICS OF PLASMAS 18, 103101 (2011).

AWAKE Project

Production of a Witness Beam



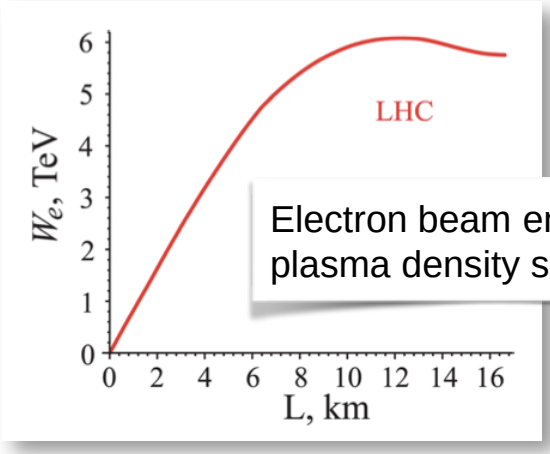


Baseline specifications for AWAKE e⁻ beam.

Table 1: Specifications for the simulation studies.

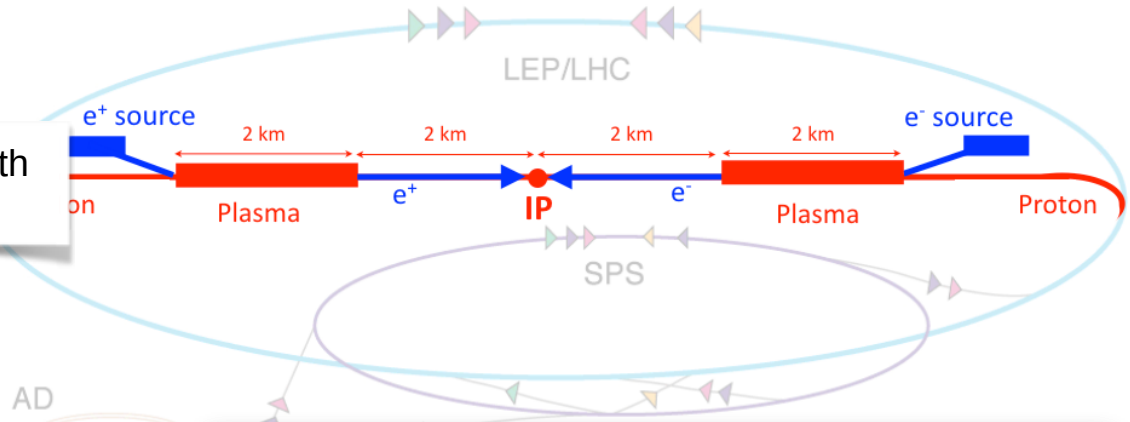
Parameter	Baseline	Range of interest
Beam energy (MeV)	16	10-20
Energy spread (σ, %)	0.5	-
Bunch length, (σ, ps)	4	0.3-10
Beam focus size, (σ, μm)	250	250-1000
Norm. emittance (rms, mm-mrad)	2	0.5-5
Bunch charge, (nC)	0.2	0.1-1

Towards the Future An electron-positron collider



Electron beam energy with plasma density step-up.

A. Caldwell, K. V. Lotov,
PHYSICS OF PLASMAS 18, 103101 (2011).



For this PDPWA-based e^+e^- collider design, half of the LHC bunches (1404 bunches) are used for driving electron acceleration and the other half for positron acceleration. Taking into account that the ramping time of the LHC is about 20 min and assuming that the loaded electron (and positron) beams have a bunch charge of 10% of the drive proton bunch, i.e. electron (and positron) bunch charge of $N_e = 1.15 \times 10^{10}$, and the beam spot sizes at IP are the same as that of the CLIC beam, as shown in Table 1, the resulting luminosity for such an e^+e^- linear collider is about $3.0 \times 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, which is about three orders of magnitude lower than that of the ILC or the CLIC.

G. Xia, O. Mete et al.,
NIMA Volume 740, 11 March 2014, 173–179

1 TeV e^+/e^- beam in 2 km of plasma

- Via plasma step up and self modulation instability.

LHC radius, 4.3 km

- Transfer and matching of protons&plasma.
- Dedicated e^- source
- 2 km plasma section (0.5 GeV m^{-1}).
- 2 km beam delivery and final focusing section.
- “Used” protons to be extracted, dumped or may be recycled.

Luminosity is limited by LHC filling time. However rather than use LHC we could develop a faster cycling machine with looser beam quality specs.

Issues of Proton Driven Plasma Wakefield Acceleration

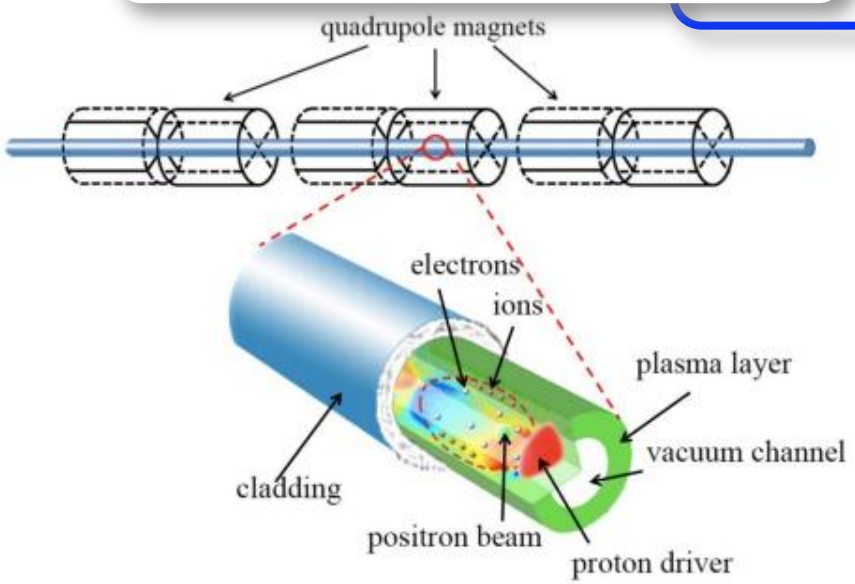
- Phase slippage
- Interaction of “driver” beam with plasma
- Interaction of “witness” beam with plasma
- Positron acceleration (in case of e^-p collider)

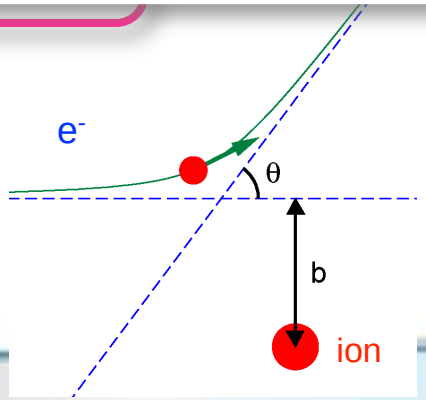
Group velocity of wakefields is the same as the velocity of the driver, protons. **Electrons may overrun the wakefields - no acceleration.**

Bunch lengthening due to energy spread and **focusing** issues of protons.

Production of accelerating field by using a **hollow plasma** for positron acceleration.

Electron beam scattering by plasma electrons and ions - **luminosity degradation through emittance growth**



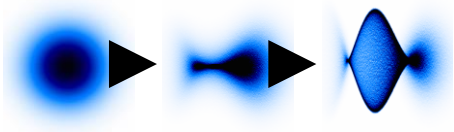


PWFA at Cockcroft Institute

PWFA at VELA user station in 2015

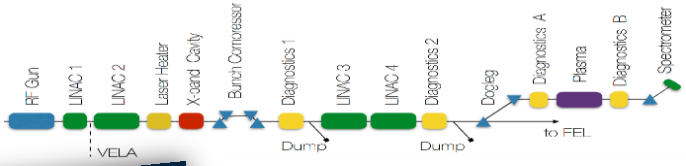
First experiment on plasma lens started in August 2015

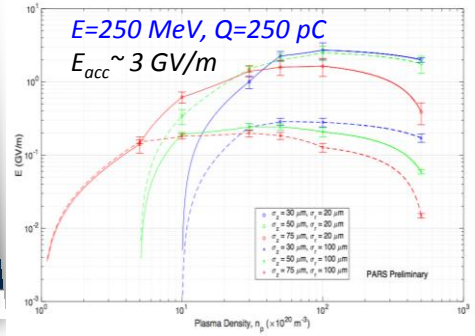
E=4.8 MeV
Q=250 pC
σ_z = 3.3 mm
σ_r = 0.45 mm
focusing gradient of 10 T/m



PWFA at CLARA in 2020

High beam quality preservation, ultrahigh brightness e-production, e.g. plasma photocathode



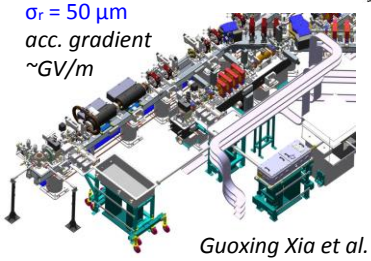


PWFA at CLARA front end in 2016

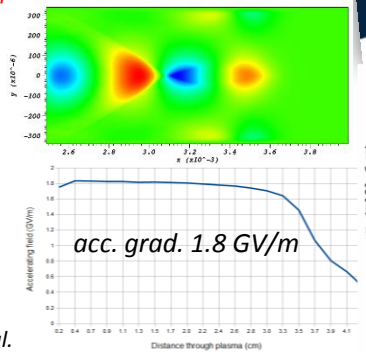
Demonstration of high acceleration gradient ~ GV/m

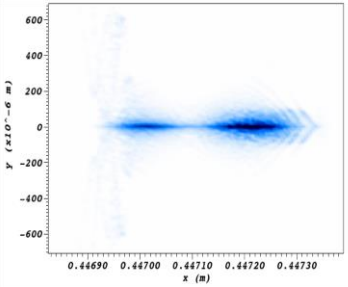
Two bunch acceleration for high quality beam production

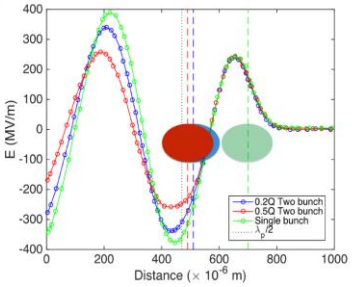
E=50-150 MeV
Q=250 pC
σ_z = 20-100 µm
σ_r = 50 µm
acc. gradient ~GV/m



Guoxing Xia et al.



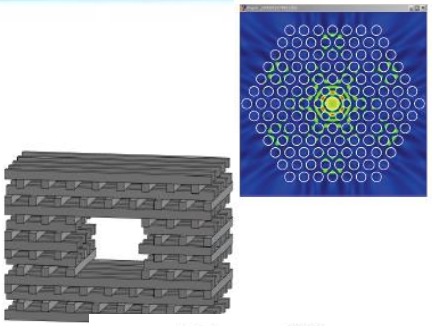


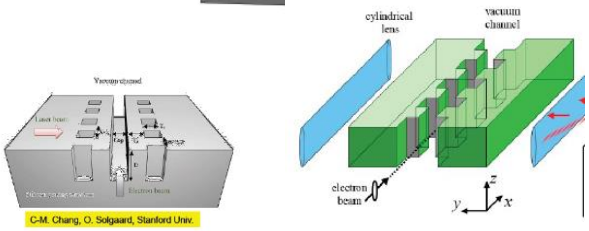


Dielectric Accelerators

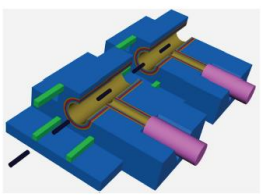
Types

- Photonic structures
- Dielectric Wakefield Accelerators (like CLIC but with dielectric)
- Dielectric RF Linacs (replace RF structure with dielectric)
- Dielectric Wall Accelerators (high voltage switches)
- THz/Laser driven dielectric accelerators (high frequency linacs)

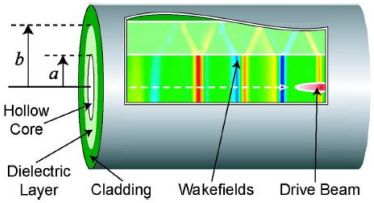




C-M. Chang, O. Solgaard, Stanford Univ.



Cylindrical Bragg accelerator on-chip via layer deposition, M. Qi (Purdue Univ).

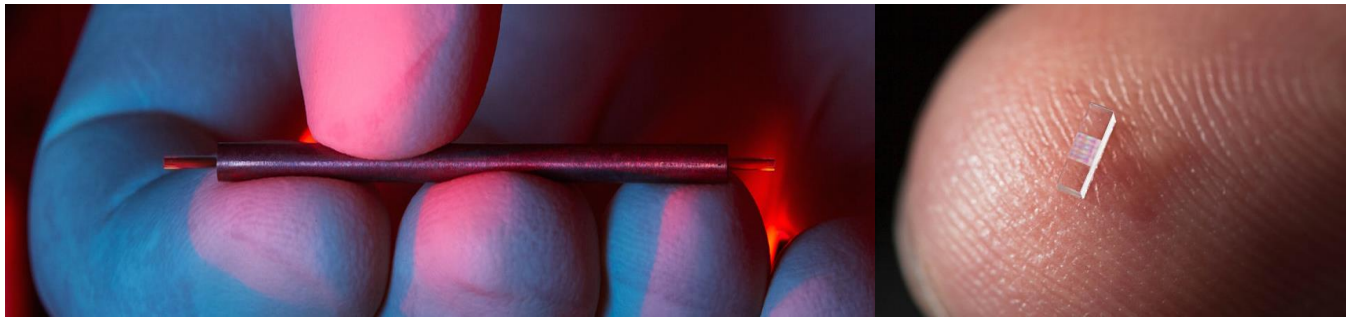


Why?

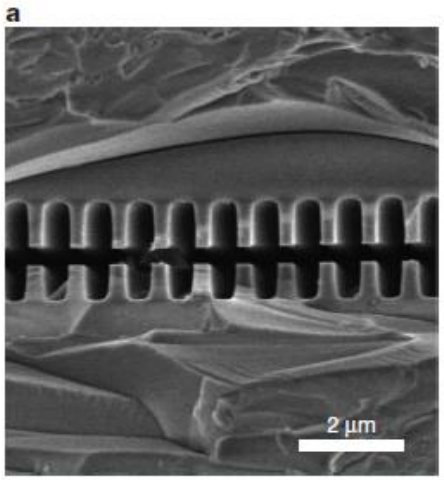
- Dielectrics can have very high gradients if the right material is used (5.5 GV/m shown in experiments but not with acceleration yet)
- They can operate at high frequencies, THz or higher (smaller)
- Can potentially have lower long-range wakefields (for photonic structures)
- Simpler to manufacture (in some cases)

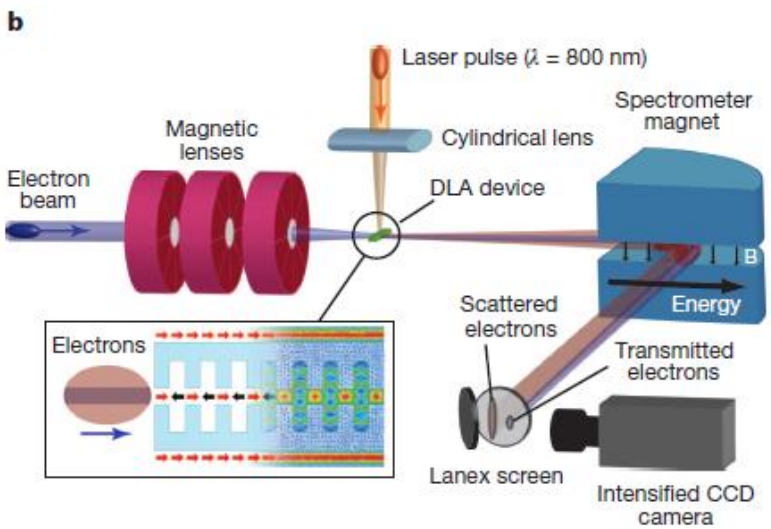
Laser-driven dielectric structures

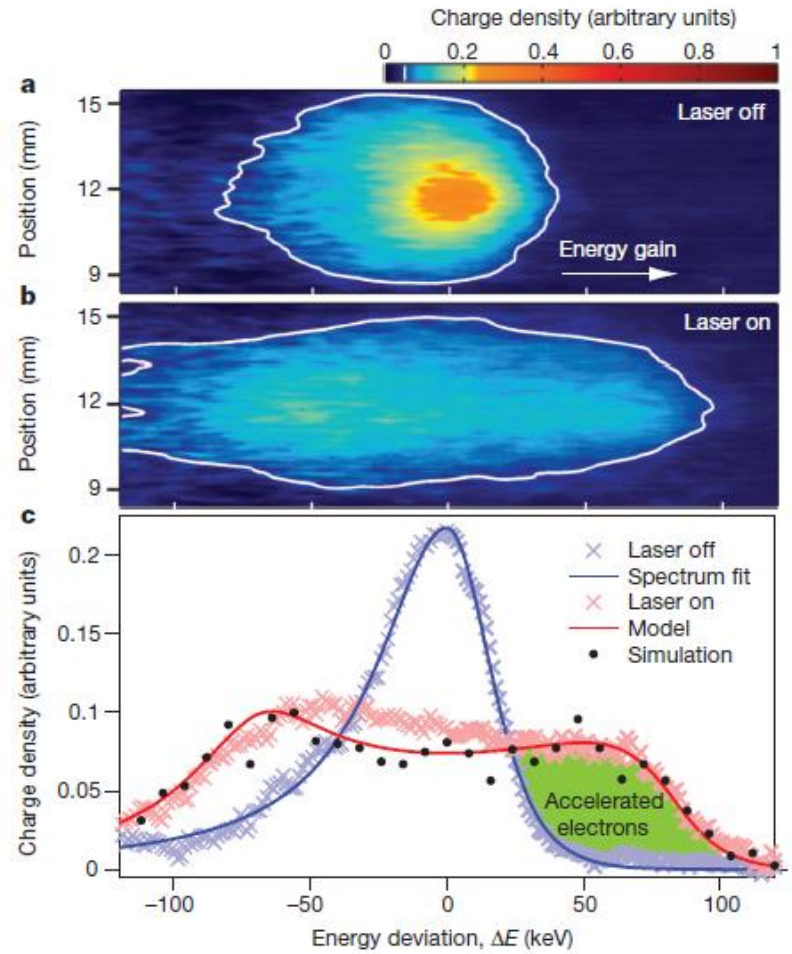
- 1 GeV/m demonstrated but low absolute energies achieved so far (emerging field)
- At present led by DESY-MIT (THz) and UCLA-SLAC (optical) collaborations
- Field is excited by either a high current beam or a laser
- Wave velocity is matched to the beam velocity using a dielectric structure
- Lots of parameter space to explore still lots of opportunity for UK to get involved and lead.
- Easy to use multiple stages unlike plasma.



Stanford, SLAC, UCLA results



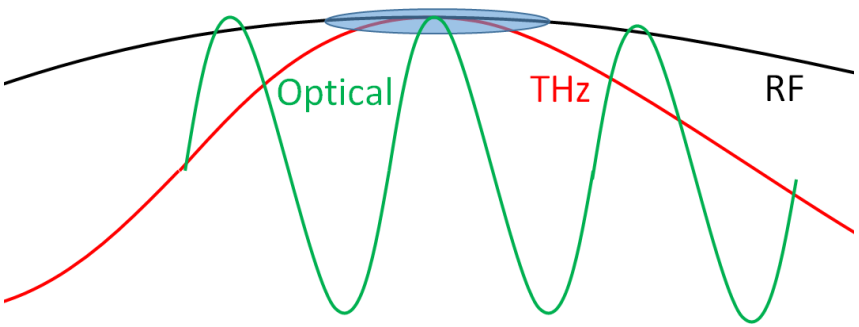




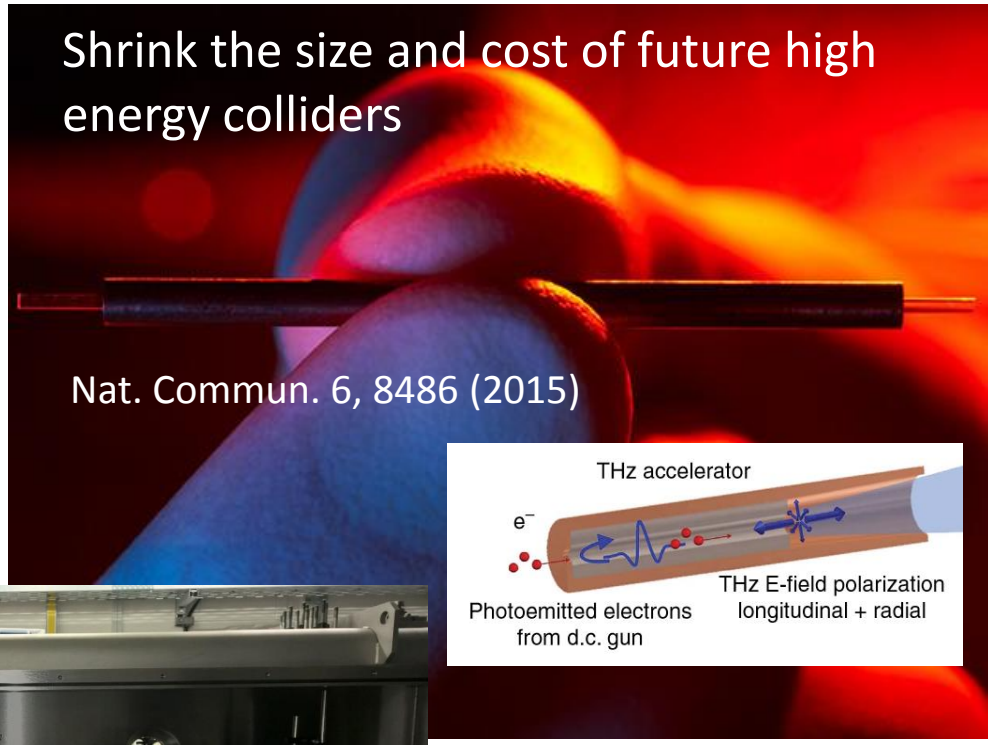
AL J

Terahertz driven dielectric linacs

Terahertz vs. optically driven



All particles are accelerated with THz



Conclusions

- The next big HEP accelerator project will be the LHC luminosity upgrade, now in the prototyping phase.
- HL-LHC-UK will develop UK accelerator contribution
- LHC results will determine what happens next
- In the far future we are looking to beam-driven plasma and dielectrics to develop higher energy colliders.