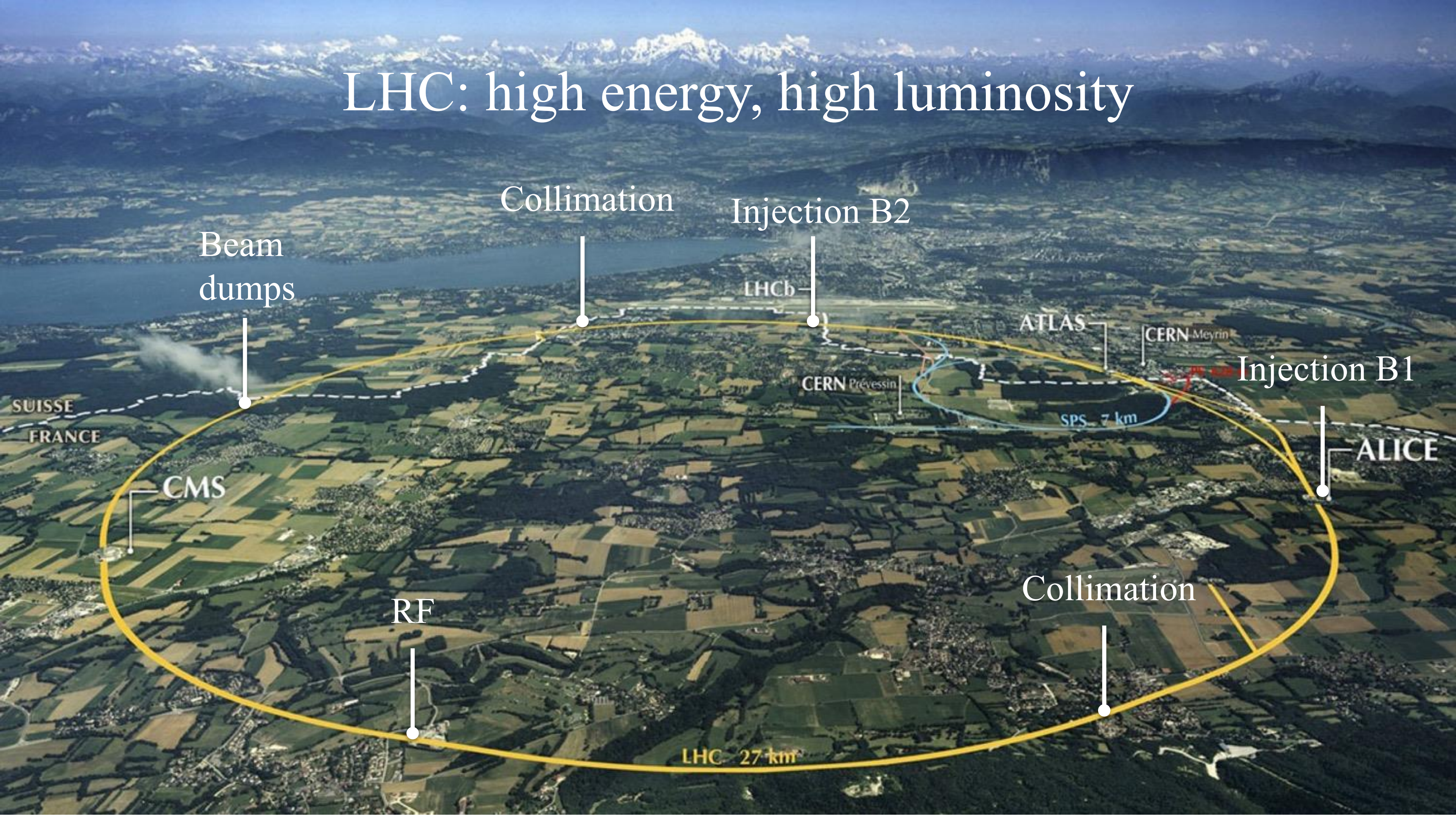
LHC, HL-LHC, FCC

Mike Lamont
3rd June 2018

First Biennial African Conference on Fundamental Physics and Astrophysics

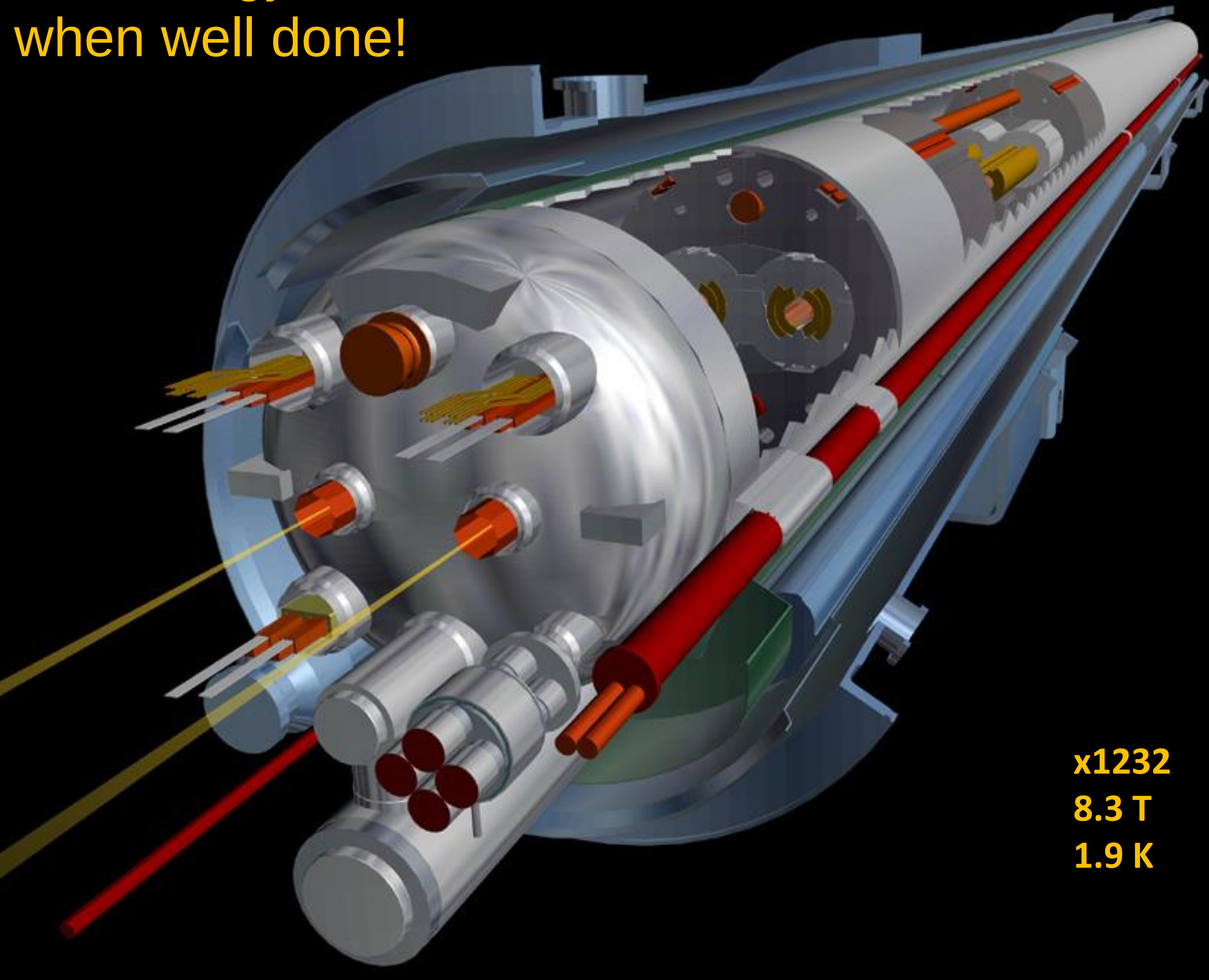
LHC: high energy, high luminosity



1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes helium, ~90 tonnes at 1.9 K
~250 MJ stored beam energy in 2018
1.2 GJ magnetic energy per sector at 6.5 TeV

Technology: beautiful, when well done!



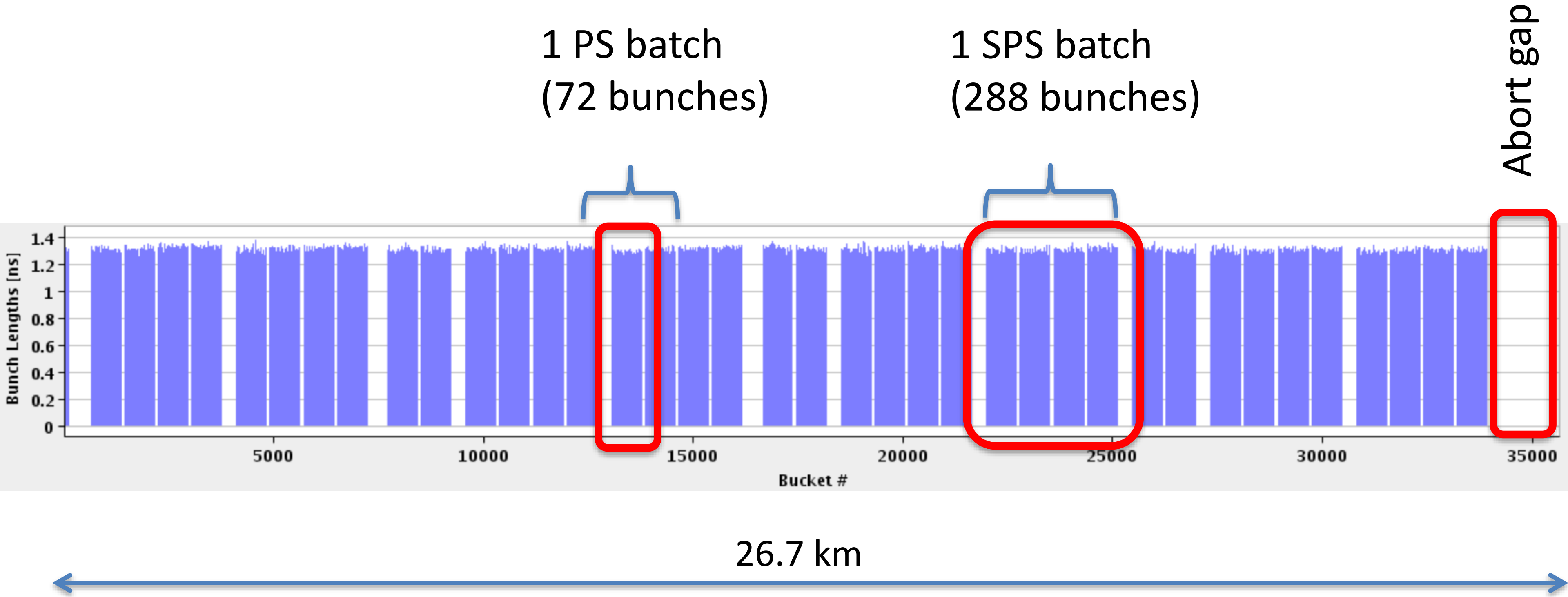
x1232
8.3 T
1.9 K

Beam dump

Video

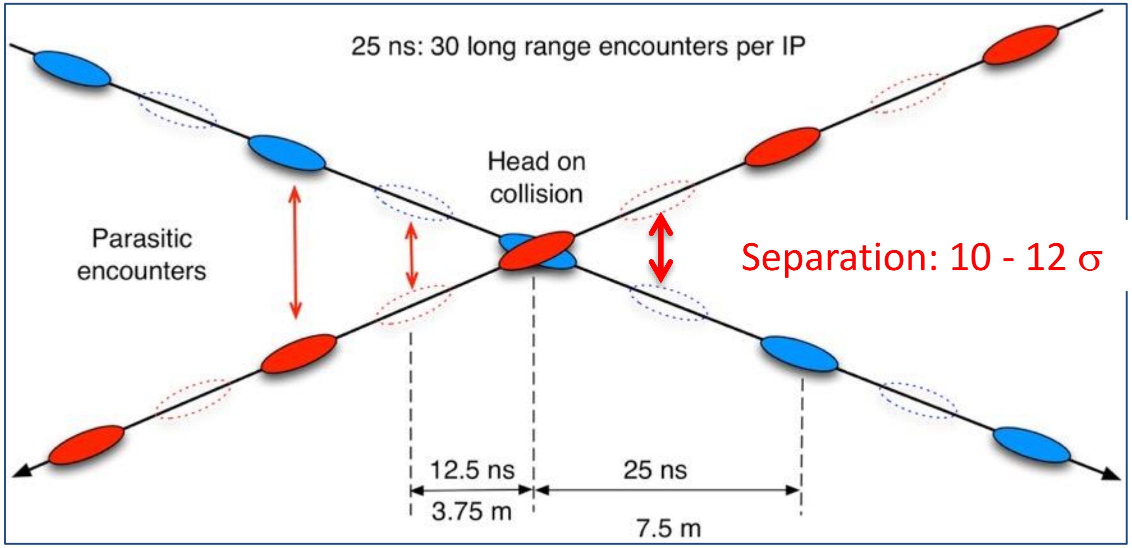
Nominal LHC bunch structure

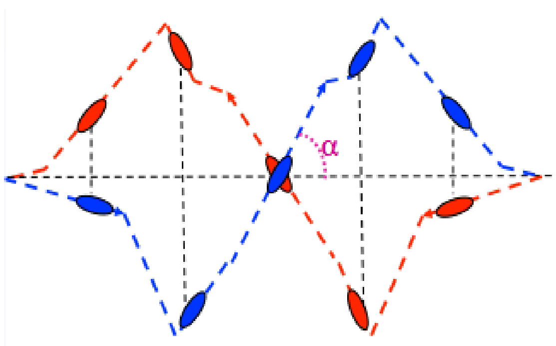
- 25 ns bunch spacing, 2800 bunches
- Nominal bunch intensity 1.15 x 10^{11} protons per bunch



Crossing angle

work with a crossing angle to avoid parasitic collisions.





Reduction factor:

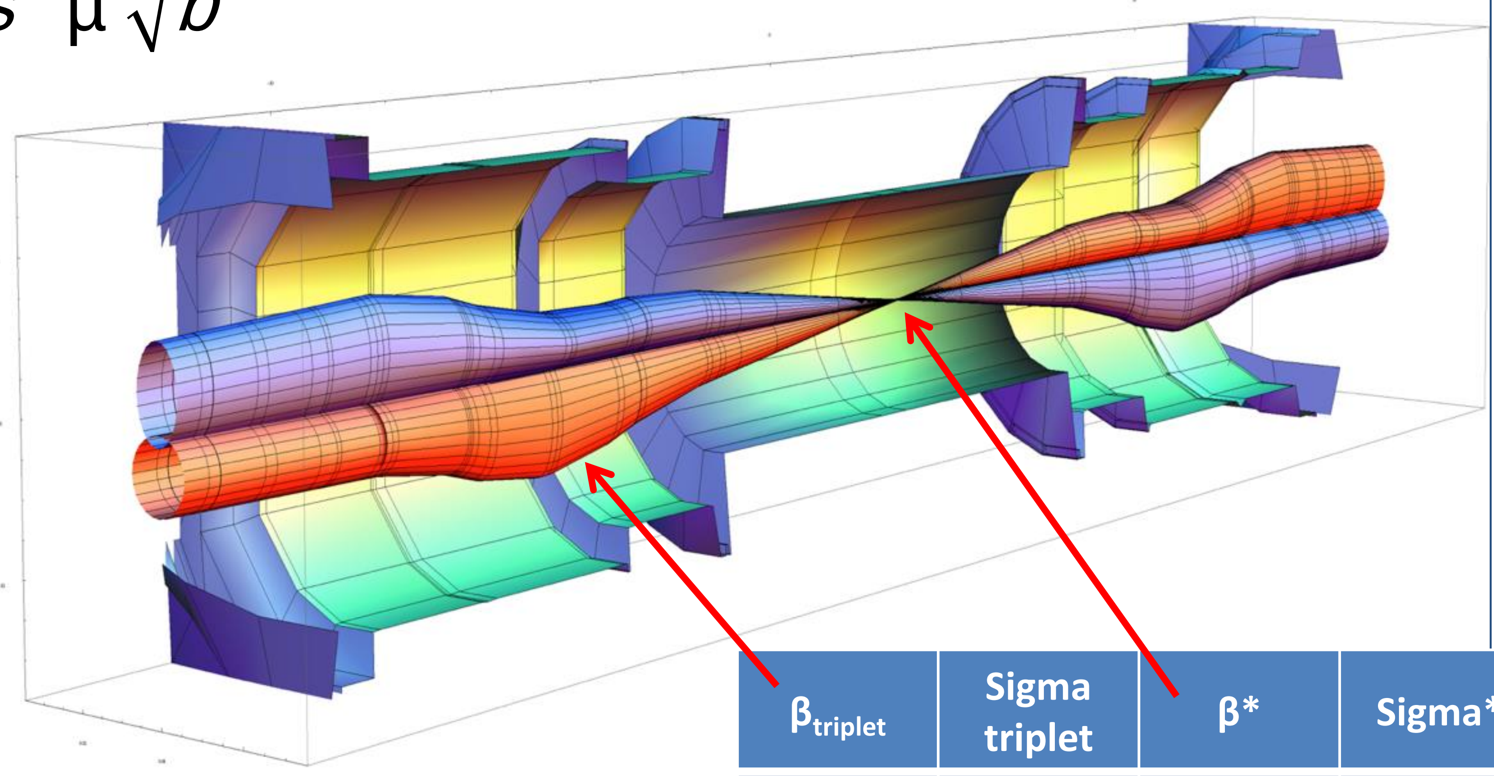
~0.6 at present

$$F = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Squeeze in ATLAS/CMS

- Lower beta* implies larger beams in the triplet magnets
- Larger beams implies a larger crossing angle
- Aperture concerns dictate caution – experience counts

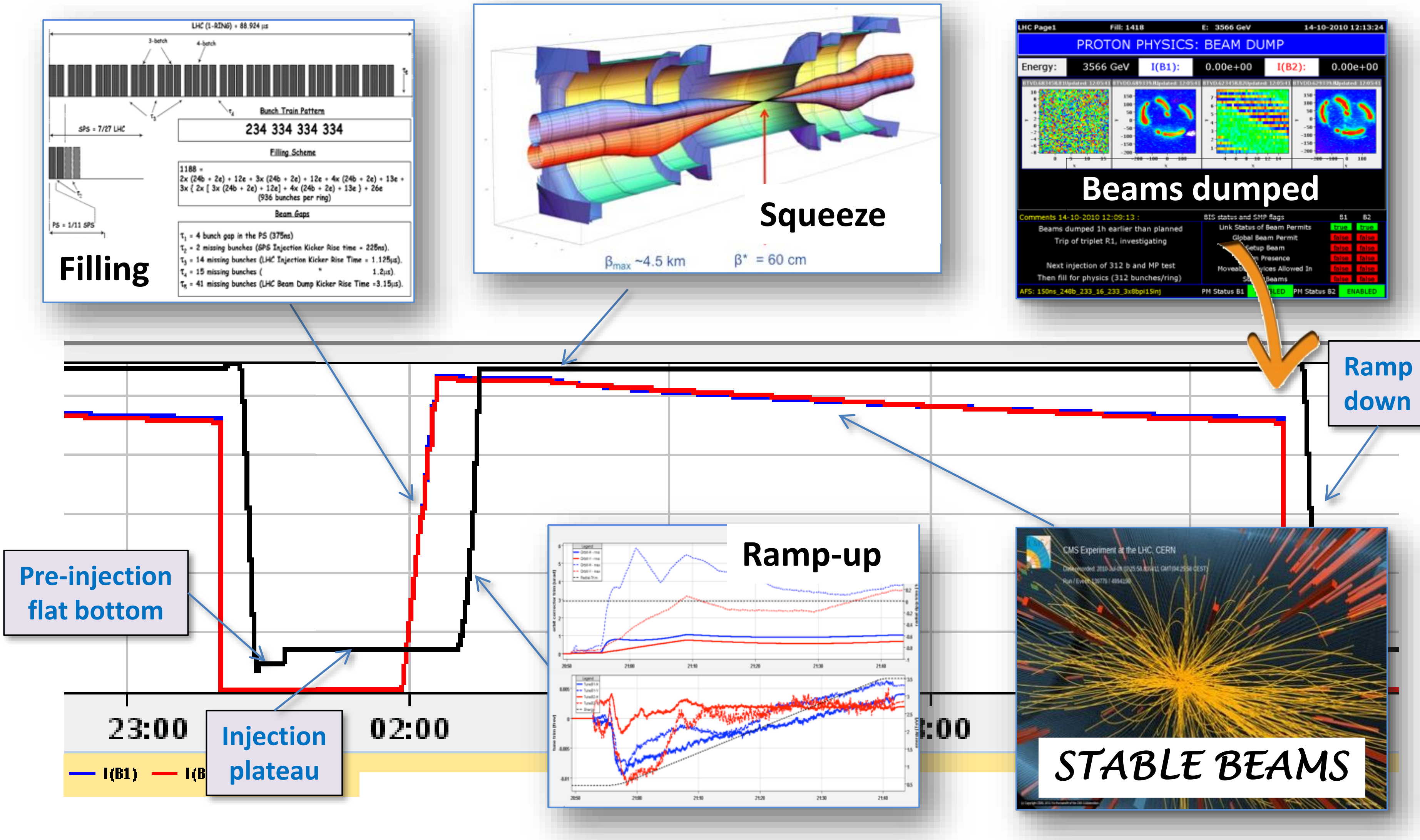
$$s^* \mu \sqrt{b^*}$$



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	**30 cm**	**10 um**

Image courtesy John Jowett

The LHC nominal cycle



Life's never easy... (1)

WEASEL

PS MAIN POWER SUPPLY

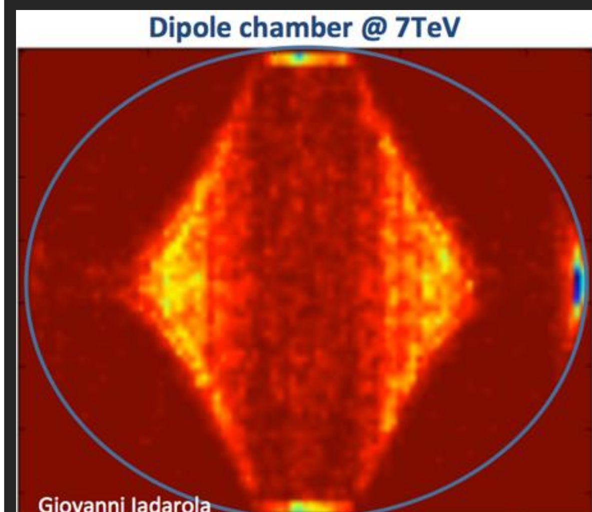
SPS BEAM DUMP

- Vacuum leak
- Limited to 96 bunches per injection

Life's never easy...(2)

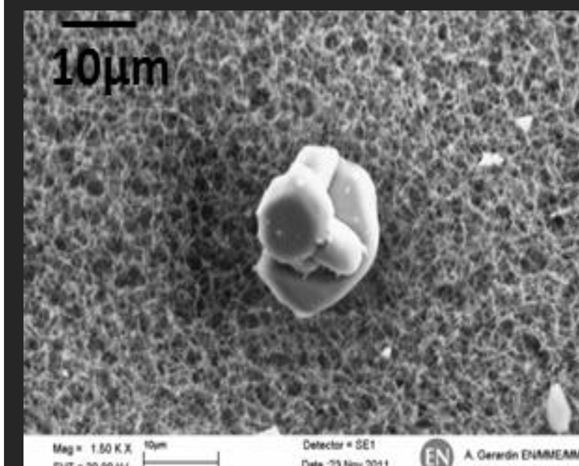
Electron cloud

- Anticipated
- Significant head load to cryogenics
- STILL WITH US



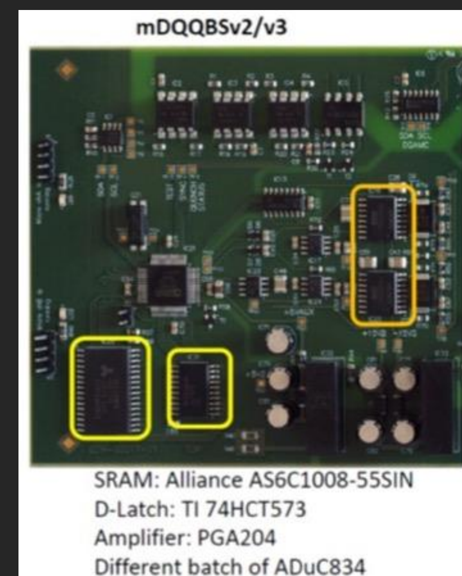
UFOs

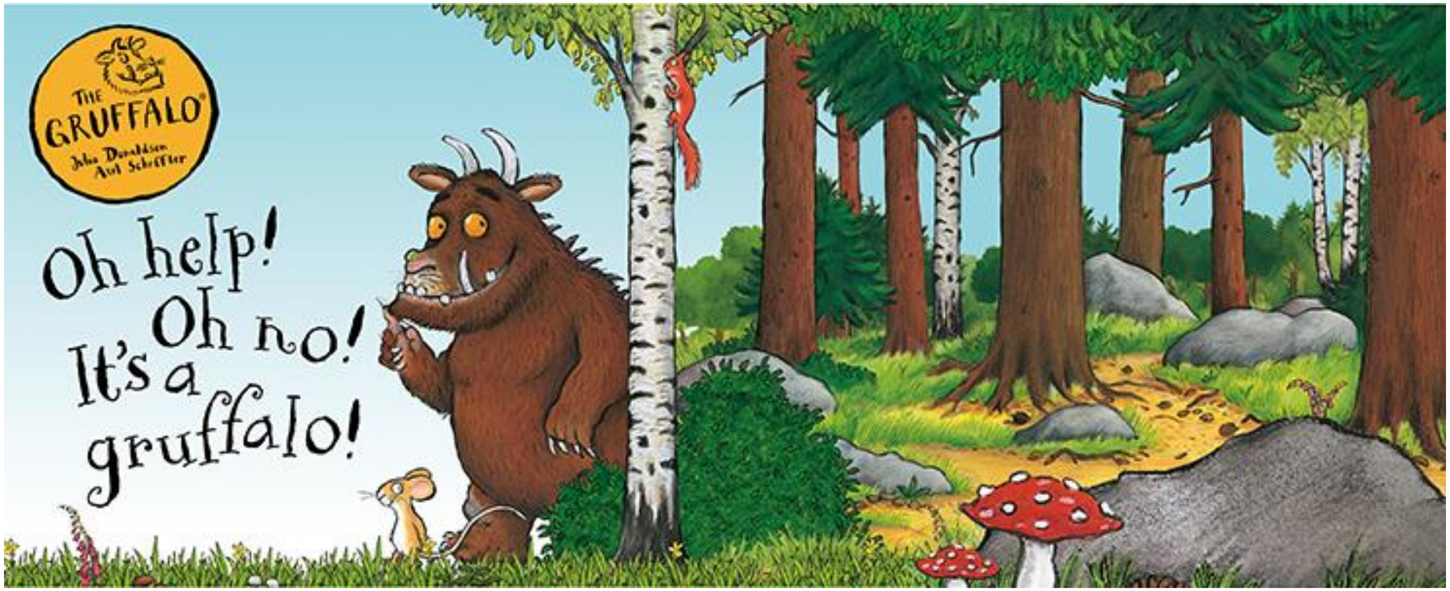
- Fall through the beam – local losses and dump
- Conditioning observed

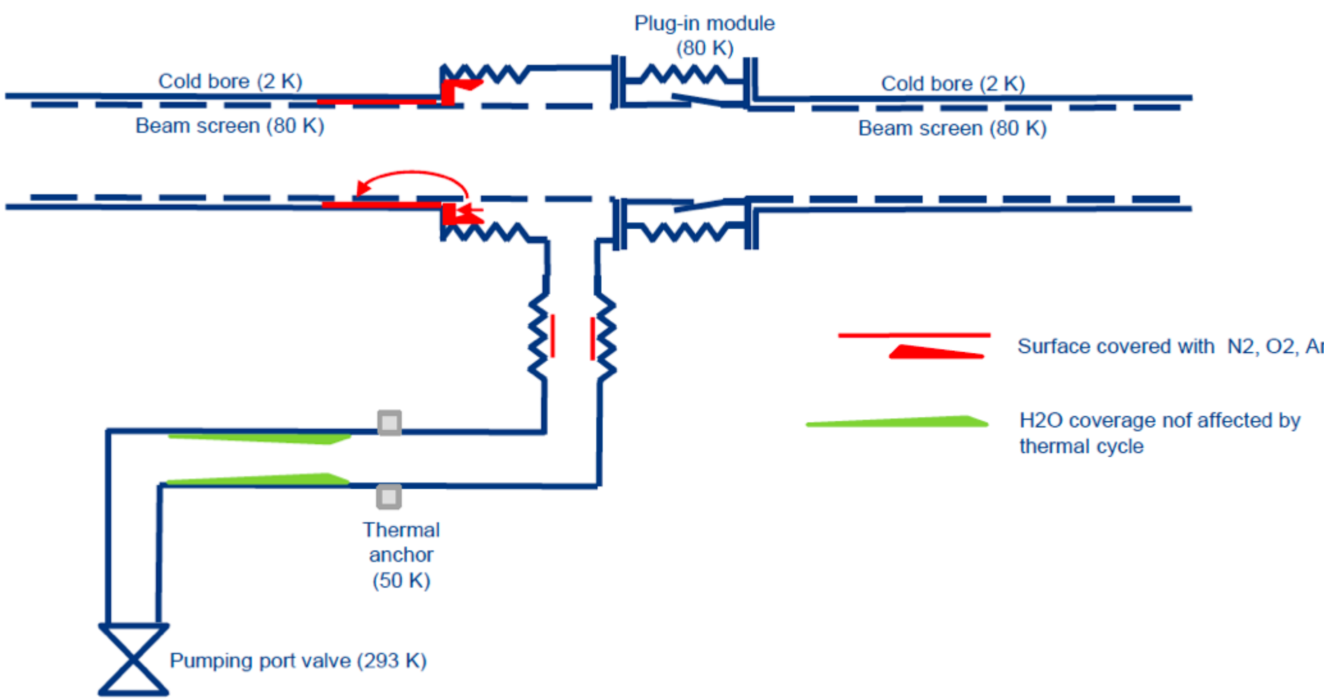


Radiation to electronics

- Mitigation measures (shielding, relocation…)
- Non-rad hard components used in LS1 upgrade




The Gruffalo
Oh help! Oh no! It's a gruffalo!


Plug-in module
(80 K)
Cold bore (2 K)
Beam screen (80 K)
Cold bore (2 K)
Beam screen (80 K)
Surface covered with N2, O2, Ar
H2O coverage nof affected by thermal cycle
Thermal anchor (50 K)
Pumping port valve (293 K)

Higher intensity

Increased bunch intensity

Number of bunches

$$\mathcal{L} = \frac{N_1 N_2 k_b f \gamma}{4\pi \epsilon_n \beta^*} F$$

Increase F – the crossing angle reduction factor:
Shorter bunches
Smaller crossing angle

$$\frac{1}{\sqrt{1 + (\frac{\phi}{2}\frac{\sigma_z}{\sigma_y})^2}}$$

Smaller emittance

Smaller beta*

Smaller beam size

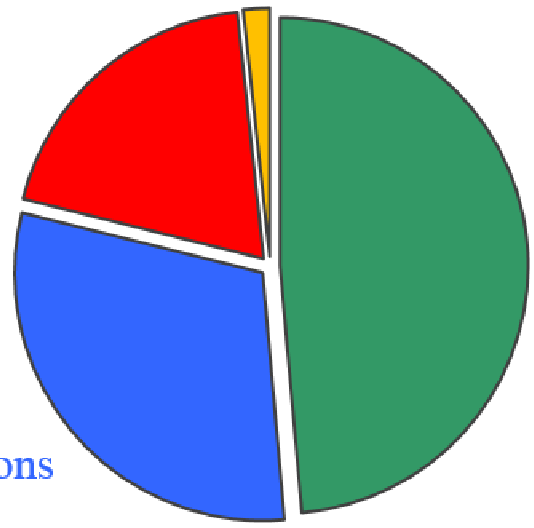
2018 parameters – IPs 1&5

	Actual
Beta* (1/5) [cm]	30 (to 25)
Half crossing angle [urad]	~170 to 130
No. of colliding bunches	2544
Protons per bunch	1.2e11
Emittance into SB [um]	~2.3
Bunch length [ns]	1.05
Peak luminosity [$cm^{-2}s^{-1}$]	~2.1e34
Peak pile-up	~59

Luminosity limit from cooling capacity of inner triplets: ~2.2 x 10^{34} $cm^{-2}s^{-1}$ at 6.5 TeV

Availability

2017: 140½ days physics ≈ 3362.1 hours

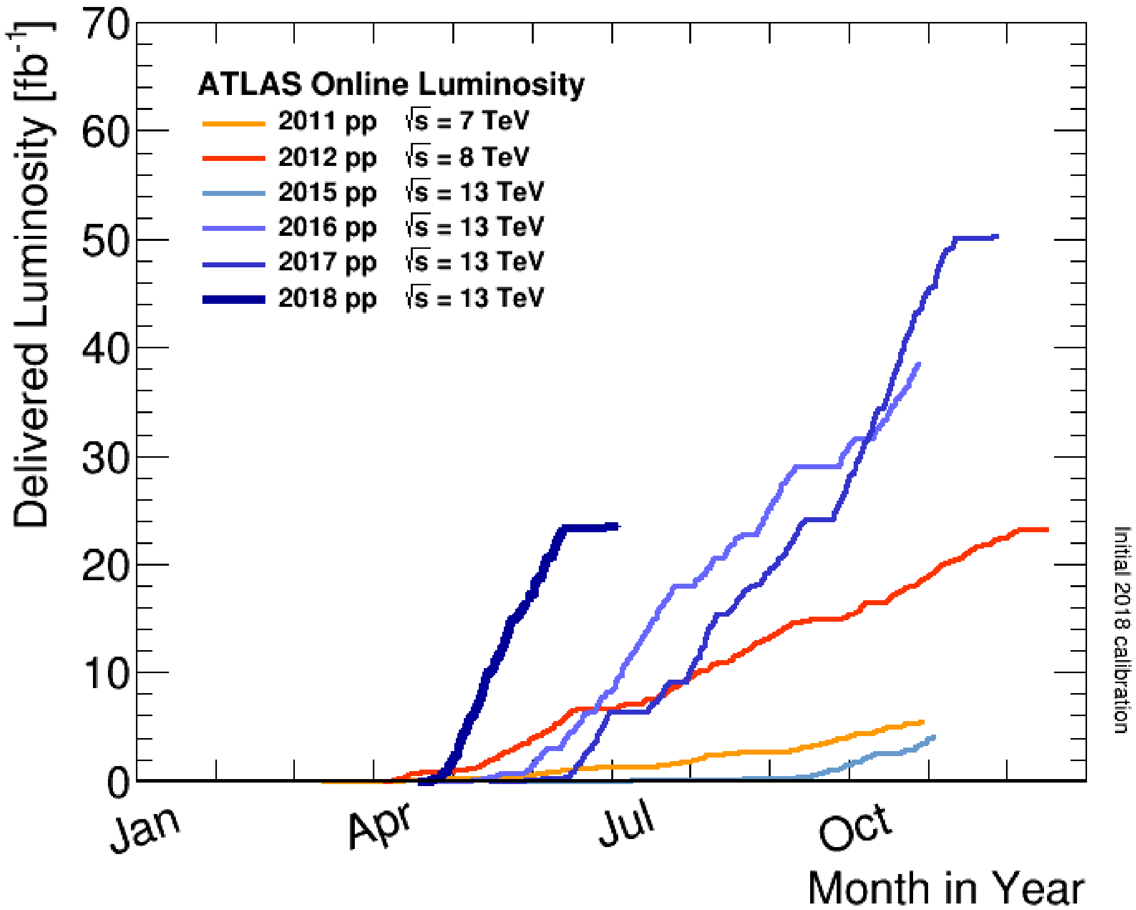


Phenomenal!

ATLAS & CMS: integrated luminosity

Peak luminosity: 2.1 x 10^{34} $cm^{-2}s^{-1}$

Maximum integrated luminosity in 1 day: 903 pb^{-1}

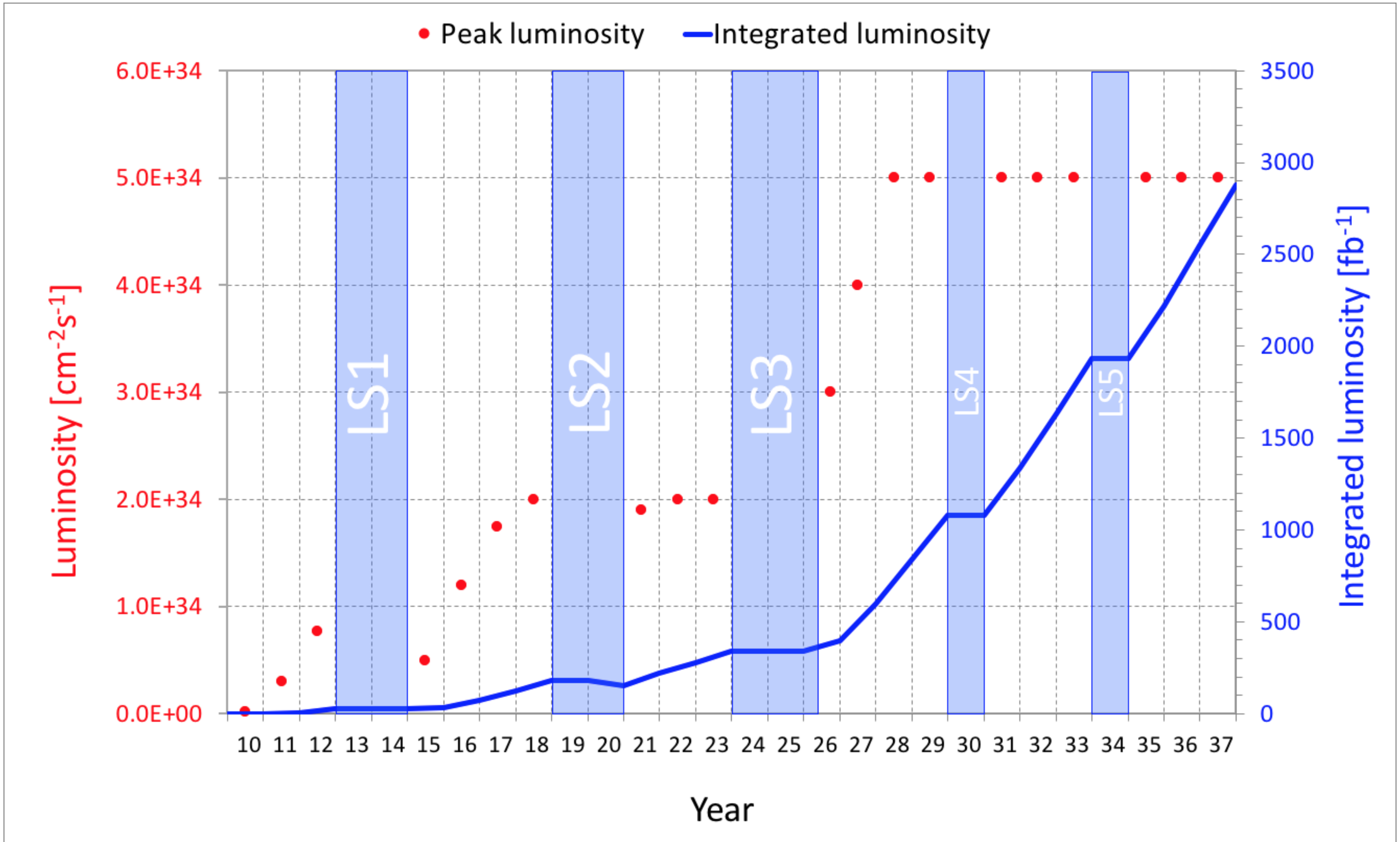


No one is more surprised than we are

- Good peak luminosity, excellent luminosity lifetime
- Stunning availability
  - Sustained effort from hardware groups
- Few premature dumps – long fills
  - UFO rate down, radiation to electronics mitigated

HL-LHC - goals

- Total integrated luminosity of 3000 fb^{-1}
- Integrated luminosity of ~250 fb^{-1} per year
- **Pile-up** ≤ 140 (peak luminosity of $5x10^{34}$ $cm^{-2}s^{-1}$)



HL-LHC How?

- Lower beta*
  - Wide aperture inner triplet magnets - Nb_3Sn
  - Large aperture NbTi separator magnets
  - Novel optics solutions
- Crossing angle compensation
  - Crab cavities
- Beam from injectors
  - High bunch population, low emittance, 25 ns
- Dealing with the regime
  - Collision debris, high radiation

Squeeze harder

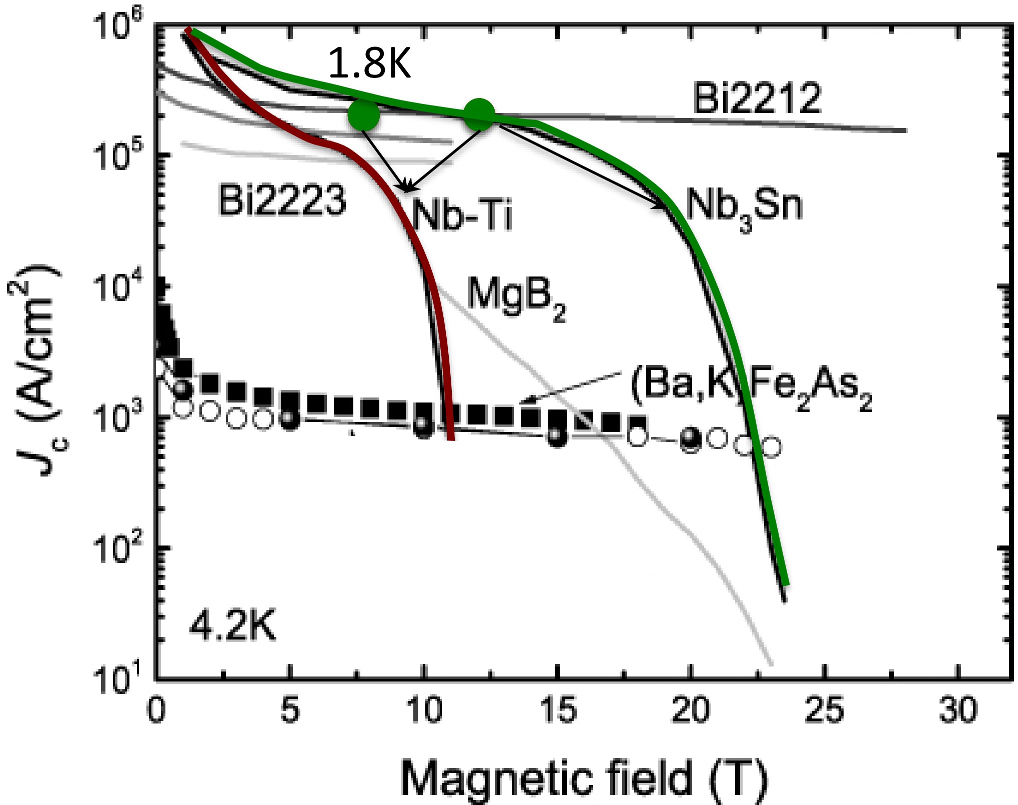
	2018	HL-LHC
β^*	30 cm	**15 cm**
Beam size at IP (sigma)	10 um	**7 um**
Crossing angle	300 urad	**500 urad**

The reduction in beam size buys a factor of 2 in luminosity but:

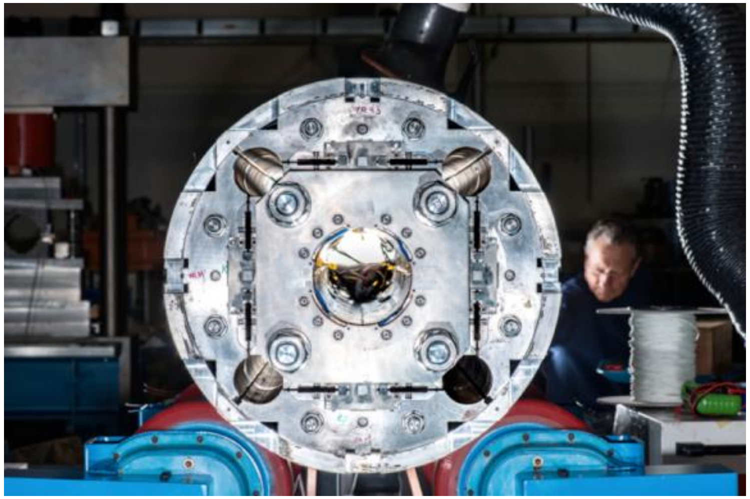
- Bigger beams in inner triplets
- Larger crossing angle
- And thus larger aperture in inner triplets is required.

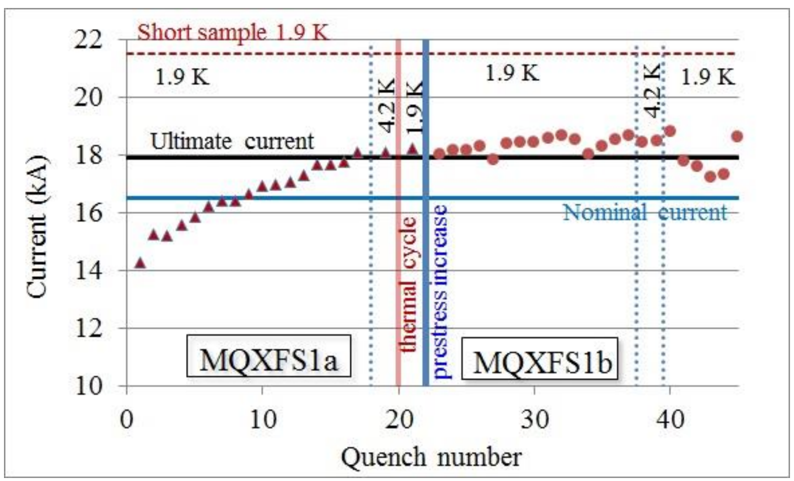
Triplets

- Present LHC triplets: 210 T/m, 70 mm coil aperture
  - 8 T @ coil - approaching limit of NbTi
- HL-LHC triplet: 140 T/m, 150 mm coil aperture
  - Around 12 T @ coil
  - **Requires Nb_3Sn technology**



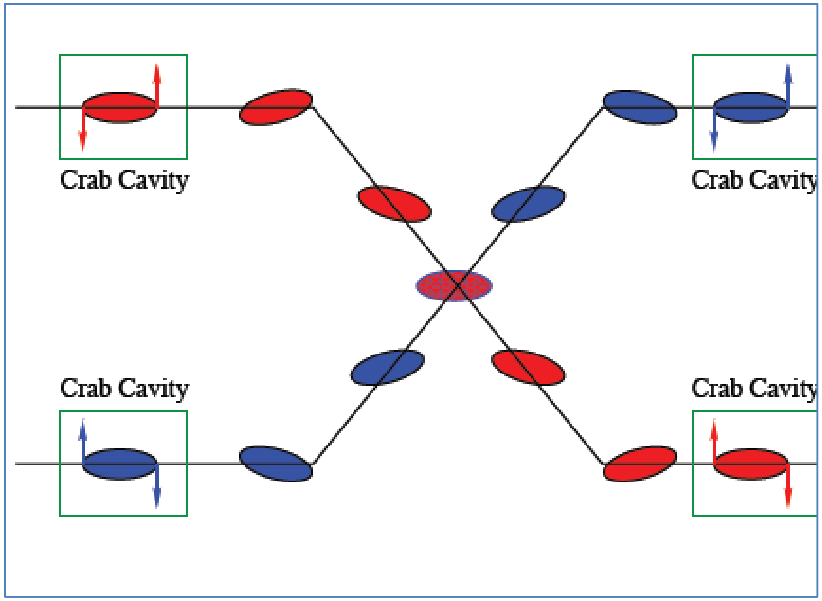
Challenge: build a wide aperture quadrupole

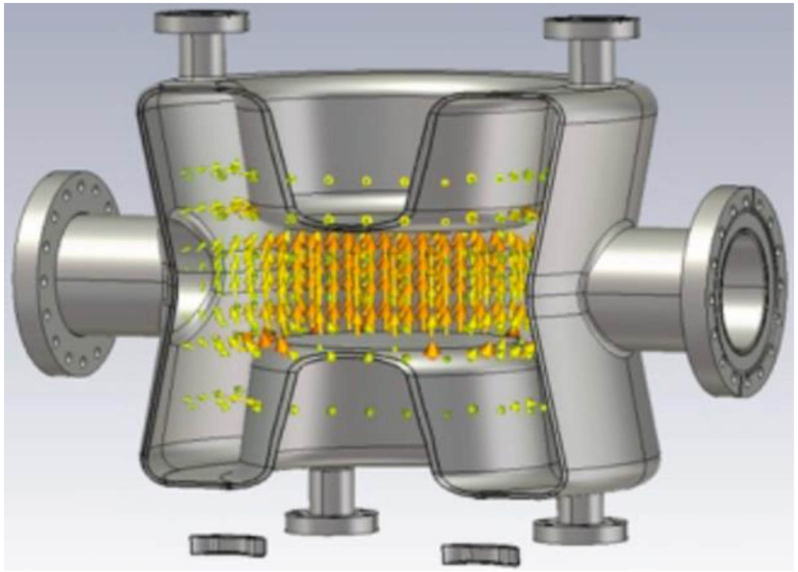




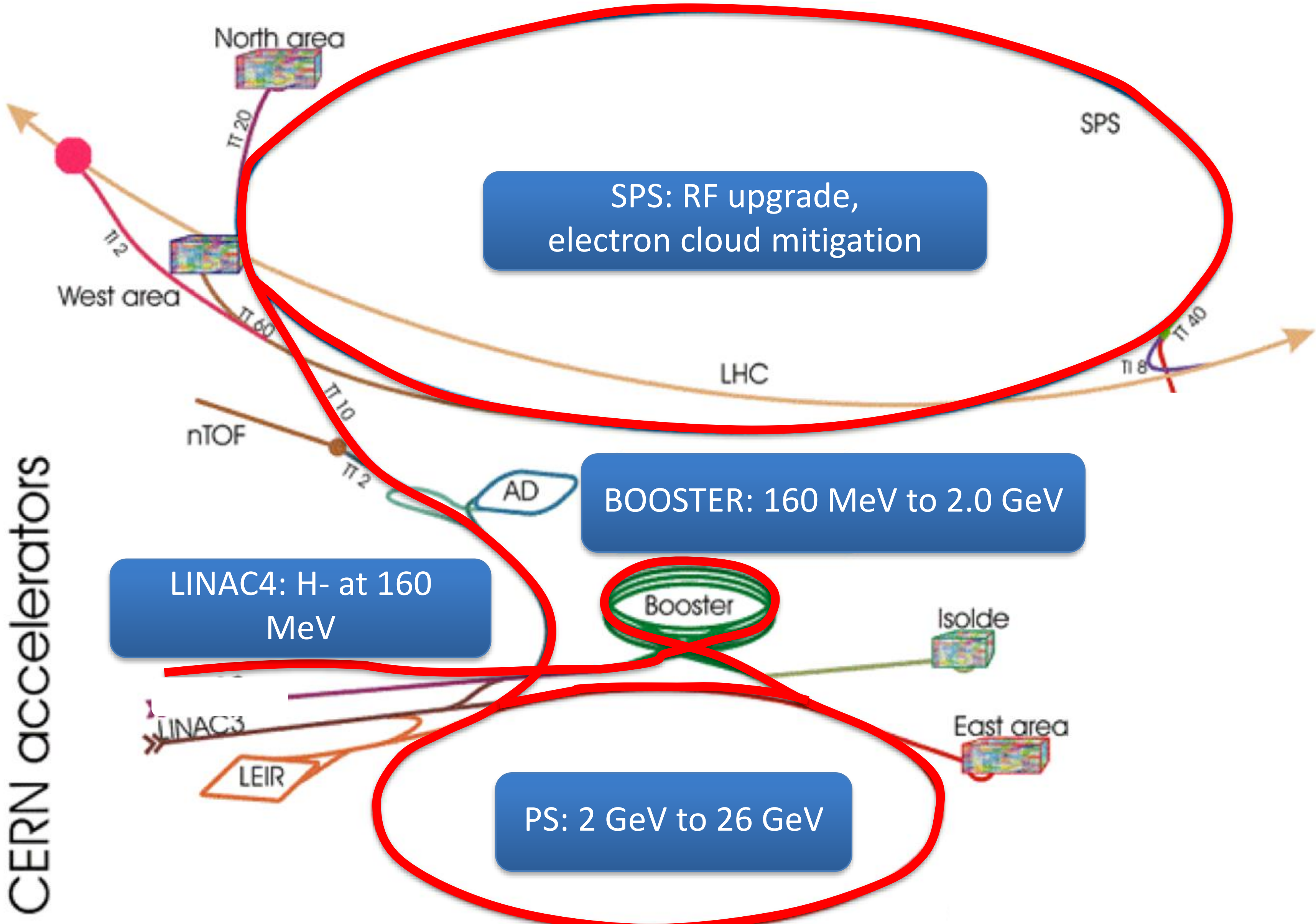
Crossing angle compensation

Attempt to claw back the very significant reduction in luminosity from the large crossing angle





Prototype now installed in the SPS.

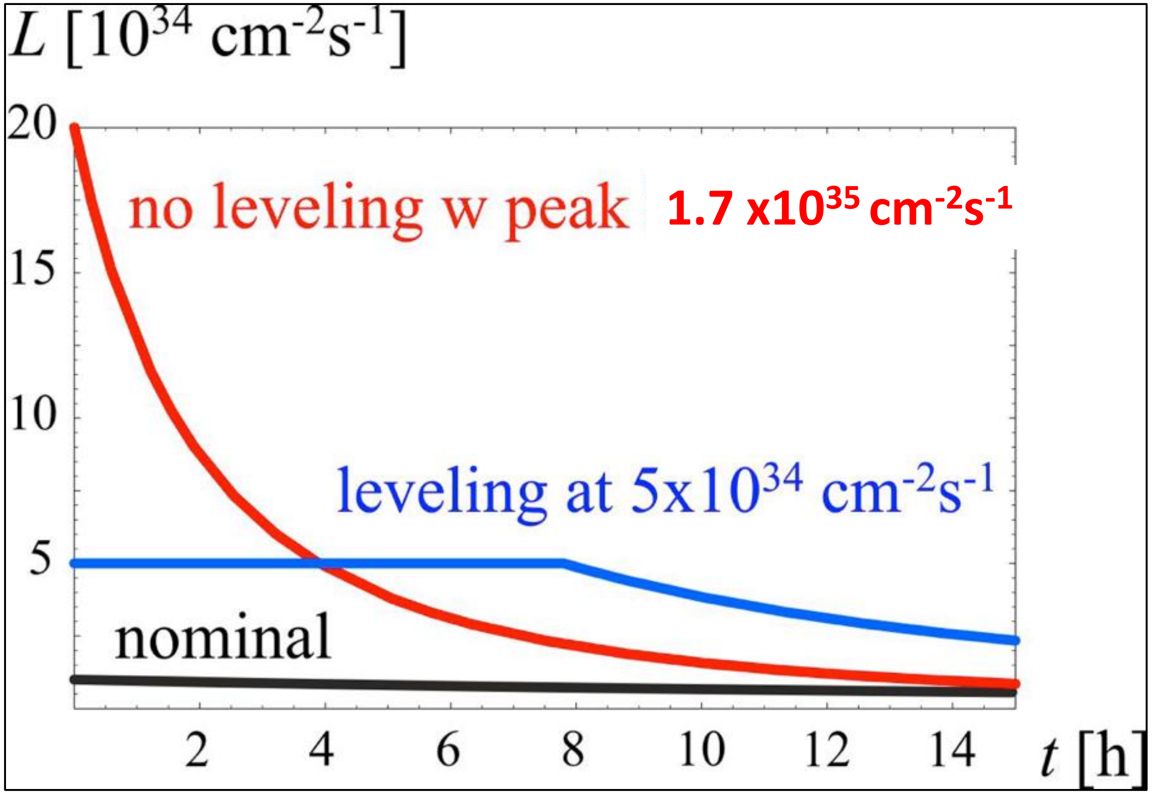


Targeting ~2.3 x 10^{11} protons per bunch

HL-LHC: key 25 ns parameters

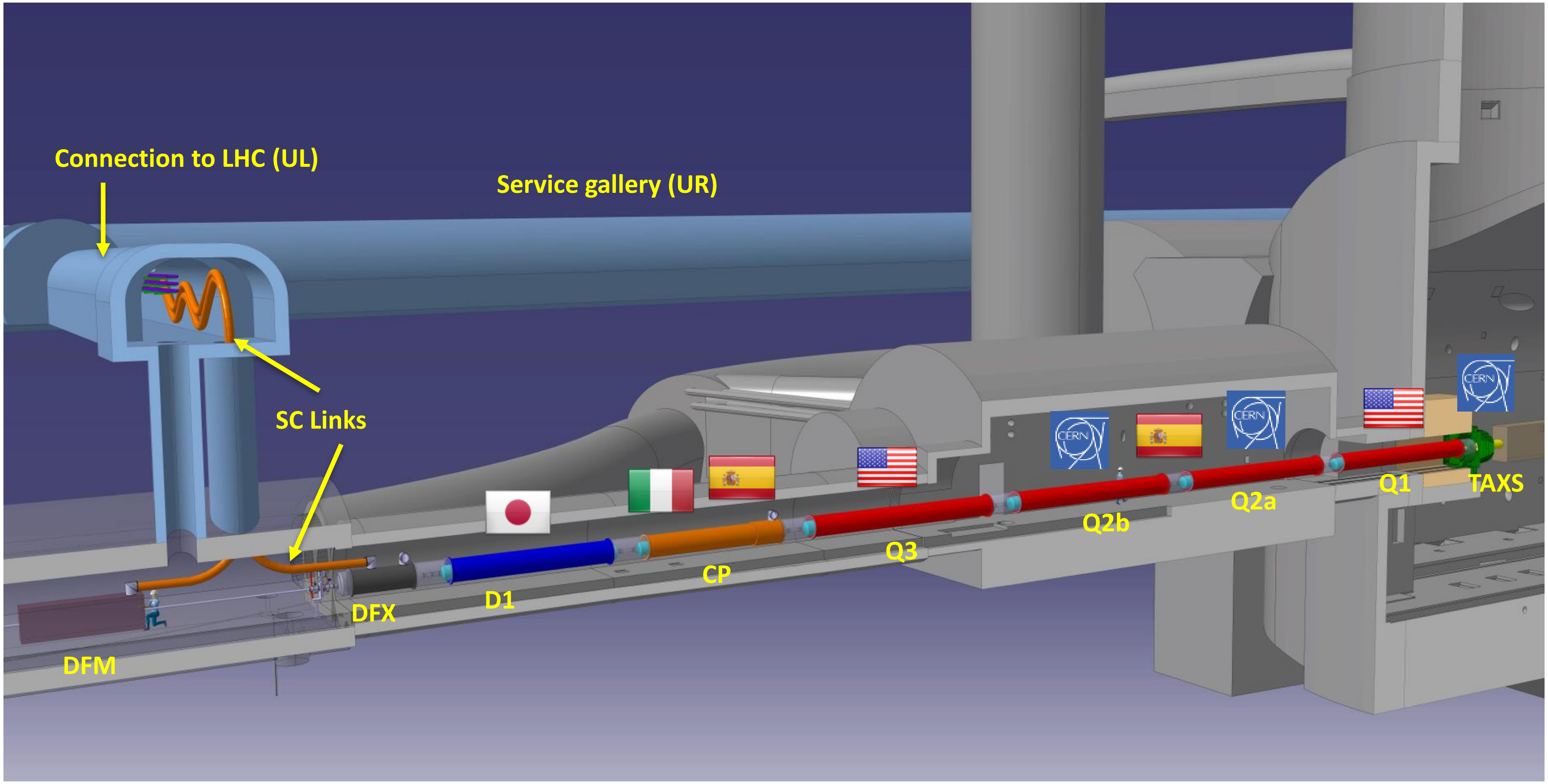
Protons per bunch	2.2×10^{11}
Number of bunches	2748
Normalized emittance	2.5 micron
Beta*	20 cm
Crossing angle	500 microrad
Geometric reduction factor	0.34
Virtual luminosity with crabs	1.7×10^{35} cm^{-2}s^{-1}
Levelled luminosity	5×10^{34} cm^{-2}s^{-1}
Levelled <pile-up>	131

Operational scenario

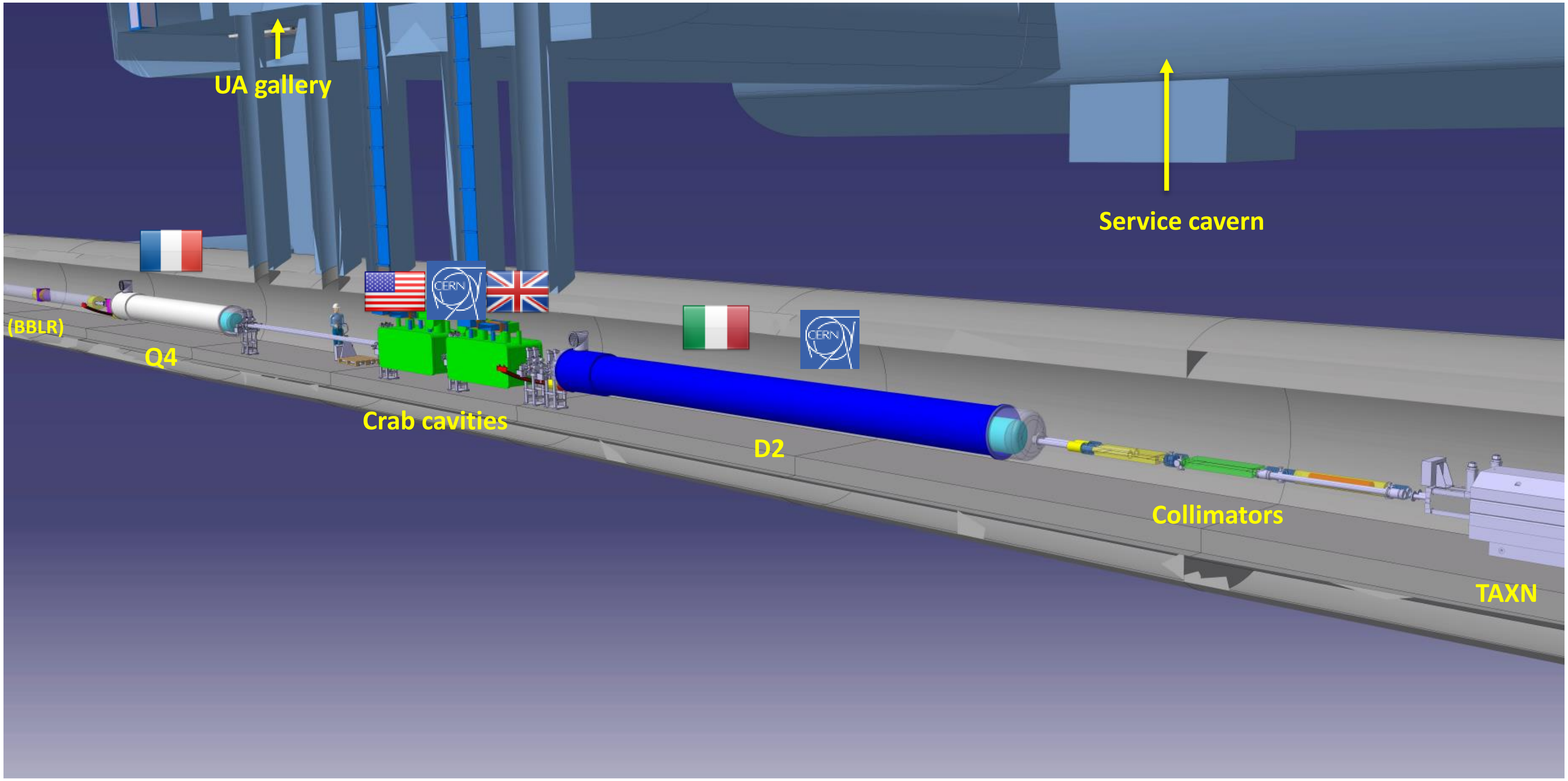


- With crossing angle compensation – $1.7\ x10^{35}\ cm^{-2}s^{-1}$
- Need to artificially reduce luminosity to stay within pile-up limit of experiments - **leveling**

The Inner Triplet region



Matching Section (MS) region

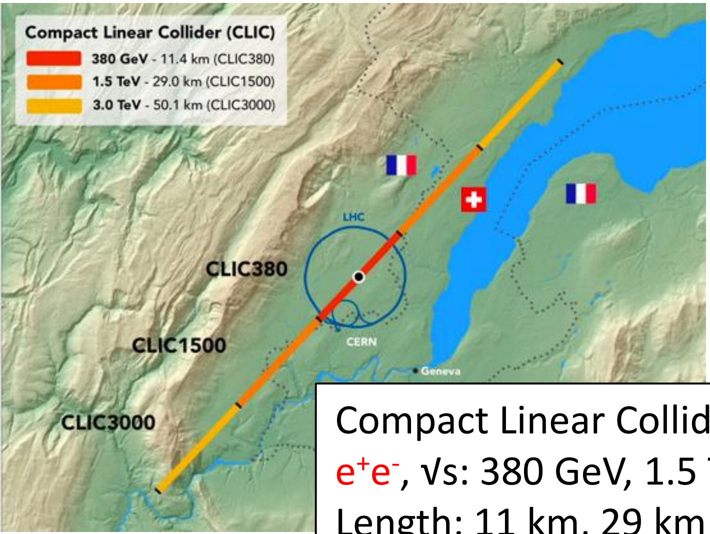


"The largest HEP accelerator in construction!"

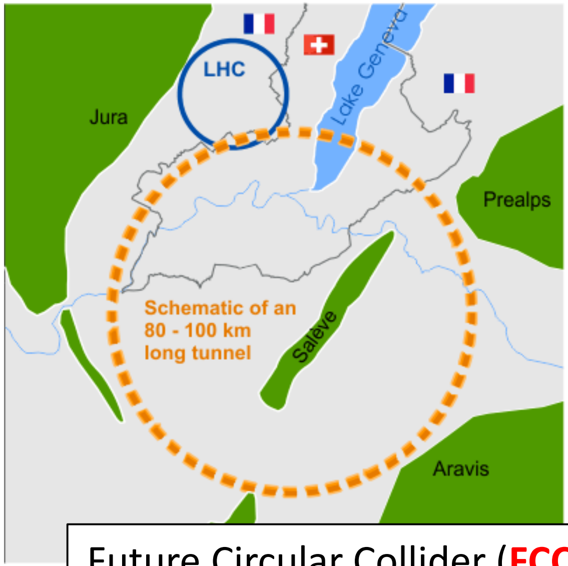
> 1.2 km of LHC !!

Civil Engineering Pt1 and Pt5 has started

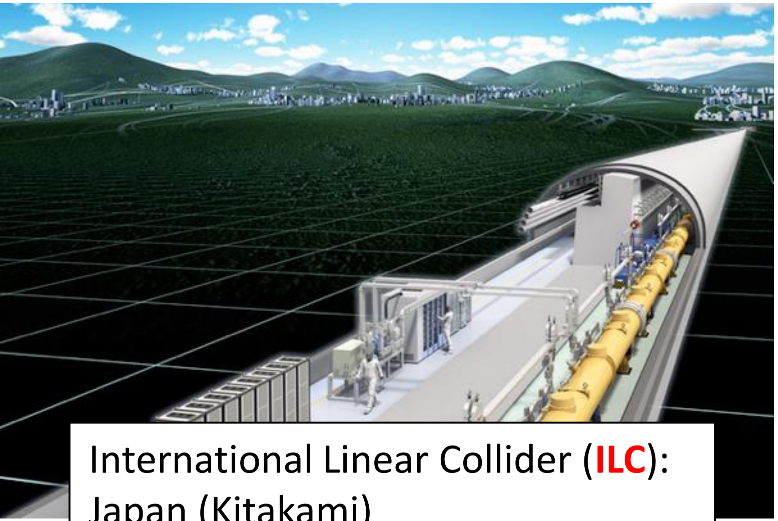
high-energy e+e- collider studies



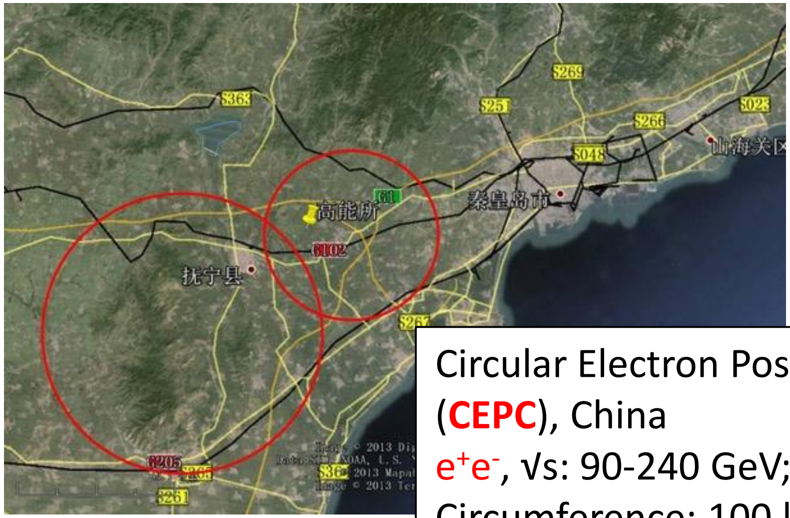
Compact Linear Collider (**CLIC**): CERN
e^+e^-, √s: 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km , 50 km



Future Circular Collider (**FCC-ee**): CERN
e^+e^-, √s: 90 - 350 (365) GeV; FCC-hh pp
Circumference: 97.75 km



International Linear Collider (**ILC**): Japan (Kitakami)
e^+e^-, √s: 250 – 500 GeV (1 TeV)
Length: 17 km, 31 km (50 km)



Circular Electron Positron Collider (**CEPC**), China
e^+e^-, √s: 90-240 GeV; SPPC pp,
Circumference: 100 km

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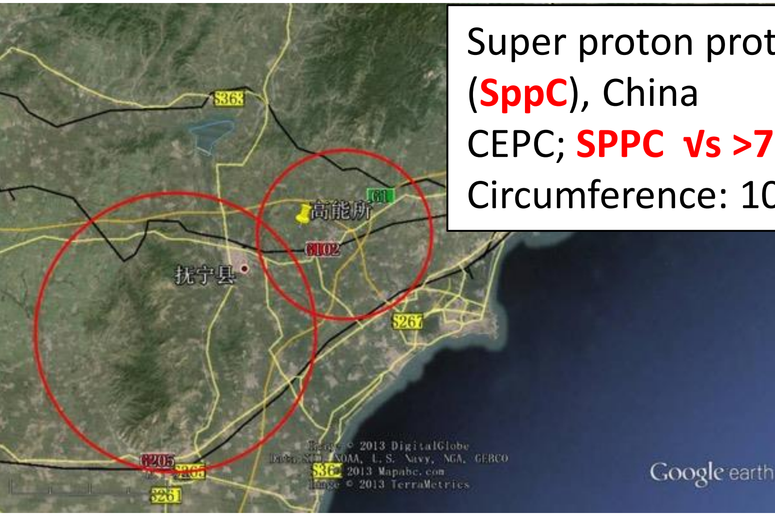
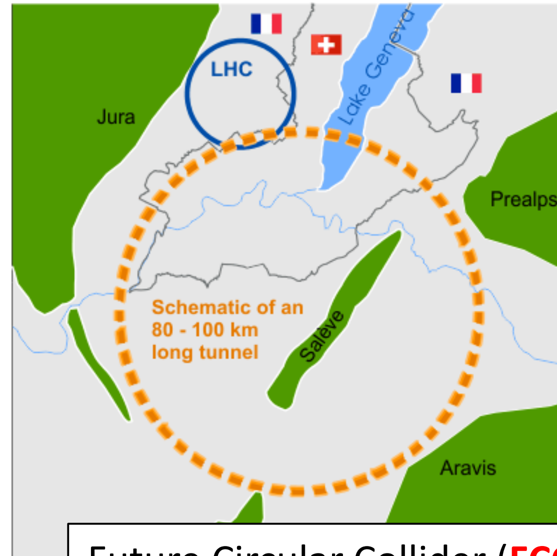
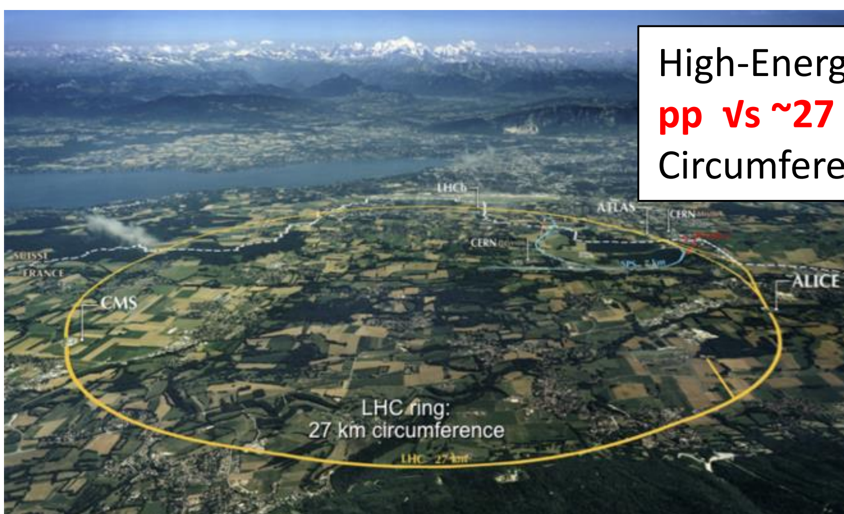
high-energy pp collider studies



Super proton proton Collider (**SppC**), China
CEPC; **SPPC √s >70 TeV**
Circumference: 100 km



Future Circular Collider (**FCC-hh**): CERN
FCC-ee; **FCC-hh √s ~100 TeV**
Circumference: 97.75 km



High-Energy LHC (**HE-LHC**): CERN
pp √s ~27 TeV
Circumference: 27 km

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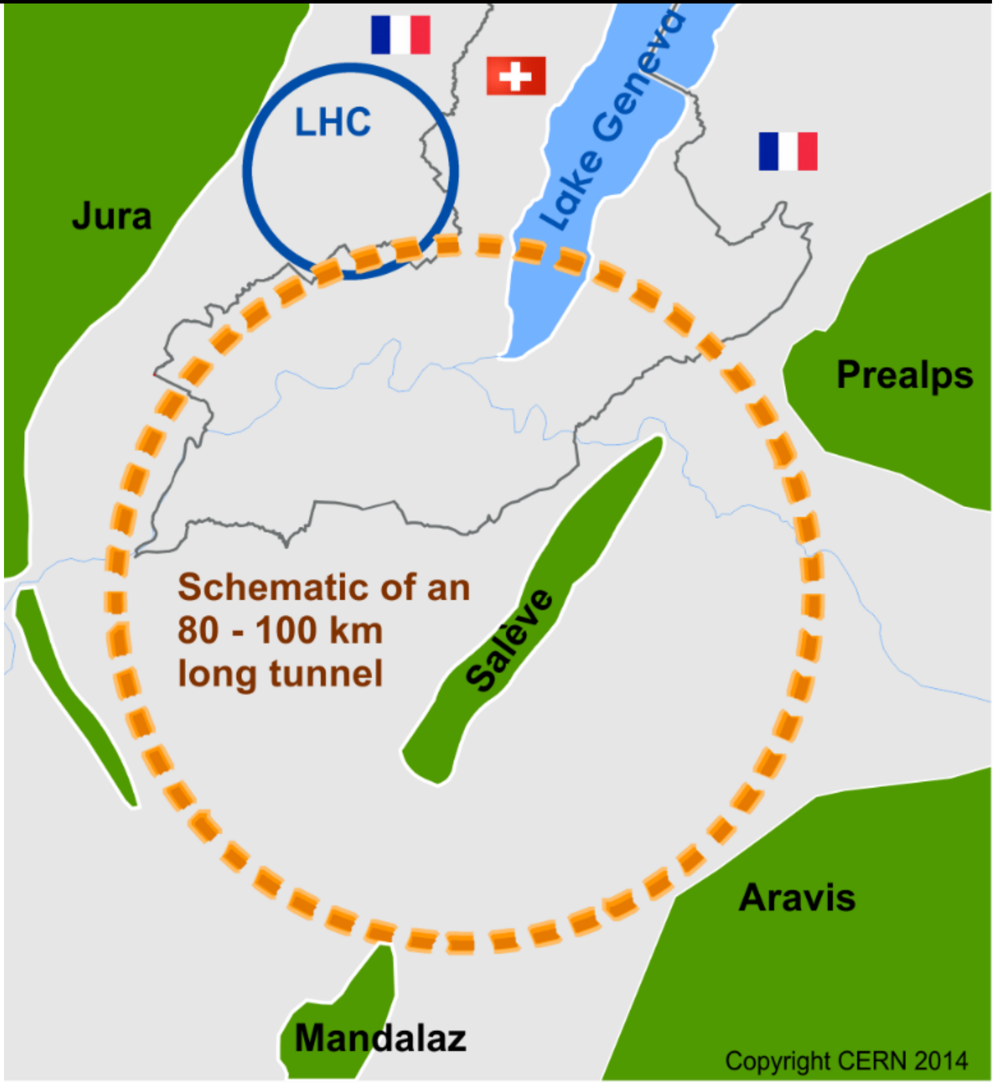
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018

International FCC collaboration (CERN as host lab) to study:

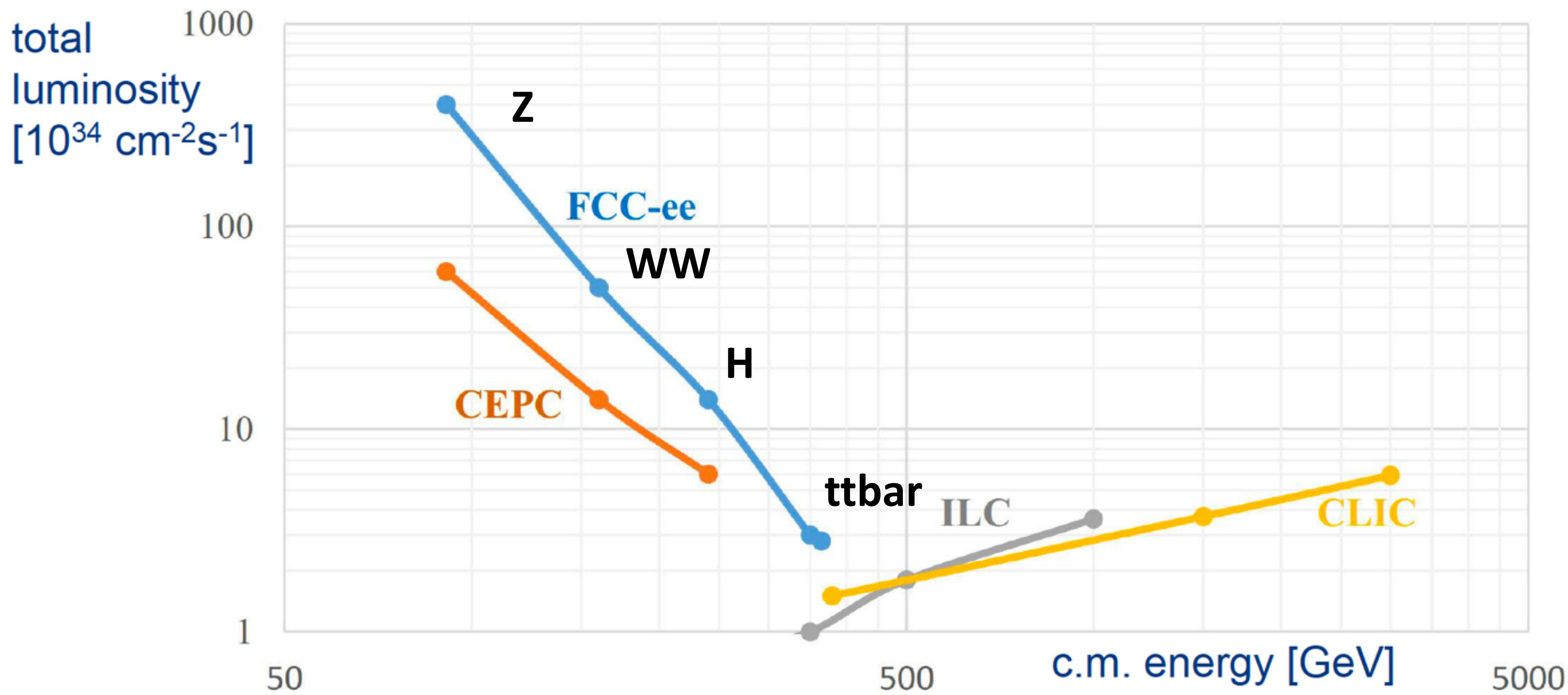
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

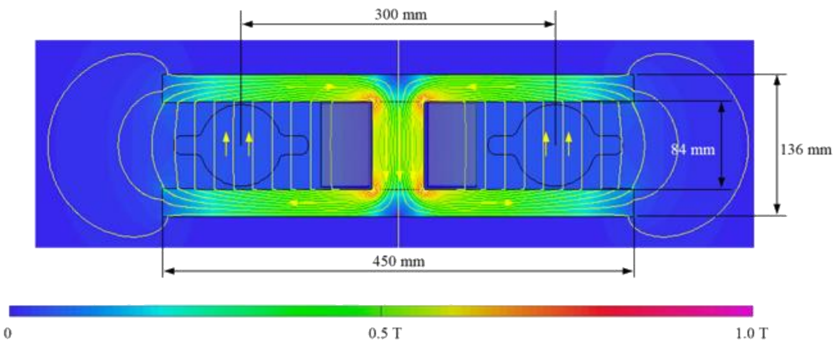
~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology

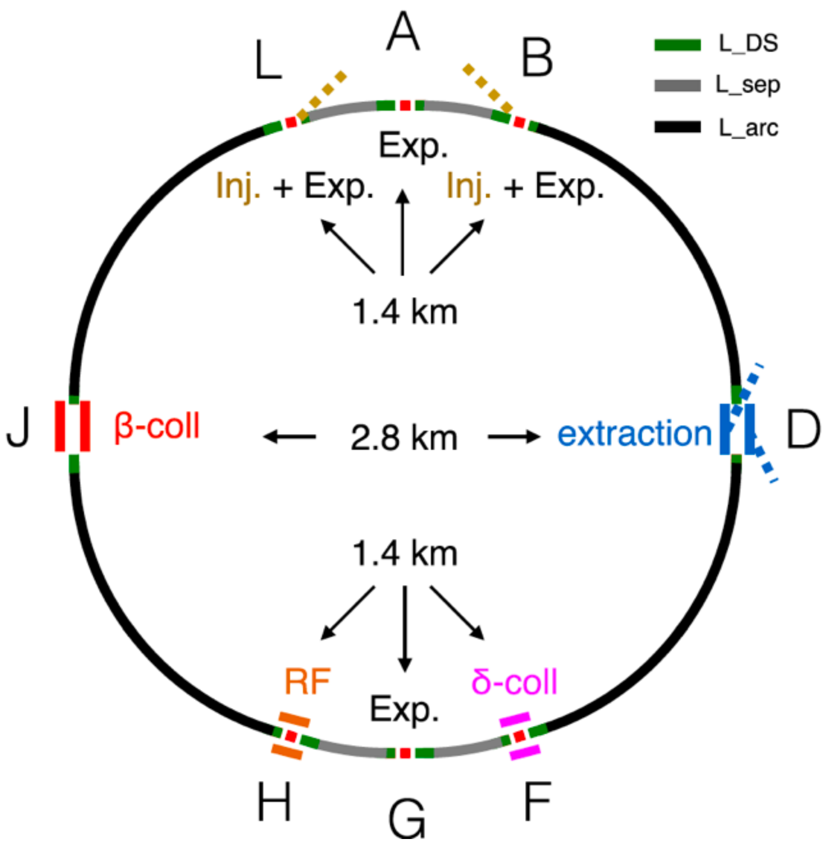


lepton collider luminosities





FCC-pp Layout



- L* 40 m
- Experimental insertion adaption
- Overall lenght 1.400 m

- Optimisation work on betatron and momentum collimation systems

- Optimisation of extraction/dump line design
- Vertical extraction

collision energy cms [TeV]	100
dipole field [T]	16
circumference [km]	97.75

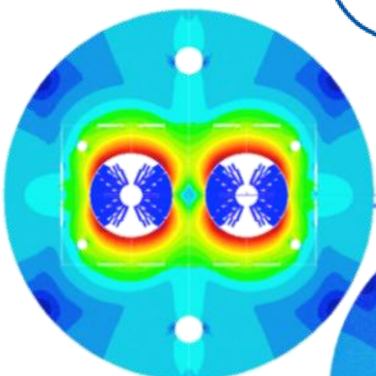
Challenging to say the least but significant work in progress.

16 T dipole design activities and options Nb_3Sn

Short model magnets (1.5 m lengths) will be built from 2017 - 2021

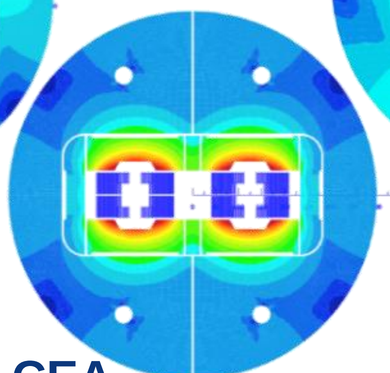
H2020 EuroCirCol – A key to New Physics

Cos-theta



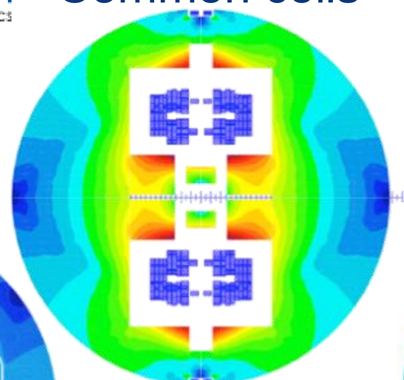
INFN

Blocks



CEA

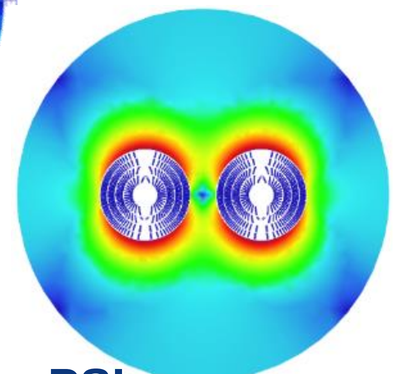
Common coils



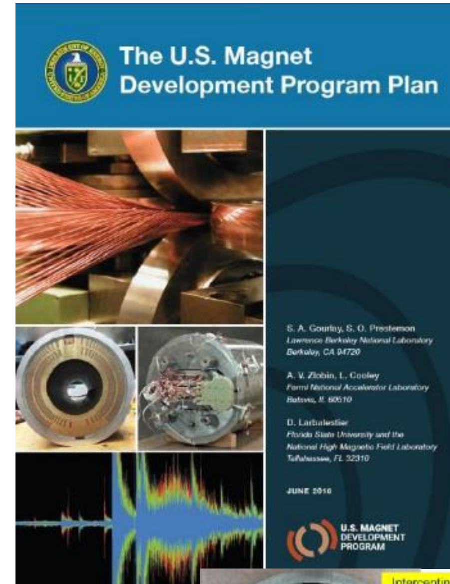
CIEMAT

Swiss contribution

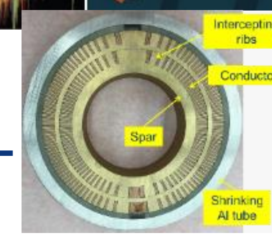
Canted Cos-theta



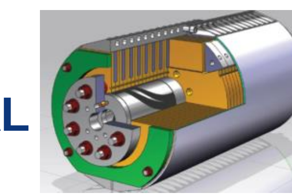
PSI



LBNL



FNAL



Development of magnets for high energy accelerators : **12 T to 16 T** (SppC, FCC, HE-LHC,...)

Performance (Jc), stress, stored energy management, field quality, and cost

Acknowledgments

That a 27 km superconducting collider has been successfully designed, constructed, commissioned and operated is a demonstration of:

- International collaboration and commitment
- The hard work and passion of an awful lot of people

That same commitment and passion is being directed to the medium and long term future!