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CERN Academic Training Lectures on
Physics Beyond Colliders at CERN
7-10 November, 2023 — CERN, Geneva, Switzerland

Physics Beyond Colliders at CERN
Lecture 3/4:
Projects related to the LHC

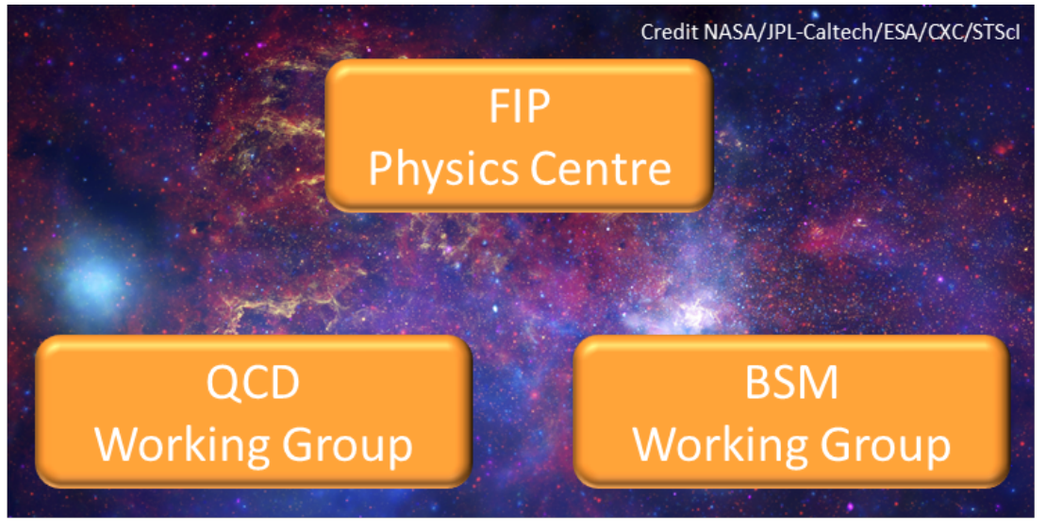
S. Redaelli, CERN, Beams Department
on behalf on the PBC teams

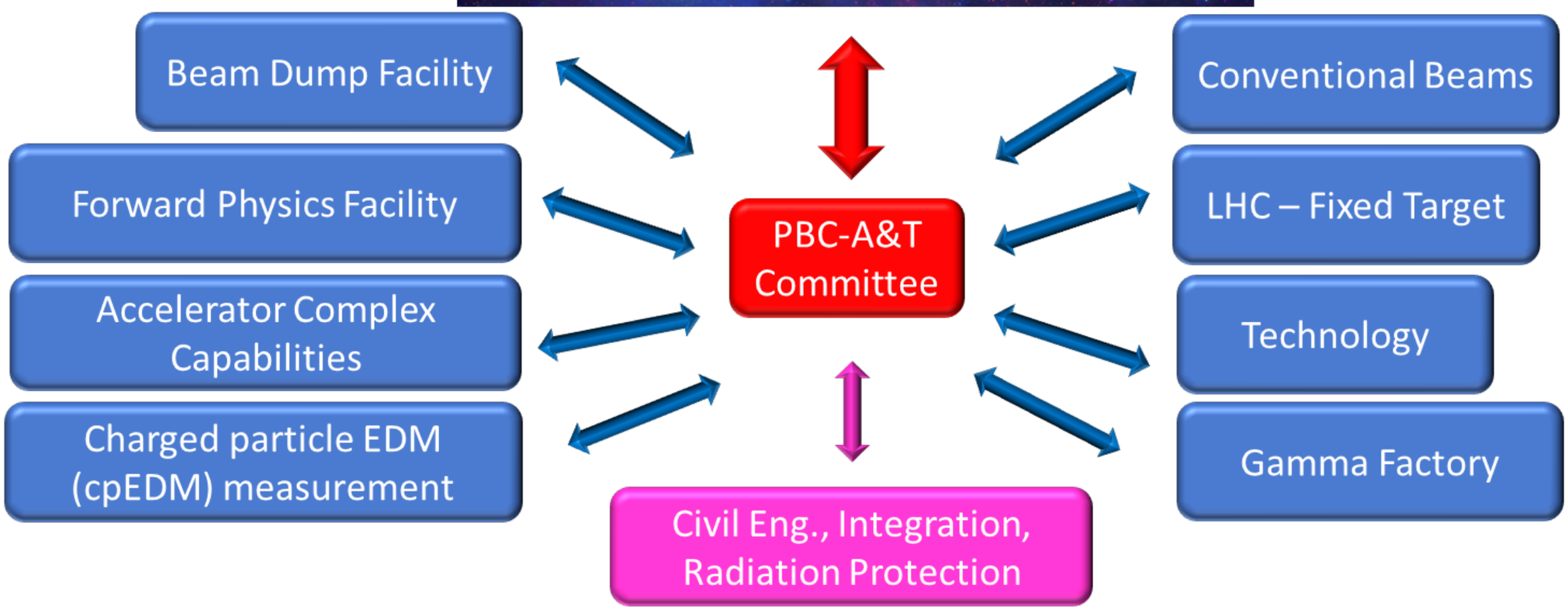
Acknowledgements

Many thanks to all the supporting teams, from CERN and outside, participating to the working groups within the PBC.

Special thanks for material provided for this lecture:
G. Arduini
M. Ferro-Luzzi
J. Boyd
S. Calatroni, W. Krasny

Physics Beyond Colliders structure





Focus of this lecture: accelerator aspects of project related to LHC

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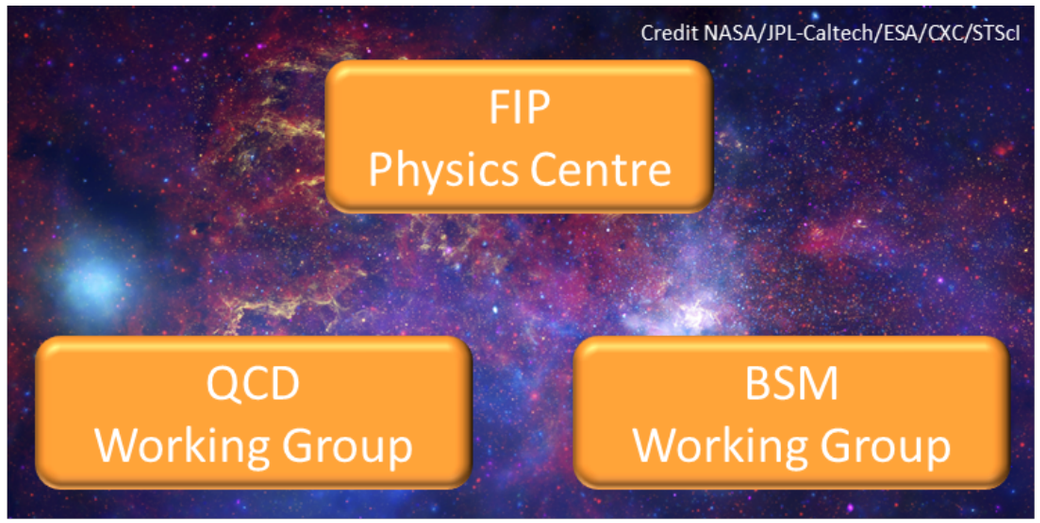

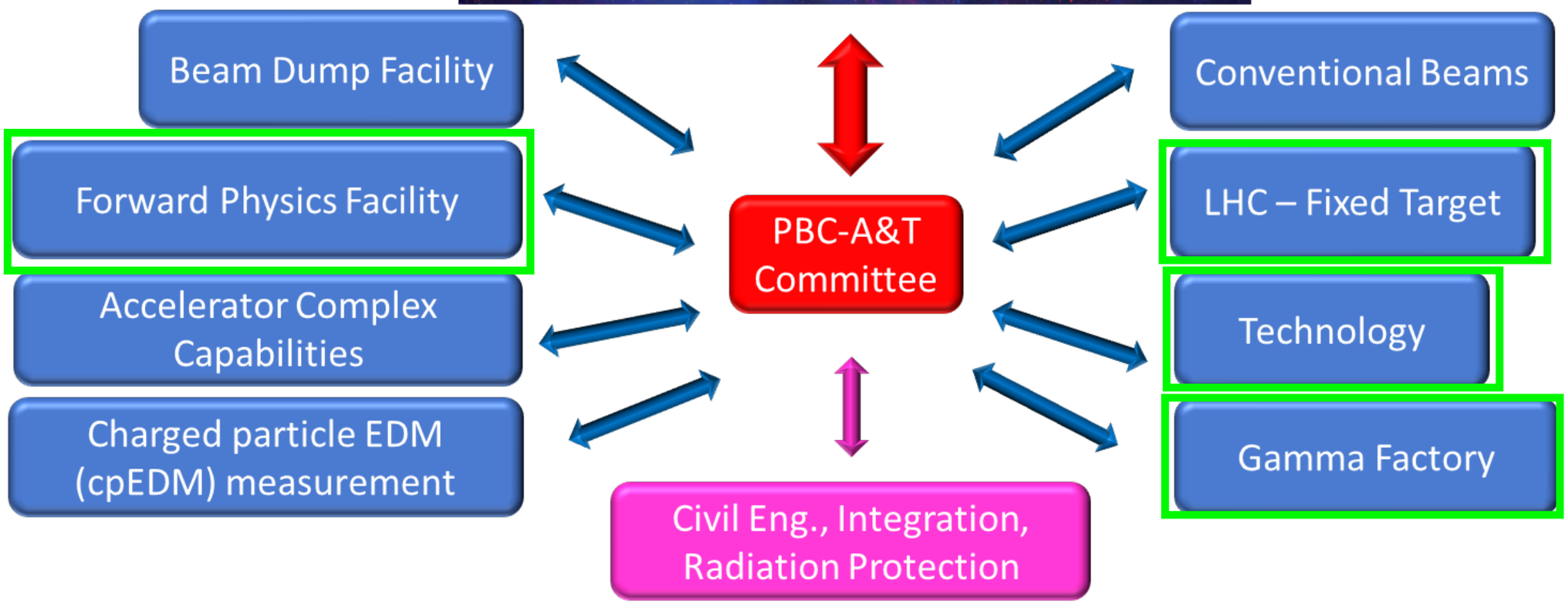

Focus of this lecture: accelerator aspects of project related to LHC

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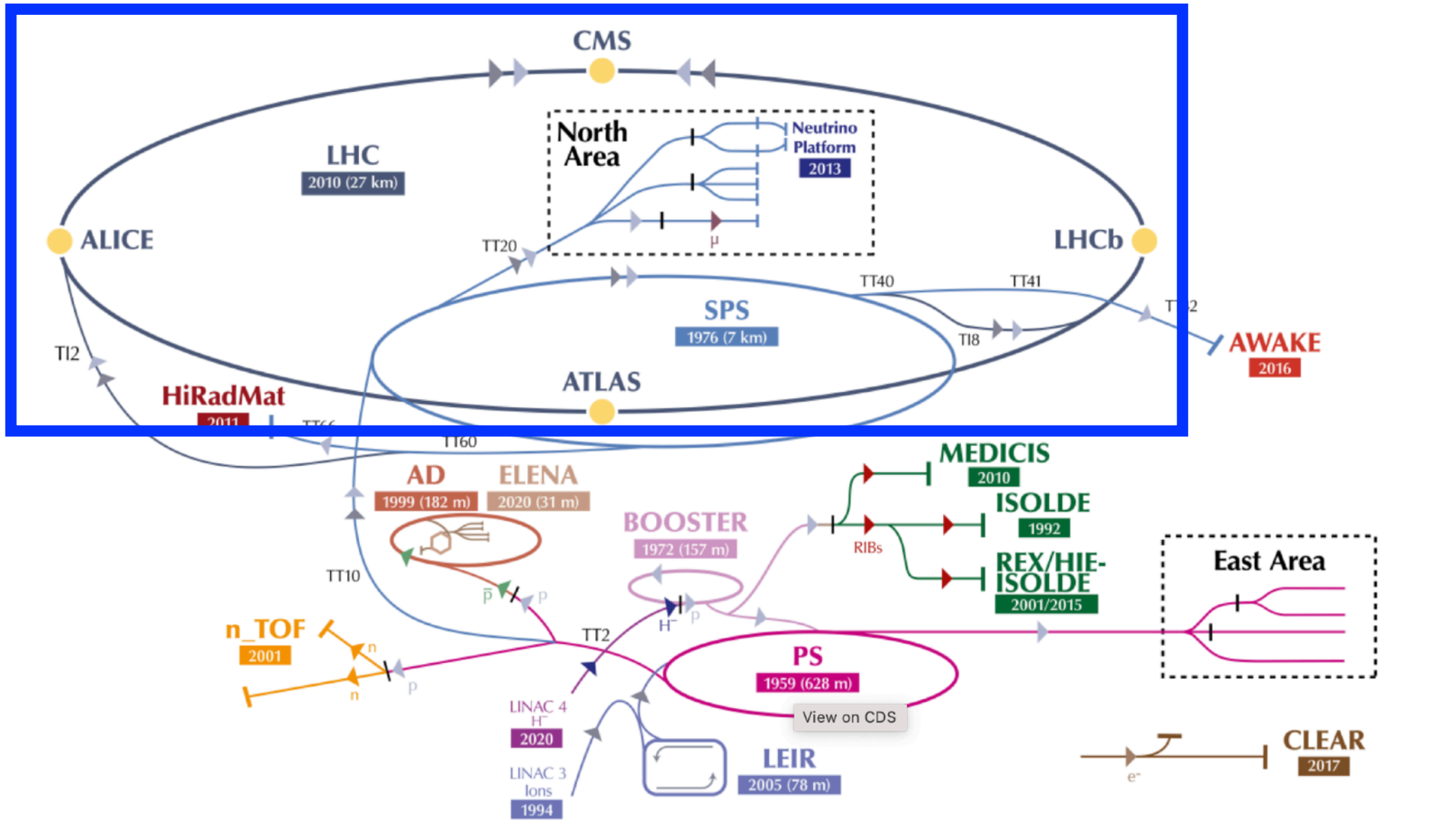
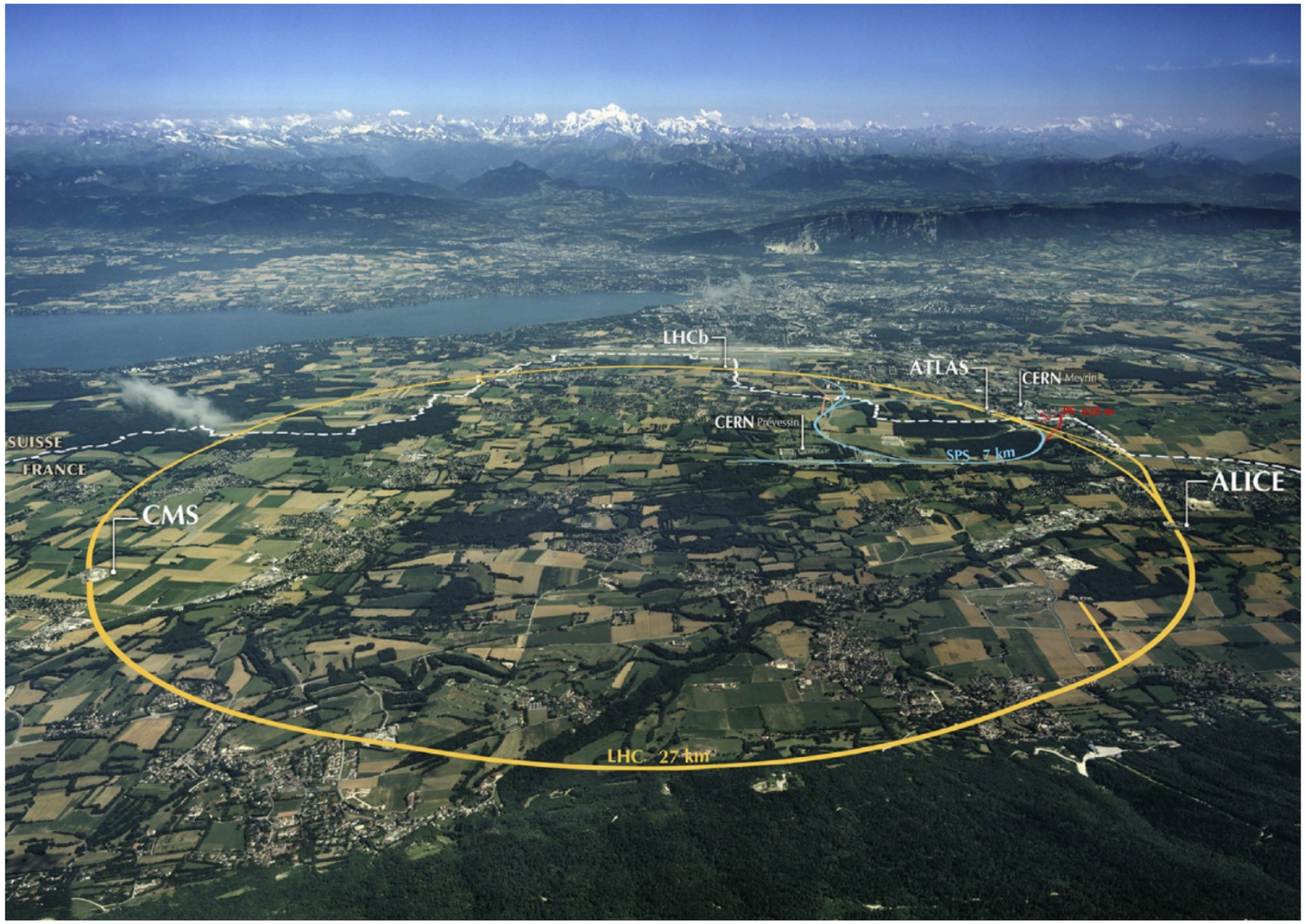
CERN Accelerator complex



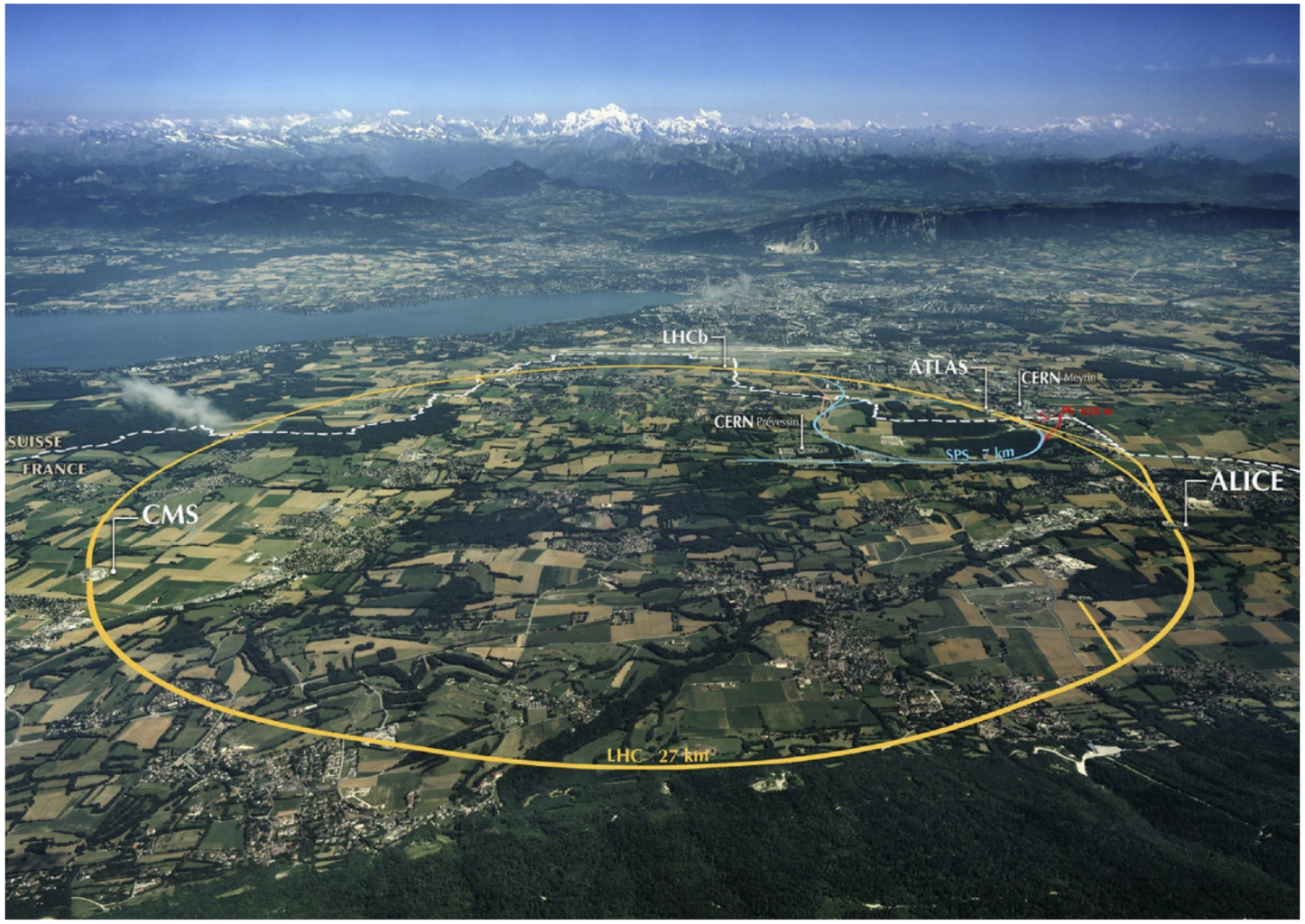
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

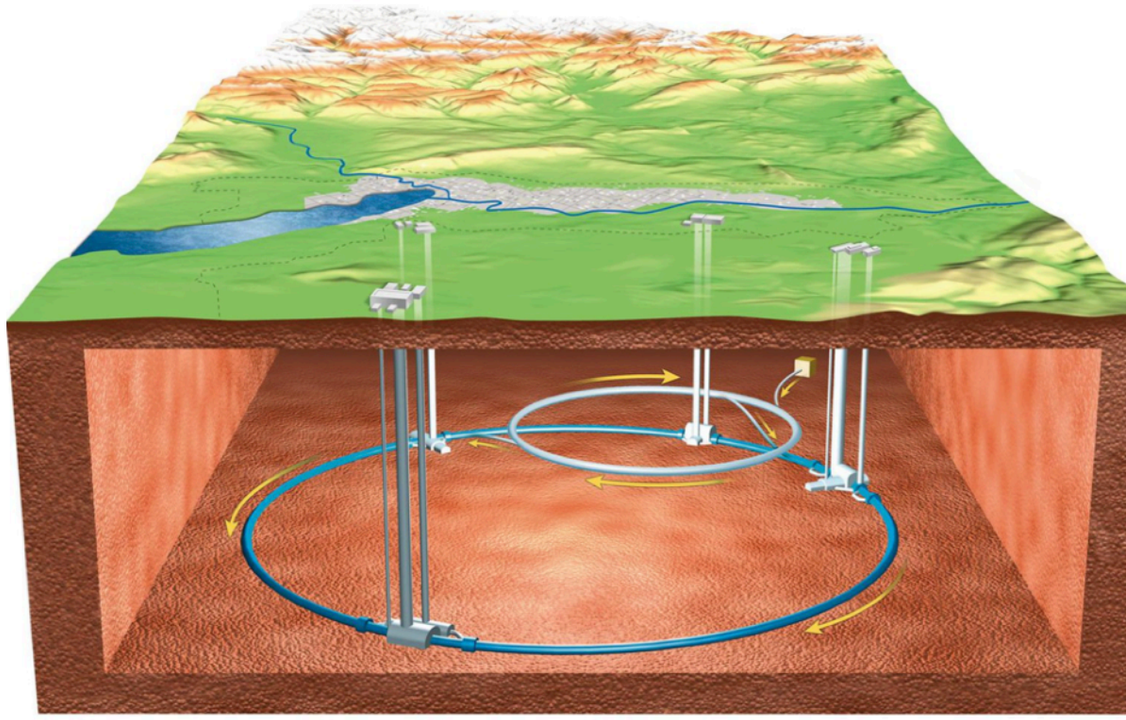
LHC tunnel layout



In addition to the unprecedented beam parameters (see below), some PBC studies were also motivated by the possibility to profit from the <u>impressive and unique infrastructure</u> made available to operate a facility like the LHC and its experiments.

LHC tunnel layout





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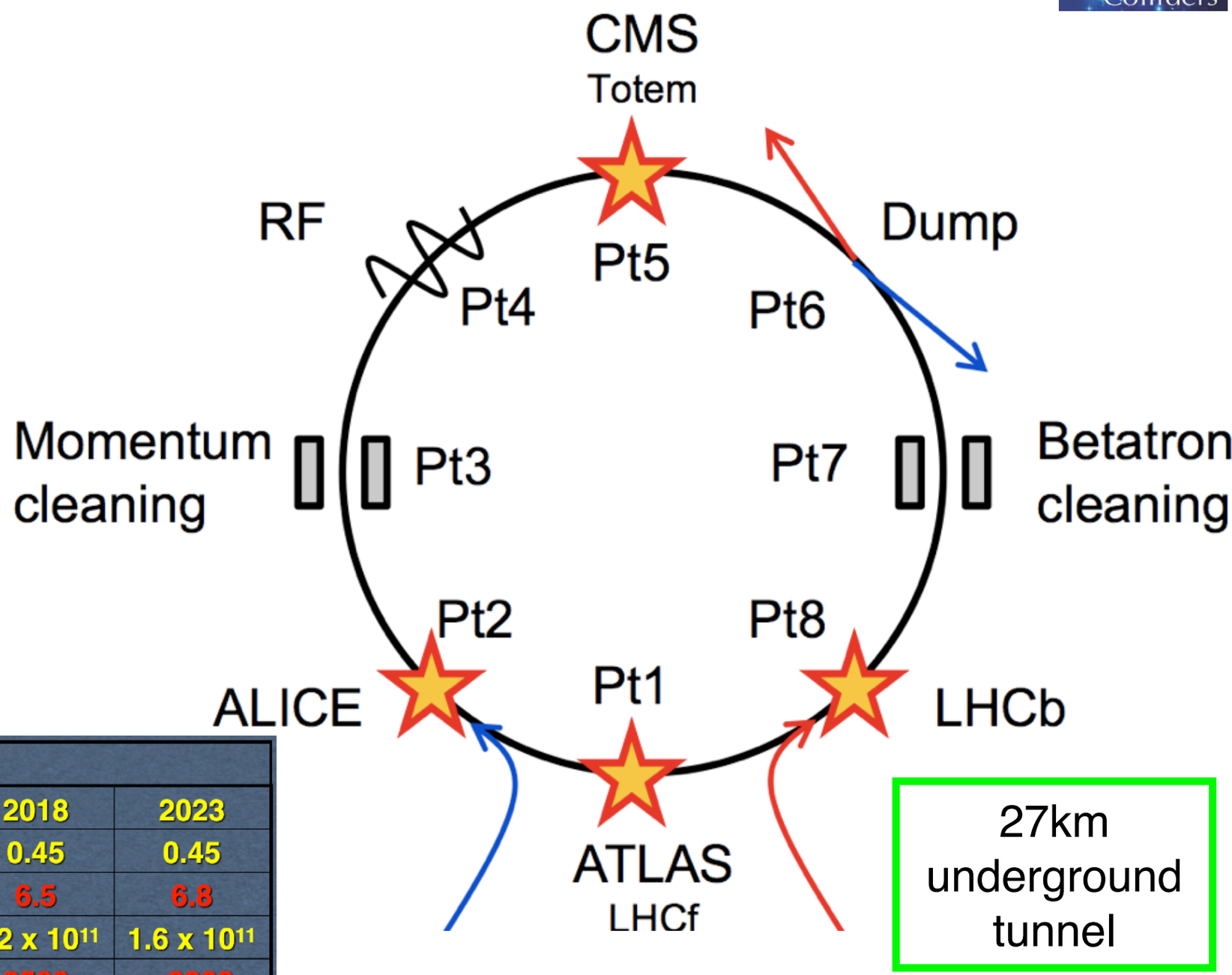
The Large Hadron Collider

LHC layout

- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- 4 interaction points (IPs): IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning



Nominal LHC parameters			
	Design	2018	2023
Beam injection energy (TeV)	0.45	0.45	0.45
Beam energy (TeV)	7	6.5	6.8
Number of particles per bunch	1.15 x	1.2 x 10^{11}	1.6 x 10^{11}
Number of bunches per beam	2808	2560	~2200
Max stored beam energy (MJ)	362	300	~430
Beam current (A)	0.58	0.48	0.56
Norm transverse emittance (μm)	3.75	2.1	1.8
Colliding beam size (μm)	16	11	9
Bunch length at top energy (cm)	7.55	7.55	7.55

The Large Hadron Collider

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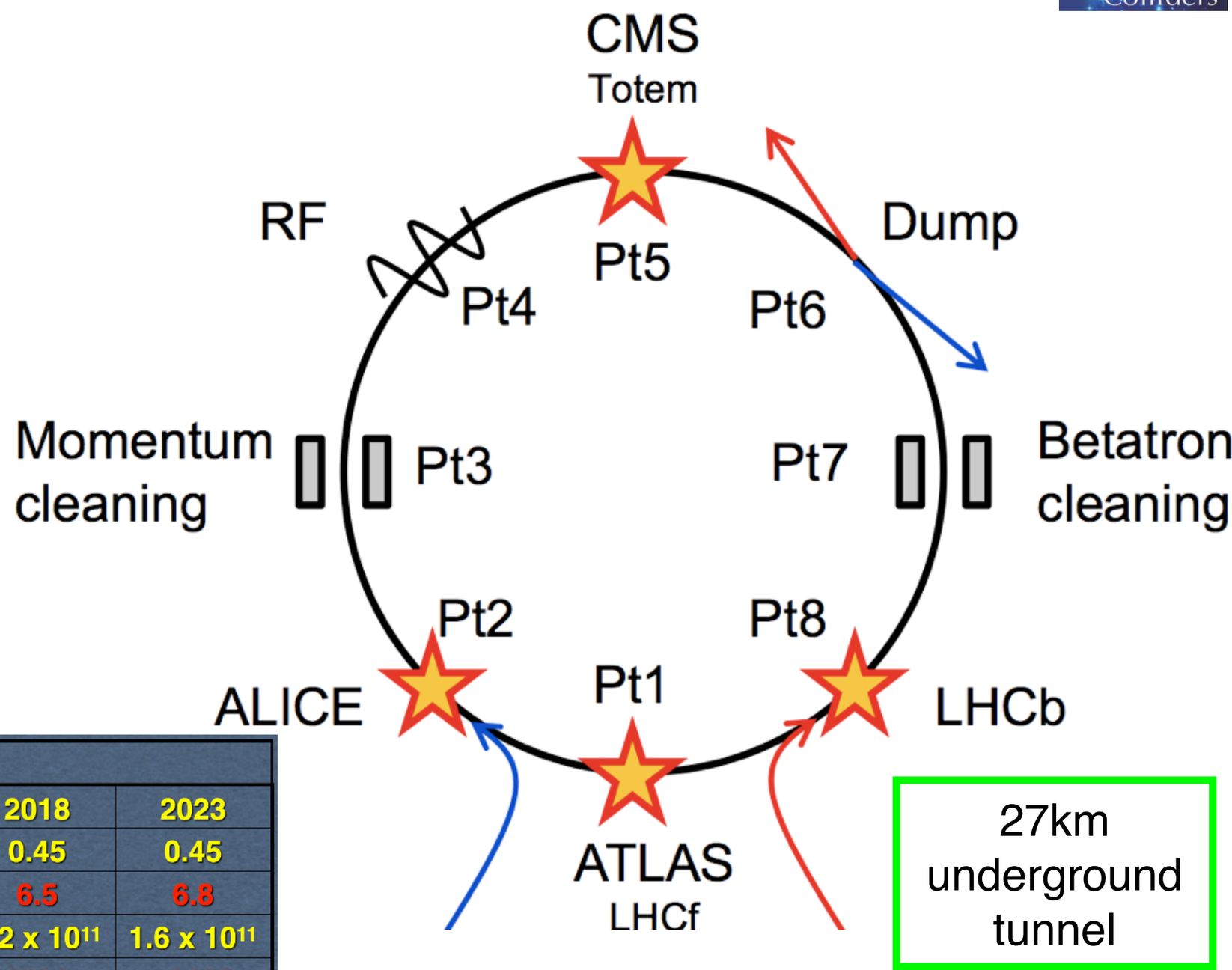

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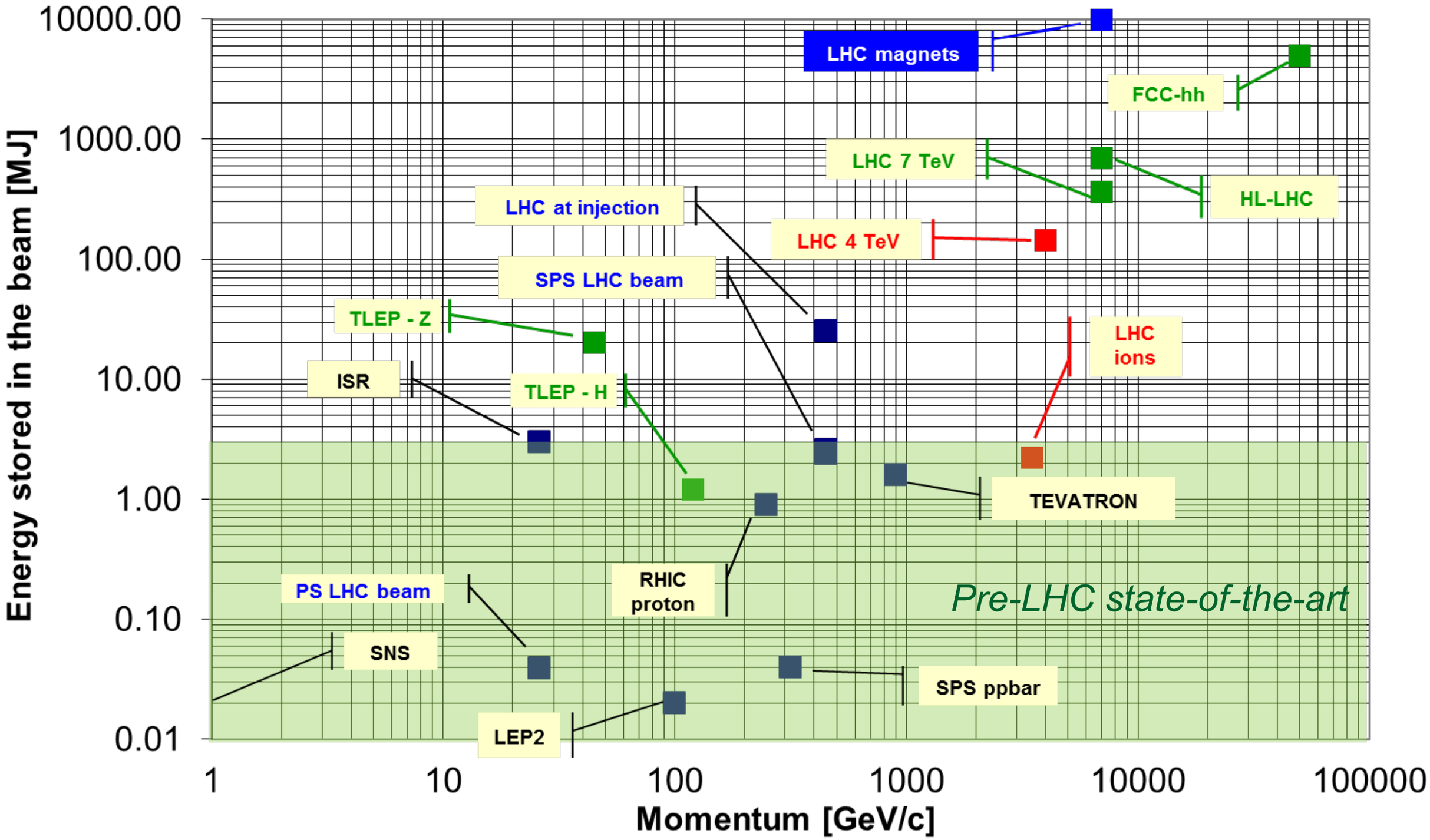
HL-LHC project aims at nearly doubling the beam intensity from the LHC design. Operation to start in 2029 until about 2041.

The LHC beam stored energy



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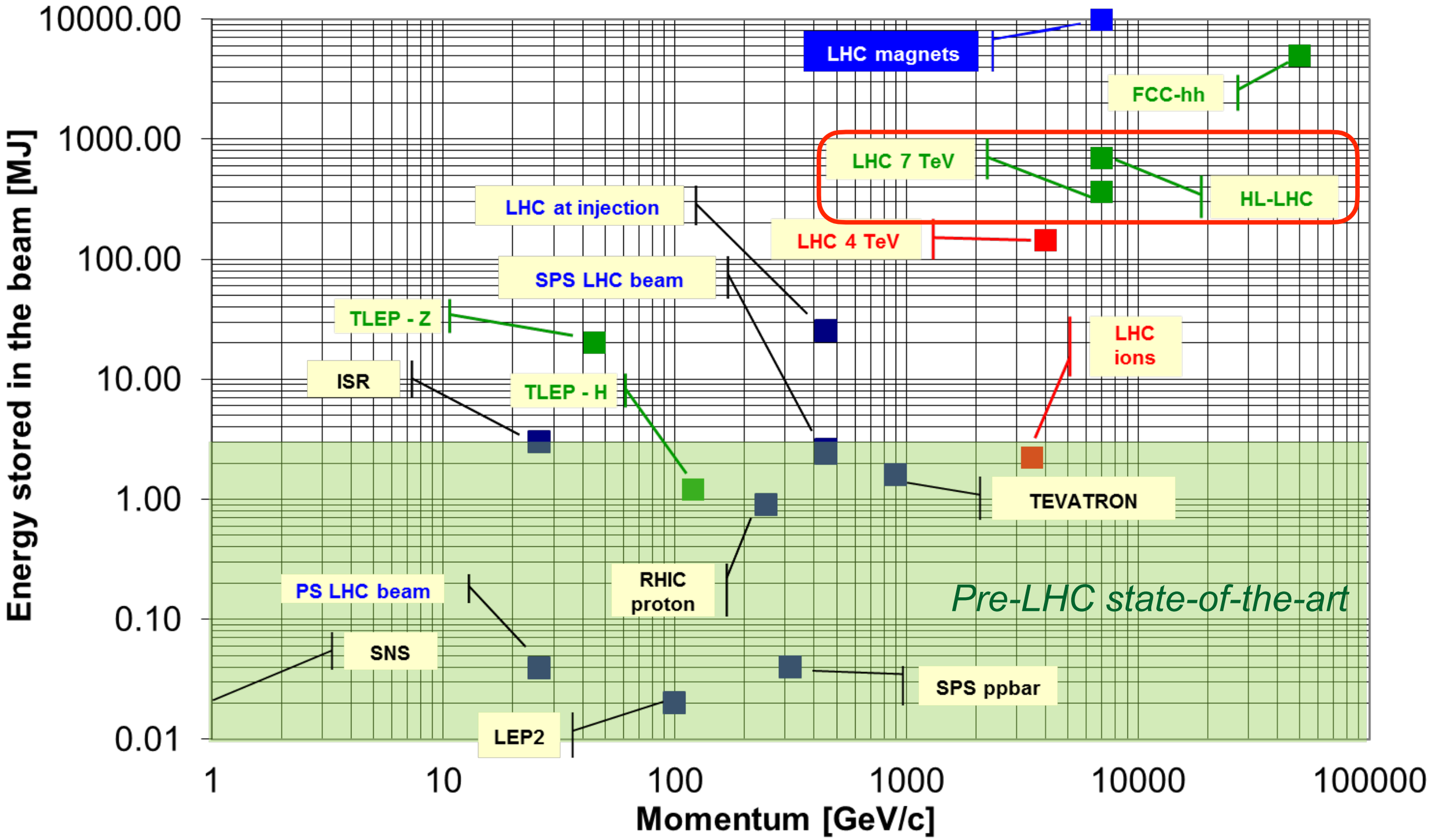
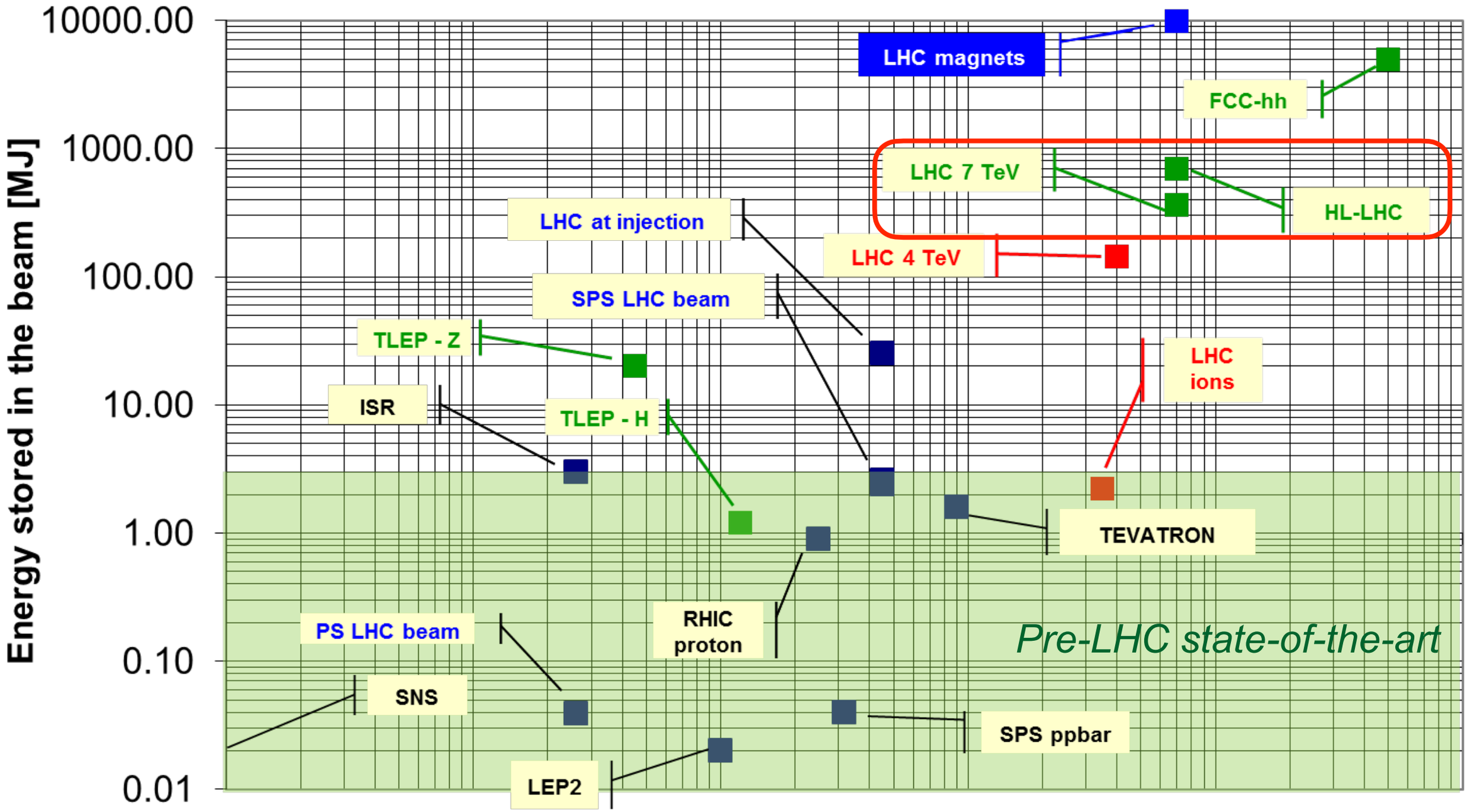


The LHC beam stored energy



Clear potential and interest in the LHC beams (energy and intensity frontier), but there are strong constrains on the manipulations of these beams in a superconducting environment.

Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or…

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90 kg of TNT

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Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or…

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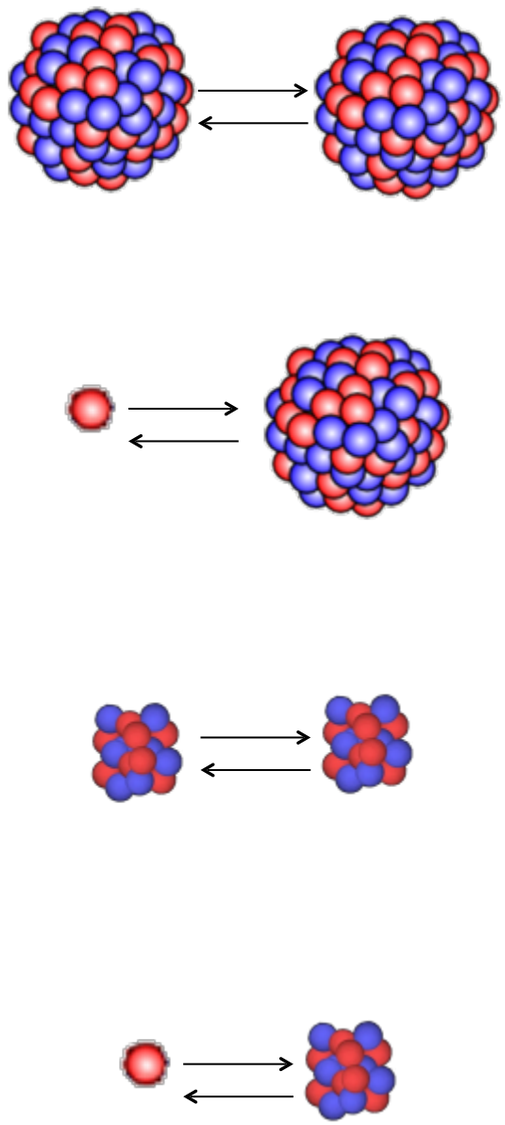
The kinetic energy of a 200 m long train at 155 km/hour

The LHC machine protection and collimation systems are designed to **handle safely** these energies for all relevant loss operational scenarios and abnormal beam failures!

Any modification and new implementation must be validated to be compatible with a safe operation of the LHC beams!

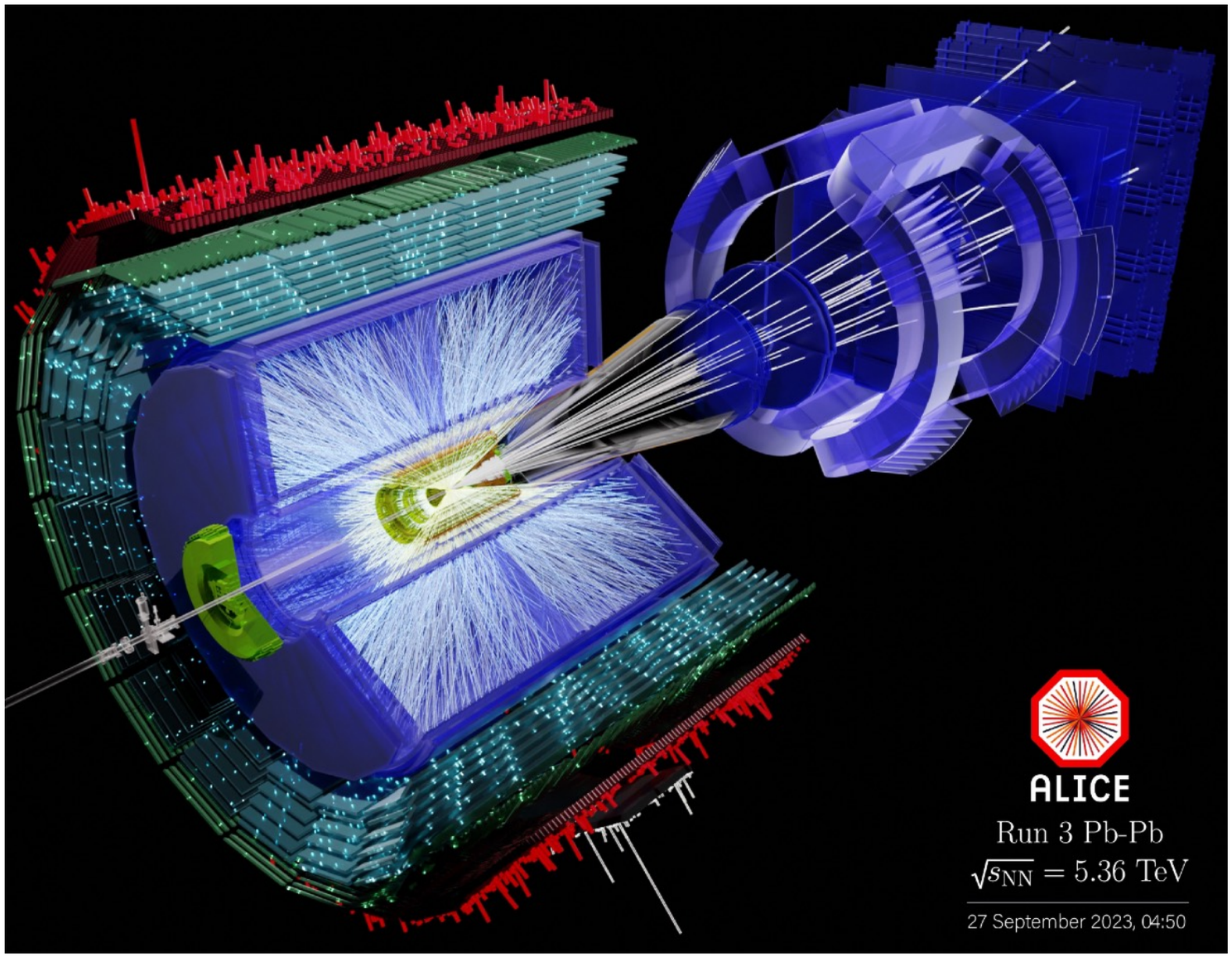
The LHC has a complex layout — new integrations are often not easy.

The LHC as an ion collider



Achieved and target Pb ion beam parameters

	LHC design	2018	Run 3
Beam energy (Z TeV)	7	6.37	6.8
Bunch spacing (ns)	100	75	50
Total n.o. bunches	592	733	1240
Bunch intensity (10^7 Pb ions)	7	21	18
Normalized transverse emittance (μm)	1.5	2.3	1.65



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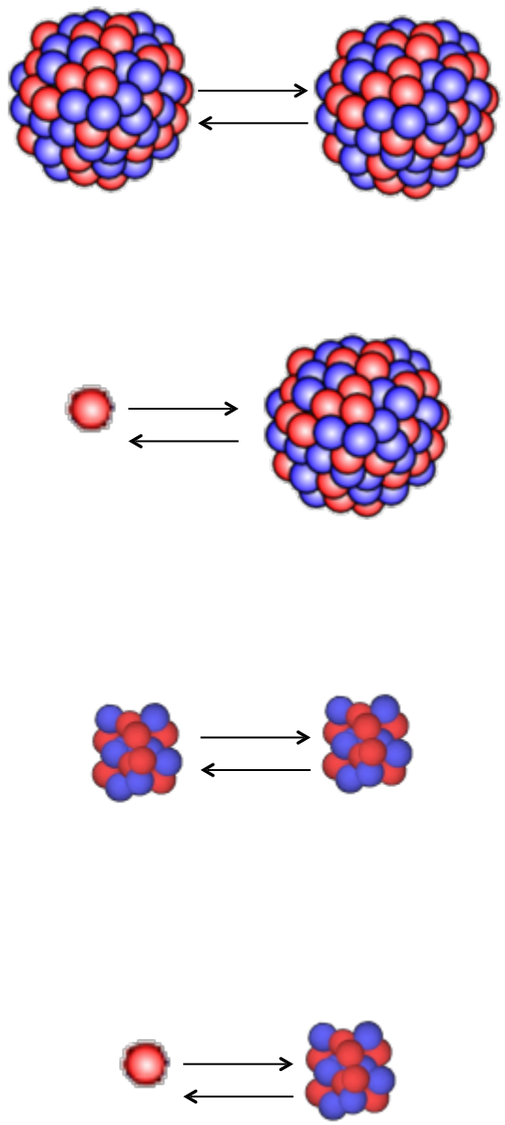

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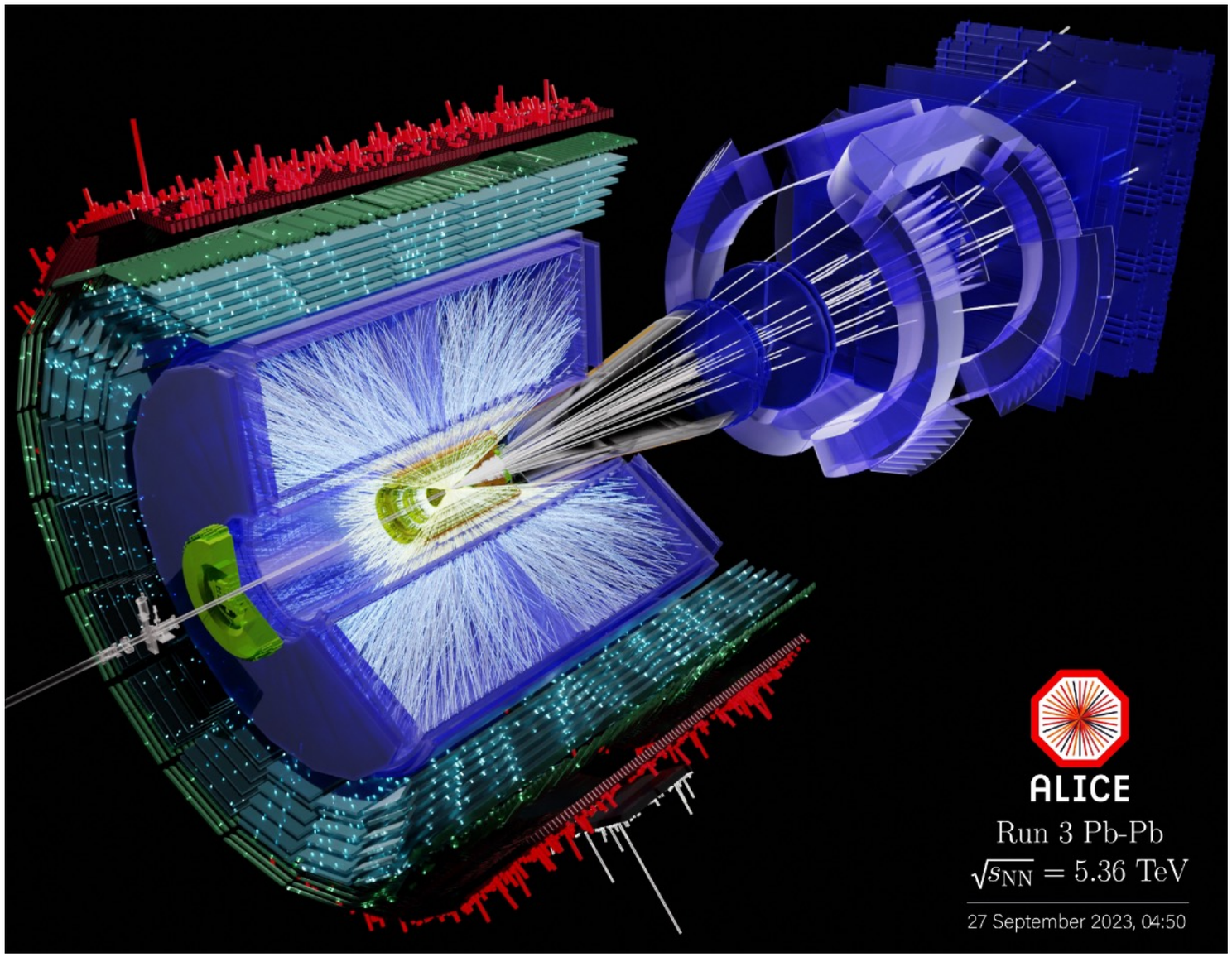


Points of contacts to PBC: ALICE targets and Partially Stripped Ions (PSIs) for γ factory.

Physics Beyond Collides at the LHC

The availability of LHC beams, running experiments & infrastructure motivated studies for different new opportunities within the PBC effort

- **New experiments directly using the LHC beams**
  - → *Typically, parasitic to main pp and PbPb physics programmes*
  - → *Need nevertheless changes of LHC layouts*
- Dedicated **operation modes with novel beam configurations**
  - → *Future gamma factory, requiring dedicated beam operations (PSI beams)*
- **Experiments on long-lived particles (LLP) produced at LHC collisions**
  - → *Typically, installed far from the collision points with no need for LHC layout changes*
- **New experiment re-using the existing, unique infrastructure**
  - → *Some examples of non-accelerator experiments using tunnel / shafts*
- **Synergies with CERN technology teams**

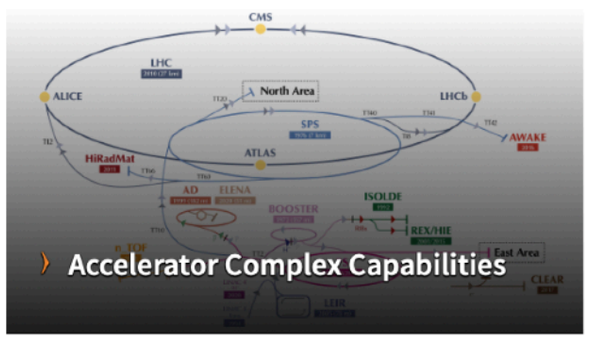
Table of contents

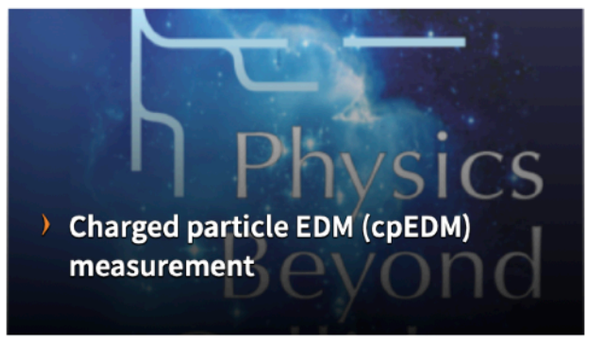
The PBC LHC fixed-target studies

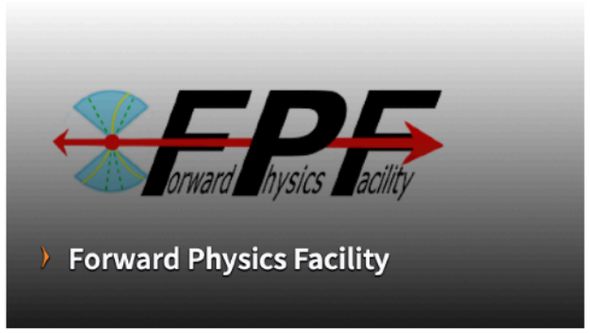
Accelerators & Technology Domain

The Working Groups in the Accelerators & Technology Domain are coordinated through the PBC Accelerators & Technology Committee, a steering committee which meets around once per month. The steering committee includes the CERN conveners of the various Working Group in the Accelerators & Technology Domain. The Working Group's core members include accelerator experts and representatives of the projects. Requests from the Working Groups (tests, prototypes, manpower) are discussed by the steering committee.

ACCELERATORS & TECHNOLOGY WORKING GROUPS







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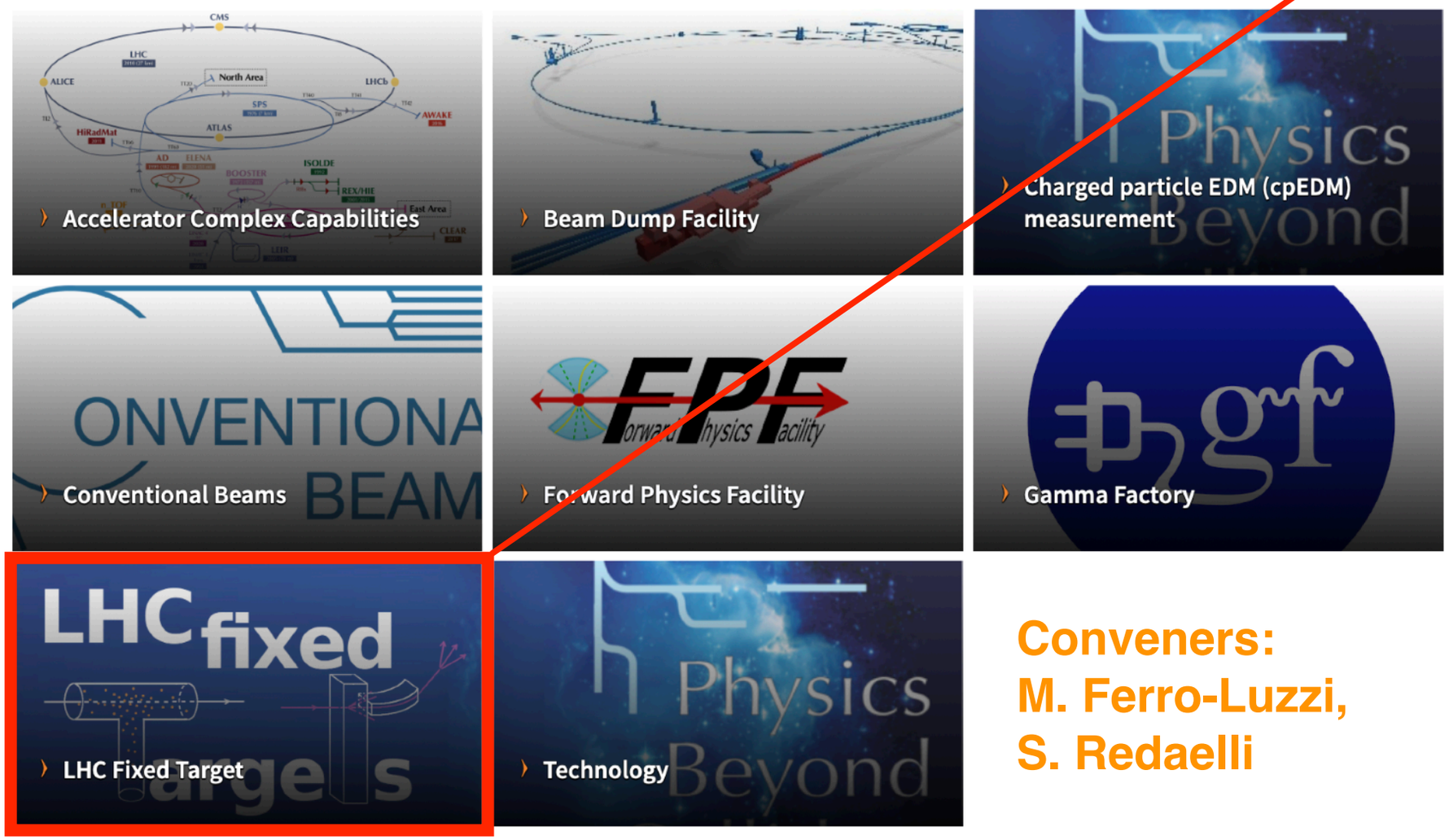
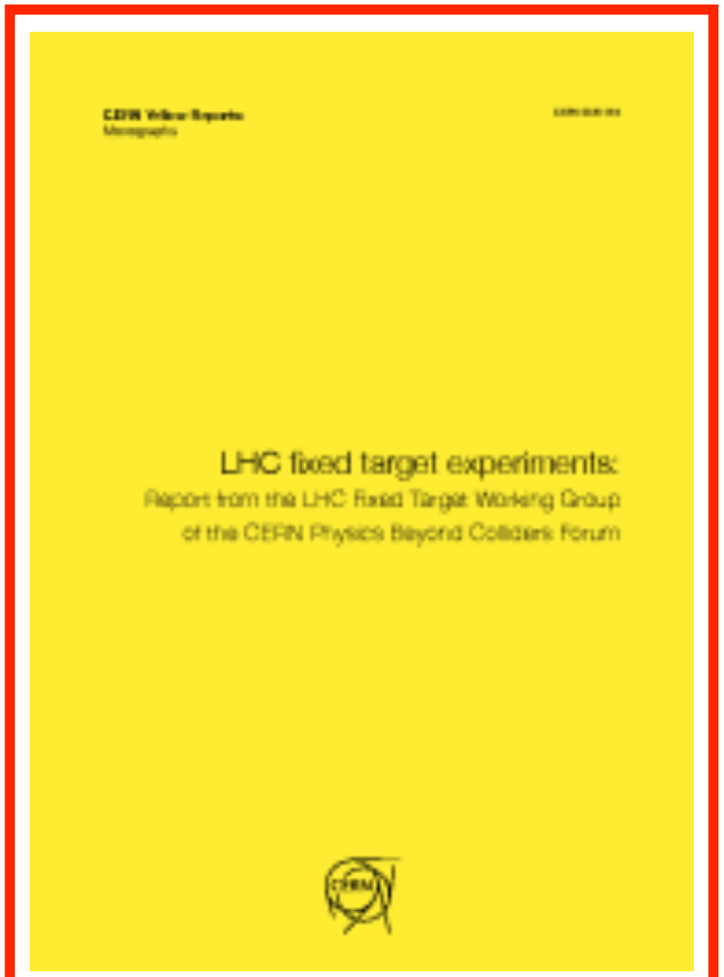


Conveners:
M. Ferro-Luzzi,
S. Redaelli



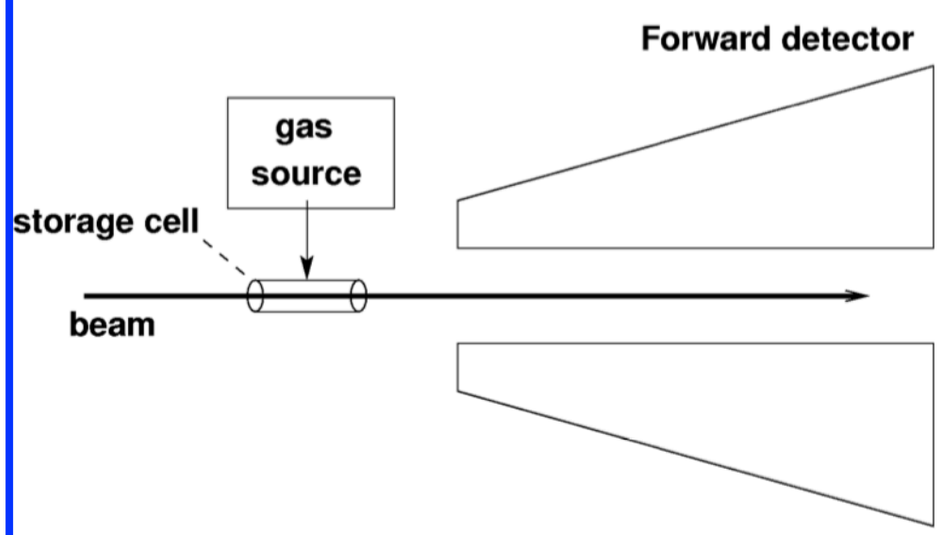
CERN Yellow Report
CERN-2020-004

*Focus on **proposals supported by experimental teams** and compatible with the LHC's main physics programme! E.g., no dedicated extraction beam lines.*

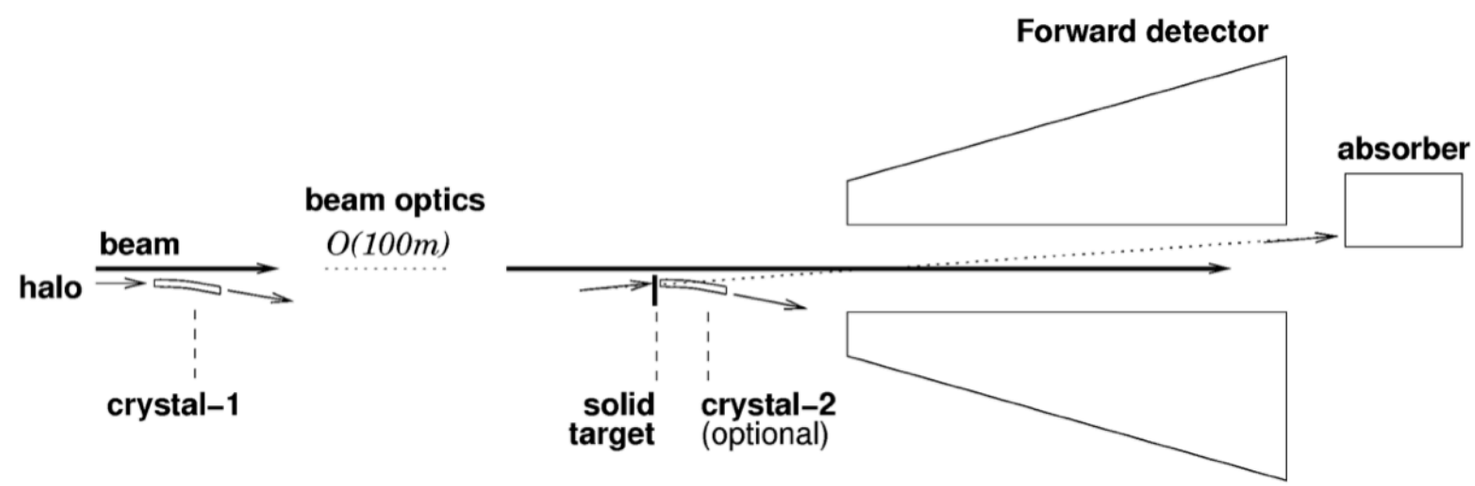
LHC fixed target (LHC-FT) studies

After initial assessments, the PBC LHC FT focused on two solutions compatible with the LHC stored beam energies and with the main proton physics programme:

Gaseous targets



Crystal-based in-vacuum targets



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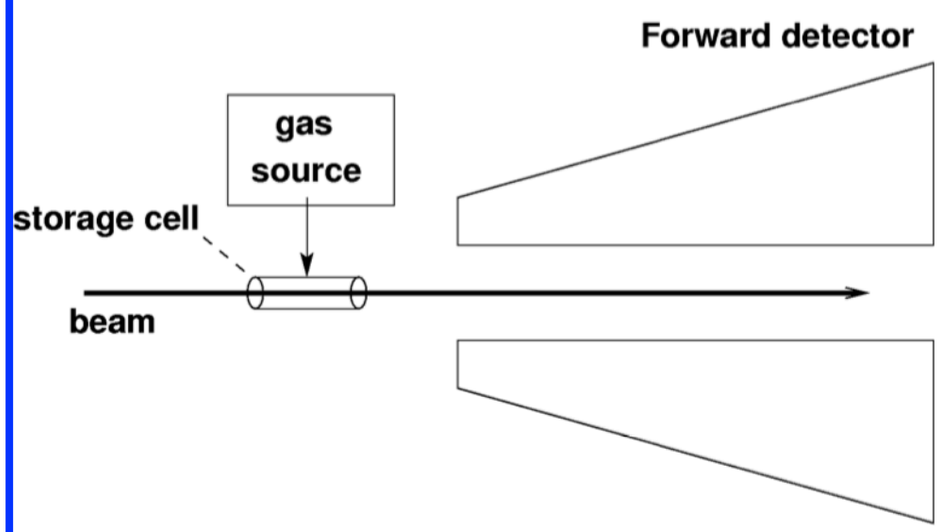

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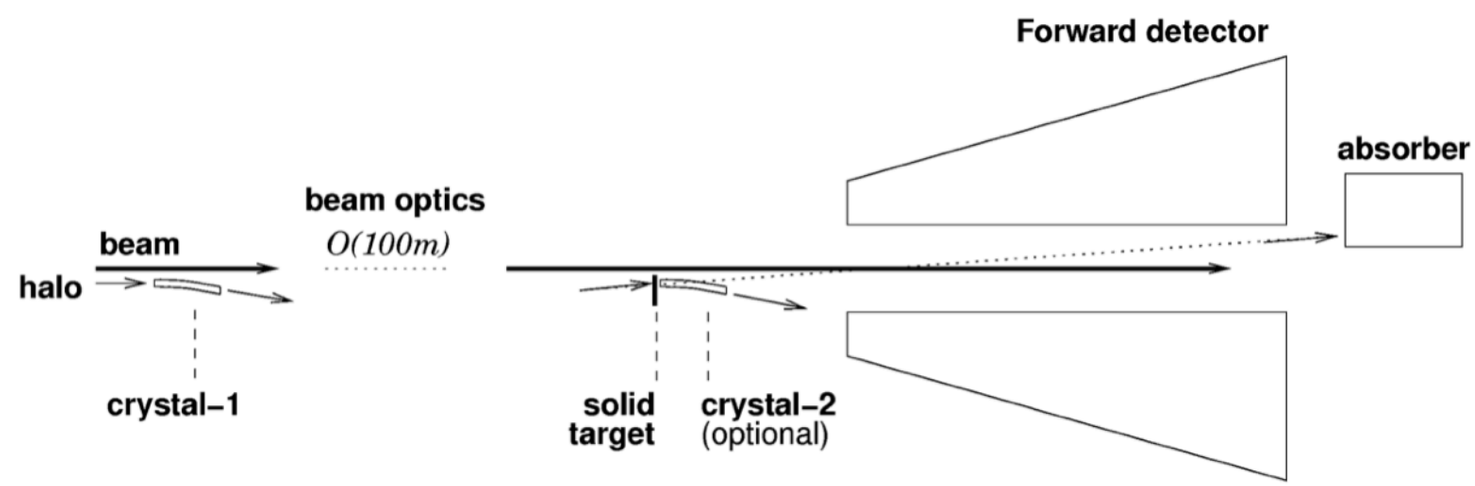

- **The LHCb SMOG-2 started operation in 2022!**
- Future studies are now focused on polarized gases

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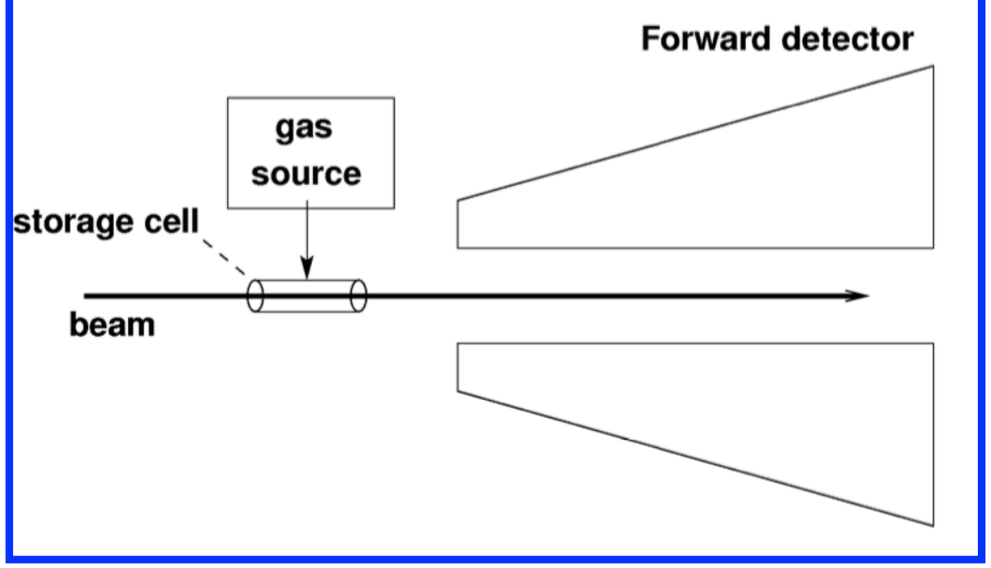

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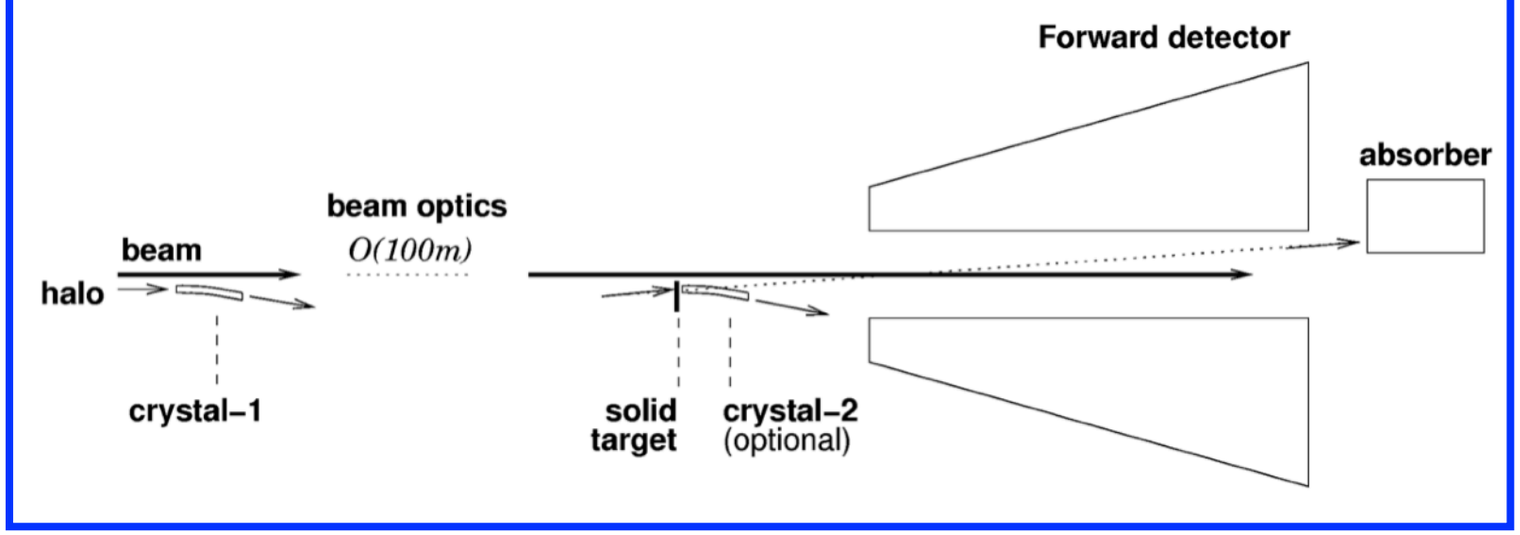
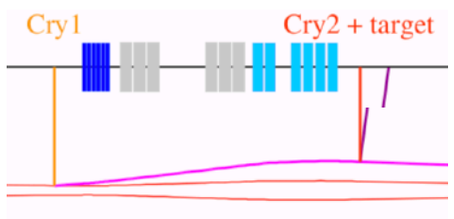


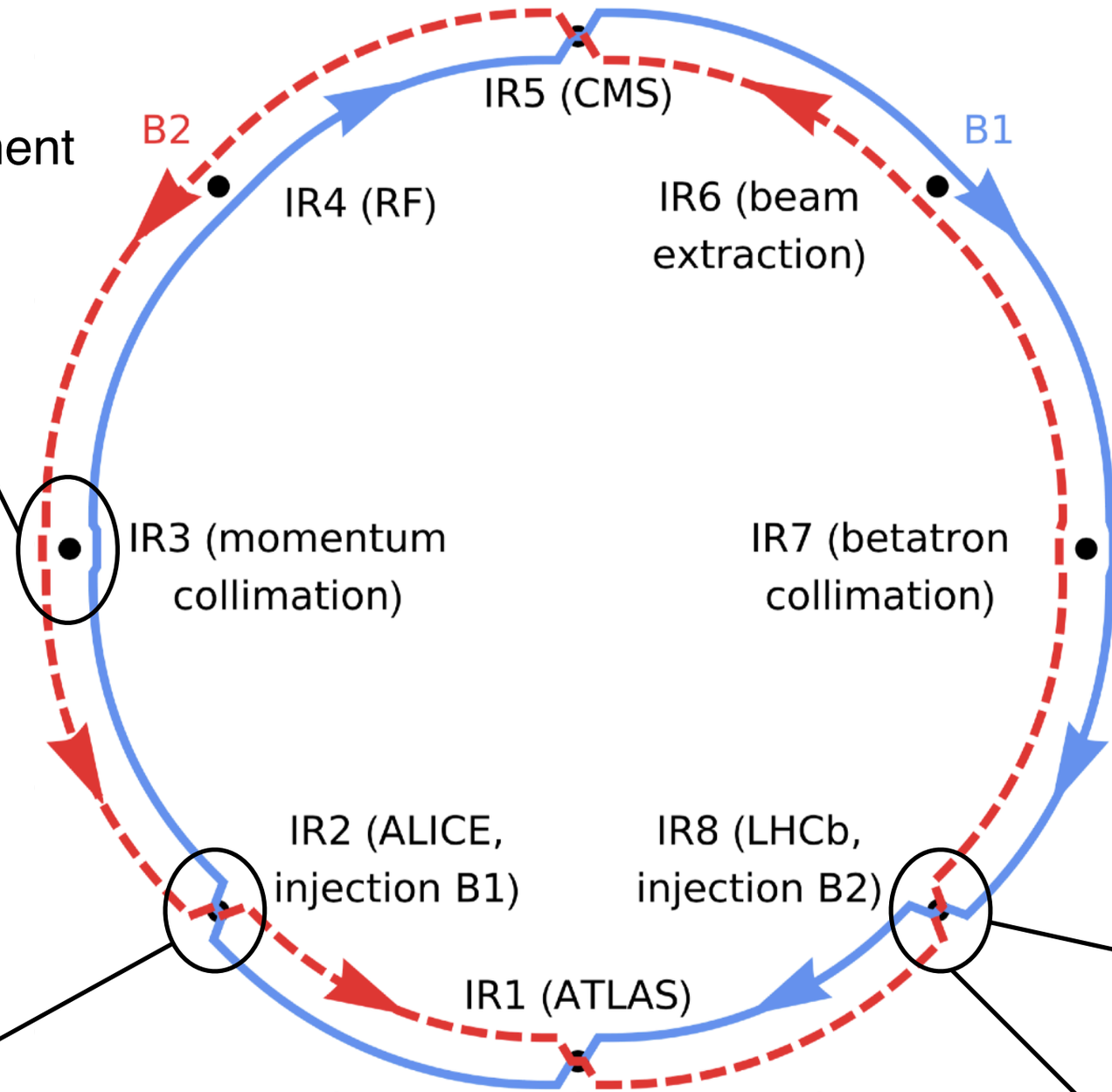
- **The LHCb SMOG-2 started operation in 2022!**
- Future studies are now focused on polarized gases

- Studies for a future experiments on double-crystal setups
- Preparing a machine test for the proof of principle of such setups

Geography of FTs at the LHC

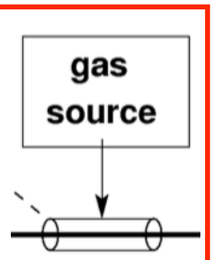
Double-crystal setup:
Proof-of-principle
(TWOCRYST) and
possible future experiment



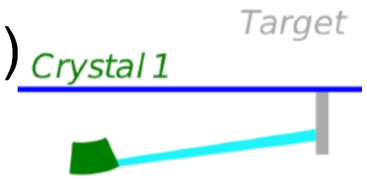


SMOG-2: approved

Gaseous
targets



Single-crystal
setup
(now discontinued)



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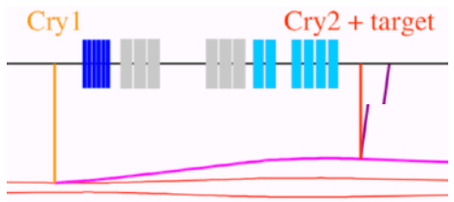
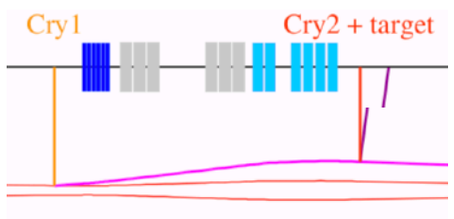
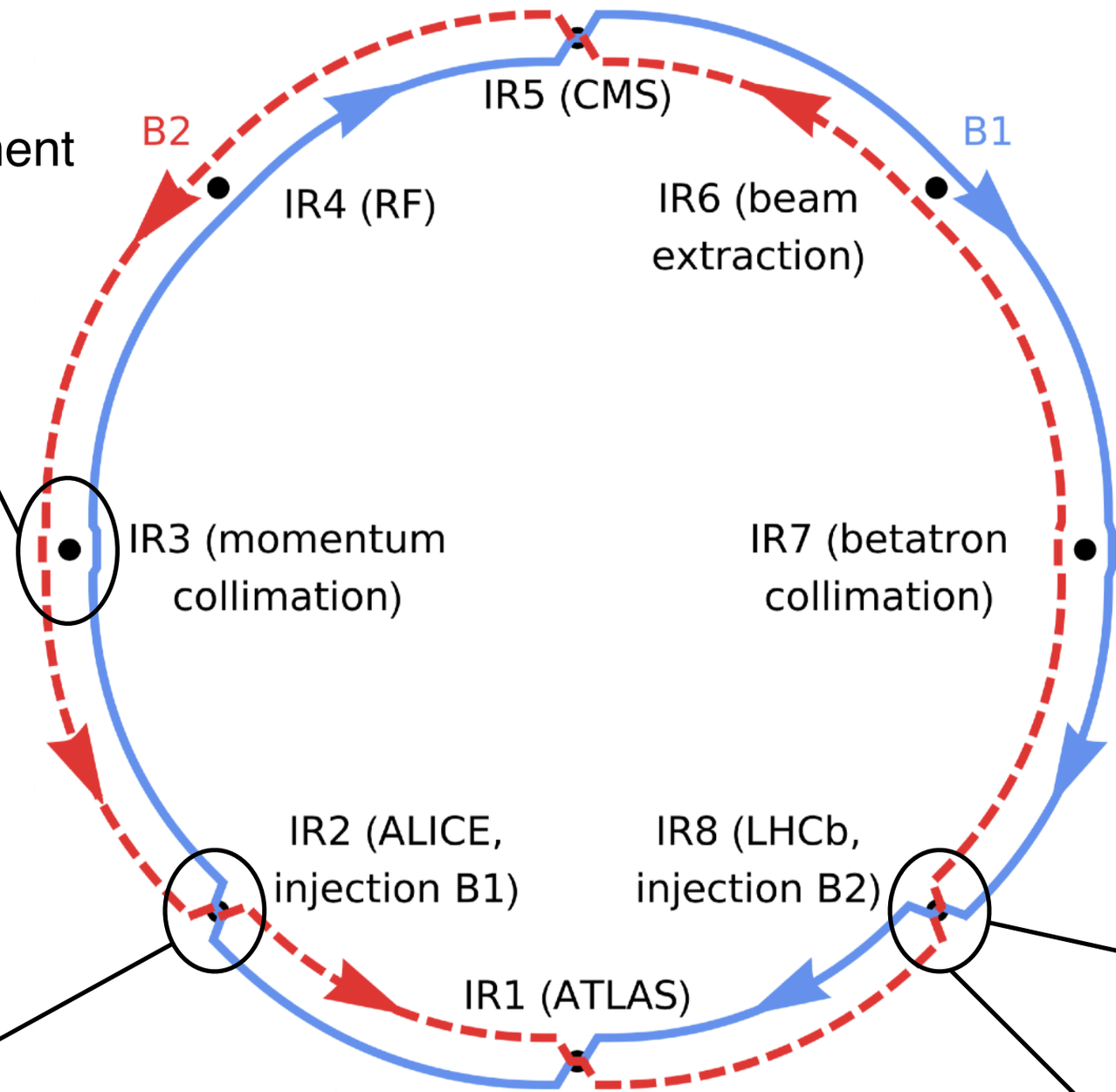


Geography of FTs at the LHC

Double-crystal setup: Proof-of-principle (TWOCRYST) and possible future experiment

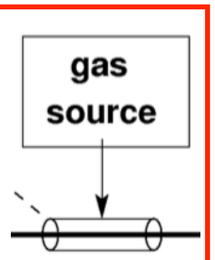




Clearly, <u>fundamental</u> when possible to rely on existing LHC experiments!

SMOG-2: approved

Gaseous targets



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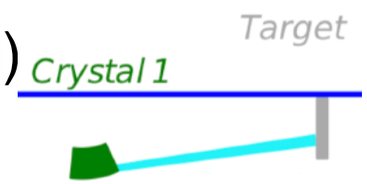
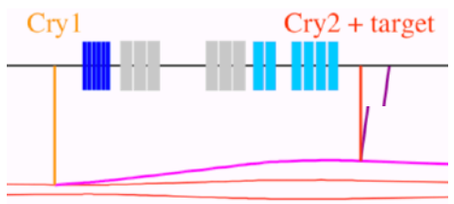
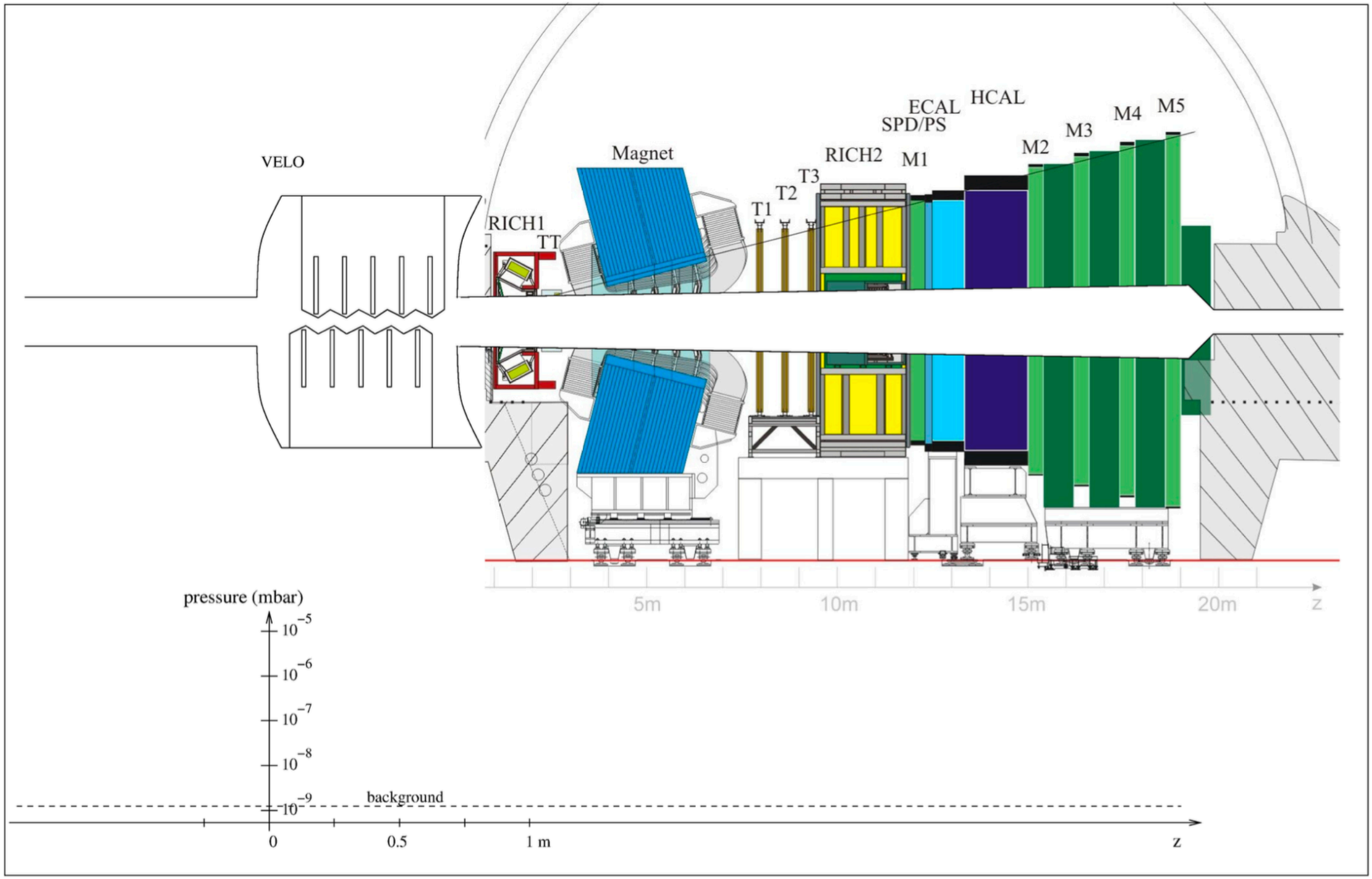


Double-crystal setup



Gaseous targets: SMOG-2



Courtesy M. Ferro-Luzzi

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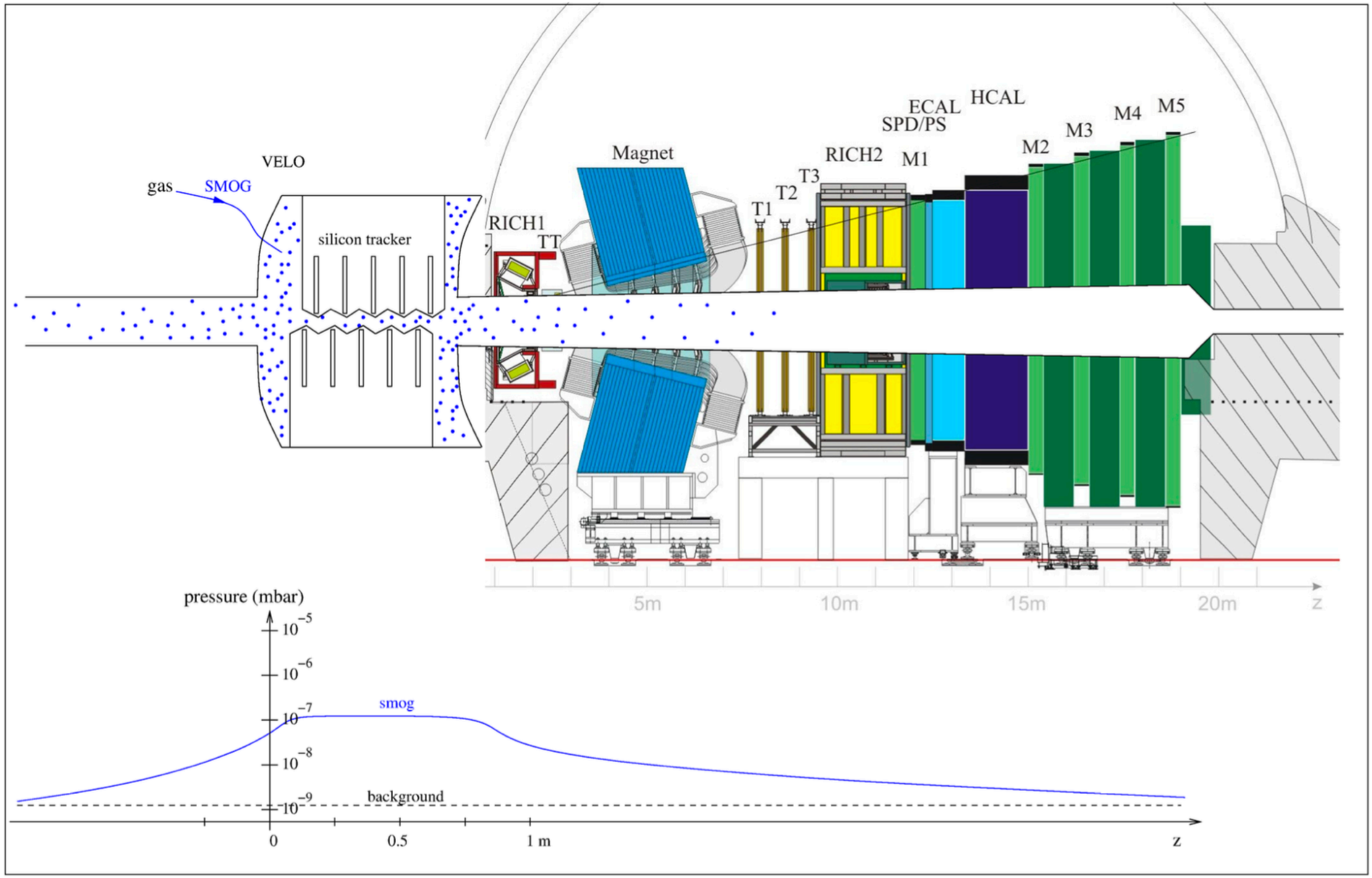

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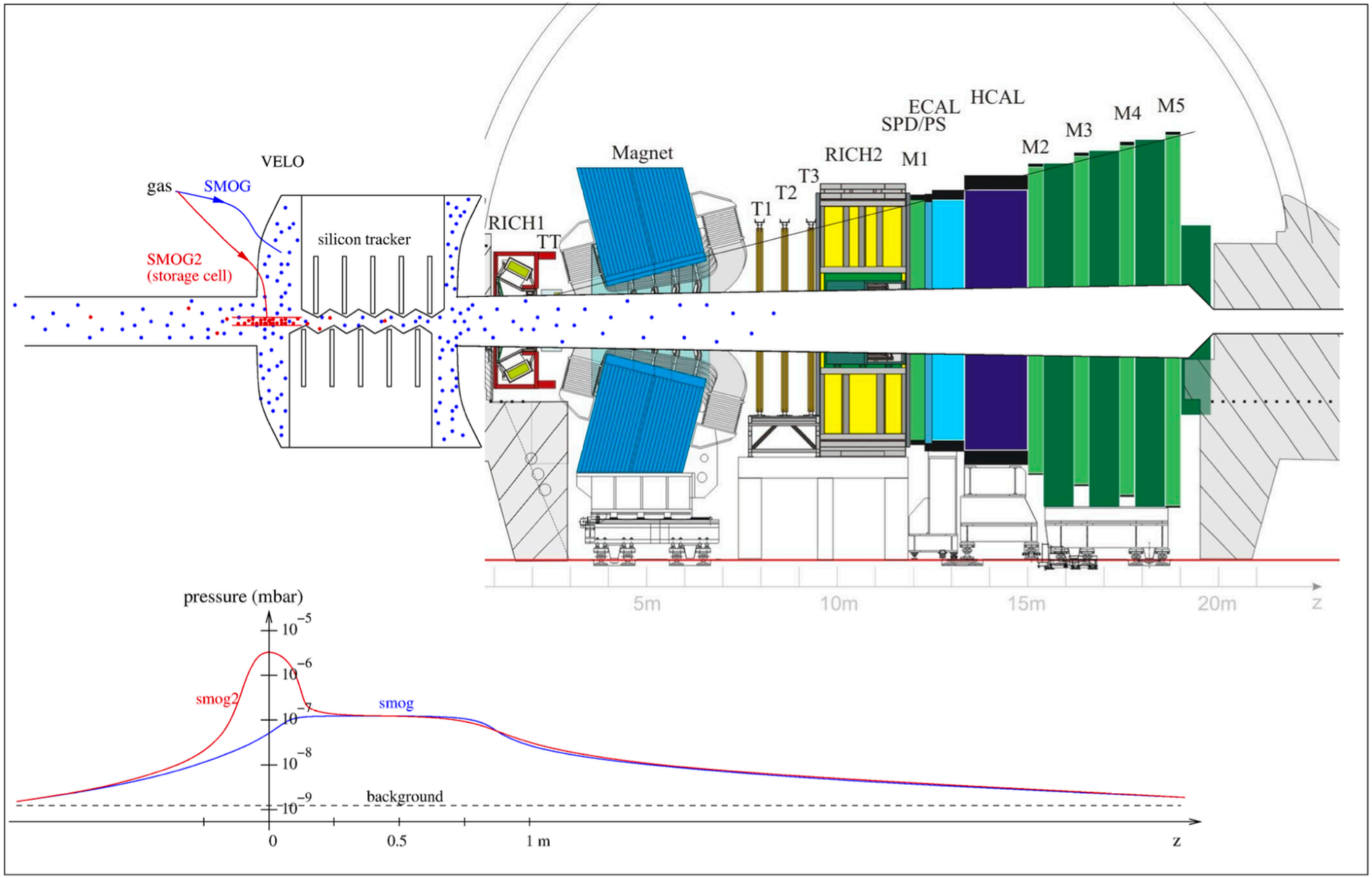
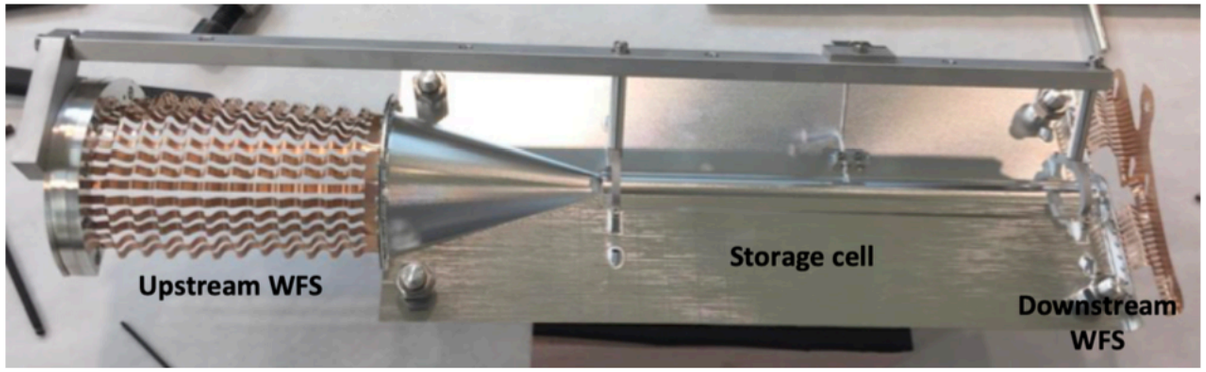


Courtesy M. Ferro-Luzzi

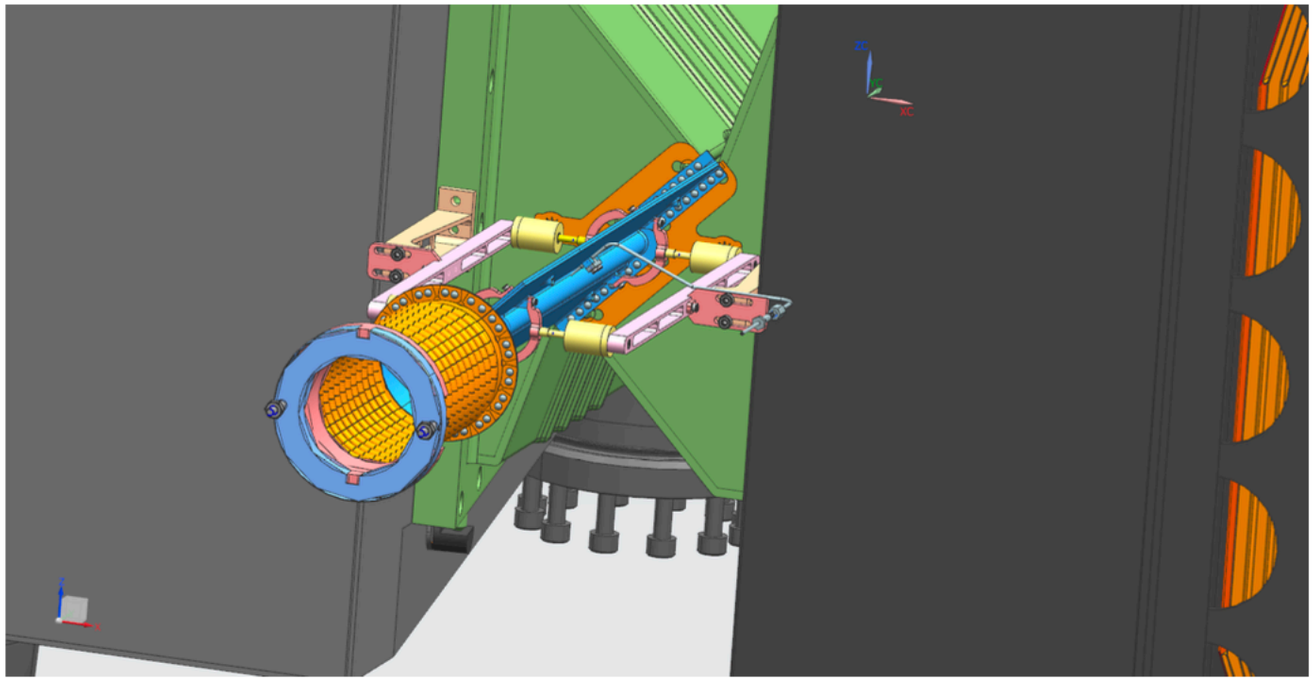
SMOG-2 at LHCb

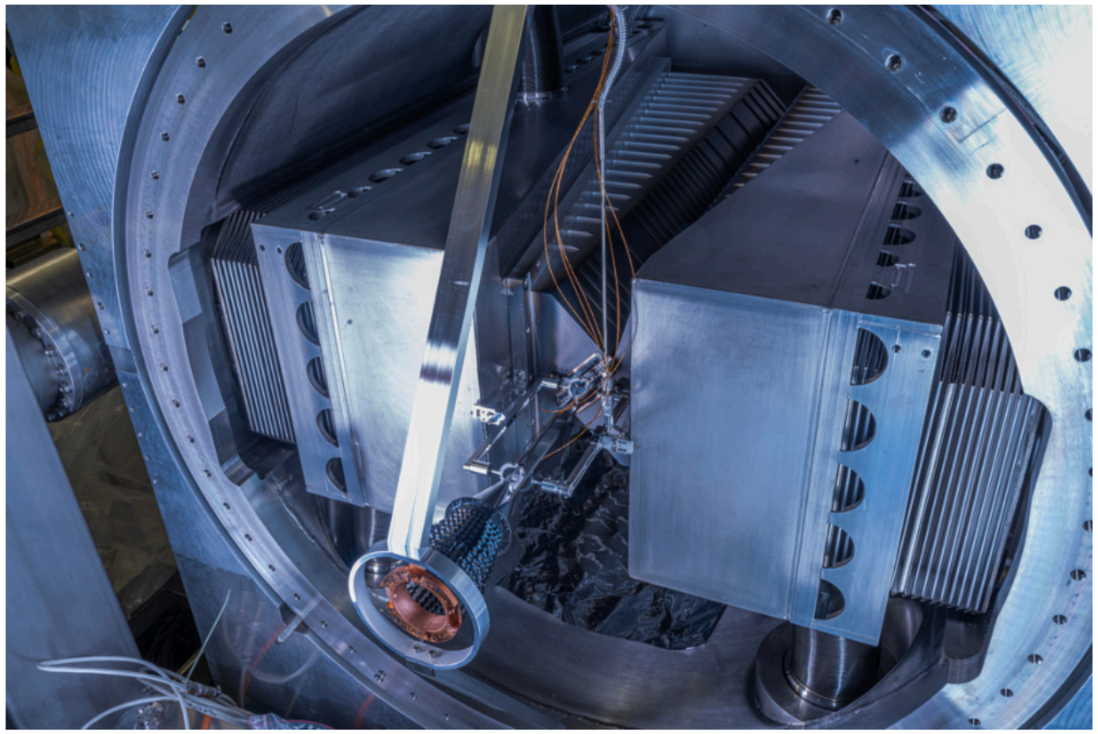
as a result of much work & cooperation (impedance, aperture, SEY/vac)...

SMOG2 Storage Cell successfully attached to LHCb VELO at IP8 (summer 2020)



before and after coating with amorphous carbon





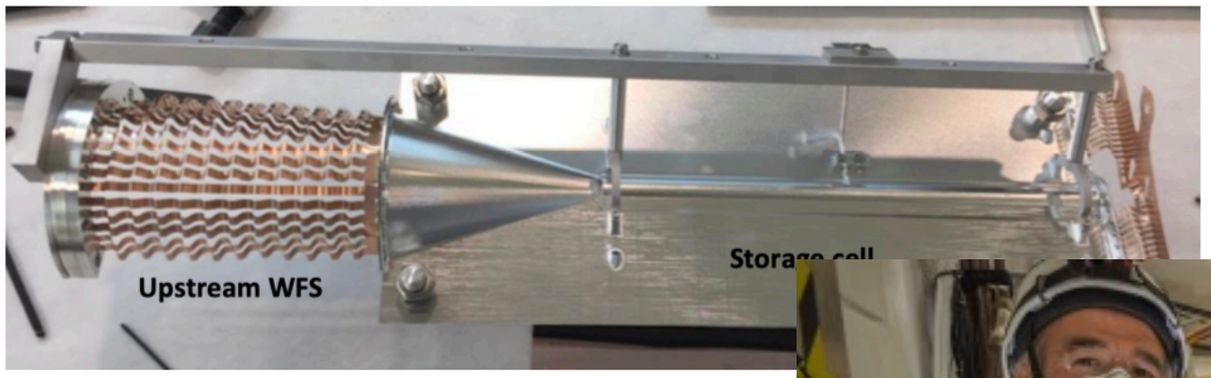
2022: gas-feed system & VELO+SC closing commissioned successfully

Courtesy M. Ferro-Luzzi

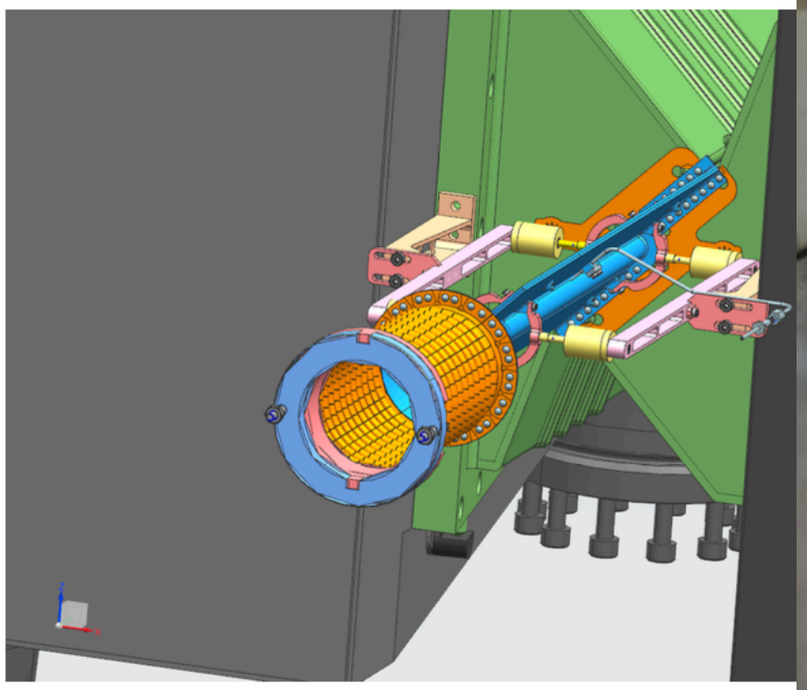
SMOG-2 at LHCb

as a result of much work & cooperation (impedance, aperture, SEY/vac)...

SMOG2 Storage Cell successfully attached to LHCb VELO at IP8 (summer 2020)



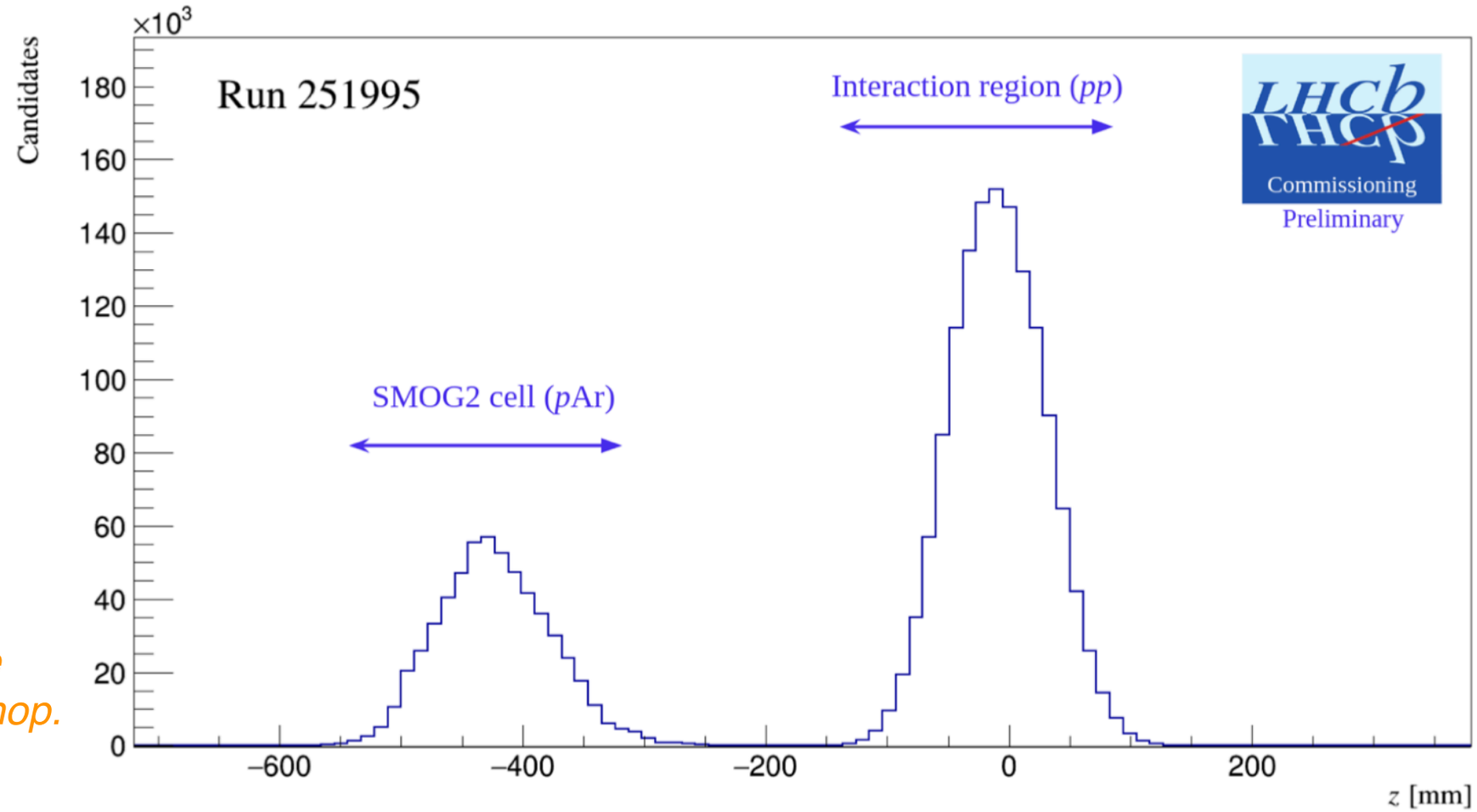
before



2022: gas-feed system & V

Courtesy M. Ferro-Luzzi

First results in 2022!



Reported by L. Pappalardo at the 2022 PBC workshop.

- The two interaction regions are clearly visible and well separated!
- PV distributions consistent with simulations
- **LHCb is now the first (unique) LHC experiment with two simultaneous interaction regions!**

2023 run affected by issues preventing the closure of the VELO — looking forward to a successful proton run in 2024!

Unpolarized gases — next steps

Various studies ongoing to use additional gases in SMOG-2:

- H_2 and D_2
  - an excess of hydrogen in the bulk may result in embrittlement (and peel off) of the NEG
- O_2
  - Risk to eventually saturate the NEG, resulting in reduce pumping speed
- Noble gases: Xe, Kr, Ar
  - Not pumped by the NEG
  - Risk to degrade secondary emission yield (SEY)

CERN: experiment to assess saturation and embrittlement of NEG coating by H_2

Beam losses in the machine also to be assessed for heavier gases.

thin-film-coatings-improved-vacuum-performance.png (516×316) (kt.cern)

Courtesy M. Ferro-Luzzi

“LHCspin”: polarized gas targets

Run 2 → **SMOG**

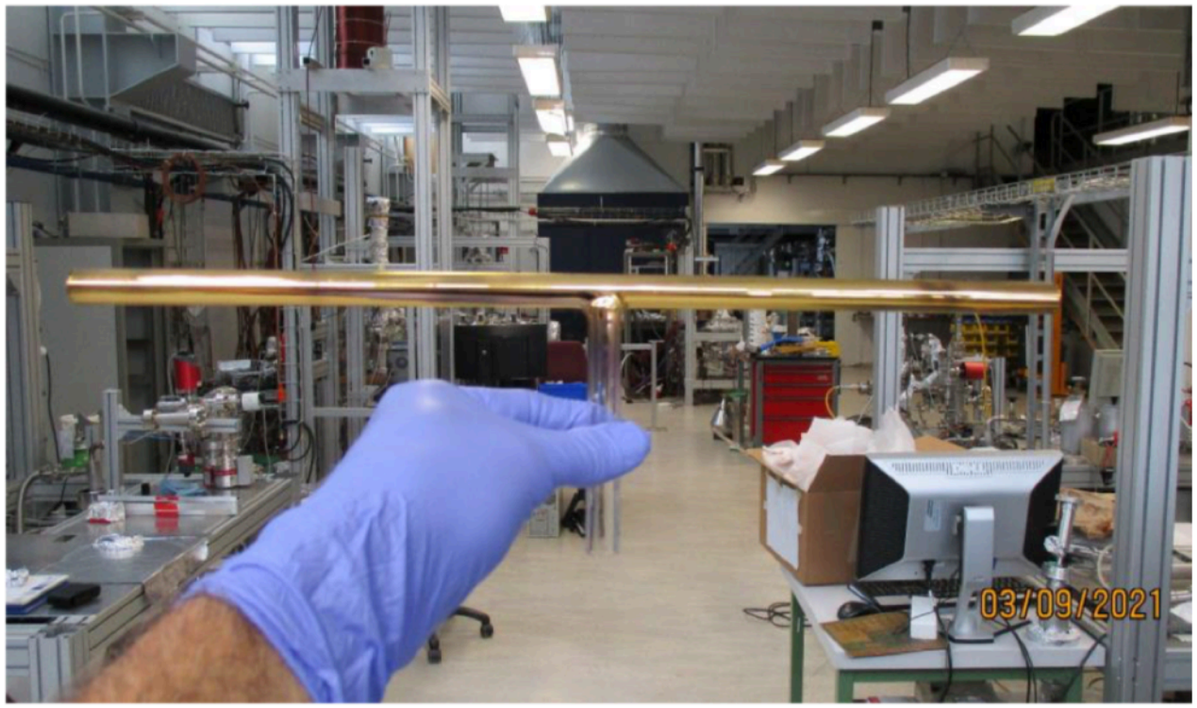
Run 3 → **SMOG2**

Run 4 (proposed) → **LHCspin**

R&D effort to identify suitable coating for $\vec{\mathrm{H}}$

- amorphous carbon has excellent SEY
- very robust, “ages well”, ...
- effect of impurities: hydrogen is bad, nitrogen is good
- does it preserve H nuclear polarization ?
- can one apply/control a few H_2O monolayers ?
- started R&D FZJ, LNF, Ferrara, CERN/TE-VSC

Carbon-coating tests to assess the preservation of polarization: CERN delivered a samples storage cell to FZJ (Jülich), tests ongoing

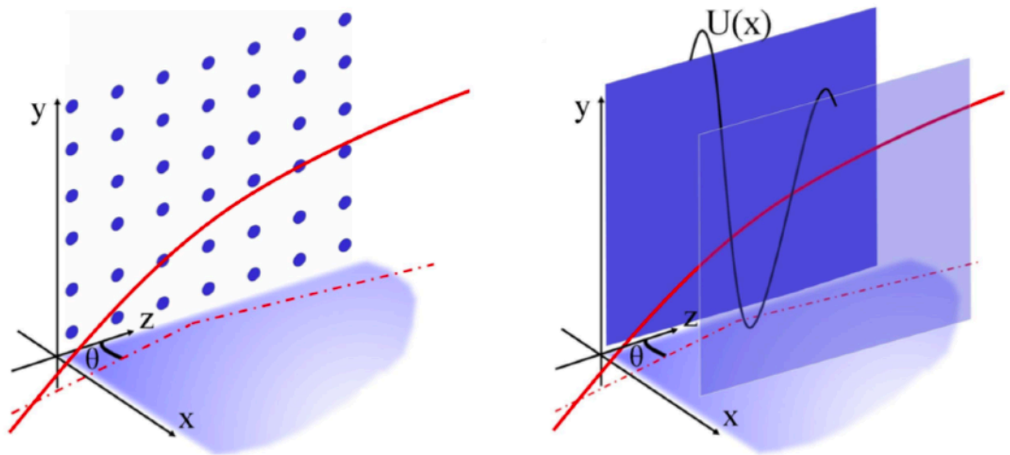


List compiled by M. Ferro-Luzzi

Crystal based implementations of LHC fixed targets

Planar channeling in bent crystals

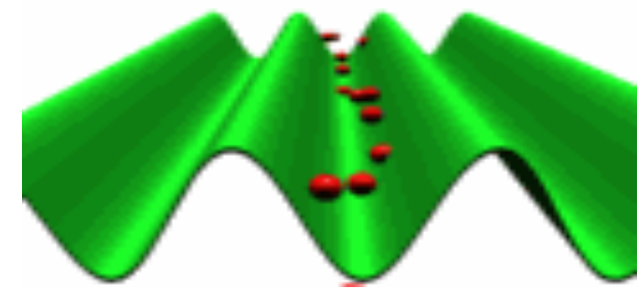
Pure crystals with regular lattices



*If the protons **have $p_T < U_{max}$***

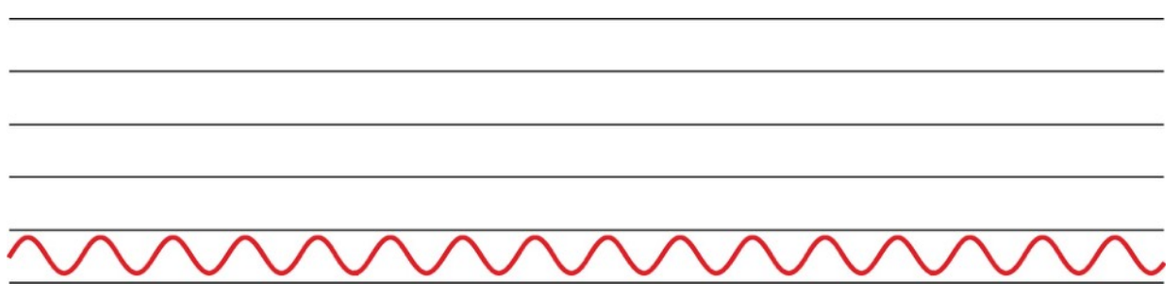
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Critical angle

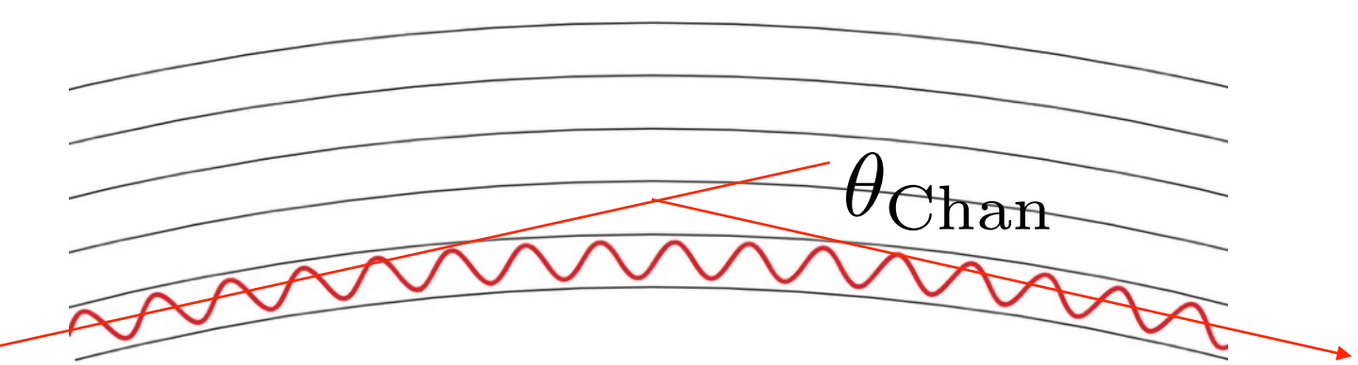


LHC 450 GeV = 9.4 μrad
LHC 6.5 TeV = **2.4 μrad**
FCC-hh 50 TeV = 0.9 μrad

Straight crystal: hadron oscillates, "trapped" between planes



Bent crystal: net bending produced



Mechanical crystal bending → net kick for particles trapped between planes

Equivalent to very high magnetic fields: e.g., a **4 mm** crystal bent to **50μrad** corresponds to ~ **300 T** at 7 TeV

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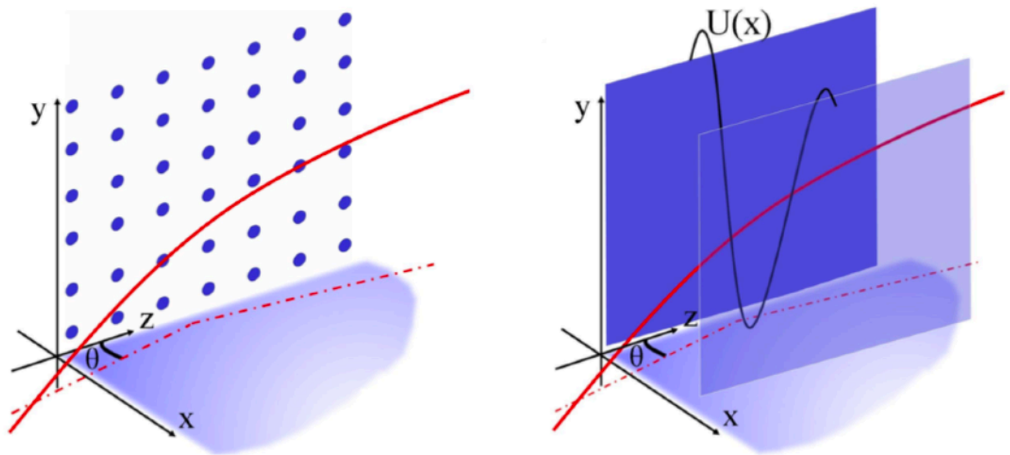
Pure crystals with regular lattices



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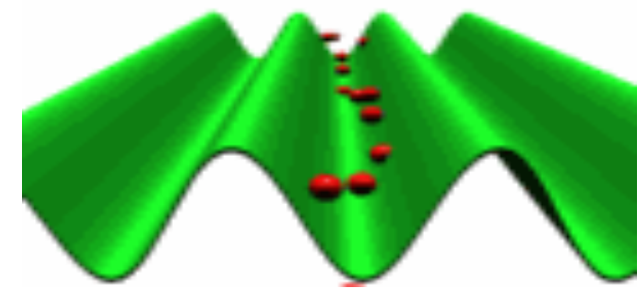

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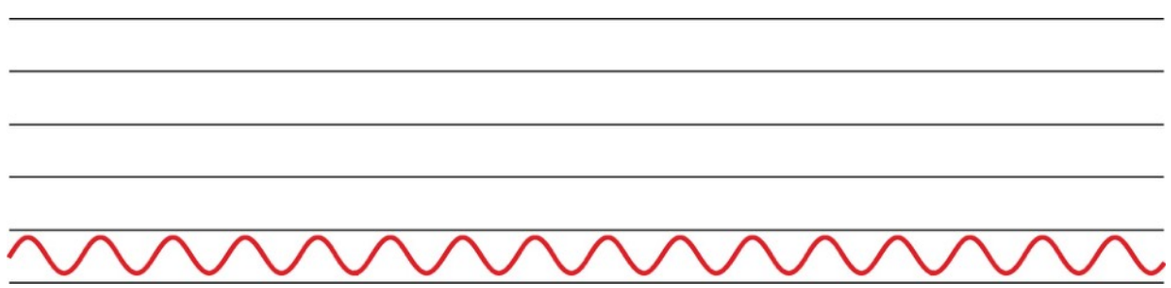

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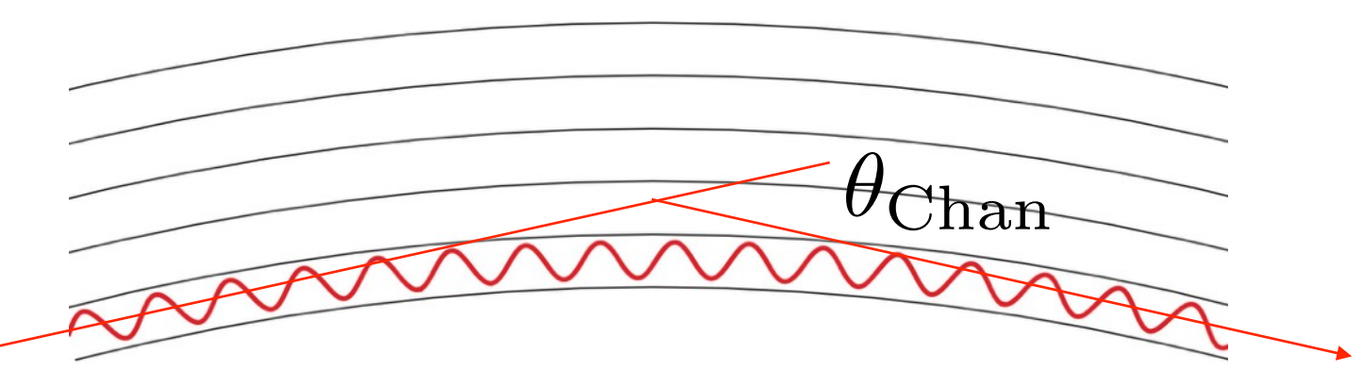

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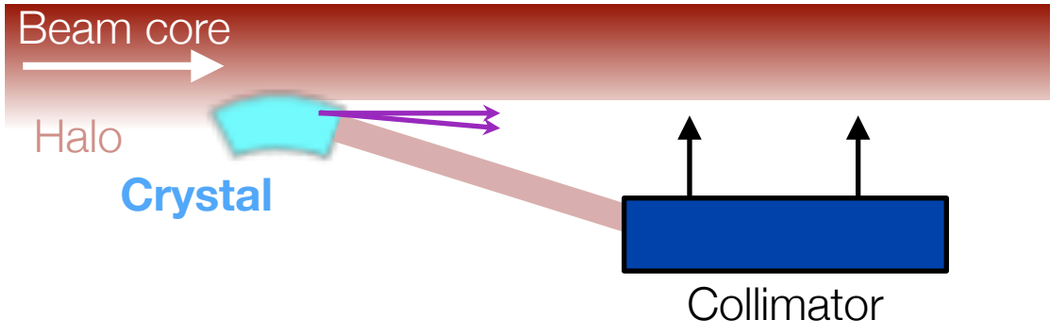
Does it really work?

Key measurements: crystal angular scans and linear collimator scans



Established in other circular accelerators, in particular: useful operational experience at the SPS (UA9 setup).

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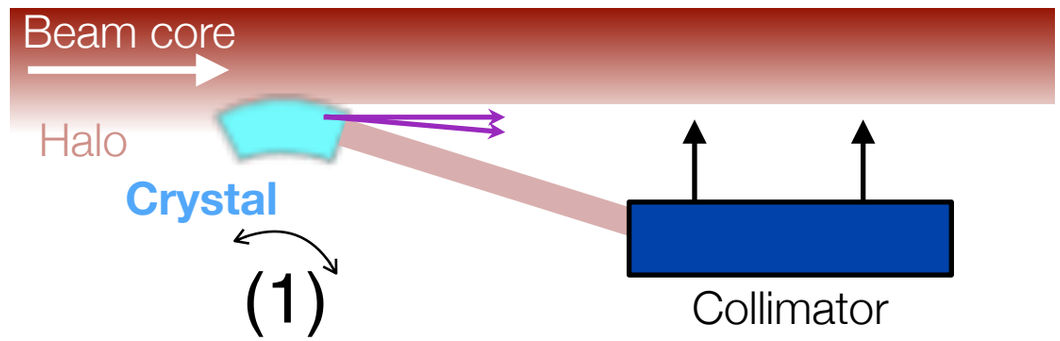
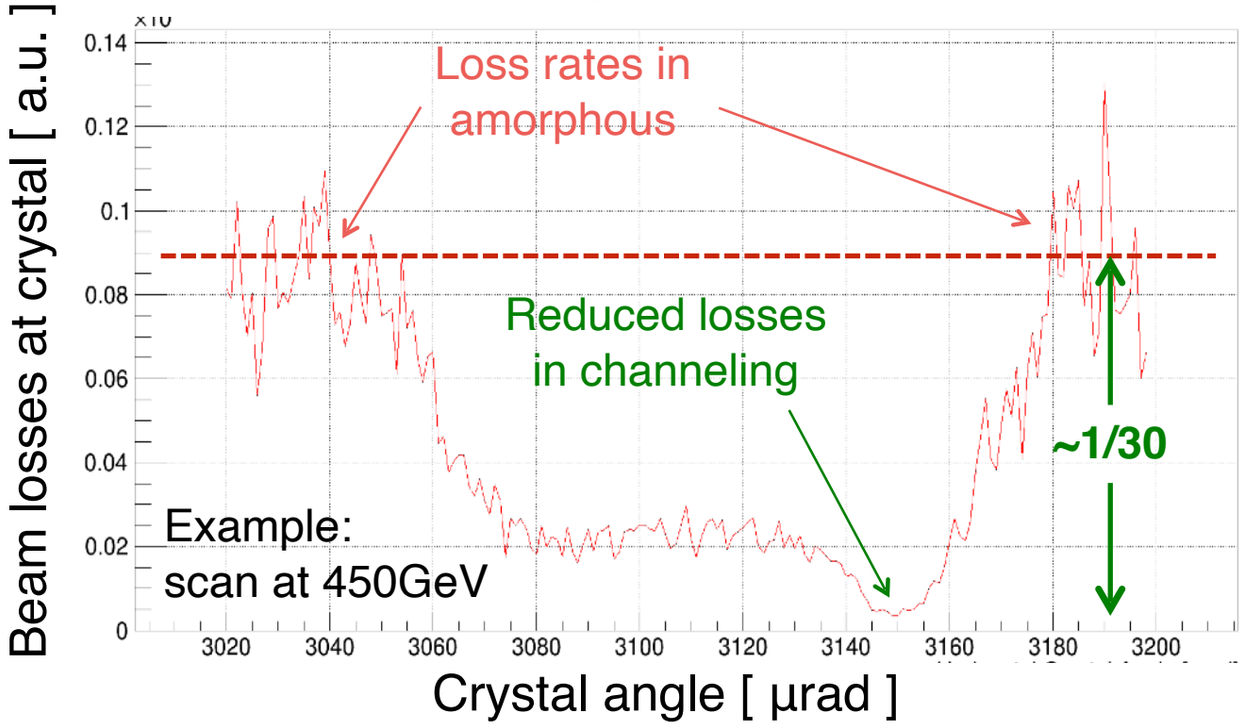


(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.



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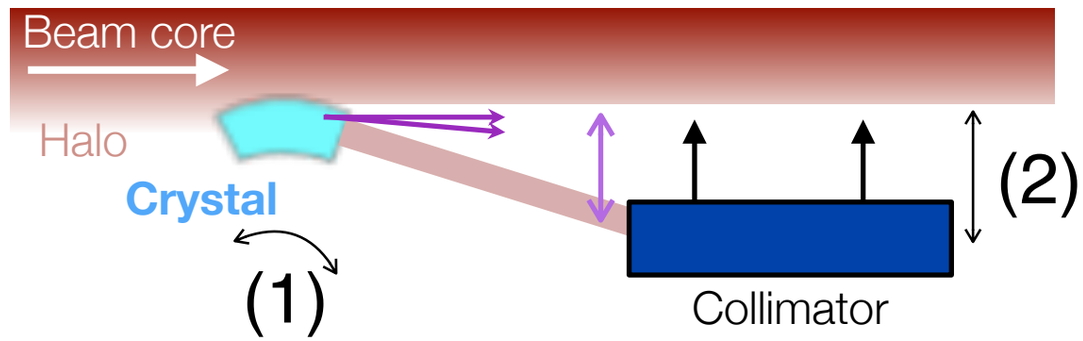

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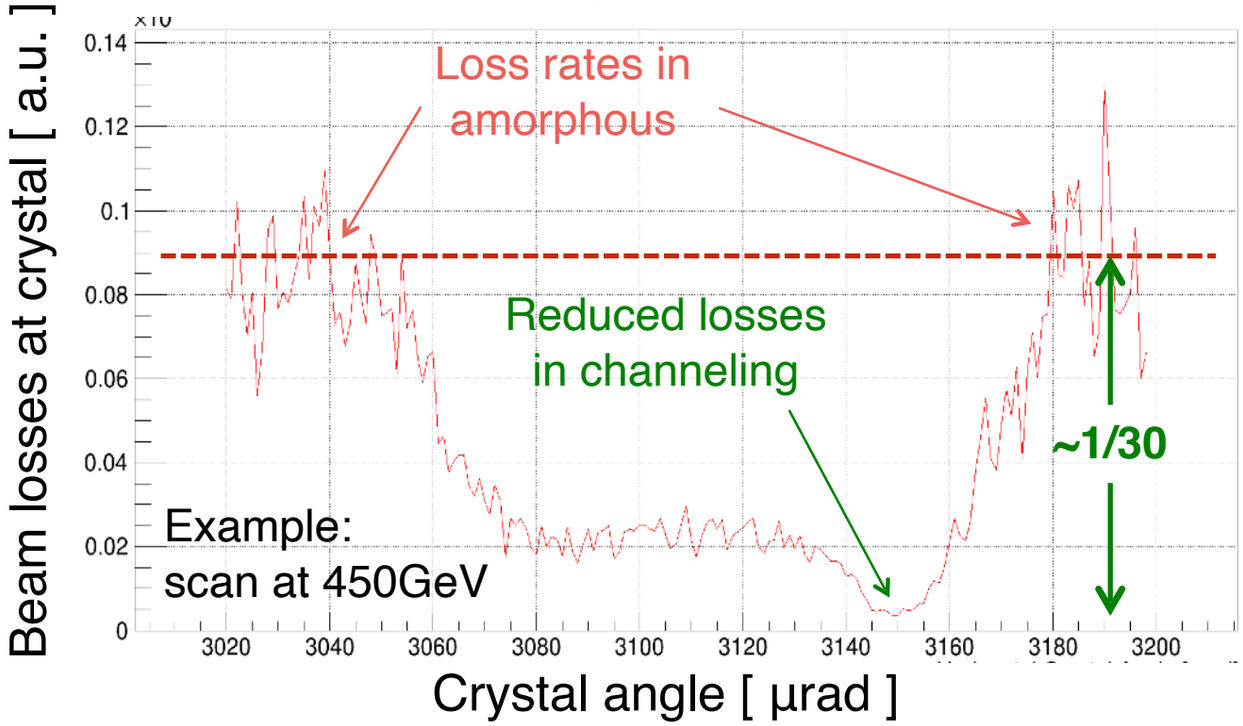
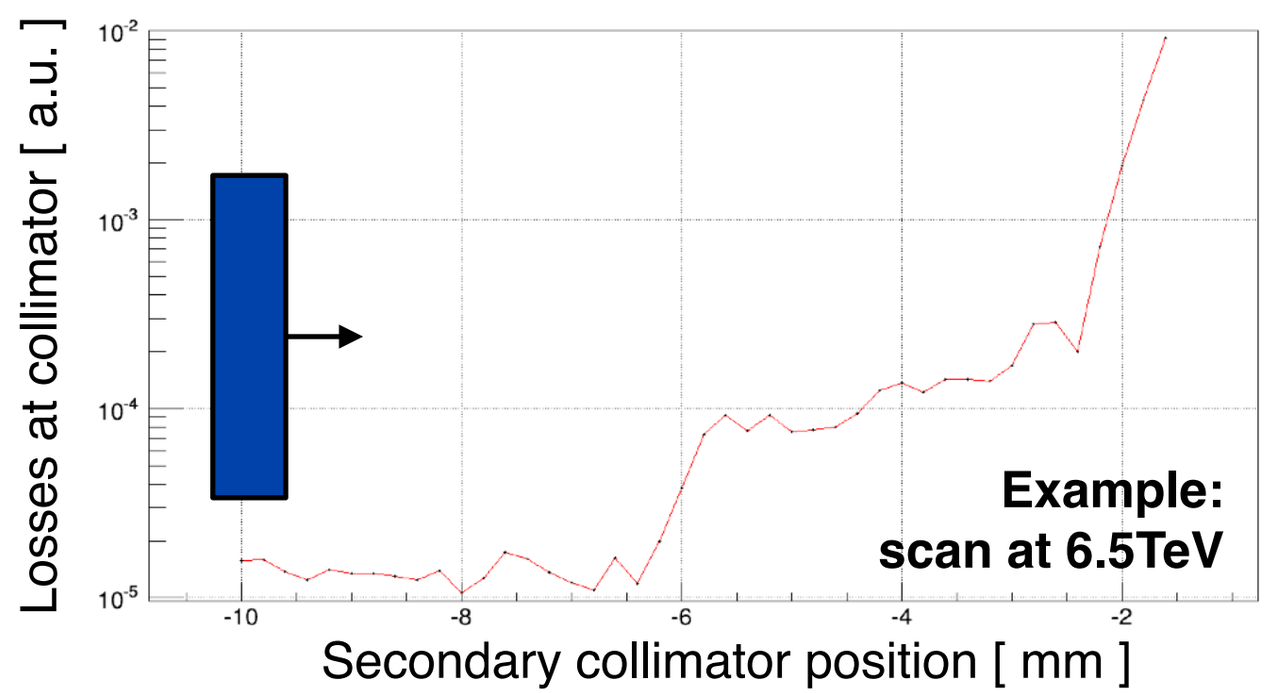


(2) **Linear collimator scan**: measures the profile of the channeled halo.



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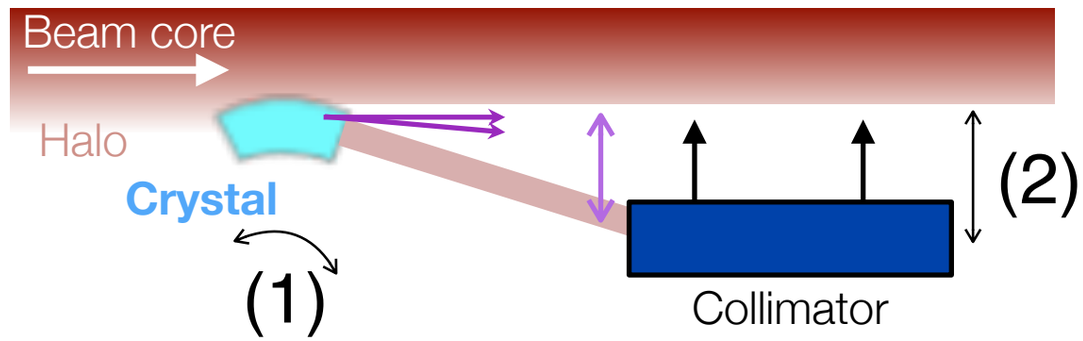

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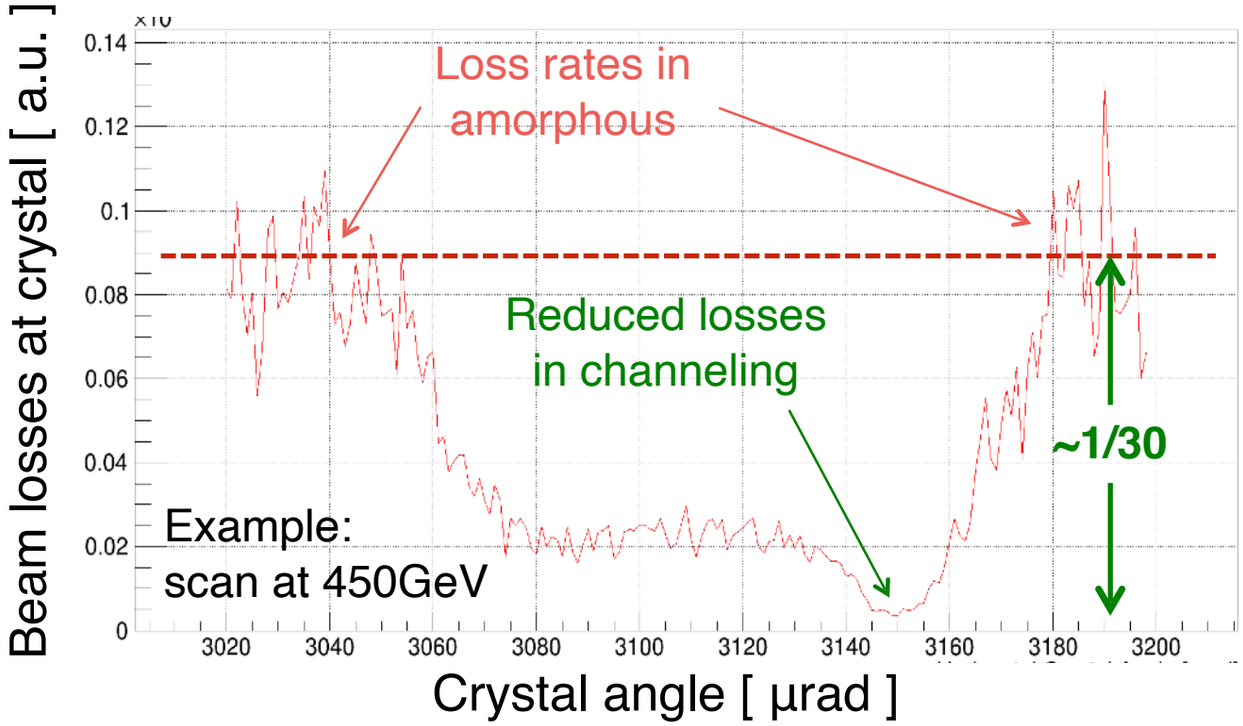

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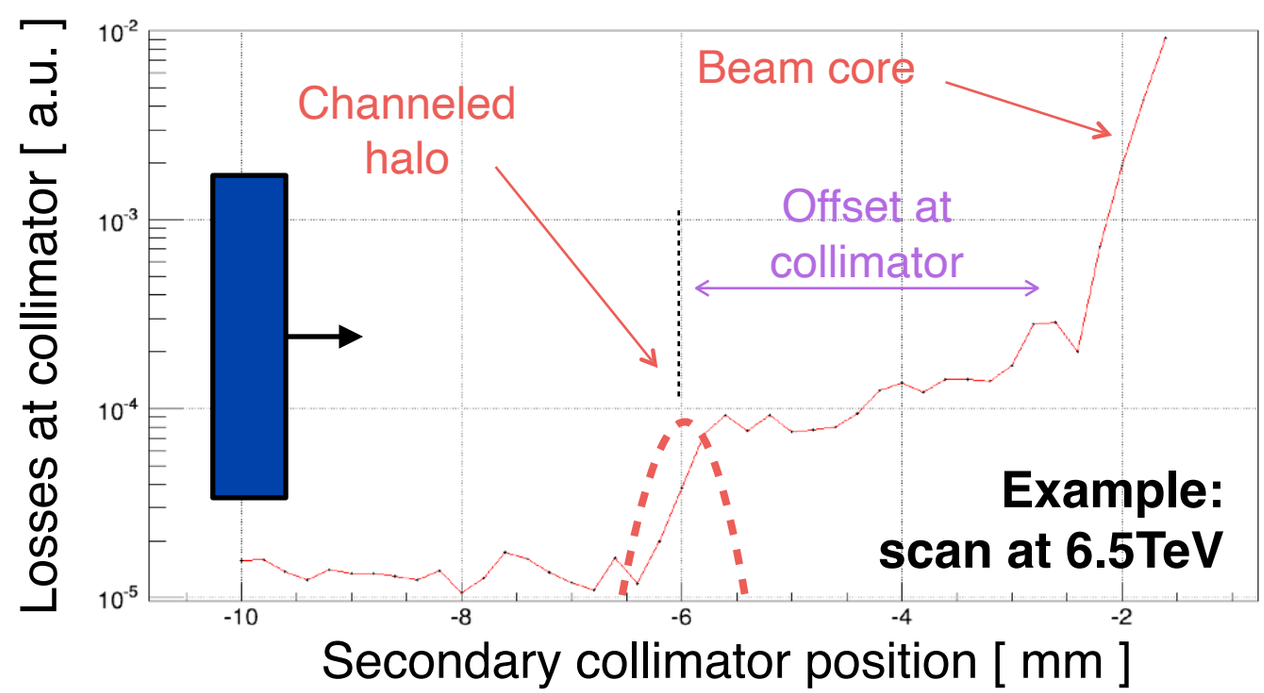
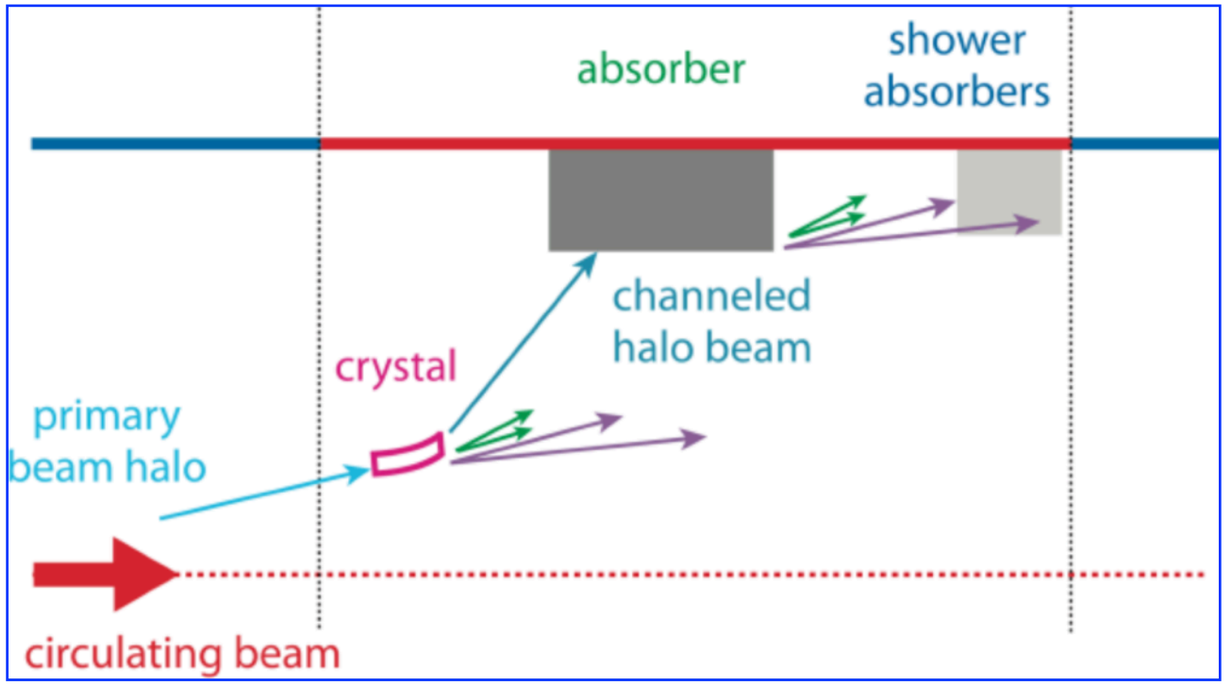


Example: application to beam collimation



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Used for ion beam collimation in 2023!

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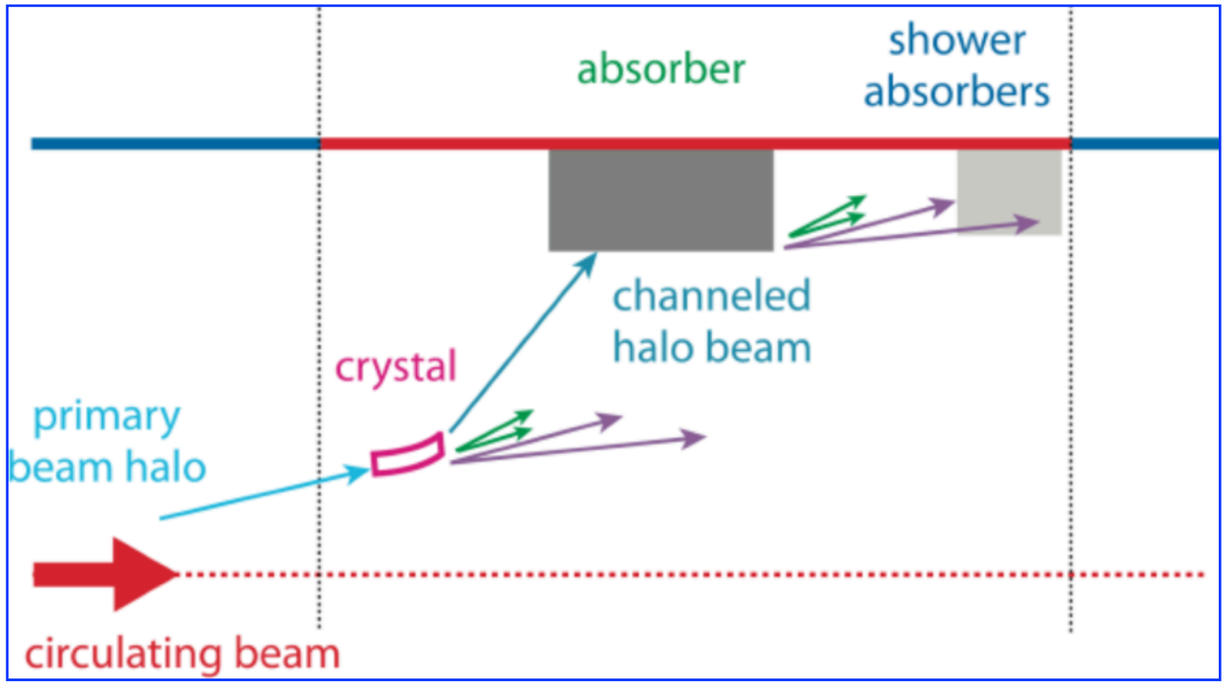

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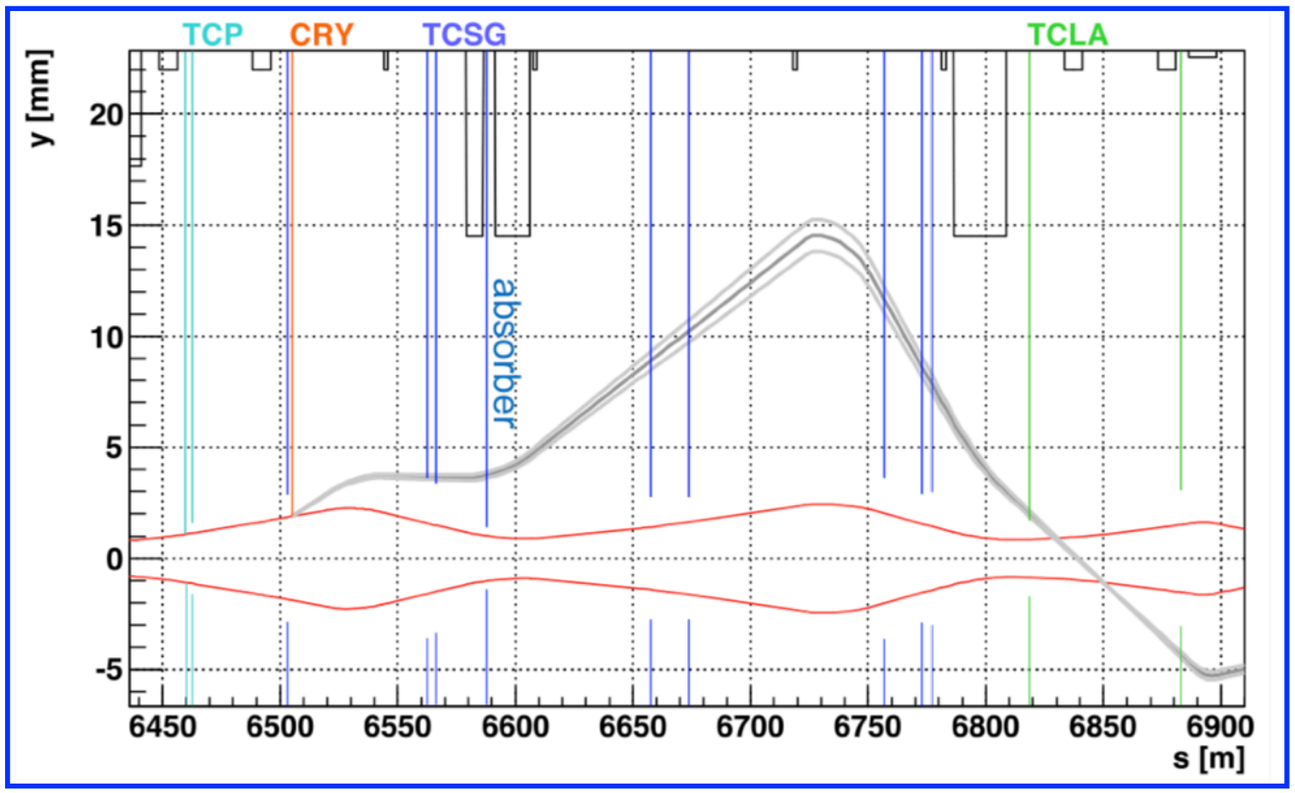


Crystal collimation scheme in IR7

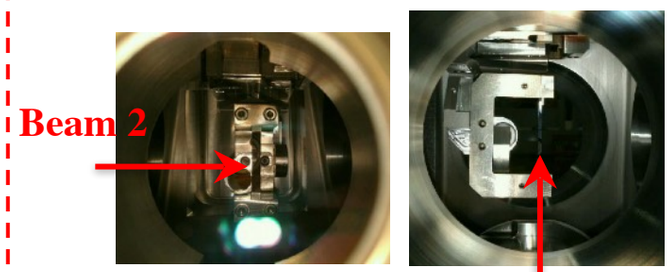
TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber

Synergy with the LHC collimation studies

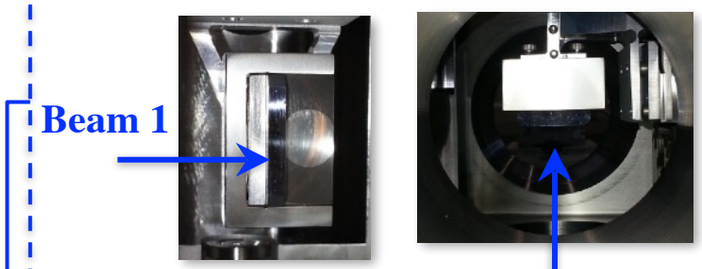
Four crystals installed in the LHC: two per beam, one per plane. Provided and validated by the UA9 collaboration. 2 producers: PNPI (3 crystals) and INFN-Fe (1).

IR7 layouts recently upgraded with new crystal assemblies as a part of the HL-LHC upgrade for ion beam collimation.

TCPCH.A5R7.B2

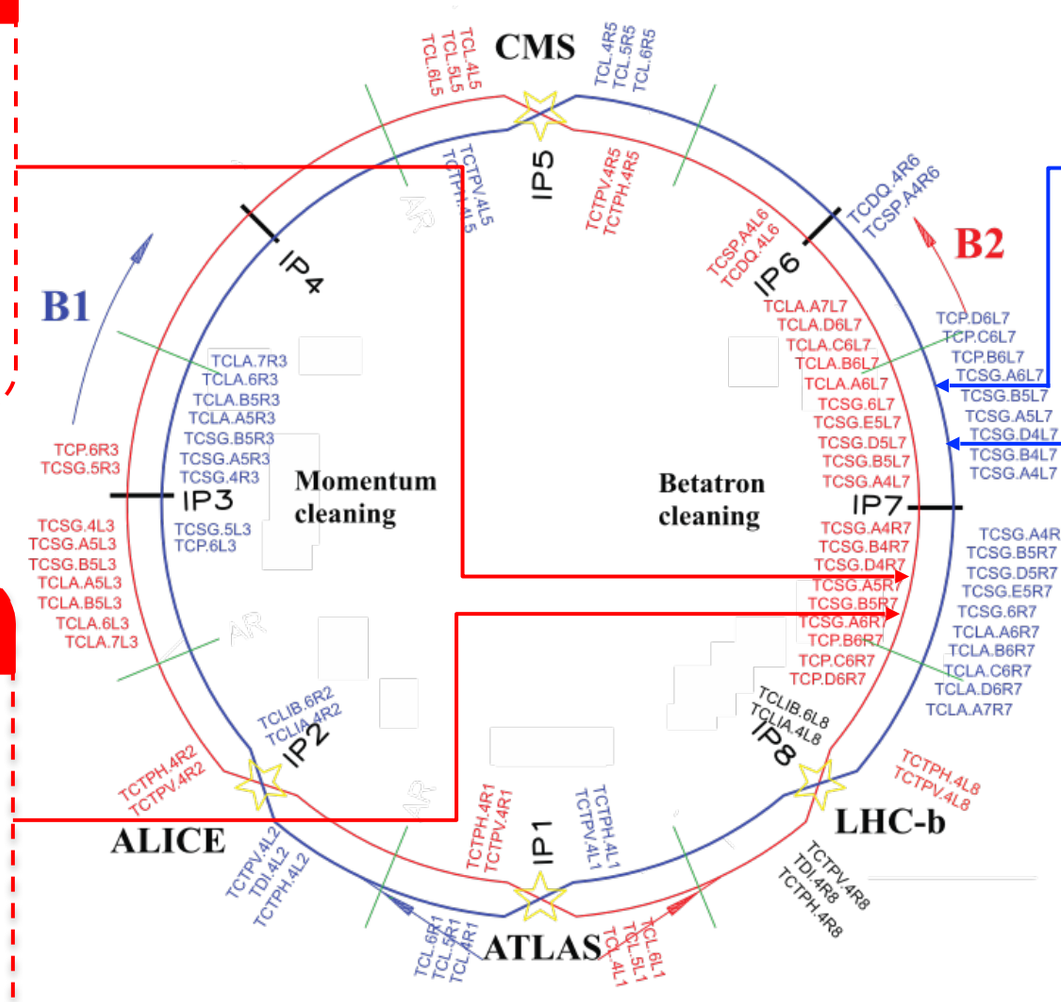


TCPCV.A6L7.B1

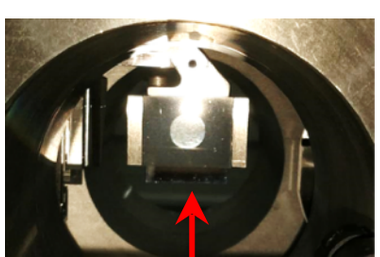


Pics. courtesy of Y. Gavrikov

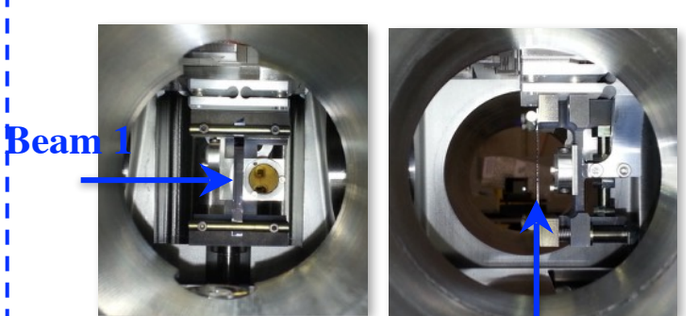
Scheme by D. Mirarchi



TCPCV.A6R7.B2



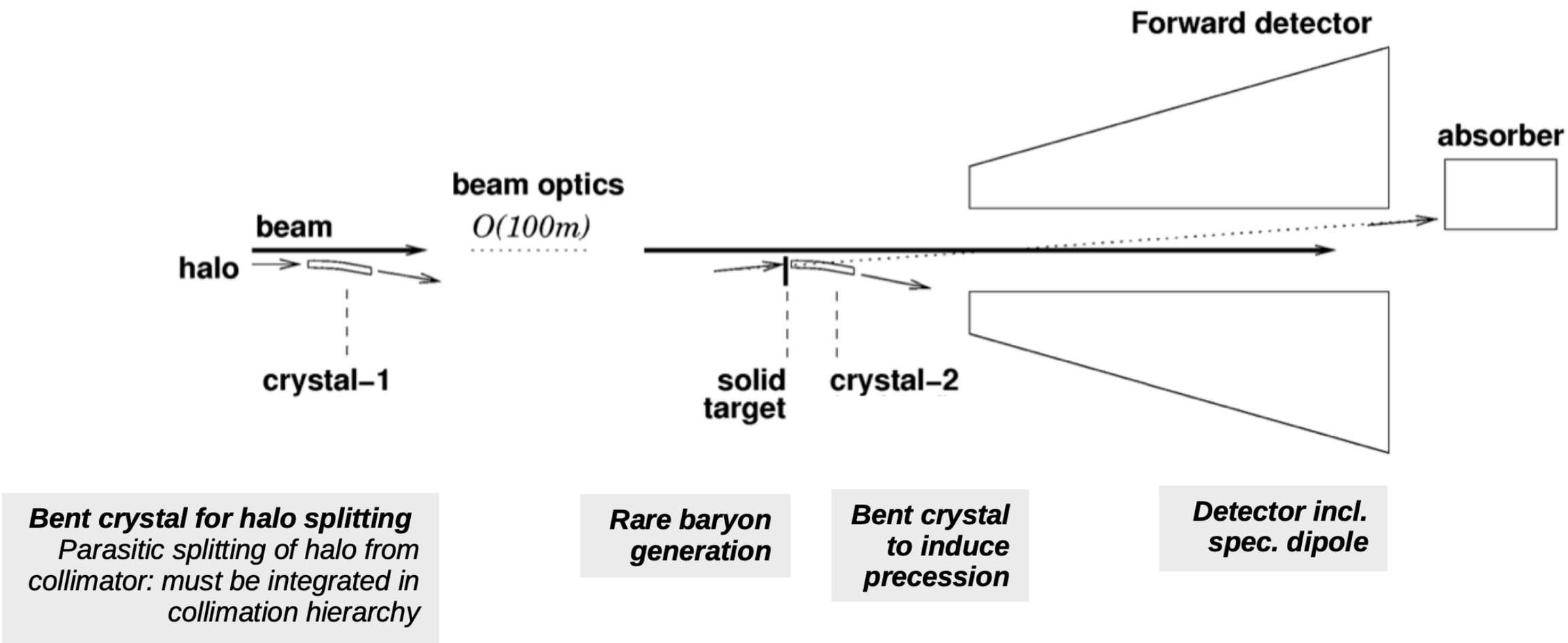
TCPCH.A4L7.B1



Crystal-based PBC FTs study were built on the well-established collaborations and know-how developed for LHC collimation.

The double-crystal setup

in circular accelerators



- Charmed baryon MDM/EDM measurements (in part., Λ_c^+):
  Can probe for physics beyond SM. Not feasible with conventional magnets
  Long-crystals behind target can provide sufficient precession!
- Strong interest from physics community
- Studied in detail in simulation, for different LHC configurations

See proposal by Stocchi and Scandale at PBC kickoff, 2016.

The double-crystal setup

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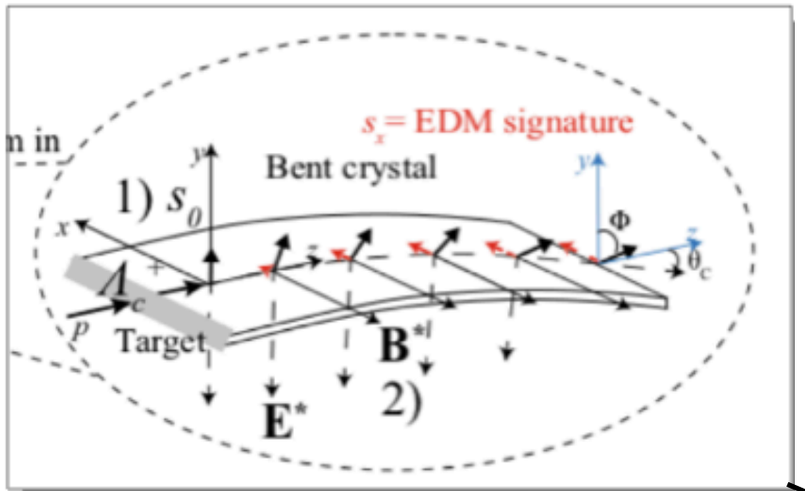
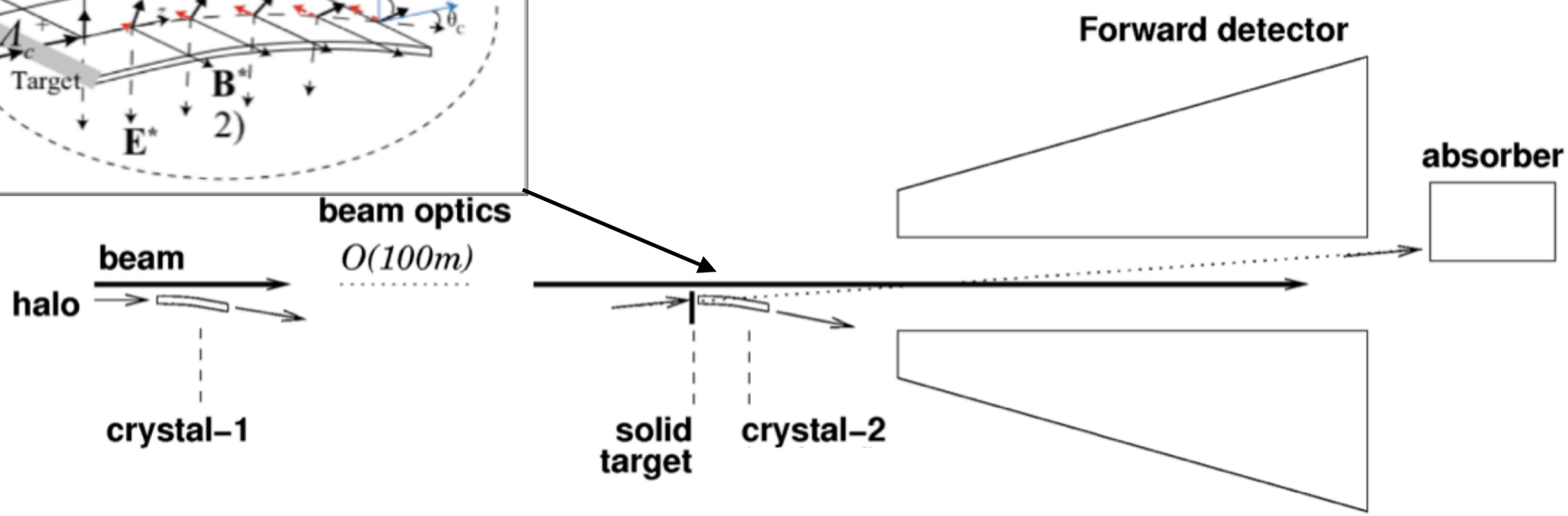


Using magnetic field for particles decaying within a few cm.



Bent crystal for halo splitting
Parasitic splitting of halo from collimator: must be integrated in collimation hierarchy

Rare baryon generation

Bent crystal to induce precession

Detector incl. spec. dipole

- Charmed baryon MDM/EDM measurements (in part., Λ_c^+):
  Can probe for physics beyond SM. Not feasible with conventional magnets
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- Studied in detail in simulation, for different LHC configurations

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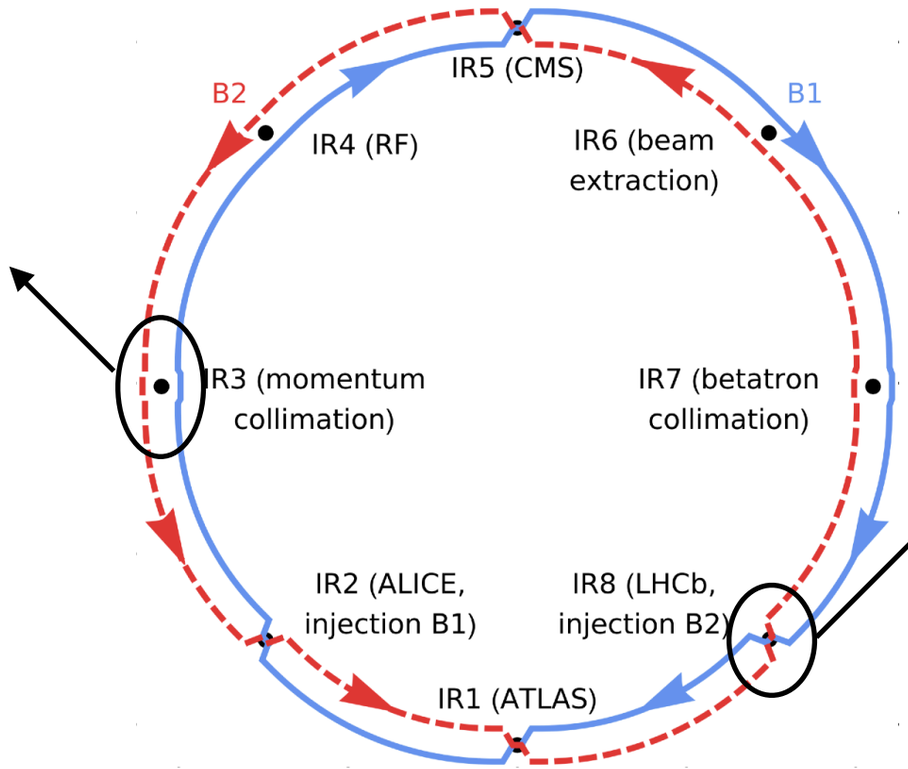
Possible solutions and open points

Studied to optimise performance and machine aspects; detector to be built



Initial proposal, relying on the LHCb detector *(CERN-SPSC-2016-030; SPSC-EOI-012)*

Detailed layout comparisons:
Eur. Phys. J. C 80, 929 (2020)
Phys. Rev. D 103, 072003. (2021)

Open points calling for a solid experimental validation:

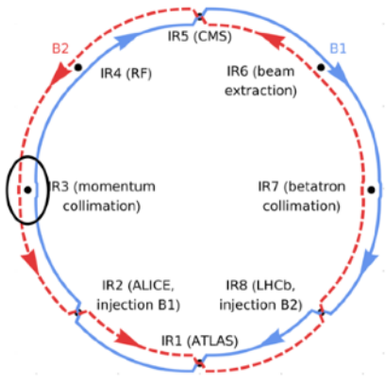
- Need to validate the long-crystal properties in the relevant TeV range
- Reliable operation of the double-crystal scheme to be demonstrated

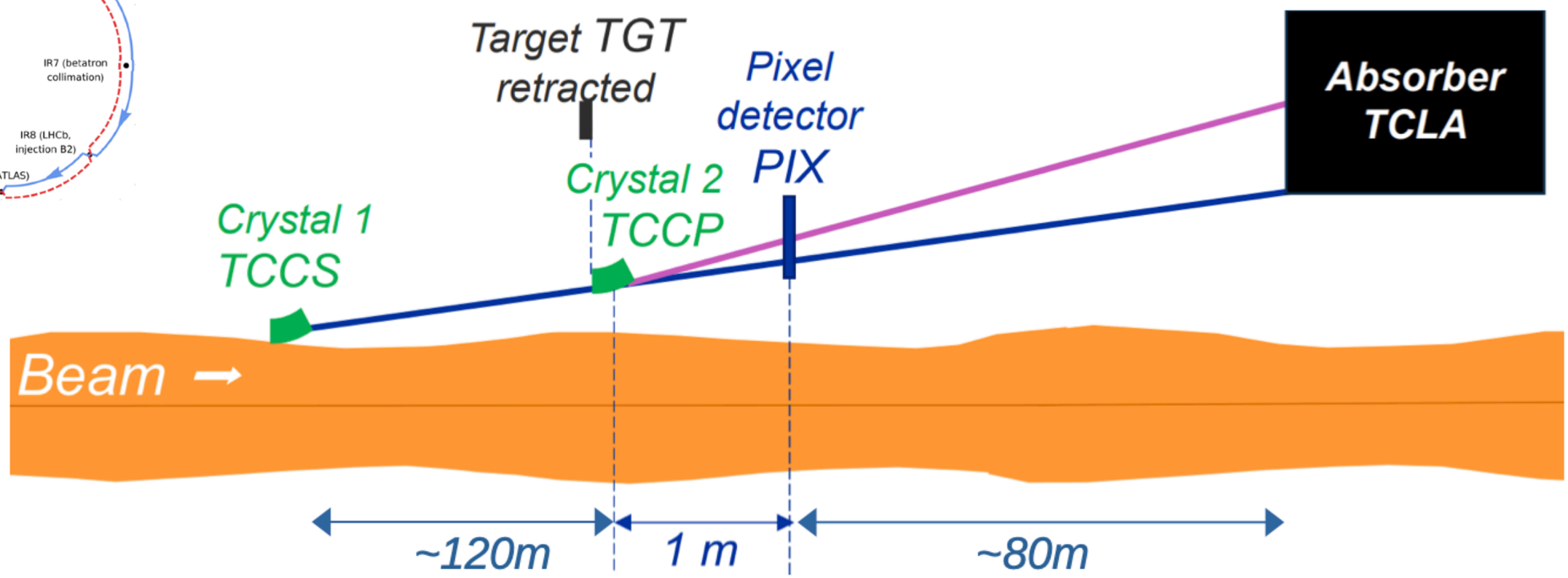
  Achievable performance with 7 TeV beam is a key input for final experiment design
- Experimental validation of simulation-based performance estimates

  Performance in simulation relies on the complex dynamics of multi-turn collimation halos

Present focus of PBC-FT: proof-of-principle machine experiment in IR3, called "TWOCRYST"

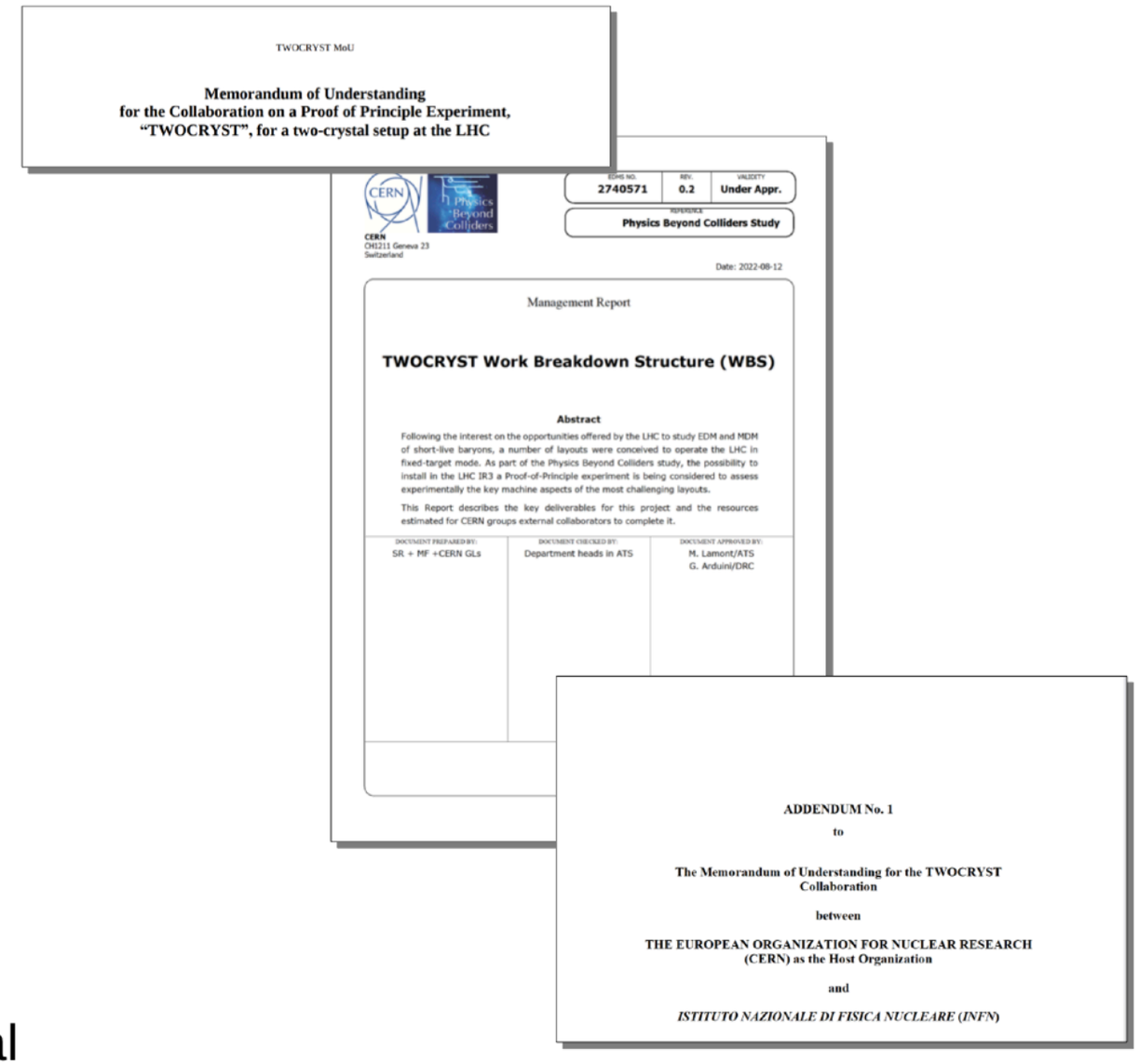
TWOCRYST: proof-of-principle





- **Scope of the proof-of-principle: two crystal assemblies + 1 target + Roman pot for detection of single- and double-channeling**
- Layout designed for integration in the LHC IR3 (off-momentum collimation): Available longitudinal space and infrastructure (cabling); low radiation levels; existing collimators that can be used in measurements
- Test stand conceived for **low beam intensities**: flexibility vs collimation constraints, simplify impedance considerations
- Compatible with measurements at different beam energies

Status of the forming collaboration


TWOCRYST MoU

Memorandum of Understanding
for the Collaboration on a Proof of Principle Experiment,
"TWOCRYST", for a two-crystal setup at the LHC

CERN
CH1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
2740571	0.2	Under Appr.

REFERENCE
Physics Beyond Colliders Study

Date: 2022-08-12

Management Report

TWOCRYST Work Breakdown Structure (WBS)

Abstract

Following the interest on the opportunities offered by the LHC to study EDM and MDM of short-live baryons, a number of layouts were conceived to operate the LHC in fixed-target mode. As part of the Physics Beyond Colliders study, the possibility to install in the LHC IR3 a Proof-of-Principle experiment is being considered to assess experimentally the key machine aspects of the most challenging layouts.

This Report describes the key deliverables for this project and the resources estimated for CERN groups external collaborators to complete it.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
SR + MF +CERN GLs	Department heads in ATS	M. Lamont/ATS G. Arduini/DRC

ADDENDUM No. 1
to
The Memorandum of Understanding for the TWOCRYST Collaboration
between
THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN) as the Host Organization
and
ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN)

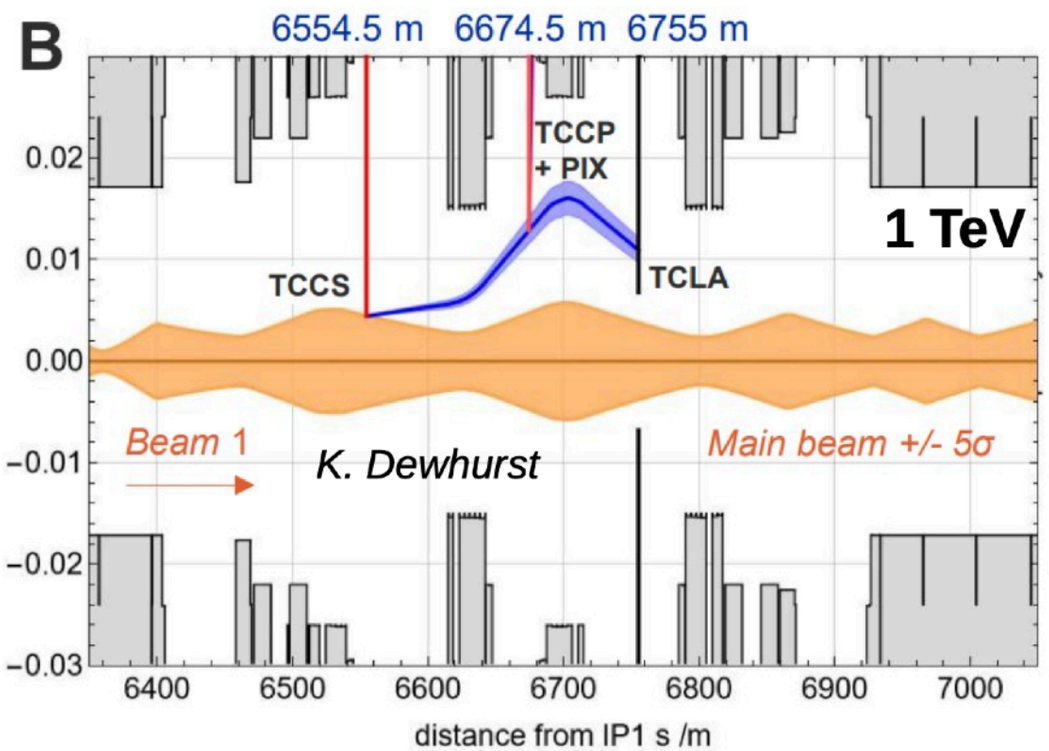
TWOCRYST management status

- **MoU signed** by CERN and 3 collaborating institutes (Dec '22 / Jan '23)
  - INFN (Milano, Milano Bicocca, Padova, Pisa, Ferrara, Legnaro)
  - University of Valencia, Spain
  - IJCLab, Orsay, France
- Other institutes interested in signing
- **Addenda** defining individual contributions by collaborators currently under preparation
- **Work Breakdown Structure (EDMS 2740571) agreed** with CERN teams: final round of GL approval

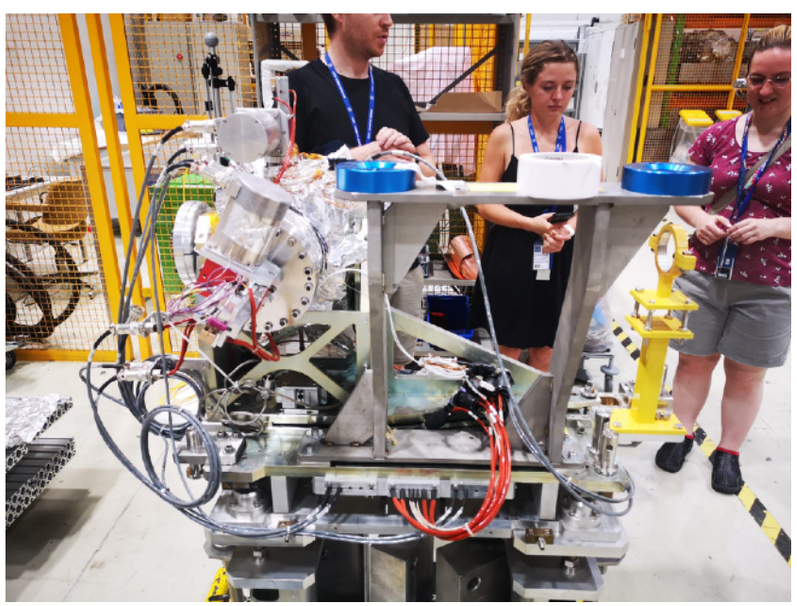
CERN study leader appointed: Pascal Hermes

Preparation of a letter of intent for an experiment to be integrated in LS3 or beyond is ongoing. Options for IR8 and IR3 still both open.

Status of layout studies



Crystal goniometer assembly taken from IR7, will be used for IR3

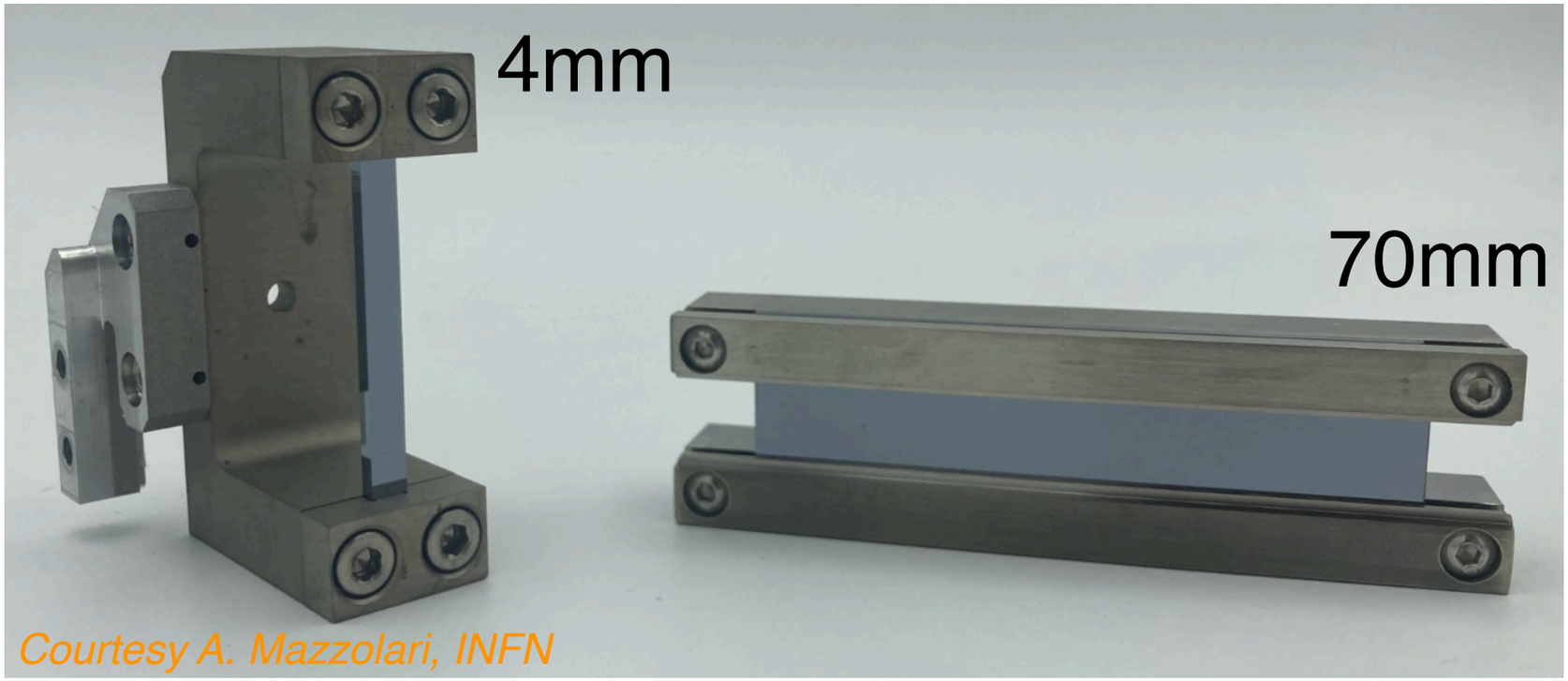


Proposed TCCS Position 6554.5m

Proposed TCCP Position 6674.5m

Beam 2 layouts were studied as well: looks more promising because of an easier integration of the required Roman pot.

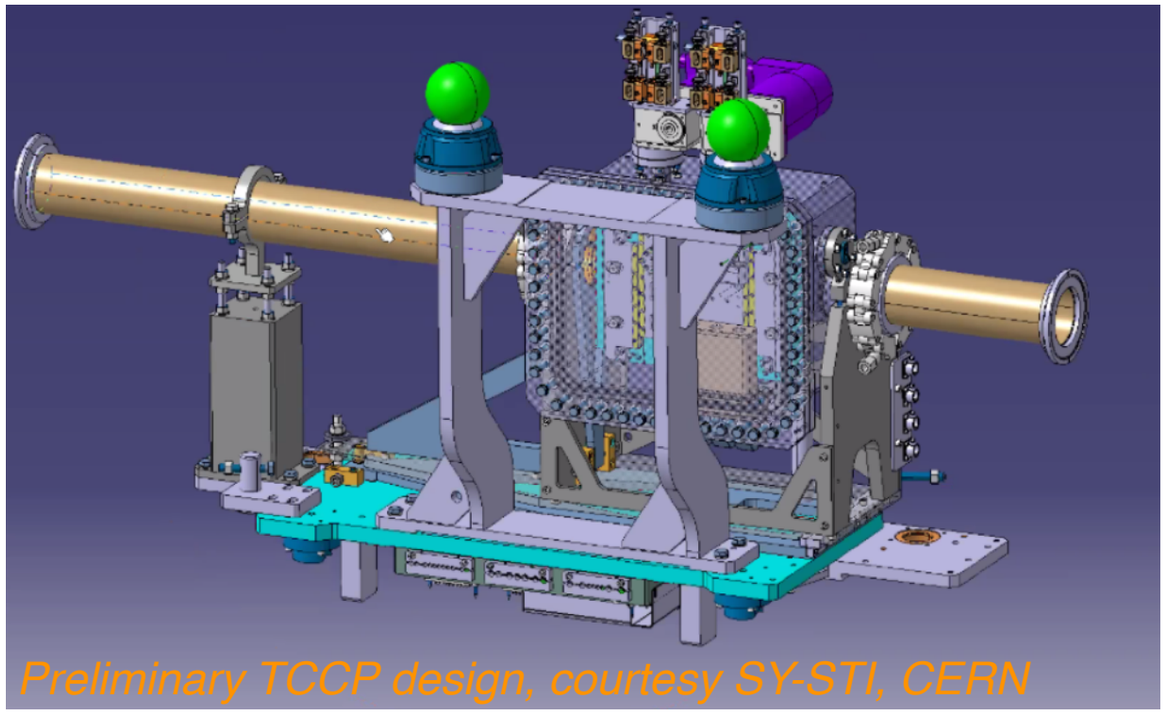
Recent hardware developments



Courtesy A. Mazzolari, INFN

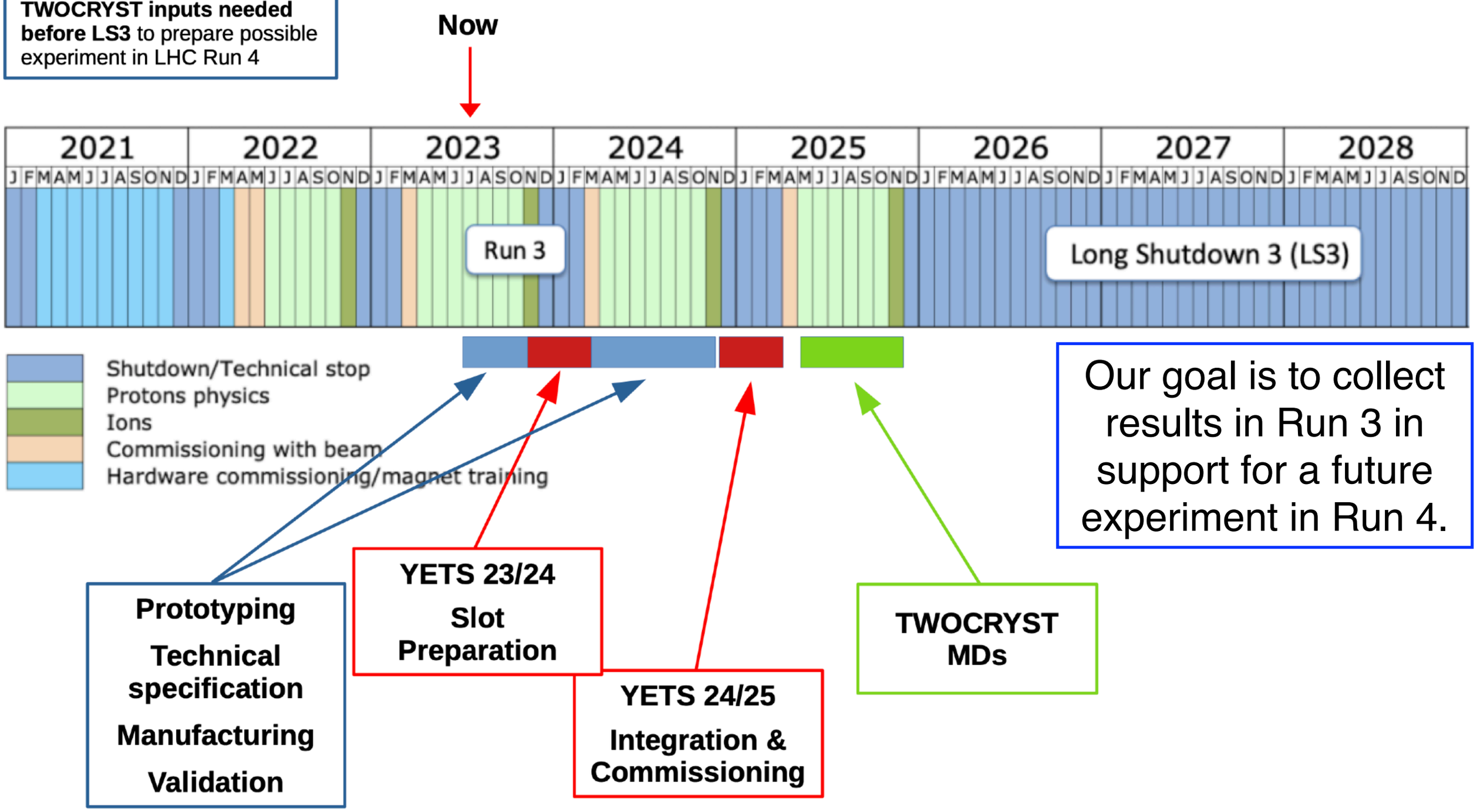
Crystals for splitting and precession delivered to CERN and tested in the SPS-H8 in August. Preliminary results look very good — data being analysed by the TWOCRYST teams.

- Proceeding with the design of the precession crystal goniometer (impedance aspects)
- Discussion ongoing with ATLAS/ALFA and TOTEM to recuperate existing unused Roman pot
- Effort by INFN/IJCLab Orsay/Valencia to procure LHCb-like sensors and DAQ


Preliminary TCCP design, courtesy SY-STI, CERN

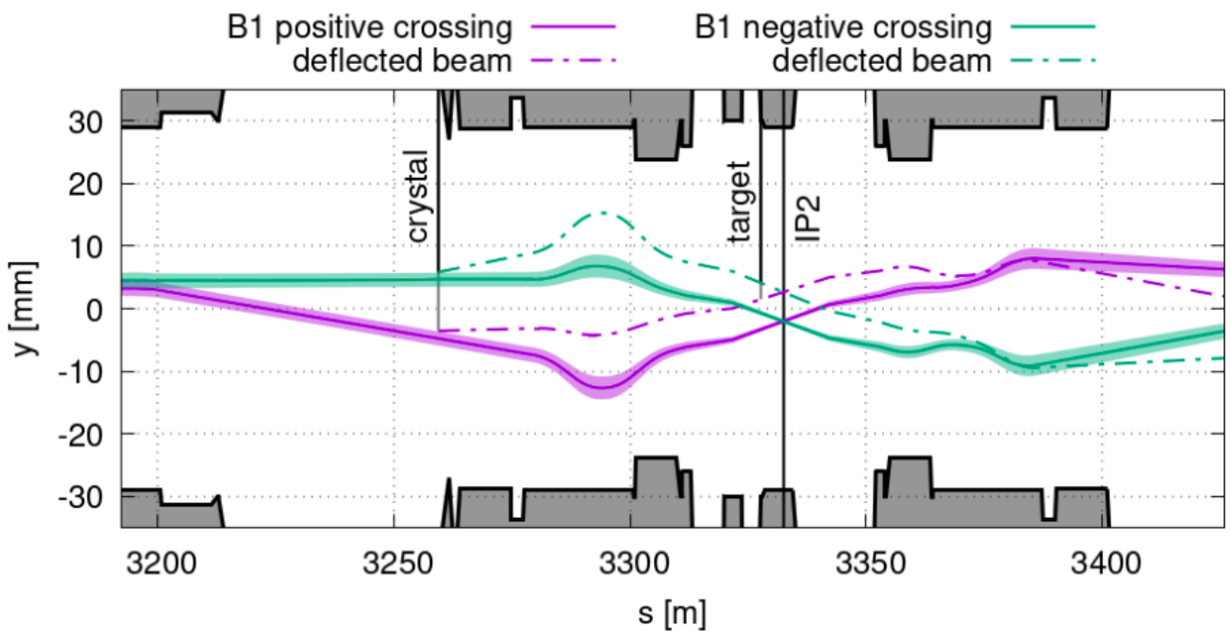
Schedule

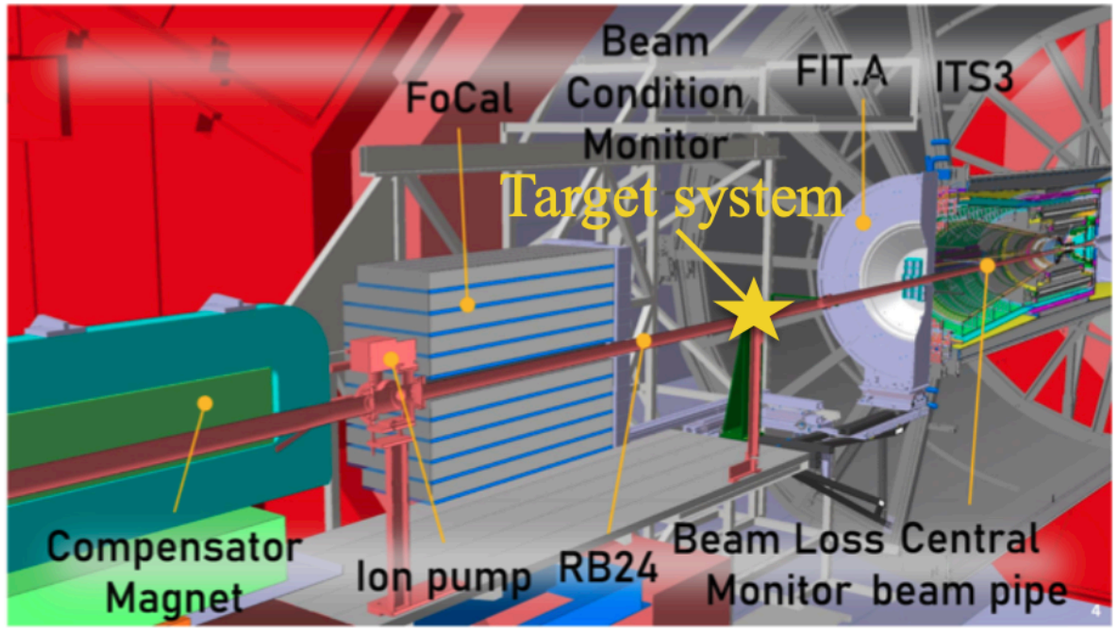
TWOCRYST inputs needed before LS3 to prepare possible experiment in LHC Run 4

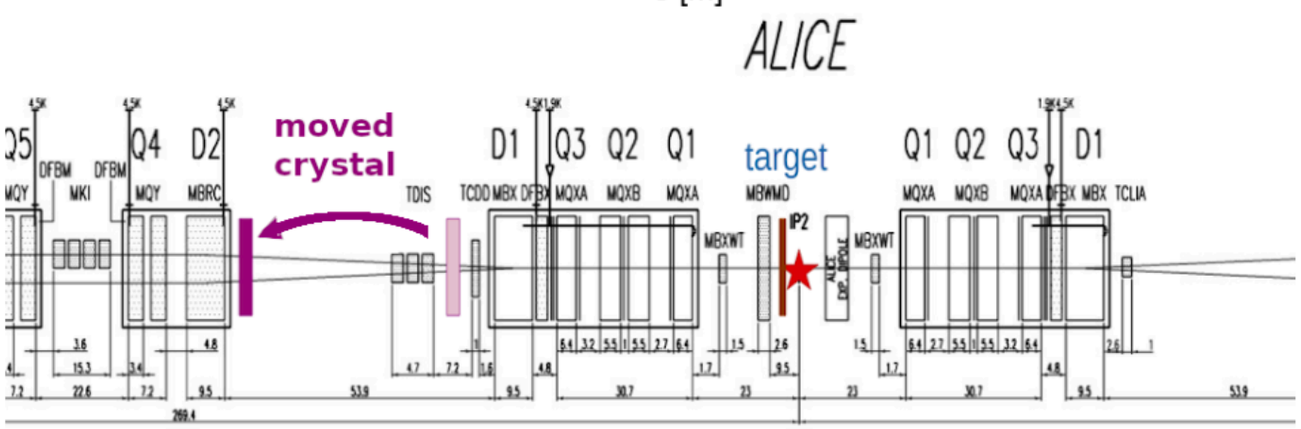


Our goal is to collect results in Run 3 in support for a future experiment in Run 4.

FT studies for ALICE







Potential for extensive data acquisition during proton runs and prospect (to be elaborated) to be used with ions.
Layout studies and optics solutions well advanced.
ALICE decided to discontinue because of conflicts with integration.

Table of contents

- Introduction to the LHC
- The LHC fixed-target (FT) studies
- **Forward Physics Facilities**
- Gamma factory
- Technology
- Conclusions

Forward Physics Facility

Accelerators & Technology Domain

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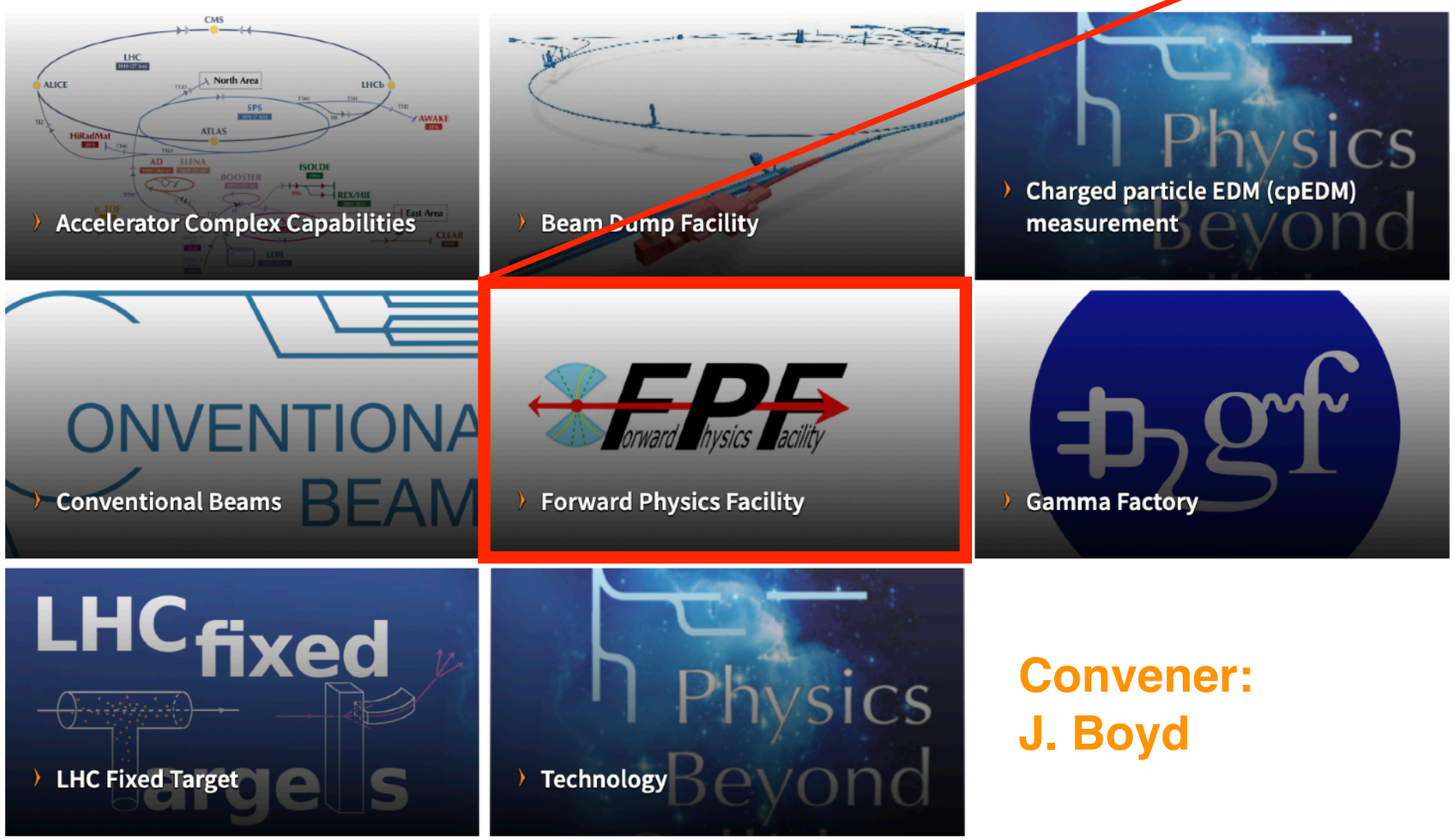
Extensive White Paper submitted to Snowmass (arXiv:2203.05090)

ACCELERATORS & TECHNOLOGY WORKING GROUPS



Convener:
J. Boyd

Dedicated detectors to record various types of long-lived particles (LLPs) produced from LHC collisions and so far unexploited — maximise the LHC physics output!

Forward Physics Facility

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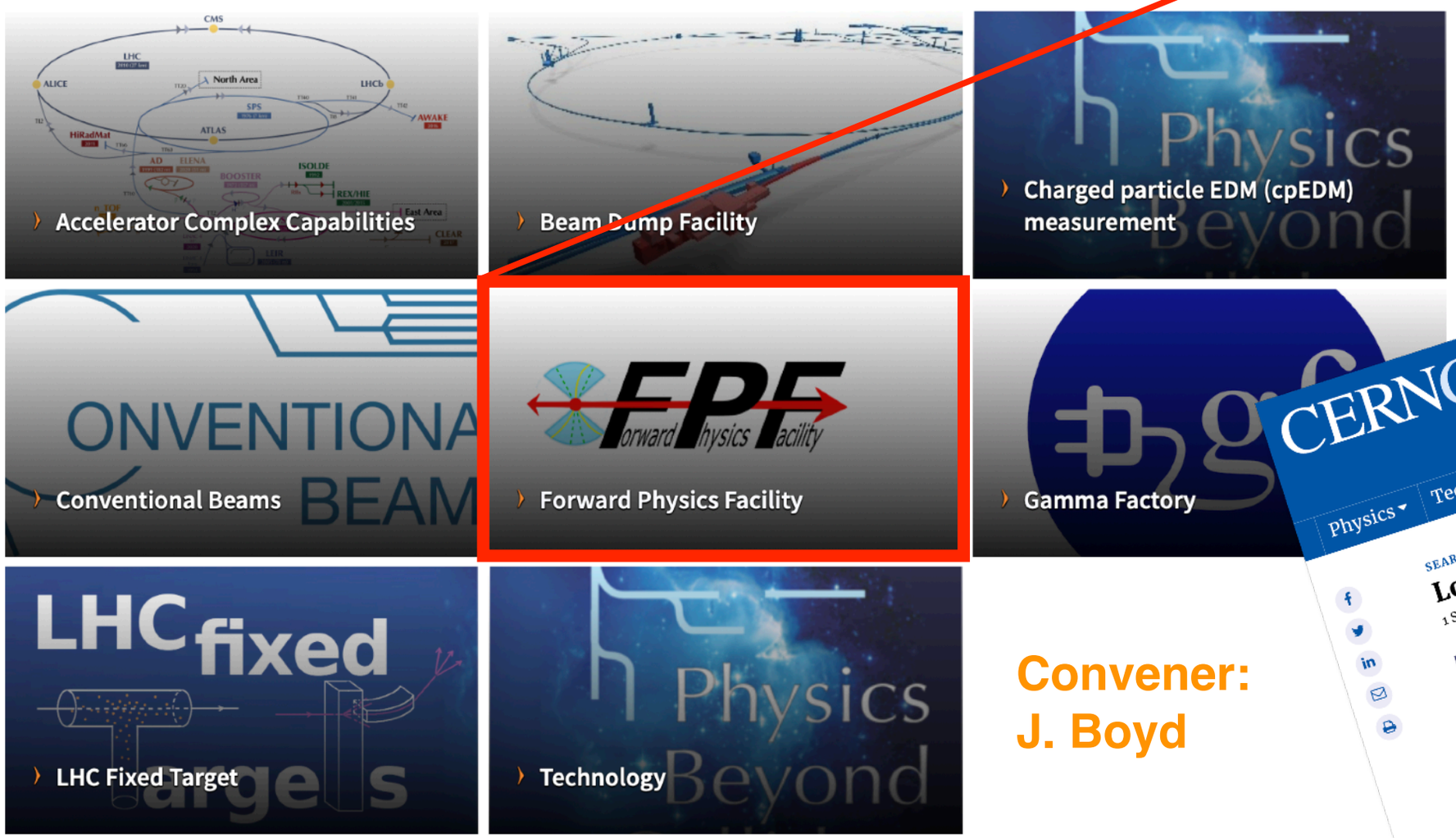

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CERNCOURIER | Reporting on international high-energy physics

Physics | Technology | Community | In focus | Magazine

SEARCHES FOR NEW PHYSICS | MEETING REPORT

Looking forward at the LHC

1 September 2023

The Forward Physics Facility (FPF) is a proposed new facility to operate concurrently with the High-Luminosity LHC, housing several new experiments on the ATLAS collision axis. The FPF offers a broad, far-reaching physics programme ranging from neutrino, QCD and hadron-structure studies to beyond-the-Standard Model (BSM) searches. The project, wh is being studied within the Physics Be Colliders initiative, would exploit th existing HL-LHC beams and thus h minimal energy-consumption requirements.

New territory 3D rendering of the proposed Forward Physics Facility and its experiments. Credit: A Navascues Cornago

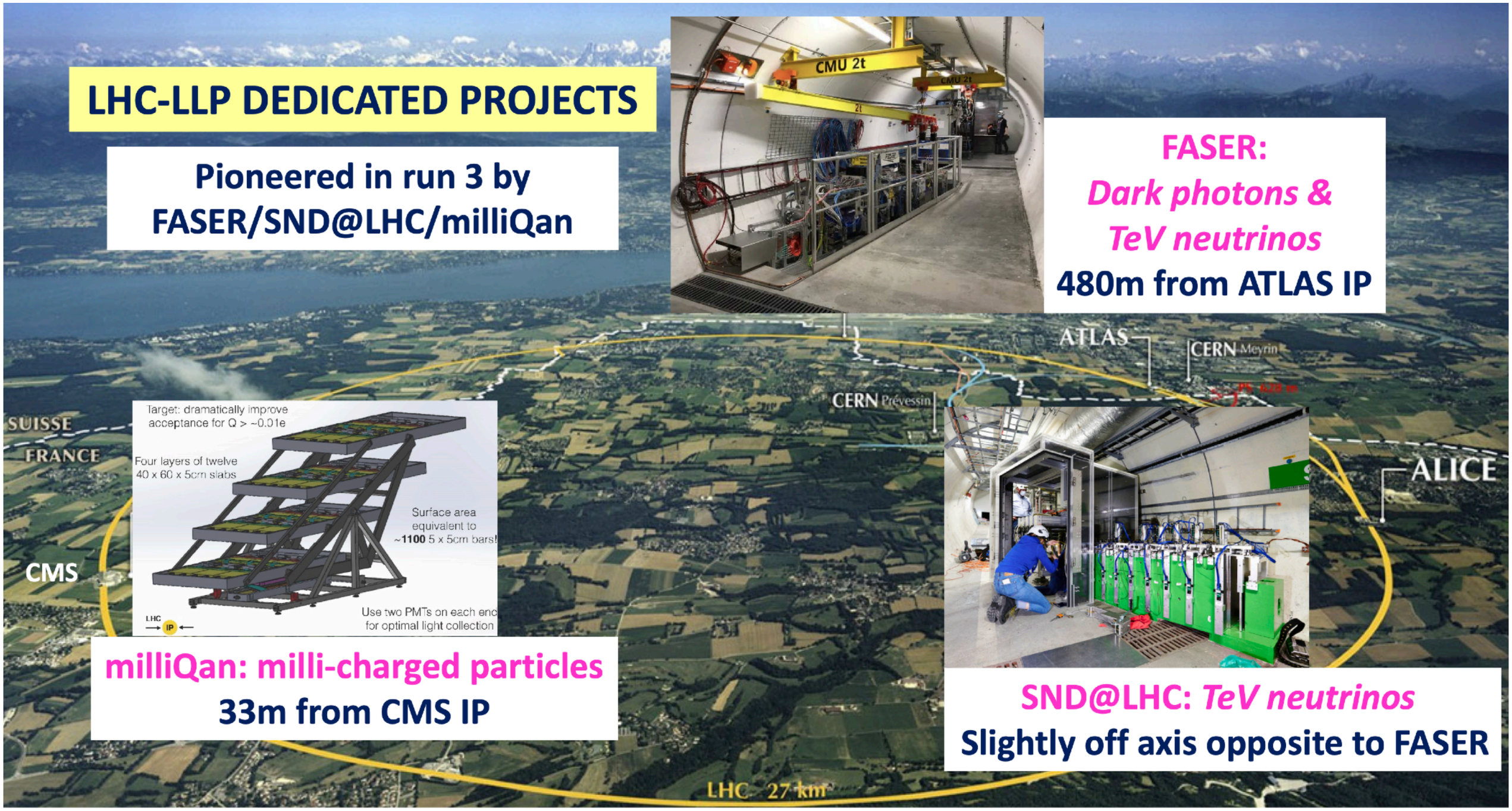
On 8 and 9 June, the 6th workshop on the Forward Physics Facility was he and online. Attracting about 160 participants, the workshop was organis focusing on the facility design, the proposed experiments and physics s time for discussion about the next steps.

https://cerncourier.com/a/look

Convener: J. Boyd

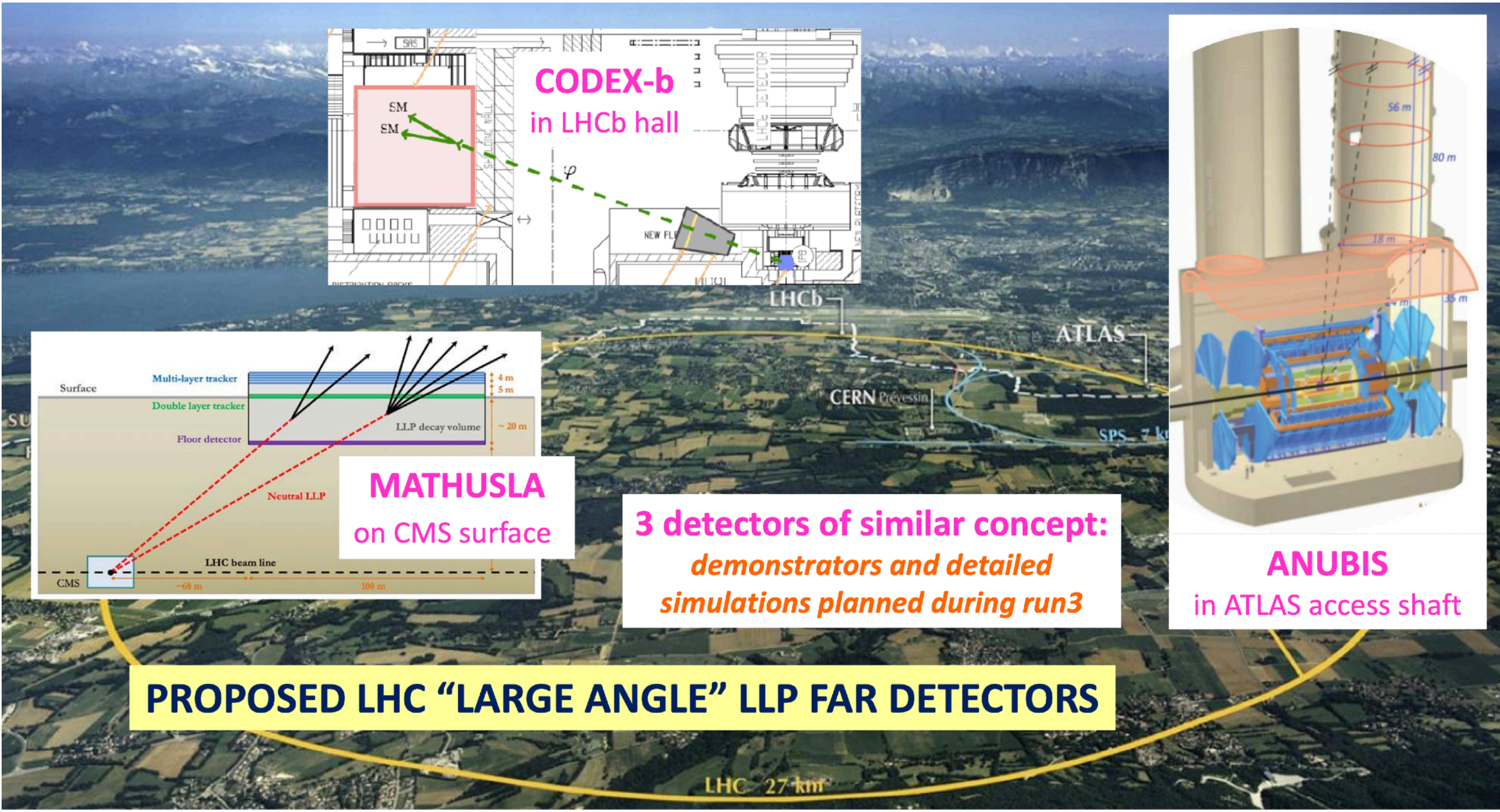
Dedicated detectors to record various types of long-l particles (LLPs) produced from LHC collisions and so unexploited — maximise the LHC physics output!

Recap. from Claude's lecture — 1



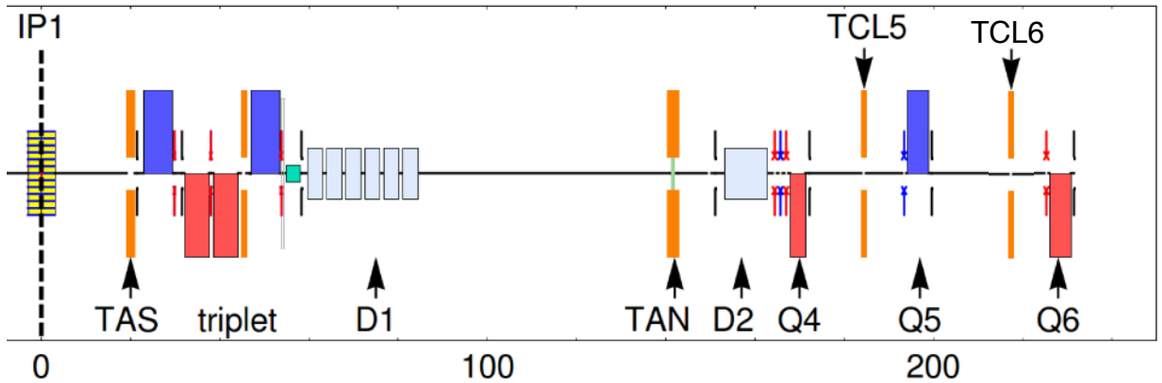
These are cost-effective implementations based on existing tunnels and infrastructures.

Recap. from Claude's lecture — 2

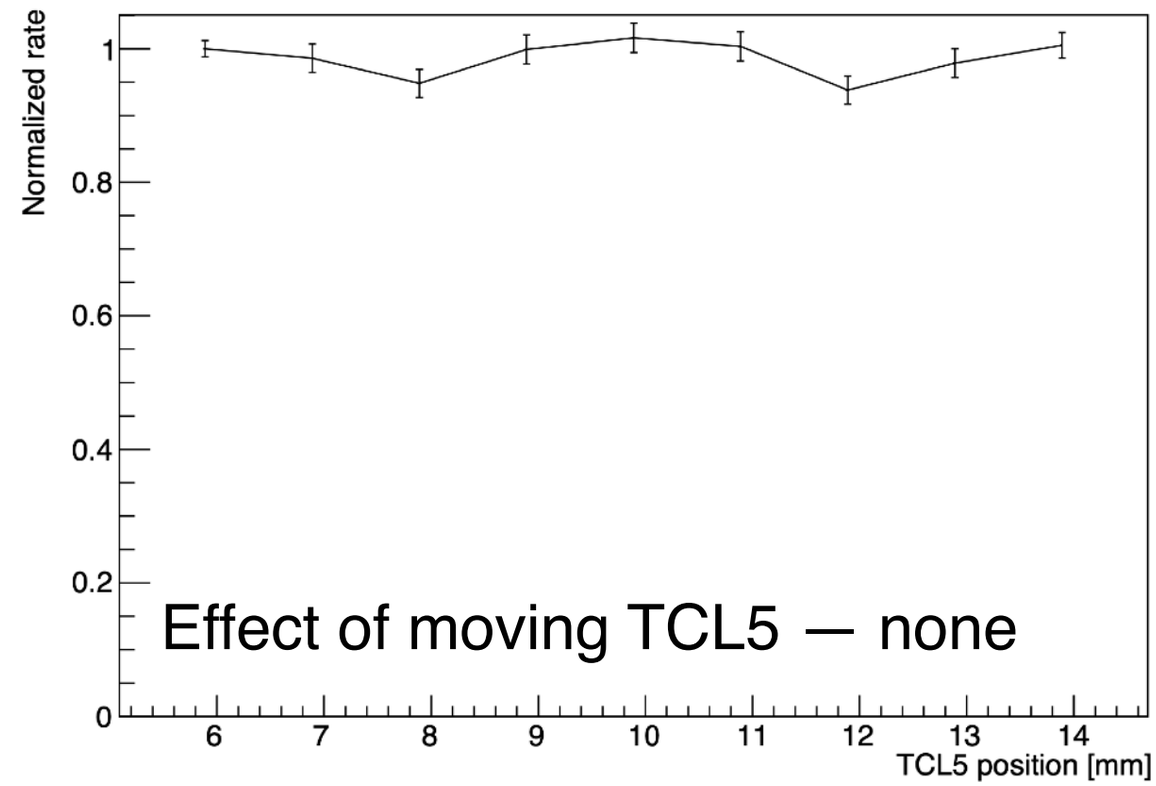


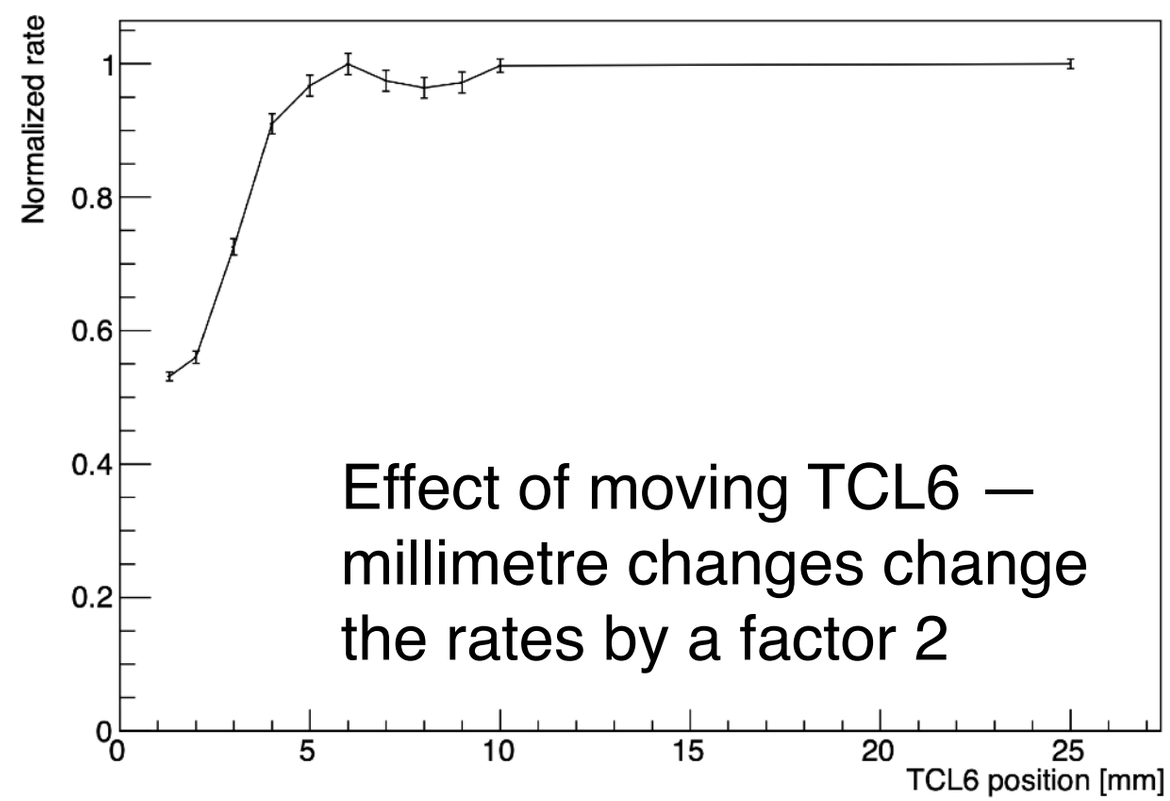
Idea is to run parasitically to the LHC operation… *correct?*

TCL collimator impact on FASER



TCL (physics-debris collimators): protect the machine from the pp collision products.





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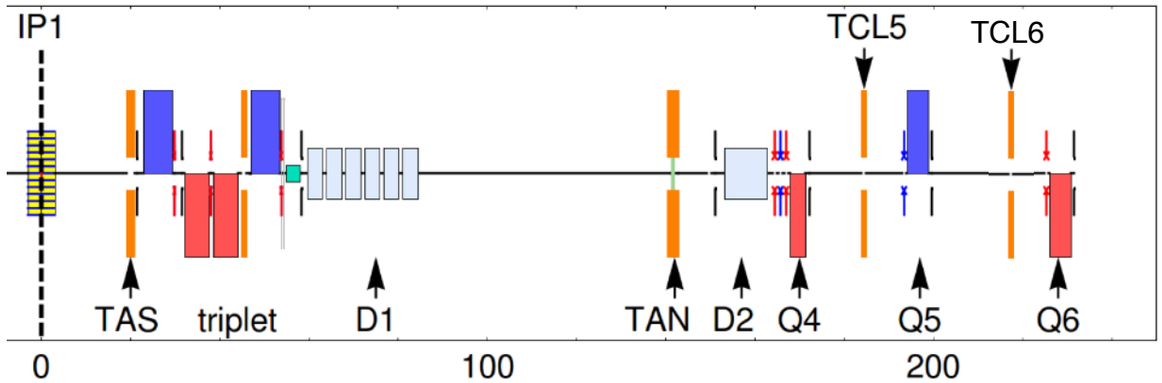

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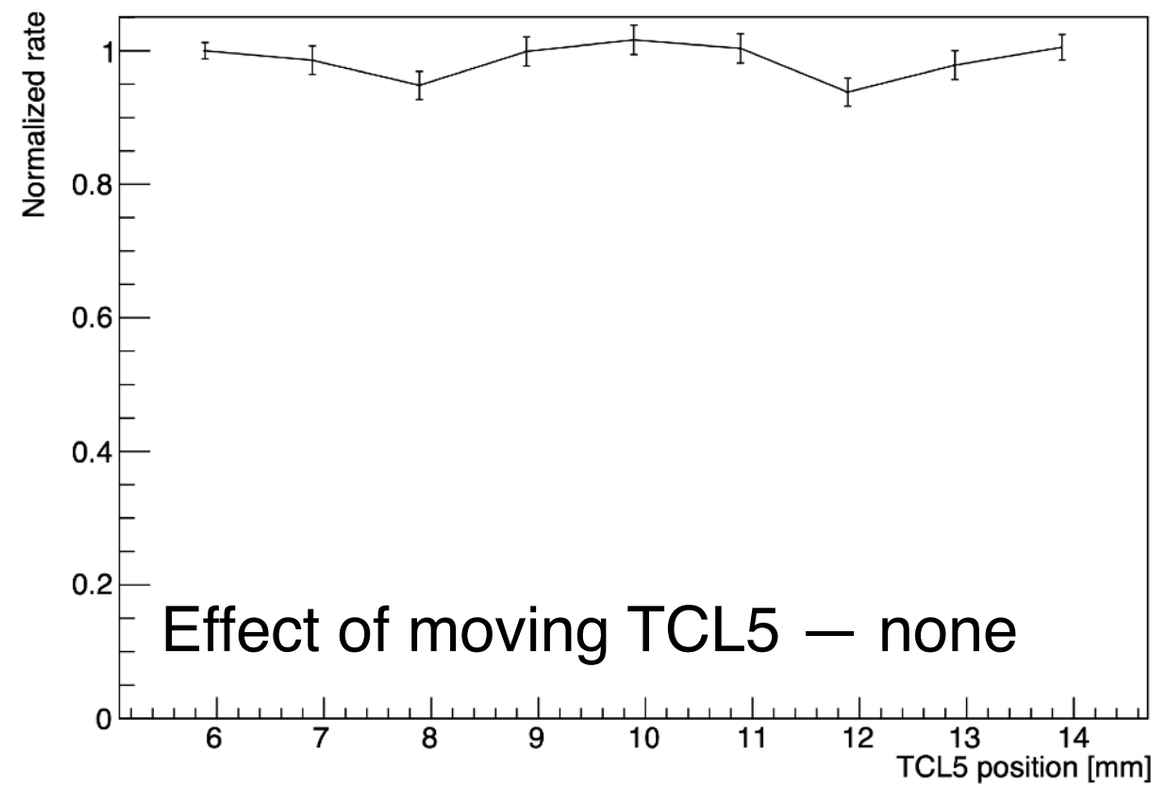
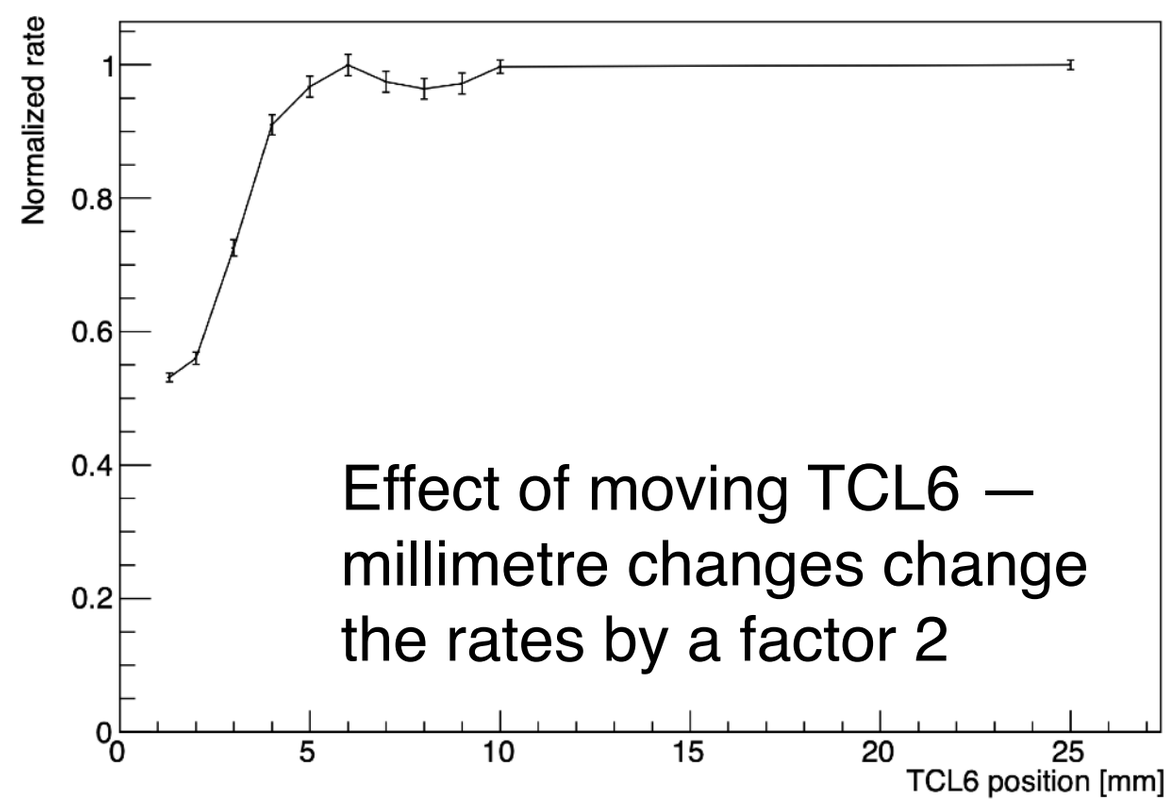




A solution was quickly be found thanks to a very good iterations between the FASER and machine teams! Shows that synergy and common studies are important for future implementations.

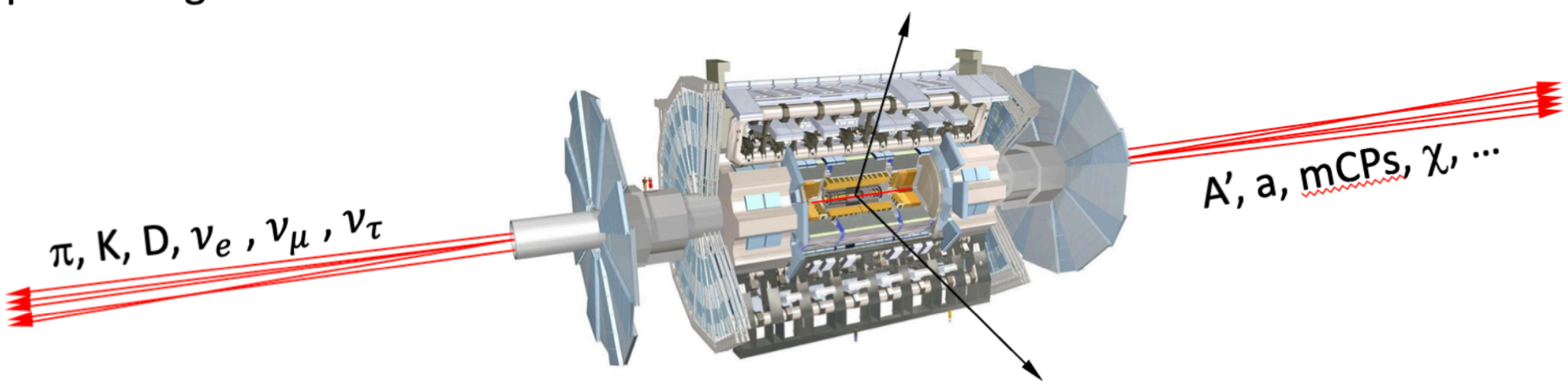
Various points to be taken into account for present and future implementations:

- *Variation of IP optics and crossing angles,*
- *Access requests for replacing emulsions,*
- *General running conditions,*
- *…*

FPF for far forward detectors at HL-LHC

FPF : Forward Physics Facility

- Collisions at the LHC produce an enormous number of particles along the beam collision axis line of sight (LOS), which escape existing LHC detectors



- These include **very high energy neutrinos**, and possible **light new particles linked to dark matter**
- The Forward Physics Facility is a proposal to build a new underground cavern to host a suite of far-forward experiments to capture this physics
- During the HL-LHC era, FPF experiments will :
  - Collect 10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ interactions at TeV energies
  - Be sensitive to LLPs produced in $\mathcal{O}(10^{17})$ π^0/η, $\mathcal{O}(10^{15})$ D–mesons, $\mathcal{O}(10^{13})$ B–mesons
    - Huge statistics to search for new particles that could be produced very rarely in the decay of these particles

Courtesy J. Boyd

FPF status

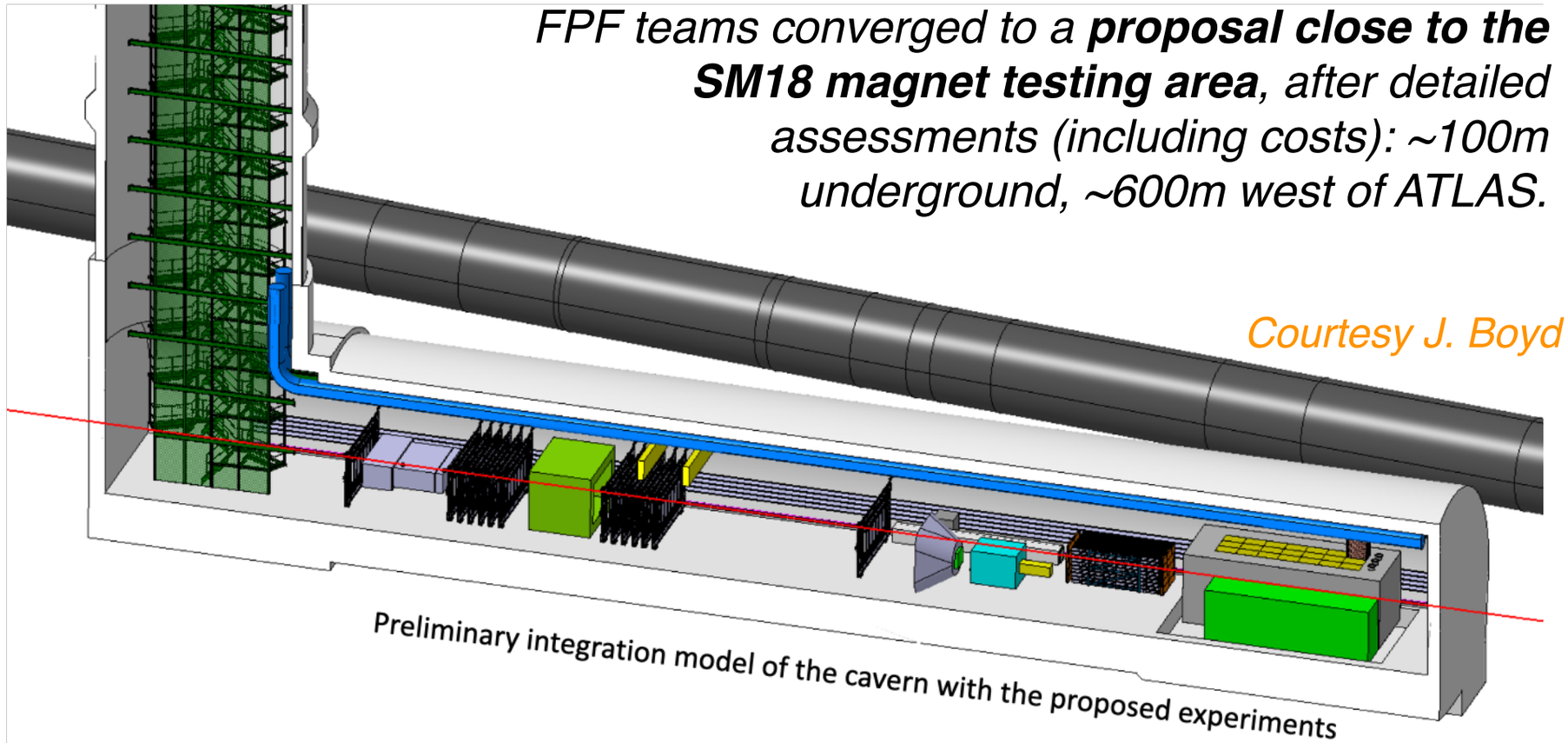
FPF Facility:

65m long, 9.7m wide, 7.7m high cavern.
Connected to surface through 88m high shaft (9.1m diameter): 617m from IP1.

Civil engineering studies benefit from recent work in point-1 for HL-LHC infrastructure (new shaft and galleries).

*FPF teams converged to a **proposal close to the SM18 magnet testing area**, after detailed assessments (including costs): ~100m underground, ~600m west of ATLAS.*

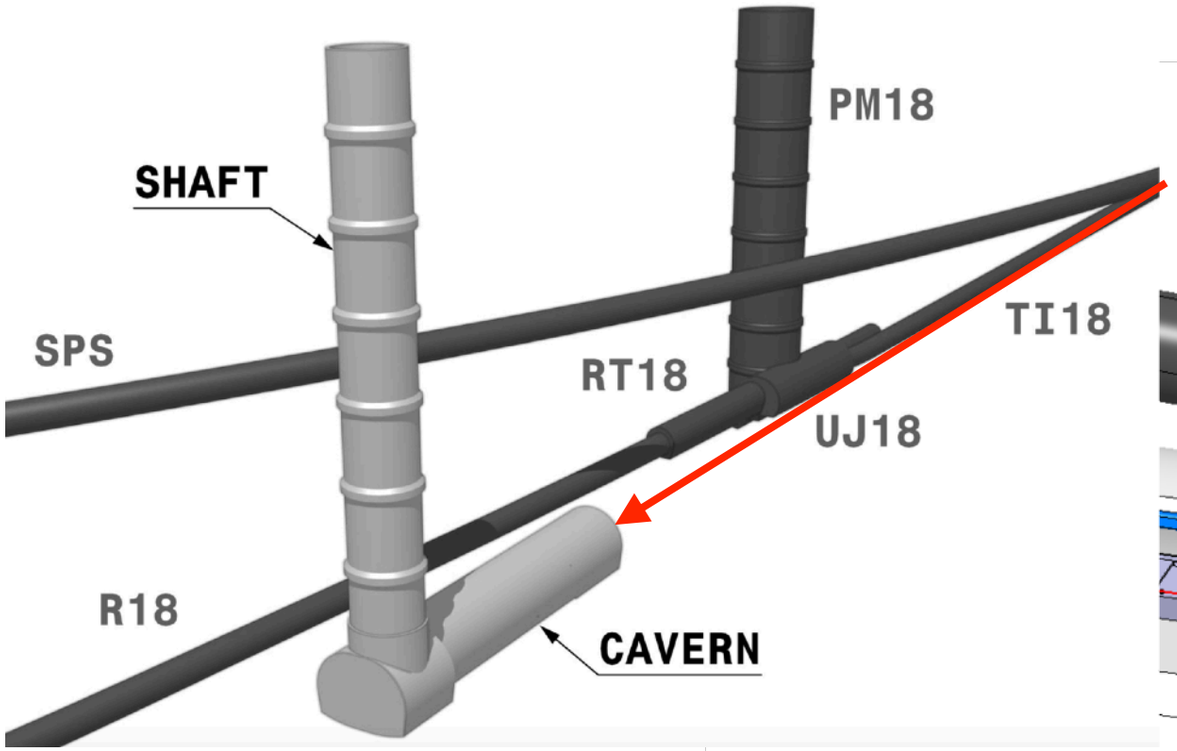
Courtesy J. Boyd



The PBC supports FPF through several technical studies

- *Site investigation for civil engineering works (1 slide below): assess local geological conditions*
  - → *A 100m deep, 20cm diameter, core drilled at the FPF shaft location*
- *A very preliminary costing of the facility was done for civil engineering works and services*
- *Simulations of muon background: flux of 0.6Hz/cm^2 is ok for proposed experiments*
  - → *Considering the possibility to install a "sweeper magnet" to deflect muons*
- *Simulation shows radiation level OK for people to be the in cavern during HL-LHC operation*
- *Studied the effect of vibrations during excavation works on the HL-LHC operation (1 slide)*
  - → *Important for scheduling reasons that works can be done during the HL-LHC operation!*

FPF status



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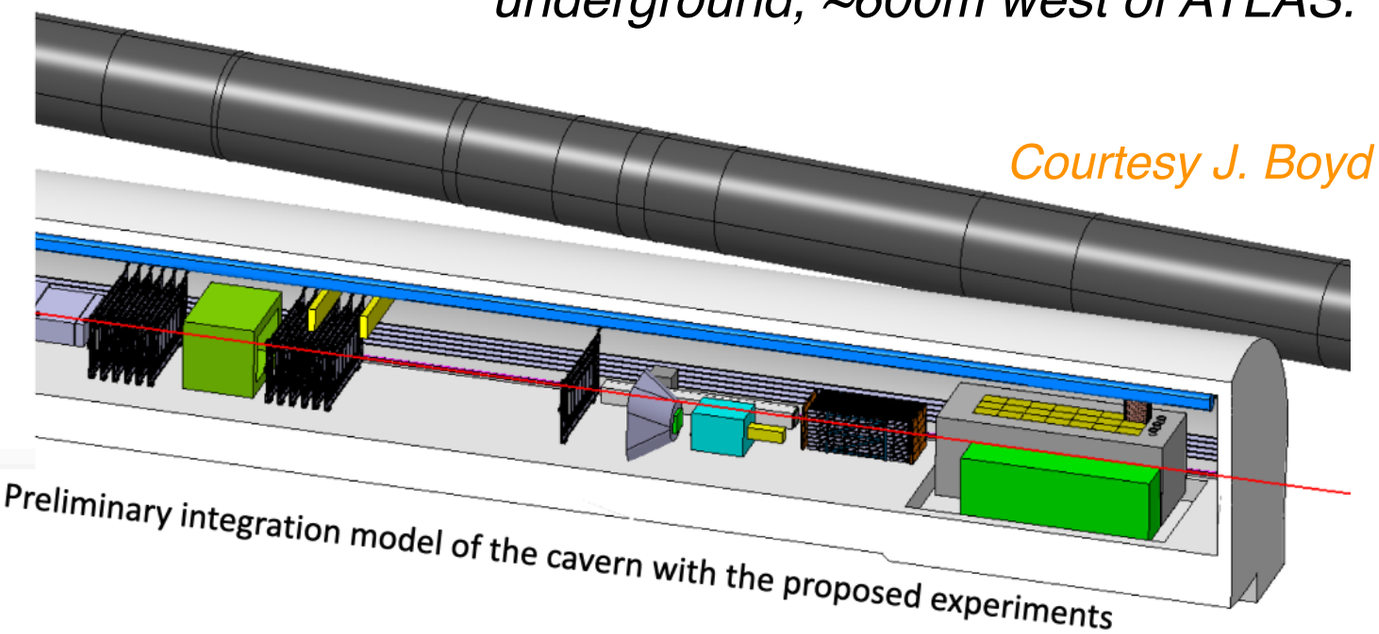

Preliminary integration model of the cavern with the proposed experiments

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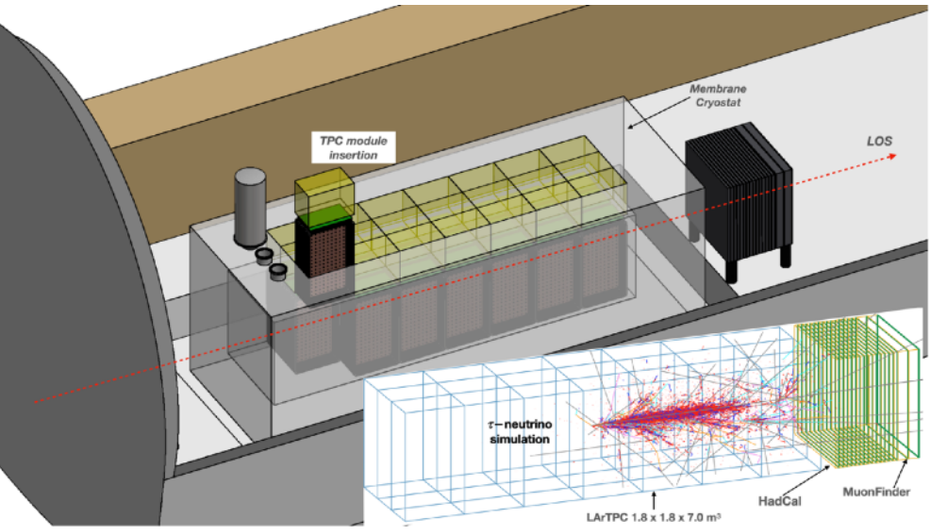
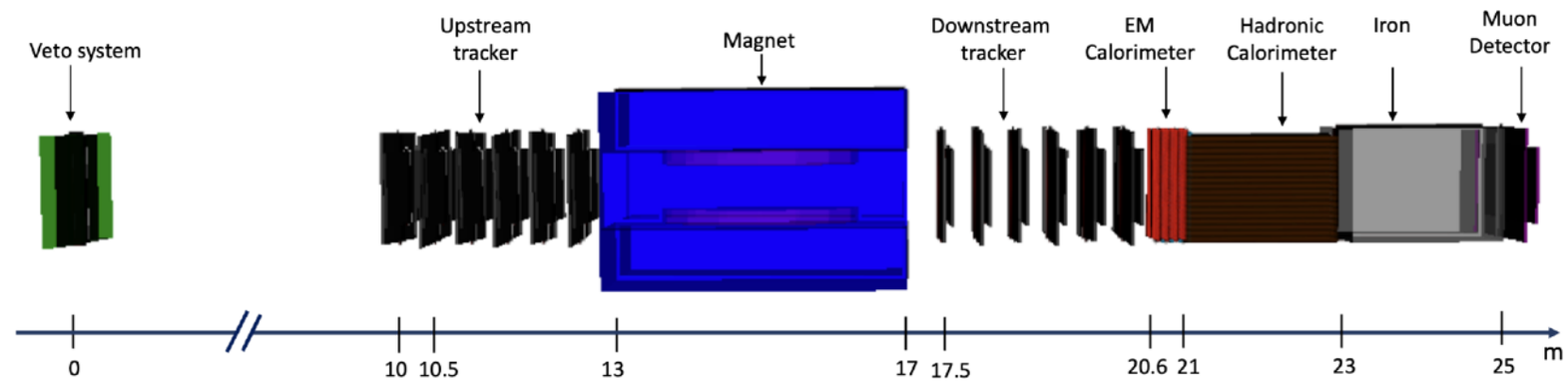
Considered experiments

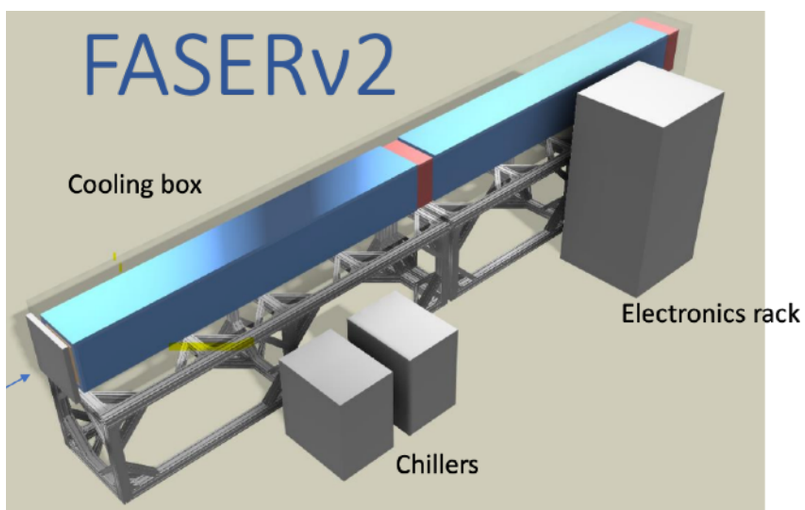
FLArE



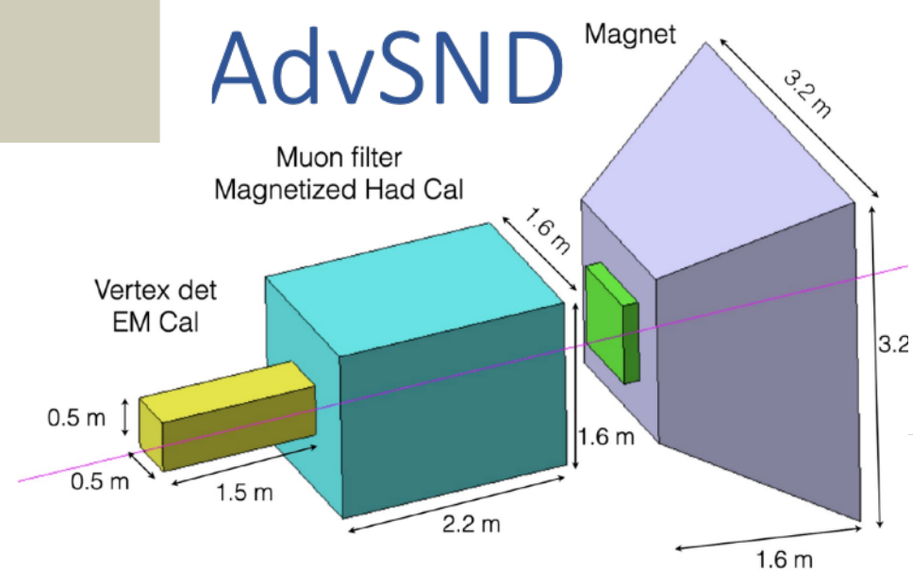
FASER2



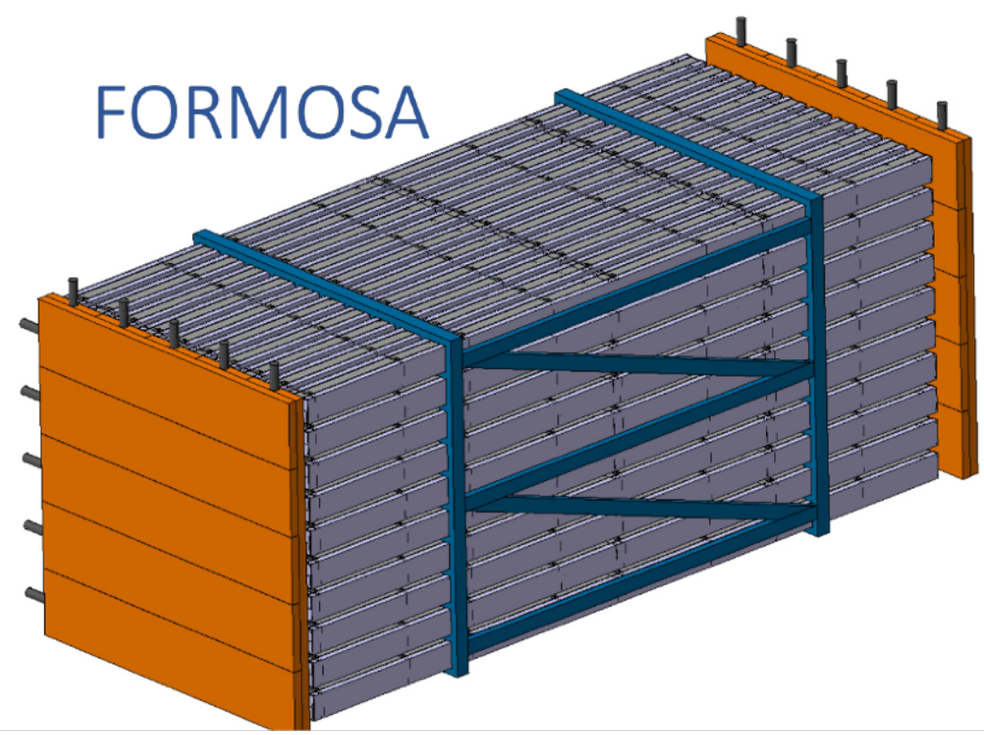
FASERv2



AdvSND



FORMOSA



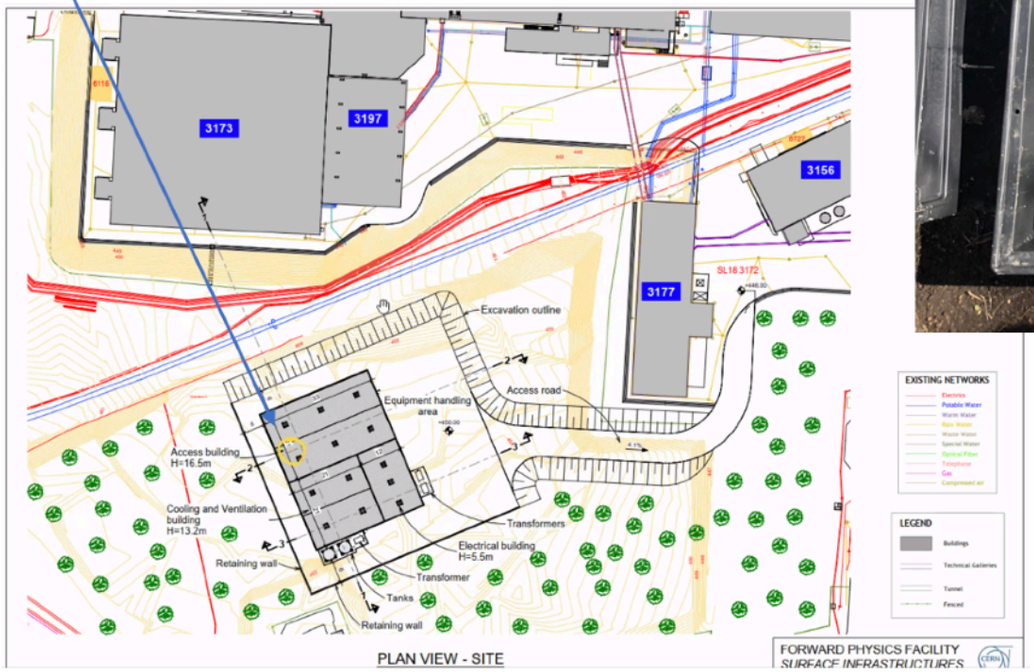
FPF site investigations

Photo credit Kincso

- Works carried out in March/April 2023
- Drilled a 20cm diameter core at location of proposed FPF shaft
  - To depth of 100m
- No problems observed with LHC/SPS


Photo credit Kincso

Drilling location



First results include the production of detailed geological study that shows for the moment no showstopper for the excavation.

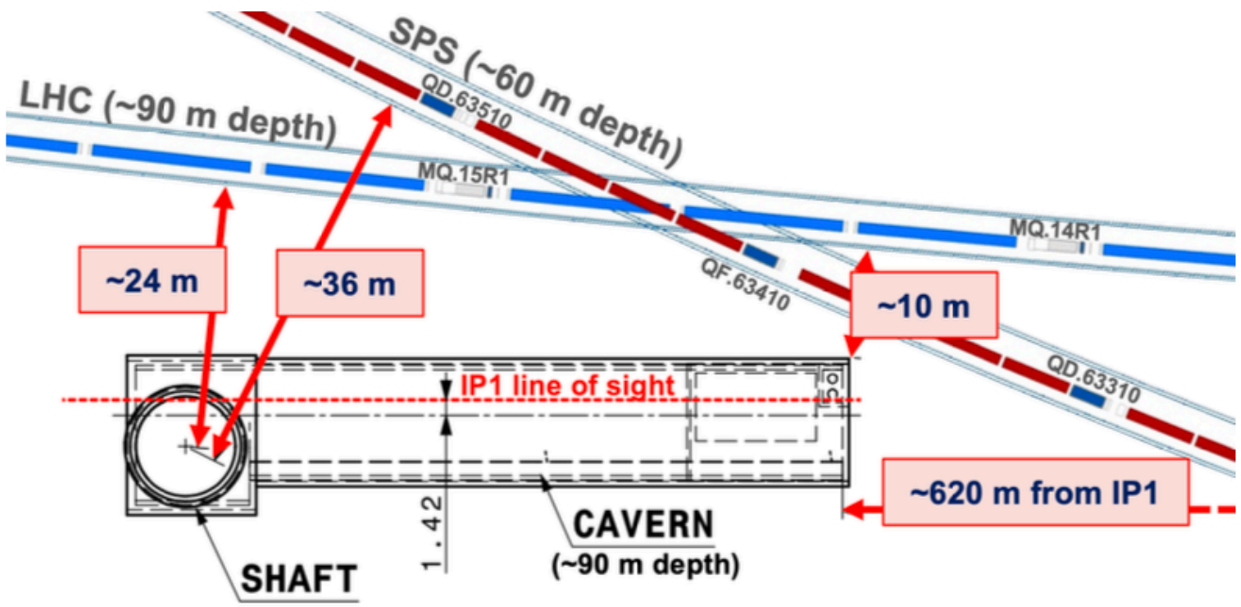
Courtesy J. Boyd

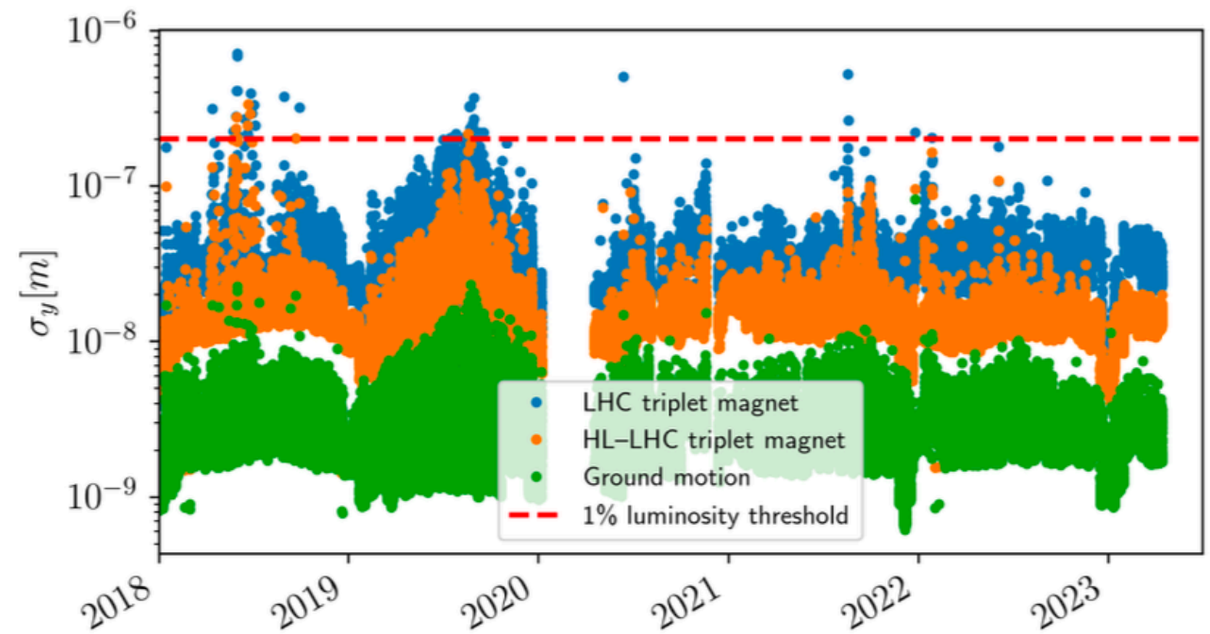
Vibration studies

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA039

IMPACT OF VIBRATION TO HL-LHC PERFORMANCE DURING THE FPF FACILITY CONSTRUCTION*

D. Gamba†, H. Bartosik, M. Guinchard, K. Pál, J. Wenninger, K. Widuch
CERN, Geneva, Switzerland





No issue seen during site investigation works.

Possible effect of long term slow movement of the tunnel still be evaluated.

CONCLUSION

The optics sensitivity of HL–LHC in the area of the FPF facility excavation works is about a factor of 10 smaller than in the triplet area, and a factor of 3 more than in the SPS optics. Vibration levels and associated impact on orbit stability and luminosity production are expected to be comparable to what was observed during HL–LHC civil engineering works during the LHC 2018 run. In case of excessive vibration levels, road headers might be employed instead of rock breakers. No major tunnel deformations are expected. If any, they could be compensated during the run with orbit correctors (at least for the HL–LHC) followed by re-alignment of the concerned area during a winter shutdown. The general conclusion is that no major disruption of HL–LHC and SPS performance is expected during the FPF excavation works.

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The PBC γ factory study

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Conveners: Y. Dutheil, W. Krasny, A. Martens (IJCLab Orsay)

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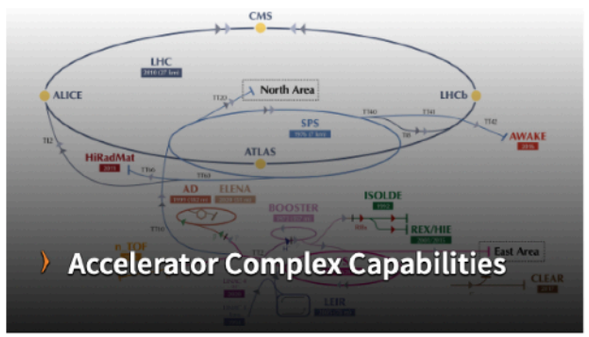

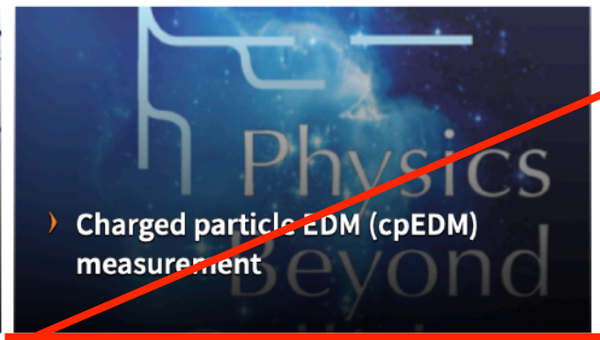

September 25, 2019

Gamma Factory

Proof-of-Principle Experiment

LETTER OF INTENT

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Gamma Factory Study Group

Contact persons:

M. W. Krasny, krasny@lpnhe.in2p3.fr, krasny@mail.cern.ch – **Gamma Factory team leader**

A. Martens, martens@lal.in2p3.fr – **Gamma Factory PoP experiment spokesperson**

Y. Dutheil, yann.dutheil@cern.ch – **Gamma Factory PoP study – CERN coordinator**

CERN-SPSC-2019-031 / SPSC-I-253
25/09/2019

Recent workshop: https://indico.cern.ch/event/1205247

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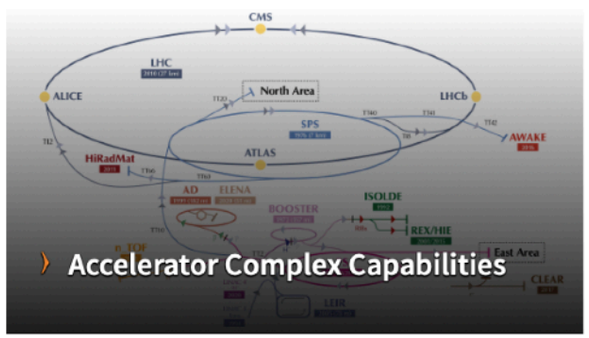

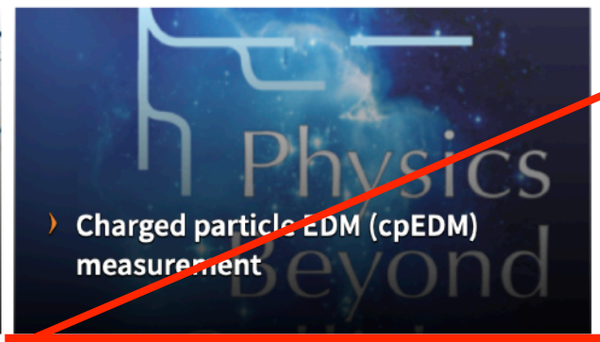

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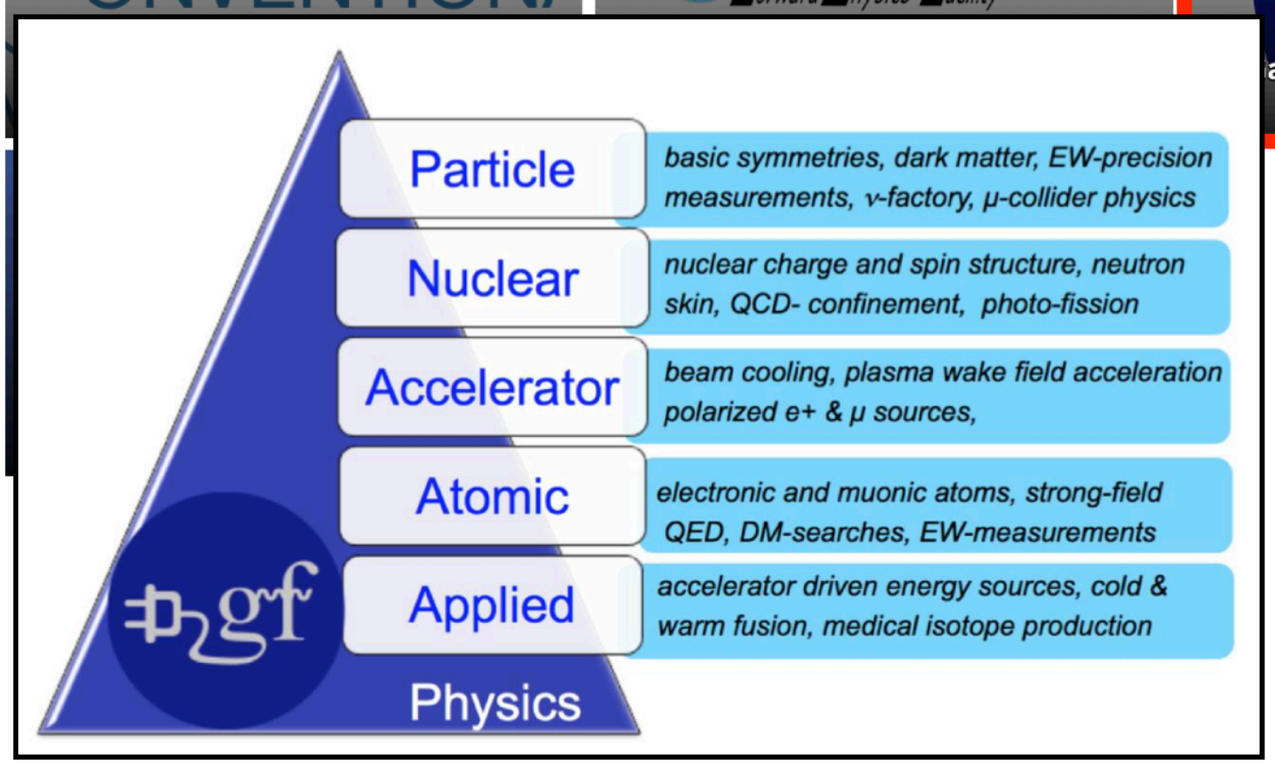
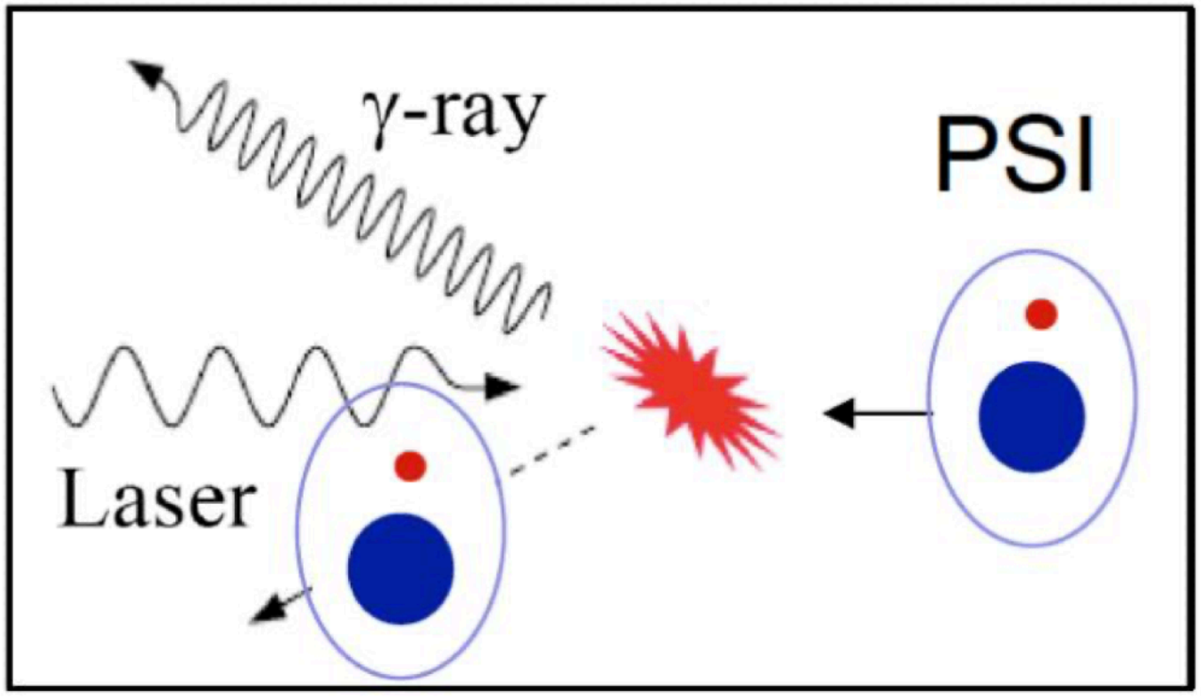


Only focus on some key accelerator aspects for the SPS and the LHC….

Gamma factory in a nutshell



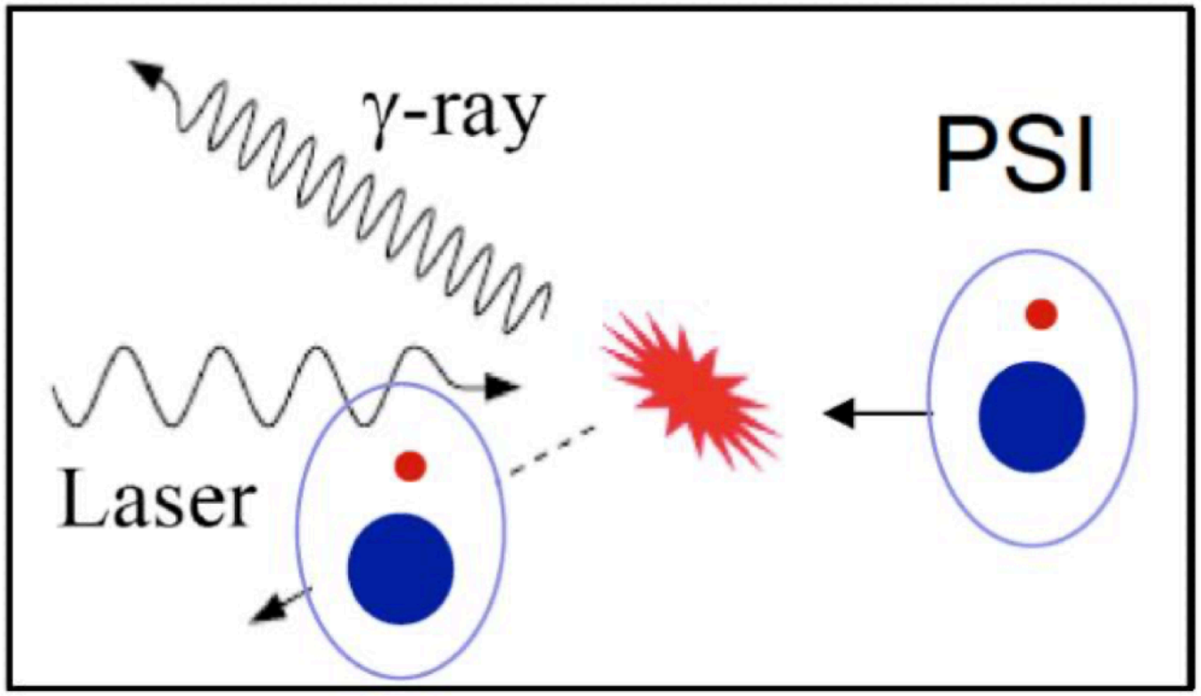
PSI = partially-stripped ion

Principle: matching the laser wave length to the target dimension, excites the electron that than emits a photon.

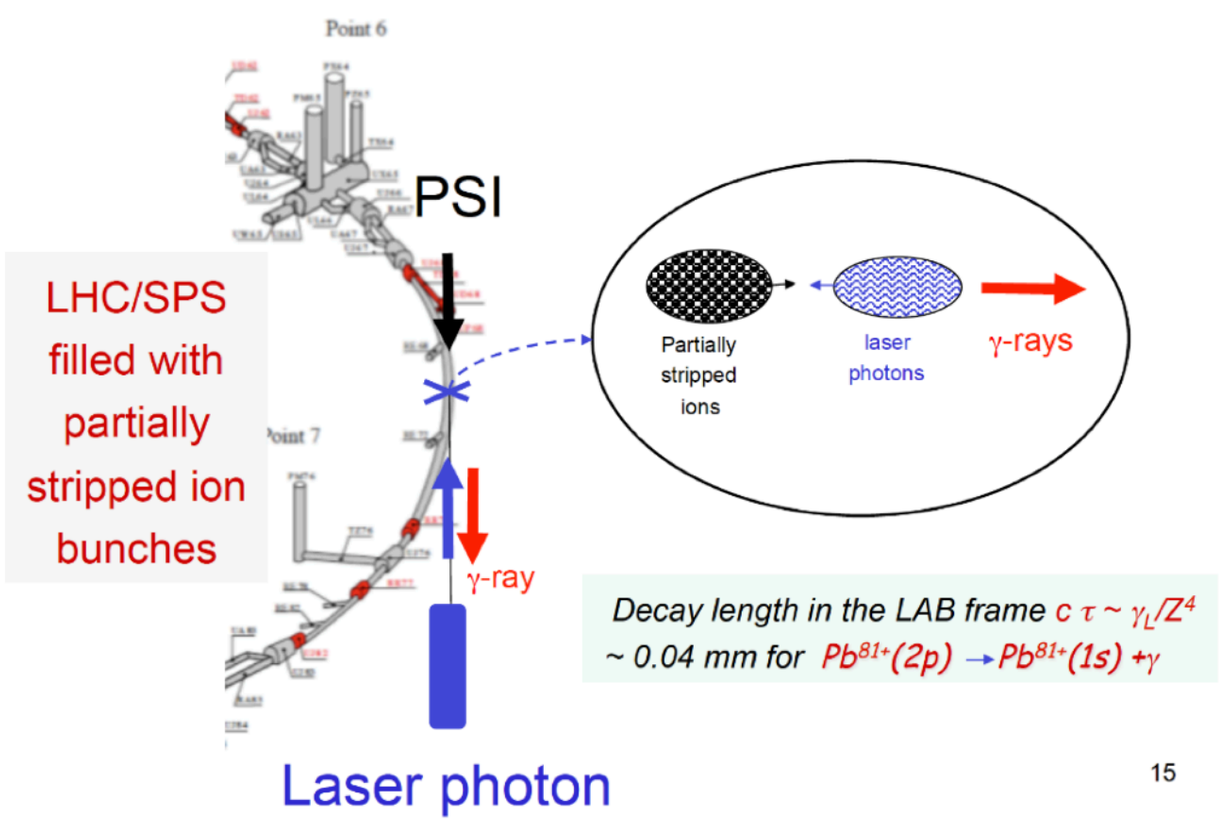
*Large range of gamma ray parameters can be tuned by choosing the PSI energy (**SPS** or **LHC**), the atom species and the number of un-stripped electrons.*

Promise: generation of high-intensity photon beams for different applications like atomic or nuclear physics, generation of positrons or muons with gammas, photo fission, …
Imminent goal: cooling of ion beams of LHC ion collisions

Gamma factory in a nutshell



The γ-ray source scheme for CERN



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W. Krasny, PBC kick-off workshop

CERN as a unique place in the world to host a project, which is capable to increase the intensity of the present γ-ray sources of up to 7 orders of magnitude in the 3 orders of magnitude wide range of the γ-ray energies. New research opportunities in many domains of particle, nuclear and atomic physics could be opened at CERN.

PBC effort on gamma factories

Gamma factory can potentially become a **novel research tool** that opens up a wide range of experiments and measurements.
Part of the PBC effort since the kickoff in 2016.

Key involvements:

- PSI test across the accelerator chain up to LHC (2018)!
- Working on a **proof-of-principle at the SPS** with $^{208}Pb^{79+}$
  - → Integration of a Fabry Perot Cavity + remote operation of the driving laser in a high intensity hadron machine is a **primer**!
  - → Plan to demonstrate the **photon emission** with PSIs
  - → Observe **beam cooling in the SPS**

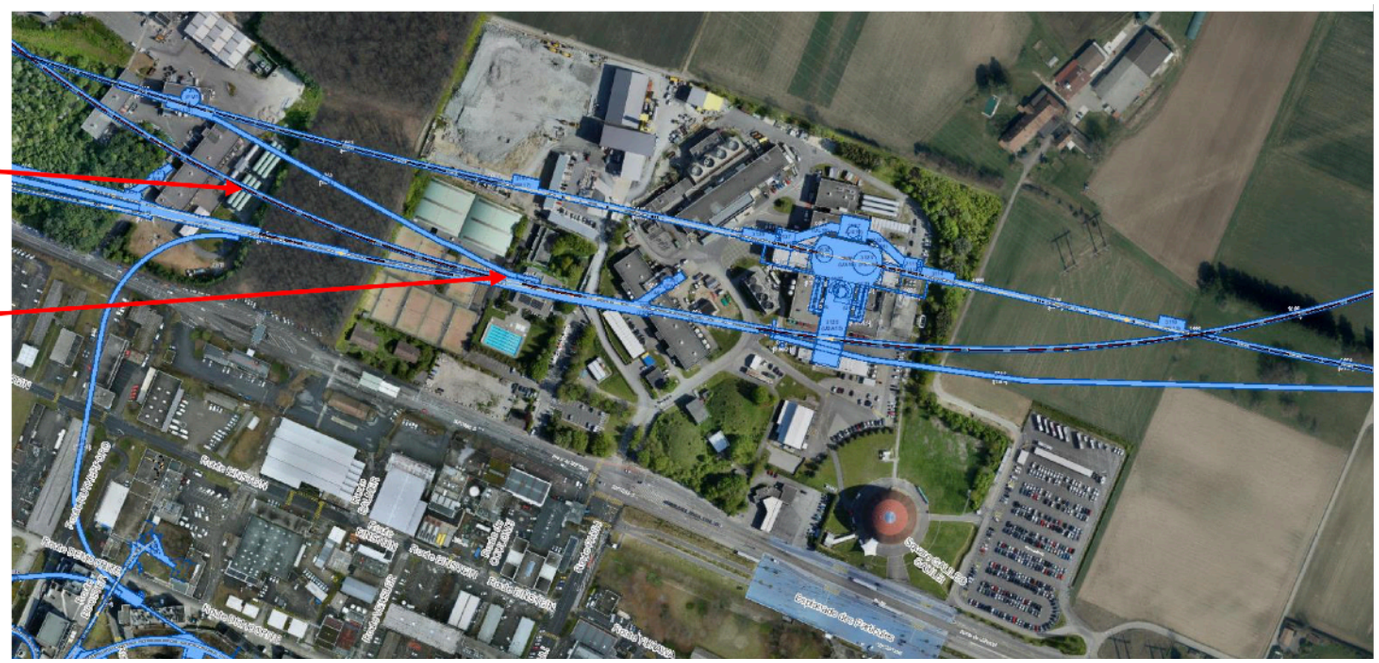
If cooling demonstrated, could be used for the LHC operation as an ion collider to deliver smaller emittance ion beams!

SPS scope

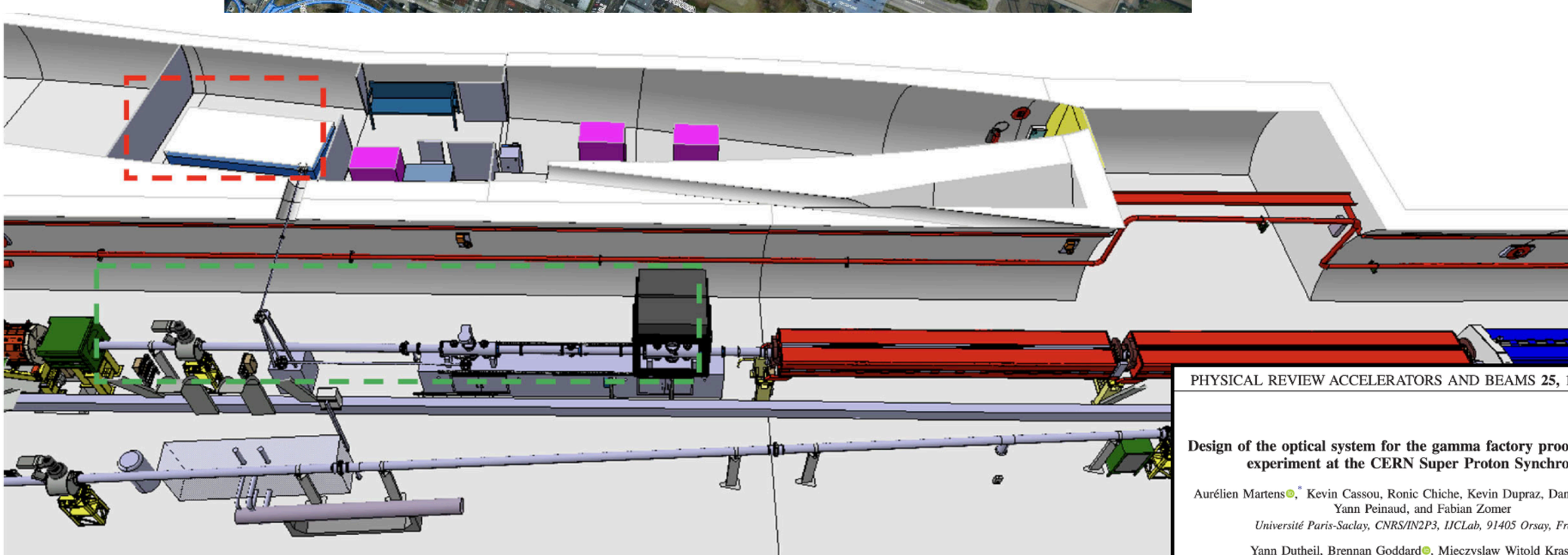
Main goals are to (1) observe X-ray photons and
(2) observe fast **cooling** of PSI beams.

SPS

PoP location



See presentation by Y. Dutheil at the last PBC meeting (Nov. 2022).



PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 101601 (2022)

Design of the optical system for the gamma factory proof of principle experiment at the CERN Super Proton Synchrotron

Aurélien Martens,* Kevin Cassou, Ronic Chiche, Kevin Dupraz, Daniele Nutarelli, Yann Peinaud, and Fabian Zomer
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

Yann Dutheil, Brennan Goddard, Mieczyslaw Witold Krasny, Thibaut Lefevre, and Francesco Maria Velotti
CERN, CH-1211, Geneva, Switzerland

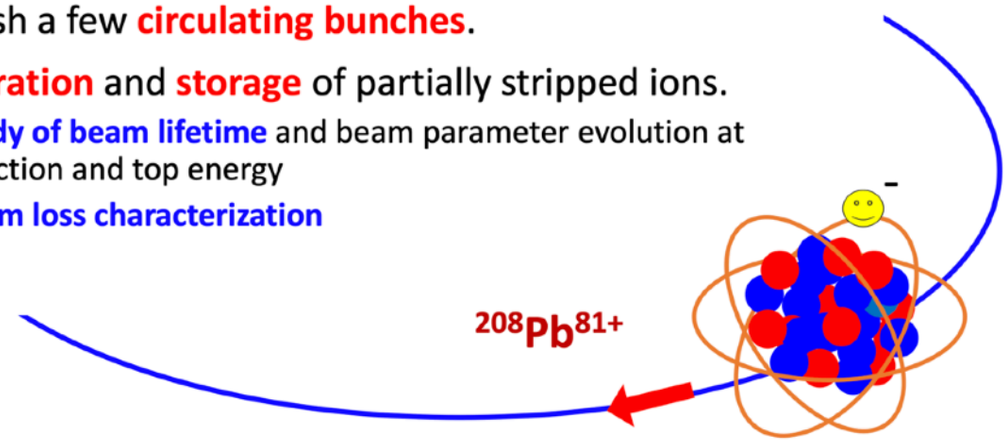
(Received 22 April 2022; accepted 26 September 2022; published 7 October 2022)

PSI beam in the LHC: “LHC atoms”

Goals of initial test in the LHC

12 hours LHC Machine Development (MD) time on 25.07.2018

- **Inject** new particle “species” in the LHC
  - Well-known Pb-208, but with one remaining electron
- Establish a few **circulating bunches**.
- **Acceleration** and **storage** of partially stripped ions.
  - ➢ **Study of beam lifetime** and beam parameter evolution at injection and top energy
  - ➢ **Beam loss characterization**



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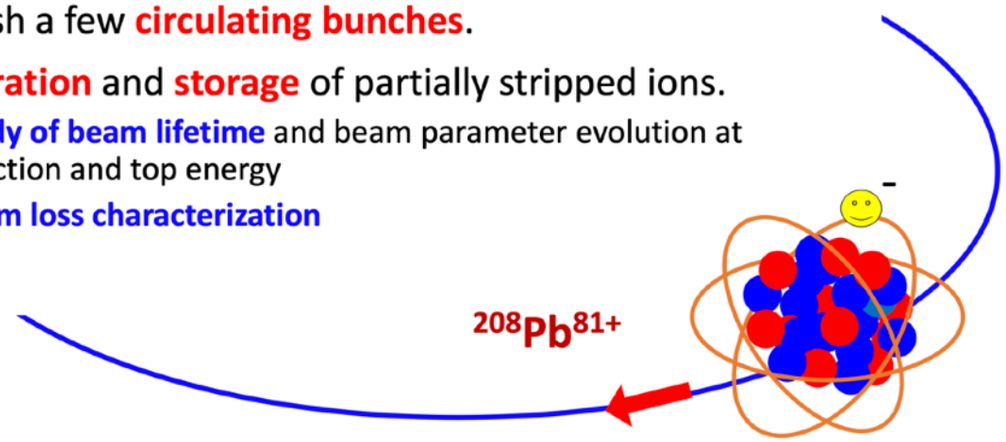
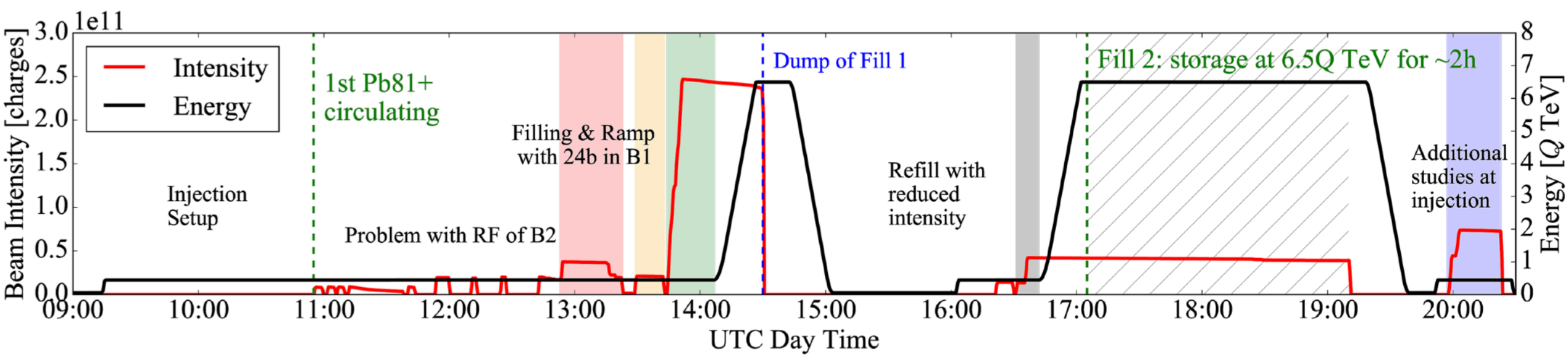


M. Schaumann et al., doi:10.18429/JACoW-IPAC2019-MOPRB055



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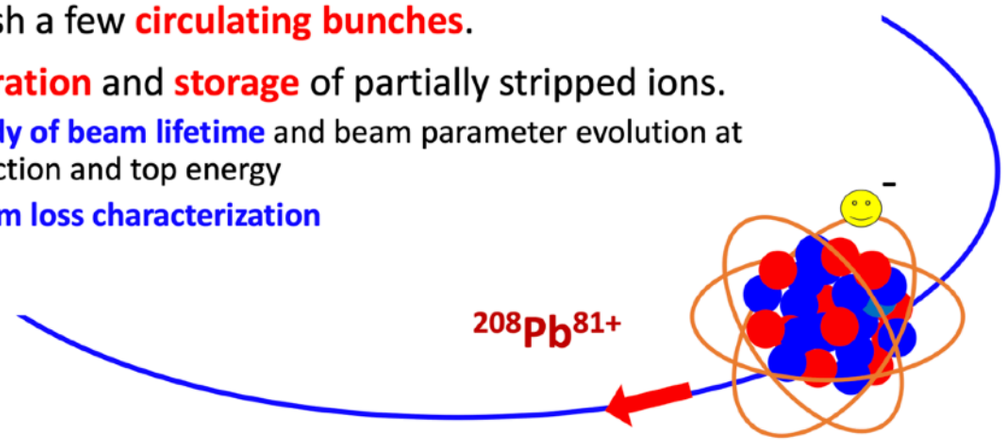

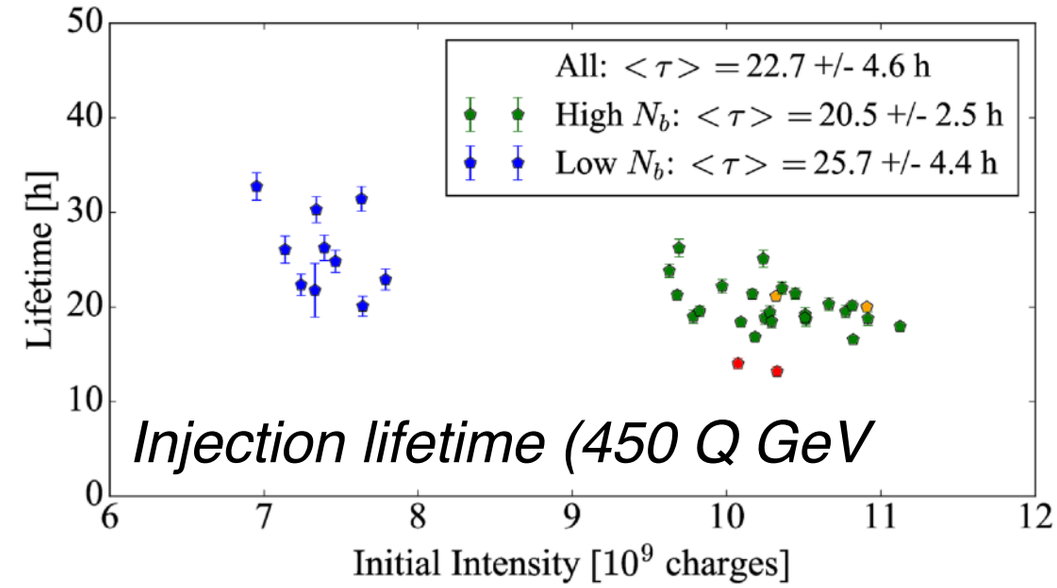

Figure 3: Fitted intensity lifetimes for all bunches shown in

Average lifetime of different PSI bunches at 6.5 Q TeV was found to be about 55h!

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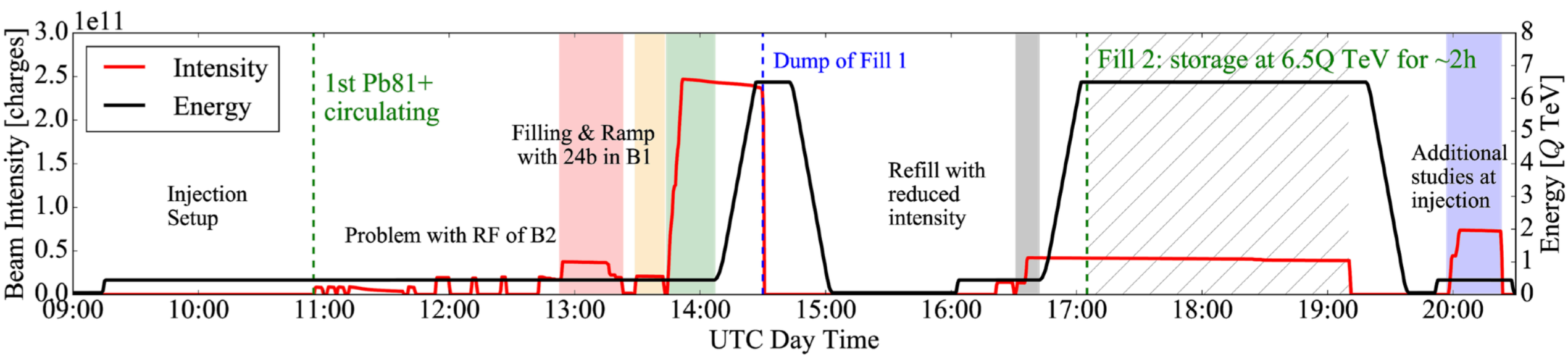

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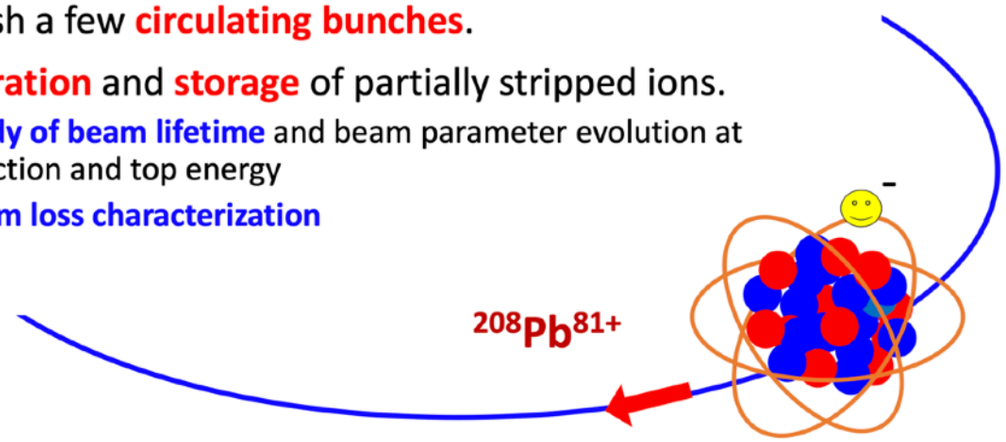

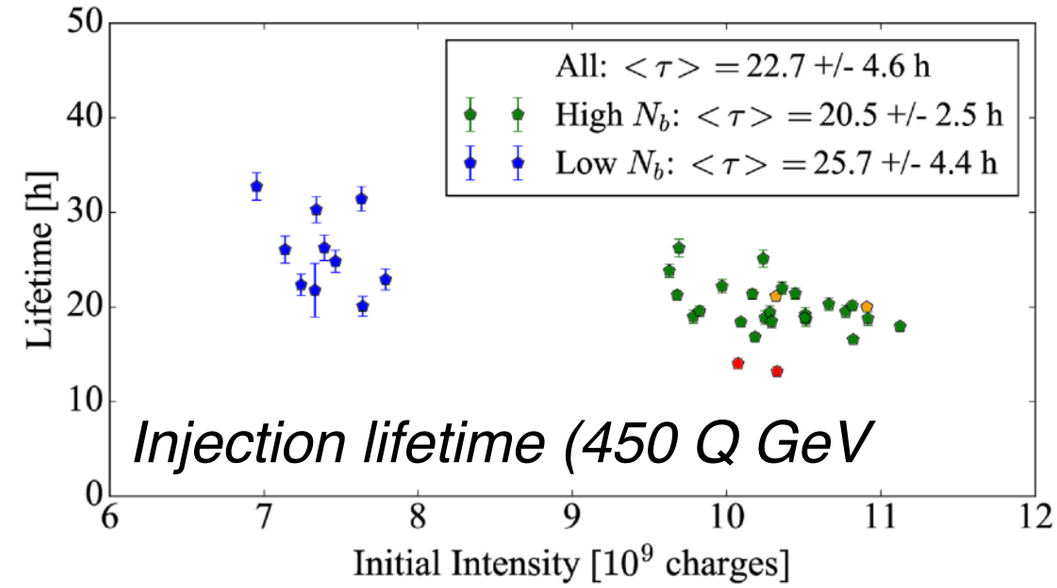

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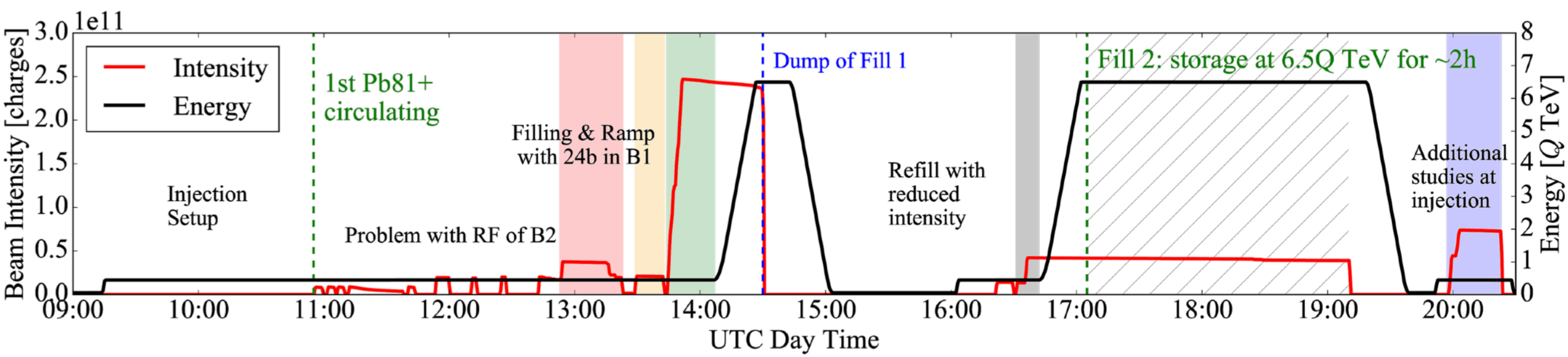
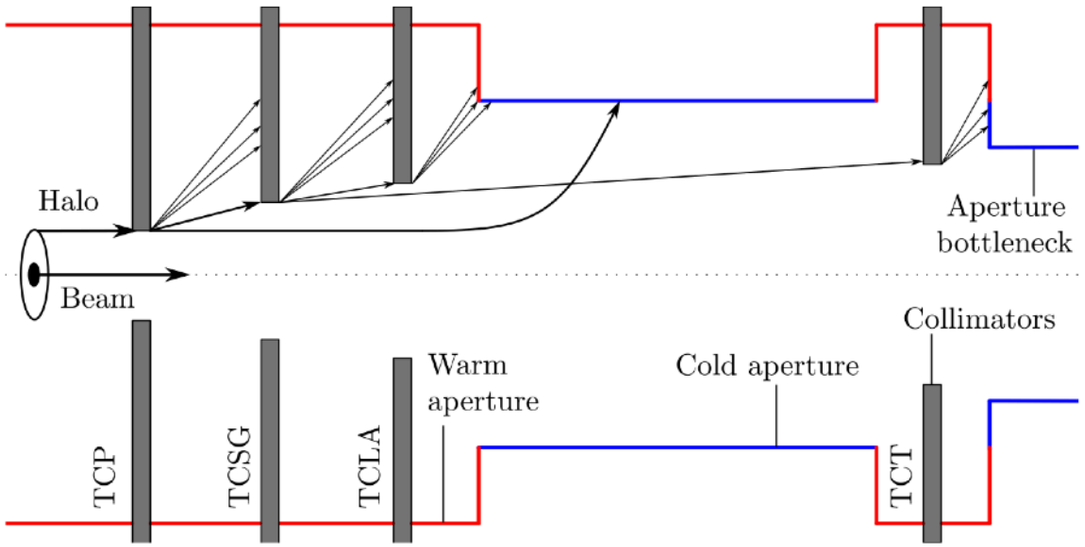
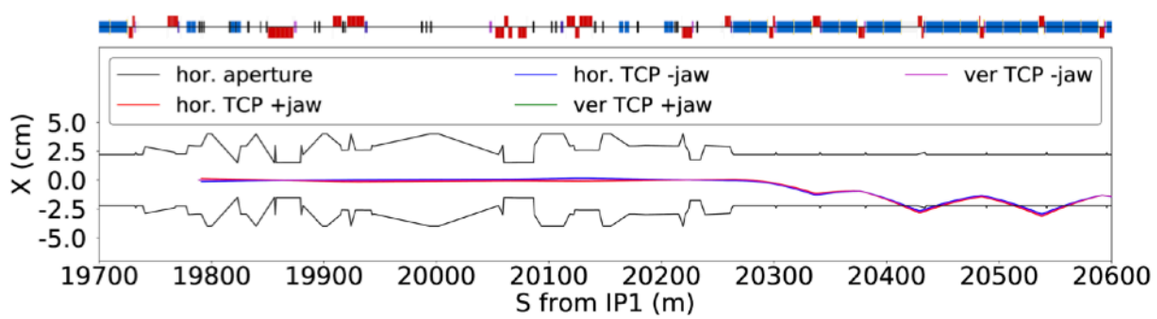
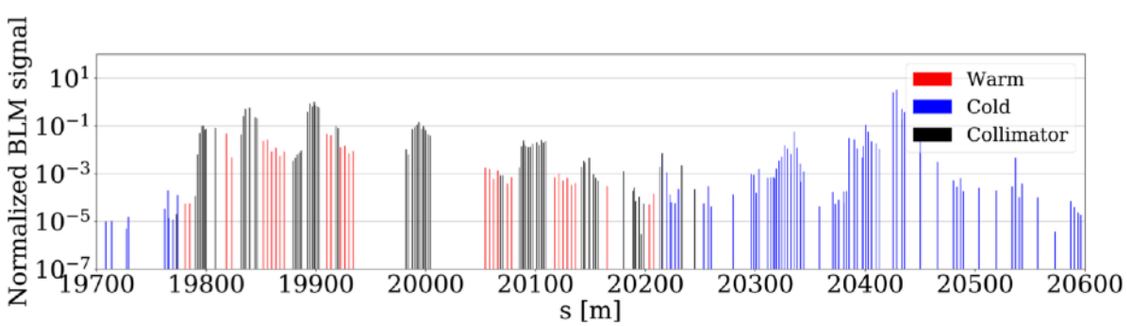


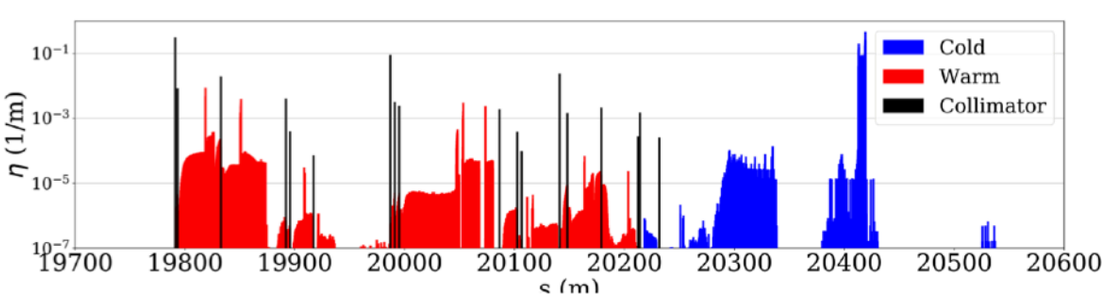
Critical issue: collimation of partially stripped ions!

PSI beam collimation at 6.5 Q TeV



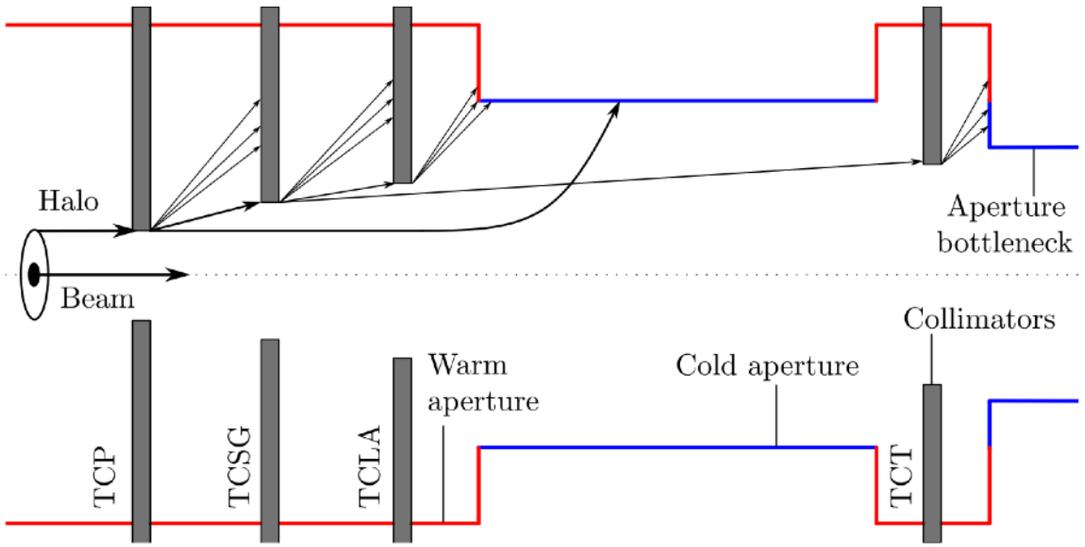


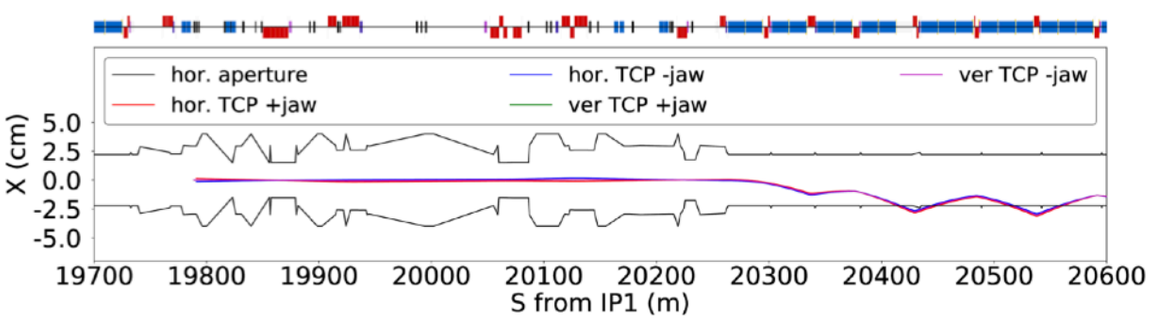


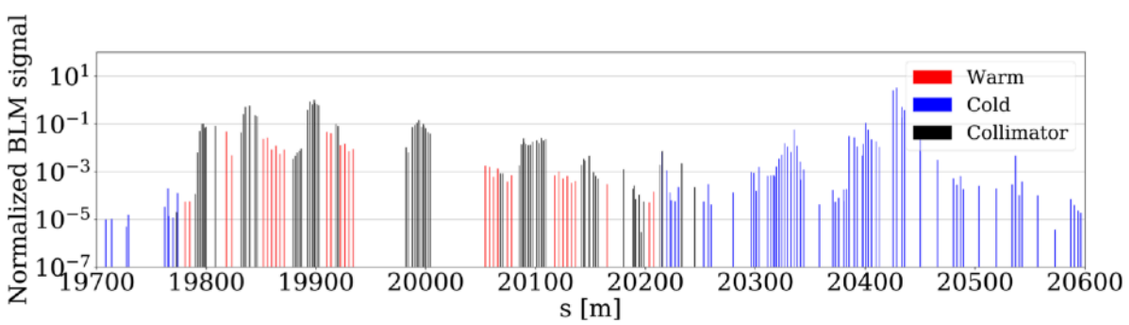


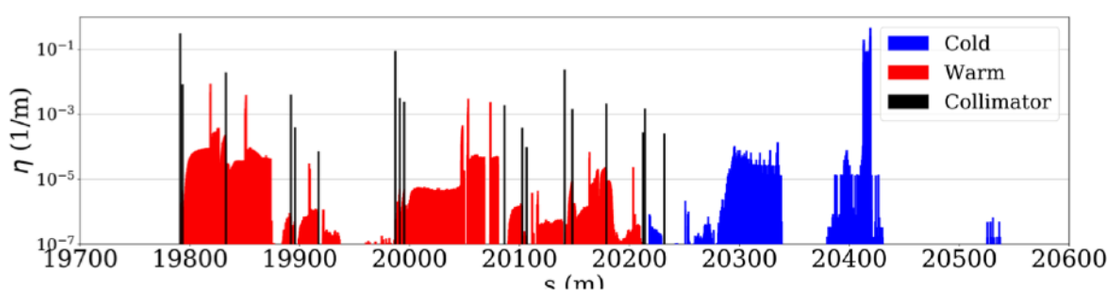
A. Abramov et al., doi:10.18429/JACoW-IPAC2019-MOPRB058
A. Gorzawski et al., PHYS. REV. ACCEL. BEAMS 23, 101002 (2020)

PSI beam collimation at 6.5 Q TeV

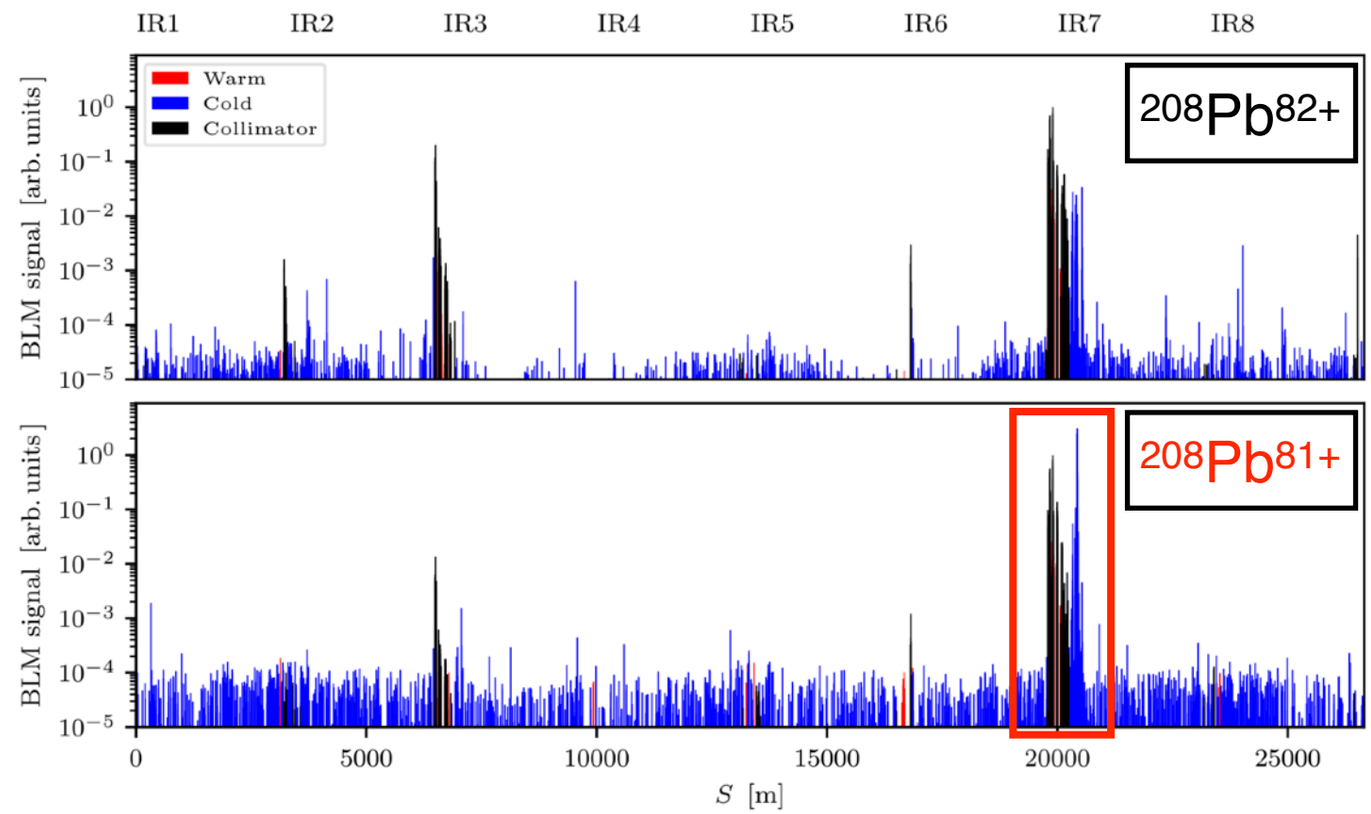








Measured losses with "hydrogen-like Pb atoms"



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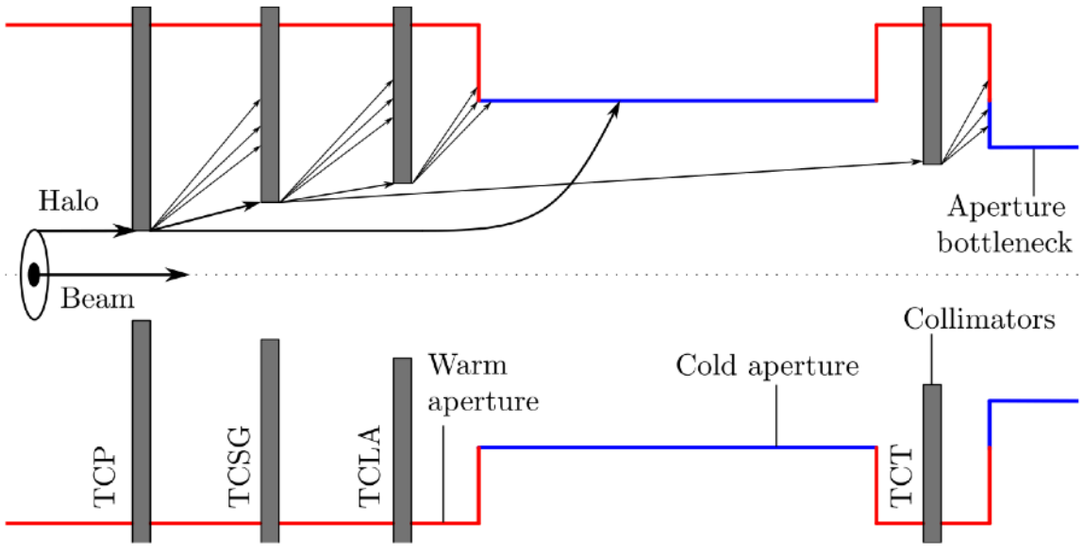

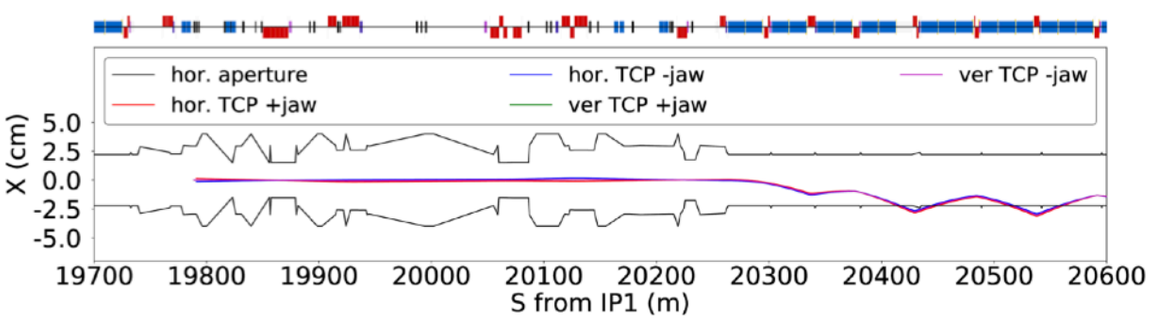

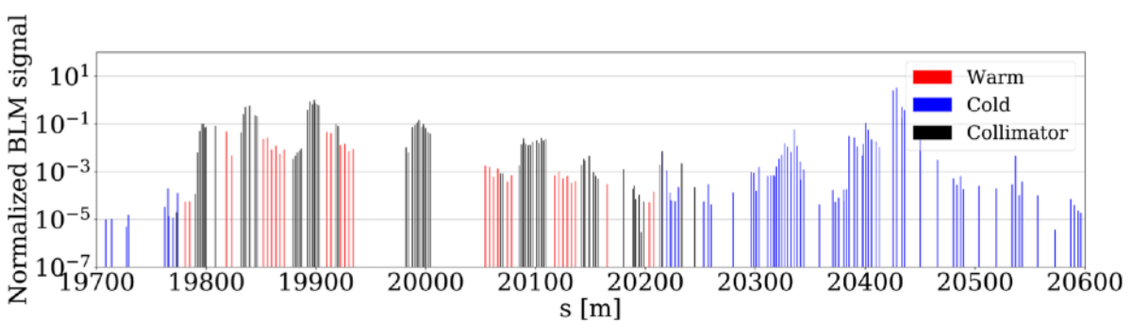

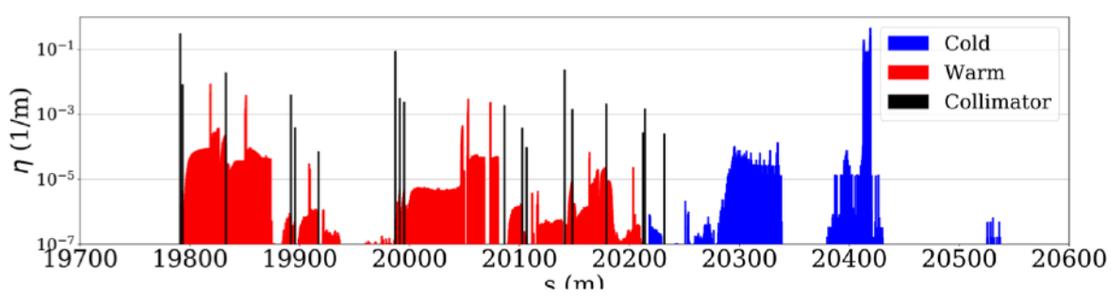

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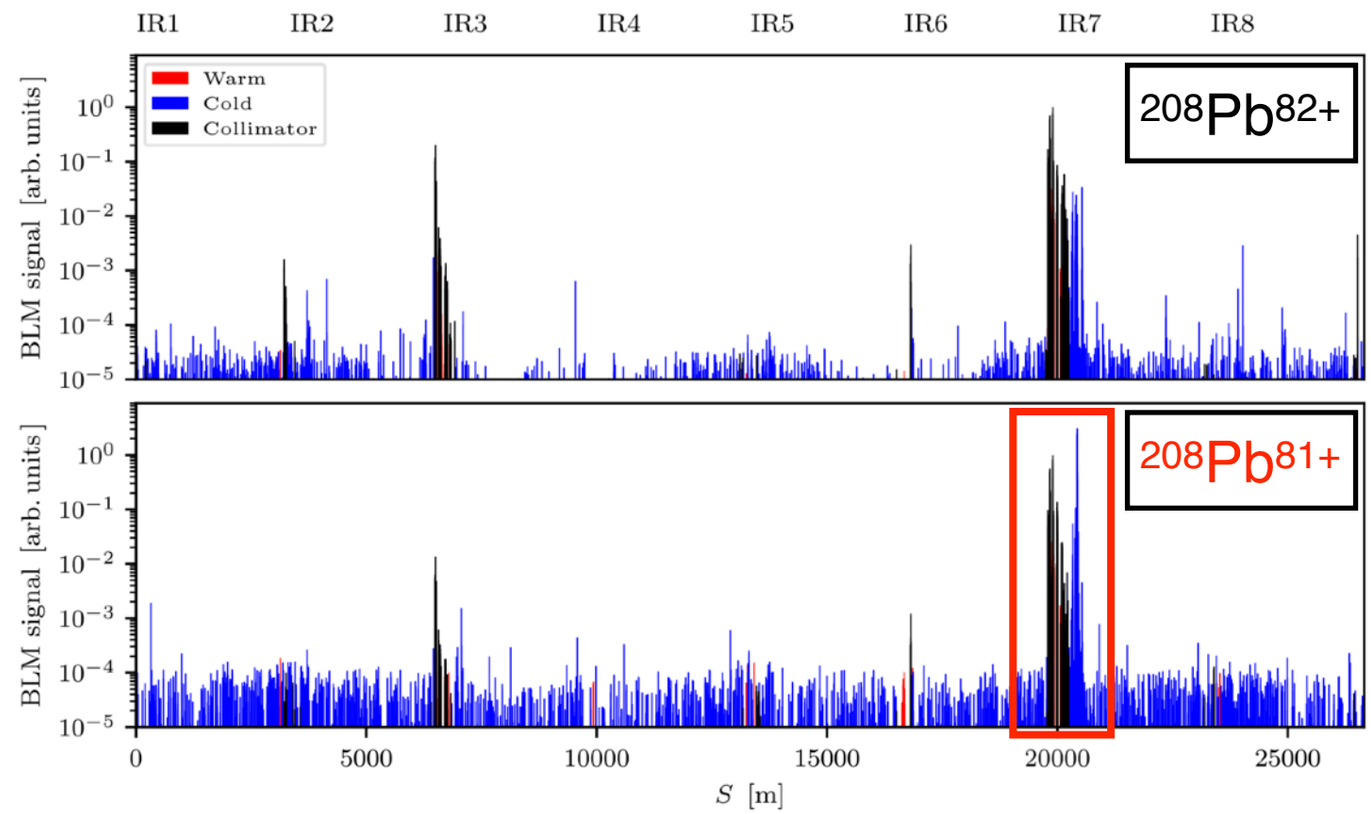

Several exciting issues ahead of us before a high-intensity deployment of PSIs at the LHC!

A. Abramov et al., doi:10.18429/JACoW-IPAC2019-MOPRB058
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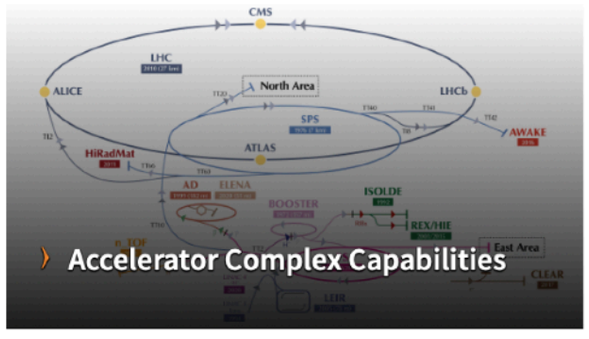
Table of Contents

PBC technology working group

Accelerators & Technology Domain

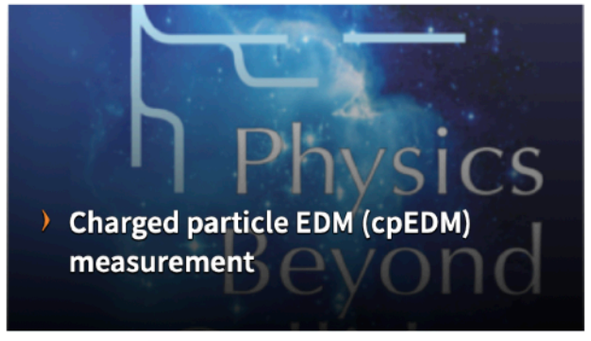
The Working Groups in the Accelerators & Technology Domain are coordinated through the PBC Accelerators & Technology Committee, a steering committee which meets around once per month. The steering committee includes the CERN conveners of the various Working Group in the Accelerators & Technology Domain. The Working Group's core members include accelerator experts and representatives of the projects. Requests from the Working Groups (tests, prototypes, manpower) are discussed by the steering committee.

ACCELERATORS & TECHNOLOGY WORKING GROUPS



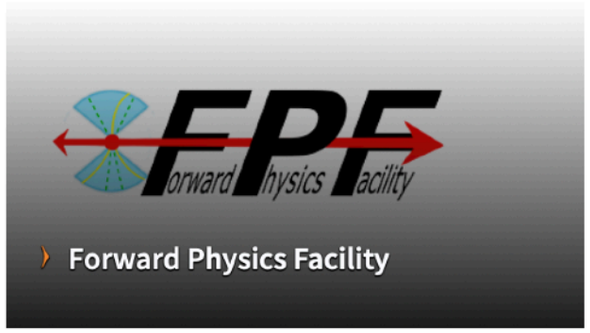
Accelerator Complex Capabilities


Beam Dump Facility



Charged particle EDM (cpEDM) measurement

Conventional Beams



Forward Physics Facility

Gamma Factory

LHC Fixed Target

Technology

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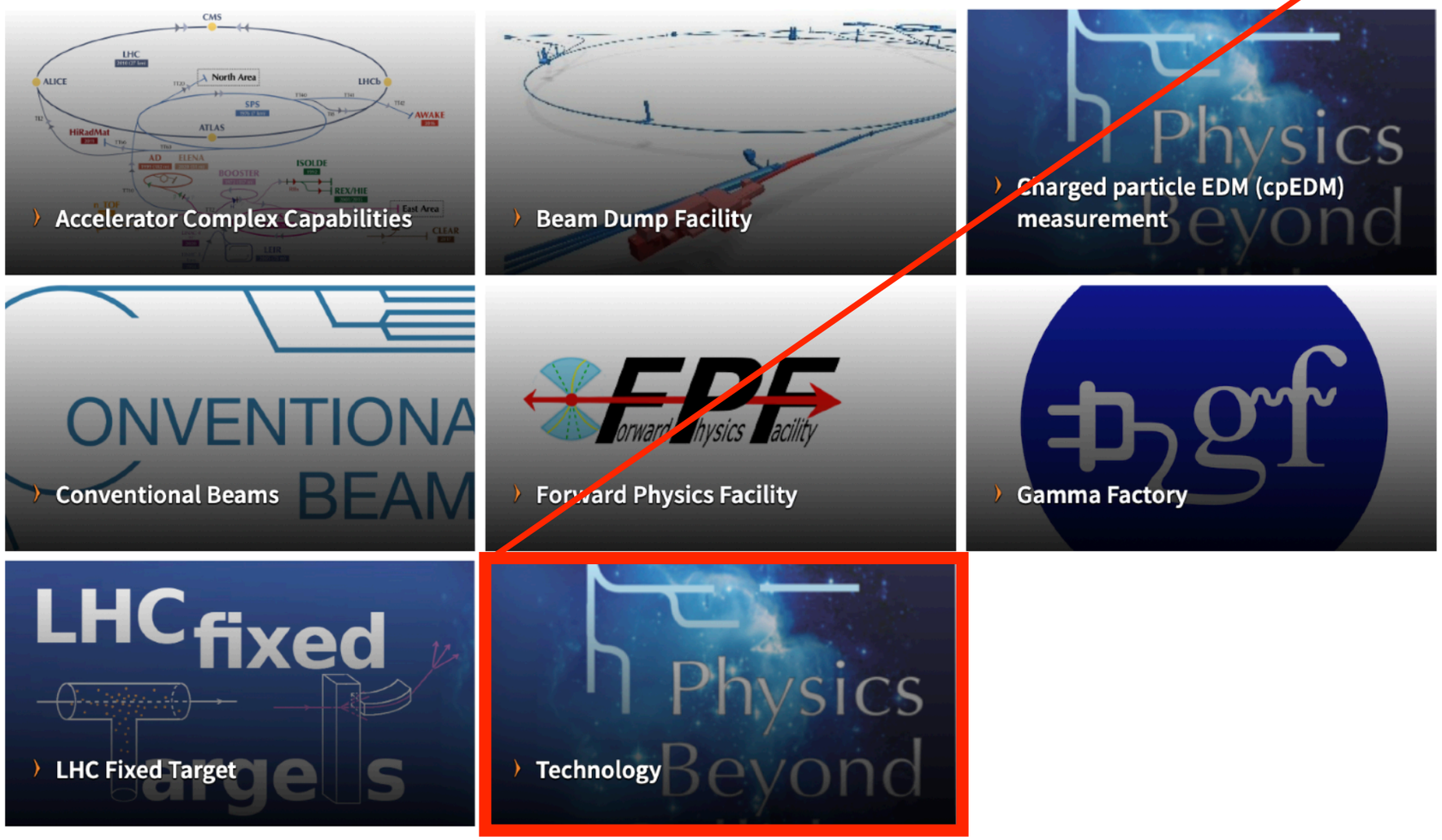


Link to "PBC technology workshops": indico category. Already 4 workshops organised so far.

Conveners:
S. Calatroni,
B. Döbrich

Technological contributions, in particular to non-accelerator experiments, exchanging experience and expertise.
Support the development of new physics experiments.

Updated list of supported studies

- ALPS-II/Jura -> axion search light-shining-through-wall with lasers
- VMB@CERN -> QED birefringence with lasers
- Grenoble Haloscope (GrAHal): -> axion search with RF cavities
- RADES/HTS -> axion search with HTS RF cavities
- DarkSide -> direct detection of WIMPS with liquid Ar TPC
- Ptolemy -> Carbon NanoTubes for cosmological neutrino background
- STAX -> axion search light-shining-through-wall with RF cavities
- Advanced-KWISP -> search for Short Range Interactions
- New: Axion Heterodyne Detection -> axion search with two-mode RF cavities
- New: AION-100 @ CERN -> vertical atom interferometer
- Now independent: babyIAXO -> axion search from the sun

Impressive !

AION-100 at CERN

AION is a vertical Atom Interferometer Observatory and Network for mid-frequency gravitational waves and ultra-light Dark Matter detection

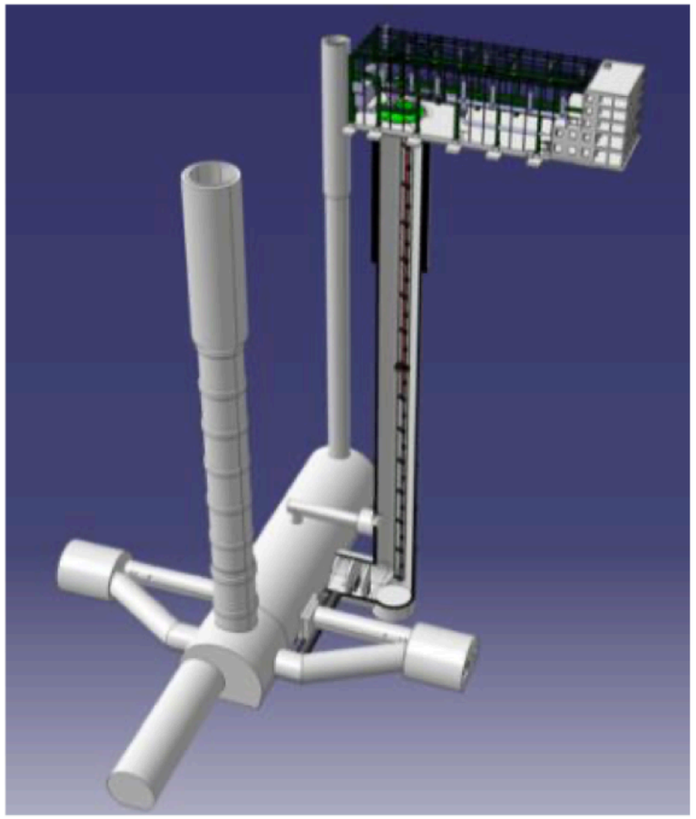
- Proof-of-Principle (10m) being built in UK
- Possible siting of a 100m setup in an LHC shaft (PX46) under investigation in PBC (Integration, RP & general safety, evaluation of EM interference -RF zone- and seismic noise /vibrations)

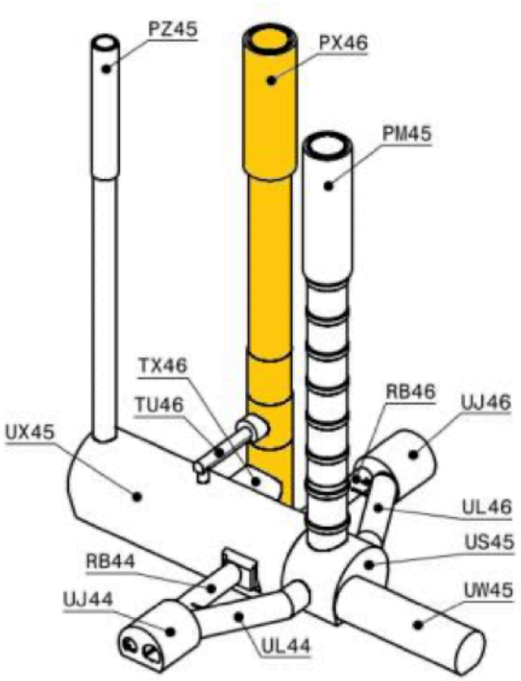
Detailed scoped of CERN PBC activities (list by S. Calatroni)

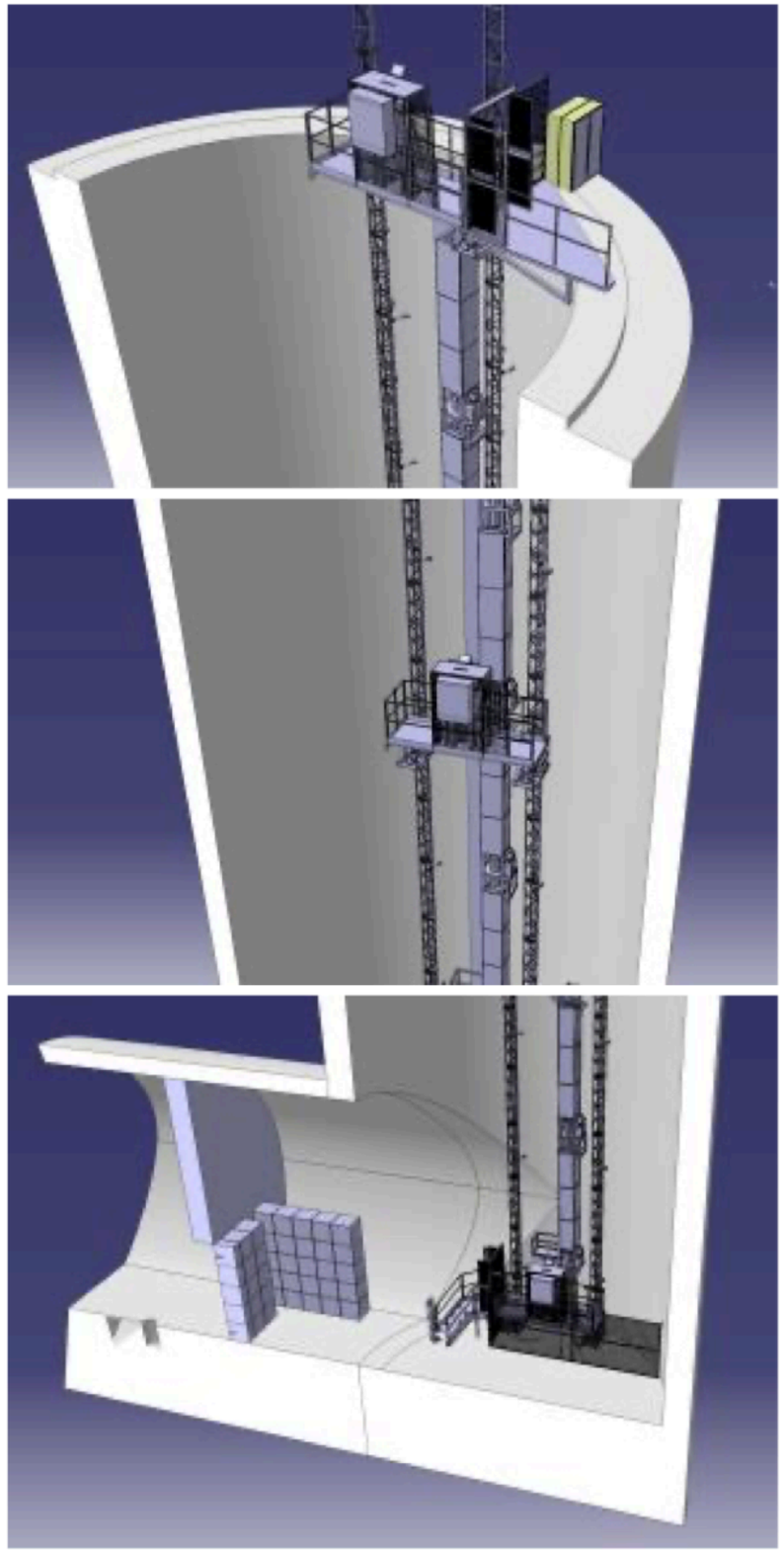
- **Identify location for a vertical AI ~100 m deep at CERN**

  (Site to be already part of a large international laboratory and experimental facility)
- **Assess technical feasibility and impact from presence of LHC machine**
- **Based on AION-100 technical requirements as guideline**
  - "A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study"
  - CERN-PBC-REPORT-2023-002, https://cds.cern.ch/record/2851946

Study for integration in LHC P4







Selected location: PX46

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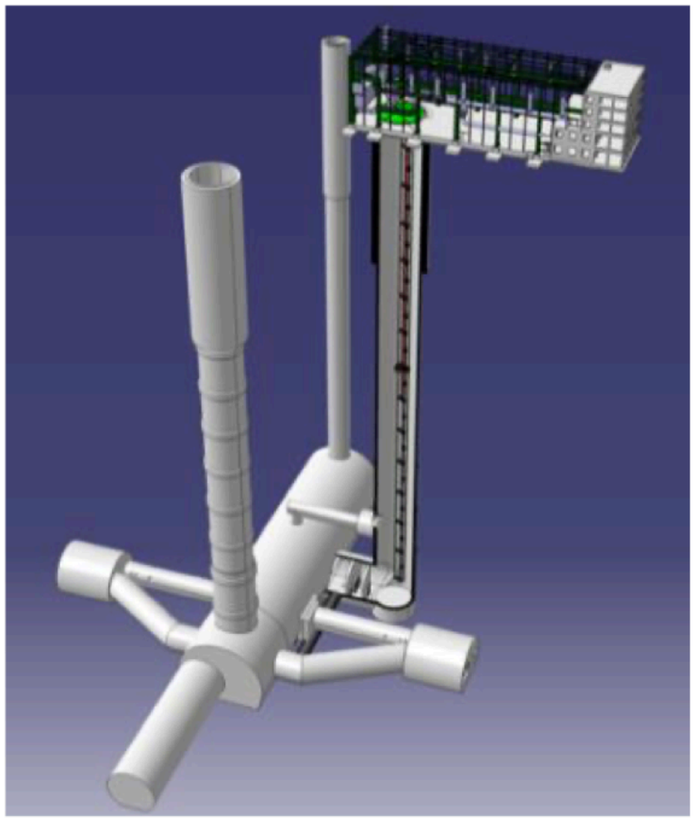

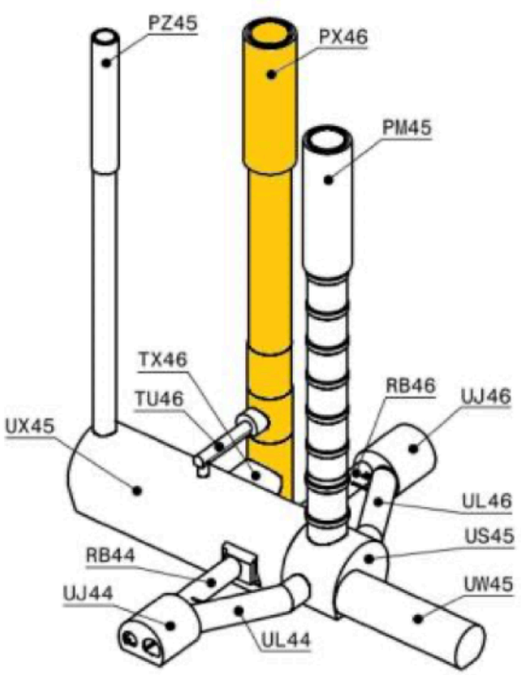

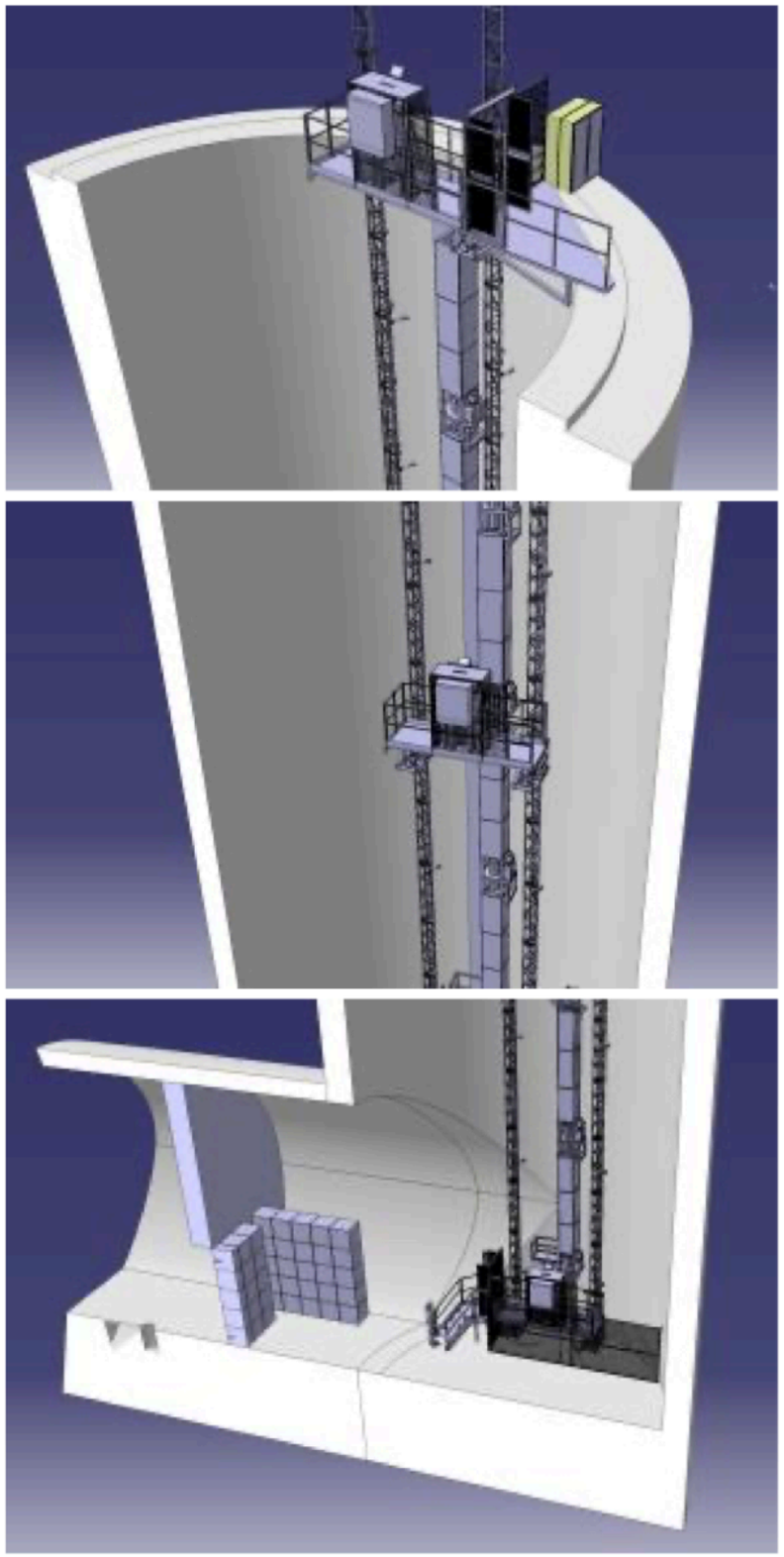

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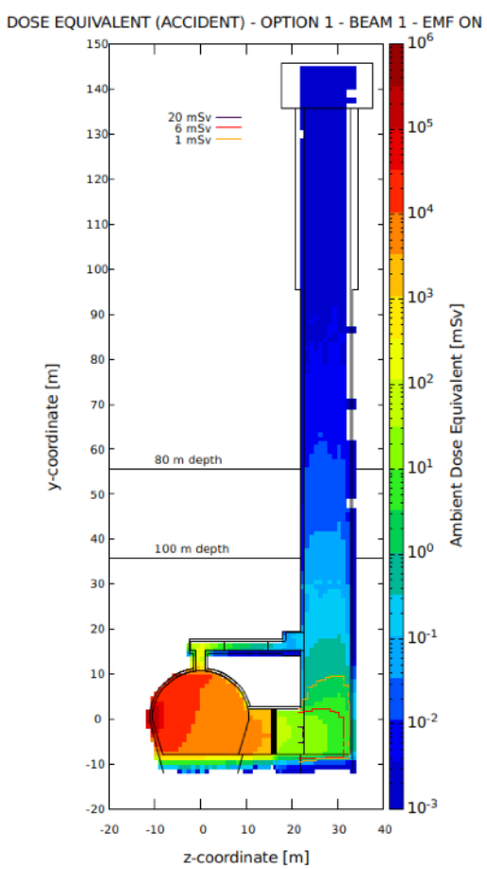
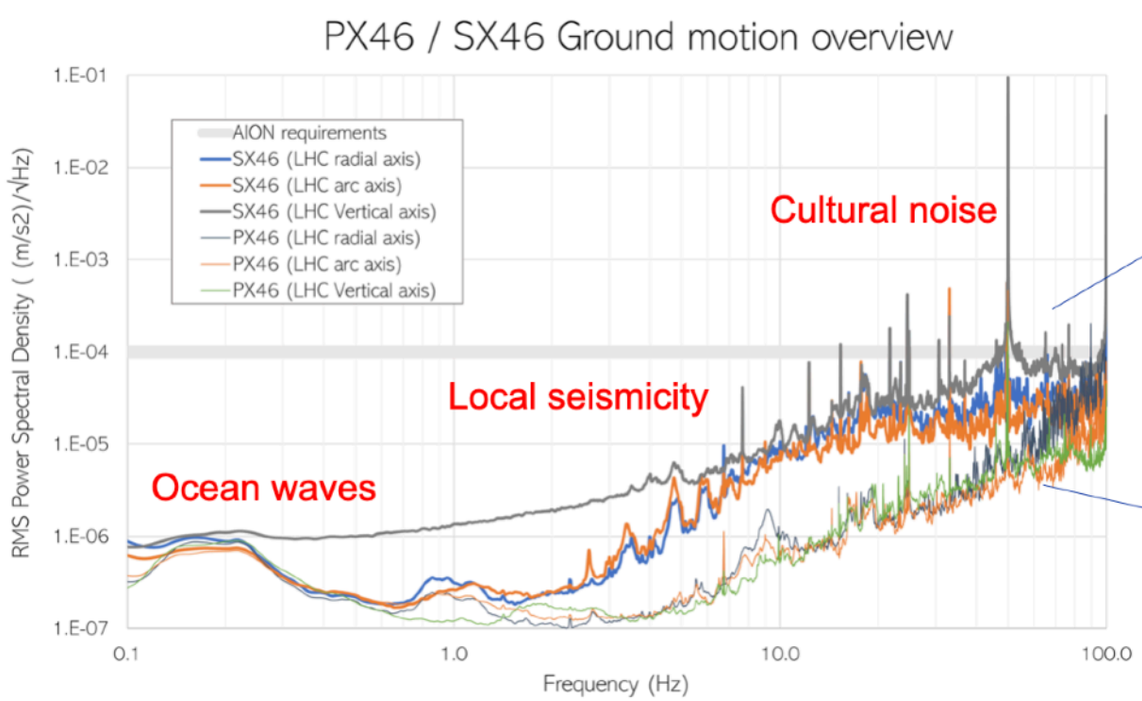
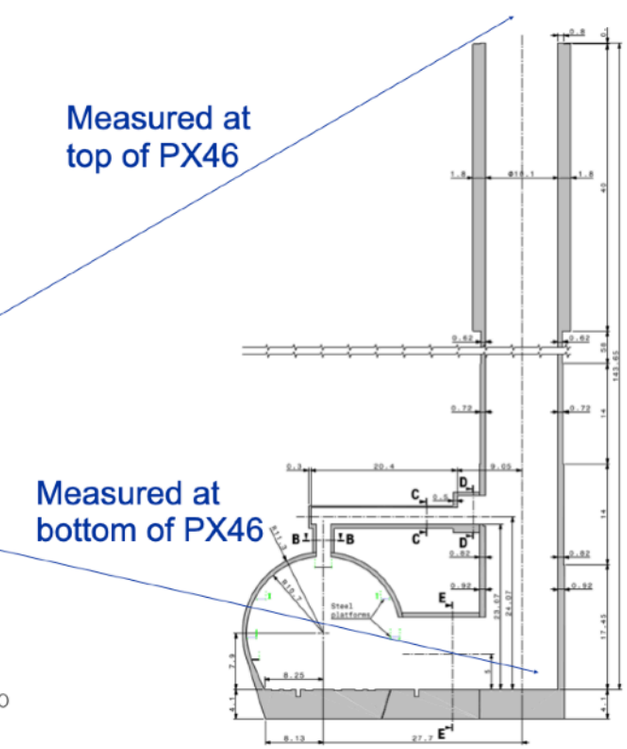
Assessment of compatibility

- **Compatibility with technical requirements for an AI – influence of the LHC**
  - Vibrations, seismic noise and local geology
  - EM noise
  - Radiation protection
  - Fire safety
  - He release hazards
  - Access control
- **Available infrastructure**
  - Electrical supply, network, etc.







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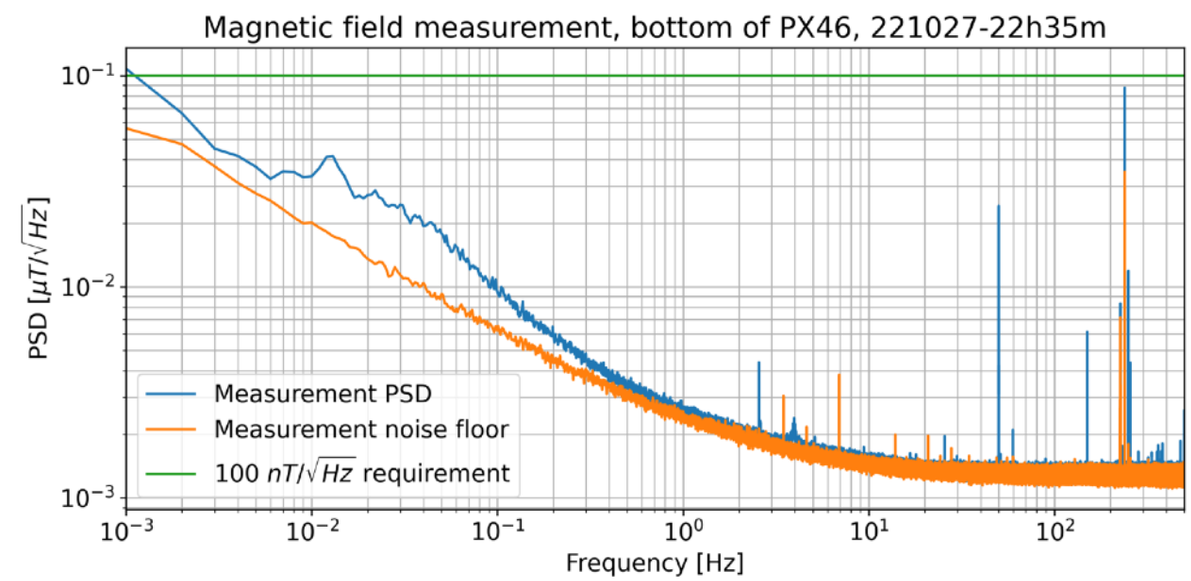
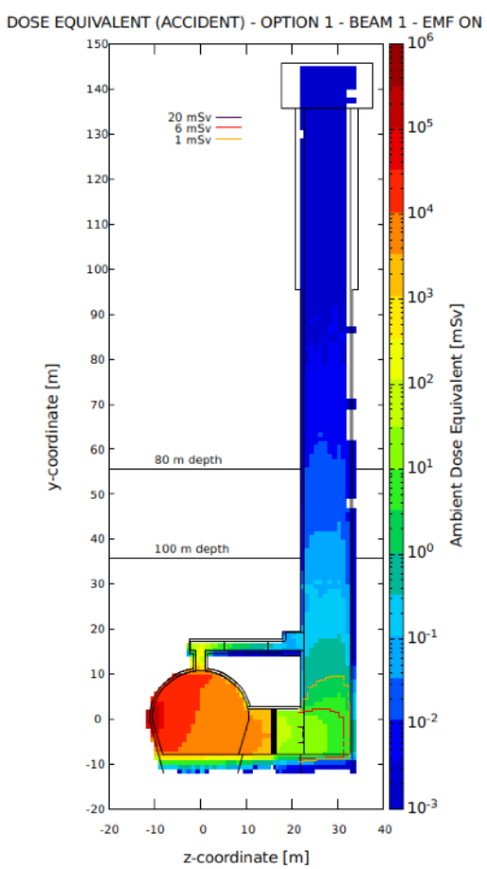
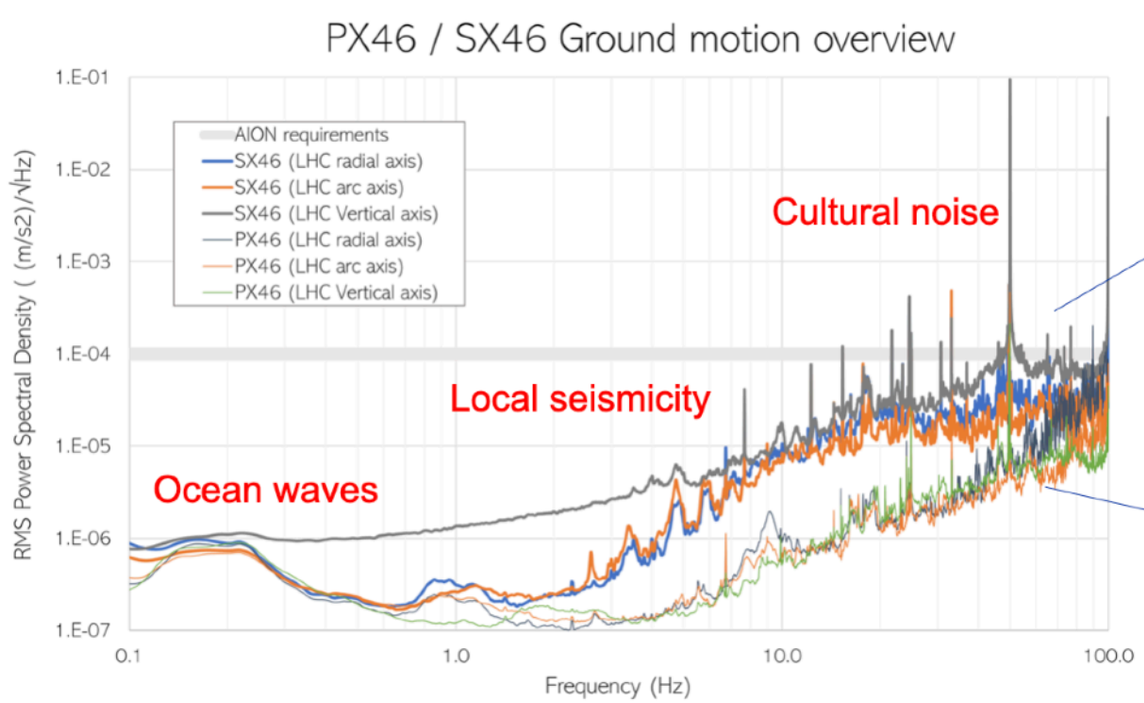
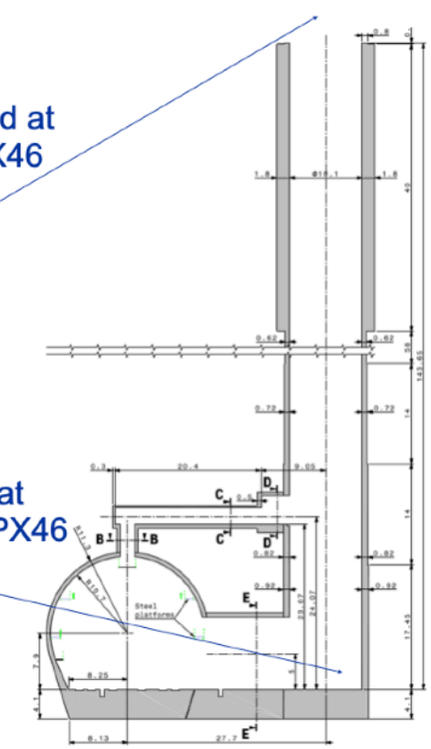






Measured at top of PX46

Measured at bottom of PX46

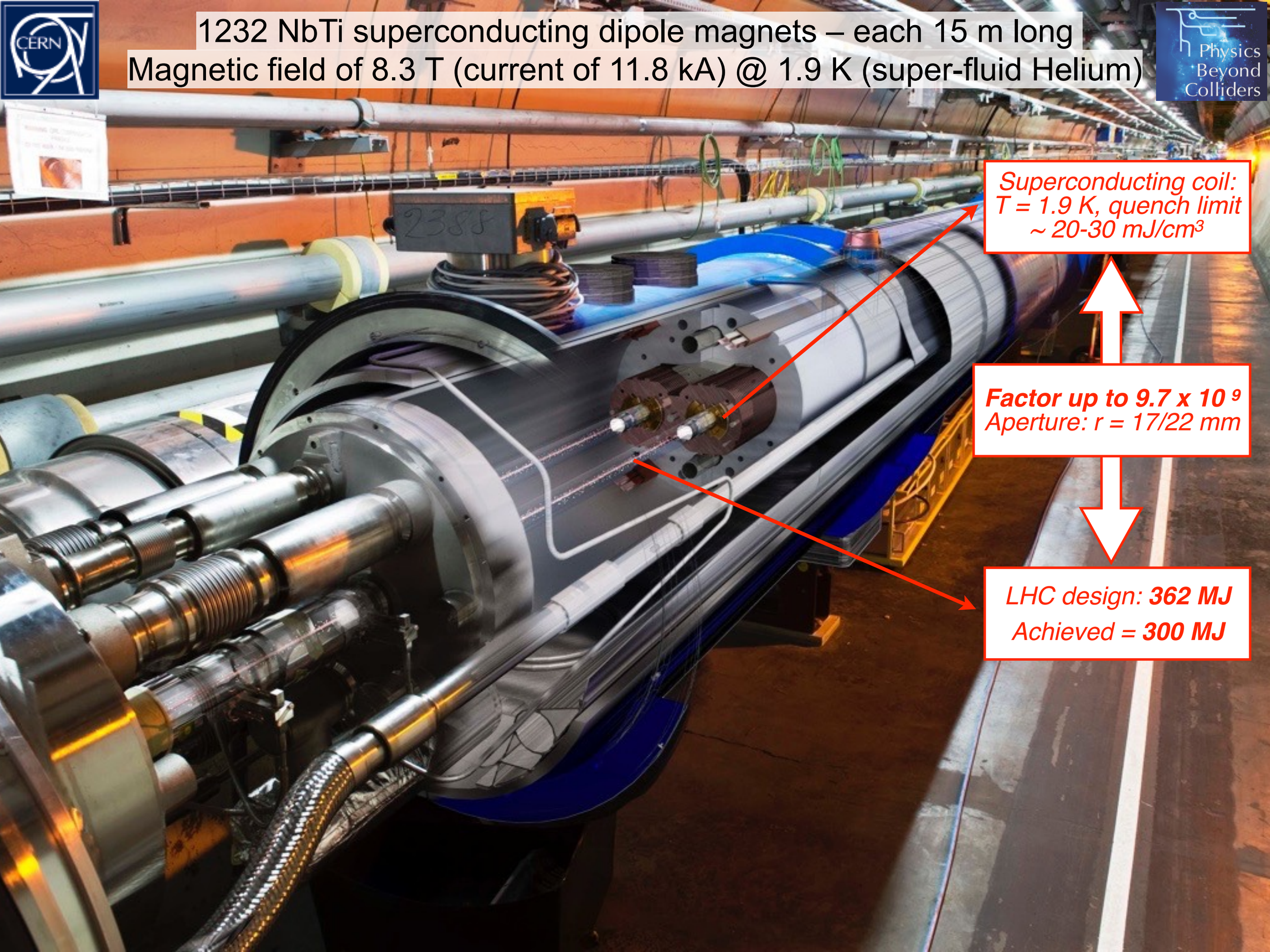


Conclusions

- The LHC is a collider and it offers unique and interesting opportunities for physics beyond colliders!
  - At the frontier of stored beam energy for protons and ion beams
  - Well established and unique underground infrastructures
  - Part of a laboratory that plays centre role in the worldwide physics community
- Various opportunities have been studied since the PBC kick-off in 2016 and are now at different stages of maturity
  - From approved experiments taking data, to new proposal that are still coming in!
  - From shift-lived baryons (~ cm) to long-lived particles (measured at hundreds of m)
- Some examples were reviewed, with focus on LHC oriented project
  - LHC fixed-target plans, FPF, gamma factories, examples of non-accelerator experiments for gravitational waves, …
- Thank you very much for your attention.

Reserve slides

1232 NbTi superconducting dipole magnets – each 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)

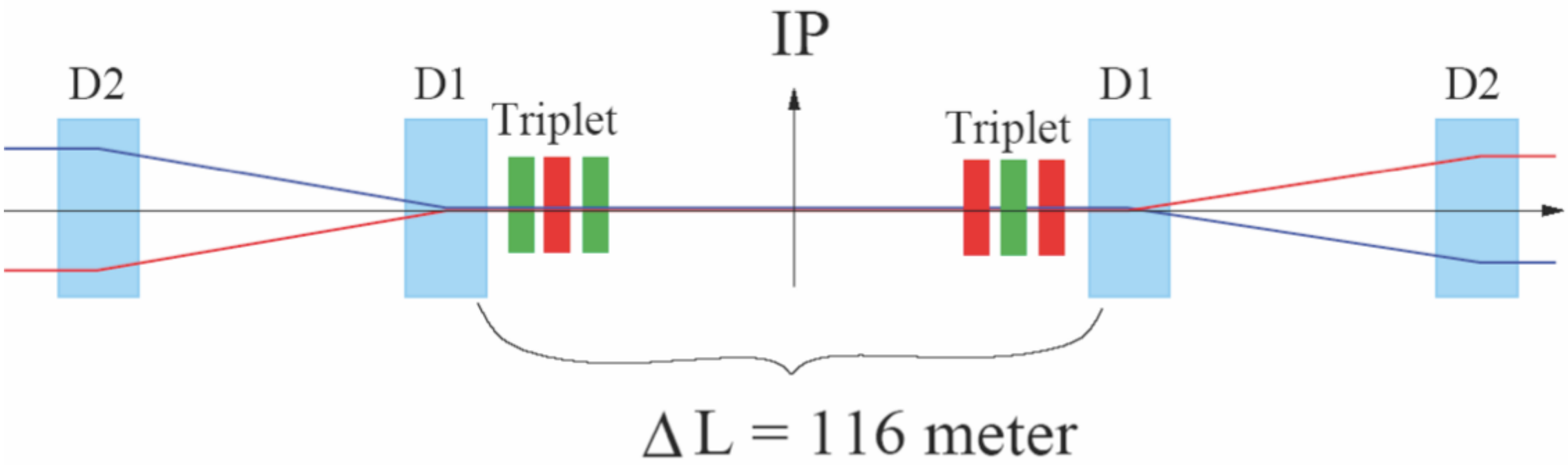


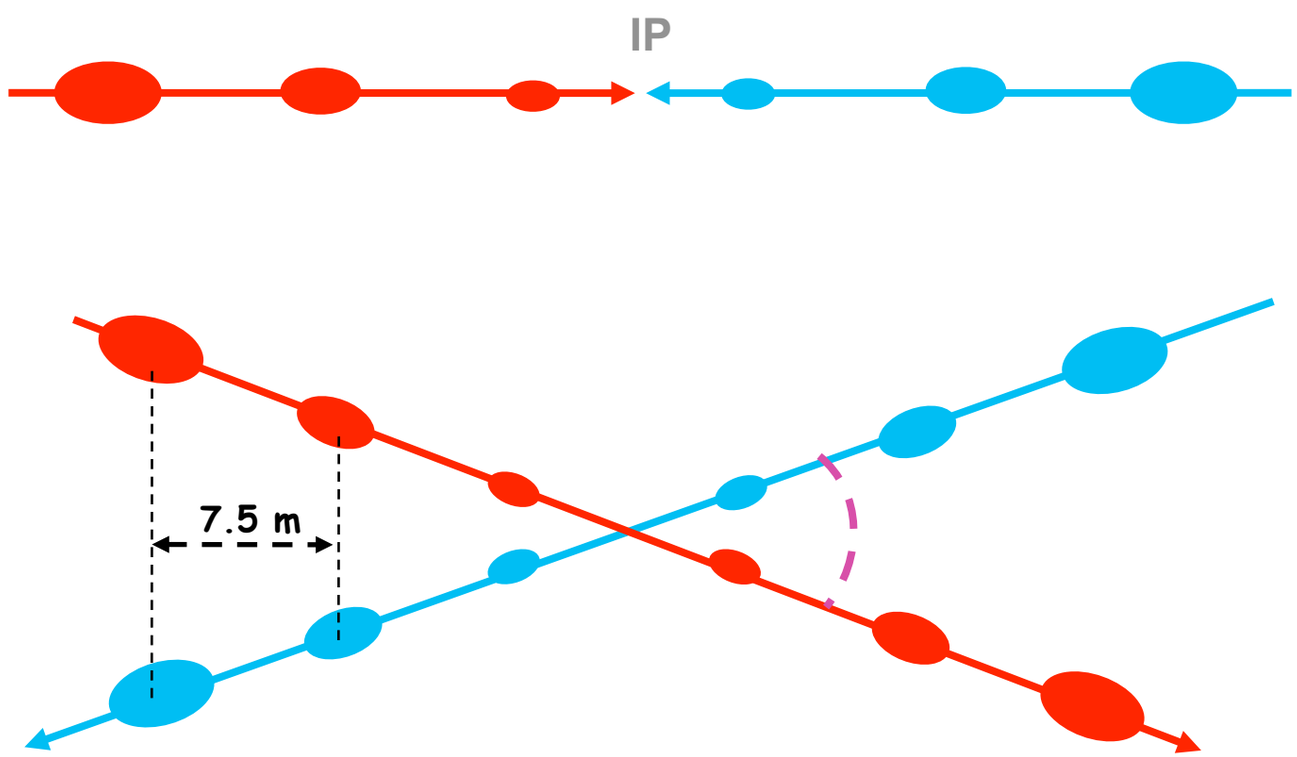
Superconducting coil:
T = 1.9 K, quench limit
~ 20-30 mJ/cm³

Factor up to 9.7 x 10 ⁹
Aperture: r = 17/22 mm

LHC design: ***362 MJ***
Achieved = ***300 MJ***

Complex layouts and configurations…

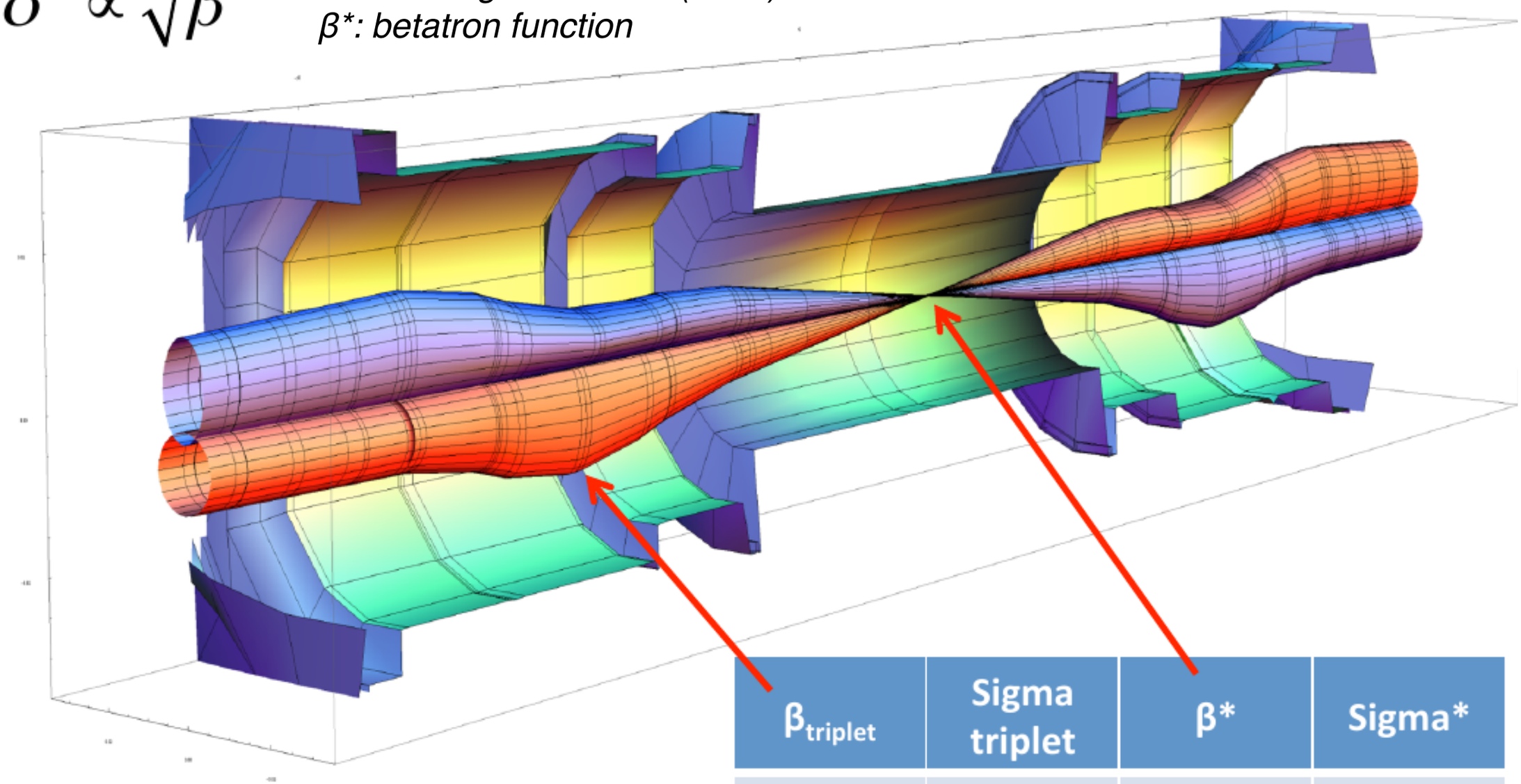




Complex layouts and configurations…

$$\sigma^* \propto \sqrt{\beta^*}$$

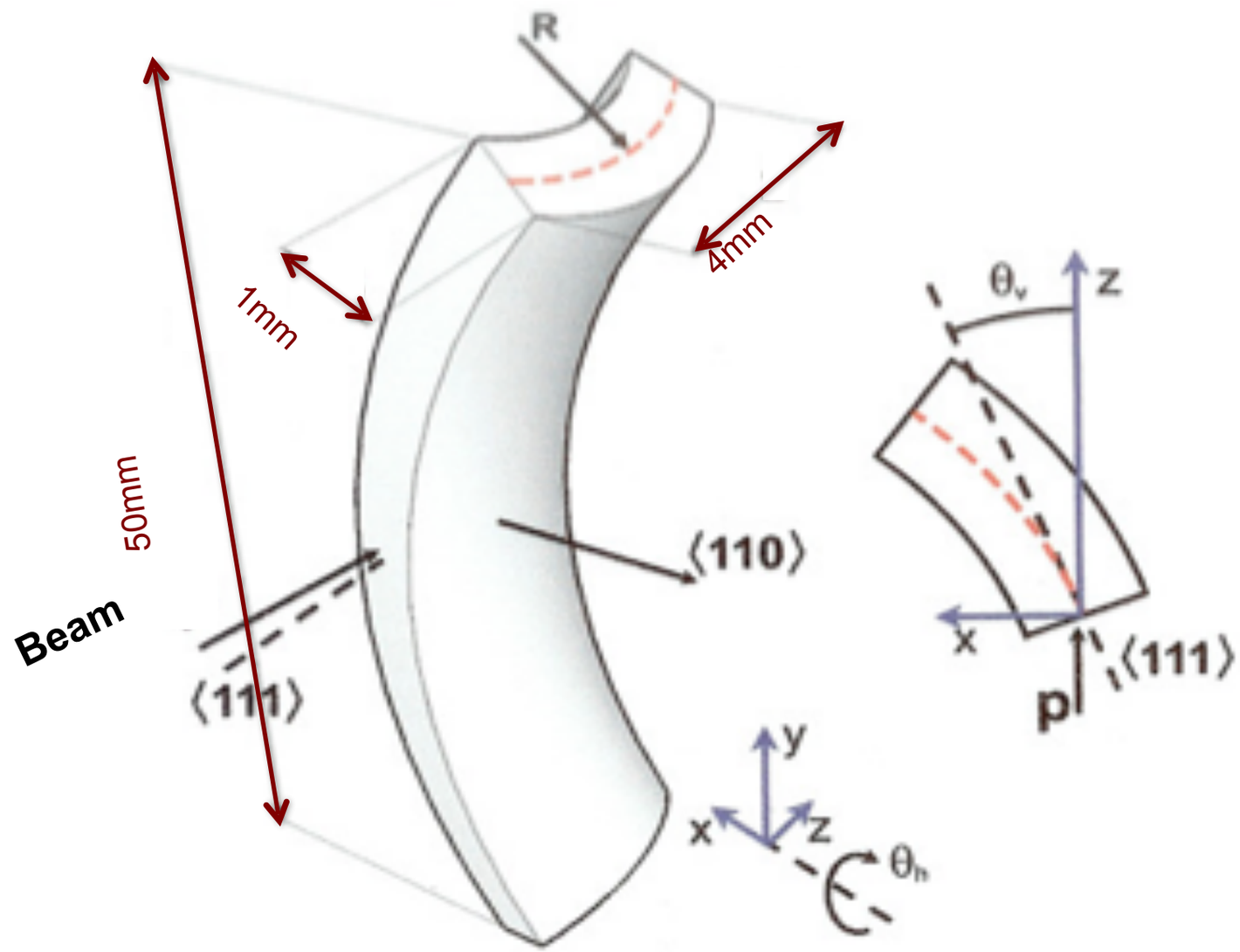
σ: colliding-beam size (RMS)*
β: betatron function*



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

Crystal bending

LHC design parameters for **Silicon crystals**



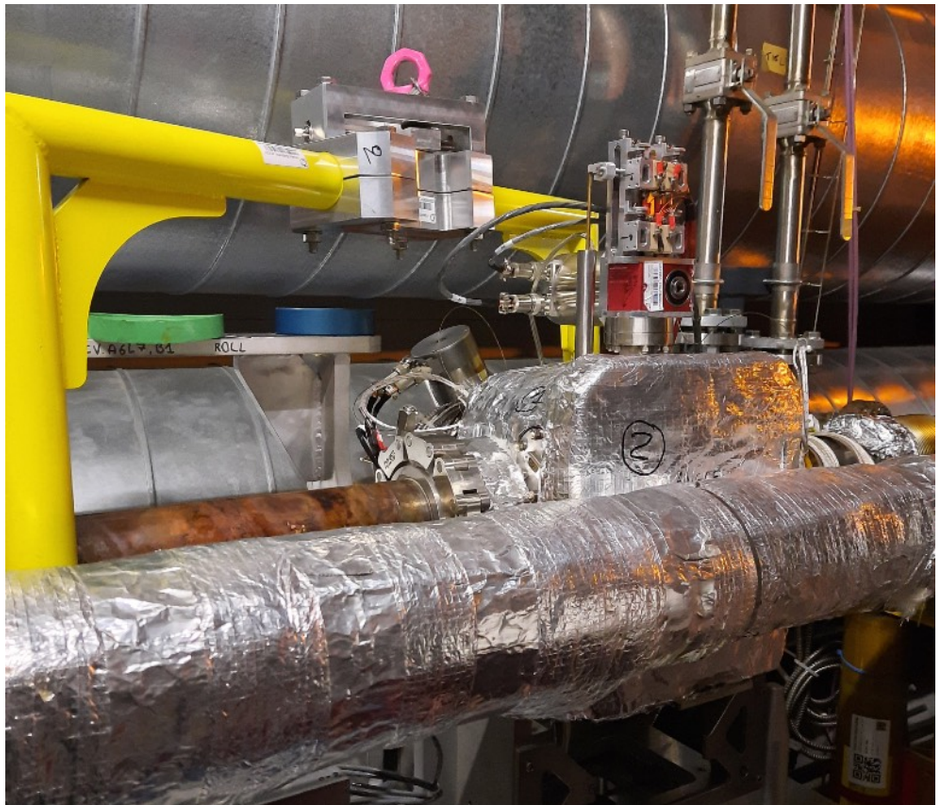
Bending 50μrad

Crystal collimation for HL-LHC

- Crystal collimation for heavy ion beam will be used in Run 3
  - Our test stand in IR7 (betatron collimation) has being upgraded with the installation of 4 new crystal primary collimators to become an operational system
  - Good results obtained already in 2018 for special forward-physics runs!
- LHC-FT studies will profit from the strong synergy with this program!
  - Already explored beam tests relevant for LHC-FT using the “collimation” crystals
  - Important know-how on key hardware and software solutions, and on operation
  - Built competence in CERN teams for crystal validation and characterization.

Latest design of the crystal primary collimator: starting point for CRY-1

One new unit installed in IR7 for HL-LHC



Courtesy HL-LHC WP5 teams

Crystal collimation for HL-LHC

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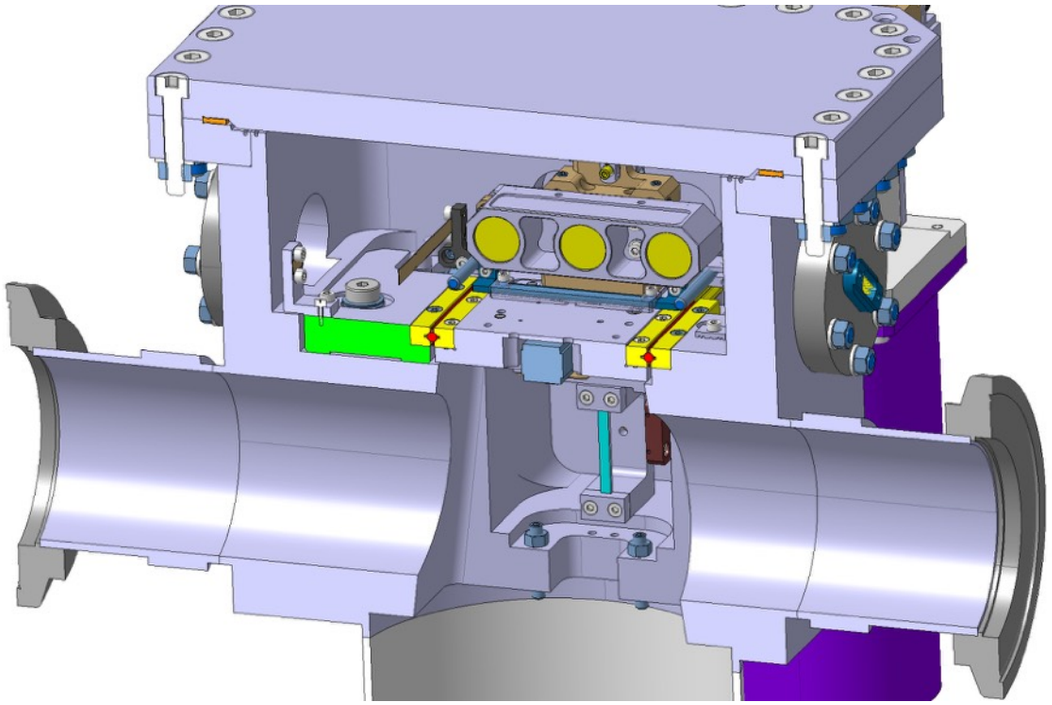
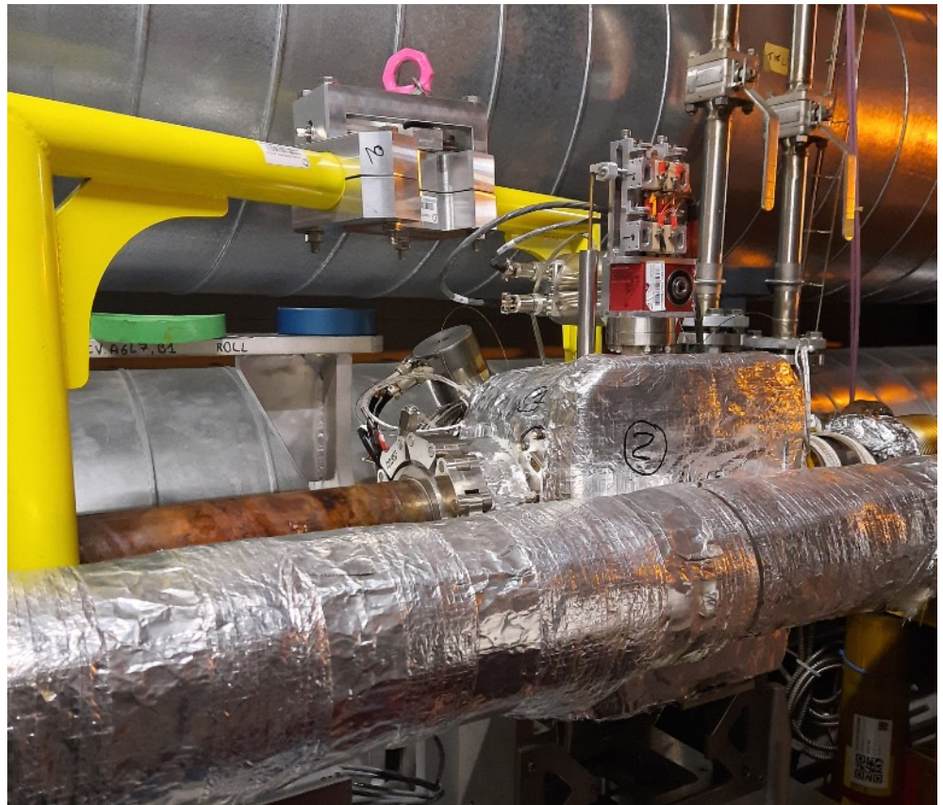


One new unit installed in IR7 for HL-LHC



Courtesy HL-LHC WP5 teams