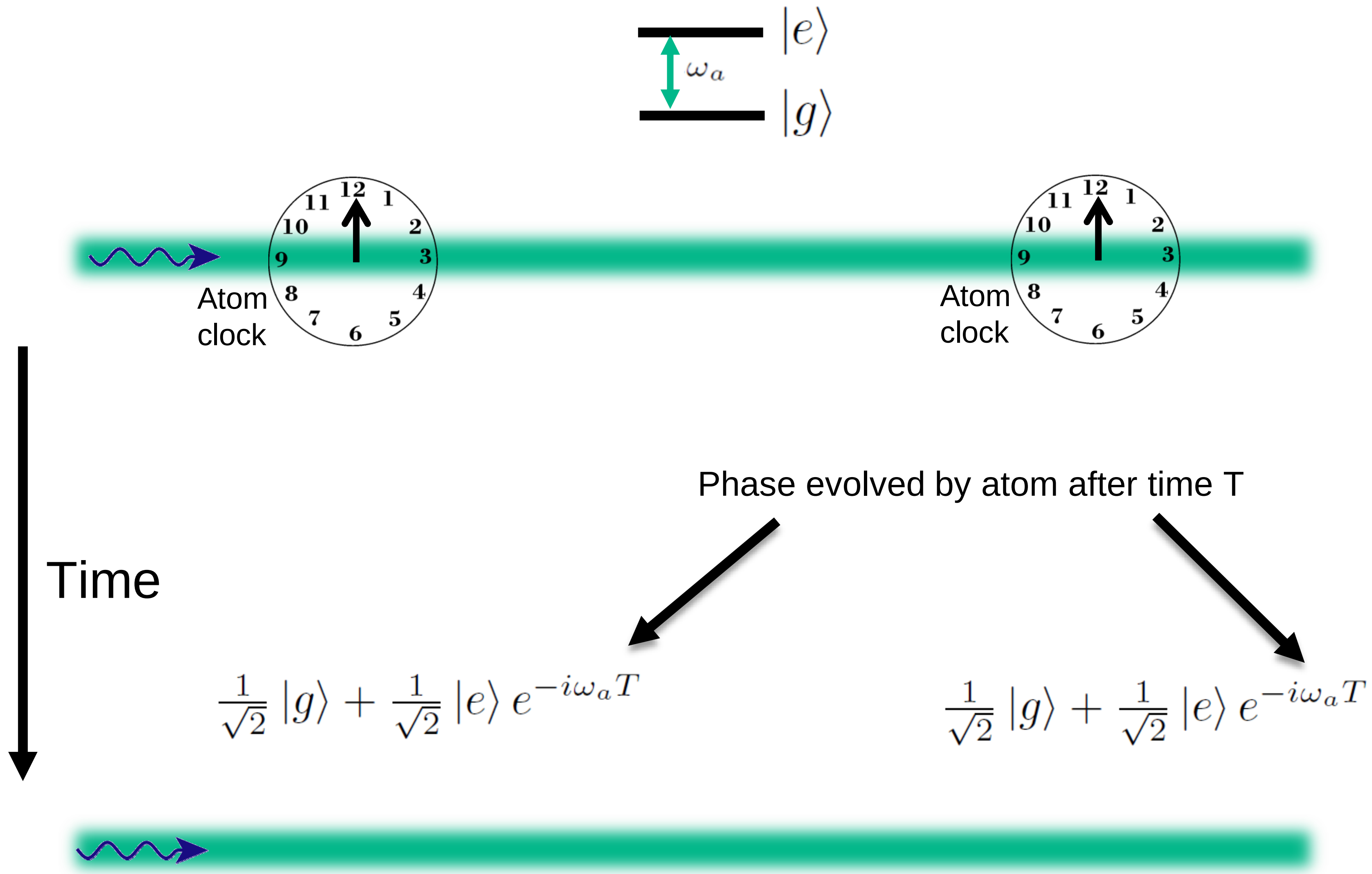
AION-100 @ CERN: feasibility study for installation at the LHC point 4, and future activities towards realization

Sergio Calatroni on behalf of the Feasibility Study Group

20.09.2024

Physics Beyond Colliders - Technology Working Group

Simple Example: Two Atomic Clocks



Courtesy of Jason Hogan!

Simple Example: Two Atomic Clocks

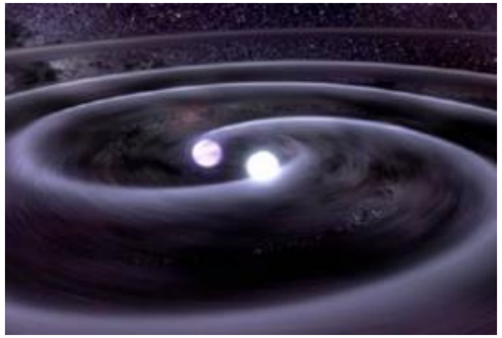
$|e\rangle$

ω_a

$|g\rangle$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

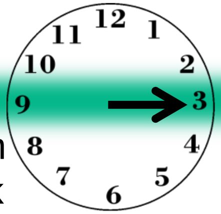
Time



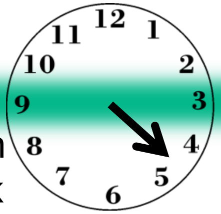
GW changes light travel time

$\Delta T \sim hL/c$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$



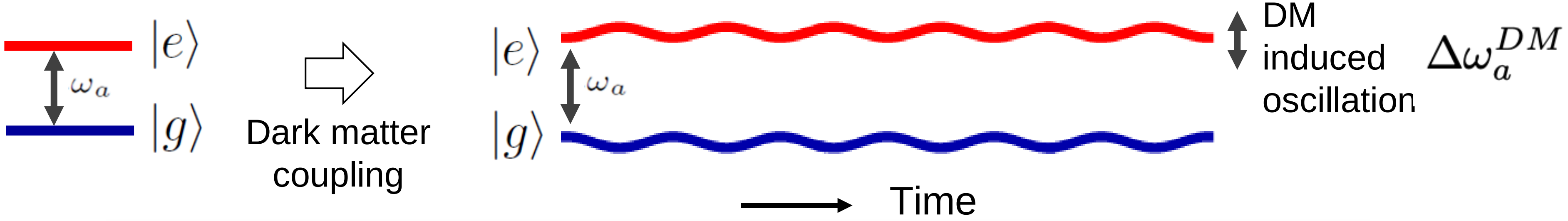
Atom clock

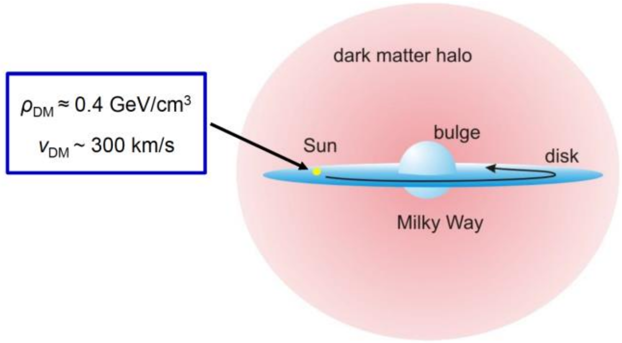


Atom clock

AION

Simple Example: Two Atomic Clocks





DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

Time

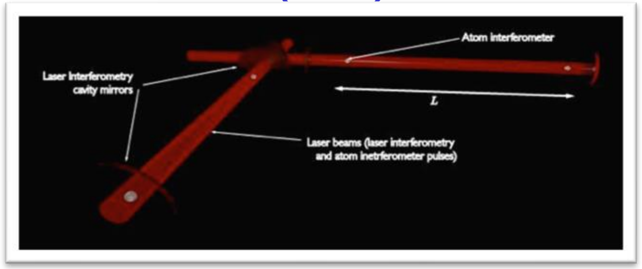
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \quad e^{-i(\omega_a + \Delta\omega_a^{DM})T}$$

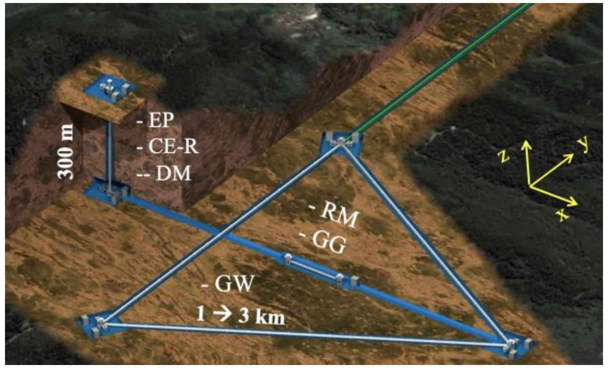
Courtesy of Jason Hogan!

Long baseline atom interferometer

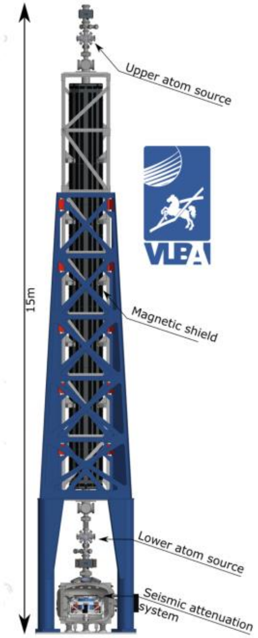
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

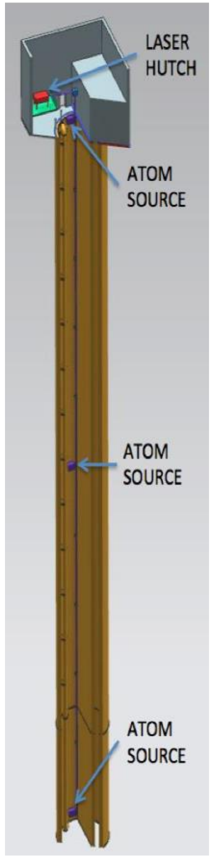


ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)

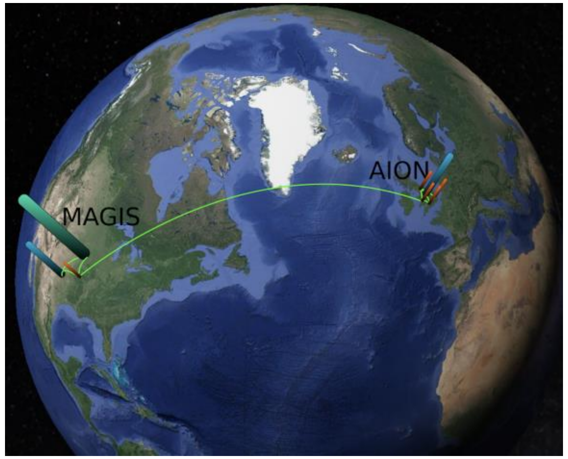


VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)



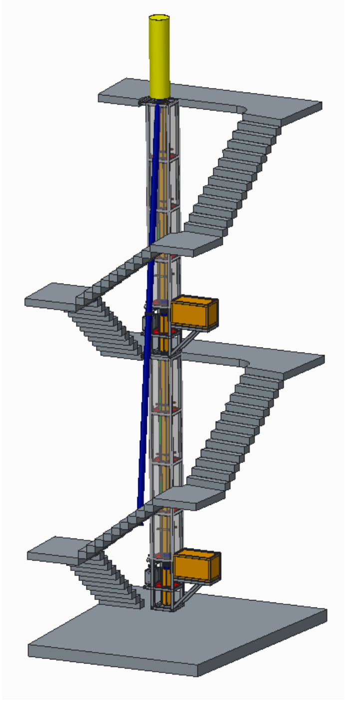


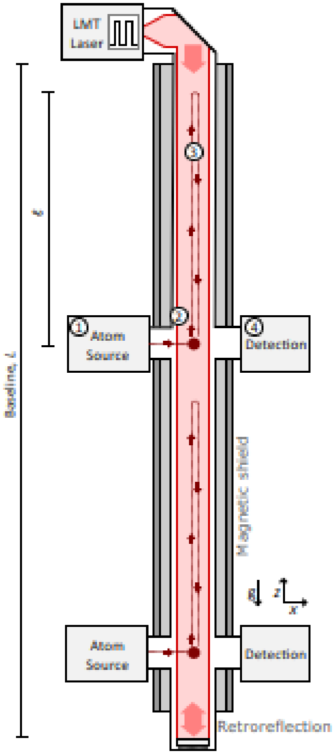
AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

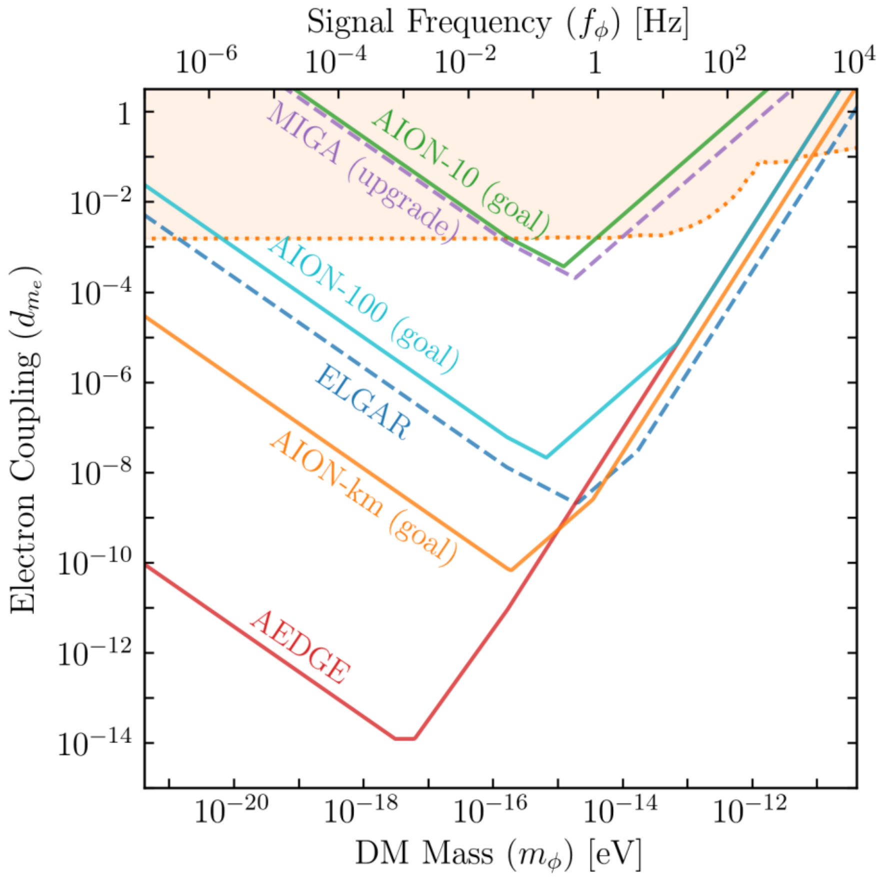


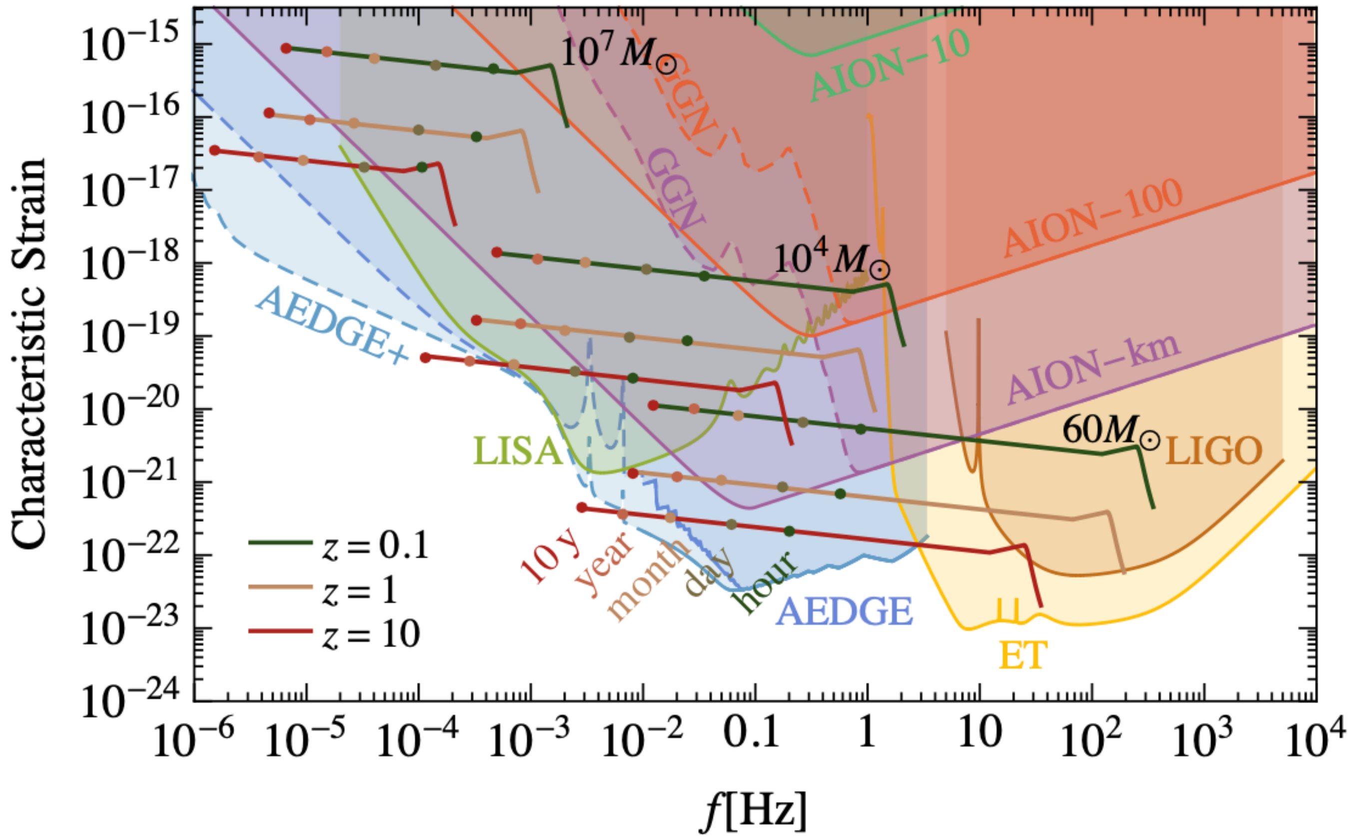


Coupled atom sources have a larger potential for measurement of Gravitational Waves and Dark Matter. AION-10 in Oxford

Motivation for atom interferometer

Unlocking the potential for observation of Ultra-Light Dark Matter and Gravitational Waves from cosmological and astrophysical sources in the unexplored mid-frequency band



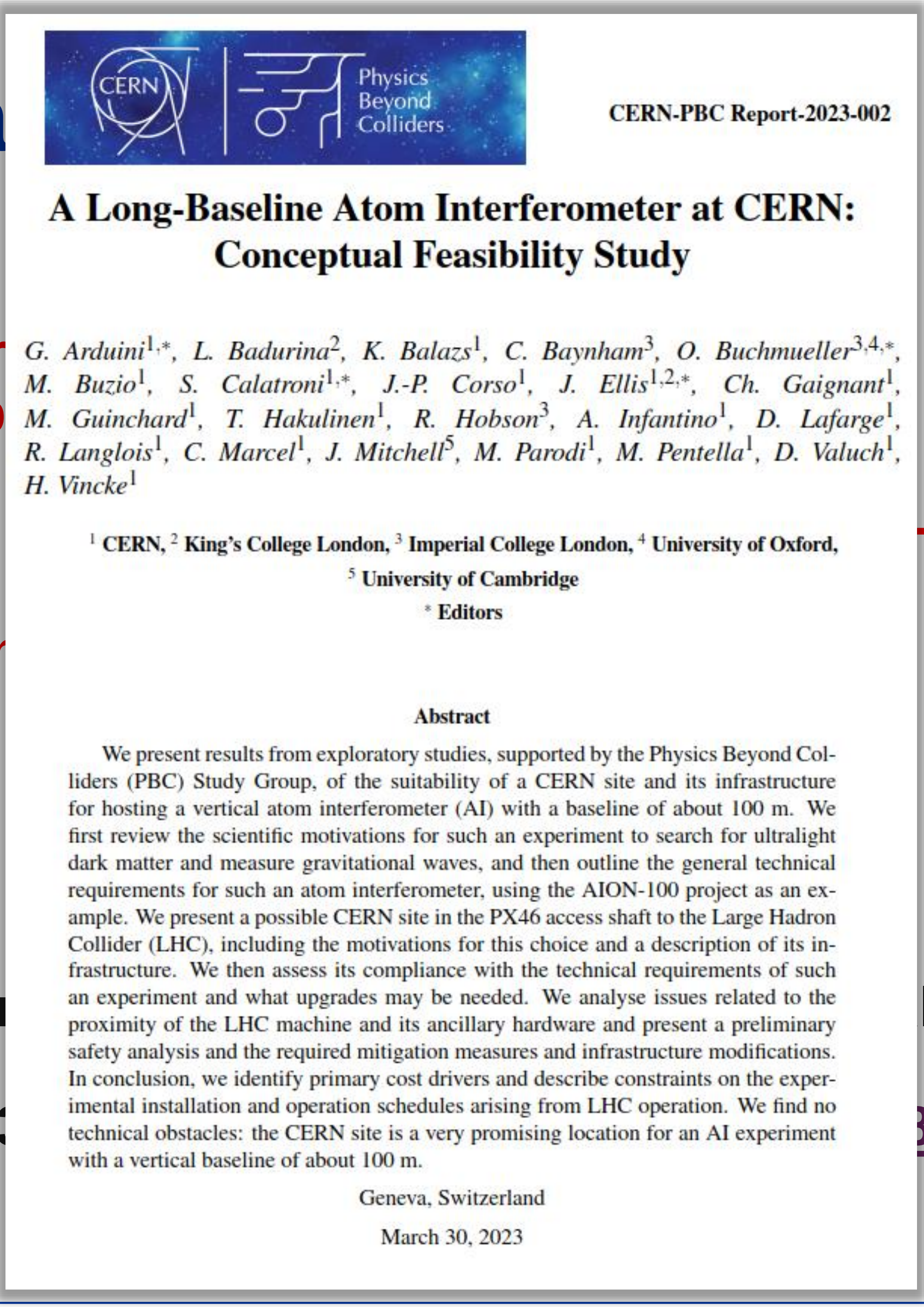


Scope of the fea

- Identify location for a ver m deep at CERN, in a location always accessib
- Assess technical feasibil HC machine
- Based on AION-100 techn

Outcome:

- "A Long-Baseline Atom I l Feasibility Study"
- CERN-PBC-REPORT-202 351946



Physics Beyond Colliders

CERN-PBC Report-2023-002

A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study

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[1] CERN, [2] King's College London, [3] Imperial College London, [4] University of Oxford, [5] University of Cambridge

[*] Editors

Abstract

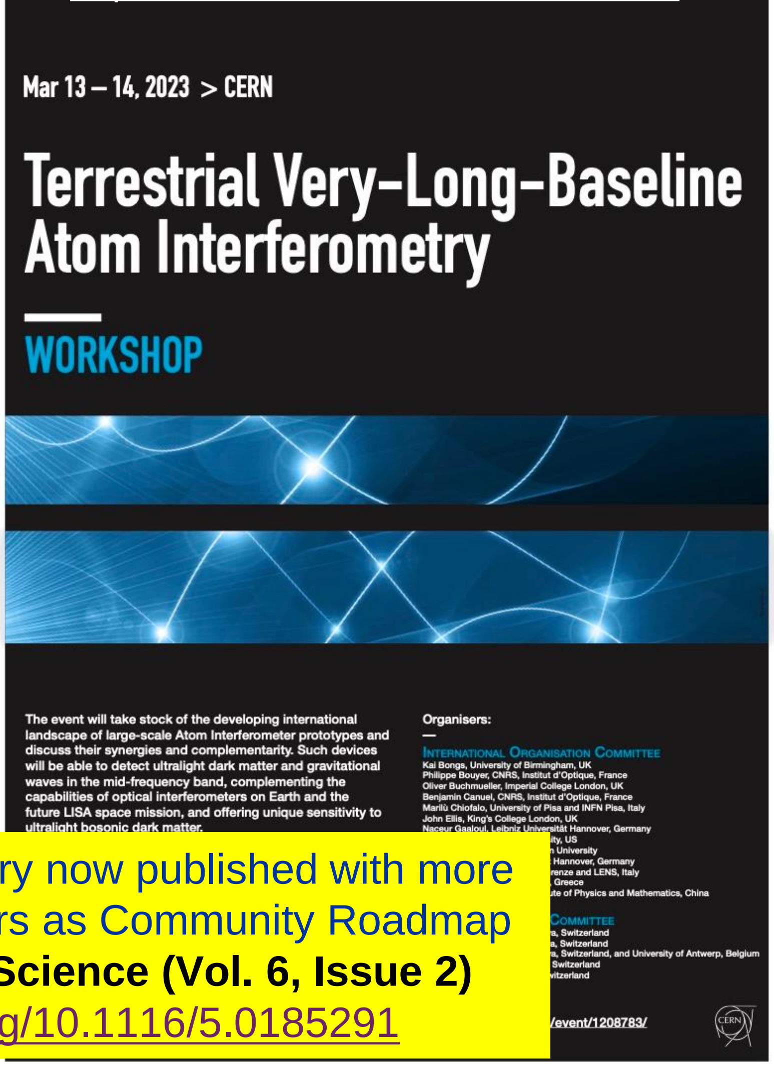
We present results from exploratory studies, supported by the Physics Beyond Colliders (PBC) Study Group, of the suitability of a CERN site and its infrastructure for hosting a vertical atom interferometer (AI) with a baseline of about 100 m. We first review the scientific motivations for such an experiment to search for ultralight dark matter and measure gravitational waves, and then outline the general technical requirements for such an atom interferometer, using the AION-100 project as an example. We present a possible CERN site in the PX46 access shaft to the Large Hadron Collider (LHC), including the motivations for this choice and a description of its infrastructure. We then assess its compliance with the technical requirements of such an experiment and what upgrades may be needed. We analyse issues related to the proximity of the LHC machine and its ancillary hardware and present a preliminary safety analysis and the required mitigation measures and infrastructure modifications. In conclusion, we identify primary cost drivers and describe constraints on the experimental installation and operation schedules arising from LHC operation. We find no technical obstacles: the CERN site is a very promising location for an AI experiment with a vertical baseline of about 100 m.

Geneva, Switzerland

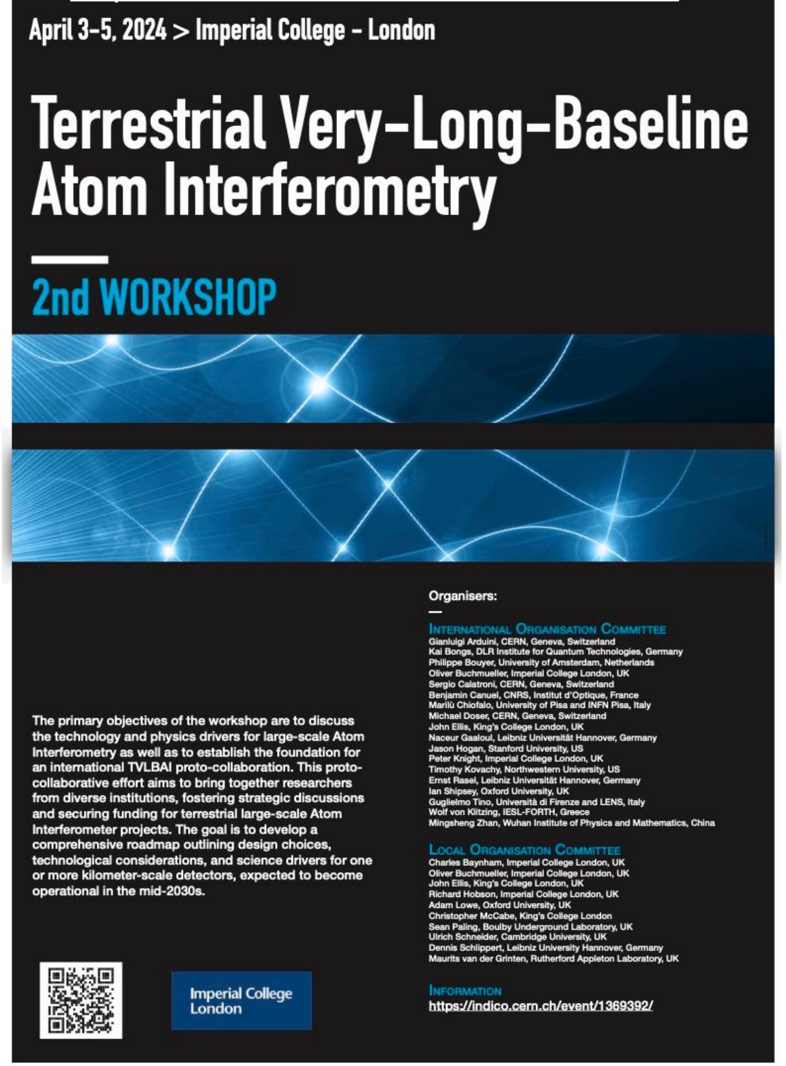
March 30, 2023

TVLBAI workshop series launched

https://indico.cern.ch/event/1208783/

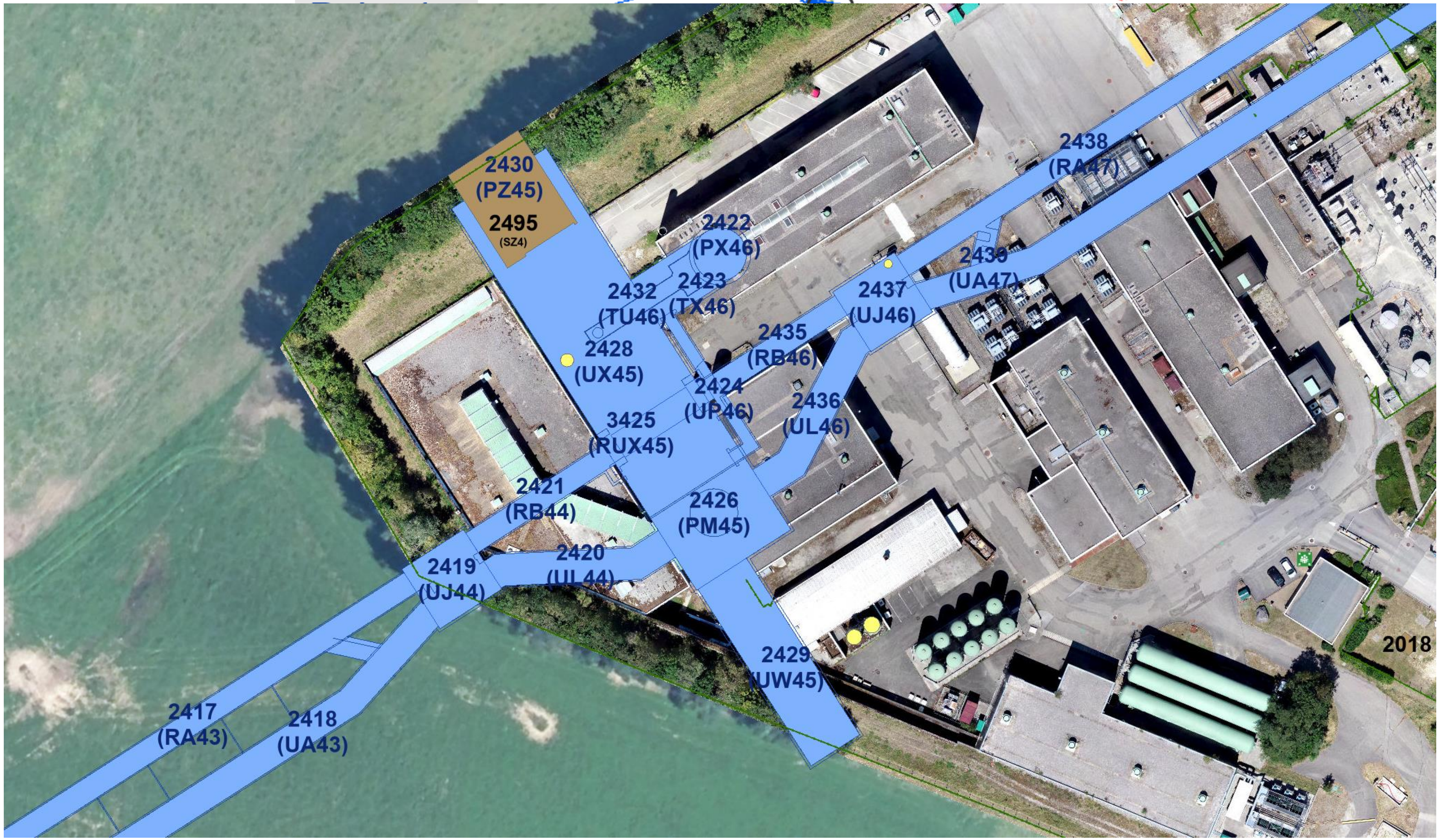


https://indico.cern.ch/event/1369392/



Workshop Summary now published with more than 250 co-authors as Community Roadmap
AVS Quantum Science (Vol. 6, Issue 2)
https://doi.org/10.1116/5.0185291

LHC Point 4



2430
(PZ45)
2495
(SZ4)
2422
(PX46)
2432
(TU46)
2423
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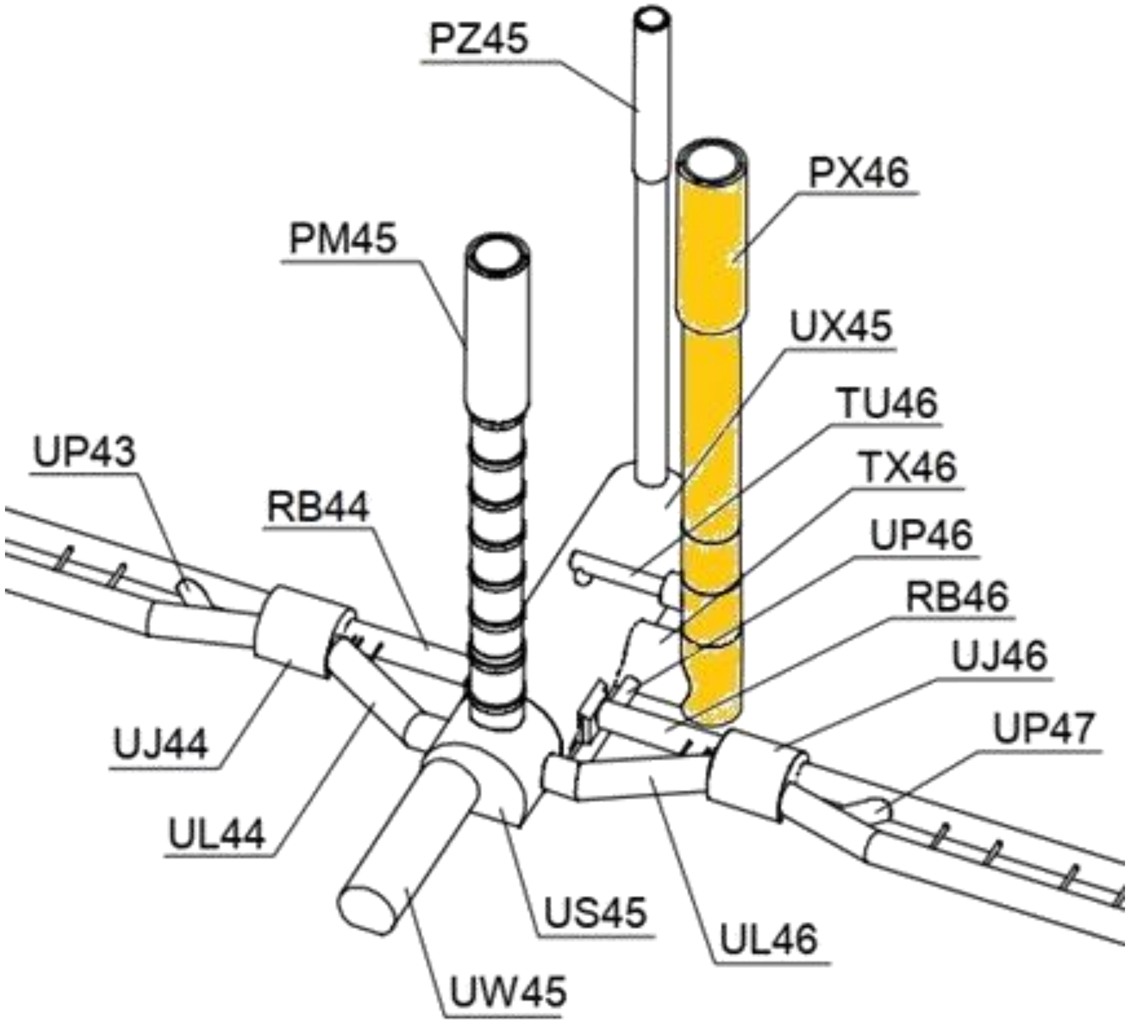
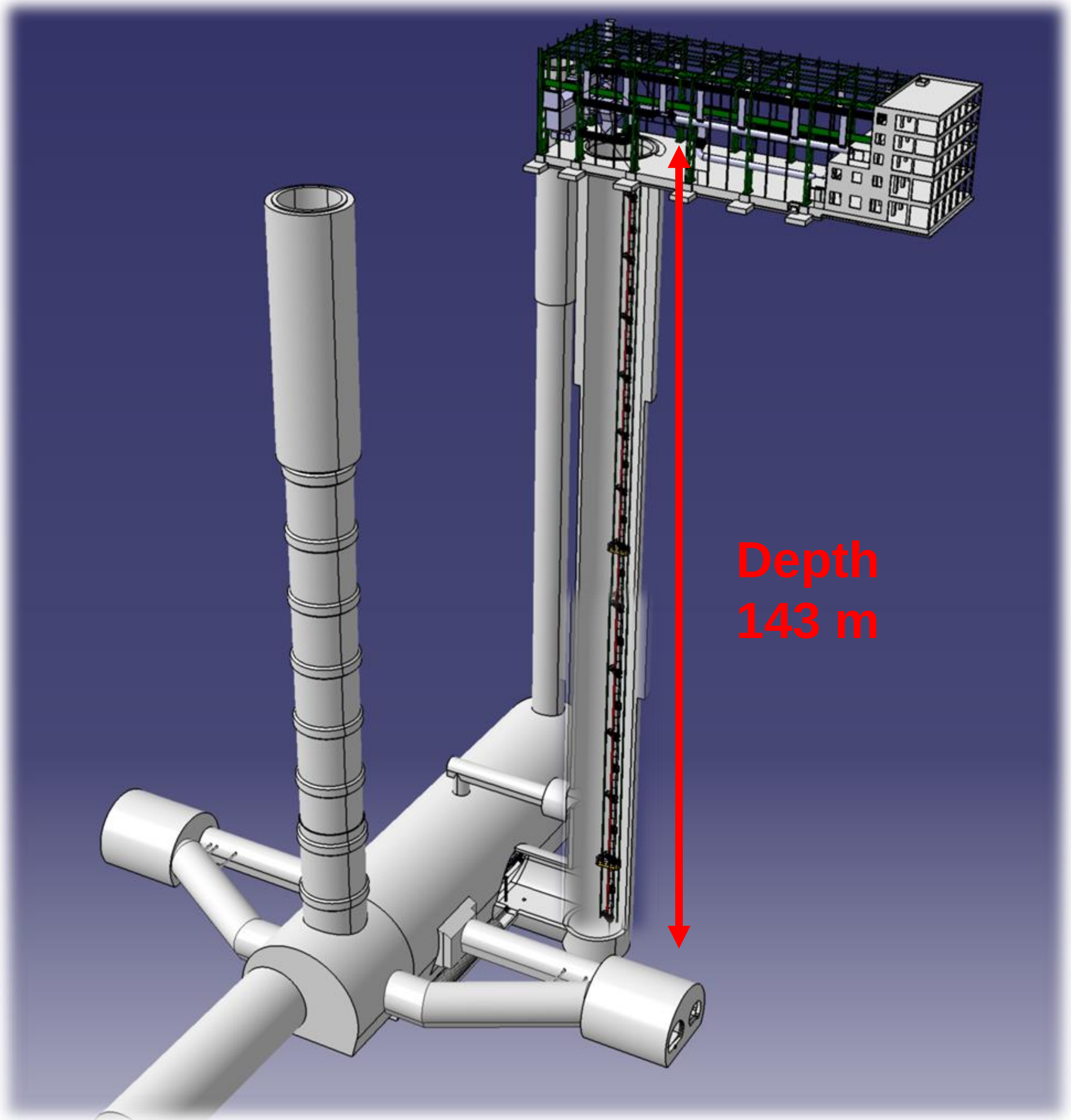
2018

Selected location: PX46



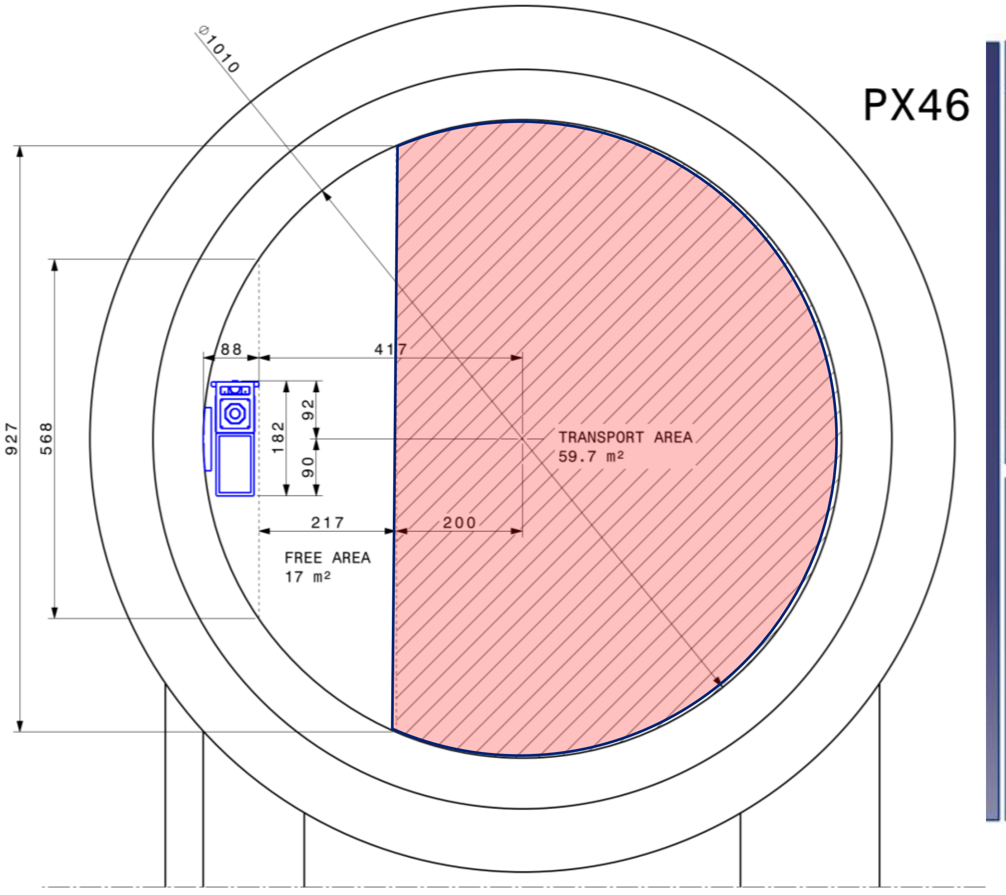


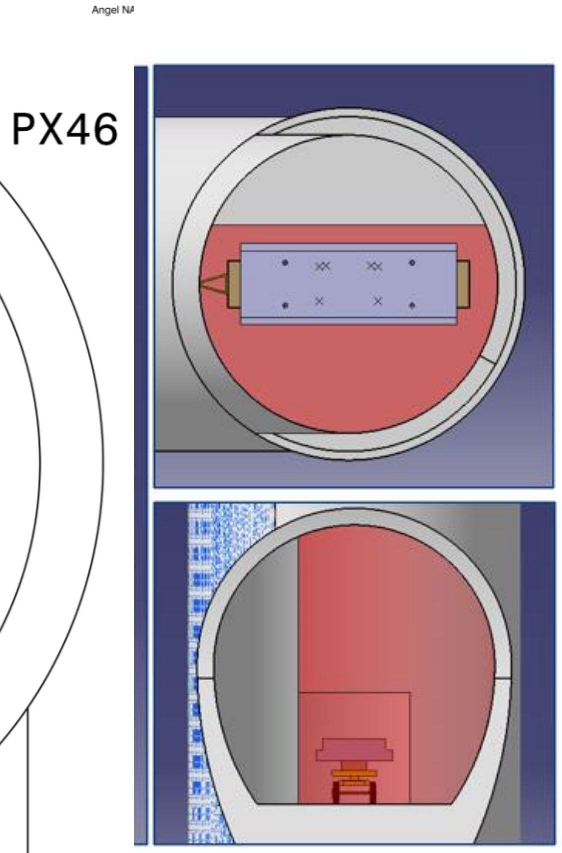
Selected location: PX46

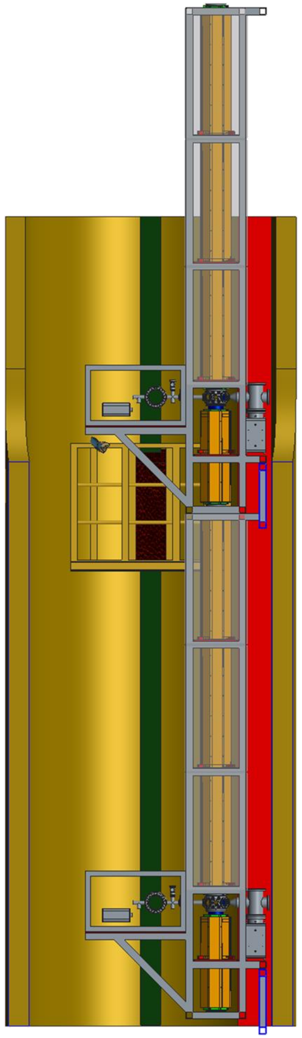
Views at the surface

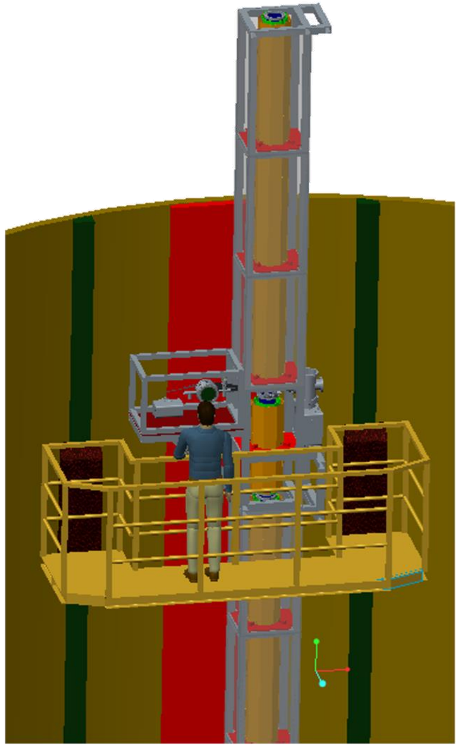
View from below

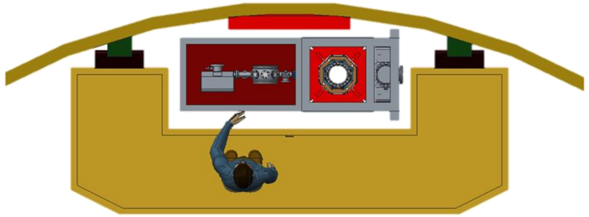
Transport of LHC components and proposed layout







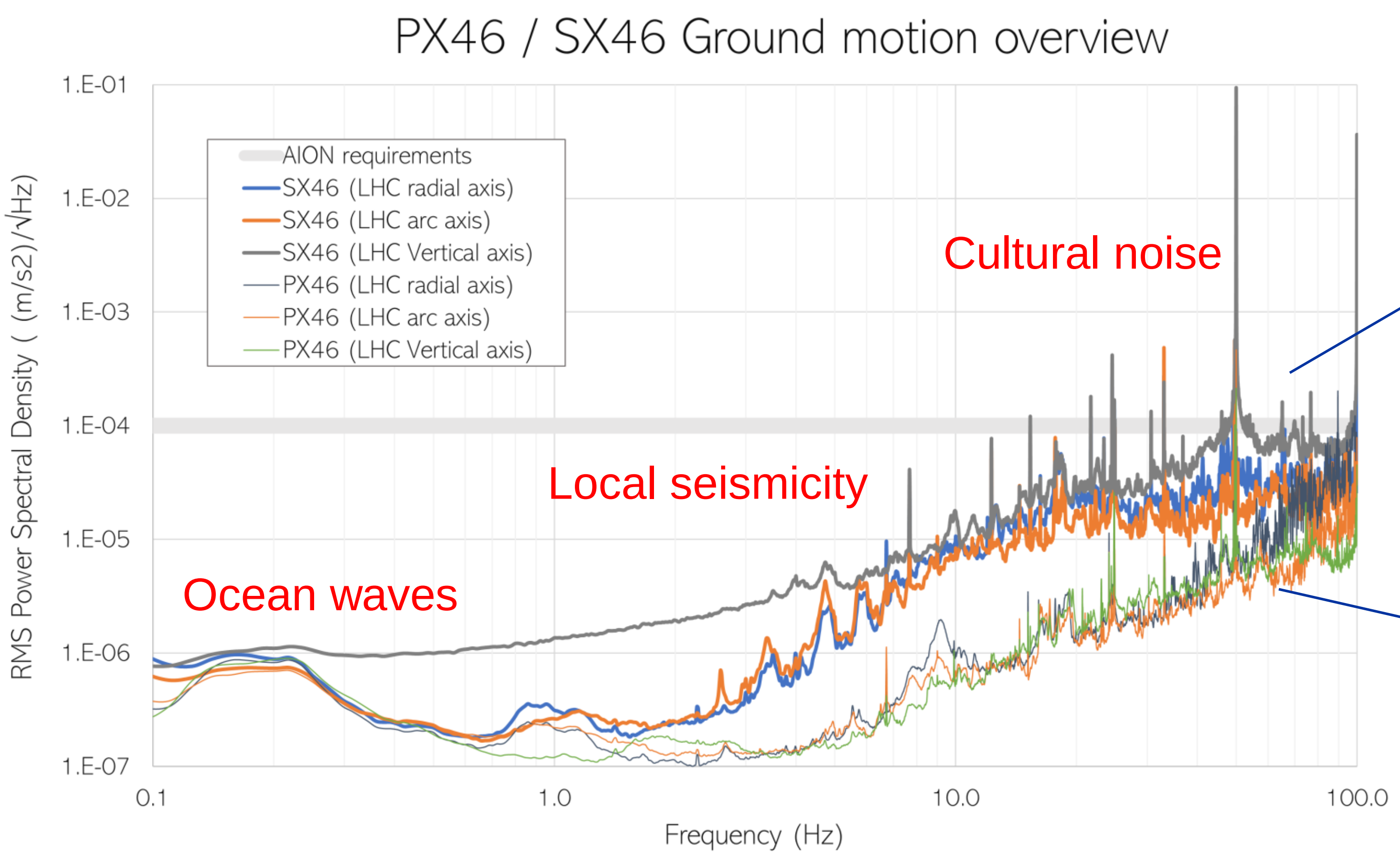




Evaluation of PX46 as suitable site for an AI
Can the AI in PX46 be accessed at all times?

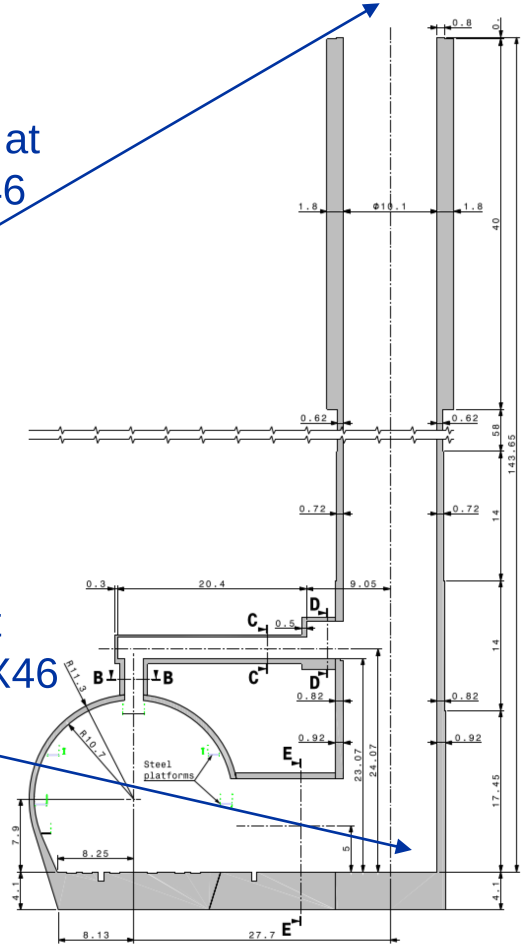
- **Compatibility with technical requirements for an AI – influence of the LHC**
  - Vibrations, seismic noise and local geology
  - EM noise
  - Radiation protection
  - Fire safety
  - He release hazards
  - Access control
- **Available infrastructure**
  - Electrical supply, network, etc.
  - HVAC

Vibrations and seismic noise



Measured at top of PX46

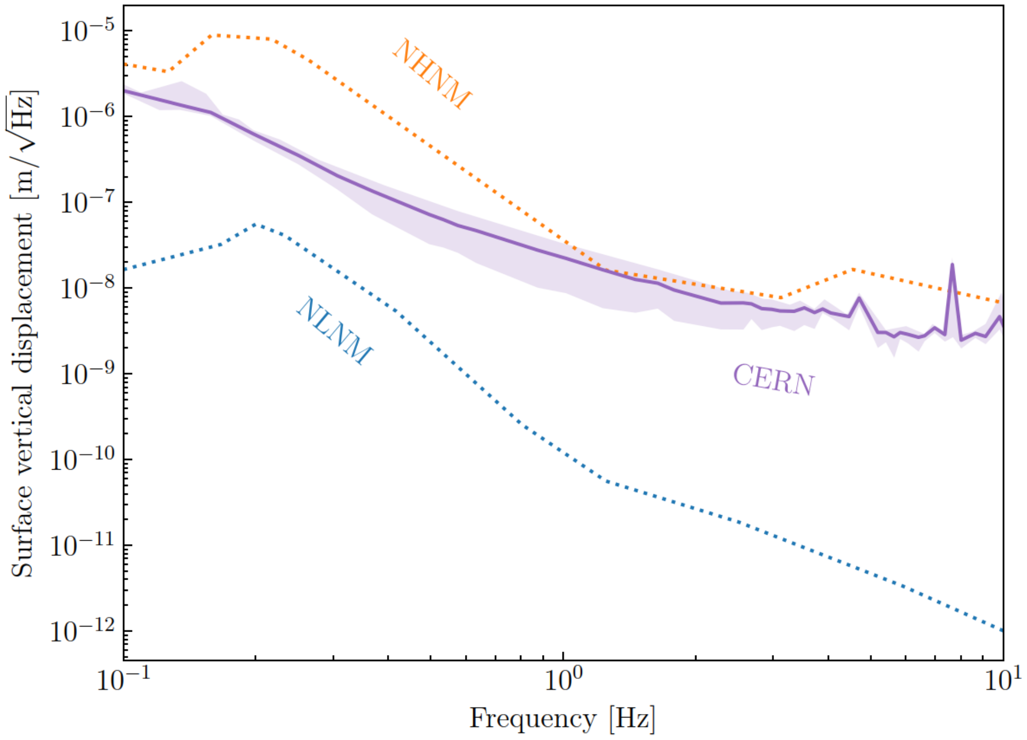
Measured at bottom of PX46



RMS power spectral density (time block 64s, averaged over the worst day)

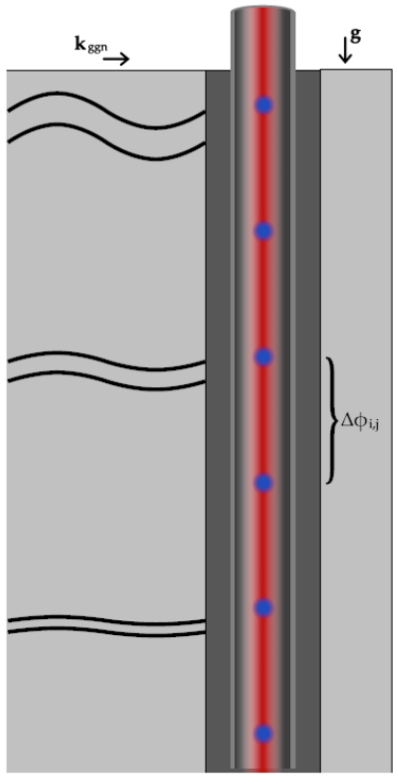
✓ Measured values within acceptable limits

Effect of local geology: gravity gradient noise

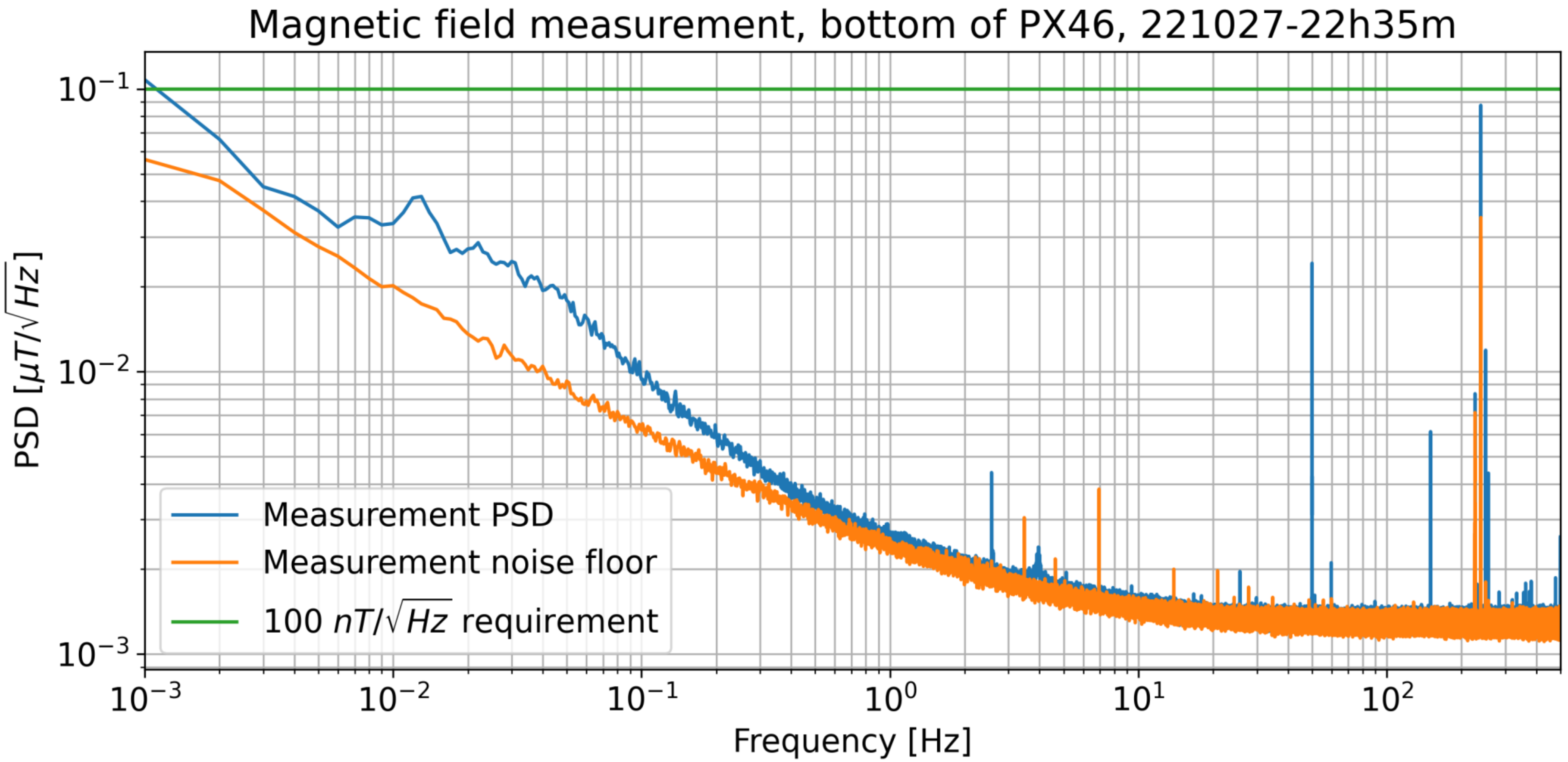


Seismic gravity gradient noise (GGN): seismic waves disturb local mass distribution, cause oscillating gravity gradient that is a noise background (especially important at lower frequencies)

Calculated using RMS spectral density of surface vertical displacement measurements, the shaded band corresponds to the difference between the minimum and maximum daily measurements. Compared with the New High and Low Noise Models (NHNM and NLNM: USGS seismic models for hypothetical quiet and noisy sites).



EM noise



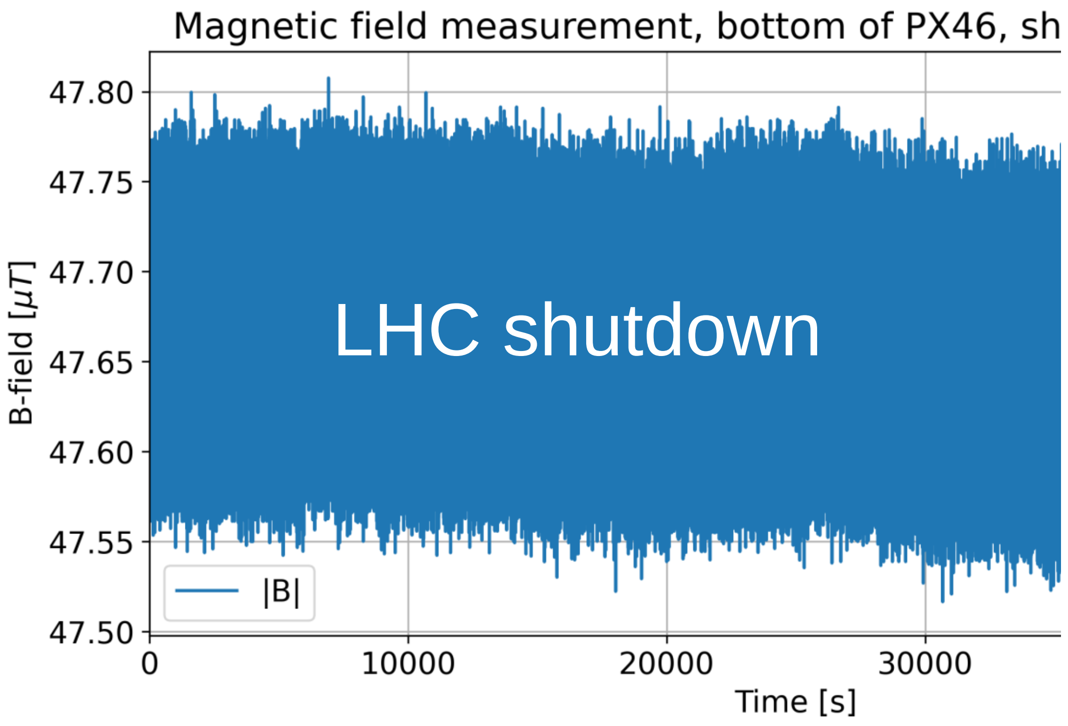
Power spectral density low-frequency magnetic field measurement

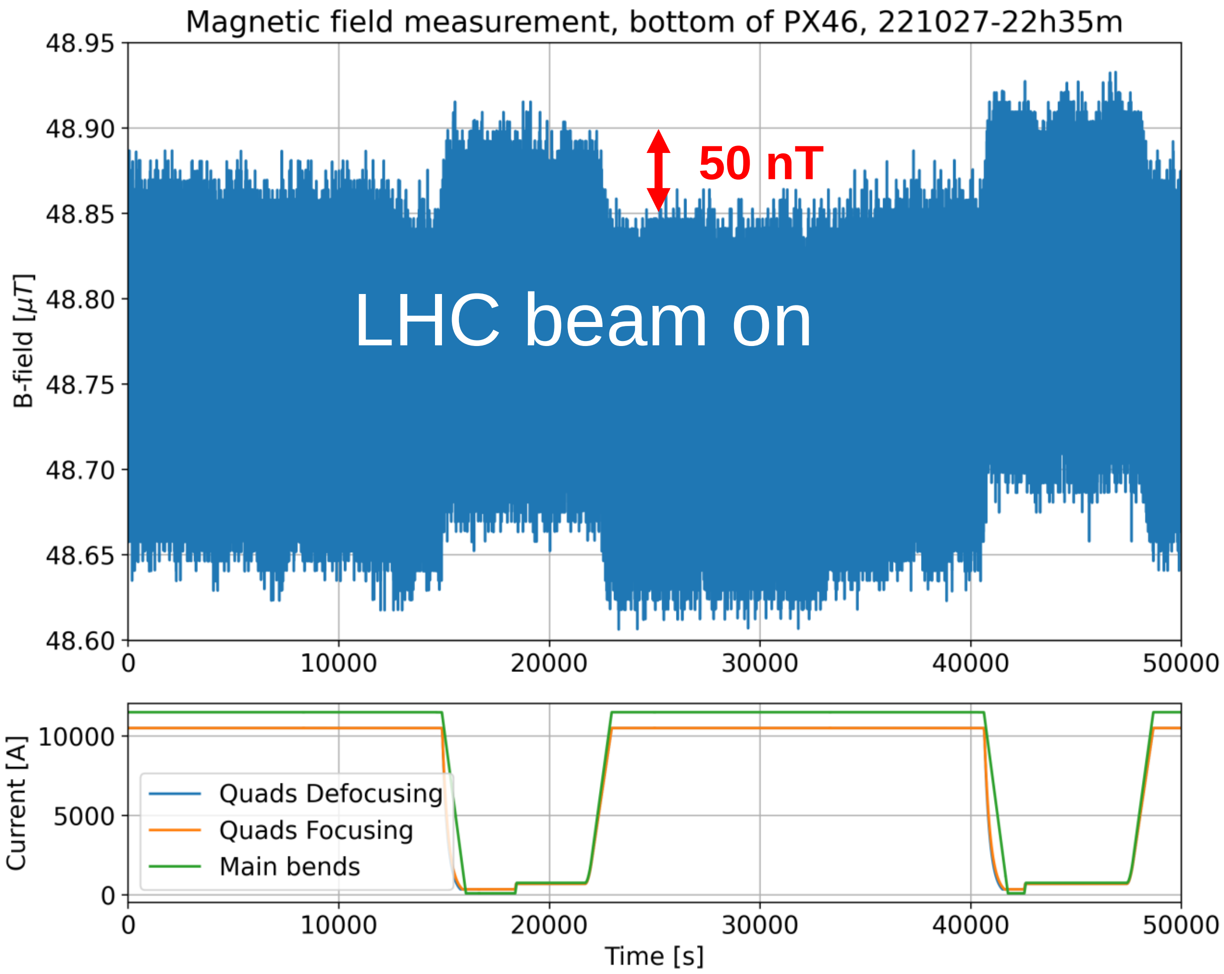
✓ Measured values within acceptable limits

Installation 2022 (thanks EN-MME, EN-ACE, EN-HE, EN-CV)

With the measurement probe

Effect of LHC magnets

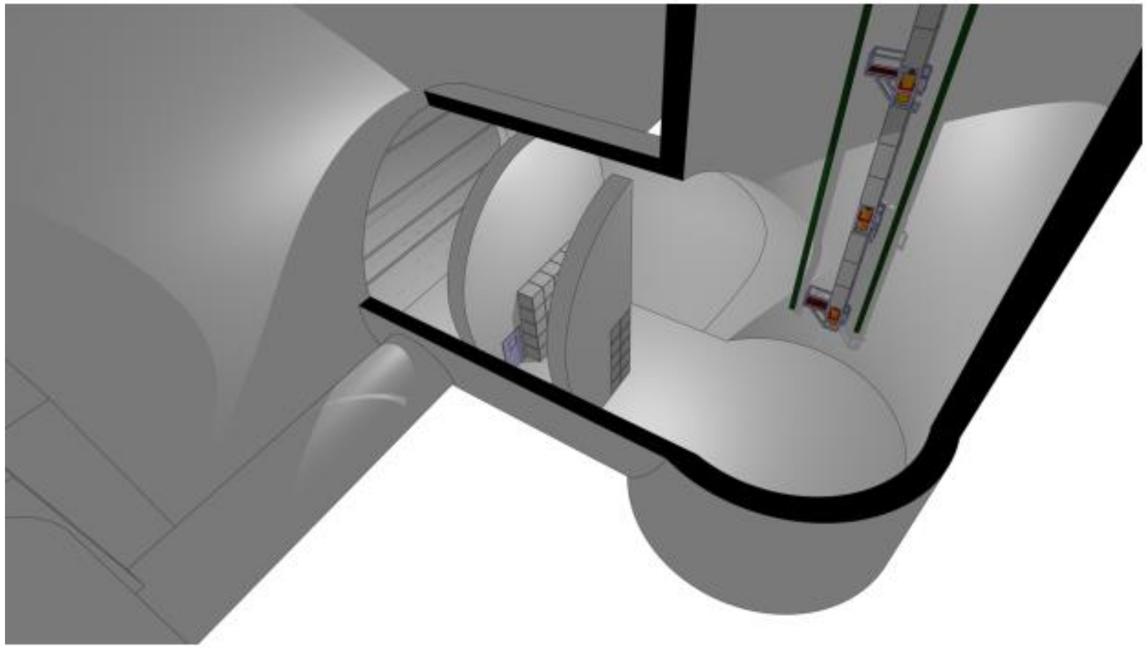




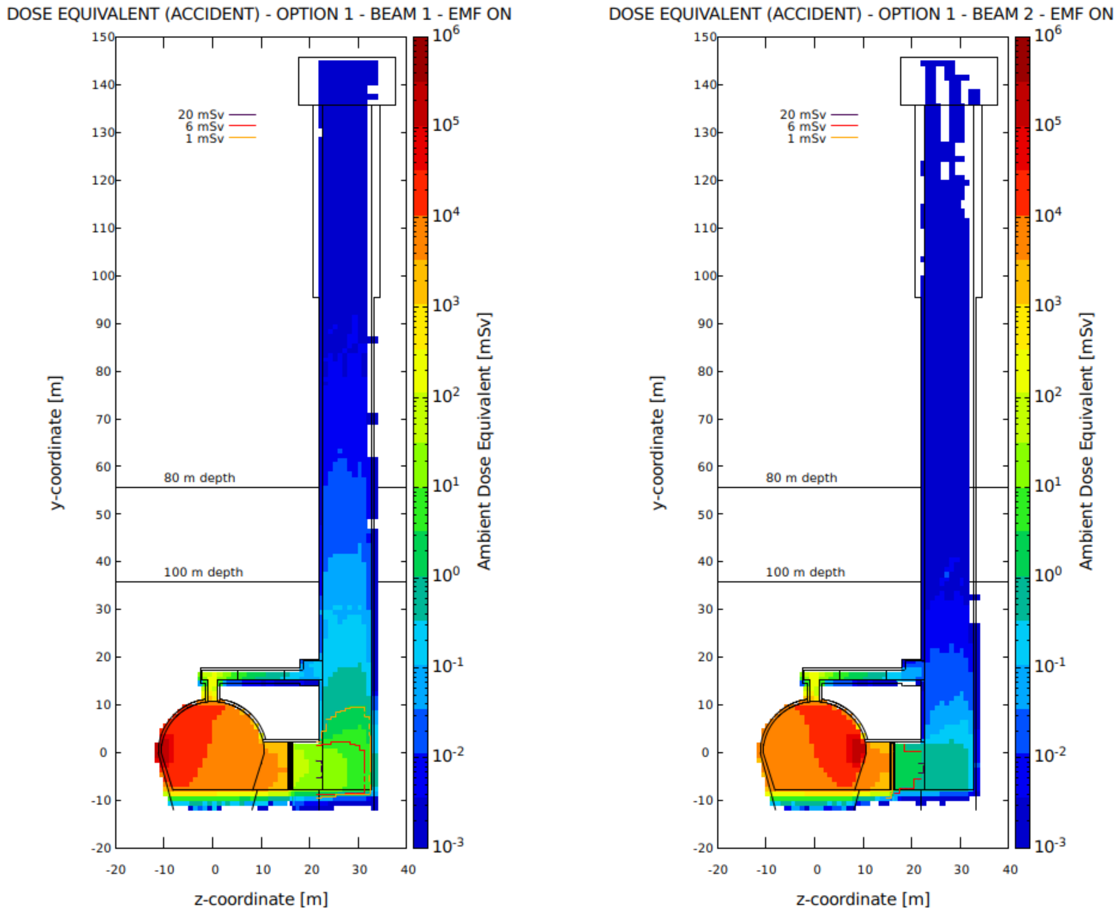
Drift or steps in magnetic field of ≳50nT are a potential concern for the side-arms and the detector.

- ➢ Measured values within acceptable limits

Radiation protection



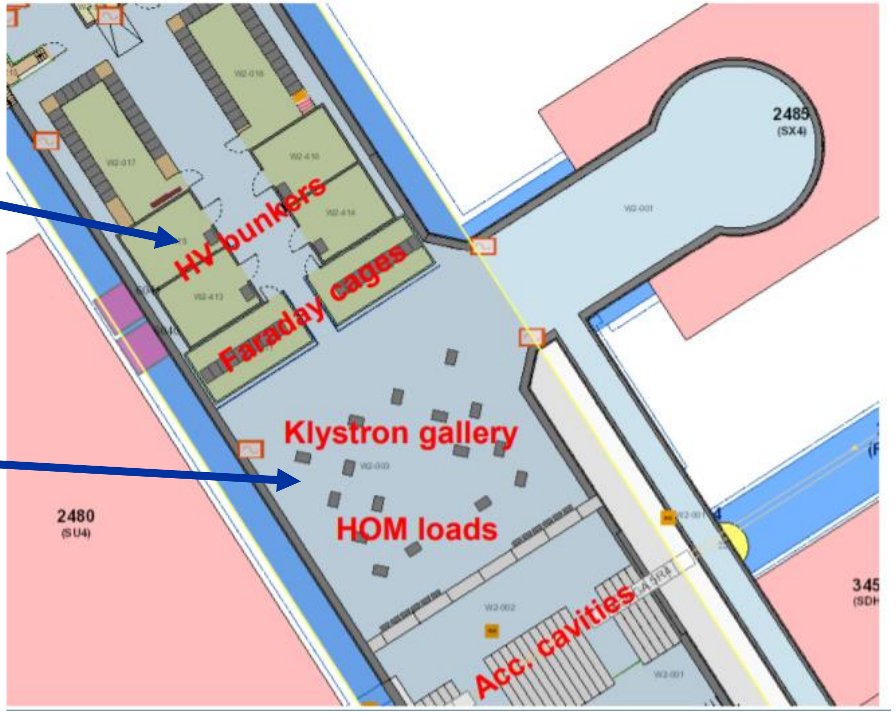
Beam loss in RUX45 with 0.8 m shielding in TX46

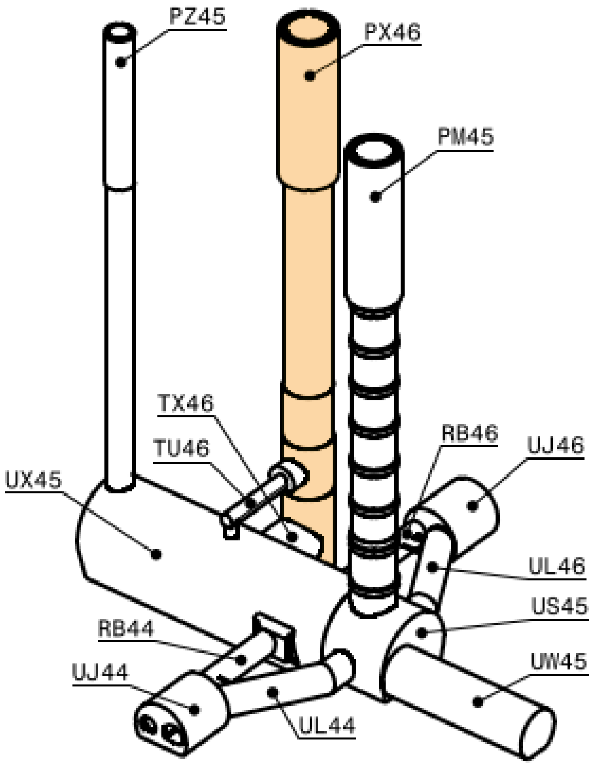


Area	Annual dose limit E [mSv] year	Assuming 20% working time Ambient dose equivalent rate $\dot{H}^*(10)$ [μSv/h] permanent occupancy	low occupancy
Non-designated	1	0.5	2.5
Supervised	6	3	15

- No concern during normal LHC beam operations
- In case of beam loss, radiation levels remain within acceptable limits (supervised area)
- Thickness of shielding wall to be optimized

Fire safety

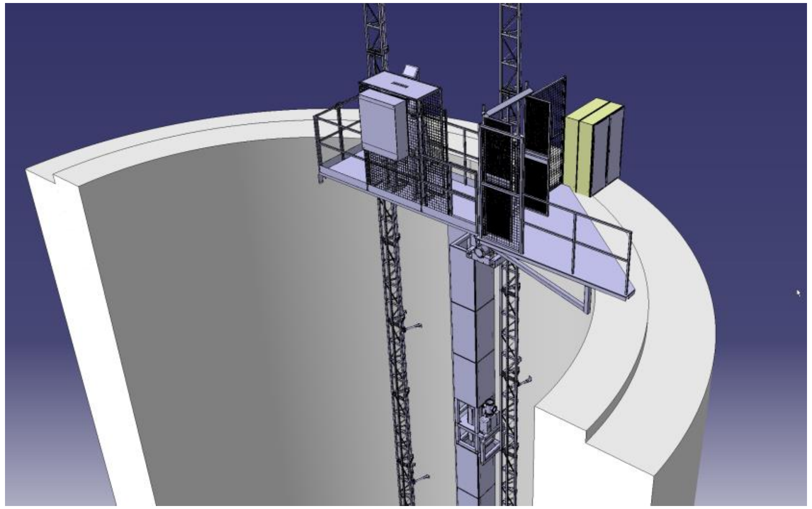


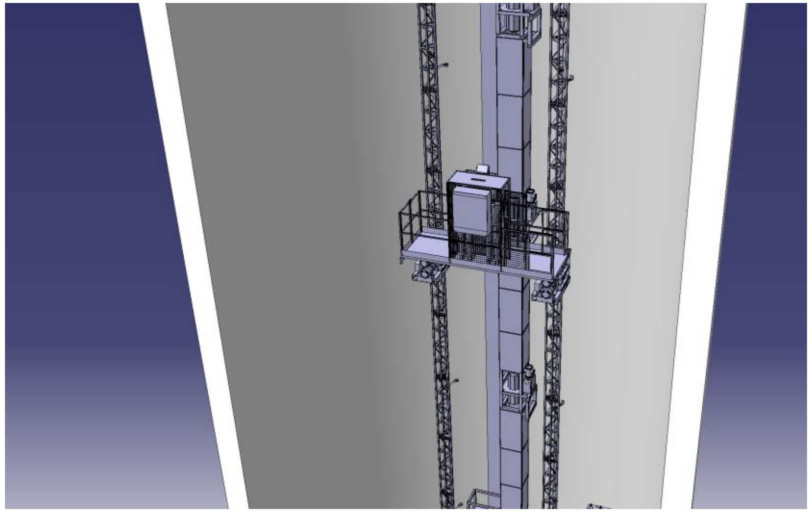


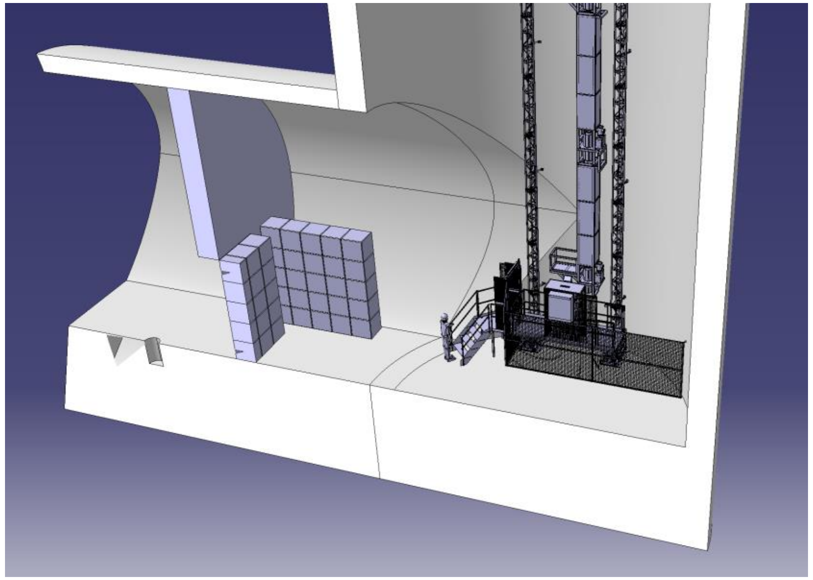
In case of a fire in UX45 (klystron gallery):

- Smoke detection -> Alarms -> Evacuation with elevator in ~2 min via top of PX46
- In case of systems failure: controlled descent in ~2 min to bottom of PX46 and exit via PM45 or PZ45

Elevator: from artist view to conceptual design



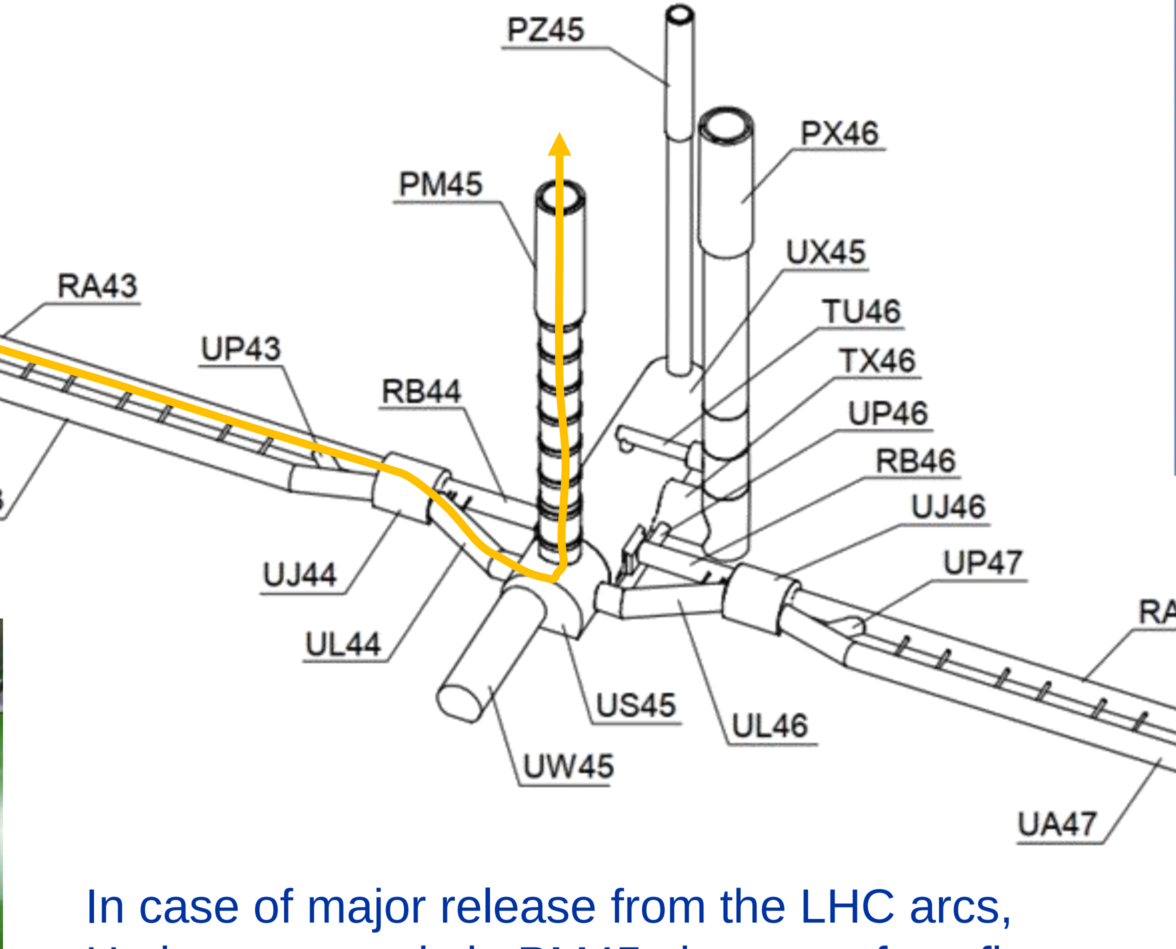


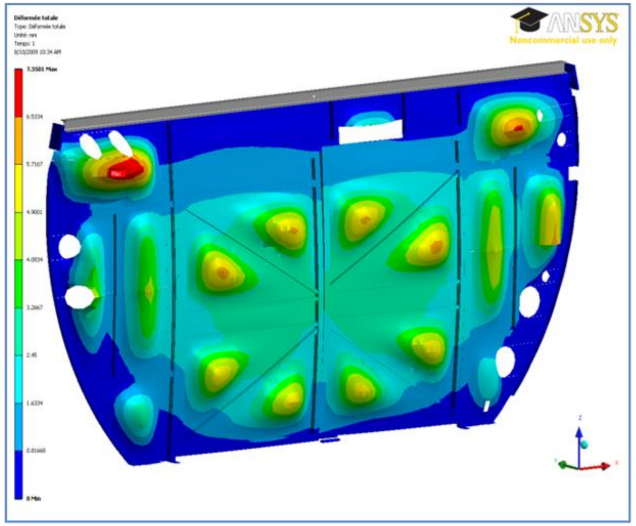


A design that complies with all requirements is technically feasible as demonstrated by an external consultant:

- Powered from electrical network
- Backup battery powered
- Controlled descent in case of battery failure

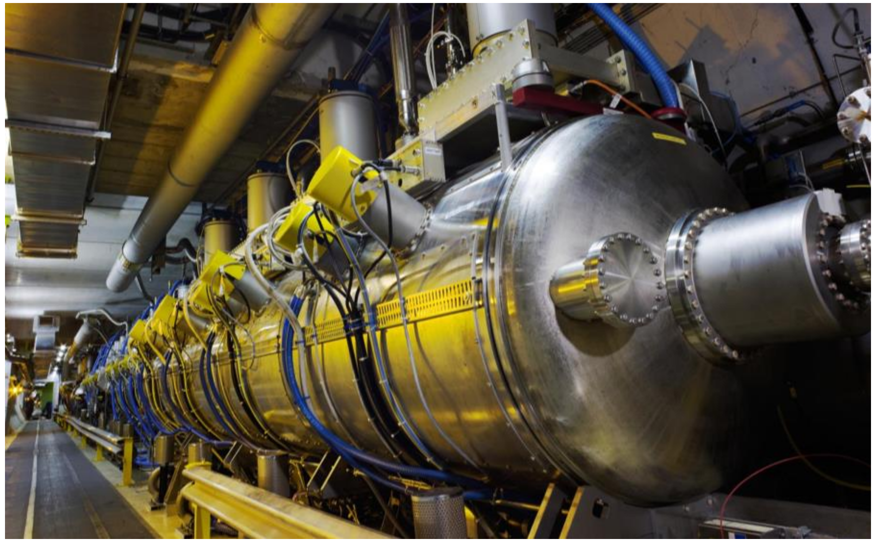
Helium release safety: LHC arcs

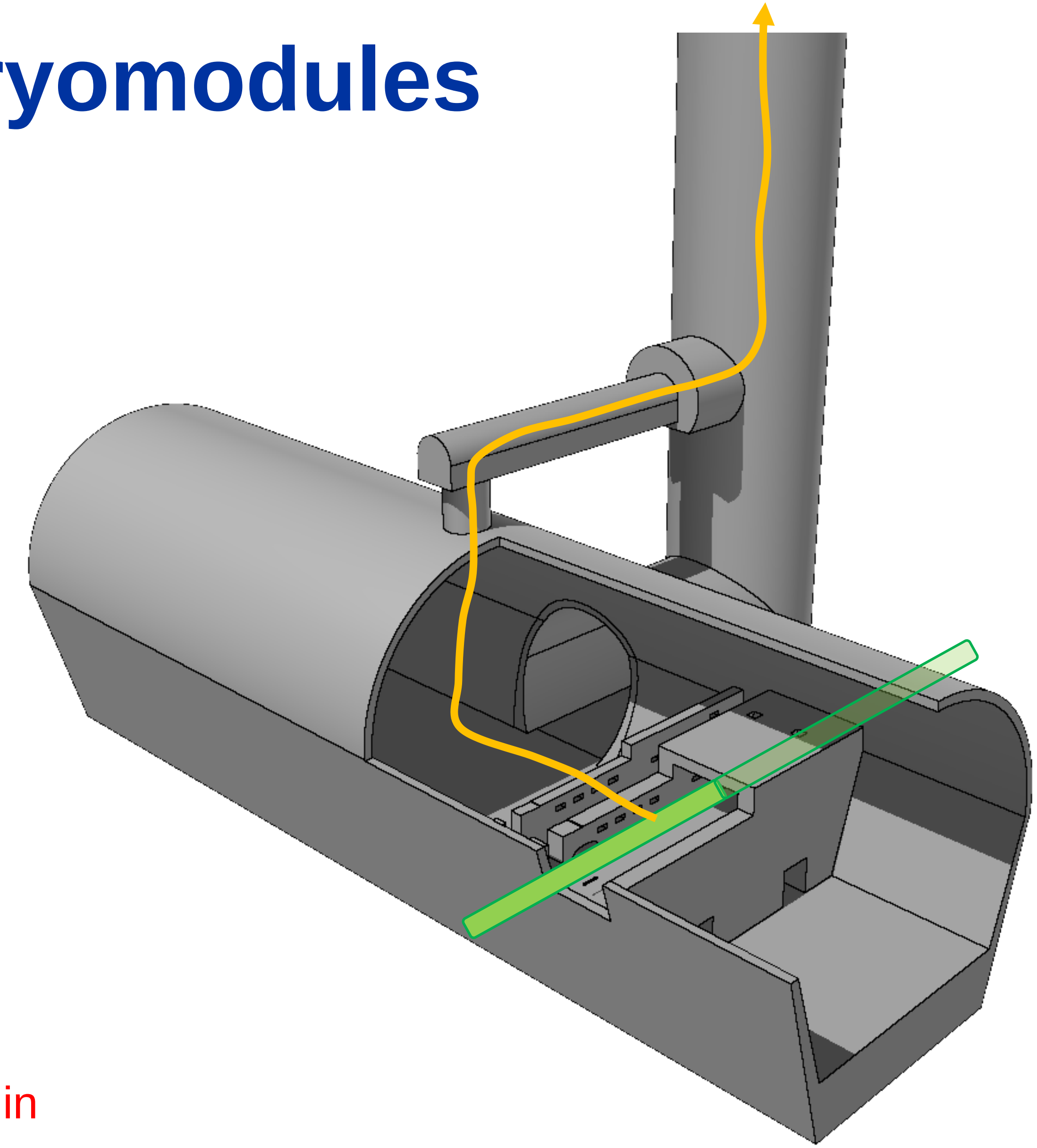




In case of major release from the LHC arcs,
He is evacuated via PM45 via a set of confinement doors
- ➢ No hazard in PX46 from He release in the LHC arcs

Helium release safety: RF cryomodules

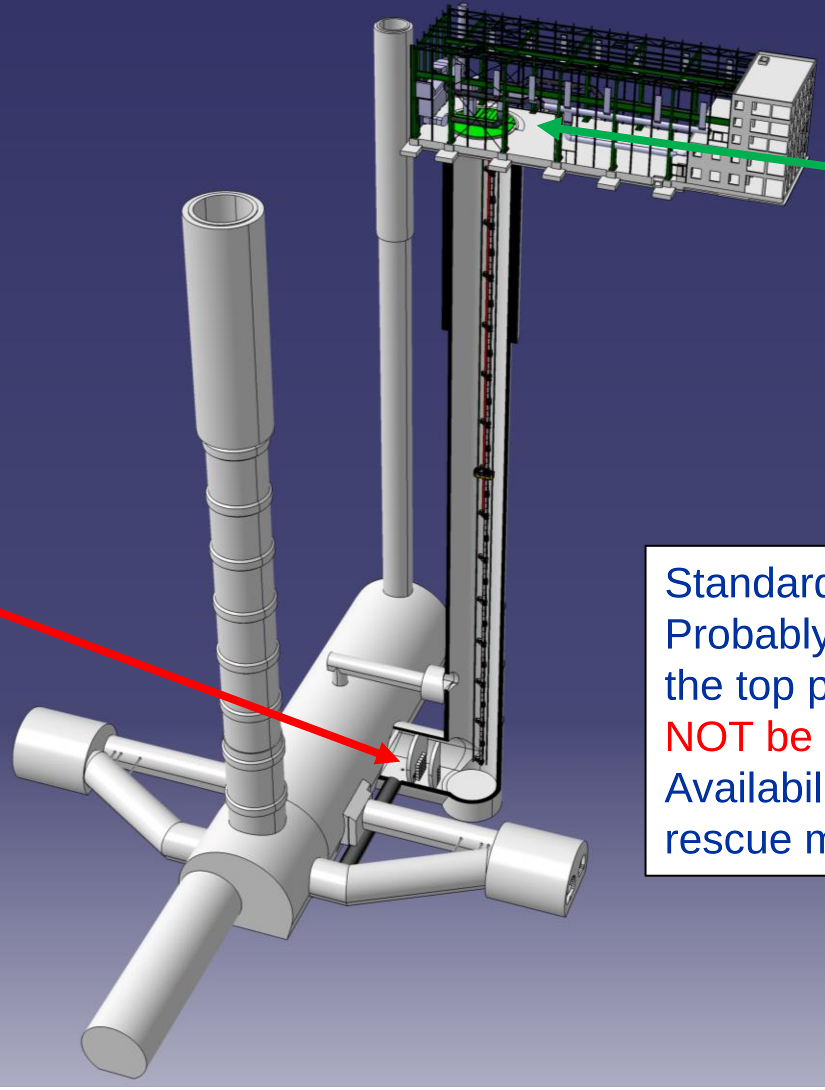




- RF cryomodules contain 320 x 4 liters of liquid He; in case of release it is evacuated via PX46
- Flow restrained by the small openings (RF waveguides)
- 970 m^3 of gas compared to 18000 m^3 of the cavern (<~ 20%), oxygen deficiency hazard is limited

➢ Measured in 2023 (info T. Hakulinen) : no change in O_2 % in TU46 due to He release from RF cryomodules

Access control



End-of-zone door of the LHC Access Safety System (LASS), for emergency exit at the bottom of PX46
Red in color and including an emergency opening handle on both sides

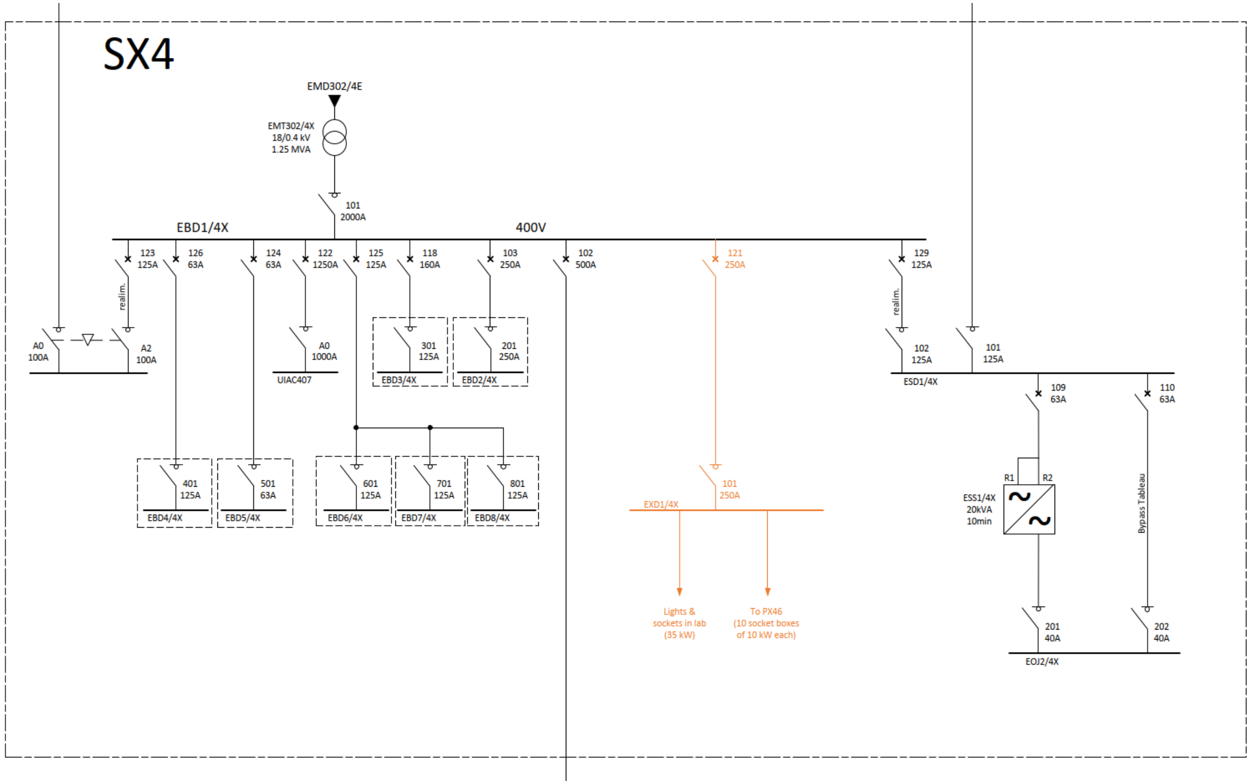
Standard LHC Access Control System (LACS) door. Probably a lightweight solution could be installed at the top platform of PX46, since access to the AI will NOT be an access to the LHC.
Availability and use of oxygen-generating self-rescue masks to be assessed

Technical requirements

Requirement	Laser Lab	Interferometry region	Side-arm (per side-arm)
Volume	Floor area $> 50\,\mathrm{m}^2$	$1\ \mathrm{m}^2$ cross-sectional area	$1\ \mathrm{m} \times 1\ \mathrm{m} \times 2\ \mathrm{m}$
Mains power	$\sim 35\,\mathrm{kW}$ (three- and single-phase outlets)	$\mathcal{O}(100\,\mathrm{W})$ diagnostic and monitoring electronics	$\mathcal{O}(10\,\mathrm{kW})$
Control cables	Ethernet, fibre, coaxial	Magnetic coils, diagnostic and monitoring electronics	optical fibres, coaxial, high-power steel-clad fibers
Temperature stability	$22\,^\circ\mathrm{C}$ w/ $\pm\ 1\,^\circ\mathrm{C}$ pk-pk	$< 1\,^\circ\mathrm{C\,h^{-1}}$	Temperature controlled, NEMA rated enclosure, $< 0.5\,^\circ\mathrm{C}$ pk-pk
Water cooling	$30\,\mathrm{kW}$ cooling capacity	n/a	$5\,\mathrm{kW}$ cooling capacity, $< \pm 1\,^\circ\mathrm{C}$ stability
Laser safety	Engineering (enclosures, interlocks); admin (training); PPE (glasses)	Already safe (enclosed)	Engineering (enclosures); admin (training); PPE (glasses)
Gases	Helium, compressed air, Argon	n/a	Helium for commissioning
Cryogenics	n/a	n/a	n/a
Ventilation	Air-handling unit capable of temp. spec.	Air-flow to maintain temp. spec.	Air-flow to move $5\,\mathrm{kW}$ of heat
Access	Year-round ($>$ 12 hrs/day)	Access for maintenance (more access during calibration and commissioning)	Year-round $\sim$ 12 hrs/day (more R& D for fully autonomous atom sources)
Smoke detector	Yes	Yes	Yes
Oxygen depletion monitor	Yes	During maintenance	n/a
Hoisting equipment	n/a	Modular sections $<$ $907\,\mathrm{kg}$	n/a

PX46 - Existing conditions: electricity

- **About 160 kW needed: interferometer + laser laboratory + elevator**
- **About 1.25 MVA available at the transformer in SX4 in front of a present consumption of 85 kVA**
- **As a consequence, no modifications of the electrical power distribution network are expected**



New preliminary single line diagram of SX4, with the new feeder of EBD1/4X, the new switchboard EXD1/4X and its feeders in orange

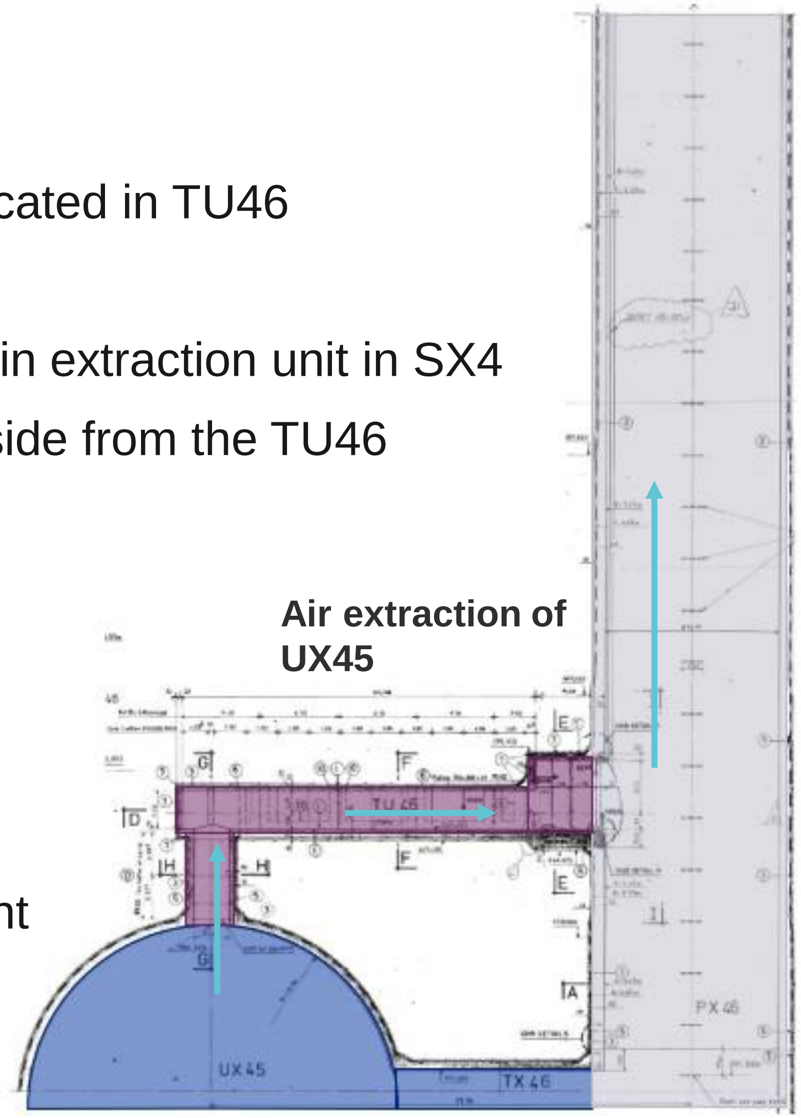
PX46 - Existing conditions: HVAC

Ventilation

- Air extraction from the UX45 is done at the top of the cavern by unit located in TU46
- Extracted air is then directly supplied in PX46 (no ducts in PX46)
- In surface, a duct is connected to the cap to collect extracted air to main extraction unit in SX4
- Existing CV platform at 24m from the bottom of the shaft, openable inside from the TU46
- All ventilation units are stopped if a fire is detected

Cooling

- Cooling system will be located on the surface and
- Water will be distributed to each side-arm
- Distribution piping will be installed along the full height of the experiment



Courtesy of R. Langlois

Conclusions and perspectives

- **No showstoppers identified for installing an AI at LHC Point 4**
  - Environmental noise measurements comply with requirements of an AI
  - Safety assessed and potential hazards identified
  - Mitigation measures related to LHC environment identified (RP, access control, etc.)
  - HVAC, electricity and other relevant services are available

- **Expected ~1.5 MCHF cost for making the site infrastructure available for an AI, granting an access 24h/24 for subsequent installation and running of the experiment**

Item	Cost [kCHF]
Shielding	400
Lifting platform	400
Access, safety systems and monitoring	200
General services and utilities	500
Total	**1500**

Class 5 estimates

Conclusions and perspectives

- **Next steps**
  - Creation of an experim ... ptual design study of an Atom Interferometer

Memorandum of Understanding
for the Terrestrial Very Long Baseline Atom Interferometer Study

THE INSTITUTES, LABORATORIES, UNIVERSITIES, FUNDING AGENCIES SIGNATORIES OF THIS MEMORANDUM OF UNDERSTANDING (“the Participants”)

Whereas

The scientific community wishes to draft a framework for the development and realization of Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) experiments, with a view to executing a Conceptual Design Study for a TVLBAI (the “TVLBAI Study”),

Signed by:

The Chair of the Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) Study	For the European Organization for Nuclear Research (CERN)
Signed by: Oliver Buchmueller 9784927EEEBB4B6...	DocuSigned by: Mike Lamont 3FE200FFB3CF46F...
Prof. Oliver Buchmueller TVLBAI Study Chair	Mike Lamont Director of CERN Accelerator and Technology Sector
Date: 9/18/2024	Date: 9/18/2024

Signed to date by 11 Institutes, more to come

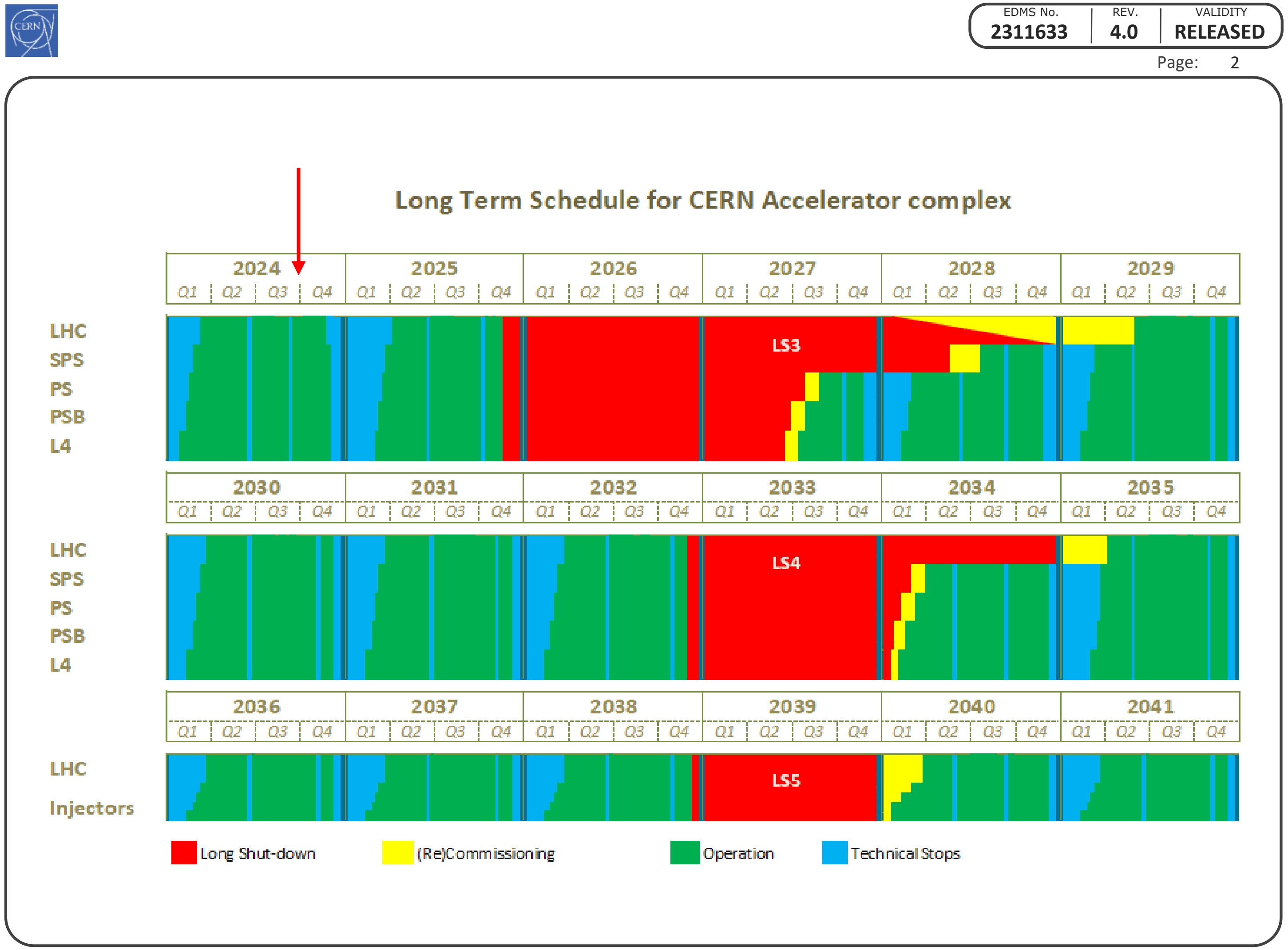
Conclusions and perspectives

- **Next steps**
  - Creation of an experimental collaboration aimed at performing the conceptual design study of an Atom Interferometer

  - Conceptual technical design, construction timeline and cost estimates for making PX46 available to the AI community for a future installation of an experiment
  - In particular -> Mandate received from Mike Lamont
    - Design of the shielding wall, in interaction between RP and CE with input from HE and AA
    - Access control and alarms design
    - Verification of CV needs (ventilation of the bottom of the shaft)
    - Assessment of immediate need of the elevator platform

  - Assess the time-frame required for detailed technical and execution design and for the construction and installation works: is LS3 a possible option?

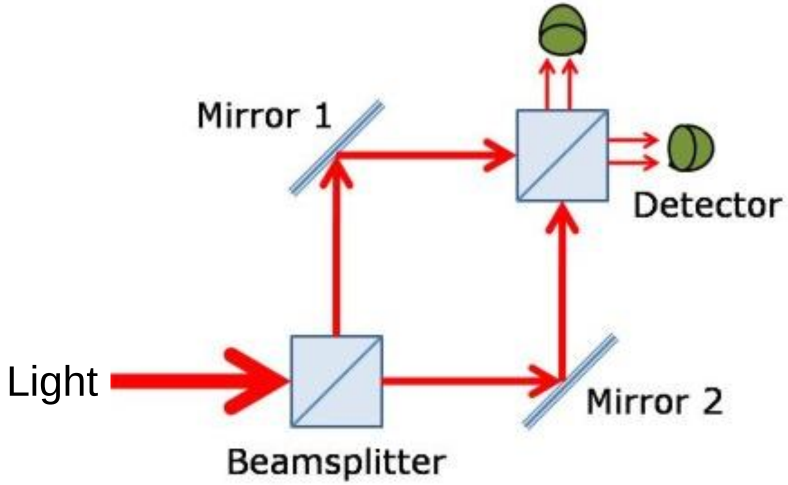
CERN accelerator complex master schedule

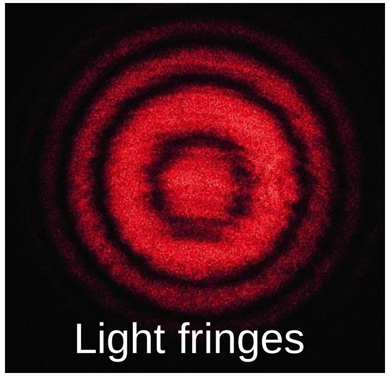


home.cern

Light vs. Cold Atoms: Atom Interferometry

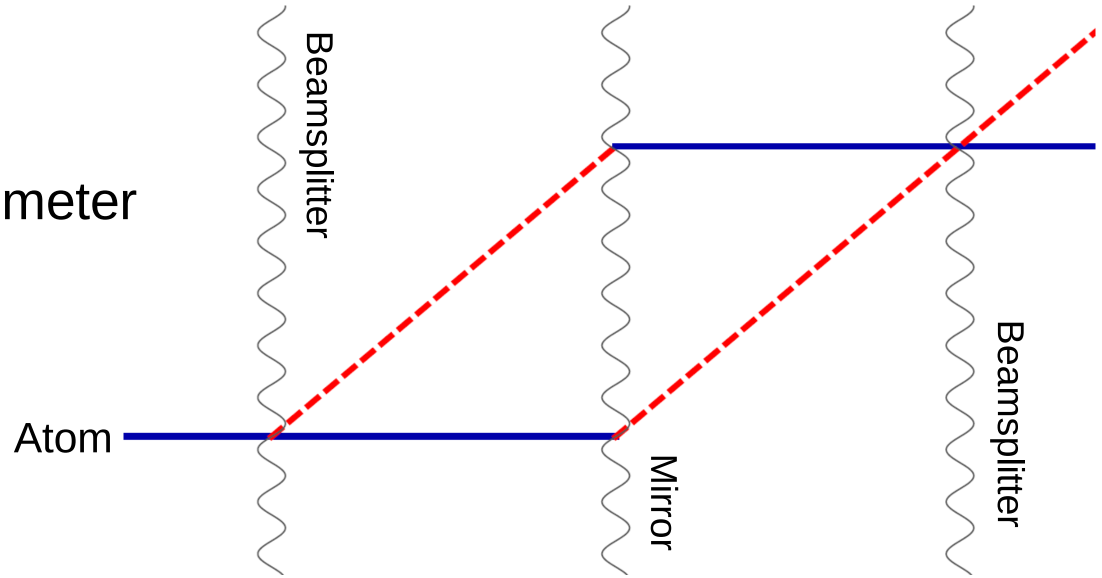
Light interferometer

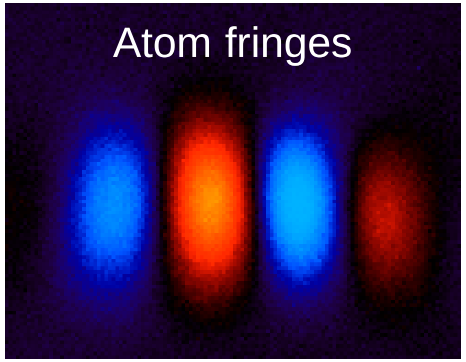




Interferometry of light waves

Atom interferometer





Interferometry of matter waves

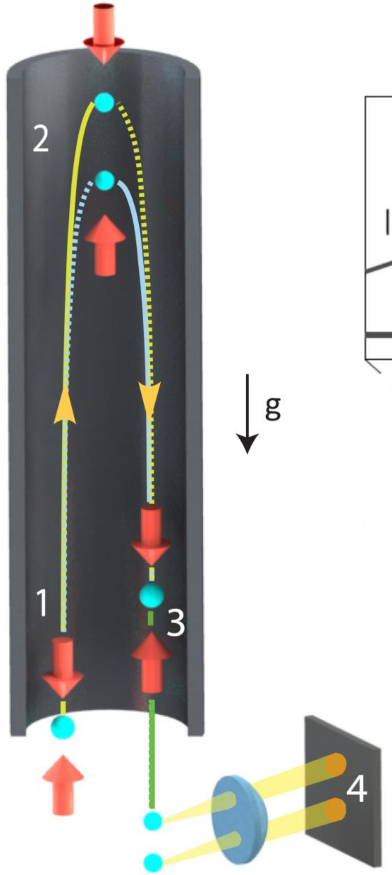
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

What is an atom interferometer? Based on atom clock

Light pulse atom interferometry

2) At t = T, the wave packet is fully separated, and a mirror sequence reverses the momentum states of the two halves of the cloud.

1) The ultra-cold atom cloud is launched vertically. At t = 0, the first laser beam splitter sequence splits the cloud into a superposition of momentum states separated by $n\hbar k$



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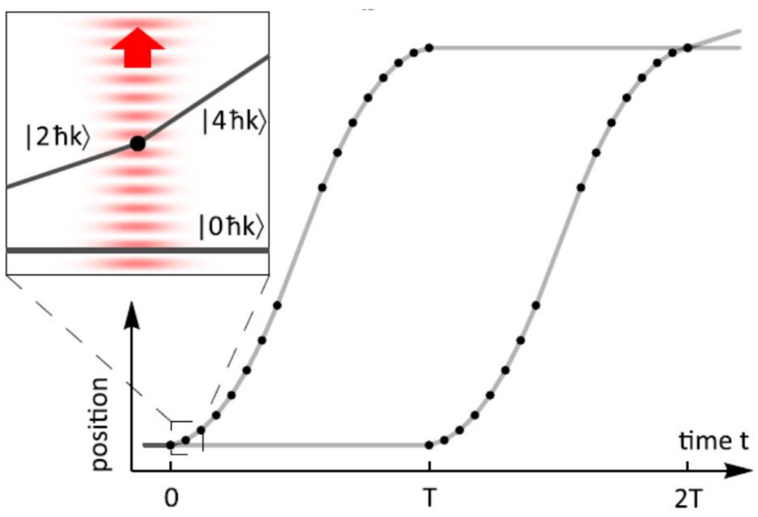
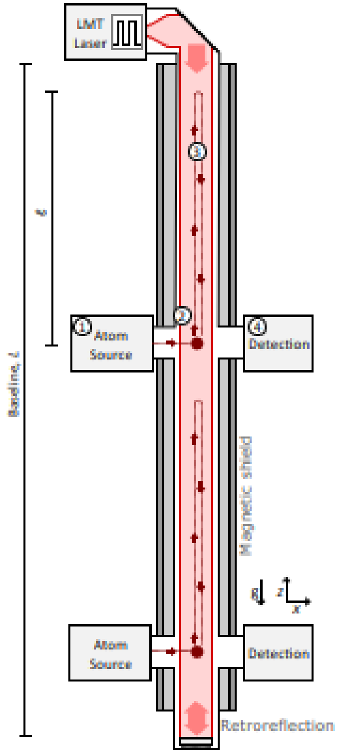


3) At t = 2T, the clouds spatially overlap.

The De Broglie waves interfere, and the pattern is extremely sensitive to the gravity g experienced by the atom clouds



Coupled atom sources have a large potential for measurement Gravitational Waves and Dark Matter

Kovachy, Nature, 2015