Future opportunities at the CERN Antimatter Factory

D. Gamba, F. Butin, L. Ponce

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09/04/2024 – Future Nuclear and Hadronic Physics at the CERN-AD workshop (FuPhy2024)

Outline

- **Today's AD/ELENA Facility**
  - What it is and how it works
- **Current Beam Performance**
  - Extrapolation toward possible short time-scale improvements
- **Possible Paths for Extending the Physics Reach of the Facility**
  - Engaging in forward-thinking to match possible future experimental requirements with (minor) changes
    - **DISCLAIMER 1: based on informal discussions only!**
- **Wrapping up and Conclusions**

- **DISCLAIMER 2: most slides based on recent talks at Chamonix 2024 and PBC 2024 workshops. No commitments from CERN for any study/upgrade of AD/ELENA at this stage!**

IMPORTANT: text in RED in this presentation is waiting for YOUR inputs!

AD/ELENA: a Unique pbar Facility!

- **The only place in the world with low energy pbars in a synchrotron!**
  - It seems unlikely to have similar capabilities elsewhere for the next 10-20 years
- **Serving 60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations**

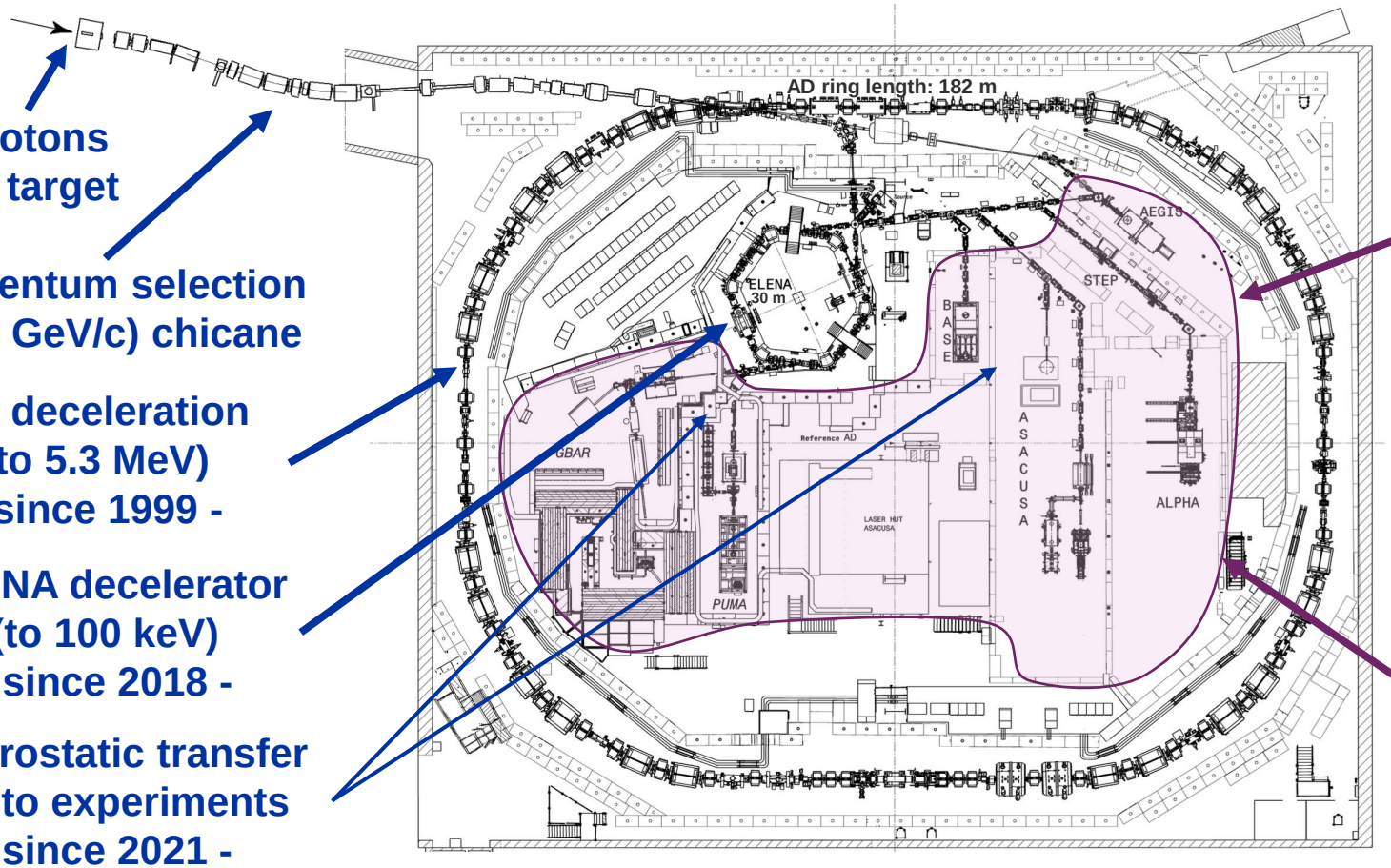
26 GeV protons on iridium target

Momentum selection (3.57 GeV/c) chicane

AD deceleration (to 5.3 MeV) - since 1999 -

ELENA decelerator (to 100 keV) - since 2018 -

Electrostatic transfer line to experiments - since 2021 -



antiprotons

ASACUSA
Antiprotonic helium spectroscopy

BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

PUMA
Antiproton/nuclei scattering to study neutron skins

antihydrogen

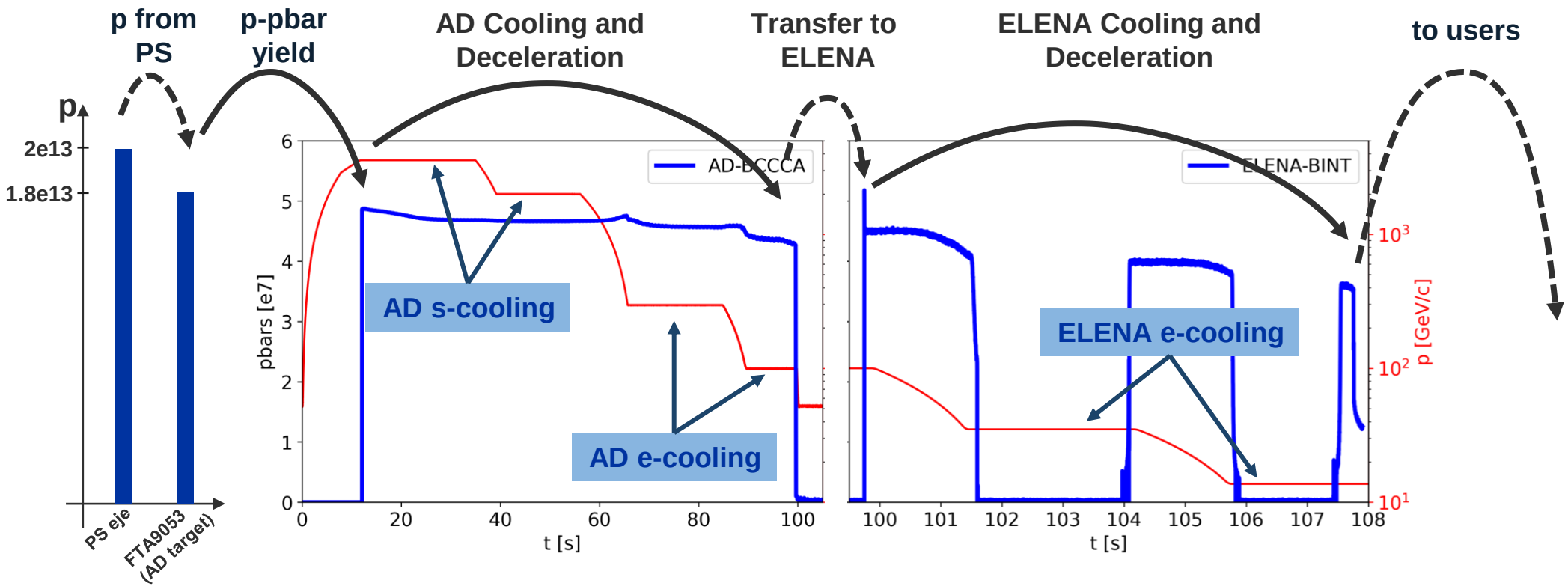
ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

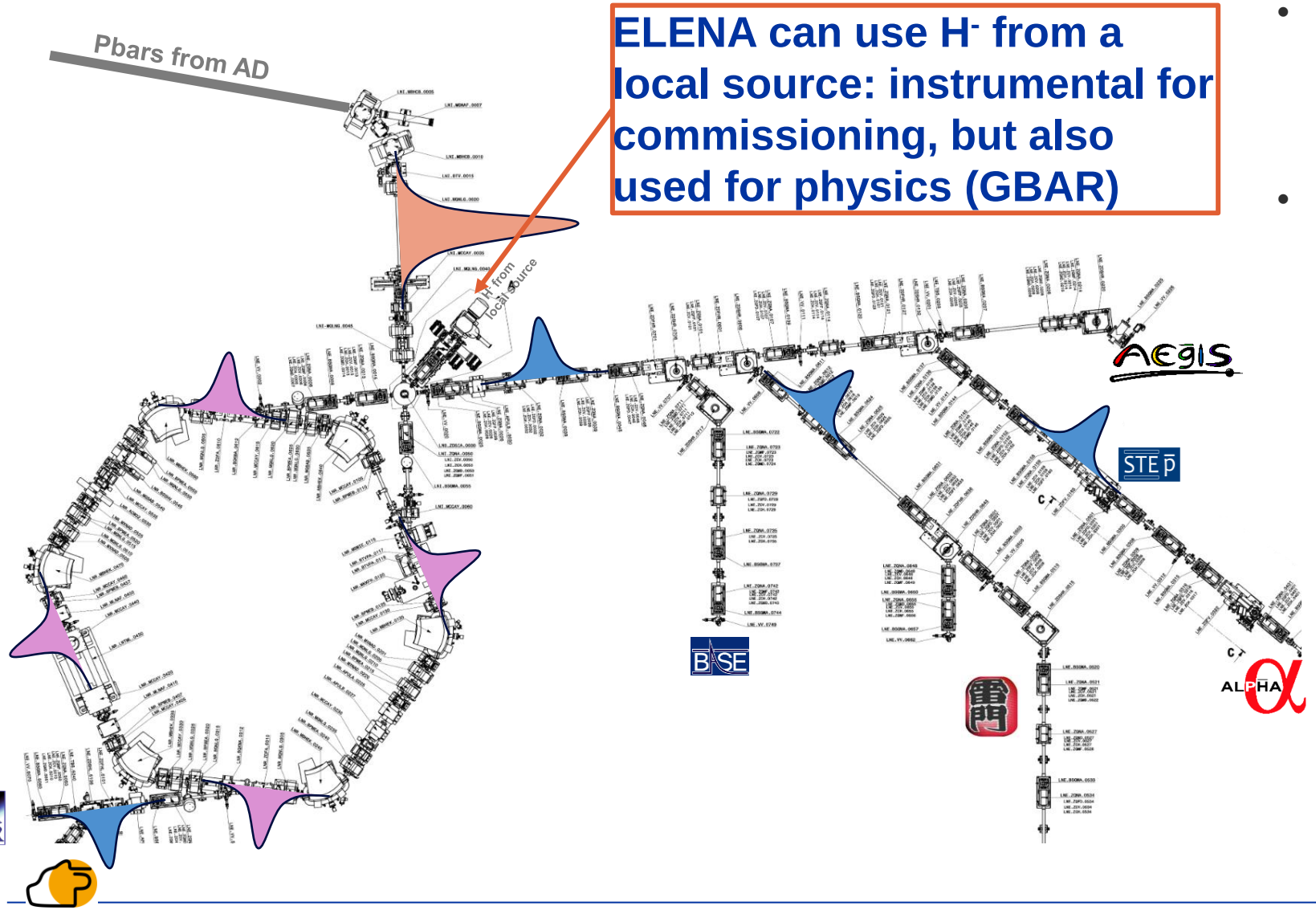
ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

From 25 GeV p to 100 keV pbar: 4e7 pbars/2’

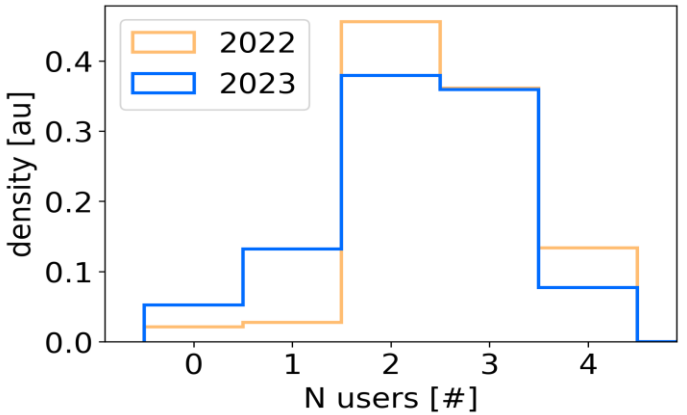
- Generating **pbars from 26 GeV/c protons** (yield of the order of 3e-6 pbar/p)
- Up to **80% deceleration efficiency from 2.75 GeV** (3.57 GeV/c) **to 100 keV** (13.7 MeV/c)
  - Thanks to **several stochastic** and **electron cooling steps**
- Up to **4e7 pbars every 2 minutes** delivered to experiments



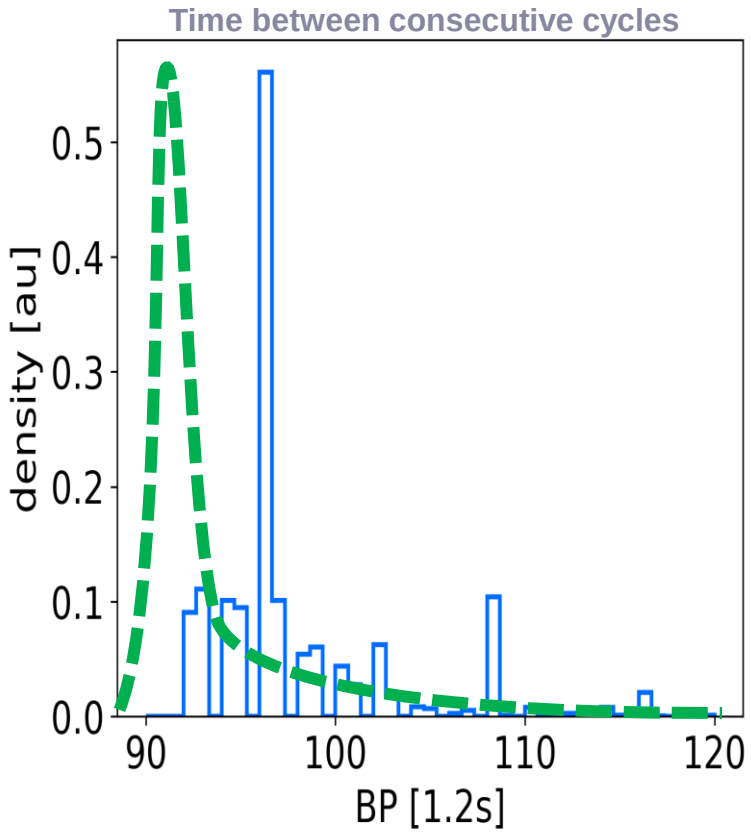
Serving 4 Users at a Time

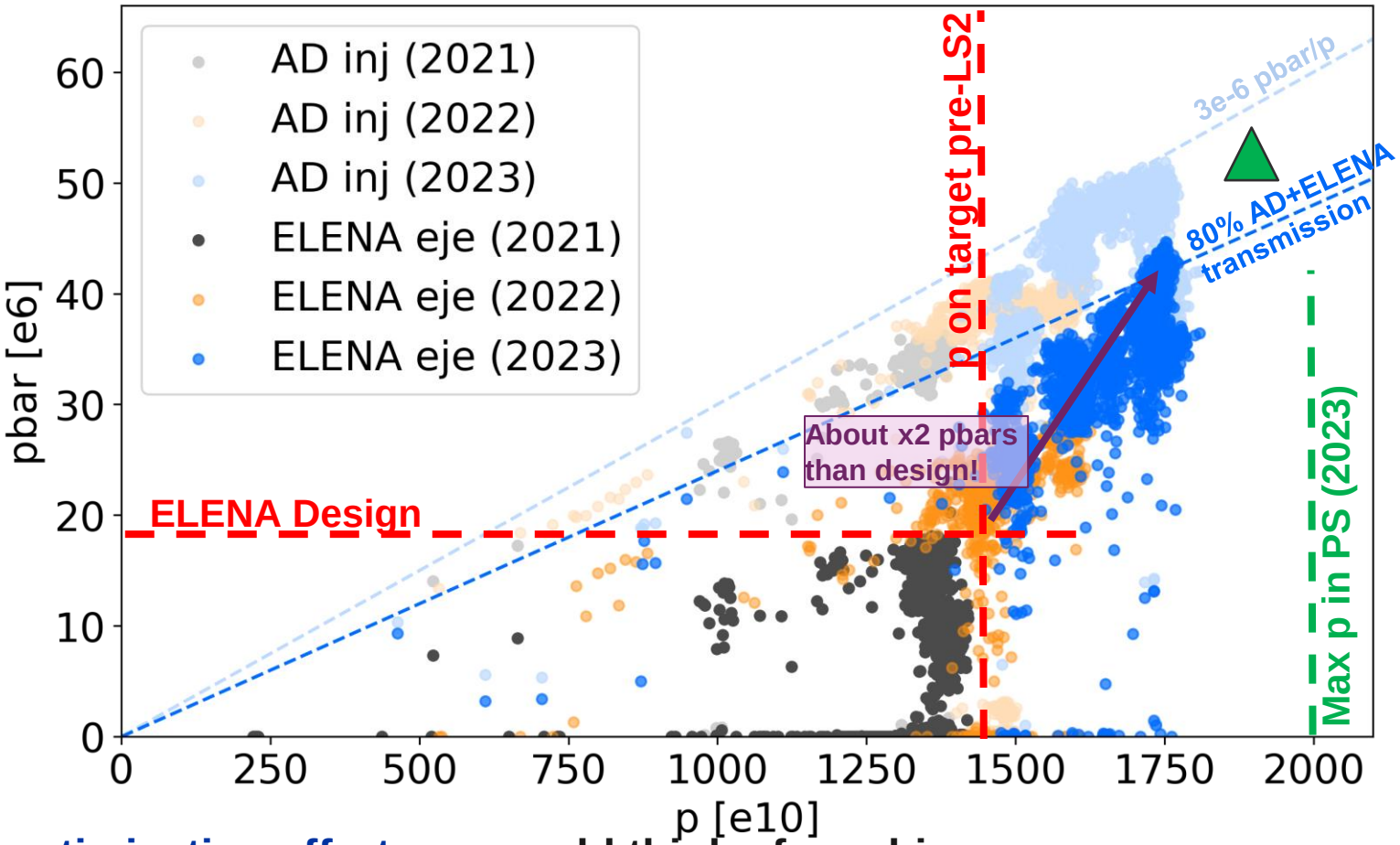


- **AD produces 1 bunch at 5.3 MeV**
- **ELENA: 4 bunches at 100 keV**
  - <150 ns FWHM
  - <1e-3 RMS dp/p
  - <4 um emittances (<2 um in 2024?)
- Up to **4 experiments served at the same time** with 1e7 pbars/bunch
  - **24/7 beam availability was the key game changer for AD users**!
  - **~30% of bunches "wasted",** but comfortable for (most) experiments present "ELENA R&D" phase…



Toward x2 pbar Flux than Design





With present hardware and ongoing optimisation efforts we could think of reaching:

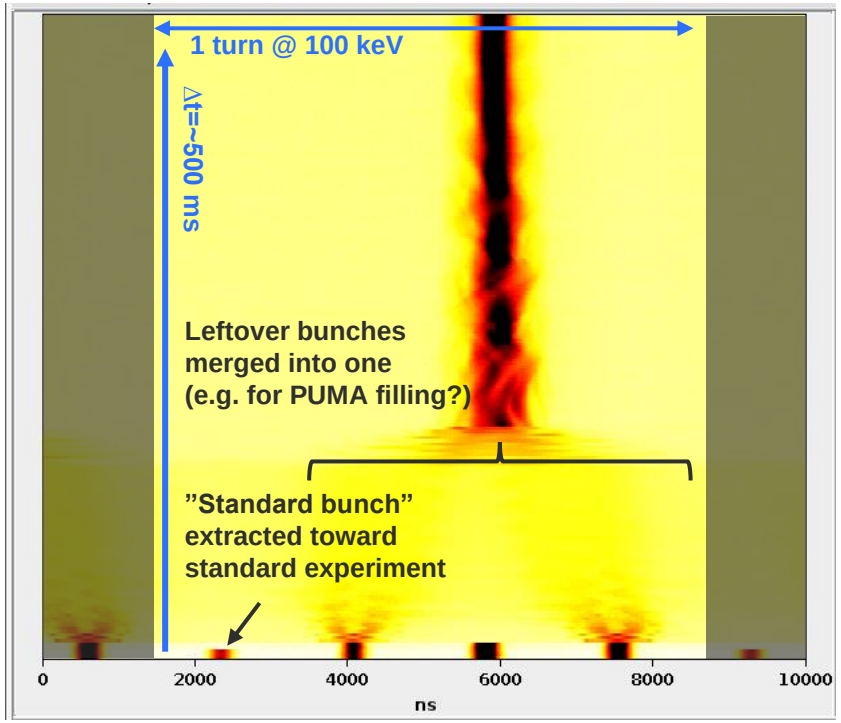
- **10-20% increase in beam intensity** (**stability to be improved** with consolidated hardware/instrumentation)
- **10-20% reduction in cycle length** (stability mainly linked to p production scheduling)

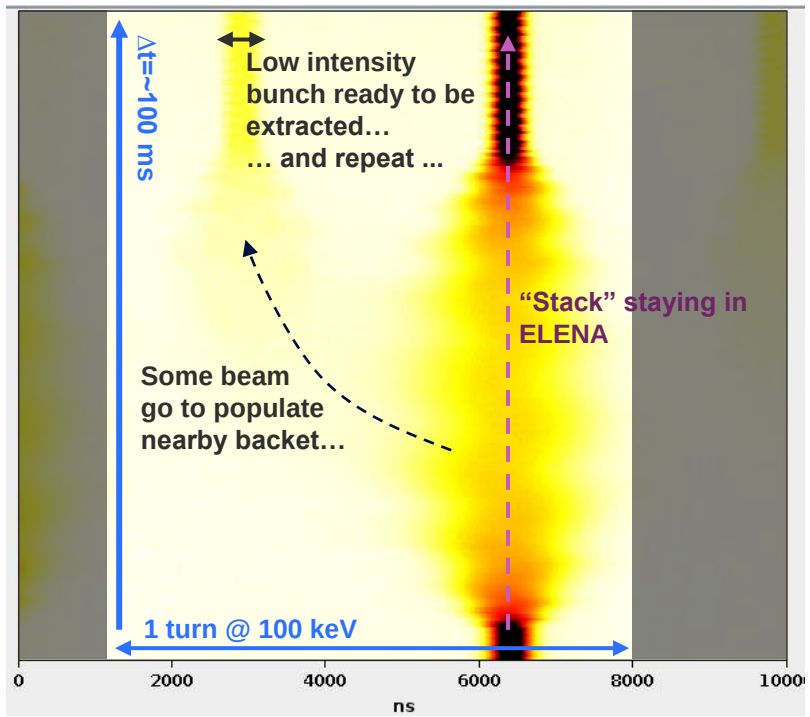
Happy Users with Ambitious Goals. Future is Now !

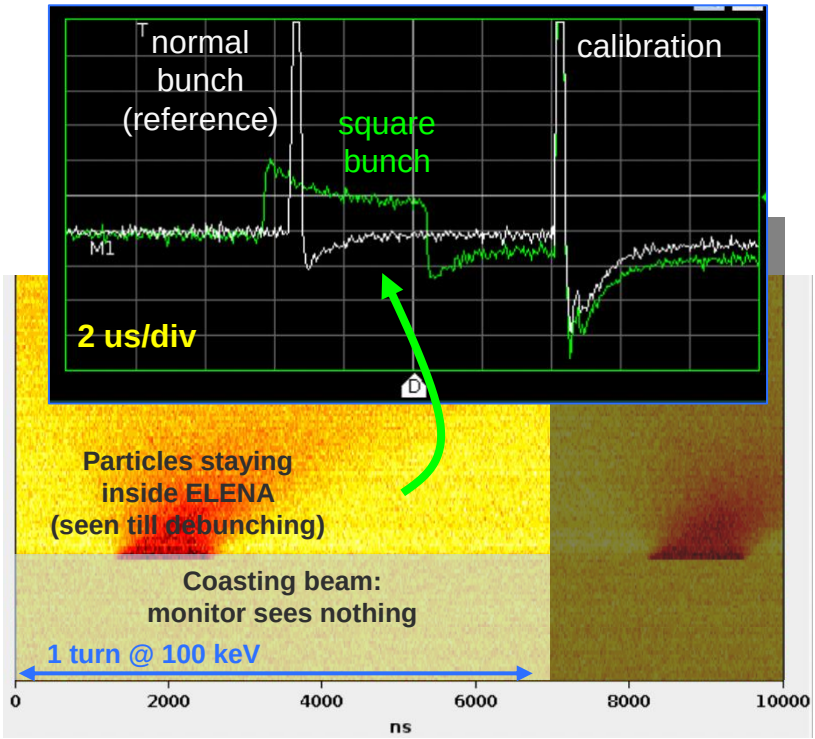
- **Present users are happy**
  - **No strong request for "better" or "more" beam: still exploring** the **potential of ELENA**!
  - **Request** for higher **shot-to-shot repeatability, beam availability** and **continuity**
    - Investment in **modern technologies/techniques crucial** for enhanced **beam stability** and **efficient operation** (this includes optics, control, instrumentation, …)
    - **Paramount** to finalise/pursue **AD consolidation** efforts
      - **This is an opportunity for AD-related upgrades, if requested !**
    - Must ensure a **long term pbar-facility lifespan (20+ years)**
- Most **technological challenges** and **ambitions** are **after the handover point!**
  - **See inspiring talk by S. Ulmer at PBC annual workshop 2024**
  - **No clear direction** for new/future (beam) requirements from AD/ELENA
    - can we **anticipate (your) future user wishes ?!**
    - **Time for triggering upgrade studies is now !**

Short-Term Opportunities Leveraging on ELENA

- **ELENA still has some un-explored potential at extraction**
  - E.g.: producing 1-to-5 bunches (instead of today's 4), or other "exotic" configurations, e.g.:





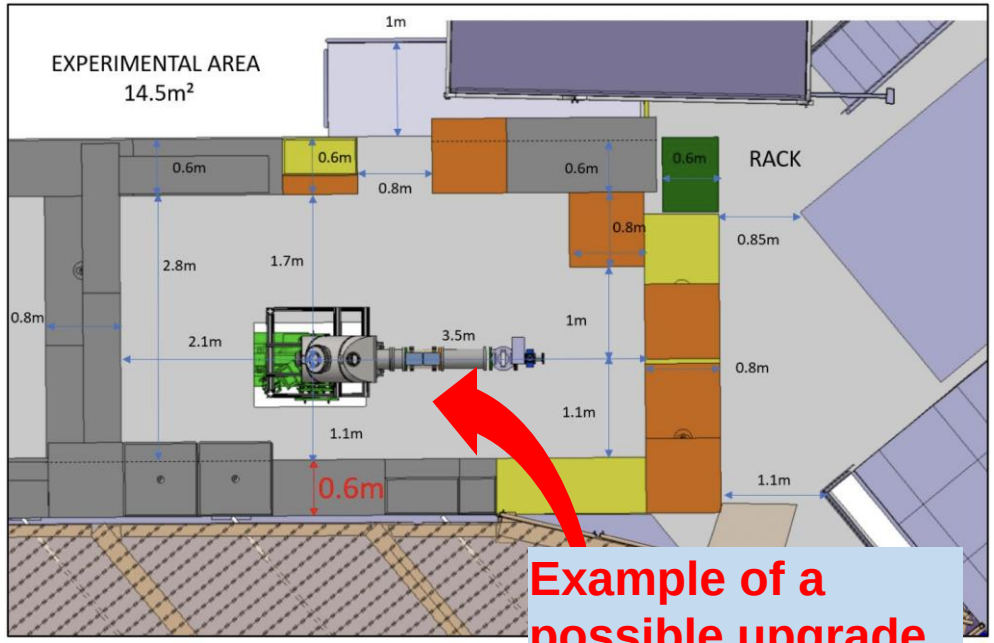


- **Mostly requiring some minor modifications, new logic, tests, …**
  - **We need user (your!) requests well in advance (months) to allow to properly test those schemes!**

TELMAX: a new Test Area for new Ideas and Users

- **Refurbishment** of the old **ATRAP2 area** and conversion **into a TEst Line for Machine And eXperiments:**
  - For **accelerator equipment tests** (e.g. instrumentation)
  - For **experimental equipment characterization** (e.g. foils, detectors R&D/calibration)
  - …
- **The area reorganized to increase usable surface :**
  - **Standard services** will be provided (electricity plugs, demineralized water, compressed air, etc.…)
  - **Changes** described in the ECR: **EDMS 2975107**
  - **Normally available by end of 2024 !**

- **Beam-time request strategy being formalized**
  - will normally be a regulated by “standard” **SPSC Beam Time Requests** as for other facilities
  - **Start expressing your interest now ! e.g. to F. Butin**
- *PS: Possible to add standard CERN diagnostics in the future...*



If one is allowed to dream…
… looking Beyond the Horizon

Higher Intensity? e.g x2?

- **Already at 80% AD+ELENA deceleration efficiency, i.e. up to 20% gain at very most**
- **Already at the maximum p intensity in the PS:**
  - **10% to gain at very most** on PS-to-AD proton transport efficiency
  - Present **target design already at engineering limits** and **radiation levels** close to **limits**!
- **Directly increasing the pbar yield (AD target/horn design? Transport in DI line?)**
  - **Not obvious gain**: lengthly and complex studies requiring dedicated beamtime

One way could be accumulation at AD injection

- Tested during early AD times (see CERN-ACC-Note-2019-0025)
- Possible to reach more than **x2 in intensity** (optimistically, up to x10), but **it requires dedicated studies**

Note 1: We might be limited by **radiation levels in the AD hall**

Note 2: **bunch properties** at ELENA extraction will be **affected** (higher emittance, length, …)

Note 3: Accumulation in traps? Your business: probably easier, but also **less efficient on flux…**

Higher Rep. Rate? e.g. x2?

- **Cycle length driven by cooling processes in AD** (~50%)
  - New AD **e-cooler** designed to hopefully gain **10%** on cycle time
  - Maybe possible to save **10%** on cycle time with an “improved” **s-coolling**?
  - Maybe trying **injecting in AD at a lower momentum**?
- **Additional inefficiencies from beam control**
  - Maybe possible to save **10%** on cycle time with “improved” **power converters**?
  - Maybe possible to save **10%** on cycle time with better **beam instrumentaton/controls**?

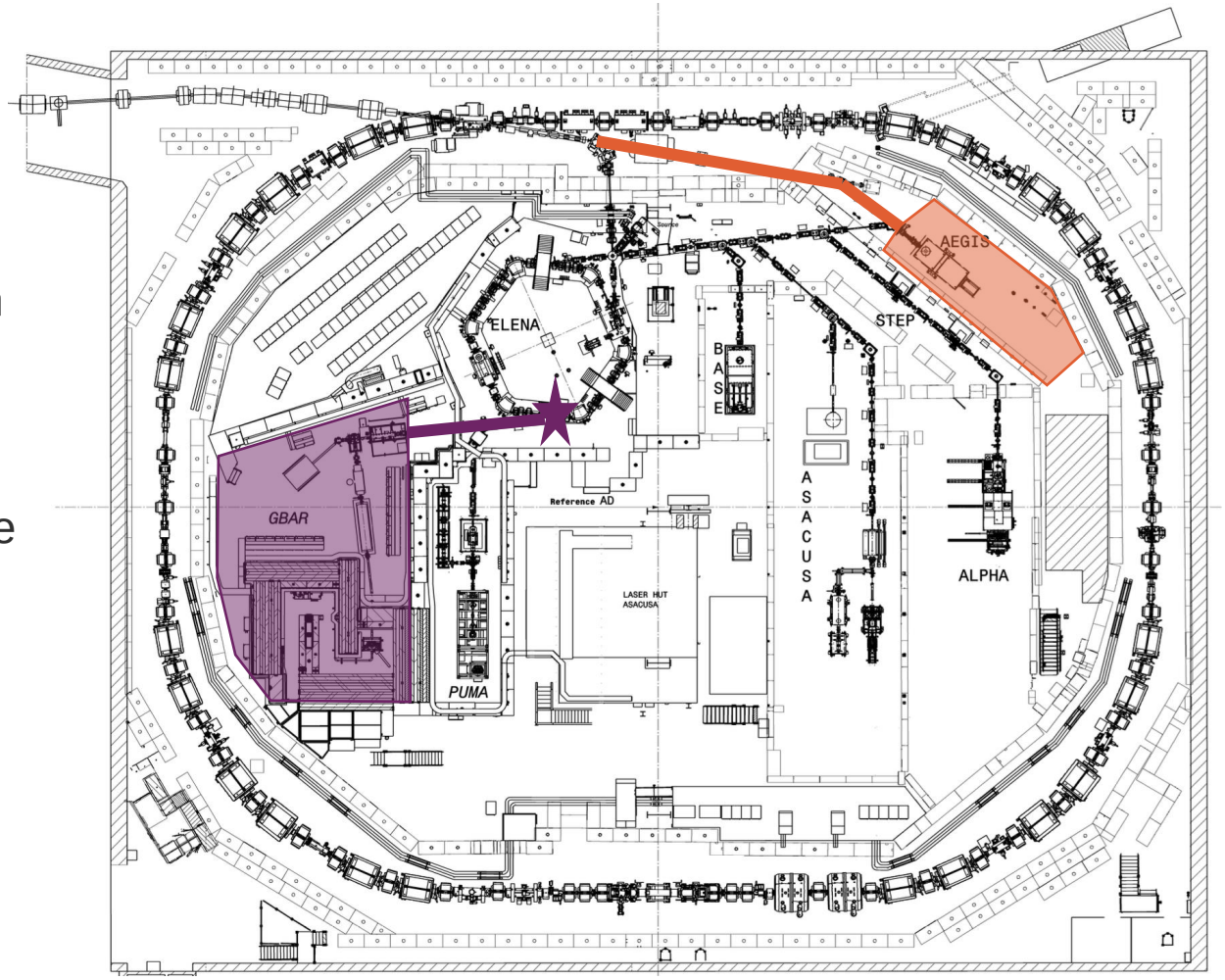
- **Overall, maybe possible to gain a factor 2, at most** (from 110 to 60 s cycle time)
  - **Investment on hardware/studies needed, if requested!**

Note 1: We might be limited by **radiation levels in the AD hall**

Note 2: It requires also higher use of **proton cycles!**

Different Energy? e.g. from 100 MeV to 50 keV?

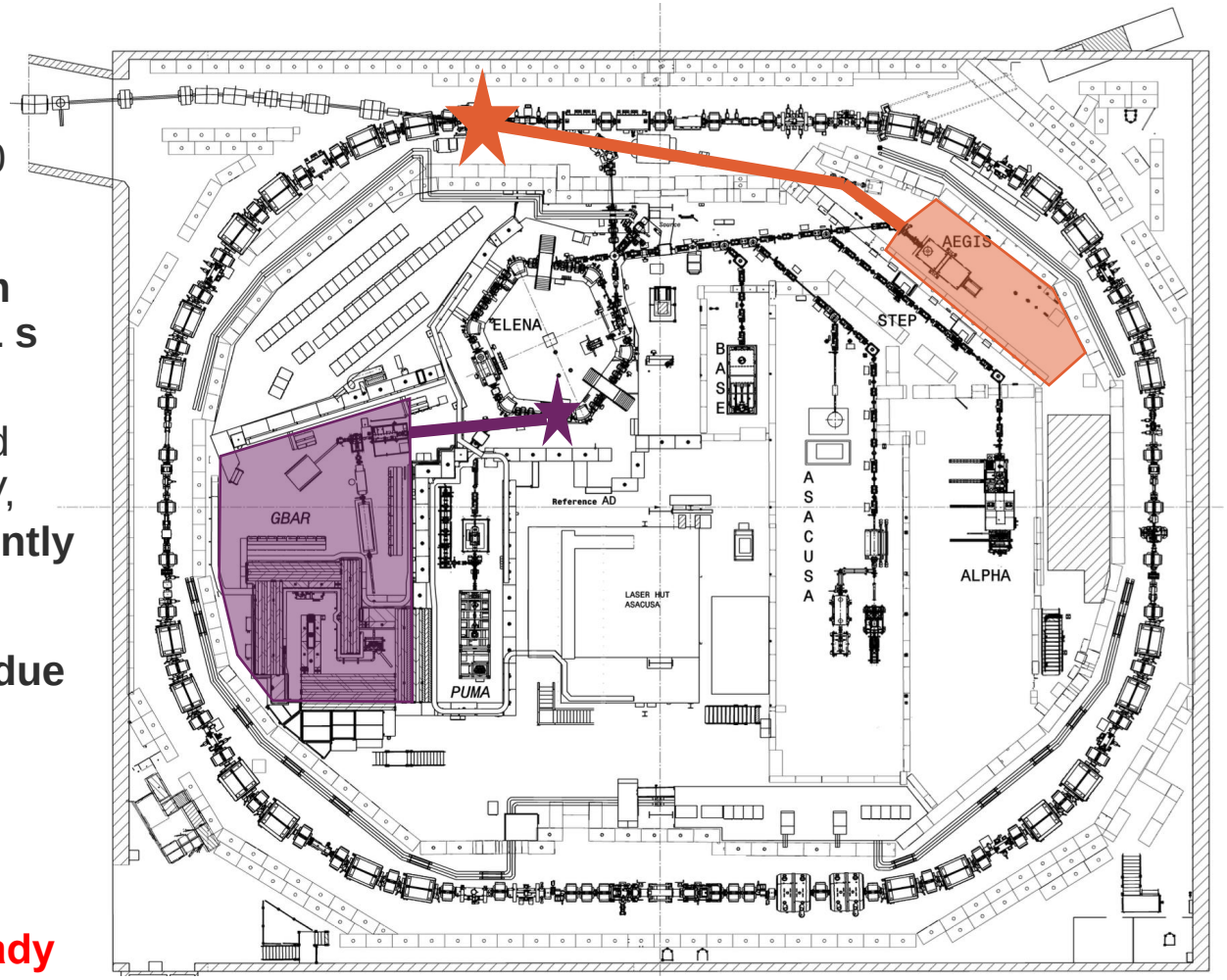
- **Note: RP aspects to be evaluated!**
- Considering reviving **AD extraction up to 500 MeV/c** (~125 MeV E_k) to, e.g., AEGIS zone
  - It **might require exclusive beam use**, limiting ELENA's multi-user capacity
  - **Could be studied, if requested!**
- **Extraction up to 100 MeV/c** (5.3 MeV E_k) **from ELENA?**
  - Requires to install a **more powerful extraction kicker + septum** (as the injection one)
  - **Adaptation or redesign of transfer line(s)** will be required, potentially using new magnets
  - **Could be studied, if requested!**
- **Lower energy possible down to ~85 keV**
  - but **never tested in operation!**
  - **below (~50 keV?) could be studied, if requested!**



Slow Extraction from ELENA and/or AD?

Courtesy Y. Dutheil et al. – CERN SY-ABT

- **In concert with experiment requests at the time, the ELENA ring wasn't designed for slow extraction and no studies were done for this**
- **Presently bunched beam is fast extracted**
  - 500 mm long device with 400 mm plates provides ~ 40 kV.m integrated field to achieve 220 mrad deflection
- **Resonant slow extraction with an electrostatic septum blade to provide continuous spill from ~100 ms to >>1 s might be possible**
  - Drop-in replacement of present extraction device could reach extraction **up to 450 keV** with a voltage of 10 kV, although **transport to an experimental area is presently limited to ~100 keV**
- **Slow extraction from the AD ring may be challenging due to higher energy and limited space on the ring lattice**



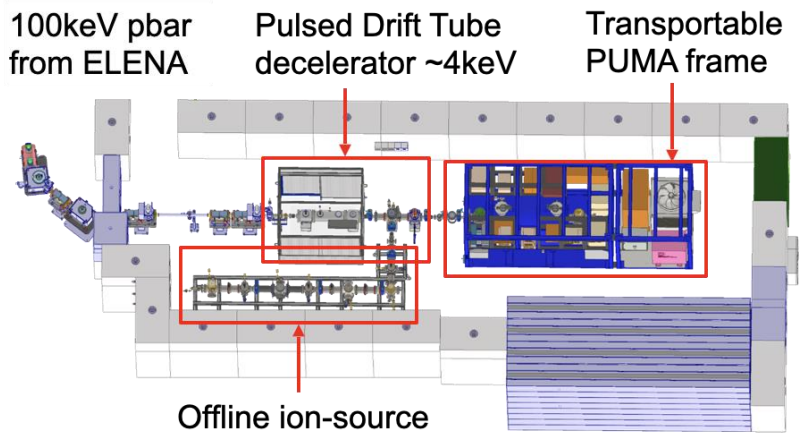
Note 1: Activities need to reach CERN approval before significant resources can be allocated!

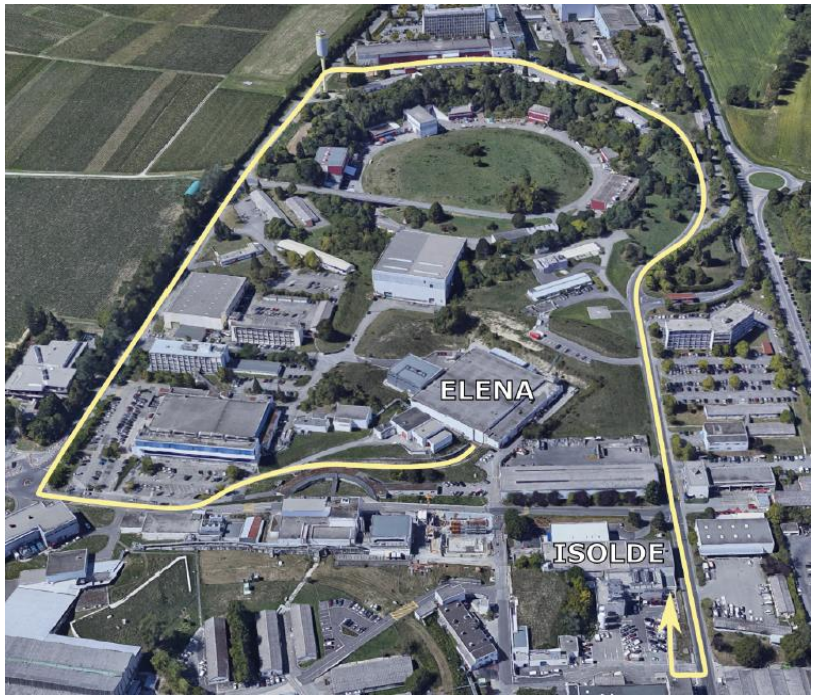
Note 2: Already done/planned within experiments at low energy (a few 100 eV) … and you seems to be happy already

More Off-Site Traps? e.g. a common portable trap?

- **PUMA** and **STEP** plan to fill a trap that will allow to **transport cold pbars to other facilities** (e.g. to ISOLDE for PUMA)
  - **Several challenges to be demonstrated!**
  - For **STEP,** the main reason is to **“escape”** the AD hall’s **electromagnetically noisy environment**
  - **First results** should come soon! See C. Klink talk

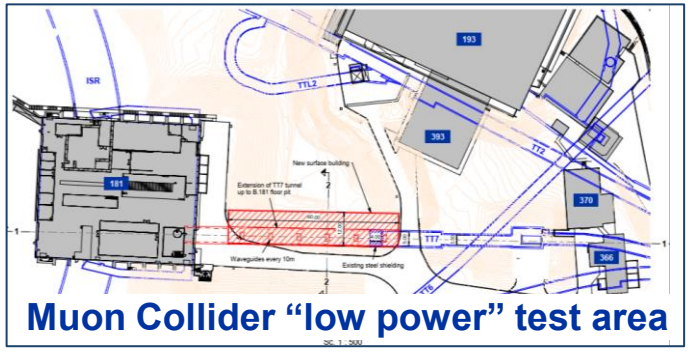
- Will this open **new experimental possibilities?**
  - Shall CERN acquire trap technology and provide “standard” pbar-filled “bottles” for users?
    - **Discarded in the past**: too different user needs… will the PUMA/STEP experience change the picture?
    - **Maybe you could produce a “common” proposal for a general-purpose trap?**

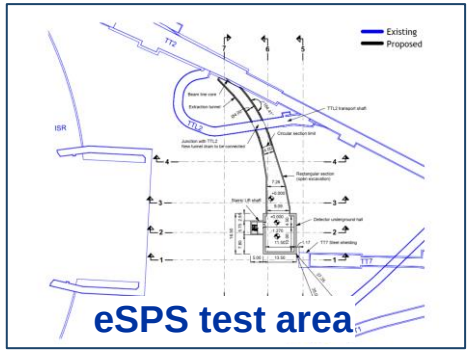


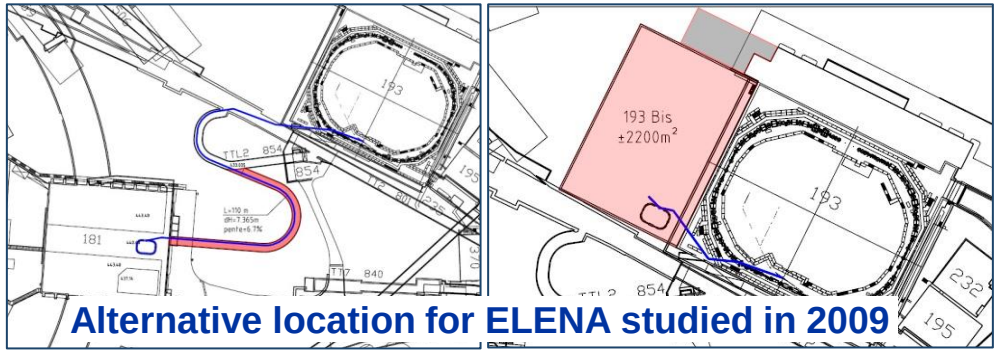


Bigger Exp. Area? e.g. 1000m^2 more?

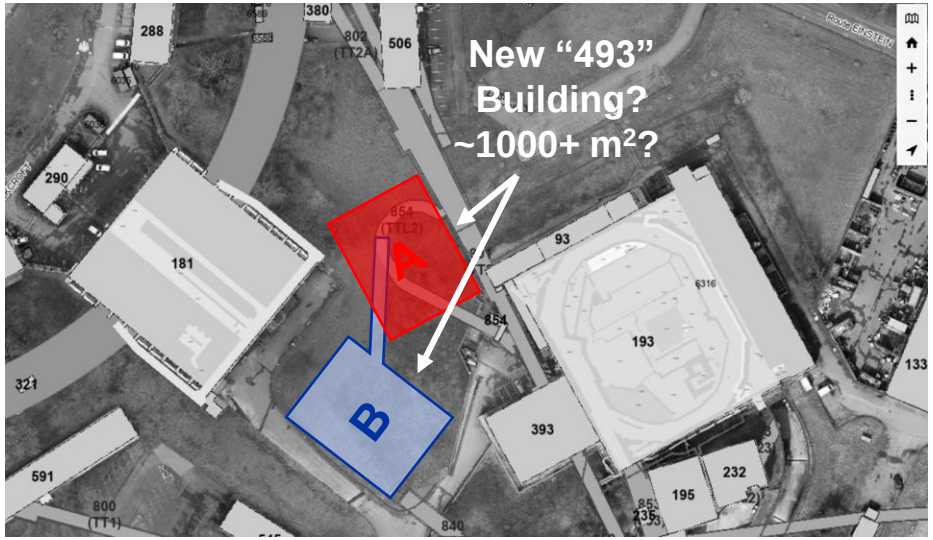
- **One must be looking outside of the AD hall, looking at other projects:**







- **TTL2** is empty and **not useful**, today.
  - What about **new building** (493?) with semi-underground experimental area for “high energy” experiments?
  - It could take **protons** from PS, **pbars** (up to 3.5 GeV/c?) from AD, e^- from **eSPS**?, used as **Muon Collider** “low power” test area? (e.g. A, B, …)…
  - **Could be studied, if requested!**
- **Hosting a COSY-like ring (184 m) will require some more thinking…**



New Particle types? What about Antideuteron?

- **From the AD target: Antideuteron**
  - **Maybe** possible to have **10 to 1e4 antideuteron** at AD injection **already today**
    - Assuming they could be decelerated/trapped, would those numbers be **interesting?**
    - **S-cooling and RF systems** are the most likely to require some **key modifications to allow deceleration**
  - **A new target and/or full facility might be required**
  - **Could be studied, if requested!**
- **In the experiments** (their core business, but **can AD/ELENA help?**)
  - **Anti-Hydrogen molecule**
    - Might benefit from **higher pbar intensity/shot**
  - **Anti-Neutrons**
    - Typically, requires **slow extraction at high energy (>100 MeV/c) on a target**
  - **Antiprotonic atoms** (see AEGIS, ASACUSA, …)
    - E.g. production of S(uuddss) hexaquark (dark matter candidate) from pbar - ^{3}He reaction in a trap
    - Might benefit from **higher pbar flux** (intensity or rep-rate)

Overview of “Independent” Upgrade Cases

- **Any of these (except TELMAX) will require well-defined physics experiment cases!**
- **The actual cost and feasibility of each option will be evaluated if and when required.**

External ”high energy” experimental hall?

TELMAX
Test Experimental Area

Higher pbar flux:
x2 on **rep rate**
x2 on pbar **intensity**

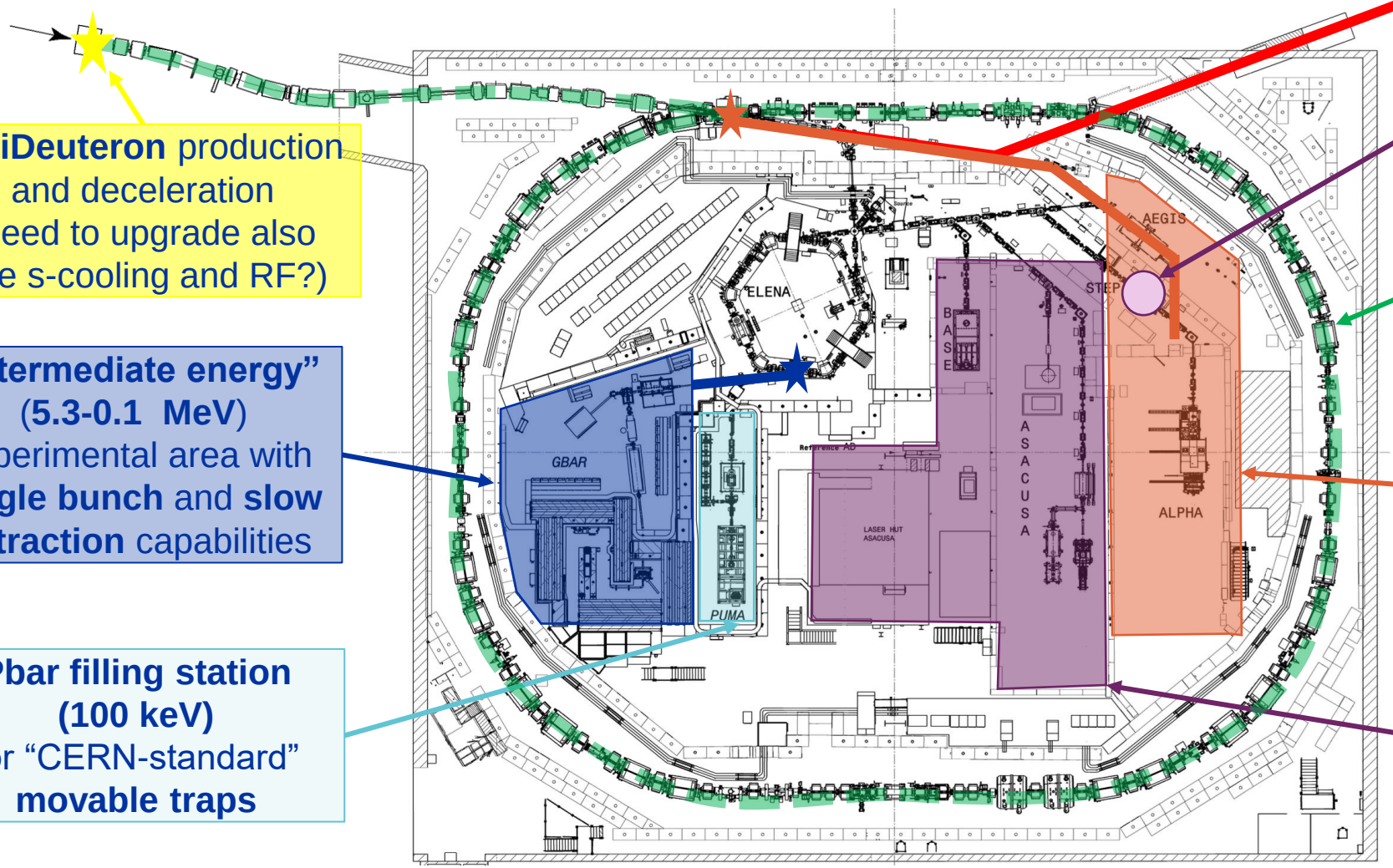
“High energy”
(**125-5.3 MeV**) Experimental area with **single bunch** and **slow extraction** capabilities

Low energy
(**100 keV**)
experimental area for present and new (e.g. H2bar) experiments

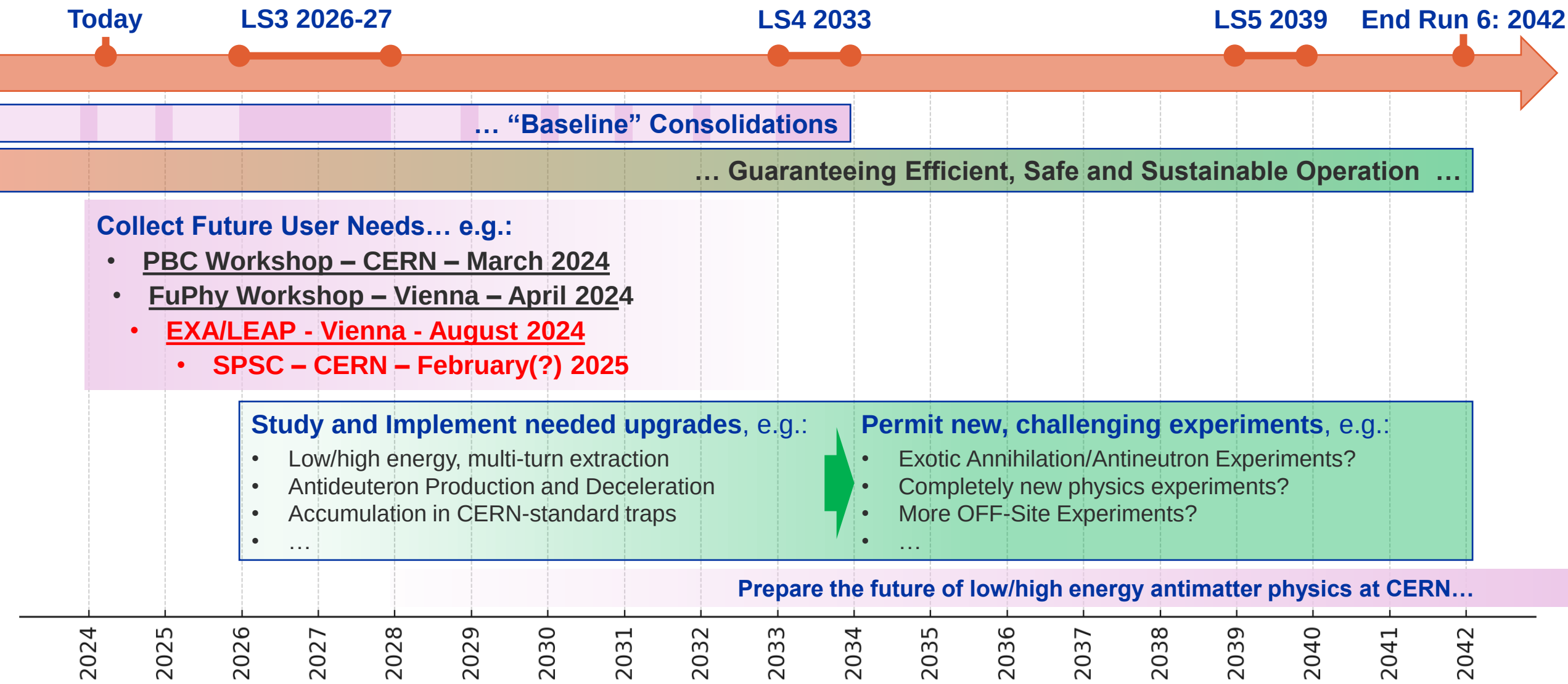
AntiDeuteron production and deceleration (need to upgrade also the s-cooling and RF?)

“Intermediate energy”
(**5.3-0.1 MeV**)
experimental area with **single bunch** and **slow extraction** capabilities

Pbar filling station
(100 keV)
for “CERN-standard”
movable traps



Overall Long-Term Timeline Proposal



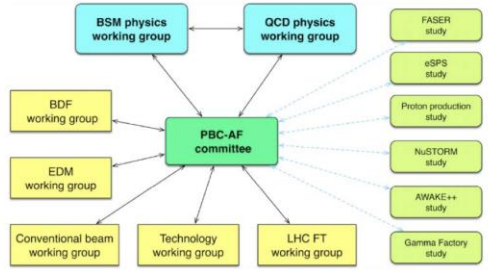
PBC Study Group at CERN is a Possible Partner

- **CERN has put in place the Physics Beyond Collider Study Group in 2016 to support studies for new experiment/proposals at CERN**
  - see for example ECFA2022 and PBC2024 and PBC official website
- **(to my knowledge) no AD/ELENA experiment is presently profiting of this programme**
  - **It is the natural interlocutor to assess and possibly fund feasibility studies for new experiments!**

PBC Phase 1 (2016-2020)

Mandate:

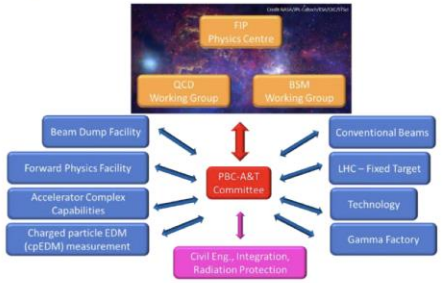
"Explore the opportunities offered by the CERN accelerator complex and infrastructure to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."



PBC Phase 2 (since 2020)

EPPSU recommendations → mandate enhanced with:

- *Increase synergies with cosmology, astroparticle, nuclear and atomic physics*
- *Strengthen collaboration of CERN with large National Laboratories*
- *Act as central forum of exchanges between theorists and experimentalists*



~100 core members in the Working Groups

PBC Phase 2: CERN PROJECTS LANDSCAPE AFTER EPPSU

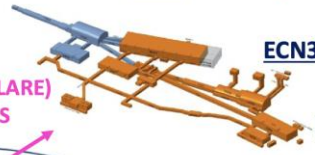
LHC-FT: LHCSpin, 2-Crystals

LHC-LLP:

- Forward: Forward Physics Facility (FASER2, FASERnu, advSND, FORMOSA, FLARE)
- Large angle: MATHUSLA, CODEXb, ANUBIS

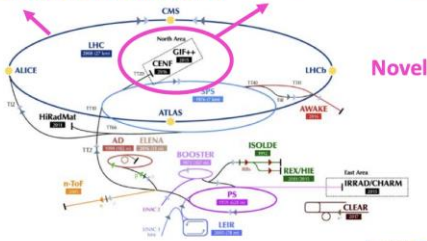
+ Gamma Factory (PoP@SPS)

EHN1: NA61++, NA60++, NA64++ (e,h)



ECN3: HIKE/SHADOWS, BDF/SHiP

EHN2: AMBER-Phase 2, NA64++(μ)



Novel neutrino beams (ENUBET/NuTag) for SBL&LBL

Non-accelerator:
AION-100
ALPs cavities
Quantum sensors
...

Low Energy:
Proton EDM ring

Slides from C. Vallee at PBC Workshop 2024

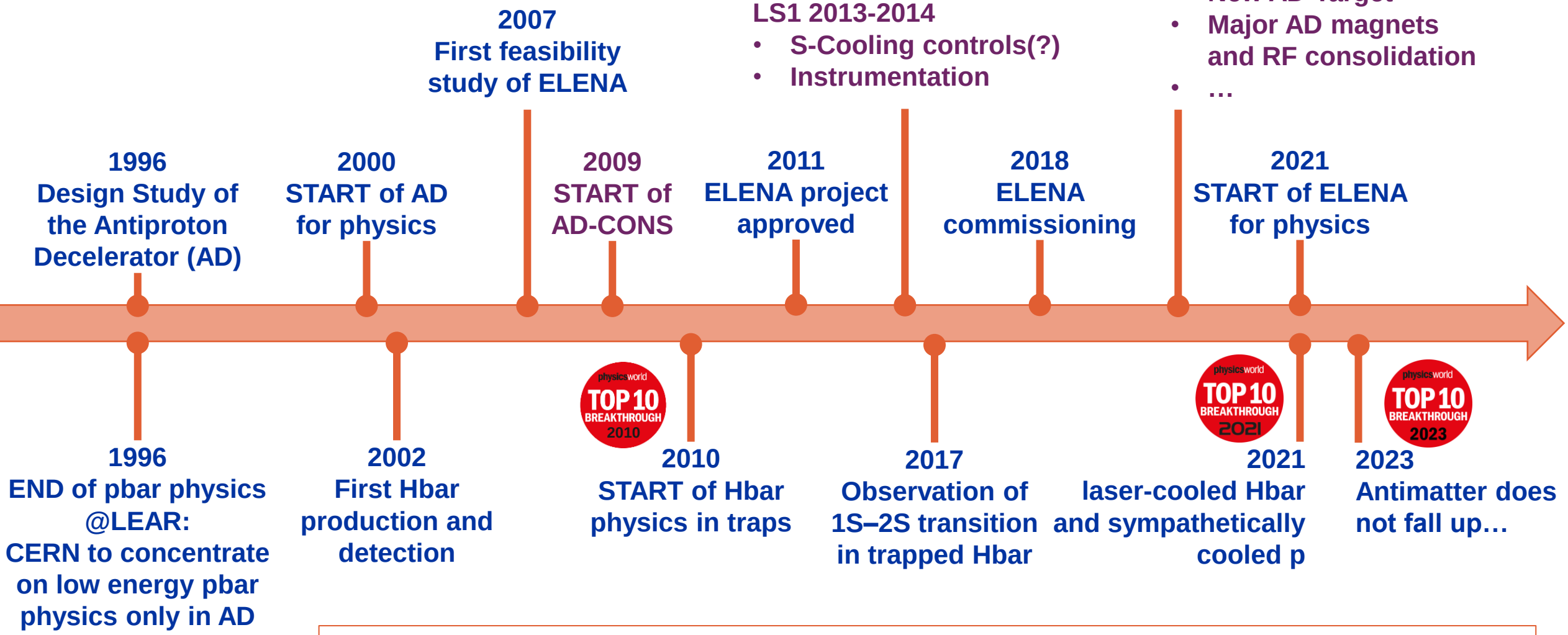
Conclusions

- **AD/ELENA Facility is a unique facility worldwide**
  - **Unique globally**, with no realistic alternative for the next 20+ years.
  - **Consistently delivers 4e7 antiprotons at 100 keV bi-minute** to six thriving collaborations
  - **High satisfaction** across the physics user community
- **Short-term Prospects**
  - Potential for minor **performance improvements** (+10-20% intensity and repetition rate)
  - We can still **take advantage of some flexibility in ELENA** (e.g. number of bunches/extractions)
  - **Establish** the **TELMAX** Beam test area to boost component development and **support new/old users**
- **Long-term Prospects**
  - **Extend facility's physics reach** is **possible**, depending on emerging cases
  - **Hardware consolidation** within AD presents new use case **opportunities**
  - **PBC is an asset** framework to intercept and actualize new requests (e.g. **support feasibility studies**)

Looking forward to new, exciting, yet realistic, user requests to trigger relevant studies!

APPENDIX

Timeline



Timestep between major results/changes: ~5-10 years

How did we get here?

- **Modest investments** relative to CERN's capabilities
  - Leveraging on the possibility of **reusing existing hardware**
- **Exceptional commitment** from a handful of individuals, coupled with the **goodwill** of numerous others
  - **Not turn-key machines:** several **unique technologies/features**!
- **Resilient user community** conducting extensive, intricate, long, and unparalleled experiments on a **restricted budget** and with **scarce resources**
  - Over two decades of **specialized expertise** challenging to replicate
- Made possible by **CERN**'s existing infrastructure and expertise

Might be impossible to replicate this anywhere else!

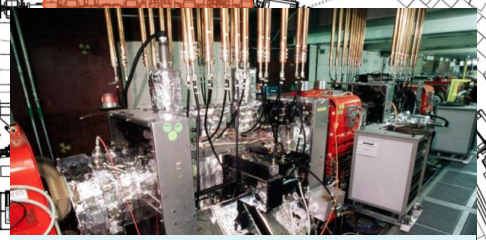
Current Facility Challenges: Infrastructure

- **Hardware Aging, especially the AD!**
  - AD made from **hardware recycled from previous facilities**
    - *Example risk:* **water leak in special magnet in 2023** disrupted 10% of physics operation time
  - Ongoing **consolidation efforts** since the facility's early days
- **Liquid Helium Demand**
  - Our users are among the **top consumers** of liquid helium at CERN
    - Presently **running at maximum helium capacity**, and often not enough…
- **Space Constraints**
  - **AD hall** predominantly **occupied** by experimental setups
  - **Complex experiments** with **lengthy timelines** (>5 years) from setup to initial results
  - **Limited space** for **new/bigger experiments** and/or **auxiliary installation,…**

Hardware: Most Critical/Aged Items

Injection line magnets with high risk of breakdown and no spare

Outdated Power Converters

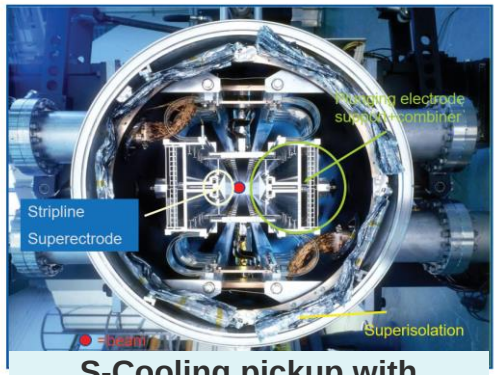


Critical reliability and spare availability for s-cooling kickers and power amplifiers

Outdated (and not very “green”) cooling and ventilation systems

Outdated e-cooler design, critical in spare parts

AD magnets consolidation being finalised

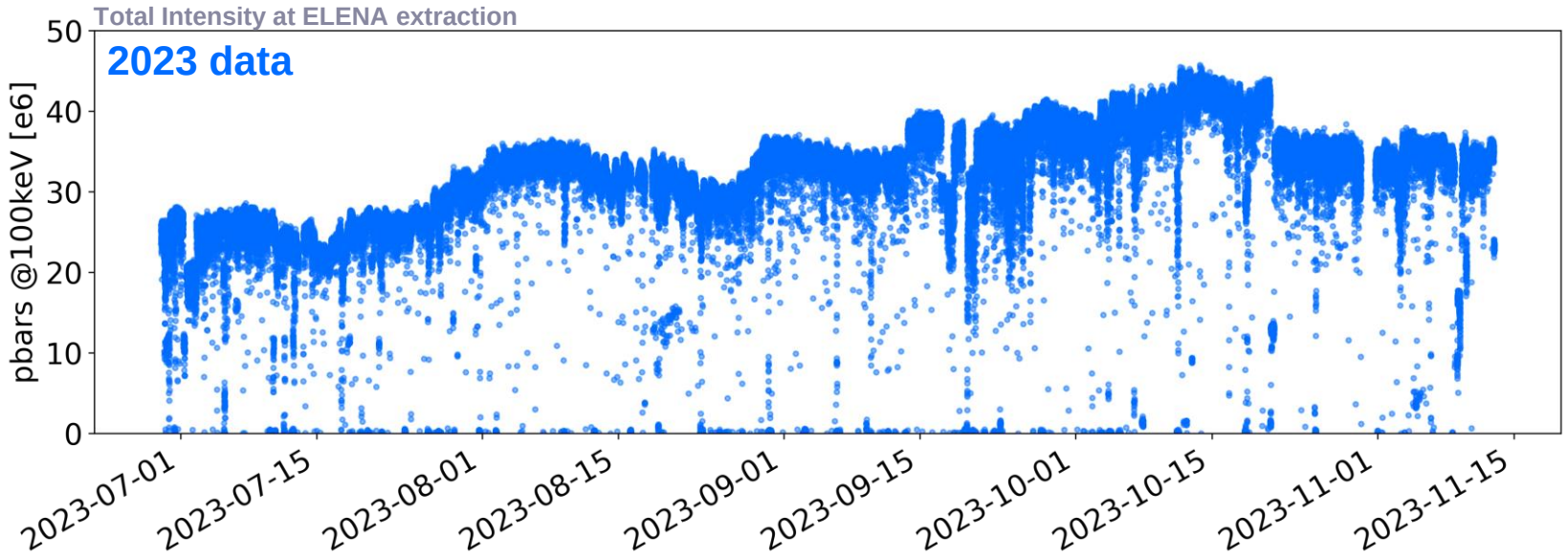


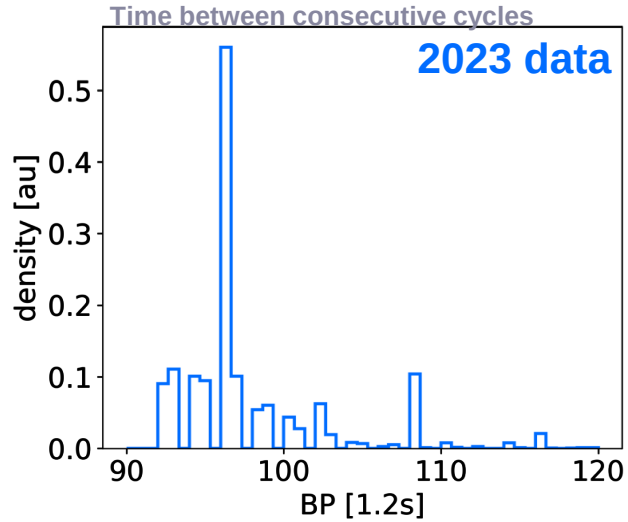
S-Cooling pickup with no spares, limited know-how

Outdated LLRF and HLRF for C10 cavities

Main user requirements: stability and reproducibility!

- **Main request: stable intensity of more than 25e6 pbar every ~120 s (typically, higher flux is better)**
  - **Acceptable** to **have slow intensity drifts** over **time scales of days/weeks**



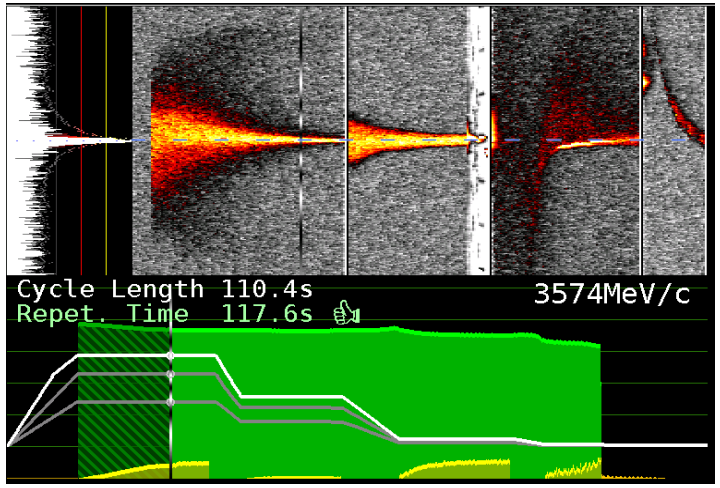


- In practice, **quite some intensity variation/fluctuation (>20%!) over the year**
  - **Slow improvements** thanks to motivated operation team
  - Slow/fast **degradations** due to **natural drifts** and **hardware faults/issues**
  - Shot-to-shot **fluctuations** due to **non-reproducibility** of several sub-systems
- Also, **repetition rate variation** driven by **PS super-cycle** composition and beam scheduling strategy
  - **Not much we can do about it**, but CERN-timing long-term plans to upgrade protons scheduling strategy

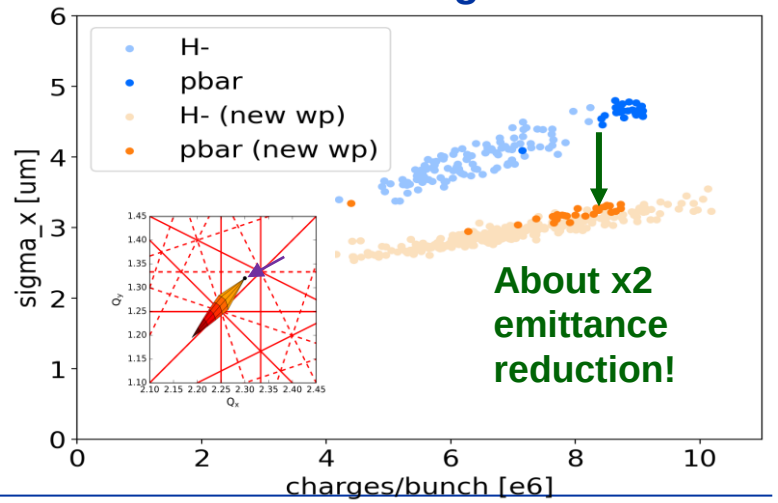
Current Facility Challenges: Beam Control

- **Challenges** in **Beam Diagnostics** in measuring very **low intensity** and **low energy beams**
  - **Mainly relying on Schottky and Intensity measurements**
    - i.e. indirect measurement of many possible faults/effects
  - **Only destructive transverse beam profile measurements**
- **Dedicated operation team :**
  - **Maintain high machine availability**
    - E.g. Finding solutions to run without BHZ-TRIM in 2022…
  - **Obtain the best performance from existing hardware**
    - E.g. toward ELENA design emittances, …
  - **Respond to user needs**
    - E.g. Optimise beam transport from ELENA to traps …
  - **Follow-up constant consolidation needs, often unique systems**
    - E.g. electron and stochastic cooling consolidations …

Schottky and Intensity (BCCCA) in AD

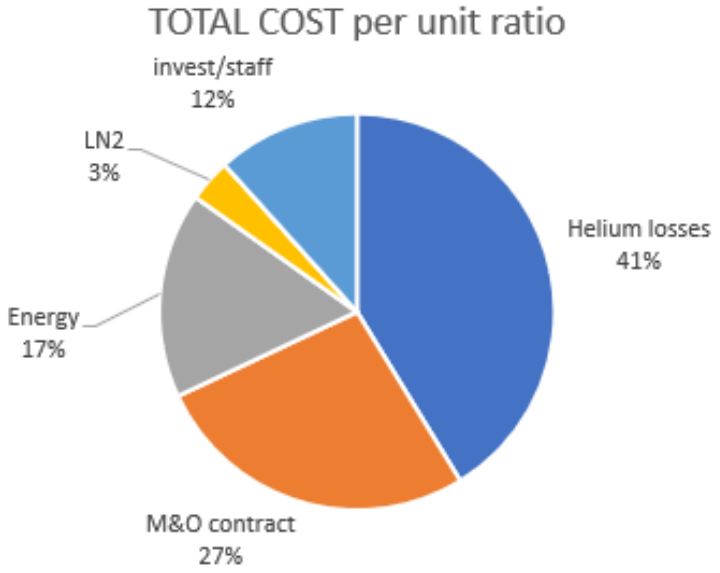


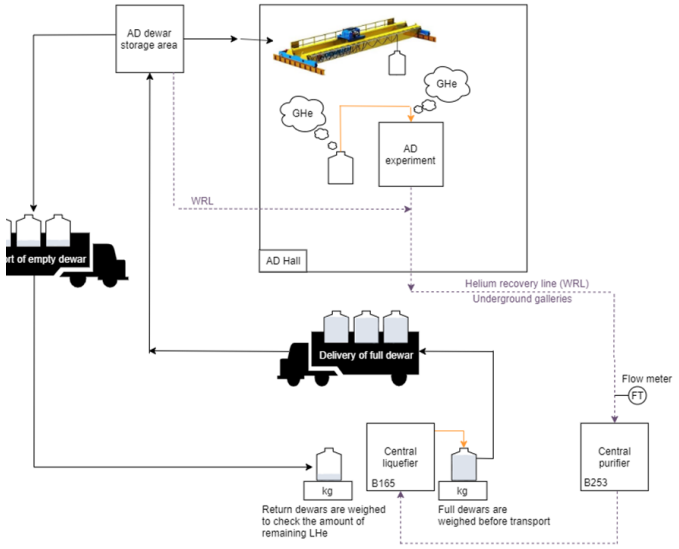
Toward ELENA design emittances!

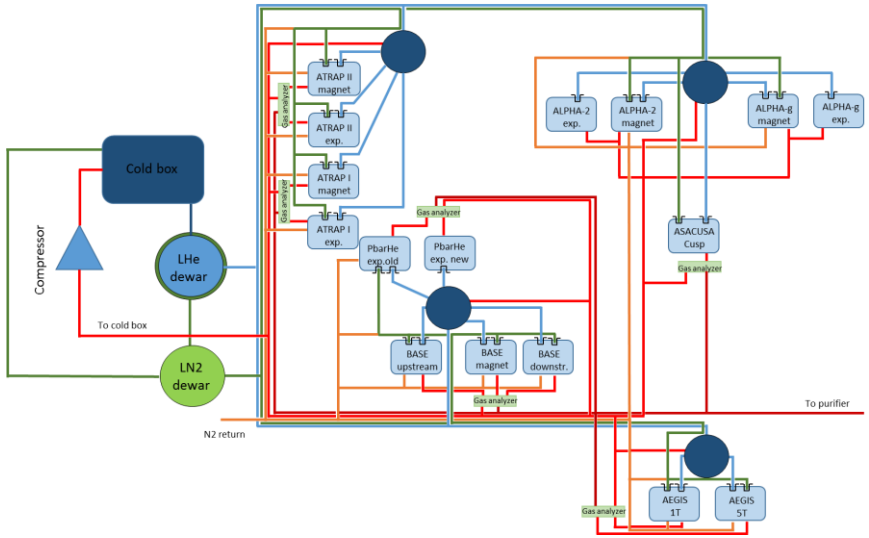


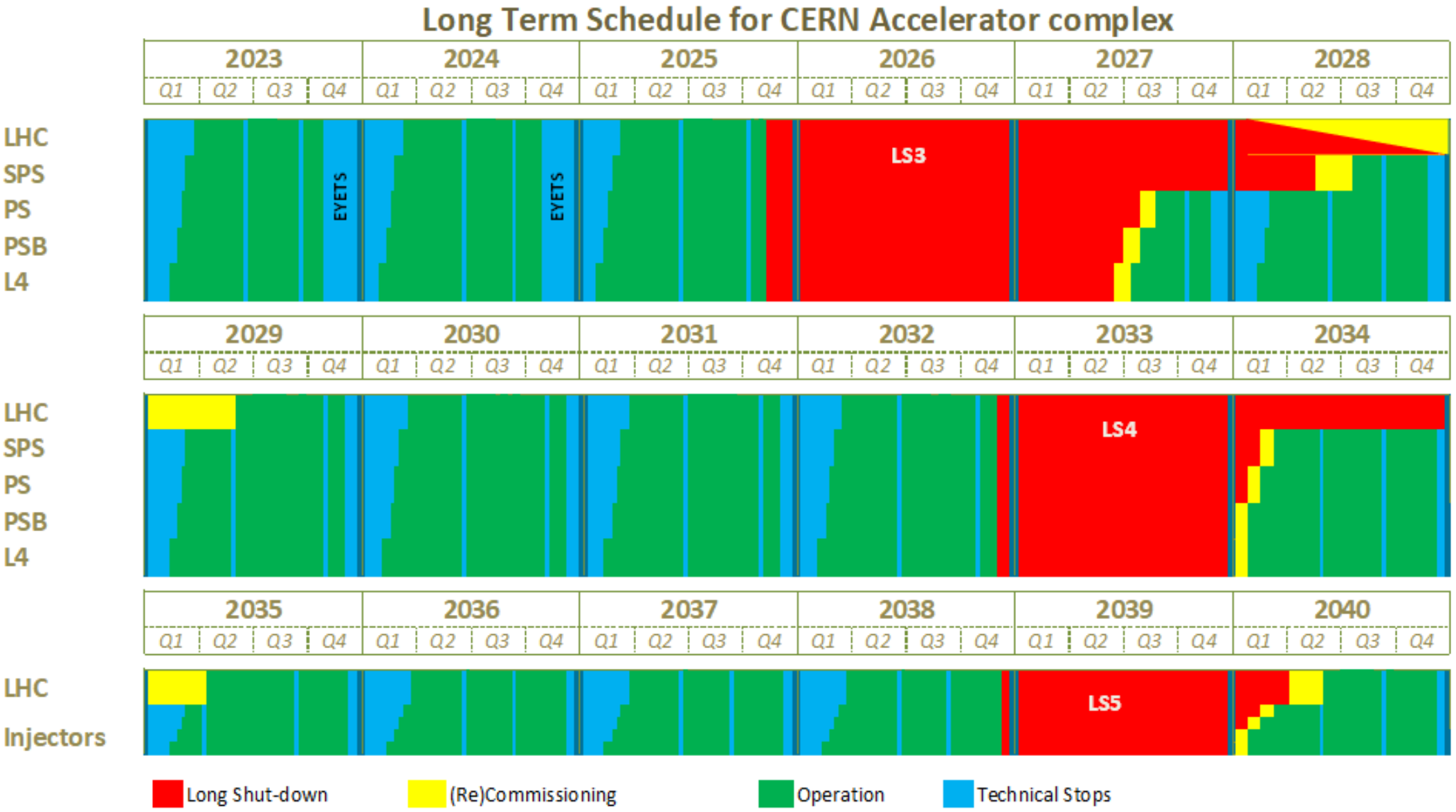
Users Helium Consumption

- **CERN cost in 2022: ~2 MCHF for ~700x500L dewars of LHe**
  - “Constantly” at 20 dewars/week delivery (CERN max capacity: 25 Dewars/week)
  - ~3140 m3/year of gHe (roughly 88 kCHF), mainly needed for pressurize Dewars for lHe transfer
- **Alternative cooling methods**, e.g. cryocoolers, **will require long/costly RD program**
- **Closed circuit system with local liquefier:**
  - **Addresses distribution** and **safety concerns,** offering a **more eco-friendly** solution!
  - **Cost 8.3 MCHF** + 8.5 FTE (only possible **after LS3**), **savings 0.6 MCHF/year!**








Long Term Schedule for CERN Accelerator complex
2023
2024
2025
2026
2027
2028
Q1 Q2 Q3 Q4
LHC
SPS
PS
PSB
L4
EYETS
EYETS
LS3
2029
2030
2031
2032
2033
2034
LS4
2035
2036
2037
2038
2039
2040
LS5
LHC
Injectors
Long Shut-down
(Re)Commissioning
Operation
Technical Stops