TOWARD PULSED PRODUCTION OF ANTIHYDROGEN AND TEST OF THE WEAK EQUIVALENCE PRINCIPLE FOR ANTIMATTER

JAKUB ZIELIŃSKI

ON BEHALF OF THE AEGIS COLLABORATION
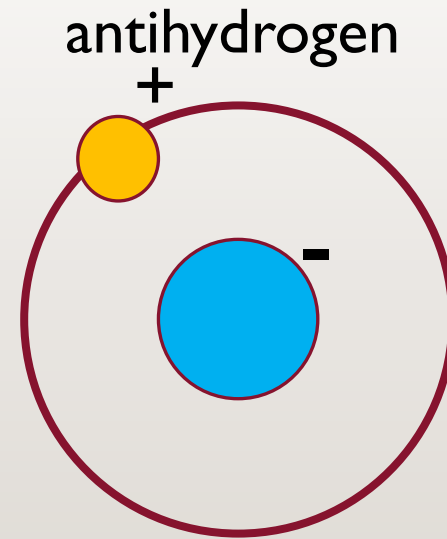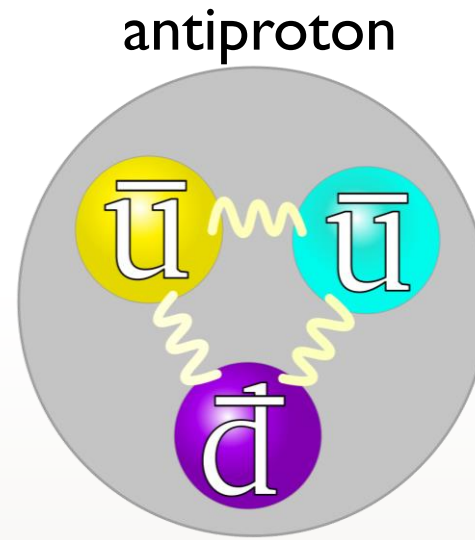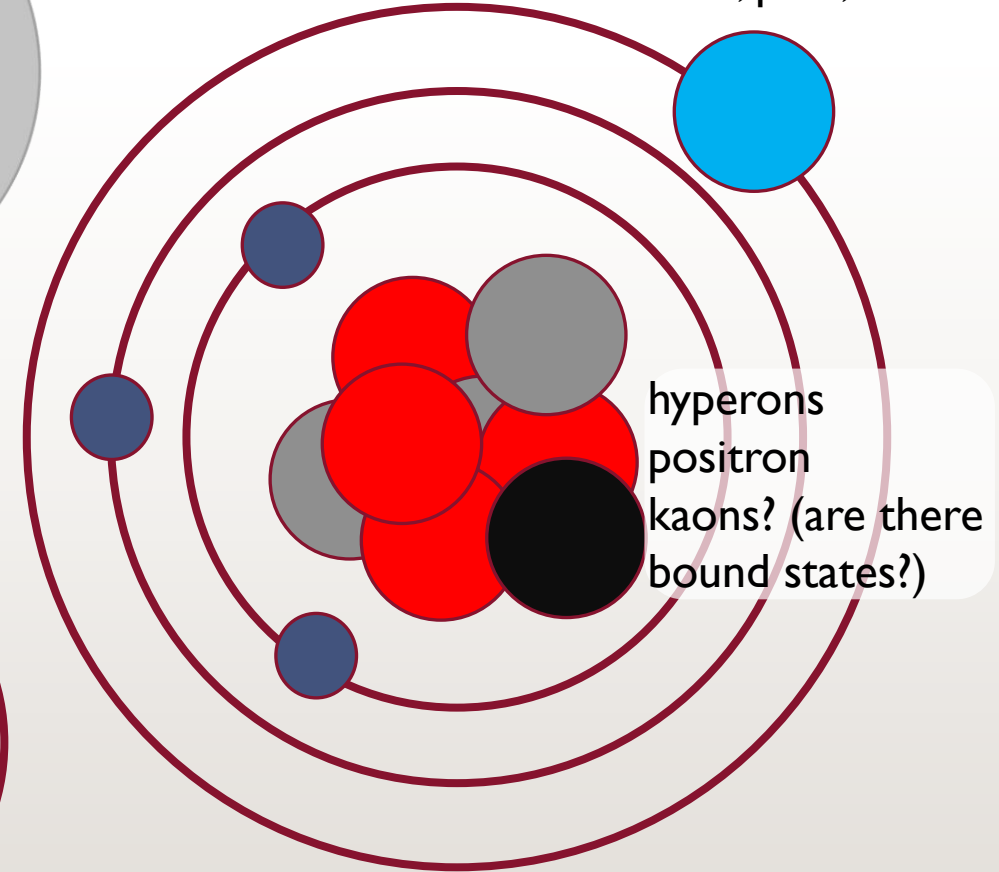

ICNFP 17.07.2023

ANTIMATTER

What's interesting?

- Matter-antimatter imbalance in the Universe
- Tests of fundamental interactions
- Atom spectroscopy

antiproton

$\bar{u}$ $\bar{u}$ $\bar{d}$

antihydrogen
+
-

Exotic atoms

antiproton, kaon, pion, muon…

hyperons
positron
kaons? (are there bound states?)

Positronium, protonium, pionic, kaonic, muonic, antiprotonic…

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THE AEgIS EXPERIMENT

A complex antimatter experiment

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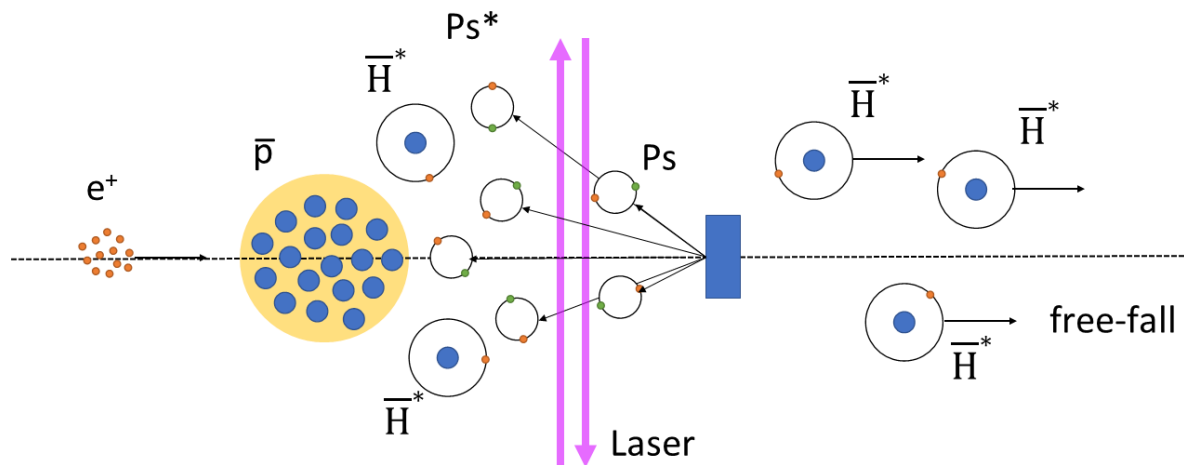
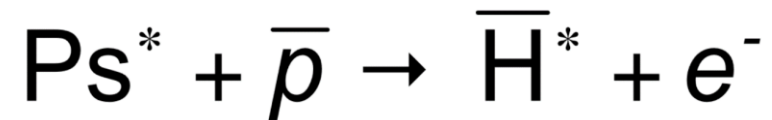CERN

THE AEGIS EXPERIMENT

The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEgIS) collaboration aims at performing spectroscopic studies and direct experimental tests of the Weak Equivalence Principle (WEP) using **antimatter-containing** neutral systems (antihydrogen, positronium atom, antiprotonic ions).

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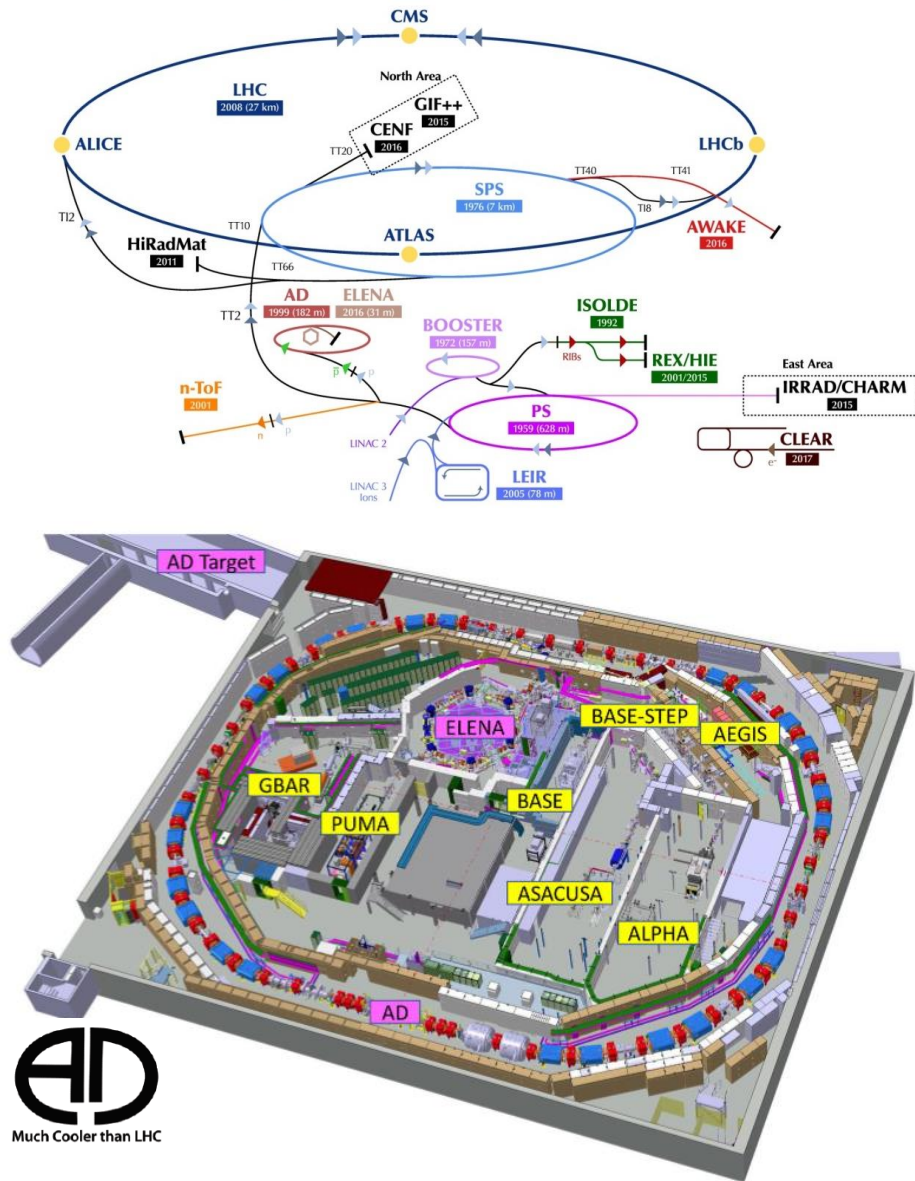
ANTI-HYDROGEN FORMATION: CHARGE-EXCHANGE REACTION

Advantages:

- Pulsed $\overline{H}$ production $\rightarrow$ TOF

- $\sigma_{form} \propto n^4$ (n = Ps Rydberg)

- $\overline{H}$ temp defined by $\overline{p}$ temp

  $\rightarrow$ cold formation

$$Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-$$

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SENSING GRAVITY: MOIRÉ DEFLECTOMETER

- No need for strongly collimated source

- A set of two gratings select the trajectories

- Probed by a position- and timing-sensitive detector

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POSITRON TRAP

POSITRONIUM EXPERIMENTS TRAP

TRANSFER SECTION

5T TRAP

$\overline{\text{H}}$ FORMATION TRAP

POSITRON SOURCE

ELENA BEAM

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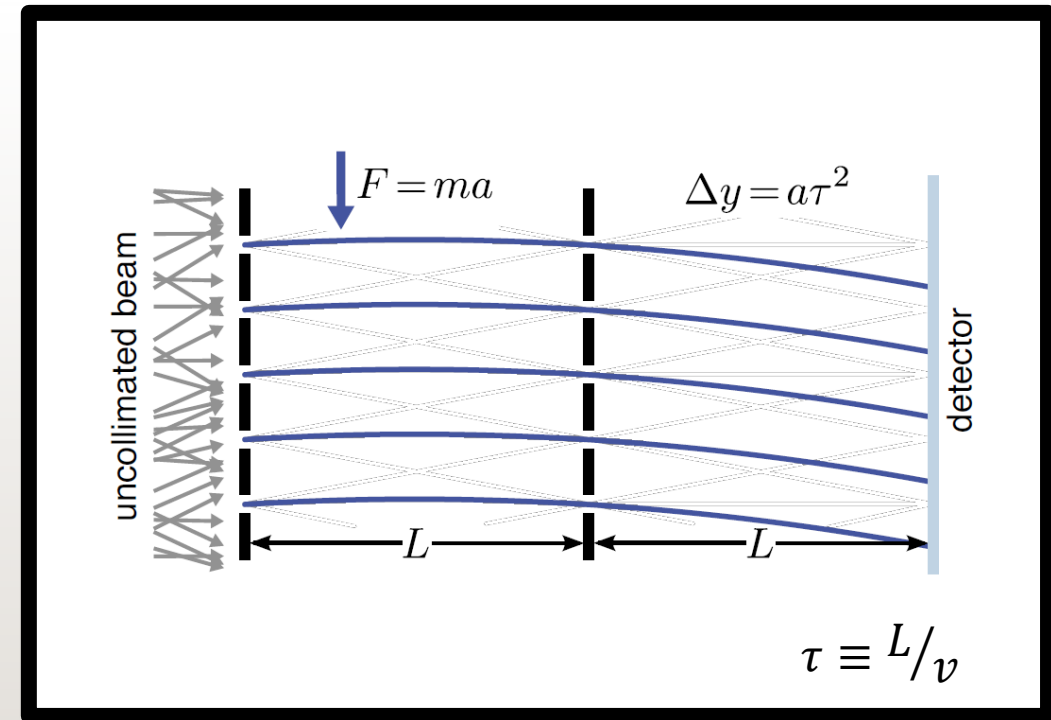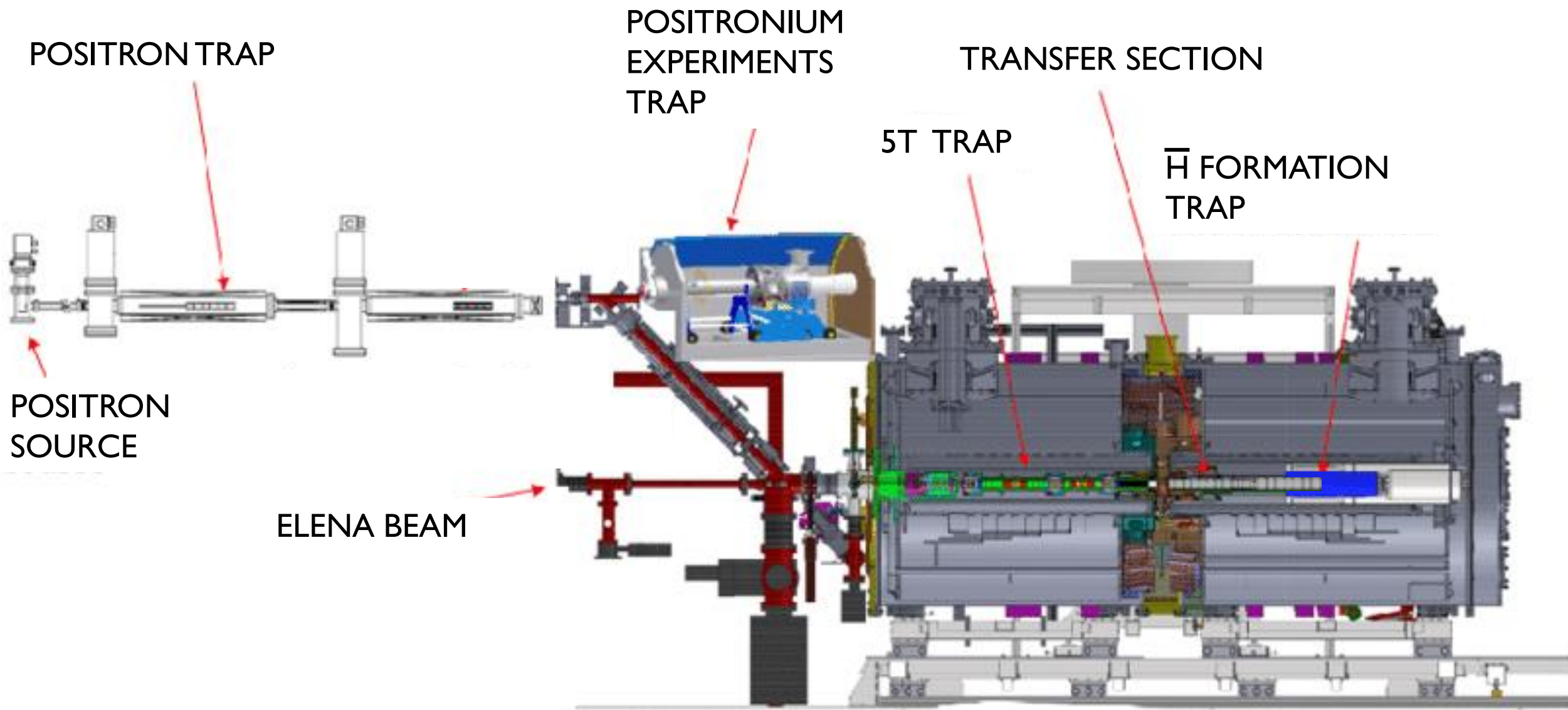
AEGIS PHASE 1

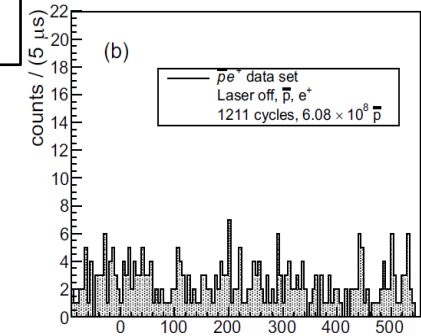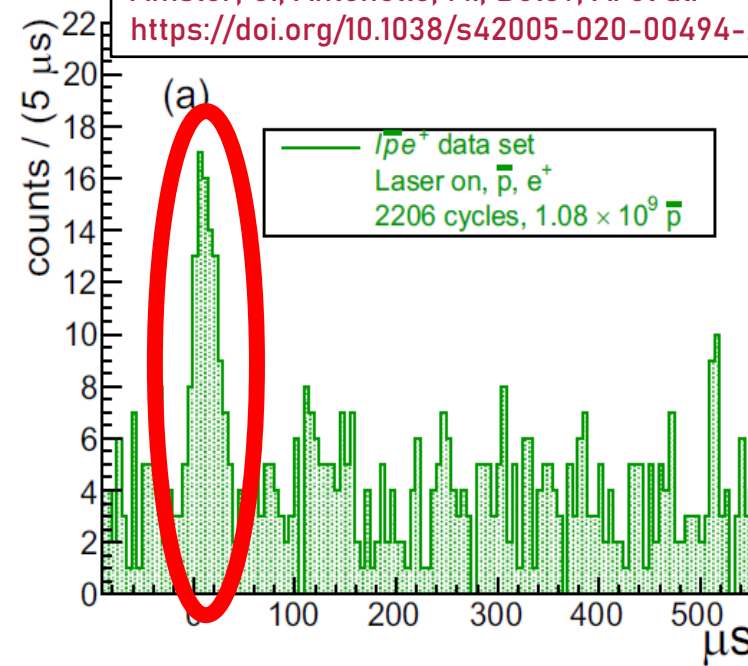- AEgIS Phase 1 was a feasibility study for the $\overline{H}$ source, and it ended in 2018 with the pulsed formation of cold **anti-hydrogen atoms** in the trap

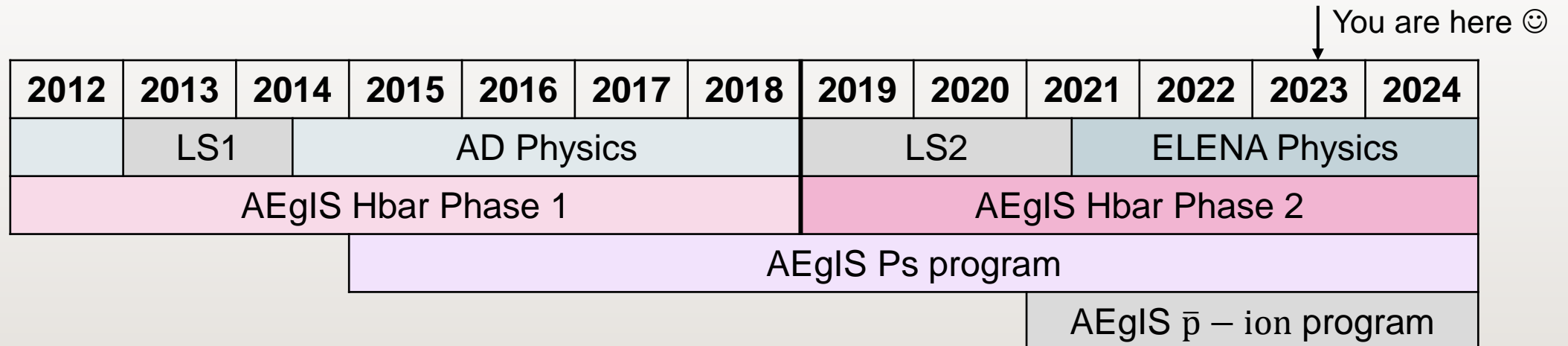- A key step towards this goal was exciting Ps to high Rydberg level (n = 17) in high magnetic field (1T)

Key finding: 0.05 $\overline{H}^*$ produced every 2 mins (with $1.0 \cdot 10^6$ antiprotons)

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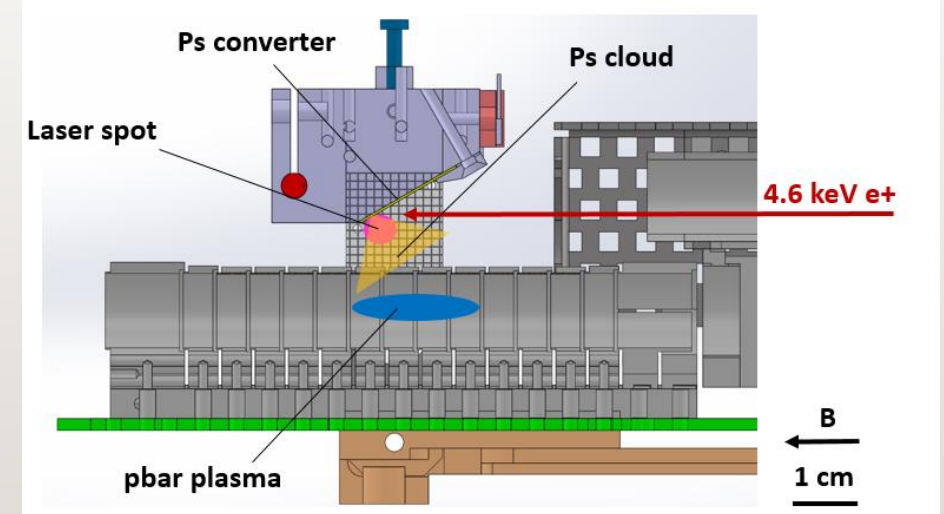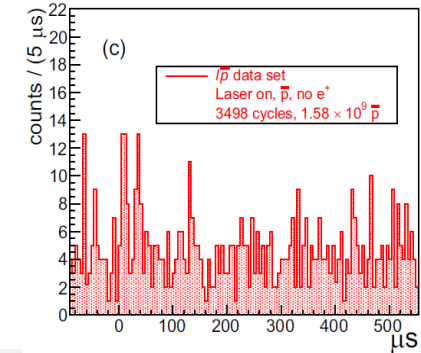
AEGIS PHASE 2

- AEgIS Phase 2 aims to consolidate and improve the anti-hydrogen formation process, while testing the first proof-of-concept inertial measurement with antimatter

You are here ☺

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
	LS1		AD Physics				LS2			ELENA Physics		
AEgIS Hbar Phase 1							AEgIS Hbar Phase 2					
			AEgIS Ps program									
									AEgIS $\bar{p} - $ ion program			

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AEGIS STATUS AND UPGRADES

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NEW ANTI-HYDROGEN FORMATION TRAP INSTALLED

LASER

PS CLOUD

POSITRONS BEAM

POSITRONIUM TARGET

$\overline{P}$ PLASMA

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Miniaturized Ps target

Positronium target holder   HV PCB   Trap support with angle alignment

Filtered electrodes

Ionization grid

Linear Cryo motor for horizontal trap alignment

Rotational cryo motor for moving the target in/out of trap center

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UPGRADED DEGRADING STRUCTURE

Linear actuator/feedthrough with various degrader foils

100 nm
200 nm
300 nm
400 nm
500 nm

Parylene degrader foil holder

Main degrader foil (1.4 um mylar) + beam position monitor

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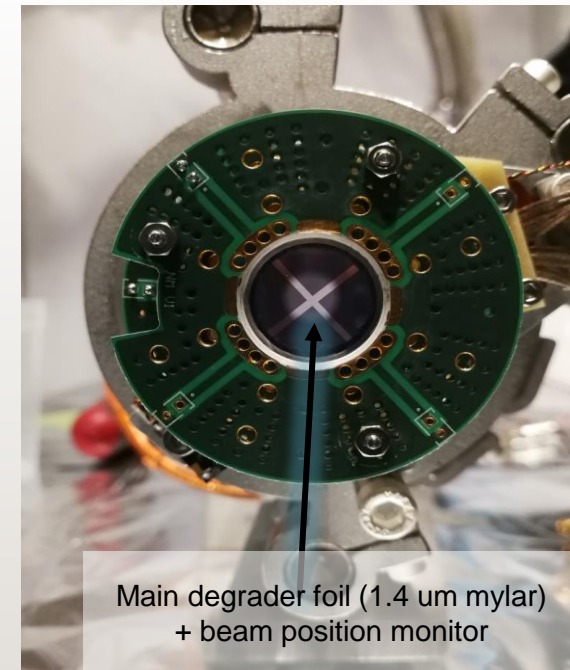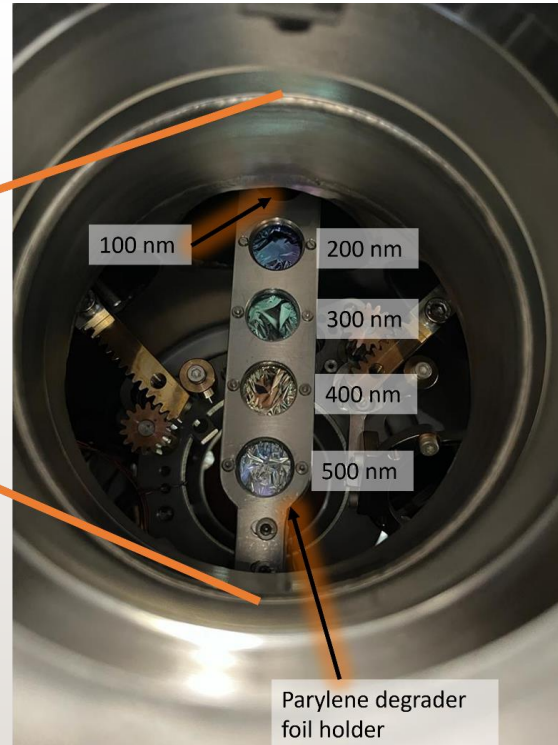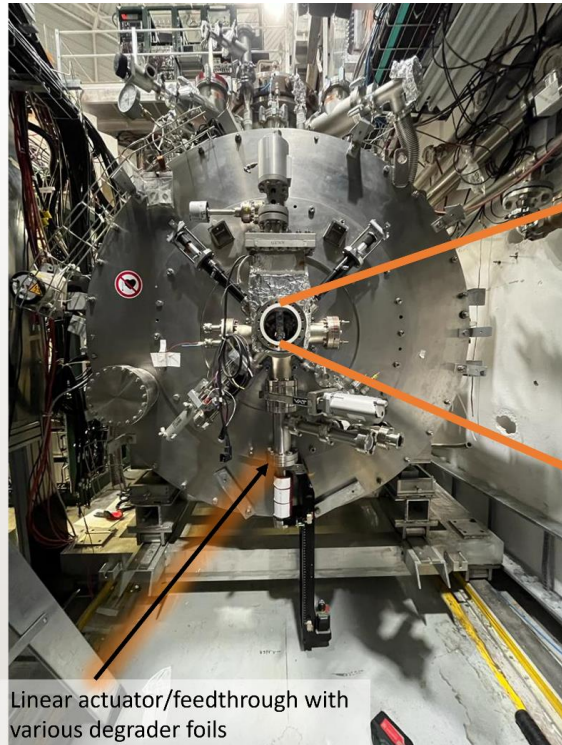
DEGRADER FOILS PERFORMANCE AND TRAPPING EFFICIENCY ANALYSIS

HV1   HV2   HV3

6 cm   trānsm. p̄

B (5T)   MCP

degraded ELENA bunch   reflected p̄

Trapping efficiency: ∼62%

80% stopping at 14 kV with 1.40 um of Mylar

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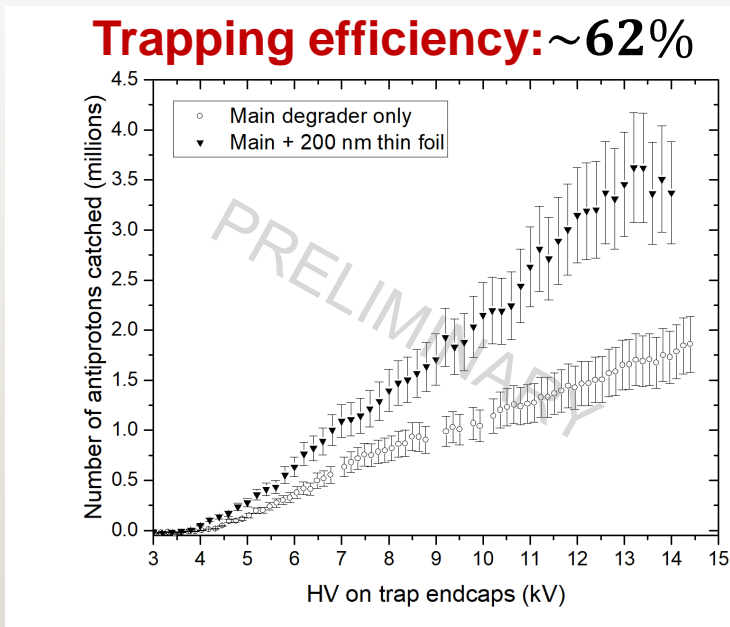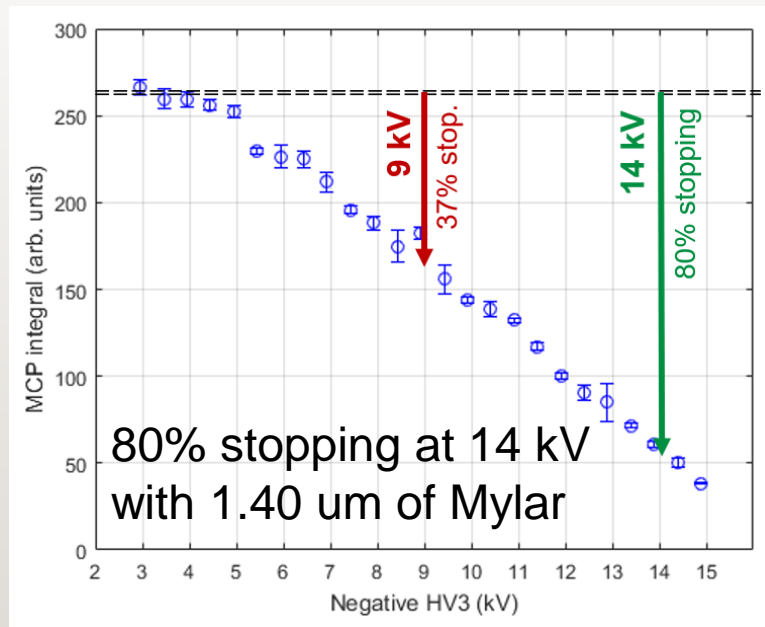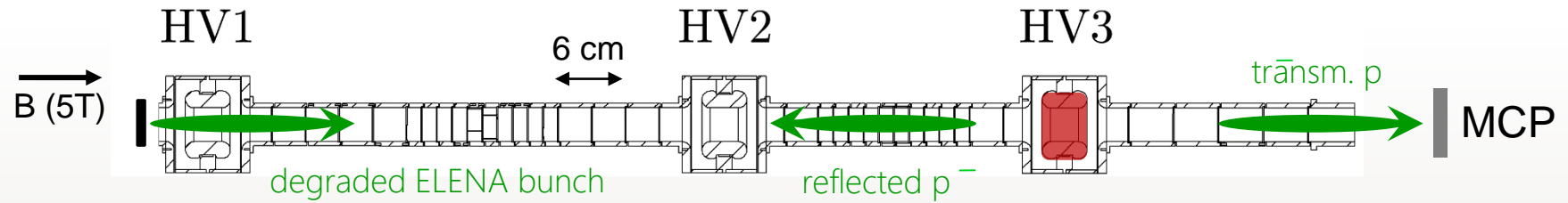
NEW CONTROL SYSTEM

ELENA works 24/7 ☢

Unmanned system

More beamtime

More reliability and safety

Less shifters workload

More time for data analyses & physics!

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TALOS
Total Automation of
Labview Operation for
Science

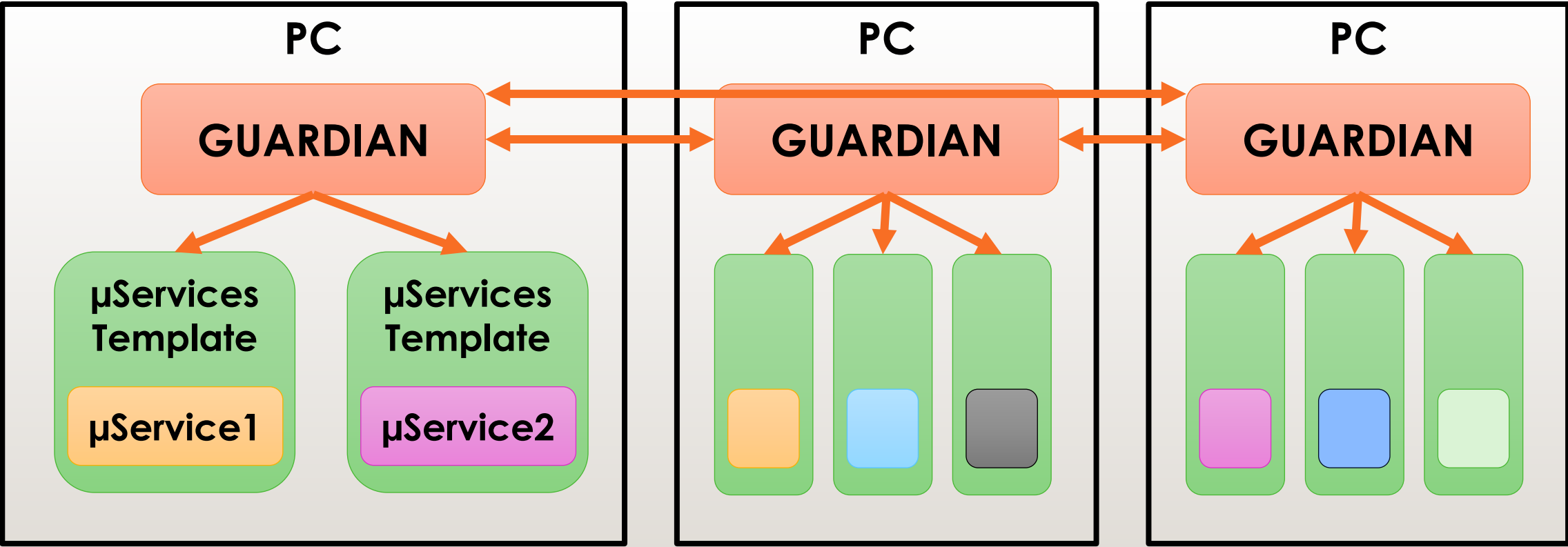# TALOS: FOUNDING PILLARS

DISTRIBUTED SYSTEM

- Unifies all the single machines in a coordinated system

- Enhances reliability, stability and safety (Watchdogs)

- Enables possibility of smart automation

"EVERYTHING IS A MICROSERVICE"

- Defined, clear scope and tasks

- Code uniformation and standardization

- Objects-orientation maximises code reuse

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TALOS: STRUCTURE

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The TAMER

Errors

PRESS CTRL TO ARM

ABORT
STOP

RUN
392238   newtrapctrlhost

uService to show
Tamer

Error Details

Size: 6   Guardians List

aegis-alex	20:59:51.889 11/07/2023
aegis-ekspla	20:59:51.814 11/07/2023
aegis-enviro3	20:59:52.089 11/07/2023

Size: 27   uServices Online

5TC1 Kasli Listener	20:59:58.850 11/07/2023
5TC1 Kasli Wrapper	20:59:58.592 11/07/2023
5TC1 Kasli Writer	20:59:58.851 11/07/2023

Open the Debug Window

STOP

Action History

2023-07-11_18-27-12.059 Received update from Monkey
2023-07-11_18-27-12.061 STOPPED:Monkey Finished
2023-07-11_18-27-12.067 Received update from Monkey
2023-07-11_18-27-12.068 STOPPED:Monkey Finished
2023-07-11_18-27-13.795 Run init successful
2023-07-11_18-27-13.795 Sending the schedule to Monkey
2023-07-11_18-27-13.814 Received update from Monkey
2023-07-11_18-27-13.815 STOPPED:Monkey Finished
2023-07-11_18-29-23.279 Tamer got new schedule(s)
2023-07-11_18-29-30.372 Run init successful
2023-07-11_18-29-30.372 Sending the schedule to Monkey
2023-07-11_18-29-43.947 Start Run
2023-07-11_18-30-00.185 Sending Error Criticality (1) to Monkey
2023-07-11_18-30-00.209 Sending Error Criticality (1) to Monkey
2023-07-11_18-43-41.111 Experiment finished! Ending the script...
2023-07-11_18-43-53.421 Received Banana from 5TC1
2023-07-11_18-43-54.435 Propagate Banana
2023-07-11_18-43-54.435 Sending message B4N4N4 to Monkey
2023-07-11_18-43-54.450 Received update from Monkey
2023-07-11_18-44-09.486 Start Run
2023-07-11_18-57-45.705 Experiment finished! Ending the script...
2023-07-11_18-57-59.868 Received Banana from 5TC1
2023-07-11_18-58-00.879 Propagate Banana
2023-07-11_18-58-00.879 Sending message B4N4N4 to Monkey
2023-07-11_18-58-00.894 Received update from Monkey
2023-07-11_18-58-00.916 All Monkeys Finished

Selector

ALL

Stop Run

Reschedule

Rerun

Reschedule - send Skipped RUNs to the Scheduler. This will overwrite the existing schedule

Rerun - send Skipped RUNs directly to Monkey and start the run.

The Cage

Monkey ID	Status
Monkey	Finished (no errors)

Continuous   With DAQ?   ETA   11/07/2023 18:45

Scripts left   skipped
0   0

Current Action
All the RUNs completed!

Report from previous RUNs
2023-07-11_18-43-54.437 PbarCatchAndDump.py finished with error code: 1. Retry another time
2023-07-11_18-58-00.881 PbarCatchAndDump.py finished well!

Monkey ID	Status

Continuous   With DAQ?   ETA

Scripts left   skipped
0   0

Current Action

Report from previous RUNs

Monkey ID	Status

Continuous   With DAQ?   ETA

Scripts left   skipped
0   0

Current Action

Report from previous RUNs

Monkey ID	Status

Continuous   With DAQ?   ETA

Scripts left   skipped
0   0

Current Action

Report from previous RUNs

Monkey ID	Status

Continuous   With DAQ?   ETA

Scripts left   skipped
0   0

Current Action

Report from previous RUNs

Monkey ID	Status

Continuous   With DAQ?   ETA

Scripts left   skipped
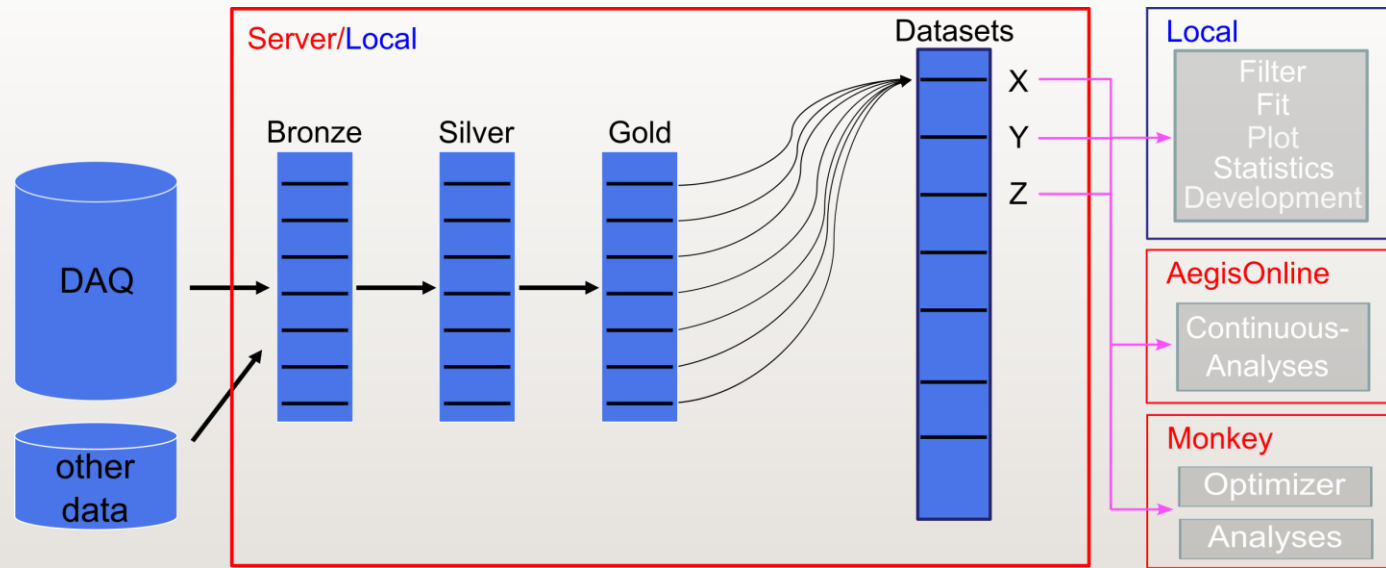0   0

Current Action

Report from previous RUNs

Kasli Log

5TC1> Arming PXI-5152 trigger
5TC1> Arming PXI-6133 trigger
5TC1> Waiting for ELENA bunch trigger ...
5TC1> ELENA bunch has arrived!
5TC1> Hot storage in progress ....
5TC1> Setting 1TCMOS config
5TC1> Arming 1TCMOS
5TC1> Opened fast HV switch ...
5TC1> Ramping down NegHV channels ...
5TC1> Setting HV relays to low voltage ...
5TC1> Getting beam intensity
5TC1> Powering down MCP1T
5TC1> Setting HV relays to shutdown ...
5TC1> Experiment finished!
5TC1> Finalizing the Run ...
5TC1> Waiting for all the uServices to properly terminate ...
5TC1> Waiting for all the data to reach the DAQ and for DAQ to stop...
5TC1> DAQ Stopped!
5TC1> TCP connection closed. Bye!
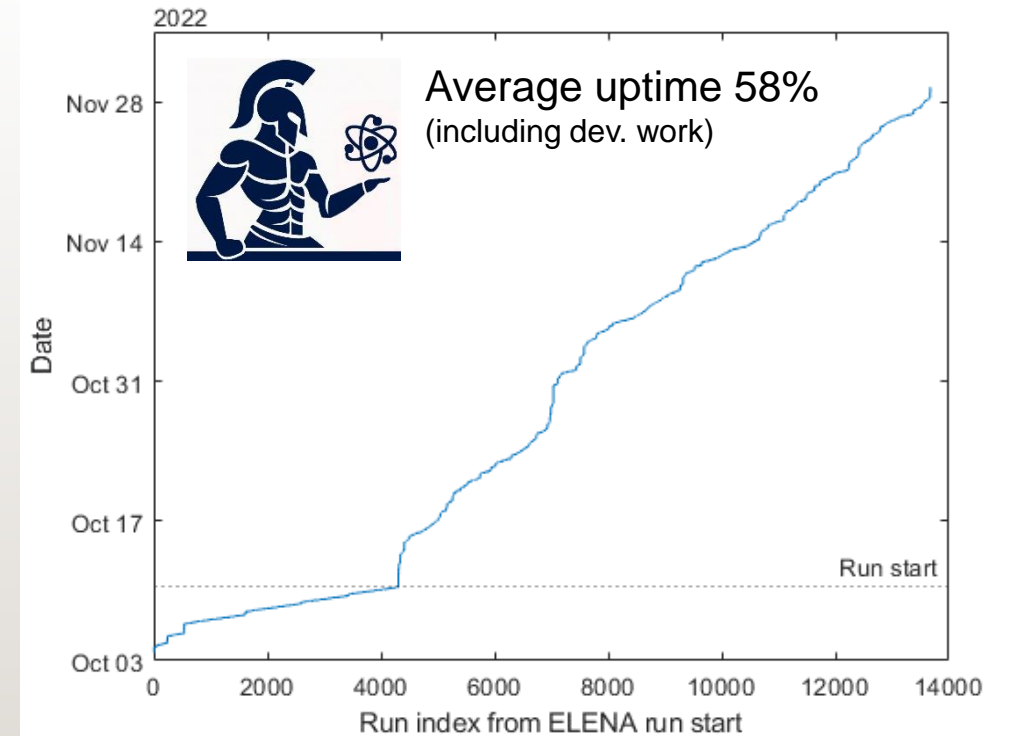5TC1> Send a b4n4n4 to the Monkey!
Return 0

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CONTINUOUS OPERATION OF CONTROL SYSTEM AND DATA ANALYSIS

All Python Analyses Code of Aegis (ALPACA)

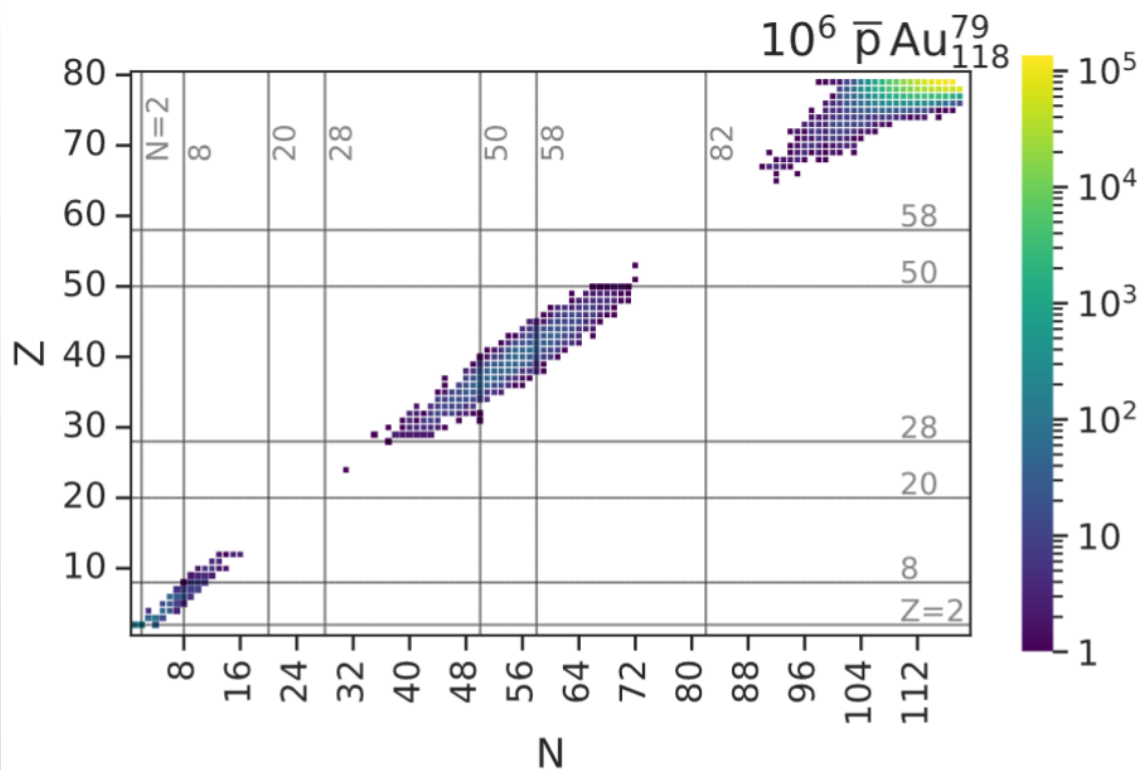**Full deployment of the TALOS control system**

Average uptime 58%
(including dev. work)

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REWORKING TO OPTIMIZE ELENA STEERING SETTINGS

October 13, 2022

ELENA beam optimization

November 27, 2022

80% of pbars in 2 cm
(trap is 6 cm)

Coarse 4D scan

Offset tuning

Angle tuning

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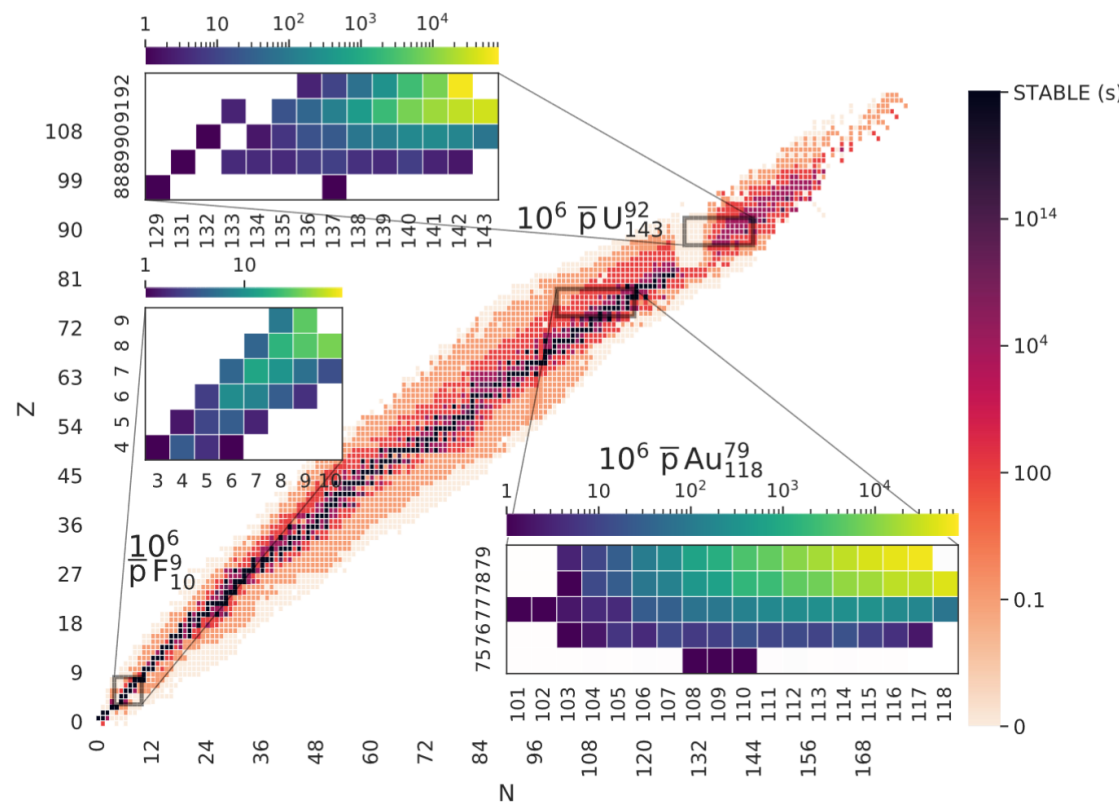WARSAW UNIVERSITY OF TECHNOLOGY

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FUTURE DEVELOPMENT

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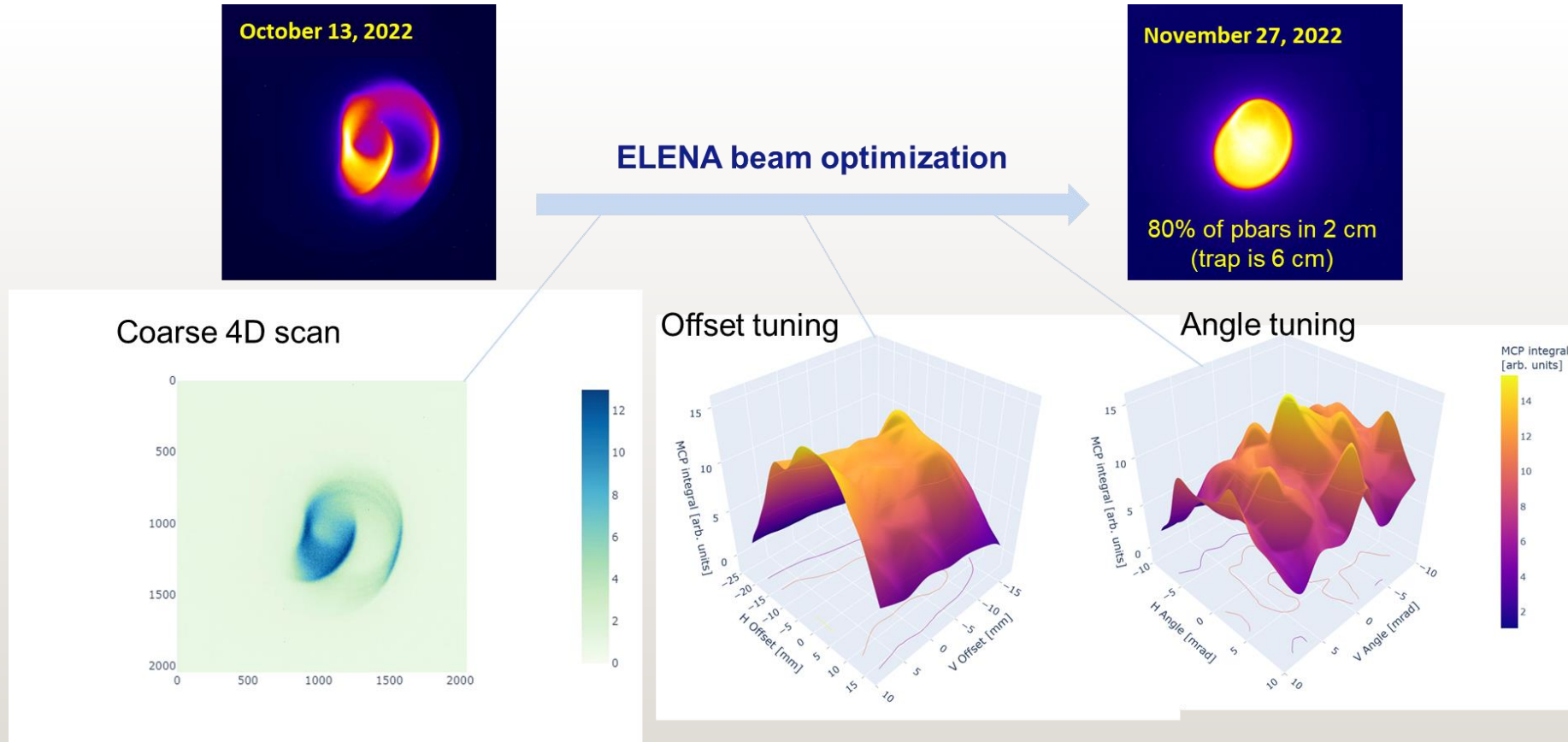
ANTIPROTONIC ATOMS SIMULATION RESULTS

Isotopes produced from antiprotonic Gold

Example isotopes production with stabilities

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FUTURE DEVELOPMENT (2023-2025)

- Produce 10^3 times $\overline{\text{H}}$ w.r.t 2018, 10 times colder

- Formation of $\overline{\text{H}}$ beams (via Stark acceleration or ballistic formation)

- Construction of Moiré Interferometer and test of a Proof-of-Concept for inertial measurement

- Proof-of-Concept of antiprotonic ions formation

- Implementation of feedback-loop between TALOS and ALPACA (on-line optimization)

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THANKS FOR LISTENING!

Comments and/or Questions?

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BACKUP SLIDES

ICNFP 17.07.2023

ANTI-HYDROGEN FORMATION IMPROVEMENT

	PHASE 1	PHASE 2	Improvement
Degrader efficiency	~ 2-3 % x 2E7	~70 % x 5E6	~ 4 x
H Form Cross Section	N=17	N = 24	~ 4x
Positronium target	7 %	25 %	~ 3.6 x
Laser Bandwidth coverage	15 %	30 %	~ 2 x
New positron source (2024)	1E6 e$^+$/min	8E6 e$^+$/min	~ 8 x
TOTAL	0.05 $\overline{H}$/min		~ 1000 x

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overview of AD facility

space for future (anti)atomic physics experiments

ALPHA-g
ASACUSA
PUMA
ALPHA
GBAR
BASE
STEP-BASE
AEḡIS
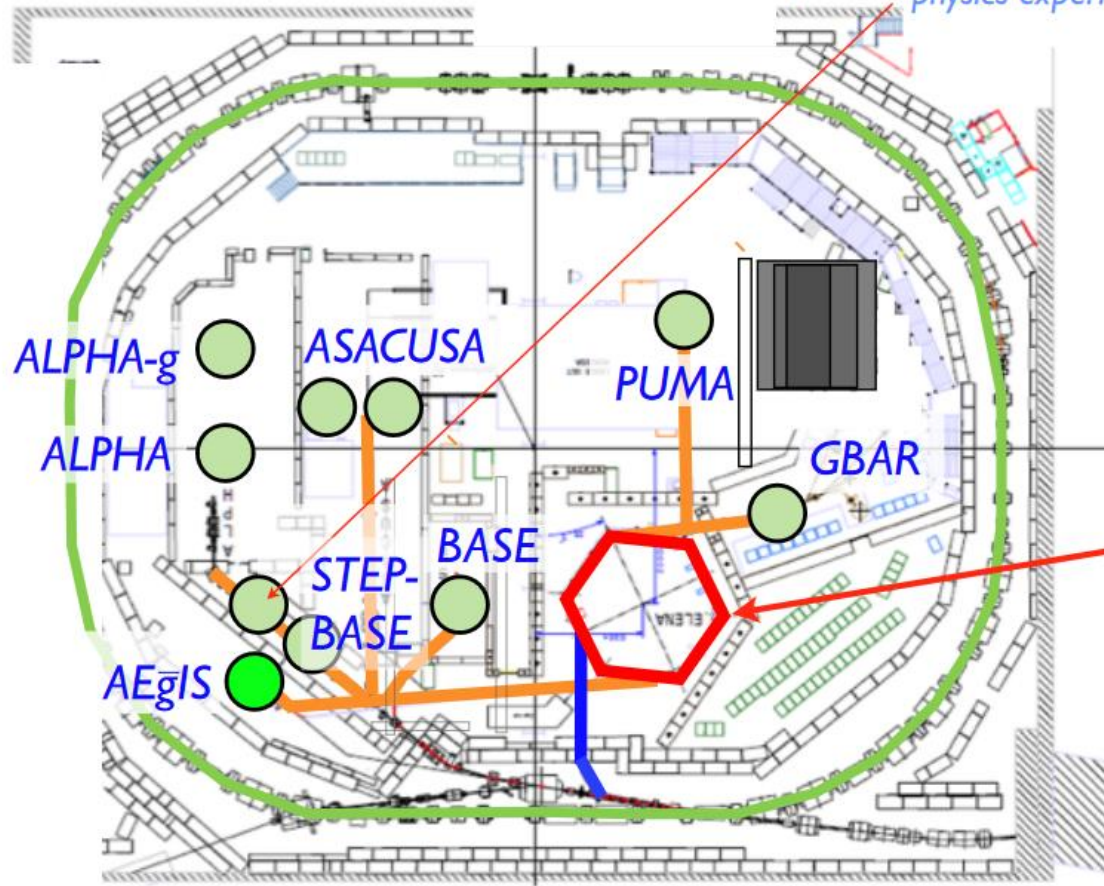
ELENA: extraction of antiprotons at 100 keV; trapping efficiency goes from ~1% at AD to O(100%);

$10^7\ \overline{p}\ /100s$

in operation since 2021

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ANTIPROTONS CATCHING AND COOLING

"Compression of a mixed antiproton and electron non-neutral plasma to high densities", the AEgIS Collaboration, Eur. Phys. J. D (2018), 72: 76
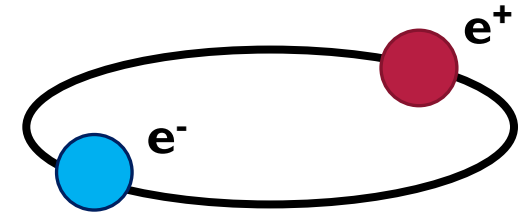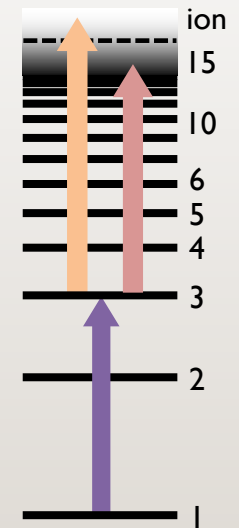
1) capture

2) e⁻ cooling

3) compression

4) transfer

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Geant4

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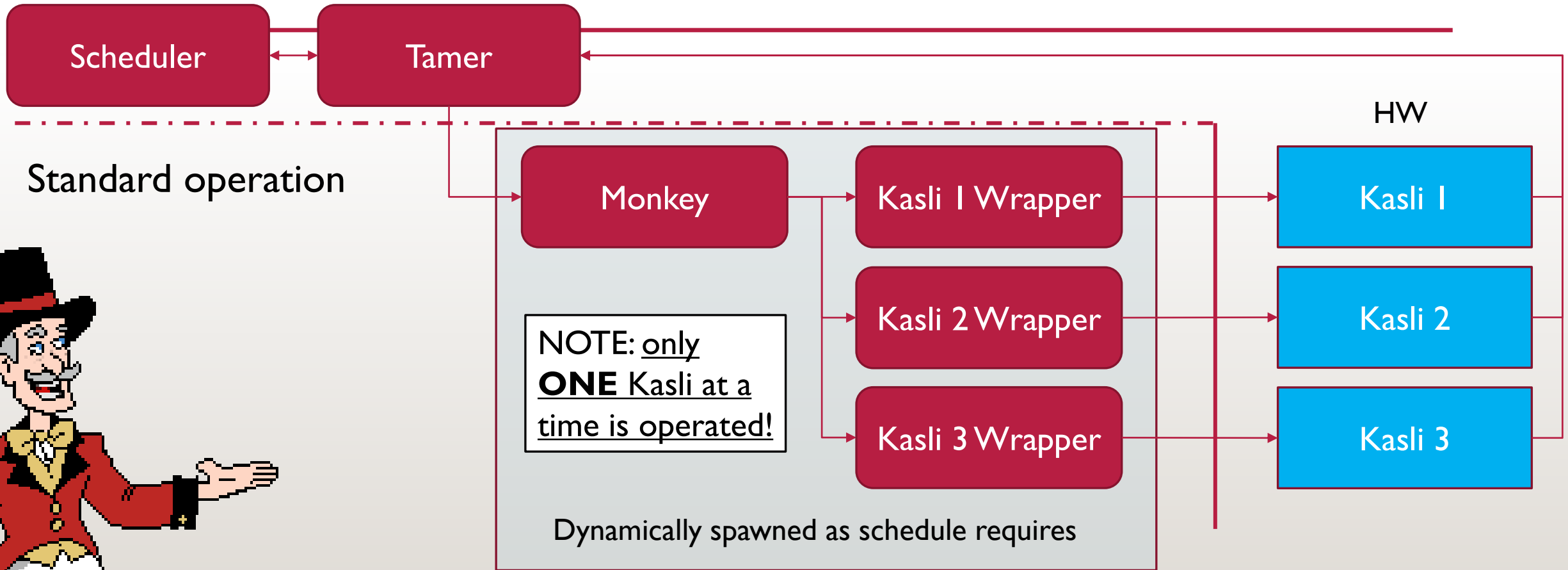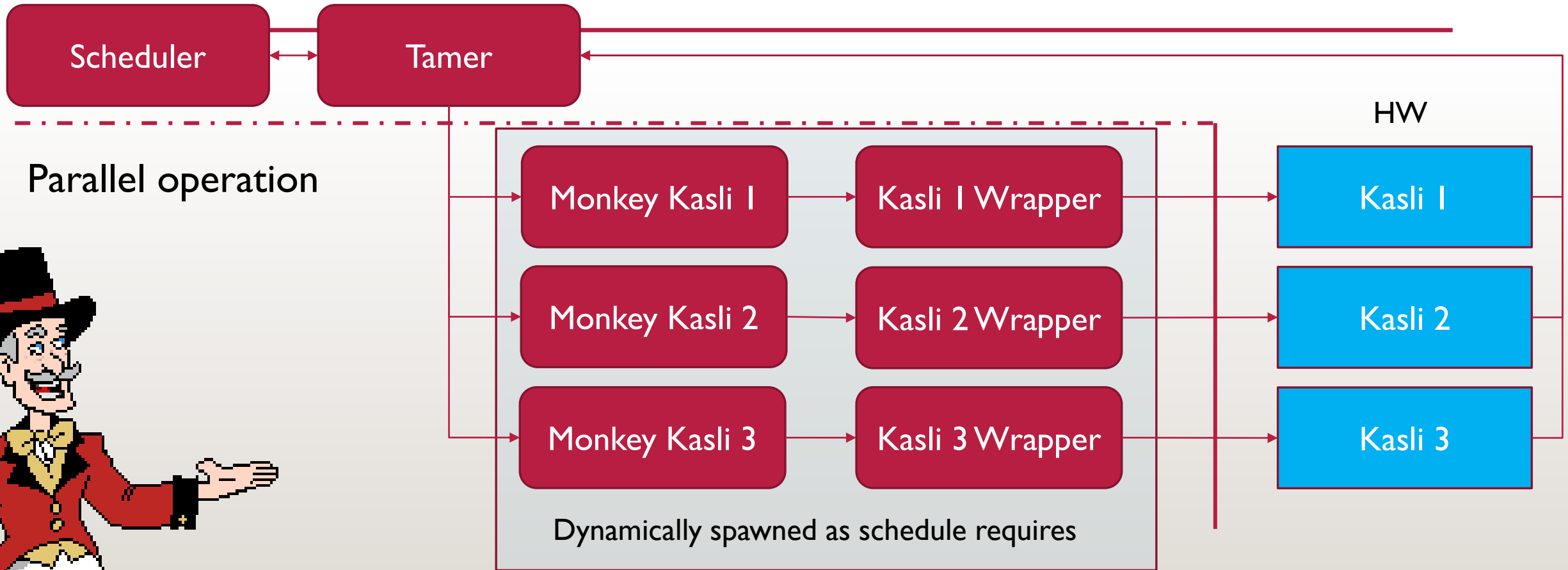WARSAW UNIVERSITY OF TECHNOLOGY

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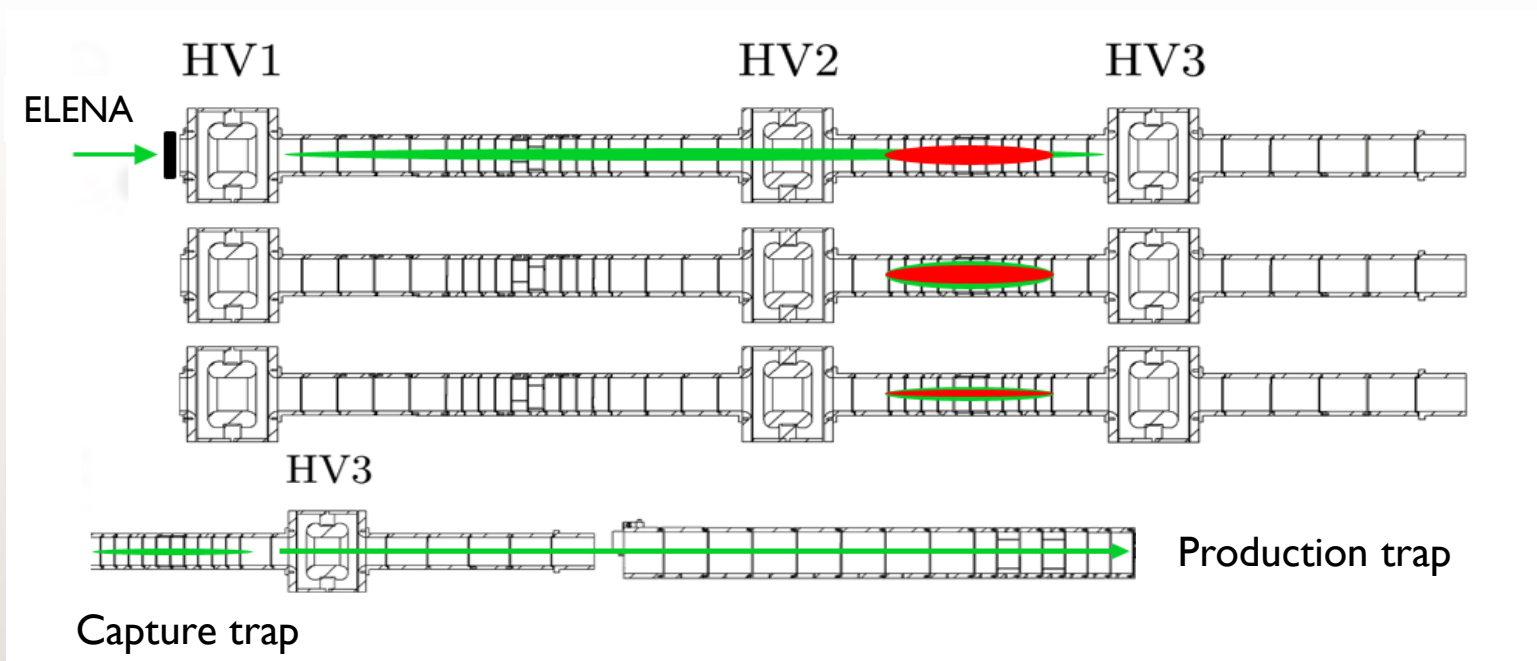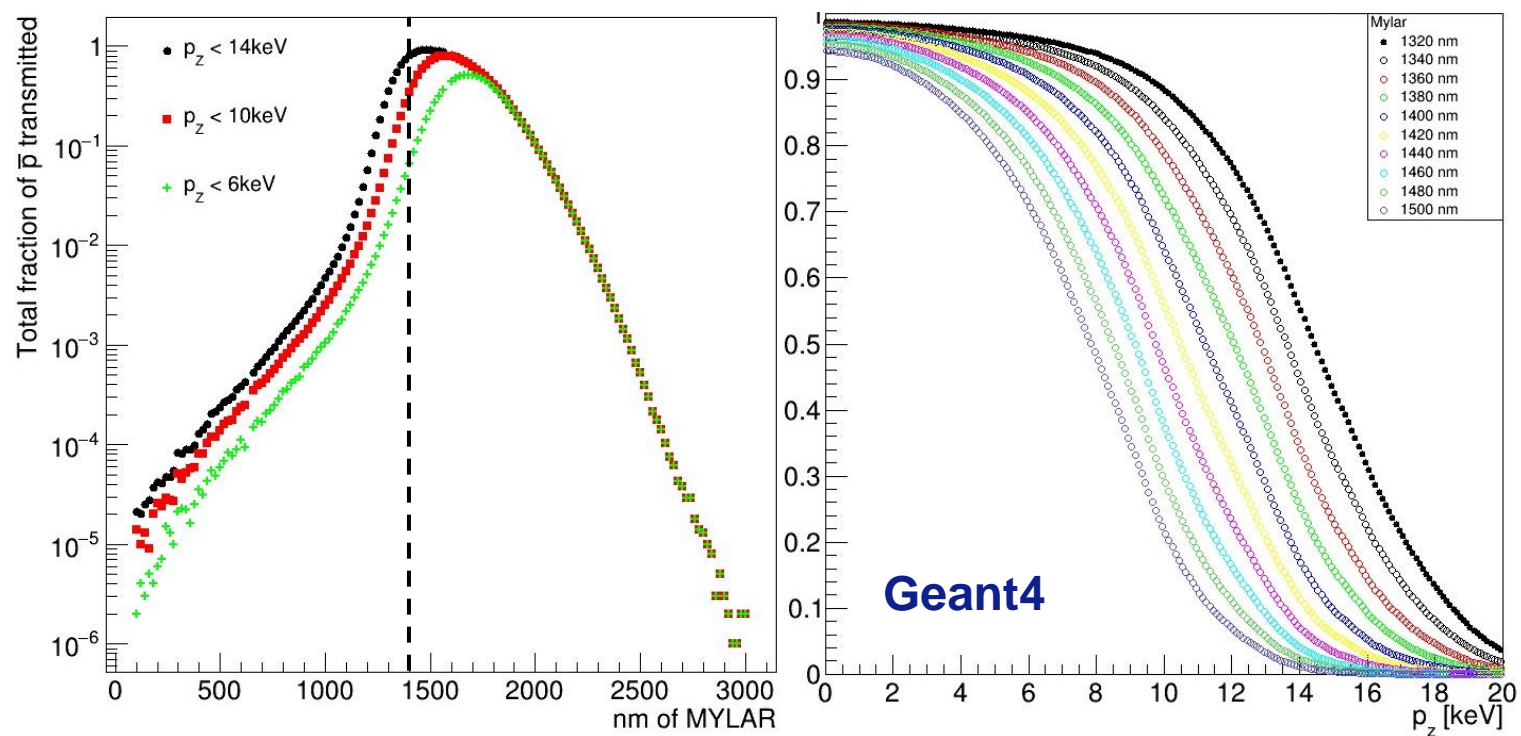
POSITRONIUM FORMATION
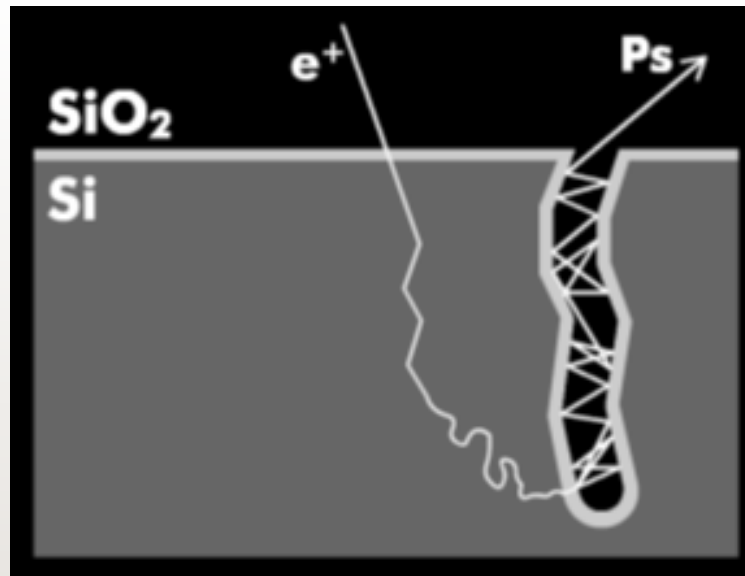
- e$^+$ implanted in the Si bulk @ keV

- Ps forms on the nanopores surface

- para-Ps annihilates, ortho-Ps cools by collisions

- ortho-Ps emitted in vacuum (25% overall eff.)

- Laser excitation to long-lived high Rydberg states (n = 17 – 28)

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RUNNING IN AUTONOMOUS MODE

Scheduler

Tamer

HW

Standard operation

Monkey

Kasli 1 Wrapper

Kasli 2 Wrapper

Kasli 3 Wrapper

NOTE: only **ONE** Kasli at a time is operated!

Kasli 1

Kasli 2

Kasli 3

Dynamically spawned as schedule requires

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RUNNING IN AUTONOMOUS MODE

Scheduler

Tamer

HW

Parallel operation

Monkey Kasli 1 → Kasli 1 Wrapper → Kasli 1

Monkey Kasli 2 → Kasli 2 Wrapper → Kasli 2

Monkey Kasli 3 → Kasli 3 Wrapper → Kasli 3

Dynamically spawned as schedule requires

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SCHEDULING SCRIPTS

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```python
from artiq.experiment import *
from artiq.coredevice.kasli_i2c import port_mapping

class test_HV_amps_trigger(EnvExperiment):

    def build(self):
        self.setattr_device("core")
        self.setattr_device("fastino0")
        self.setattr_device("ttl_hvamp1_sw0")
        self.setattr_device("ttl0")
        self.setattr_device("dio_mcx_dir_switch")
        self.setattr_device("i2c_switch0")

        self.dio_mmcx_i2c_port_1 = port_mapping["EEM0"]
        self.voltage = 0.05

    @kernel
    def set_dio_outputs1(self):
        self.i2c_switch0.set(self.dio_mmcx_i2c_port_1)
        self.dio_mcx_dir_switch.set(0b00000101)
        self.core.break_realtime()
        self.ttl0.input()
        self.core.break_realtime()

    @kernel
    def waitingtrigger(self):
        t_gate = self.ttl0.gate_rising(200*s)
        t_trig = self.ttl0.timestamp_mu(t_gate)
        if t_trig != -1:
            at_mu(t_trig)
            self.core.break_realtime()
            self.fastino0.set_dac(8, self.voltage)

    @kernel
    def run(self):
        self.core.reset()
        self.fastino0.init()
        self.ttl_hvamp1_sw0.on()
        self.core.break_realtime()
        self.set_dio_outputs1()
        self.waitingtrigger()
```


NEW CONTROL ELECTRONICS

- Based on ARTIQ/Sinara

- ns synchronisation over extended periods of time

- Extremely easy to program! Script are based on Python

- Possibility to create experiment libraries with custom-defined functions (e.g. Catch_Hbar())

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