Development and Commissioning of a Hydrogen Ion Source for the CERN ALPHA Experiment

Mark Johnson
STFC Daresbury Laboratory†

8th Symposium on Negative Ions, Beams and Sources NIBS'22
October 2-7, Padova, Italy

mark.johnson@stfc.ac.uk
† Formerly: The University of Manchester, UK

Acknowledgements

MANCHESTER 1824

University of Manchester (UK)
Will Bertsche
Mark Johnson

UKRI Science and Technology Facilities Council

STFC ISIS Neutron and Muon Source (UK)
Low Energy Beams Group
Dan Faircloth
Olli Tarvainen
Scott Lawrie

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

University of Jyväskylä (Finland)
Taneli Kalvas

CERN
ALPHA Collaboration

COMILLAS UNIVERSIDAD PONTIFICIA ICAI ICADE CIHS

Comillas Pontifical University (Spain)
Ana Megia Macias
Elena Barrios Diaz
Daniel Cortazar

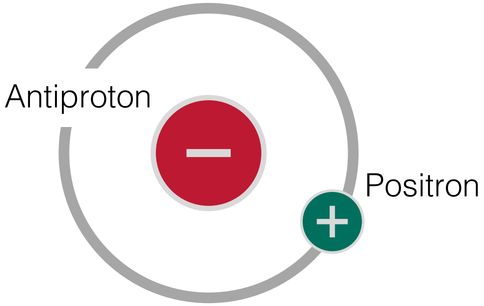
Science and Technology Facilities Council

The ALPHA Experiment

Motivations

[1] C. J. Baker *et al.*, Nature **592**, 35-42 (2021)
[2] A. Matveev *et al.*, Phys. Rev. Lett. **110**, 230801 (2013)

- ALPHA Collaboration based at the **CERN Antiproton Decelerator** (AD) facility since 2005
- ALPHA targets **spectroscopy**, gravitational measurements and other **precision studies** of cold, trapped **antihydrogen** atoms
- Comparisons with hydrogen provide unique tests of **fundamental symmetries** and models of new physics
- Recent demonstration of antihydrogen **laser cooling** could lead to spectroscopy at hydrogen-like precision [1,2]



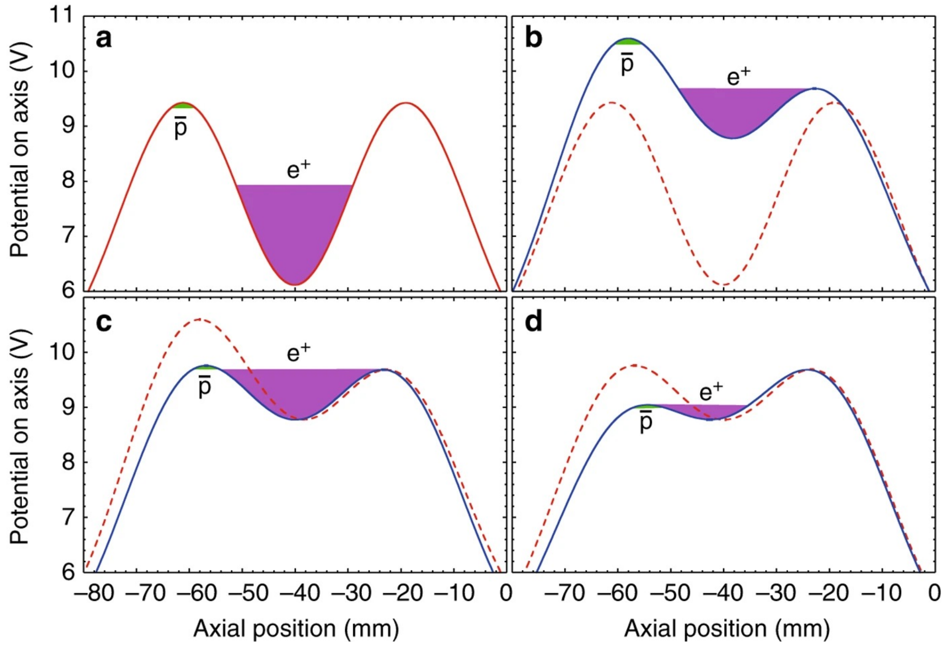
Antihydrogen Synthesis

[1] M. Ahmadi *et al.*, Nat. Commun. **8**, 681 (2017)

- Clouds of cold (~100 K) **positrons and antiprotons slowly mixed** inside a cylindrical Penning trap, forming antihydrogen mainly through three-body recombination [1]

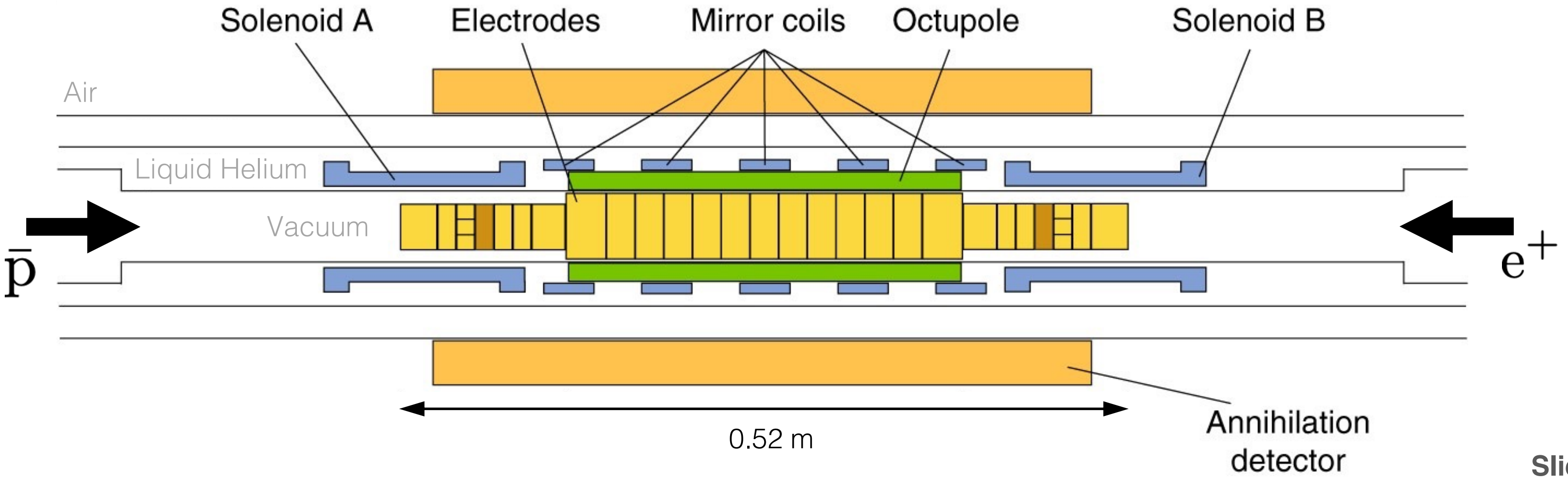
- Several thousand $\bar{H}$ produced per mixing cycle, of which ~20 are **sufficiently cold** to be trapped (T < 0.54 K)

- Trapped $\bar{H}$ counted using a three-layer silicon **vertex detector** upon annihilation with the trap walls



Above: On-axis electric potentials and particle distributions at various stages of positron-antiproton mixing [1]

Bottom: Schematic view of the ALPHA-II atom trap region



Antihydrogen Trapping

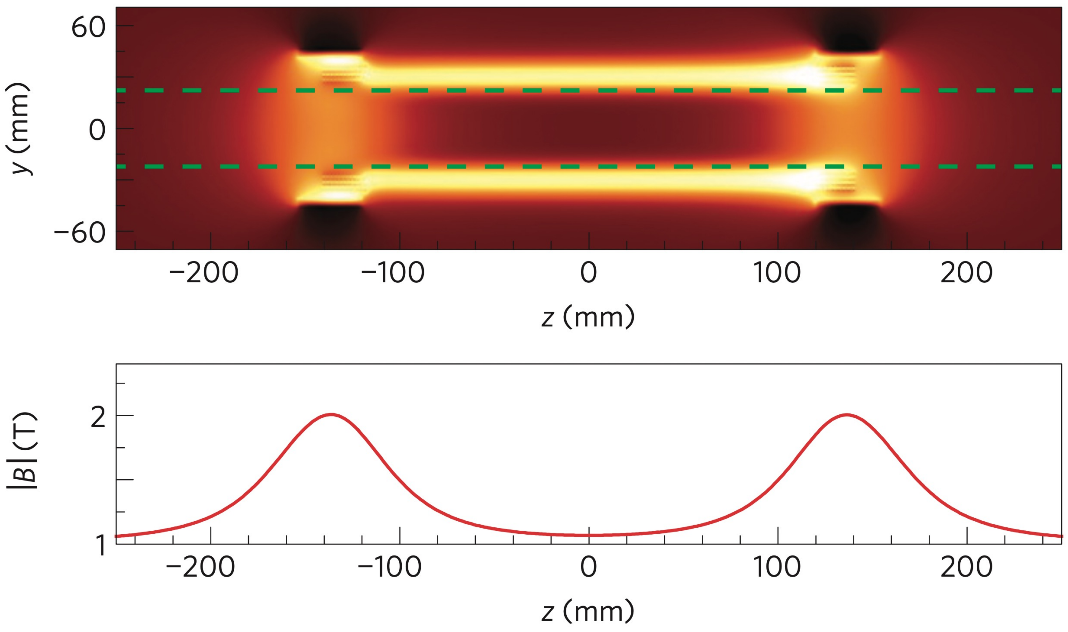
[1] M. Ahmadi *et al.*, Nat. Commun. **8**, 681 (2017)
[2] G.B. Andresen *et al.*, Nature Phys. **7**, 558-564 (2011)

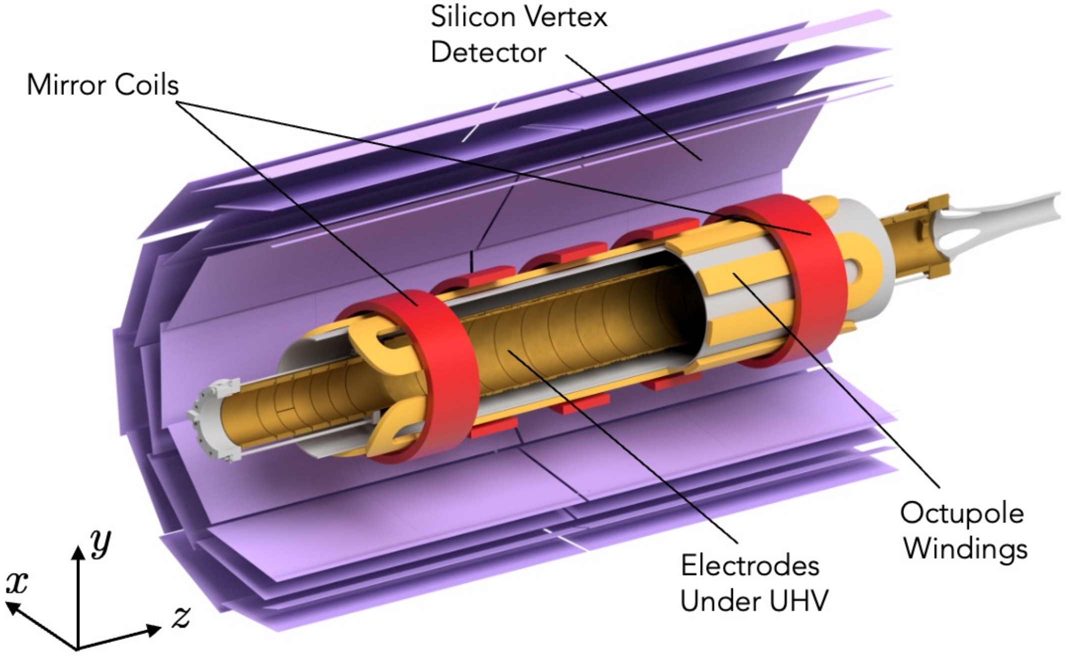
Antihydrogen is produced and trapped inside a superconducting **magnetic minimum trap**:

✓ Octupole provides radial confinement

✓ Five mirror coils provide axial confinement and fine tuning of magnetic field shape

Trap depth (in temperature units) is only ~ 0.54 K!





$$\vec{F} = -\nabla \vec{\mu} \cdot \vec{B}$$

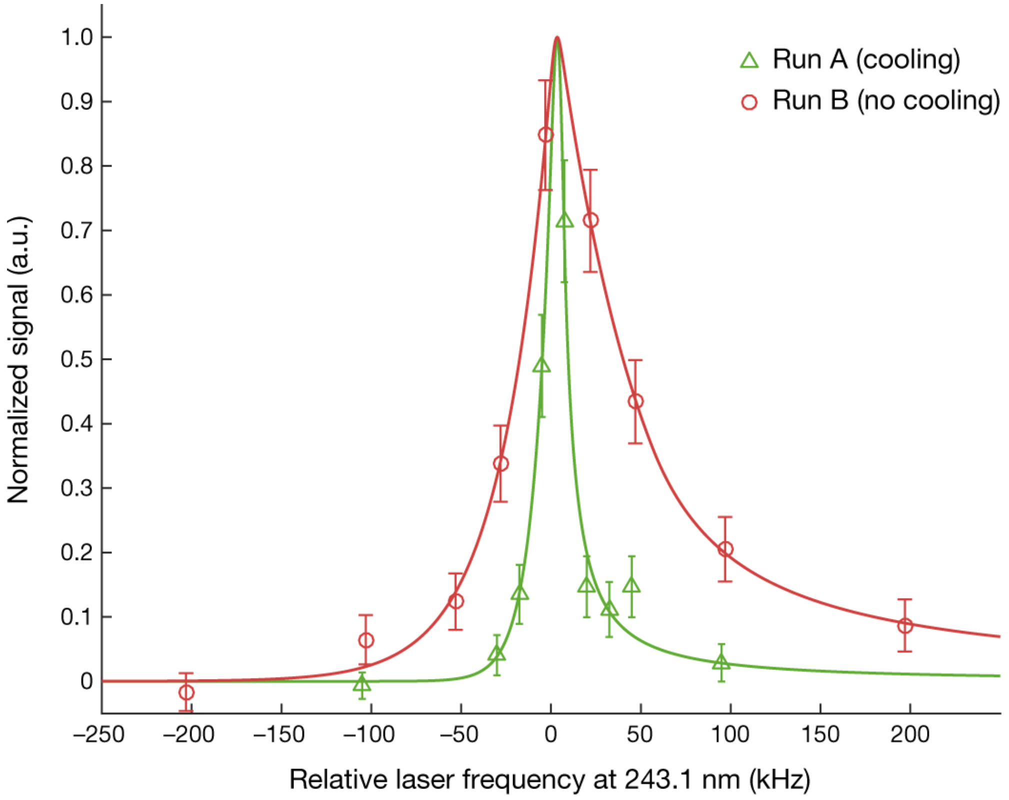
Above: ALPHA-II atom trap region (simplified) and force on a neutral atom within the trap
Left: Typical magnetic field strength inside the atom trap [2]

Recent Physics Results

[1] M. Ahmadi *et al.*, Nature **557**, 71-75 (2018)
[2] M. Ahmadi *et al.*, Nature **561**, 211-215 (2018)
[3] C. J. Baker *et al.*, Nature **592**, 35-42 (2021)

- Spectroscopy primarily targets the narrow antihydrogen **1S-2S transition** at 243 nm [1]
- Recent observation [2] of 1S-2P Lyman-α transitions and **laser cooling** [3] of H will lead to **improved precision**
- **Systematic uncertainties** will dominate future spectroscopy measurements, preventing **model-independent** comparisons to hydrogen

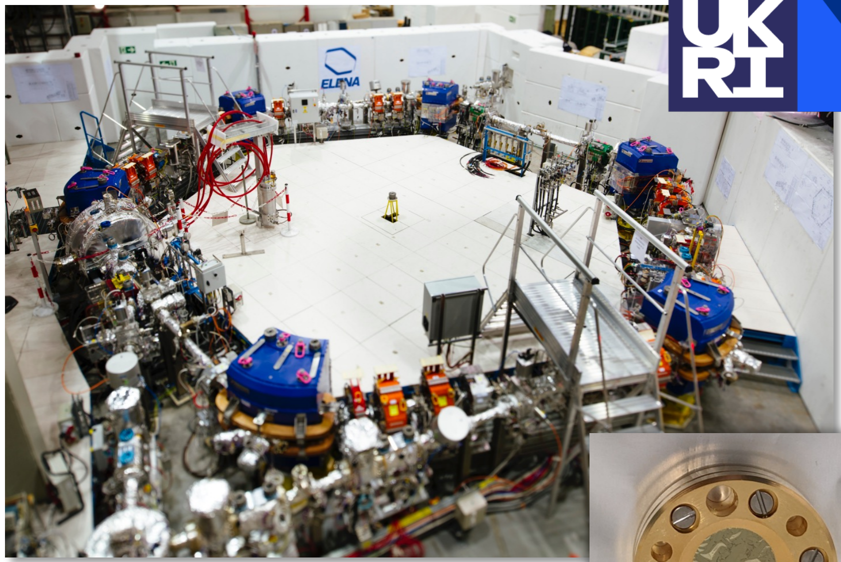
Study	Relative Precision
Hydrogen 1S-2S	
Hänsch et al. (2013)	4.5 x 10^{-15}
Antihydrogen 1S-2S	
ALPHA Collab. (2017)	2 x 10^{-10}
ALPHA Collab. (2018)	2 x 10^{-12}

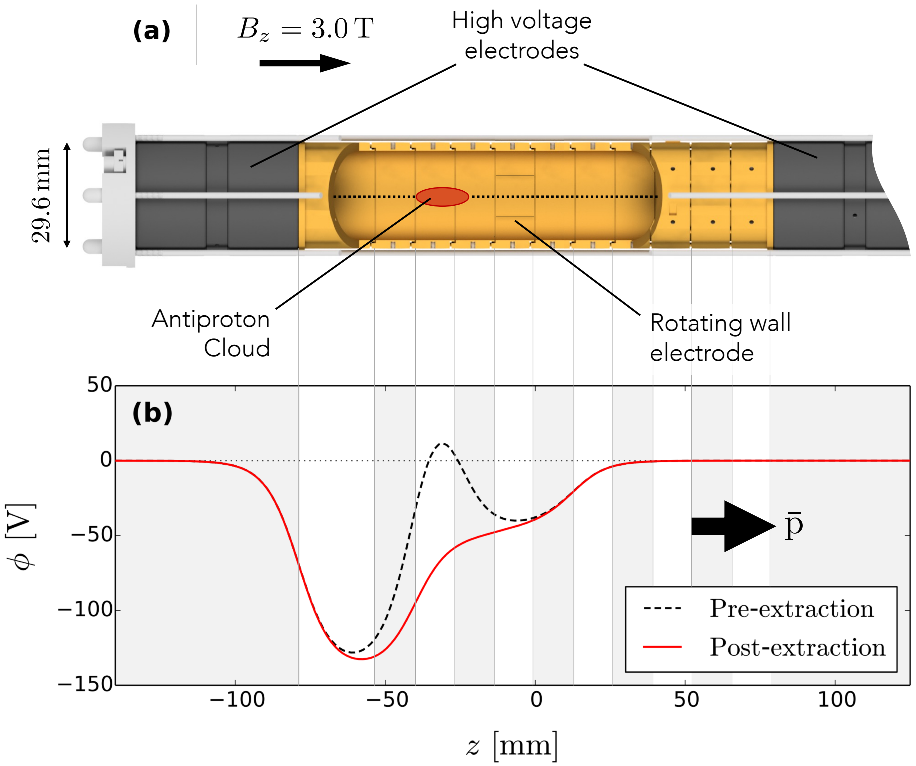


Clear motivations to pursue **hydrogen spectroscopy** in the ALPHA antihydrogen atom trap!

Antiproton Source

- ALPHA receives ~10^7 **antiprotons** from ELENA every 100 seconds, at beam energy 100 keV
- Around 1% of particles traverse a degrader foil with energies < 5 keV, and are captured in a high-voltage **cylindrical Penning trap** at 3 T
- The trapped antiproton cloud is **cooled** and **compressed** before extraction
- ~10^5 antiprotons **transported** along a magnetic beamline at **energy ~100 eV**, limited by the trap electrode voltages





Images (clockwise): CERN ELENA storage ring, an antiproton beam degrader foil, and a schematic of the ALPHA antiproton catching trap showing the on-axis electric potential for trapping

Ion Source Requirements

- Ideally, the extracted H^- beam should have **similar properties** to an **antiproton bunch** in transit within ALPHA.
- This presents several **challenges** in terms of **source design** and **integration**

Beam Energy
Initial: 10 keV **Target:** < 100 eV
Solution: Low-energy extraction, deceleration in transport line

Vacuum
Initial: 10^{-2} mbar **Target:** < 10^{-9} mbar
Solution: Differential pumping within extraction optics

Desired H^- Bunch Parameters	
Parameter	Value
Final Energy [eV]	50 – 100
Energy Spread [eV]	< 2
Ions per bunch	10^7
Bunch length [μs]	~1.0
Equiv. DC Current [μA]	1.6
Vacuum pressure [mbar]	$<10^{-9}$

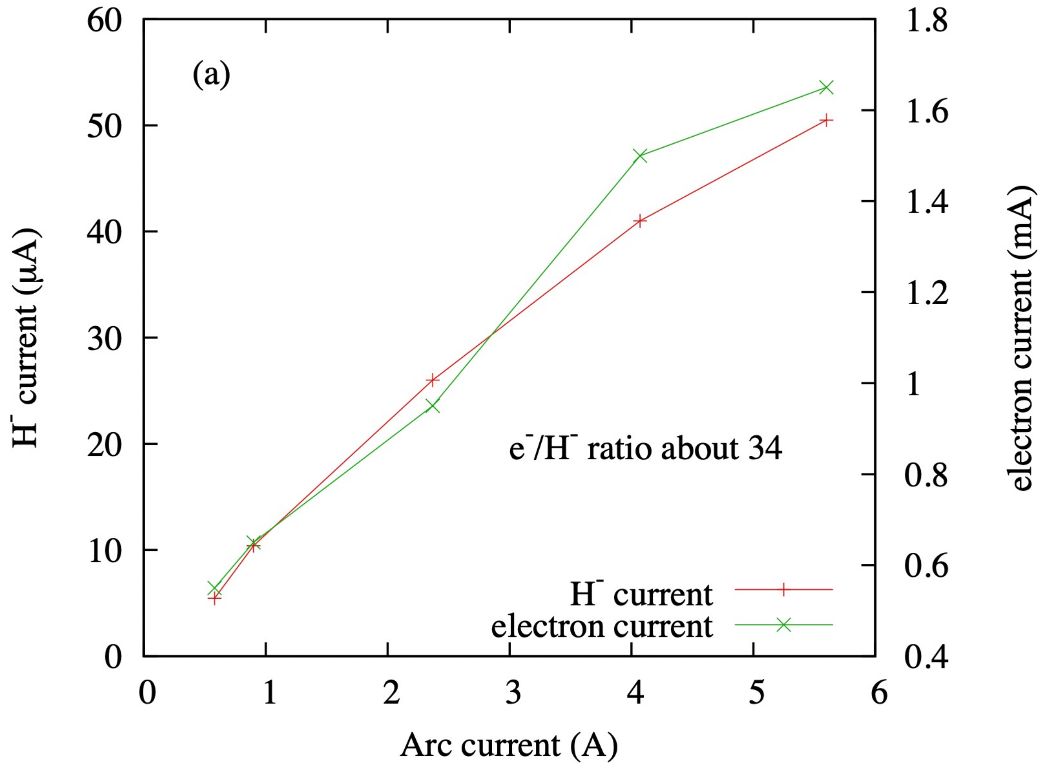
Above: Initial H^- bunch specifications for the ALPHA ion source and transport beamline

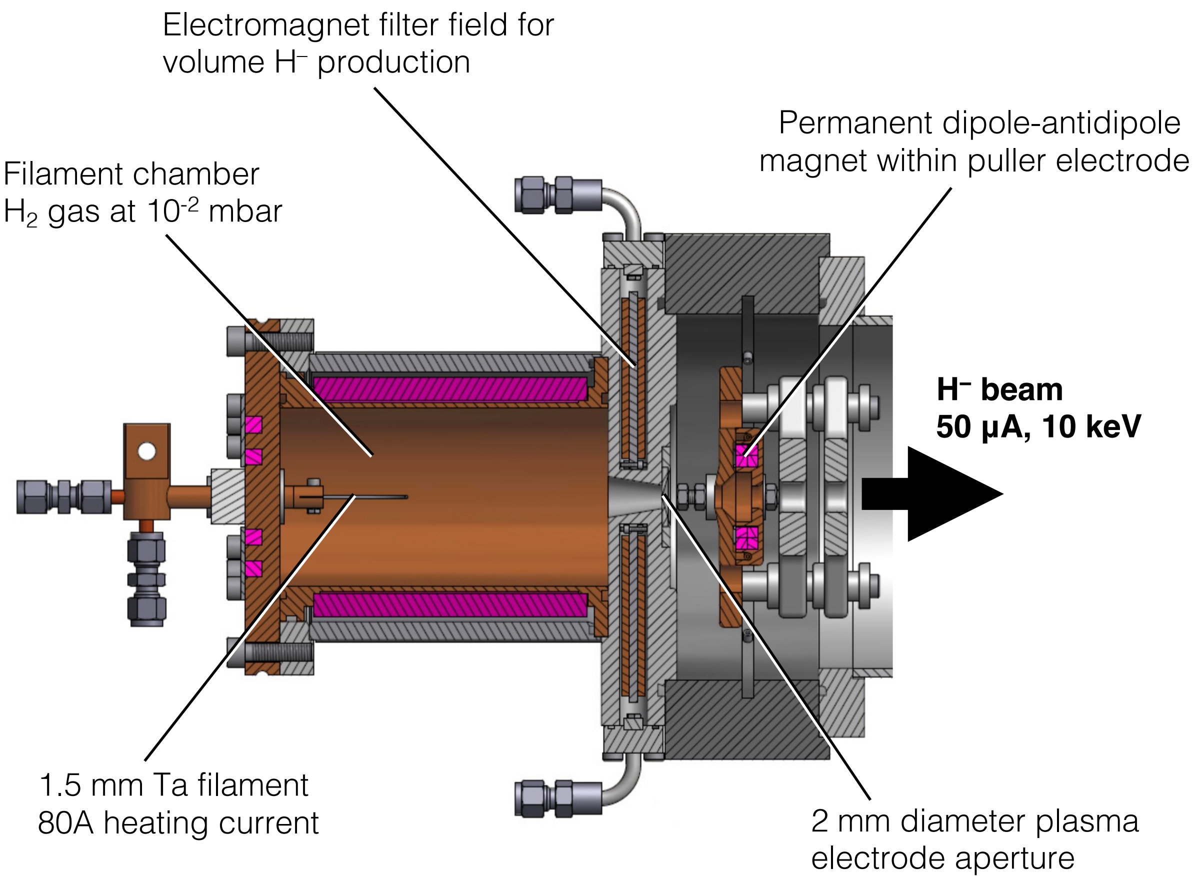
Straightforward operation is important: Most ALPHA shifts won't include an ion source specialist!

PELLIS Ion Source

[1] T. Kalvas *et al.*, AIP Conference Proceedings **1515**, 349 (2013)

- **Filament-driven** multicusp 10 keV **H^- ion source** originally developed at JYFL in 2012
- Low transverse **emittance** (ε_N = 0.012 mm mrad) for extracted currents up to ~50 µA



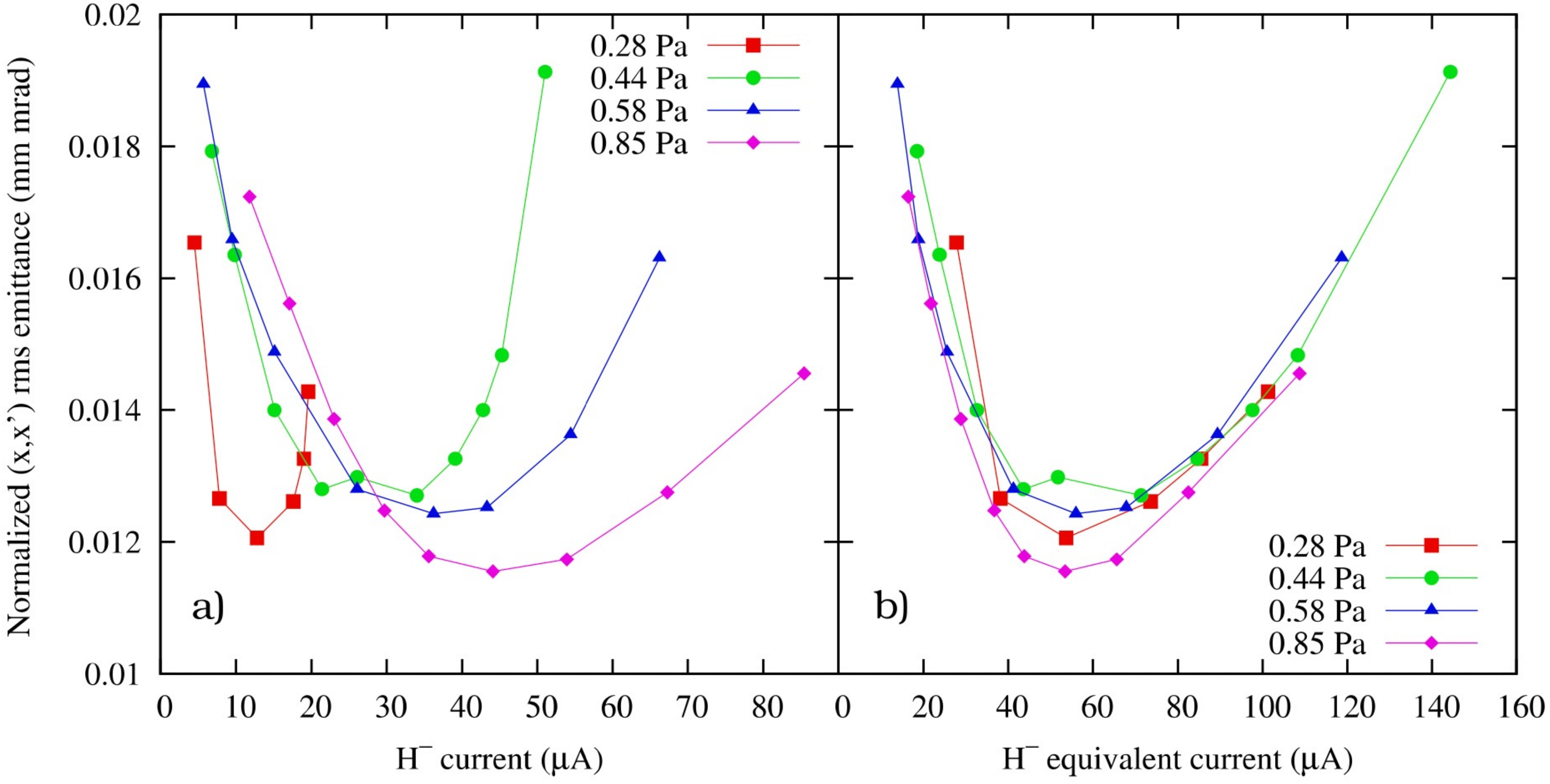


Above: Cross section of the original PELLIS source installed at JYFL
Left: Extracted H^- beam current versus arc current, with an optimised filter field

PELLIS Ion Source

[1] T. Kalvas, PhD Thesis, Univ. Jyväskylä (2013)

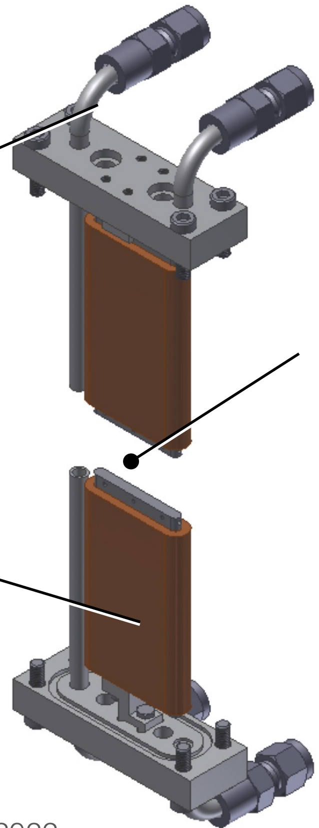
PELLIS source is **low-current** but very **high brightness**. Well suited to ALPHA's requirements.
Emittance measurements [1] from the JYFL PELLIS source (2012):

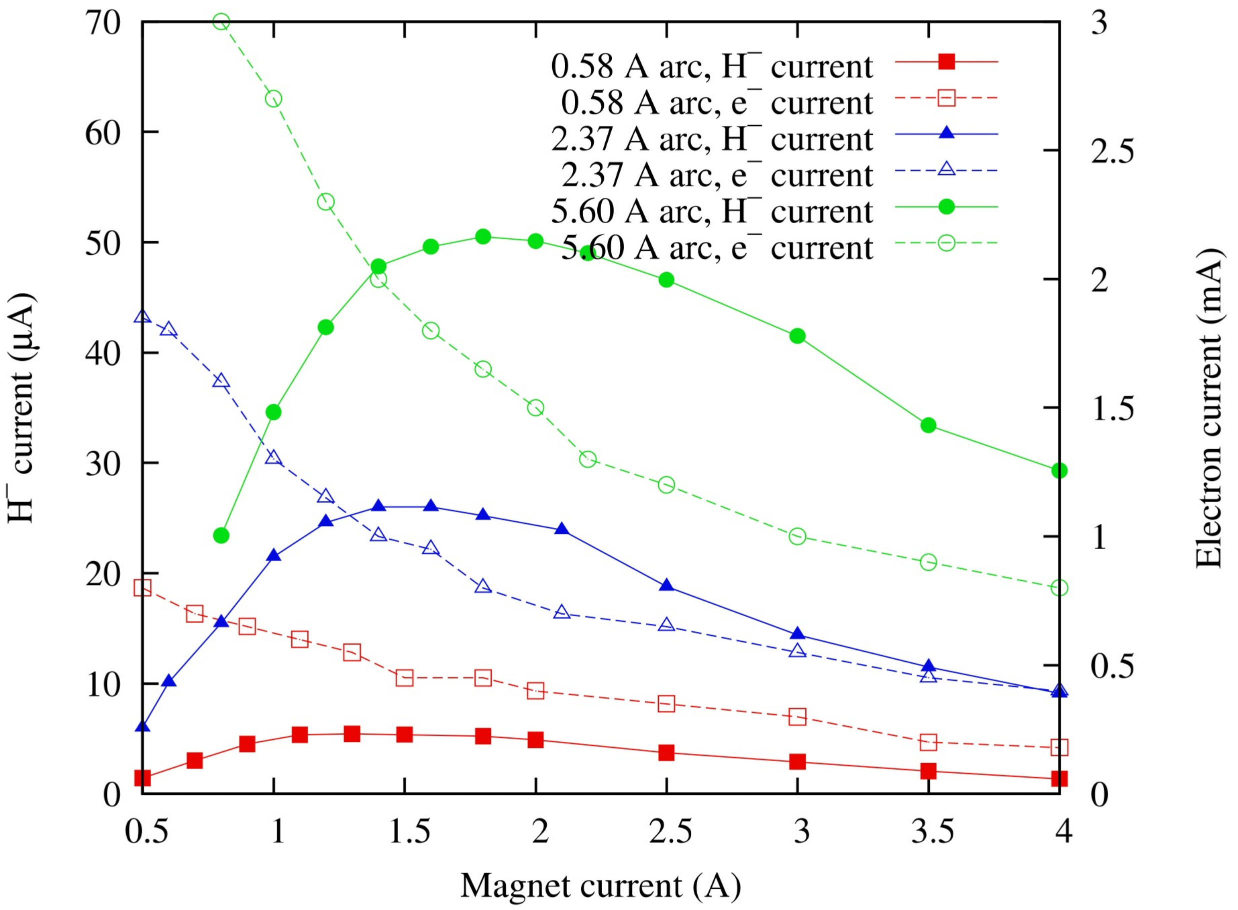


Electromagnet Filter Field

[1] T. Kalvas *et al.*, AIP Conference Proceedings **1515**, 349 (2013)

- **Electromagnet filter field** allows for optimisation of H^- volume production in the PELLIS source
- Filter magnets mounted within the **front plate** of the PELLIS source, immersed in **cooling water**





Left: PELLIS filter magnets, shown separately from the ion source itself
Above: Extracted beam current as a function of filter magnet current [1]

Full Design

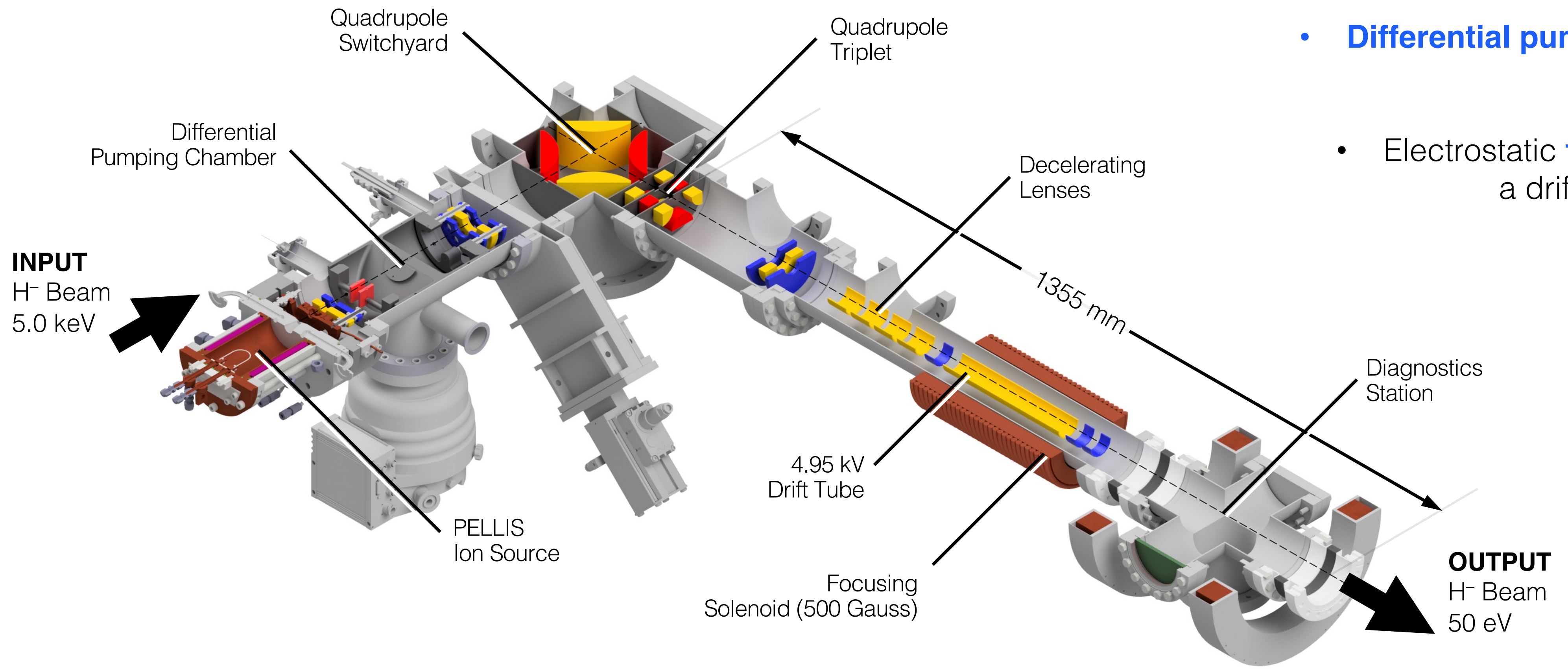
Ion Source and Transport Beamline

[1] W.A. Bertsche *et al.*,J. Phys: Conf. Ser. **2244**, 012080 (2022)

Proposed transport beamline for installation on ALPHA in **1-2 years**

PELLIS integration into ALPHA considered as part of a wider design study [1]:

- Modified **PELLIS source** and extraction optics (`IBSimu`)
- **Differential pumping** system (`Molflow`)
- Electrostatic **transport beamline**, with a drift tube for H^- deceleration 5 keV → 50 eV (`SIMION`)



ALPHA PELLIS Source

Modified Extraction Optics

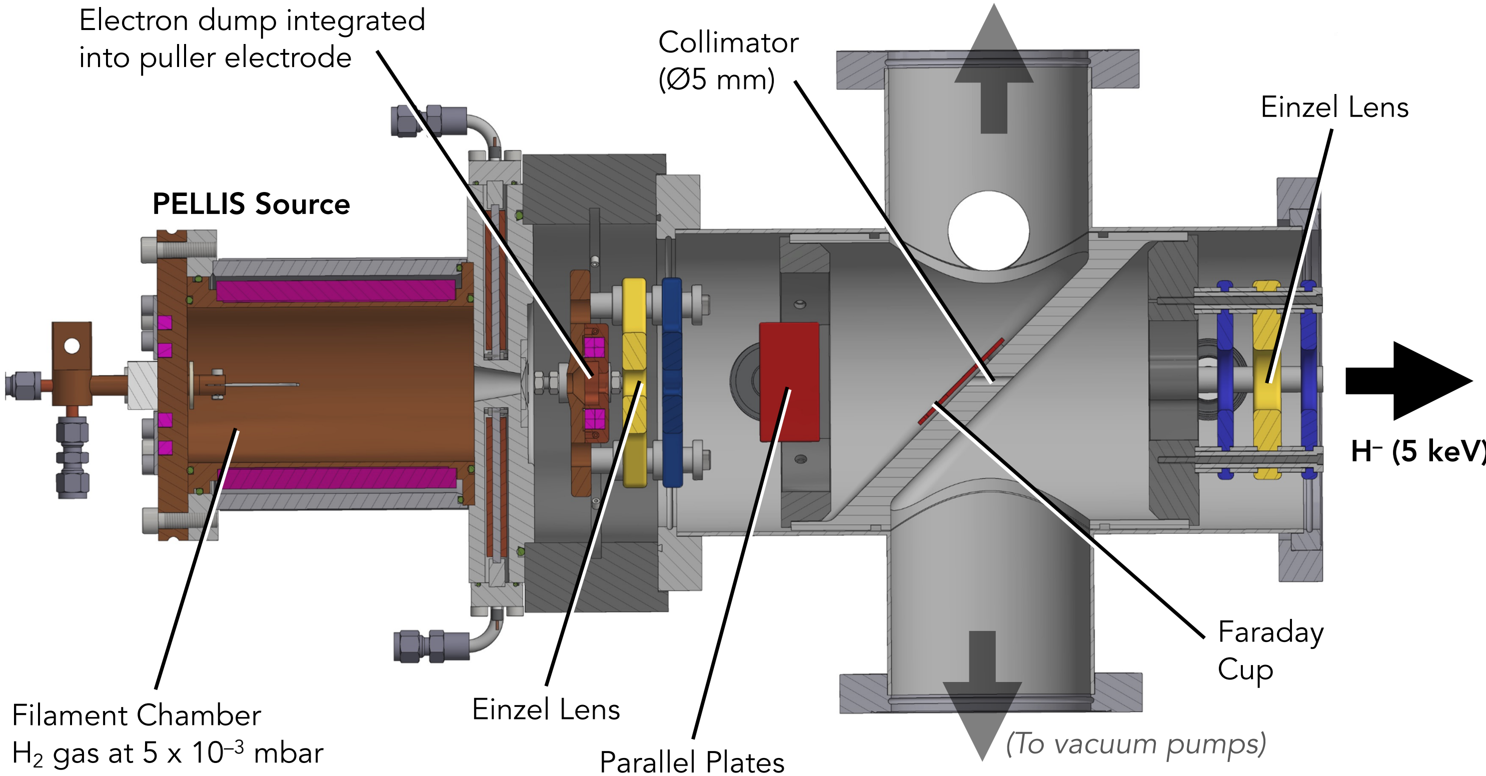
[1] W.A. Bertsche *et al.*,J. Phys: Conf. Ser. **2244**, 012080 (2022)

- Extraction optics integrated into a **differential pumping** system, including a 5 mm aperture / collimator

- Additional **Einzel lens** for matching into the quadrupole switchyard

- **Parallel plates** correct residual deflection from the PELLIS electron dump:

  → Voltage pulsed to produce **H^- bunches** of length ~1μs



Extraction Optics

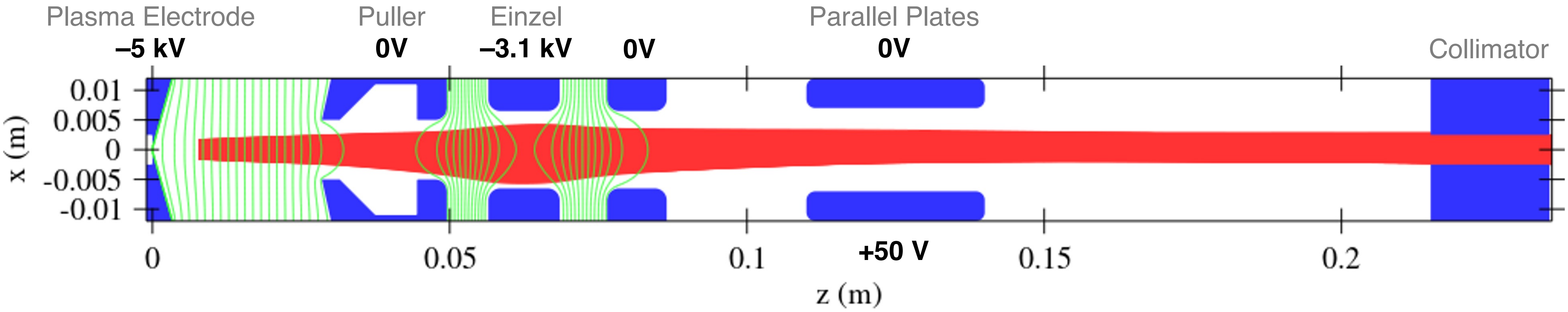
IBSimu Simulations (1 of 2)

[1] T. Kalvas *et al.*, Rev. Sci. Instrum **81**, 02B703 (2010)

- Design of the **extraction optics** and differential pumping chamber informed by **ion tracing** with `IBSimu` [1]
- PELLIS **extraction energy** reduced to **5 keV** to assist with H^- deceleration further along the transport line

Beam Parameters at Collimator - IBSimu		
Parameter	Horizontal	Vertical
Energy [keV]	5.0	
H^- Current [μA]	50	
ε_N [μm]	4.54	4.38
β [m]	0.129	0.144
α	-0.247	-0.141

Above: IBSimu beam parameters at the collimator midplane
Below: H^- trajectories through the extraction optics up to the collimator



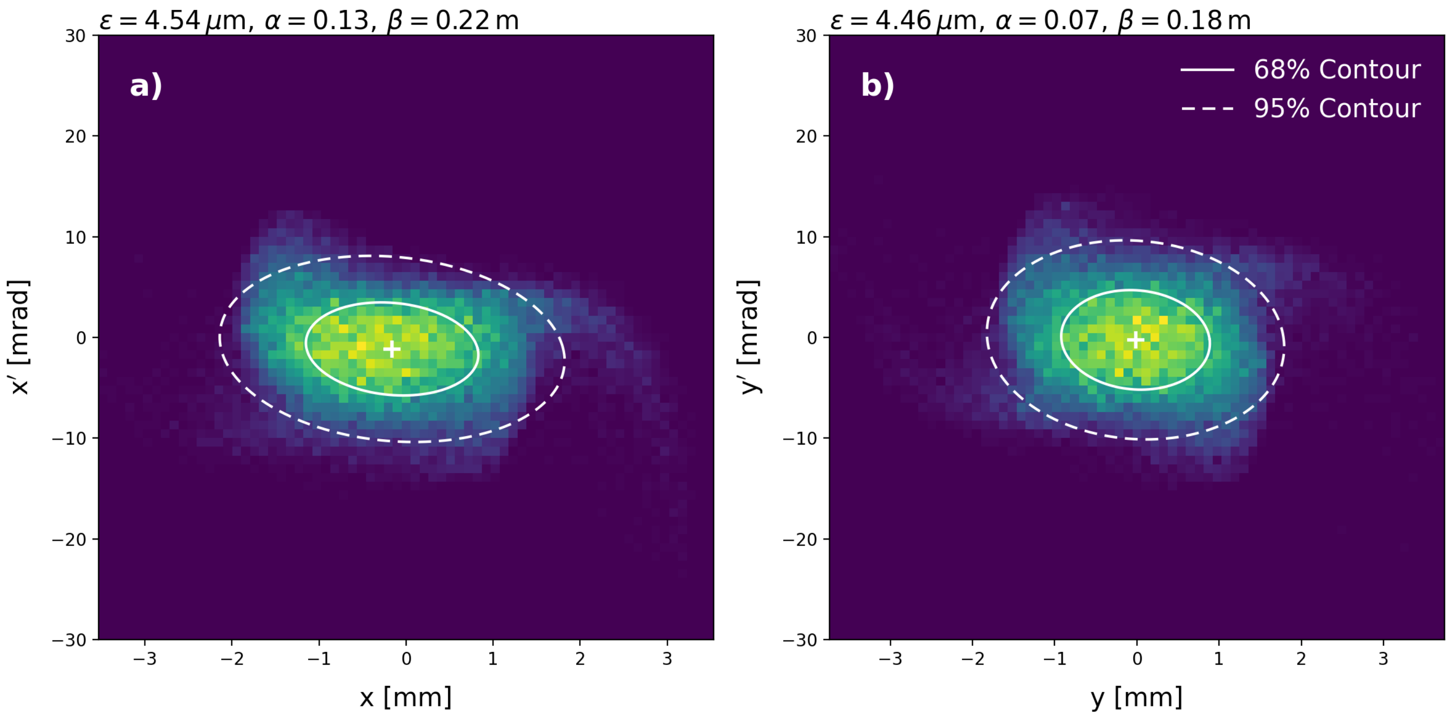
Extraction Optics

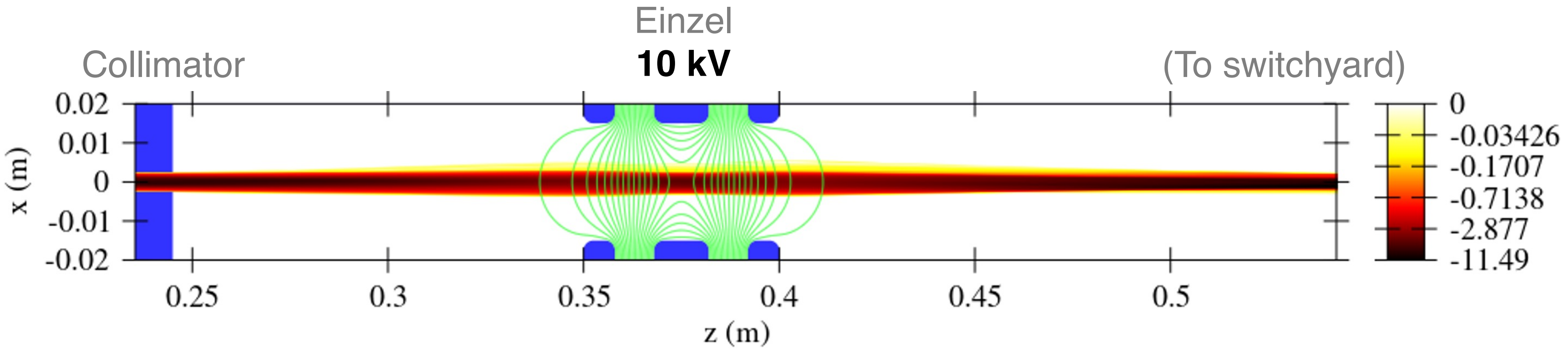
IBSimu Simulations (2 of 2)

- Final **Einzel lens** is used for matching into the **quadrupole switchyard**. Nominally biased to +10 kV

- Plots show the **transverse phase spaces** just before the switchyard entrance

- H^- trajectories from `IBSimu` shown below



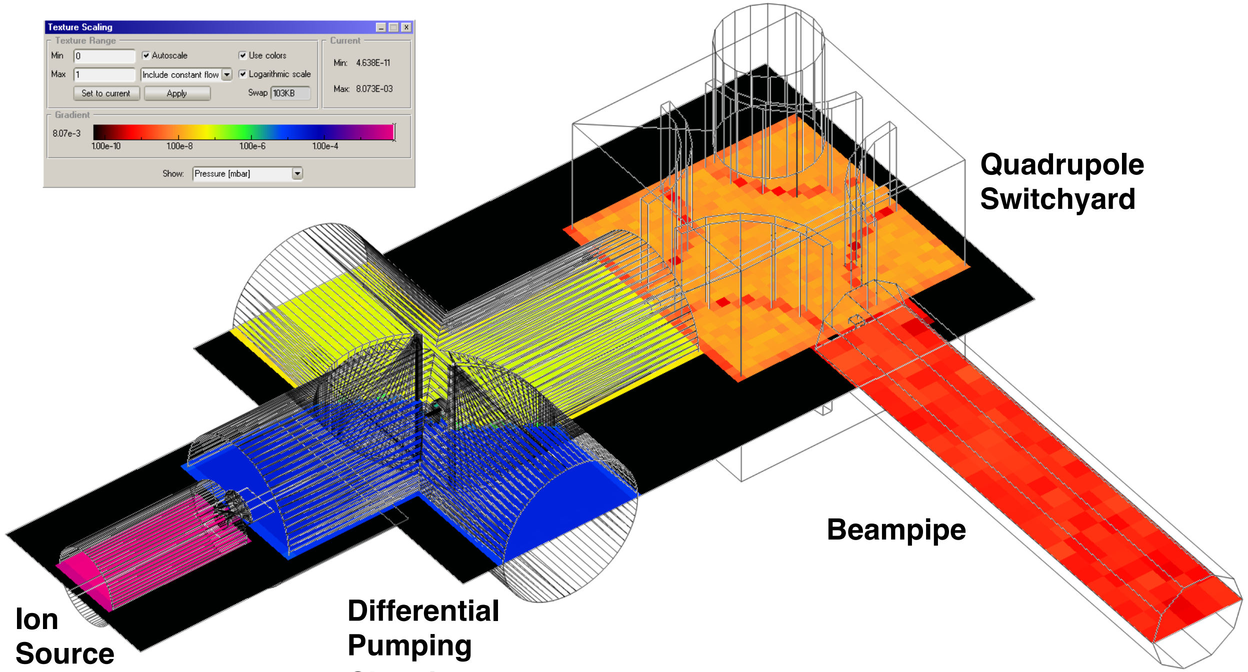


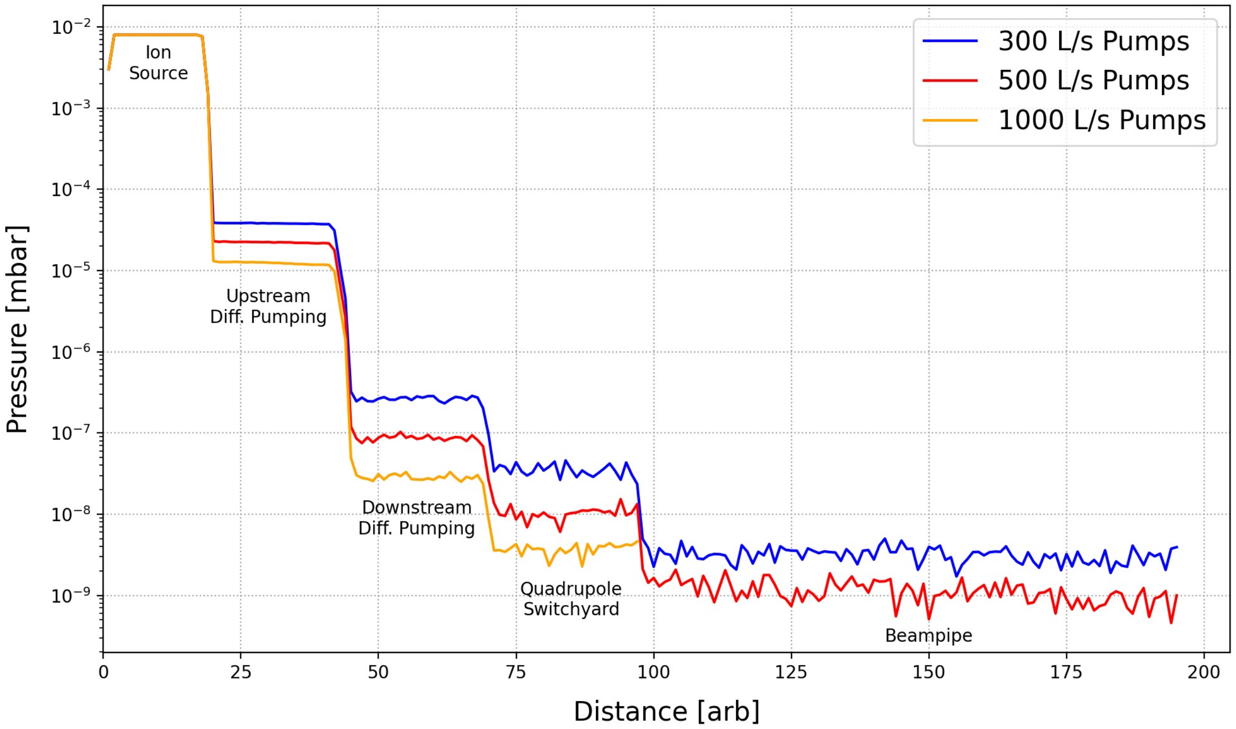
Differential Pumping

- **Differential pumping** for the ion source and transport beamline simulated in `Molflow`
- Apertures defined with input from `IBSimu` beam optics calculations

- Pressure of **~10^{-9} mbar** achieved in the main transport beamline, with two 500 L/s turbo pumps around the extraction optics

Left: Molflow screen capture showing the vacuum system geometry
Below: Calculated pressure in each section of the proposed transport beamline





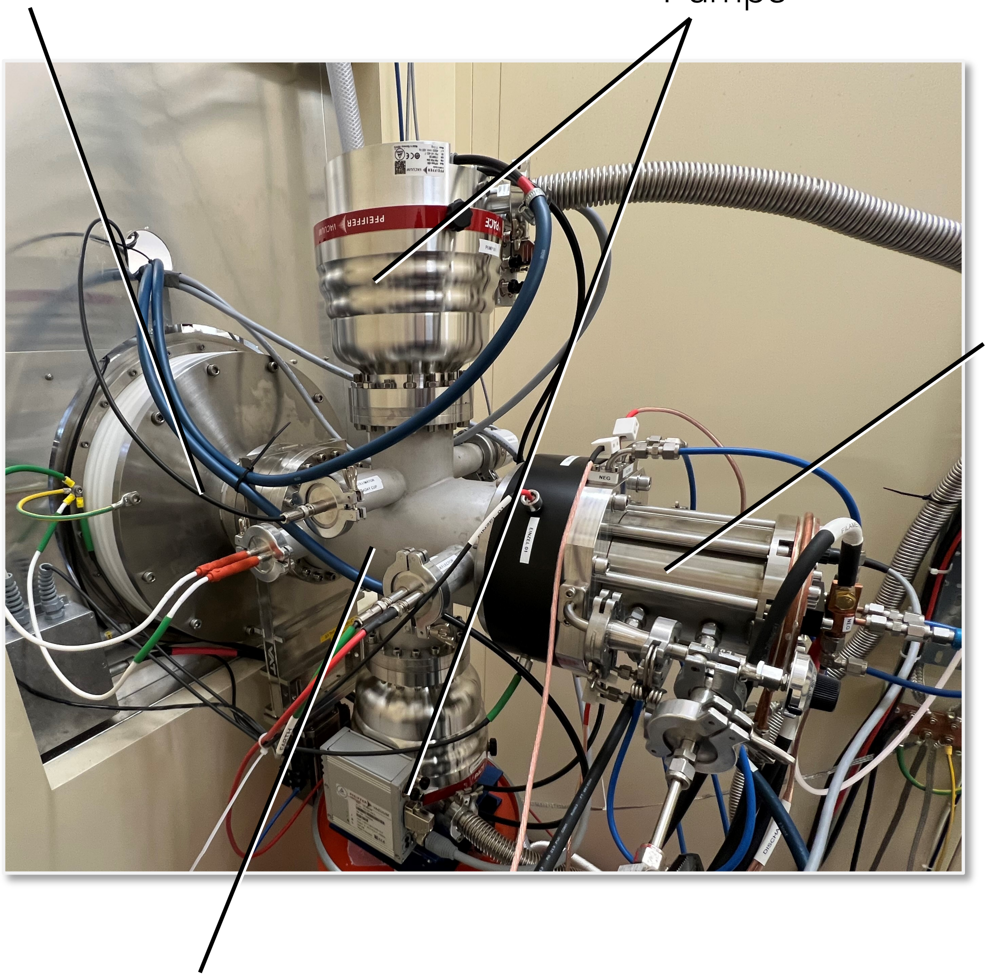
Experimental Setup

VESPA Test Stand at STFC ISIS [1]

- **Beam current** measured on a **Faraday Cup** after the first differential pumping stage
- No optics measurements at present: VESPA Allison scanner unavailable during commissioning
- Validation of **differential pumping** design:

Upstream pressure:	2 x 10^{-5} mbar
Downstream pressure:	3 x 10^{-7} mbar

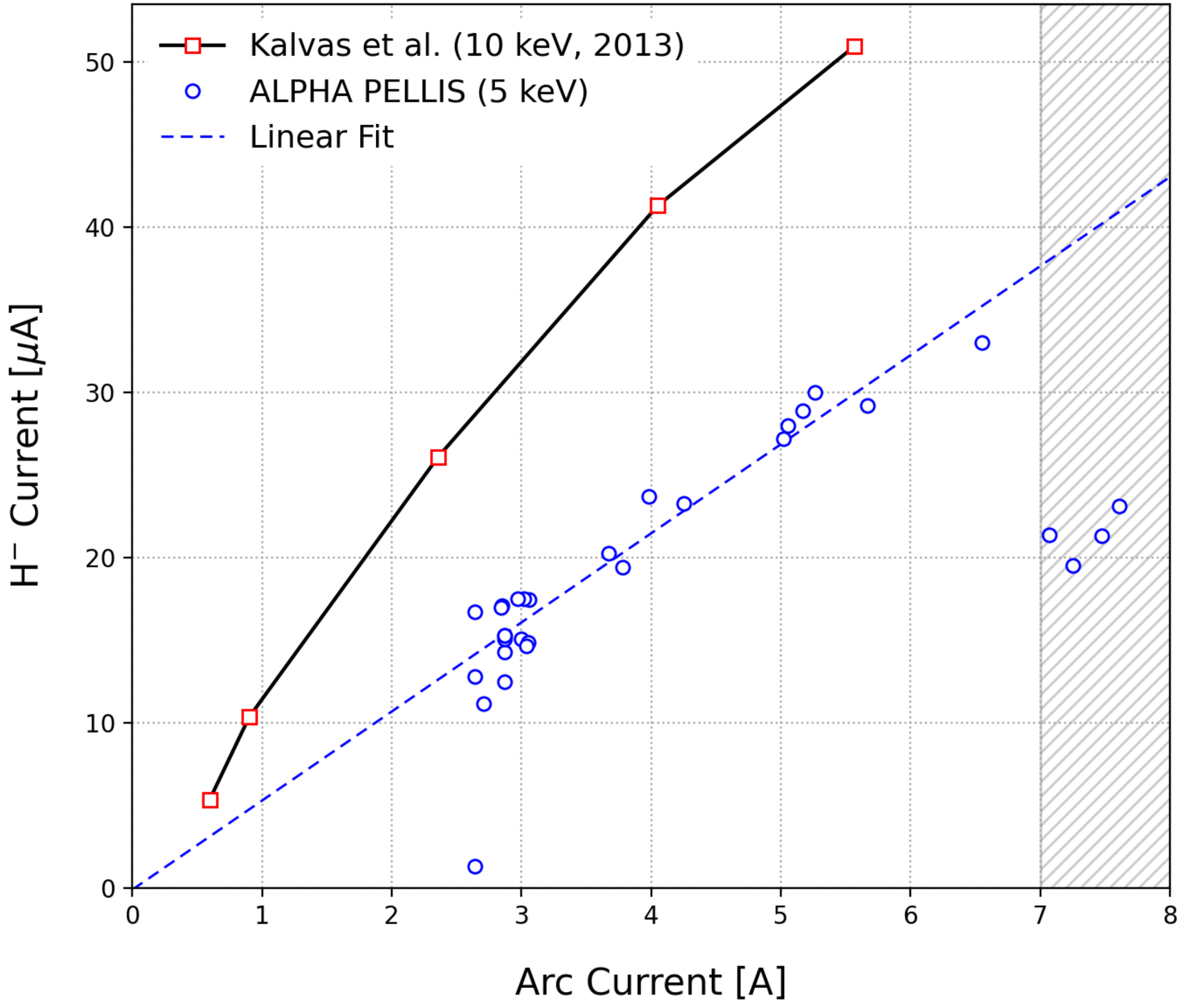
Good agreement with MOLFLOW calculations



[1] S. Lawrie *et al.*, **MOPRI015**, Proceedings of IPAC 14 (2014)

Negative Ion Commissioning

April 2022



Achieved up to **30 μA H⁻ current** through the extraction optics at 5 keV

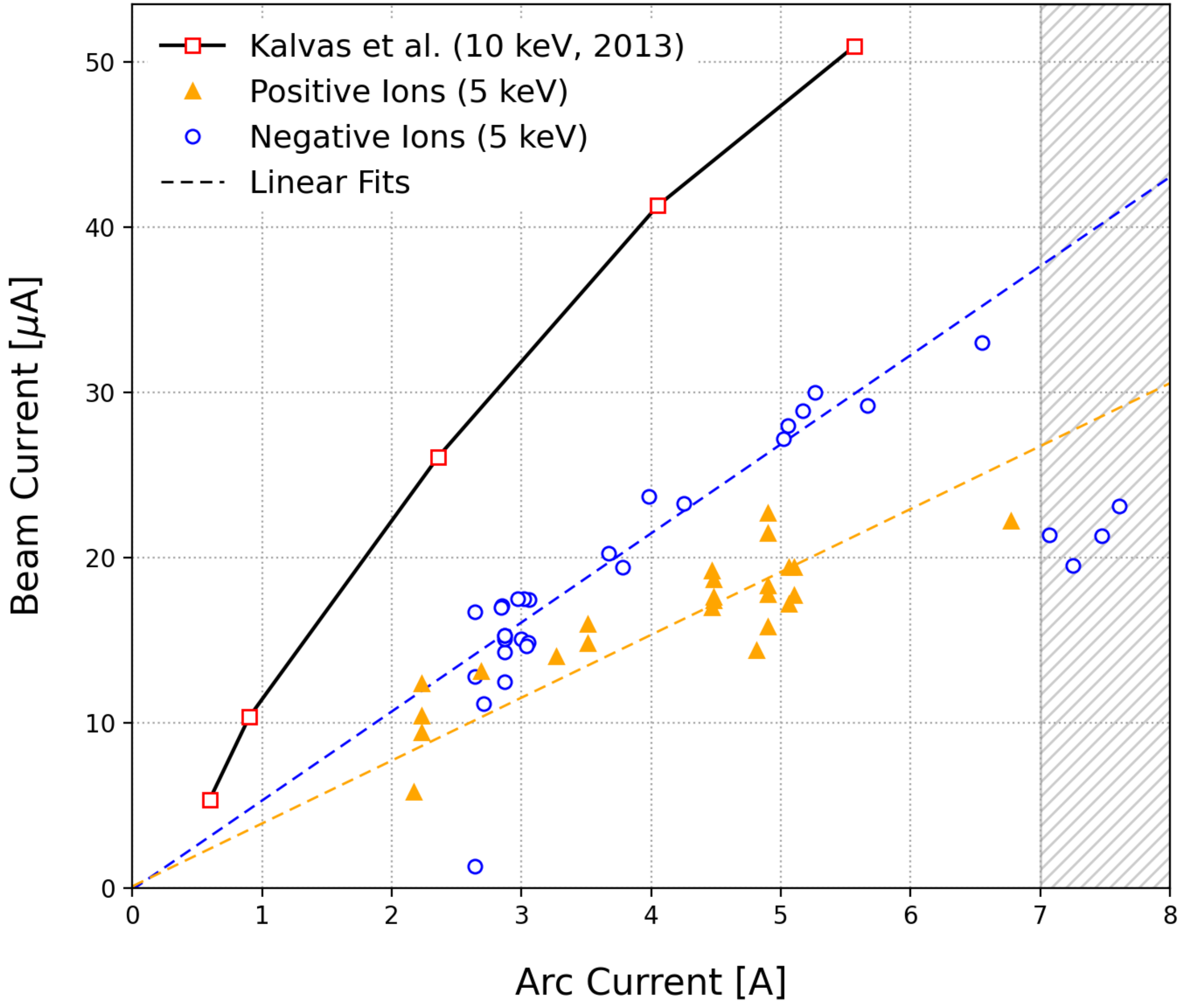
Slightly lower beam currents compared to original PELLIS source at JYFL (10 keV):

- **Lower extraction energy** (~5 keV)
- Relatively coarse optimisation (e.g. filter field, H_2 gas flow)
- Faraday cup located **further downstream**

Initial performance already exceeds ALPHA requirements!

Positive Ion Commissioning

May 2022



- Reconfigured the source to extract **positive hydrogen ions** (H^+, H_2^+, H_3^+) at 5 keV
- Achieved maximum **total current of ~22 μA** at the Faraday Cup with no filter field

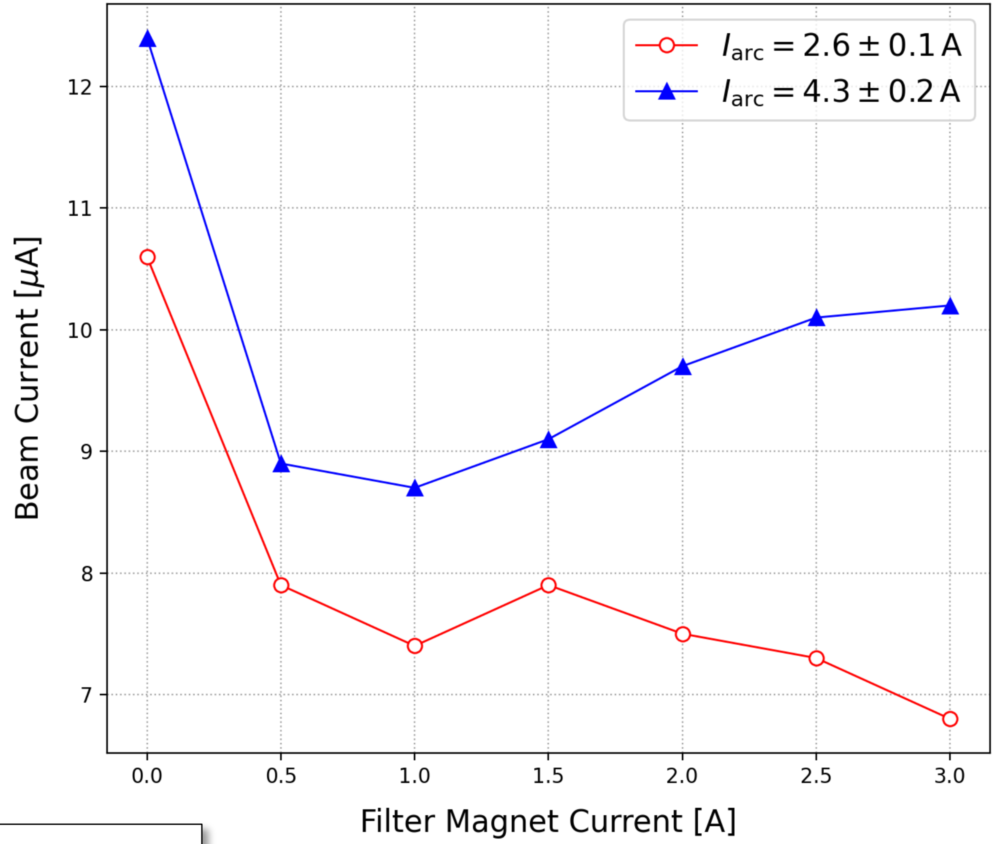
Source achieves similar beam currents for both positive and negative ions

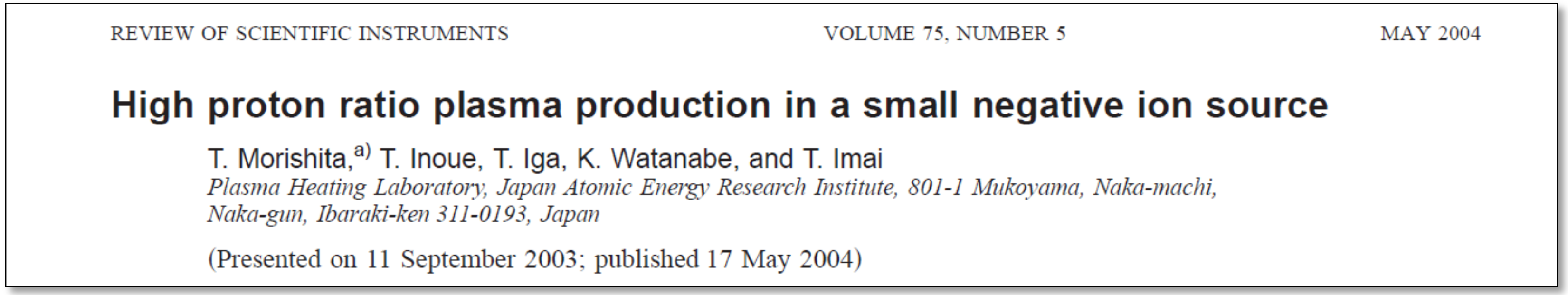
Filter Field Ion Selection

Variable Species Fraction

[1] K.W. Ehlers and K.N. Leung, Rev. Sci. Instrum. **52**, 1452 (1981)
[2] T. Morishita et al., Rev. Sci. Instrum. **75**, 1764 (2004)

- Addition of a magnetic filter field **supresses** the extraction of **molecular ions** (H_2^+, H_3^+) [1] due to mass effects in diffusion across the filter field
- For strong filter fields, the **proton ratio** can approach **90%** in small multicusp ion sources [2]
- PELLIS design has a variable, **electromagnet filter field**




REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 5 MAY 2004

High proton ratio plasma production in a small negative ion source

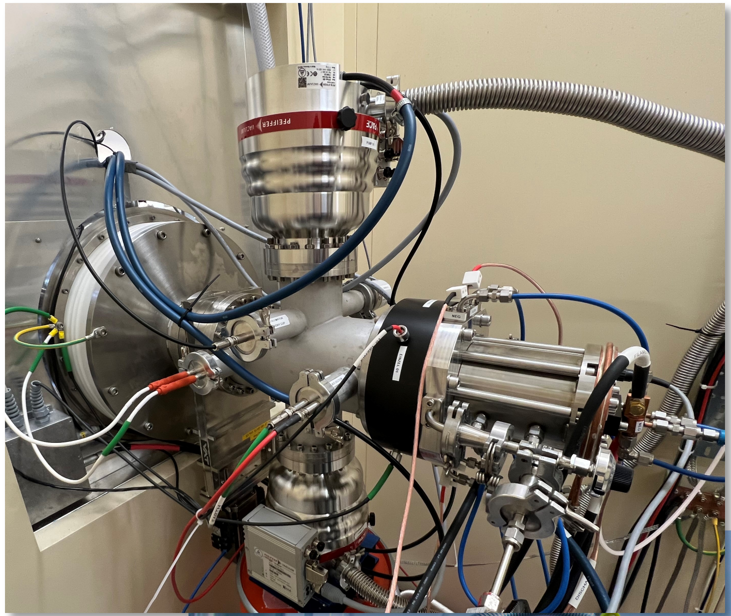
T. Morishita,[a] T. Inoue, T. Iga, K. Watanabe, and T. Imai
Plasma Heating Laboratory, Japan Atomic Energy Research Institute, 801-1 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan

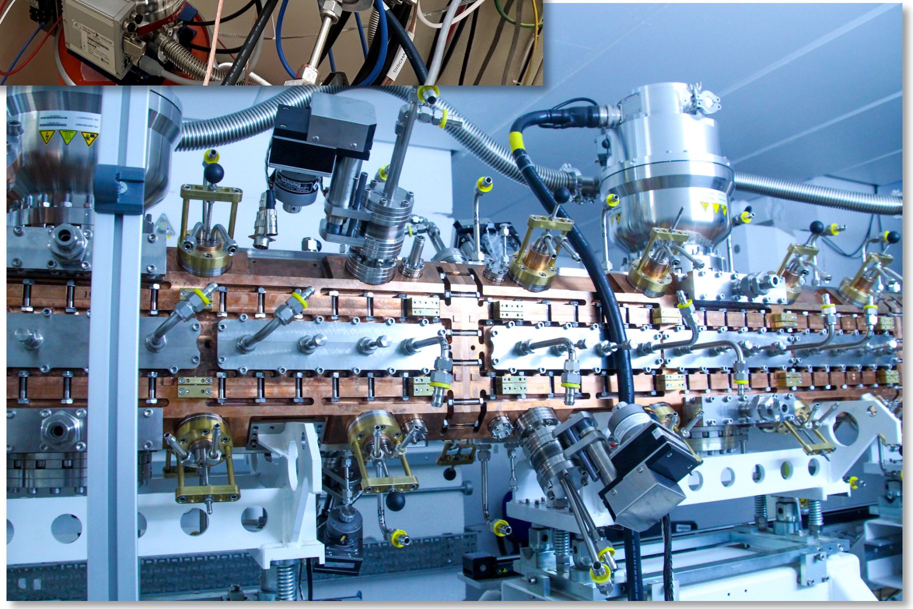
(Presented on 11 September 2003; published 17 May 2004)

Outlook and Conclusions

Conclusions

- The existing **PELLIS source** design (JYFL) has been **adapted** for the ALPHA antihydrogen experiment
- The source **exceeded initial requirements** during a short commissioning run on the VESPA test stand
- PELLIS source achieves **comparable beam current** (20 – 30 μA) for both **positive and negative ions**





Above: ALPHA PELLIS source during testing
Below: ISIS Front End Test Stand RFQ

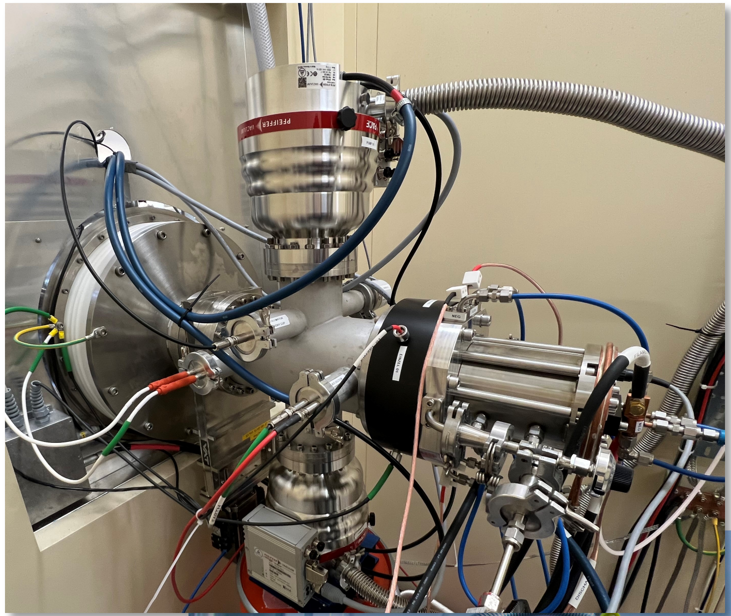
Outlook and Conclusions

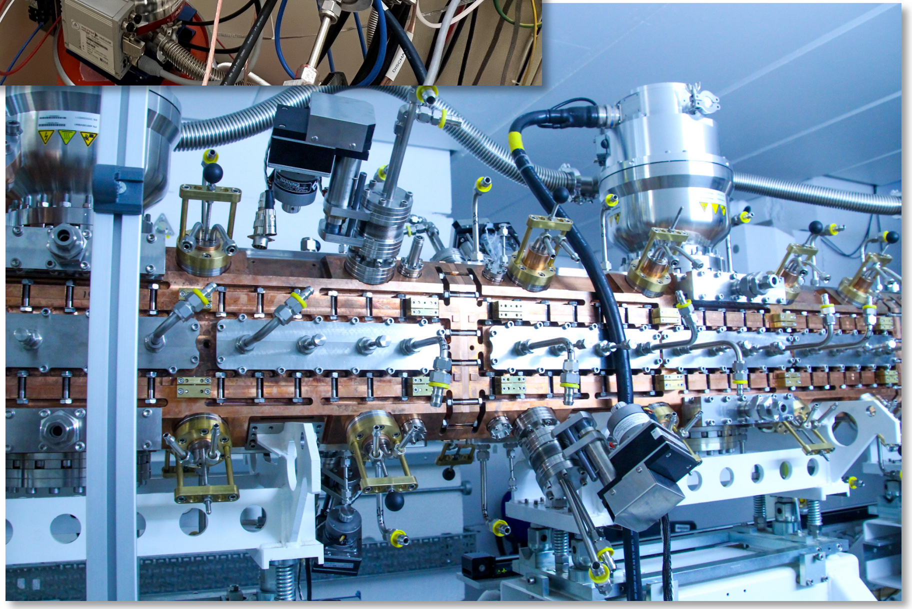
Conclusions

- The existing **PELLIS source** design (JYFL) has been **adapted** for the ALPHA antihydrogen experiment
- The source **exceeded initial requirements** during a short commissioning run on the VESPA test stand
- PELLIS source achieves **comparable beam current** (20 – 30 μA) for both **positive and negative ions**

Next Steps

- ALPHA PELLIS source **delivered to CERN** summer 2022. Further in-situ testing planned before installation.
- Two additional sources built at STFC ISIS for future FFA testing on the **ISIS Front End Test Stand (FETS)**





Above: ALPHA PELLIS source during testing
Below: ISIS Front End Test Stand RFQ

Thank You for Listening

Questions are very welcome!

See also:
https://alpha.web.cern.ch