Science and
Technology
Facilities Council

A Carbon-Neutral, Emission-Free, Particle Accelerator for Ion Beam Analysis

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Dan Faircloth, Olli Tarvainen
ISIS Low Energy Beams Group
UKRI STFC Rutherford Appleton Laboratory

Taneli Kalvas, Ville Toivanen
Accelerator Laboratory
University of Jyväskylä, Finland

Particle accelerators traditionally use a lot of power…

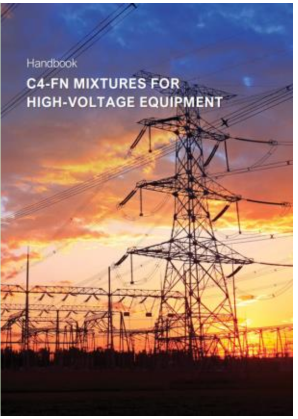
ISIS uses approximately 11 MW
to produce a 160 kW proton beam
(which is then dumped into the targets!)

The only solution is to build a communal heating system that can be switched off when ISIS is running

…or require large amounts of SF_6 (for high voltage insulation)

SF_6 is the most potent greenhouse gas:
1 kg SF_6 “lost” = 23 tonnes of CO_2
stays in the atmosphere for 3,200 years

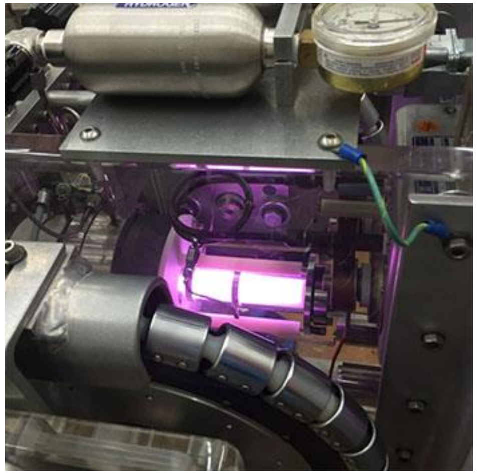
A possible solution is to modify the system to use a modern alternative e.g.
C4-FN (fluoronitrile) mixture
(O_2 / CO_2 / N_2)



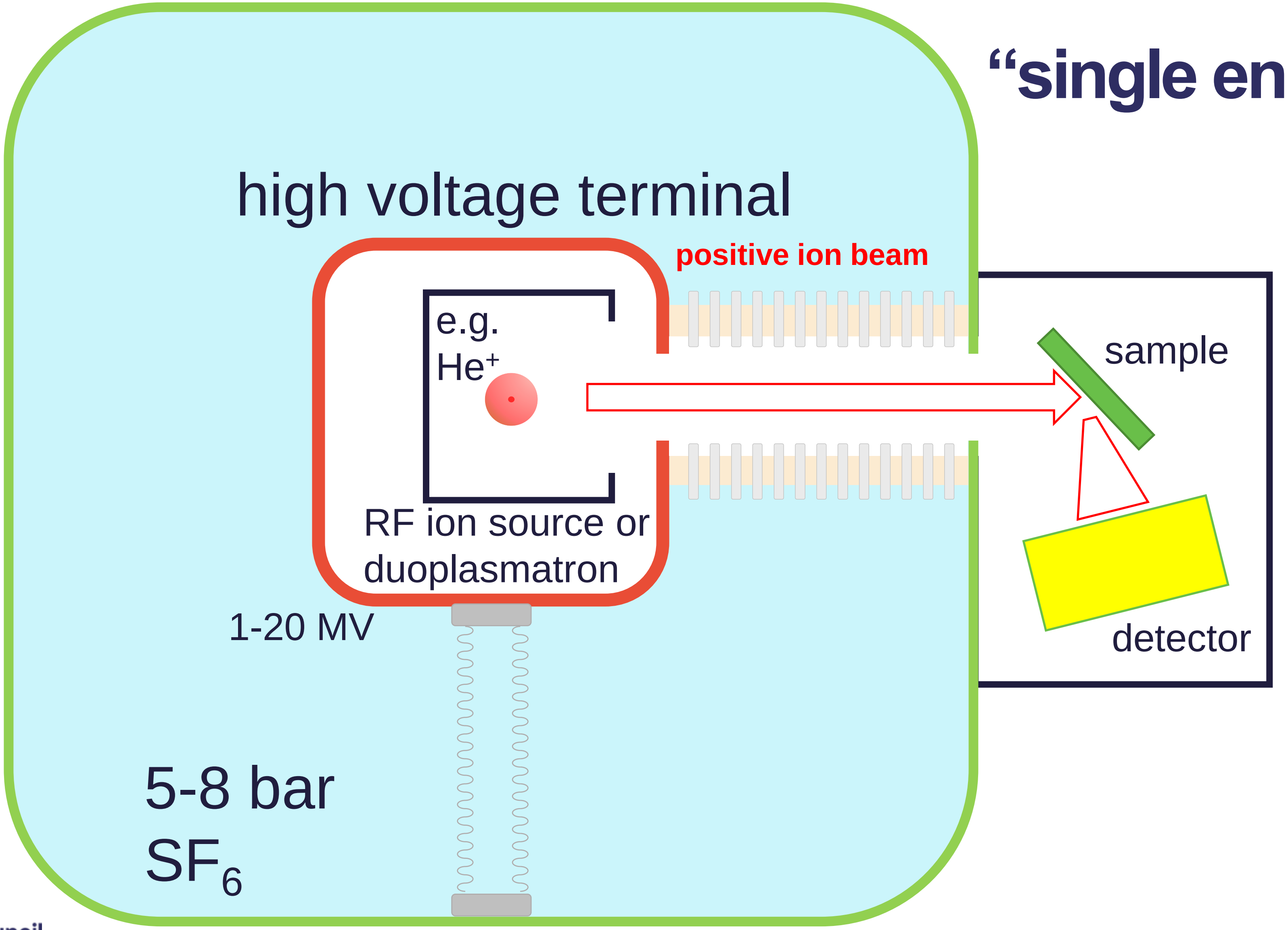
GE and Hitachi

…or use a design that eliminates the need for insulating gas entirely:

Typical IBA Acceleration Schemes and Sources



very compact
and hard to
access ion
source ✗



“single ended”

high voltage terminal

positive ion beam

e.g.
He$^+$

RF ion source or
duoplasmatron

1-20 MV

sample

detector

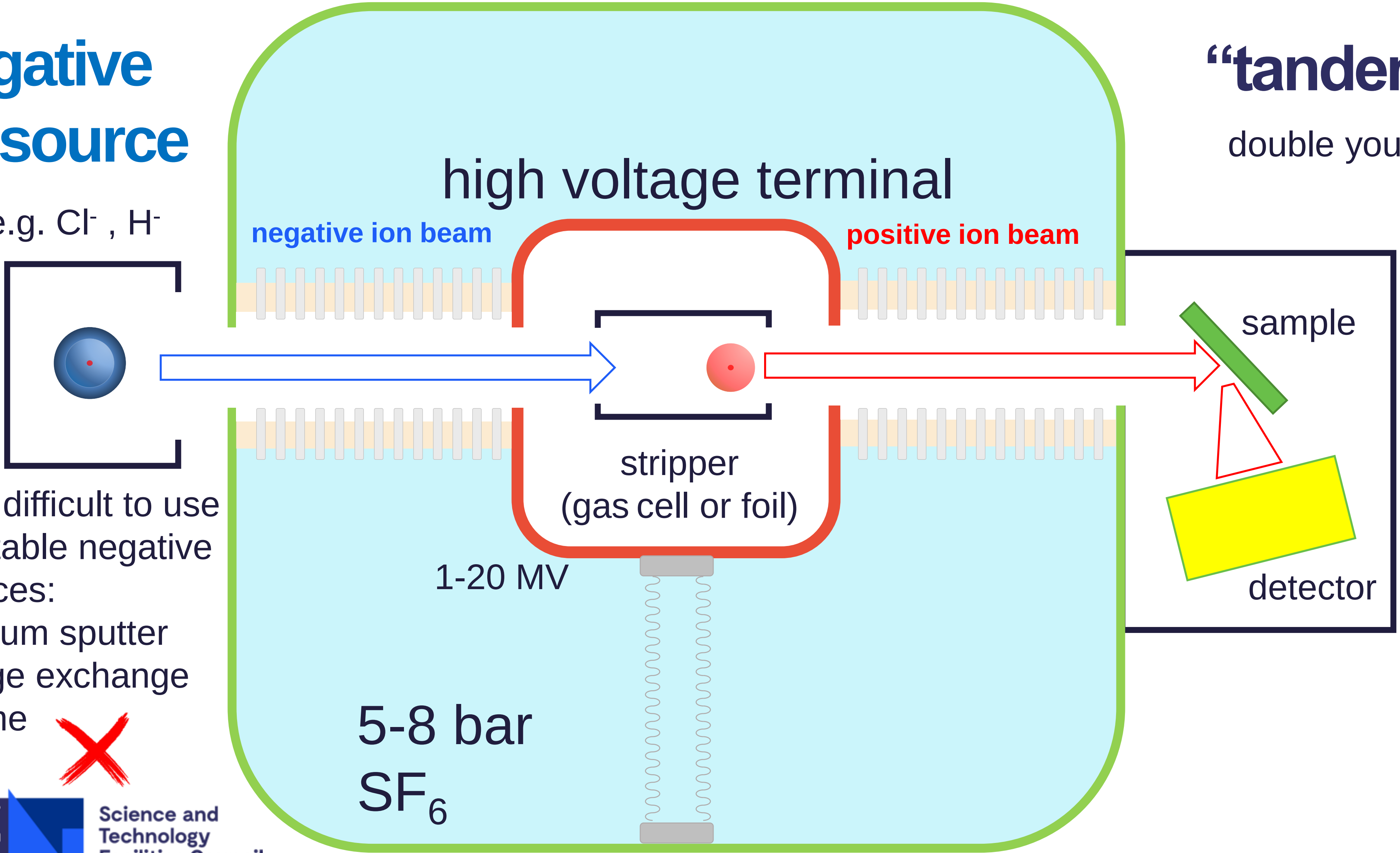
5-8 bar
SF_6

Science and
Technology
Facilities Council

Typical IBA Acceleration Schemes and Sources

negative ion source

e.g. Cl^- , H^-



high voltage terminal

negative ion beam

positive ion beam

stripper
(gas cell or foil)

1-20 MV

5-8 bar
SF_6

sample

detector

“tandem”

double your energy for free ✓

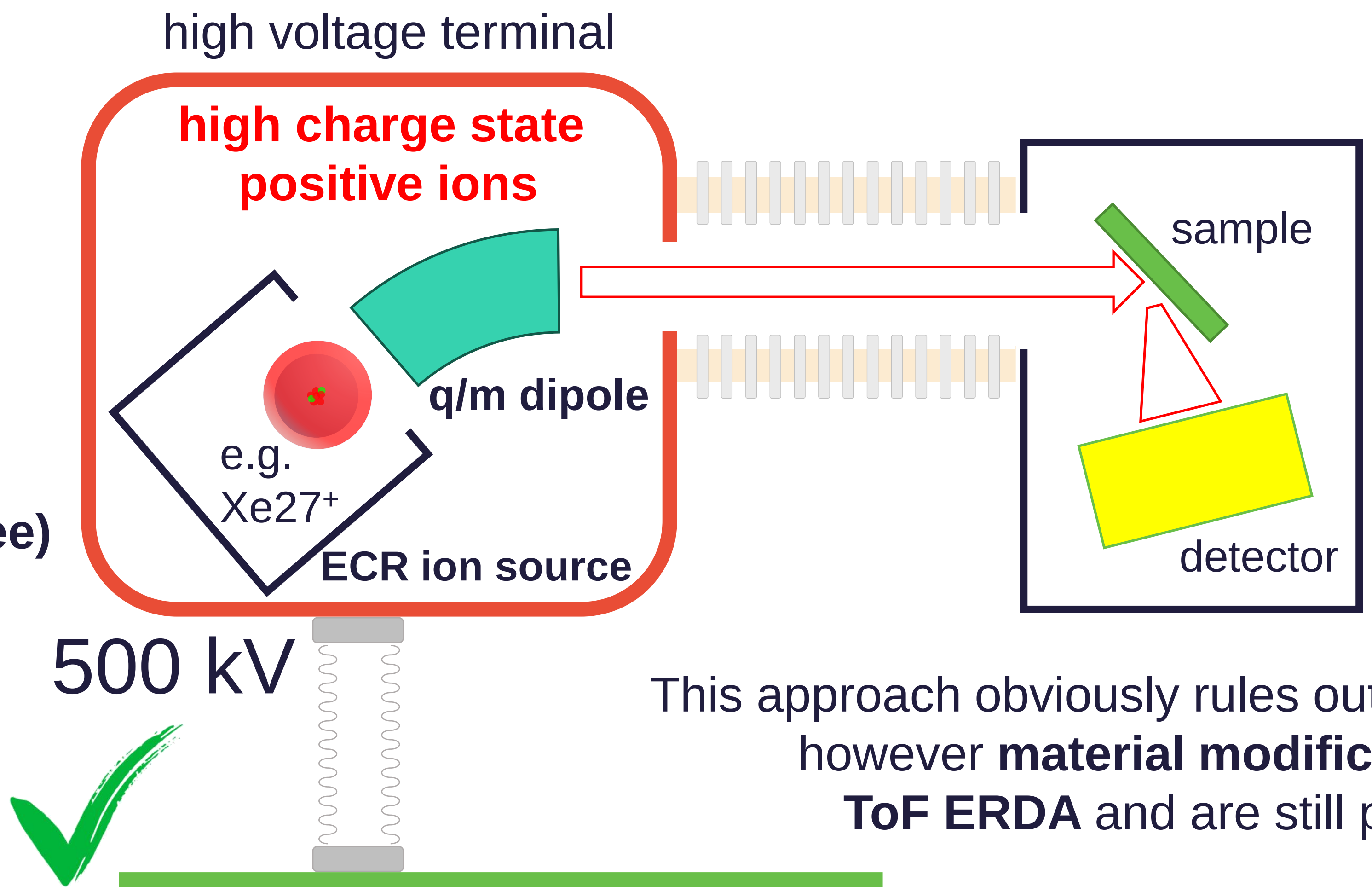
A zoo of difficult to use and unstable negative ion sources:

- Caesium sputter
- Charge exchange
- Volume ✗

Science and
Technology
Facilities Council

Emission-Free, Zero-Carbon, IBA Concept:

use high charge state ions
= much lower accelerating voltage required



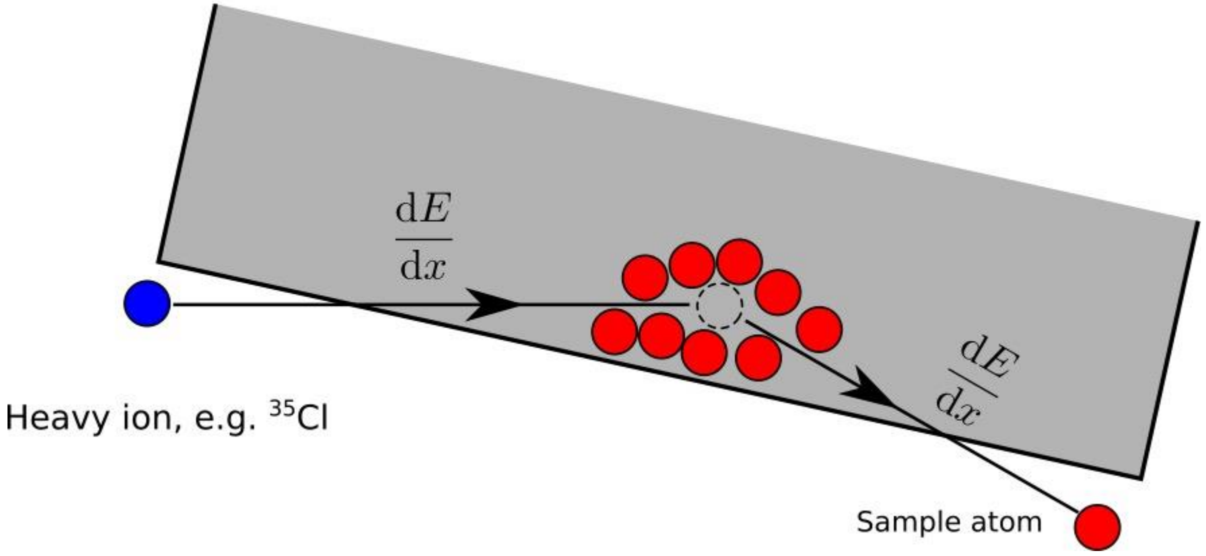
air insulated (SF$_6$ free) high voltage design

This approach obviously rules out using light ions, however **material modification** and **ToF ERDA** and are still possible

Science and Technology Facilities Council

Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA)

A method to measure the elemental depth profile in materials



Simple principle:

- Bombard the sample with heavy ions
- Measure the velocity and energy of the recoiling particles
- Use known energy loss in material to obtain depth profile

Lighter than beam particles are ejected, scattered beam provides information on heavier elements.

Best suited for light elements including H, Li, C, N and O.

These elements cannot be detected using photon-based (x-ray) methods.

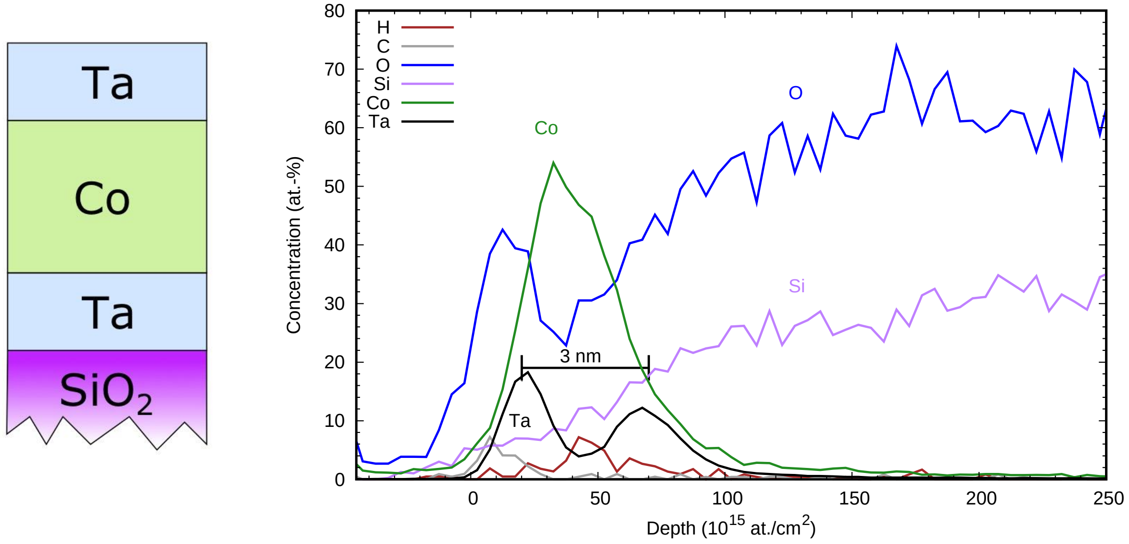
Hydrogen is “invisible” to Rutherford Backscattering Spectrometry (RBS), which makes ToF-ERDA unique.

Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA)

Useful tool for developing thin-film/surface technologies:

- Superconducting RF
- Electronic devices
- Sensors
- Functional surface coatings
- Catalytic surface chemistry
- Energy applications
- Battery technology
- …

Example: metal tri-layer on silicon-oxide substrate



Typical ToF-ERDA ion beam requirements

Beam	Energy
$^{35/37}Cl$	3 - 6 MeV
$^{79/81}Br$	8 - 11 MeV
^{127}I	9 - 16 MeV

The required particle flux at the sample is 1-10 pnA

Lower limit: Reasonable measurement time, typically less than an hour / sample.
Upper limit: The maximum count rate of the energy detector.

… to limit the platform voltage to 500 kV

Beam	Energy
$^{35/37}$Cl	3 - 6 MeV
$^{79/81}$Br	8 - 11 MeV
^{127}I	9 - 16 MeV

we need →

Ion	Charge state required	Energy
^{40}Ar	6+ … 12+	3 - 6 MeV
^{84}Kr	16+ … 22+	8 - 11 MeV
^{136}Xe	18+ … 32+	9 - 16 MeV

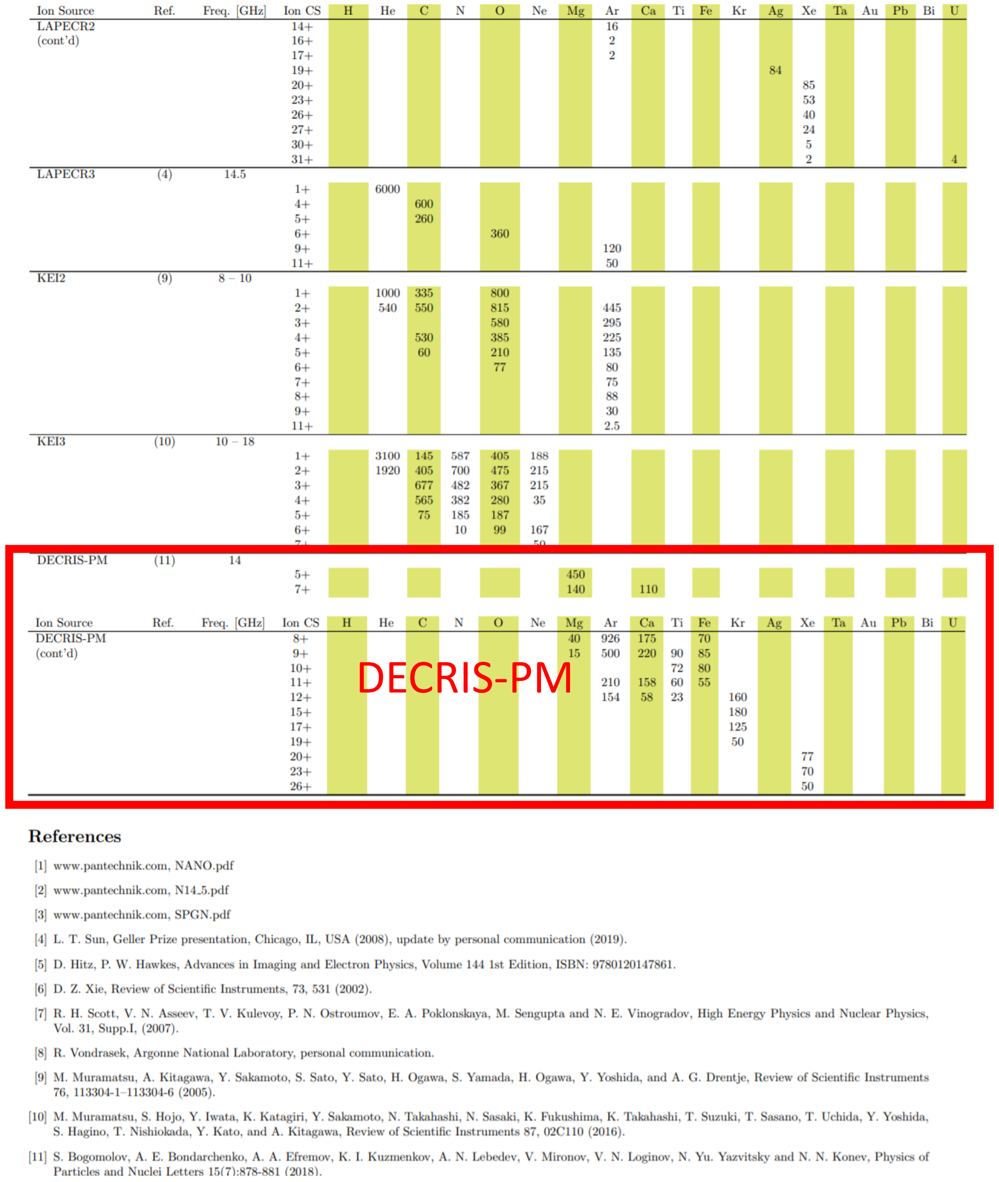
1-10 pnA of these charge states

We need an Electron Cyclotron Resonance (ECR) ion source
it needs to be a permanent magnet based ion source

Science and
Technology
Facilities Council

Permanent magnet ECR ion sources

Ion Source	Ref.	Freq. [GHz]	Ion CS	H	He	C	N	O	Ne	Mg	Ar	Ca	Ti	Fe	Kr	Ag	Xe	Ta	Au	Pb	Bi	U
NANOGAN	(1)	10																				
			1+	1000	1000						100											
			2+		100																	
			4+								140								10			
			6+								45								9			
			8+								20							10	8			
			9+								5								6			
			12+														10	10				
			14+														5	5	2			
NANOGAN 14.5	(2)	14.5																				
			1+	1500	1500						700											
			2+		200																	
			4+								280								20			
			6+								100								20			
			8+								60							10	20			
			9+								20								15			
			12+														20	20				
SUPER-NANOGAN	(3; 4)	14.5																				
			1+	2000	2000	500	1000	1000	1000		1000				1000	500						
			2+		1000	350	300	400	300		350											
			4+			200	100	300	200		250					250						
			6+			3	10	200	160		200					250						
			8+						25		200					200	220					
			9+								90					90						
			11+								30				25	30						
			14+								1				15							
			20+												4	15	4	20	10			
			23+														14	1				
			26+														5		10	3		
			27+														1		6	1		
			30+																1			
SOPHIE	(5; 4)	12 – 14.5																				
			6+					630														
			7+					90														
			8+								500											
			9+								310											
SOPHIE (cont'd)			11+								90											
			12+								35											
			20+														52					
			23+														31					
			26+														24					
			27+														18					
			30+														1					
BIE100	(6; 7; 8)	12.75 + 14.5																				
			4+			503	600															
			5+			507	525															
			6+			120	500															
			7+				81															
			8+					440			260											
			9+					265			263											
			10+								264											
			11+					64			240											
			12+					19			213											
			13+					3			142											
			14+								80											
			15+								38											
			17+								5									7		
			18+																	8		
			19+																	9	50	
			20+																	9	50	
			21+																	10	46	
			22+																	8	42	
			23+																	8	35	
			24+																	7	26	
LAPECR1	(4)	14.5																				
			1+		5000																	
			2+		2500		1700															
			5+				160															
LAPECR2	(4)	14.5																				
			6+					1000														
			7+					130														
			8+								460											
			9+								355											
			11+								166											
			12+								62											



Ion Source	Ref.	Freq. [GHz]	Ion CS	H	He	C	N	O	Ne	Mg	Ar	Ca	Ti	Fe	Kr	Ag	Xe	Ta	Au	Pb	Bi	U
LAPECR2 (cont'd)			14+								16											
			16+								2											
			17+								2											
			19+													84						
			20+														85					
			23+														53					
			26+														40					
			27+														24					
			30+														5					
			31+														2					4
LAPECR3	(4)	14.5																				
			1+		6000																	
			4+			600																
			5+			260																
			6+					360														
			9+								120											
			11+								50											
KEI2	(9)	8 – 10																				
			1+		1000	335		800														
			2+		540	550		815			445											
			3+					580			295											
			4+			530		385			225											
			5+			60		210			135											
			6+					77			80											
			7+								75											
			8+								88											
			9+								30											
			11+								2.5											
KEI3	(10)	10 – 18																				
			1+		3100	145	587	405	188													
			2+		1920	405	700	475	215													
			3+			677	482	367	215													
			4+			565	382	280	35													
			5+			75	185	187														
			6+				10	99	167													
DECRIS-PM	(11)	14																				
			5+							450												
			7+							140		110										
DECRIS-PM (cont'd)			8+							40	926	175		70								
			9+							15	500	220	90	85								
			10+										72	80								
			11+								210	158	60	55								
			12+								154	58	23		160							
			15+												180							
			17+												125							
			19+												50							
			20+														77					
			23+														70					
			26+														50					

References

[1] www.pantechnik.com, NANO.pdf

[2] www.pantechnik.com, N14_5.pdf

[3] www.pantechnik.com, SPGN.pdf

[4] L. T. Sun, Geller Prize presentation, Chicago, IL, USA (2008), update by personal communication (2019).

[5] D. Hitz, P. W. Hawkes, Advances in Imaging and Electron Physics, Volume 144 1st Edition, ISBN: 9780120147861.

[6] D. Z. Xie, Review of Scientific Instruments, 73, 531 (2002).

[7] R. H. Scott, V. N. Asseev, T. V. Kulevoy, P. N. Ostroumov, E. A. Poklonskaya, M. Sengupta and N. E. Vinogradov, High Energy Physics and Nuclear Physics, Vol. 31, Supp.I, (2007).

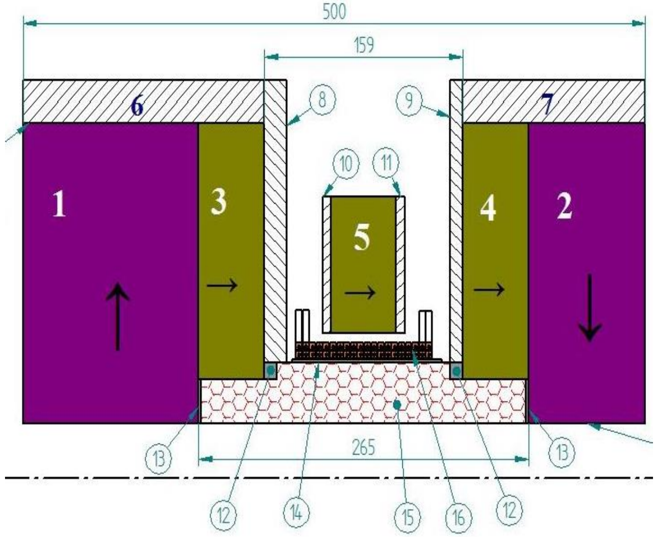
[8] R. Vondrasek, Argonne National Laboratory, personal communication.

[9] M. Muramatsu, A. Kitagawa, Y. Sakamoto, S. Sato, Y. Sato, H. Ogawa, S. Yamada, H. Ogawa, Y. Yoshida, and A. G. Drentje, Review of Scientific Instruments 76, 113304-1–113304-6 (2005).

[10] M. Muramatsu, S. Hojo, Y. Iwata, K. Katagiri, Y. Sakamoto, N. Takahashi, N. Sasaki, K. Fukushima, K. Takahashi, T. Suzuki, T. Sasano, T. Uchida, Y. Yoshida, S. Hagino, T. Nishiokada, Y. Kato, and A. Kitagawa, Review of Scientific Instruments 87, 02C110 (2016).

[11] S. Bogomolov, A. E. Bondarchenko, A. A. Efremov, K. I. Kuzmenkov, A. N. Lebedev, V. Mironov, V. N. Loginov, N. Yu. Yazvitsky and N. N. Konev, Physics of Particles and Nuclei Letters 15(7):878-881 (2018).

Dubna ECR Ion Source



1~5： PM rings
6, 7： soft iron rings
8~11： soft iron plates
12~14： auxiliary elements,
15： hexapole
16： coil

Ion	DECRIS-PM
Ar^{8+}	920
Ar^{9+}	500
Ar^{11+}	210
Ar^{12+}	150
Xe^{20+}	75
Xe^{26+}	50

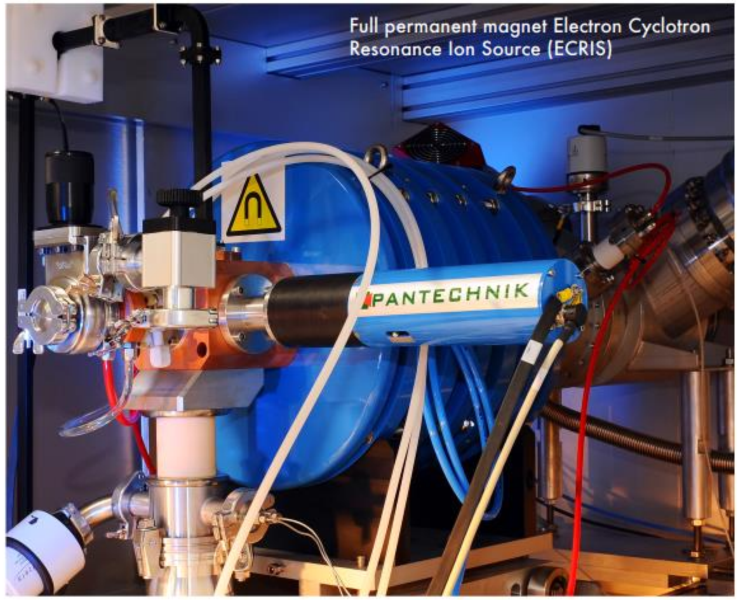
Design parameters of DECRIS-PM	
Microwave frequency	14.0 – 14.5 GHz
B_{inj}	≥ 1.3 T
B_{min}	0.4 T
B_{extr}	1.0 ~1.1 T
B_r	1.05~1.15 T
Plasma chamber ID	70 mm

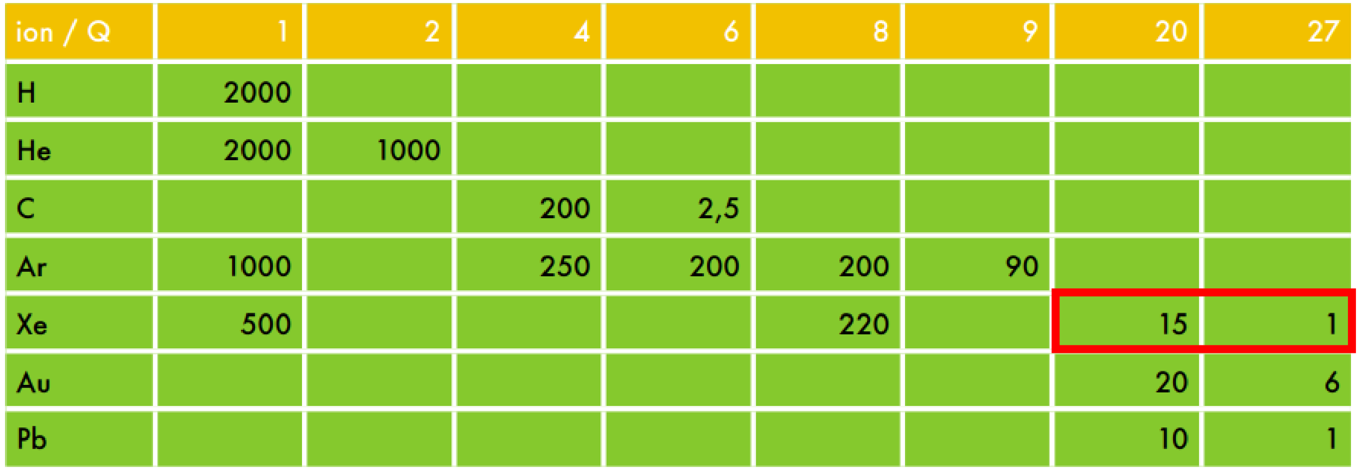
525 kg of PM material

Commercial permanent magnet ECRIS

PANTECHNIK

Supernanogan


Full permanent magnet Electron Cyclotron Resonance Ion Source (ECRIS)



ion / Q	1	2	4	6	8	9	20	27
H	2000							
He	2000	1000						
C			200	2,5				
Ar	1000		250	200	200	90		
Xe	500				220		15	1
Au							20	6
Pb							10	1

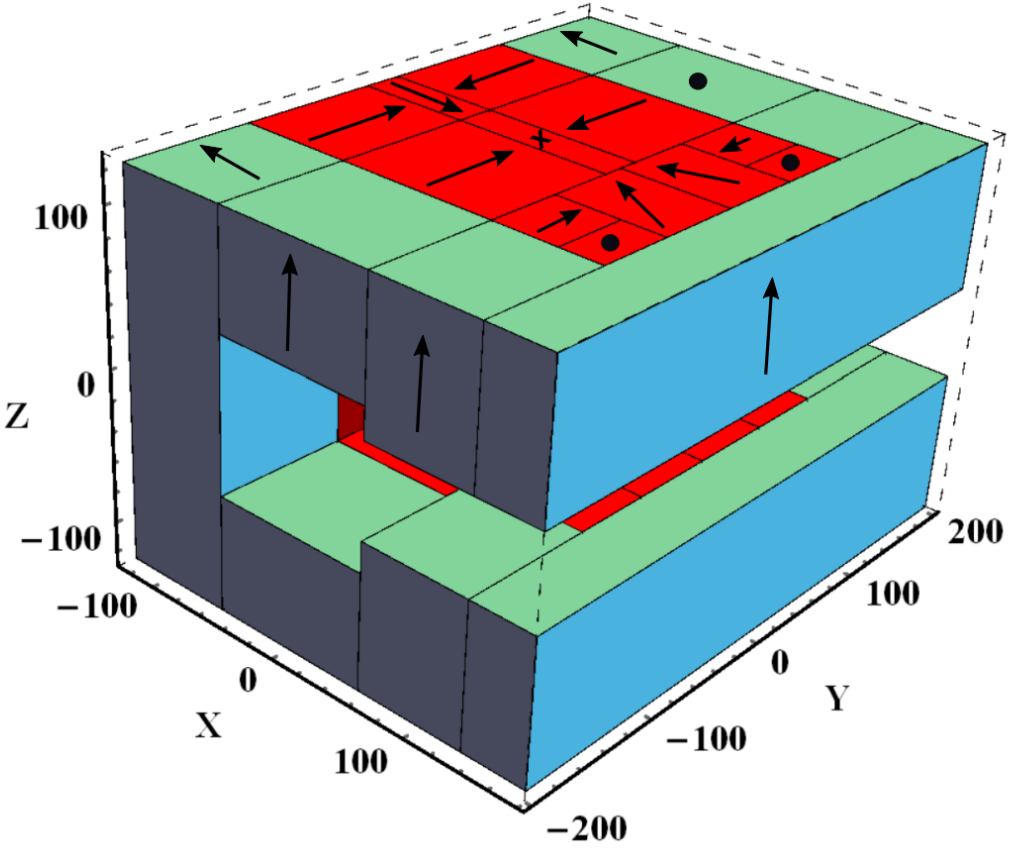
Beam intensity for various charge states given in electric μA. This table indicates typical intensities for selected charge states.

WWW.PANTECHNIK.COM

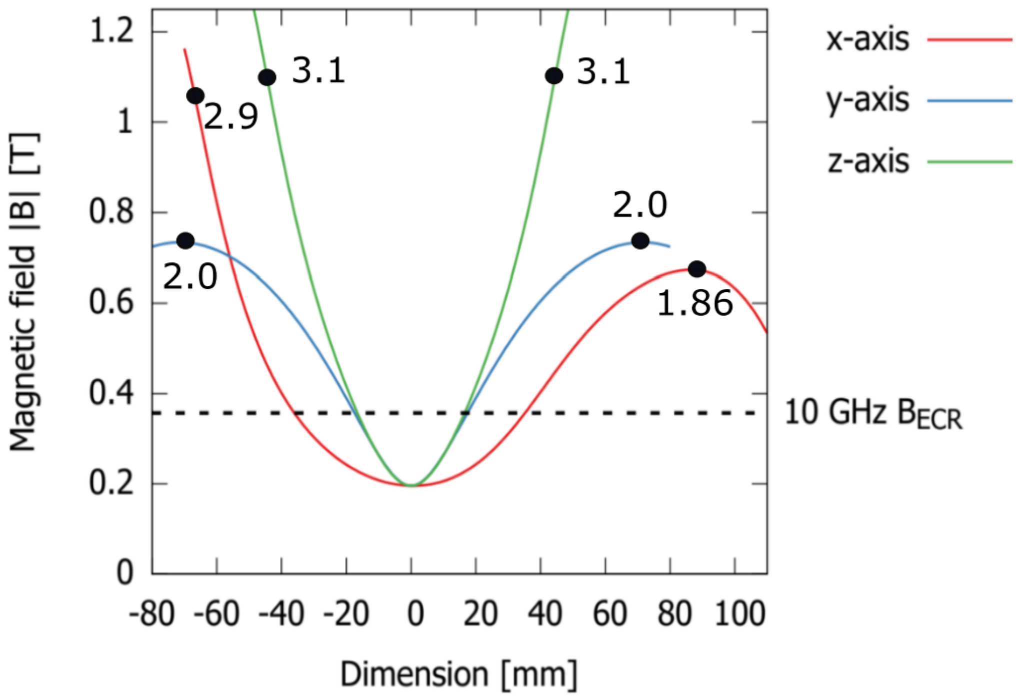
approx. £1M

Science and
Technology
Facilities Council

Permanent magnet CUBE-ECRIS



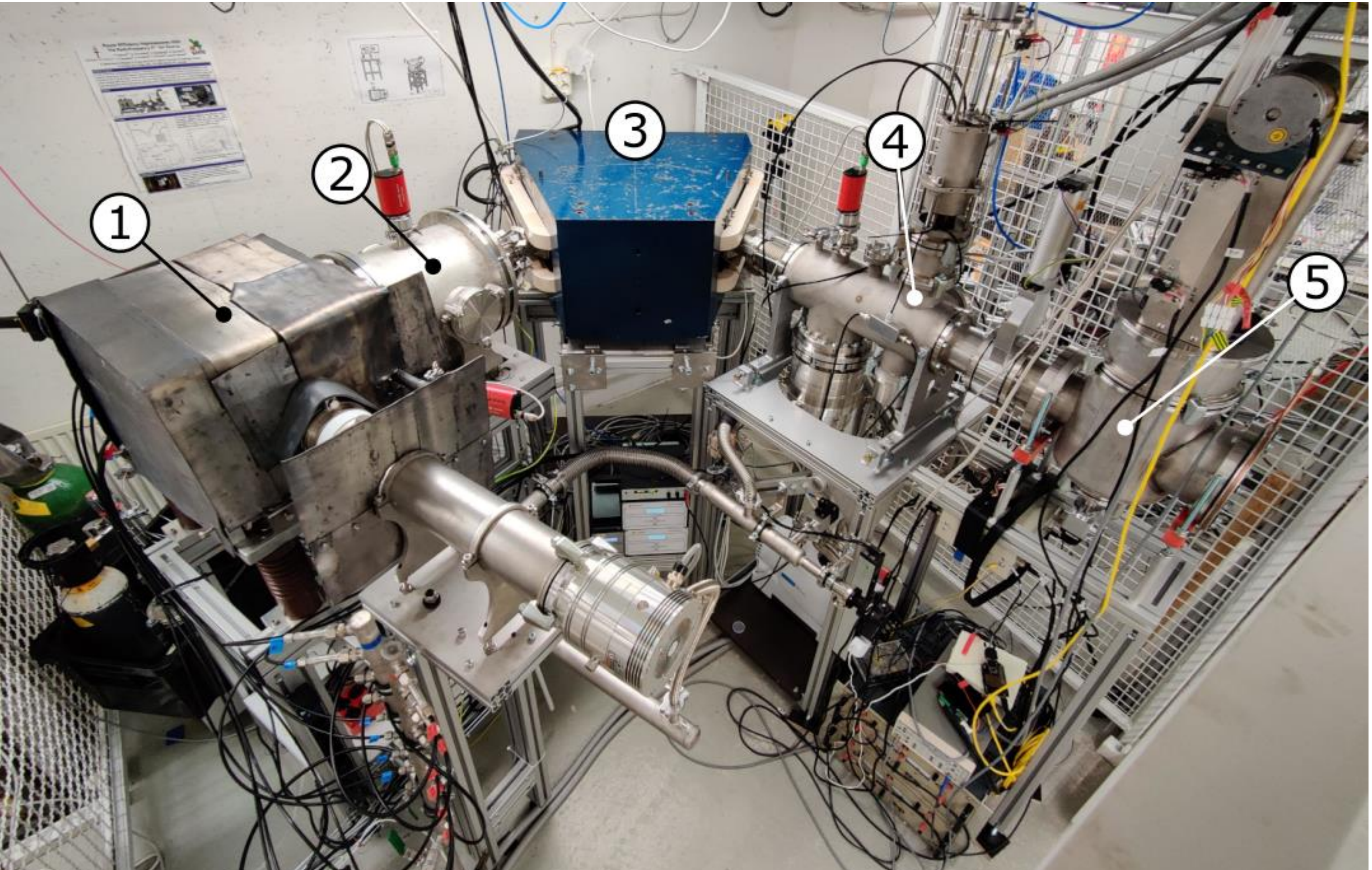
Novel quadrupole minimum-B structure



160 kg of PM material

Permanent magnet CUBE-ECRIS

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

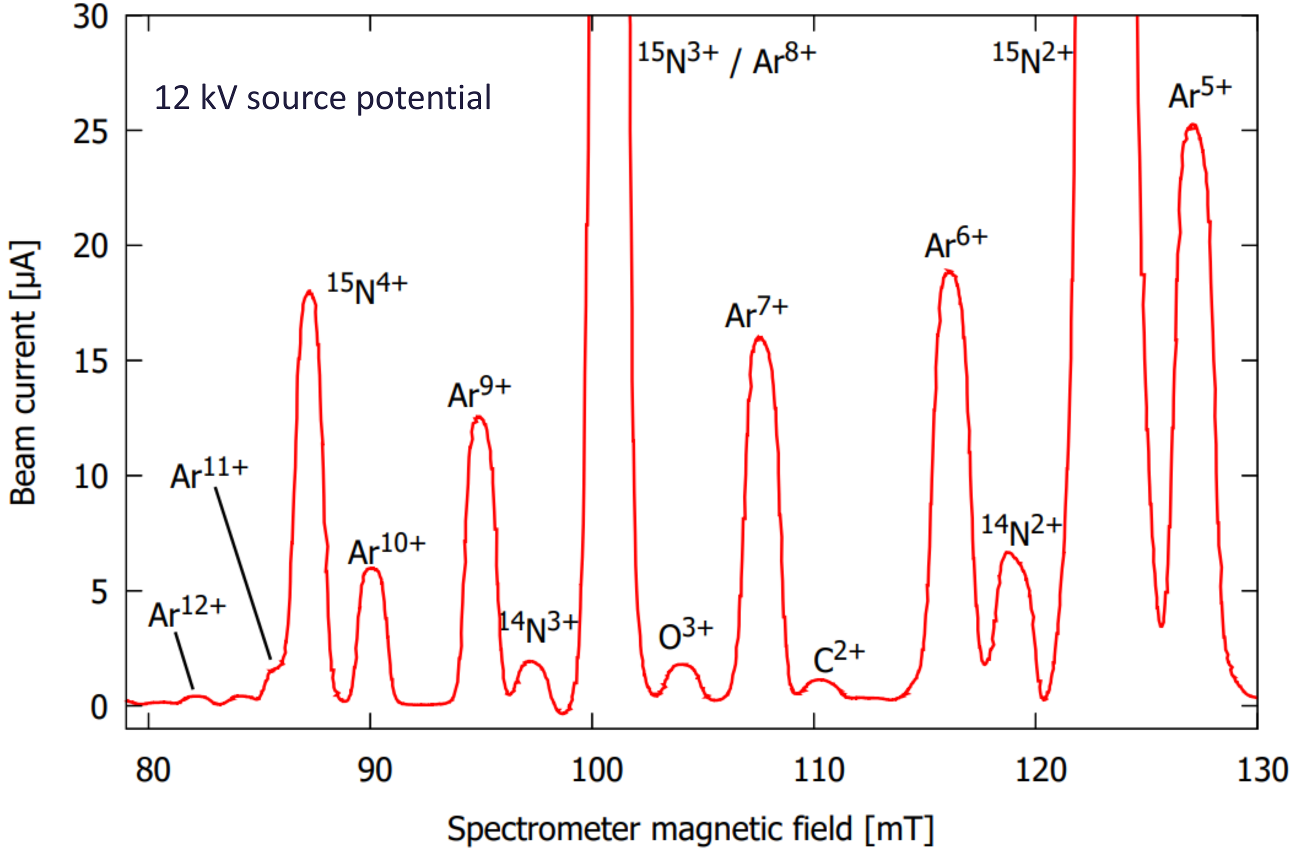


(1) CUBE-ECRIS
(2) Electrostatic quadrupole doublet
(3) m/q-analysis magnet
(4) Faraday cup
(5) Emittance scanner

Permanent magnet CUBE-ECRIS

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Argon charge state distribution with 15-nitrogen buffer gas to measure Ar^{12+} without overlapping buffer gas ions



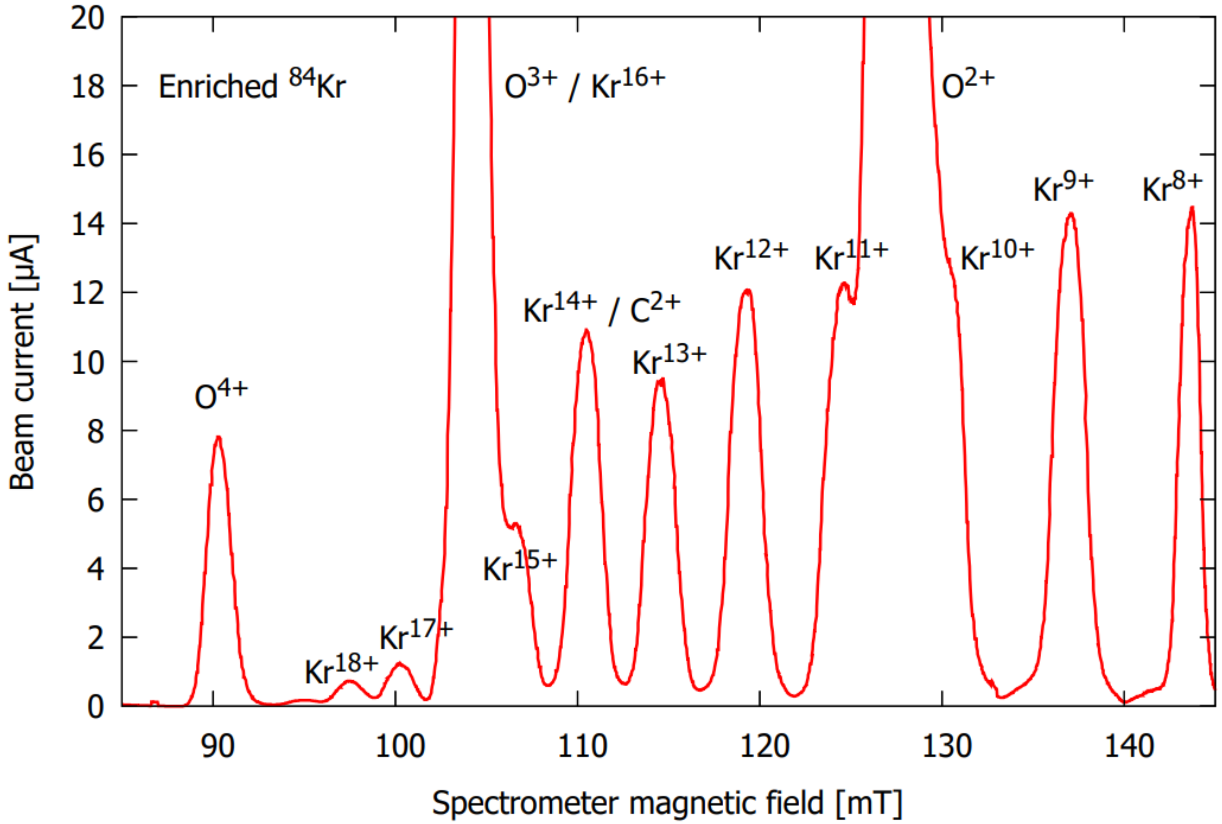
Charge state	Current [μA]	Flux [pnA]
5+	25	5000
6+	18	3000
7+	15	2140
8+	-	-
9+	12	1330
10+	5.8	580
11+	1.5	140
12+	0.4	33

TOF ERDA suitable @ 500 kV ✓

Science and Technology Facilities Council

Permanent magnet CUBE-ECRIS

Krypton (enriched 84-isotope) charge state distribution



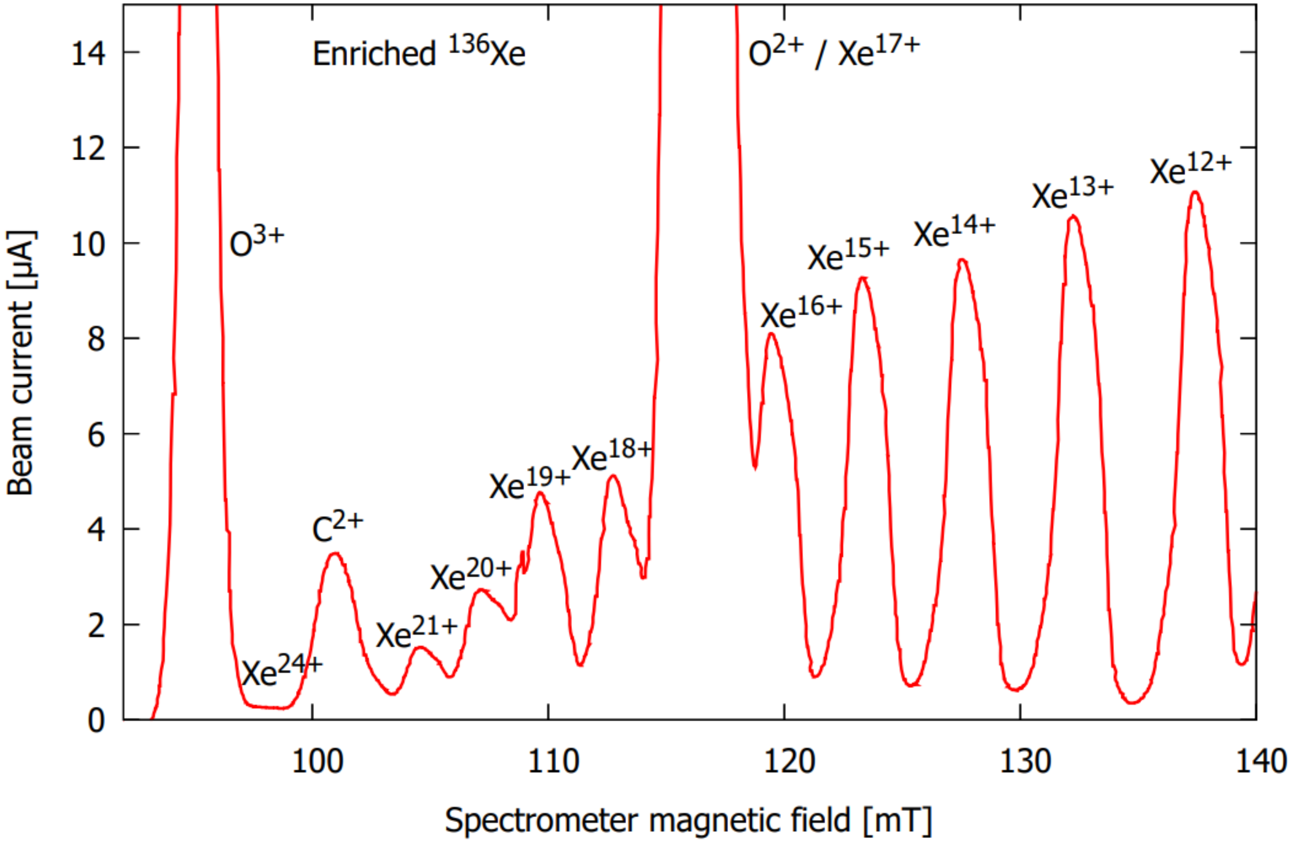
Charge state	Current [μA]	Flux [pnA]
17+	1.25	100
18+	0.73	40
19+	0.23	12

TOF ERDA suitable
@ 500 kV
(9.5 MeV) ✓

Permanent magnet CUBE-ECRIS

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Xenon (enriched 136-isotope) charge state distribution



***Enriched 131-isotope**

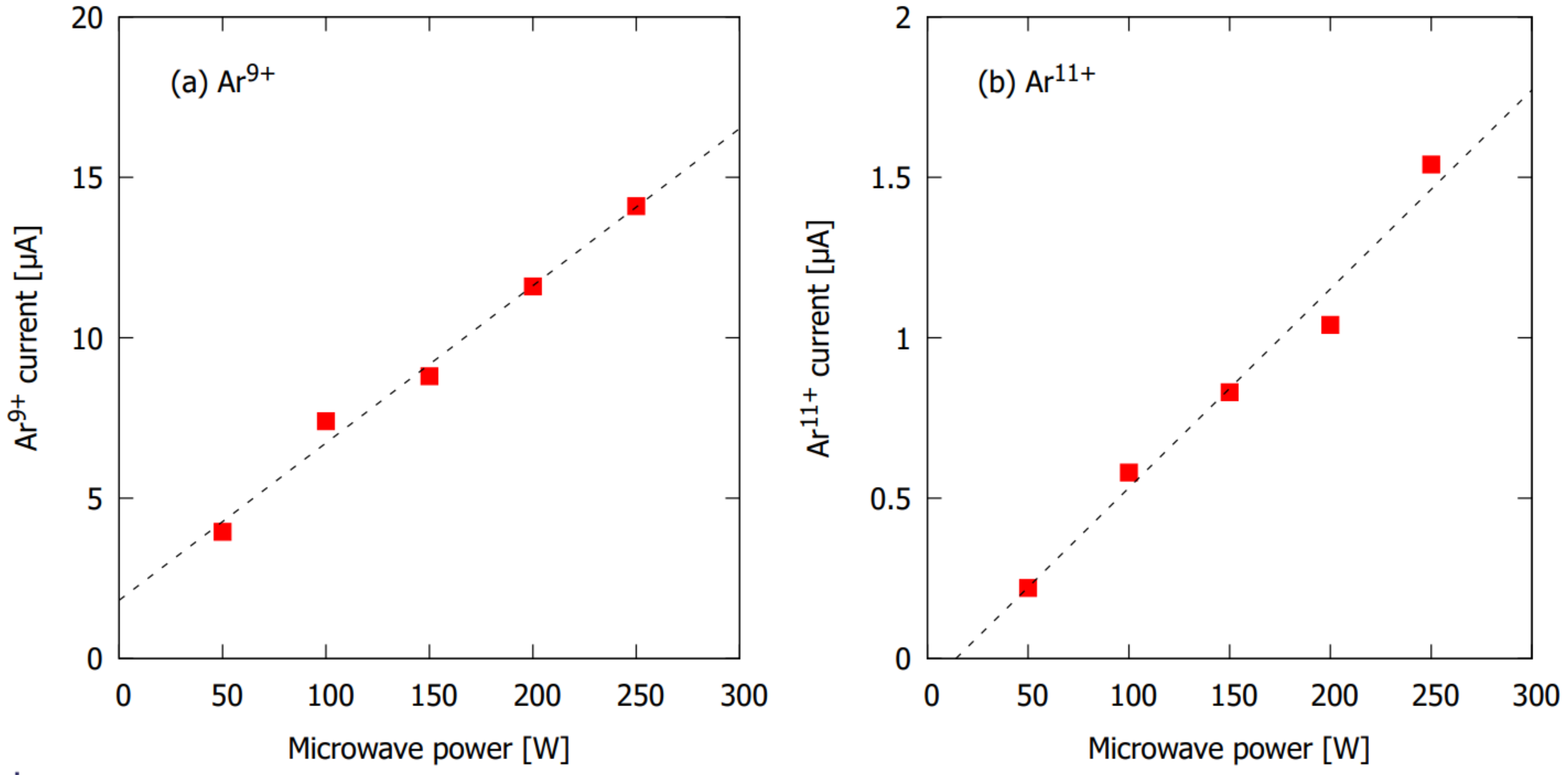
Charge state	Current [μA]	Flux [pnA]
18+	4.9	270
19+	4.55	240
20+	2.7	135
21+	1.5	70
22+	-	-
23+	0.5*	22*
24+	0.2	8

TOF ERDA suitable
@ 500 kV
(12 MeV) ✓

Science and
Technology
Facilities Council

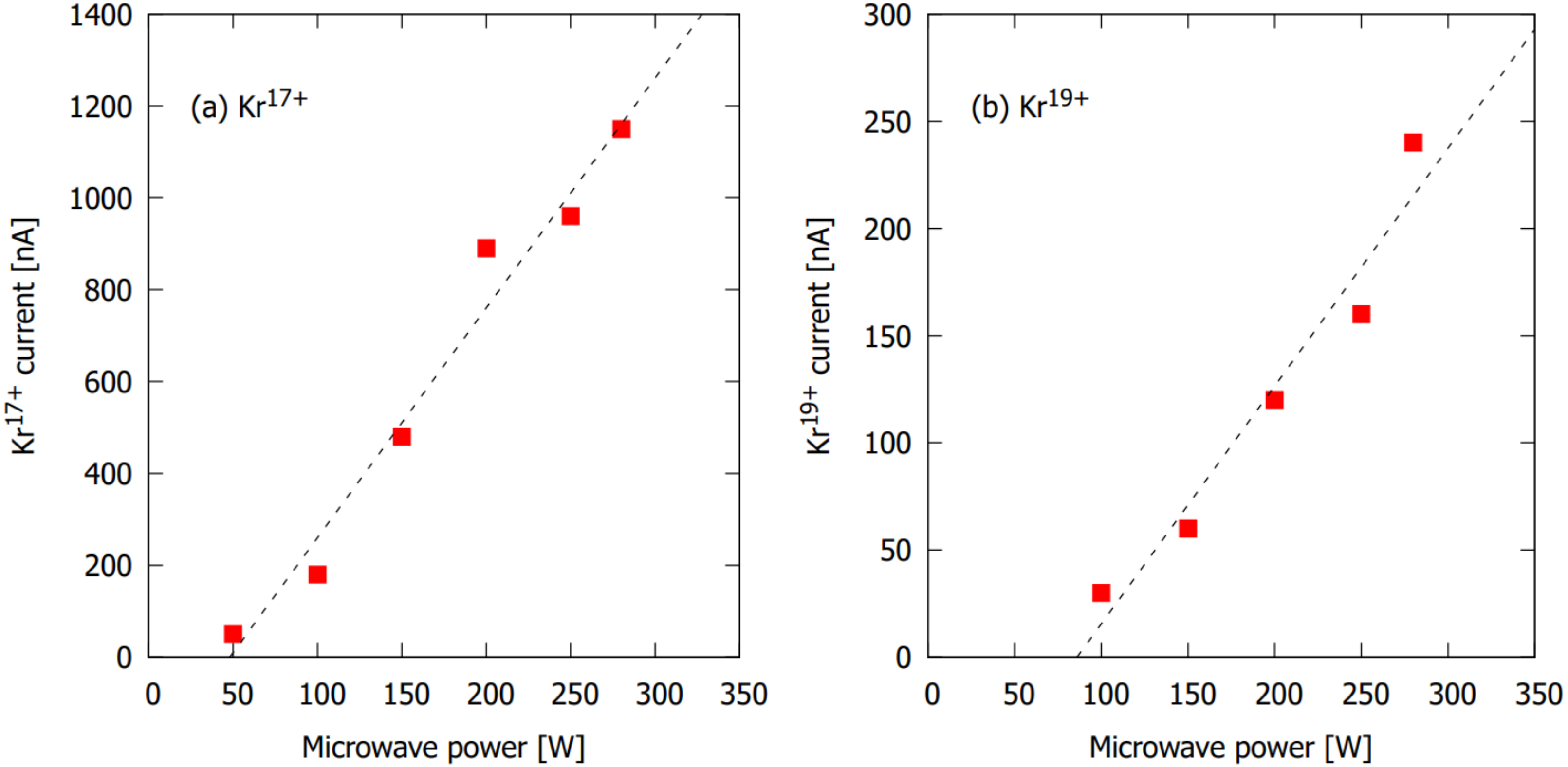
Permanent magnet CUBE-ECRIS

One possibility to increase the beam currents of high charge state Kr and Xe beams is to increase the microwave power. The high charge state currents are power limited as shown here for argon.



Permanent magnet CUBE-ECRIS

One possibility to increase the beam currents of high charge state Kr and Xe beams is to increase the microwave power. The high charge state currents are power limited as shown here for krypton (enriched ^{84}Kr isotope).

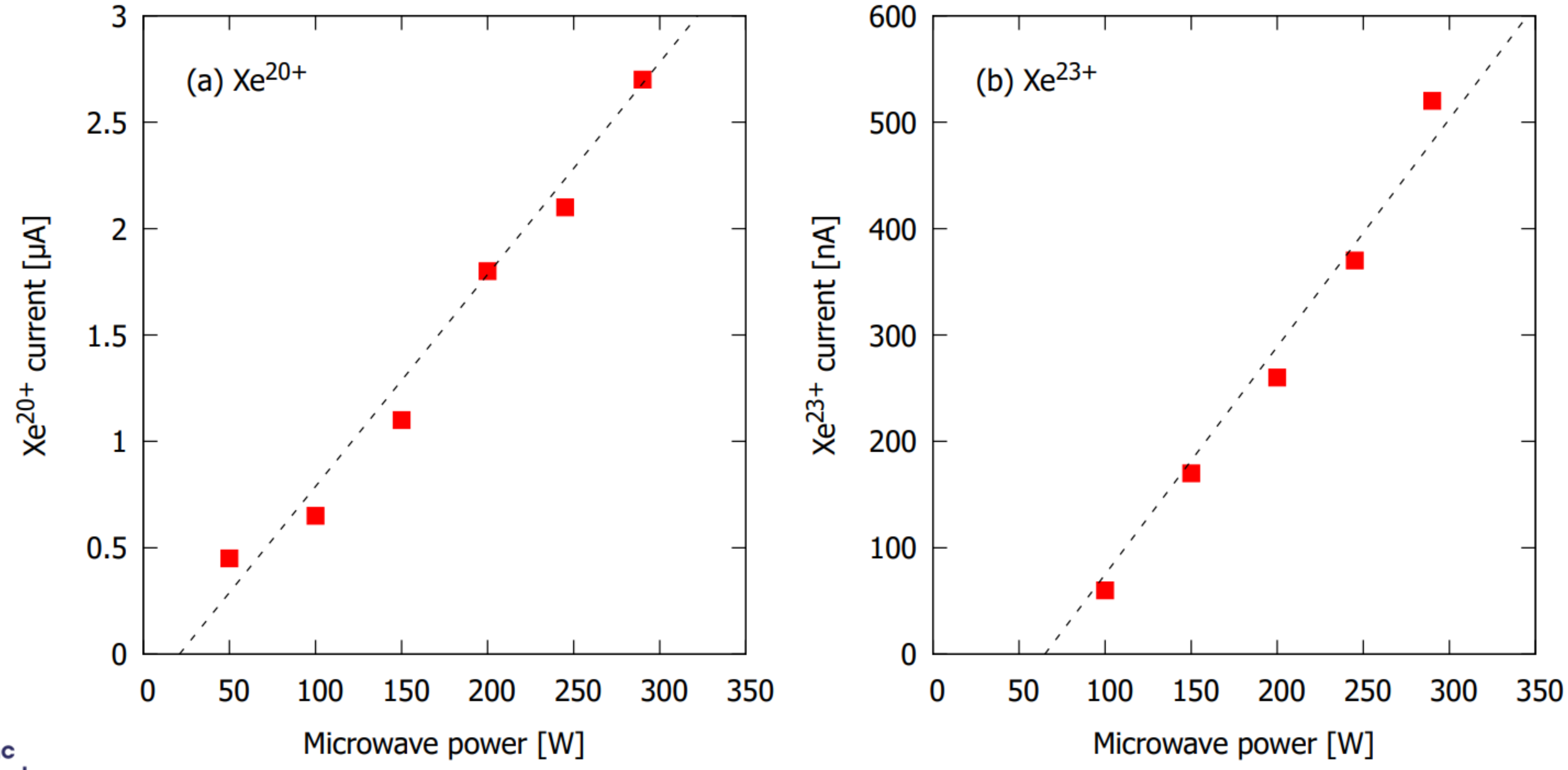


Science and Technology Facilities Council

Permanent magnet CUBE-ECRIS

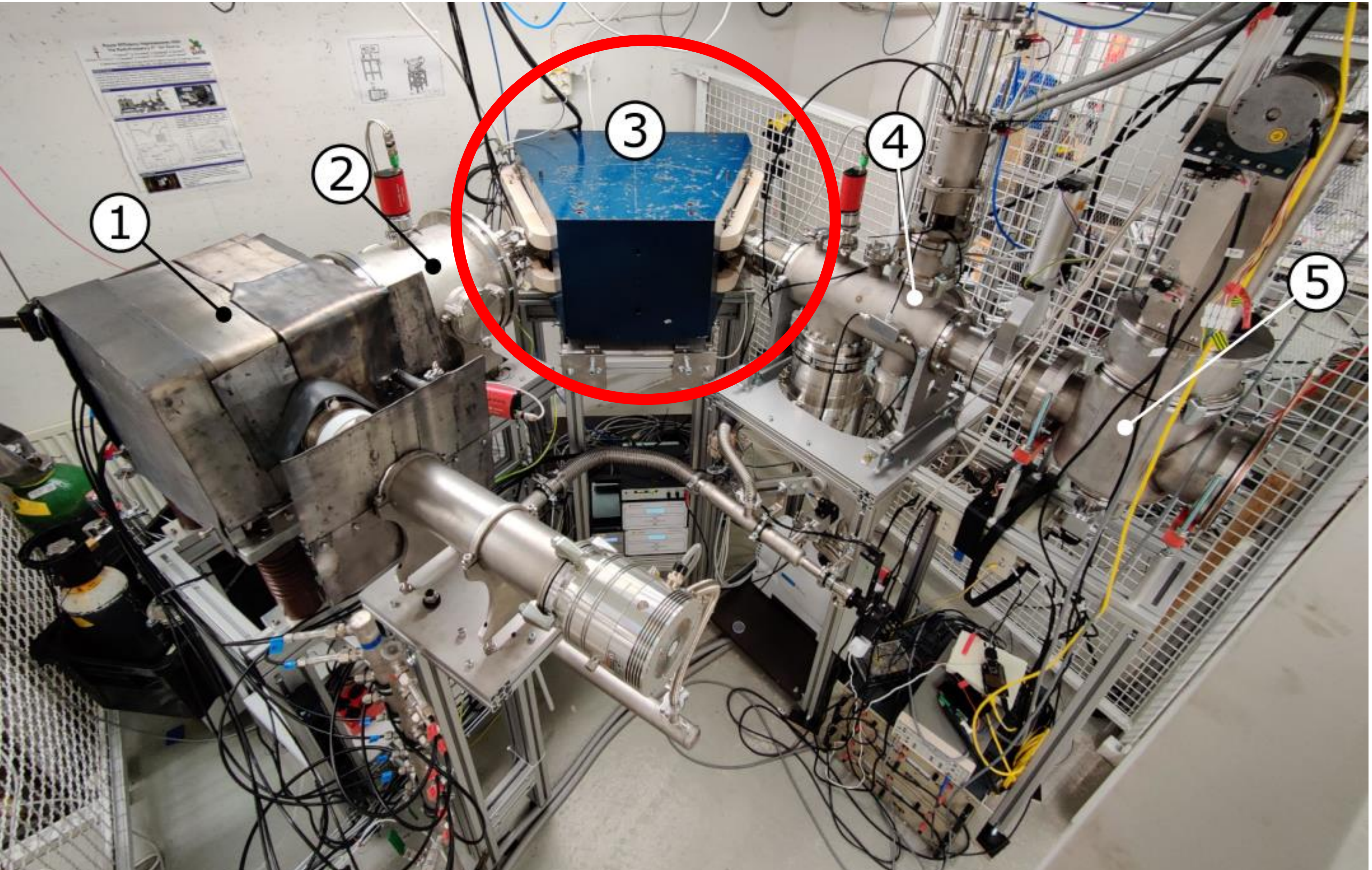
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

One possibility to increase the beam currents of high charge state Kr and Xe beams is to increase the microwave power. The high charge state currents are power limited as shown here for xenon (enriched ^{131}Xe isotope).



Scienc
Technology
Facilities Council

Permanent magnet CUBE-ECRIS

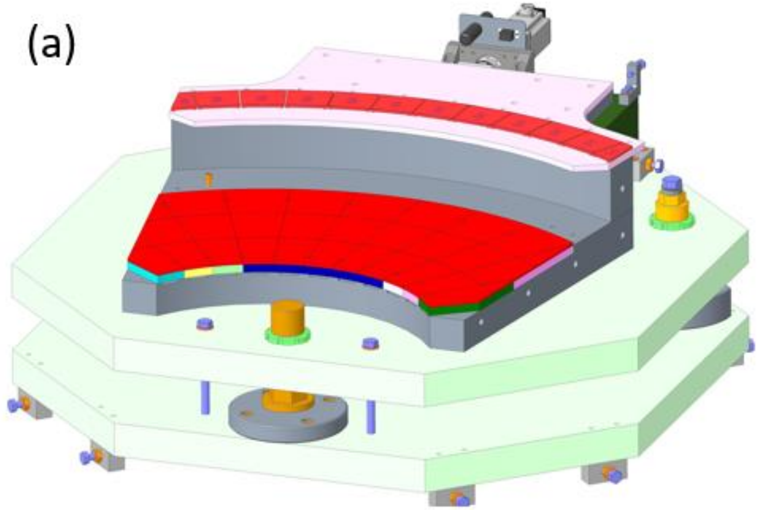


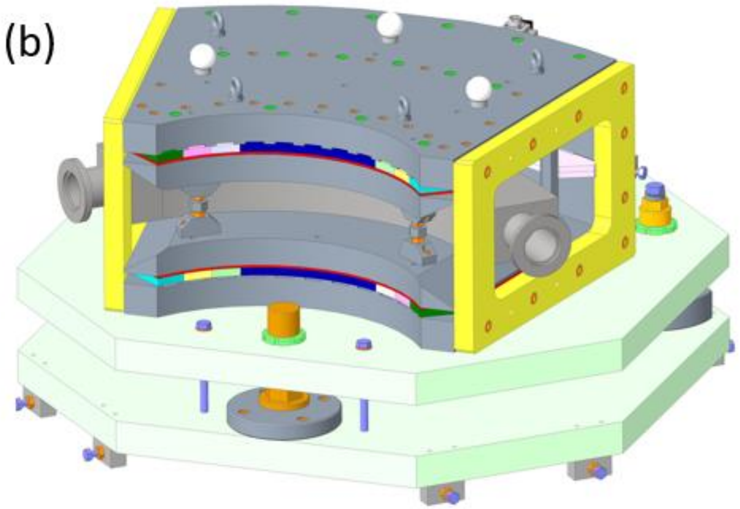
(1) CUBE-ECRIS
(2) Electrostatic quadrupole doublet
(3) m/q-analysis magnet
(4) Faraday cup
(5) Emittance scanner

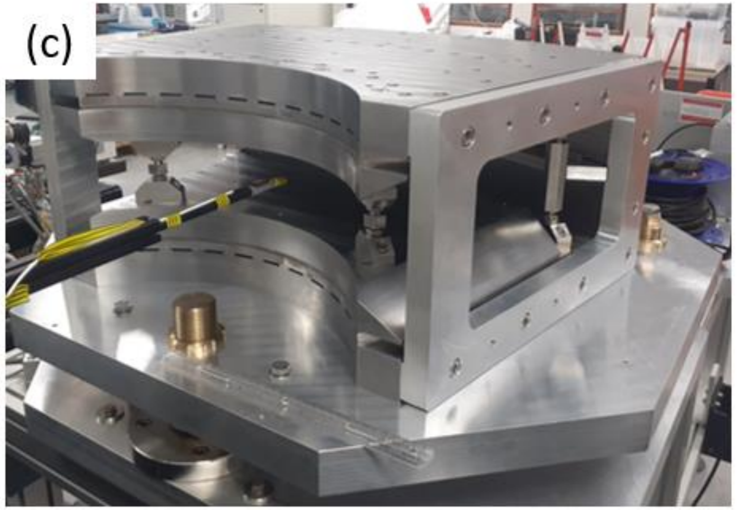
Adjustable field permanent magnet dipole for charge state selection

funded by: UKRI Science and Technology Facilities Council

STFC Horizons Programme: investigating solutions for net zero







UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

Physics design and simulation

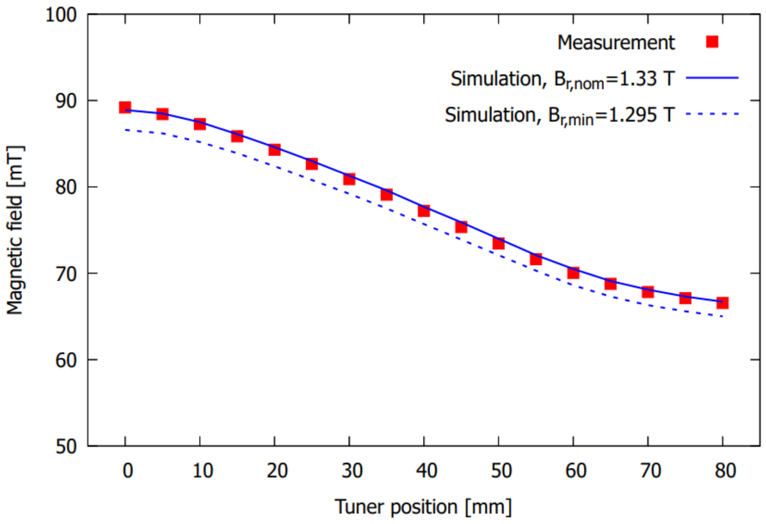
UKRI Science and Technology Facilities Council
Technology

Engineering design and assembly

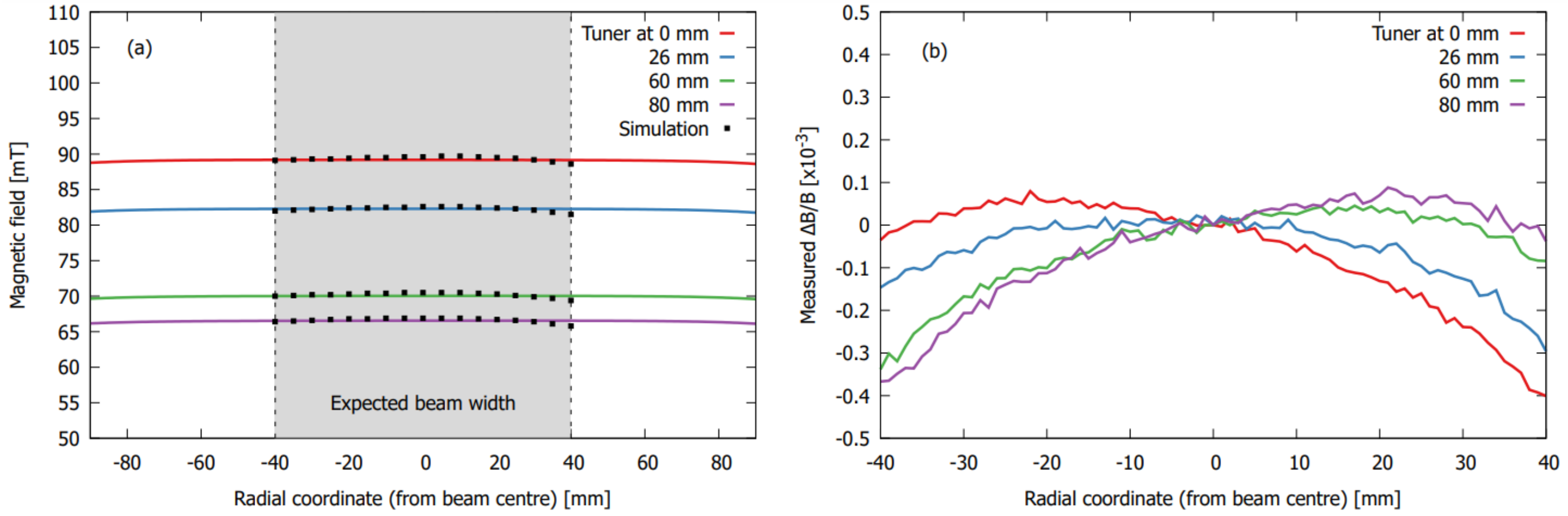
UKRI Science and Technology Facilities Council
ASTeC

Field measurement and validation

Adjustable field permanent magnet dipole for charge state selection



Perfect match between simulation and measured field with varying tuner position



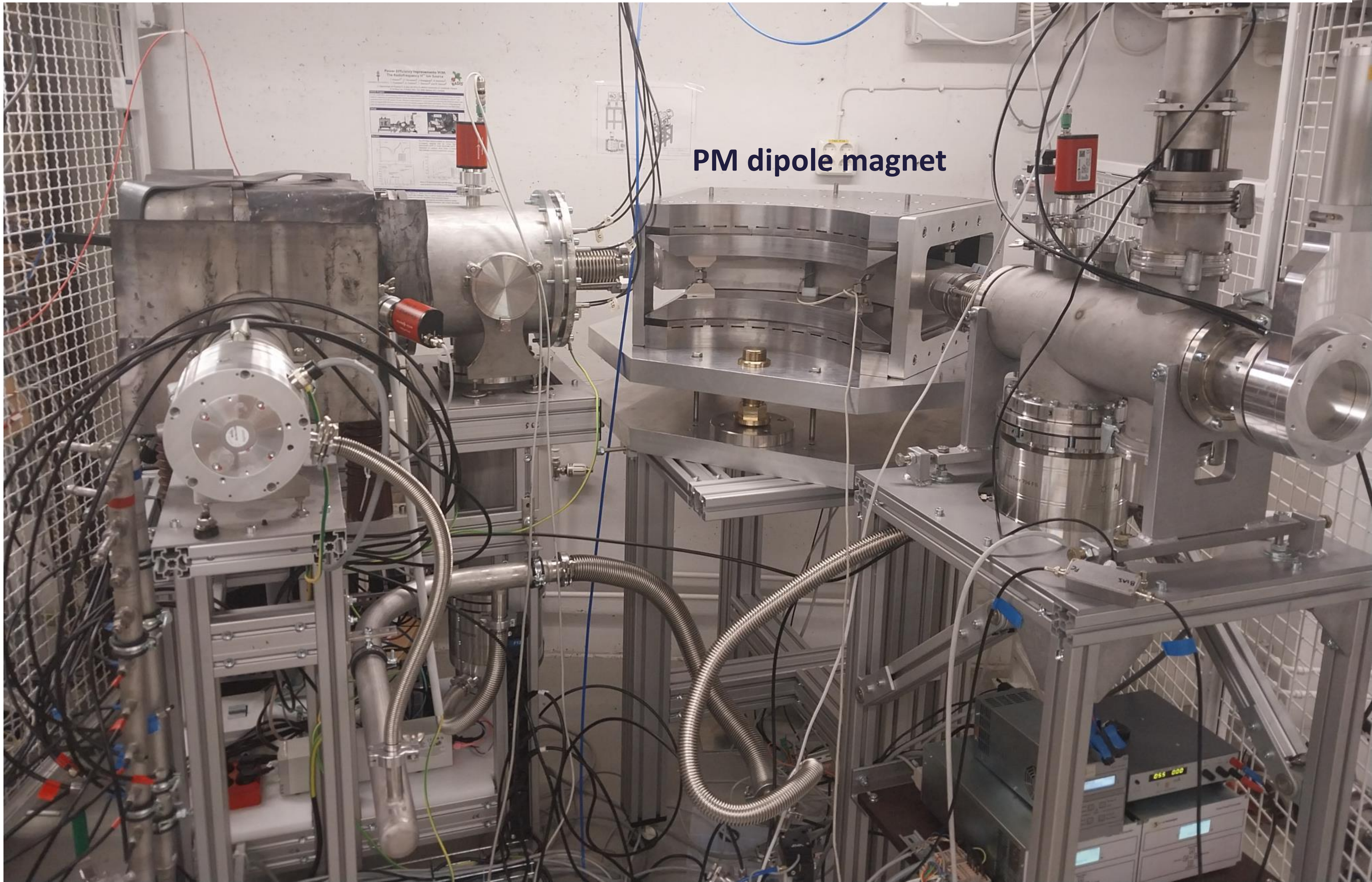
Excelllent field uniformity radially across the magnet pole, $\Delta B/B < 5\text{x}10$^$^{-4}$ (the specification is $1\text{x}10^{-3}$)

Other potential applications of the magnet:

- accelerator based nuclear physics
- accelerator mass spectrometry
- isotope separation

Science and
Technology
Facilities Council

First beam transport tests with the PM dipole – May 2024

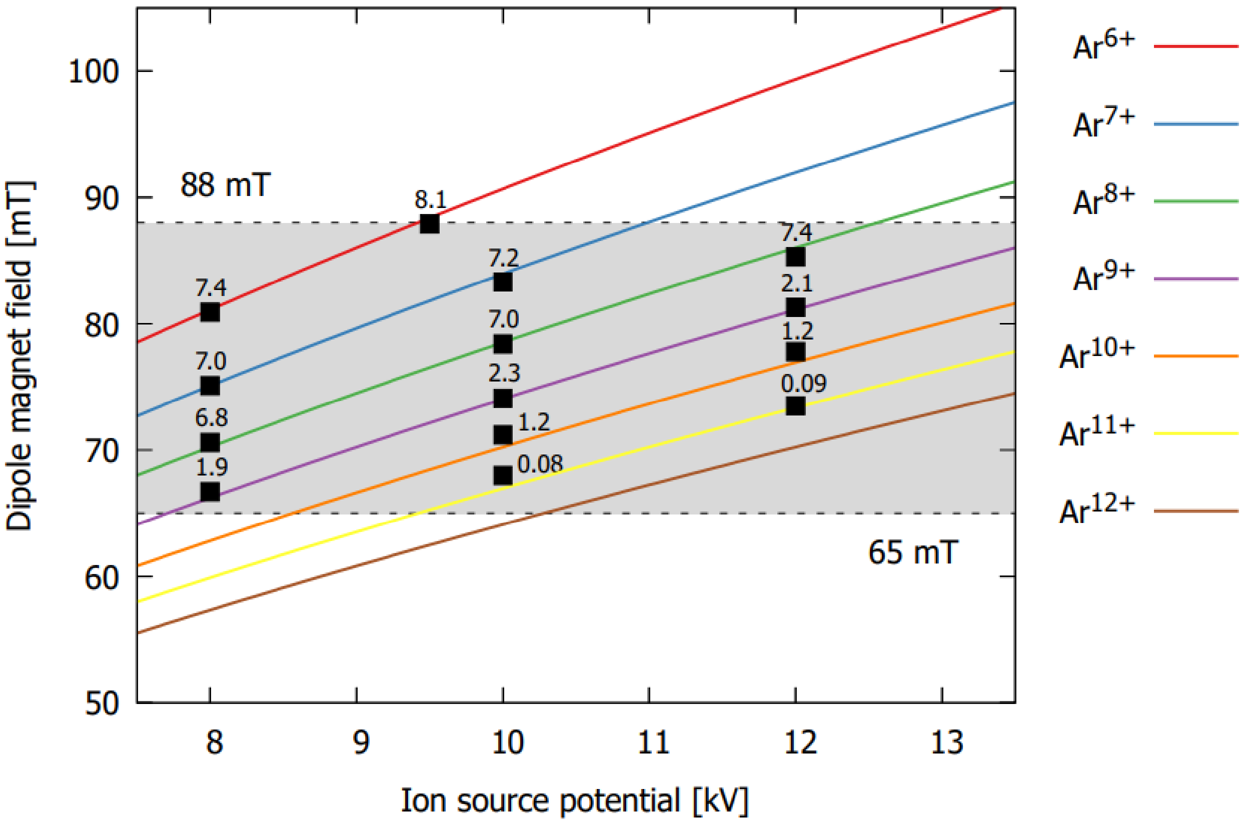


JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

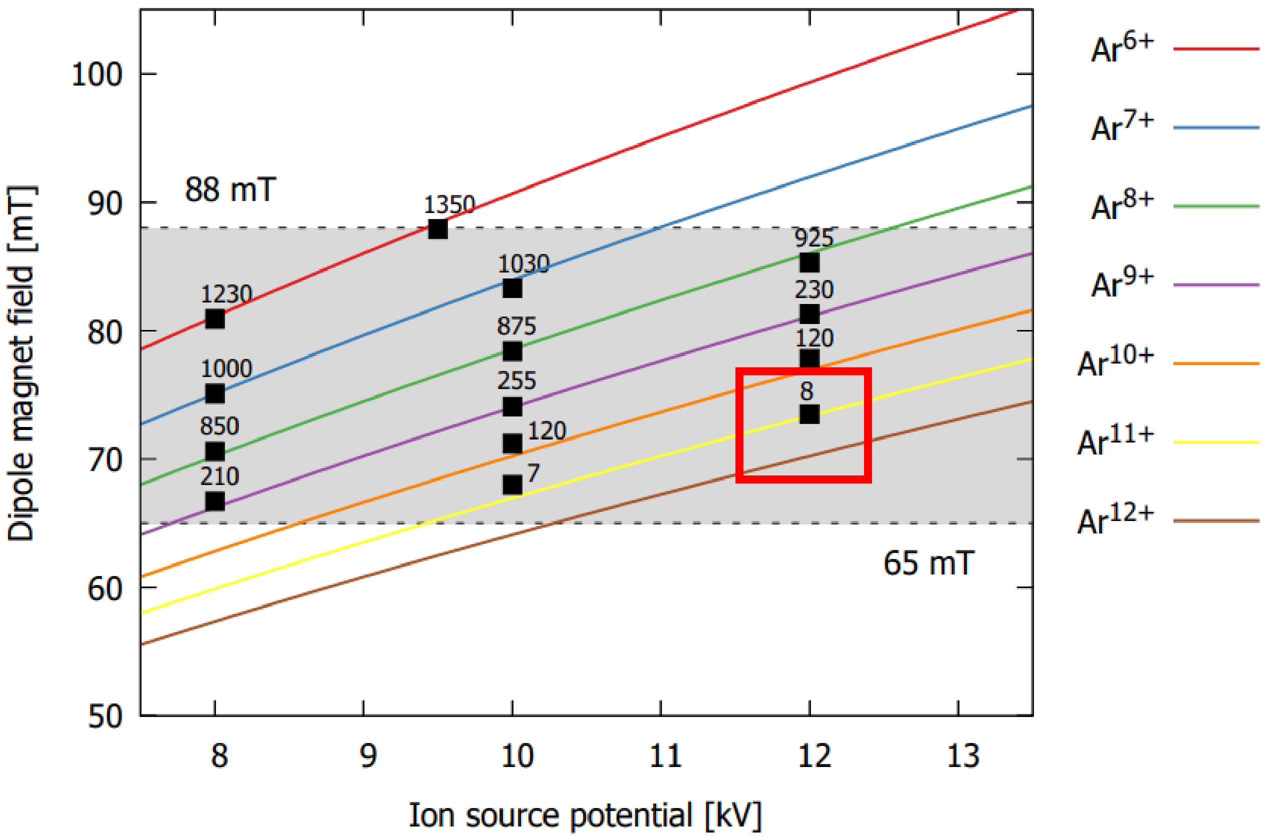
Science and
Technology
Facilities Council

First beam transport tests with the PM dipole – May 2024

Argon beam currents in μA



Argon beam currents in pnA



Science and
Technology
Facilities Council

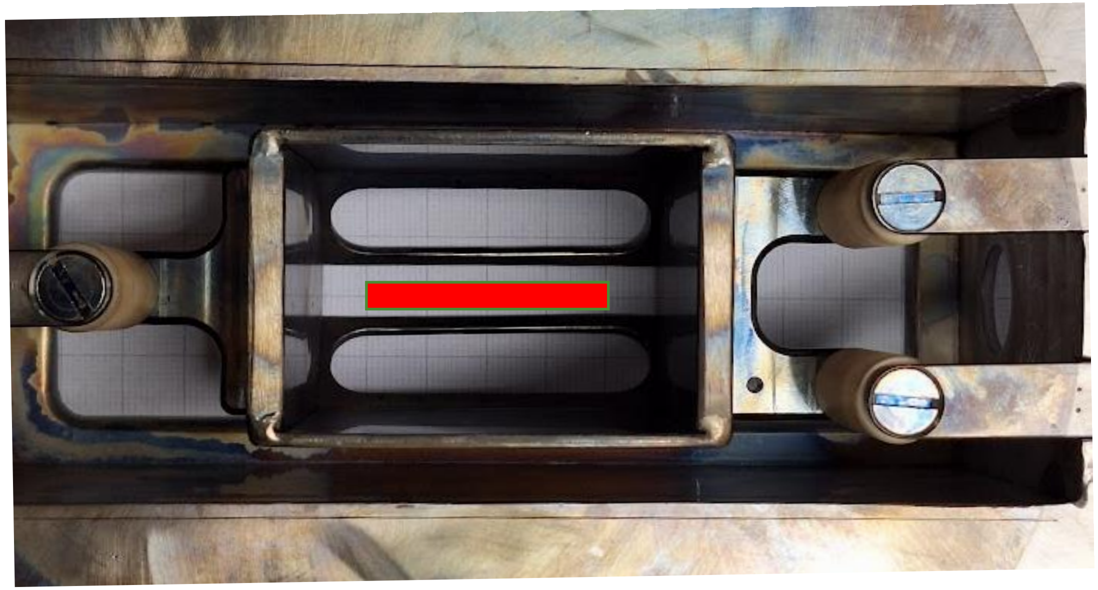
First beam transport tests with the PM dipole – May 2024

Argon beam currents are lower than with the electromagnet

This is due to lack of optimisation:

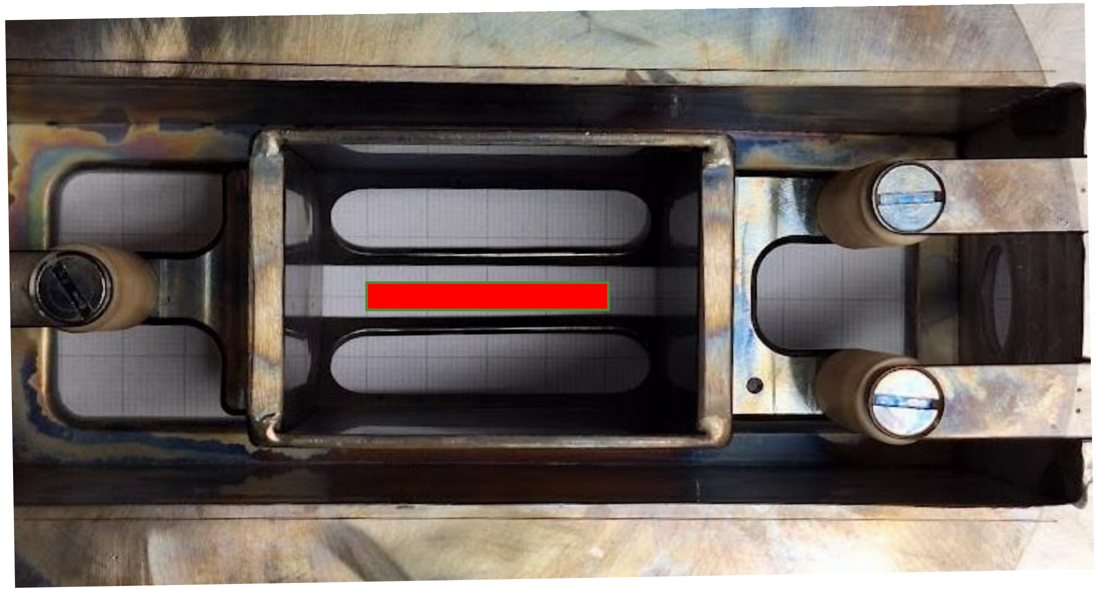
- **No double frequency heating**
- **Higher than normal drain current**
- **Beam losses due to severe extraction misalignment**

Beam transport simulations of the whole LEBT to confirm the effect on total transmission

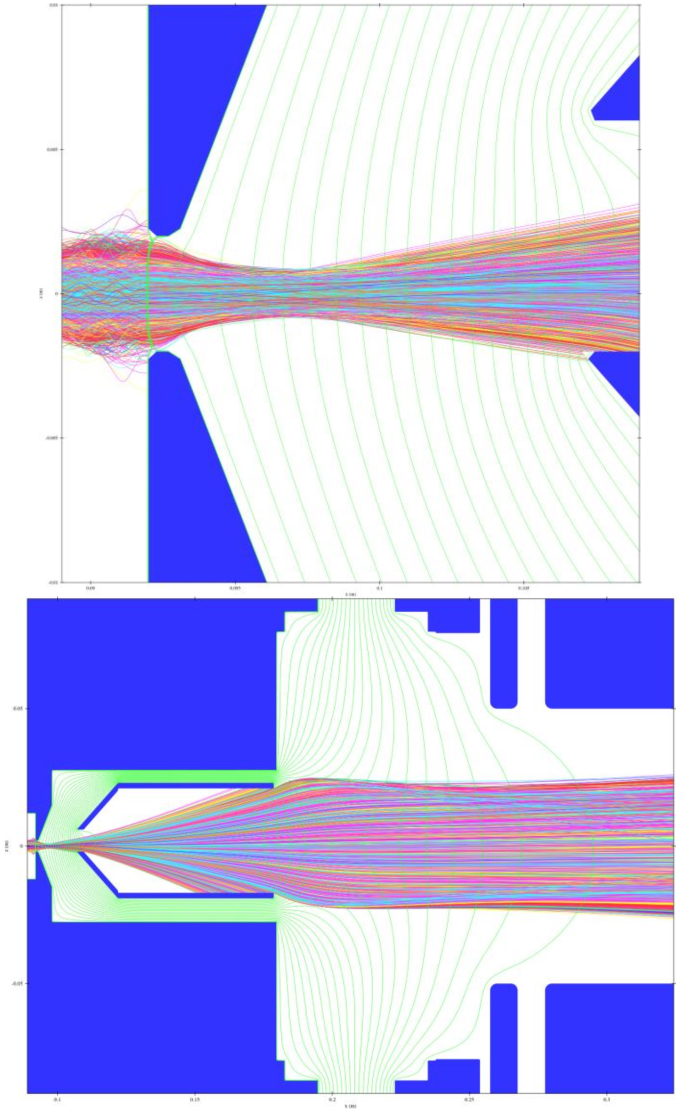


Puller electrode offset and rotation wrt the extraction slit

First beam transport tests with the PM dipole – May 2024



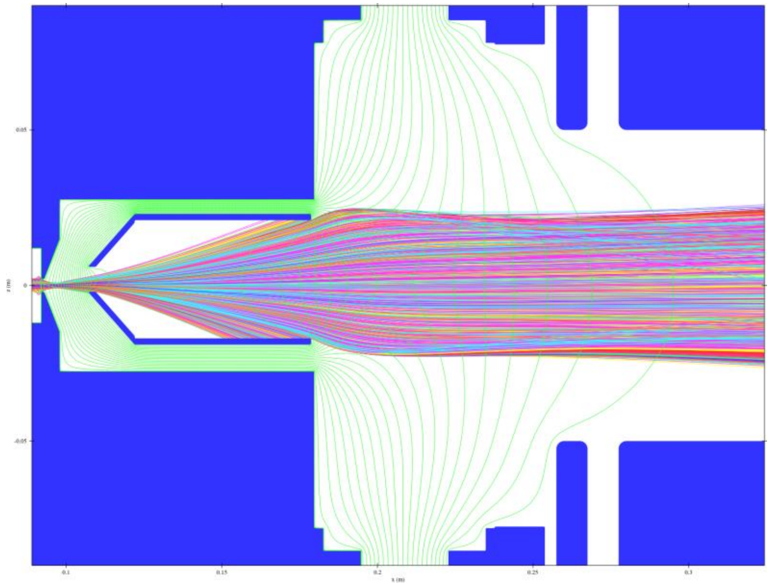
Puller electrode offset and rotation wrt the extraction slit

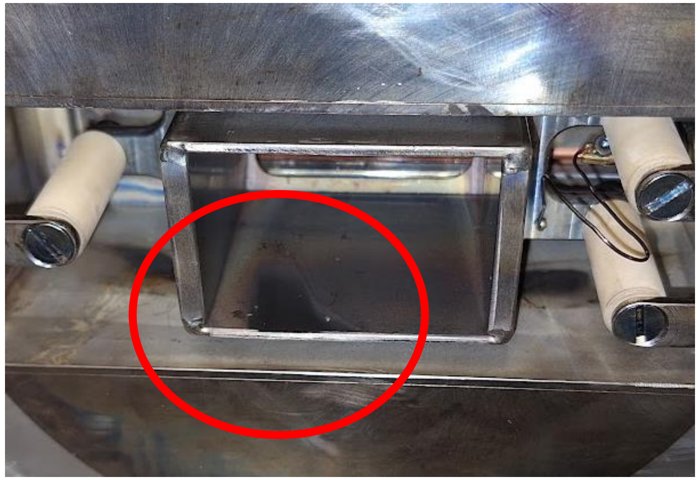


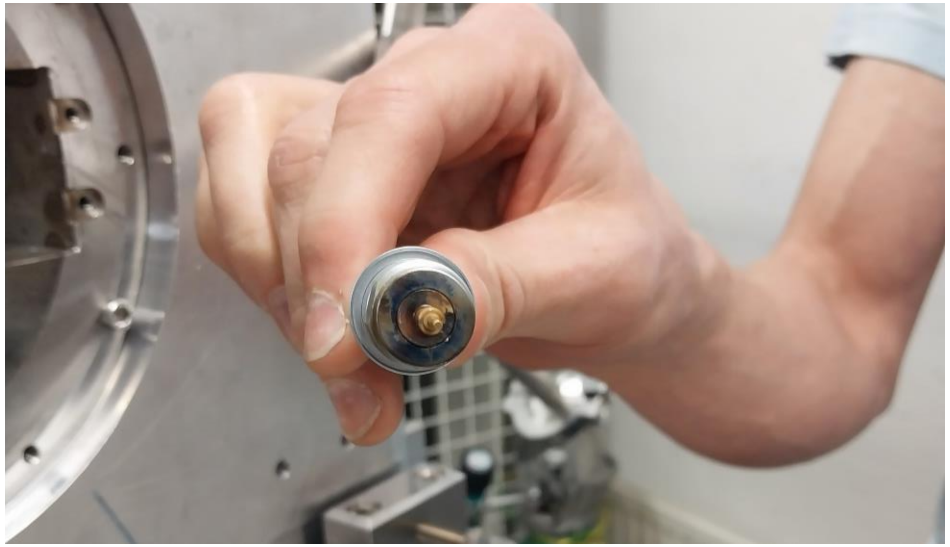
Asymmetric beam losses in the puller electrode and poor quality beam into the LEBT

Science and
Technology
Facilities Council

First beam transport tests with the PM dipole – May 2024







Beam burn mark matching the simulation with puller offset

Beam induced sputtering
→ coating of the puller feedthrough
→ failure ending the experiment

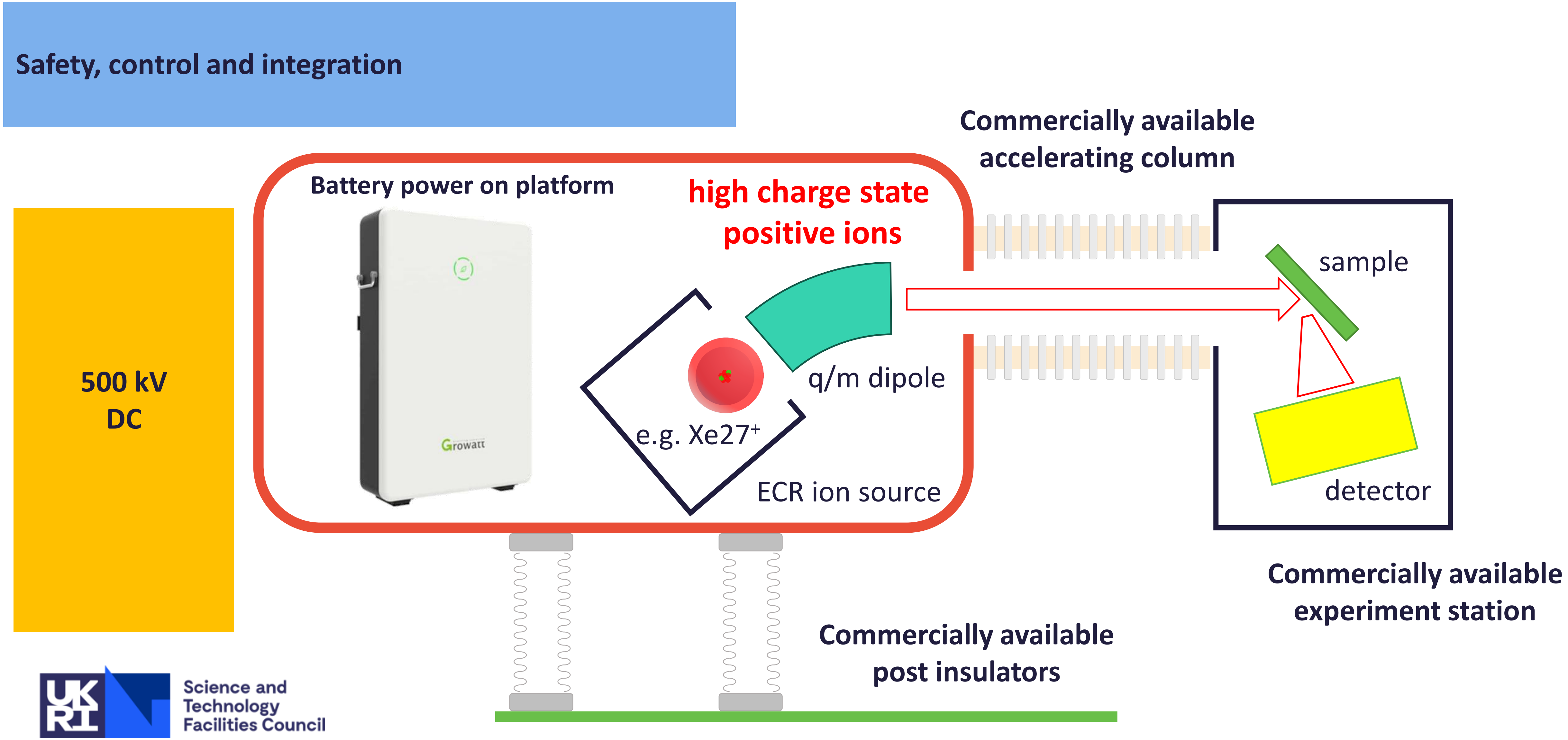
Requires correcting the misalignment and changing the puller feedthrough location

Science and
Technology
Facilities Council

Next steps

- Continue optimisation of front end
- Develop the rest of the system

Emission-Free, Zero-Carbon, IBA Concept – Required Components



Safety, control and integration

500 kV DC

Battery power on platform

high charge state positive ions

e.g. $Xe27^{+}$

q/m dipole

ECR ion source

Commercially available accelerating column

sample

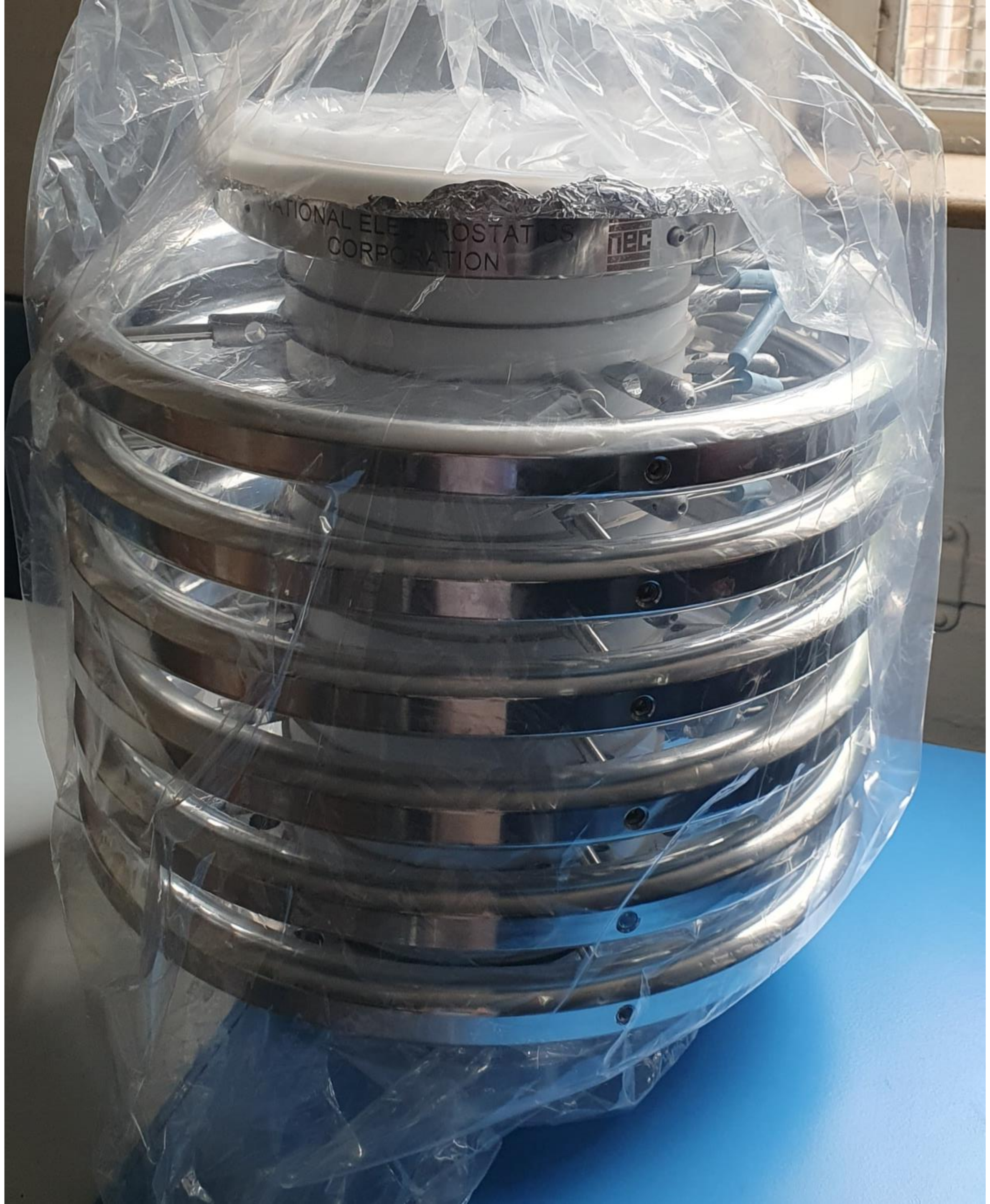
detector

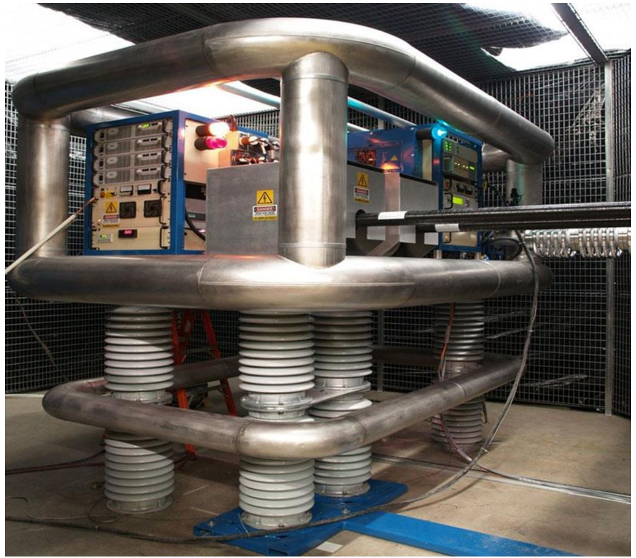
Commercially available experiment station

Commercially available post insulators

Science and Technology Facilities Council

5 x 100 kV NEC air-insulated acceleration tubes received (100 W leakage power)





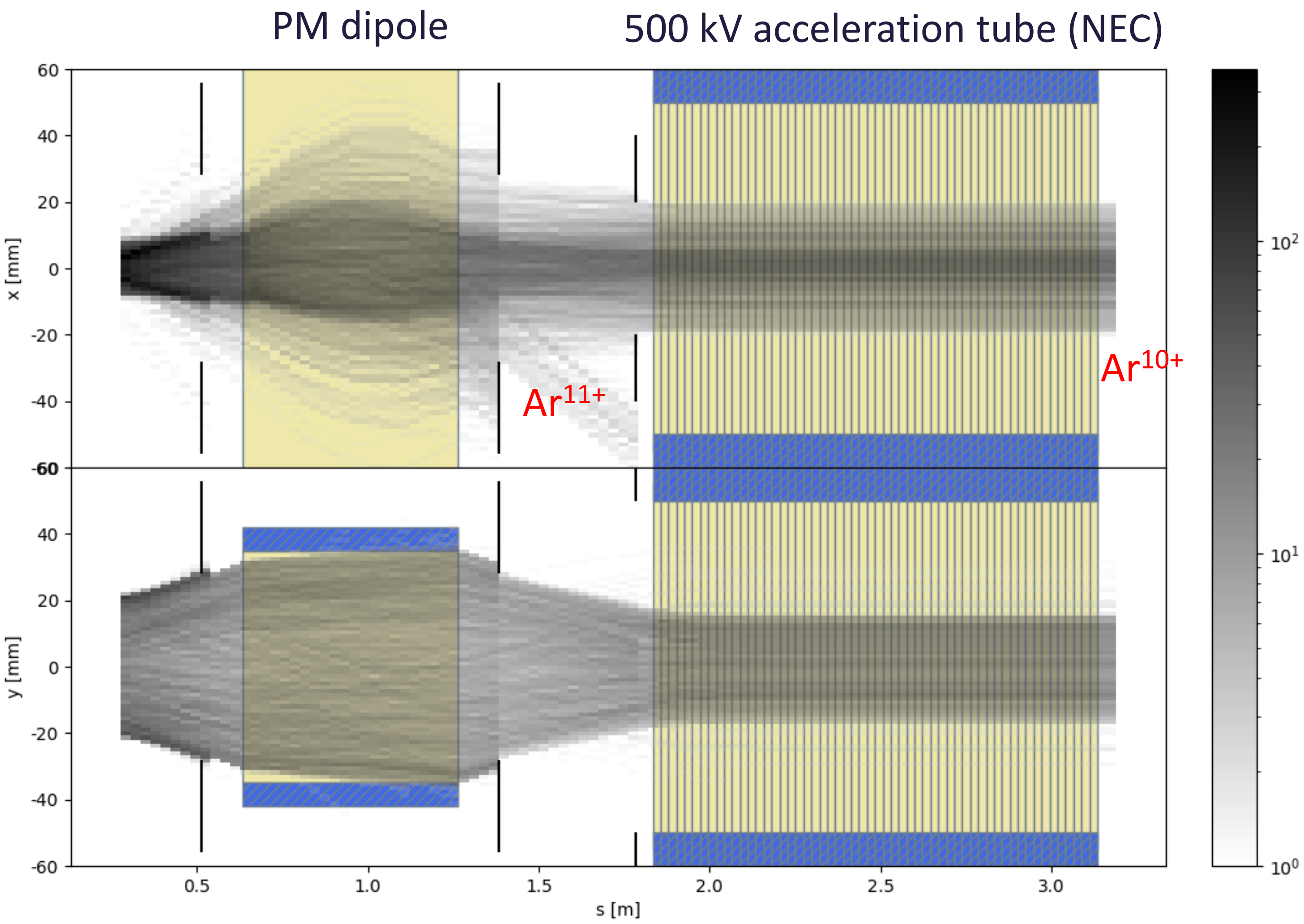
500 kV NEC

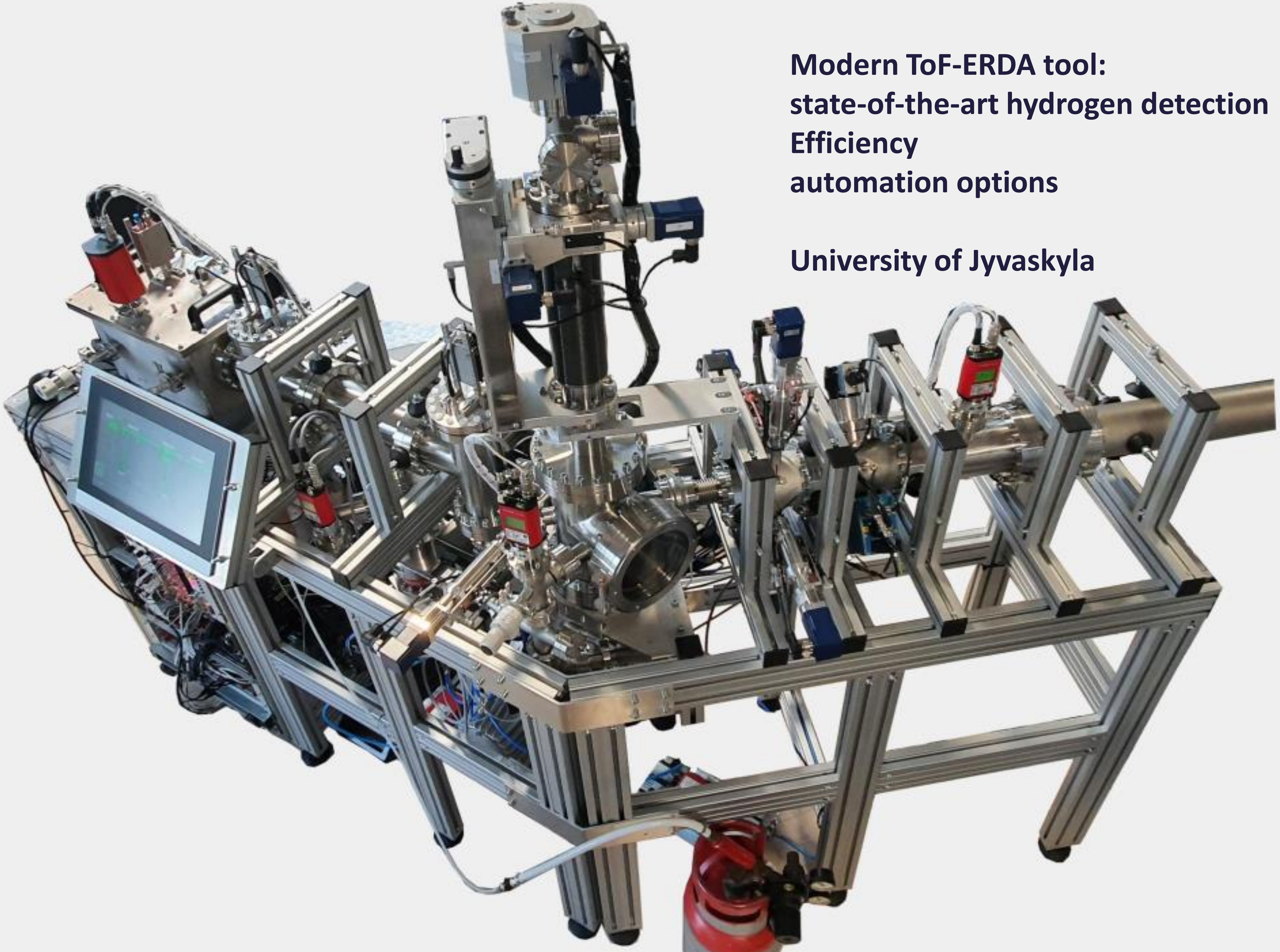
Science and Technology Facilities Council

Beam transport simulations

Taneli Kalvas, University of Jyvaskyla

Same overall transport efficiency for higher charge states - 5 MeV Ar^{10+}



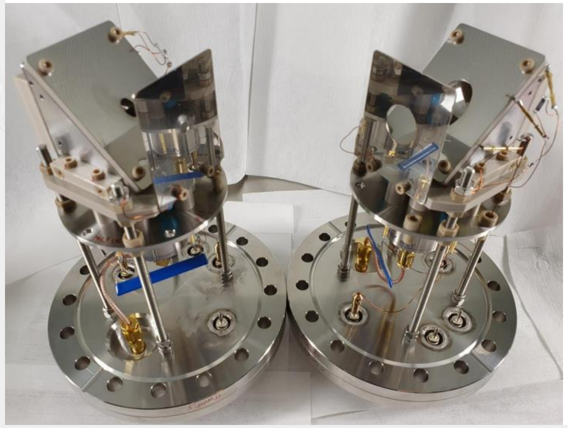


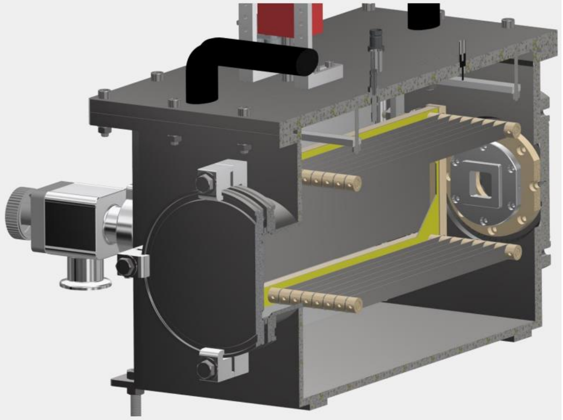
Modern ToF-ERDA tool:

state-of-the-art hydrogen detection
Efficiency
automation options

University of Jyvaskyla

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ





Courtesy of Mikko Laitinen, University of Jyvaskyla

Carbon Neutral!

24x7 base load: 2 kW
+ when operating: 1.5 kW

Operating 8 hours/day
5 days/week

= 20,000 kWh per annum

Based on UK average:

11 m x 11 m of solar panels required
(approximately the building footprint)

✓

Science and
Technology
Facilities Council

Summary

- Power consumption low enough to use 100% local solar
- Zero emission - SF_6 eliminated
- Reliable, flexible and stable ion source
- Reduced maintenance
- Turn-key/push button system
- A critical tool for developing thin-film/surface technologies

Thankyou
Questions?

Science and
Technology
Facilities Council