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Conceptual Design of Heavy Ion ToF-ERDA Facility Based on Permanent Magnet ECRIS and Variable Frequency RFQ Accelerator

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JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Motivation

Daresbury Laboratory plans to host UK's National Thin Film Deposition and Characterisation Centre

Several £10M project creating a hub for thin film physics and technology

Quantitative Ion Beam Analysis (IBA) methods are used for thin film characterisation

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Outline

1 ToF-ERDA for Ion Beam Analysis
Principle and an example facility

2 Proposed ToF-ERDA facility
Permanent magnet ECRIS
Low energy beam transport
Accelerator options
Variable frequency RFQ accelerator
High energy beamline
ToF energy telescope

3 Outlook
Project status and prototyping

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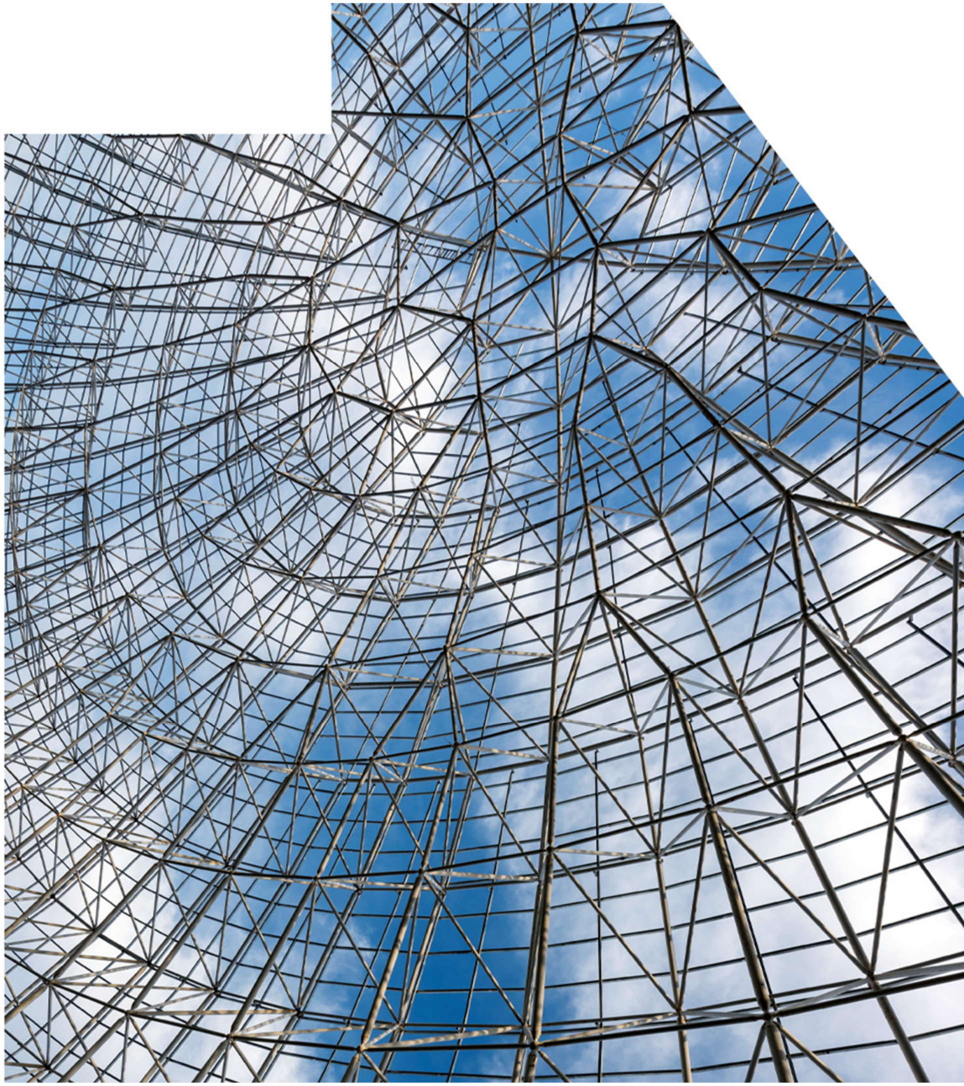

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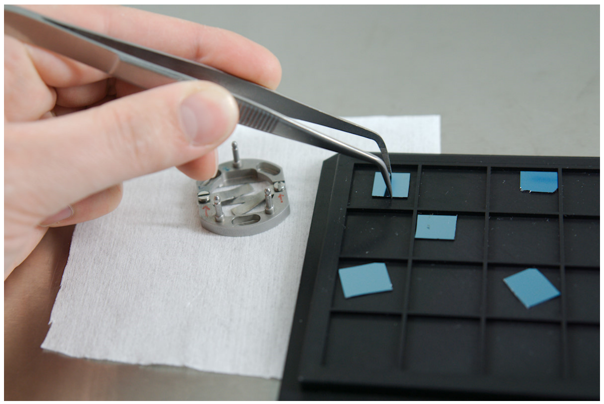
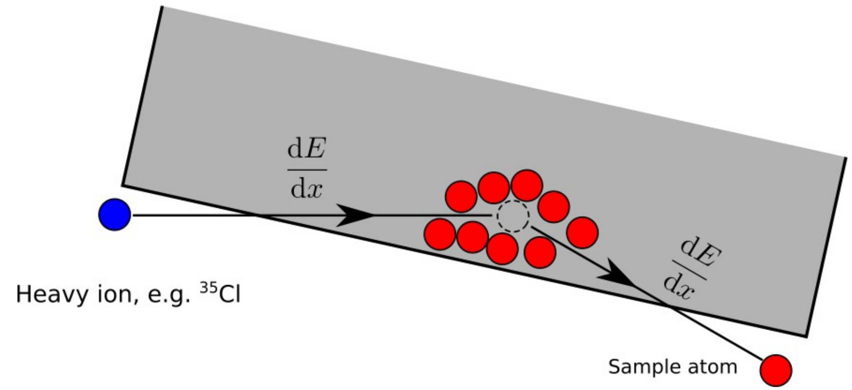
ToF-ERDA for Ion Beam Analysis

Time-of-Flight Elastic Recoil Detection Analysis



Thin film (1 nm – 1 µm) samples



- All elements can be detected
- Best suited for light elements (including H, Li, C, N, O)
- Energy loss in sample → depth information
- Elastic collisions, Rutherford cross sections

- No reference samples needed

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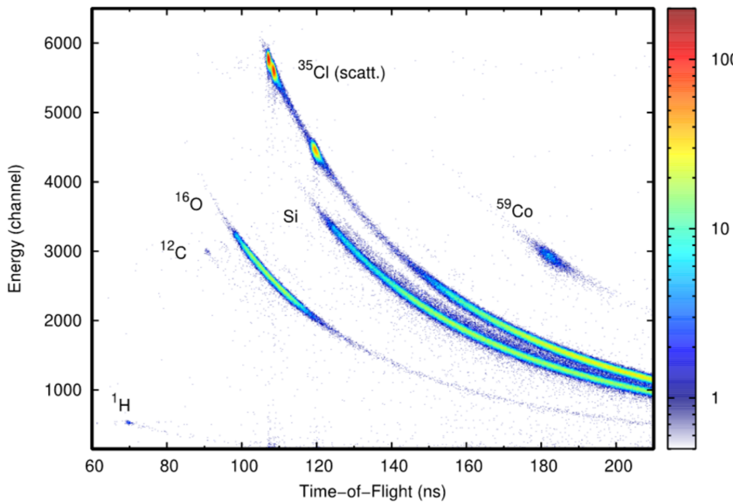
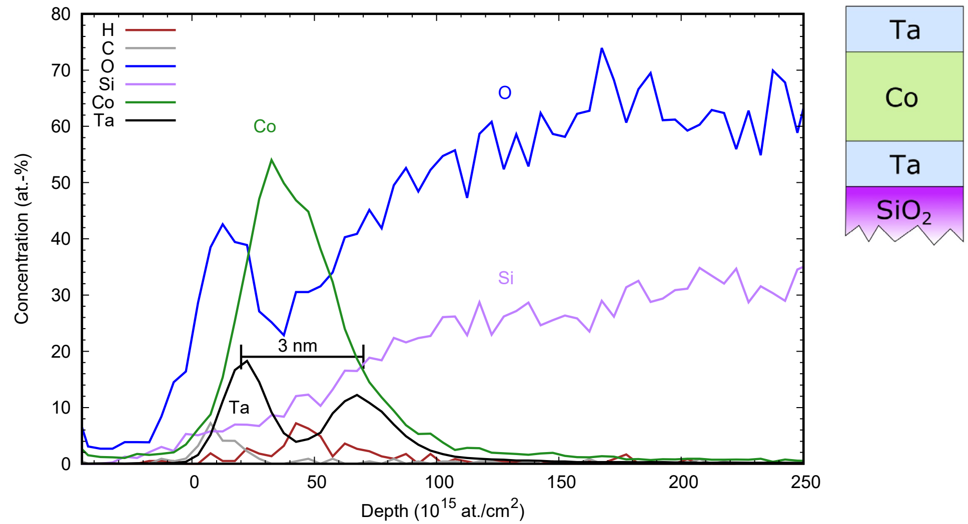
Time-of-Flight Elastic Recoil Detection Analysis





- Time-of-Flight calibration same for all recoils
- Energy detector used in coincidence to identify masses

- Depth resolution at surface – close to 1 nm, degrades deeper in the sample.
- Amount of matter in sample (in units of at./cm^2) can be quantified, concentrations (in at.-%) more accurate.

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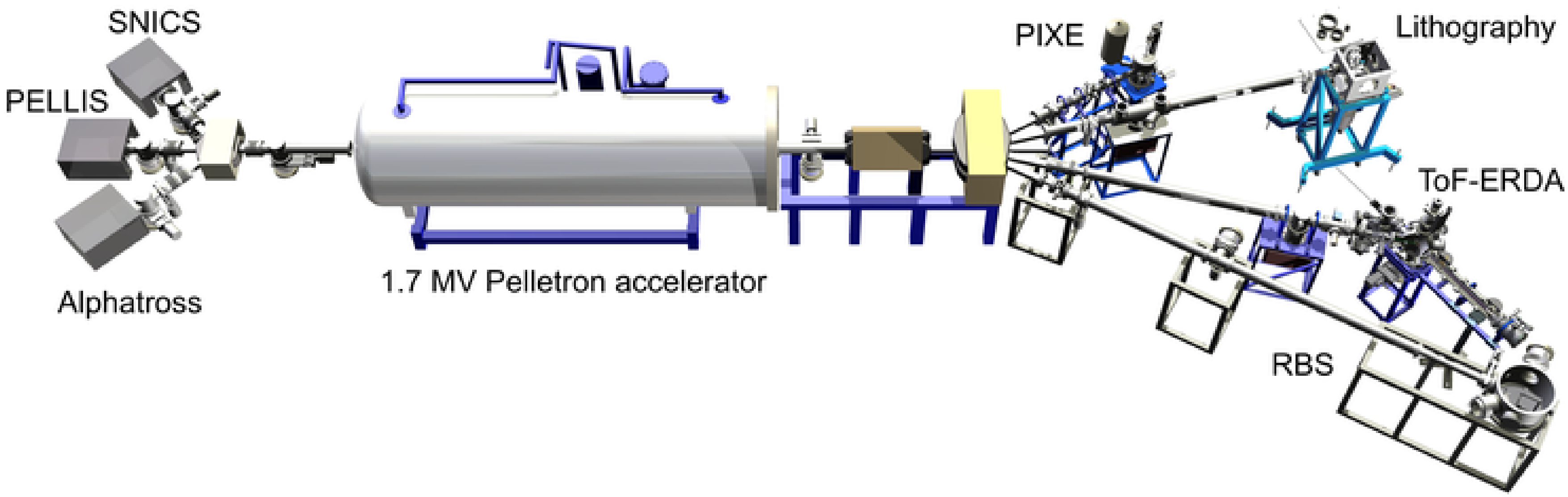
Typical IBA facility

Negative ion source → $X^- ... Z^-$ → m/q-magnet → X^- → Electrostatic accelerator → X^{n+} → m/q magnet → X^{q+} → Sample chamber → recoils → ToF - Energy telescope



Typical IBA beams

IBA method	Beam	Energy
NRA (H)	^{15}N	6.3 – 6.5 MeV
NRA (T)	d	0.2 - 0.7 MeV
NRA (D)	^{3}He	0.5 - 1.5 MeV
RBS	^{4}He	> 1.4 MeV
TOF-ERDA	$^{35/37}Cl$	4 - 10 MeV
TOF-ERDA	$^{79/81}Br$	10 - 15 MeV
TOF-ERDA	^{127}I	13 - 20 MeV

Particle flux on the order of 1 - 10 pnA

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Proposed ToF-ERDA concept

Goals of the proposed ToF-ERDA concept

Replace negative ions with high charge state noble gas positive ions for

- Increased reliability of the ion source
- Reduced operational effort (turn-key system)
- Reduced maintenance effort of the ion source.

Reduce the laboratory footprint of the accelerator

Eliminate the use of SF_6, which is a potent green house gas with an estimated 23900 times the ”global warming potential” of CO_2

Proposed ToF-ERDA beams

Ion	Energy range	Beam current from ion source
$^{35/37}Cl \rightarrow \mathbf{^{40}Ar^{8+}}$	4 - 7 MeV	0.1 – 1.0 µA
$^{79/81}Br \rightarrow \mathbf{^{84}Kr^{17+}}$	10 - 15 MeV	0.2 – 2.2 µA
$^{127}I \rightarrow \mathbf{^{129}Xe^{24+}}$	13 - 20 MeV	0.3 – 3.0 µA

The beam currents are based on simulations of the low energy beam transport, accelerator transport efficiency and energy spread of the high energy beams

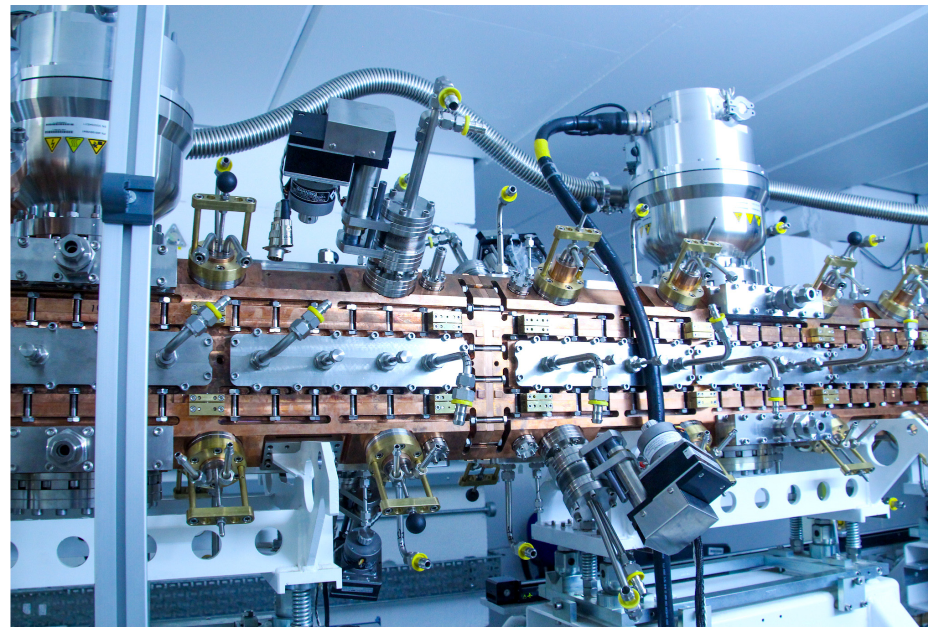
Accelerator options

High voltage platform – DC beam

ITER-NBI 1 MV platform – photo by D. Faircloth

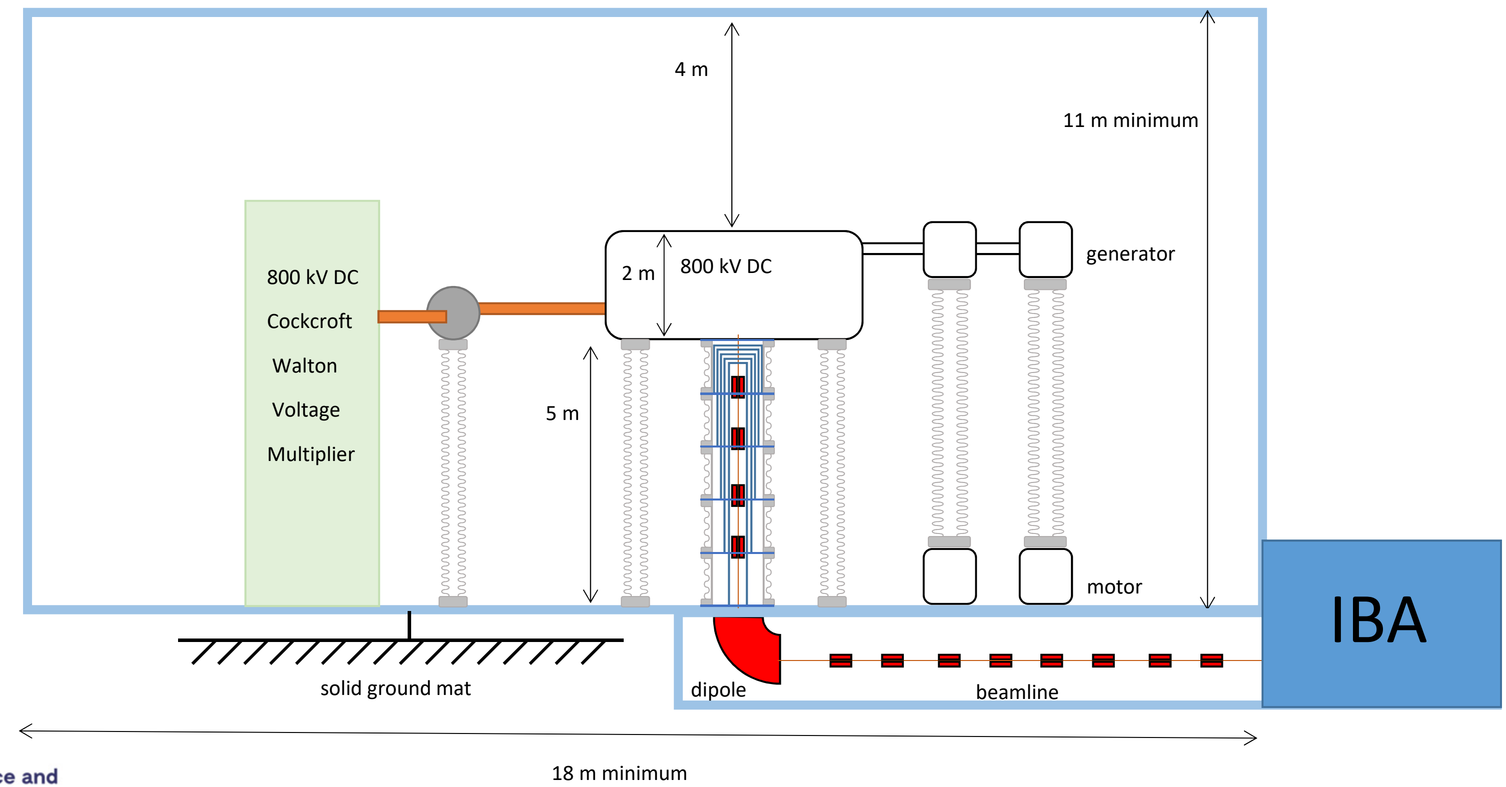
OR

RadioFrequency Quadrupole – Pulsed beam



Front End Test Stand (FETS) RFQ at RAL

SF_6 free 800 kV platform (to enable RBS)



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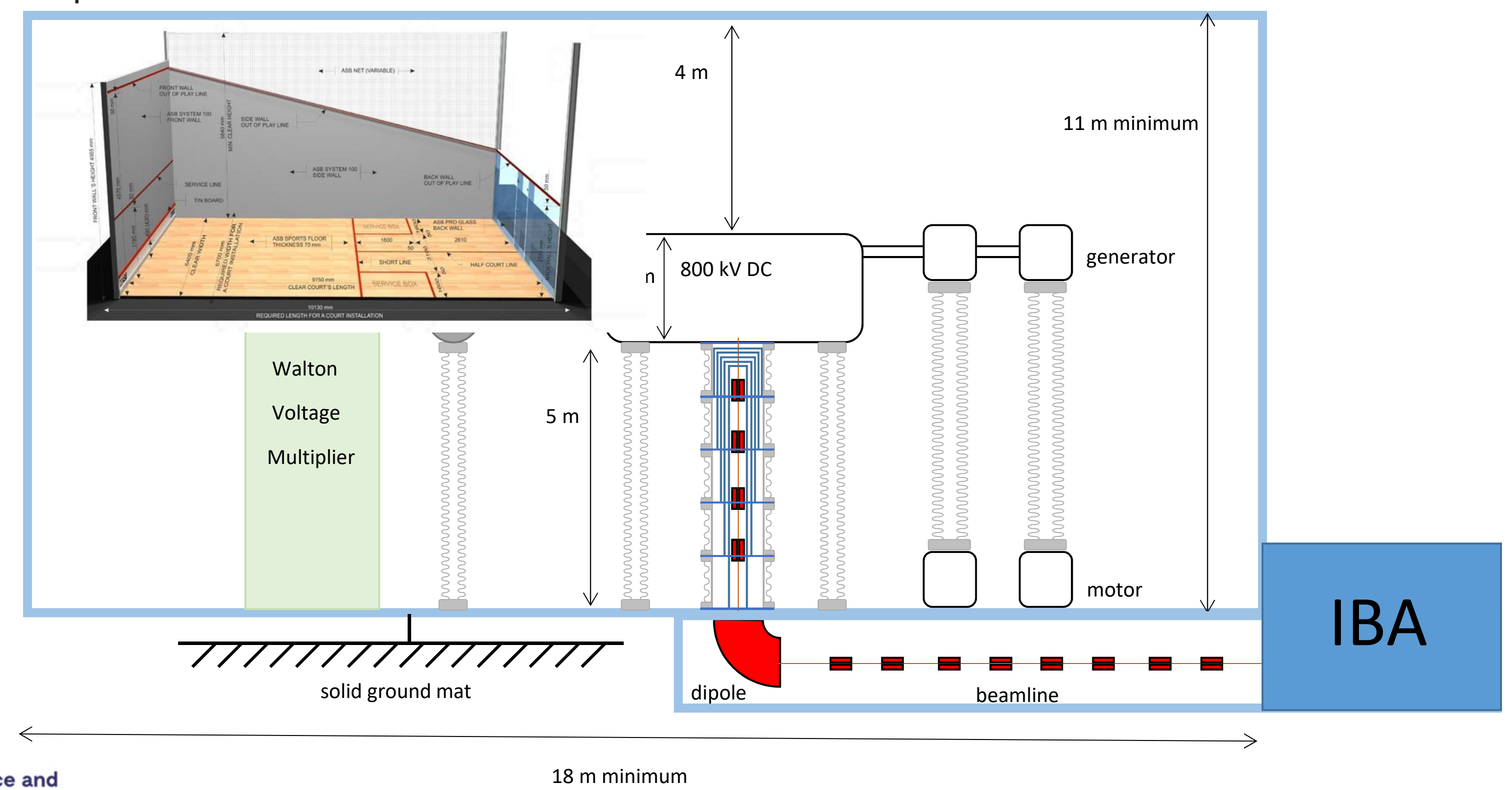
SF_6 free 800 kV platform (to enable RBS)

Squash court: 9.75 m x 6.4 m x 5.64 m



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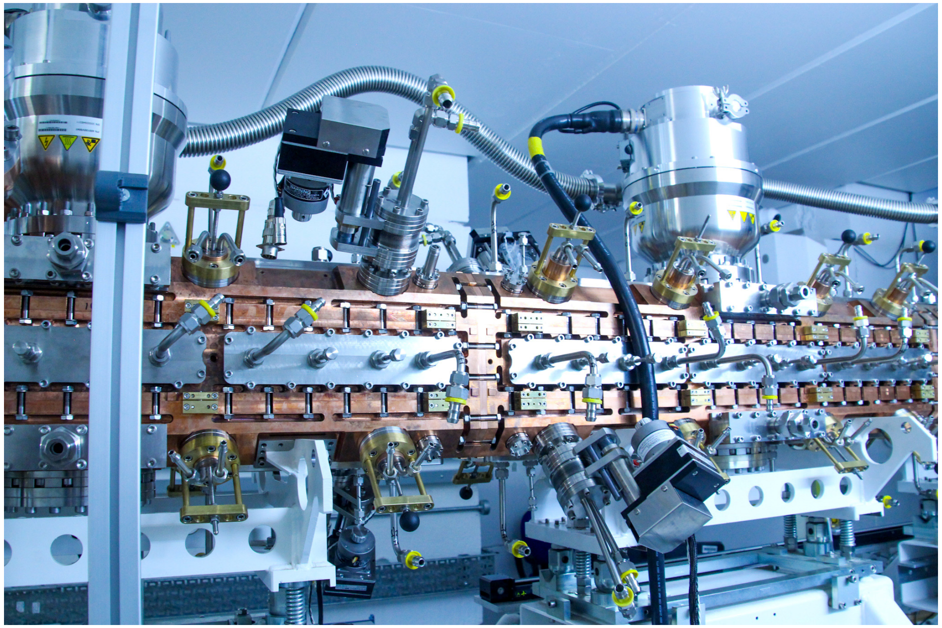
Accelerator options

High voltage platform – DC beam

OR

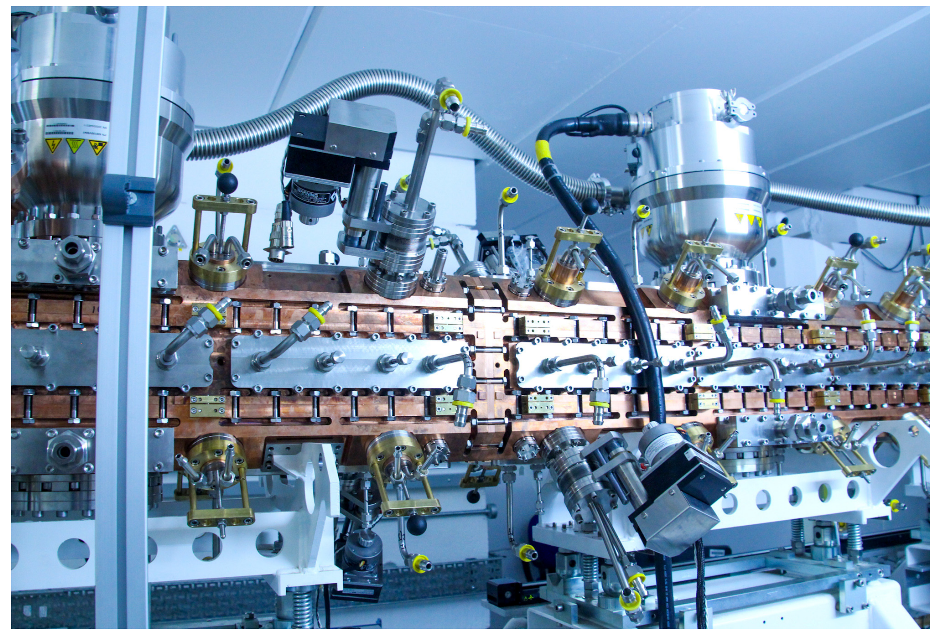
RadioFrequency Quadrupole – Pulsed beam



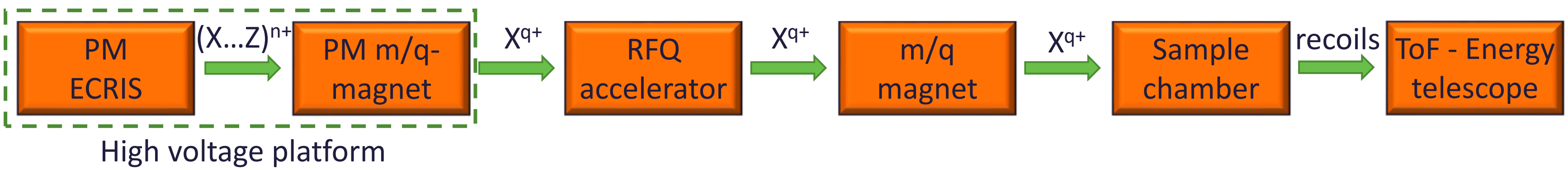
Accelerator options

High voltag… m

RadioFrequency Quadrupole – Pulsed beam

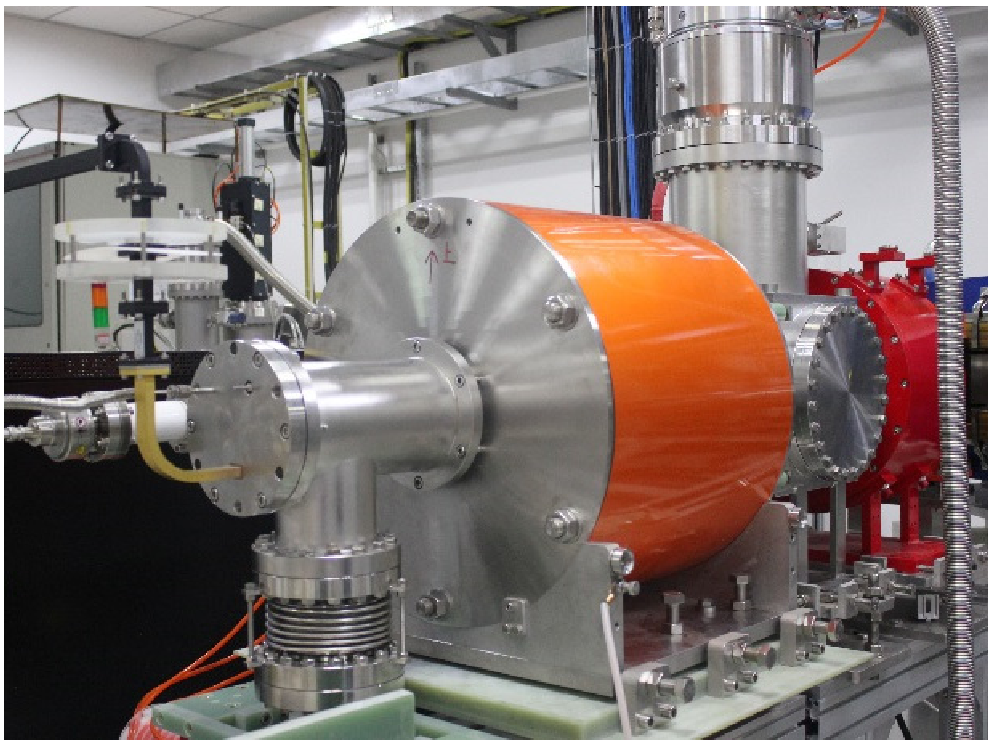


Proposed ToF-ERDA concept



Permanent magnet ECRIS

Example: LAPECR3 – photo courtesy of L. T. Sun



Ion	Beam current from ion source
$^{40}Ar^{8+}$	0.1 – 1.0 μA
$^{84}Kr^{17+}$	0.2 – 2.2 μA
$^{129}Xe^{24+}$	0.3 – 3.0 μA

Literature survey by Kalvas et al. concludes

∴ NO PROBLEM

(https://doi.org/10.1088/1748-0221/15/06/P06016)

Permanent magnet CUBE- ECRIS

Jinst

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Design of a 10 GHz minimum-B quadrupole permanent magnet electron cyclotron resonance ion source

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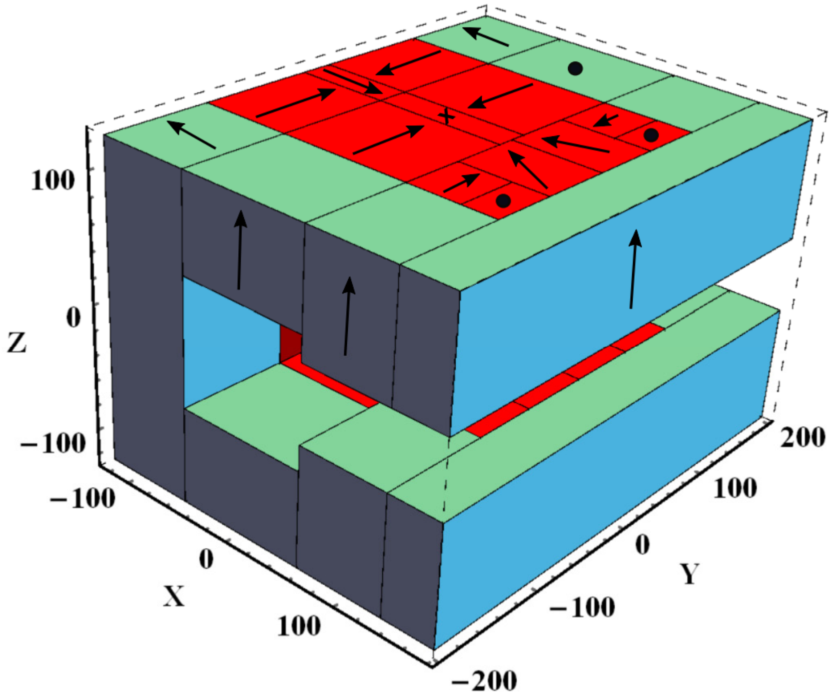
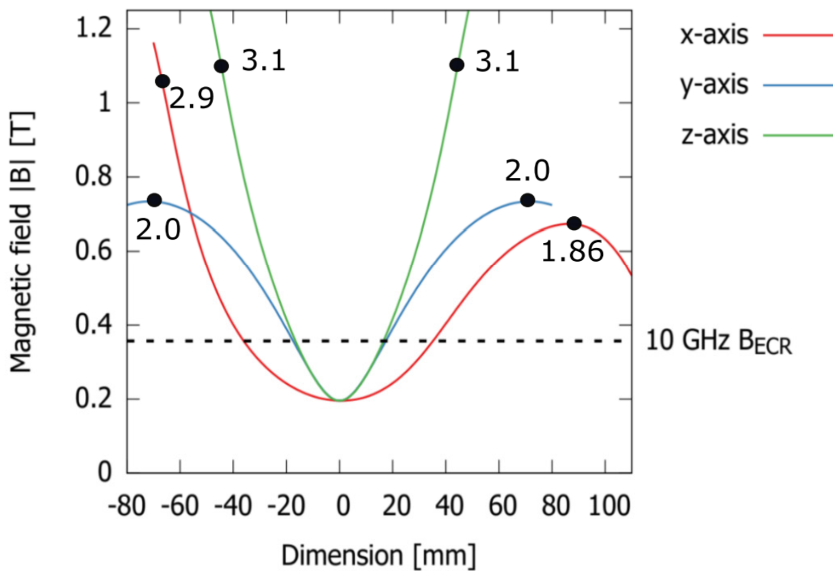
[b] *ISIS pulsed neutron and muon source, U.K. Research and Innovation, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Chilton OX11 0QX, U.K.*

The following CUBE-ECRIS simulation results are from this paper

Permanent magnet CUBE- ECRIS B-field





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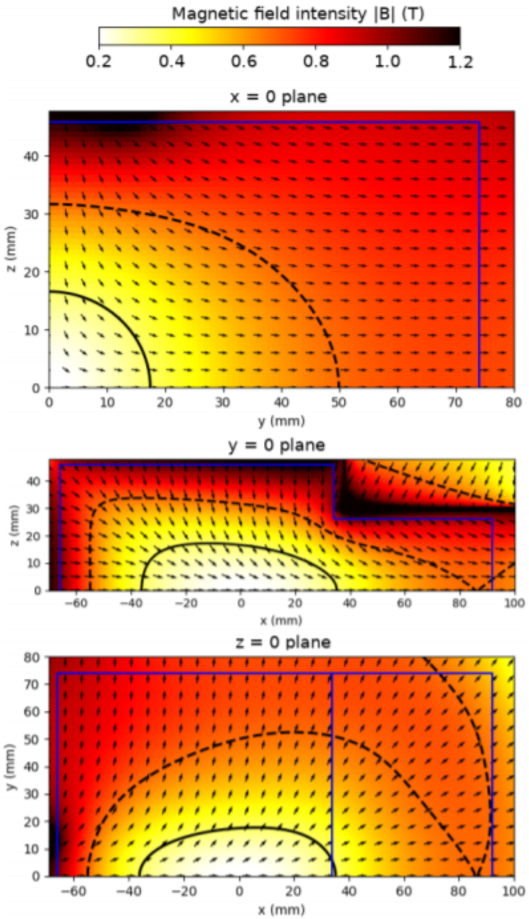
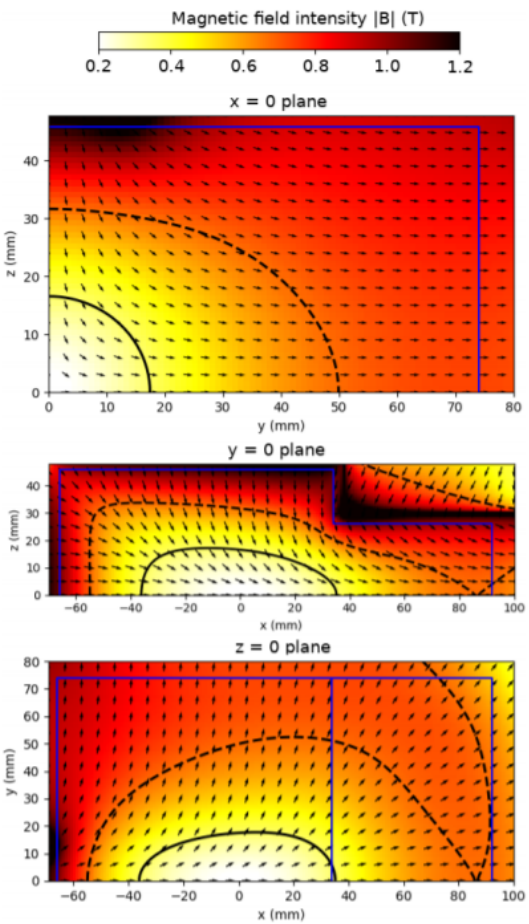
Quadrupole minimum-B structure with very simple PM array fulfilling the scaling laws (if applicable)

Permanent magnet CUBE- ECRIS not only for IBA



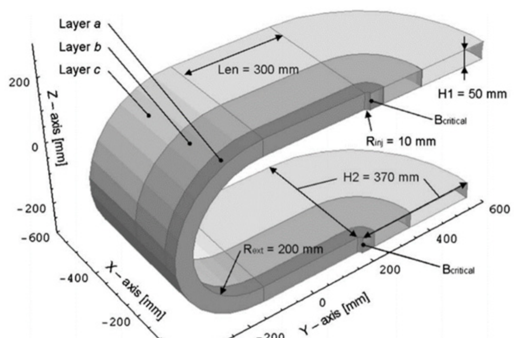
Permanent magnet CUBE- ECRIS not only for IBA



Electron cyclotron resonance ion sources with arc-shaped coils

Cite as: Rev. Sci. Instrum. **79**, 02A305 (2008); https://doi.org/10.1063/1.2805209
Submitted: 15 August 2007 . Accepted: 04 October 2007 . Published Online: 30 January 2008

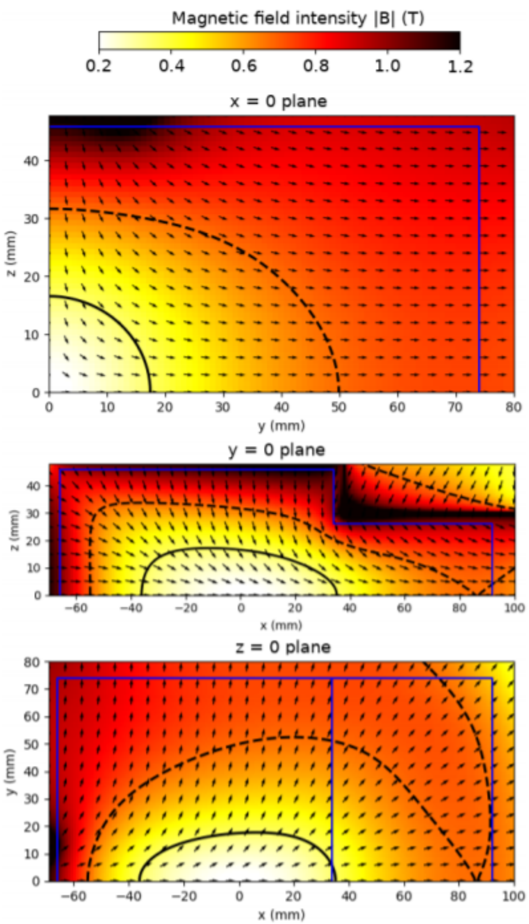
P. Suominen, and F. Wenander



Coordinates	X	Y	Z
B_{inj}	0	$-Len/2-R_{ext}$	0
B_{min}	0	0	0
B_{ext}	0	$Len/2+R_{inj}+H2/2$	0
B_{radX}	$\pm(R_{inj}+H2/2)$	0	0
B_{radZ}	0	0	$\pm(R_{ext})$
$B_{critical}$	0	$Len/2+R_{inj}$	$\pm(R_{ext}+H1/2)$

The minimum-B magnetic field structure of electron cyclotron resonance ion sources (ECRIS) has conventionally been formed with a combination of solenoids and a hexapole magnet. However, minimum-B structure can also be formed with arc-shaped coils. Recently it was shown that multiply charged heavy-ions can be produced with an ECRIS based on such a structure. In the future, the ARC-ECRIS magnetic field structure can be an interesting option for radioactive ion-beam sources and charge-breeders as well as for high performance ECRIS allowing for 100 GHz plasma heating. This paper presents some design aspects of the ARC-ECRIS. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2805209]

Permanent magnet CUBE- ECRIS not only for IBA



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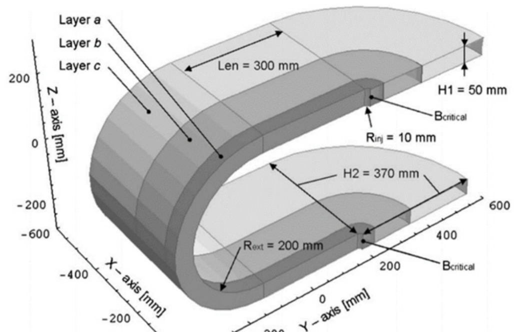


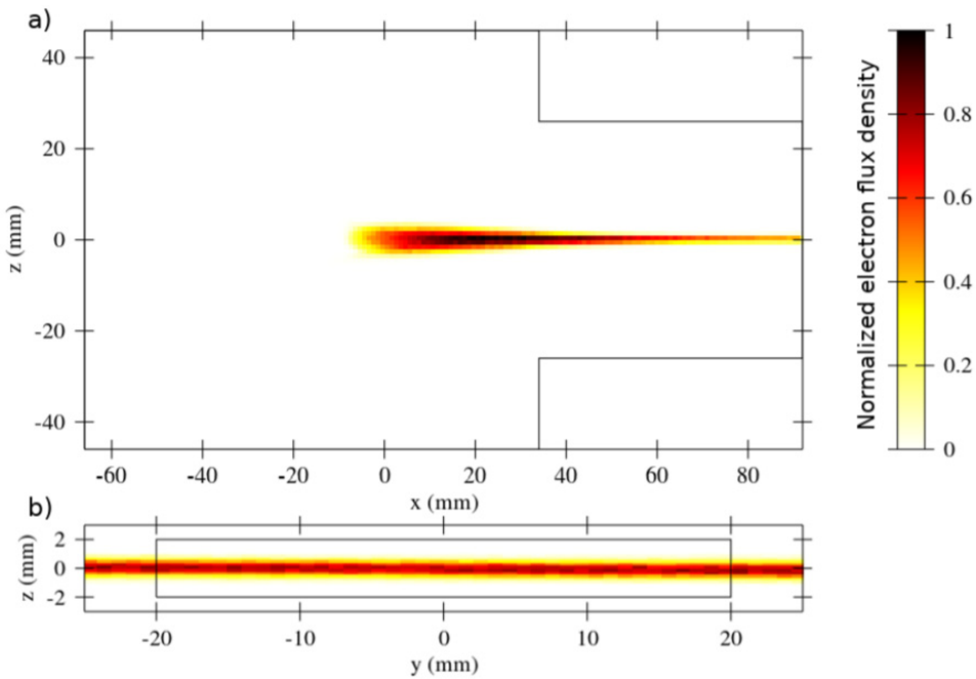
Coordinates	X	Y	Z
B_{inj}	0	-Len/2-R_{ext}	0
B_{min}	0	0	0
B_{ext}	0	Len/2+R_{inj}+H2/2	0
B_{radX}	±(R_{inj}+H2/2)	0	0
B_{radZ}	0	0	±(R_{ext})
$B_{critical}$	0	Len/2+R_{inj}	±(R_{ext}+H1/2)

The minimum-B magnetic field structure of electron cyclotron resonance ion sources (ECRIS) has conventionally been formed with a combination of solenoids and a hexapole magnet. However, minimum-B structure can also be formed with arc-shaped coils. Recently it was shown that multiply charged heavy-ions can be produced with an ECRIS based on such a structure. In the future, the ARC-ECRIS magnetic field structure can be an interesting option for radioactive ion-beam sources and charge-breeders as well as for high performance ECRIS allowing for 100 GHz plasma heating. This paper presents some design aspects of the ARC-ECRIS.

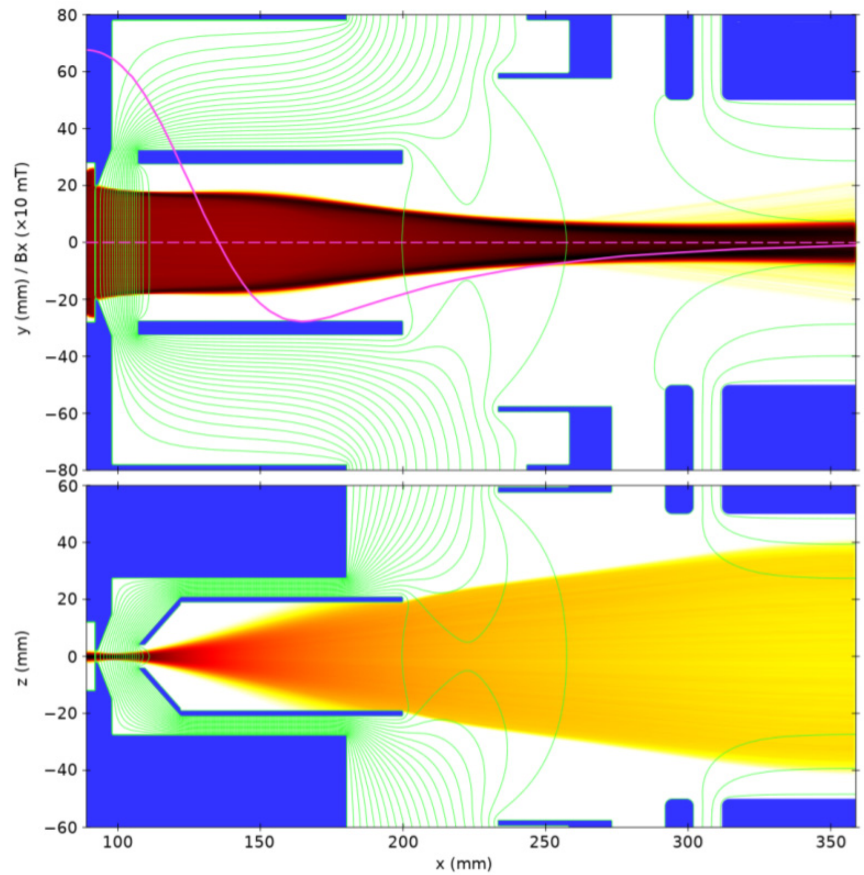
 [DOI: 10.1063/1.2805209]

100 GHz!

Permanent magnet CUBE- ECRIS – plasma flux and extraction



IBSimu result for Ar^{8+} / 10 kV extraction



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Permanent magnet CUBE- ECRIS – status

Magnet assembly completed (September 2020)

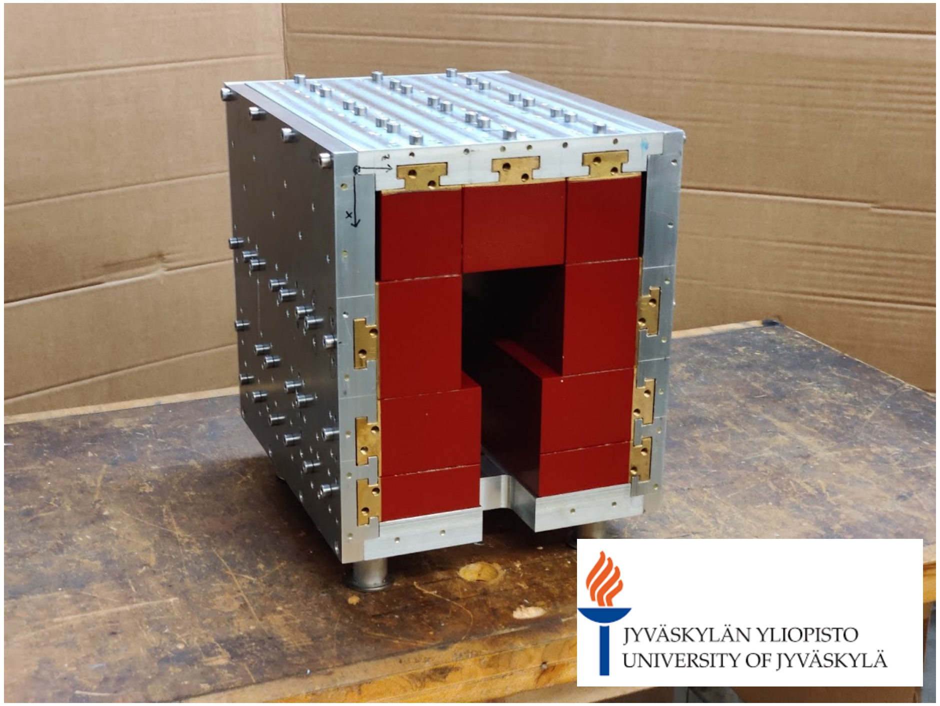

Photo courtesy of Ville Toivanen and Hannu Koivisto
Further details in the presentation of M. Marttinen
(Tuesday 15:15 – 16:20 session)

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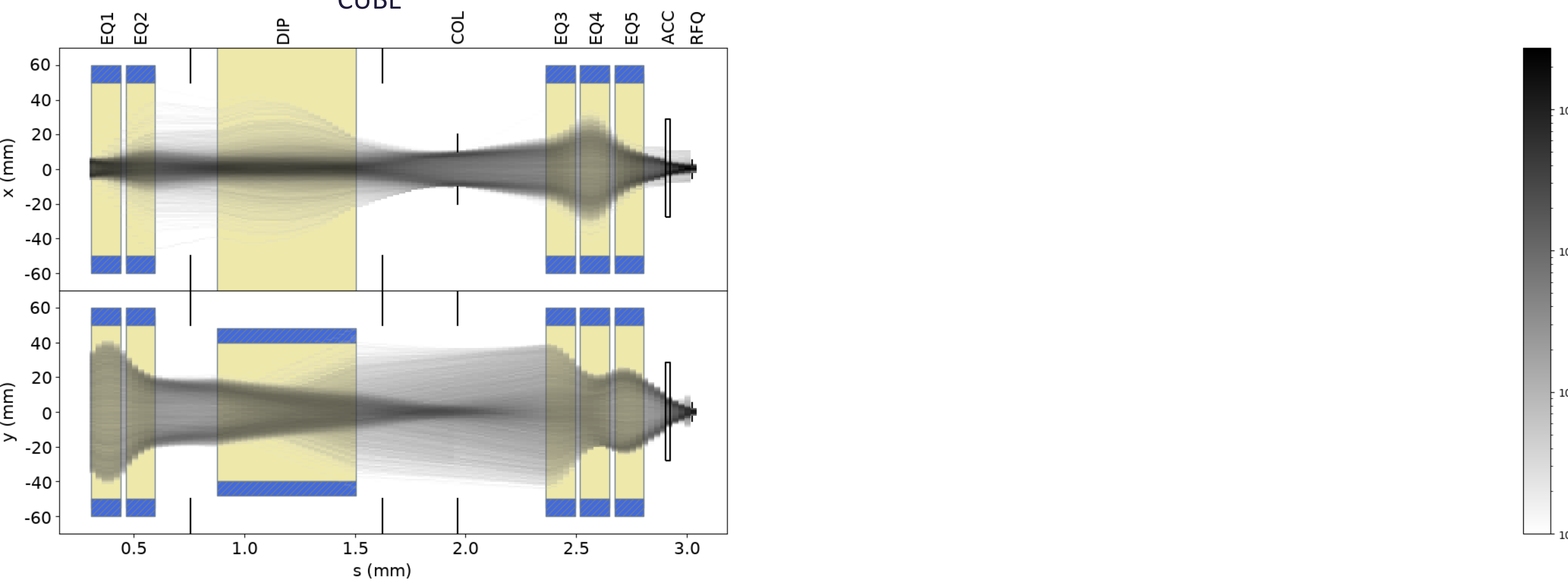
LEBT design – two options

CUBE



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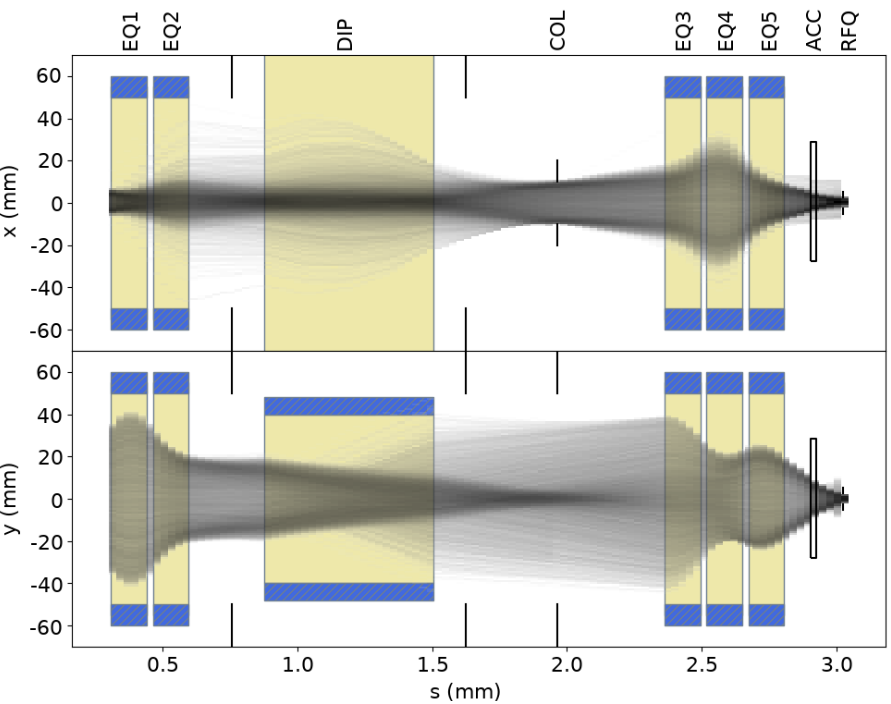
~ 95 % transmission efficiency (similar to the CUBE prototype beamline)

T. Kalvas, J. Saren and W. Gins, "PIOL – Python-driven Ion Optics Library"

LEBT design



Ion	Ion source potential
$^{40}Ar^{8+}$	18.7 – 32.9 kV
$^{84}Kr^{17+}$	22.0 – 33.1 kV
$^{129}Xe^{24+}$	20.3 – 31.3 kV

These ion beams have very similar m/q.

PM dipole and selection of the ion species by small adjustment of the extraction voltage.

The final energy at the RFQ injection is set by the platform voltage

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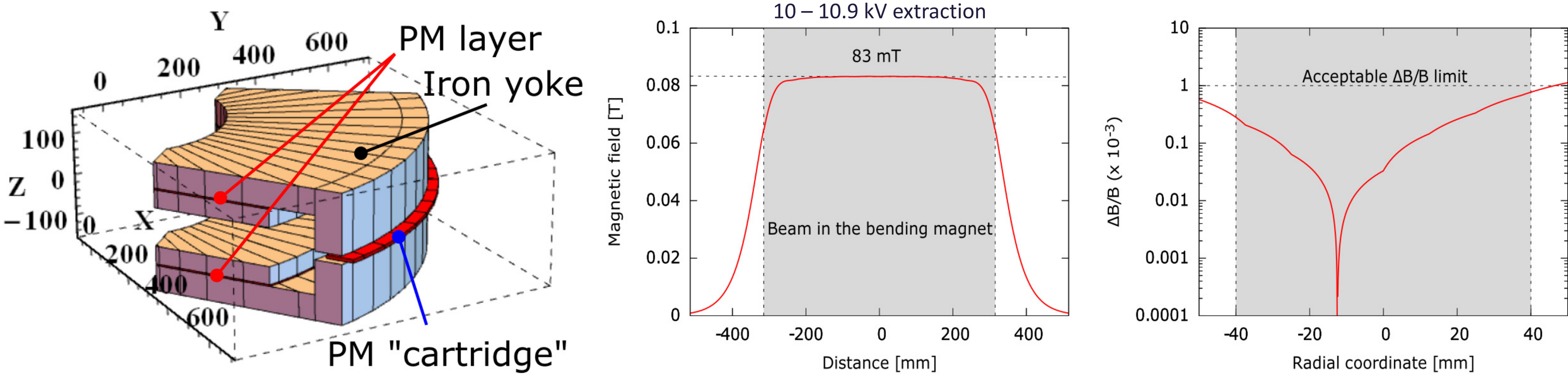
PM dipole



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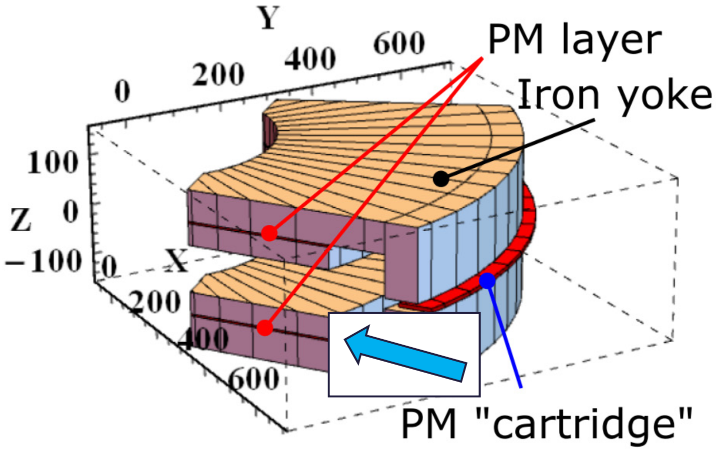
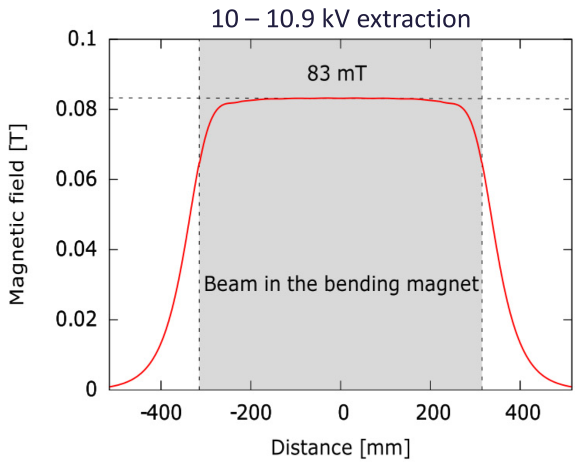
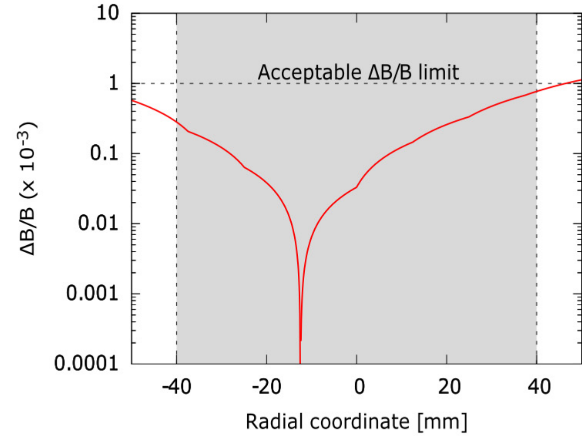
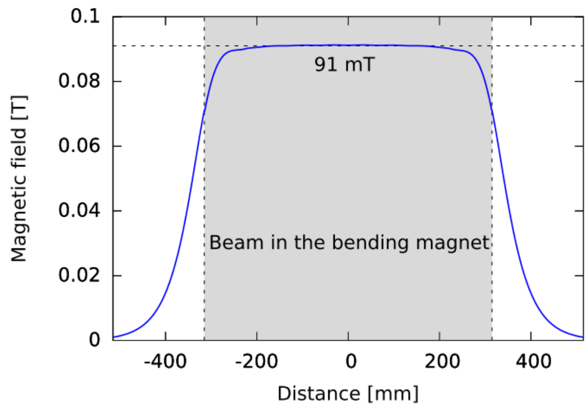
PM dipole









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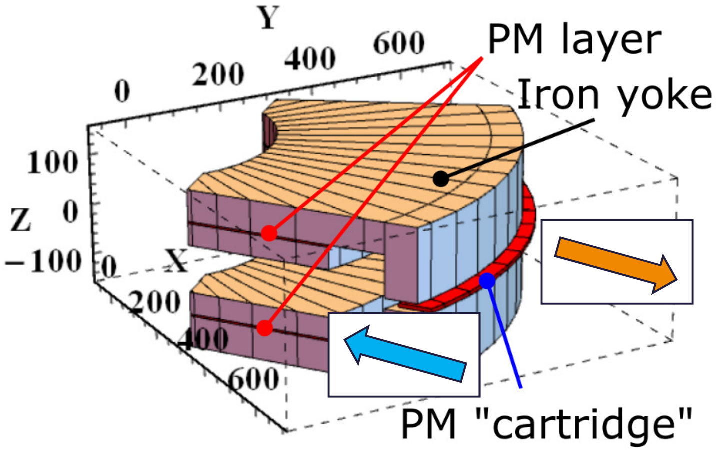
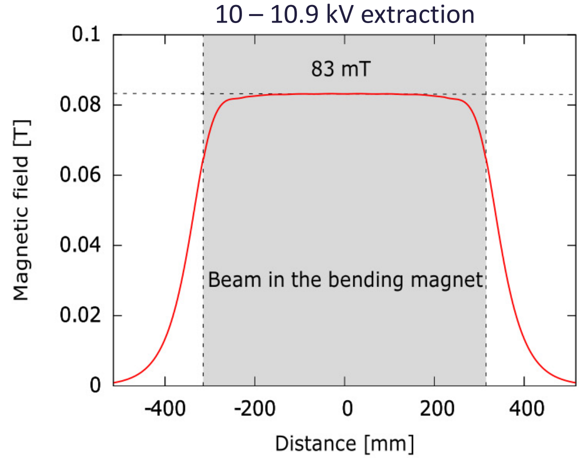
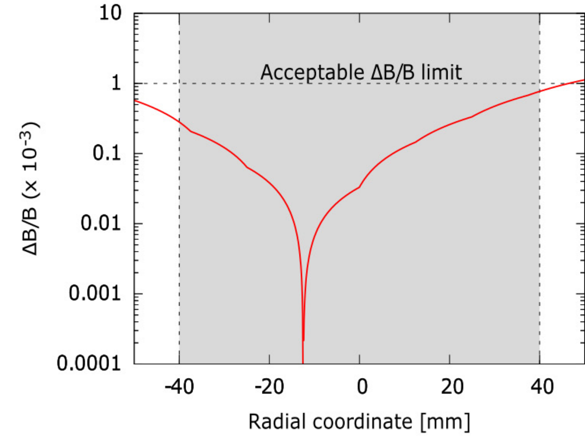
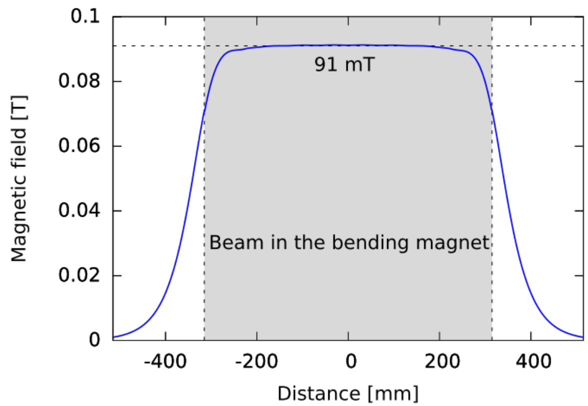
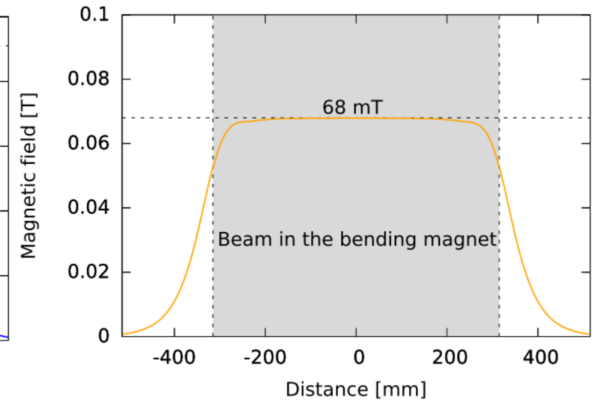
PM dipole











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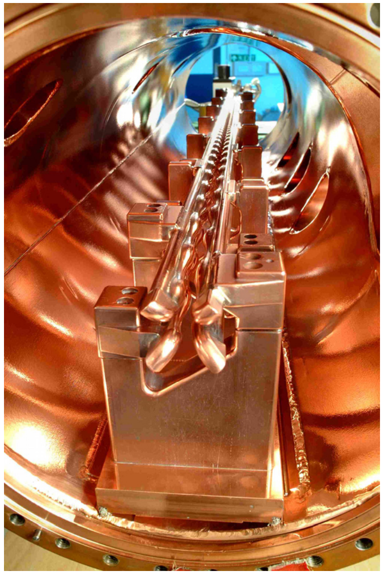
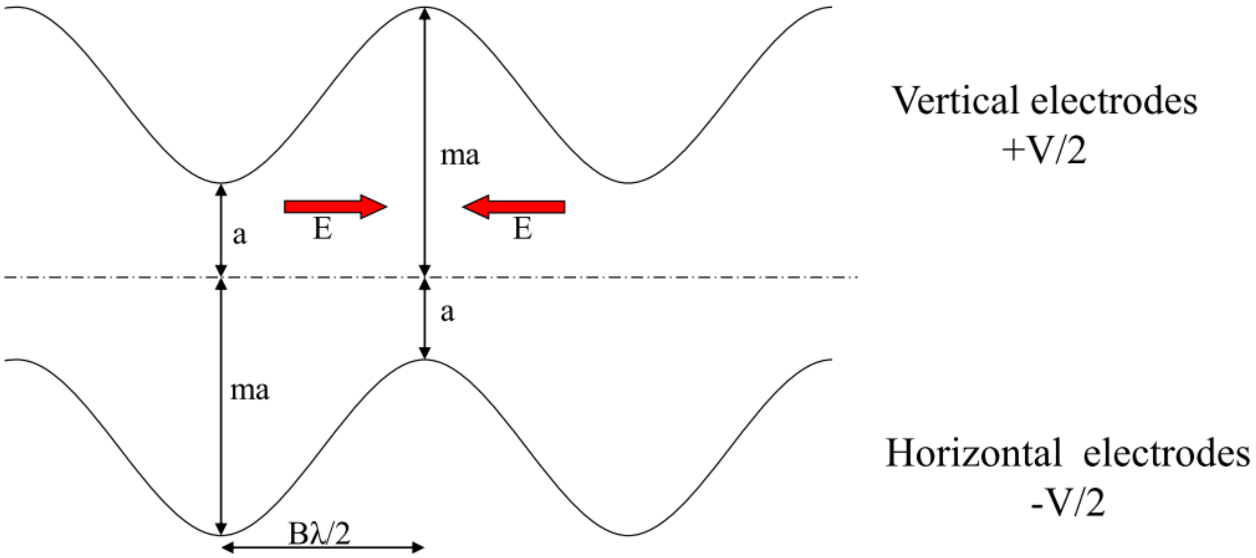
Why variable frequency?



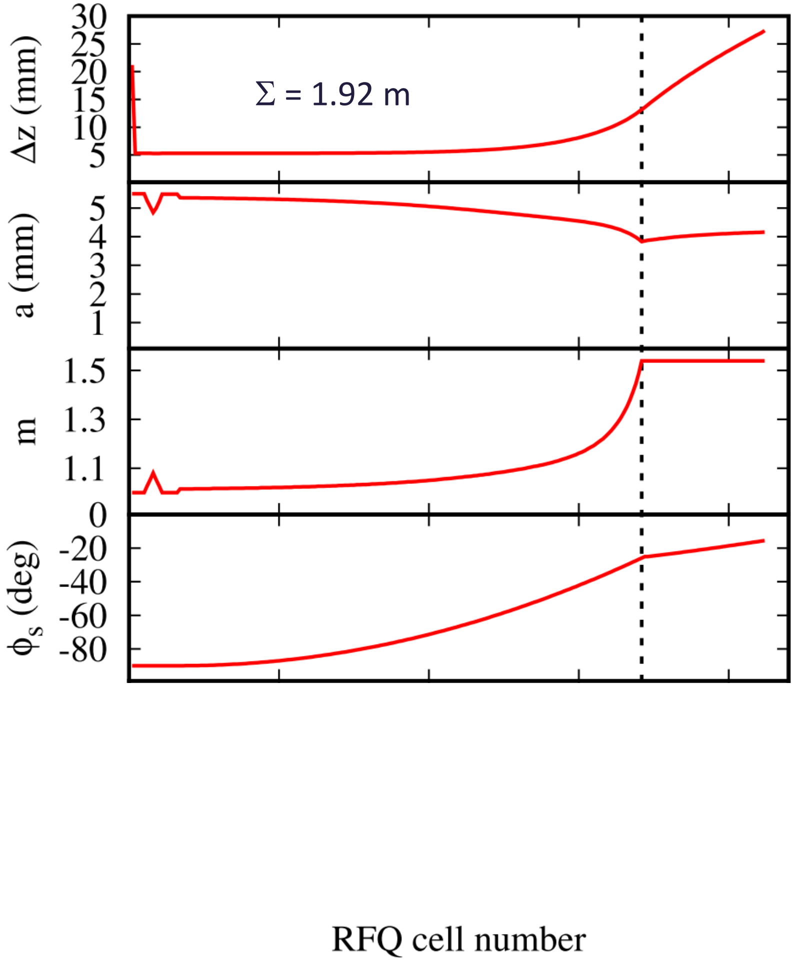


The RFQ uses a time-varying electric field to both focus and accelerate ions.

The RFQ is a synchronous accelerator which means that ions to be accelerated must always have their velocity synchronous with the structure and time varying field.

In order to achieve energy variability the RFQ has to be able to operate at a range of RF frequencies, in this case **79 – 107 MHz**.

Variable frequency RFQ – beam dynamics design



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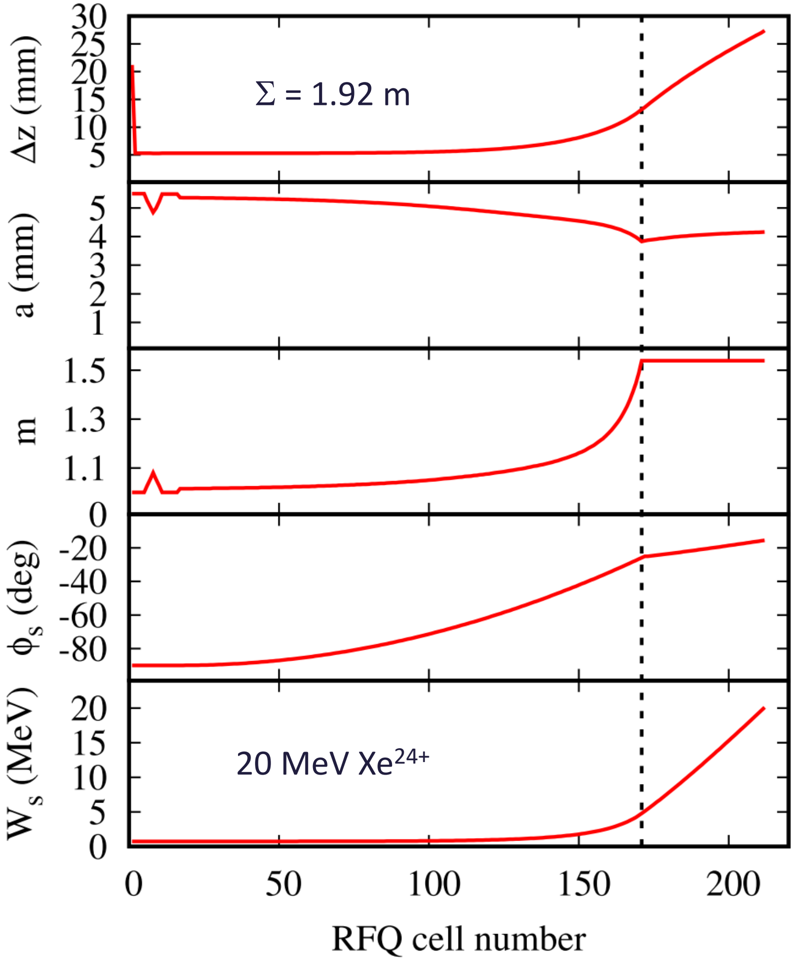
Variable frequency RFQ – beam dynamics design



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Variable frequency RFQ – two implications for ToF-ERDA

Pulsed beam:

The beam at the sample will be pulsed contrary to electrostatic accelerators.

At 100 MHz frequency the beam pulses are approximately 2 ns arriving every 10 ns.

It turns out that with typical ToF-ERDA spectrometer design the beam can be considered semi-continuous as the recoils from each beam pulse hitting the first timing gate will overlap.

Variable frequency RFQ – two implications for ToF-ERDA

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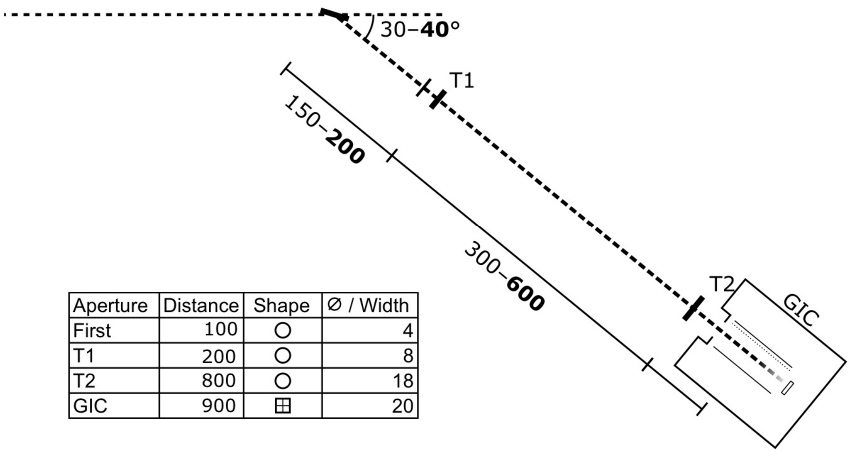
It turns out that with typical ToF-ERDA spectrometer design the beam can be considered semi-continuous as the recoils from each beam pulse hitting the first timing gate will overlap.

Energy spread:

The energy spread of the beam incident on the sample affects the resolution.

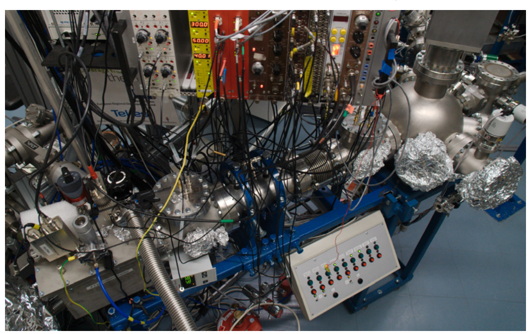
A spectrometer design was simulated to set the limit for acceptable $\Delta E/E$

Time-of-Flight spectrometer



Aperture	Distance	Shape	⌀ / Width
First	100	○	4
T1	200	○	8
T2	800	○	18
GIC	900	⊞	20

Ion	**E** MeV	^{1}H %	^{16}O %	^{28}Si %	^{197}Au (sc.) %
$^{40}Ar^{8+}$	4	0.56	0.41	0.39	0.31
$^{40}Ar^{8+}$	7	0.53	0.42	0.39	0.33
$^{84}Kr^{17+}$	10	0.54	0.42	0.39	0.29
$^{84}Kr^{17+}$	15	0.54	0.46	0.42	0.31
$^{129}Xe^{24+}$	13	0.56	0.41	0.39	0.27
$^{129}Xe^{24+}$	20	0.53	0.45	0.42	0.28



Spectrometer energy resolution for **surface** recoils (and scattered beam)

- Detector and electronics timing resolution (200 ps)
- Energy loss straggling in 2 μg/cm^2 T1 carbon foil
- Position resolution – changing recoiling angle affects kinematics

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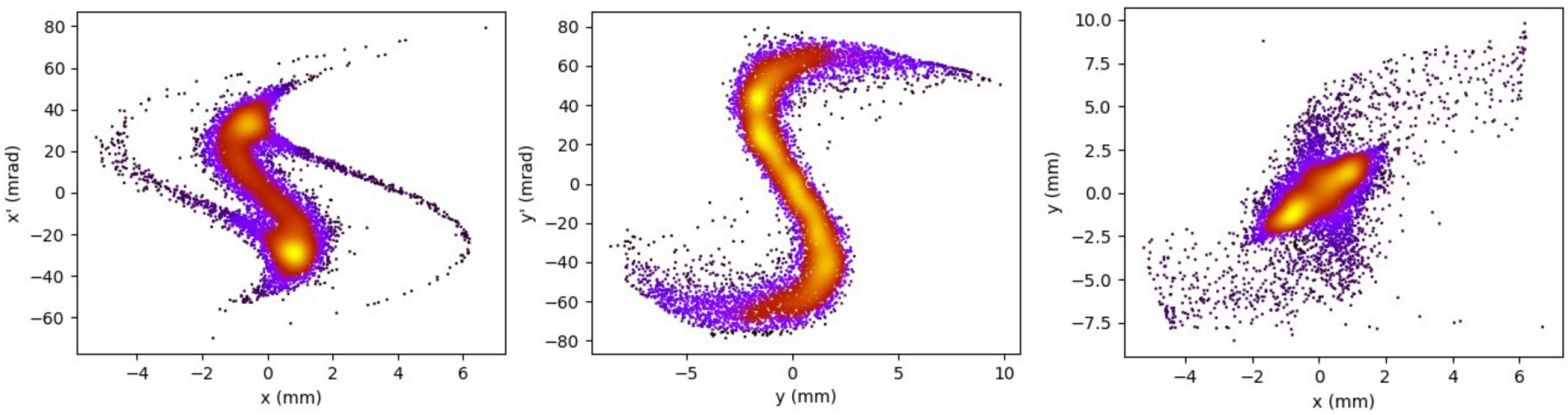
RFQ particle tracking

CUBE LEBT output particle distributions for Ar^{8+} with 7 MeV final energy



→ Total transmission and transmission within required ΔE/E through the RFQ

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RFQ operational parameters and transport efficiency CUBE and (conventional ECRIS)

Ion	E [MeV]	f [MHz]	V_{vane} [kV]	V_{source} [kV]	η [%]	$\Delta E/E < 0.5$ %	$\Delta E/E < 0.2$ %
$^{40}Ar^{8+}$	4	79.687	56.7	18.75	69 (84)	23 (29)	9 (11)
$^{40}Ar^{8+}$	7	105.416	63.0	32.81	76 (93)	25 (29)	9 (9)
$^{84}Kr^{17+}$	10	86.946	42.4	22.06	70 (87)	20 (27)	8 (13)
$^{84}Kr^{17+}$	15	106.486	63.5	33.09	76 (93)	21 (28)	9 (13)
$^{129}Xe^{24+}$	13	79.995	39.0	20.31	70 (81)	22 (29)	8 (13)
$^{129}Xe^{24+}$	20	99.222	60.0	31.25	70 (87)	25 (29)	8 (10)

RFQ operational parameters and transport efficiency CUBE and (conventional ECRIS)

Ion	E [MeV]	f [MHz]	V_{vane} [kV]	V_{source} [kV]	η [%]	ΔE/E < 0.5 %	ΔE/E < 0.2 %
$^{40}Ar^{8+}$	4	79.687	56.7	18.75	69 (84)	23 (29)	9 (11)
$^{40}Ar^{8+}$	7	105.416	63.0	32.81	76 (93)	25 (29)	9 (9)
$^{84}Kr^{17+}$	10	86.946	42.4	22.06	70 (87)	20 (27)	8 (13)
$^{84}Kr^{17+}$	15	106.486	63.5	33.09	76 (93)	21 (28)	9 (13)
$^{129}Xe^{24+}$	13	79.995	39.0	20.31	70 (81)	22 (29)	8 (13)
$^{129}Xe^{24+}$	20	99.222	60.0	31.25	70 (87)	25 (29)	8 (10)

Required ΔE/E somewhere between these values, only small difference between CUBE and conventional ECRIS.
The high-energy beamline must have a dipole magnet and slits to control the energy spread.

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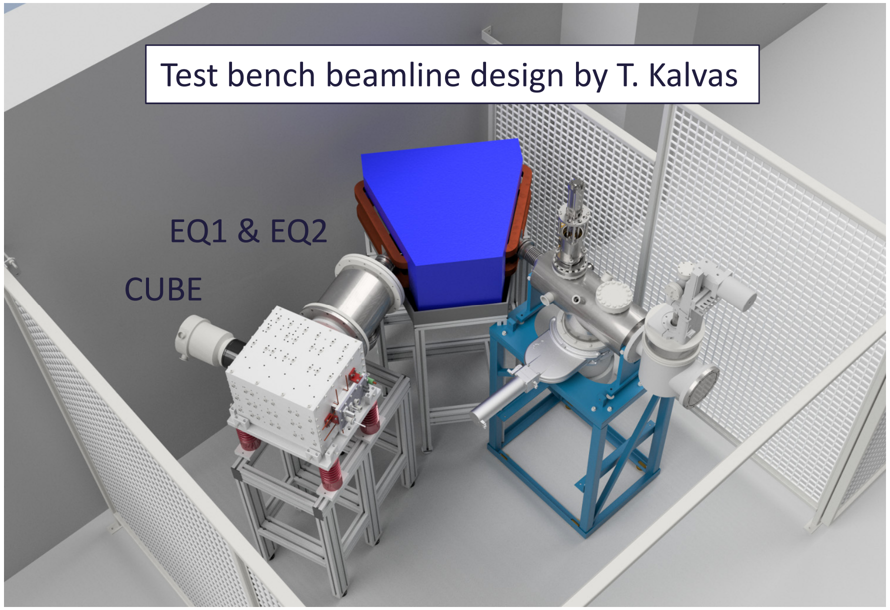
Outlook

Project status

National Thin Film Deposition and Characterisation Centre –proposal is under review by STFC International Advisory Committee

The CUBE-ECRIS assembly and commissioning underway at JYFL – see M. Marttinen et al. (Tuesday 15:15 – 16:20 session)

The LEBT of CUBE-ECRIS test bench at JYFL consists of electrostatic quadrupoles and a dipole magnet loaned from GANIL.



The goal is to demonstrate:

Ion	Beam current from ion source
$^{40}Ar^{8+}$	0.1 – 1.0 μA
$^{84}Kr^{17+}$	0.2 – 2.2 μA
$^{129}Xe^{24+}$	0.3 – 3.0 μA

The development of high frequency ECR in sources has been pivotal for the renaissance of nuclear physics over the past decades.

Only few of us enjoy the privilege of pushing the performance limits of ECR ion sources with 4^{th} generation superconducting devices.

We need to test bold concepts and develop new applications.

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Contributions and acknowledgements

Olli Tarvainen

CUBE-ECRIS B-field and PM dipole

Alan Letchford

Variable frequency RFQ design and simulations

Dan Faircloth

HV platform concept

Taneli Kalvas

CUBE-ECRIS extraction and LEBT

Jaakko Julin

ToF-ERDA simulations

Hannu Koivisto

Ville Toivanen

CUBE-ECRIS assembly and commissioning – stay tuned in 2021

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Thank You for listening – time for questions

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