Workshop on Advanced Laser and Mass Spectroscopy
ALMAS-1: Innovative Physics Ideas
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Superfluid helium and cryogenic noble gases as stopping media for ion catchers

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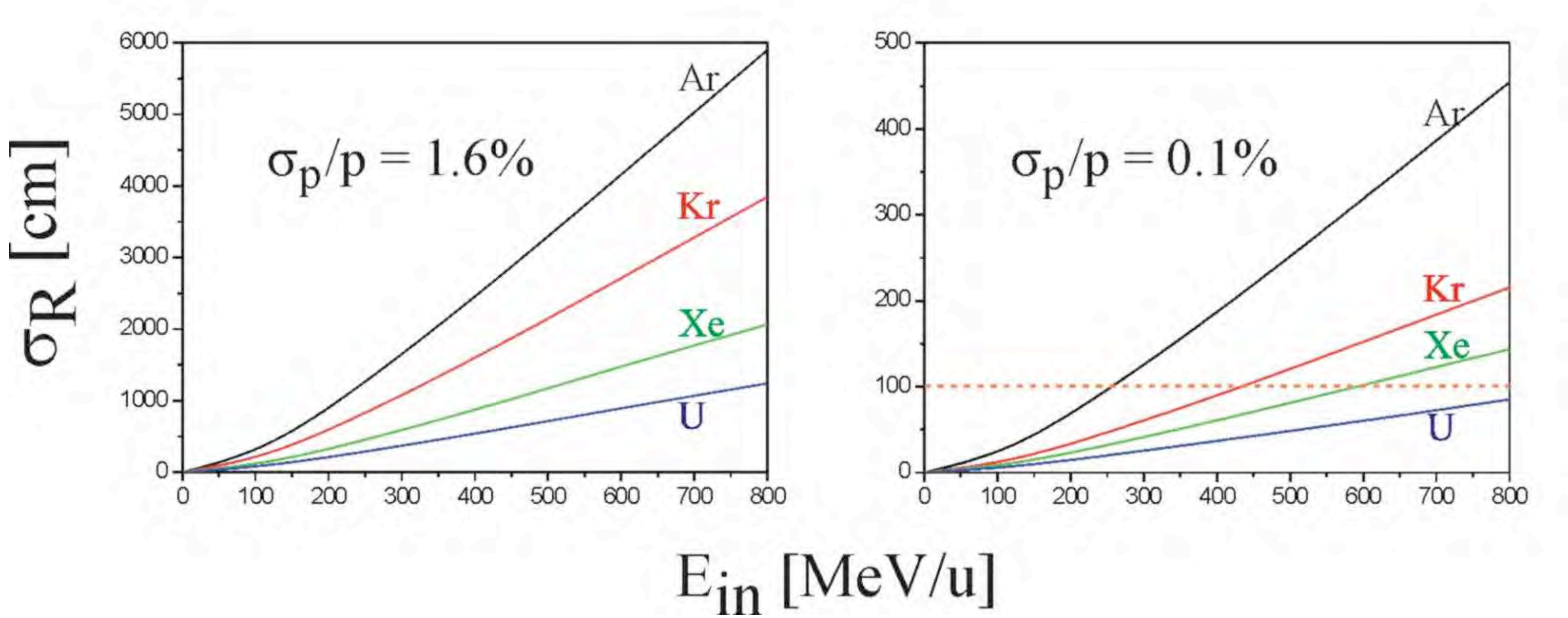
  - high-density stopping media
- Results & Status
  - superfluid helium
  - cryogenic gas
- Summary & Outlook

Required stopper thickness

range straggling (σ_R) of fragment beams in 1 bar helium at room temperature
(from C. Scheidenberger et al.)

with range bunching

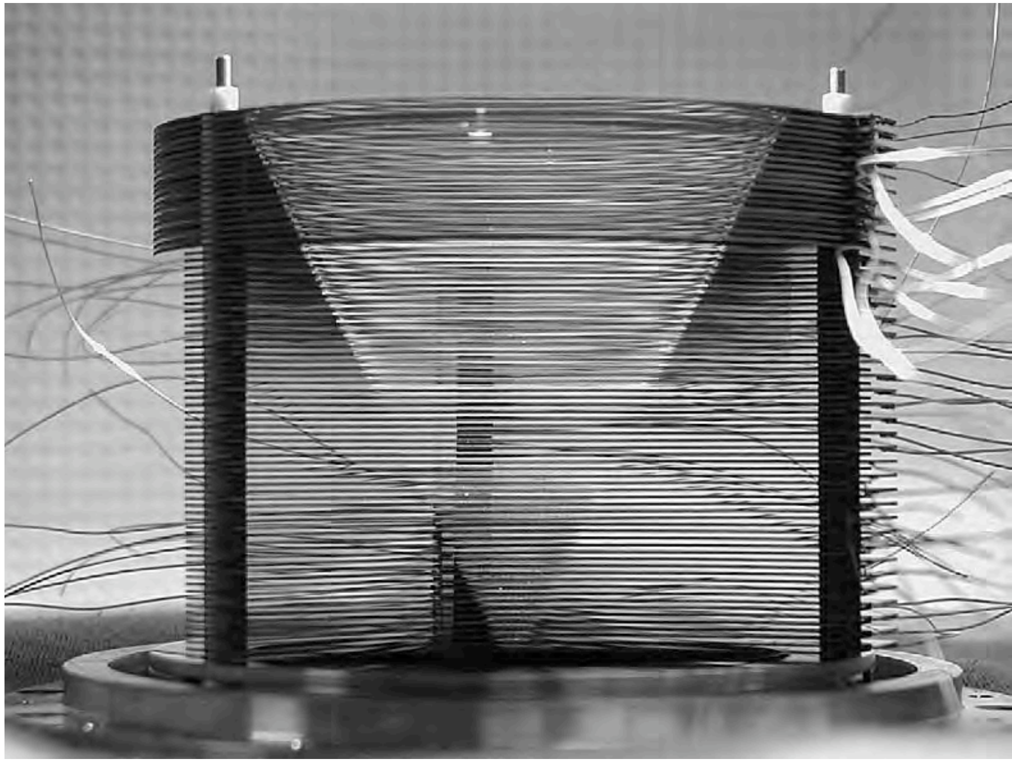


$$\frac{\text{maximum useful energy}}{\text{stopping power}} \approx \text{element - independent}$$

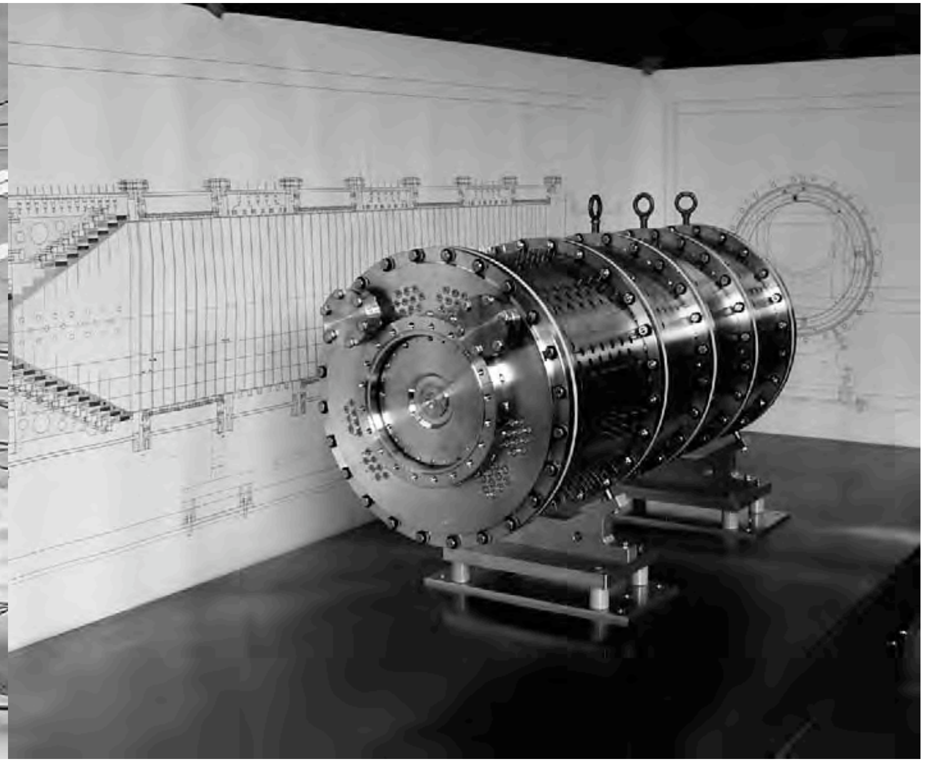
same σ_R for all ions ≈ 1 meter bar helium

1 meter bar is not trivial

UHV compatible - bakeable - helium purification < ppb

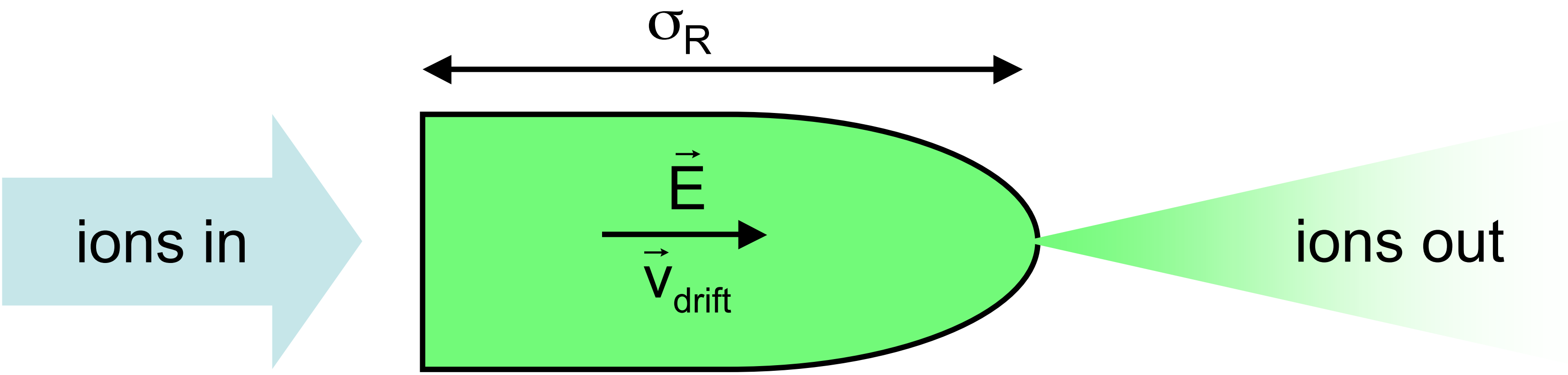


Prototype “Argonne/GSI”
G. Savard et al., NIM B 204 (2003) 582



1.2 m long, I.D. 25 cm
7300 parts (>4000 UHV)

Figures of merit: $\mu \times \rho$, $\mu \times \rho^2$



$$T_{ev} = \frac{\sigma_R}{v_{drift}} = \frac{\sigma_R}{\mu \times E}$$

$$\sigma_R \propto \frac{1}{\rho}$$

constant E $\quad T_{ev} \propto \dfrac{1}{\mu \times \rho}$

$$E = \frac{V}{\sigma_R}$$

constant V $\quad T_{ev} \propto \dfrac{1}{\mu \times \rho^2}$

Note: μ decreases for high E !

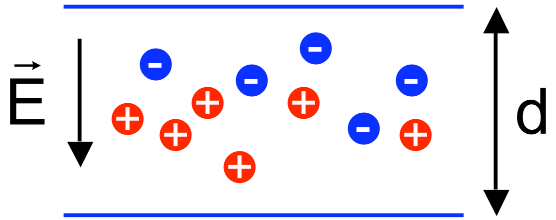
Figures of merit: the numbers

	T (K)	ρ (mg/cm^3)	$\mu \times \rho$ (rel.)	$\mu \times \rho^2$ (rel.)
1 bar He gas	293	0.17	1	1
1 bar He gas	77	0.65	1	3.8
1 bar He gas	4.2	11.9	1	**70**
liquid He	4.2	125	1.3	(735)
superfluid He	1.2	145	**65#**	#

SF He: Landau critical velocity (20 m/s) perpendicular extraction over several cm in a few ms

Recombination loss - f

important loss factor: 3-body recombination **$X^+ + e^- + He \rightarrow X + He$**



$$f = \frac{Q\,\alpha\,d^2}{6\,v_-\,v_+}$$

$$v = \mu\,E$$

Q : ionisation rate (ion-e^- pairs /cm^3 /s)
α: recombination coefficient (cm^3/s)
v_-, v_+ : drift velocity e^-, ion (cm/s)
μ : mobility (cm^2 V/s)
E : electric field (V/cm)
T : temperature (K)
P : pressure (bar)
n : atom density (/cm^3)

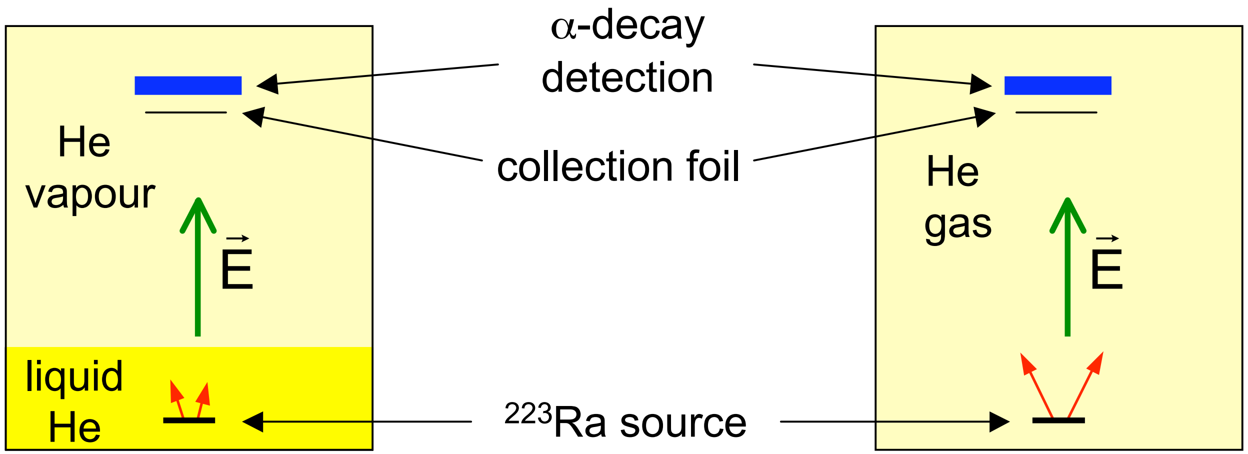
for gases: $\mu_+ = \mu_0 \dfrac{T}{273\,P}$

$\mu_- \uparrow$ with $T \downarrow$, $E/n \downarrow$

$$f \propto \frac{Q\,P}{E^2\,T\,\mu_-(T,E/n)}$$

C. Colmenares, NIM 114 (1974) 269
M.Huyse et al., NIM B 187 (2002) 533
G. Ramanan et al., J. Chem. Phys. 93 (1990) 3120

Tests using α-decay recoils



liquid helium

recoil range ~ 0.5 μm
α range ~ 0.5 mm

ionization density
Q ~ 10^{11} He^+-e^- pairs /cm^3 /s

1 bar room temperature helium gas

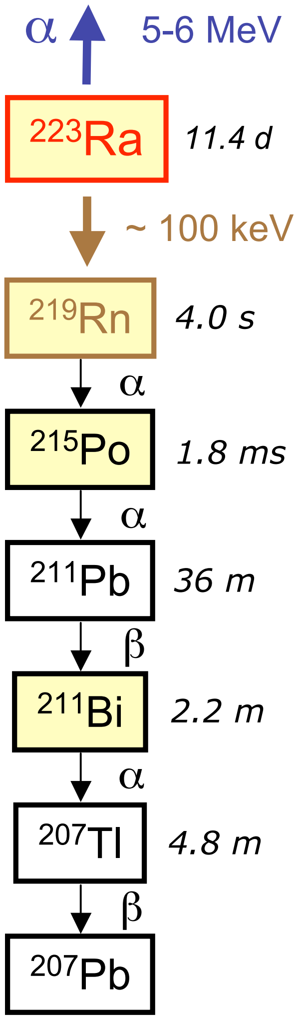
recoil range ~ 0.5 mm
α range ~ 50 cm

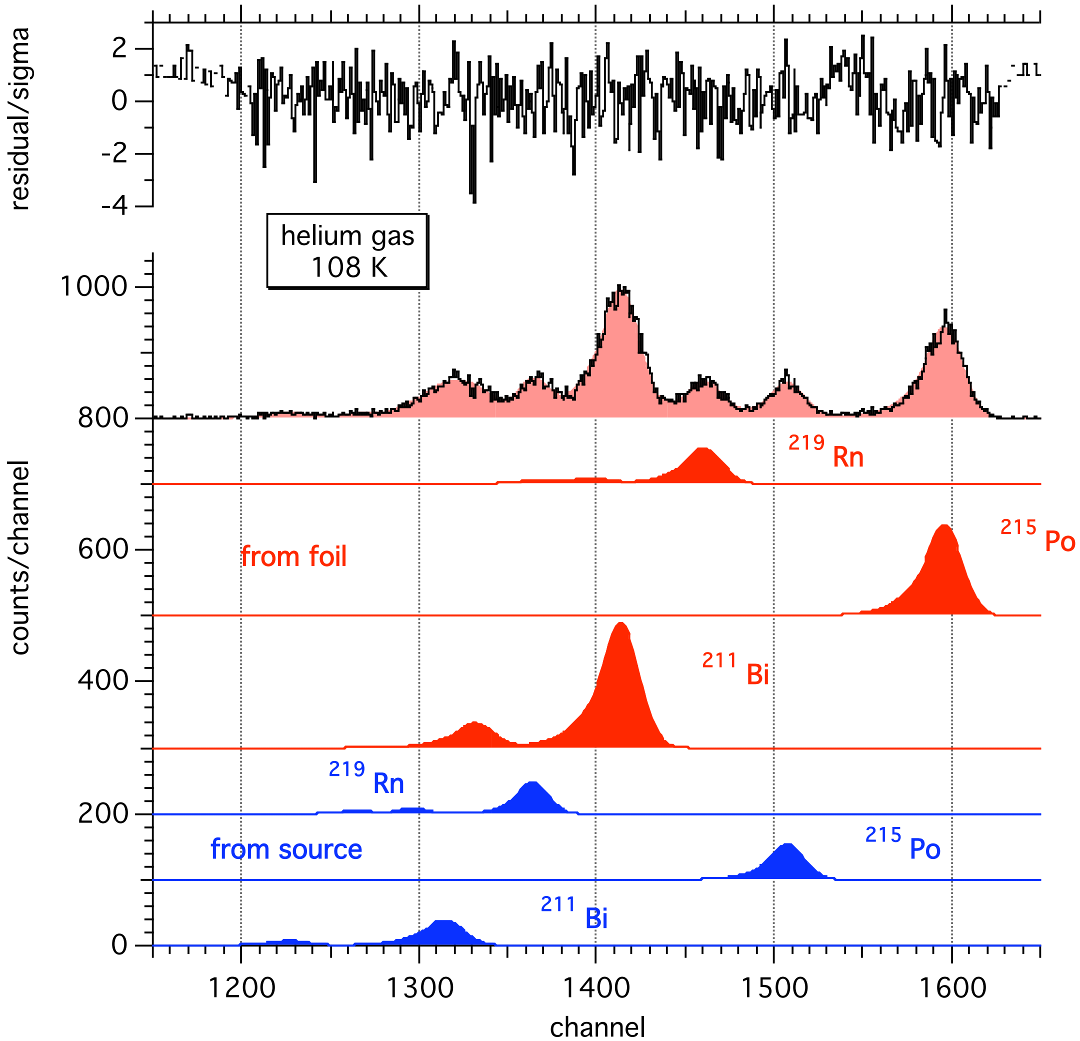
ionization density
Q ~ 10^8 He^+-e^- pairs /cm^3 /s

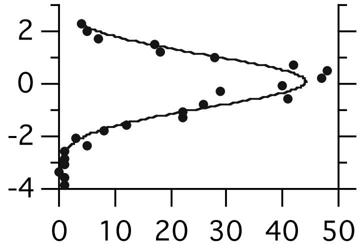
closed cell → transport of ionic species

Information from alpha spectra

^{223}Ra: source of ^{219}Rn ions

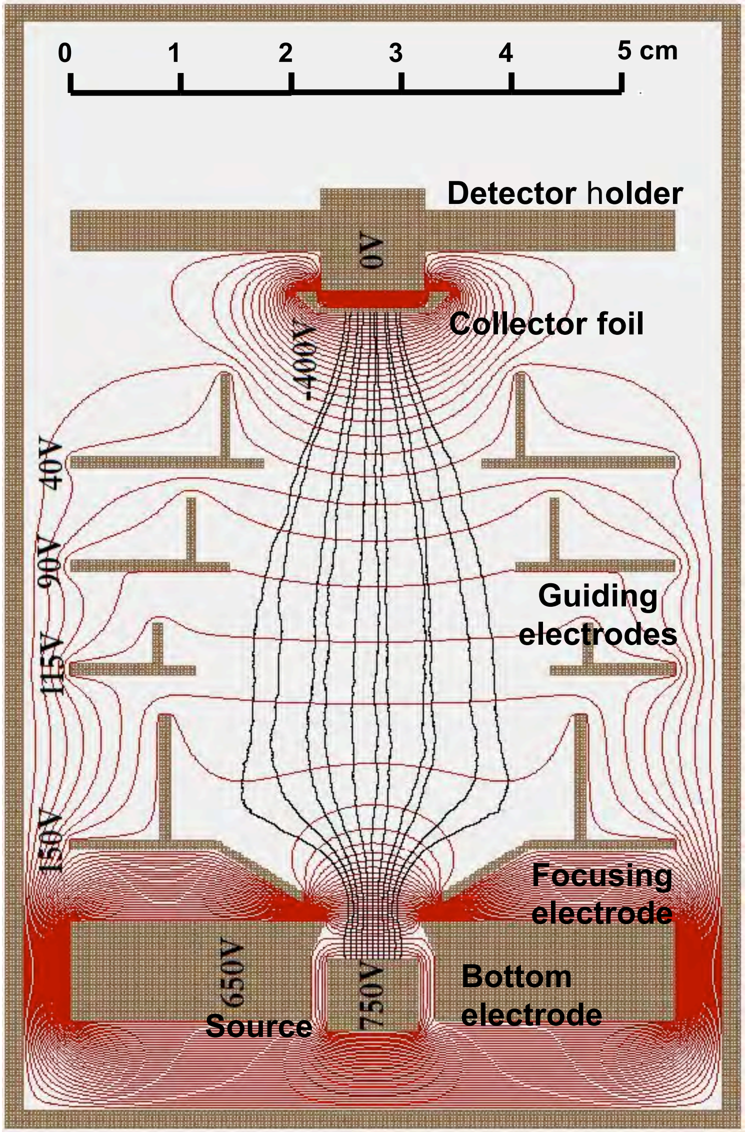


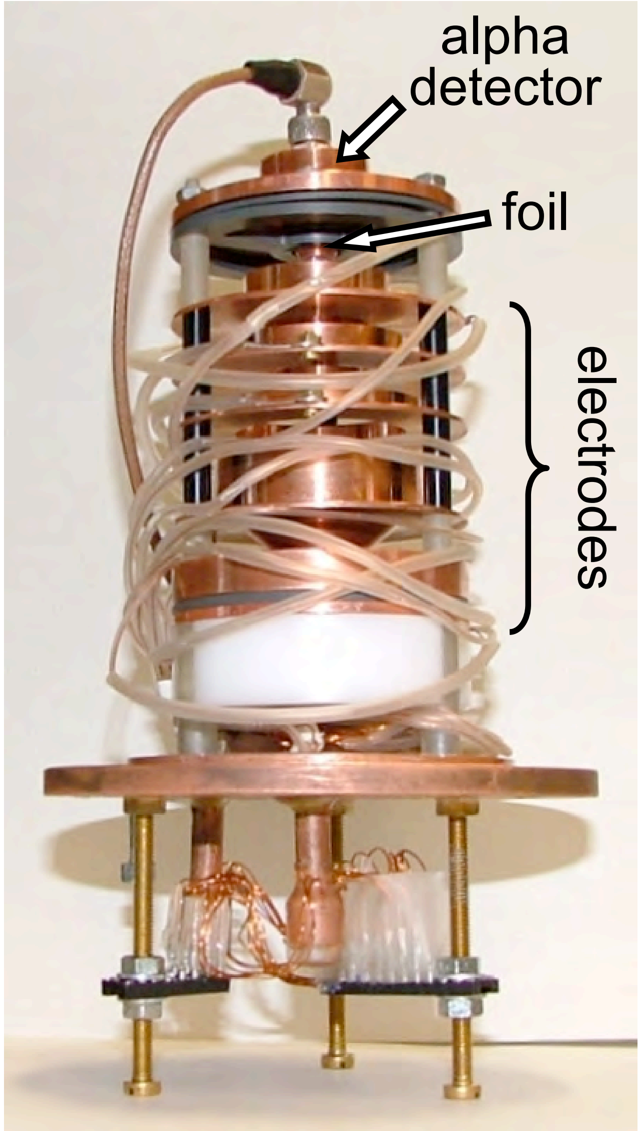




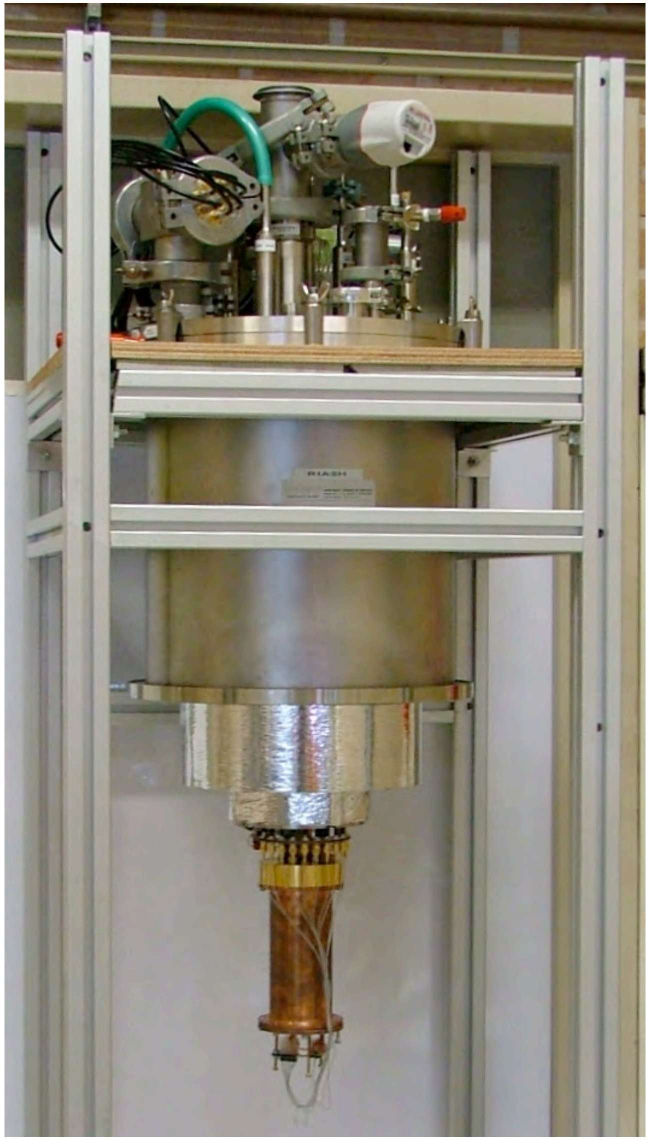
$\sigma = 0.99 \pm 0.07$
$x_0 = 0.10 \pm 0.05$

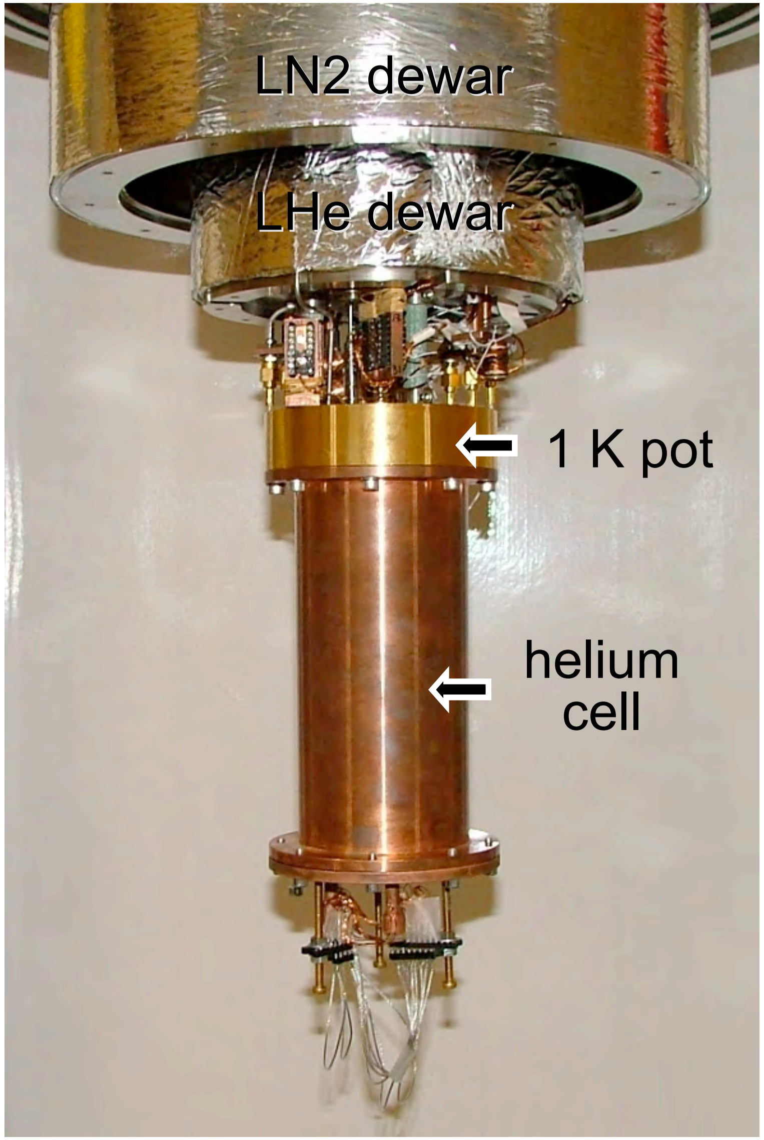
Electrode structure: an example



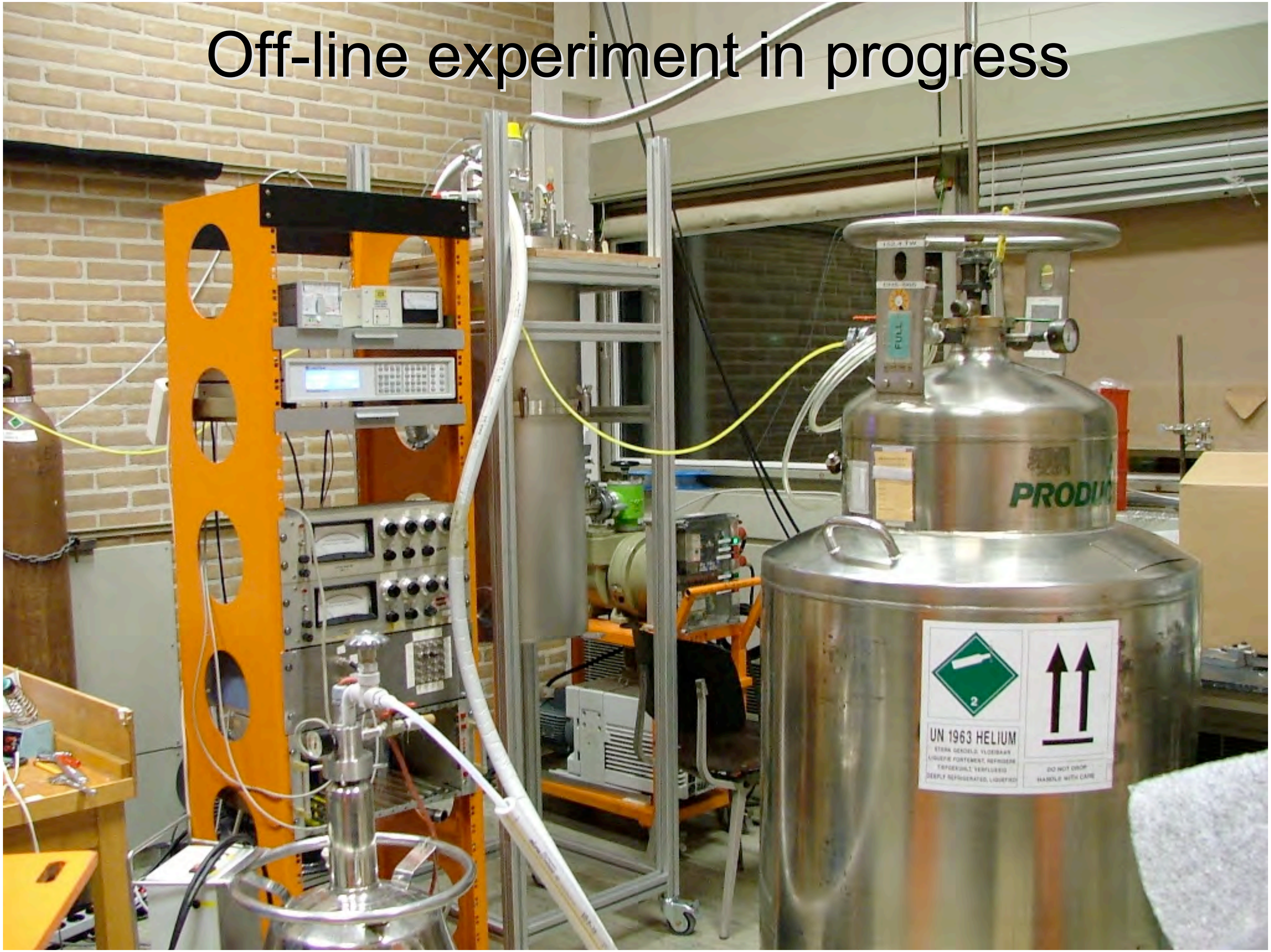


1 K Cryostat

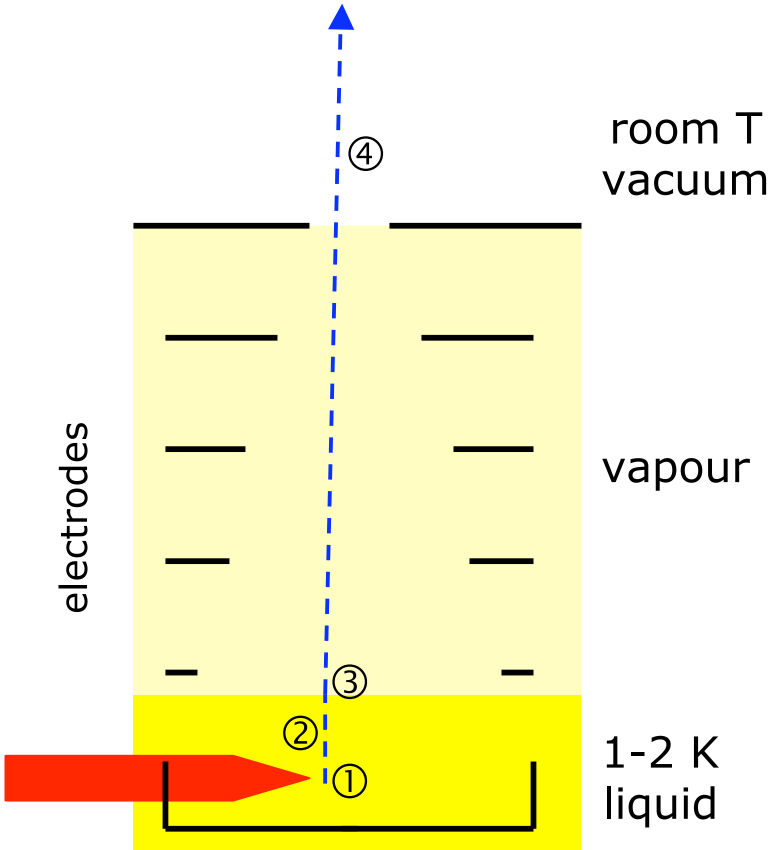




Off-line experiment in progress



RIBs from SF helium: concept



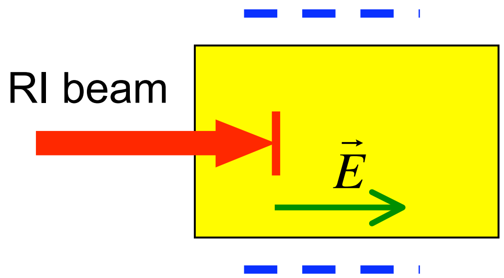
main issues

1. stop high-energy radioactive ions in superfluid helium
   snowball formation
2. transport to the surface
3. extraction across the surface into the vapour region
   barrier at the surface
4. transport to a vacuum, room-temperature region

Snowball formation: 10s of %

high-energy RIBs

(N. Takahashi et al.)



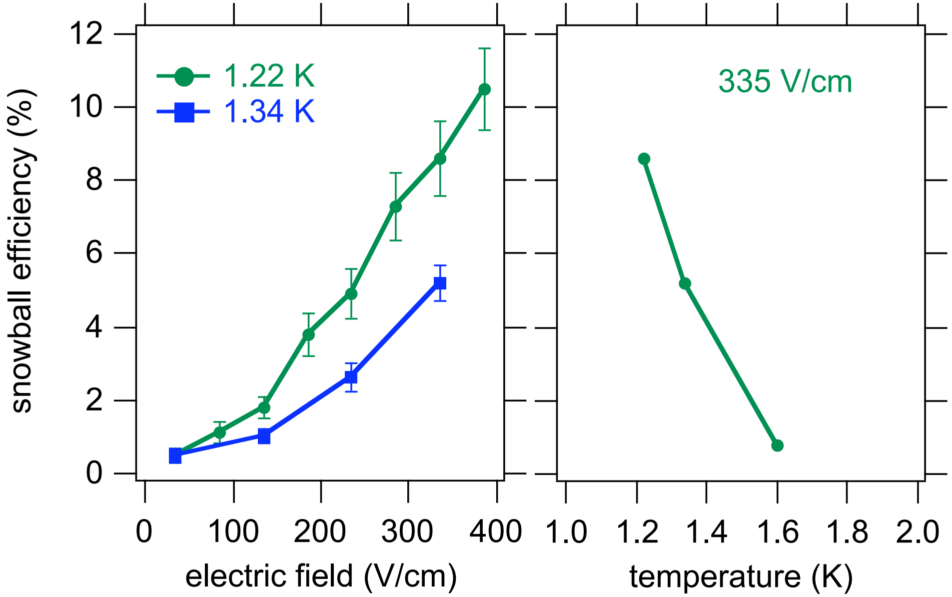
formation efficiencies

^{8}Li: 35%
^{12}B: 30%
^{12}N: 10%

ion survival time up to seconds
(outside of stopping region)

N. Takahashi, Physica B 284-288 (2000) 89
S. Shimuzu et al., OULNS Annual Report 2000, p.37
N. Takahashi, Fizika B 12 (2003) 135–144

^{219}Rn recoils



W.X. Huang et al., Europhys. Lett. 63 (2003) 687

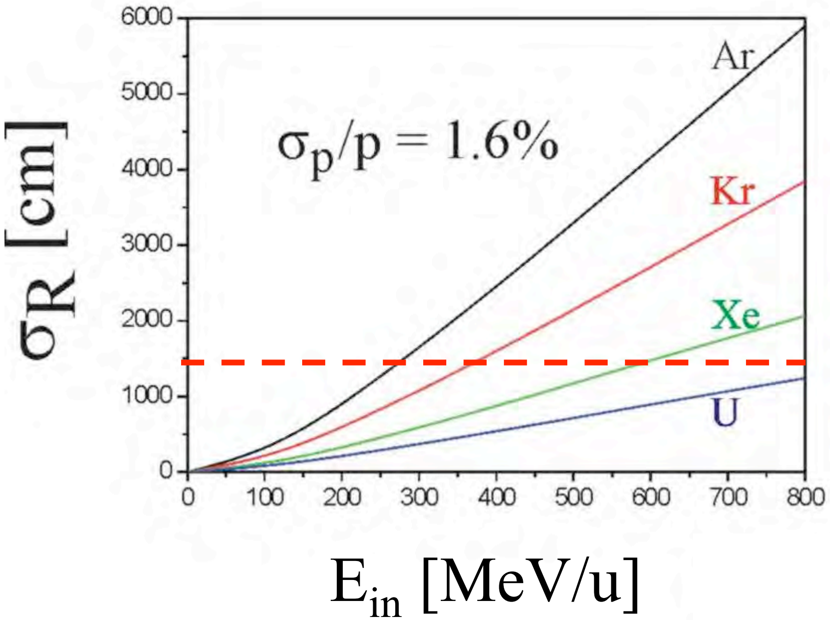
need
low temperature: high mobility
high electric field: large velocity

Is liquid helium too dense ?

1 meter bar ~ 1 mm liquid
more practical: few cm

if **no range bunching**:
15 meter bar ~ 15 mm liquid

- apply range stretching ?
- relax seperator tuning ?

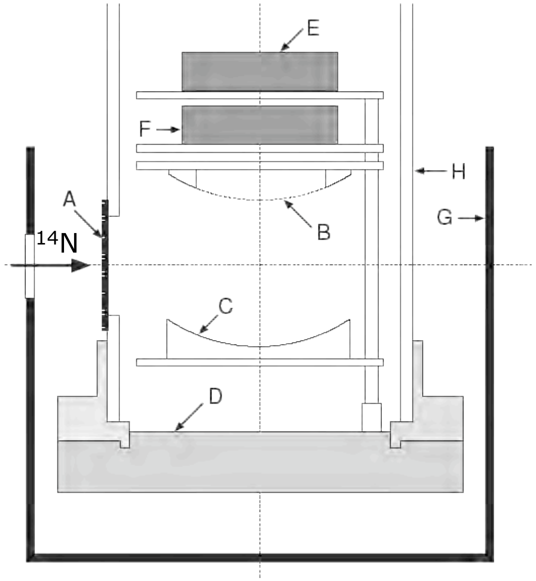


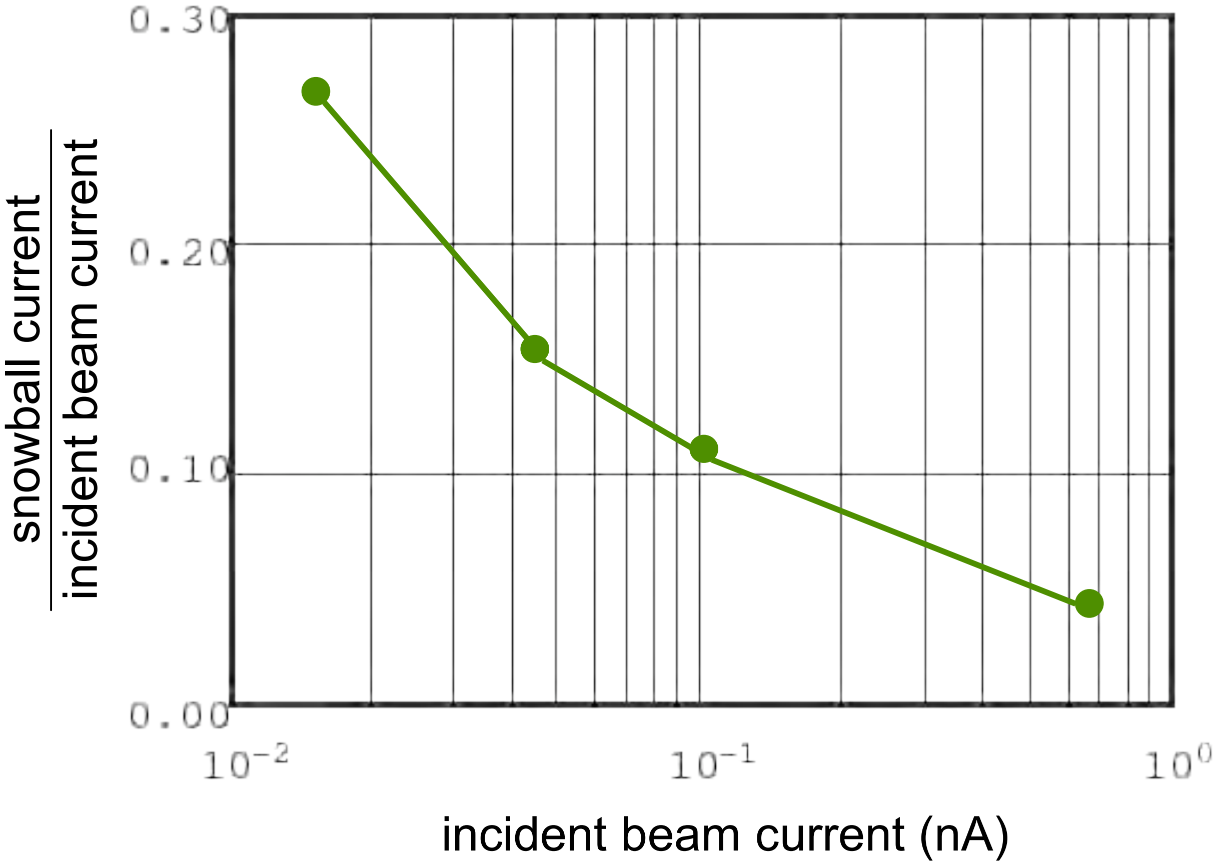
snowball (i.e. ion) survival is good due to

- fast neutralisation of helium ions (helium snowballs are hard to make)
- high mobility

Snowball formation vs. I_{beam}

135 MeV ^{14}N
T = 1.88 K, E ~ 100 V/cm





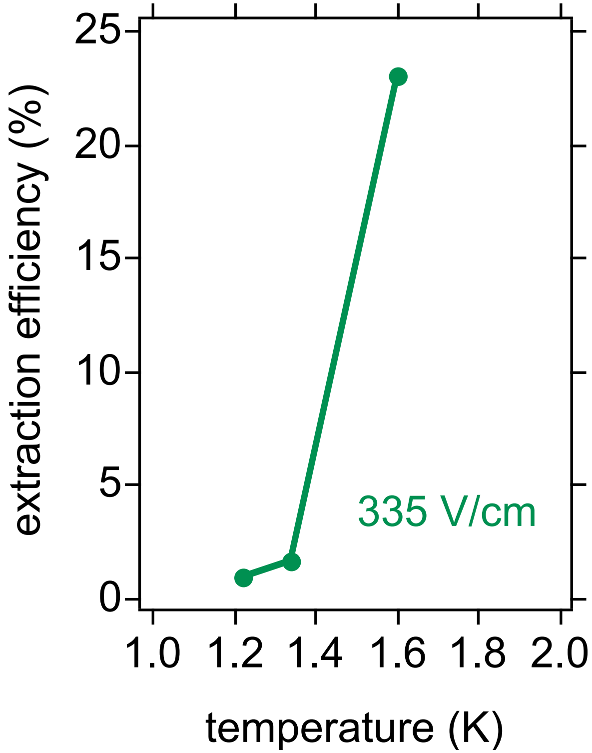
10^{16} 10^{17} 10^{18}

ionisation rate (/cm^3 /s) (approximate)

N. Takahashi, Fizika B 12 (2003) 135

Snowball extraction efficiency

^{219}Rn snowballs



need high temperature

W.X. Huang et al., *Europhys. Lett.* 63 (2003) 687

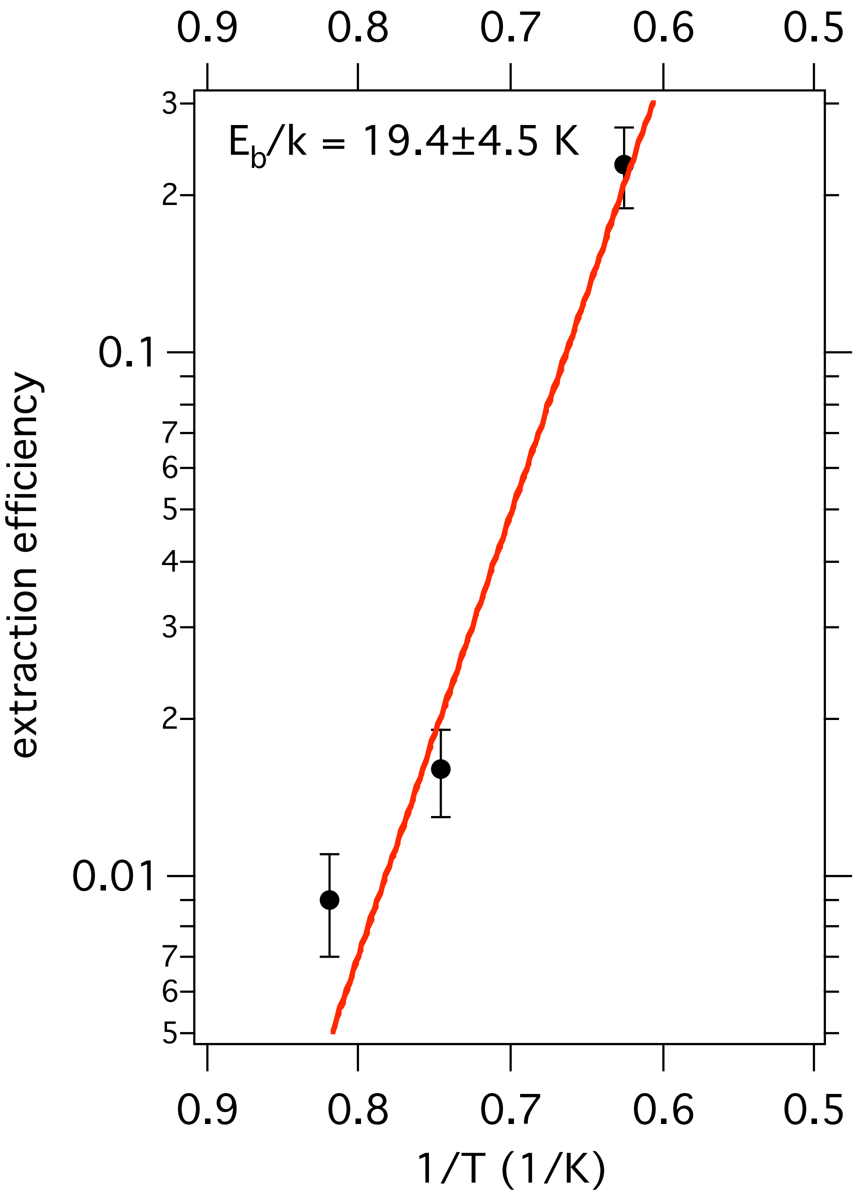
Barrier for extraction: 20 K

ions under Brownian motion in a potential well will eventually escape

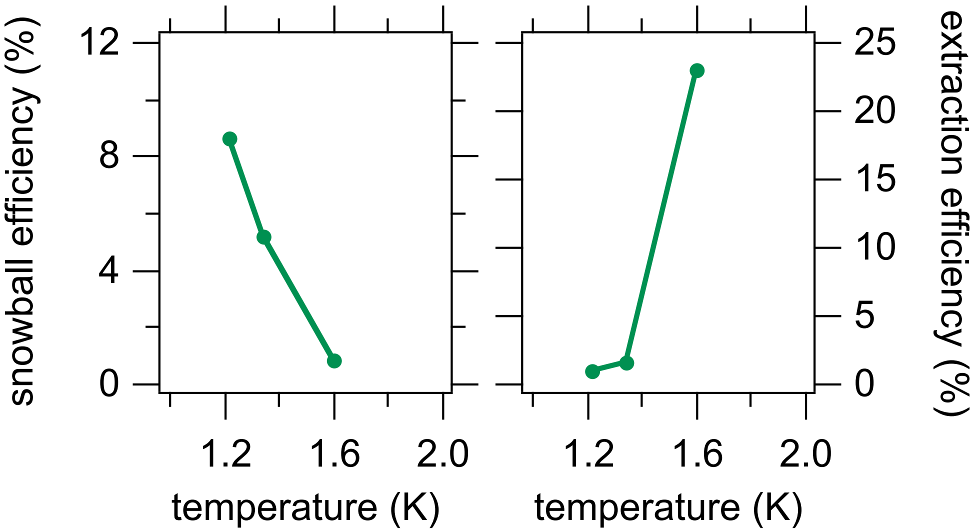
$$P = A\ e^{-E_b/kT}$$

P: escape rate
E_b: well-depth (barrier height)

R.J. Donnelly and P.H. Roberts, Proc. Roy. Soc., Ser. A 312 (1969) 519
S. Chandrasekhar, Rev. Mod. Phys. 15 (1943) 1



Snowball extraction at low temperature



conflicting temperature requirements

*W.X. Huang et al., NIM B **204** (2003) 592*
*N. Takahashi et al., Physica B **329** (2003) 1596*
*W.X. Huang et al., Europhys. Lett. **63** (2003) 687*

- choose low temperature for good snowball formation and fast transport
- **how to extract at low temperature ?**

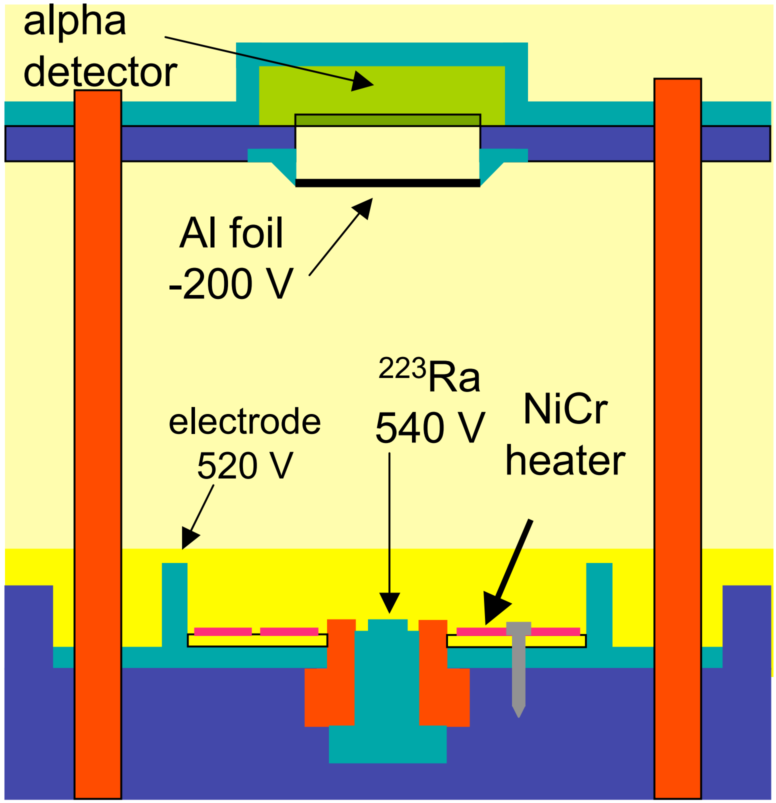
1. electric field to push ions over the barrier

   experiment: no effect up to 1200 V/cm

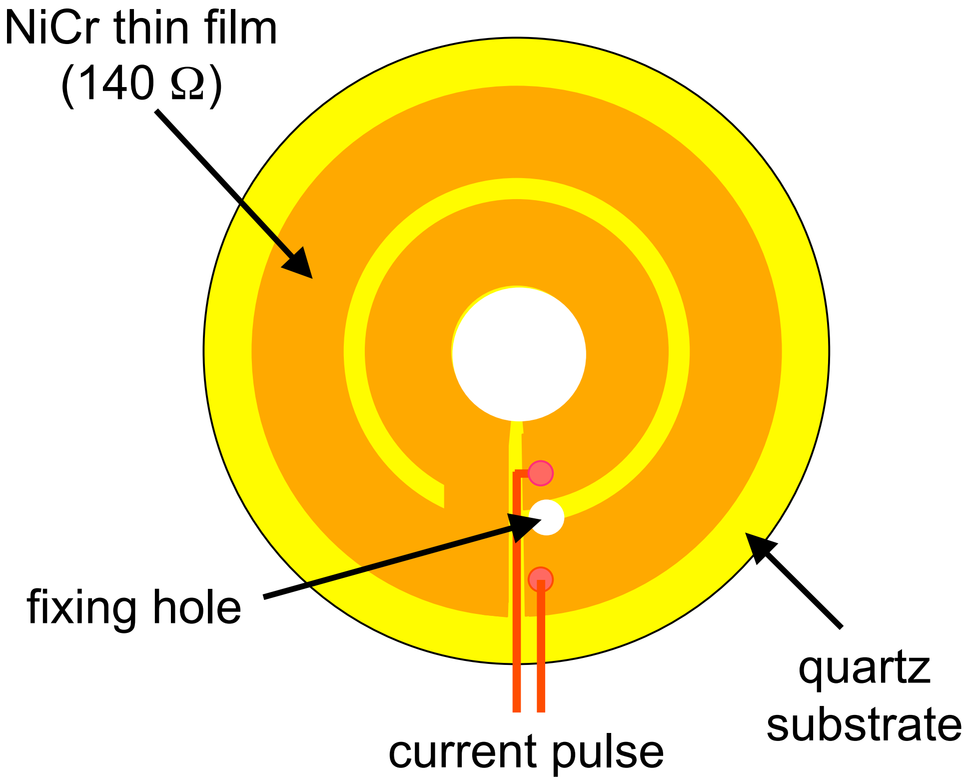
2. pulsed second sound waves

Evaporation by second sound

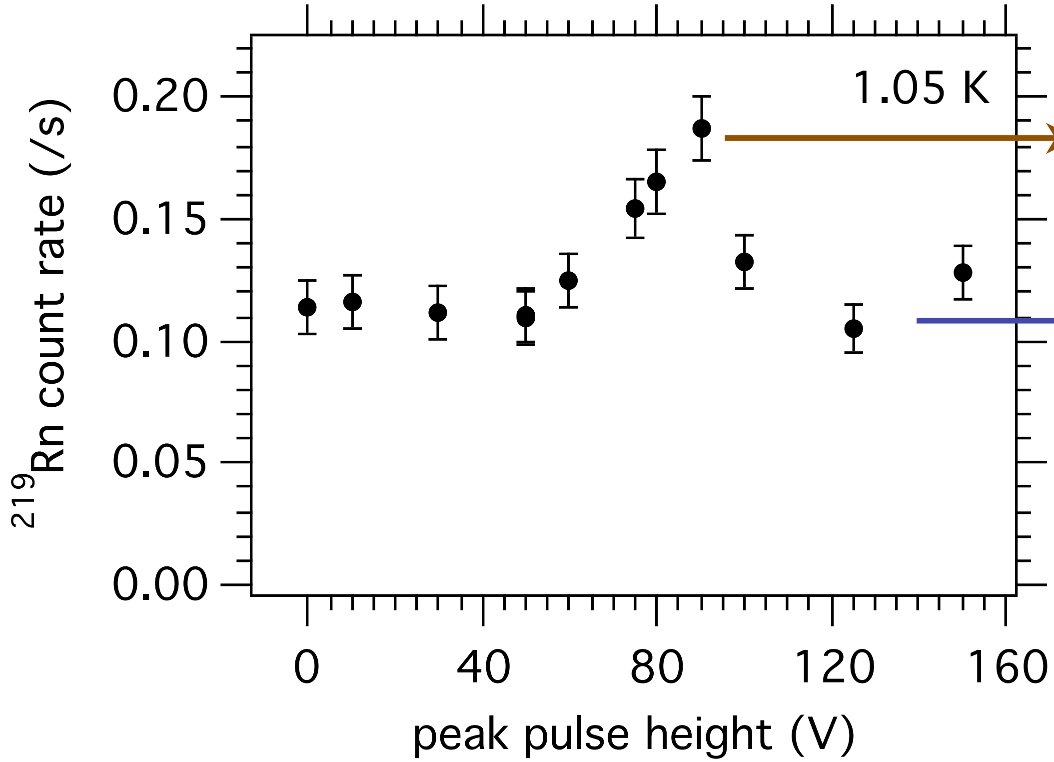
SF helium cell configuration



heater design



Release of ions by evaporation



square current pulse to the second sound heater
width: 50 μs, period: 500 ms

^{219}Rn released from the surface and transported to the foil

^{219}Rn trapped at the surface

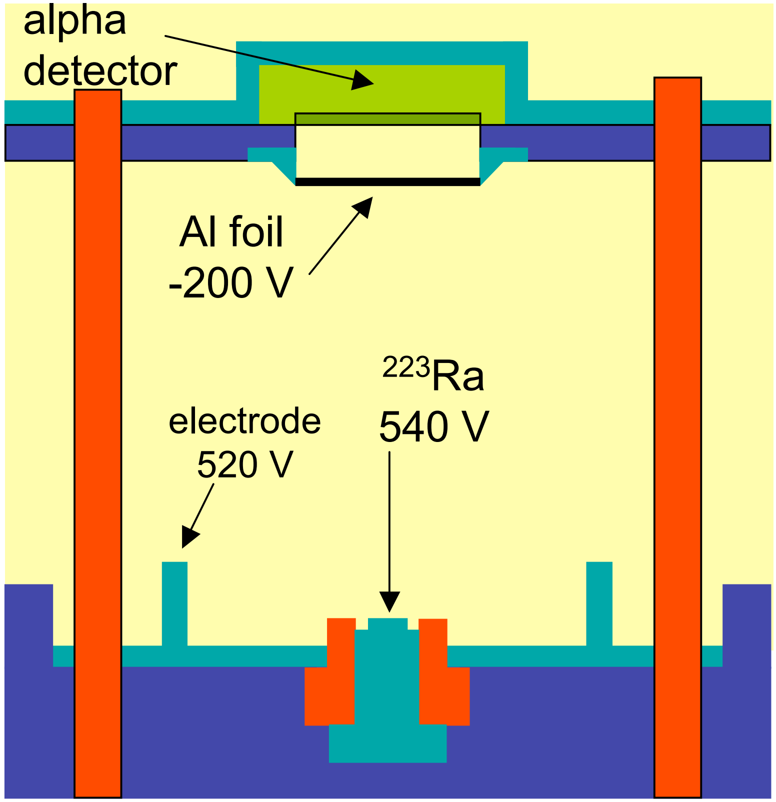
7.2(6) % extraction efficiency

thermal motion across 20 K barrier: 0.04 %

few % overall efficiency

needs confirmation

A cryogenic gas catcher

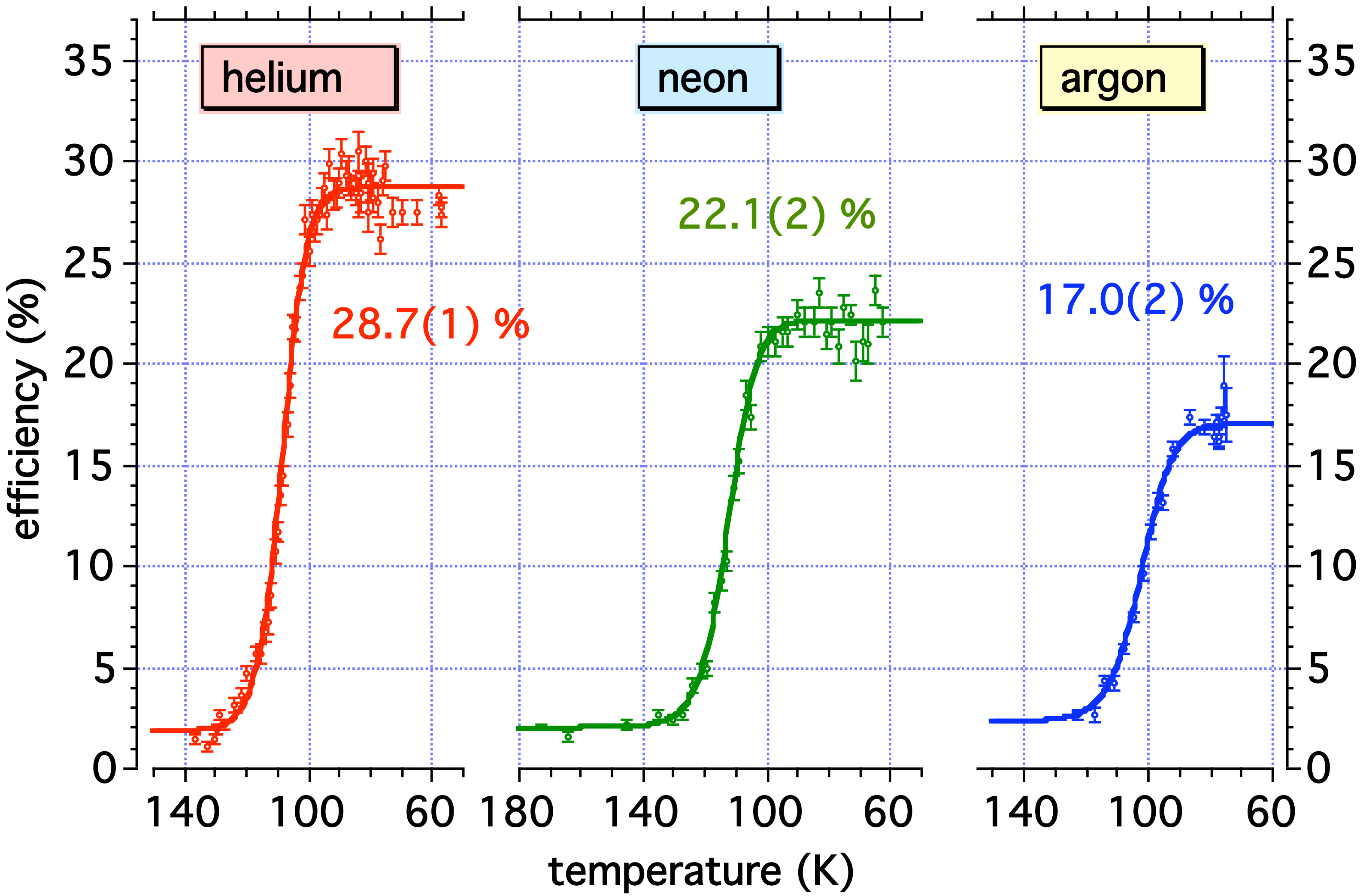


1 bar at room temperature

helium
neon
argon

transport efficiency vs. temperature of ^{219}Rn ionic species

Efficiencies in cryogenic noble gases



P. Dendooven et al., NIM A 558 (2006) 580

Ultrahigh purity of cryogenic gases

impurities in noble gas ion catchers limit the performance:

- neutralization of ions (near or at thermal velocities)
- formation of molecules/adducts

remove impurities

1) ultra-clean system
    - UHV compatible
    - bakeable
    - helium purification < ppb

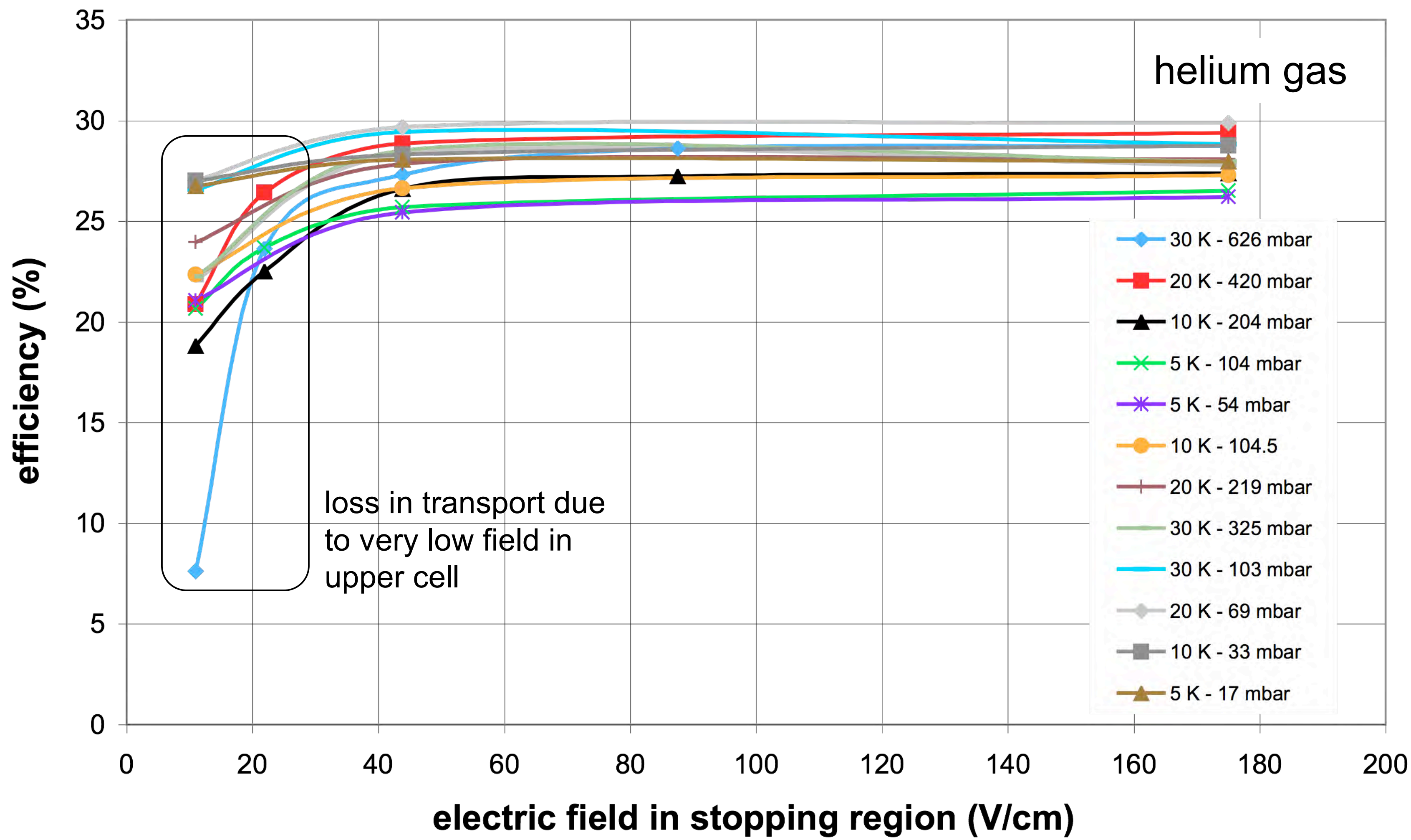
    → not trivial (esp. large cells)

2) **freezing the impurities**

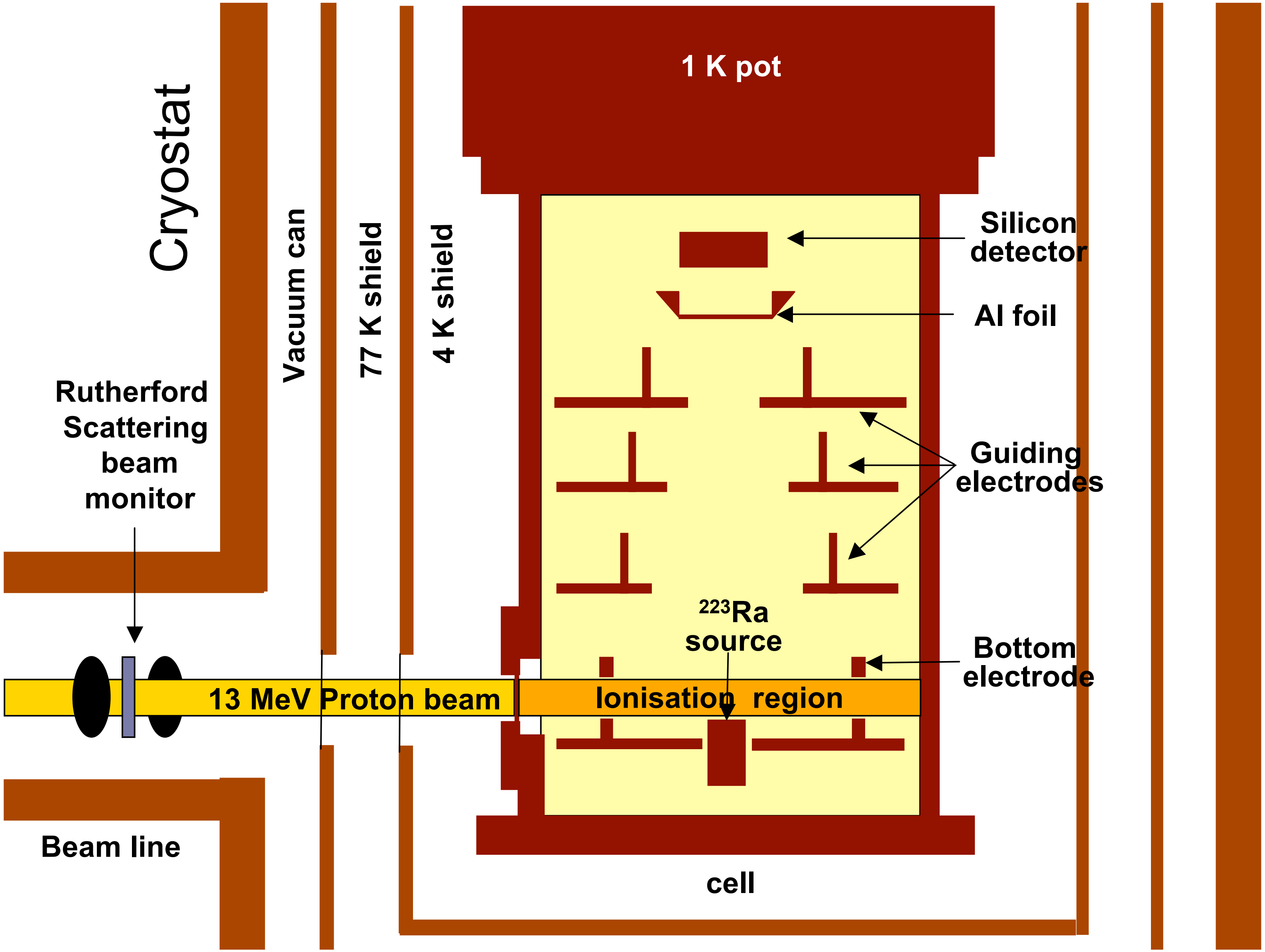
➢ **freezing out of impurities works**
technically easier than ultra-pure at room temperature

➢ **fundamental upper limit**
the measured efficiencies are determined by the charge exchange cross sections during slowing down

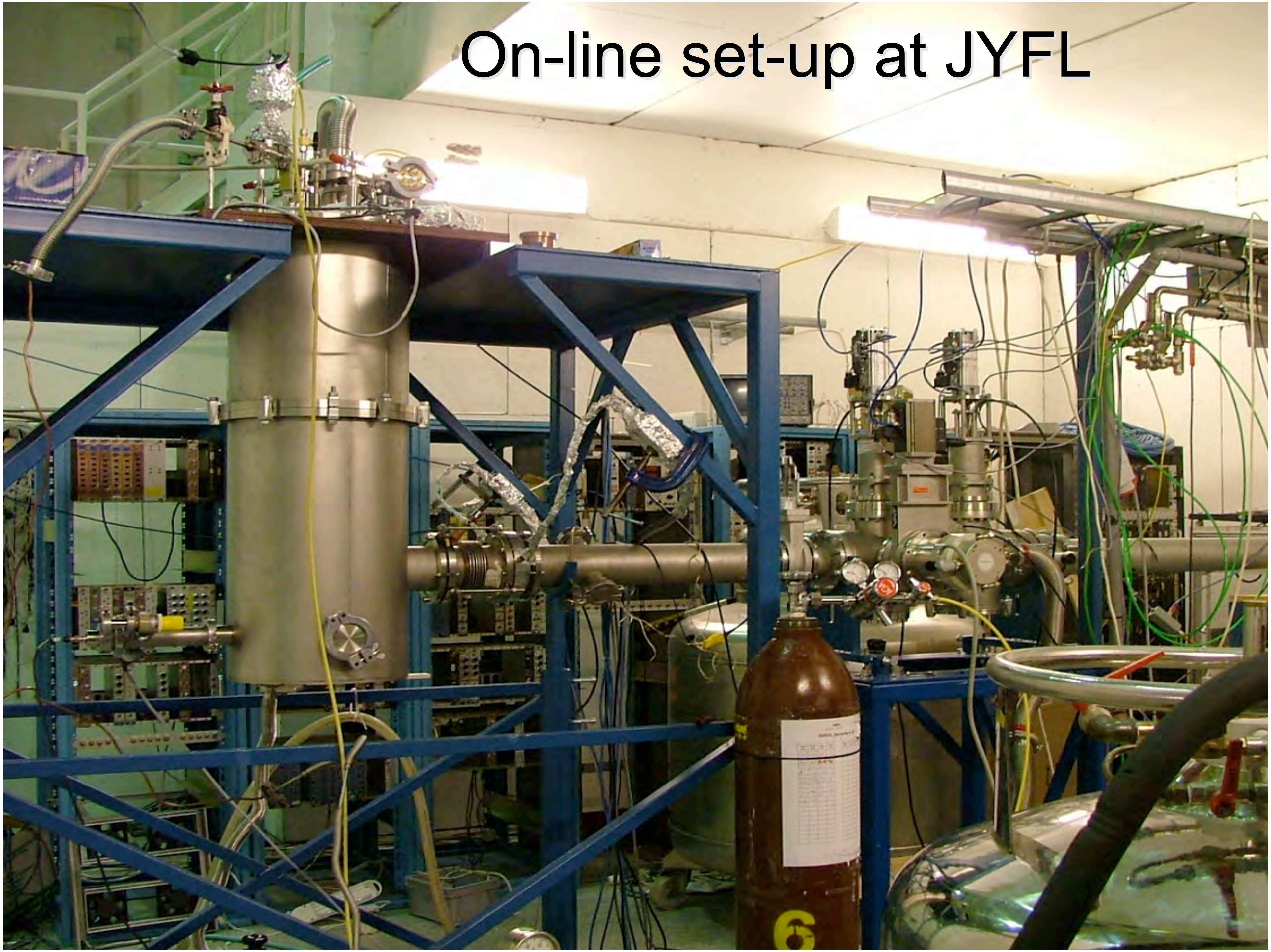
Efficiency is constant vs. E, P and T



Ionisation of cold helium gas



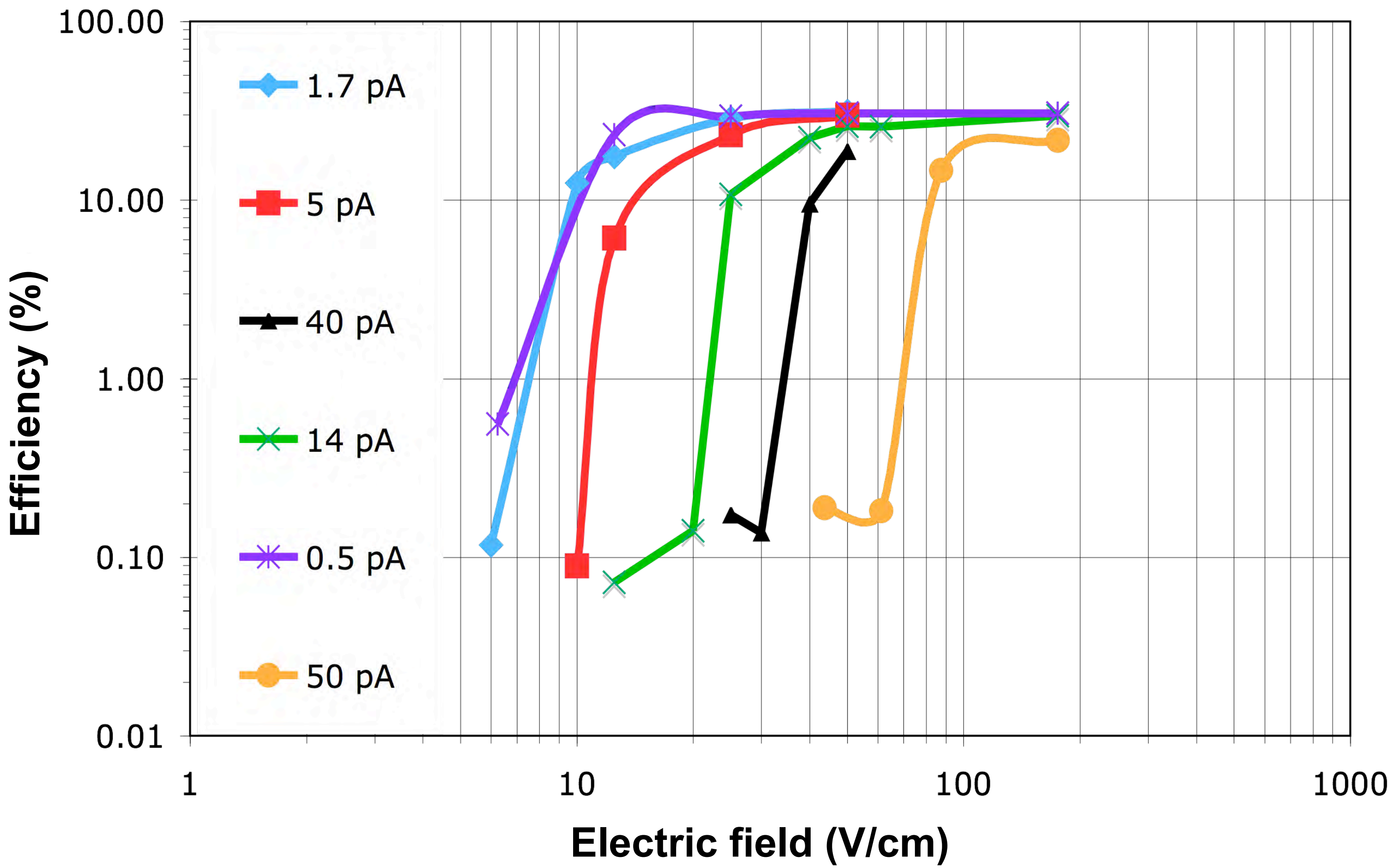
On-line set-up at JYFL




17 Inch Entry
Color Monitor

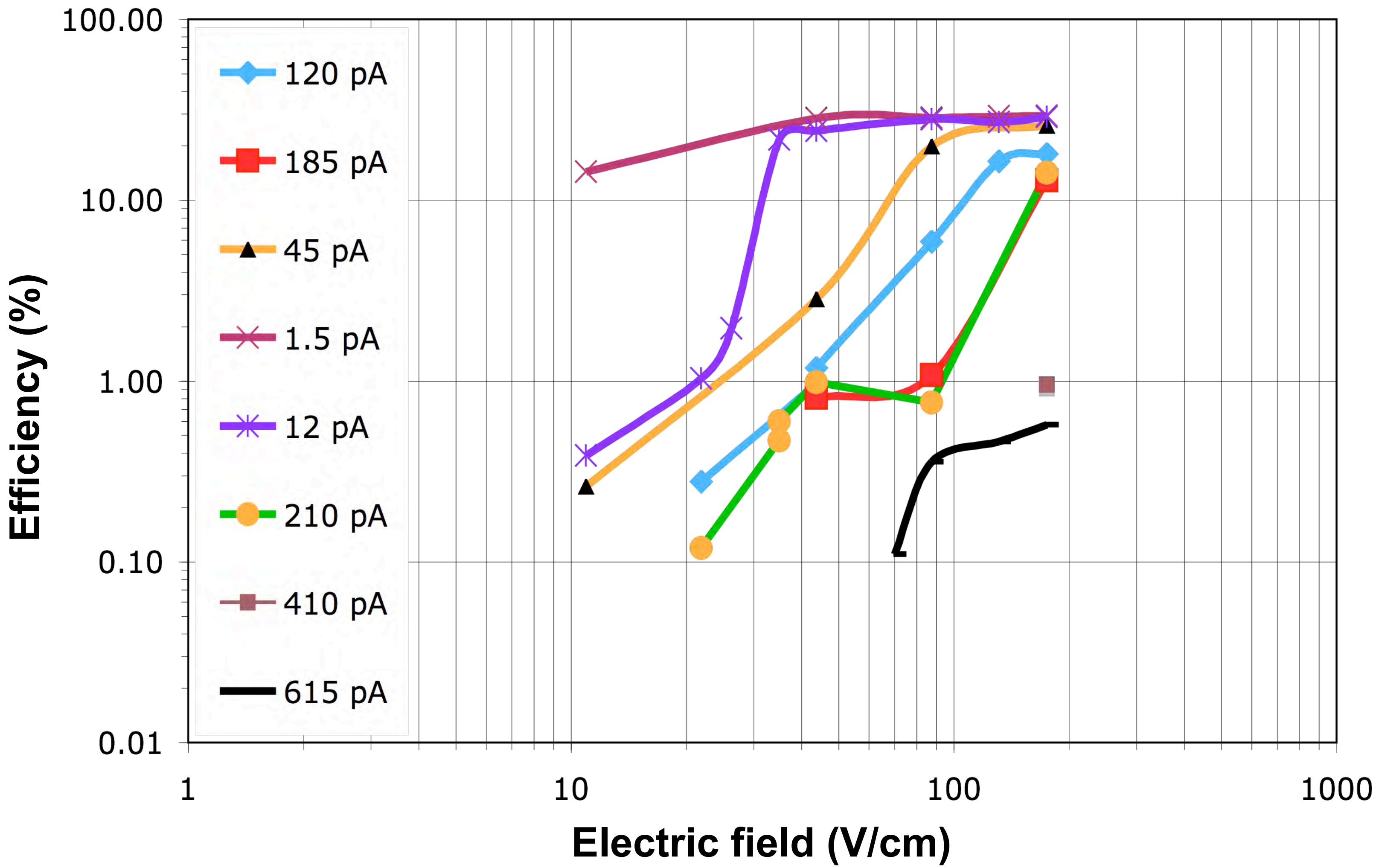
Ionisation by proton beam

78 K, 280 mbar (1 bar at room temperature)



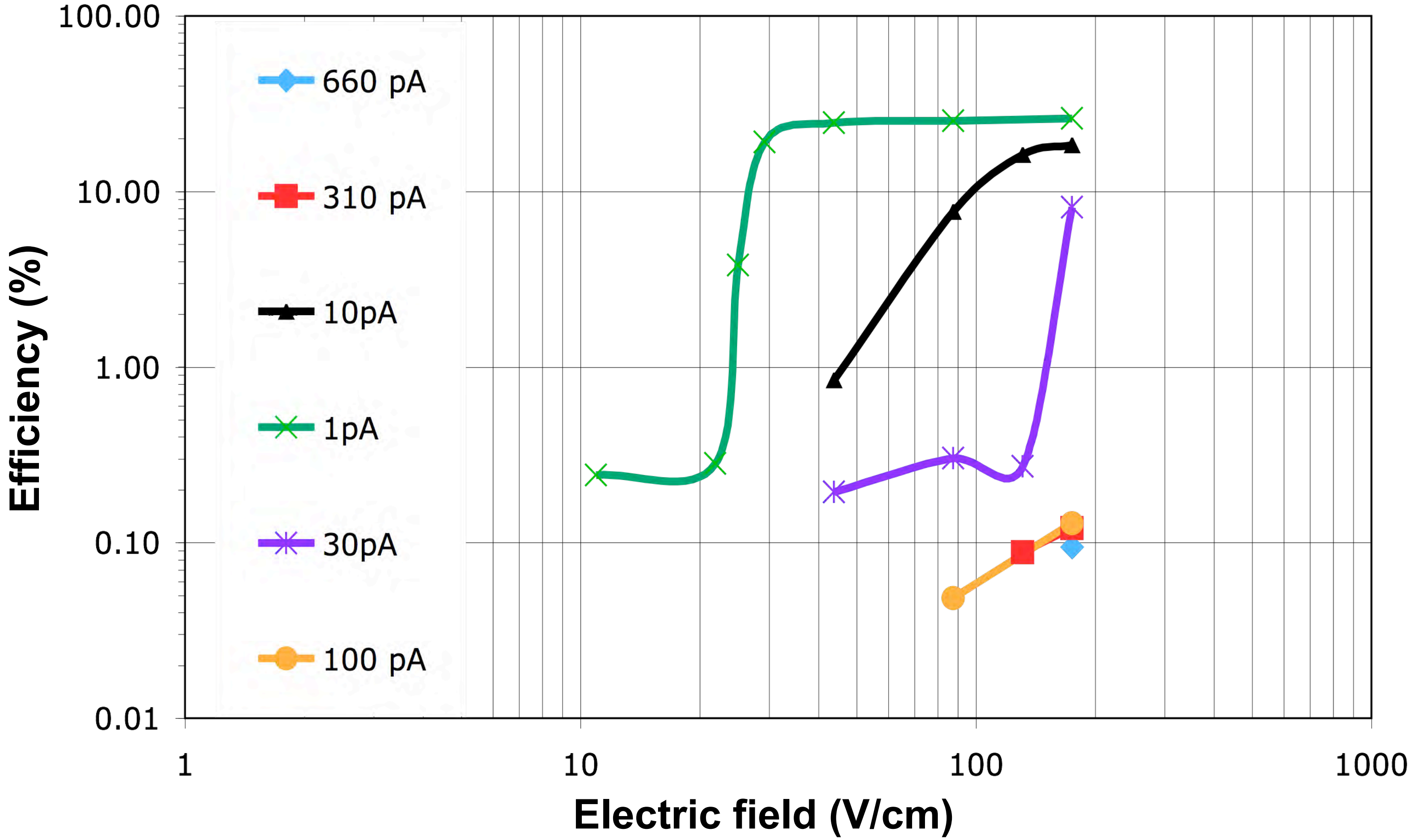
Ionisation by proton beam

10 K, 35 mbar (1 bar at room temperature)

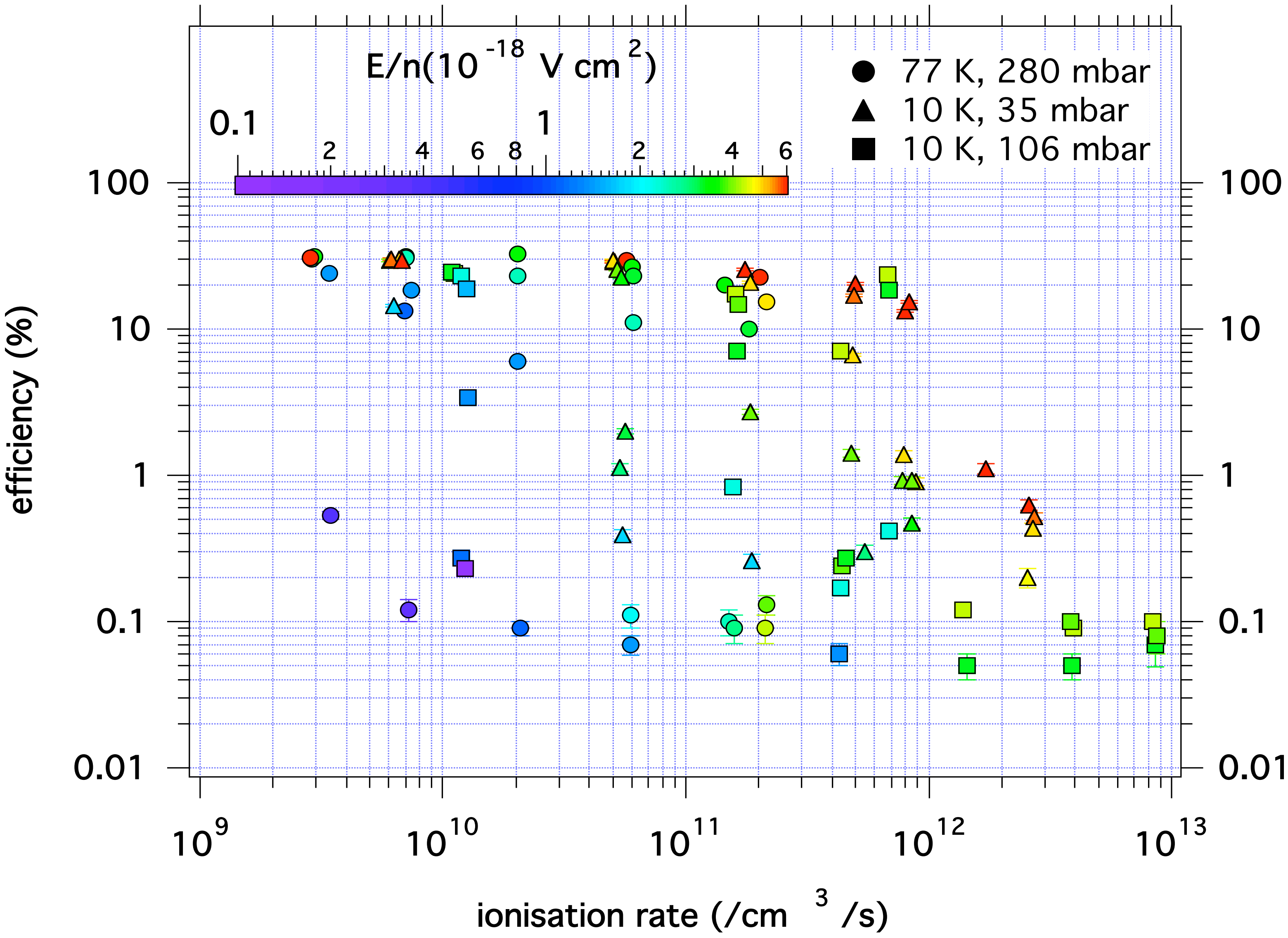


Ionisation by proton beam

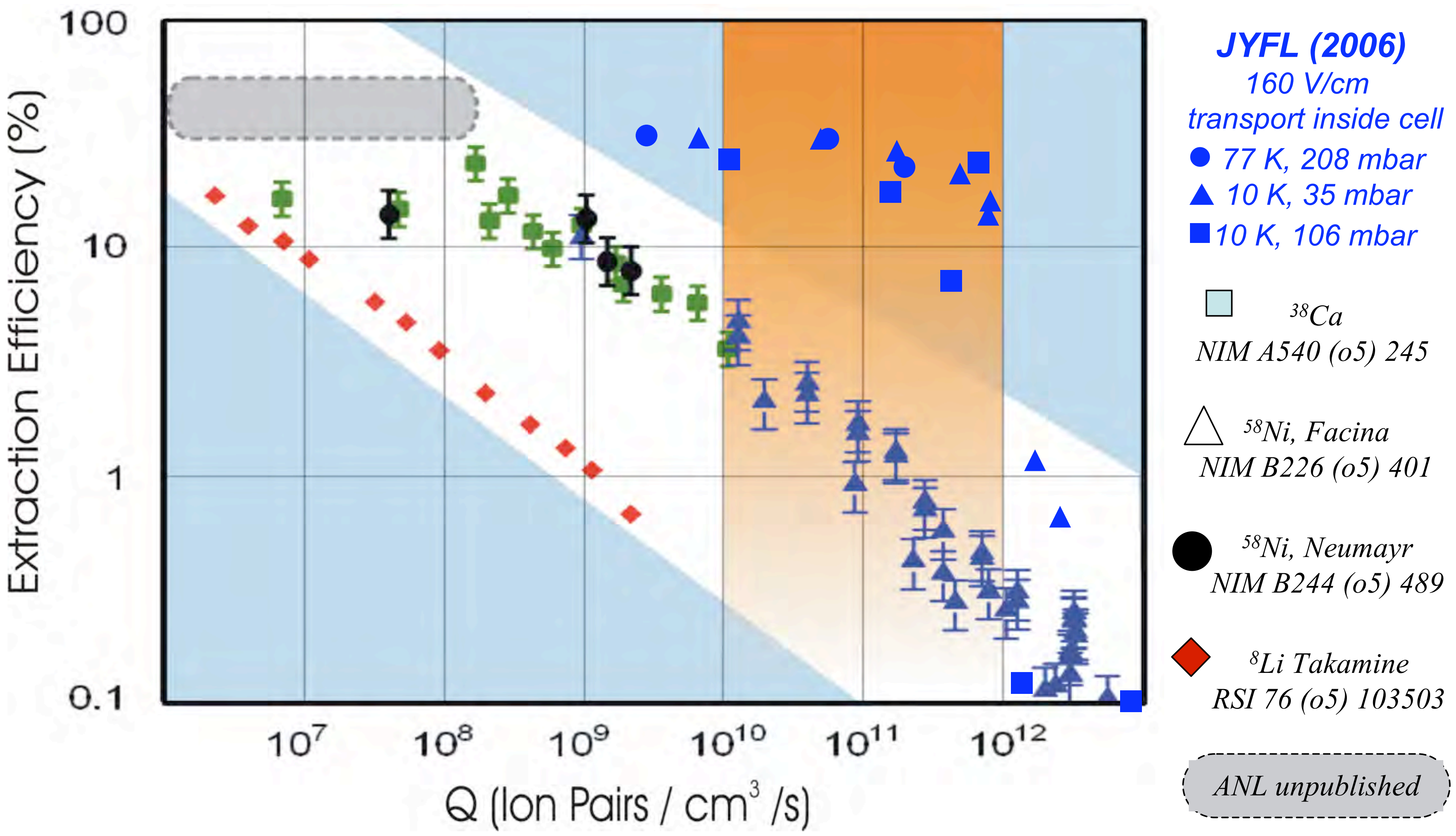
10 K, 106 mbar (3 bar at room temperature)



Efficiency vs. ionisation rate

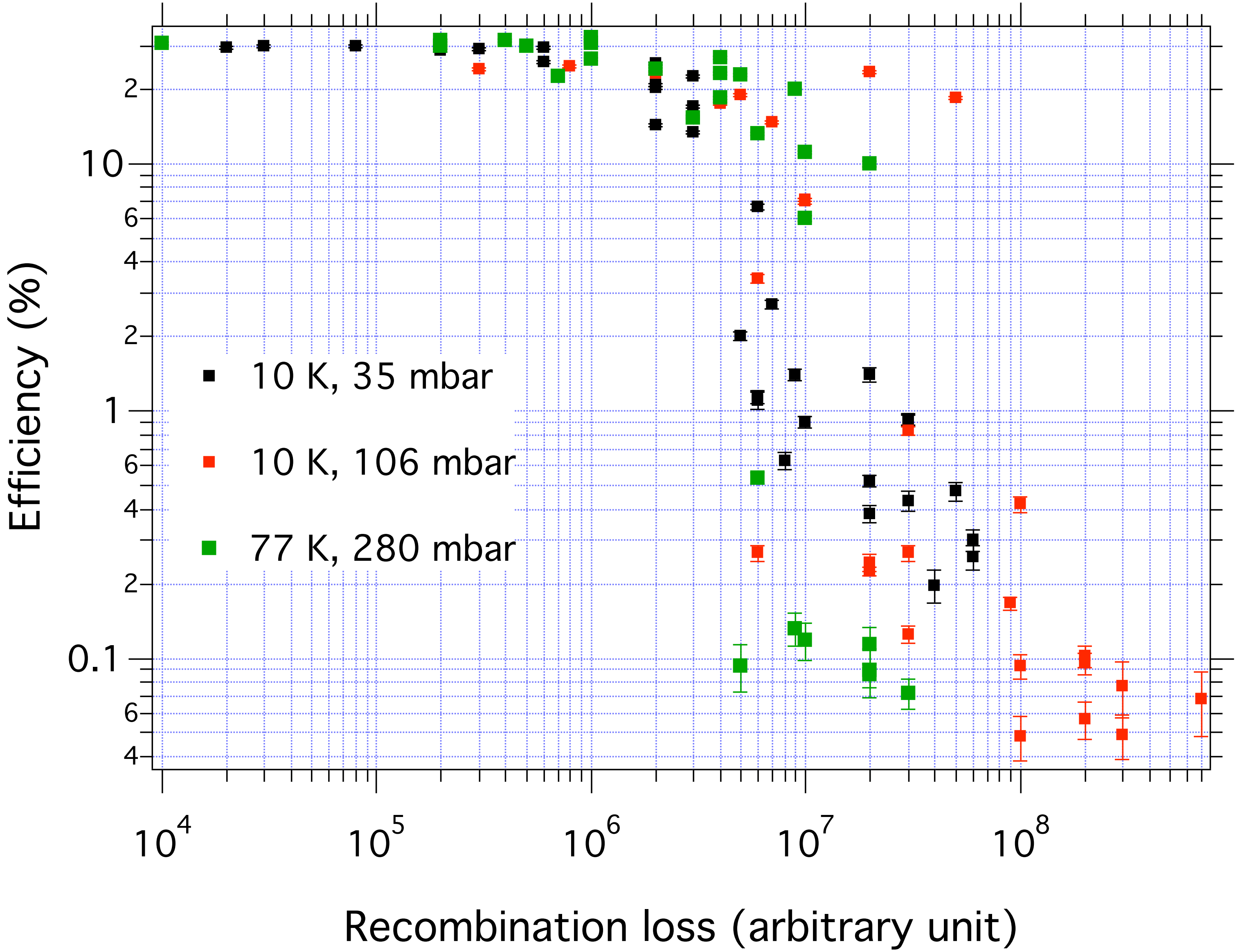


Extraction efficiency, summary figure



Summary figure from D. Morrissey

Efficiency vs. recombination loss



Summary - status

- good efficiency for ion survival and transport in superfluid helium
- evidence for 2nd sound assisted extraction from superfluid helium

- no basic problem for cryogenic gas catchers
- high beam intensities require high electric fields

Future steps

- off-line test of second sound assisted extraction from superfluid helium (late 2006 – early 2007)
- ionisation of superfluid helium, closed cell (at KVI)
- extraction of ions from cryogenic environment

- on-line test of cryogenic gas catcher at IGISOL/JYFL with stable beams
- implementation at fragment separator

- if all goes well, development of a full-scale system

Collaborators

KVI	Siva Purushothaman, Peter Dendooven
	(graduate student opening)
JYFL	Antti Saastamoinen, Tetsu Sonoda, Iain Moore, Juha Äysto, Heikki Penttilä, Perttu Ronkanen, IGISOL group
University of Turku	Kurt Gloos
Osaka Gakuin University	Noriaki Takahashi
GSI	Christoph Scheidenberger
University Giessen	Wolfgang Plass et al.