TRIUMF

CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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Charge State Boosters for Radioactive Ion Acceleration

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1. Introduction
2. State of the art charge breeding with EBIS and ECRIS
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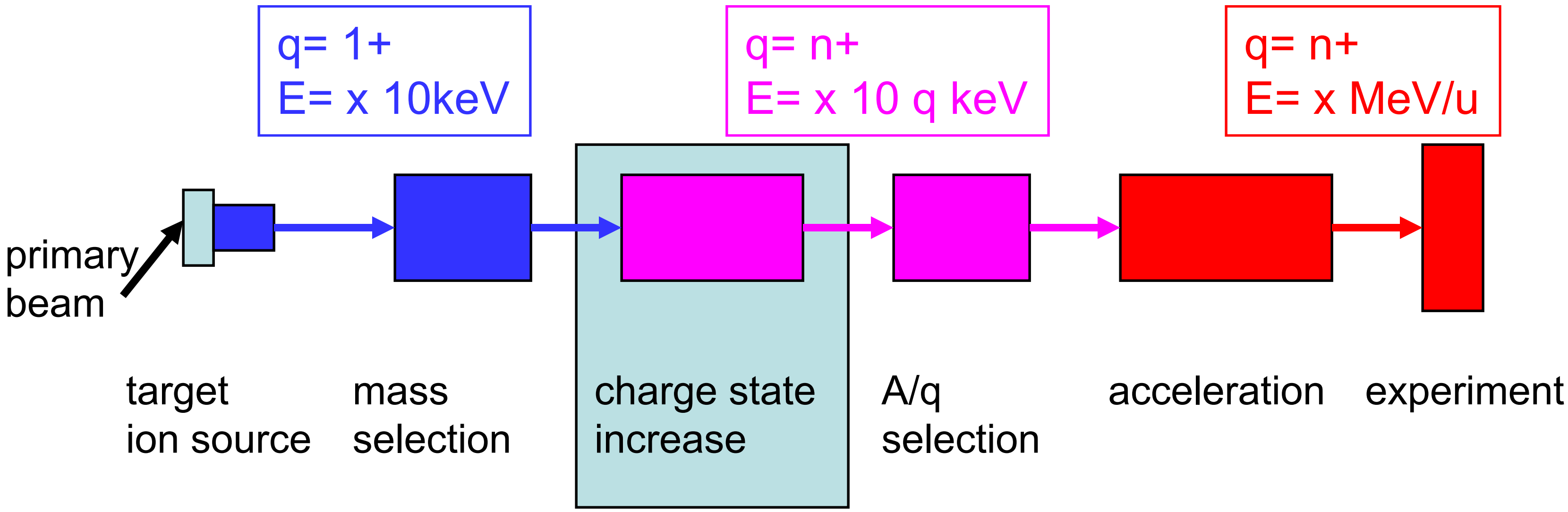
LINAC08, Victoria, October 2, 2008

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

acceleration of radioactive ions at an ISOL faciliy:



methods for charge state increase:

passive

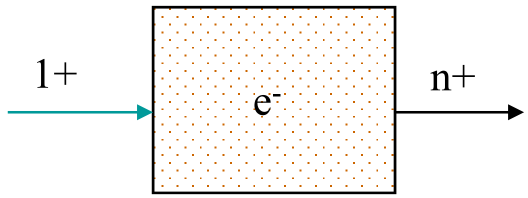
•stripping after first acceleration

(ISAC I)

simple, fast, high efficiency for light ions,

pure beams

low efficiency for heavy ions



fast 1+ ions
slow electrons

active

•charge state breeding with an EBIS

(REX-ISOLDE, MSU, GSI,…)

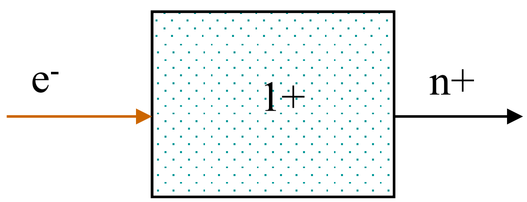
•charge state breeding with an ECRIS

(ISAC II, GANIL, KEK-JAERI, ANL,…)

high charge states, works for all masses

complicated, slow,

background from residual gases



fast electrons
slow 1+ ions

charge state evolution in EBIS or ECRIS

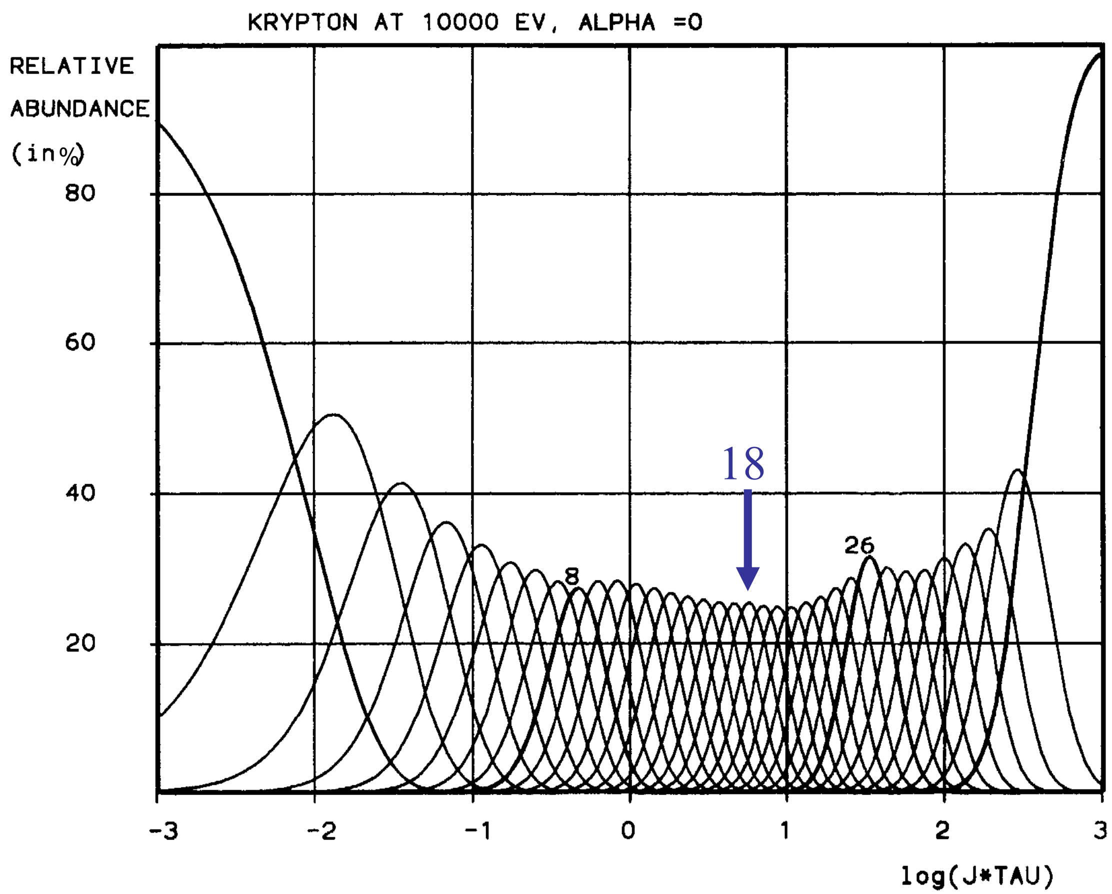
system of rate equations
only changes by one charge are considered

$$\frac{dn_i}{dt} = n_e v_e \left[\sigma^{ion}_{i-1\to i} n_{i-1} - \left(\sigma^{ion}_{i\to i+1} + \sigma^{RR}_{i\to i-1}\right) n_i + \sigma^{RR}_{i+1\to i}\right]$$
$$- n_0 v_{ion} \left[\sigma^{chex}_{i\to i-1} n_i - \sigma^{chex}_{i+1\to i} n_{i+1}\right]$$
$$- \nu^{coll}_i \frac{exp\left\{-\frac{ieU_w}{kT_{ion}}\right\}}{-\frac{ieU_w}{kT_{ion}}} n_i$$

n_e, n_i, n_0	density of electrons, ions with charge i and neutrals
v_e, v_i	velocity of electrons and ions
σ^{ion}, σ^{RR}, σ^{chex}	cross section for ionization, radiative recombination and charge exchange
ν^{coll}	coulomb collision frequency
T^{ion}	ion temperature
U_w	electrostatic trapping potential

in an ECRIS electron energy distribution function has to be known

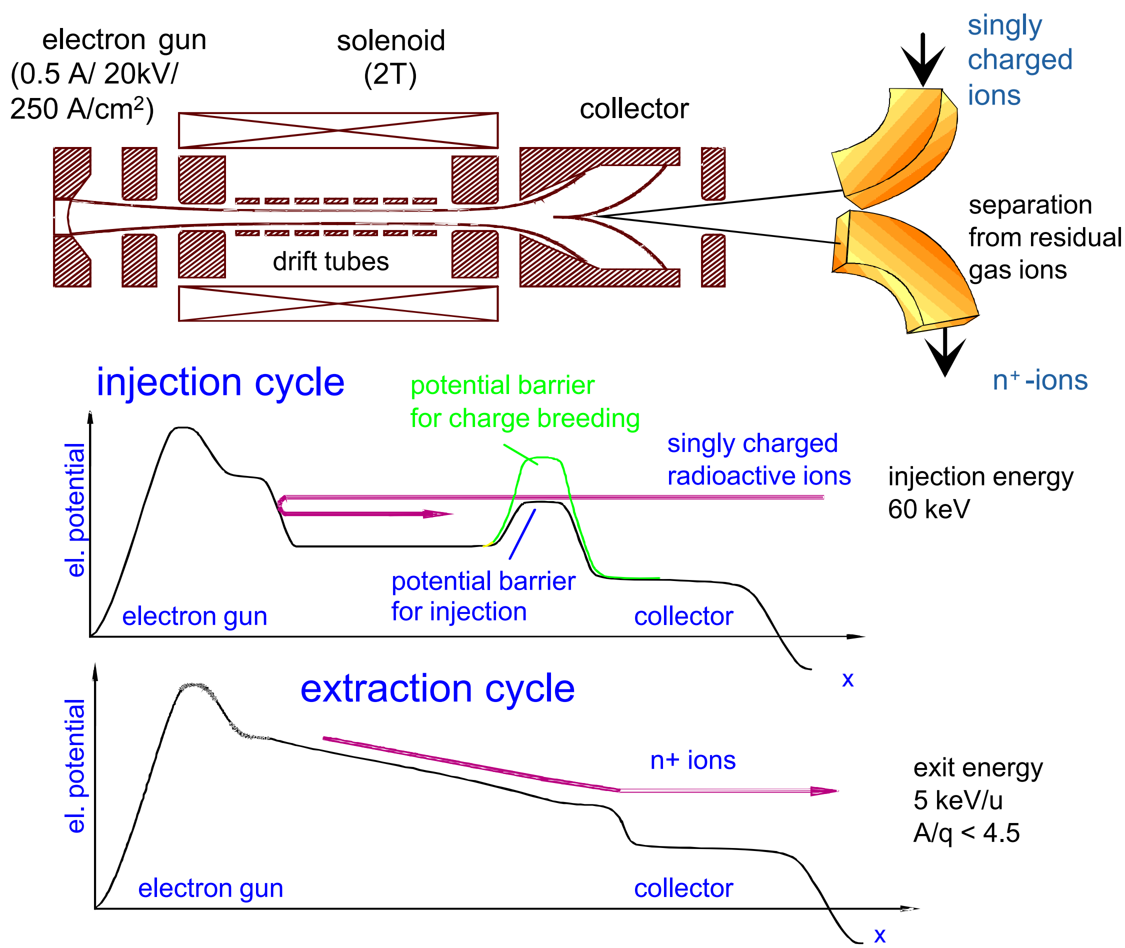
charge state breeding of Krypton in an EBIS



A=84
q=18
⇒q/A = 0.21

j =250 A/cm^2
τ = 19 ms

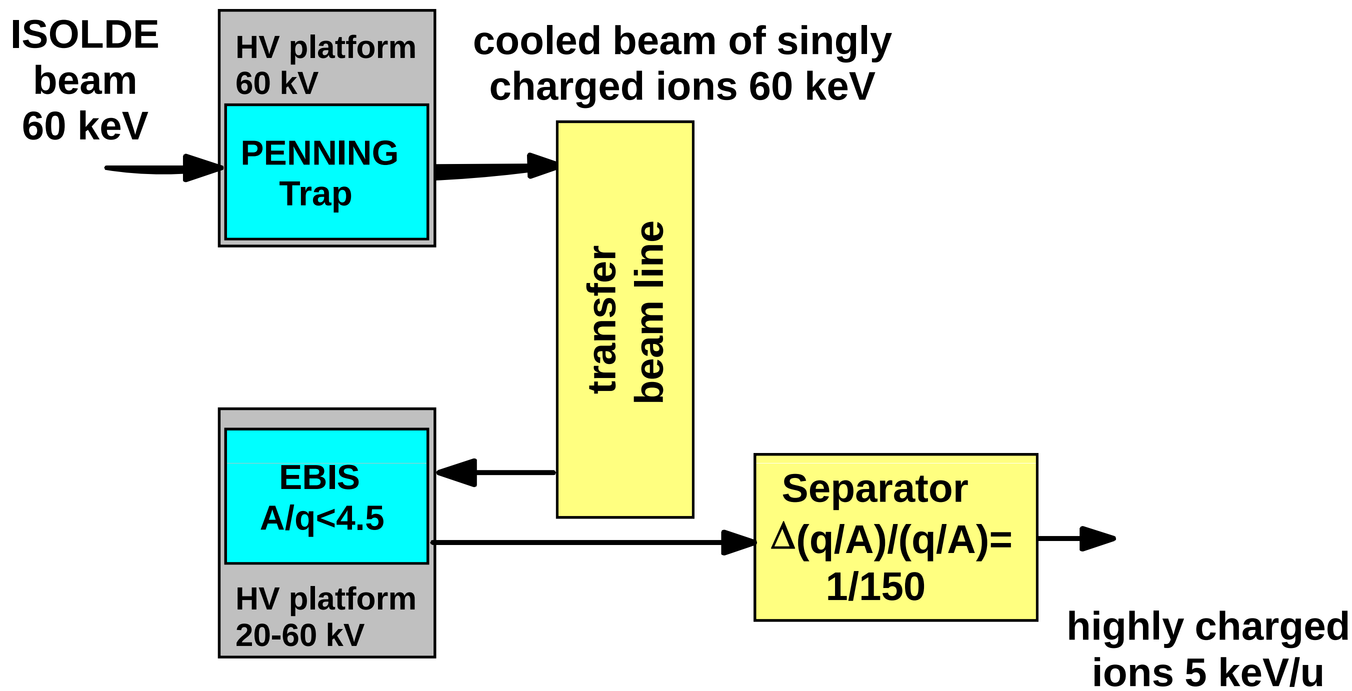
Electron Beam ion source (EBIS)



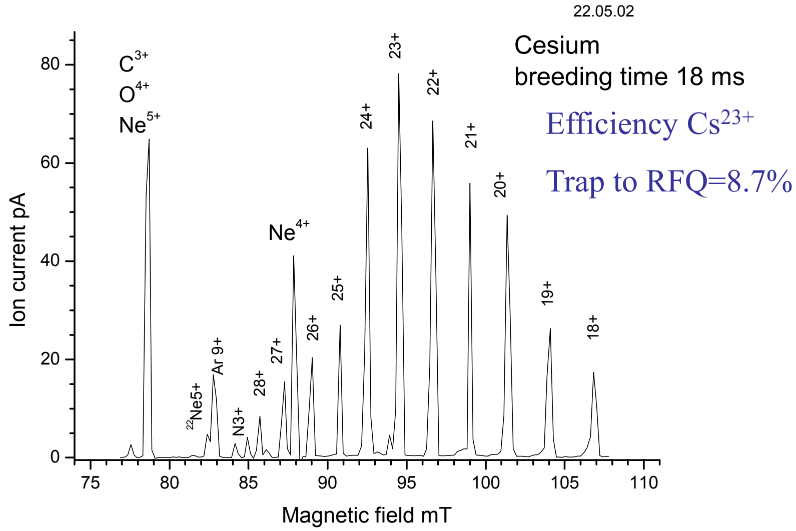
REXEBIS (ISOLDE – CERN)

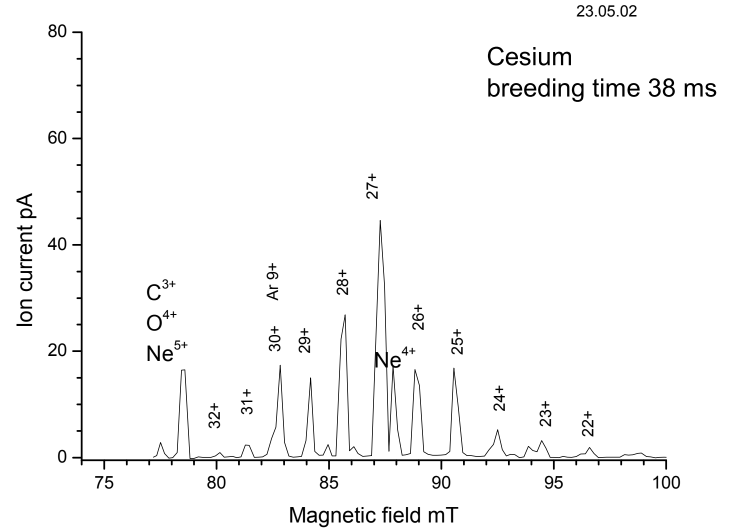
requires cooling and bunching of incoming beam (REXTRAP)

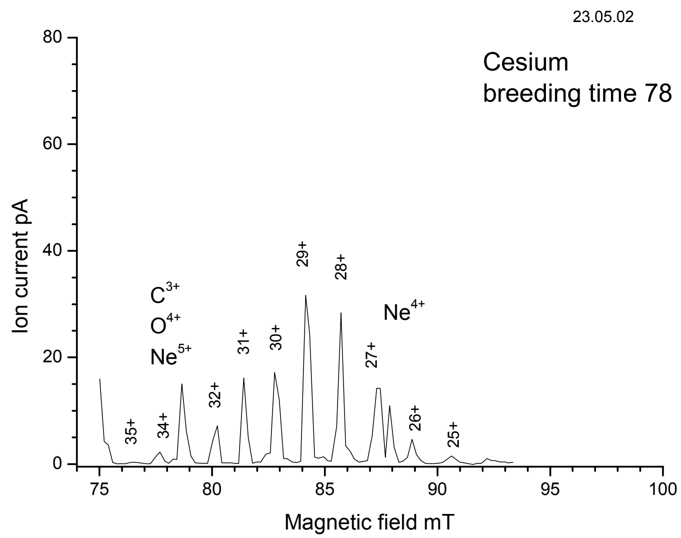
REXTRAP/REXEBIS charge breeding system

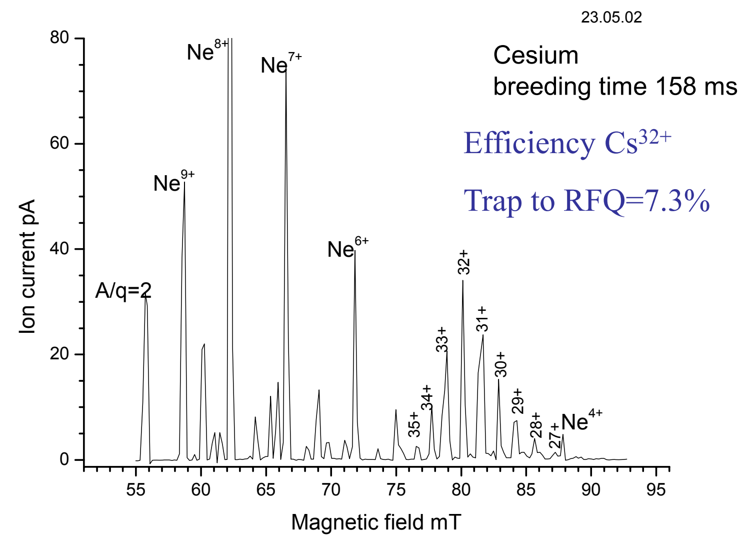


Charge breeding of ^{133}Cs









A selection of elements charge bred during the 2006 measurement campaign

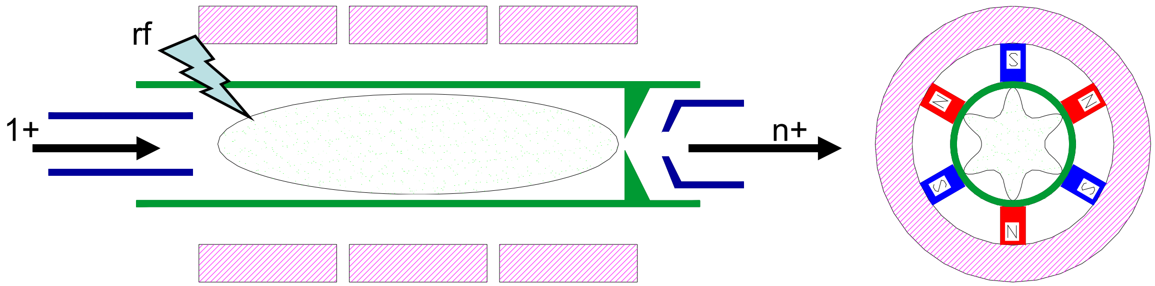
Element	A/q	Total eff. (%)	$T_{cool} + T_{breed}$ (ms)		Comments
$^{7}Li^{3+}$	2.333	6.0	20 + 18	Stable	
$^{9}Li^{3+}$	3.000	5.0	50 + 15	Radio	Low rep rate due to linac
$^{10}Be^{3+}$	3.333	5.0	50 + 15	Radio	Low rep rate due to linac
$^{19}F^{5+}$	3.800	7.8	20 + 7	Stable	
$^{23}Na^{9+}$	2.555	10.0	30 + 28	Stable	
$^{27}Al^{7+}$	3.857	>15	20 + 10	Stable	Injected to EBIS as AlF+ molecule
$^{29}Mg^{9+}$	3.222	6.0	30 + 28	Radio	Very large error bars
$^{39}K^{10+}$	3.900	15.0	20 + 12	Stable	
$^{65}Cu^{19+}$	3.421	11.1	100 + 68	Stable	
$^{65}Cu^{20+}$	3.250	7.8	100 + 68	Stable	Too short breeding time
$^{67}Cu^{19+}$	3.526	12.6	100 + 68	Radio	
$^{68}Zn^{21+}$	3.238	12.4	80 + 78	Stable	For 80Zn21+
$^{71}Cu^{20+}$	3.550	11.0	100 + 98	Stable	Large error → overestimated?
$^{116}Cd^{31+}$	3.742	9.6	250 + 248	Stable	For 124Cd30+ and 126Cd31+ run
$^{133}Cs^{33+}$	4.030	10.8	200 + 198	Stable	For 124Cd30+ and 126Cd31+ run
$^{136}Xe^{34+}$	4.000	8.7	200 + 198	Stable	For 144Xe34+ run
$^{181}Ta^{40+}$	4.525	2.9	200 + 198	Stable	Not optimum tuning
$^{238}U^{52+}$	4.577	4.3	500 + 498	Stable	

The total efficiency is the combined REXTRAP + REXEBIS + mass separator efficiency.

bunching and cooling efficiency ≈ 50%

F. Wenander, NIM B (2008) in press

Electron Cyclotron Resonance Ion Source (ECRIS)



PHOENIX ECR source:

$\nu_{rf} = 14.5\ \mathrm{GHz}$

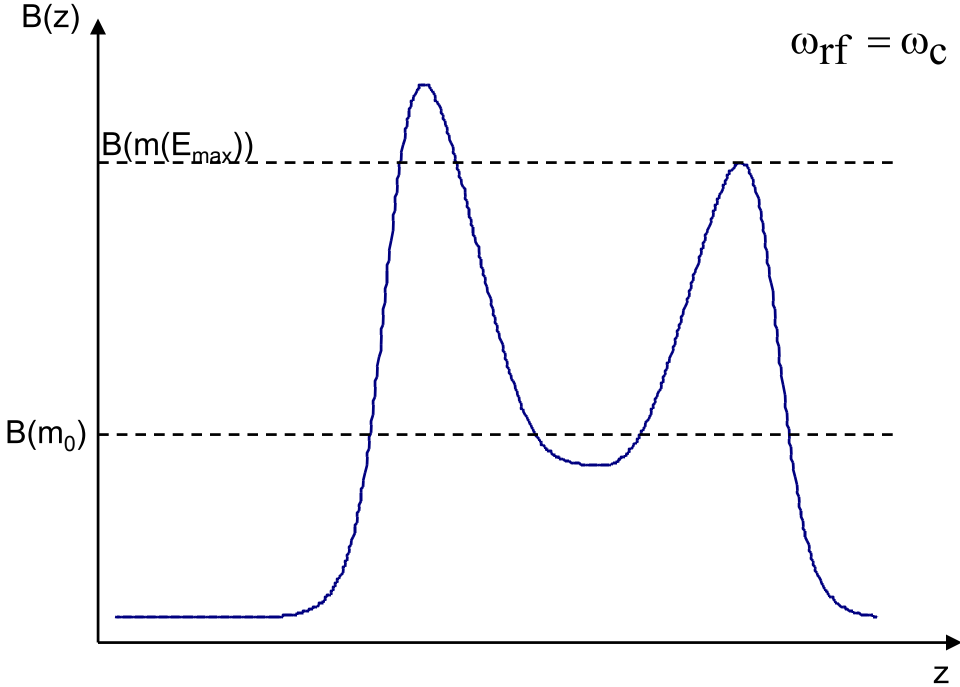
$\Rightarrow B(m_0) = 0.52\ \mathrm{T}$

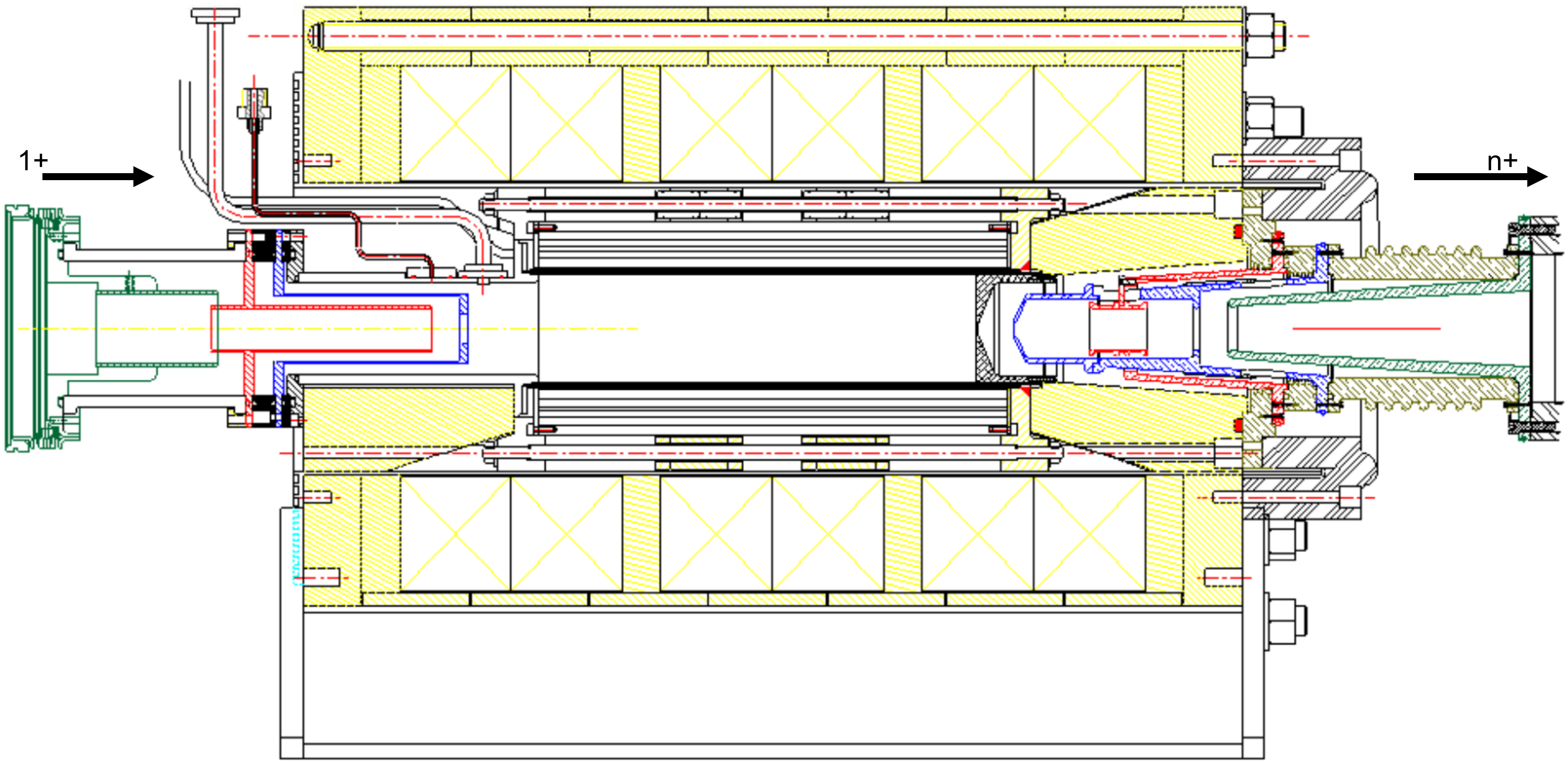
$B_{max} = 1.25\ \mathrm{T}$

$\Rightarrow E_{max} = 730\ \mathrm{keV}$

$n_e = 10^{11} \ldots 10^{12}\ \mathrm{cm}^{-3}$

$$\omega_{rf} = \omega_c = \frac{q}{m(E)} B$$





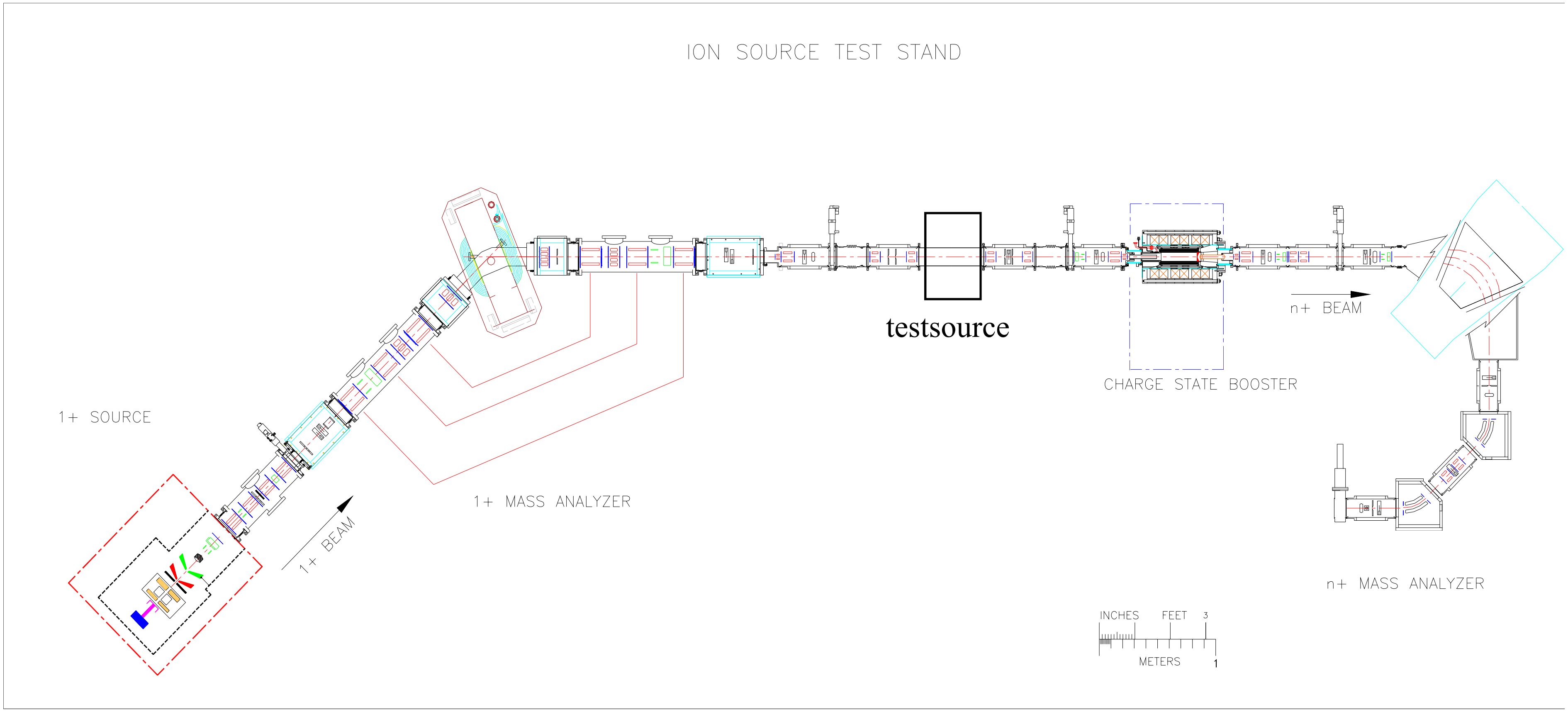
modified PHOENIX source for ISAC

2 step deceleration for the injection of singly charged ions

2 step acceleration scheme + Einzel lens focusing

for the extraction of the highly charged ions

CSB test stand at TRIUMF

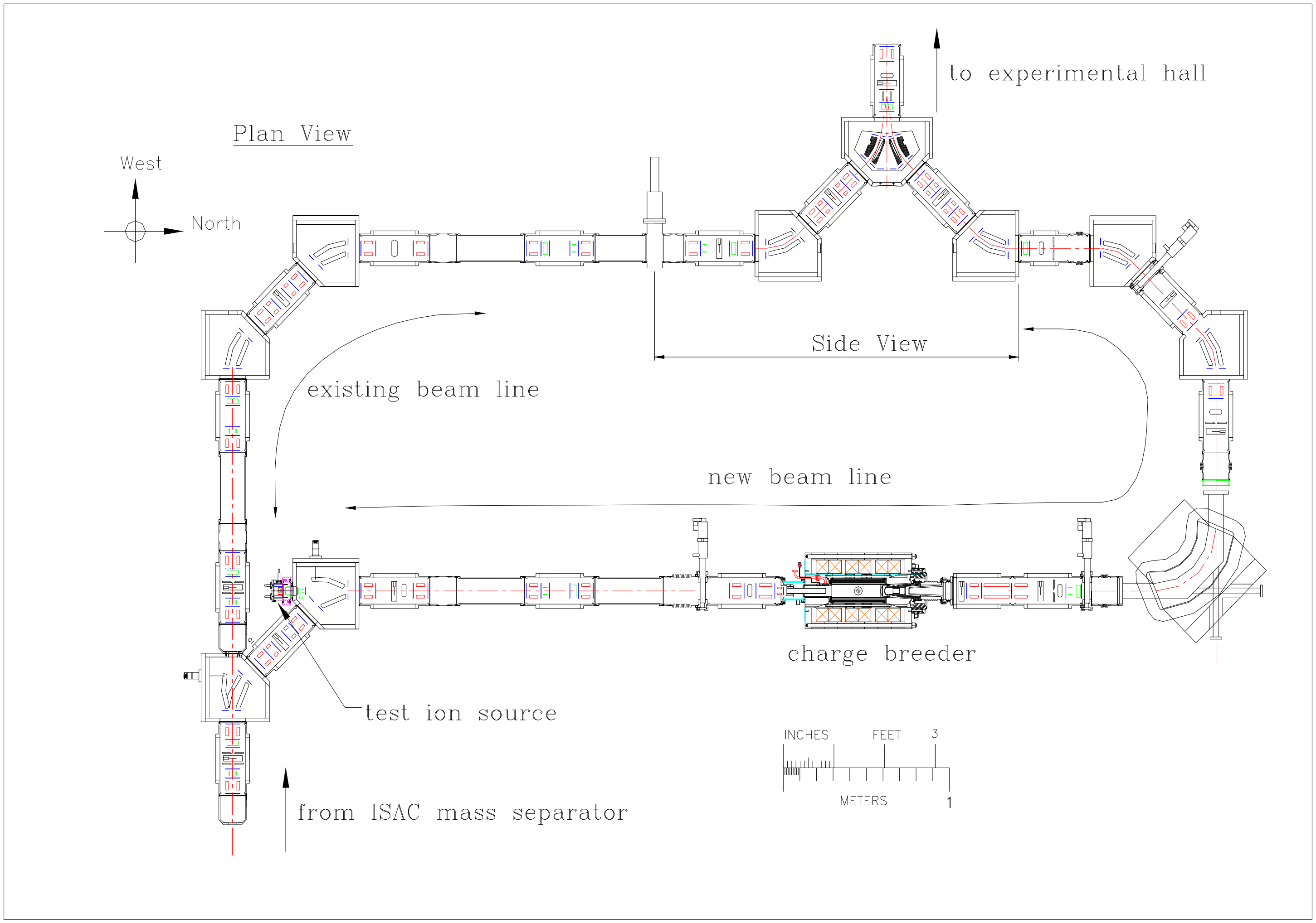


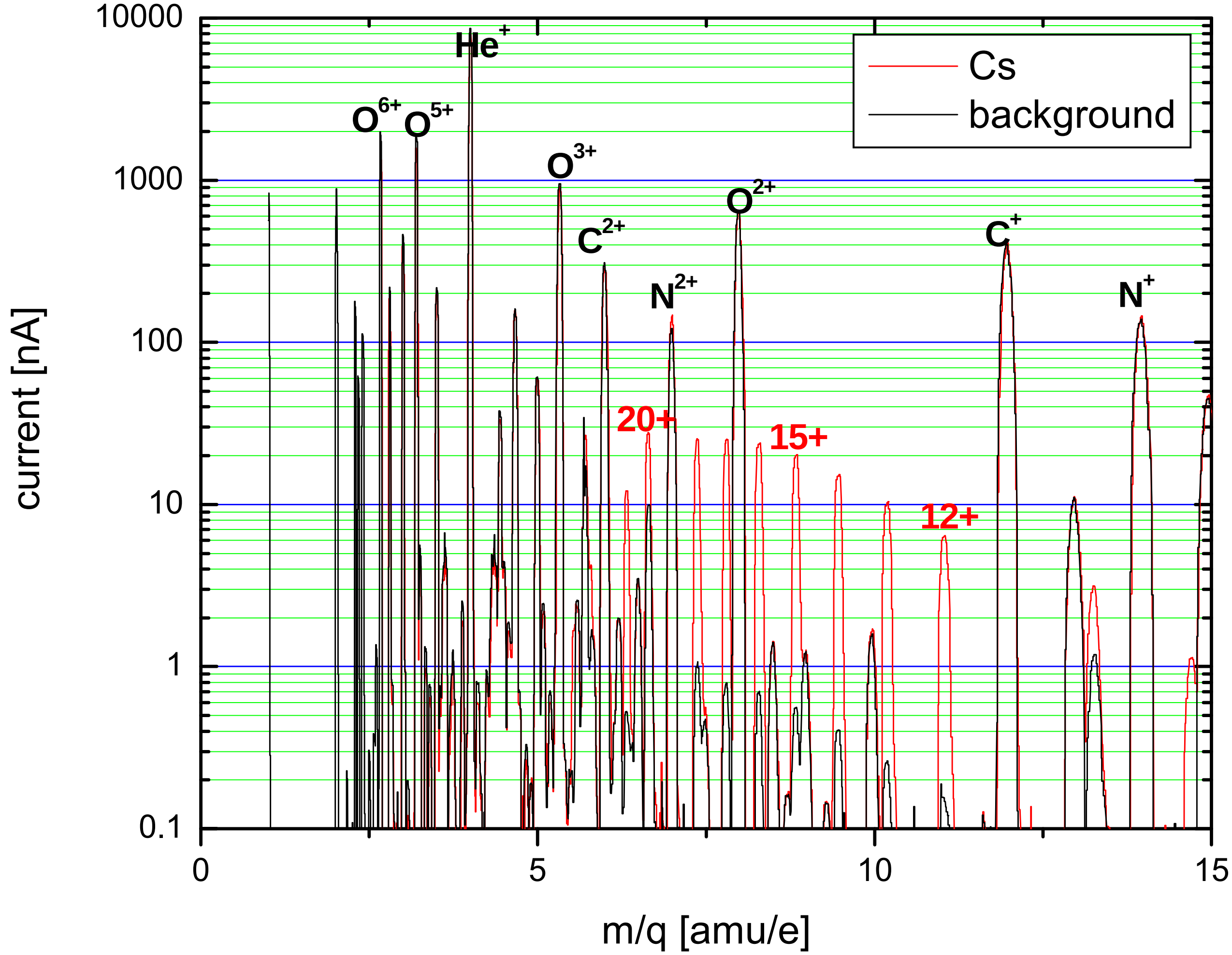
14.5 GHz ECR source PHOENIX from Pantechnik

elements measured : Ar, Kr, Xe from ECR ion source

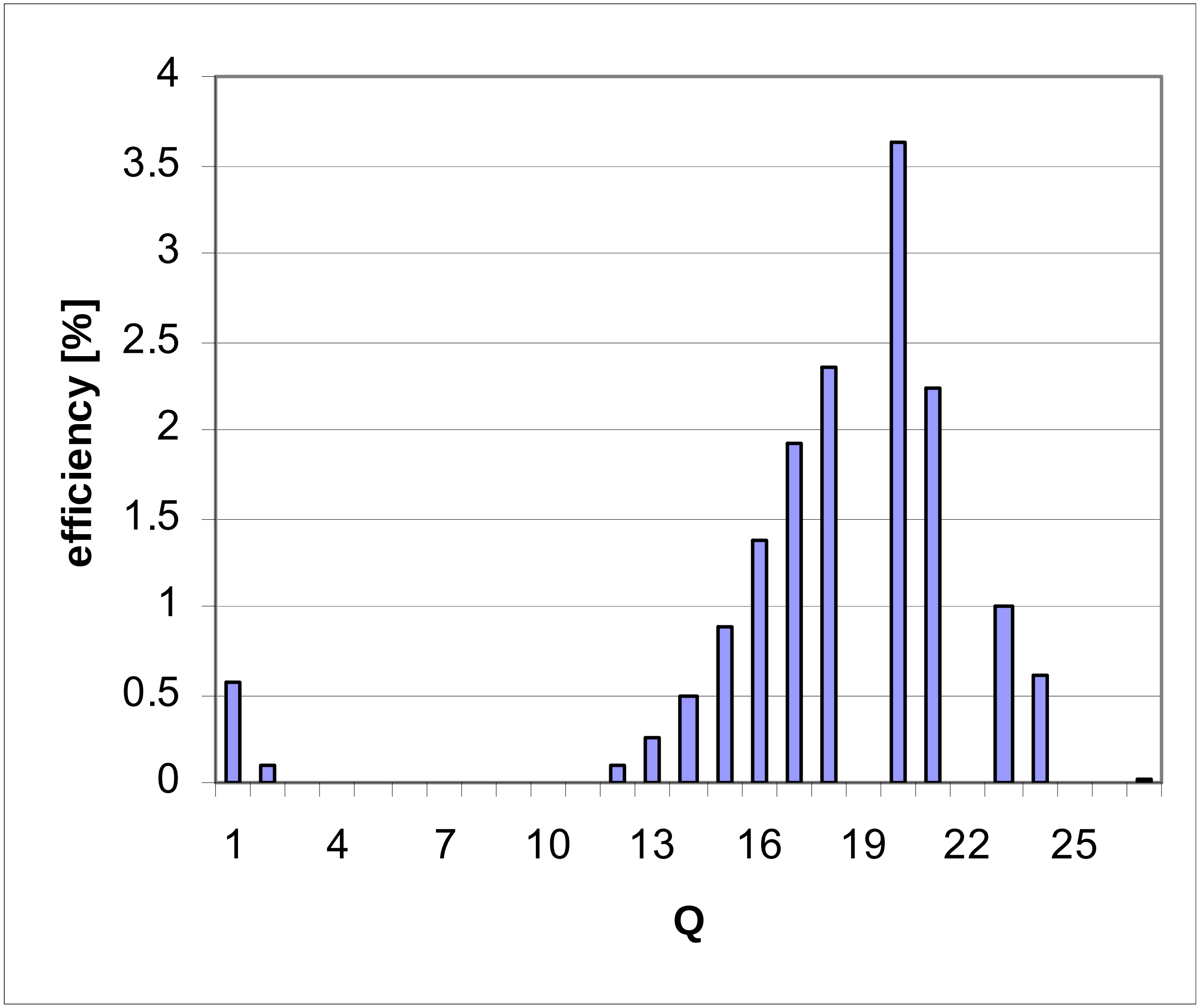
K, Rb, Cs from surface ion source

installation of the charge state breeder at ISAC





mass spectrum with and without Cs^+ injection (500 W rf power)



charge state distribution of Cs 15 nA Cs^{1+} injected
total efficiency >20%

charge breeder results from ISAC test stand

Measurements with ions from standard ISAC ion sources

Element	Mass	Charge state with maximum efficiency (A/Q)	Efficiency (%)	rise time (90%) for charge state with maximum efficiency (ms)	1+ ion source
Ar	40	8+ (5)	5.5	102	ECR
Kr	84	12+ (7)	6.3	401	ECR
Xe	129	17+ (7.6)	4.8	432	ECR
K	39	9+ (4.3)	2.1		surface
Rb	85/87	13+ (6.5)	3	230	surface
Cs	133	20+ (6.7)	3.5	300	surface + testsource

- emittance of Cs^{n+} measured < 20 π mm mrad @ 15q keV

ongoing developments

•EBIS/T

increase of electron beam current density

⇒higher capture efficiency
higher capacity
faster ionization

continuous mode operation
continuous injection, pulsed extraction at REXEBIS 2% for K^{10+}

selective ionization by adaptation of electron energy
dielectronic recombination
J.R. Crespo Lopez-Urrutia et al. Rev Sci. Instr. 75 (2004) 1560

TESIS (tubular electron string ion source)
⇒high efficiency
pulsed and continuous mode operation possible
E.D. Donets et al. Rev Sci. Instr. 75 (2004) 1566

ongoing developments (cont.)

•ECRIS

optimization of injection optics

⇒higher capture efficiency

increase of rf frequency and / or 2 frequency heating

⇒higher plasma density
capture efficiency
higher charge states
faster ionization

ultra high vacuum

⇒smaller background from residual gas
higher charge states

summary

	EBIS	ECRIS
state of the art	high charge states A/q ≈ 4	medium charge states A/q < 9
	fast x 10 ms	medium fast x 100 ms
	efficient EBIS alone ≈ 20%	efficient ≈ 3-10%
	pulsed semi continuous mode	continuous beams only long pulses (ms @ 1 Hz)
	pure beams	high beam contamination
	intensity limitation 10^9 /s	high intensity 10^{12} /s
	pre bunching and cooling necessary	
goals for developments	higher capacity higher efficiency selective ionization	higher efficiency faster breeding lower beam contamination higher charge states

thank you

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