Acceleration of Heavy Ions generated by ECR and EBIS

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OUTLINE

Ion production in ECR and EBIS is governed by the same collision physics, however with different weights:

1) Stepwise electron impact ionization for producing highly charged ions

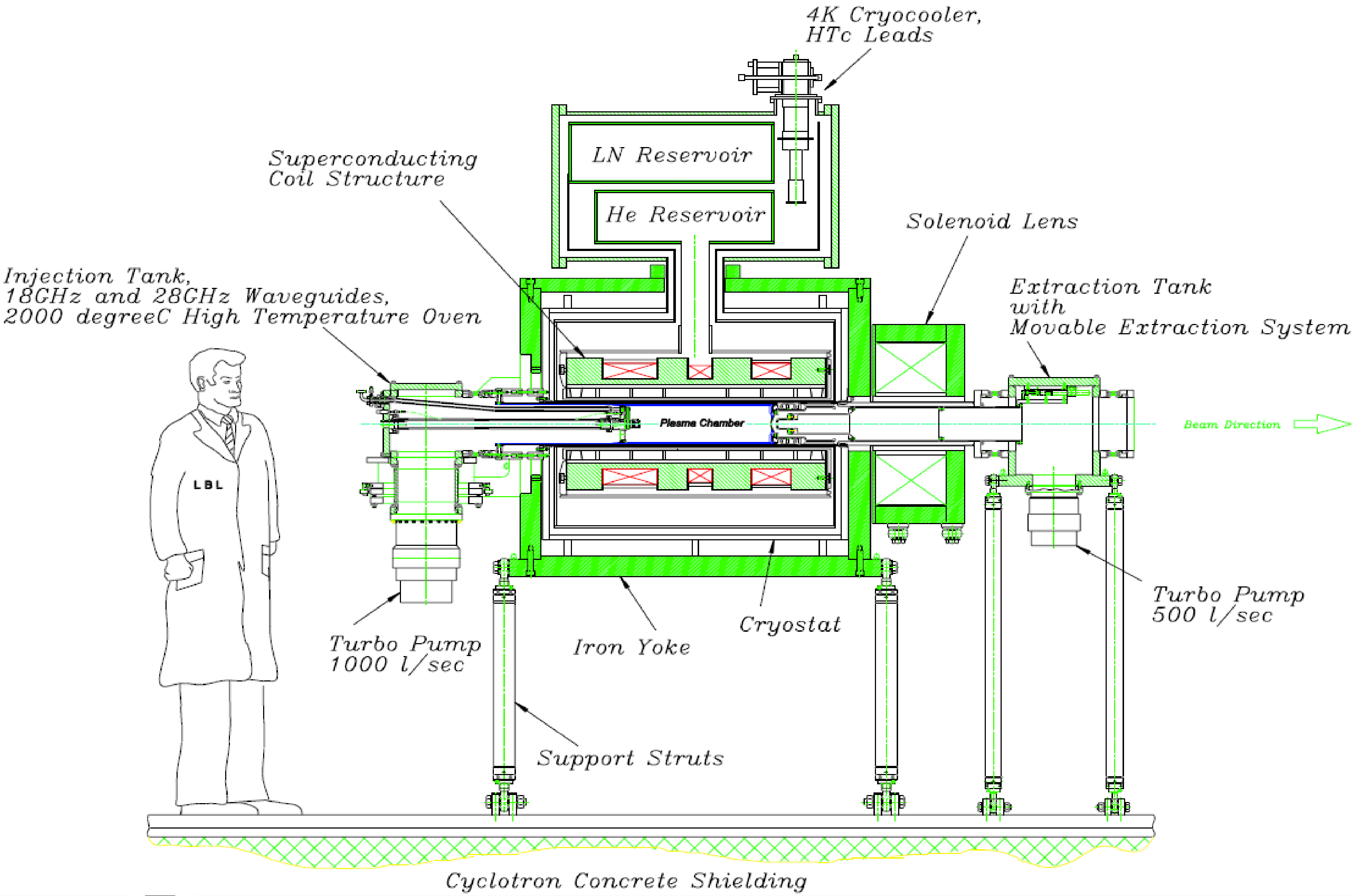
2) Charge exchange limits the highest charge states

3) Radiative Recombination (RR) asks for highest electron energies

4) Ion heating by small angle elastic Coulomb collisions raises emittances

5) ion-ion-cooling (gas mixing) improves high charge state performance

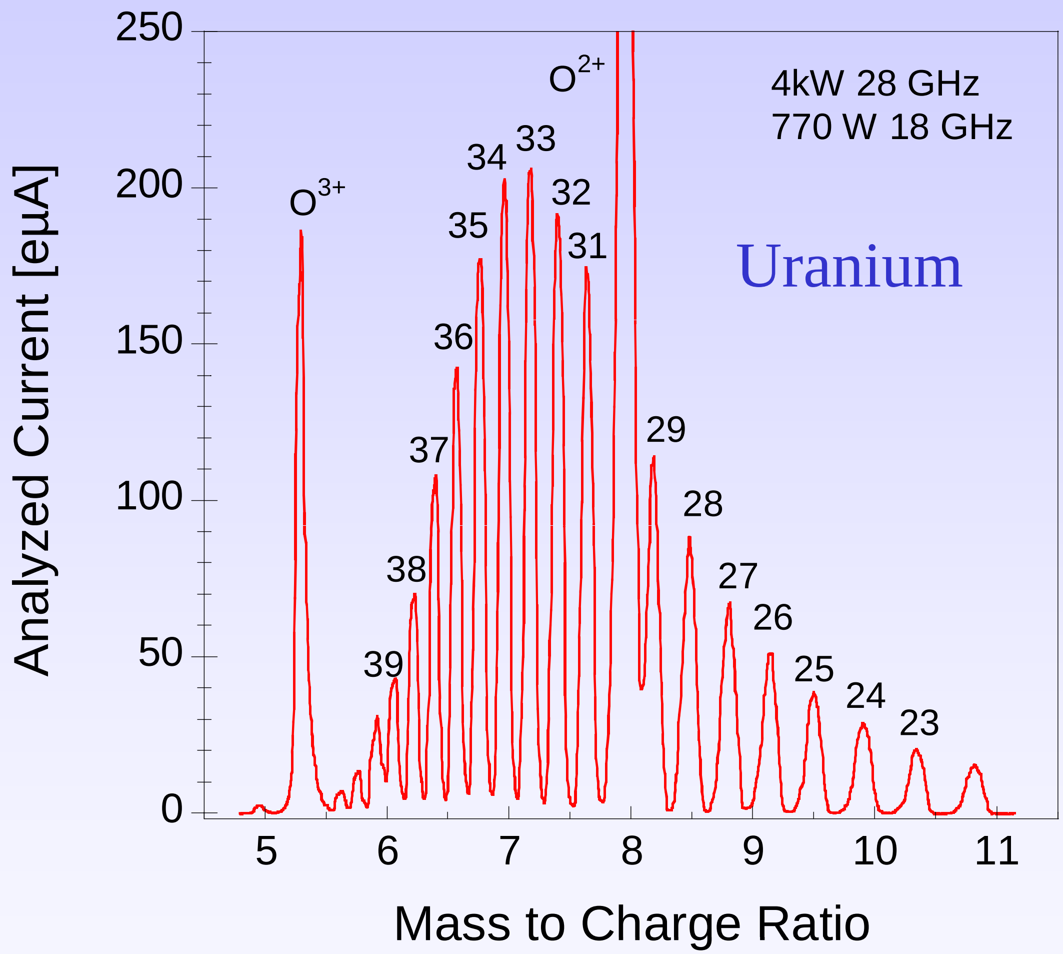
The magnetic emittance requires careful design of the LEBT, especially for ECRs.


4K Cryocooler,
HTc Leads
LN Reservoir
He Reservoir
Superconducting
Coil Structure
Solenoid Lens
Injection Tank,
18GHz and 28GHz Waveguides,
2000 degreeC High Temperature Oven
Extraction Tank
with
Movable Extraction System
LBL
Plasma Chamber
Beam Direction
Turbo Pump
500 l/sec
Turbo Pump
1000 l/sec
Iron Yoke
Cryostat
Support Struts
Cyclotron Concrete Shielding

Recent Results with VENUS in comparison
with other high performance sources
SECRAL: IMP, Lanzhou, Zhao et al.
GTS: Grenoble, Hitz et al.

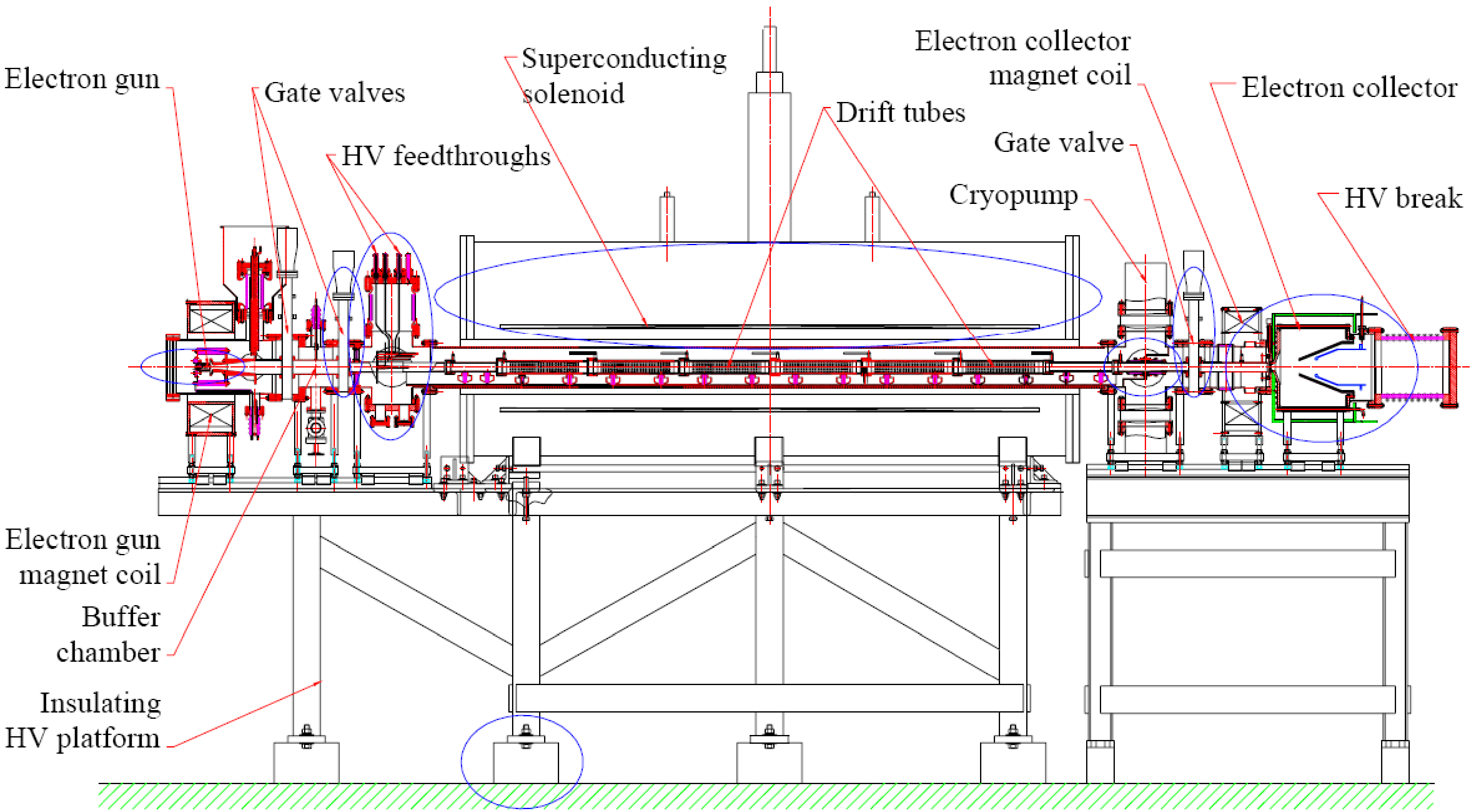
Venus results

		VENUS	*SECRAL*[3,8]	*GTS*[11]
f(GHz)		*28 or18 +28*	*18*	*18*
^{16}O	6^+	2850	2300	1950
	7^+	850	810	
^{40}Ar	12^+	860	510	380
	14^+	514	270	174
	16^+	270	73	50
	17^+	36	8.5	4.2
	18^+	1		
^{129}Xe	28^+	222		120
	29^+	168		*
	30^+	116	101	60
	31^+	86	68	40
	34^+	41	21	8
	37^+	12	5	
	38^+	7	2.4	
	42^+	.4		
^{238}U	33^+	205		
	34^+	202		
	35^+	175		
	47^+	5		
	50^+	1.9		



Daniela Leitner et al.

example: RHIC EBIS test setup



E. Beebe et al.

Oliver Kester, CB06, 22.-24.05.06, Darmstadt, Germany

example: RHIC EBIS test setup

	Achieved	RHIC
Ion	Au^{32+}	Au^{32+}
I_e	10 A	10 A (20)
J_e	~575 A/cm^2	575 A/cm^2
$t_{confinement}$	35 ms	35 ms
L_{trap}	0.7 m	1.5 m
Capacity	0.51×10^{12}	1.1×10^{12}
Au neutralization	70%*	50%
% in desired Q	20%	20%
Extracted charge	55 nC	85 nC
Ions/pulse	1.5×10^9 (Au^{32+})*	3.3×10^9 (Au^{32+})
Pulse width	10-20 μs	10-40 μs

B field of test EBIS solenoid: 5 T
B field of RHIC EBIS solenoid: 6 T

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Charge balance

$$\frac{dn_i}{dt} = n_e \upsilon_e \left[\sigma^{ion}_{i-1\to i}\, n_{i-1} - \left(\sigma^{ion}_{i\to i+1} + \sigma^{RR}_{i\to i-1} \right) n_i + \sigma^{RR}_{i+1\to i}\, n_{i+1} \right]$$

$$- n_o \upsilon_{ion} \left[\sigma^{chex}_{i\to i-1}\, n_i - \sigma^{chex}_{i+1\to i}\, n_{i+1} \right]$$

$$- \nu_i^{coll} \frac{\exp\left\{ -\dfrac{ieU_w}{kT_{ion}} \right\}}{\dfrac{ieU_w}{kT_{ion}}} n_i$$

Growth by ionisation

Loss by ionisation

Loss by radiative radiation

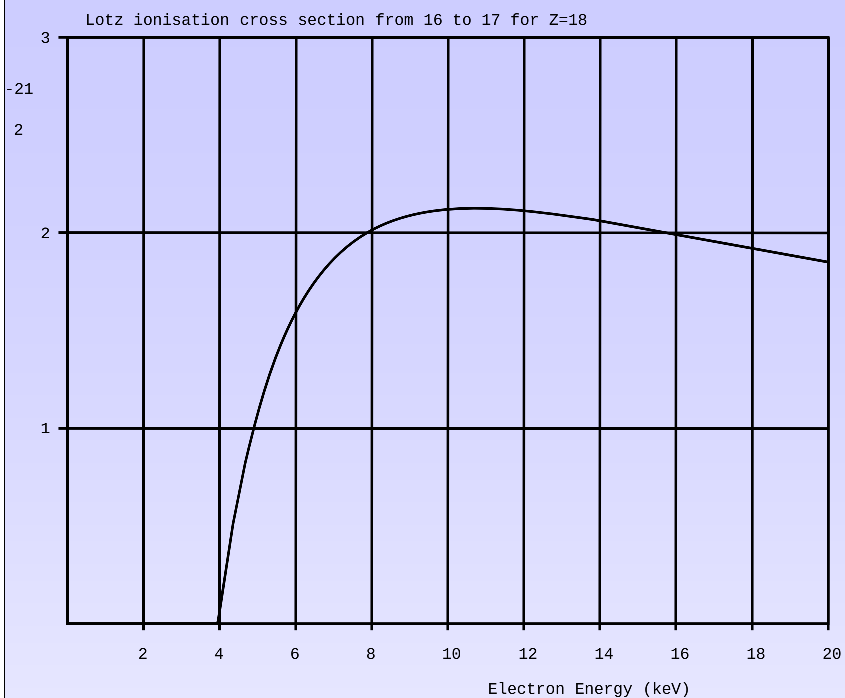
Win from radiative radiation

Loss by charge exchange

Win frim charge exchange

Loss of confinement of heated ions

$Ar^{15+} \rightarrow Ar^{16+}$ x 10^{-21} cm^2

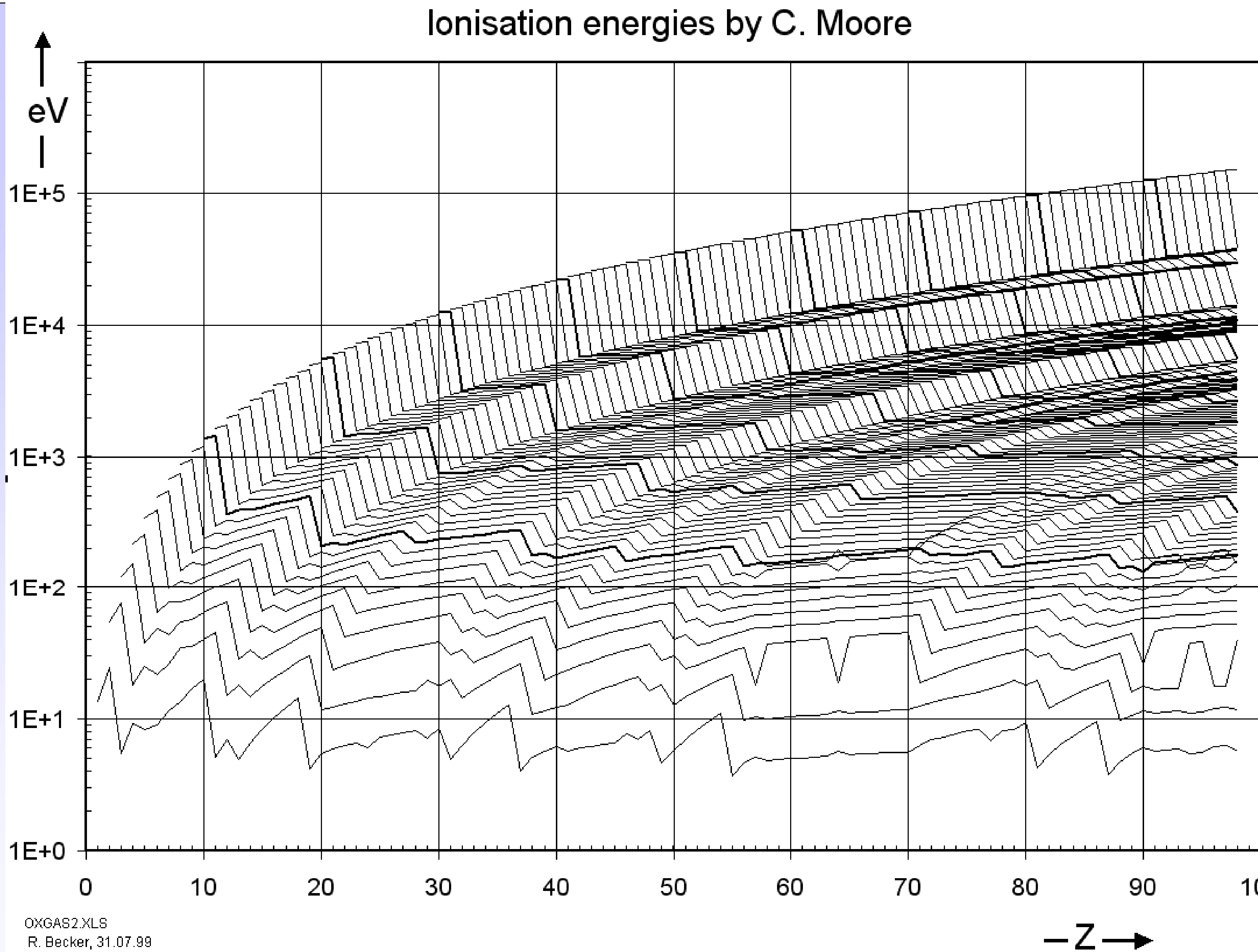


Lotz cross sections

Approximate ionisation energies,
ionisation cross sections
and required jτ-values for bare ions

Ion	E_i [eV]	σ [cm^2]	j*τ [Cb/cm^2]
C^{6+}	490	$7.7*10^{-20}$	2.1
N^{7+}	666	$4.2*10^{-20}$	3.8
O^{8+}	870	$2.4*10^{-20}$	6.5
Ne^{10+}	1360	$1*10^{-20}$	16
Ar^{18+}	4400	$9.5*10^{-22}$	170
Kr^{36+}	17600	$6*10^{-23}$	2700
Xe^{54+}	39700	$1.2*10^{-23}$	13600
Pb^{82+}	91400	$2.2*10^{-24}$	72300
U^{92+}	115000	$1.4*10^{-24}$	115000

$$\sigma_{i \rightarrow i+1} = 4.5*10^{-14} \sum_{nl} \frac{\ln\left\{E_e / E_{i,nl}\right\}}{E_e * E_{i,nl}} \quad \left[cm^2\right]$$


Ionisation energies by C. Moore
eV
1E+5
1E+4
1E+3
1E+2
1E+1
1E+0
0
10
20
30
40
50
60
70
80
90
10
OXGAS2.XLS
R. Becker, 31.07.99
Z

Charge exchange

The approximation formula of Salzborn and Müller is based on many measurements with low chage states, however, we have nothing better!

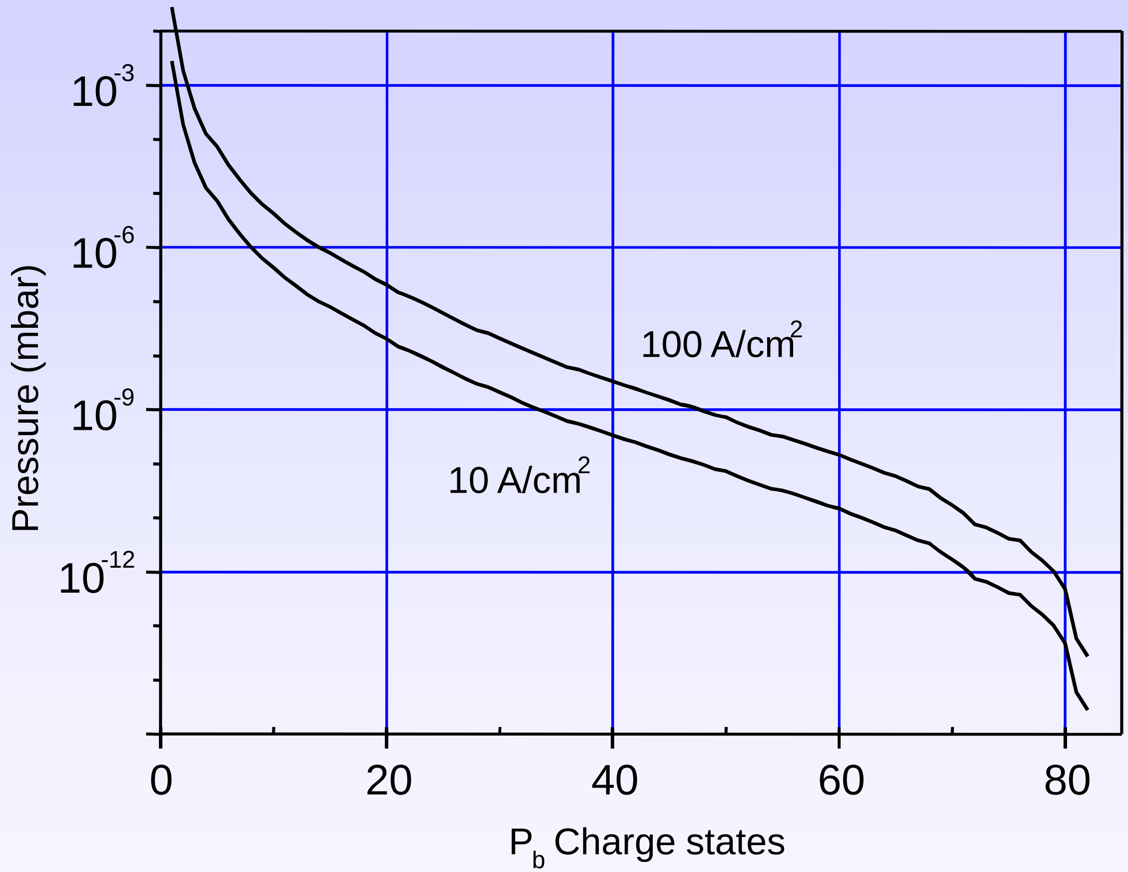
$$\sigma_{i \to i-1} = 1.43 \times 10^{-12}\, i^{1.17}\, P_0^{-2.76} \quad [cm^2]$$

In EBIS/T the pressure usually is low enough to avoid CX, only dangerous for extremely high charge states, where ion cooling becomes necessary.

In ECRs CX usually limits the build up if higher charge states and produces the wide range of charge state with almost identical abundance.

Charge exchange versus Ionisation

Vacuum pressure at which gain by ionization equals the loss by charge exchange for lead ion



Radiative Recombination

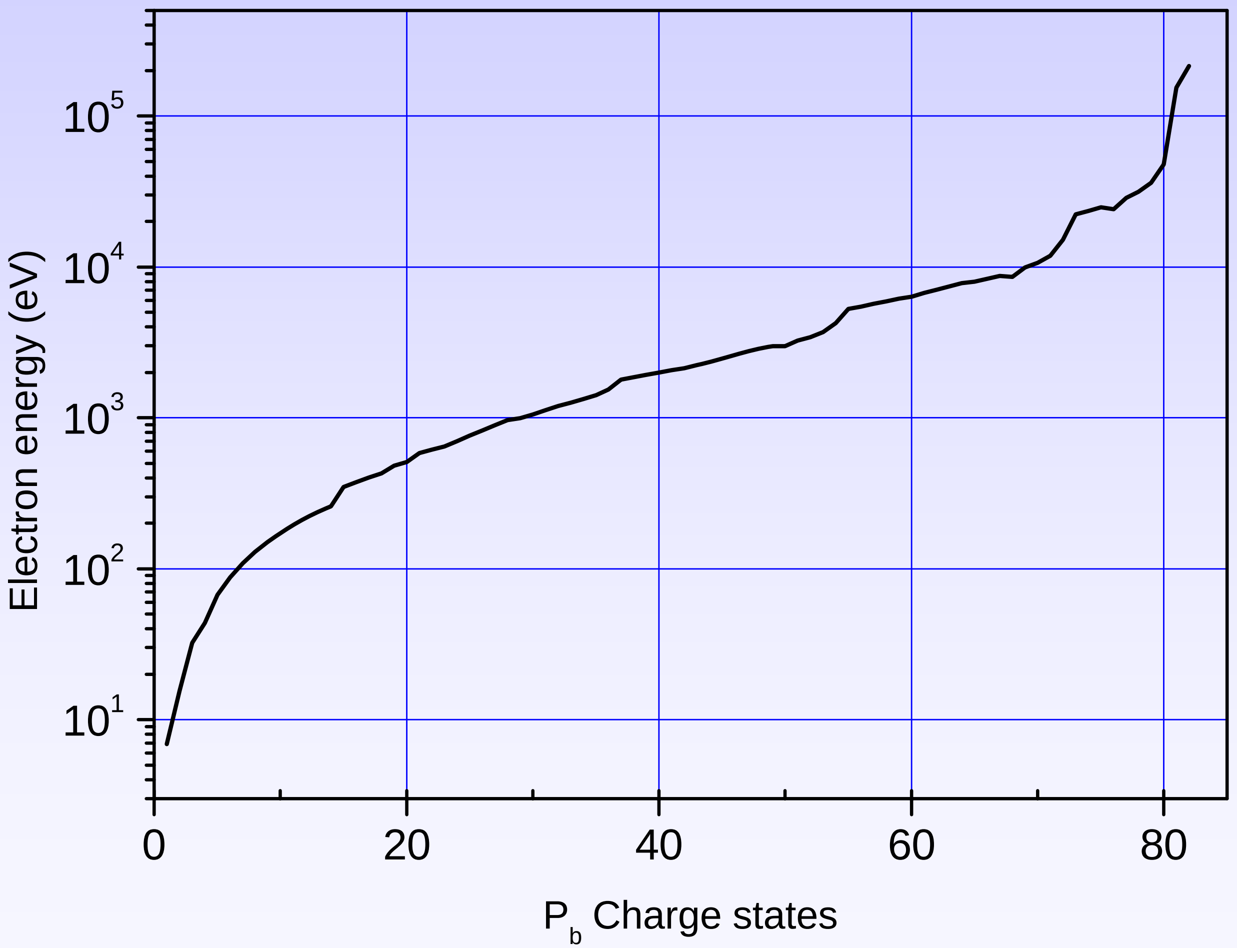
RR is time-reversed photo-ionisation. Therefore RR cross sections may be calculated from cross sections for photo ionisation, which is a well established procedure (T. Stöhlker) :

$$\sigma_{\mathrm{nl}}^{\mathrm{ph}}(k) = \left(\frac{4\pi\alpha a_0^2}{3}\right)\frac{n^2}{Z^2}\sum_{l'=l\pm1}\frac{l_>}{2l+1}(1+n^2\kappa^2)\times\left|g(n,l;\kappa,l'\right|$$

$$\sigma_{nl}^{RR}(k) = \frac{(h\nu)^2}{k^2}\frac{1}{2m_e c^2}\sigma_{nl}^{ph}(k)$$

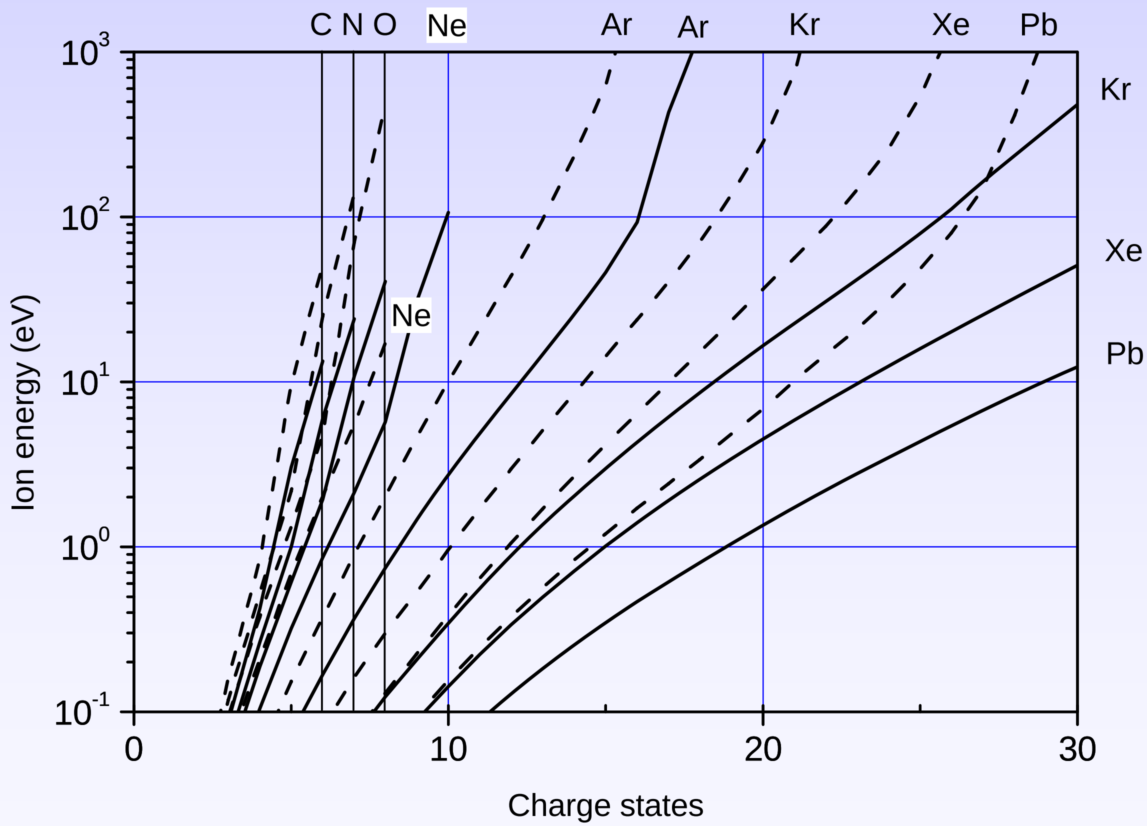
RR versus Ionisation

"Balance energy" at which the gain by ionization equals loss by radiative recombination for lead ions

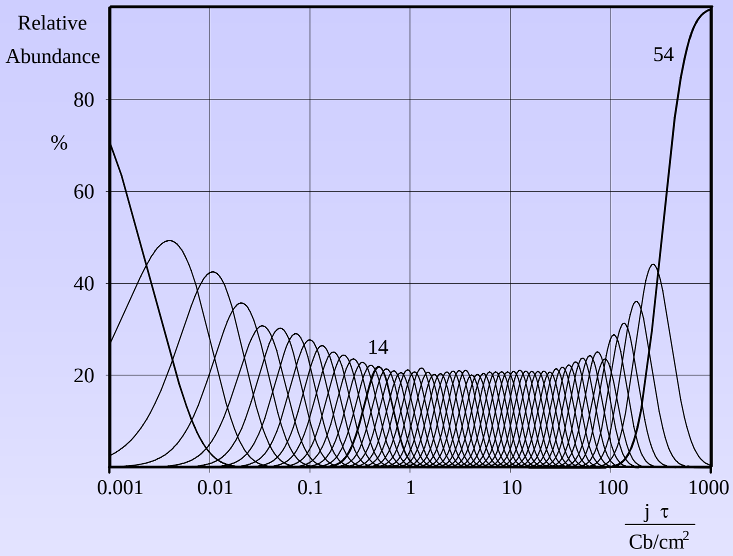


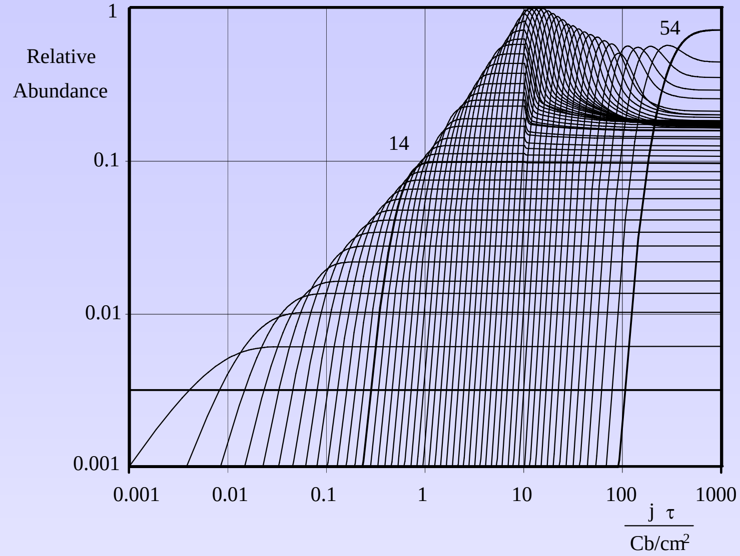
Heating

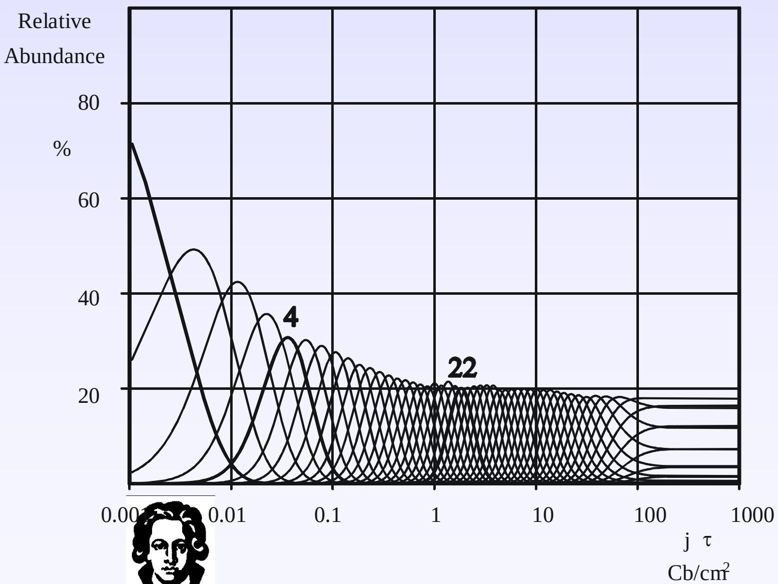
Radial well voltages $eqU_{-w}=kT_i$ to trap multiply charged ions heated by electrons of energy 1 keV (dashed lines) and 10 keV (full lines), typical for ECR and EBIS/T

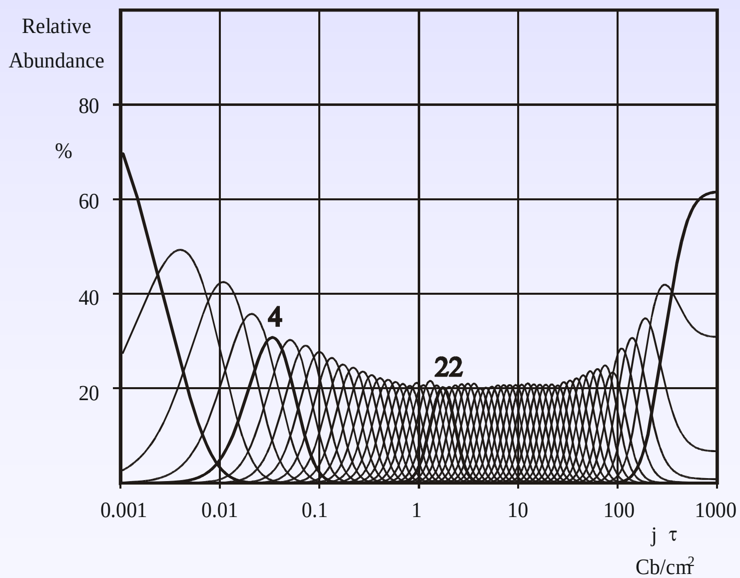


Results of CBSIM

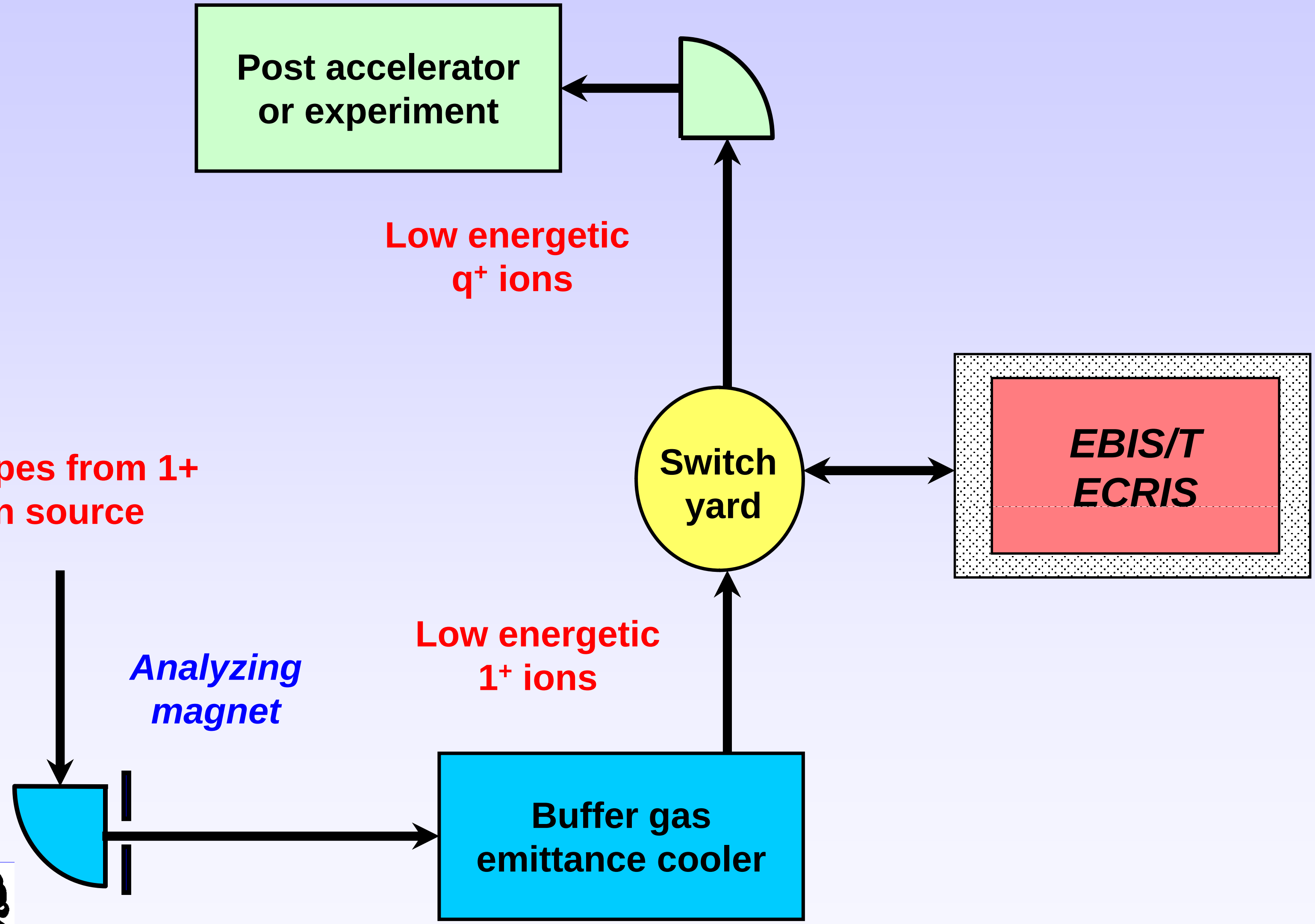








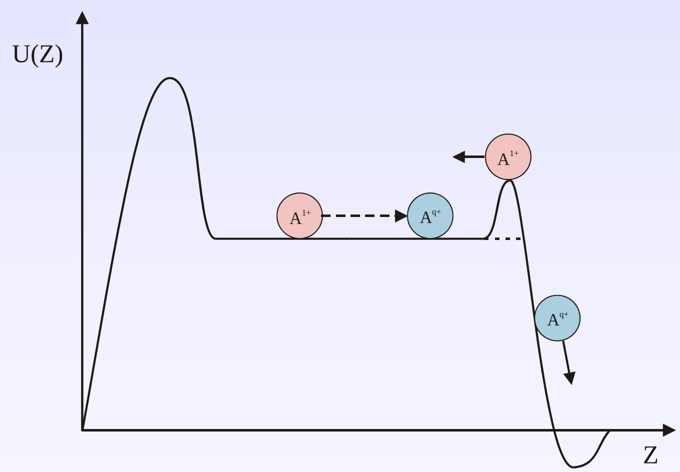
Charge state breeder setup



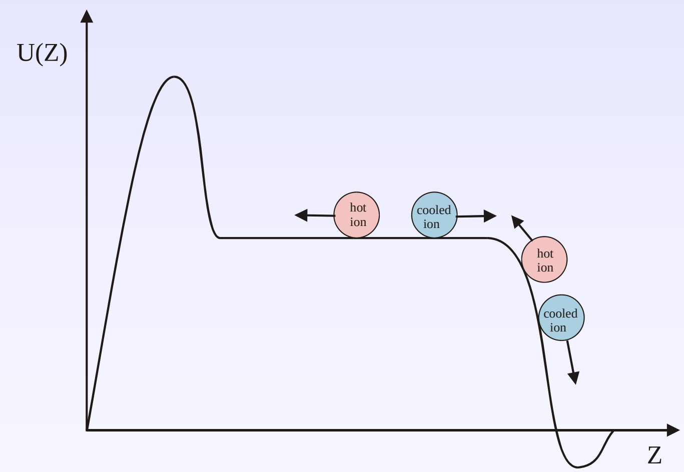
Charge breeding

ECRs and EBIS have become popular as „charge breeders“. Nevertheless these are still ion sources for highly charged ions, but the problem of generating simple or difficult or rare singly charged ions has been „outsourced“ – leave the hard work to the specialist !

ACCU-EBIS



TOFEBIS-COOLER



R. Becker, Proc. EPAC 1992, Berlin, March 24-28

Magnetic Emittance

The conservation of the magnetic moment (Busch's theorem) results in skew trajectories outside of the magnetic field. When this beam is treated as a round one, it has a considerable „magnetic" emittance:

$$\varepsilon_{abs} = \frac{\pi}{4}\sqrt{\frac{2eq}{M}}\,\frac{Br^2}{\sqrt{U_0}} \quad [m]$$

For modern ECR and EBIS B_z=3T and U_0=20 kV. For bare nuclei we then obtain:

r (m)	ε_{abs} (m)
10^{-3}	5.2×10^{-6}
10^{-2}	520×10^{-6}

Note that dimension m for the emittance gives the same numbers as the old fashioned mm x mrad *)

EBIS beam are usually smaller than 1 mm, therefore the magnetic emittance will be negligible in contrast to ECRs, where special attention must be given to transport such a beam through a LEBT, especially, when this is including an analyzing magnet for mass separation.

*) R.Becker and W.B.Herrmannsfeldt, Rev. Sci. Instrum.**77** (2006) 03B907

Accelerator applications

ECR is an intense dc source, with afterglow also for ms pulses

EBIS is an intense pulsed source –exceeding ECRs in pulse current and charge-to-mass - ratio. Dc beams at low intensity have ultra-low emittances.

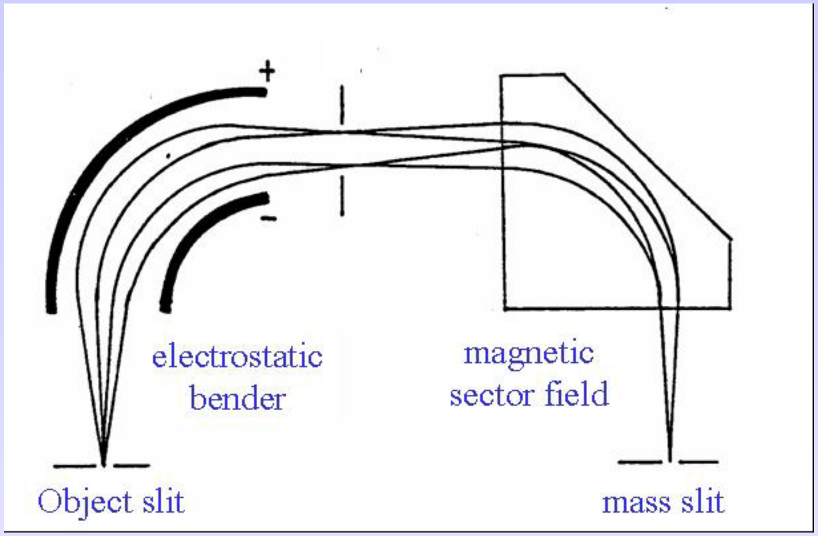
ECR, dc beams: cyclotrons (all over the world)

ECR, pulsed beams: Synchrotrons (CERN, NIRS, GSI)

EBIS, pulsed beams: Synchrotrons (Dubna, BNL)

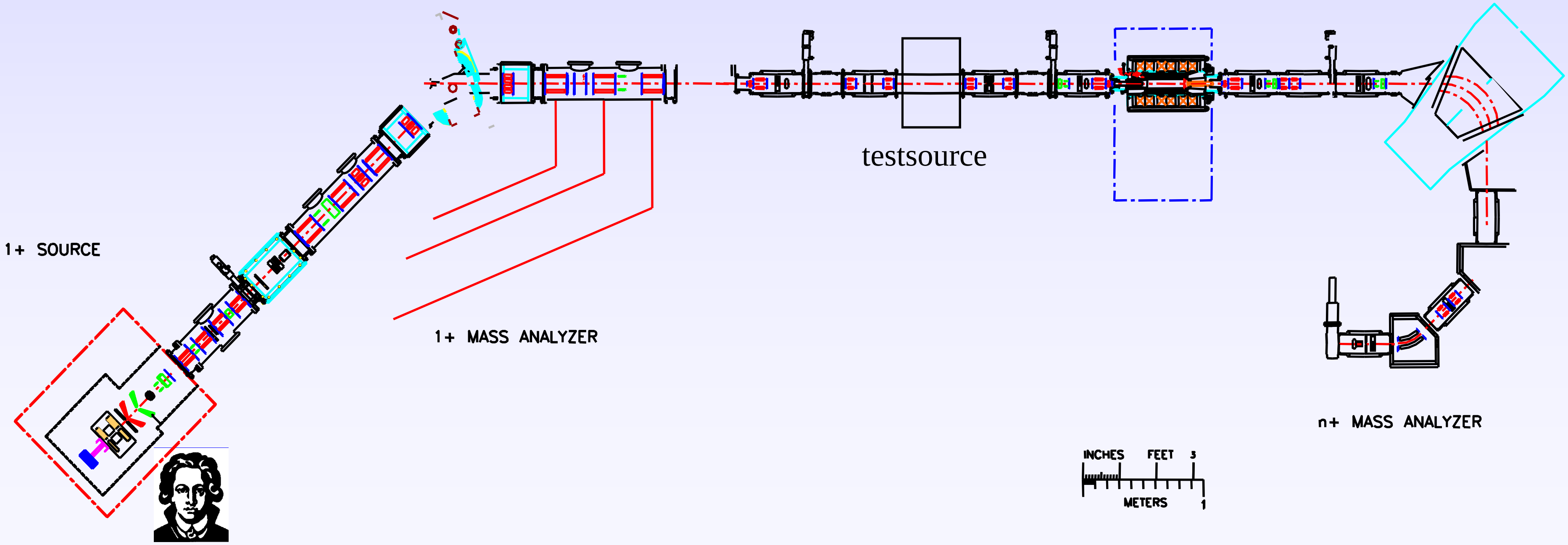
EBIS, dc beams: atomic physics studies (Frankfurt, SNLL, KSU)

Charge selection in LEBT



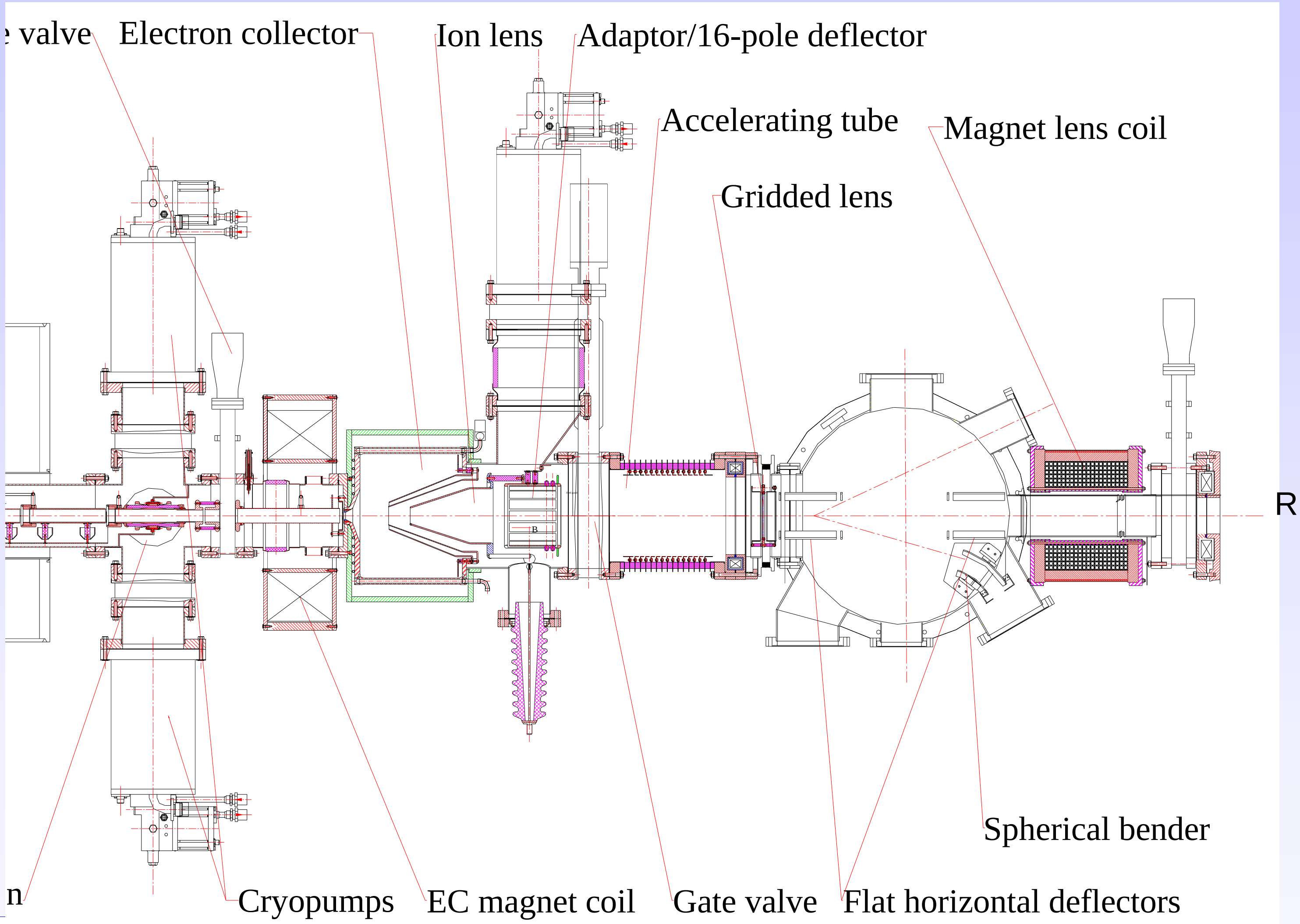
EBIS:
- REX-ISOLDE
- MSU ReA3

ECRIS:
- TRIUMF charge state booster



BNL LEBT without charge selection

EBIS
TRAP



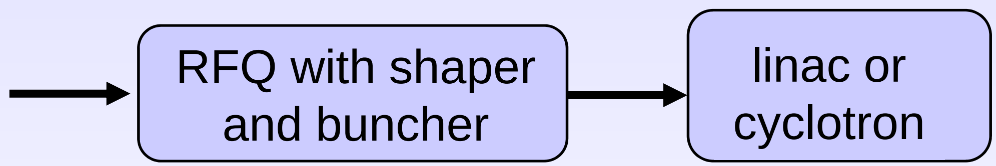
Matching to the accelerator

pre-bunching scheme

ISAC facility (TRIUMF), ReA3 (MSU)

HMI (Berlin)

RFQ-bunching scheme



REX-ISOLDE (CERN)

GSI (High charge state injector), BNL (RHIC EBIS injector)

Conclusions

EBIS and ECR are complementary ion sources for accelerators, either as primary sources or as charge state breeders:

EBIS is naturally a pulsed source with high intensity (mA) in short (10 – 100 μs) pulses of highest charge states.

ECR are naturally dc sources of high intensity for medium charge states.

The atomic collision physics is the same in both sources, however with different influence of charge exchange and radiative recombination, due to vacuum pressure and electron energy distribution.