Can 5 A, 150 keV, 20 kA/cm2 be attained practically in a charge breeder?

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Conclusions

It can be done !

Outline

A beam of 5 A, 150 kV, 20 kA/cm^2

Brillouin Flow vs. Immersed flow

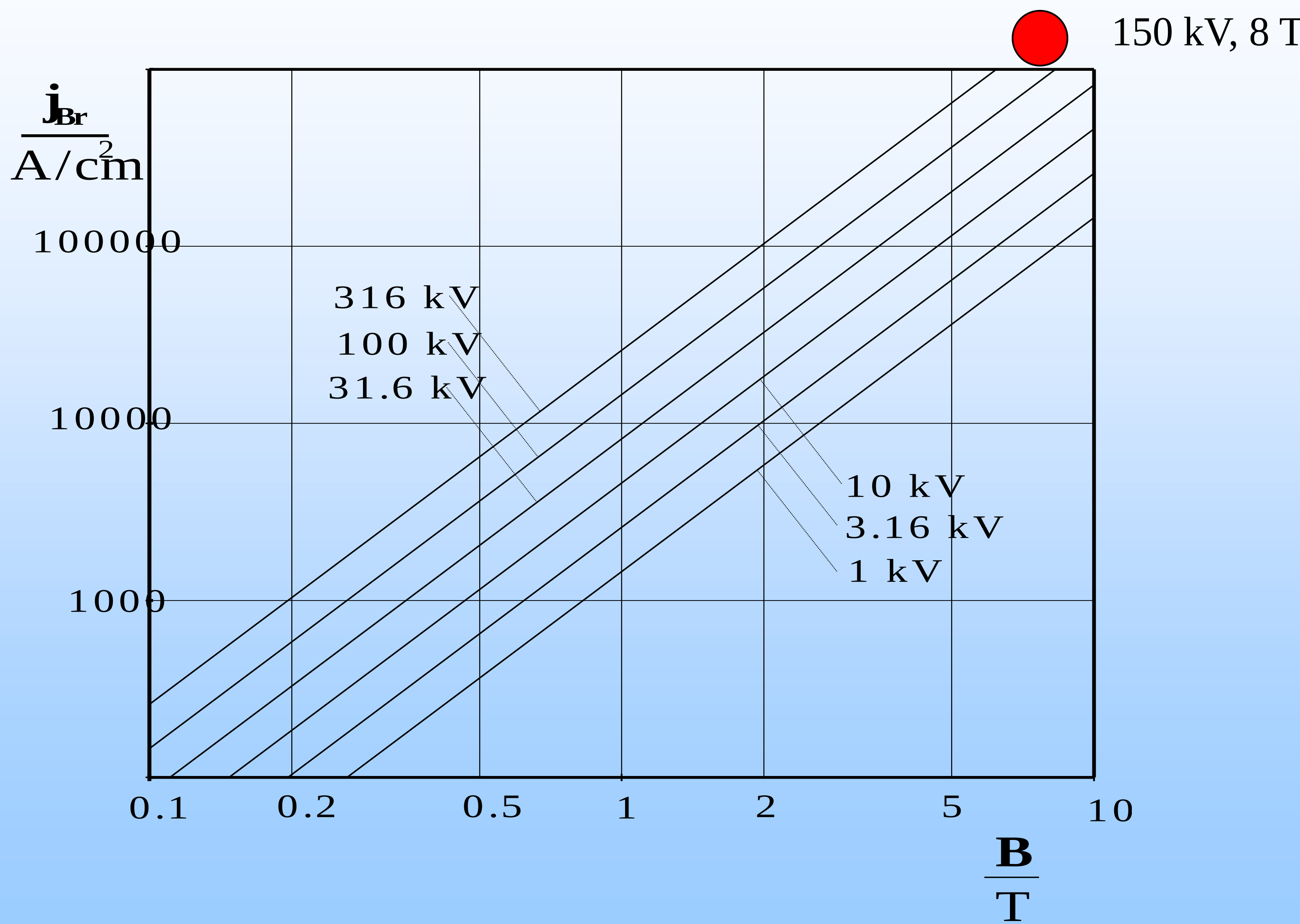
Design ideas for a charge breeder

Properties of a 5A, 150 kV, 20 kA/cm^2 beam

ΔU	= 196 V	say 200 V		
r_b	= 0.009 cm	say 0.1 mm		
r_t	= 1 cm		10 cm	
$U_t - U_0$	= 2963 V	say 3000 V	3884 V	say 4000 V
$(r_c/r_b)^2$	= 667 with 30 A/cm^2 emission from cathode (LaB_6 111)			
r_c	= 0.23 cm	say d_c = 0.5 cm		
T_b	= 133 eV			
P	= 8.607 x 10^{-8} A/V$^{3/2}$			
$B_{Br,b}$	= 1.06 T,	$B_{Br,c}$	= 0.041 T	(ratio $\sqrt{667}$ = 26)
$B_{Im,b}$	= 8 T,	$B_{Im,c}$	= 0.012 T	(ratio 667)
β=v/c	= 0.634, $\gamma = m/m_0$ = 1.294, $1-\beta^2$ = 0.598			

Brillouin flow

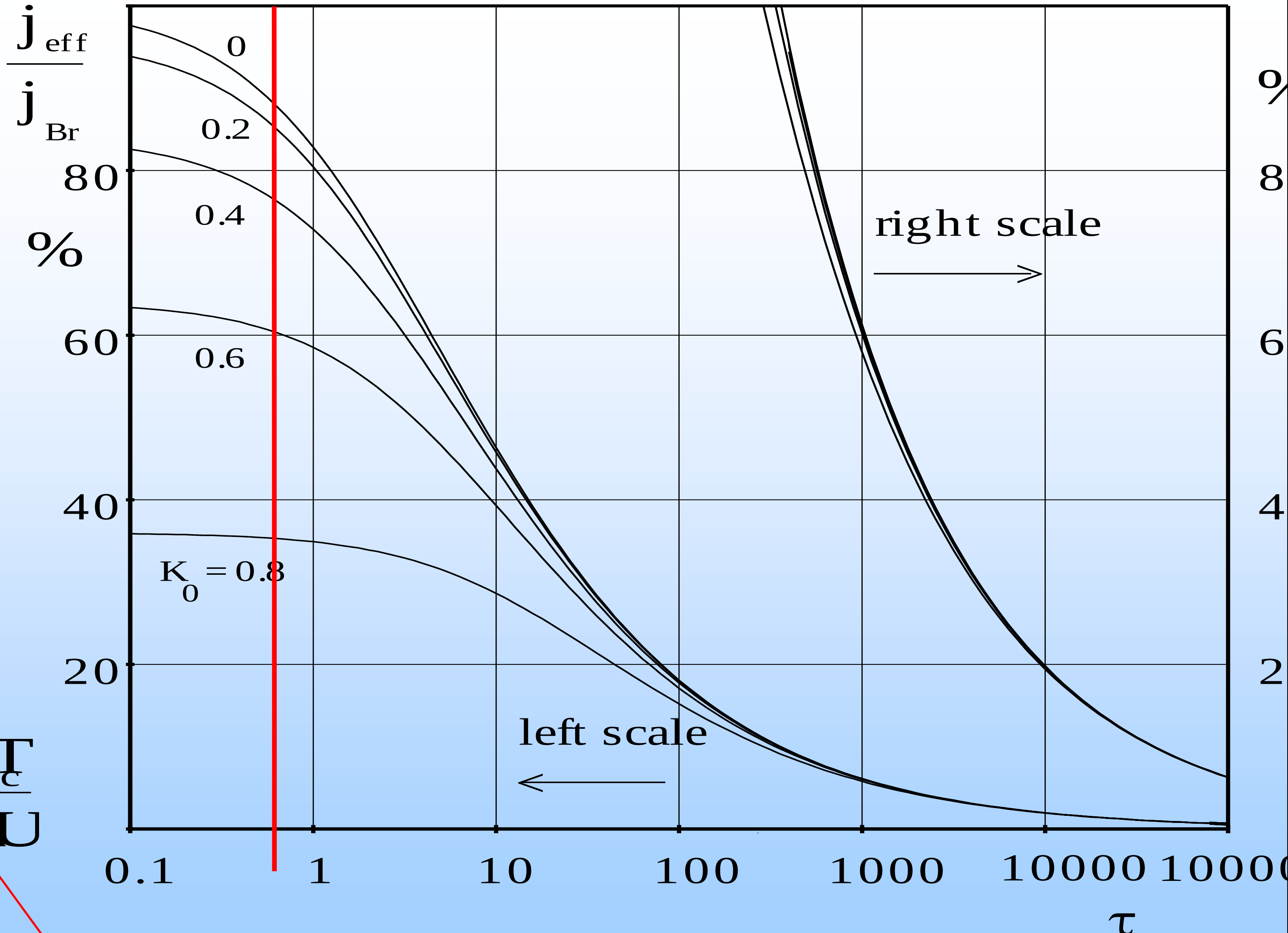
$$j_{Br} = \varepsilon_0 \frac{e B^2}{2m} \sqrt{\frac{2e_0}{m}}$$



From Handbook of Ion Sources, ed. B. Wolf, CRC Press, 1995, ISBN 0-8493-2502-1

However:

At 8 T and 150 kV a current density of 10^6 A/cm^2 is deduced from the plot. This high current density, however, is not accessible, because cathodes can deliver only 30 A/cm^2, needing an area compression in the rising magnetic field of about a factor of 667. By this, the transverse temperature of the beam will increase accordingly, resulting in a beam being dominated by transverse thermal motion. Herrmann has given a formula to calculate the required increase of the magnetic field in order to overcome the tranverse thermal behaviour. Fögen has shown, that the optical thermal treatment of Herrmann predicts the same increase of magnetic field as the statistical thermal theory of Pierce and Walker in order to obtain a certain current density inspite of thermal effects. Amboss used the Herrmann theory to calculate the radius of a thermal beam, that contains 80% of the current. His result can be put in a simple form to show the degradation of current density by cathode flux and transverse temperature:



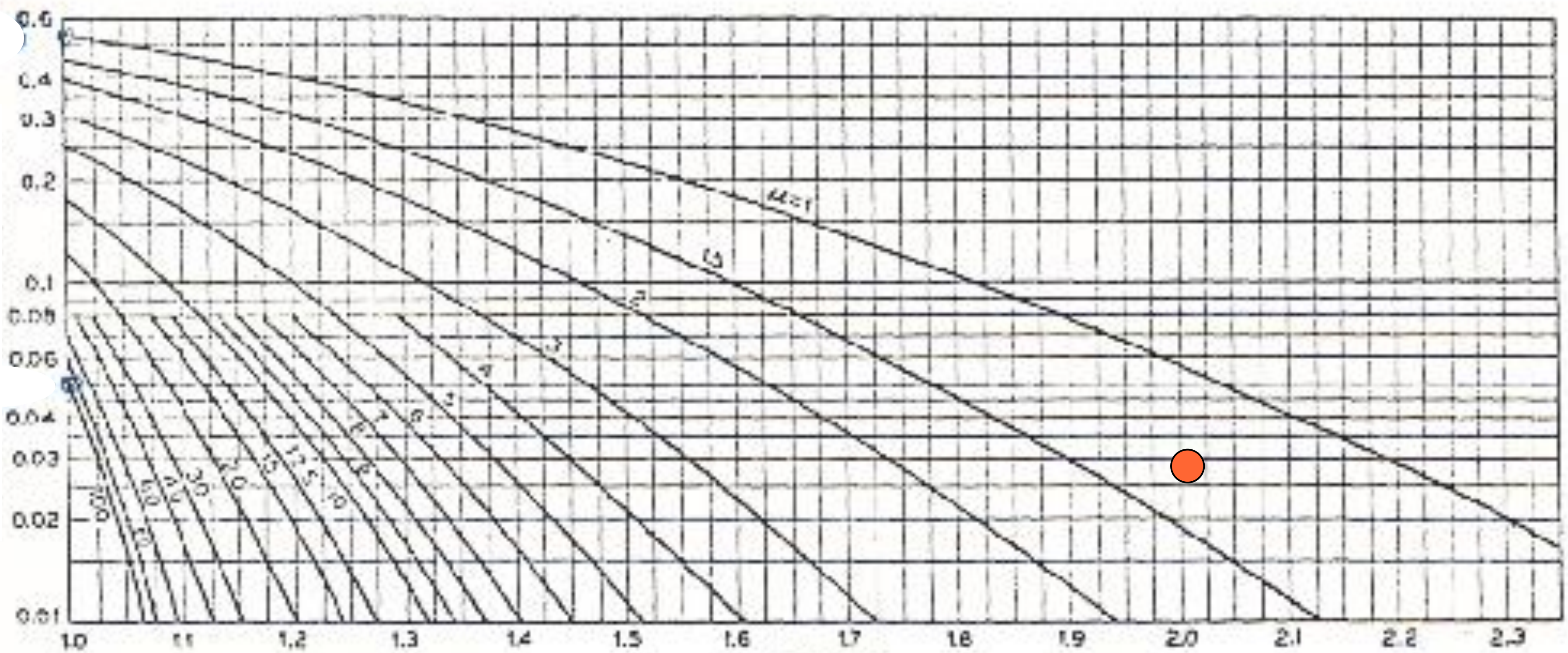
$$K_0 = \frac{B_c r_c^2}{B r_0^2}$$

$$\tau = \frac{r_c^2}{r_0^2} \frac{kT_c}{e\Delta U}$$

667 X 0.2/200 = 10^{-3} = 0.667

From Handbook of Ion Sources, ed. B. Wolf, CRC Press, 1995, ISBN 0-8493-2502-1

Pierce and Walker calculated the fraction of a thermal beam that is found outside of the “cold“ Brillouin radius.



The parameter μ is the potential depression over the beam temperature, which is about 1.33 for the 5 A, 20 kA/cm² beam under consideration. 3% of the beam is outside of twice the beam radius which is about 0.1 mm.

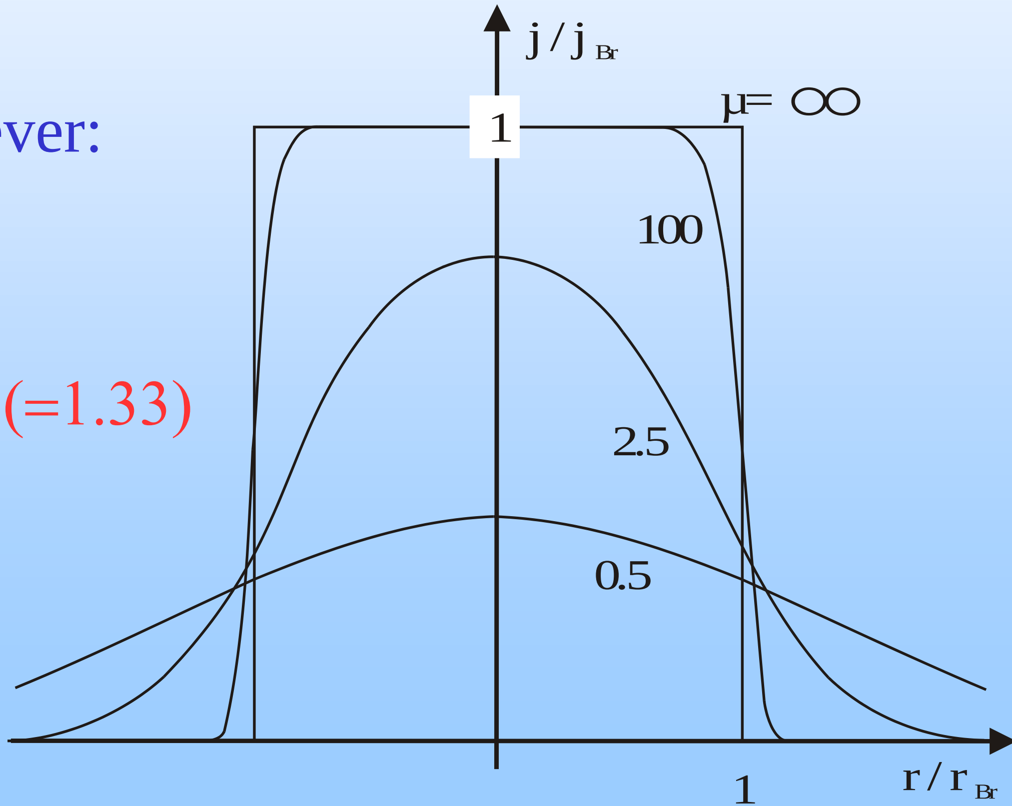
J.R. Pierce and L.R. Walker, “Brillouin Flow“ with Thermal Velocities, J.Appl. Phys. 24,10 (1953) 1328

How about Brillouin Flow at 5A, 20 kA/cm^2 at 150 kV?

A single crystal LaB_6 cathode emitting 30 A/cm^2 at about 1800 K requires a compression of 667 which increases the transverse electron energy to about 133 eV. In a beam with ΔU=200V the normalised beam temperature τ will become 0.67 and the focused current density will be decreased to 90 % of the Brillouin density, strongly dependent of the cathode flux. This does not look so bad!

However:

$\mu = 1/\tau$ (=1.33)



thermal profiles have considerable amount of electrons outside of the beam radius!

Bad for an EBIS

Bernd Fögen, Thesis, IAP, Frankfurt 1985

How many electrons can reach the drift tubes?

The radius of gyration for 150 keV electrons is 0.16 mm. This prevents even scattered electrons with maximal energy to reach the drift tube without many collisions.

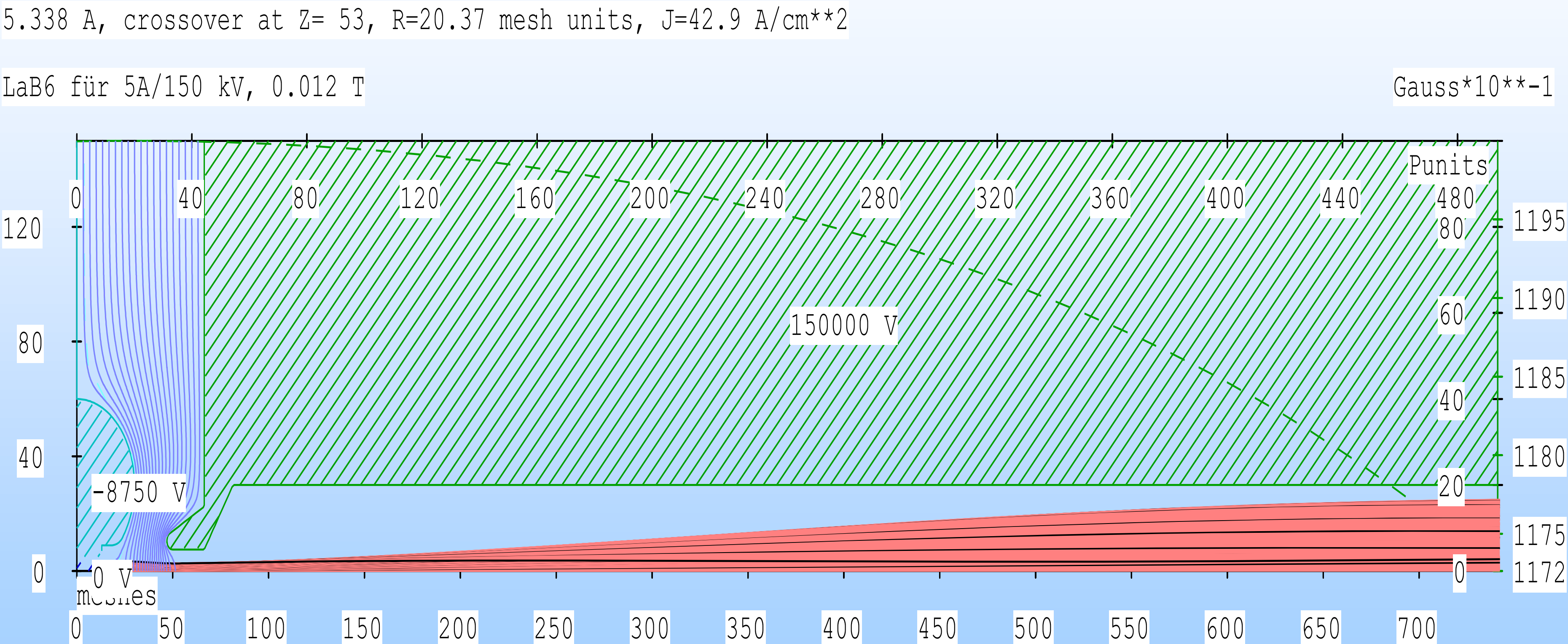
For thermal electrons of 133 eV in a well of 3 keV the density reaching the wall is according to Boltzmann 1.6 x 10^{-10} of the central density (without consideration of the magnetic trapping). If we transport a beam of 5A then 7 x 10^{9} electrons/s are reaching the drift tube with radius of 1 cm.

10^{10} electrons/s desorb 10^{10} atoms/s.
At a vacuum of 10^{-10} mbar this corresponds to a gas load of 3.5 l/s, which needs attention.

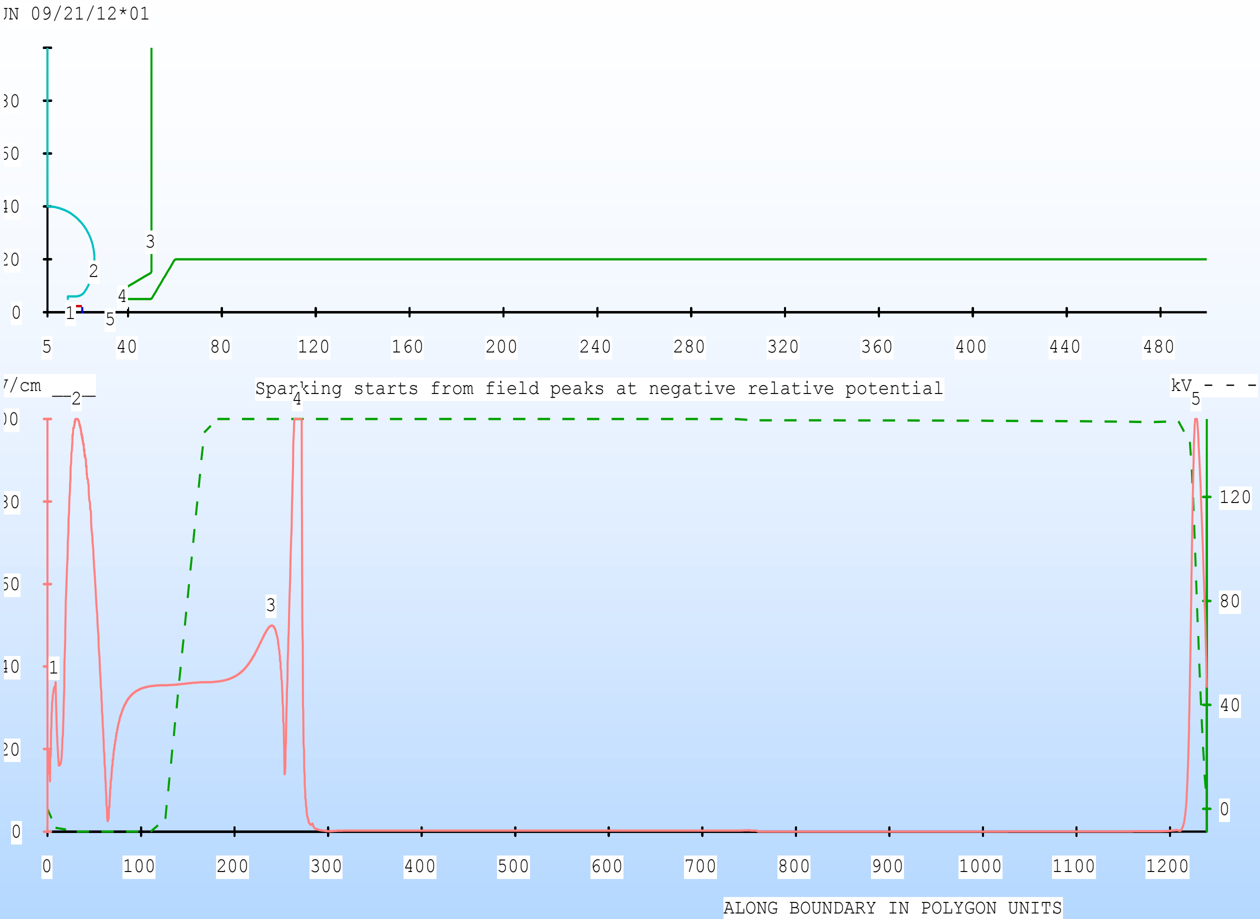
It is believed that in immersed flow the confinement of electrons to the beam is much better, hence the desorption will become totally unimportant.

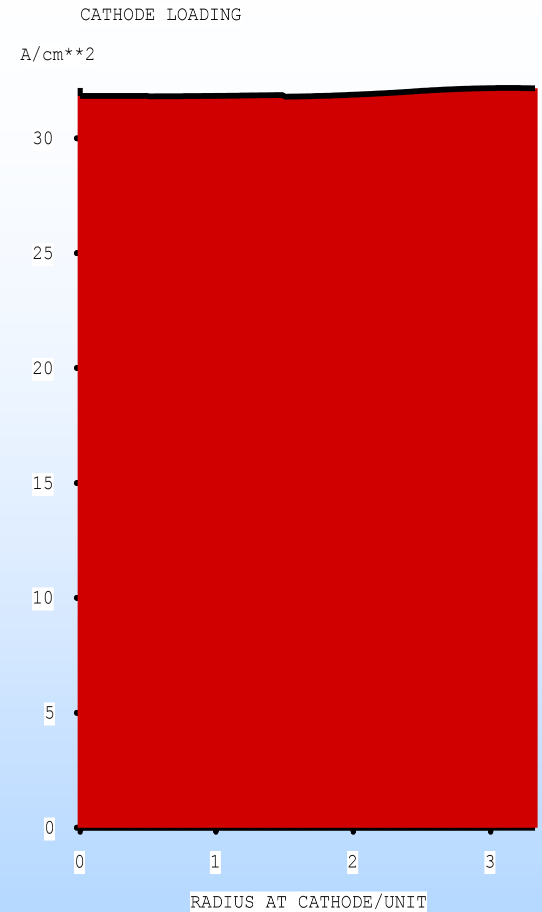
How about immersed flow?

At 30 A/cm^2 the field is about 667 times lower than the maximum field, which is 8 T at the best. How does a beam look like, which is started in such a low field like 0.012 T? This is best answered by a simulation:



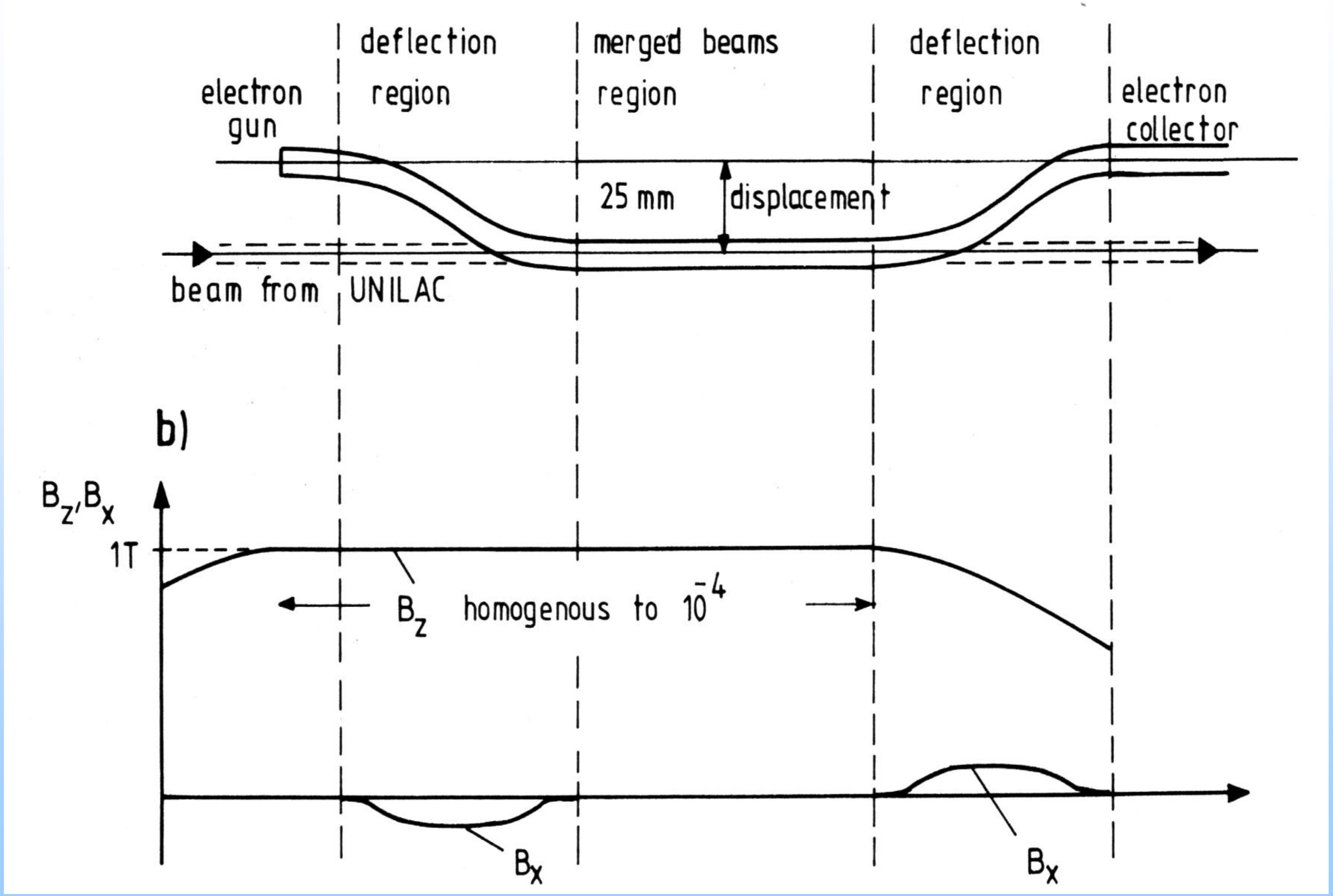
The beam is well focused and well immersed, which is the result of relativistic aid in focusing.





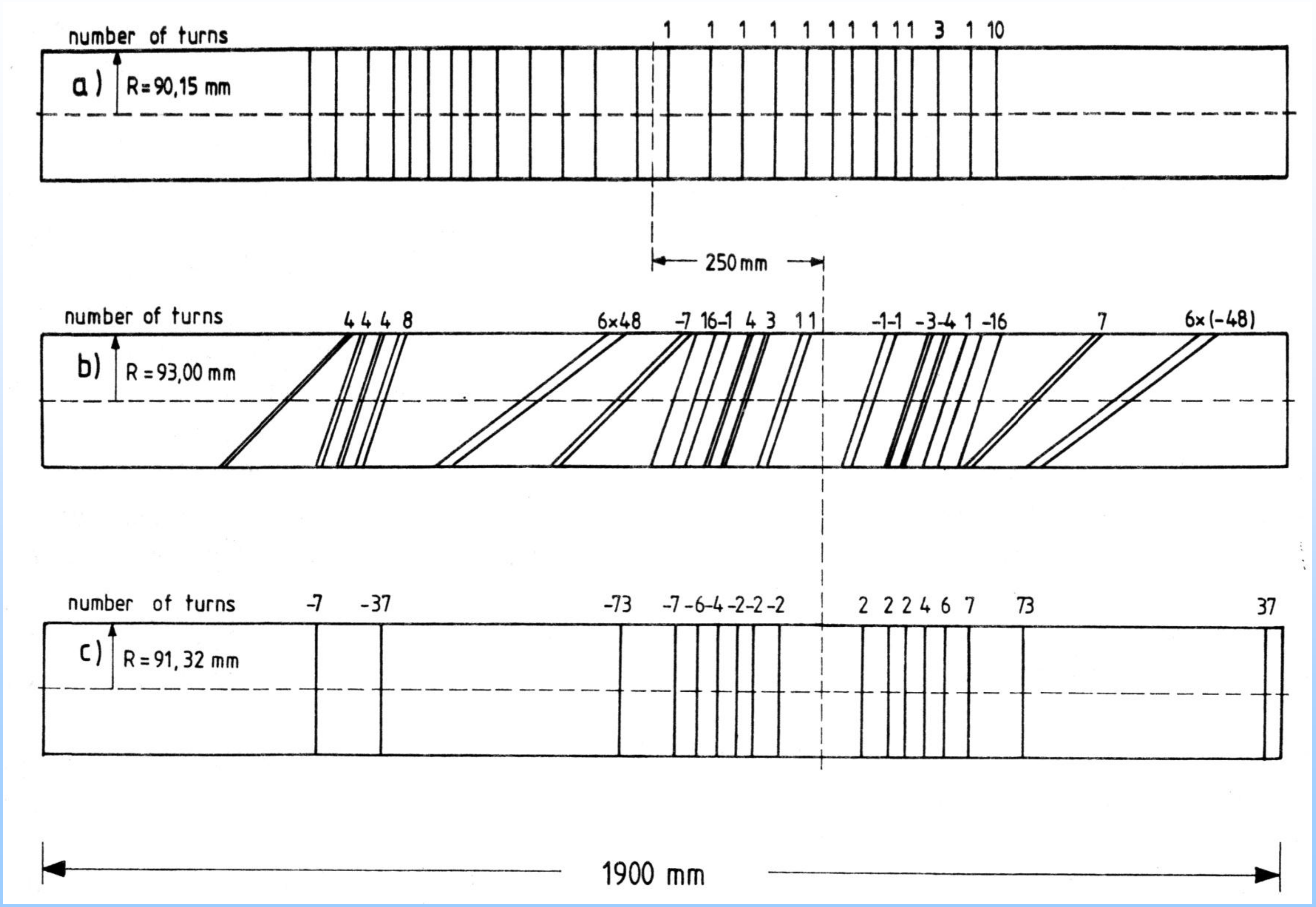
Surface fields are at the limit – probably requires 2-gap acceleration.
Cathode loading is reasonably uniform.

How to make an easy entrance and exit for the ion beam?



R. Becker and E. Jennewein, Current Loops to Add Axial and Transverse Fields to Solenoids, Nucl. Instrum. Meth. A258 (1987) 503

Complicated, but working set of sc correction windings



R. Becker and E. Jennewein, Current Loops to Add Axial and Transverse Fields to Solenoids, Nucl. Instrum. Meth. A258 (1987) 503

The LEIR electron cooler at CERN

This configuration has distinct advantages:

- Gas load from cathode and collector best shielded from ionzation region
- Best suppression of secondary electrons from the collector
- Common high voltage terminal for gun and collector
- Gun, benders and collector in normal conducting low field coils
- Central part by sc 8T solenoid

5 A, 150 keV, 20 kA/cm^2 can be attained practically in a charge breeder !

Use immersed flow

0.012 T at cathode, 8T full field

0.5 cm dia. LaB_6 single crystal cathode (30 A/cm^2)

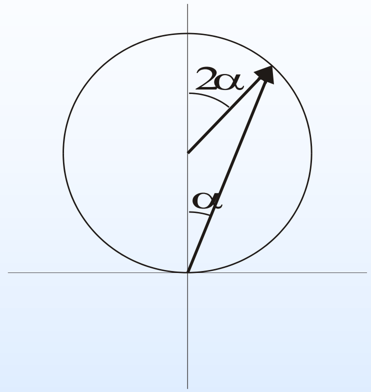
CB with the layout of an electron cooler

Cathode and collector in common high voltage cage and well separated from vacuum of ionization region.
Axial access for ions from both sides ideal for ion-ion cooling

Busch's theorem

$\omega_c = \frac{e}{m} B$ Cyclotron frequency

$\dot{\varphi} = \frac{e}{2m} B$ “Larmor” frequency



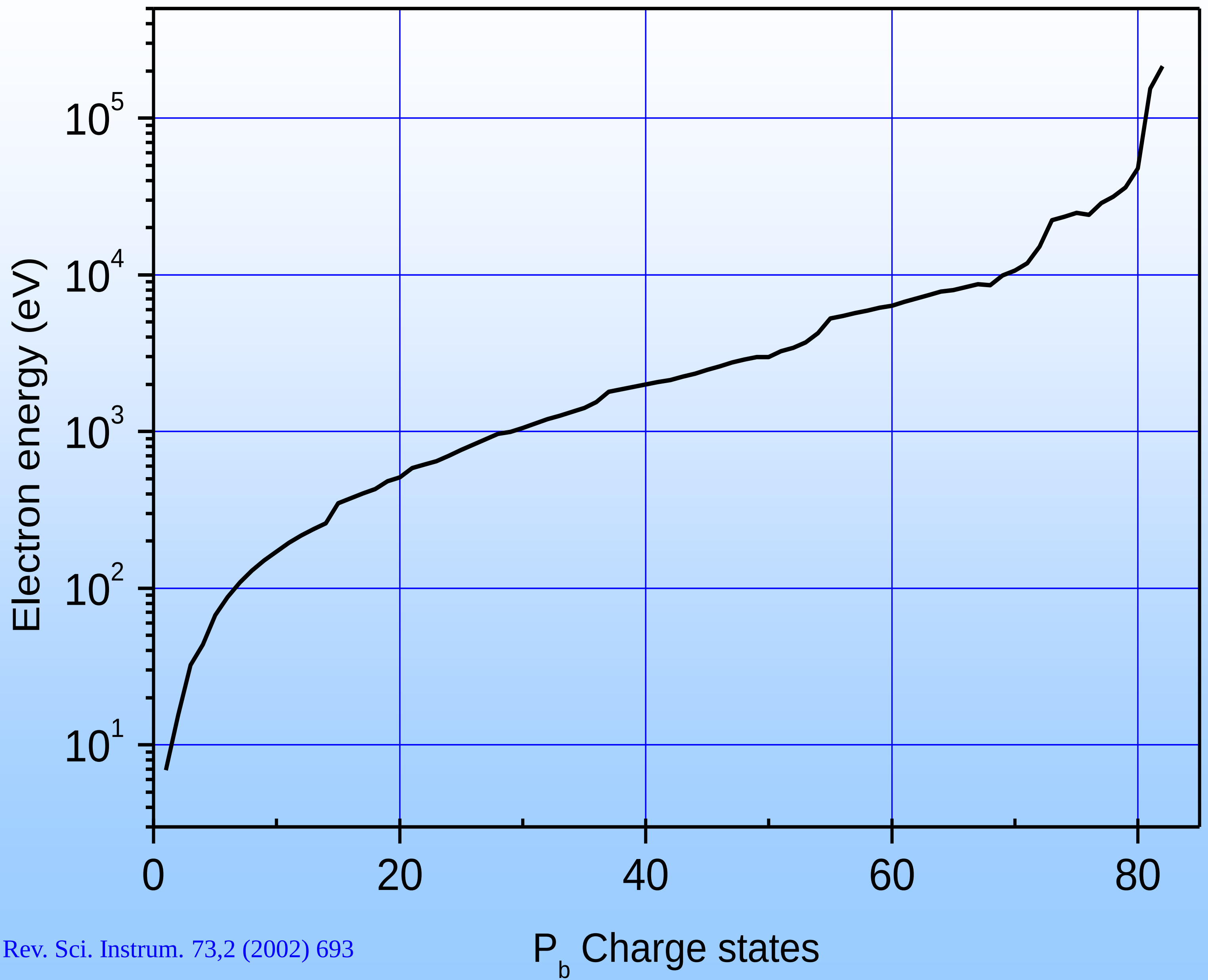
center angle 2α and angle α to the circumference

The “Larmor“ frequency has nothing at all to do with precession of spins in a magnetic field – it is the mere result of a coordinate transformation and reflects the conservation of the angular momentum – wich is Busch's theorem. It should be called Busch frequency in electron/ion optics to distinguish it from the “Larmor“ frequency, even if the numbers are the same!

Solution: the “Larmor“ frequency is seen from a point at the circumference of the gyration circle and therefore is half of the cyclotron frequency!

Recombination versus Ionization

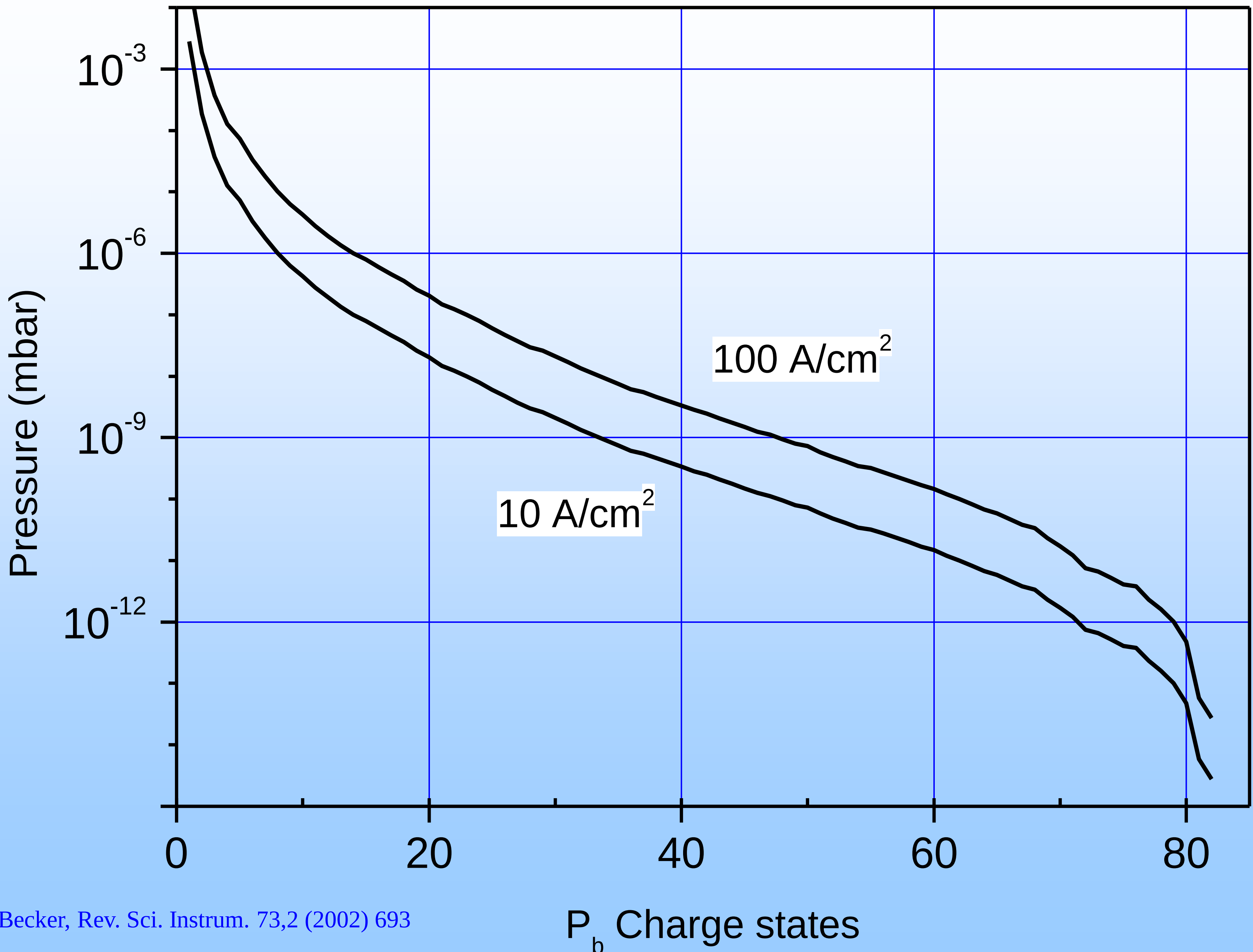
Energy at which ionization becomes more efficient than recombination for Pb ions



R. Becker, Rev. Sci. Instrum. 73,2 (2002) 693

Charge exchange versus Pressure

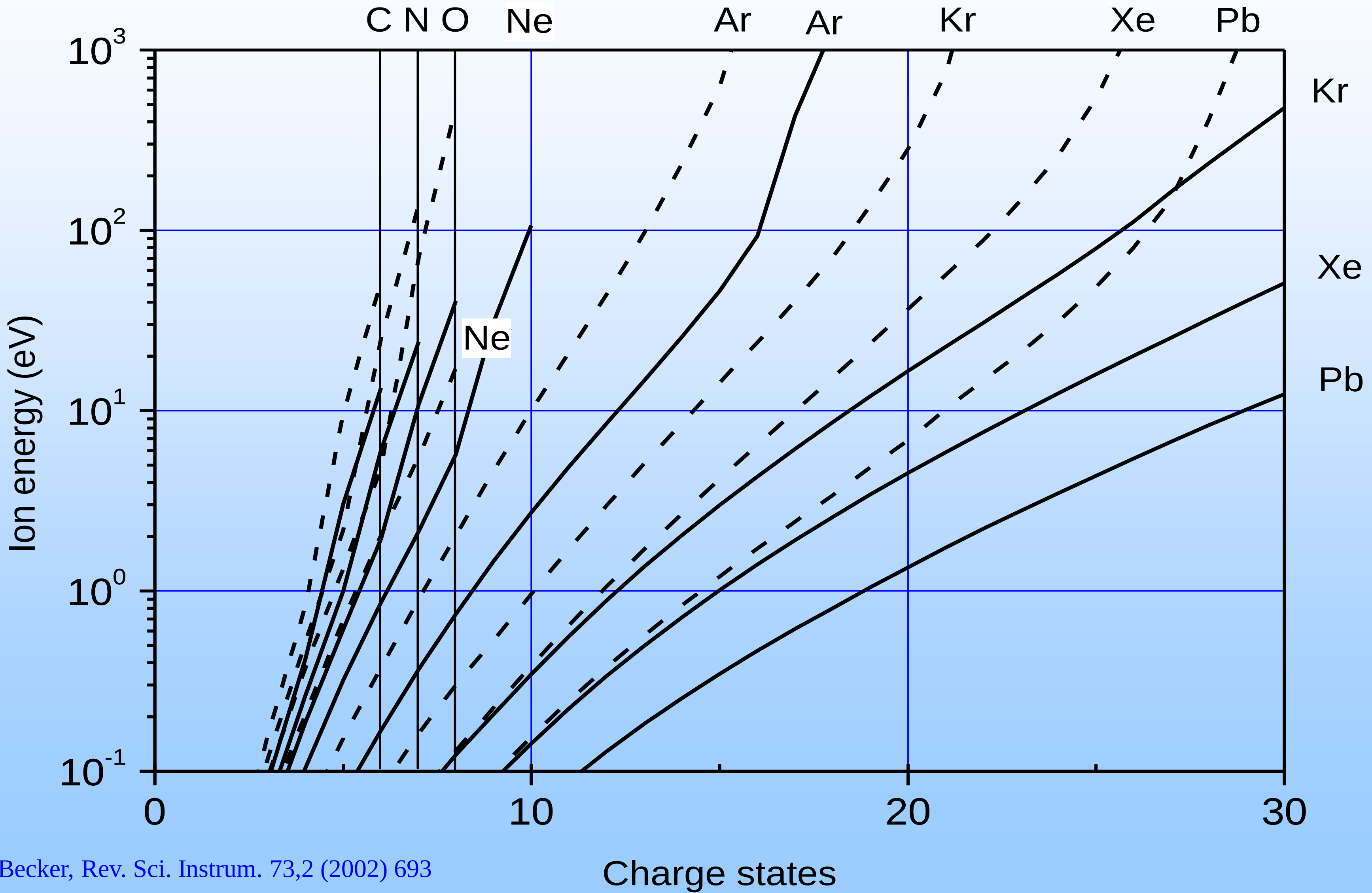
Vacuum pressure at which gain by ionization equals the loss by charge exchange for lead ions



R. Becker, Rev. Sci. Instrum. 73,2 (2002) 693

Heating of multiply charged ions by electron collisions

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



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