CONTINUOUS AND PULSED OPERATION OF

A HIGHLY EFFICIENT 18 GHZ PLATEAU-ECRIS

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This a historical talk since our experiments ended in 2003 !

The first results had been presented at the
ECRIS02 Workshop in Jyväskylä in 2002

But the work until the end has never been published

Therefore I begin with a reminder of the essentials of that presentation

Some important corrections are added to what had been said before

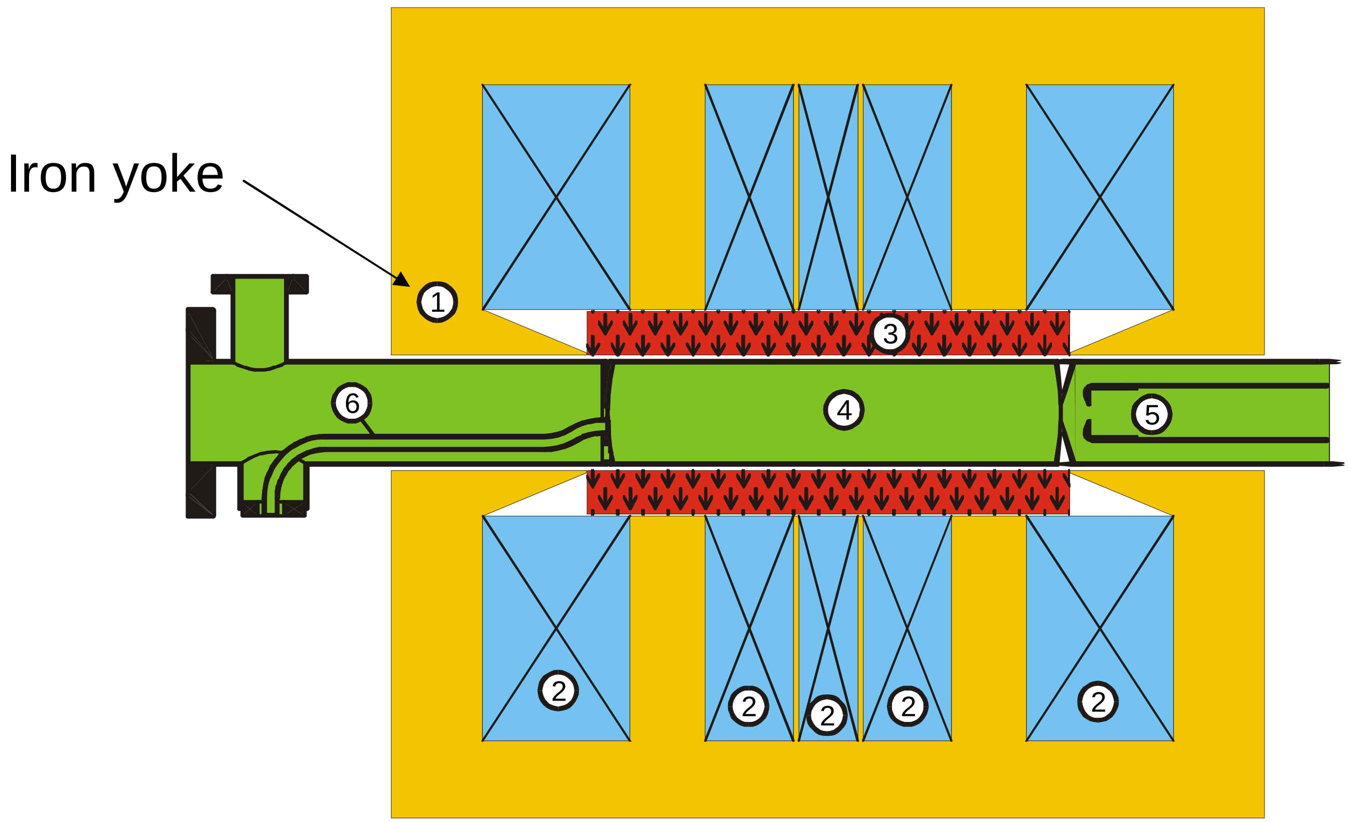
Then we show how to operate a plateau ECRIS (PECRIS) and why

The improvement of PECRIS V by surface treatments is shown and explained

Some further results conclude the continuous operations

For feeding accelerators the PUlsed MAgnetic EXtraction is introduced

49 µA of Ar16+ observed in pulses of 150 µs length !



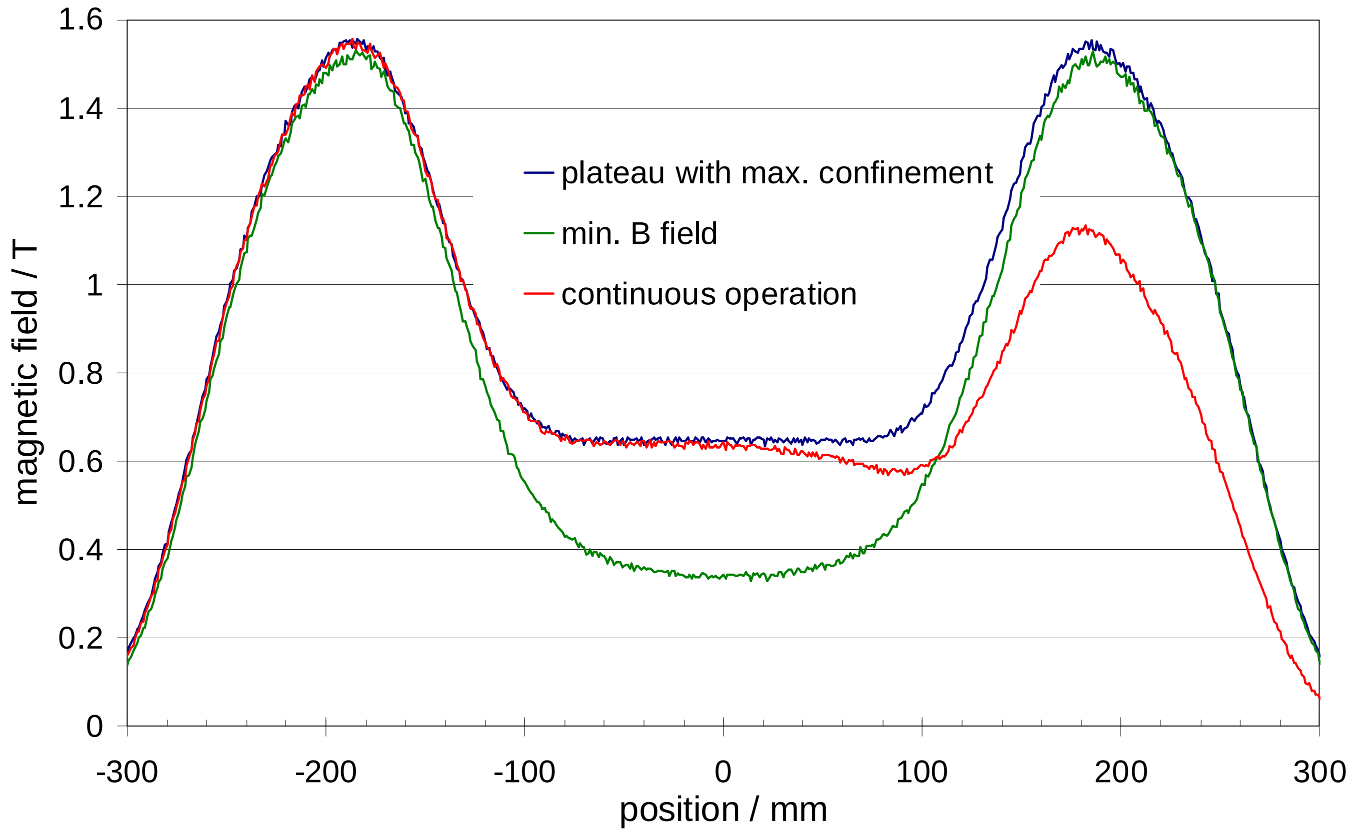
(2) 5 independent power supplies for the 5 coils

(3) Hexapole from American Magnetics with asymmetry of 5 % !!!

(5) Puller electrode with concave curvature to focus secondary electrons into plasma

(4) Concave end plates to approach confocal microwave cavity

(6) Special microwave window from CPI had to be cooled !! Loss of 50-100 W !!

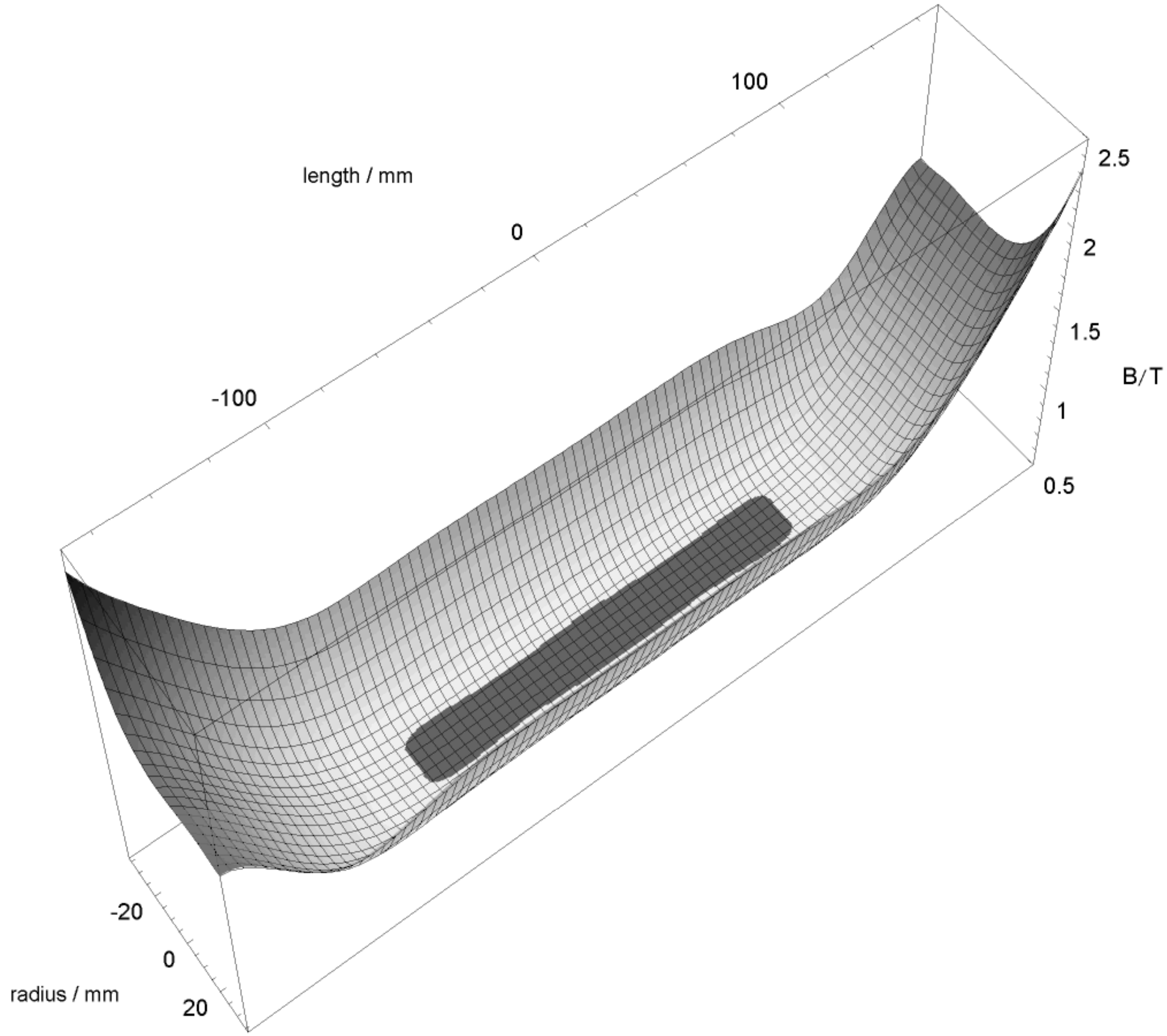


Red configuration with 10mm shift for Ar8+

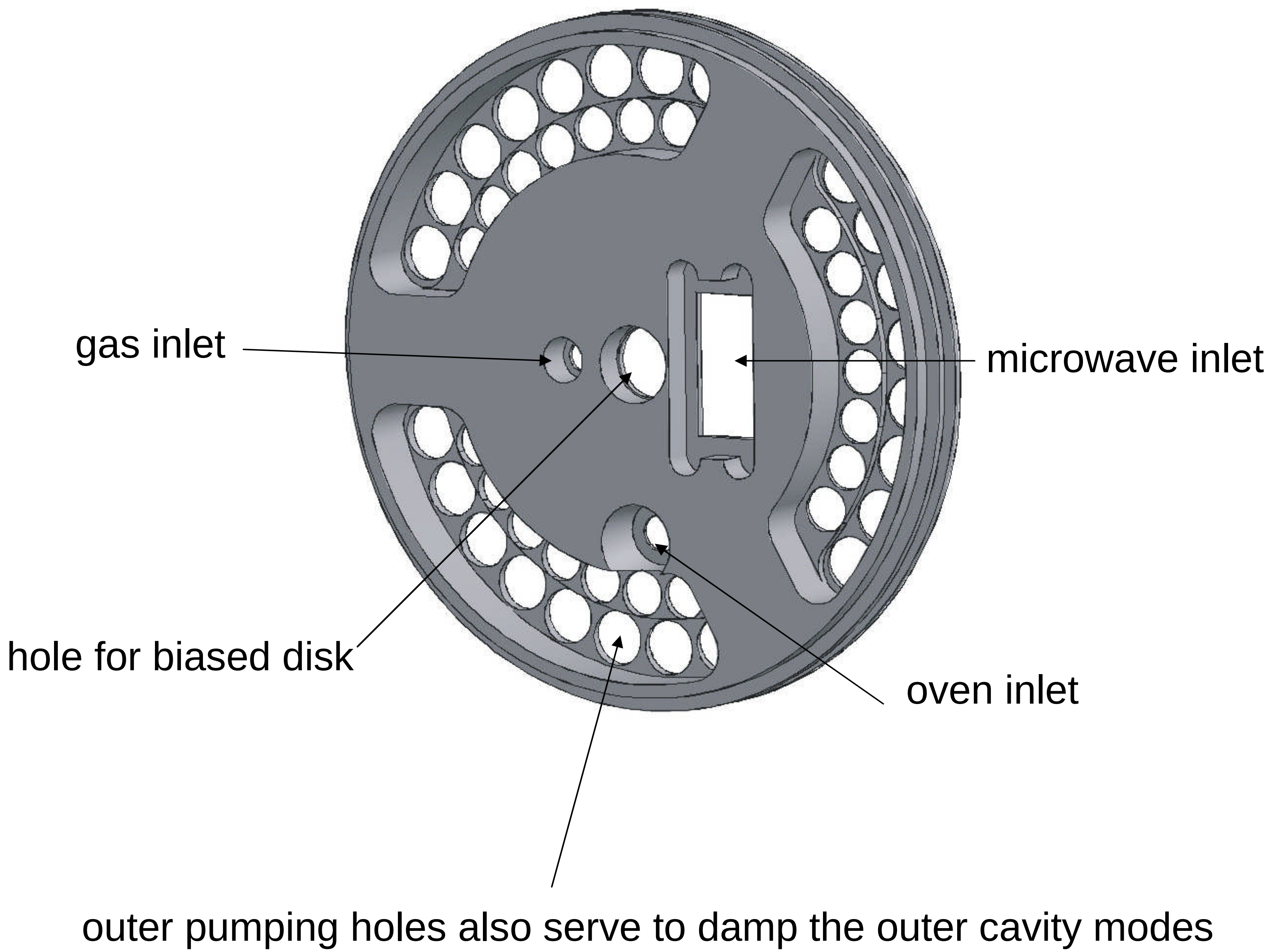
Max. confinement with right mirror lowered to 1.4 T for Ar16+

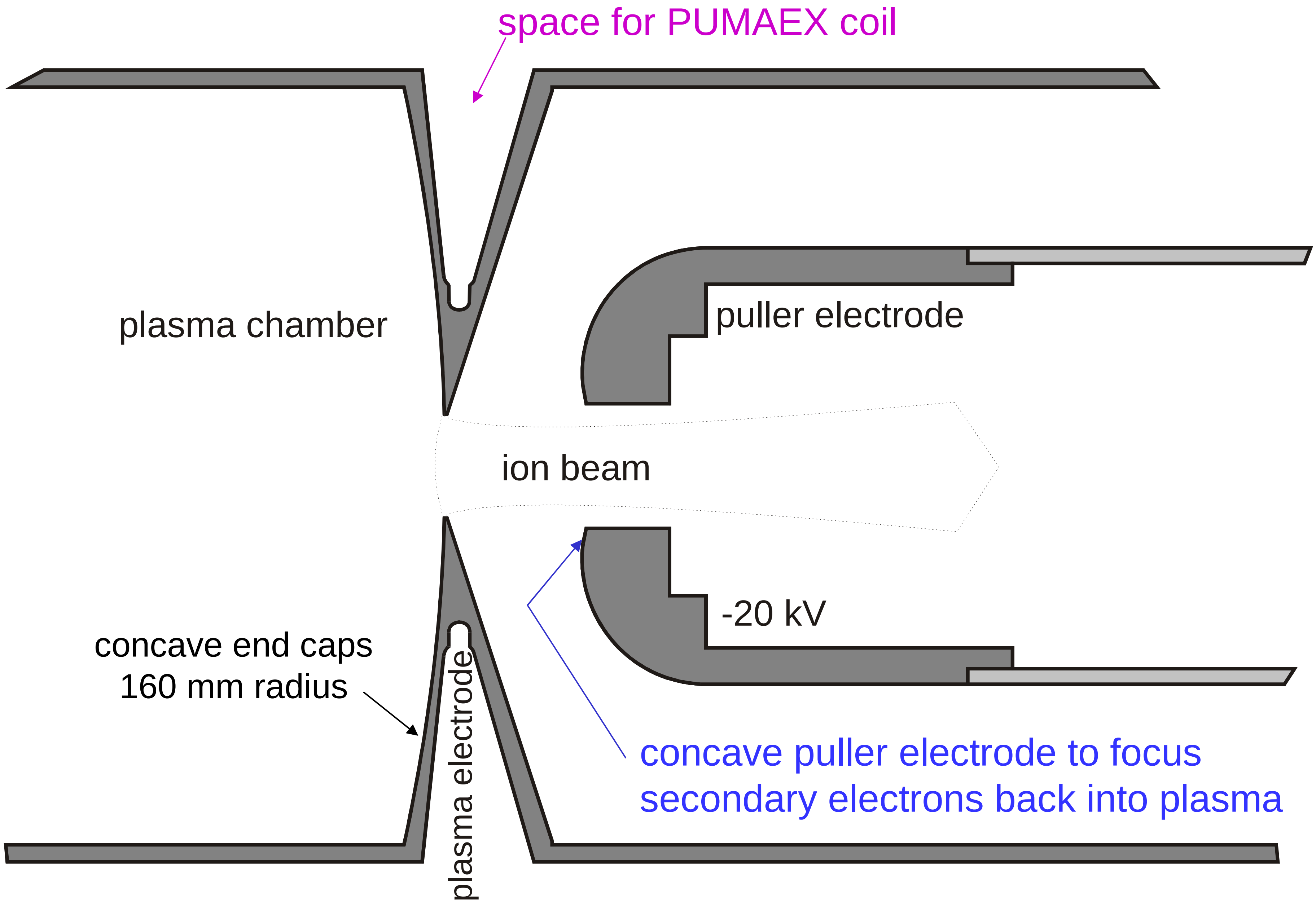
Max. confinement used for PUMAEX

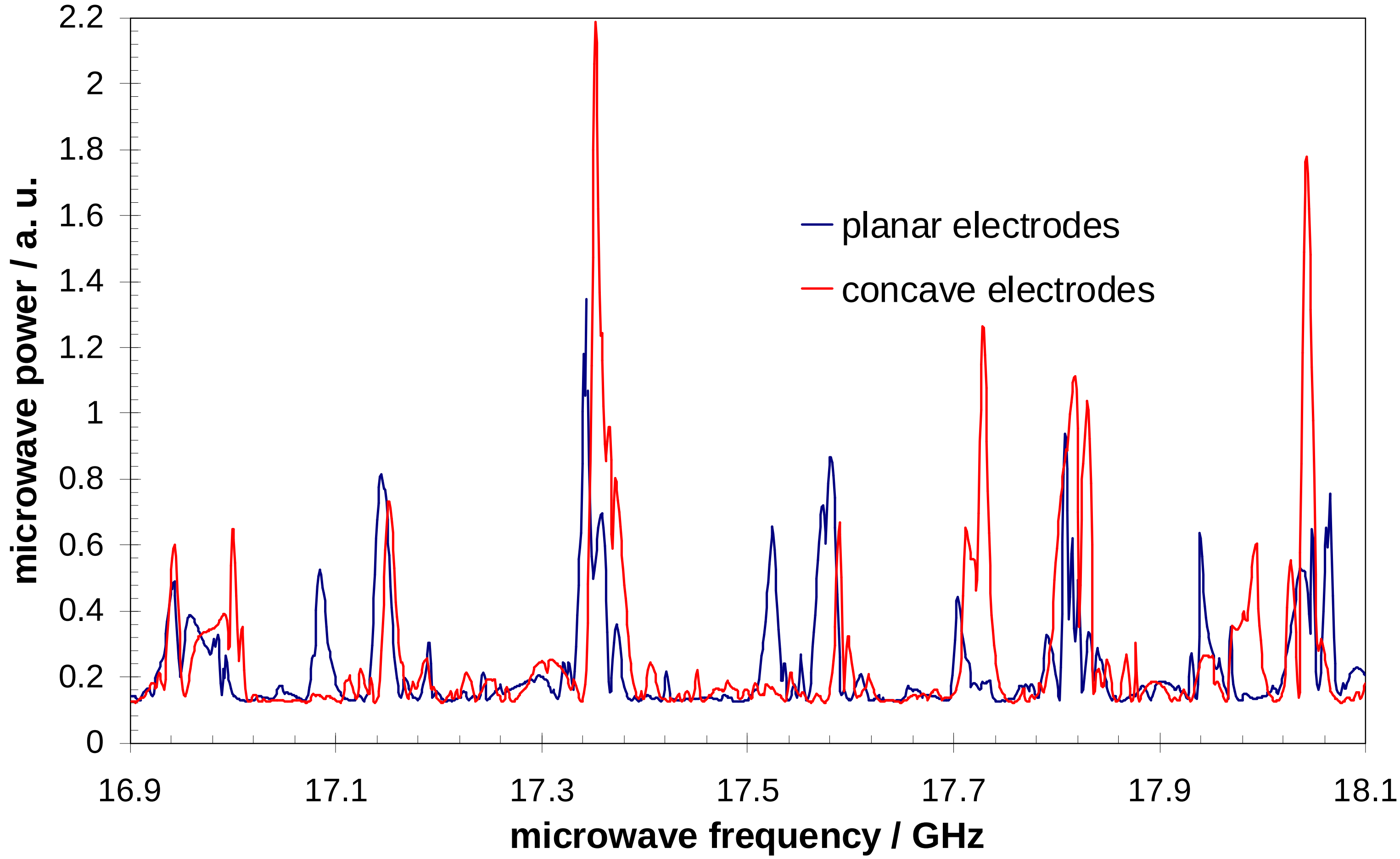
Min. B-field never used



Absolute value of the magnetic field in PECRIS V
The black area in the centre indicates the large resonance volume


gas inlet
microwave inlet
hole for biased disk
oven inlet
outer pumping holes also serve to damp the outer cavity modes

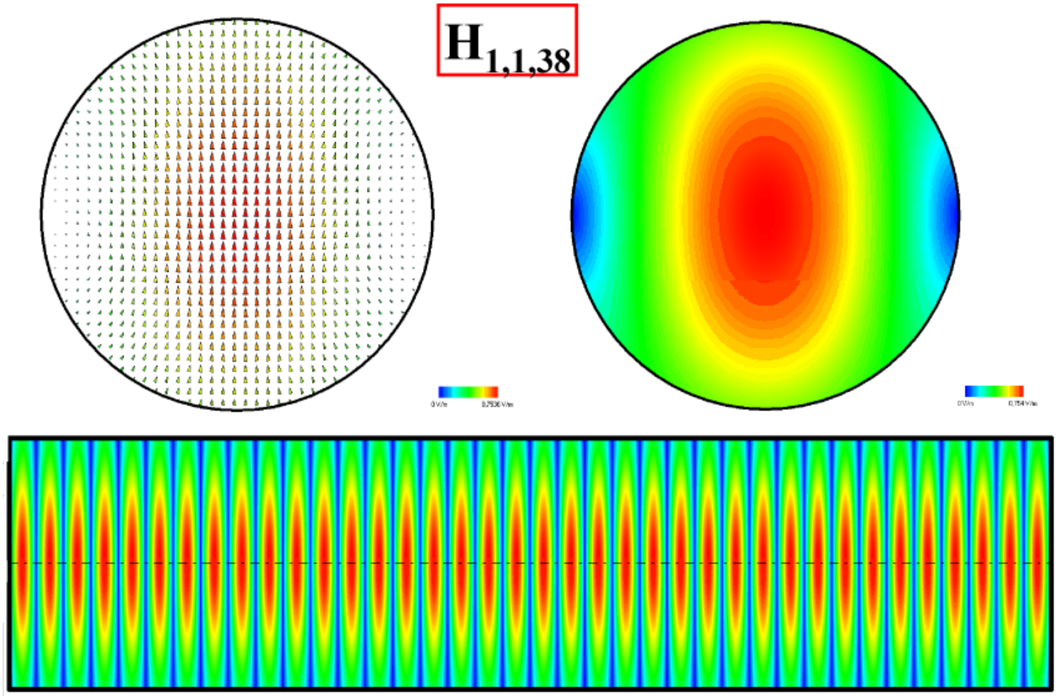

space for PUMAEX coil
plasma chamber
puller electrode
ion beam
-20 kV
concave end caps
160 mm radius
plasma electrode
concave puller electrode to focus
secondary electrons back into plasma



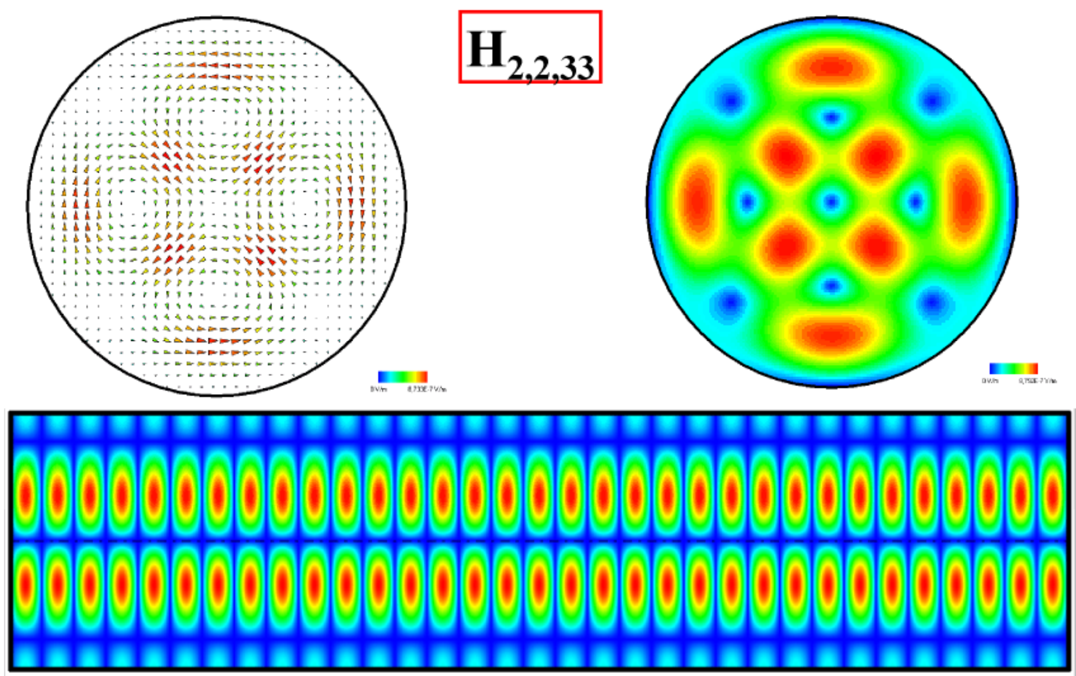
Microwave amplitude on the axis versus microwave frequency
A plasma chamber with concave end caps
is compared to a chamber with planar end caps

The concave end caps do have a significant effect on the central modes

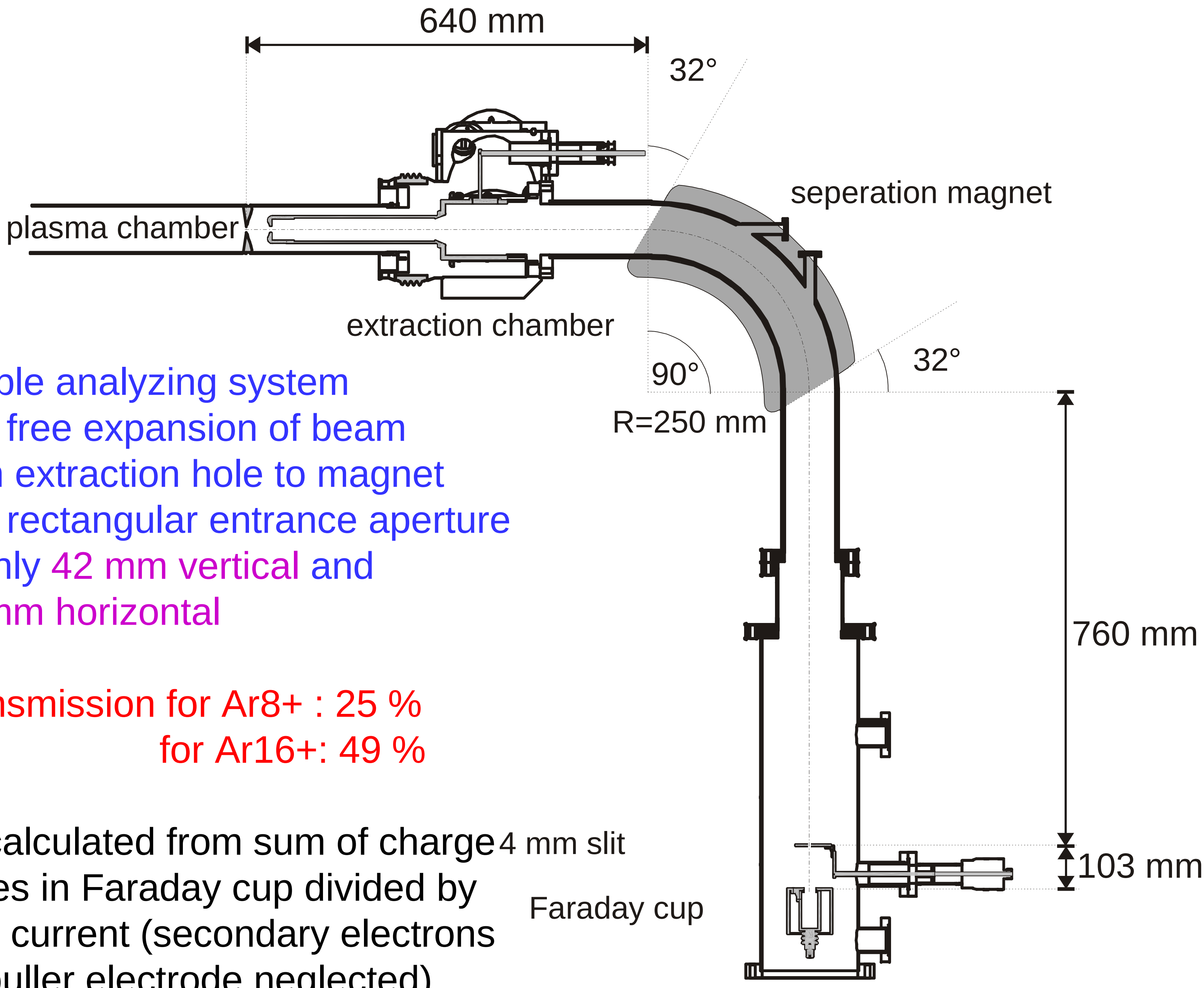
The effect of the pumping holes on outer modes has not been measured



Favored by
concave end caps



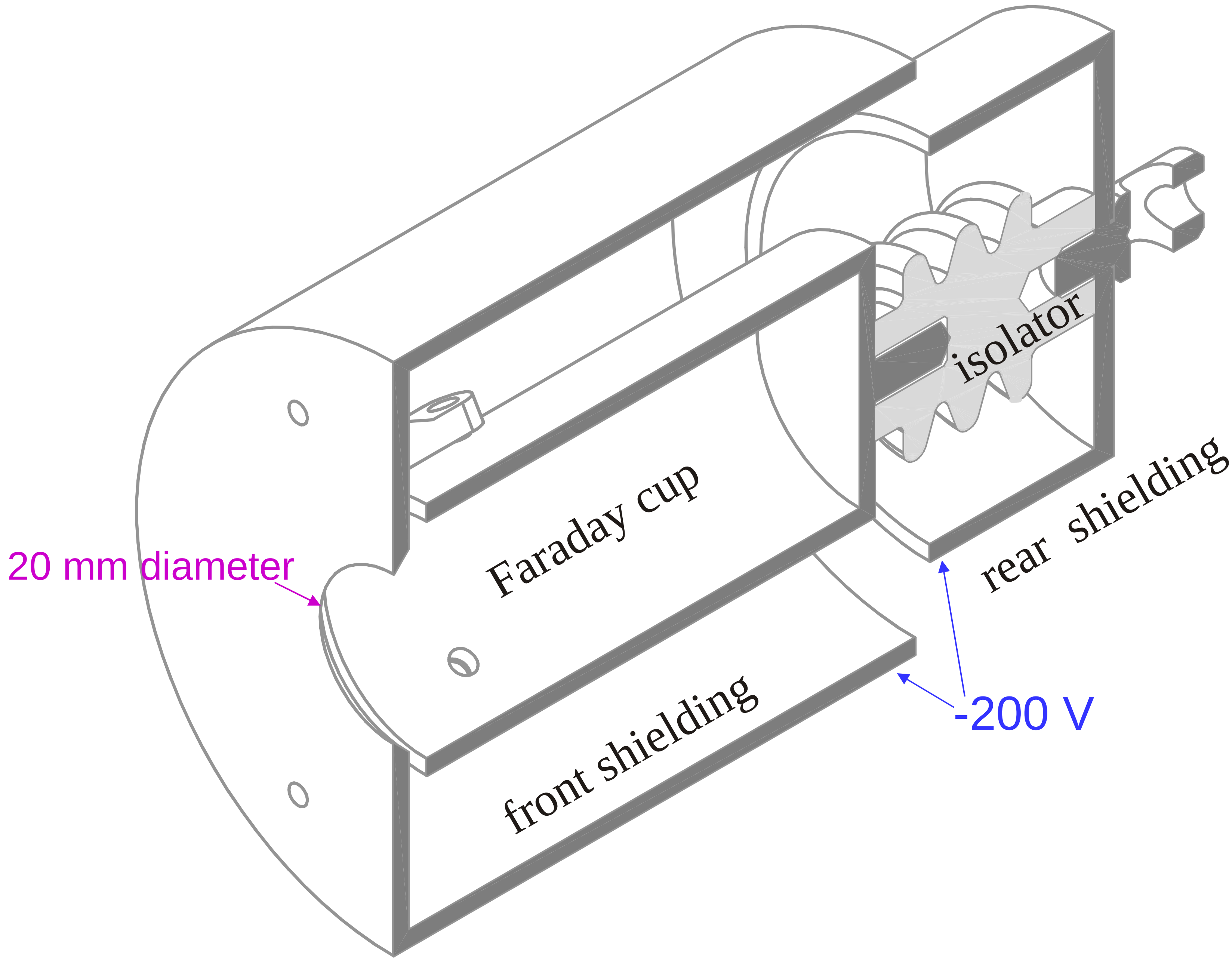
Damped by
Concave end caps
and by
pumping holes



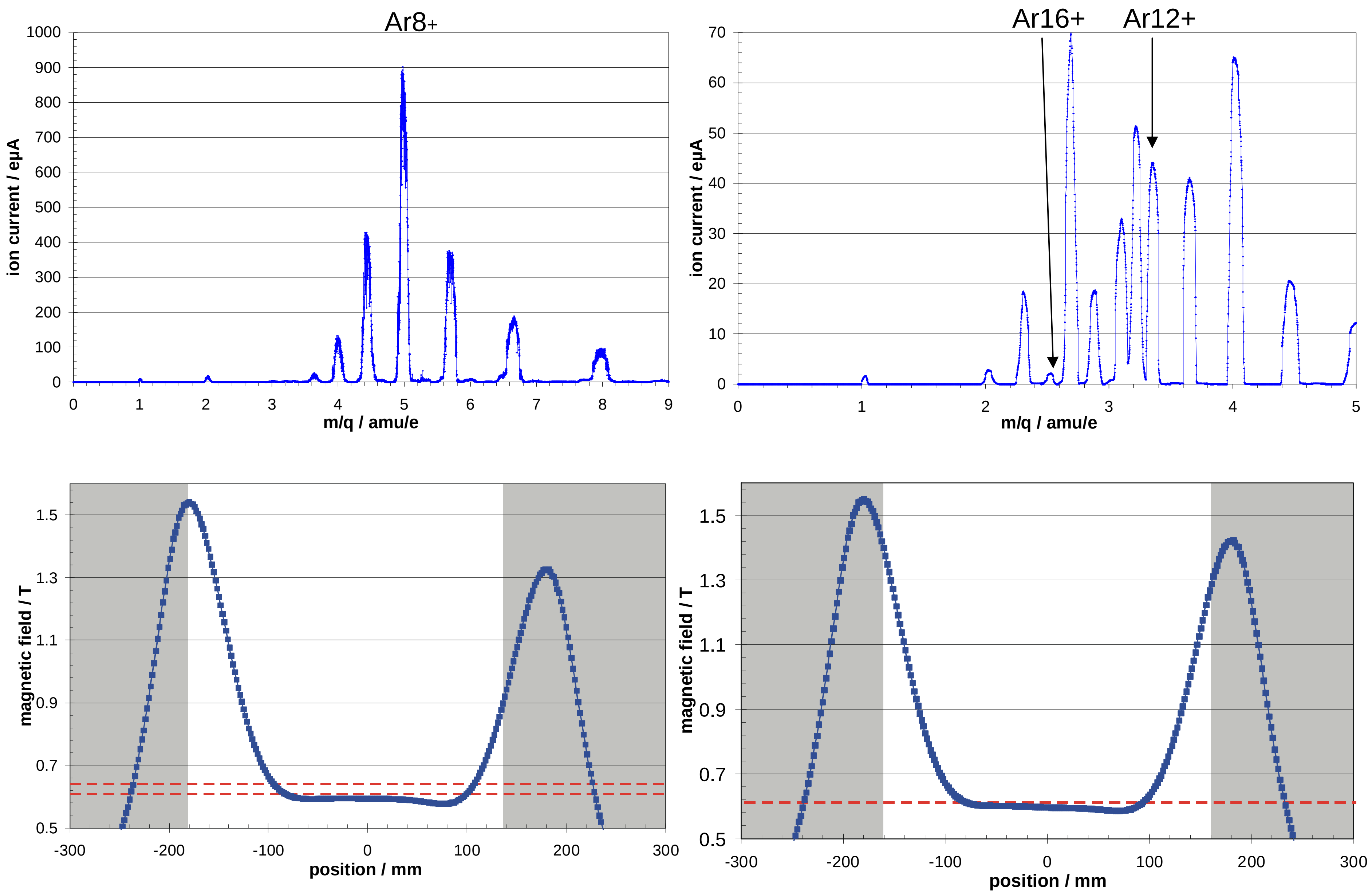
Simple analyzing system
with free expansion of beam
from extraction hole to magnet
with rectangular entrance aperture
of only 42 mm vertical and
80 mm horizontal

Transmission for Ar8+ : 25 %
for Ar16+: 49 %

As calculated from sum of charge
states in Faraday cup divided by
total current (secondary electrons
on puller electrode neglected)



isolator
rear shielding
Faraday cup
20 mm diameter
front shielding
-200 V



White areas indicate the plasma chamber. Red dashed lines : resonance fields of microwave frequencies. The two frequencies of the Ar16+ are very close together.

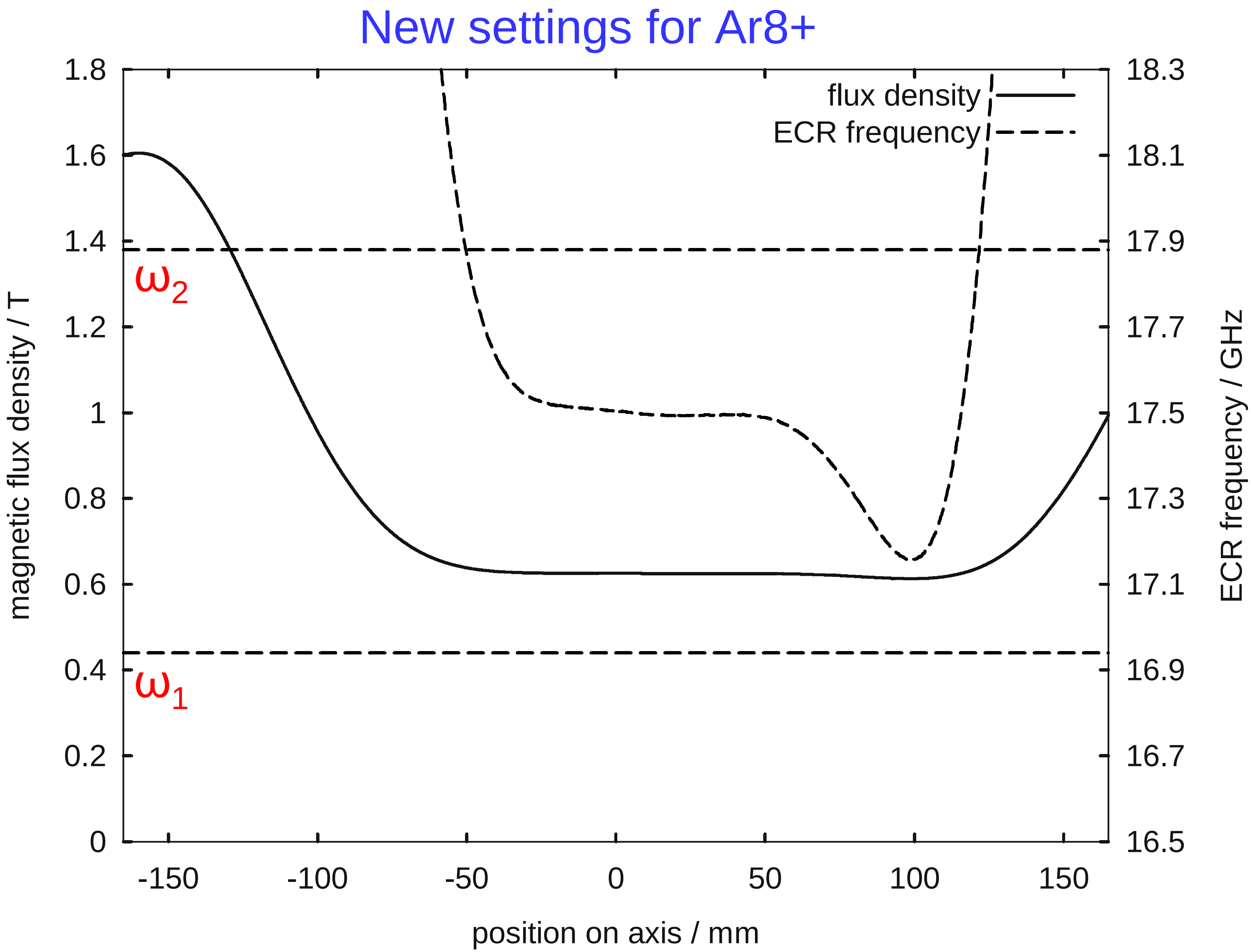
Comment on old results :

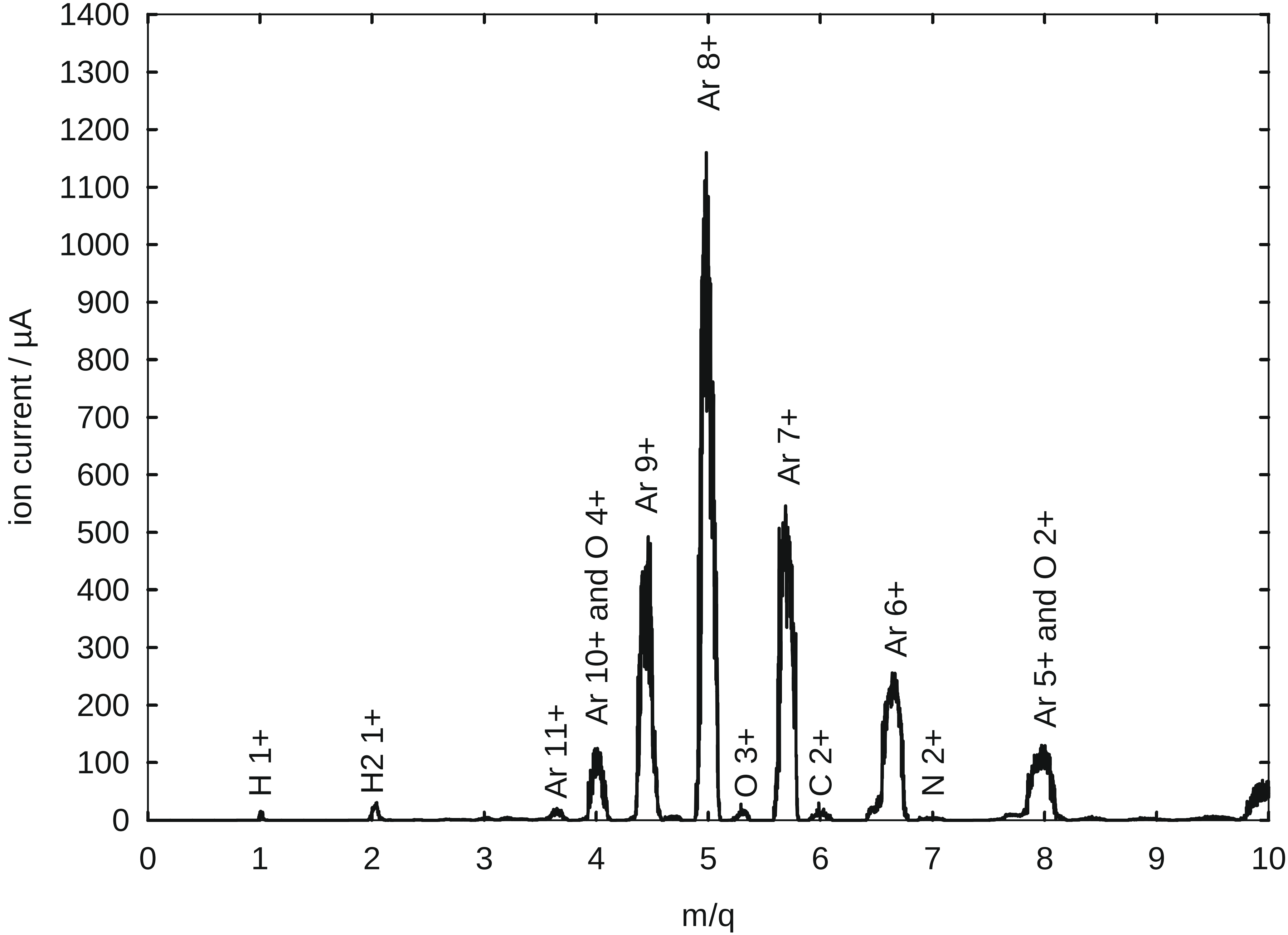
The magnetic field measurements were not precise

With better magnetometer it was clearly established that

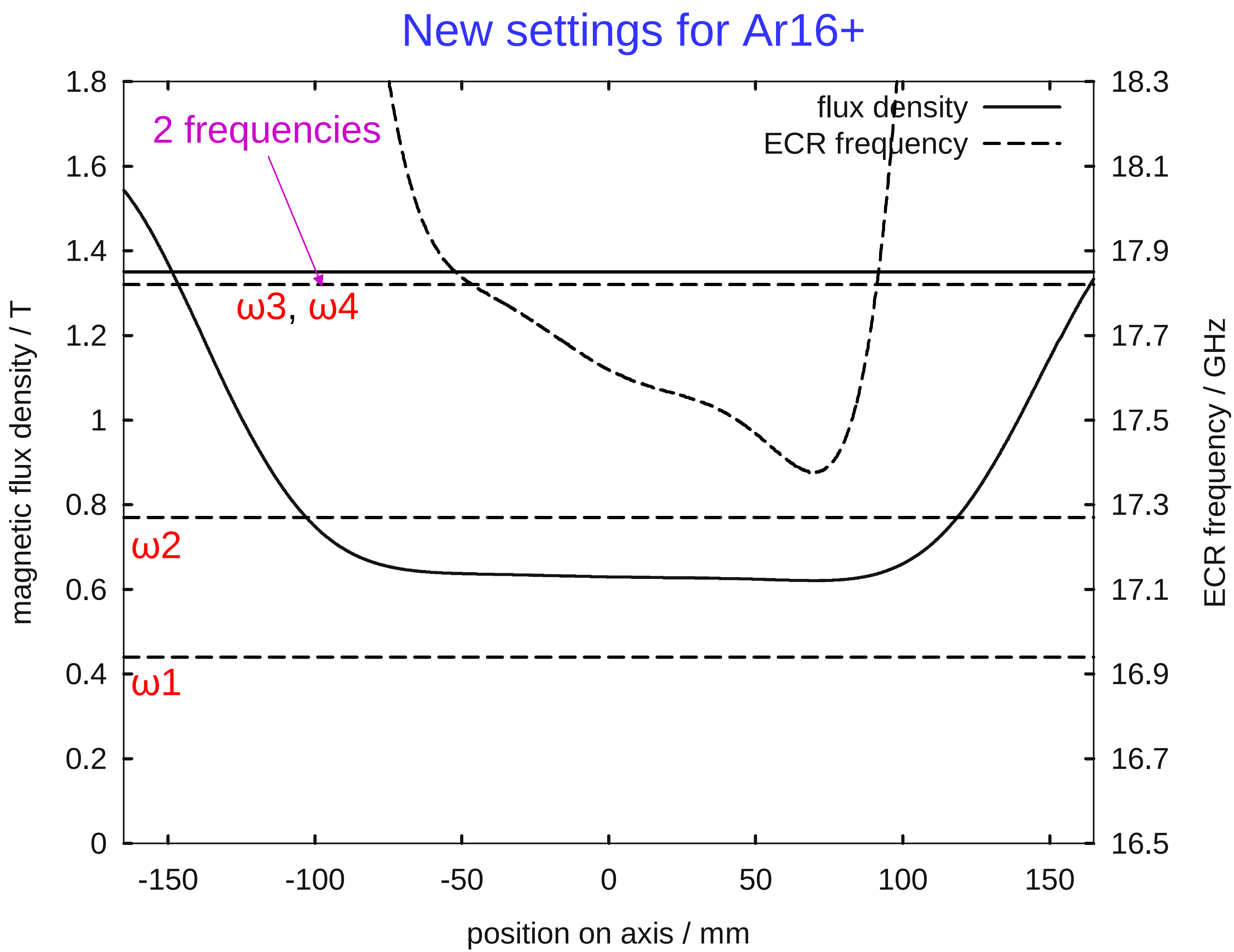
lowest frequencies were below f_{res}(Bmin on axis)

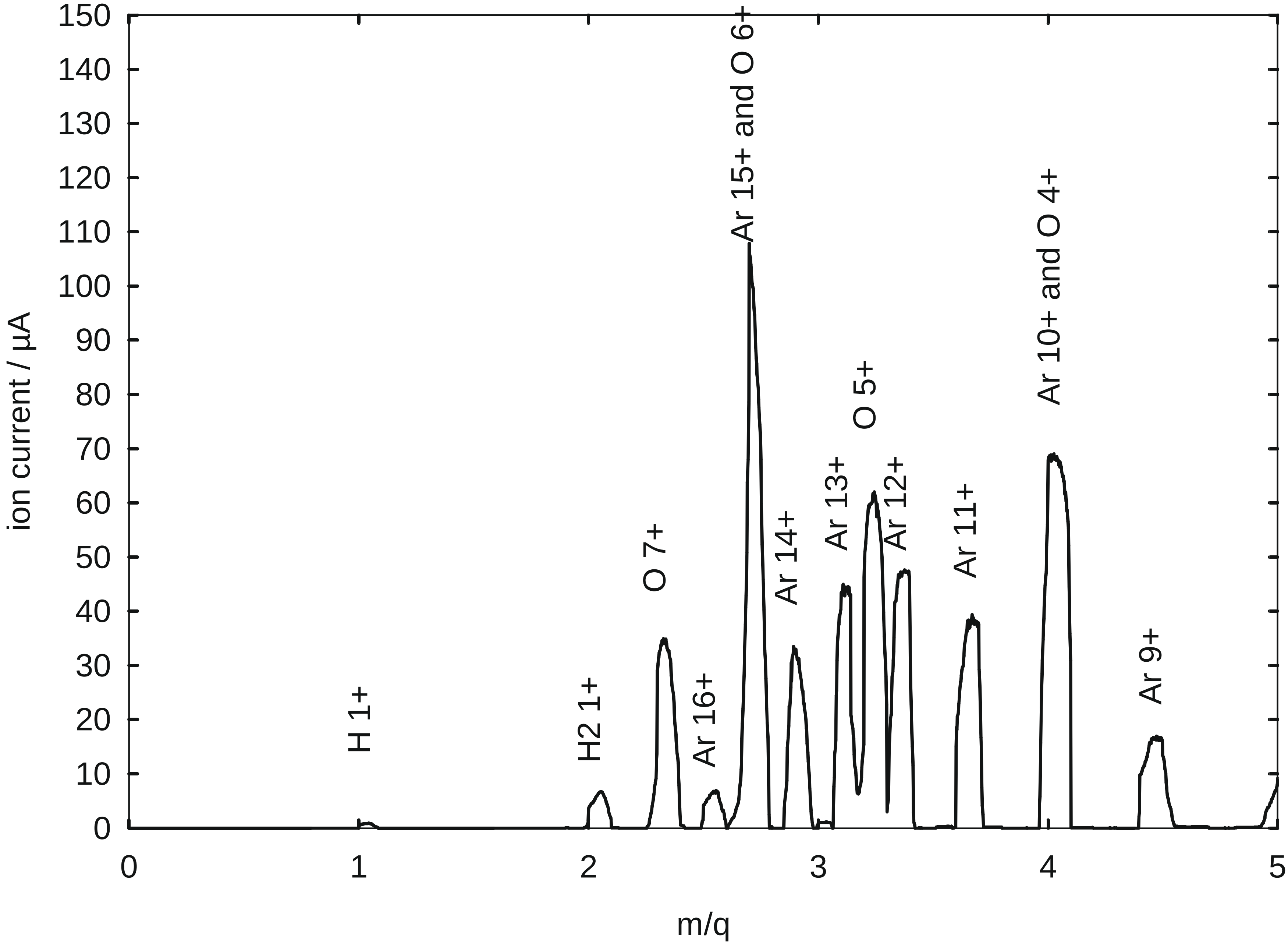
New measurements with known frequency positions


New settings for Ar8+
magnetic flux density / T
ECR frequency / GHz
position on axis / mm
flux density
ECR frequency
ω2
ω1
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
18.3
18.1
17.9
17.7
17.5
17.3
17.1
16.9
16.7
16.5
-150
-100
-50
0
50
100
150



ion current / µA
m/q
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
0
1
2
3
4
5
6
7
8
9
10
H 1+
H2 1+
Ar 11+
Ar 10+ and O 4+
Ar 9+
Ar 8+
O 3+
Ar 7+
C 2+
Ar 6+
N 2+
Ar 5+ and O 2+


New settings for Ar16+
2 frequencies
flux density
ECR frequency
ω3, ω4
ω2
ω1
magnetic flux density / T
ECR frequency / GHz
position on axis / mm
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
18.3
18.1
17.9
17.7
17.5
17.3
17.1
16.9
16.7
16.5
-150
-100
-50
0
50
100
150



150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ion current / µA
0
1
2
3
4
5
m/q
H 1+
H2 1+
O 7+
Ar 16+
Ar 15+ and O 6+
Ar 14+
Ar 13+
O 5+
Ar 12+
Ar 11+
Ar 10+ and O 4+
Ar 9+

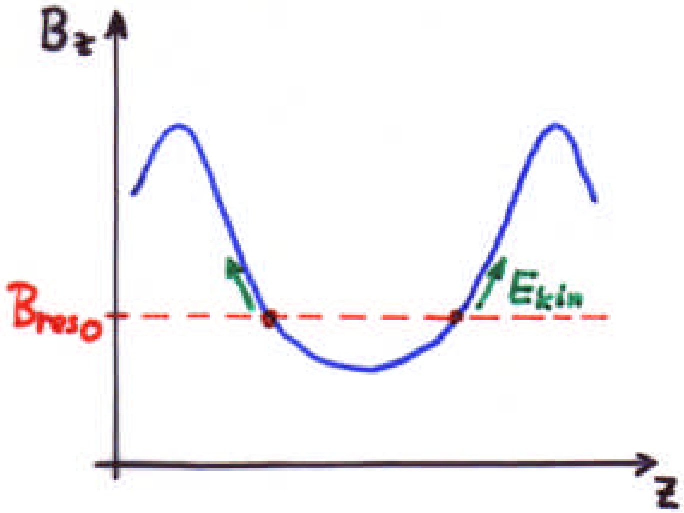
Why these frequencies below f_{res}(Bmin on axis) ??

The answer was given at the

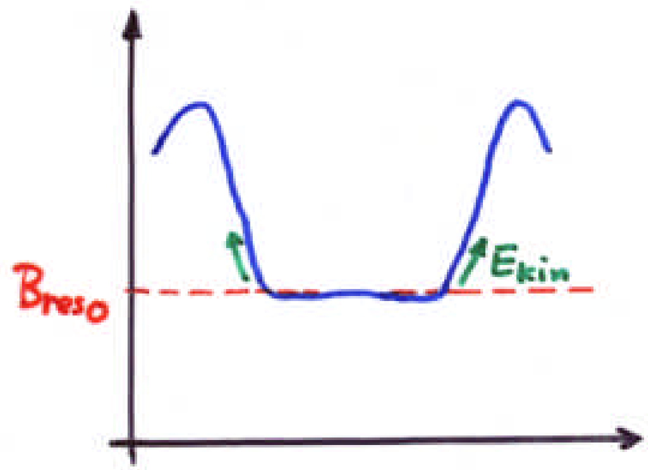
ECRIS99 Workshop at CERN in Geneva

Relativistic effects
in

Standard ECRIS



Plateau ECRIS

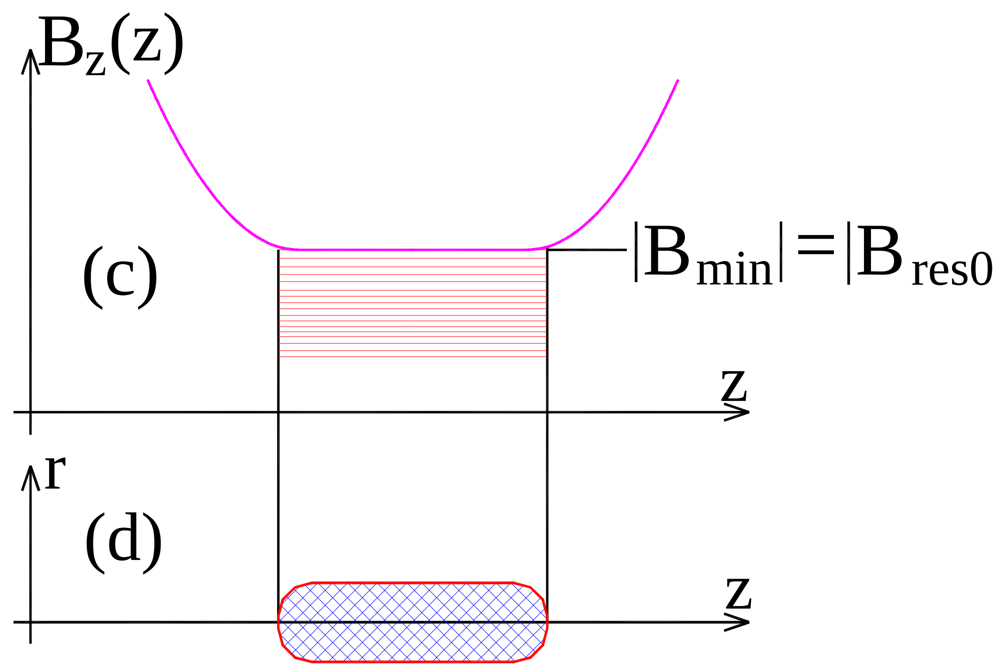


$$B_{reso} = \frac{\omega_{ext} \cdot m_0}{e}$$

$$B_{res} = B_{reso} \left(1 + \frac{E_{kin}}{m_0 c^2}\right)$$

$\omega_0 = e \cdot B_{res0}/m_0$ for E_{kin} small

$\omega = \omega_0/(1+E_{kin}/m_0c^2)$ for $E_{kin} > 1$ keV

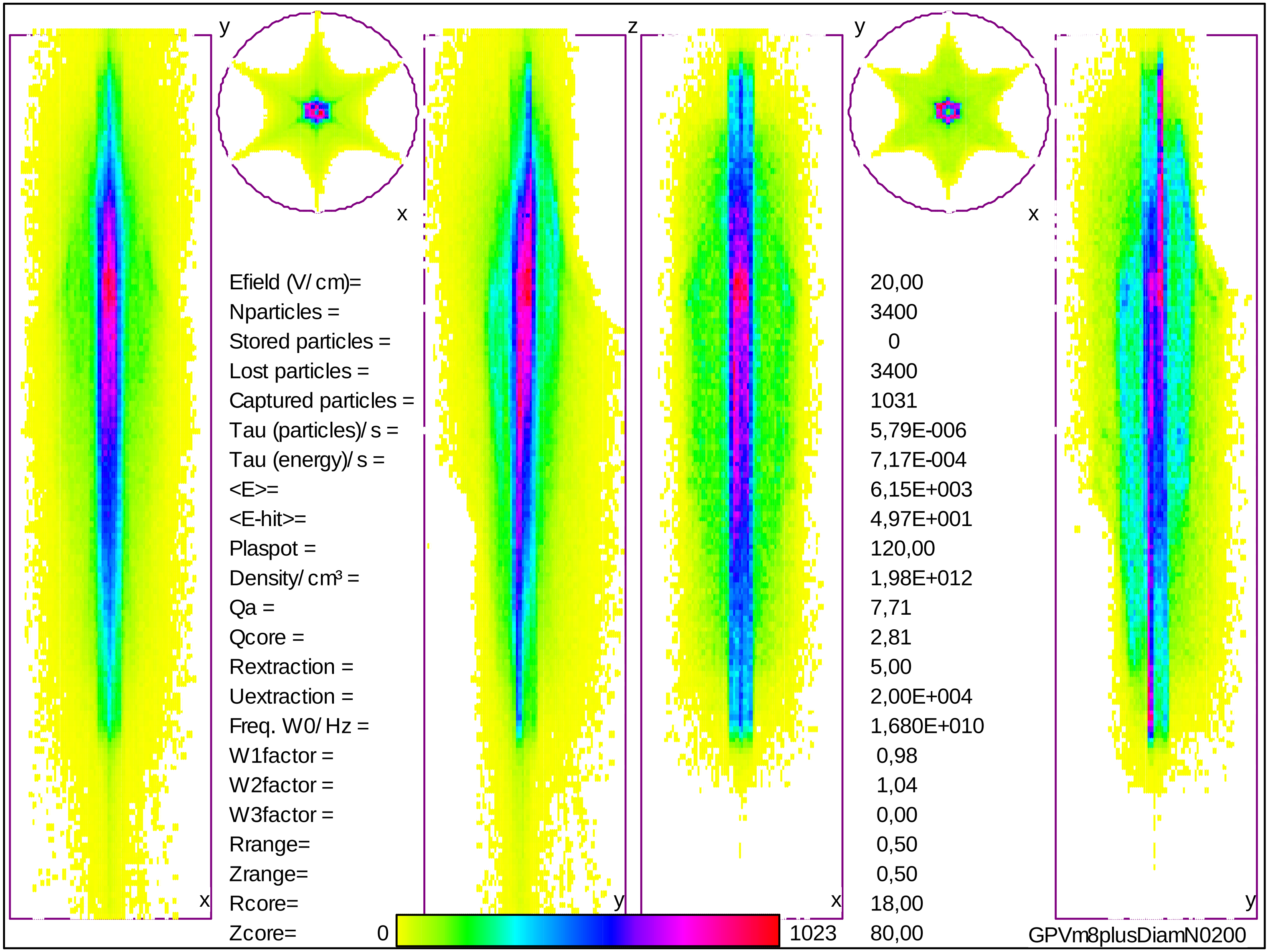


In order to keep electrons of all energies in the initial resonance volume one should use a series of frequencies below f_{res}.

Unfortunately we have only one frequency below f_{res}

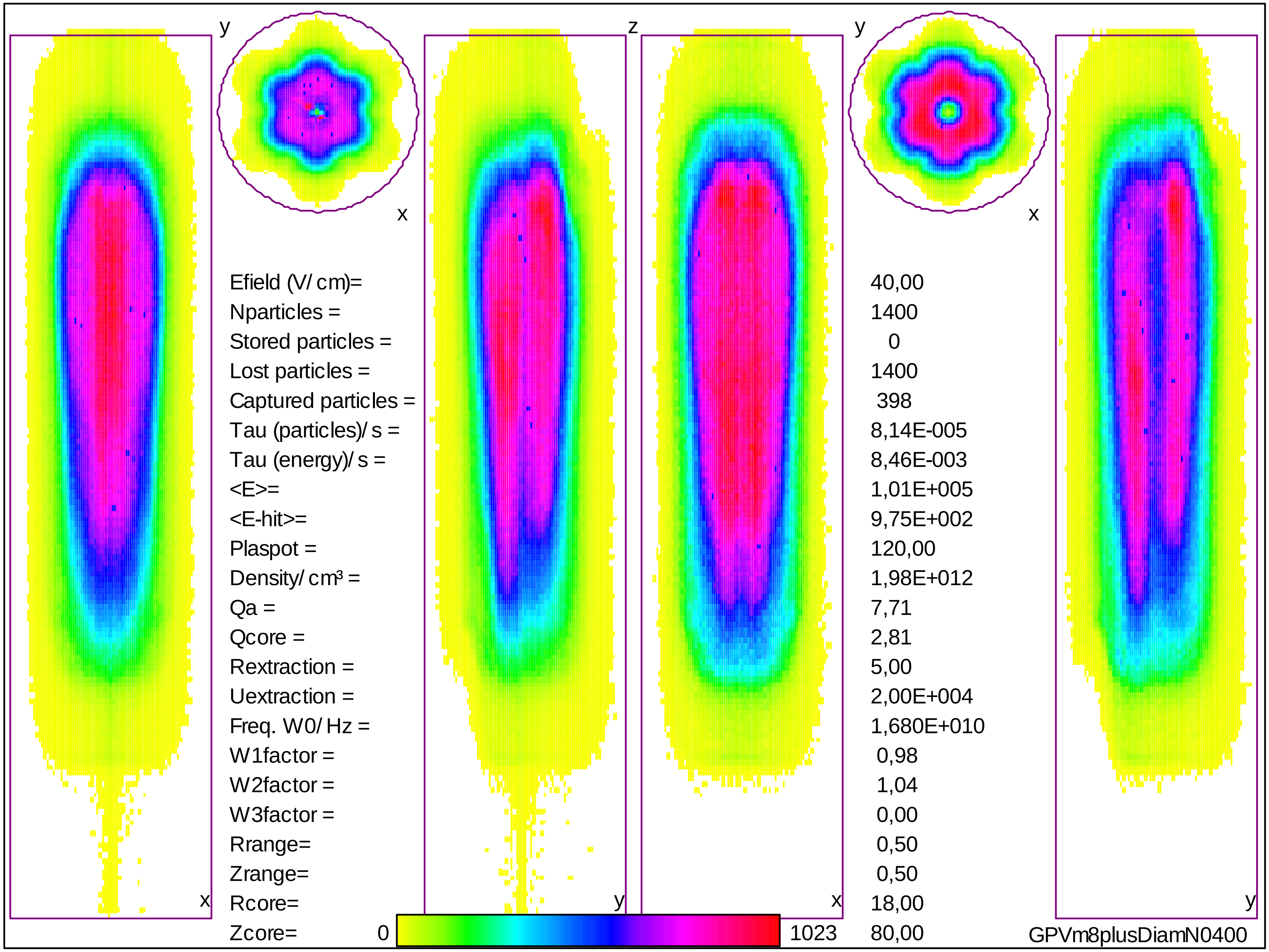
We can only keep electrons up to 7.5 keV in the resonance volume

Simulation for Ar8+ : Low power : Low <E> = 6.2 keV : Density in centre !

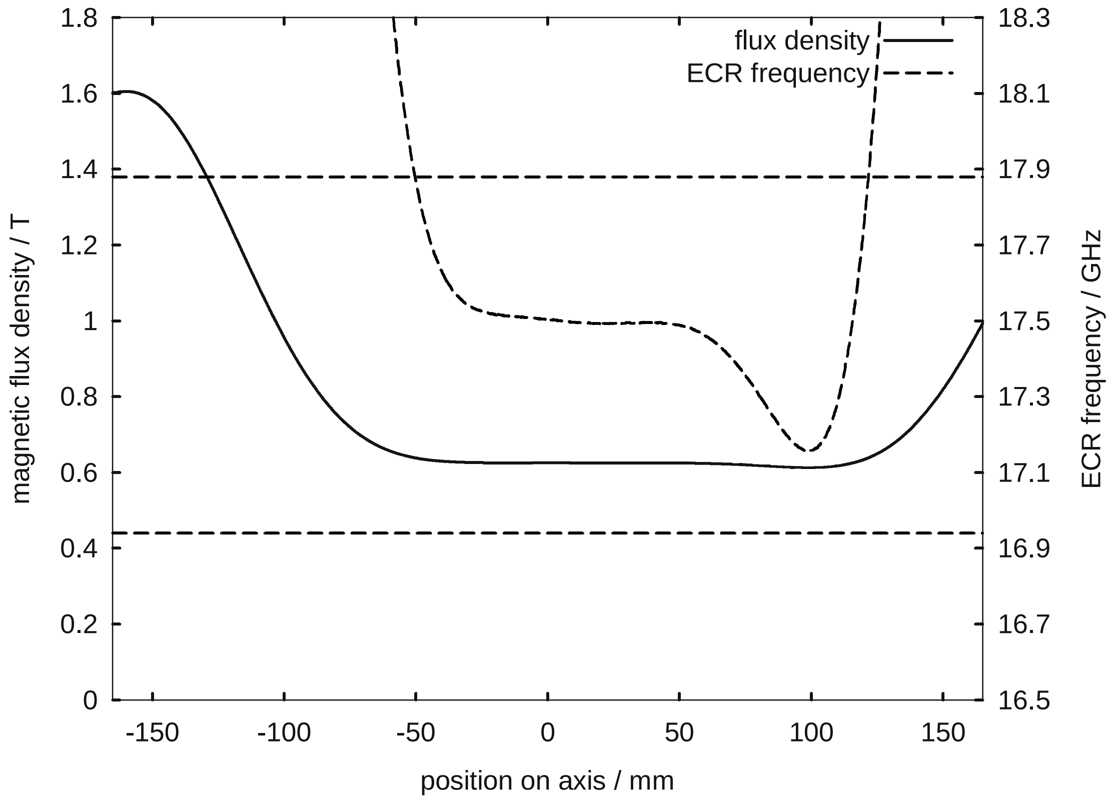


Simulation for Ar8+ : High power : High <E> = 101 keV : Extended density

In particular true for energy density on the right



How to operate a PECRIS ?



1. Start the plasma spontaneously with a frequency well above the plateau just like any SECRIS : the ion currents are low.

2. Add the second frequency below the B-mininmum and search for a µW-cavity resonance. This was initially the longest part of the optimization of PECRIS V. Once known it was often the same cavity mode at 16.925 GHz which was strong enough to heat and keep relativistic electrons in the centre and to so produce the highest ion currents observed. Extremely sensitive to frequency !

Since we need a stainless steel chamber

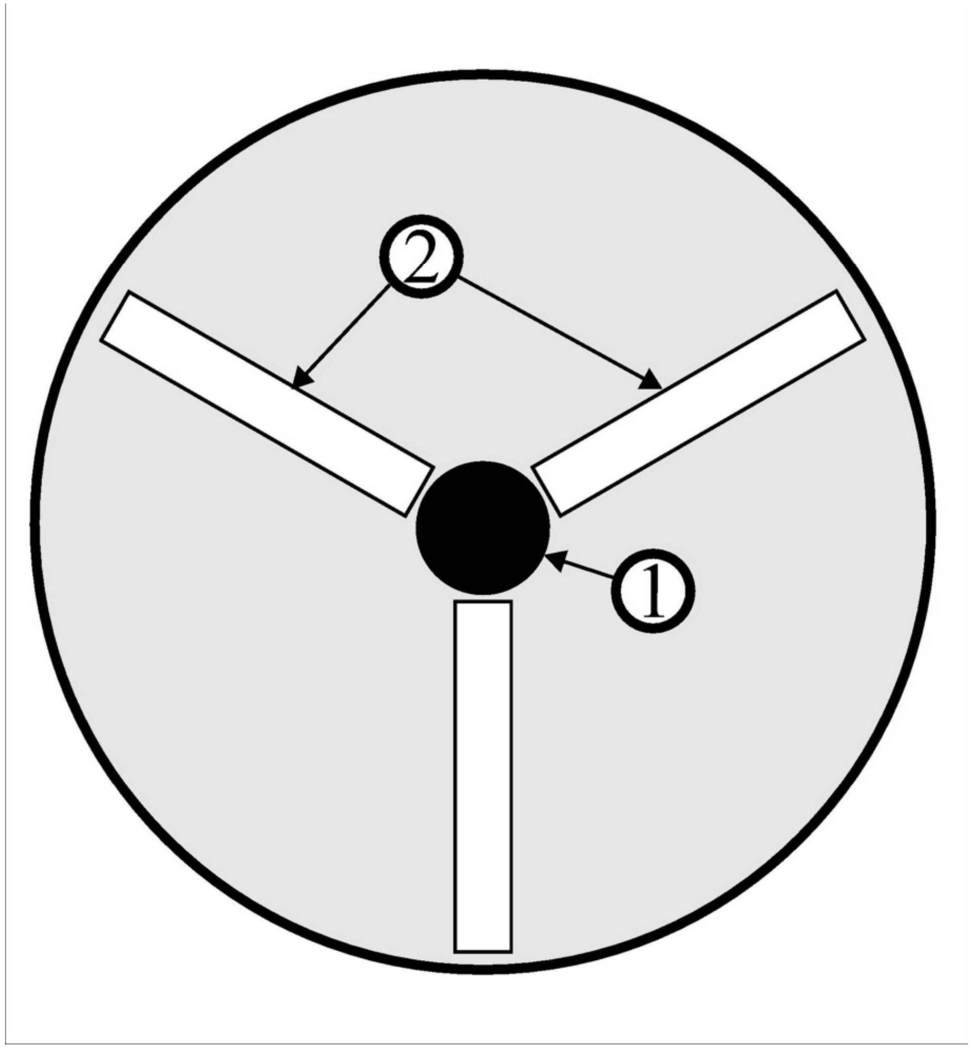
for pulsed magnetic extraction

we had to use SiO_2 coating to achieve the good results

Since SiO_2 coating does not last

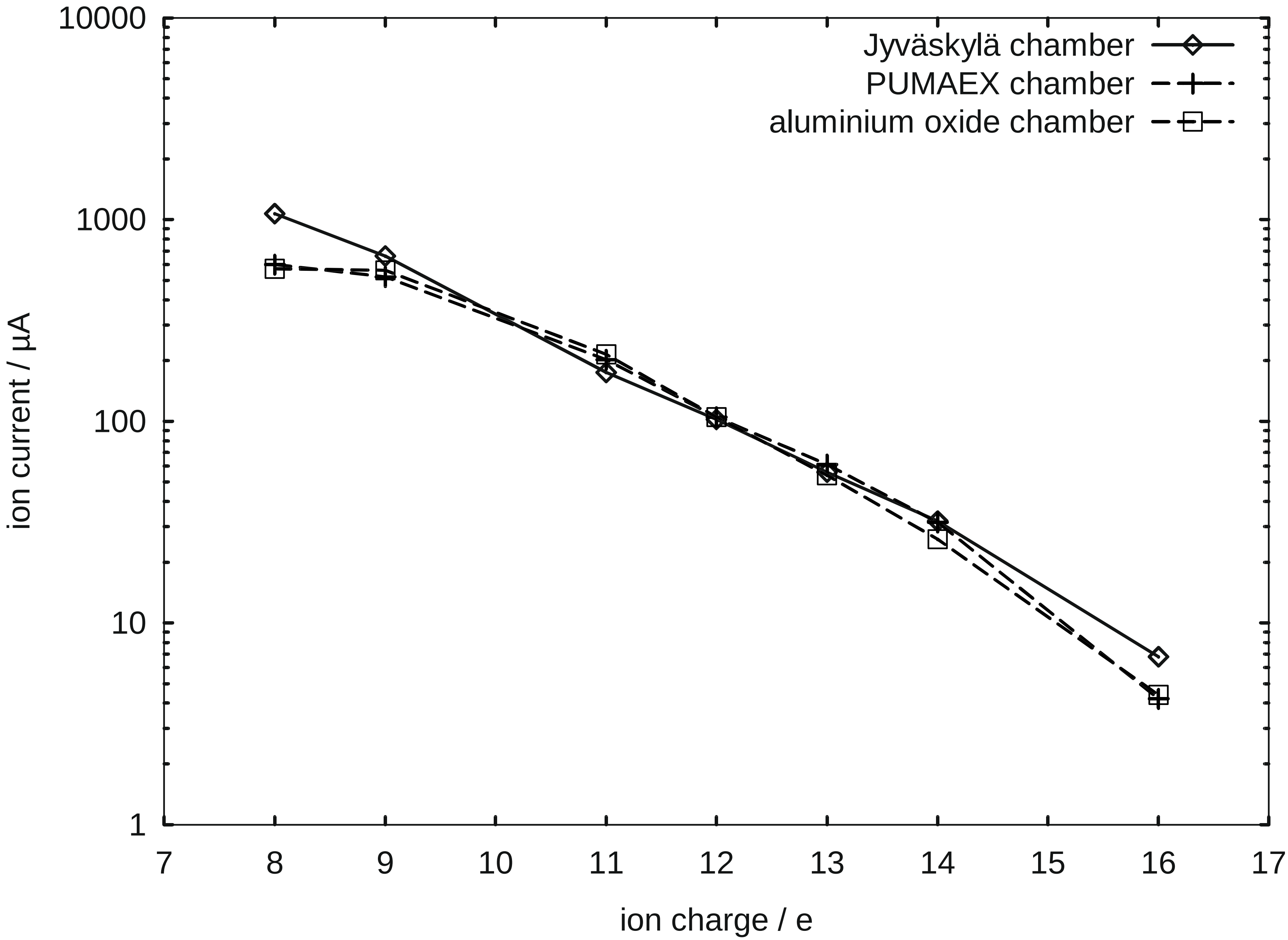
we replaced it by stripes of Al_2O_3

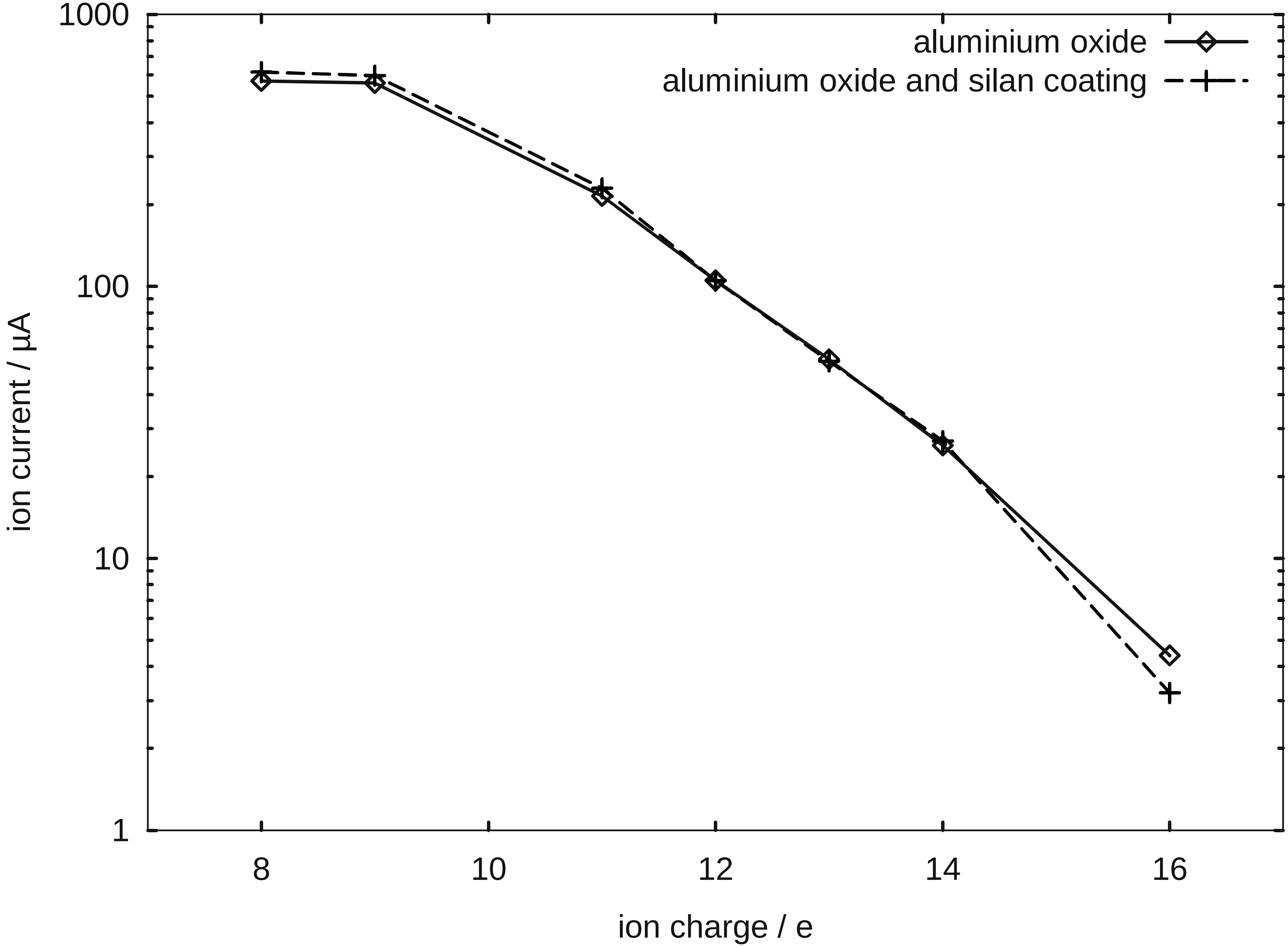
soldered with pure Al on the inner extraction end cap in next figure



With these three stripes of Al_2O_3

we obtained the same results as with SiO_2 coating


10000
1000
100
10
1
7
8
9
10
11
12
13
14
15
16
17
ion current / µA
ion charge / e
Jyväskylä chamber
PUMAEX chamber
aluminium oxide chamber



1000
100
10
1
8
10
12
14
16
ion current / µA
ion charge / e
aluminium oxide
aluminium oxide and silan coating

The philosophy:

Floating biased disks are known to charge up negatively,

in our case to about -120 V

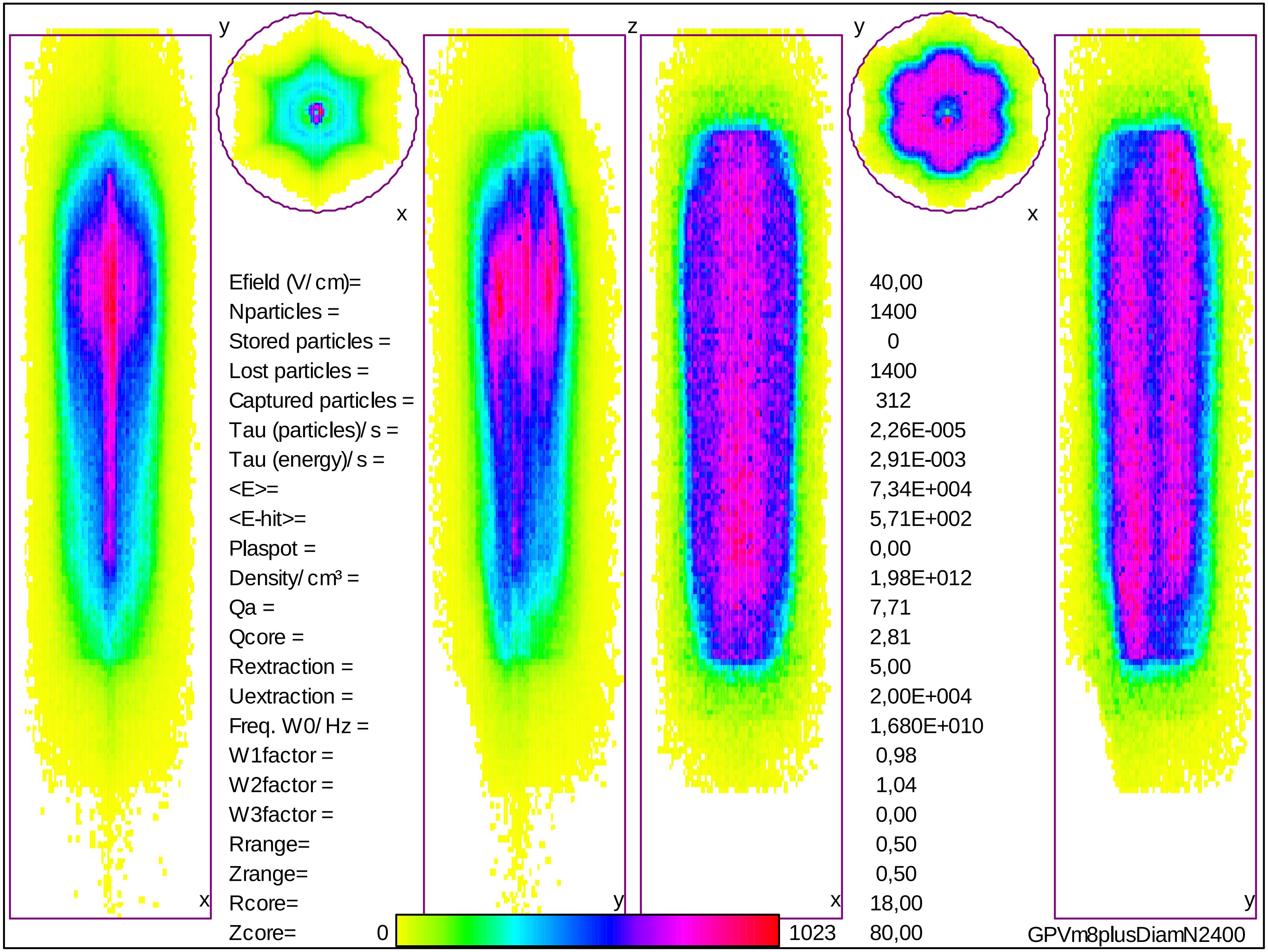
Insulators like Al_2O_3 can be considered to charge up to the same voltage

They do thus reflect electrons

with „perpendicular“ kinetic energy below this value

Which effect on the plasma ?

To this end we have incorporated this reflection in the simulations:



y
x
z
y
x
x
y
x
y
Efield (V/ cm)= 40,00
Nparticles = 1400
Stored particles = 0
Lost particles = 1400
Captured particles = 312
Tau (particles)/ s = 2,26E-005
Tau (energy)/ s = 2,91E-003
<E>= 7,34E+004
<E-hit>= 5,71E+002
Plaspot = 0,00
Density/ cm³ = 1,98E+012
Qa = 7,71
Qcore = 2,81
Rextraction = 5,00
Uextraction = 2,00E+004
Freq. W0/ Hz = 1,680E+010
W1factor = 0,98
W2factor = 1,04
W3factor = 0,00
Rrange= 0,50
Zrange= 0,50
Rcore= 18,00
Zcore= 80,00
0
1023
GPVm8plusDiamN2400

Result at 40 V/cm:	τ/µs	<E>/keV
Without reflection:	22.6	73.4
With reflection:	81.4	101.0

Particularly efficient with shift of e-cloud towards extraction

for Ar^{8+} optimization

Insulating coverages can thus

improve electron densities by considerable factors

Is this the reason why

oxygen is such a good mixing gas

in contrast to nitrogen ?

Oxygen does permanently reproduce insulating oxide layers

which are of course permanently sputtered off

This phenomenon works better in Al-chambers

than in stainless steel chambers

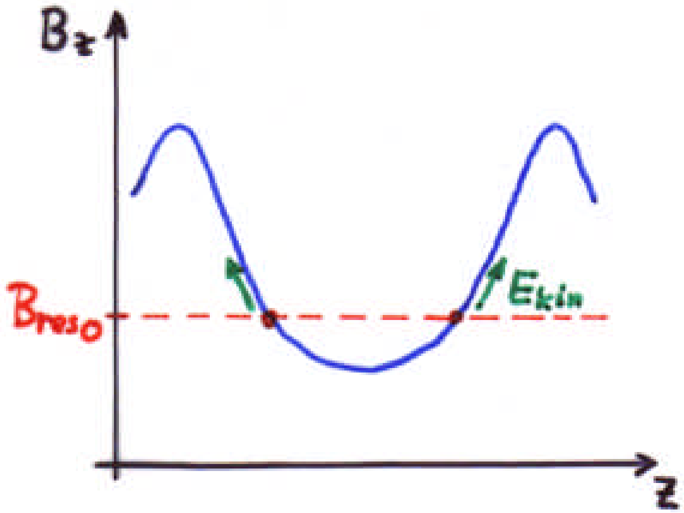
This could also explain the isotope effect:

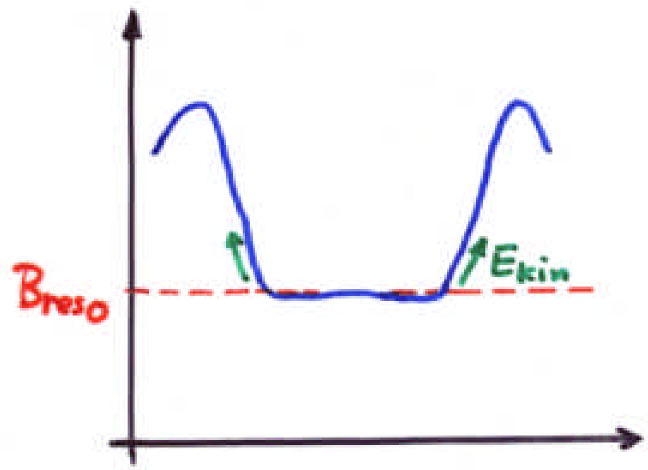
^{18}O is sputtered off less rapidly than ^{16}O

and thus forms more stable oxide layers

Relativistic effects
in

Standard ECRIS   Plateau ECRIS





$$B_{reso} = \frac{\omega_{ext} \cdot m_0}{e}$$

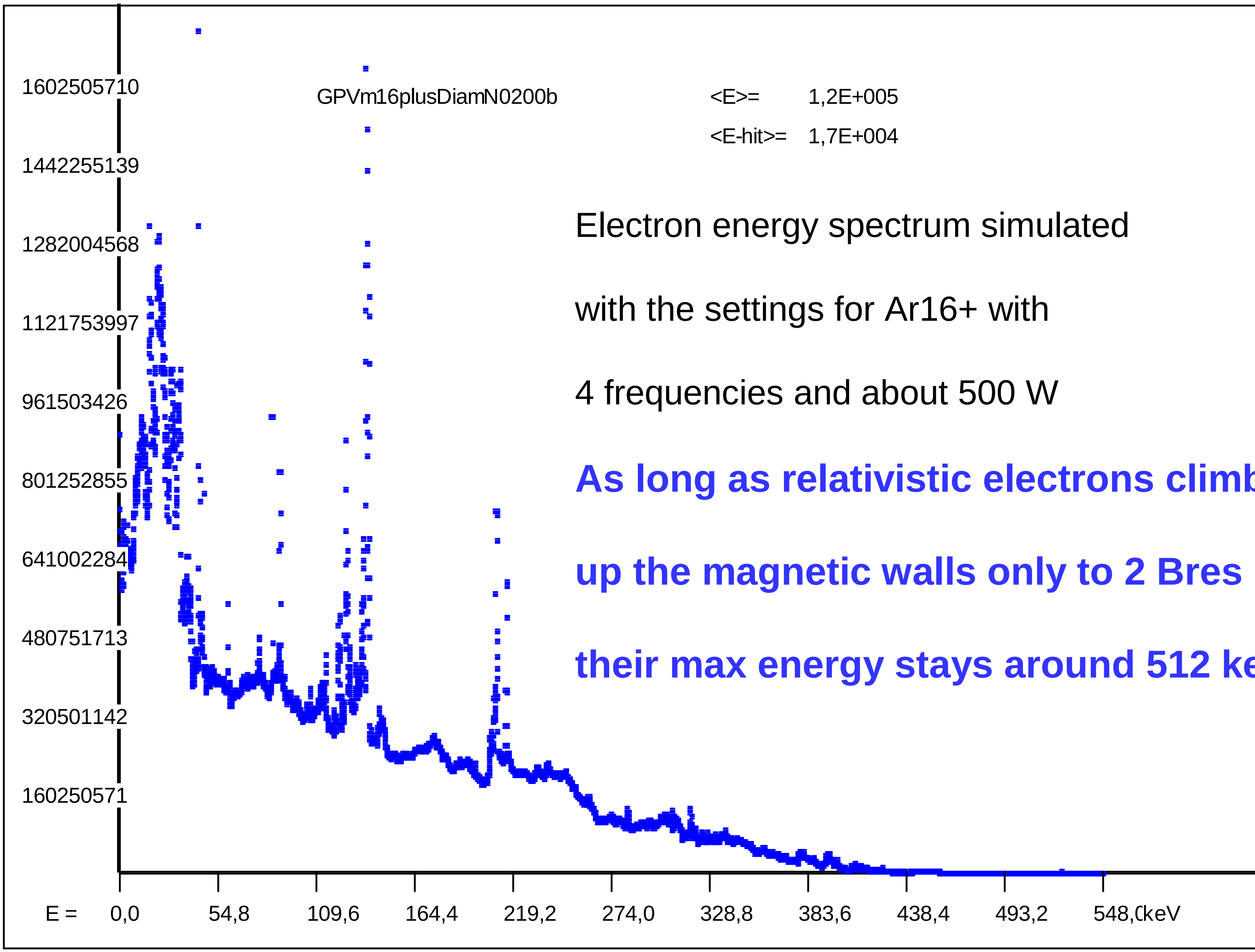
$$B_{res} = B_{reso}\left(1 + \frac{E_{kin}}{m_0 c^2}\right)$$

Inversion of formula

$E_{kin}(max) = m_0c^2(B_{res}(max)/B_{res0} - 1)$

= Max. energy of X-rays

in an ECRIS



Electron energy spectrum simulated

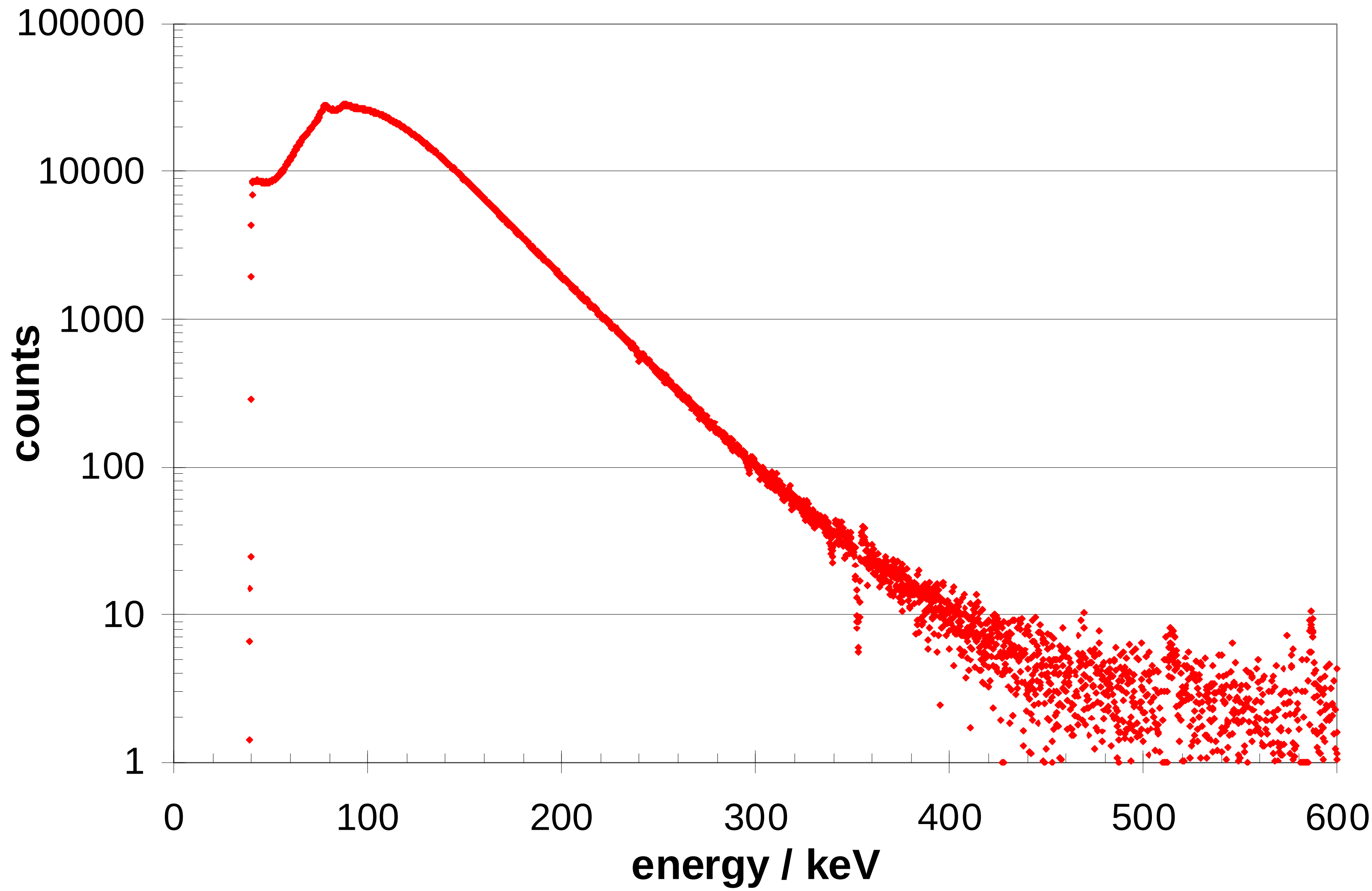
with the settings for Ar16+ with

4 frequencies and about 500 W

As long as relativistic electrons climb

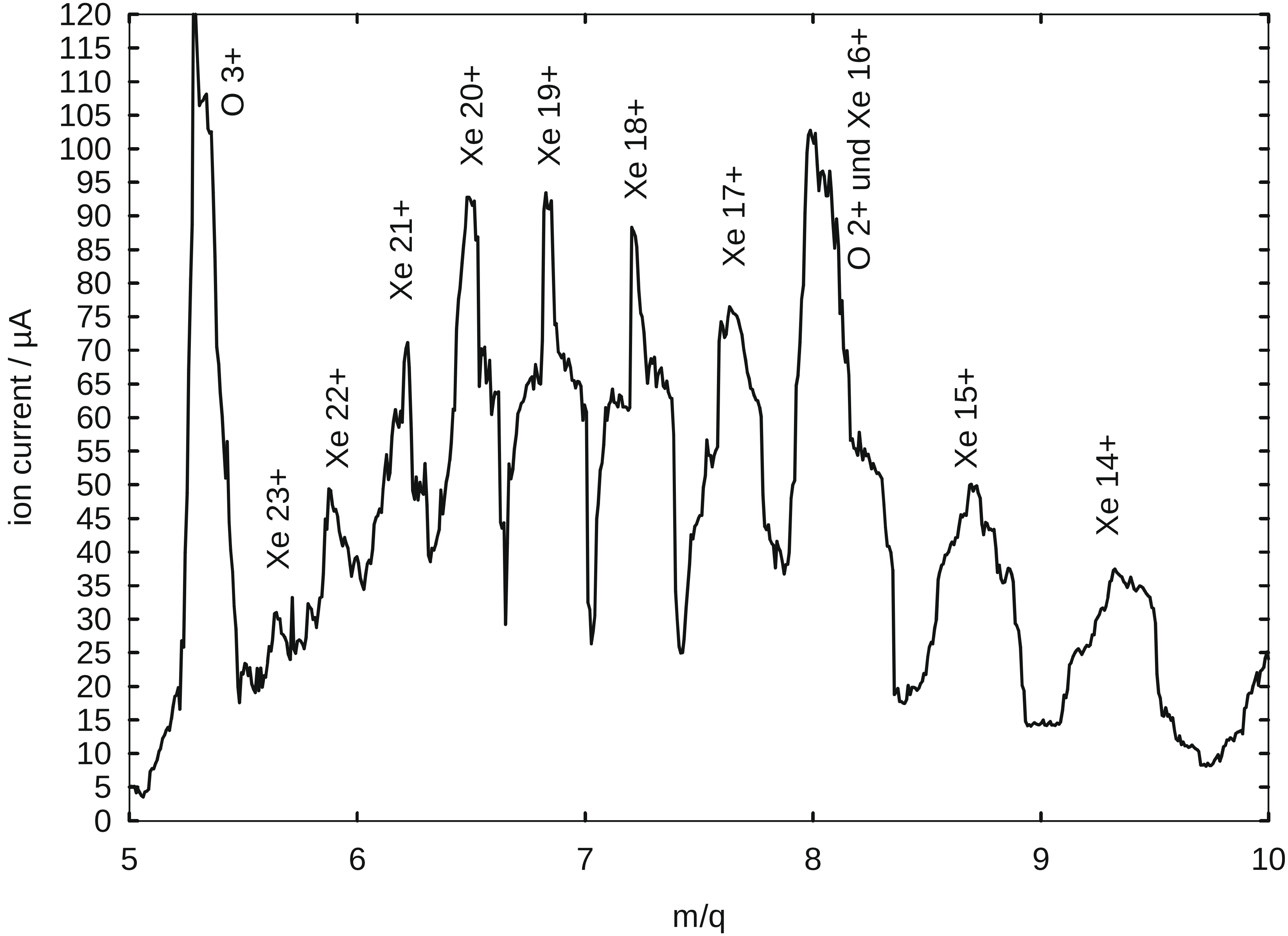
up the magnetic walls only to 2 Bres

their max energy stays around 512 keV



This was a typical X-ray measurement with the former settings

With extreme µW power one could push electrons into the corner with the highest field in PECRIS V of 2.03 T : Result would be X-rays up to 1.1 MeV

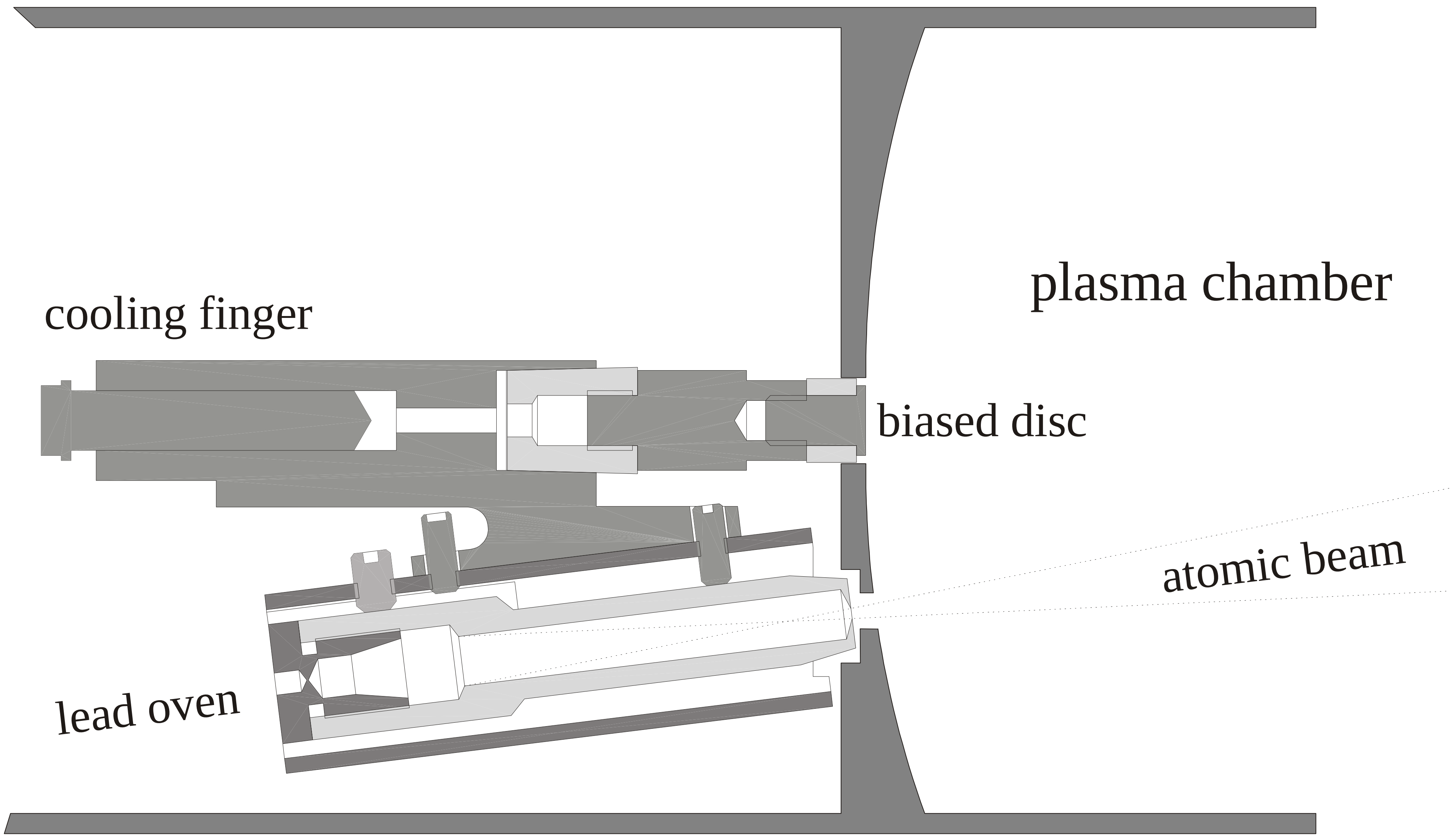


As preparation for PUMAEX with isotopically pure Xe

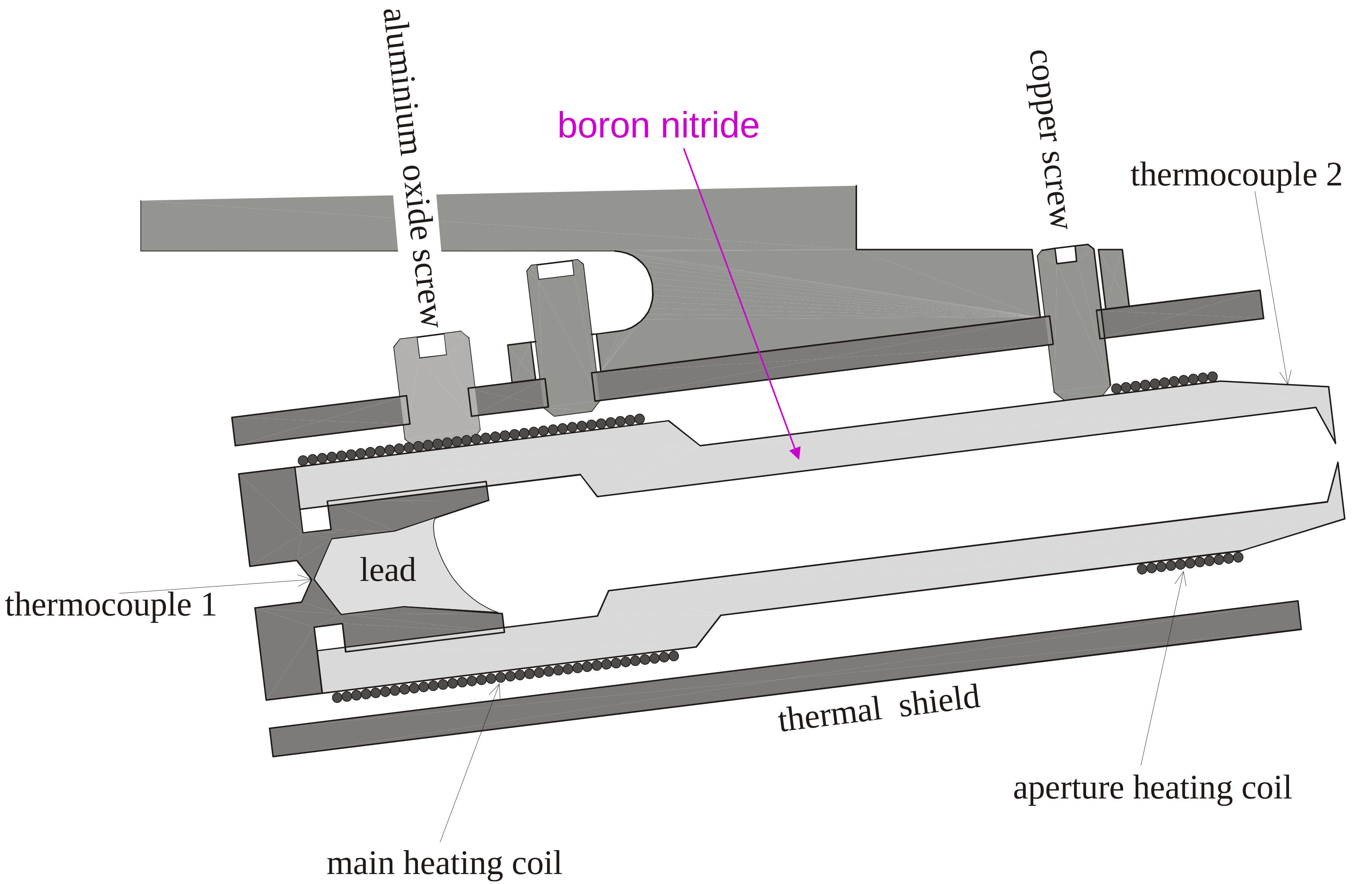
short attempt with natural isotope mixture of Xe : good result in 2002

Also as preparation for PUMAEX with Pb a lead oven was developed.

Atomic beam with **only 9° half width**. It perfectly worked externally for days.

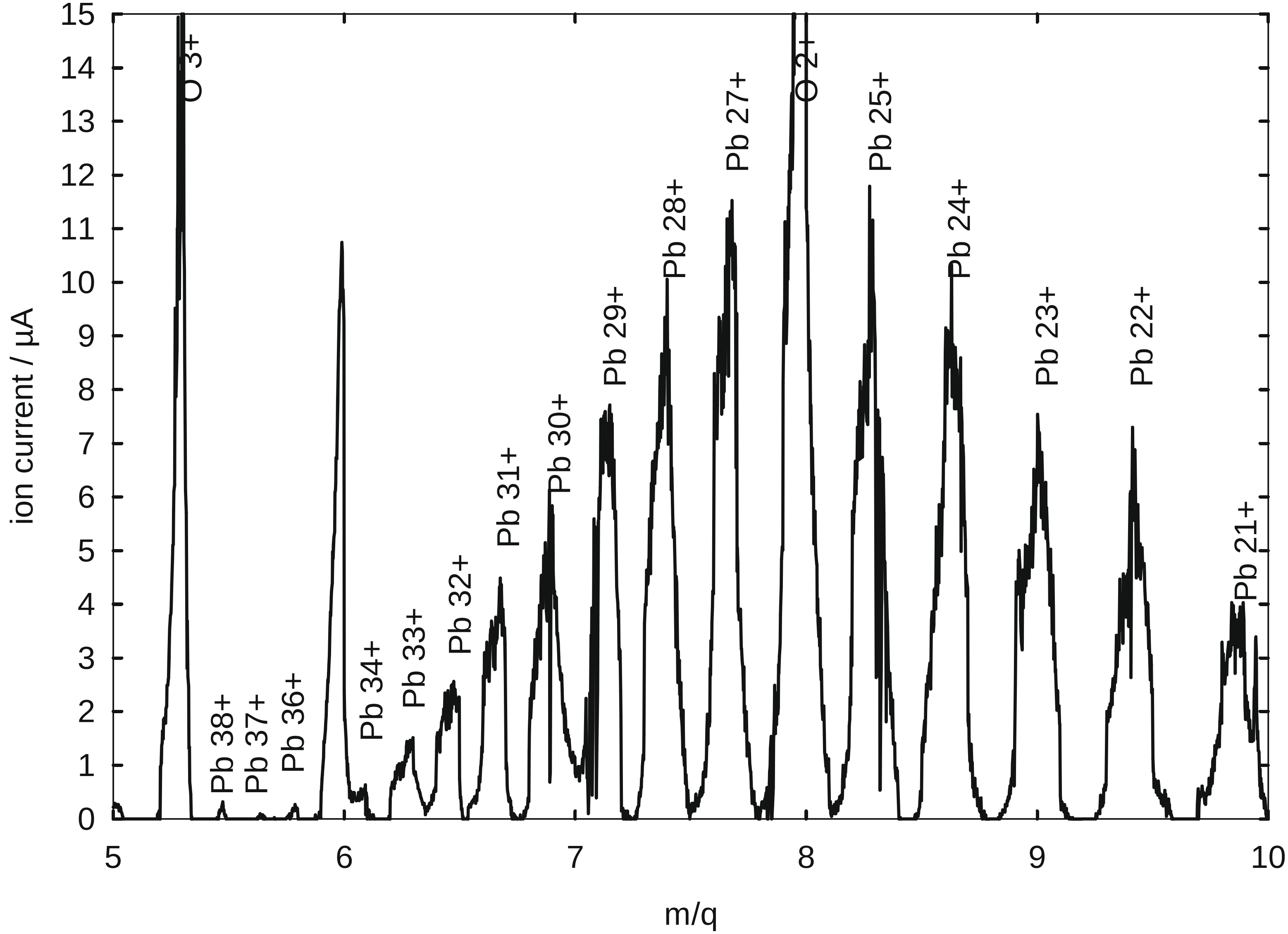


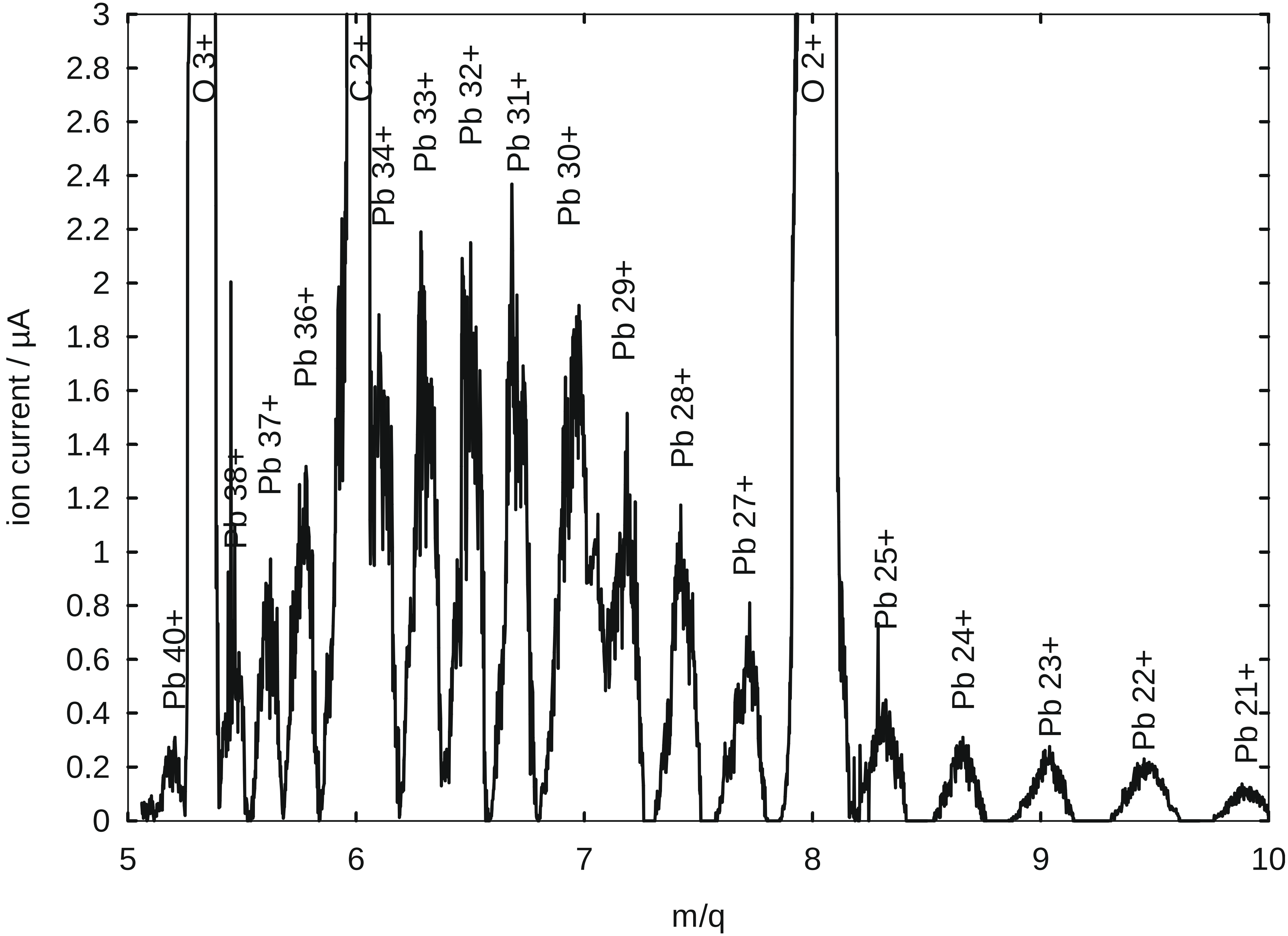
Once built in, the thermocouples saw too much µW and produced wrong temperature readings: The lead was overheated and obscured the exit. When heating it off with the aperture coil, this coil was overheated and broke.



A repair of the oven was impossible for reasons of time.

Disappointing resultswith lead vapor only stemming from the obscuring lead heated by the main heating coil – very far away





ion current / µA
m/q
O 3+
C 2+
O 2+
Pb 40+
Pb 38+
Pb 37+
Pb 36+
Pb 34+
Pb 33+
Pb 32+
Pb 31+
Pb 30+
Pb 29+
Pb 28+
Pb 27+
Pb 25+
Pb 24+
Pb 23+
Pb 22+
Pb 21+

Back to Ar^{16+} measurements:

Since the total gas pressure at the gauge was $2.6 \cdot 10^{-6}$ Pa

a particle density of $n_{gas} = 8.4 \cdot 10^{9}$ cm^{-3} in the plasma chamber is

calculated with molecular conductance from the chamber to the gauge:

a factor of 430 below the electron

cut-off density of $3.6 \cdot 10^{12}$ cm^{-3} at 17.04 GHz !!

Assumption: ion density equal to the gas density in the plasma core

To store this ion density with an averaged charge state $q_a = 8.3$

an electron density of $n_e = n_{gas} \cdot q_a = 7 \cdot 10^{10}$ cm^{-3} is required

still a factor of 50 below the cut off density

(another estimate gave a factor of 10)

In PECRIS V: $n_e >> n_{gas} \approx n_{ion}$

The stiff electron cloud of high energy near axis

serves as ion cage

for long lifetimes of the ions since

ions are detained by force ~ q^2

due to image charge

How to extract these ions ?

In particular in short pulses of 100 μs length as for the LHC

Answer: By PUlsed MAgnetic EXtraction PUMAEX

First tried by C. Möhle at GSI (1995) by brute force--but given up

Reduced version realized on PECRIS III with great success

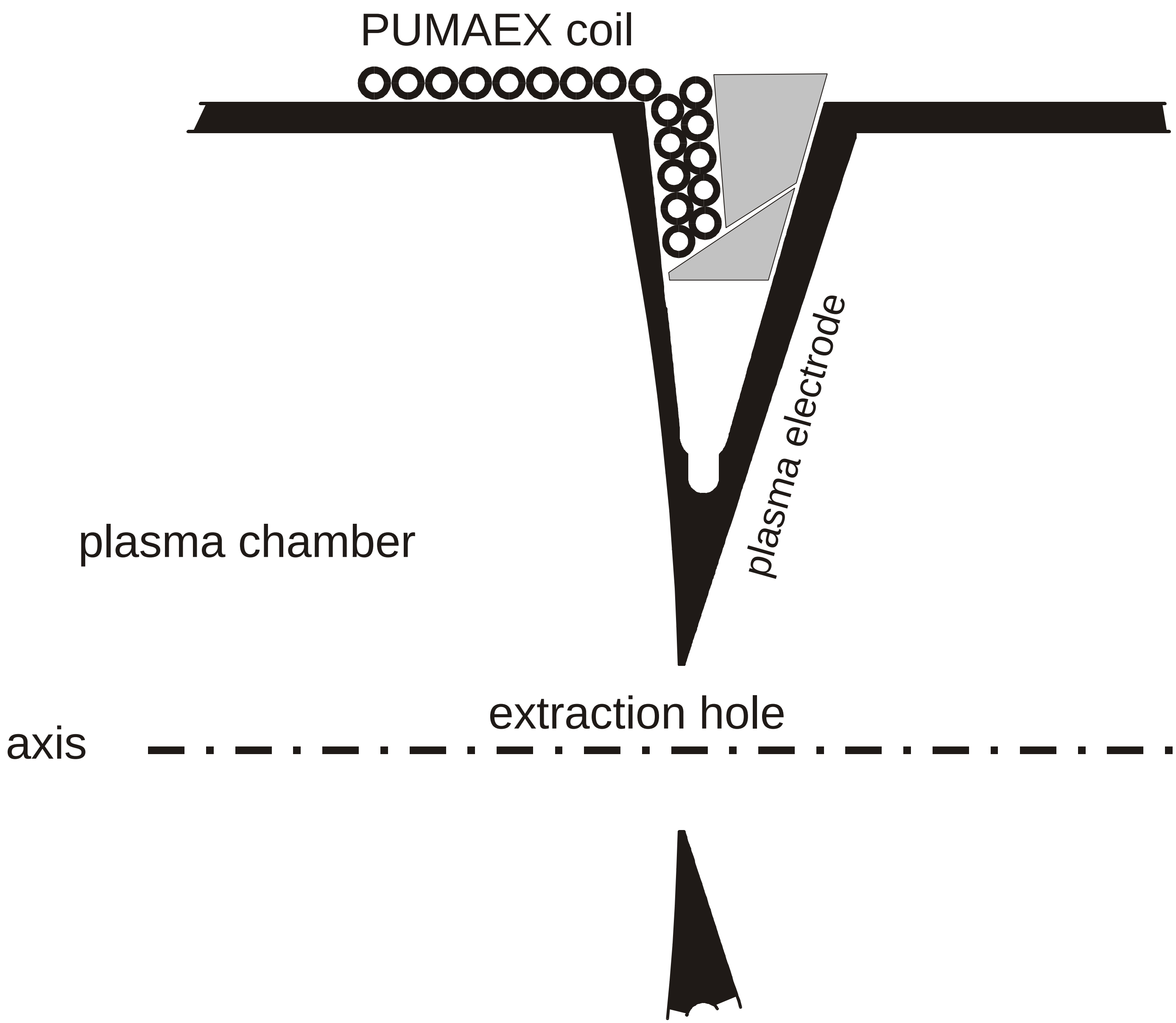
presented on Berkeley meeting and published in

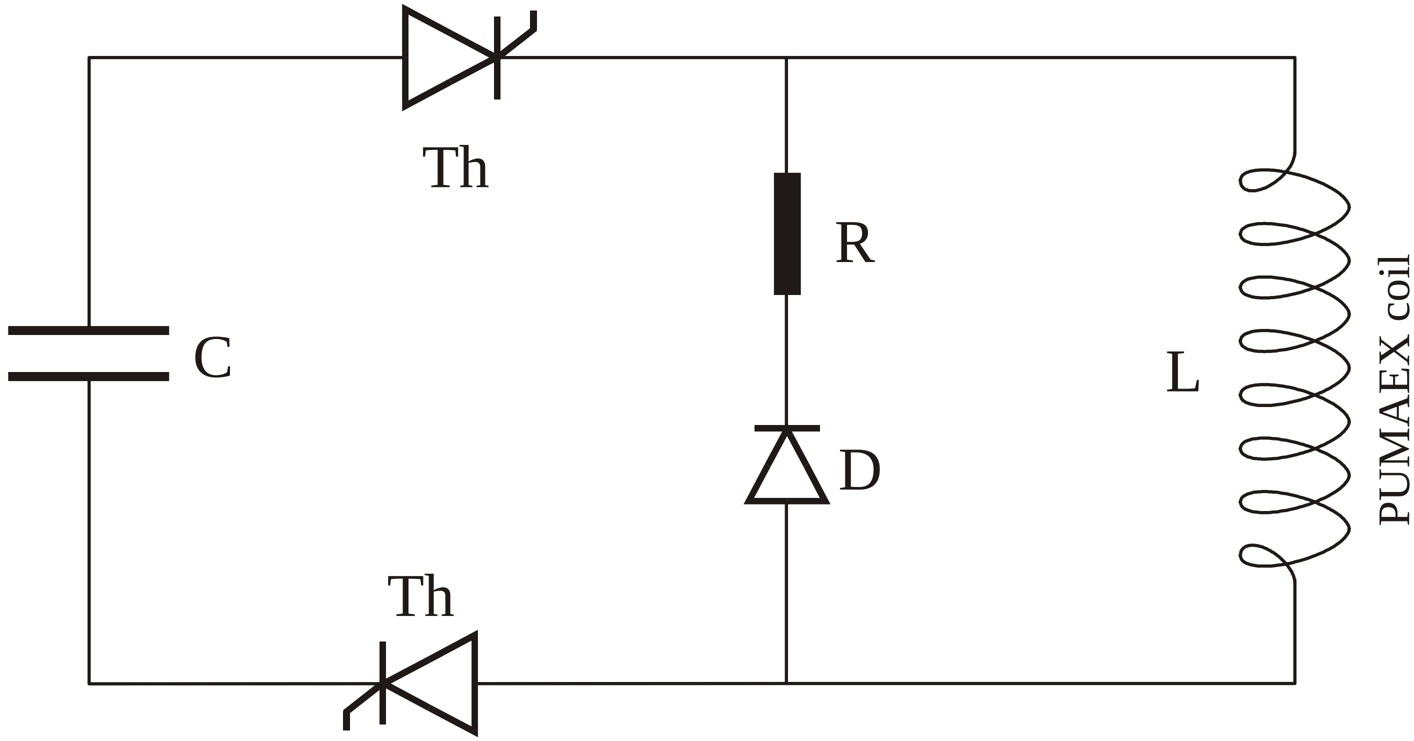
Rev. Sci.Instr. 73, 1140 (2002)

Idea: Lower the magnetic mirror field at extraction

by a short current pulse in a coil wound around extraction hole

PUMAEX works when Afterglow fails

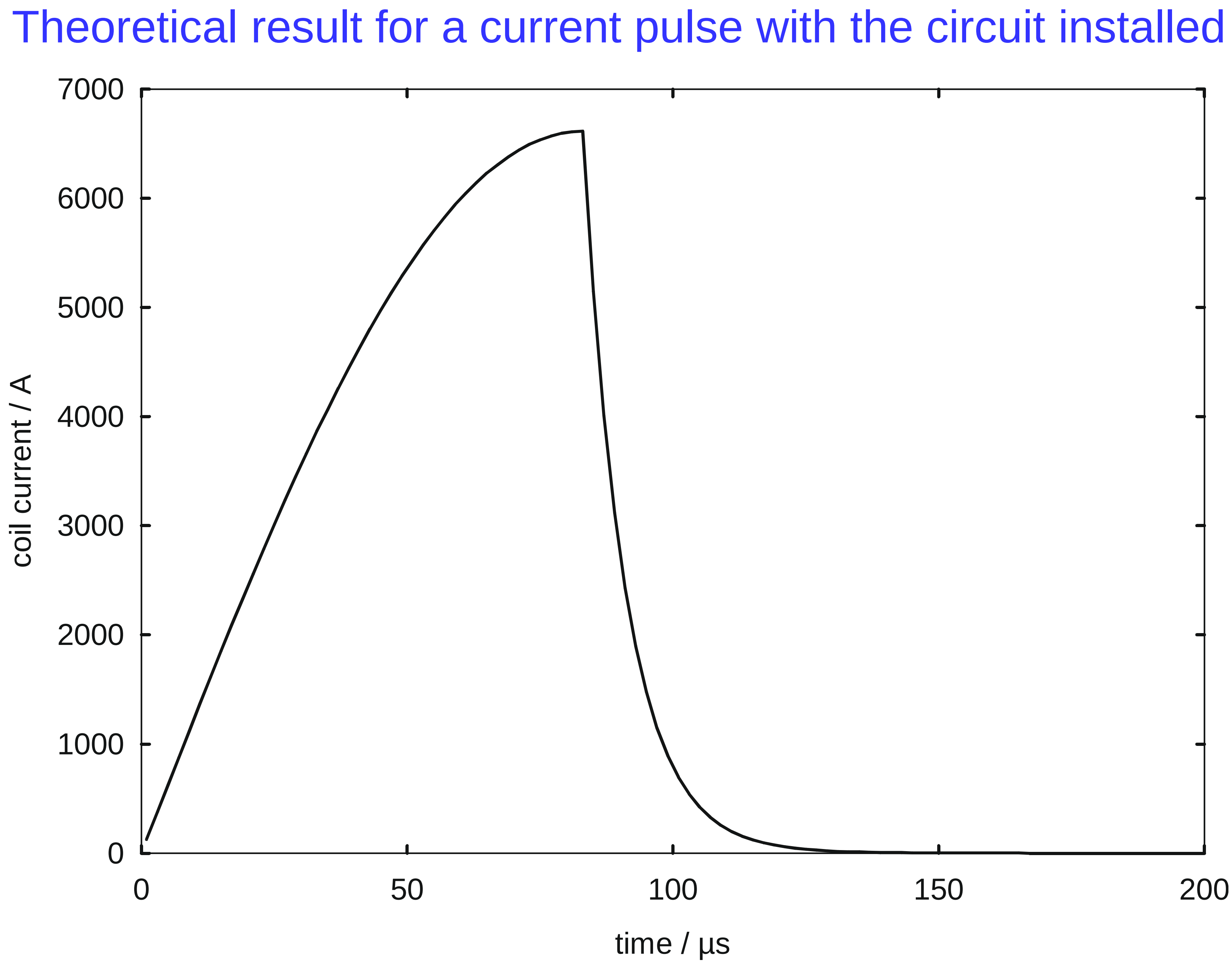

PUMAEX coil
plasma electrode
plasma chamber
extraction hole
axis



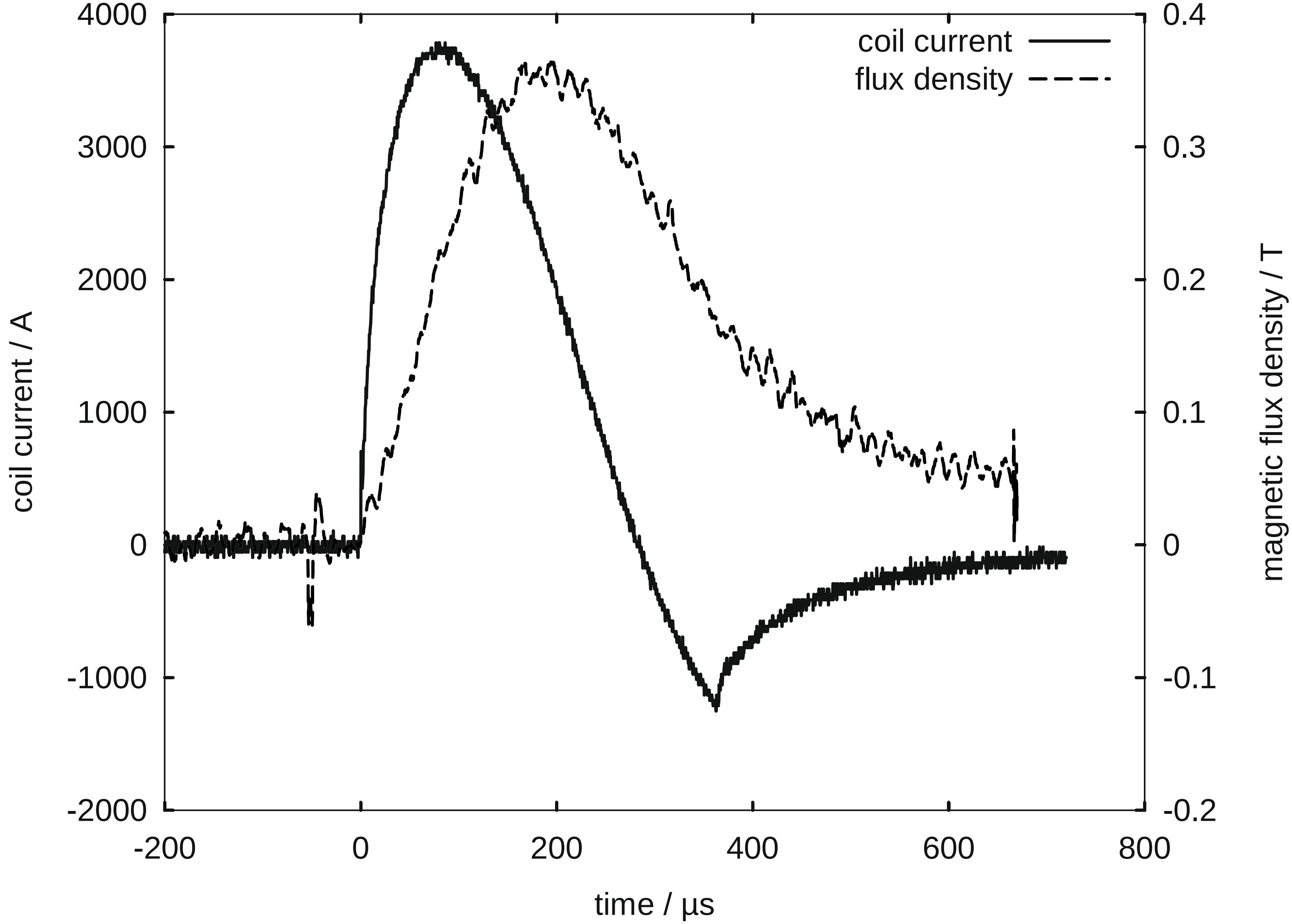
$$\mathbf{I(t) = I_0 \sin[t/\sqrt{(LC)}]} \quad \text{for } 0 < t < t_{max} = \pi/2 \sqrt{(LC)}$$

$$\text{and with } I_0 = U_0 \sqrt{(L/C)}$$

$$I(t) = I_0 \exp[-R/L(t\text{-tmax})] \quad \text{for } t > \text{tmax}$$

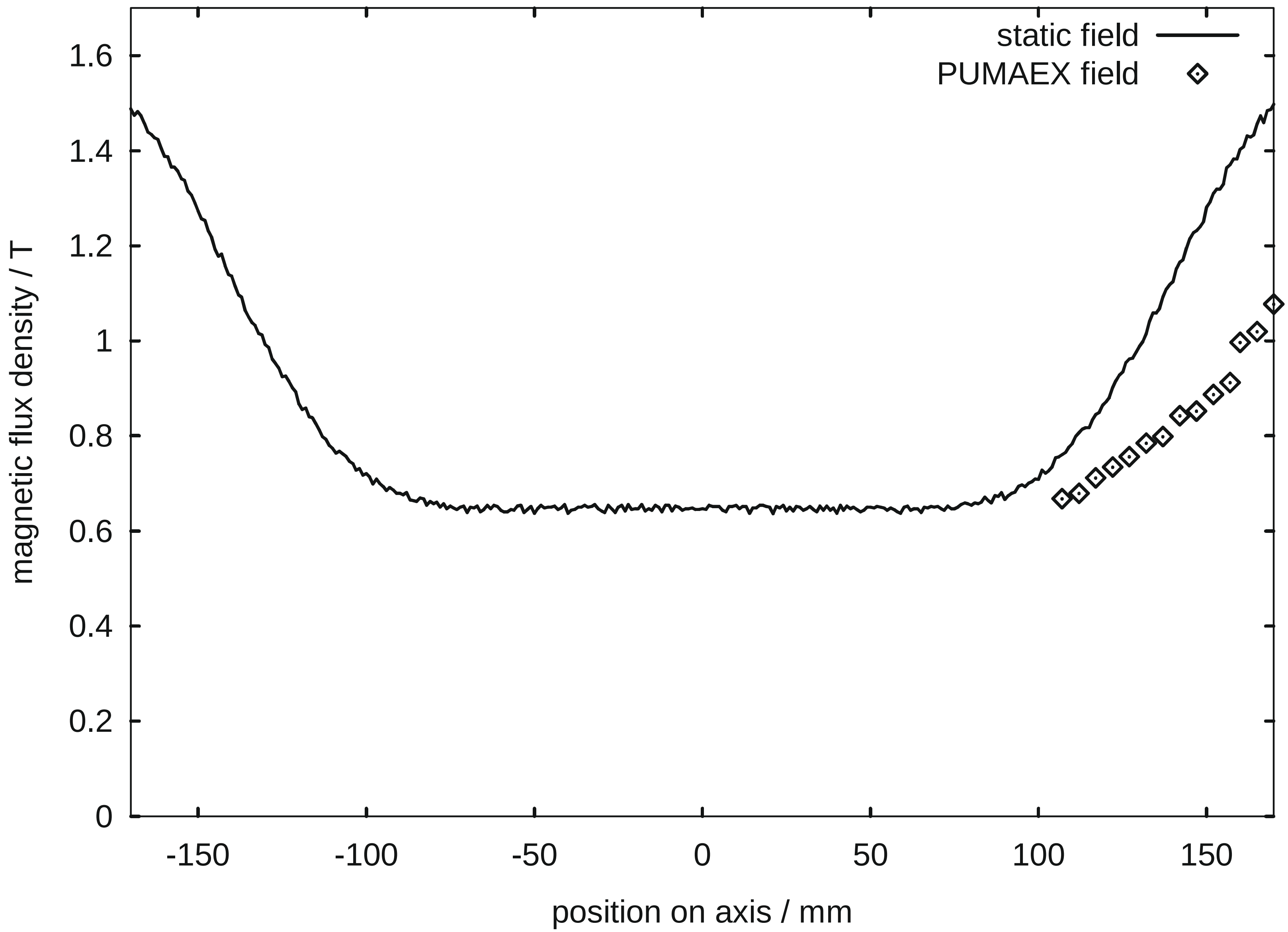


Theoretical result for a current pulse with the circuit installed
7000
6000
5000
4000
3000
2000
1000
0
coil current / A
0
50
100
150
200
time / µs

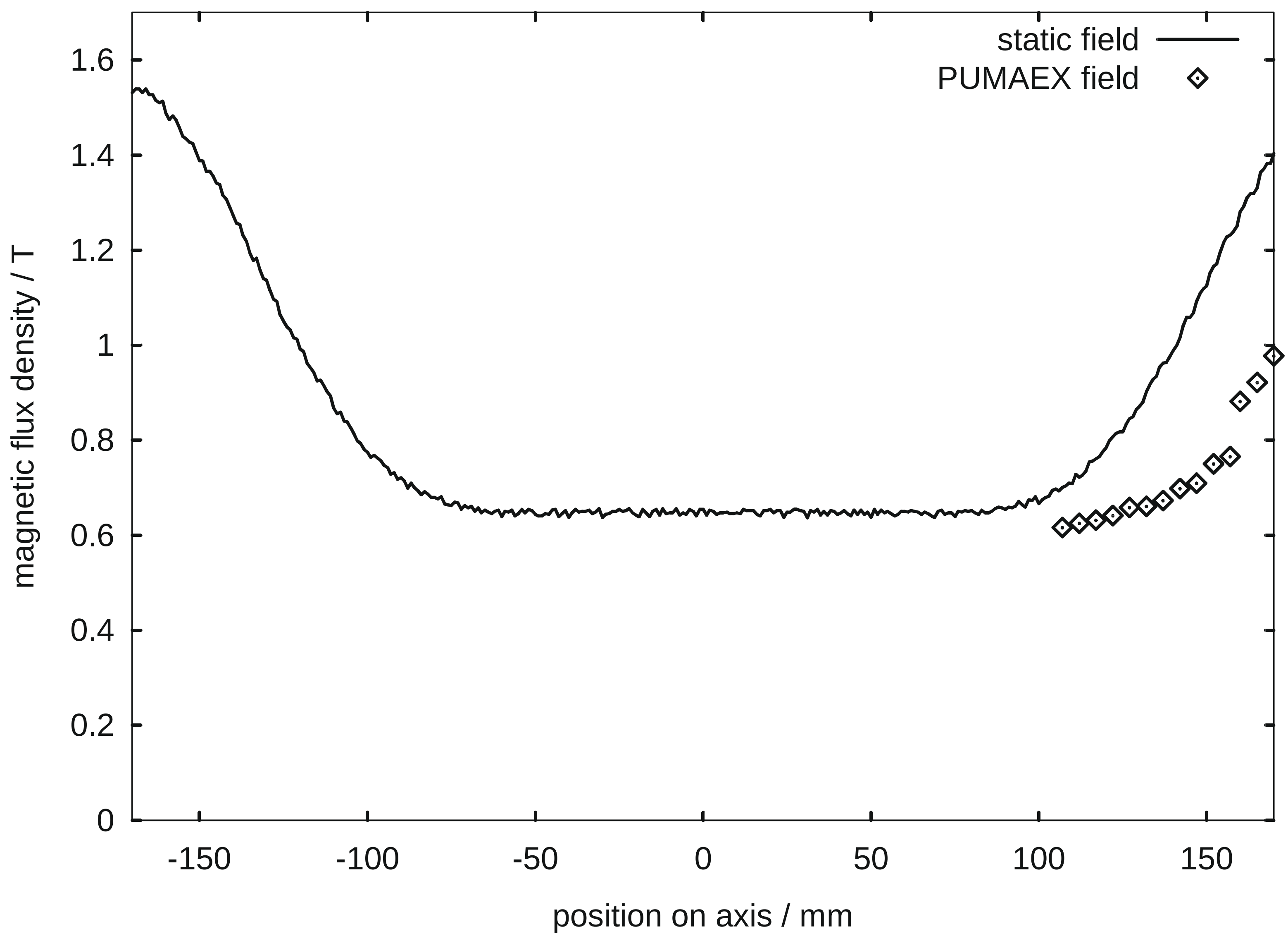


Eddy currents in metal reduce the useful current

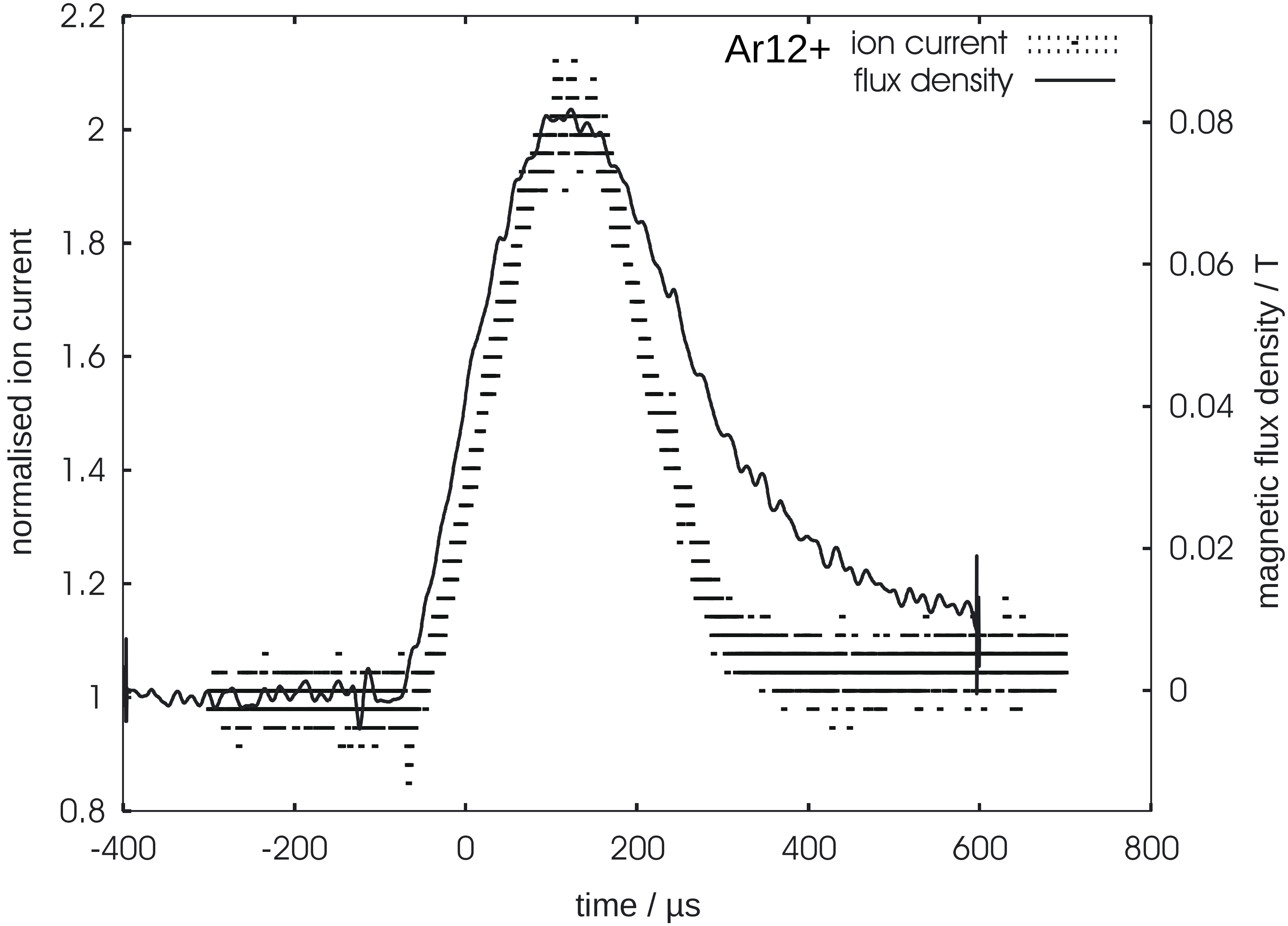
Therefore bad conductor as wall material : here stainless steel



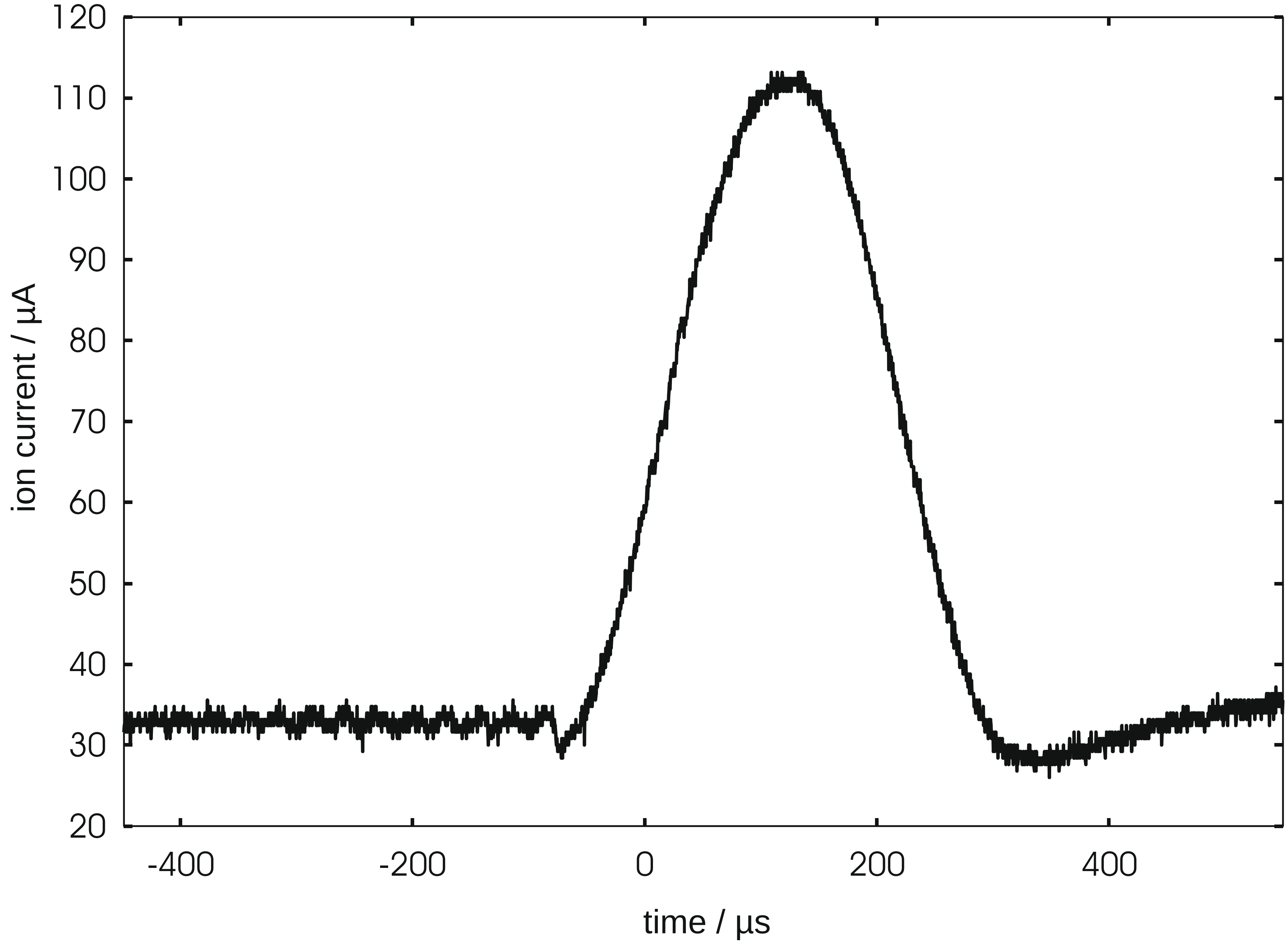
Central position of mirror field with respect to plasma chamber



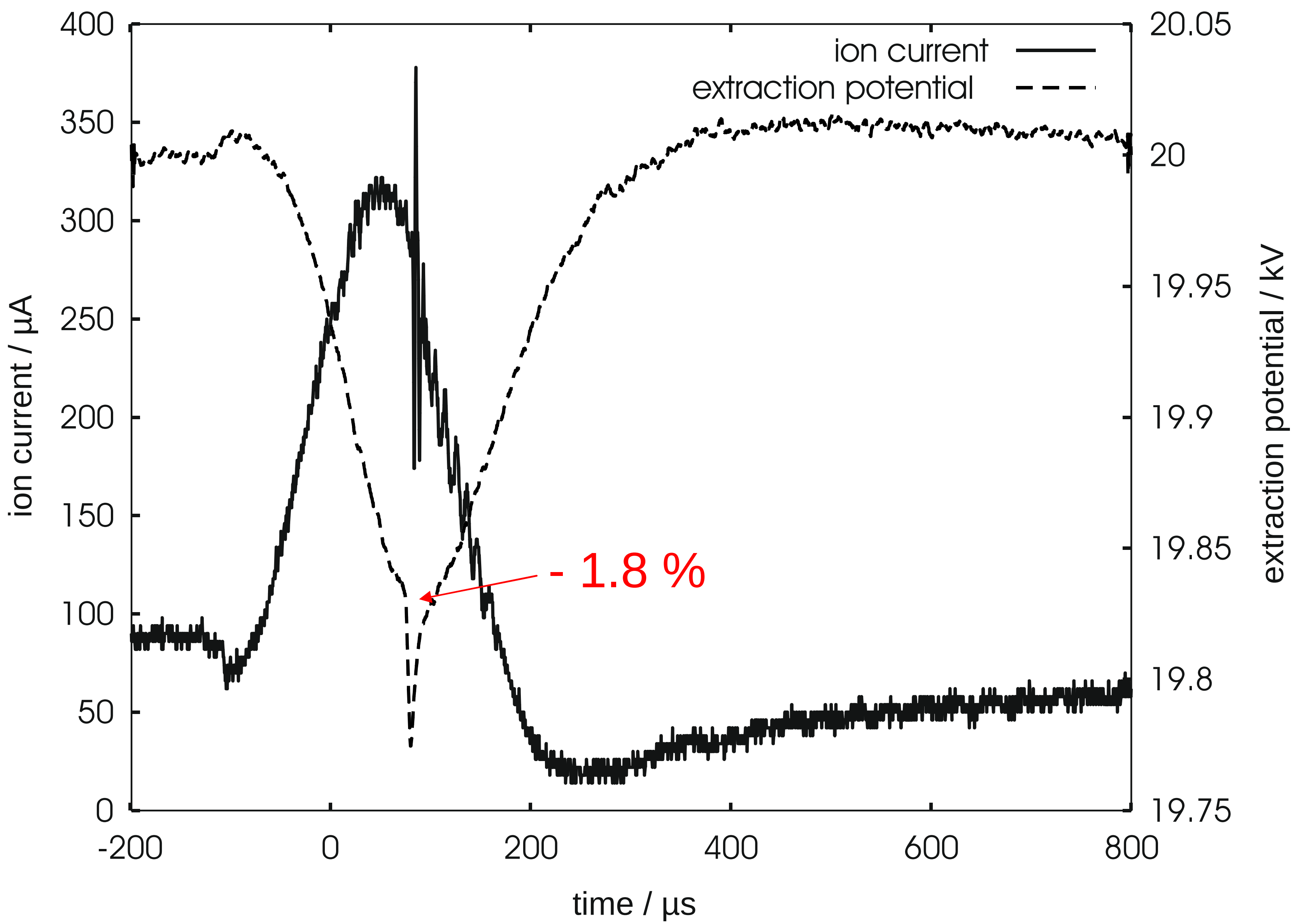
Mirror field shifted by 10 mm with respect to plasms chamber


Ar12+
ion current
flux density
normalised ion current
magnetic flux density / T
time / µs
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.08
0.06
0.04
0.02
0
-400
-200
0
200
400
600
800

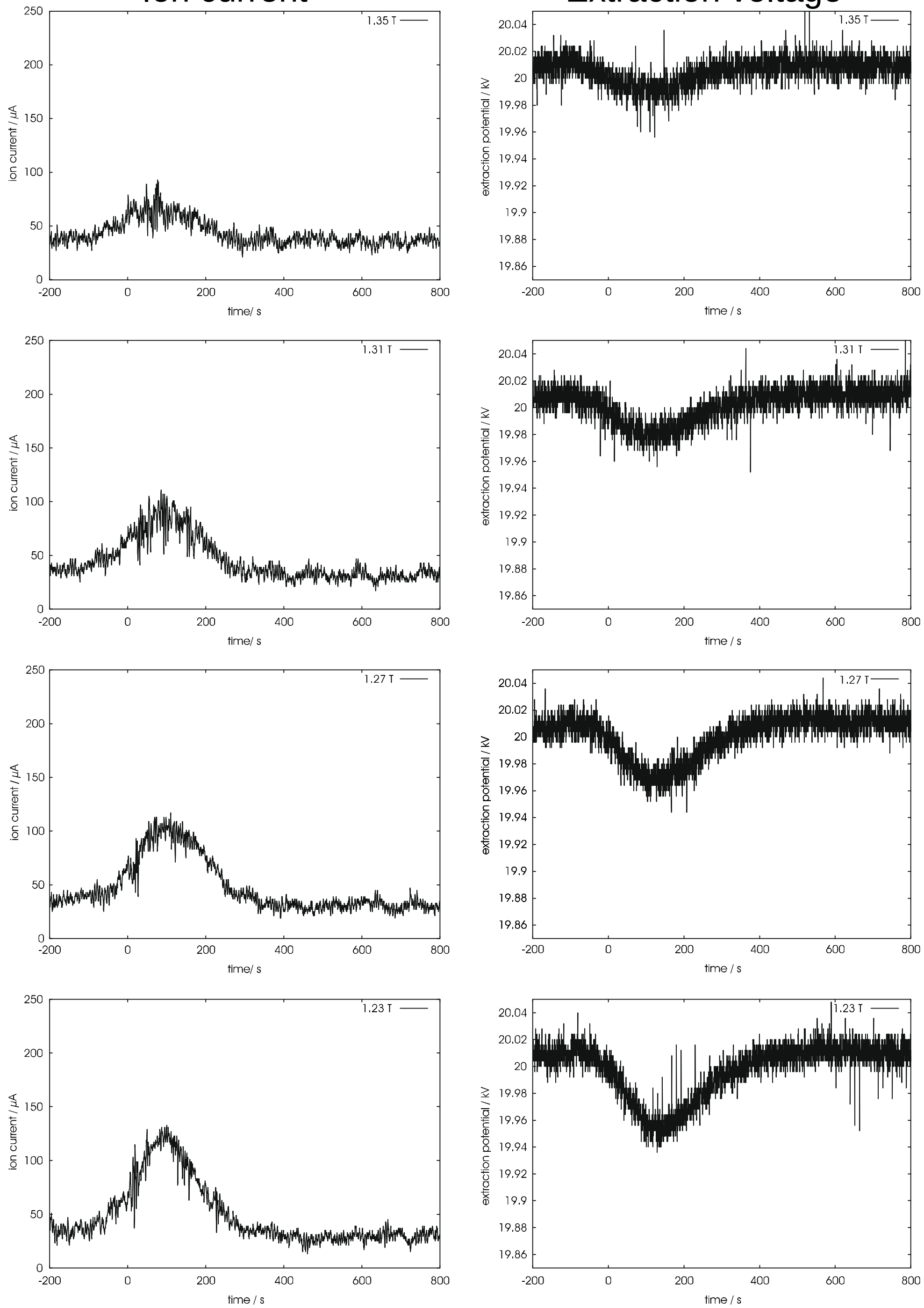
PUMAEX pulse of Ar^{12+}



Ar^{12+} current and extraction voltage as function of time



Ion current | Extraction voltage



1.35 T

1.31 T

1.27 T

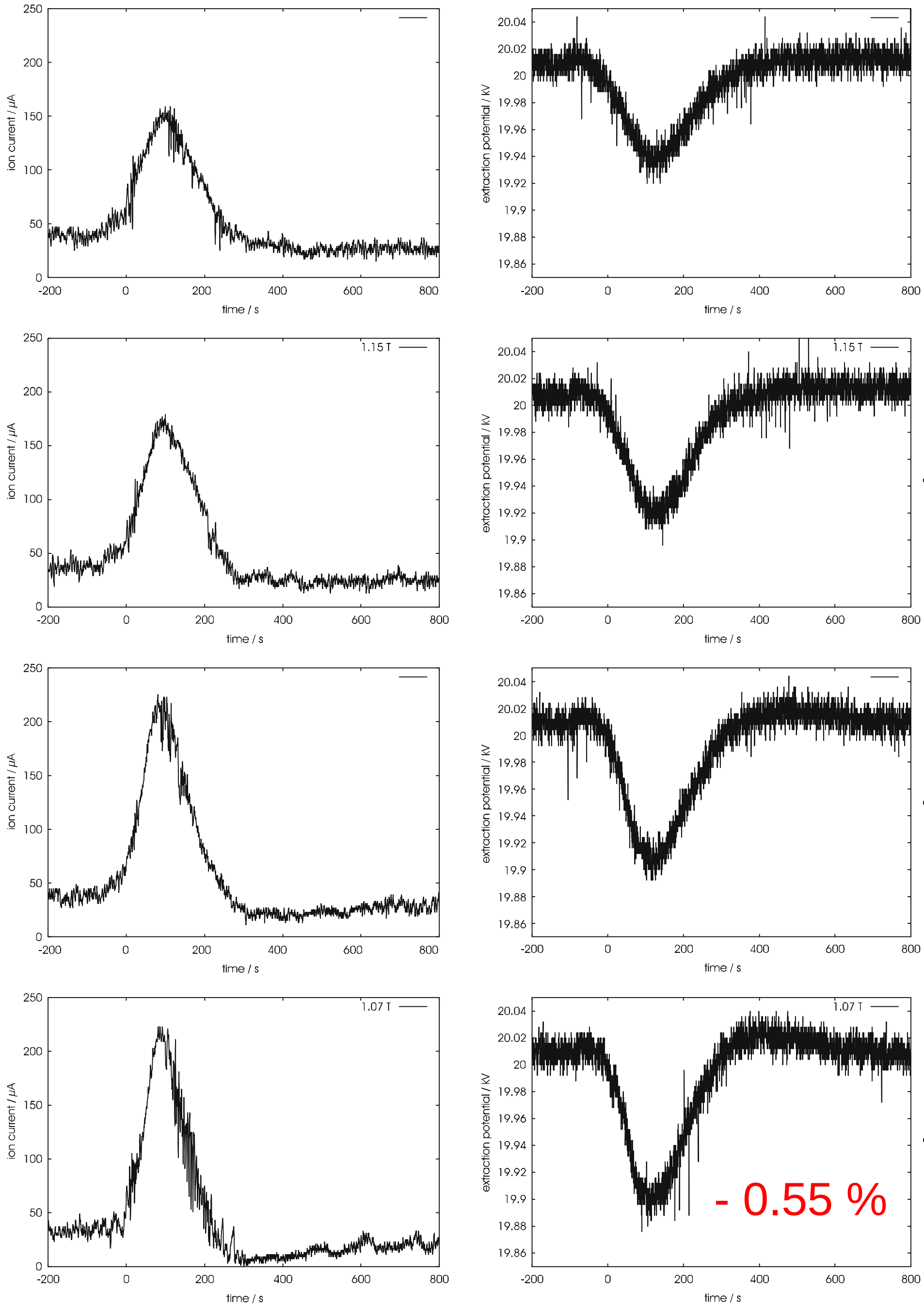
1.23 T

The field at extraction was

1.5 T without PUMAEX

The observed ion is Ar12+

Ion current | Extraction voltage



1.19 T

1.15 T

1.11 T

1.07 T

The field at extraction was

1.5 T without PUMAEX

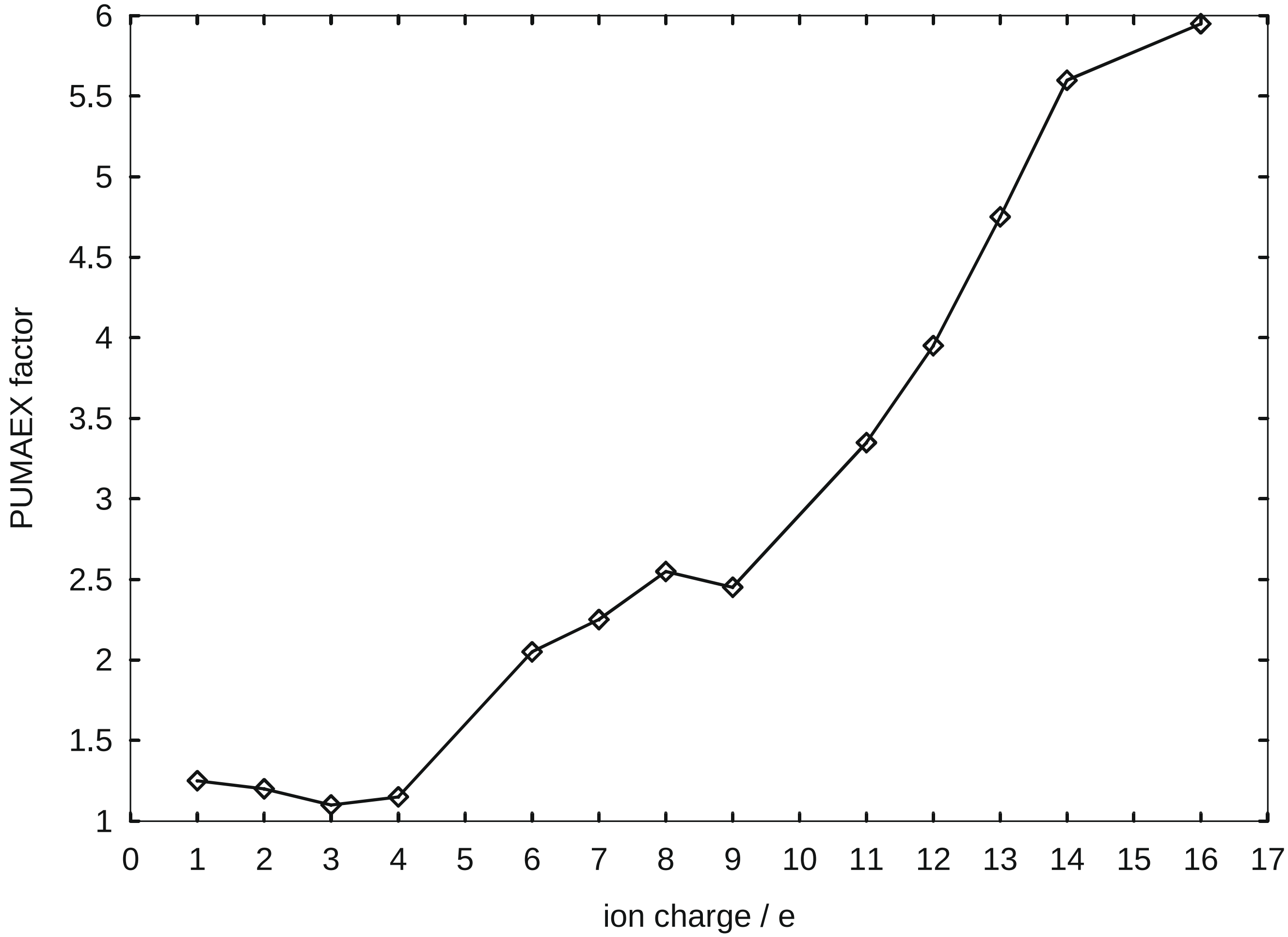
The observed ion is Ar12+

In order to compare the PUMAEX pulses with the continuous currents

PECRIS V was optimized for Ar 11+,

an integration over 50 µs was applied around the peak height,

and the ratio of peak content to continuous current was plotted:



The Pumaex-technique allows to look into the source

The charge state distribution obtained with PUMAEX

is very different from the one continuously extracted

It is considerably shifted to higher charge states

which evidently exist in PECRIS V

They cannot be continuously extracted due to the

magnetic mirror and the electrostatic retrieving force $\sim q^2$

which are necessary for their production with long confinement

The best stable 50 µs pulses were obtained with

240 µA of Ar^{14+}

and

49 µA of Ar^{16+}

with peak heights up to 60 µA of Ar^{16+}

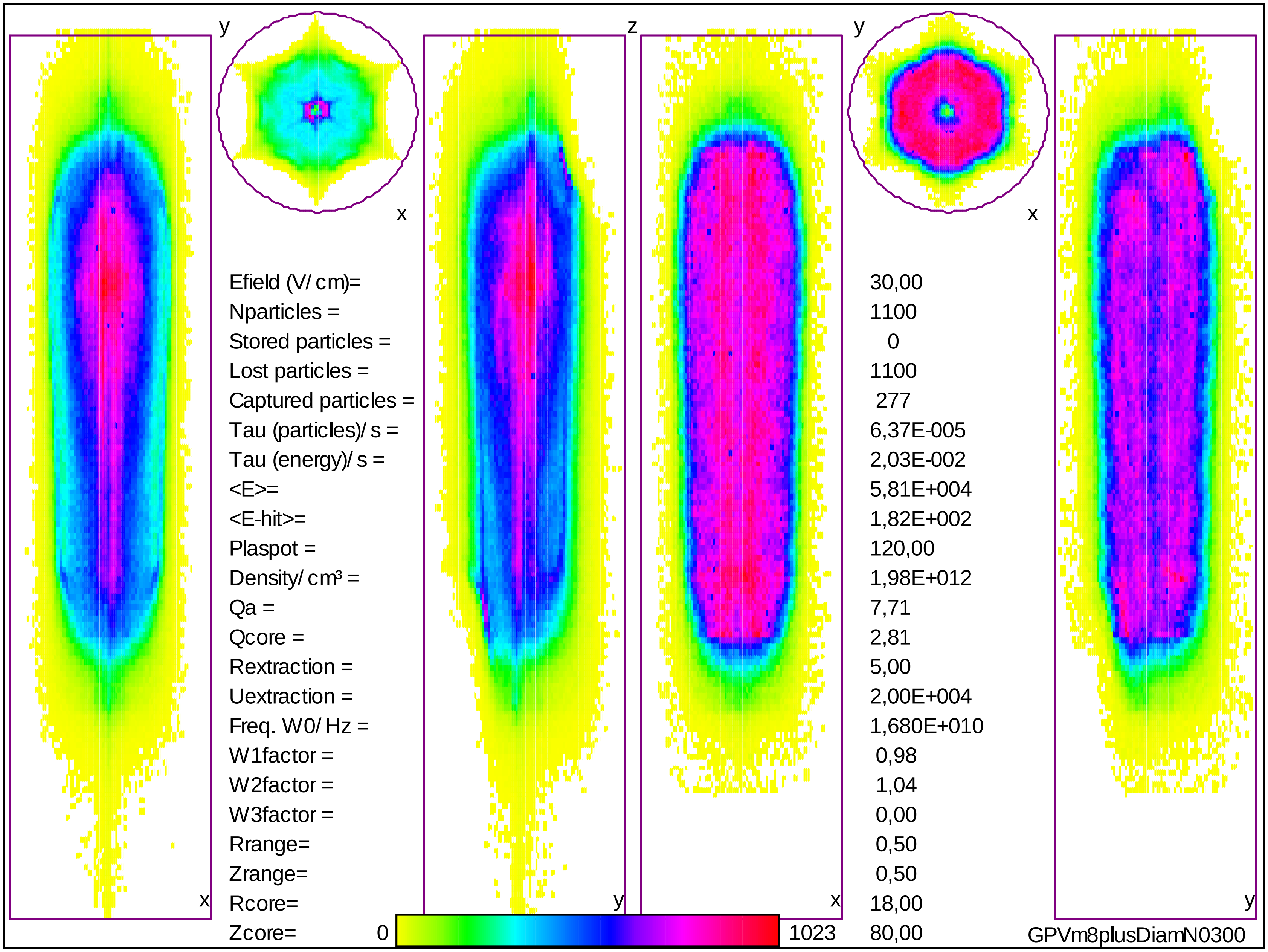
Unfortunately we could not pursue these promising results,

in particular not for Xe and Pb, our main goal,

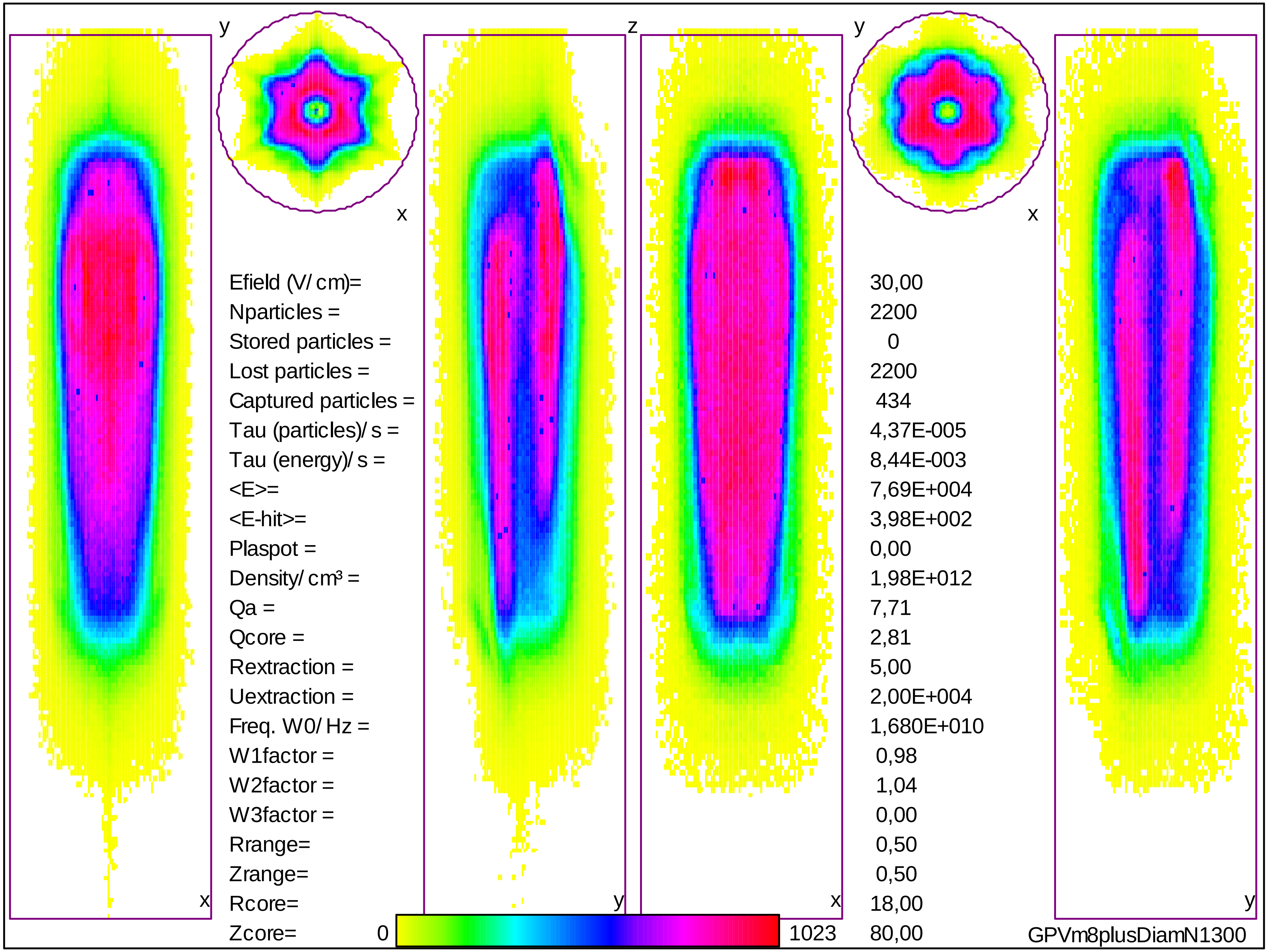
since the hexapole lost more and more strength on one pole

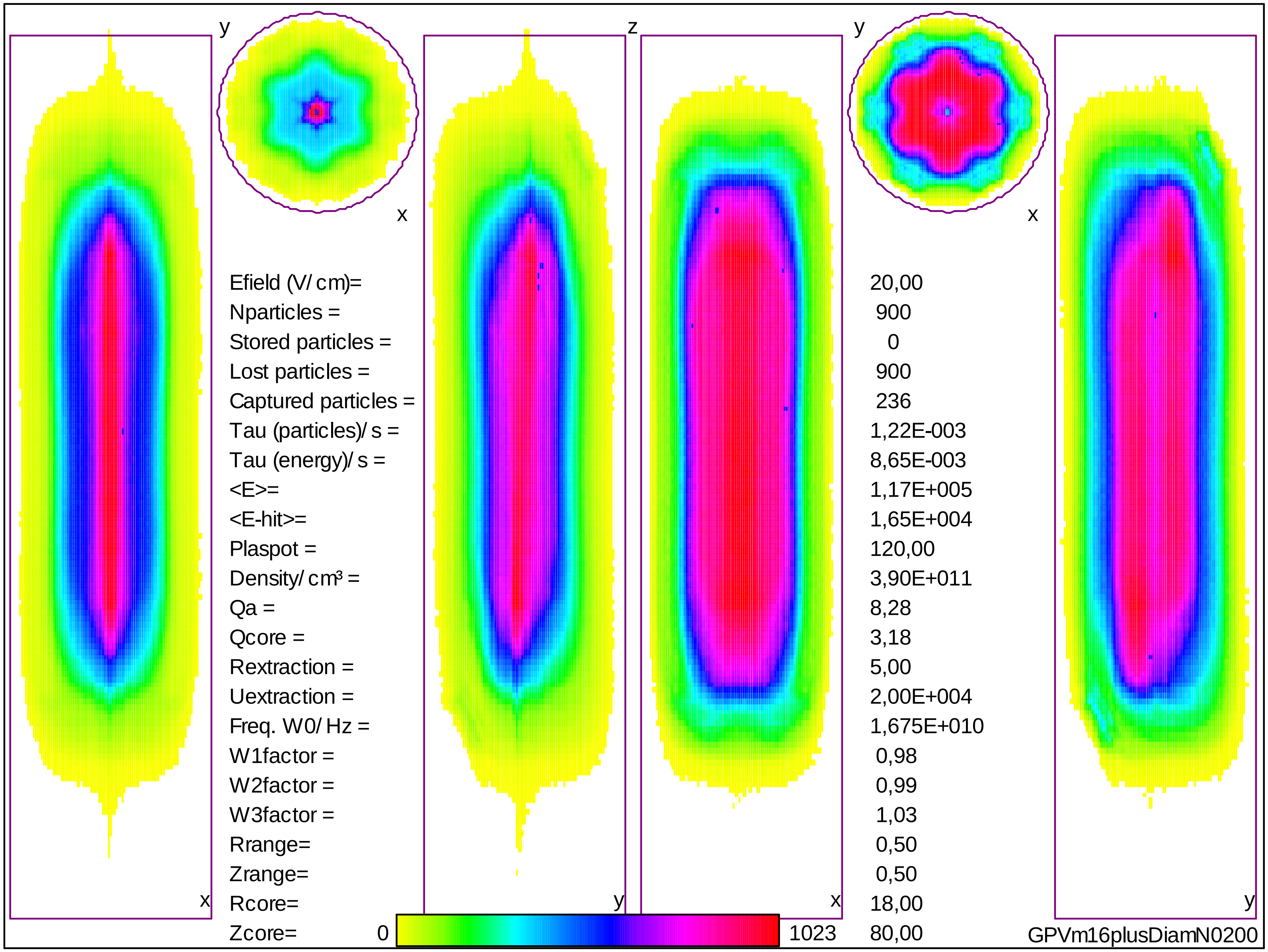
and the CPI-TWT-tube broke down during the ICRH-runs

which we report on tomorrow

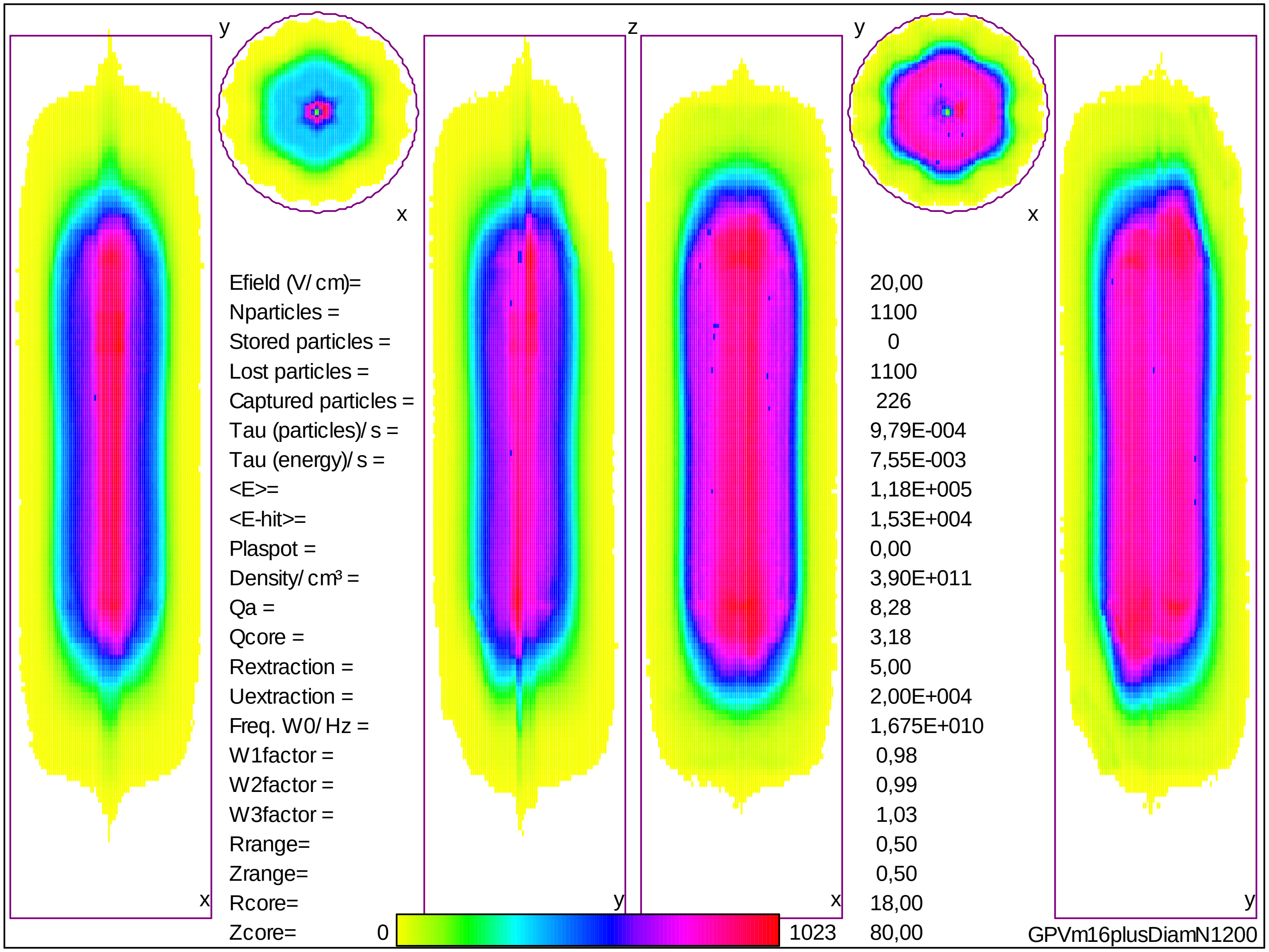


y
x
z
y
x
y
x
x
y
Efield (V/ cm)= 30,00
Nparticles = 1100
Stored particles = 0
Lost particles = 1100
Captured particles = 277
Tau (particles)/ s = 6,37E-005
Tau (energy)/ s = 2,03E-002
<E>= 5,81E+004
<E-hit>= 1,82E+002
Plaspot = 120,00
Density/ cm^3 = 1,98E+012
Qa = 7,71
Qcore = 2,81
Rextraction = 5,00
Uextraction = 2,00E+004
Freq. W0/ Hz = 1,680E+010
W1factor = 0,98
W2factor = 1,04
W3factor = 0,00
Rrange= 0,50
Zrange= 0,50
Rcore= 18,00
Zcore= 80,00
0
1023
GPVm8plusDiamN0300


y
x
z
y
x
x
y
x
y
Efield (V/ cm)= 30,00
Nparticles = 2200
Stored particles = 0
Lost particles = 2200
Captured particles = 434
Tau (particles)/ s = 4,37E-005
Tau (energy)/ s = 8,44E-003
<E>= 7,69E+004
<E-hit>= 3,98E+002
Plaspot = 0,00
Density/ cm³ = 1,98E+012
Qa = 7,71
Qcore = 2,81
Rextraction = 5,00
Uextraction = 2,00E+004
Freq. W0/ Hz = 1,680E+010
W1factor = 0,98
W2factor = 1,04
W3factor = 0,00
Rrange= 0,50
Zrange= 0,50
Rcore= 18,00
Zcore= 80,00
0
1023
GPVm8plusDiamN1300



y
x
z
y
x
x
y
x
y
Efield (V/ cm)= 20,00
Nparticles = 900
Stored particles = 0
Lost particles = 900
Captured particles = 236
Tau (particles)/ s = 1,22E-003
Tau (energy)/ s = 8,65E-003
<E>= 1,17E+005
<E-hit>= 1,65E+004
Plaspot = 120,00
Density/ cm³ = 3,90E+011
Qa = 8,28
Qcore = 3,18
Rextraction = 5,00
Uextraction = 2,00E+004
Freq. W0/ Hz = 1,675E+010
W1factor = 0,98
W2factor = 0,99
W3factor = 1,03
Rrange= 0,50
Zrange= 0,50
Rcore= 18,00
Zcore= 80,00
0
1023
GPVm16plusDiamN0200



With the good confinement for these measurements the reflection of the electrons does improve their lifetime by only 25 %

Is this a lack of statistics or does the seconary electron production also contribute to improve the electron density which shows