Ion Cyclotron Resonance Heating in a Plateau-ECRIS

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*presented by H.J. Andrä because M. Kahnt could not come for financial reasons

ECRIS-performance ~ $n_e \bullet \tau_{ion}$

Nearly all effort was devoted to better electron confinement and density

τ_{ion} could only be indirectly influenced by the electron cloud as ion cage

An active prolongation of τ_{ion} by delivering rotational energy to the ions through

Ion Cyclotron Resonance Heating (ICRH)

not attempted in a SECRIS because ICR-conditions not well defined

The only attempts were interpreted as enhanced loss of the heated H+.

In a PECRIS well controlled ICRH conditions in big resonance volume

since ions are concentrated in this volume

All ions in this volume of a given q/M can selectively be heated by ICRH

if and only if an oscillating electric field can penetrate into this volume

Waves with frequencies below the so called plasma frequency

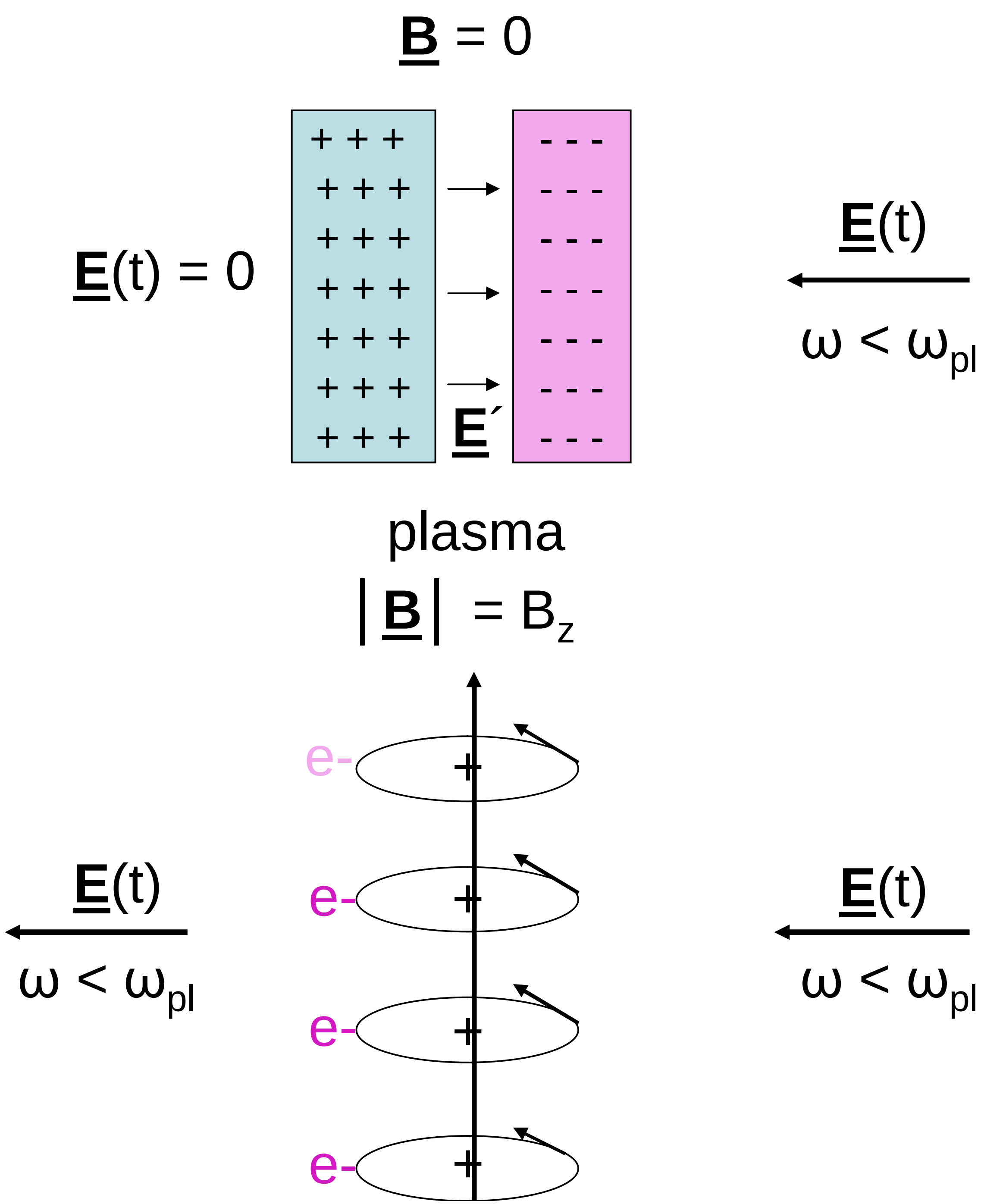
$\omega_{pl}=\sqrt{(e^2 n_e/(\varepsilon_0 m_0))} \approx 5.7$ GHz PECRIS V

can not penetrate

into a non-magnetized plasma.

Electric fields perpendicular to **B** can penerate

into a magnetized plasma


B = 0
E(t) = 0
+ + +
- - -
E´
E(t)
ω < ωpl
plasma
|B| = Bz
e-
e-
e-
e-
E(t)
ω < ωpl
E(t)
ω < ωpl

First we present how to produce electric

MHz-radio-frequencies (RF) inside the plasma of PECRIS V

Then we give experimental proof of selective ion heating and also

of the lengthening of ionic lifetimes in the plasma

The subsequent improvement of specific ion currents yields

a consistent scenario of the ion dynamics in PECRIS V

We finally venture on the consequences of ICRH in bigger superconducting

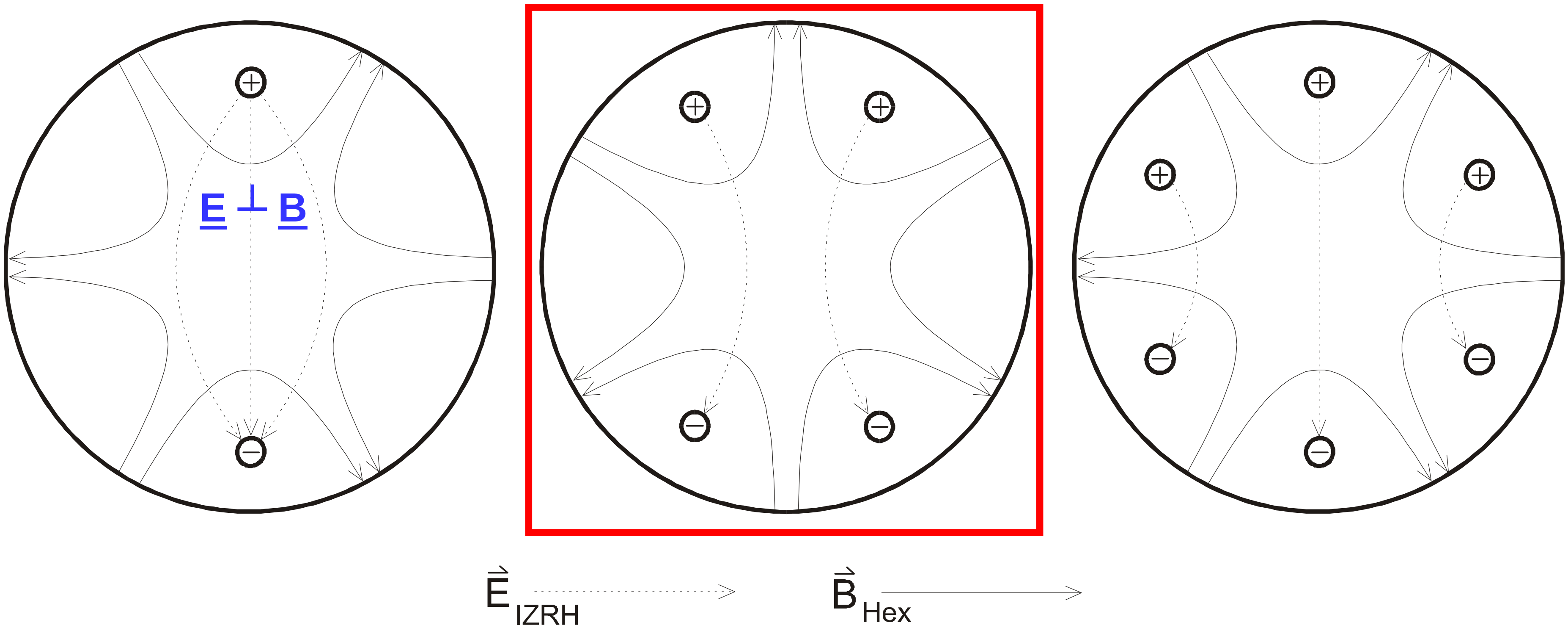
SECRIS or PECRIS with the help of the statistics of trajectory calculations

Inductive production of RF-electrif fields via RF-magnetic fields

is power consuming and limited by eddy currents

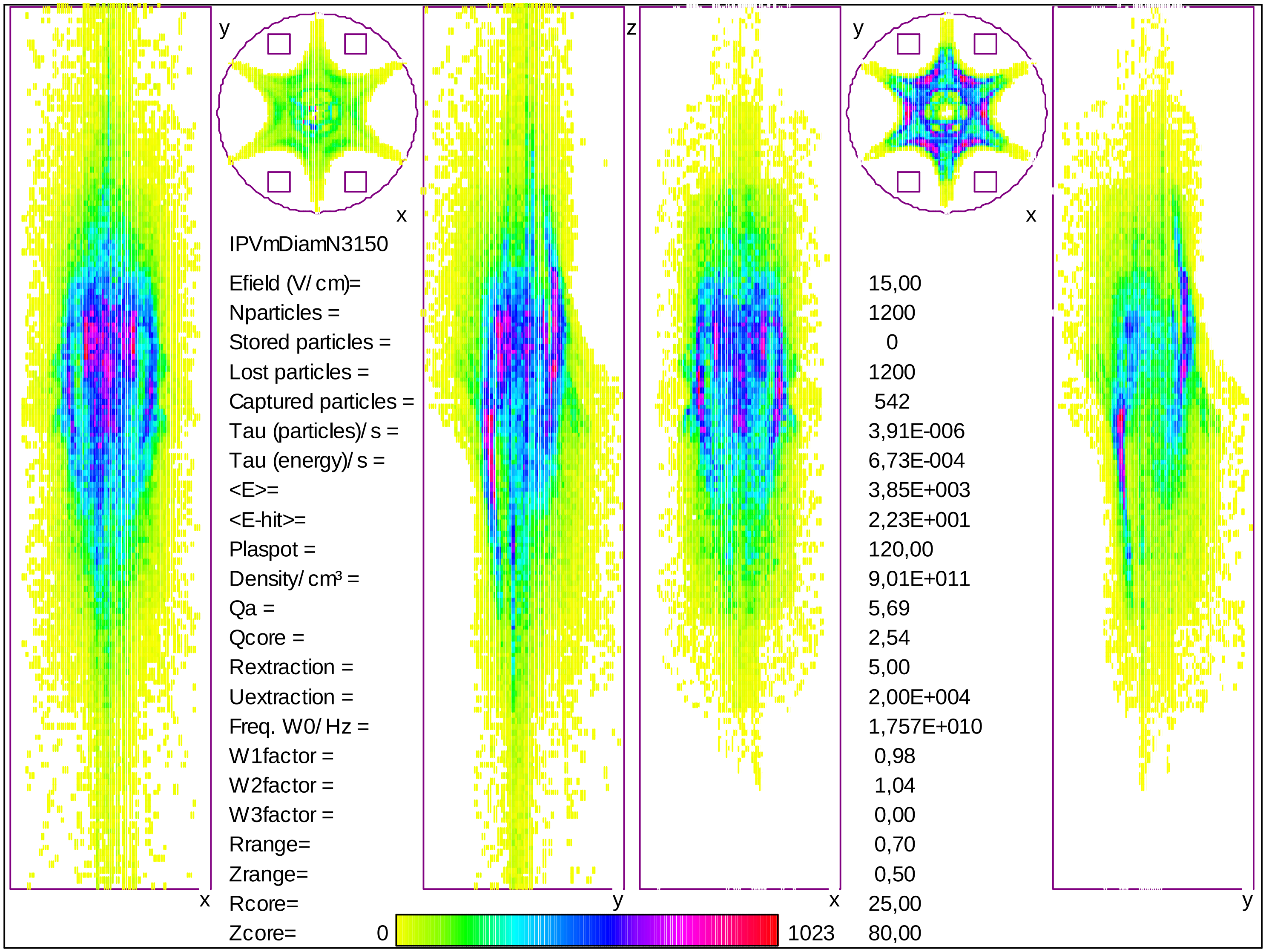
Therefore: RF-electric fields produced by electrodes all along the

plasma chamber in the lobes of the hexapole with negligible plasma density

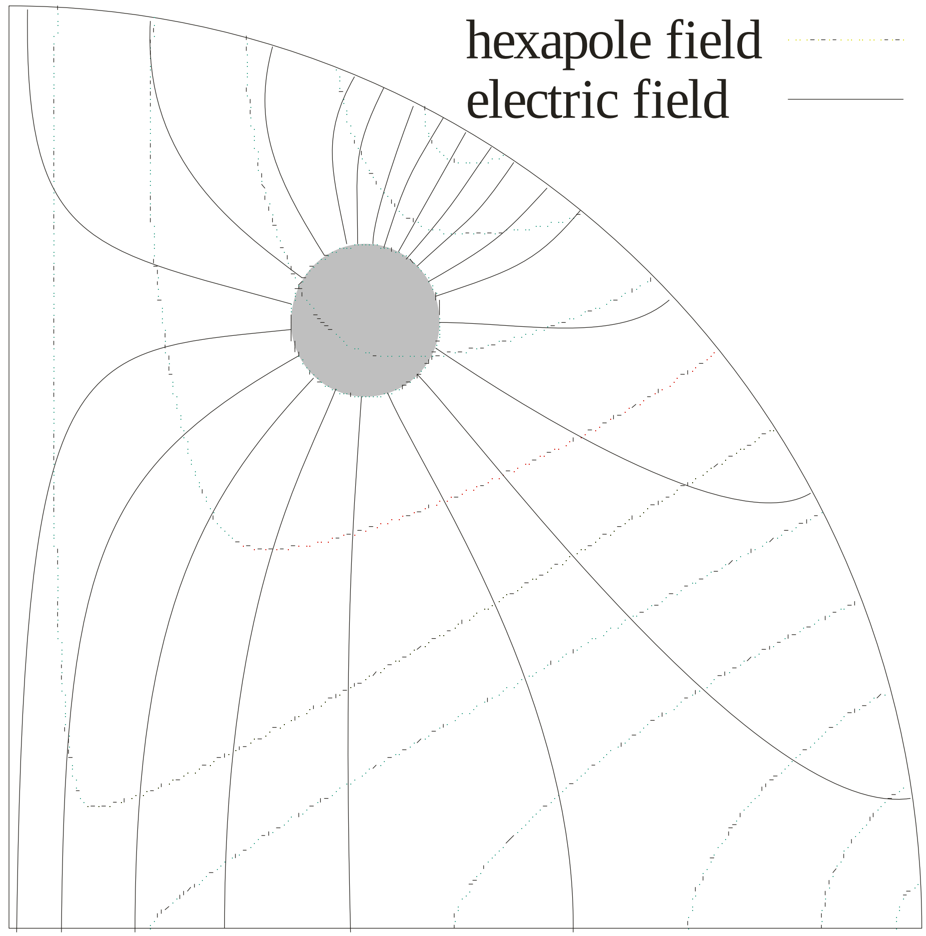


Our choice with smallest electric field between electrodes and wall

At weak µW power the plasma avoids the regions of the electrodes



IPVmDiamN3150

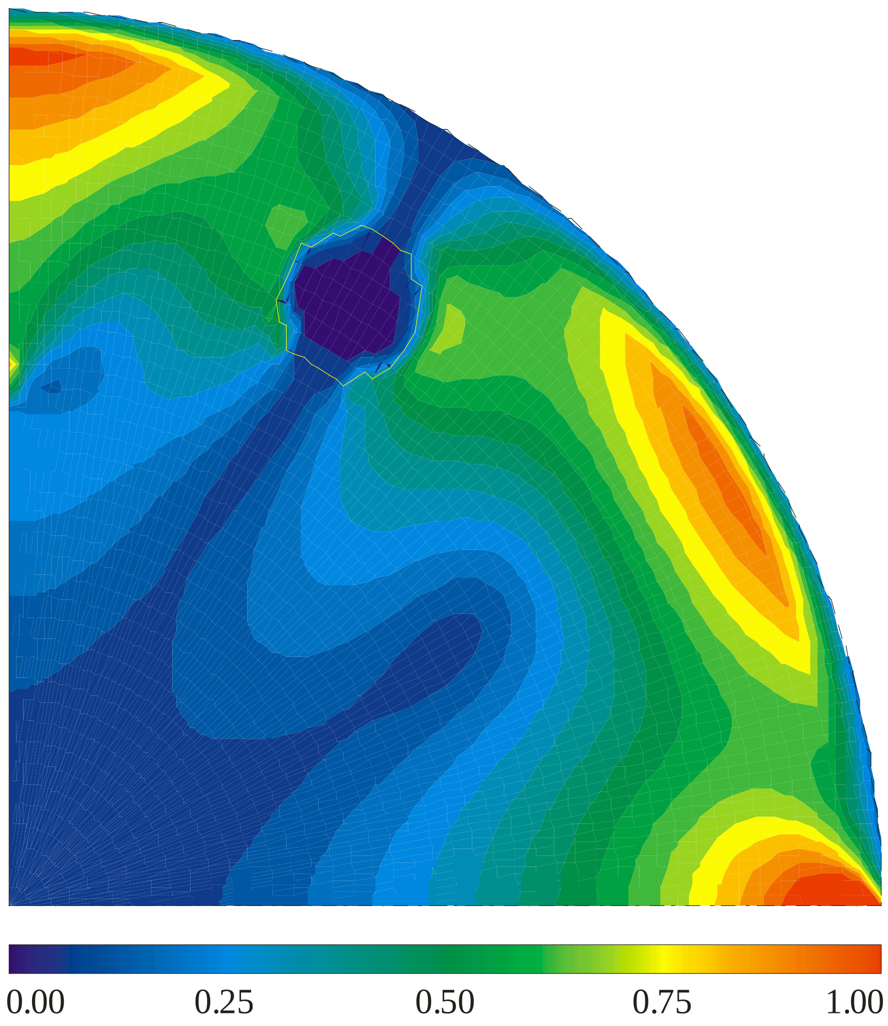


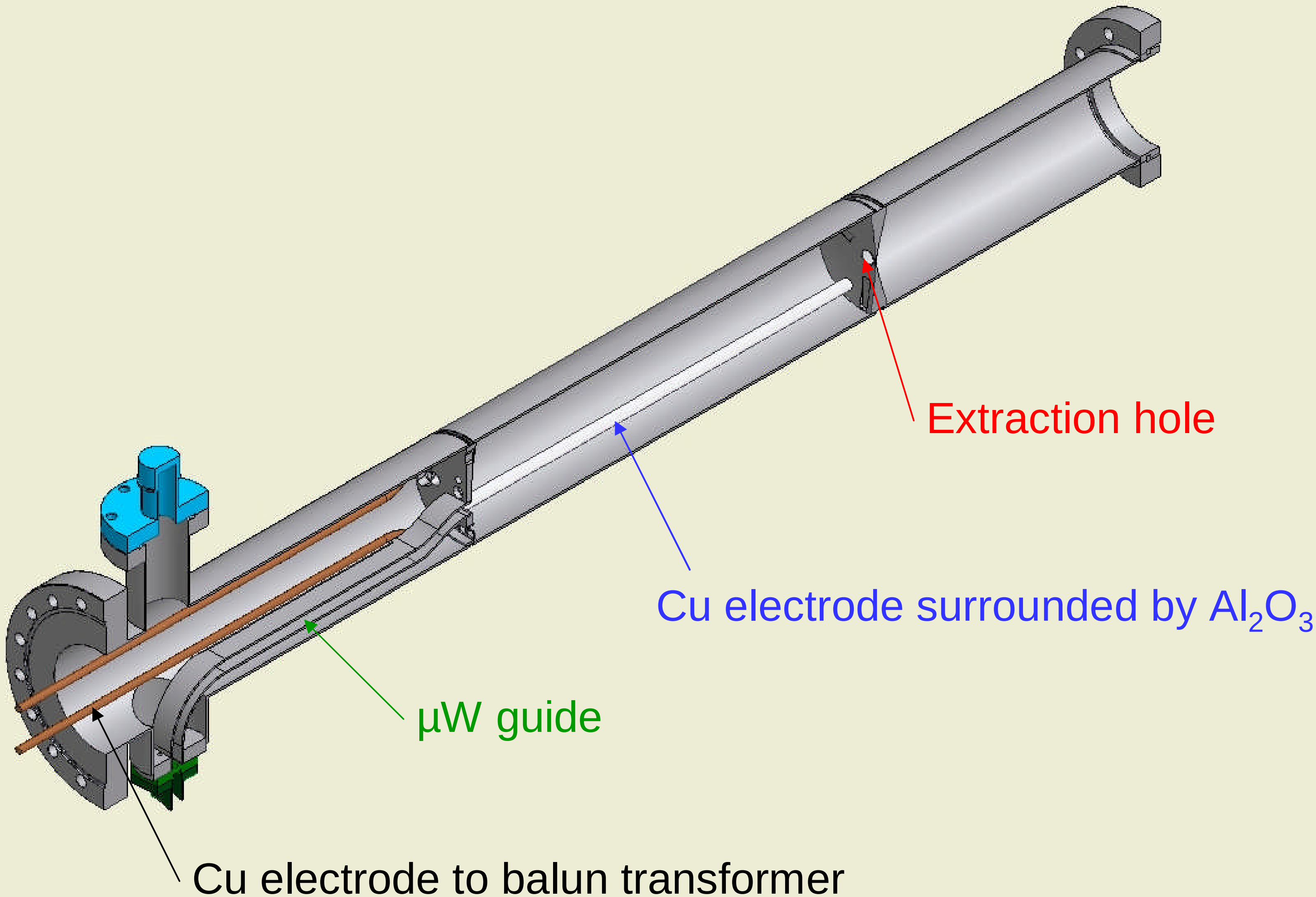
The electric field can penetrate where the electric field ⊥ hexapole field

Fortunately the hexapole field becomes very weak close to axis

The scalar product $\underline{\mathbf{E}} \cdot \underline{\mathbf{B}}_{hex}/|E|$ may serve as measure

for the penetration of $\underline{\mathbf{E}}$ through the plasma.





Extraction hole
Cu electrode surrounded by Al2O3
µW guide
Cu electrode to balun transformer

Goal :

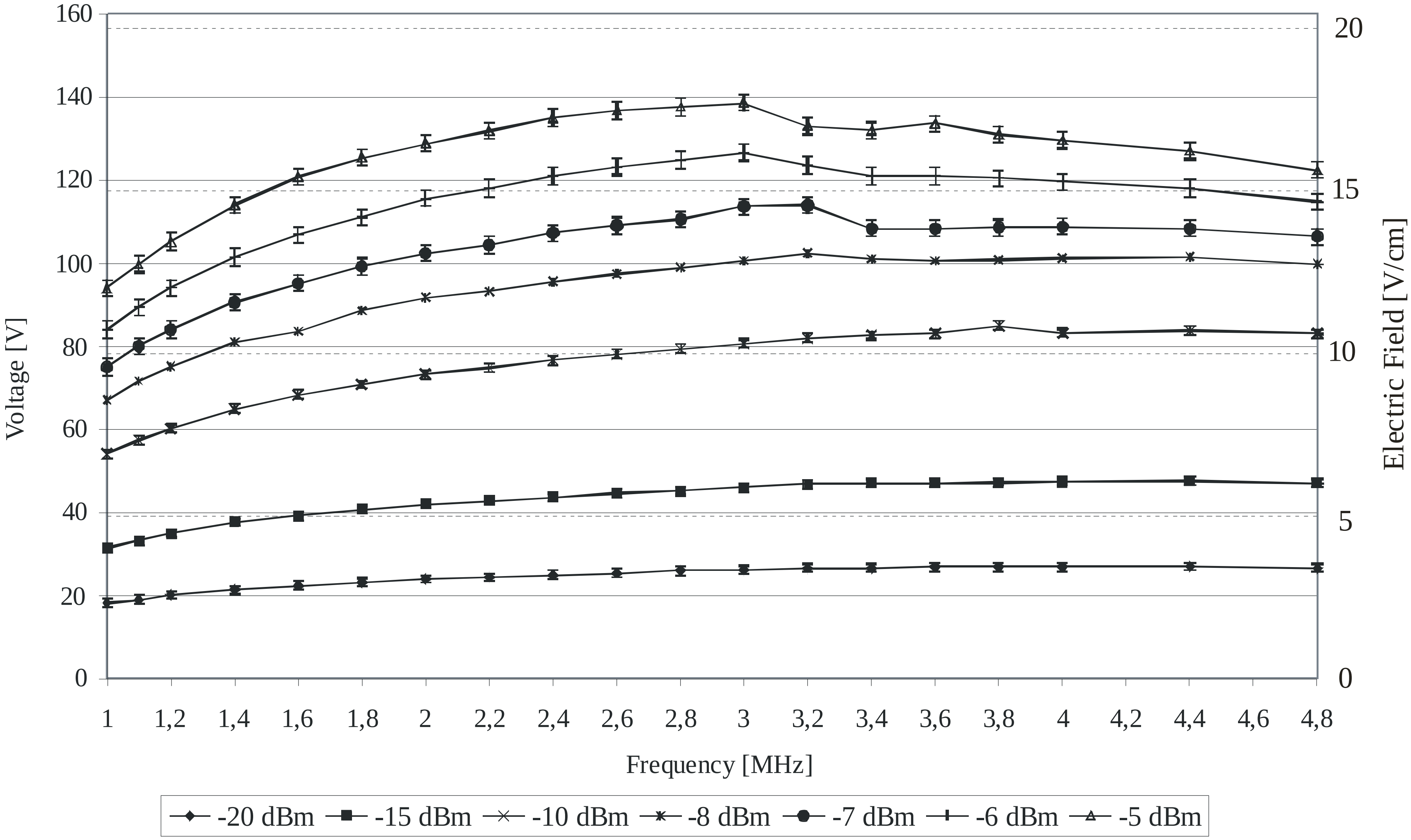
±100 V on the electrodes in the frequency band 1 to 10 MHz

A remote controlled 13 dBm-RF generator (Marconi 2019A)

fed through a remote controlled damping element a

broad band amplifier (ENI 525 LA) with 25 W into

a balun transformer directly coupled to the electrodes



Nearly flat RF-field amplitudes as function of frequency and damping

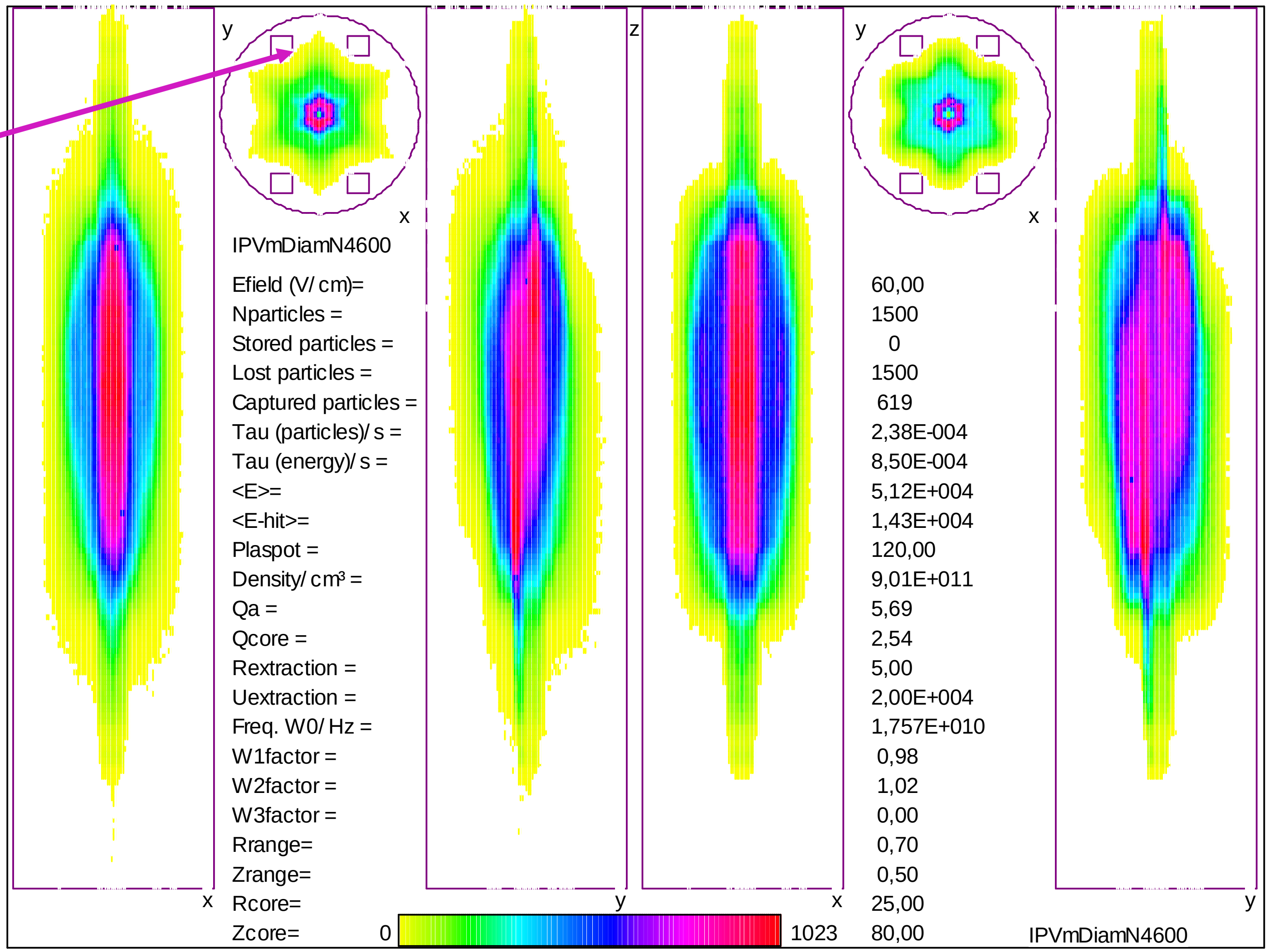
Everything was ready for good ICRH-experiments, but…………

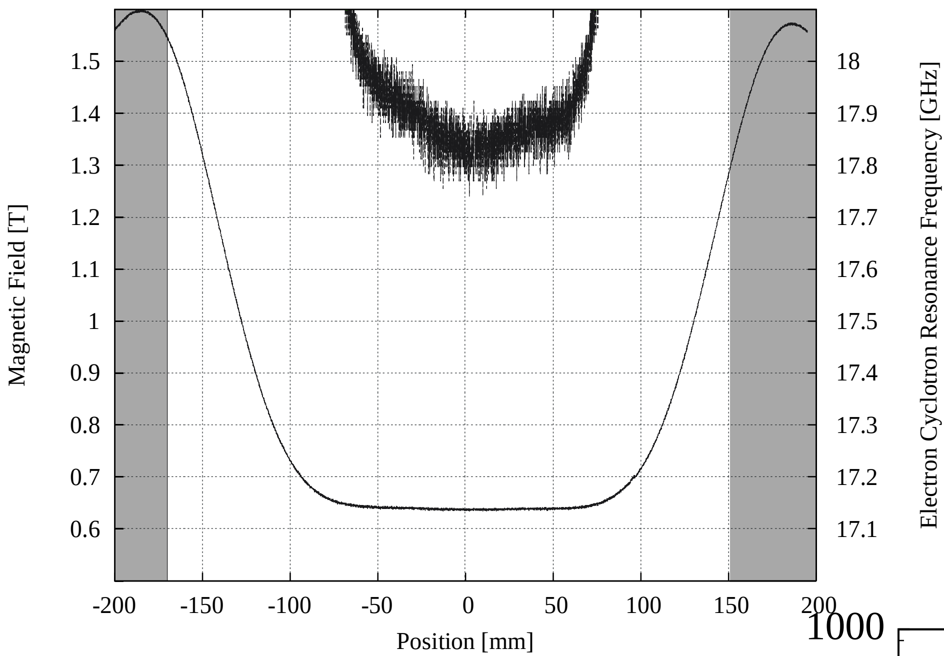
As µW-power increased **brilliant, terrifying light emission from electrodes**

In particular one electrode was glowing due to weak pole of hexapole

The µW-power had to be reduced to 50 (max.100) W !

Hot spot





Magnetic field on axis

for this measurement

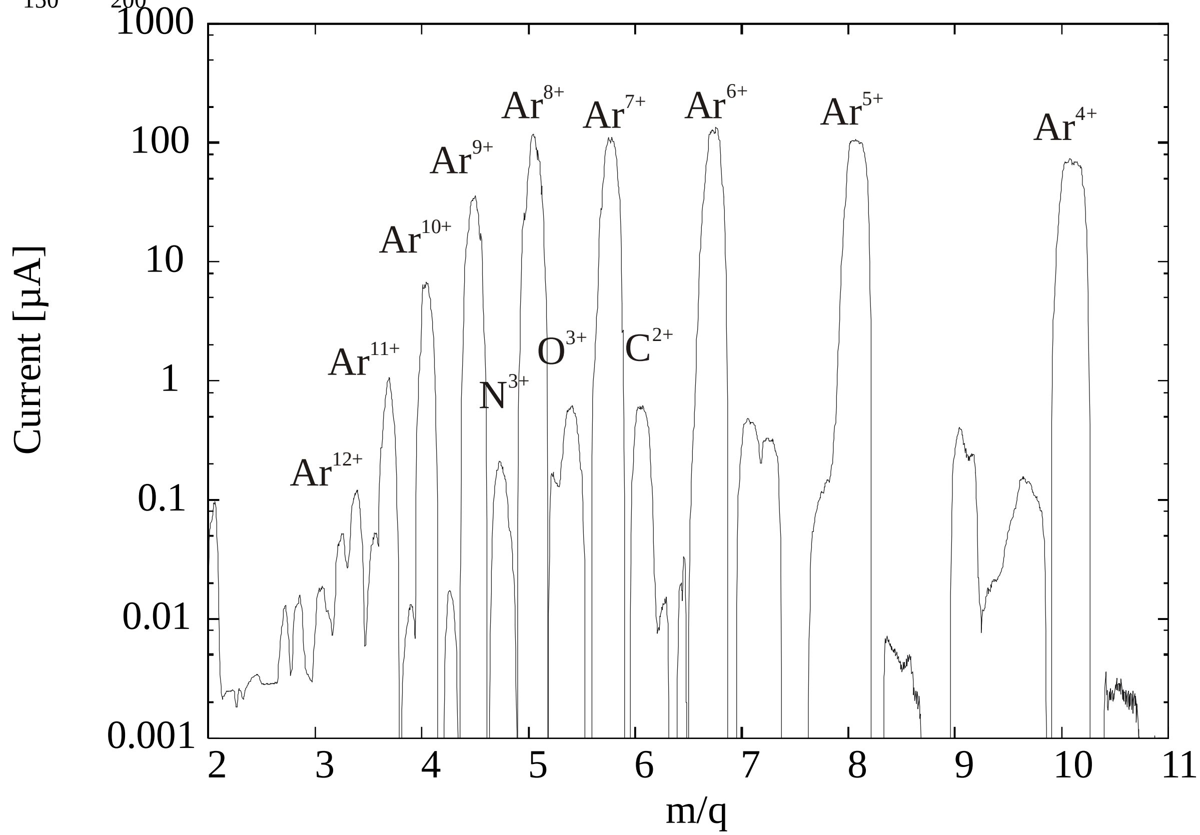
Performance of PECRIS V

at 50 W

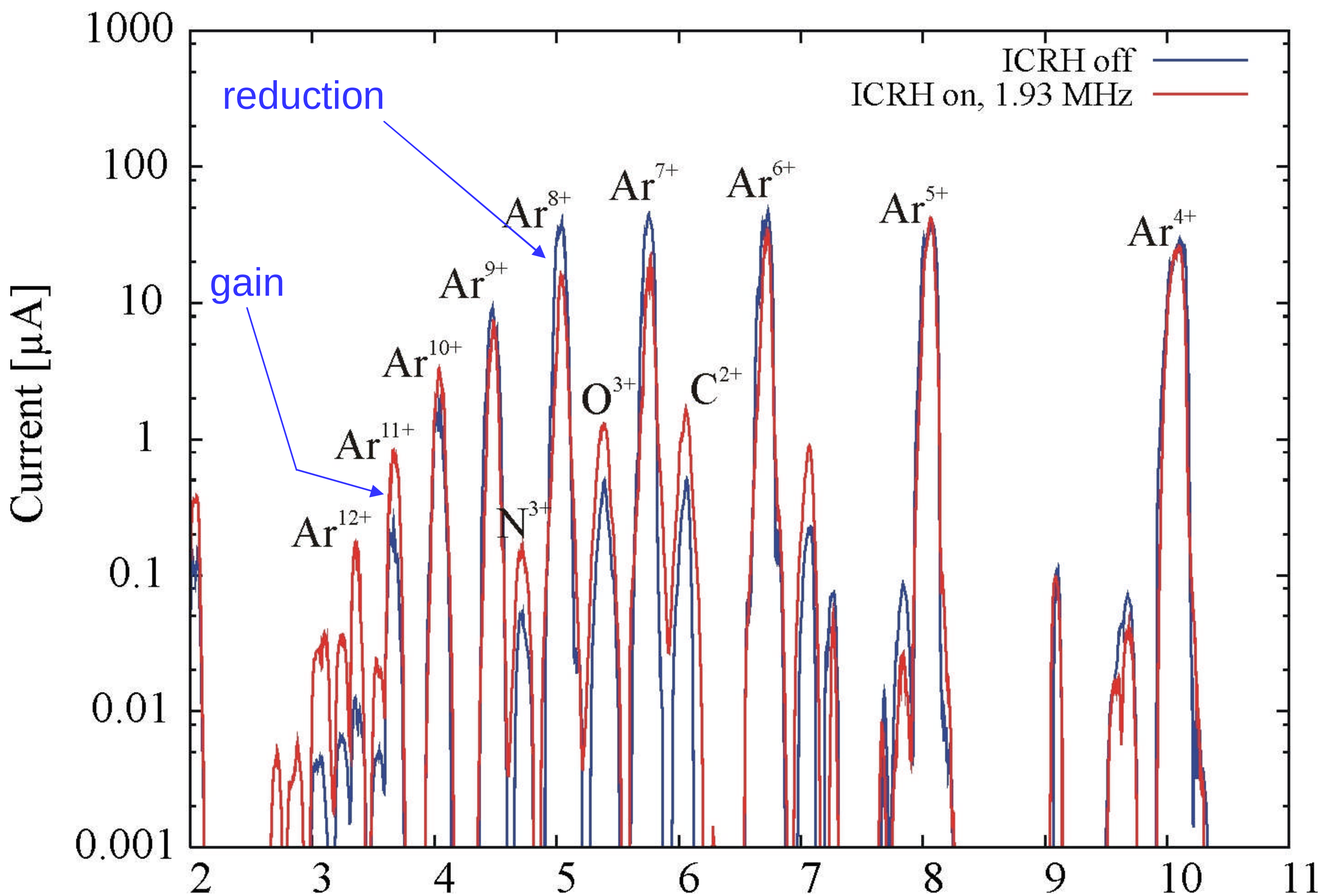
with Al_2O_3 stripes and

ICRH-setup mounted

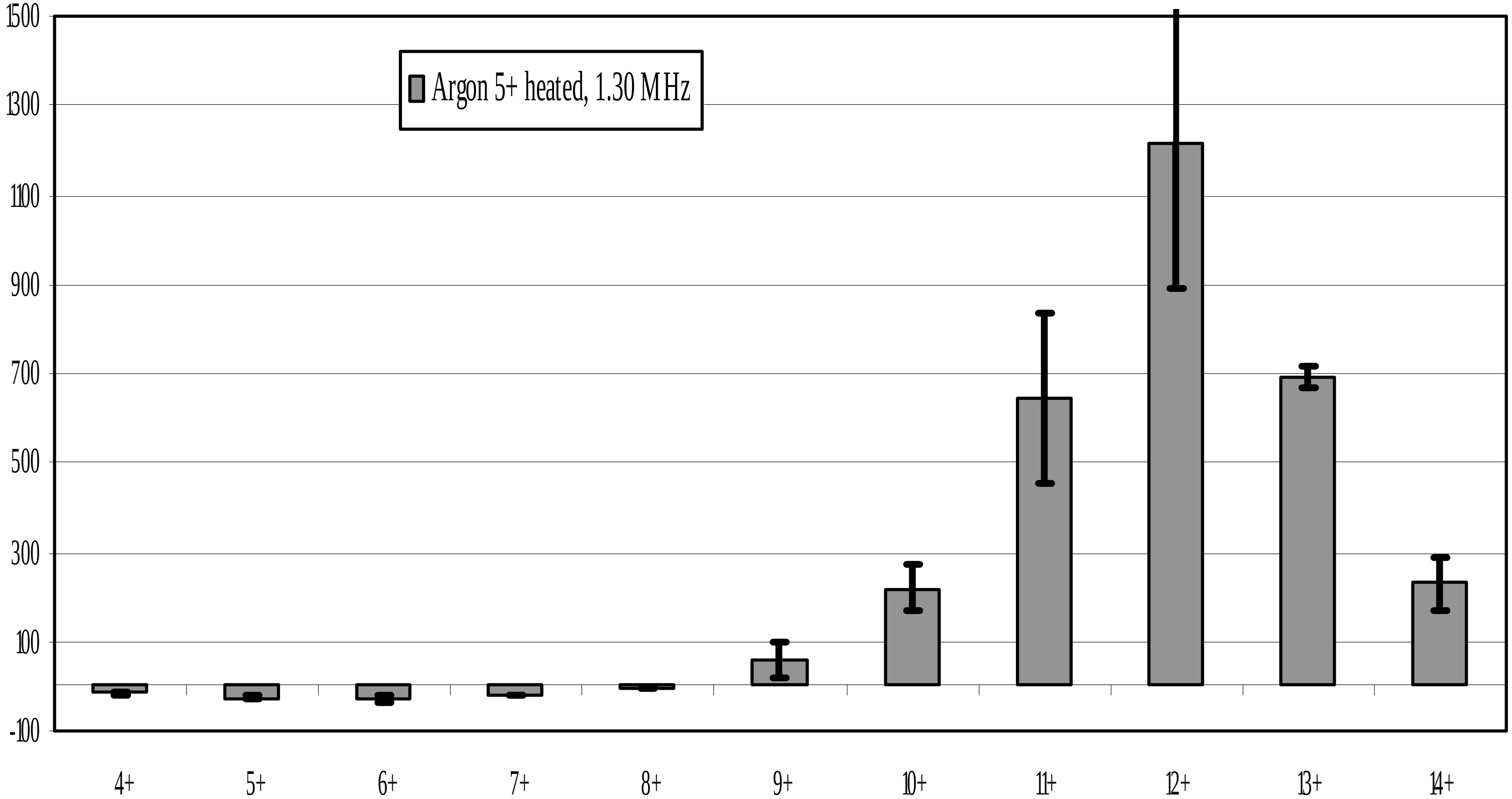
but not activated



First type of experiment: Heat one q and observe currents of other q



Outgazing from the volume between the Cu-electrodes and the Al_2O_3-cylinders causes important fluctuations of all currents measured !!



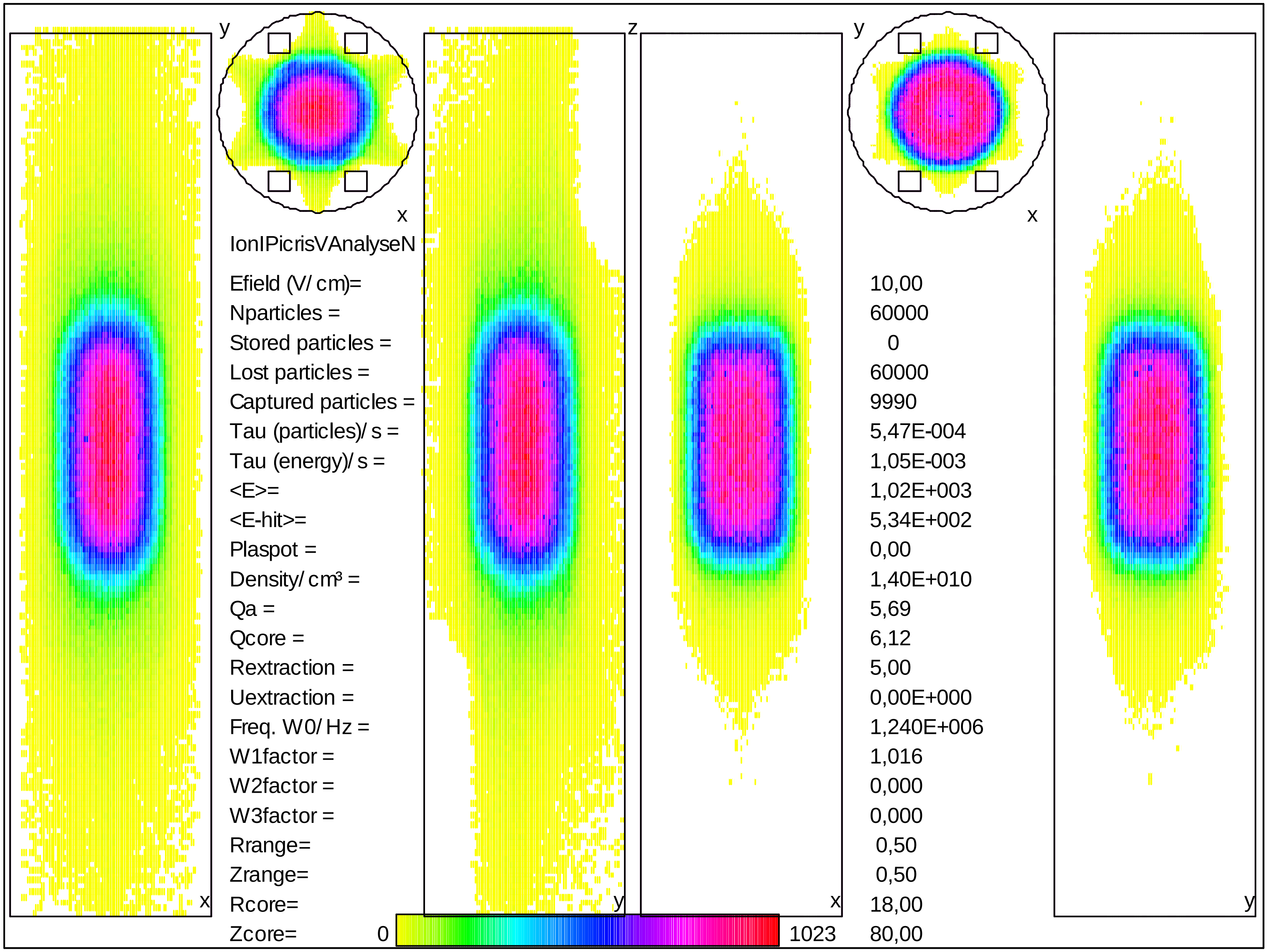
ICR-heated q show the greatest losses of ion current

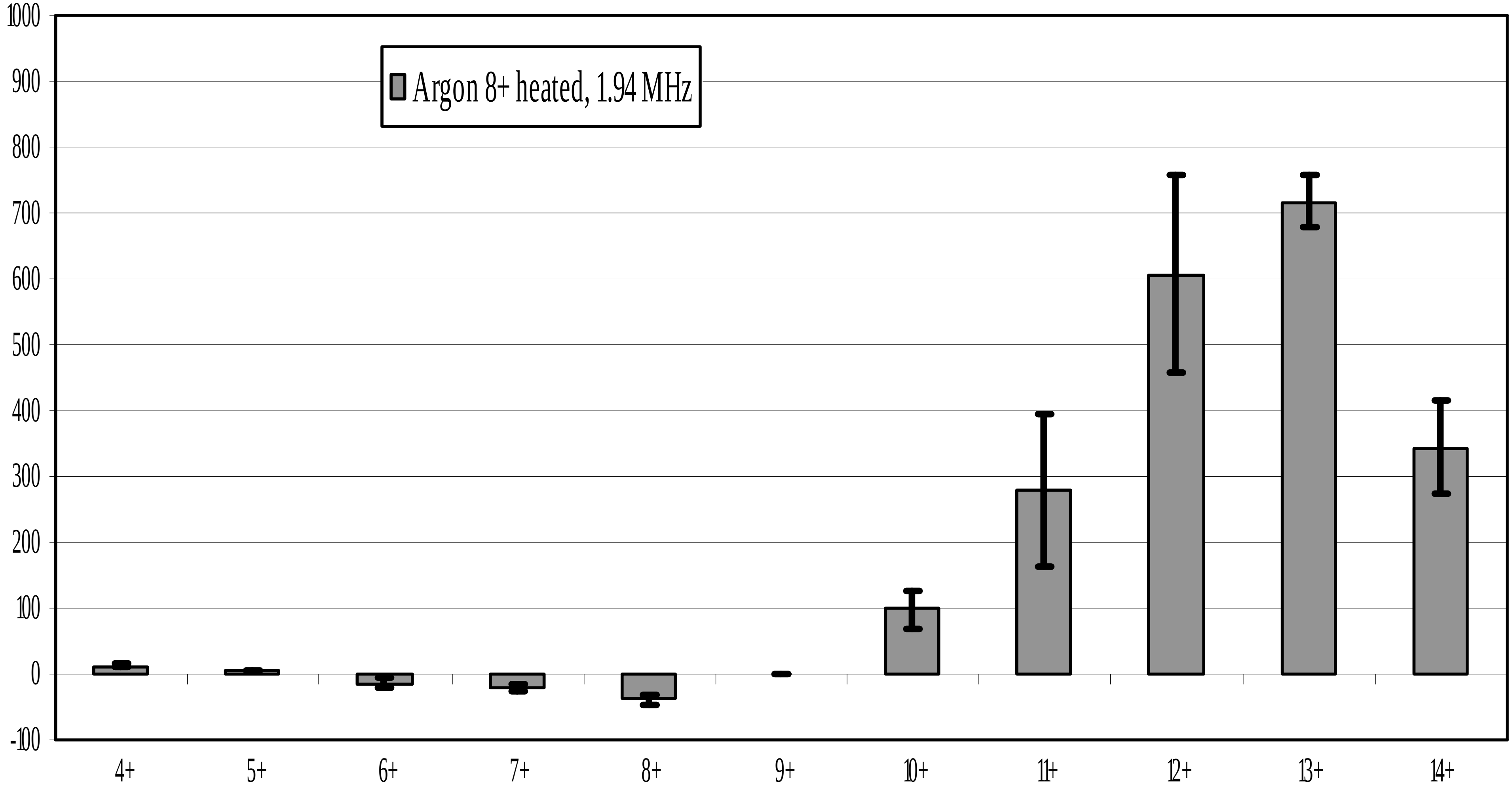
The loss of current of heated q accompanied by loss of current of the adjacent

higher q and then by an increase of the currents of higher q

Ar^{5+} ICR-heated with 10 V/cm

<E> = 1 keV   <tau> = 0.55 ms

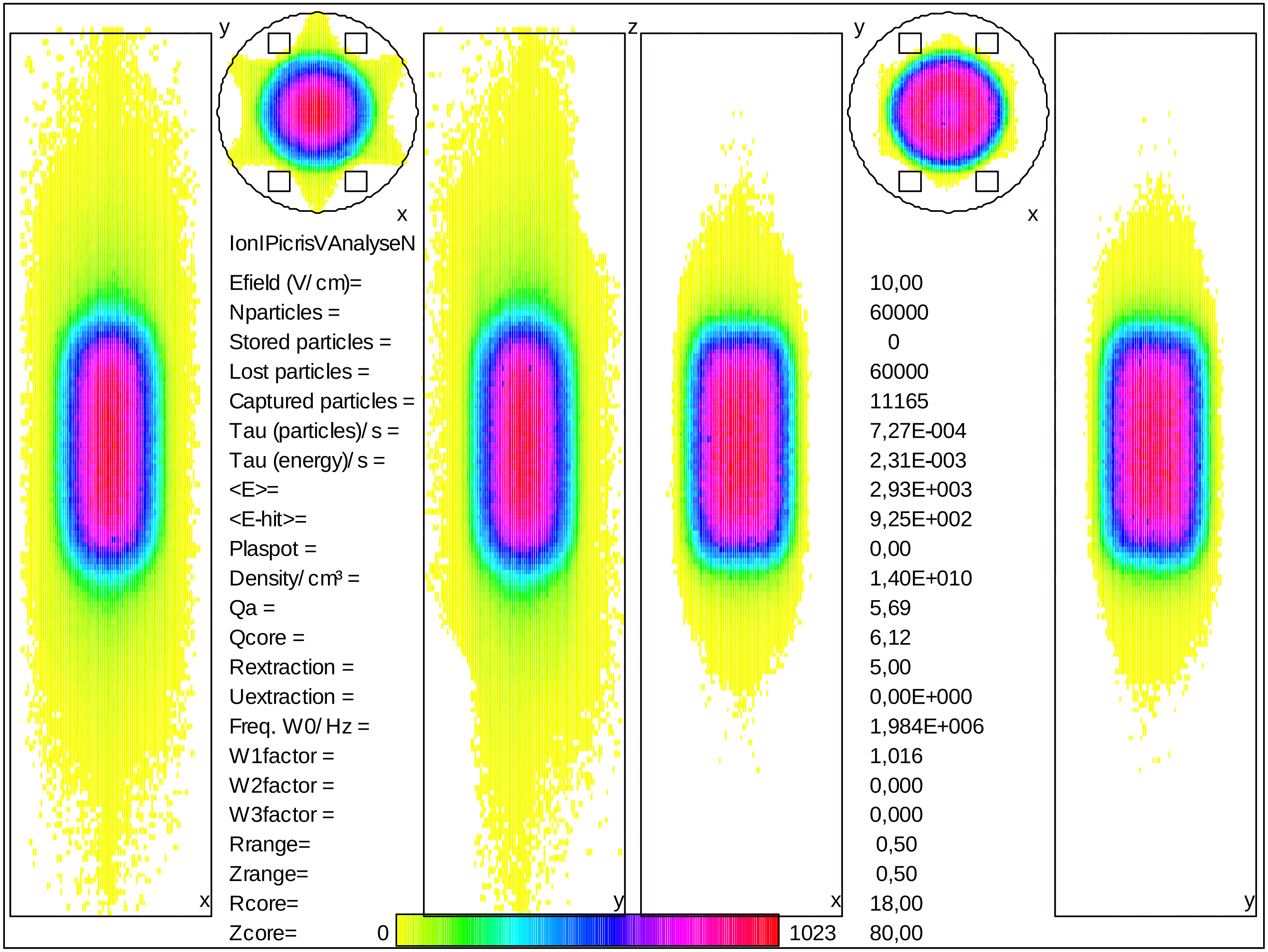


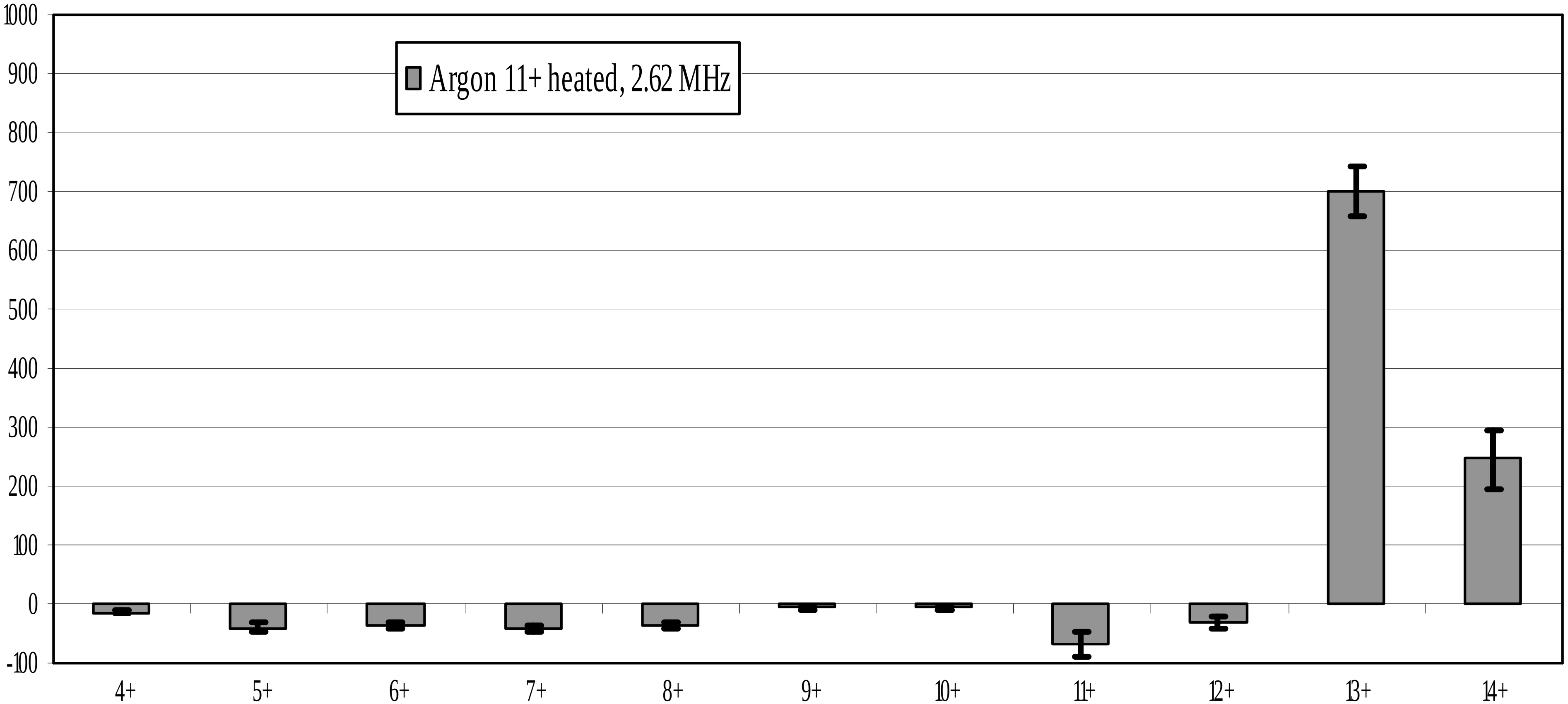


1000
900
800
700
600
500
400
300
200
100
0
-100
Argon 8+ heated, 1.94 MHz
4+
5+
6+
7+
8+
9+
10+
11+
12+
13+
14+

Ar^{8+} ICR-heated with 10 V/cm

<E> = 2.3 keV <tau> = 0.73 ms





The difference in charge between

the heated q and the q with highest gain

reduces when heated q increases

		Heated Charge State							
		5+	6+	7+	8+	9+	10+	11+	12+
Observed Charge State	4+	-16 ± 3	-19 ± 4	-21 ± 4	11 ± 2	-17 ± 5	-13 ± 3	-15 ± 3	-2 ± 0
	5+	-27 ± 5	-40 ± 10	-32 ± 5	7 ± 1	-19 ± 5	-35 ± 8	-41 ± 8	-39 ± 9
	6+	-31 ± 6	-42 ± 9	-40 ± 8	-14 ± 6	-25 ± 6	-38 ± 8	-36 ± 7	-64 ± 16
	7+	-21 ± 3	-35 ± 5	-52 ± 8	-20 ± 4	-19 ± 4	-35 ± 7	-41 ± 6	-64 ± 7
	8+	-5 ± 1	-24 ± 7	-20 ± 4	-38 ± 9	-37 ± 9	-51 ± 30	-37 ± 7	-65 ± 33
	9+	59 ± 37	65 ± 30	41 ± 20	-1 ± 0	-37 ± 24	-33 ± 15	-7 ± 3	-23 ± 11
	10+	220 ± 54	322 ± 76	310 ± 107	99 ± 29	27 ± 9	-40 ± 12	-7 ± 2	10 ± 3
	11+	644 ± 188	988 ± 322	1323 ± 487	281 ± 116	188 ± 66	-57 ± 21	-67 ± 21	-42 ± 15
	12+	1214 ± 323	2093 ± 593	3494 ± 1076	607 ± 150	606 ± 203	-3 ± 1	-32 ± 8	-82 ± 22
	13+	689 ± 24	850 ± 42	898 ± 56	717 ± 41	743 ± 75	749 ± 30	701 ± 44	658 ± 36
	14+	229 ± 56	316 ± 64	511 ± 99	345 ± 72	285 ± 57	293 ± 63	246 ± 50	134 ± 28

All ICR-heated q show the greatest losses of ion current in the light grey boxes

(Exception is q=10, but error bars of q=10 and q=11 are big)

The loss of current of heated q accompanied by loss of current of the adjacent

higher q and then by an increase of the currents of higher q

Interpretation by gain of rotational energy of heated q. Rotational energy yields better confinement of this q so that its extracted current is reduced

Rotational energy is conserved while the ion is ionized to the next higher q

This explains relative loss of ion currents of the adjacent higher q

The ion looses rotational energy due to collisions with other ions

This takes time of thermalization τ_{th} : The ion can be extracted again after τ_{th}

Current of the q attained after successive ionizations during τ_{th}

is the one with highest relative gain

Or the highest relative gain is observed for the q for which $\tau_{ioniz} = \tau_{th}$

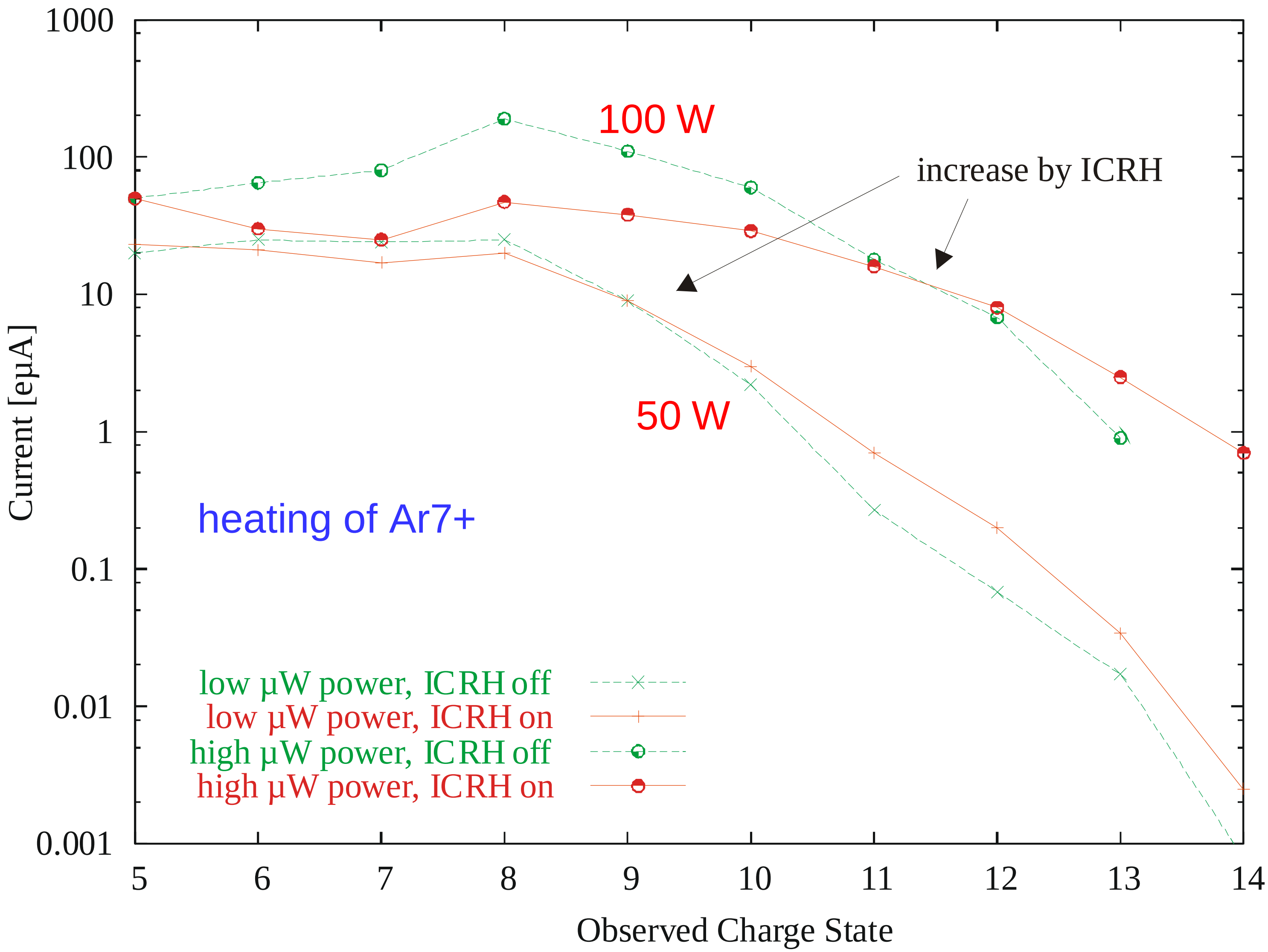
The other q with relative gain are distributed around the q with highest gain

For the ICR-heating of Ar^{5+} one thus obtains

the impressive relative gain of 12 ± 3 for Ar^{12+}

of a weak PECRIS V – we admit

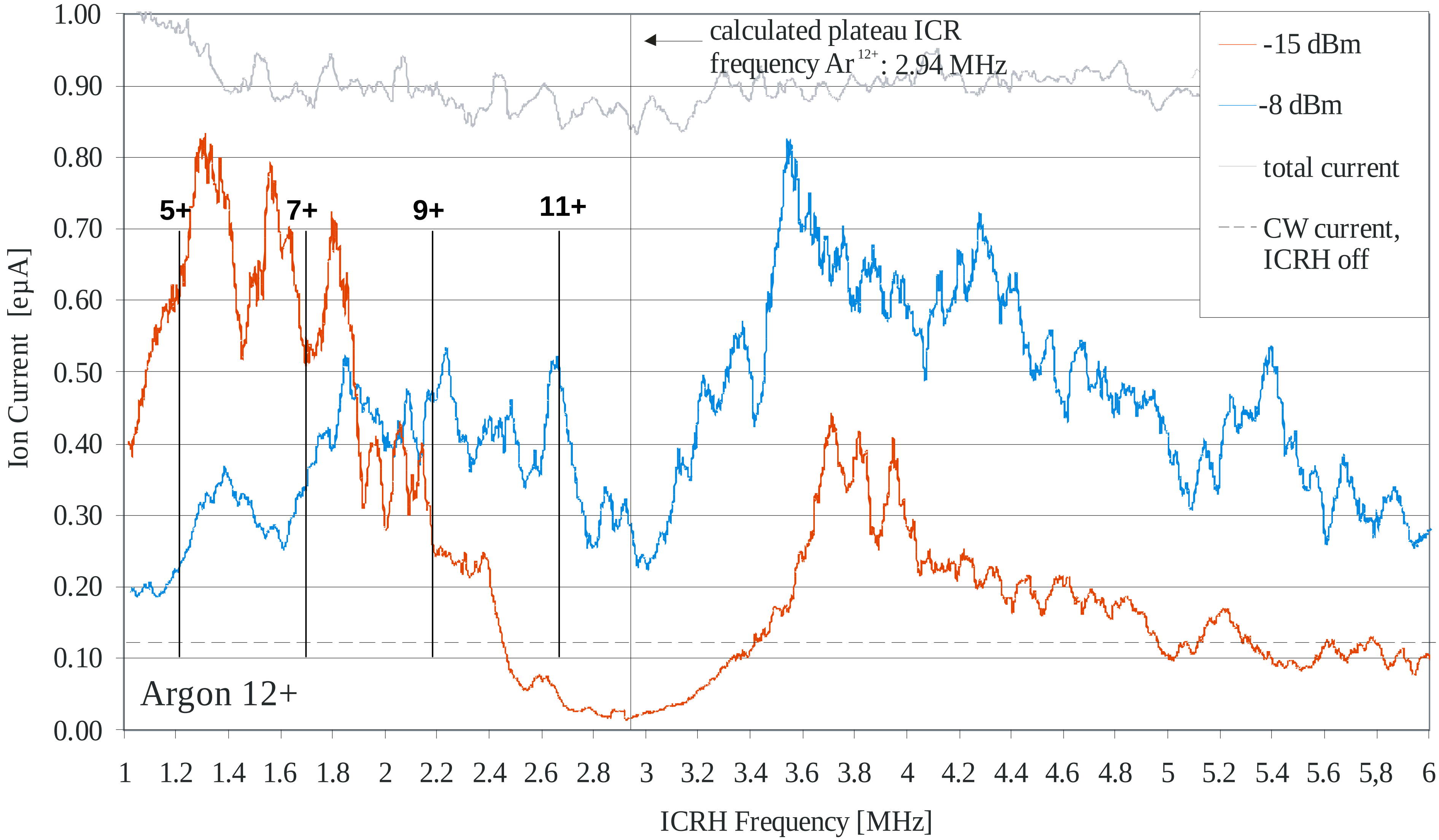
On an absolute scale this looks less impressive but stays significant



Result of very different source conditions, however

Second type of experiment: Observe one q and heat all other q

Example: Observation of Ar12+ at -8 dBm



ICRH-frequency is stepped by increments of 100 kHz

At RF field amplitudes (-8 dBm ≈ 12 V/cm) three well separated peaks with

separation of 244 kHz the difference of ICR-frequency of two adjacent q

Highest peak result of ICRH of Ar^{5+} : increases the current of Ar^{12+} to 0.82 μA

Next peak result of ICRH of Ar^{6+} with a current of Ar^{12+} of 0.77 μA

Next peak and shoulders correspond to the ICRH of Ar^{7+}, Ar^{8+}, and Ar^{9+}

ICRH of Ar^{11+} clearly reduces Ar^{12+} current as does ICRH of Ar^{12+} itself

ICR-frequency of Ar^{12+} centred at minimum of the Ar^{12+} current at 2.94 MHz

Please note: the total current of extraction is constant during every such scan

Up to this point these observations completely corroborate

the results and interpretations of the former method

Surprise is regain of Ar^{12+} currents to a maximum of about 0.4 μA at 3.7 MHz

Explanation is ICR-heating of Ar^{12+} itself at a magnetic field of 0.81 T on axis,

i.e. about 55 mm from the extraction hole

Here gradient of B is important so that ICRH efficiency is much reduced

In phase small ICRH produces small E_{rot} : Competition between better

confinement or better extraction due to scattering into the loss cone

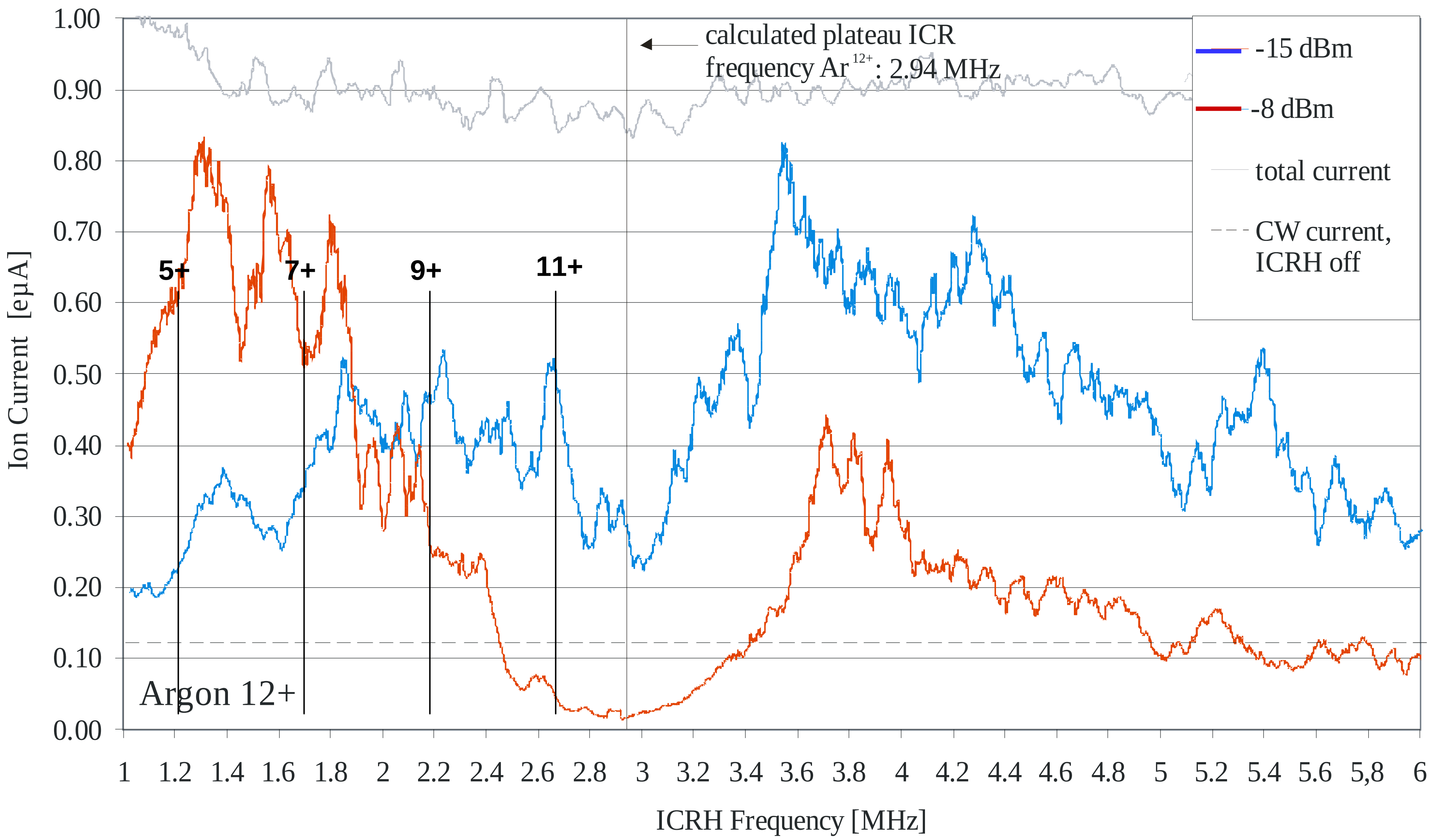
This competition favours confinement for higher and extraction for lower ICRH

In anti-phase small ICRH reduces an existing E_{rot} through zero

Since $E_{rot} = 0$ leads to best extraction one finds again

a better confinement for higher and better extraction for lower ICR-interaction

Now the weak RF-field at -15 dBm :



Observation and conclusion for weak RF-fields

At RF field amplitudes (-15 dBm ≈ 5 V/cm) effect on Ar12+ current is

weaker and less resolved for heating of lower q

Heating of q = 9 to 11 yields higher Ar12+ current

with good resolution and at the right positions

Minimum of Ar12+ current is again at 2.94 MHz = ICR-frequency of Ar12+,

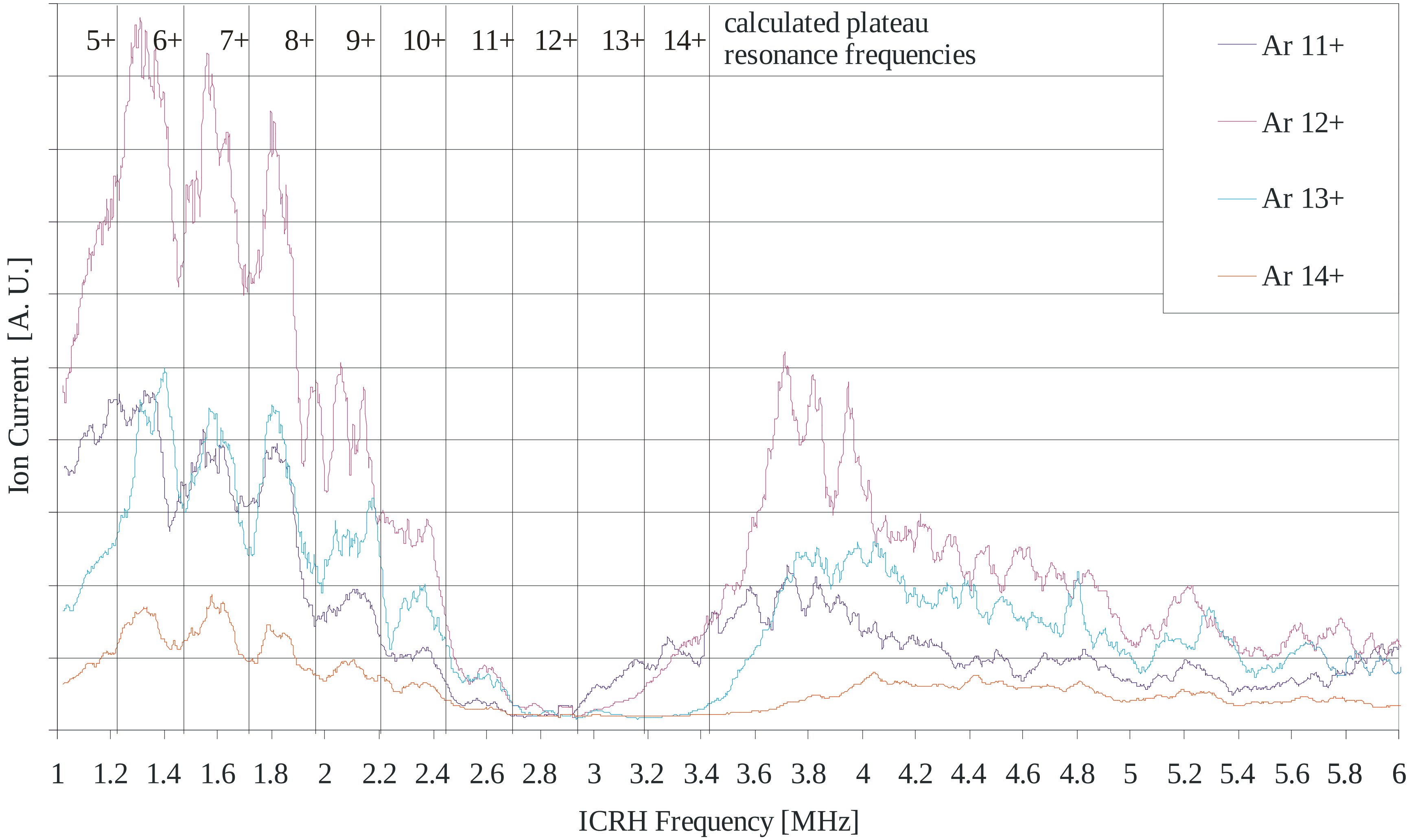
it is narrower and the current is higher than the initial one !

Again an increase of Ar12+ current is observed above this frequency !

This increase as important as the gain by ICRH of Ar5+ at -8 dBm !

Might be a method to increase extraction of high charge states in general

with installation of electrodes only close to the extraction



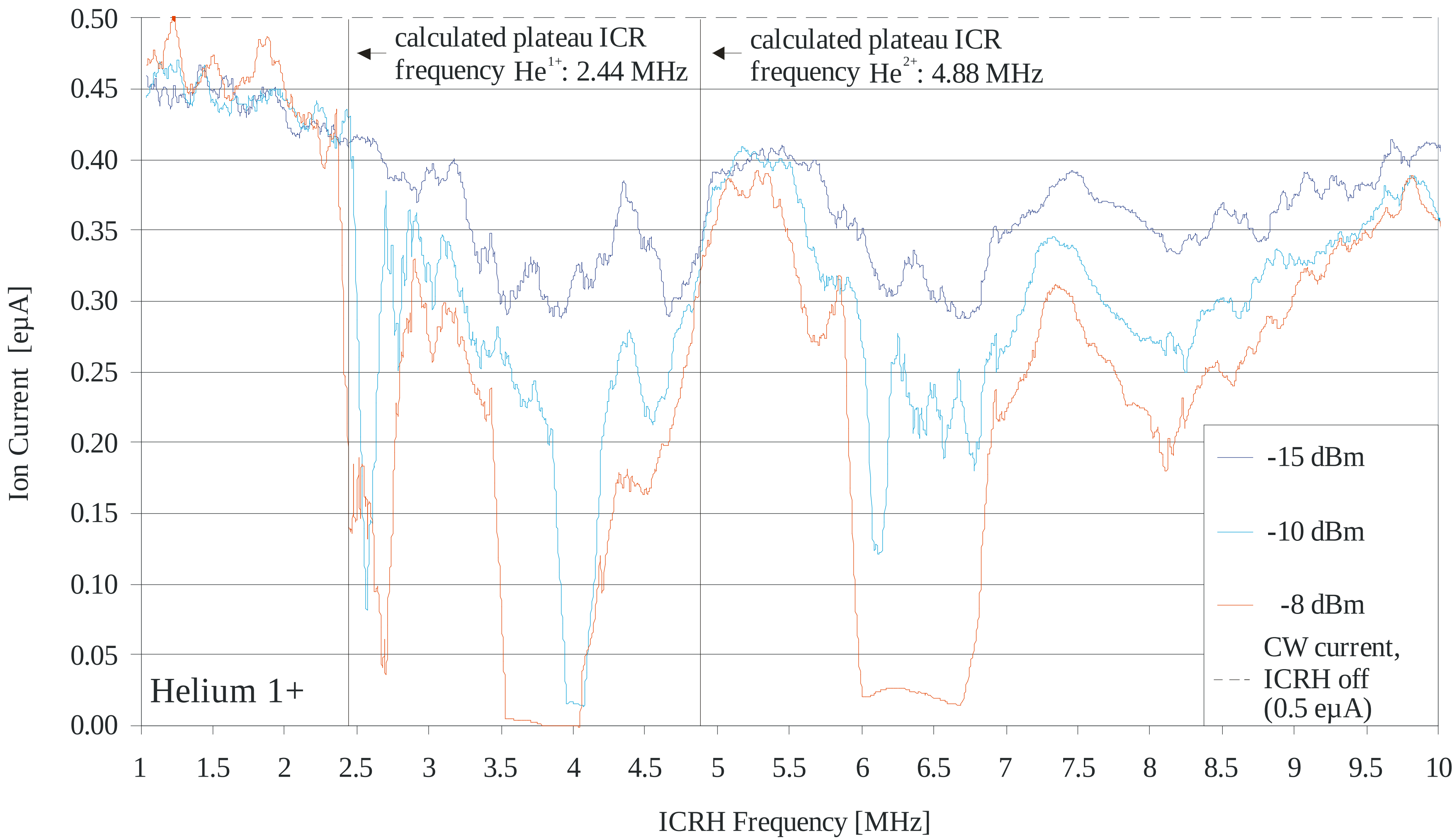
For observation of Ar11+ to Ar14+ at -8 dBm ≈ 12 V/cm the resonances for ICRH

of the lower q are all at the same and shifted frequencies

Shift may be due to ICRH of more than one q in different radial regions

since field of hexapole increases ~ r^2

ICRH of He^{+} and He^{++} : Observation of He^{+} -current



RF is varied in steps of 100 kHz from 1 to 10 MHz at B = 0.64 T

Only two species **He^{+}** and **He^{++}** dominant

impurities of C, N, and O accumulate to some percent

Both He-ions concentrated close to axis but will also be

present everywhere else in the plasma chamber

RF is varied in steps of 100 kHz from 1 to 10 MHz at B_{res}=0.64 T

At -15 and -12 dBm only indications for ICRH occur

Significant signals show up at -10 and -8 dBm ≈ 10 and 12 V/cm:

With the interpretations for Ar in mind,

we find again a minimum of the He+ -current at 2.6 MHz when

He+ is ICR-heated slightly above its plateau ICR frequency

He+ gains enough $\mathbf{E_{rot}}$ for a better confinement

which leads to a reduction of its extracted current

The current dips become more pronounced with increasing RF- field

Their frequency positions suggest ICRH at 14 to 16 mm radial distance

This may be result of the increase of the field strength with radial distance and

of the spatial distribution of **He+** in the source

This interpretation is well corroborated by our trajectory calculations in Table 2

Constant density of He+ of $8 \cdot 10^{10}$ cm^{-3} in the core and half this density outside

He++ and impurities are neglected. The plateau field is 0,64 T

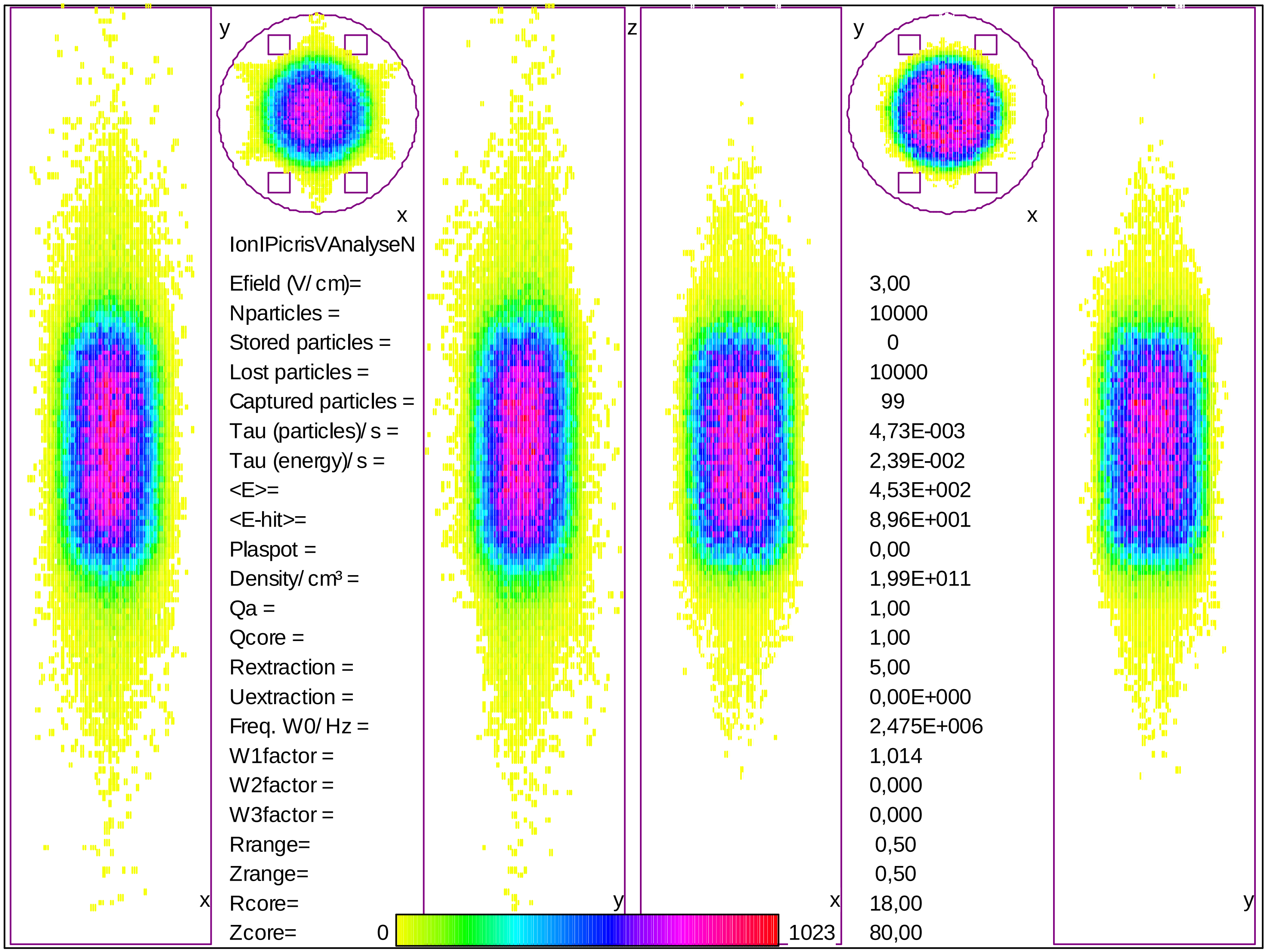
frequ./MHz	Bres/T	radius/mm	field/V/cm	<tau>/ms	<E>/eV
2,475	0,640	5,00	1,00	2,480	299
2,475	0,640	5,00	2,00	3,650	387
2,475	0,640	5,00	3,00	3,840	419
2,475	0,640	5,00	6,00	2,550	470
2,475	0,640	5,00	10,00	1,730	542
2,475	0,640	5,00	14,00	1,110	503

Average rotational energie <E> and averaged lifetimes <tau> of He+

Are calculated as a function of the RF field strength

He^+ ICR-heated at $\omega = 1.014\omega_0$ and 3 V/cm

<E> = 453 eV   <tau> = 4.7 ms



The rotational energies <E> reproduce the resonance dips of He+

they increase up to about 12 V/cm and then saturate

The ions with high <E> are concentrated in the resonance volume

in perfect agreement with our interpretation that E_{rot} reduces the extraction

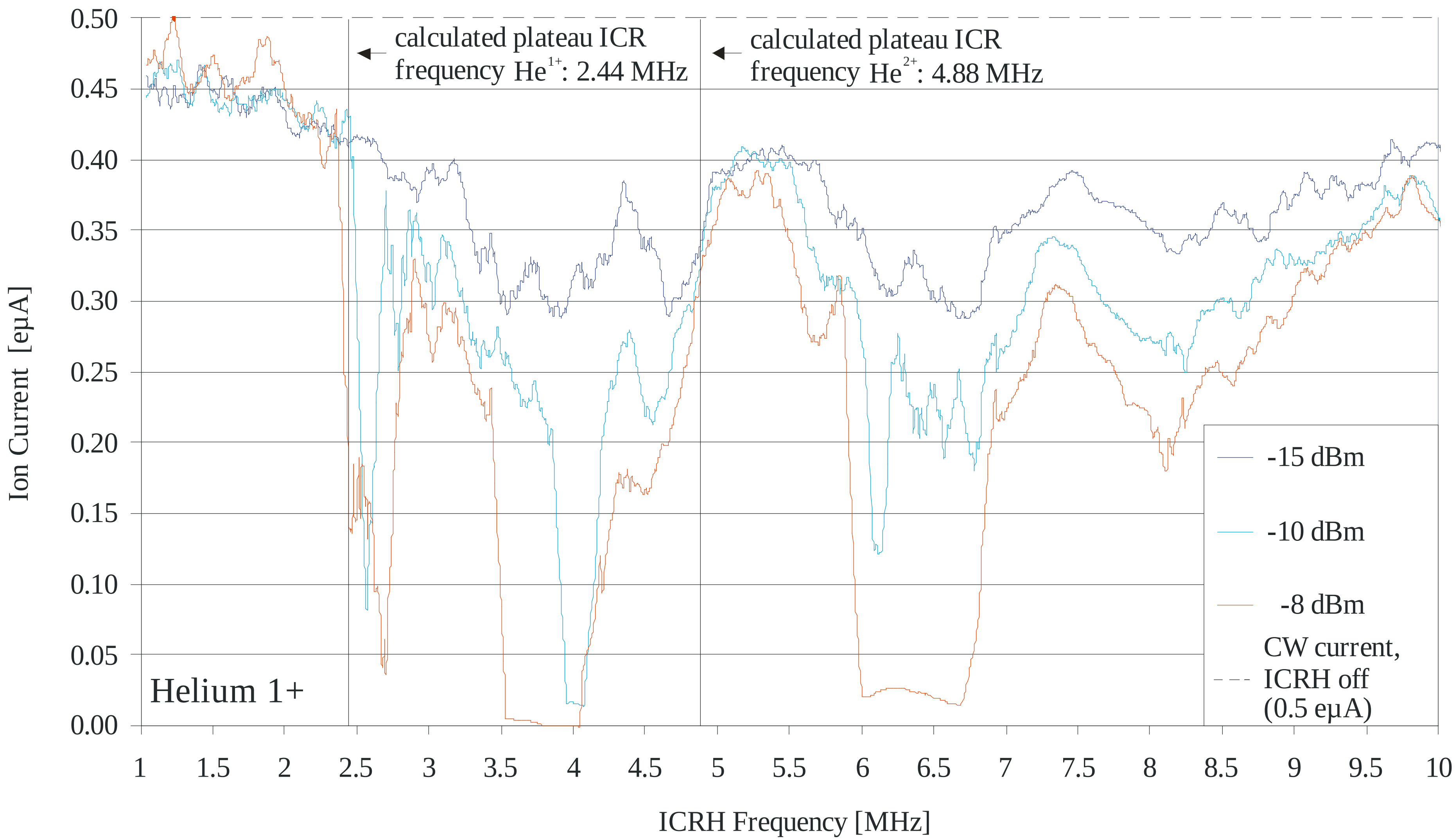
<tau> has a maximum of 3,84 ms at 3 V/cm and then

reduces rapidly with increasing RF

Reductions of <tau> are dominated by losses towards the walls and electrodes,

i.e. by He+ far away from the axis with small probability for extraction

ICRH of He^+ and He^{++} : Observation of He^+ -current



RF is varied in steps of 100 kHz from 1 to 10 MHz at B = 0.64 T

Above this resonance, deep additional minima at 4 MHz (-10 dBm)

and from 3.5 to 4.1 MHz (-8 dBm) are observed

The first corresponds to He+ -ICRH at 1T near the wall and the

second to He+ -ICRH between 0.86 and 1T between electrodes and the wall

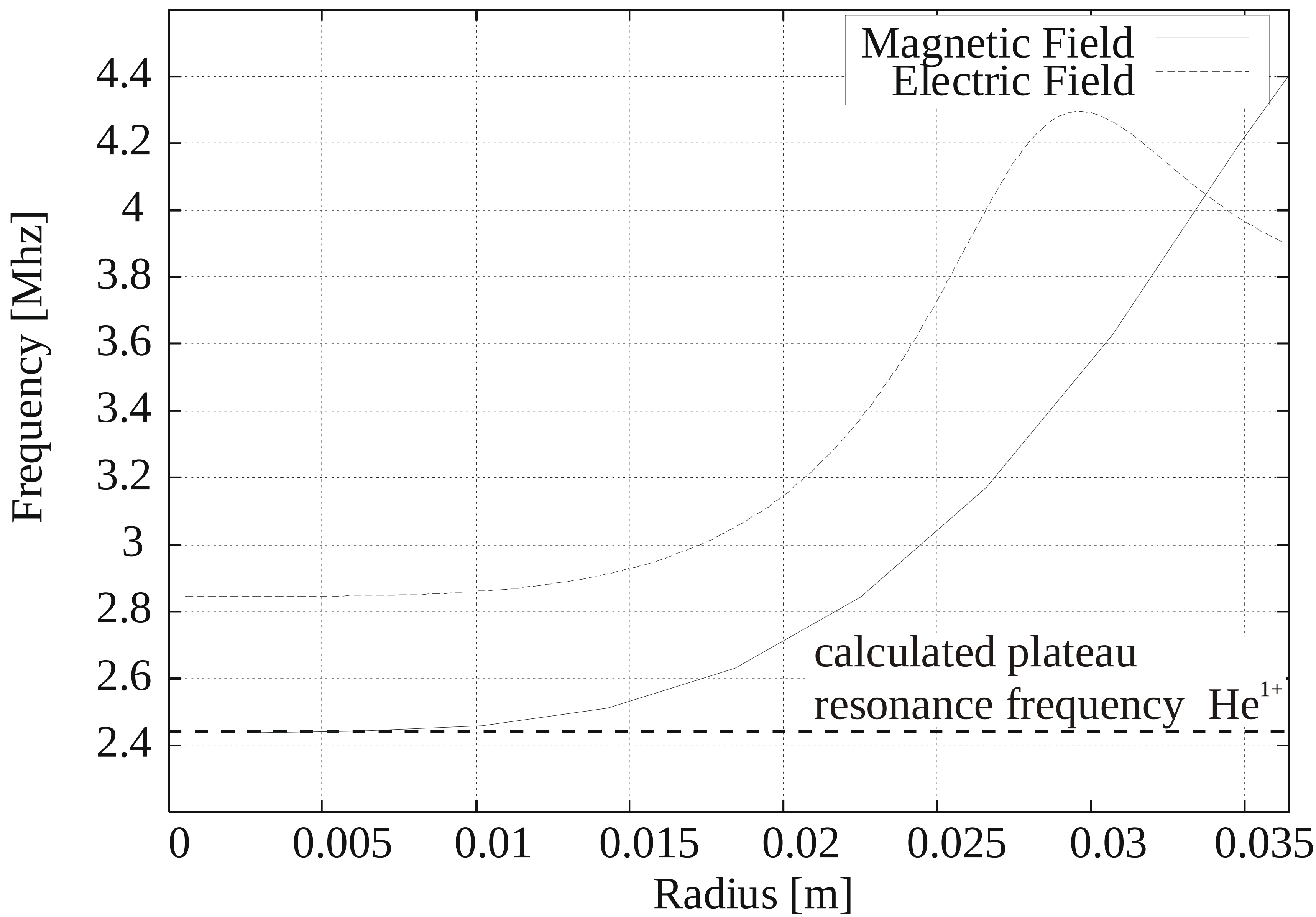
It is the result of a complete breakdown of the plasma !

As expected minima at the He++ -ICR-frequency are not observed

Surprisingly, however, deep minima occur at frequencies above it

They correspond to He++ -ICRH at radial distances of 20 to 25 mm

which again produces a breakdown of the plasma at -8 dBm


Magnetic Field
Electric Field
calculated plateau
resonance frequency He^{1+}
4.4
4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
Frequency [Mhz]
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
Radius [m]

At these distances the electric field amplitudes are increased by 40 to 200 %

ICRH of ions at these distances and field strengths produces trajectories

which rapidly end up on the electrodes or on the walls

Such ions are not only lost for extraction but do provoke an out-gazing which

strongly perturbs the plasma up to a complete break down

The strong influence of He+ - or He++ -ICR-heating on the He+ current is thus

mainly the result of the He+ - or He++ -wall interaction

This interpretation is perfectly corroborated by trajectory calculations in Table 3

Ions ICR-heated in these spatial regions indeed end up

rapidly on the electrodes or on the walls

They show a considerable reduction of the averaged lifetime and energy

Ions ICR-heated in these spatial regions indeed end up

rapidly on the electrodes or on the walls

frequ./MHz	Bres/T	radius/mm	field/V/cm	<tau>/ms	<E>/eV
2,475	0,640	5,00	3,00	3,840	419
2,554	0,669	16,00	3,40	0.940	122
2,709	0,710	20,00	4,80	0,820	95
3,100	0,813	26,50	12,00	0,298	76

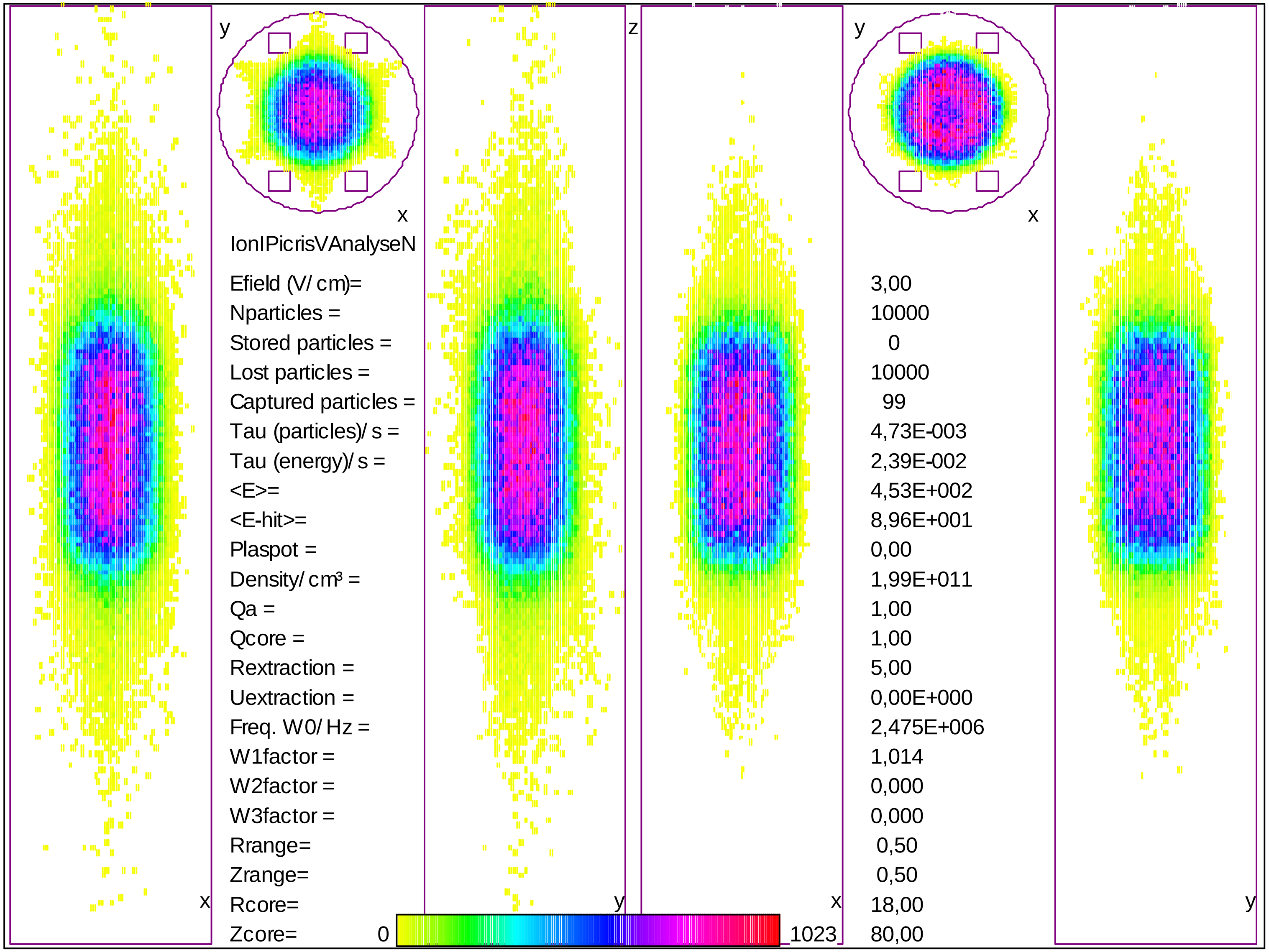
They show a considerable reduction of the

averaged lifetime and averaged energy

when the radius of ICR-interaction increases

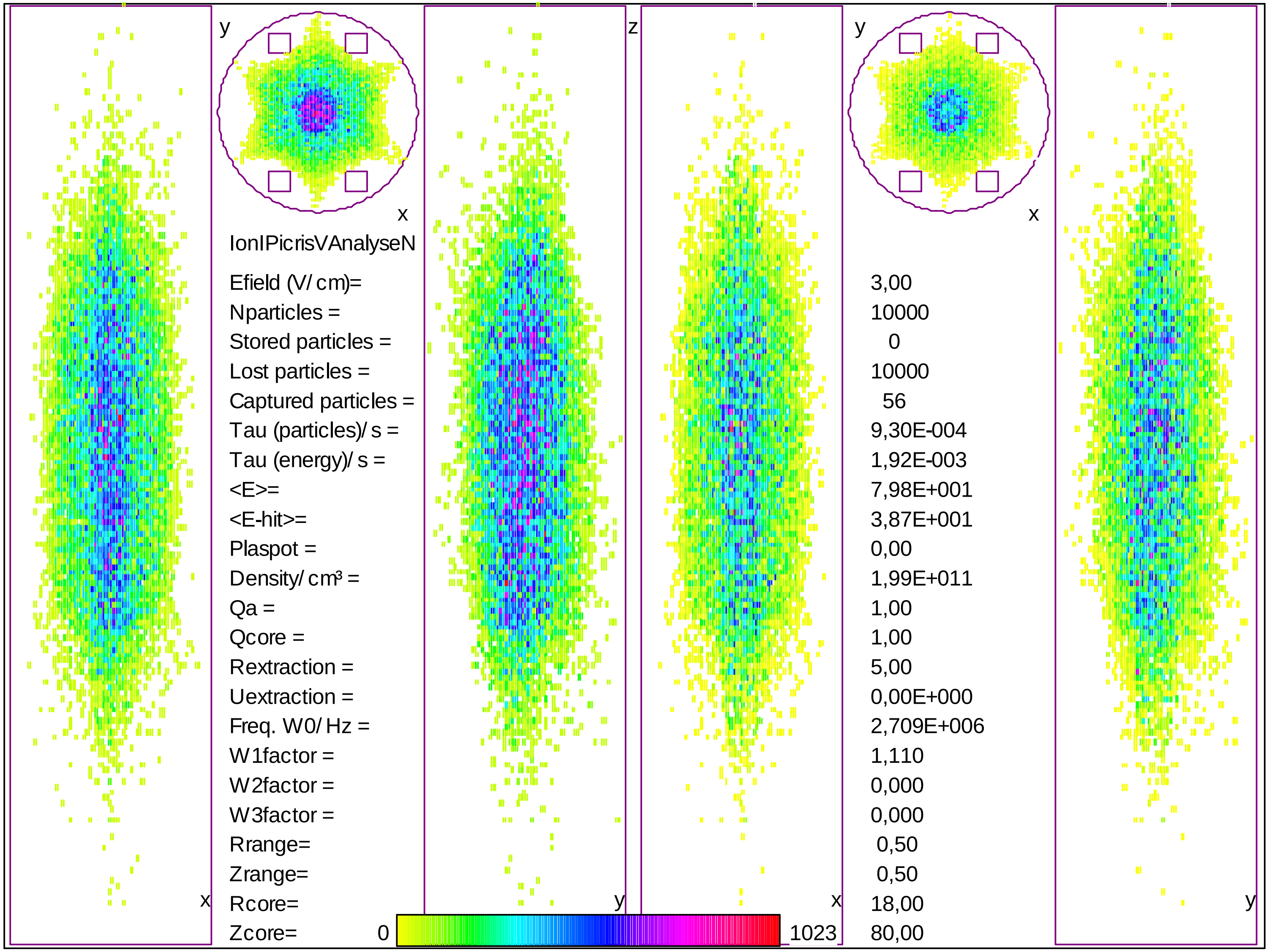
Similar results have been obtained for the ICRH of H+ and H_2+

but the RF-fields were too low to see the current-dip at the H+ -ICR-frequency frequ = 2.475 MHz radius = 5 mm <E> = 453 eV <tau> = 4.73 ms



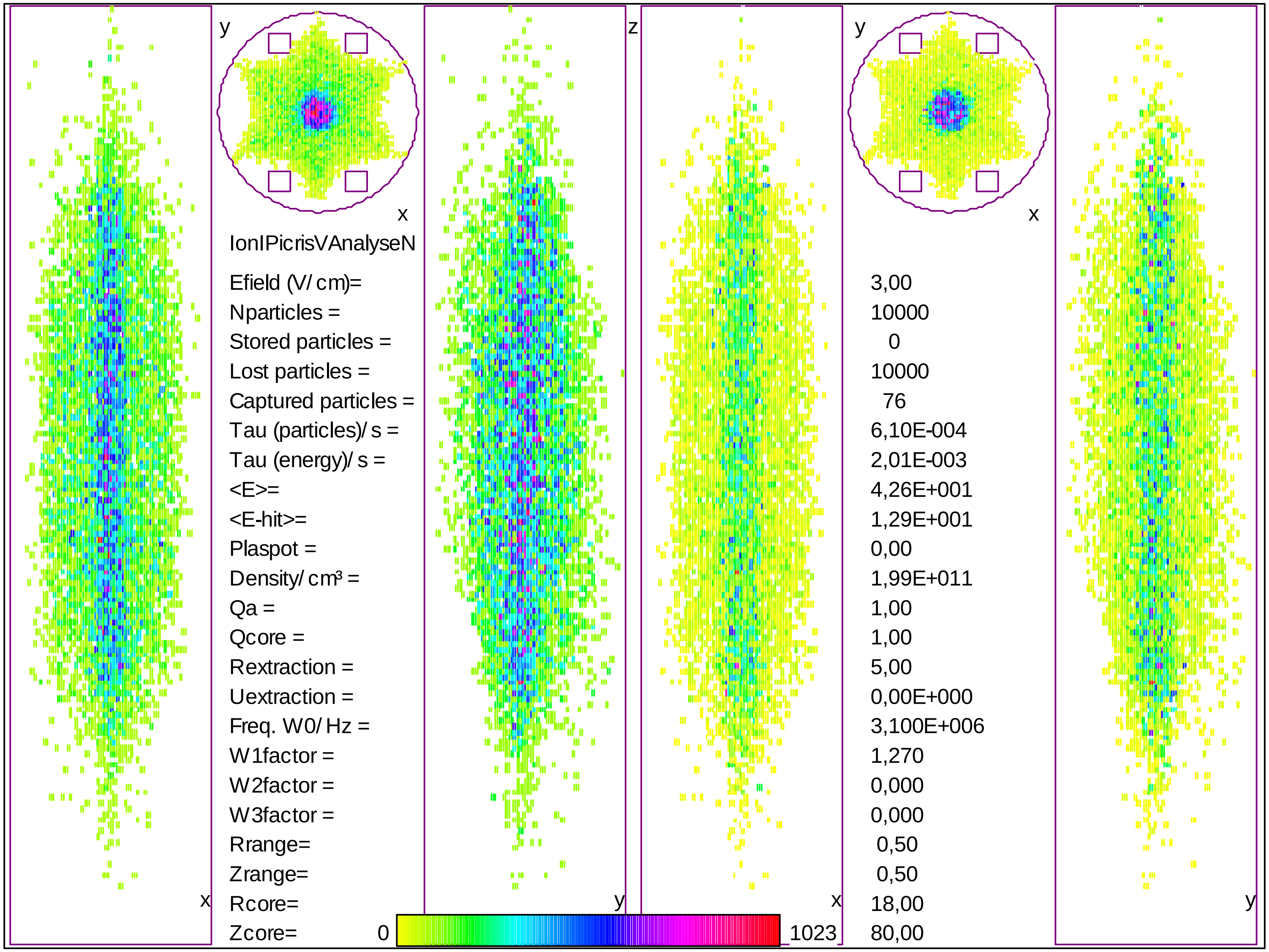
IonIPVNHe14030f

frequ = 2.709 MHz radius = 20 mm <E> = 79.8 eV <tau> = 0.93 ms



IonIPVNHe12030f

frequ = 3.10 MHz radius = 26.5 mm <E> = 42.6 eV <tau> = 0.61 ms



IonIPVNHe13030f

Ultimate proof

for our interpretations with gain of E_{rot} by ICRH

would be measurement of E_{rot} :

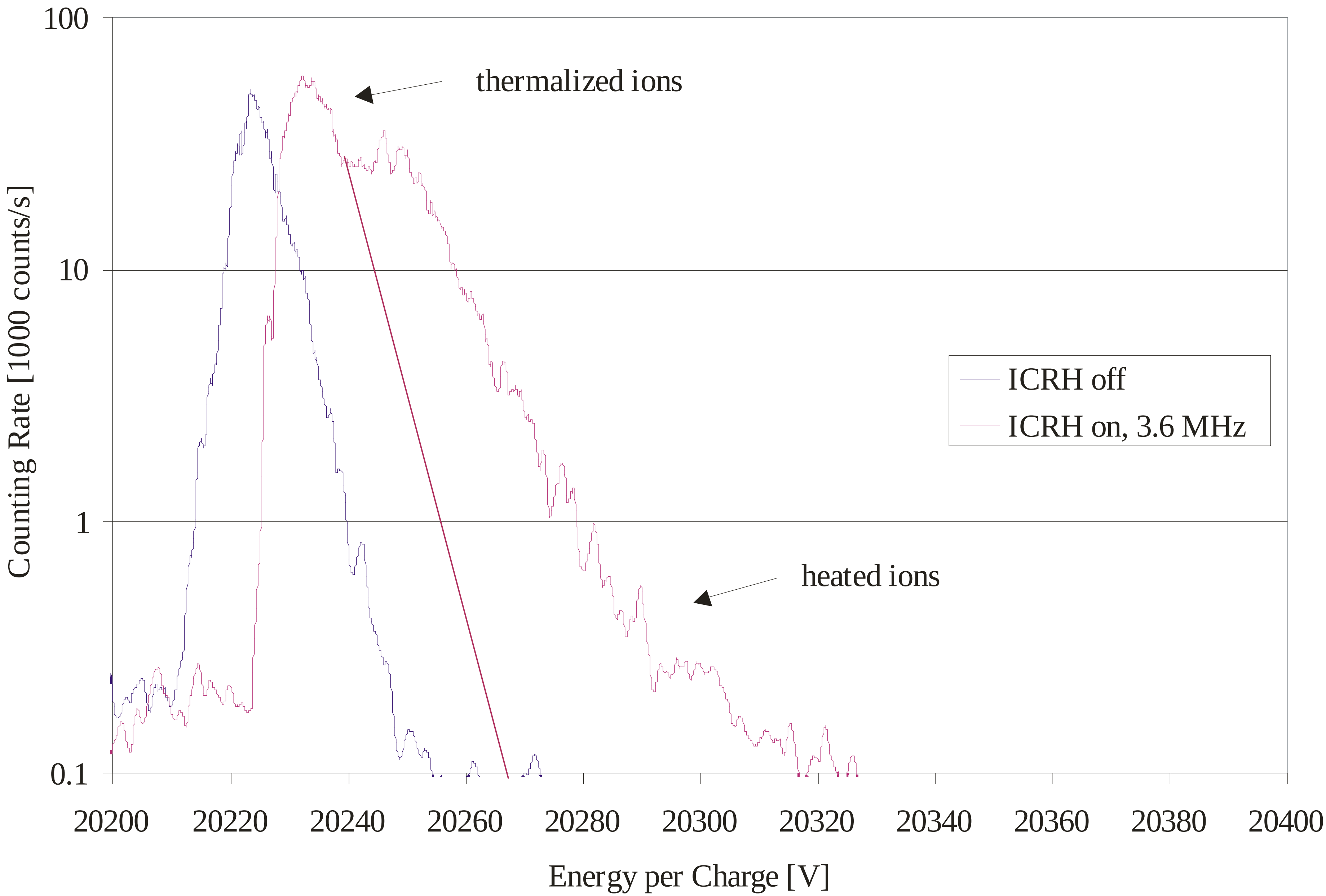
Electrostatic energy analyzer with $E/\Delta E \approx 10^5$ behind the analyzing chamber

RF was set to 3.4 MHz on slope of breakdown which we believed at that time

to be the dominant resonance yielding high E_{rot} and yet still enough current

! 2.44 MHz would have been much better !

Final proof of our interpretations: energy measurement of ICR-heated He+



Without ICRH energy of He+ is peaked at 20223 V

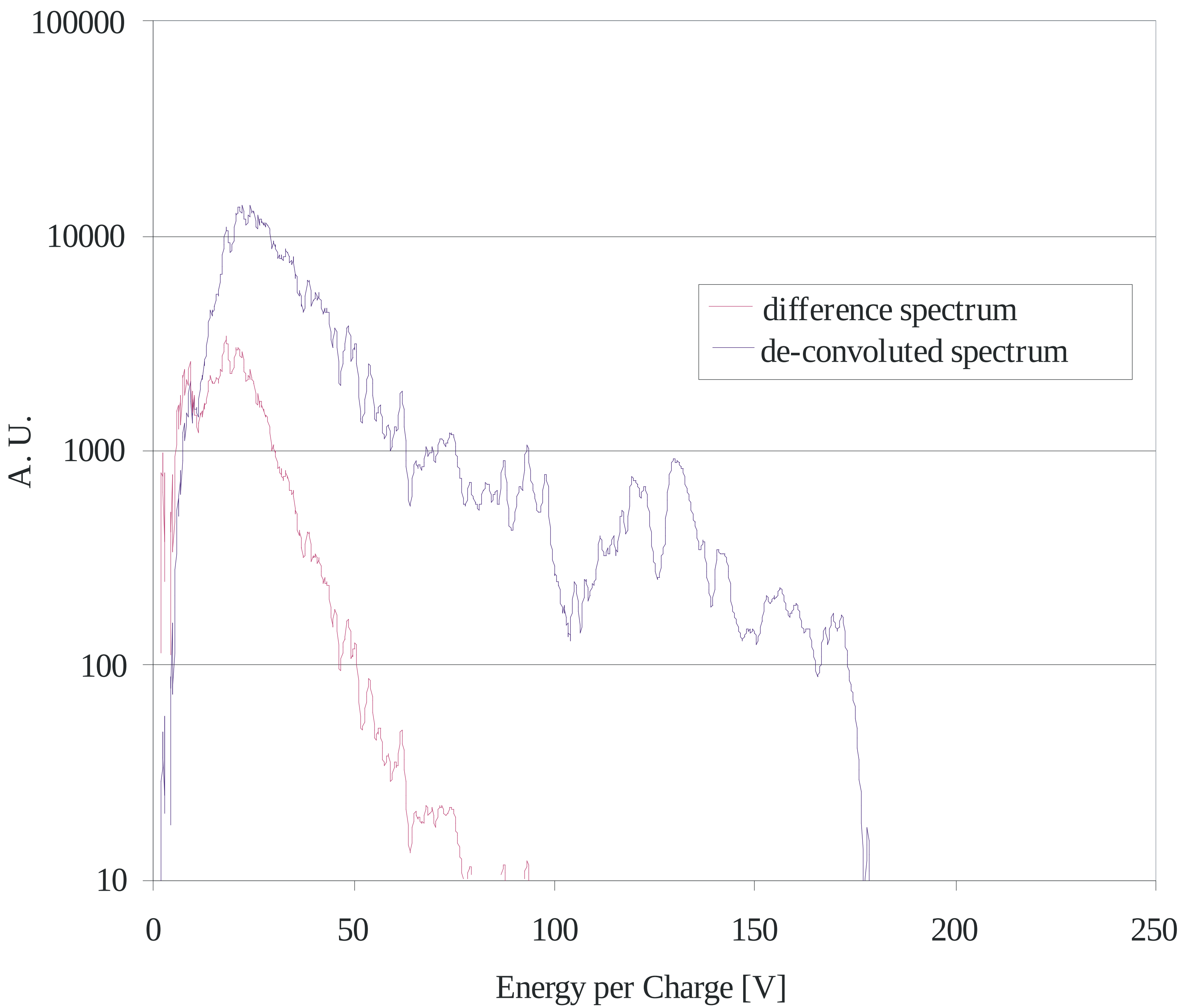
with half width of about 8 V

The energy spectrum of ICR-heated He+ seems to be composed

of a contribution of thermalized ions and

of heated ions up to 20390 eV

Subtraction of the thermalized ions yields the next figure


100000
10000
1000
100
10
A. U.
0
50
100
150
200
250
Energy per Charge [V]
difference spectrum
de-convoluted spectrum

This spectrum has further to be corrected for the fact that

ions with rotational energy are stored and can not be extracted

They need to make on the average a 90° collision in order to convert

the rotational into longitudinal energy which can then be detected

The probability for such a Rutherford-collision is proportional to $\mathbf{E_{rot}^{-2}}$

De-convolution yields the spectrum up to 170 eV

This is definite proof for the production of rotational energy by ICRH

The averaged rotational energy is in relatively good agreement with

the result of our trajectory calculations in Table 3

Summary

The ICRH of argon, helium, and hydrogen has irrefutably shown

that RF electric fields can penetrate

into the magnetized plasma of a PECRIS

with cut off frequency orders of magnitude higher.

It can produce rotational energy in selected ion populations

by ICR-heating at various locations in this plasma

ICRH can be used to increase currents of selected ion species

All these experiments have been carried out, however,

at rather low µW power

One has to repeat ICRH in ECRIS in chambers with greater

diameter in order to avoid perturbations of

electrons and ions by the RF-electrodes

In a 28 GHz SECRIS one could simultaneously

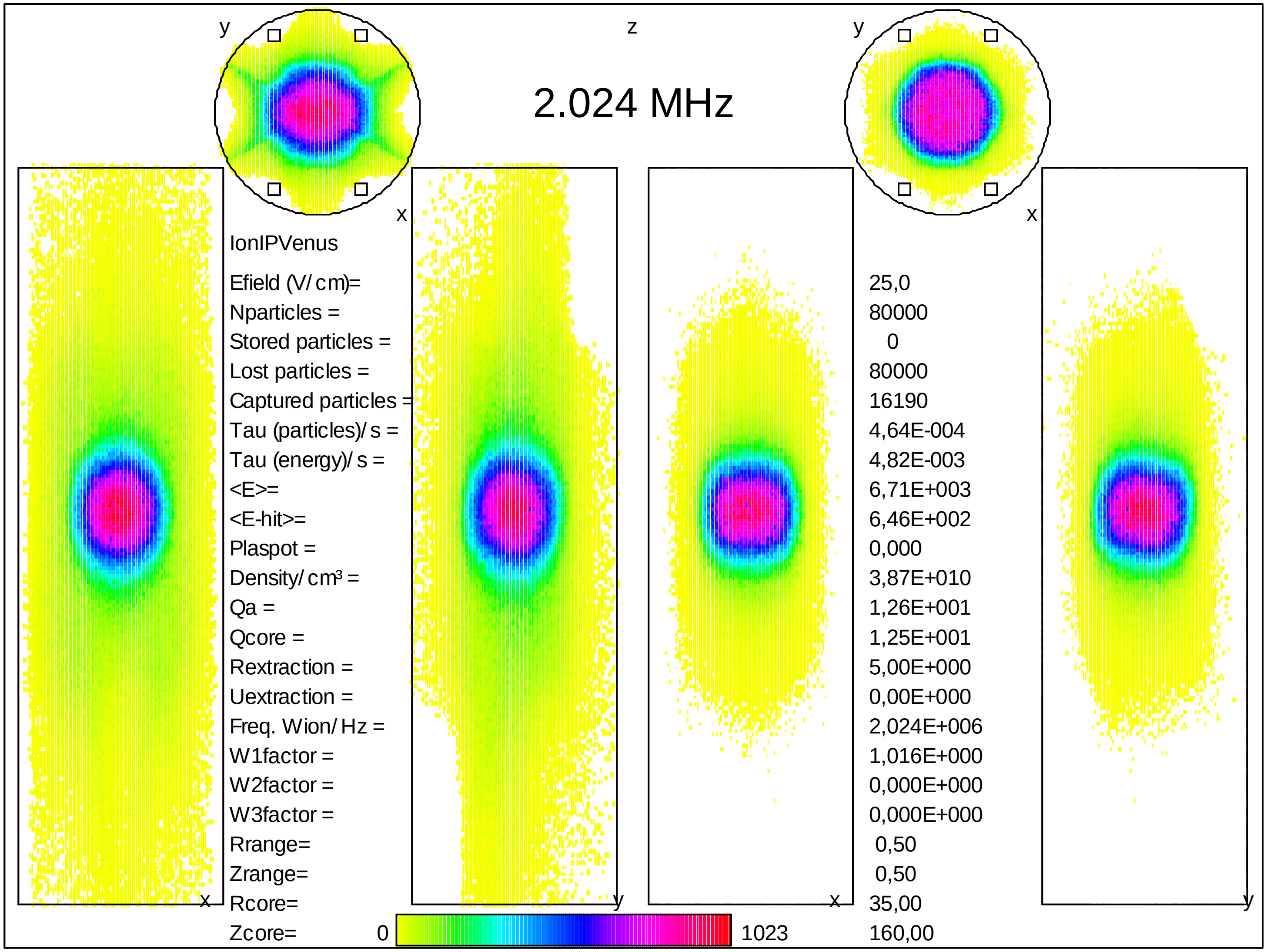
ICR-heat the Ar charge states 5+ through 8+

with the same RF of 2.02 MHz at different locations,however

ICRH of Ar8+ at 1.6 % above the central B_{min} of VENUS

Assumption of Ar8+ being present in the centre of VENUS ?

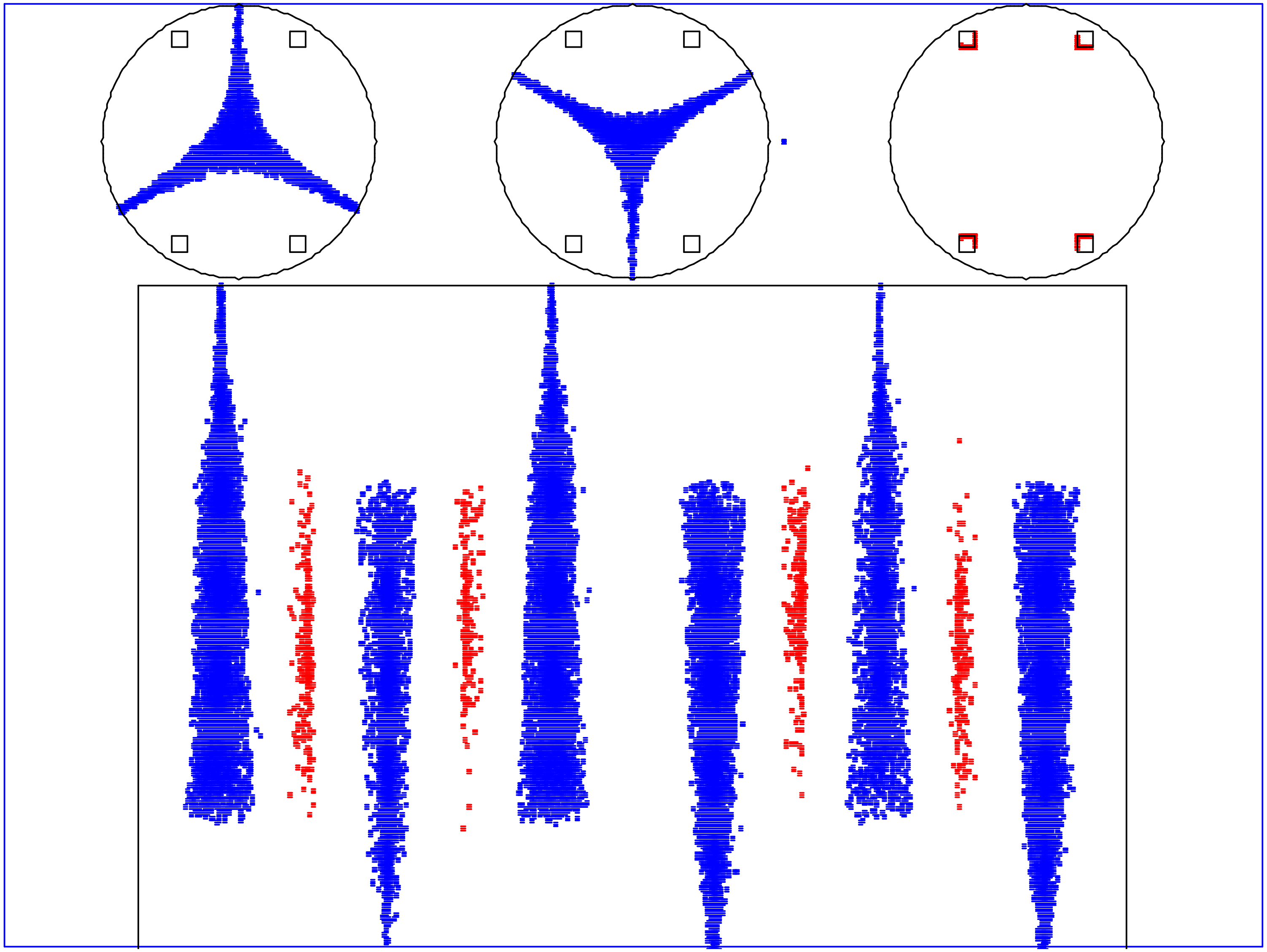
<E> = 6.7 keV ! and <tau> = 4.8 ms !



IonIPhVenusNar8b1250

Impact pattern of Ar8+ ICR-heated at B_{min} in VENUS

Are these impacts of ions perturbing the VENUS plasma ?

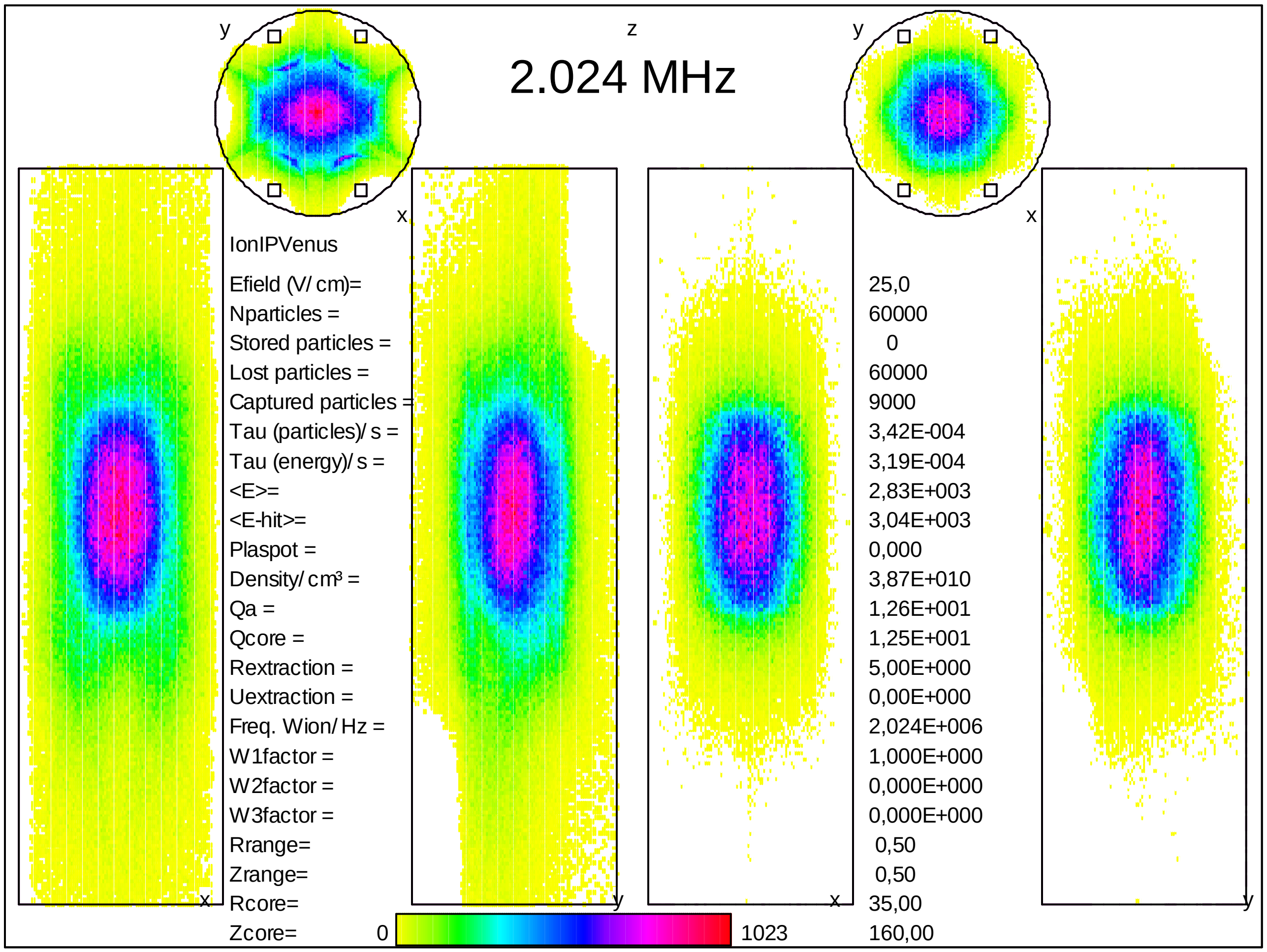


IonIPhVenusNAr8b1250a

ICRH of Ar7+ at 0.7586 T, i.e. 16.2 % above the central B_{min} of VENUS

<E> = 2.8 keV, E_{max} = 34.5 keV, <tau> = 0.34 ms, and tau_{max} = 13 ms

<Ehit> = 3 keV

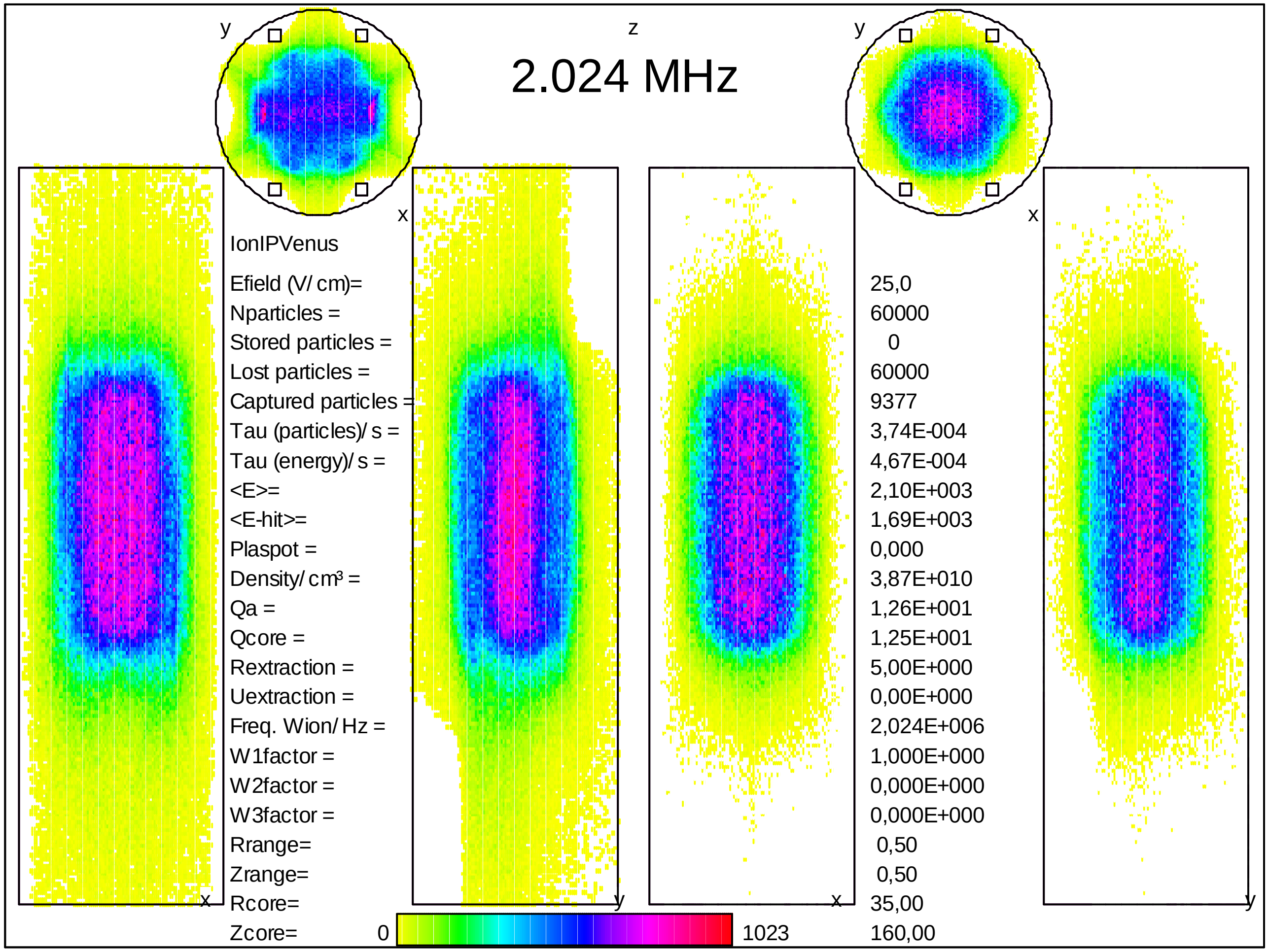


IonIPhVenusNAr7c1250

ICRH of Ar6+ at 0.8851 T, i.e. 35.5 % above the central B_{min} of VENUS

$\langle E \rangle$ = 2.1 keV, E_{max} = 19.6 keV, $\langle tau \rangle$ = 0.37 ms, and tau_{max} = 16 ms

$\langle E_{hit} \rangle$ = 1.7 keV



ICRH of Ar5+ at 1.062 T, i.e. 62.7 % above the central B_{min} of VENUS

$\langle E \rangle$ = 1 keV, E_{max} = 9.9 keV, $\langle tau \rangle$ = 0.36 ms, and tau_{max} = 11 ms

$\langle E_{hit} \rangle$ = 0.95 keV