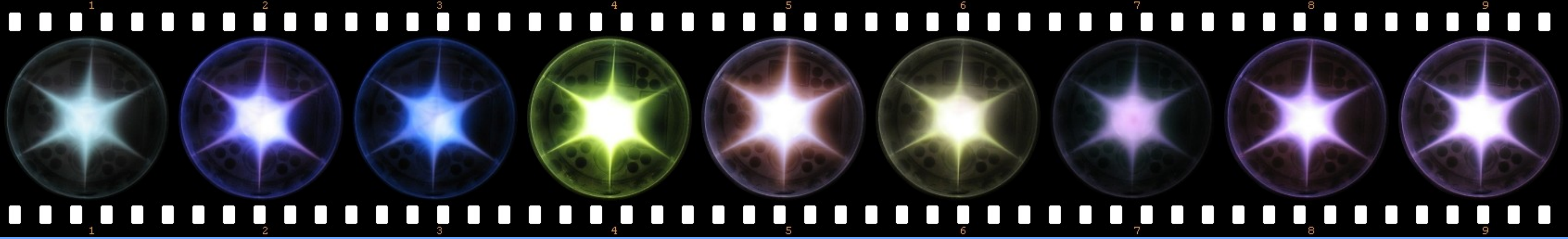

Studies of the ECR plasma in the visible light range

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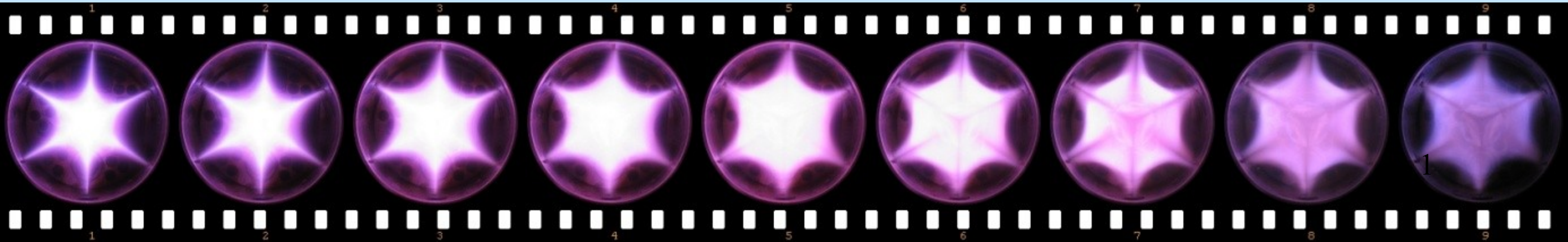

Outline

- Motivation
- Experimental setup

1. ECRIS settings effects
2. Cold and warm electrons
3. The color of plasmas (Xe, He)

- Conclusion

Motivation

ECR plasmas can be investigated by different ways

Electrostatic (Langmuir) probes

- Normal, double, emission types etc.
- Local information
- Plasma density, potential
- Technical difficulties

EM-radiation recording

- Ranges: IR, VL, UV, XR
- Imaging techniques (photos)
- Spectrum analysis
- Integrated axial information

Computer simulations

- Different methods
- Many nice graphical results
- Initial conditions…
- Prove: comparison with experiment

XR-region: ion excitation, brehmstrahlung: **plasma ions and lost electrons**

VL-region: atom excitation: **cold plasma electrons**

VL-region: Why? (an ECRIS is not a light source…)

There are at least two reasons worth studying the VL-part of ECR plasmas.

1.

- The cold electron population is the "first product" of the step-by-step ionization process.
- To get warm and hot electrons later we need cold electrons first.
- Cold electrons: starting phase toward the high charge ionization.

2.

- The application area of the ECR ion sources is broadening. Main field is still to produce highly charged ions (HCI).
- ECR-heating principle (+ B-minimum): LCI high current beams (e.g. proton, carbon) also by ECR ion sources.
- Medical applications, European Spallation Source (ESS, proton).
- In such sources the energy of the electron population is much lower than in the traditional HCI ECRISs.

Therefore we made high resolution ECR plasma photo series and movies

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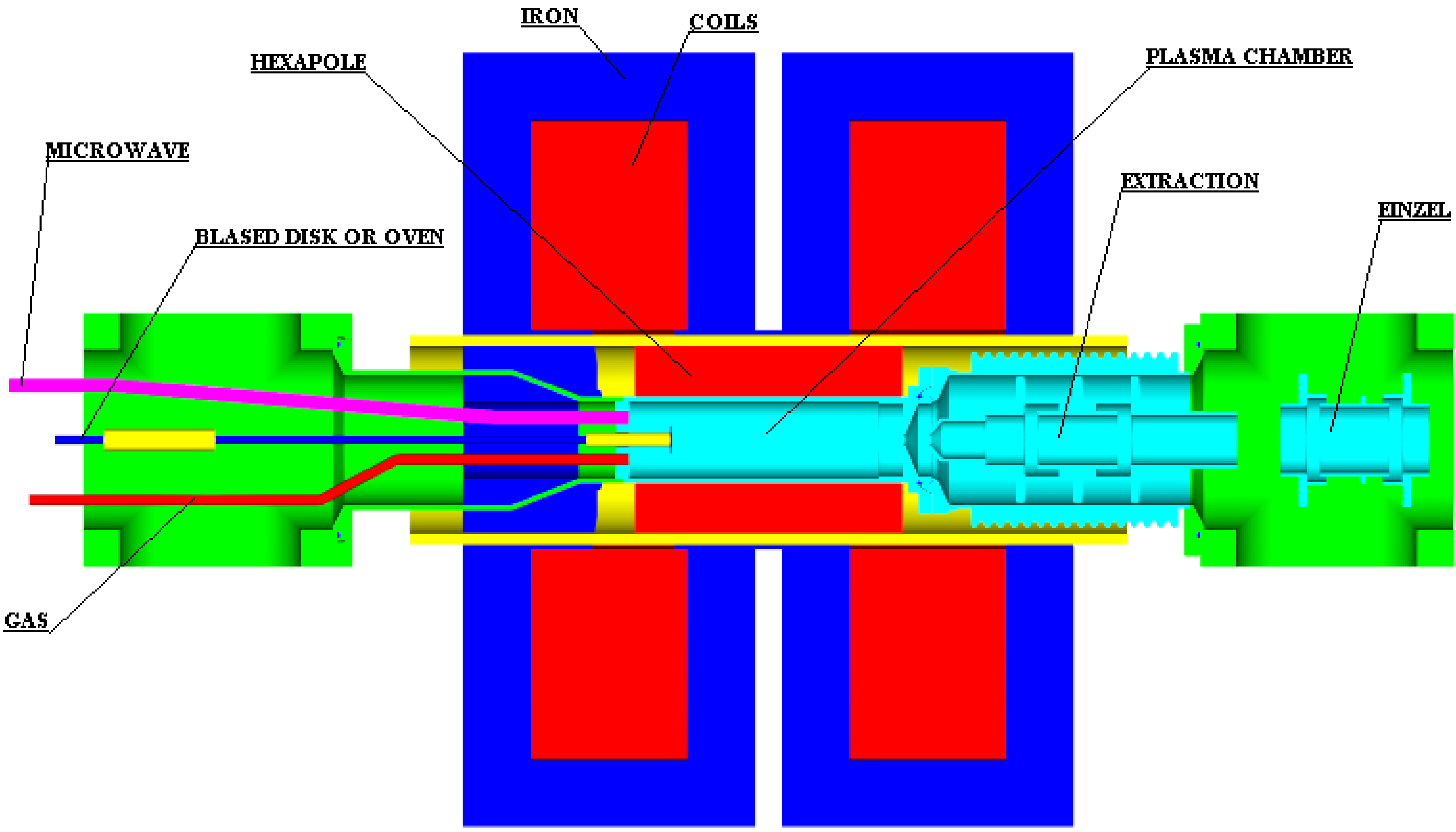
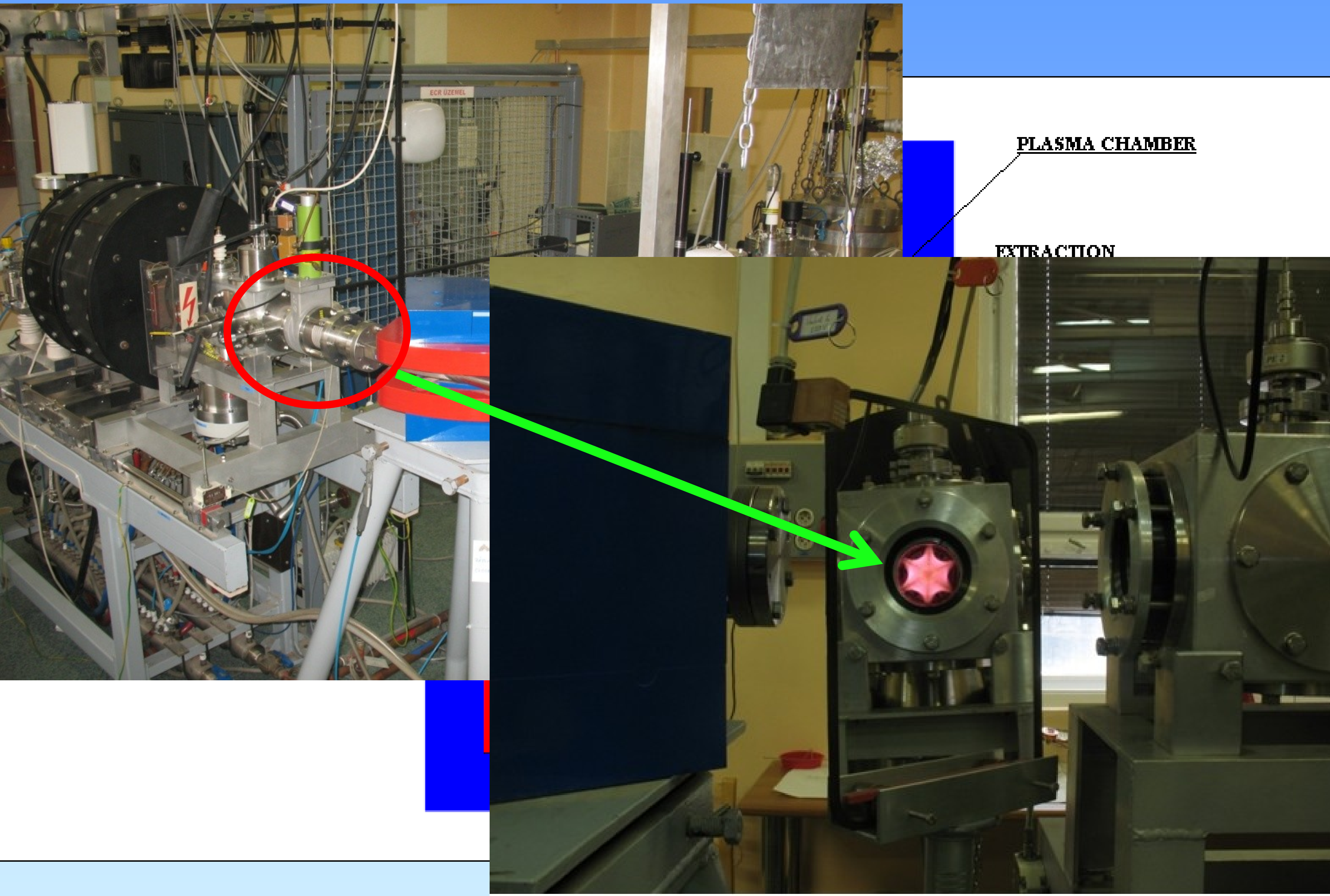
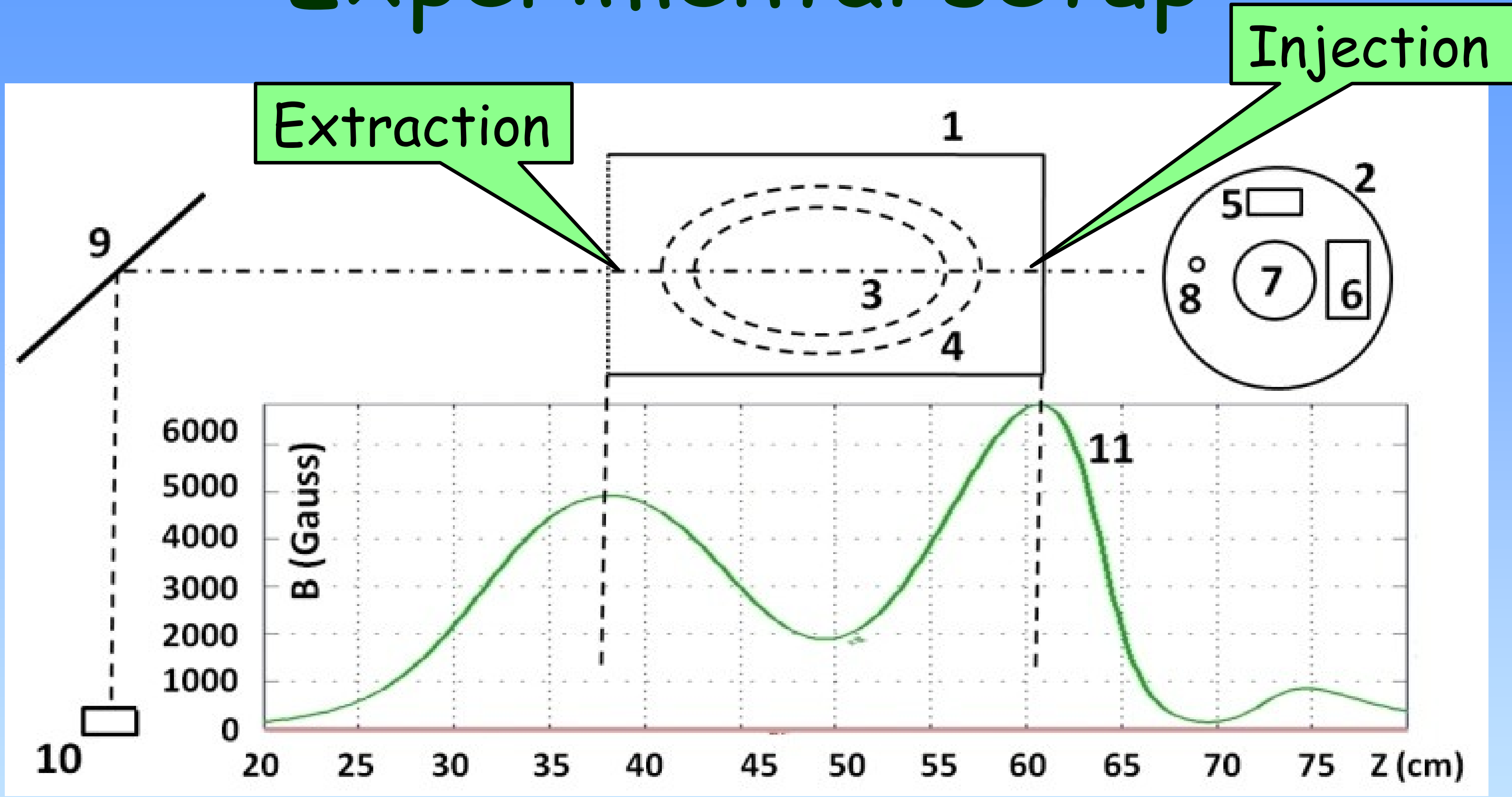
The ATOMKI-ECRIS




PLASMA CHAMBER
EXTRACTION

Experimental setup



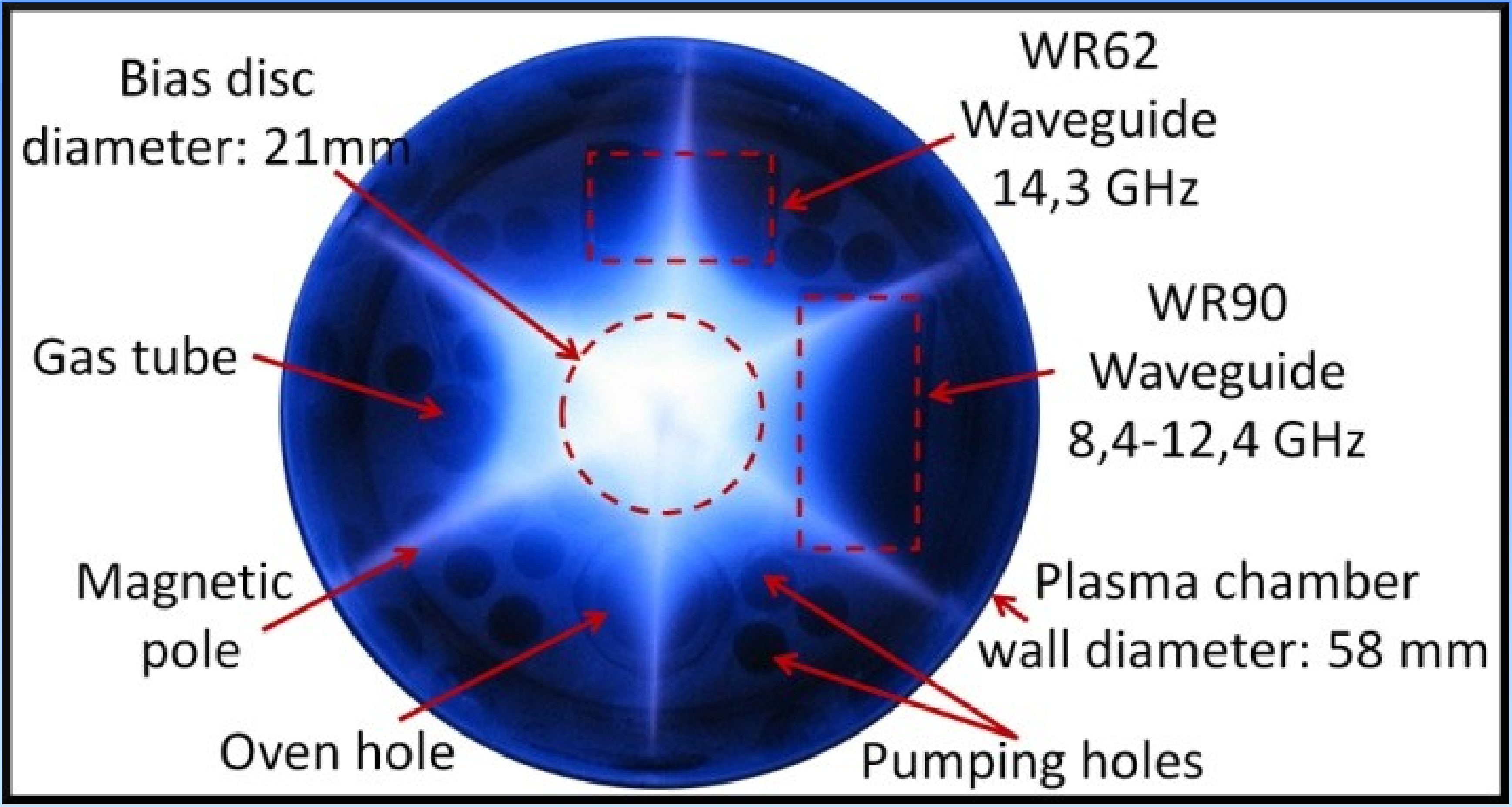
Layout of the experiment, top view. Plasma chamber side view (1), plasma chamber end wall (2), resonance zones (3, 4), waveguides (5,6), bias disc (7), gas tube (8), mirror (9), camera (10). At bottom the axial magnetic field distribution made by middle-powered solenoids, is shown (11).

Camera settings

- The ECR plasma is not an ideal photo model.
- Its longitudional length is about 20 cm.
- It is partly transparent and diffuse.

- Cameras: Canon A630 and Sony HDR-FX7E
- Picture size: 8 MP
- Exposure time: 0.8-4 sec
- Iris value: 8
- ISO value: 80
- Distance: 100+40=140 cm

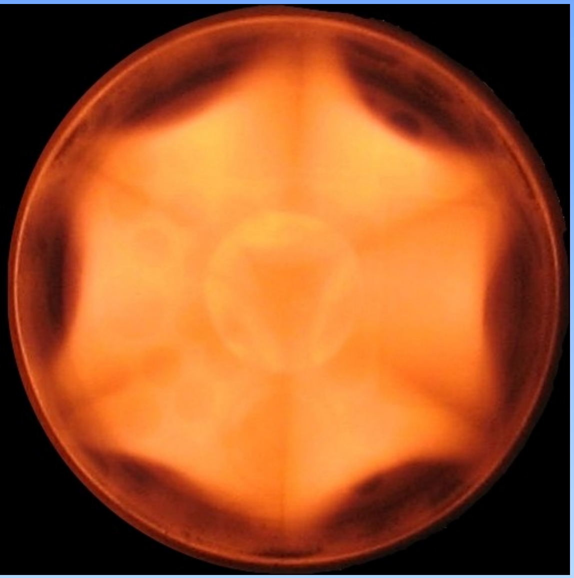
What we see…



Plasma „spider": only 6 legs, not 8

The 3+3 legs or arms fed by bunches of loss lines.

Operation modes



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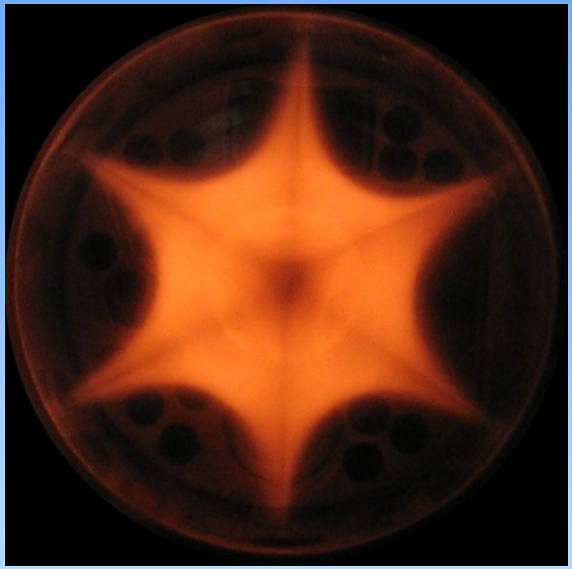

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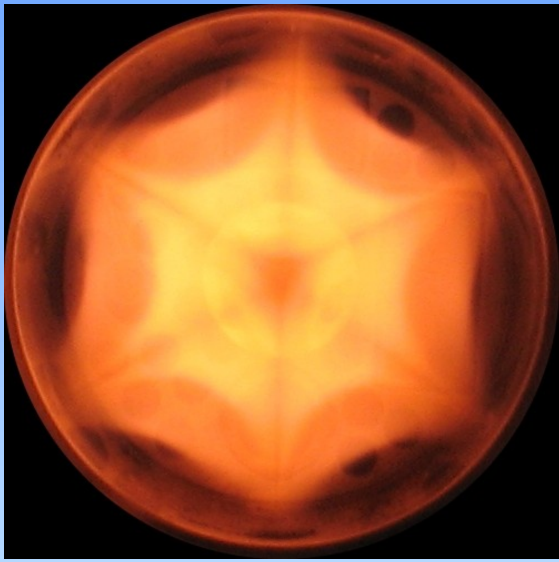

14.3 GHz, Klystron, 10-100 W

8.4-12.4 GHz TWT, 5-20 W

Klystron+TWT, double plasma

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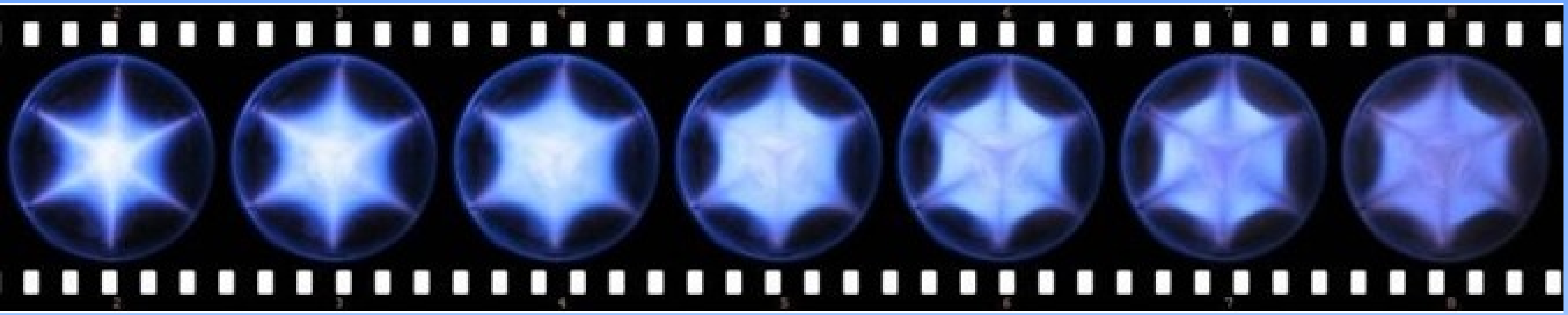
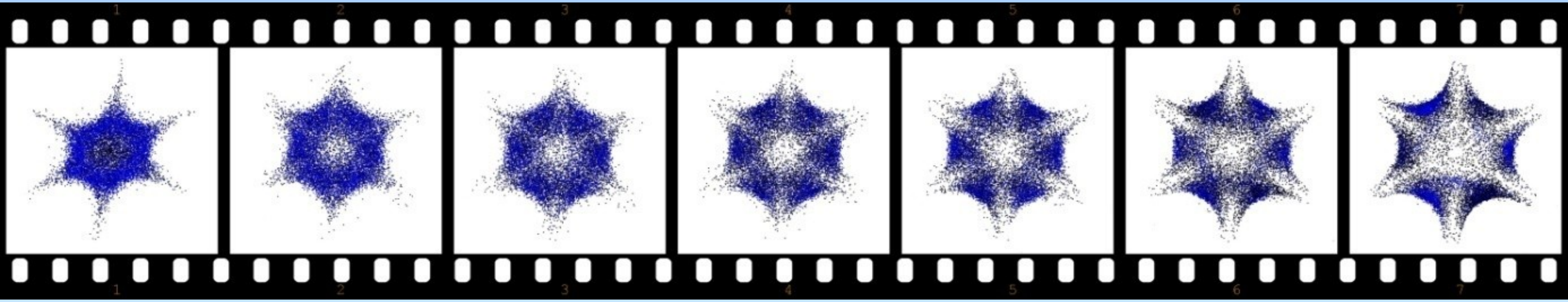
ICIS09 poster, R. Rácz et al., (RSI 81, 2010, 02B708)

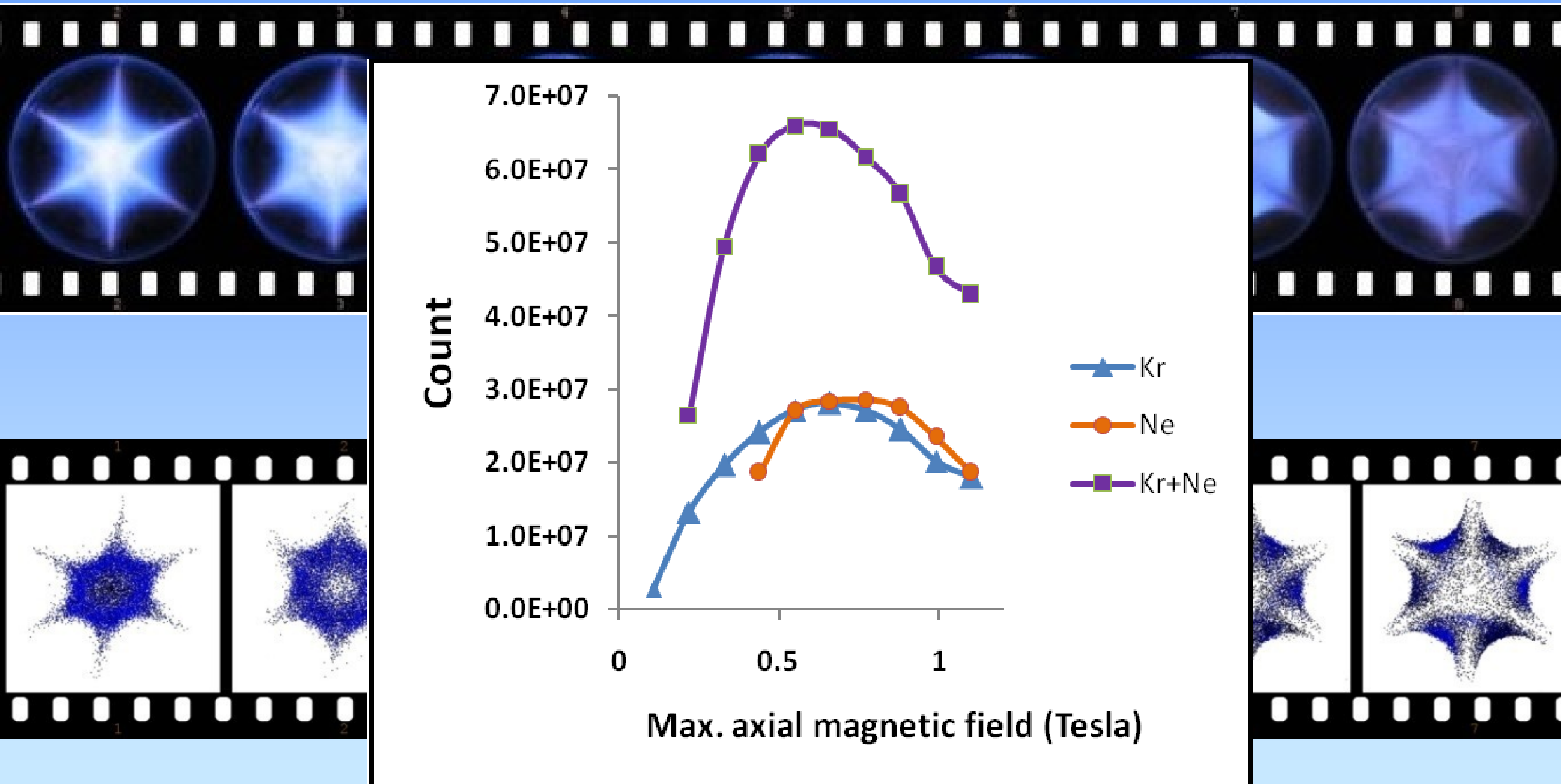


Effect of the decreasing magnetic field



TrapCAD simulation

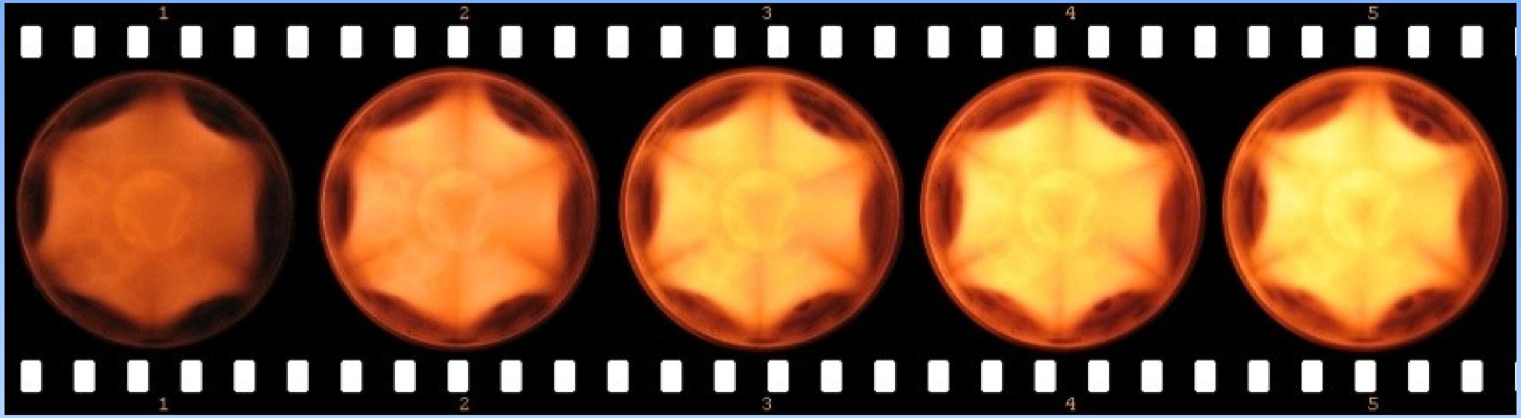
ICIS09 poster, R. Rácz et al., (RSI 81, 2010, 02B708)



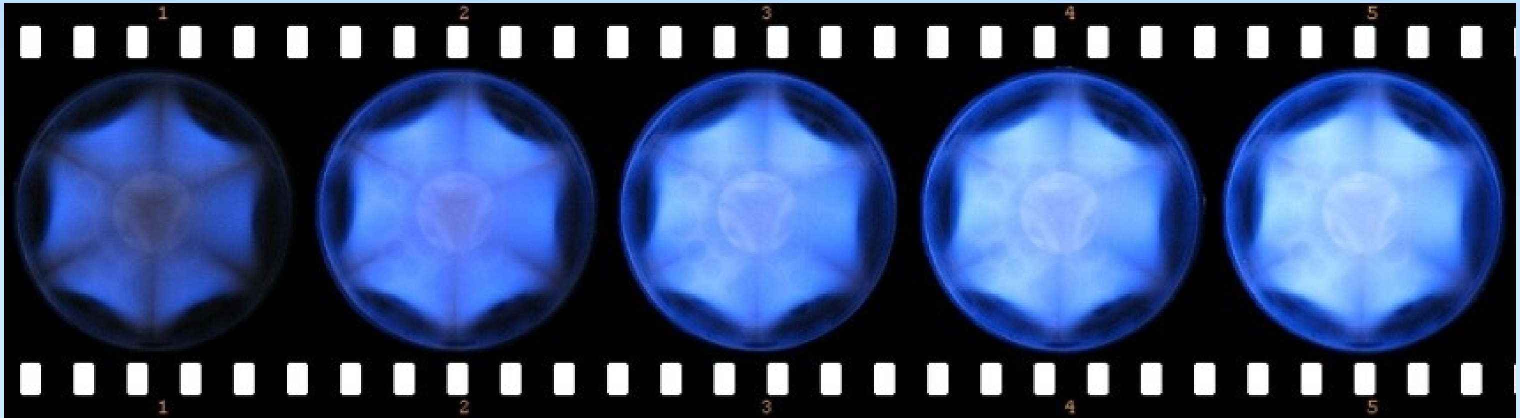
TrapCAD simulation

Effect of the microwave power

Neon	60W	70W	80W	90W	100W



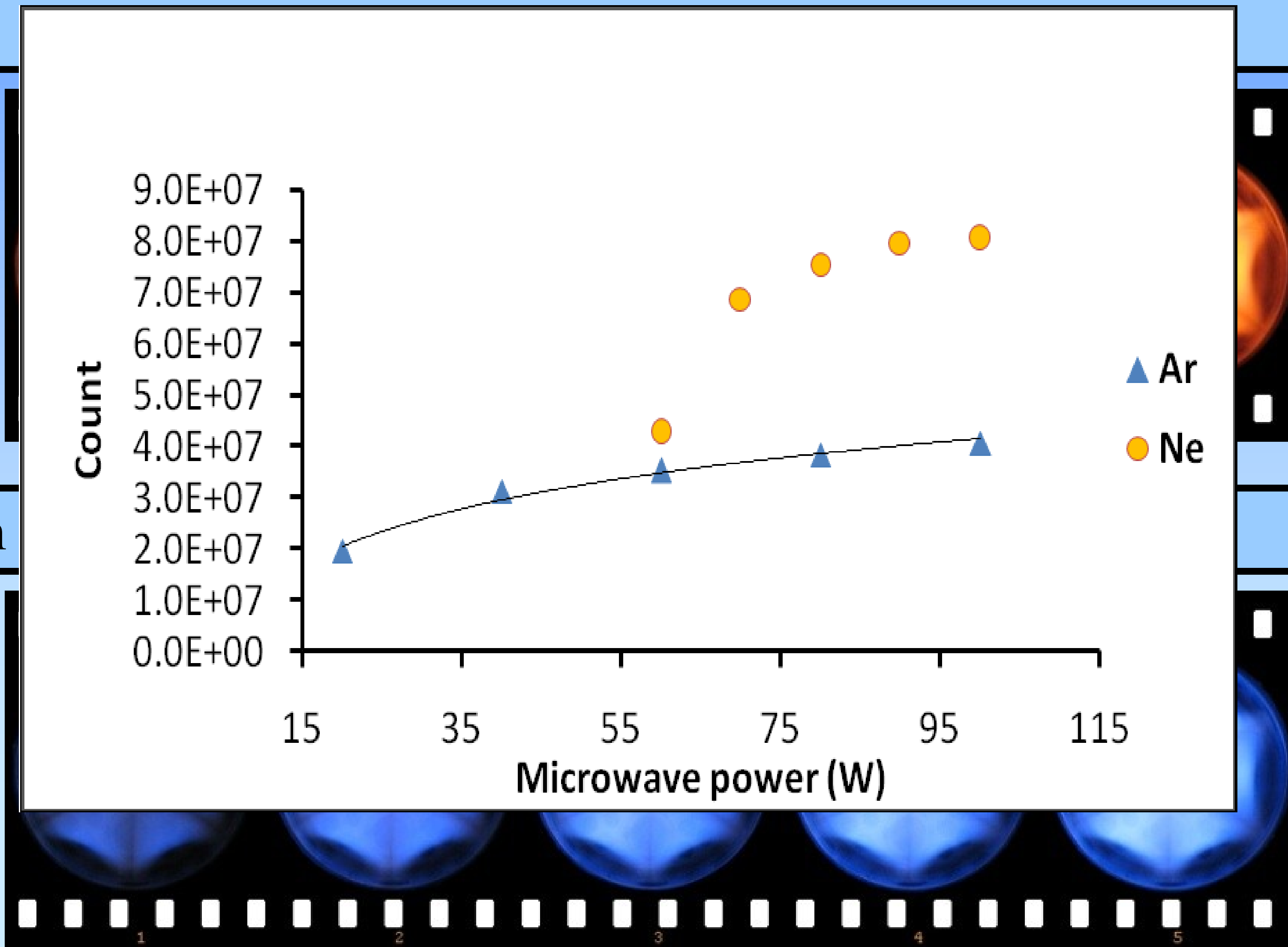
Argon	20W	40W	60W	80W	100W



Effect of the microwave power

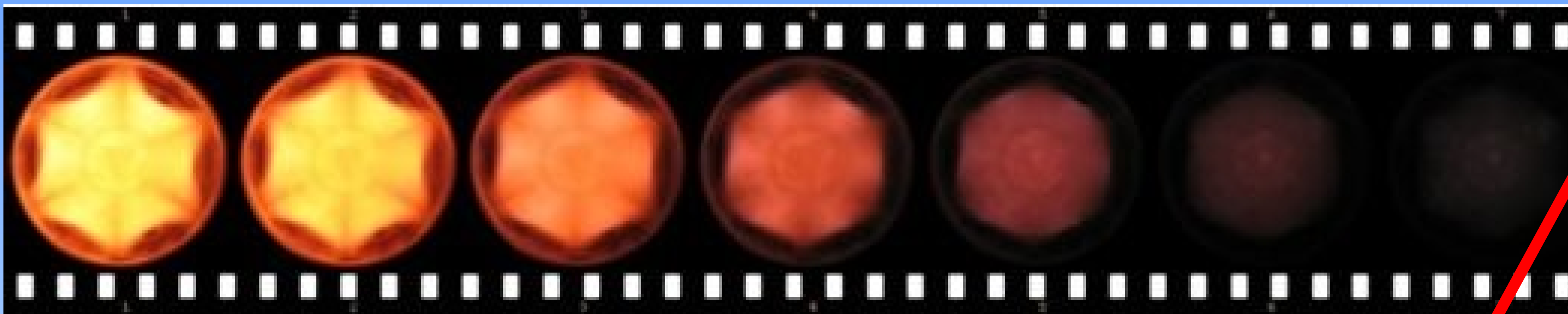
Neon

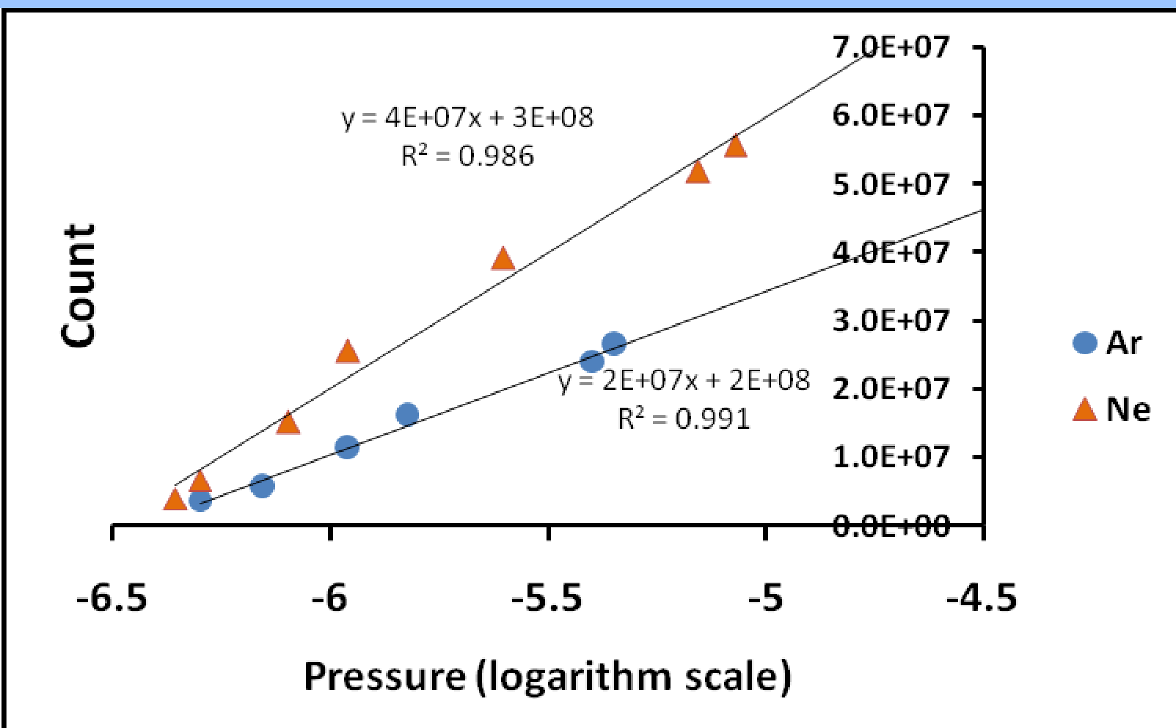
Argon

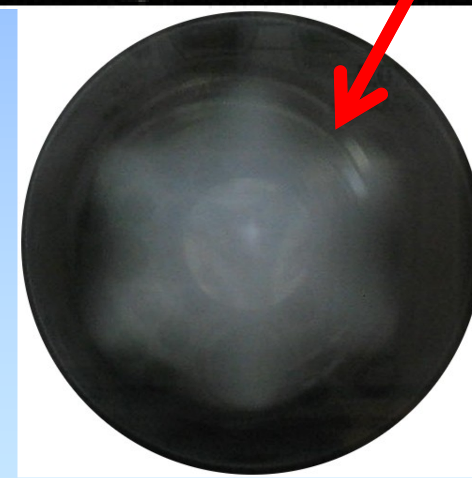


Gas dosing rate

Neon(mbar) 8,5E-6 7,0E-6 2,5E-6 1,1E-6 8,0E-7 5,0E-7 4,4E-7







Residual gas plasma (valves closed).

15 sec exp. time

YouTube, ANL ECRIS movie, 8 min.
More than 3000 visitors since 2007!

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Cold and warm electrons study

(some results submitted to Plasma Sources Science and Technology)

ECR plasma electron components: 3 **artificial** populations

cold electrons: 1-200 eV

Comparison:

Visible-light photo

AND

Simulation

warm electrons: several keV

Comparison:

X-ray photo

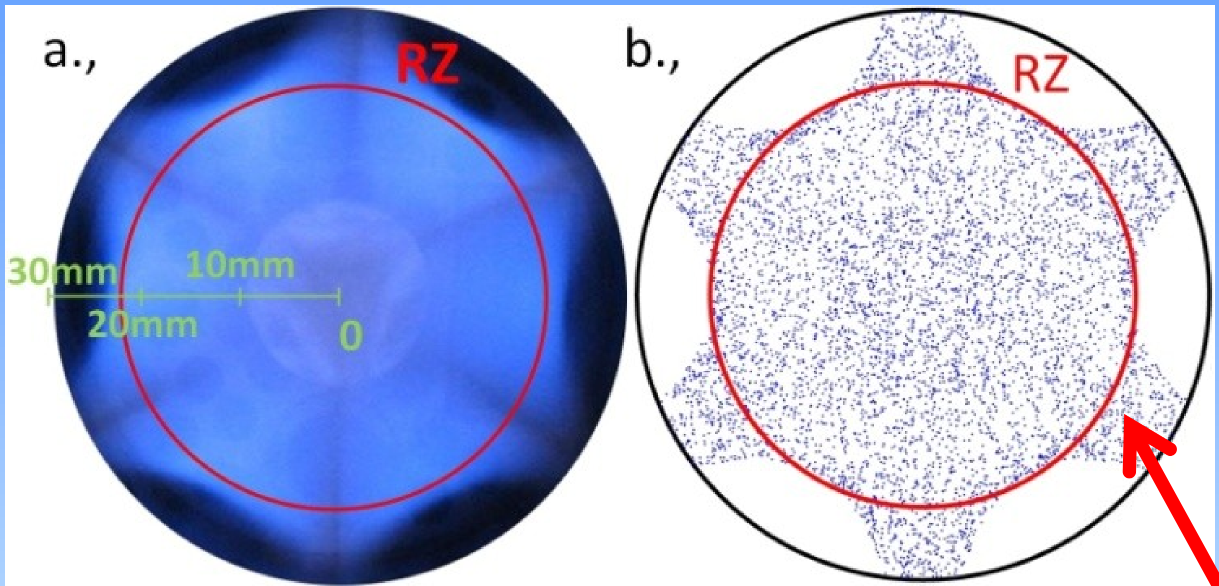
AND

Simulation

hot electrons: hundreds of keVs

(do not deal here)

Comparison: VL-photo and electron simulation



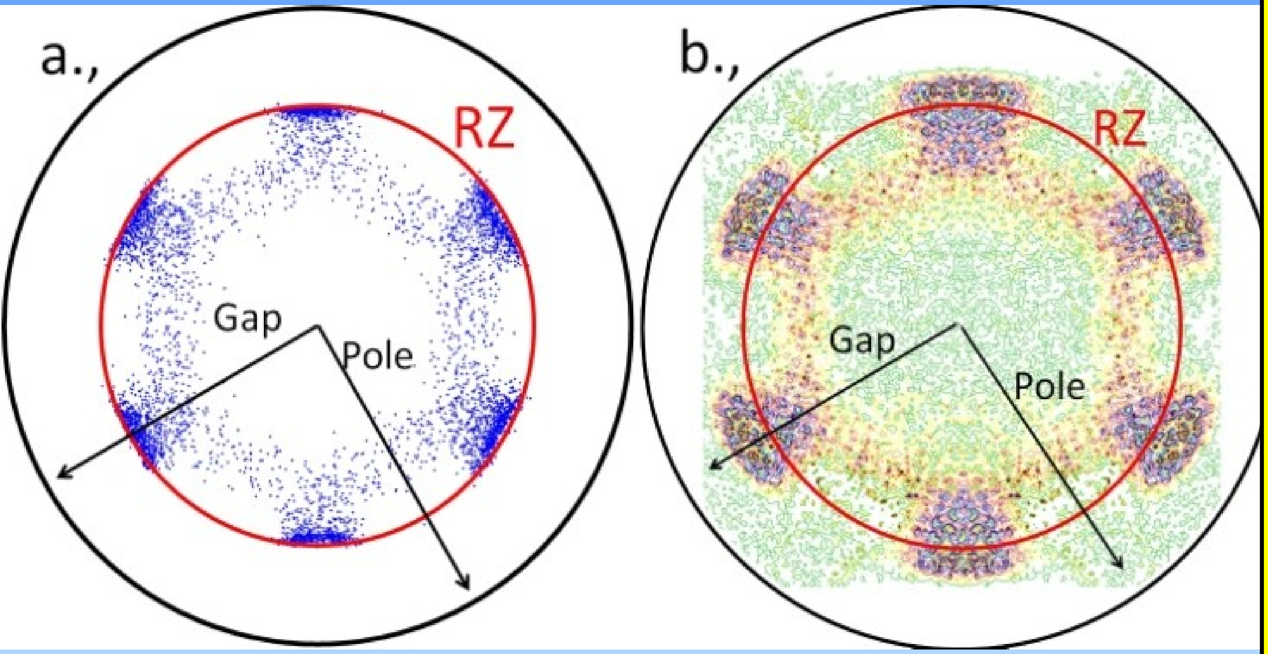
Typical argon plasma. Photons from excited atoms and ions. 14 GHz, 50 W

TrapCAD simulation, 14 GHz, electrons

- $5*10^5$ starting particle
- start from resonance zone
- start energy: 1-100 eV
- random direction
- ECR heating ON
- Calculation time: enough statistics for lost and non-lost electrons
- filtered energy: 1-200 eV
- 5000 electrons left

- Good agreement between the photons and electrons.
- Cold electrons are not so well bounded: the plasma is not empty.
- In contrast to high energy electrons, cold electrons are very effective in exciting visible light.
- VL-photographs show the plasma region with cold electrons confined almost equally inside the RZ.

Comparison: electron simulation and X-ray-photo

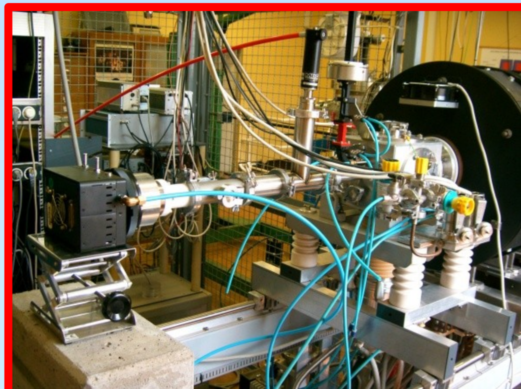


- Good agreement between simulation and XR-photo.
- Warm electrons are trapped at magnetic **gap**.
- Argon ions locate at the **same** positions.
- Strong azimuthal and radial inhomogenity.

TrapCAD simulation, 14 GHz, warm electrons. The same output file was used as for cold electrons. Filtering here: 3-10 keV

X-ray photo, argon Kα radiation (cca 3 keV) *14 GHz, 50 W*

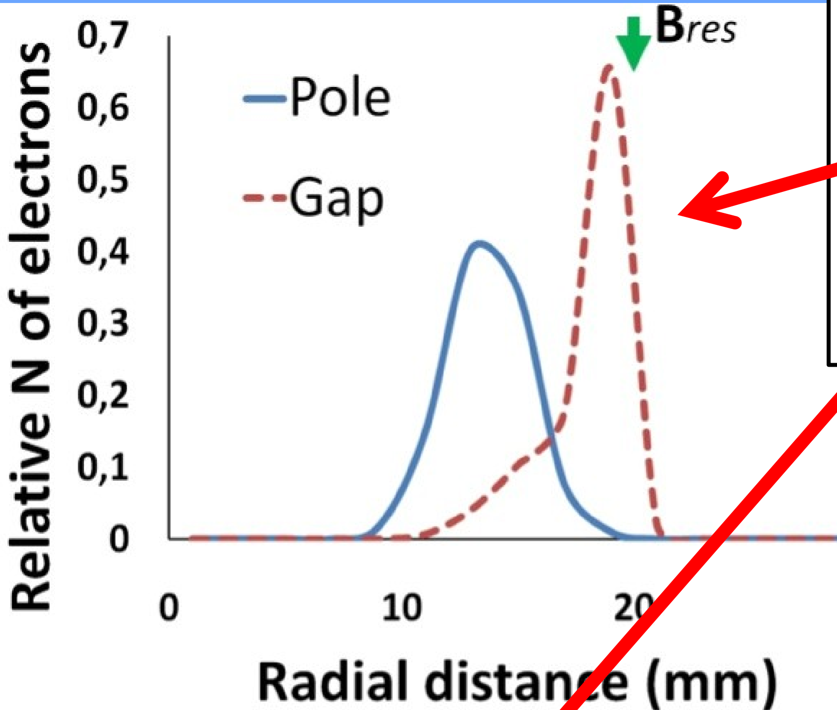
S. Biri, ECRIS2010, Grenoble

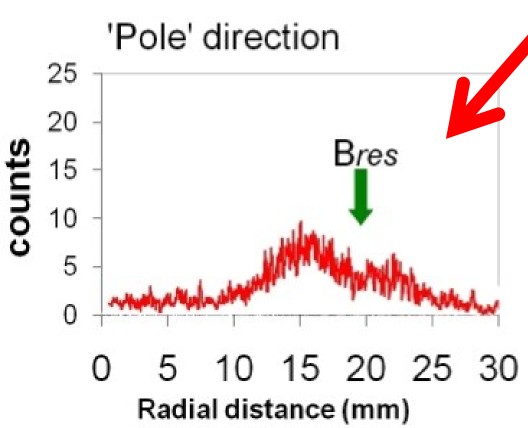


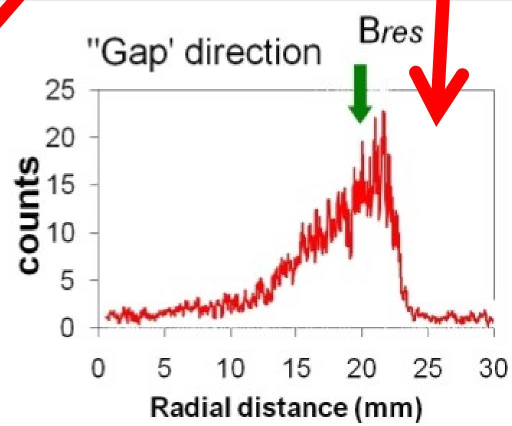
Comparison of density profiles

Particle density profiles from the center toward the magnetic pole and gap.
Simulation: 3-10 keV warm electrons

Measurement: 3 keV X-ray photons from argon ions







- Calculation and photo clearly show strong azimuthal and radial **inhomogenity** of the plasma.
- The **central plasma density** is much lower for the case of ions and warm electrons than for cold electrons and VL-photons.
- This information is very important for future ion source designers (extraction optical system).

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The color of the ECR plasmas

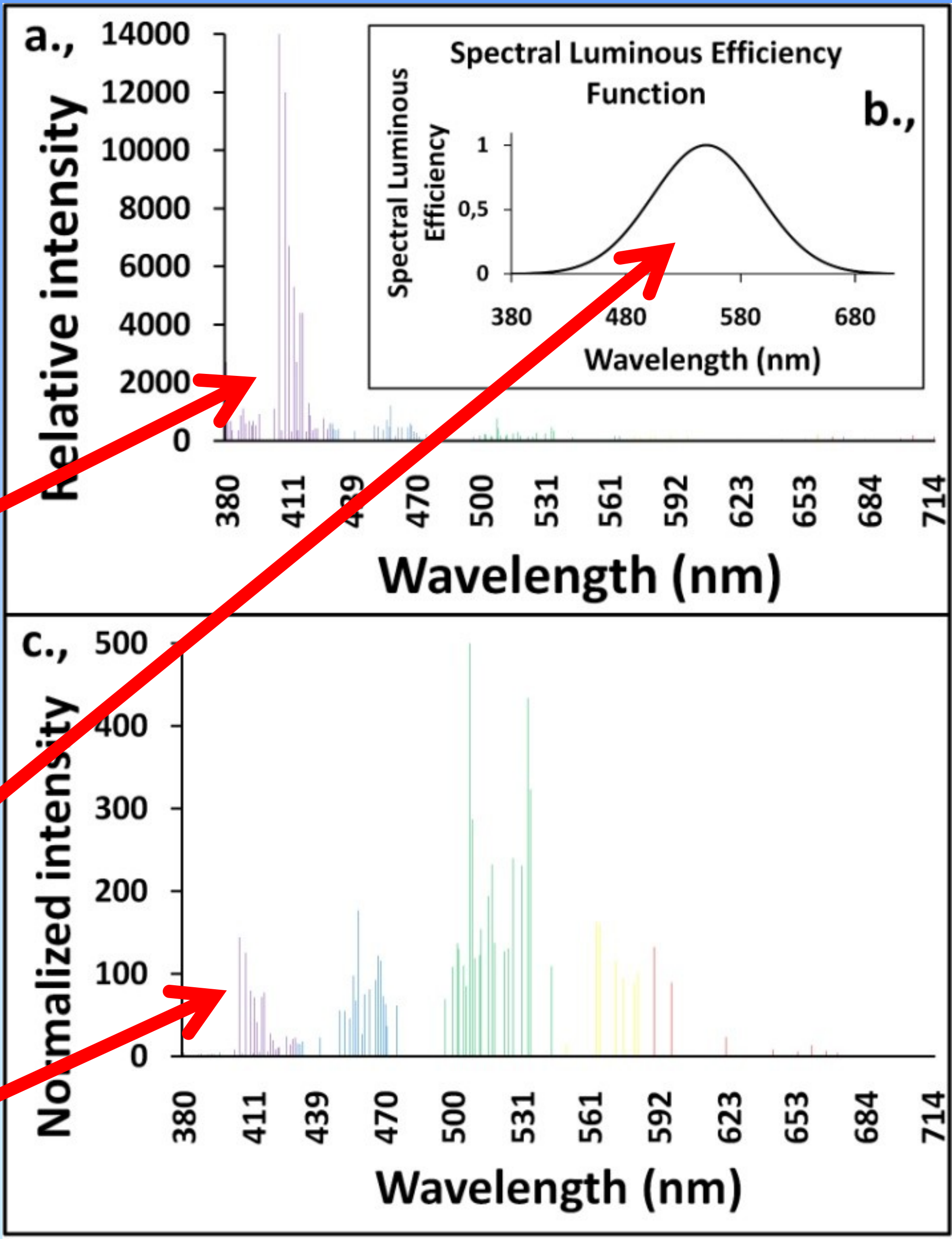
It is a challenging task to understand the color of different ECR gas plasmas.

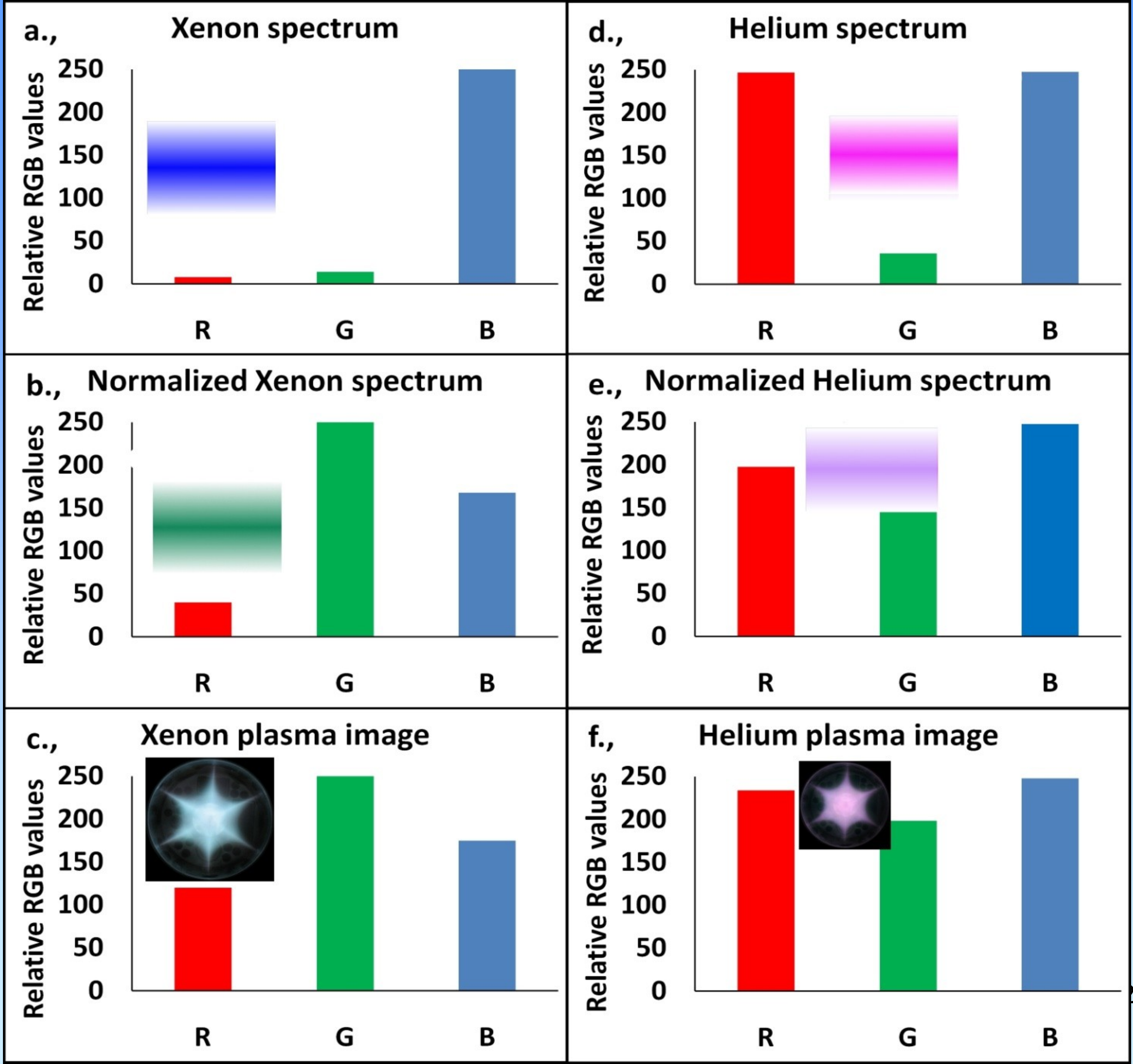
The color of the plasma can be determined by visible light electron transitions of plasma components (atoms and ions).

Examples: Xe spectrum (CRC Handbook of Chemistry and Physics 2009). Electromagnetic radiation in the VL-range from 360 nm (violet) to 820 nm (red)

Human eye peak sensitivity: the spectral luminous efficiency function (SLEF) peaks at 555 nm (green)

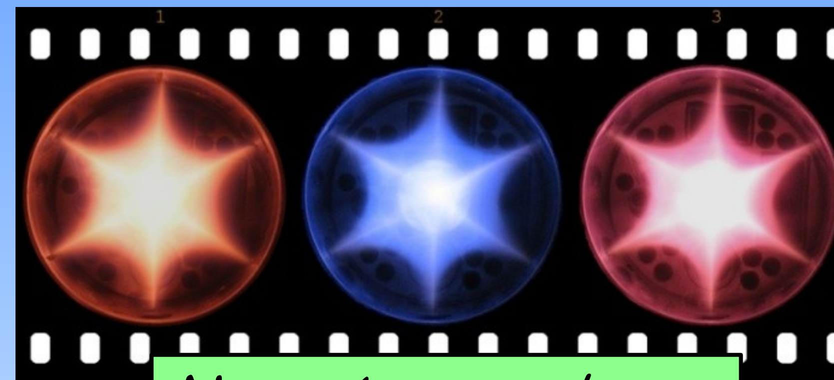
Xenon spectrum normalized with SLEF.



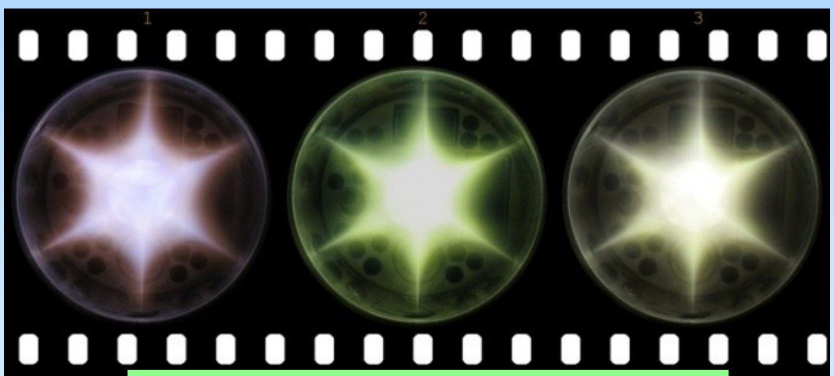

a.,
Xenon spectrum
d.,
Helium spectrum
b.,
Normalized Xenon spectrum
e.,
Normalized Helium spectrum
c.,
Xenon plasma image
f.,
Helium plasma image
Relative RGB values
0
50
100
150
200
250
R
G
B

- There is a good visual agreement between the calculated normalised color and the real color of the plasmas.
- Also there is good agreement between the RGB values of the decomposed normalized spectrum lines and of the photos.
- Thus this process is able to explain and understand the color of ECR plasmas.

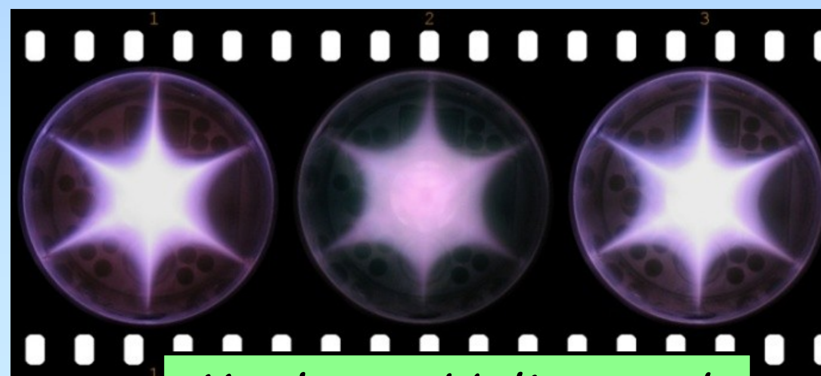
Krypton, Xenon and mixed (50%) plasmas.



Neon, Argon and mixed (50%) plasmas.



Nitrogen, Oxygen and mixed (50%) plasmas.



Methane, Helium and mixed (50%) plasmas.

Conclusion

- Visible light (VL) photos transform information mainly on the cold electron component of the plasma. Cold electrons are confined in the central plasma part.

- X-ray (XR) photos show the spatial distribution of ions. These ions and the warm electrons are well confined by the magnetic field lines structure showing strong asymuthal and radial inhomogenity.

- The color of the ECR plasmas can be explained and understood by the atomic transitions combined with human eye sensitivity.

- We are convinced that VL and XR photos hide many more interesting and valuable information on the ECR plasma…

Thank you for your attention!