XXIV International Workshop on ECR Ion Sources
September 28th - 30th, 2020

High resolution X-ray Imaging as a powerful diagnostics tool to investigate ECRIS plasma structure and confinement dynamics

Istituto Nazionale di Fisica Nucleare
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Outline

- **Motivations and Physical Background**
- **Experimental Setup**
- **Data Analysis: Integrated X-ray Imaging**
- **Analytical Methods**
- **Data Analysis: Spatially and Spectrally-Resolved Imaging and Spectroscopy**
- **Conclusion**

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Goal: to investigate ECRIS plasma structure and confinement dynamics in stable and turbulent regimes

Motivation: in ECR ion sources turbulent regimes of plasmas cause performance deterioration in the extracted ion beam, in terms of:

- Beam ripple
- Decrease of high charge state production
- Decrease of beam intensity

IOP Publishing — Plasma Sources Science and Technology
Plasma Sources Sci. Technol. 18 (2009) 045016 (10pp) — doi:10.1088/0963-0252/18/4/045016

Considerations on the role of the magnetic field gradient in ECR ion sources and build-up of hot electron component

S Gammino[1], D Mascali[1,2], L Celona[1], F Maimone[1] and G Ciavola[1]
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[2] Dipartimento di Fisica e Astronomia, Università di Catania, via S. Sofia 64, 95123 Catania, Italy

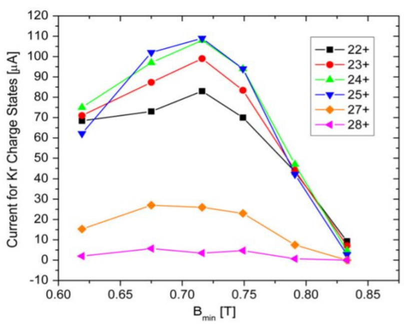
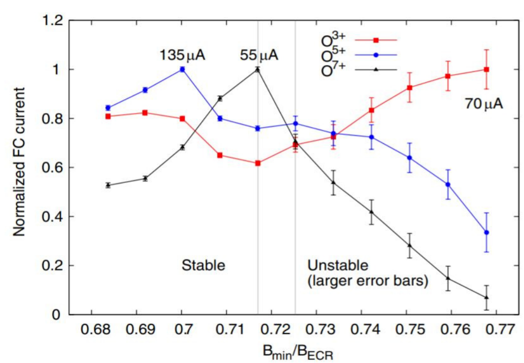


Figure 1. Trend of the Kr charge states with respect to the B_{min} field ($P_{RF} = 3000$ W, $B_{ext} = 2.16$ T, $B_{inj} = 3.34$ T, $B_{hex} = 2$ T).

IOP Publishing — Plasma Sources Science and Technology
Plasma Sources Sci. Technol. 23 (2014) 025020 (8pp) — doi:10.1088/0963-0252/23/2/025020

Beam current oscillations driven by cyclotron instabilities in a minimum-*B* electron cyclotron resonance ion source plasma

O Tarvainen[1], I Izotov[2], D Mansfeld[2], V Skalyga[2,3], S Golubev[2,3], T Kalvas[1], H Koivisto[1], J Komppula[1], R Kronholm[1], J Laulainen[1] and V Toivanen[4]



the instability threshold depends on $\frac{B_{min}}{B_{ECR}}$

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Method: high resolution SPATIALLY and SPECTRALLY RESOLVED diagnostic tool

- In 2014 X-ray space resolved-spectroscopy was performed but only in low power regimes: up to 30 W of RF pumping power

R. Racz et al. Plasma Sources Science and Technology, Vol. 26, No. 7

*D. Mascali et al., Review of Scientific Instruments **87**, 02A510 (2016)*

NOW → 3 important novelties

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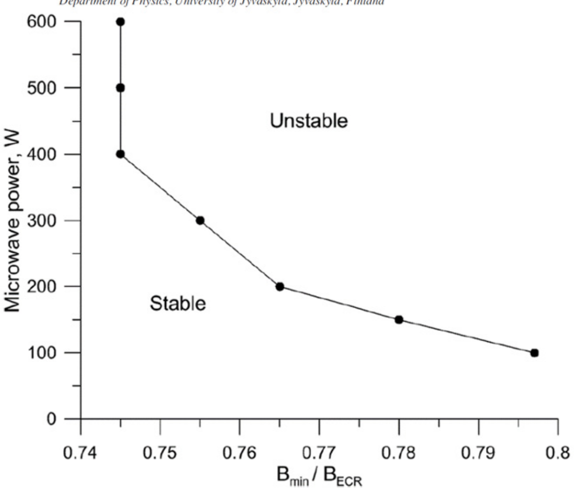
PHYSICS OF PLASMAS **22**, 083509 (2015)

Suppression of cyclotron instability in Electron Cyclotron Resonance ion sources by two-frequency heating

V. Skalyga,[1,2] I. Izotov,[1] T. Kalvas,[3] H. Koivisto,[3] J. Komppula,[3] R. Kronholm,[3] J. Laulainen,[3] D. Mansfeld,[1] and O. Tarvainen[3]

[1]*Institute of Applied Physics of Russian Academy of Sciences, 46 Ulyanova st., Nizhny Novgorod, Russia*
[2]*Lobachevsky State University of Nizhny Novgorod (UNN), 23 Gagarina st., Nizhny Novgorod, Russia*
[3]*Department of Physics, University of Jyväskylä, Jyväskylä, Finland*



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It is NOT ENOUGH to probe UNSTABLE PLASMA REGIMES!

1) → Re-design the whole pin-hole system TO PERFORM high resolution X-ray imaging at HIGH POWER REGIMES: up to 200 W!

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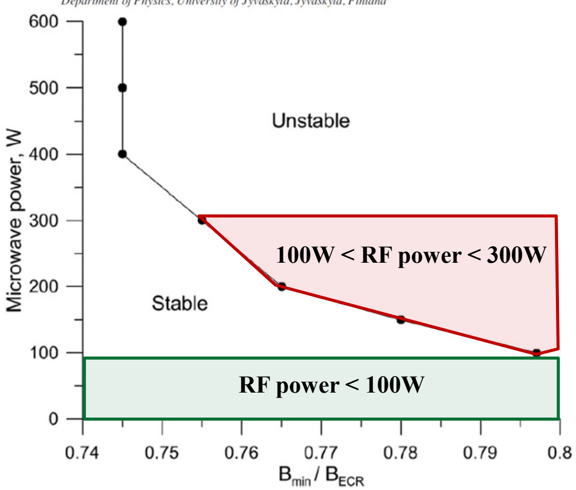

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R. Racz et al. Plasma Sources Science and Technology, Vol. 26, No. 7

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PHYSICS OF PLASMAS **24**, 032111 (2017)

Kinetic instabilities in a mirror-confined plasma sustained by high-power microwave radiation

A. G. Shalashov,[a] M. E. Viktorov, D. A. Mansfeld, and S. V. Golubev

Institute of Applied Physics of the Russian Academy of Sciences, 46 Ulyanov Str., 603950 Nizhny Novgorod, Russia

Simultaneously to the plasma emission in the 2–20 GHz frequency band, we measure precipitations of energetic electrons (>10 keV) from the trap ends using a pin-diode detector with a time resolution of about 1 ns.

Measurement of the energy distribution of electrons escaping minimum-B ECR plasmas

I.Izotov[1], O.Tarvainen[2], V. Skalyga[1], D. Mansfeld[1], T. Kalvas[2], H. Koivisto[2], R. Kronholm[2]

1 Institute of applied physics of Russian academy of sciences, Nizhny Novgorod, Rus

2 University of Jyvaskyla, Finland

was discovered that the EED in the range of 5 - 250 keV is strongly non-Maxwellian and exhibits several local maxima below 20 keV energy. It was observed that the most influential ion source operating parameter on the EED is the magnetic field strength, which affected the EED predominantly at energies less than 100 keV. The effects of the microwave power and frequency, ranging from 100 to 600 W and 11 to 14 GHz respectively, on the EED were found to be less significant. The presented technique and

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R. Racz et al. Plasma Sources Science and Technology, Vol. 26, No. 7

*D. Mascali et al., Review of Scientific Instruments **87**, 02A510 (2016)*

NOW → 3 important novelties

It is very useful to investigate about losses dynamics

2) → New design of the plasma chamber

3) → Advanced analytical method to get info about where the electrons collide on the chamber walls

Outline

- **Motivations and Physical Background**
  → Probing ECRIS plasma structure and confinement dynamics
- **Experimental Setup**
  - X-ray pin-hole CCD camera
  - → Innovative multi-disks collimator (high power domain ~ 200W)
  - → Innovative design of plasma chamber (to investigate losses dynamics)
- **Data Analysis: Integrated X-ray Imaging**
- **Analytical Methods**
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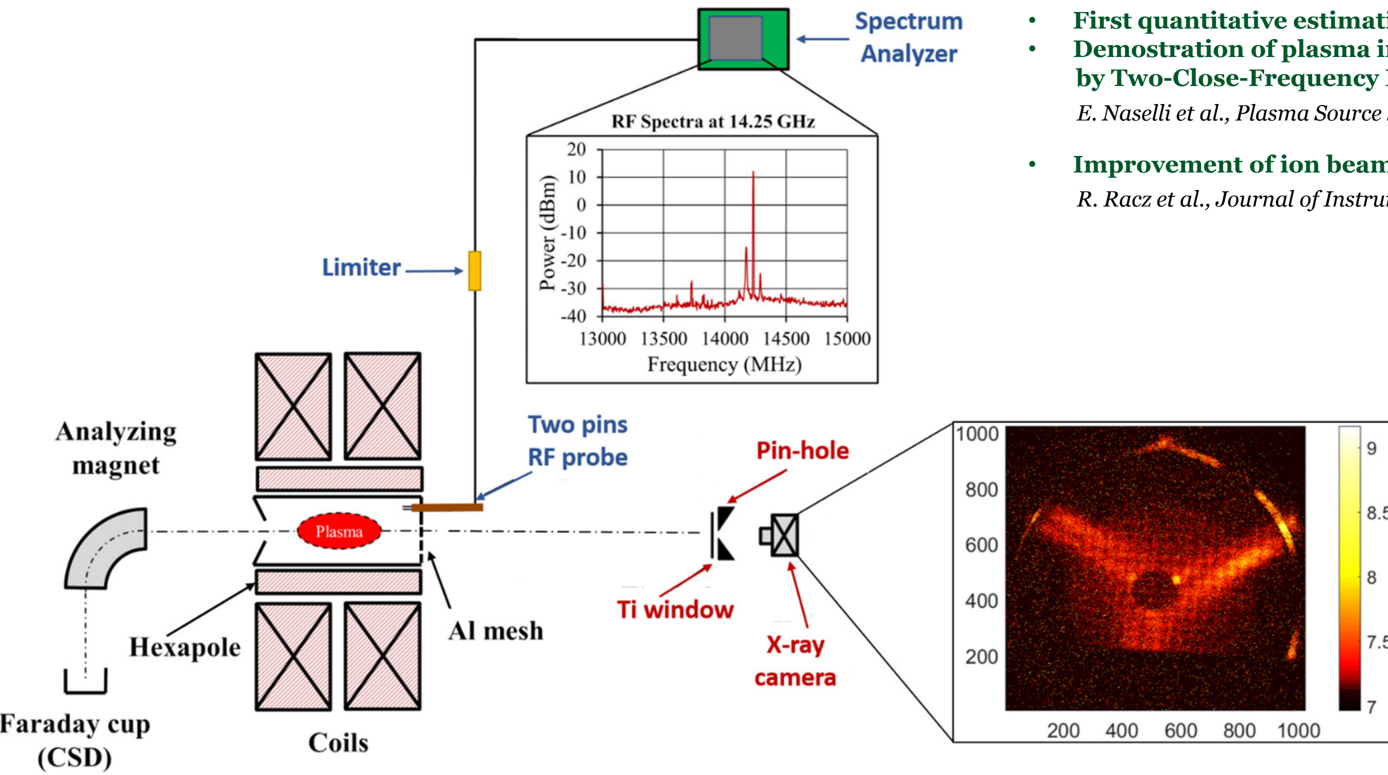
Experimental Setup – the Multi-diagnostic system

Plasma investigation in stable and unstable regimes has been already performed by means multi-diagnostic system:



A flashback to ECRIS-2018, Catania, Italy

- **First quantitative estimation of plasma instability strength**
- **Demostration of plasma instability damping by Two-Close-Frequency Heating (TCFH)**

  E. Naselli et al., Plasma Source Science and Technology (PSST), 2019

- **Improvement of ion beam performances by TCFH**

  R. Racz et al., Journal of Instrumentation (JINST), 2019

- **Effect of the TCFH in ECRIS plasmas by X-ray Imaging investigation**

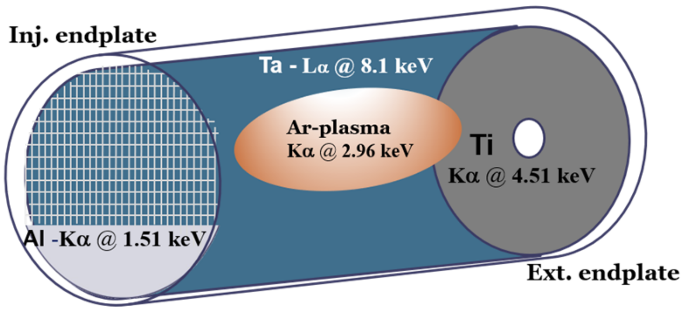
  Richard Racz, Talk ECRIS 2020, 28th September

  "Imaging in X-ray ranges to locally investigate the effect of the Two-Close-Frequency Heating in ECRIS plasmas"

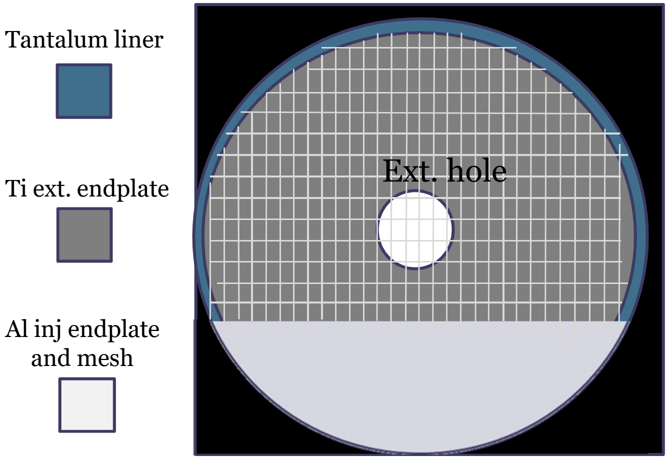
- **ECRIS plasma structure and confinement dynamics investigation**

  Eugenia Naselli, Talk ECRIS 2020, 28th September

Advanced design of the plasma chamber walls oriented to spatially-resolved X-ray spectroscopy



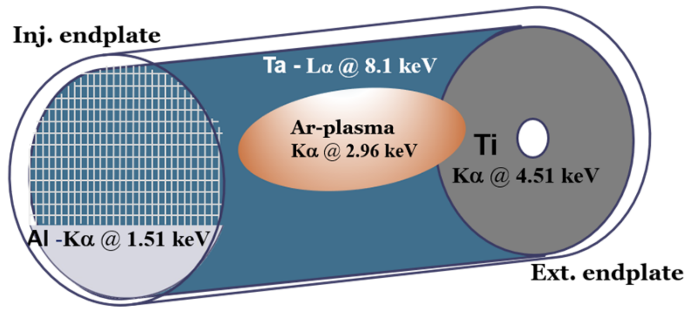
Perspective front-view of the plasma chamber in the FULL-FIELD X-ray pin-hole camera setup



Fluorescence lines can be used to get info about where the electrons collide on the chamber walls

in order to have well separated component of the emitted X-ray:
→ Special design of plasma chamber for studying confinement dynamics
(plasma vs. losses X-radiation emission)

Advanced design of the plasma chamber walls oriented to spatially-resolved X-ray spectroscopy



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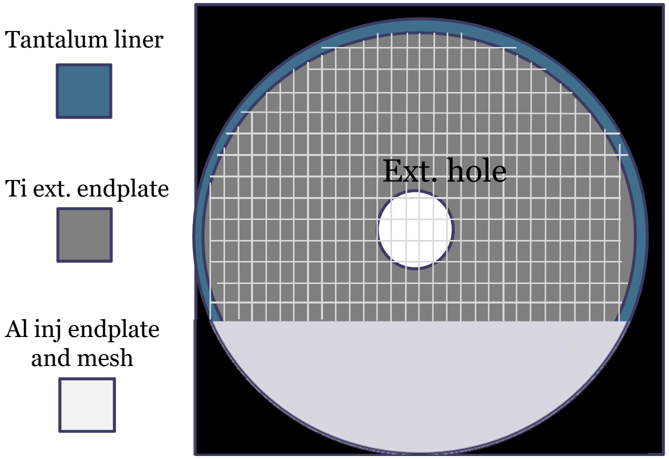

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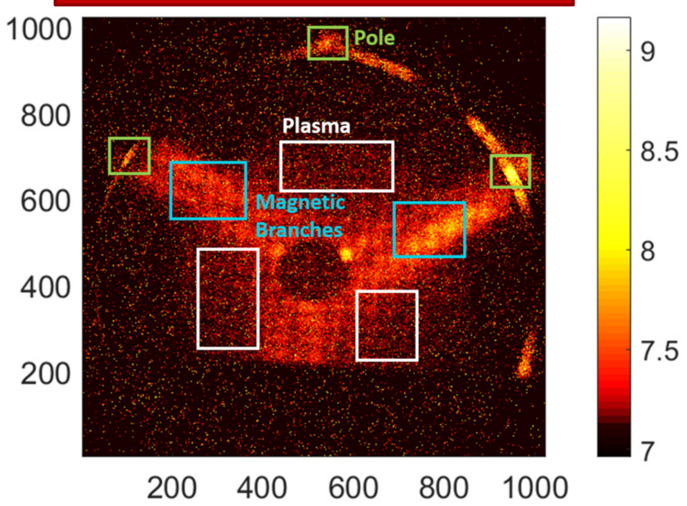
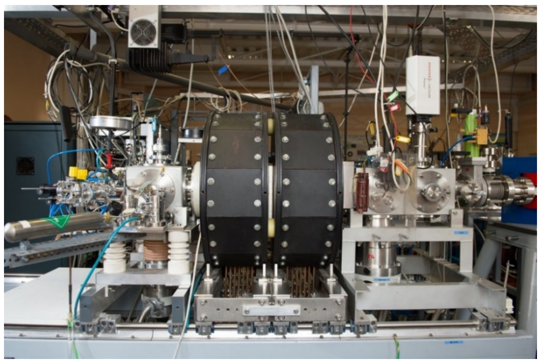
in order to have well separated component of the emitted X-ray:
→ Special design of plasma chamber for studying confinement dynamics
(plasma vs. losses X-radiation emission)

- X-rays coming from **Plasma** are mostly due to ionized **Ka Argon lines**
- X-rays coming from **Magnetic Branches** consist of mostly **fluorescence from Ti**
- X-rays coming from **Poles** are mostly due to radial losses impinging on the **Ta liner**

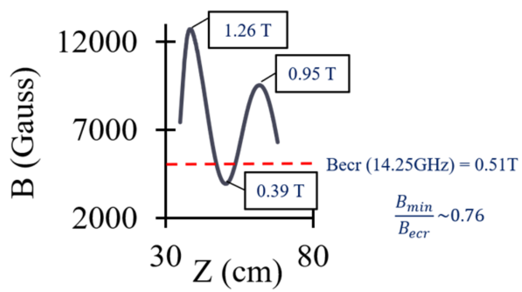
Whole Image with Exp time: 50 sec



ECRIS Atomki Laboratory (Debrecen, Hungary)

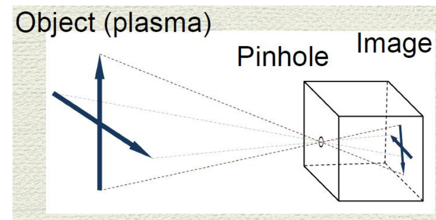


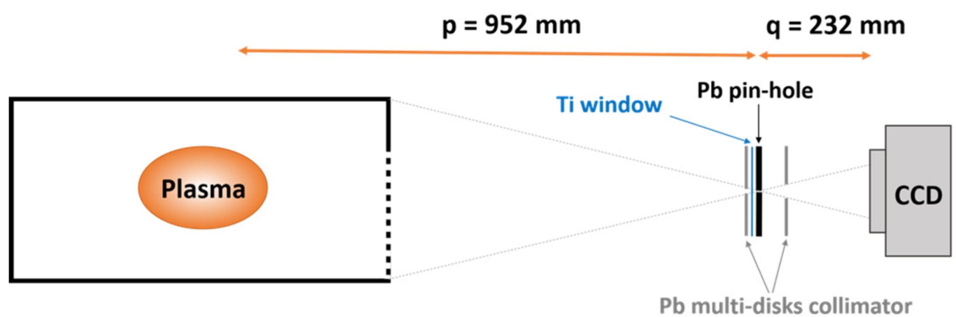
- B-min magnetic field



- 14.25 GHz ECRIS
- Permanent magnet hexapole and room temperate coils
- No post acceleration
- Used for atomic physics, material science, ECR plasma physics

Soft X-ray pin-hole camera tool



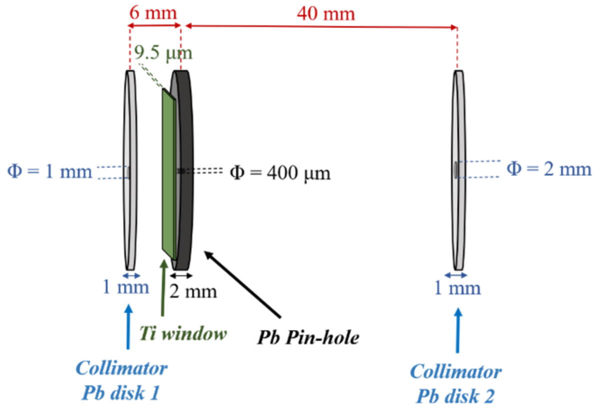


- Sensitivity range ~ 2 ÷ 15 keV
- Sensor Size: 13.3 mm x 13.3 mm (1024 x 1024 Pixels)
- Max Energy Resolution ~ 150 eV
- Lead Pin-hole (diameters 400 μm)

A single pin-hole is not enough for measuring at high power domain: → noise due to scattering becomes very high!

X ray imaging: performance improvement for high RF power

A multi-disks collimator has been designed on purpose in order to perform high resolution X-ray imaging at high energy (until 200 W)



By means the use of the multi-disks collimator it is possible:

- Reduce the noise
- Improve the signal/noise ratio
- Increase the resolution

Referring the power level to the plasma chamber volume in order to get the power density:

ATOMKI:

plasma chamber volume = 555 cm^3, @ 200 W → corresponding to a power density of 0.36 W/cm^3.

SECRAL source at IMP-Lanzhou (China):

plasma chamber volume ~ 5200 cm^3 → our power corresponds to a level of power in the order of 2 kW.

L. Sun et al., 23th Int. Workshop on ECR Ion Sources ECRIS2018, Catania, Italy JACoW doi:10.18429/JACoW-ECRIS2018-TUA5

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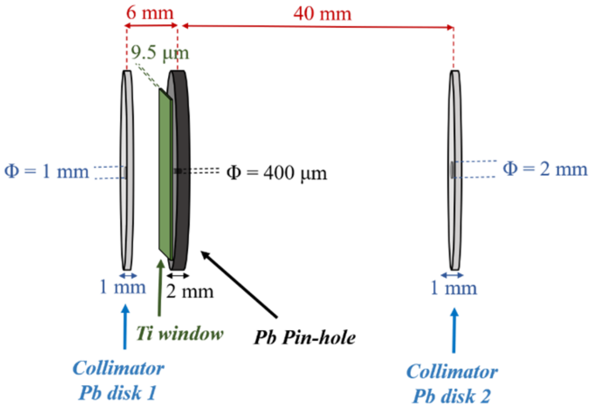

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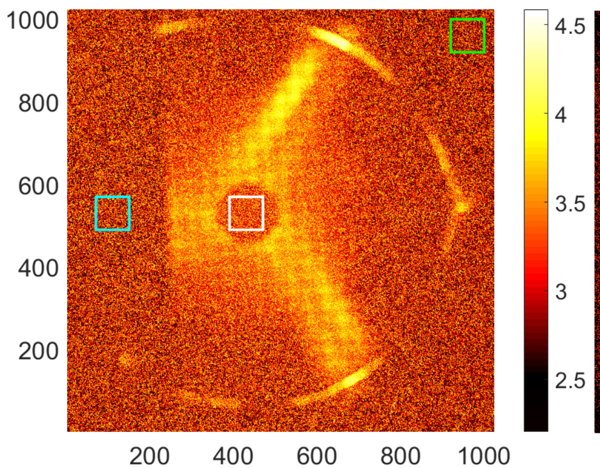
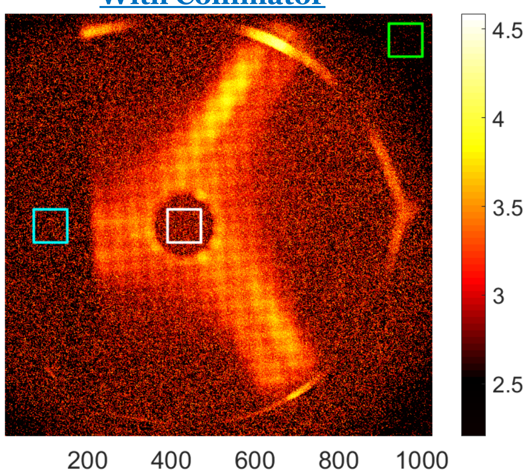
- ❑ Increase the resolution

RF frequency: 13.9 GHz
RF power: 200 W

Without Collimator



With Collimator



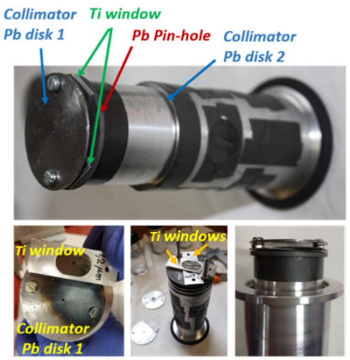
	With Collimator	Without Collimator	Discrepancy Percentage
N_{hole}	2889 ± 54	4441 ± 67	- 54 %
$N_{bkg_{out}}$	332 ± 18	1677 ± 41	- 405 %
$N_{bkg_{in}}$	847 ± 29	2136 ± 46	- 152 %
$\frac{N_{hole}}{N_{bkg_{out}}}$	8.70 ± 0.50	2.65 ± 0.08	+ 70 %
$\frac{N_{hole}}{N_{bkg_{in}}}$	3.41 ± 0.13	2.08 ± 0.05	+ 39 %

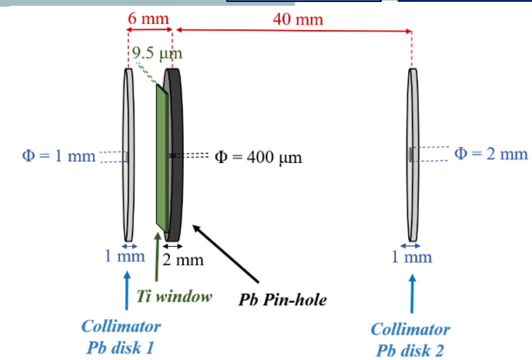
X ray imaging: performance improvement for high RF power

A multi-disks collimator has been designed on purpose in order to perform high resolution X-ray imaging at high energy (until 200 W)

By means the use of the multi-disks collimator it is possible:

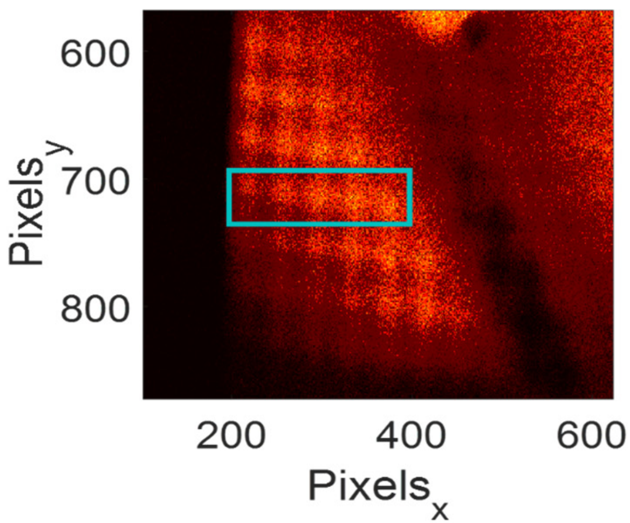
- ❑ **Reduce the noise**
- ❑ **Improve the signal/noise ratio**
- ❑ **Increase the resolution**

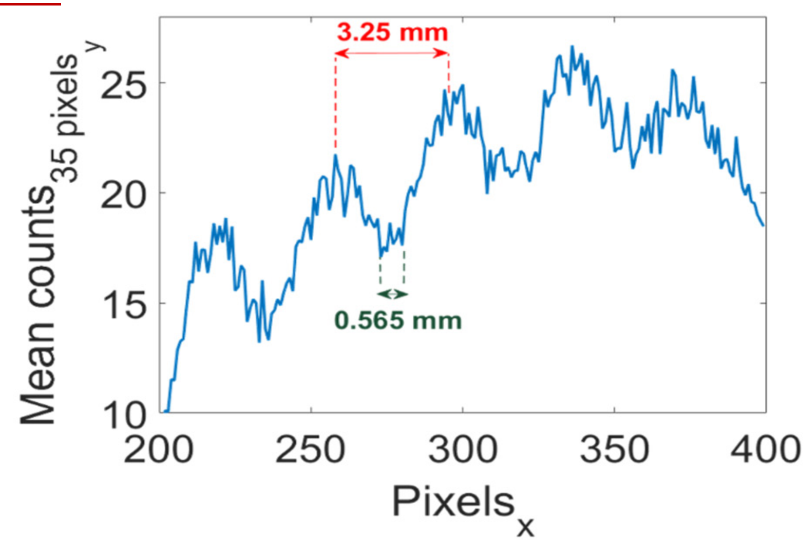




Al injection plate
wire diameter: 0.4 mm
transparency: ~ 65%

Very high spatial resolution → Al mesh with wire diameter ~ 0.4 mm





Data Analysis

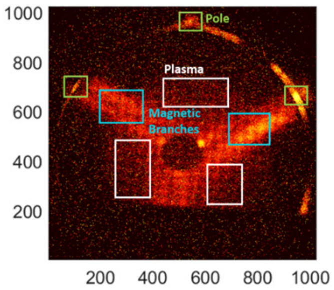
Integrated X-ray Imaging

VERY FAST RESPONSE and «Easy» Analysis for "Live" investigations

Photon Counted X-ray Imaging

SLOW RESPONSE and «Advanced» Analysis for quantitative and POWERFUL (local energy determination) investigations

Whole Image with Exp time: 50 sec



Data Analysis

Integrated X-ray Imaging

- acquiring **1 only image**
- single frame exposure time ~ **tens of seconds**
- Total measurement time ~ **tens of seconds**

  → **VERY FAST MEASURE**

- **Simple analysis**
- "**Live**" plasma structure and emission investigations (vs. ECRIS operative parameters)

Photon Counted X-ray Imaging

- acquiring **thousand of image-frames ~ 5000**
- single frame exposure time ~ **50-500 milliseconds**
- Total measurement time: **~ 4 hours**

  → **SLOW MEASURE**

- **Advanced Analysis**
- Simultaneously **SPATIALLY** and **SPECTRALLY RESOLVED IMAGING** and **SPECTROSCOPY**

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  - → Innovative design of plasma chamber (for spectrally and spatially resolved analysis)
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  - "Live" plasma structure and emission investigations
  - Plasma shape investigation: RF power and magnetic field scalings
  - Plasma diameter evaluation
- **Analytical Methods**
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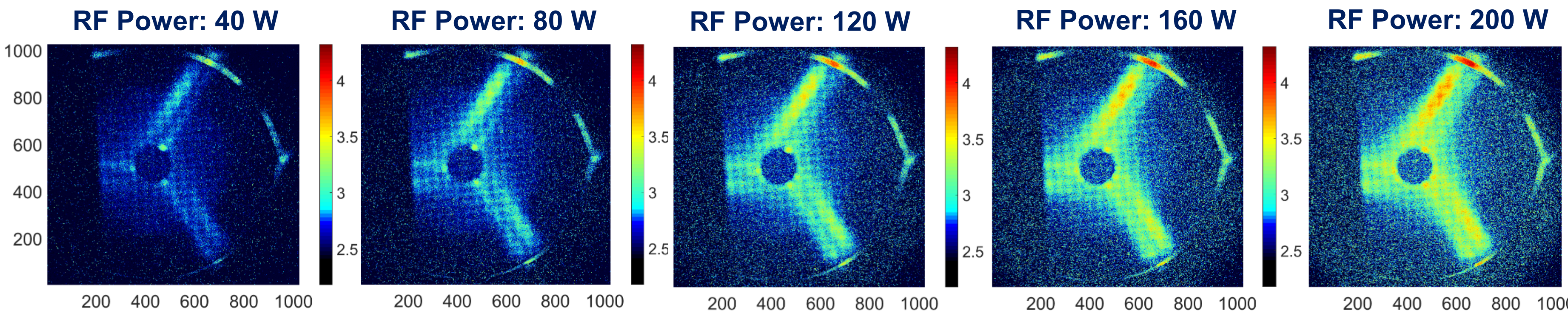
- **Conclusion**

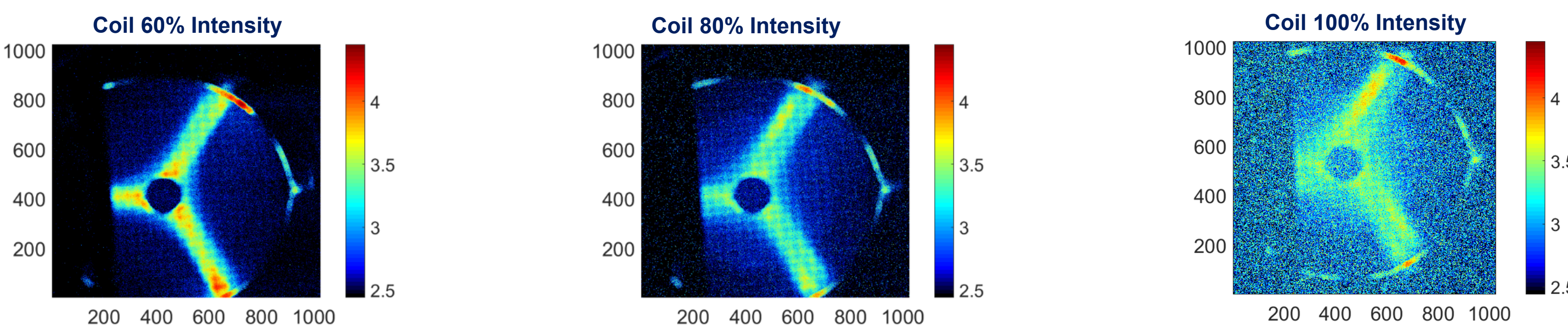
X-ray images at different operative configurations

X-ray Imaging vs. RF pumping power

RF frequency: 13.9 GHz

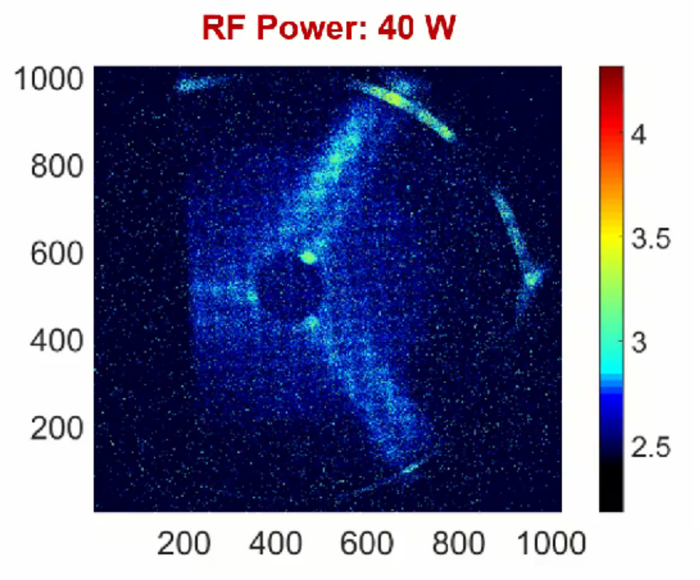


X-ray Imaging vs. magnetic field profile

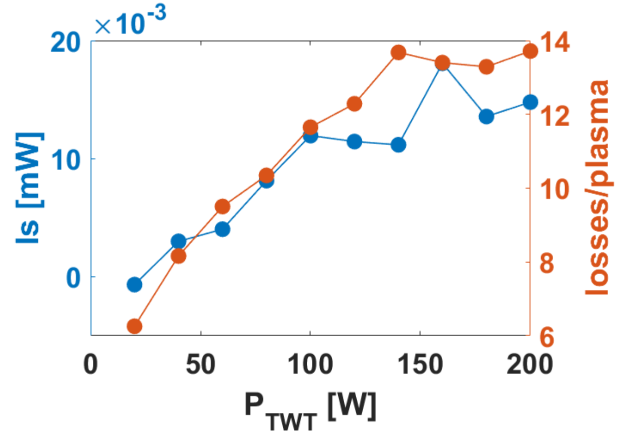


X-ray Imaging vs. RF pumping power

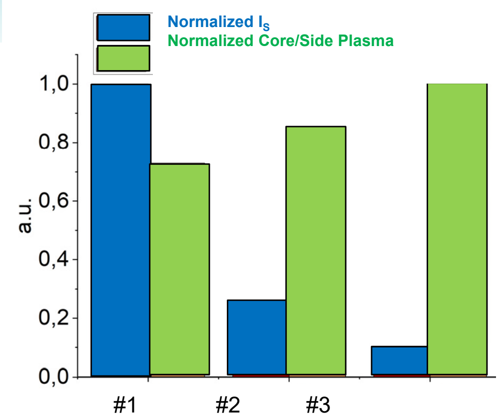
E. Naselli et al., Plasma Source Science and Technology (PSST), 2019



Losses vs. Plasma

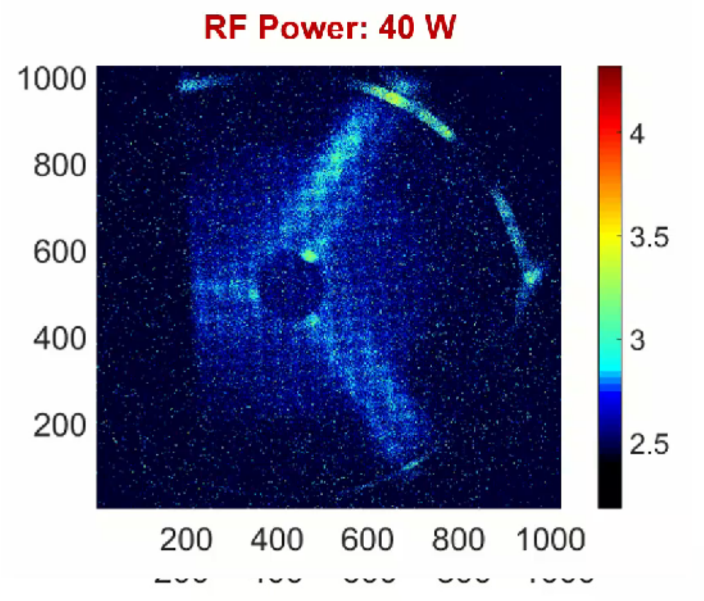


Plasma$_{Core}$ vs. Plasma$_{Side}$



"Live" plasma structure and emission investigations

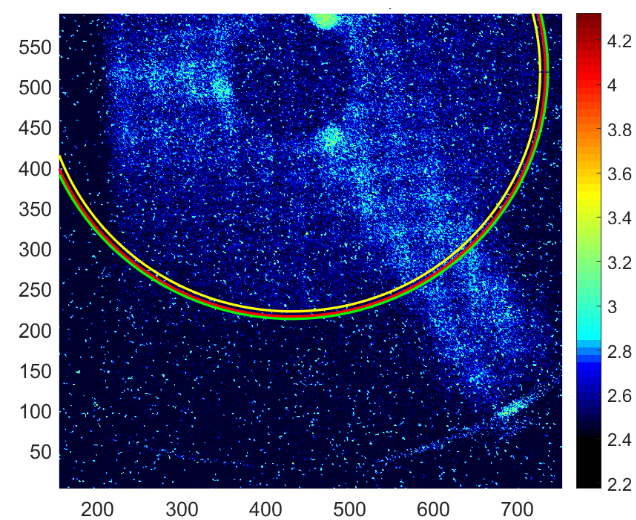
X-ray Imaging vs. RF pumping power



"Live" plasma diameter measurement

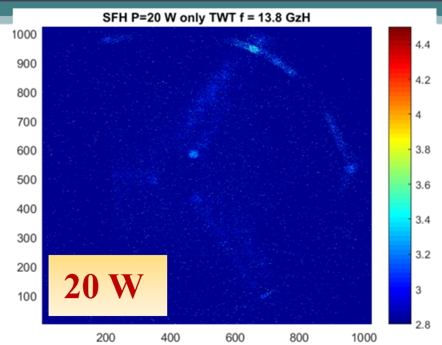
Plasma Radius = 16.04 ± 1.44 mm

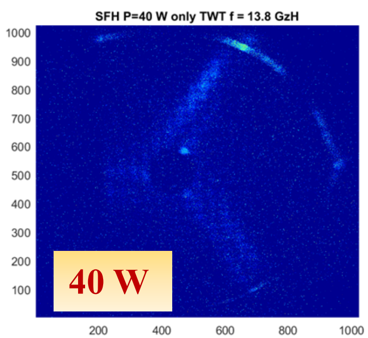
Using the realistic magnetic field of the Atomki-ECRIS, the radius of the ECR-ellipsoid is **15.5 mm**

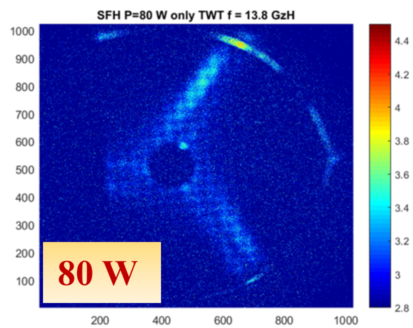


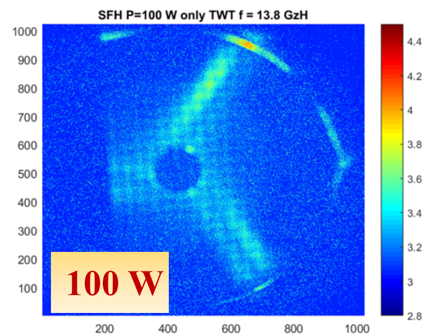
X-ray Imaging: RF power scalings

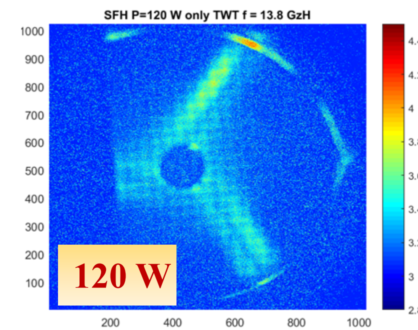
**X-ray Imaging vs. RF pumping power (20W – 200W)
@ RF frequency: 13.8 GHz**

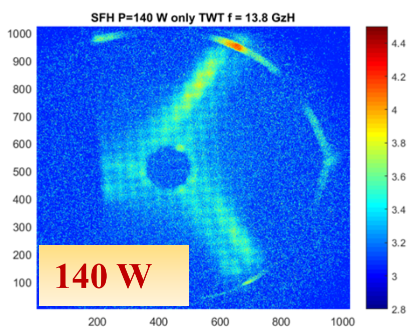


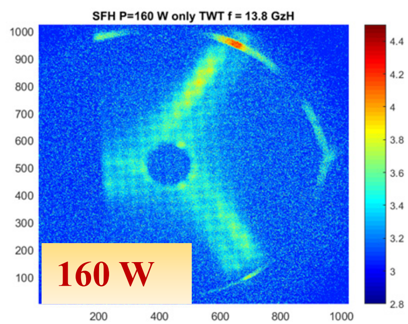


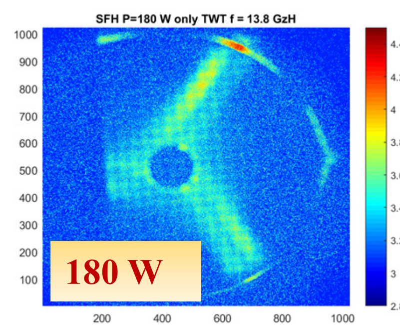


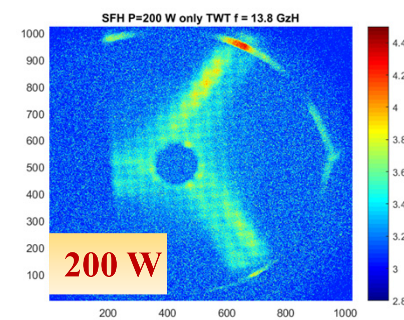




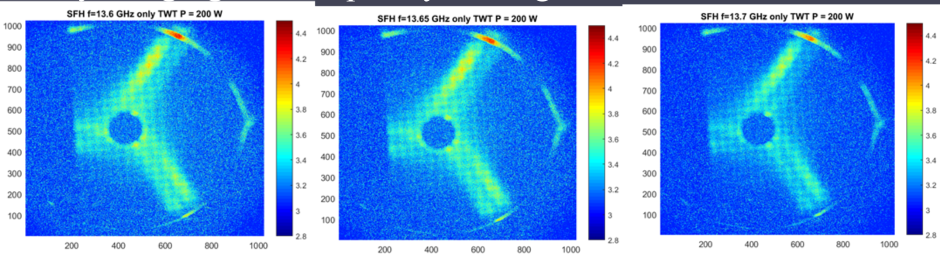




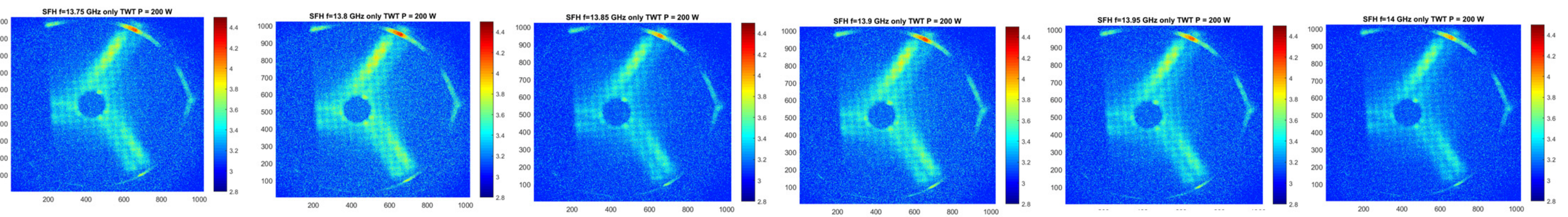


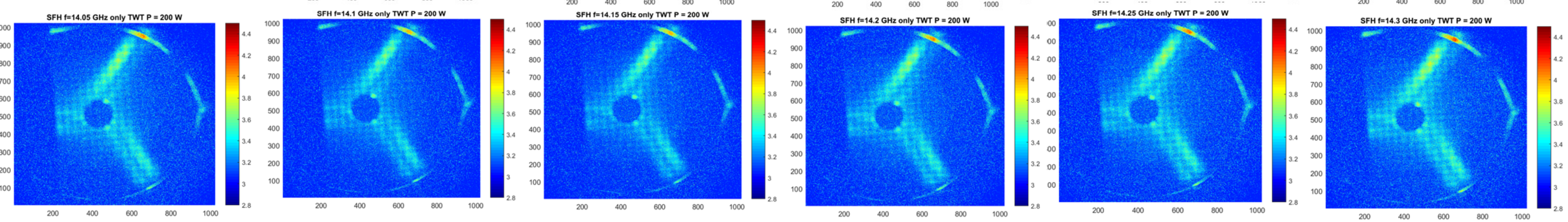


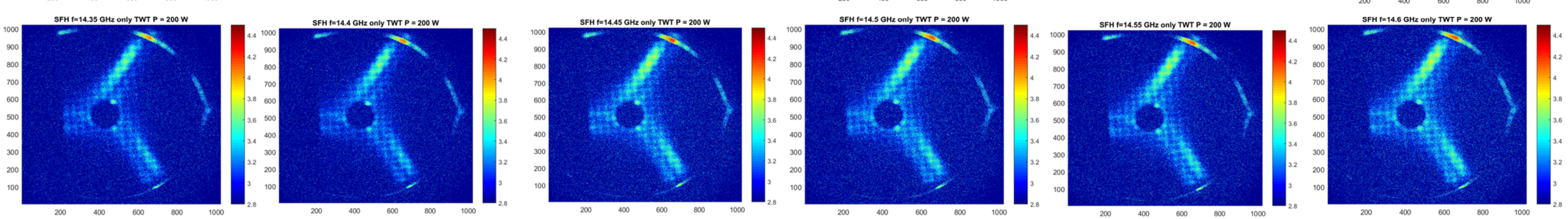
X-ray Imaging: RF frequency scalings



X-ray Imaging vs. RF frequency (13.6 GHz – 14.6GHz) @ RF power: 200W







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Data Analysis

Integrated X-ray Imaging

CCD: Sensitive position detector
→ investigate the intensity

Photon Counting X-ray Imaging

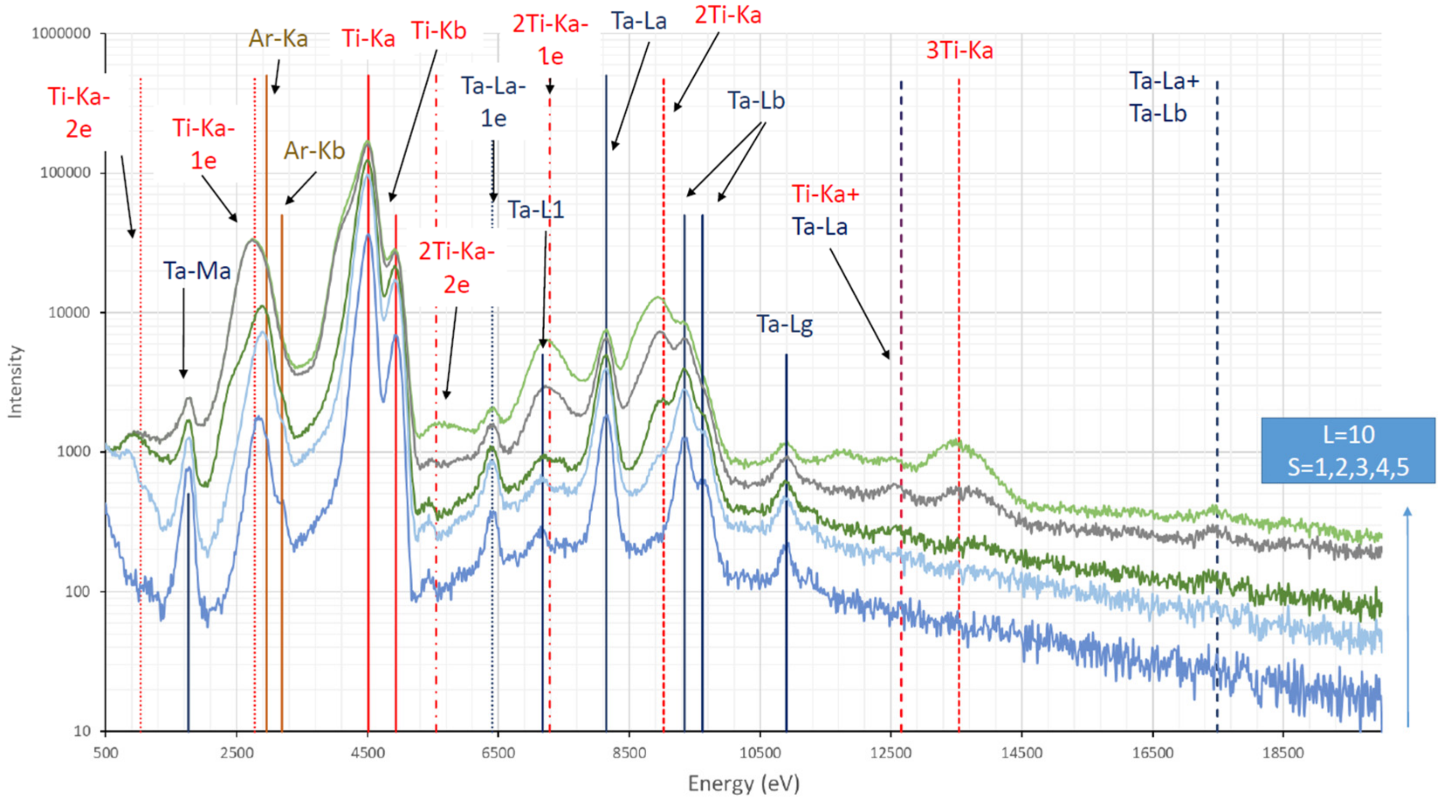
Each pixel becomes an indipendent spectrally-sensitive detector:
→ SPATIALLY-RESOLVED SPECTROSCOPY pixel-by-pixel

→ **decoupling of photon number versus energy**

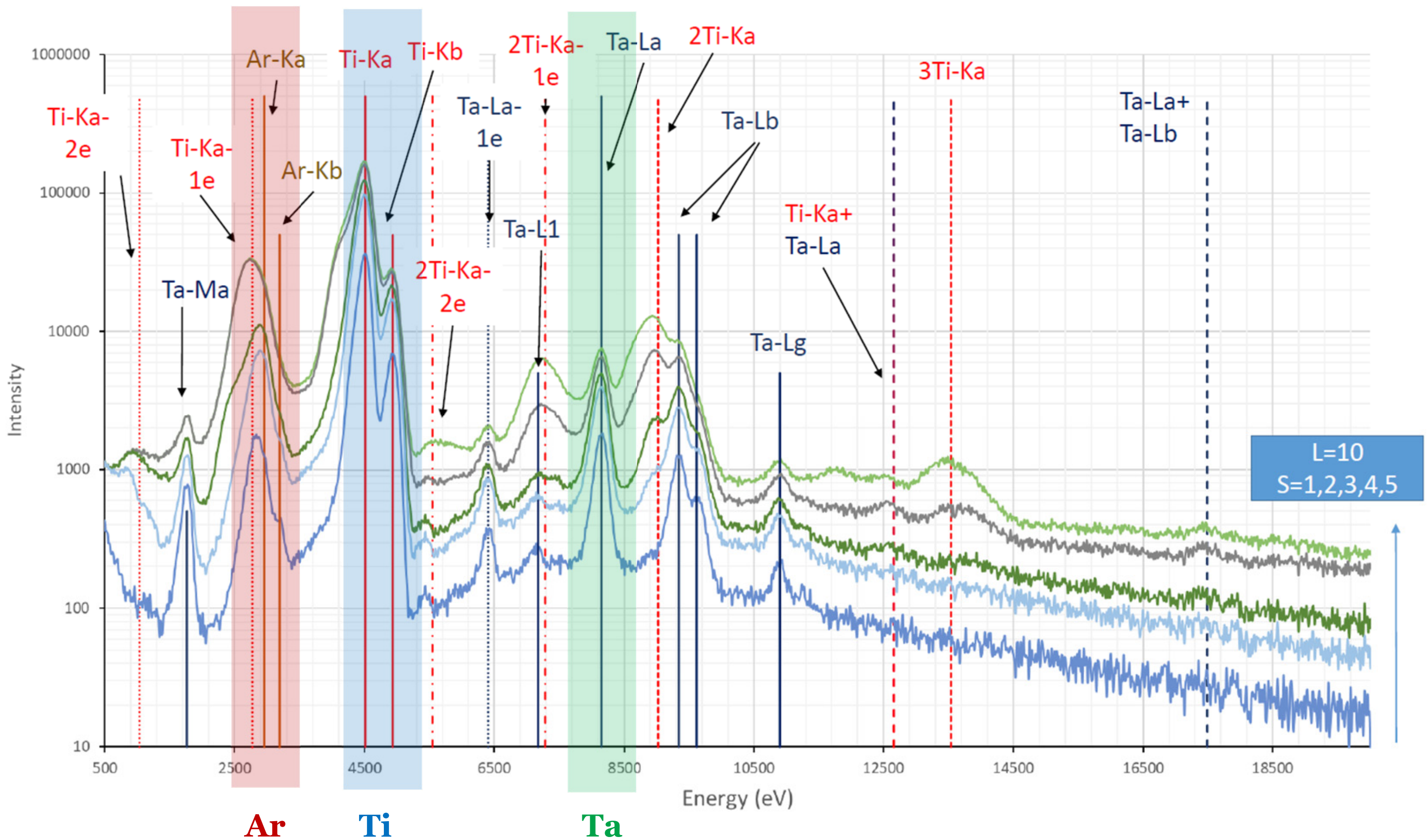
- **very short exposure-time (tens milliseconds)**
- **thousands of SPhC frames**

→ the **probability that two (or more) photons hit the same pixel** during the exposure of a single image-frame **is minimized**;

→ **single photon events carry the information on the energies** of the incident photons



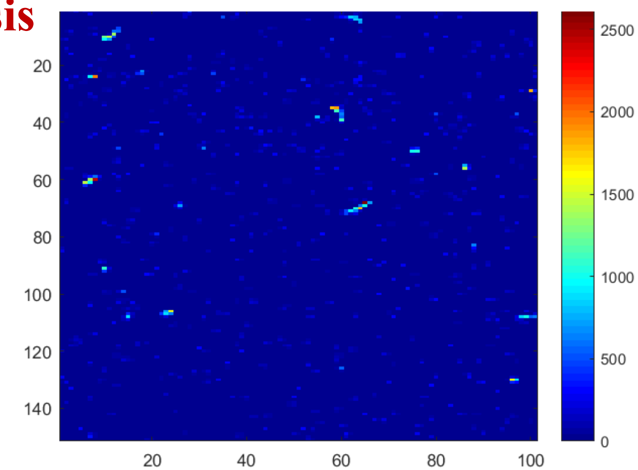
Energy Resolution ~ 230 eV at 8.1 keV (Ta-Lα fluorescence line)

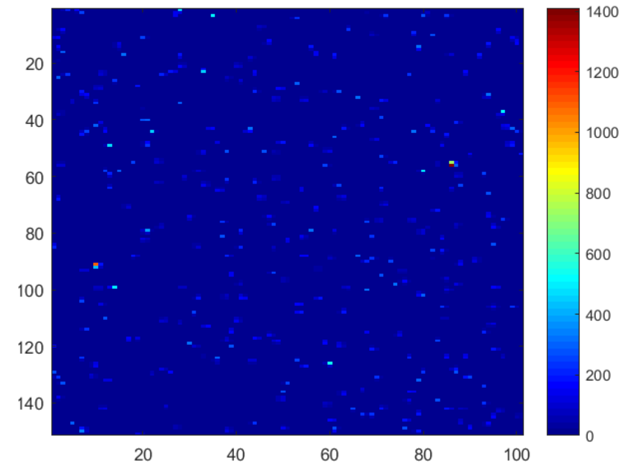


Energy Resolution ~ 230 eV at 8.1 keV (Ta-Lα fluorescence line)

SPhC Analysis

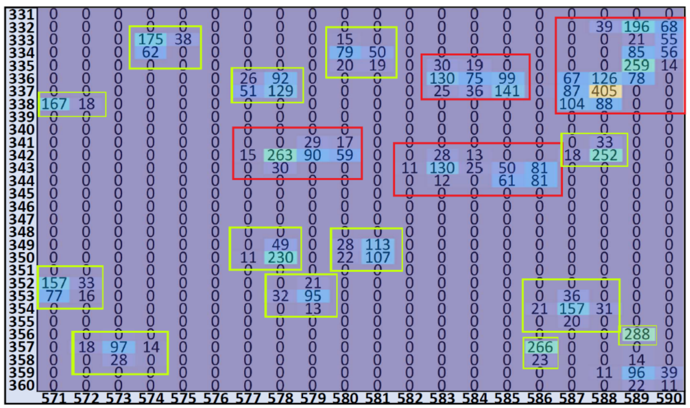
single frame

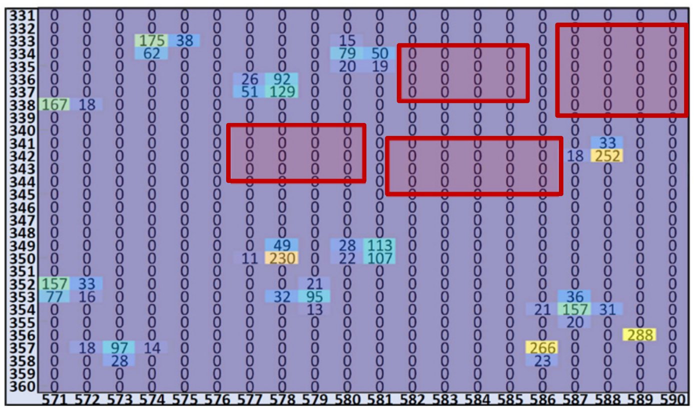




S parameter: Maximum Cluster Size

S = 5

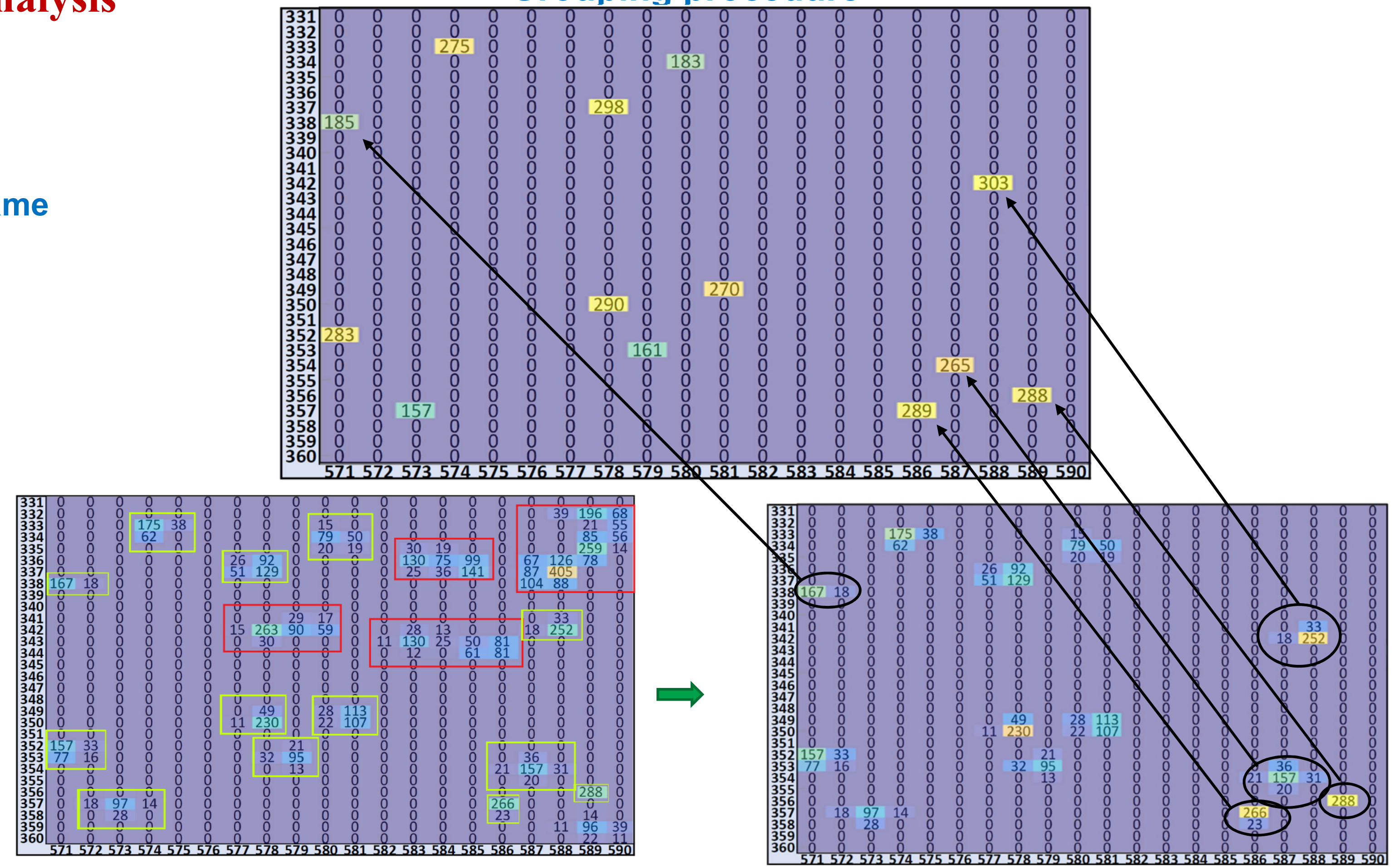




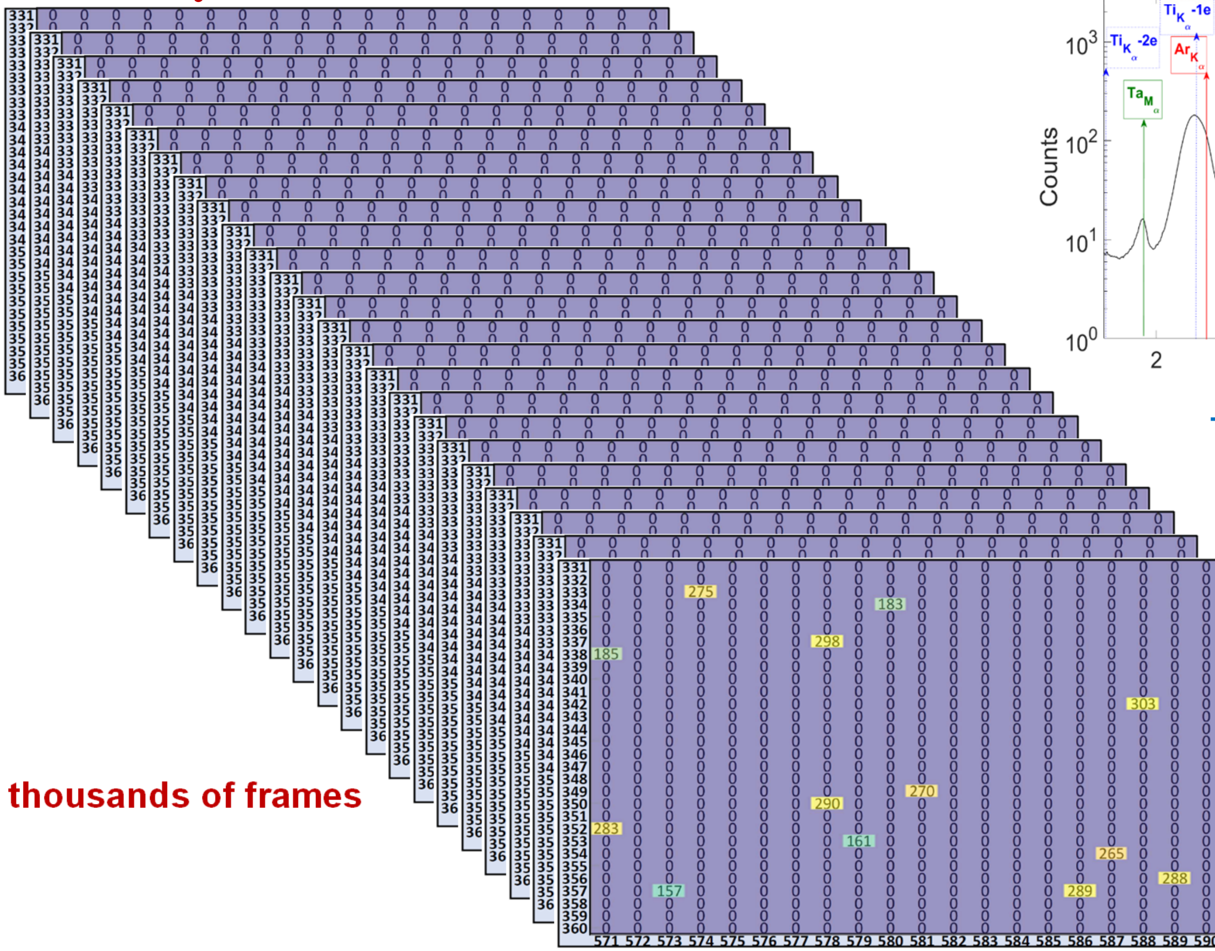
SPhC Analysis

Grouping procedure

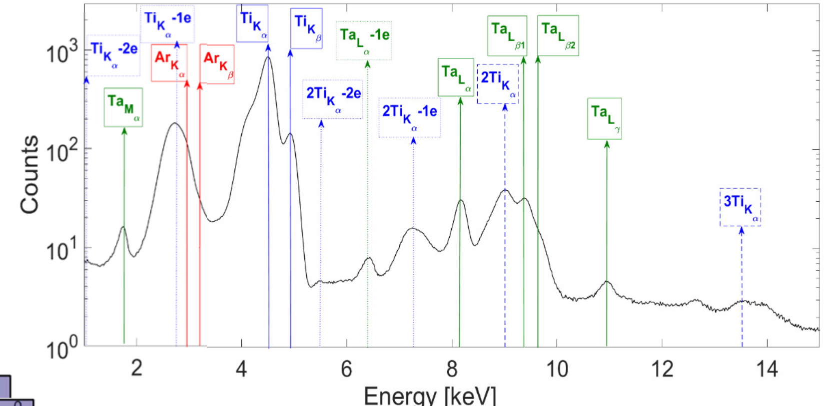
single frame



SPhC Analysis



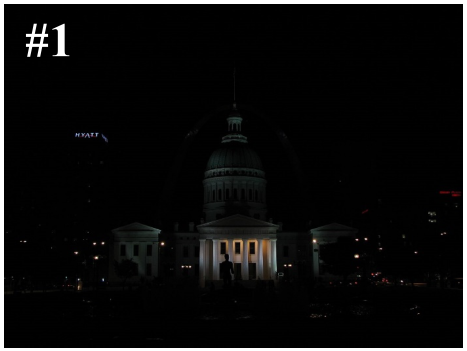
thousands of frames



The thousands of image-frames, allows gaining the statistics necessary for elaborating high quality X-ray fluorescence spectra and images

High Dynamical Range (HDR) Analysis

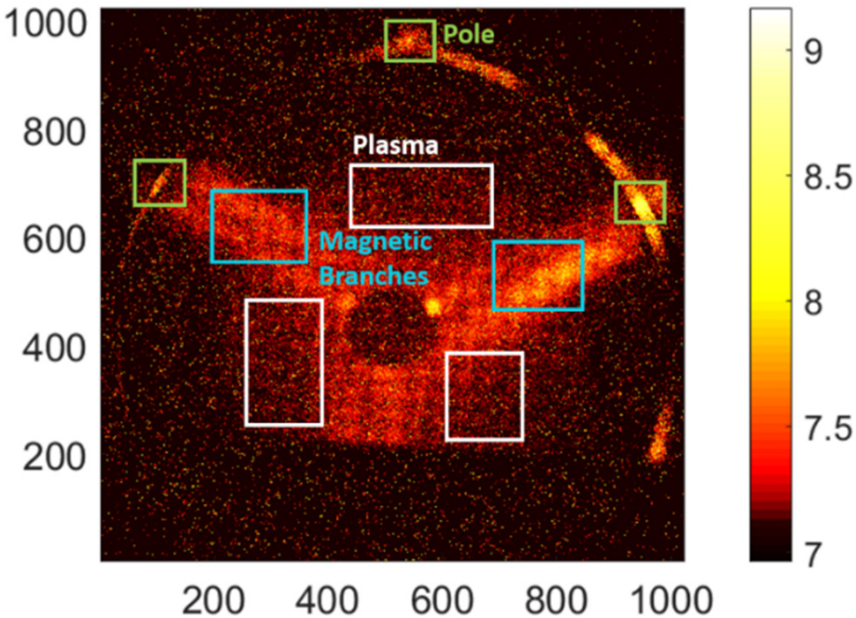
when the **ROIs intensities** of an image **vary of order of magnitude**, it is very **challenging to determine the exposure time:**



To acquire the same image setting **two or more different exposure time**

→ **advanced analysis** in order to elaborate a **weighted convolution image: <u>the HDR image</u>**

High Dynamical Range (HDR) Analysis



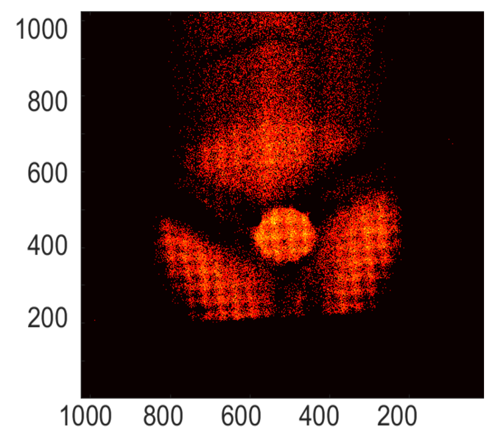
	Exp time [s]	N° frames
Plasma ROI	0.5	4200
Pole ROI	0.05	1000

Energy filtering analysis

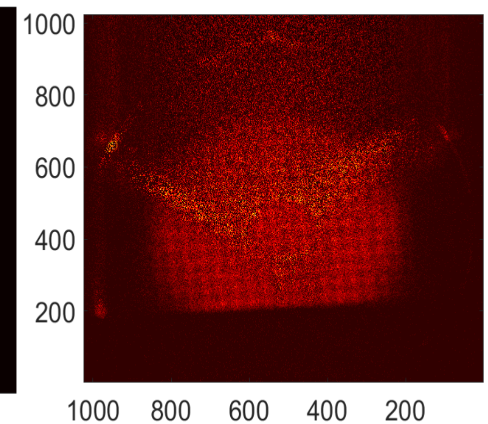
Photon counting

advanced HDR analysis in order to elaborate the **weighted convolution image starting from two different exp times images**

Not HDR



HDR



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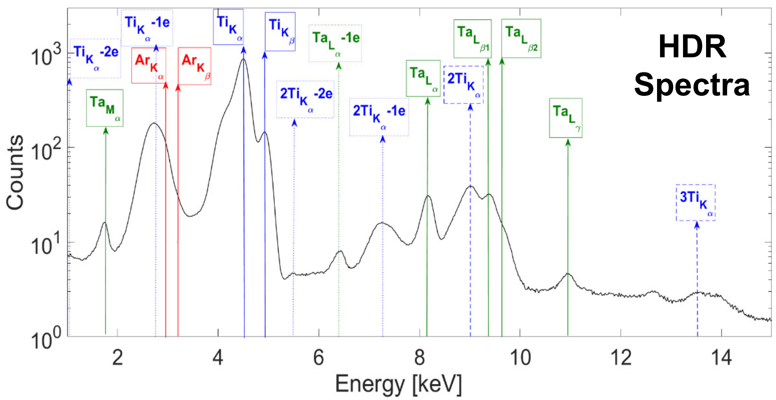
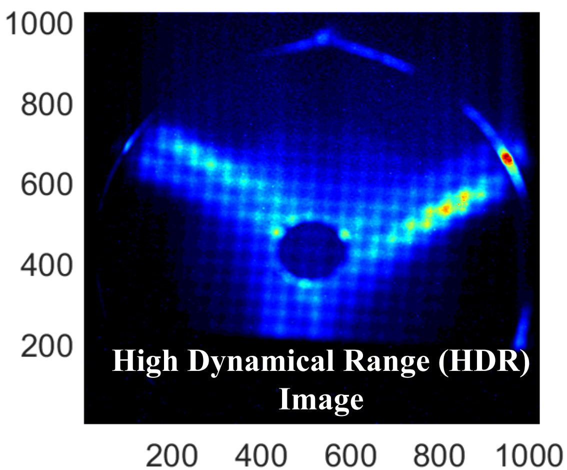
  - Losses Dynamics Investigation (Losses vs. Plasma)

- **Conclusion**

Single Photon Counting (SPhC) imaging for simultaneously SPECTRALLY and SPACE resolved analysis



Energy Resolution ~ 230 eV at 8.1 keV (Ta-La fluorescence line)



SPhC mode → Energy filtering analysis

- Thousand of image-frames acquired
- Very low exposure time (~ 10/100 mseconds)

	Exp time [s]	N° frames
Plasma ROI	0.5	4200
Pole ROI	0.05	1000

Innovative analytical method
→ PhC-HDR images elaboration

In SPhC mode each pixel becomes a independent detector:

→ **we can analyze the whole collection of detectors;**

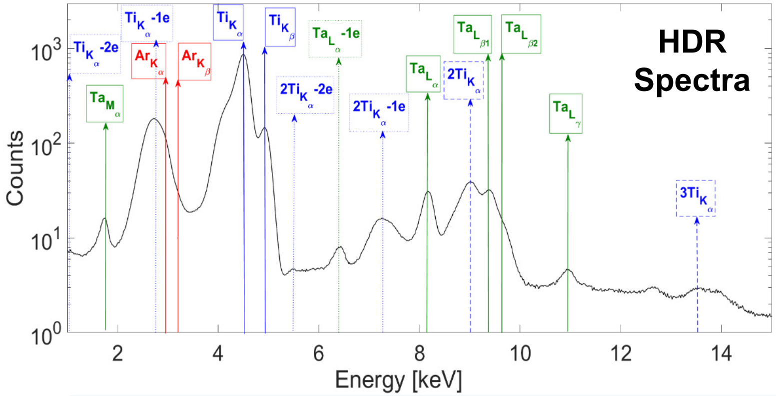
or

→ **only a given collection of detectors, selecting only pixels in a given ROI**

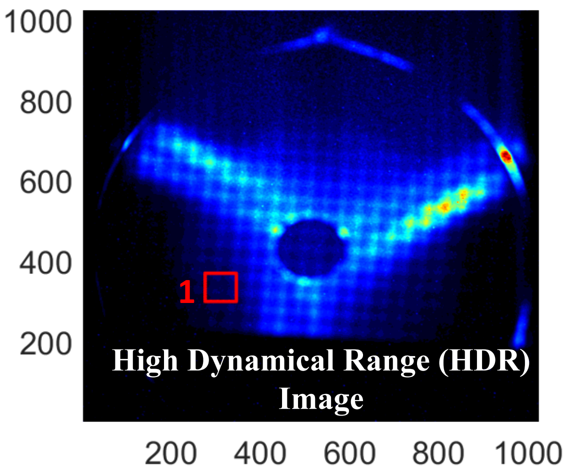
The power of this technique consists in the possibility to perform, simultaneously, two complementary investigation:

→ HDR image
→ HDR spectra

Single Photon Counting (SPhC) imaging for simultaneously SPECTRALLY and SPACE resolved analysis



Energy Resolution ~ 230 eV at 8.1 keV (Ta-La fluorescence line)



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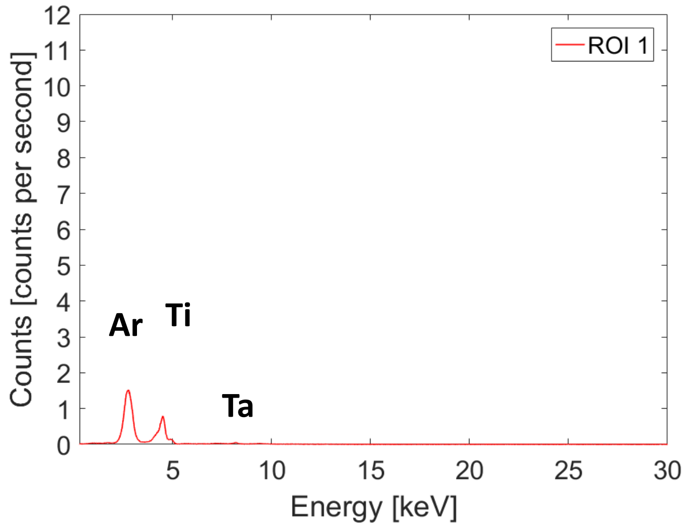
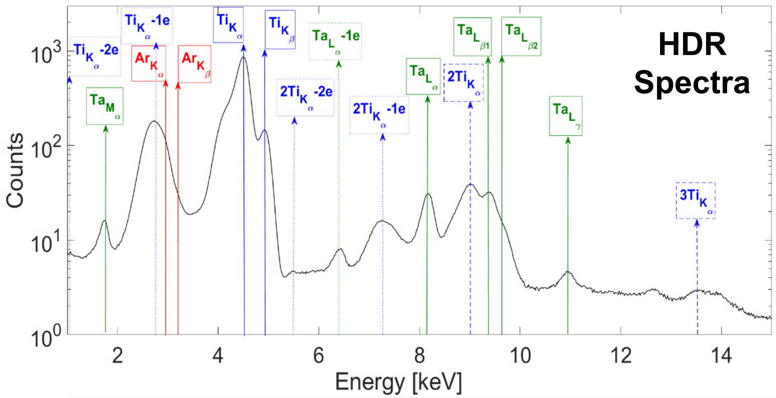
ROI1: Ar and Ti (Ti lower than Ar) and there is not Ta

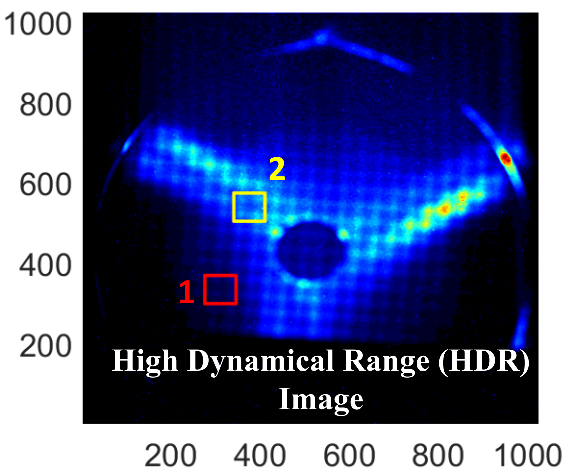


Photon Counting Imaging: Spectrally Resolved Analysis

Single Photon Counting (SPhC) imaging for simultaneously SPECTRALLY and SPACE resolved analysis



Energy Resolution ~ 230 eV at 8.1 keV (Ta-La fluorescence line)



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or

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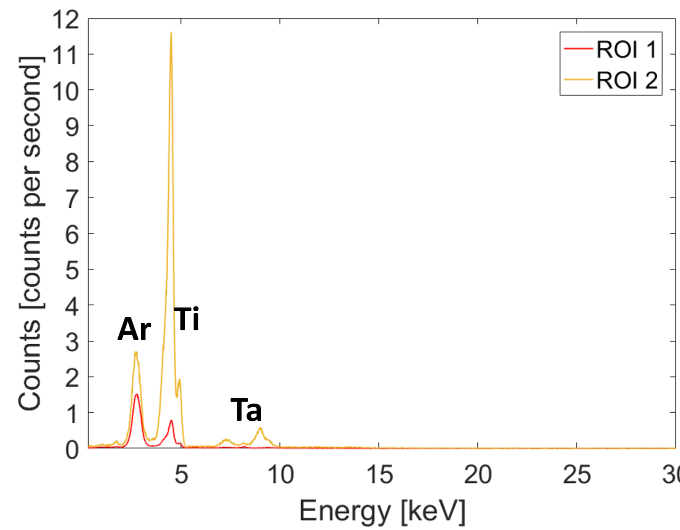
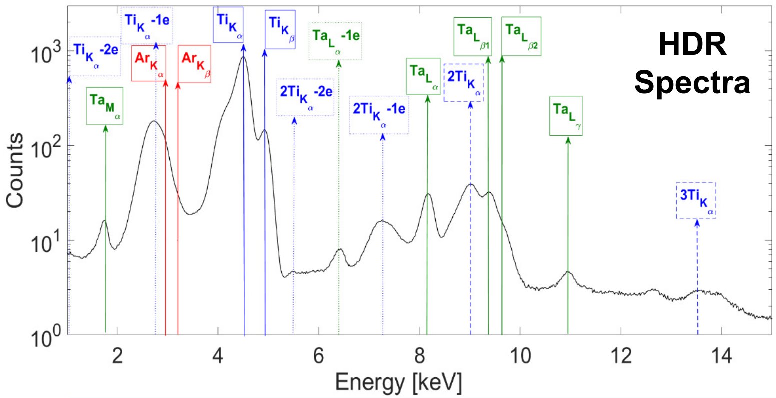
ROI1: Ar and Ti (Ti lower than Ar) and there is not Ta

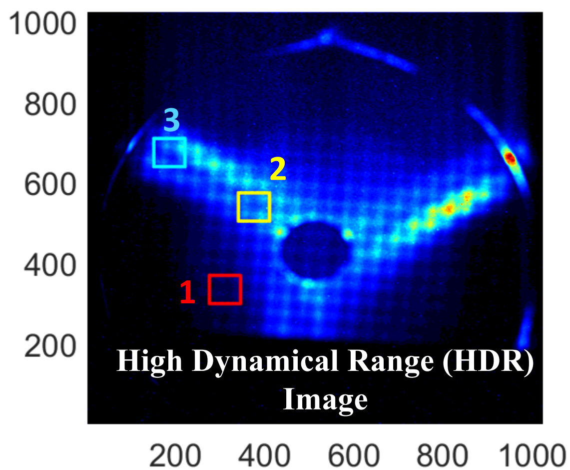
ROI2: Ar increases and Ti is 1 order of magnitude higher than Ti in ROI1



Single Photon Counting (SPhC) imaging for simultaneously SPECTRALLY and SPACE resolved analysis



Energy Resolution ~ 230 eV at 8.1 keV (Ta-La fluorescence line)



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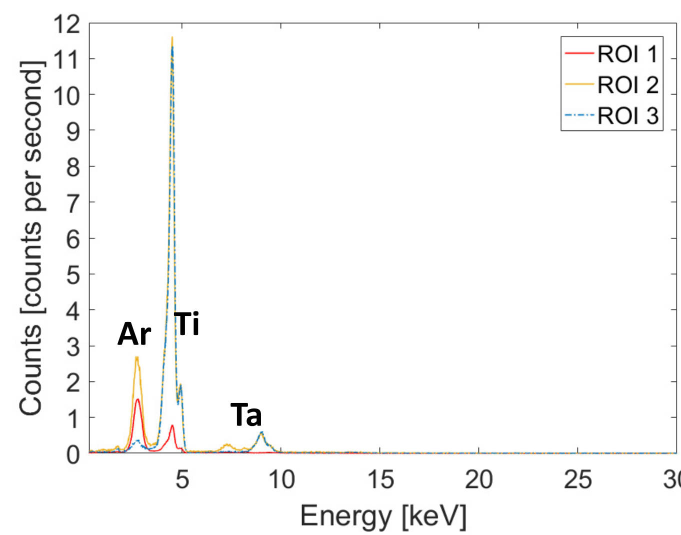
or

→ **only a given collection of detectors, selecting only pixels in a given ROI**

ROI1: Ar and Ti (Ti lower than Ar) and there is not Ta

ROI2: Ar increases and Ti is 1 order of magnitude higher than Ti in ROI1

ROI3: Ti is the same of Ti in ROI2, but Ar decreases



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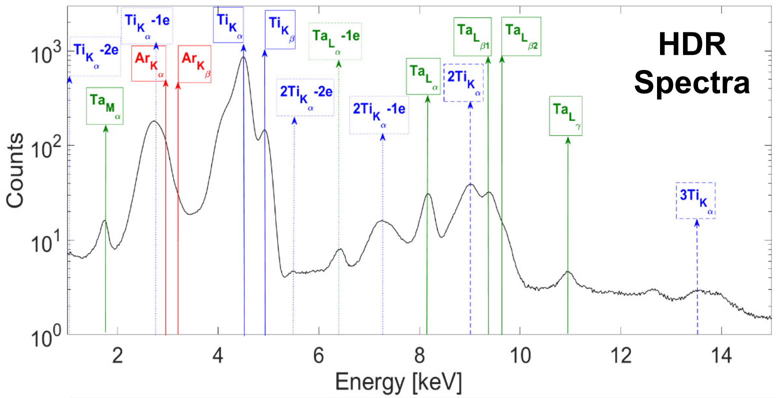

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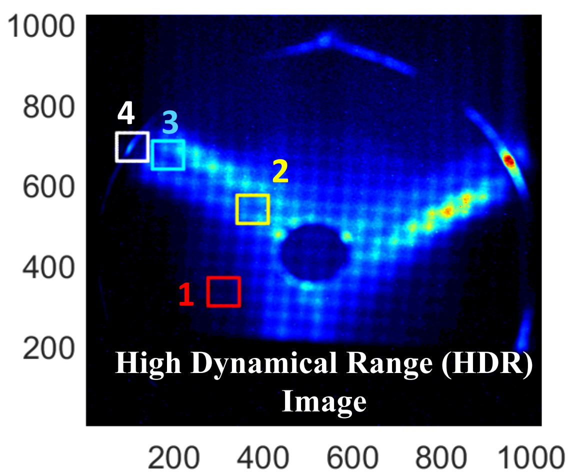

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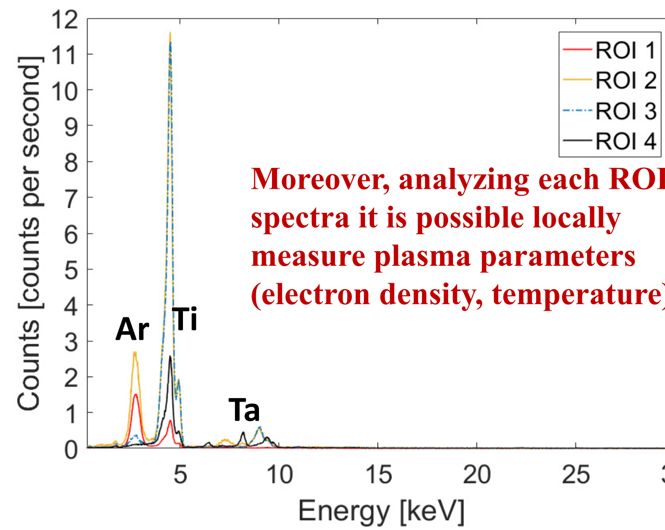
ROI2: Ar increases and Ti is 1 order of magnitude higher than Ti in ROI1

ROI3: Ti is the same of Ti in ROI2, but Ar decreases

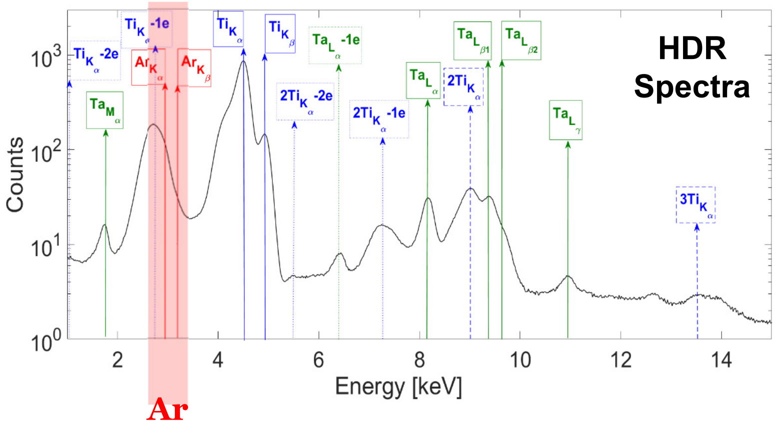
ROI4: Ar disappeares, Ti decreases and there is Ta



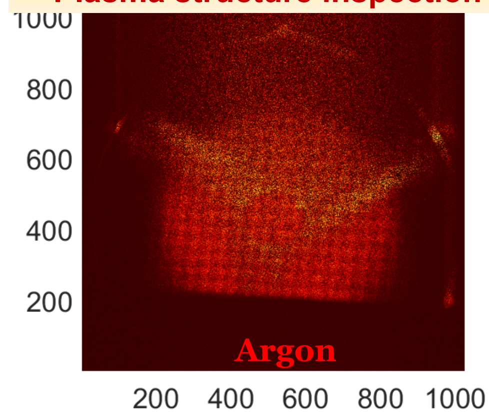
Moreover, analyzing each ROI spectra it is possible locally measure plasma parameters (electron density, temperature)

Photon Counting Imaging: Spectrally Resolved Analysis

Single Photon Counting (SPhC) imaging for simultaneously SPECTRALLY and SPACE resolved analysis



HDR Imaging
Plasma structure inspection



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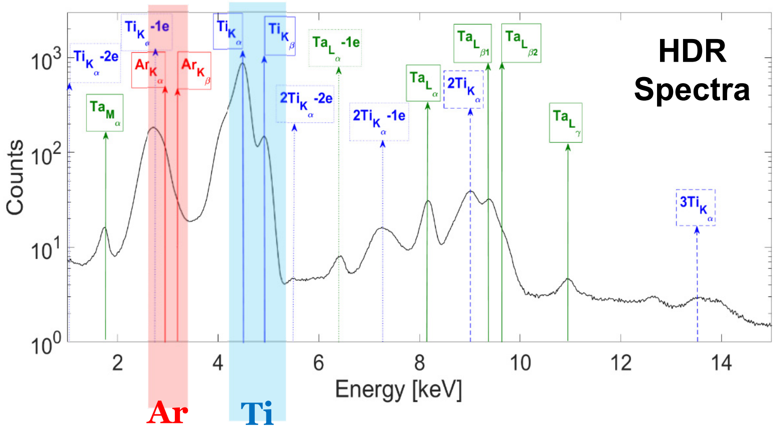

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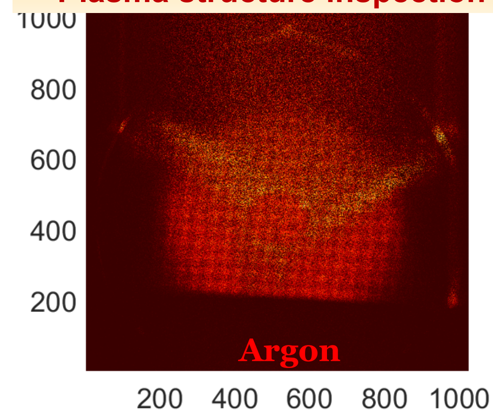
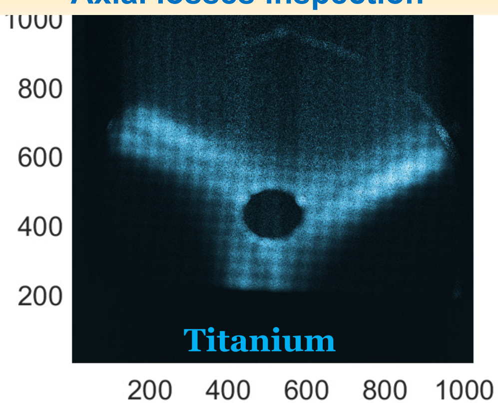
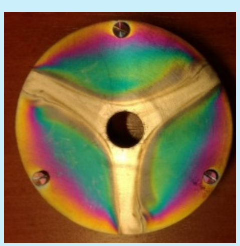
Plasma structure inspection



HDR Imaging
Axial losses inspection



Titanium Endplate



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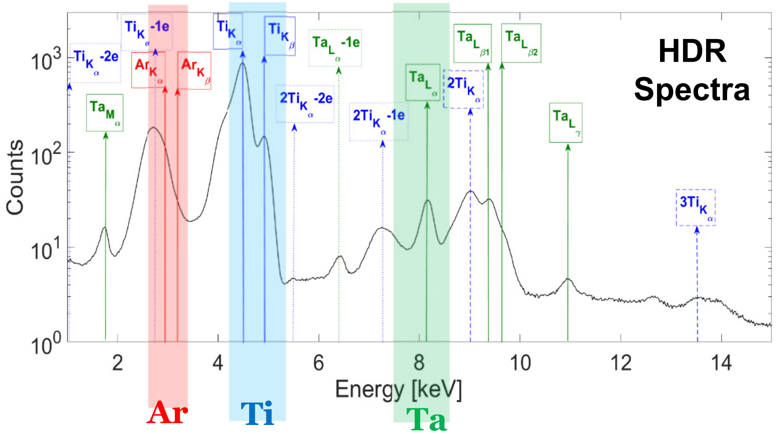

HDR Imaging
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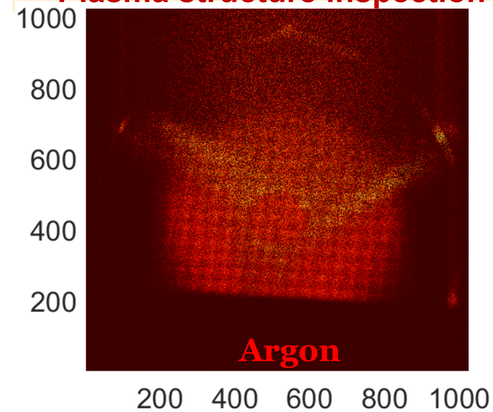
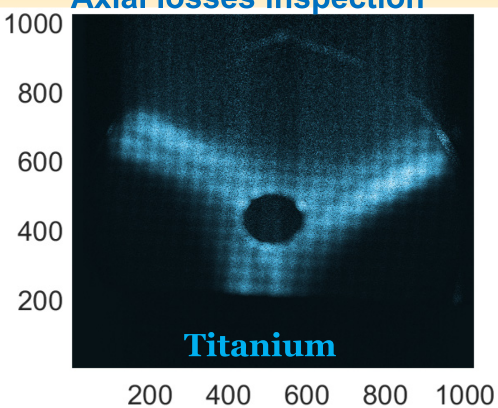
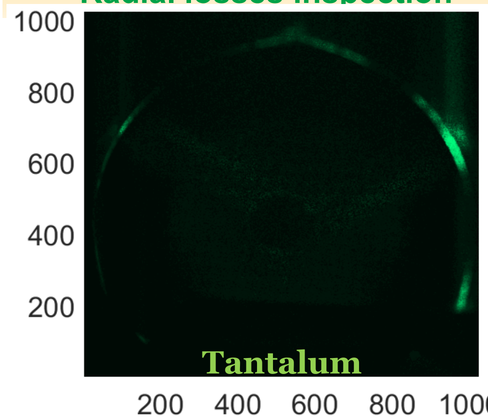


HDR Imaging
Axial losses inspection



Titanium Endplate

HDR Imaging
Radial losses inspection



Tantalum Liner

Photon Counting Imaging: Spectrally Resolved Analysis

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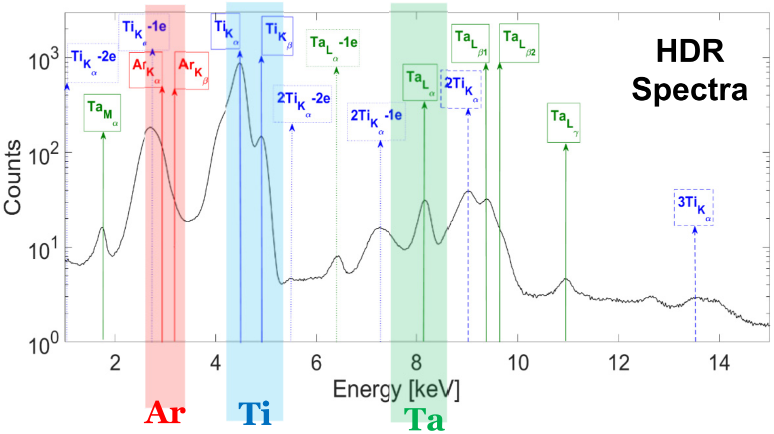
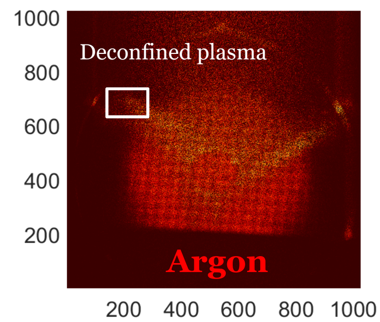
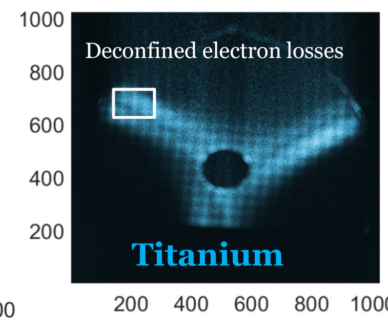


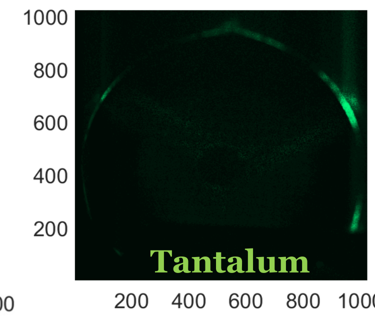
Plasma structure inspection

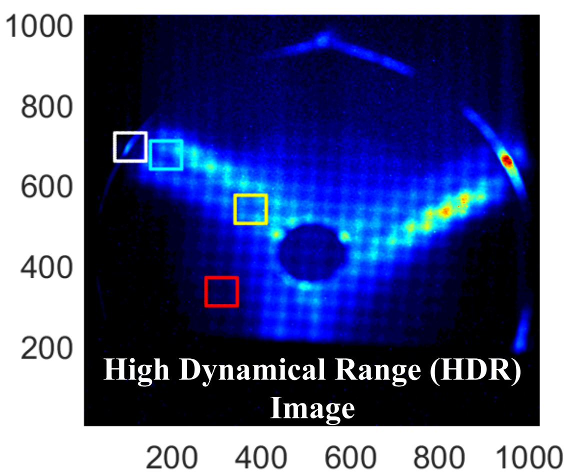


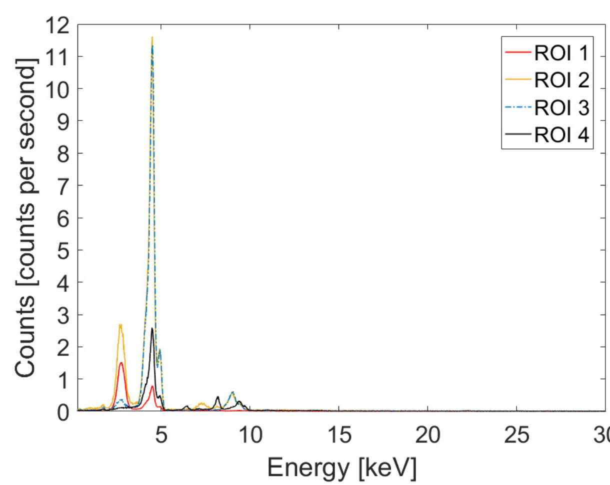
Axial losses inspection



Radial losses inspection







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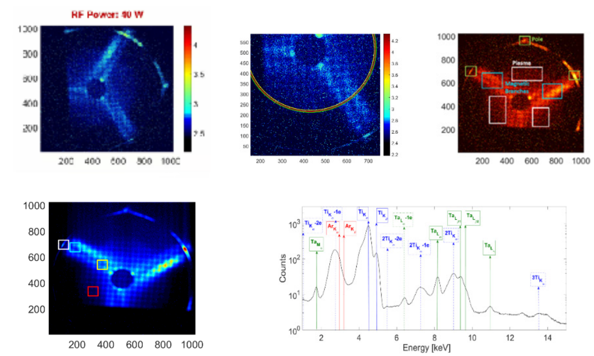
- **Conclusion**

Summary

Tool, Analytical Methods and Preliminary Results
of a powerful system for making plasma physics investigation:

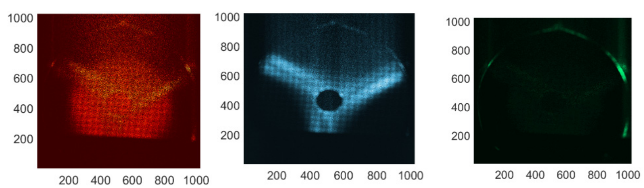
Now we are ready:

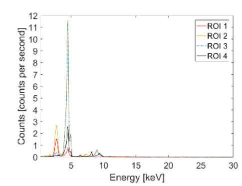
→ "Live" plasma structure and emission investigations
(vs. ECRIS operative parameters)



→ Spatial-Resolved Spectroscopy and Energy-Resolved Imaging:

→ quantitative estimation of deconfined fluxes in stable vs. unstable regimes
→ quantitative elementar composition pixel-by-pixel
→ locally plasma parameters (electron density, temperature) measurements



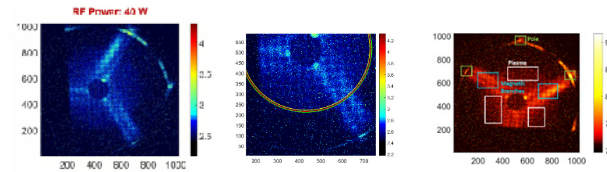


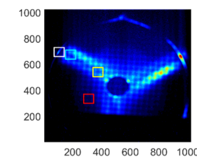
Complete characterization and studies are in progress…

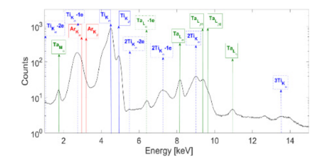
Summary

Tool, Analytical Methods and Preliminary Results
of a powerful system for making plasma physics investigation:

Now we are ready:



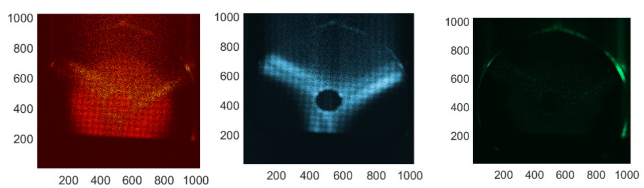


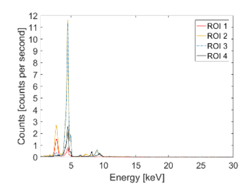


→ "Live" plasma structure and emission investigations
(vs. ECRIS operative parameters)

→ Spatial-Resolved Spectroscopy and Energy-Resolved Imaging:

→ quantitative estimation of deconfined fluxes in stable vs. unstable regimes
→ quantitative elementar composition pixel-by-pixel
→ locally plasma parameters (electron density, temperature) measurements

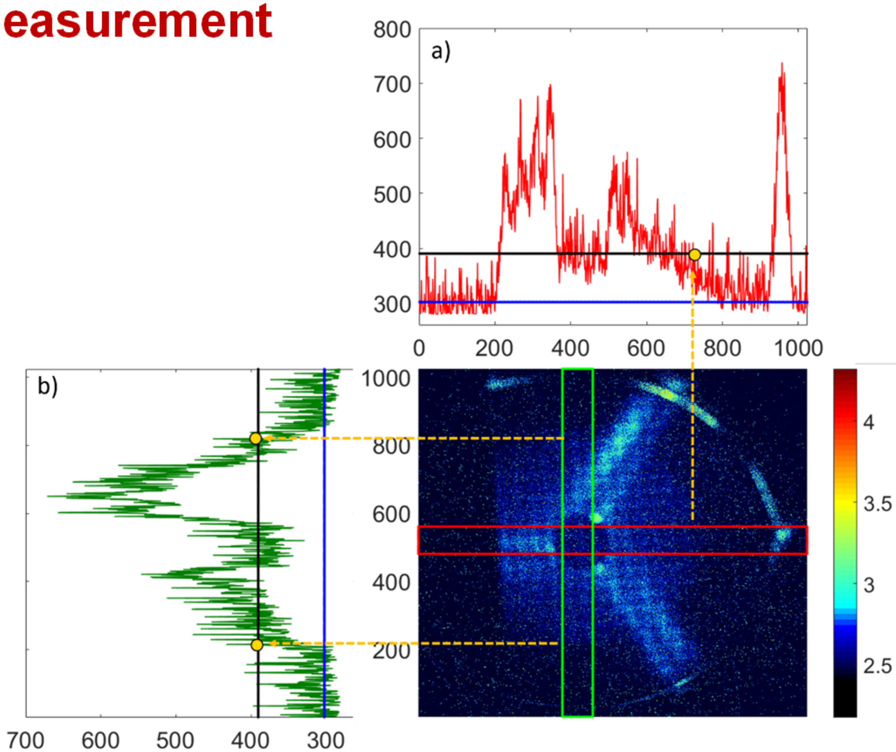




Complete characterization and studies are in progress…

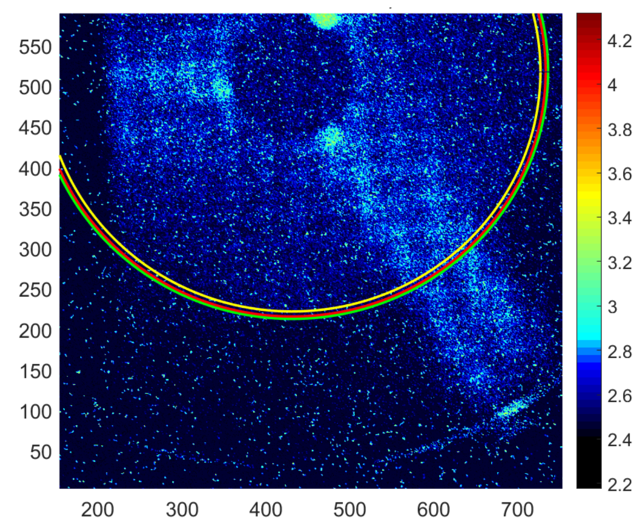
Thanks for your attention!

Plasma diameter measurement



	Plasma Radius [mm]
I point$_{Spectra\ fig\ \boxed{5.19}\ a)}$	15.77± 2.24
II point$_{Spectra\ fig\ \boxed{5.19}\ b)}$	16.25± 1.92
III point$_{Spectra\ fig\ \boxed{5.19}\ b)}$	16.10± 1.92
Mean value	$\boxed{16.04 \pm 1.44}$

Using the realistic magnetic field of the Atomki-ECRIS, the radius of the ECR-ellipsoid is **15.5 mm**



- **Blu line is the mean value of the noise (0–200 pixels)**
- **The black line is the mean value in the hole region, where the emission comes from plasma only (400–500 pixels)**

"Live" plasma diameter measurement