12th International Workshop on Mechanisms of Vacuum Arcs
(MeVArc 2025)

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Enhanced Multi-Spectral Imaging via Optical-Path Reuse: Spatiotemporal Evolution of Plasma Species in Vacuum Arcs

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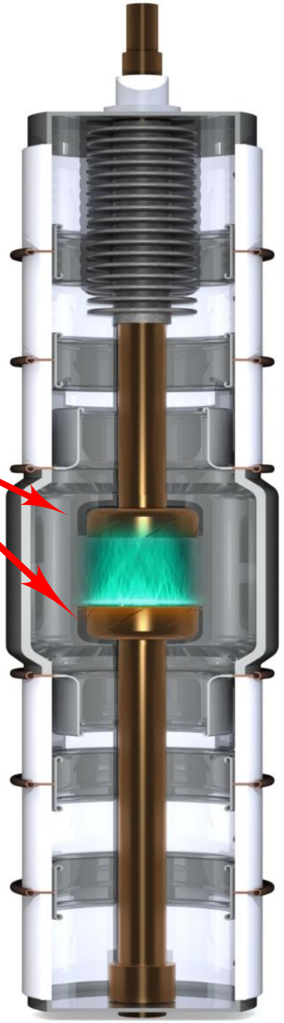
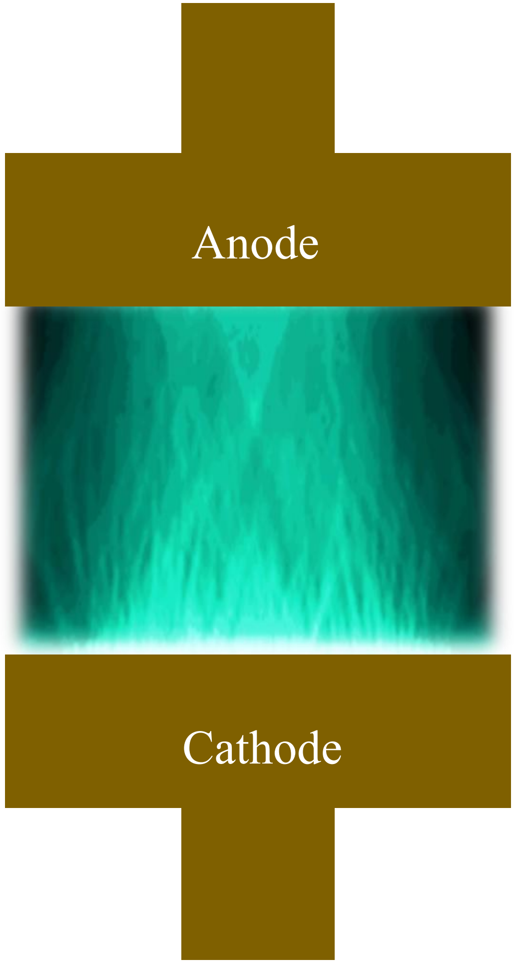
Experiments and diagnostics

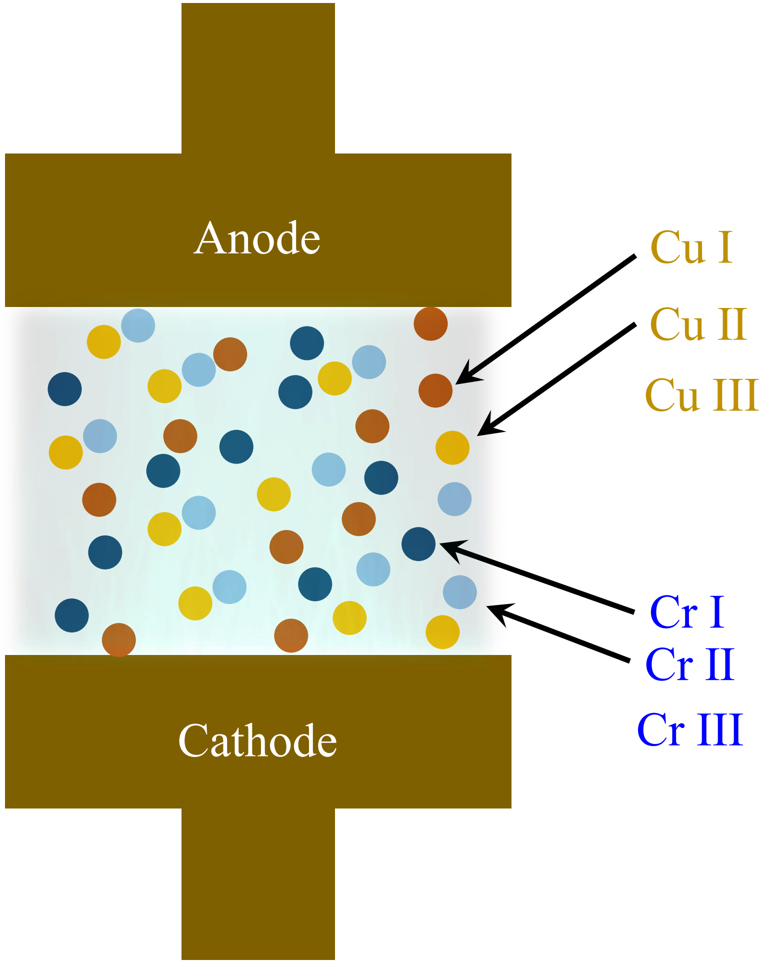
1. Introduction

There are numerous species of plasma particles in vacuum circuit breakers' arcs.





Conventional high-speed camera imaging of vacuum arc



The characteristics of the arc are determined by its constituent particles

1. Introduction

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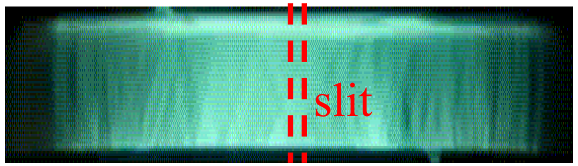
Optical Emission Spectroscopy (OES) is a commonly used method in plasma diagnostics.

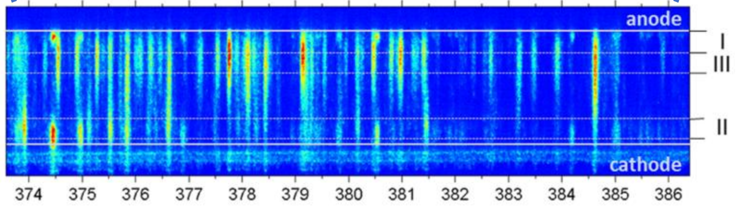


Vacuum arc light

Spectroscopy

Spectrometer

1D



Spectral line$_1$ Spectral line$_2$

Spectral line$_1$ Spectral line$_2$

Partical$_1$

Intensity of spectral line$_1$

Intensity of spectral line$_2$

⋮

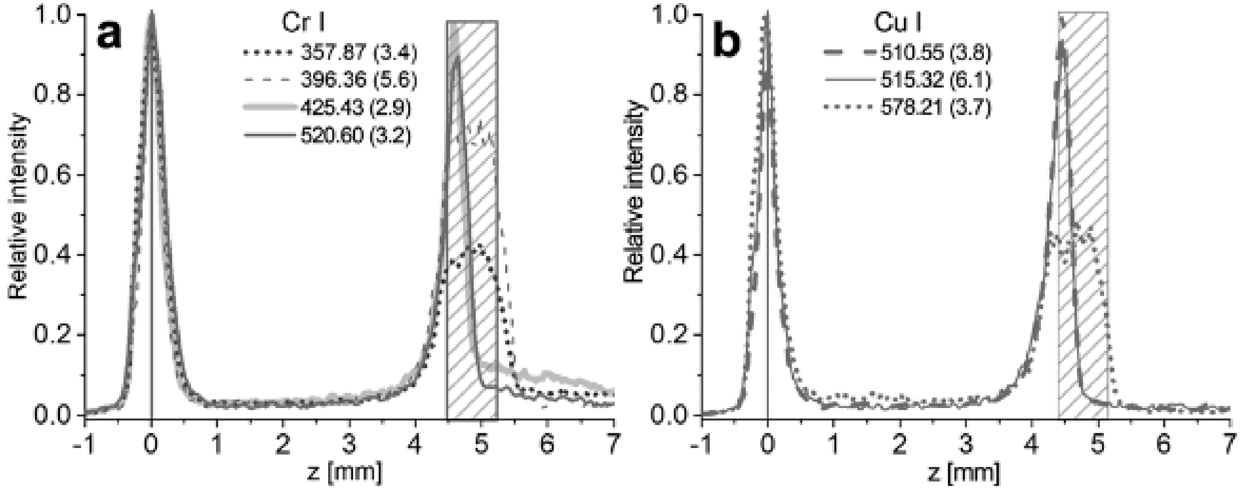
Partical$_2$

Intensity of spectral line$_1$

Intensity of spectral line$_2$

⋮

Relative intensity



We need to determine the particle distribution and its temporal evolution throughout the entire arc region.

Reference:

[1]M. Lisnyak, et al., Overview spectra and axial distribution of spectral line intensities in a high-current vacuum arc with CuCr electrodes. J. Appl. Phys. 28 September 2015; 118 (12): 123304.

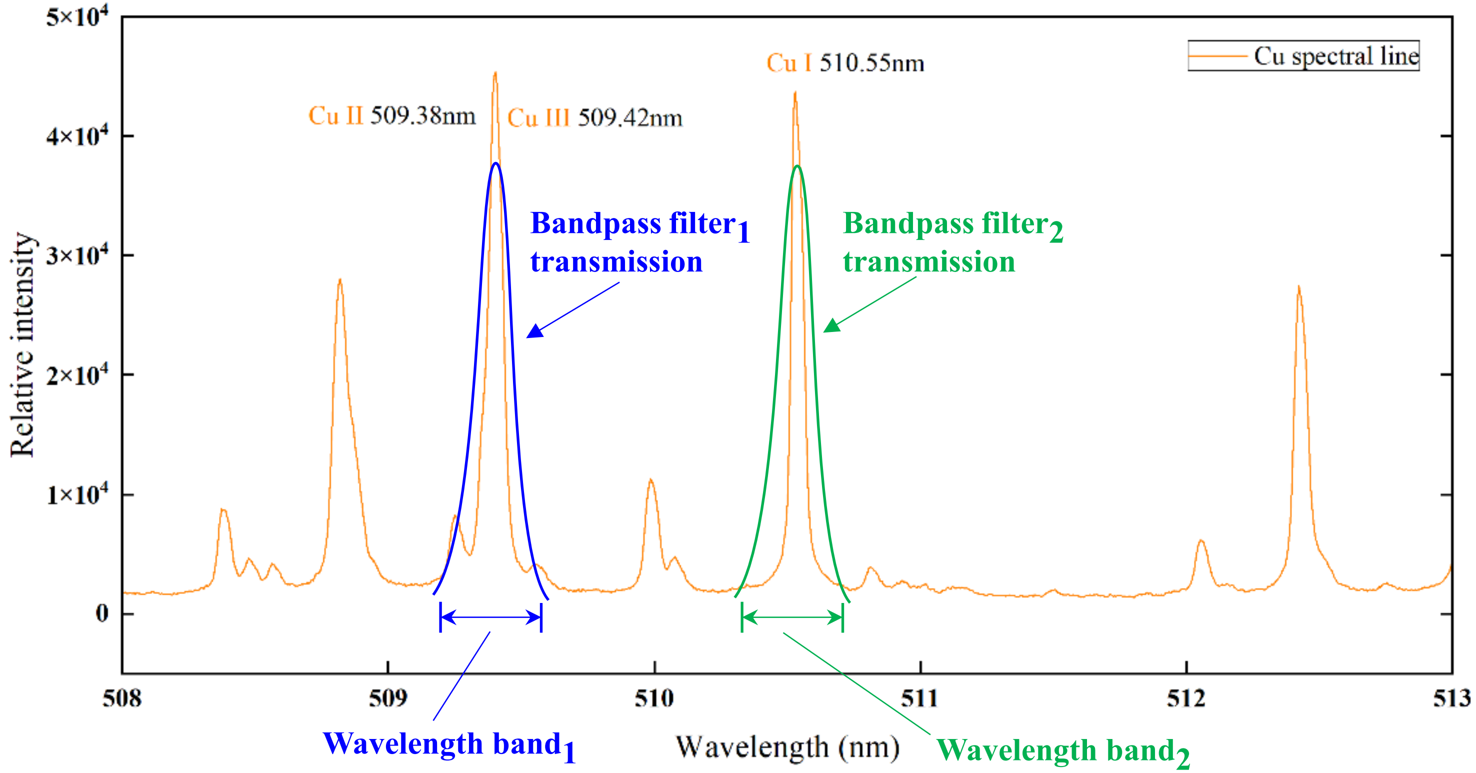
1. Introduction

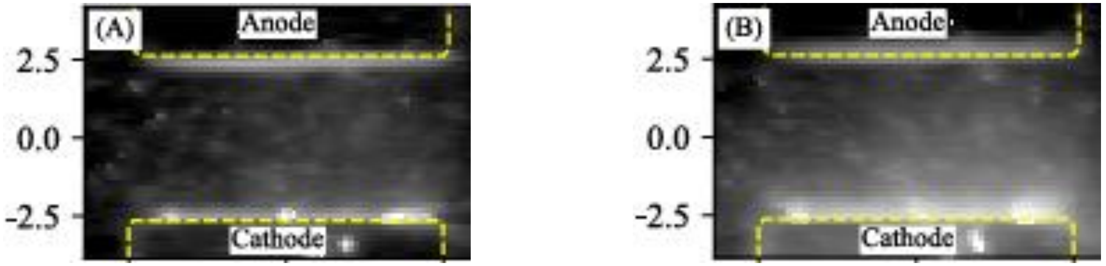
Each bandpass filter isolates the emission from a specific transition of one species.

Bandpass filter

↓

2D





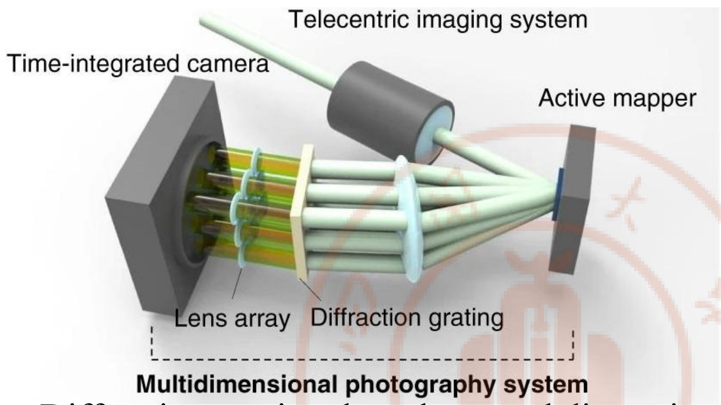
More channels, more species

Reference:

[1]H. Ejiri et al., "Excitation Temperature Imaging of Vacuum Arc Based on Two-Line Radiance Method. IEEE Transactions on Plasma Science. June 2021.

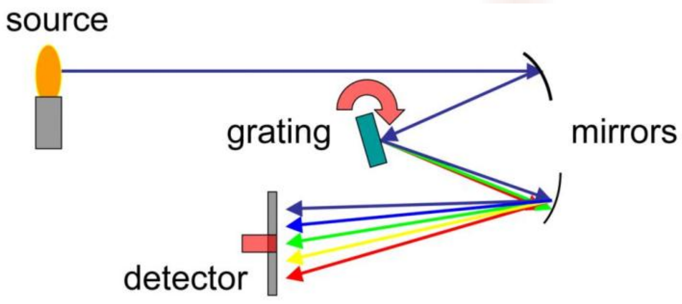
1. Introduction—Multispectral Camera Architectures

Diffraction imaging



Diffraction-grating–based spectral dispersion integrated with an imaging optics system.

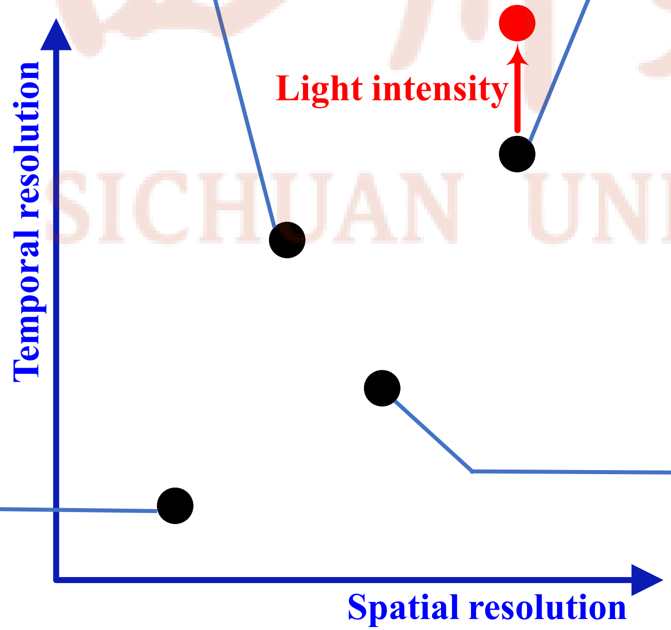
Classical spectrometer



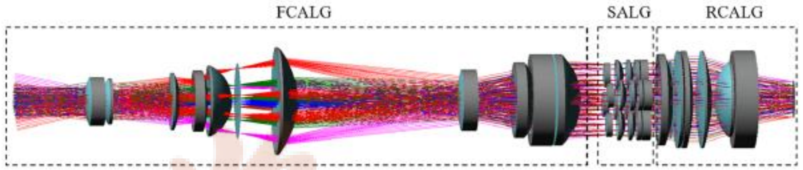
Spectral dispersion via a prism or grating, recorded by a CCD array.

Enhanced spectral imaging

High spatiotemporal resolution
Low light intensity attenuation rate

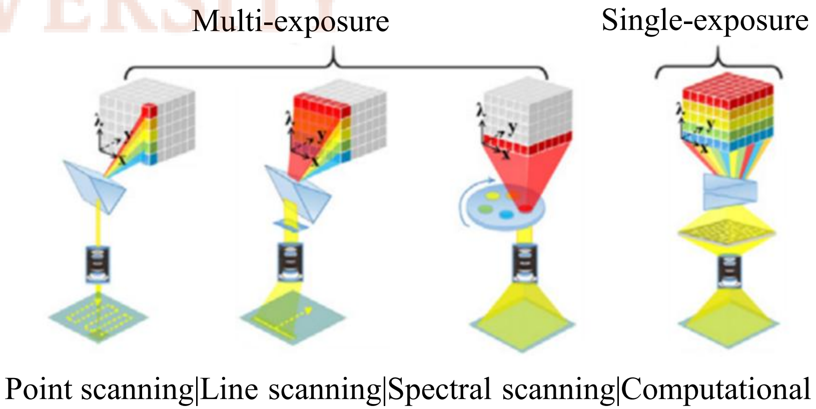


Sub-aperture imaging



Use an optical setup to split the target beam into multiple sub-beams, and image each spectral band with filters of different bandwidths.

Scanning imaging



Sequentially scan the target area by moving optical components (e.g., a slit or a 2D detector) to capture spatial and spectral information.

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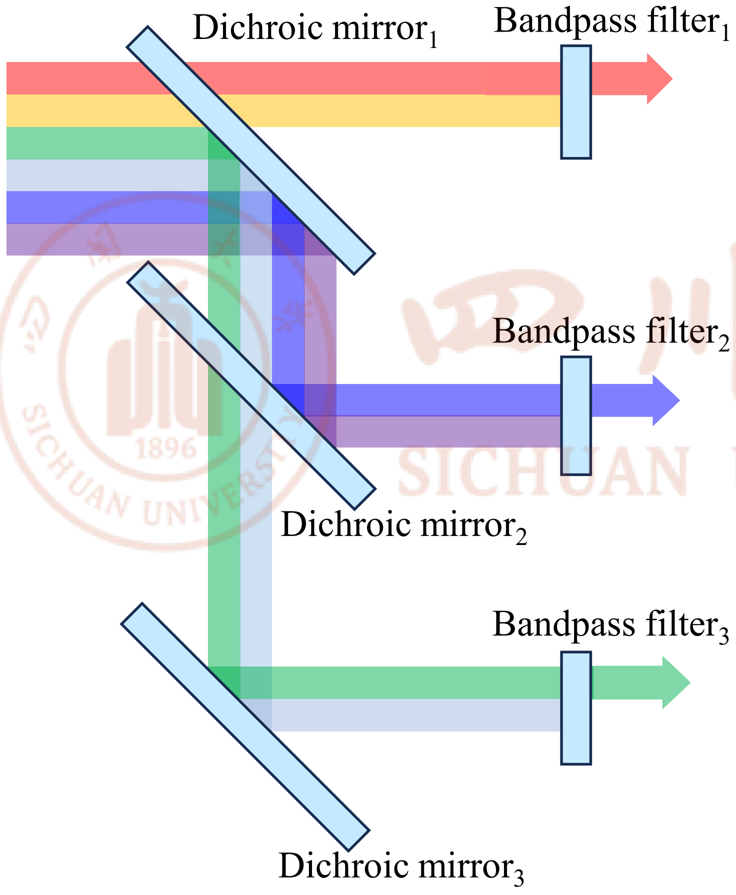
Dichroic mirror reflects short-wavelength light and transmits long-wavelength light.

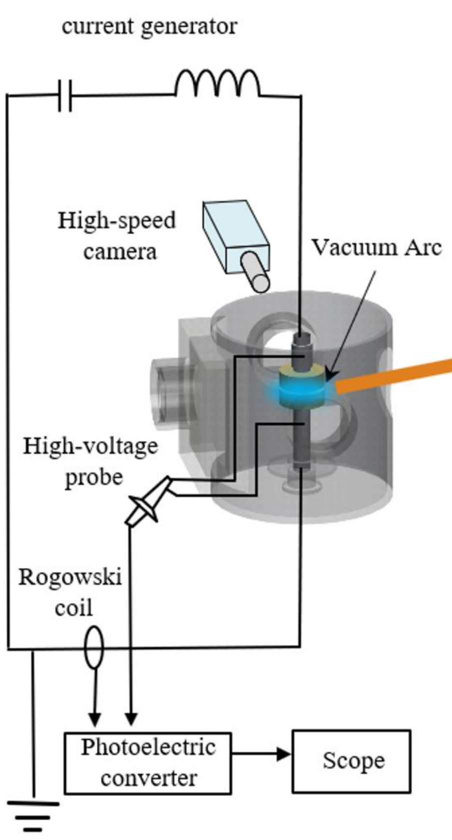


- By arranging multiple dichroic mirrors in series, each with a different cutoff wavelength, one can sequentially separate out several narrow-band beams.
- The transition between reflected and transmitted bands is typically only a few nanometers wide (edge steepness < 2 nm), yielding an extremely sharp separation.
- Nearly all incident light is either reflected or transmitted, so there is almost no intensity loss.
- Between stages, only minimal interference losses occur in the dielectric coatings, resulting in a very low overall attenuation for the optical system.

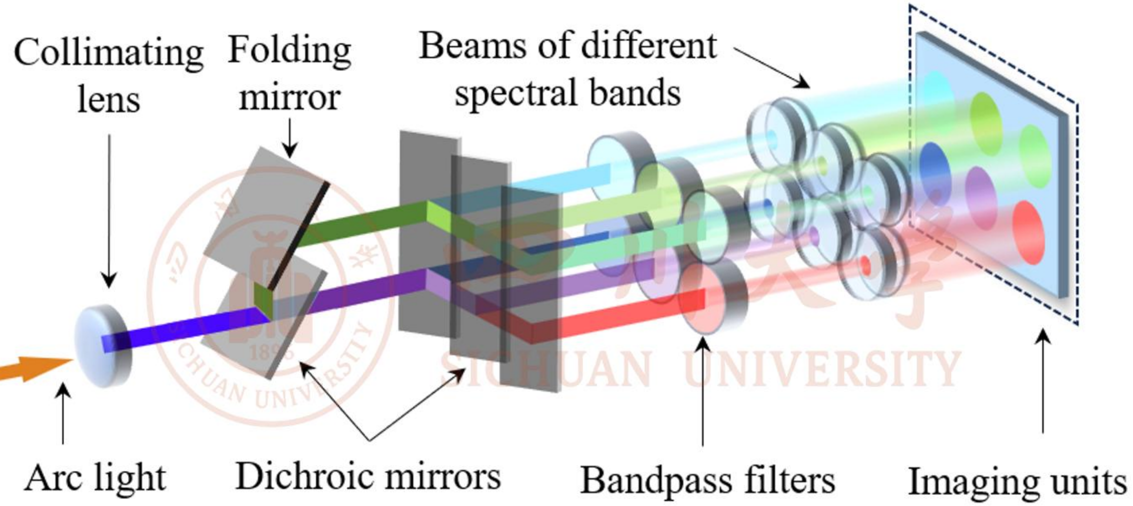
2. Methods

Optical path design and implementation using 3D-printed components.

Experimental Setup

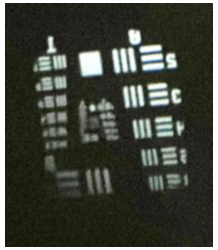


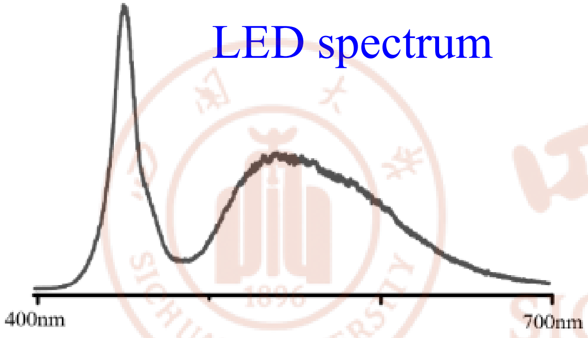
Multi-spectral Synchronous Imaging System

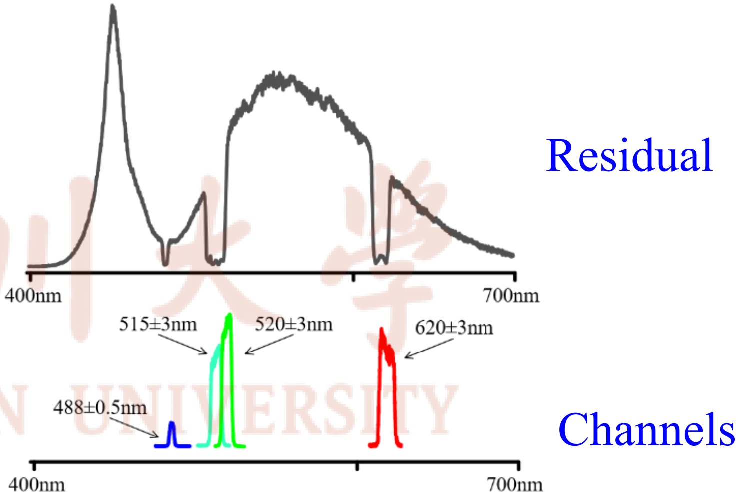


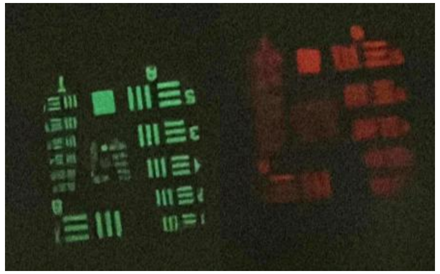
2. Methods

A backlight LED source was used for optical-path calibration.

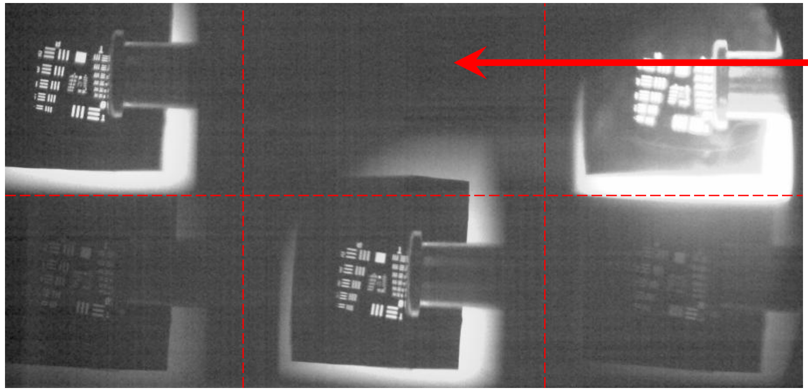








Measurement of imaging resolution
(Imaging unit: Highspeed Camera)

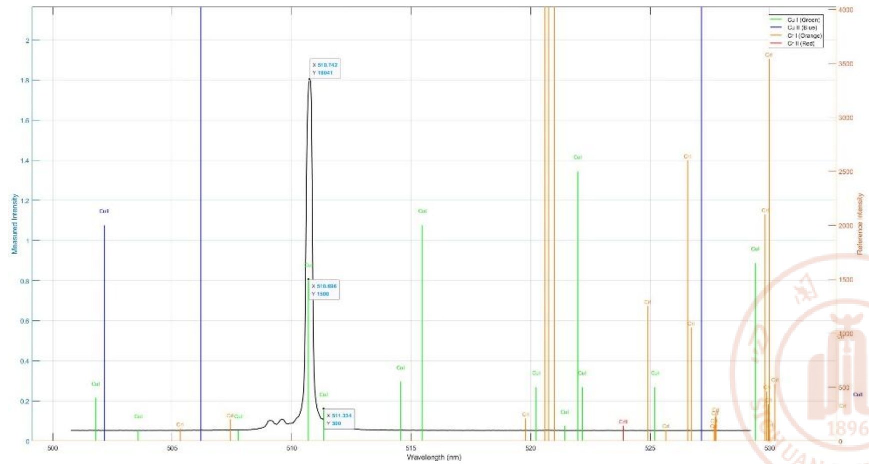


- The imaging unit exhibits low responsivity outside the visible spectrum
- The LED light source does not emit light in the near-ultraviolet range.

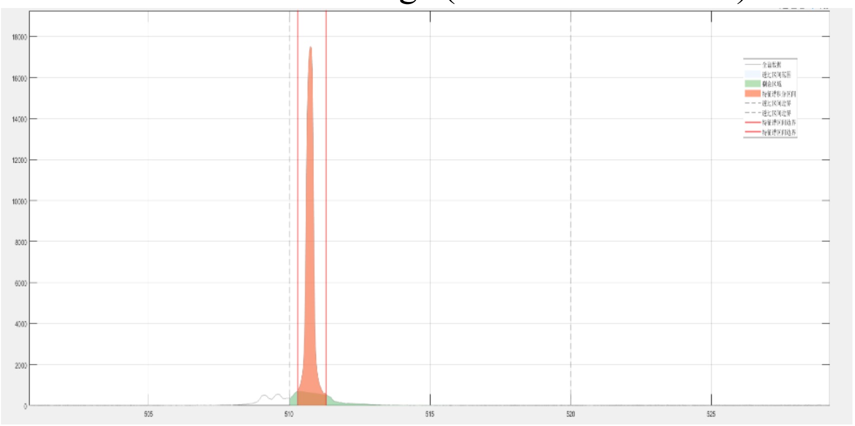
2. Methods

Capture DC 180A vacuum arc images and measure the spectral lines recorded in each channel.

Spectra of each channel



Spectral profiles of each channel during actual arc discharge (Electrode: CuCr50)



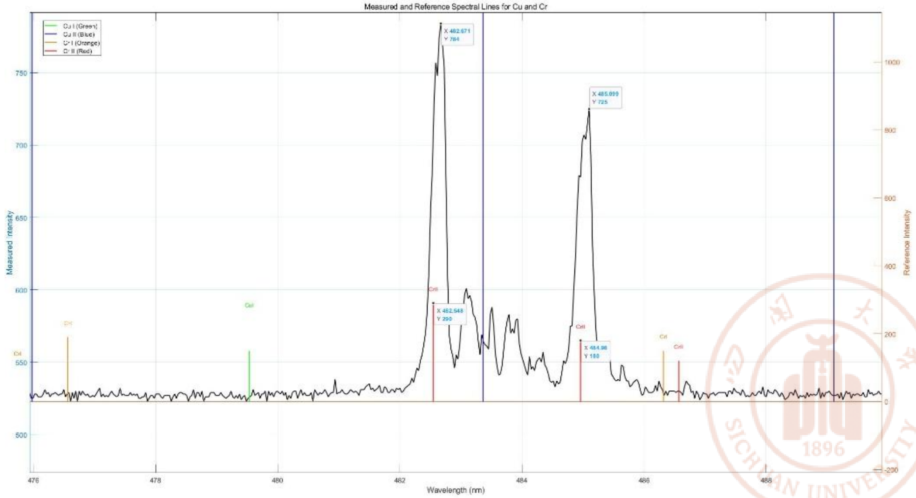
Intensity ratio of the characteristic spectral line within the captured image

- First, we need to identify which particle species correspond to the captured spectral lines.
- Using the measured spectra from each channel, we can calculate the proportion of the total intensity contributed by our target spectral lines.

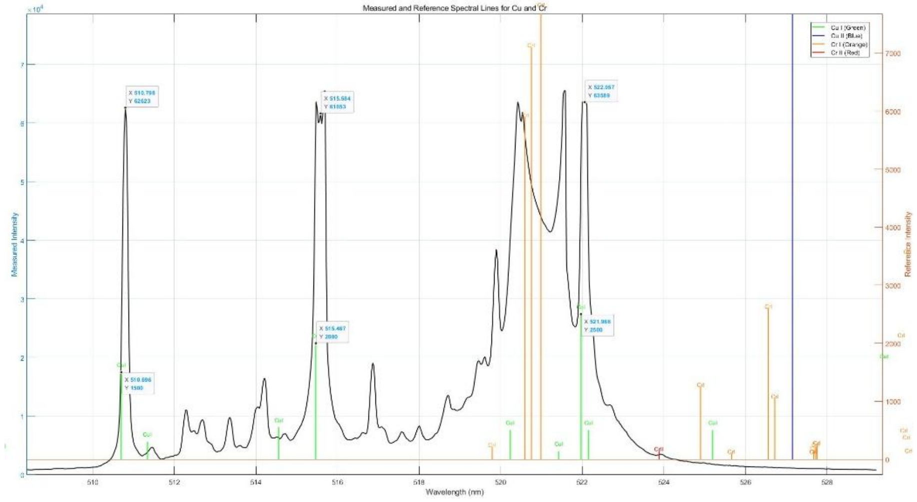
2. Methods

Capture DC vacuum arc images and measure the spectral lines recorded in each channel.

488±1.5nm



520±5nm



- The continuum's intensity contribution may exceed that of the characteristic lines, even if the lines themselves appear prominent in the spectrum.

- Filter with too large a bandwidth transmits both numerous characteristic lines and continuum emissions, making it impossible to obtain accurate information.

3. Result

Imaging target:

Vacuum arc

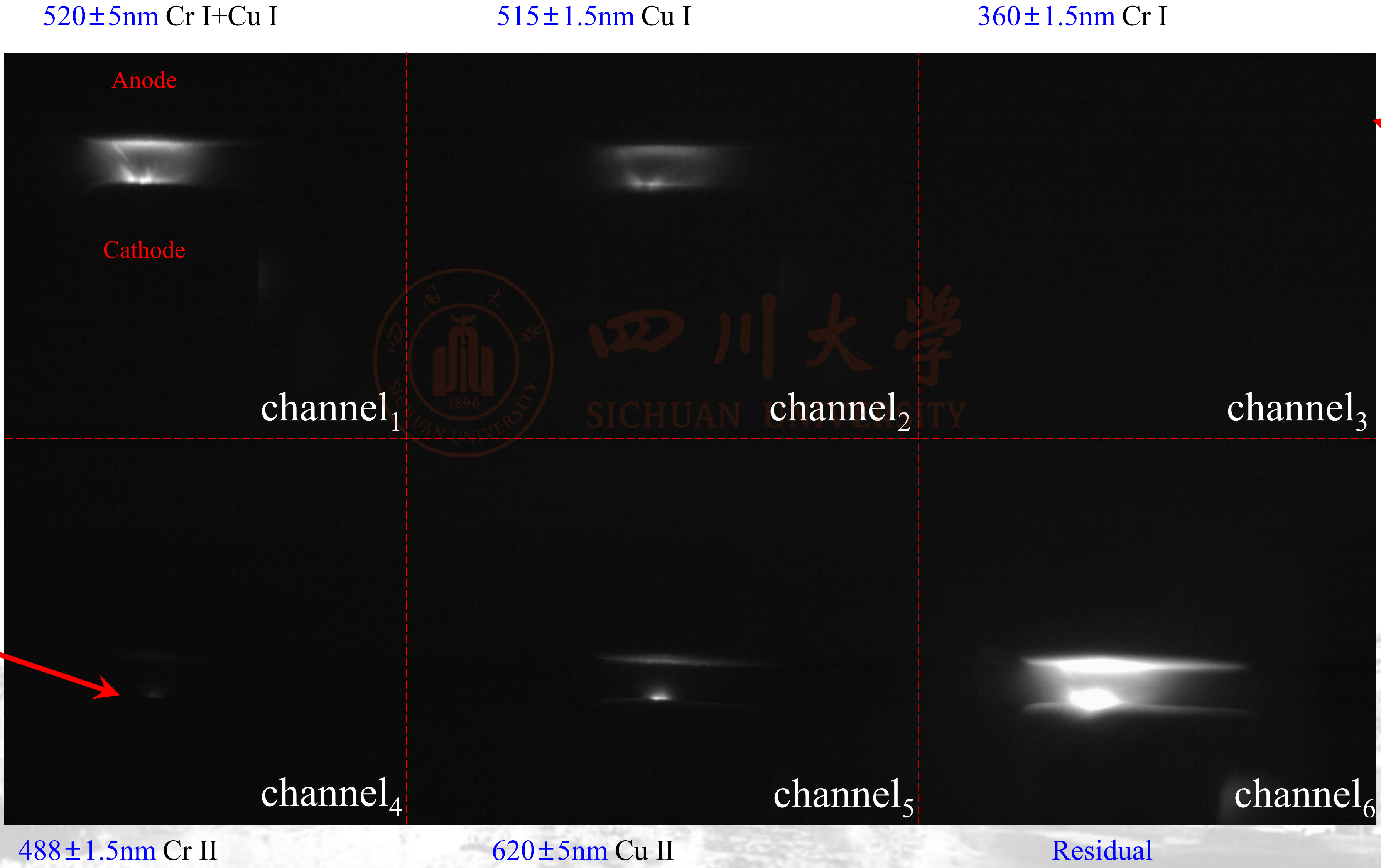
180A

DC

Electrode:

Cu100

The Cr ion signal is an artifact induced by spectral overlap.



The imaging unit exhibits low responsivity outside the visible spectrum

4. Discussion—Spectral Line Identification and Selection

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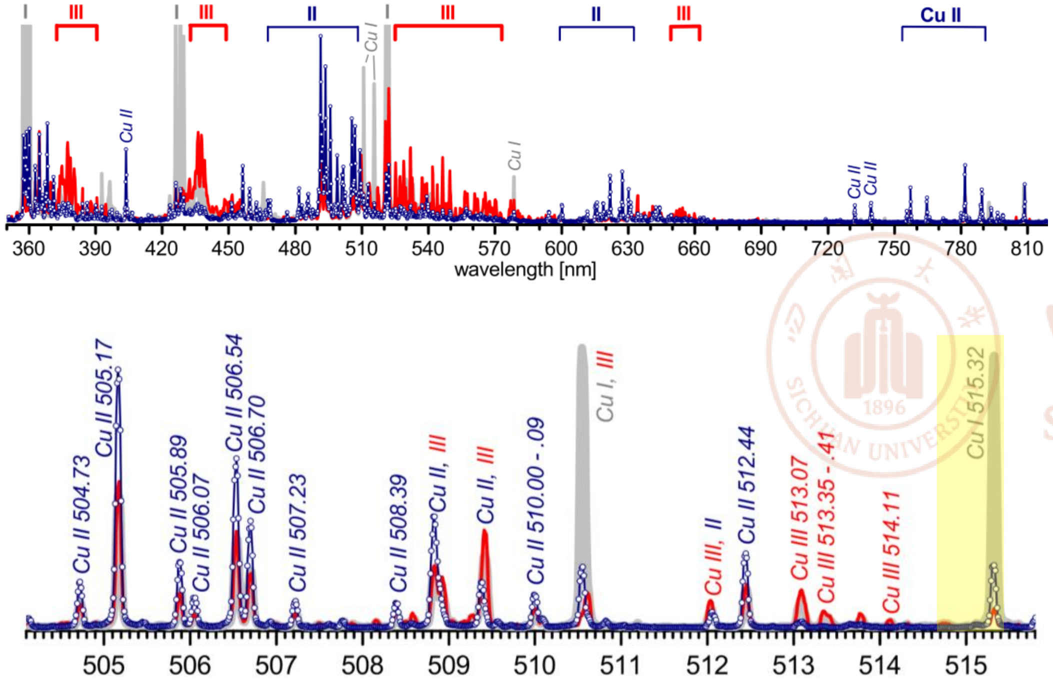
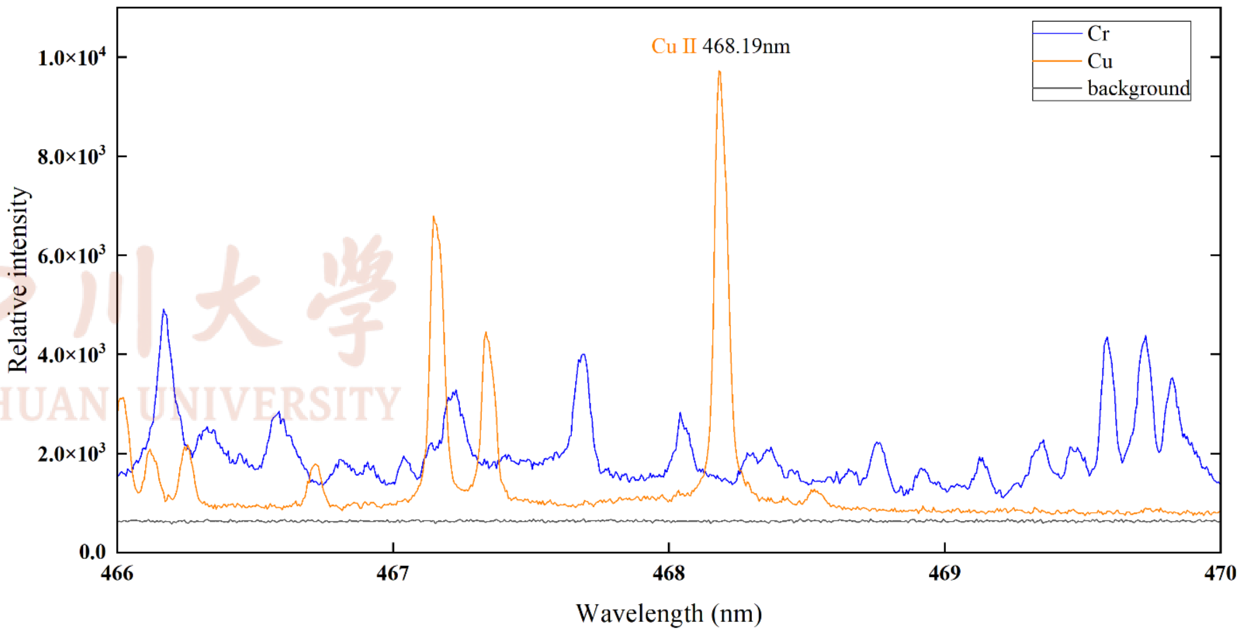
Line blending introduces multi-species contributions to the observed signal.

The present work introduces the results of a spectroscopic investigation of the HCVA with **CuCr** electrodes.



Identification and separation of spectral components were assisted by fingerprint matching with reference spectra.

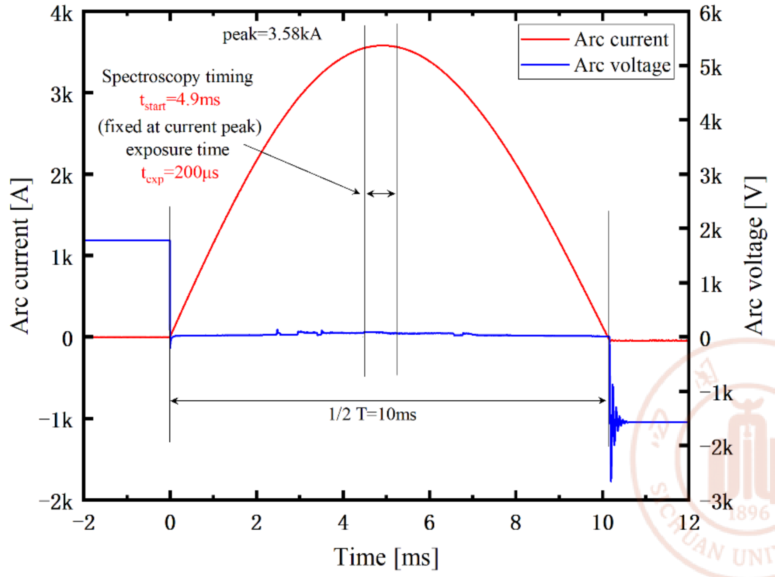
Spectroscopic line identification under identical discharge conditions using **pure Cu** and **pure Cr** electrodes.

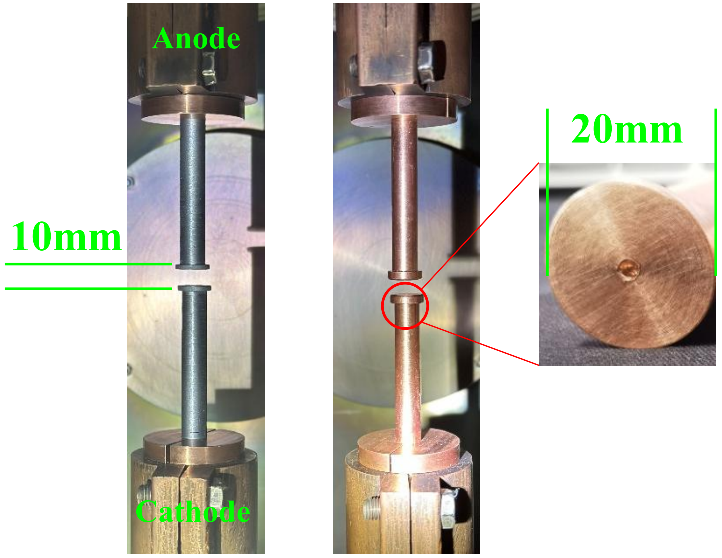


Identified spectral lines using atomic spectral databases such as NIST and Kurucz.

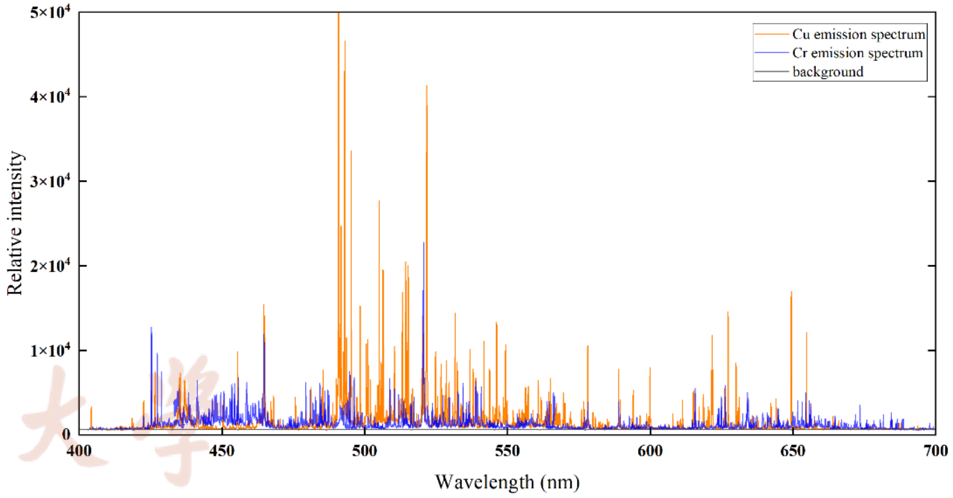
Reference:
[1]M. Lisnyak, et al., Overview spectra and axial distribution of spectral line intensities in a high-current vacuum arc with CuCr electrodes. J. Appl. Phys. 28 September 2015; 118 (12): 123304.

4. Discussion—Spectral Line Identification and Selection

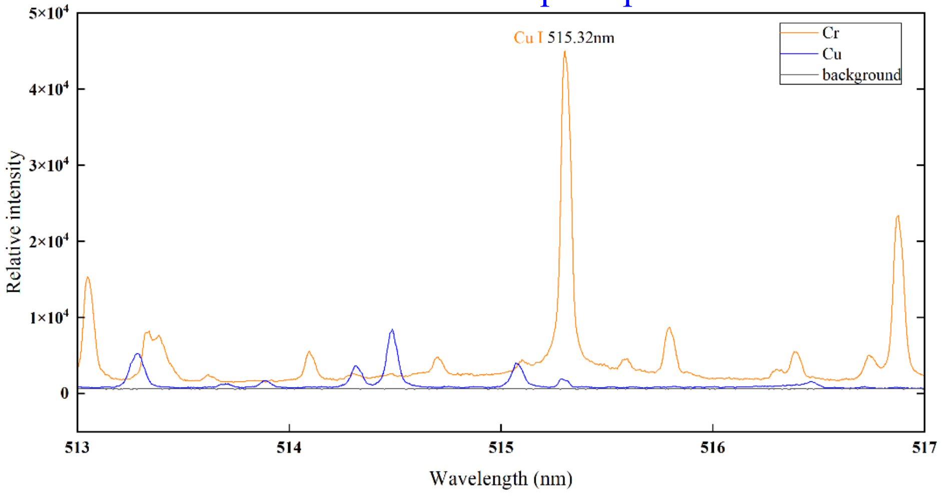




1200 lines/mm: The entire visible band



2400 lines/mm: Overlap of spectral lines

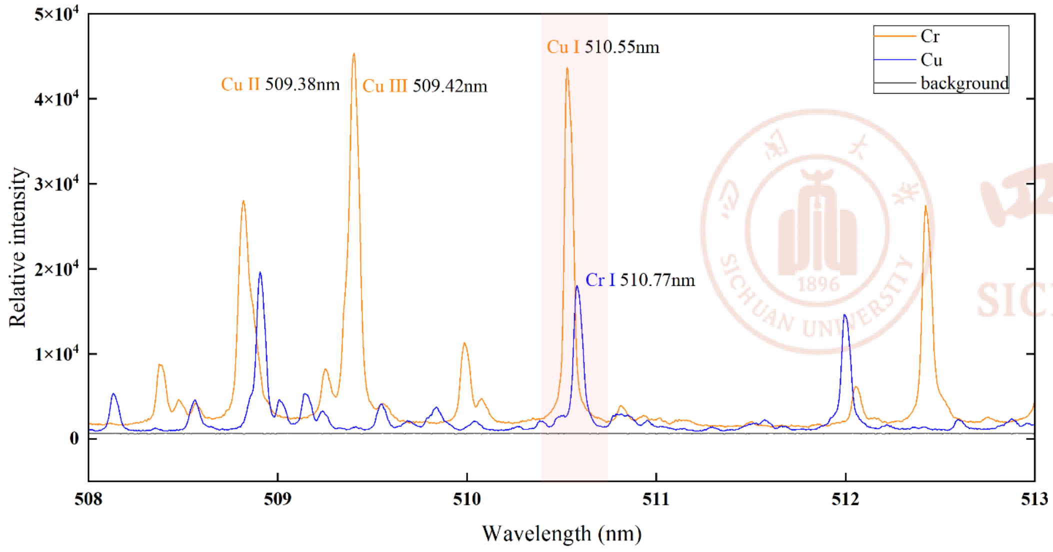


4. Discussion—Spectral Line Identification and Selection

Spectral overlap within the wavelength bands of commonly used spectral lines

Target specie: Cu I

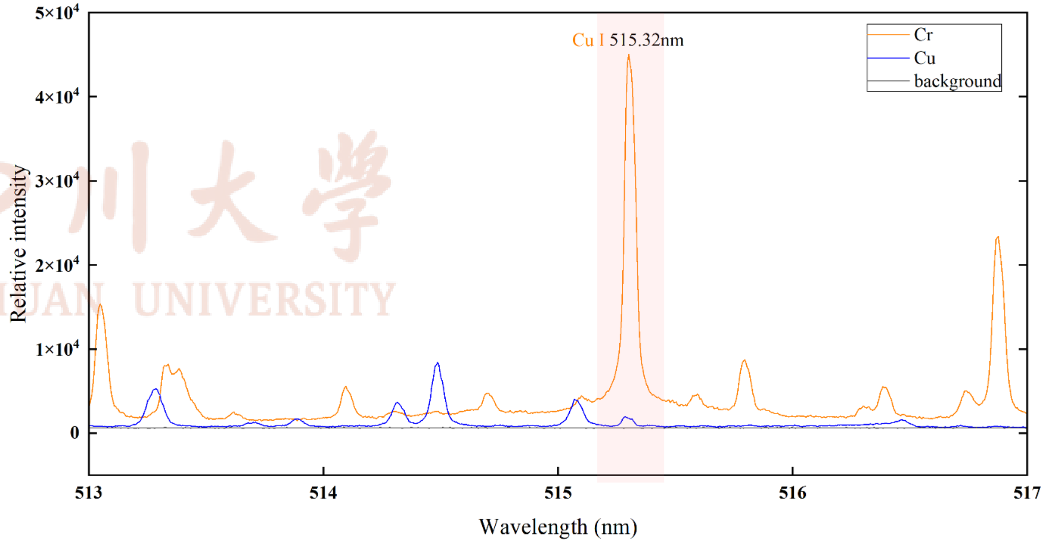
Wavelength： 510.55nm



The 510.55 nm Cu I line, significant spectral overlap occurs.

Target specie: Cu I

Wavelength： 515.32nm



The 515.32 nm Cu I line, no significant spectral overlap is observed

The intensities of the spectral lines change with current

The above conclusions are only valid near the specified current values.

5. Conclusion

- The implemented non-invasive dispersion scheme enables multispectral measurements with minimal light-intensity loss.
- For higher accuracy, spectral-line selection must be more stringent.
- The bandwidth of each bandpass filter should be less than 3 nm.
- When choosing spectral lines, one must account for the effects of current density (i.e., plasma temperature) on line emissivity.

Sequence for determining optical component parameters

Spectral line identification and selection

↓

Center wavelength and bandwidth

↓

Select bandpass filter

↓

Select Dichroic mirror

5. Outlook

Each bandpass filter isolates the emission from a specific transition of one species.

Same observation perspective

↓

Bandpass filter$_1$ | Bandpass filter$_2$ | …

↓

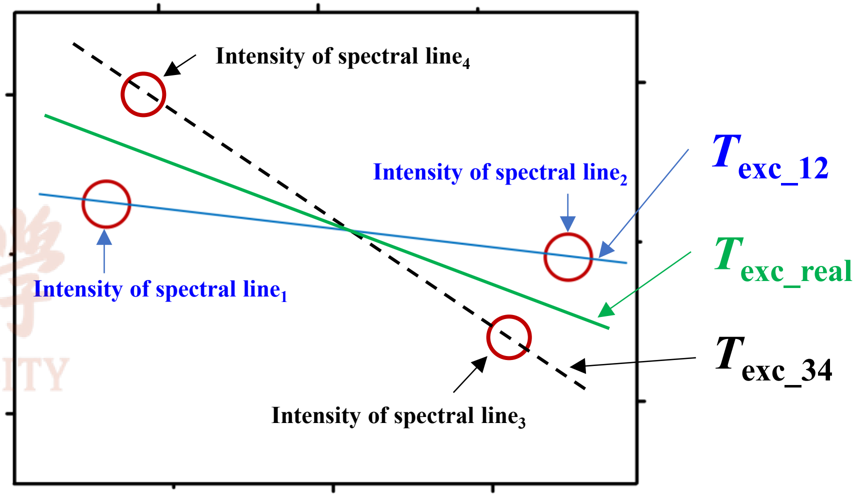
Bandwidth$_1$ | Bandwidth$_2$ | …

↓

Intensity of spectral line$_1$ | Intensity of spectral line$_2$ | …

↓ Boltzmann plot Method

Excitation temperature of partical$_1$ …



More channels,

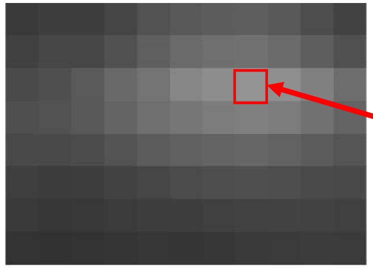
more species,

more accurate *T*

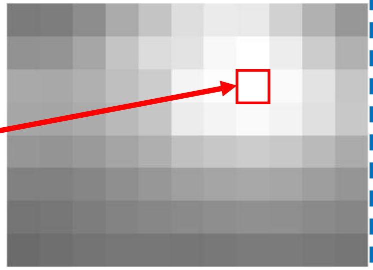
At least two channels, can calculate the excitation temperature.

5. Outlook—Pixel-Wise Temperature & Density Mapping

Temperature mapping



The intensities at the same pixel location across different channels: the emission strengths of the respective spectral lines at that pixel.



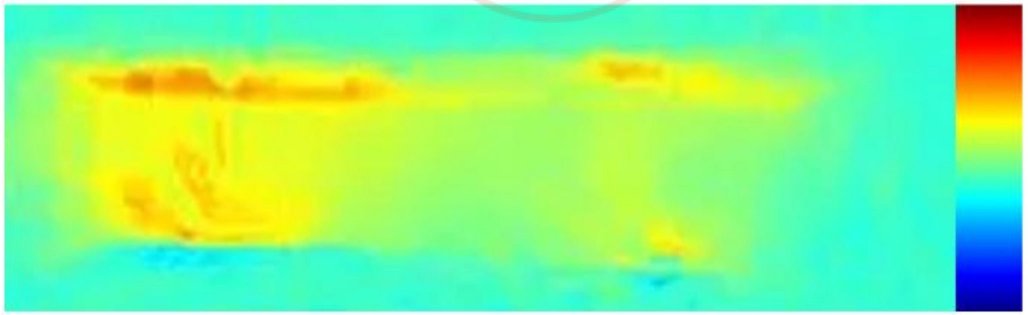
Spectral line intensity

$$\ln\left(\frac{I_i\lambda_i}{g_iA_i}\right)-\ln\left(\frac{I_j\lambda_j}{g_jA_j}\right)=-\frac{E_i}{k_BT}+\frac{E_j}{k_BT}$$

Pixel intensity

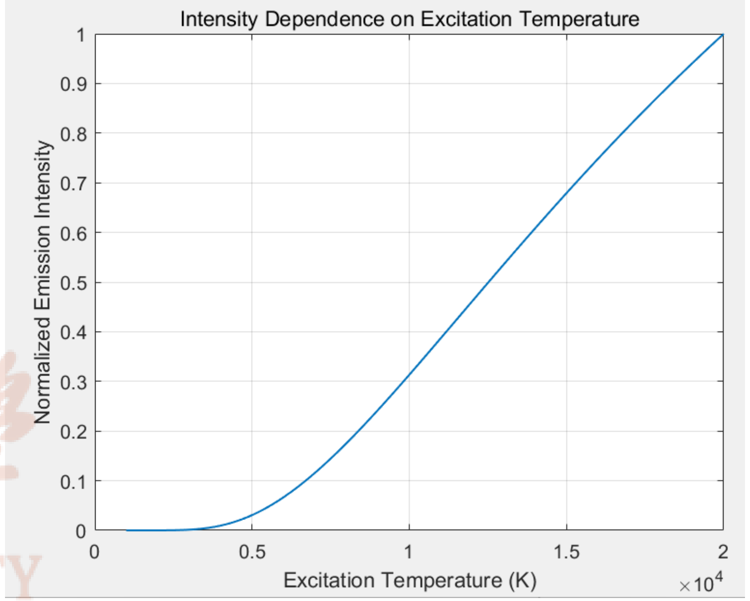
$$T(x,y)=\frac{E_2-E_1}{k\cdot\ln\left(\frac{I_1(x,y)gA_2\lambda_2}{I_2(x,y)gA_1\lambda_1}\right)}$$

Anode



Cathode

Density mapping



$$I_i=N\cdot\frac{e^{-E_i/k_BT}}{Z(T)}\cdot\frac{g_iA_ihc}{4\pi\lambda}$$

N —— Number of particles

T —— Excitation temperature

To calculate particle density, the excitation temperature must be determined first.

THANK YOU

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