Spectral characterization of pulsed plasma discharges at CCHEN and NSF Engineering Research Center for EUV Science and Technology.

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Acknowledgments: Fondecyt Iniciacion 11121587, Conicyt Inserción 791100020 and Anillo ACT 1115

The talk is divided in:

Spectral observations at CCHEN:

- Visible spectroscopy (Plasma Focus)
- VUV (X-pinches)

Spectral observations at NSF ERC EUV

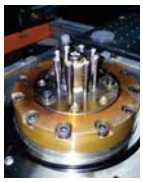
- EUV and Soft X-ray (Pulsed capillary discharge)

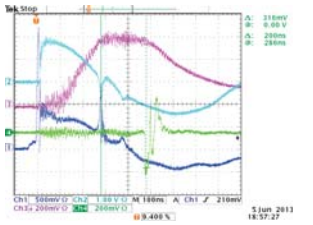
Joint ICTP-IAEA Advanced School and Workshop on Modern Methods in Plasma Spectroscopy. Trieste, Italy .16 March – 27 March 2015

Thermonuclear Plasma Department Chilean Nuclear Energy Commission

Spectral observations at CCHEN: Plasma Focus Discharge PF-400J

Stored Energy: 400J
Peak Current: 130kA
T/4: ~ 300ns
Working gases:
- Hydrogen @ 9 mbar
- Hydrogen and Neon, Nitrogen or Krypton mixture.





- "Neutron emission from a fast plasma focus of 400 Joules", Silva P, Moreno J, Soto L, Birstein L, Mayer R E and Kies W, App. Phys. Lett. **83** 3269–3271 (2003)
- "Potentiality of a small and fast dense plasma focus as hard x-ray source for radiographic applications", C. Pavez, J. Pedreros, M. Zambra, F. Veloso, J Moreno, A. Tarifeño-Saldivia and L. Soto, Plasma Phys. Control. Fusion **54** 105018 (2012)

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Diagnostics and Experimental Setup Plasma Focus observations

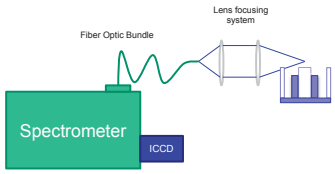
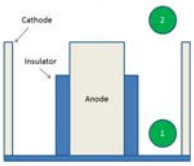


Image shows focusing spot of fiber optic



Diagnostics
- VIS Spectrometer Czerny-Turner 0.5m
  - Grating: 300 g/mm and 1200 g/mm
  - ICCD with integration time: 20 ns
  - Fiber Optic Bundle: 19 F.O. Line to circular bundle.

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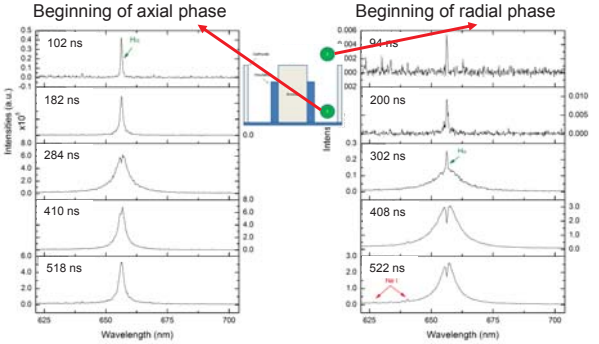
Plasma Focus: 98% H_2 + 2% Ne

VIS spectroscopy



"Time resolved visible spectroscopy studies of the plasma sheath evolution in a low energy plasma focus device" Avaria, G; Cuadrado, O; Moreno, J; Soto, L; J. Phys: Conf. Series **591** 12024

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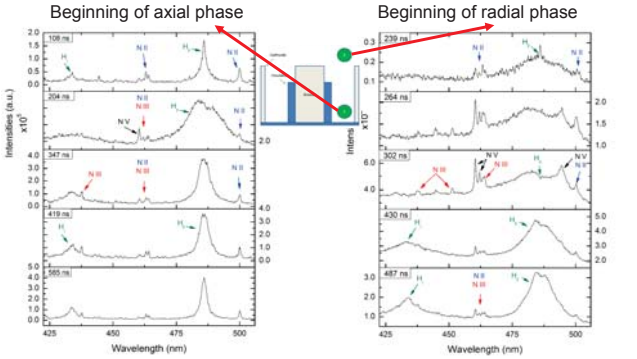
Plasma Focus: 98% H_2 + 2% N_2

VIS spectroscopy



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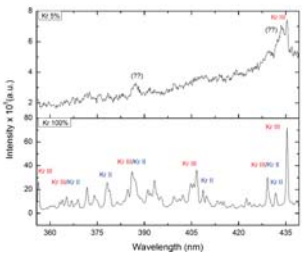
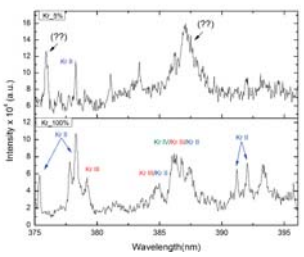
Plasma Focus: 95% H_2 + 5% Kr

VIS spectroscopy

Mixture and pure Krypton: Lines dissapear when gasses are mixed.



Trying to look for missing lines, not even in high resolution lines are observed.



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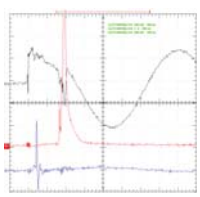
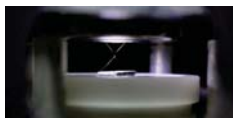
Multipurpose Discharge X-Pinch

Stored Energy: 350J
Peak Current: 120kA
T/4: ~ 450 ns
Wires: Aluminum (Al) 25 µm , Copper (Cu) 10 µm.
Charging voltage: 24kA





- "Design and characterization of a small multipurpose capacitor bank for plasma physics and pulsed power experiments", A. Tarifeño, C. Pavez and L. Soto, Phys. Scr. **T131** 014029 (2008)
- "Wire array experiments in a low impedance and low current generator", N. Cabrini, C. Pavez, G. Avaria, P. San Martin, F. Veloso, B. Zúñiga, A. Sepúlveda, L. Soto, J. Phys.: Conf. Series **591** 012026 (2015)

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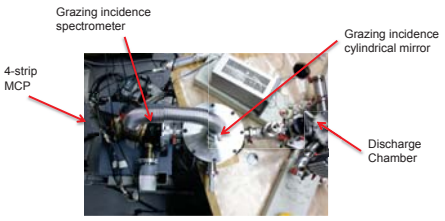
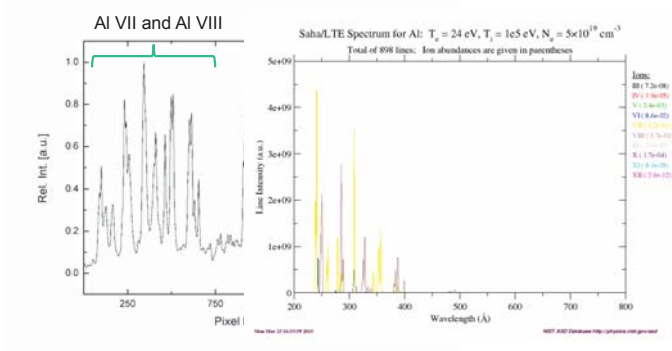
Diagnostics and Experimental Setup
X-pinch observations



Time resolved XUV measurements (X-pinch)

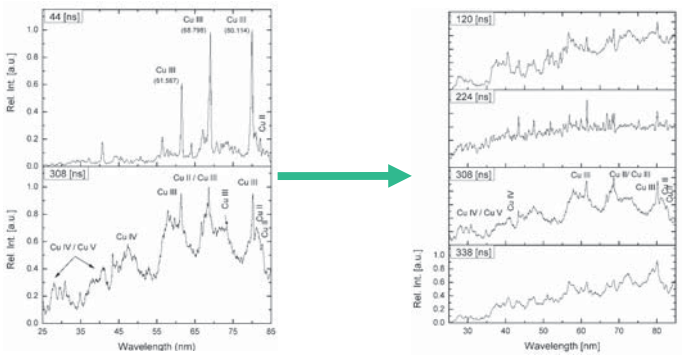
- Grazing incidence cylindrical mirror to focus radiation into spectrometer slit.
- Grazing incidence spectrometer, with 300 l/mm grating and 10μm slit.
- 4 strip MCP with 10 ns integration time and 15 ns between frames
- DSLR acquisition

X-pinch: Aluminum 25 μm
Calibration



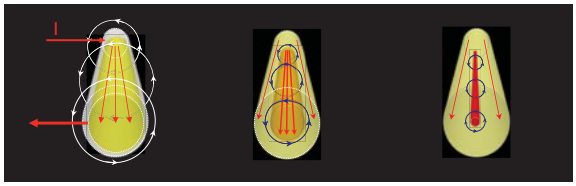
X-Pinch: Cu 10 μm

Grazing incidence spectrometer



Spectral observations at NSF ERC EUV:

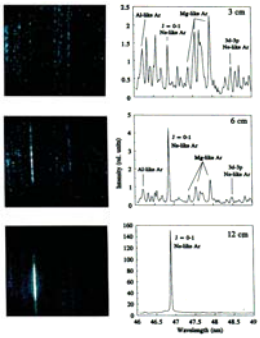
Extreme Degree of Ionization in Homogenous Micro-Capillary Plasma Columns Heated by Ultrafast Current Pulses*

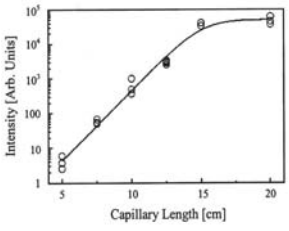


*Phys. Rev. Lett. **114** 095001 (2015)

Capillary plasma columns generate gain-saturated soft X-ray amplification in Ar^{+8}

Exponential amplification in Ar^{+8} $3p^1S_0$-$3s^1P_1$ line at 46.9 nm

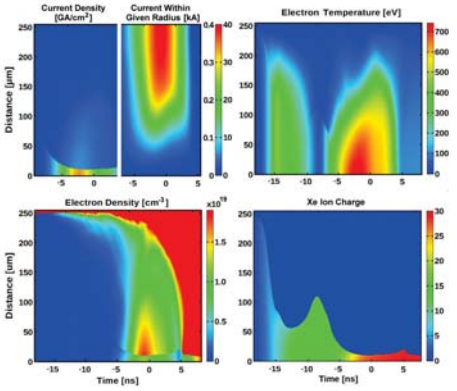




*Phys. Rev. Lett. **73** 2192 (1994)

3-4 mm diameter Capillary, 25-40 kA, >30 ns rise time
Electron Temperature: 60-100 eV, Electron Density: 0.2-1.0×10^{19} cm^{-3}

How hot and highly ionized plasmas can capillary discharges produce?

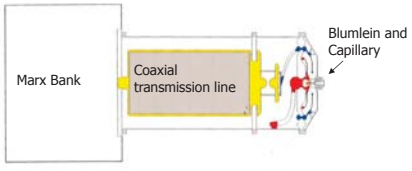


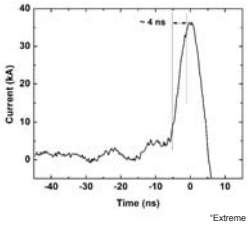
- Pressure: 4 Torr Xe
- Current: 40 kA
- Cap. ID: 520 μm
- Current Pulse width: 7 ns FWHM
- Current rise time 10-90%: 4 ns
- Highest ionization degree: **Ni-like Xe (Xe^{26+})**

"Extreme Degree of Ionization in Homogenous Micro-Capillary Plasma Columns Heated by Ultrafast Current Pulses", G. Avaria, M. Grisham, J. Li, F.G. Tomasel, V.N. Shlyaptsev, M. Busquet, M. Woolston, J.J. Rocca, Phys. Rev. Lett. **114** 095001

Ultrafast High Current Capillary Discharge

- Currents ranging from 30-40 kA
- Rise times 10-90% < 4 ns
- 500 μm ID Al_2O_3 Capillaries





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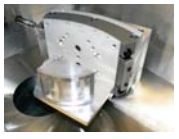
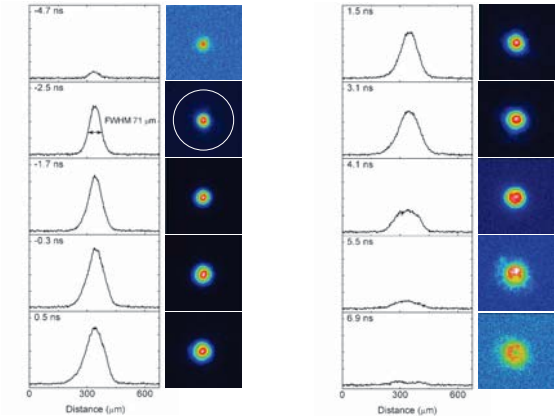
Diagnostics

- Time Resolved Spectra
  - Hettrick SXR Flat field spectrometer
  - Range 10-200 Å
  - Gated MCP, 2.5 ns integration
- Time Integrated Spectra
  - Convex KAP or PET crystal
  - Range first order: 3-23 Å
- Pinhole Imaging
  - 38 μm diameter pinhole
  - Magnification 8.3×



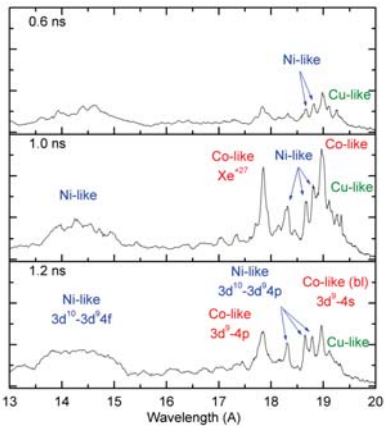
Time Evolution: pinhole images $h\nu > 0.6$ keV

Current: 35.9±0.8 kA, Filter: 1 μm Mylar + 0.5 μm Aluminum



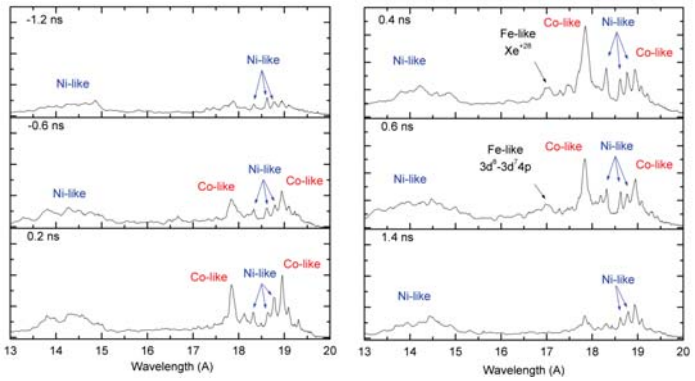
Xe^{+27} ions dominate the spectra

Current 34.6 ± 0.5 kA, Xenon at 0.5 Torr

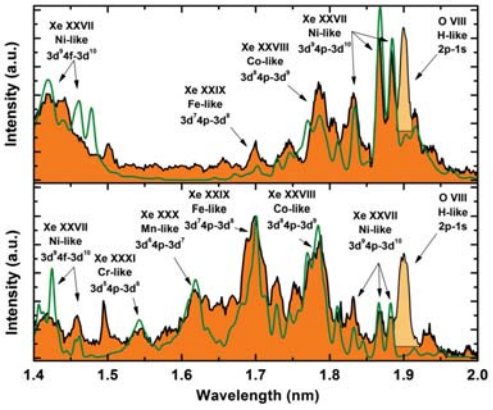


Xe^{+28} observed at higher currents

Current 37.6 ± 0.6 kA, Xenon @ 0.5 Torr



Simulations agree with experimental observations:



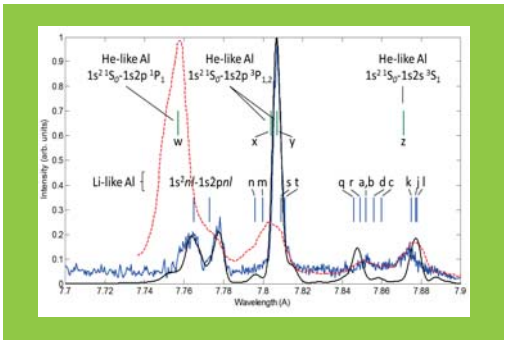
P_{xe} ~ 0.5 Torr
N_e ~ 3 x 10^{19} cm^{-3}
T ~ 350 eV

80:1 H_2:Xe
N_e ~ 1-1.5 x 10^{19} cm^{-3}
T ~ 700 eV

"Extreme Degree of Ionization in Homogenous Micro-Capillary Plasma Columns Heated by Ultrafast Current Pulses", G. Avaria, M. Grisham, J. Li, F.G. Tomasel, V.N. Shlyaptsev, M. Busquet, M. Woolston, J.J. Rocca, Phys. Rev. Lett. **114** 095001

Interesting spectroscopic observations:

Intercombination line dominating over resonance line for many elements.



Conclusions:

CCHEN:

1. Different observations done, many of them developing in the last weeks. Encouraging quantitative results in sight.
2. A lot of open questions that need answers (you are invited to join the ride).

NSF ERC EUV

1. Simulations and experimental observations show that the use of ultrafast currents in microcapillary discharges have the potential to generate highly ionized Xenon, up to Fe-like levels.
2. Interesting spectroscopic phenomena is observed: Intercombination line over resonance line intensity ratio.
3. Excelent conditions to obtain laser gain at 10 nm, from Ni-like Xenon.

Acknowledgments: Fondecyt Iniciacion 11121587, Conicyt Inserción 791100020 and Anillo ACT 1115