Dramatic Improvement of the 41.8 nm Xe^{8+} Laser Output using a Multi-mode, Gas-filled Capillary Waveguides

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Outline

I. **Introduction**

II. **Experiment with sapphire capillary**
(proof-of-principle)

III. **Experiment with glass capillaries**
(detailed investigation)

IV. **Summary**

I. Introduction

1994 - 3 specific schemes for collisional OFI XRL proposed (Xe^{8+}, Kr^{8+}, Ar^{8+})

1995 - demonstration of the **Xe^{8+}** laser at **41.8 nm** (Stanford University)

2000 - **saturated amplification** of the Xe^{8+} laser (LOA)

2002 - demonstration of the **Kr^{8+}** laser at **32.8 nm** (LOA)

Major problem: length of **plasma too short** due to ionization–induced refraction

Need to guide !

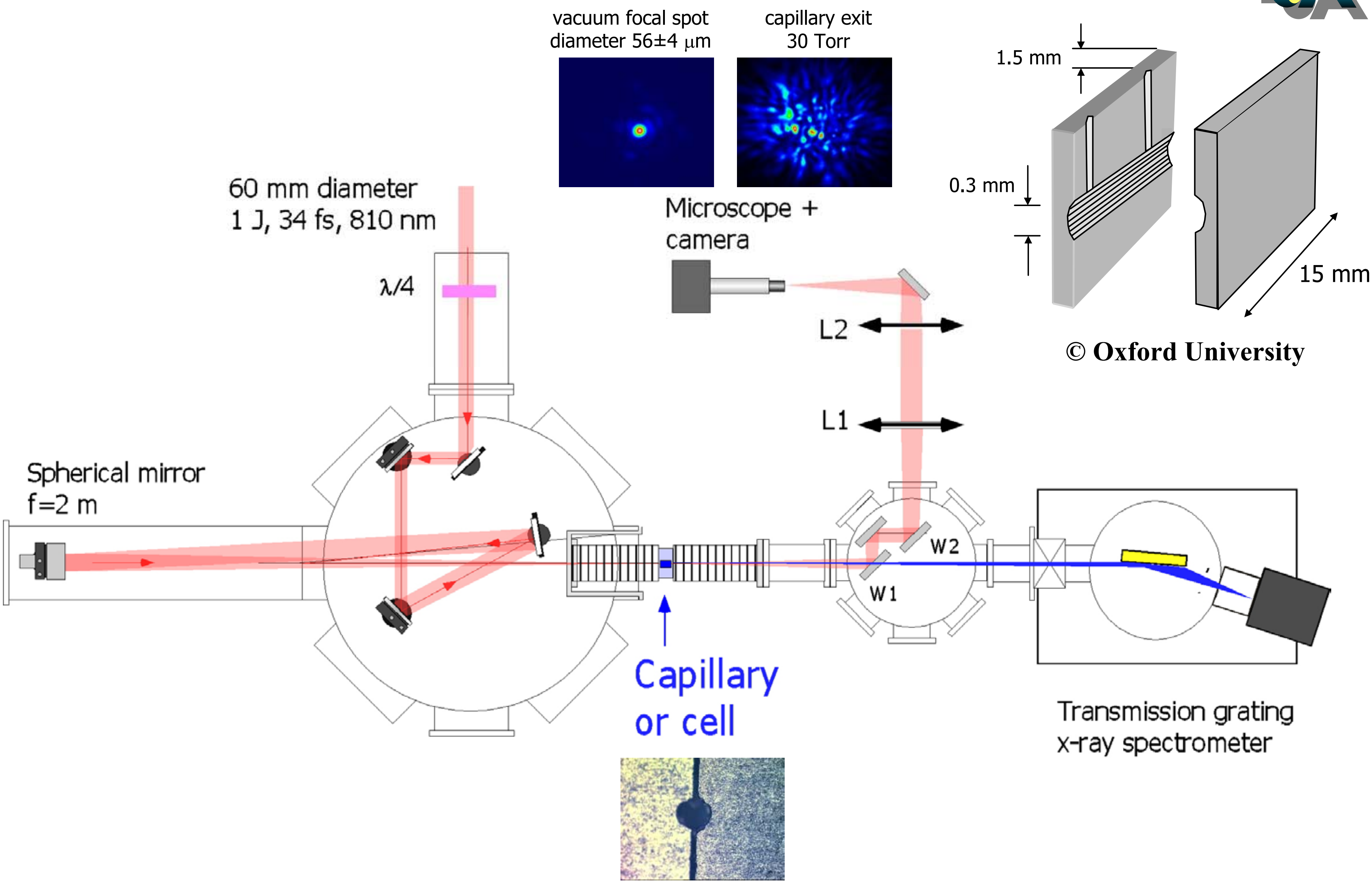
2003 - demonstration of **Xe^{8+}** laser in a **plasma waveguide** (LOA/Oxford/LPGP)

Alternative: **gas-filled capillary**

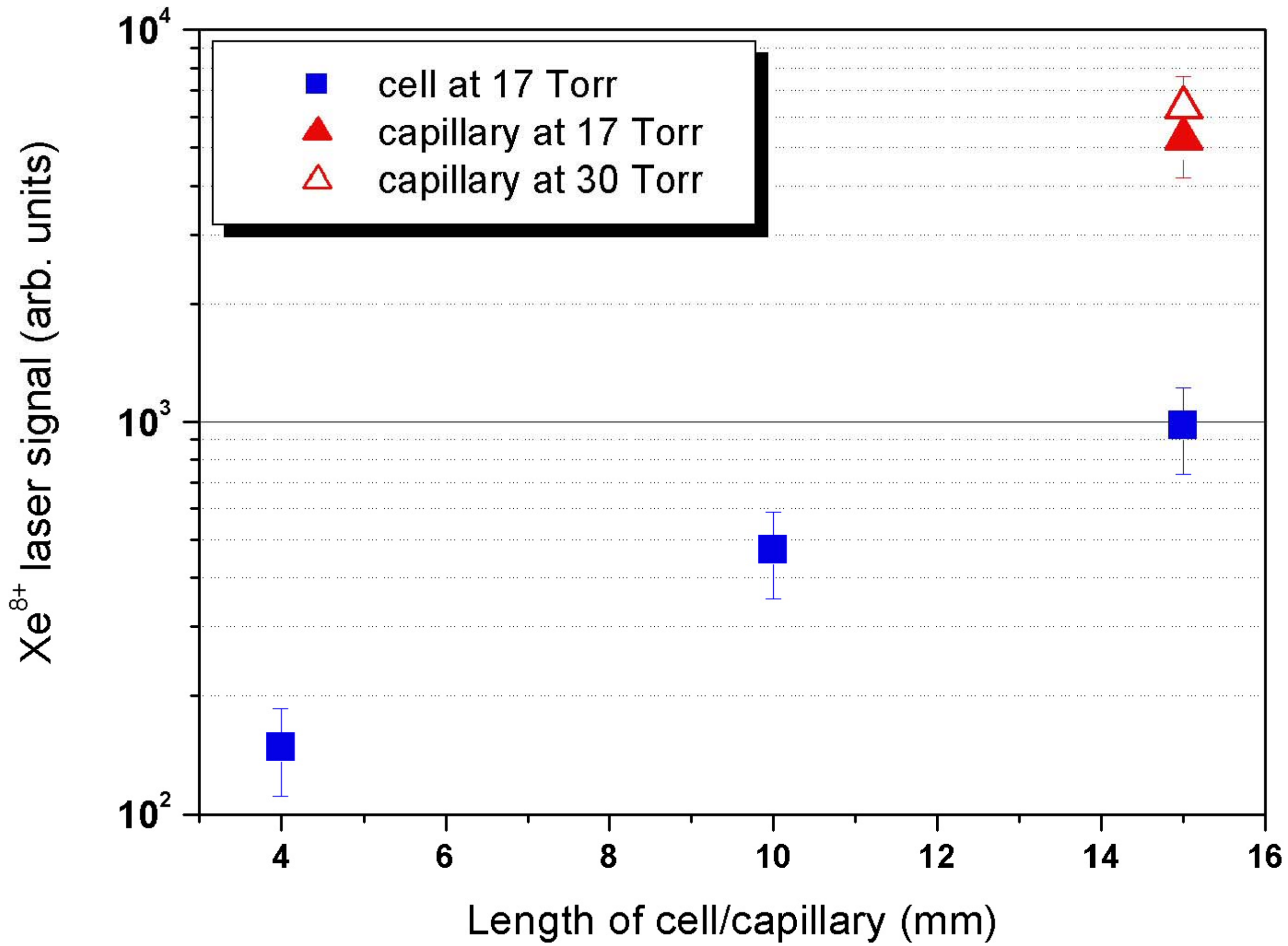
Problem with ”small” (mono-mode) capillary is its **lifetime**

→ **”large” (multi-mode) capillary** ???

II. Experiment with sapphire capillary



Optimized lasing with cell and capillary



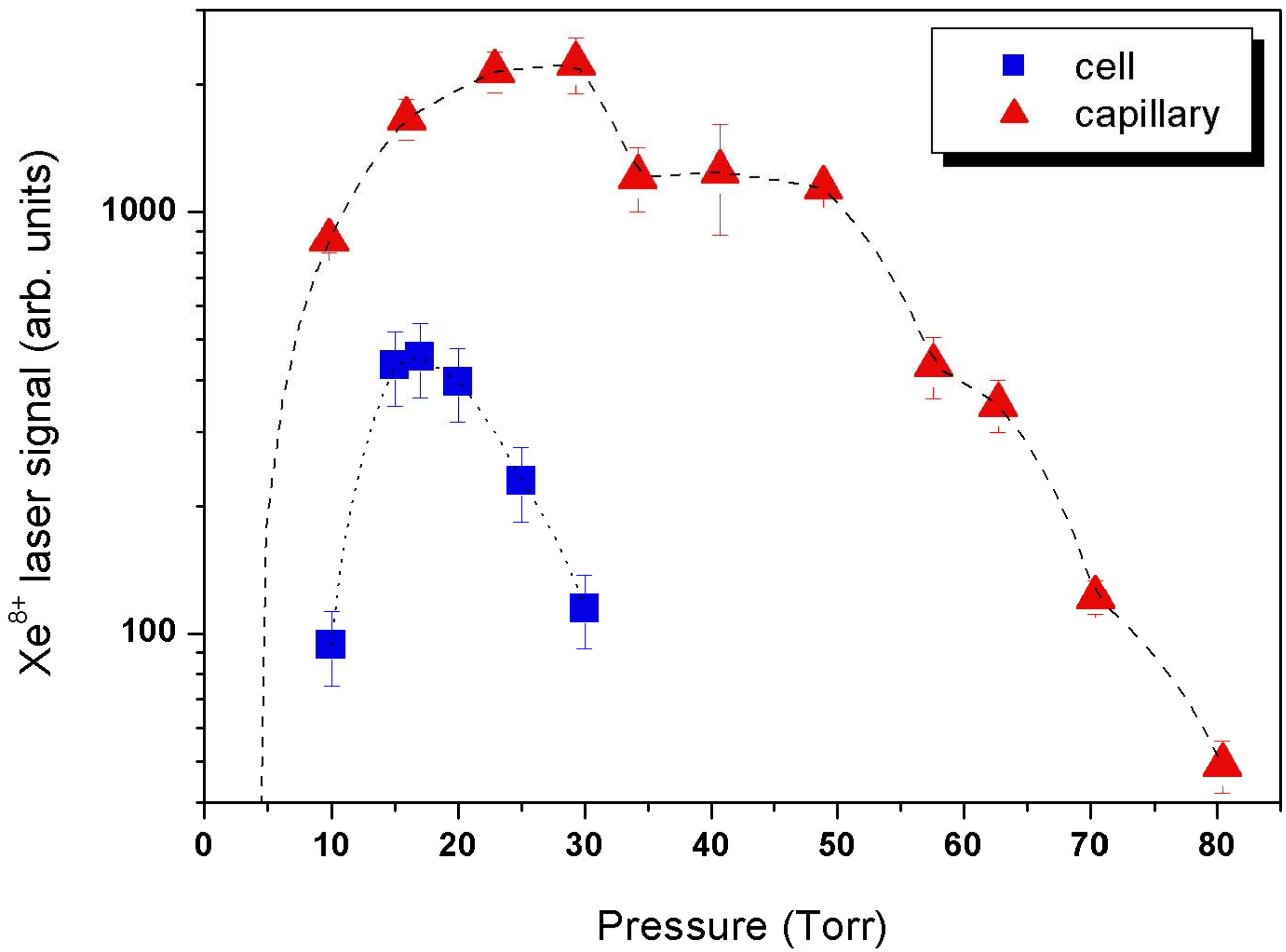
Enhancement:

7x

43x

Pressure dependence

15-mm long cell/capillary



cell

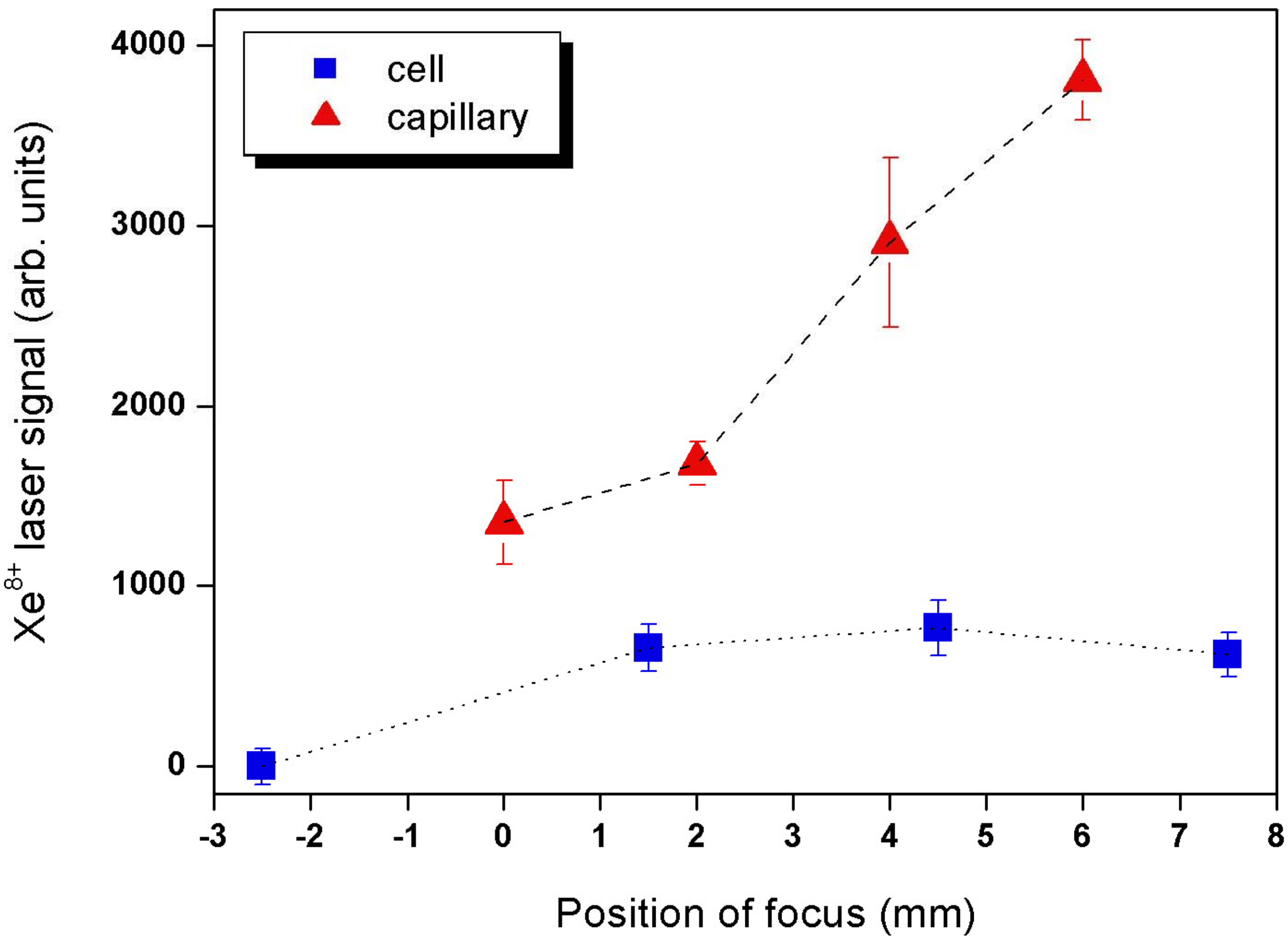
p_{opt} = 17 Torr
range: 10 - 30 Torr

capillary

p_{opt} = 30 Torr
range: 10 – 70 Torr

Effect of the focus position

15 mm cell/capillary, Xe at 17 Torr



cell

weak effect
z_{opt}= ~5 mm

capillary

strong effect
z_{opt} = 6 mm

Numerical simulation of propagation

Time-dependent propagation of the driving pulse (developed from the original code of G.J. Pert, University of York):

1. paraxial wave equation solved in cylindrical geometry

2. gas ionization (OFI) is taken self-consistently

Included: - ionization induced refraction
- relativistic self-focusing

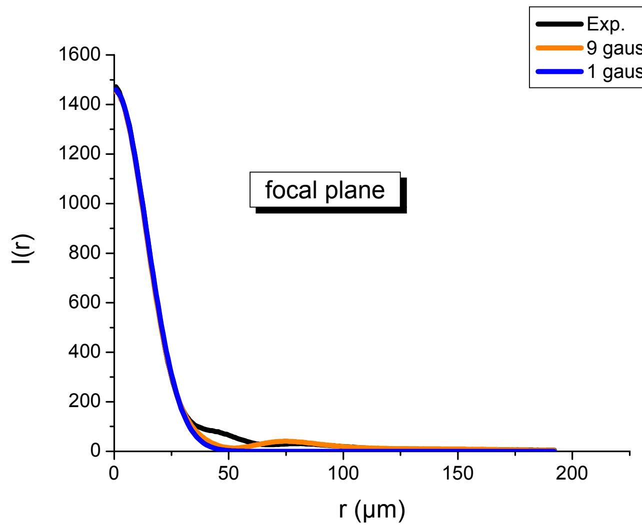
Excluded: - hydrodynamic effects

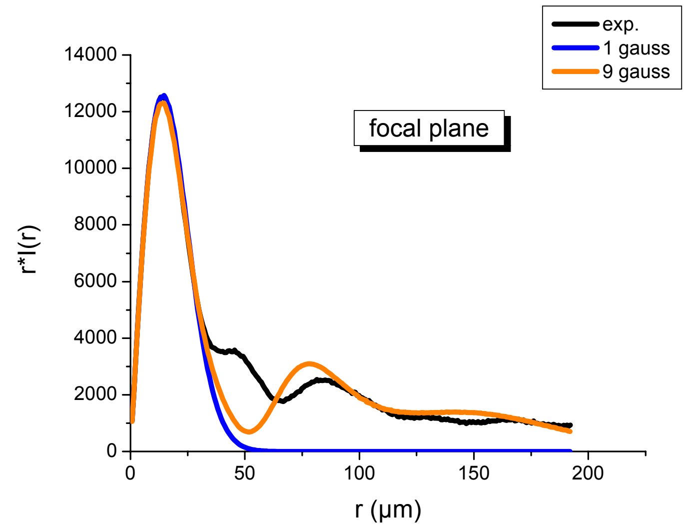
Capillary wall: simulated by a boundary layer with a dielectric constant which is adjusted so as to reproduce the measured value of transmitted pump energy (80% at 17 Torr, 40% at 25 Torr)

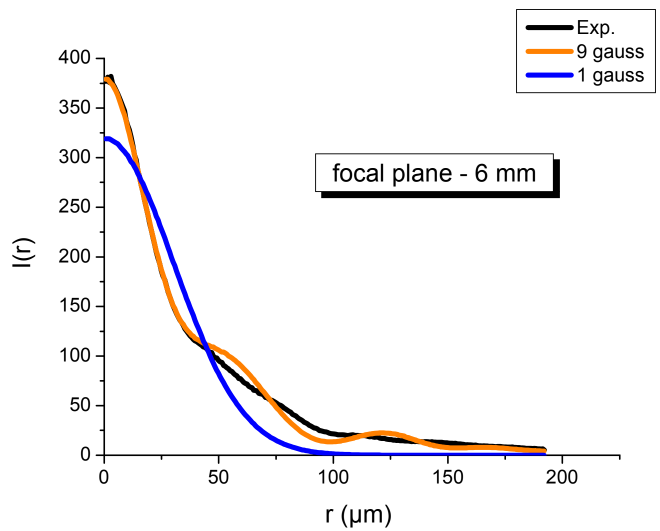
Laser field: sum of several Gaussian modes as the best fit of the experimentally measured fluence profile in vacuum

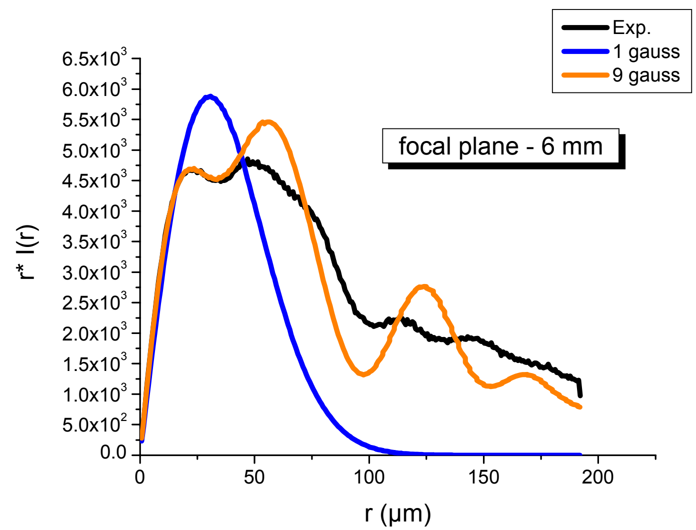
Importance of the beam profile

As the **radius** of the capillary is **5 x** larger than the **focal spot**, a large part of the energy which is outside the central spot can enter the capillary tube.





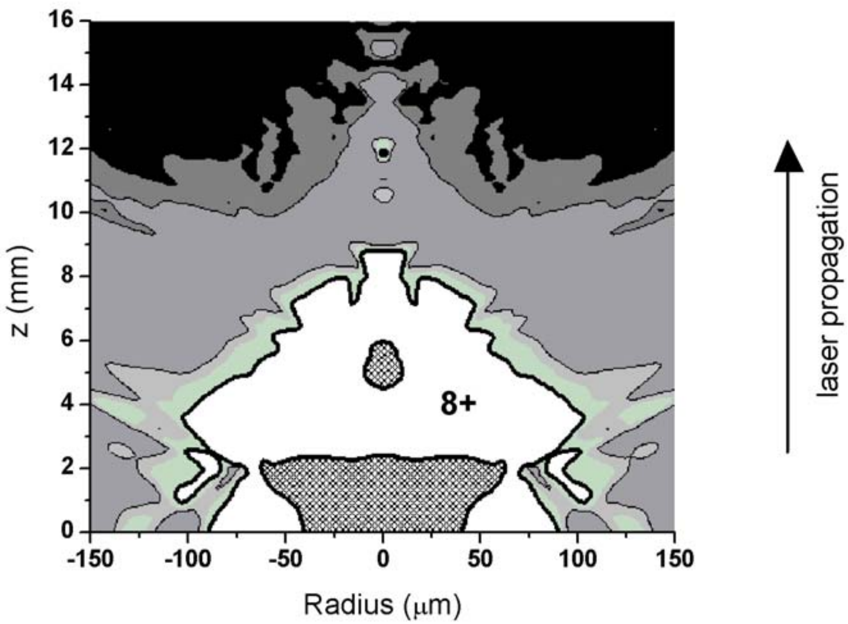




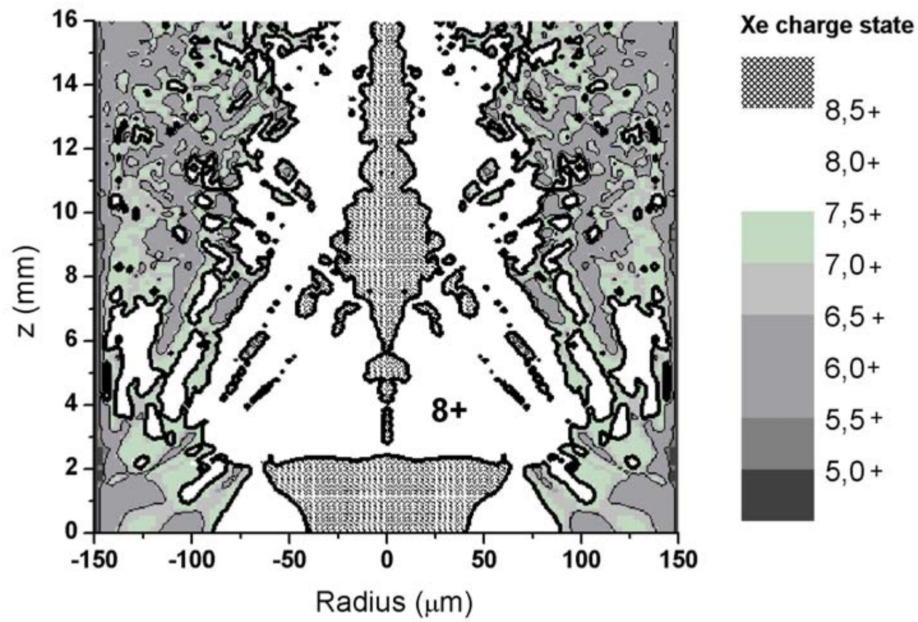
Calculated distribution of charge states

- 0.81 μm laser, 1 x 10^{18} Wcm^2, 34 fs, circular polarization
- position of vacuum focus 6 mm inside, Xe at 17 Torr

cell



capillary



- Xe^{8+} generated up to z=8 mm
- **no improvement** when focusing beyond 6 mm

- Xe^{8+} over the **whole length**
- **sensitive** to the focusing, region of Xe^{8+} is largest for z=6 mm

Modeling of radiative transfer

Amplification of axial emission in an active medium

$$\frac{\partial I}{\partial z} = gI + J_0 \qquad g(z) = \frac{G_0}{1 + I(z)/I_{sat}}$$

+

Refraction of the XUV laser beam

$$\frac{d}{ds}\left(n\frac{d}{ds}\vec{r}\right) = \vec{\nabla} n(\vec{r})$$

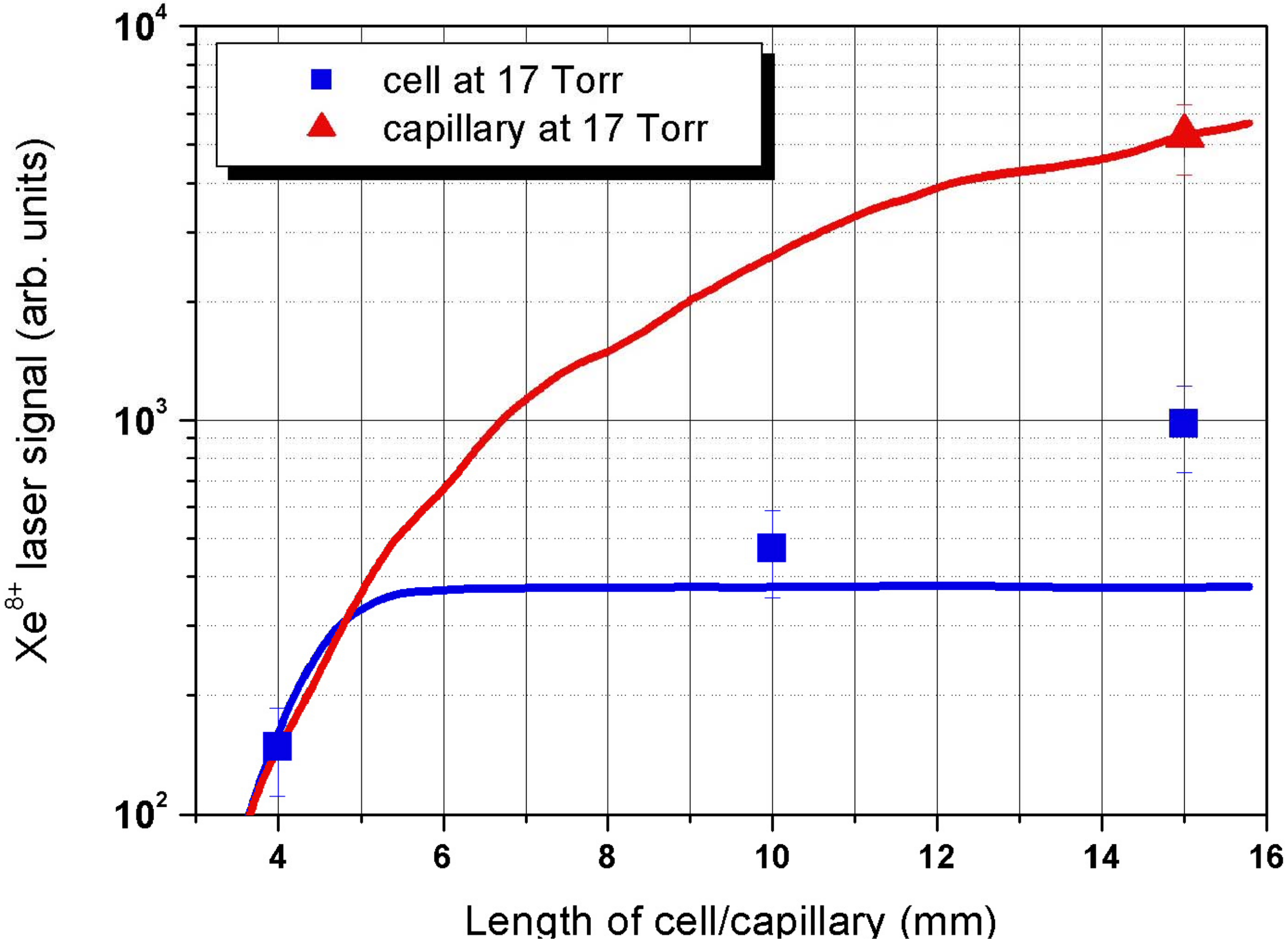
$\Rightarrow$ $I_{XRL}(z,r,\theta)$

Assumptions:

- G_0 and J_0 are constant along the amplifier axis
- previously measured values of G_0 and J_0 were used
- delay between the IR and XUV photon is neglected
- only photons travelling in the positive direction are considered

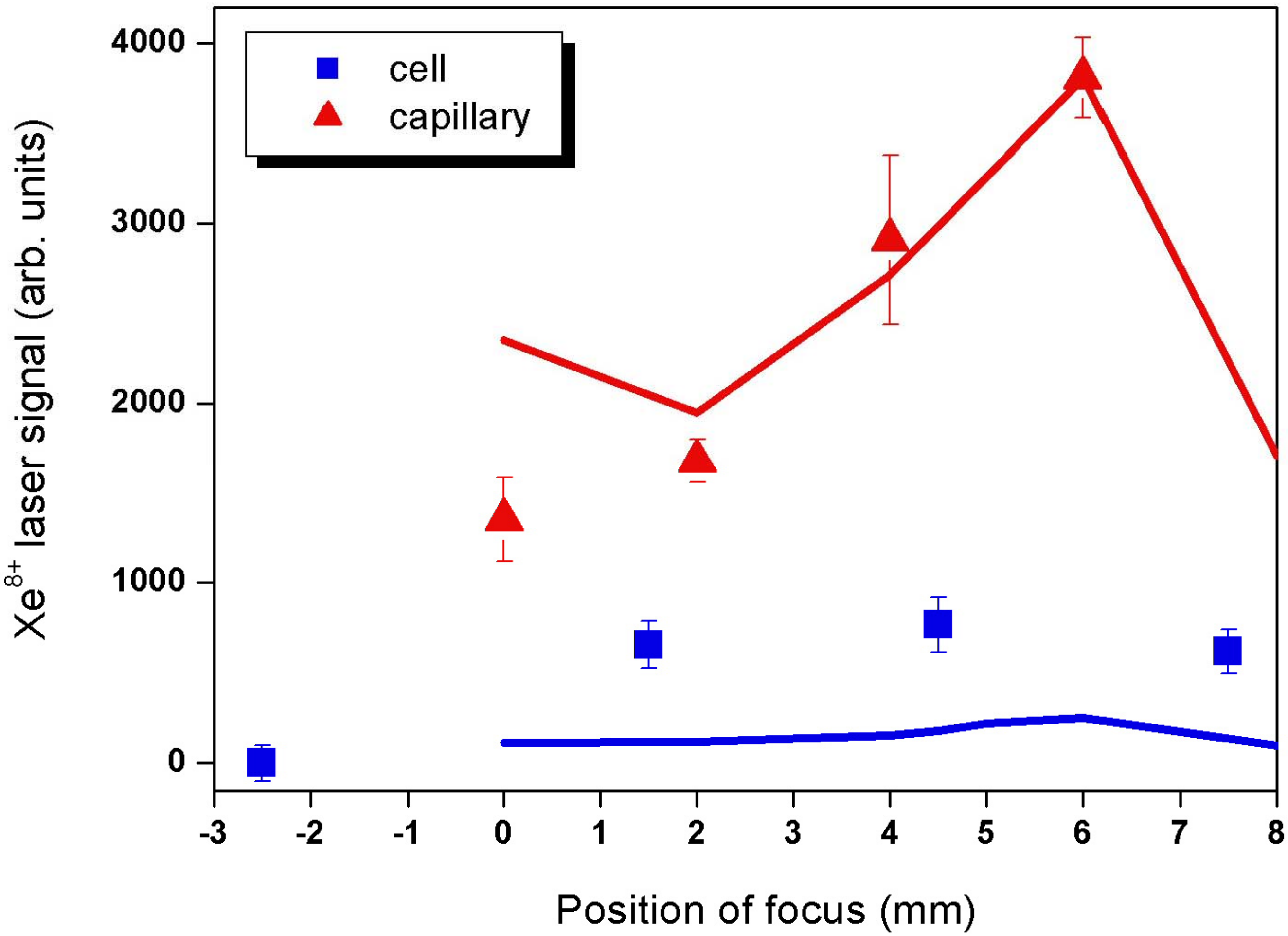
Experiment vs. modeling: length

Position of vacuum focus 6 mm inside

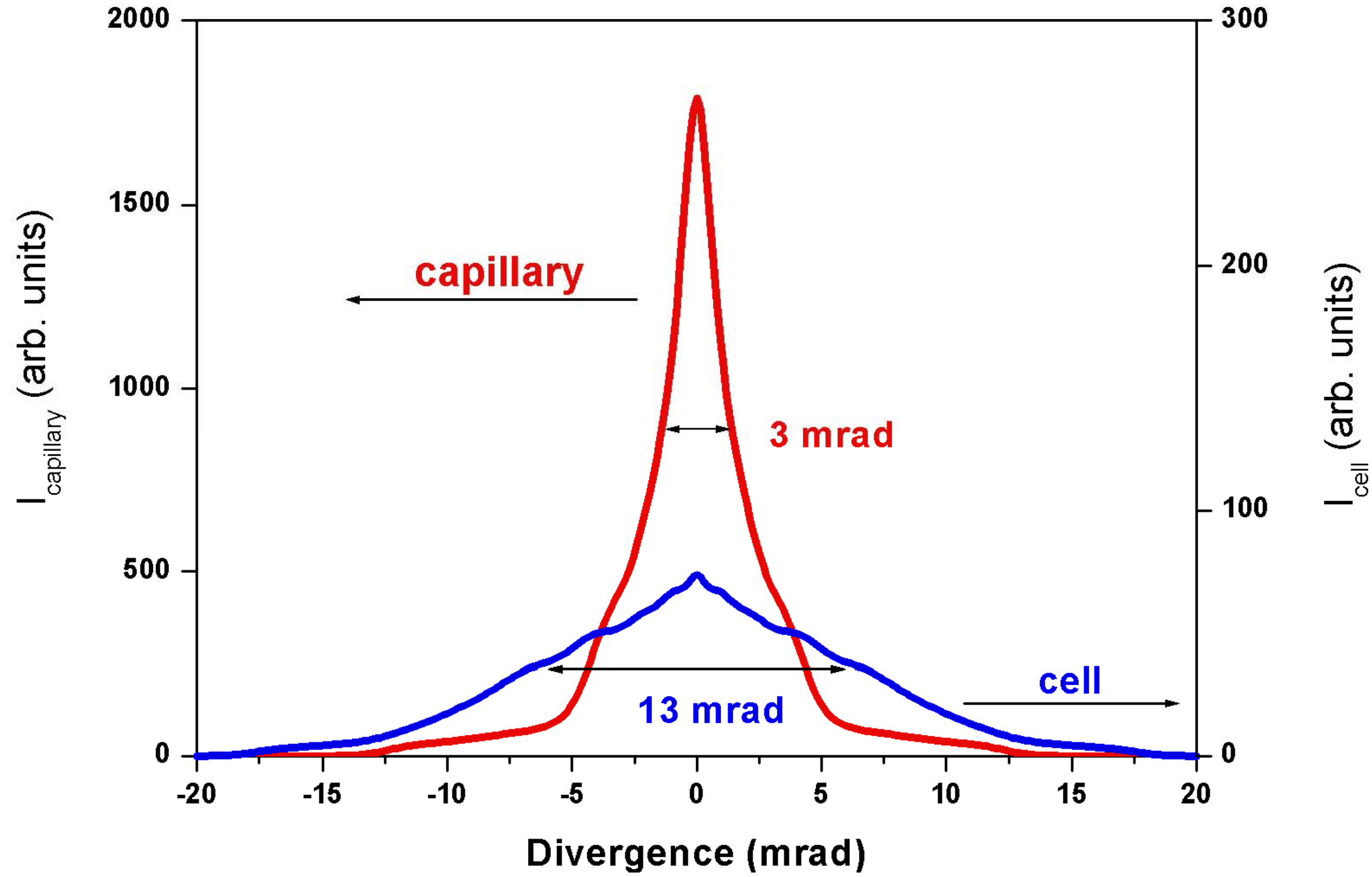


Experiment vs. modeling: focus

15 mm cell/capillary, Xe at 17 Torr

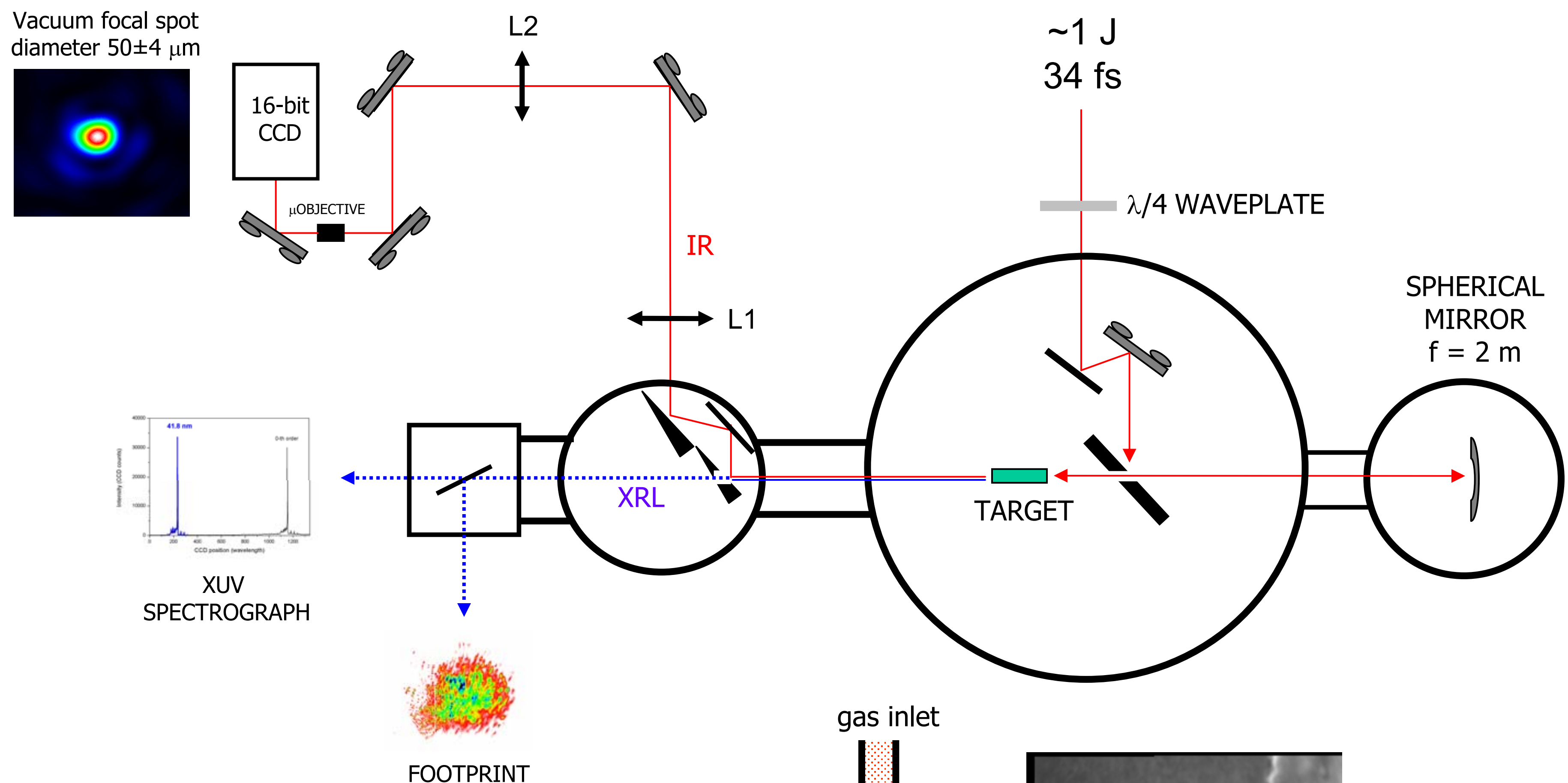


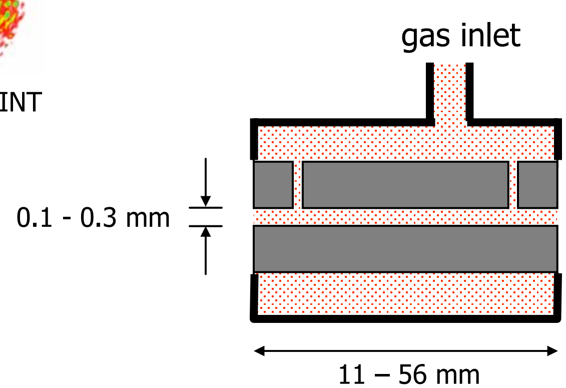
Calculated divergence of the Xe^{8+} laser

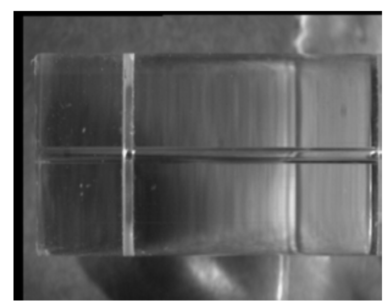


Large improvement of the XUV beam quality is expected…

III. Experiment with glass capillaries

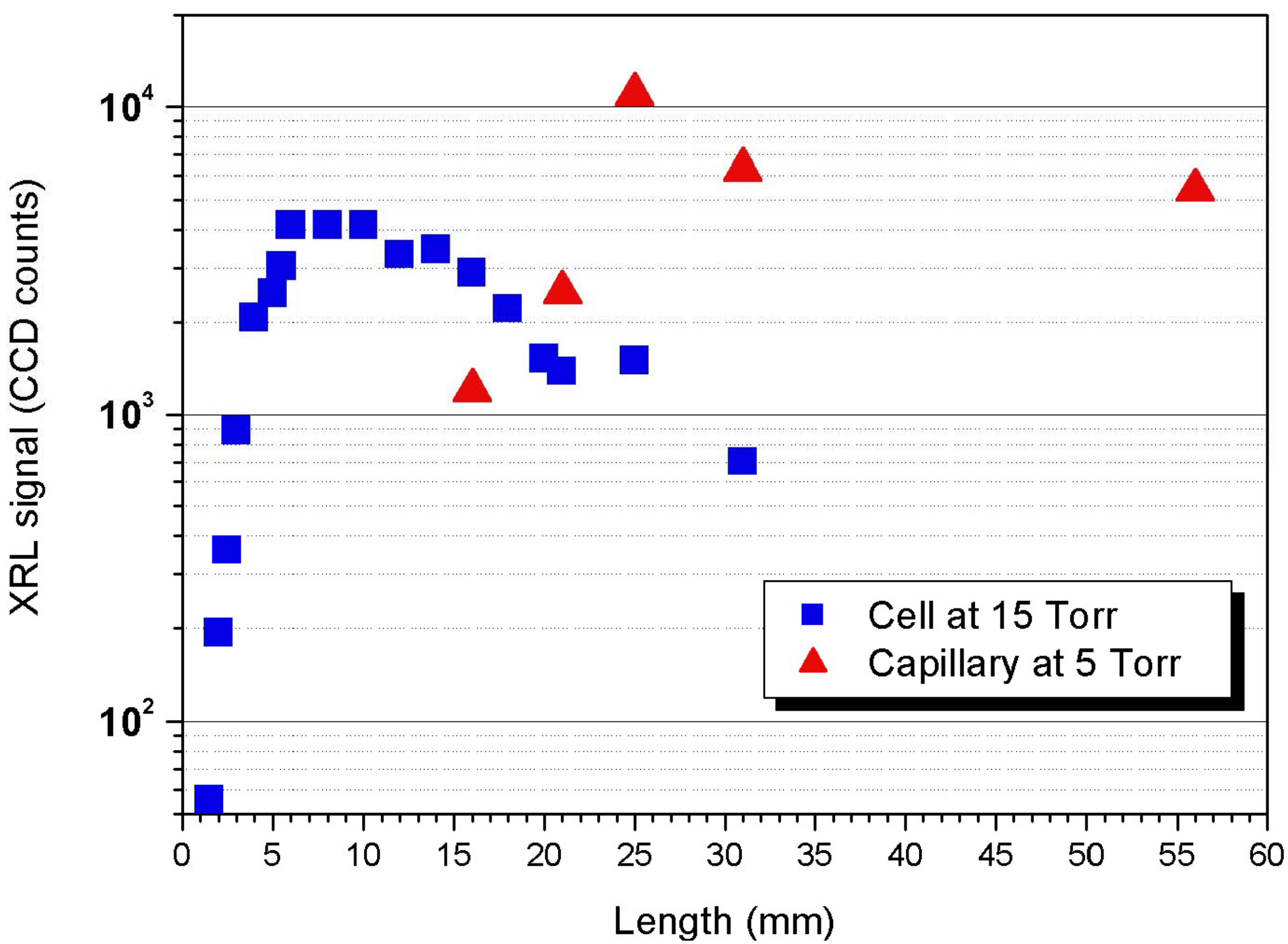






Cell vs. capillary

capillary diameter 300 μm

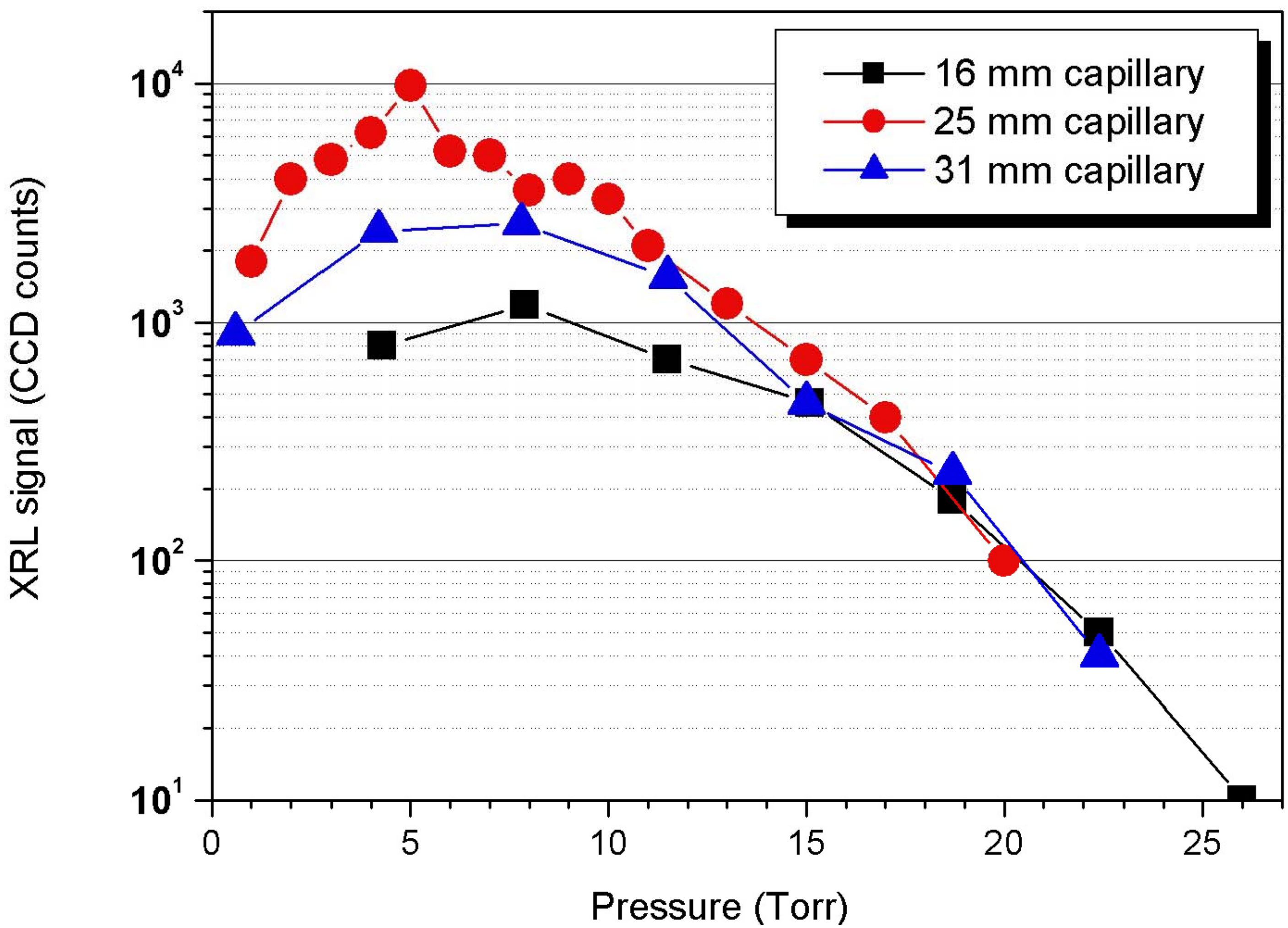


Guiding over **56 mm**

To be clarified: effect of surface quality, laser propagation, capillary alignment

Pressure dependence

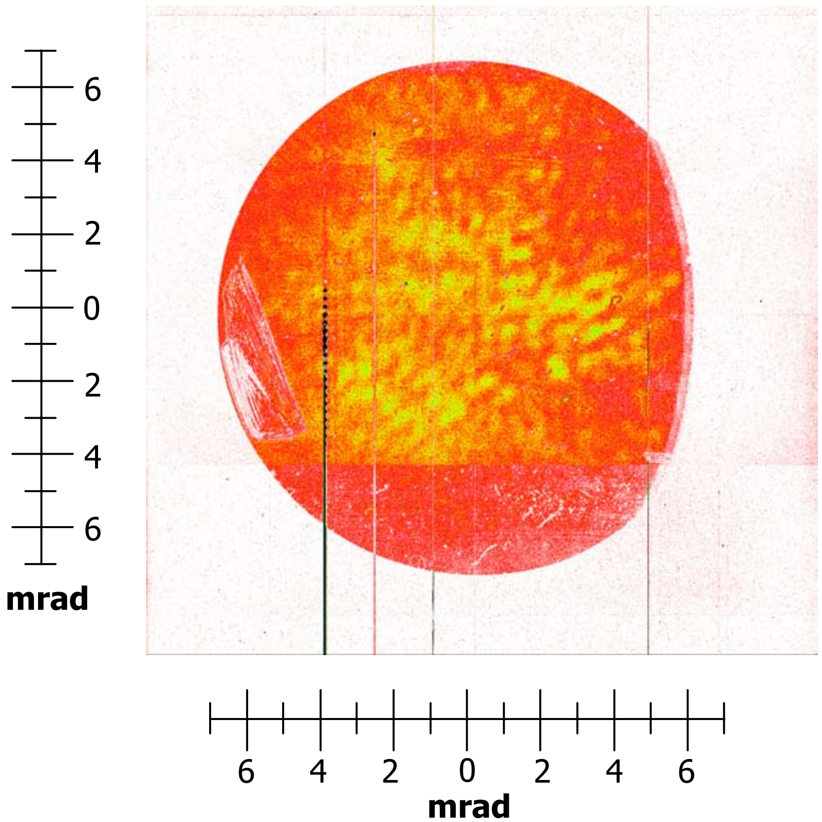
capillary diameter 300 μm



Footprint measurement

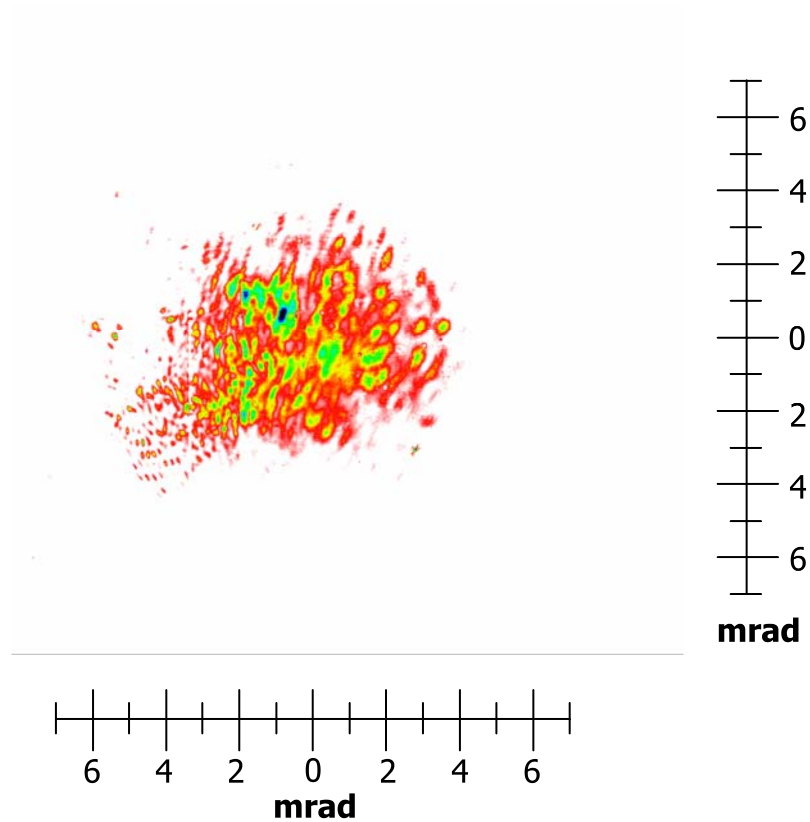
cell

optimum: 15 Torr, 8 mm



capillary

optimum: 5 Torr, 25 mm



divergence: **~8 mrad**

divergence: **~4 mrad**

Summary

- Demonstration of X-ray laser using multi-mode, gas-filled capillary
- Large enhancement of the Xe^{8+} laser output

⇒ **$\sim 10^{11}$** photons/pulse (**0.8 μJ**) at 10-Hz, stable operation

- Improvement of divergence: **~4 mrad**
- Very good agreement between experiment and simulations
- Advantages of capillary: robustness, simple design

Acknowledgments: LOA laser team, G.J. Pert & L.M. Upcraft (University of York)

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