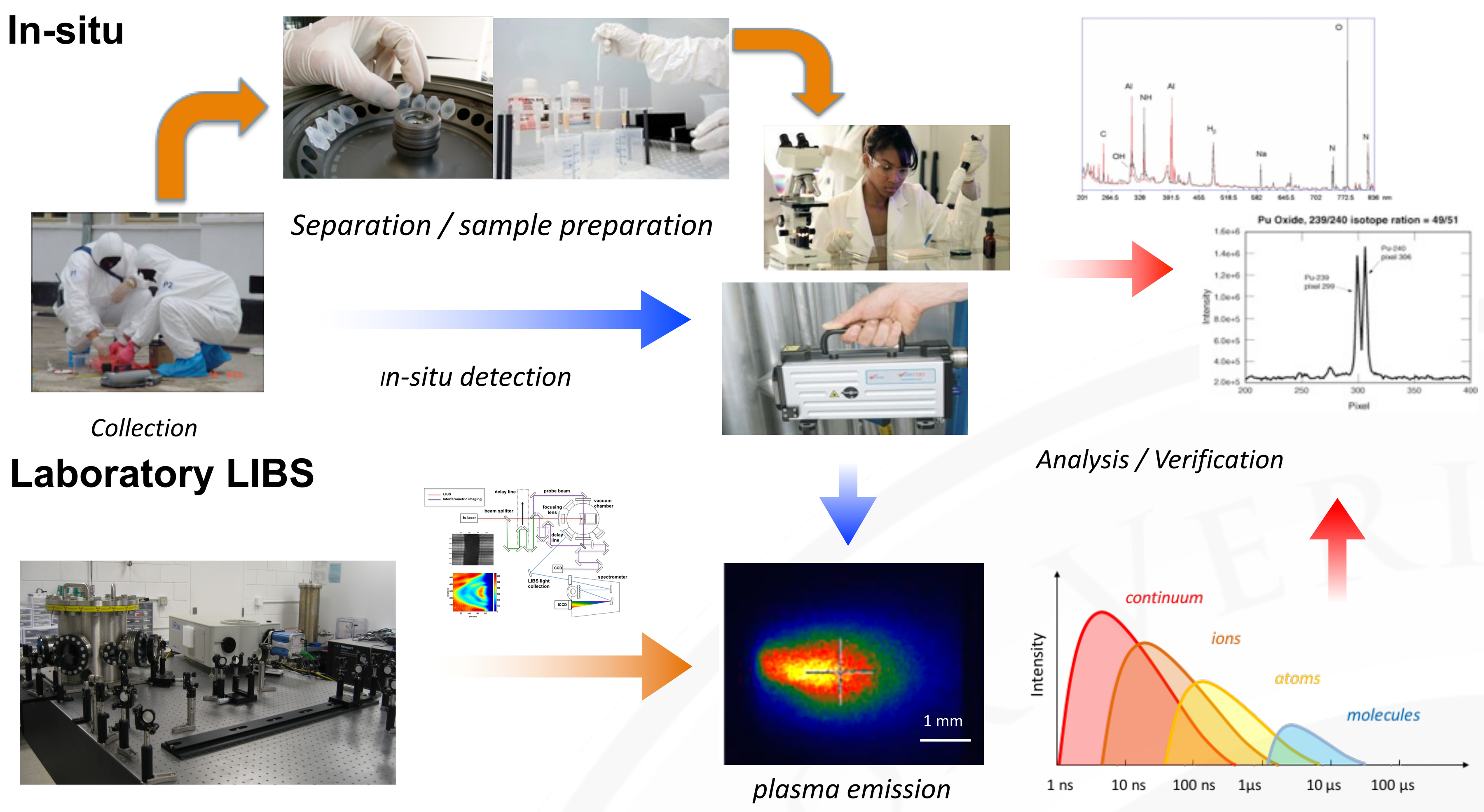
Development of Plasma Diagnostics for Studies of Filamentation Induced Breakdown Spectroscopy

M. Burger[1,2], P. Skrodzki[1,3], K. Hartig[3], and I. Jovanovic[1,2]
[1]Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109
[2]Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109
[3]Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352
PI: Prof. Igor Jovanovic, ijov@umich.edu
Consortium for Verification Technology (CVT)

OPTICAL (REMOTE) SENSING FOR NONPROLIFERATION, SAFEGUARDS, AND VERIFICATION

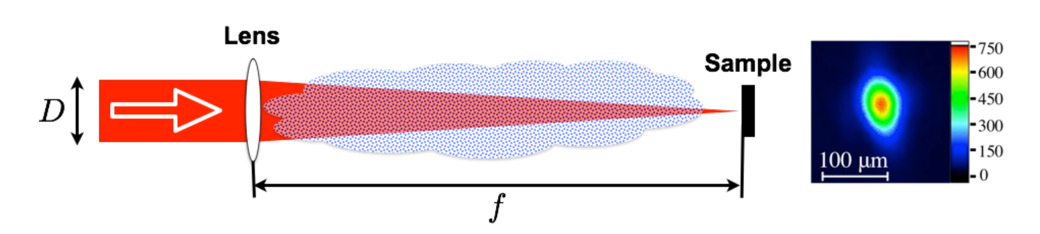
The goal of nuclear material verification is to obtain information about an interdicted or remotely interrogated sample or material that can be used to verify that signatory states are meeting their disarmament and nonproliferation obligations.



FILAMENTATION LASER-INDUCED BREAKDOWN SPECTROSCOPY (F-LIBS)

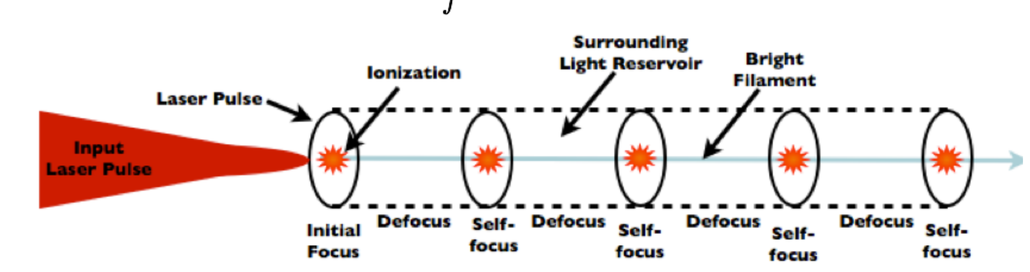
Filamentation induced by high-power laser pulses propagating in air can be utilized for remote sensing.
Performing LIBS at large standoff distances leads to two main challenges associated with beam delivery:

- Prohibitively large optics
- Absorption and atmospheric turbulence



Spot size: $w_0 \geq 1.22\ \lambda f/D$

Self-focusing: $n = n_0 + n_2 I$

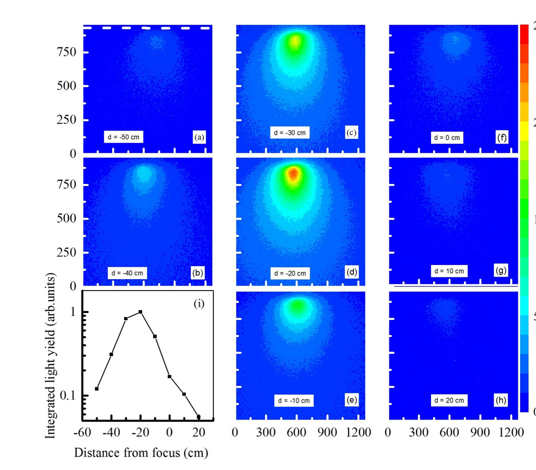


Balance of lensing/defocusing results to intensity clamped propagating filaments.

Ionization defocusing:

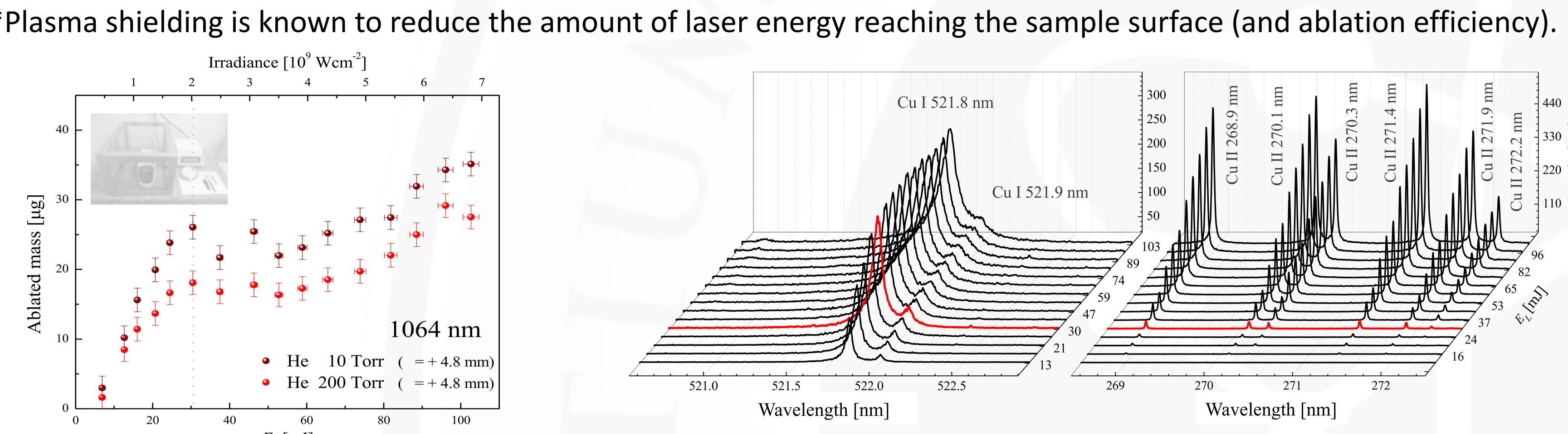
$$\Delta n_{plasma} = -\frac{e^2 N_e(t)}{2 m_e \varepsilon_0 \omega_0^2}$$

Potentially extreme distances (Téramobile, C. Wedekind)



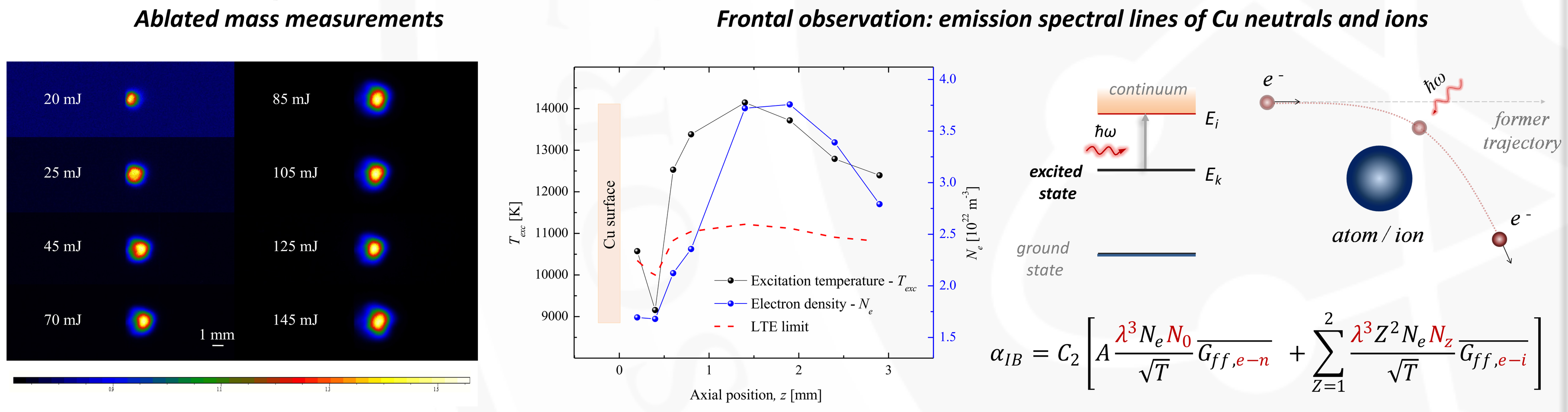
ns LIBS: PLASMA SHIELDING OF INCIDENT NANOSECOND INFRARED LASER RADIATION

Fundamental research is performed towards understanding of underlying processes within a plasma.
Better accuracy in determining its thermodynamic parameters provides more reliable quantitative measurements.
*Plasma shielding is known to reduce the amount of laser energy reaching the sample surface (and ablation efficiency).



Ablated mass measurements

Frontal observation: emission spectral lines of Cu neutrals and ions

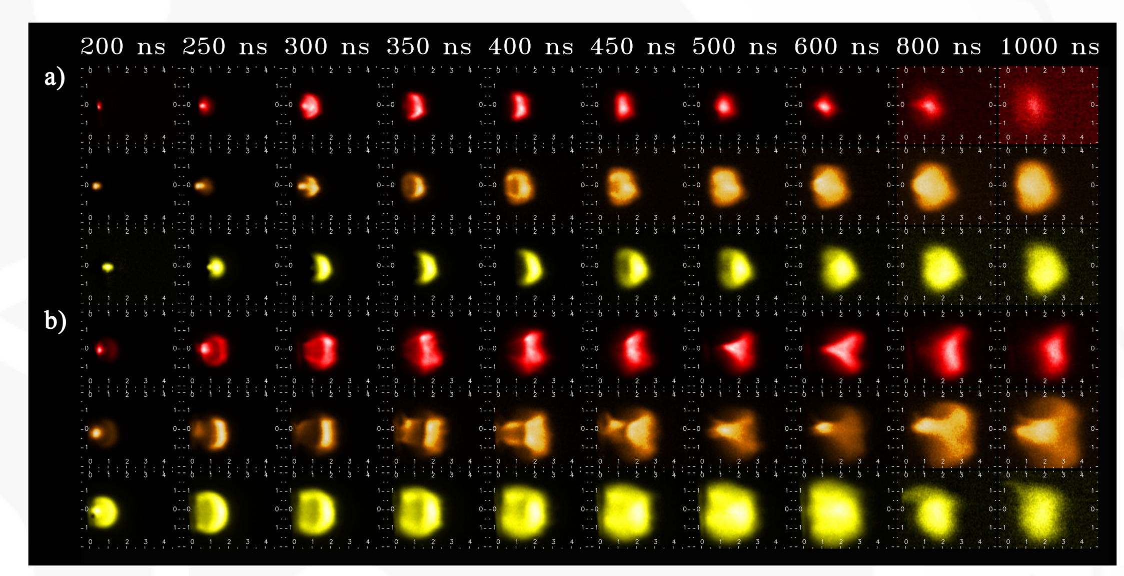


$$\alpha_{IB} = C_2\left[A\frac{\lambda^3 N_e N_0}{\sqrt{T}} G_{ff,e-n} + \sum_{Z=1}^{2}\frac{\lambda^3 Z^2 N_e N_Z}{\sqrt{T}} G_{ff,e-i}\right]$$

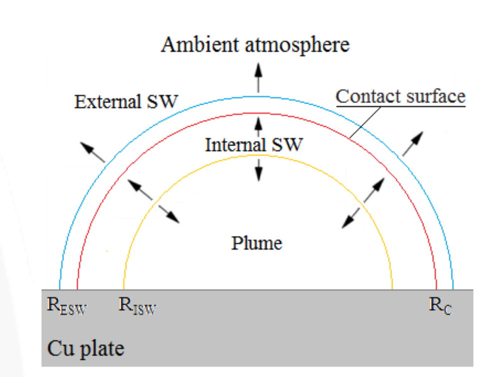
Side-on observation: plasma morphology and axially resolved diagnostics

Photoionization vs Inverse bremsstrahlung

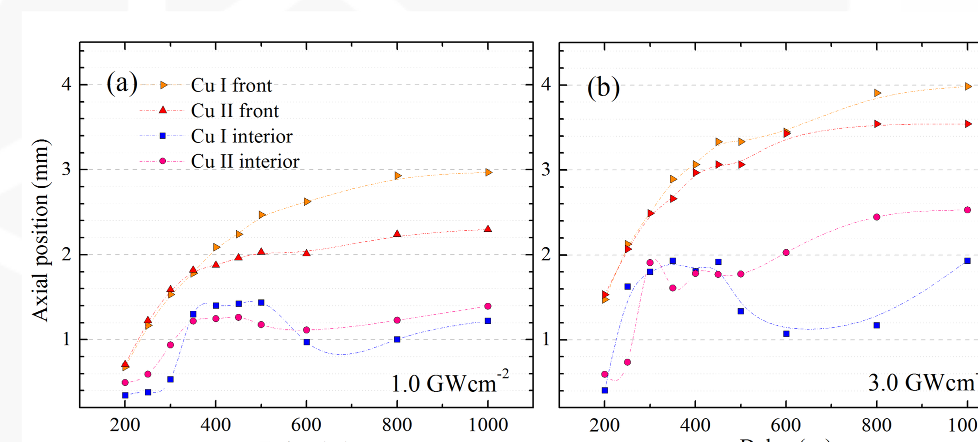
ns LIBS: DISTRIBUTION OF SPECIES WITHIN A PLASMA DURING FIRST μs AFTER PULSE

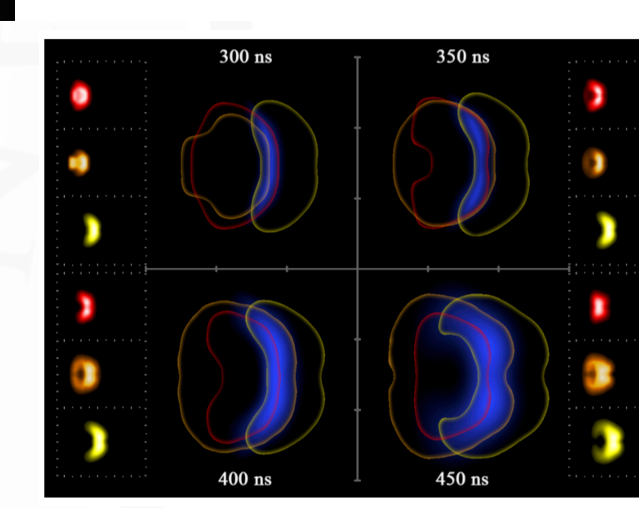


- Cu ions
- Cu atoms
- He atoms



$$E_k = 2\pi \int_{R_i|0}^{R_c|R_i} \rho_i v_i^2 r^2 dr \qquad E_t = 4\pi \int_{R_i|0}^{R_c|R_i} \frac{p_{c|i}}{\gamma_p - 1} r^2 dr$$



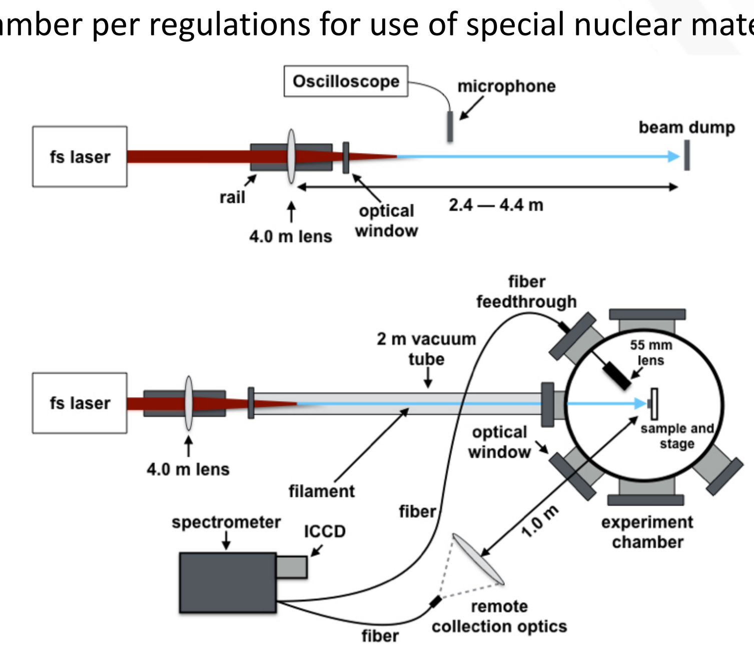


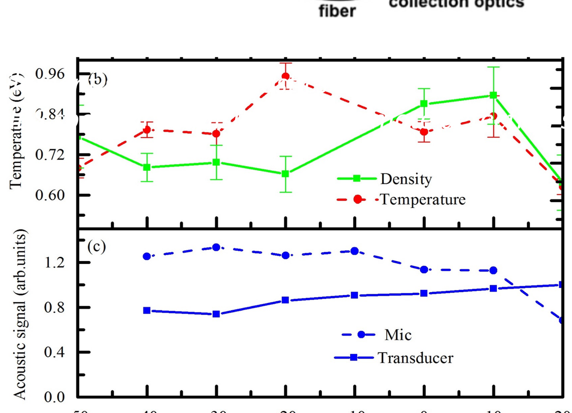
Dynamics of Cu species at (a) 1.0 GW cm^{-2} and (b) 3.0 GW cm^{-2}

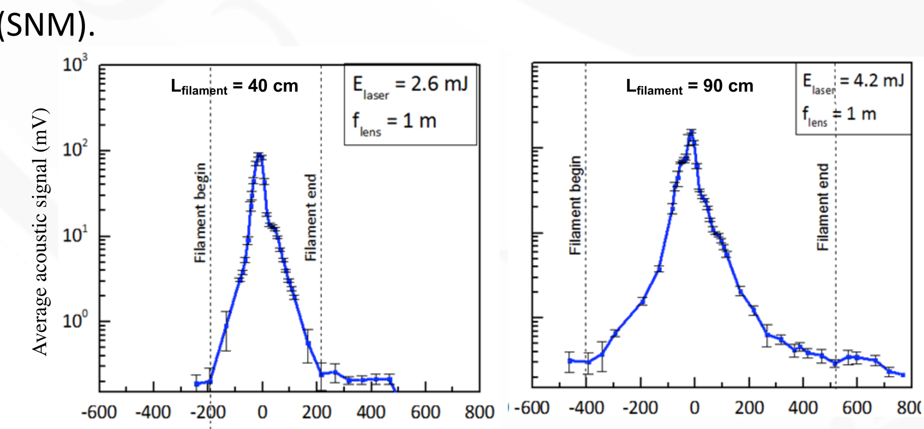
Radially resolved mixing zones between Cu and He

fs LIBS: CORRELATION OF FILAMENT ACOUSTIC RESPONSE WITH SPECTROSCOPIC DATA

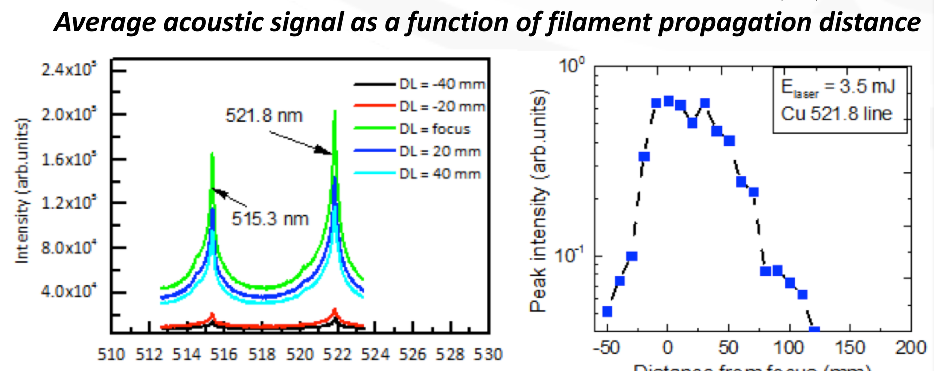
A custom experimental apparatus was designed to allow for fs laser filamentation to occur within a sealed experimental chamber per regulations for use of special nuclear material (SNM).







Average acoustic signal as a function of filament propagation distance



Spectroscopic observation of Cu emission along the filament

- F-LIBS signal onset at -50 mm from focus;
- F-LIBS plateau for over 5 cm along the filament;
- Detectable F-LIBS signal at a remote distance of 12.5 cm from the lens focus.
- Correlation with plasma thermodynamic parameters need further investigation.

FUTURE WORK: UO_2F_2 DETECTION USING FREQUENCY COMB ABSORPTION SPECTROSCOPY

Dual purpose - remote sensing of:

- Uranium enrichment;
- Possible leakage of depleted UF_6.

Challenges:

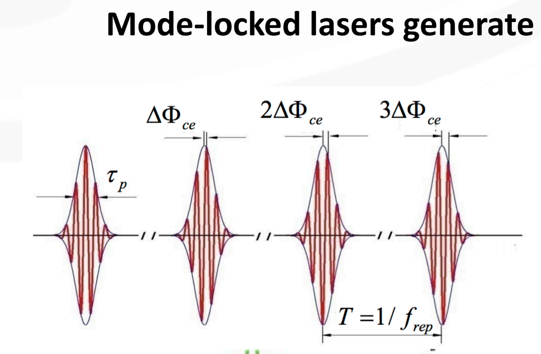
- Trace (aerosol) detection - these signatures are very weak;
- Very little research work has been done in this field to date.

Storage yard at Portsmouth, OH

When released into the atmosphere:

UF_6 (g) + $2H_2O$ (g) —> UO_2F_2 (s) + 4HF (g)

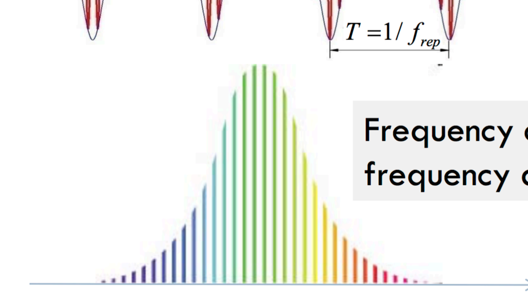
Mode-locked lasers generate femtosecond pulses



Pulse train in the time domain

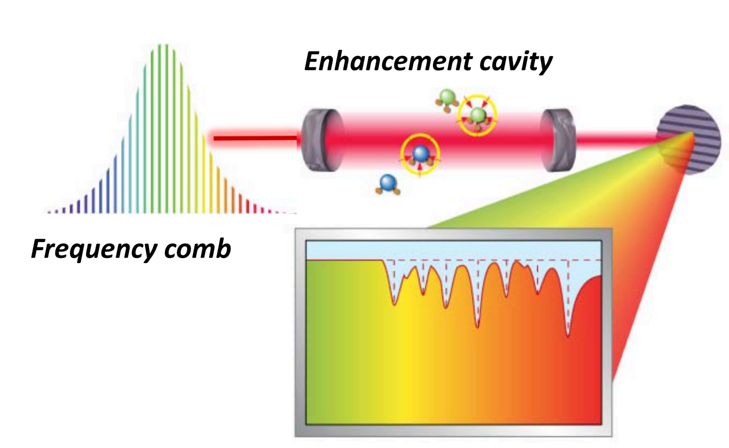
$$E_T(t) = \sum_{n=0}^{m}\left[\varepsilon(t - nT)e^{in\Delta\Phi_{ce}}\right]e^{i\omega_c t}$$

$$\Delta\Phi_{ce} = \left(\frac{1}{v_g} - \frac{1}{v_p}\right) l\,\omega \bmod 2\pi$$



Frequency comb in the frequency domain

$$f_{rep} = 1/T \qquad f_o = \frac{1}{2\pi} f_{rep} \Delta\Phi_{ce}$$



Highly dispersive detection system

Courtesy of JILA group

References:
[1] I. Ghebregziabher, K.C. Hartig, and I. Jovanovic, Optics Express 24 (2016) 5263-5276
[2] M. Burger, D. Pantić, Z. Nikolić, and S. Djeniže, J. Quant. Spectrosc. Radiat. Transf. 170 (2016) 19
[3] D. Pantić, M. Burger, Z. Nikolić, and S. Djeniže, submitted
[4] M.J. Thorpe, K.D. Moll, R.J. Jones, B. Safdi, J. Ye, Science (2006) 1595-1599

This work was funded in-part by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534.

National Nuclear Security Administration