Ion-beam-heating and diagnostic-II: application of pyrometry and laser interferometery

Pavel Ni

Ernest Orlando Lawrence Berkeley National Laboratory

Introduction

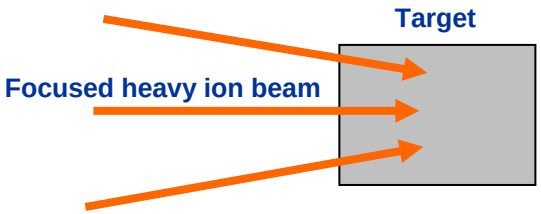
-Presented version of the talk differs from the version in handouts.

-Physics motivation is in the talk of Frank Bieniosek.

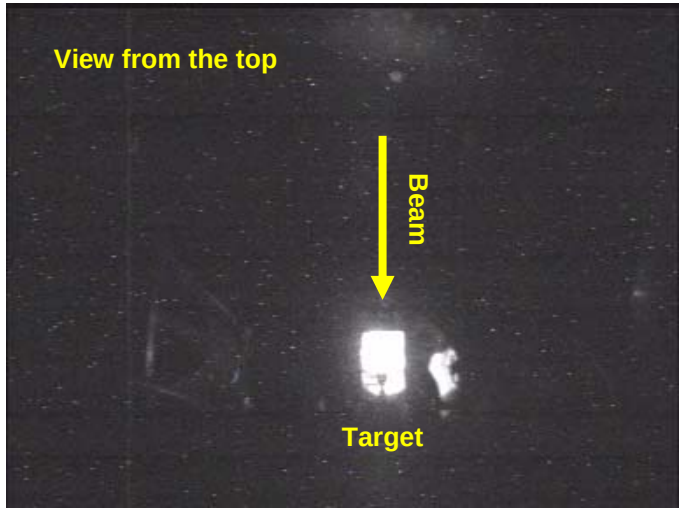
-Presentation is based on experiments at GSI and LBNL.

-Discussing the low temperature "Warm Dense Matter" regime, i.e temperature 1000 K-100,000 K, solid state density, optically thick and pressure up to several kilobars.

WDM generation with intense heavy ion beam

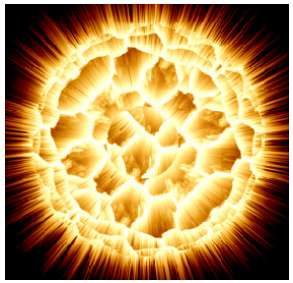


Explosion of lead target during irradiation
by Uranium beam from SIS-18 (GSI-Darmstadt)



How hot is it and what is the expansion velocity?

Diagnostic‘s strategy



Thermal light

Record thermal emission with a spectrometer (temperature)

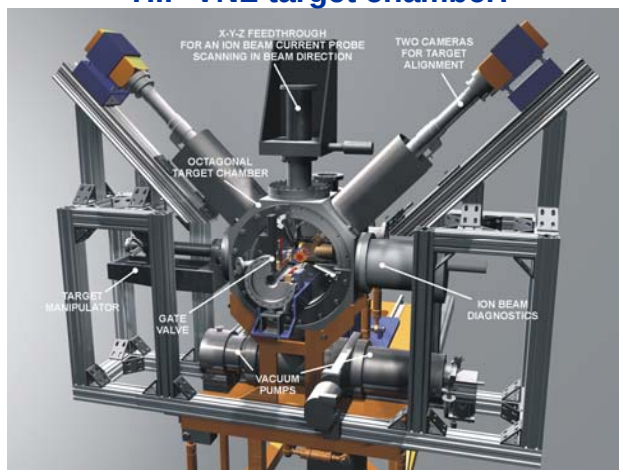
Probing laser beam

Record reflection of probing laser from expanding surface (pressure)

Take a snapshot by fast camera

Observe expansion with a streak camera

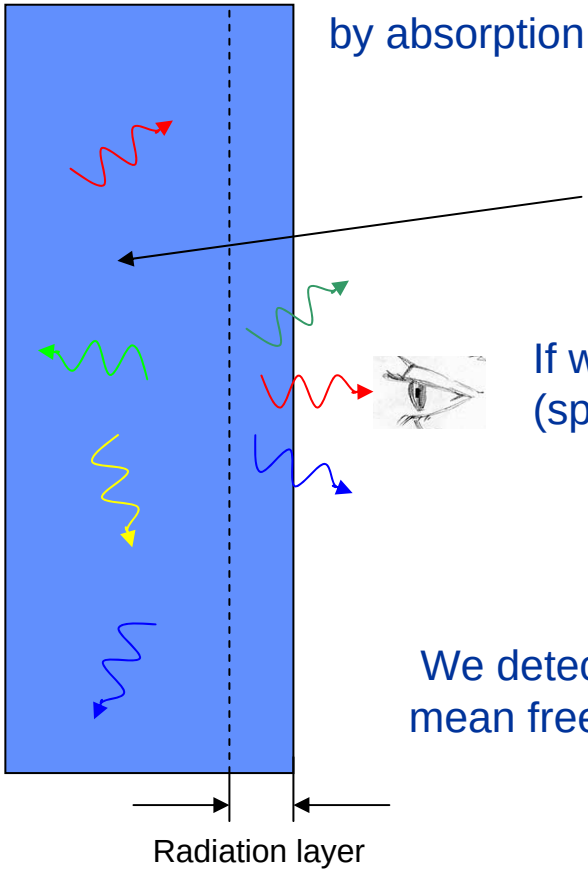
HIF-VNL target chamber:



Arising difficulties in dynamic WDM experiments with heavy ions:

-Too hot, i.e. non-contact methods only
-Very fast (down to nanosecond time scale), i.e limited choice of detectors
-Electro-magnetic interference from charged ions and pulsed magnets
-Radioactive contamination

Temperature measurement: ideal case



In bulk of body: spontaneous and stimulated emission is balanced by absorption. Following Bose statistic the photon energy density is:

$$u_{\text{Planck}}(\nu,T)=\frac{8\pi h\nu^3}{c^3\left(\exp\left(\frac{h\nu}{k_bT}\right)-1\right)}.$$

If we look at the surface of the body from outside, distribution (spectra) will be

$$I_{\text{Planck}}(\nu,T)=\frac{c}{4}u_{\text{Planck}}(\nu,T).$$

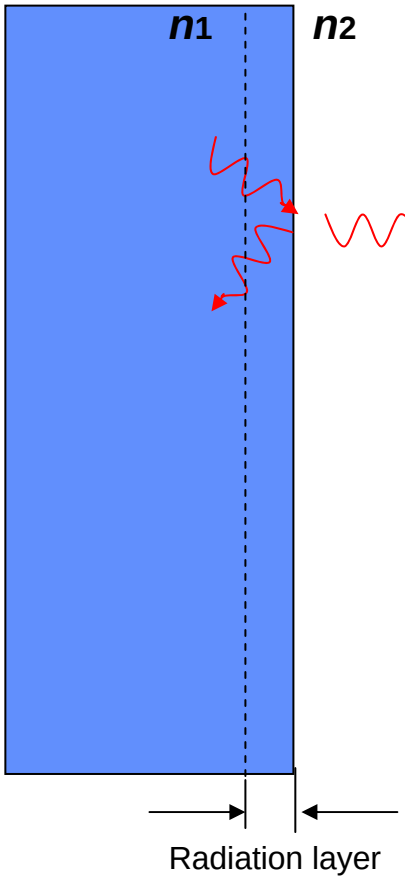
We detect photons originating from a thin layer *d,* equal to an absorption mean free path of a photon in material. Rule of thumb for *d* is

$$d\approx\frac{\lambda}{10}$$

The principle of pyrometry is to measure radiation spectra of a surface at various wavelengths

D.P. Dewitt, Therory and practice of radiation thermometry, John wiley and&Sons, Inc., (1998).

Temperature measurement: real case



In reality, reduced radiation will be observed due to partial reflection off the boundary between two media with different ***n***.

$$\mathrm{I}(\lambda,T) = \left(1 - R(\lambda)\right)\cdot \mathrm{I}_{\mathrm{Planck}}(\lambda,T).$$

For example for a sample in vacuum, normal reflectivity, ***R***, is related to ***n*** and ***k*** *as*

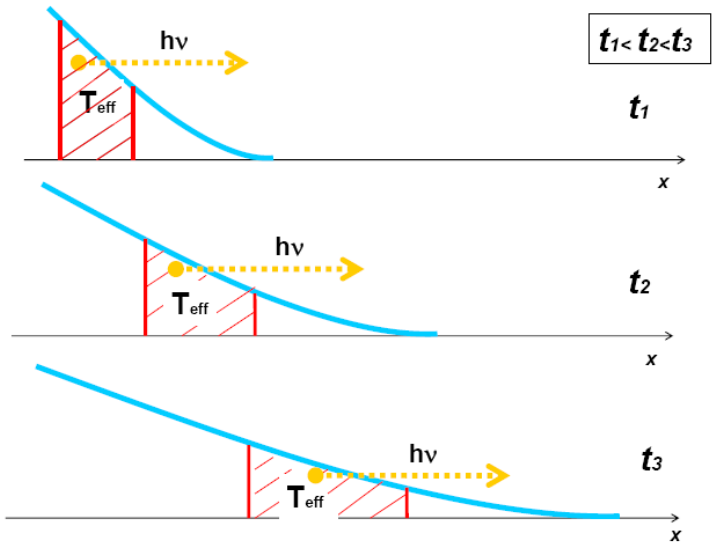
$$\mathrm{R}(\lambda) = 1 - \frac{4n}{(n+1)^2 + k^2}$$

Where ***k*** and ***n*** functions of conductivity σ

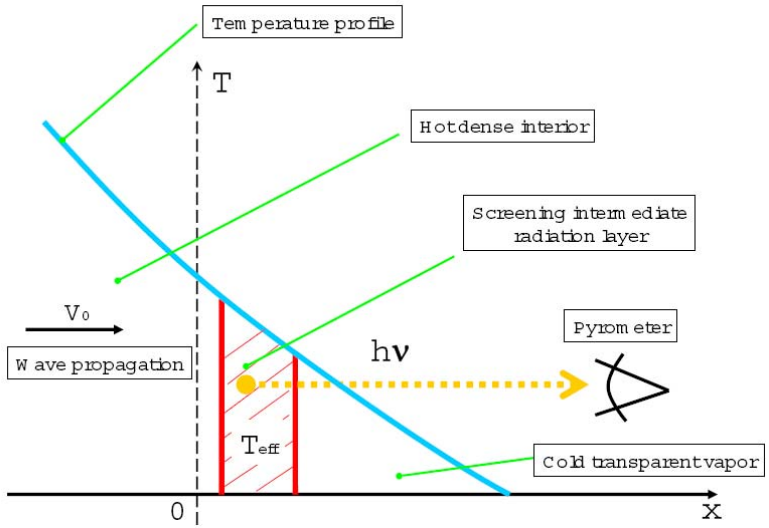
In addition, contaminations (oxides, nitrides, etc.) and surface roughness make exact analytical representation very difficult.
However the contaminants contribution decreases with increase of T.

Temperture measurment in dynamic experiemts

Radiation layers and density profiles of expanding matter:



Anatomy of density/temperature profile of expanding matter:



Y. B. Zeldovich, Y. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, Academic Press, New York (1966).

Temperature measurement: real case

Thermal surface radiation can be represented as:

$$I(\lambda, T) = \varepsilon(\lambda) \cdot \frac{C_1}{\lambda^5} \frac{1}{e^{\frac{C_2}{\lambda T}} - 1}, \text{ where emissivity } \varepsilon(\lambda, T) \le 1. \quad \varepsilon(\lambda) = ?$$

$$\frac{dT}{T} \approx \frac{\lambda T}{1.43 \cdot 10^7} \cdot \frac{d\varepsilon}{\varepsilon}.$$

50% erorror in emissivty will produce 10% error in temperature at T=5000 K and 800 nm

Two ways to reduce effect of unknown emissivity

Measure

-Laser reflectivity
-Laser polarimetry

Works fine for slow processes.
Big errors when applied to fast moving curved surfaces.

Assume a model

-Black body
-Ratio pyrometry
-"Grey" and linear behavior

Much less technical effort.
May produce big errors.
Sensitive to noise.

L. Michalski, K. Eckersdorf, J. Kucharski, J.McGhee, Temperature Measurement, Second Edition, 2001 John Wiley.

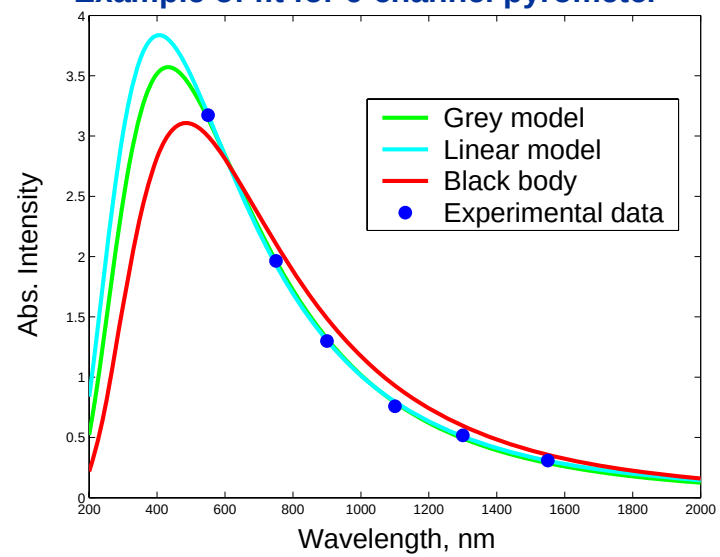
D.P. Dewitt, Therory and practice of radiation thermometry, John wiley and&Sons, Inc., (1998).

Realistic representation of emissivity

$$\begin{bmatrix} I_{experim}(\lambda_1) \\ \dots \\ I_{experim}(\lambda_N) \end{bmatrix} \xrightarrow{\text{nonlinear fit}} \begin{bmatrix} \varepsilon(\vec{A},\lambda_1)\cdot I_{Planck}(\lambda_1, T) \\ \dots \\ \varepsilon(\vec{A},\lambda_N)\cdot I_{Planck}(\lambda_N, T) \end{bmatrix}$$

$\vec{A}$ and T are the fitting parmeters

Example of fit for 6-channel pyrometer



$$\varepsilon(\lambda) = 1 \rightarrow T_{brightness}$$

Assumes black body radiation

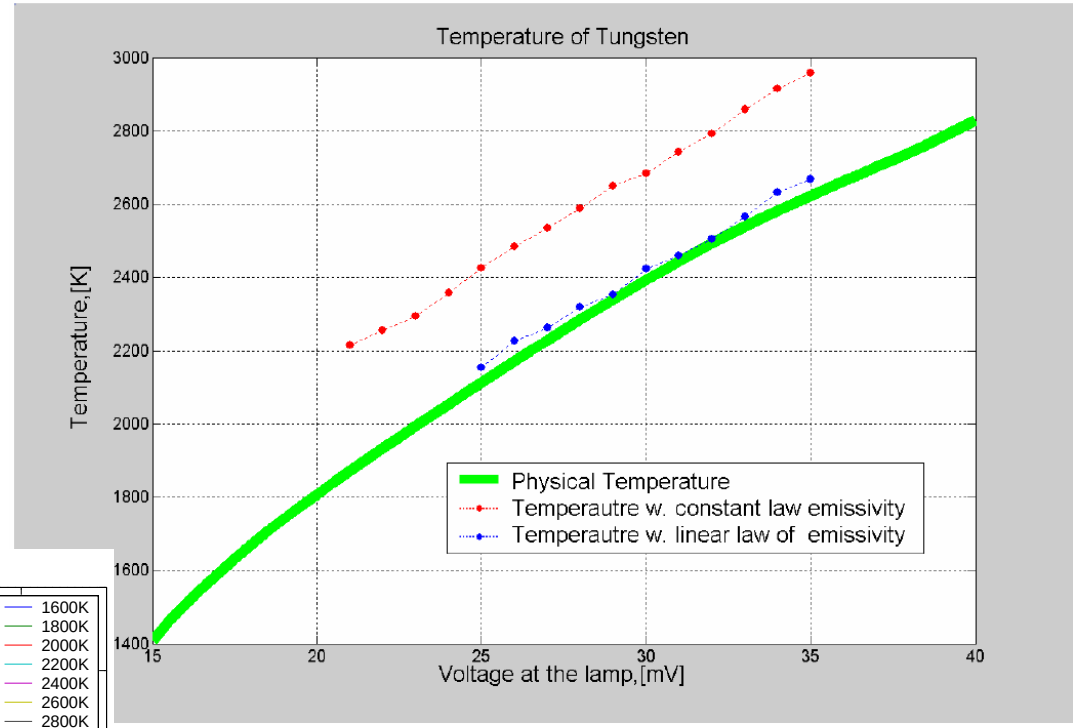
$$\varepsilon(\lambda, T) \approx const = \varepsilon_{grey}(T) \rightarrow T_{grey}$$

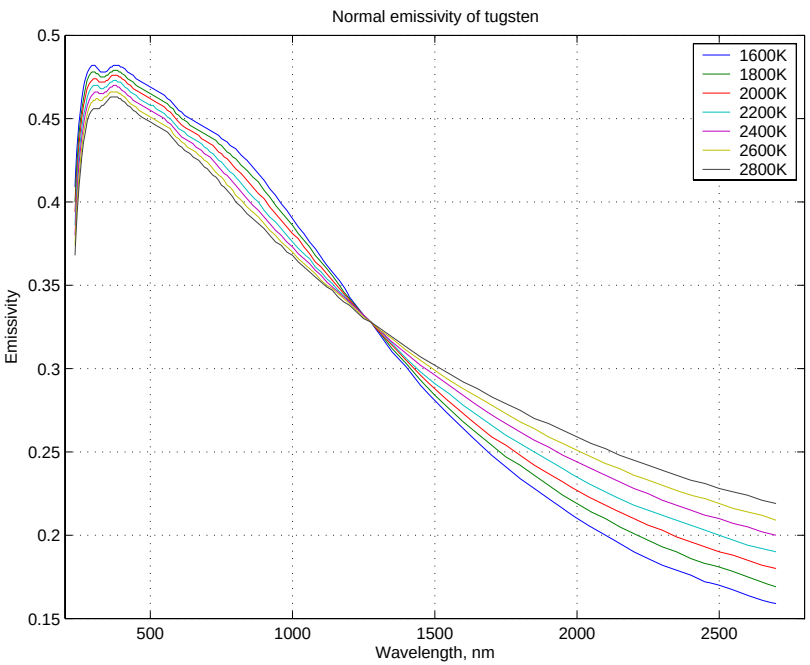
Follows from Drude model of conductivity for near infrared through visible and T~0.5 eV

$$\varepsilon(\lambda, T) = A_1(T)\cdot\lambda + A_2(T) \rightarrow T_{linear}$$

P.Drude, Annalen der Physik 14, 936 (1904)

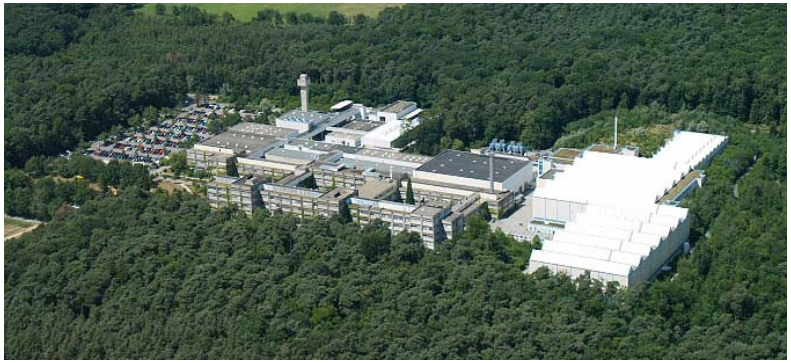
Results of fit (applied to tungsten filament)

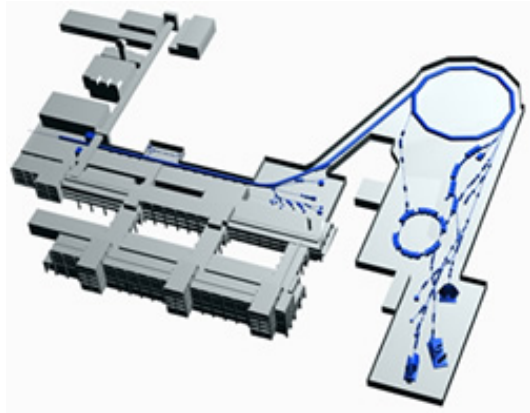


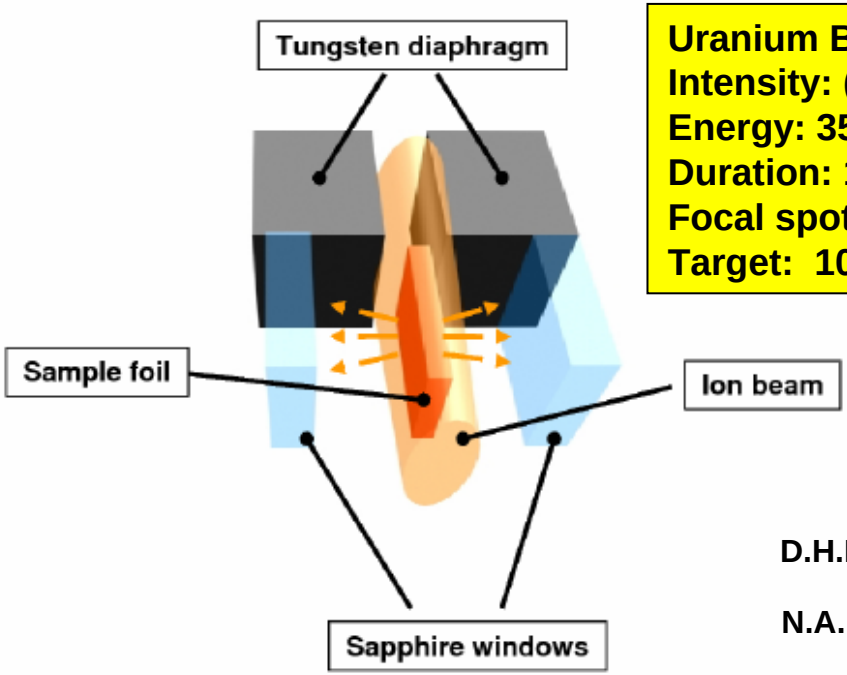


-“Grey” model gives about 15% discrepancy, while linear model several per cents only.

Real pyromrtric system: example from GSI







Uranium Beam(+74)
Intensity: (1-4.2)x10^9
Energy: 350 AMeV (85GeV)
Duration: 120 ns
Focal spot: 150-1500 μm
Target: 100-500 μm

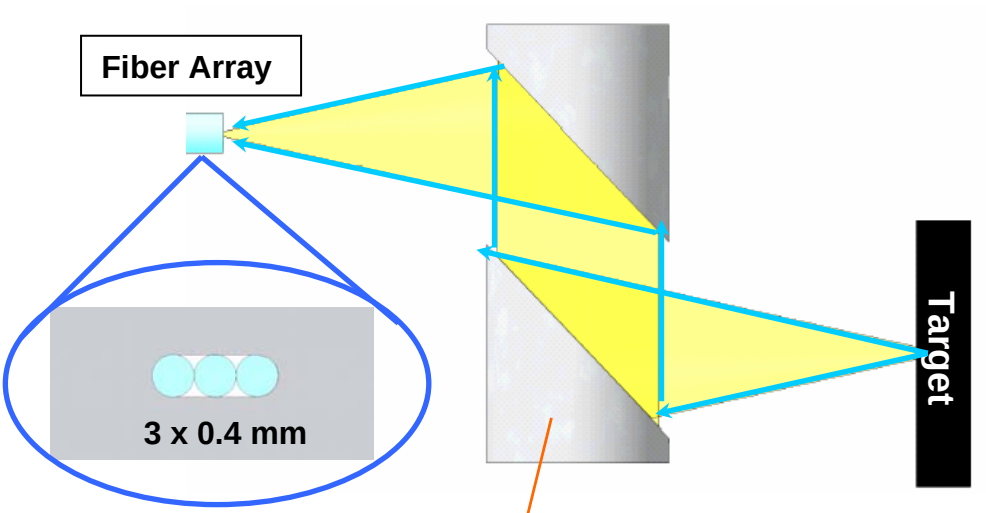
The pyrometer should record thermal light emission of an object in a broadrange of the spectrum (VIS/NIR) with high temporal (ns) and spatial (20-50 μm) resolution.

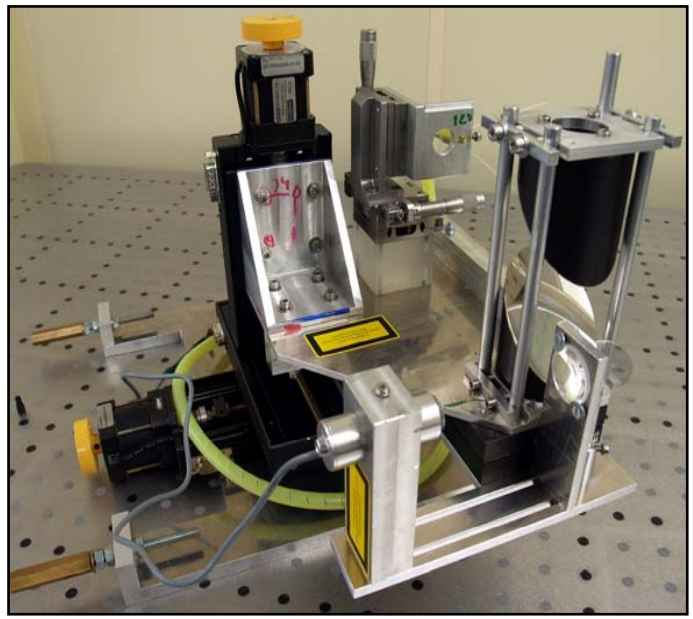
D.H.H. Hoffmann et al., Laser Part. Beams **23**, 47 - 53 (2005)

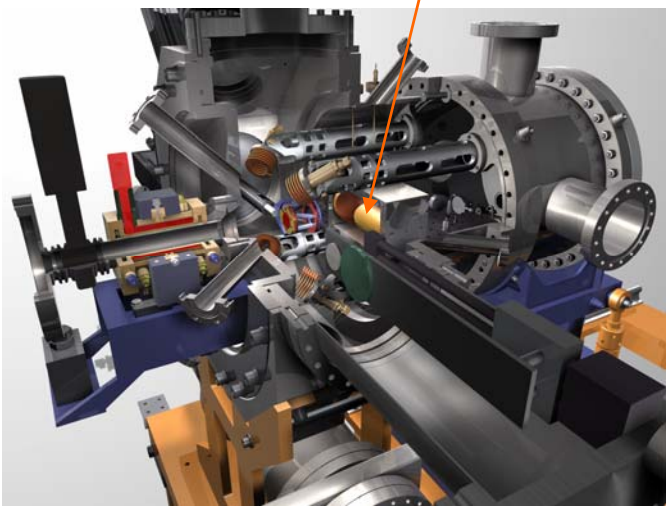
N.A. Tahir et al., Nucl. Instrum. and Meth. A **577**, 238 - 249 (2007)

Light collection system

Design:





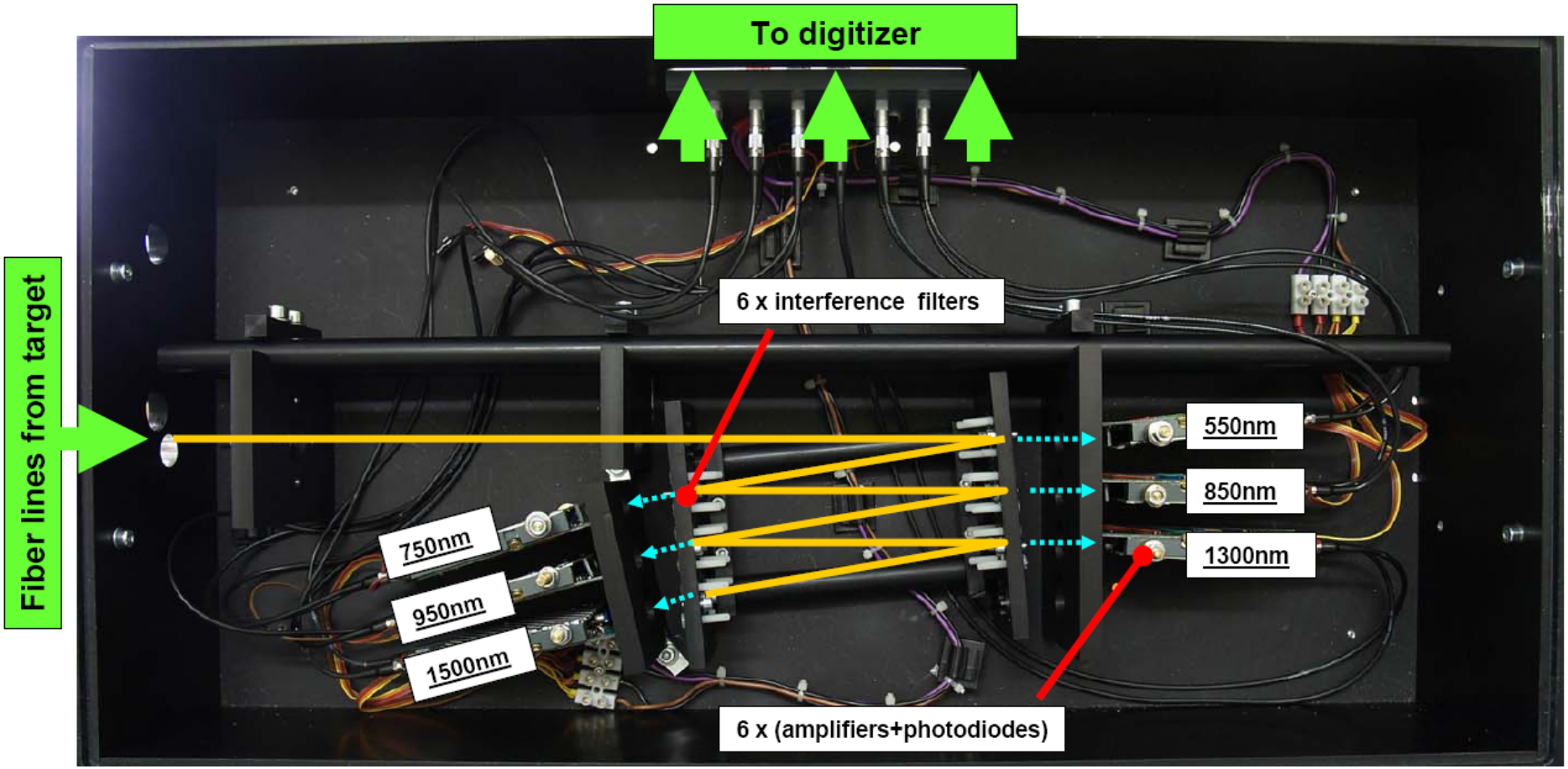


- high efficiency: f/2
- 1:1 imaging
- no chromatic aberrations
- high resolution (20-400 μm)
- compact
- motorized 0.01 mm positioning accuracy

Multi-channel pyrometer (GSI-Darmstadt)

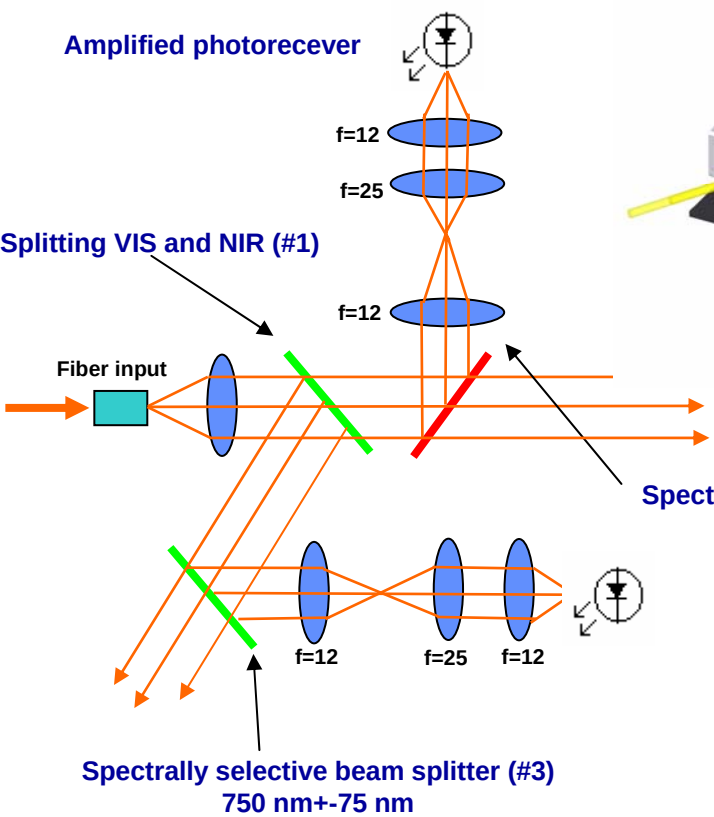
-6 interference filters (550, 750, 850, 950, 1300, 1500 nm)
-spectral width 10 nm
-No beam splitting: high efficiency

-fast photodiodes (used in linear regime)
-two cascade, low noise, broad band amplifiers
-1 ns temporal resolution

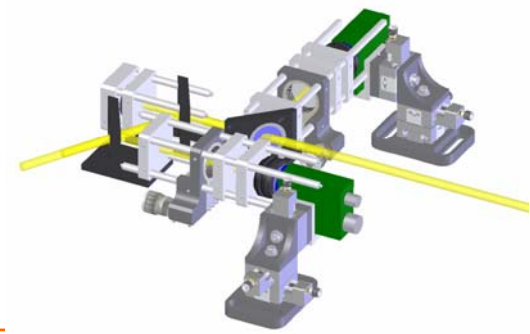


2-channel pyrometer (LBNL)

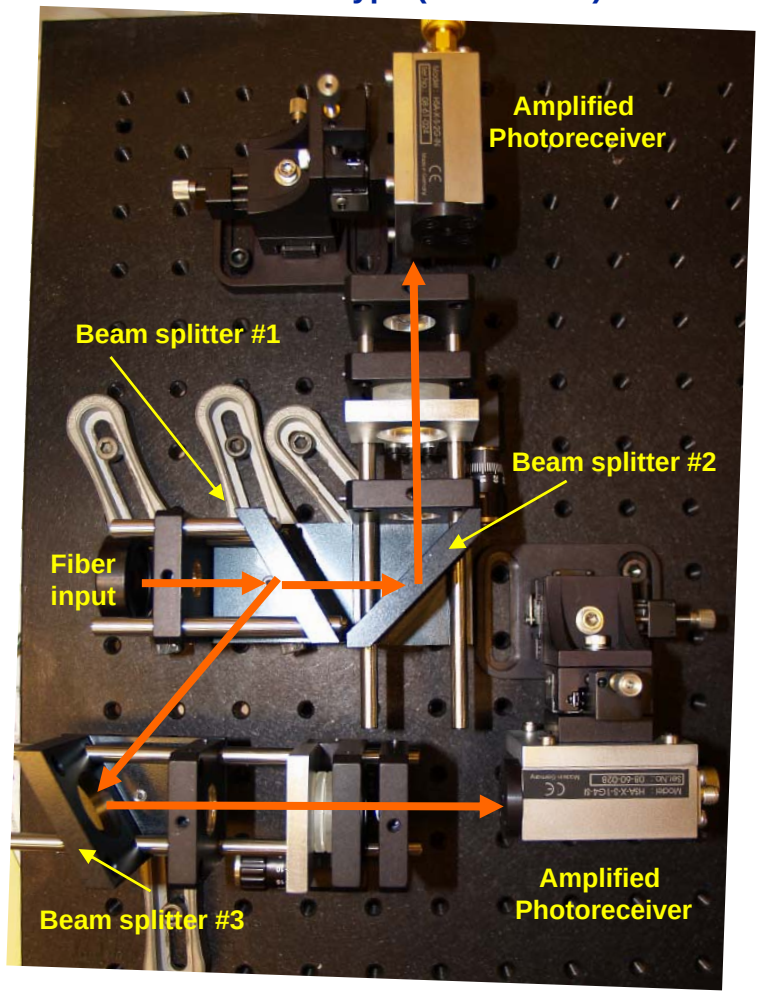
Working scheme:



CAD model:



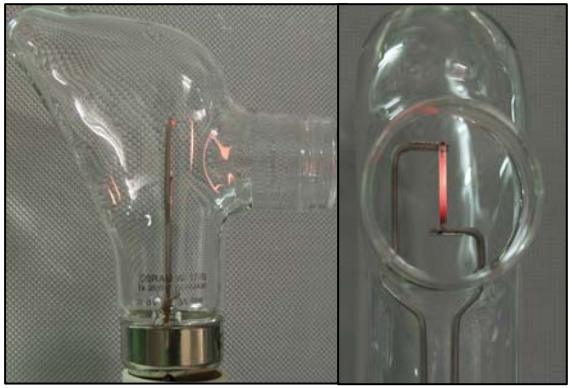
First Prototype (2 channels):

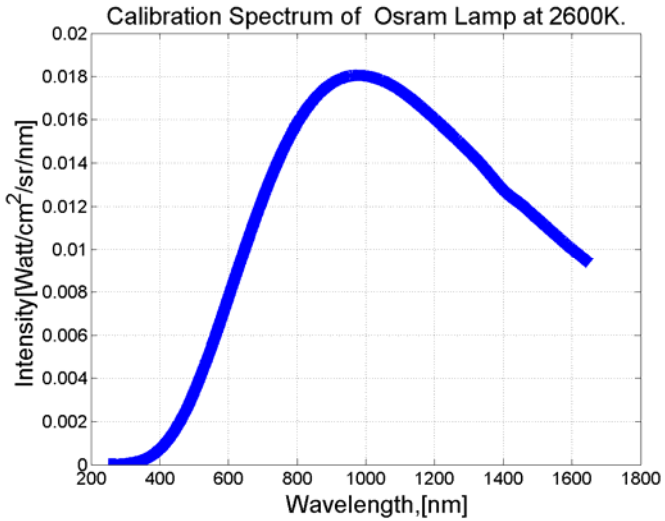


- Measures brightness temperature at 750 nm and 1200 nm with 50 ps temporal resolution
- High sensitivity (from 2000 K)
- Can be upgraded up to 7 wavelengths

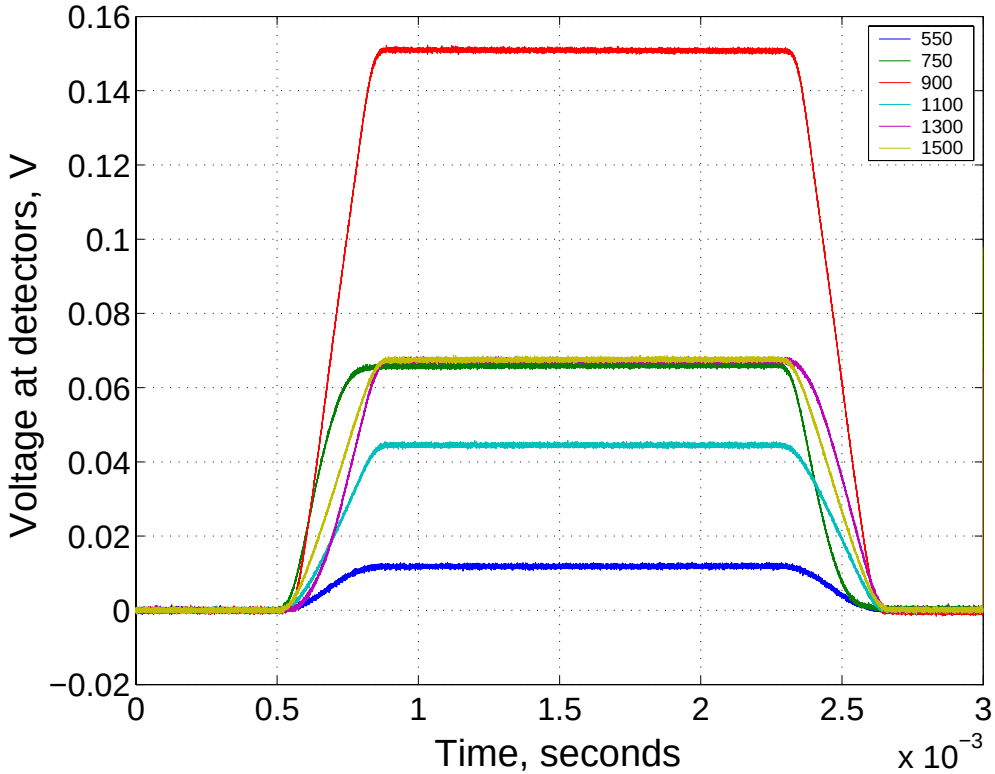
Absolute calibration of pyroemter

Calibration lamp: Osram W 17/G

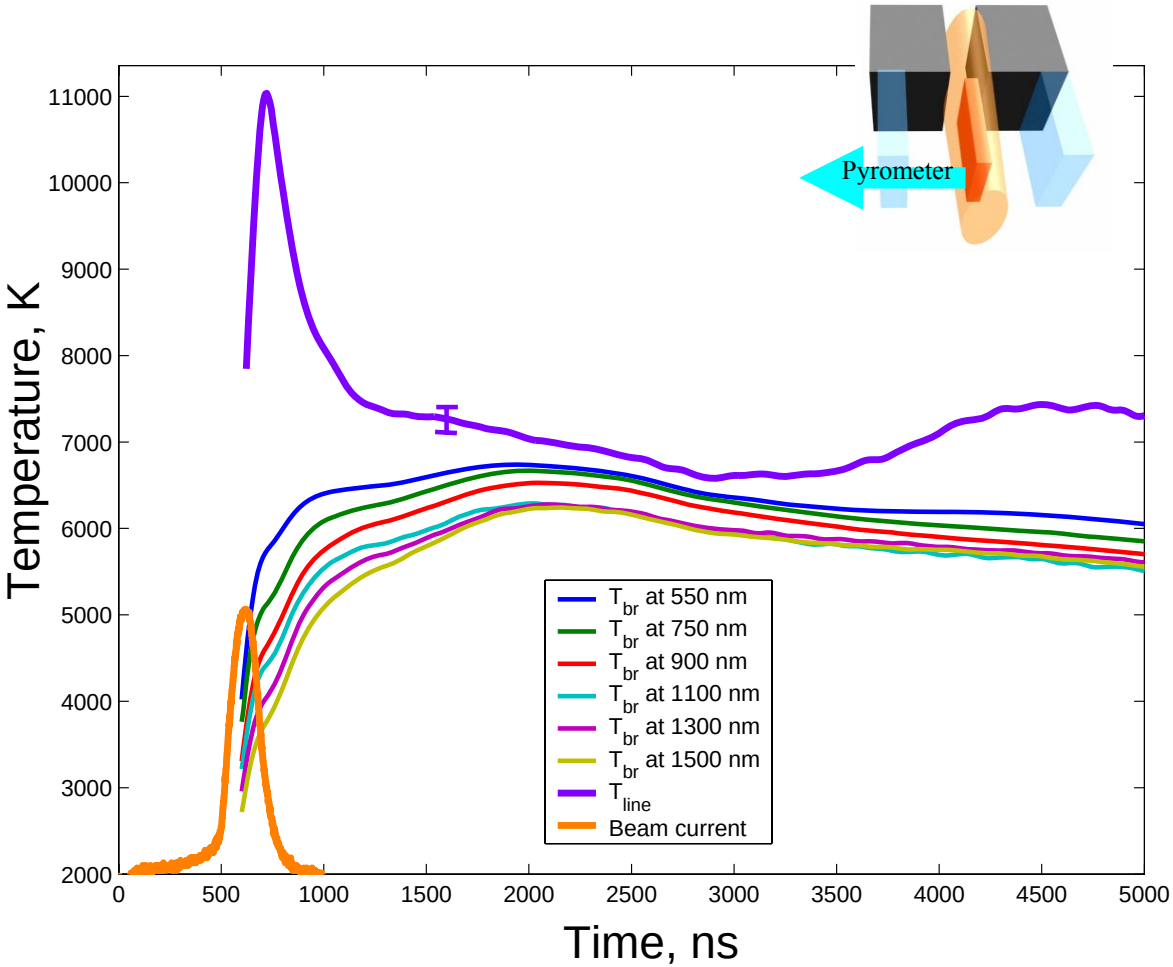




Calibration voltages of the pyrometer

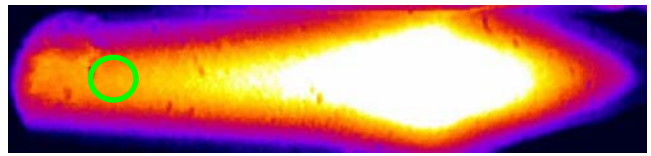


Temperature of tungsten foil



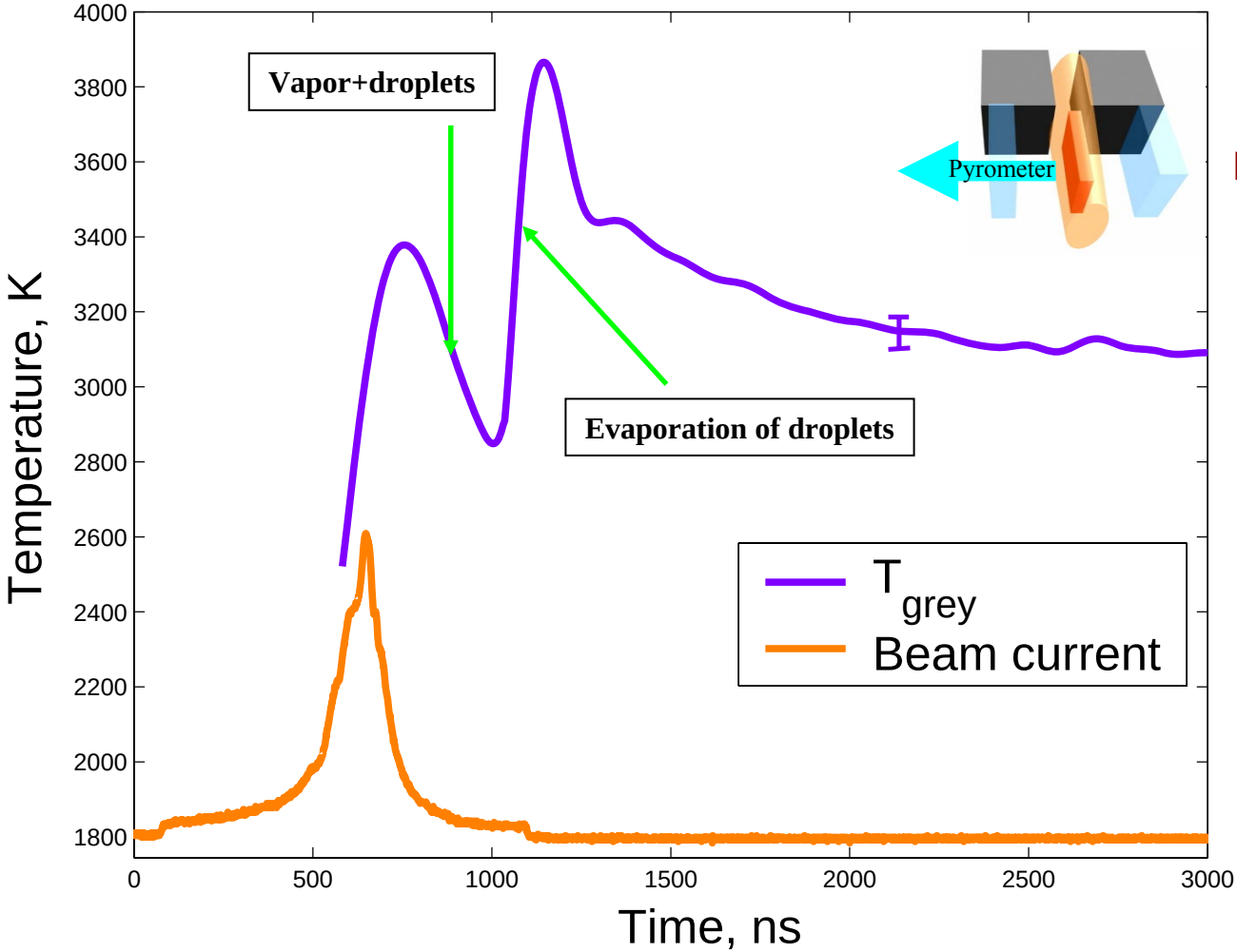
Beam: ^{238}U, 350 AMeV, 120 ns, 2·10^{9}

Target: W foil, 100 μm thickness, 3 mm gap



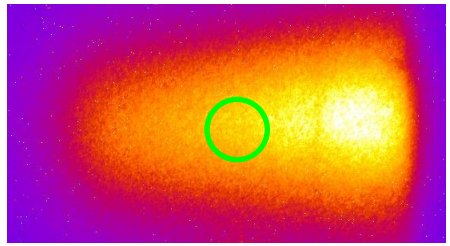
T_{melt}=3700 K,
T_{boil}=5800 K

Temperature of lead foil



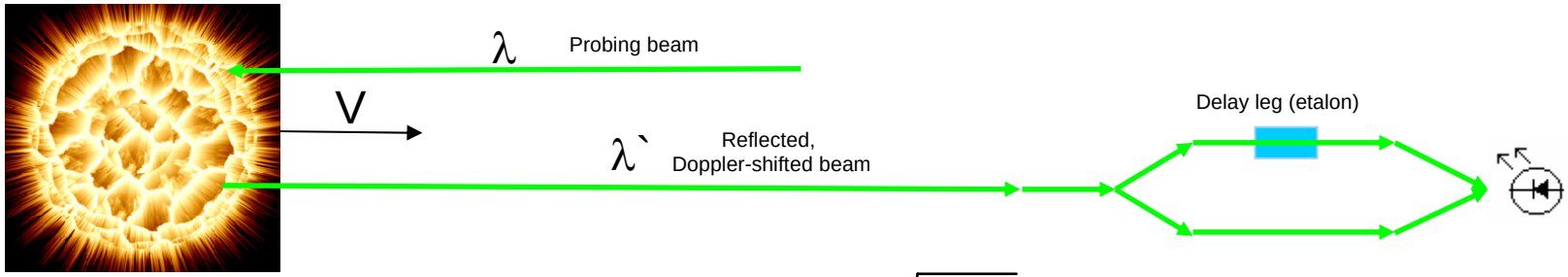
Beam: ^{238}U, 350 AMeV, 120 ns, $1.28 \cdot 10^9$

Target: Pb foil, 240 μm thickness, 0.2 mm gap



T_{melt}=600 K,
T_{boil}=2000 K

Velocity Interferometer System for Any Reflector (basic principle)



$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\delta)$$

$$\delta(t) = 2\pi \cdot F(t)$$

$$V(t) = (\lambda / 2\tau) \cdot F(t)$$

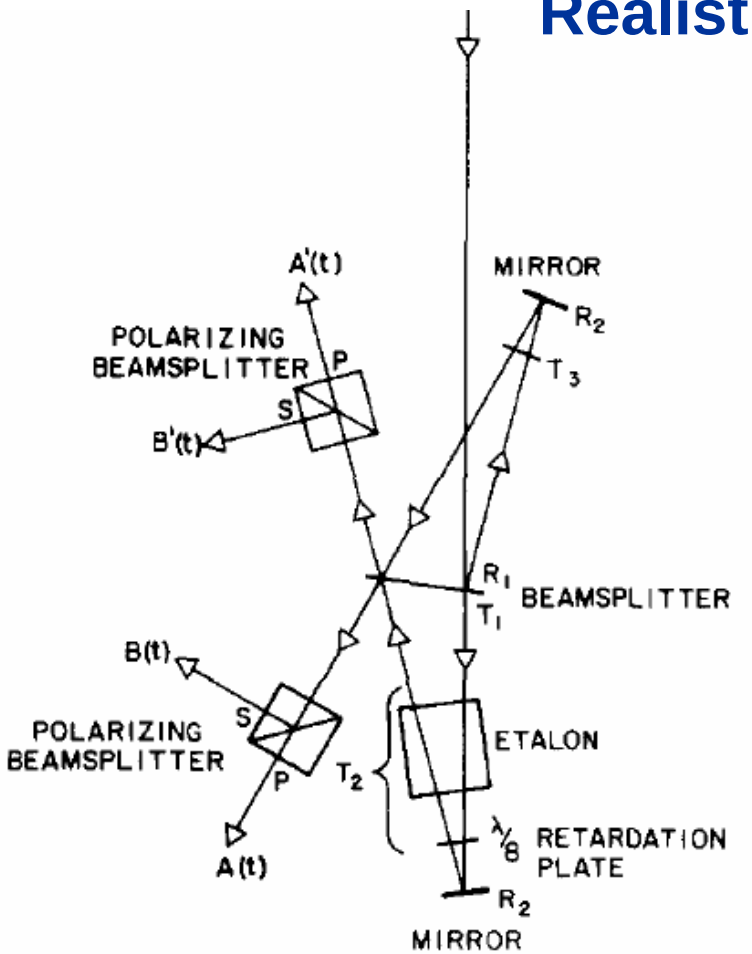
In reality following factors emerge:
-Thermal light "contaminates" probing beam
-Modulation of laser intensity (changes in surface reflectivity, surface tilt, laser instability, etc.)
-Presence of acceleration and deceleration in the same experiment (need to distinguish)

L.M. Barker Rev. Sci. Instrum. **42**, 276 (1971)

L.M. Barker and R.E. Hollenbach, J. Appl. Phys. **43,** 4669 (1972)

Realistic VISAR system

Original scheme by Hemsing (1978):



Output at every detector can be represented as:

$$A(t) = P(t) \cdot g_1 \, [1 + \sin(2\pi \cdot V(t)/K_f + \psi_0)] + BG$$

$$B(t) = P(t) \cdot g_2 \, [1 + \cos(2\pi \cdot V(t)/K_f + \psi_0)] + BG$$

$$A'(t) = P(t) \cdot g_3 [1 - \sin(2\pi \cdot V(t)/K_f + \psi_0)] + BG$$

$$B'(t) = P(t) \cdot g_4 [1 - \cos(2\pi \cdot V(t)/K_f + \psi_0)] + BG$$

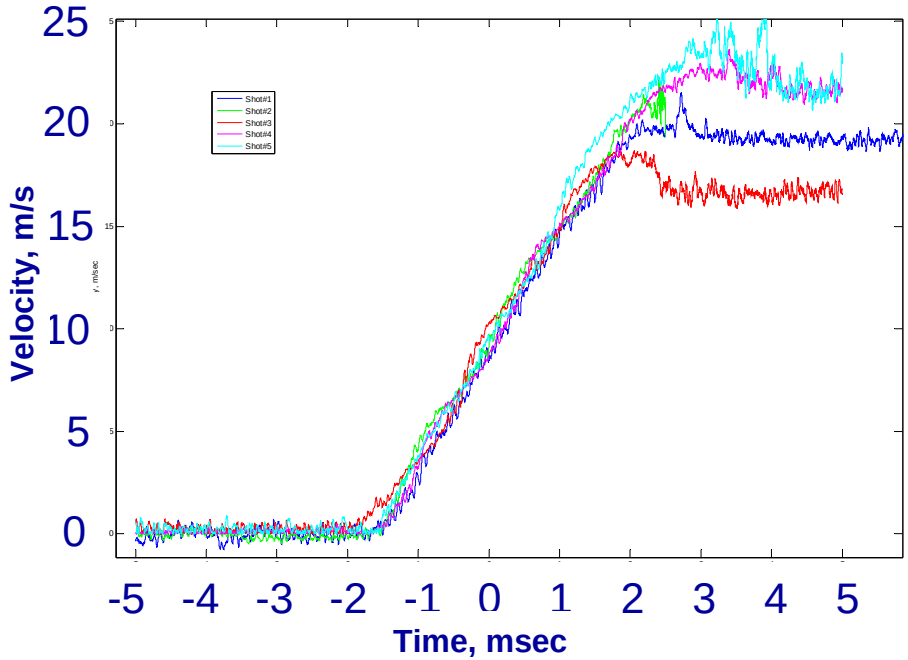
$$V(t) = K_f/2\pi \cdot \text{arctangent}([B(t) - B'(t)]/[A(t) - A'(t)])$$

Willard F. Hemsing, Rev. Sci. Instrum. **50**, 73 (1979)

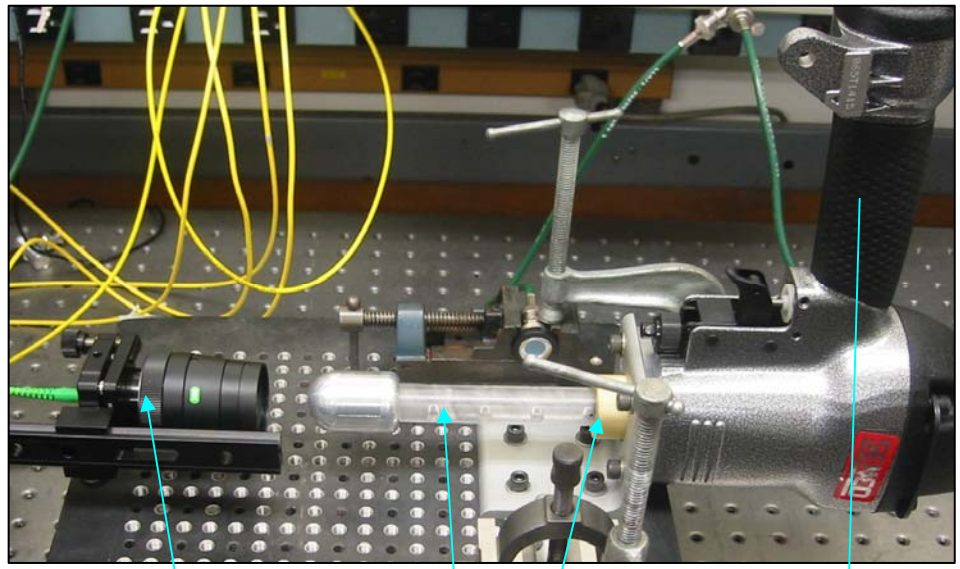
L	K_f	V_{res}	T_{res}	Example Applications
10 mm	15 km/s/fr	20 m/s	50 ps	High Energy Density, Laser Effects, Exploding Foils
100 mm	1.5 km/s/fr	2 m/s	0.5 ns	Explosives, Shock Hydrodynamics, Space Debris
1 m	150 m/s/fr	0.2 m/s	5 ns	Interior Ballistics, Impacts, Damage Propagation
10 m	15 m/s/fr	0.02 m/s	50 ns	Acoustics, Machining, Materials Science
100 m	1.5 m/s/fr	0.002 m/s	0.5 ì s	Seismic studies, Vibration, Motion Stability

Example: test of VISAR at LBNL

Velocity of a piston (6 shots):



Setup for testing of VISAR:



Protection enclosure

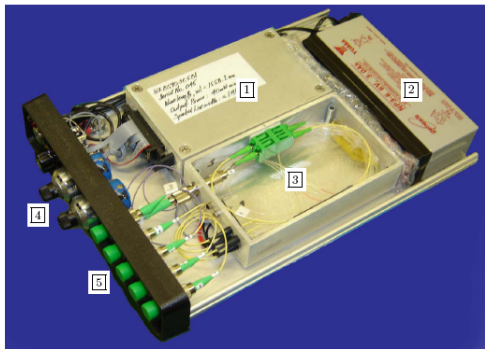
Mirror-polished aluminum foil

Lens

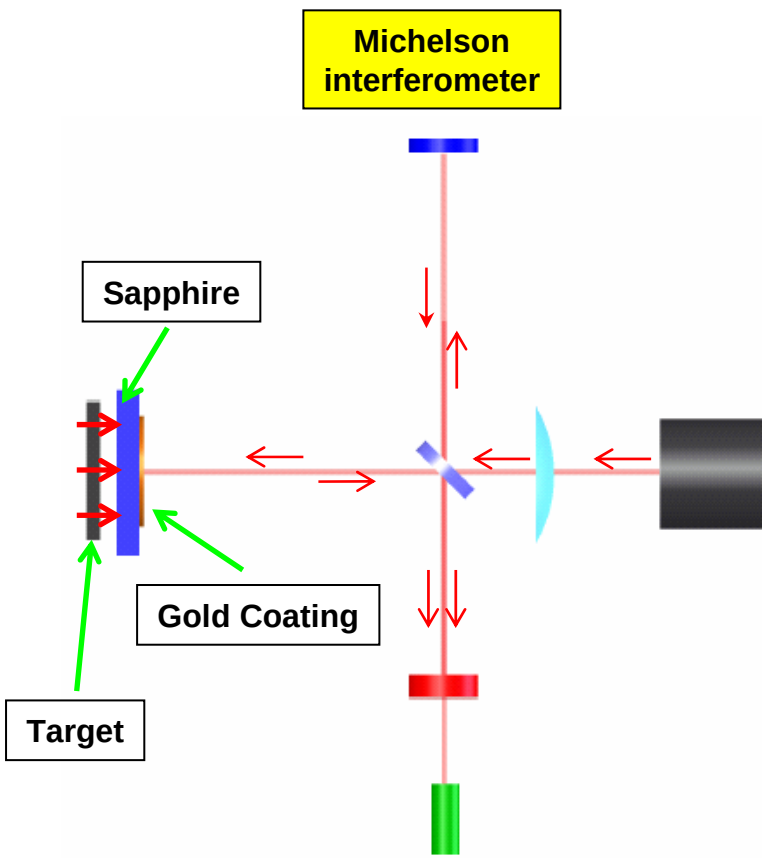
Probing laser beam

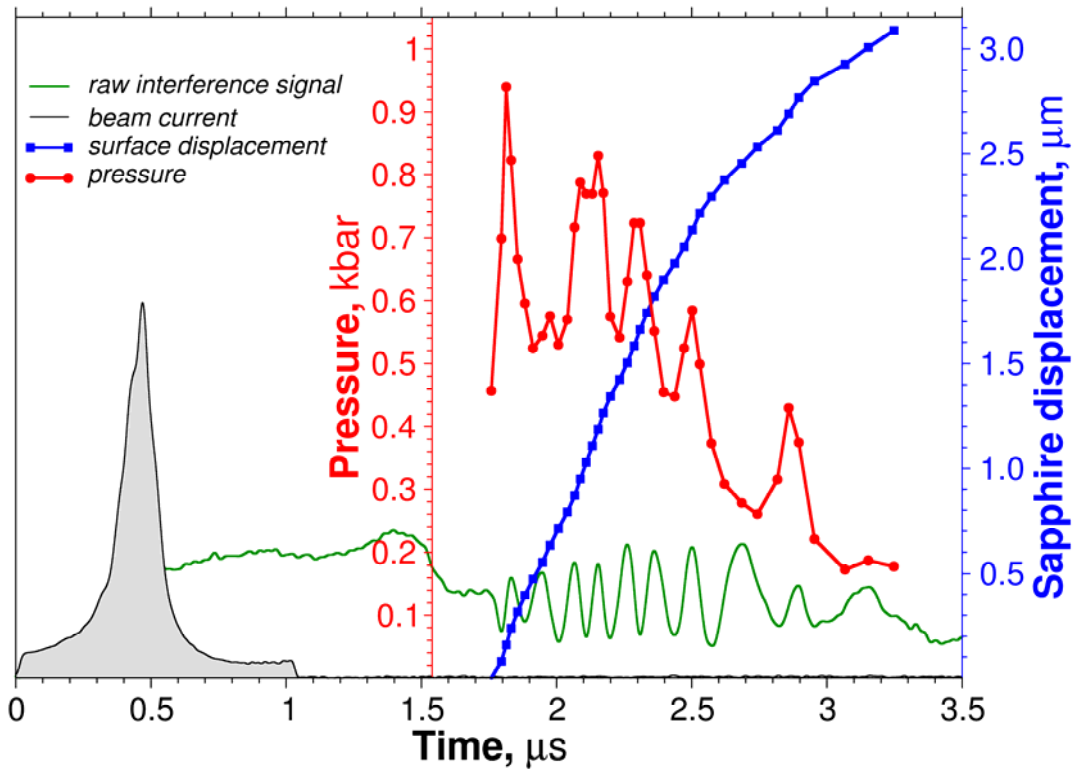
Piston

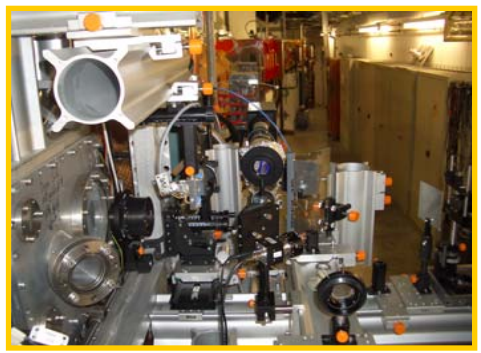
Martin, Froeschner & Associates All Fiber Push-Pull Doppler Velocity Interferometer (VISAR)



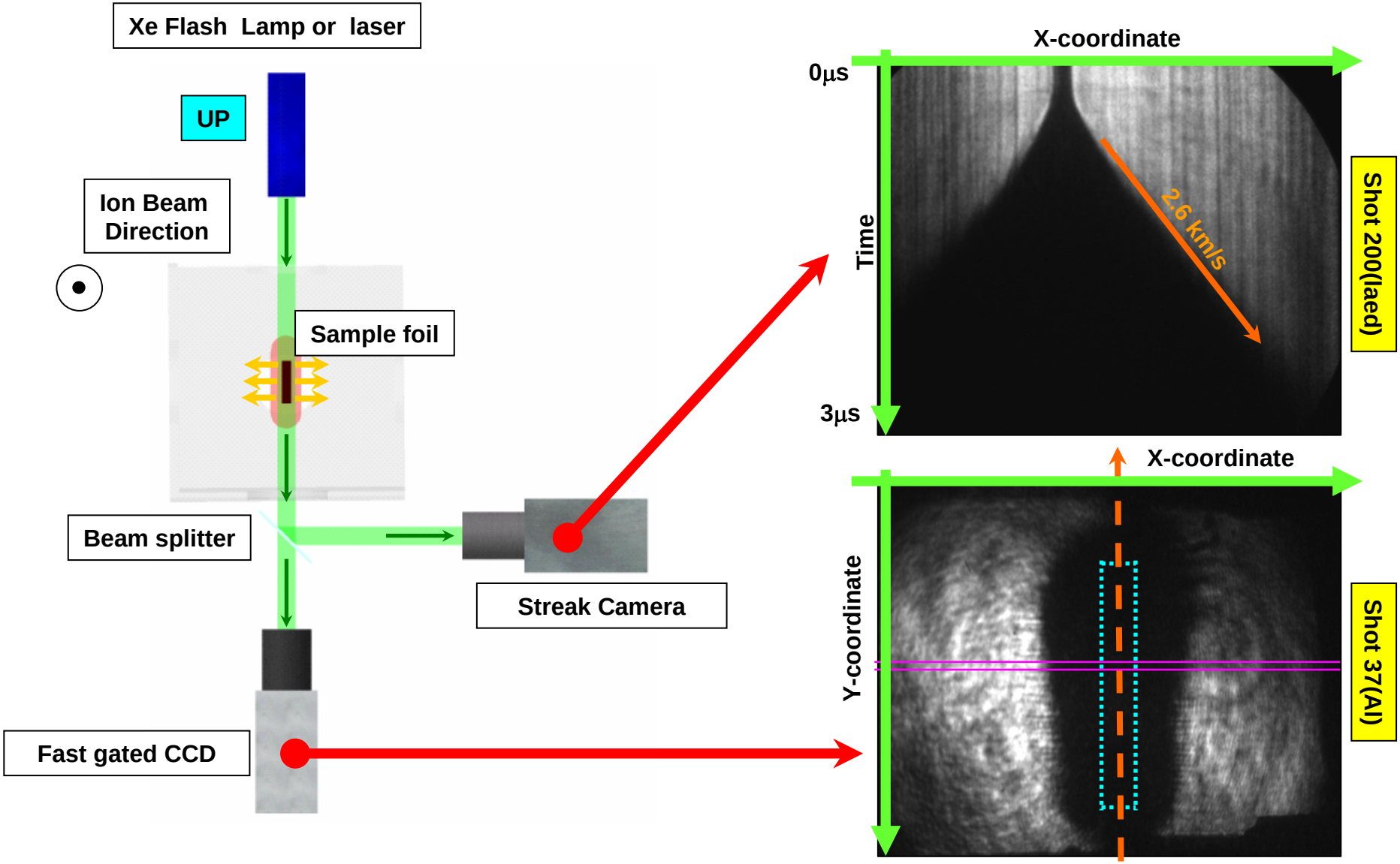
Michelson displacement interferometer (GSI)





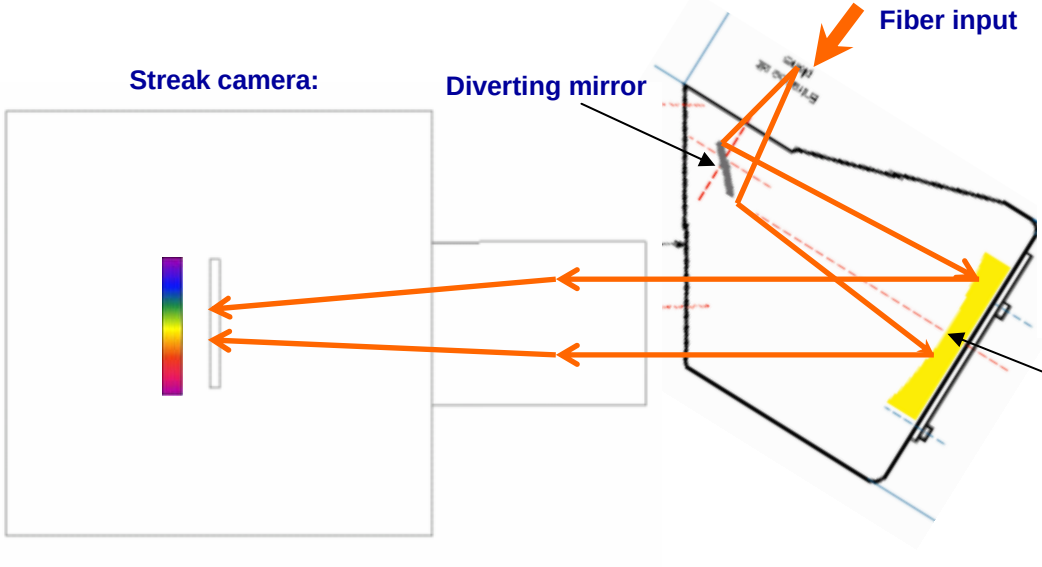


Backligting and streak camera



Streak camera for time resolved spectroscopy of target

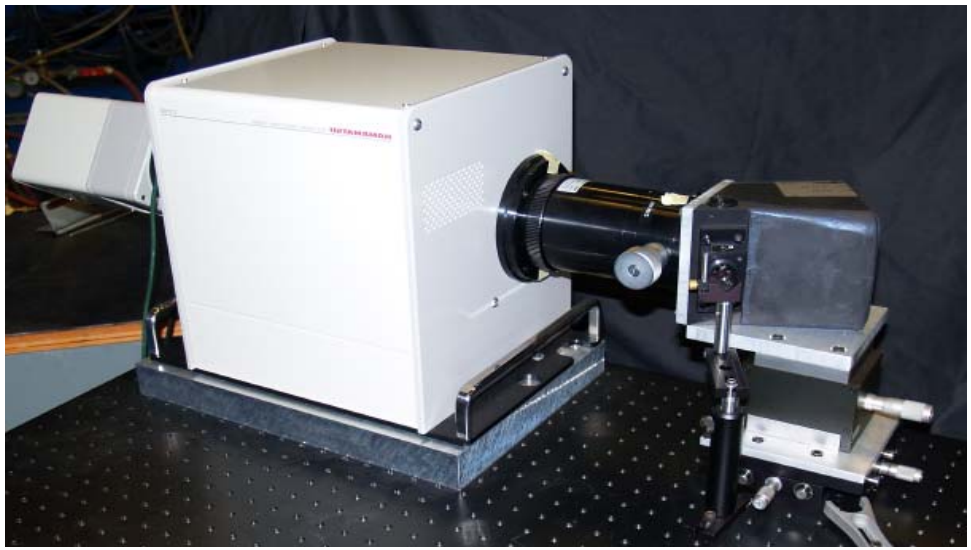
Working scheme:

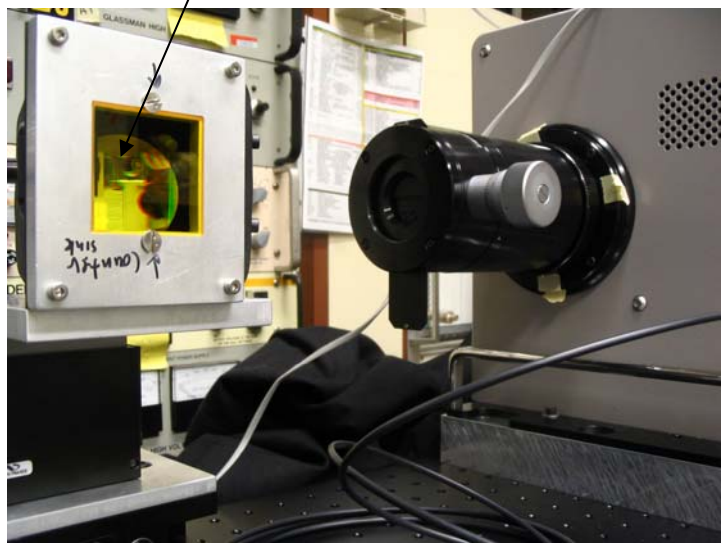


- Records continuous spectrum from 500 nm to 850 nm
- Temporal resolution down to 5 ps
- When calibrated with tungsten lamp, can be used for temperature determination

Holographic grating etched on parabolic mirror

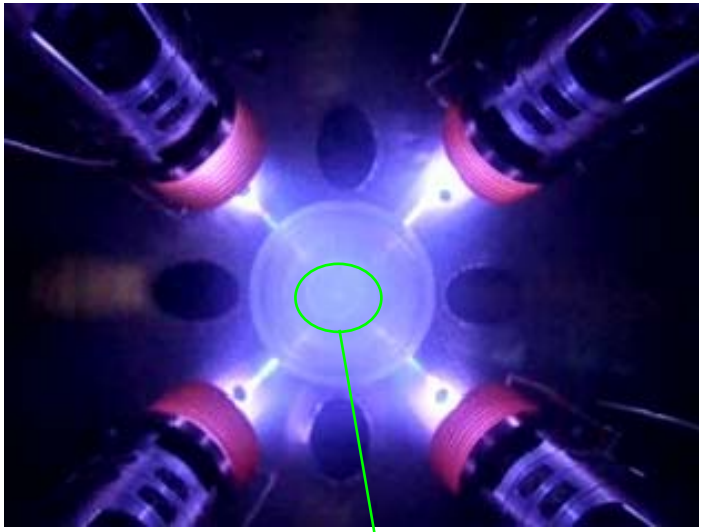
Implementation:



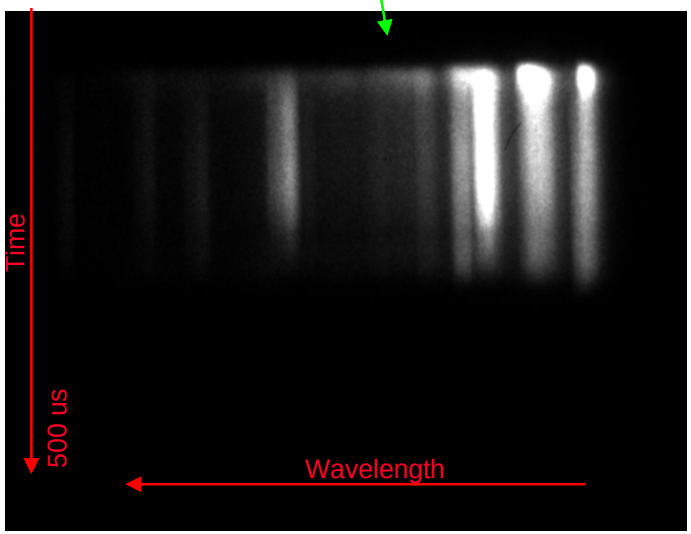


Streak spectrometer applied to neutralization plasma at NDCX

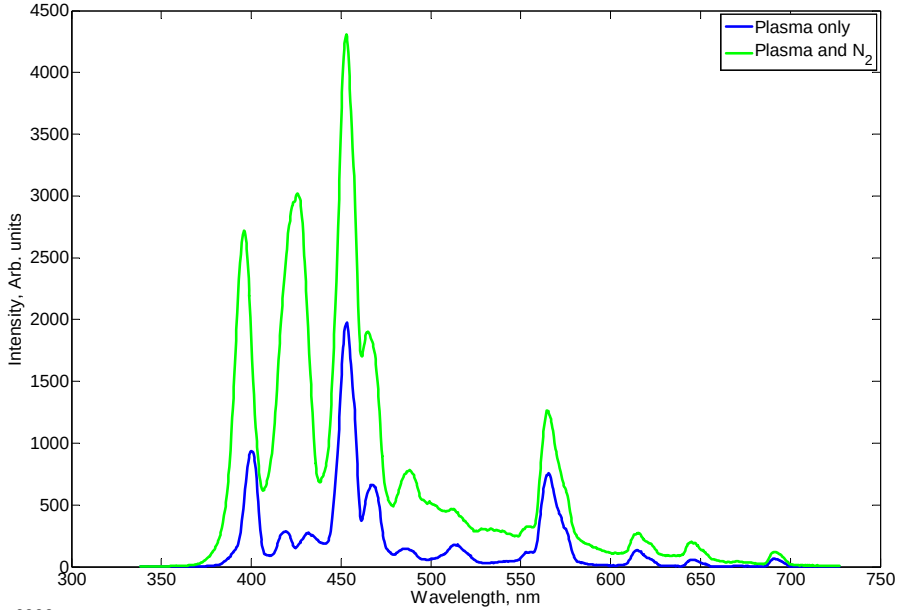
Neutralization plasma in target chamber:



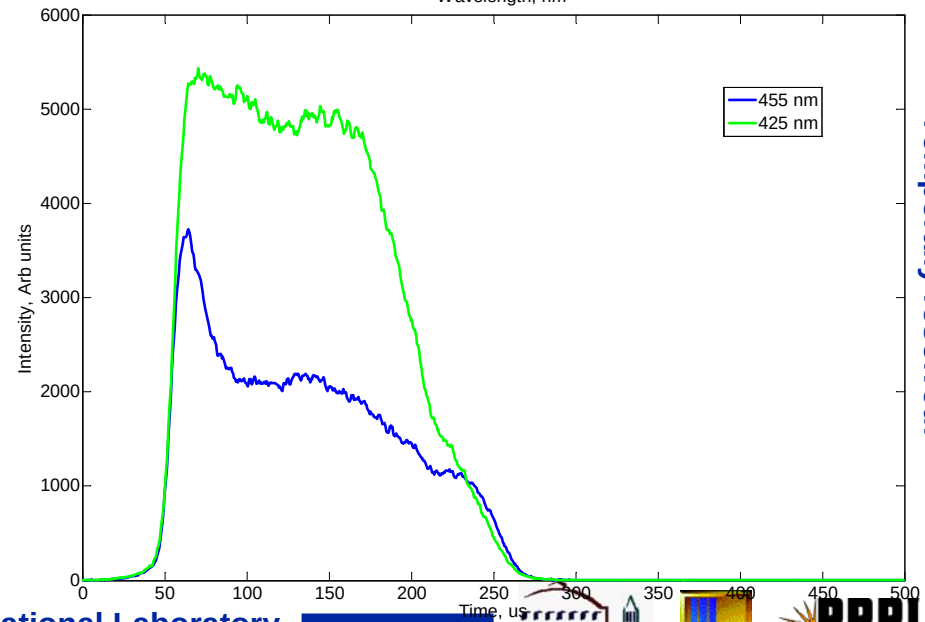
Spectrum of plasma:



Spectrally resolved:



Temporally resolved:



Summary

-Presented basic diagnostic for low-temperature WDM experiments

-Even though it has been invented in first half of the last century, it remains a “work horse” in modern experiments.

-With present development in detector and optics, it can be easily built by students and it is VERY “cheap”.