FOCUS ON IMAGING

In Application

Thermographic Phosphor Particles for simultaneous Velocimetry and Thermometry

Department of Mechanical Engineering, Imperial College London, UK

Introduction

Particle Image Velocimetry (PIV) is widely employed in the field of optical flow and combustion diagnostics. For PIV, micrometre-size particles or droplets are seeded into a fluid flow and their movement is tracked in time to determine the velocity field. However, the presence of these particles makes the simultaneous measurement of scalar quantities, such as the gas phase temperature, difficult.

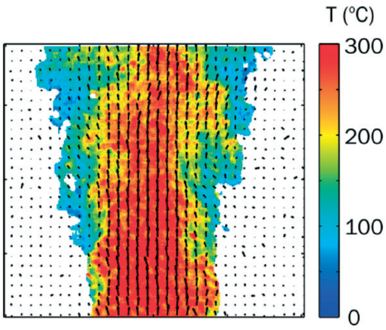


***Figure 1:** Example instantaneous temperature and velocity field from a heated jet*

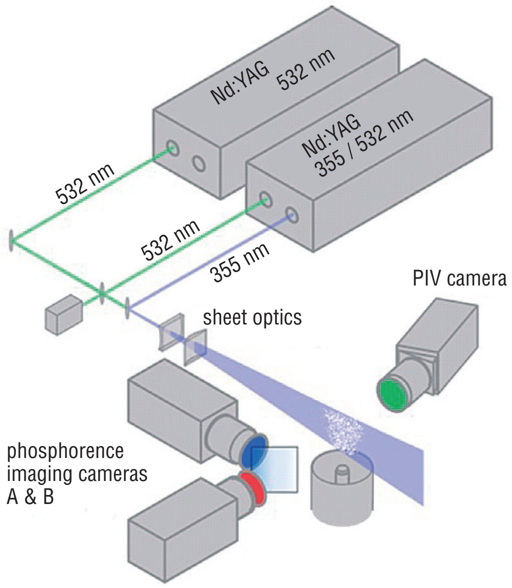
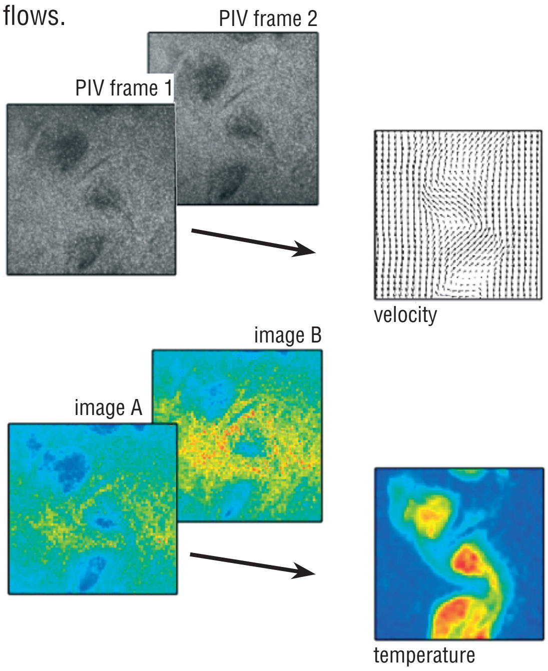


***Figure 2:** Experimental setup for phosphor thermometry and velocimetry*

Principle

An extension of the classical PIV approach to simultaneous temperature measurements can be achieved by using tracer particles from thermographic phosphor materials. After illumination with ultraviolet light, these particles emit phosphorescence with a temperature dependent emission spectrum which can be used for thermometry. Using heat transfer modeling, it can be shown that sufficiently small particles track the gas temperature very well, even in turbulent flows.



Experimental Setup

For thermometry, two non-intensified CCD cameras simultaneously capture spectrally filtered images A and B of the particle phosphorescence. The two images are divided and converted to a temperature image using calibration data. The velocity field is determined using a conventional PIV approach.

Images by courtesy of
B. Fond, C. Abram, A.L. Heyes, A.M. Kempf and F. Beyrau,
Optics Express 20 (2012), 22118-22133
C. Abram, B. Fond, A.L. Heyes and F. Beyrau,
Applied Physics B (2013), 111:155–160

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Thermographic Phosphor Particles for simultaneous Velocimetry and Thermometry

Department of Mechanical Engineering, Imperial College London, UK

Advantages

- simultaneous single-shot planar velocimetry and thermometry using a single tracer
- experimental simplicity – apart from a standard PIV setup, only a frequency tripling crystal, two non-intensified CCD cameras and two spectral filters are needed
- straightforward data evaluation – temperature is evaluated using standard image processing and calibration data

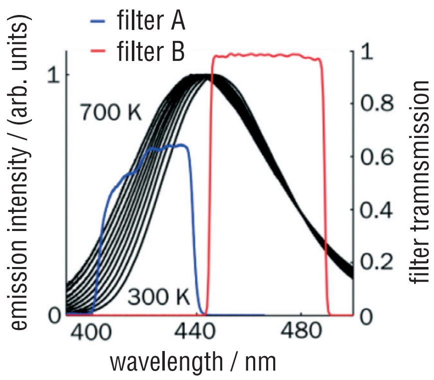

Figure 3: *Phosphorescence spectra of the BAM:Eu^{2+} particles for different temperatures between 300 K and 700 K.*

Tracer Properties

- tracer particles are chemically inert, resistant to high temperatures and insensitive to gas composition and pressure
- phosphorescence emission is short enough (< 1µs) to ensure efficient signal collection, even in turbulent flows

kHz Repetition Rate Measurements

Excitation and imaging at high repetition rates permit visualization of unsteady phenomena related to combustion and heat transfer. The combined phosphor thermometry / velocimetry technique can also be applied at kHz rates using high-speed CMOS cameras and diode-pumped solid state lasers at 355 and 532 nm.

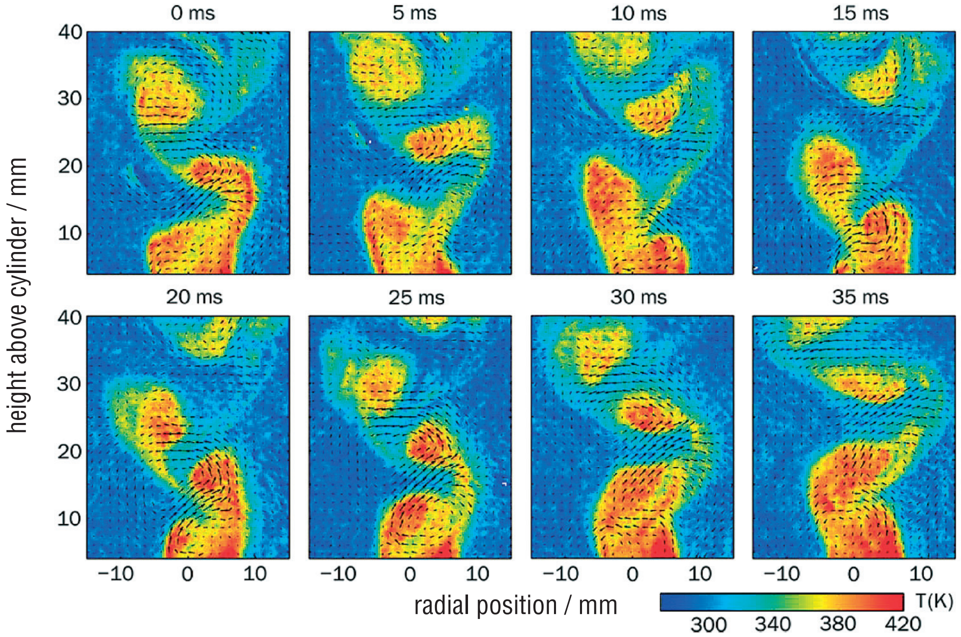

Figure 4: *Time-series of temperature and velocity measurements in the wake of a heated cylinder. The recording was made using a high-speed system at a repetition rate of 3 kHz. Only every fifteenth image is displayed for clarity, and the mean velocity has been subtracted from the instantaneous fields to better visualize the movement of the wakes.*

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FOCUS ON IMAGING

In Application

Temperature Imaging in Thermal Gas Flows

Comparison of imaging techniques

Temperature imaging techniques for gaseous flows

Four imaging techniques for temperature measurements in gas flows are discussed. Each technique is using another physical temperature effect featuring certain advantages as well as experimental limitations for a particular thermographic measurement. Three laser imaging techniques and one line-of-sight technique are compared and tested in a heated air jet.

Imaging Technique	Measured Temperature Effect
Rayleigh Thermometry	Total gas density ~ 1/T
Laser **I**nduced **P**hosphorescence, **LIP**	Thermographic phosphor particles
Laser **I**nduced **F**luorescence, **LIF**	Thermographic LIF gas tracers
Background **O**riented **S**chlieren, **BOS**	Temperature induced density gradients

Laser light sheet imaging techniques like Rayleigh, LIP and LIF are planar measurements stopping the flow motion with very short laser pulses. BOS is a line-of-sight technique recording a dot pattern in the background of the thermal flow. Temperature induced density gradients in the flow are detected as image distortions of the dot pattern (Schlieren). Due to the line-of-sight character of the BOS imaging technique these image distortions can only be converted to temperature for 2D or axisymmetrical flows. The tomographic version of BOS using multiple viewing directions overcomes this limitation and measures 3D temperature fields also in non-stationary and turbulent flows.

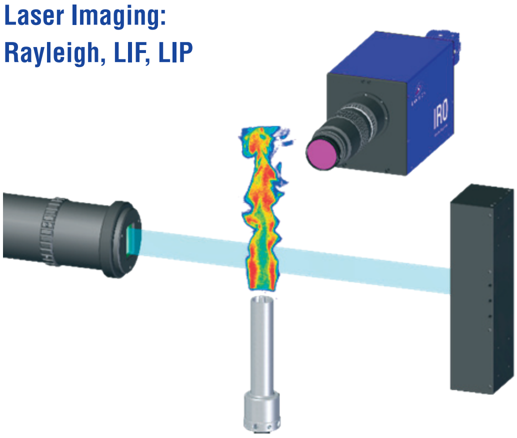
While BOS and Rayleigh are working in clean gas flows, LIF and LIP both need flow seeding with temperature sensitive LIF active gas tracers or thermographic phosphor particles, respectively. Particle seeding allows simultaneous temperature and flow field measurements with a combined LIP and PIV approach called "Thermographic PIV".

	Rayleigh	2-color LIP	2-color LIF	BOS
Max. Temperature	> 1000 K	800 K	900 K	> 1000 k
Field of View	50 mm	200 mm	200 mm	1 m
Precision†	3 %	10 %	6 %	5 %
Seeding	no	phosphor particles	LIF gas tracer	no
Pros	accuracy	T + flow field	sensitivity	simplicity
Cons	stray light	complex setups		simple flows

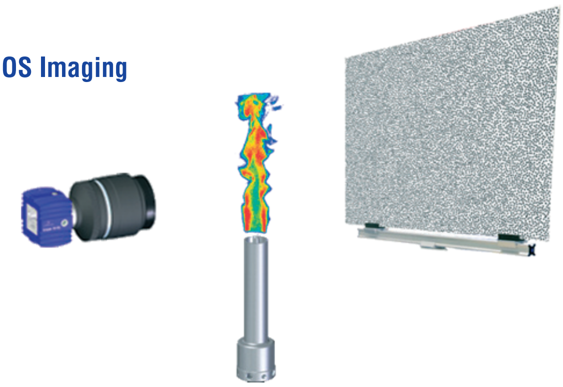
† these are only guidelines depending on experimental parameters

Benchmarking chart comparing the four investigated temperature imaging techniques

Laser Imaging:
Rayleigh, LIF, LIP



BOS Imaging



Laser imaging on light sheets (top) and the line-of-sight imaging configuration of BOS (bottom)

LIP and LIF are based on the change of the tracer's emission spectrum with temperature. Both use a 2-color ratiometric imaging approach to compensate for seeding density as well as laser intensity fluctuations.

Rayleigh is based on the elastic light scattering from gas molecules. Its signal strength is proportional to the local number density, which depends on temperature applying the ideal gas law. The gas mixture composition needs to be known.

Laser imaging can be prone to stray light especially when applied close to surfaces. This unwanted interference can be effectively suppressed applying the newly developed structured light sheet illumination technique called "SLIPI" (see LaVision Application Note "**Scalar Laser Imaging without Stray Light**").

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Temperature Imaging in Thermal Gas Flows

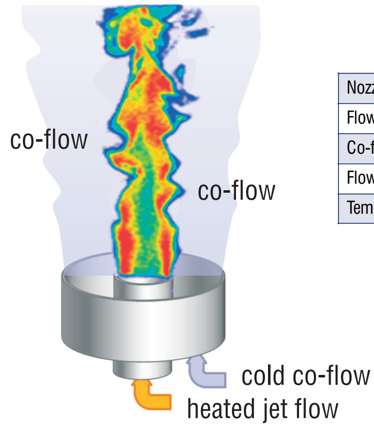
Comparison of imaging techniques

Performance tests in a heated air flow

All four imaging techniques were applied in the same heated air jet close to the nozzle in a nearly laminar and stable flow region of almost axisymmetric structure. The covered temperature was in the range of 300 K to 800 K. Some of the experimental parameters for each method are given in the table below. More detailed information can be found in the paper of Fuest et al. [1].

	Light Source	Flow Tracer	Detection System
2-color LIF	Nd:YAG: 266 nm, 3 mJ/cm	Anisole	2x (IRO+M-lite 2M)
2-color LIP	Nd:YAG: 355 nm, 5 mJ/cm	BAM:Eu	2x M-lite 2M
Rayleigh	Nd:YAG: 355 nm, 60 mJ/cm	-	IRO+M-lite 2M
BOS	LED Flash: white, 200 μs	-	M-lite 5M

IRO: image intensifier   M-lite 2M: 12-bit 2 Megapixel CMOS camera



Nozzle diameter	9 mm
Flowrate jet	10 lpm (unheated air)
Co-flow diameter	35 mm
Flowrate co-flow	200 lpm (cold air)
Temperature range	300 K to 800 K

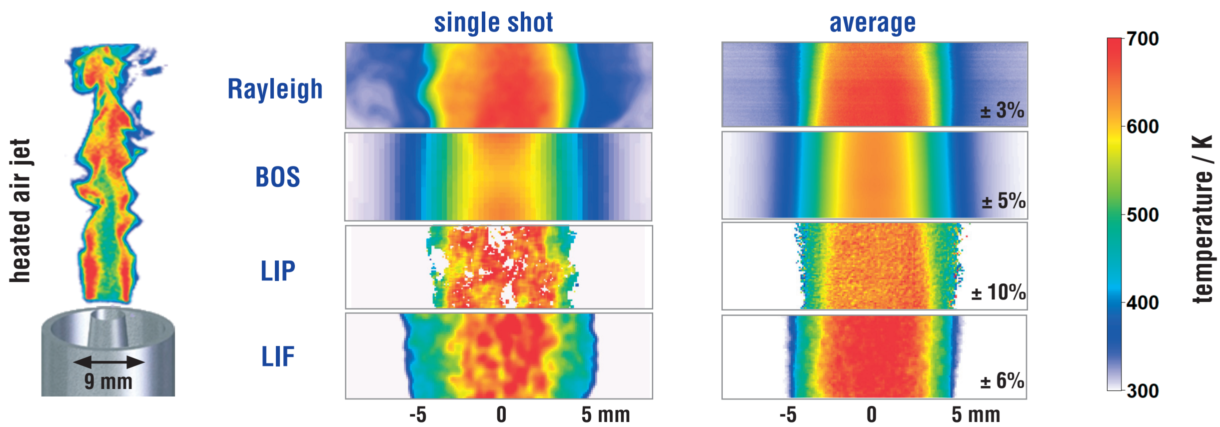
Sketch of the heated air jet nozzle with operation conditions

For the flow seeding techniques LIF and LIP anisole tracer gas and BAM:Eu phosphor particles were used, respectively. The applied laser pulse energies per cm light sheet height (mJ/cm) are quite different, reflecting the large differences in light scattering efficiency of the three applied laser imaging techniques: compared with LIF, Rayleigh imaging needs roughly 20x higher laser energy in the light sheet.

2D BOS measurements have to be averaged until an axisymmetric deformation pattern is achieved, only from which radial temperature profiles can be derived. Tomographic BOS based on multiple camera views overcomes this limitation.

Temperature fields of the air jet at 700 K measured with the four optical methods are shown in the figure below. The standard deviation of each averaged temperature field is also indicated.

Rayleigh thermometry shows the highest precision, while LIP temperatures are measured with a higher uncertainty mainly due to inhomogeneous particle seeding of the flow. Both seeding techniques LIF as well as LIP used much less pulse energies compared with Rayleigh allowing temperature measurements on much more extended light sheets. All laser imaging techniques can be performed with nearly the same hardware setup proving the versatility of LaVision's laser imaging systems for quantitative flow visualization.



Single-shot (left) and averaged (right) temperature fields measured in the heated air jet at 700 K for each of the four indicated temperature imaging techniques

Reference

[1] F. Fuest et al., "Gas thermometry using four different optical methods", 19th Intl. Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, Lisbon 2018

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In Application

Temperature Imaging in a Heated Jet Flow

2-color Anisole-LIF Thermometry

Gas temperature imaging using 2-color Anisole-LIF

Temperature imaging using Anisole-LIF is applied in a heated air jet close to the nozzle in a nearly laminar and stable flow region of almost axisymmetric structure. The covered temperature was in the range of 300 K to 800 K. More detailed information can be found in the paper of Fuest et al. [1].

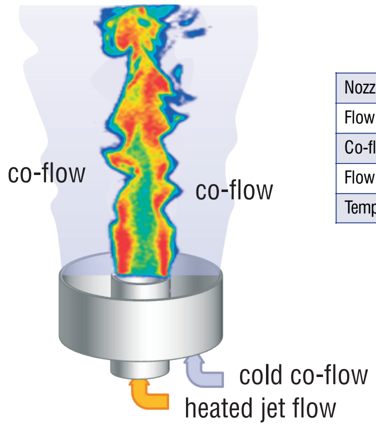
Compared with traditional LIF tracers the anisole tracer generates higher LIF signals at much lower seeding concentration levels [2]. The applied LIF method is based on the change of the anisole fluorescence spectrum with temperature. A 2-color ratiometric imaging approach is used to compensate for seeding density variations as well as laser intensity fluctuations.

Experimental setup

A schematic drawing of the measurement system is shown in Figure 2. The beam from a frequency-quadrupled Nd:YAG laser at 266 nm is guided through a sheet forming optics to generate a divergent light sheet of 55 mm height at jet center line. The laser sheet has a thickness of about 1mm and is placed in the central symmetry plane of the heated jet. The average laser pulse energy in the observation area is 15 mJ.

In LIF applications the fluorescence signal is spectrally separated from the excitation wavelength using optical filters. The Anisole-LIF filter set and corresponding beamsplitter are specifically designed for 2-color LIF measurements such as ratiometric temperature measurements in gaseous flows using anisole tracing.

Following a 2-color strategy for measuring the temperature the anisole fluorescence is spectrally separated into a “blue” and a “red” part by means of a 310 nm dichroic beamsplitter (LP 310).



Nozzle diameter	9 mm
Flowrate jet	10 lpm (unheated air)
Co-flow diameter	35 mm
Flowrate co-flow	200 lpm (cold air)
Temperature range	300 K to 800 K

***Figure 1**: Sketch of the heated air jet nozzle with operation conditions*

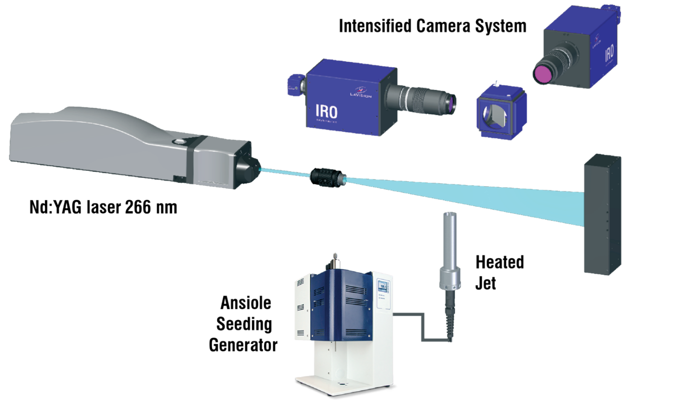


***Figure 2:** Experimental setup for gas temperature imaging using 2-color Anisole-LIF*

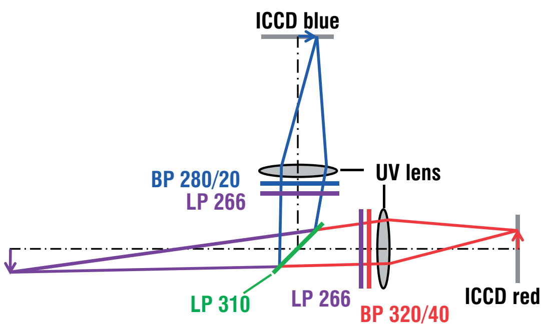


***Figure 3**: Schematic setup of the 2-color Anisole-LIF imaging system including filter set and beamsplitter*

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Temperature Imaging in a Heated Jet Flow

2-color Anisole-LIF Thermometry

A 266 nm longpass edge filter (LP 266) in front of each camera lens suppresses remnants of excitation laser light. In addition, bandpass filters at 280 nm ± 10 nm and 320 nm ± 20 nm further narrow the “blue” and “red” spectral range of LIF signal detection, respectively.

Two intensified CMOS cameras (IRO image intensifier lens-coupled with Imager M-lite 2M camera) with UV lenses (f=100 mm, f/2.0) record the spectrally separated LIF signals.

The anisole seeding generator is used to produce a homogeneous and stable anisole seeding of the N_2 gas jet.

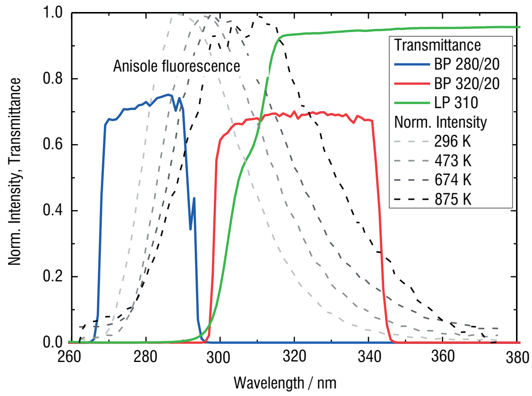

Figure 4: *Typical spectral transmission of filter set and beamsplitter*

Figure 5: *Anisole seeding generator*

Image processing and data evaluation

The recorded data are preprocessed applying background and white field correction, image mapping and signal ratioing. Finally, the corrected ratiometric data are converted to temperature values including uncertainty quantification using the previously recorded calibration curve. This dedicated processing sequence is executed in the right order with a single keystroke in our DaVis LIF software package.

Such measured temperature fields in the air jet at 700 K are shown in Figure 6 below.

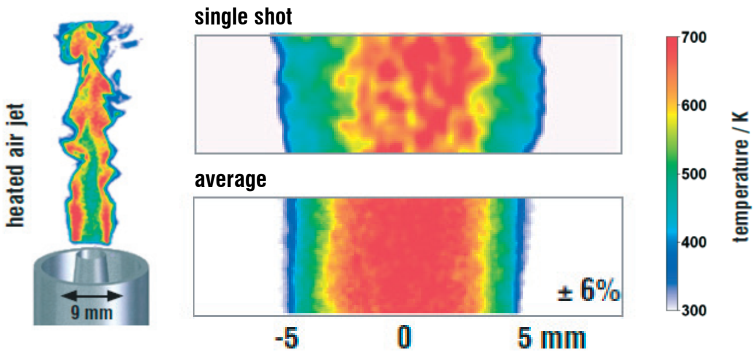

Figure 6: *Single shot and averaged temperature fields measured in the heated air jet at 700 K using 2-color Anisole-LIF*

Reference

[1] Fuest, Frederik et al. ”Gas thermometry using four different optical methods”, 19th Intl. Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, Lisbon 2018

[2] Faust, Stephan et al. „A comparison of selected organic tracers for quantitative scalar imaging in the gas phase via laser-induced fluorescence“, Applied Physics B 117.1 (2014): 183-194

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