White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 17, 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	X
Either Oral or Poster	
Will not attend	

Title:	Nanosecond Dynamics and Plasma Instability
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

Late Prof. Richard Feynman stated turbulence as "the most important unsolved problem of classical physics.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The approach is to directly measure the non equilibrium Boltzmann distribution instant by instant. It requires a new experimental research instrument called interferoceiver, which is an interferometric receiver.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

The impact of this research will lead to a new industrial revolution in the 21 century; such as advancing plasma physics, achieving success in controlling thermo nuclear reactions, reversing global warming, eliminate air pollution, managing weather, overcoming fresh water shortage, and advancing technology in space travel.

Nanosecond Dynamics and Plasma Instability

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Abstract

Plasma state is described by a velocity dependent distribution function, which changes every nanosecond in a thermonuclear process. If we are able to measure its change from nanosecond to nanosecond, we will be able to find how plasma changes itself from a stable state to an unstable state under external conditions. Through detailed investigations, the nanosecond dynamics will emerge to prevent instability of thermonuclear reactions. Without nanosecond dynamic, we might never be able to control plasma instability and nuclear fusion.

Introduction

Our main objective is to directly measure the transient and velocity dependent non-equilibrium distribution functions, which satisfy nonlinear integral and differential Boltzmann equation. There had been difficulties with all kinds of nonlinear equations. Forty years ago, regularities concerning the onset of chaos were discovered among nonlinear algebraic equations, which change themselves step by step algebraically. These discoveries led us to believe there must also be regularities of distribution functions describing thermonuclear processes, when they change from stable to unstable states. Unfortunately we were unable to experimentally measure the transient distribution functions directly. Such difficulty is deeply embedded in modern physics that we were unable to measure transient velocity nanosecond by nanosecond or microsecond by microsecond.

We are greatly involved in nanotechnology on physical structures in the order of nanometers. This is resulted from our understanding on their dynamics, namely the quantum mechanics. In special relativity, space and time are equivalent. Why we have no understanding on dynamics of physical processes happening within nanoseconds? The reason is the same that we were unable to measure transient velocity in terms of nanosecond by nanosecond.

Interferoceiver

A pulse reflected by a moving target is Doppler shifted and contains micro Doppler information on target internal motions. But we were unable to decipher them from a single pulse with conventional methods. For instance, when microsecond radar pulse with radio frequency of 10 GHz is reflected by a moving object with velocity 300 m/s, the reflected pulse is Doppler shifted with frequency 20 KHz. Conventional methods require us to deploy forty thousand pulses and engage the target for one second in order to measure 20 KHz Doppler frequency with a

resolution of 1.0 Hz. Within one second, the target has changed itself, the Doppler information being averaged and micro Doppler information becoming washed out.

Now changes are coming. It is a new instrument called interferoceiver, which is based on the principle of Michelson interferometer along with replica reproducers, as shown in Fig. 1, of the incident and reflected pulses. Through the reproduced replicas, an incident pulse and its reflected pulse are repeatedly interfered. Thus, we are able to decipher transient Doppler and micro Doppler information. Interested readers should read the published papers on this topic.

A non equilibrium distribution function in one dimension has a form of $f(t,x,v)$, which is a function of position and velocity and changes with time. The experimental set up for measuring such a function is depicted in Fig. 2. The measured intensity variation as a function of the replica number m and pulse component ω has a form

$$\int dv' \int dx' f(t_0, x', v') Exp\{i2\omega \frac{(x'_0 + x' - x_0)}{c}\} \times Exp\{i\omega \frac{2v'}{c} \frac{(x'_0 + x' + mL)}{c}\} + c.c..$$

The notation t_0 is the instant when the pulse is reflected by the medium. The random medium and reference positions are denoted by x'_0 and x_0 respectively, the spatial separation between replicas by length L. In the above equation, two dimensional Fourier components of the non distribution function $f(t,x,v)$ at instant t_0 are experimentally measured directly. After the measurements, we can Fourier transfer back to get the distribution function $f(t, x, v)$ instant by instant. The spatial resolution of the measured function $f(t, x, v)$ is determined by pulse length, and the velocity resolution by replica spacing L and total number of replicas. Single pulse Doppler radar and optical coherence tomography (OCT) are special cases of the above equation. For OCT, the spatial resolution is term of microns. Interferoceiver for radar application requires pulse length about micro seconds and is under active development. Technology exists to develop interferoceiver with spatial resolution in order of microns and pulse length sub picosecond, if we are attracted to discover nanosecond dynamics.

Our interest in controlling thermo nuclear reaction started in 1950s. Now sixty years later, its success is still remained to be seen. Chemical energy for weapon uses appeared in China around at 12th century, but for industrial uses about 500 years later. In these years Newton dynamics and thermo dynamics were found and established. It is difficult to image that without these dynamics the industrial revolution could occur in England. By the same token, the author believes that we need the help of a new dynamics to control thermo nuclear energy for industrial uses. Whoever masters the nanosecond dynamics in the 21 century will be the leader of a new industrial revolution.

References:

Onset of Chaos

"Quantitative universality for a class of nonlinear dynamics," M. J. Feigenbaum, J. Stat. Phys., vol. 19, p. 25, 1978.

"The universal metric properties of nonlinear transformations," M. J. Feigenbaum, J. Stat. Phys., vol. 21, p. 69, 1979.

Interferoceiver was proposed in 1995 for radar applications. It is based on a mechanism of photon detours invented in 1970s to measure super fine atomic spectrum with a pair of photons.

"Optical Fiber-based Interferoceiver, " Ming-Chiang Li, IEEE Technical Digest on RF Optoelectronics, p. 72, 1995 Summer Topical Meetings, Keystone, Colorado (August, 1995).

"Doppler-Free Two-Photon Absorption of Two Coherent Beams, " Ming-Chiang Li, Phys. Rev. A 16, 2480 (1977).

"Resonance Fringes in the Two-Photon Absorption with a Doppler Shift, " Ming-Chiang Li, Phys. Rev. A 22, 1323 (1980).

The mechanism was later utilized in investigations of photon entanglement, quantum encryption, and quantum computing. Detours provide a pair of photons with multiple opportunities in interaction with an atom. In interferoceiver, detours become replica reproducers, which provide multiple opportunities for an incident pulse to interfere with its reflected pulse. The detailed theory of interferoceiver for radar and electronic warfare applications is in following publications.

"A High Precision Doppler Radar Based on Optical Fiber Delay Loops," Ming-Chiang Li, IEEE Transactions on Antennas and Propagation, 52, pp. 3319-3328 (2004).

"New Channelized Receivers," Ming-Chiang Li, Transactions of the AOC, **1**, pp. 76-97 (2004).

Spectrum separator based optical coherence tomography is several hundred times faster than time domain optical coherence tomography:

"High Speed Inspection of a Sample Using Superbroad Radiation," Ming-Chiang Li, Patent No. 5,892,583, Date of Patent: April 6, 1999.

Interferoceiver will revolutionize radar and electronic warfare technologies, and is under active development.

"The Use of Interferoceiver for the Prevention of Fratricide in Missile Defense," Ming-Chiang Li", in Signal Processing, Sensor Fusion, and Target Recognition XVII, edited by Ivan Kadar, Proc. of SPIE Vol. 6968, 69681K, (2008).

"Revolutionizing Doppler Radar With RF-Photonics," Weimin Zhou, Ming-Chiang Li, Olukayode Okusaga, and Michael Stead, Army Research Laboratory, Defense Technical Information Center, NOV 2006.

"Demonstration of an RF-Photonic Microwave Channelizer using an Optical Fiber recirculating Loop," Michael Stead, and Weimin Zhou, Army Research Laboratory, Adelphi MD, and Ming-Chiang Li, Liceimer, Mitchellville, MD, Defense Technical Information Center, DEC 2008.

"Method and apparatus for analyzing the spectrum of radio-frequency signals using a fiber optic recirculation loop," Ming-Chiang Li, and Weimin Zhou, Patent Number 8861567, Date of Patent: October 14, 2014.

Figures

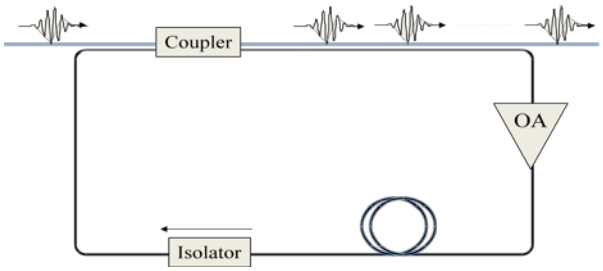


Fig.1 An optical fiber recirculation loop as shown is one kind of replica reproducers. OA denotes optical amplifier and isolator prevents pulse circulating in both directions. After one circulation of an input pulse, a replica is reproduced.

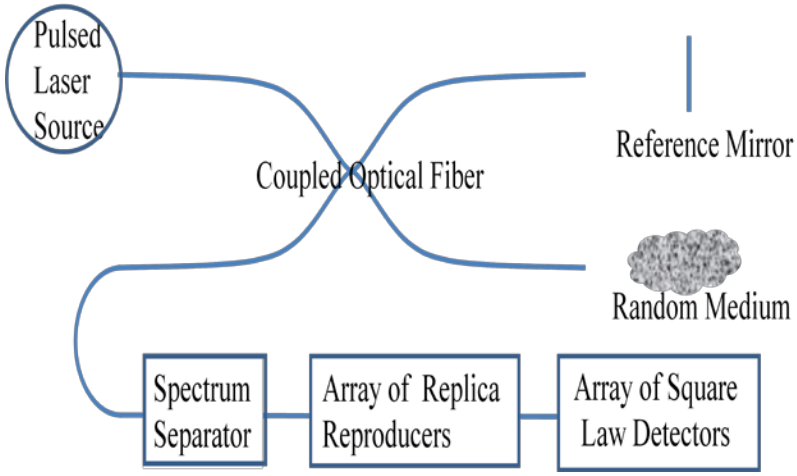
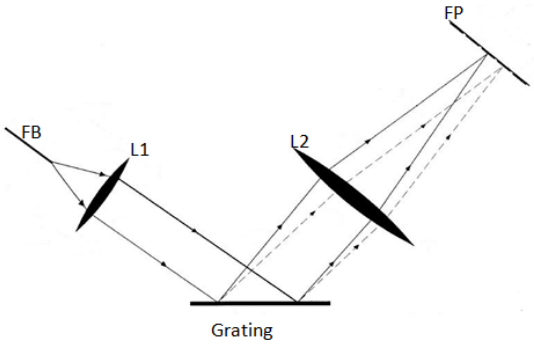


Fig. 2 Proposed experimental set up. It is essential a set up for spectrum separator based optical coherence tomography (frequency domain OCT) with insertion of replica reproducers.
A pulse emitted from the source through the coupled fiber is reflected by the reference mirror and the random medium. Both reflected pulses through coupled optical fiber are fed to the spectrum separator.



Depicted spectrum separator consists of optical fiber FB, grating, lens L1 and L2. Different frequency components in both reflected pulses are focused into the different points on the focal plane FP. Every point on FP sits a replica reproducer. At the end of each replica reproducer is a square law detector.