*Proceedings of ITC18,2008*

# Plasma Diagnostics in the Formation Stage of "LCDC"

## The Local Cold and Dense Compress Formed by Injected Pellets

Masaru. Irie[1], Miyoko.Kubo-Irie[2], FBX Team[1]
[1]*Waseda University, Tokyo, Japan*
[2]*Denji Ohyoh Kenkyuujyo (Research Institute for Applied Electro-Magnetism), Tokyo, Japan*

The most efficient fueling scheme so far is said to be a frozen deuterium pellet injection, even though it is still very difficult to accomplish central fuelling (to inject fuel into the burning plasma core) into nuclear fusion reactors. On the other hand, this scheme forms very cold (~$10^1$eV)and very dense (~$10^{23}$) plasma along the magnetic field line on the rational surface in the time scale of about $10^0$ms. This is called LCDC (Local Cold Dense Compress). The detailed experimental observation has not been reported so far because of the difficulty stated below. This paper deals with the experimental proposal in this direction. The fundamental diagnostic scheme is 3D image reconstruction technique developed in our laboratory. This is originally developed in nuclear fusion research as a Soft X-ray Tomography. This technique is going to be used in many fields: CXT (Constrained X-ray Tomography)in medical field, CEBT (Constrained Electron Beam Tomography) in biological field and quantum entanglement detection for quantum computer research.

Keywords: LCDC (Local Cold and Dense Compress), Pellet Injection, Bremsstrahlung radiation , ablation, plasmoid

## Inroduction

The injected pellet goes under intense heat up and is ablated by bulk plasma and evaporated. The neutral hydrogen vapour-clusters go under free diffusion until they are ionized. These clusters form dense plasmoid, which is partially ionized plasma above the order of $10^{25}/m^3$. Because of the high collisionality, this plasmoid shields the solid pellet core from the main plasma and it travels almost the same speed as the injection speed crossing many rational surfaces. In their simulation, Nakamura and Wakatani estimated the plasmoid parameters as below in 1986 and well within the experimentally obtained parameters.

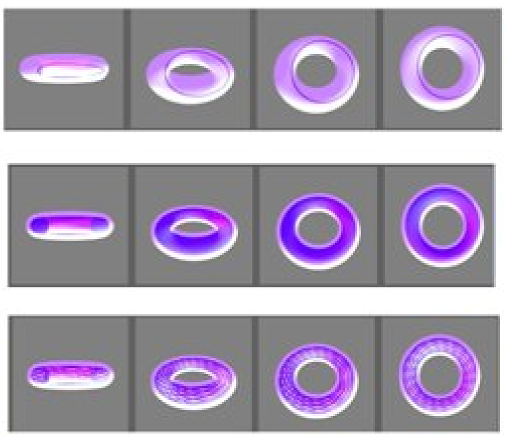

Fig.1. LCDC on the rational surfaces.
The plasma diffusion allows the LCDC density decay about 100 times faster on q=1.01 than on q=1.1 magnetic surface.
1st raw q=1.0, 2nd raw q=1.01 3rd raw q=1.1

Pellet core : ~$10^1$K , $10^{30}/m^3$
Plasmoid: $10^{24}/m^3$ , $10^0$ eV
Bulk Plasma: $10^{20}/m^3$ , $10^4$ eV

This plasmoid in this phase contains neutral hydrogen and radiates strong spectral emission. Because of this nature the plasmoid has been studied both intensively and extensively.
In due course, after about duration of $10^{-4}$ sec, the plasmoid develops to be nearly fully ionised and the radiation changes into continuum. Because of the fast

*author's e-mail: fbx3@waseda.jp*

diffusuion in the direction parallel to the magnetic field, the plasma diffuses rapidly into the magnetic surfaces. However on the rational surfaces, because of the short connection length, the low temperature and high density plasma forms a filament type local loop called LCDC (Local Cold and Dense Compress) and show quite different behavior from those on the irrational surface, Irie [1]. Fig.1 shows the basic image of this LCDC near q=1, q=1.01 and q=1.1 surface. The plasma diffusion velocity along the magnetic field line is about a half km/s. So the LCDC volume is minimum at q=1 and the volume is roughly 100 times larger at q=1.01.
The plasma density in the latter decays about two orders of magnitude lower than the former within few ms.
Here we would like to show the diagnostic scheme of thermalization and diffusion process of this LCDC plasma with the fundamental technique used in our laboratory in the field of the quantum computation.

## Radiation Intensity estimation

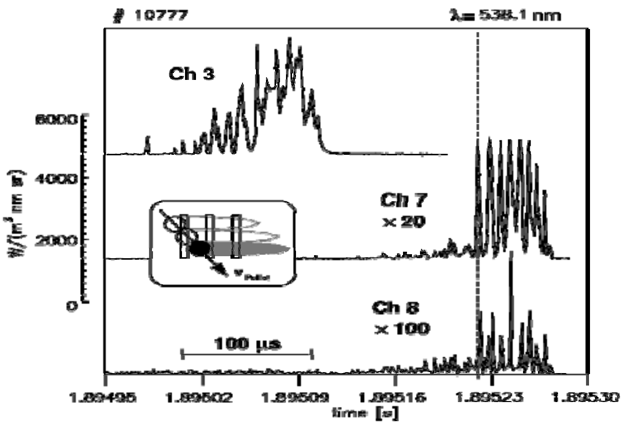


Fig.2. High density plasma drift with Continium radiation measurement in ASDEX-U
W.M.Muller et al. Phys.Rev.Lett, 83,p2199 (1999)

In 1999 W. M. Muller and his co-workers published their experimental result of pellet injection into the ASDEX-U tokamak as shown in Fig.1[2]. The pellet is injected from the high field side and the plasmoid drifts to lower field side. The plasmoid is striated and split into many clouds. The radiation is observed through many slits and each plasmoid blocks shows each plasmoid sequentially as in the figure. a train observed spectral radiation the Balmer line spectra decays in due course. The movement is monitored with an array of slits as shown in the figure. Drifting plasmoids initially radiates clear and strong Balmer line spectra similar to those in Channel.3 and when it reaches to the plasma center, Channel.8, the radiation in 5384.1 even though their intensity becomes weaker by few orders of magnitude but still keeps well distinguishable sequential radiation peak. In their paper they do not mention the detailed radiation process, however here we would like to write down the fundamental Bremsstrahlung formula for reference.

$$\varepsilon=6.8\text{x}10^{-33}Z^2 n_e n_i T^{-1/2} g_n \exp(-h\nu/kT)\,\text{Wm}^{-3}\text{Hz}^{-1} \qquad (1)$$

This clearly shows the strong density dependence and indicates the possibility to detect these emission from the LCDC plasma along the magnetic field line in the downstream zone of the Balmer radiation points.

## Density estimation: Diffusion Equation

In their web page V. M. Timokhin, et al, in the State Polytechnical University of St. Petersburg, Russia shows a

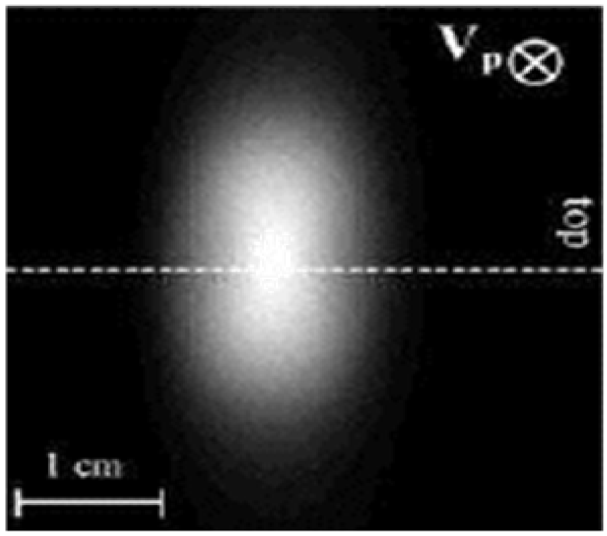


Fig.3. Plasmoid from carbon pellets in the W7-AS Plasma.
V. M. Timokhin, et al. (2005)

nice picture of the plasmoid form the carbon pellet shown in Fig.3.
The three dimensional diffusion equation with non-isotropic diffusion coefficient is

$$\frac{\partial N}{\partial t} = D_x \frac{\partial^2 N}{\partial x^2} + D_y \frac{\partial^2 N}{\partial y^2} + D_z \frac{\partial^2 N}{\partial z^2}$$

$$N(r,z,t) = \frac{1}{8(\pi t)^{3/2} D_r (D_z)^{1/2}} \exp\left[-\frac{(r-r_0)^2}{4D_r t} - \frac{(z-z_0)^2}{4D_z t}\right] \qquad (2)$$

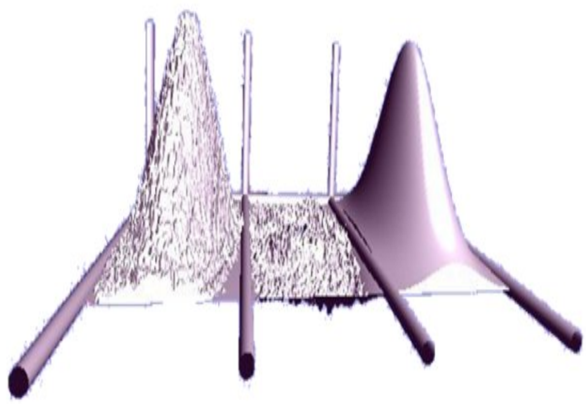

Fig.4. The three dimensional plot of the radiation intensity (left), the best fit surface of this image profile based on the equation (2) (right) and the difference between the two surfaces profiles (middle). The agreement is within 0.5% in this case.

This image and the classical diffusion model agrees very well as shown above. The three dimensional plot of the intensity (left), the best fit surfaces of these image profiles based on the equation (2) (right) and the difference between the two profiles (middle) is shown in Fig.4. This simple model with only two adjustment parameters describes the basic feature of the radiation profiles well within our requirement. The mean discrepancy is less than 0.5% in this case. In this model we can trace around where and around when the LCDC are most probable to exist.

## Three dimensional reconstruction detection

The next problem is how to distinguish the LCDC radiation out of the strong background radiation from the edge plasma. Let us see the example. In fug.5 the picture of ELM filament in MAST Spherical Tokamak is presented taken from Dudson et al[3]. The image is in focus a little behind the center colum so the front ELM filament is strongly blurred and the rear ELM filament is less blurred. If the physical If the physical system is optically thin and the Dynamic range of the image sensor is broad enough, we should be able to obtain the three dimensional information by using focusing technique based on the geometrical optics.In other word, we should be able to identify the position of the radiation source as shown in Fig.6. The plane at P1 receives the converging ray from the source. The plane P2 the ray is just in focus and The plane at P3 receives the diverging ray from the source. In P2 plane clear two dimensional image is recorded but on the other plane the image is blurred and the spatial correlation factor is larger than the focusing plane.

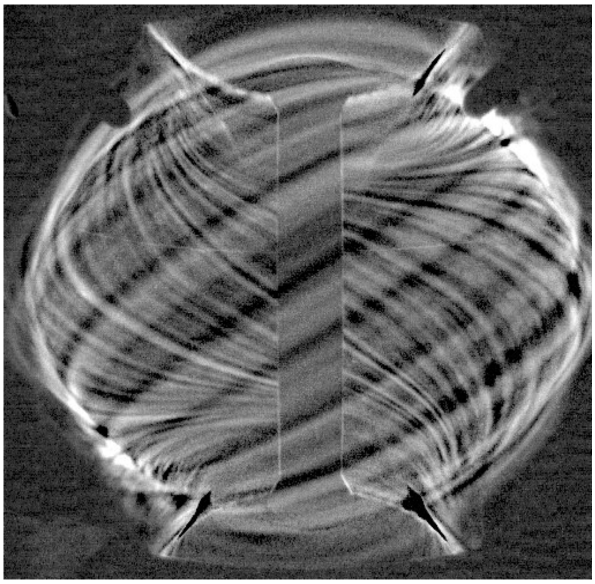

Fig.5. The sample of off-focus image taken from
The ELM filament in MAST L-Mode plasma
B. Dudson et al. p.92, Programme 35th EPS Conf. Plasma Phys. 2008.

The two dimensional image taken on the camera sensor plate is understood as the convolution of all the ray passing through the lens.

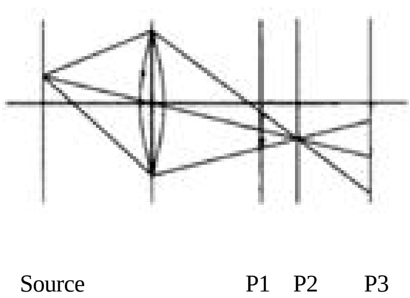


Fig.6. Out of focus blurred image in geometrical optics / ray tracing model. The plane at P1 receives the converging ray from the source. The plane P2 the ray is just in focus and The plane at P3 receives the diverging ray from the source.

The simplest imaging method to meet this requirement is attained by tandem camera system shown in Fig.7 , which is in principle modified version of the conventional 3-CCD camera for RGB separation in instrumental engineering sense. Here spatial resolution is determined by the lens aperture and the camera position. The detailed description shall be published elsewhere.

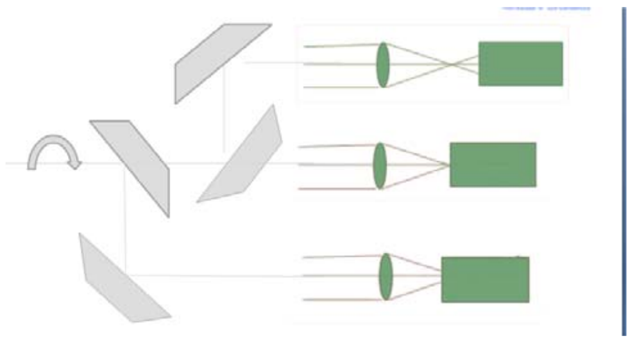

Fig.7. Tandem camera configuration to obtain 3-dimensional spatial resolution.

For LCDC measurement, strong background radiation is originated from the plasma boundary and LCDC is within the main plasma region. The image distance should be clearly distinguished even with conventional camera lens aparture and modidied version of the conventional 3-CCD camera system similar to Fig.7. At the same time on the wave optical assumption, we can expect the image co-relation in the off-focus plane.

## Low intensity detection

Even though the emission intensity of LCDC itself is expected to be few orders of magnitude higher than the main plasma, this localized nature means total volume observed by the camera is again few orders of magnitude samaller than the peripheral

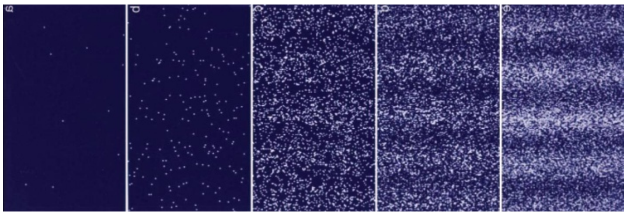

Fig.8 Schematic example of low intensity photon imaging
(Electron Beam version of Young's Double Slit )
Taken from
Build-up of an electron interference pattern.
Numbers of electrons are
10 (a), 200 (b), 6,000 (c), 40,000 (d), and 140,000 (e).
Tonomura A,, Proc. Natl. Acad. Sci. USA 102 No. 42 (2005): 14952.

plasma. In this sense it is difficult to detect unless the initial estimation of the position is vague or the plasma perturbation is not small to shift the rational surface. In these occasion the photon correlation type detection is necessary. This sort of problems is solved in the developing stage of Thomsom Scattering Experiment neary half a century ago.

In Fig.8, we show the similar classical example. This is the Young's double slit experiment by Tonomura.This nature is also seen in the quantum entanglement experiment aiming for the quantum computer.

## Conclusion

We have discussed the fundamental diagnostic plans for

LCDC (THE LOCAL COLD AND DENSE COMPRESS)

narrow filamentary plasma channel which is supposed to lie on the rational surface. Even though this zone occupies only local zone but it shows very interesting diagnostic information. The detailed assumptions identifies the rough estimation of their nature.
The starting point should be identified from the time history started from initial plasmoid phase from Balmer Radiation. The radial density profile is well assumed to be in Gaussian Profile and it lies on the Magnetic field line.

## References

1. M.Irie & M. Kubo-Irie et al.
35th EPS Conf. Plasma Phys. 2008.
2. Y.Nakamura, H.Nishighara and M.Wakatani, Nuclear Fusion 26,907(1986)
3. W.M.Muller et al.
Phys.Rev.Lett, 83,p2199 (1999)
4. V. M. Timokhin, et al.
32th EPS Conf. Plasma Phys. 2005
5. B. Dudson et al.
35th EPS Conf. Plasma Phys. 2008.
6. Tonomura A.,
Proc. Natl. Acad. Sci. USA 102 No. 42 (2005): 14952.