LABORATORY EXPERIMENTS TO STUDY COLLISIONLESS SHOCKS

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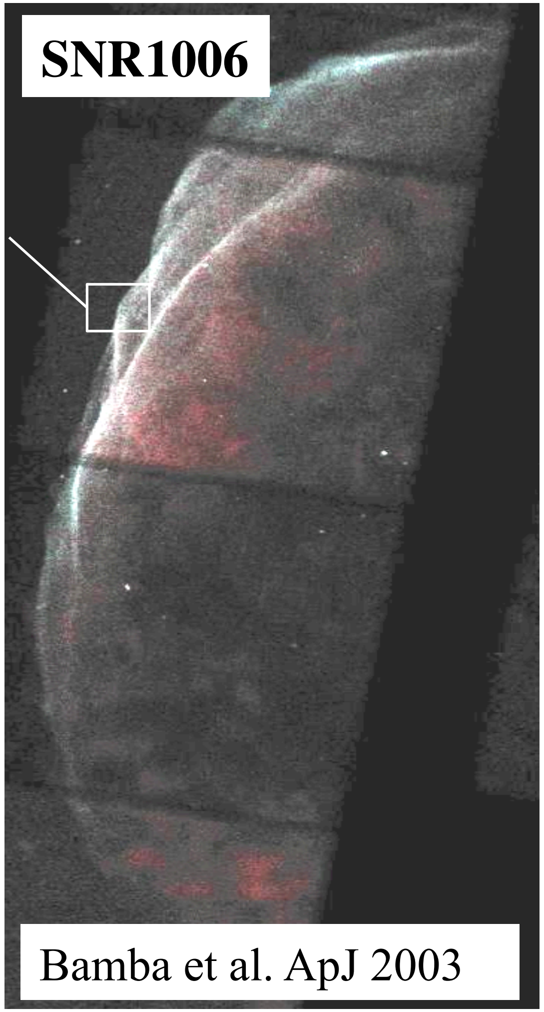
2012.05.03 HEDLA2012 (Florida State University, USA)

SNR collisionless shocks are sources of cosmic-rays

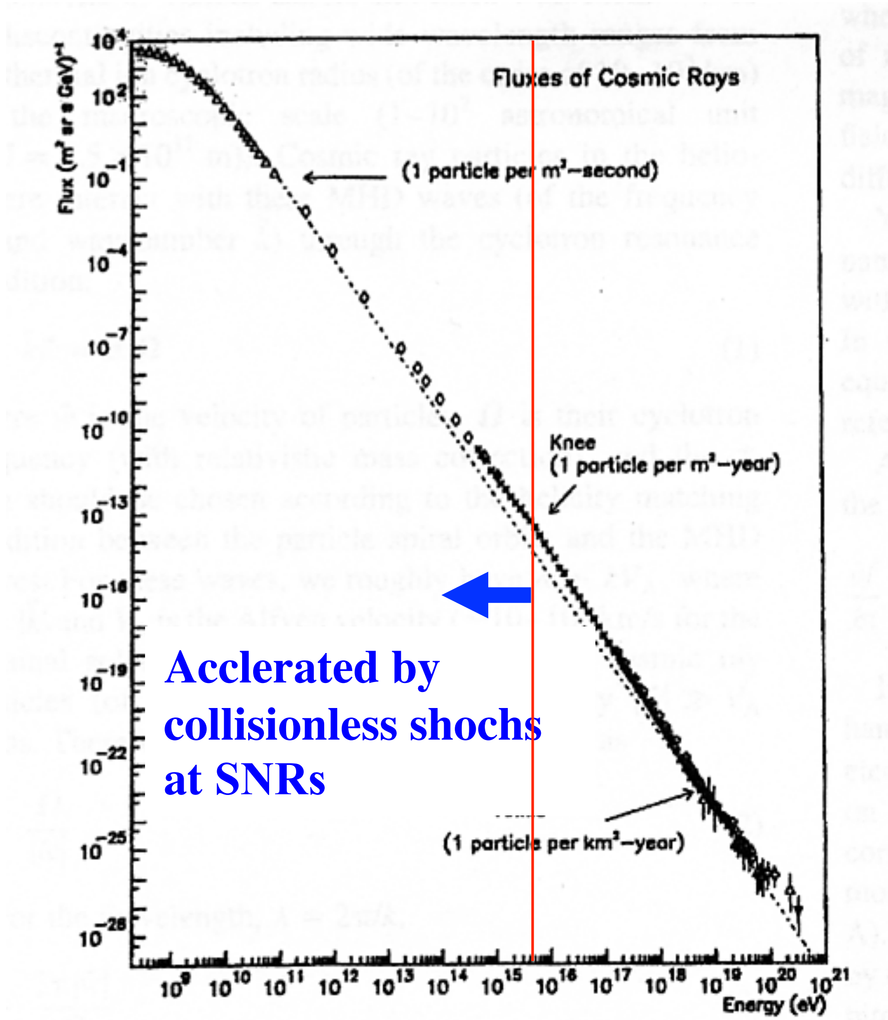
Shock width



Coulomb mfp ~ 13 pc >> Shock width ~ 0.04 pc

⇒ Collisionless shock

Energy distribution of cosmic-rays



Collisionless shock experiments

Collisionless shocks are studied using 2D PIC Simulation without external magnetic field

⇨ Shock waves are generated by the interaction between counter-streaming plasmas

Two possibilities for the production of collisionless shocks

(1) Electrostatic shock (Shanguang II, Gekko XII, LULL200)

⇨ Time evolution

Shock electric filed

Shock parameters using Thomson scattering

(2) Weibel-instability mediated shock with a self-generated magnetic field

⇨ Shock width W ~ 100 x ion inertia length

⇨ high-density (ne ~ 10^{20} cm^{-3}) and

high-velocity (V_{flow} ~ 1000 km/s) plasmas are required

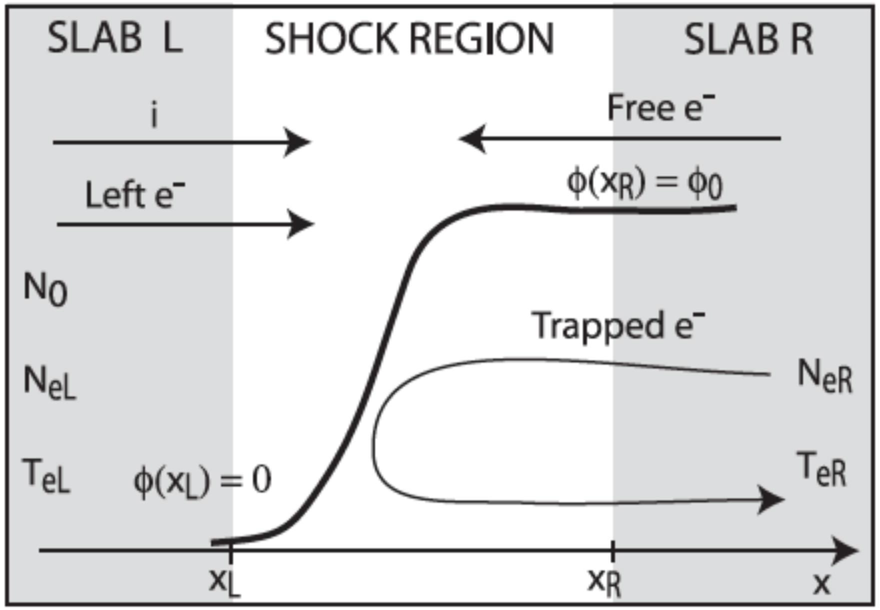
⇨ OMEGA, OMEGA EP, NIF experiments

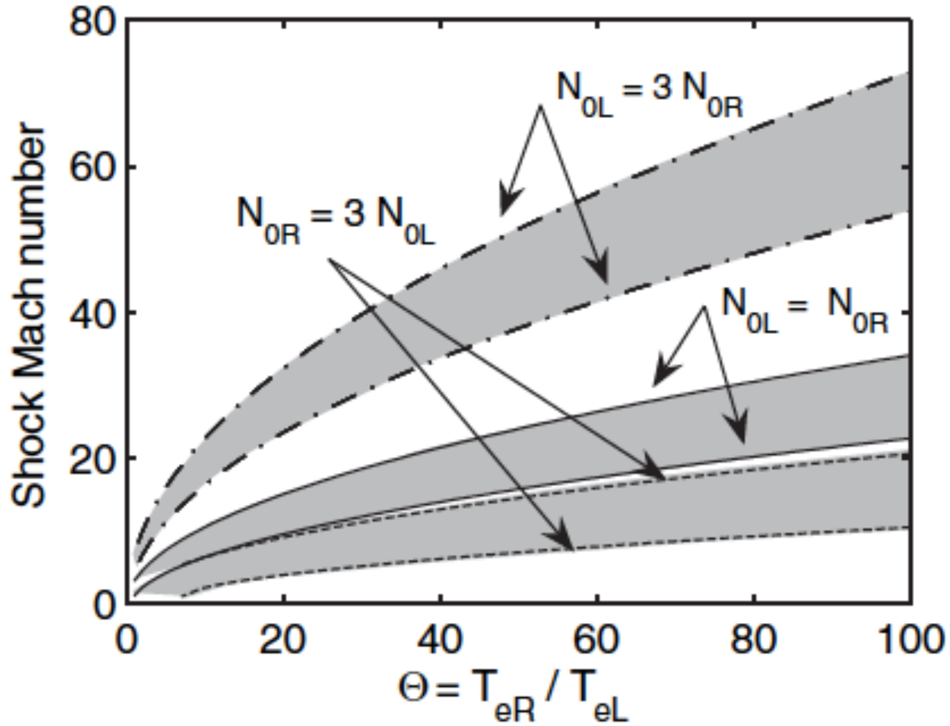
Interaction of two plasma slabs with different T and n → collisionless ES shocks with M>>10

PRL **96**, 045005 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

Very High Mach-Number Electrostatic Shocks in Collisionless Plasmas

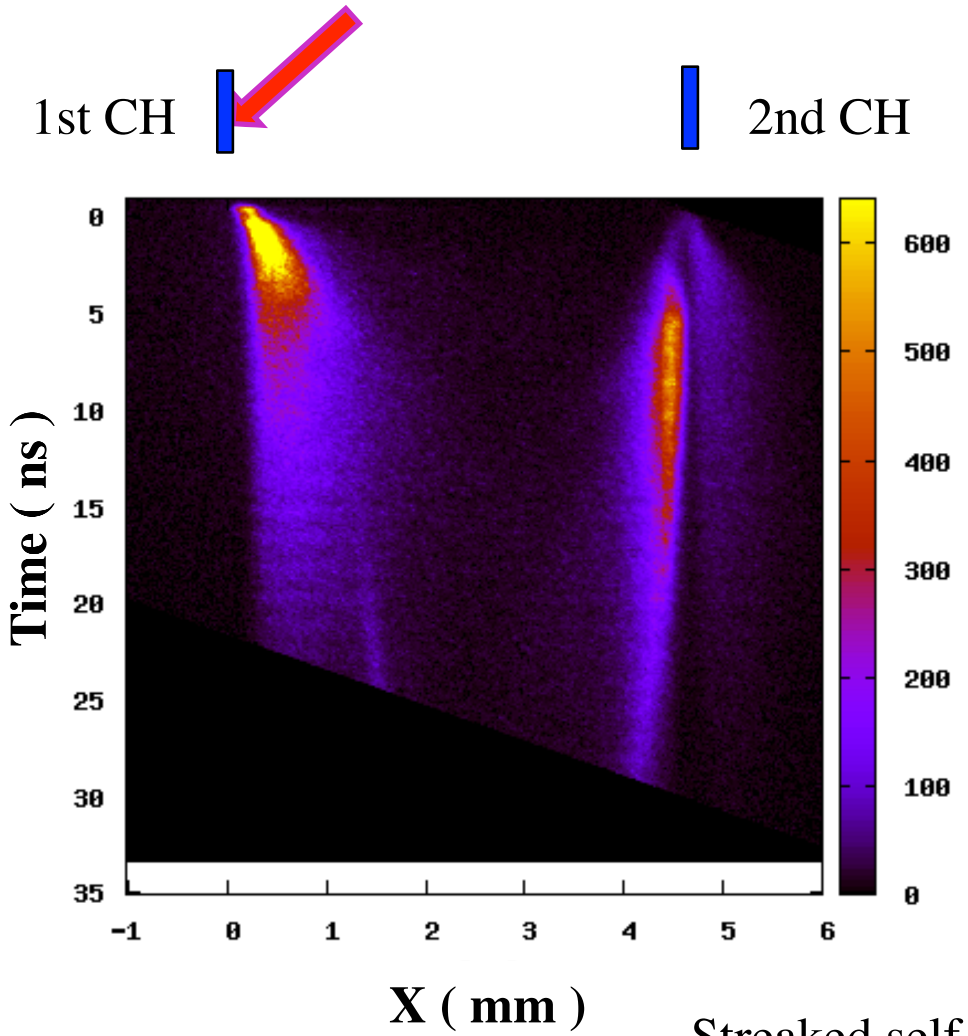
G. Sorasio,* M. Marti, R. Fonseca,† and L. O. Silva‡
GoLP/Centro de Física dos Plasmas, Instituto Superior Técnico, Avenida Rovisco Pais, 1049-001 Lisbon, Portugal
(Received 22 November 2005; published 2 February 2006)





Sorasio et al, PRL (2006)

Counter-streaming plasmas are generated by one-directional laser irradiation using a double-plane target



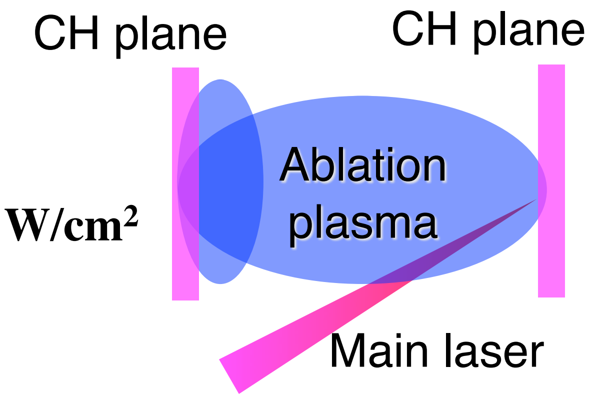
Streaked self-emission

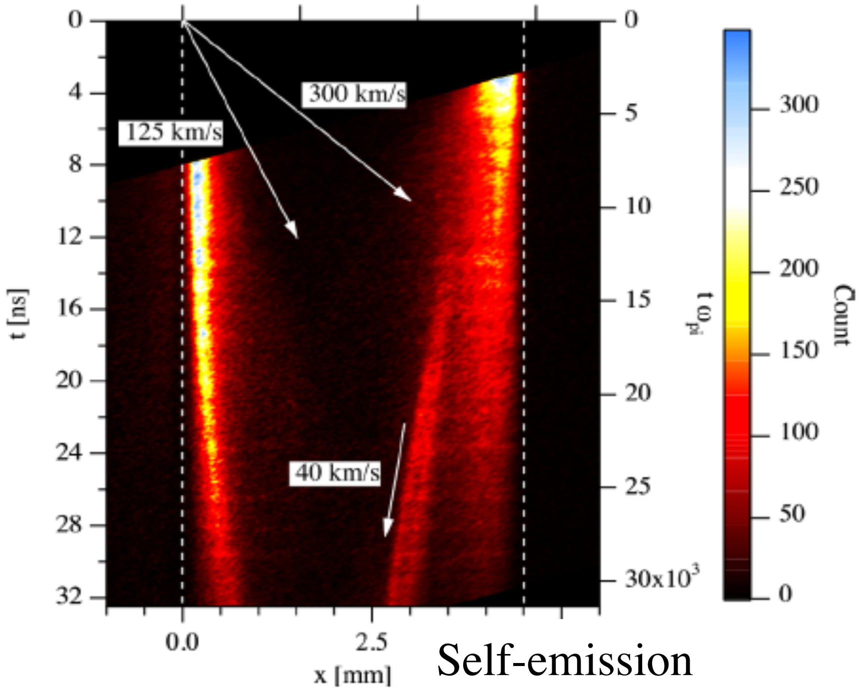
2nd CH plasma is generated

- **by radiation from the 1st CH plasma at t ~ 0**
- **by ablation of 1st CH plasma at t > 4 ns (later in this talk)**

Density- and emission-jumps and temporal evolution of ES shock

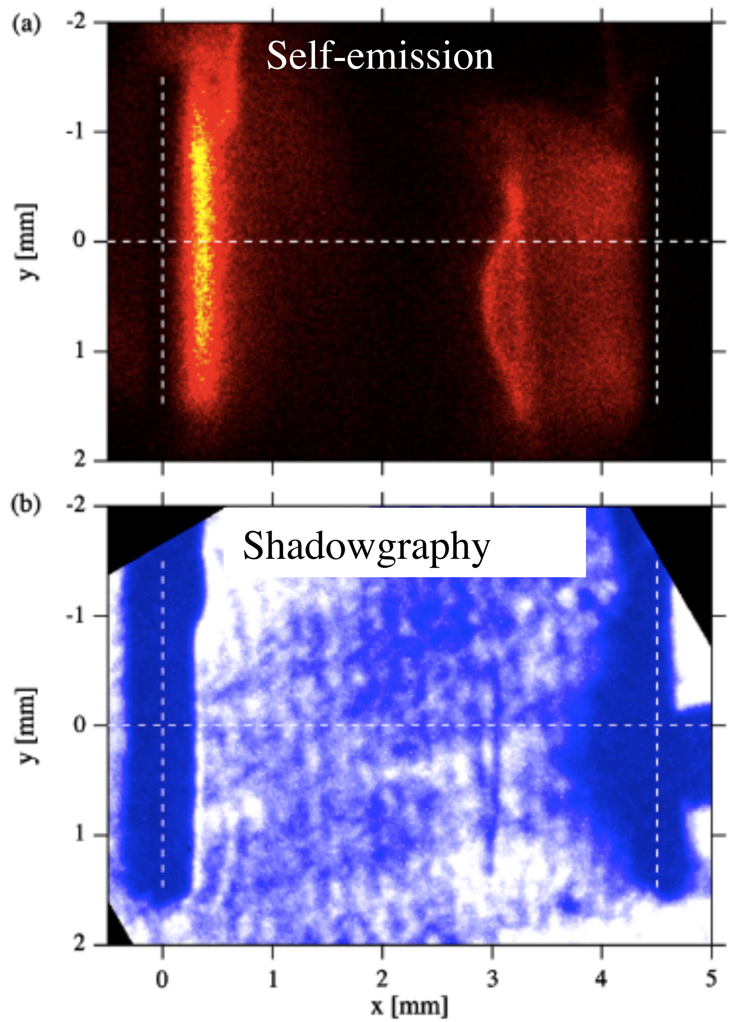
Gekko XII
I ~ 3 x 10^{14} W/cm^2





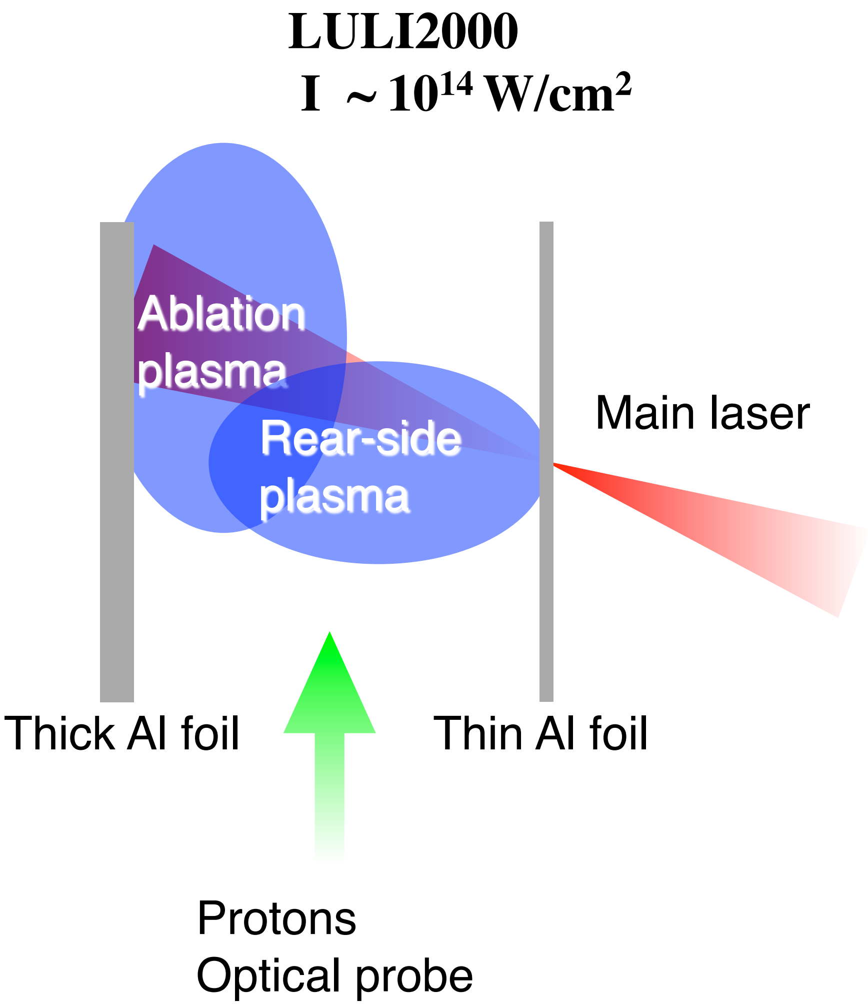
Self-emission

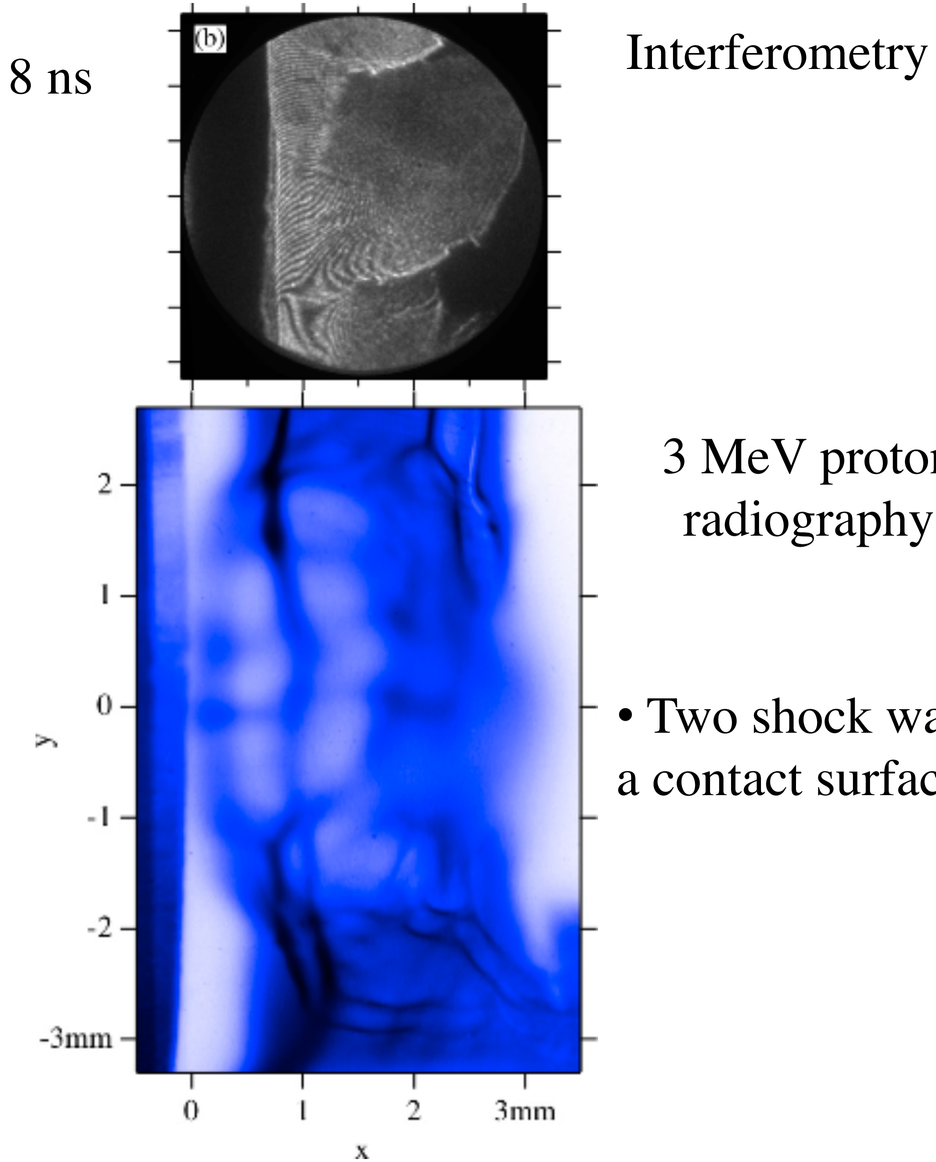
25 ns



Kuramitsu et al, PRL (2011)

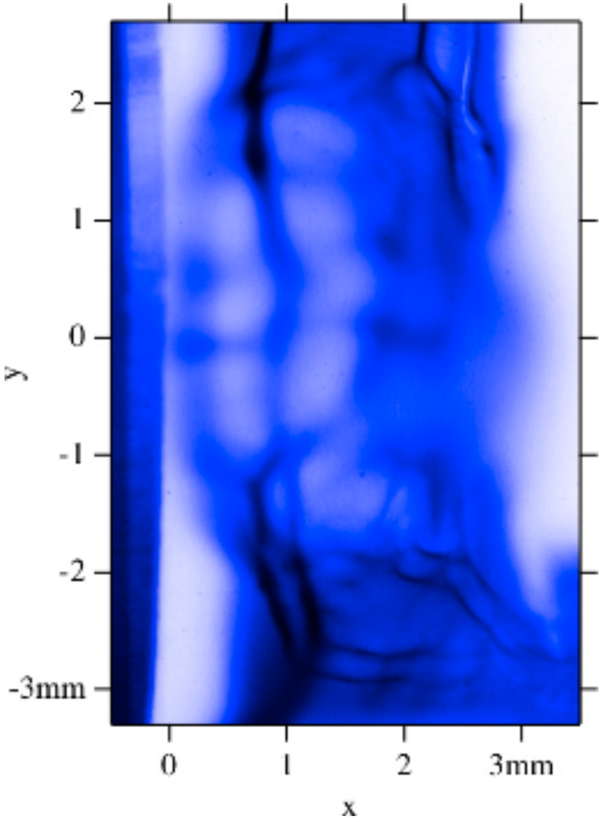
Shock electric field measurement using Proton radiography





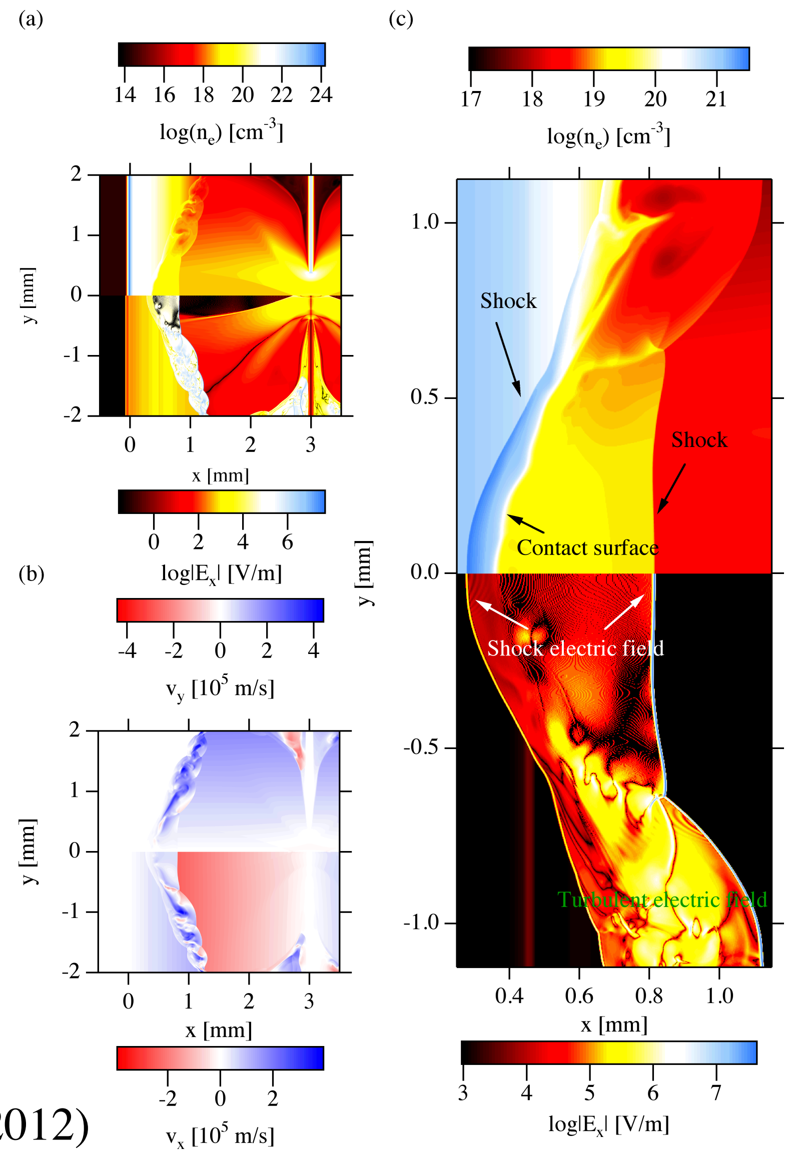
- Two shock waves and a contact surface

Turbulent electric field is driven by Kelvin-Helmholtz instability



• Transverse modulation on the contact surface

Kuramitsu et al, PRL accepted (2012)



Hydrodynamic simulation

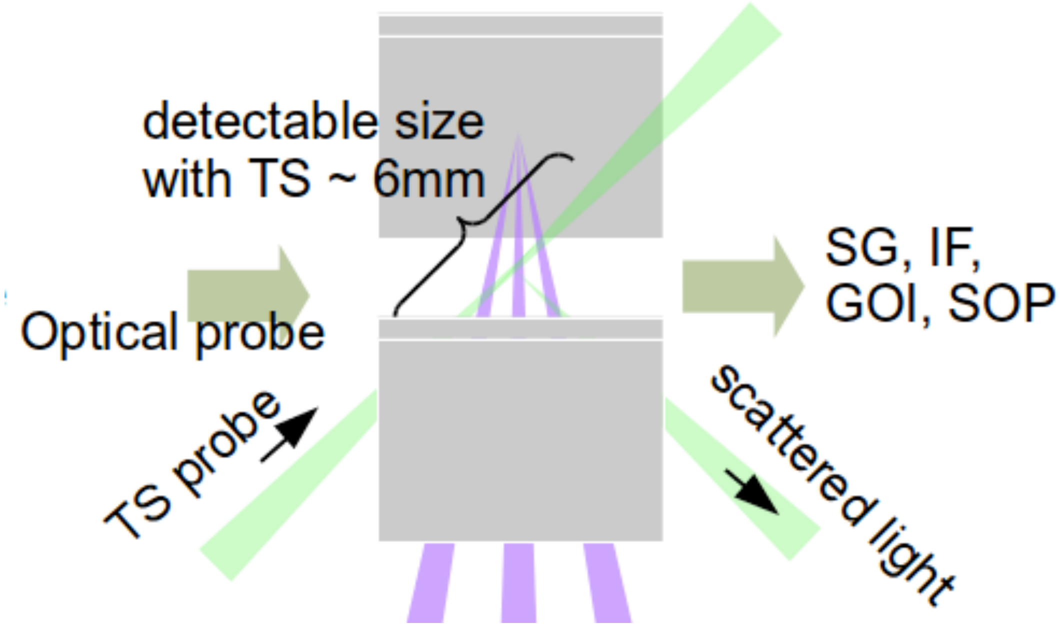
• Shear flows appears on the contact surface

• Kelvin-Helmholtz (KH) instability is excited

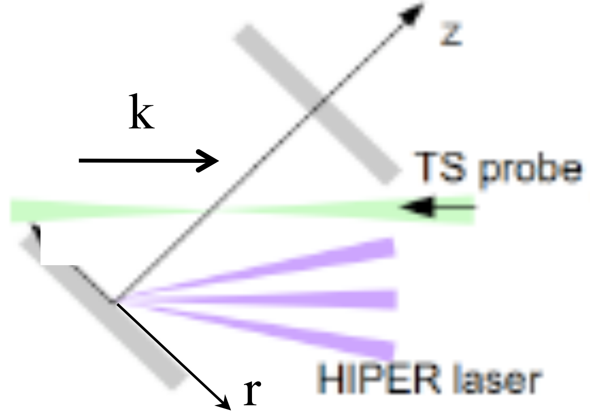
• KH vortices in velocity field appears

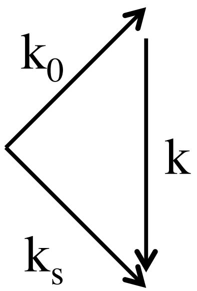
• Turbulent electric field is driven in the downstream

Thomson scattering measurements



Gekko XII
I ~ 10^{15} W/cm²





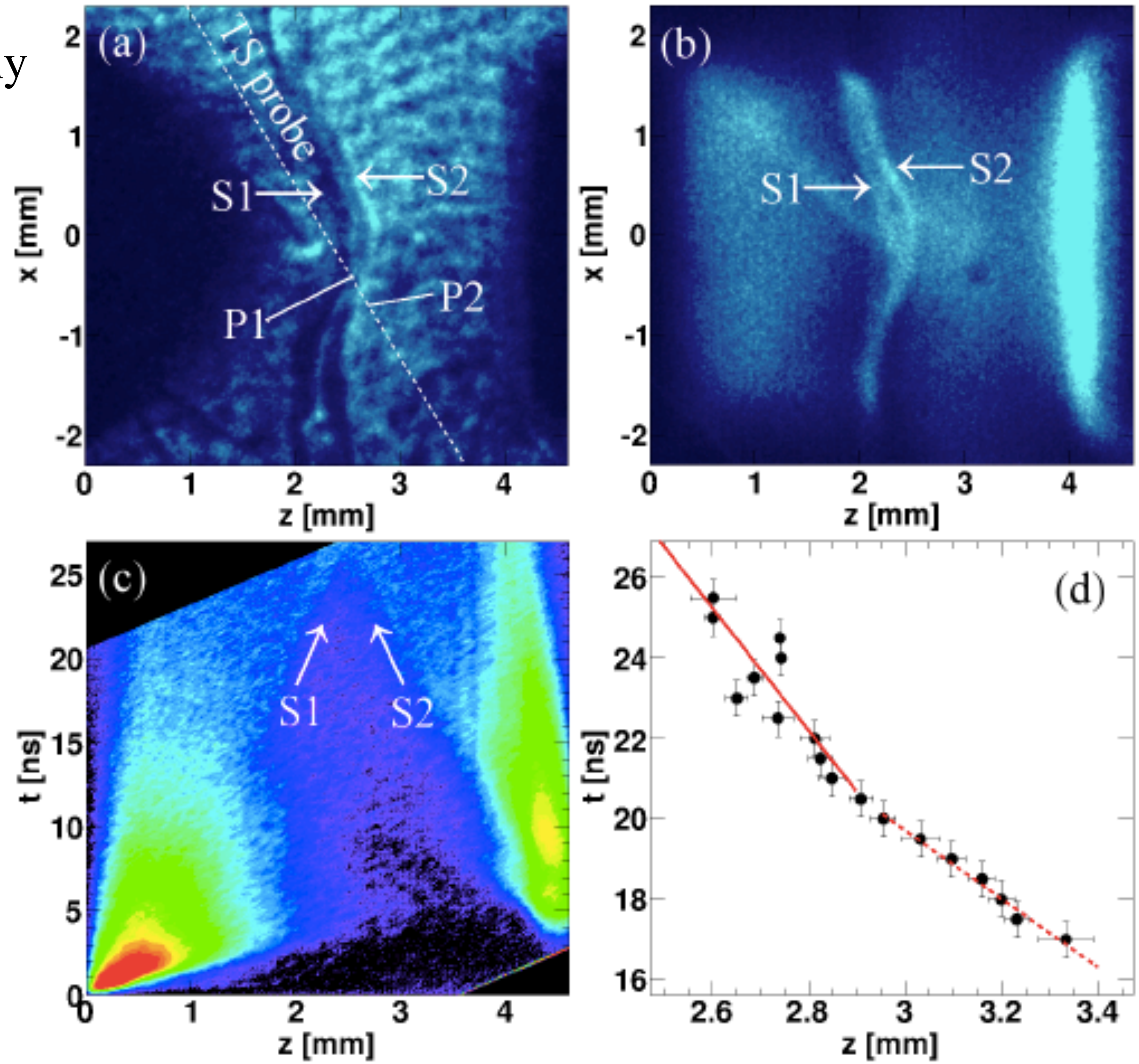
Plasma parameters along k vector are measured from Thomson scattering ion-acoustic feature ($\alpha \sim 3$)

- Flow velocity
- Electron density
- Electron and ion temperatures
- Charged state
- Mach number

Density- and emission-jumps and temporal evolution of ES shock

Shadowgraphy
30 ns

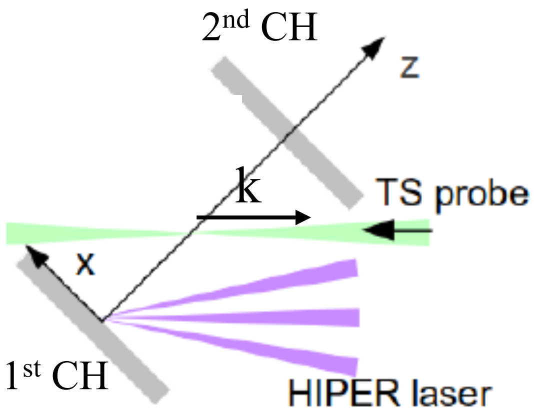
Self-emission
30 ns

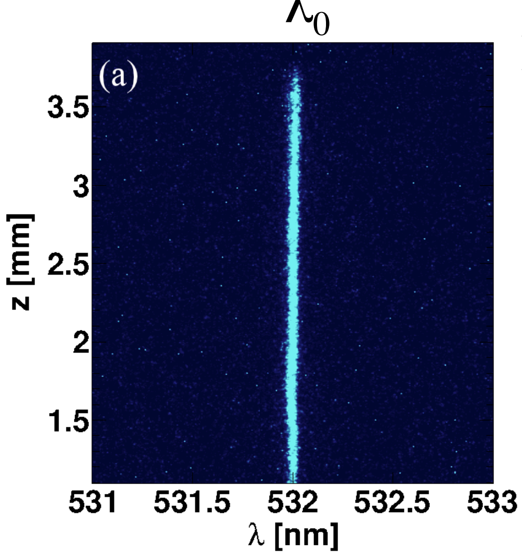


Self-emission

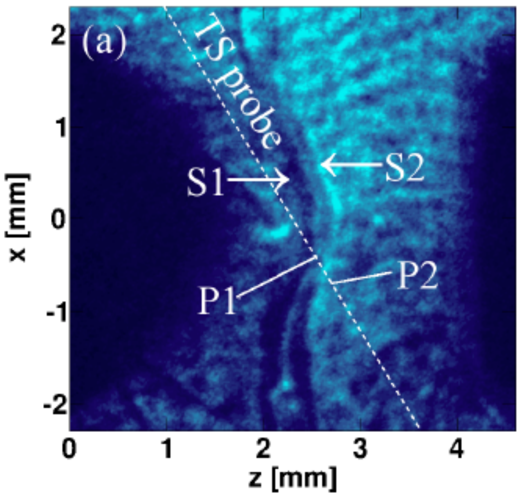
Shock velocity of S2
vs = 66 km/s
at 25 ns

Plasma parameters for a shock wave are obtained by Thomson scattering ion-acoustic feature

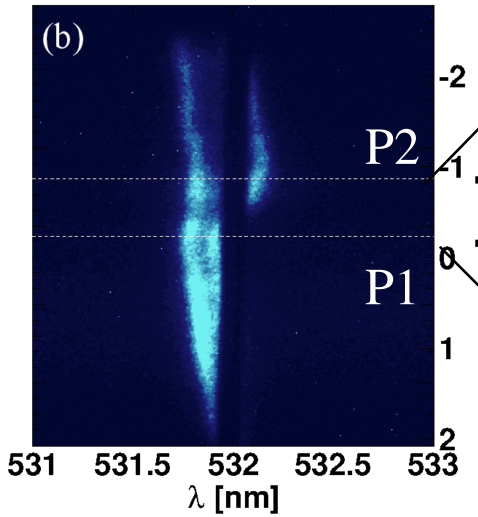




Blue shift : Plasmas from the 1st CH



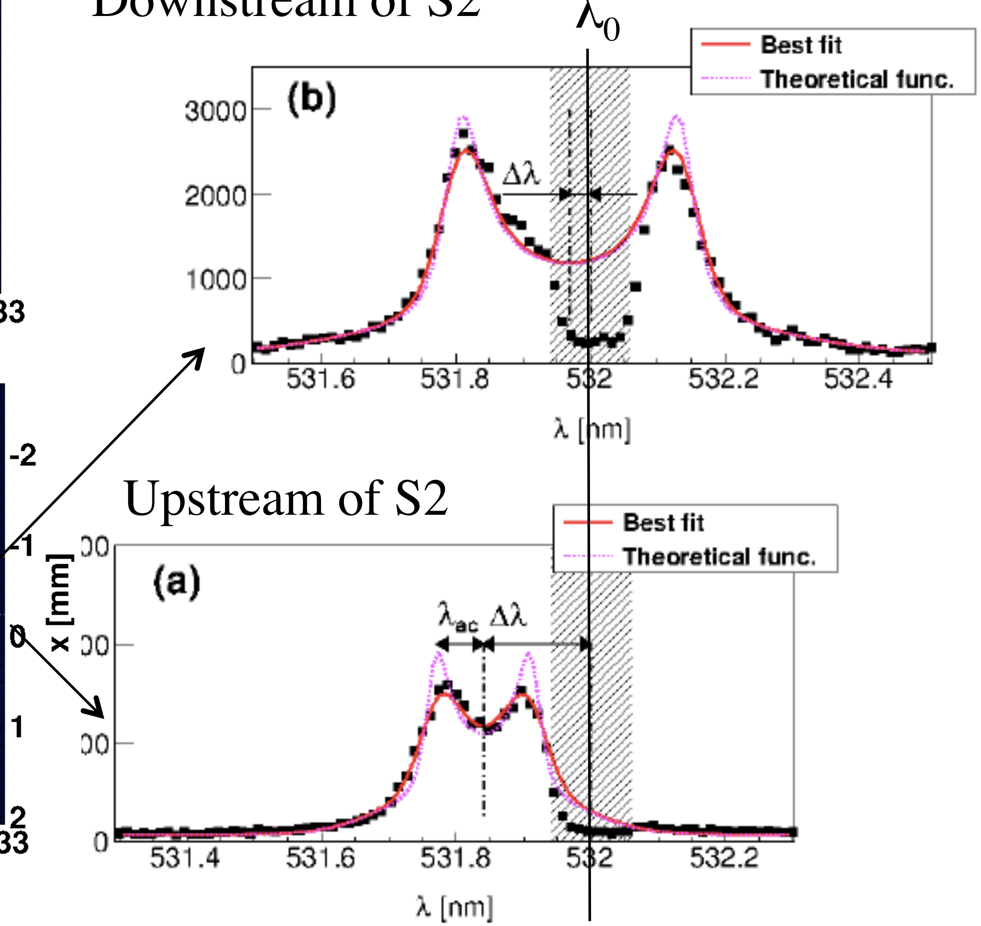
Shadowgraphy



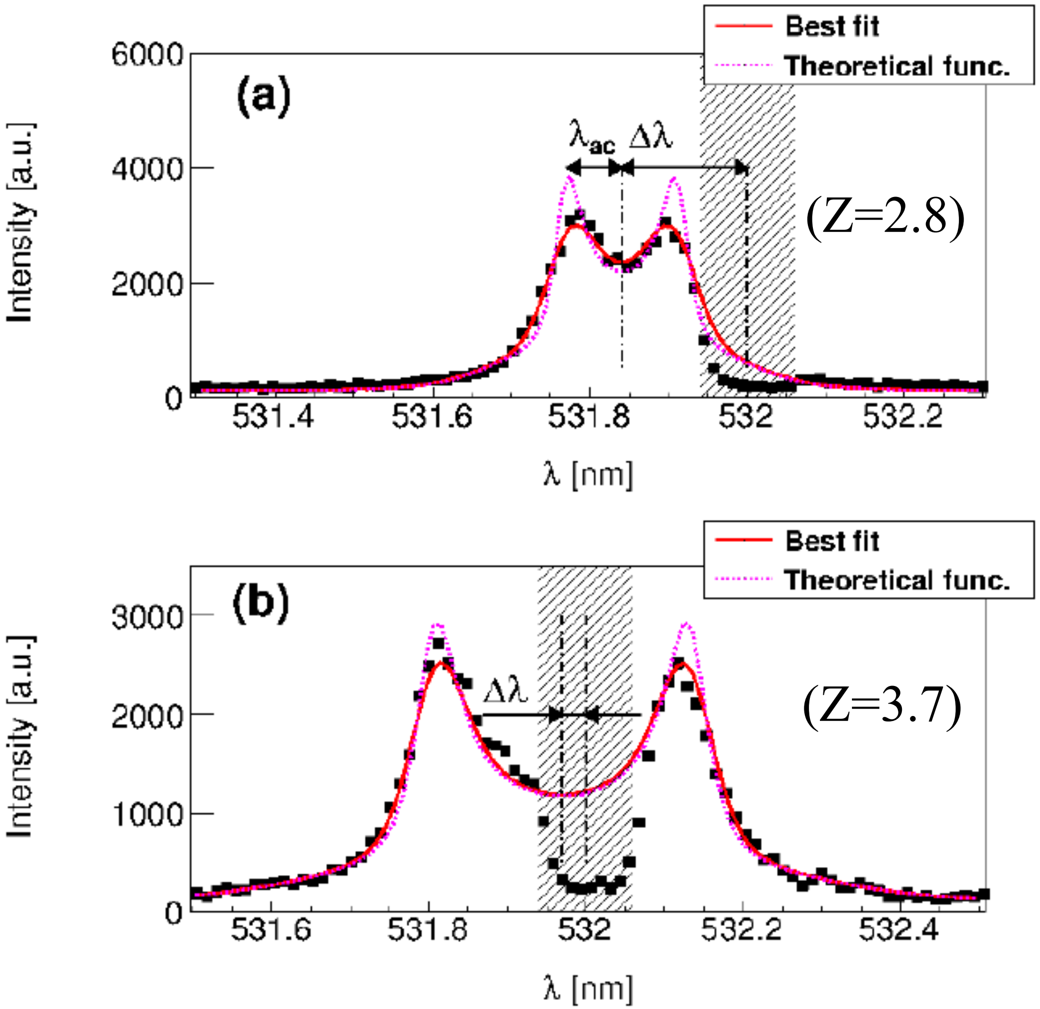
t = 30 ns

Downstream of S2

Upstream of S2



Plasma parameters and Mach number M_0 are obtained



- H and C ions
- $T_i = T(H^+) = T(C^{z+})$
- $n_i / 2 = n(H^+) = n(C^{z+})$
- $v_d = v_e = v(H^+) = v(C^{z+})$

Upstream

T_{e0} = 24 eV, T_{i0} = 18 eV

C_{S0} = 27 km/s , V_{d0} = 90.1 km/s

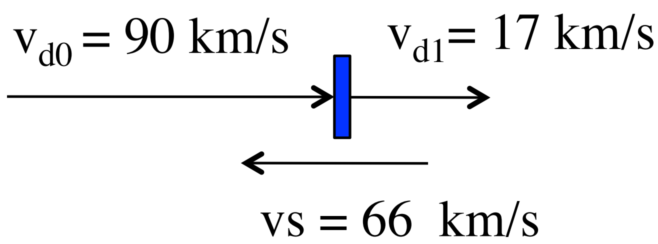
$M_0 = (V_{d0} + v_s) / C_{S0} = 5.5$

Downstream

T_{e1} = 110 eV, T_{i1} = 75 eV

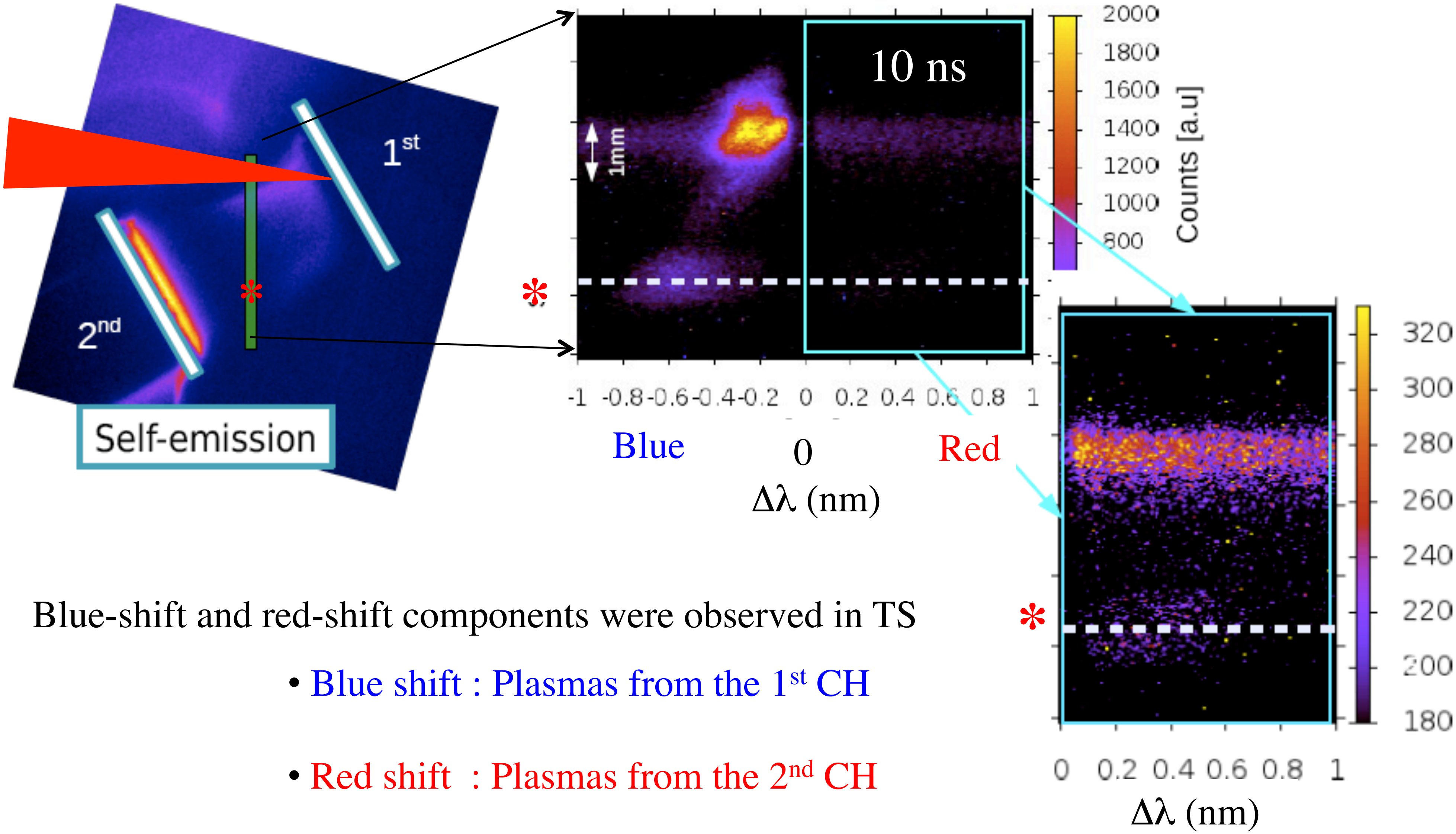
C_{S1} = 62 km/s , V_{d1} = 17.2 km/s

$M_1 = (V_{d1} + v_s) / C_{S1} = 1.3$



T. Morita et al

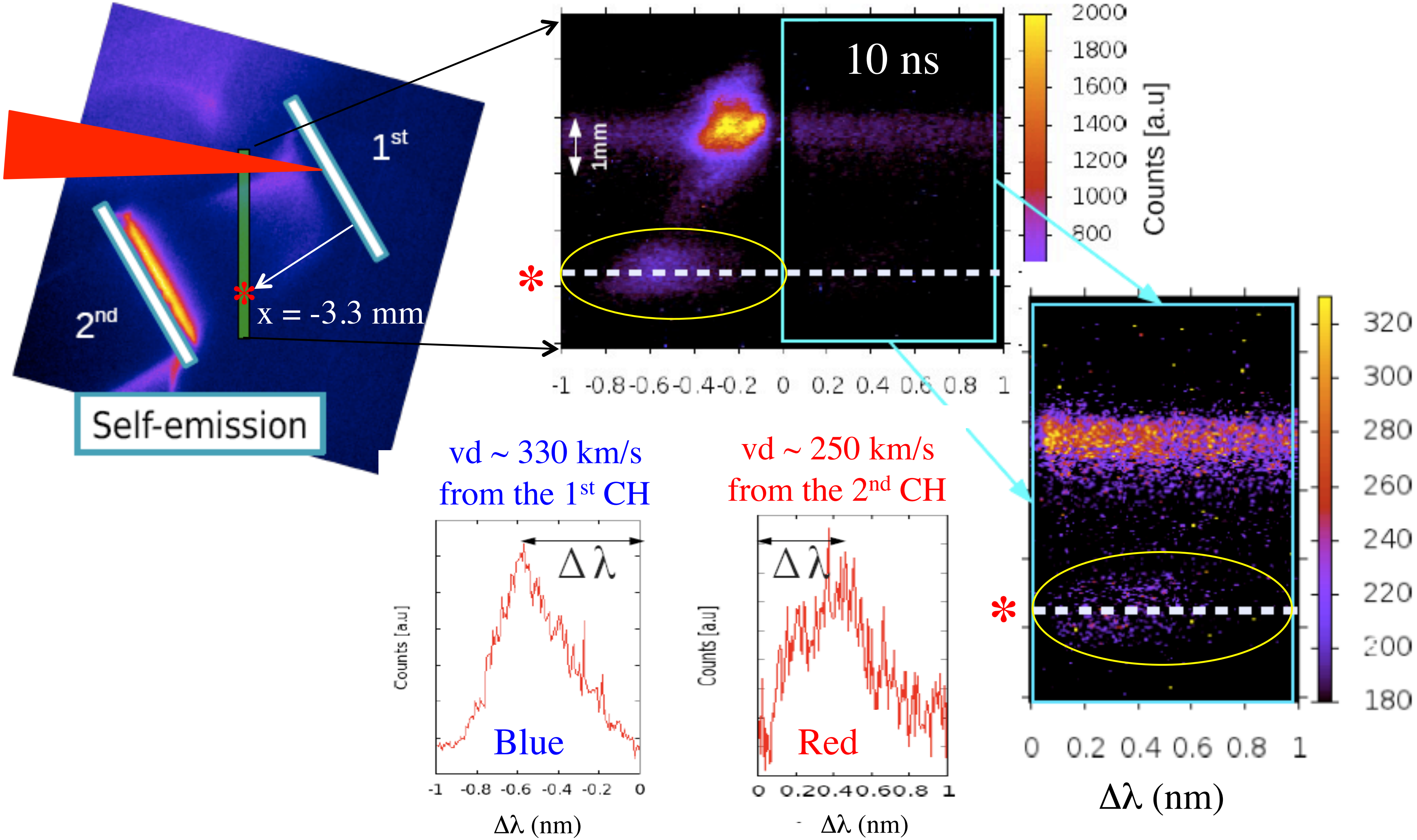
Counter-streaming plasmas are created: What is the mechanism?



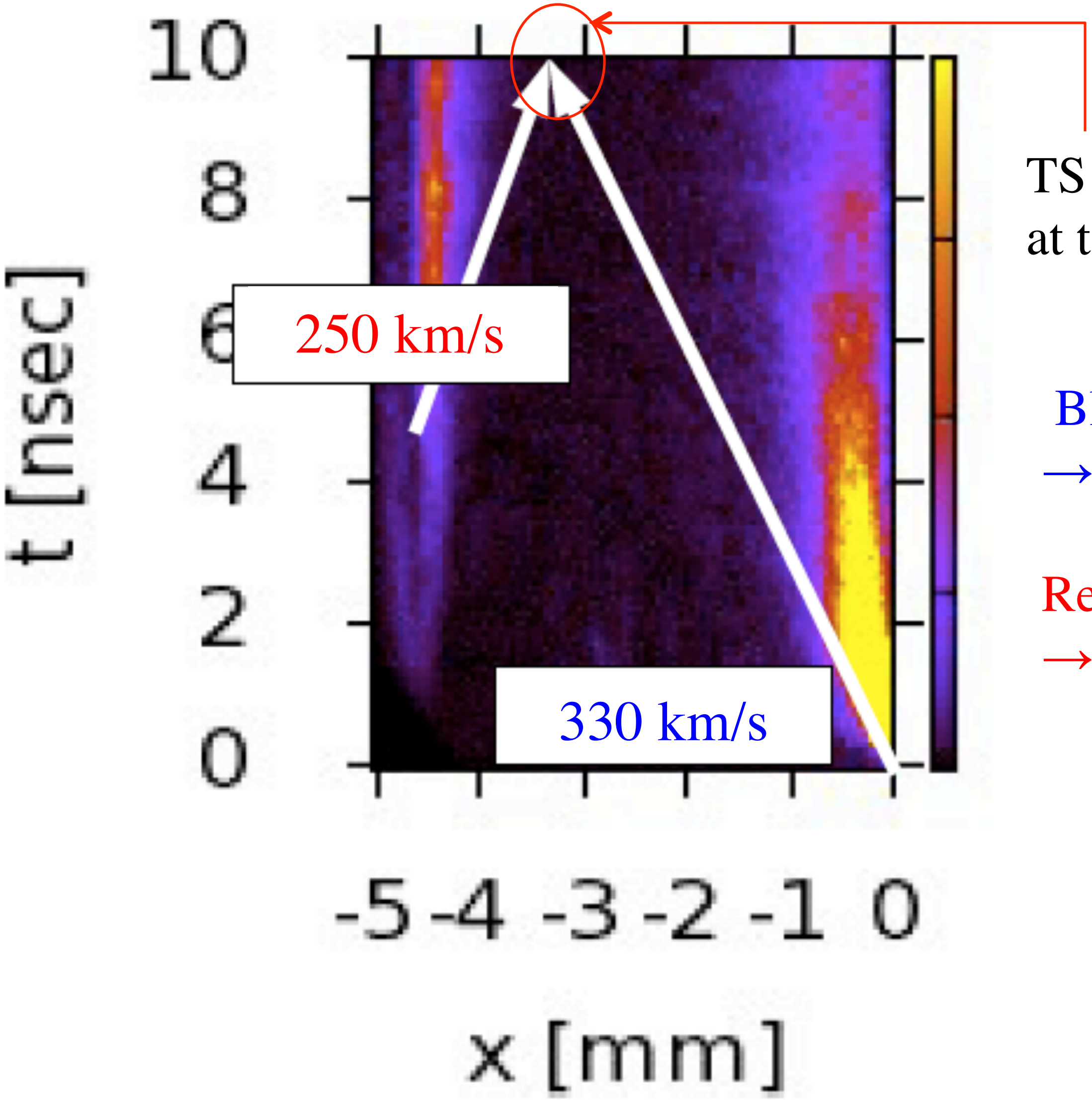
Blue-shift and red-shift components were observed in TS

- Blue shift : Plasmas from the 1st CH
- Red shift : Plasmas from the 2nd CH

Drift velocities of counter-streaming plasmas are obtained by Thomson scattering



2nd CH plasma at t > 4.5 ns is generated by fast plasma from the 1st CH



TS measurement
at t = 10 ns, x = -3.3 mm shows

Blue shift : vd = 330 km/s from 1st CH
→ ablation by laser generated at t = 0

Red shift : vd = 250 km/s from 2nd CH
→ ablation by the fast plasma from 1st CH
generated at t = 4.5 ns

Ide et al

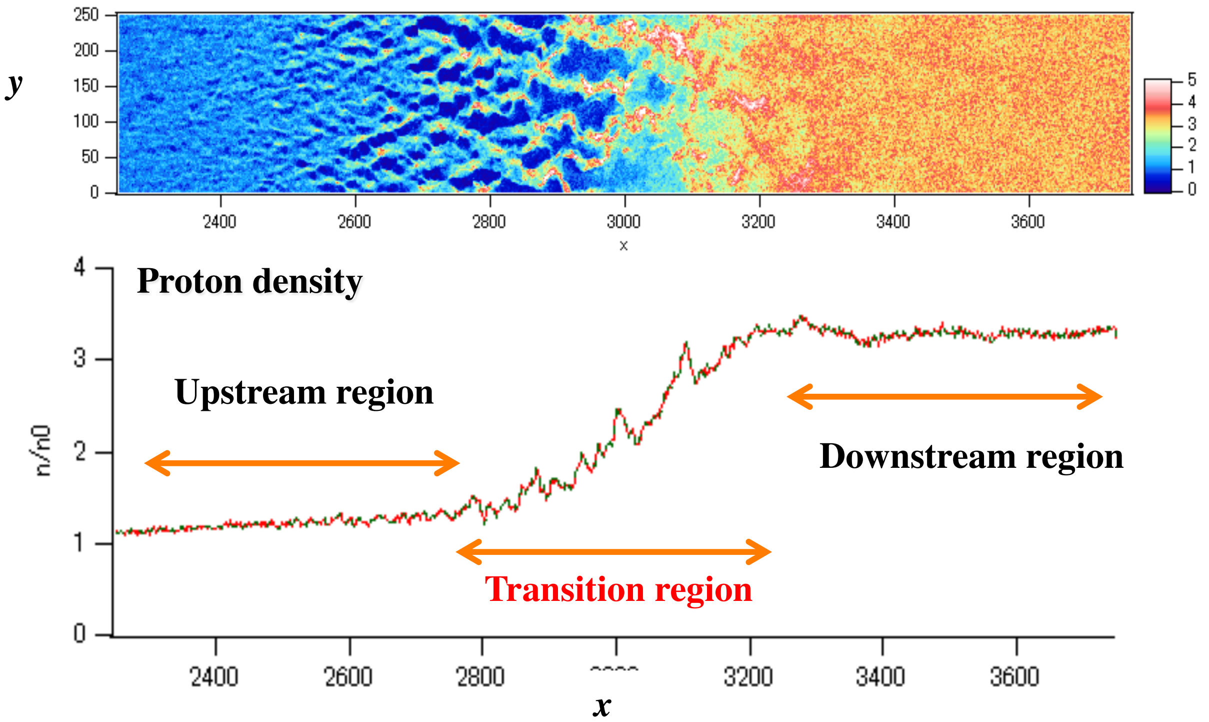
Weibel-instability mediated collisionless shock

Weibel-instability mediated shock with a self-generated magnetic field

⇨ **Shock width W ~ 100 x ion inertia length**

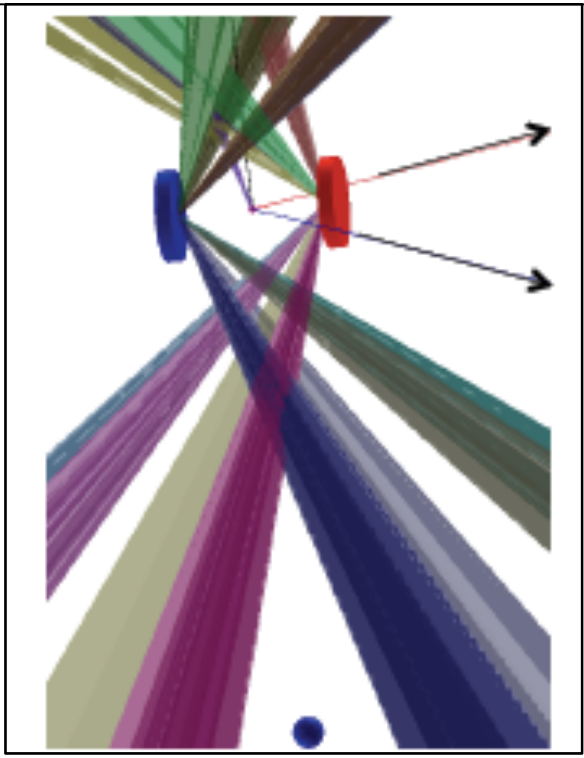
⇨ **high-density (ne ~ 10^{20} cm^{-3}) and high-velocity (V_{flow} ~ 1000 km/s) plasmas are required**

⇨ **OMEGA, OMEGA EP, NIF experiments**

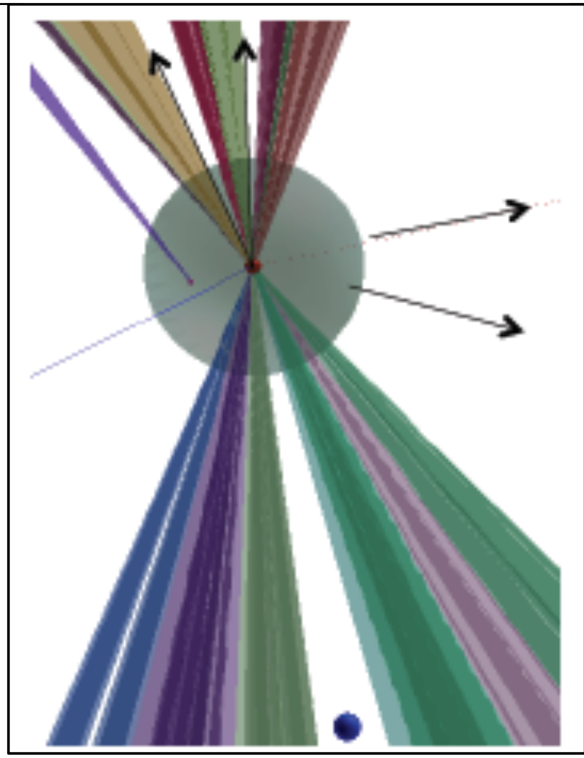


NIF facility time proposal “Collisionless Shock Generation Mediated by Weibel Instability in Counter-Streaming Ablation Plasmas by NIF” has been approved ⇒ from 2013+

Collisionless Weibel Shock Generation in Counter-Streaming Plasmas
PI : Y. Sakawa (ILE, Osaka Univ., Japan)

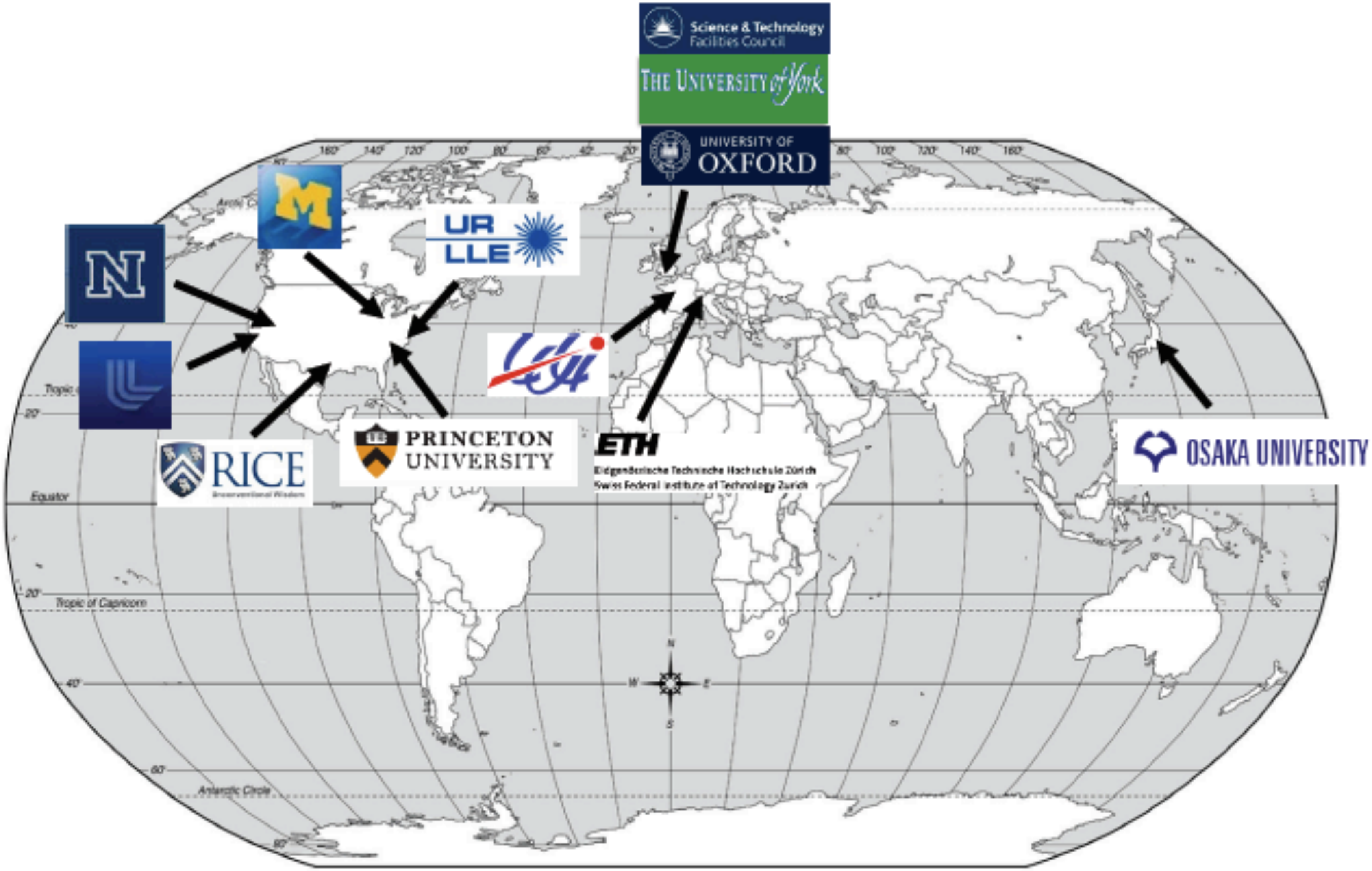


Cosmological Magnetic Fields and Cosmic Ray Generation
PI : G. Gregori (Oxford Univ., UK)



Two proposals are combined to “Astrophysical Collisionless Shock Experiments on NIF”
Liaison scientist : Hye-Sook Park

Collisionless shock experiments using OMEGA & EP have started with ACSEL collaboration network : Astrophysical Collisionless Shock Experiments with Lasers



Summary

- We investigated laboratory experiments to study high-mach collisionless ES shocks

  Time evolution

  Shock electric filed

  Shock parameters and mach number

- 2D PIC simulation shows that the formation of Weibel-mediated collisionless shocks requires $n_e \sim 10^{20}$ cm^{-3} and $V_{flow} \sim 1000$ km/s
- An experimental proposal to demonstrate the Weibel shock using NIF was approved

  - NIF is the only laser system that can produce fully developed Weibel shock

- We started Omega and Omega EP experiments (ACSEL collaboration)

Collaborators

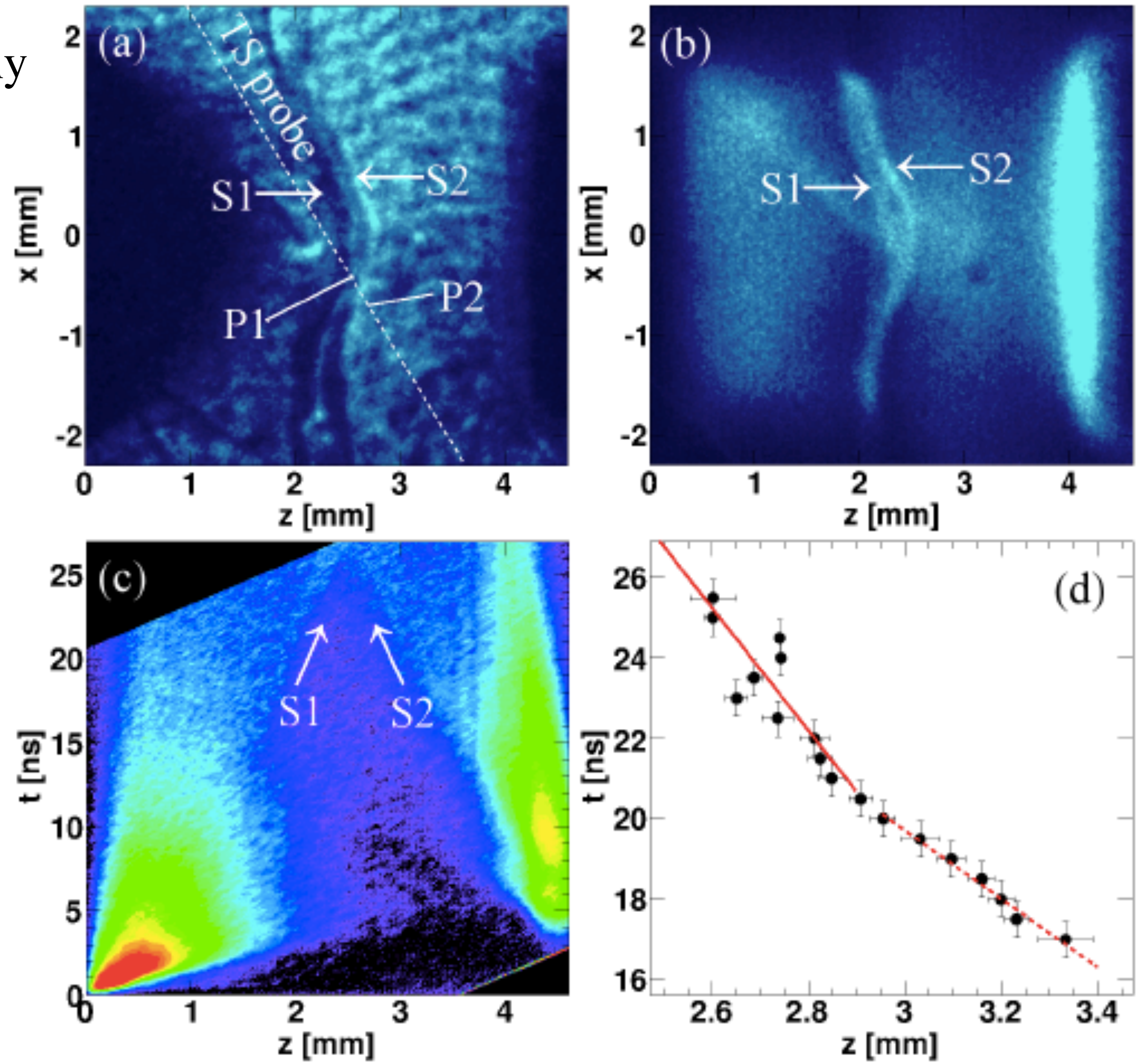
Osaka University (Japan):	Y. Sakawa, Y, Kuramitsu, T. Morita, H. Tanji, T. Ide, K. Nishio, M. Kuwada, M. Koga, T. Norimatsu, N. Ozaki, R. Kodama, T. Sano, T. N. Kato, H. Azechi, H. Takabe, K. Tanaka
Tohoku U; KEK; U Elect. Comn (Japan) :	N. Ohnishi ; A. Mizuta; H. Yoneda
Kyusyu University (Japan):	K. Tomita, K. Nakayama, K. Inoue, K. Uchino
York University (UK):	N. Woolsey, C. Gregory, J. Waug
LULI; CEA; LUTH (France):	M. Koenig, A. Ravasio, A. PelkaA. Diziere; B. Loupias; C. Michaut
Oxford University (UK):	G. Gregori, C. Murphy, K. Schaar, A. Bell
IOP (China)	Y. Zhang, X. Liu, S. Wang, Q. Dong, Y. Li
NAO (China)	J. Zhong,
Shanghai Jiao Tong University (China) :	J. Zhang
LLNL (USA):	H-S. Park, D. Ryutov, B. Remington, S. Pollaine, S. Ross, N. Kugland, C. Plechaty
Princeton University (USA):	A. Spitkovsky, L. Gargate, L. Sironi
LLE, Univ. of Rochester (USA):	D. Froula, J. Knauer, G. Fiskel
ETH Zurich (Switzerland):	F. Miniati
Rice University (USA):	E. Liang
University of Michigan (USA):	E. Rutter, M. Grosskopf, C. Kuranz, P. Drake
University of Nevada, Reno (USA):	R. Presura

Density- and emission-jumps and temporal evolution of ES shock

Shadowgraphy
30 ns

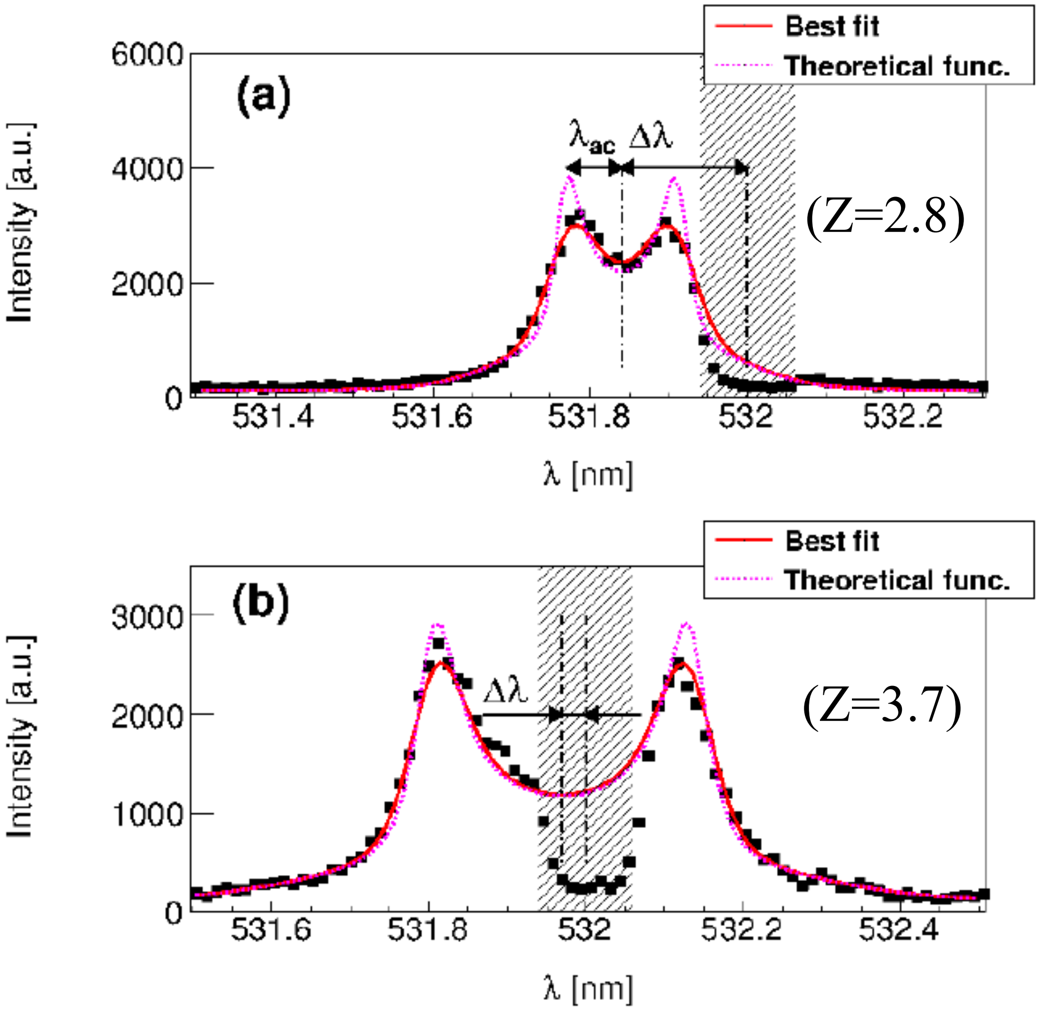
Self-emission
30 ns

Self-emission



Shock velocity of S2
vs = 66 km/s
at 25 ns

Plasma parameters and Mach number M_0 are obtained



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$T_{e0} = 24$ eV, $T_{i0} = 18$ eV

$C_{S0} = 27$ km/s , $V_{d0} = 90.1$ km/s

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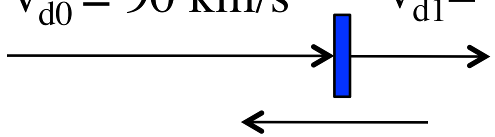
Downstream

$T_{e1} = 110$ eV, $T_{i1} = 75$ eV

$C_{S1} = 62$ km/s , $V_{d1} = 17.2$ km/s

$M_1 = (V_{d1} + v_s) / C_{S1} = 1.3 \sim 0.28$



at 30 ns

vs = 66 km/s ~ 0 km/s

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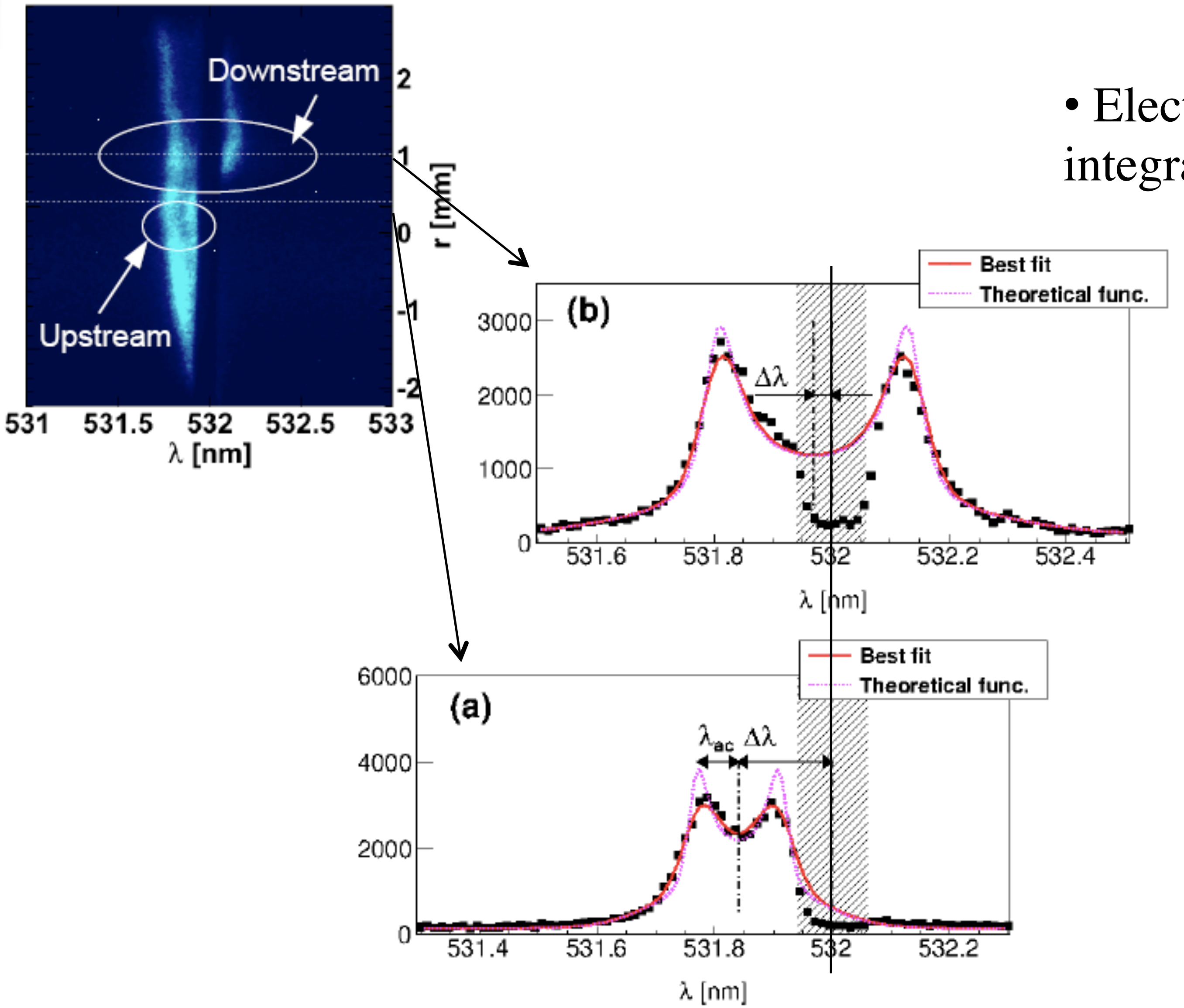
Plasma parameters for a shock wave are obtained by Thomson scattering ion-acoustic feature



• Electron densities derived from integrated intensities of TS

Downstream

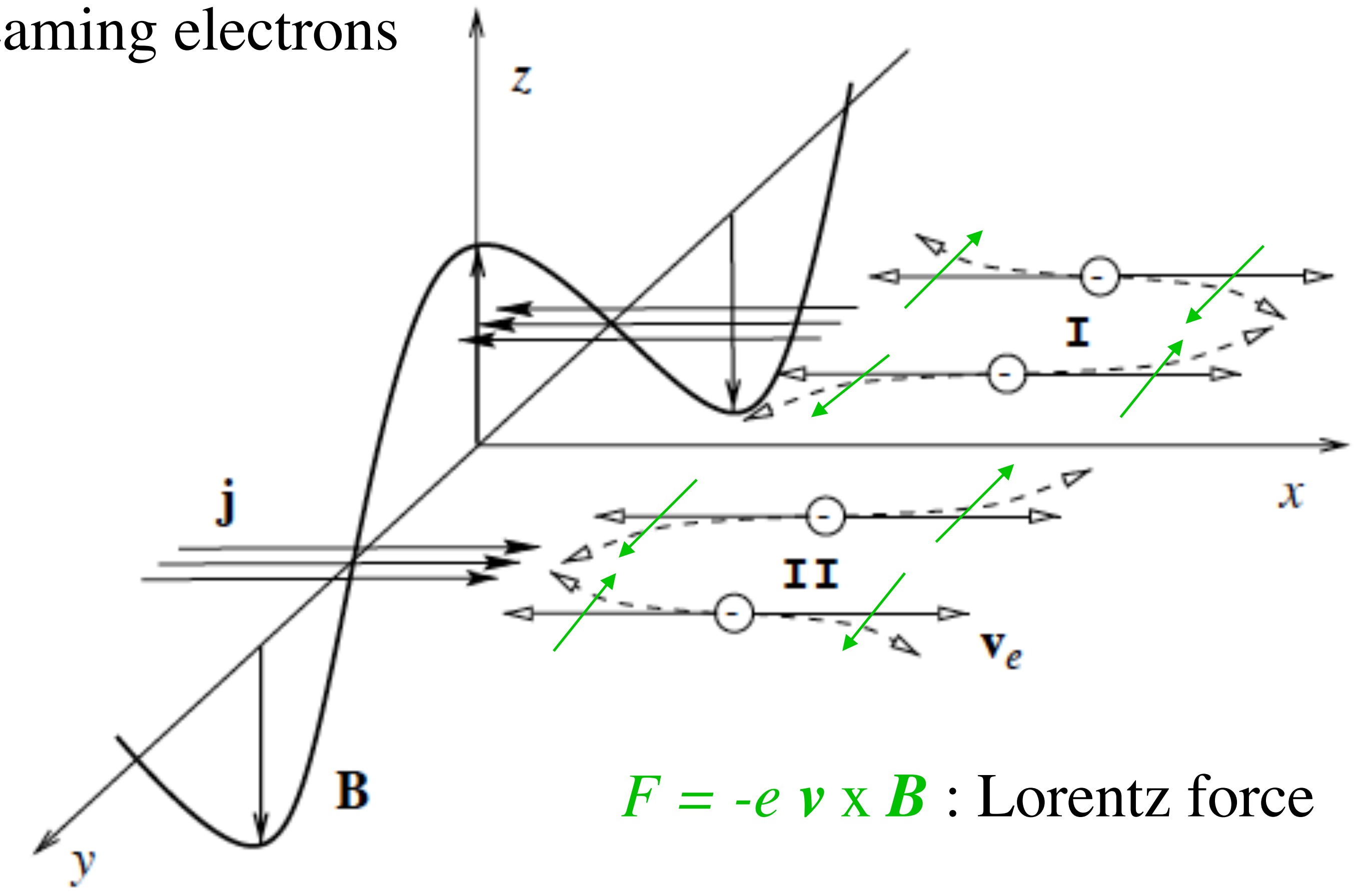
$n_{e1} = 1.1\text{x}10^{19}\ cm^{-3}$

Upstream

$n_{e0} = 7.8\text{x}10^{18}\ cm^{-3}$

The Wiebel Instability

Counter-streaming electrons

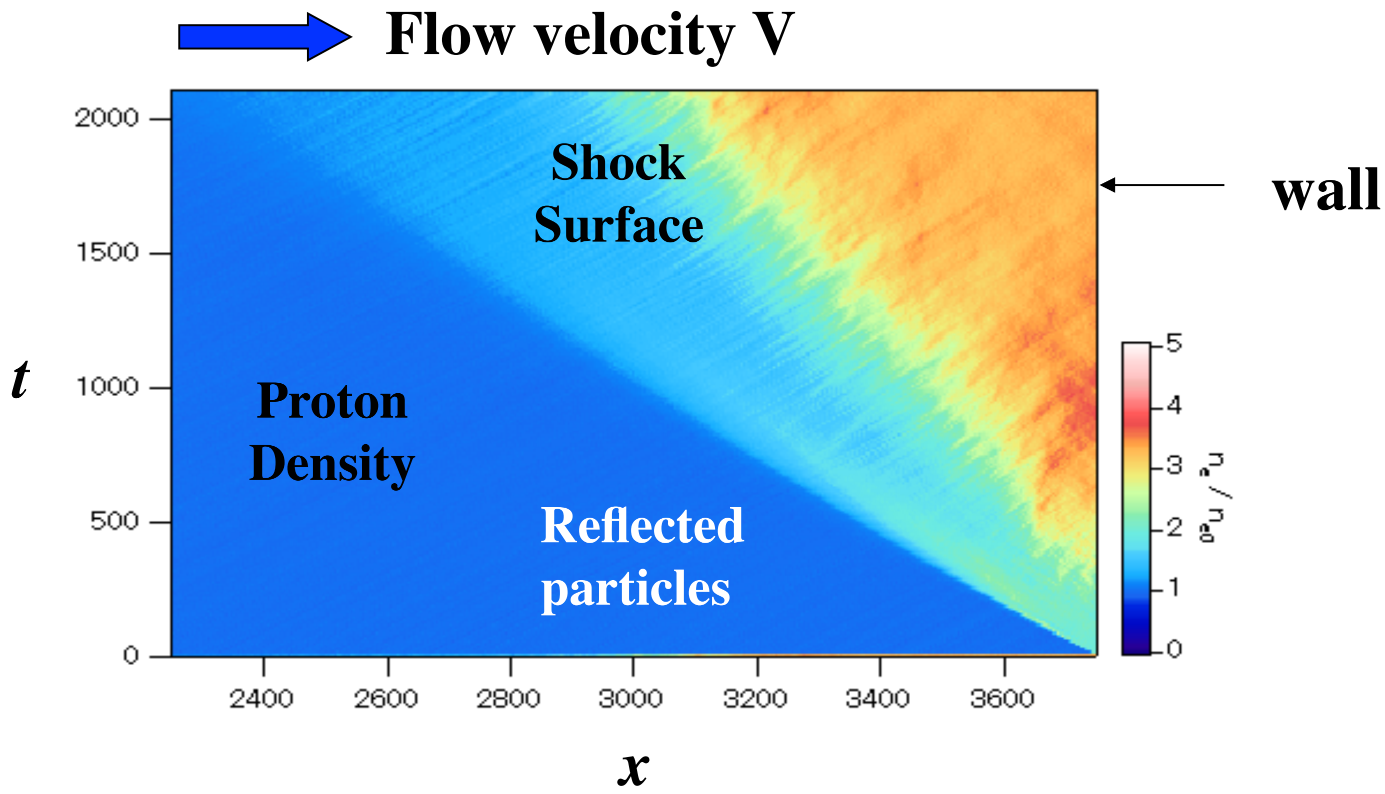


$F = -e\,\boldsymbol{v} \times \boldsymbol{B}$: Lorentz force

Current sheets j appear and it increase the initial magnetic field fluctuation

M. Medvedev and A. Loeb, THE ASTROPHYSICAL JOURNAL, 526, 698 (1999)

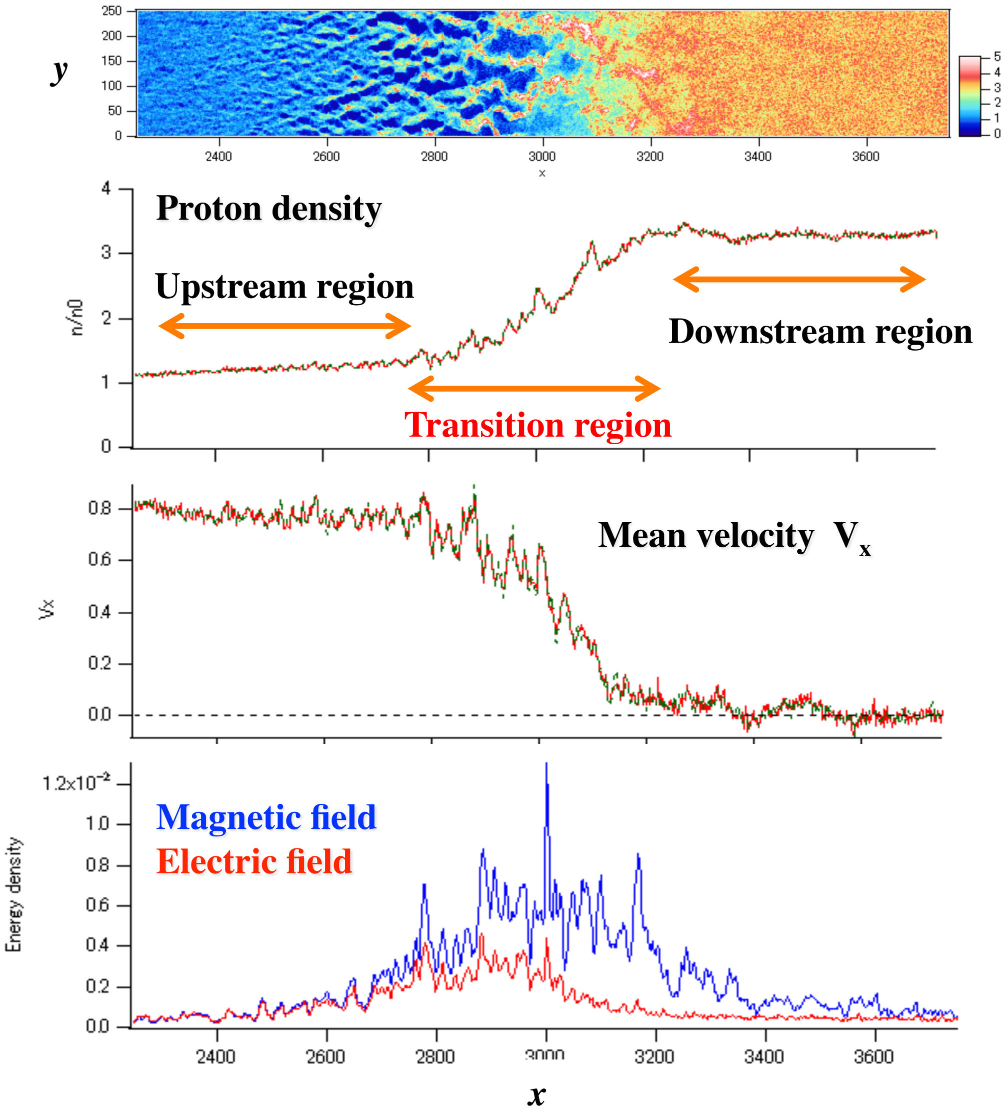
2D PIC simulation of Weibel-mediated collisionless shock



Reflection of the plasma by the wall
⇨ Production of counter-streaming plasmas

T. N. Kato and H. Takabe, Astrophy. J. Lett. 682, L93 (2008)

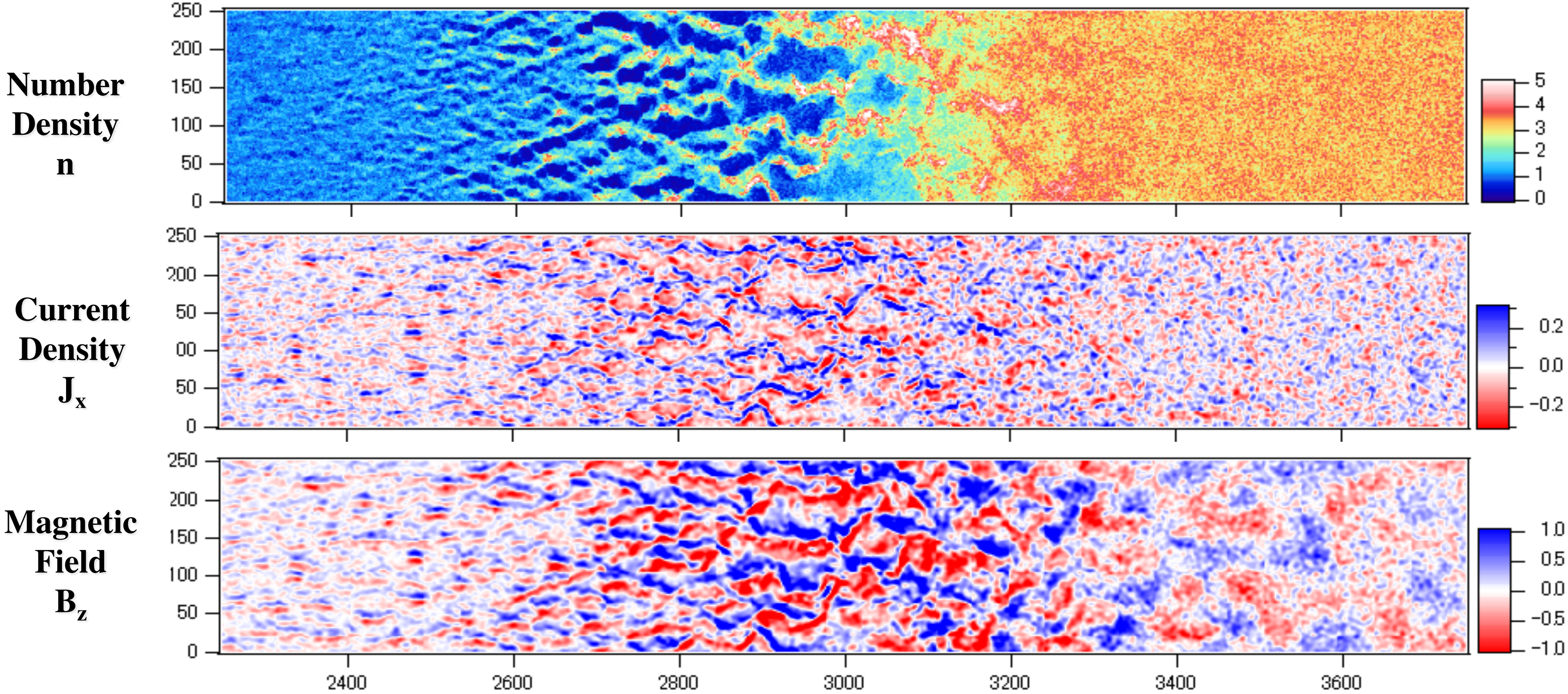
2D PIC : A shock wave structure



t =2100

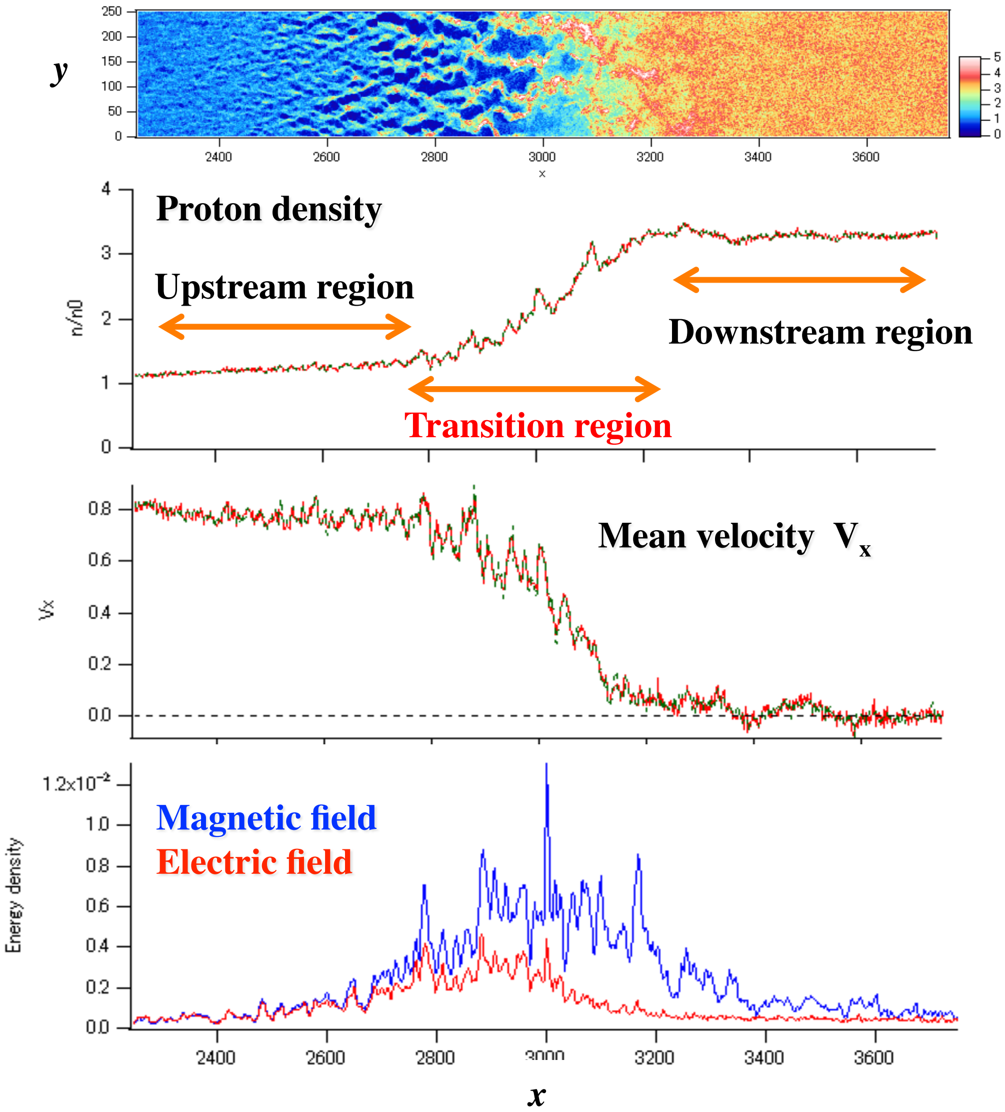
- A shock wave structure appears later in time
- Current filaments and strong magnetic fields are generated at the shock transition region

2D PIC: Current and Magnetic Field Generation by Weibel Instability



Current filaments and strong magnetic fields are generated at the shock transition region by Weibel Instability

2D PIC simulation of Weibel-mediated collisionless shock



• Self-generated magnetic field is ~1% of the kinetic energy of the bulk plasma in the upstream region

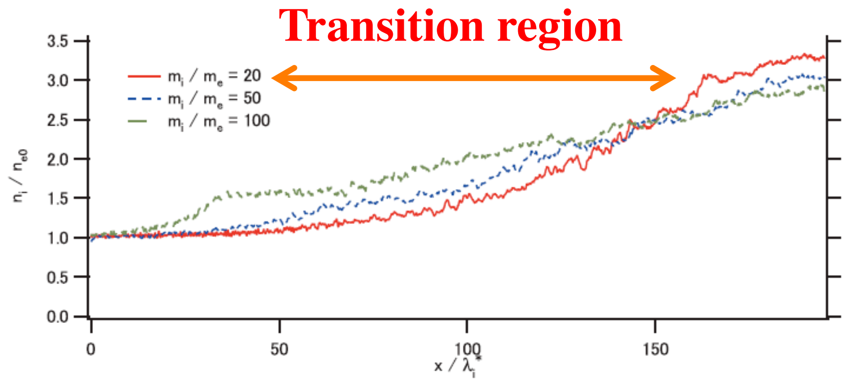
⬇

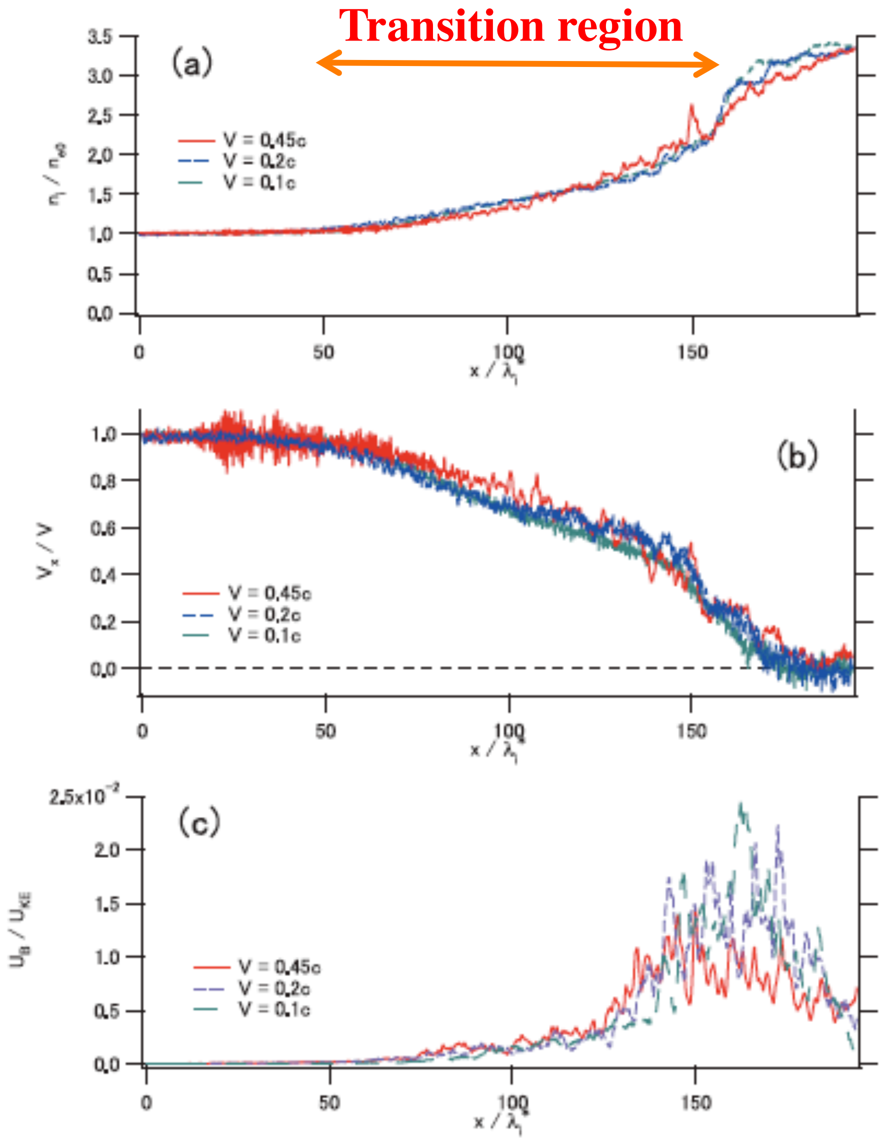
• Strong self-generated magnetic field in the transition region deflects the particles coming from the upstream

⬇

• This provides an effective dissipation mechanism for the collisionless shock

2D PIC simulation shows Weibel-mediated shock structures are independent of V/c and m_i / m_e





Scaling law from 2D PIC simulation

V/c = 0.45, 0.2, 0.1

m_i / m_e= 20, 50, 100

↓

Shock width W ~100 x ion inertia length

T. N. Kato and H. Takabe, Astrophy. J. Lett. 682, L93 (2008)

Possibility for the Weibel-mediated shock experiments

Scaling law from 2D PIC simulation by T. Kato

V/c = 0.45, 0.2, 0.1

m_i / m_e= 20, 100

↓

CH plasma (z = 3.5, A = 6.5)

n = 10^{20} cm^{-3}, V_{flow1} = 1200 km/s

⇨ **Shock width W ~100 x ion inertia length ~ 3 mm, λ_{ii} ~ 55 mm**

Shock formation time ~ 6 ns, B ~ 4 T

⇨ **Weibel-mediated collisionless shocks can be generated**

↓

NIF-class high-power laser system is required for Weibel-mediated collisionless shock experiemnt.