Collective Deceleration

Toshi Tajima
Norman Rostoker Chair, UC Irvine

In memory of Denis Perret-Gallix and Burton Richter

A. Chao, H. C. Wu, X. M. Zhang, T. Saeki, A. Suzuki, D. Habs, G. Xia, B. Richter, A. Caldwell, D. Perret-Gallix, ……..

Mini-Workshop on plasma beam dump
University of Manchester
Aug. 30, 2018

From "Kitchen Science" to "Toilet Science"

Human are superior in working together via communication, which won out over Neanderthals.
They have been extremely good in "**kitchen science**" to get to "food".
However, they have been negligent or weak in thinking "**toilet science**" to "treat waste".

Examples:

1. Petroleum civilization: Convenient modern life ----→ Homo Sapiens-triggered **climate change**
2. Nukes: Only 4 years to get Fermi's Chicago pile (1940) ----→ Nowhere to flush **radioactive waste**
3. Space: Sputnik in 1957 ----→ Millions of **space debris** endanger astronauts and satellites
4. Particle physics: appetite for **higher energy** acceleration -----→ need to **compactify and nontoxic**, including high energy **beam dump**

自己責任を果たす新しい哲学とサイエンス New Philosophy and Science to Fulfill Self-responsibility

20th Century:
Science of Discovery

↓

21st Century:
Toilet Science:
Responsive to self-inflicted societal issues

Tajima
(Jan. 18,2005)

Homo Sapiens and Civilization

Human:
Good in communication to **get food**; won over Neanderthal
Not good in treating beyond kitchen, i.e. **toilet**

Tajima (2018, CEA)

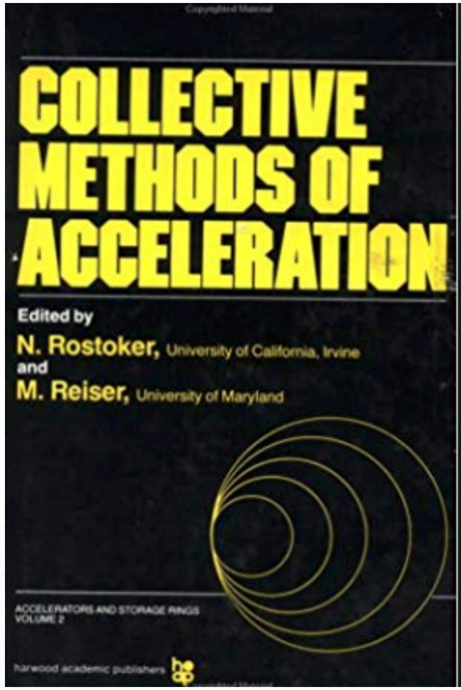
Neanderthal:
larger frame of muscles and brains

→ Homo Sapiens:
superior coordination

→ Medieval epidemics

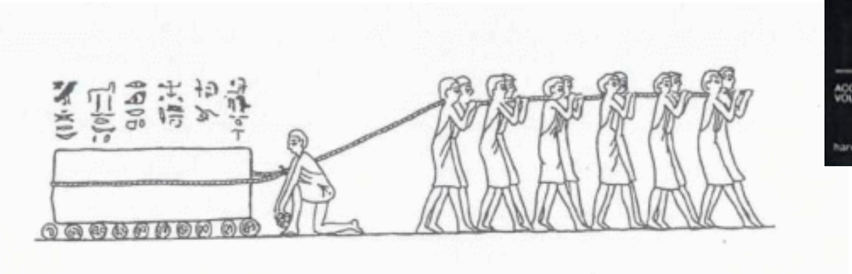
Collective Force and Wakefields

What is *collective force*? :Secret behind wakefield accelerator



Rostoker(1978)

How can a Pyramid have been built?



Individual particle dynamics → Coherent and collective (N^2) interaction / dynamics

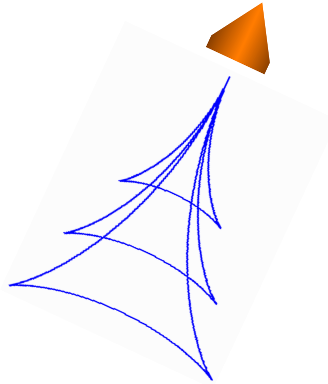
Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)
Collective radiation (N^2 radiation)
Collective ionization (N^2 ionization)

→ beam driven plasma collective accelerating field (wakefield) :
compactification of accelerators by many orders

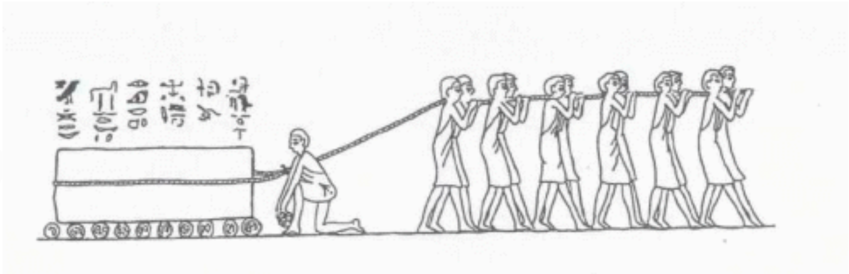
Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

Kelvin wake

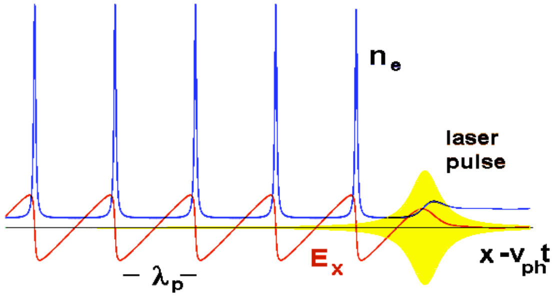


Colletive dynamics



(cf. individual particle dynamics)

No wave breaks and wake **peaks** at v≈c



← **relativity regularizes**

Wave **breaks** at v<c

Hokusai

Collective acceleration → Collective deceleration


Collective decelerator
in a plasma

Individual and collective stopping powers

Bethe-Bloch stopping power

$$-(dE/dx)_I = (F/\beta^2)[\ln(2m_e\gamma^2 v^2/I) - \beta^2]$$

where $F = 4\pi e^4 n_{e,m}/m_e c^2 = e^2 k_{pe,m}^2$

Plasma stopping power due to individual particles

$$-(dE/dx)_{ind} = (F/\beta^2)\ln(m_e v^2/e^2 k_D)$$

Plasma collective stopping power

$$-(dE/dx)_{coll} = (F/\beta^2)\ln(k_D v/\omega_{pe})$$

Enhance collective force ← **wake excitation by resonance**

Plasma stopping power by wakefield excitation of bunched beams

$$-(dE/dx)_{coll-wavebreak} = m_e c\omega_{pe}(n_b/n_e)$$

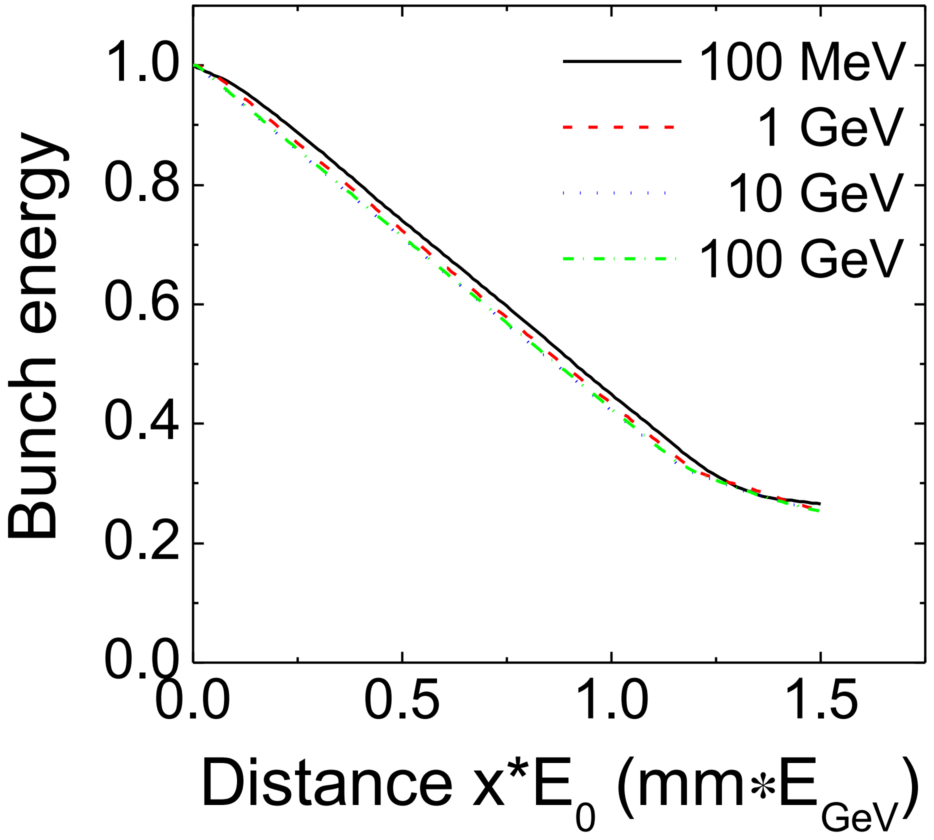
Ratio of wakefield vs. individual stopping powers

$$R = \frac{(dE/dx)_{coll-wavebreak}}{(dE/dx)_{ind}} \approx \frac{m_e c\omega_{pe}\beta^2}{F\Lambda} = \frac{n_e}{n_{e,m}}\frac{\lambda_{pe}}{r_0}\frac{\beta^2}{2\pi\Lambda}$$

Bunched beam ($\lambda_{bunch} = \lambda_{pe}/2$)

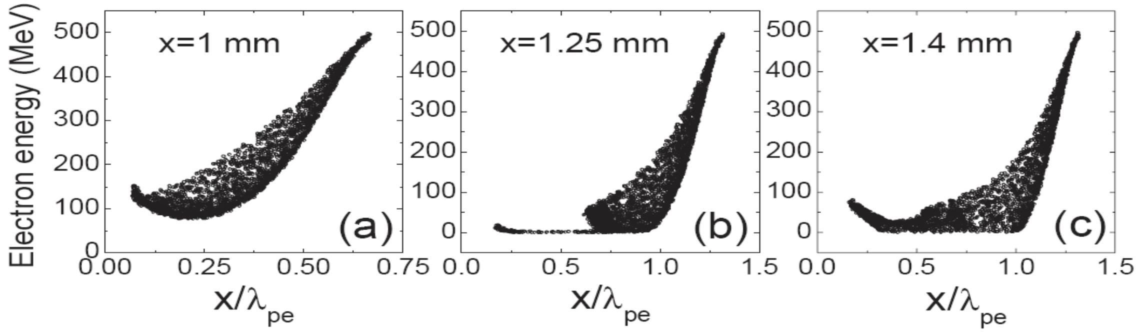
energy decay due to

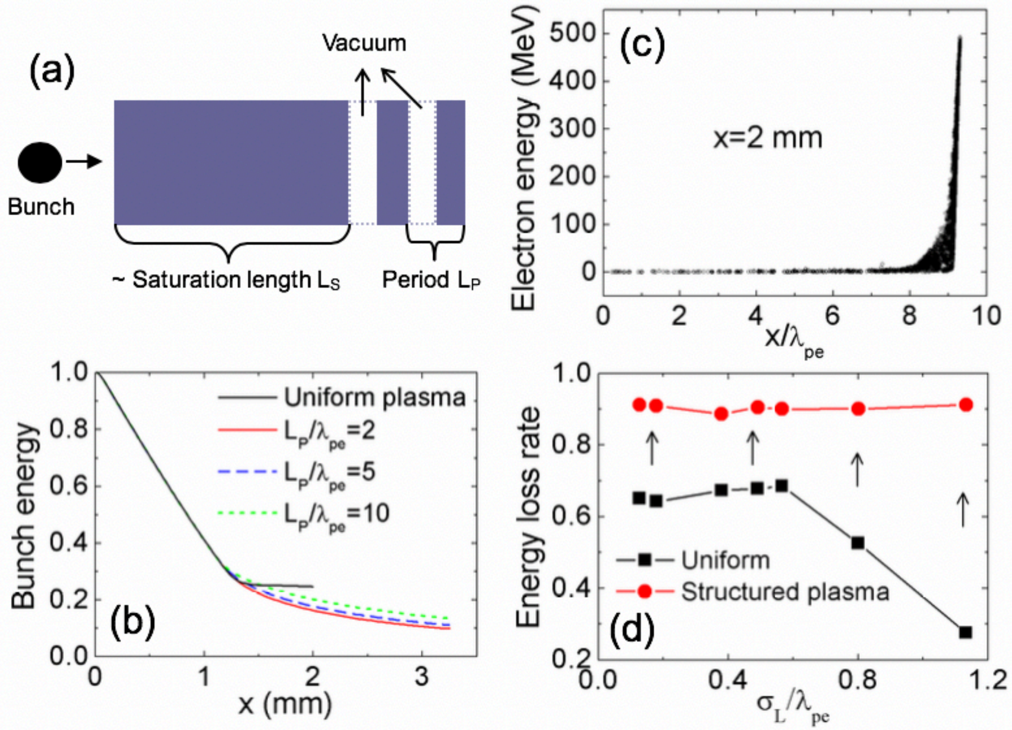
→ **wake deceleration** stopping power



Wu et al. (2010)

Structured Reentry Strategy into plasma





PIC simulation of wakefield stopping power

FIG. 3. (Color) Suggested beam dump. (a) The proposed structured plasma consisting of a stopping layer with thickness L_s and periodic plasma slabs separated by a vacuum gap. L_p is period of the structured plasma. In each period, the plasma slab length is equal to the vacuum length. (b) Evolution of bunch energy for both uniform plasma and structured plasma with $L_P/\lambda_{pe}=2$, 5 and 10. (c) Electron energy vs. x position at x=2 mm for the case of $L_P/\lambda_{pe}=2$. (d) Improvement of energy loss rate due to the structured plasma for different plasma densities plotted in terms of σ_L/λ_{pe}, keeping bunch sizes $\sigma_T=10\,\mu$m and $\sigma_L=3\,\mu$m constant.

Exploration of a strategy:

periodic vacancies and plasma

←re-engage beam into wakes

Wu et al. (2010)

PIC simulation:
re-engage beam with wakes with periodic foils

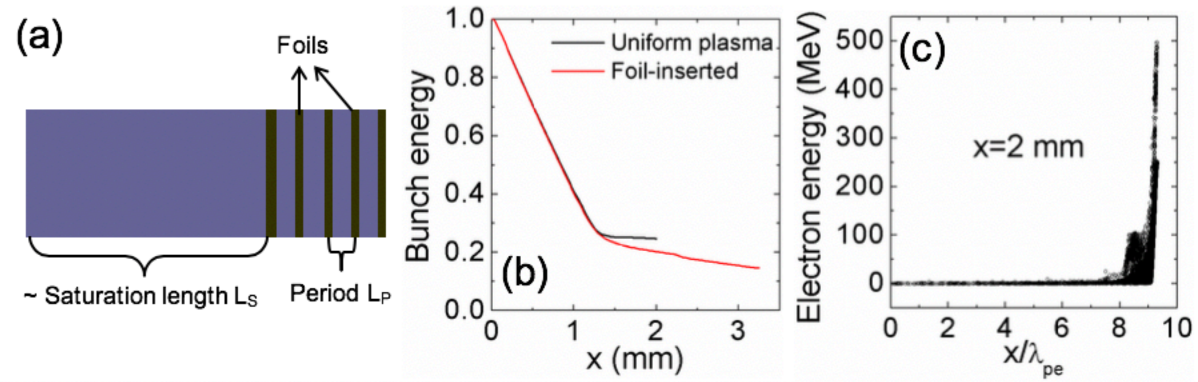


FIG. 4. (Color) Suggested beam dump. (a) The structured plasma with periodic thin foils inserted. L_P is the separation of the neighboring foils. (b) Bunch energy evolution for both uniform plasma and the structured plasma with $L_P/\lambda_{pe} = 1$, foil length $0.1\lambda_{pe}$, and density $n_{foil} = 100n_e$. (c) Electron energy vs. x position at x=2 mm.

Development of micro-bunches

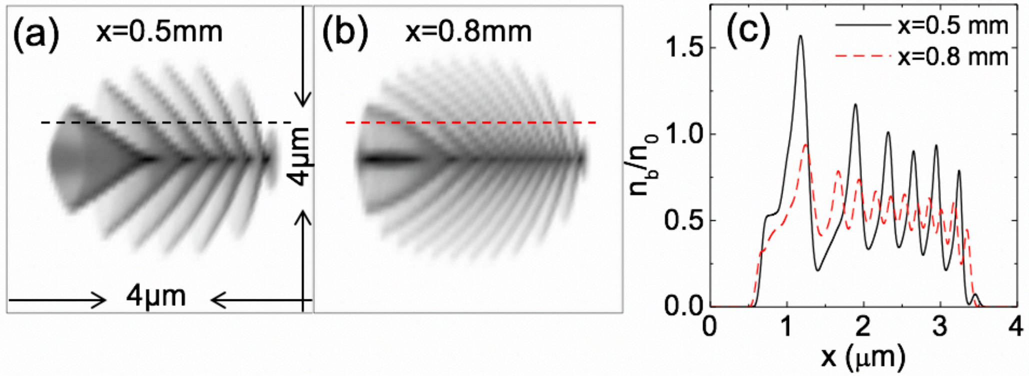


FIG. 5. (Color) Microbunching during deceleration. Snap shots of bunch density for the propagation distances (a) x=0.5 mm and (b) x=0.8 mm. (c) Display of bunch density distributions along the dashed lines in (a) and (b). Simulation parameters are the same as in Fig. 2.

Phys. Plasmas **22**, 083106 (2015)

Active and passive beam dump
Bonatto (2015)

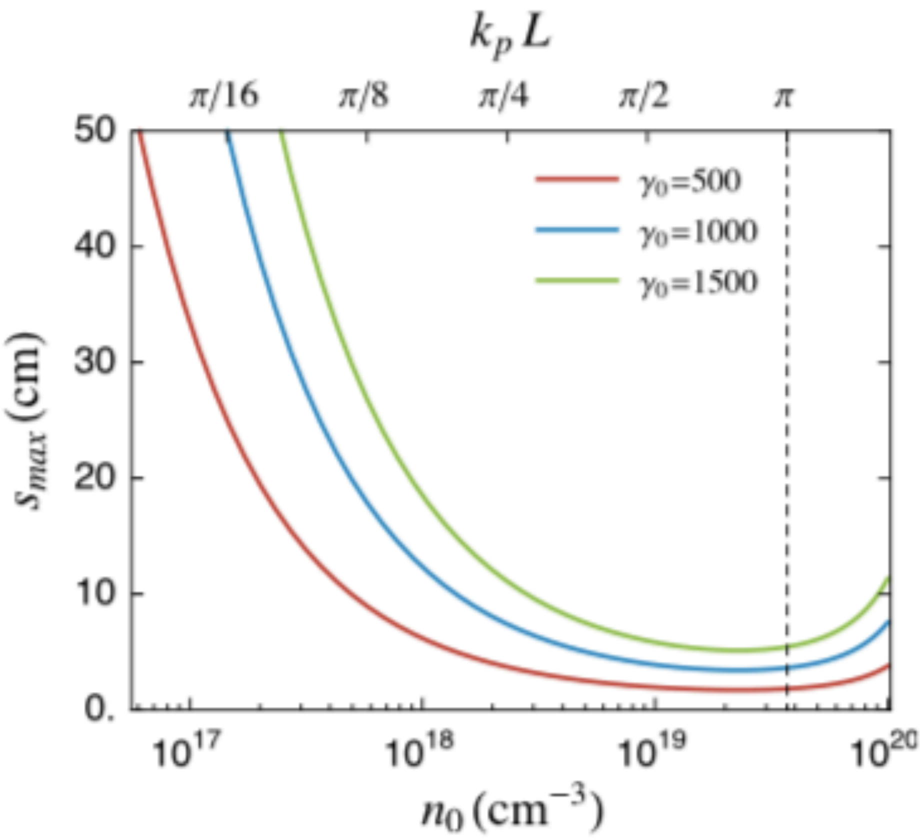
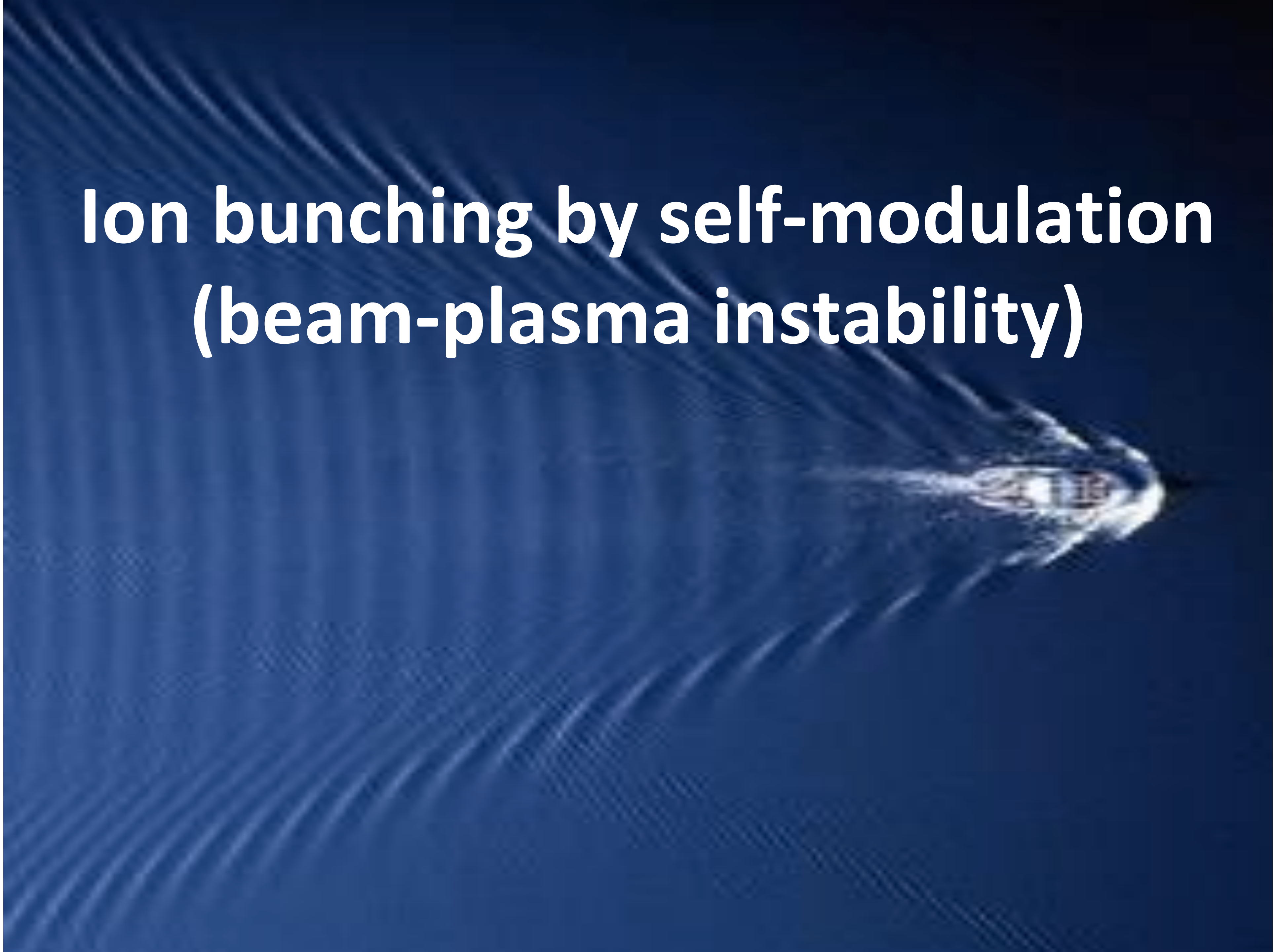


FIG. 3. Dependence of s_{max} on ζ, plasma density, n_0, and beam initial energy, γ_0, for a passive beam dump. The beam profile is given by $n_b(\zeta, r)/n_0 = (n_b/n_0)\sin(\pi\zeta/L)(1 - r^2/r_b^2)$, if $0 \le \zeta \le L$ and $r \le r_b$, or zero otherwise, with $n_b/n_0 = -Q/(n_0 e\, r_b^2 L)$, $L = r_b \simeq 2.7\,\mu\mathrm{m}$, and charge $Q \simeq -10$ pC. For a fixed beam length L, the higher the density, the longer $k_p L$ is inside the decelerating region of the beam-driven wakefield, requiring a shorter distance s_{max} to be dumped. If $k_p L = \pi$, the energy loss is maximum and s_{max} is minimum. For $k_p L > \pi$, the beam is partially inside the accelerating region of the wake, causing s_{max} to grow again.

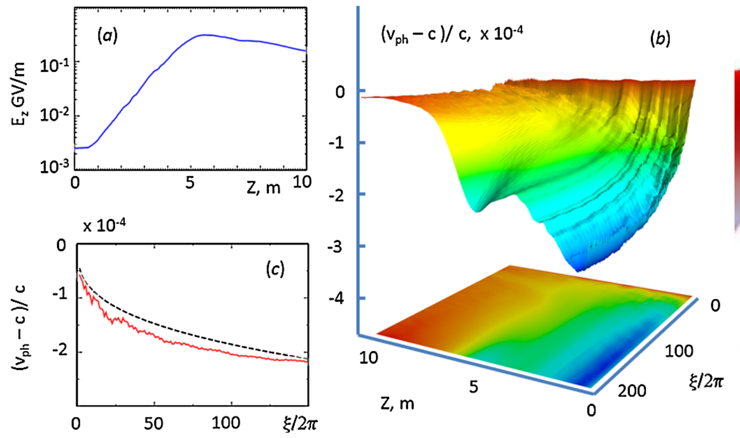
Bonatto et al., Phys. Plas. (2015)

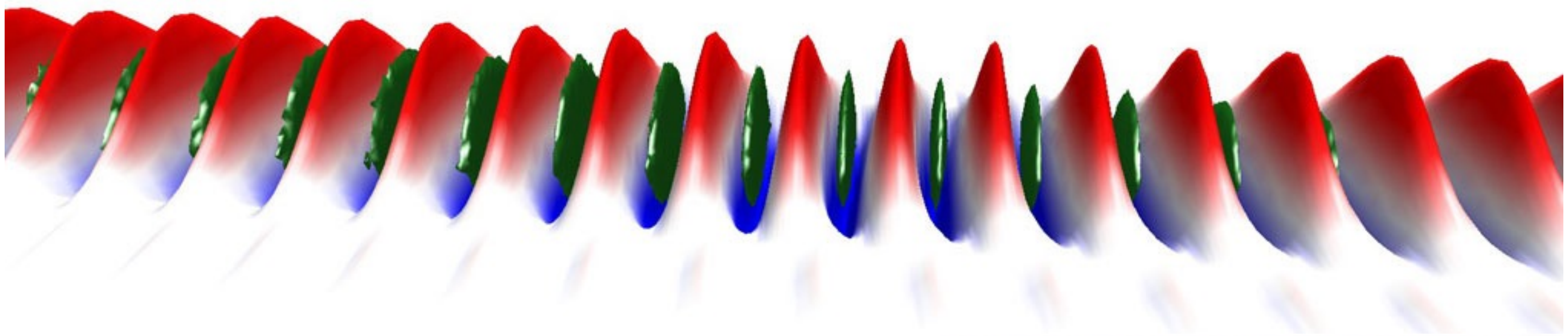
Ion bunching by self-modulation (beam-plasma instability)



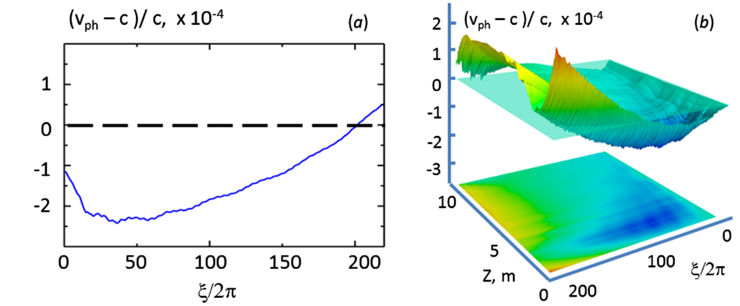
Proton-driven wakefield by self-modulation

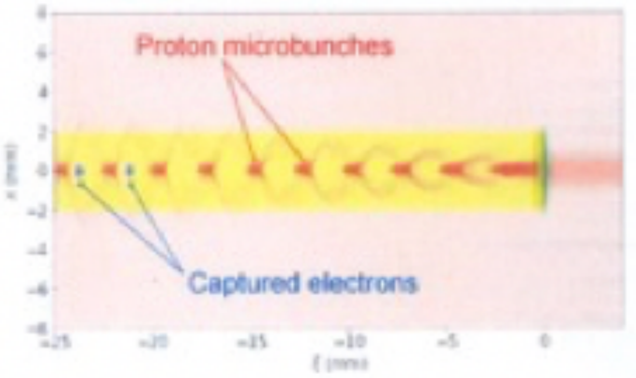
Secret behind ion wakefield = **self-modulation** of ion beam in preplasma





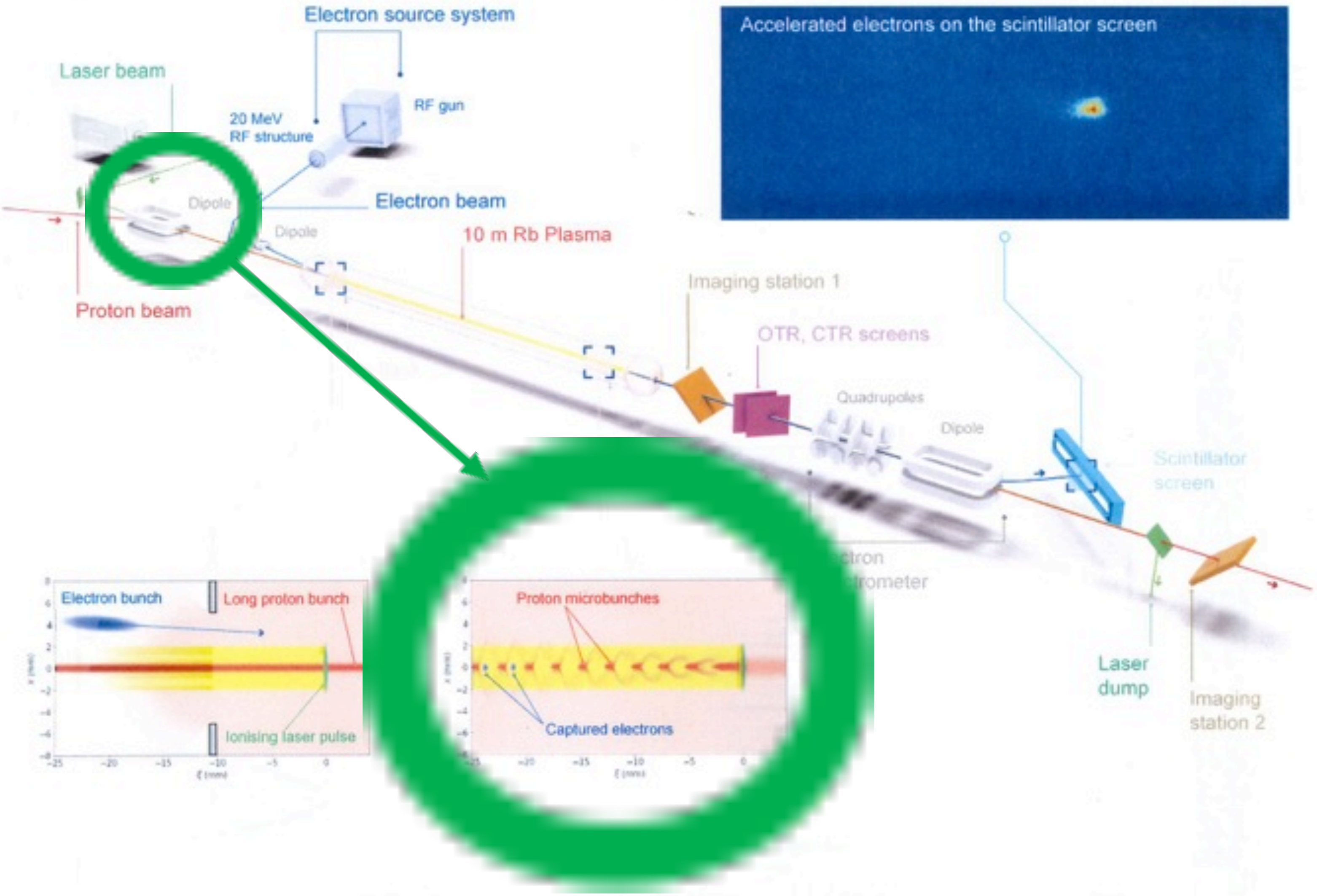
Schroeder (2011)





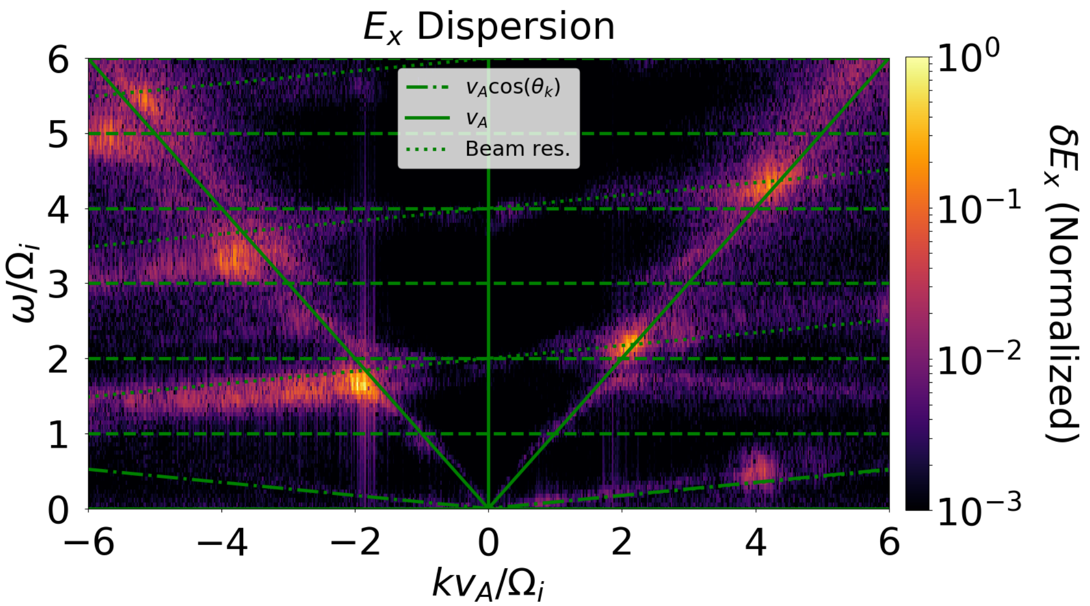
Wing et al., (to be published 2018)

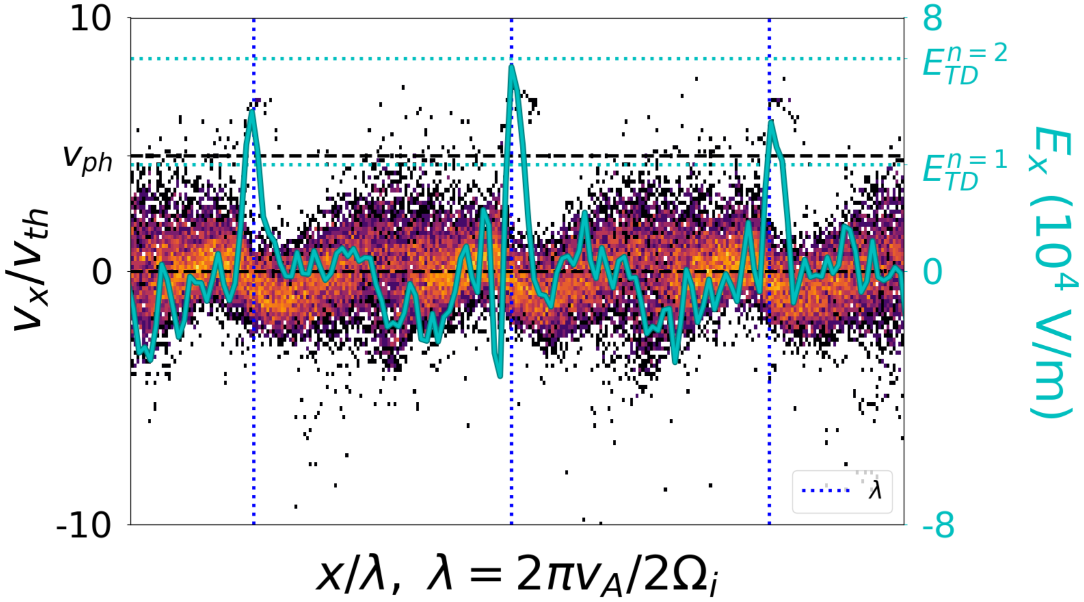
Ion beam bunching at CERN



Wing et al., Nature (2018)

Ion Beam modulation via beam-driven ion cyclotron instability



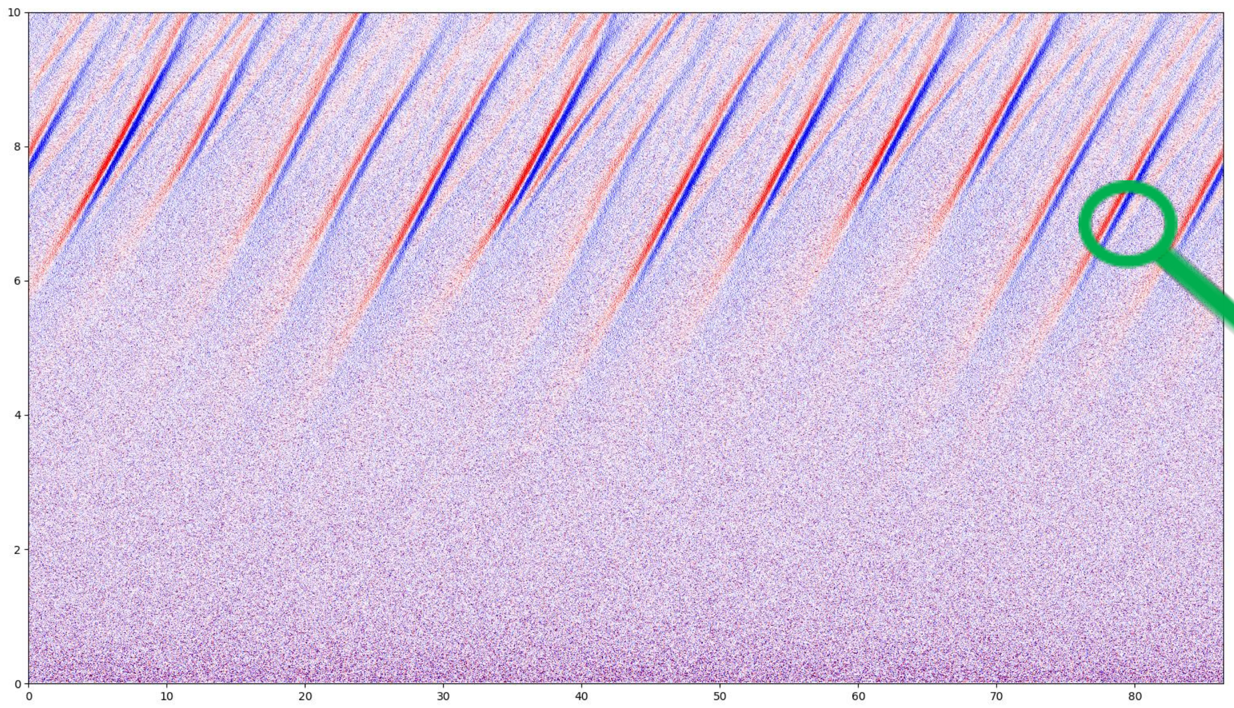


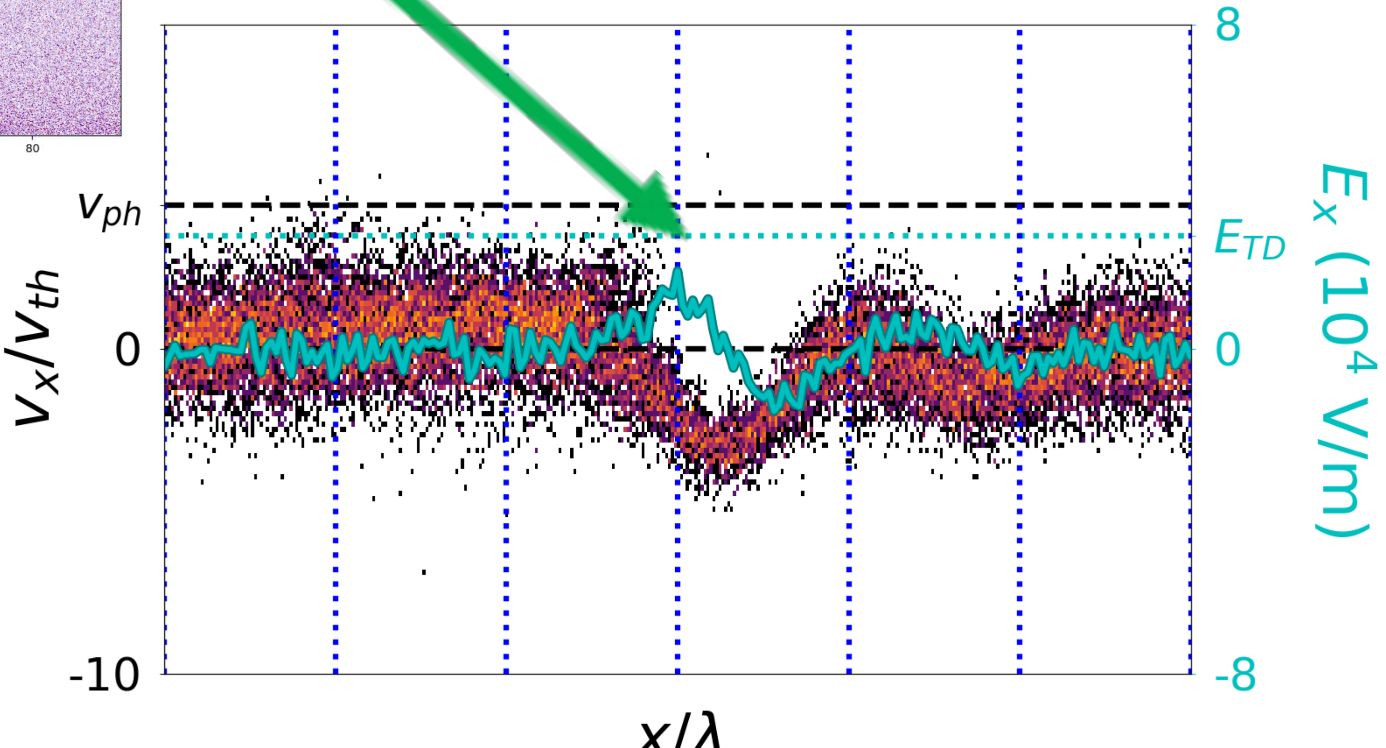
= Bunch length

Ion bunching: A novel method = Maybe done by ion beams in a magnetic field (and plasma)

S. Nicks, A. Necas, and T. Tajima (2018)

Bunch length structure of Tajima-Dawson field driven by ion beam in magnetized plasma





Conclusions and Future Tasks

- Plasma “behaves” or even “surprises us” under certain treatments (s.a. wakefield excitation). Bring plasma as part of accelerator components
- Importance of **pre-plasma microbunches** → **microsurgery of beams by plasma**

  cf. CPA (chirped pulse amplification) of laser, attosecond photonics
- Boundary between materials and plasma will blur in **fs and as regimes**
- Optimal plasma structure to re-engage wakefields:

  plasma-voids-foils, periods, **profiled densities**
- Bunching strategies

  electron bunches for electron dump. ← **preplama self-modulation (RF pre-massage** helps, too**)**,

  ion bunches for ion dumps
- Ion bunching

  recent experiments and PIC simulation, further experiments
- Beam dump for LWFA: **ideal** playground for collective decelerators (as their bunches are very short). s.a. ELI-NP
- Energy recovery

Thank you very much!