How robust is the high energy beam-plasma interaction?

Norman Rostoker Memorial Symposium
Fairmont Hotel, Newport Beach, Aug. 24, 2015

Toshi Tajima, UC Irvine (also at TAE)

In dedication to the late Professor Norman Rostoker

Acknowledgements: G. Mourou, F. Mako, A. Necas, R. Magee , E. Trask, T. Roche, B. Deng, X. Yan, M. Binderbauer, S. Ichimaru, the late J.M. Dawson, X. M. Zhang, Y. M. Shin, D. Farinella, T. Saeki, N. Naumova, K. Nakajima, S. Bulanov, A. Suzuki, T. Ebisuzaki, J. Koga, X. Q. Yan, M. L. Zhang, U. Wienands, U. Uggerhoj, A. Chao, N.V. Zamfir, V. Shiltsev, M. Hogan, P. Taborek, K. Abazajian, G. Yodh, S. Barwick, Z. Lin, W. Heidbrink, L. Chen, S. Nickes, T. O'Neil, R. Kulsrud, M. Yamada, D. Hammer, M. Spiro, R. Heuer, A. Caldwell, K. Abazajian, N. Canac, B. Richter, A. Penzias

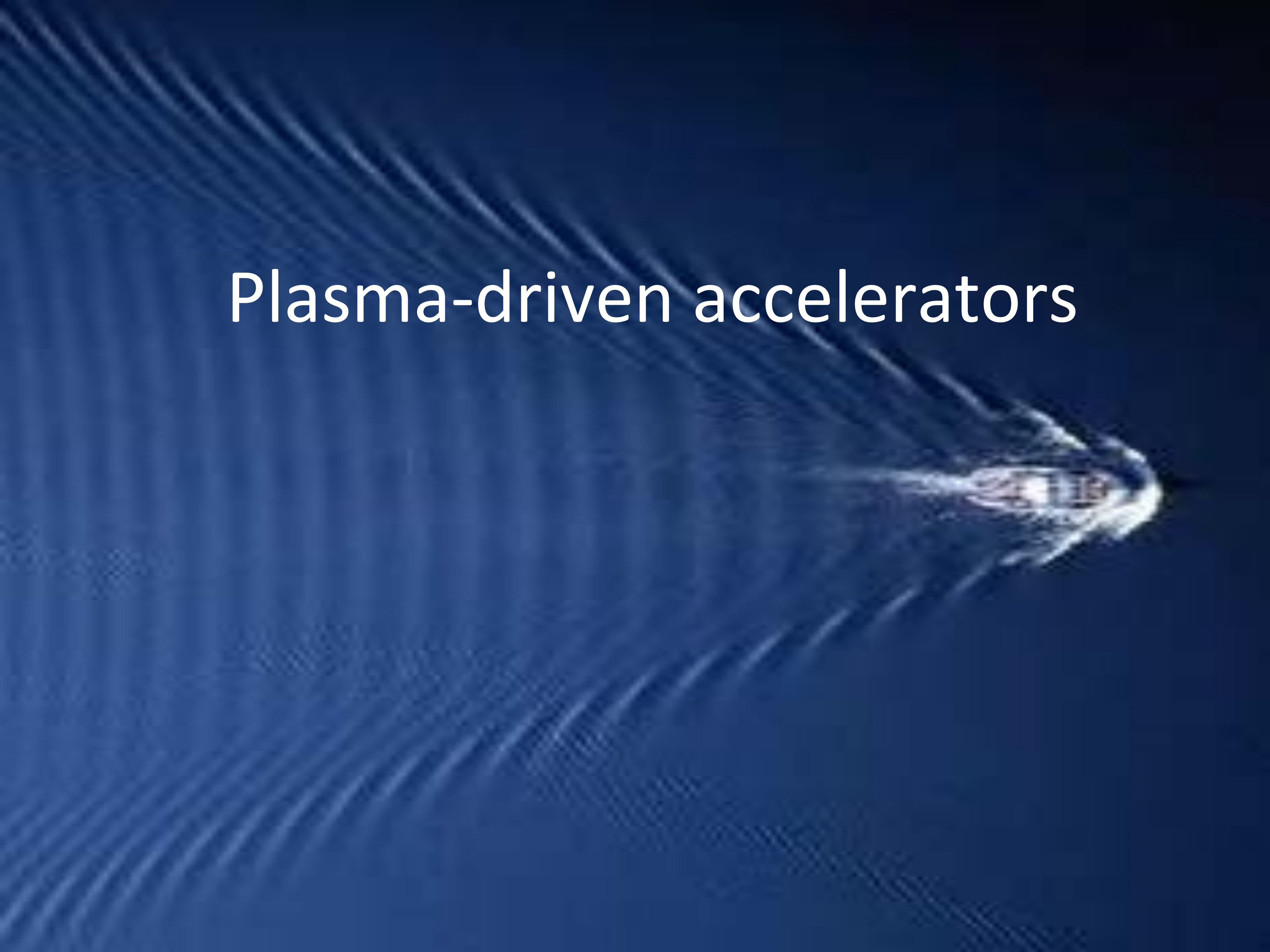
Confluence of accelerator and plasma:
plasma-driven accelerator and accelerator-driven plasma

- Collective accelerator (Norman's lab, 1970's)
- History of plasma acceleration
- Tsunami wave vs. wake wave (the issue of high phase velocity)----Tajima-Dawson field

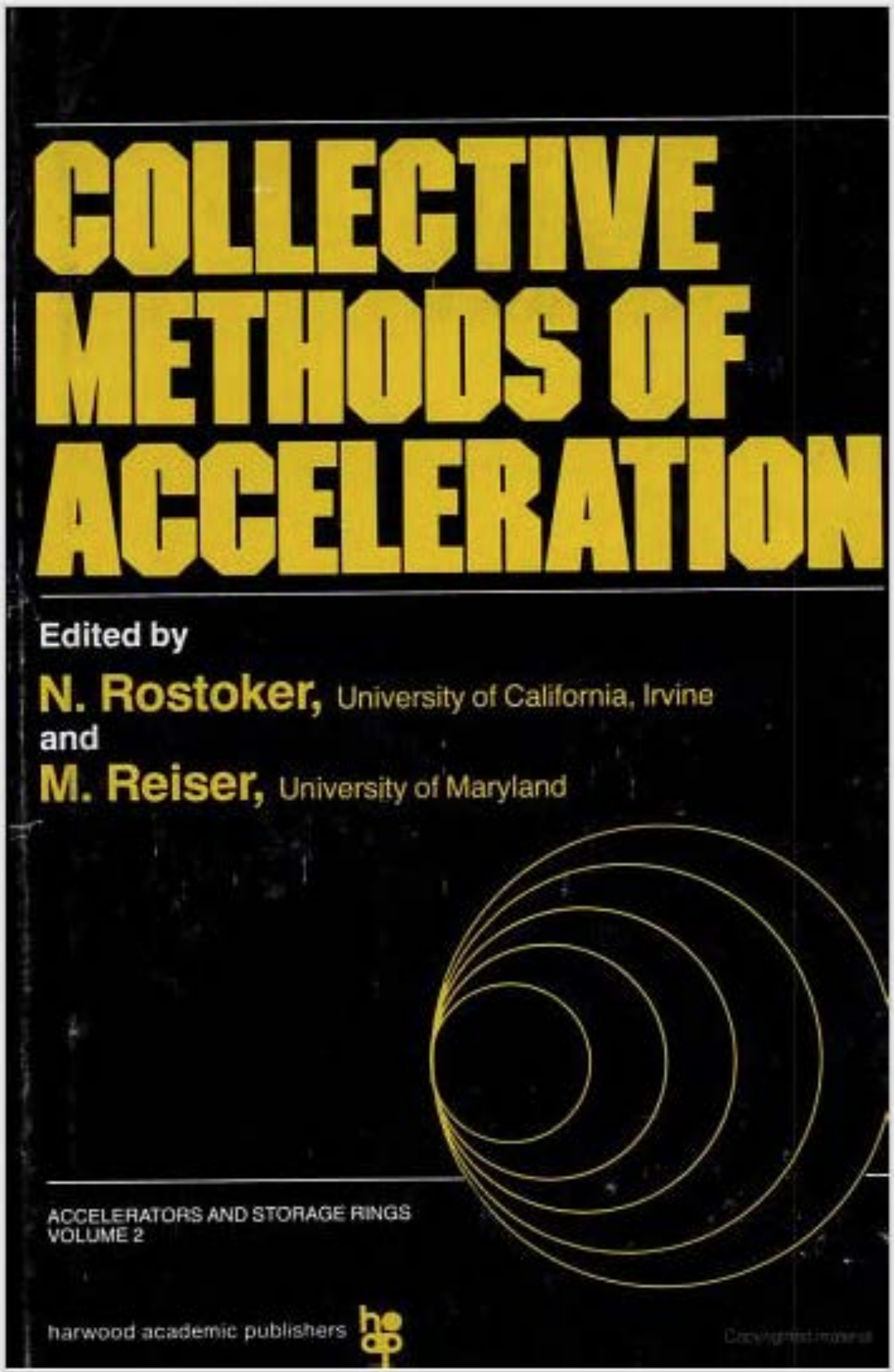
- Beam-driven TAE FRC (Field Reversed Configuration): beam-plasma instability helps to increase fusion reactivity
- Recent phenomenology of the beam-driven TAE FRC: recurrent mini-bursts

- Emerging Conjecture of High Phase-Velocity

Plasma-driven accelerators



Collective accelerators



Professor N. Rostoker

(1960's Cornell; ~ 70's UCI)

Acceleration by plasma wake waves

V. Veksler

J. Dawson

Collective acceleration suggested:
Veksler (1956, CERN)
(ion energy)~ (M/m)(electron energy)

Many experimental attempts of plasma acceleration (~'70s, Rostoker's lab UCI included)
led to no such amplification
(ion energy)~ (2α+1)x(electron)

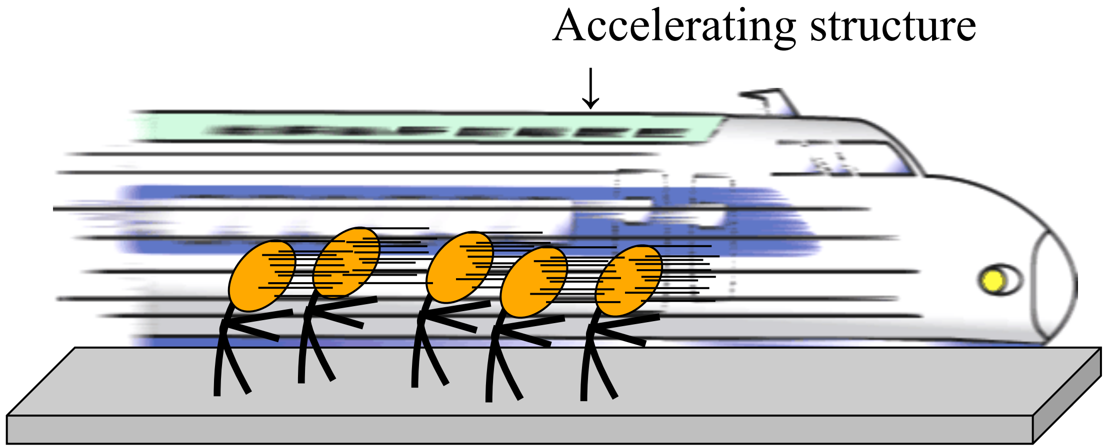
Mako-Tajima (UCI) analysis (1978;1984)
sudden acceleration, ions untrapped,
electrons return, while some run away
→ #1 **gradual acceleration necessary**

→ **Tajima-Dawson (1979, UCLA) wakefield**
#2 **electron acceleration** possible
with **trapping** **(with Tajima-Dawson field)**, more tolerant for sudden process

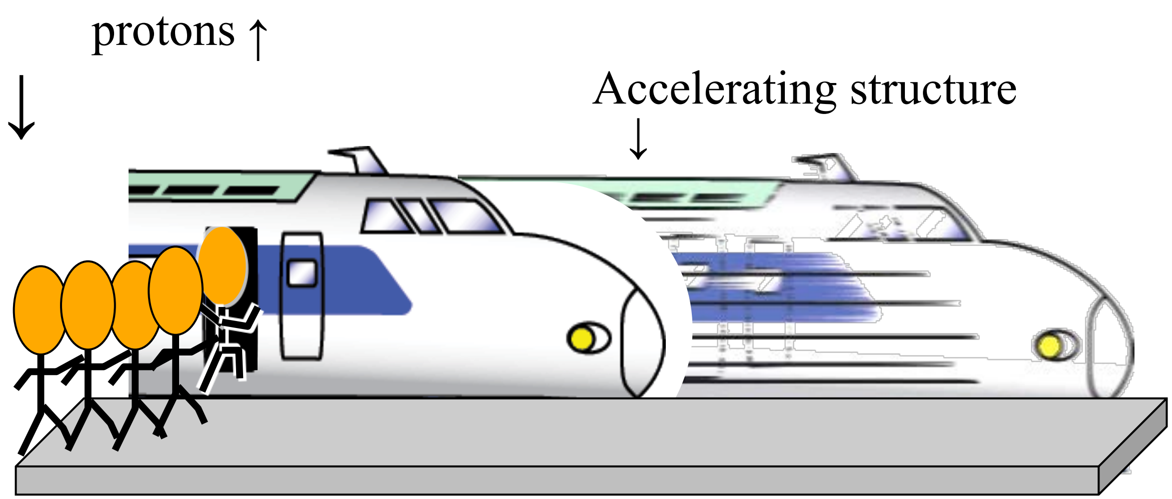
Target Normal Sheath Acceleration (LLNL)
laser-driven ion acceleration (2000)

Adiabatic (Gradual) Acceleration

From lesson of the Mako-Tajima problem



Inefficient if <u>suddenly</u> accelerated



(cf.human trapping width: $v_{tr,human}$ ~ 1m/s << c_s)

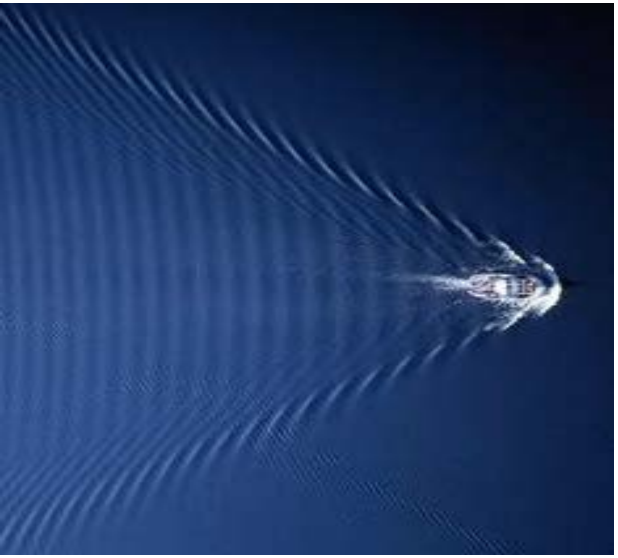
Efficient when <u>gradually</u> accelerated

Lesson: gradual acceleration → Relevant for ions

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed

Tsunami phase velocity becomes ~0, it causes wavebreak and damage

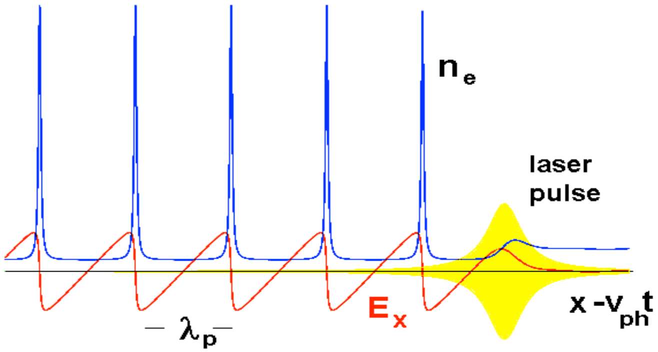


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph} / e$

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

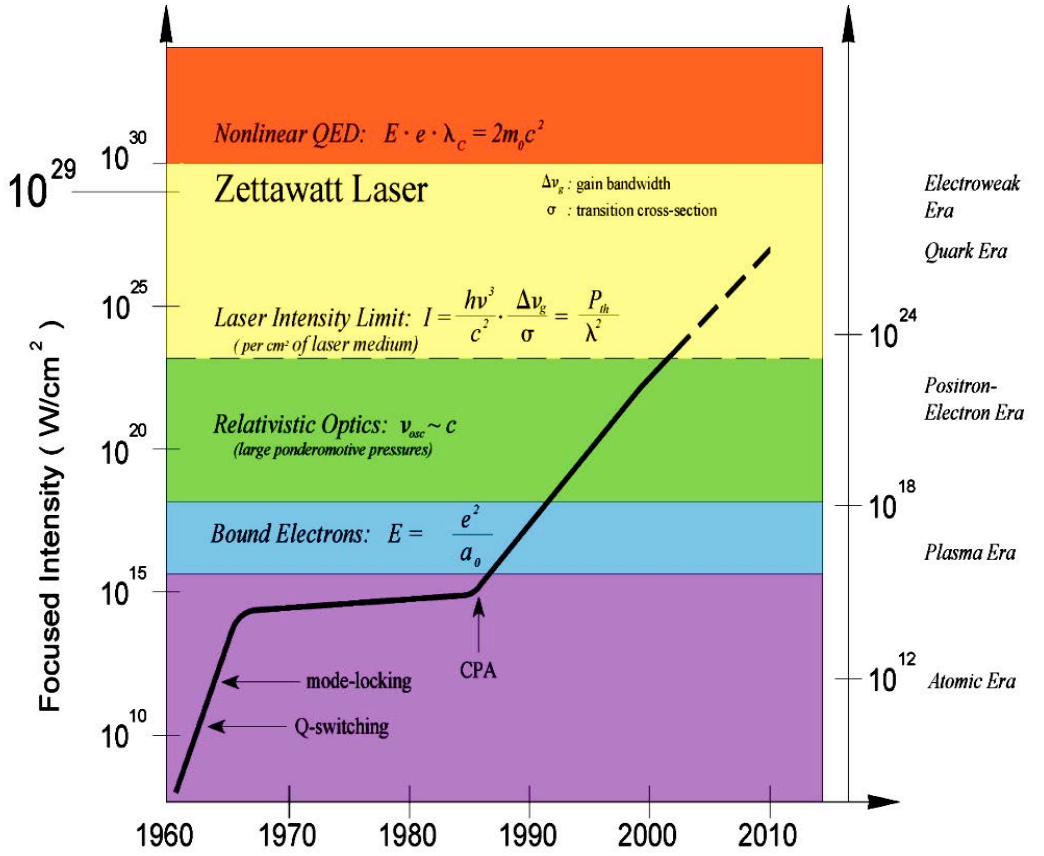
Wave **breaks** at v<c



← relativity regularizes (*relativistic coherence*)

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c / e$ (~ GeV/cm)

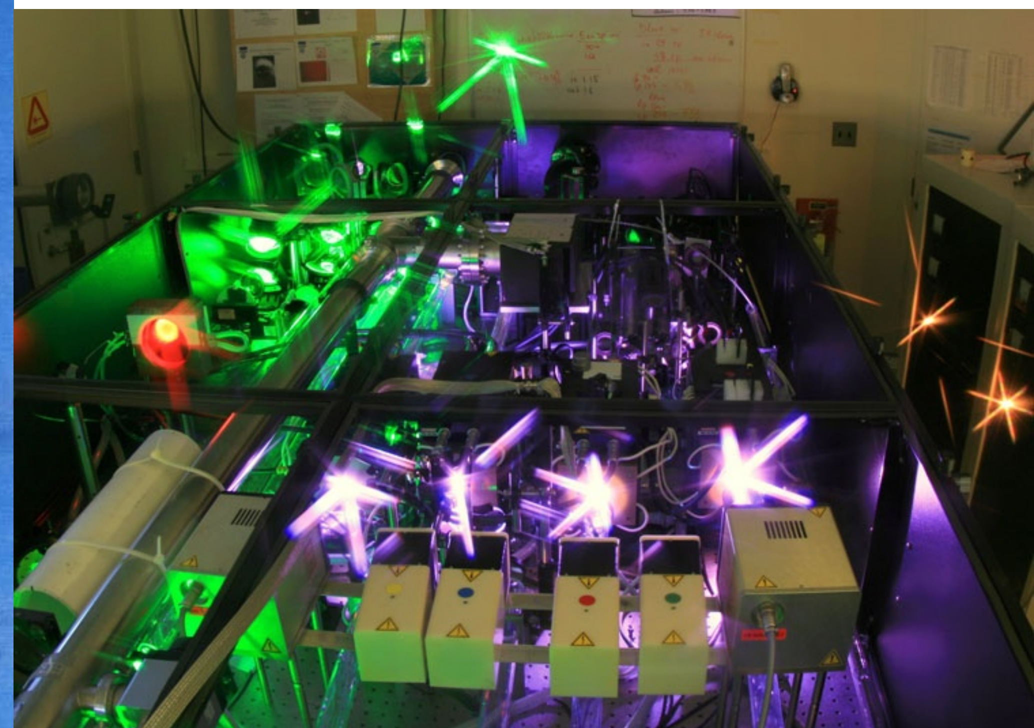
Enabling technology: laser revolution



G. Mourou invented "Chirped Pulse Amplification" in 1985
Laser intensity exponentiated since then,
to match the required laser intensity for Tajima-Dawson's LWFA

Demonstration and Realization of laser wakefield accelerators

three papers on laser plasma accelerator (2006, Nature)

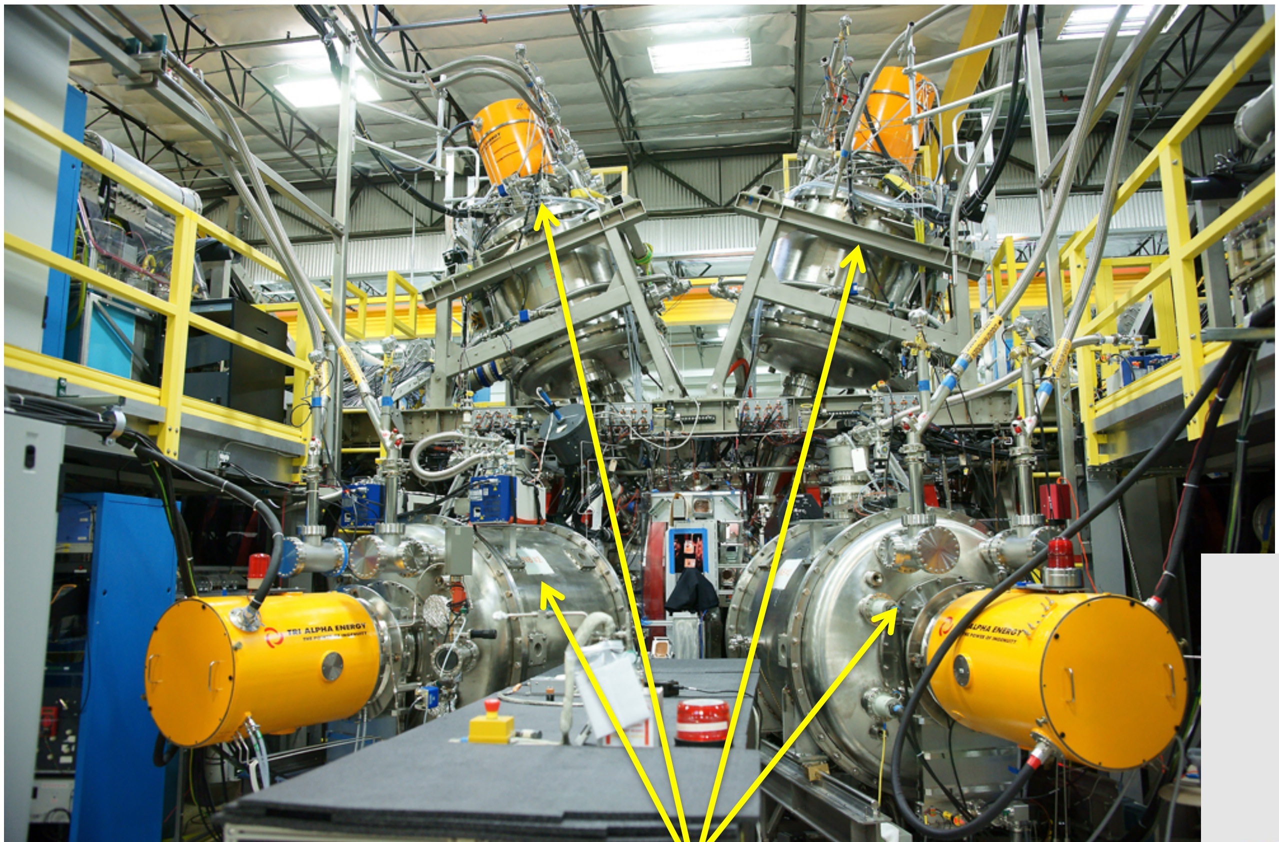


Typical laser and plasma accelerator (Michigan)

Accelerator-driven plasma

Beam-driven plasma (FRC)

TAE's C-2U machine + beams

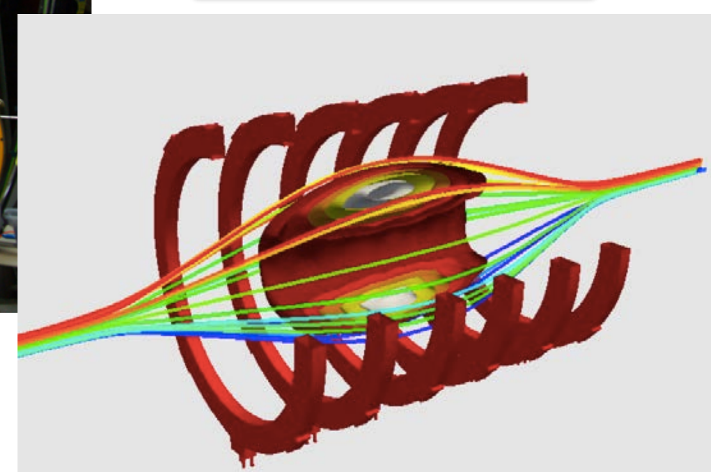


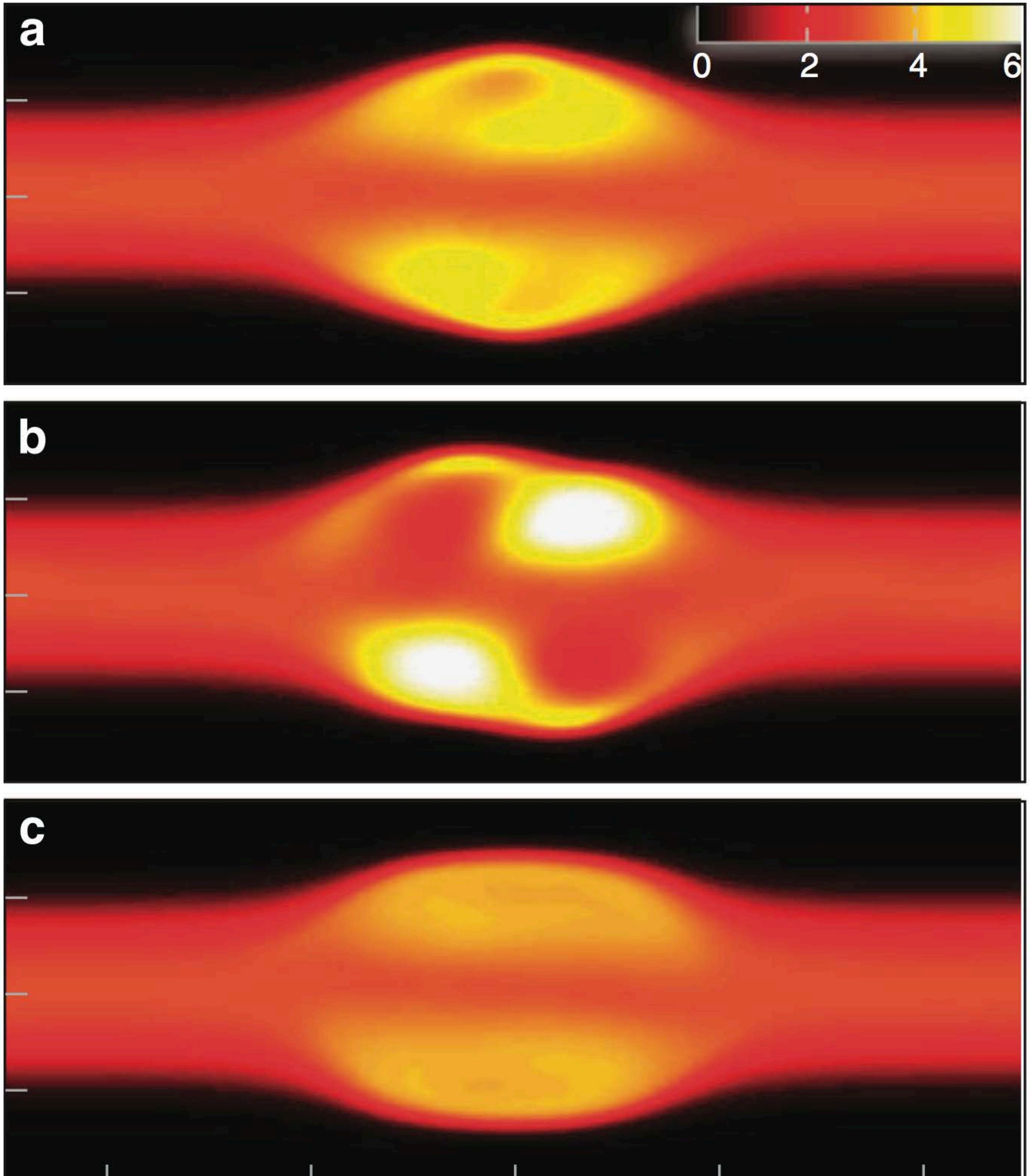
Beams (only 4 visible)

6 beam systems
15 keV
10+ MW
20 degree angle
Operate with:

- Hydrogen – H
- Deuterium – D
- Mixture of H/D

FRC plasma + coils





Prior to tilt. Quiescent plasma

Destructive tilt mode starts

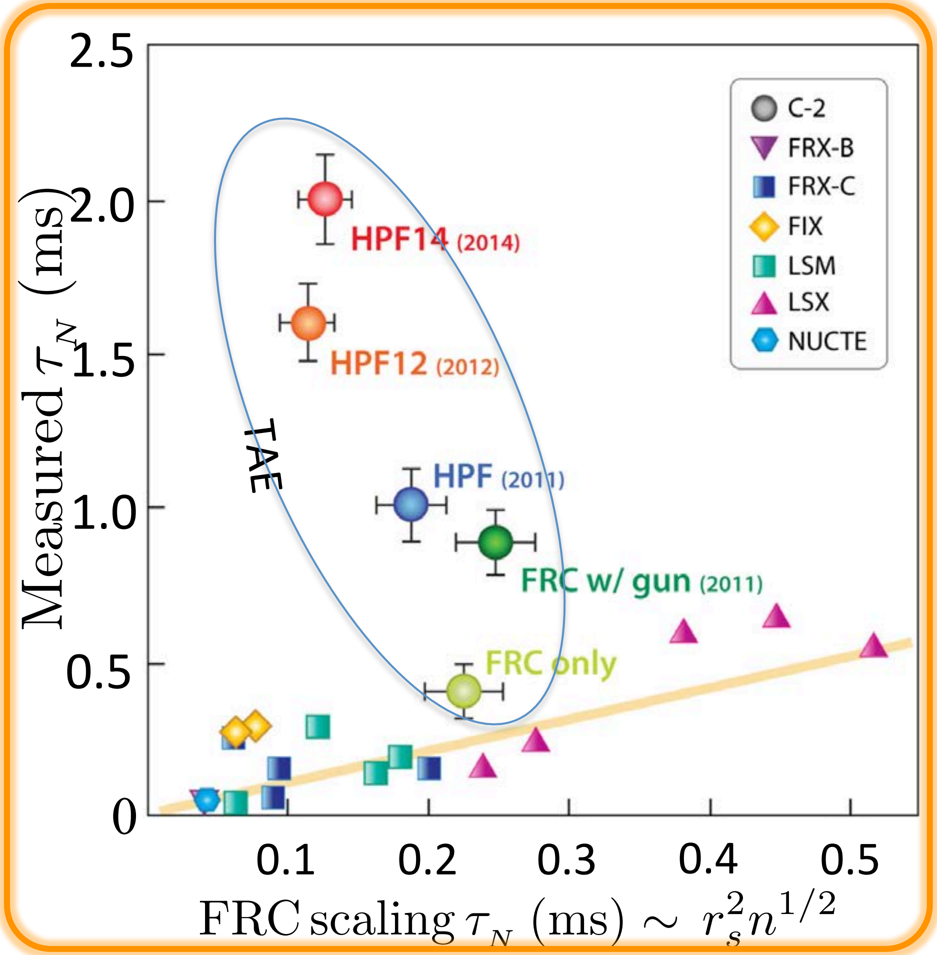
Beam stabilizes

Quiescent plasma recovery

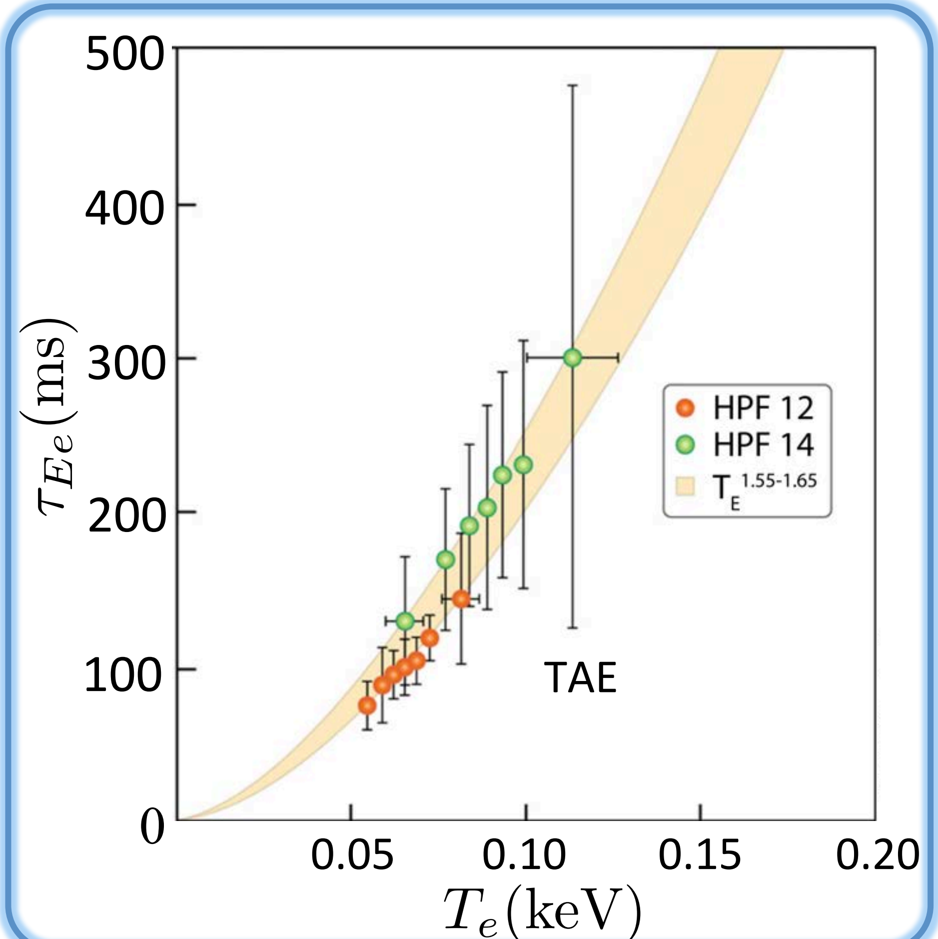
H.Y. Guo et al., *Nature Comm.*, 2014

Plasma confinement improves dramatically in beam-driven FRC (TAE)

Particle confinement time

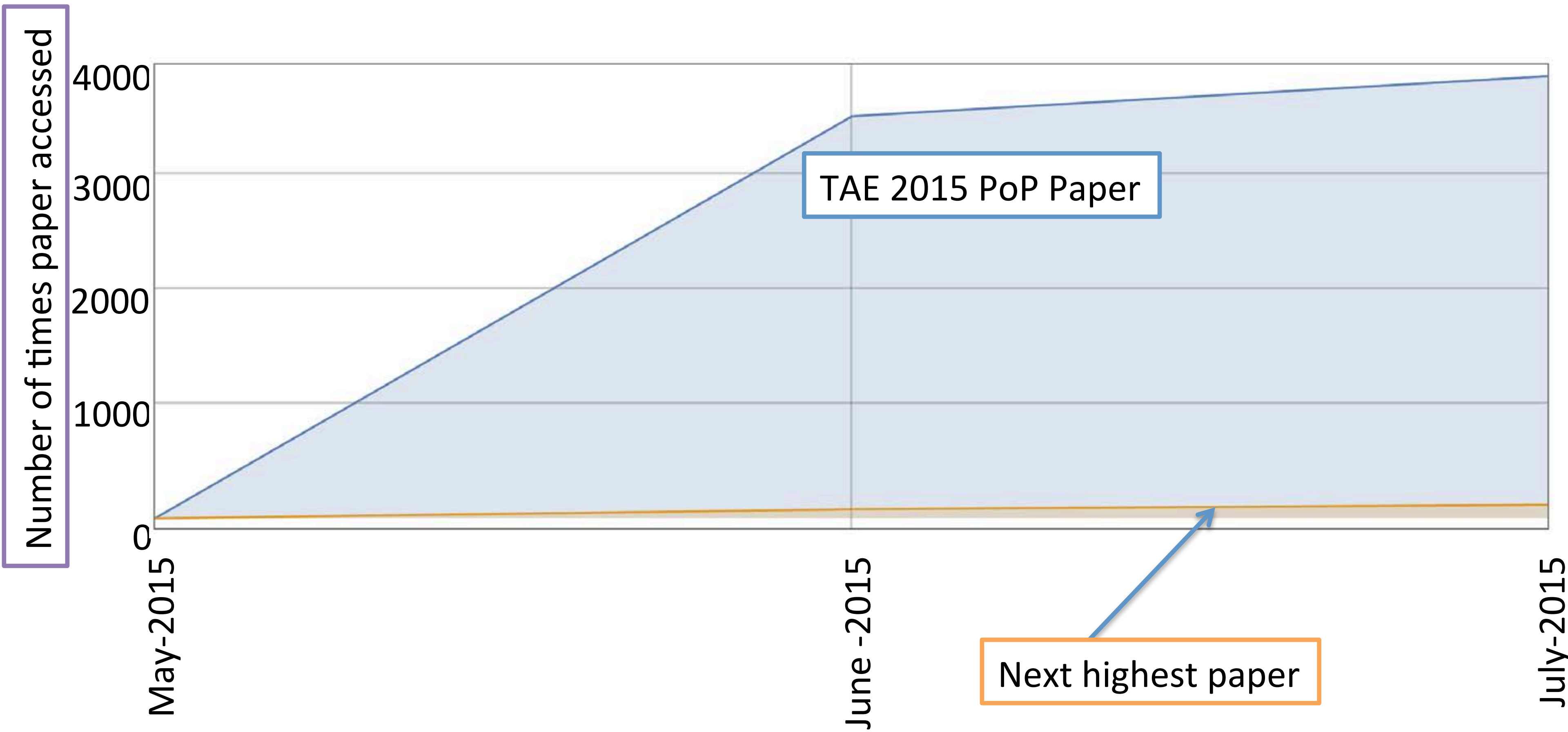


Electron energy confinement time



Guo, Tajima, Trask, et al.

Huge access number since publication in May 2015 to the paper on the beam-driven FRC:



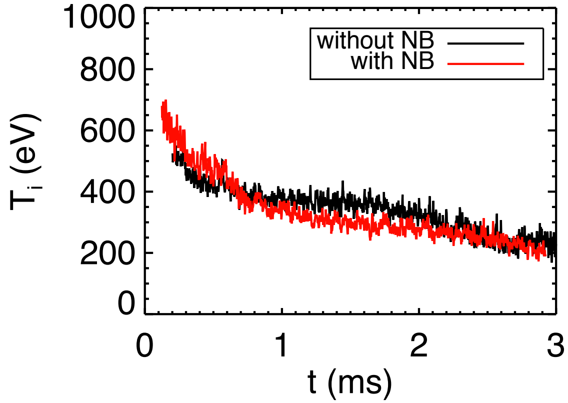
This TAE FRC reports: The beam-driven FRC capable

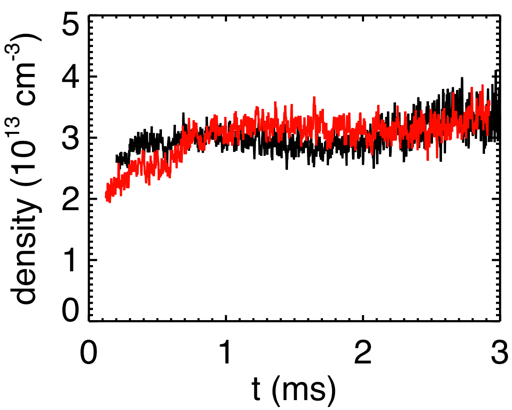
(1) stabilize dangerous tilt instability

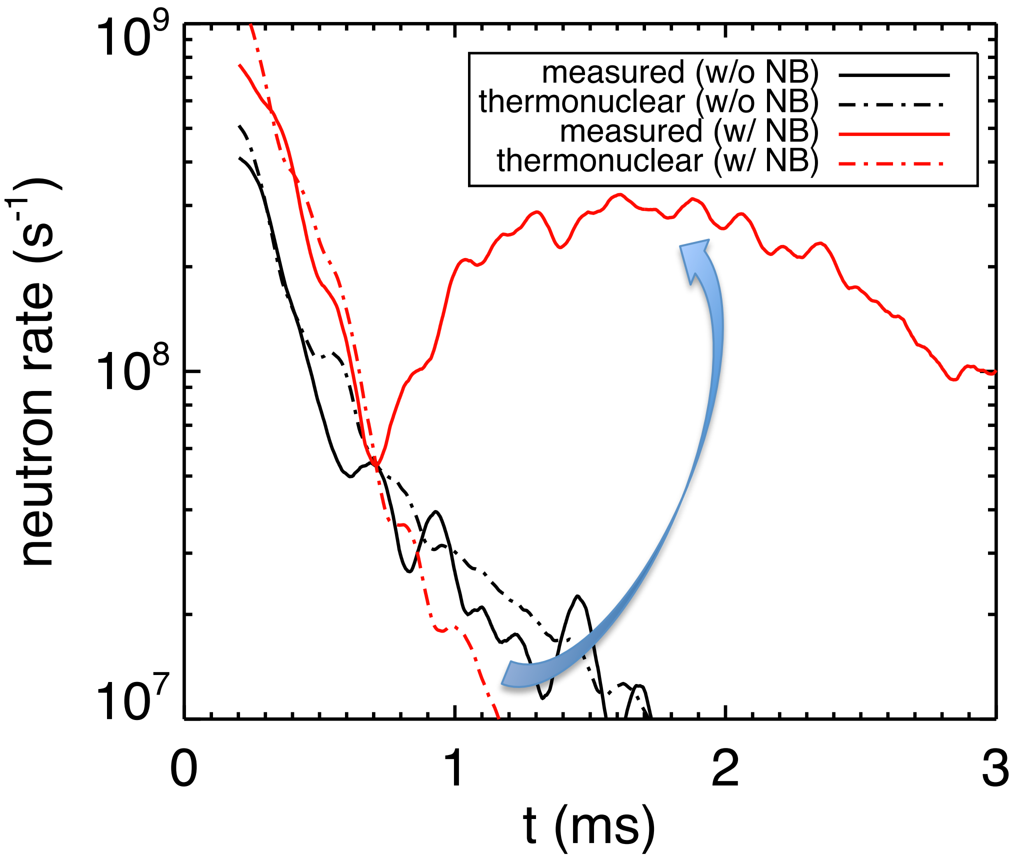
(2) increase confinement time dramatically

M. Binderbauer et. al., *PoP* 22.5 (2015): 056110

TAE C-2 observes 100 folds neutron yield over D-D thermonuclear yield due to the beam-plasma





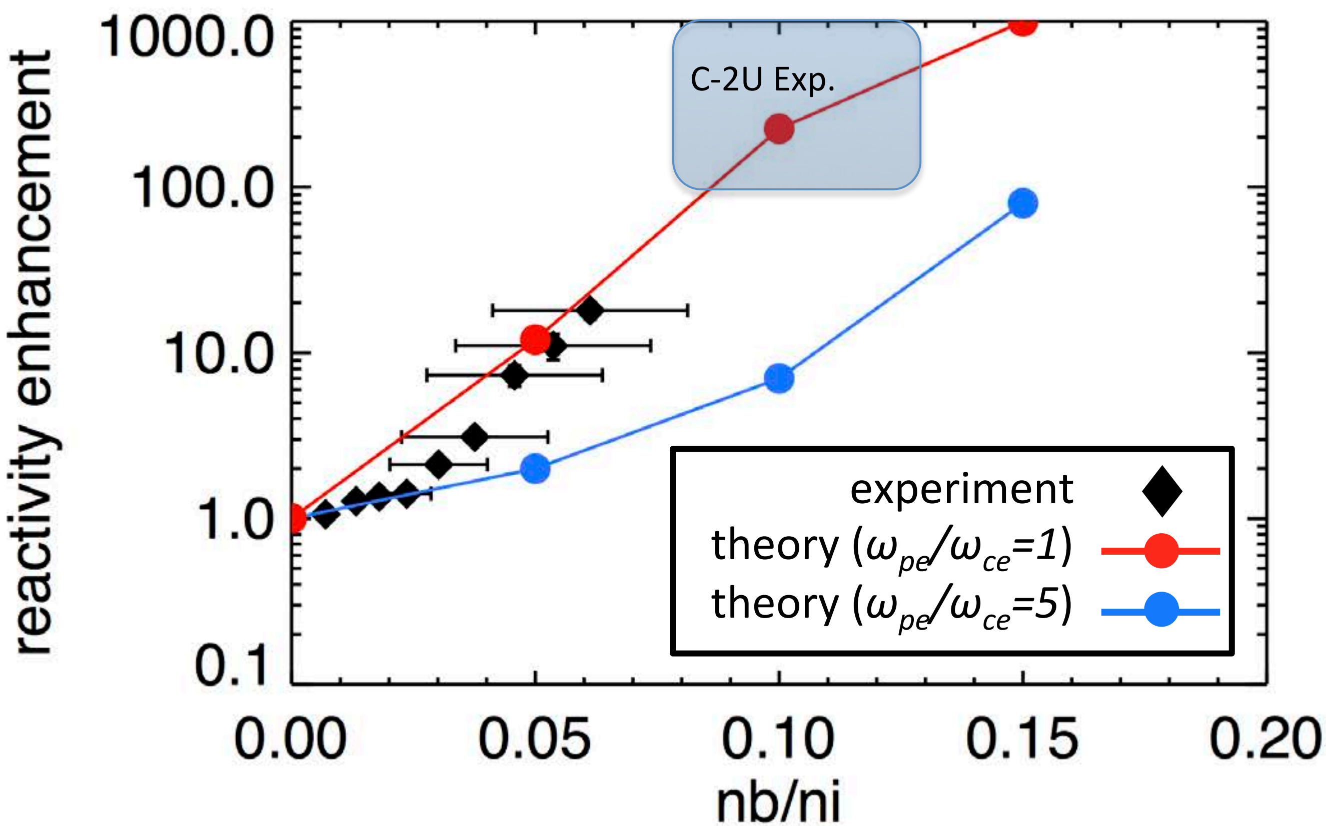


Courtesy: R. Magee

- Shot w/o hydrogen NB (black) has neutron yield consistent with thermonuclear calculation.
- Shot w/ hydrogen NB (red) has neutron yield above thermonuclear.

D-D fusion enhanced by 100 times or more by injected H-beam in TAE FRC :

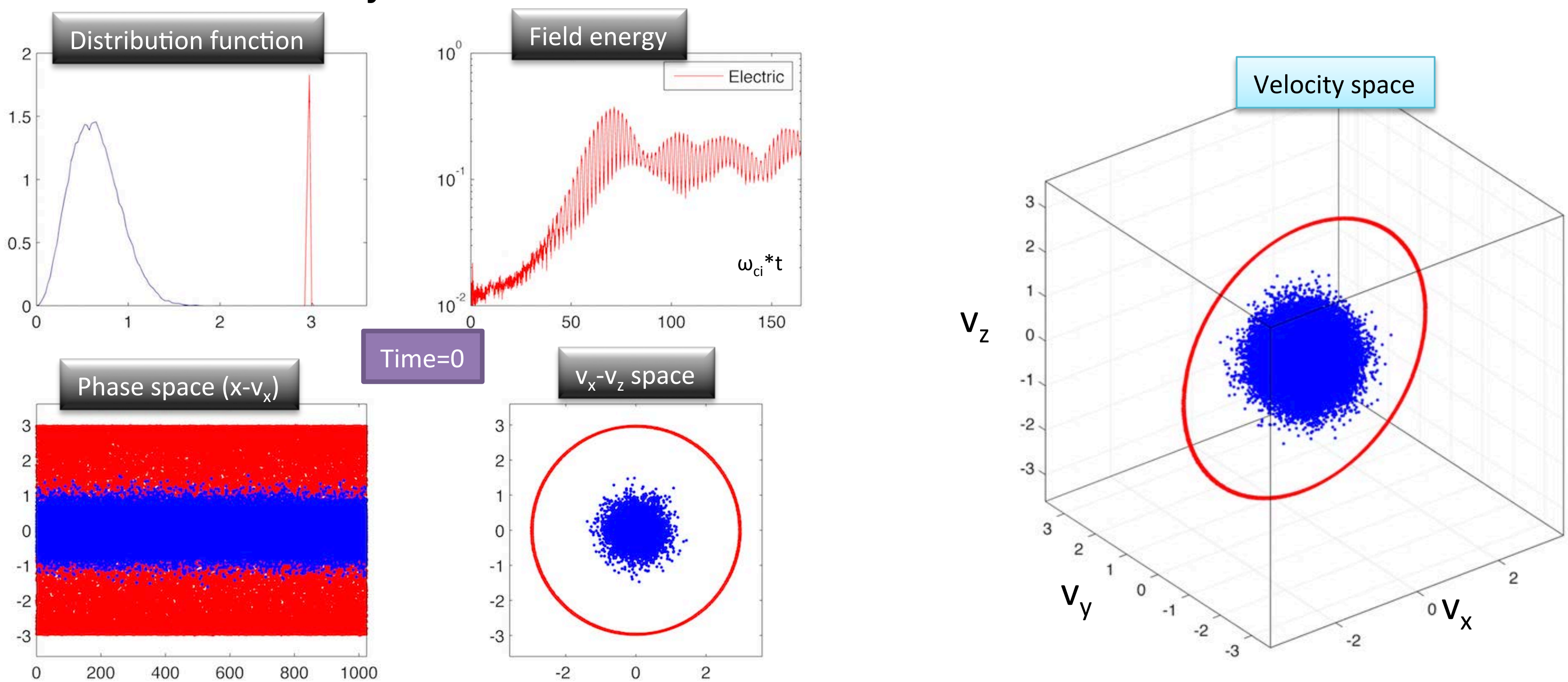
- TAE hydrogen beam-driven FRC deuteron plasma: fusion reactivity enhanced by 100 -1000 over thermonuclear expected value, when beam is sufficiently strong
- Beam-driven plasma instability (theory) can enhance fusion



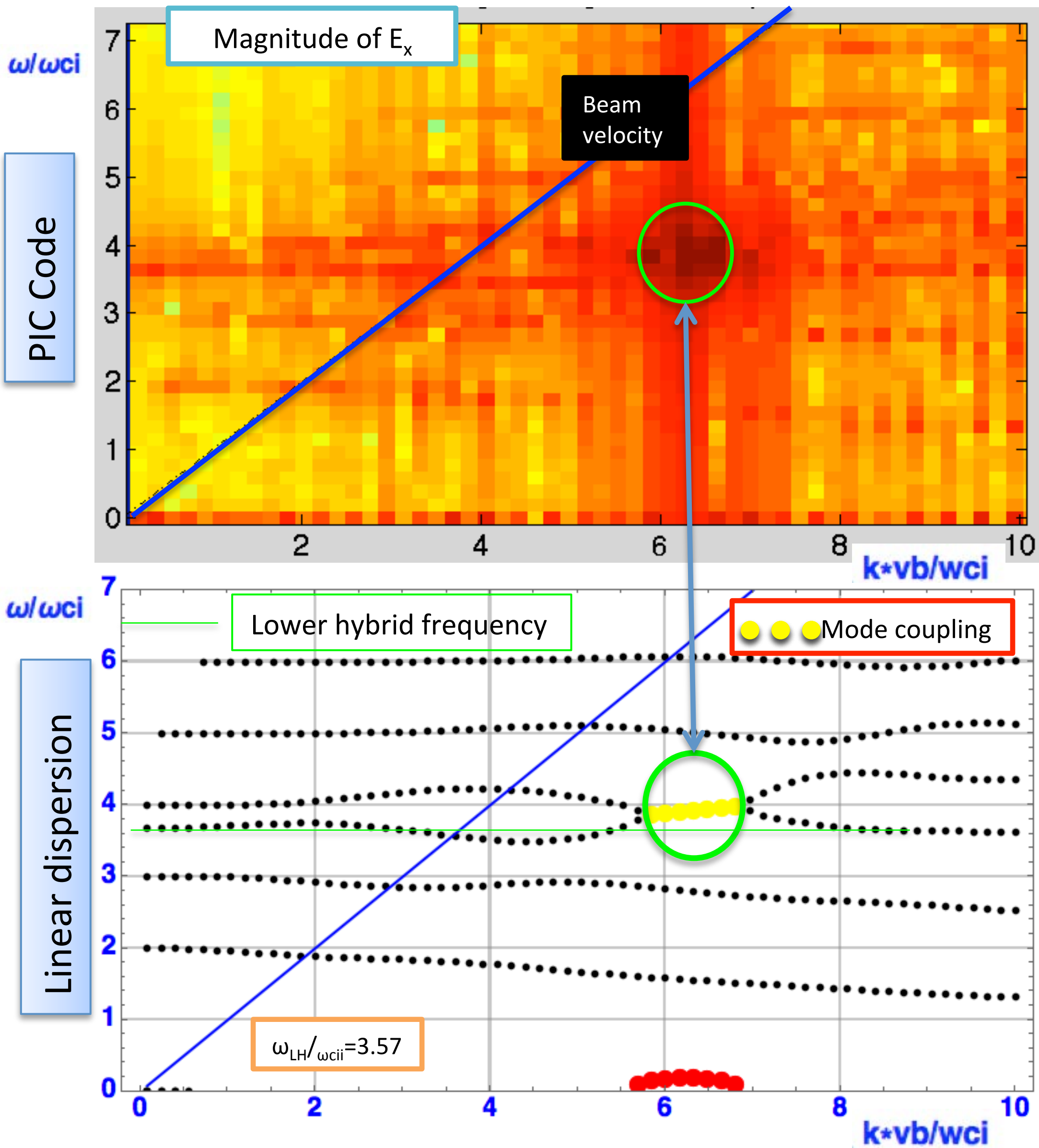
(Courtesy: A. Necas and R.Magee)

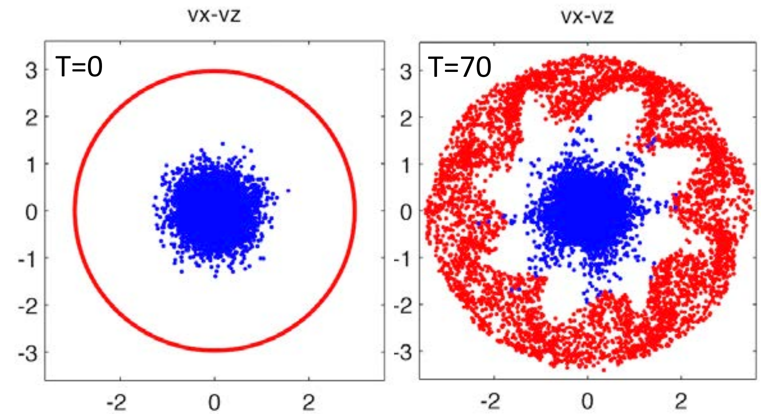
Plasma with perpendicular beam injection : $v_b \gg v_{th}$ (PIC set-up)

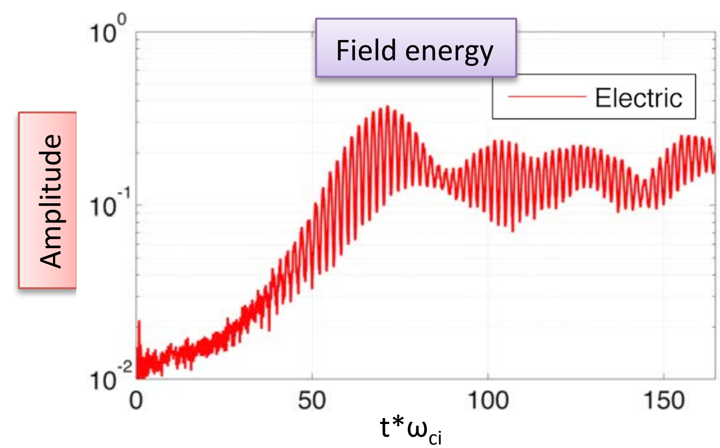
- 1D3V code: 1 spatial and 3 velocity dimensions.
- Lorentz & Maxwell equations.
- Fully electromagnetic, can be run in electrostatic mode.
- Beam is initiated as a ring in velocity space w/o thermal spread
- Ring-beam diffuses in velocity and couples to the plasma giving rise to instability
- Particle interaction only via electromagnetic fields
- Periodic boundary conditions



Beam-driven plasma in FRC is robust in the regime $v_b >> v_{th}$



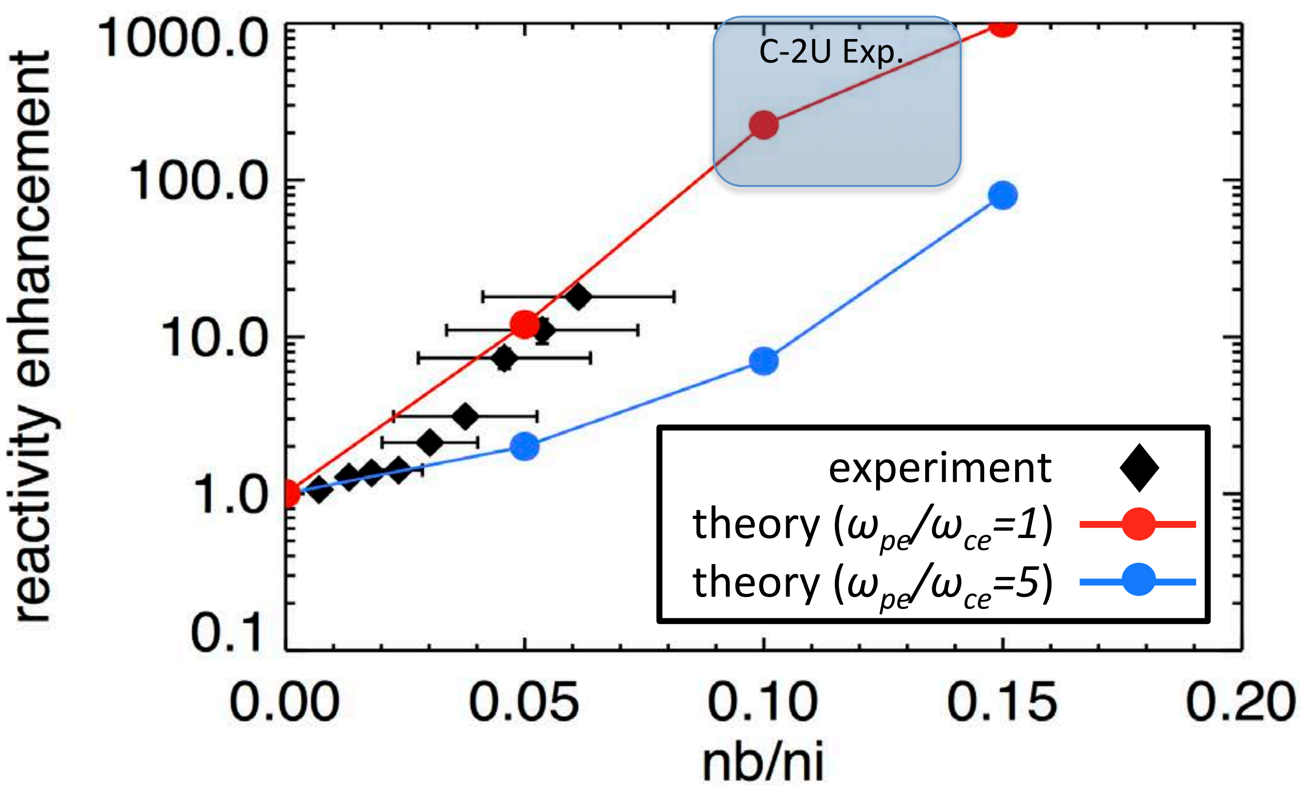




Lower hybrid wave interaction with 4^{th} Bernstein harmonics

Beam-driven plasma instability in FRC enhances fusion reactivity by 100 or more

- ❑ **TAE FRC observes 100-1000 fusion reactivity enhancement with beam over that without beam**
- ❑ **Our theory/simulation shows the beam-driven instability enhances fusion reactivity**
- ❑ **Hydrogen beam induces deuteron talk formation**

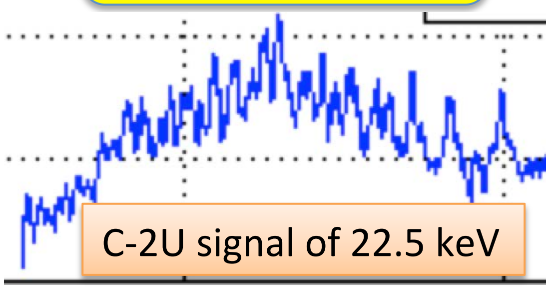


Courtesy: A. Necas and R.Magee

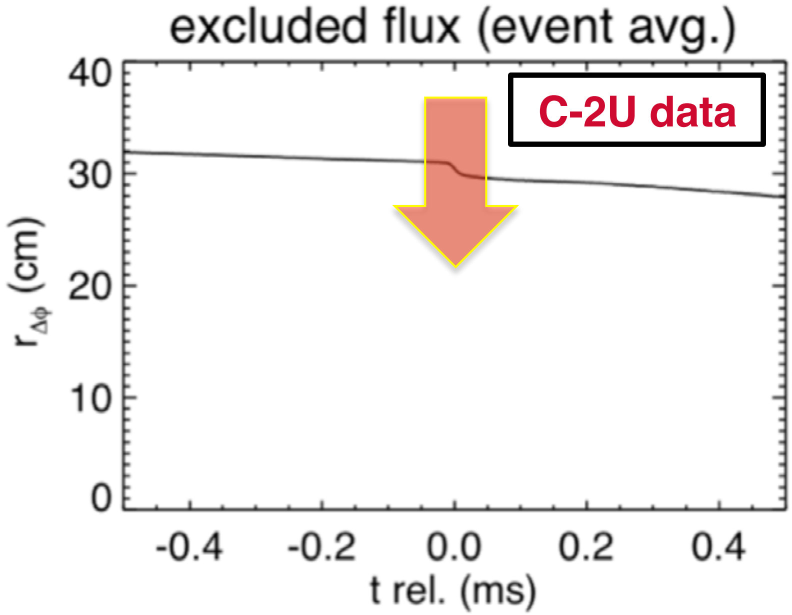
Anomalous neutron bursts synchronous with the step-like rupture of beam-driven FRC (C-2U)

Small decrease in $r_{\Delta\phi}$

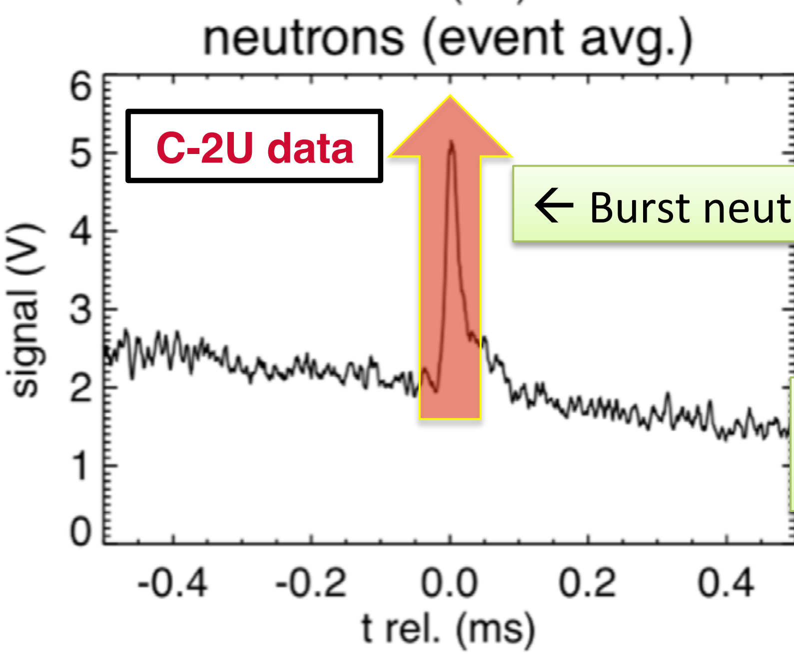
15 keV beam particle acceleration



Large change in neutron signal



Needs beam-driven instability to catalyze enhanced neutron bursts



← Burst neutron yield

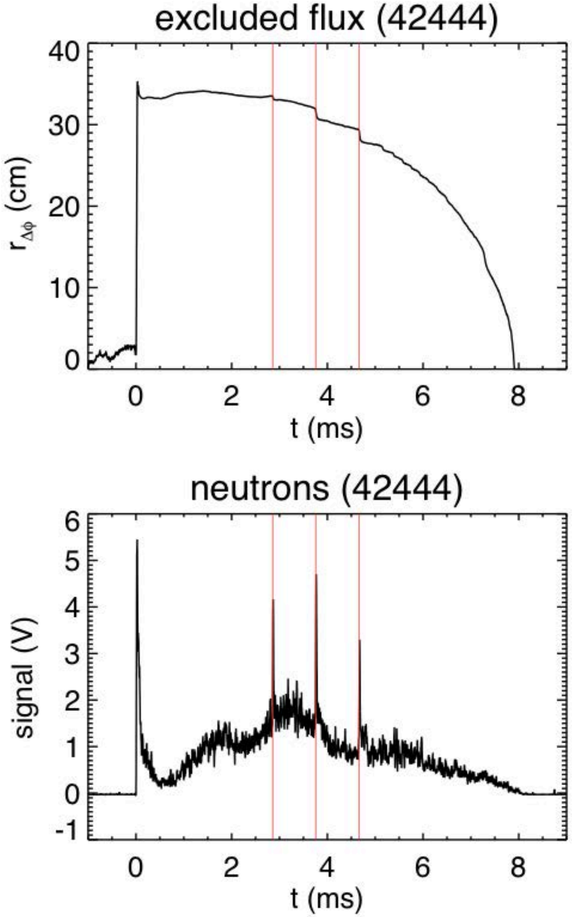
←-Baseline anomalous neutron yield

Courtesy: R. Magee

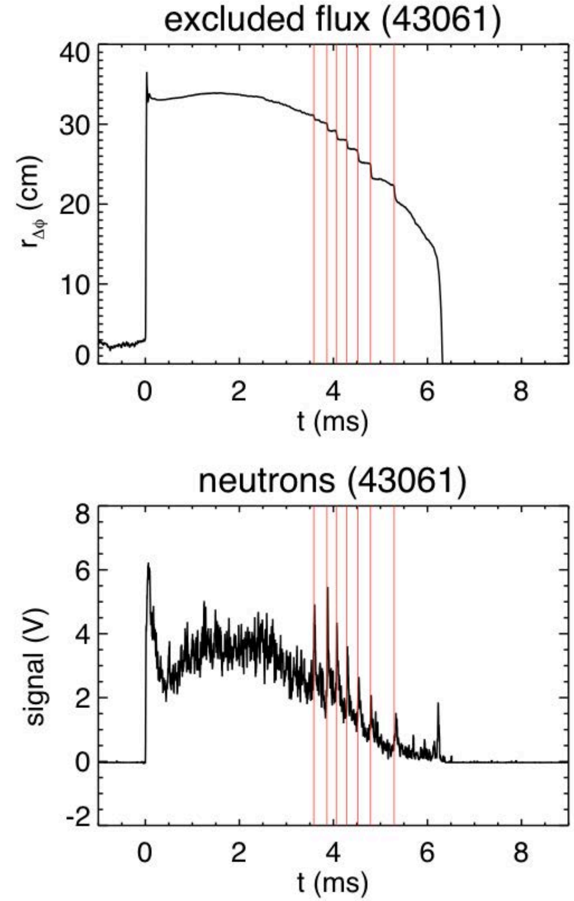
New phenomenology in strongly beam driven FRC (C-2U)

Neutron bursts coincide with staircase phenomena

2% D in the beam



Hydrogen beam mode staircase

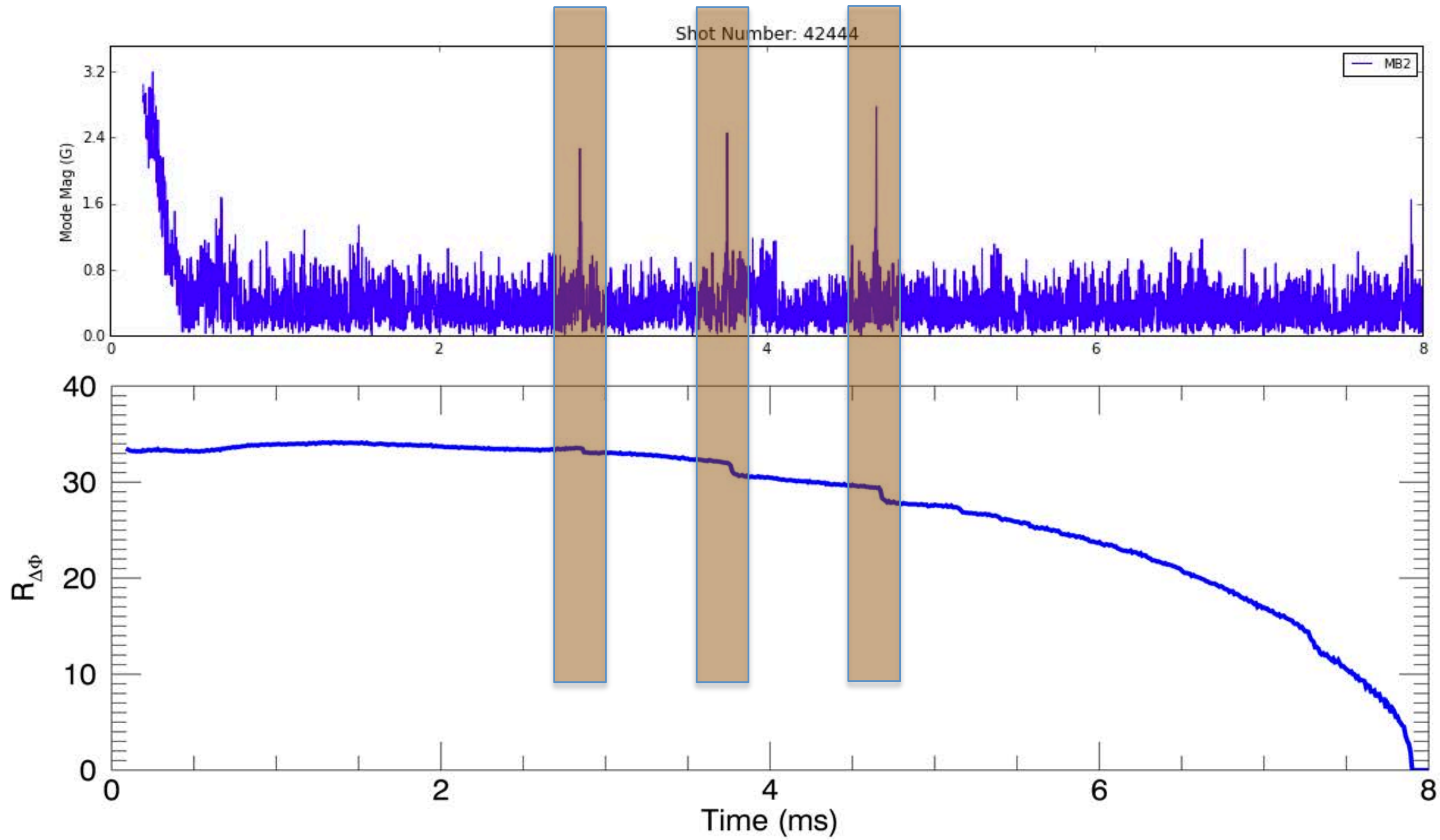


Courtesy: R. Magee

Pure hydrogen beam destabilizes the beam instability (in agreement with analysis)

Magnetic bursts synchronize with the stair-steps

Magnetosonic instability (of very fast buildup) synchronous with the stair-steps



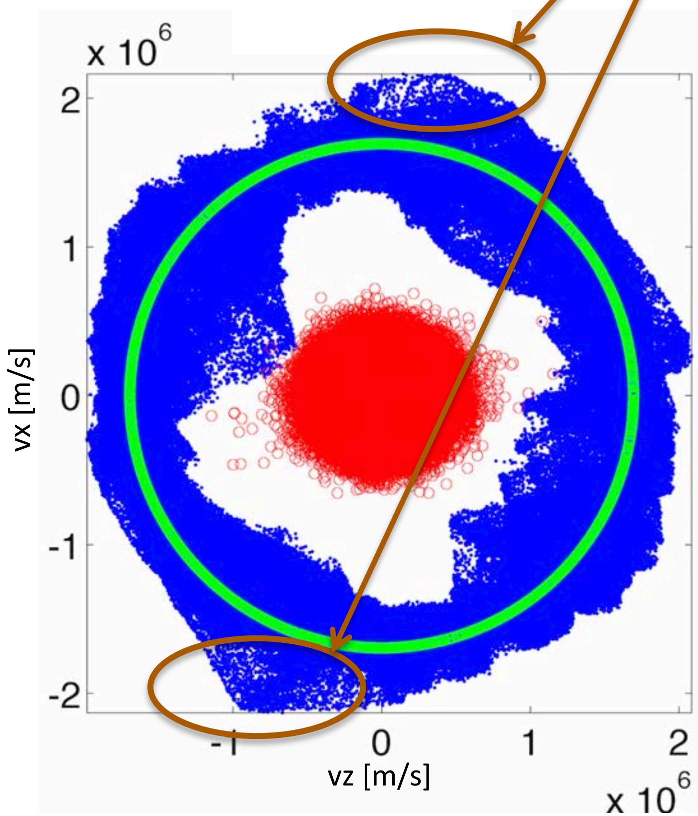
Courtesy: T. Roche

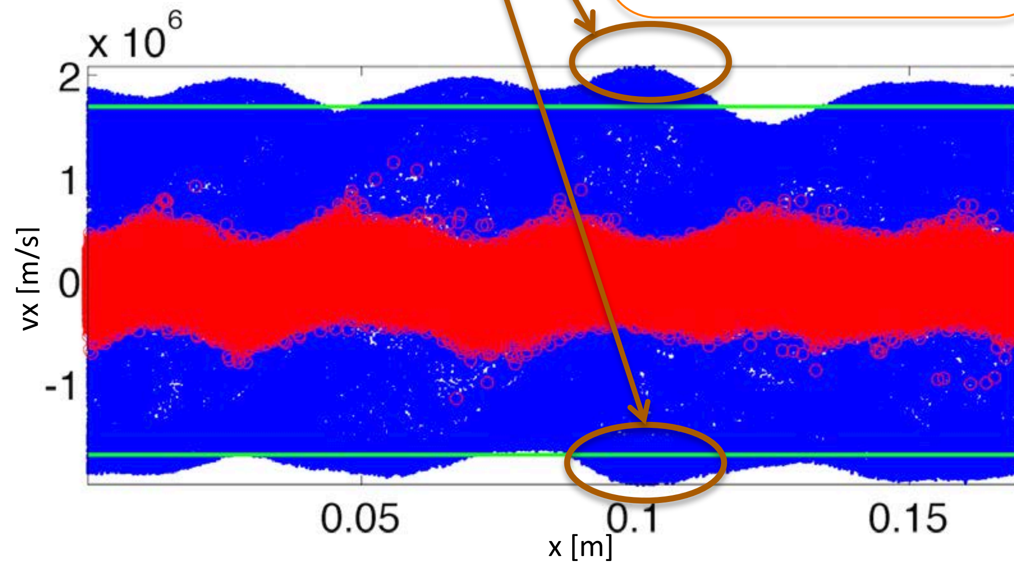
Finger formation in beam causes bursts of plasma rupture

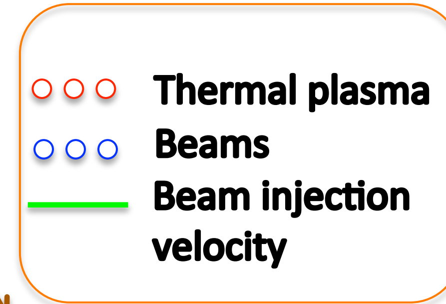
Violation of local pressure equilibrium

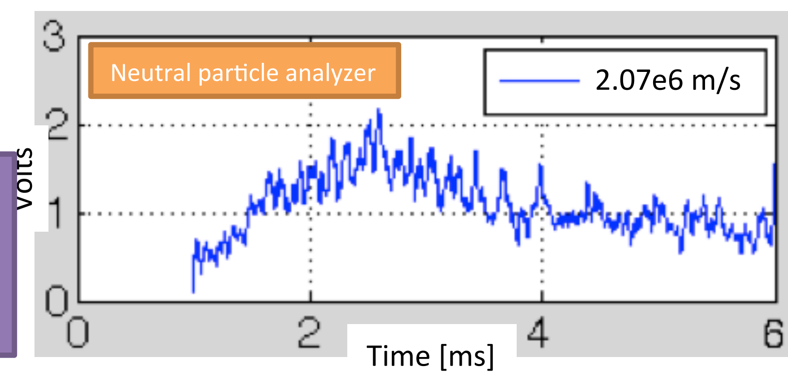
Field line rupture

Loss of beam particles



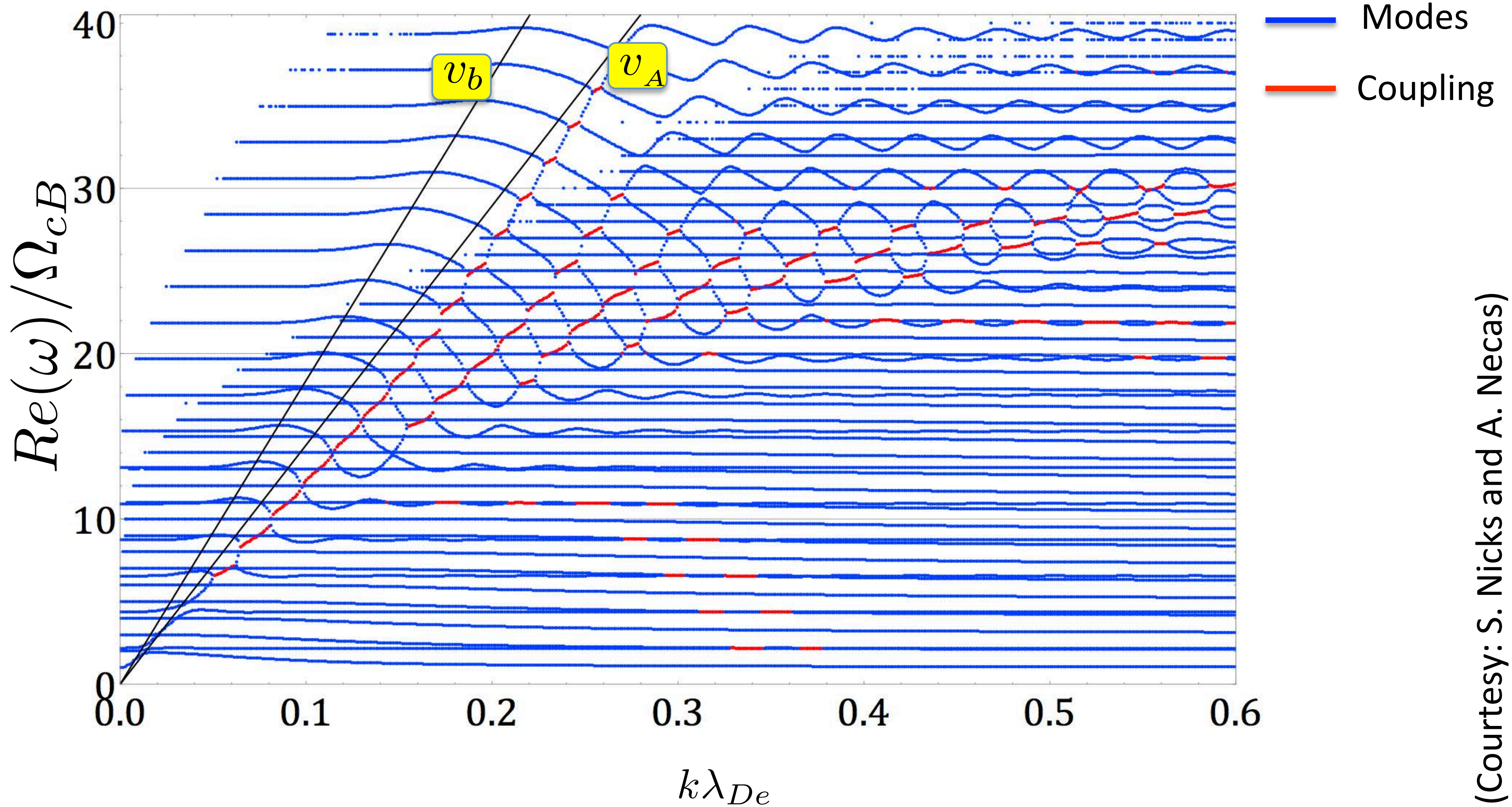






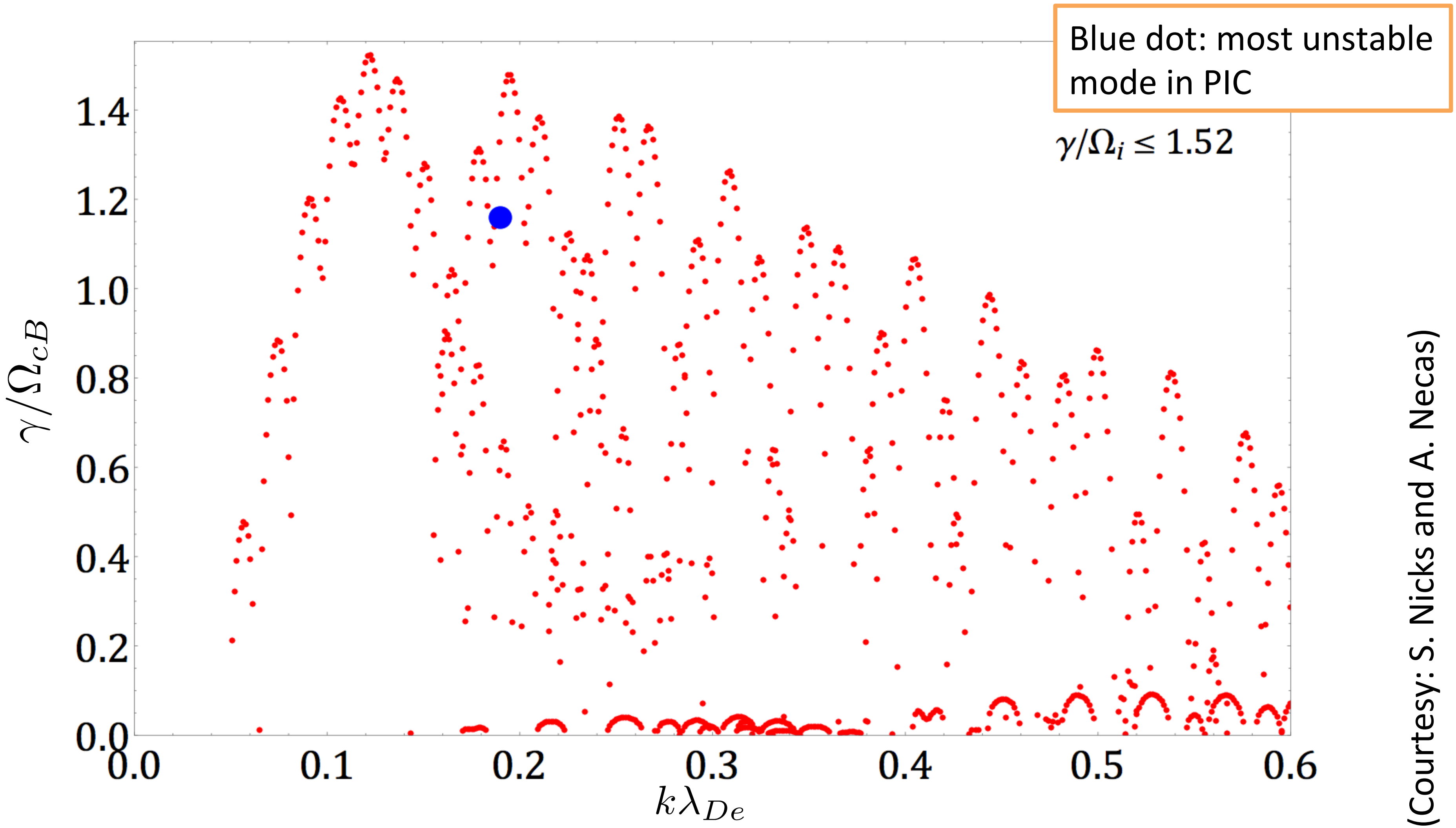
- Beam ions are accelerated due to collective effects
- Could result in rapture of beam component – longest fingers
- Rise several cyclotron periods
- Rapture – radially extended as beam particles

Aneutronic fuel plasma p-B^{11}: beam-driven plasma instability (p: beam, B^{11}: plasma)



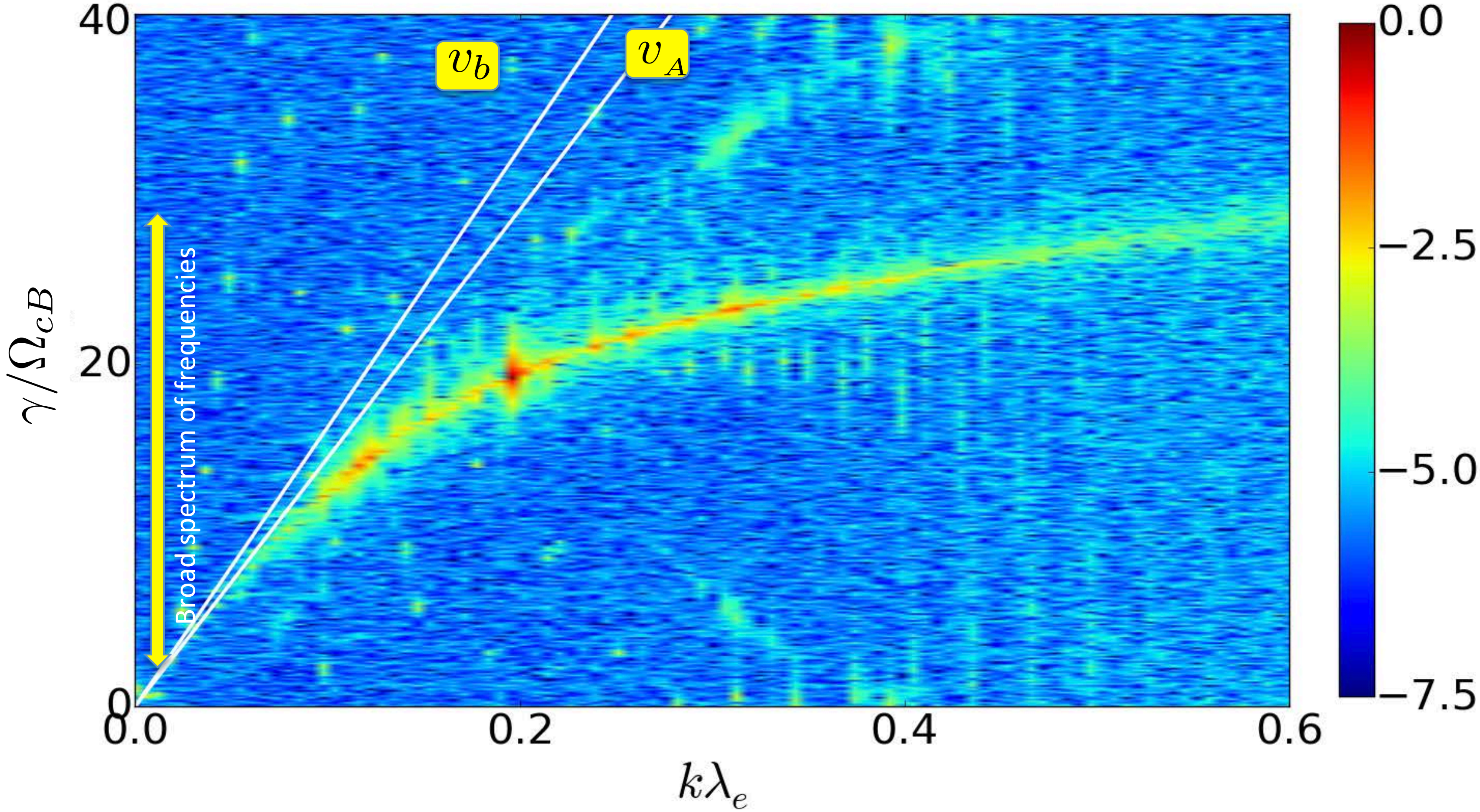
(Courtesy: S. Nicks and A. Necas)

Beam-driven plasma growth rate (Theory/PIC) : p-B[11]



(Courtesy: S. Nicks and A. Necas)

PIC simulation of beam-driven instability in p-B^{11}: Magnetosonic branch resonating with ion Bernstein modes



(Courtesy: S. Nicks and A. Necas)

The "High phase-velocity conjecture": $v_\phi >> v_{th}$

Saturation: $E = \frac{m_e \omega v_\phi}{e}$

LWFA

$$E = \frac{m_e \omega_p c}{e}$$

Tajima-Dawson [T-D] Field

Relativistic coherence*

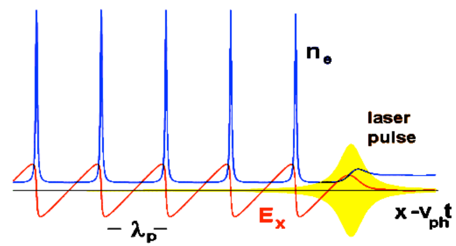
$$E = \frac{m_e \omega_p c a_0 \gamma_\phi}{e}$$

*T. Tajima, PJAS, (2010)

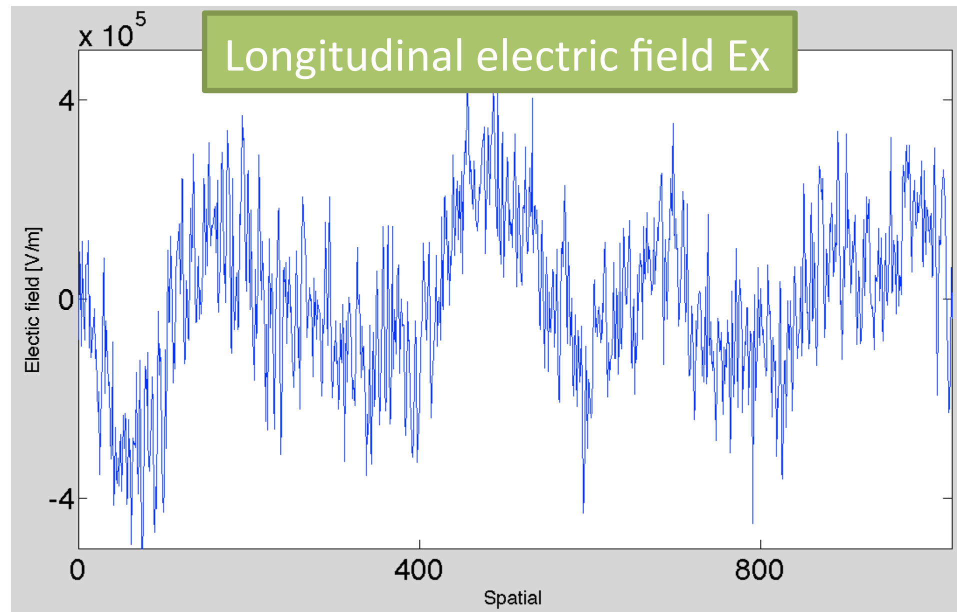
TAE

$$E = \frac{m_D n \omega_{cp} v_b}{e} = n * 10^5 \text{ V/m}$$

$$\text{with } n = 3 - 4$$



vs.



PIC simulation E field magnitude is equivalent to T-D field

Conclusions

- Plasma sustains beam-driven wakefields with robust fields to accelerate particles---high phase velocity = the key
- Plasma remains serene and robust while this immense wakefield generation

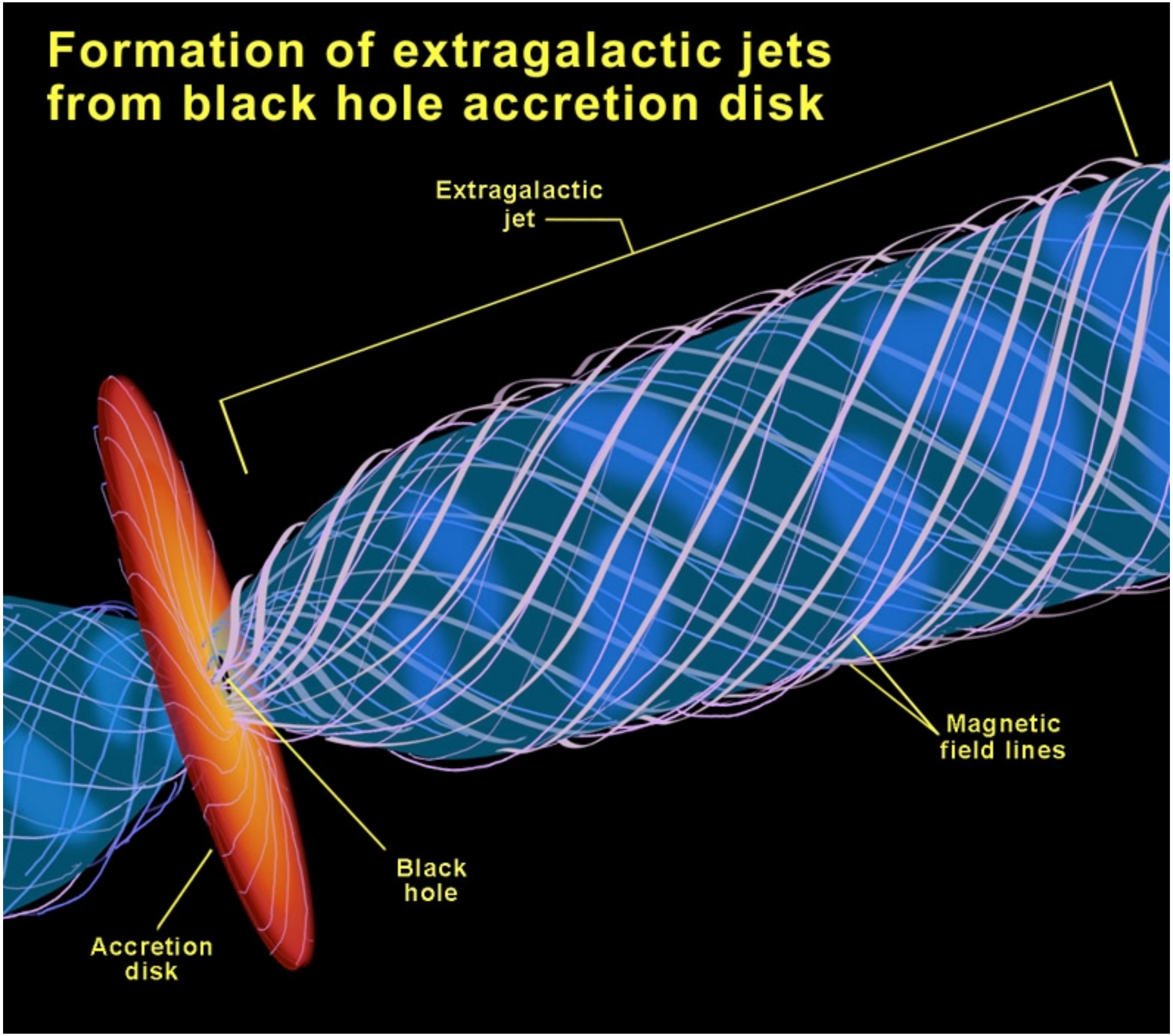
- Accelerated beam driven plasma (FRC) stabilizes gross instabilities and improves confinement
- Beam-driven FRC can enhances fusion reactivity
- FRC observes mini-bursts in beam-driven FRC that may be related the above beam-plasma instability, with the plasma still remains robust

- When the phase velocity is high, such a wave becomes robust, while still keeping the bulk plasma robustly intact

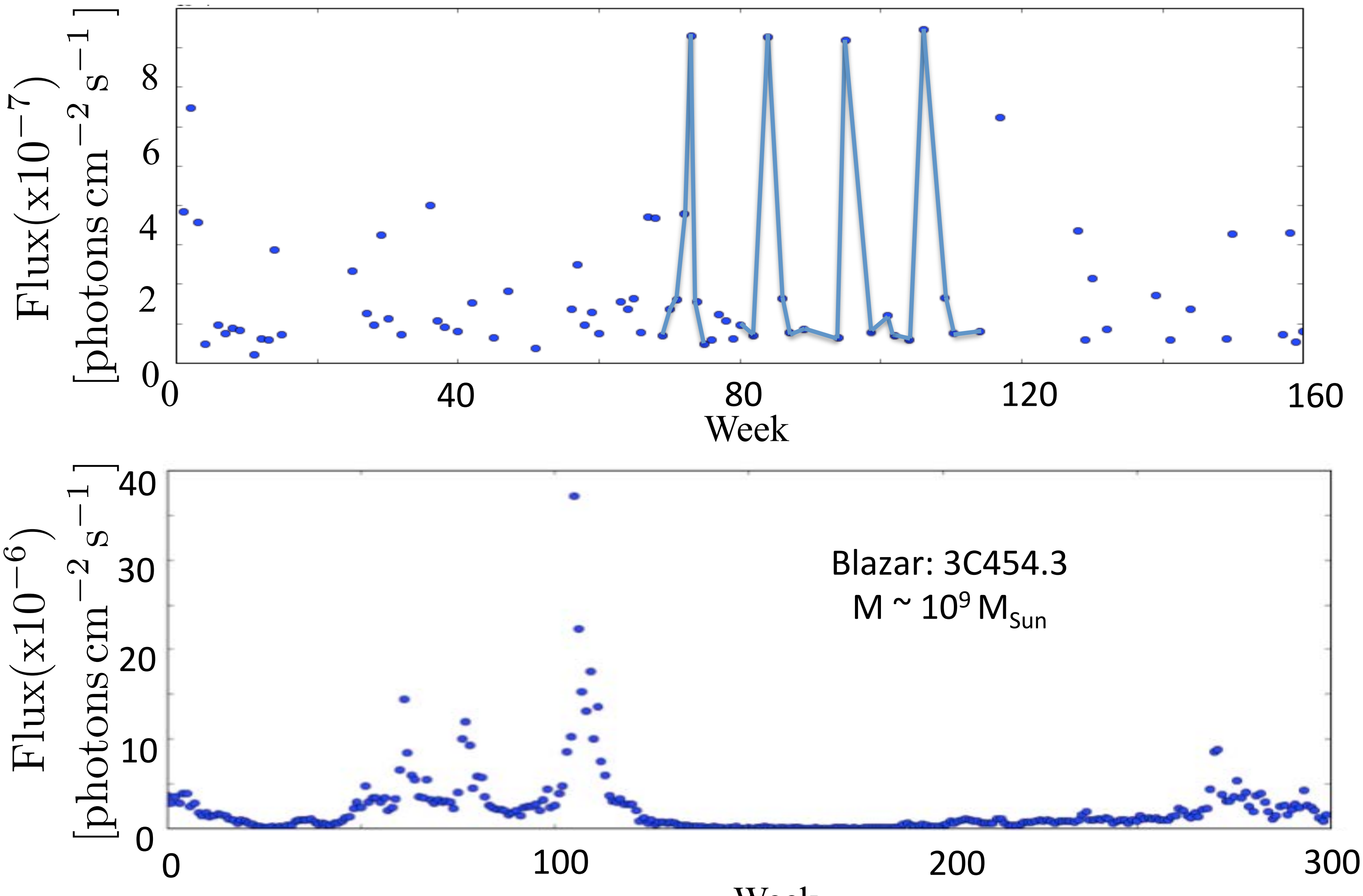
Extra slides

Analogous phenomenon in astrophysics: accretion disk episodic disruption

cf: FRC mini-burst episodes in TAE FRC

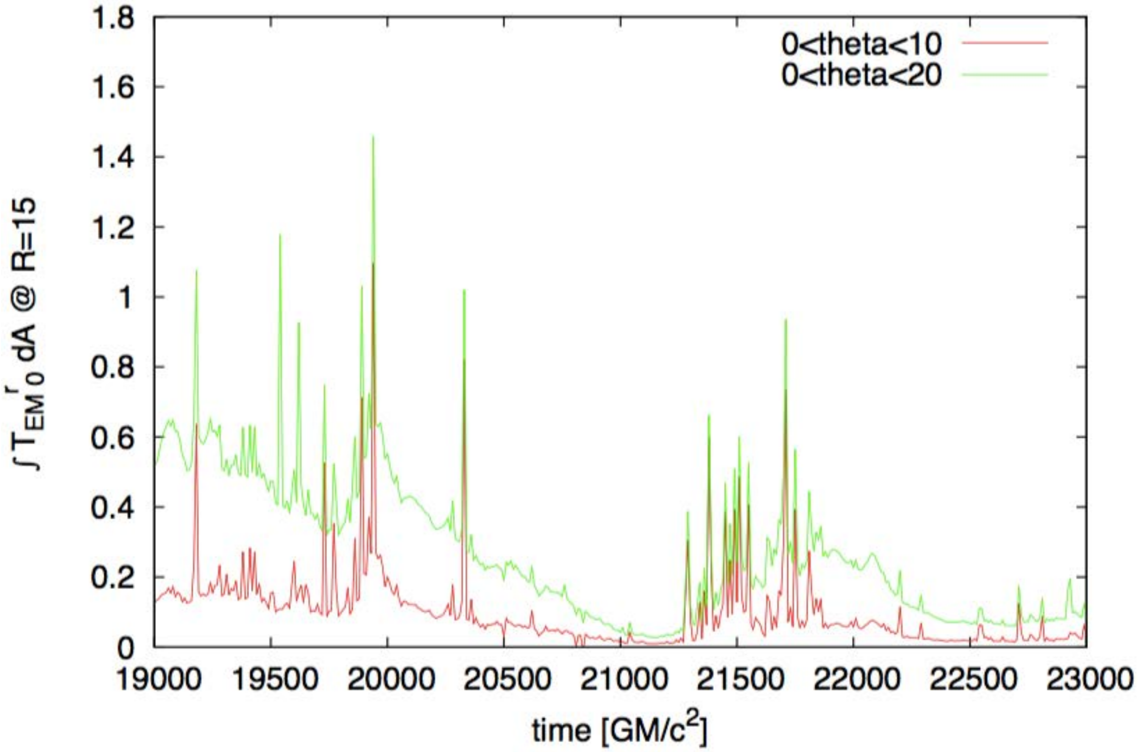

Formation of extragalactic jets
from black hole accretion disk
Extragalactic
jet
Magnetic
field lines
Black
hole
Accretion
disk

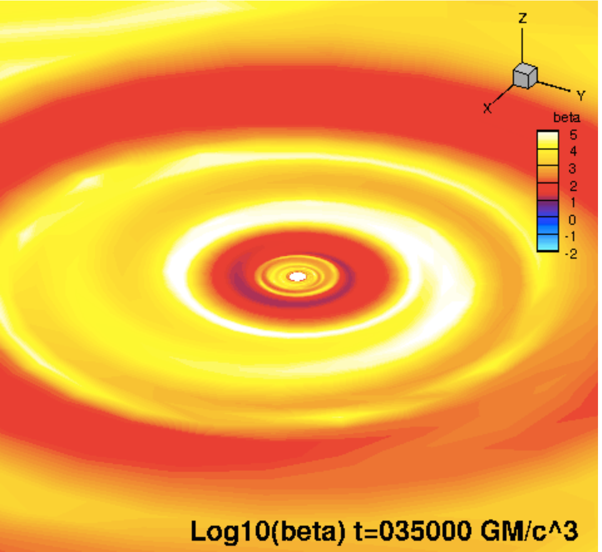
Blazar shows anti-correlation between γ burst flux and spectral index



Abazajian and Canac

Relativistic MHD simulation: episodic recurrence of bursts in accretion disk





A. Mizuta and T. Ebisuzaki

by A. Mizuta