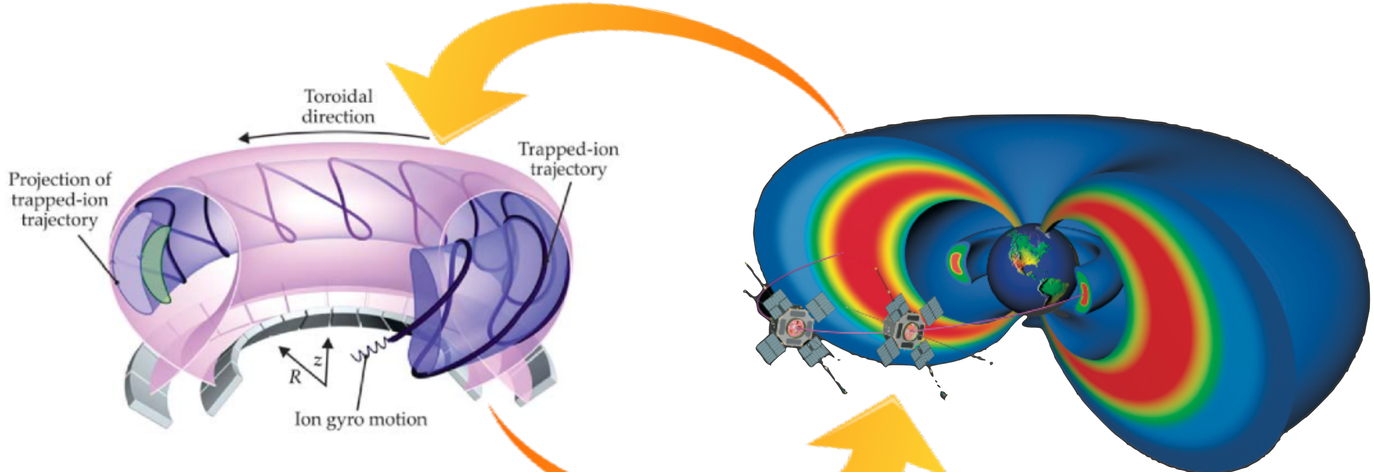
Advancements of Basic Plasma Physics enabling Progress in Magnetic Fusion Energy

Mike Mauel
Columbia University

Historical Comment

Exploring Links between
Magnetospheric Physics and Laboratory Fusion Physics

Three Physics Challenges for the Future



(Credit: EUROfusion)

(Credit: NASA/Goddard)

20TH ANNIVERSARY WORKSHOP FOR THE NSF/DOE PARTNERSHIP IN
BASIC PLASMA SCIENCE AND ENGINEERING, January, 2017

Historical Comment (1996)

Advance Plasma Science:

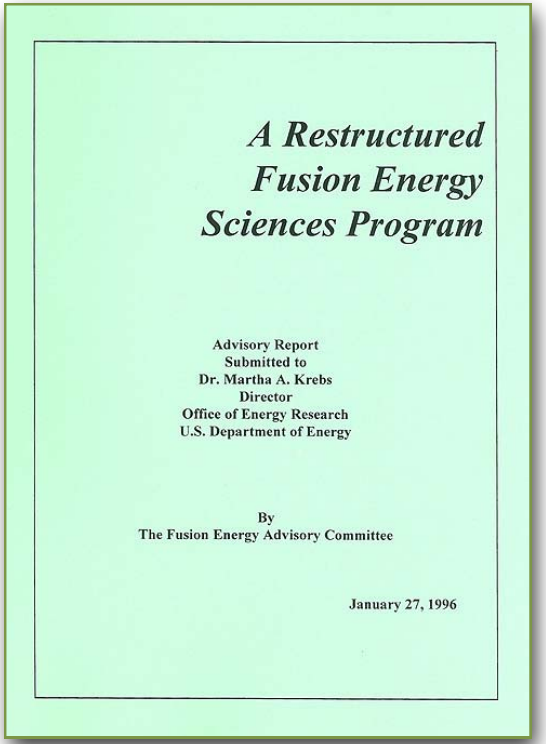
"Plasma science is a cornerstone of the scientific infrastructure of the country, and is a prerequisite competency to pursue many national science and technology goals, ….

Fusion Energy is the Grand Challenge of Plasma Science and is the largest driver for the intellectual development of Plasma Science.

The people tackling the scientific and technological issues involved [with plasma research] have created a wellspring of knowledge and capability which is a national asset of enduring value.

As the centerpiece of the nation's plasma science infrastructure, FES must explicitly move to broaden it's intellectual and institutional base in fundamental plasma science and attendant enabling technologies, preferably in partnership with other agencies."

FEAC (1996)


A Restructured Fusion Energy Sciences Program

Advisory Report
Submitted to
Dr. Martha A. Krebs
Director
Office of Energy Research
U.S. Department of Energy

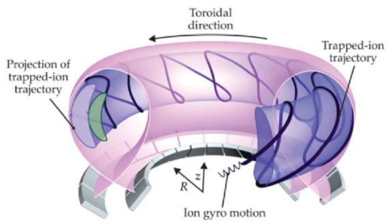
By
The Fusion Energy Advisory Committee

January 27, 1996

Personal Comment (Today)

- Fusion Energy is ***still*** the ***Grand Challenge of Plasma Science***
- Today, progress in fusion research requires sophisticated, and costly, experiments that ***need the highest levels of plasma science*** …
  - Confidence in the techniques to heat and produce plasma and to control instabilities and turbulence
  - Campaign planning to gain highest scientific value requires precise high-resolution measurement and whole-plasma simulation and prediction
  - New technologies and ideas for the plasma heat flux of fusion experiments that may approach the heat flux found on surface of sun
  - …
- Fusion research ***still needs*** the benefits from a broad intellectual base for plasma science and technology linking fusion research ⇔ related fields.

Fusion and Magnetospheric Physics are Linked



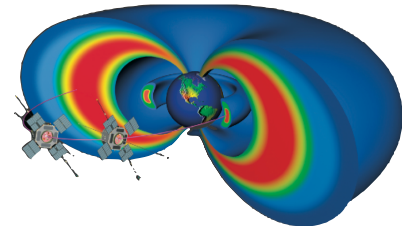
- Strongly magnetized plasma torus
- Dense thermal plasma (*i.e.* fusion fuel)

  Waves, turbulence, and confinement are the critical metrics for fusion

- Fast energetic ions from fusion reactions (*e.g.* 3.5 MeV alpha-particles)

  Fast ions orbit every 50 μsec and must be confined for 100's of orbits

- When instabilities resonate with energetic particles, they will damage the first wall and prevent sustained fusion energy production.



- Strongly magnetized plasma torus
- Dense inner plasmasphere

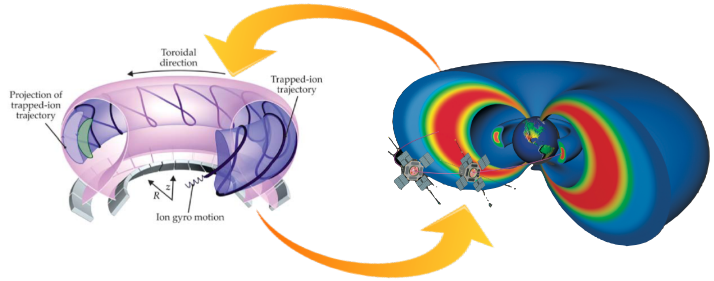
  Waves, disturbances from rotation and solar wind are critical for space weather

- Radiation belts contain MeV ions and electrons

  Fast particles orbit every 50 min and can persist for days

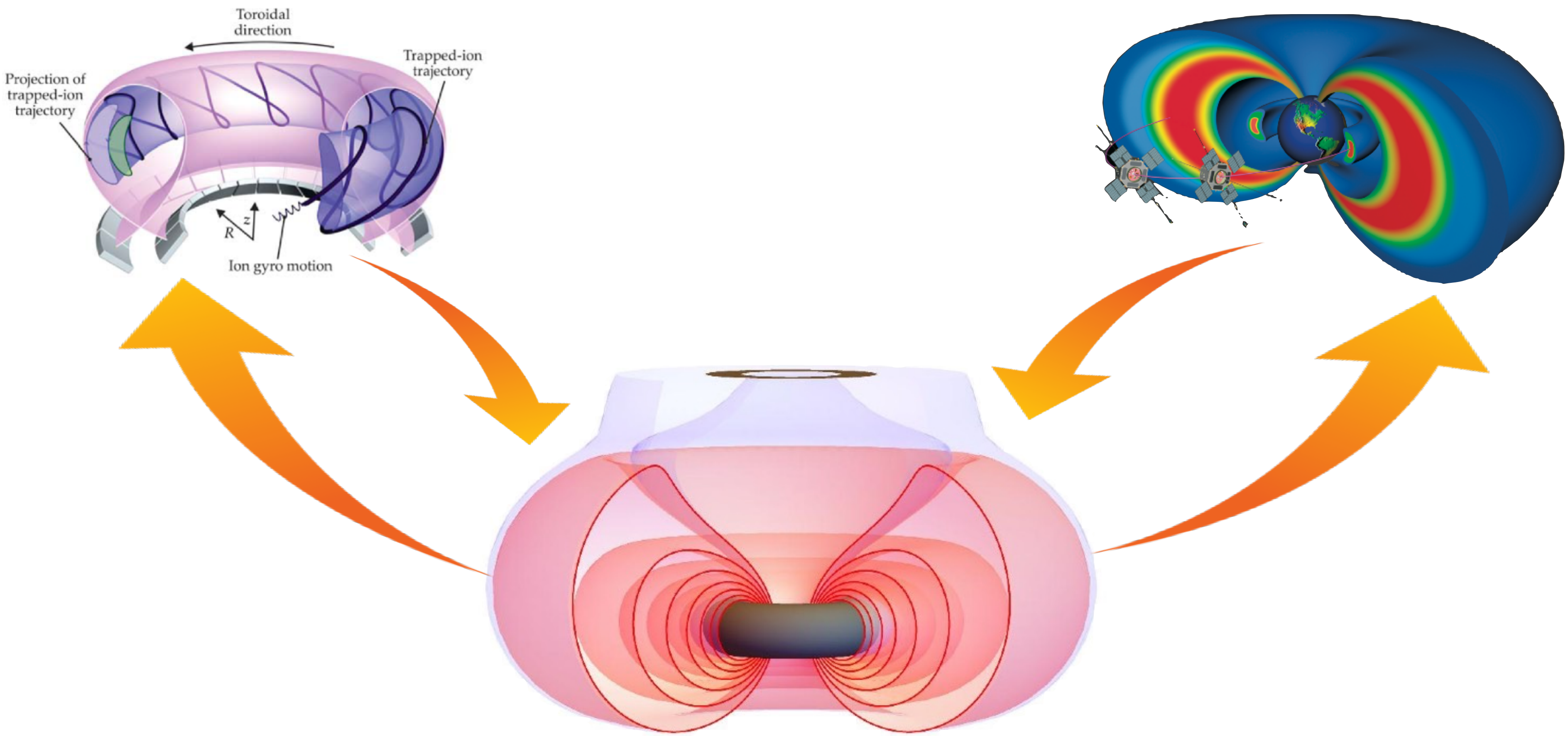
- High-energy protons leave ionization tracks that upset space electronics and relativistic electrons can be devastating to spacecraft.

Common Scientific Questions



- How do waves and fluctuations **energize** particles?
- How do energetic particles **excite** waves and fluctuations?
- How does the **strong magnetic field** influence motion of plasma energy, momentum, and particle number?
- How does the **field-line geometry** within the magnetic torus influence plasma stability and dynamics?
- Can laboratory study of magnetized plasma help to validate predictive models for **space weather**?
- Can understanding magnetospheric plasma help to scientists achieve **the fusion grand challenge**?

Bringing the Physics of Magnetosphere to the Laboratory



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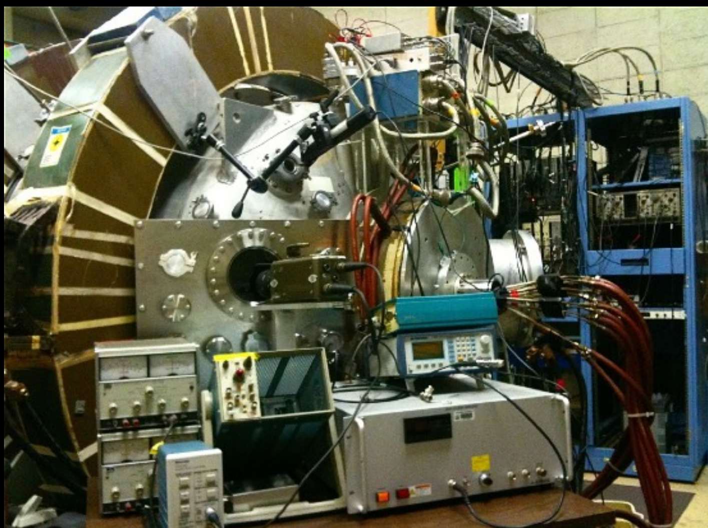
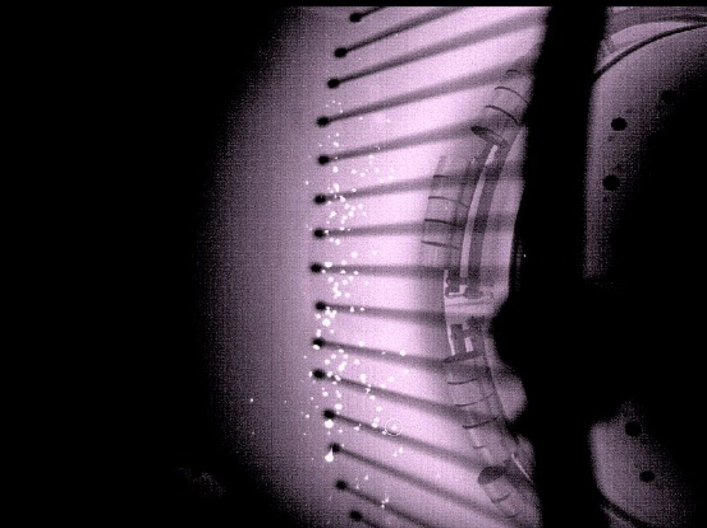
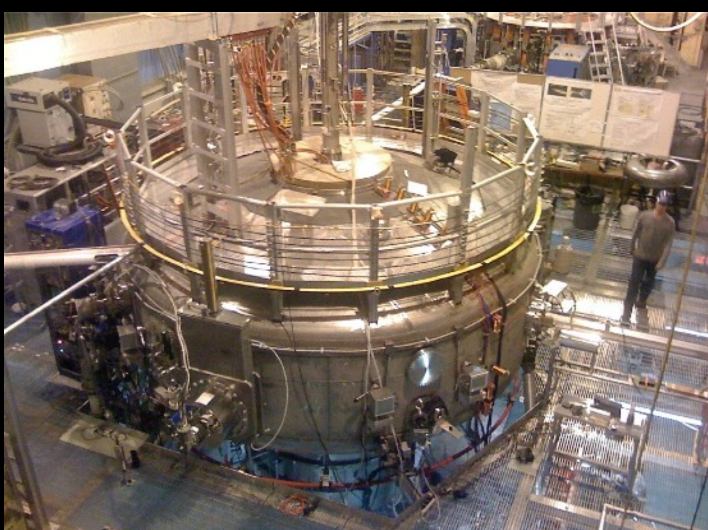
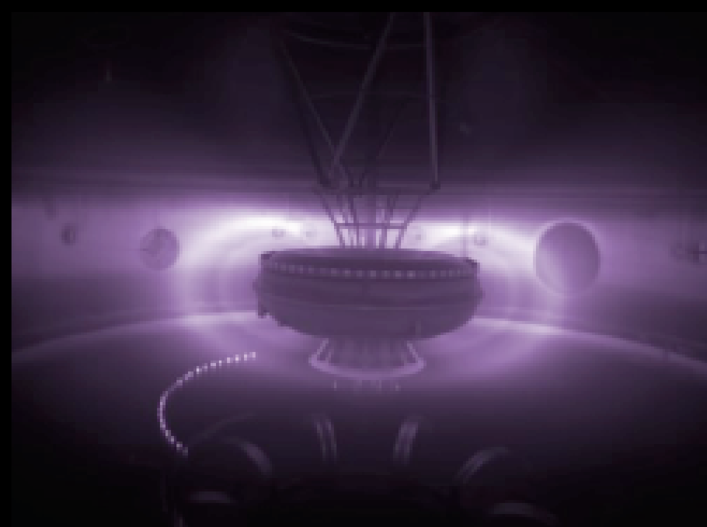
Laboratory Magnetospheres

Large space chambers with small *strong* magnets

(plus Japan, Germany, India)


NSF/DOE Partnership Allowed Students to *Discover* Many Fundamental Processes

- Energetic particle instabilities and drift-resonant transport
- Low-frequency turbulence, turbulent cascades, and transport
- "Whole-plasma," nonlinear, bounce-averaged, drift-kinetic simulation reproduces both ***energetic particle modes*** and ***low-frequency turbulent cascades***
- Turbulent "profile self-organization" and the "curvature" pinch
- Centrifugal instability at high-speed plasma rotation
- Whole-plasma imaging of turbulence and "swarm" multi-point measurements of plasma dynamics
- Dynamics of an "artificial moon" with fast mass injection
- Controlling turbulent convection with an "artificial ionosphere"

Each study involved undergraduate students, were lead by doctoral students, and gave opportunities to explore new physics relevant to both space and fusion science.

Acknowledging the Pioneers

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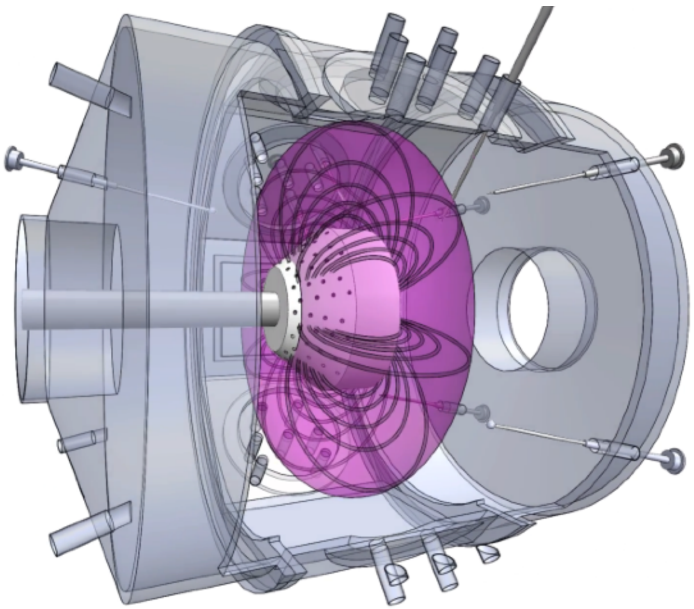
Laboratory Magnetospheres are Simple and Flexible



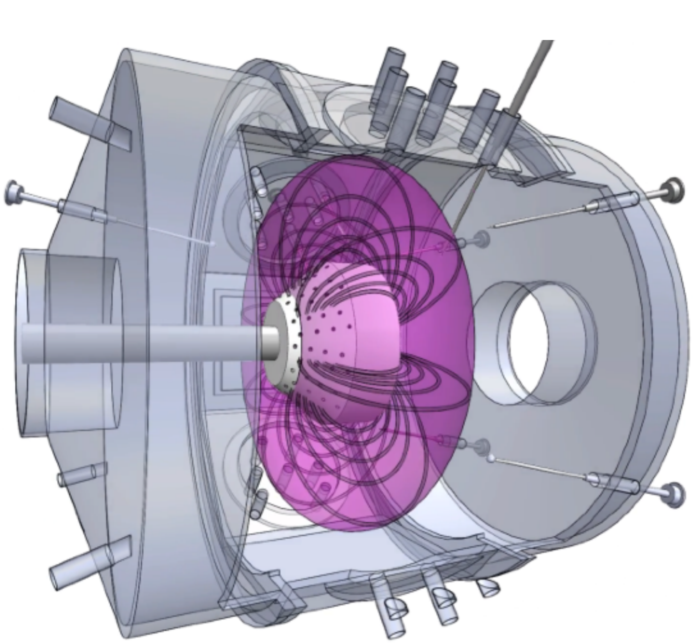
Simple…

- Large plasma with small magnet
- Apply heat and inject gas
- Observe steady-state transport of heat & particles

Flexible…

- Heat electrons at **low plasma density**
  - Energetic particle pressure dominates over thermal plasma
  - Excite **energetic particle modes**
- Heat plasma at **high plasma density**
  - Thermal plasma pressure dominates
  - Excite interchange/entropy mode **turbulence**

Laboratory Magnetospheres are Simple and Flexible



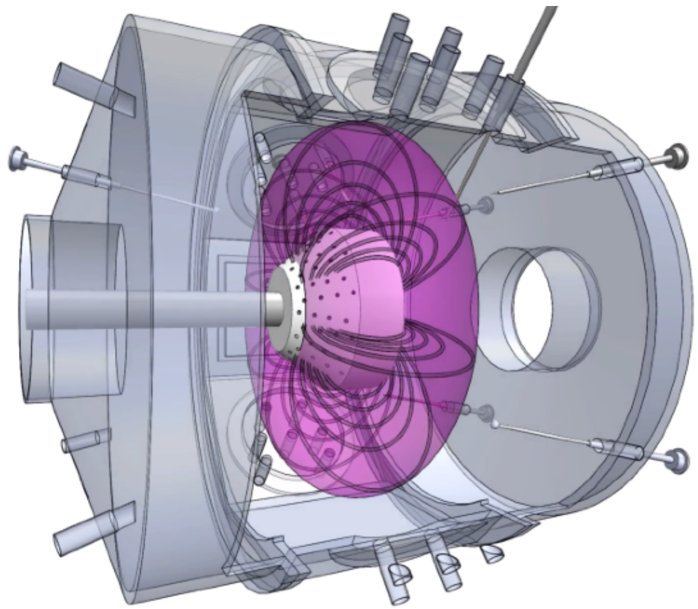
Flexible…

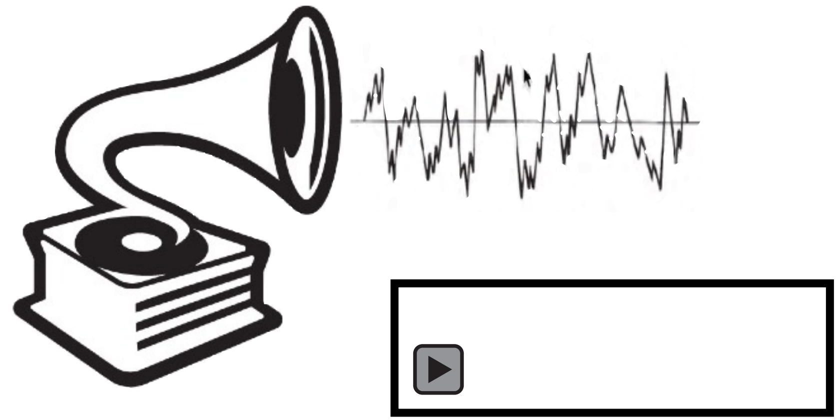
- Heat electrons at **low plasma density**
  - Energetic particle pressure dominates over thermal plasma
  - Excite **energetic particle modes**

"Chirping" Nonlinear Wave Resonances with Energetic Particles

Instability saturates *coherently* and slowly convects energetic particles around buoyant drift-resonant phase-space "bubbles"

Laboratory Magnetospheres are Simple and Flexible





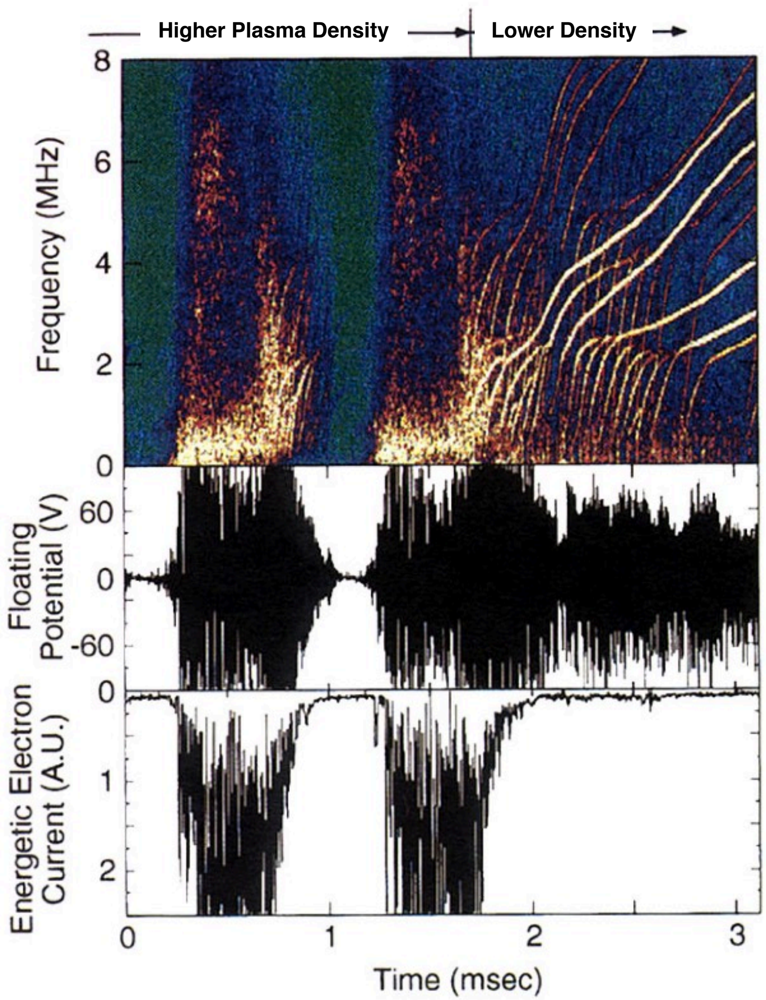
Flexible…

Turbulent Cascade and Diffusion of Magnetized Plasma Filaments

Instability saturates *incoherently* with spectrum of interacting chaotic modes driving "bursty" radial transport of plasma-filled flux tubes

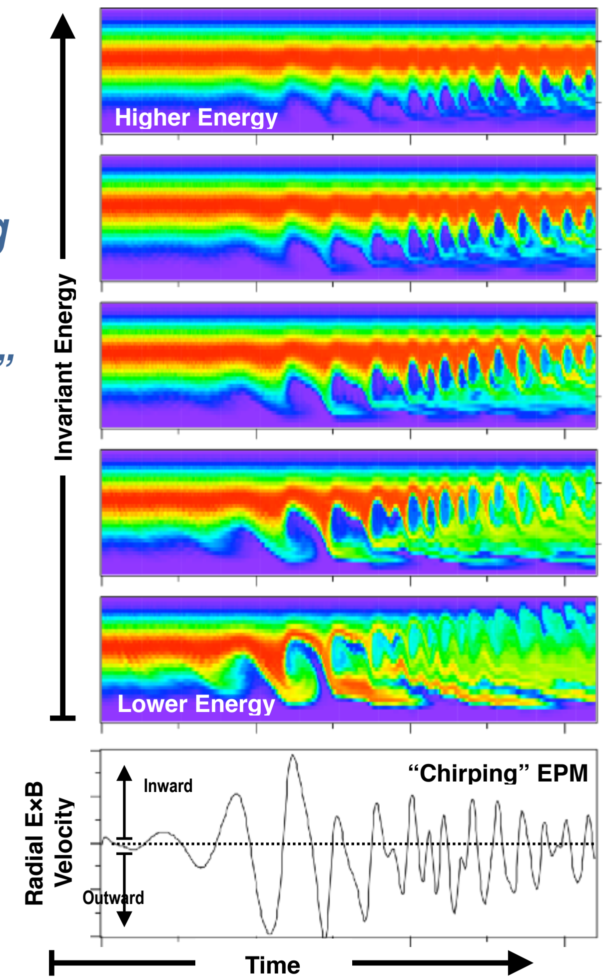
- Heat plasma at **high plasma density**
  - Thermal plasma pressure dominates
  - Excite interchange/entropy mode **turbulence**

Inward Moving “Holes” in Energetic Particle Phase-Space



Frequency sweeping creates inward moving “phase-space holes”

“Drift Echoes”

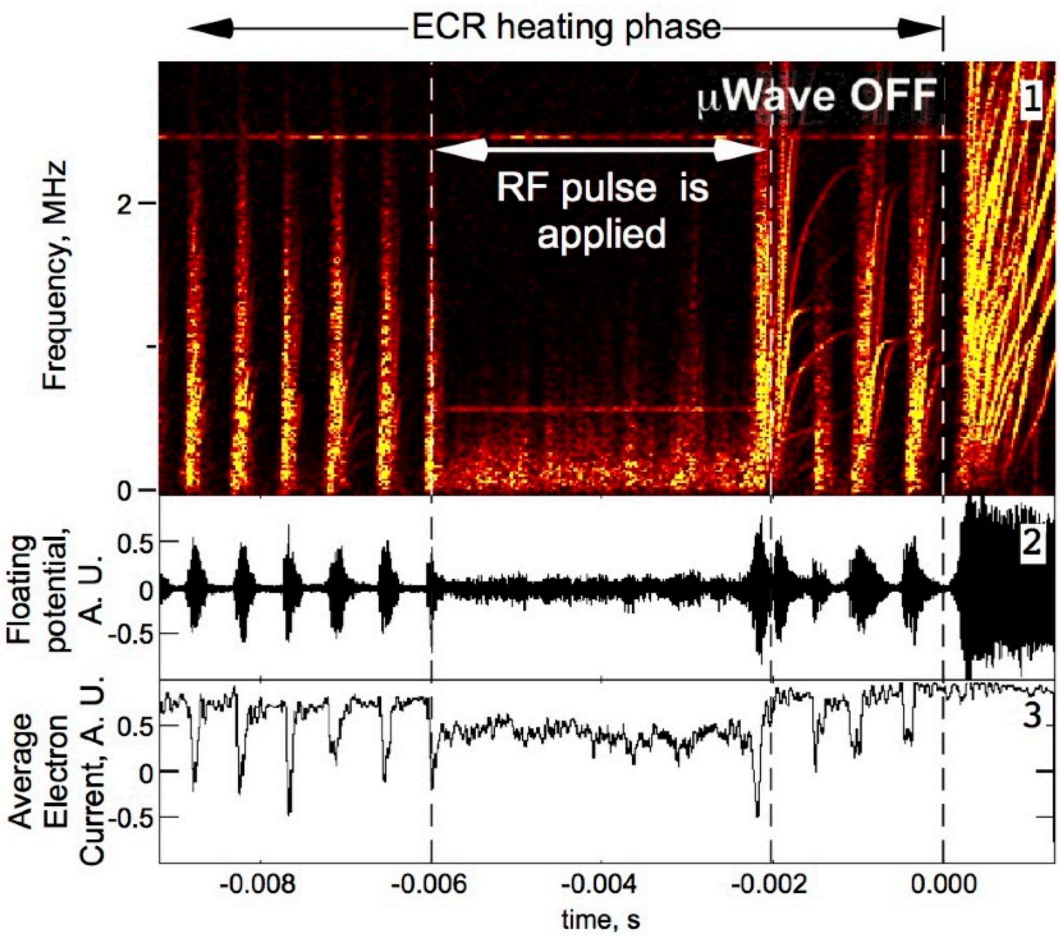


Drift Resonance $\omega \sim m\omega_d \propto \mu/L^2$

RF Pulse “pops” Phase-Space Holes

Validating model for frequency sweeping used to predict alpha-particle resonant diffusion in tokamaks.

H. L. Berk, B. N. Breizman, *et al.*, *Phys. Plasmas*, **6**, (1999)



Enhanced scattering of energetic particles prevents “chirping”

and

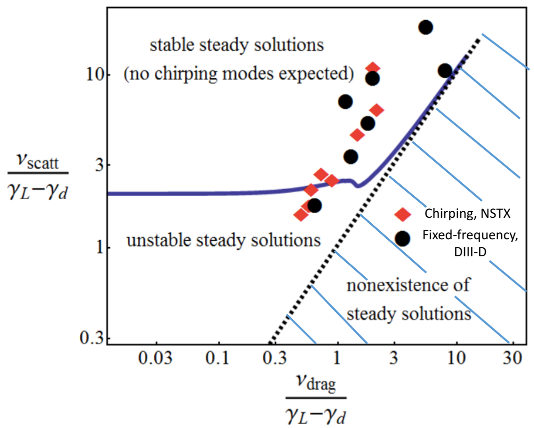
smooths outward bursts of energetic particles

Energetic Particle Physics Key to Burning Plasma Physics

October 2015

USBPO

Monthly Newsletter of the
U.S. Burning Plasma Organization
December 31, 2016 (Issue 115)



Vinícius Duarte
December 2016

Controlling Energetic Particle Modes in Laboratory Magnetosphere

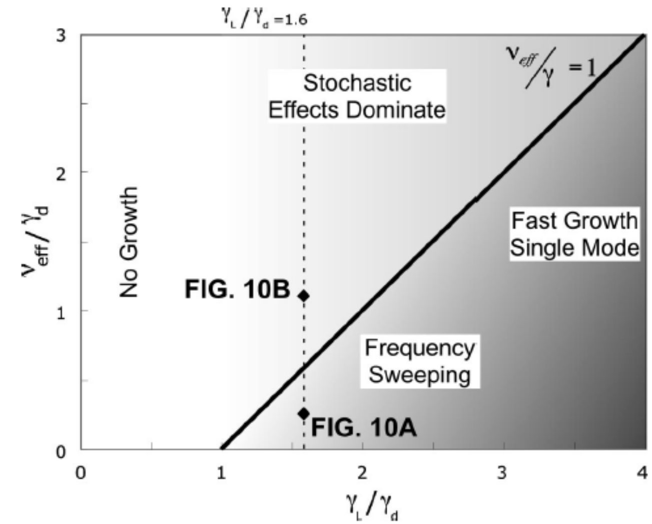
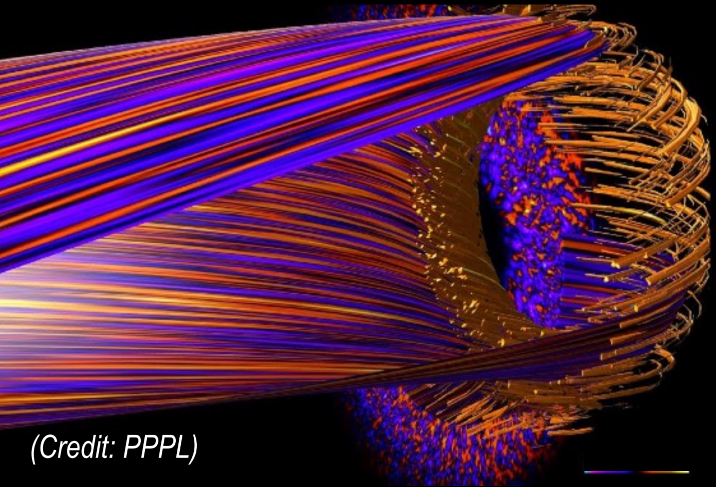


FIG. 9. Possible ways for interchange instability to develop as prescribed by Berk and co-authors. By changing the effective collisionality of the system, we destroy the phase-space "holes" and arrest the frequency-sweeping as shown in Fig. 10.

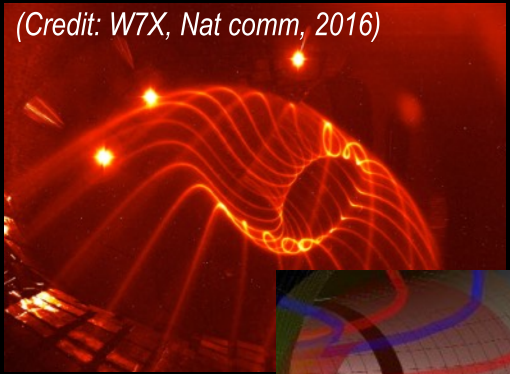
Dmitry Maslovsky
PRL, POP, 2003

Magnetized Tubes of Plasma

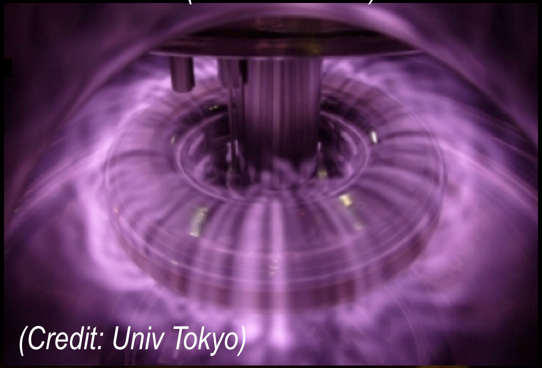


(Credit: PPPL)

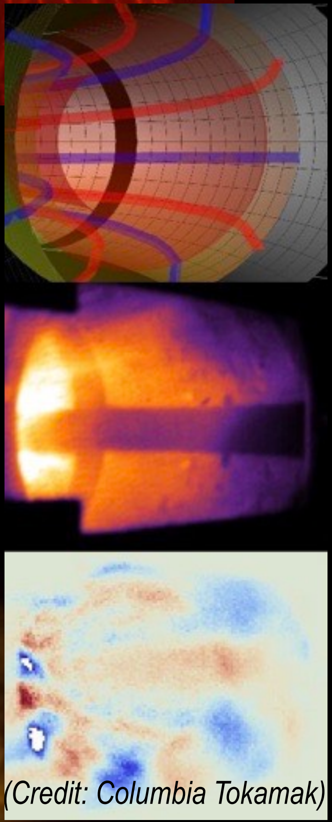
(Credit: Culham)



(Credit: W7X, Nat comm, 2016)



(Credit: Univ Tokyo)



(Credit: Columbia Tokamak)

(Credit: NASA ISS)

(Credit: NASA Goddard SDO)

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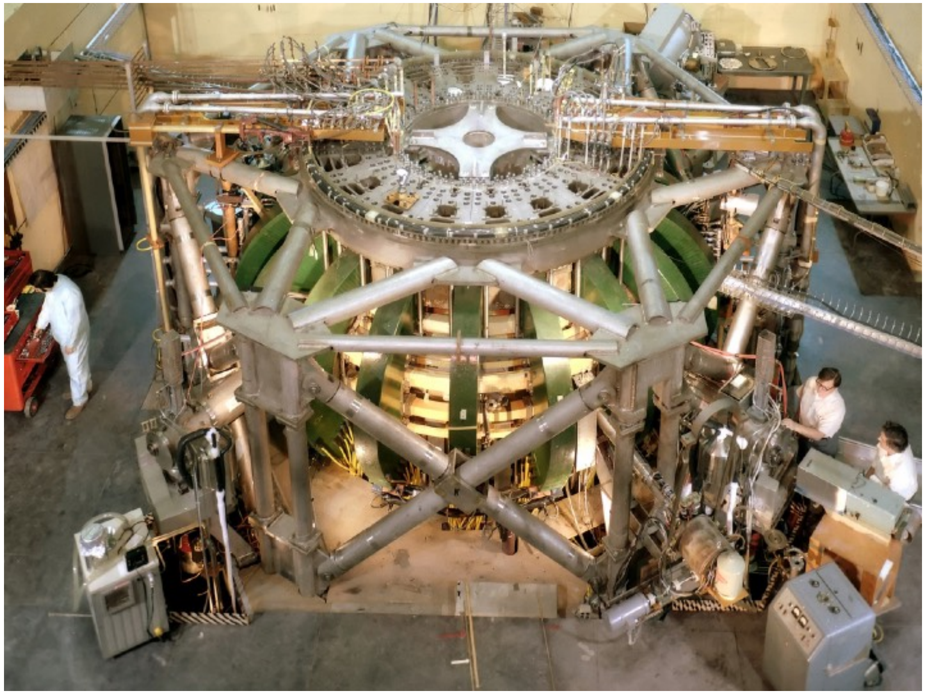
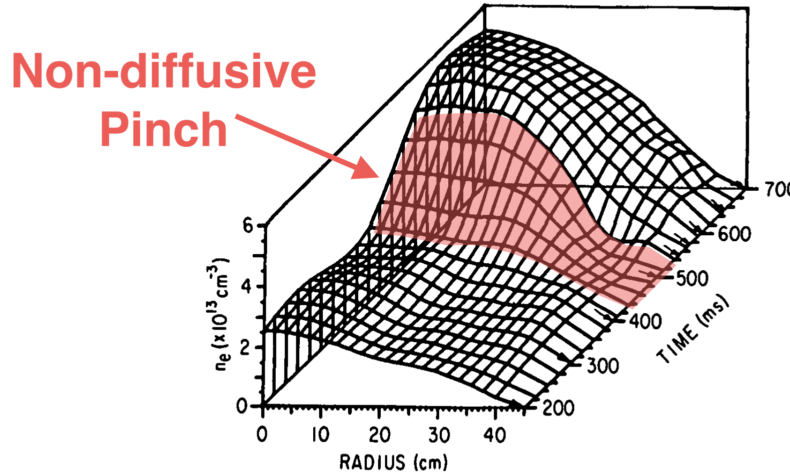
“Profile Consistency” and the Inward Pinch

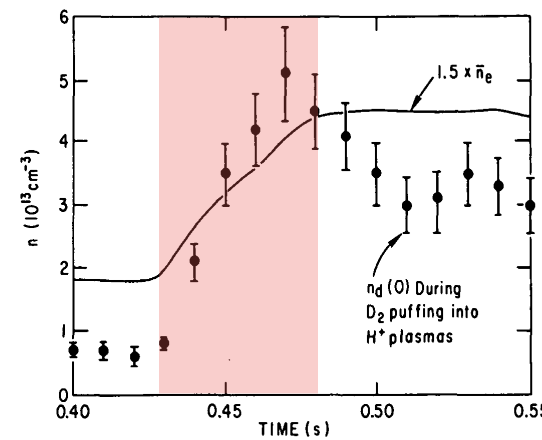


Princeton Large Torus (PLT)

17 MA Copper Toroid
1 sec pulses
750 kW Ohmic
75 kW LHCD
2.5 MW NBI & 5 MW ICRF

A (Historic) Density Rise Experiment on PLT
Jim Strachan, *et al.*, *Nuc. Fusion* (1982)

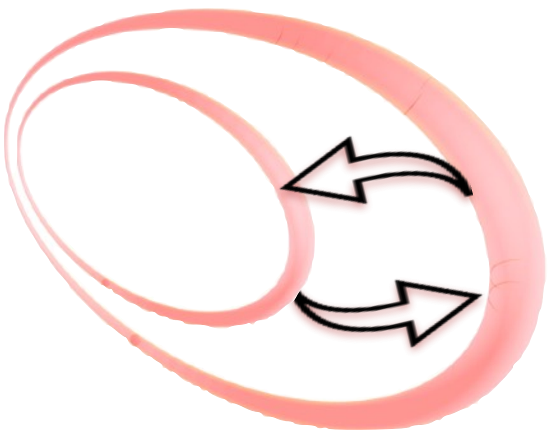




Inward pinch “*is necessary to model the experimental results*” of peaked density from edge gas source.

Inward "Curvature Pinch" is *largest (?)* in (Laboratory) Magnetospheres

Turbulent "Self-Organization" creates highly peaked profiles



$$V = \int \frac{dl}{B} \propto L^4$$

$$2\langle \kappa_\psi \rangle = -\frac{\partial}{\partial \psi} \log V$$

$$\Delta\,(nV) \sim 0$$

$$\text{Particle Flux} = n \underbrace{2D\langle \kappa_\psi \rangle}_{\text{inward pinch}} - \underbrace{D\frac{\partial n}{\partial \psi}}_{\text{diffusion}}$$

$$\Delta\left(PV^{5/3}\right) \sim 0$$

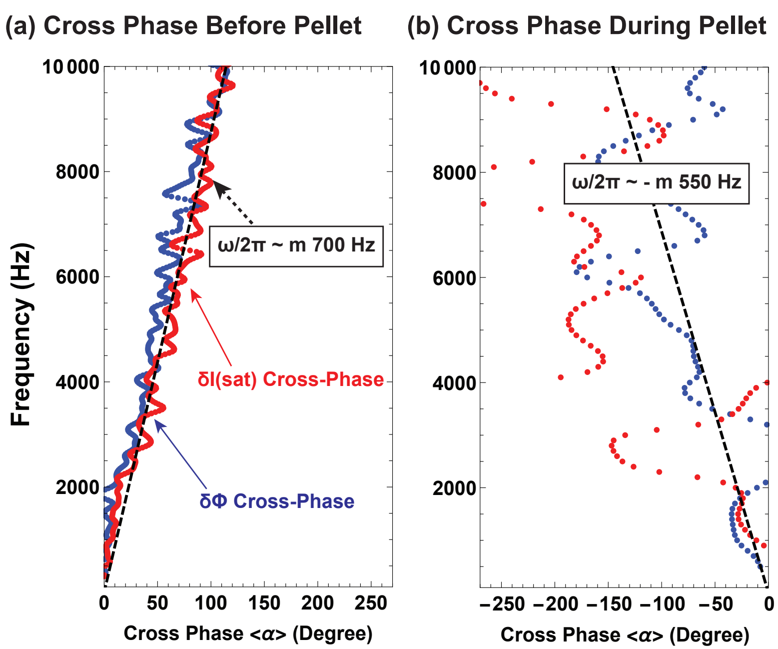
$$\text{Temperature Flux} \approx \frac{2}{3} T \underbrace{2D\langle \kappa_\psi \rangle}_{\text{inward pinch}} - \underbrace{D\frac{\partial T}{\partial \psi}}_{\text{diffusion}}$$

Inward "Curvature Pinch" is *largest (?)* in (Laboratory) Magnetospheres

Indirect measure of inward temperature pinch

"Artificial moon" reverses direction of entropy modes.

Measured Entropy Mode Dispersion



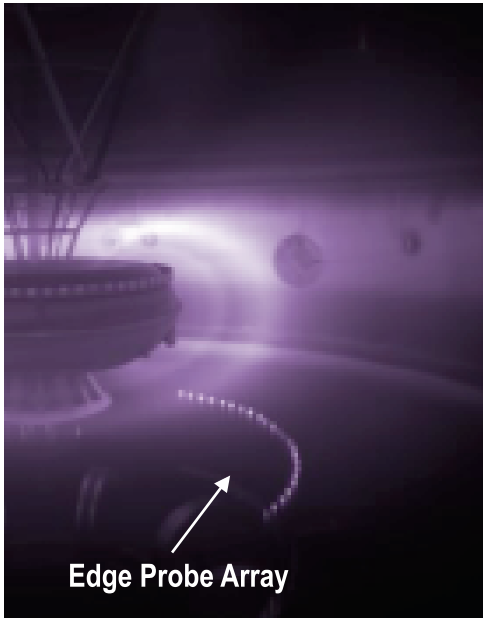
$$\Delta\,(nV) \sim 0$$

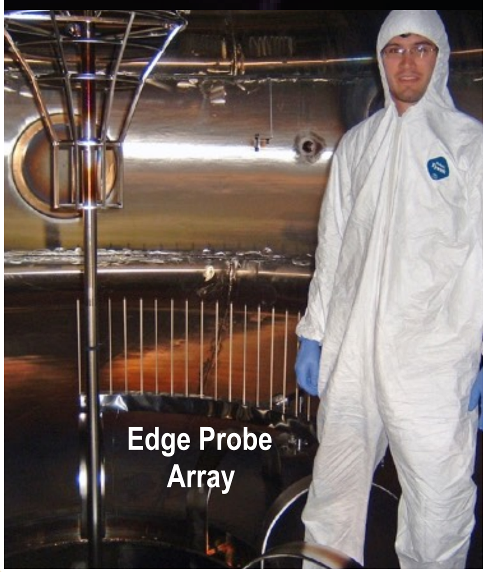
$$\text{Particle Flux} = n\,\underbrace{2D\langle\kappa_\psi\rangle}_{\text{inward pinch}} - \underbrace{D\,\frac{\partial n}{\partial\psi}}_{\text{diffusion}}$$

$$\Delta\left(PV^{5/3}\right) \sim 0$$

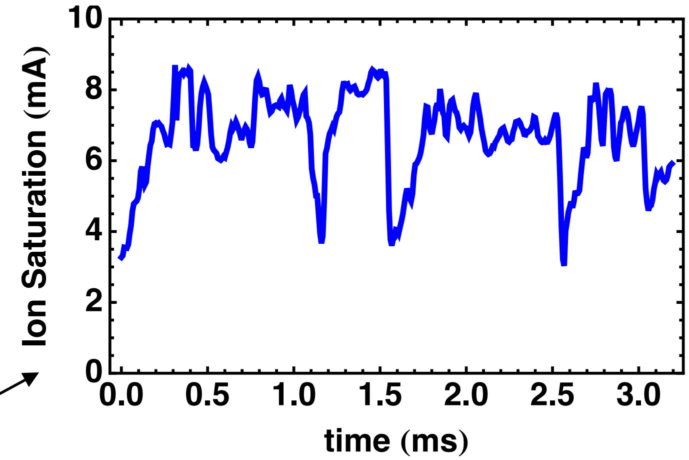
$$\text{Temperature Flux} \approx \frac{2}{3}T\,\underbrace{2D\langle\kappa_\psi\rangle}_{\text{inward pinch}} - \underbrace{D\,\frac{\partial T}{\partial\psi}}_{\text{diffusion}}$$

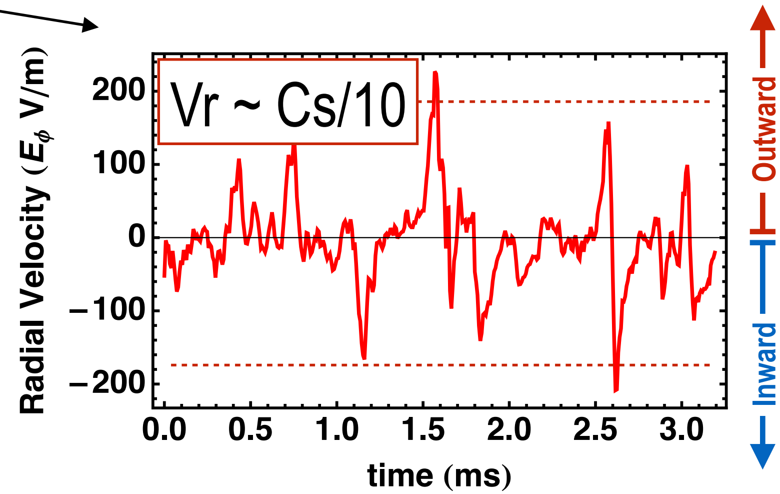
"Bursty" Turbulence with Inward and Outward moving Plasma Filaments





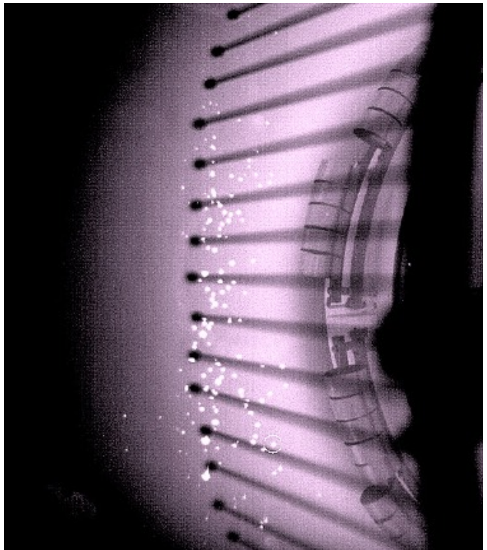
High-Speed
Bursty
Radial Flow



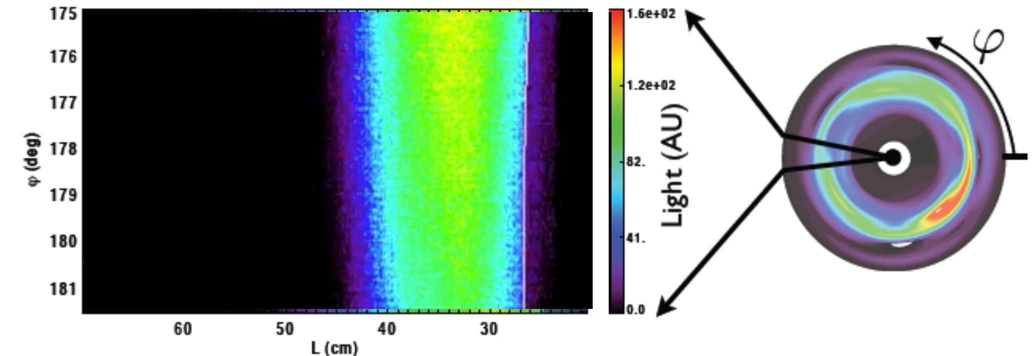


$$RE_\varphi \sim \Delta\Phi/\Delta\varphi$$

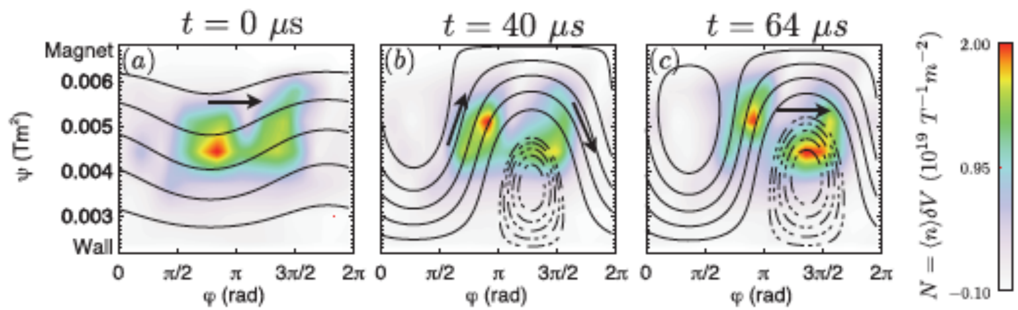
Direct Imaging of Turbulent Mixing of Plasma Filaments



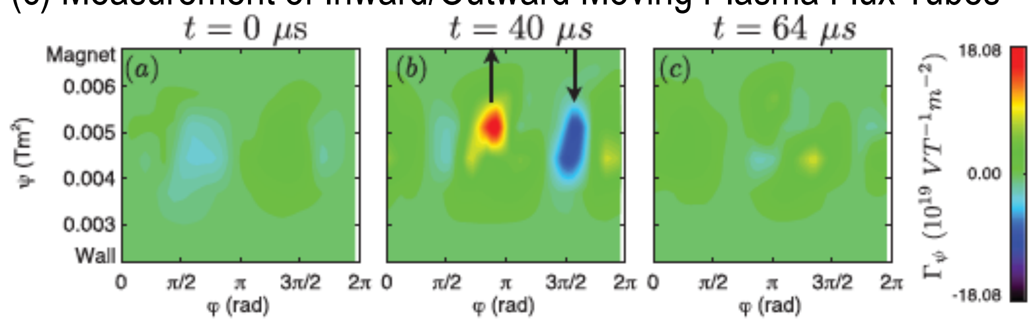
(a) Fast Videography/Polar Imaging of Density Fluctuations



(b) Global Reconstruction of Potential / Density Fluctuations



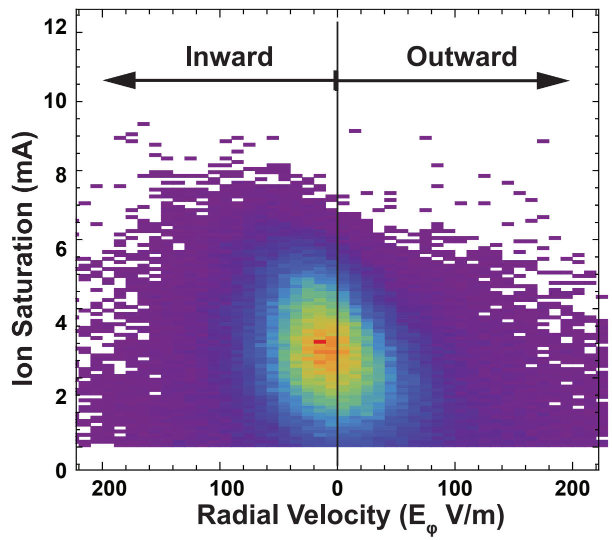
(c) Measurement of Inward/Outward Moving Plasma Flux Tubes



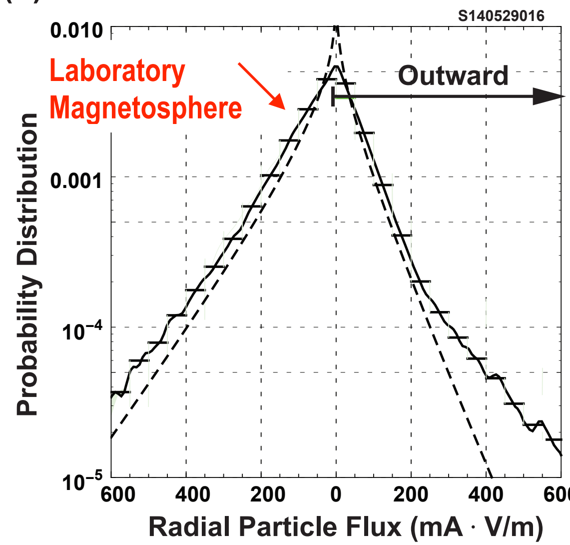
Surprising "Universal" Turbulence Statistics of the Plasma Torus

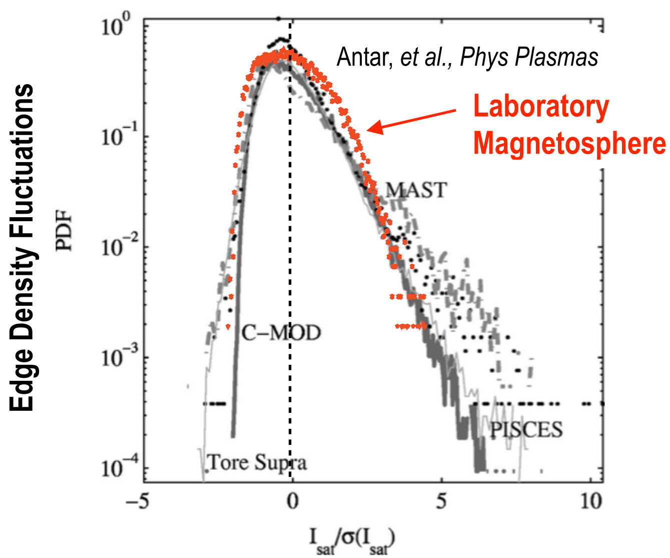
[Fusion tools GS2 Simulation: Kobayashi, *et al.*, *PRL* (2009), *PRL* (2010)]

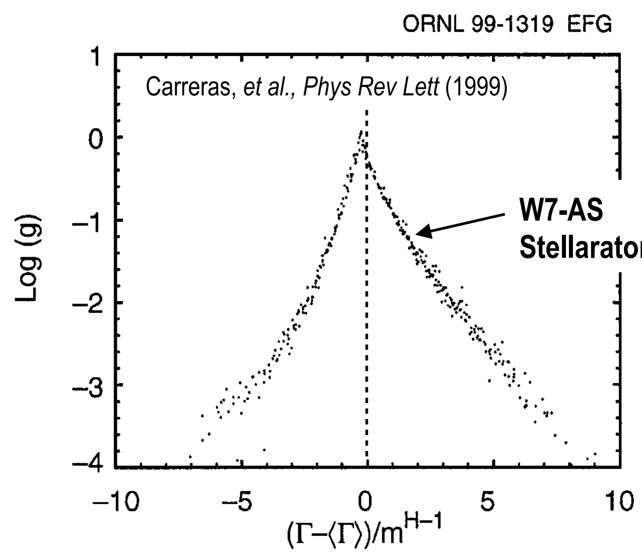
(a) Probe Array Histogram



(b) Local Radial Flux







Three Challenges for the Future

(i) Can we fully regulate turbulent mixing of strongly magnetized plasma, *e.g.* by connecting the "artificial ionosphere"?

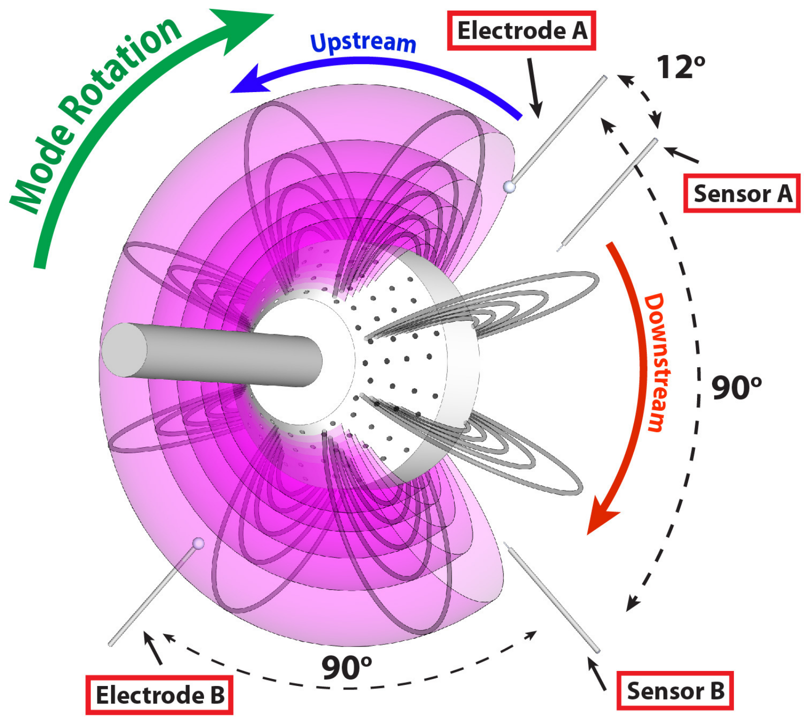
(ii) Can we validate "whole-plasma" predictive models, *e.g.* with reduced dimensional models and the "simplest" steady-state plasma torus?

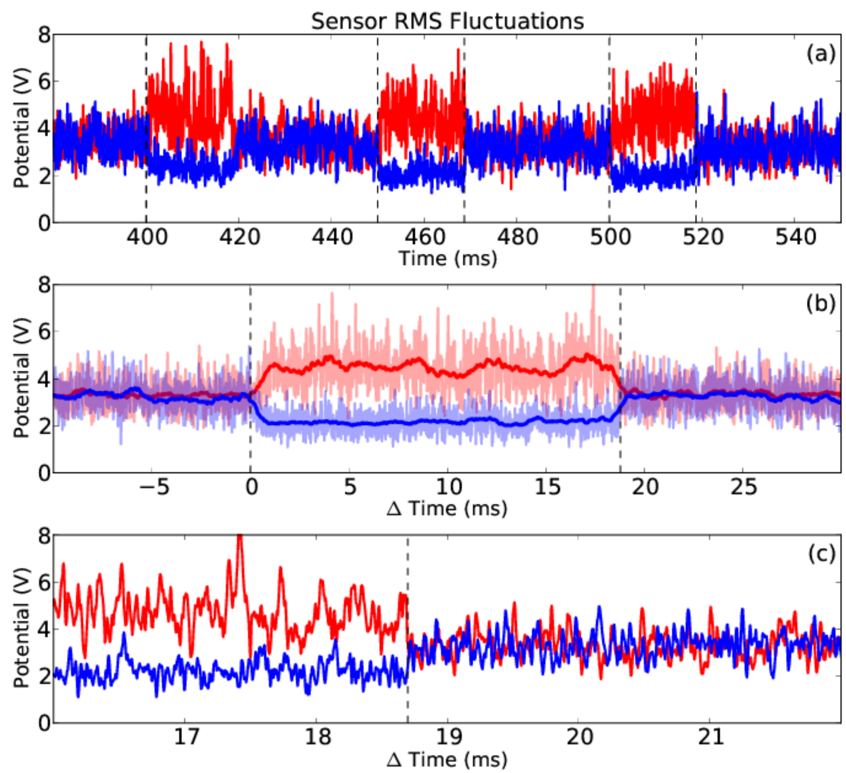
(iii) Can we explore turbulent transport across the "Extreme Scales" found in space, *e.g.* through increased plasma density of the laboratory magnetosphere?

Contributing to…

- Can laboratory study of magnetized plasma help to validate predictive models for **space weather**?
- Can understanding magnetospheric plasma help to validate predictive models for **the fusion grand challenge**?

(i) Controlling turbulent convection with an "artificial ionosphere" (*i.e.* field-aligned current injection feedback)

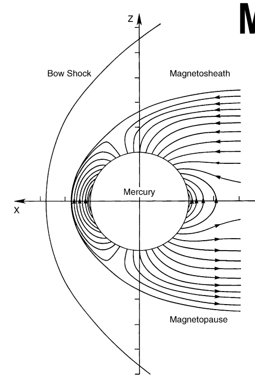




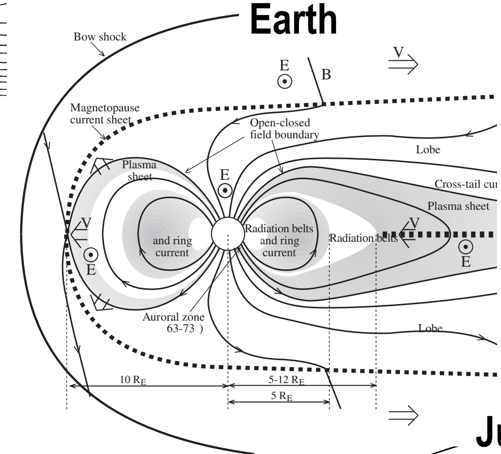
Can we regulate only part (*yes!*) or the whole laboratory magnetosphere?

(III) Explore turbulent transport across the "*extreme scales*" found in space

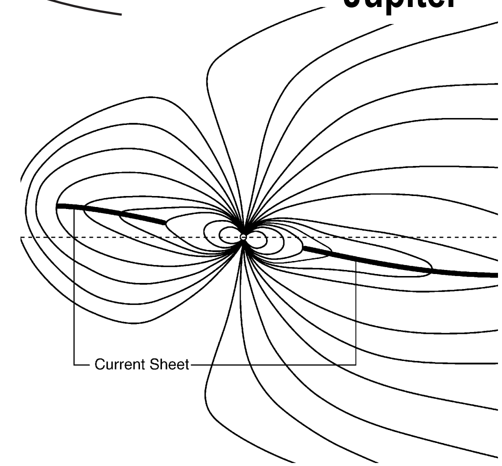
Mercury



Earth



Jupiter

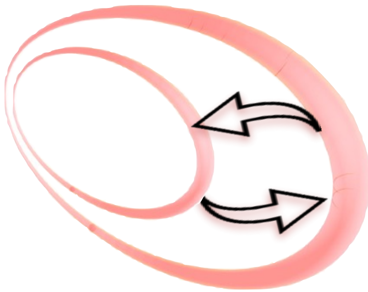


Next-step discoveries are significant…

- Magnetospheric Alfvén wave turbulent emission at high plasma β
- FLR and isotope effects in bounce-averaged gyrokinetics and turbulent self-organization
- Explore critical plasma physics linking space science and high-β toroidal confinement

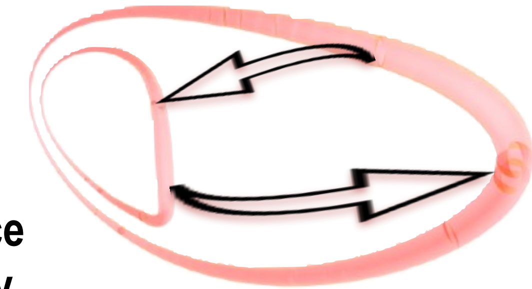
	Mercury	Earth	Jupiter
Size	$2R_H$	$10R_E$	$100R_J$
Density $(c/\omega_{pi}L)$	0.1	0.003	0.00001
New Physics	$(V_A/L) \sim \omega_{ci}$	Alfvén Resonances	Propagating Alfvén Waves

(III) Explore turbulent transport across the "*extreme scales*" found in space



$\lambda^* \sim 0.1$

Alfvén wave emission and dynamics will appear as turbulence bends flux-tubes at higher density



$\lambda^* \sim 0.01$

Strongly Magnetized

$$\rho^* = \rho/L \ll 1$$

Dense and Big

$$\lambda^* = \lambda_i/L = \rho^*/\sqrt{\beta/2} \ll 1$$

Collisionless

$$\nu^* = \nu/\omega_b = L/\lambda_{mfp} = \frac{16}{\lambda^{*2} S} = \frac{2\beta}{\rho^{*6}} \times \left(\frac{2}{B_G^4 L_{cm}^5}\right) \ll 1$$

Very Big Plasma Needed (Earth Magnetosphere ~ 10^{12} × LabMagnetosphere)

With high-β and good high-temperature confinement, ***only the laboratory magnetosphere*** can achieve these these three requirements in steady-state.

Acknowledging the Pioneers