Laboratory Astrophysics on the SSX device

Michael Brown

Swarthmore College

with contributions from

M. Kaur, D. Schaffner, T. Gray, C. Cothran (postdocs)
J. Shrock ‘18, E. Lewis ‘18, L. Barbano ’18
K. Gelber ‘20, H. Srinivasulu ’21, M. Membratu ‘21, L. Dyke ‘20… 60 total

GPAP Plasma Astrophysics Summer School (APS/NSF)
June 18-20, 2019

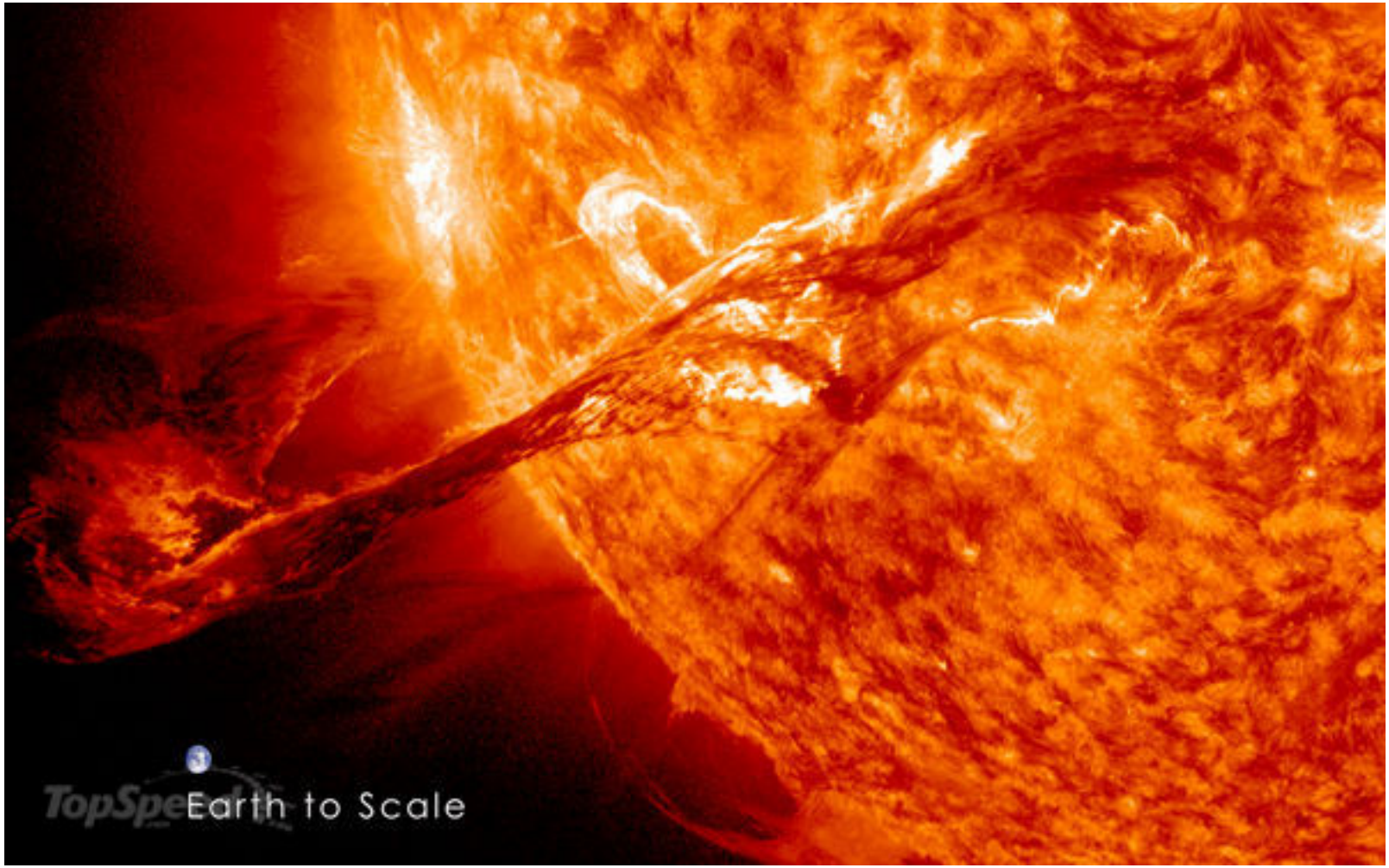
Research supported by DOE APRA and NSF

SSX background

(undergraduate research program)

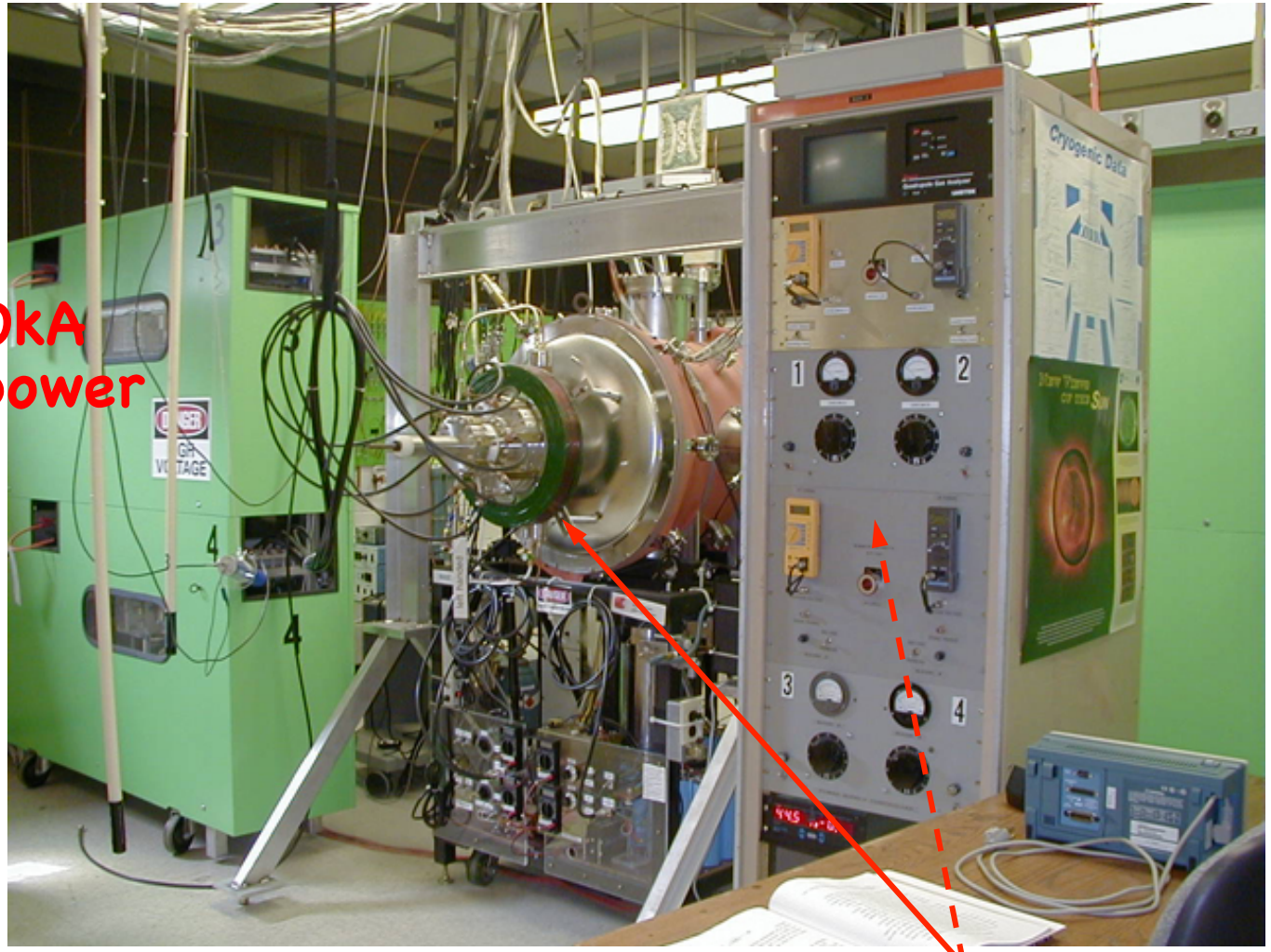
- 25 years, 60 students (many now at R1 places)
- Magnetic reconnection, MHD turbulence
- Single user "table top" laboratory experiment
- Some aspects relevant to solar/space physics

Solar plume (CME) and wind (plasma)



400 km/s plasma with entrained magnetic fields (SDO, 8/12)

The SSX Laboratory



10kV/100kA
Pulsed power

Cylindrical vacuum chamber
(D = 0.5 m, L = 1 m)

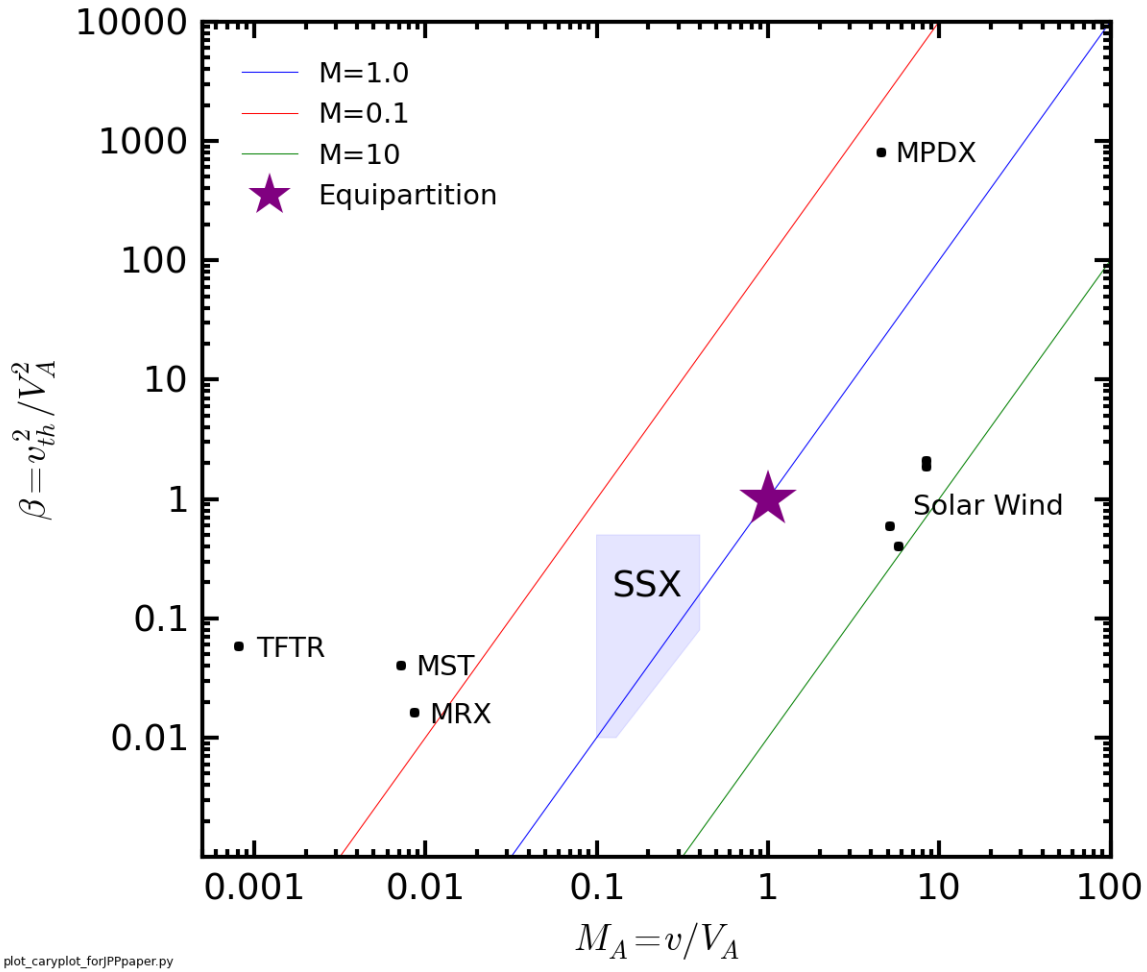
High voltage plasma
guns on each end

SSX parameters

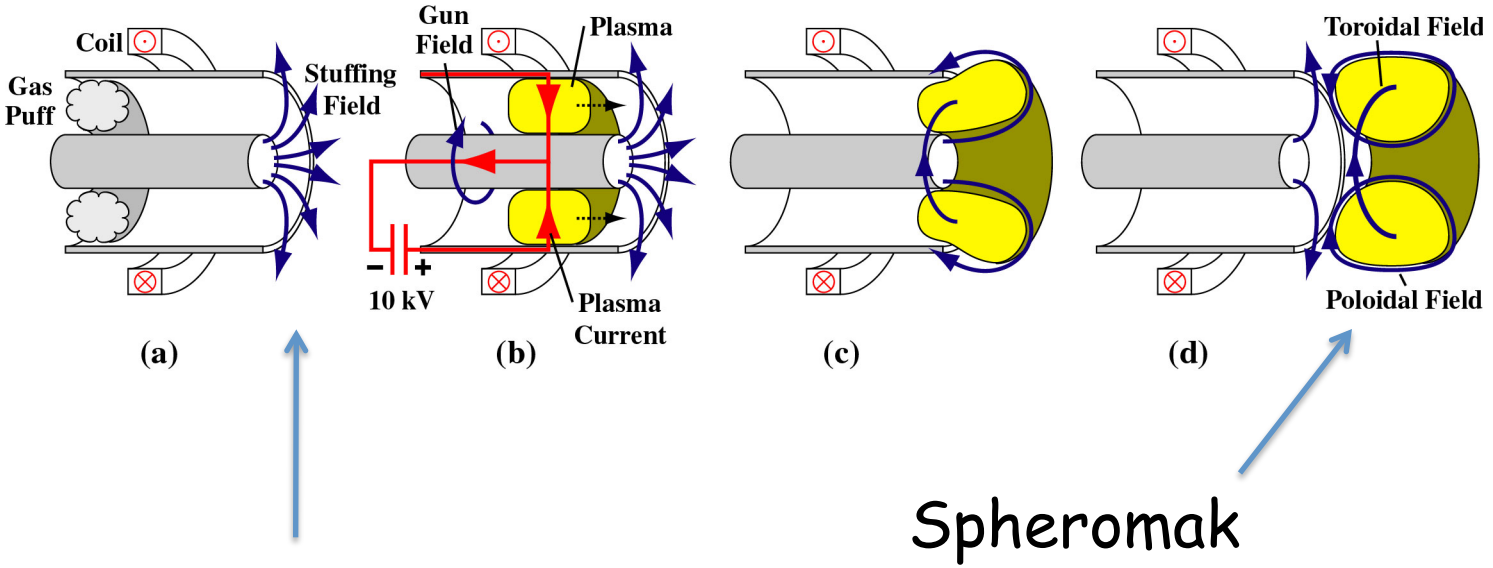
Ion Density (protons)	10^{14} -10^{15} cm^{-3}
Temperature (T_e,T_i)	20 - 60 eV
Magnetic Field	> 0.1 Tesla
Ion gyroradius	< 0.5 cm
Alfvén speed	100 km/s
S (Lundquist number)	> 1000
Plasma β	0.1-1

ρ<< R, so treat as MHD fluid… no intrinsic scale!

Equipartition of flow, thermal, and magnetic energy

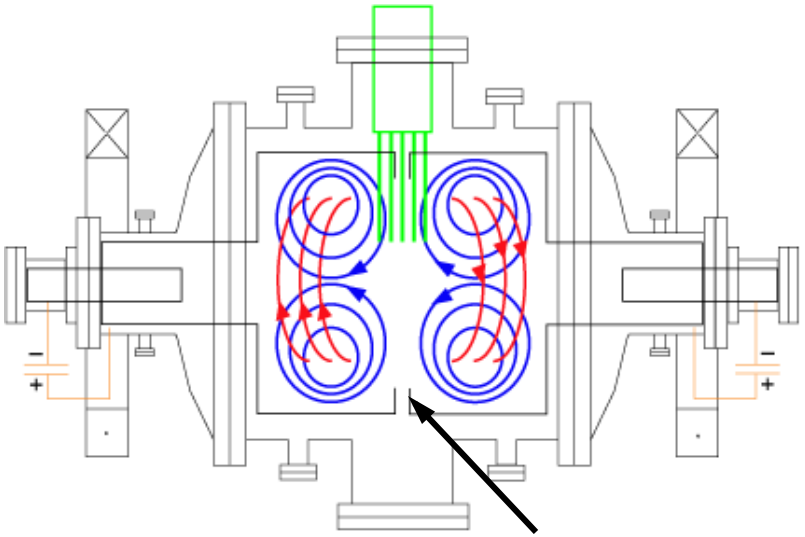


Spheromak formation

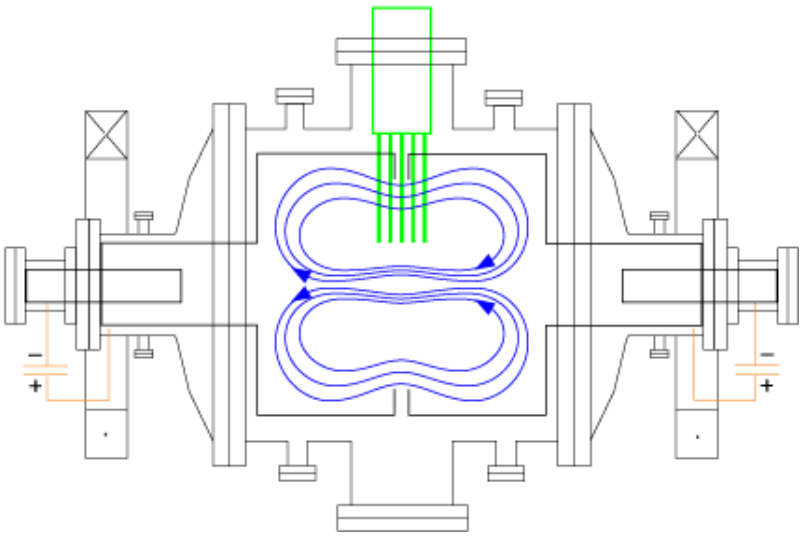


Stuffing flux acts like a nozzle

Plasma merging scenario (old SSX)



Rapid merging of two rings

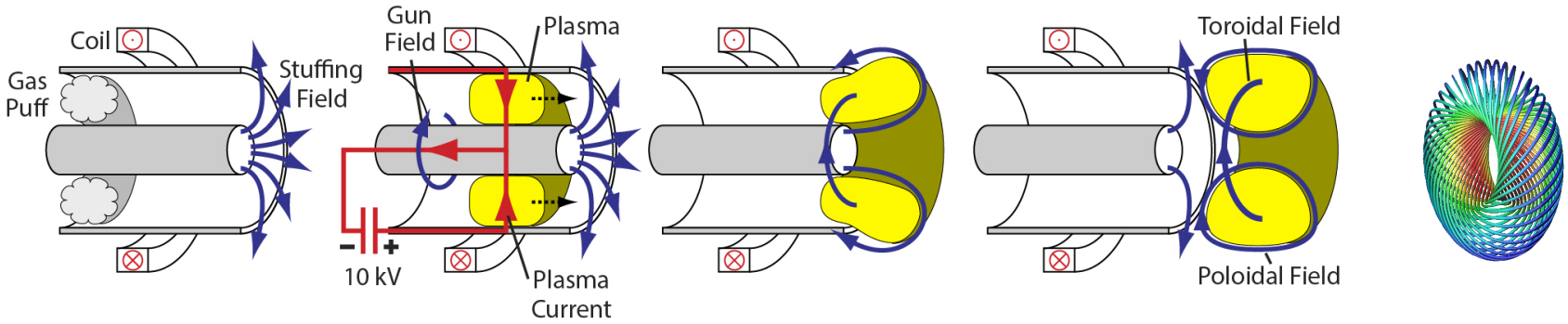


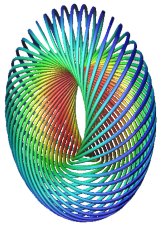
Single structure is formed

MHD wind tunnel (since 2014)

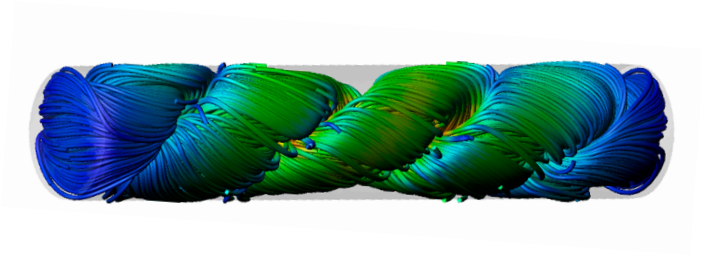
- 50 km/s flows, fully ionized and magnetized
- Kinetic, magnetic, thermal energies comparable
- Single plume (10 kJ)
- Characterization of MHD turbulence
- MHD simulation

Taylor state formation

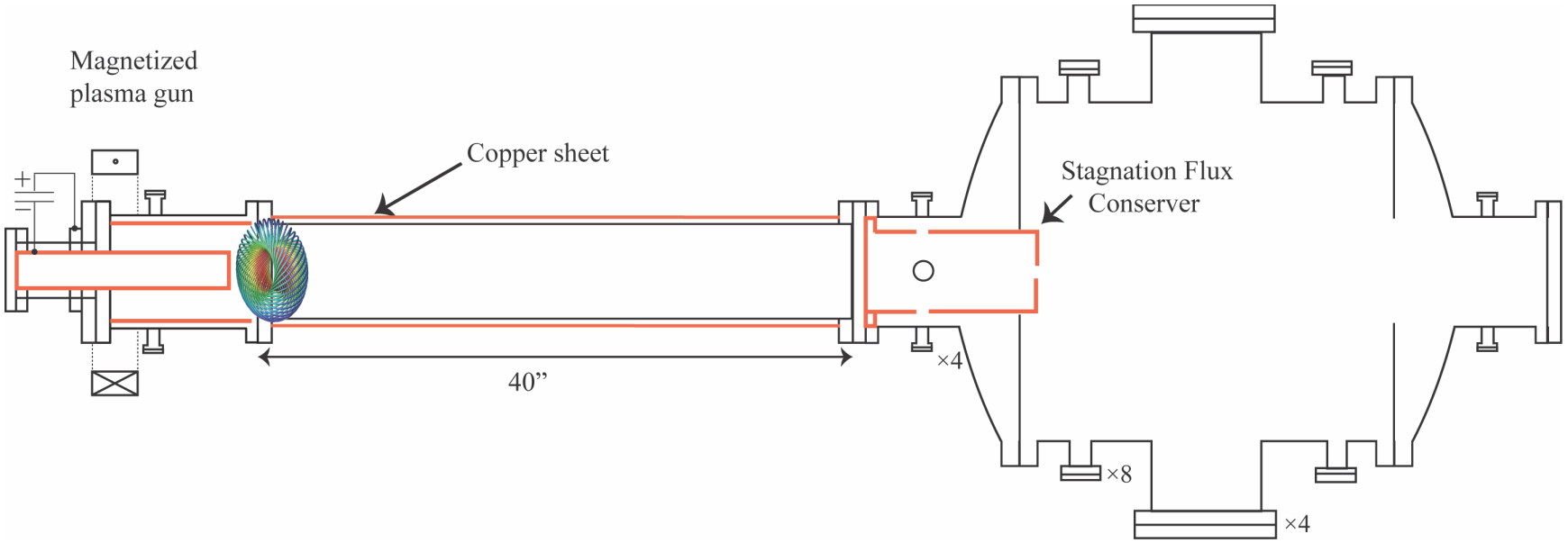




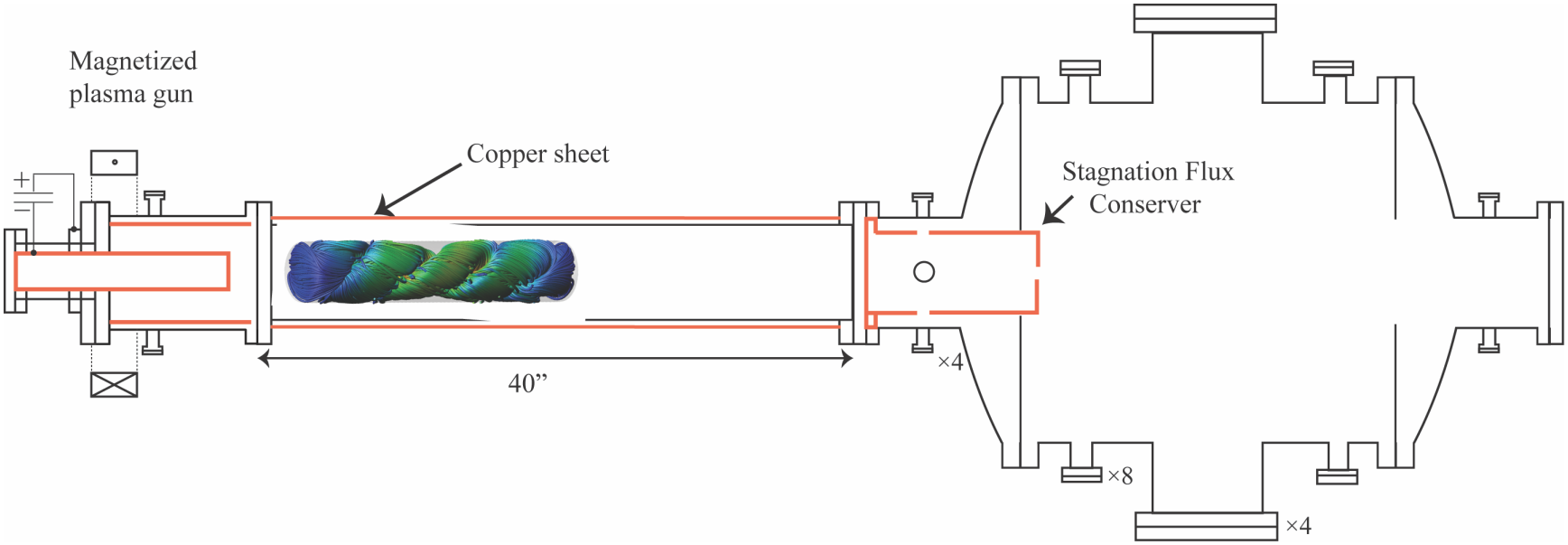
Taylor relaxation



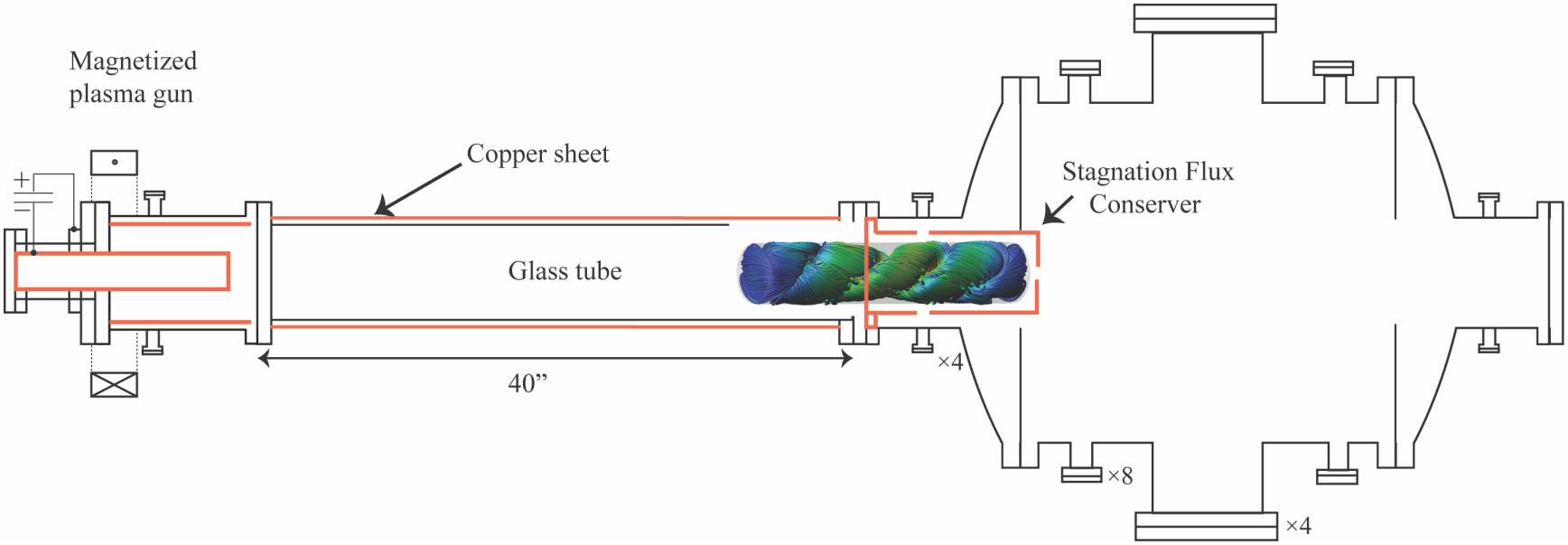
Taylor state formation



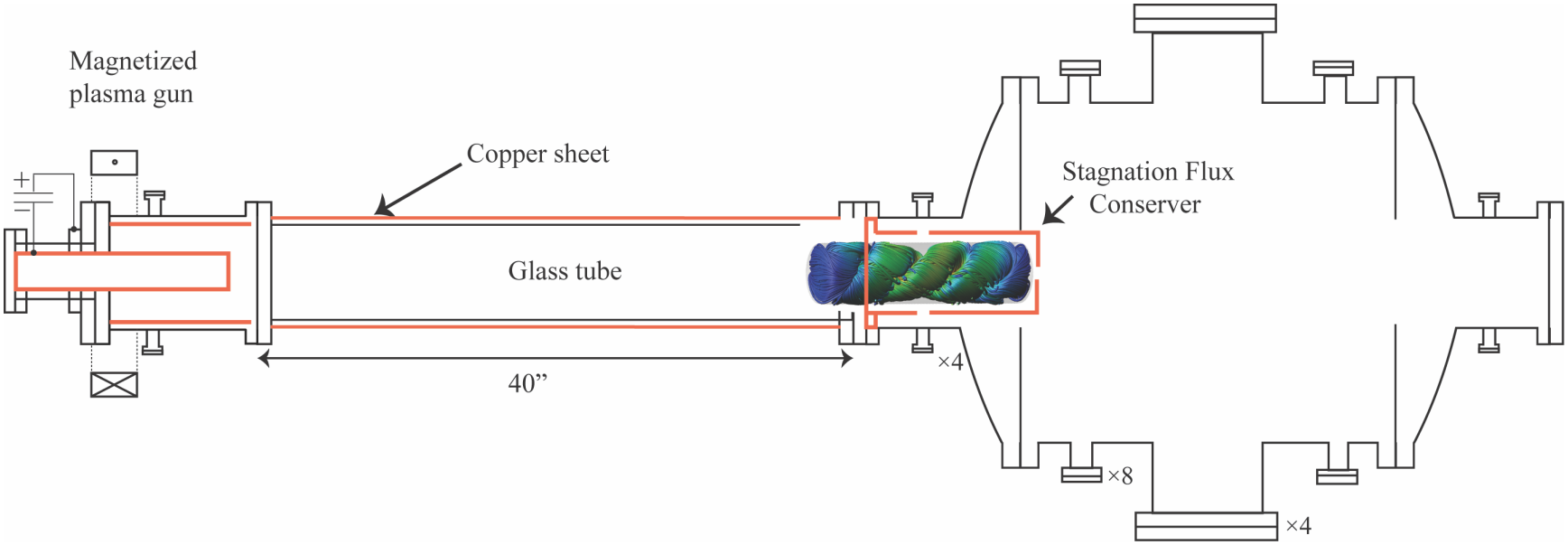
Taylor state formation



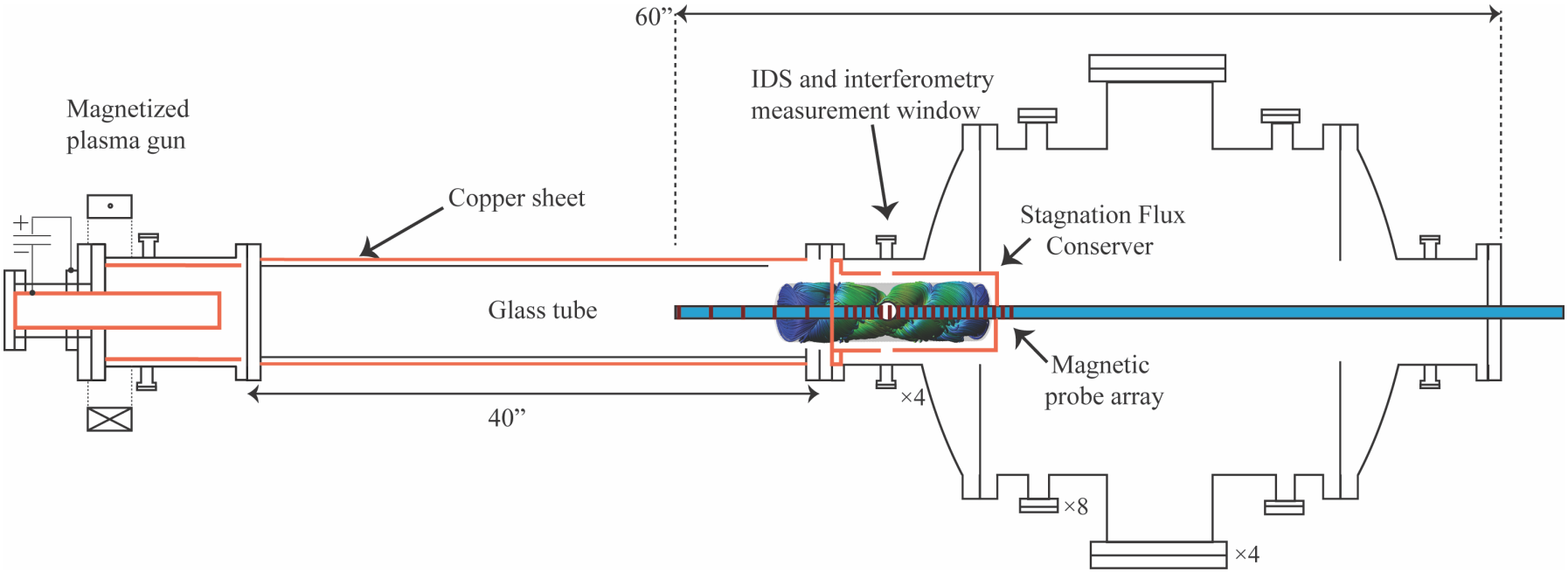
Translation



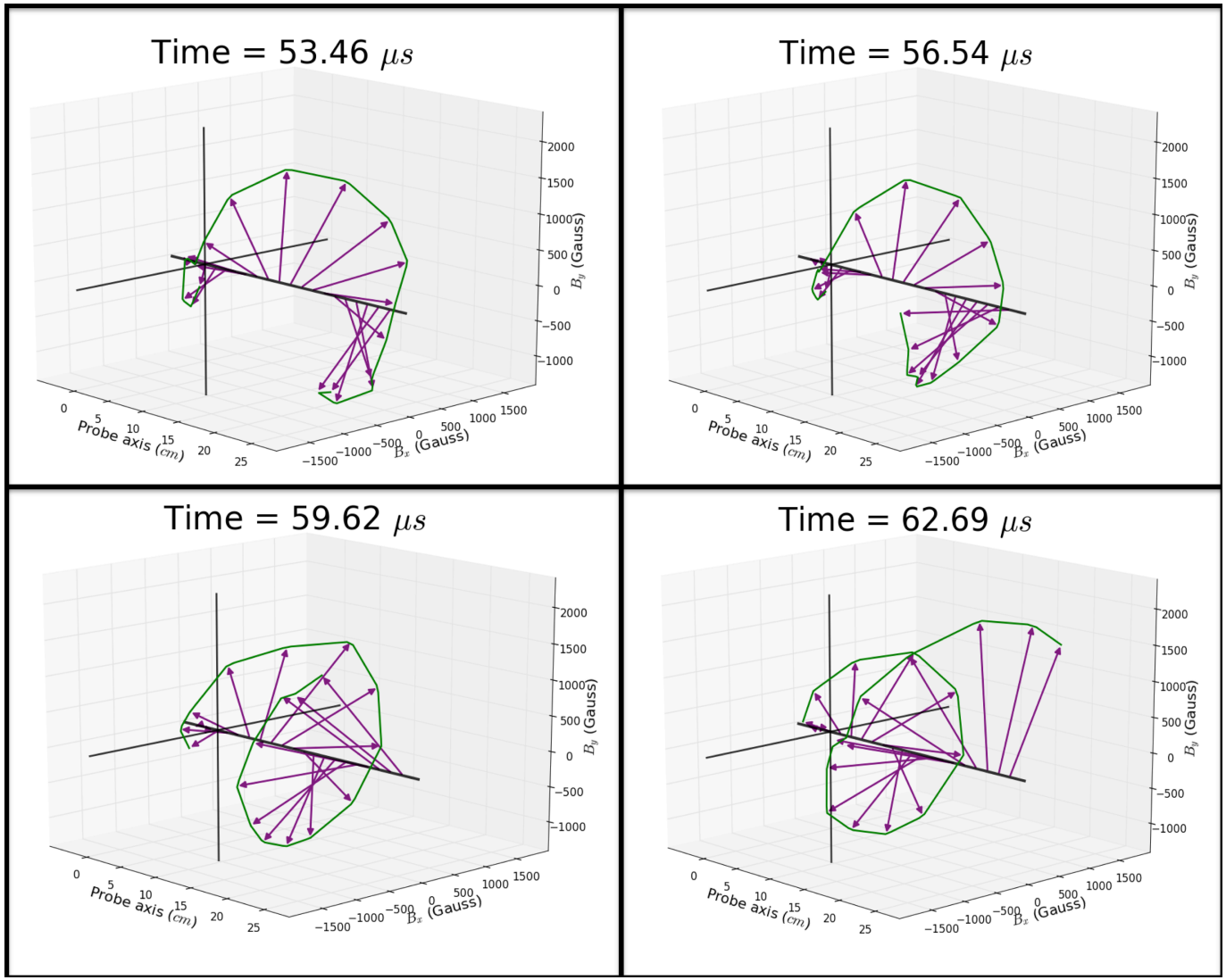
Compression

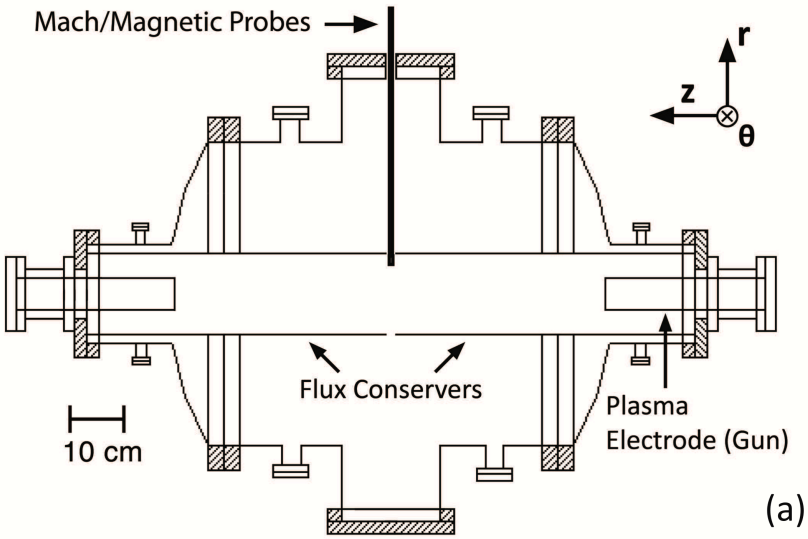


Diagnostics for compression

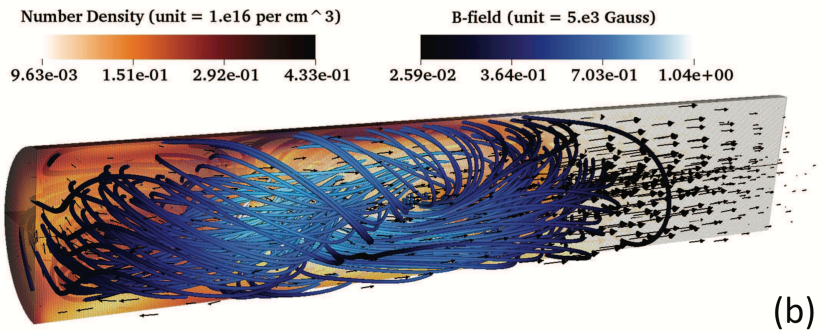


Compression

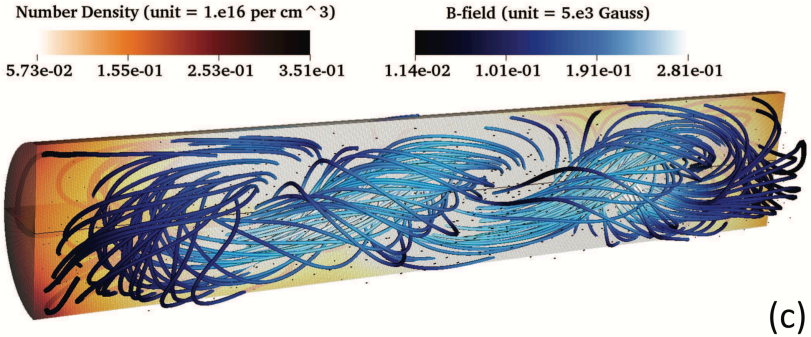



Mach/Magnetic Probes
r
z
θ
Flux Conservers
Plasma
Electrode (Gun)
10 cm

(a)

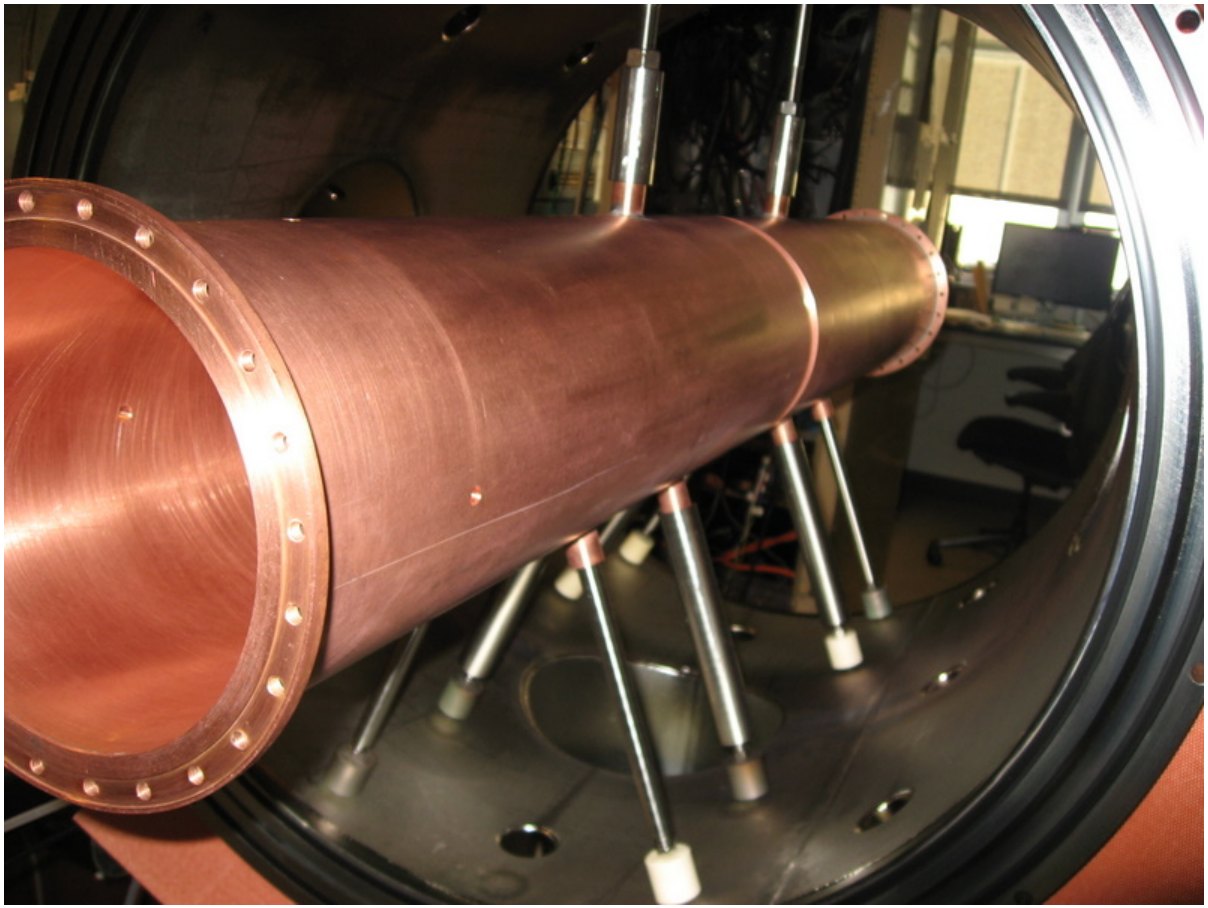

Number Density (unit = 1.e16 per cm ^ 3)
9.63e-03 1.51e-01 2.92e-01 4.33e-01
B-field (unit = 5.e3 Gauss)
2.59e-02 3.64e-01 7.03e-01 1.04e+00

(b)


Number Density (unit = 1.e16 per cm ^ 3)
5.73e-02 1.55e-01 2.53e-01 3.51e-01
B-field (unit = 5.e3 Gauss)
1.14e-02 1.01e-01 1.91e-01 2.81e-01

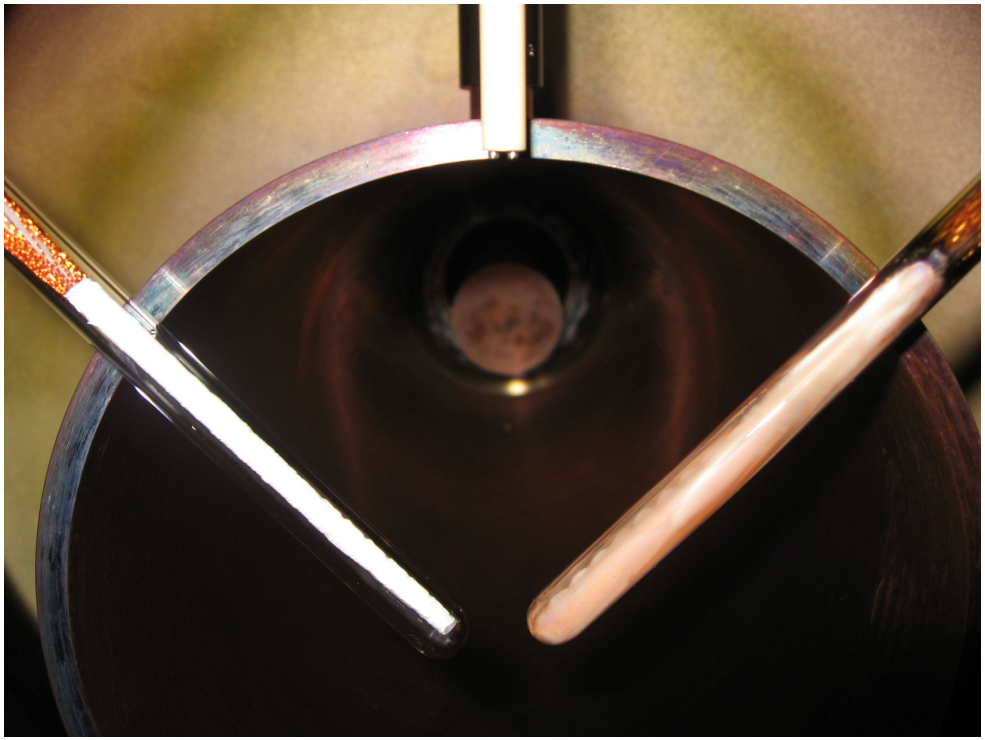
(c)

SSX MHD wind tunnel
50 km/s, magnetic and fluid turbulence



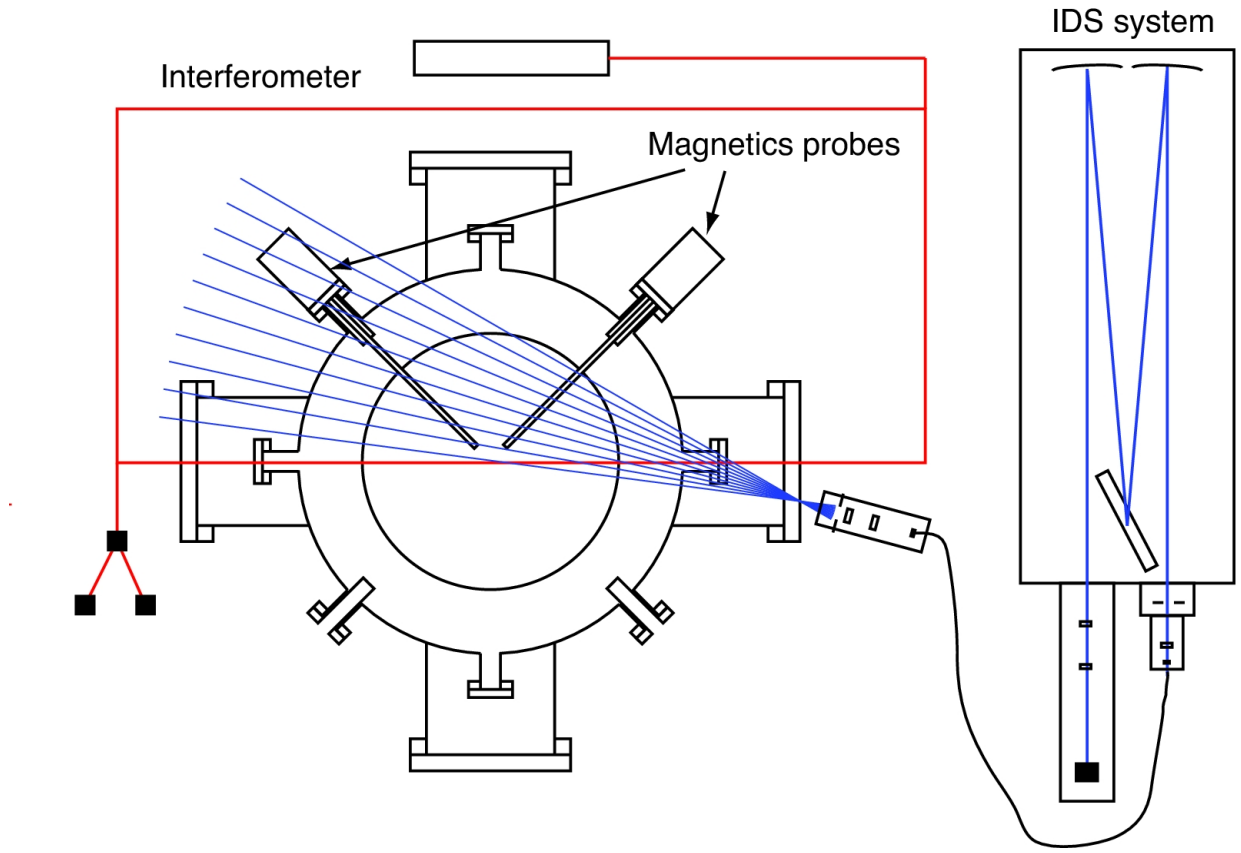
Diagnose with arrays of magnetic and velocity probes

Diagnostics at midplane (B and n_e)



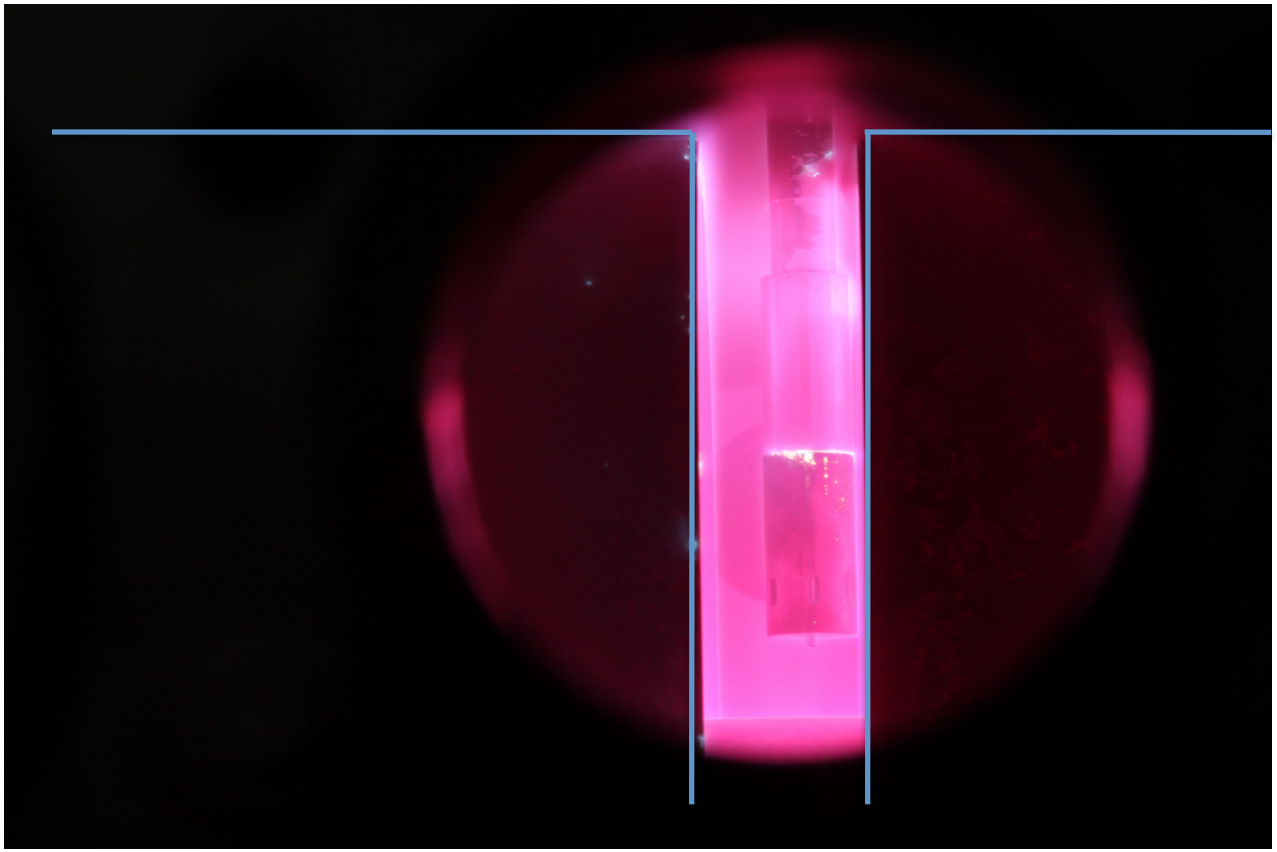
Line-averaged density with He-Ne, temperature from IDS

Ion Doppler spectrometer on SSX

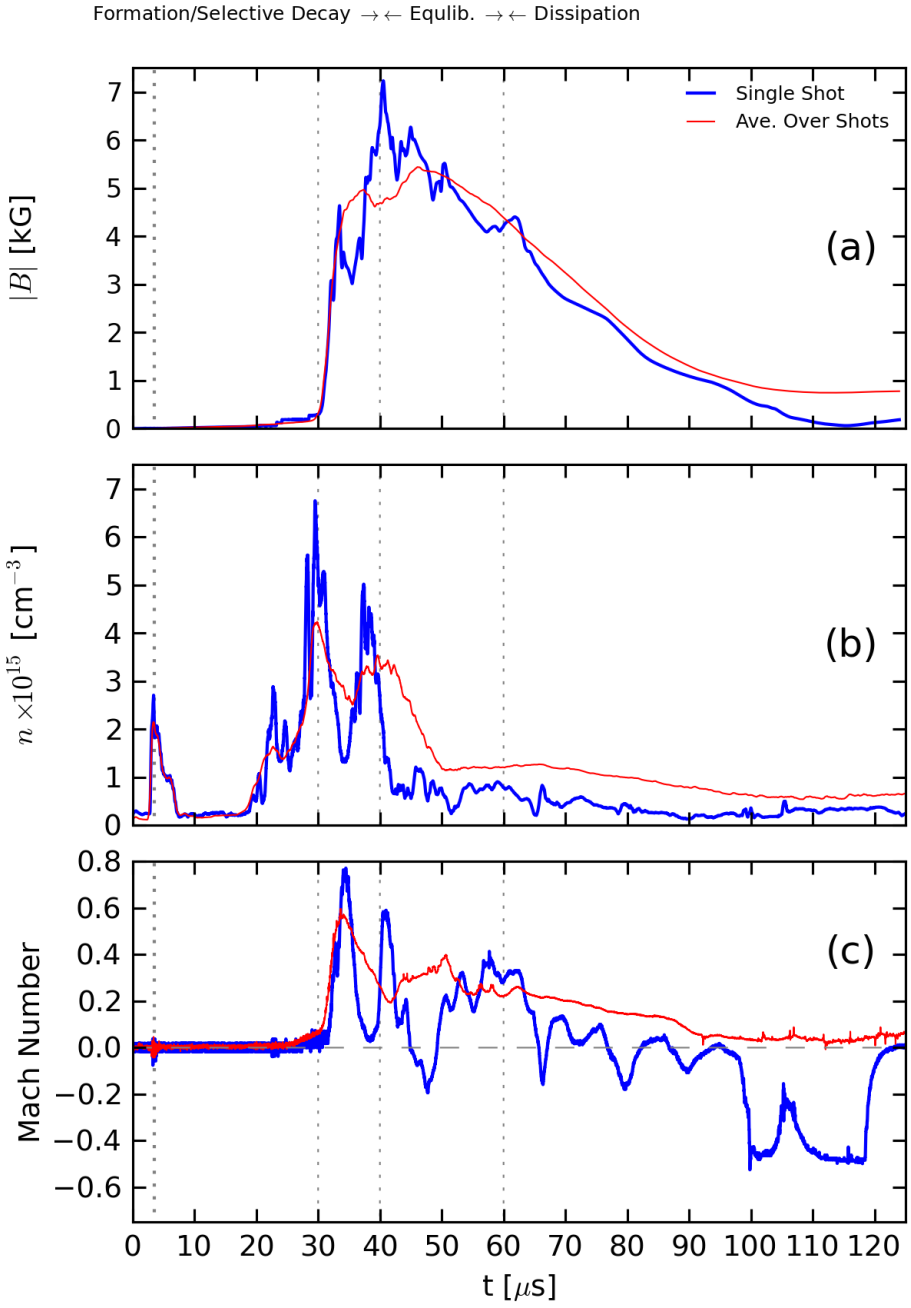


Interferometer chord and two magnetic probes also shown

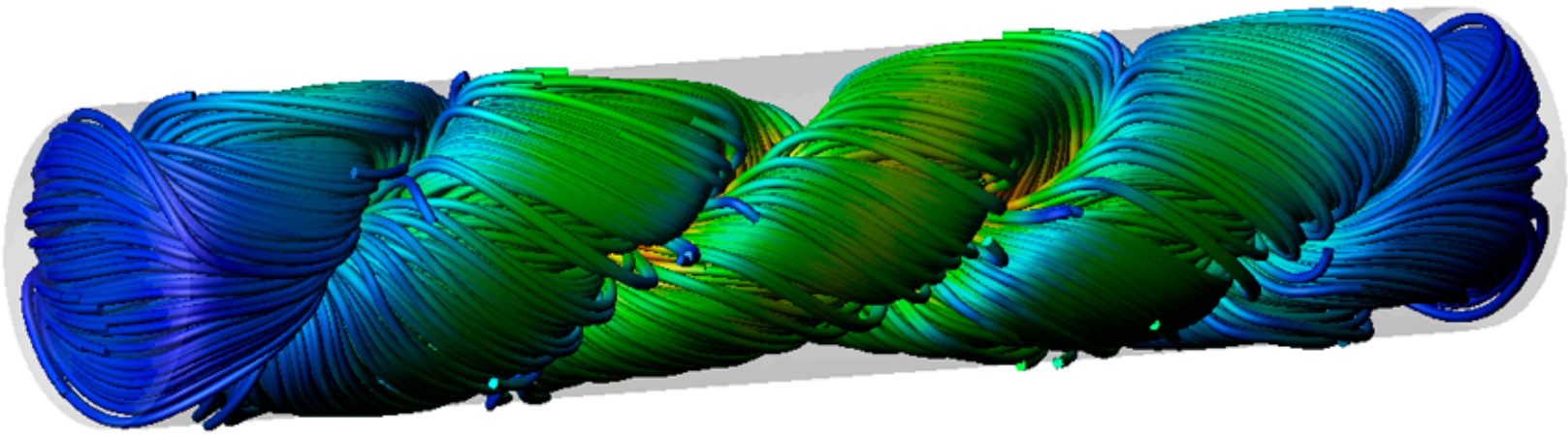
Mach probe measures local flow



X. Zhang

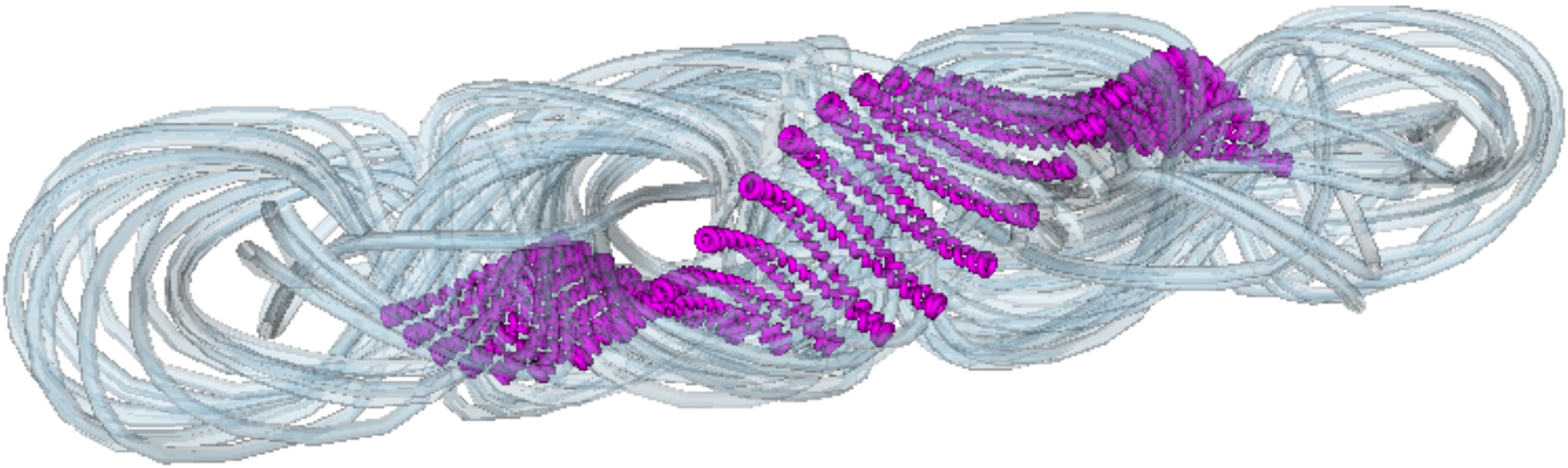

Formation/Selective Decay →← Equlib. →← Dissipation
Single Shot
Ave. Over Shots
(a)
(b)
(c)
$|B|$ [kG]
$n \times 10^{15}$ [cm^{-3}]
Mach Number
t [μs]
0
1
2
3
4
5
6
7
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
10
20
30
40
50
60
70
80
90
100
110
120

Comparison with predicted helical state



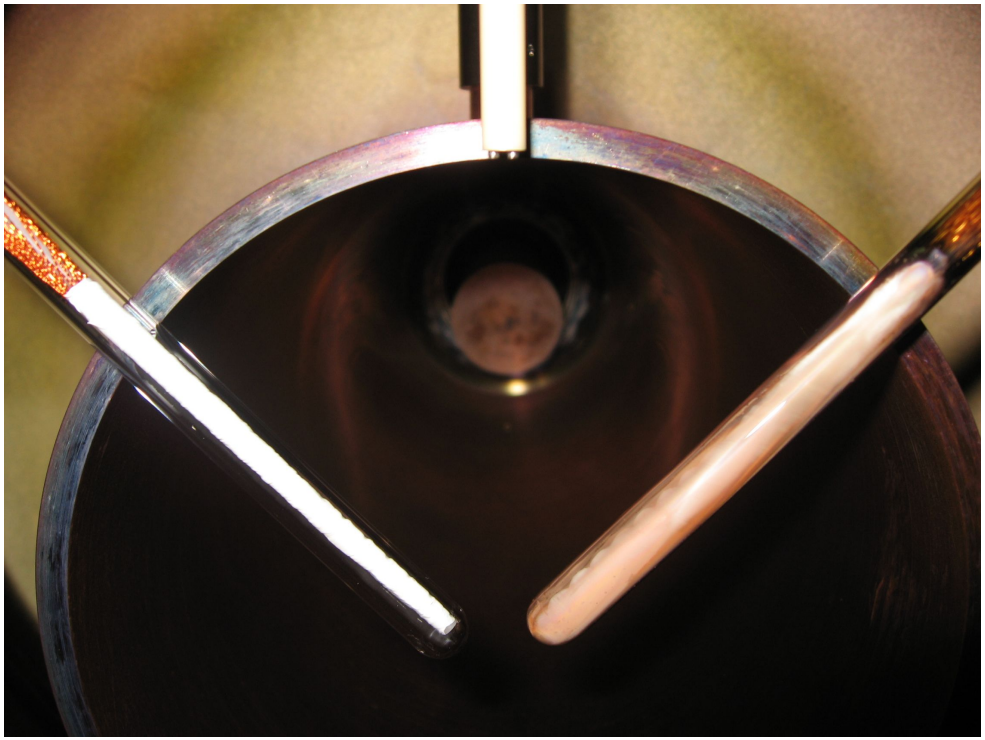
State with the minimum magnetic energy
(subject to certain constraints)
Originally predicted by J. B. Taylor

Trapped proton orbits



A. D. Light, H. Srinivasulu, et al (in preparation)

Diagnostics at midplane (B and n_e)



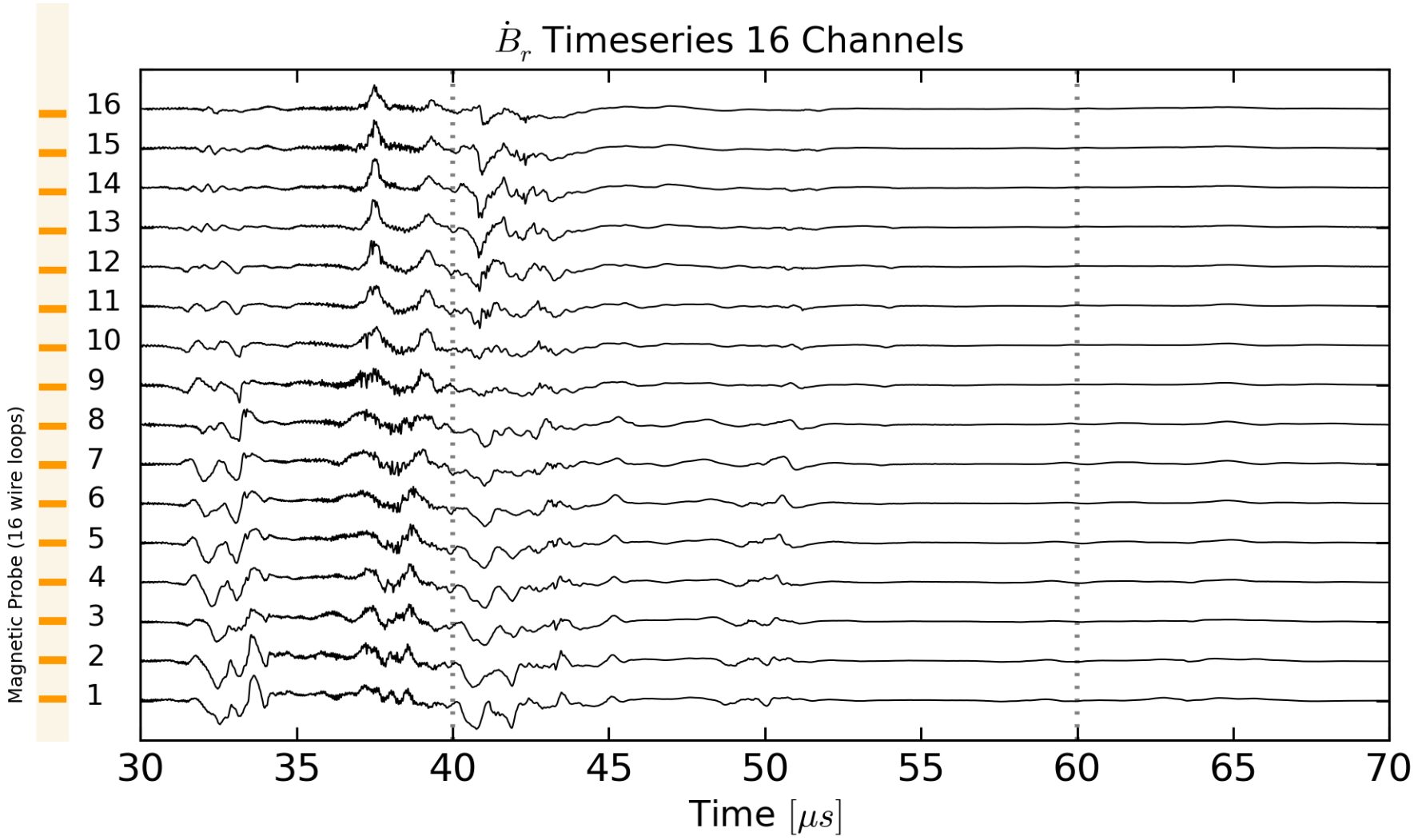
Line-averaged density with He-Ne, temperature from IDS

PDF of temporal increments

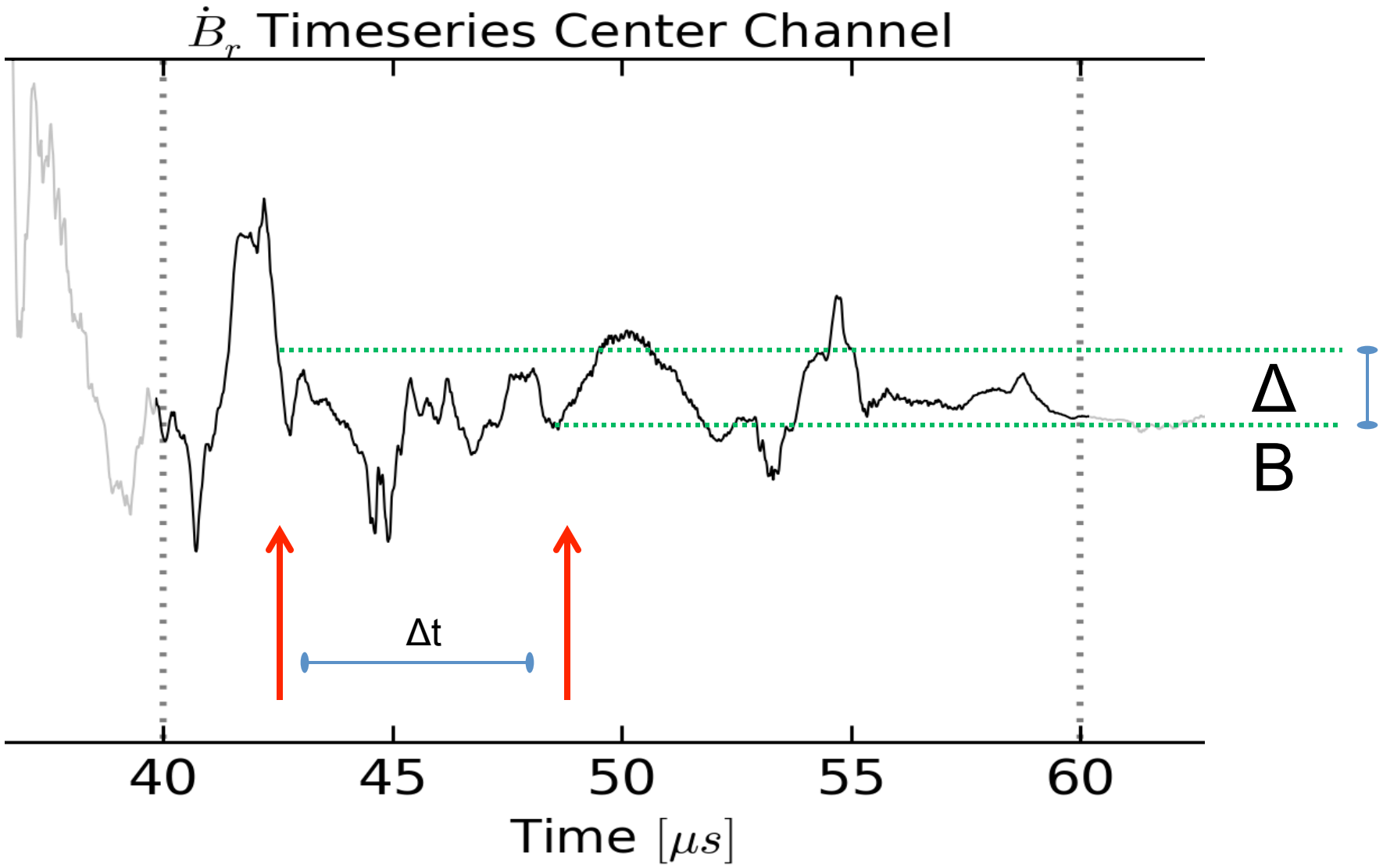
$$\Delta \mathbf{b}(t, \Delta t) = \mathbf{b}(t + \Delta t) - \mathbf{b}(t)$$

$$S^2(\Delta t) = \langle (\mathbf{b}(t + \Delta t) - \mathbf{b}(t))^2 \rangle$$

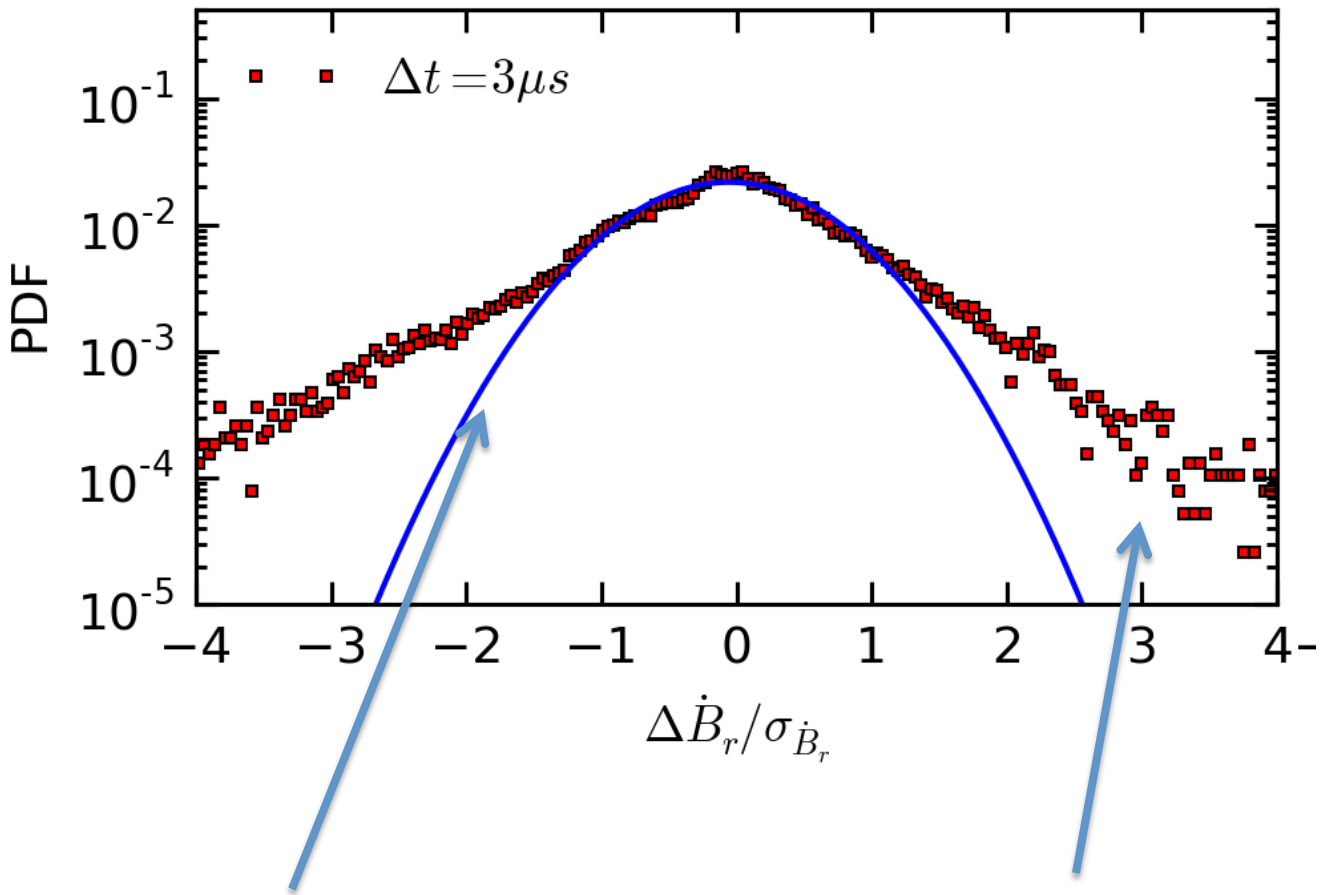
$$S^2(\Delta r) = \langle (\mathbf{b}(r + \Delta r) - \mathbf{b}(r))^2 \rangle$$


$\dot{B}_r$ Timeseries 16 Channels
Magnetic Probe (16 wire loops)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
30
35
40
45
50
55
60
65
70
Time $[\mu s]$

PDF of Increments



PDF of Increments

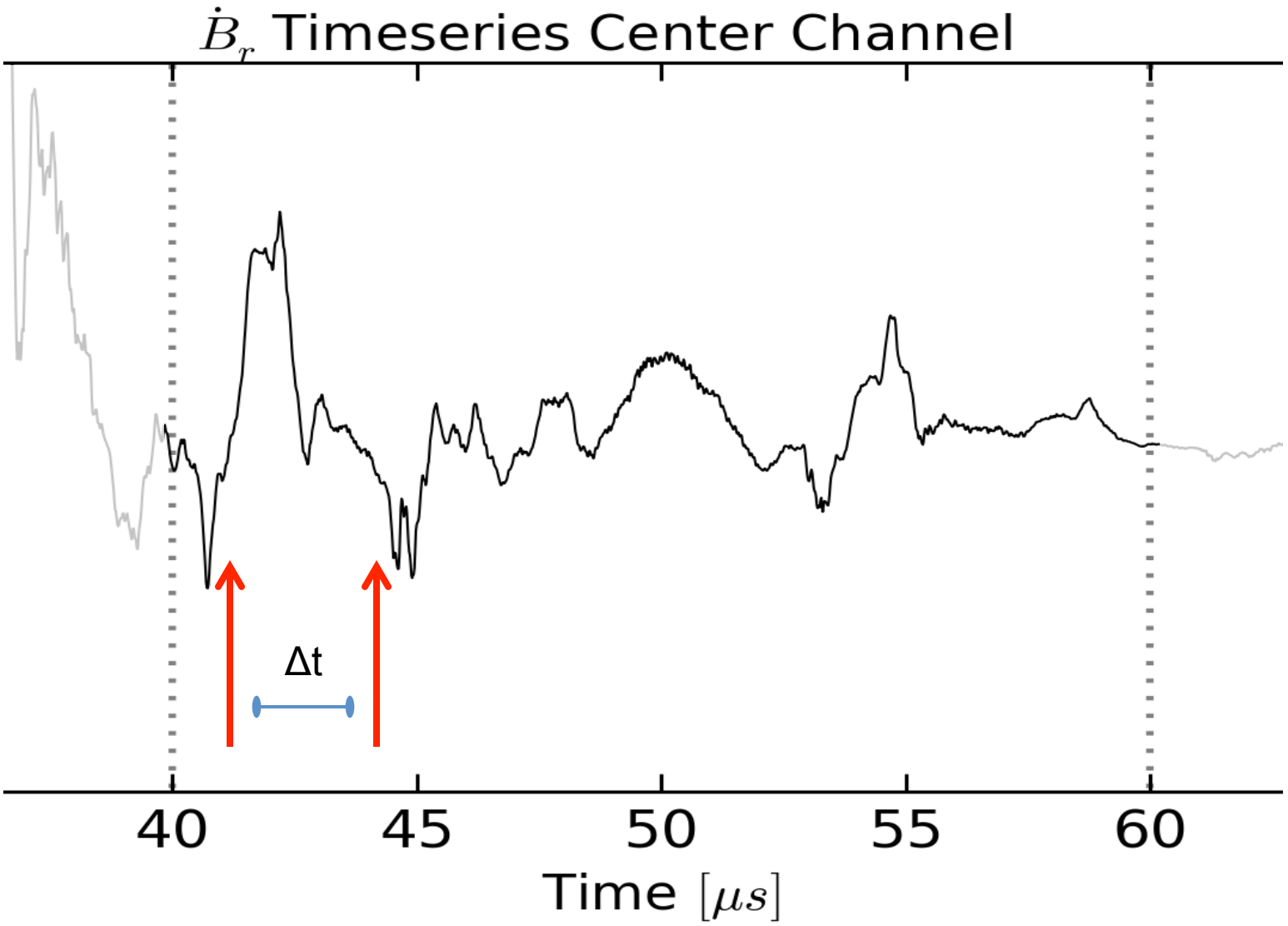


Best fit Gaussian

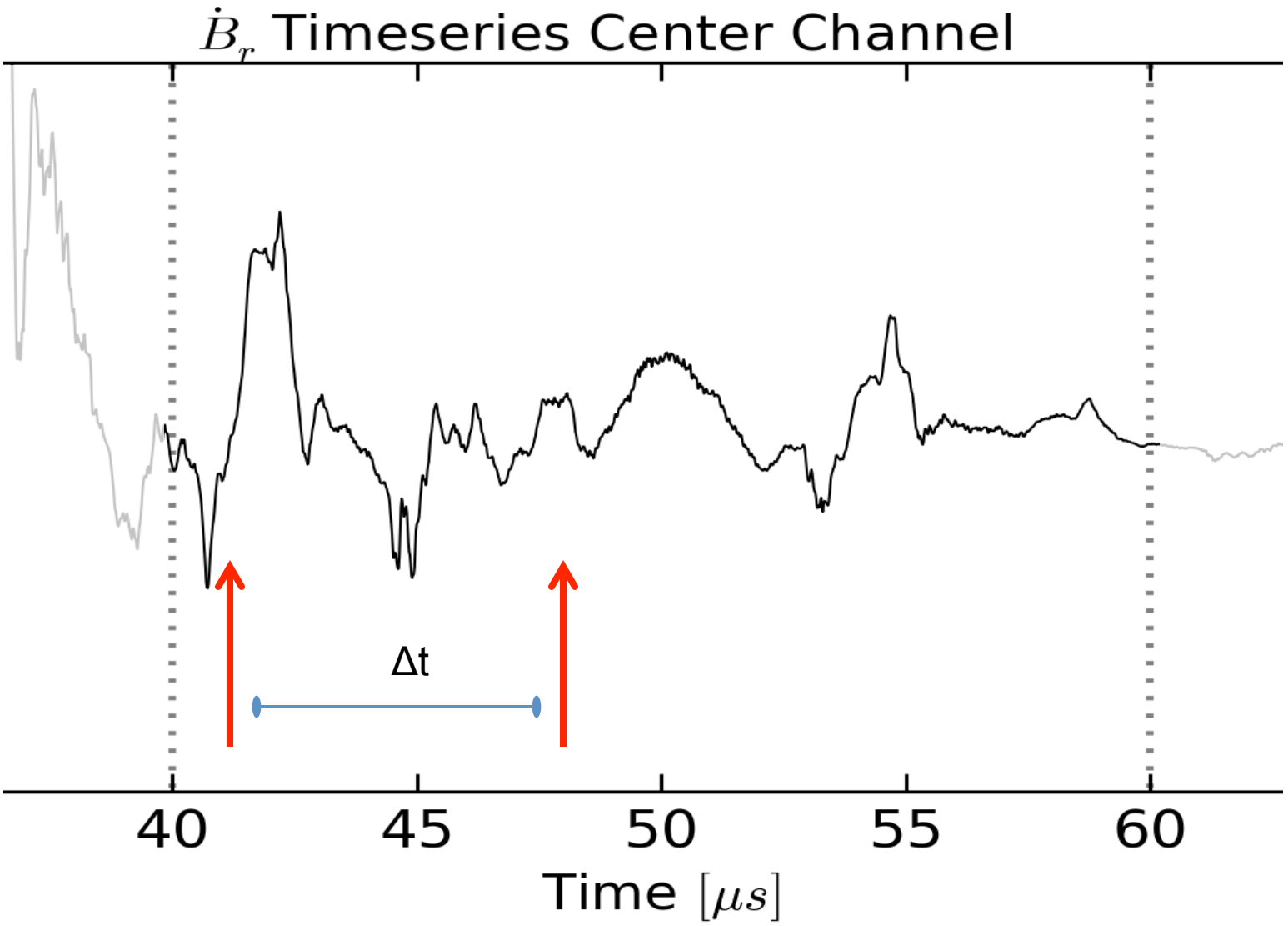
A preponderance of large fluctuations

a.k.a. “Fat Tails”

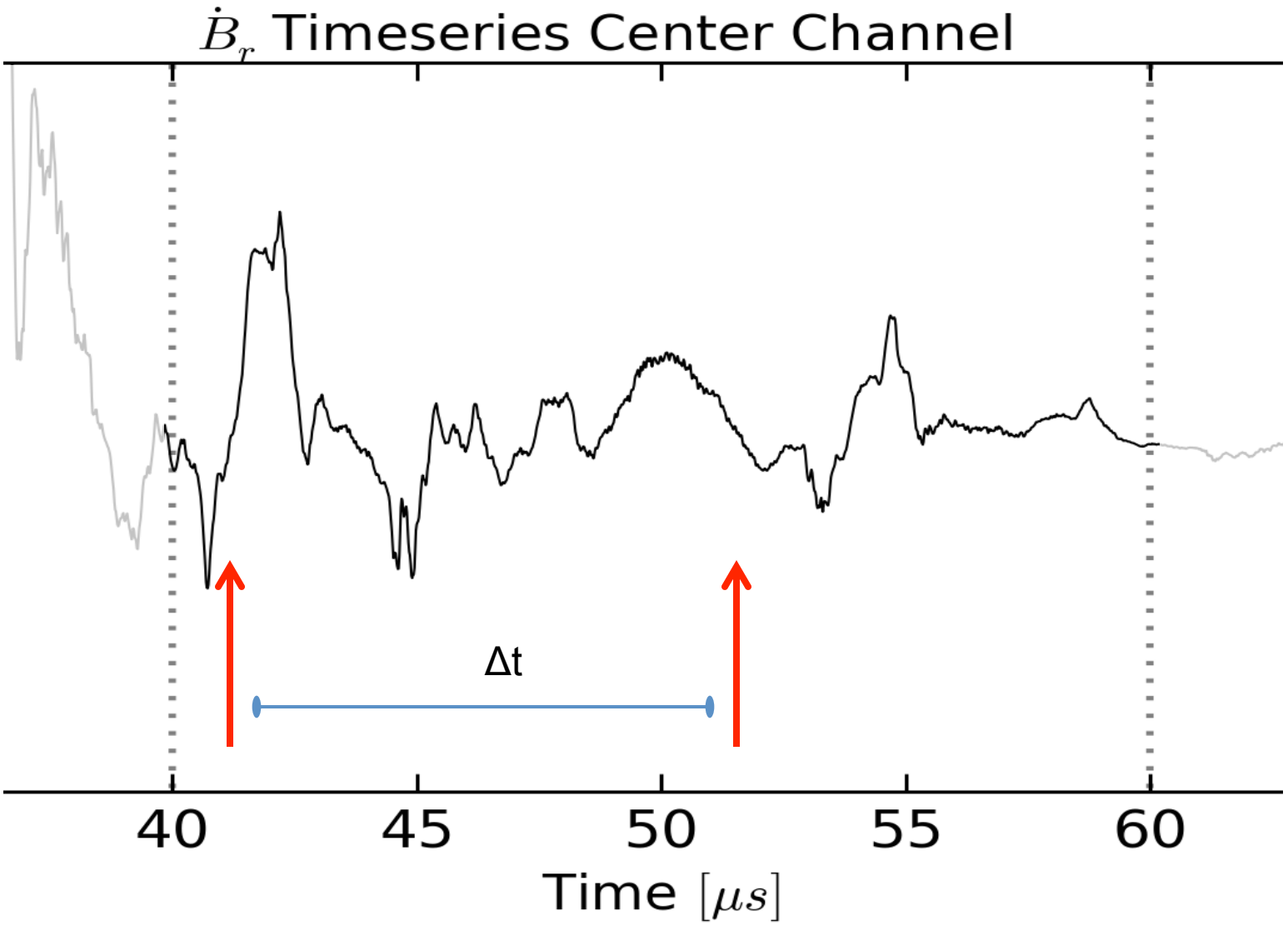
PDF of Increments



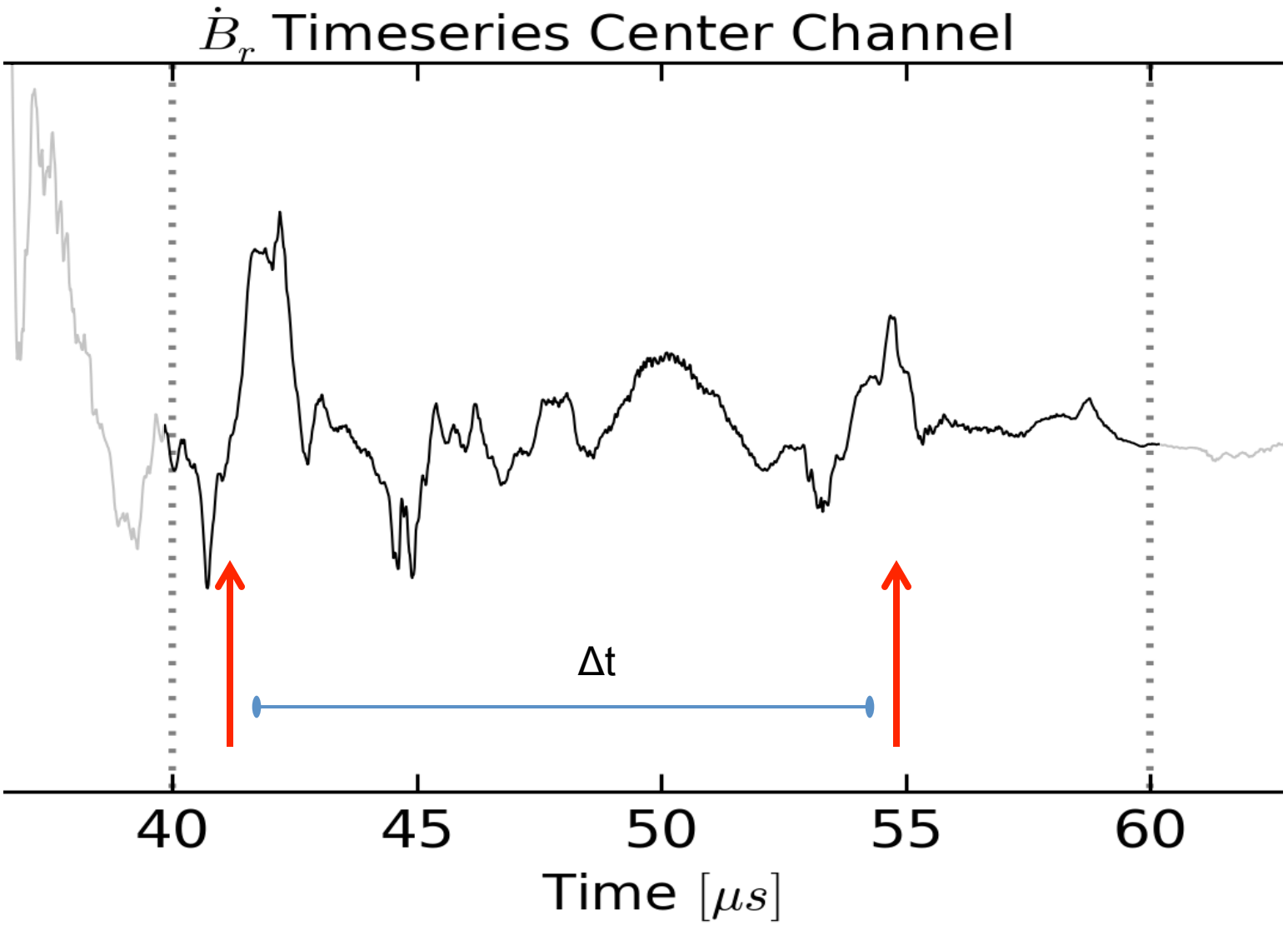
PDF of Increments



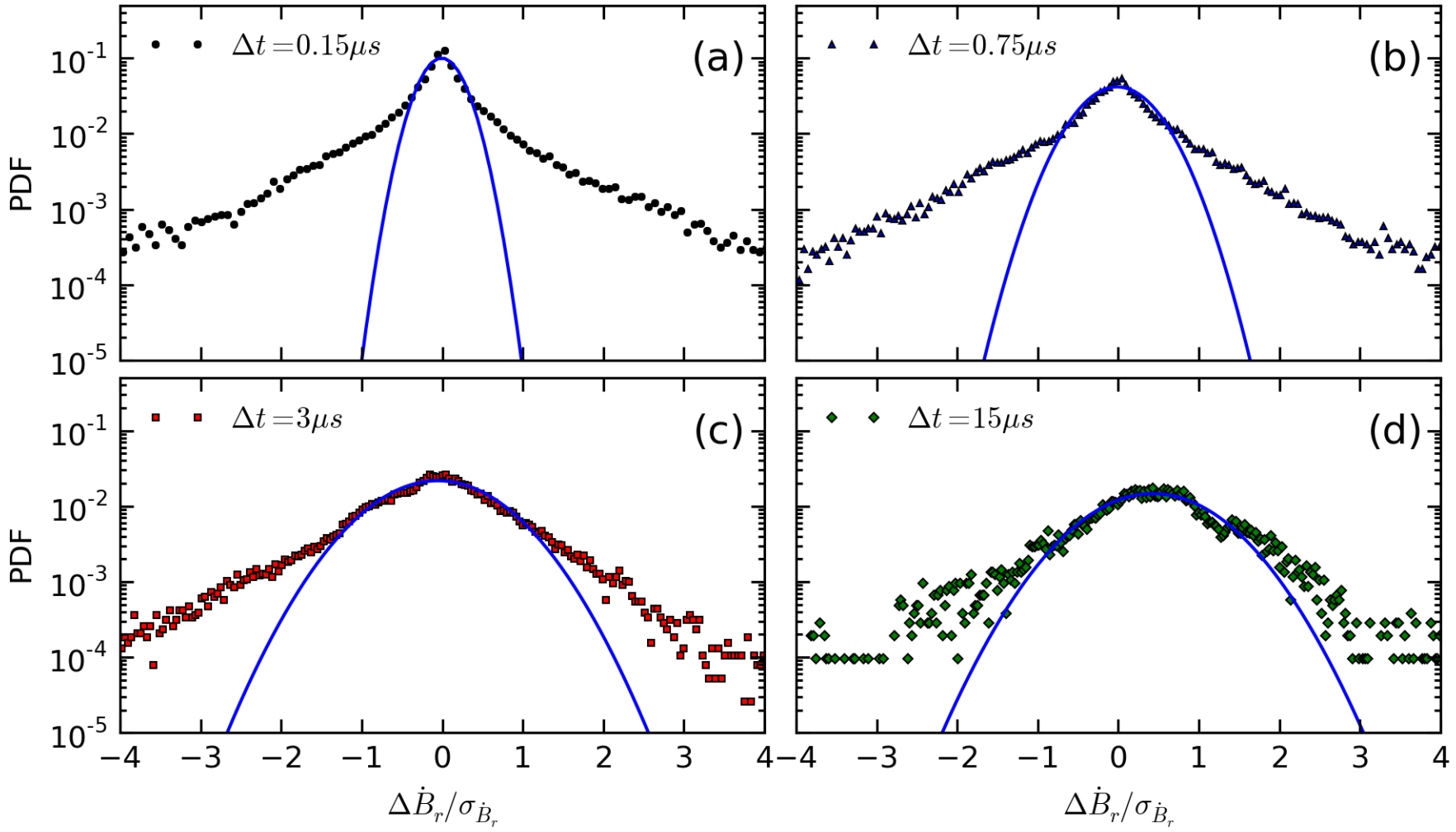
PDF of Increments



PDF of Increments



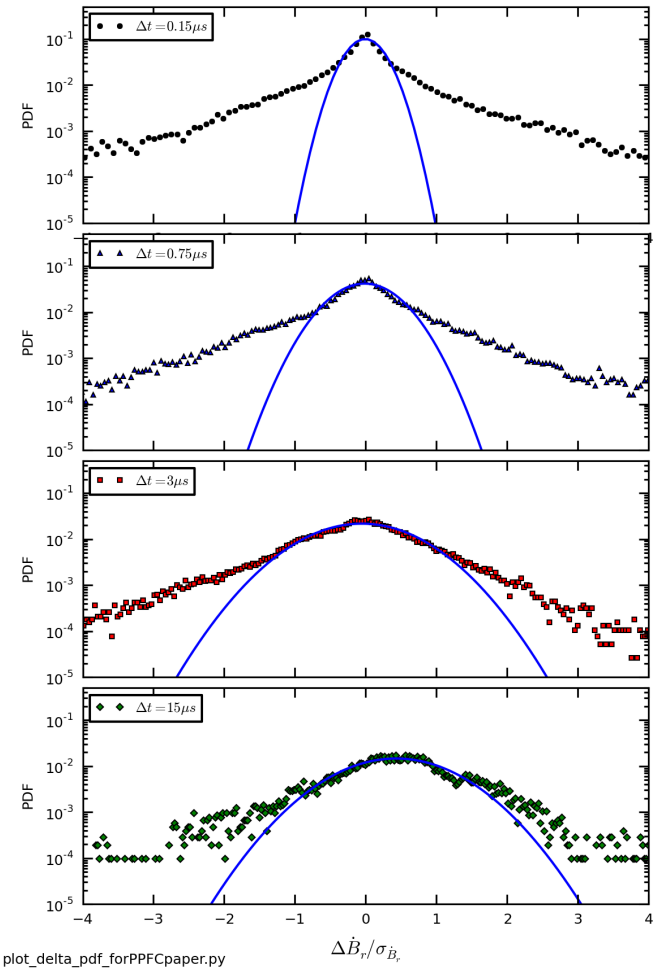
PDF of Increments



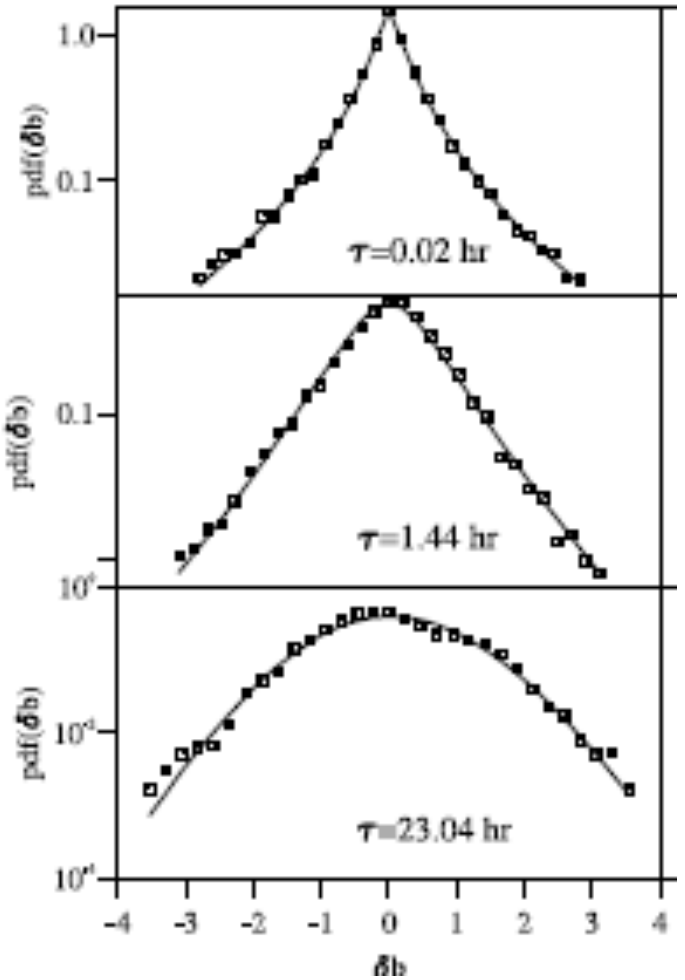
From A to D (small Δt to large Δt)→ More Gaussian, Less Intermittent

PDF of Increments

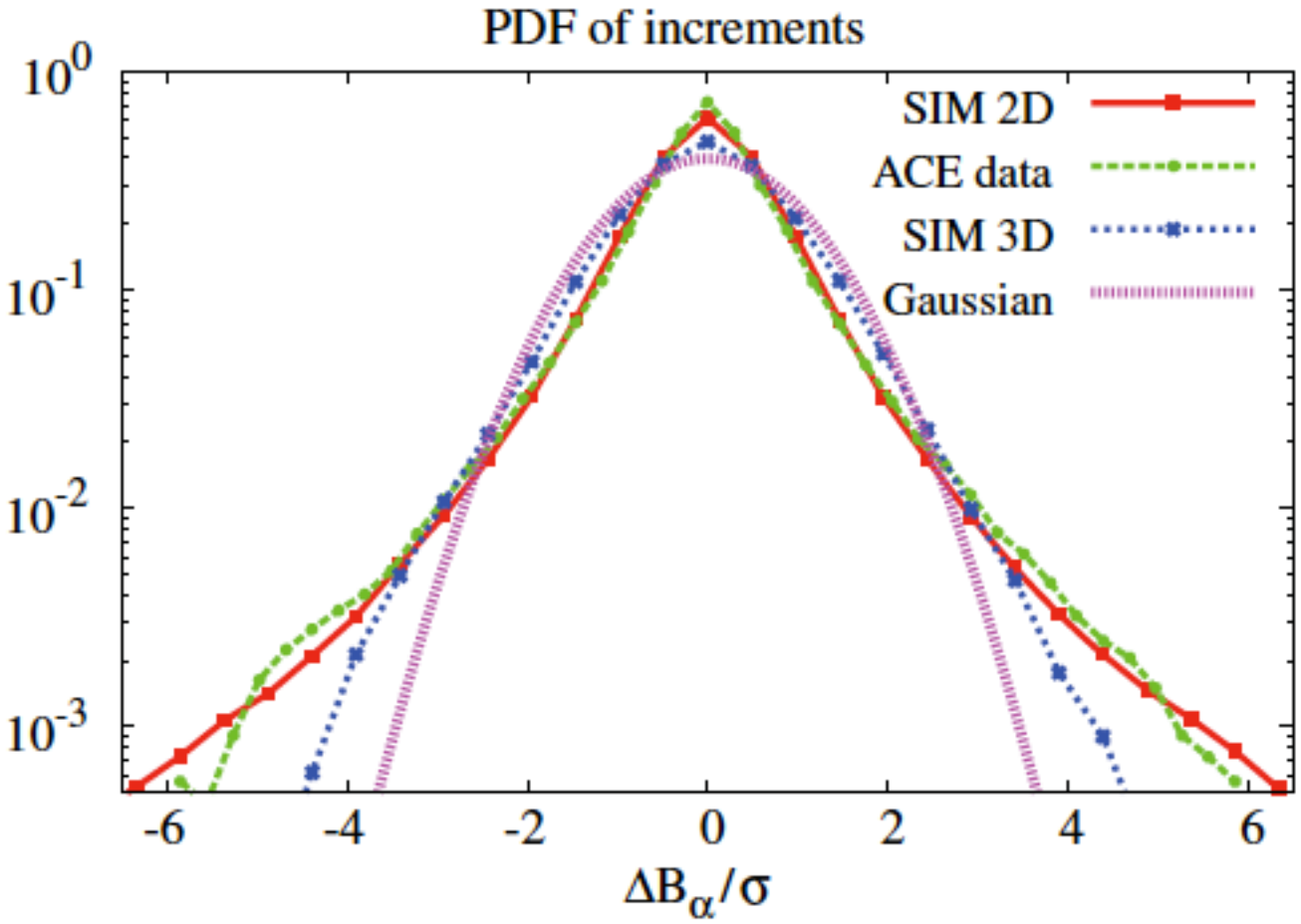
Comparison to Solar Wind



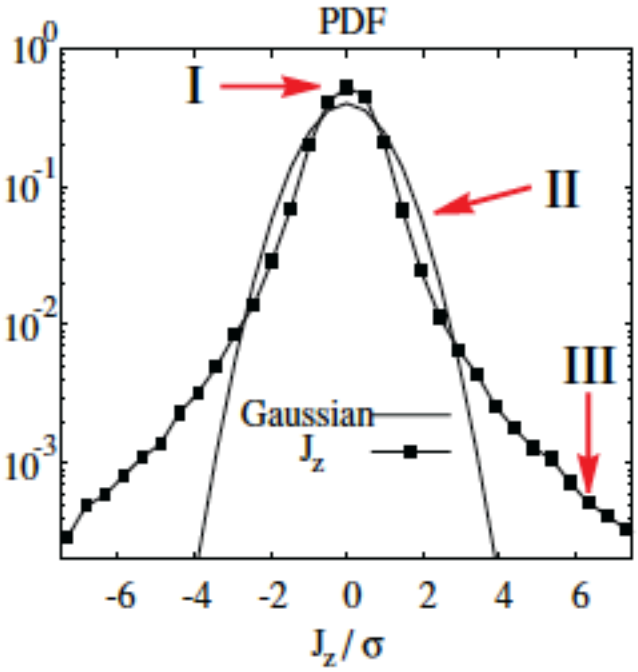
plot_delta_pdf_forPPFCpaper.py

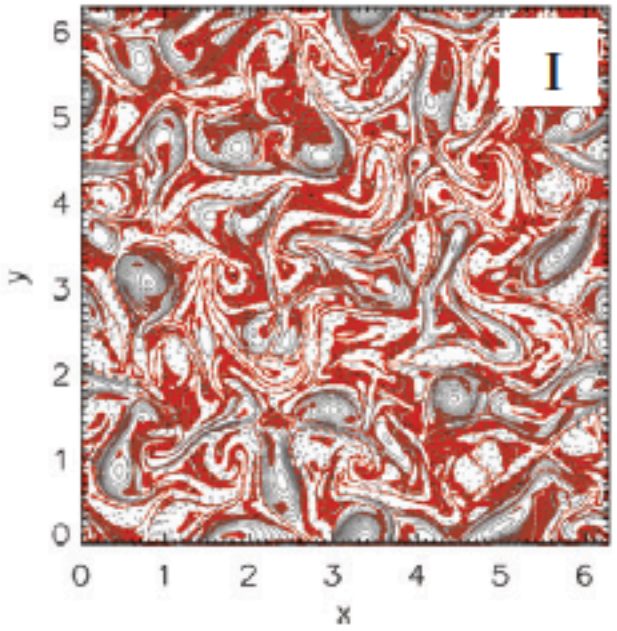


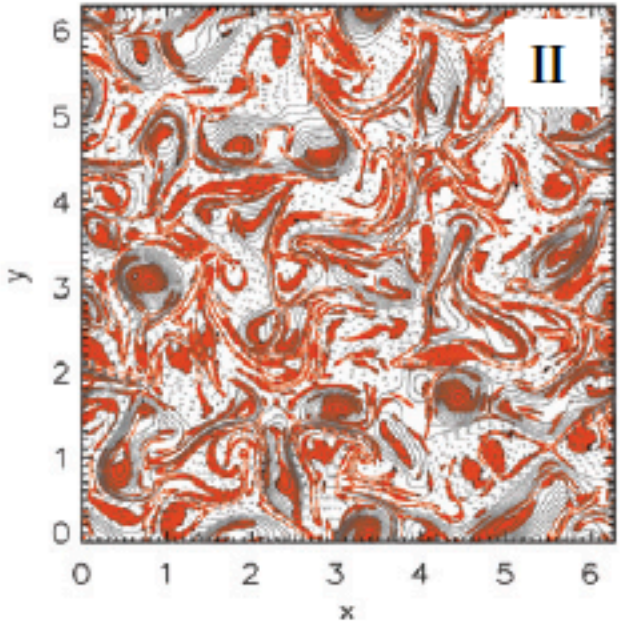
*Dudok de Wit, Space Science Review 2013

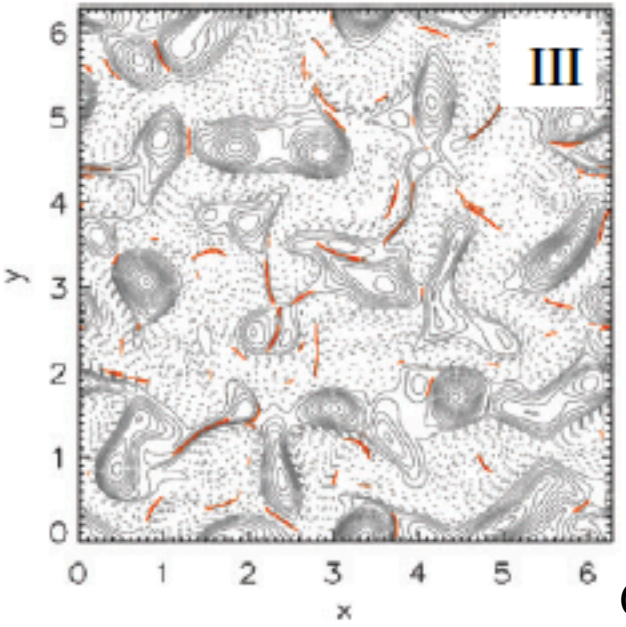

PDF of increments
SIM 2D
ACE data
SIM 3D
Gaussian
10^0
10^{-1}
10^{-2}
10^{-3}
-6
-4
-2
0
2
4
6
$\Delta B_\alpha/\sigma$

Greco, 2009

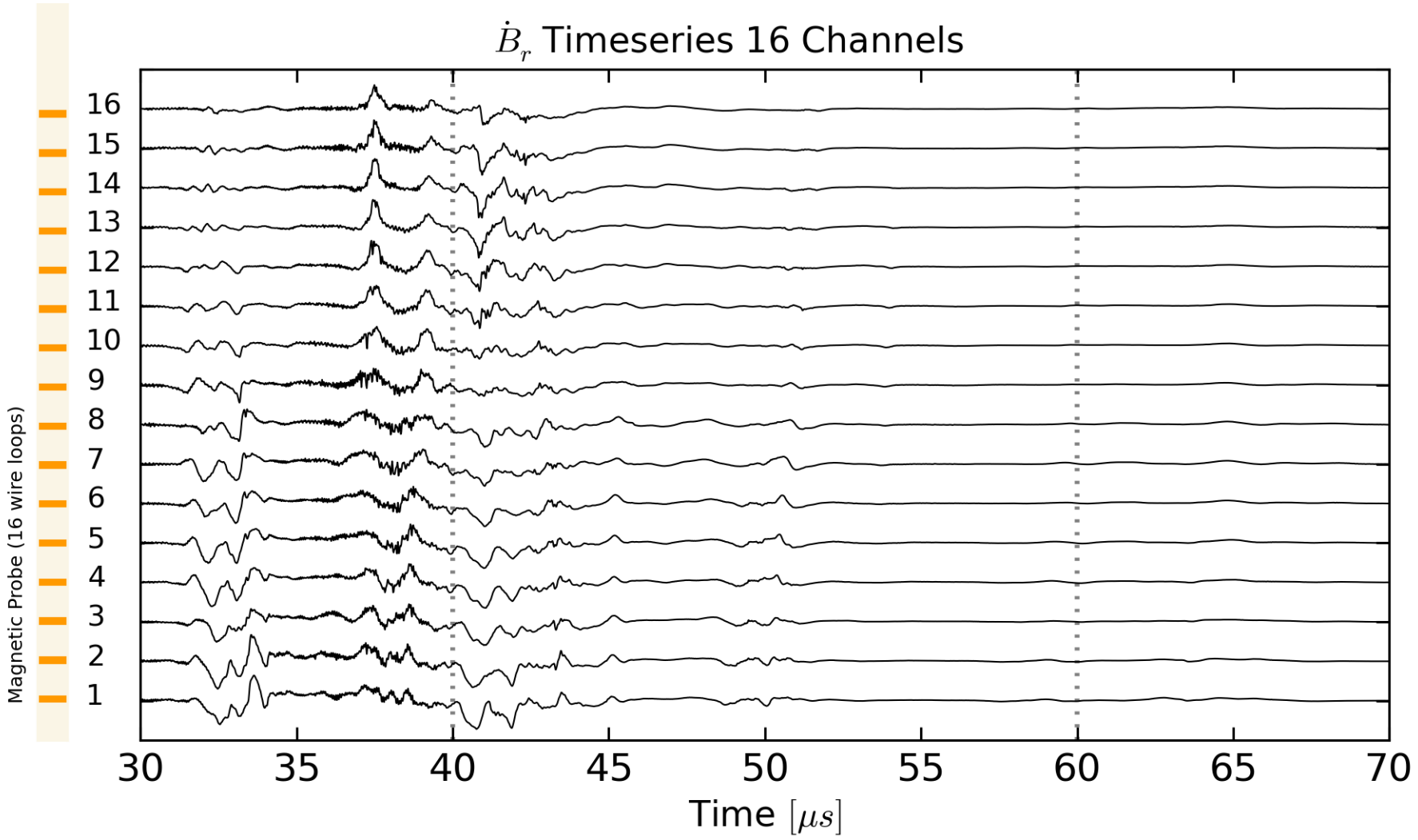

PDF
I
II
III
Gaussian
J_z
10^0
10^{-1}
10^{-2}
10^{-3}
-6 -4 -2 0 2 4 6
J_z / σ


I
y
x
0 1 2 3 4 5 6


II
y
x
0 1 2 3 4 5 6

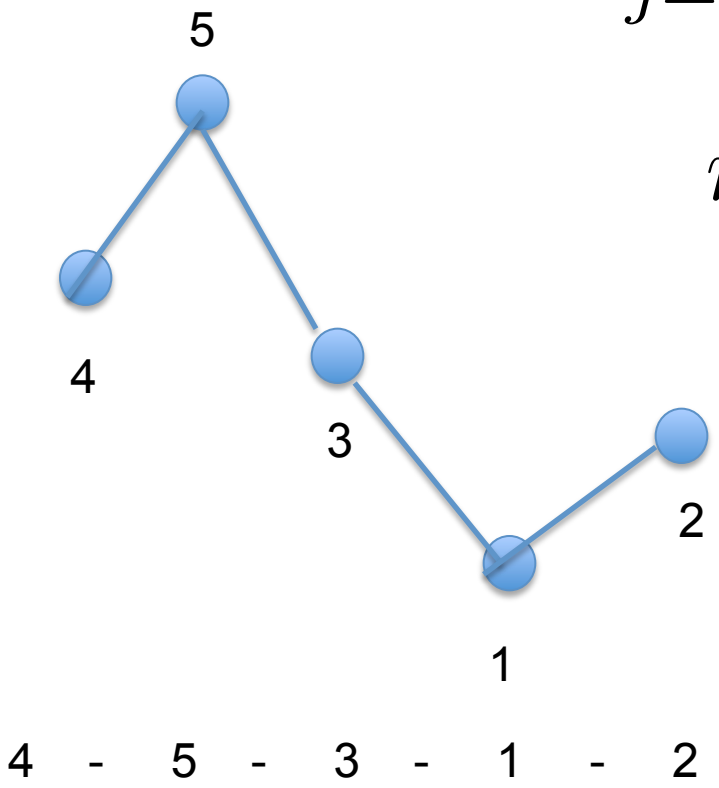

III
y
x
0 1 2 3 4 5 6

Greco, 2009

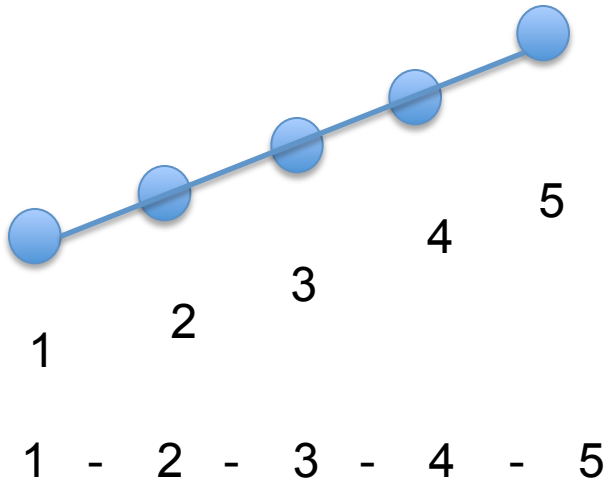

$\dot{B}_r$ Timeseries 16 Channels
Magnetic Probe (16 wire loops)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
30
35
40
45
50
55
60
65
70
Time $[\mu s]$

Permutation Entropy

$$S[P] = -\sum_{j=1}^{N} p_j ln(p_j)$$



$$n = 5, N = n! = 120$$



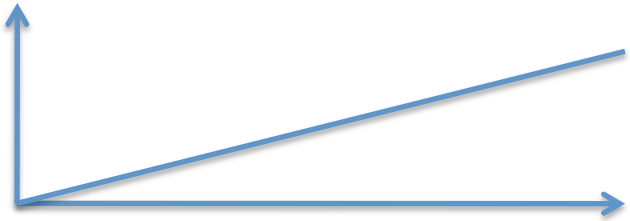
Permutation Entropy

$$S[P] = -\sum_{j=1}^{N} p_j ln(p_j)$$

Case 1: all N=120 permutations equally likely...
S = ln(N)… maximum

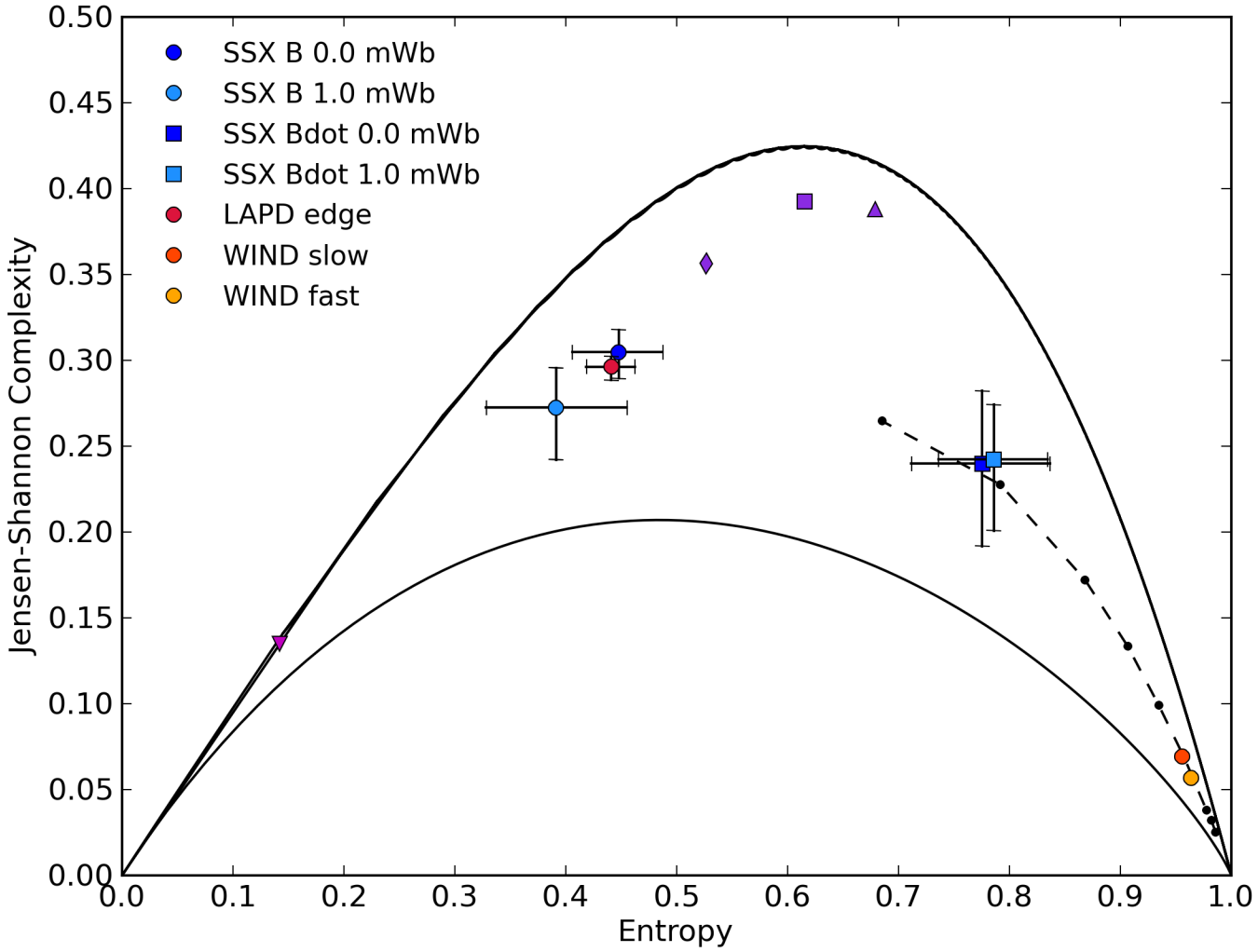
$$S = -\sum_{j=1}^{N} \frac{1}{N} ln(1/N) = N\frac{1}{N} ln(N) = ln(N)$$

Case 2: linear ramp so only one permutation appears… S = 0… minimum



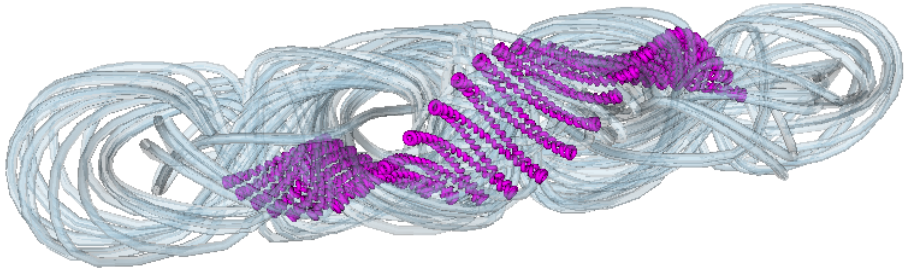
Complexity-Entropy map (SSX, solar wind, deterministic chaos)

PRE, Weck, et al (2014)

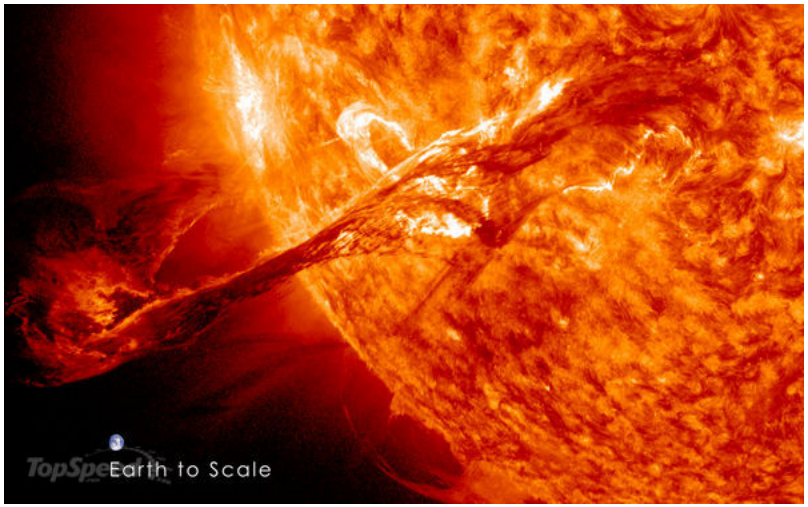


Summary

Turbulent relaxation shows the emergence of a twisted helical magnetic structure in SSX that is a good trap for protons



Similar to magnetic structures observed in solar/space plasmas



Thank you!
Questions?