Experimental studies of the Bullard-von Kármán dynamo

Sophie Miralles[1,2],
Nicolas Plihon[1] & Jean-François Pinton[1]

article: Miralles et al. JFM, 2015

[1]Laboratoire de Physique, Ecole Normale Supérieure de Lyon
[2] Institute für Geophysik, ETH Zürich, Switzerland

Problem

<u>Experimental turbulent dynamo main issues:</u>

Influence of the turbulent fluctuations on the dynamo mechanism
Lorentz force influence on the flow (= saturation of B)

Study of the coupled problem U $\leftrightarrows$ B

Outline

- MHD equations and experimental setup
- Semi-synthetic dynamo (bifurcation)
- Power budget and flow measurements

MHD relevant equations

$$(\partial t B + (U \cdot \nabla) B) = (B \cdot \nabla) U + Rm^{-1} \nabla^2 B$$

Induction equation

$$(\partial t U + (U \cdot \nabla) U) = Re^{-1} \nabla^2 U + N j \times B$$

Navier Stokes

$$\boxed{Rm = \mu \sigma L U} \gtrsim 1$$

Magnetic Reynolds number
= control parameter

$$Re = \frac{LU}{\nu} \sim 10^6$$

Kinetic Reynolds number

$$\boxed{N = \frac{|j \times B|}{|\rho (U \cdot \nabla U)|}}$$

Interaction parameter

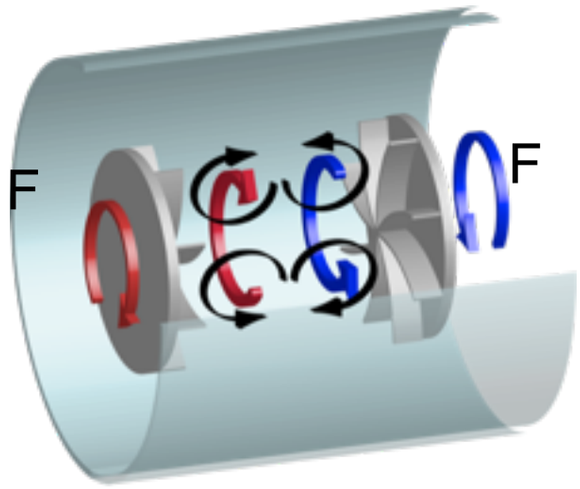
classical study: $N \to 0$

here: N up to 0.2

Lorentz dominant

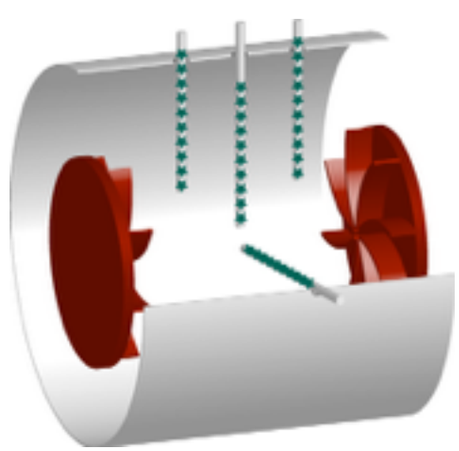
Von Karman sodium dynamo

$$U = 2\pi L F$$
$$Re \sim 10^6$$



Écoulement moyen
Von Kàrmàn

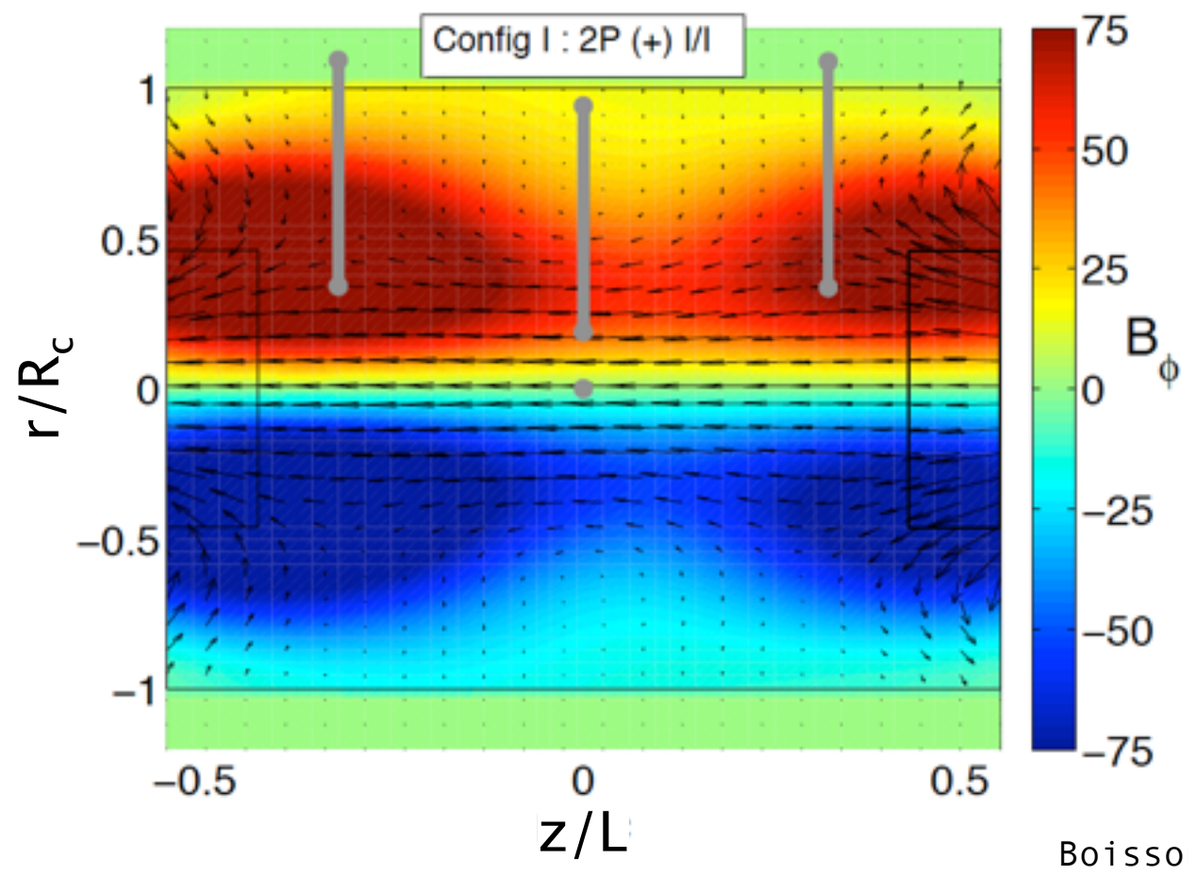
liquid sodium



m = 0 axial dipole

Magnetic field reconstruction
24 Galerkin modes, with (r,φ,x)
modes (3,2,4)

Boisson & Dubrulle, NJP (2011)



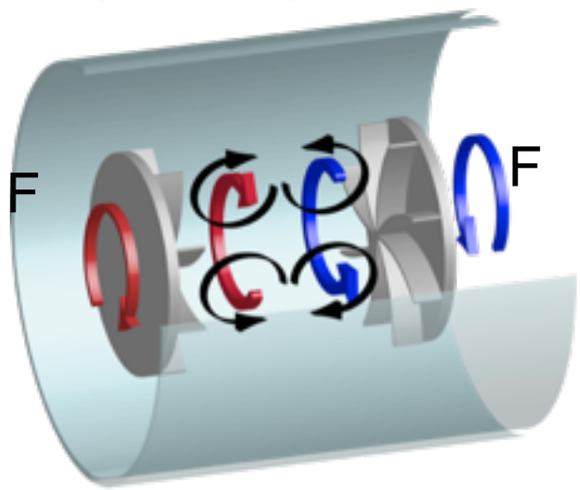
Boisson et al.
NJP 14 (2012)

$$Rm^{\max} \sim 90 \qquad Rm^{c} \sim 44$$

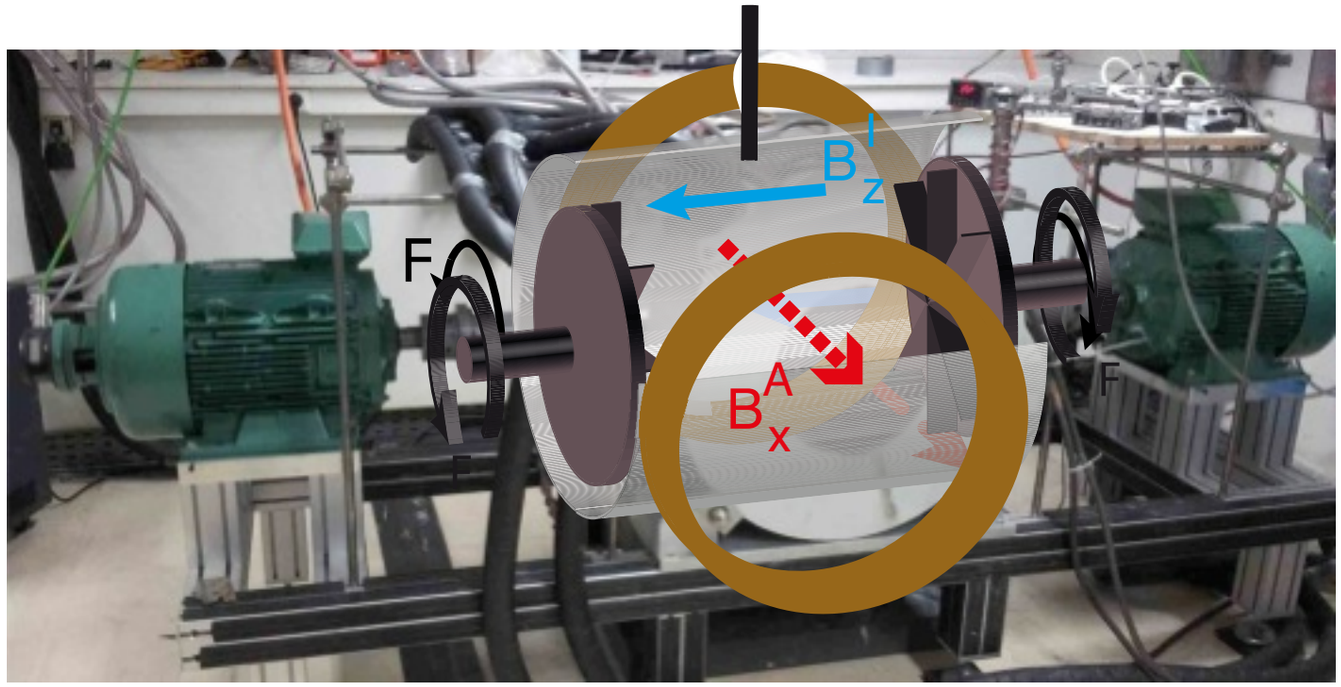
Von Karman gallium flow

$$U = 2\pi L F$$

$$Re \sim 10^6$$



Écoulement moyen
Von Kàrmàn



Transverse applied magnetic field

liquid gallium

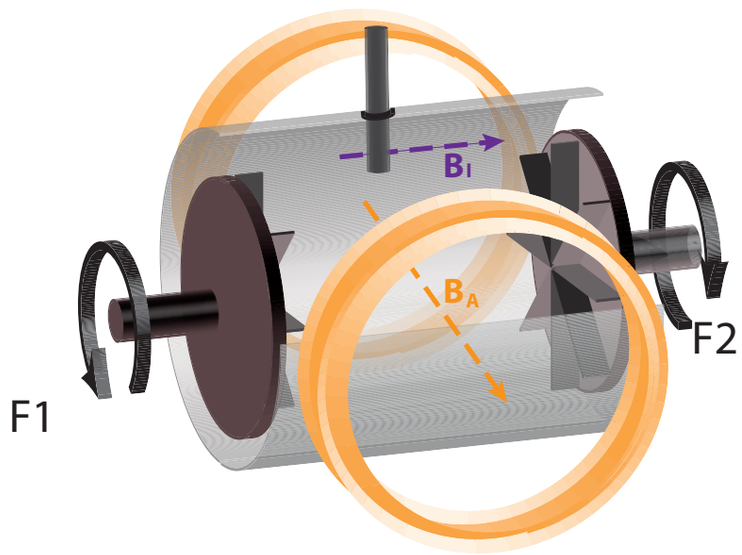
No dynamo effect

B^A up to 1500 G

N up to 0.2

$$Rm^{\max} \sim 5$$

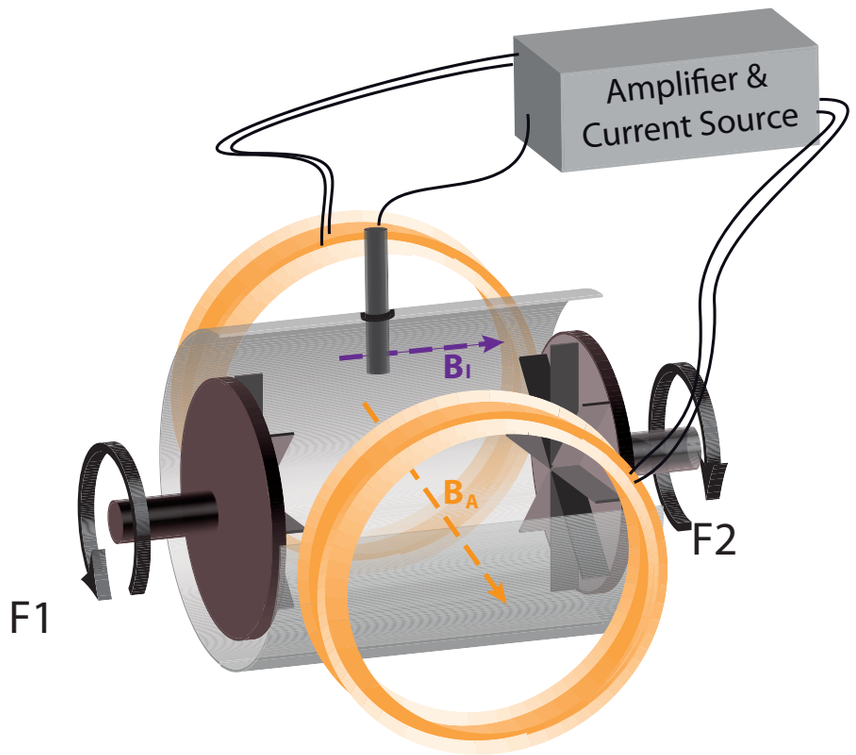
Bullard von Karman Dynamo



Von Karman Gallium flow

$$Rm^{max} \sim 5 \ll Rm^c(\mathrm{VKS})$$

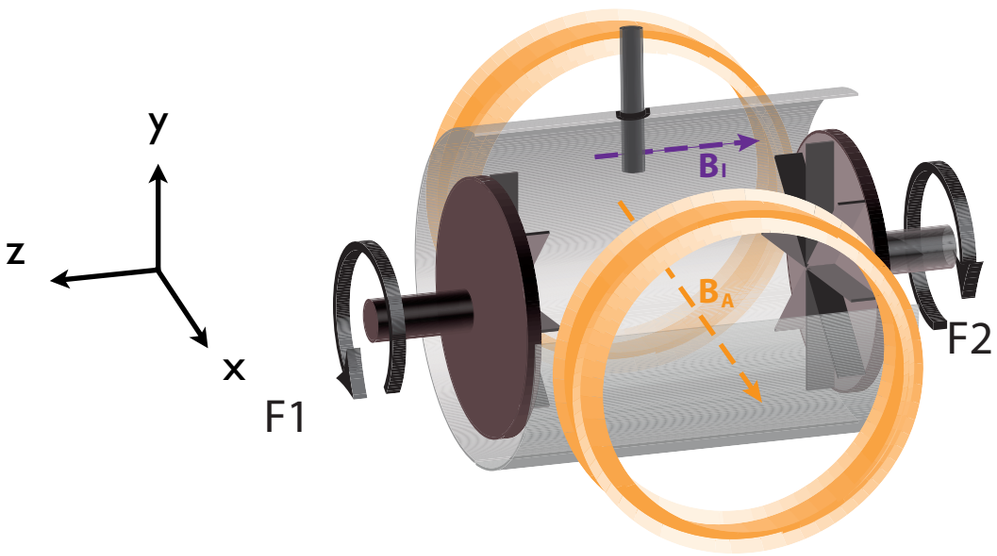
Bullard von Karman Dynamo



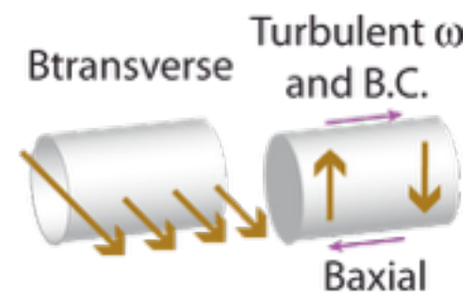
Bullard von Karman
synthetic dynamo

$$Rm^{max} \sim 5 \ll Rm^c(\mathrm{VKS})$$

Bullard von Karman Dynamo



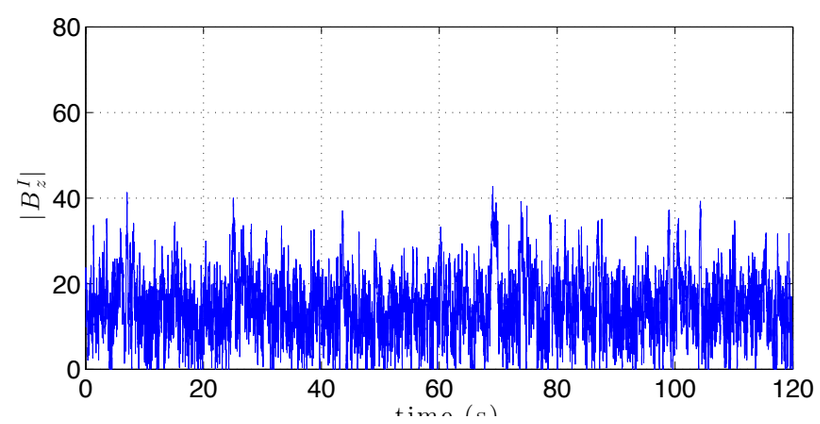
Von Karman Gallium flow



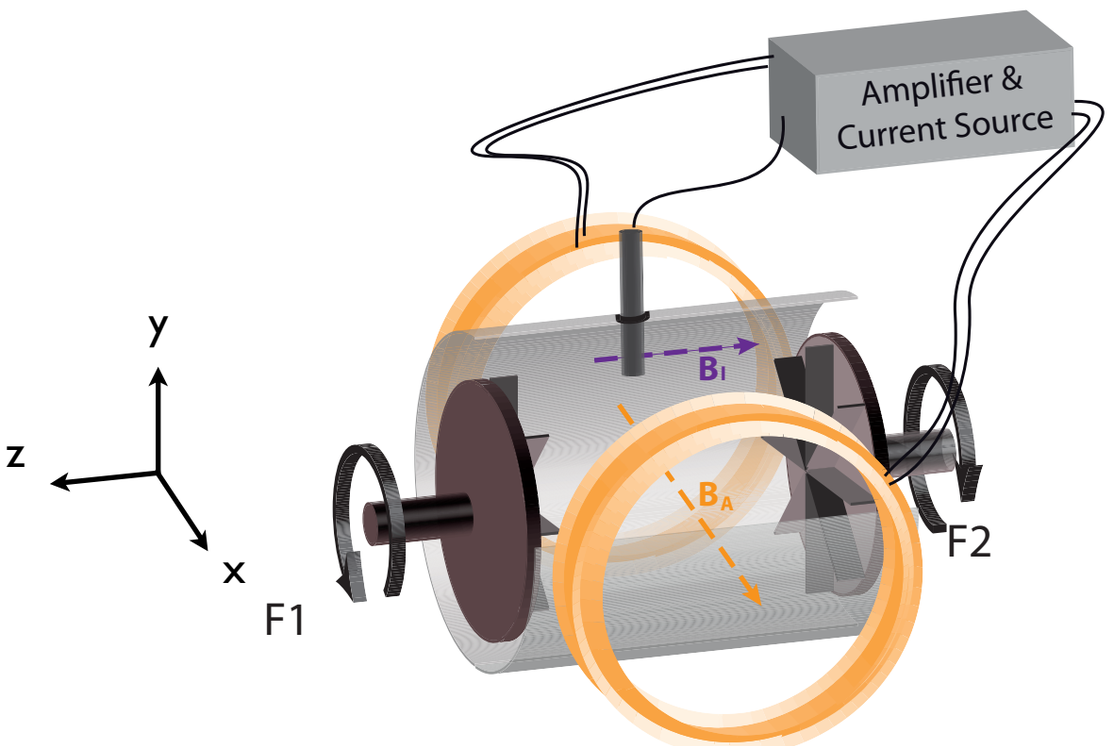
$$< Bz >= kRm < Bx >$$

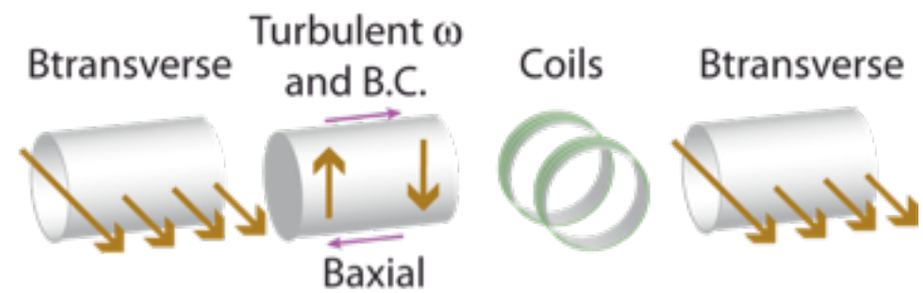
Turbulent induction process

$$Rm^{max} \sim 5 \ll Rm^{c}(\mathrm{VKS})$$



Bullard von Karman Dynamo





$$< Bz >= kRm < Bx > \qquad Bx = ABz$$

Turbulent induction process — External amplification

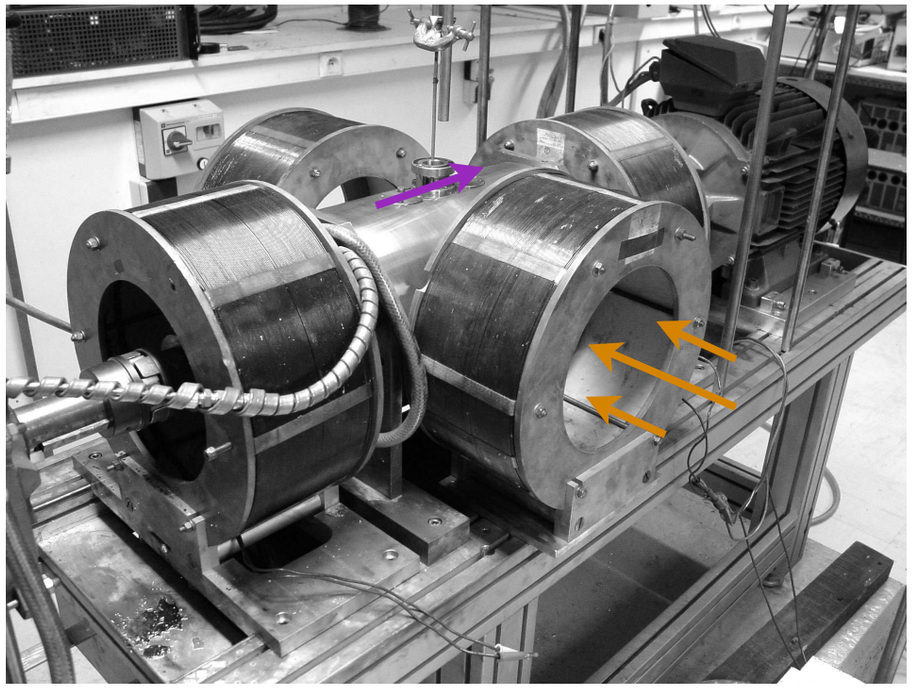
Bullard von Karman
synthetic dynamo

$$Rm^{max} \sim 5 \ll Rm^c(\mathrm{VKS})$$

Instability if:

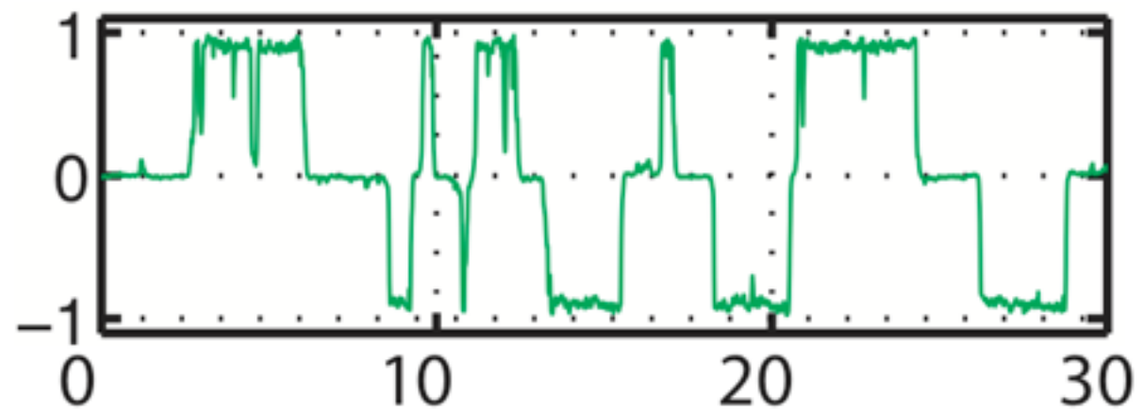
$$\boxed{Rm > Rm^c = \frac{1}{kA}}$$

Kinematic studies



Saturation with Power supply limitations

B^x up to 80 G



Interaction parameter

$$N = \frac{j \times B}{\rho (u \cdot \nabla) u} \sim \frac{\sigma L B^2}{\rho u} \quad << 10^{-4}$$

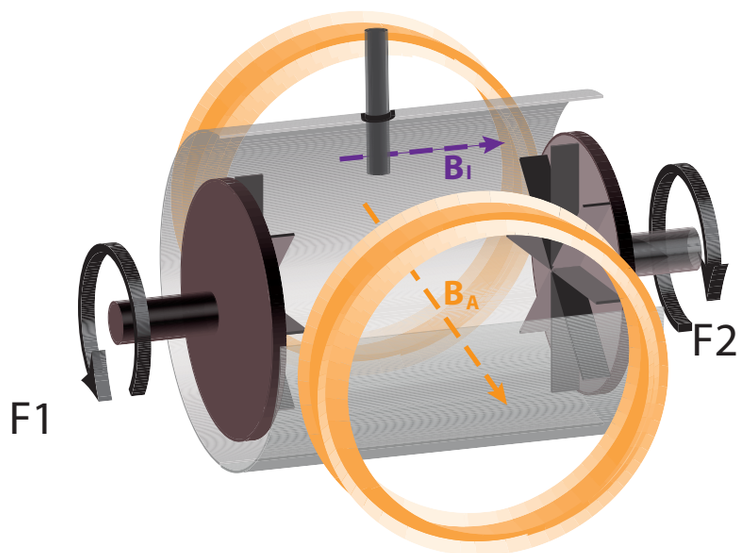
Is the saturation by Lorentz force possible?

Bourgoin et al. NJP, 8 (2006)
Verhille et al. GAFD, 104 (2010)

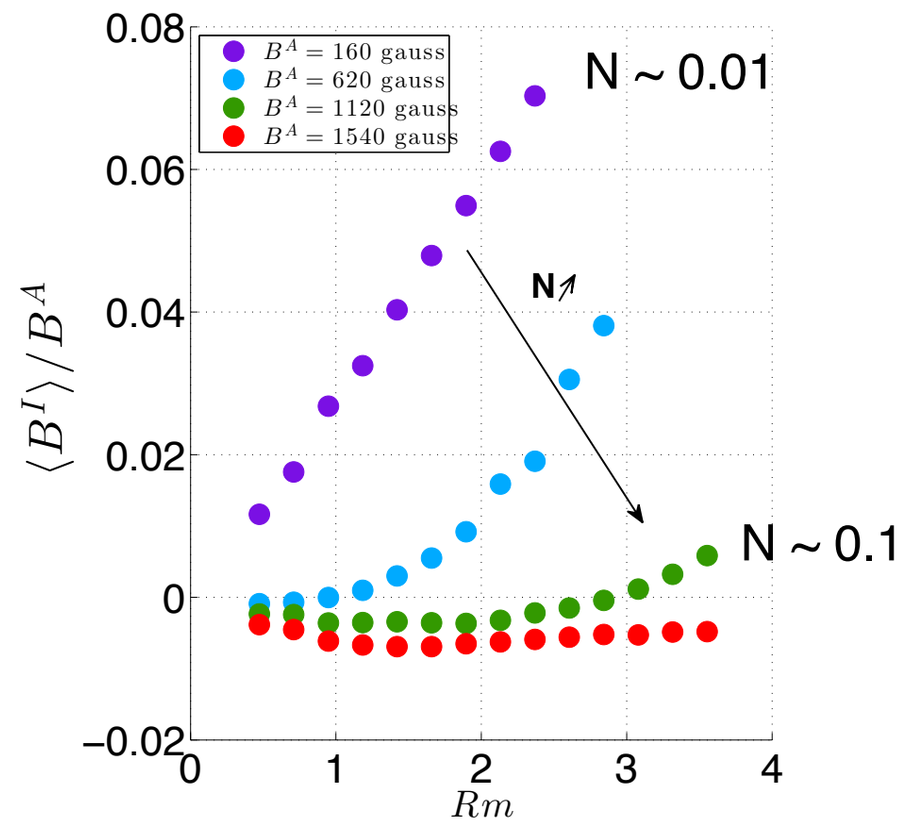
Induction at high interaction parameter

Is the saturation by Lorentz force possible?

B^x up to 2000 G



Induction with Transverse applied field

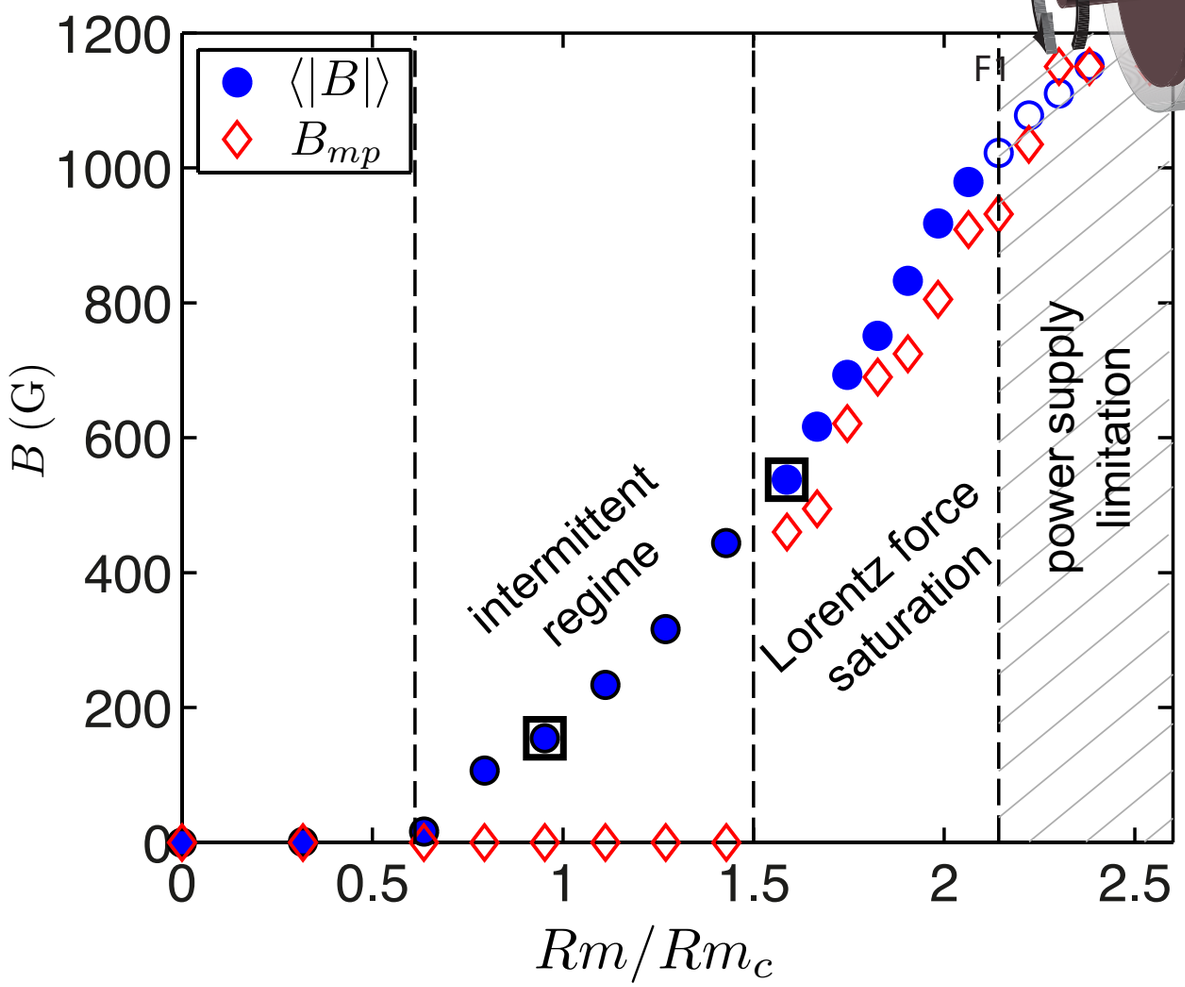


Non linear induction at N ~1

$$Bz = kRm(1 - \alpha\sqrt{N})Bx$$

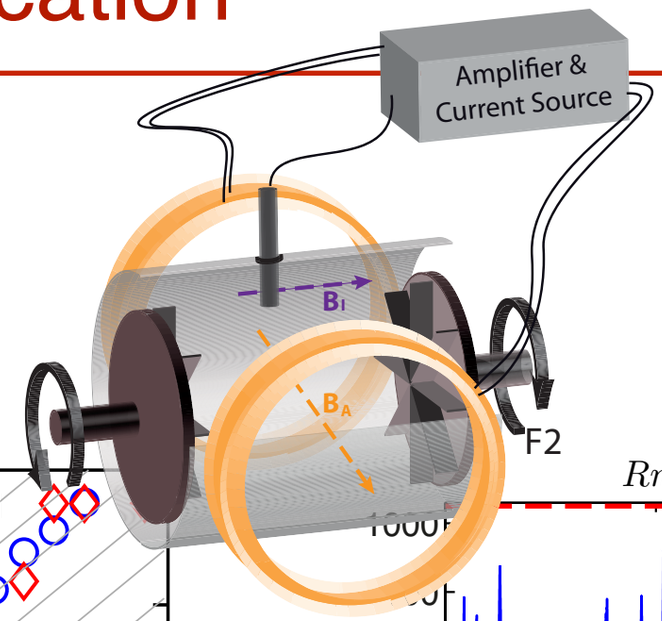
Verhille et al., JFM (2012)

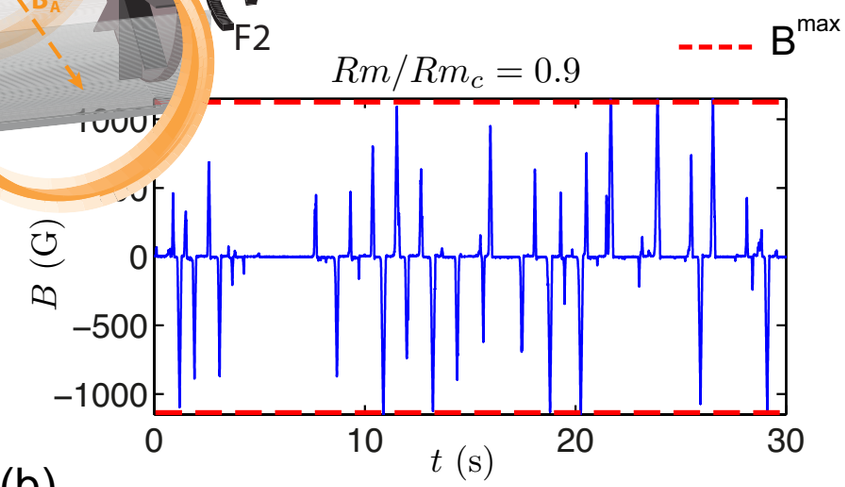
Bifurcation



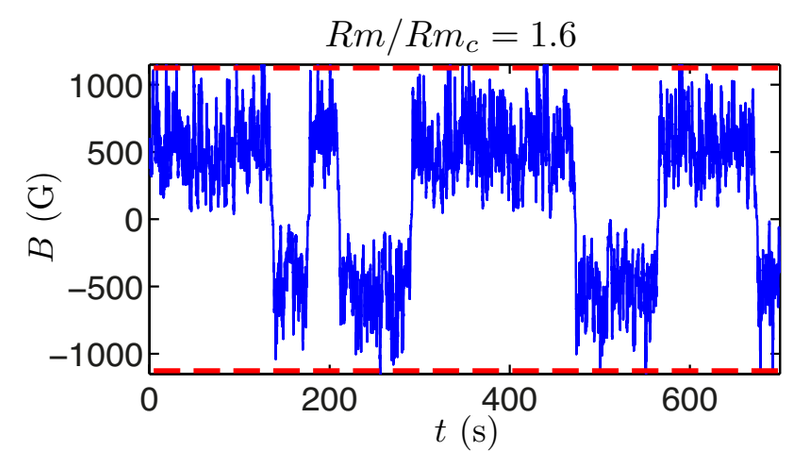
(a)

Bifurcation diagram





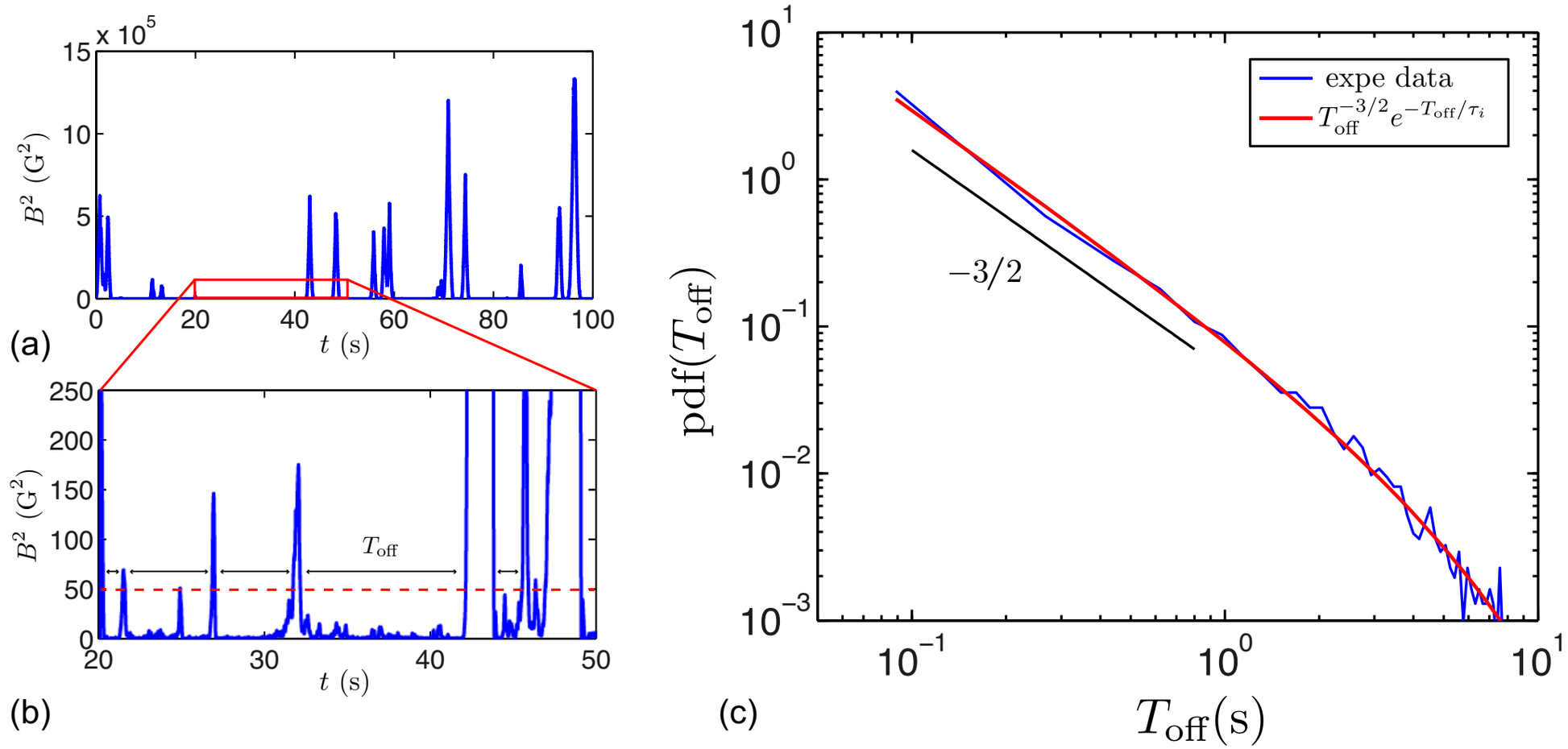
(b)



(c)

Time series

On-off intermittency



Intermittent regime: magnetic field bursts

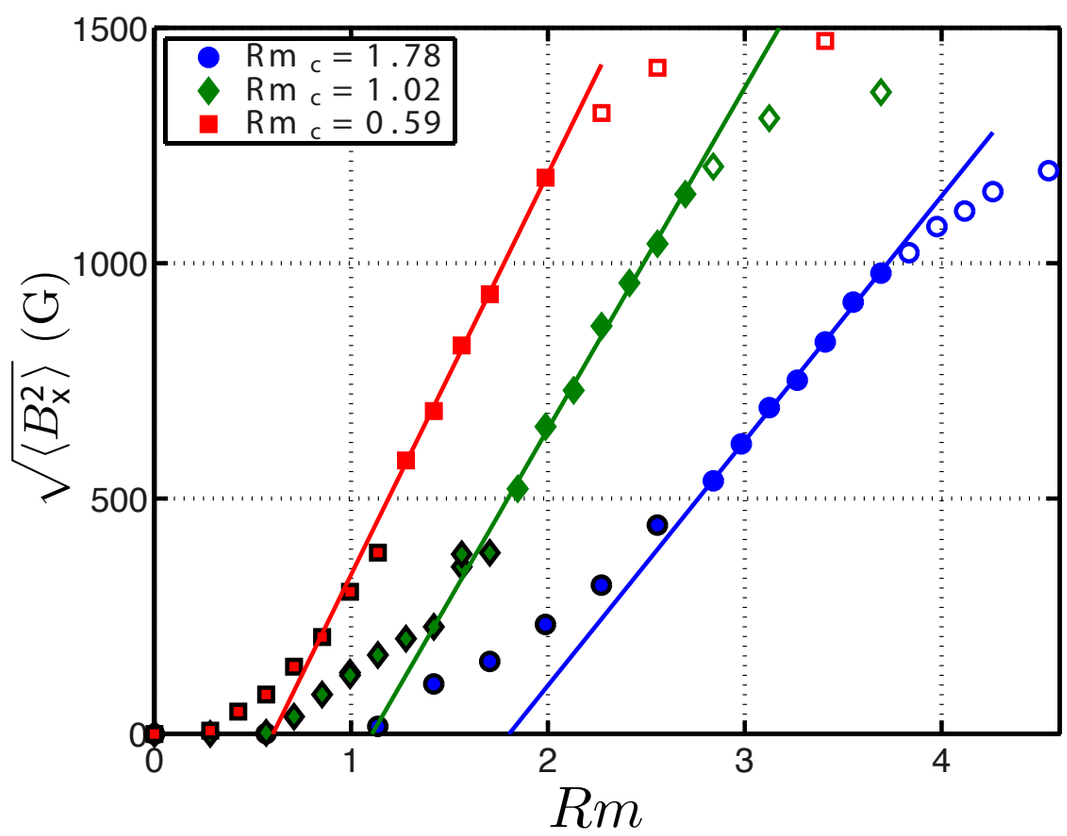
Statistics of the on-off intermittency: pdf(T_{off}) ~$T_{off}^{-3/2}$ e $^{-Toff/Ti}$

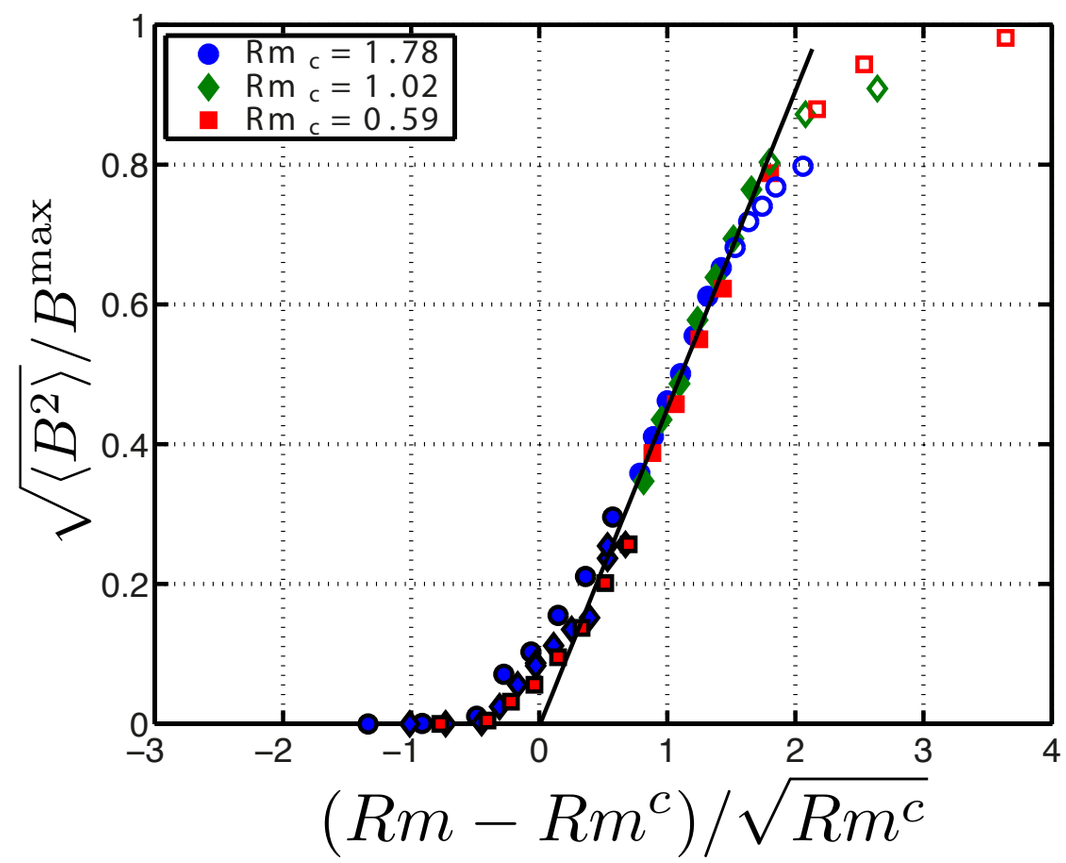
Saturation regime

$$B = \sqrt{\frac{\rho}{\mu_0}} \frac{1}{\alpha \sigma R_0} \left(\frac{Rm - Rm^c}{\sqrt{Rm^c}} \right)$$

with $Rm^c = \frac{1}{kA}$

Scaling law: linearity with the control parameter





Power budget

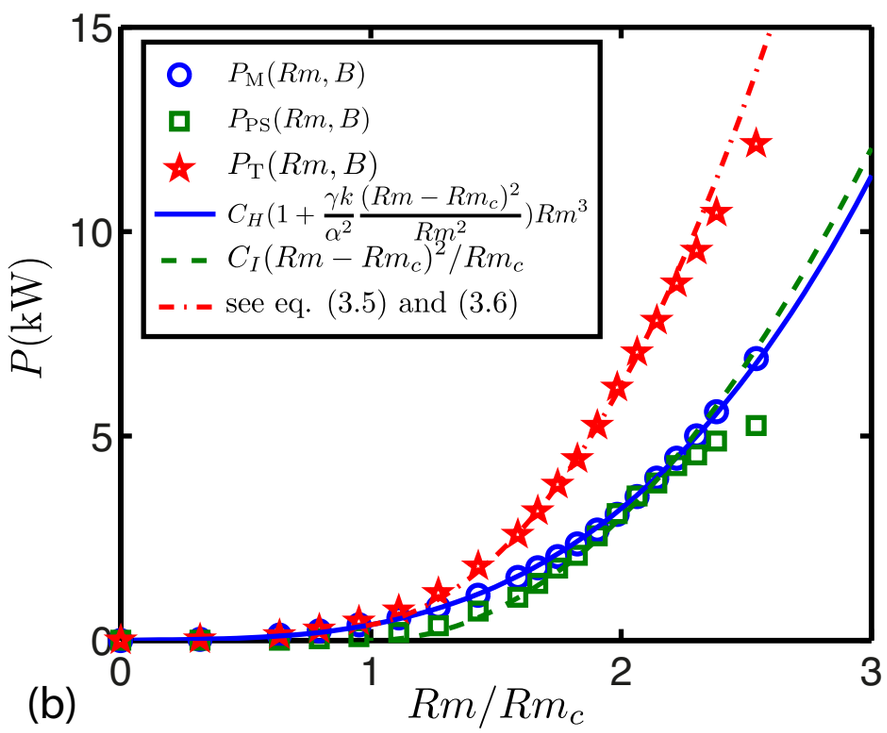
Bullard von Karman dynamo power budget

$$P_{tot} = P_M + P_{\mathrm{PS}}$$

Total power

mechanical power

Power supply

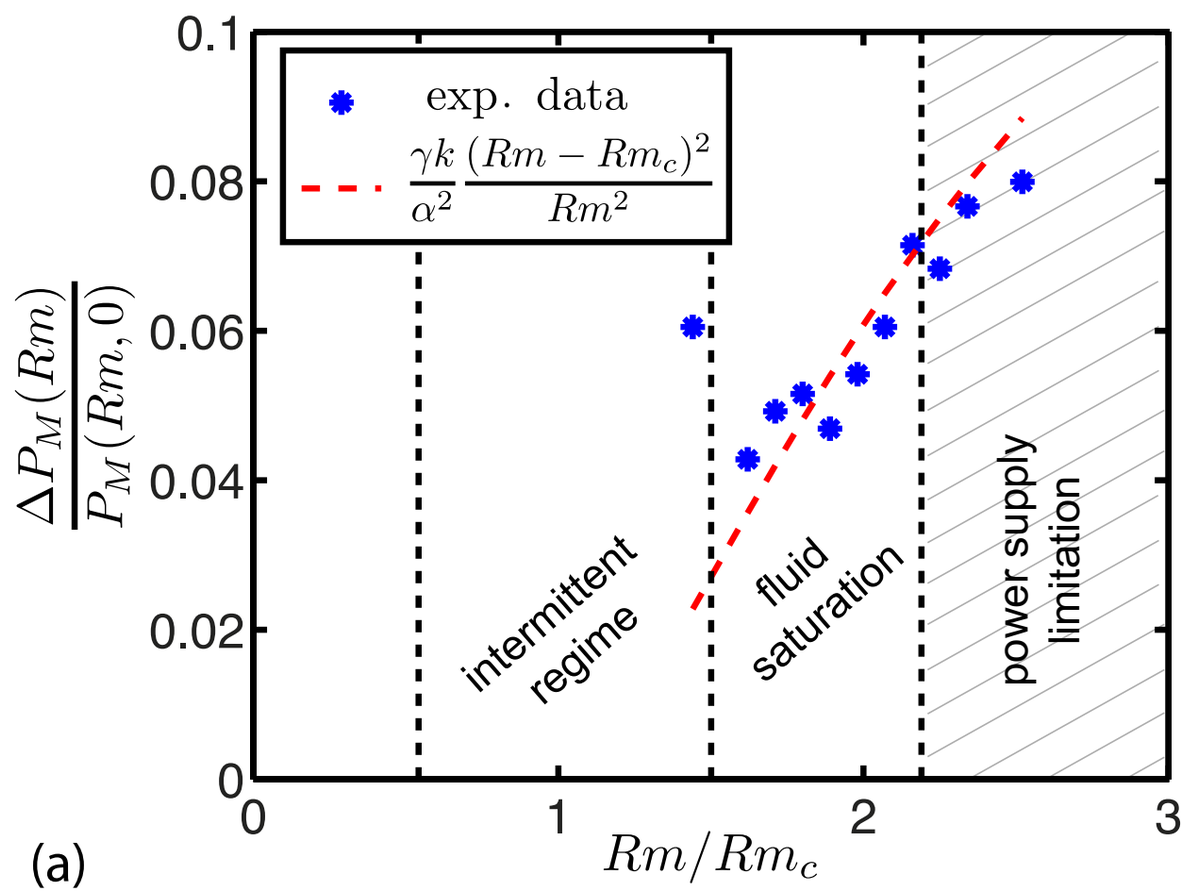


Power budget

$$\frac{\Delta P_M(Rm)}{P_M(Rm,0)}$$ remains small even for the Lorentz force saturation regime < 10%

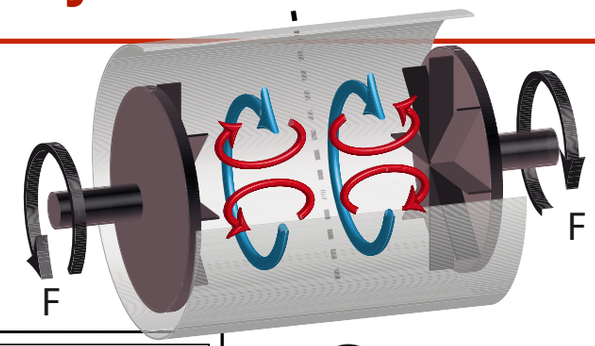
↑

Mechanical power required to maintain the dynamo

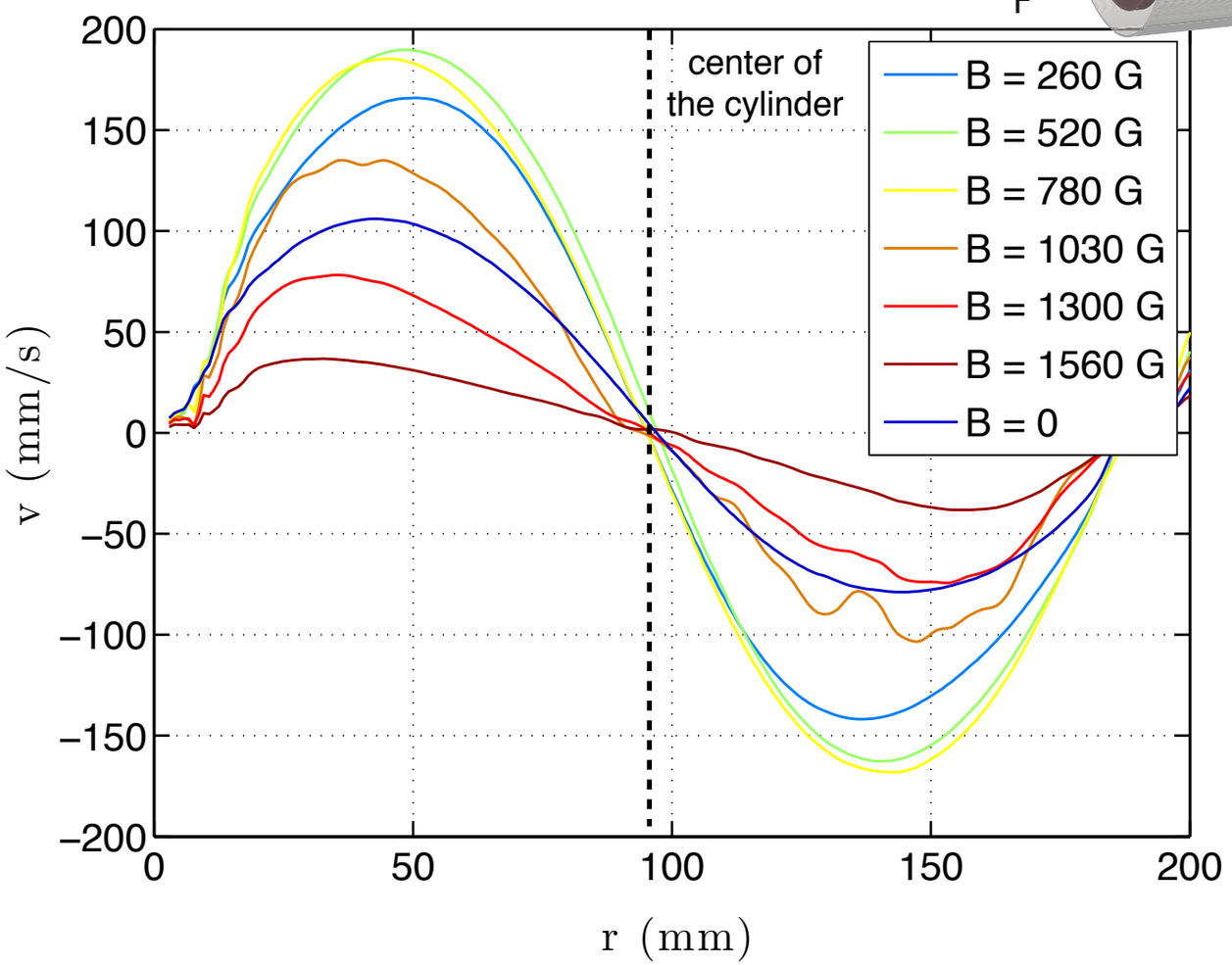


Velocity measurements

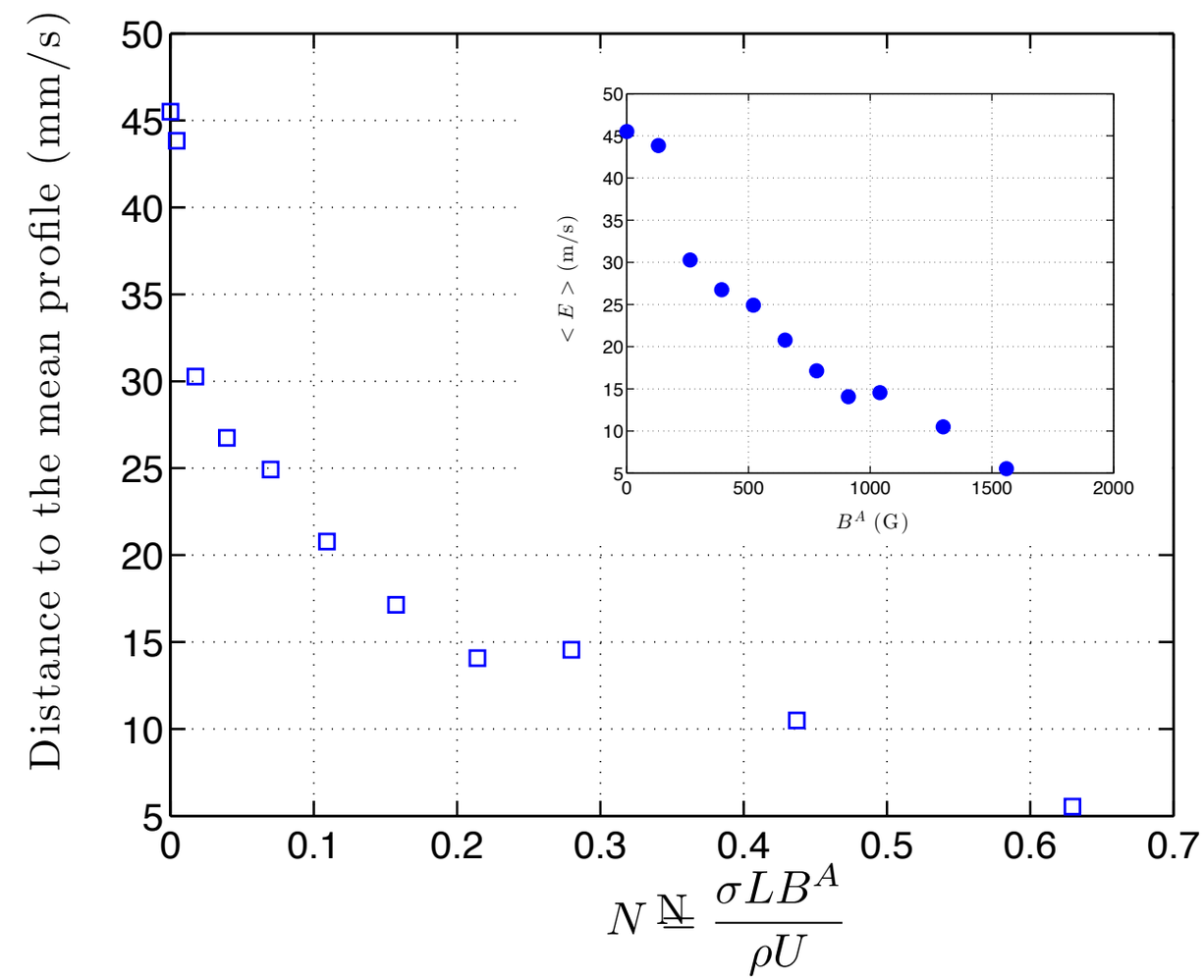
Doppler ultrasound velocimetry



---- direction of measurement



radial profiles in the mid plane

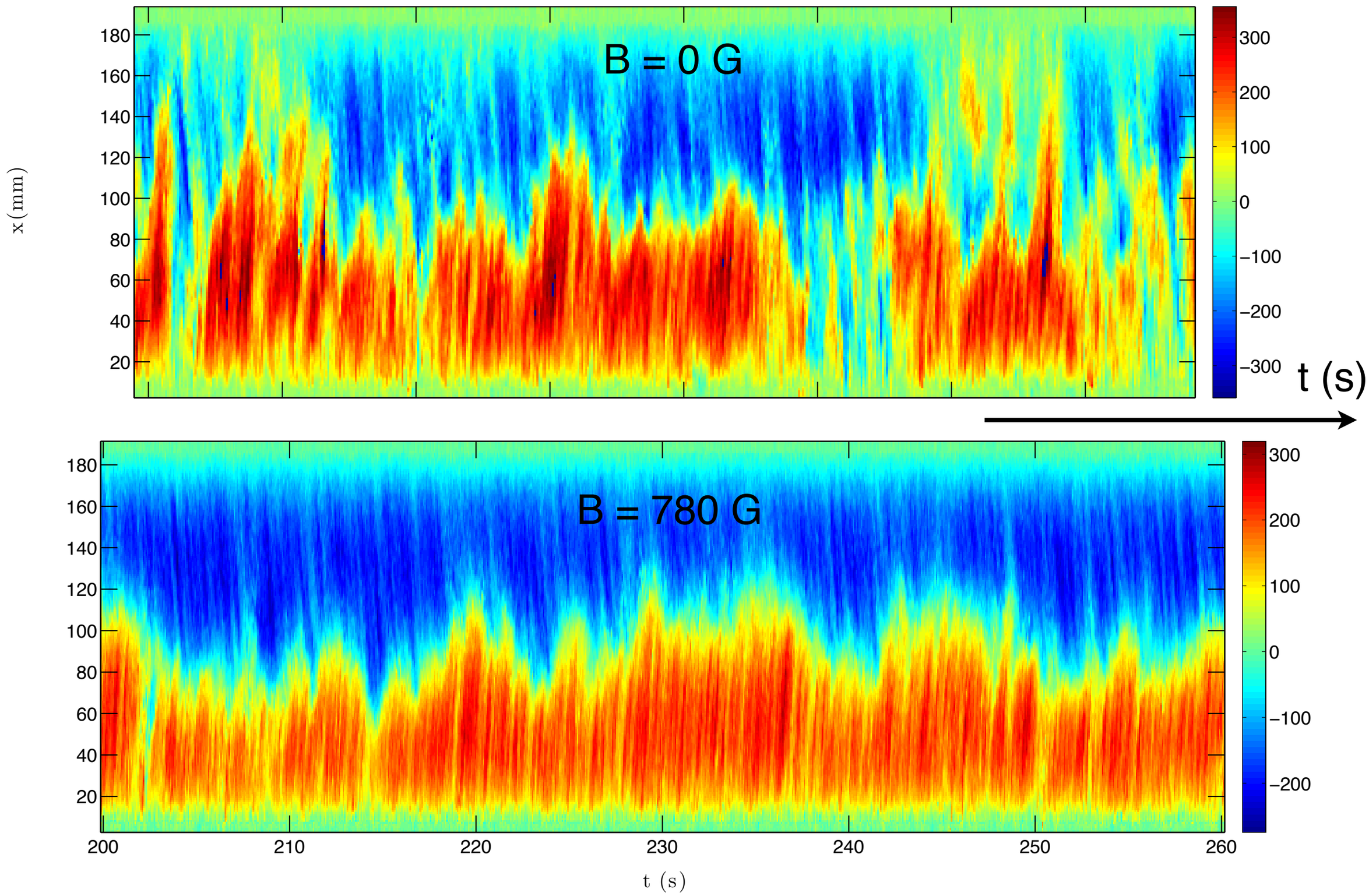


Distance to the mean profile <E>

F = 1 Hz

$$E = \sqrt{\frac{1}{T}\sum_{i=1}^{T}(V_i - < V >)^2}$$

Velocity measurements



Conclusion

Semi-synthetic fluid dynamo:

- Lorentz force saturation
- low Rm
- m = 1 dipole in a von Karman flow

Dynamo regime far above threshold

Detailed power budget

- Estimation of the modification of the flow

Influence of the magnetic field on the flow :

- Damping of the velocity fluctuations by the Lorentz force