Electrostatic Current Drive in Tokamaks

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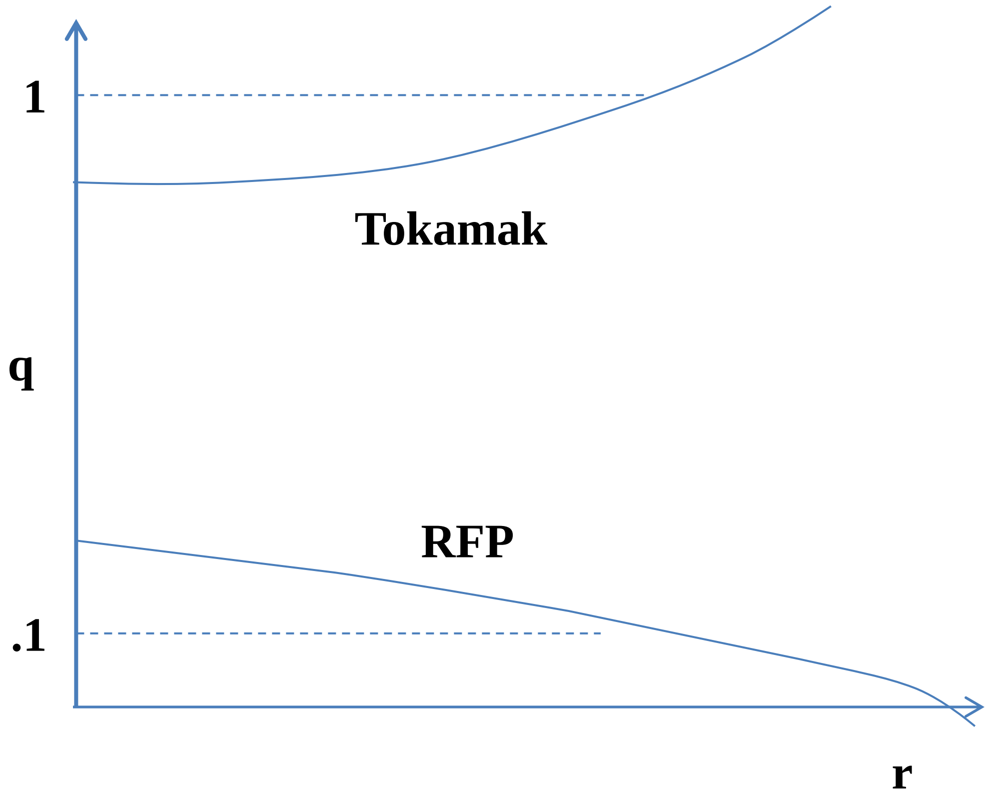
OUTLINE

- **Boundary Conditions**
- **3-D MHD Demonstration of Mode Locking in RFPs**
- **Evidence that Mode Locking Occurs on Ideal MHD Timescales**
- **m=1, n=1 Drive**
- **m=1, n=2 Drive**
- **m=2, n=1 Drive**
- **Debye Screening**
- **Velocity Boundary Drive**
- **DC-DC Transformers and HVDC**
- **Summary**

MHD Stability



Most Unstable Modes for RFP are m=1, n~7-14

Boundary Conditions

I. Perfect Conductor Boundary Conditions

$E_\theta(m,k) = E_z(m,k) = 0$

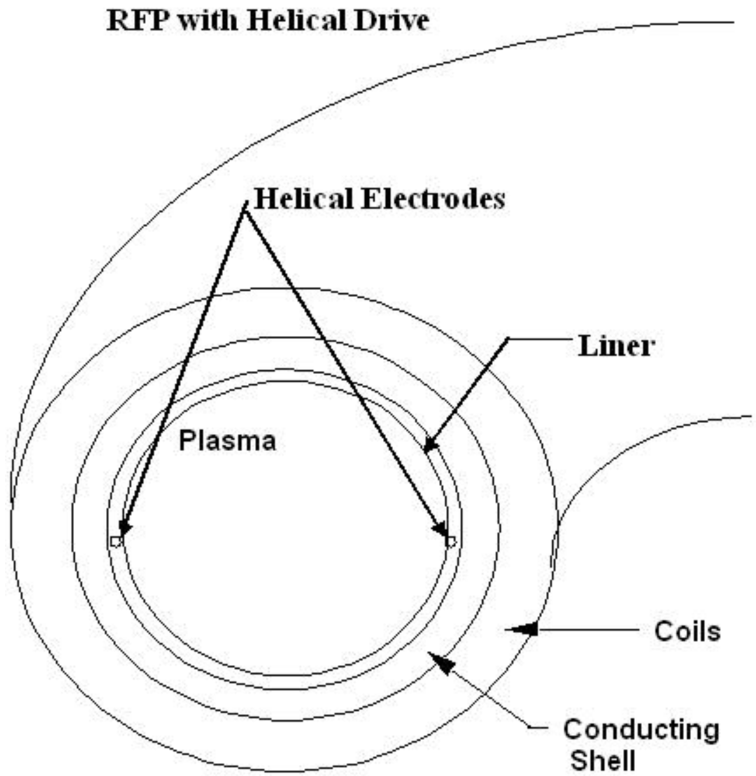
II. Our Boundary Conditions

$\partial B_r/\partial t = 0$ or $E_\theta(m,k) = m/(kr)\, E_z(m,k)$
$E_r(m.k) = \eta J_r(m,k) =$ Constant
$v = 0$

III. Magnetically B.C.s Look Like an Ideal Conductor, but the Electrostatic Potential Varies on the Surface.

How These B.C.s Can be Made

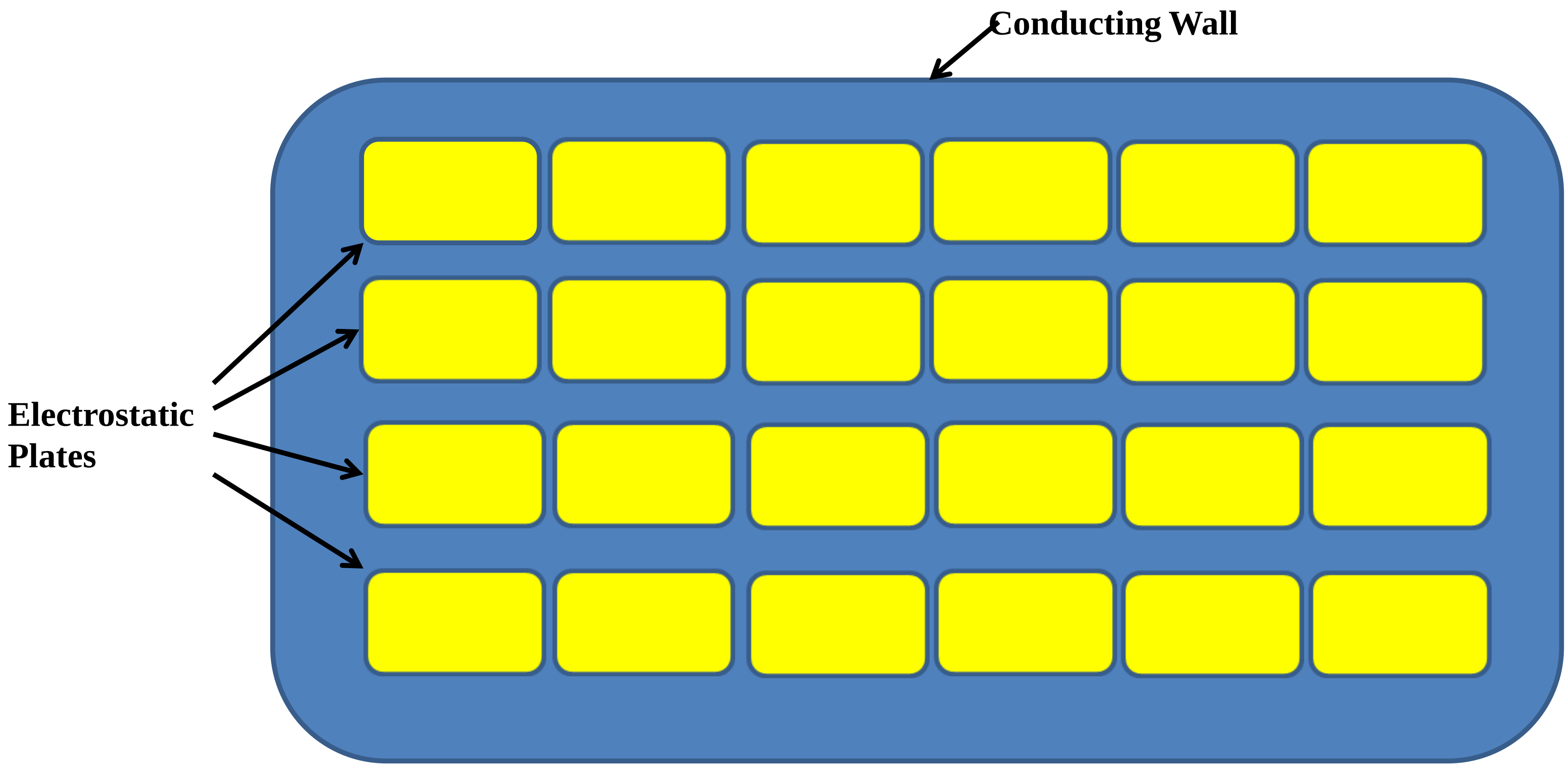
I. **Single Helicity RFP**



Helical Electrodes Produce a Helical Potential Profile to Lock RFP into a Single Helix

How These B.C.s Can be Made

II. Tokamaks or RFPs

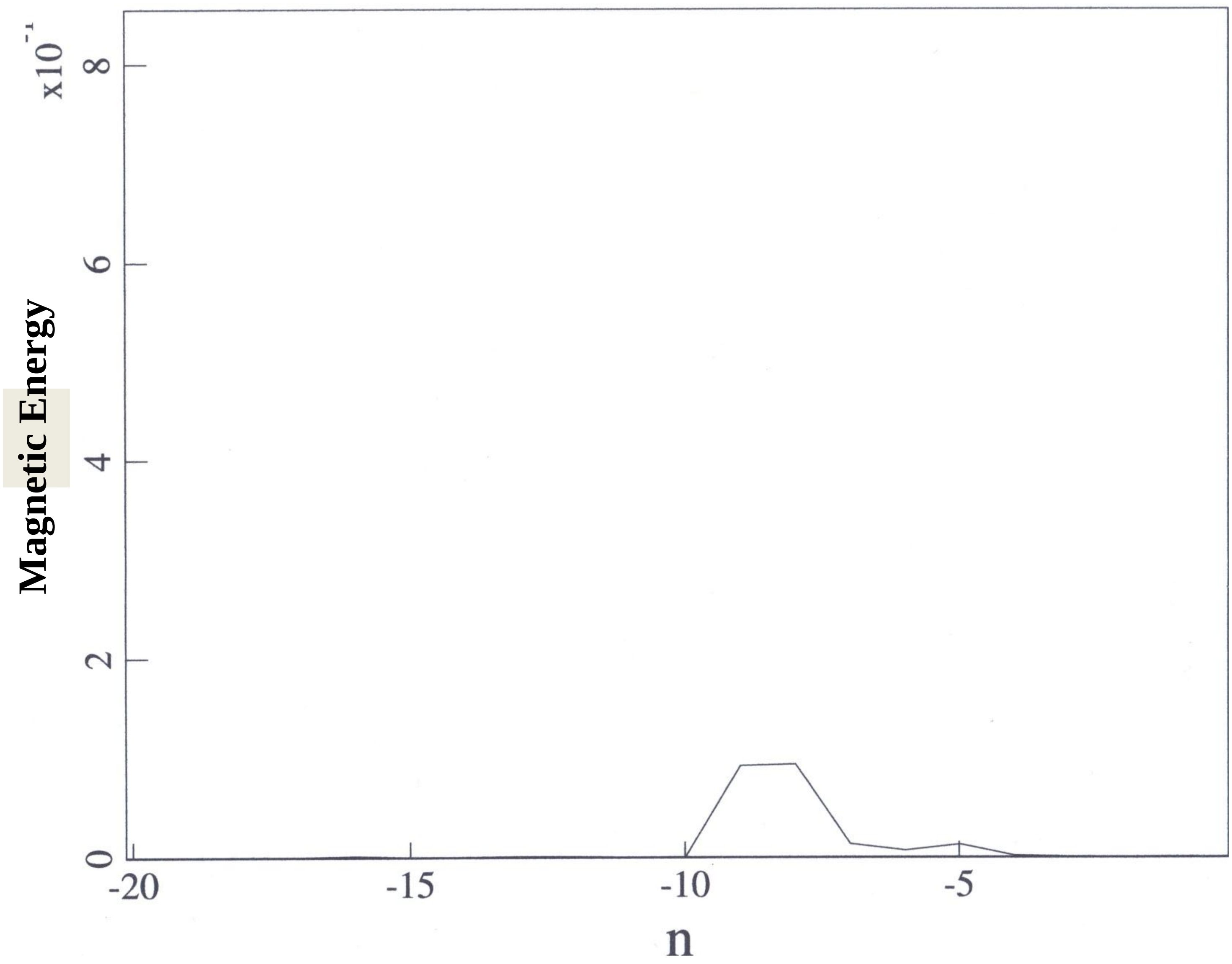


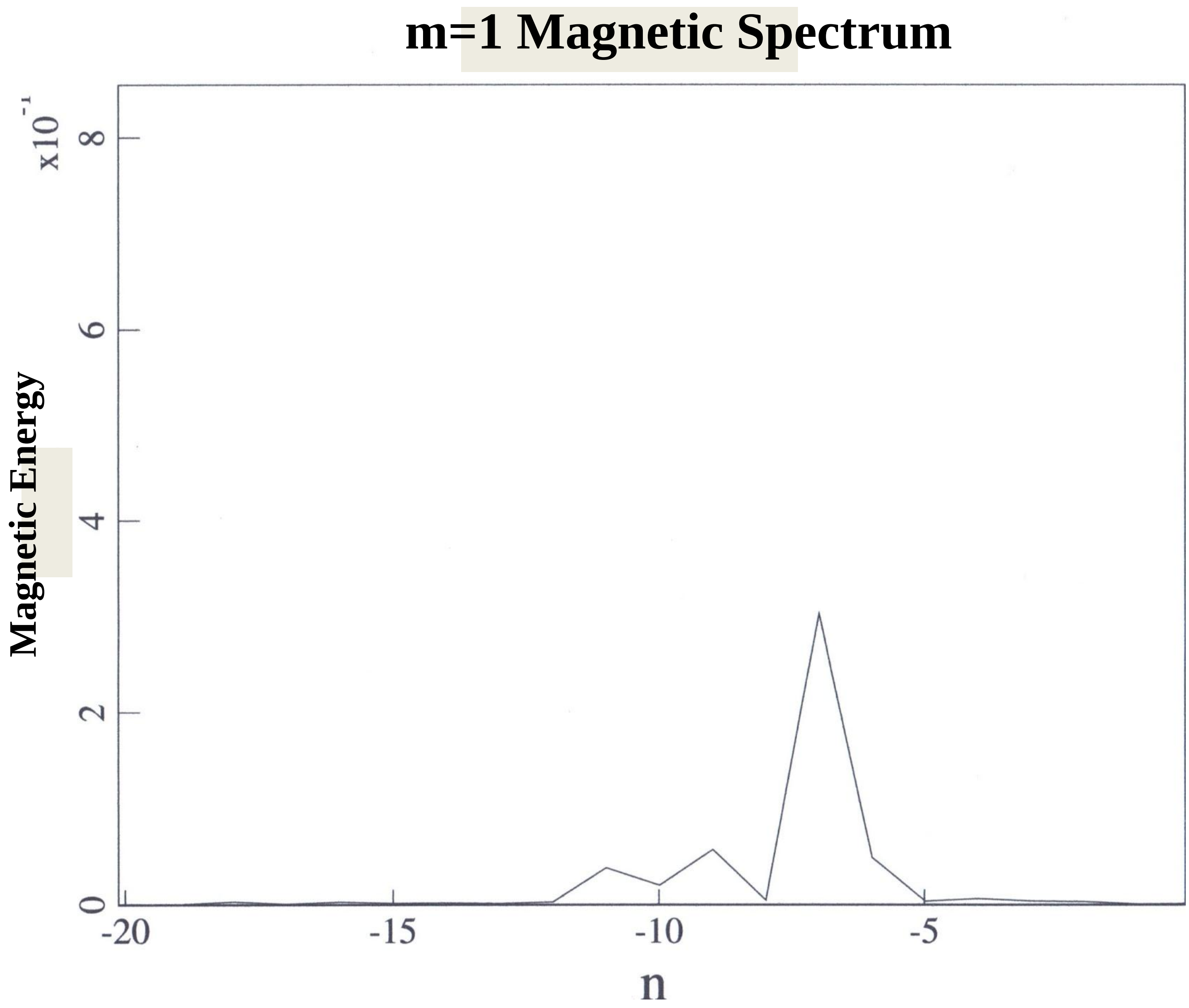
Electrostatic Programmable Plates Attached to a Conducting Wall

Single Helicity RFPs

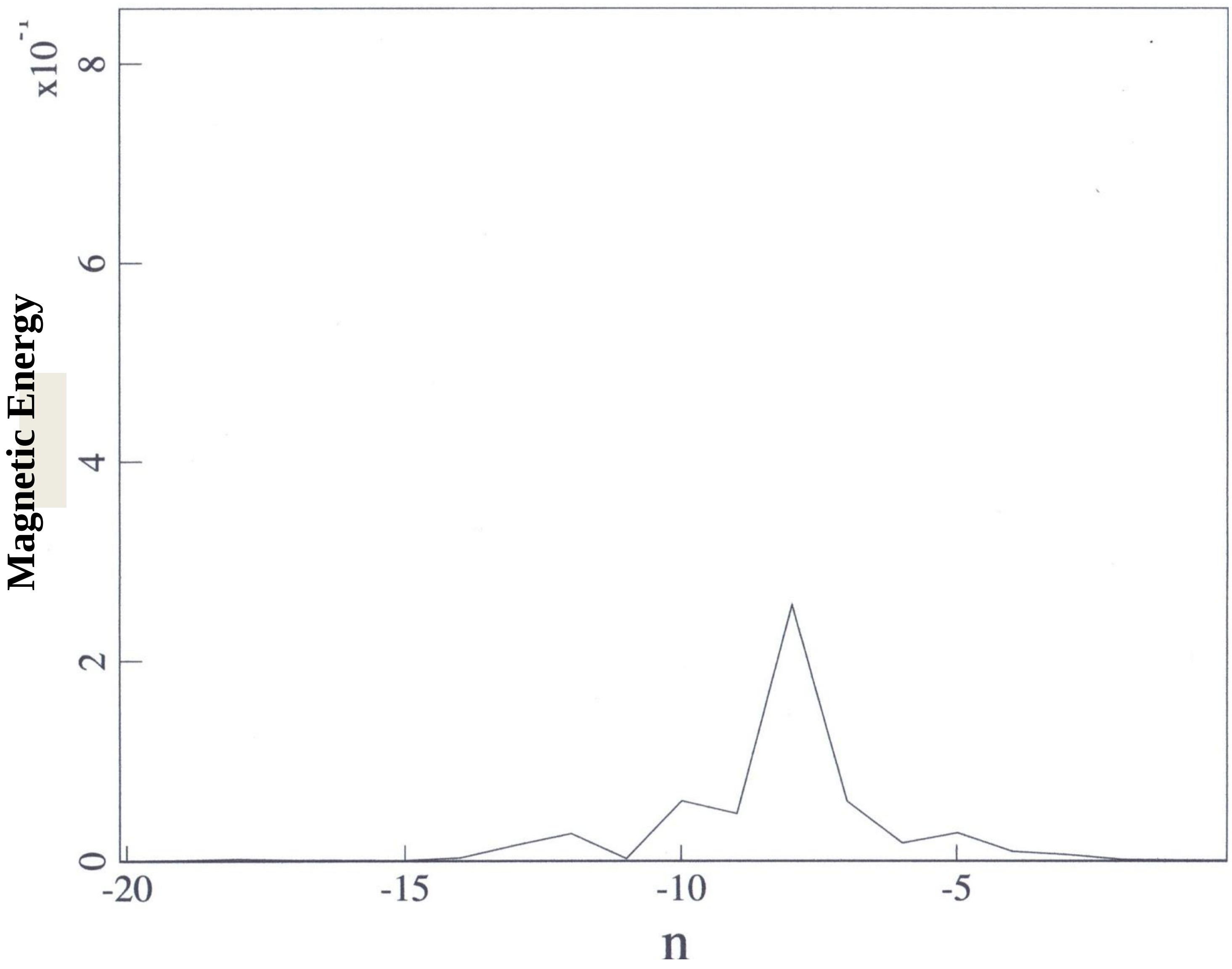
- **Most RFPs Are Multi-Helical and Have Few Good Flux Surfaces.**
- **Single Helix RFPs Have Good Flux Surfaces Everywhere.**
- **Can We Electrostatically Lock an RFP into a Single Helix?**

m=1 Magnetic Spectrum

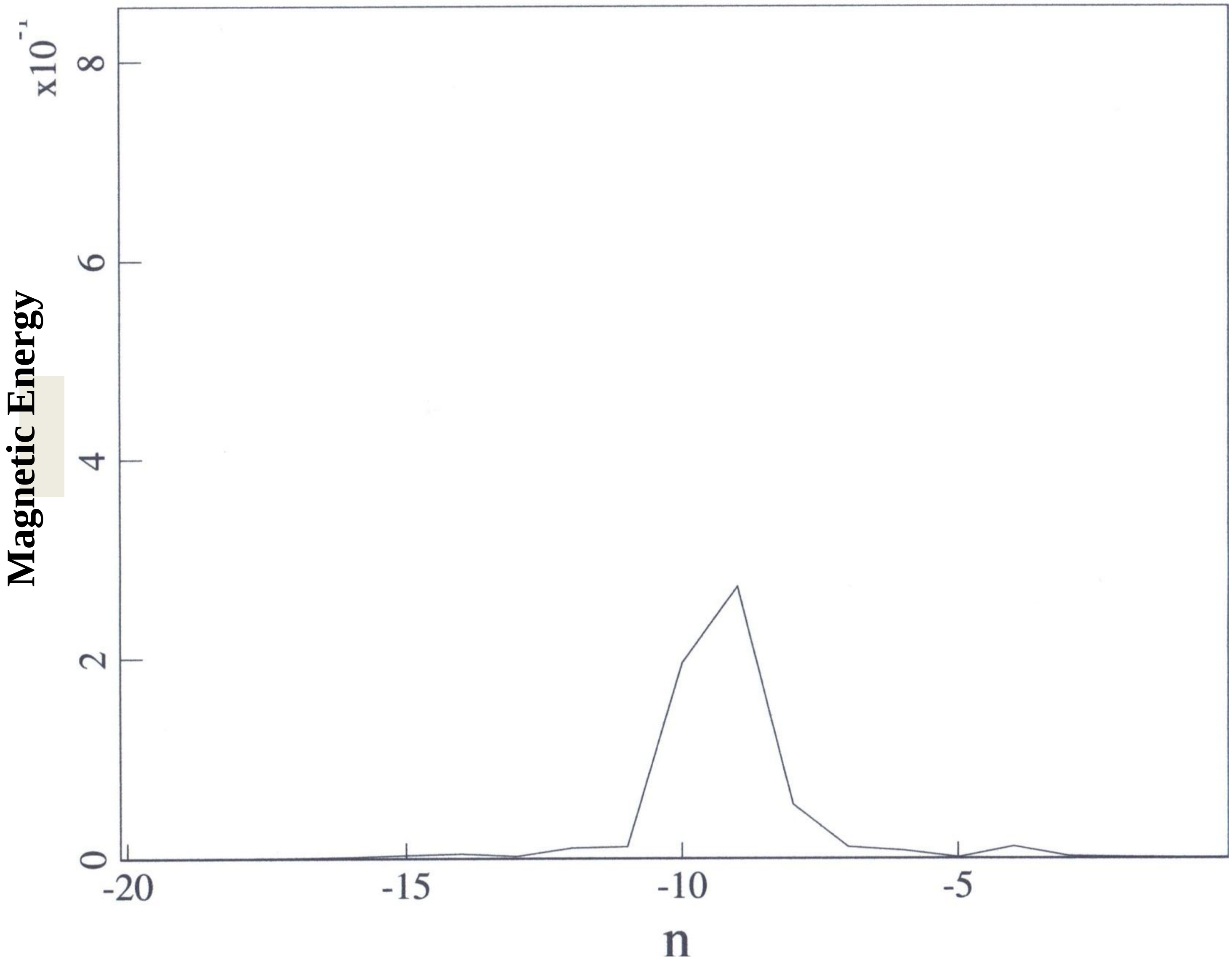



m=1 Magnetic Spectrum
Magnetic Energy
x10⁻¹
0
2
4
6
8
-20
-15
-10
-5
n

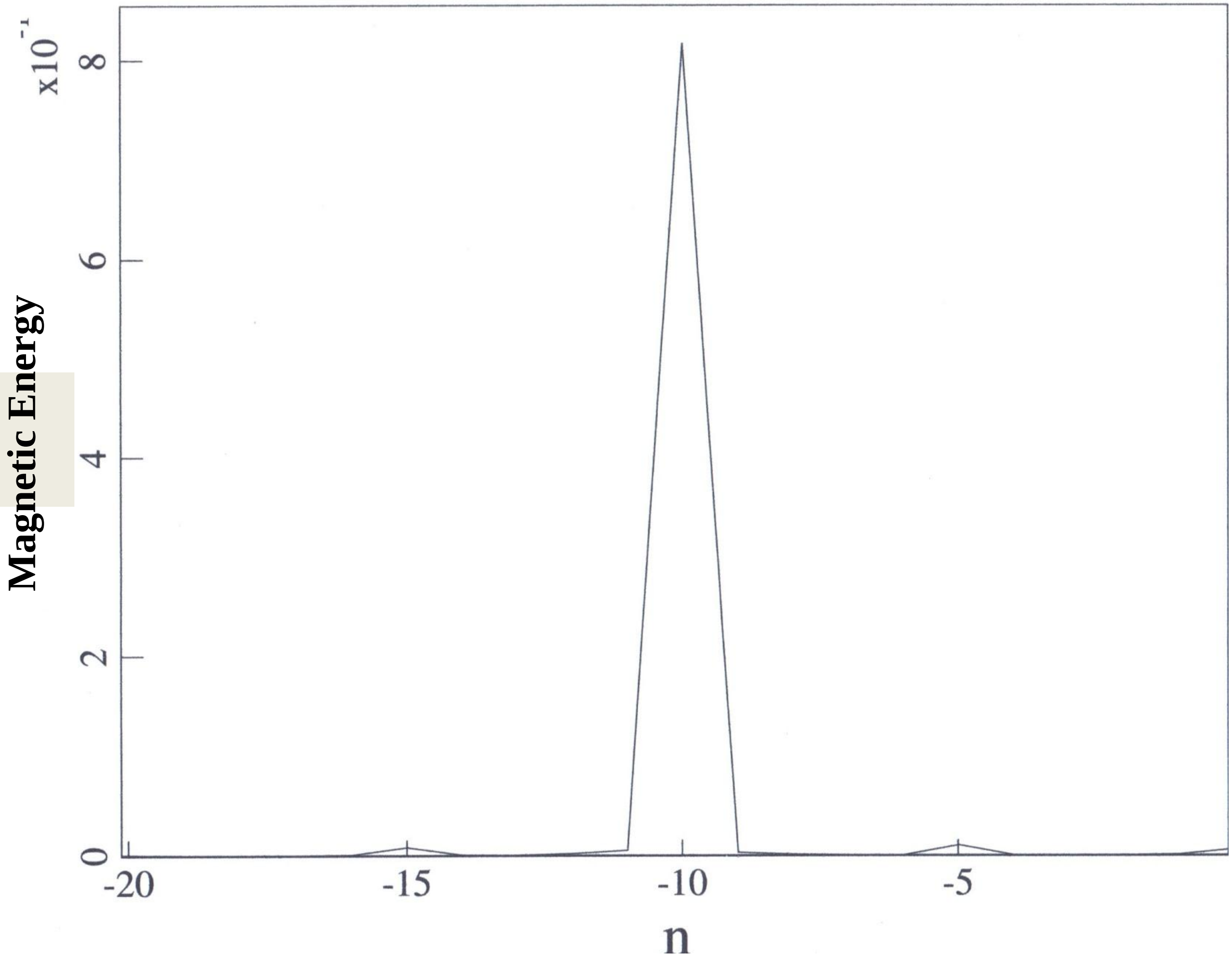
m=1 Magnetic Spectrum



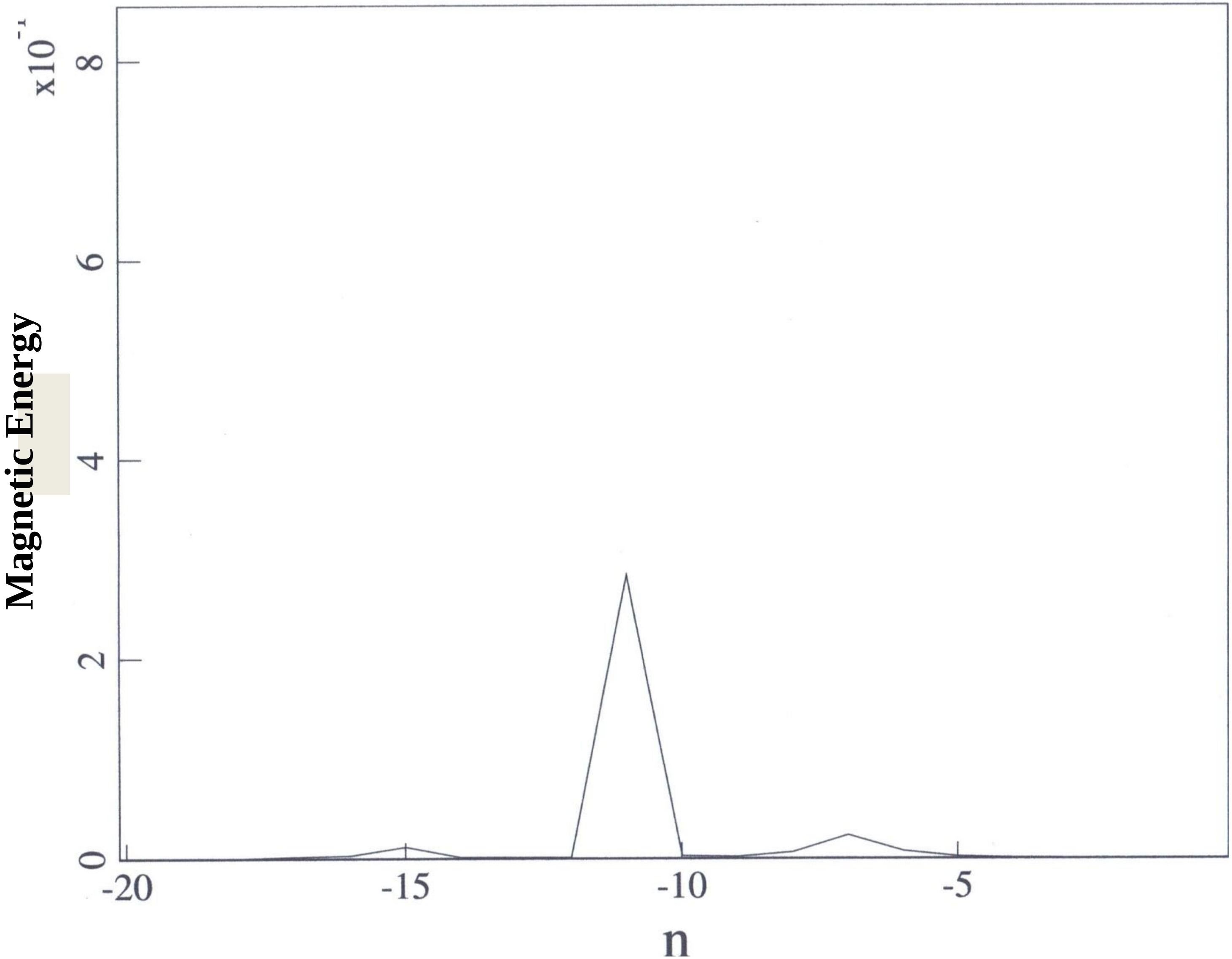
m=1 Magnetic Spectrum



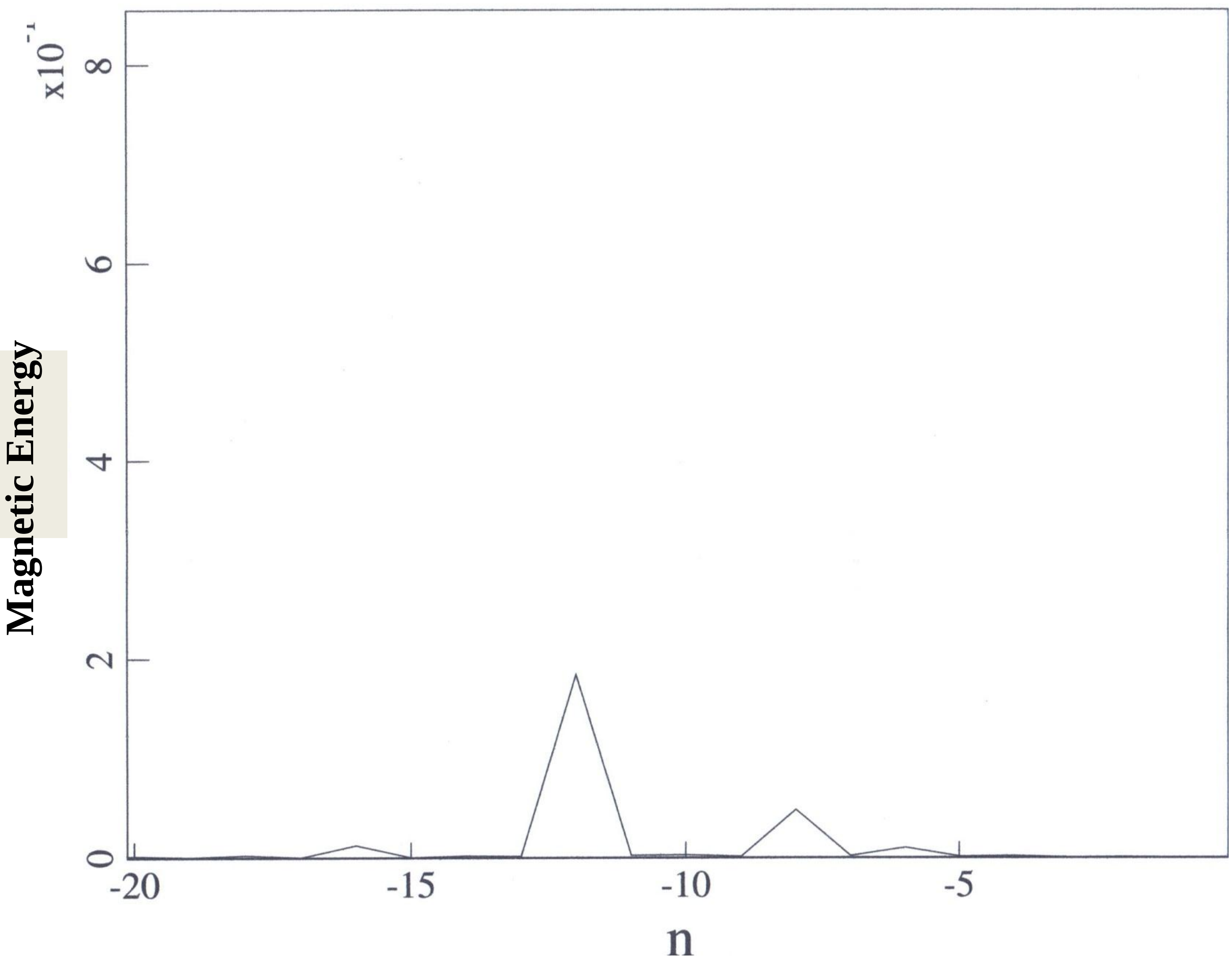
m=1 Magnetic Spectrum



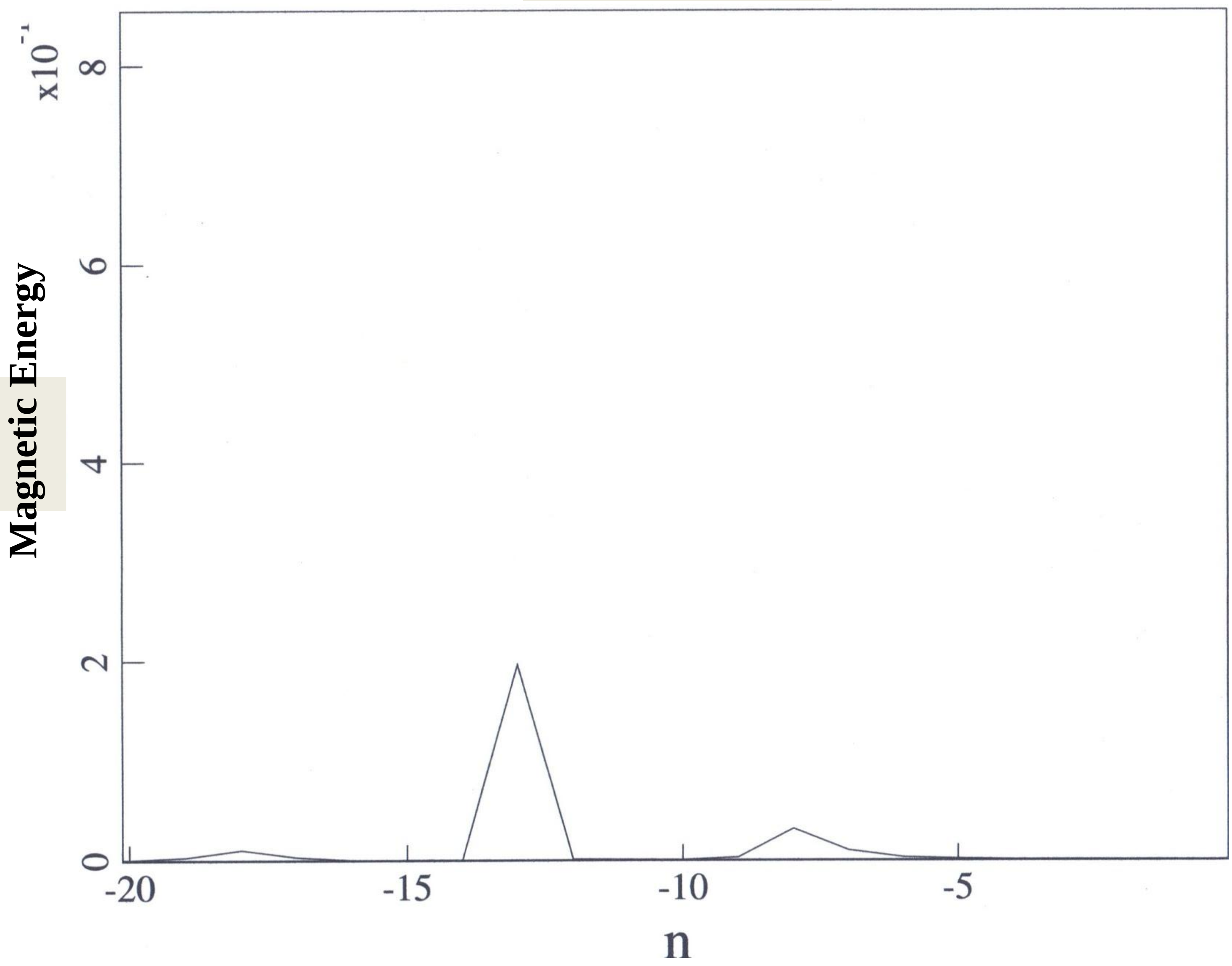
m=1 Magnetic Spectrum



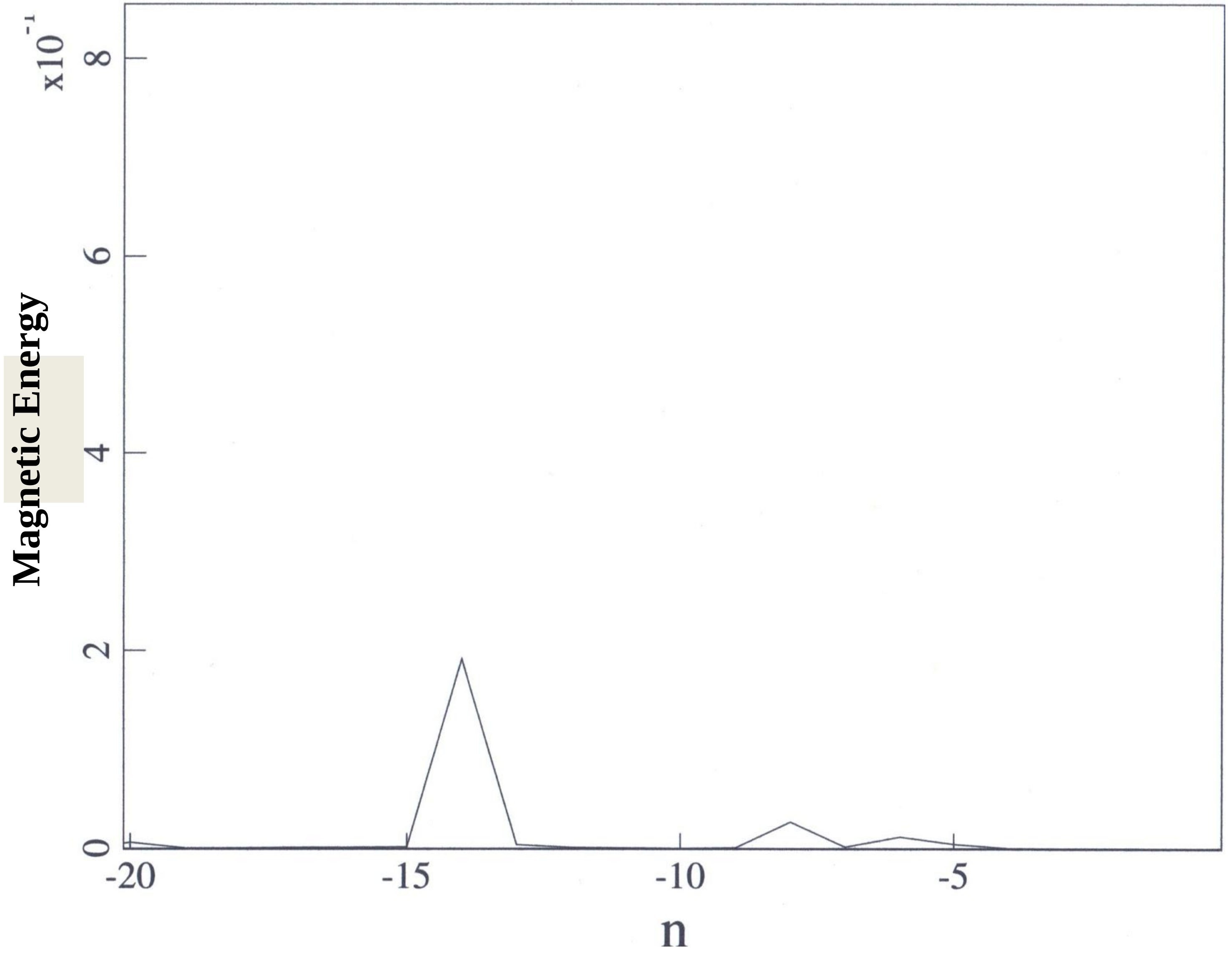
m=1 Magnetic Spectrum



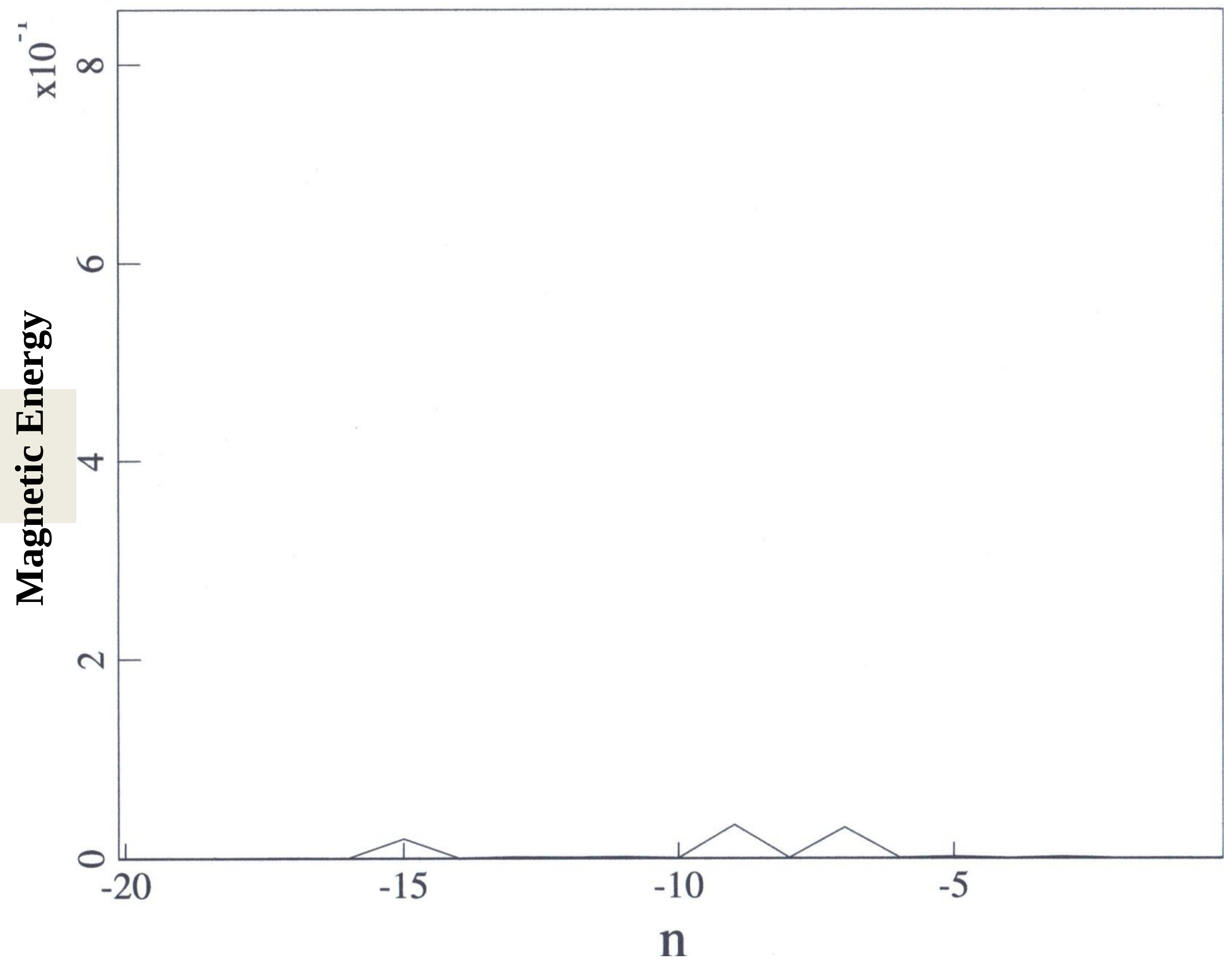
m=1 Magnetic Spectrum



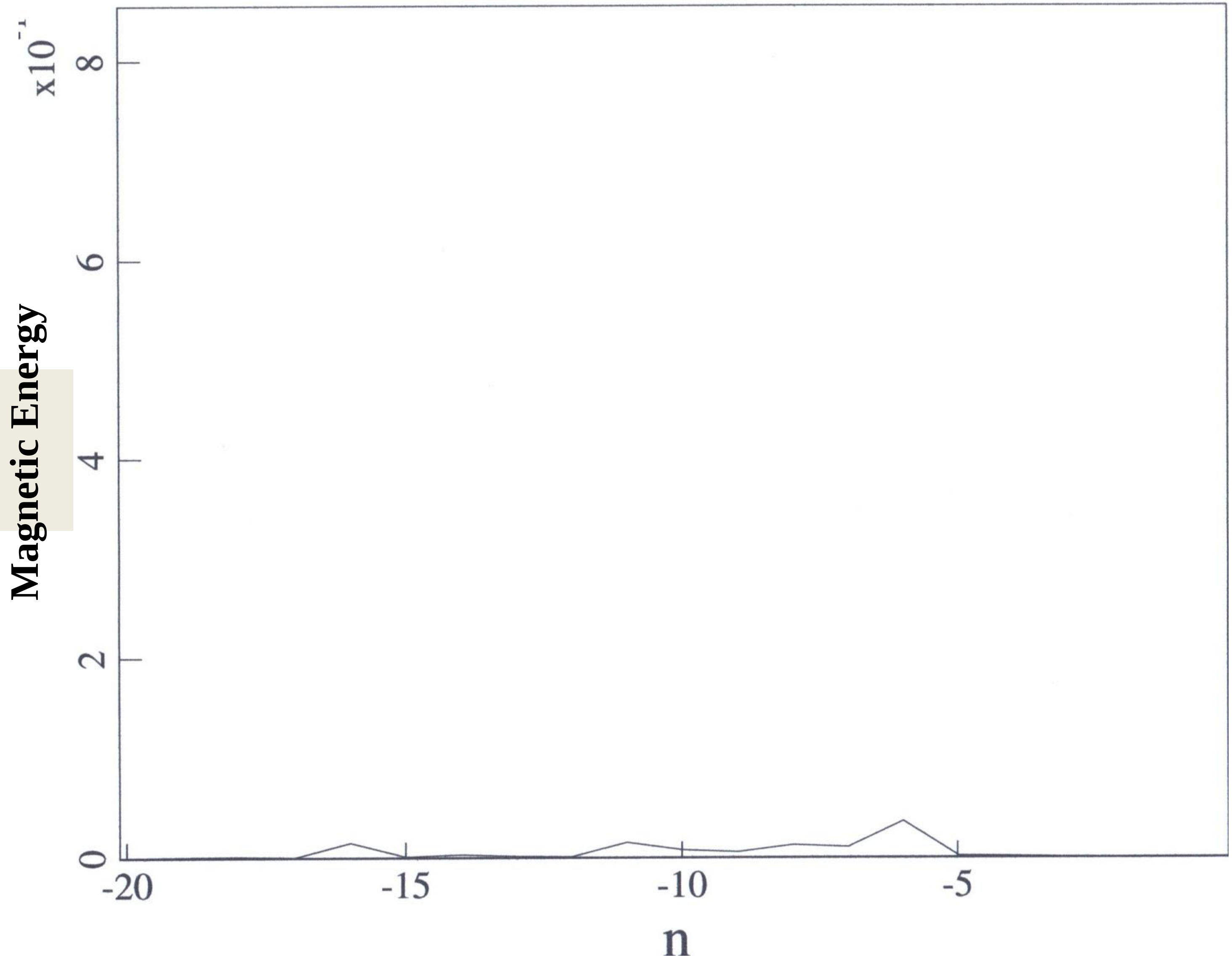
m=1 Magnetic Spectrum



m=1 Magnetic Spectrum



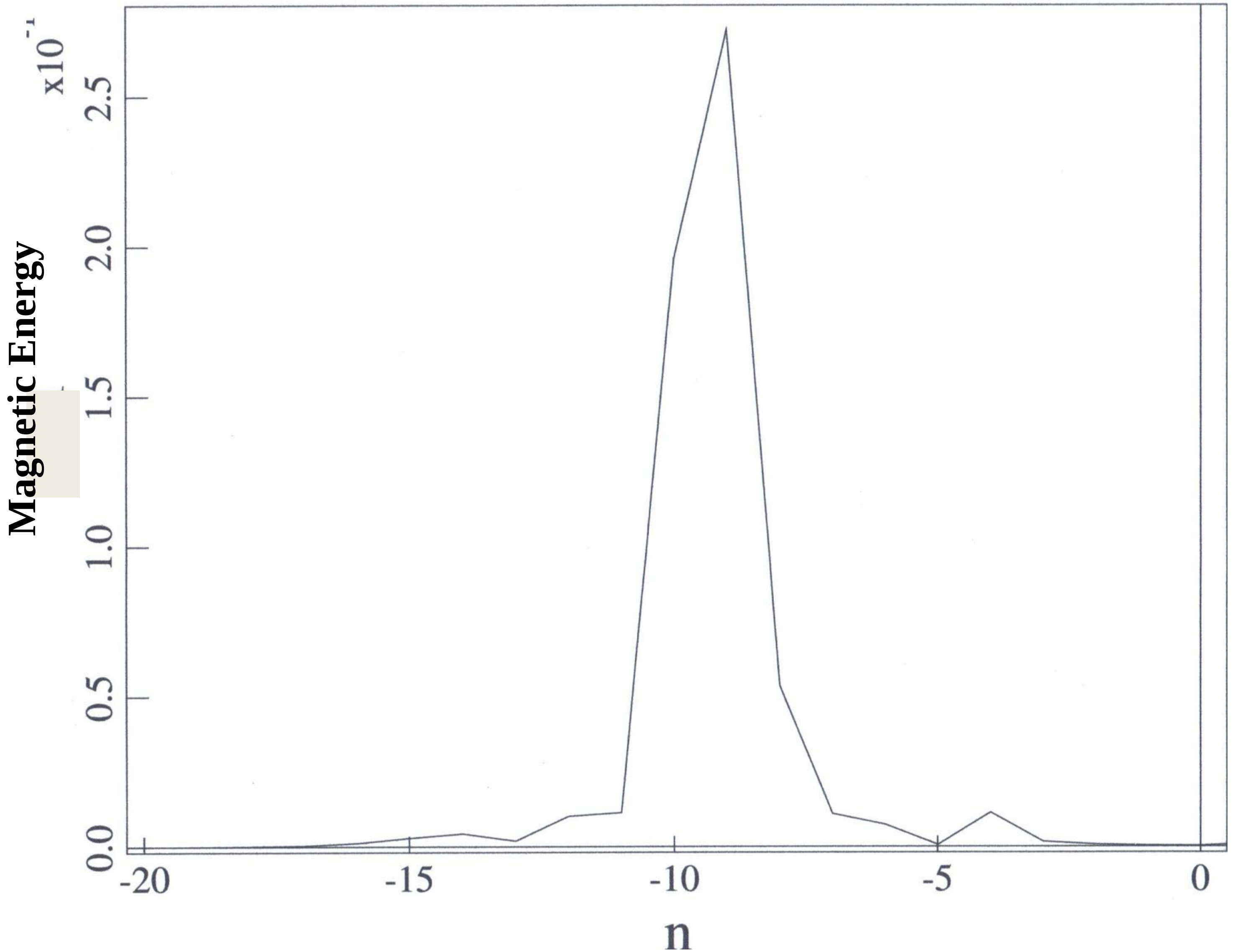
m=1 Magnetic Spectrum



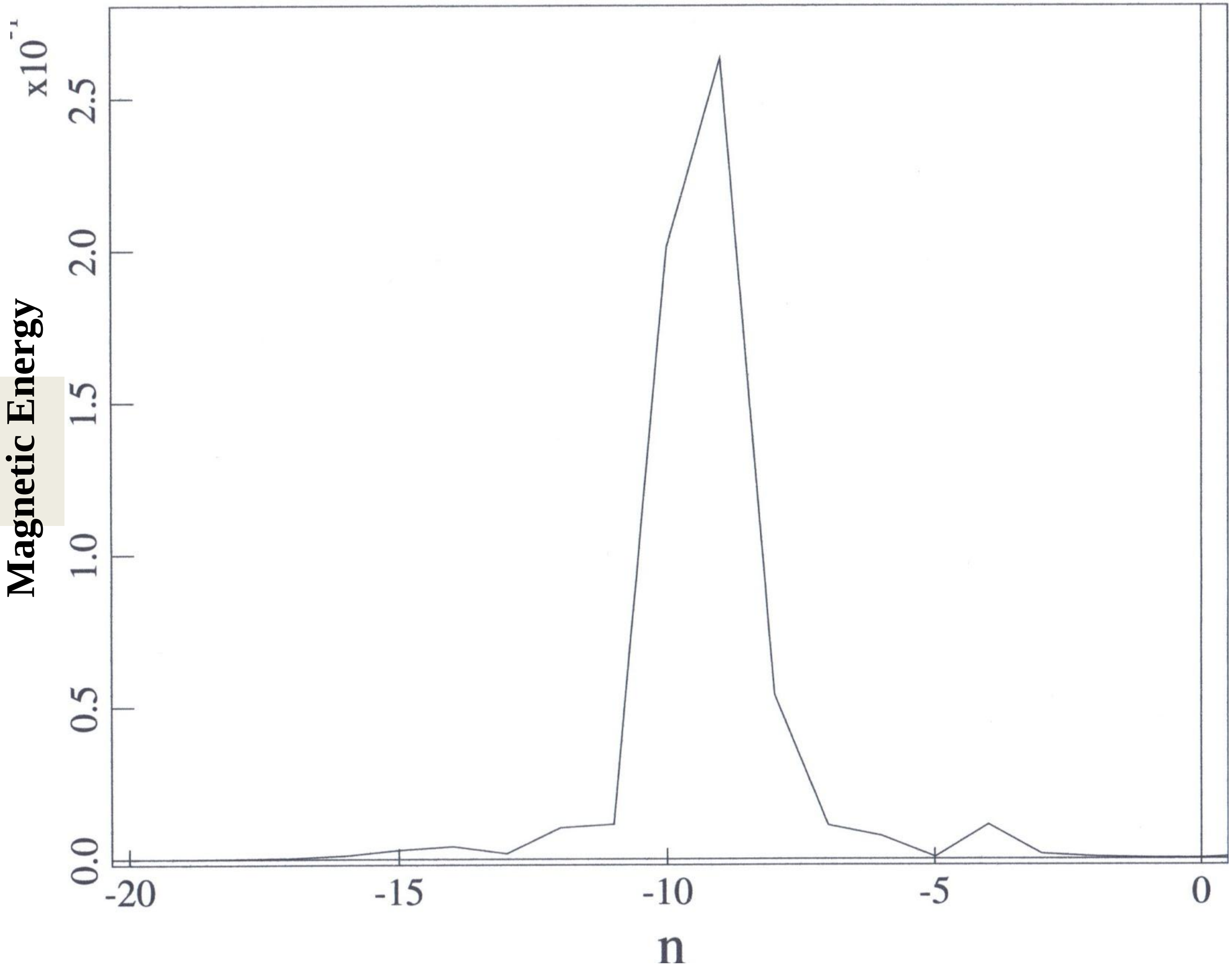
The Spectrum Peaks at the Applied Perturbation Some States Appear to be Close to Single Helicity

Does the Plasma Respond to the Edge Perturbations on an Ideal MHD or a Resistive MHD Timescale?

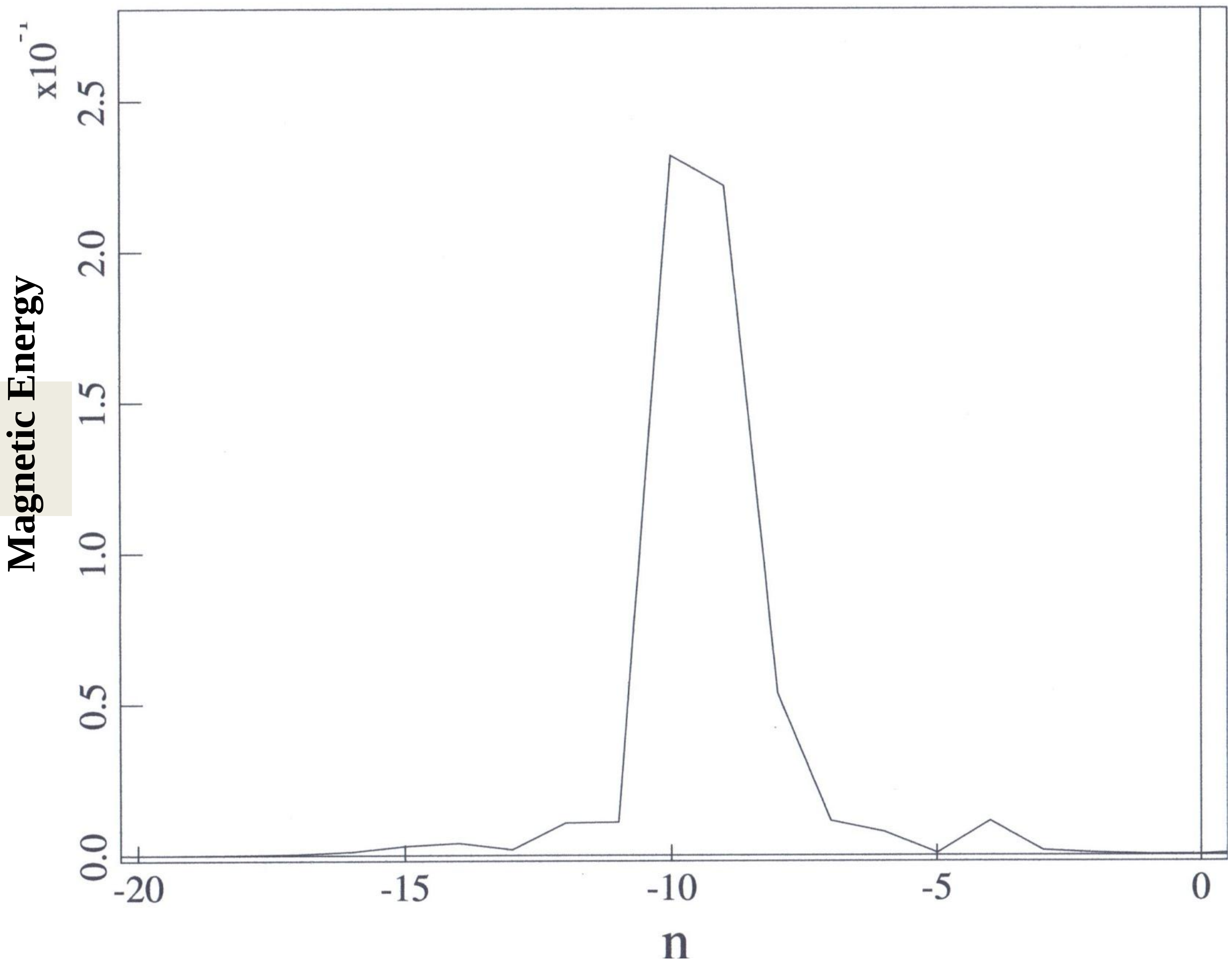
m=1 Magnetic Spectrum



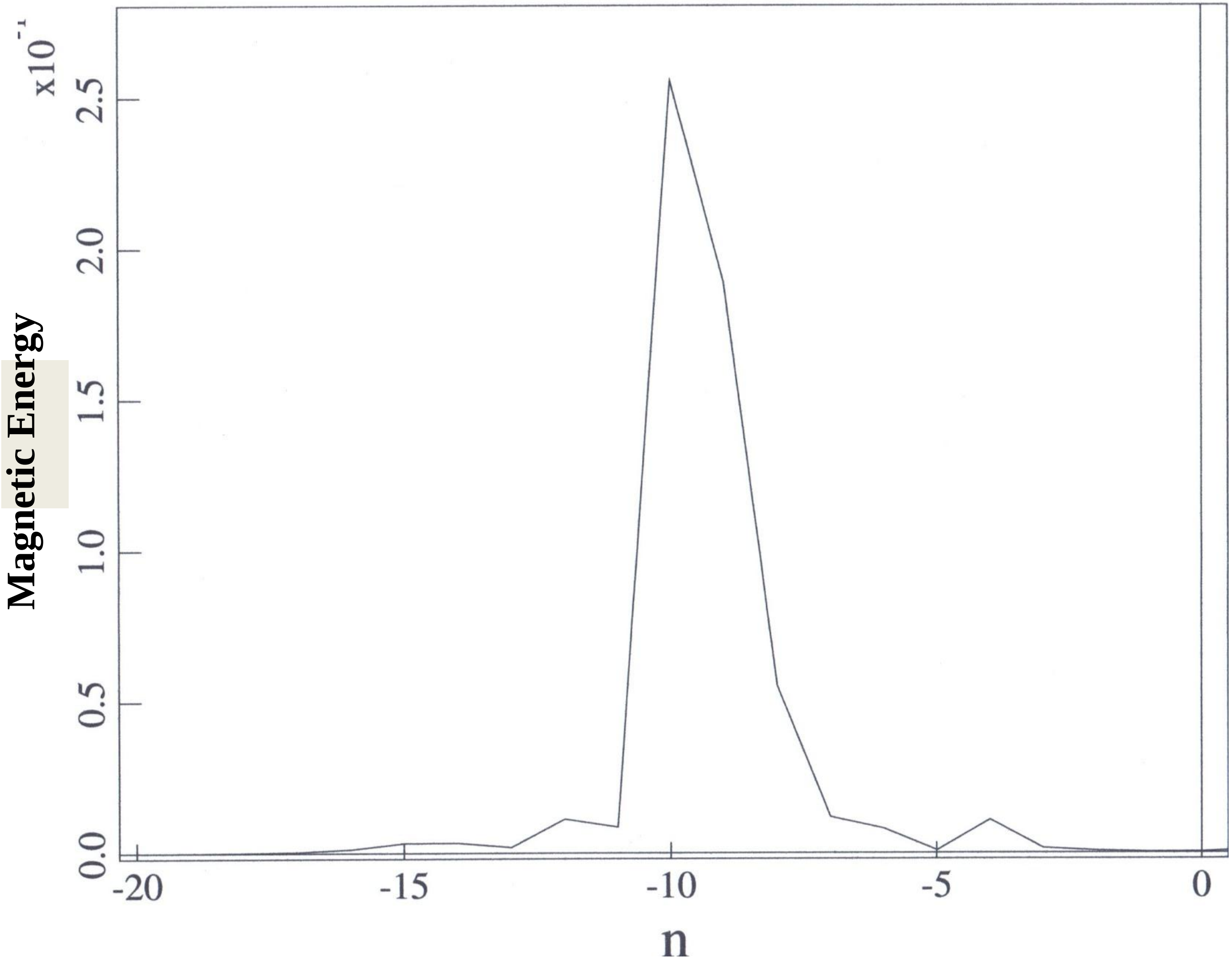
m=1 Magnetic Spectrum



m=1 Magnetic Spectrum



m=1 Magnetic Spectrum



Plasma Responds in a few Alfven Times (Ideal MHD Timescale)

Linear Ideal MHD in a Cylinder

- For modes near marginal stability, perturbations amplify from the edge into the interior.

- For stable modes, perturbations damp from the edge into the interior.

- This is consistent with the driven RFP modes.

Characteristics of Electrostatic Mode Inducement and Suppression

- **Electrostatic Response Times are Very Fast.**
- **Does not Require the Diffusion of Magnetic Fields Through Conductors.**
- **Edge Perturbations on Unstable Modes Amplify into the Interior.**
- **Gain Is High so energy Requirements are Modest.**
- **Amplitudes and Sensitivities Need to Be Determined.**
- **Can This be Demonstrated Experimentally?**

Bismark Device
(under construction)

Hybrid Magnetic/Electrostatic Device
Axial Magnetic field

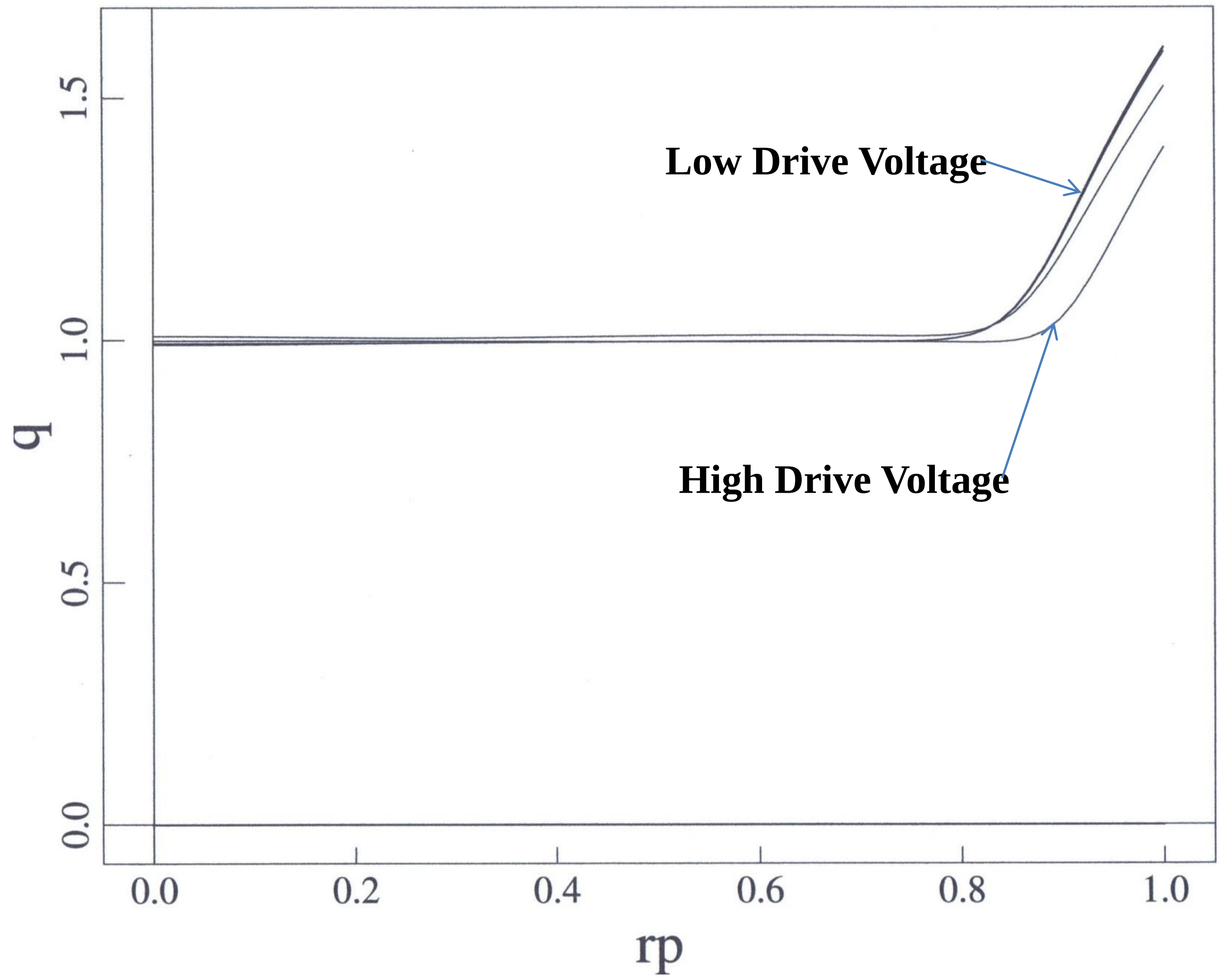
Projected Parameters

Chamber Diameter	4 inches
Chamber Length	22 inches
Coil Length	12 inches
Number of Turns in Coil	1000
Peak magnetic field	1 kΓ
Peak Coil Current	24 Amperes
Peak voltage	5 kV

Can We Test Mode Electrostatic Mode Amplification with the Bismark Device?

- Straight Axial Magnetic Field.
- Marginally Stable to Interchange Modes.
- m=1, n=0 Electrostatic Boundary Perturbations Should Show Large Flows.
- This is Confirmed by the 3-D MHD simulations.
- m=1, n=1 Electrostatic Boundary Perturbations Should Damp.
- The 3-D MHD Simulations Unexpectedly Produced Current Drive…

q Profiles



Low Drive Voltage
High Drive Voltage
1.5
1.0
0.5
0.0
q
0.0
0.2
0.4
0.6
0.8
1.0
rp

Dynamo Current Drive

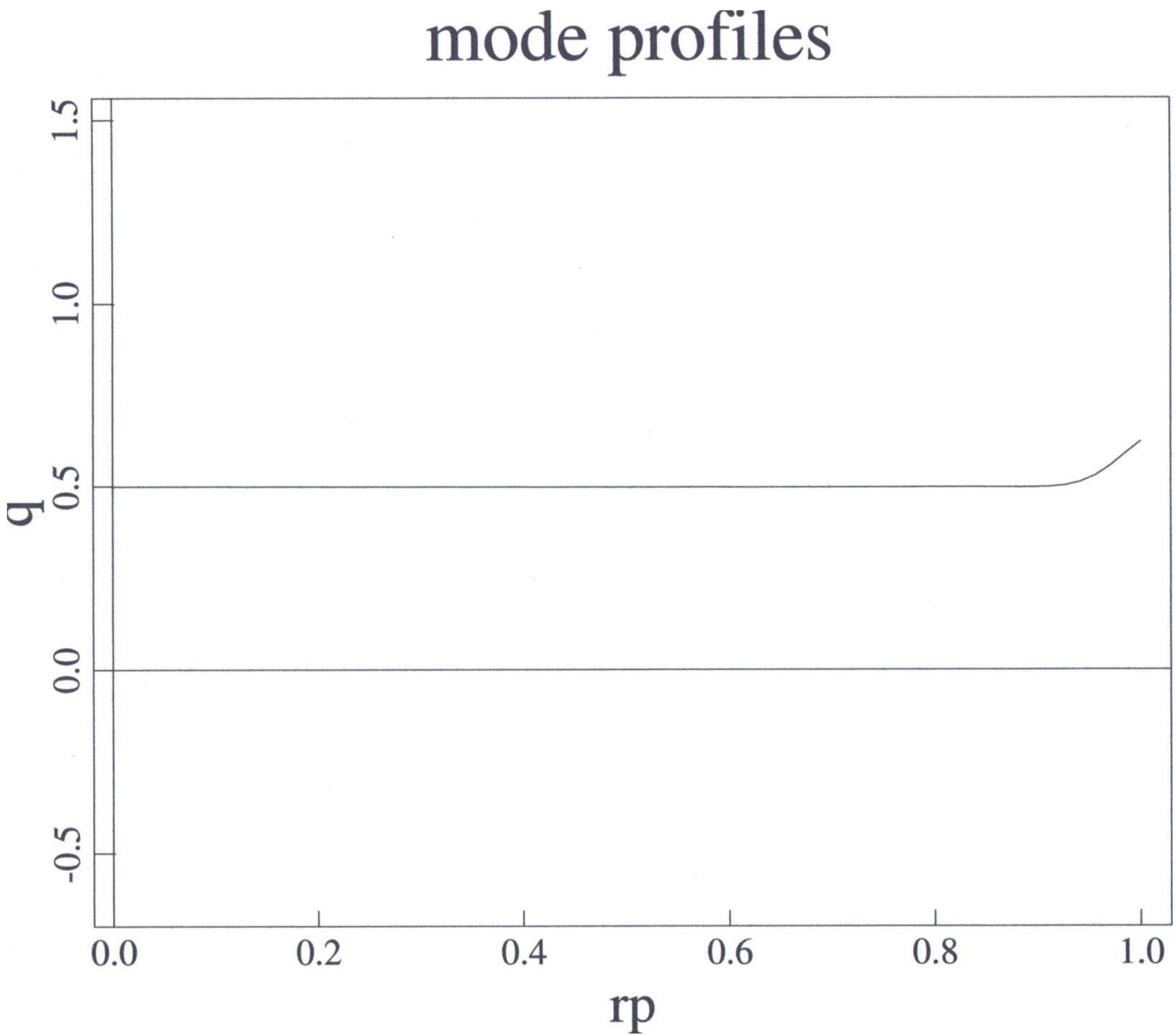
- **Small Electrostatic Boundary Perturbations Damp as Predicted by the Linear Theory.**
- **Larger Perturbations Drive The Plasma Nonlinearly.**
- **There is a Bifurcation in the Solutions Depending on the Magnitude of the Perturbations.**
- **New Relaxation Principle: The Magnetic Field Tries to Align Itself with the Electrostatic Electrodes, Resulting in Current Drive.**
- **States are Stationary, Universal Attractors. These States are Found Independent of the Initial Conditions.**
- **States Are Single Helicity With Very Little Radial Magnetic Field?**
- **Why Does This Happen?**

Caveats

- **Theorem states that steady-state single helicity states with net current drive do not exist!**
  - **Are states truly single helicity?**
  - **Are states truly stationary?**
  - **Did we screw up the boundary conditions?**
- **V_r is forced to be zero at the boundary.**
  - **$E_z = \eta J_z$, $E_\theta = \eta J_\theta$**
  - **If $V_r = (ExB)_r / B^2$ then flow into boundary will be large.**
- **Neither of these situations are happy solutions.**

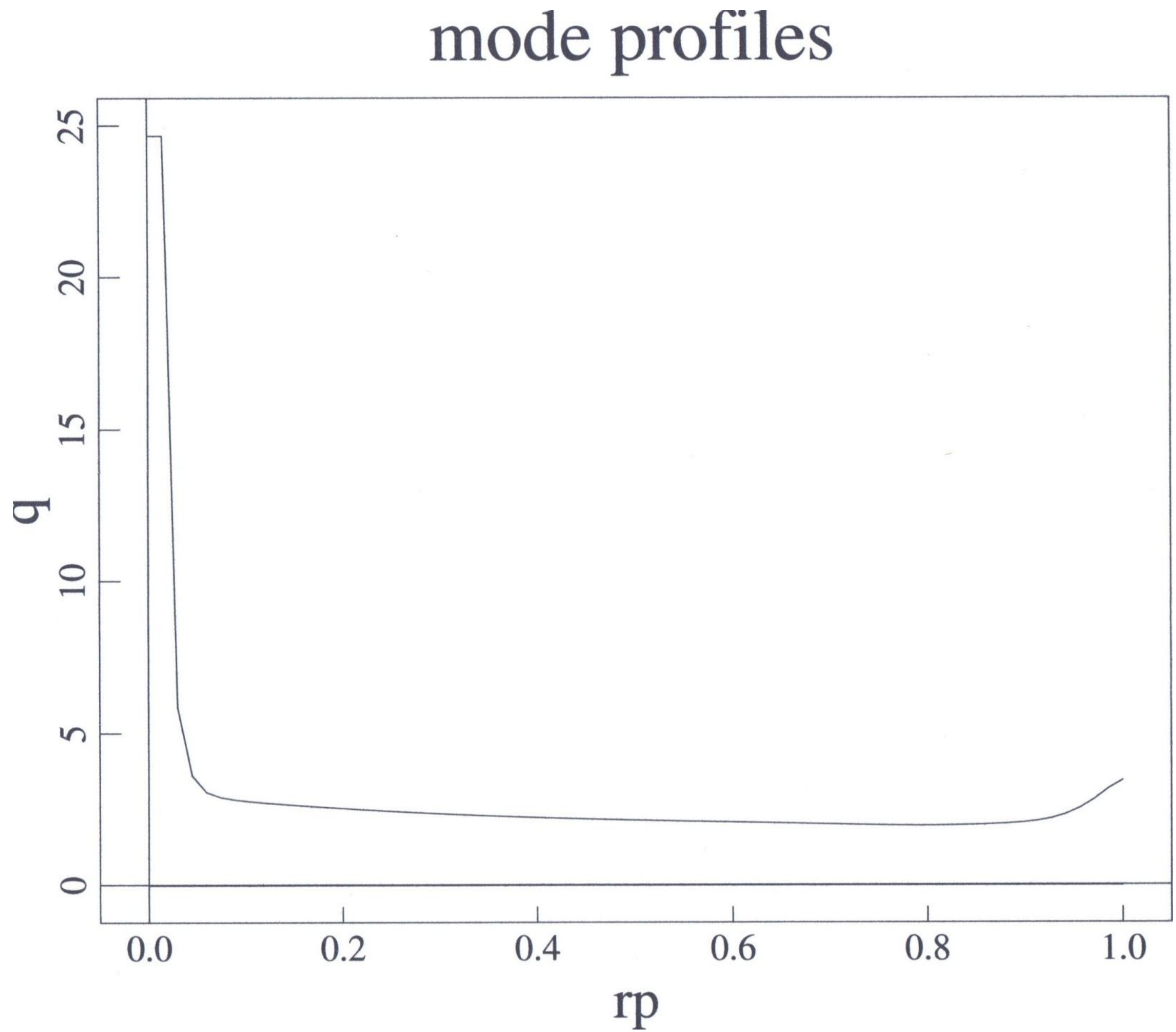
Dynamo Current Drive

- **States are Stationary, Universal Attractors. This Eliminates Disruptions.**
- **ExB Flow Velocities Need to be Comparable to the Alfven Speed to bend the Magnetic Fields (2%-20% observed).**
- **ExB Flow Velocities Cannot Exceed the Alfven Speed or Equilibrium is Lost.**
- **A Boundary Layer Forms near the Plasma Boundary. The Layer Width Shrinks as the Voltage is Increased.**
- **All Other Modes Are Stabilized By the Flow.**
- **The Stronger the Driving E Field, the Smaller the Radial magnetic Field.**
- **Does This Work for Other Helicities like the m=1, n=2 mode?**


mode profiles
q
1.5
1.0
0.5
0.0
-0.5
0.0
0.2
0.4
0.6
0.8
1.0
rp

Dynamo Current Drive

- **Dynamo Drive Also Works for Fractional q values.**
- **Larger Current Allows for Ohmic Ignition in Reactors.**
- **Drive Voltage Required is ~16 Times Higher Than for the m=1, n=1 Mode**
- **A Layer Again Forms near the Plasma Boundary.**
- **States Are Single Helicity With Very Little Radial Magnetic Field?**
- **The Stronger the Driving E Field, the Smaller the Radial magnetic Field.**
- **All Other Modes Are Stabilized By Flow.**
- **Does This Work for Other Helicities like the m=2, n=1 mode?**



mode profiles
q
rp
0
5
10
15
20
25
0.0
0.2
0.4
0.6
0.8
1.0

Dynamo Current Drive

- Dynamo Drive Also Works for Multiple q values.
- <δvxδB> Vanishes at r=0 Due to Regularity Conditions for the m=2, n=1 Mode.
- No Current is Driven at r=0 so q goes to Infinity.
- Drive Voltage Required is ~16 Times Higher Than for the m=1, n=1 Mode
- A Layer Again Forms near the Plasma Boundary.
- All Other Modes Are Stabilized By Flow.
- States Are Single Helicity?

Boundary Conditions

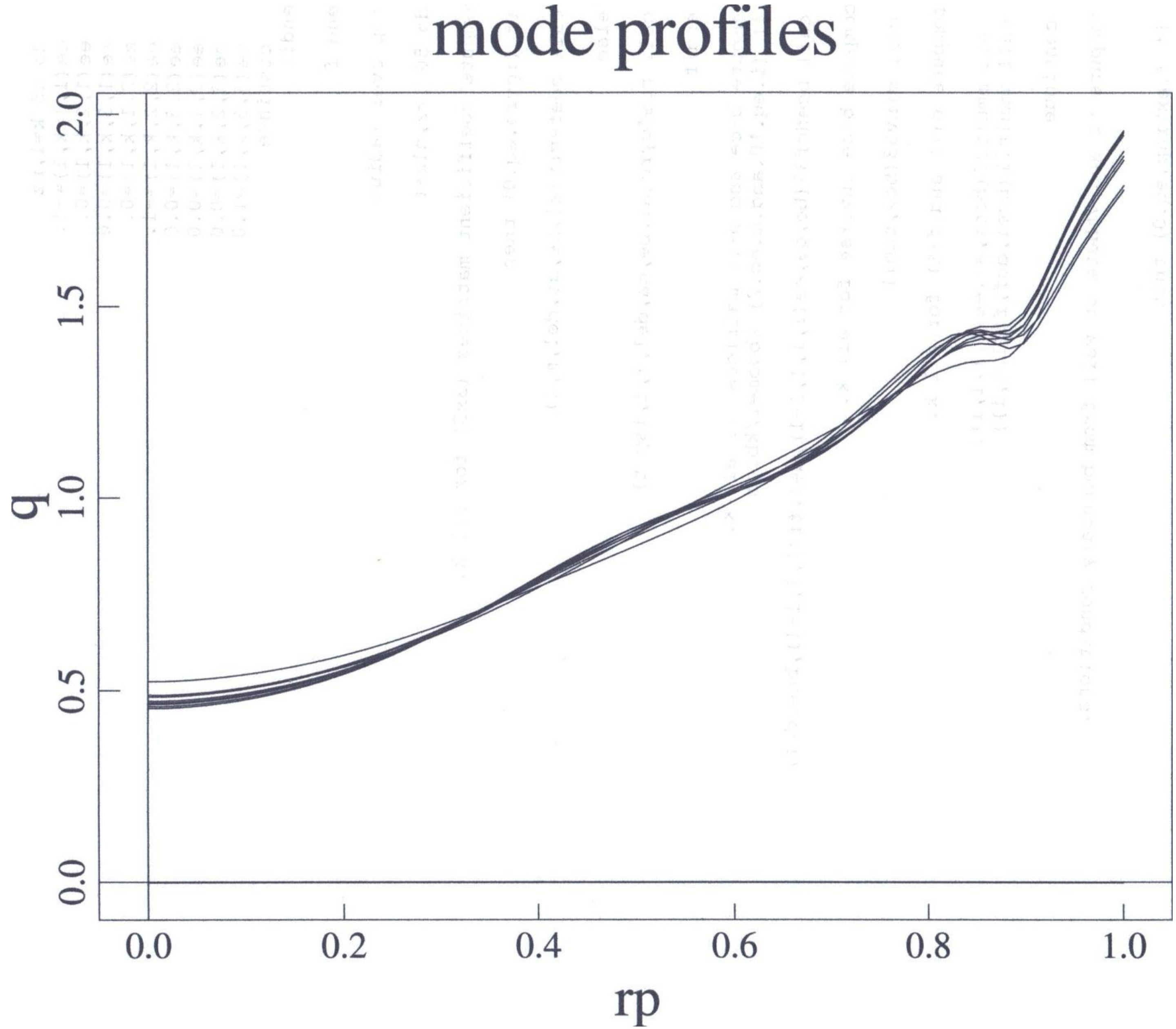
I. Perfect Conductor Boundary Conditions

$E_\theta(m,k) = E_z(m,k) = 0$

II. Free Flow Boundary Conditions

$\partial B_r/\partial t = 0$ or $E_\theta(m,k) = m/(kr)\, E_z(m,k)$
$E_r(m.k) = -v(m,k)xB(0,0) = \text{Constant}$

III. Magnetically B.C.s Look Like an Ideal Conductor, but the Electrostatic Potential Varies on the Surface. No Radial B Field at the Wall, But Flow is Imposed


mode profiles
q
rp
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0

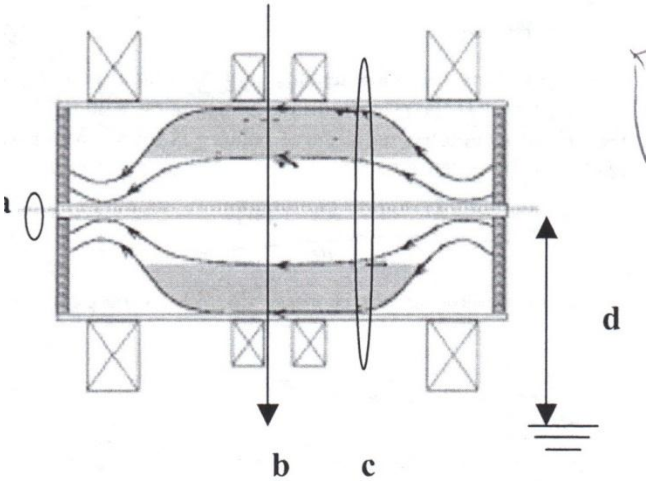
Dynamo Current Drive

- **Velocity BCs Show the Same Principle of the Magnetic Field Trying to Align with the Electrodes.**
- **States Are Single Helicity With Significant Radial Magnetic Field?**
- **All Other Modes Are Stabilized By the Flow.**
- **The Stronger the Driving E Field, the Smaller the Radial magnetic Field.**

Dynamo Current Drive

- **The Same Relaxation Principle Works, But Final States Have More Shear.**
- **All Other Modes Are Stabilized By the Flow.**
- **States Are Single Helicity But the Radial Magnetic Field is Much Larger Than in Previous Cases?**
- **The Stronger the Driving E Field, the Flatter the q Profiles.**

Debye Screening



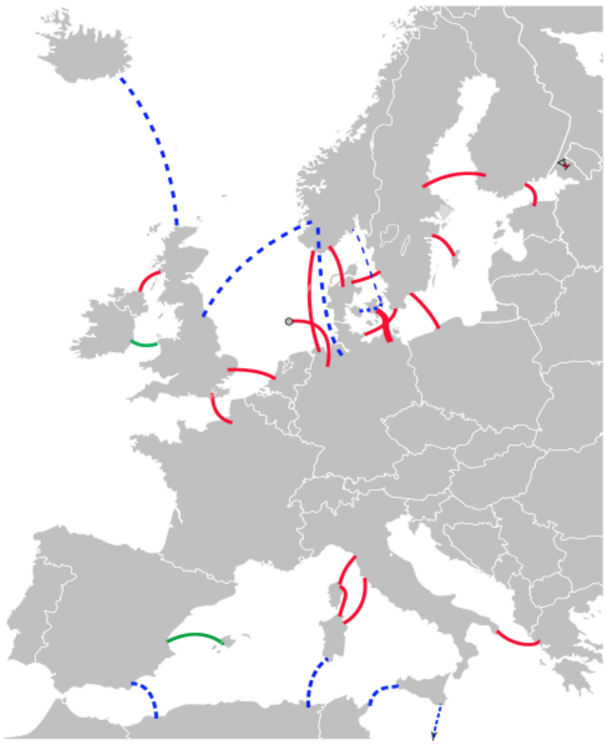
IG. 5. Diagnostics location: Rogowski coil (a), plasma beam of interfer-
meter (b), diamagnetic loop (c), and voltage divider (d).

- **Will These Fields Exhibit Debye Screening?**
- **Possible, but not Likely.**
- **MCX Spins Plasmas in a Similar Manner and it Works Fine.**

DC – DC Transformers

- **Dynamo Current Drive is Effectively a DC – DC Transformer.**
- **High Voltage/Low Current Perpendicular to the B Field Yields Low Voltage/High Current Along the B Field.**
- **A Linear Version of This Device May be Usable as a Transformer.**
- **This is the Key Enabling Technology for High Voltage DC Transmission.**
- **If Inexpensive DC-DC Existed in the Early 1900s We Would Have a DC Grid Rather Than an AC Grid.**
- **DC – DC Transformers Are Possible, but They are So Expensive That it Cannot Be Done Economically for Less Than 20 MW.**

High Voltage DC



HVDC Lines in Europe

- AC Power Can Only be Shipped Economically for ~ 400 Miles.
- AC Couples to the Environment Which Causes Losses.
- HVDC Doesn’t Do This and Can Even be Transmitted Underground or Underwater with Low Losses.
- With HVDC One Could Make a World-Wide Electrical Grid.
- Eliminates the Need For Energy Storage in PV and Wind Systems.

Summary

- m=1 Modes Can be locked into Single Helicity by Electrostatic Boundary Conditions in RFPs.
- Mode Locking Occurs on Ideal MHD Timescales.
- Electrostatically Driven m=1, n=1 Mode can Drive Current in Tokamaks.
- Electrostatically Driven m=1, n>1 Modes May allow for Ohmic Ignition.
- Electrostatically Driven m=2, n=1 Mode Result in Reverse Shear q Profiles.
- All of these States Are Stationary, Single Helicity, Stable to All Perturbations, and Arrived at Independent of the Initial Conditions?
- Debye Screening is Unlikely to be a Problem.
- Velocity Boundary Drive Shows the Same Relaxation Principle.
- Dynamo Drive can be Used to Make DC-DC Transformers.
- A Proof of Principle Experiment is Presently Being Built.