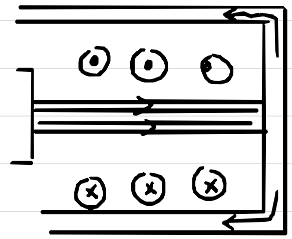
Project / Research Paper Idea. (By Mahat Joshi)

To determine whether a Z-pinch admits a spatially localized, delay-limited hardware-implementable feedback mechanism that can detect the incipient spatial structure of low order MHD instabilities and apply targeted electromagnetic correction before non-linear growth renders it impossible.

Section A



Scope: feasibility check for designing active, delay-limited feedback stabalization for low order Z-pinch MHD instabilities ($m = 0, 1$) with a focus on sensing to actuation electromagnetic hardware chain.

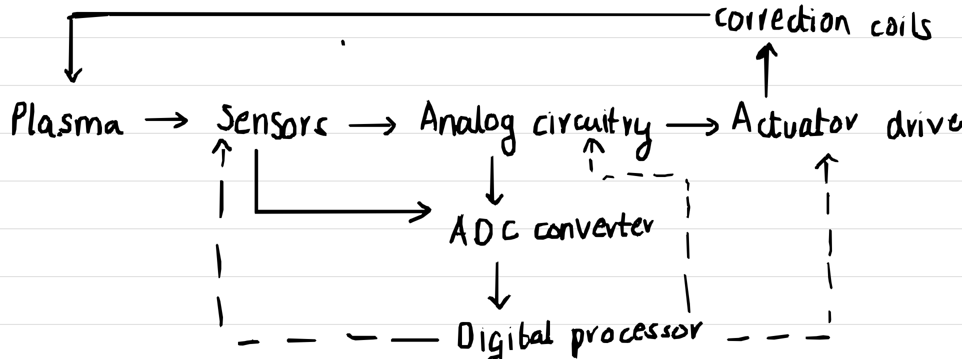
Sensing : what sensors are possible
bandwidth
mode observability

Signal chain: cable delay
amplifier bandwidth
ADC v/s comparator
EMI constraints

Control feasibility: delay limits
stability margins

Actuation feasibility: coil inductance limits
required voltage rise times
coupling into main current path.

Section B



— real time
-- observer loop.

(for fine turning analog components later and analysis)

(a) Bandwidth: sensor's ability to see very high frequencies.

MHD transit time: $\tau \sim \frac{a}{v}$ $\frac{\text{pinch radius}}{\text{relevant wave speed}}$

Instability growth rate $\gamma \sim \frac{1}{\tau}$

Bandwidth must be comparable to inverse of instability growth time, often set by Alvén timescales.

Bandwidth target = margin × $\frac{1}{\text{time taken for fastest change}}$.

(b) latency: the delay due to each component in the control loop (real time)

(c) Electro magnetic inteference: Too fast sensors, too much noise due to mega amp current, megavolt voltage, external noise.
Coupling: Unwanted inductance in wiring.
Capacitive coupling.
Ground coupling.

We wish to detect very small changes very fast.
But very high bandwidth = more noise

Section (3)

Latency Budget

Instabilities grow on the Alvén transit timescale

$\tau_A = \frac{a}{v_A}$ # pinch radius / magnetic speed of sound

$v_A = \frac{B}{(\mu_0 \rho)^{1/2}}$ # magnetic field strength, permeability of free space, plasma mass density

Zap/FuZe ($a = 1$ cm, $B \simeq 1$ T)

$\tau_A \simeq 20-50$ ns

$t = 0$, seed noise
$t = \tau_A$, linear growth
$t = 3\tau_A$, dent
$t = 5\tau_A$, distortion
$t = 7\tau_A$, pinch breaks

growth for uncontrolled pinch

unstable pole: $\lambda = \frac{1}{\tau_A}$

response $x(t) = x_0 e^{\lambda t}$

time to blow up. $t_{thresh} = \frac{1}{\lambda} \ln\left(\frac{x_{irreversible}}{x_0}\right)$

Question: At what point is it irreversible?
Current (intuitive assumption) $t_{thresh} < 3\tau_A$

B-dot: tiny wire loop that measures how fast magnetic fields change
Rogowiski: Air core current sensor that picks up current detected using
compered law.
photodiode: light detector.

Kink instability leads to local compression which the photodiode picks up as hot spots.

B-dot (1ns) 2 GHz
Rogowski (5 to 10ns) 500 MHz
Photodiode (0.5 to 5ns) 1 GHz

Sensor data → analog circuit
(gain + filtering)

Question: what components would be required in the analog detector circuitry before it goes to the actuator?

Key assumption: Due to lack of data, I am assuming that we need to react within $2\tau_A$

Section 4

Bandwidth vs rise time

Rise time is how long it takes a signal sensor to go from 10% to 90% of it's final value when there's a sudden change.

$$v(t) = V_f\,(1 - e^{(-t/RC)})$$

$$1 - e^{-t/RC} = 0.1$$
$$0.9 = e^{-t/RC}$$
$$0.105 = \frac{t_{10\%}}{RC}$$

$$1 - e^{-t/RC} = 0.9$$
$$0.1 = e^{-t/RC}$$
$$2.302 = \frac{t_{90\%}}{RC}$$

$$t_{90\%} - t_{10\%} = 2.197RC \approx 2.2RC$$
$$t_r \approx 2.2RC$$

Bandwidth: Highest frequency w/o distortion

$$H(j\omega) = \frac{1}{1 + j\omega RC}$$

$$|H(j\omega)|^2 = \frac{1}{1 + (\omega RC)^2}$$

-3db is the point where a system loses half it's power

$$|H(j\omega)|^2 = 1/2$$

$$\frac{1}{1 + (\omega RC)^2} = \frac{1}{2}$$

$$(\omega RC)^2 = 1$$

$$\omega_{-3db} = \frac{1}{(RC)}$$

$$\text{Bandwidth} = \omega_{3db} = \frac{1}{RC}$$

$$\omega = 2\pi f$$
$$f = \frac{\omega}{2\pi}$$
$$BW(Hz) = \frac{1}{2\pi RC}$$

$t_r = 2.2RC$

$BW(Hz) = \frac{1}{2\pi RC}$

$t_r BW = 0.35$

If our electronics are too slow, we miss the instability.

1 GHz reacts in 0.35 sec

100 MHz reacts in 3.5 nS

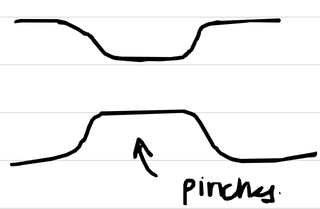
Thus : $\frac{0.35}{BW}$ = reaction time

Section 5

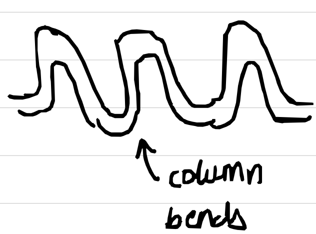
probe setup

Question: How should probes be set up so that we can detect the specific instability at the specific location?

sausage instability (m=0)



kink instability (m=1)



Questions:

1. What sensor types can be used reliably?
2. How to deal with electromagnetic interference that affect these sensors and my circuits.
3. How to approach designing the analog circuitry for this.

4. What is the upper limit on bandwidth before noise drowns out useful signals?
5. Is it possible to do this w/o DC conversion to reduce latency?
6. Is grounding or shielding necessary? And if so, how to?

7. Signal chain that preserves high frequency in a noisy environment.
8. What are the measurement approaches, can we trade resolution for speed?
9. Is it useful to pre-process signals on analog sensors rather than digital.

(7)