OUTLINE OF A CONTROL SCHEME FOR MAJOR DISRUPTIONS IN ITER

A. K. Sen

Columbia University

I. MOTIVATION

- Major disruptions in ITER remain as major unresolved headaches.
- Disruption mitigation schemes are good, but too late in the destructive scenario.
- Avoidance should be the goal.

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Feedback Control

Of what? MHD precursors!

Tearing Modes

Neoclassical Tearing Modes

Resistive Wall Modes

Good schemes are already on the table.

INTERNAL / INFERNAL

NEAR IDEAL MHD MODES

No proposals yet!

II. NEED FOR NON-MAGNETIC SENSORS & SUPPRESSORS

For INTERNAL MHD MODES!

Magnetic sensing via Minnov coils **X**

Saddle coil suppressors **X**

NON-MAGNETIC SENSORS:

ECE (electron cyclotron emission) diagnostics for electron temperature fluctuations is well developed.

Particularly, 2D imaging of r-θ plane.

NON-MAGNETIC SUPPRESSORS:

A novel scheme of a radially injected ECH (electron cyclotron heating) beam, modulated at the mode frequency.

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Will create a near instantaneous non-thermal electron “pressure”.

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At an appropriate phase and amplitude, it can push the kink mode radially inward in opposition to the natural mode dynamics.

III. A NOVEL SUPRESSOR:

MODULATED ECH FEEDBACK FOR INTERNAL MHD MODES

Consider purely radial ECH injection: The transverse energy of electrons $W_{e\perp} \sim 'p_{e\perp}'$ will nearly instaneously (compared to γ, ω_r) increase with resonance response!

$\therefore$ $'\tilde{p}_{e\perp}'$ is the suppressor action!

A NAÏVE MODEL OF CONTROL ACTION:

$$\frac{dW_\perp}{dt} + \nu_d W_\perp = P^{ECH} = P_0^{ECH}(1+\alpha e^{-i\omega_r t})$$, where α is mod. depth

$$\therefore \quad \tilde{p}_{e\perp}^{f.b.} \approx W_\perp = \left(\frac{\alpha P_0^{ECH}}{\nu_d - i\omega_r}\right) e^{-i\omega_r t} \sim i\alpha P_0^{ECH} e^{-i\omega_r t}/\omega_r \qquad (1)$$

IV. MODEL DYNAMICAL EQUATION AND FEEDBACK

The linearized ideal MHD equations can be written in the following well known form with the inclusion of an externally injected electron pressure term from the ECH beam:

$$\rho \frac{\partial^2 \vec{\xi}}{\partial t^2} = F(\vec{\xi}) + \vec{e}_r \frac{dp_e}{dr} \qquad (3)$$

where ξ , ρ , p_e are perturbed plasma displacement, density, and feedback modulated electron pressure respectively, and the force operator is given by

$$F(\vec{\xi}) = (\nabla \times \vec{B}) \times [\nabla \times (\vec{\xi} \times \vec{B})] / \mu_0$$

$$+ \nabla (\vec{\xi} \cdot \nabla p + \gamma p \nabla \cdot \vec{\xi})$$

$$+ \{\nabla \times [\nabla \times (\vec{\xi} \times \vec{B})]\} \times \frac{\vec{B}}{\mu_0}$$

where γ is the ratio of specific heats and p is the plasma pressure.

Writing $d\phi_e / dr \sim p_e / L_d$ and $\underline{\tilde{p}_e^{fb} / p_0 = G(\vec{\xi} / a)}$ in Eq. (3), taking its scalar product with $\vec{\xi}^*$, assuming $\vec{\xi} \sim \exp(-i\omega t)$, and integrating over the plasma volume, we have the following feedback modified energy principle.

$$\omega^2 \int \frac{1}{2}\rho\left|\vec{\xi}\right|^2 dV + dG\int \frac{1}{2}\rho\left|\xi_r\right|^2 dV = \delta W_F(\vec{\xi}^*, \vec{\xi}); \quad \text{G=feedback gain}$$

and only the fluid part of the variational energy δW_F is shown. Noting that $\left|\xi_r\right|^2 / \left|\vec{\xi}\right|^2 \approx 1$ for low *m*, *n* kink modes, we can obtain the following more complete energy principle:

$$\omega^2 + dG = \frac{\delta W_F(\vec{\xi}^*, \vec{\xi}) + \delta W_V + \delta W_S}{\int \frac{1}{2}\rho\left|\vec{\xi}\right|^2 dV} = -\gamma_0^2 \qquad (4)$$

For marginal stability: $$G = -\frac{\gamma_0^2}{d}, \quad d = \frac{KT_e}{m_e L_d a_0} \qquad (5)$$

V. COUPLING COEFFICIENT OF THE LOCALIZED ECH SUPPRESSOR

The geometrical coupling coefficient is proportional to the modal coefficient of the double Fourier series expansion of the toroidal dimension L_t and poloidal dimension L_P of the ECH beam footprint. The coupling coefficient can be written as

$$C_0 \approx (L_t L_p / 4\pi R a_0)\Re \qquad (6)$$

where $\Re$ is determined from a radial convolution of the ECH deposition profile and the radial structure of the mode.

We can now estimate the feedback power requirements for ITER like parameters using only one beam: $R \sim 8.1m, a_0 \sim 2.8m, L_p \sim 8cm, L_d \sim 5cm, T_e \sim 10keV, \nu_d \sim \nu_e \sim 10^4$ For a typical $\gamma_0 \sim 10^5 s^{-1}$ (nearly ideal growth rate modified by diamagnetic and other effects), we find from Eq.(5) that $|G| \sim 10^{-6}$. Using Eq.(6) we find $C_0 \sim 3.6x10^{-6}$ and for $\Re = .5$ yields $|G|_{actual} \sim |G|/C_0 \sim .28$.

Then we have: $p_e / NkT = |G|_{actual}(\xi_r / a)NkT \sim |G|_{actual}(B_p / B_{p0}) \sim 2.8x10^{-3}$

for a detectable level of $B_p / B_{p0} \sim 10^{-4}$, where B_{p0}, B_p are the equilibrium and fluctuation poloidal fields, respectively. Then $P_0^{ECH} \sim \gamma_d p_e \sim .12MW < 1MW$ from one wave-guide in ITER

For an ideal mode with $\gamma_0 \sim 10^6, P_0^{ECH} \sim 12MW < 20MW$ from 24 wave-guides in ITER

VI. SENSORS FOR MHD INTERNAL MODES (ECE) EMISSION DETECTORS

- Located in the equatorial plane. Schematic in Fig. 1.
- ECE at electron cyclotron frequency resonance (ECR) layer at frequencies:

  $$l\omega_{ce} = l\omega_{ce}(R) = l\omega_{ce0}\frac{R_0}{R}, \quad l = 1, 2$$

  Optically thick for $l = 2$: Blackbody radiation $\tilde{I}(\omega) = \tilde{T}_e\omega^2/8\pi^3c^2$
- In our case the relevant resonance layers are mode rational surfaces:

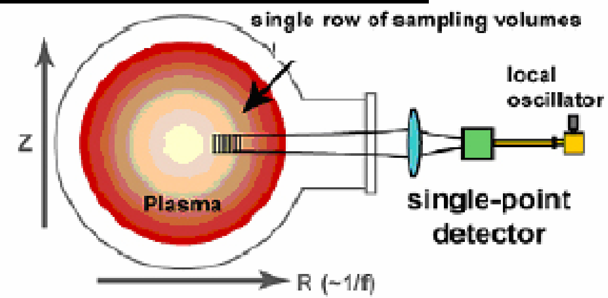
  $$m = nq;\ q = f(R) = m/n;\ n = 1, 2;\ m = 2-6$$

- FFT of total ECE ➔ $2\omega_{ce}$ ➔ Initial setting of LO.
- Feature extraction from 2D ECE ➔m, R
- Stored MSE➔q➔$2\omega'_{ce}$➔frequency tuning of LO (for heterodyne detection)
- Also q, m➔n
- Frequency sweep the LO frequency (via varactor diodes) over a small range for optimality, which can be done on line.

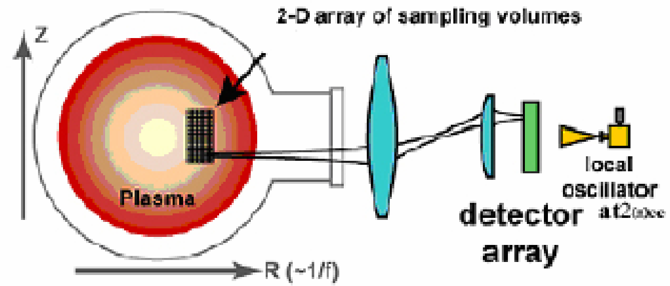
VII. 2D ECE IMAGING SYSTEM

H. Park & TEXTOR Team

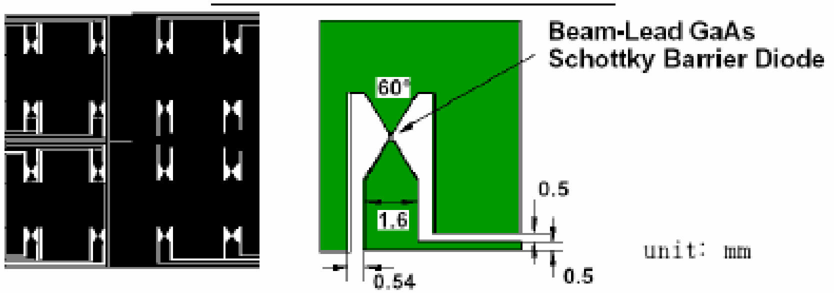
Conventional 1-D ECE system



2-D ECE imaging system

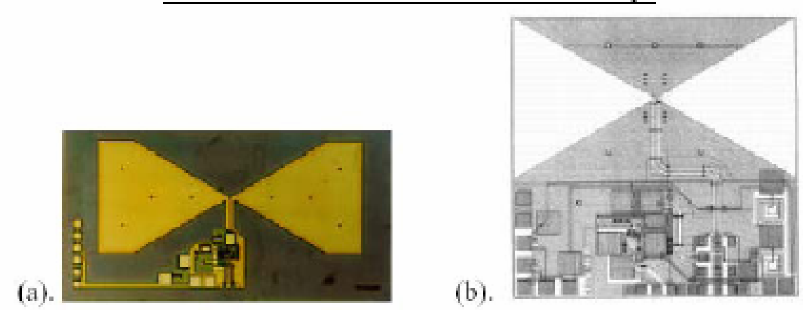


2-D DETECTOR ARRAY



Schematic of the 2-D imaging array

MIMIC DETECTOR Teratec Corp.



Mask patterns of the monolithic detectors integrated with bow tie antennas, Schottky diodes, and HBT amplifiers (a) is the first mask pattern, and (b) is a more recent one.

Fig. 1

VIII. SCHEMATIC OF THE FEEDBACK SYSTEM

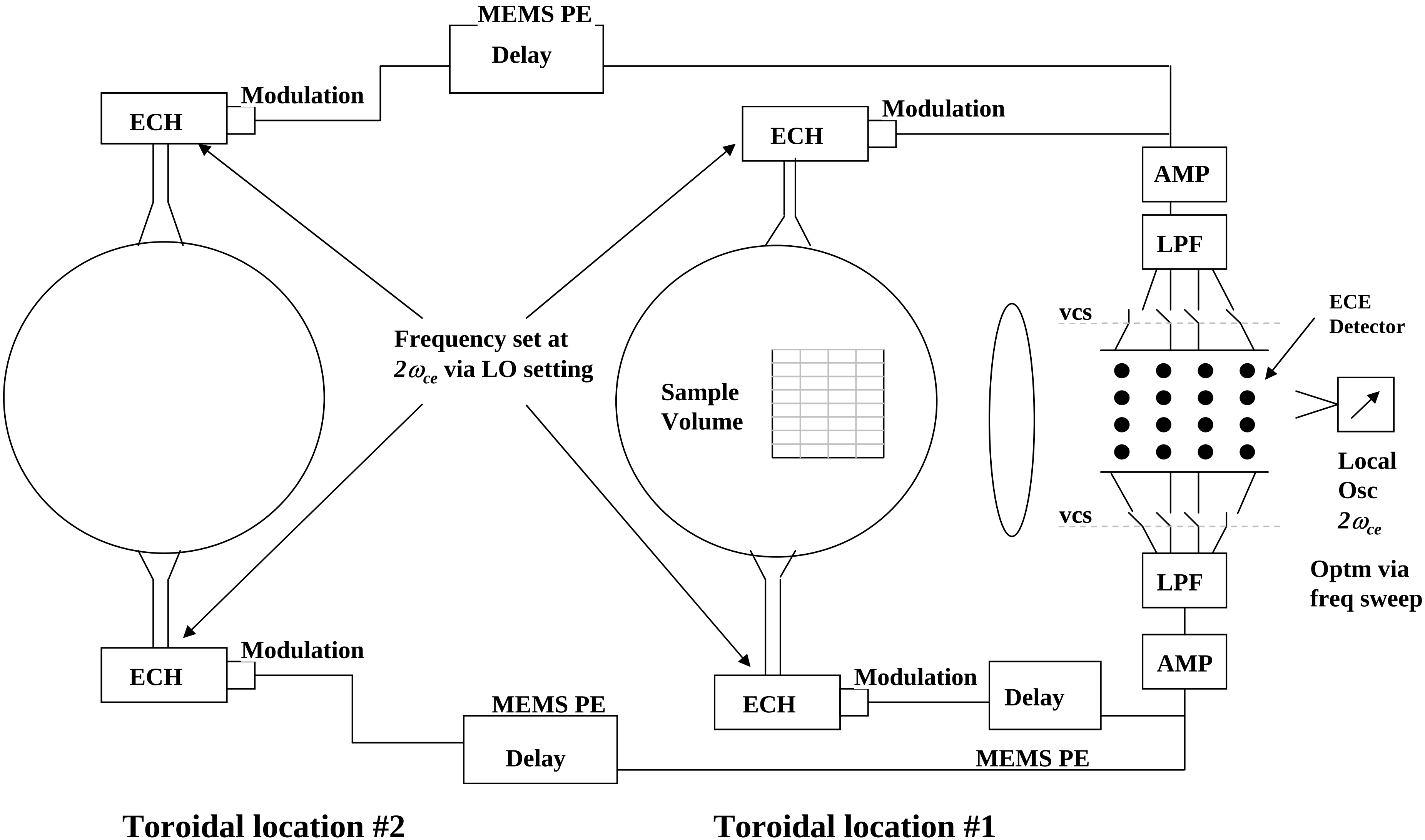


Fig. 2

IX. ECH SUPPRESSORS

- **<u>LOCATED AT THE EQUATORIAL PLANE</u>**. A schematic of the entire feedback system in Fig. 2.
- **<u>AUTOMATIC TARGETING OF THE MODE.</u>**
- **<u>RADIAL TARGETING</u>**
  - Borrow $2\omega_{ce}$ from the LO of ECE detectors for ECH suppressor frequency. The mismatch between this and the 170MHz of gyrotrons already designed for ITER is a problem. It may be resolved by using tunable gyrotrons now under development. (Thumun, Piosezyk)
- **<u>TOROIDAL AND POLOIDAL TARGETING</u>**
  - More complex.
  - ECH suppressor gyrotrons are fixed, say at $\theta_s=0$, $\phi=\phi_s$, shown in Fig. 3. The helical structure of an arbitrary kink mode with initial co-ordinates $\phi(0)$, $\theta(0)$ will intercept the gyrotron location only if

$$\frac{\phi_s - \phi(0)}{\Omega_t} = \frac{0 - \theta(0)}{\Omega_p}$$

which is impossible for arbitrary parameters.

X. AUTOMATIC TARGETTING SCHEME

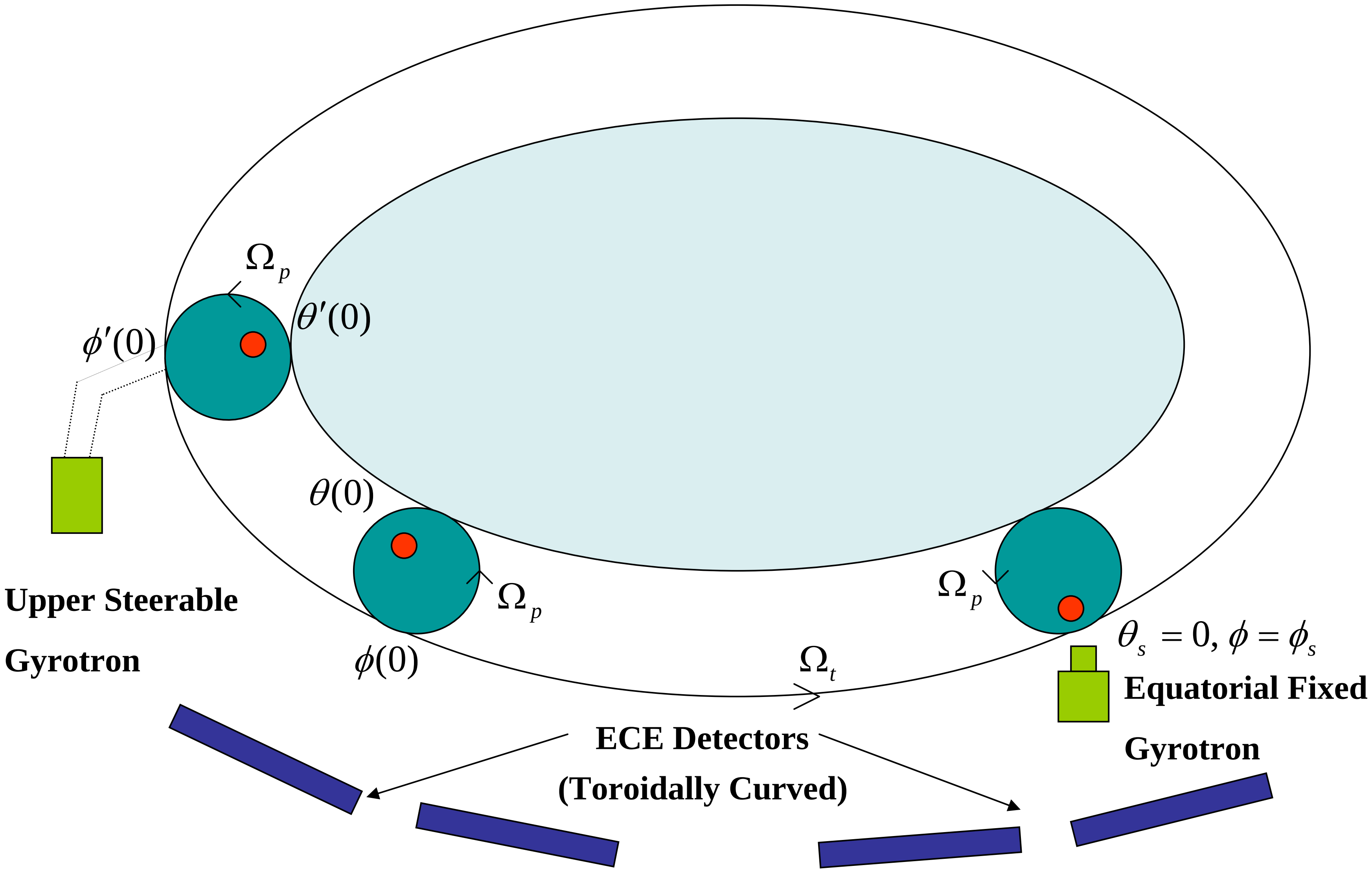


Fig. 3

However, this can be made possible, if a real frequency ω_r of the kink mode is generated via feedback and we consider the above equation at time t:

$$\frac{\phi(t)-\phi(0)}{\omega_r(G_i)+\Omega_t}=\frac{\theta(t)-\theta(0)}{\omega_r(G_i)+\Omega_p} \qquad (7)$$

Where G_i is the imaginary part of the complex gain of the feedback necessary to generate a real frequency. The feedback G can be based on many simple feedback schemes including the proportional plus derivative feedback:

$$G=G_0+iG_1\omega/\omega_0, \quad \omega_0=band\ width$$

which modifies the dispersion relation of Eq. (5) as

$$\omega^2=-\gamma_0^2-dG_0+iG_1 d\omega/\omega_0$$

For marginal stability γ=0:

$$G_0=-\gamma_0^2/d, \quad \omega_r=dG_1/\omega_0$$

- **Experimental Determination of Unknown Parameters in Eq.(7)**

  With no feedback (G_i=0), one needs simple online experiments/computation as:

$$\Omega_t = (\phi(\Delta t) - \phi(0)) / \Delta t$$

$$\Omega_p = (\theta(\Delta t) - \theta(0)) / \Delta t$$

- **Experimental Implementation of Generation of $\omega_r(G_i)$ and Targetting:**

- This ω_r generating feedback must also be based on proper targeting:

  Solution: Use of a steerable (via mirrors) upper gyrotron of ITER for targetting.

  Feedback switched on for ω_r

- Adjust ω_r via G_i to ensure interception of the mode by the equatorial suppressor gyrotron. With feedback gain G_r, fire this gyrotron.

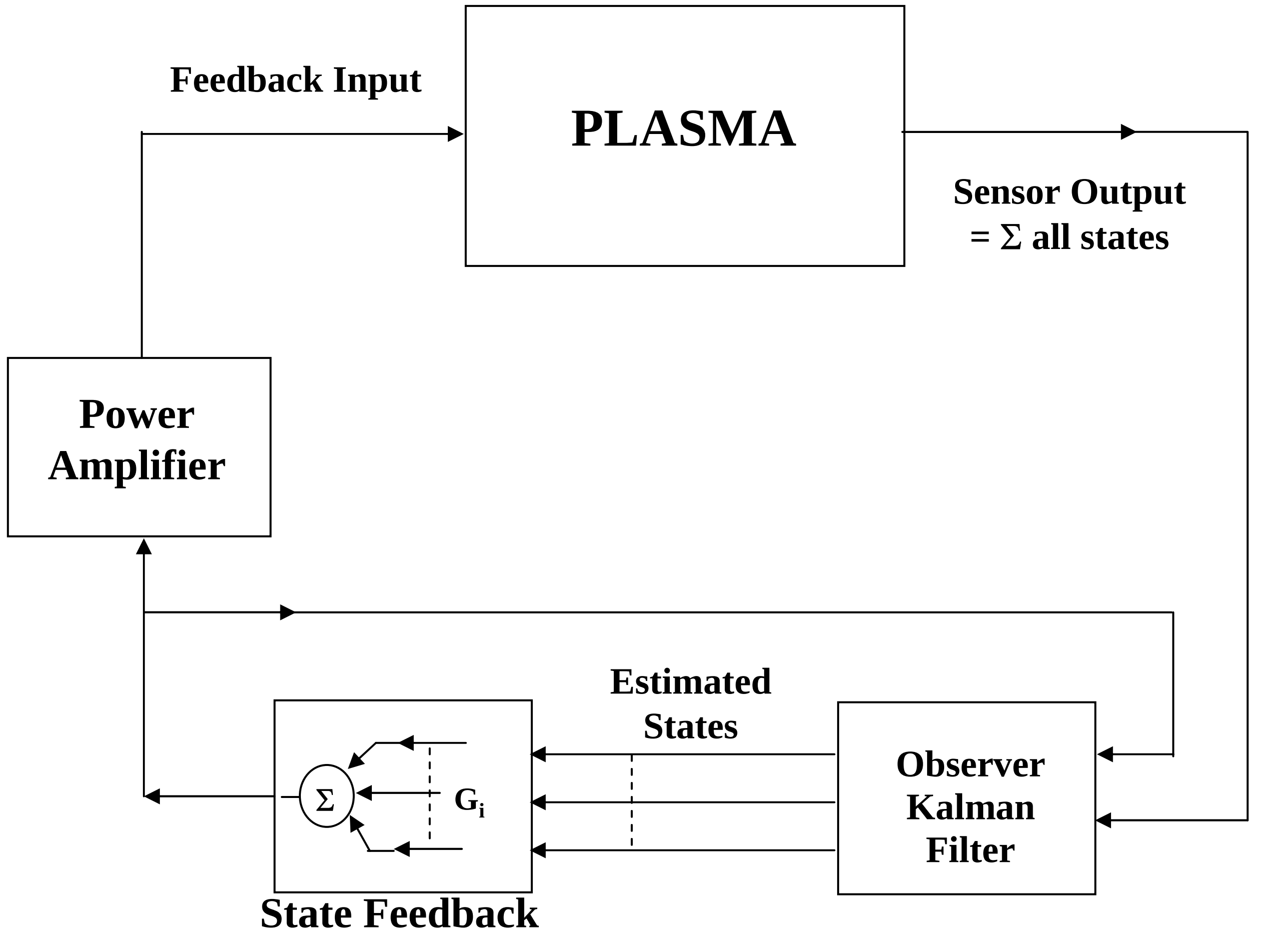
XI. Quasi-steady State

- The suppressor gyrotron firing will be periodic with frequency $\Omega_t+\omega_r$. If once a cycle firing is not adequate, consider several suppressor gyrotrons around the torus.

- After the first cycle, the role of ω_r generation by the steerable upper gyrotron can be shifted to the equatorial suppressor gyrotron. (The former is less efficient because of its broad deposition profile).

FEEDBACK SYSTEM DESIGN OPTIONS

XII. SCHEMATIC OF STATE FEEDBACK FOR MULTIMODE MHD MODES



Really Need Adaptive Optimal Control

A la Sun, Sen and Longman, POP **13**, 012512, 2006; Sun, Sen and Longman, POP **13**, 092508, 2006

XIII. A SIMPLE IMPROVEMENT IN THE USE OF KALMAN FILTER

- Kalman filter strongly depends on a system model incorporated.
- This model can be derived simply from the experimental data of ECE.
- Assume that the system parameters [A] in the following dynamic model are largely unknown or poorly known:

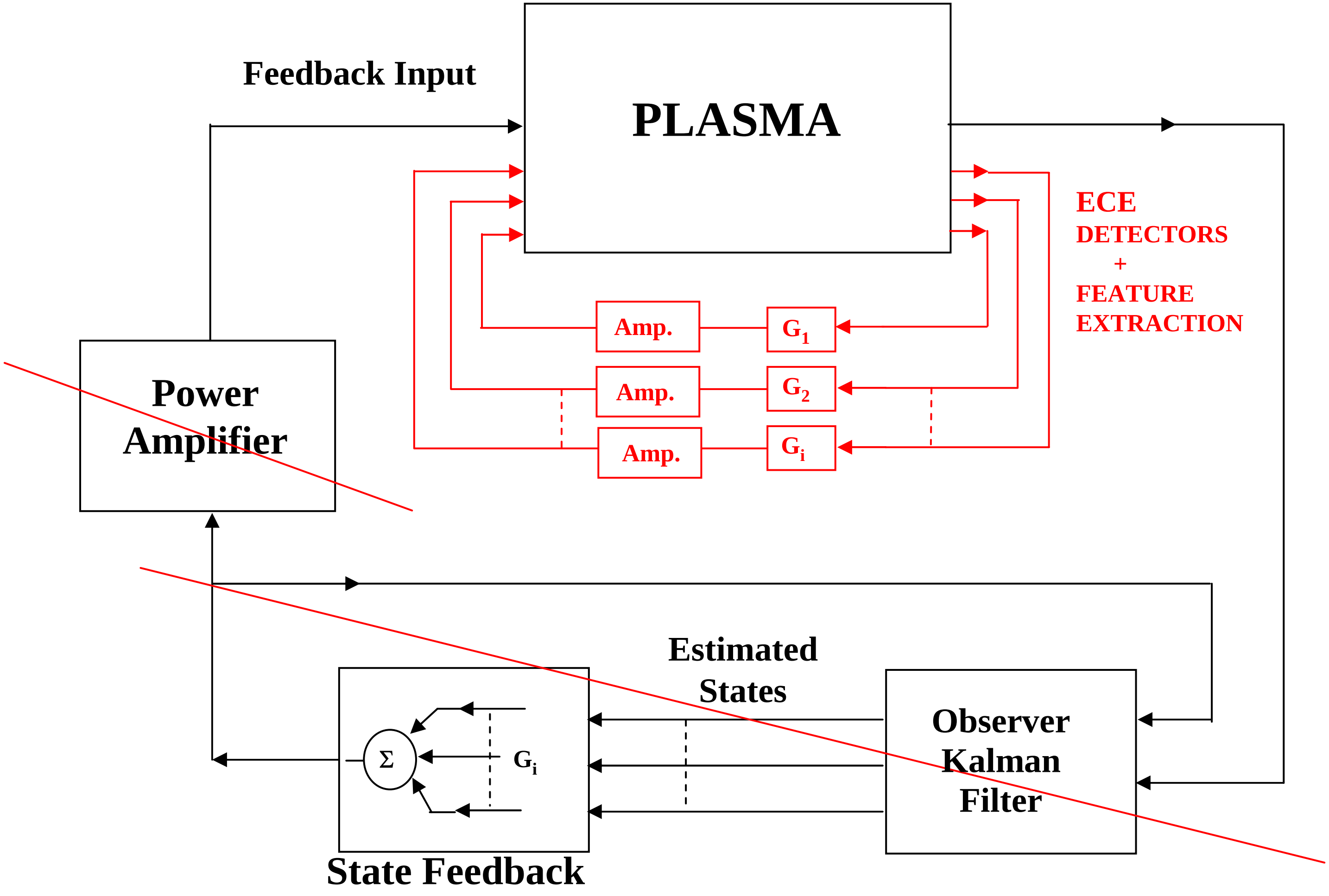
$$[\dot{a}] = [A] \cdot [a], \quad a = Mode\ Amplitude \equiv System\ State$$

System → $[A]$ Insert ECE Data → $[a]$

- Then solve the above equation numerically and iteratively as a system identification on problem.
- It can be done on line, but may take several ms. Therefore, start with a priori model, with minor updates on line.
- Then Kalman filter with much better system model may produce much better results.

XIV. SIMMPLER STATE FEEDBACK FOR MULTIMODE MHD MODES

USING EXPERIMENTALLY MEASURED STATES



XV. LOSS OF CONTROL INFORMATION VIA DRIFTS AND DIFFUSION

NOTE: STRONGLY ECH 'HEATED' ELECTRONS ARE DEEPLY TRAPPED ELECTRONS!

1. TOROIDAL DRIFTS:

$$\frac{\omega_{de}}{2\pi} = \frac{k'T_{e\perp}'}{eB_p}\frac{1}{R^2} << \gamma_0 \sim 10^5 - 10^6$$ Not a problem!

2. RADIAL THERMAL CONDUCTION:

$$\tau_{cond} \sim a_0^2 \kappa^{GB} \sim \sec s \geq \gamma_0^{-1} \sim 10^{-5} - 10^{-6}$$ Not a problem!

3. THERMAL CONDUCTION ON MAGNETIC SURFACE:

$$\tau_{cond} \sim \vartheta((1-2)\times \nu_e^{-1})10^{-4} >> \gamma_0^{-1} \sim 10^{-5} - 10^{-6}$$ Not a problem!

XVI. ACKNOWLEDGEMENT

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