

Kinetic control of tokamaks

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Outline I

① Kinetic control

- 0D model of tokamak confinement

- Sources of power, particles and current

 - Plasma self-generated sources

 - Auxiliary sources of heat and current

- Sinks of power and particles

 - Confinement transitions

- Particle transport

- Sensors/Diagnostics for kinetic control

- Current practice for kinetic control

Section 1

Kinetic control

Subsection 1

0D model of tokamak confinement

0D models of tokamaks

- Energy balance equation for plasma pressure

$$p = (n_e T_e + n_i T_i) \approx 2nT \text{ (or thermal energy density } w_{th} = \frac{3}{2}p)$$

$$\frac{3}{2} \frac{dp}{dt} = S_{source} - S_{sinks} \quad (1)$$

where

- $S_{sources}$ is the source power density
- S_{sinks} is the sink power density

See the book by Freidberg for an overview of power balance considerations for reactors, Lawson's criterion, etc. [?]

0D models of tokamaks

- Particles

$$\frac{dn}{dt} = S_{source,n} - S_{sink,n} \quad (2)$$

- $S_{sources,n}$ is the source of particles
- $S_{sinks,n}$ is the sink of particles

- Global current balance

$$I_{pl} = I_{p,inductive} + I_{p,non-inductive} \quad (3)$$

- Inductive current: current driven by (induced) loop voltage.
- Non-inductive current: other sources, self-generated by plasma or auxiliary current drive.

Subsection 2

Sources of power, particles and current

Fusion power

- $\frac{4}{5}$ of each fusion reaction's energy is in the fast 14MeV neutron. To be used by breeder to breed tritium and to extract energy.
- $\frac{1}{5}$ of each fusion reaction is contained in a 3.5MeV α -particle.
- Alpha particle power density (for DT reactions) is

$$S_{\alpha} = E_{\alpha} n_D n_T \langle \sigma v \rangle = \frac{f_{DT}}{(1 + f_{DT})^2} E_{\alpha} n^2 \langle \sigma v \rangle \quad (4)$$

where $f_{DT} = n_D/n_T$ and we have used $n_T + n_D = n$

- For sustained fusion reaction, significant fraction of plasma thermal energy must come from α -particles.

$$P_{\alpha}/P_{in} = 1 \leftrightarrow Q = P_{fus}/P_{in} = 5$$

Ohmic power

- The plasma current causes resistive heating $P_{oh} = V_{loop} I_p = I_p^2 R_p$.
- ‘Ohmic plasmas’ are plasmas heated purely by Ohmic power, no auxiliary sources.
- Unfortunately, resistivity decreases with plasma temperature, so P_{oh} decreases. Purely ohmic tokamak plasmas can’t reach high enough temperatures for ignition.

Bootstrap current

- Self-generated plasma current due to neoclassical (trapped particle) effects (see [1] for the physical explanation).
- Caused by pressure gradient, proportional to $\frac{\partial p}{\partial \psi}$.
- For steady-state tokamaks, we want the entire plasma current driven non-inductively. But auxiliary current drive is expensive.
- For steady-state tokamaks, we would like a *large bootstrap current fraction*, $I_{BS}/I_p > 50\%$, rest by auxiliary current drive.
- Active field of research in ‘advanced scenarios’: most current driven by bootstrap + auxiliary.

Neutral beam injection

- Inject high-energy beam of neutral particles, ionize upon entering plasma
 - Beam ions thermalize by colliding with plasma ions, kinetic energy of beam becomes thermal energy of plasma
 - Also drive electrical current and give momentum (rotation) to the plasma
-
- Advantages
 - ‘Workhorse’, good for bulk heating and current drive.
 - Disadvantages
 - Power can only be on or off for each injector.
 - Technologically difficult for high energy and high power. Need ‘negative ion’ beams.

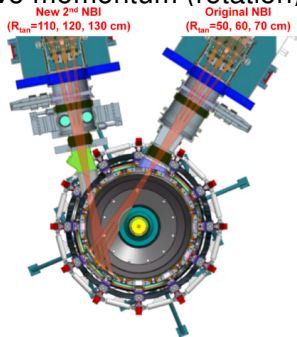
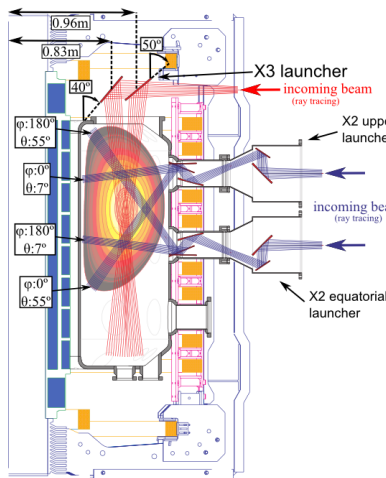


Figure: NSTX

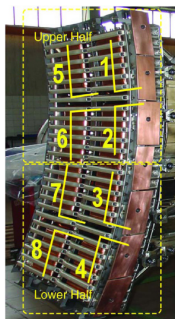
Electron Cyclotron Heating & Current Drive

- Electrons gyrate around field at cyclotron frequency $\omega_c = \frac{eB}{m}$
- EM waves resonantly heat electrons.
- Advantages:
 - Waves propagate through vacuum, no coupling problems.
 - Steerable: highly localized heating/cd location in plasma.
 - Can drive electric current.
- Disadvantages:
 - Heats electrons only.
 - Concentrated stray radiation may damage wall or diagnostics, need protection.
 - Difficult technology for sources ($f \sim 170\text{GHz}$) - but good progress.

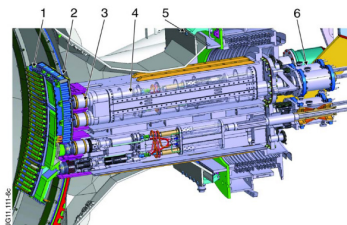


Ion Cyclotron Heating and Current Drive

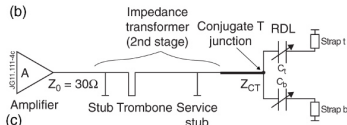
- Advantages:
 - Source technology easy, $f \approx 50\text{MHz}$.
 - Heats the ions: good for fusion.
- Disadvantages:
 - Antennas must be close to plasma to couple power: antenna-plasma interaction and problems with impedance matching



(a)



(b)



(t, b) = (1, 2), (3, 4), (5, 6), (7, 8)

Lower Hybrid Heating and Current Drive

- Advantages:
 - Source and transmission technology is easy, 1 – 8GHz.
 - Good at driving non-inductive plasma current.
- Disadvantages:
 - Only electron heating.
 - Technologically difficult coupling of antenna to plasma.
 - Hard to tell where the power/current will go.

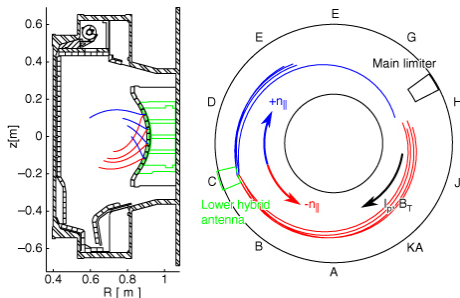


Figure: LHCD wave propagation according to Genray code. From [2]

Subsection 3

Sinks of power and particles

Radiation

- Physical origin
 - Cyclotron: radiation due to centripetal acceleration of gyrating particles.
 - Line radiation: ionization processes involving bound charge states.
 - Bremsstrahlung: radiation due to acceleration (change of velocity direction) of particles during collisions.
- Bremsstrahlung is usually dominant for large hot tokamaks.
 - Approximate model:

$$S_{brem} = 5.35 \times 10^3 Z_{\text{eff}} (n_{e20})^2 T_e^{1/2} \quad (5)$$

- Here, $Z_{\text{eff}} = \frac{1}{n_e} \sum_j Z_j^2 n_j$ is the effective charge. (j sums over impurity species). Impurities have higher charge and cause electrons to radiate more. Important to keep Z_{eff} low.
- If high-Z impurities accumulate in plasma, then impurity line radiation may dominate.

Conductivity losses

- The temperature gradient from core to edge causes outward thermal diffusion.
- Ultimately, energy flows out of the plasma into the limiter or divertor.
- This is quantified by the energy confinement time. Neglecting all other sources and sinks we have

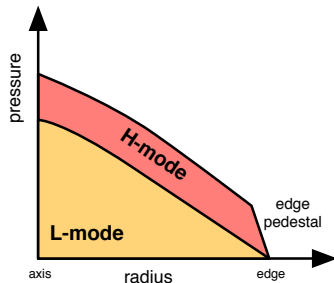
$$\frac{dp}{dt} = -S_{cond} = -\frac{1}{\tau_E} p \quad (6)$$

so the pressure decays with characteristic time τ_E .

- Unfortunately, τ_E decreases with increasing input power. Otherwise we could reach any temperature by just heating sufficiently.
- Until very recently, tractable first-principle models for τ_e did not exist: use *scaling laws* instead.

L-H transition

- L-mode: 'normal' model of operation for tokamaks.
- H-mode: Transport is locally suppressed near the edge. Edge Transport Barrier gives *edge pedestal*.
 - Pressure pedestal gives extra pressure in entire plasma
 - Occurs in diverted plasmas, after reaching *power threshold*
 - Detailed mechanisms not understood, involves complex turbulence and flow.
 - Edge pedestal can repetitively collapse, origin of Edge Localized Mode (ELM).



Subsection 4

Particle transport

Gas valves/pellet injectors

- Gas valves

- Inject gas into vacuum chamber
- Neutral gas particles become ionized soon after they enter the plasma.
- Time delays if valves are far away.
- Gas stays near edge and does not penetrate into the plasma in certain conditions.

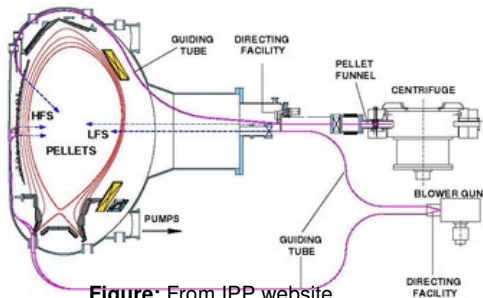


Figure: From IPP website

- Pellet injectors

- Inject small pellets of frozen D_2 or H_2 ice at high speed.
- Penetrates into the plasma before ablating.
- Can be used for localized fuelling deep in the plasma.

0D model of tokamak particle confinement

- Three ‘reservoirs’: plasma, vacuum, wall.
- Flows:
 - **Ionization**: neutrals in vacuum get ionized when entering the plasma.
 - **Recombination**: ions in plasma get neutralized and leave plasma
 - **SOL losses**: plasma from the *scrape-off layer* exit plasma and impact limiter/diverted.
 - **Recycling**: Particles from wall pushed out by new incoming particles.

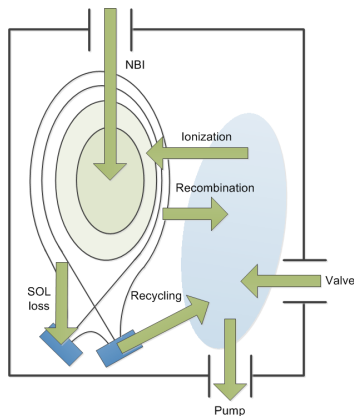


Figure: Particle flows in a tokamak reactor [T. Blanken Fus.Eng.Des 2017]

Subsection 5

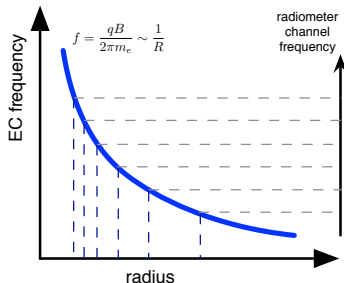
Sensors/Diagnostics for kinetic control

Sensors, aka Diagnostics

- Measurements of high-temperature plasma are not easy.
- Entire courses exist on plasma diagnostics.
- Here we look only at diagnostics that are used for real-time control.

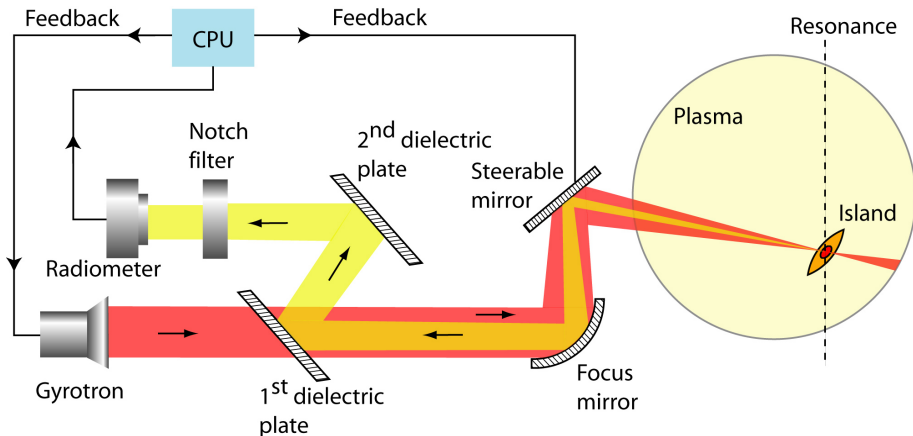
ECE - Electron Cyclotron Emission

- Measure EC radiation leaving the plasma.
- Choose measured frequency $\rightarrow$ nominal emission location inside plasma.
- In practice, thermal, supra-thermal, and relativistic effects play an important role, often source of radiation is not well-localized.
- Advantages
 - High temporal resolution.
 - Viewing angle can be steered (in-line ECE).
- Disadvantages
 - Measurement location depends on B field.
 - Cutoff at high density.



In-line ECE

- ECE line of sight shared with ECRH launcher [3].
- Steerable line of sight, sensing and actuating in same location.



Thomson scattering

- Laser scatters off plasma electrons.
- Intensity of scattered light is proportional to plasma density.
- Broadening of scattered spectrum is proportional to plasma temperature.
- Advantages
 - Localised measurement.
- Disadvantages
 - Laser repetition rate limits temporal resolution.

Radiation measurements

- Soft X-ray
 - Plasma core Bremsstrahlung and line radiation is mostly in the X-ray part of the EM spectrum
 - X-ray detectors can be used to measure line-integrated X-ray radiation in given portion of the spectrum.
 - Can be processed by tomographic inversion techniques to get pictures of plasma position, shape, or internal plasma fluctuations.
- Bolometry
 - Broadband measurement of Visible + UV + X-ray radiation
 - Used to get total radiated power.

Interferometry

- Laser beam follows 2 paths, one through plasma, one not.
- Beam through plasma travels more slowly, phase shift w.r.t. unperturbed beam.
- Interference pattern with other beam gives measure of plasma density.
- Measurement of *line-integrated electron density*:

$$\Delta\phi = \frac{\lambda e^2}{2\pi\epsilon_0 m_e c^2} \int_L n_e dl \text{ where } L \text{ is the path of the chord.}$$

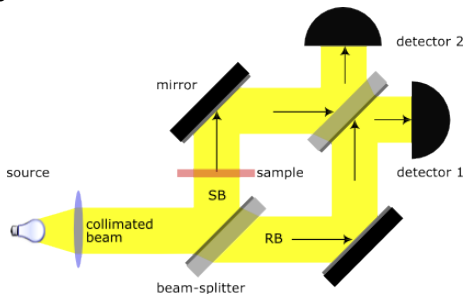


Figure: Schematic diagram of a Mach-Zehnder interferometer.

Motional Stark Effect diagnostic

- Neutral particles (from NBI source) passing through magnetized plasma experience $E = v \times B$ field.
- When they ionize the visible light is split under the influence of this E field (Stark effect)
- Polarization of light is aligned with B field: localized measurement.
- Advantages
 - Localized measurement of internal plasma B field: hard to obtain otherwise.
- Disadvantages
 - Technologically difficult, stray polarized light, difficult to calibrate.

Inverting line-integrated measurements

- Given measurements $y_j = \int_{L_j} x(R, Z) dl$ along multiple chords j , how do we reconstruct $x(R, Z)$?
- Tomographic, or Abel inversion. Assume x is parametrized, for example

$$x = \sum f_i(\psi_N(R, Z)) b_i \quad (7)$$

where $\psi_N = (\psi(R, Z) - \psi_a)/(\psi_b - \psi_a) \in [0, 1]$ and f is some basis function. Then given $\psi_N(R, Z)$ (from equilibrium reconstruction) we can construct $x(R, Z) = \sum_i F_i(R, Z) b_i$ and write

$$\hat{y}(x) = \sum_i b_i \int_L F_i(R, Z) dl \quad (8)$$

and we can solve the least-squares problem

$$\min_b \sum_i \sum_j \left(y_j - \sum_i b_i \int_{L_j} F_i(R, Z) dl \right)^2 \quad (9)$$

New development: state observers

- Tomographic inversion methods are *static*, they treat each measurement sample as independent in time.
- Ongoing work: State observers for interpreting measured signals from plasma including model knowledge.

Standard solution: **static inversion**

$$y = Cx \rightarrow x = C^+ y \quad (10)$$

Observer: **dynamic state estimator**

$$\dot{\hat{x}} = A\hat{x} + Bu + K(\hat{y} - y) \quad (11)$$

$$\hat{y} = C\hat{x} \quad (12)$$

where C^+ is some inverse of C .

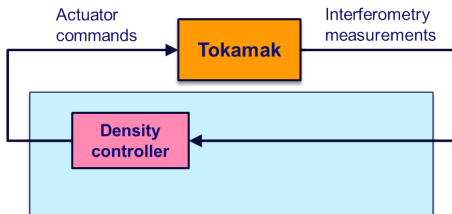
- Simple and robust.
- Does not take time evolution of the system into account.

Where K is the *Kalman Gain*. This scheme is known as a **Kalman Filter**.

- K can be designed from knowledge of A, B, C, D and the covariance of the expected noise.
- It can be shown that this is the *optimal* filter for this system, for which $E[(x - \hat{x})^2]$ is minimal.
- See course/book on systems theory or estimation for details.

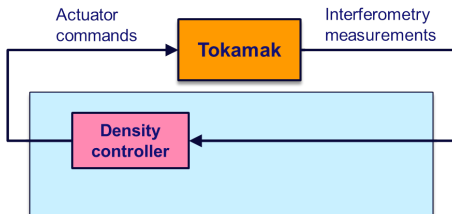
State observer: example for density control

- Current practice - control of gas valve via single interferometer chord

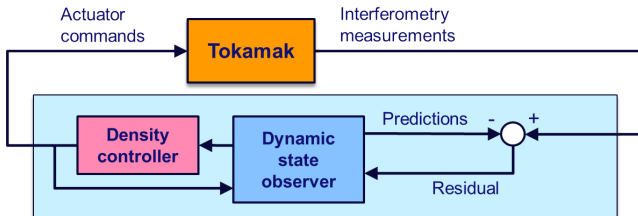


State observer: example for density control

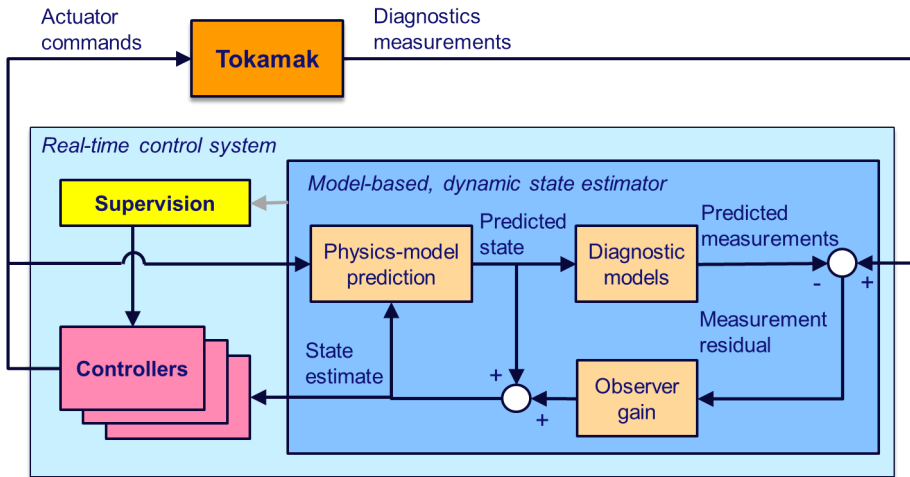
- Current practice - control of gas valve via single interferometer chord



- New approach: model-based observer



State observer: example for density control



Subsection 6

Current practice for kinetic control

Common practices, challenges for kinetic control

- Series of SISO control loops. Direct link between diagnostic and actuator.
 - Single interferometer chord $\rightarrow$ plasma gas valve
 - Plasma β from magnetic measurements $\rightarrow$ NBI or ECRH power.
 - Individually tuned PID controllers.

Common practices, challenges for kinetic control

- Series of SISO control loops. Direct link between diagnostic and actuator.
 - Single interferometer chord $\rightarrow$ plasma gas valve
 - Plasma β from magnetic measurements $\rightarrow$ NBI or ECRH power.
 - Individually tuned PID controllers.
- β control usually works quite well.
- Some issues with density controllers:
 - Single-sided actuator: at most can *close* the valve valve, can not extract more particles. Need *anti-windup* compensation.
 - Most simple controllers do not work well for all density regimes. Need to re-tune and re-commission controllers.
 - Gas valve vs pellet fuelling, different efficiency depending on density/temperature

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 - Most simple controllers do not work well for all density regimes. Need to re-tune and re-commission controllers.
 - Gas valve vs pellet fuelling, different efficiency depending on density/temperature
- Ongoing research topics:
 - Control of radiation fraction and heat flux to mitigate wall loads.
 - Actuator management: RT allocation of actuators to various tasks.
 - Burn control: nonlinear control problem & solution.

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