Fusion Reactor Technology I
(459.760, 3 Credits)

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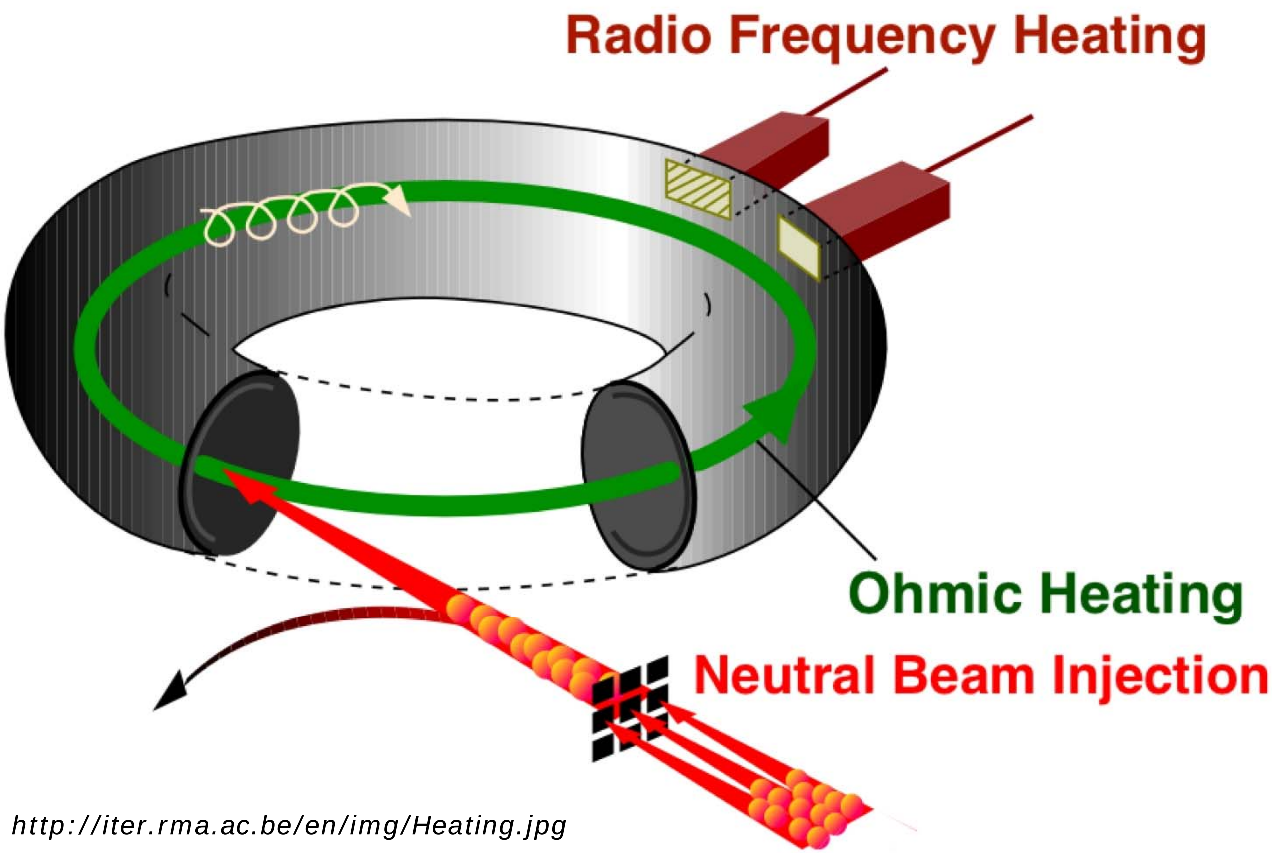
Contents

Contents

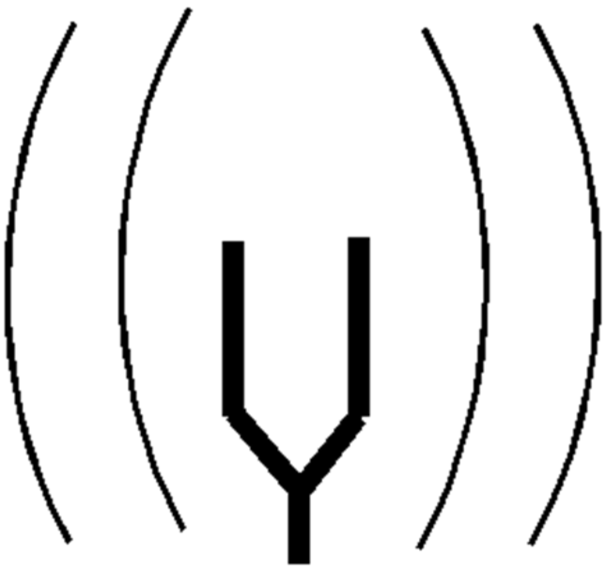
Heating and Current Drive



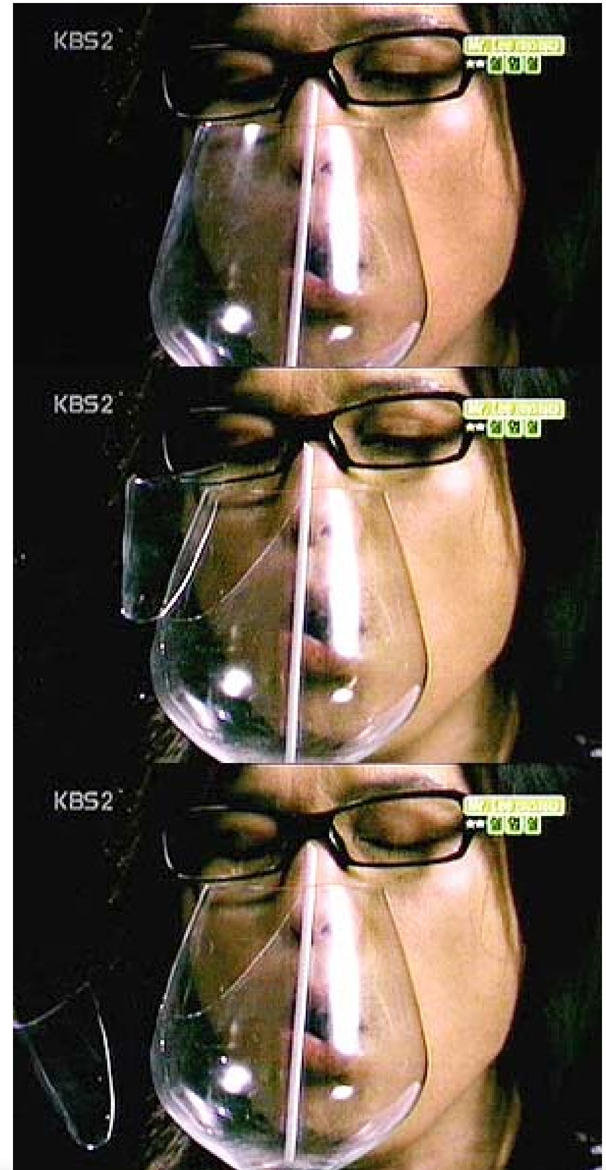
http://iter.rma.ac.be/en/img/Heating.jpg

Electromagnetic Waves

Tuning fork



Resonance



Electromagnetic Waves

Tacoma Narrows Bridge
(1940. 11. 4)

Electromagnetic Waves

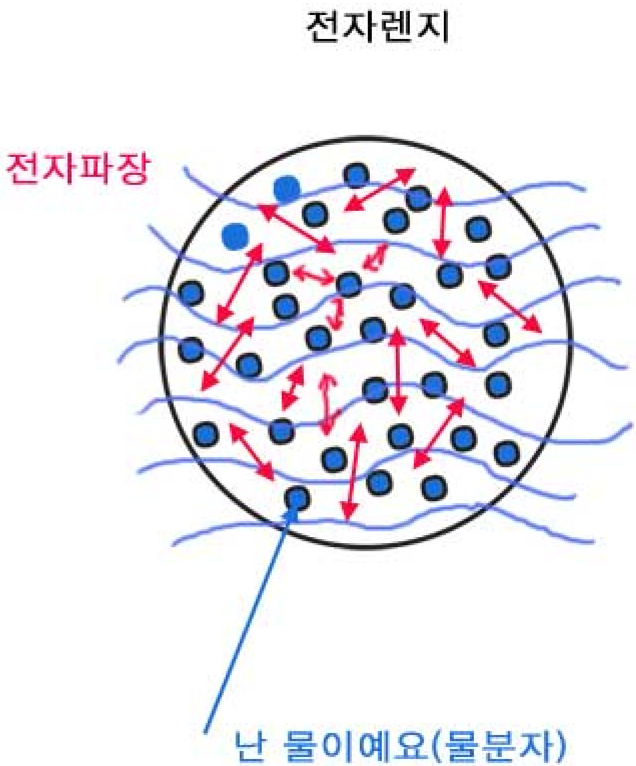
Broughton Suspension Bridge

http://www.joysf.com/?mid=forum_sf&document_srl=4265290&page=5

Electromagnetic Waves

테크노마트 건물 흔들려..수백명 대피
(서울=연합뉴스)
5일 오전 서울 광진구 구의동 테크노마트의 사무동 건물인 `프라임센터'가 흔들려 시민 300~500명이 대피했다. 소방당국에 따르면 이날 오전 10시10분부터 약 10분간 테크노마트 39층짜리 사무동 건물의 중・고층부가 상하로 흔들려 이 건물의 상주인원 3천명 중 300~500명이 스스로 대피했다. 광진구는 이 건물에 대해 3일간의 입주자 퇴거명령 조치를 취할 예정이다.
<< 연합뉴스 DB >> 2011.7.5

Electromagnetic Waves

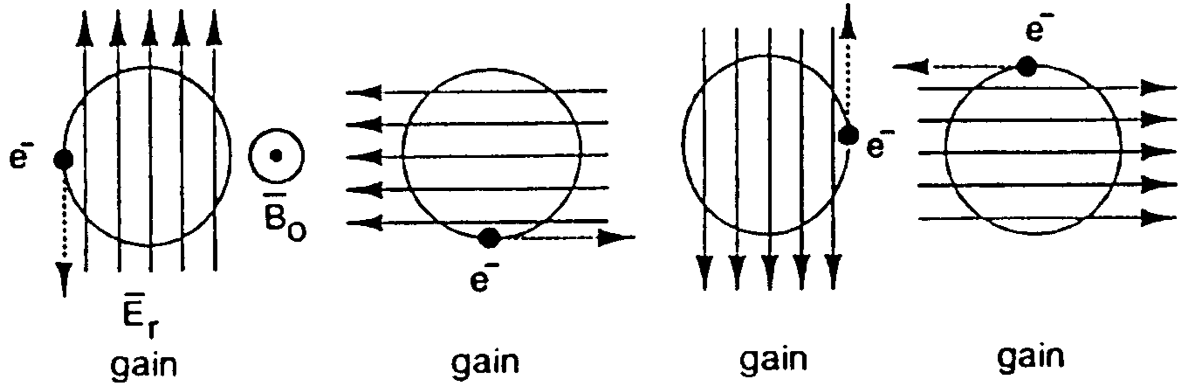


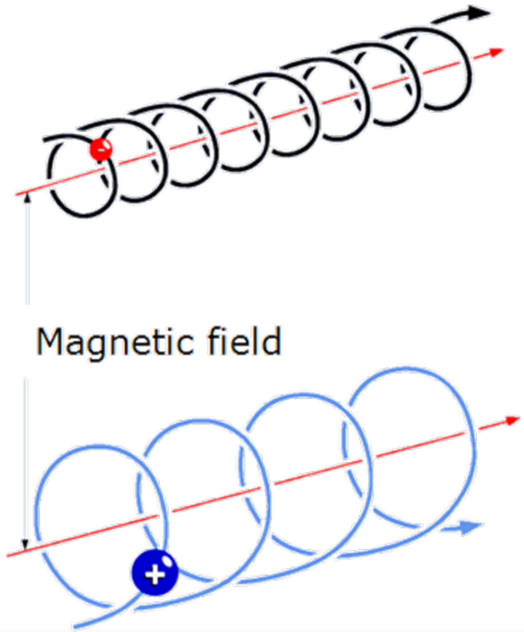
Microwave oven

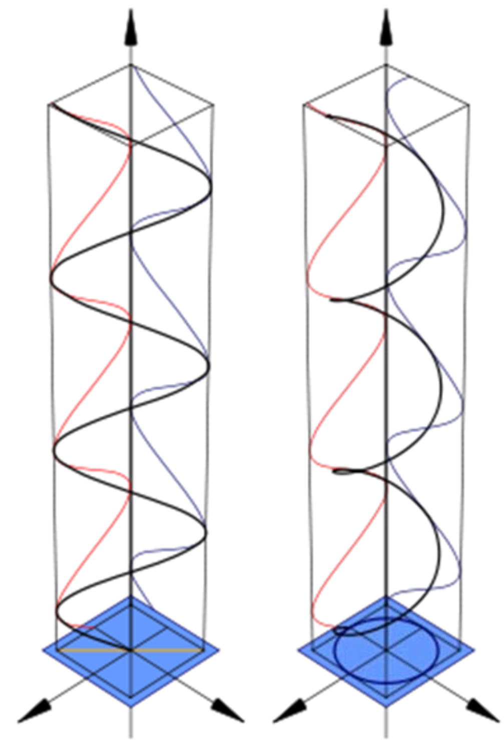
http://cafe.naver.com/nadobaker.cafe?iframe_url=/ArticleRead.nhn%3Farticleid=82
http://blog.naver.com/rlhyuny27?Redirect=Log&logNo=30029307561

Electromagnetic Waves

- Electron Cyclotron Resonance Heating (ECRH)





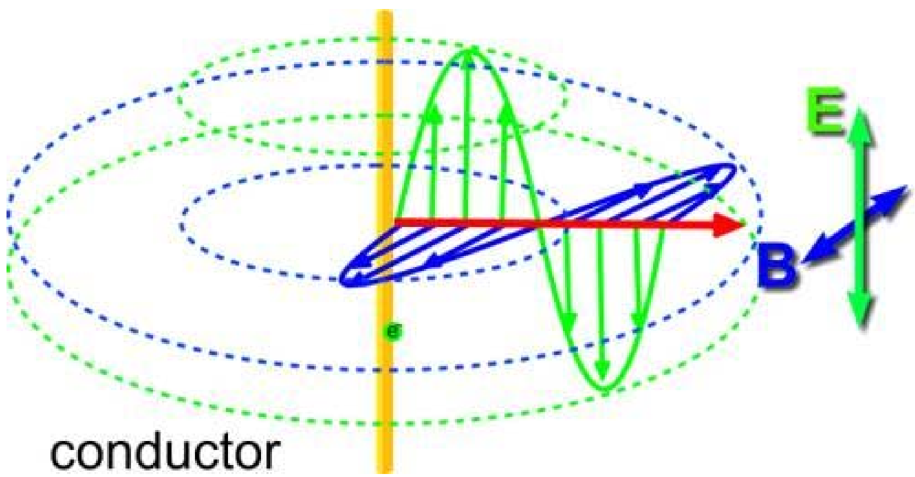


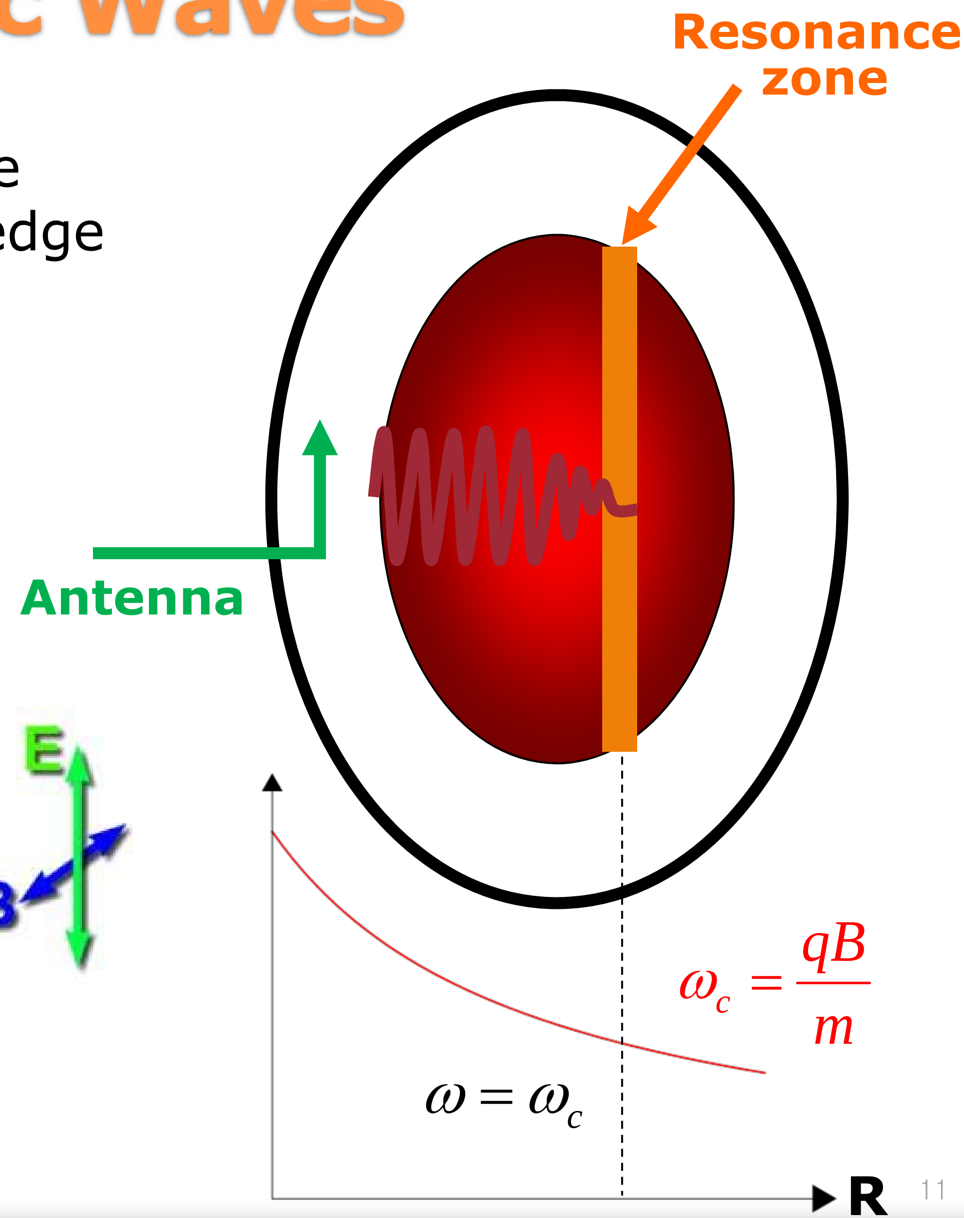
Linear / Circular polarization

http://ko.wikipedia.org/wiki/%ED%8E%B8%EA%B4%91

Electromagnetic Waves

Excitation of plasma wave (frequency ω) near plasma edge





Electromagnetic Waves

Excitation of plasma wave
(frequency ω) near plasma edge

⇓

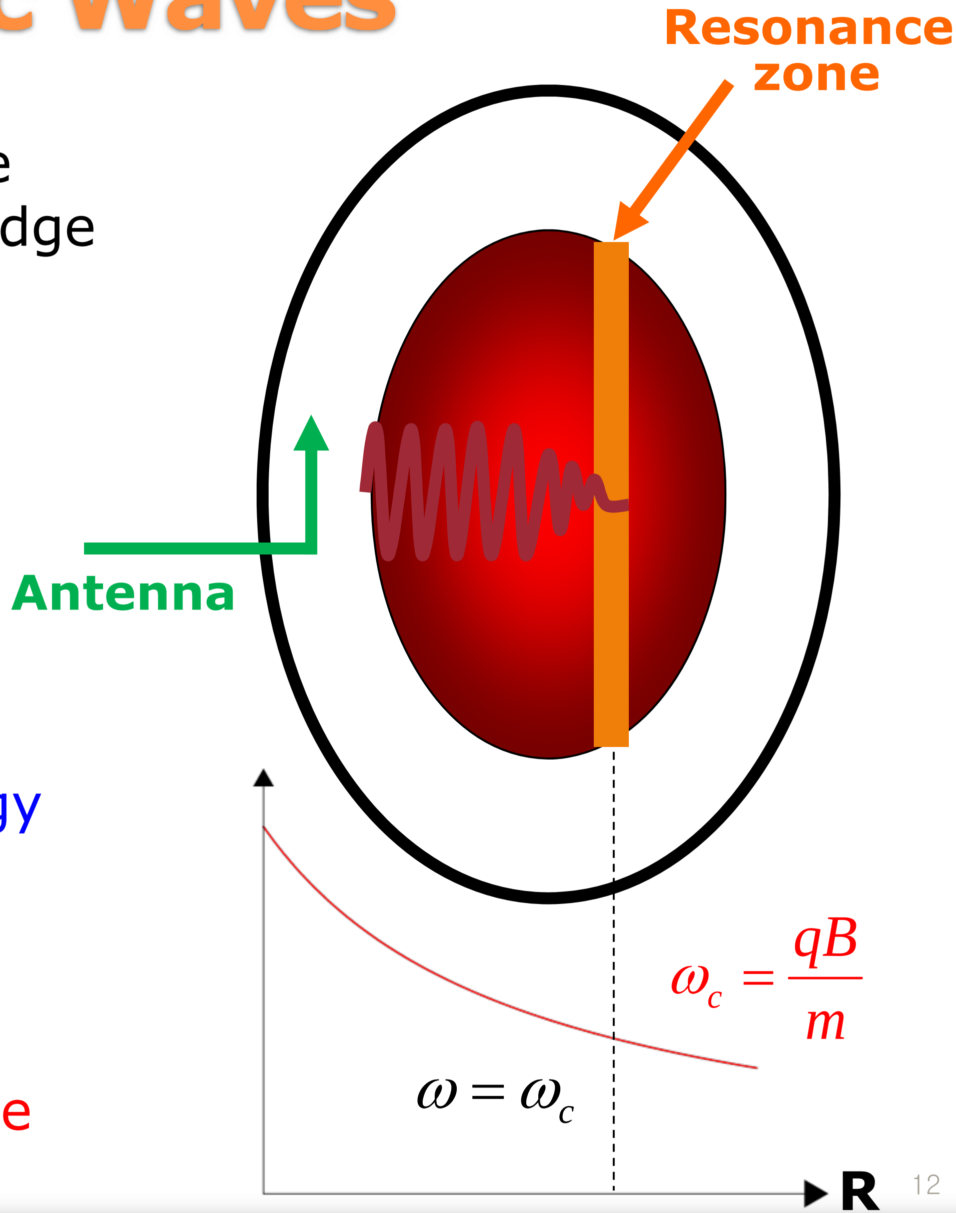
wave transports power
into the plasma center

⇓

absorption near resonance,
e.g. $\omega \approx \omega_c$,
i.e. conversion of wave energy
into kinetic energy of
resonant particles

⇓

Resonant particles thermalise



Electromagnetic Waves

- **Ion Cyclotron Resonance Heating (ICRH):**

  occurring only when two or more ion species are present

  $\omega \sim \omega_{ci}$, 30 MHz – 120 MHz (~10 m)

  Ion-ion resonance frequency

$$\omega_{ii}^2 = \frac{\omega_{c1}\omega_{c2}(1 + n_2 m_2 / n_1 m_1)}{(m_2 Z_1 / m_1 Z_2 + n_2 Z_2 / n_1 Z_1)}, \quad \omega_{ci} = \frac{z_i e B}{m_i}$$

- **Lower Hybrid (LH) Resonance Heating:**

  $\omega_{ci} < \omega < \omega_{ce}$, 1 GHz – 8 GHz (~10 cm)

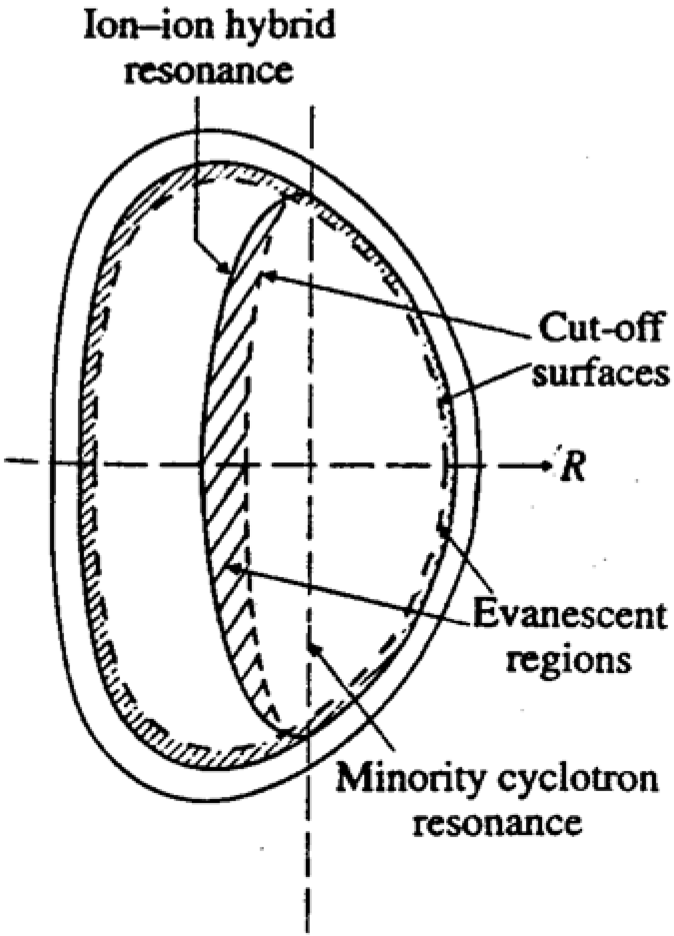
$$\omega_{LH}^2 \approx \omega_{pi}^2 / (1 + \omega_{pi}^2 / \omega_{ce}^2), \quad \omega_{pi}^2 >> \omega_{ci}^2$$

- **Electron Cyclotron Resonance Heating (ECRH):**

  $\omega \sim \omega_{ce}$, 100 GHz – 200 GHz (~mm)

$$\omega_{UH}^2 \approx \omega_{pe}^2 + \omega_{ce}^2$$

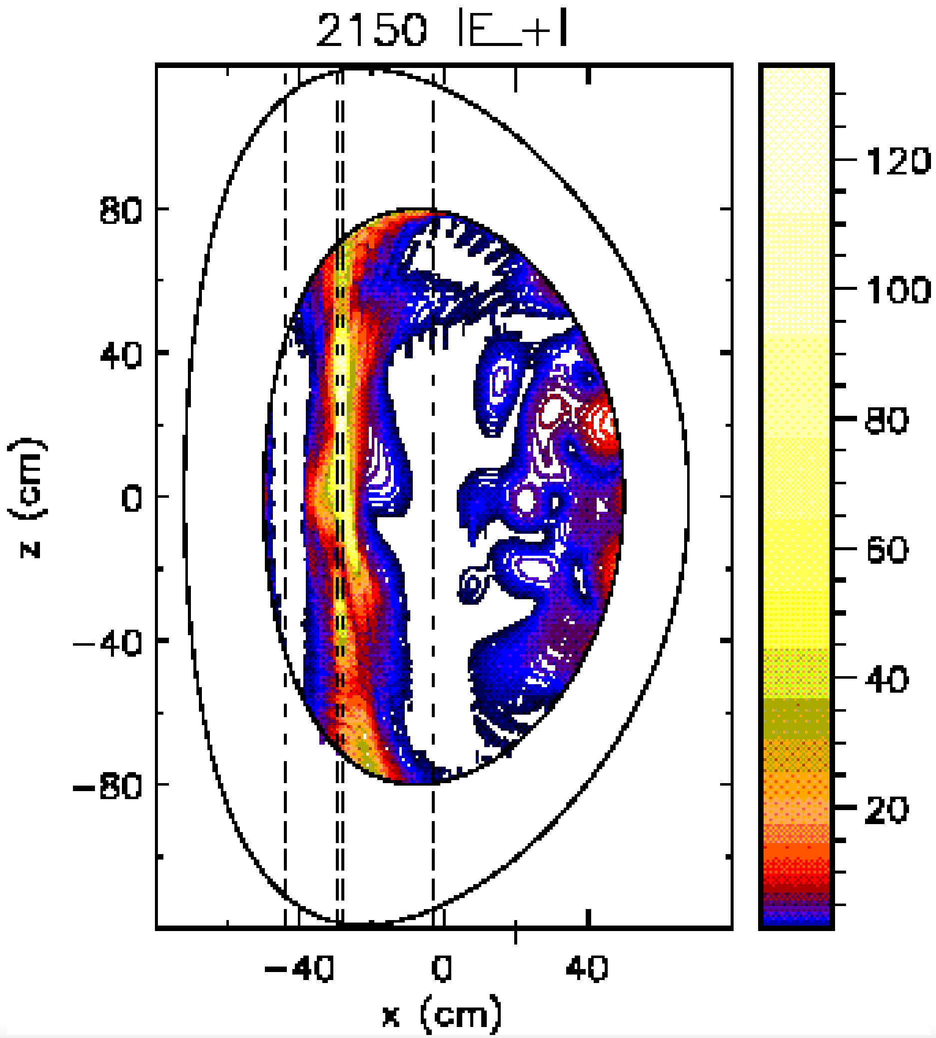
ICRH – Wave Propagation



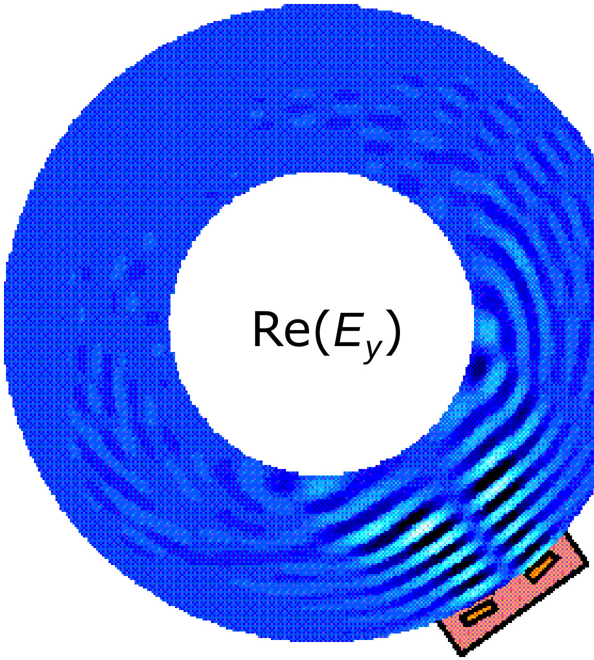
- Loci of cut off and resonances in the poloidal cross section of a tokamak.
- Excite fast wave at plasma edge, however since the fast wave is evanescent in the hatched region, it needs to tunnel cutoff region.

ICRH – Wave Propagation

ASDEX Upgrade

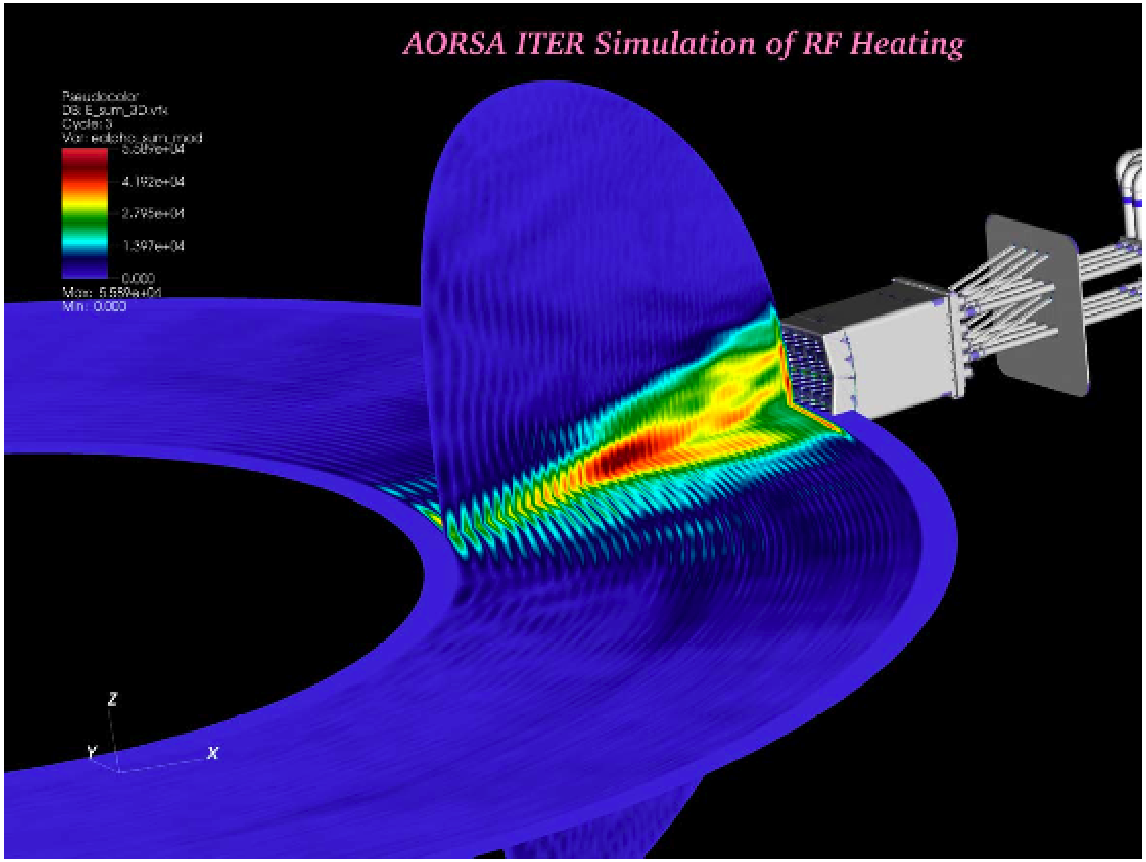


Alcator C-Mod

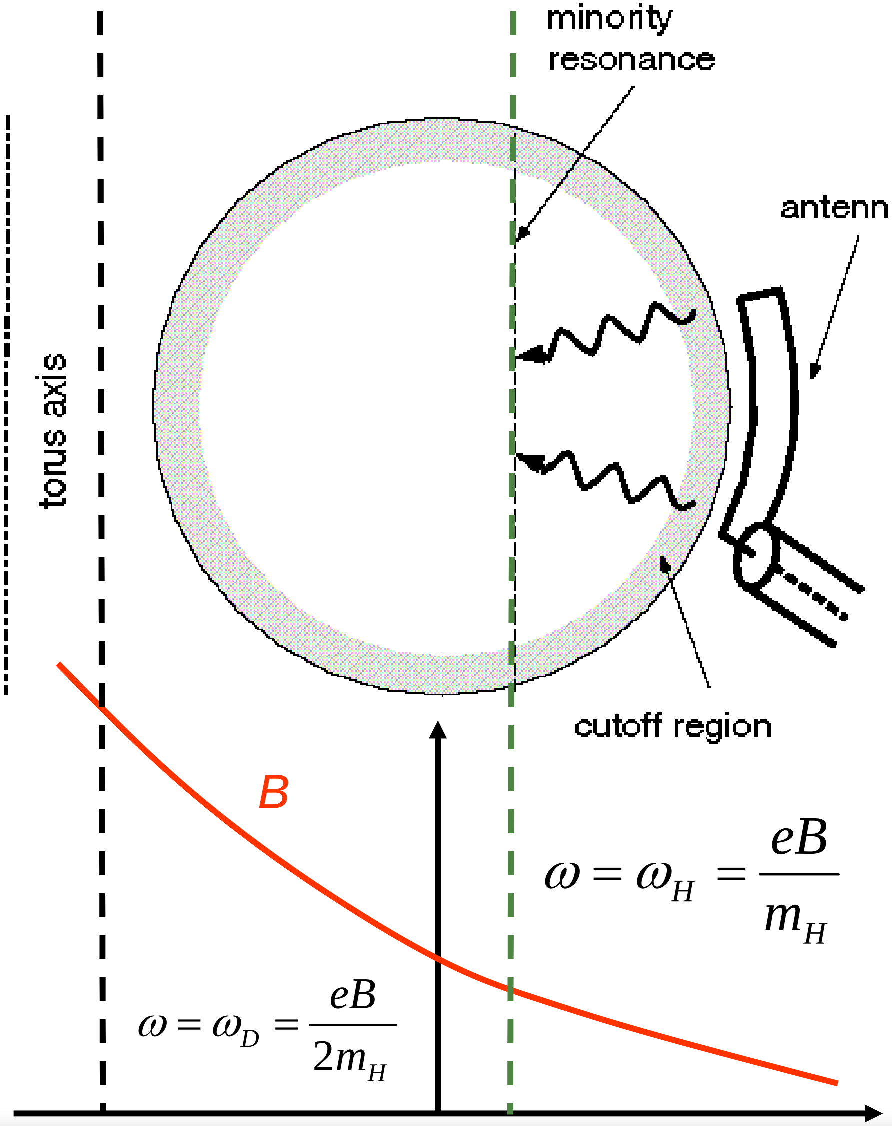


Multiple current straps

ICRH – Wave Propagation



ICRH – Wave Propagation



- Plasma with mixture of H and D with $n_H << n_D$

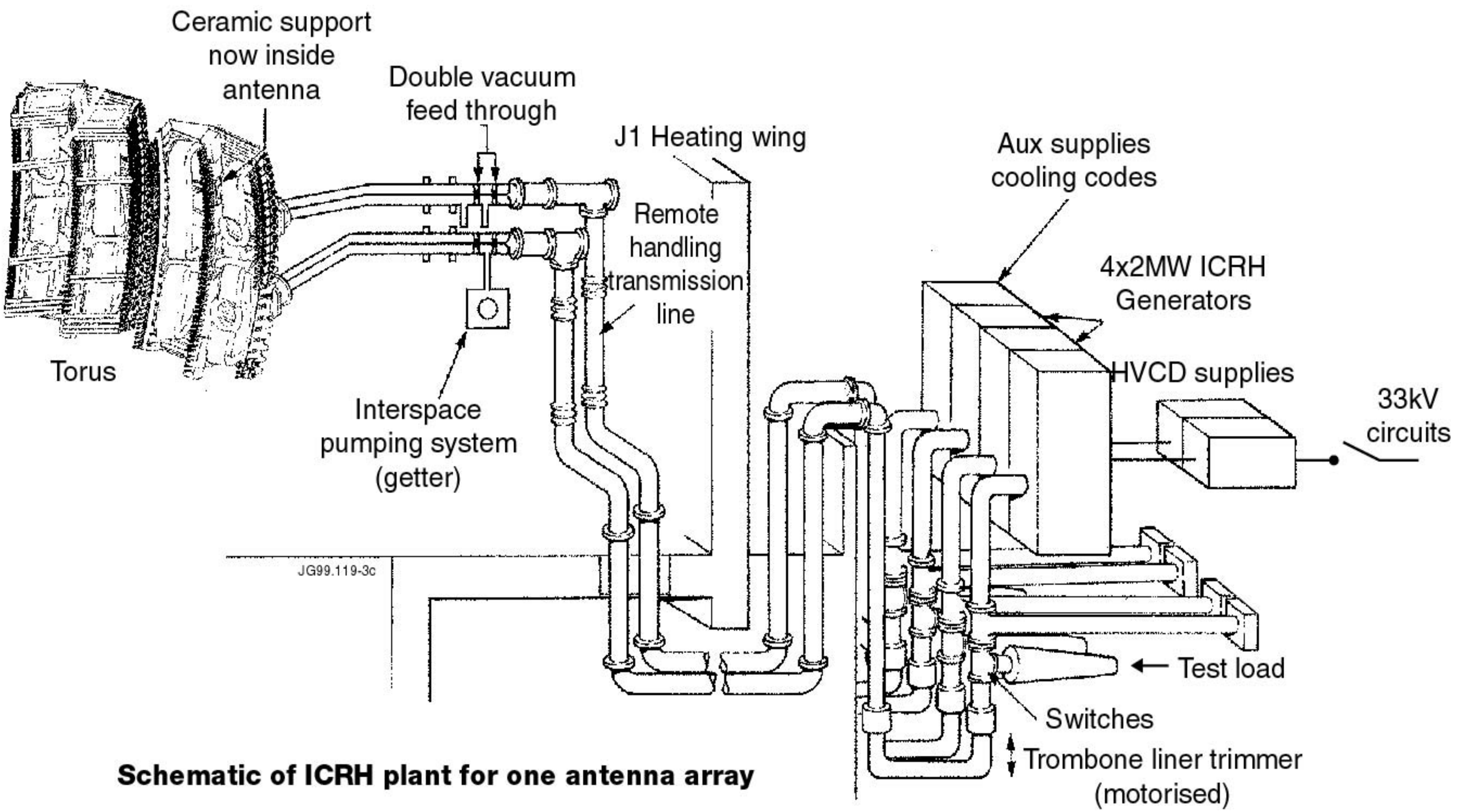
$n_D \rightarrow$ polarization propagation

$n_H \rightarrow$ absorption

- Production of tail in H velocity distribution function
- Good single pass absorption

Ion Cyclotron Resonance Heating

- **JET ICRH System**

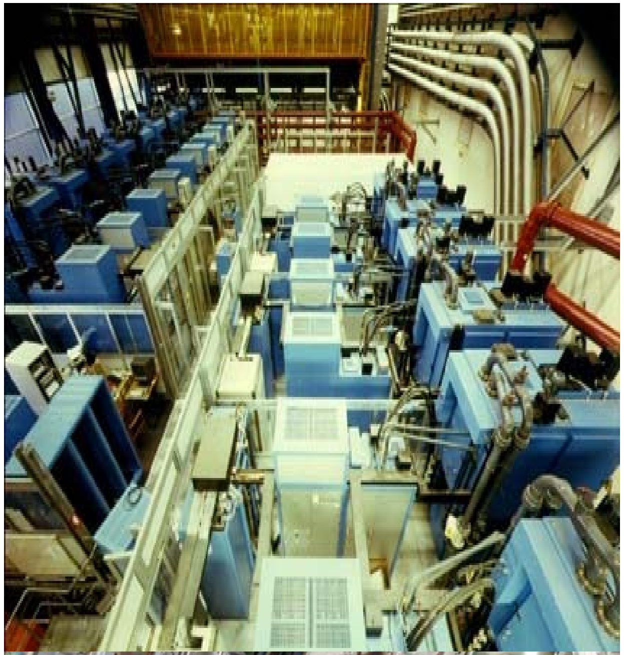


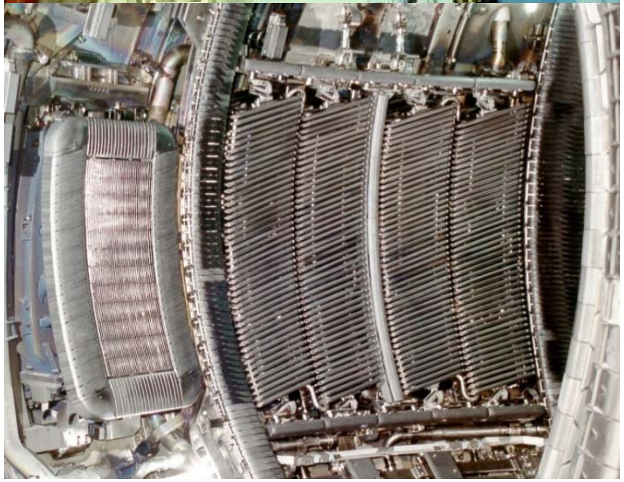
Schematic of ICRH plant for one antenna array

Ion Cyclotron Resonance Heating

- **JET ICRH System**

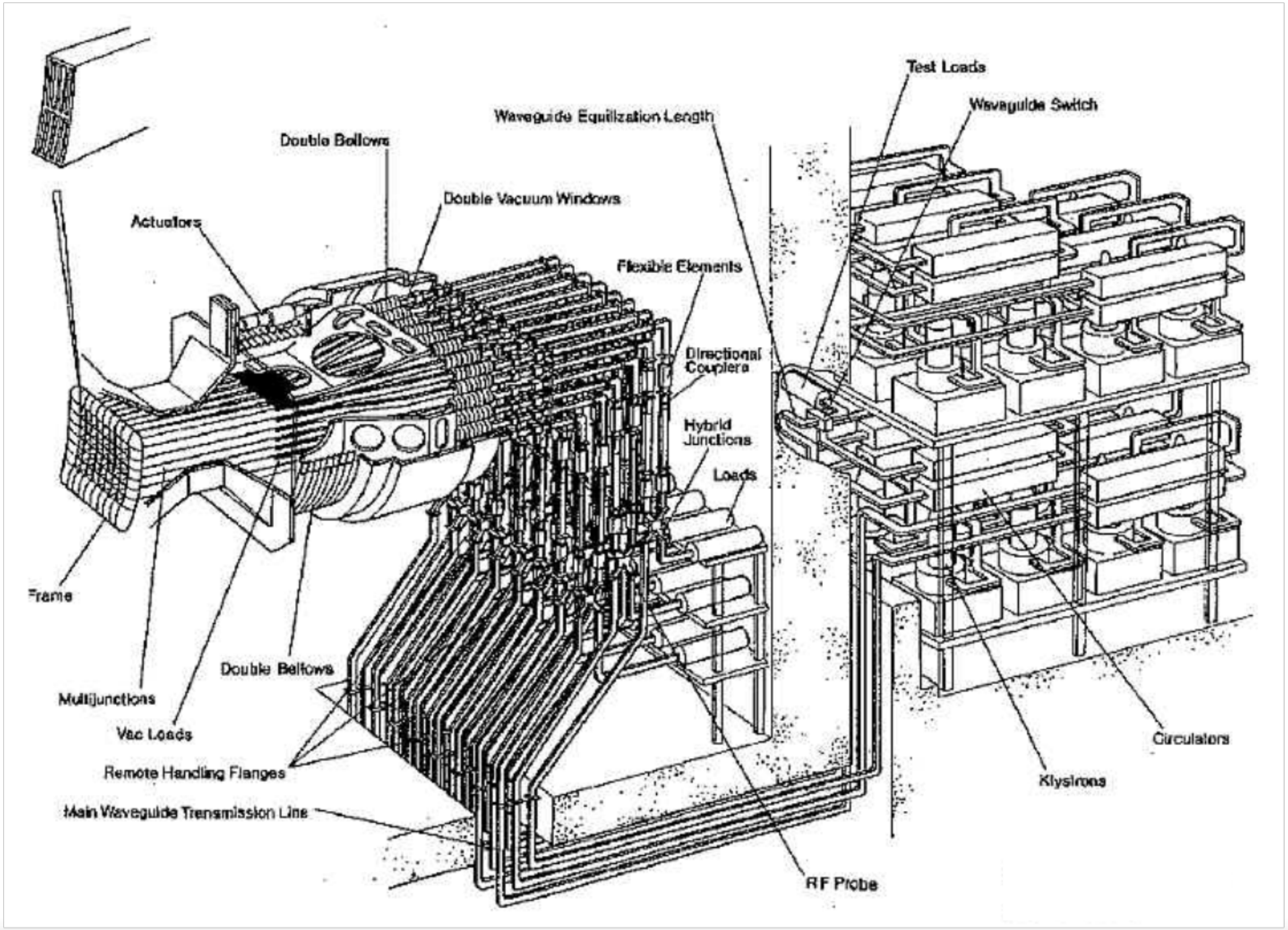
- 8 x 4 MW RF generators, each one has two 2 MW outputs giving a possible 32 MW total
- Frequency range 23 MHz -57 MHz (excluding 39-41MHz)
- 8 HVDC Power supplies
- 4 x 4 strap antenna system with vacuum interspace, Getter pumping and Penning gauge protection





Lower Hybrid Heating

- **JET LH System**



Lower Hybrid Heating

- **JET LH System**

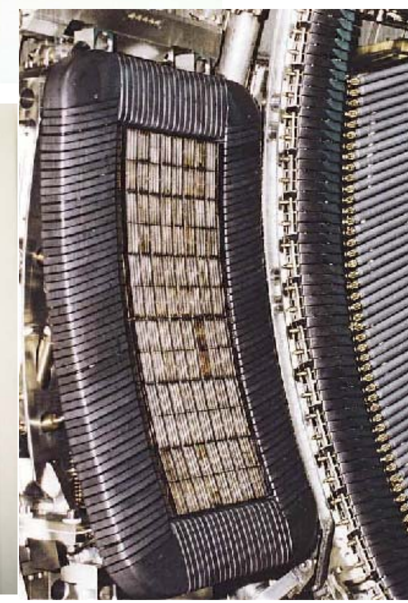
- 24 klystrons @ 3.7 GHz,
  650 kW/10s or 500 kW/20s

- For control purposes, klystrons grouped in 6 modules of 4 klystrons (modules A to F)

- High voltage power supplies: Two 33 kV circuit breaker, LH01 & LH02, each feeds 3 modules (12 klystrons)

- PS limits long pulse operation
→ Total power available at generators: 12 MW for 10s
4.8 MW for 20s

Power coupled to plasma depends on launcher power handling and plasma conditions.



LH grill in JET: 12 rows of 32 waveguides

α-Particle Heating

- Intrinsic self-heating by Coulomb collision of fusion α particles with plasma particles in D-T reactions

$$D + T \rightarrow \underbrace{n\,(14.1\,MeV)}_{\text{leaves plasma}} + \underbrace{He^4\,(3.5\,MeV)}_{\substack{\text{heats plasma} \\ \text{if sufficiently long} \\ \text{confined}}}$$

- Heating power density: $0.2 \cdot n_D \cdot n_T \cdot \langle \sigma v \rangle \cdot E$

  where $\langle \sigma v \rangle \propto T_i$

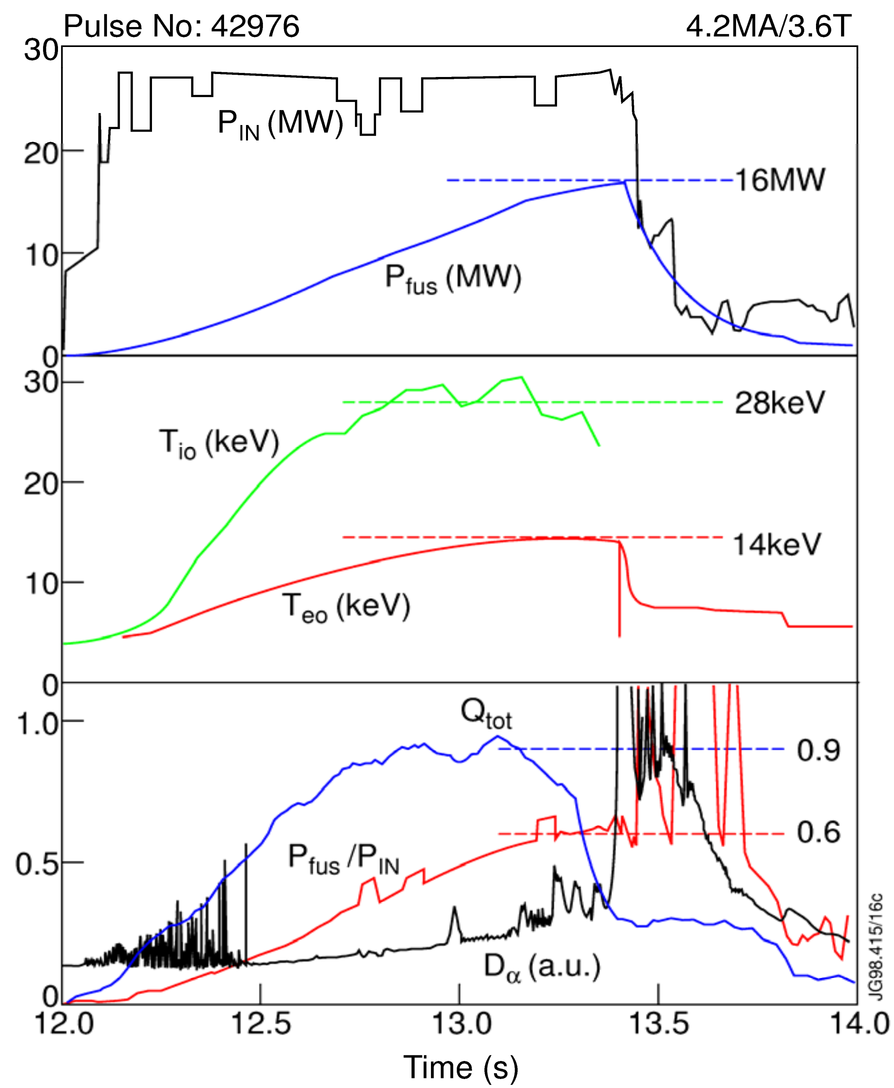
  $\Rightarrow$ peaked heating profile

- α-particle loss mechanisms: field ripples
  MHD events e.g. Alfvèn Eigenmode (AE)

α-Particle Heating

- DT-Experiments only in
- JET
- TFTR

- with world records in JET:
- P_{fusion} = 16 MW
- Q = 0.64



Adiabatic Magnetic Compression

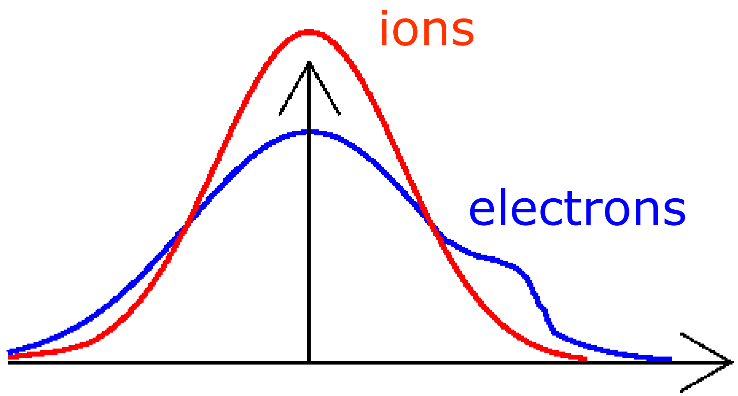
- **Heating by increasing magnetic pressure adiabatically**

$$pV^{\gamma} = \text{constant}$$

$$p = nkT$$

Non-inductive Current Drive

- Asymmetric velocity distribution can be a side effect of plasma heating.



$$j = \sum_s q_s n_s \int v_{\parallel} f\left(v_{\parallel}\right) dv$$

- **Needed for:** Steady-state tokamak
  current profile control in tokamaks
  bootstrap current compensation in stellarators

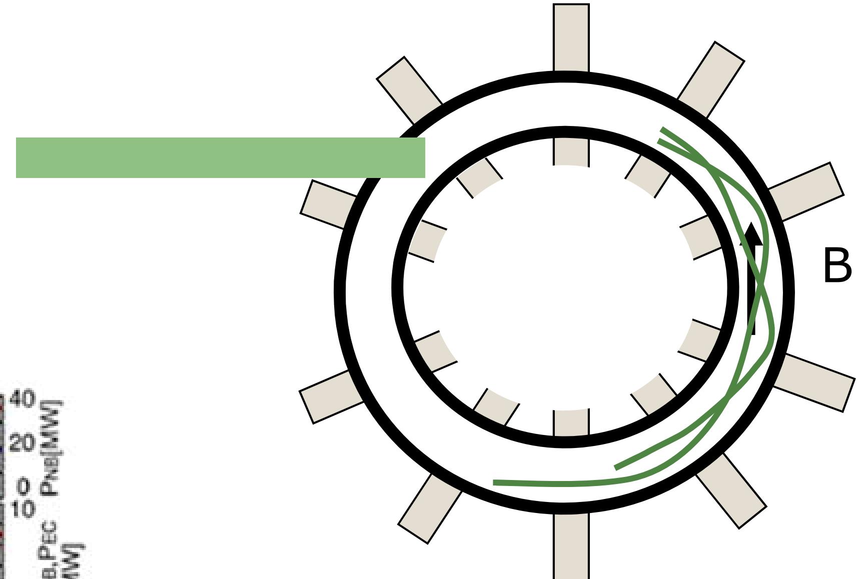
- **Efficiency**

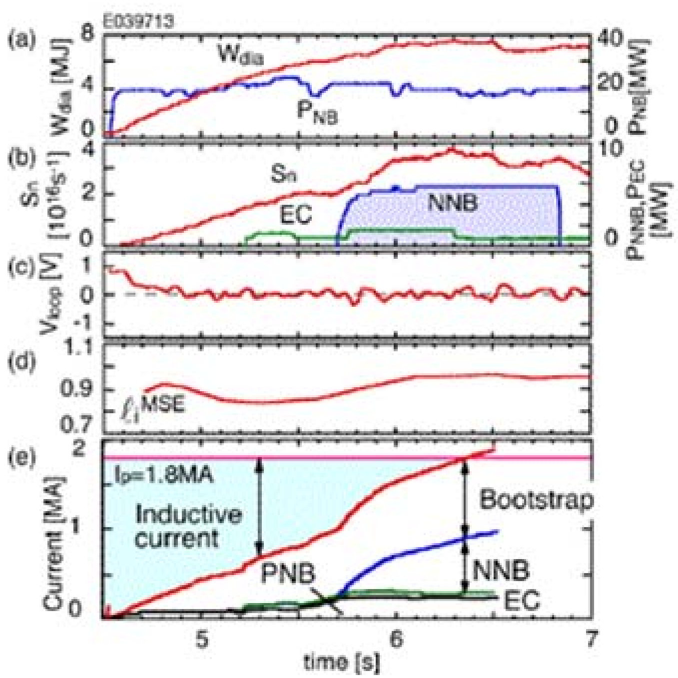
Theory: $$\eta_{th} = \frac{j}{p} = \frac{e \cdot n_{e\parallel} \cdot v_{\parallel}}{\left(n_{ell} \cdot m_e v_{ll}^2 / 2\right) \cdot \nu_{coll}} \propto \frac{1}{v_{\parallel} . \nu_{coll}}$$

Experiment (Figure of merit): $$\gamma = \frac{n_e\left[10^{20} m^{-3}\right] \cdot R[m] \cdot I[A]}{P[W]} \propto \eta_{th}$$

Neutral Beam Current Drive

Tangential injection





JT-60U high β_p ELMy H-mode

- Circulating ions carry current partially compensated by
  - concurrent electron drift
  - trapping
  - dependence on collision frequency

Total driven current

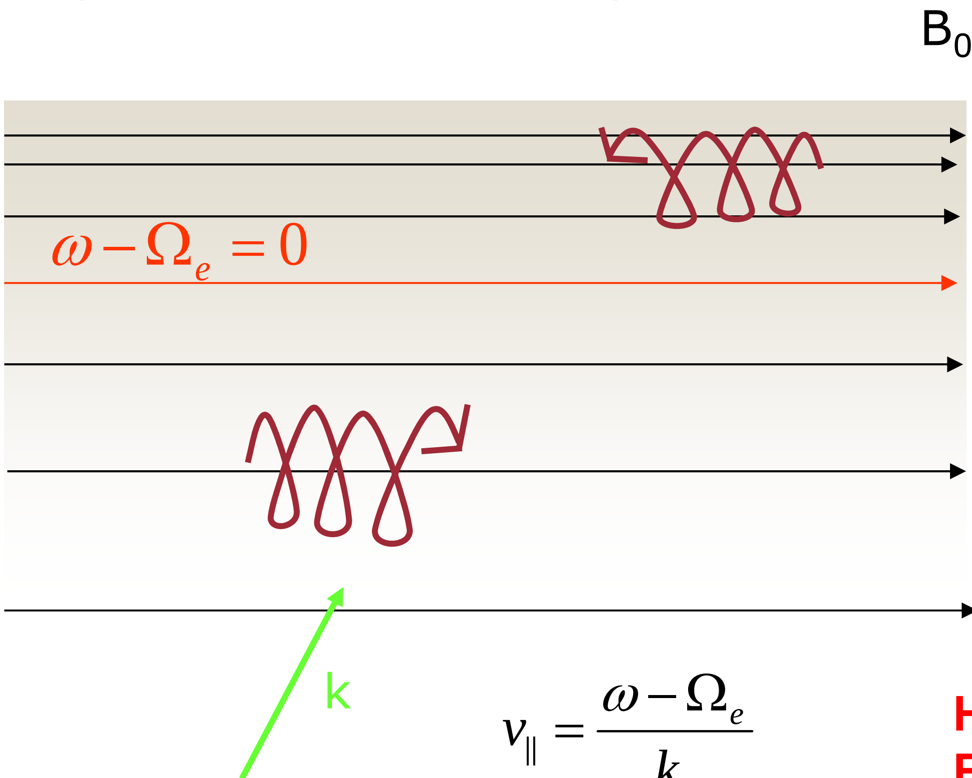
$$\frac{I}{I_f} = 1 - \frac{Z_f}{Z_{eff}} + 1.46\varepsilon^{\frac{1}{2}} \frac{Z_f A(Z_{eff})}{Z_{eff}}$$

Friction by trapped electron

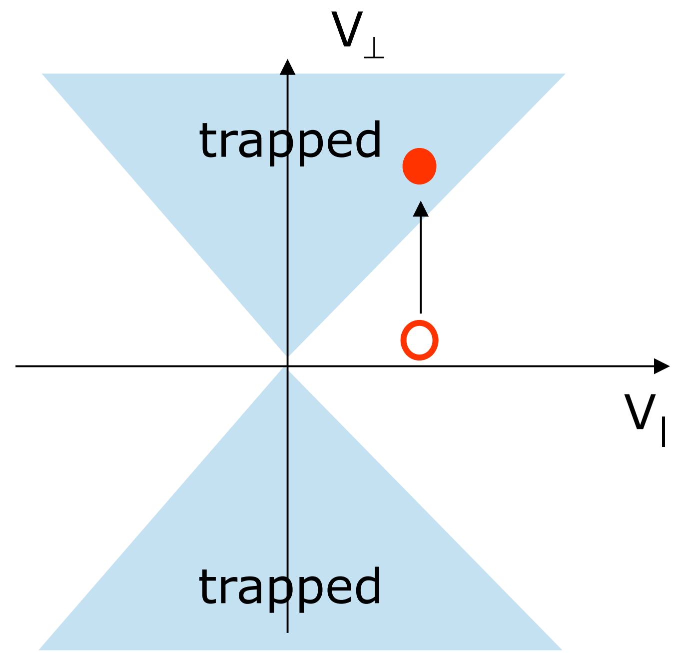
Reverse electron current

Electron Cyclotron Current Drive

Asymmetric collision frequencies



$$v_{\|} = \frac{\omega - \Omega_e}{k_{\|}}$$



Homework: principles of ECCD
Ex) Ohkawa current

- Current drive simply by changing the launch angle. Faster electrons collide less often.
- Trapped electrons reduce efficiency.

Non-inductive Current Drive

	Efficiency
LHCD	0.35-0.4
ICCD	0.1xT_e [10keV]
ECCD	< 0.1xT_e [10keV]
NBCD	0.2xT_e [10keV]

$$\eta_{th} = \frac{j}{p} = \frac{e \cdot n_{e\|} \cdot v_{\|}}{\left(n_{ell} \cdot m_e v_{ll}^2 / 2\right) \cdot \nu_{coll}} \propto \frac{1}{v_{\|} . \nu_{coll}}$$

$$\gamma = \frac{n_e\left[10^{20} m^{-3}\right] \cdot R[m] \cdot I[A]}{P[W]} \propto \eta_{th}$$

Heating and Current Drive

Heating Scheme	Advantages	Disadvantages
OH	Efficient	Cannot reach ignition
NBI	Reliable	Close to torus Negative ions necessary
LH	Efficient current drive	Antenna close to plasma off-axis
ECRH	Reliable Flexible	Electron heating (density limit)
ICRH	Ion heating Central heating	Antenna close to plasma Antenna coupling

References

- *Weston M. Stacey, "Fusion Plasma Physics" WILEY-VCH (2005)*
- *Dirk Hartmann, "Plasma Heating", IPP Summer School, IPP Garching, September 20, 2001*