EC17
ECRH Experiment Summary

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General Remarks

• Real time control, feedback control
  – Oral 3/11, Poster 3/9
  – Specific feature of ECRH
    • spatially, temporally controllable power deposition
      (current profile)

• Further Upgrading of ECRH system

• Detailed Physics Study

• Breakdown study

• EBW

• Long pulse/CW operation
EC characteristics are different than NBI, leading to many new experiments as the ECH power is increased.

- EC waves interact only with the near-thermal electrons, typically 1.5-3 times $v_{\text{thermal}}$
  - some ability to do “phase space engineering”
- EC effects are highly localized in space
- Location can be controlled by the experimenter through pointing the EC beam and control of the toroidal field
- EC H&CD injects no toroidal torque
- EC H&CD injects no particles
- EC waves can optionally drive current

All of these characteristics are different than those of NBI, and exploiting these differences supports a broad range of new experiments.

ECH is an excellent proxy for alpha-heating

R. Prater
System Upgrades

Gyrotrons
Transmission Line
Antenna Control
Status: 4 MW in plasma (almost) reached ASDEX-U (J. Stober)

Power in plasma

New system:
2.4 MW @ 140 GHz
(0.82 + 0.76 + 0.85)
or
2.1 MW @ 105 GHz
(0.76 + 0.56 + 0.75)

Old system:
1.5 MW for 2 s @ 140 GHz
Status and long term plans

DIII-D (J. Lohr)

Chewbacca II Installation
7th DIII-D gyrotron 110 GHz 1.2 MW

<table>
<thead>
<tr>
<th>Year</th>
<th>Task</th>
<th>Status</th>
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<tbody>
<tr>
<td>2010</td>
<td>Design 1.2 MW gyrotron</td>
<td>Complete</td>
</tr>
<tr>
<td>2011</td>
<td>Build 1.2 MW (ARRA), design 1.5 MW</td>
<td>Complete</td>
</tr>
<tr>
<td>2012</td>
<td>Operate 7 gyrotron at 110 GHz, build 1.5 MW gyrotron at 117.5 GHz</td>
<td>In progress (+ additional tube)</td>
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<tr>
<td>2013</td>
<td>Operate 7 gyrotron at 110 GHz</td>
<td>Committed</td>
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<tr>
<td></td>
<td>Replace 2 old 110 GHz gyrotron with 1.5 MW 117.5 GHz tubes,</td>
<td></td>
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<tr>
<td></td>
<td>operate 8-10 gyrotrons</td>
<td>Desired</td>
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<tr>
<td>2014</td>
<td>Install 2 more tubes, order n more, operate 8-10 gyrotrons</td>
<td>Desired</td>
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<tr>
<td>2015</td>
<td>Replace 4 old 110 GHz gyrotrons with 1.5 MW 117.5 GHz tubes,</td>
<td></td>
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<tr>
<td></td>
<td>operate 8-10 gyrotrons</td>
<td></td>
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<tr>
<td>2016</td>
<td></td>
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R.F. power

0  4  8  12  16

P_{\text{GEN}} (MW)  P_{\text{INU}} (MW)
HL-2A is a medium-size tokamak (R=1.64m and a=0.4m). The ECRH with about 3MW power is main heating system in the device.

- $R$: 1.65 m
- $a$: 0.40 m
- $B_T$: 2.7 T
- $I_p$: 450 kA
- $n_e$: $\sim 6.0 \times 10^{19} \text{ m}^{-3}$
- $T_e$: $> 4.0 \text{ keV}$
- $T_i$: $> 2.0 \text{ keV}$
- Duration: $\sim 4.3 \text{ s}$
- Configuration: Limiter, LSN divertor
Eight transmission lines and antennas. For high power (~1MW) transmission, three 88.9mm waveguides (WG) are evacuated. One 88.9 mm WG and one 31.75 mm WG transmission lines were used for measurements (CTS and EBE)
RT feedback/forward control

- TCV
- FTU
- TEXTOR-ASDEX
- DIII-D
The TCV tokamak:
flexible actuators matched with a flexible controller

- Flexible actuators
  - 16 independently controllable PF coils
  - Flexible and powerful ECH/ECCD system, real-time steerable launchers

- Hundreds of diagnostic channels
  - Magnetic measurements
  - X-rays & interferometry with high spatial & temporal resolution

- A flexible digital control system
  - Multi-node, distributed, scalable, modular
  - Simulink® programmable

- Sawtooth control
  - New control method by EC power: sawtooth pacing

- ELM control
  - Edge localized EC power increases ELM frequency w.r.t. central power.

- NTM control
  - Scanning EC across island sufficient for NTM stabilization

- Multi-gyrotron integrated MHD control
  - Simultaneous sawtooth period regulation control, NTM preemption and NTM suppression

TCV experimental results: Constant $\tau_{\text{set}}$ gives very stable ST period

- First example: set constant 20ms $\tau_{\text{set}}$
  - Immediately obtains fixed period [T. Goodman et. al. PRL 2011]
Example of Real Time Feedback Control (C. Sozzi)

**motor control system**

- **Diagnostics signals**
- **Reference signals**

- **Prometeo FTU Main control**
- **RT Control System**
- **Protection system**

- Antenna position provided by encoders (incremental only)
- Absolute RT position (20μs) measured by resolvers and sent to the PLC
- Fast stop is provided by a dedicated FPGA breaker box if the boundaries of operation are hit
RT control elaboration (C. Sozzi)

**Correlation ECE-ECH**

- Poloidal scan of the deposition radius $R_{dep}$ is monitored during RT elaboration of the ECE-ECH data.
Broad ECCD more effective in avoiding tearing modes that limit the discharge duration

- Broad vs narrow deposition
- With vs without broad ECCD
NTM control – First feed-back attempts (28.4.2012) in ASDEX (J. Stober)

After ~ 100 ms minimum in n=2 amplitude

\[ \rho (\text{NTM}) = \rho (n=2) - 0.025 \]

rho (NTM) = rho (n=2) - 0.025

lose robust localization / tracking

J. Stober, EC17, Deurne, May 2012
Example: O2 heating with FB control in ASDEX (J. Stober)

FB – control corrects launching angle within 50 ms

Beam position before feedback control
Beam position after feedback control

TC for beam control and interlock

Controller threshold

\( (T_{TC,b} - T_{TC,t}) \) \( K_p \) [a.u.]

Poloidal launcher angle [mm]

"Beam position before feedback control"
"Beam position after feedback control"
Confinement Study
Perturbative measurement (M. van Berkel)

- Perturbative measurements have been used in NF to measure the components of the thermal transport
- Localized excitation signal, e.g. ECRH
- Spatially distributed temperature measurements by means of ECE
Estimated $\chi_e$ and $V_e(M. \text{van Berkel})$

Considered model:

$$\frac{\partial T_e}{\partial t} = \left( \chi_e (\rho) \frac{\partial^2 T_e}{\partial \rho^2} + V_e (\rho) \frac{\partial T_e}{\partial \rho} \right) + P (\rho, t),$$

Simulated with Finite Difference with $\rho = \frac{r}{0.46}$:
Example of MECH analysis in LHD (H. Igami)

In the case of Cntr. ECCD, the phase delay inside $\tau/2\pi = 0.5$ surface is larger than the cases of Co and Co+ECH.
EBW Heating

• LHD
• NSTX plan
• MAST
  • EBE
Launching geometry for EBWH via O-X-B mode conversion

Top slice at z=0m

- Flux surfaces
- Final mirror
- ECR layer

View from the final mirror

Aiming area

$T_{OXB} > 50\%$

$\Delta_{OXB} \sim 0.4 \text{ deg.}$
High Energy Electrons
Many Instabilities have been observed during High power ECRH (X.T. Ding)

- **TAE:** >200kHz
- **EPM:** 70-150kHz
- **BAE:** 10~23kHz
- **KBAE:** 10~35kHz
- **E-FISHBONE:** 3-8kHz
- **FISHBONE jump:** 8-15kHz
- **MHD:** <10kHz

*Note: F(kHz)*
TAE Induced by fast electrons with High power ECRH in HL2A (X.T.Ding)
ECE spectra show highly non-thermal feature in the low density case.

- 2nd harmonic X mode
  - $t = 3.7$-3.8
  - $t = 4.0$-4.1

- 3rd harmonic X mode
  - $t = 3.8$-3.9
  - $t = 4.2$-4.3
pre-ionization/ start up

• T-10 breakdown study
• KSTAR startup exp.
Breakdown experiments in T-10 (A. Borshchegovski)

For all discharges deuterium was used as the pre-fill gas.

**Fig. 3**

Time evolution of line density $n_e L$, $I_{Da}$ intensity, injection RF timing.

**Fig. 4**

Allocation discharge in ECR zone [1]

$P_{rf}=0.55$MW, toroidal injection angle $\alpha=10^\circ$, initial gas pressure $P=(4.5\pm6)\times10^{-3}$Pa.
Conclusion

• Real time control, feedback control
  – Important issue to be investigated more
• Further Upgrading of ECRH system
  – Demonstrated its potential
  – Demand for extending parameter region
  – Further refined control for higher and complete stabilization are under investigation
• Detailed Physics Study
  – Confinement
  – High energy electrons
    • Energetic particle mode, Effect of high energy electrons on ECRH
• EBW
  – little heating exp.→ EB-Emission expected to applied to EB Heating
• Breakdown/start-up
  – ITER start-up scenario established (DIII-D, JT-60U, KSTAR, T-10)
• Long pulse/CW operation
  – needs demonstration operation