Design of the ITER Electron Cyclotron Heating and Current Drive Waveguide Transmission Line

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**ITER needs flexible wave heating systems**

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<td>20MW 170 GHz in SS 126 GHz</td>
<td>Heating, central and profile CD, MHD control (NTM). Assisted Start-up.</td>
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<td><strong>ICRF</strong></td>
<td>20MW 40-55MHz in SS</td>
<td>Localised ion heating, central CD, sawtooth control, VV cleaning</td>
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<td><strong>LH</strong></td>
<td>20MW 5GHz in SS</td>
<td>Off-axis CD for SS regimes. AT scenarios. Assisted Start-up.</td>
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Modified from J. Jacquinot

ITER needs a flexible and balanced set of heating and current drive systems to meet the physics goals, insure reliability and to take advantage of synergistic effects.
Tasks underway to study and recommend baseline changes.
Waveguide layout considerations

- Minimize loss
  - minimum bends & length
  - efficient coupling to gyrotron output & launcher input
- Use only 90° miter bends or use other bend angles?
- Provide adequate supports and alignment fixtures for straightness requirements
- Allow for waveguide thermal expansion or minimize with cooling
- Allow for vacuum vessel thermal expansion
- Allow for disruptions and seismic events
- Minimize cost and maintain or improve performance
- Provide access for maintenance
The T-line layout is evolving

4th Upper launcher
Thermal & seismic isolation

Building integration & penetrations
Port reallocation
T-line schedule - Iterative design & testing

• R&D 2006-9
  – Prototype component construction
  – Low power testing at MIT & ORNL
  – High power testing at several locations
  – High power test stand in US to qualify design

• Design 2006-10

• Production and QA tests 2009-13

• Delivery 2013-14
Near and midterm objectives:

• Revision of the T-line lay-out and specific subcomponent lists.
• Identification of key interfaces.
• Investigation of compatibility of T-Line components with 2 MW unit power.
• Safety considerations
  - Conceptual design of safety related components
  - Strategy for tritium release prevention
  - Seismic events
• Construction of a high power test stand.
• Testing of prototype components.
Recent Design and R&D

- Optimized waveguide routing studies
- Incorporation of component design envelopes into waveguide layout
- Evaluation of component power handling & cooling with models and measurements
- Alternatives for reducing manufacturing costs
- High power test stand design
- Evaluation of waveguide straightness and support issues
- Low power tests of mode conversion and loss
- Investigation of methods to reduce miter bend loss
Initial layout design efforts in tokamak hall

Port reallocation
Launcher interface
Port cell routing
Building penetrations
Design visualization tools are required
Alternate layout for upper launcher feeds

90° bends
Improved port access
What is required to deal with seismic or vessel displacement events

DDD specifies “no microwave leakage”
Enlarged Auxiliary Building plan will allow symmetric placing of another 24-27 gyrotrons.
Need to adjust gyrotron layout to aid access for maintenance

Baseline gyrotron layout  Proposed alternative
Place components under a raised floor?

Improved access
More miter bends?
Tritium release prevention strategy and requirements are needed

ITER requirements ???

In-situ leak testing

Are two sets of diamond window assemblies required? Can the windows be moved from the port to the port cell?
Prototype component evaluation and test

- Test components to full power/pulse length for many cycles.
- Set of typical components will be tested individually.
- A full scale mock-up is planned to qualify the entire line before final component purchase.
- High power > 2 MW test capability using a resonant ring.
- Investigate helically grooved waveguide for lower manufacturing cost and longer sections.
- Switch heating, cycle time and lifetime are a concern. Alternative ideas are interesting.
High power testing

• Long pulse testing at JAEA with 170 GHz 1 MW cw
  – Component temperatures
  – Thermal expansion and cooling effectiveness
• Component tests underway at CRPP & IPP
• Dedicated, full scale prototype T-Line testing planned in US

K. Sakamoto, A. Kasugai, K. Kajiwara, K. Takahashi and K. Noriyuki
Resonant ring to be used in US test stand

- 140 GHz ~ 300 kW cw gyrotron available now
- A >500 kW cw 170 GHz gyrotron system will be purchased for prototype testing
- Test full scale system at > 2 MW (gain of 10-30)
  - Long waveguide runs
  - Miter bends
  - Polarizers & loads
  - Pump-outs & bellows
CW coupler is being designed

- Polarization insensitive coupling factor is desired
- Need ~ -10 to -20 dB coupling factor
- A Grating coupler or Perforated Plate coupler needs to be developed
Minimize waveguide sag mode conversion

- Establish specifications for acceptable system mode conversion
- Waveguide support design optimized for straightness and ease of installation
- Straightness verification and cleanliness can be verified with a pull-through “rabbit” (teflon plug) with camera and x-y offset detector
170 GHz HE11 high mode purity testing

- Testing of transmission line components at MIT and ORNL
  - Mode purity
  - Losses
  - Polarization rotation
- Network analyzer & 170 GHz source
- Up-taper with high mode purity
- Automated 2-D pattern scanning
Preliminary FDTD analysis of losses and peak fields for a square groove polarizer

• How much margin exists on design of current components for 1 or 2 MW cw?
• Plane wave excitation 45° to normal
  – Absorbing boundaries
  – 170 GHz ramped sinusoid excitation
  – FDTD grid ~ 0.15 mm for initial runs
  – Analysis underway for various incident polarization and angle cases
Example: $E_{\text{inc}}$ plane perpendicular to grooves, TM

Grooves 0.25 λ deep case

$E_{\text{inc}}$ plane perpendicular to grooves, TM
Miter bend loss - Reduction possibilities?

• Miter bend is a complicated 3D structure
• Several schemes proposed to reduce mode conversion loss
  – Curvature (marginally effective)
  – Up-tapers, curvature and down-tapers (add space and cost)
• The mirror resistive loss is comparable to the mode conversion loss at 170/63.5mm
  – Not many good options to lower resistive loss.
  – LN2 cooled mirrors with polished Au or Cu plating?
• Geometric Optics analysis shows successful ray paths
  – Can also include diffraction correction terms - GTD
• Some energy is just lost
  – Appears as higher order “modes” (forward and reflected)
Miter bend geometric optics analysis

\[ A_b = 2 \int_0^{\frac{\pi}{2}} \int_{-w(\phi)}^{w(\phi)} \rho \, d\rho \, d\phi = 4 \, a^2 \tan \alpha \left( 1 - \frac{\pi}{4} \tan \alpha \right) \]

where: \( w(\phi) = 2 \, a \, \tan \alpha \cos \phi \)

\( \alpha = 1.24^\circ \) @ 170 GHz

Projected region of successful rays

Region of forward scattered rays

Region of backward scattered rays

w(f)
ECH waveguide specifications (short list)

- Nominal operating frequency of 170 GHz - Compatible with 126.7 GHz
- Capable of low loss operation between 110-170 GHz
- Al tube $63.5 \pm 0.1$ mm ID, $76.2$ mm OD
- Straight to within a maximum deviation of $0.25$ mm over a 2-m length
- Allowable tilt at a waveguide junction is $0.057^\circ$
- Vacuum tight to $< 10^{-8}$ Torr-l/s
- Corrugated for pure HE11 mode - Typical (other values will work)
  - Period: $0.66 \pm 0.05 / -.025$ mm
  - Width $0.41 \pm 0.08$ mm (@half-depth)
  - Depth $0.46 \pm 0.10$ mm
- Tapered with rounding (top, corners) or sinusoidal?
- Miter bend angles within $\pm 0.1^\circ$
- Polished Cu mirrors $0.2$ µm Ra
- Cu polarizers
- Miter bend switches with 2 second response and 10,000 cycle lifetime
- Corrugated isolation gate valves with 10,000 cycle lifetime
- Corrugated pump-out and bellows expansion joint sections
- Provisions for attachment of water cooling
Summary

• Revision of the T-line lay-out and specific subcomponent lists is underway
• In the process of identifying key interfaces
• Studying the compatibility of T-Line components with 2 MW unit power (is it just a cooling issue?)
• Develop concepts for safety related components
• Testing prototype components at low power
• Designing a high power test stand to test a prototype line
• Procuring a 170 GHz gyrotron for the test stand