

# Contents

|          |                                                                     |           |
|----------|---------------------------------------------------------------------|-----------|
| <b>1</b> | <b>Velocity Measurements in Tokamaks</b>                            | <b>1</b>  |
| 1.1      | Doppler Shifts of Atomic Transitions                                | 1         |
| 1.1.1    | Passive Spectroscopy                                                | 1         |
| 1.1.2    | Active Spectroscopy                                                 | 6         |
| 1.2      | MHD Mode Rotation                                                   | 9         |
| 1.3      | Probe Measurements                                                  | 10        |
| 1.4      | Microwave Doppler Reflectometry and Scattering                      | 11        |
| 1.5      | Comments                                                            | 14        |
| <b>2</b> | <b>Momentum Sources</b>                                             | <b>21</b> |
| 2.1      | Direct Rotation Drive                                               | 21        |
| 2.1.1    | Neutral Beam Injection                                              | 21        |
| 2.1.2    | Ion Cyclotron Range of Frequencies Waves                            | 24        |
| 2.1.2.1  | Ion Bernstein Waves                                                 | 24        |
| 2.1.2.2  | Mode Conversion Flow Drive                                          | 25        |
| 2.1.2.3  | Fast Magnetosonic Waves                                             | 28        |
| 2.1.3    | Lower Hybrid Waves                                                  | 31        |
| 2.1.4    | Electron Cyclotron Waves                                            | 33        |
| 2.1.5    | Compact Torus Injection                                             | 35        |
| 2.2      | Indirect Rotation Drive                                             | 35        |
| 2.2.1    | Orbit Shift $j \times B$ Forces                                     | 35        |
| 2.2.2    | Ion and Electron Loss Due to Toroidal Magnetic Field Ripple         | 39        |
| 2.2.3    | Edge Thermal Ion Orbit Loss                                         | 41        |
| 2.3      | Comments                                                            | 43        |
| <b>3</b> | <b>Momentum Sinks</b>                                               | <b>45</b> |
| 3.1      | Neutral Damping                                                     | 45        |
| 3.2      | Mode Locking, Magnetic Braking and Neo-Classical Toroidal Viscosity | 46        |
| 3.3      | Edge Localized Modes                                                | 51        |
| 3.4      | Comments                                                            | 51        |

|                                                                                         |     |
|-----------------------------------------------------------------------------------------|-----|
| <b>4 Comparison with Neo-Classical Theory</b> .....                                     | 53  |
| 4.1 Poloidal Rotation $v_\theta$ .....                                                  | 53  |
| 4.2 Toroidal Rotation $v_\phi$ .....                                                    | 54  |
| 4.3 Poloidal Asymmetries in Edge Toroidal Rotation .....                                | 58  |
| 4.4 Comments .....                                                                      | 60  |
| <b>5 Intrinsic Rotation and the Residual Stress <math>\Pi^{\text{res}}</math></b> ..... | 61  |
| 5.1 Enhanced Confinement Regimes .....                                                  | 62  |
| 5.1.1 Ohmic H-Modes .....                                                               | 63  |
| 5.1.2 ICRF H- and I-Modes .....                                                         | 63  |
| 5.1.3 ECH H-Modes and Adding ECH .....                                                  | 72  |
| 5.1.4 H-Modes with LH .....                                                             | 77  |
| 5.1.5 NBI H-Modes .....                                                                 | 77  |
| 5.1.6 Plasmas with ITBs .....                                                           | 82  |
| 5.1.7 Comments .....                                                                    | 83  |
| 5.2 Low Confinement Mode .....                                                          | 87  |
| 5.2.1 Magnetic Configurations .....                                                     | 87  |
| 5.2.2 Current Driven Reversals .....                                                    | 92  |
| 5.2.3 Ohmic Rotation Reversals and LOC/SOC .....                                        | 95  |
| 5.2.4 Auxiliary Heated L-Mode .....                                                     | 117 |
| 5.2.5 Comments .....                                                                    | 119 |
| <b>6 Momentum Transport</b> .....                                                       | 121 |
| 6.1 Momentum Diffusivity $\chi_\phi$ .....                                              | 121 |
| 6.2 Momentum Pinch $V_p$ .....                                                          | 125 |
| 6.3 Residual Stress $\Pi^{\text{res}}$ .....                                            | 128 |
| 6.4 Comments .....                                                                      | 131 |
| <b>7 Discussion and Future Outlook</b> .....                                            | 133 |
| <b>References</b> .....                                                                 | 137 |
| <b>Index</b> .....                                                                      | 147 |