Development of RF Tools and Scenarios for ITER on JET

J.-M. Noterdaeme[1,2], M. Mantsinen[3a], V. Bobkov[1], A. Ekedahl[4], L.-G. Eriksson[4], P.U.Lamalle[5], A. Lyssoivan[5], J. Mailloux[6], M.-L. Mayoral[6], F. Meo[7], I. Monakhov[6], K. Rantamaki[3b], A. Salmi[3a], M. Santala[3a], S. Sharapov[6], D. Van Eester[5], JET-EFDA Task Force H and JET-EFDA Contributors*

*[1]Max Planck Institute for Plasmaphysics, EURATOM Association, D-85748 Garching, Germany, [2]Gent University, EESA Department, B-9000 Gent, Belgium, [3]Euratom Association-Tekes,[a] HUT,[b]VTT, Helskini, Finland, [4]Association Euratom-CEA, CEA, Cadarache, France, [5]Association Euratom-Belgian State, LPP, Trilateral Euregio Cluster, EMR-KM,S Brussels, Belgium, [6]Euratom-UKAEA Fusion Association, Culham, UK, [7]Association Euratom-Denmark, Riso, Denmark *See the Appendix of J.Pamela et al., Fusion Energy 2004 (Proc. 20th Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004)*

Abstract. The improvement of LH coupling with local puffing of D_2 gas, which made operation at ITER relevant distances (10 cm) and with ELMs a reality, has been extended to ITER- like plasma shapes with higher triangularity. With ICRF, we developed tools such as (1) localized direct electron heating using the ^{3}He mode conversion scenario for electron heat transport studies, (2) the production of ^{4}He ions with energies in the MeV range by 3 ω_c acceleration of beam injected ions at 120 keV to investigate Alfven instabilities and test α diagnostics, (3) the stabilisation and destabilisation of sawteeth and (4) ICRF as as a wall conditioning. Several ITER relevant scenarios were tested. The (^{3}He)H minority heating scenario, considered for the non-activated start-up phase of ITER, produces at very low concentration energetic ^{3}He which heat the electrons indirectly. For $n_{3He}/n_e > 2\%$, the scenario transforms to a mode conversion scenario where the electrons are heated directly. The (D)H minority heating is not accessible as the concentration of C^{6+} dominates the wave propagation and always leads to mode conversion. The minority heating of T in D is very effective heating for ions and producing neutrons. New results were obtained in several areas of ICRF physics. Experimental evidence confirmed the theoretical prediction that, as the larmor radius increases beyond 0.5 times the perpendicular wavelength of the wave, the second harmonic acceleration of the ions decreases to very small levels. An exotic fusion reaction (pT) must be taken into account when evaluating neutron rates. The contribution of fast particles accelerated by ICRF to the plasma rotation was clearly identified, but it is only part of an underlying, and not yet understood, co-current plasma rotation. Progress was made in the physics of ELMs while their effect on the ICRF coupling could be minimized with the conjugate-T matching scheme. The addition of 3 dB couplers is a step in increasing the power capability of the ICRF heating on JET in ELMy plasmas. The installation of an ITER-like, ELM resilient antenna in 2006 will further improve this and be a test of the ICRF scheme for ITER.

Keywords: tokamak, LH, ICRF, ICRH, heating, coupling, plasma production, rotation
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INTRODUCTION

The focal points of the Task Force Heating (TF H) at JET are plasma heating, current drive and plasma rotation as well as the optimization of the systems. The very intense 2003-2004 campaigns included reversed I_p, B_T operation, the use of tritium in trace amounts, and of H and He as majority gas. We emphasized the development of tools and scenarios for progress towards ITER, and collected some interesting physics results only obtainable in JET.

LH COUPLING

The coupling of the LH can be improved by using CD_4 as additional gas. Up to 3 MW was coupled at distances of up to 10 cm. However, the possible use of CD_4 in ITER raised concerns about T co-deposition. D_2 as an additional gas had not been successful. Prior to the 2003 campaign, the pipe which extends poloidally along the launcher and through which the gas is delivered, was modified. The top holes, whose poloidal location was near the top of the launcher, but magnetically above the field lines connected to the launcher, were plugged. Since, D_2 can be used as effectively as CD_4. Fig. 1 compares two pulses, one with CD_4 and one with D_2 gas injection. The CD_4 gas flow rate was 12 x 10^{21} el/s; the D_2 gas flow rate was smaller by 1/3 (8 x 10^{21} el/s). The discharge with CD_4 injection had the last closed flux surface (LCFS) at 9 cm and a coupled LH power of 2.5 MW; the one with D_2 injection, the LCFS at 10 to 10.5 cm and a power of 3 MW. The ELMs were smaller in the discharge with D_2 (due to the gas puffing), but the plasma performance of both discharges was similar [1] [2, 3]. LH was now also coupled to high triangularity ($\delta \sim 0.4$-05) ITB plasmas. D_2 injection (4 x 10^{21} el/s) to improve the LH coupling was used together with strong D_2 and Ne puffing for ELM control. The plasma-launcher distance was 7 cm and the coupled LH power 2 MW (in combination with 18 MW of NBI and 2.5 MW of ICRF)[4, 5].

Bright spots have been observed on the divertor apron during LH operation. They are due to the impact of fast particles, created in front of the LH grill mouth and travelling along magnetic field lines. The heat load increases with LH power, edge density and temperature but decreases when the LH grill is operated at a larger distance[6, 7]. This is beneficial for ITER, where the distance between LCFS and LH grill will be large.

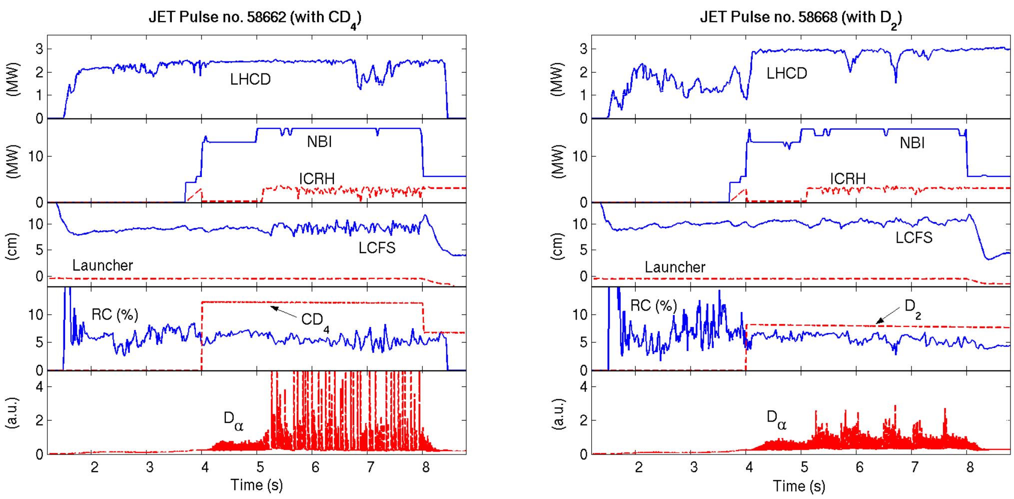

FIGURE 1. Comparison of CD_4 and D_2 injection to improve the LH coupling

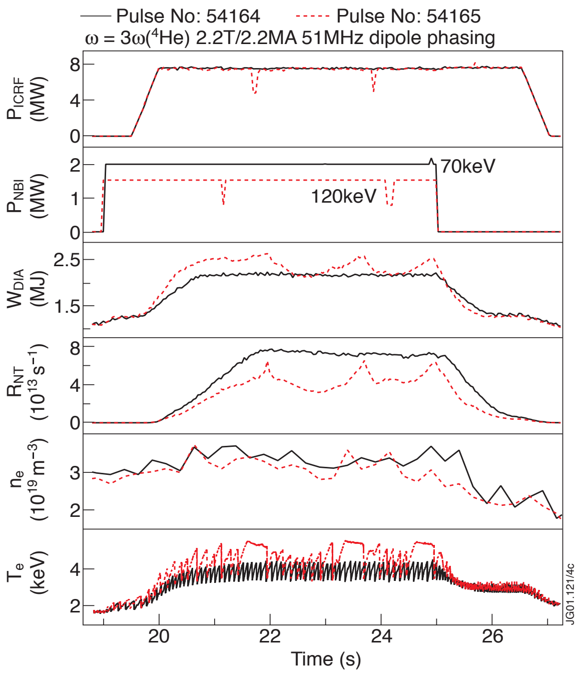

FIGURE 2. Acceleration of beam injected ^{4}He ions (at 70 keV and 120 keV) with 3 ω_c.

ICRF TOOLS

Four major tools were developed.

One is ^{3}He-D mode conversion, which provides in JET a very localized e-heating method[8]. It was used extensively for the investigation of electron heat transport [9, 10] and also pushed the ITB discharges on JET, in combination with minority heating to some of the highest performance (T_i = 27 keV, T_e = 13 keV)[9]. With the second tool MeV energy ^{4}He ions can be produced by acceleration at 3 ω_c of beam injected ^{4}He (at 120 kV)[11]. In a recent extension of the third tool, where Ion Cyclotron Current Drive (ICCD) is used to influence sawteeth[12, 13], we showed for the first time that it is possible to destabilize long sawteeth initially stabilized by fast ions. The stabilization was obtained by central H minority heating, the destabilization by the application of off-axis ICCD. This has potential application for the avoidance of neoclassical tearing modes. The fourth tool, whose development was only started, is the application of ICRF to condition a machine in the presence of a permanent magnetic field[14]. We discuss here only in some more detail the second and fourth topics.

Production of ^{4}He at MeV Energy without Activation

Figure 2 compares two discharges with injection of ^{4}He ions at 70 keV and 120 keV (at 2 MW and 1.5 MW respectively). An ICRF power of 8 MW at 3 ω_c of ^{4}He was applied. The discharge with the 120 keV shows stabilization of the sawteeth, an indication of a high fast particle pressure in the center. Gamma ray diagnostics [15] [16]confirm that a steady-state distribution of ^{4}He ions with

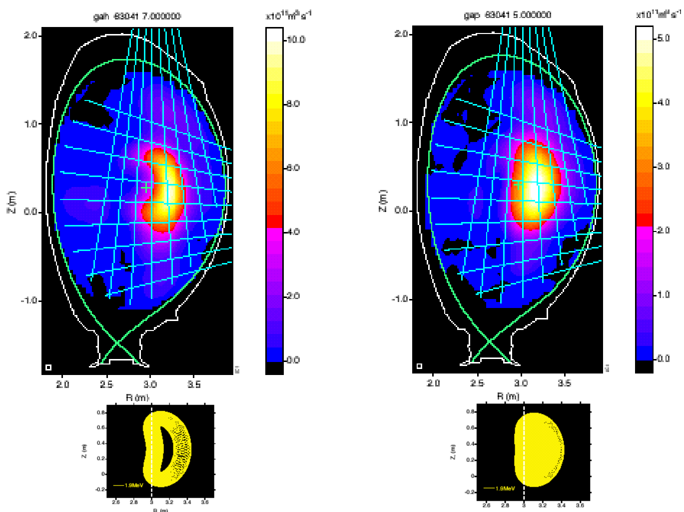

FIGURE 3. Gamma ray emissivity showing the location of the fast ^{4}He particles for two shapes of the q profile (monotonic-left, and reversed q-right) and comparison with the calculated orbits with those q- profiles

energies above 1 MeV have been achieved. The calculated fraction of fast particle (n_H/n_e) is 10^{-3}, close to the record DT discharge with 4 x 10^{-3}, but with a neutron rate lower by 4 orders of magnitude. This method thus lends itself perfectly, both on JET and on ITER to test α-diagnostics[17].

The technique was used to investigate Alven eigenmodes produced by the fast particles and can provide, together with γ-ray images, qualitative information on the confinement of fast particles for different types of q-profiles. Figure 3 shows the difference in location of the γ-ray emission for fast ^{4}He in monotonic and reversed q-profiles. The emission are in agreement with the calculated orbits of ^{4}He ions (E=1.9 MeV), taking into account the q-profile[17].

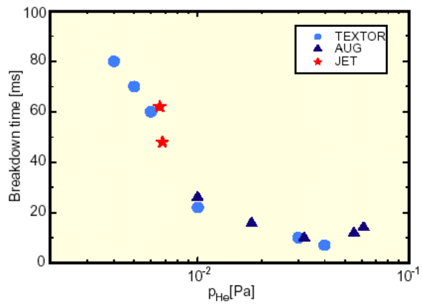

FIGURE 4. Gas breakdown time as a function of He pressure for several machines

ICRF for Vessel Conditioning in the Presence of a Magnetic Field

Conditioning of the vessel walls using glow discharge, as is usually done, will be prevented in superconducting machines by the presence of the magnetic field. After similar experiments in TEXTOR, Tore Supra and ASDEX Upgrade, ICRF was used on JET to produce an RF discharge[14]. The ^{4}He gas pressure was in the 7 x 10^{-3} Pa range. The gas breakdown time (time between application of the power and appearance of H_ light) was 50 to 60 ms. Since similar values were obtained in smaller machines at similar antenna voltages (8-12 keV), frequencies (30-34 MHz) and at the same pressures (see Fig. 4) the breakdown time is independent of machines size. The radial distribution of the plasma density (measured through multi-channel far infrared interferometry) could be varied by adding H to the He. This provides a way to scan the position of highest density for example across a divertor. High energy fluxes of H and D atoms with energy EH < 60 keV and ED < 25 keV were observed. The partial pressure of the masses 2, 3, 4, 6, 18, 20 all increase for about 100 s by an order of magnitude after an RF pulse of 245 kW for 4 s.

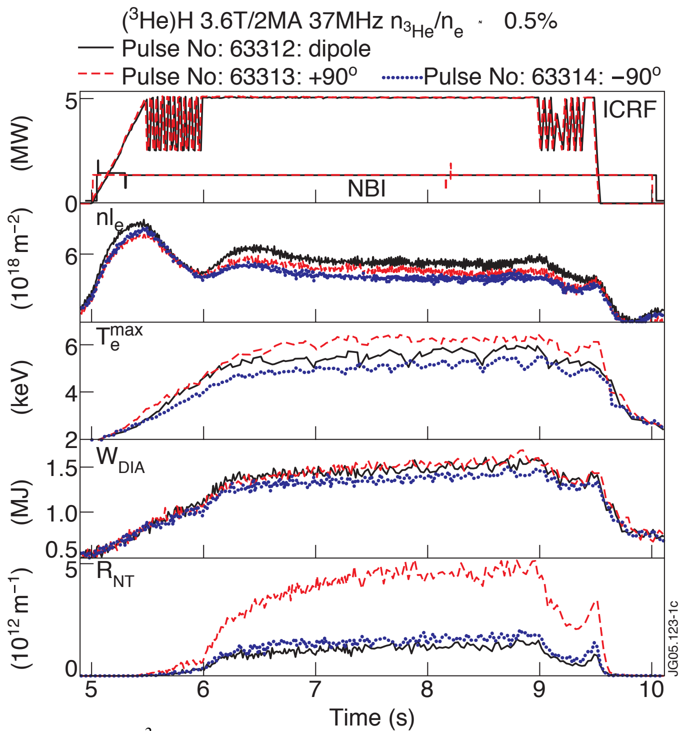

FIGURE 5 (^{3}He)H minority scenario with different phasings

ICRF SCENARIOS

The flexibility of the JET ICRF system, the possibility to use tritium, and the good confinement of energetic particles are key capabilities of JET. Campaigns where H was used as majority gas, or T in trace amounts provided the opportunity to investigate ITER relevant scenarios.

^{3}He minority in H, D minority in H, and T minority in D are three scenarios of a somewhat unusual type, called "heavy minority scenario", since the minority has a larger M/Z ratio than the majority. In this case, the fast wave, launched from the low field side, first encounters the mode conversion, before encountering the cyclotron resonance of the minority.

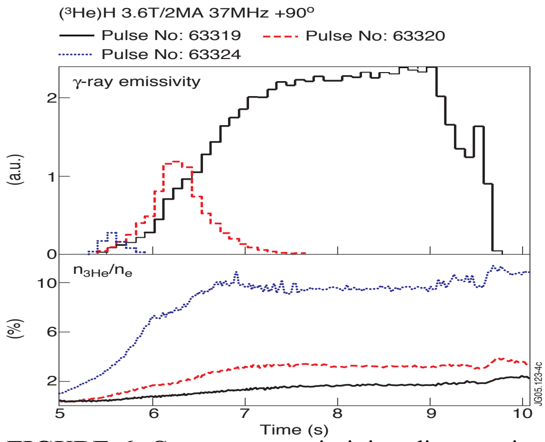

FIGURE 6. Gamma ray emissivity, disappearing as the ^{3}He concentration raises above 2 %

^{3}He minority regime in H

The frequency for ^{3}He minority in H is the same as for the main ITER scenario (2 ω_c of T in D) and can be used in ITER both to test the ICRF system at its intended frequency and to heat the plasma in the non-active phase. In order to explore the ^{3}He minority regime and its transition to the mode conversion regime, a precise control of the ^{3}He concentration is useful. The feedback control of the ^{3}He concentration had been developed at high concentration values to investigate the mode conversion regime used for e- heating and heat transport studies (mentioned above). An extension of the feedback control allowed the required precise control of very low ^{3}He concentration. Figure 5 shows three discharges with similar density (n_{e0}=3 x 10^{19} m^{-3}), ^{3}He concentration (< 1 %), and power (NBI 1 MW, ICRF 5 MW), but with different phasing. The higher electron temperature as well as the higher neutron rates with the +90° phasing (wave propagates co-current) are clear indication of the pinch effect, by which the fast particles produced by the ICRF are transported towards the center. Higher tail energies, with tails of up to 0.3 MeV, are obtained. As the ^{3}He concentration is increased, the tail temperature decreases, and at 2 %, a very abrupt transition to the mode conversion regime occurs. This is shown in Fig. 6 where the γ-ray emissivity (produced by fast ^{3}He reactions on ^{9}Be and ^{12}C) disappears when the ^{3}He concentration is above 2%[18, 19].

D minority in H

D minority in H has also been investigated but was shown not to be accessible because the presence of C in the machine. The C^{6+} ion has the same Z/M as D. Its presence is, for the wave propagation, as an additional sixfold concentration of D pushing the scenario directly into the mode conversion regime[19].

Heating of Low Concentrations of T

Both minority heating of T and second harmonic heating of trace T was investigated. Minority heating of T is a quite challenging scenario in JET as it requires operation at the highest magnetic fields (B_T = 3.9 – 4T) and at the lowest RF frequency (23 MHz), where the available power is low (1.5 MW) and the coupling is poor. With T concentrations of up to 3 %, energetic tails of 80 to 120 keV were obtained, a very efficient energy range of neutron production and ion heating[18].

Second harmonic of tritium, which is the main ICRF scenario on ITER was attempted but further investigation will require campaigns where the T concentration is higher.

ICRF PHYSICS

Second harmonic heating

Second harmonic heating is a finite larmor radius effect (FLR). If the magnitude of wave field is constant over the motion of a particle along its cyclotron motion, then, because the field will accelerate and decelerate the ion along its orbit, no net energy can be transferred between wave and ion. If the diameter of the cyclotron motion (2 ρ) of the ion is approximately equal to half the wavelength of the wave, the wave amplitude will have changed sign along the second half of the ion orbit and the energy transfer is maximized. The energy transfer goes again to zero, if the wavelength is approximately equal to the diameter of the cyclotron motion. The net transfer of energy thus stops for a particular value of k_{perp} ρ. This affects strongly the distribution function of the fast particles and was investigated by varying kperp through its dependence on density. Figure 7 shows the measured distribution functions at high and low density and at high and low power. Whereas the discharge with high power has more energetic ions than the one at low power, the shape of the distribution function is the same. On the other hand, when the ratio k_{perp} ρ was modified by changing the density, the distribution function, and in particular the energy at which the distribution function drops rapidly (no more acceleration of the ions) changed markedly. The shapes were shown to be in agreement with theory, when finite larmor radius effects [20] are taken into account.

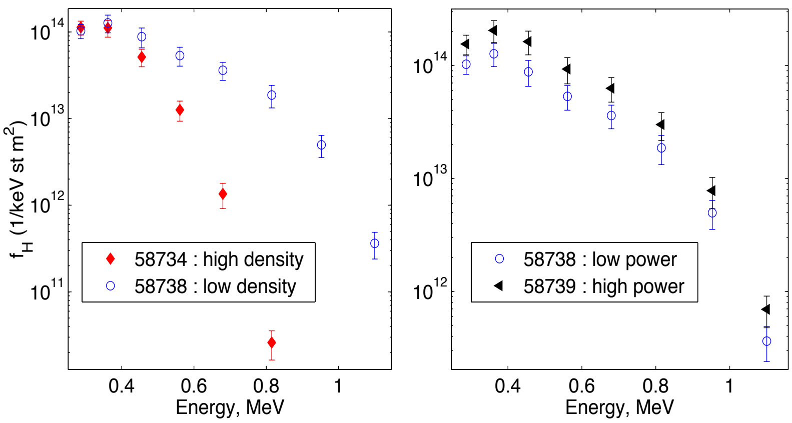

FIGURE 7. Perpendicular proton energy distribution for two densities (left) and two power levels (right)

ELMs

ELMs cause a strong variation of the plasma density in front of the antenna, and can be a source of significant problems both for matching and voltage stand-off[21]. By using a 3 dB coupler, the first problem can be alleviated[22]. Two of the four antennas on JET will be connected in this way in 2005. An alternative method is to use the conjugate matching scheme: in a proof of principle experiment, the connection of

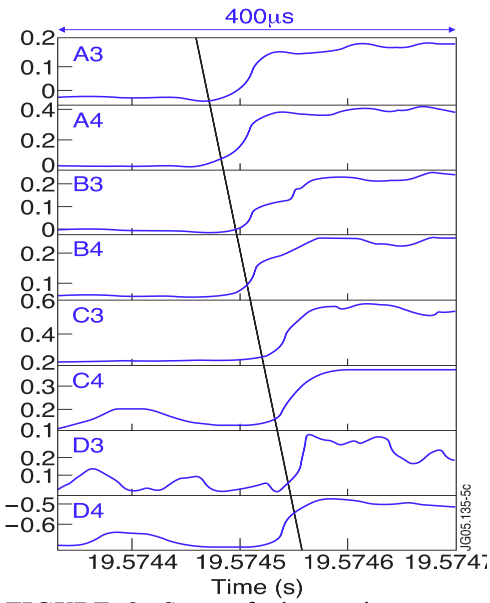

FIGURE 8. Start of change in antenna coupling due to an ELM for the different straps of the antennas. Antennas are labeled A, B, C ,D. Antenna A and C are 180° apart. The straps within an antenna numbered 1, 2, 3, 4. Only 3 and 4 are shown.

two straps of one antenna were reconfigured. With those straps the power to the plasma was little affected by the ELMs[23]. In 2006, the scheme will be extended to the other two antennas.

The variation of the coupling with the ELM arrival at the antenna provides some interesting information on the evolution of an ELM. The time delay of this variation between the toroidally spaced antennas gives information about the toroidal development of an ELM. Figure 8 shows how an ELM appears successively in front of the different antennas, takes about 100 μs for a full toroidal rotation, and rotates in the counter-current direction[24].

pT fusion

During the trace T experiment, the endothermic fusion reaction T+ p -> n + 3H + Q with Q= -764 keV was investigated. It can act a source of neutrons which must be taken into account in the analysis of DD and DT neutrons[25].

Plasma Rotation

Tokamak plasmas show a significant toroidal rotation even with only a small momentum input. A systematic analysis of plasma rotation with ICRF was done on JET[26, 27]. Recent results have identified the component predicted by theories that rely on fast particle effects for the rotation drive. Plasmas with waves injected in the co- and counter-current direction show a different rotation profile. While the difference in the profile is in agreement with theory, its magnitude is moderate and comes on top of a still unexplained dominant co-current rotation[28].

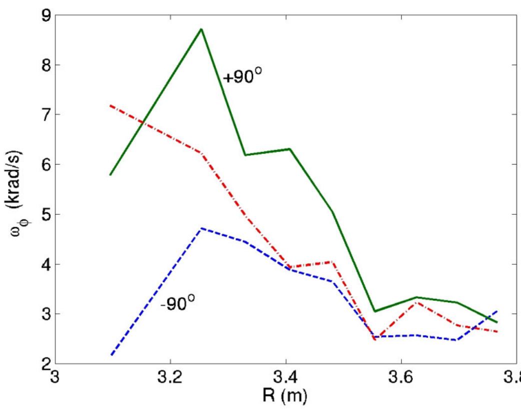

FIGURE 9. Toroidal rotation for three discharges: ICRF with +90° phasing, LH and ICRF with –90° phasing. The difference in rotation between co- and counter-current phasing is in agreement with theory, the discharge with LH is for control.

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