Abstract. New measurements on the ferromagnetic heavy-fermion superconductor UGe$_2$ are reported. Thermal expansion measurements via strain gage allow us to locate precisely the critical end point (CEP) of the first order boundary between the large moment ferromagnetic phase FM$_2$ ($M_0 = 1.5 \mu_B$) and the small moment phase FM$_1$ ($M_0 = 0.9 \mu_B$). The field dependence of the CEP is compared with that of the paramagnetic-FM$_1$ transition above the tricritical point.

1. Introduction

UGe$_2$ is a ferromagnet below 53 K at ambient pressure. The Curie temperature can be driven to 0 K with applying pressure : $p_c \approx 1.49$ GPa. Pressure studies have revealed two ferromagnetic ground states : FM$_1$ and FM$_2$. Both phases have the magnetization along the a-axis of the orthonhombic structure (space group $Cmmm$) but different ordered moments : $M_0 = 1.5 \mu_B/U$ in FM$_2$ and $0.9 \mu_B/U$ in FM$_1$. Figure 1 shows the boundary between these phases in the $p$-$T$ phase diagram. FM$_2$ exists only below $p_x$ and the transition line, which is of first order [1, 2], terminates at a critical end point (CEP). This means that below $p_{CEP}$, a crossover regime exists between FM$_1$ and FM$_2$. With magnetic field applied along the a-axis, the critical pressures $p_x$ and $p_c$ are shifted to higher pressure [2]. In this paper, we report on the field evolution of $p_{CEP}$ and $T_{CEP}$. Interest of the studies of the FM$_1$-FM$_2$ transition has been enhanced by the discovery of superconductivity in the ferromagnetic state (below $p_c$) with $T_{SC_{MAX}}$ around $p_c$ [3].

This study is quite complementary with our recent results on the FM$_1$-PM boundary which revealed the tricritical point (TCP) of UGe$_2$ [4] by resistivity measurements. The FM$_1$-PM transition changes from second order to first order at a TCP (see fig. 1 : $T_{TCP} \approx 24$ K and $p_{TCP} \approx 1.42$ GPa). Under magnetic field, the first order transition line occurs at higher pressure, which leads to a plane of first order transition in the $p$-$T$-$H$ space. At a given field, or pressure, the first order transition ends up at a critical point which can be driven with pressure, or field, to 0 K at a quantum critical end point (QCEP) [5]. Between 1.42 GPa and 1.85 GPa, we found that the critical point decreases from 24 K at 0 T to 16.5 K at 2.5 T, so that we roughly estimate $p_{QCEP_{PM-FM1}} \approx 3$ GPa and $H_{QCEP_{PM-FM1}} \approx 9$ T for the PM-FM$_1$ transition [4]. By symmetry, there are two first order planes for positive and negative magnetic field, so that they are called wings [6]. The same wing structure is expected for the FM$_1$-FM$_2$ transition studied here : we will show that the CEP is found at higher magnetic field with increasing pressure, but that $T_{CEP}$ does not decrease significantly up to 8 T.
Figure 1. (Color online) Phase diagram of UGe$_2$ determined by our resistivity (open symbol) and thermal expansion measurements (full symbol). Vertical arrows show the temperature scans presented in fig. 2(a) and horizontal dashed lines show the pressure scans of fig. 2(b). The superconducting phase is not shown here.

2. Experimental technique
For the determination of the CEP of the first order line ($T_x$, $p_x$) of the FM1-FM2 transition, thermal expansion experiments via strain gage have been used. And for the location of the FM1-FM2 wings $T_{CEP}(H)$ under magnetic field, resistivity measurements have been performed. The single crystal of UGe$_2$ was grown by the Czochralski pulling method in a tetra-arc furnace. The residual resistivity ratio (RRR) is higher than 300. For the thermal expansion measurements, the pressure was applied via a CuBe piston cylinder cell with Daphne 7373 as a pressure-transmitting medium. Thermal expansion was measured along the b-axis via strain gage. Silicon was used as a reference material. Another sample was used for resistivity measurements. Pressure was applied via a NiCrAl-CuBe hybrid piston-cylinder cell with Daphne 7373. Electrical resistivity was measured down to 2 K and at high fields up to 9 T, by the 4-probe AC-method with current parallel to the a-axis. Magnetic field was applied along the easy magnetization a-axis.

3. At $H = 0$ T : first order nature of the FM1-FM2 transition, CEP and crossover
The inset of figure 2(a) shows the temperature dependence of the relative elongation $\Delta L_b/L_b$ at different pressures. The expansion coefficient $\alpha_b$ corresponding to the temperature derivative is shown in figure 2(a). A sharp anomaly corresponding to the Curie temperature $T_C$ is observed. Such feature in $\alpha_b$ is observed up to 1.24 GPa, and thus confirms that the PM-FM1 transition is second order at least up to 1.24 GPa [7]. Further experiments located the tricritical point at $p_{TCP} \approx 1.42$ GPa [4].

In addition, below $T_C$, we observe a clear anomaly at 1.14 GPa at $T_x$ which disappears completely at 1.21 GPa, above $p_x \approx 1.19$ GPa. At low pressure, only a large hump can be
recorded confirming that the switch from FM1 to FM2 corresponds to a broad crossover regime at ambient pressure [8] and thus the existence of the CEP which terminates the first order line between FM1 and FM2.

The non magnetic contribution to the relative elongation can be determined by fitting $\Delta L_b / L_b$ (inset of fig. 2(a)) in the paramagnetic regime by $T^2$ [9]. Then, we obtain the spontaneous magnetostriction $\Delta L_b / L_b^{\text{magn}}$ by subtracting the non magnetic part to $\Delta L_b / L_b$. Fine tuning of the pressure allows us to draw $\Delta L_b / L_b^{\text{magn}}$ as a function of pressure in fig. 2(b). The anomaly at 45 K and 35 K is associated to the PM-FM1 transition. By comparison to the continuity of the spontaneous magnetostriction at that second order transition, we observe a discontinuity at low temperature at the FM2-FM1 transition. This discontinuity changes to a continuity above 7 K (curve at 15 K for fig. 2(b)). Thus, the FM1-FM2 transition is first order below 7 K, and the transition line ends up at a CEP.

For pressure lower than $p_{\text{CEP}}$, anomalies can be detected as one inflection point or two (0.4 and 0.88 GPa in fig. 2(a)). Closer to the CEP, a minimum is also visible in $\alpha_b$ similar to the minimum observed above the CEP at the first order transition. The CEP coordinates have been determined when the minimum in the thermal expansion coefficient is the deepest : $p_{\text{CEP}} \approx 1.16$ GPa, $T_{\text{CEP}} \approx 7$ K. As we will show, our resistivity measurements confirm these values. In fig. 1, the anomalies corresponding to the crossover between FM1 and FM2 are reported. Our resistivity data are in good agreement with previously reported resistivity measurements [10, 11] but does not perfectly agree with the thermal expansion data. Above $p_{\text{CEP}}$, at the genuine FM1-FM2 transition, the agreement is very good, as well as for the PM-FM1 transition.

4. Evolution of $T_{\text{CEP}}$ in magnetic field : the FM1-FM2 wings

**Figure 3.** (Color online) Temperature derivative of resistivity $d\rho / dT$ for three typical pressures : (a) below $p_{\text{CEP}}$ ; (b) near $p_x$ ; (c) above $p_x$. (a1) The anomaly smears out with magnetic field. (a2) The value of $d\rho / dT$ at the maximum (i.e. at $T_x$) decreases. (b1) Up to 1.2 Tesla, the FM1-FM2 transition is sharper. At higher field, the anomaly is broadened and disappears. (b2) Below 1.2 T, $d\rho / dT_{\text{max}}$ increases with field (full line) which is interpreted here as the first order FM1-FM2 transition and then decreases (dashed line) as in a crossover regime. (c1) Below 1.5 Tesla, there is no anomaly (FM1 state). From 1.5 to 2.5 Tesla, anomalies are detected. Above 2.5 Tesla, the anomaly is broadened. (c2) The feature is the same as for 1.2 GPa but shifted to higher fields.
To determine the field evolution of the FM1-FM2 boundary and CEP, accurate resistivity measurements were realized. Figure 3 shows the temperature variation of $d\rho/dT$ (temperature derivative of the resistivity $\rho$) at different magnetic fields for three pressures: at 1.1 GPa just below $p_{CEP} \approx 1.14$ GPa, at 1.2 GPa just above $p_x = 1.19$ GPa and at 1.27 GPa between $p_x$ and $p_c = 1.49$ GPa. Two different behavior are observed: the peak of $d\rho/dT$, characteristic of the FM1-FM2 transition, is either sharpened with magnetic field or broadened. The first case is interpreted as the first order FM1-FM2 transition and the second as the crossover regime. The magnetic field value between these two behavior is thus defined as $H_{CEP}$. The corresponding $T_{CEP}(H)$ is obtained as explained in fig. 4. Clearly, the field dependence of $T_{CEP}$ must be very small up to 8 T.

![Figure 4. (Color online) Temperature-pressure-magnetic field phase diagram of UGe$_2$ drawn from resistivity measurements. Gray planes are planes of first order transition. Full red lines are second order lines. For the magnetic field dependence of $T_{CEP}$, each point is determined as follow (see arrows in fig.3(b) and (c)): first $H_{CEP}$ is determined by taking the maximum position of $d\rho/dT_{\text{max}}$ (for example 1.2 T from the data in fig. 3(b2) at 1.2 GPa), and then $T_{CEP}$ is obtained as the position of the peak on the $d\rho/dT$ curve at $H_{CEP}$ (7 K in the data of fig. 3(b1) at 1.2 GPa and 1.2 T). Details of the field dependence of the TCP will be presented in ref. [4] .](image)

The fact that $T_{CEP}$ of the FM1-FM2 transition does not decrease significantly up to 8 T is in contrast with the reduction from 24 K to 16.5 K at 2.5 T of the critical point of the PM-FM1 transition [4]. These results agree with the theoretical prediction that $H_{QCEP}$ varies as $m_0^3$ where $m_0$ is a microscopic magnetization parameter [5].

In summary, we have performed thermal expansion and resistivity measurements under pressure. The magnetic field evolution of the CEP has been determined up to 8 T and 1.6 GPa. Within the resolution of the field steps of the experiment, the CEP seems to remain at roughly the same temperature.

Acknowledgments
This work was financially supported by ANR-CORMAT and SINUS.

References
This work was financially supported by ANR-CORMAT and SINUS.

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