stellarator news

Published by Fusion Energy Division, Oak Ridge National Laboratory
Building 5700 P.O. Box 2008 Oak Ridge, TN 37831-6169, USA

Editor: James A. Rome Issue 118 December 2008
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On the Web at *http://www.ornl.gov/sci/fed/stelnews*

UST_1, a small, low-cost stellarator

UST_1, Ultra Small Torus (shown in Fig. 1), is a very small (R = 119 mm) modular stellarator built in a personal laboratory. Two main objectives were pursued: developing innovative low cost construction techniques and allowing the author to learn all aspects of stellarator design, construction, and operation. UST_1 is located 65 km north of Valencia, Spain, and was designed and built during 2005/06 and operated during 2006/07. Successful experiments to validate the quality of the design and construction have been carried out, particularly field mapping experiments and basic plasma pulses. UST_1 has proved that low-cost techniques to build accurate stellarators exist. Very probably it is the third modular stellarator in the world, the most economical with acceptable quality, and the first designed and built by only one person.

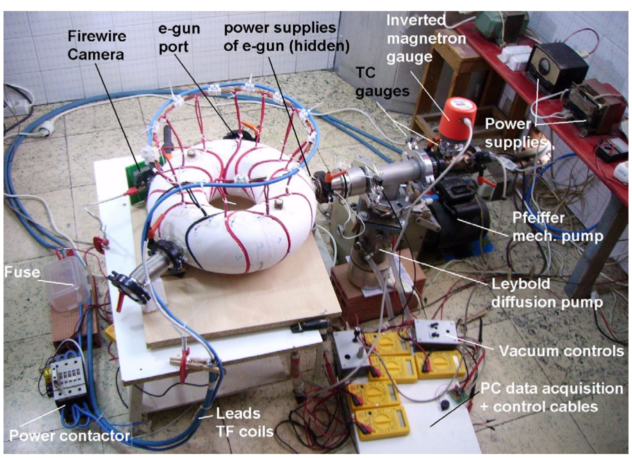

Fig. 1. The UST_1 stellarator and some of its auxiliary systems.

Similar small devices with reactor-like geometries probably would be useful to improve the conceptual designs and maintenance procedures for future fusion reactors.

Summary of features and parameters

UST_1 is a 2-field period modular stellarator with an aspect ratio ≈ 6 formed by 12 resistive partially optimized modular coils. Each coil is formed by 6 turns of flexible copper conductor wound in a groove machined in a circular torus. The grooves were accurately machined into a single plaster frame by a specially designed toroidal milling machine. Electron cyclotron radio-frequency heating (ECRH) at the second harmonic (B_0 = 46 mT and eventually B_0 = 90 mT) heats the plasma using a 0.8-kW, 2.45-GHz commercial magnetron. Typical length of the plasma pulse is 2 s at 46 mT. Toroidal field (TF) current per coil is 2.3 kA-turn.

Additionally, a vacuum system, control and diagnostics systems, and power supplies complement the stellarator.

In this issue . . .

The cost of the installation was minimized and only 2700 € were spent on materials for the whole facility. The size of the device was adapted to the available economical and technical resources and to the indeterminacies of building a first device.

The plasma volume is 1.1 L, major radius R = 119.2 mm, average minor radius $\langle a \rangle \approx$ 21mm. I selected a low shear configuration with $ι_0$ = 0.32 and $ι_a$ = 0.28, optimized to occupy a narrow range just below 1/3 in order to avoid high-order rationals and large magnetic islands. Additionally, UST_1 is optimized for other important plasma parameters, such as large plasma size, deep magnetic well, low ripple, and low variance of the minima of $|\boldsymbol{B}|$. Optimization is modest because the coils are constrained to lie on a circular torus.

Plasma parameters for this small device deduced from ISS04v1 [1] with B_0 = 0.1 T, enhancement factor = 0.1, and P_{ECRH} = 400 W are very modest, on the order of $T_e \sim 2$ eV, $n \sim 2 \times 10^{17}$ m^{-3}, and $\tau_E \sim 0.2$ µs, with $\beta \sim 0$.

Chronological description of the development

A description of UST_1 in chronological order is presented to better show not only what the stellarator is, but also what it was not, and why.

The conception of UST_1 started in June 2005. All the initial decisions were critical because frequently revising the base design of the project could have easily led to a dead end. Some of the key decisions taken are described next.

What to build?

Only tokamaks and stellarators were considered due to pragmatic reasons.

A tokamak?

Initially the idea of a small tokamak around 6 times smaller than the Brazilian tokamak ETE seemed attractive. The power supplies, coils, heating power, length of pulse, etc., were estimated by rough calculations. These estimates were sufficient to rule out the construction of a tokamak due to three insolvable difficulties: (i) the high voltage and power (~ 1 MW) needed for the central solenoid (CS) coil presented insurmountable cost and safety issues. (ii) T_e was too low for adequate plasma resistivity and plasma current. (iii) Pulses would be of the order of milliseconds or less because of CS flux and heat limitation (very expensive diagnostics). The idea of such a small tokamak was abandoned.

A stellarator?

Estimates for UST_1 and study of W7-X [2], CTH [3], and also LHD, TJ-II, and NSCX gave the first ideas for the design. A 1/10-scale CTH torsatron was the starting point. The estimates provided insight that at least a stellarator working at some few eV of plasma temperature could be obtained without major difficulties. A stellarator was chosen.

Superconducting or resistive coils?

The need for vigorous power supplies was already a concern. Therefore some research was done to check the feasibility of high temperature superconducting (HTS) coils. Bi2223 HTS was chosen and conceptual design and calculations were performed. However, the cost of the HTS wire alone would have been 6300 € — too much. I selected resistive coils.

Coils outside the vacuum vessel or inside?

More global drawbacks than global advantages were discovered for coils inside (e.g., QPS, CNT). I picked coils outside the vacuum vessel.

Classical stellarator, torsatron or modular stellarator?

A modular stellarator seemed favorable due to construction and power supply simplicity but no means to calculate and build the modular coils were available at that moment. Thus the starting point was the definition of the coils kindly supplied by the CTH team. A similar classical stellarator was also considered.

A JAVA code named SimPIMF was developed to calculate three-dimensional (3D) magnetic fields. Later, and partially because the use of NESCOIL was impossible, the code evolved, and it is now able to calculate/simulate by field line tracing: Poincaré plots (Fig. 2), rotational transform and magnetic well profile, plasma size, orbit simulation with drifts, particle losses, other 'plasma' parameters, minimum distance between coils, and optimization of such parameters by iterative generation of parametric 3D coils.

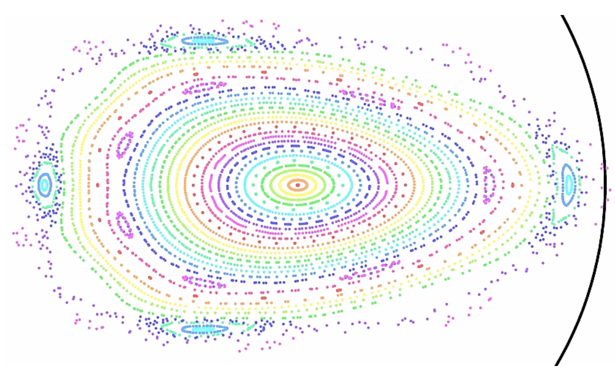

Fig. 2. Magnetic surfaces, magnetic islands and stochastic region in UST_1 for $\varphi = 0°$.

Simultaneously, more accurate estimates of the voltage, current, power, and heating rate of the coils, magnetic field B_0, and other key parameters for several sizes of stellarators and combinations of winding packs were carried out. Forces on the support frame were negligible for B_0 = 0.1 T. Pulses about 1 s long were achievable without excessive coil temperature rise (<35ºC). A test of a power supply consisting of a commercial 12V battery was carried out, obtaining pulsed current of 1200 A. Also τ_E and T_e were calculated (ISS04v1 [1]) for diverse combinations of inputs (ECRH power, enhancement factor and plasma size).

A basic vacuum system, composed of a mechanical pump, a diffusion pump, and a thermocouple gauge, was installed and tested. This basic system has been upgraded several times. Also, after some fruitless tries, a toroidal vacuum vessel was conceived and built using five commercial copper elbows.

As a result of the parallel development of all the different components of the stellarator, including the SimPIMF code, partially optimized classical coils were obtained in January 2006.

However, just then, and inspired by the code developed for classical stellarators and by the work of Dolan [4], a new idea for the optimization of modular coils was conceived. As a result, a modular stellarator was chosen and modular coils were defined and optimized during the next months. Tens of thousands of coil structures were evaluated by simulation until the UST_1 coils were selected.

How to build the modular coils?

Modular coils have the advantage of requiring, in the simplest way, only one layer of coils and only one set of coils connected in series. Therefore the system is much less sensitive to inaccuracies, specially of the power supply. Nevertheless, accurate (~0.1% optimum, ~0.3% maximum errors) fabrication and installation of modular coils is not an easy task. Some methods that had been used to build modular coils (HSX, W7-X, NCSX, CTH frame [3]) were studied.

Device to mechanize modular coils.

A device to mechanize modular coil construction for stellarators was conceived, and such a machine (Fig. 3) was constructed after some first tests and some improvements. It is a milling machine working on toroidal coordinates able to machine grooves on a toroidal surface that is kept fixed on the milling machine for the whole series of 12 coils. The result was successful and it is one of the main results of the project: the demonstration that low-cost techniques to build accurate stellarators exist.

The main advantages of this machine are:

1. Positioning and adjustment of the coils is not necessary because all the grooves are machined on a single toroidal surface. Only machining of the grooves is performed.
2. Fabrication errors are similar to those in CNC milling machines—very small. Errors <~0.3 mm with respect to the designed position of the coils have been achieved using a medium quality toroidal milling machine. This is critical in such a small machine where a given error in millimeters is a larger fraction of the size.
3. Construction time is reduced and the process simplified.

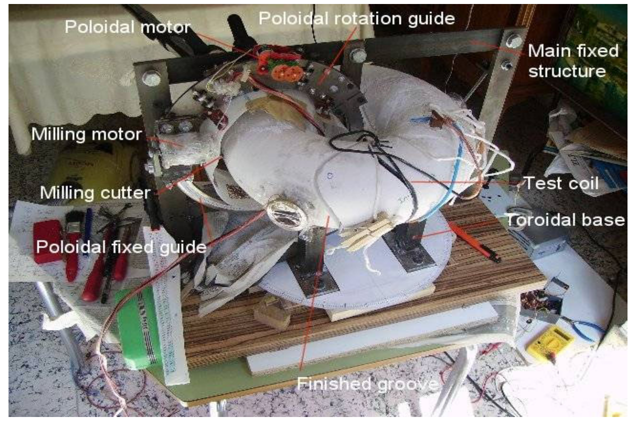

Fig. 3. Milling machine working on toroidal coordinates.

A special conductor slightly over 3.5 mm in diameter was finally selected and manufactured. The conductor is formed by copper threads compacted by a commercial shrinkable sleeve. The winding pack is a double pancake of 3 layers and 2 rows. The width of the grooves was thought to laterally compress the two pancakes on the sides of the groove in order to facilitate the winding of the coil (otherwise many stops and fasteners are necessary during the winding process), avoid unwinding and reduce positioning errors. A groove of 7 mm width and 12 mm depth was finally defined.

The 12 grooves in the plaster frame were satisfactorily finished in May 2006, Fig. 4. The machining of each groove took ~2 h. Adequate crossovers for the conductors were chosen and the conductor was compressed against the bottom of the groove for an accurate positioning. The low number of turns implies increased field errors due to positioning errors of only one turn. The final assembly is shown in Fig. 5.

Fig. 4. Grooves for the coils in a plaster toroidal surface.

Fig. 5. Top view of UST_1. 12 modular coils located in machined grooves.

Validation and operation of UST_1

Field line mapping

The traditional fluorescent movable rod method was considered [5, 6] and implemented. A very simple mechanism was used, composed of fluorescent ZnO deposited on a copper wire of 1.5 mm diameter and ~120mm length that is balanced as shown in Fig. 6. A short external magnetic pulse is applied to a tiny ferromagnetic piece fixed on one end of the wire so it oscillates at a frequency compatible with the frame rate of the digital camera (30 fps) and the length of the pulse (~2 s at $B_0 = 46$ mT). Two e-guns were built following the method used in CNT [7] and a commercial FireWire camera was installed.

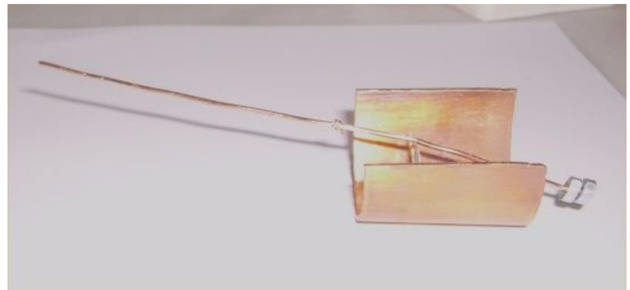

Fig. 6. The oscillating wire used for the flux surface measurements, showing the pivot and the ferromagnetic piece (right). The wire is not yet coated in this photo.

Figure 7 shows the experimental setup and Fig. 8 a sample experimental image, obtained from pulses 198 and 202. The image is a superposition of frames at 30 fps.

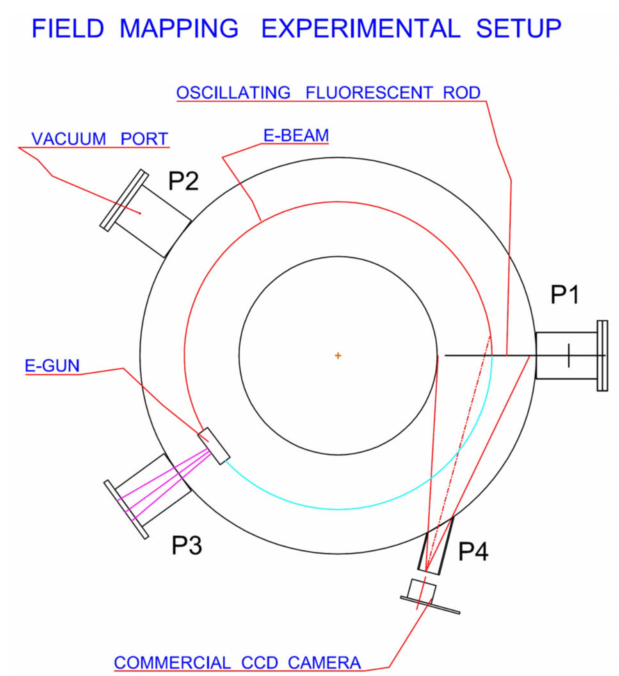

Fig. 7. Field mapping experimental setup.

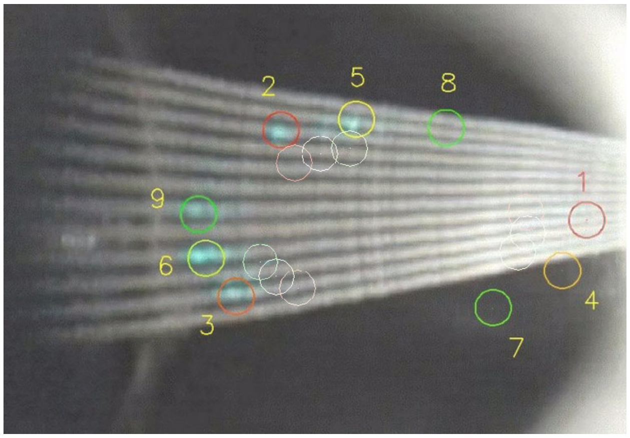

Fig. 8. Comparison of experimental field mapping results (cyan points) and simulated points (circles). Note: Some experimental points faded due to the superposition process, but they are visible in the original frames.

The experimental conditions during pulses 198 and 202 were B_0 = 34 mT, e-beam 84 and 95 eV respectively, vacuum 3 $\times 10^{-3}$ Pa, plasma flat top = 2.5 s, date 24 August 2006. During pulse 204 the e-gun filament failed and field mapping was concluded.

The recording of such low-quality images was really difficult. Some of the difficulties were:

- Collision of the beam with the rear part of the e-gun after the third turn of the beam due to ɫ ~ 1/3. A very small diameter e-gun and accurate strategic positioning of the e-gun were required to solve the rear collision.
- The size of the e-gun (only 8 mm external diam), makes it a tiny fragile device.
- Inadequate vacuum level resulting in an electron mean free path corresponding to 10–100 beam turns.
- Low sensitivity of the digital commercial camera, which meant that maximum energy of electrons is favorable for higher brightness but large drifts appear because of the small size of UST_ 1 and low B_0, see Fig. 9.

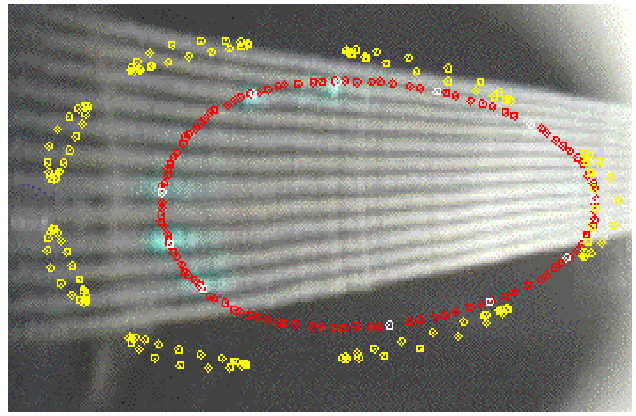

Fig. 9. Magnetic surfaces for: (a) electrons at ~90 eV (red points, large drifts) and, (b) electrons at ~0 eV (yellow, no drifts). The simulated electrons are emitted from the same point in both cases.

Main conclusions from field mapping

A notable degree of accuracy has been achieved in the design and construction of the stellarator and in the simulation code, because magnetic surfaces agree with the designed surfaces.

Adequate accuracy was obtained because the whole process from the conception to the manufacturing and assembling (type of stellarator, type of conductor, method to build modular coils, etc) has been successful and suitable to the technical and budget constrains.

Heating system and plasma pulses

The objective was to measure T_e and n_e for certain power absorbed in the plasma to roughly compare with calculations from scaling laws.

A simple heating system based on a commercial microwave magnetron at 2.45 GHz was installed. The microwave power is transmitted into the vacuum vessel (VV) by a coaxial cable and an antenna because the small size of the VV port hinders the use of a waveguide for 2.45 GHz.

The system is composed of a waveguide to coaxial adapter located inside the microwave oven (for extra safety), a dual directional coupler, two biased Schottky diode detectors to measure the forward and reflected power, a double stub microwave tuner to tune impedances, a ¼ lambda stub antenna, two microwave leak detectors, and RF cables and connectors.

The data acquisition system receives signals from: one inverted magnetron for vacuum measurement, current (voltage) in the modular coils, two signals from the ECRH Schottky diode detectors, and two signals from the Langmuir probe.

Pulses from 248–260 produced acceptable plasmas. In particular, the chronogram for pulse 251 is shown in Fig. 10. The conditions during this pulse were B_0 = 4 6mT, plasma flat top = 2 s, pressure before the pulse = 2 mPa.

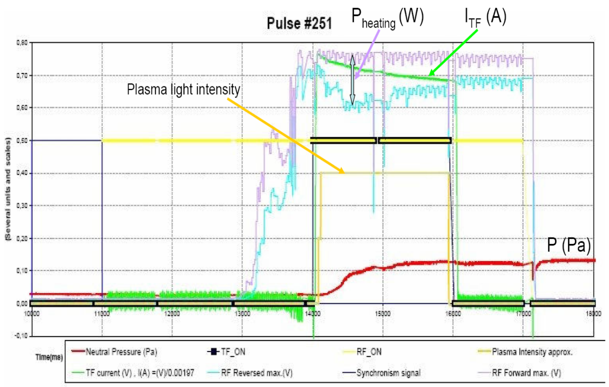

Fig. 10. Chronogram for pulse 251.

The pressure (red line) increases immediately after the plasma starts, probably as a result of desorption of gases from the walls. The difference between the RF forward and reflected power is small, indicating poor coupling, although the absorbed power is higher during the pulse. The plasma is generated only when the TF current is ON even if the RF power is kept on longer. It suggests that, at least partially, heating is produced by resonance at the second harmonic.

Pulses from #261 to #265 additionally recorded the signal from a Langmuir probe located at ~0.5*a* from the magnetic axis. The experiments stopped at the end of June 2007 and improvement of the Langmuir experiments was not carried out. Only relatively inaccurate data were obtained.

Summary and comments

The construction of a modular stellarator was decided on as a good candidate for a low-cost fusion device. Other alternatives were abandoned due to excessive cost or technical difficulties. An innovative construction method was devised, a milling machine working on toroidal coordinates able to create a groove in only one poloidal turn and able to create all the grooves in a single plaster frame. It notably increases accuracy and avoids the need for 3D adjustment of the coils.

The low cost is achieved by the use of inexpensive materials and the particular construction of the coils. A few turns of conductor are compressed inside the accurate grooves, therefore simplifying the winding process.

The validation of the correctness and precision of the design has been achieved up to a certain degree. Field mapping experiments have been carried out. Even if the quality of the experiments is poor, mainly due to economic limitations, agreement between the simulations and the experimental results indicates that a notable degree of accuracy in the magnetic field has been achieved.

The comparison of the experimental data with the theoretical energy confinement time has only been started, but the preliminary results are promising. Nevertheless the scaling laws might be inapplicable to such a small stellarator, and besides the absorbed ECRH power is unknown.

Despite the innumerable difficulties that appeared during the project a very low cost stellarator fusion device of acceptable quality has still been possible.

The experiments stopped in June 2007 due to a change in the labor conditions of the author. My interest now has somewhat shifted to the development of innovative designs to lower the construction and downtime cost in fusion reactors. Small-scale devices of industrial reactor-like structure would probably be useful to improve the conceptual designs and maintenance procedures for future reactors.

Presently a small stellarator is being developed in the Instituto Tecnológico de Costa Rica in order to learn and experiment with magnetically confined plasmas and, particularly in fusion technologies, simulation and plasma physics. The general idea of the stellarator is similar to the UST_1 but it is aimed an improvement in the plasma volume, heating, and number of diagnostics [8].

Further details about the conception, design, constructive methods, manufacturing, JAVA code, field mapping, plasma pulses, photos, and videos are available at http://www.fusionvic.org

Acknowledgement

The author thanks the companies, friends, and researchers who altruistically contributed to the UST_1 development, and the friends and relatives who patiently endured my concentration on UST_1.

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Retirement ceremony and Stern-Gerlach medal for Friedrich Wagner

More than 180 invited guests celebrated the retirement of Prof. Friedrich ("Fritz") Wagner (Fig. 1) at the Greifswald branch of the Max-Planck Institut für Plasmaphysik on Thursday, Nov. 27. After early works at the Tokamak Pulsator in Garching, Friedrich Wagner discovered the H-mode on the ASDEX tokamak; his corresponding paper "Regime of Improved Confinement and High Beta in Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak" [1], remains the most cited plasma physics paper ever. In 1986 he became the head of the ASDEX project and was appointed Scientific Member and Director of the Max-Planck Institute für Plasmaphysik. In 1993, soon after he moved to the stellarator field and became responsible for Wendelstein 7-AS, he showed that the H-mode regime could also be achieved for the first time in a non-tokamak device, thereby demonstrating the universality of this toroidal confinement regime. After moving to the new Institute branch in Greifswald, Wagner was the head of the Wendelstein 7-X (W7 -X) project from 2003 to 2005. In his role as the speaker of this second IPP branch (1999–2007) he managed the embedding of the new fusion research site into the frame of the old Hanseatic and university town, Greifswald. Since 1999, Wagner has been lecturing as a Professor of the Ernst Moritz Arndt University. In 2007 he became the President of the European Physical Society (EPS). As recently announced, Prof. Friedrich Wagner will receive the Stern-Gerlach medal, which is the highest award of the Deutsche Physikalische Gesellschaft (DPG) given for extraordinary contributions in experimental physics.

Fig. 1. Friedrich Wagner giving a sketch of the main development lines in 33 years of fusion research. (Photo: F. Noke)

The celebration colloquium was chaired by the scientific director of IPP, Prof. G. Hasinger. The first scientific talk was delivered by Prof. K. Itoh, "Quarter Century of H-mode—A view of theorists," and complemented Wagner's Hannes Alfvén lecture at the EPS conference 2007 "25 years H-mode research—an experimentalist's view" [2]. Referring to the fact that the total cost of a fusion reactor scales with the H-factor as $\sim H^{-1.3}$, which for $H \sim 2$ yields a cost reduction of about 60%, Itoh finally concluded that "he brought the sun closer to earth." In a more personal review, Prof. Th. Klinger, now scientific head of the W7-X project, spoke on building science by indicating parallels with the history of German enlightenment and the creativity in building devices as well as theories, publications and paintings—such as Friedrich Wagner did. Prof. Pinkau, for a long period the scientific director of IPP, reminded the audience that a long-term commitment and measure of anticipation have been, and still are, the basis for successful fusion research. Finally, regards were also given by the Faculty of Physics connected with thanks for the mutual support of the plasma physics institutes in Greifswald.

Such an event is also a good occasion for presents: As Fritz is known to relax by playing cards with others, the Wendelstein team gave him a collection of self-made games—such as a memory game with pictures of all his co-workers, said to be for keeping his brain sharp. Furthermore, a mock-up of the plasma experiment WEGA and an artist's impression of W7-X were presented to Friedrich Wagner. Finally Friedrich Wagner himself gave an overview of the structures, teams, and people that over the years have developed all around him (many of them attending the ceremony) and gave thanks to all those who supported and contributed to his efforts.

Fig. 2. A good view of Wagner's paintings, many of them showing structures in nature. The two celebrants are Maurizio Gsparotto and Lars Sonnerup. (Photo: B. Kemnitz)

Fig. 3. The vernissage of "meer and mehr" at the main gallery of IPP, which is regularly used for exhibitions. (Photo: F. Noke)

After a reception the celebration continued with the opening of the exhibition "meer und mehr" ("The sea and beyond it") giving an overview of Fritz Wagner's paintings from the last few years (Figs. 2–4). On his initiative the bright central axis of the Greifswald IPP building has been regularly used for exhibitions that bring together inspiring arts and everyday research. For most of the guests and co-workers the ceremony continued next day when Fritz Wager spoke in the IPP colloquium on the main lines that developed—and still guide—"33 years in fusion research."

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Fig. 4. "Kurzer Moment der Reflexion / Short moment of reflection" oil painting by F. Wagner.This picture was used on the poster for the exhibition.