2015

核工业西南物理研究院年报

Southwestern Institute of Physics Annual Report

核工业西南物理研究院　编

中国原子能出版社

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序 言

2015 年，是我院“十二五”规划的收官之年。一年来，我院紧紧围绕聚变研究、高等教育、等离子体技术应用三个板块协调发展的思路，按照全院总体工作部署和要求，抓主业、重创新、保增长，圆满完成中国核工业集团公司下达的年度任务。在这一年中，中国环流器二号 A（HL-2A）装置物理实验取得多项新的科研成果；HL-2A 装置改造与升级建设全面推进；ITER 计划及国内配套项目均实现年度预期目标。我院综合实力进一步增强，顺利实现了我院“十二五”规划目标。

1. HL-2A 物理实验进展

HL-2A 装置上新建了具有新型天线的 2MW/3.7GHz 低杂波系统，2MW/105GHz/3s 电子回旋加热系统和多发激光吹气系统，并投入物理实验研究。多项新的诊断，如多道激光干涉 / 极化仪、多道复合光谱、电子回旋辐射成像（ECEI）和微波反射系统等有大的改进和升级，在实验中发挥了重要作用。物理实验取得了多项新的科研成果。在 H 模条件下，首次利用新型天线进行电流驱动，总反射率小于 10%；用强中性束加热实现具有内部输运垒的等离子体放电；在 H 模物理研究方面，对径向电场的产生机制、杂质在 L-H 转换中的作用及台基动力学过程又有新的发现；首次观测到低环向模数阿尔芬离子梯度模、非共振电子鱼骨模及双电子鱼骨模的存在。另外，在 ELM 缓解和控制，NTM 的控制及等离子体破裂控制和缓解方面也做出了很好的结果，这些研究和 ITER 的运行有很大的关系，受到了国际聚变界的广泛关注。我院自主设计并成功研制了大功率射频工程（RF）离子源。

2. HL-2M 建设进展

2015 年已经完成 HL-2M 主机线圈加工中的五个重点工艺评审和环向场（TF）线圈绝大部分工艺试验；主机真空室 20 个扇形段已经基本完成，进入真空室整体加工阶段；主机支撑结构主材下料及焊接工作正在进行；完成 4 号脉冲发电机组总装及电动机、辅助系统安装工作，具备试车运行基本条件；全面完成 TF、中心螺线管线圈（CS）电源设备加工、出厂试验，固化极向场（PF）电源设计方案，签订了 PF 整流变压器合同；进一步细化 HL-2M 主机安装方案，完成相关关键工艺技术储备，确定第一版安装技术文件；顺利完成主机厅、电机厅、水泵房扩建工程竣工验收并交付使用。

3. ITER 计划及相关任务

ITER 采购包任务：ITER 第一壁制作取得关键性技术突破。成功解决了 Be/Cu 连接质量不稳定的关键工艺问题，初步完成第一壁生产线建设，具备自主生产制造第一壁板的能力。磁体支撑（MS）采购包认证阶段任务顺利通过 ITER 执行中心合同验收；完成气体注入系统（GIS）采购包气体分配系统最终设计评审，对汇集管道管件关键部件进行加工制造研究，完成相关系统结构设计；继续开展中子诊断（NFM）7 号窗口采购包最终设计，开展其余窗口采购包初步设计；开展屏蔽包层模块（SB）采购包设计优化、热氦检漏设备研制和插件涂层工艺研发等工作。ITER 氦冷固态实验包层模块（TBM）进入初步设计阶段。完成国内首个用于聚变研究的高温高压小型氦气回路建设。新承接辉光放电系统（GDC）采购包和朗缪尔探针系统（LP）采购包设计阶段任务，开展主要方案和技术难点的研究攻关。

ITER 国内配套项目方面：完成中性束项目研究任务，完成 5MW 中性束系统部件加工；完成 ITER 计划专项电子回旋共振加热项目研究任务，新建 2MW/105GHz/3s 电子回旋加热系统；2015 年 ITER 计划国内专项 3 个项目（12 个课题）及院外合作项目（3

个课题）顺利启动。

同时，成功搭建国内运行压力最高的氦气回路实验平台，用于开展氦气冷却运行与控制技术研究，这些设备将为今后的聚变研究提供重要的支持。

4. 应用技术研发及其他

等离子体应用技术方面：加强技术创新与研发，推动技术成果转化。改进完善“用于生产两层型挠性覆铜板的离子镀膜设备”定型线，成功解决聚酰亚胺膜（PI）粘膜及起皱等技术问题。批量生产出合格的两层型挠性覆铜板产品并通过验收，达到了设计技术指标；完成高洁净度离子束表面处理设备的研制，用于不同尺寸的激光元器件（光学元件）损伤修复，以及离子束抛光及刻蚀处理，已交由用户开展大量工艺实验，即将开展正式产品（激光元器件）损伤修复的表面处理。针对产品耐磨损及耐腐蚀性要求，在异形件表面成功制备高均匀性类金刚石（DLC）涂层，并进行了小批量化处理，该工艺技术已获得设备订单；根据电子材料市场发展趋势，研制开发了电子材料氧化铝陶瓷覆铜板金属化工艺和环氧板（FR-4）金属化工艺：氧化铝陶瓷覆铜板金属化工艺将替代现有的热压粘接方法，其性能指标将大大提高；开展环氧板（FR-4）金属化处理再电镀铜增厚，单层实验样品达到了用户的使用性能指标，正在进行多层环氧板（FR-4）覆铜板工艺开发研究；不断优化处理工艺，完成碳纤维复合材料微波喇叭导电涂层沉积批量处理工艺开发，并完成卫星天线地面测试件的产品加工。注重产品质量，对隔热膜镀膜设备缺陷和镀膜工艺进行大量工艺改进，产品性能得到提高，满足客户需求。

成都理工大学工程技术学院进一步深化教育教学改革，探索人才培养新模式。坚持发展以工学为主体，以培养高素质应用型人才为支撑，全力升级打造工程类、核工程与核技术类和经管类三个省级教学实践示范中心，成功申报 6 个专业，学科专业增至 89 个。荣获“2015 中国创新人才培育示范院校”等荣誉。

2015 年，全院在国内外主要刊物发表学术论文 77 篇，学术会议交流报告 107 篇。申请专利 78 件（其中发明专利 42 件），国家专利局授权专利 43 件（其中发明专利 7 件）。由我院承担的国际热核聚变实验堆（ITER）磁体支撑采购包“极低温环境材料及部件力学性能测试系统研制”项目荣获中核集团公司科学技术奖一等奖，同时还获得中核集团公司科学技术奖三等奖 3 项。

《核工业西南物理研究院年报》是回顾、宣传和反映我院当年科研、技术开发和应用等各方面进展的重要平台，也是科研院所学术成果的重要组成部分。本期年报继续以内容精炼、主题突出为特点，重点反映全院在聚变科研及产品开发等领域的亮点，以帮助读者方便、快捷地了解我院年度科研、技术开发和应用等方面的主要进展。期待全院各部门以及广大读者继续支持和关注院年报，并提出积极建议和宝贵意见。

核工业西南物理研究院

院长 刘永

Preface

2015 is the ending year of "the twelfth five-year plan" at the Southwestern Institute of Physics (SWIP). In 2015, according to the SWIP overall working plans and major objectives to carry on the harmonious development on the fusion research, higher education, and plasma technology application, SWIP has focused on the main research tasks, guaranteed the profit increase, and put emphasis in innovation, thus accomplished favorably the yearly tasks assigned by the China National Nuclear Corporation (CNNC).

In the year of 2015, many scientific results were obtained for the first time on the HL-2A; modification of HL-2A also progressed well in various perspectives; and the anticipated goals were realized in the ITER project as well as ITER-related tasks in China. The comprehensive strength of SWIP has been enhanced, and the objective of the "the twelfth five-year plan" at SWIP has been fulfilled.

1. Progress in the HL-2A physical experiments

On the HL-2A, a 2MW/3.7GHz Lower Hybrid Current Drive (LHCD) system with the new type PAM antenna, a 2MW/105GHz/3s Electron Cyclotron Resonance Heating (ECRH) system and a multi-channel laser blow-off system have been developed and put into use in the physical experiments. A number of new diagnostics, including the multi-channel laser interferometer/polarizer, multi-channel charge exchange recombination spectroscopy, Electron Cyclotron Emission Imaging (ECEI) and Microwave Reflectometers, have been successfully upgraded and played important roles in the experimental studies.

Many research results have been achieved for the first time in the experiments. The current drive was done with the PAM antenna for the first time during the H-mode and the reflectivity was below 10%; The internal transport barrier was realized during plasma discharges with high power neutral beam heating; In the study of H-mode physics, new findings have been obtained on the generation mechanisms of the radial electric field, the role of the impurities during L-H transition, and the dynamical process of the pedestal. In addition, the low-n Alfvénic ion-temperature-gradient mode, the non-resonant e-fishbone and the double e-fishbone modes were all observed for the first time. Significant results were also achieved in the ELM mitigation and NTM control as well as the control and mitigation of the plasma disruption. These studies are highly relevant to the ITER operation, thus have drawn extensive attention in the international fusion community. Besides, SWIP has designed and developed the high-power RF ion source independently. The helium circuit experimental platform with the highest operation pressure in China has been built up for the helium cooling operation and control technology research. This equipment will support the fusion research in the future.

2. Progress in the HL-2M construction

In year 2015, five key technical reviews for the machining of the HL-2M coils and most technical tests for the toroidal field (TF) coils have been finished. Twenty sectors of the vacuum vessel have been manufactured and the overall machining of the whole vessel has been started. The principal materials for the machine supporting structure were being prepared and the welding was being done at the same time. The final assembly of the 4# Generator Motors was completed, and the electromotor and auxiliary systems were also installed. The preparation work for the commissioning was basically fulfilled. The machining and the delivery tests for power supplies for the TF coils and the central solenoid (CS) were completed. The design scheme for the poloidal field (PF) power supply was fixed, and the contract for the PF rectifier transformer was signed. The installation scheme for the HL-2M machine was further refined, the related key technologies have been

prepared, and the first edition of the installation documents was finished. The final acceptance check for the extension project for the HL-2M machine hall, Generator Motors hall, water pump room was completed and related files were recorded in the local government. These halls have been put into use.

3. ITER related tasks

Breakthroughs have been made in the manufacture of the ITER first wall. The technical problem with regard to the unstable Be/Cu connection has been solved. The production line for the first wall has been basically built up, which shows that SWIP is capable of manufacturing the first wall panels independently. The certification of the magnet support (MS) procurement package passed the contract acceptance check by the Chinese ITER DA. The final review for the procurement package of the gas injection system (GIS) and the gas distribution system was completed. The research on the machining of the key components of the converge tube assembly has been carried out and related system structural design has been executed.

The final design for the Neutron Flux Monitor (NFM equatorial window #7) procurement task has been in good progress and the preliminary design for the procurement packages of other windows has been started. The design optimization for the Shield Blanket (SB) module procurement package, development of the thermal helium leak test equipment, and development of the plug-in coating technologies have all been commenced. The ITER Helium Cooled Solid Breeder Test Blanket Module (HCSB-TBM) has been preliminarily designed. The first small-size helium circuit with high temperature and high pressure for the fusion research in China has been built up. New short-term design tasks were assigned in the Glow Discharge Cleaning (GDC) procurement package and Langmuir Probe (LP) system procurement package, which are carried out to solve problems on the main schemes and technical difficulties.

For the ITER related projects in China, researches on the neutral beams were completed, and the 5MW neutral beam system components have been machined. The researches for the ITER special project -- ECRH project were completed, and the 2MW/105GHz/3s ECRH has been built up; Three of the 2015 ITER related special projects in China (including 12 research topics) and 3 research projects with other institutes have been inaugurated.

4. Application technology R&D and other fields

Technological innovation and R&D have been improved to promote the technological achievement transformation in the plasma technology application. The finalized production line for the two-layer FCCL type ion plating equipment has been improved so that the polyimide film adherence and wrinkling problems have been solved. This is the novel technique in China and abroad as well. The two-layer FCCL type products have been manufactured by batch. All of the products have passed the acceptance check and met the design technical specifications. The surface treatment equipment with high cleanness ion beams was developed to repair the damage of the laser parts (optic parts) with different sizes and do the ion beam polishing as well as etching treatment. Related technological tests have been handed to users. Surface treatments for the damage repair of formal products (optic laser parts) were about to be carried out.

Based on the need to resist wear, tear, and corrosion of the high-end home decoration production, a new technology has been developed to prepare the DLC coating on the special shaped products, and this coating has been produced in small batch. This technology has already won orders. According to the trend in the electronic materials

market, the metallization technologies for the alumina ceramics copper clad laminate and the epoxy laminate (FR-4) were developed: the alumina ceramics copper clad laminate metallization will replace the present hot pressing bonding method, therefore, the performance and quality will be greatly improved. The epoxy laminate (FR-4) has been metallized and electro-coppering thickened, and the one-layer sample has met the usability indicators. The multi-layer epoxy laminate (FR-4) technology was being developed. Besides, the treatment technologies have been constantly optimized. The batch treatment technology to the carbon fiber composite microwave horn conductive coating deposition has been developed, and the ground test piece of the satellite antenna has been machined. According to the technical requirement of the new type military electronic products, emphasis has been put in the development of batch treatment technology for insulating coating of military electronic components, and the technology has been fixed. The product quality has been stressed so that the defects of the window film plating equipment have been remedied and the plating technology has been greatly improved. Therefore, the product performance has been improved to meet the user' s need.

The Engineering and Technical College of Chengdu University of Technology has further promoted the education and teaching reform to explore new modes for talent cultivation. Based on the concept of putting the engineering disciplines first, with the objective of cultivating high-quality application orientation talents, the College has focused on the building of three provincial teaching practice demonstration centers on engineering, nuclear engineering and technologies and economic managements, respectively. Six new disciplines have been approved, so the total disciplines have been increased up to 89. It won the honor of "Demonstration College for Creative Talents Cultivation of China in 2015".

In year 2015, 77 papers were published in domestic and international journals and 107 papers and posters were presented in scientific conferences. 78 patents were applied (including 42 invention patents), and 43 patents have been approved (including 7 invention patents). The project of "Development of Mechanical Property Test System for the Low Temperature Environment Materials and Components" for the ITER magnet support procurement package undertaken by SWIP won the first prize of Science and Technology of CNNC. Three other projects won the third prize of Science and Technology of CNNC.

The Annual Report summarizes the important progression in the scientific research and technology developments and applications in SWIP. Thus, it is deemed as an indispensable part of the academic achievements of SWIP. The 2015 Annual Report has kept to be concise but topic prominent, featuring the highlights in fusion research and plasma technology application, to facilitate the quick understanding of our progress in various fields for the readers. We hope that all staffs and readers pay special attention to the Annual Report and feel free to let us know your suggestions or comments.

Director of Southwestern Institute of Physics

Liu Yong

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Nuclear Fusion

HL-2A 最新实验进展综述

许敏，段旭如，董家齐，丁玄同，严龙文，刘仪，HL-2A 课题组

最近几年，HL-2A 托卡马克的大量实验时间用于研究与 ITER 实验相关的关键物理问题，其中包括实现高约束模，边缘局域模（ELM）缓解和破裂缓解。HL-2A 的实验研究主要集中在 L-I-H 模转换和台基物理、MHD 物理、高能粒子物理、非局域输运和 ELM 缓解等。特别在以下几个方面取得了明显进展：在 L-I-H 模转换过程中发现了一种新型的（J 型）极限环振荡（LCO）；一个扭曲类 MHD 模坍塌在触发 I-H 模转换中的关键作用；杂质堆积对无 ELM-H 模和 H-I 模转换的影响；准相干模对台基稳定的影响；阿尔芬模和撕裂模耦合所激发的 $n=0$ 的模；发现了上下扫频反剪切阿尔芬本征模；低频 MHD 模之间的转换；MHD 不稳定性所引起的高能粒子损失；新经典撕裂模和非局域热输运间的相互作用；SMBI 缓解 ELM 期间离子温度和环向旋转的演化规律。本文综述了上述主要实验结果，更详细的实验结果已在其他文章中发表。

1 L-I-H 模转换和台基物理

1.1 L-I-H 模转换过程中的两类 LCO

在 L-I-H 模转换的实验上，首次发现了归一化径向电场和密度扰动包络之间的相位关系改变符号的现象。密度和电场均由进入最外闭合磁面以内约 1 cm 的静电探针测得。在中间模（I-phase）的初始阶段，密度扰动包络导致径向电场扰动（顺时针方向），同时 LCO 对湍流的调制作用很强（图 1）。

1.2 MHD 模在 I-H 模转换过程中的作用

在 I-H 模转换前发现了一个频率约为 $f\approx13.6$ kHz 的 MHD 模。这个模的崩塌与 I-H 模转换密切相关。这个 MHD 模在 I-phase 阶段增长得非常快。它的崩塌导致芯部电子温度和密度的减少，以及边缘区电子温度和密度的增加。这清楚地表明这个 MHD 模的崩塌使得等离子体的粒子和能量从芯部释放到边缘区，从而导致了边缘等离子体的密度和温度的增加。这种快速释放的粒子和能量显著增加了边缘区的压强梯度，增加了平衡流，大概是通过剪切降低湍流相关性，并触发了 I-H 模转换。

1.3 杂质在激发 L-H 模转换中的作用

在 HL-2A 托卡马克上，已经发现了 I-phase 期间的多次转换以及无 ELM 的高约束模。在 I-phase 期间，LCO 的振荡频率在 0~7 kHz 之间，它引起了大量的粒子损失并进入刮削层。这减少了杂质堆积并限制了台基区的密度梯度。多普勒反射数据的进一步分析表明，在 LCO 期间的径向电场的扰动导致密度包络扰动。在无 ELM 期间，台基具有高的电子密度梯度，同时杂质密度也在逐渐增加。最

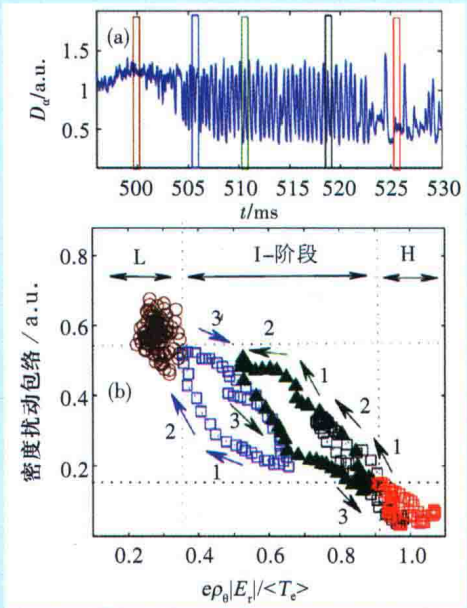

图 1 （a）D_α辐射谱；（b）归一化径向电场和密度扰动包络之间的相位关系

Fig. 1. (a) Evolution of D_α emission; (b) Lissajous diagram between normalized radial electric field and the envelope of density fluctuations in the phase space.

终，H 模由于杂质堆积引起的辐射效应而终止。

1.4 台基不稳定性

HL-2A 托卡马克上已经研究了边缘等离子体不稳定性特征和它们对台基演变的影响的特性。在陡峭的台基区，发现了频率范围约为 50～100 kHz 的密度扰动准相干模。该模在 L-H 转换后约 5 ms后出现。它们直到第一个 ELM 出现后才消失。该模的激发需要达到台基密度梯度阈。进一步的分析表明，这种模与台基梯度饱和度相关，同时在 ELM 期间也观察到这种模。

2 MHD 和高能粒子物理

2.1 MHD 模之间的非线性相互作用

首次发现了阿尔芬本征模（AE）和撕裂模（TM）非线性共振所激发的两种 $n=0$ 的模。磁场扰动的自功率谱表明，$n=0$ 的模都伴随着很强的 TM 和 AE 模（图2）。研究发现，能够激发 $n=0$ 的那些模是环向波数为 $n=1$ 的 TM 模和 $n=1$ 或 -1 的 AE 模。它们的频率满足共振条件；即 $f_{n=0}=f_{AE2}-f_{TM}$ 和 $f_{n=0}=f_{AE1}+f_{TM}$。AE 和 TM 之间的相互作用也满足共振条件则要求其波数垂直于阿尔芬速度 V_A。这是因为在低 β 情况下，V_A 是沿着磁场线的。

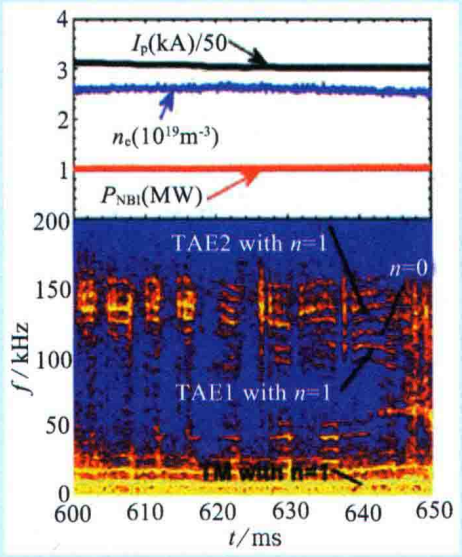

图 2 HL-2A 上 TAEs 模（HF，$n=\pm1$）和 TMs（LF，$n=1$）自功率谱

Fig. 2. Typical discharge with axi-symmetric magnetic activities in HL-2A with TAEs (HF, $n=\pm1$) and TMs (LF, $n=1$).

2.2 低频 MHD 模之间的转换

在 NBI 放电期间，观测到低频 MHD 模之间的转换和相互作用。研究发现，①长寿模（LLM）和鱼骨模之间的转换；②鱼骨模可以激发 TM；③LLM 和 TM 之间的非线性耦合。这一观测表明，鱼骨模 LLM 和 TM 之间存在相互作用。鱼骨模不仅可以导致高能粒子的损失和分布改变，甚至可以引发其他低频 MHD 模，如 LLM 或 TMs /新经典撕裂模（NTMs）。在高功率 NBI 加热过程中，不仅发现了从鱼骨模转换到 LLM 模，而且发现了从 LLM 模到鱼骨模的转换。

2.3 MHD 不稳定性所引起的高能粒子损失

HL-2A 实验发现高能粒子损失与 MHD 不稳定性相关。在 MHD 不稳定性出现之前，高能粒子损失图像发现一个光点，这与单一能量和偏转角的高能粒子损失相一致。与由 LLM 所引起的发光点相比，锯齿坍塌所引起的发光点具有一个更宽的能量和偏转角范围。