2nd Helmholtz-CAS Workshop
5th Jun, 2023

中國科學院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

面向二氧化碳的光子科学建制化研究平台

CO_2-oriented Institutional Research Platform of Photon Science

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中国科学院上海高等研究院（SARI）科研单元布局

Research departments at Shanghai Advanced Research Institute (SARI)

低碳转化科学与工程中心
Low carbon science and engineering

先进能源系统与装备研究与发展中心
Advanced energy system and equipment

绿色化学工程技术研究与发展中心
Green chemistry and chemical engineering

上海同步辐射光源
Shanghai Synchrotron Radiation Facility (SSRF)

国家蛋白质科学研究设施（上海）
National center for protein science SH

基础交叉研究中心
Interdisciplinary fundamental researches

智能信息通信技术研究与发展中心
Information and communication

碳中和愿景下CCUS的定位和作用

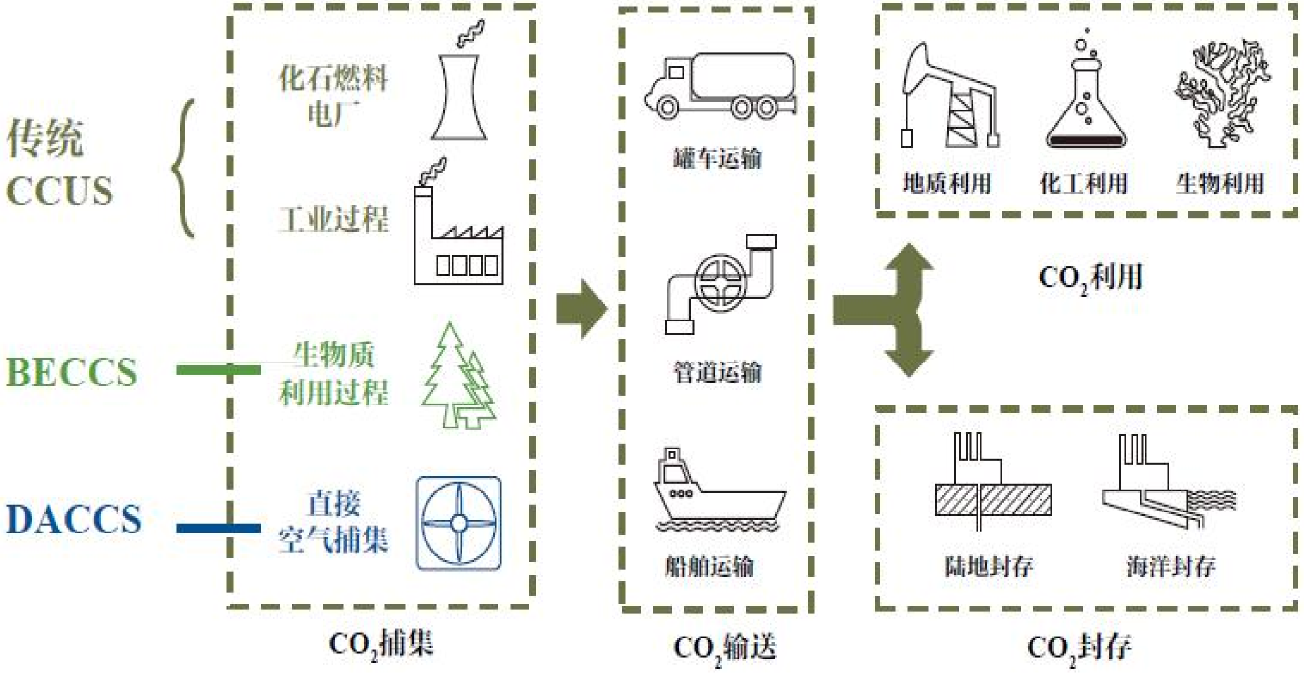
Orientation and role of CCUS in a carbon neutral vision

碳捕集利用与封存（CCUS）的概念和定位

Position and concept of Carbon Capture, Utilization and Storage (CCUS)

CCUS是指将CO_2从碳利用过程与大气中分离出来，直接加以利用或注入地层以实现CO_2减排的工业过程

CCUS: Separate CO_2 with the following utilization or injection into geological formations



来源：中国CCUS年度报告（2021） Source: Annual report of CCUS in China

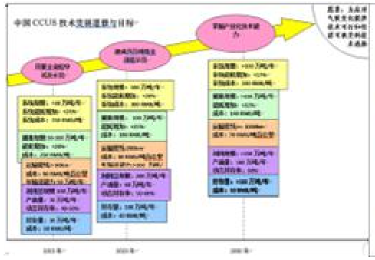
- 目前实现**大规模化石能源零排放利用**的唯一选择/**low-carbon use of fossil energy** on a large scale
- 保持**电力灵活性**的主要手段/Maintaining **electrical flexibility**
- 钢铁、有色、化工、水泥等**难减排行业**的必要方案/Solution for steel, non-ferrous, chemical, cement and other **process industries**
- **非化石能源“碳元素”**获取和循环利用的主要手段/Source of **non-fossil** carbon element
- 与新能源等耦合的**负排放技术**是实现碳中和目标的托底保障/**Negative emission technologies** coupled with new energy are the underpinning guarantee for achieving carbon neutrality

上海高研院在CCU领域已具备了显著的学术和行业影响力

SARI’s focus and influence in CCU

牵头制定国家战略

National CCUS Strategy



中国CCUS技术发展路线图（2011）

CCUS Roadmap China (2011)

中国CO_2利用技术评估报告（2013）

Tech. Evaluation on CCU in China (2013)

中国CCUS技术发展路线图（2019）

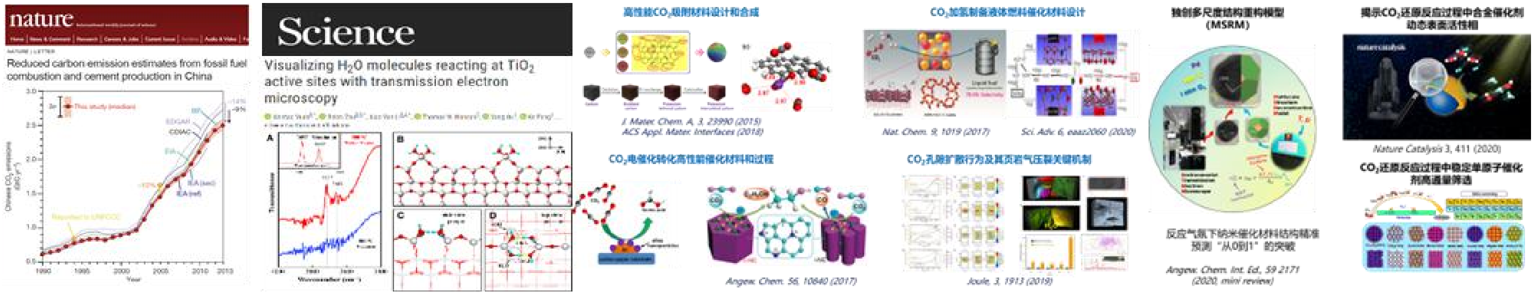
CCUS Roadmap China (2019)

中国CCUS技术评估报告（2021年）

Tech. Evaluation on CCUS in China (2021)

基础前沿系列突破

Fundamental Researches



知名期刊论文400余篇

Over 400 High Profile Papers

关键技术形成示范

Industrial Demonstration

二氧化碳吸附法捕集技术的千吨级中试

Adsorption-based CO_2 capture

全球首套万方级甲烷CO_2重整示范

CO_2 reforming of CH_4

全球最大规模（5000吨/年）CO_2加氢制甲醇工业试验

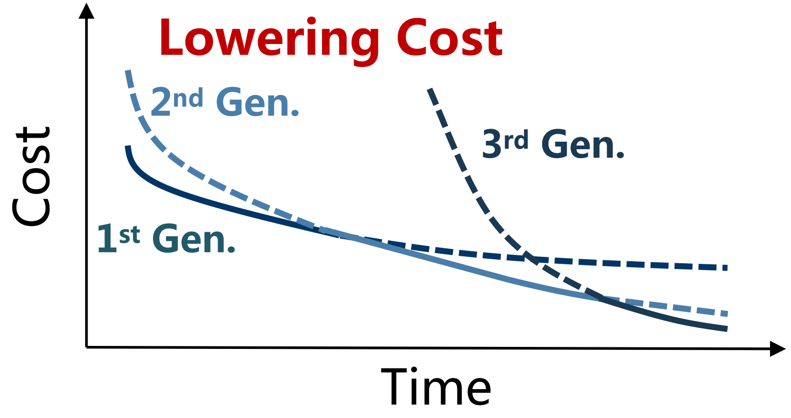
CO_2 hydrogenation to MeOH

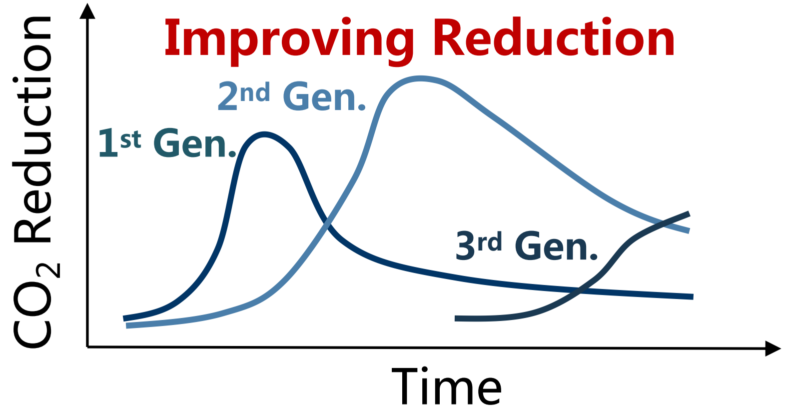
二氧化碳合成微藻工程化及土壤利用的大田试验

Microalgae-based CO_2 fixation

CCU发展趋势：降能耗、降成本

Future of CCU: Energy reduction, lowering cost





碳排放
Carbon Emission

碳捕集 CO_2 Capture

高性能捕集介质设计
(High performance capture agent)
吸脱附原位动态机制
(In-situ dynamic mechanism)
低能耗捕集过程强化
(Process intensification)

碳转化CO_2 Conversion

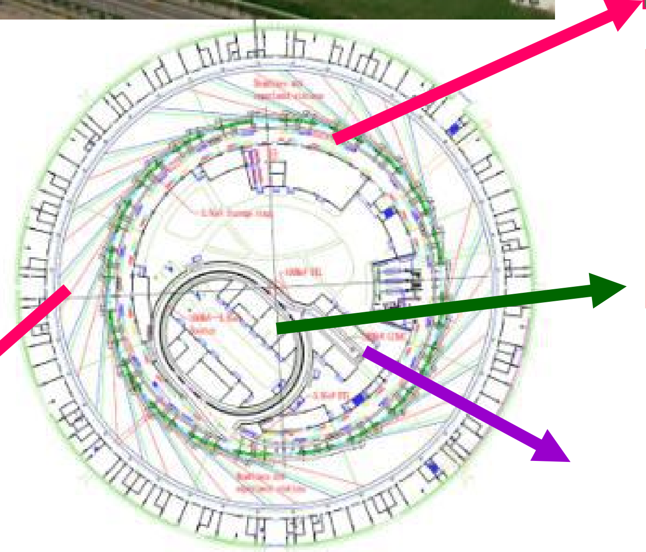
高活性高选择性催化剂
(High performing catalysts)
CO2高效定向活化机理
(Effective and selective activation)
多尺度碳利用过程机制
(Multi-scale mechanism)

上海光源：中能第三代同步辐射光源

SSRF: Medium Energy Third Generation Synchrotron Radiation Light Source

上海光源目前有**27线39站**服务用户, **10线20站**在建，总投资近**35亿**，是我国目前服务**用户最多、成果产出率最高**的大科学装置。SSRF provides **27 beamlines and 39 endstations** in operation, and there are **10 beamlines and 20 endstations** under construction, with a total investment of nearly **3.5 billion Yuan**. The **largest number of users and the highest output rate** in China.

27线39站运行



电子能量 Electron Energy： 3.5 GeV
周长 Perimeter： 432 m
流强 Beam Current:260 0.5mA (Top up)
自然发射度Natural Emittance： 3.9 nm-rad

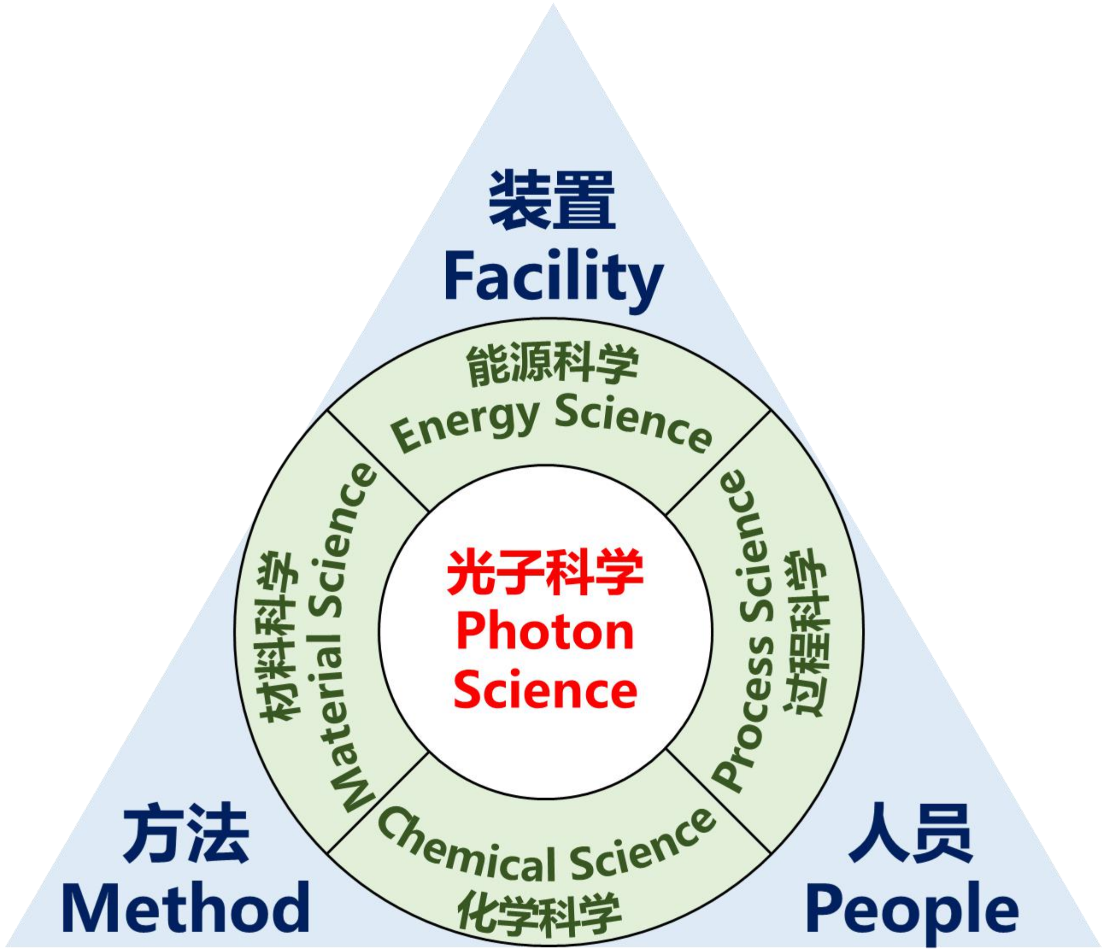
693 User Unit	3795 Groups	18602 Proposals Executed	494449 hrs Beamtime Allocated
37587 User Number	77234 User Visits	~100 International Users	156 CNS Top Journals

面向二氧化碳的光子科学建制化研究平台

CO_2-oriented Institutional Research Platform of Photon Science

CCU领域基础科学问题

Scientific fundamentals on CCU



建制化团队 Institutional Team

上海高等研究院(SARI)

大连化学物理研究所(DICP)

上海应用物理研究所(SINAP)

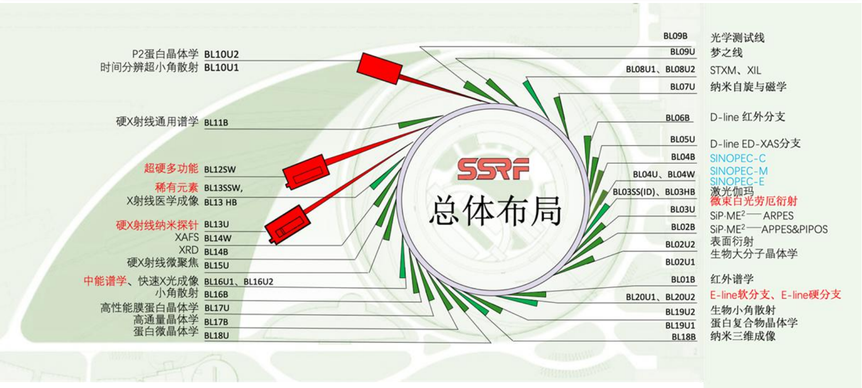
化学研究所(IC-CAS)

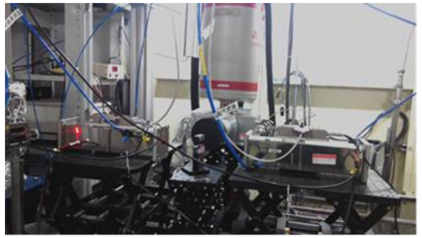
CCU领域的新理论、新方法、新过程

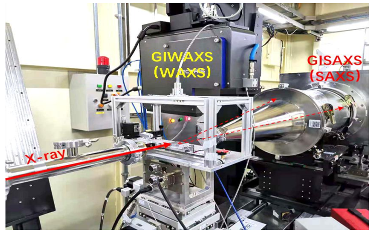
New theory, new methods, new process for CCU

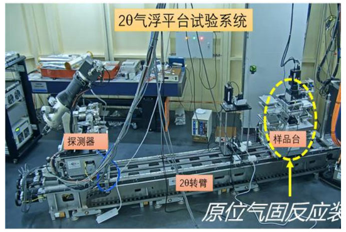
建制化研发能力
Institutional Research Capability

基于光子科学的先进表征平台 Photon Science-based Advanced Characterization Platform

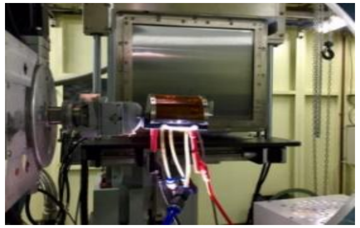


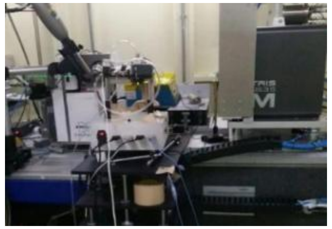






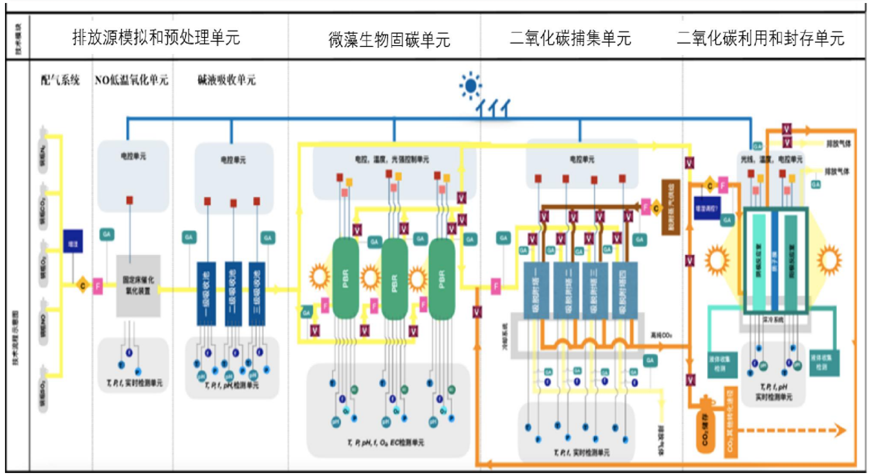
BL14W1-XAFS线站 | 硬X射线通用谱学线站 | BL16B1超快成像线站 | BL05U ED-XAS





动力学线站 D-line | 能源材料线站 E-line | 高通量XRD/SAXS

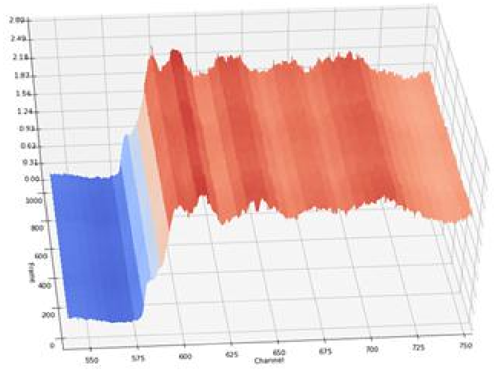
CCUS技术专属研发平台 Dedicated R&D platform for CCU



立方级评价装置
Nm³-scale evaluation

建制化研发能力
Institutional Research Capability

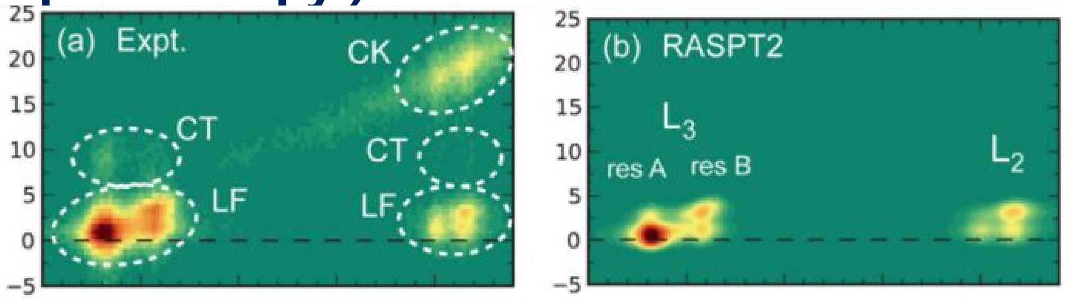
- 能量色散X射线吸收谱（Energy dispersive XAS）



40000 images/s collection

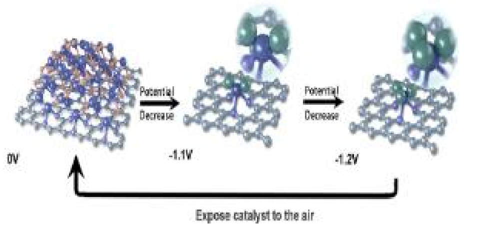
Processing software for time-resolved structural dynamics

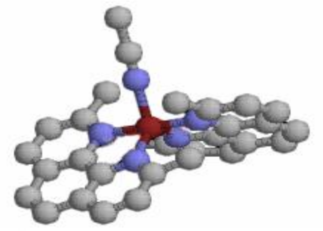
- X射线共振发射谱（Resonant X-ray Emission Spectroscopy）



基于软X射线的精细电子结构
Fine electronic structure based on soft-X-Ray

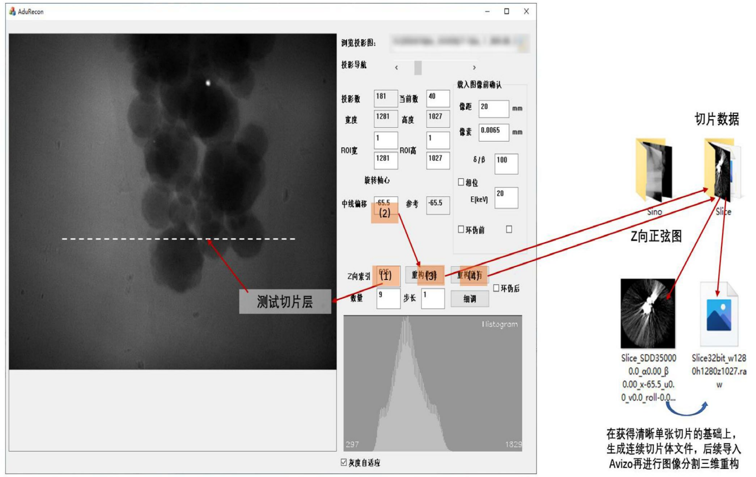
- 吸收谱多重散射模拟（Multiple-Scattering Calculations of XAFS）





谱学计算解析局域结构/吸附基团信息
XAFS calculations to determine local structure/adsorption group

- 全场纳米CT（Full Field NanoCT）



GPU加速的重构算法，大幅度提升实验效率和重构速度
GPU accelerated reconstruction algorithms

研究领域1：低成本碳捕集

Research area 1: Low-cost CO_2 capture

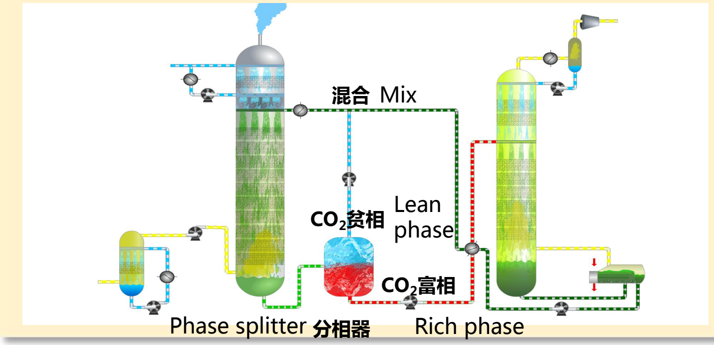
针对传统碳捕集技术能耗高、成本高的关键瓶颈，改变二氧化碳解吸过程热力学驱动力，构建碳捕集新方法，大幅提升捕集时效并降低反应能耗，从而大幅降低碳捕集及利用综合减排成本

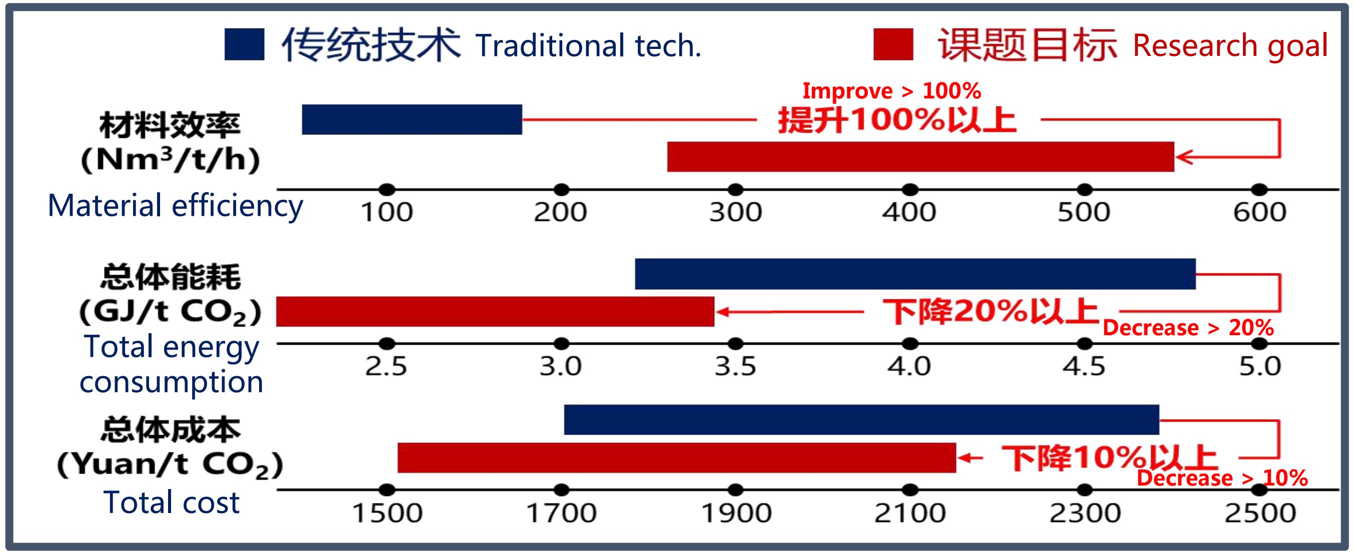
Developing new capture process using alternative thermodynamic driving force of CO_2, so as to increase the capture efficiency and reduce the energy consumption

碳捕集关键技术瓶颈
Key technical bottlenecks

能耗 Energy consumption >2.5 GJ/t CO_2

成本 Cost >260 RMB/t CO_2





- **共反应物化学活性推动CO_2捕集-转化一体化**
  Chemistry potential promotes integrated capture & conversion
- **吸附剂结构柔性推动“呼吸式” 吸脱附**
  Flexible structure promotes "breathing" adsorption & desorption
- **原位、实时、动态表征 In situ, real-time, dynamic characterization**

理论/方法创新推动技术创新
Theoretical/methodological innovation promotes technological innovation

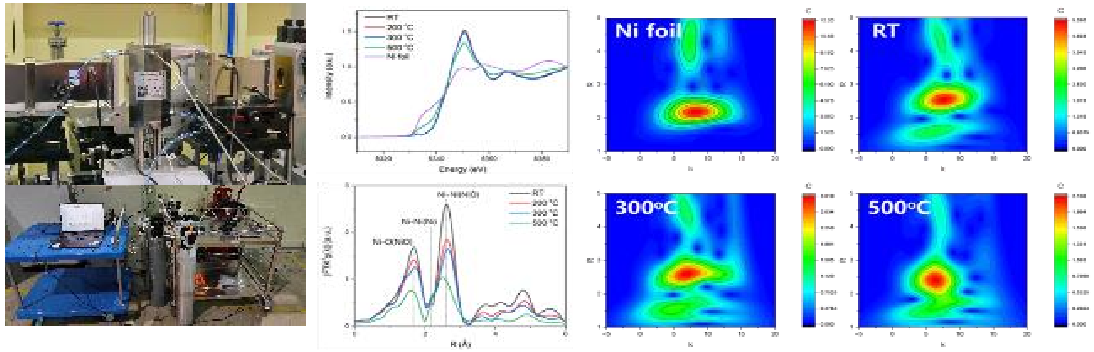
- **捕集率、转化率均大于90%**
  Capture rate & conversion rate > 90%
- **吸附容量大于12wt.%**
  Adsorption capacity > 12wt.%

研究领域1：低成本碳捕集

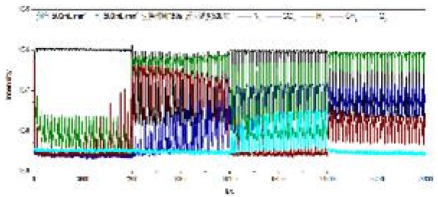
Research area 1: Low-cost CO_2 capture

通过原位XAS技术深入研究了CO_2捕集-甲烷化一体化过程在临氧条件下的失活机理，构建了具备“牺牲位点”的吸附-催化双功能材料，支撑完成了千方级小试，碳捕集率和转化率均达到90%以上

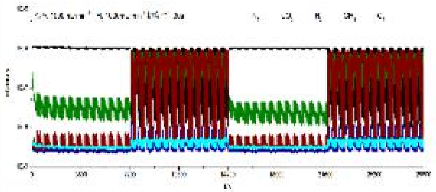
In-depth investigation on the deactivation under aerobic condition was investigated using in-situ XAS, and new materials with “sacrificial sites” were designed, based which 1000-Nm3 scale testing was carried out, achieving over 90% CO_2 capture and conversion ratio



基于XAS的原位失活机制研究组件和数据拾取、分析方法
In-situ XAS data collection, processing, and interpretation



临氧条件快速失活



高耐氧稳定性运转

95%
CO_2捕集
CO_2 capture

93%
CO_2转化
CO_2 conversion

94%
温室效应降低
GHG reduction

	现有报道	本工作
操作方式	间歇式	连续式
CO_2捕集率（%）	<10	>90
捕集时效（L/h/kg）	<50	>250
烟气处理规模（L/h）	<10	>100

千方级双塔连续运行装置

Ni-based DFMs with high oxygen-resistance for integrated CO_2 capture and conversion，Publication preparation

研究领域2：高选择性CO_2转化

Research area 2: Selective CO_2 conversion

针对CO_2热催化中**表界面结构动态演变**和电催化还原**C_{2+}产物选择性调控**问题，发展**高压动态**XAS及IR表征方法和**高灵敏**液固界面探测的XAS及XPS表征方法，实现**CO_2热催化还原精准调控**和**工业电流密度高选择制C_2新过程**

Aiming at **the dynamic evolution of surface interface structure** and the **selective conversion**, **high pressure dynamic** XAS and IR characterization methods and **highly sensitive** liquid-solid interface detection of XAS and XPS characterization methods were developed to realize **precise regulation of CO_2 conversion** and particularly **new processes of C_2 production with high selectivity of industrial current density**

科学问题 Question

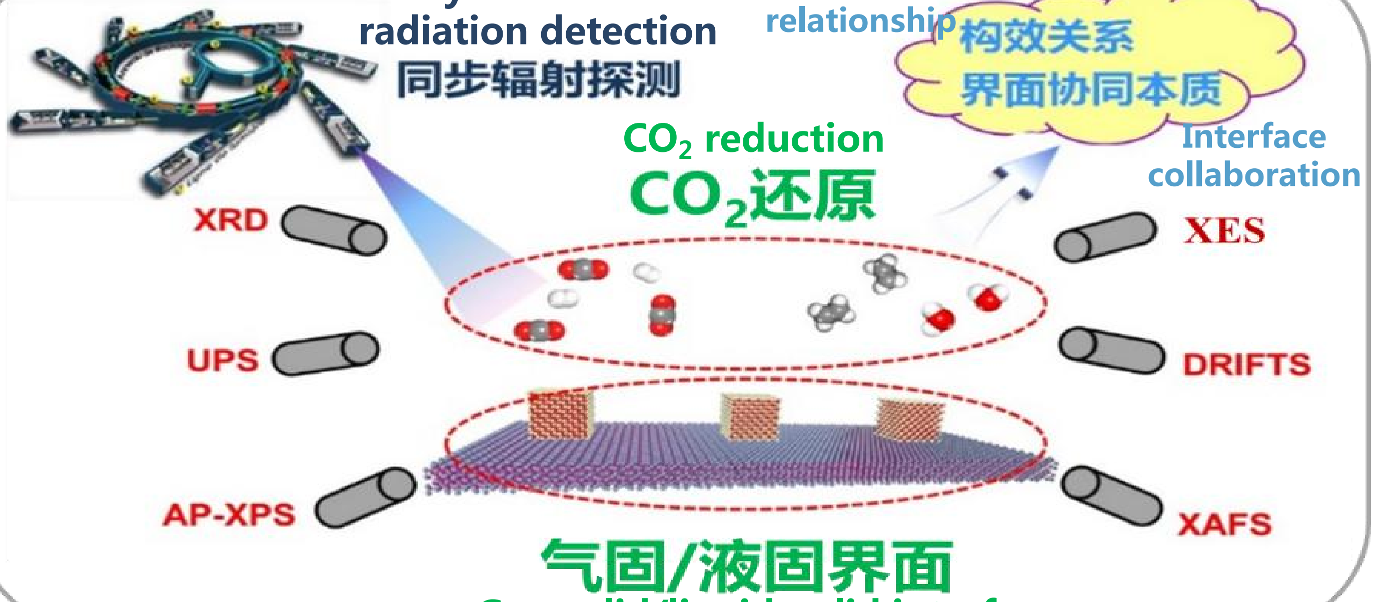
气固/液固界面的动态演变

Dynamic evolution of gas-solid/liquid-solid interface

研究手段 Methodology

Synchrotron radiation detection

Structure-function relationship



Gas-solid/liquid-solid interface

科学目标 Objective

CO_2活化及产物选择性控制

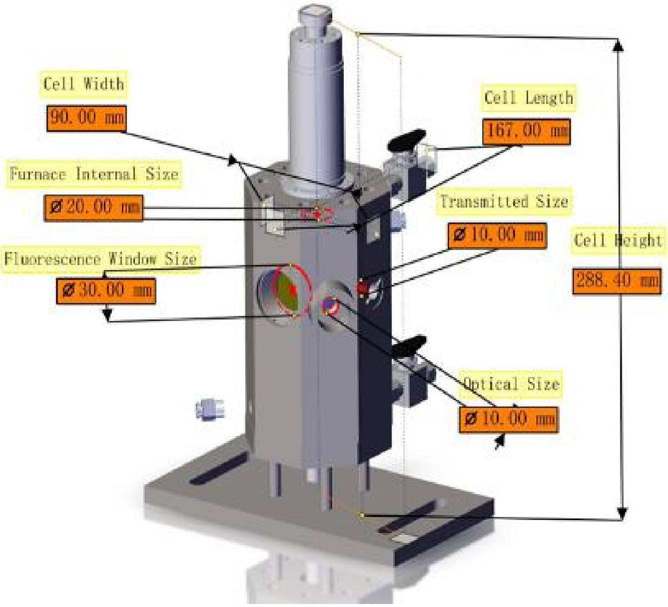
CO_2 activation & product selective control

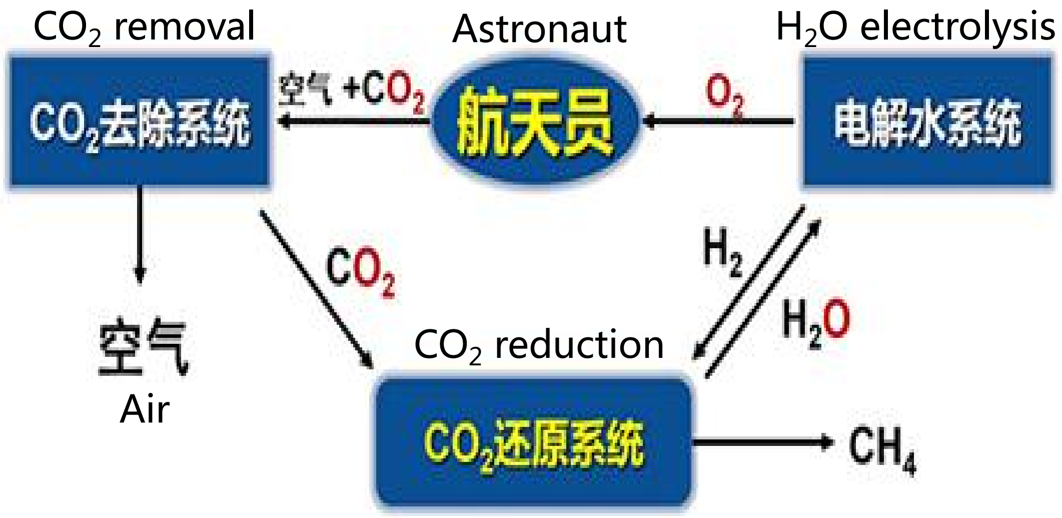
研究领域2：高选择性CO_2转化

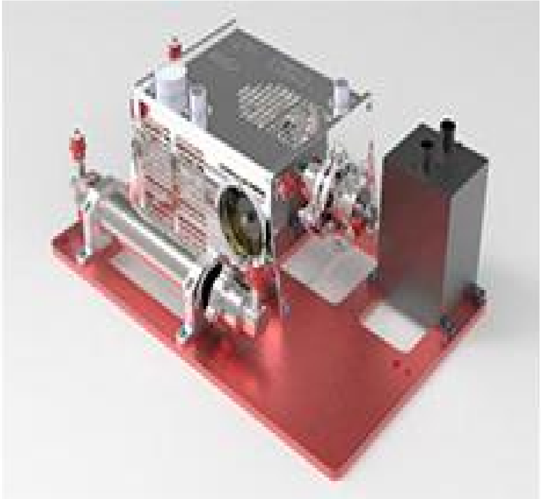
Research area 2: Selective CO_2 conversion

通过钌（Ru）与氧化物的界面调控实现CO_2定向还原生成CH_4或CO，研制高性能Ru基CO_2甲烷化催化剂并成功应用于我国空间站

Directed reduction of CO_2 to CH_4 or CO was achieved by interfacial regulation of ruthenium (Ru) and oxide. The high-performance Ru-based CO_2 methanation catalyst was developed and successfully applied to the Chinese space station







二氧化碳还原组件在空间站核心仓稳定运行超过6个月

The CO_2 reduction module operated steadily in the station's core module for more than 6 months

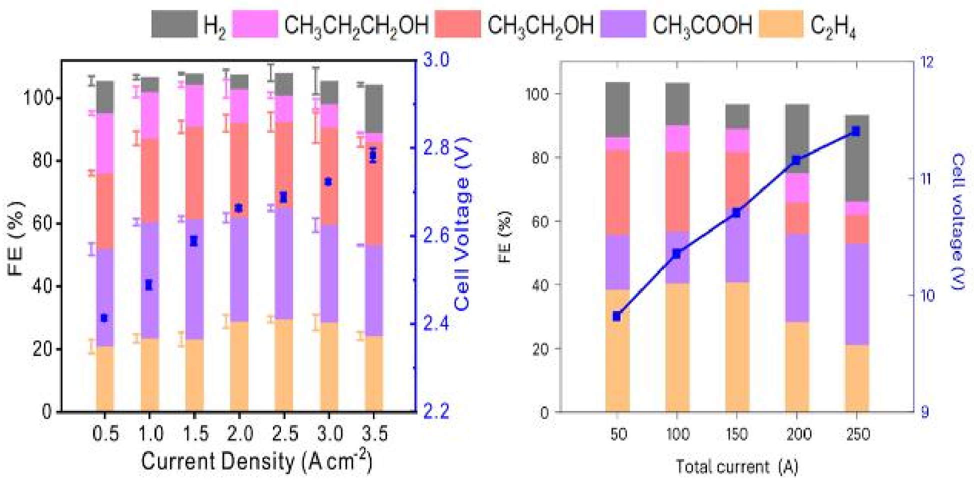
H. Xin, Q. Fu*, XH Bao*, ***J. Am. Chem. Soc.*** 2022, 144, 11, 4874

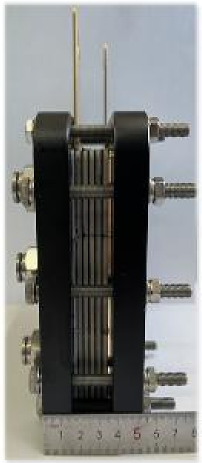
研究领域2：高选择性CO_2转化

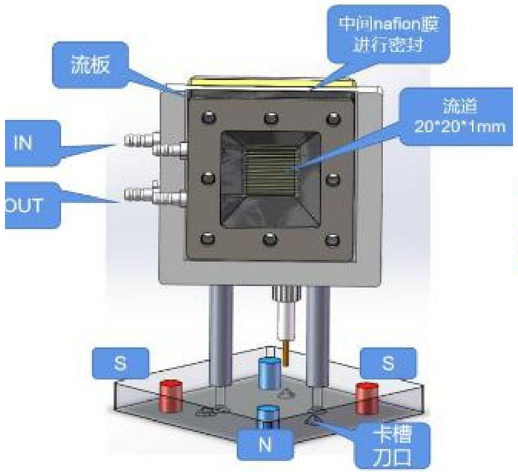
Research area 2: Selective CO_2 conversion

揭示覆盖度驱动的C_2产物选择性变化机制，实现安培级（ 3.1 A cm^{-2} ）电流密度CO_2电催化还原制乙酸等C_{2+}产物，乙酸的碳选择性达到70%，CO单程转化率达到75%

The selectivity change mechanism of C_2 products driven by coverage was revealed, and C_{2+} products such as acetic acid were produced by CO_2 electrocatalytic reduction at ampere-level (3.1 A cm^{-2}) current density. The carbon selectivity of acetic acid reached 70% and the conversion rate of CO reached 75%

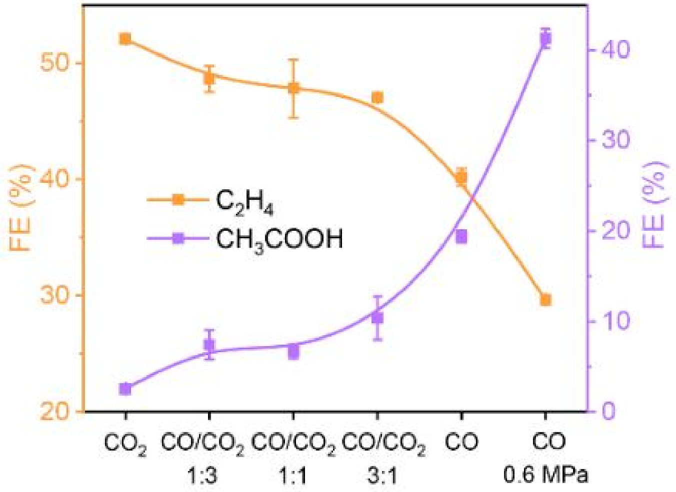






组装出最高功率2.85千瓦的电解电堆

Assemble an electrolytic reactor with the highest power of 2.85 kW



C_2产物乙烯和乙酸选择性的精准调控

Precise selective regulation of ethylene/acetic acid production

P. F. Wei, D. F. Gao, T. F. Liu, G. X. Wang, X. H. Bao, *et al.*, ***Nature Nanotechnology***, in press.

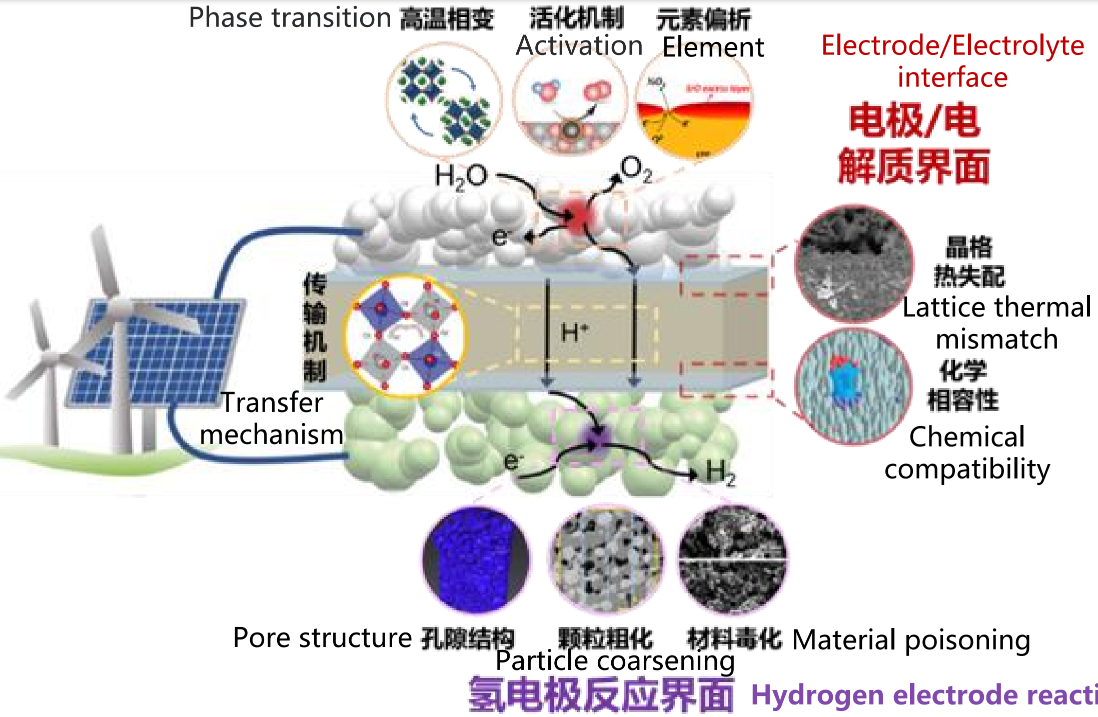
研究领域3：高温电解水制氢

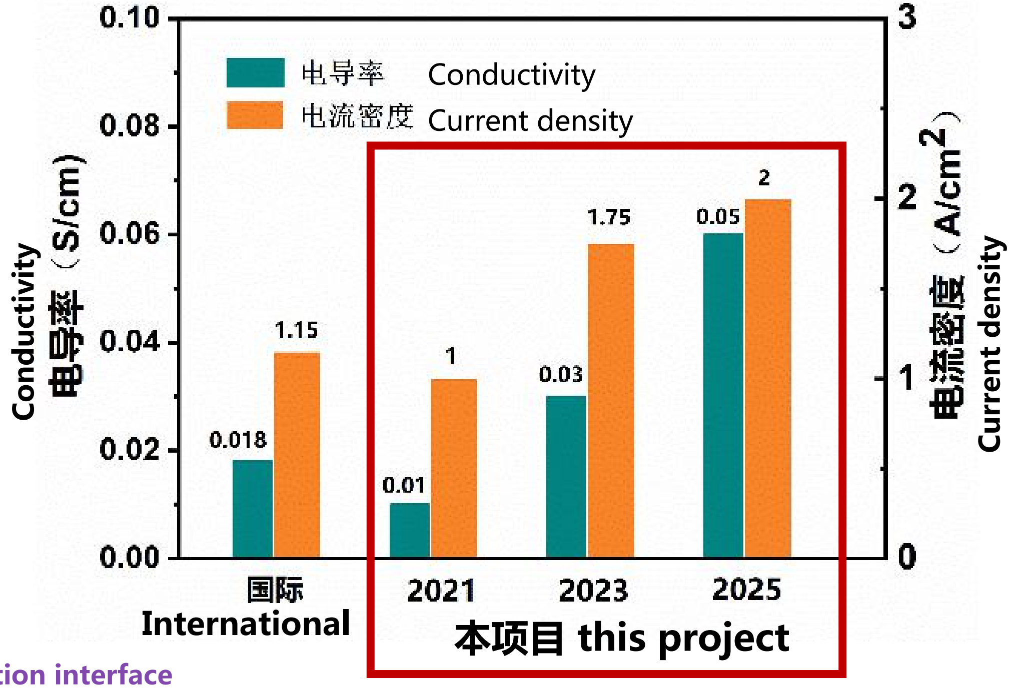
Research area 3: High-temperature H_2O electrolysis

针对固体氧化物电解池高温制氢材料界面活化机理、输运机制及反应过程等关键科学问题，发展同步辐射原位衍射、吸收和成像方法，建立国际先进的高温电化学同步辐射原位研究平台，解析界面结构演变与电池性能衰减的关联机制，研制高电流长寿命电解池，达到国际领先水平

Focusing on the interfacial activation mechanism, transport mechanism and reaction process of high temperature H_2 production materials in solid oxide electrolytic cell, we developed in-situ diffraction, absorption and imaging methods of synchrotron radiation, established an internationally advanced in-situ research platform for high temperature electrochemical synchrotron radiation, analyzed the correlation mechanism between interface structure evolution and battery performance attenuation, and developed high current and long life electrolytic cell

不同电解制氢技术 Different Tech.	ALK	PEM	SOEC
工作温度 (℃) Temperature	80	70	700
电流密度 (A/cm²) Current density	0.25	1.0	0.5
制氢效率% (LHV) Efficiency	≥60	≥70	≥90
电解能耗 (kWh/Nm³) Energy consumption	4.3	4.5	3



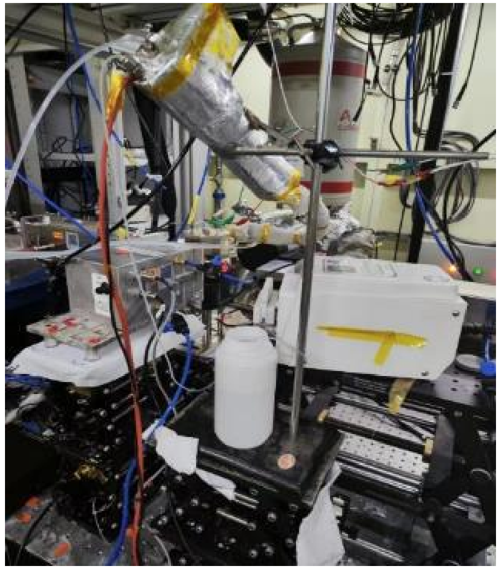


研究领域3：高温电解水制氢

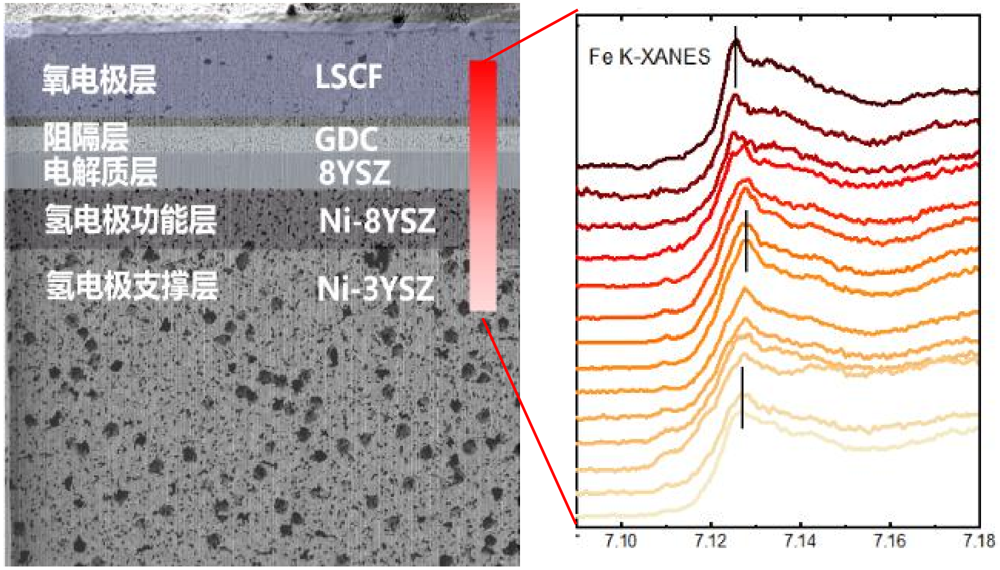
Research area 3: High-temperature H_2O electrolysis

实现高温700°C原位电化学同步辐射实验测试，提升了电解电流密度（≥1.75A/cm²），经1000h长期运行性能衰减率≤1%，保障了国内规模最大的200kW高温制氢示范装置开车成功（武威）

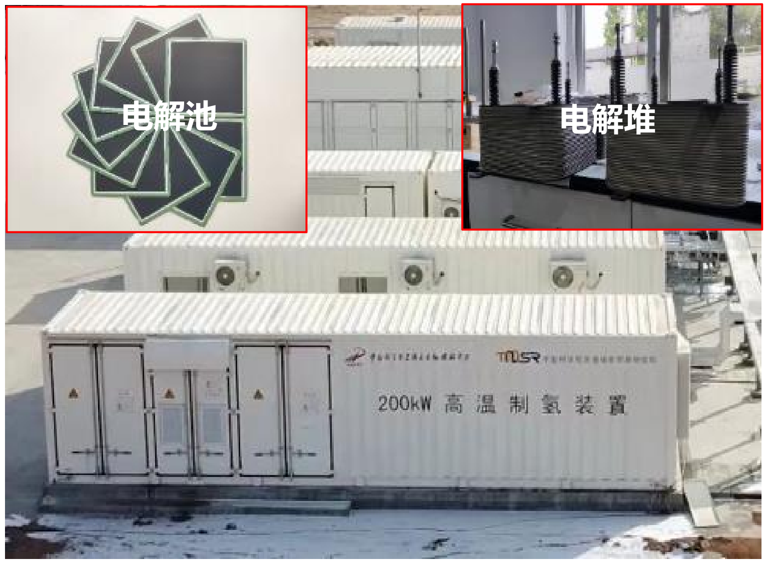
Achieved 700°C in-situ electrochemical synchrotron radiation test at high temperature and improved the electrolytic current density (≥1.75A/cm²). After long-term operation for 1000 h, the performance attenuation rate was ≤1%, achieving the successful operation of the largest domestic high temperature hydrogen production demonstration device of 200 kW



同步辐射原位实验
Synchrotron radiation in situ test



电解池界面微束XAS实验
Microbeam XAS experiment at electrolytic cell interface



200kW-SOEC制氢系统
Hydrogen production system

J. Zhou, J.-Q. Wang et al. ***ACS Catalysis*** 2022, 12: 3138−3148; C. Jing, J.-Q. Wang et al. ***ACS Catalysis*** 2022, 12: 10276-10284

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面向二氧化碳的光子科学建制化研究平台

CO_2-oriented Institutional Research Platform of Photon Science

孙楠楠（Nannan SUN）

Thank You