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HIRFL

兰州重离子研究装置

HEAVY ION RESEARCH FACILITY IN LANZHOU

2021年度报告

HIRFL

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2021年度报告

（中文）

一、综述及基本情况

兰州重离子加速器国家实验室以中国科学院近代物理研究所为依托单位，1991 年 8 月 13 日由原国家计委批准成立，主要从事重离子物理前沿和应用研究，包含了原子核物理、高离化态原子分子物理、核天体物理、材料科学、生命科学、先进粒子加速器等研究领域。

兰州重离子加速器（HIRFL）主要由国家“一五”、“七五”、“九五”时期的三代大科学工程组建而成，包括ECR 离子源、扇聚焦回旋加速器（SFC）、分离扇回旋加速器（SSC）、冷却储存环主环和实验环（CSR）、放射性束流线（RIBLL）、实验终端等研究设施。兰州重离子加速器具有加速从氢到铀全离子的能力，可提供多种类、高品质、宽能量范围的稳定核束和放射性束，主要技术指标已达到国际先进水平，年运行时间超过 7000 小时，年供束时间超过 5000 小时，为国内外两百多个用户提供了实验条件，是我国规模最大、世界短寿命核素质量测量精度最高的重离子加速器，也是我国开展重离子物理及交叉学科研究最重要的装置。

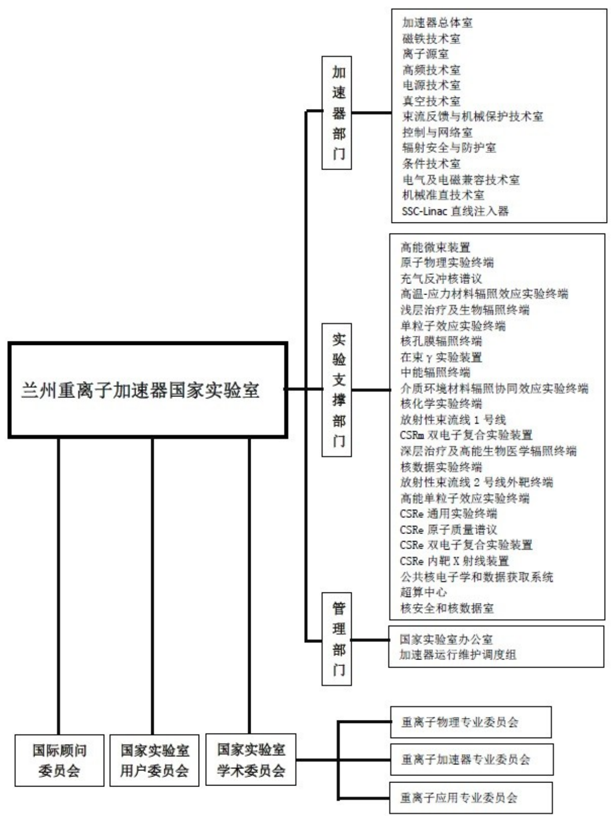
近年来，中国科学院近代物理研究所对兰州重离子加速器进行了一系列升级改造，研制的国内首台连续波高电荷态强流重离子直线注入器（SSC-Linac）与分离扇回旋加速器（SSC）联合调试出束，拓展了重核束流的能量范围，提高了使用效率和供束能力。兰州重离子加速器成为国际上首次采用直线+回旋+同步的三种不同类型加速器独特组合运行的大科学装置。

兰州重离子加速器建设以来，取得了以新核素合成、短寿命原子核质量精确测量为代表的一批重大基础研究成果，提供了以“国防 2 号”任务、空间元器件单粒子效应检测、暗物质粒子探测卫星“悟空”塑闪阵列探测器为代表的国家重大战略技术保障，研发并转移转化了以重离子治癌、辐照诱变育种、核孔膜为代表的多项服务经济社会发展的科技成果。通过多年发展，兰州重离子加速器国家实验室已经培养和造就了一支国家可信赖的核科技战略力量。

设施负责人

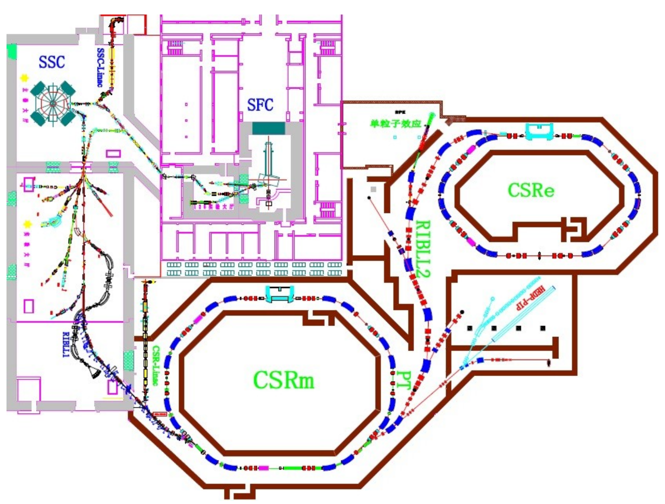
国家实验室主任	沈文庆	副主任	肖国青、赵红卫、夏佳文、徐瑚珊
国家实验室学术委员会主任	张肇西	副主任	陈森玉、叶沿林、周小红

组织框架



设施系统构成图

兰州重离子研究装置主要由 ECR 离子源、扇聚焦回旋加速器（SFC）、HIRFL 直线注入器（HIRFL-Linac）、分离扇回旋加速器（SSC）、冷却储存环（CSR）、放射性束流线（RIBLL）、实验终端等主要部分组成，可实现 H 到 U 的全离子加速。



HIRFL 平面布局图

二、重要进展与成果

2021 年，兰州重离子加速器国家实验室的用户依托 HIRFL 取得一批重要的研究进展与成果。

首次合成铀元素中最轻同位素 ^{214}U

中科院近代物理研究所的科研人员及合作者利用兰州重离子加速器（HIRFL）装置，首次合成铀元素中的最轻同位素 ^{214}U，并在重核区首次发现 α 衰变中 α 粒子形成几率反常增强的实验现象。相关研究成果于 2021 年 4 月 14 日以亮点文章"编辑推荐"（Editors' Suggestion）的形式发表于国际顶级物理学期刊 Physical Review Letters 上，并被美国物理学会的 Physics 杂志和英国 Nature 杂志作为研究亮点进行报道。

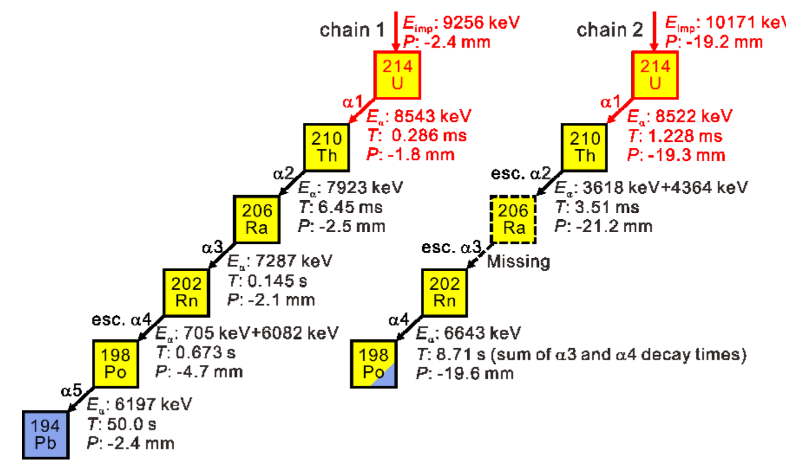


图 1. 实验测量的新核素 ^{214}U 的两条 α 衰变链

GeV 重离子曝光制备亚 5nm 纳米线

湖南大学与中科院近代物理研究所研究人员合作，利用兰州重离子加速器高能微束装置提供的 2.15 GeV 氪离子作为曝光源，在光刻负胶 HSQ（氢硅倍半环氧乙烷）中利用单离子曝光获得了特征尺寸小于 5nm 的超长径比纳米线结构。

该项工作不仅首次展示了利用单个重离子进行单纳米光刻的潜力，也证明了无机负胶 HSQ 具有可靠的亚 5nm 光刻分辨能力。利用先进的重离子微束直写技术和单离子辐照技术，单个重离子曝光技术有望在极小尺度加工中发挥独特的作用，同时可用于先进光刻胶分辨率极限的评价。 文章发表在 Nano Letters 2021, 21, 6, 2390-2396。

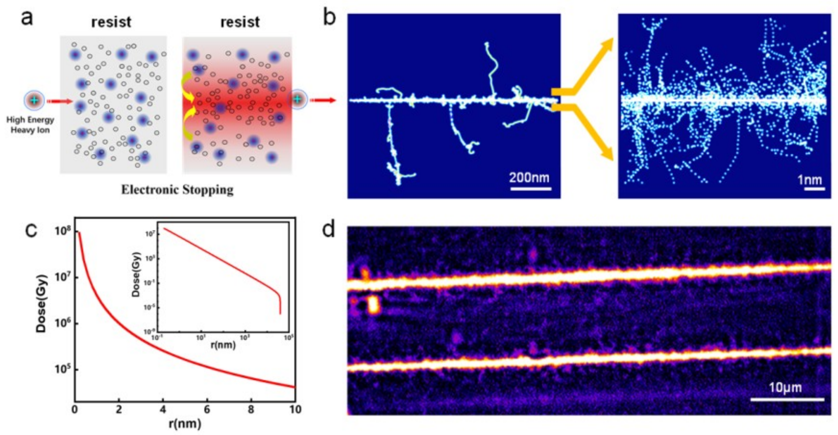


图 2. 氪离子径迹中心能量沉积模拟计算及其在探测器中的显微观测

先进水冷堆候选材料的辐照/高温水腐蚀研究

利用兰州重离子加速器研究装置（HIRFL）提供的重离子束和高温高压水动态腐蚀装置，科研人员开展了超临界水冷堆候选材料——SIMP 和 T91 铁素体/马氏体钢的高温水腐蚀动力学及辐照/高温水腐蚀行为研究。近代物理研究所和金属所联合研制的先进核能系统候选材料 SIMP 钢在以往的研究中已经展示出优异的液态金属腐蚀抗性。进一步的高温水腐蚀结果表明，SIMP 钢比 T91 钢具有更优越的抗水腐蚀性能（图 3）。另外，研究表明，在水冷堆的强辐照和腐蚀环境中，辐照导致材料腐蚀速率的显著增大。这些成果为先进水冷堆候选材料的快速筛选评价提供了重要的研究平台、实验方法和科学数据。相关成果发表在材料腐蚀领域专业期刊 Corrosion Science（Corros. Sci. 187（2021）109474;　Corros. Sci.189（2021）109602）上。

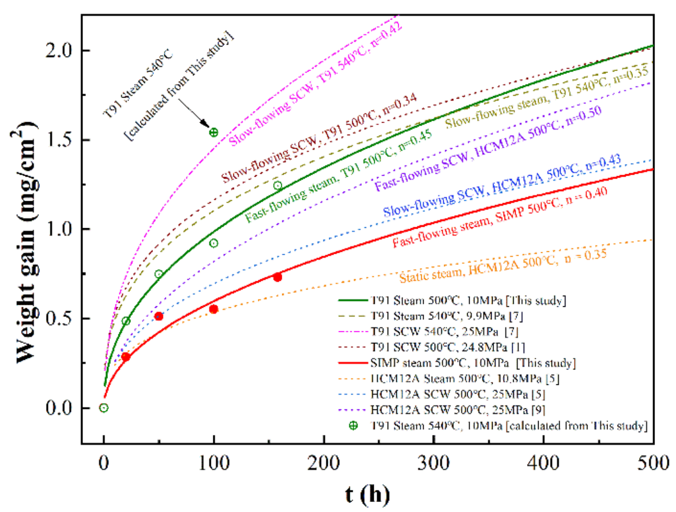


图 3. SIMP 和 T91 钢的腐蚀动力学曲线（流速 5 m/s、氧含量 5 ppb）

温度响应的核径迹微纳米孔道形貌演化与反常形变

对于传统的核径迹孔道而言，为了保持其稳定性，通常选用化学、力学稳定性较好的材料。西北工业大学及近代物理研究所科研人员反其道行之，提出了一种利用薄膜自身特性来二次调控孔道尺寸及形貌的方法。

科研人员依托兰州重离子加速器研究装置辐照 PET 薄膜制备微纳米核径迹孔道。实验表明，通过提高环境温度，利用热收缩型 PET 高分子薄膜中的残余应力，可实现实时温度和环境调控的微纳米孔道。研究发现，在特定的孔隙大小和温度范围内，孔隙开口呈现出特殊的“眼睛”形状。另外，随着环境温度的升高，单孔的离子电流逐渐减小，而对于多孔薄膜，随着环境温度的升高，最高可以截断 99%的流量。

研究成果发表在 Nano Lett. 2021, 21, 2766−2772。

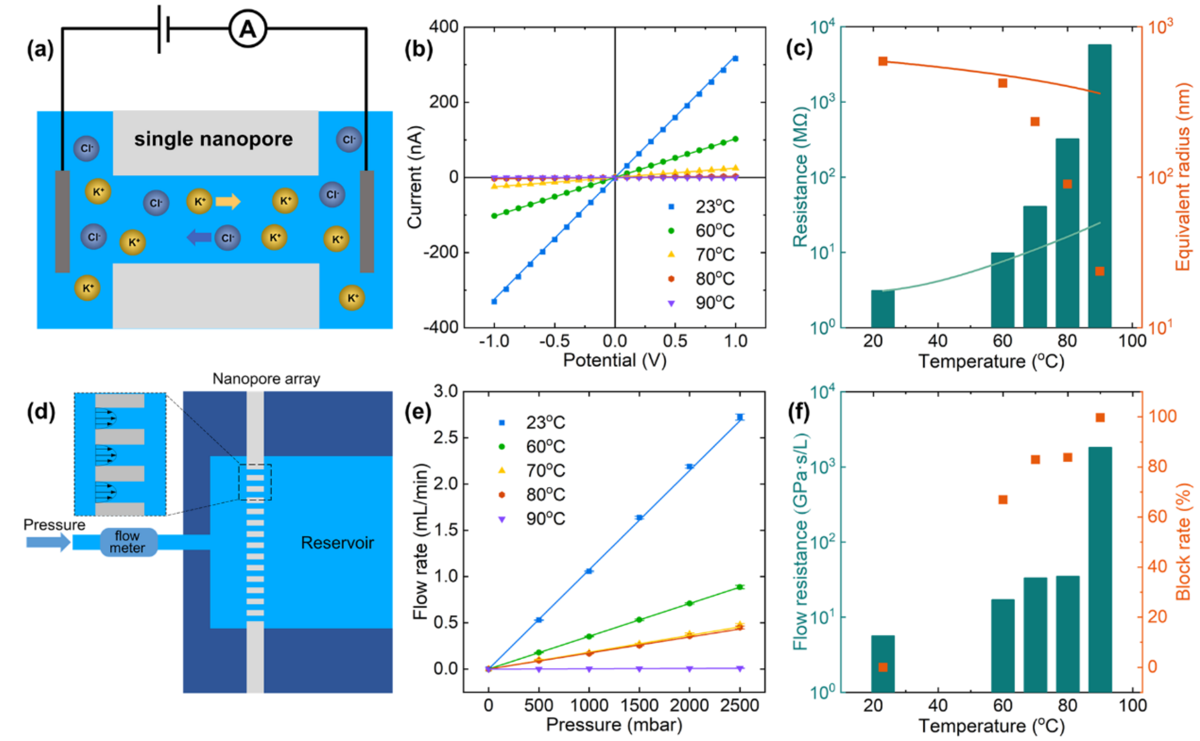


图 4. 单孔及多孔热收缩薄膜的温度调控

应用重离子束诱变技术获得粳稻新品种“东稻 122”

中国科学院近代物理研究所和中国科学院东北地理与农业生态研究所科研人员依托兰州重离子加速器研究装置（HIRFL）共同研发完成的“东稻 122”，是国内首个采用高能重离子束辐射诱变育种技术培育出来的北方粳稻新品种，2020 年通过吉林省农作物

品种审定，2021 年入选吉林省农业主导品种。经过两年的示范推广，“东稻 122”表现出耐盐碱、活秆成熟、抗倒伏、高产的特点，在适应性等方面也表现出色，还拥有出米率高、商品性好等特点。2021 年 10 月 13 日，“东稻 122”田间现场观摩会暨百亩连片实收测产会在苏打盐碱典型稻区大安市叉干镇举行。经专家组测定，耐盐碱水稻新品种“东稻 122”在大安示范区平均产量为 632 公斤/亩，比当地主推品种增产 10.6%。


主要农作物品种
审定证书

审定编号：吉审稻 20200004
品种名称：东稻 122
品种来源：中高能重离子束辐照诱变通禾 899 后代
申 请 者：中国科学院东北地理与农业生态研究所
育 种 者：中国科学院东北地理与农业生态研究所
审定意见：该品种符合吉林省水稻品种审定标准，通过审定。适宜吉林省吉林、长春、通化、白城、延边的中早熟稻区种植。
公 告 号：吉林省农业农村厅公告〔2020〕2 号
证书编号：2020-1-0166

2020 年 06 月 24 日

图 5. 东稻 122 的主要农作物品种审定证书

重离子治疗研究与产业化取得重大进展

2021 年 1 月 30 日，“碳离子治癌研究及大型肿瘤治疗装置研发与产业化”项目荣获甘肃省科技进步奖特等奖。10 月，近代物理所的医用重离子加速器成果入选国家“十三五”科技创新成就展和 2021 年全国大众创业万众创新活动周。

截至 2021 年底，国内首台具有自主知识产权的武威医用重离子加速器累计完成 503 例肿瘤患者治疗（含临床实验 46 例受试者），疗效显著。续武威、兰州示范装置后，我国在建医用重离子加速器商业装置还有 5 台。2021 年，南京、长春重离子项目合同也已签订。

2021 年，近代物理所继续开展重离子治癌生物基础研究，并开展了精准治疗技术研究，物理精准方面主要针对生物视听引导反馈呼吸门控系统，PET 在线监控关键技术；生物精准方面为细胞等组织对重离子适应症的预测等。

重离子微孔膜成果转化与应用

近代物理所基于兰州重离子研究装置开展重离子微孔膜特性研究、生产制备技术研发及产业应用工作。

2021 年，重离子微孔膜产业化团队建成重离子微孔膜河道修复创新研究基地和重离子微孔膜垃圾压滤液处理创新示范基地两个示范项目。

此外，依托重离子加速器辐照、化学蚀刻技术等方面的技术积累，团队还突破性地研发出了重离子微孔膜超黑材料，经中国计量研究院检验，该材料的电磁波吸收率最高可达 0.9999，达到了国际领先水平。重离子微孔膜超黑材料拥有广泛的应用前景，如空天探测、精密测量、红外隐身等。

2021 年新申请专利 9 件，授权发明专利 5 件、实用新型专利 7 件、软件著作权 1 件，获甘肃省专利发明人奖、甘肃省专利一等奖各一项。

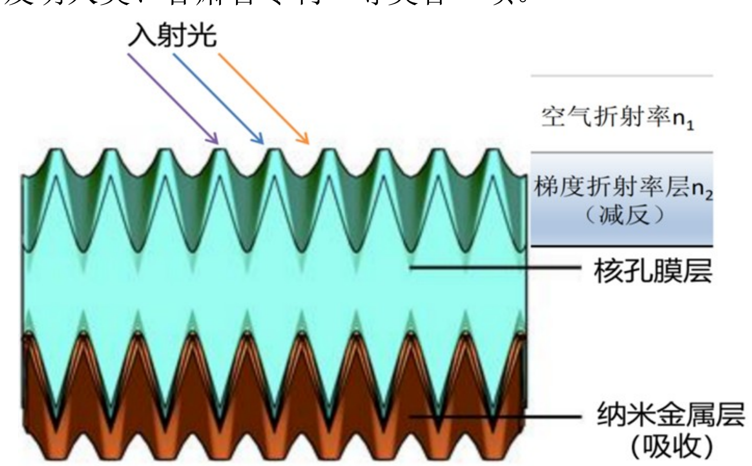


图 6. 超黑材料电磁波吸收新机制示意图

科技论文发表、获奖、专利

SCI 收录论文数	论文引用数	国外发表论文数	用户相关论文数	获省部级以上奖数	发明专利授权	实用新型专利授权	软件著作权
216		180	216	2	66	13	18

三、设施建设、运行与改造

2021 年 HIRFL 计划运行 7000 小时，实际运行 7848+774(并行)小时。计划实验供束

时间 4600 小时，实际实验供束时间 5797.5+312.5(并行)小时，机器研究 641+230(并行)小时；换束耗时 1321.5 小时，其中 Linac 换束耗时占 178.5 小时。全年为各类科学实验提供 24 种束流，其中 13 种为首次调试的新束流，共完成 186（含 Linac 供束完成的实验 5 项）项用户实验。

2021 年 HIRFL 机器维护改造主要的亮点工作有：

1. 通过重新优化理论加速曲线，详细测量铁氧体高频腔在低端频率时给定值与输出腔压之间的偏差，提高注入能量下高频谐波次数，降低束团平均线密度等方法，显著提高了 CSRm 重离子束流在流强提高时的俘获和加速效率，平均俘获加速效率由近年来的 85%上升到 95%左右。
2. 通过优化超导离子源，提升 SFC 聚束器工作电压，实施 CSRm 注入能量下闭轨校正等方法，提高了 CSR 中重离子束流的流强，首次实现了 Ar、Kr 等束流的储存离子数目超过 10^9。
3. 通过优化 CSRm 引出踢轨磁铁角度，调整引出点与储存环光学参数匹配，详细设计引出束流线光学设计等方法，提升了高能实验终端 PISA 的束流品质，实验终端束斑半径小于 1 毫米，束斑位置偏差小于 0.1 毫米。
4. 通过对 SFC 高频馈线以及 SFC 耦合电容的重新设计与改造，明显提升了 SFC 高频腔体的 Q 值（提升 10%）与有效高频电压（提升 11%）、降低 SFC 高频腔体与发射机之间的传输损耗（传输损耗≤0.3%），同时将 SFC 高频系统更换频率的时间由 3 小时缩短至 0.5 小时，极大地提升了 SFC 高频系统的工作效率。
5. 采用 Afterglow 脉冲模式，在全超导 ECR 离子源 SECRAL-II 上成功获得部分高电荷态离子束流强世界纪录，比如 $^{129}Xe^{34+}$ 266 euA，$^{129}Xe^{38+}$ 169 euA，$^{129}Xe^{42+}$ 50 euA。相比直流模式，束流强度增益 2-7 倍。脉冲宽度（FWHM）达到 6~10ms。目前，该项技术已成功应用在 HIMM 项目，实现储存环束流强度约 60%增益。

HIRFL2021 年运行情况

兰州重离子研究装置	运行总机时(小时)	换束机时（小时）		供束机时（小时）		故障机时	其它
		1321.5		6981			
		换束准备	换束调试	用户实验	机器研究		
		603.5	718	6110	871	282.5	37
常规运行	7848	547.5	595.5	5797.5	641	229.5	37
并行运行	774	56	122.5	312.5	230	53	0

HIRFL 用户实验

设施名称	实验束线数	实验终端数	用户单位数	用户计划实验课题数	用户完成实验课题数	用户实验参加人数	用户实验涉及领域及比例	故障机时
兰州重离子研究装置	-	21	76	150	184	981	原子物理与核物理 66.7%，生命科学 4.9%，材料科学 22.6%，空间科学 5.8%	317

HIRFL2021 年供束离子种类

序号	SFC/Linac			SSC		CSR		
	离子种类	能量（MeV/u）	流强（uA）	能量（MeV/u）	流强（uA）	能量（MeV/u）	CSRm 流强（uA）	CSRe 流强（uA）
1	$^{78}Kr^{26+}$	6	10			460	2000-4000	次级束
2	$^{129}Xe^{22+}$	1.844	2.6	19.5	0.23			
3	$^{78}Kr^{24+}$	4.75	7					
4	$^{54}Fe^{16+}$	4.82	6					
5	$^{181}Ta^{35+}$	1.5202	0.2	16	0.01			
6	$^{12}C^{4+/6+}$	7	2.7	80.55	0.1			
7	$^{14}N^{4+}$	4.3	5					
8	$^{12}C^{4+}$	5.2	4					
9	$^{12}C^{3+}$	4.2	2					
10	$^{4}He^{1+}$	4	3					
11	$^{30}Si^{8+}$	4.33	2					
12	$^{20}Ne^{7+}$	6.17	3					
13	$^{129}Xe^{32+}$	4	8			276	2600	
14	$^{64}Ni^{19+/25+}$	5.361	1.8	60	0			
15	$^{133}Cs^{27+/55+}$	2.2	1.6			204、75	300-350	200
16	$^{14}N^{6+}$	8.4	3					
17	$^{86}Kr^{28+}$	6.5	2					
18	$^{129}Xe^{35+}$	5	0.8					
19	$^{7}Li^{3+}$	9	1					
20	$^{36}Ar^{15+}$	8.5	15			376、445	4000	次级束
21	$^{16}O^{5+/8+}$	5.361	9	60	0.65			
22	$^{129}Xe^{22+}$	0.58	40	5.98	2.3			
23	$^{40}Ar^{7+/16+}$	0.58	50	5.98	6	320、400	1000	
24	$^{40}Ca^{12+}$	5.4	5					

**：黄色为首次调试的离子

四、科技队伍与人才培养

设立“突出成果奖”“青年科技奖”等，培养、稳定优秀团队和年轻人才；推进协同创新战略，与国内大学联合培养创新型人才；充分利用国际合作的良好契机，与国外著名的研究机构、大学联合培养实用型的科技人才。

设施人员总数	按岗位分			按职称分			学生			在站博士后	引进人才
	运行维护人员	实验研究人员	其他	高级职称人数	中级职称人数	其他	毕业博士	毕业硕士	在读研究生		
426	252	163	11	259	127	40	50	36	483	23	2

五、合作与交流

2021 年，受疫情影响，全球科研人员的互访交流严重受阻。为了不影响正常的科研交流，我所科研人员积极开展视频会谈、远程办公以及线上国际会议等方式保证科研工作的顺利开展。

2021 年我所与美国、韩国、德国等 3 个国家的 4 所大学或科研机构签订或续签了合作协议，共获得中国科学院国际人才计划资助 14 项，科技部外国专家项目 9 项，中国科学院特别交流计划 3 项，5 人获得国家公派留学资助，组织线上国际会议 2 项。“国际反质子与离子大科学研究国际科技合作基地 ” 在科技部 2020 年度国际科技合作基地评估中获得优秀。截止 2021 年 12 月份，我所共招收 31 名外籍人员，其中 11 名外籍员工、12 名外籍博士后、1 名 Fellowship 与 7 名外籍留学生。

2021 年 5 月 22 日至 23 日，兰州重离子加速器国家实验室举办第十七届公众科学日，活动主题为“百年复兴路，科学正当时”。兰州重离子加速器国家实验室作为全国科普教育基地和全国中小学生研学实践教育基地，共吸引超过 5000 余名社会公众前来参观学习。

六、大事记

1 月 30 日，“碳离子治癌研究及大型肿瘤治疗装置研发与产业化”项目荣获甘肃省科技进步奖特等奖，这也是甘肃省科学技术奖首次设立特等奖。

4 月 17 日，兰州重离子加速器国家实验室 2021 年束流评审会在兰州召开，最终批准实验供束 4600 小时，计划并行供束 1000 小时。

4 月 19 日，近代物理所刘杰研究员荣获“全国五一巾帼奖章”、“全国五一巾帼标兵”，并作为科研领域获奖代表在大会上交流发言。

10 月 21 日至 27 日，国家“十三五”科技创新成就展在北京展览馆举行。近代物理所的医用重离子加速器、缺中子锕系核区新核素合成 2 项成果入选参展。

12 月 9 日，2021 年中央级高校和科研院所等单位重大科研基础设施和大型科研仪器开放共享评价考核结果公布。近代物理所被评为优秀，在参评的 346 家单位中名列第七。

HIRFL

兰州重离子研究装置

HEAVY ION RESEARCH FACILITY IN LANZHOU

2021年度报告

（英文）

I. Overview

The Heavy Ion Research Facility in Lanzhou (Lanzhou Heavy Ion Accelerator, HIRFL), operated by the Institute of Modern Physics, Chinese Academy of Sciences (IMP), is the largest heavy ion research facility in China and one of a few large-scale full-ion accelerating systems in the world, which can accelerator ions from hydrogen to uranium to high energy. HIRFL comprises a number of conventional and superconducting magnet Electron Cyclotron Resonances (ECR) ion sources, the Sector Focused Cyclotron (SFC), the Sector-Separated Cyclotron (SSC), the experimental Cooler Storage Ring (CSR) which is a multi-purpose research system consisting of a Main Ring （CSRm）, an Experimental Ring （CSRe）and a radioactive beam line (RIBLL2) connecting the two rings, a fragment separator – the radioactive Ion Beam Line (RIBLL1) and some experimental devices, etc.. It serves as a base for domestic and growing international user communities focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. Based on HIRFL, IMP dedicates to fundamental researches in nuclear physics, nuclear astrophysics and atomic physics, including high precision mass measurement of short-lived nuclides, nuclear structure and reaction, properties of nuclear matter, synthesis of new heavy isotopes, chemistry of super-heavy elements, nuclear reaction in stellar environment, spectroscopies and interactions of highly-charged ions.

The SFC is a 1.7m Sector Focus cyclotron upgraded from the 1.5m classic cyclotron built in 1962. Running alone, it can provide beams for low energy heavy ion physics studies.

In December 1988, Lanzhou Heavy Ion Accelerating System (SFC+SSC), designed and constructed by IMP, was completed and put into operation. In August 1991, the National Laboratory of Heavy Ion Accelerator of Lanzhou was approved by the State Planning Committee and opened to the public.

In July 1997, a middle energy radioactive ion beam line (RIBLL) with innovative structure was constructed at HIRFL, which has paved the way for the research on radioactive ion beam physics in China. With the superconducting ECR ion source built in 2005 having the best performance in the world at that time, the operation of HIRFL has reached an internationally advanced level. In June 2005, the successful acceleration of the uranium ions was carried out.

The Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) was commissioned in 2008. The HIRFL-CSR is a multi-functional facility, not only accumulating and cooling but also accelerating heavy ions from Carbon to Uranium up to 1 GeV/u to hundreds of MeV/u. Internal target experiments with highly charged ions, external target experiments with both extracted stable and radioactive beams and high precision mass measurement experiment have been carried out. It can provide experiment complex for researches in heavy ion physics and its interdisciplinary subjects in China.

IMP has achieved many innovations at HIRFL over the past year: 30 plus new nuclides have been synthesized for the first time in the world, among which two are super-heavy nuclides; the mass of 35 radioactive nuclides have firstly been measured in the isochronous mode and the relative measurement precision of more than fifty nuclides has increased; the independently researched and developed heavy ion medical machine (HIMM) has realized the zero breakthrough of domestic heavy ion therapy equipment; new species and strains of several crops have been fostered by utilizing heavy ion irradiation induced mutation; and that the popular plantation of optimized sweet sorghum in western China has developed into a stable industrial chain, contributing to the regional economic development.

II. Research progress and results

Significant results and achievements at HIRFL – 2021.

Scientists report remarkable enhancement of α-particle clustering in uranium isotopes

Published in Physical Review Letters as an Editors' Suggestion, a study has reported the observation of ^{214}U, a new uranium (U) isotope, and has revealed for the first time the abnormal enhancement of α-particle clustering in uranium isotopes.

The study was led by scientists at the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences. Researchers carried out the experiments at the gas-filled recoil separator, Spectrometer for Heavy Atoms and Nuclear Structure (SHANS), at the Heavy Ion Research Facility in Lanzhou (HIRFL), China.

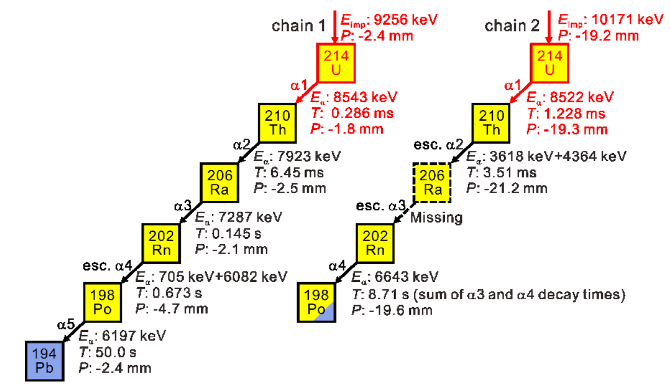


Fig. 1 Observed α-decay chains for the new isotope ^{214}U

Fabrication of sub-5nm nanowire using single GeV ion lithography

The research group of Hunan University and Institute of Modern Physics of Chinese Academy of Sciences, using the 2.15 GeV Krypton ion provided by the High Energy Microbeam Facility of Heavy Ion Research Facility in Lanzhou as the exposure source, obtained the ultrahigh aspect ratio nanowire structure with a characteristic size of less than 5nm by single ion exposure in the negative photoresist HSQ (hydrogen silicon sesquioxide).

This work not only shows the potential of single nano lithography using a single heavy ion for the first time, but also proves that the inorganic negative photoresist HSQ has reliable sub-5nm lithography resolution. Using advanced heavy ion microbeam direct writing technology and single ion irradiation technology, single heavy ion exposure technology is expected to play a unique role in microscale fabrication, and can be used to evaluate the resolution limit of advanced photoresist.

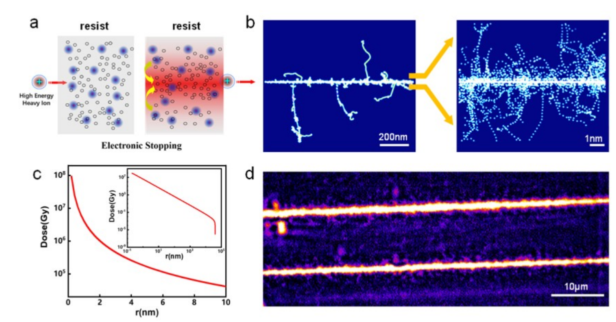


Fig. 2 The simulation of the energy deposition and the radial dose calculation along the ion trajectory.

Study of the irradiation/corrosion behavior of candidate materials for advanced

water-cooled reactors

The corrosion kinetics and irradiation/corrosion behavior of SIMP and T91 ferrite/martensitic steel candidates for supercritical water-cooled reactor were studied by using heavy ion beam provided by the Heavy Ion Research Facility in Lanzhou (HIRFL) and high-temperature and high-pressure water dynamic corrosion device. SIMP was a martensitic Steel (S) designed by Institute of Modern Physics (IMP) and Institute of Metal Research (IM), Chinese Academy of Sciences. The steel has displayed good irradiation resistance and corrosion resistance in liquid lead alloys. The results of high-temperature water corrosion study showed that SIMP steel has superior water corrosion resistance than T91 steel (Fig. 2). The results of heavy-ion irradiation/high-temperature water corrosion experiments confirm that irradiation causes a significant increase in the corrosion rate of materials. According to the experimental results, the high-temperature water corrosion behavior of the material and the mechanism of corrosion resistance degradation under irradiation are discussed. These results provide an important research platform, experimental methods and scientific data for the rapid screening and evaluation of candidate materials for advanced water-cooled reactors.

The related results have been published in (Corros. Sci. 187 (2021) 109474, Corros. Sci.189 (2021) 109602).

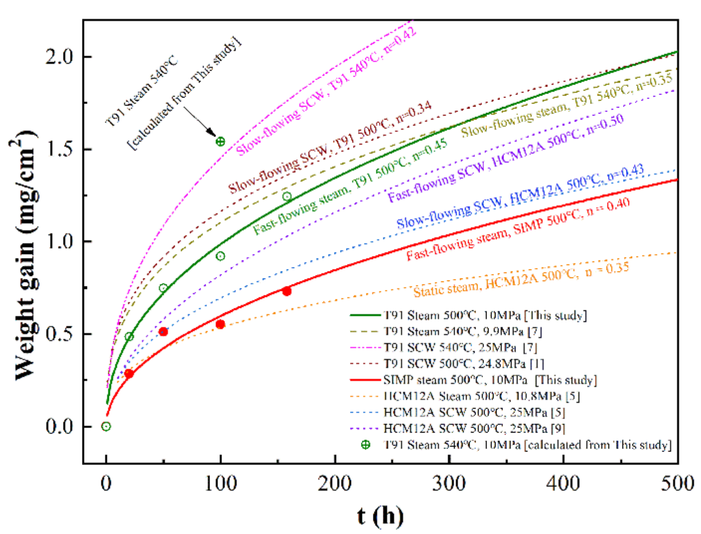


Fig. 3 Corrosion kinetics curves of SIMP and T91 steels (5m/s, 5ppb)

Temperature Induced Dimensional Tuning and Anomalous Deformation of Micro/Nanopores

Artificial nanopores have become a common toolbox in nanotechnologies, with dimension and geometry as predominant factors. Most fabrication technologies determine the pore size beforehand, but few exist that enable size-tuning post- manufacturing. In this work, we reported a type of ion track etched micro/nanopores on uniaxially drawn PET foils that enable irreversible thermal shrinkage, thus tuning the pore dimensions by increasing ambient temperatures. Importantly, we found a complex pore deformation process, which for a specific range of pore sizes and temperatures resulted in a peculiar “eye”-shaped appearance of the pore openings. We analyzed the mechanical stresses and theoretically illustrated the complex deformation process by a phase diagram. Temperature-induced dimensional tuning nanopores reduced maximally over 98% of ionic conduction in a single nanopore and 99% of pressure-driven flow in a pore-array membrane within few seconds at 90 °C, which is useful for temperature-modulated mass transport in nanotechnology and energy applications.

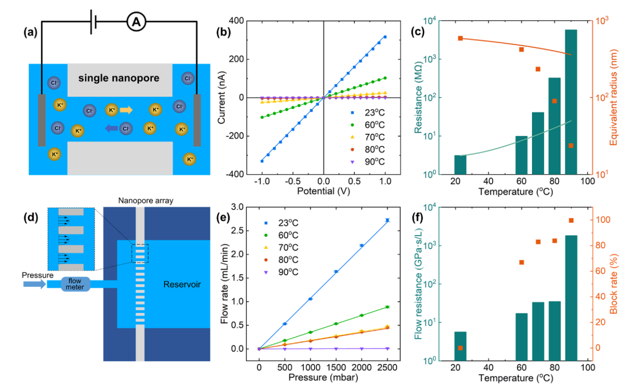


Fig. 4 Temperature control of single-hole and multi-hole heat-shrinkable film

A new japonica Rice cultivar “Dongdao 122” obtained by heavy ion beam mutation breeding

"Dongdao 122" was carried out by the Institute of Modern Physics, Chinese Academy of Sciences (CAS) and the Institute of Geography and Agroecology, CAS. It is the first new Northern Japonica rice variety cultivated by high-energy heavy ion beam radiation mutation breeding technology in China by using HIRFL.

In October, 2021, "Dongdao 122" was planted as a new salt-tolerant rice cultivar in Da 'an Demonstration Zone of "Black Soil Granary" Science and Technology Campaign of CAS with a planting area of 100 mus. Da 'an City is located in the hinterland of Songnen Plain, which is one of the three soda-type saline-alkali land in the world. After testing in strict accordance with relevant national standards, the expert group announced that the average yield of “Dongdao 122” was 632 kg/mu (the yield of high-yield plots reached 721 kg/mu), which was 10.6% higher than that of the local main cultivars. “Dongdao 122” is the first *japonica* rice cultivar bred by high-energy heavy ion beam radiation mutation breeding technique in the northeast of China. After two years of demonstration and popularization, this cultivar has been popularized in soda saline-alkali rice area for more than 200,000 mu. It has the characteristics of salt tolerance, mature with living stalks, lodging resistance and high yield, and is also excellent in adaptability. "Dongdao 122" has been selected as the leading agricultural cultivar in Jilin Province, and it will have a greater promotion prospect in the soda-saline-alkali rice planting area of northeast China in the future.


主要农作物品种
审定证书

Fig. 5 In 2020, Dongdao 2016-M4122 was approved by Jilin Crop Variety Approval Committee and named as "Dongdao 122".

Significant progress on Carbon-ion therapy research and industrialization

On Jan. 30th, 2021, the project of “R&D and industrialization of carbon ion cancer treatment and large tumor treatment device” was awarded the special prize of Gansu Provincial Science and Technology Progress Award in 2020. On October, the achievements of medical heavy ion accelerator at IMP were selected into several national exhibition, for example, the National “13th Five-Year Plan” Scientific and Innovational Achievements

Exhibition.

By the end of 2021, Wuwei carbon-ion therapy system had treated 503 cancer patients (including 46 subjects in clinical trials) with significant effect. The year of 2021 has also witnessed medical institutions in Nanjing and Changchun signed the contracts for heavy ion therapy facilities.

Commercialization and Application of Ion-track Etched Membrane

The Institute of Modern Physics (IMP) performs the characteristic research on Ion-track Etched Membrane, R&D on production technology and its industrial application via the Lanzhou-based heavy-ion research devices.

In 2021, two projects using ion-track etched membrane related to innovative demo base were set up by , respectively located at river-way recovery innovative research base and garbage treatment base through hydraulically filtrated liquid.

In addition, the ion track etched membrane industrial team under the supports of technologies in the terms of Heavy-ion Accelerator Irradiation, Chemical Etching and Vacuum Magnetron Sputtering et al, historically researched and developed the ultra-black material for ion-track etched membrane, in which the electromagnetic wave absorptivity of this material is up to 0.9999 maximum as tested by China’s National Institute of Metrology (NIM), a leading technical level worldwide.

In 2021, the new patent applications were up to NINE, as well as FIVE authorized patent inventions, patent for utility models up to SEVEN, copyright for ONE software, and ONE Gansu Provincial patent inventor prize and the first prize of patent awarded in Gansu Province.

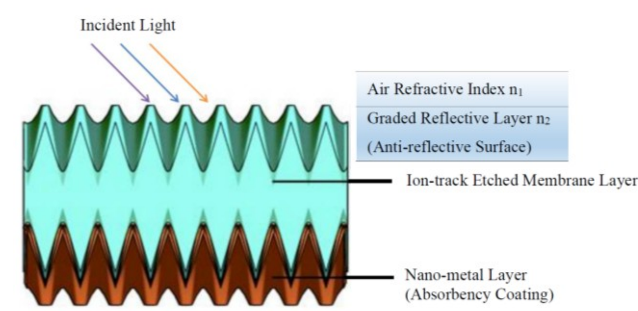


Fig. 6 A New Mechanism Schematic Diagram for ultra-black Material Electromagnetic Wave Absorptivity.

III. Construction, operation and upgrading

In 2021, HIRFL has been operating for about 7848+774 (parallel execution) hours, including 641+230 (parallel execution) hours for the accelerator study and 5797.5+312.5 (parallel execution) hours for 181+5(parallel execution) experiments on the targets. The operation efficiency is about 73.9%+40.4% (parallel execution). During this year, 3917.5+156.5 (parallel execution) beam hours were used for the nuclear and atomic physical experiments, 1222.1+156 (parallel execution) beam hours for the material sciences, 301 beam hours for life sciences (biological sciences), and 356.9 beam hours for space sciences.

HIRFL has provided 24 kinds of heavy ion beams for various experiments, especially, 16 kinds of which have been provided for the experiments firstly by HIRFL in the past year. A summary of the HIRFL operation is shown in Table 2.

The main highlights of 2021 HIRFL machine maintenance and transformation are as follows:

1. A new theoretical acceleration curve was applied on the RF cavity in CSRm. In addition, the output frequency error of the ferrite RF cavity was measured in CSR, and change the harmonic number from 2 to 3 to decrease the ion bunch density at injection energies. According to these optimizations, the capture and acceleration efficiencies of heavy ion beams were improved from 85% to 95%.

2. By optimizing the superconducting ECR ion source, increasing the voltage of RF buncher in SFC and correction the closed orbit at injection energies in CSRm, the stored heavy ion number were increased significantly. The stored beams of Ar and Kr ions were achieved 1E9 for the first time.

3. By optimizing the extraction kicker angle, matching of the twiss parameters between CSRm and RIBLL-2 and calculation of the beam line in detail, the beam quality at the experimental terminal PISA was improved. The beam radius is about 1 mm and the vibration of position is less than 0.1 mm.

4. Through the redesign and alteration of transmission line and coupling capacitance of SFC RF system, the Q value of the SFC RF cavity (increased by 10%) and the effective RF voltage (increased by 11%) significantly are improved, the transmission loss(transmission loss ⩽ 0.3%) between the SFC RF cavity and the power sourcer is reduced, and the frequency replacement time of the SFC RF system is reduced from 3 hours to 0.5 hours.

5. With Afterglow pulsed mode, some record beam intensities of highly charged ions have been produced on the SECRAL-II fully superconducting ECR ion source platform, like 266 euA of $^{129}Xe^{34+}$, 169 euA of $^{129}Xe^{38+}$, 50 euA of $^{129}Xe^{42+}$, and so on. Compared with the CW mode, the beam intensity gain is 2-7 times. The pulse width (FWHM) reaches 6-10ms, which is 2-3 times that of the traditional afterglow mode. At present, this technology has been applied in HIMM project successfully and achieved about 60% beam intensity improvement in the storage ring.

Table1. Distribution of HIRFL Operation Time in 2021

Operation time distribution	SFC		Linac	
	Time (h)	Percentage (%)	Time (h)	Percentage (%)
Total operation time	**7848**	**100**	**774**	**100**
Failure time	**229.5**	**2.9**	53	6.9
Preparation of beam	**547.5**	**7.0**	56	7.2
Beam testing	**595.5**	**7.6**	122.5	15.8
Other time	**37**	**0.5**	0	0
Target beam time	**6438.5**	**82**	**542.5**	**70.1**
Nuclear physics	3917.5	60.8	156.5	28.8
Material sciences	1222.1	19.0	156	28.8
Biophysics	301	4.7	0	0
Space sciences	356.9	5.5	0	0
Machine study	641	10	230	42.4

Table2. the Typical Ion Beams Provided by HIRFL in 2021

Index	SFC/Linac			SSC		CSR		
	Beam	Energy（MeV/u）	Current（uA）	Energy（MeV/u）	Current（uA）	Energy（MeV/u）	CSRm Current（uA）	CSRe Current（uA）
1	$^{78}Kr^{26+}$	6	10			460	2000-4000	次级束
2	$^{129}Xe^{22+}$	1.844	2.6	19.5	0.23			
3	$^{78}Kr^{24+}$	4.75	7					
4	$^{54}Fe^{16+}$	4.82	6					
5	$^{181}Ta^{35+}$	1.5202	0.2	16	0.01			
6	$^{12}C^{4+/6+}$	7	2.7	80.55	0.1			
7	$^{14}N^{4+}$	4.3	5					
8	$^{12}C^{4+}$	5.2	4					
9	$^{12}C^{3+}$	4.2	2					
10	$^{4}He^{1+}$	4	3					
11	$^{30}Si^{8+}$	4.33	2					
12	$^{20}Ne^{7+}$	6.17	3					
13	$^{129}Xe^{32+}$	4	8			276	2600	
14	$^{64}Ni^{19+/25+}$	5.361	1.8	60	0			
15	$^{133}Cs^{27+/55+}$	2.2	1.6			204、75	300-350	200
16	$^{14}N^{6+}$	8.4	3					
17	$^{86}Kr^{28+}$	6.5	2					
18	$^{129}Xe^{35+}$	5	0.8					
19	$^{7}Li^{3+}$	9	1					
20	$^{36}Ar^{15+}$	8.5	15			376、445	4000	次级束
21	$^{16}O^{5+/8+}$	5.361	9	60	0.65			
22	$^{129}Xe^{22+}$	0.58	40	5.98	2.3			
23	$^{40}Ar^{7+/16+}$	0.58	50	5.98	6	320、400	1000	
24	$^{40}Ca^{12+}$	5.4	5					

**: The ions with yellow shading were provided firstly by HIRFL in 2021.

IV. Scientific & technical personnel and talent training

The total number of staff for HIRFL is up to 426, composed of 252 operating and maintaining staff, 163 researchers and other 11 employees. 259 out of the 426 have senior and 127 have intermediate title. In addition, regarding to the postgraduate education at IMP in 2021, up to 86 students have graduated from IMP with a doctoral degree or a master degree whereas 483 students have been doing their postgraduate work.

IMP established "Outstanding Achievement Award" and "Youth Science and Technology Award" to cultivate and stabilize excellent teams and young talents, promoted collaborative innovation strategy to jointly cultivate innovative talents with domestic universities, and made full use of the good opportunity of international cooperation to jointly cultivate practical scientific and technological talents with foreign famous research institutions and Universities.

V. Cooperation and exchange

Due to the outbreak of COVID-19 in 2021, international exchange by scientific researchers have been suspended around the world. In response to fight against the risk, video talks, telecommuting and online international conferences are carried out by scientific personnel to continue their research.

In 2021, The Institute signed agreements with 4 universities or institutions in 3 countries, including USA, Korea, Germany. During this year, 14 CAS President's International Fellowship Initiative (PIFI) are supported by Chinese Academy of Sciences, 9 Foreign Researcher Grants financed by Ministry of Science and Technology, 3 CAS' Special Exchange Programme, and 5 students and staff in all are supported by China Scholarship Council (CSC), 2 International Conferences online organized.

International Large-Scale Scientific Research Base on Antiproton and Ion was rated outstanding in the review on International Science and Technology Cooperation Base by the Ministry of Science and Technology in 2020. As of December 2021, 31 foreigners including 11 foreign employees, 12 foreign postdoctors, 1 fellowship and 7 foreign students have been introduced to IMP.

From May 22nd to 23rd, 2021, the 17th Public Science Day organized by the National Laboratory of Heavy Ion Research Facility in Lanzhou (NLHIRFL). In this event HIRFL received more than 5000 visitors.

VI. Chronicle of events

On Jan. 30th, 2021, the project of "carbon ion cancer treatment research and R & D and industrialization of large tumor treatment devices" won the special prize of Gansu Provincial Science and technology progress award, which is also the first special prize established by Gansu Provincial Science and technology award.

On Apr. 17th, 2021, the 2021 review meeting of applications for NLHIRFL beam time was held in Lanzhou.