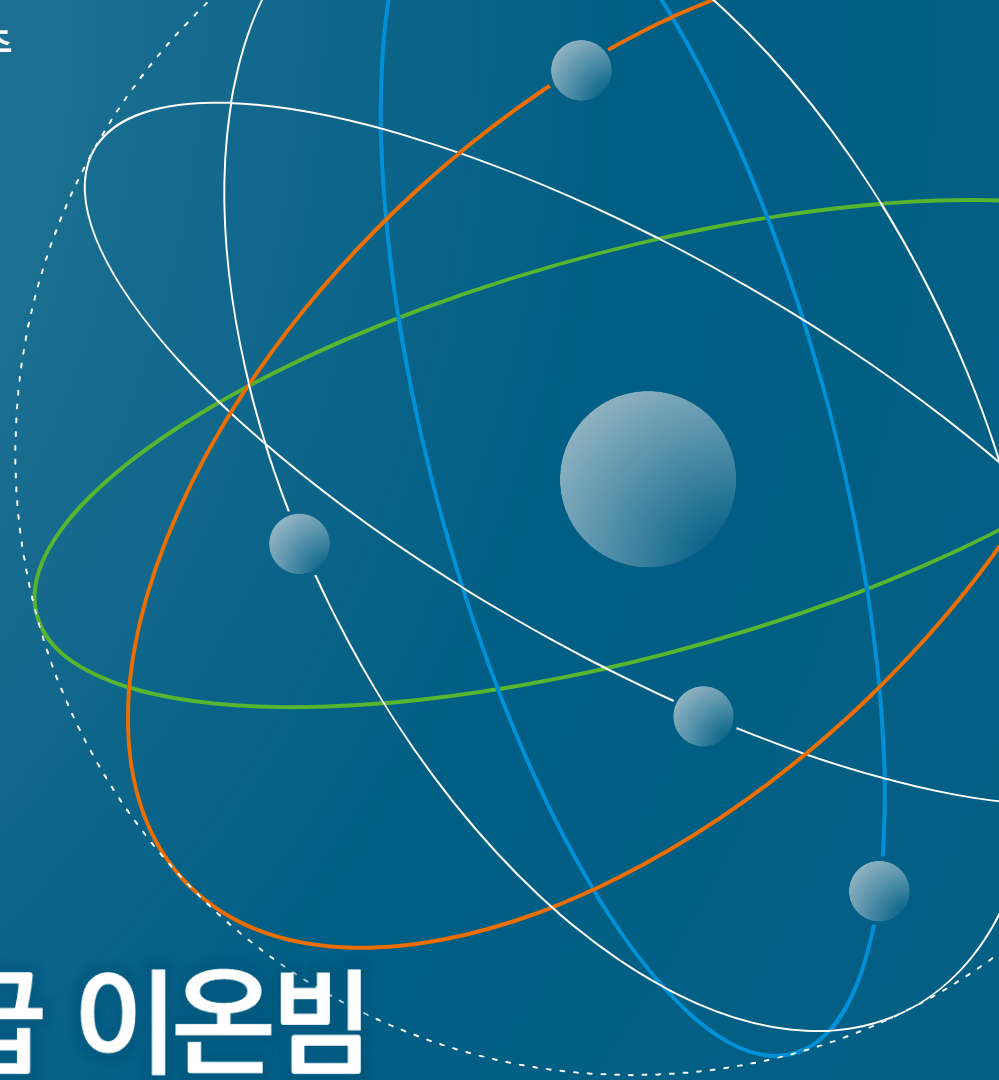


2025 춘계원자력학회 Workshop, 2025년 5월 21일, 제주

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KOMAC의 MeV급 이온빔 장치 현황 및 활용 계획

한국원자력연구원 가속기개발연구부
김한성

더 나은 세상을 위한 원자력기술
국민과 세계가 지지하는

한국원자력연구원

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- 04 1 MeV/u RFQ 기반 가속기
- 05 활용 계획



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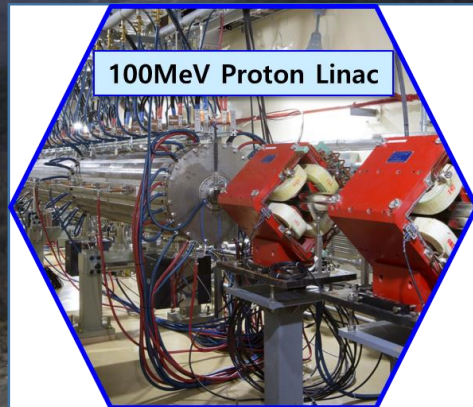
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01

양성자과학연구단 시설 개요



한국원자력연구원, 양성자과학연구단 (KOMAC)



Generator building

Main Hall

Main Gate



Ion beam building





한국원자력연구원
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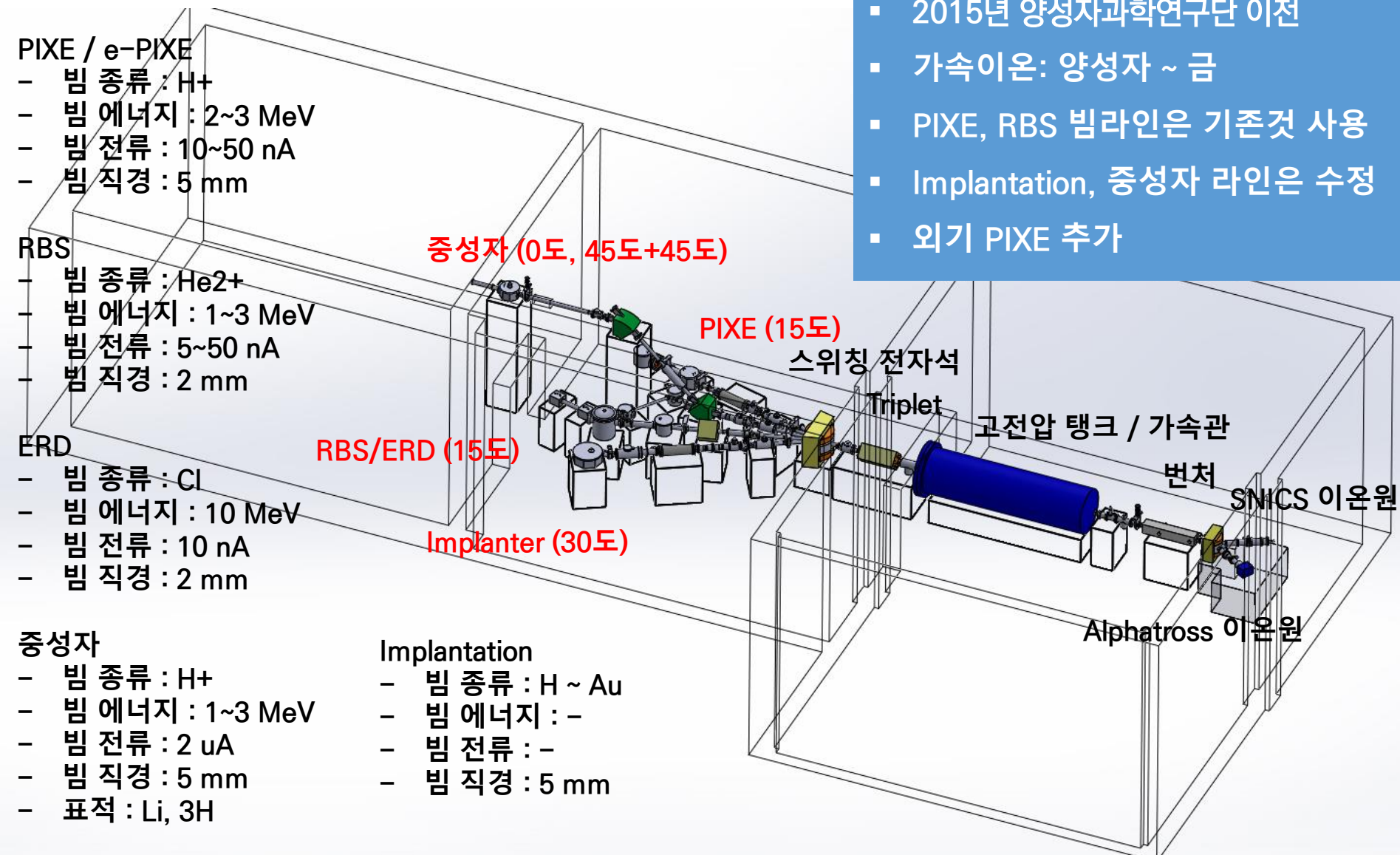


02

탄DEM 가속기

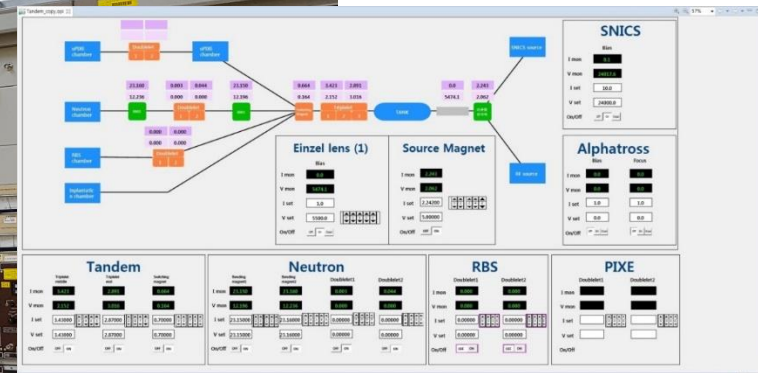
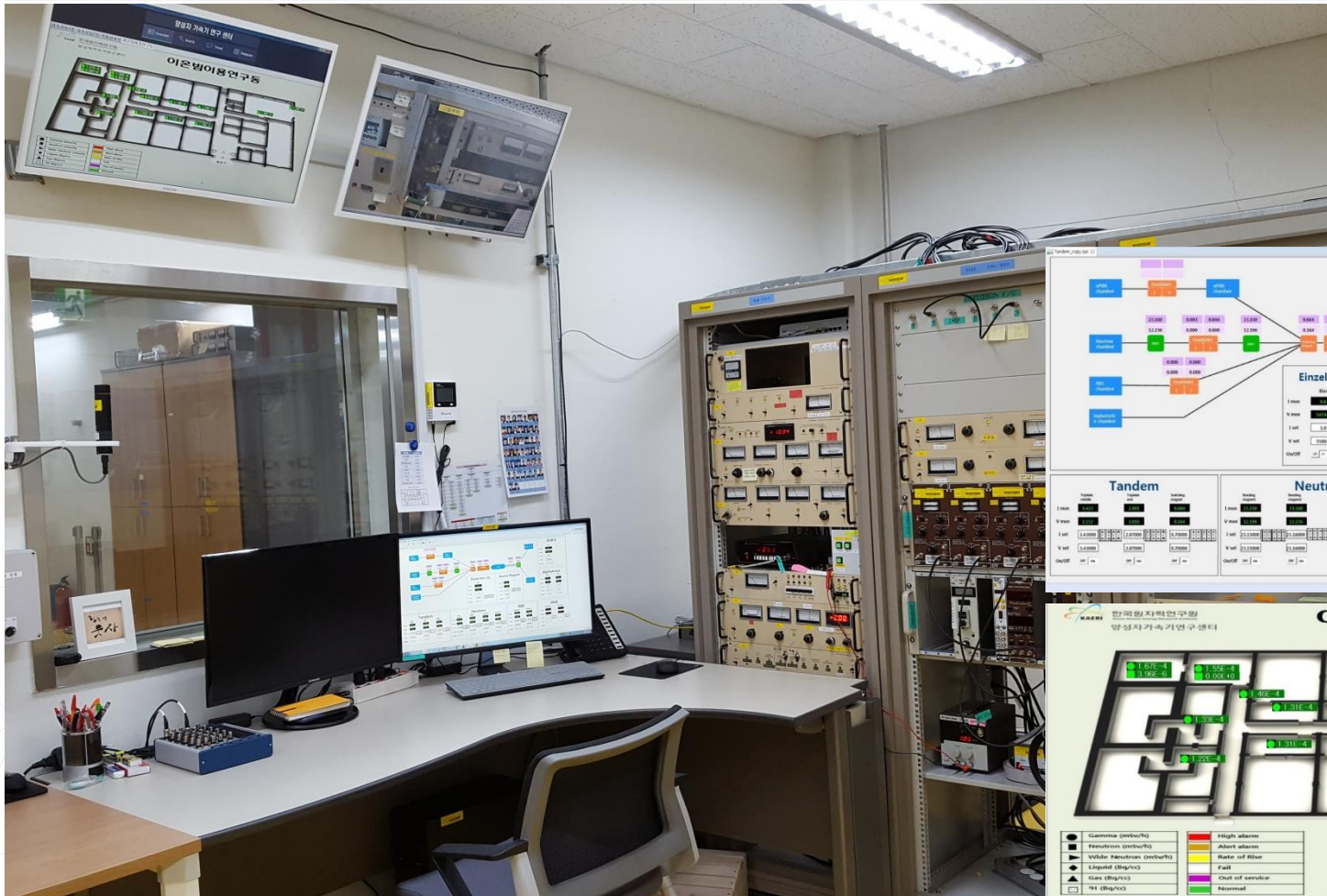
1.7 MV 탄뎀 가속기 개요

- 1988년 지질연 설치, 운영
- 2015년 양성자과학연구단 이전
- 가속이온: 양성자 ~ 금
- PIXE, RBS 빔라인은 기존것 사용
- Implantation, 중성자 라인은 수정
- 외기 PIXE 추가



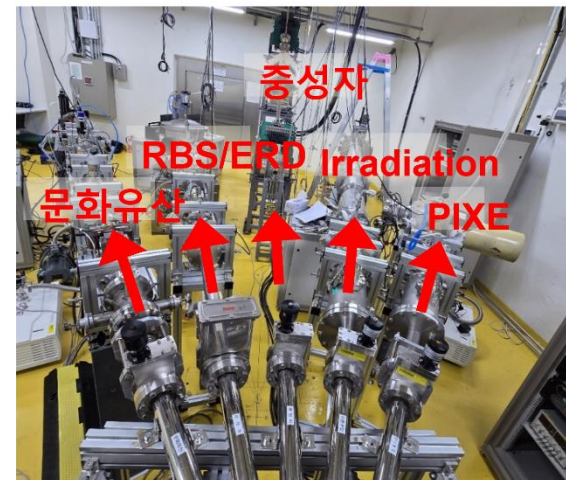
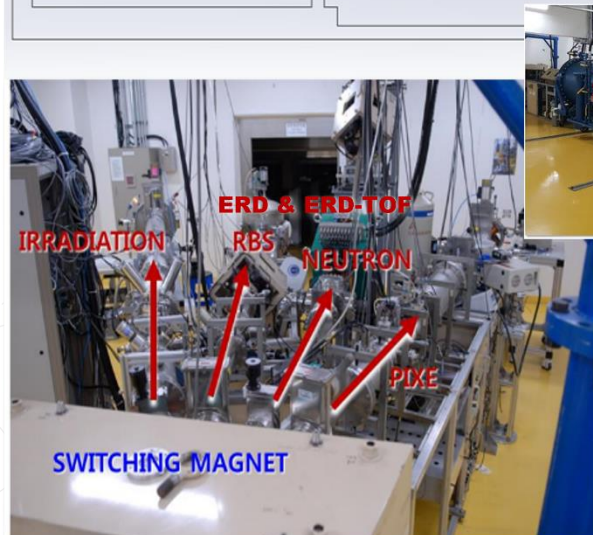
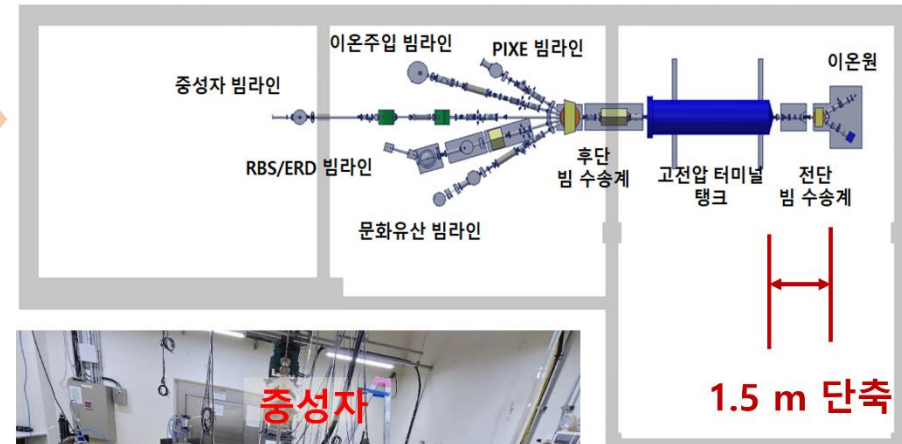
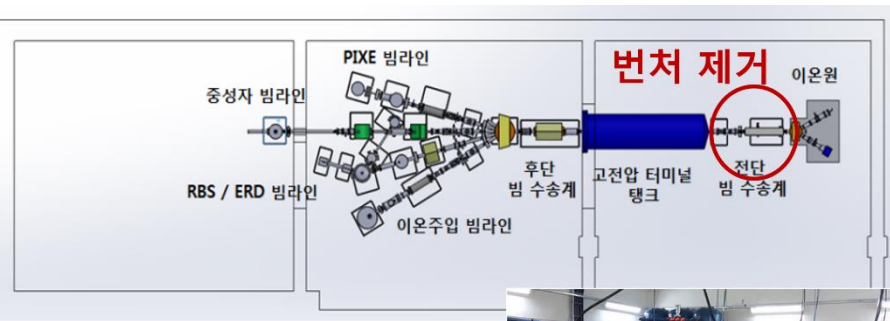
장치 개선 및 추가 구축

- 빔라인 및 전자석, 진공시스템(TMP, Gauge), 조사챔버, 가속기 제어, 방사선 감시
- 고전압 터미널, 이온원 전원, 스티어링 전원 등은 기존 아날로그 제어 방식 사용
- 새로 설치한 장비 (전자석 전원 등) 은 EPICS 기반 제어 시스템 구축



장치 개선 및 추가 구축

- 빔라인 개수 : 4개 => 5개
- 빔라인 위치 변경 및 추가 : 문화유산 분석용 외기빔 PIXE 빔라인 추가

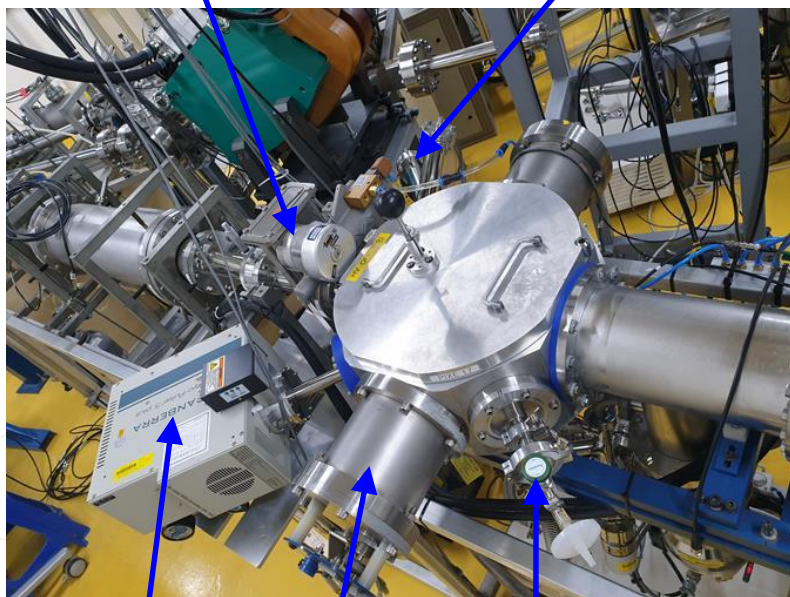


PIXE 빔라인

- 양성자 빔 이용
- 미량 원소 분석
- 검출기: SDD (Silicon Drift Detector), LEGe (Low Energy Germanium) Detector

게이트밸브

SDD 검출기 feedthrough



LEGe 검출기 냉각기

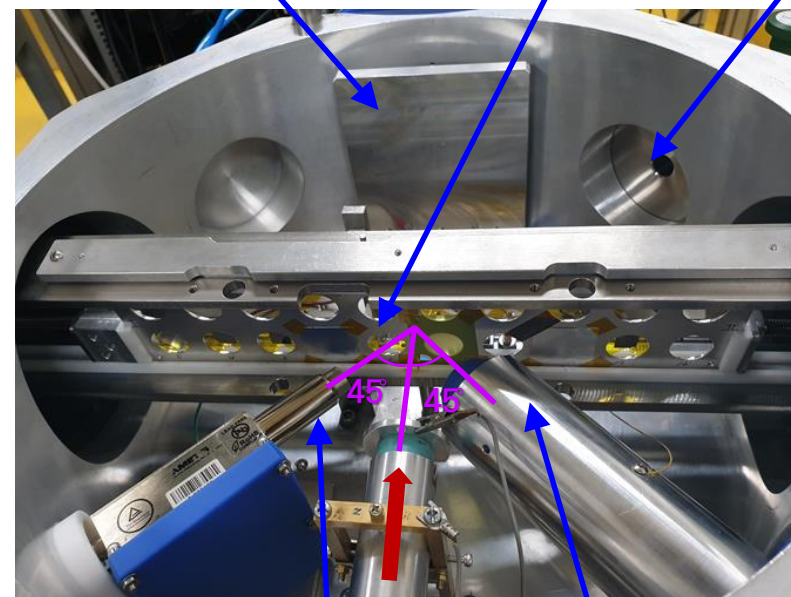
Venting 밸브

시료 위치 변경 장치

- SDD (Silicon Drift Detector) : 저에너지 X-선 측정
- LEGe (low Energy Germanium Detector) : 고에너지 X-선 측정

빔 덤프

시료



SDD 검출기

LEGe 검출기

외기 PIXE 빔라인

- 빔창: Kapton film (FCV 설치)
- 빔창과 공기층의 영향: XRF 표준시료를 이용한 분석 비교
- X-Y-Z 3축 스테이지

PIXE Chamber

Gate Valve

Si(Li) Detector

Sample Holder

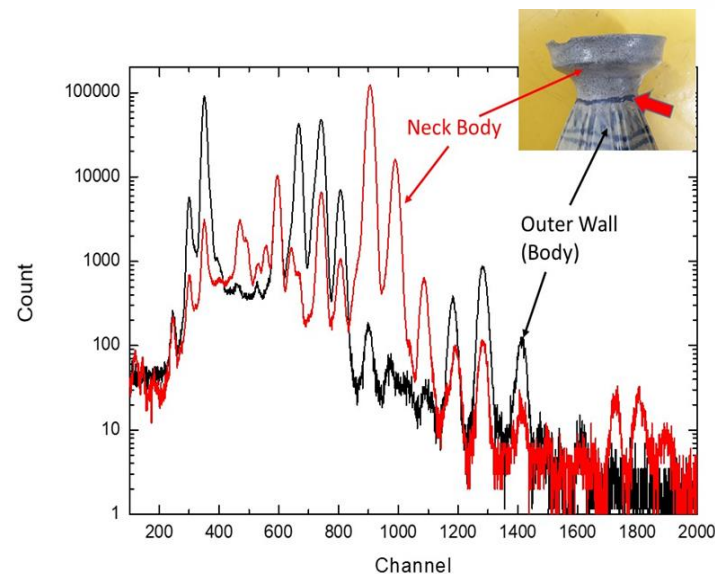
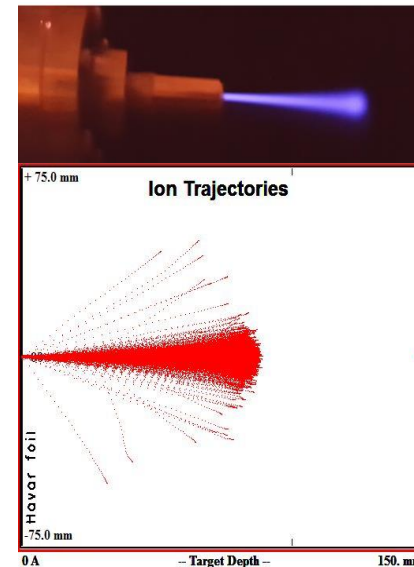
X-Y-Z Motion Stage

Fast Closing Valve

MQD

Quartz Beam Monitor

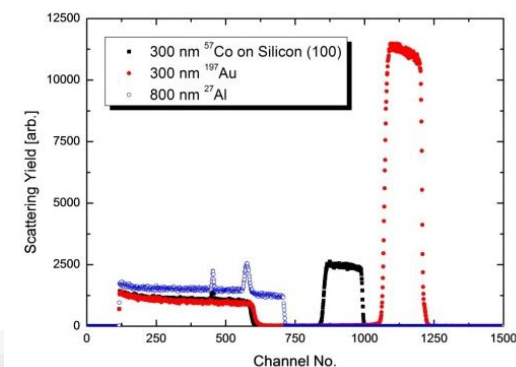
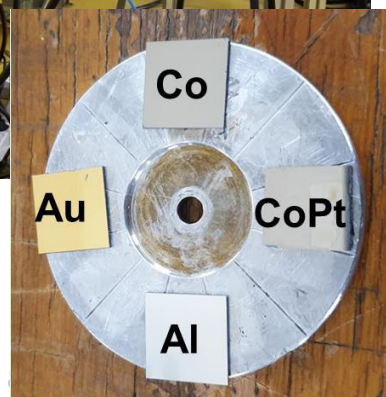
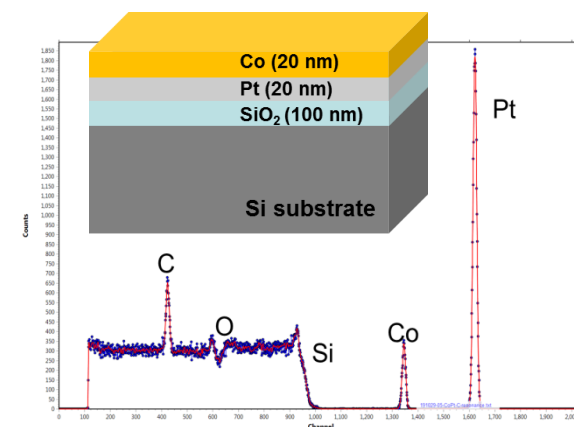
SDD Detector



문화재시료 측정스펙트럼

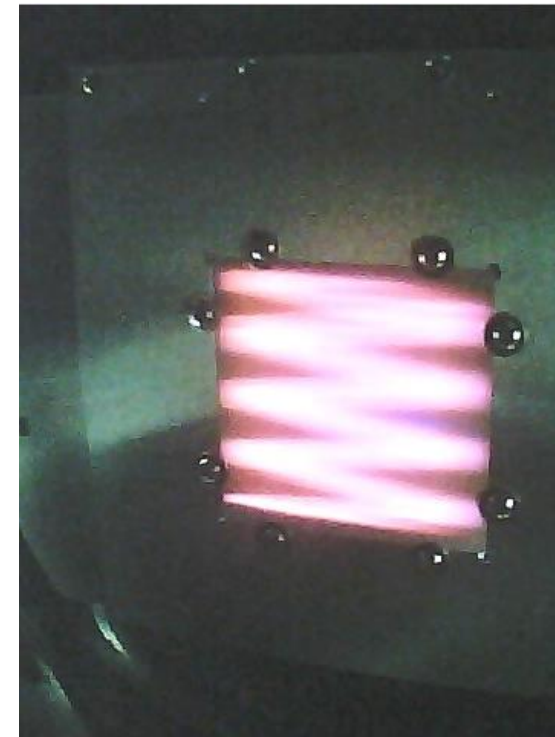
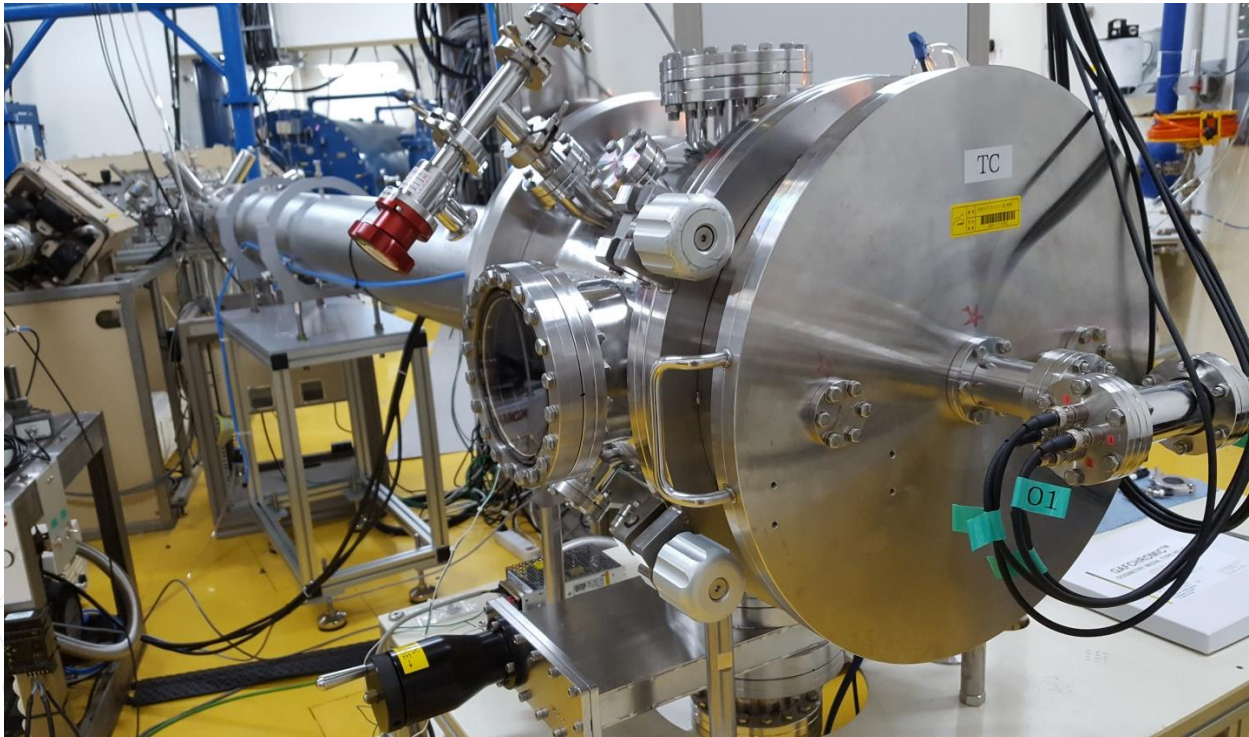
RBS 빔라인

- 1~3 MeV 헬륨빔 이용
- 깊이에 따른 성분 분석이 장점
- 검출기: SSB (Silicon Surface Barrier) Detector



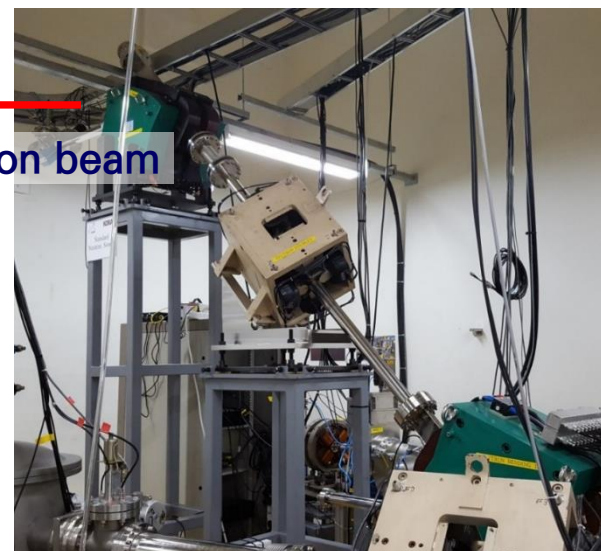
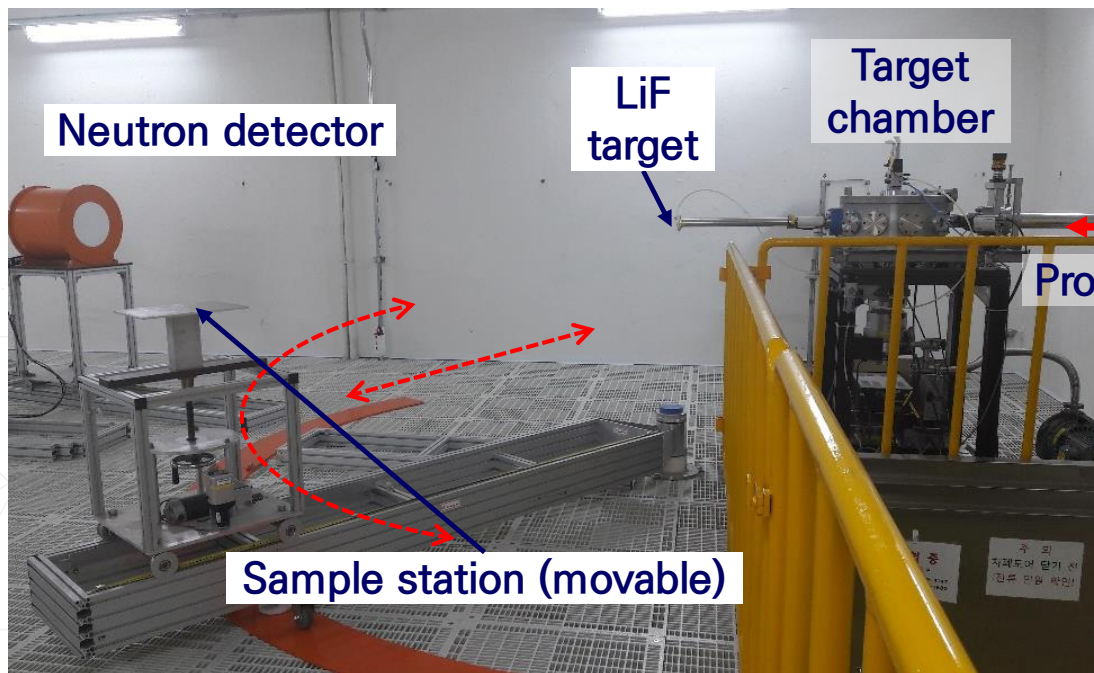
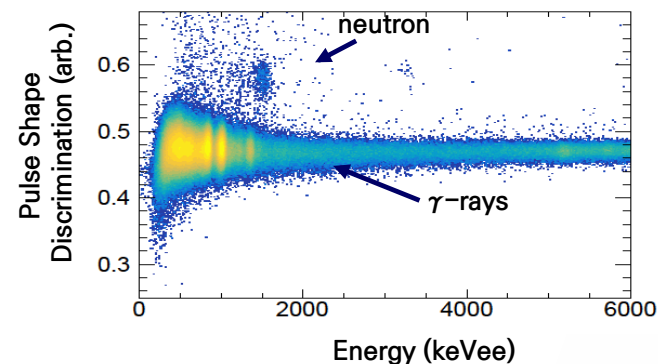
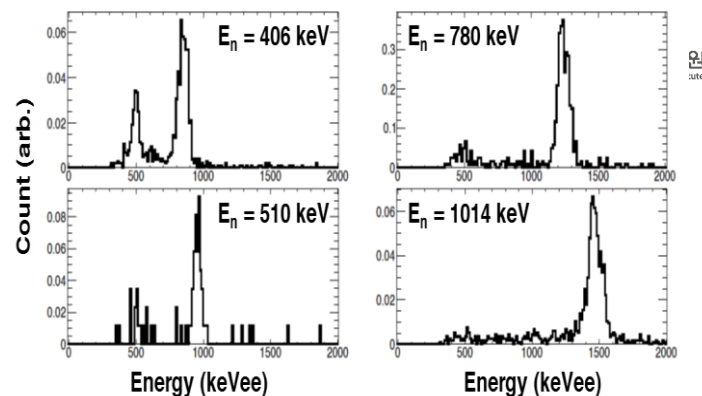
Implantation 빔라인

- 다양한 종류의 이온빔
- 6" 웨이퍼 기준, 조사 선량 uniformity: < 10%
- 조사 선량: $5 \times 10^{15} / \text{cm}^2$ / 4시간
- Raster scanner 이용 (517 Hz, 64 Hz)
- 여러 개의 Faraday cup을 이용한 실시간 uniformity 측정



중성자 빔라인

- Neutron target room
 - Neutron production target: LiF
 - ${}^7\text{Li}(p, n){}^7\text{Be}$ reaction
 - ($E_{\text{th}} = 1.881 \text{ MeV}$, $Q = -1.644 \text{ MeV}$)
 - Detector: Plastic scintillator, CLYC, He3
 - Under pilot operation for users



3 MV 탄뎀 가속기

- Application : AMS, Material damage test by ion beam
- Specifications
 - Ion species: C, He, Fe etc.
 - Acc. Voltage: max. 3.0 MV
 - Beamlines: AMS, irradiation, PIGE
- Status : Under installation and test



3 MV Tandem under installation



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03

1 MV Single-Ended 정전형 가속기

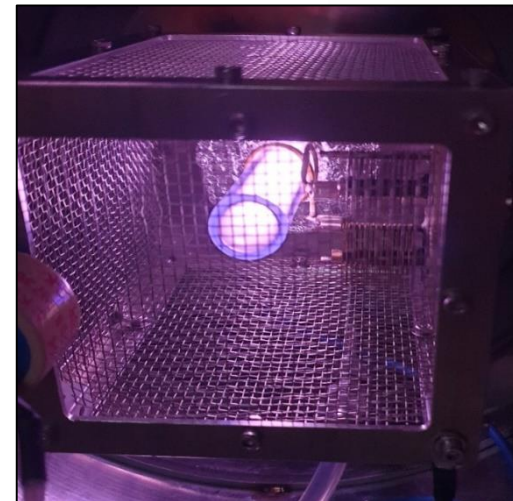
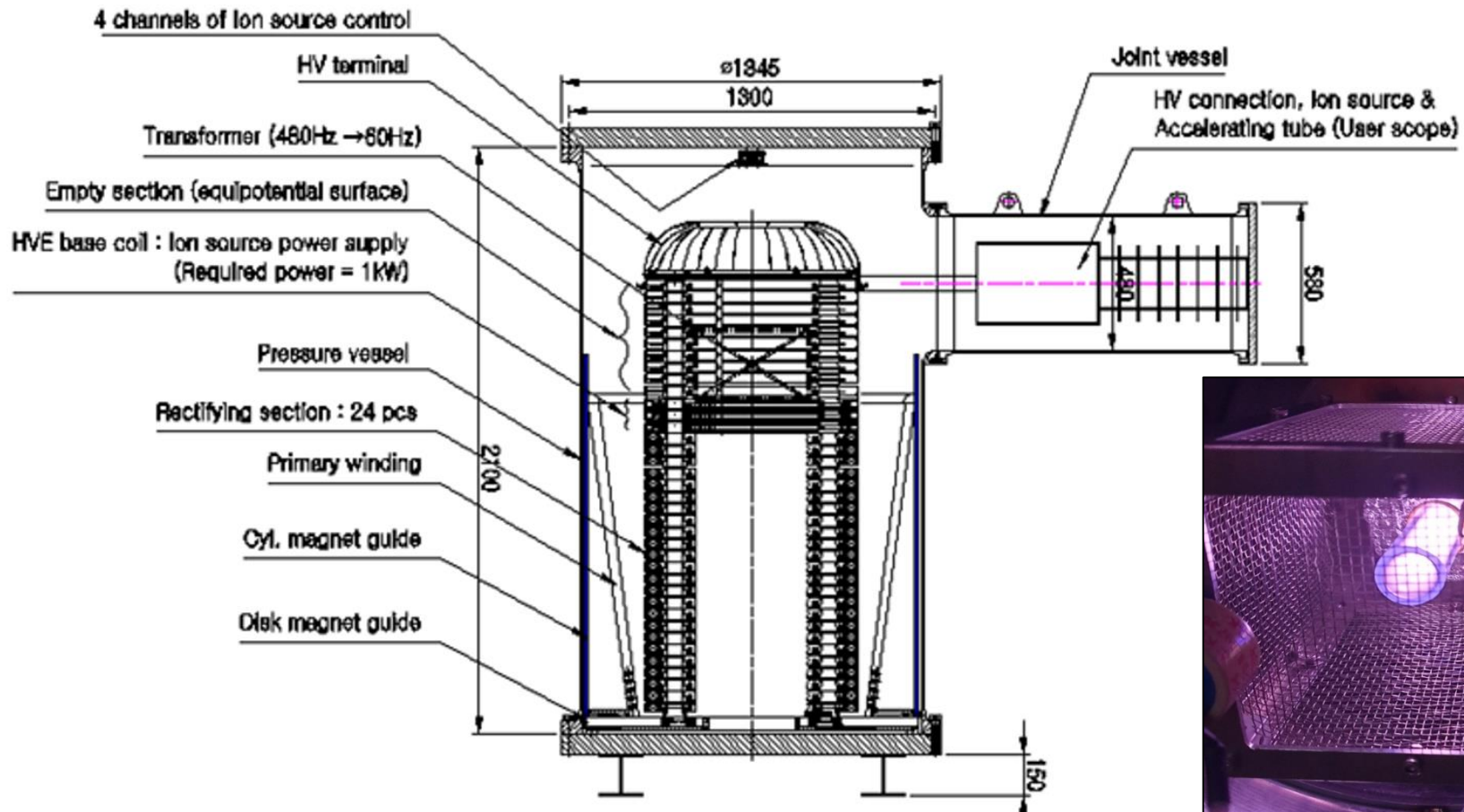
1 MV Single-Ended 정전형 가속기 개요

- 최대 전압: 1 MV
- 핵심기술: 1 MV 전원, 소형 이온원, 이온원 전원
- 구성: 이온원, 가속관, triplet, 스위칭 전자석, raster scanner, 조사 챔버
- Raster scanner 이용 (517 Hz, 64 Hz)
- 여러 개의 Faraday cup을 이용한 실시간 uniformity 측정
- 반도체 웨이퍼 조사용 load lock 챔버 설치



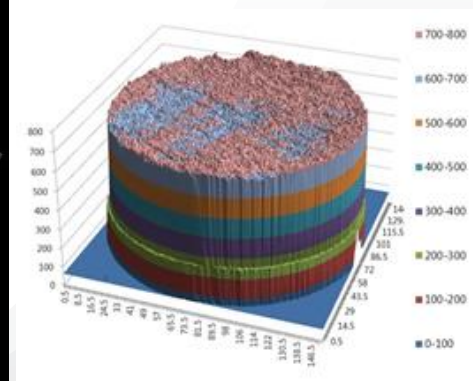
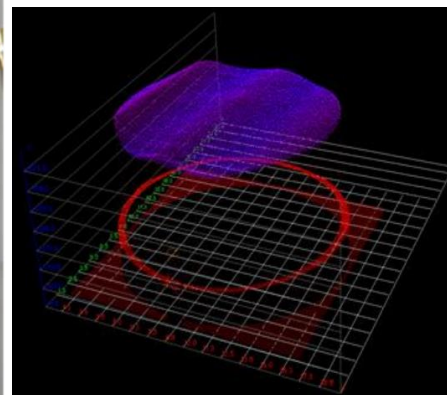
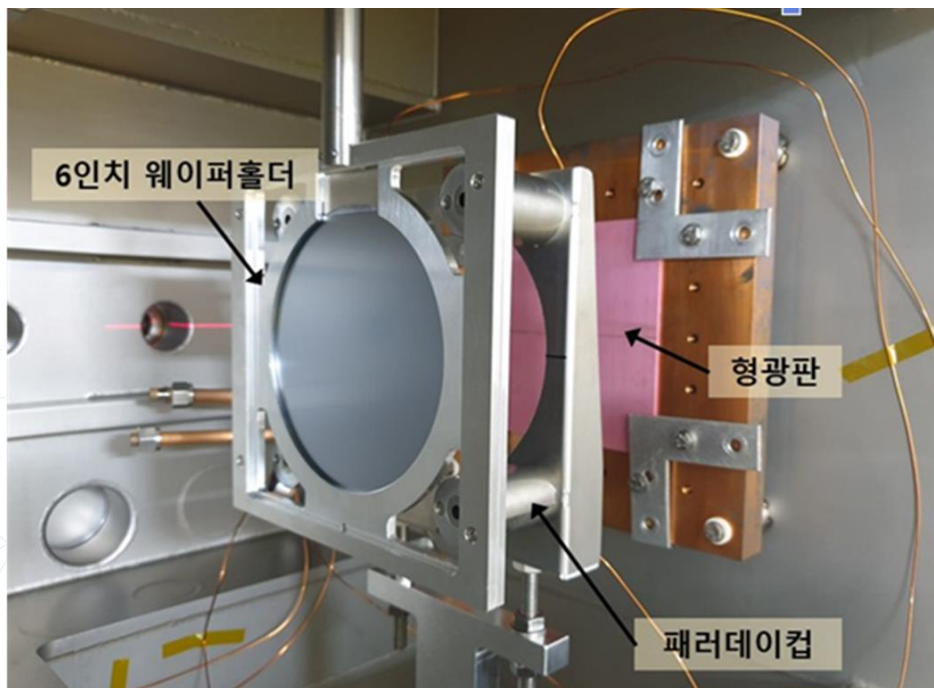
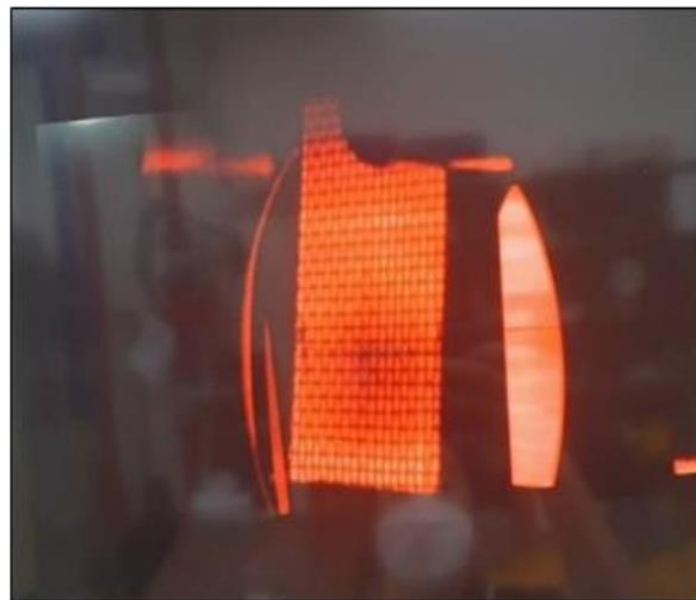
핵심 기술: 1 MV 전원, 소형 이온원, 이온원 전원

- 1 MV 전원: 전자빔 조사용 전원 사용 (ELV 형)
- 소형 이온원: 200 MHz 고주파 이온원 (1 turn loop + air variable capacitor)
- 이온원 전원: 전원 코일 + LC 공진 회로 + 정류기



1 MV 가속기를 이용한 반도체 웨이퍼 조사에

- 반도체 웨어퍼 조사용 Load lock 챔버 설치
 - : 6인치 웨이퍼
 - : 빔 스캐닝 electrostatic raster scanner
 - : 빔 조사 균일도 < 10%





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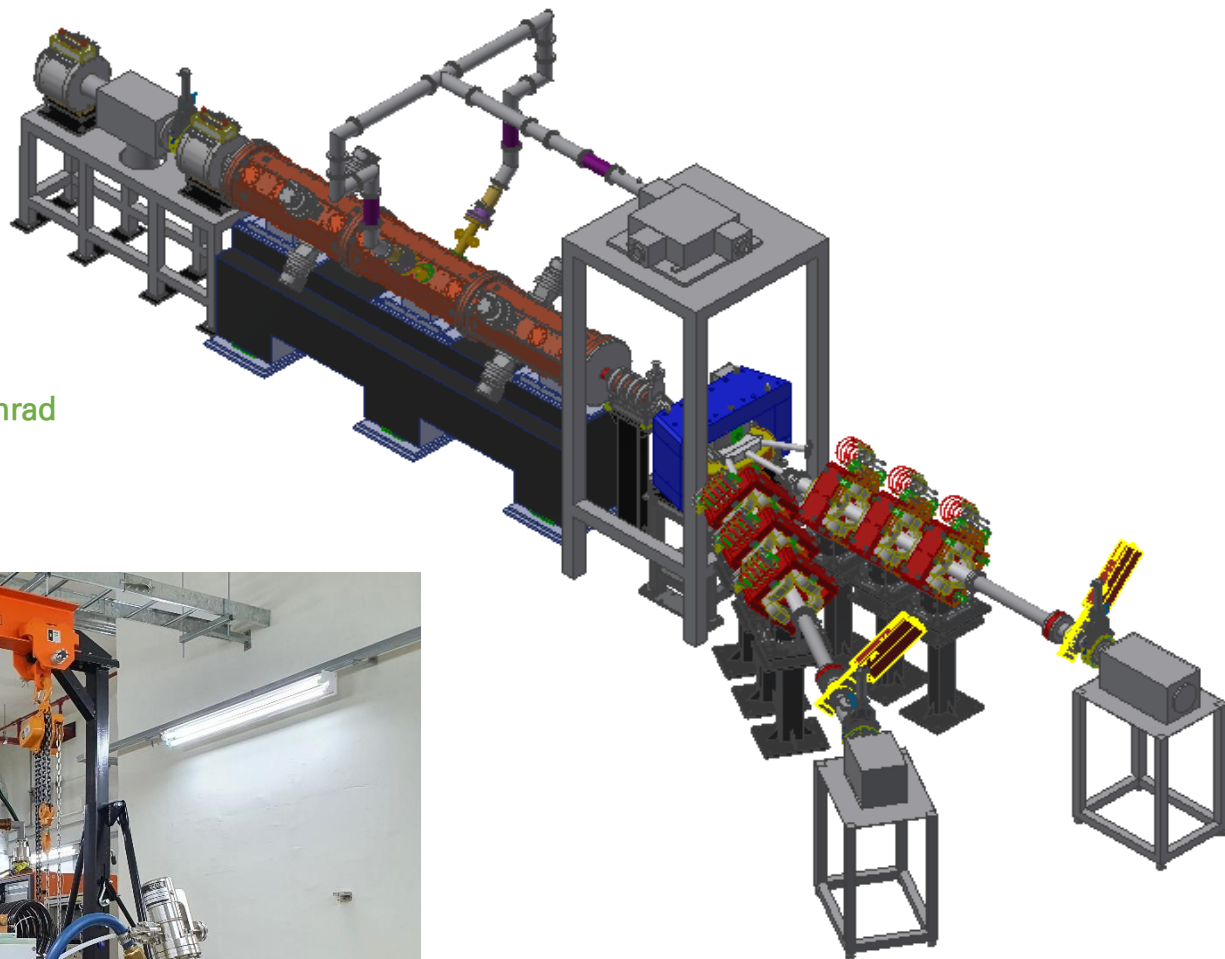


04

1 MeV/u RFQ 기반 가속기
Beam Test Stand:BTS

BTS 개요

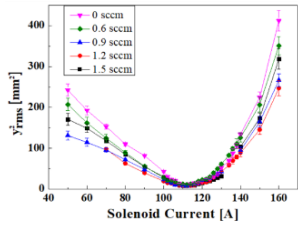
- Input beam energy: 25 keV/n
- Output beam energy: 1 MeV/n
- Design particle: $^4\text{He}^{2+}$
- Peak beam current: 10 mA
- Emittance (normalized rms): $0.2 \pi \text{ mm mrad}$
- RF: 200 MHz, 130 kW
- Vane Voltage: 72 kV



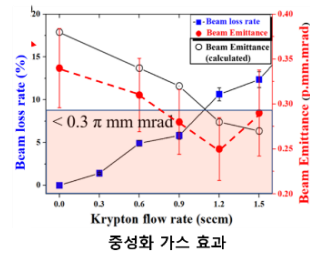
- 한국 원자력연구원 RFQ 개발 이력
 - 국내 최초 개발 (2002)
 - 국내 최근 개발 (2022)
- 기술개발을 위한 시험시설
 - 장치기술, 운영기술, 빔물리
- 이온빔 이용 (proton, deuteron, helium)

BTS를 이용한 빔물리 및 장치 연구

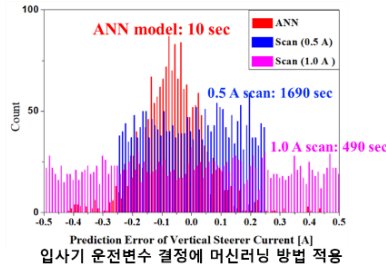
이온원 테스트 스탠드



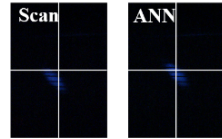
솔레노이드 스캔에 의한 에미턴스 측정



중성화 가스 효과



입사기 운전변수 결정에 머신러닝 방법 적용



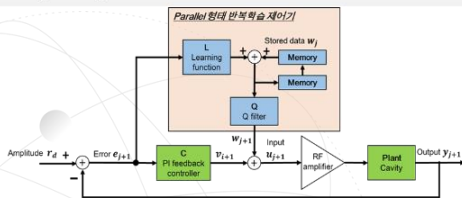
Steerer = (4.0 A, 1.0 A) (3.59 A, 1.36 A)

	Time	Steerer [A]		Position [mm]	
	[sec]	X	Y	X	Y
Neural Network	10	3.59	1.36	+0.3	-1.4
Parametric Scan	490	4.0	1.0	-2.0	-3.2

고주파 테스트 스탠드

□ 반복학습을 이용한 adaptive feed forward 알고리즘 실증

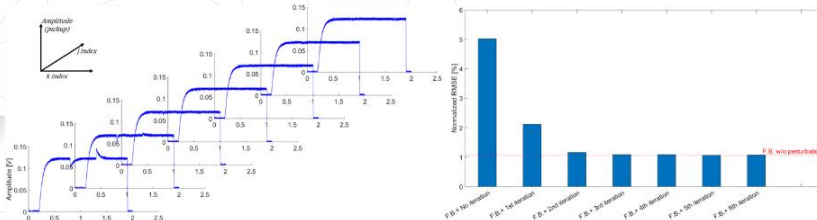
- Dummy cavity를 이용한 실험실 단계의 반복학습 제어기 검증 완료



반복학습 제어 알고리즘



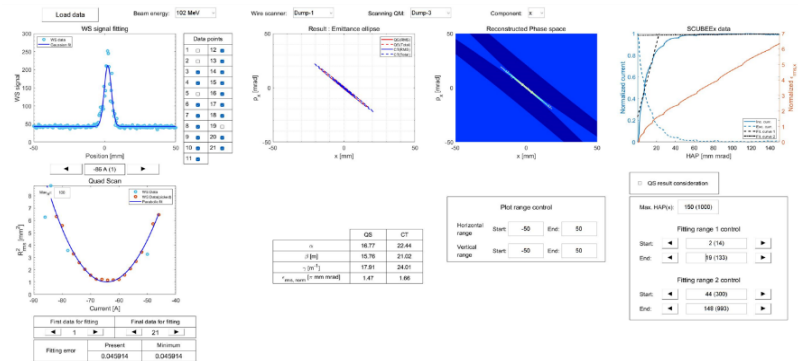
Dummy cavity 실험



빔로딩 등 과도응답에 대한 제어성능향상

빔진단 테스트 스탠드

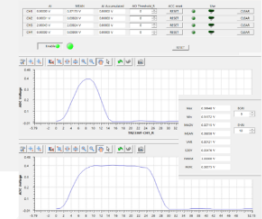
- 기존 방법의 경우 빔물리 변수 측정은 가능하나, 다차원 빔 분포를 측정하는 것은 어려움
- 최근 주목받고 있는 대용량 양성자가속기 빔물리 주제: 4차원, 6차원 빔 분포 측정
- 100 MeV 가속기를 이용하는 경우, 실험 시간의 제한 및 일관성 있는 데이터 획득의 한계로 기술 적용의 어려움
- 1 MeV/n RFQ를 이용한 빔 위상공간 분포 측정기술 개발



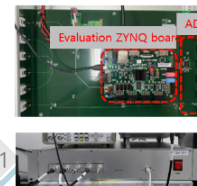
제어 테스트 스탠드

□ DAQ 시스템 성능시험

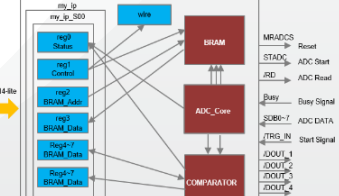
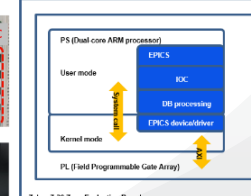
- 빔 진단 계통 : BCM, BLM, wire scanner DAQ 성능 시험
- 고주파 계통 : 파형, 이상신호 수집
- 최적 하드웨어와 소프트웨어 개발 및 시험 필요
- 저비용, 재사용 높은 SoC(System on Chip) 기반 DAQ 도입
 - 자체 개발, 신제품 (Libera, NI-DAQ, PENTEK ADC) 구배
- XILINX zynq-7020 SoC 자체 개발
 - Artix-7 FPGA, ARM core, Analog Device (AD7605)



ADC DAQ 시스템



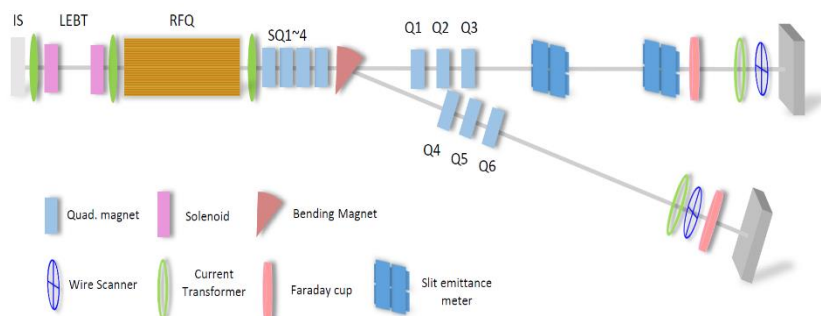
Zilinx Zynq 7000 Family



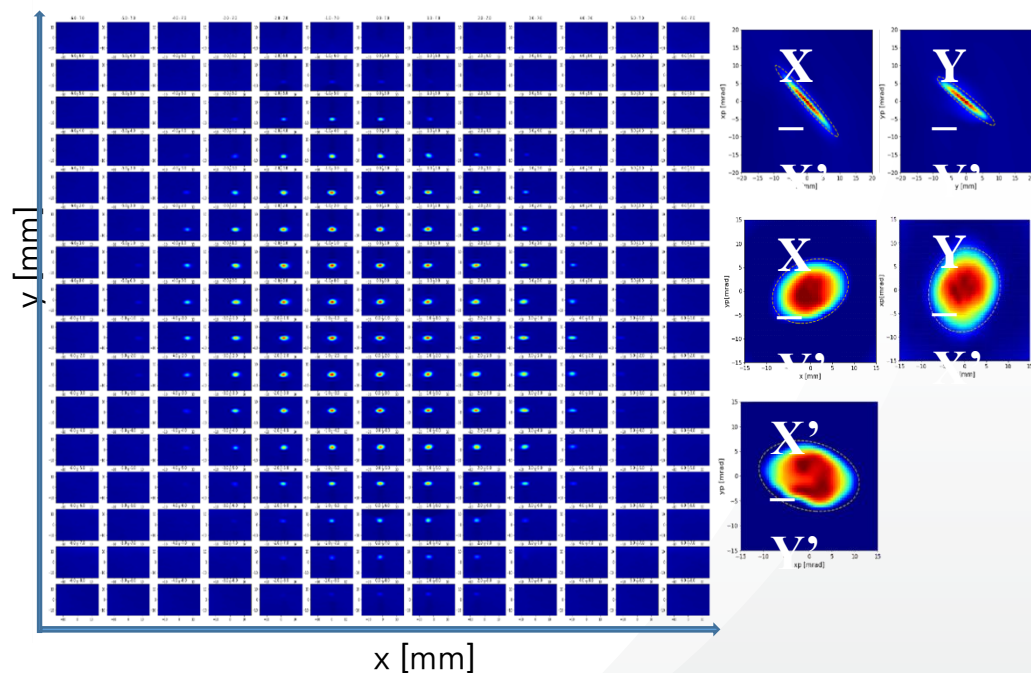
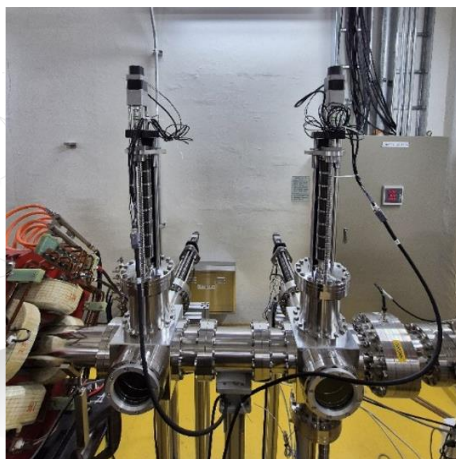
BTS를 이용한 빔물리 및 장치 연구

4D Beam Phase Space Measurement (2024)

Schematic view of experiment setup



View of 4D slit scan system

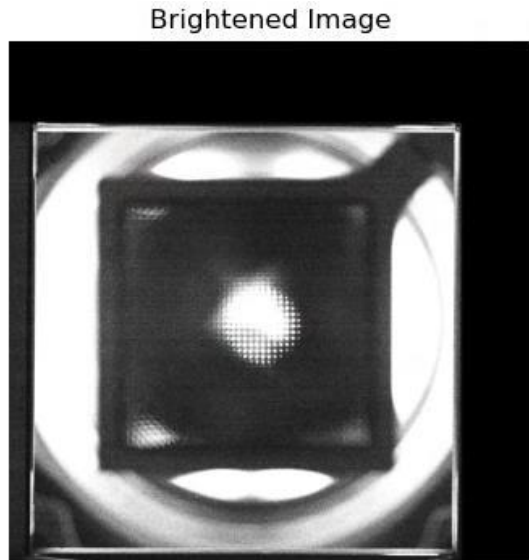


Direct & Precise Measurement of 4D Phase Space

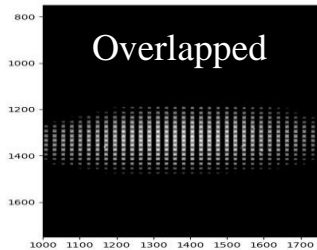
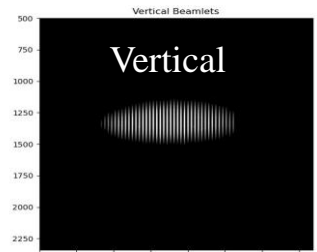
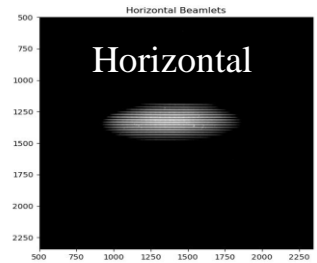
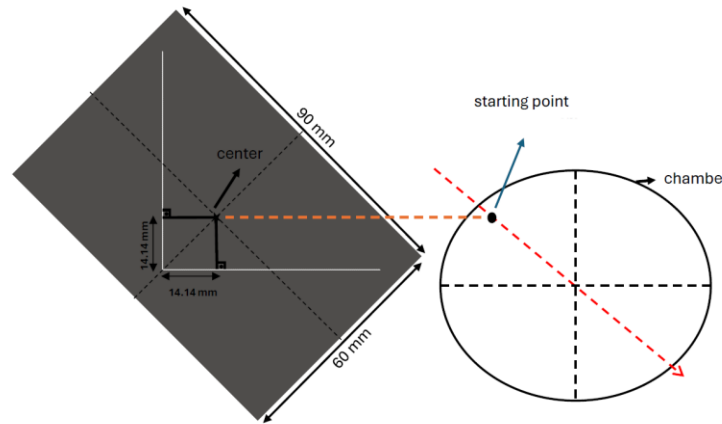
BTS를 이용한 빔물리 및 장치 연구

Pepper Pot & Virtual Pepper Pot Phase Space Measurement (2025)

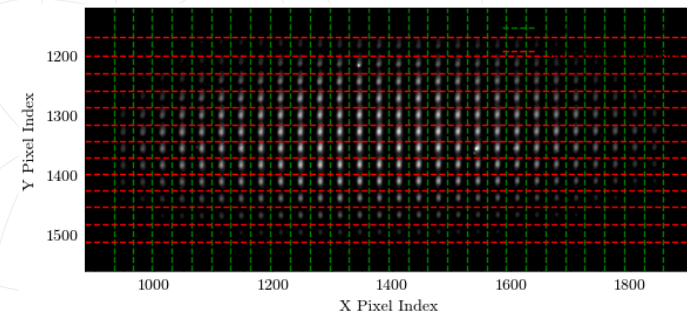
Pepper pot slit and screen



Schematic of Virtual Pepper Pot Measurement

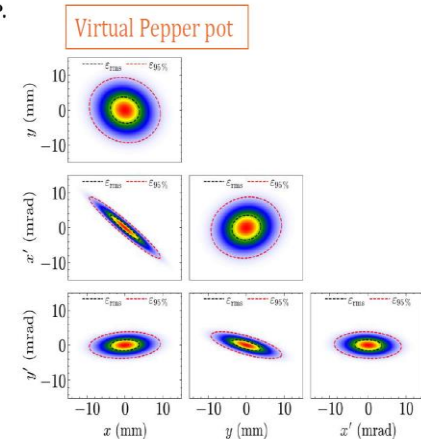
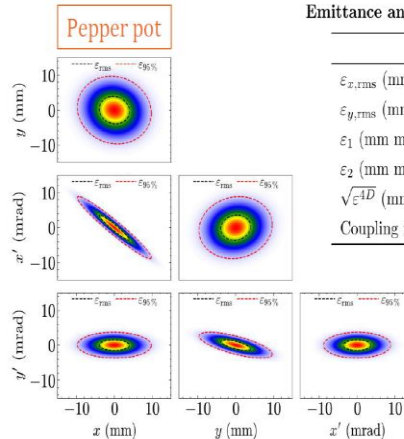


Measurement image with Pepper Pot



Emittance and coupling factor between Pepperpot and VPP.

	Pepper pot	Virtual Pepper pot
$\varepsilon_{x,rms}$ (mm mrad)	3.937	3.755
$\varepsilon_{y,rms}$ (mm mrad)	4.267	4.270
ε_1 (mm mrad)	4.489	4.430
ε_2 (mm mrad)	3.700	3.583
$\sqrt{\varepsilon^4 D}$ (mm mrad)	4.075	3.983
Coupling factor (t)	0.0112	0.0101





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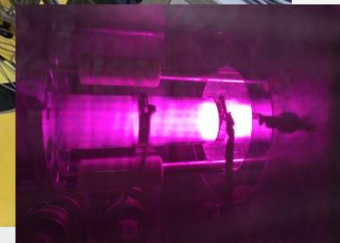
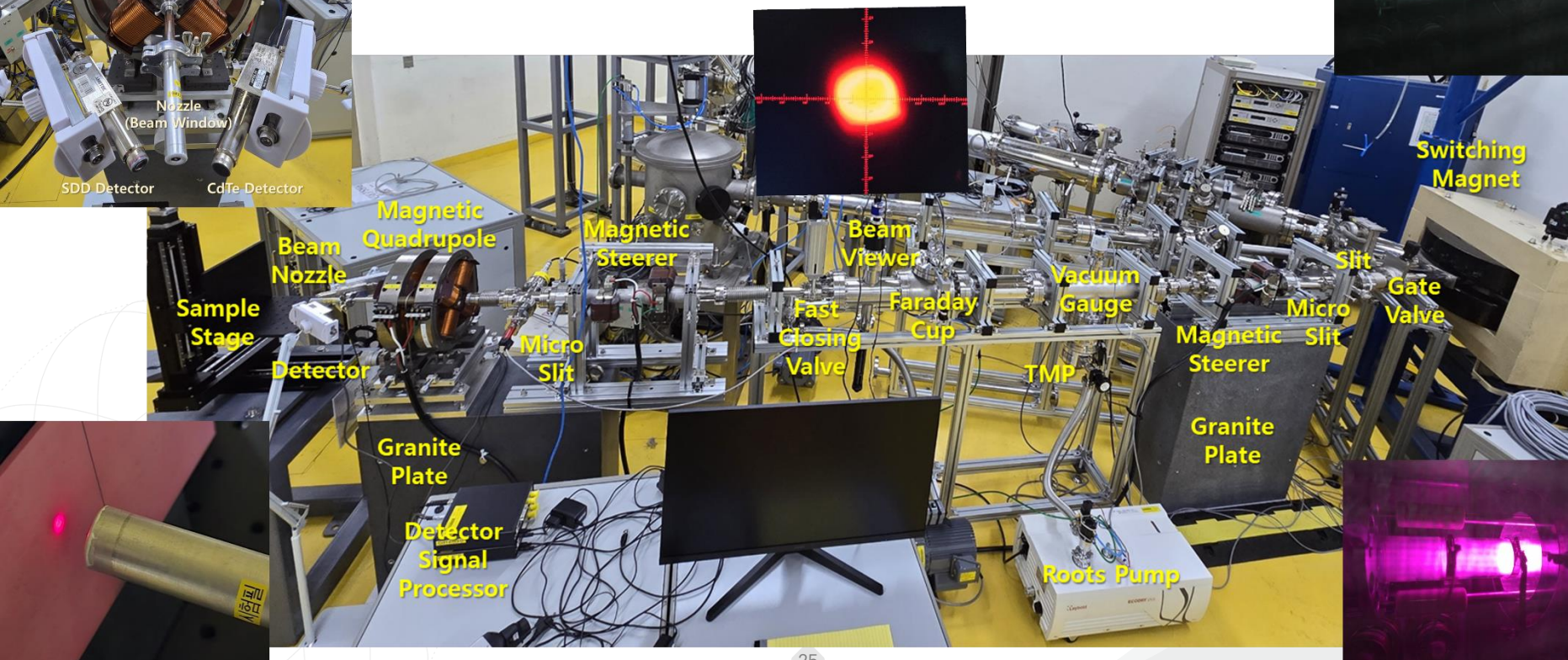
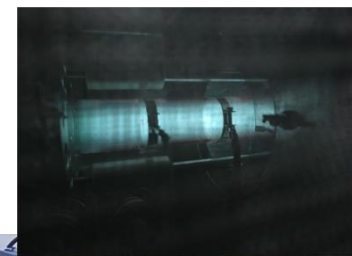


05

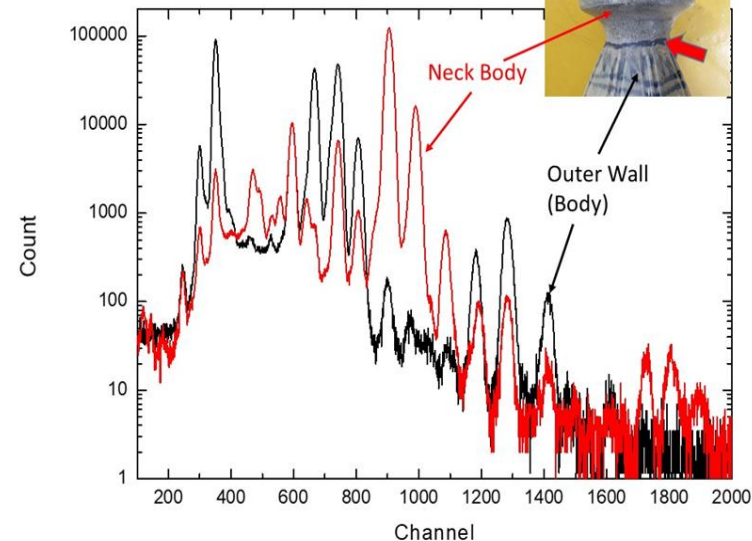
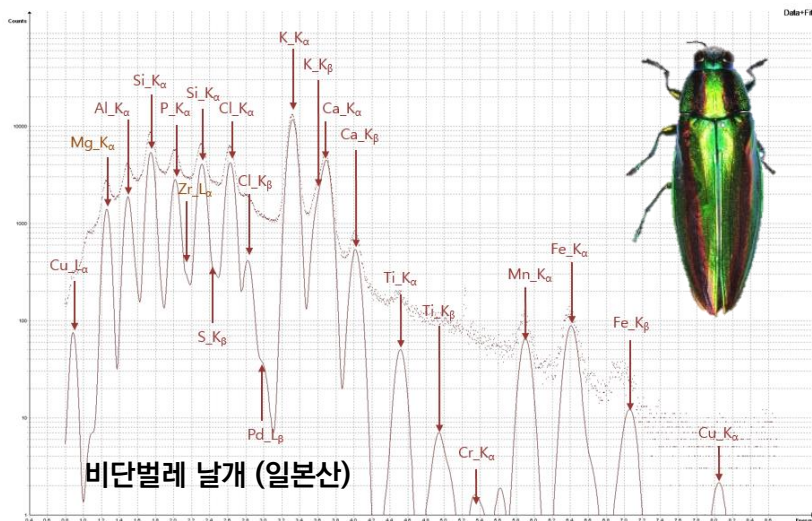
MeV급 가속장치 활용 계획

이온빔을 활용한 국가유산 연구

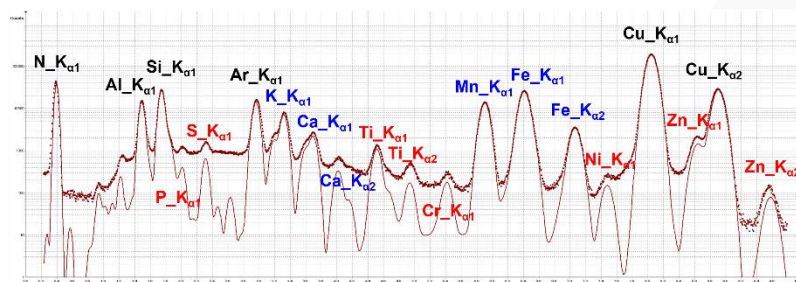
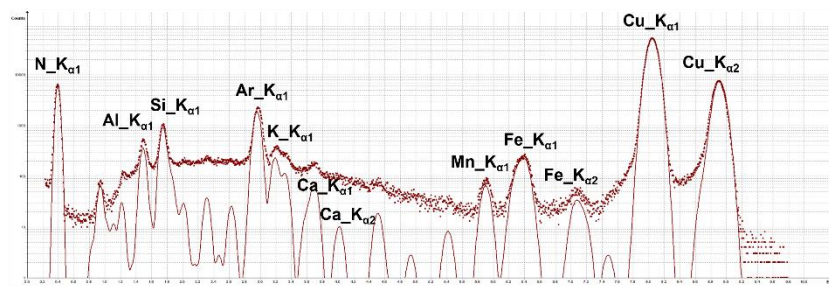
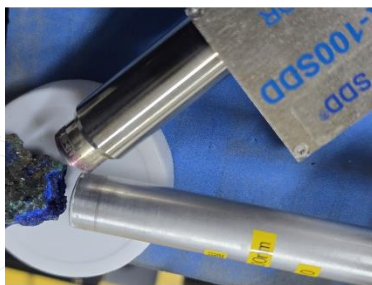
문화유산 분석용 외기빔 PIXE 빔라인 구축



이온빔을 활용한 국가유산 연구



천연 광물 안료용 남동광석 (Azurite) 분석 결과



이온빔을 활용한 전력반도체 성능 향상



이온원

1단계 : 대면적 (8인치) 양성자 조사시스템 구축



알파트로스 이온원
 - 헬륨, 양성자 가능 모드
 - 에너지 0.5~3 MeV
 - 빔전류 : ~1 uA

알파트로스 이온원
 - 양성자 전용 모드로 업그레이드
 - 에너지 0.5~3 MeV
 - 빔전류 : ~3 uA

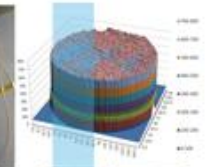
빔라인



빔라인 및 조사 챔버 설계, 제작, 시험

조사챔버

조사 균일도 측정 기술 및 장치 개발



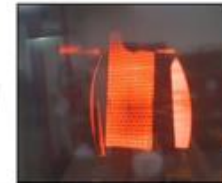
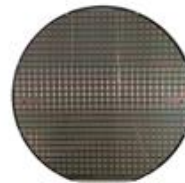
2단계 : 양성자빔 조사 기반 전력소자 에너지 효율 향상 연구

양성자빔 전류 향상



듀오플라즈마트론 이온원
 - 양성자 전용
 - 에너지 0.5~3 MeV
 - 빔전류 : ~20 uA

8인치 Si, SiC 전력반도체 소자 웨이퍼 조사



웨이퍼 조사량 정밀 실시간 모니터링 기술

균일도 $\leq \pm 5\%$ 

Si, SiC 전력반도체 소자의 성능 향상

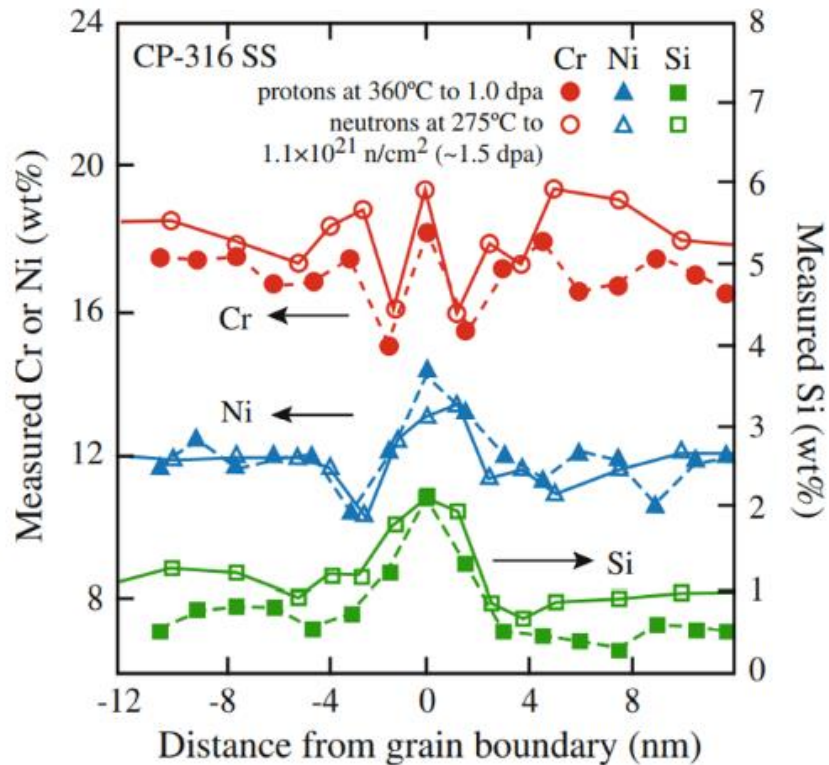
이온빔을 활용한 원자력 재료 연구

Ion Beam v.s. Test Reactor

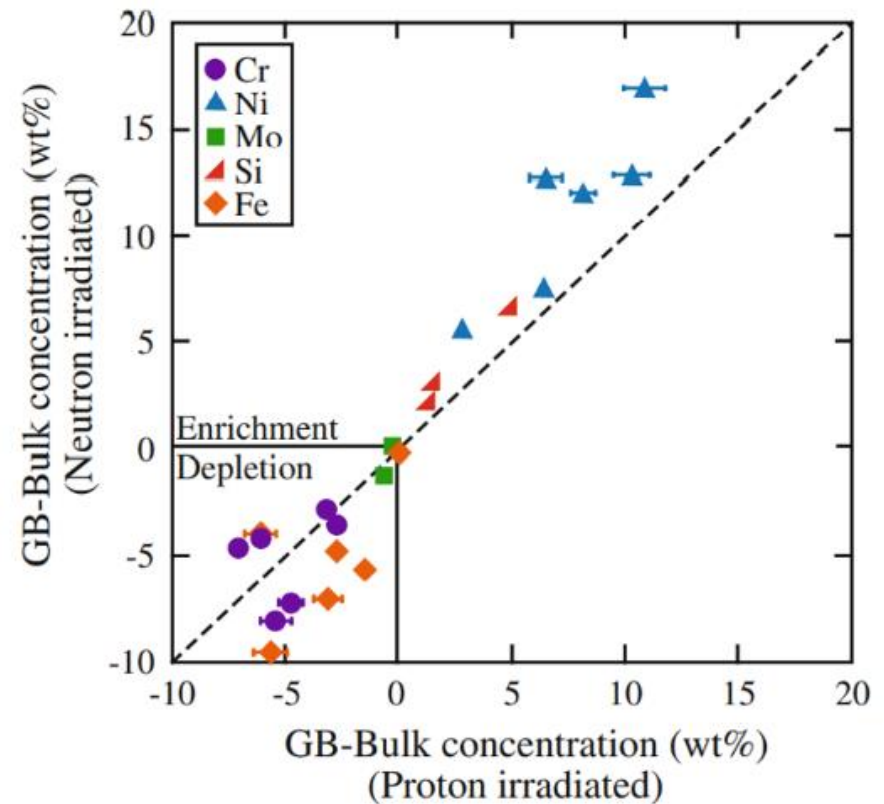
Parameter	Ion beam	Test reactor
Dose	> 500 dpa	10–20 dpa max
Dose rate	100–10000 times reactor rates	Few times reactor rates
Energy	Controlled by ion type (keV ~ 100 MeV)	Neutron spectrum
Transmutants/FP	Separable	Controlled by nuclear physics
Temperature	Better than $\pm 10^{\circ}\text{C}$	Variable to several 10s of $^{\circ}\text{C}$
Residual activity	Low to none	High
In-situ observation	TEM, RS, GC, etc.	Generally PIE only
Cost	Relatively low	Relatively high
Simultaneity	Corrosion, SCC, creep, diffusion, etc	Bulk materials, doable but difficult
Sample thickness	A few nm to ~ 100 μm	Bulk

Equivalence – RIS and Microchemistry

[G. Was, Fundamentals of Radiation Material Science]



(a)

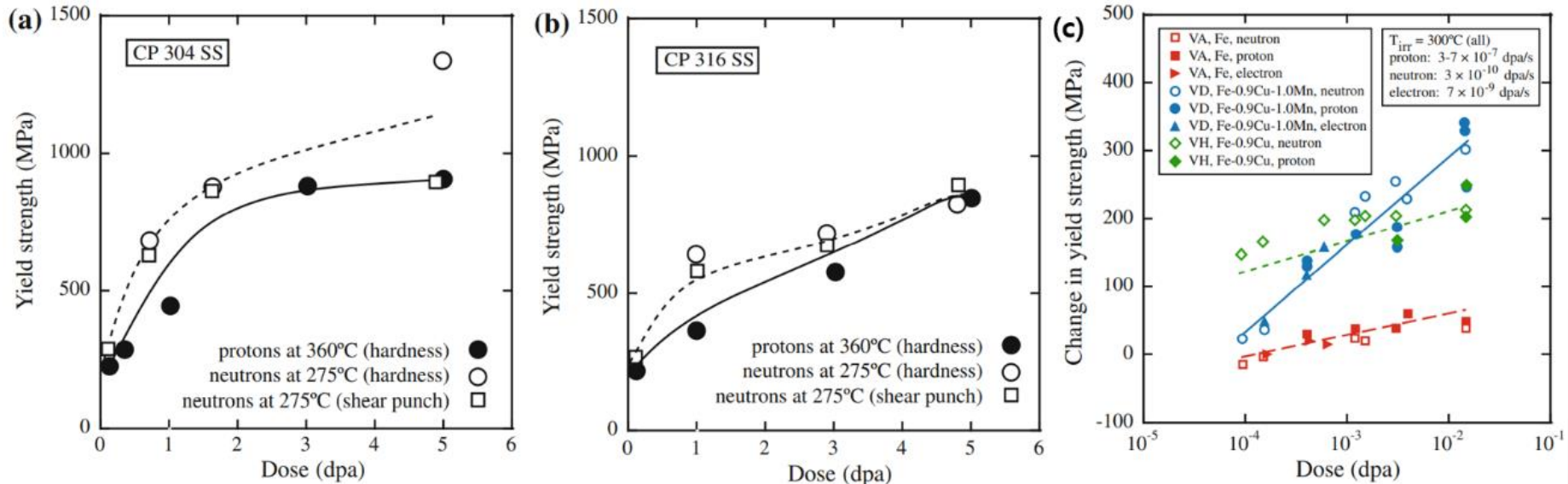


(b)

- (a) Comparison of GB segregation of Cr, Ni and Si in STS316 following irradiation with either proton or neutron to similar dpa level
- (b) Comparison of elemental enrichment and depletion in GB from bulk as a result of neutron and proton irradiation

Equivalence – Mechanical Property

[G. Was, Fundamentals of Radiation Material Science]

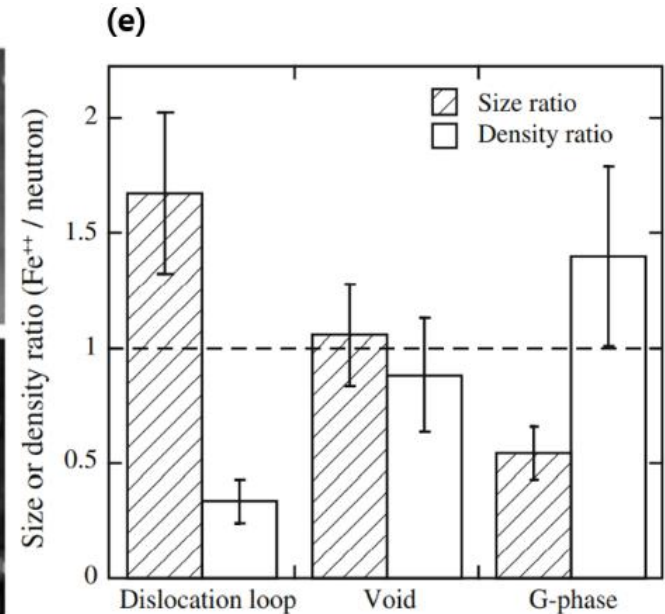
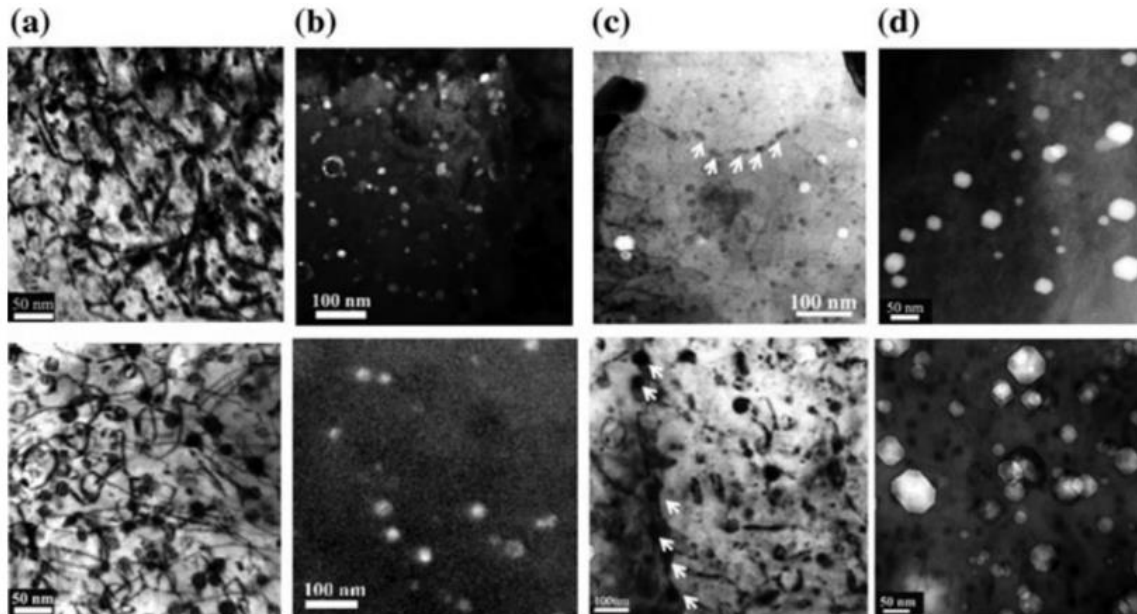


- (a) Comparison of hardening in STS304 irradiated with neutron or proton to similar dose
- (b) Comparison of hardening in STS316 irradiated with neutron or proton to similar dose
- (c) Irradiation hardening in model reactor pressure vessel steels following neutron, proton and electron irradiation at 300°C

Equivalence – Microstructure

[G. Was, Fundamentals of Radiation Material Science]

Proton irradiation (188 dpa, 460°C)



Neutron irradiation (155 dpa, 443°C)

- (a) Bright field TEM images of line dislocations and loops
- (b) Dark field TEM images of G-phase precipitates in the matrix
- (c) Bright field images of G-phase precipitates along grain boundaries
- (d) Voids
- (e) Comparison of size and number density ratio of defect clusters

Ion Beam Irradiation Test Standard – ASTM



Designation: E821 – 16

Standard Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation¹

This standard is issued under the fixed designation E821; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.



Designation: E942 – 16

Standard Guide for Investigating the Effects of Helium in Irradiated Metals¹

This standard is issued under the fixed designation E942; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

PART I—EXPERIMENTAL PROCEDURE

2. Referenced Documents

- 2.1 *ASTM Standards:*²
 E170 Terminology Relating to Radiation Measurements and Dosimetry
 E521 Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation

Terminology

3.1 Definitions:

- 3.1.1 Descriptions of relevant terms are found in Terminology E170.

Specimen Characterization

4.1 Source Material Characterization:

- 4.1.1 The source of the material shall be identified. The chemical composition of the source material, as supplied by the vendor or of independent determination, or both, shall be stated. The analysis shall state the quantity of trace impurities, the material, heat, lot, or batch, etc., number shall be stated for commercial material. The analytical technique and compositional uncertainties should be stated.

- 4.1.2 The material form and history supplied by the vendor shall be stated. The history shall include the deformation process (rolling, swaging, etc.), rate, temperature, and total extent of deformation (given as strain components or geometrical shape changes). The use of intermediate anneals during processing shall be described, including temperature, time, environment, and cooling rate.

4.2 Specimen Preparation and Evaluation:

- 4.2.1 The properties of the test specimen shall represent the properties of bulk material. Since thin specimens usually will be experimentally desirable, a specimen thickness that yields bulk properties or information relating to bulk properties could be selected. This can be approached through either of

¹For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on ASTM website.



Designation: E521 – 16

Standard Practice for Investigating the Effects of Neutron Radiation Damage Using Charged-Particle Irradiation¹

This standard is issued under the fixed designation E521; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

This practice is intended to provide the nuclear research community with recommended procedures for using charged-particle irradiation to investigate neutron radiation damage mechanisms as a surrogate for neutron irradiation. It recognizes the diversity of energetic-ion producing devices, the complexities in experimental procedures, and the difficulties in correlating the experimental results with those produced by reactor neutron irradiation. Such results may be used to estimate density changes and the changes in microstructure that would be caused by neutron irradiation. The information can also be useful in elucidating fundamental mechanisms of radiation damage in reactor materials.

1. Scope

1.1 This practice provides guidance on performing charged-particle irradiations of metals and alloys, although many of the methods may also be applied to ceramic materials. It is generally confined to studies of microstructural and microchemical changes induced by ions of low-penetrating power that come to rest in the specimen. Density changes can be measured directly and changes in other properties can be inferred. This information can be used to estimate similar changes that would result from neutron irradiation. More generally, this information is of value in deducing the fundamental mechanisms of radiation damage for a wide range of materials and irradiation conditions.

1.2 Where it appears, the word "simulation" should be understood to imply an approximation of the relevant neutron irradiation environment for the purpose of elucidating damage mechanisms. The degree of conformity can range from poor to nearly exact. The intent is to produce a correspondence between one or more aspects of the neutron and charged particle irradiations such that fundamental relationships are established between irradiation or material parameters and the material response.

1.3 The practice appears as follows:

Section	Section
Apparatus	4
Specimen Preparation	5 – 10
Irradiation Techniques (including Helium Injection)	11–12
Damage Calculations	13
Postirradiation Examination	14 – 16
Reporting of Results	17
Correlation and Interpretation	18 – 22

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 This standard does not purport to address the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determining the applicability of regulatory limitations prior to use.

2. Referenced Documents

- 2.1 *ASTM Standards:*²
 C859 Terminology Relating to Nuclear Materials
 E170 Terminology Relating to Radiation Measurements and Dosimetry
 E821 Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation
 E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance, E706 (IIIC)
 E942 Guide for Simulation of Helium Effects in Reactor Metals

¹This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.08 on Procedures for Neutron Radiation Damage Simulation. Current edition approved Oct. 1, 2016. Published December 2016. Originally approved in 1976. Last previous edition approved in 2009 as E521 – 96 (2009)². DOI: 10.1520/E521-16.

²For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

● ASTM E521–96 (Reapproved 2009)

Standard Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation

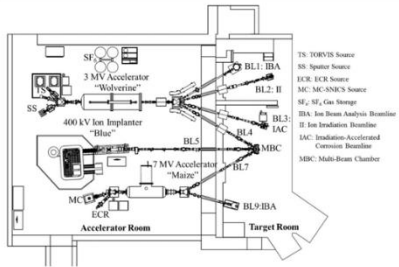
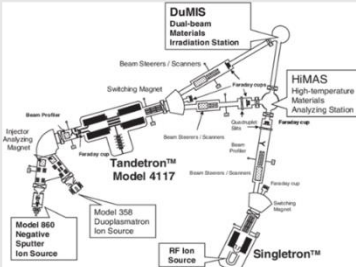
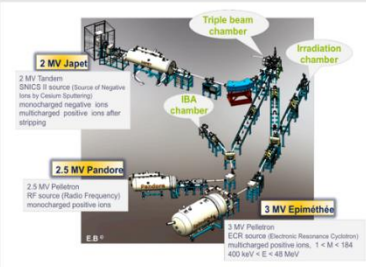
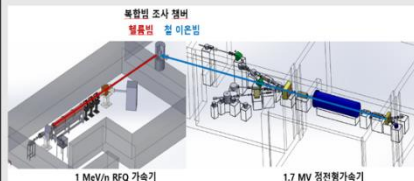
● ASTM E942–16

Standard Guide for Investigating the Effects of Helium in Irradiated Metals

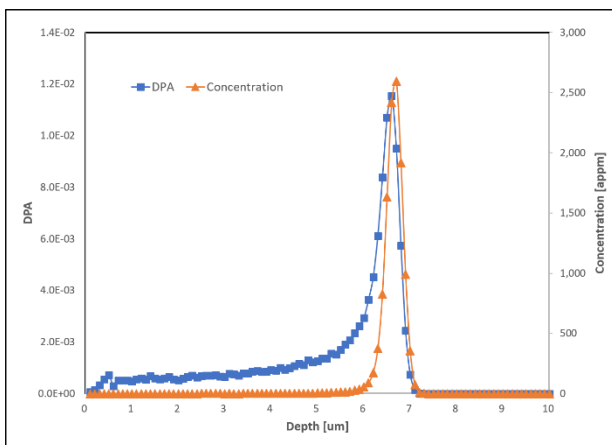
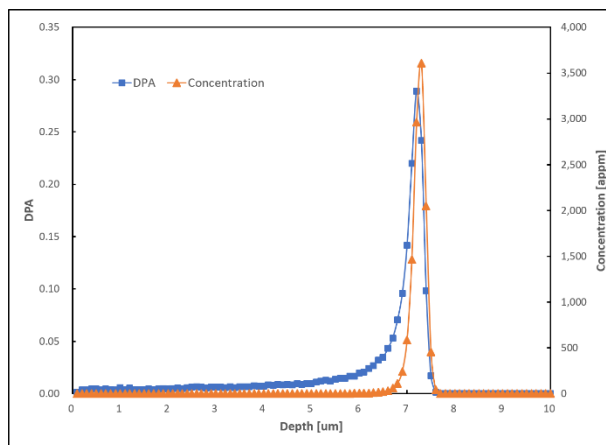
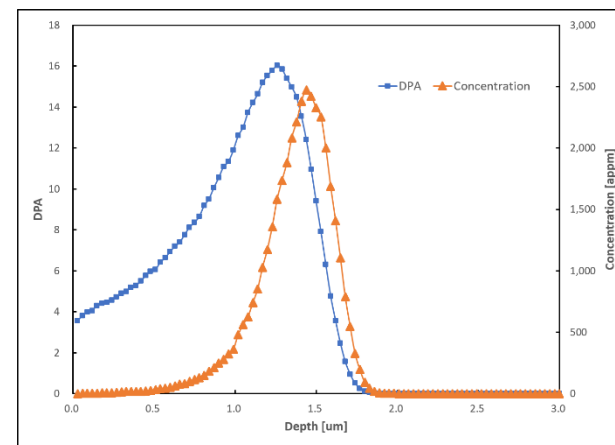
● ASTM E821–16

Standard Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation

원자력 재료 시험 기관 및 보유 장비

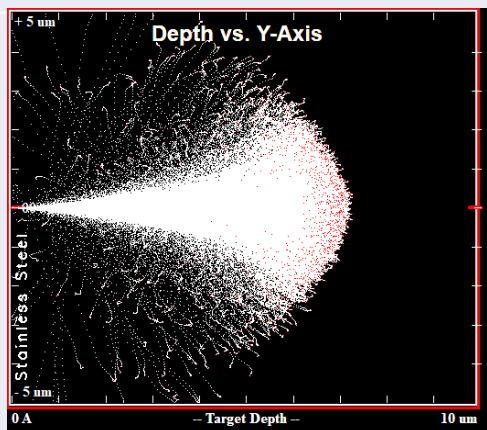
국가 기관	미국 Univ. of Michigan	일본 Kyoto univ.	프랑스 CEA등	대한민국, KAERI
시설	MIBL	DuET	JANNuS	KOMAC
장치	400 keV 정전형 1.7 MV 탄뎀 3 MV 탄뎀	1.7 MV 탄뎀 1 MV 정전형	3 MV 탄뎀 2.5 MV 탄뎀 2 MV 탄뎀	1 MeV/n 고주파 1 MV 정전형 1.7 MV 탄뎀 3 MV 탄뎀
비고	TEM in-situ	-	TEM in-situ	복합빔시설 없음
구조				

DPA and Range Estimation

Proton 1 MeV, $1.0 \times 10^{16} \text{ #/cm}^2$ Helium 4 MeV, $1.0 \times 10^{16} \text{ #/cm}^2$ Fe 5 MeV, $1.0 \times 10^{16} \text{ #/cm}^2$ 

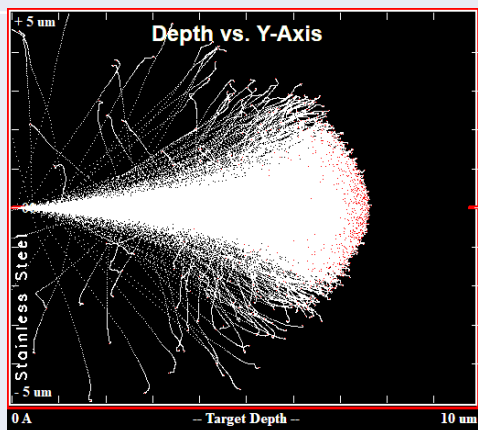
1 MeV proton range

6.6 μm



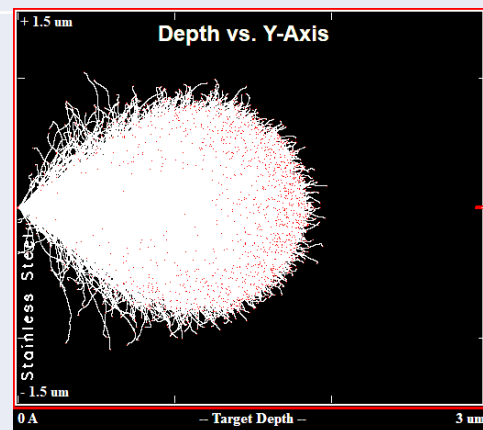
4 MeV Helium range

7.2 μm



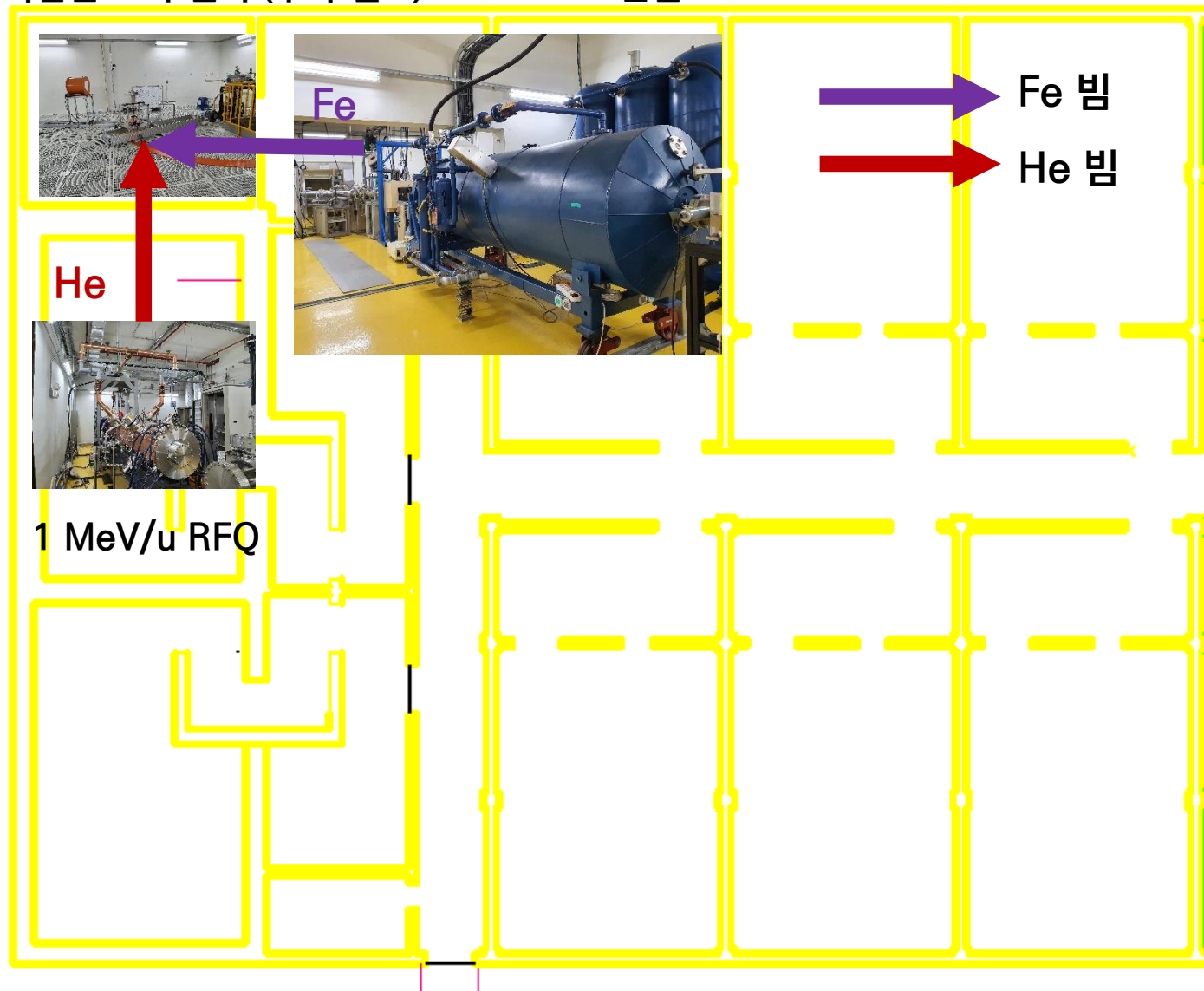
5 MeV Fe range

1.4 μm



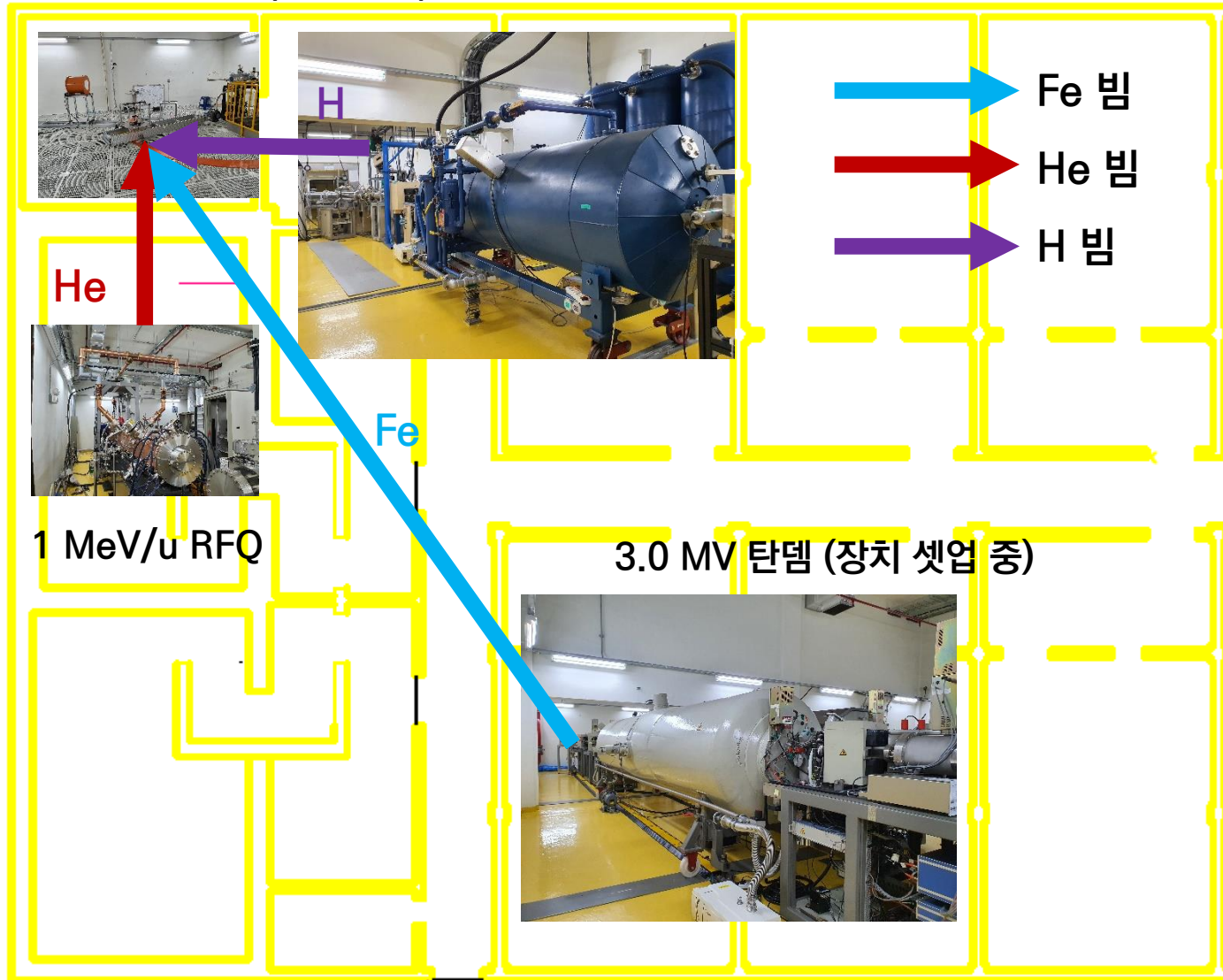
원자력 재료 시험을 위한 복합빔 조사: Dual Beam

복합빔 조사 챔버 (구축 필요) 1.7 MV 탄뎀



원자력 재료 시험을 위한 복합빔 조사: Triple Beam

복합빔 조사 챔버 (구축 필요) 1.7 MV 탄뎀



재료연구에 활용 가능한 KOMAC 보유 분석장치

표면물성분석

나노인덴테이션
(2016년)



반도체특성분석기
(2016년)



에칭두께측정기
(2014년)



4-point probe
(2014년)



접촉각측정기
(2019년)



원소분석

ICP-MS
(2017년)



휴대용 XRF
(2016년)



HPGe
(2017년)



물질구조분석

XRD
(2018년)



Xray-CT
(2017년)



FE-SEM
(2016년)



FT-IR
(2016년)

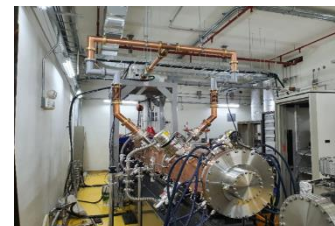


+ IBA, TEM, NMR, ESR

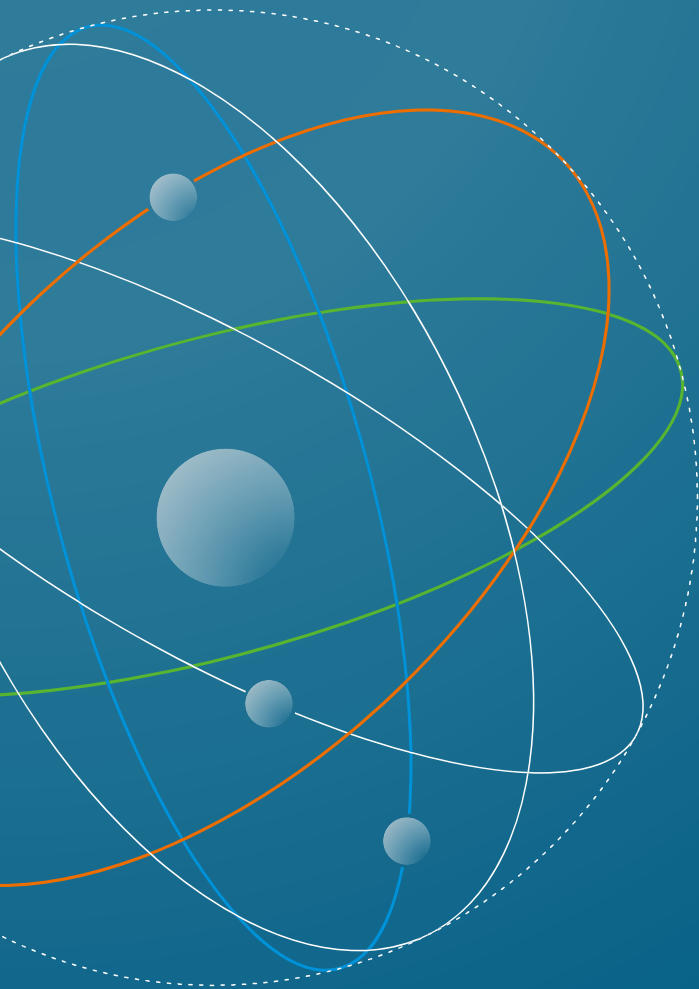
Summary

	1.7 MV Tandem	1 MV Single-End	1 MeV/n RFQ	3 MV Tandem
Type	Electrostatic Accelerator	Electrostatic Accelerator	RF linac	Electrostatic Accelerator
Ion species	H, He, Fe , Cl, etc	Proton	$A/q < 2.5$ (D ⁺ , He ²⁺ , Ar ⁺¹⁶)	From H to Au
Energy	Proton 3.4 MeV Fe ²⁺ 5.1 MeV	1 MeV	He 4 MeV	Proton 6 MeV Fe ²⁺ 9 MeV
Status	Operational	Operational	Operational	Under Test
Note	PIXE RBS, ERD Irradiation Neutron	Wide scanning with wobbler	High current (He beam > 1 mA)	Initially for AMS

Photo



활용과 관련한 소중한 의견 부탁드립니다.



더 나은 세상을 위한 원자력기술
국민과 세계가 지지하는 한국원자력연구원

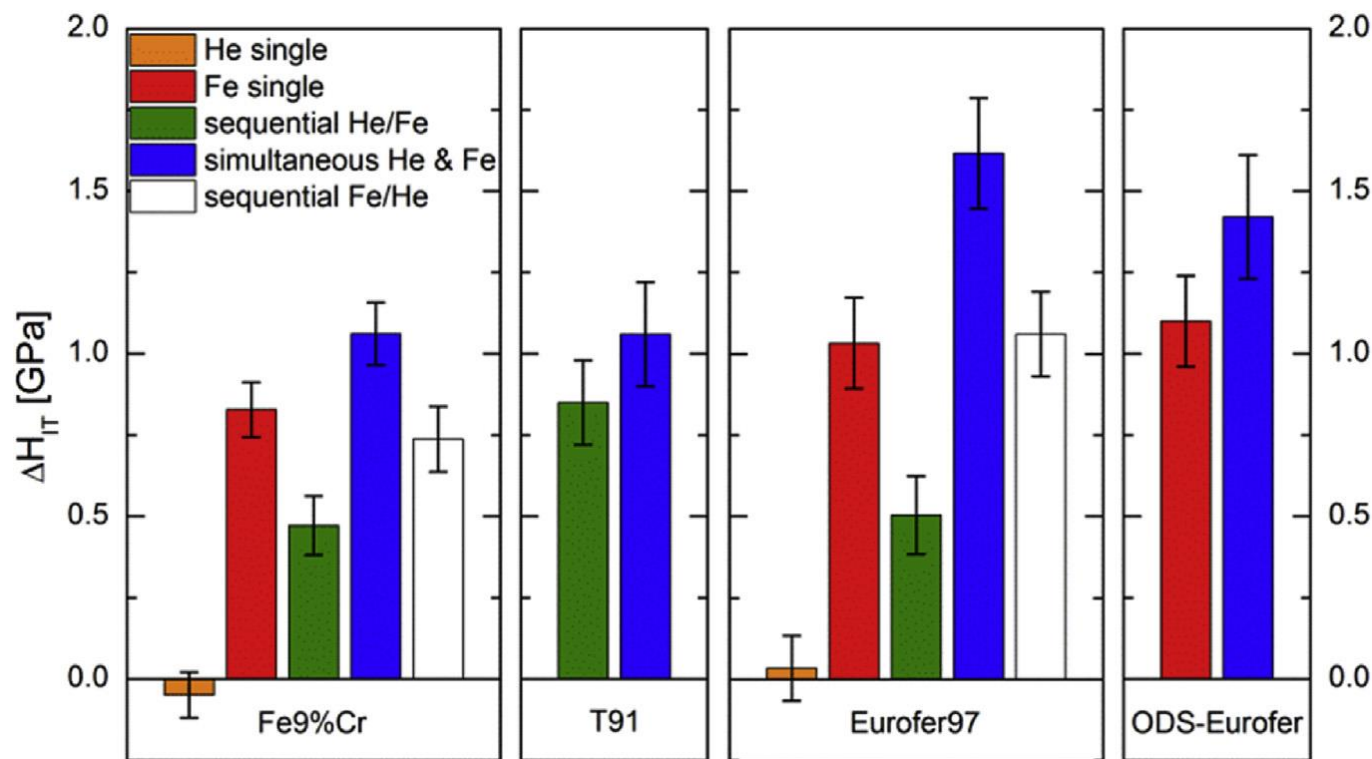


감사합니다.



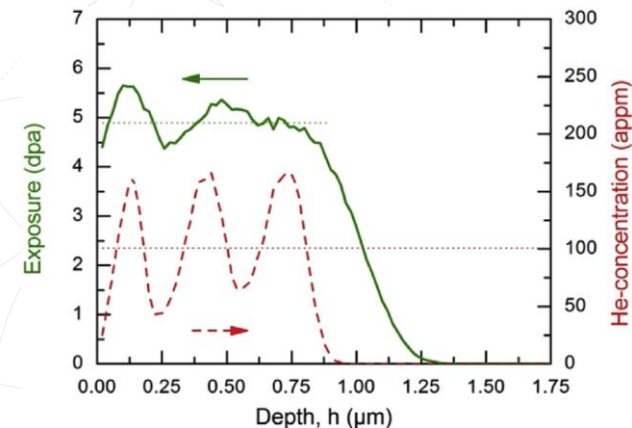
한국원자력연구원
Korea Atomic Energy Research Institute

복합빔 조사: Synergistic effect – Dual Beam

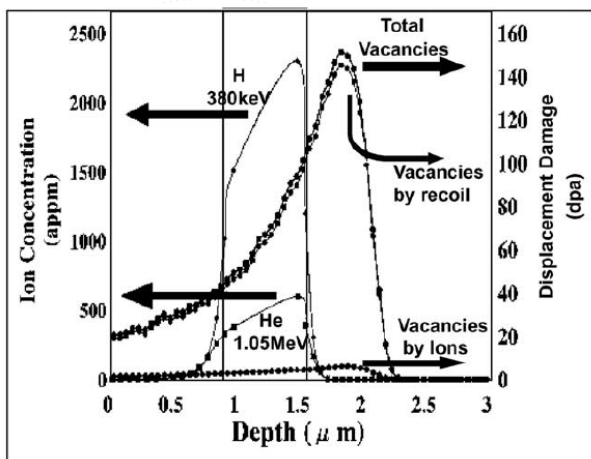
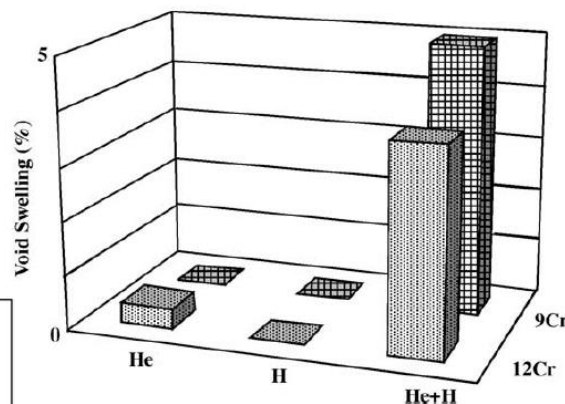
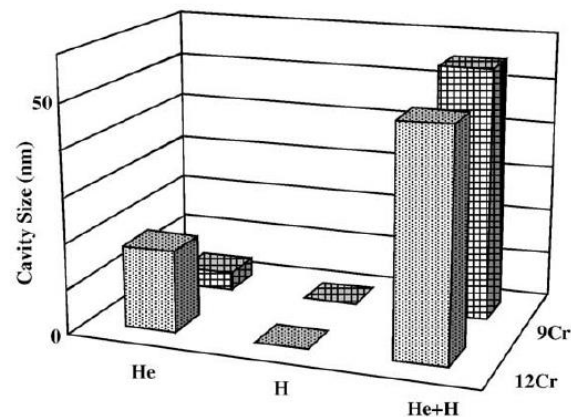
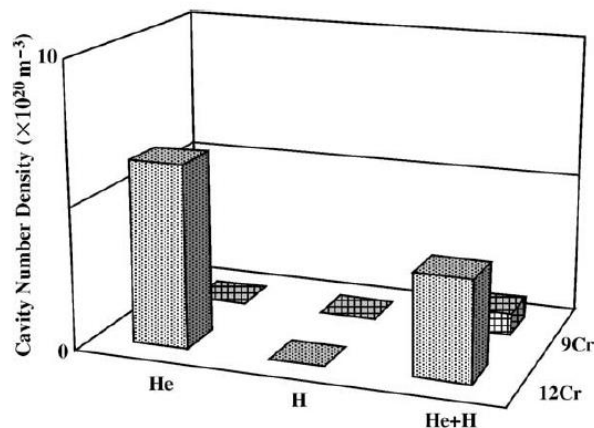


[Irradiation-induced hardening]

- Fe: ~ 5 dpa (0.5 MeV, 1.5 MeV, 3 MeV)
- He: ~100 appm (30 keV, 150 keV, 350 keV)
- Temperature: 300 °C



복합빔 조사: Synergistic effect – Triple Beam



- Fe: ~ 50 dpa (10.5 MeV)
- He: ~10 appm/dpa (1.05 MeV)
- H: ~40 appm/dap (380 keV)
- Temperature: 510 °C