The Major National Science and Technology Infrastructure Facility in China

Progress and status of HIAF

High Intensity Heavy-ion Accelerator Facility

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Outline

- Project Progress and Brief Facility Introduction
- Civil Construction and Facility Installation
- Experimental Setups and Related Physics
- Timetable, Budget and perspective
- Summary

Project Progress

Milestones of HIAF Project

Jul. 2010	May 2011	Dec. 2015	Apr. 2017	Jun. 2018	Aug. 2023	Dec. 2024
Proposal	Assessment	Approval	Budget	Start-up of construction	Installation	Commissioning

The preliminary goals: exploration of the unknown nuclear chart and study of exotic nuclear structure and properties, synthesis of super-heavy elements and nuclides, understanding of the origin of heavy elements in the Universe, and development of new heavy-ion applications

Physics discussion

Design Review

Technical assessment

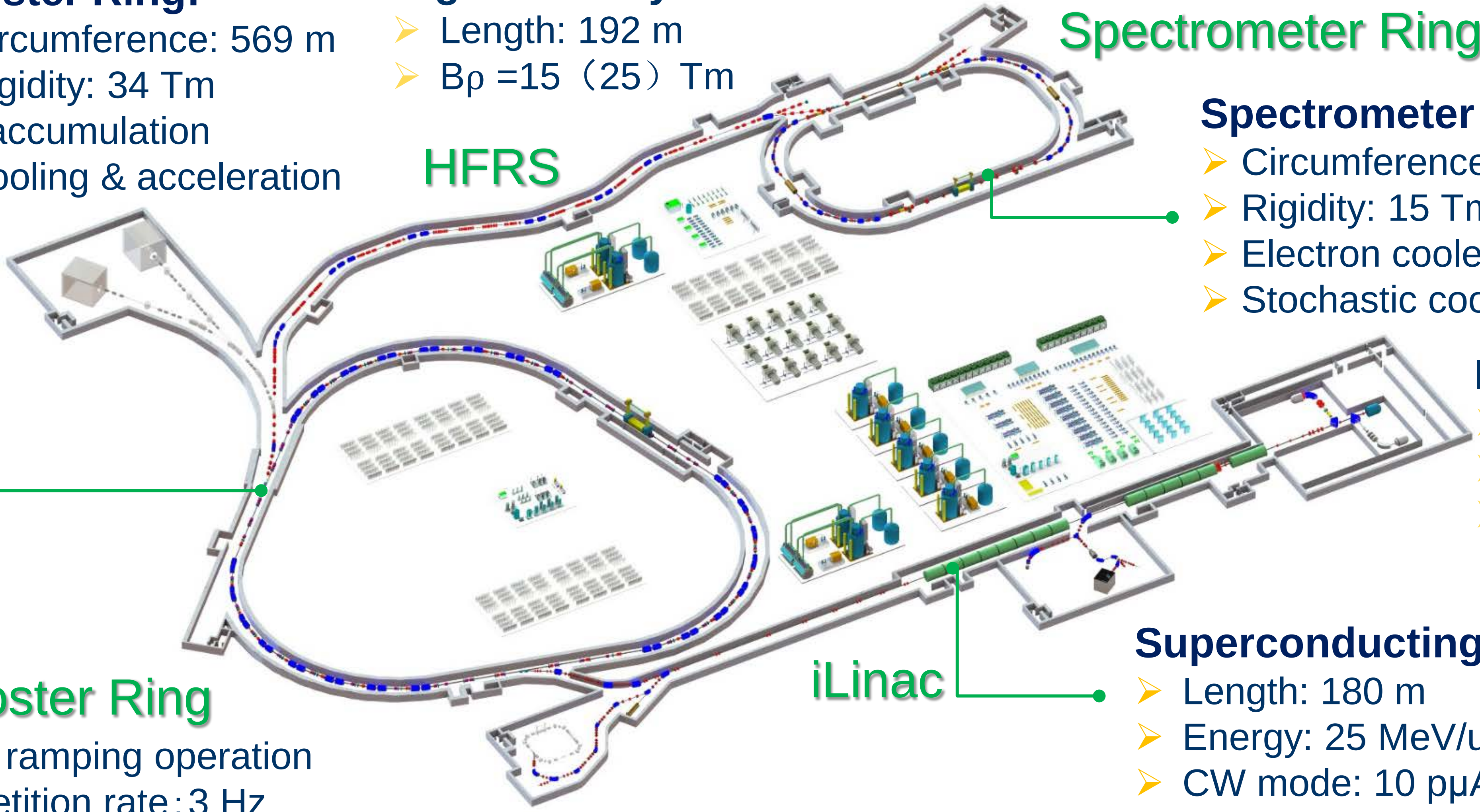
Ground-breaking ceremony

Funding agency:** The National Development and Reform Commission and local governments ,* ***2.67 billion CNY

Accelerator Complex

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Aaccumulation
- Cooling & acceleration

High Intensity Radioactive Beam Line:
- Length: 192 m
- Bρ =15（25）Tm



Spectrometer Ring:
- Circumference: 277.2 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

Ion Sources:
- a 45 GHz FECR
- a 28 GHz SECRAL
- a 2.45 GHz ECR

Fast ramping operation
Repetition rate：3 Hz

Superconducting Ion Linac:
- Length: 180 m
- Energy: 25 MeV/u ($^{238}U^{34+}$)
- CW mode: 10 pμA with A/Q=2~5
- Pulse mode: 1.0 emA with A/Q=2~7

Facility Capability

Typical Beam Parameters From the Booster Ring

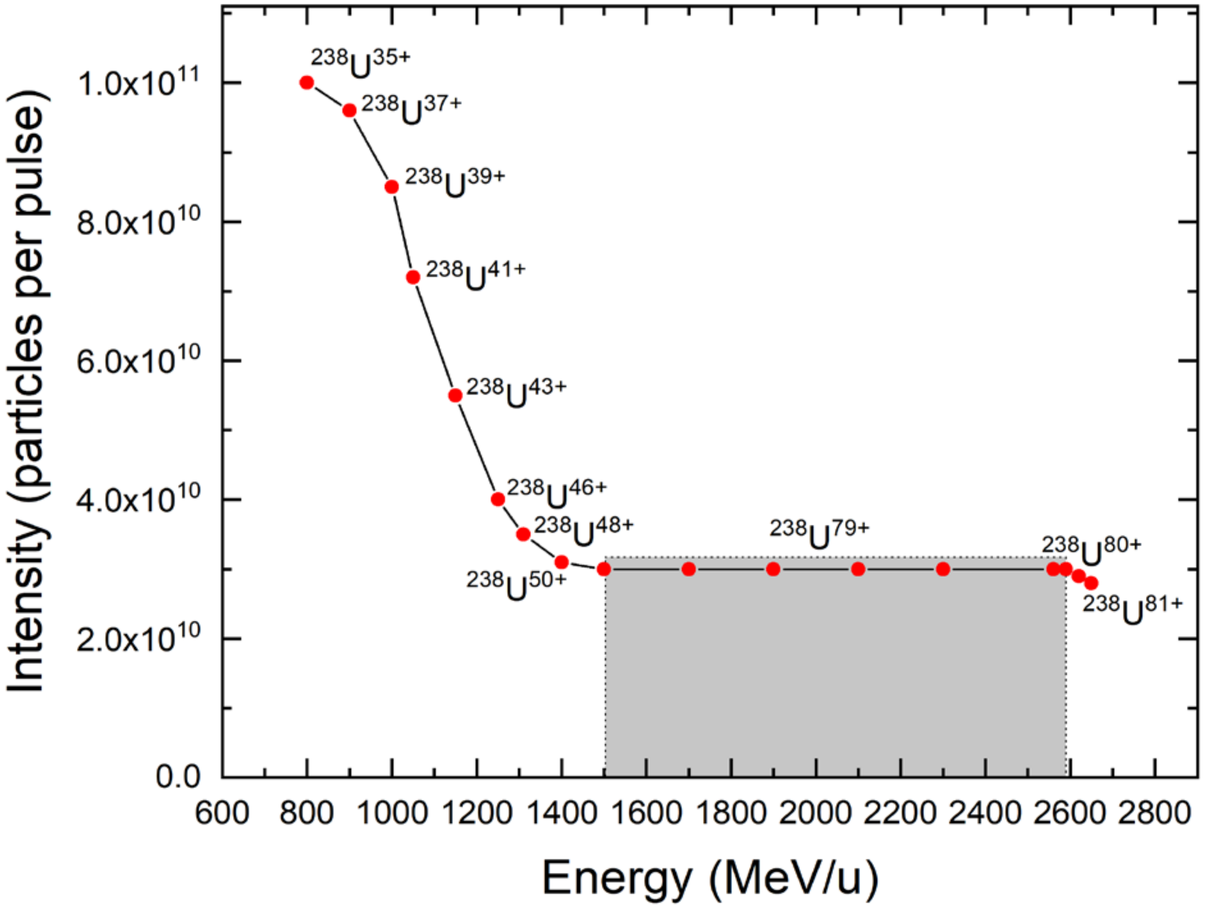
Ions	Energy(GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{35+}$	0.835	1.0×10^{11}

The maximum beam intensities were estimated by optimizing the charge number

Higher beam energies available on a tradeoff of the beam intensities

Facility Capability

Intensity-energy Diagram of ^{238}U Beam Stored

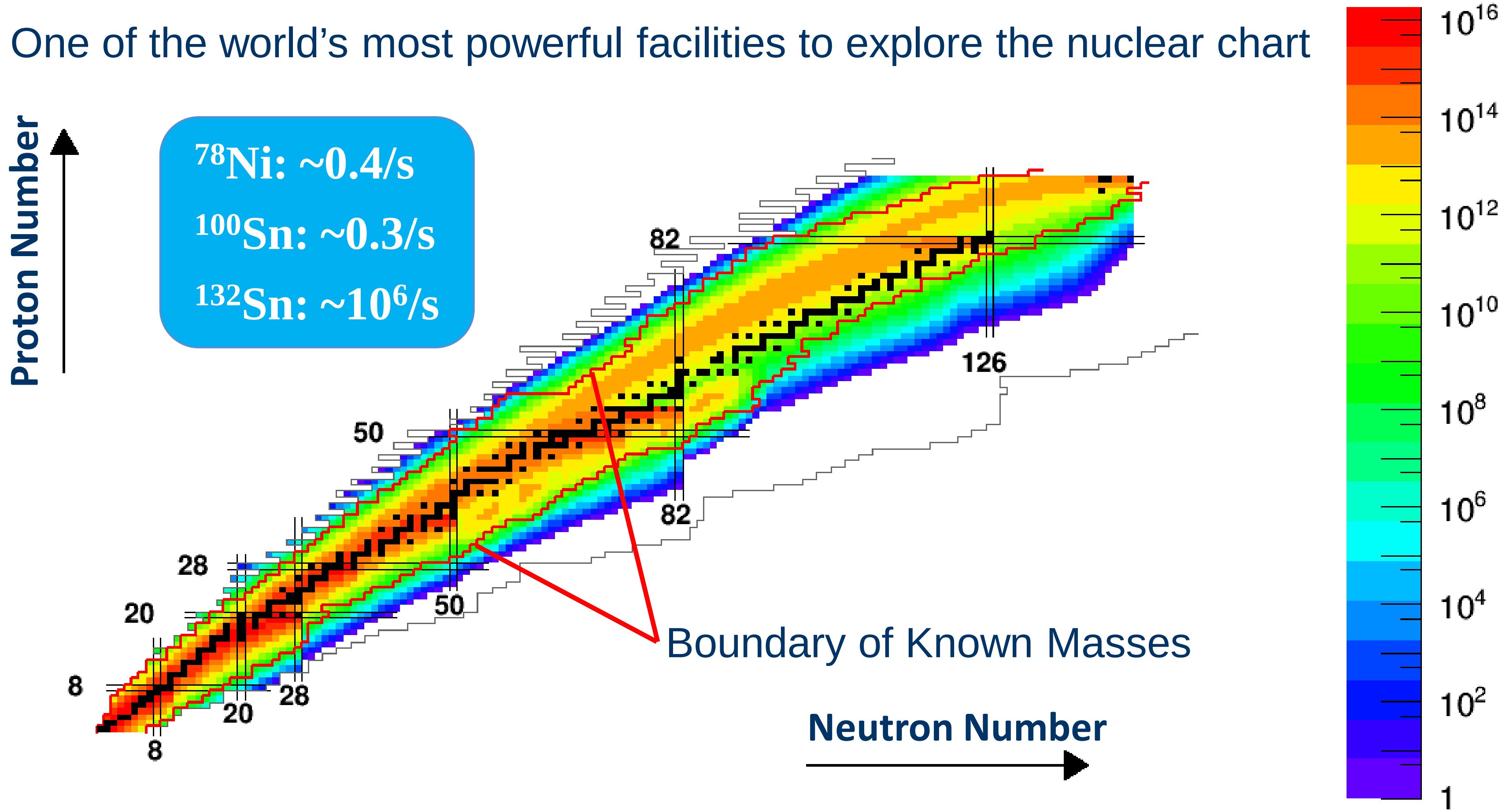


The maximum particle numbers stored at the corresponding charge states

Capability of Producing Nuclides

Nuclides Available (Daily Production Yield) at HIAF

One of the world's most powerful facilities to explore the nuclear chart



Prolific sources of nuclides far away from the stability line will be provided using various reactions. The limits shown are the production rate of one nuclide per day, which enable the "discovery experiments"

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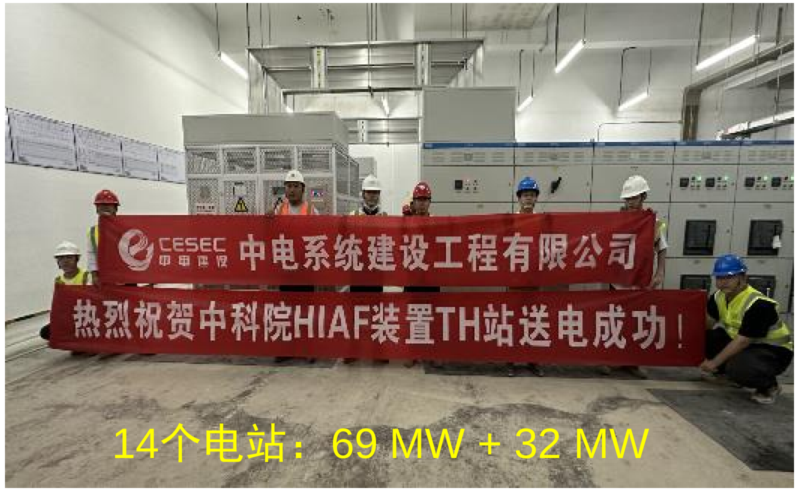
Civil Construction

The civil construction was completed in June, 2024

Civil Construction

Infrastructure: Power distributions, water supplies, and liquid helium stations



Civil Construction

2400 m tunnel, 13 m underground, is ready for facility installation

Completed cooling water pipes, air conditioning ducts and cabling bridges

Facility Installation

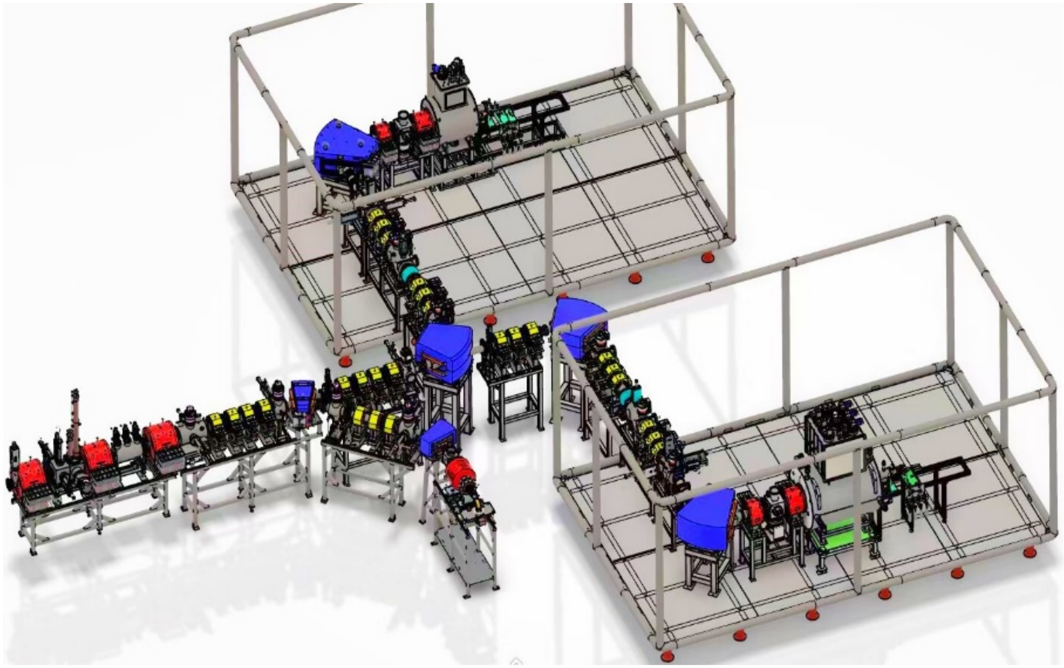
Testing Halls and Equipment Transfer Rooms **– Full load operation**

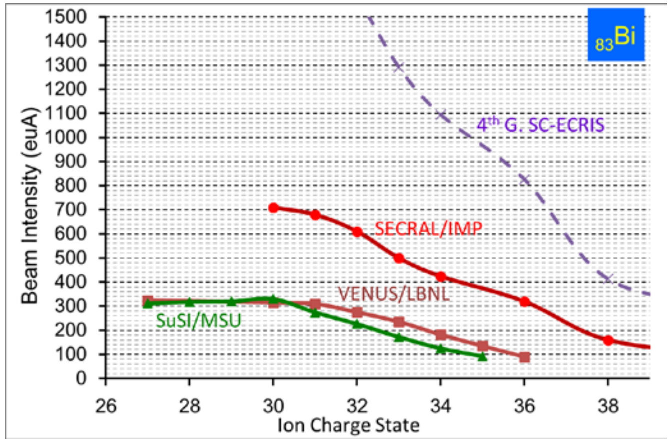





Accelerator Complex

The first 45 GHz superconducting ECR in the world: 50 pμA (U^{35+}) ~1 ms



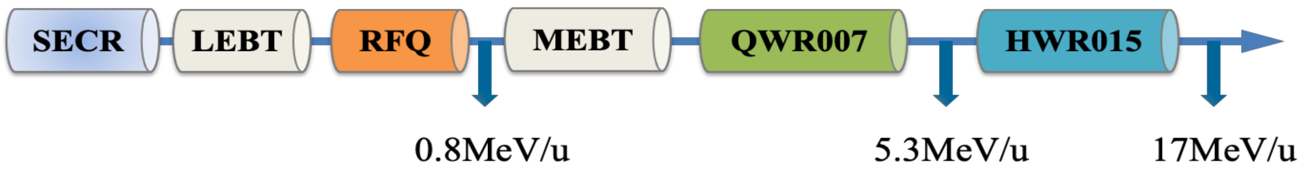


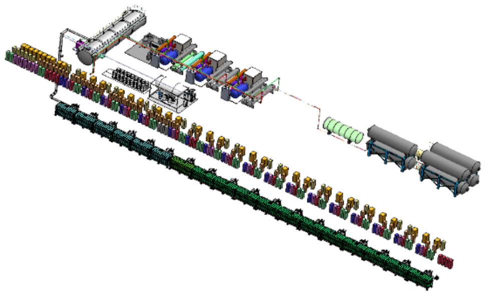
- Fabricated a fully Nb_3Sn superconducting magnet
- The beam front end is assembled
- The first beam at 45 GHz is expected in Sep., 2025

Microwave	45 GHz/20 KW
Magnet conductor	Nb_3Sn
Axial fields (T)	6.5/1.0/3.5
Sextupole field （T）	3.8@r=75 mm
Maximum field (T)	11.8 T
Magnet bore (mm)	Ø161~165
Extraction （kV）	50
Typical beam	1.0 emA U^{34+}

Accelerator Complex

High current superconducting ion linac – iLinac





Assembly & Cold Test of RFQ

Cavity 66+10, Cryomodule 11

Cavity 30+8, Cryomodule 6

All cryomodules are completed in 2025

The first beam from RFQ was seen in June 2024. We installed the cryomodules in this year, and the iLinac will provide first beam in September, 2025

Accelerator Complex

Fast cycle booster synchrotron – Booster Ring (BRing)

- Novel two planes painting injection scheme - 2.0×10^{11} ppp
- Fast ramping rate - 12T/s; High repetition frequency of 3--5Hz

Magnets

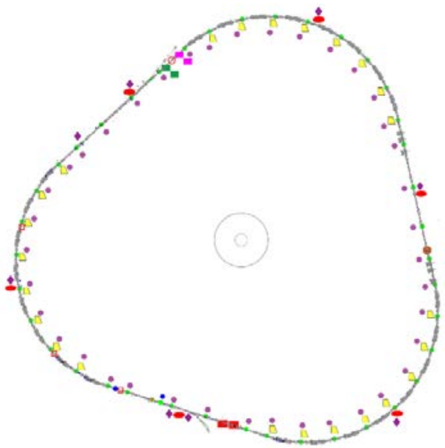
Power Supplies

Kicker

Vacuum chambers

RF Cavities

Beam diagnostics



48 D-magnets

78 Q-magnets

30 S-magnets

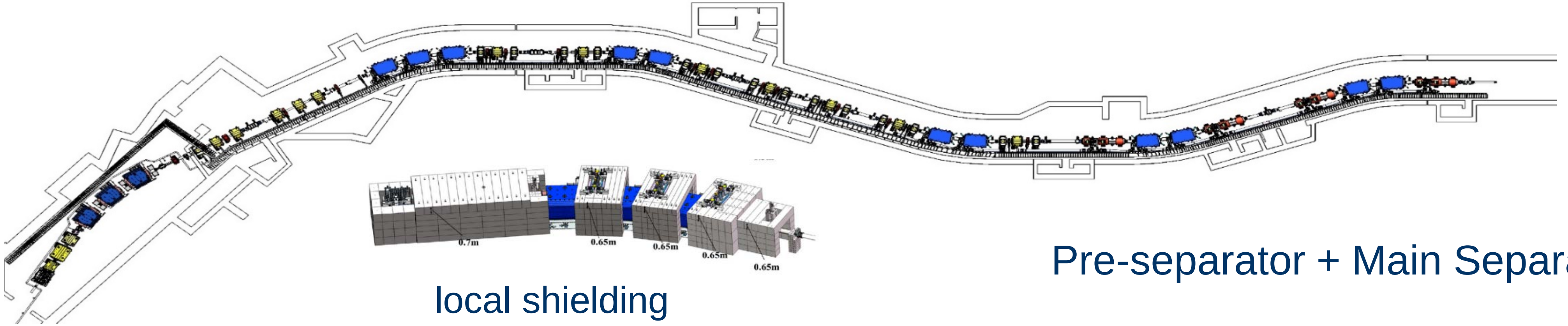
80 correctors.

All components fabricated

Complete Installation in 2024

Accelerator Complex

High Intensity Radioactive Beam Line – HIRBL



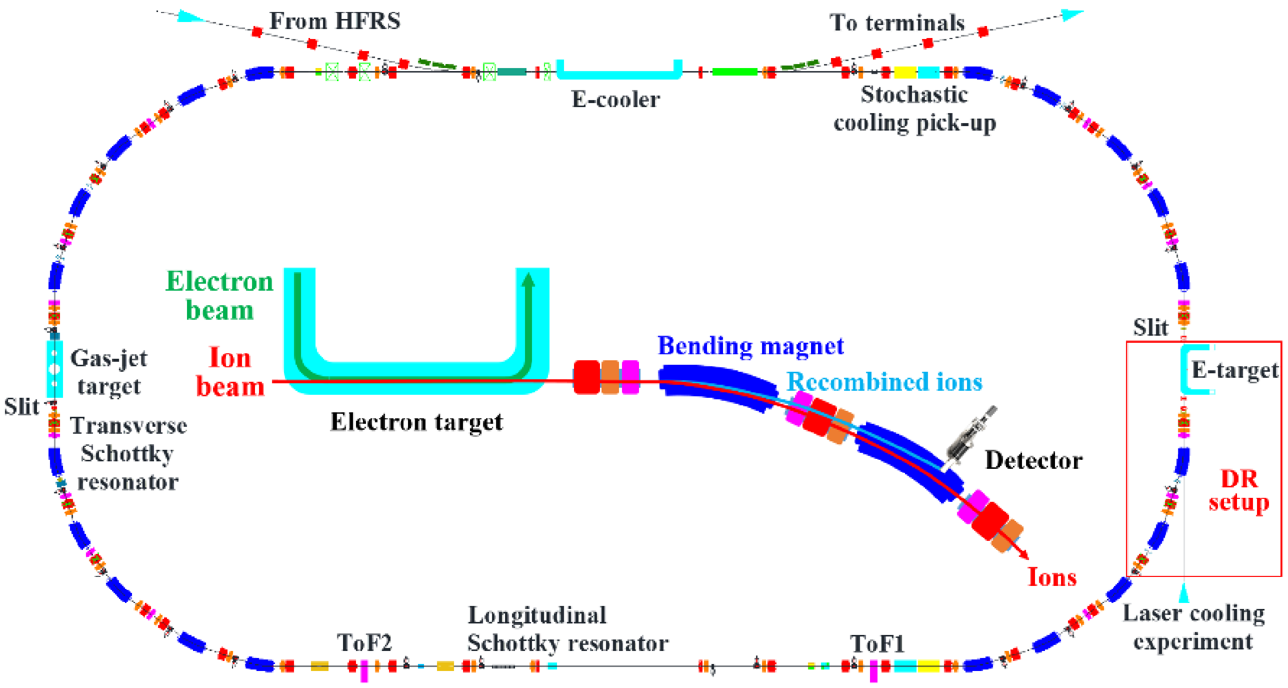
local shielding

Pre-separator + Main Separator 192 m

All components were already Installed

Accelerator Complex

High precision Spectrometer Ring – Spectrometer Ring (SRing)



- ✓ Isochronous Mass Spectrometer
- ✓ Schottky Spectrometer
- ✓ DR Spectrometer
- ✓ In-ring Nuclear Reaction Set up

Complete Installation in September, 2024

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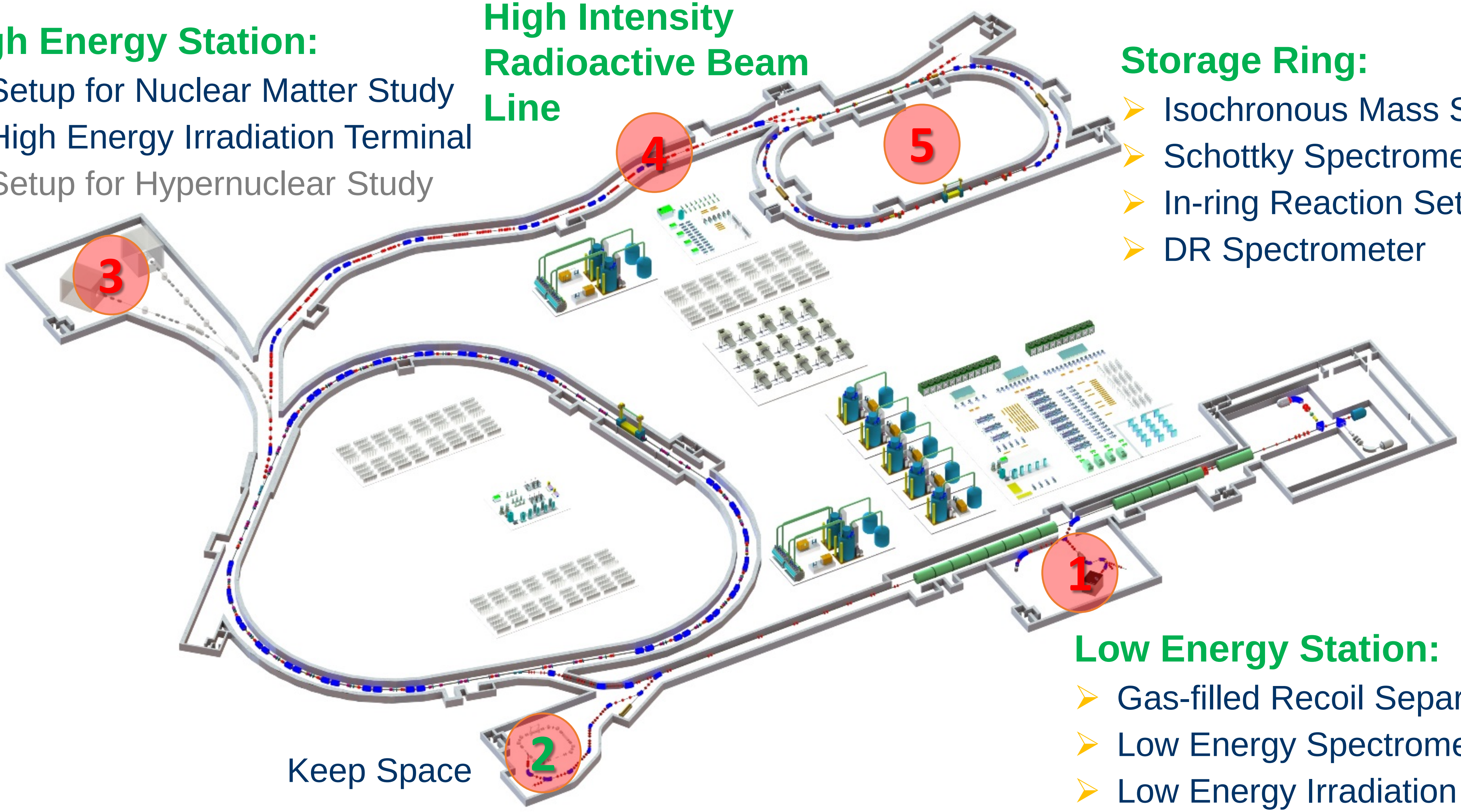
Experimental Setups

High Energy Station:
- Setup for Nuclear Matter Study
- High Energy Irradiation Terminal
- Setup for Hypernuclear Study

High Intensity Radioactive Beam Line

Storage Ring:
- Isochronous Mass Spectrometer
- Schottky Spectrometer
- In-ring Reaction Setup
- DR Spectrometer



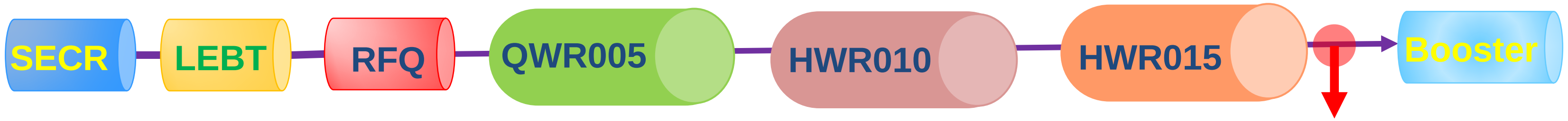
Keep Space

Low Energy Station:
- Gas-filled Recoil Separator
- Low Energy Spectrometer
- Low Energy Irradiation Terminal

Experiments @iLinac

Low Energy Station

Pulse Mode: injector of the Booster; **CW Mode:** deliver intense beams for low-energy experiments



Energy Adjustable

Pulse mode:

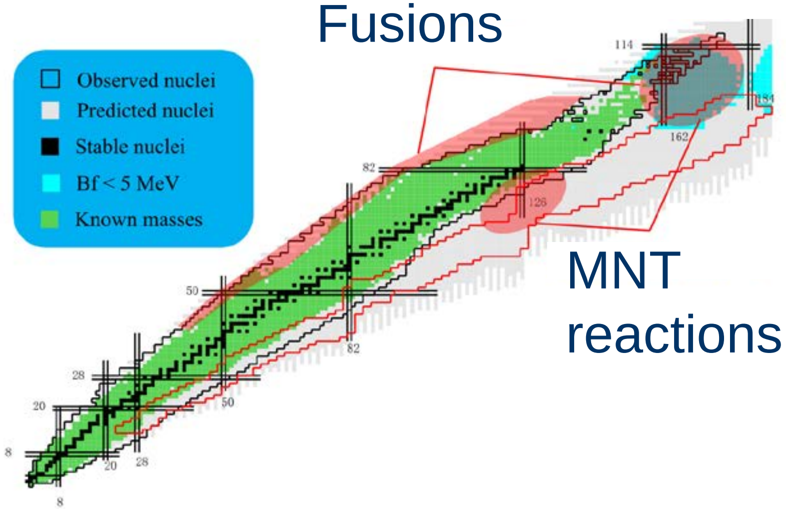
1.0 emA beams with A/Q=2~7

CW mode:

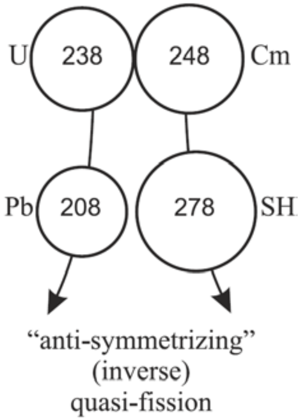
10 pμA beams with A/Q=2~5

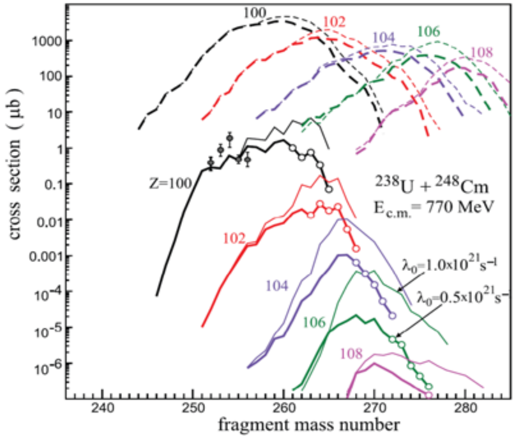
Fusion and MNT Reactions

Fusions



MNT reactions



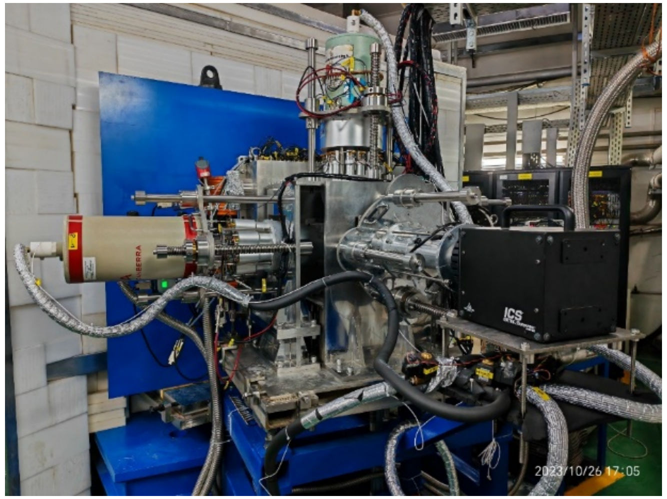


- synthesize new elements and isotopes
- measure nuclear masses and lifetimes
- build the decay schemes
- map out the drip lines
- build a bridge to the island of SHN
- simulate the *rp* and *r* processes
- study the evolution of shell structure

To produce heavy and super-heavy nuclei by fusion reactions and by multi-nucleon transfer reactions

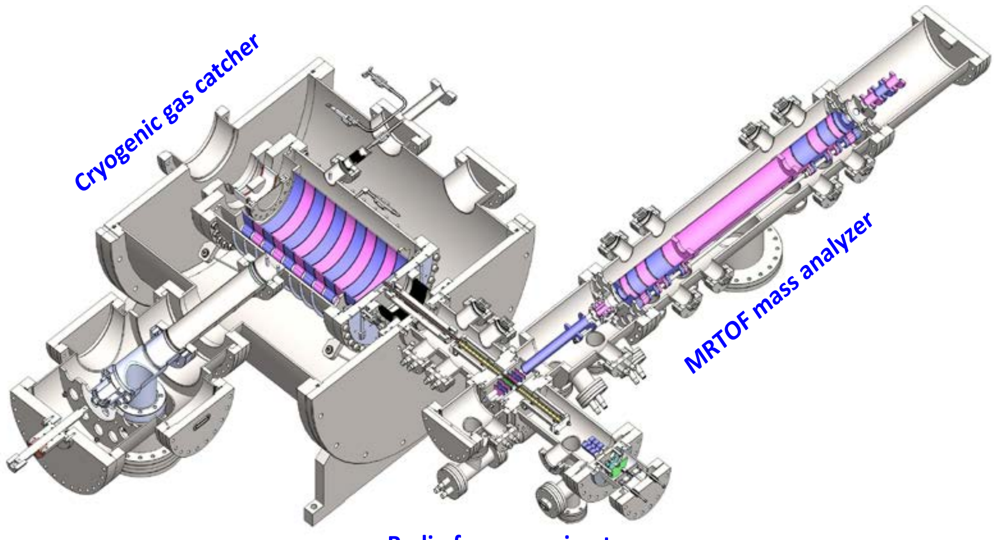
Experiments @iLinac

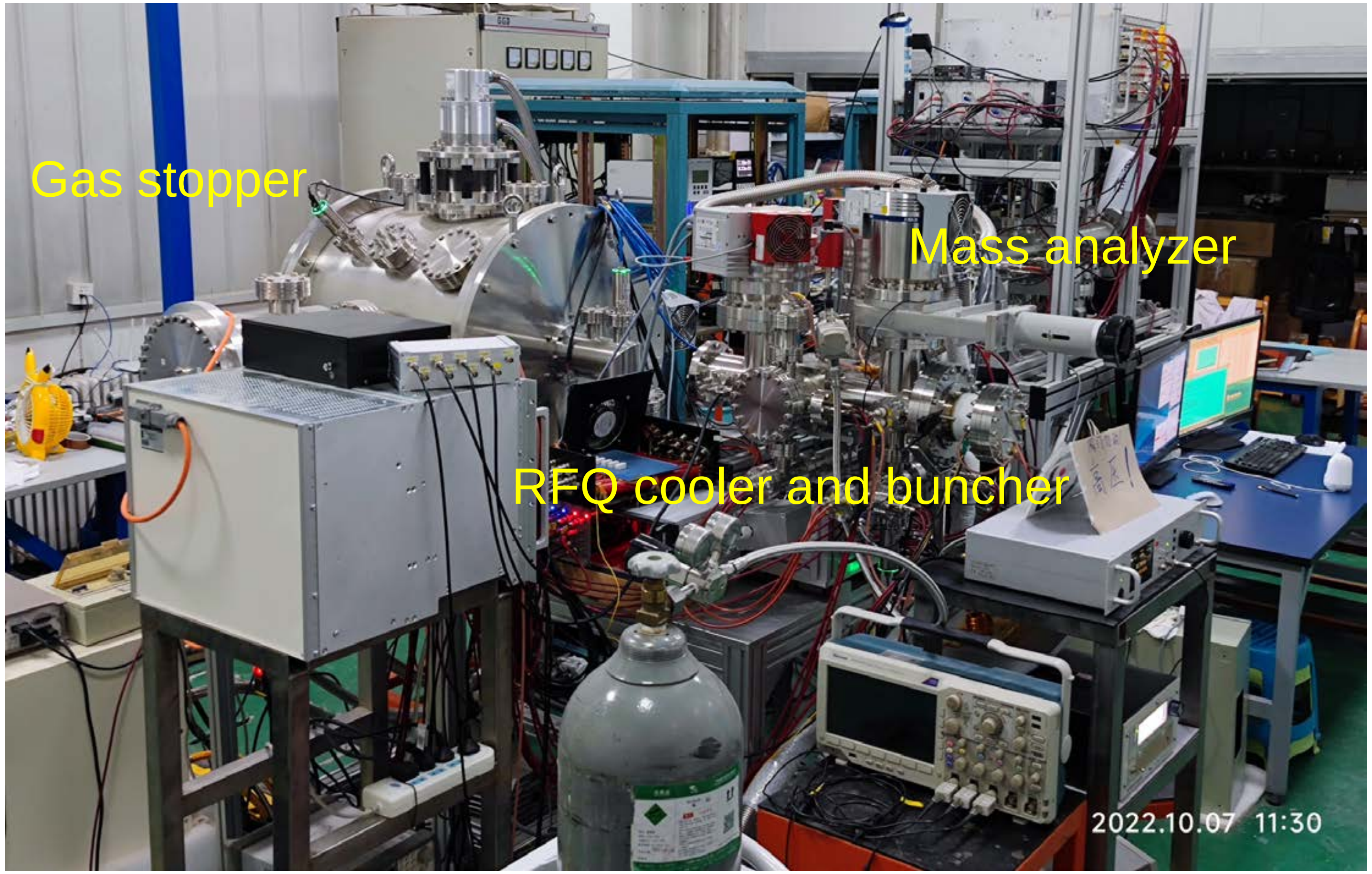
A high-efficient Gas-filled Recoil Separator



Experiments @iLinac

A high-efficient Gas-filled Recoil Separator



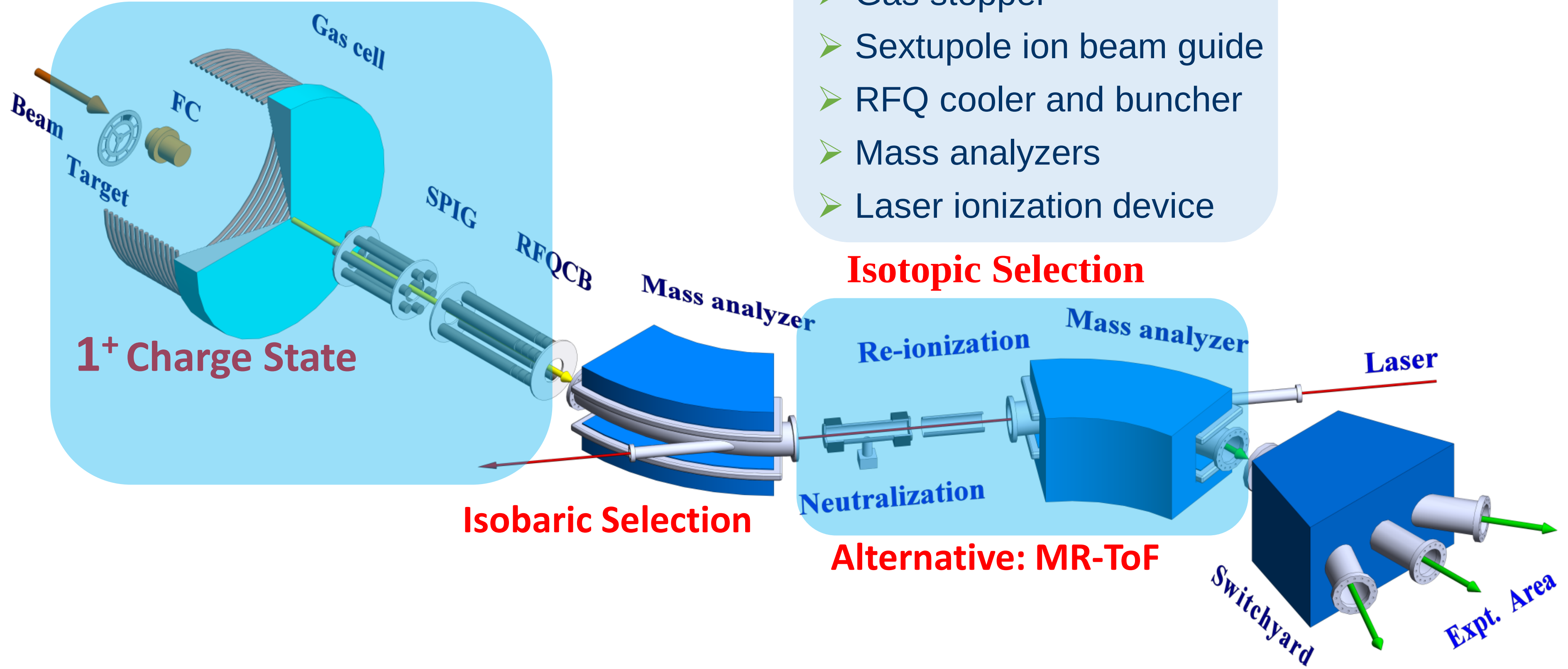


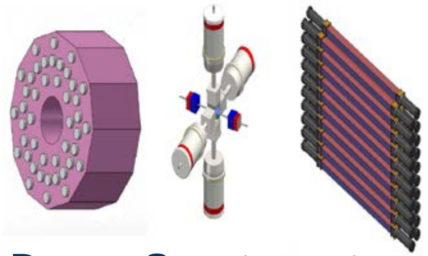
By coupling with a gas cell followed by a RFQ cooler and buncher, pulsed high-quality, low-energy beams are available for mass spectroscopy and collinear laser spectroscopy

Experiments @iLinac

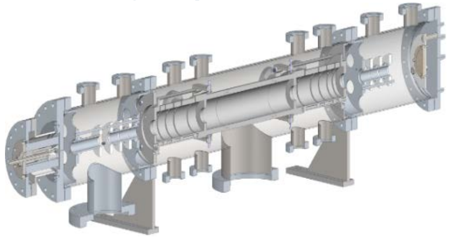
Separator for Products of MNT Reactions

- Rotating target system
- Gas stopper
- Sextupole ion beam guide
- RFQ cooler and buncher
- Mass analyzers
- Laser ionization device

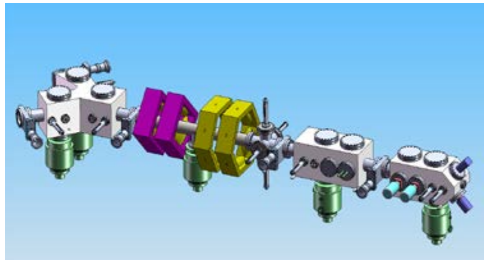




Decay Spectrometer



MR-ToF Mass Spectrometer

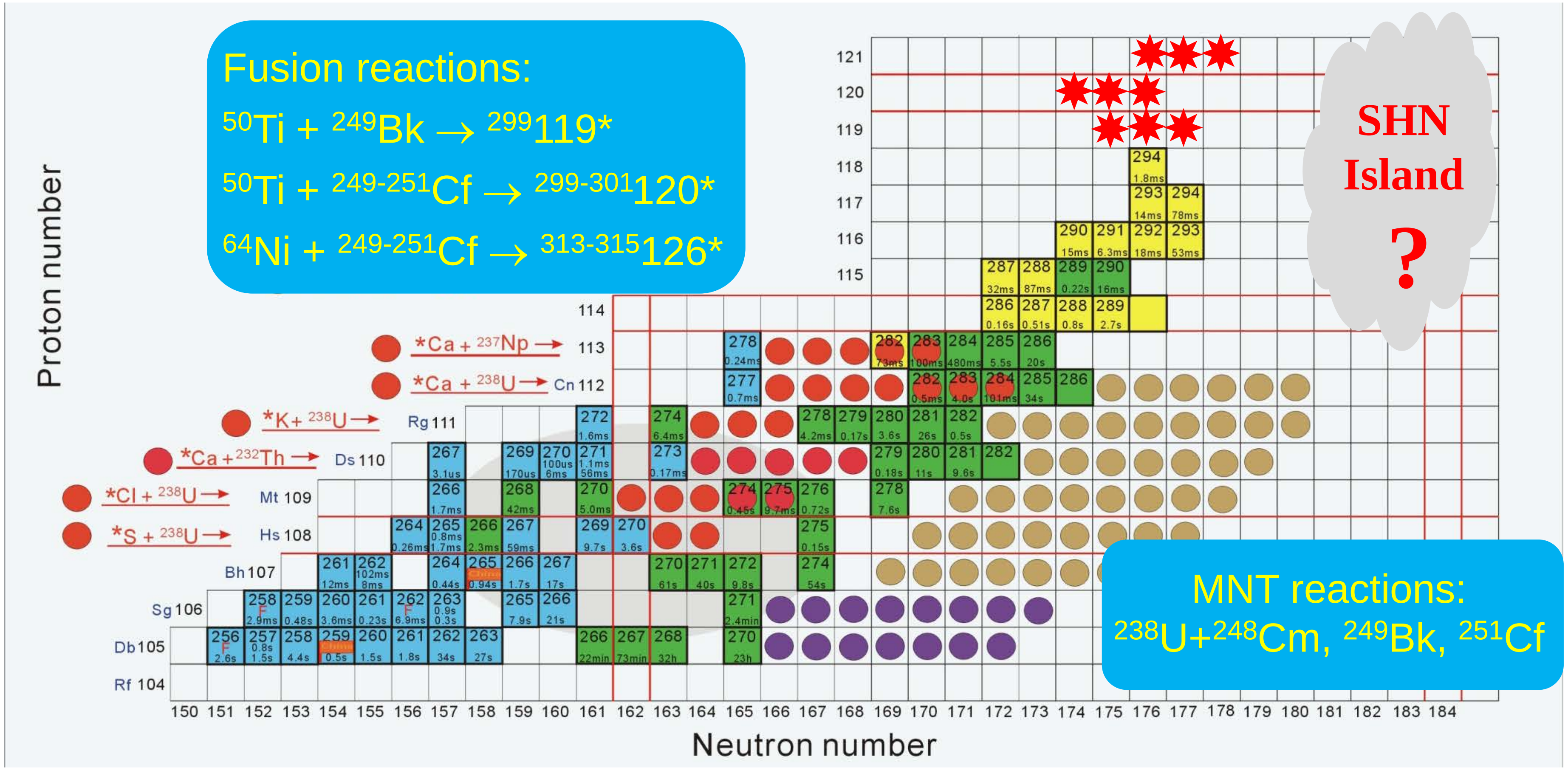


Collinear Laser Spectrometer

The separator provides pulsed low-energy, high-quality n-rich beams with mass and atomic numbers identified, and then distributes the beams to various measuring apparatuses

Physics @iLinac

Is there a limit, in terms of proton and mass numbers, to the existence of nuclei?

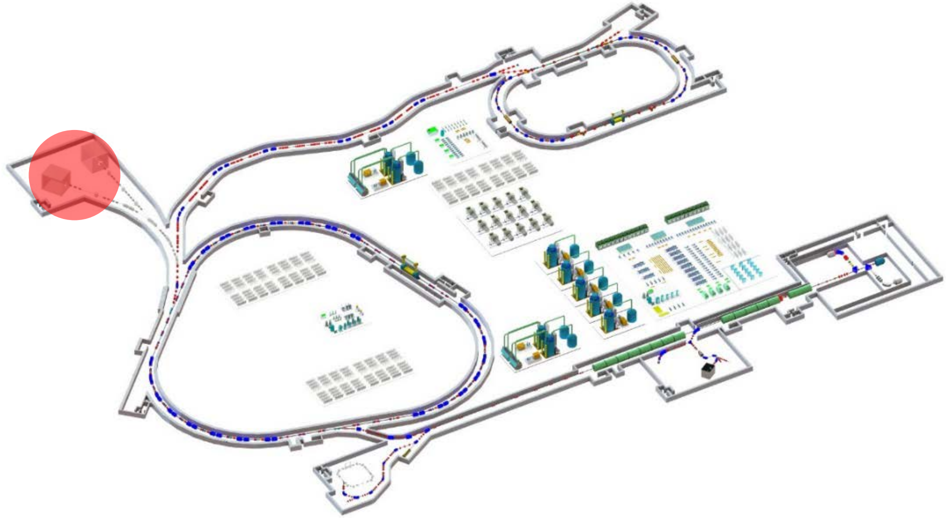


- Search for new elements and isotopes
- Bridge to the Island of Super-heavy Stability
- Measure nuclear masses and lifetimes
- Perform chemistry with the heaviest elements
- Hunt for new K-isomers
- Obtain information on the single particle states

Experiments @Booster Ring

High Energy Station

- Stable beams provided by the Booster
- DC-type extraction from the Booster



Typical beam parameters from the Booster Ring

Ions	Energy(GeV/u)	Intensity (ppp)
p	9.3	2.0×10^{12}
$^{18}O^{6+}$	2.6	6.0×10^{11}
$^{78}Kr^{19+}$	1.7	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{34+}$	0.8	1.0×10^{11}

Slow extraction: ~ 3s beam duration

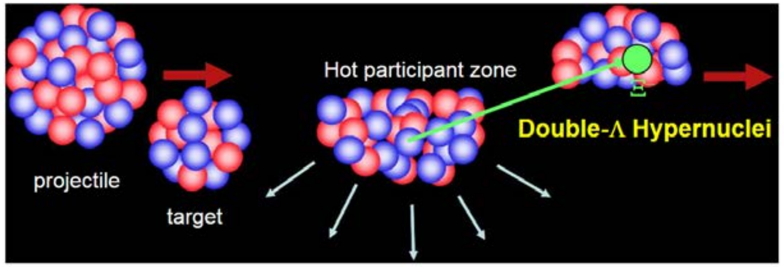
Not supported by the approved budget

The high-energy stable beams are ideal to produce hypernuclei and nuclear matter

- Properties of nuclear matter: supported already by CAS and NSFC, about 200 Million CNY
- Synthesis of new hypernuclei: seeking for financial support, international collaboration?

Moderate beam intensity and higher energies. A/Z=2 primary beams up to 4.25 GeV/u energy will be available

Experiments @Booster Ring

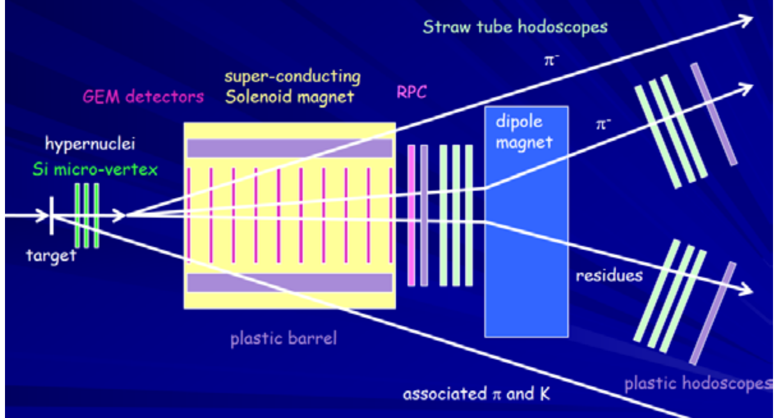


Expected reconstructed rate

- $^{20}Ne + {}^{12}C$ at 4.25 A GeV
- Beam intensity: 10^7 /s

	Single-Λ hypernuclei	Double-Λ hypernuclei
per day	8×10^5	9×10^1
per week	6×10^6	6×10^2
per month	2×10^7	3×10^3

Possible hypernuclear setup at HIAF



Cost of ~60 million CNY

Courtesy: T. Saito

Synthesis of New Hypernuclei

- Hypernuclei can be produced in high-energy peripheral collisions
- Above 3.75 GeV/u, double-Λ hypernuclei can be produced!

High energy & moderate intensity

Open New Domain: Hypernuclei with Double Strangeness

Production of ΛΛ hypernuclei

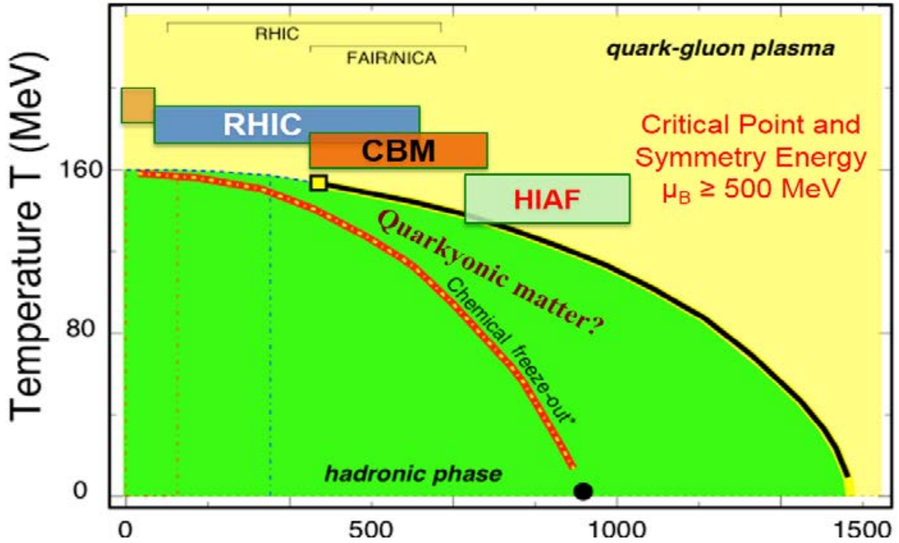
- $d + \Xi^- \rightarrow n\Lambda\Lambda$
- $t + \Xi^- \rightarrow nn\Lambda\Lambda$
- $^3He + \Xi^- \rightarrow {}^4_{\Lambda\Lambda}H$
- $^4He + \Xi^- \rightarrow {}^5_{\Lambda\Lambda}H$
- $^6Li + \Xi^- \rightarrow {}^7_{\Lambda\Lambda}He$
- $^7Li + \Xi^- \rightarrow {}^8_{\Lambda\Lambda}He$
- $^9Be + \Xi^- \rightarrow {}^{10}_{\Lambda\Lambda}Li$
- $^{10}Be + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}Li$
- $^{10}B + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}Be$
- $^{11}B + \Xi^- \rightarrow {}^{12}_{\Lambda\Lambda}Be$
- ...

Decay of ΛΛ hypernuclei

- $n\Lambda\Lambda \rightarrow {}^3He + \pi^- + \pi^-$
- $nn\Lambda\Lambda \rightarrow {}^4He + \pi^- + \pi^-$
- ${}^4_{\Lambda\Lambda}H \rightarrow p + {}^3He + \pi^- + \pi^-$
- ${}^5_{\Lambda\Lambda}H \rightarrow p + {}^4He + \pi^- + \pi^-$
- ${}^7_{\Lambda\Lambda}He \rightarrow {}^7Be + \pi^- + \pi^-$
- ${}^8_{\Lambda\Lambda}He \rightarrow {}^4He + {}^4He + \pi^- + \pi^-$
- ${}^{10}_{\Lambda\Lambda}Li \rightarrow {}^{10}B + \pi^- + \pi^-$
- ${}^{11}_{\Lambda\Lambda}Li \rightarrow {}^{11}B + \pi^- + \pi^-$
- ${}^{11}_{\Lambda\Lambda}Be \rightarrow {}^{11}C + \pi^- + \pi^-$
- ${}^{12}_{\Lambda\Lambda}Be \rightarrow {}^{12}C + \pi^- + \pi^-$
- ...

Experiments @Booster Ring

Study of the QCD Phase Structure



Baryon Chemical Potential μ_B (MeV)

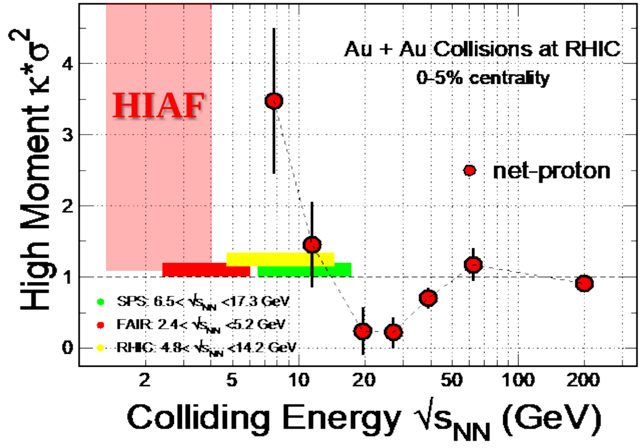
Lattice QCD: from the QGP to the hadronic phase

At μ_B~0, the smooth cross-over transition

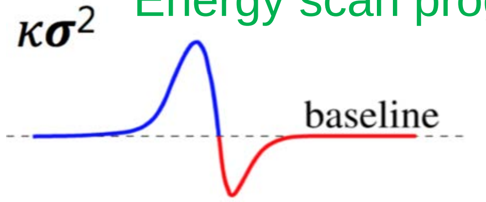
At finite μ_B, the first-order phase transition

Thermodynamically, **a critical point** must exist:

the end point of the first-order phase transition line



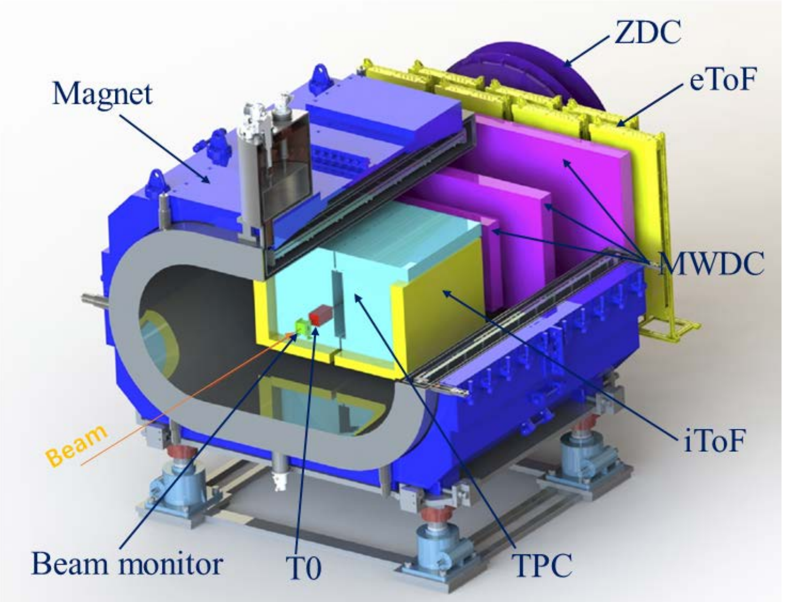
Energy scan program!



Observables:

net-proton fluctuation

net-baryon collectivity

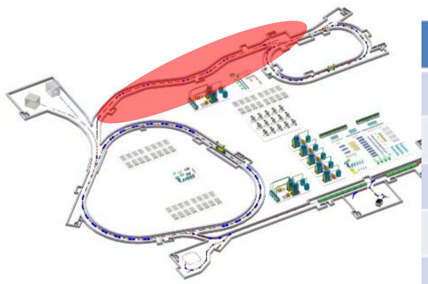


The External Target Experiment Setup

Experiments @HIRBL

High Intensity Radioactive Beam Line (HIRBL)

- Slowly extracted beams from the Booster
- Radioactive ion beams produced by HFRS



Beams from the Booster Ring

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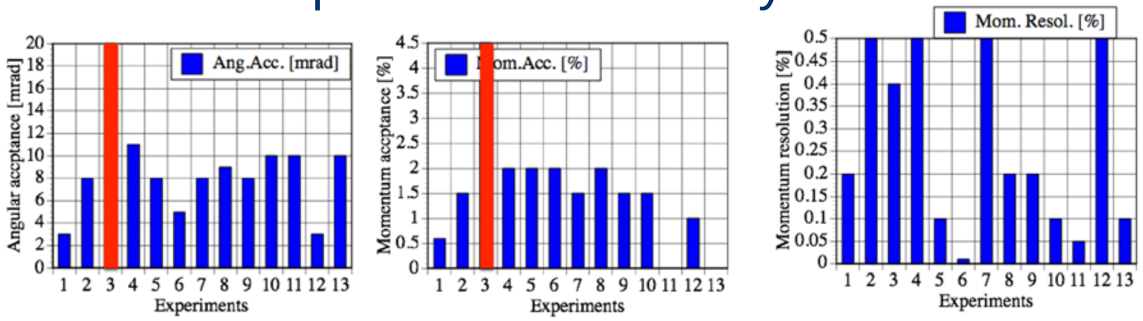
Requirements from Physics



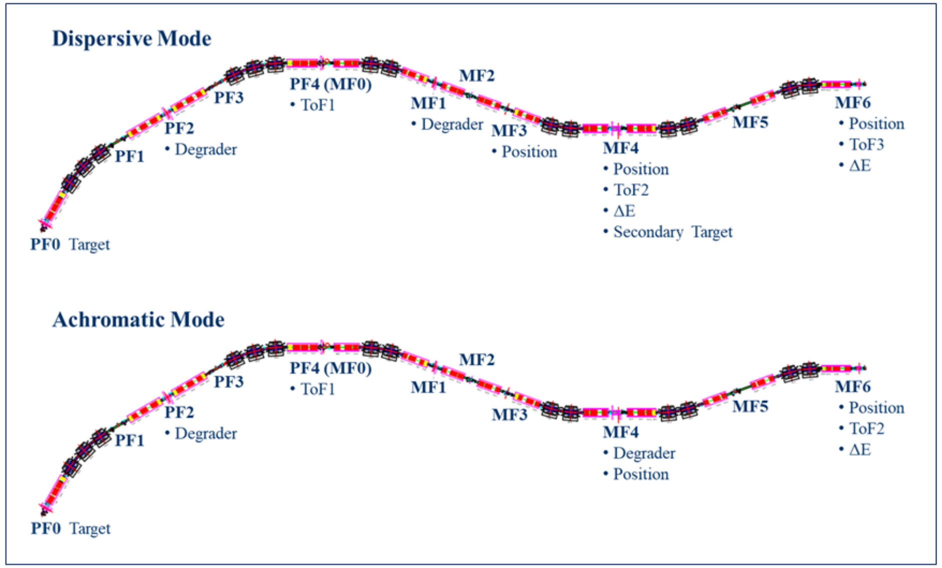
Acceptance, and Momentum Resolution

Physics Cases @HIRBL

- ✓ New isotopes in the south east of ^{208}Pb (PF of ^{208}Pb and ^{238}U)
- ✓ Neutron dripline up to Ni isotopes (PF of Kr and Xe)
- ✓ New isotopes by ^{238}U fission (In-flight fission of ^{238}U)
- ✓ New isotopes using two step projectile fragmentations
- ✓ Synthesis of neutron rich hypernuclei
- ✓ Study of tensor interactions: a basic change in structure model
- ✓ Particle decay in flight of unbound nuclei
- ✓ Nuclear matter radii (Interaction cross sections)
- ✓ Nuclear proton radii (Charge changing cross sections)
- ✓ Charge exchange reactions and β decay of r-process nuclei
- ✓ Nucleon excitations in nuclei
- ✓ Giant resonance of neutron rich nuclei
- ✓ Elastic scattering and transfer reactions
- ✓ Spectroscopy of meson-nucleus bound system
- ✓ …

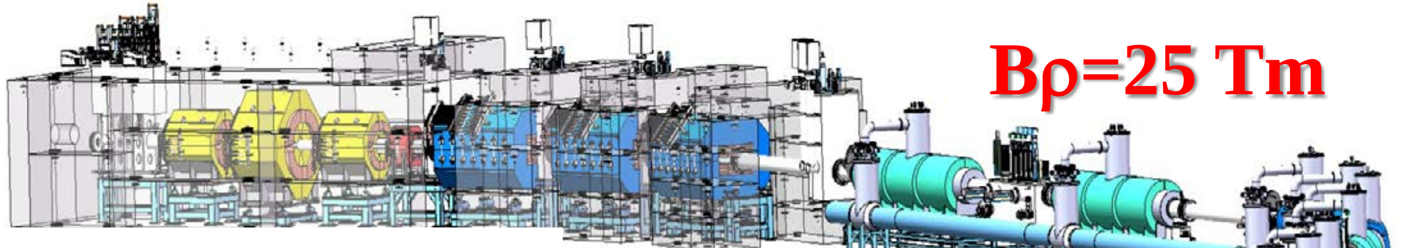
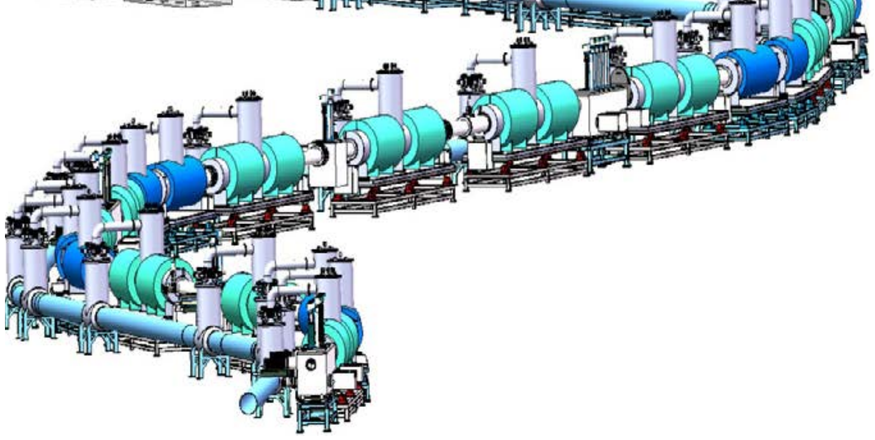
Various experiments can be done at HFRS

Structure and Performance of HIRBL



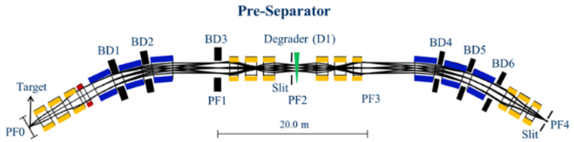
- ✓ **The dispersive mode:** a separator-spectrometer. A degrader at MF1 and a reaction target at MF4. The second part from MF4 to MF6 works as a zero-degree spectrometer
- ✓ **The achromatic mode:** a point-to-point focusing optical system with an achromatic degrader at MF4

Bρ=25 Tm

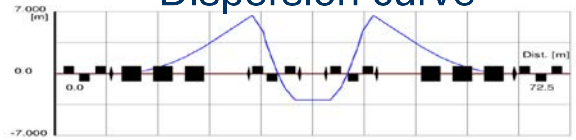
Characteristics of HIRBL

Max. magnetic rigidity	15（25）Tm
Angular acceptance	± 30 mrad (x) ± 15 mrad (y)
Momentum acceptance	± 2.0%
Momentum resolution	750, 700, 1100
Total length	180 m



Beam envelope

Dispersion curve



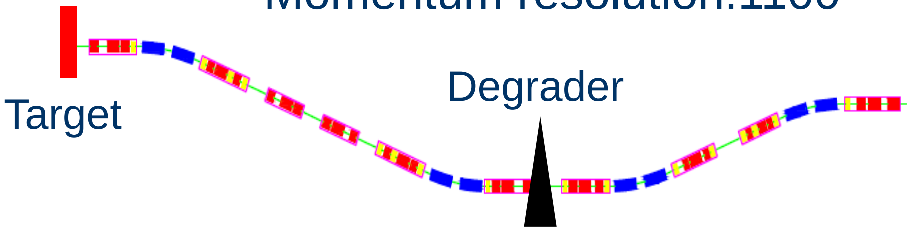
Design completed

Structure and Performance of HIRBL

Main-Separator: Separator + Spectrometer

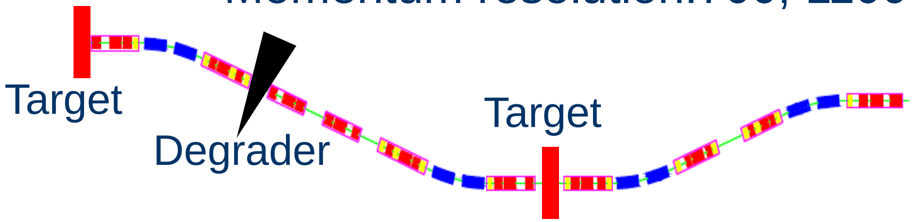
Achromatic Mode

Momentum resolution:1100



Dispersive Mode

Momentum resolution:700, 1100



The peculiarities of the HIRBL:

- A maximum Bρ=15（25）Tm, and thus high-energy secondary beams available
- High separation power, and fully stripped ions of all elements available
- Versatile spectrometer modes by different combinations of separator sections

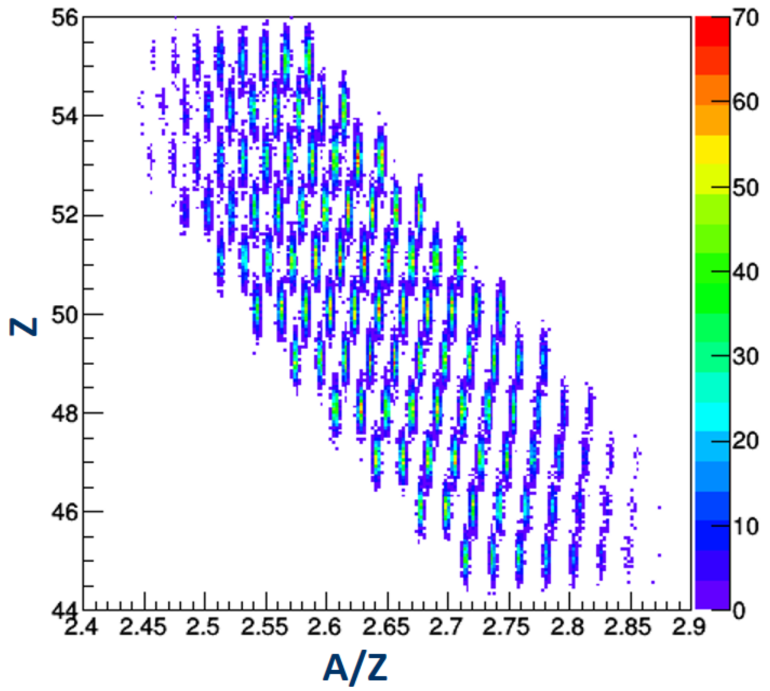
Bρ=25Tm
Unique Experiments

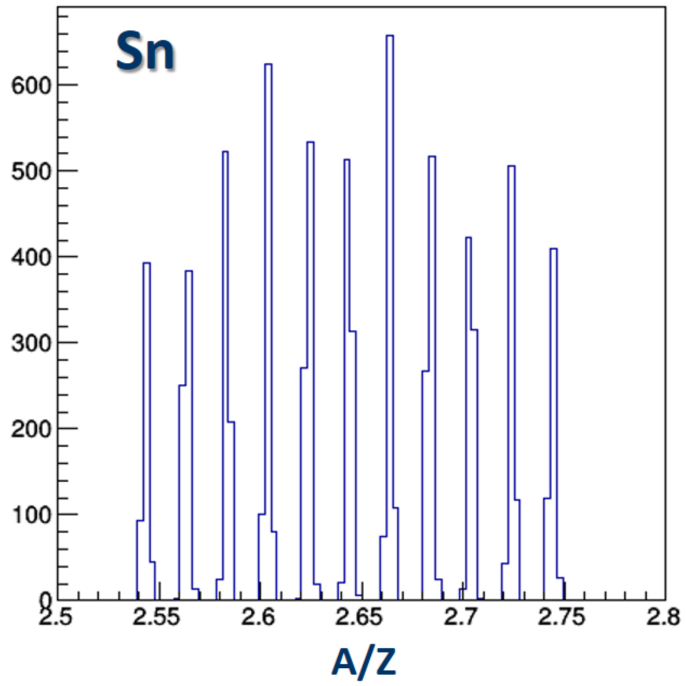
- Synthesis of neutron rich hypernuclei
- Nucleon excitations (Δ resonance and N*) in nuclei
- Giant resonance of neutron rich nuclei
- Spectroscopy of meson-nucleus bound system

Structure and Performance of HIRBL

Capability of Separation and Identification

In-flight fission of ^{238}U with energy of 800 MeV/u





Particle ID:

$\Delta E - ToF - B\rho$

ΔE measurement: Multiple sampling ionization chambers

ToF measurement: Diamond detectors

$B\rho$ measurement: GEM-TPC detectors

Physics @HIRBL

To explore the hitherto unknown territories and find new phenomena

Nuclear Structure and Dynamics

Systematic measurements of mass and lifetime

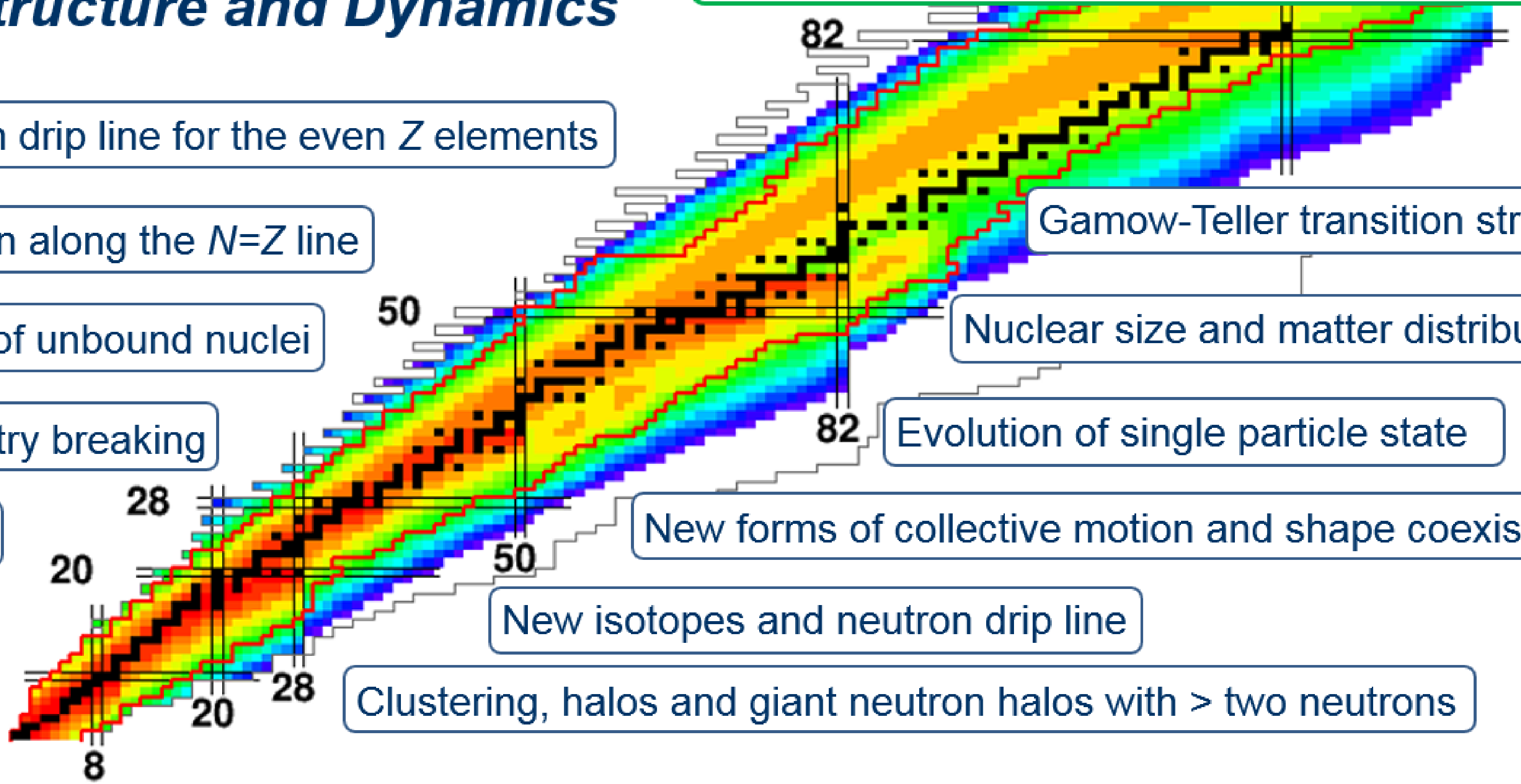
Proton drip line for the even *Z* elements

Shape evolution along the *N*=*Z* line

In-flight decay of unbound nuclei

Isospin symmetry breaking

New *np* paring



Gamow-Teller transition strengths B_{GT}

Nuclear size and matter distribution

Evolution of single particle state

New forms of collective motion and shape coexistence

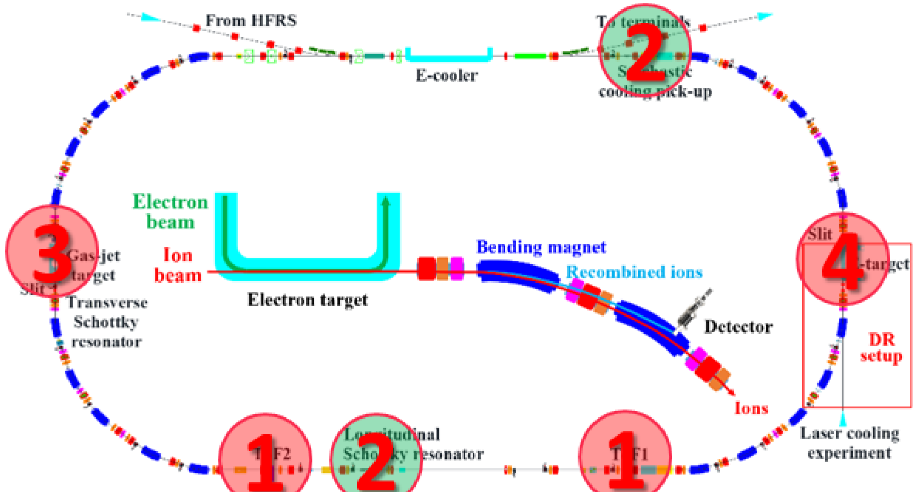
New isotopes and neutron drip line

Clustering, halos and giant neutron halos with > two neutrons

See following talks

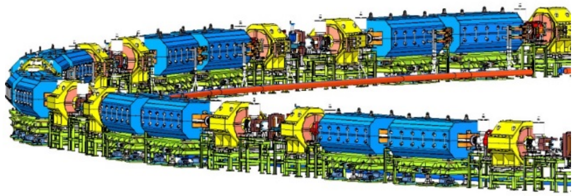
Experiments @Spectrometer Ring

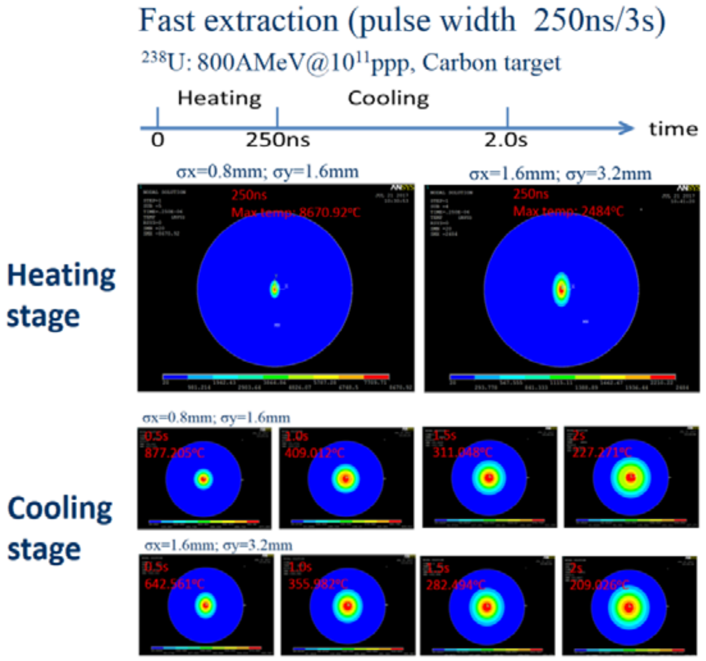
Spectrometer Ring: Multi Working Modes of Storage Ring



With fast extracted projectiles from the Booster, HFRS produces, separates and injects the isotopes of interests into the Spectrometer Ring

Fast Extraction： Repetition rate 3 Hz; 50~200ns length





Carbon target sustainable to beam power

Experiments:

- Isochronous Mass Spectroscopy
- Schottky Spectroscopy
- DR Spectroscopy
- In-ring Nuclear Reactions

Spectrometer Ring:

- Circumference:188.7 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

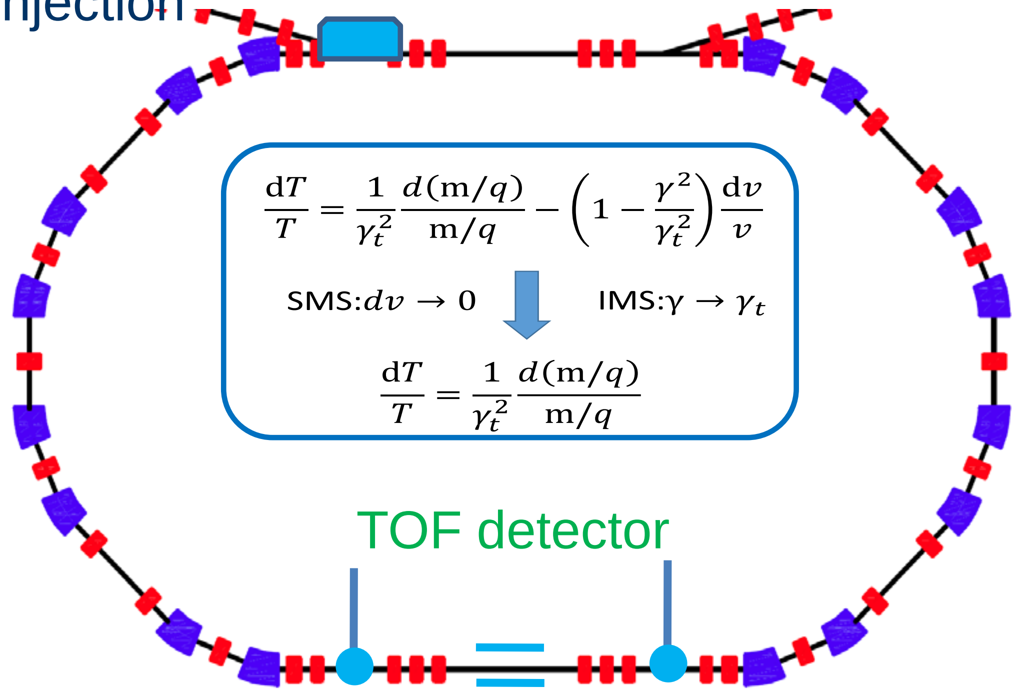
Experiments @Spectrometer Ring

Isochronous Mass Spectrometry and Schottky Spectrometry

Injection

Electron cooler

Extraction



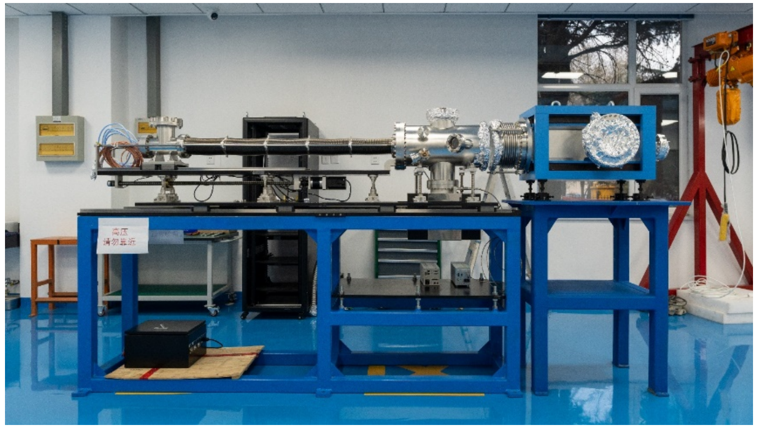
$$\frac{dT}{T} = \frac{1}{\gamma_t^2}\frac{d(m/q)}{m/q} - \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{dv}{v}$$

SMS: $dv \rightarrow 0$ IMS: $\gamma \rightarrow \gamma_t$

$$\frac{dT}{T} = \frac{1}{\gamma_t^2}\frac{d(m/q)}{m/q}$$

TOF detector

Schottky resonator



Timing Detector

Schottky Probe

Conventional IMS: $\frac{\Delta m}{m} = 10^{-6} \sim 10^{-7}$, small Isochronous window

Measurements of mass, lifetime, and rare decay mode of highly-charged ions

Experiments @Spectrometer Ring

Bρ - Defined Isochronous Mass Spectrometry

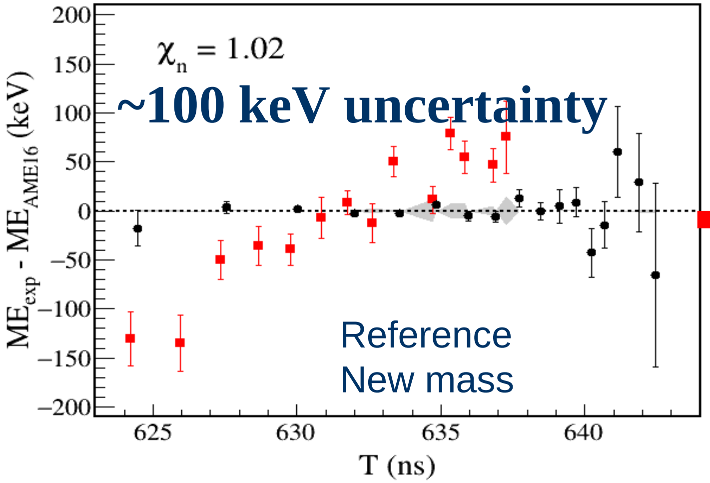
ToF detector #1   ToF detector #2

The revolution time T and velocity v of the ion are measured simultaneously. The circulating length of the ion $C = T \cdot v$

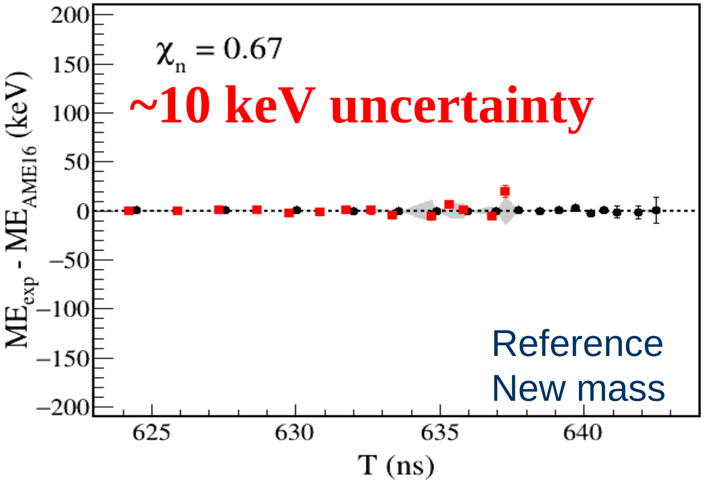
With known masses, determine the best $B\rho = f(C)$

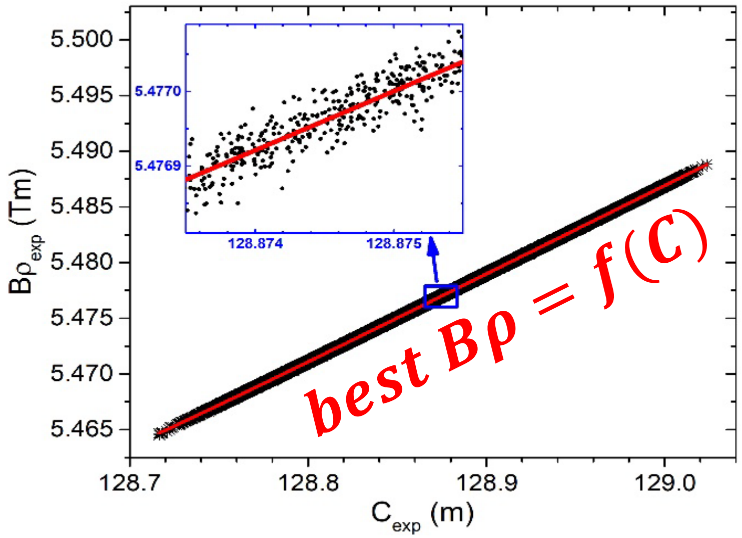
New masses obtained from $$(m/q)^i_{exp} = \frac{f(C^i_{exp})}{(\gamma v)^i_{exp}}$$

Conventional IMS



Bρ-Defined IMS



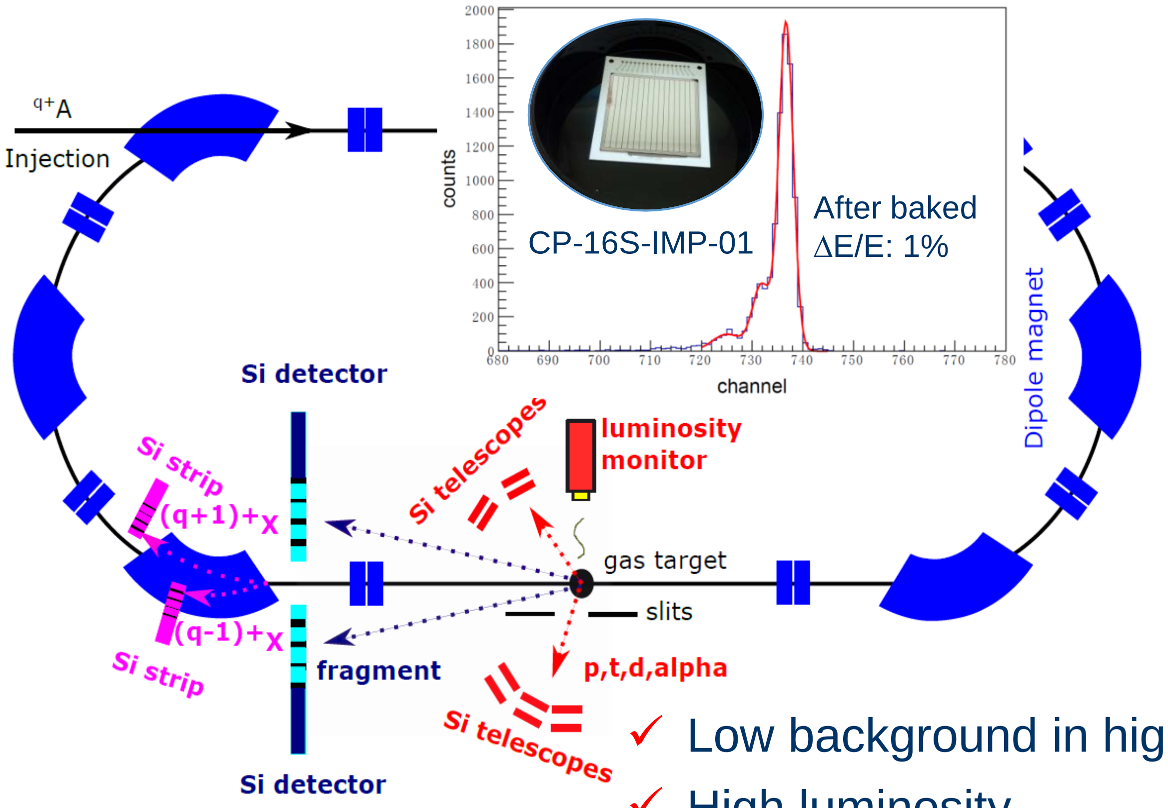


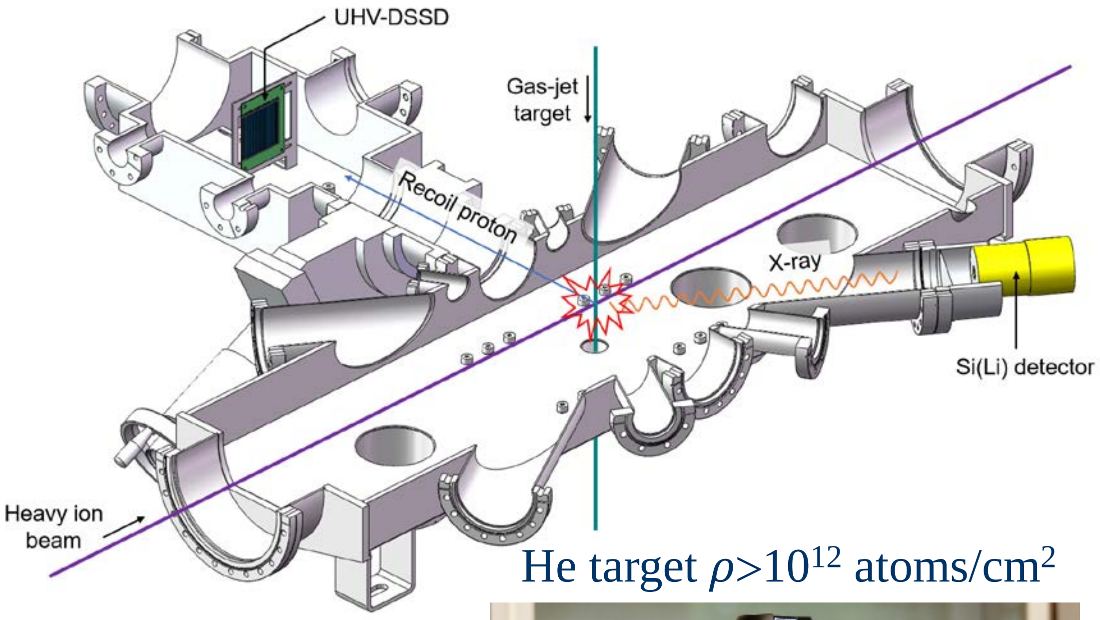
- ✓ Eliminate the systematic errors
- ✓ Single-ion sensitivity
- ✓ Applicable to short-lived nuclides
- ✓ ....

Phys. Rev. Lett. 135, 012501 (2025); Phys. Rev. Lett. 133, 222501(2024); Nature Physics 19, 1091-1097 (2023)

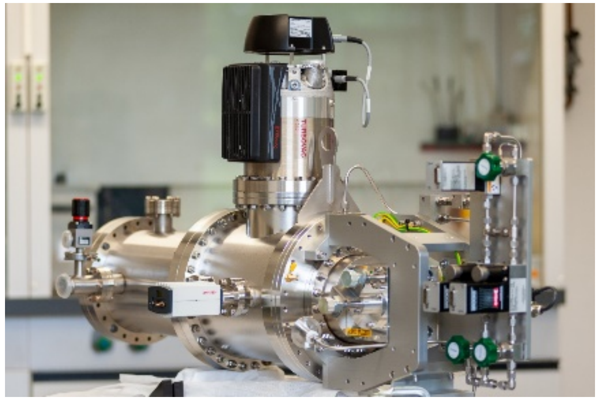
Experiments @Spectrometer Ring

Setup for In-ring Nuclear Reactions





He target $\rho > 10^{12}$ atoms/cm^2



- ✓ Low background in high vacuum
- ✓ High luminosity
- ✓ High-resolution measurement

Nuclear Reactions:

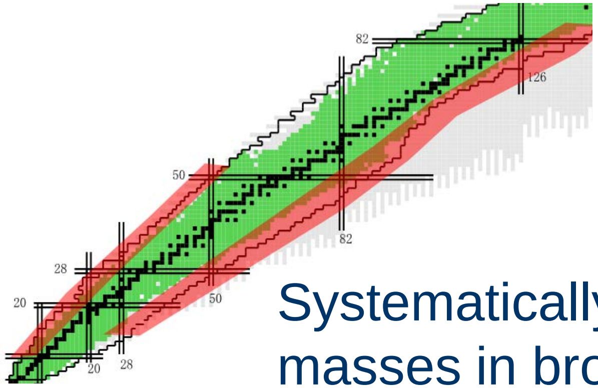
(p, p), *(p, p')*, *(p, γ)*, *(α, p)*, and *(α, γ)* reaction rates

Solid target and active target with ion energy compensation

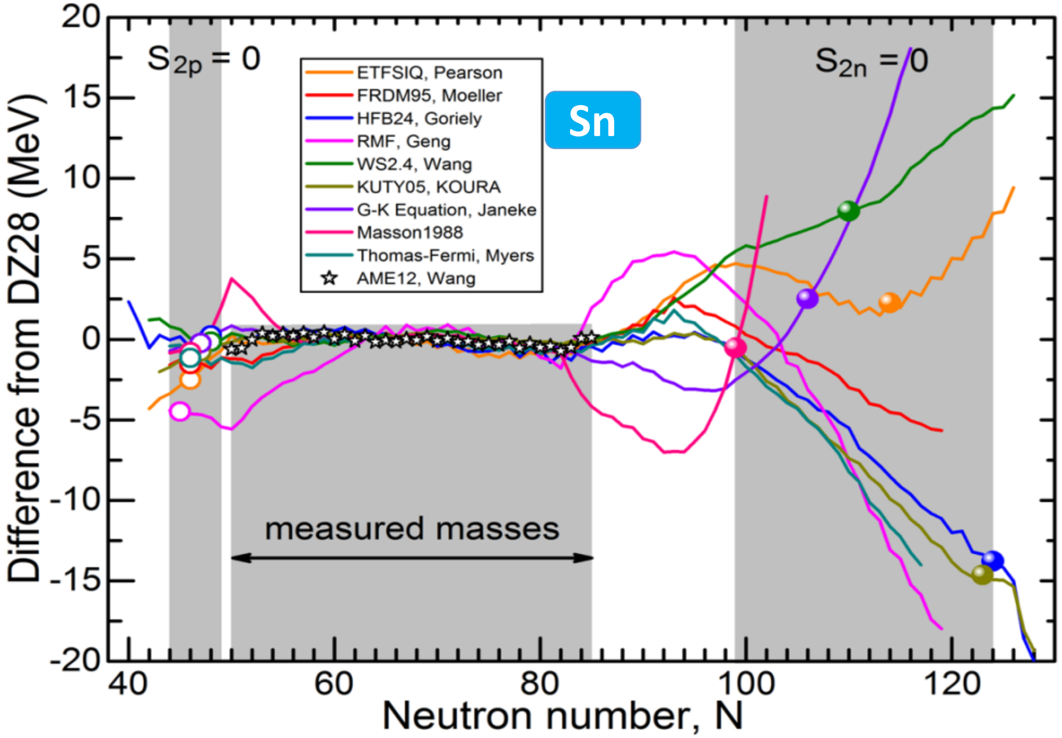
Physics @Spectrometer Ring

Experimental Measurements:

- **Nuclear Masses with Highest Priority**
- Nuclear Half-lives
- Exotic Decay Modes



Systematically measure nuclear masses in broad regions

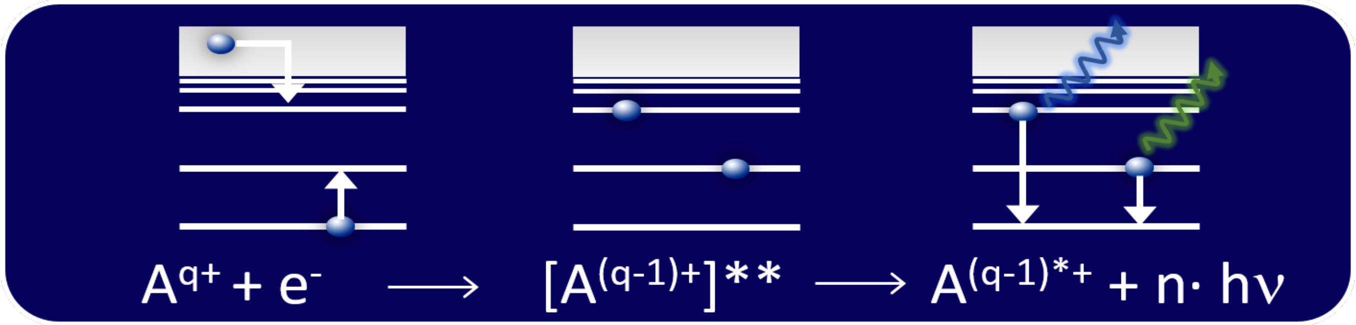


Physics:

- map out the mass surface in broad regions and determine the drip lines
- reveal the evolution of the effective interactions while changing the *N/Z* ratios
- study the quenching of the known shell gaps and development of new ones
- find out the deformation change and onset of exotic shapes along isotopic chains
- simulate the *rp* process and *r* process

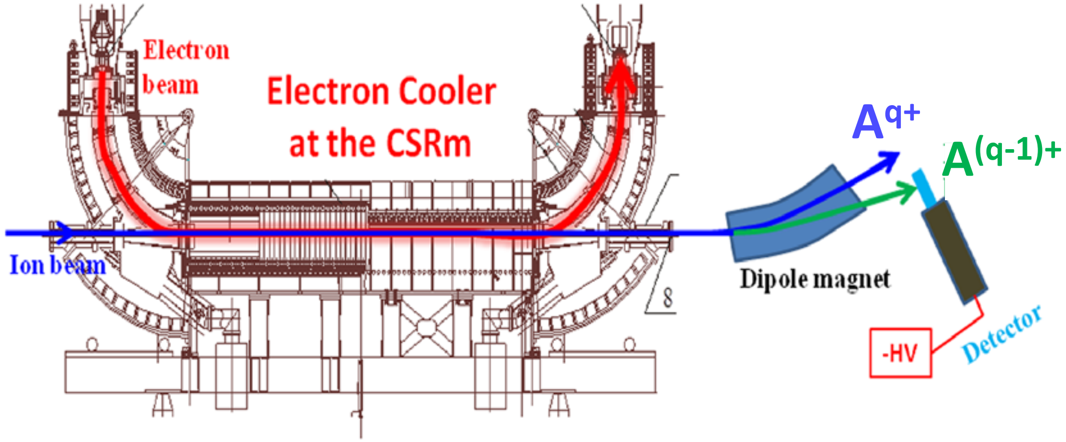
Experiments @Spectrometer Ring

Spectrometer for Dielectronic Recombination



- In e-gun, the electron beam has a longitudinal temperature of less than 1.0 meV
- The cooling results in a very narrow momentum spread for the ion beam of ~10^{-5}

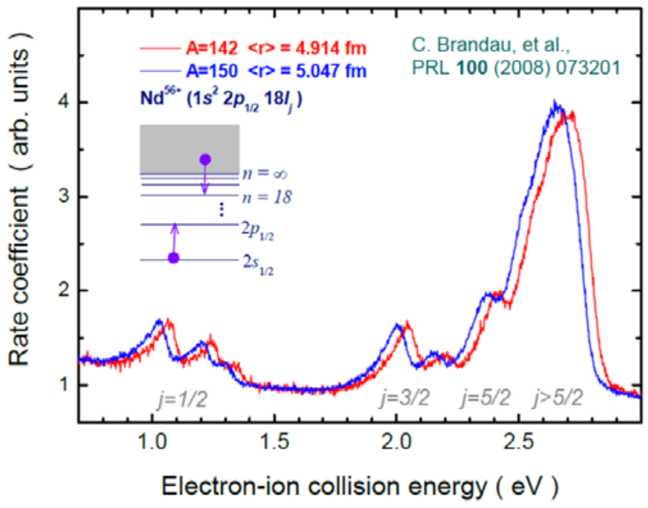
Dielectronic Recombination: While the ion A^{q+} captures a free electron with well defined energy provided by the electron gun, a bound electron is excited simultaneously



Recombination Rate:

$$\alpha(E_{rel}) \propto N(A^{(q-1)+})/N(A^{q+})$$

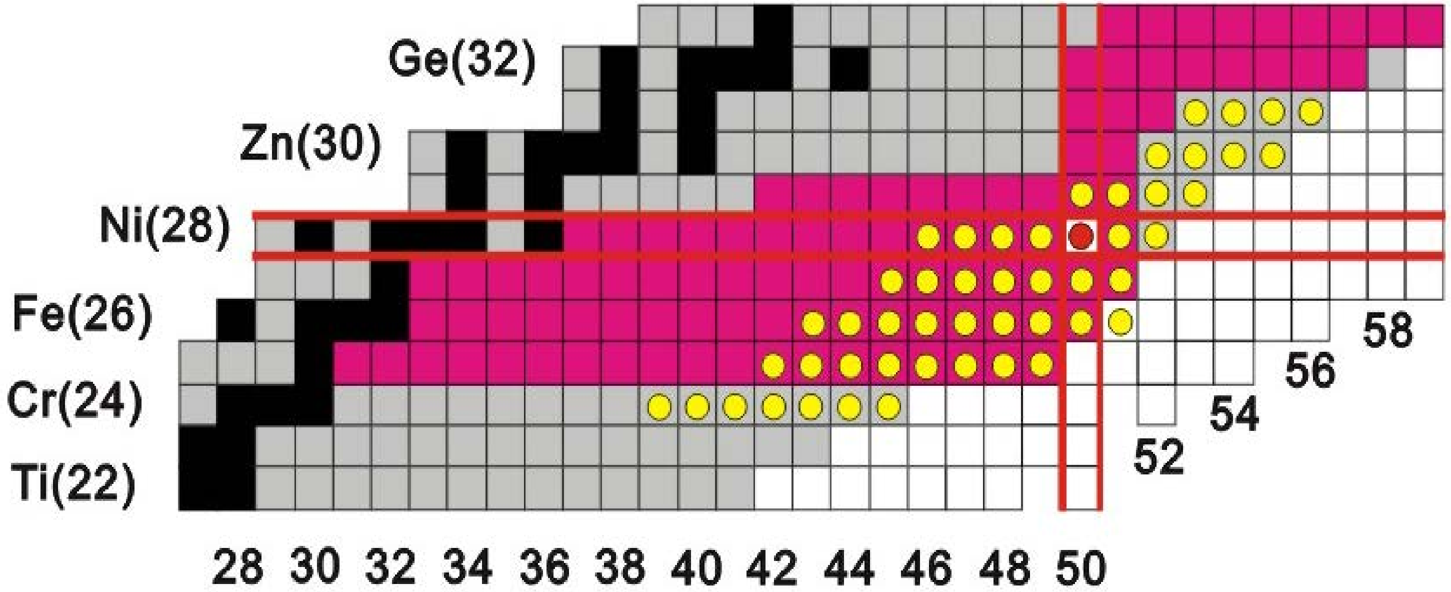
ESR storage ring at GSI: DR of Li-like Nd^{57+}



To tune precisely the electron energy and count the recombined ions, fine or hyperfine spectra are obtained

Day-One Experiment @ HIAF

Mass Measurements of N-rich Nuclides around ^{78}Ni



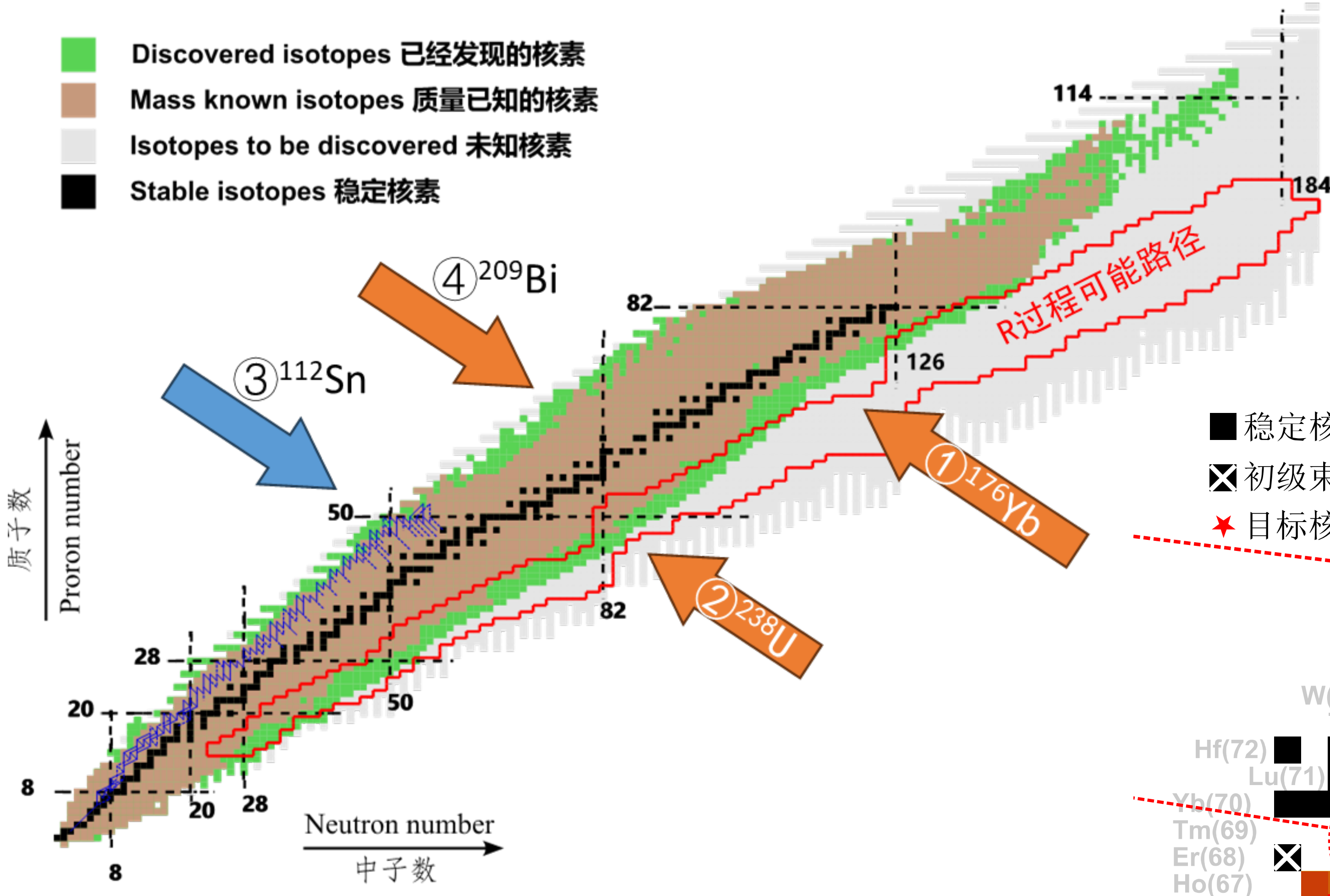
Production: Fragmentation of Projectile ^{86}Kr Using the HFRS

Measurement: The Isochronous Mass Spectrometer with Double ToF Detectors

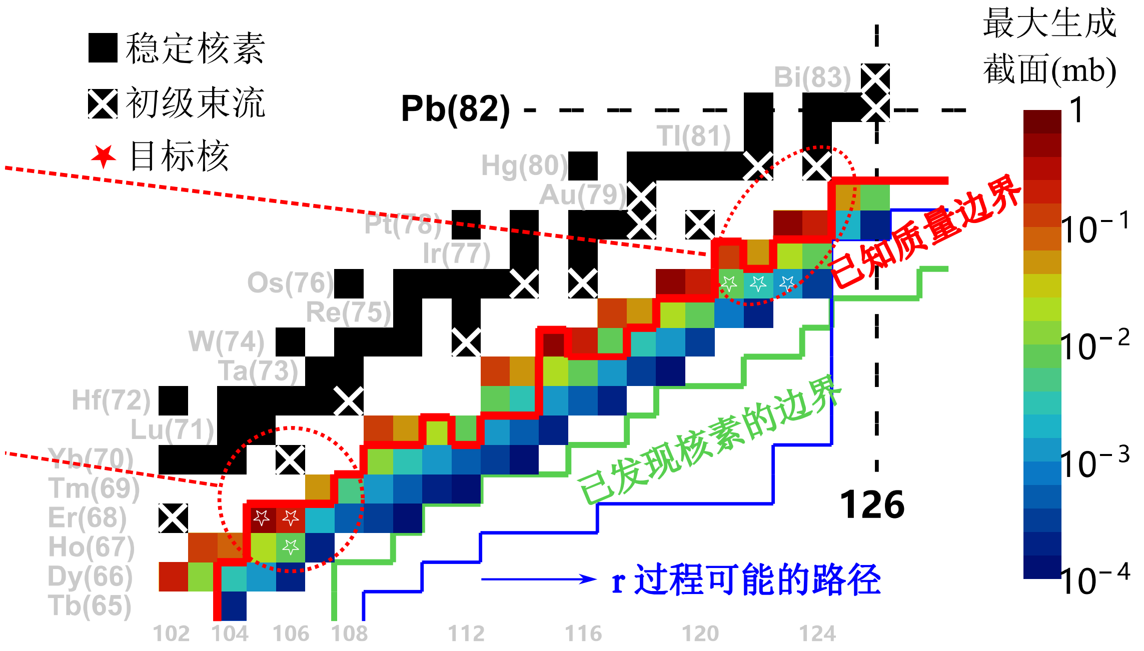
Systematically measure nuclear masses with a precision of ~ 50keV, and deduce one-neutron and two-neutron separation energies

Study the evolution of the *N*=50 shell closure and Simulate the r-process

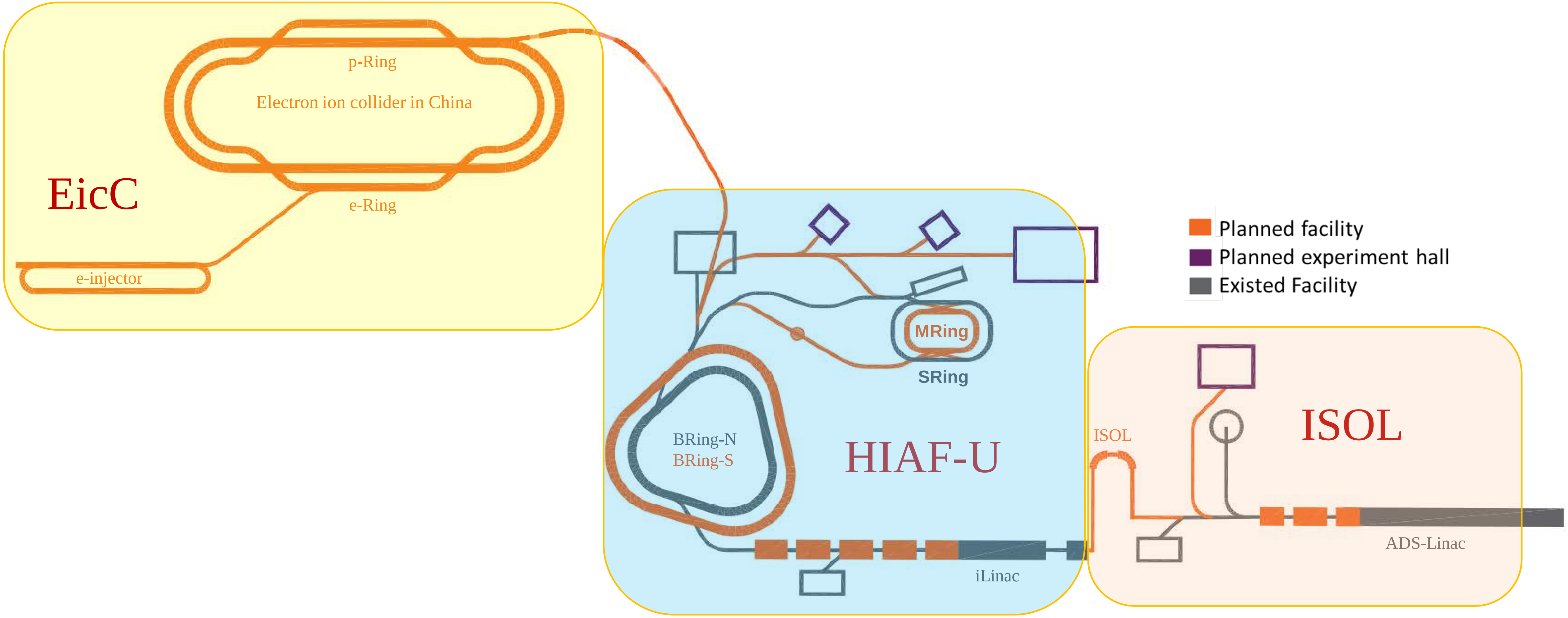
Day-one Experiments @HIAF



- ✓ To look for new isotopes
- ✓ To measure masses
- ✓ To measure lifetimes



Future HIAF



p-Ring
Electron ion collider in China
EicC
e-Ring
e-injector
MRing
SRing
BRing-N
BRing-S
HIAF-U
iLinac
Planned facility
Planned experiment hall
Existed Facility
ISOL
ISOL
ADS-Linac

Budget

Items	Cost（Million CNY）
iLinac	360
Booster Ring	350
Beam line	50
Experimental setups	380
Cryogenics	80
Others	350
Contingency	100
	1670 (Central government)
Infrastructure & deficiency	1000 (Local government)
Total	**2670**

Unit: Million Chinese Yuan (one U.S. dollar ≈ 6.5 Chinese Yuan)

Time Schedule

2019	2020	2021	2022	2023	2024	2025	2026
Civil construction							
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.					
ECR design & fabrication		SECR installation and commissioning			First beam		
	Linac design & fabrication			iLinac installation and commissioning		Day one exp	
Prototypes of PS, RF cavity, chamber, magnets, etc.			fabrication	BRing installation and commissioning	Complete Installation	Day one exp	
					HFRS installation & commissioning		
				SRing installation & commissioning	Complete Installation	Day one exp	
				Terminals installation			

The facility should be commissioned at the end of 2025

Summary

HIAF will be “next generation” type facility

RIBF, RAON and HIAF are complementary to each other

Let us work together to build a world’s leading unparalleled center for research and education in nuclear physics, accelerator physics and technology, and applications of energetic heavy ions

For details, please refer to: Status of the high-intensity heavy-ion accelerator facility in China, Zhou et al. AAPPS Bulletin (2022) 32:35

Thank you for your attention!

Acknowledgment

IMP: X.D.Tang, Zh.Liu, W.X.Huang, Z.G.Gan, J.Yang, X.Ma, Y.H.Zhang, M.Wang, X.C.Chen, X.L.Tu, Z.Y.Sun, J.S.Wang, M.L.Liu, B.Ding, Y.L.Tian, …

Beihang University: I.Tanihata, B.H.Sun, S.Terashima, …

Beijing Normal University: F.S.Zhang and K.Zhao

Peking University: Y.L.Ye, F.R.Xu, …

CIAE: C.J.Lin, …

CNS: S.Kubono

GSI: Y. Litvinov, T. Saito and C. Scheidenberger

Thank you for your attention!

Physics @HFRS

Example: Revealing the Effect of Tensor Force

The tensor forces are not treated explicitly in models such as mean field models and shell models

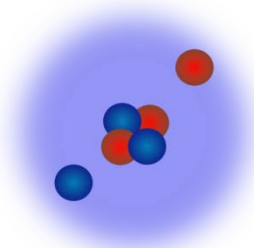
The pion interaction:

$$\vec{\sigma}_1 \cdot \vec{q}\vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3}q^2 S_{12}(\hat{q}) + \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 q^2$$

The tensor force is as important as the central forces!

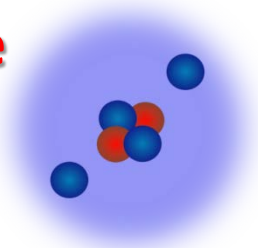
In a three-body model

^{6}Li



$\alpha + n + p$

^{6}He

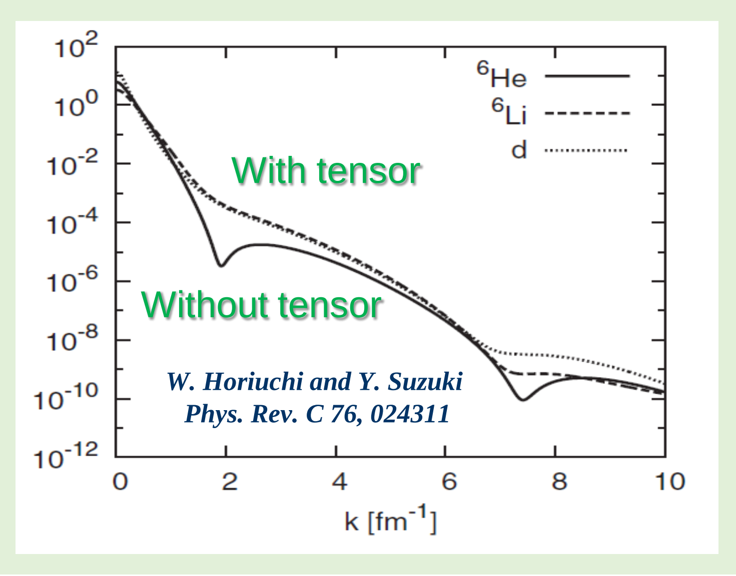


$\alpha + n + n$

Tensor force: a strong *np* correlation and high-momentum nucleons in nuclei

Probe the effects:

Comparing correlations between *pn* pairs and *pp* or *nn* pairs using (*p*, *pd*), (*p*, *nd*) and (*d*, *pt*) reactions



Proposed by I.Tanihata and S.Terashima

Physics @HFRS

Example: Nuclear Matter and/or Charge radii

To provide the most original evidences for halos, neutron skins, and new magic numbers

Nucleon distributions or radii

Total interaction cross sections

Elastic proton scattering

Proton distributions or radii

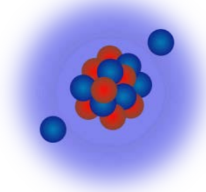
Isotope shifts

Electron scattering

μ atom

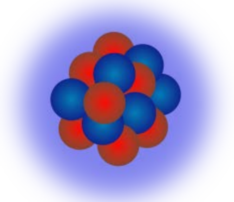
Charge changing cross sections

Halo



- Halos in heavier nuclides
- Giant neutron halos with > two neutrons
- Deformed halos
- Coupling of continuum and discrete states

Neutron distributions or radii



Skin

- Nuclear size evolution of n-rich nuclides
- New shell closures in n-rich regions
- Constrains on nuclear theories
- EOS for cold asymmetric nuclear matter

The equation of state (EOS) for cold asymmetric nuclear matter:

$$E(\rho, \delta)=E(\rho,0)+\delta^2 E_{sym}(\rho)+O(\delta^4) \quad \delta \equiv (\rho_n-\rho_p)/(\rho_n+\rho_p)$$

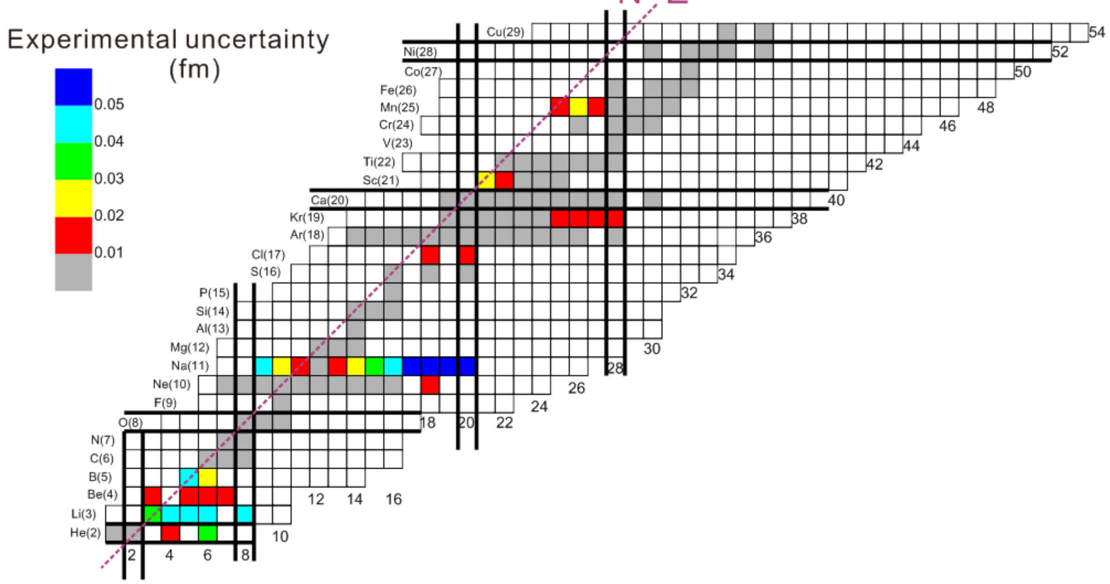
A systematic change of neutron skin thicknesses provides sensitive constraints on the EOS

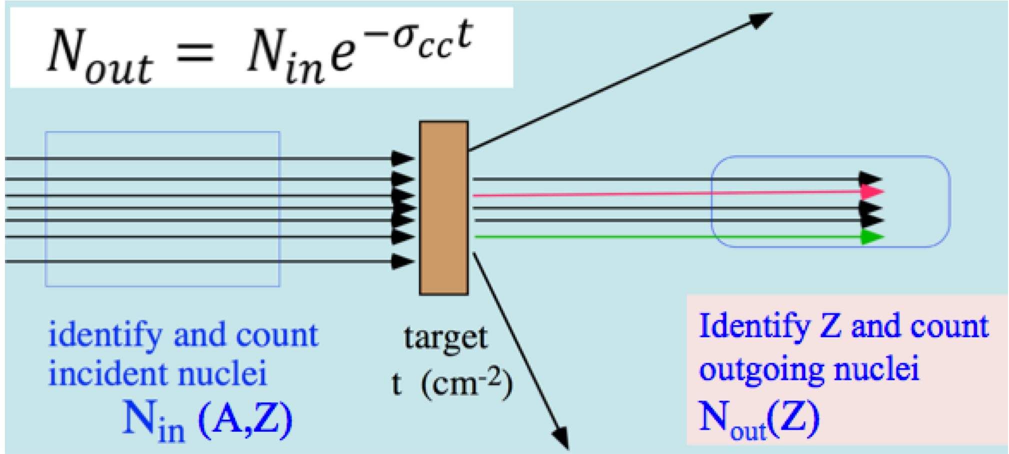
Physics @HFRS

Example: A New Approach for Determining Nuclear Charge Radii

<u>C</u>harge <u>C</u>hanging <u>C</u>ross <u>S</u>ection (CCCS) measurement at relativistic energies + Glauber Model

Angeli, Marinova, ADNDT 99, 69 (2013)





CCCS at high energies:

- Weak energy dependence
- Clean reaction mechanism
- Statistic, $N_{in} > 10^5$

At high energies, CCCS, reflecting interaction probability between the valence protons and the target nuclide, is sensitive to the proton distribution in the projectile nuclide. Analogous to the total cross section measurement, nuclear charge radii can be deduced from the CCCS

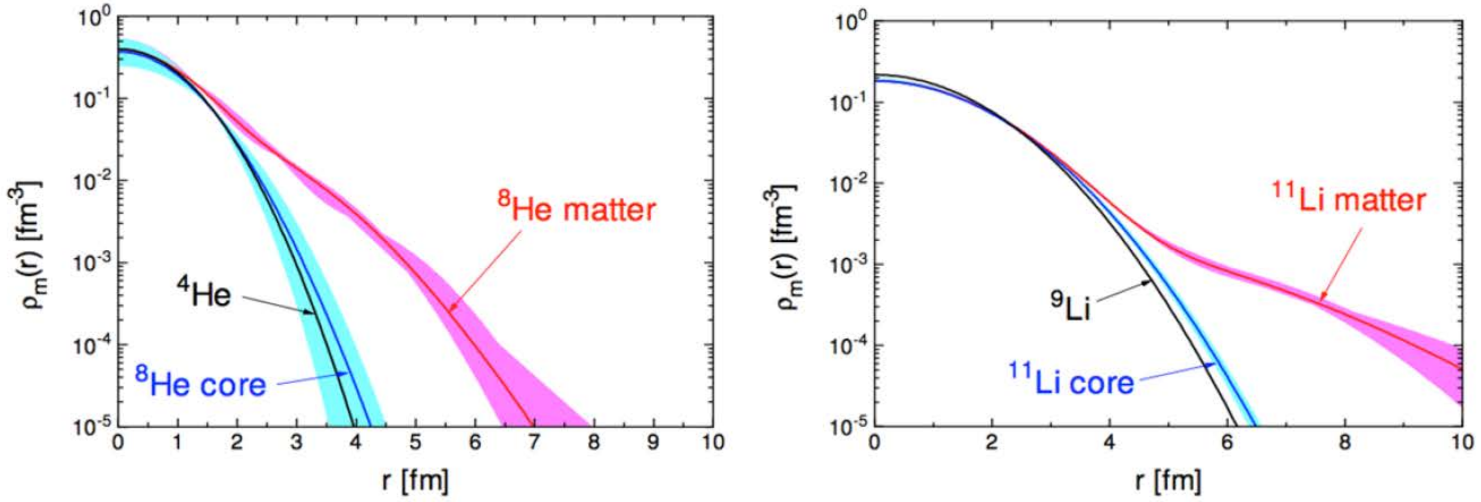
Proposed by B.H.Sun and I.Tanihata

Physics @HFRS

Example: Low-q Experiments with an Active Target

Inverse kinematic proton scattering with low-momentum transfer

Pilot IKAR experiments performed at FRS.



Pprecisely measure the angular distribution in a broad angular region including the first diffraction minimum

In the center-of-mass frame, proton wavelength of ~ 1 fm at an incident energy of 500 MeV/u

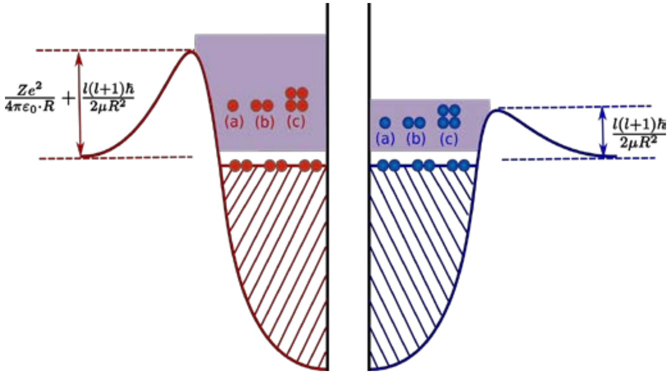
- Determination of the nucleon density distribution in exotic nuclides
- Study of the *N/Z* ratio dependence of the saturation density; the nuclear density near the maximum of $r^2\rho(r)$ sensitive to the saturation density of nuclear matter

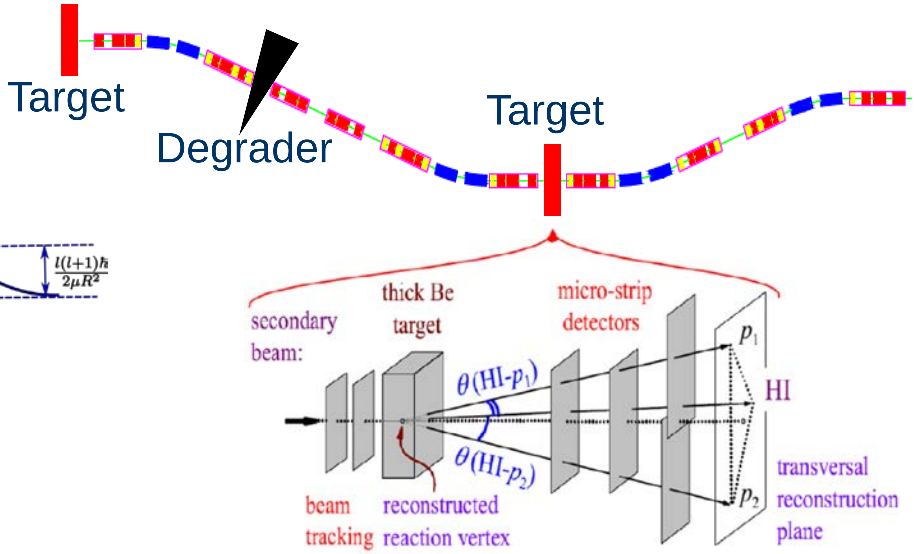
Physics @HFRS

Example: Properties of Un-bound Nuclides

Nuclei beyond the drip-lines show interesting phenomena, and their surviving time are determined by the centrifugal and Coulomb barriers and nucleon correlations

Nucleon and cluster emissions from the ground and excited states of nuclides





- Directly determine the drip lines
- Study the *pp* and *nn* correlations
- Understand the decay mechanism
- Study the *n-n* and *p-p* interactions
- Reveal the properties of neutron matters

Two-step reaction to produce the nuclides of interest, relatively large cross section and low background

The in-flight decay technique coupling to inclusive measurement is most suitable for the study of particle emission of unbound nuclei with lifetimes from ~1 ps to 1 ns

Physics @HFRS

Example: Few Nucleon Removal reactions

In order to understand the properties of nuclides far away from the stability, it is crucial to precisely locate the position of single particle states near the Fermi surface, and to investigate the degree to which their wave functions reflect pure single-particle motion

The momentum distributions of fragments following one- or two-nucleon removal is the spectroscopic method well established, that gives knowledge on the wave function of the initial nucleons

Using very low intensity beam (~10 /s)!

Systematic study along isotopic and/or isotonic chains:

Evolution of single particle states while changing neutron numbers?

Robustness of the shell closures far from the stability line?

T=0, S=1 proton-neutron pairing along the N=Z line?

Single particle states coupling to the continuum in weakly bound nuclides? ...

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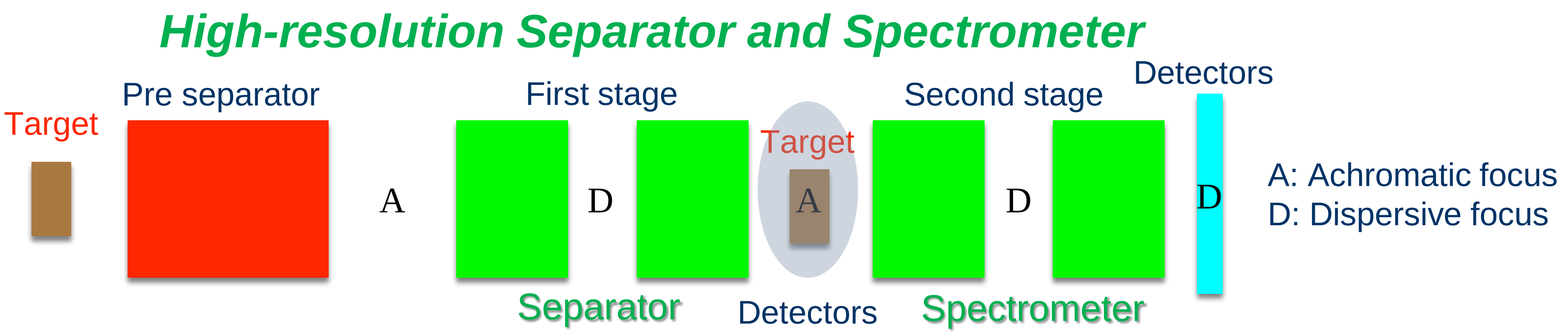
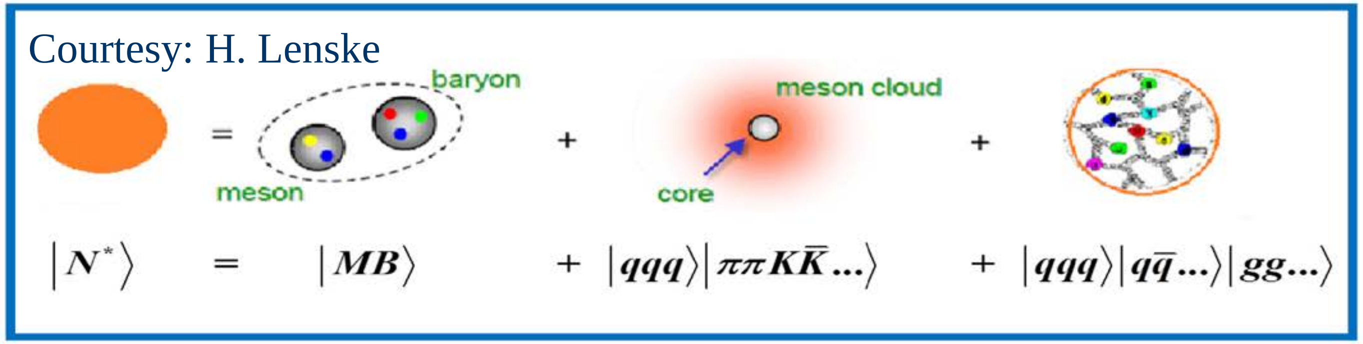
Example: Δ resonance and N in nuclei*



In charge-exchange reactions, Δ-resonances in nuclei can be produced

The Δ-resonance is a $\Delta S = 1$, $\Delta I = 1$ spin- and isospin-flip intrinsic excitation of the nucleon



Are the masses and lifetimes of N*-resonances modified in nuclear medium? What is the origin of the three-body force? What is the isospin dependence of resonance potentials? …

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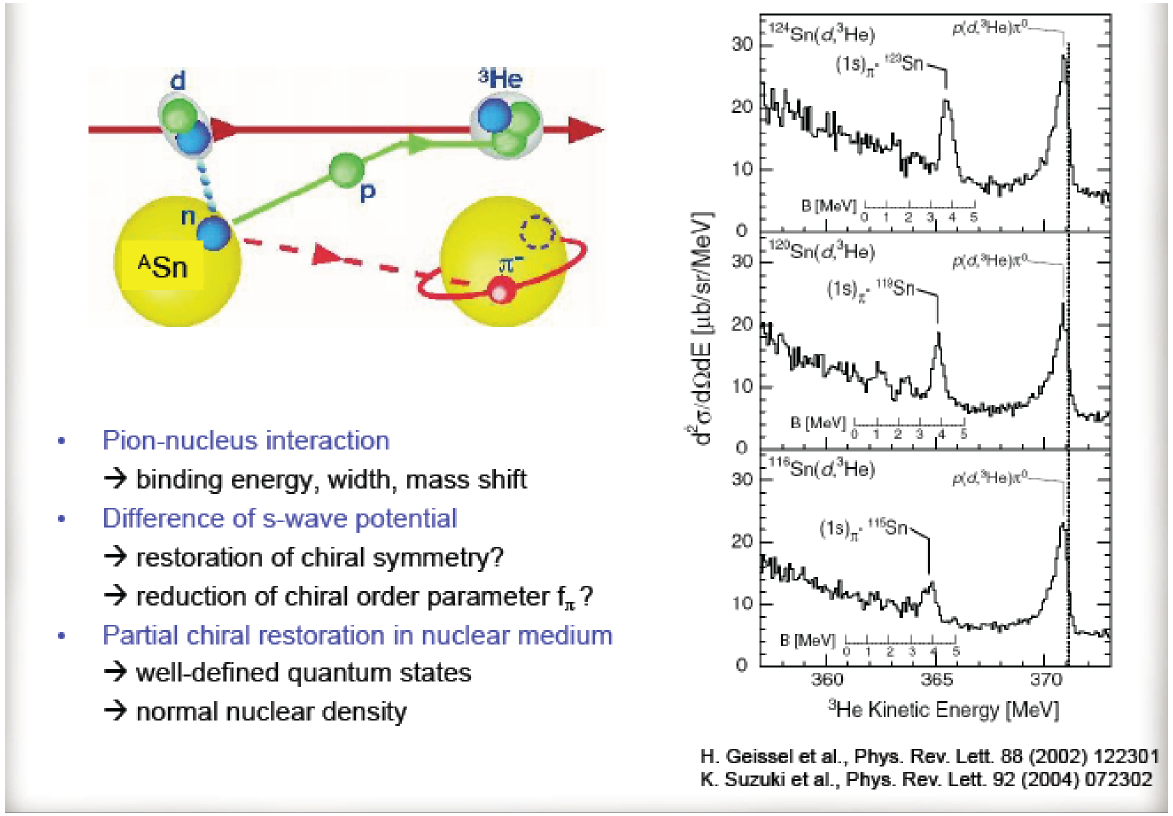
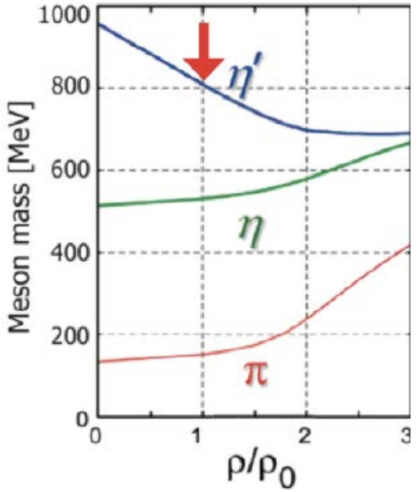
Example: Spectroscopy of Mesonic Atoms





η′ bound nuclei and η bound nuclei

The properties of bound mesonic states in heavy atoms are related to the meson-nucleus interactions, and can contribute to the understanding of the QCD vacuum structure

(p, d), (d, ^{3}He) or (p, ^{3}He) reactions

Method: missing mass spectra

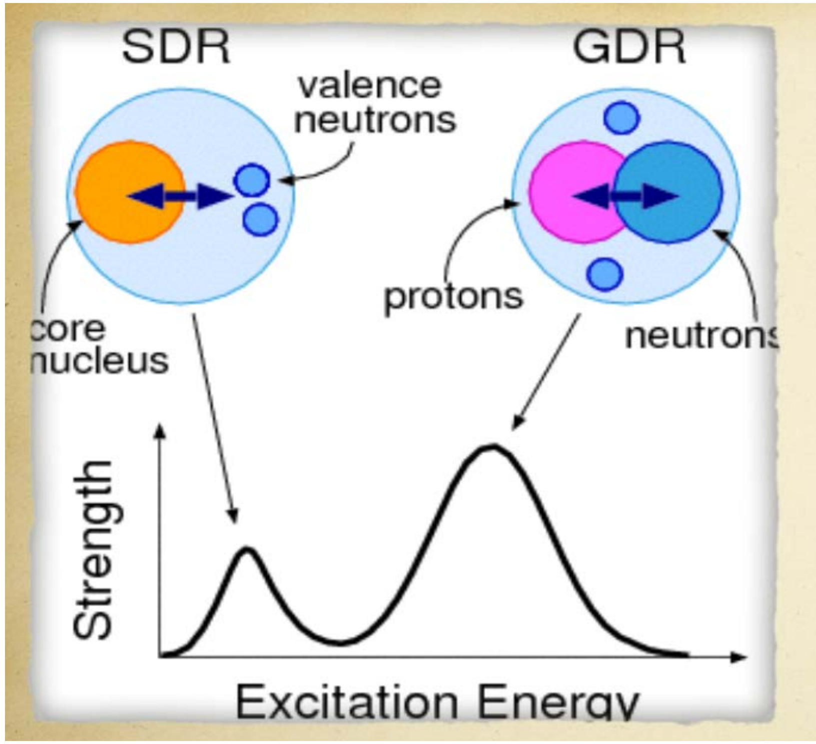
Motivation:

- ✓ Look for the existence of the mesonic atoms
- ✓ Reveal modification of meson properties inside nuclear matter

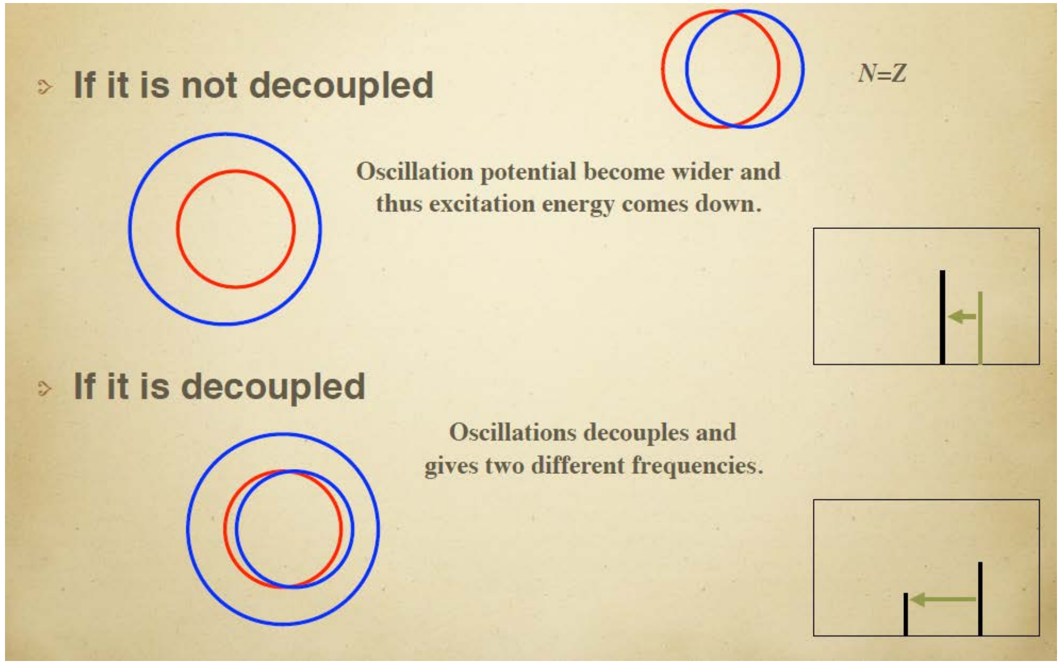
Physics @HFRS

Example: Giant resonance of neutron rich nuclei

High-energy radioactive beams of energy provide new opportunities to study giant resonances in asymmetric nuclei including a new mode (isoscalar E1)



Is a neutron skin decoupled from the core?



Physics @HFRS

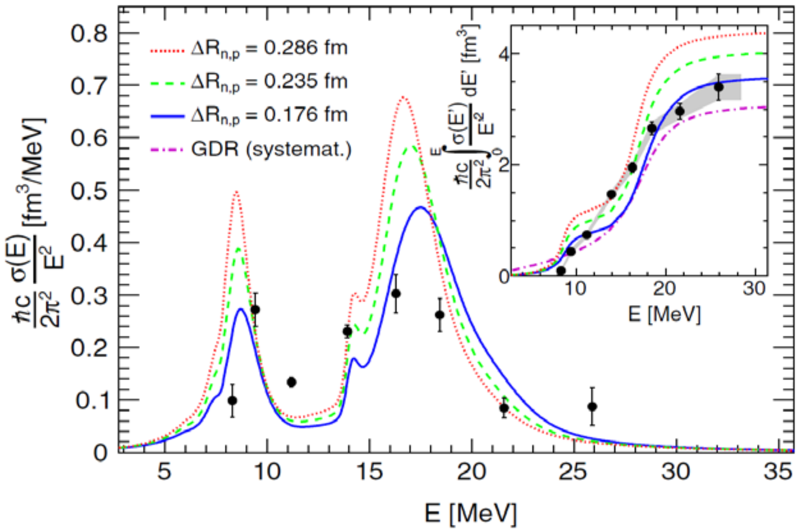
Example: Giant resonance of neutron rich nuclei

The α_D is a robust and less model dependent observable to extract neutron-skin thickness

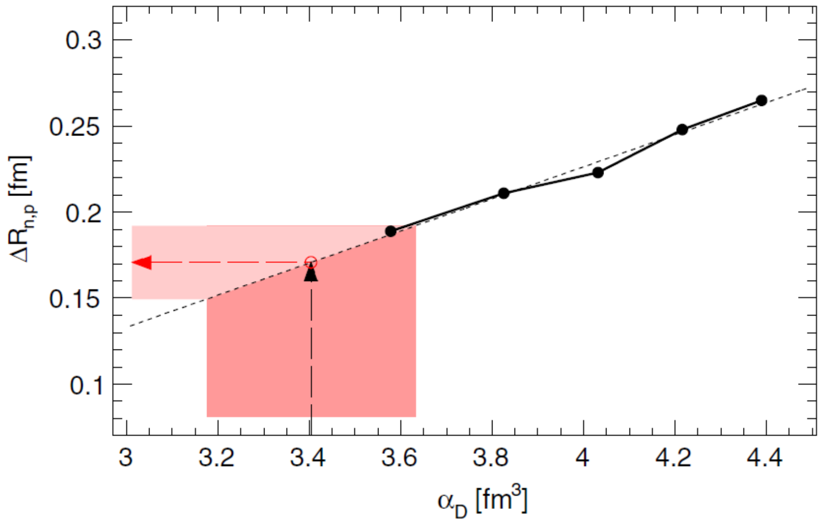
The electric dipole polarizability: $$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE,$$ $\sigma(E)$: photo absorption cross section

Giant dipole resonance of n-rich nuclei: a precise determination of neutron skins

α_D has a nearly linear relationship with the neutron-skin thickness



Inverse energy-weighted dipole strength for ^{68}Ni. Inset: experimental dipole polarizability



Correlation between neutron-skin thickness and electric dipole polarizability in ^{68}Ni

D. Rossi et al. PRL 111, 242503 (2013)

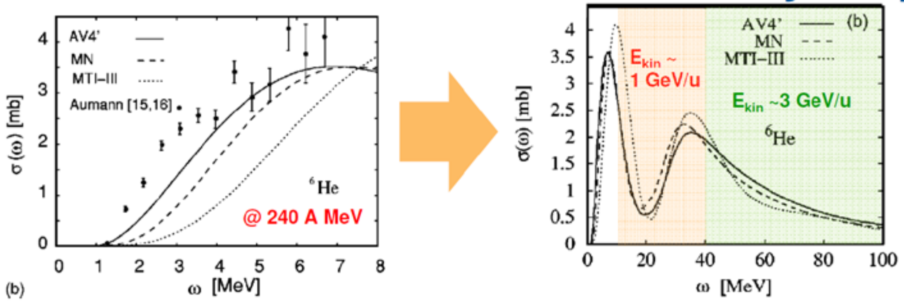
Physics @HFRS

Example: Giant resonance of neutron rich nuclei

High excitation energies

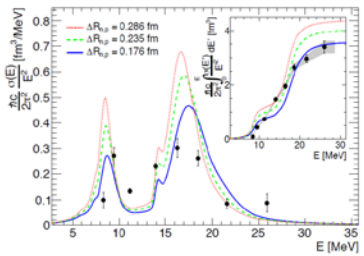
Example: dipole strength distribution in very heavy n-rich systems

Core vs. neutron skins & halos → density / asymmetry



S. Bacca et al.
PRL **89** (2002) 052502
PRC **69** (2004)057001

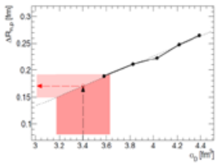
Access to EOS (density dep. of symmetry energy)

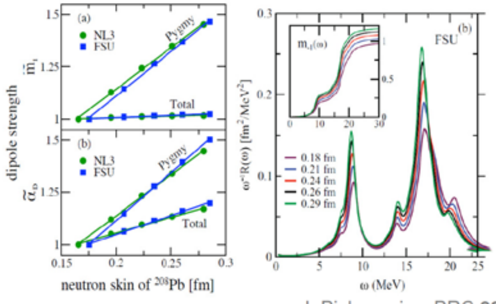


$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE$$

D. Rossi et al.
PRL **111** (2013) 242503

skin thickness ^{68}Ni
0.175(21) fm





Pb chain &
N=126 isotones

~1 A GeV →

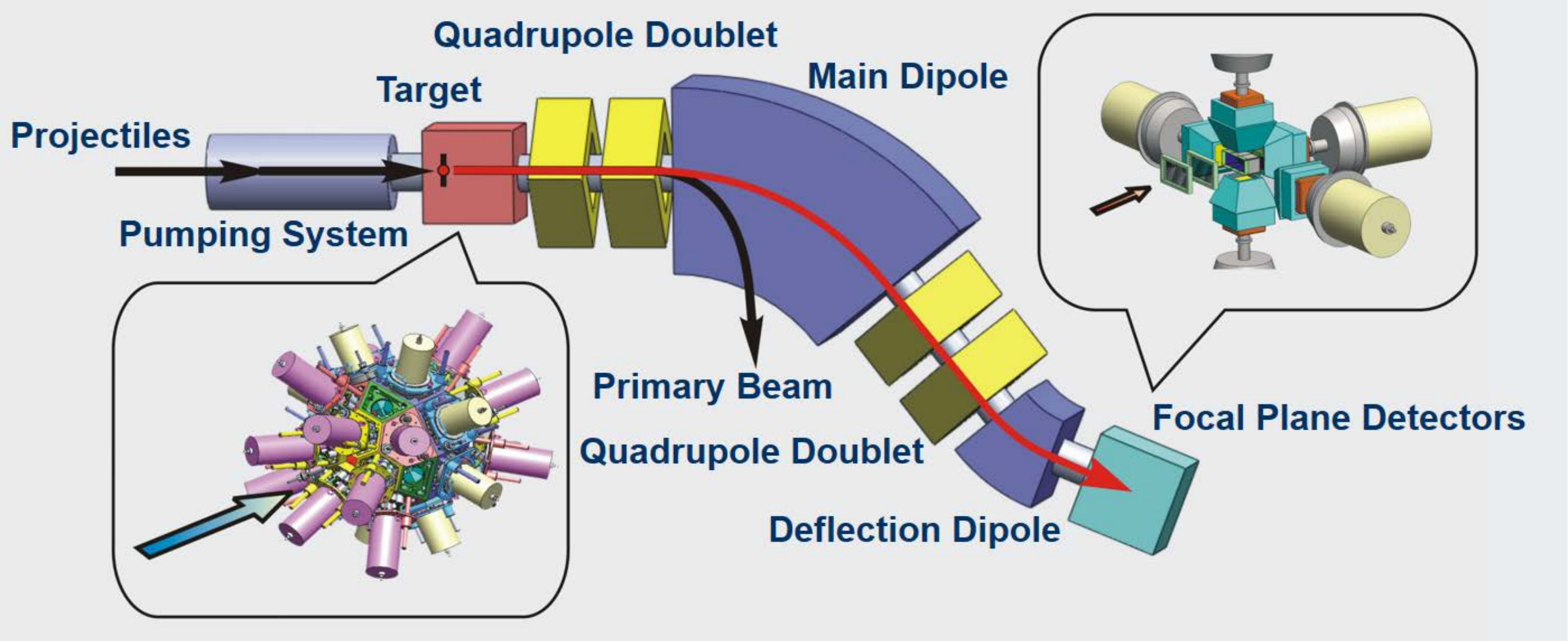
bare ions
fragment
identification

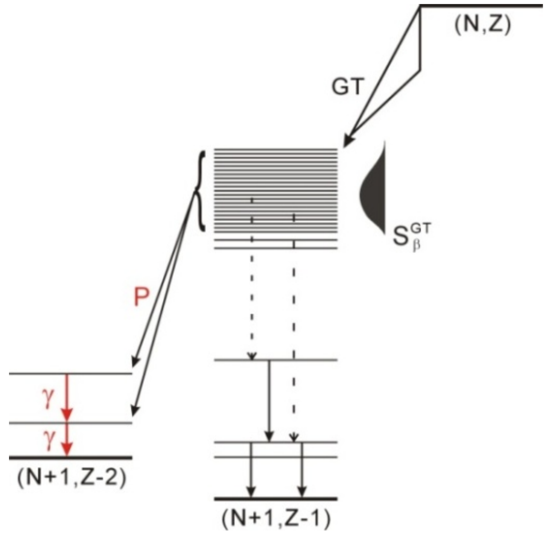
J. Piekarewicz, PRC **83** (2011)034319

Courtesy: T. Aumann

Day-One Experiment @ HIAF

Synthesis of New Isotopes ^{143}Er, ^{157}Yb and ^{153}Hf





Beta-delayed proton decays

Devices: The superconducting iLinac and the Gas-filled Recoil Separator

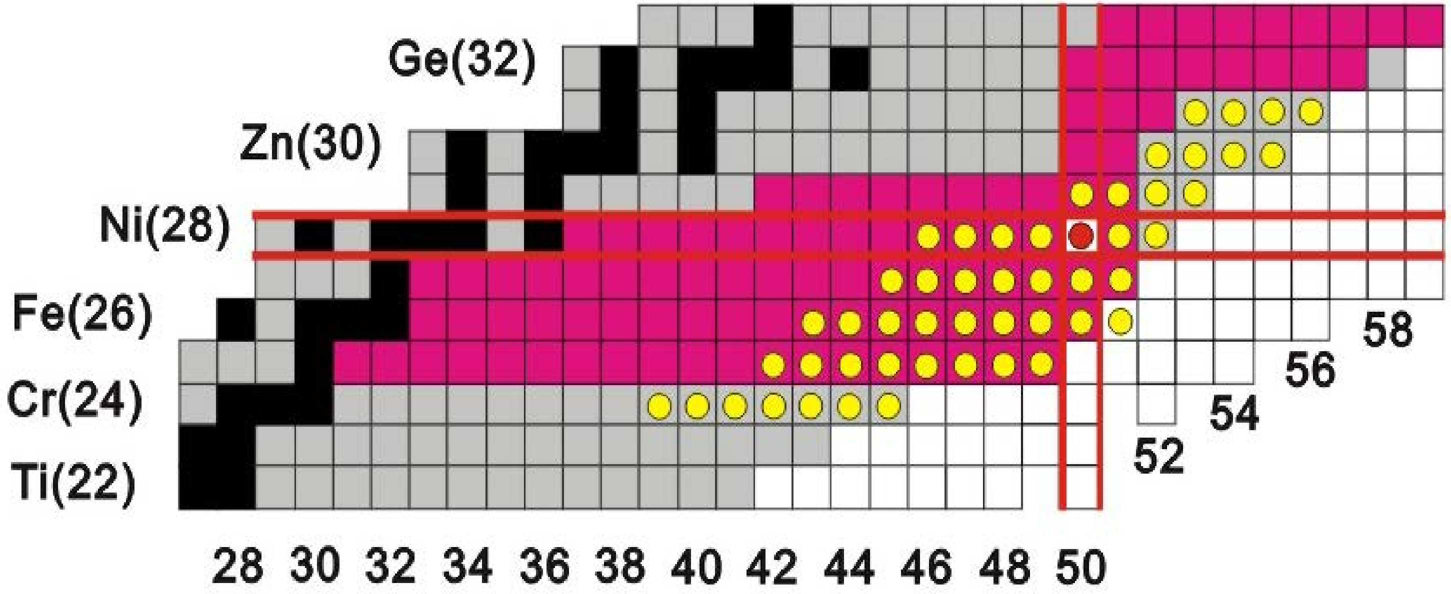
Reactions： $^{40}Ca + ^{106}Cd \rightarrow ^{143}Er + 3n$; $^{58}Ni + ^{92}Mn \rightarrow ^{157}Yb + 3n$; $^{54}Fe + ^{102}Pd \rightarrow ^{153}Hf + 3n$

Expected cross sections: 20~300 nb

Expected half-lives: 100~300 ms

Day-One Experiment @ HIAF

Mass Measurements of N-rich Nuclides around ^{78}Ni



Production: Fragmentation of Projectile ^{86}Kr Using the HFRS

Measurement: The Isochronous Mass Spectrometer with Double ToF Detectors

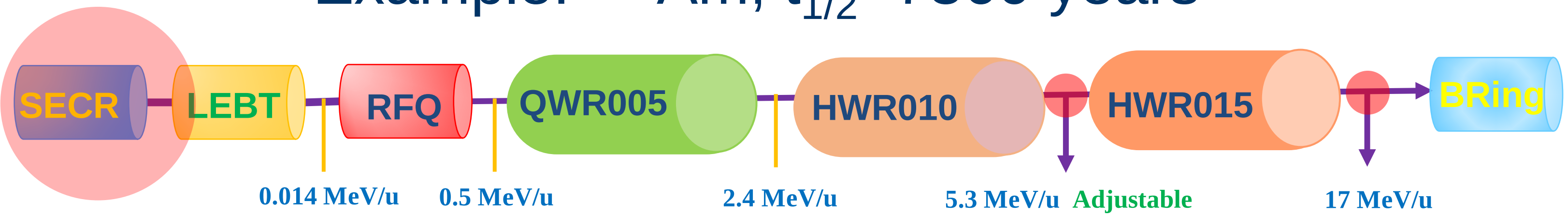
Systematically measure nuclear masses with a precision of ~ 50keV, and deduce one-neutron and two-neutron separation energies

Study the evolution of the *N*=50 shell closure and Simulate the r-process

Acceleration of Heavy Long-lived Beams

Feasibility for Acceleration of Heavy Long-lived Beams

Example: ^{243}Am, $t_{1/2}$=7360 years



Assuming beam intensity of 10^{12} particles/s

In the sections of superconducting cavities: beam loss < 0.01%

For an experiment of 100 hours: 0.01% beam loss in the cavities

Resulting in total radioactivity of about 100/s, distributed in about 100 meters

In the injecting section from ion source into the front-end RFQ: beam loss ~1%

For an experiment of 100 hours: 1% beam loss in the injection point

Resulting in total radioactivity of about 10^4/s, severe contamination!

Also the ion source is badly contaminated!

Solutions:

To replace the inner cavity of ion source and injecting device after experiment

To use the ISOL ion-source technique to deal with the radioactivity

Bound-state β decay of $^{205}Tl^{81+}$

Understanding of the solar pp neutrinos

LOREX project: ^{205}Tl in lorandite at Allchar mine is used for long-time detection of solar pp neutrinos with the by far lowest threshold of netrino energy of 52 keV

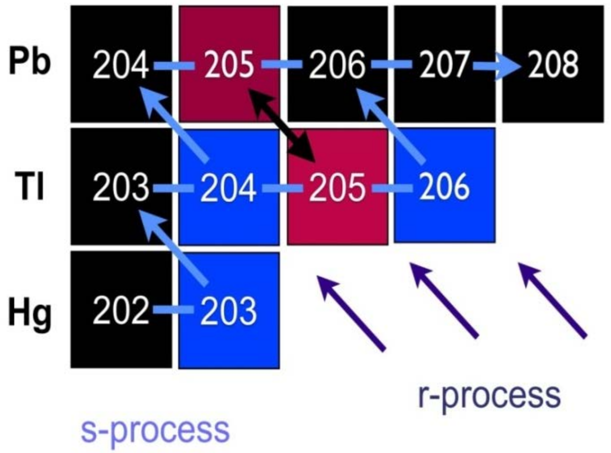
The neutrino caputure σ_{ve} can be deduced from the half-life of bound-state β decay of $^{205}Tl^{81+}$

LOREX: $^{205}\mathrm{Tl} + \nu_e \rightarrow {}^{205}\mathrm{Pb}^* + e^- \Longrightarrow <\Phi_{\nu_e} \cdot \sigma_{\nu_e}>$

Share common M_{if}

β_b decay: $^{205}\mathrm{Tl}^{81+} \rightarrow {}^{205}\mathrm{Pb}^* + e^- + \tilde{\nu}_e \Rightarrow \sigma_{\nu_e}$

Understanding of the abundance of ^{205}Pb



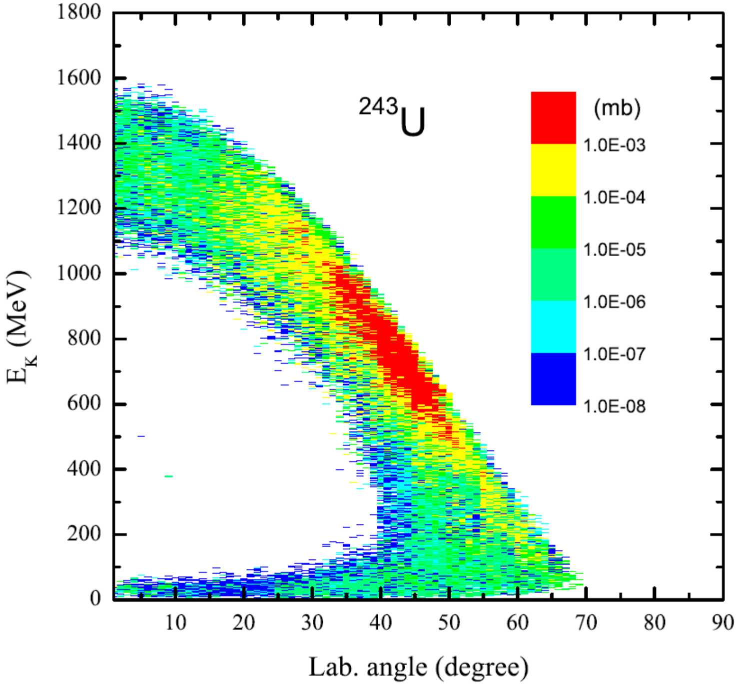
$N(^{205}Pb)/N(^{204}Pb)=P(^{205}Pb)/P(^{204}Pb) \times T(^{205}Pb)/T_G$

~10^{-3}	~1	~ $2.5 \cdot 10^{-3}$
in inter-stellar media	s-production ratio	lifetime raio of the Galaxy

In the s-process enviroment, ^{205}Pb is strongly reduced by free electron capture. The mean lifetime of ^{205}Tl is determinde by $\lambda_{\beta b}$ of bare ^{205}Tl. Is ^{205}Pb counter-balanced by the β_b decay of bare ^{205}Tl?

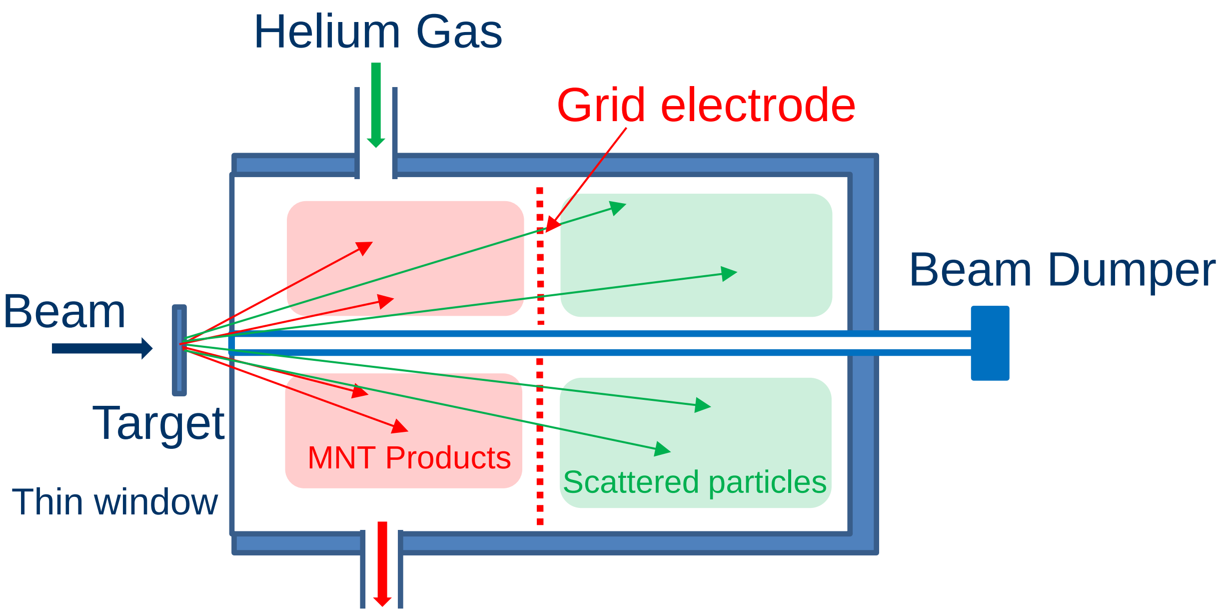
Experiments @iLinac

^{238}U + ^{248}Cm @750 MeV



Broad distributions of **E**, **θ** and **Q**!

How to suppress the intense scattered projectiles?



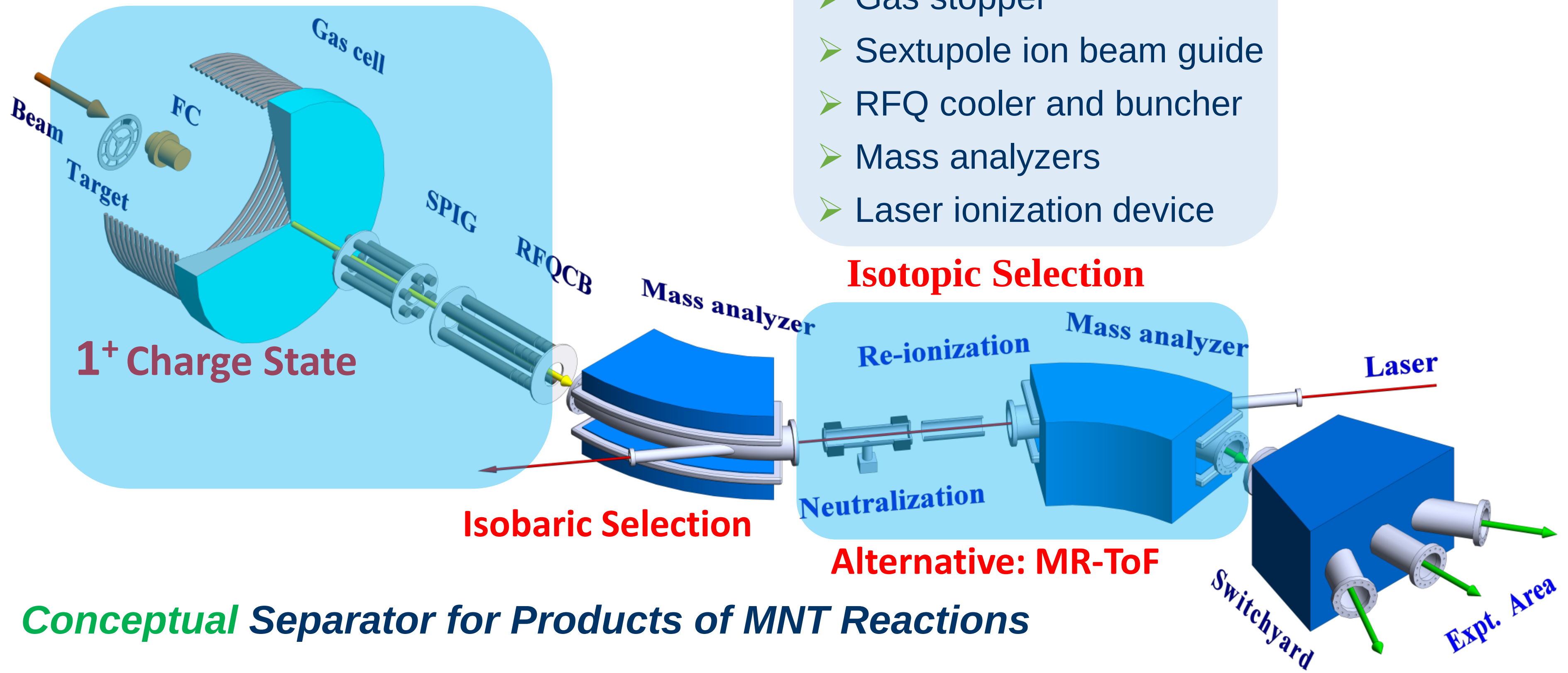
For ^{238}U + ^{248}Cm, the kinetic energies of the target-like products are much lower than those of the scattered projectiles, and therefore their penetrating ranges in the gas cell are very different

The grid electrode separates the gas cell into two parts, and the scattered projectiles deposit their major energy in the right part, hopefully reducing the plasma effect in the left part

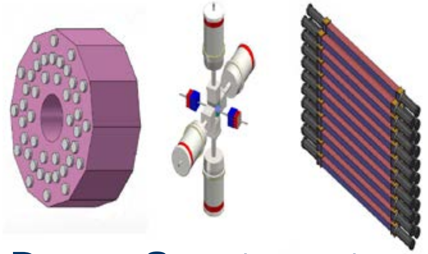
Experiments @iLinac

Separation and Identification of MNT Products

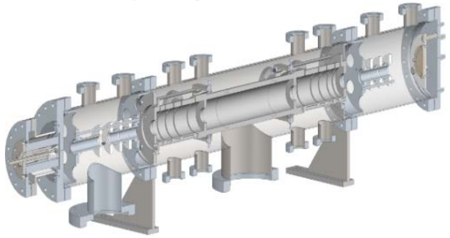
- Rotating target system
- Gas stopper
- Sextupole ion beam guide
- RFQ cooler and buncher
- Mass analyzers
- Laser ionization device



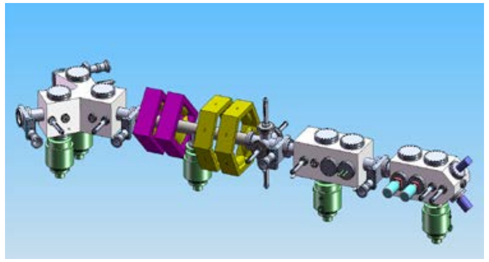
***Conceptual* Separator for Products of MNT Reactions**



Decay Spectrometer



MR-ToF Mass Spectrometer

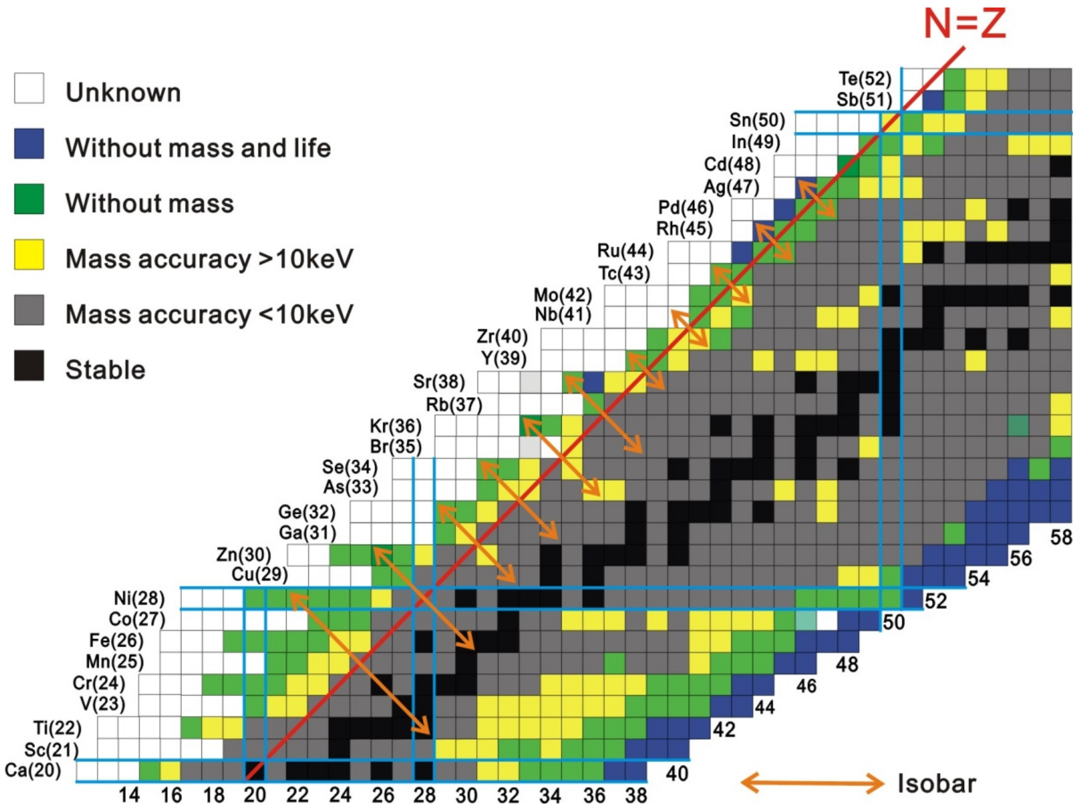


Collinear Laser Spectrometer

The separator provides pulsed low-energy, high-quality n-rich beams with mass and atomic numbers identified, and then distributes the beams to various measuring apparatuses

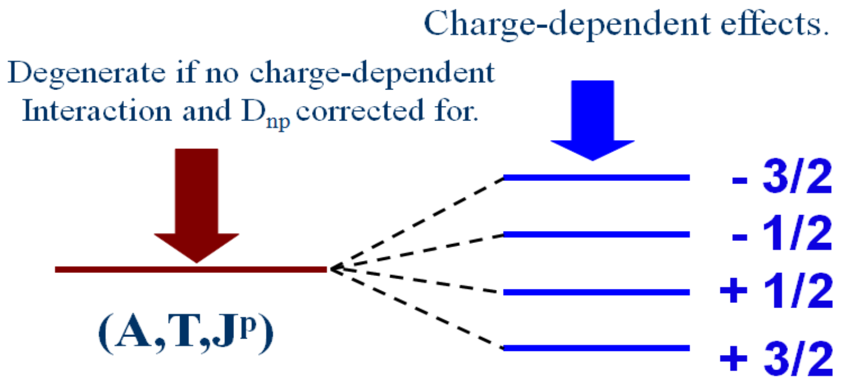
Physics @Spectrometer Ring

Physics along the N=Z line



- Understanding of the *rp* process path and end point
- Shape evolution for the nuclei along the *N*=*Z* line
- Study of the isospin symmetry breaking
- Search for the new form of *n*-*p* paring
- Precision tests of the shell model around ^{100}Sn

Test the Isospin Multiplet Mass Equation

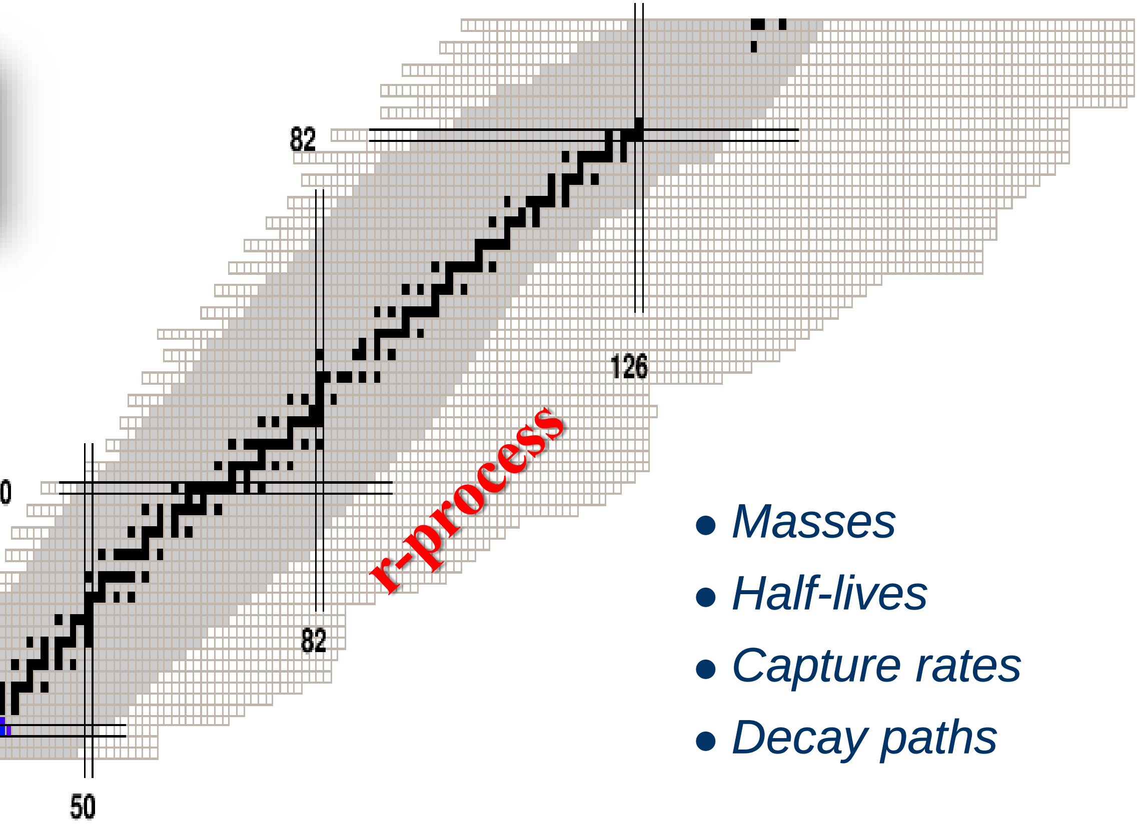


$$M(T,A,T_3) = a(T,A,) + b(T,A)T_3 + c(T,A)T_3^2 + d(T,A)T_3^3$$

Complementary to the related researches at the HFRS and low-energy station

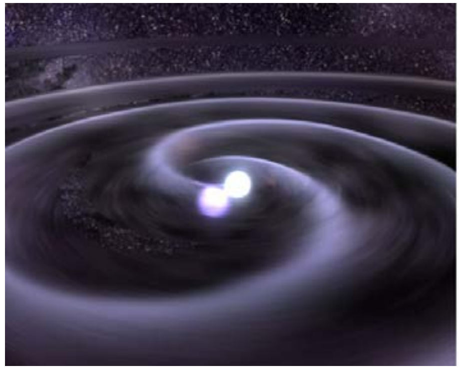
Physics @Spectrometer Ring

How are the elements from iron to uranium produced in the Universe?



- *Masses*
- *Half-lives*
- *Capture rates*
- *Decay paths*

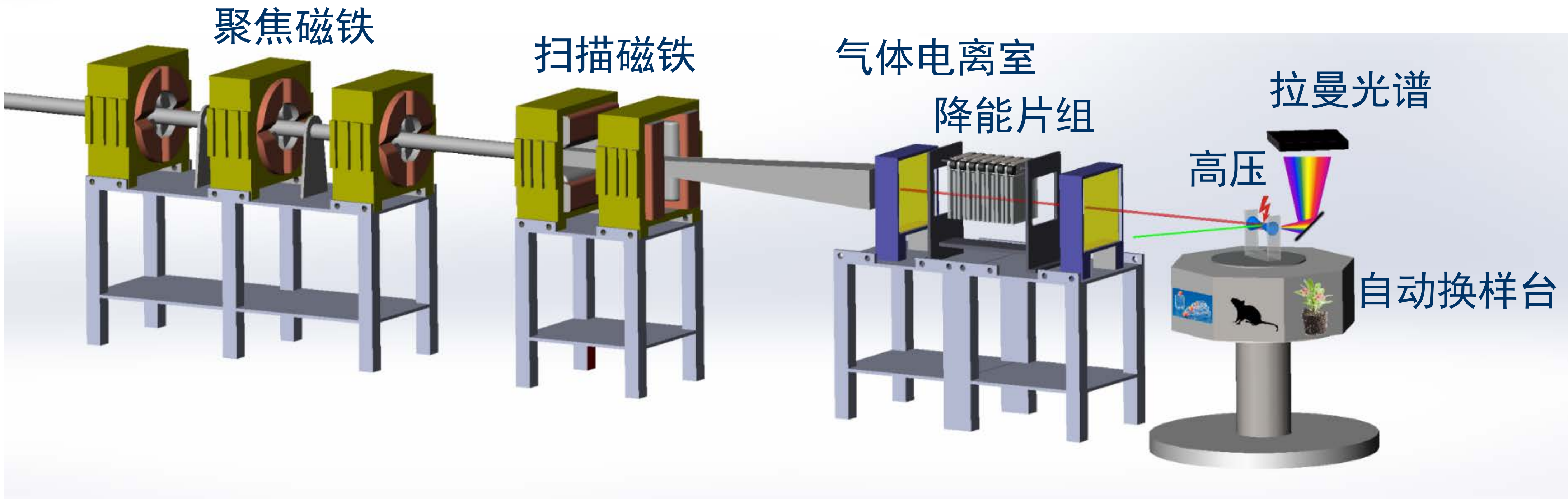
Core collapse supernovae



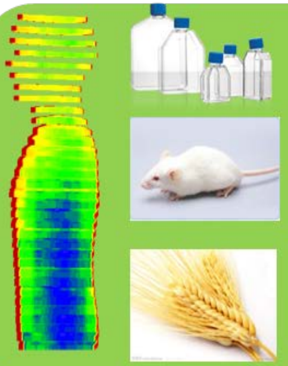
Merging of two neutron stars

By reproducing the observed abundance distribution, the network calculations with precision nuclear inputs would put constraints on the environments in which the *r*-process may happen

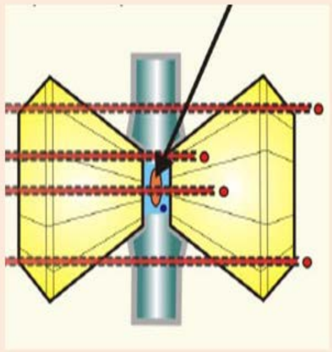
Heavy-ion Application



- 材料辐照效应
- 航天器件评估



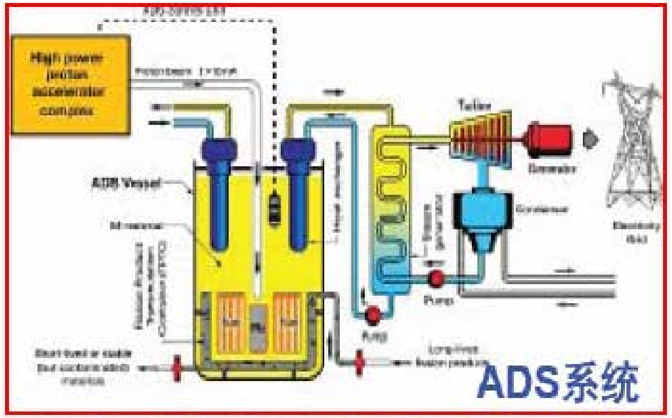
- 空间放射生物
- 放射医学研究
- 育种

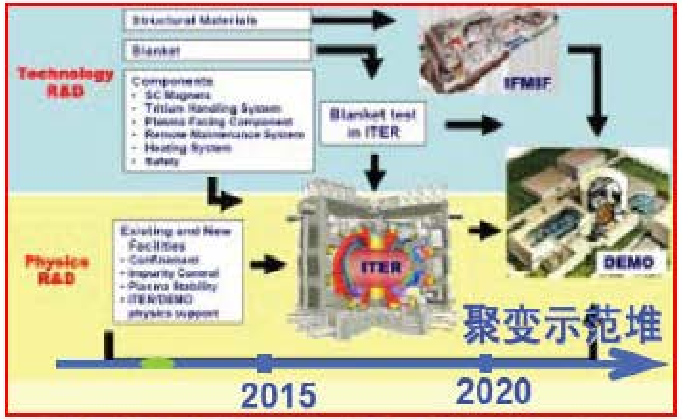


- 极端高压条件下的辐照效应
- HEDP性质研究

Heavy-ion Application

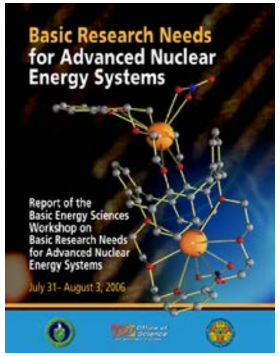
装置类别





材料耐受

温度 625-1275 K 损伤 3-180dpa, 0.1-5 ppm He/dpa 腐蚀环境	温度 >650 K， 瞬变高应力 损伤~100dpa, 0.1-5 ppm He/dpa 腐蚀环境	温度 575-1100 K, 瞬间高热负载 损伤~200dpa, ~10 ppm He/dpa 腐蚀环境



材料成为限制先进核能发展主要瓶颈之一

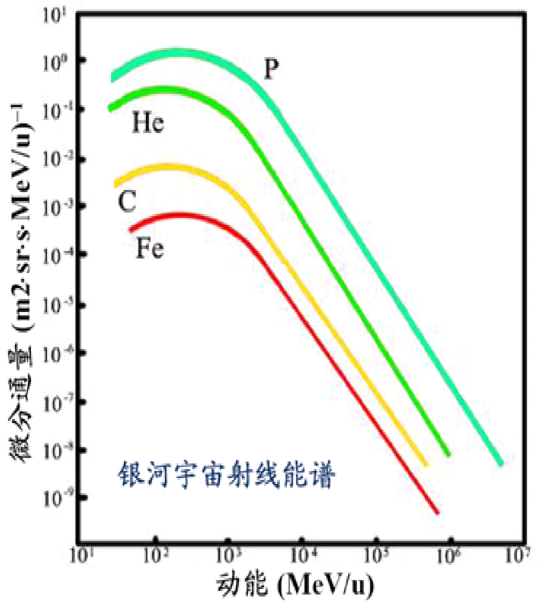
→ **强辐照、高温、腐蚀环境等极端条件下的材料使役性能**

发展在役/候选核材料快速评价新方法、研发新抗强辐照耐高温耐腐蚀材料

建造装置，形成具有自主知识产权的核能材料快速评价与筛选的方法和标准

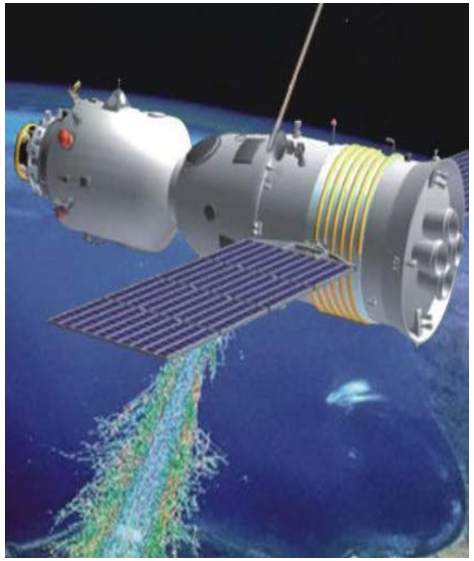
Heavy-ion Application

我国航天事业高速发展：卫星、载人航天、空间站、深空探测等



空间高能质子和重离子辐射

- 航天器安全：单粒子、总剂量效应…
- 宇航员安全：低剂量、HZE效应…



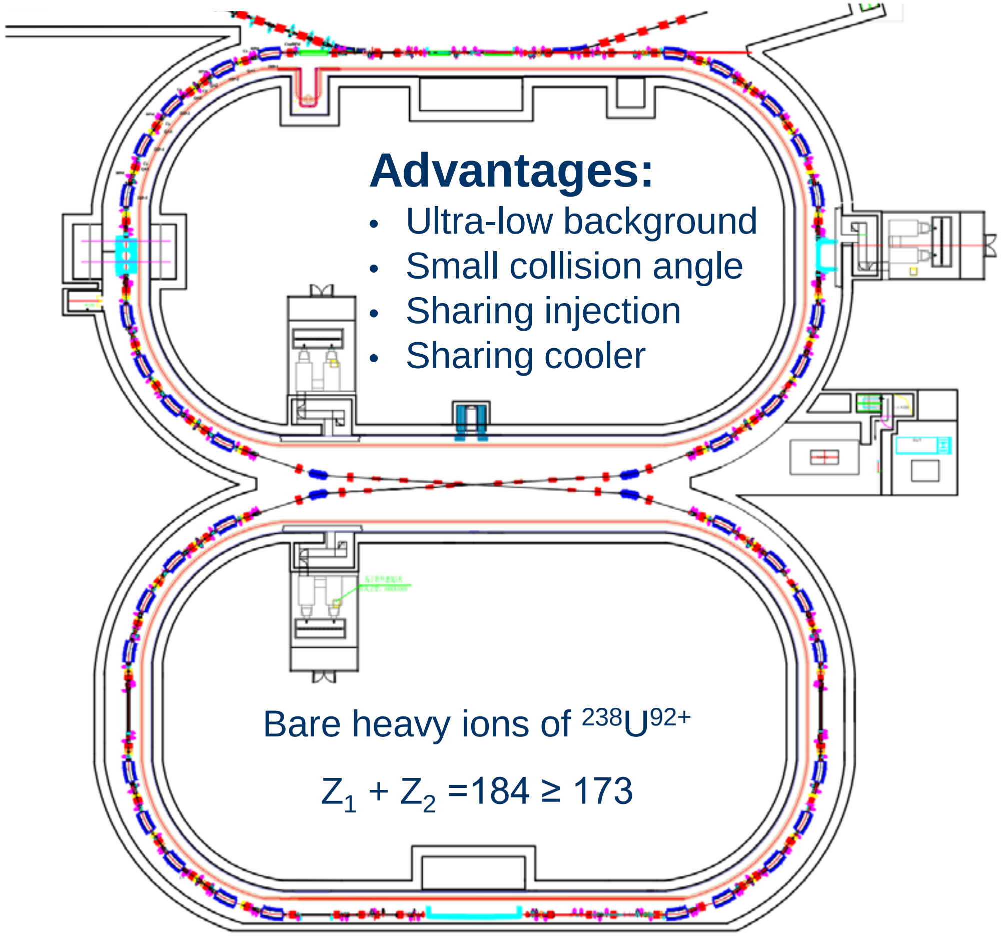
为保障航天器与宇航员的安全必须开展辐照效应研究

天基实验： 真实，昂贵、周期长、难控；**地基实验：模拟空间环境，周期短、可控**

建造空间离子辐射环境模拟平台，开展航天电子器件单粒子效应研究，为器件抗辐加固和研发提供支撑；研究空间辐射生物效应，为评价航天员健康与安全提供重要数据

Upgrade II: Ion-ion Merging Facility

“8” shape of two rings



Advantages:
- Ultra-low background
- Small collision angle
- Sharing injection
- Sharing cooler

Bare heavy ions of $^{238}U^{92+}$

$Z_1 + Z_2 = 184 \geq 173$

Decay of the Vacuum (U + U collision)

Merging beam parameters

Parameter	**Value**
Ion	$^{238}U^{92+}$
Energy (MeV/u)	637(800)
Circumference (m)	277.2
Frequency (MHz)	0.50(0.52)
Crossing angle (◦)	6.8
C.M energy (MeV/u)	6(8)
Particle number	**$7(8)\times10^{10}$**
$\varepsilon_{x,rms}/\varepsilon_{y,rms}$ (π mm mrad)	1/1
β^*_x/β^*_y(m)	1/0.03
$\sigma_{x,rms}/\sigma_{y,rms}$ (mm)	1/0.173
Laslett tune shift	-0.1(-0.077)
Hourglass factor	0.9
Luminosity($cm^{-2}s^{-1}$)	**$4.4(5.4)\times10^{23}$**