FRIB

High Rigidity Spectrometer (HRS) at FRIB for Fission Measurements

Remco Zegers - HRS Scientific Spokesperson

With thanks to Shumpei Noji for several slides and figures

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MICHIGAN STATE UNIVERSITY

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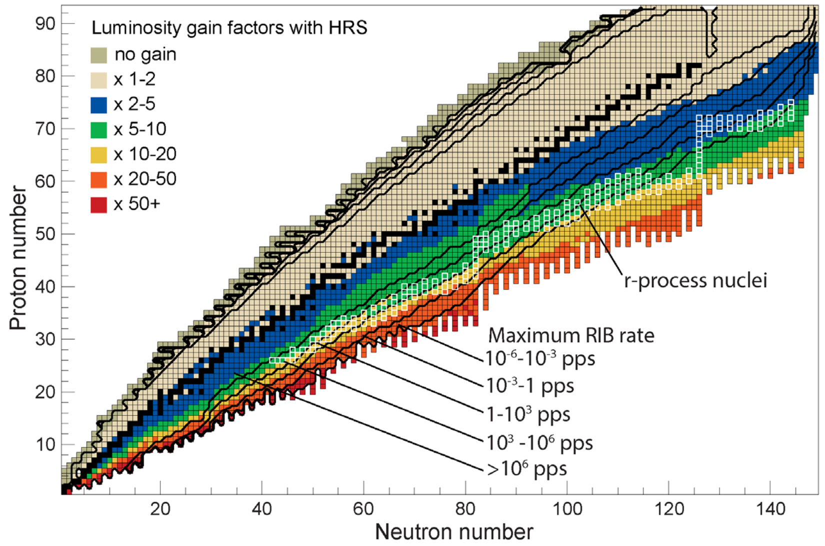
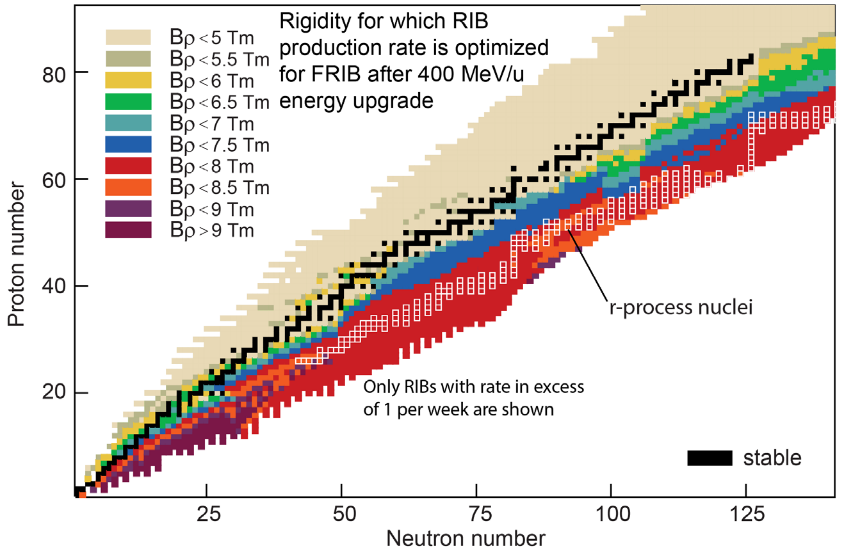
Scientific Impact of the High Rigidity Spectrometer

- HRS enhances the scientific reach of FRIB through increased luminosity
  - Use rare-isotope beams at the rigidity that optimizes production (up to 8 Tm)
  - Use thick reaction targets at the HRS to maximize yield
- For over 90% of neutron-rich isotopes gain factors of 2-100 are achieved
- For the most asymmetric neutron-rich nuclei, gain factors are larger than 50
- For nuclei in the path of the astrophysical r-process gain factors are 5-20
- Additional gain factors of ~10 for FRIB at 400 MeV/u
- The HRS scientific program is broad, covering topics in nuclear structure, nuclear astrophysics, fundamental symmetries, and applications of isotopes
- HRS Accommodates Ancillary Detectors Developed by the Community to Meet the Scientific Objectives of FRIB, such as the Gamma-Ray Energy Tracking Array (GRETA) and the MOdular Neutron Array (MoNA-LISA)
- NIM Paper: S. Noji et al., Design of the HRS
- Physics Today: R. Zegers, The HRS at FRIB



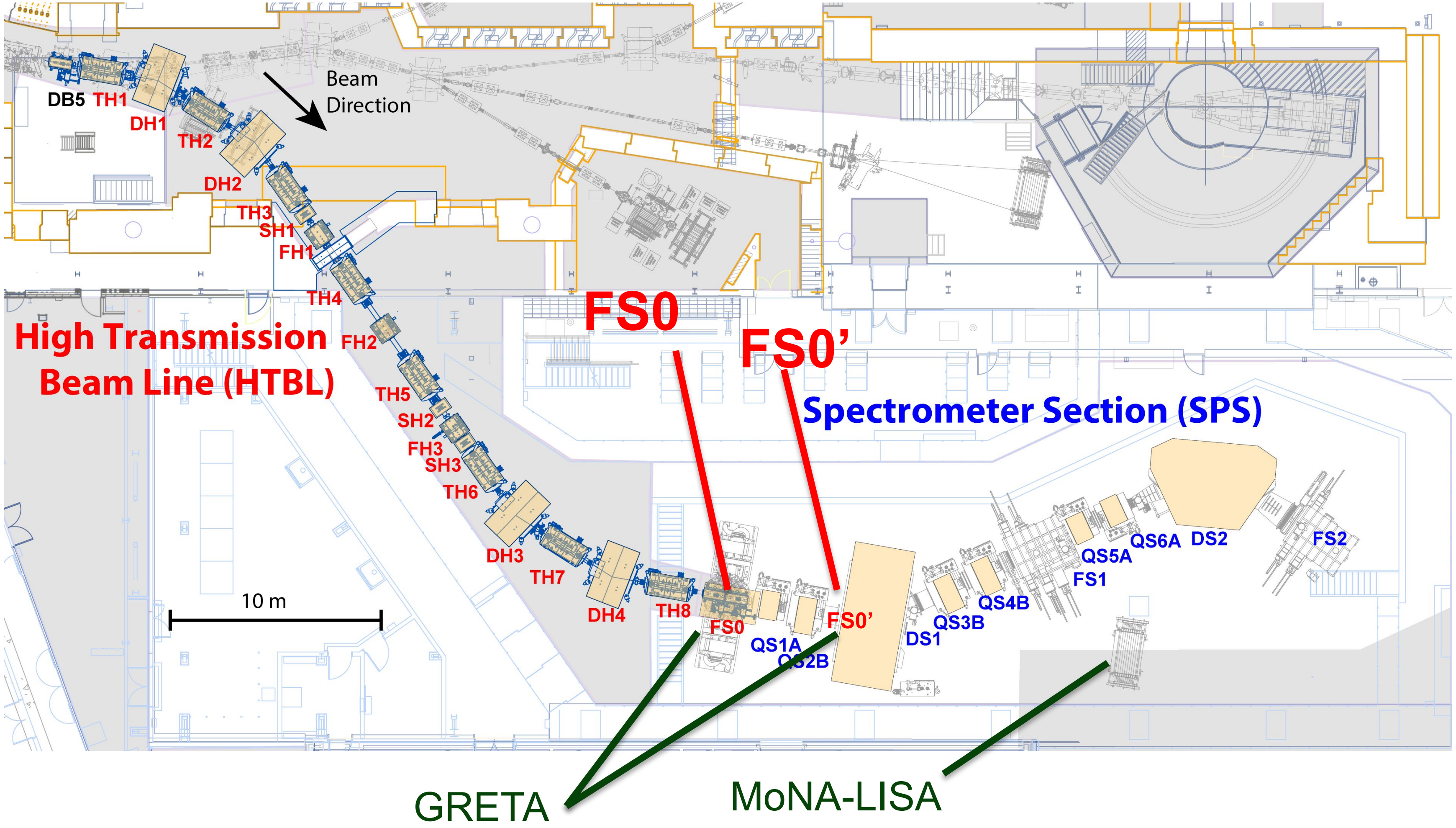


Key Characteristics for Fission Studies at the HRS

- HRS design requirements are in part based on the ability to perform in-flight fission studies
- The high rigidity (up to 8 Tm) of the HRS increases the efficiency for the detection and identification of both forward-boosted fission fragments
- The ability to measure both in-flight fission fragments puts constraints on the angular and momentum acceptance of the HRS
- The HRS enables fission studies with the simultaneous measurement of emitted photons and neutrons using ancillary detector systems.
- Opportunities for measuring the excitation energy of the nucleus prior to fission
- Detailed information about the properties of the HRS can be found at: S. Noji et al., Nuclear Instruments and Methods in Physics Research Section A, Volume 1045, 167548 (2023).

The Layout of the HRS Supports a Versatile Fission Program

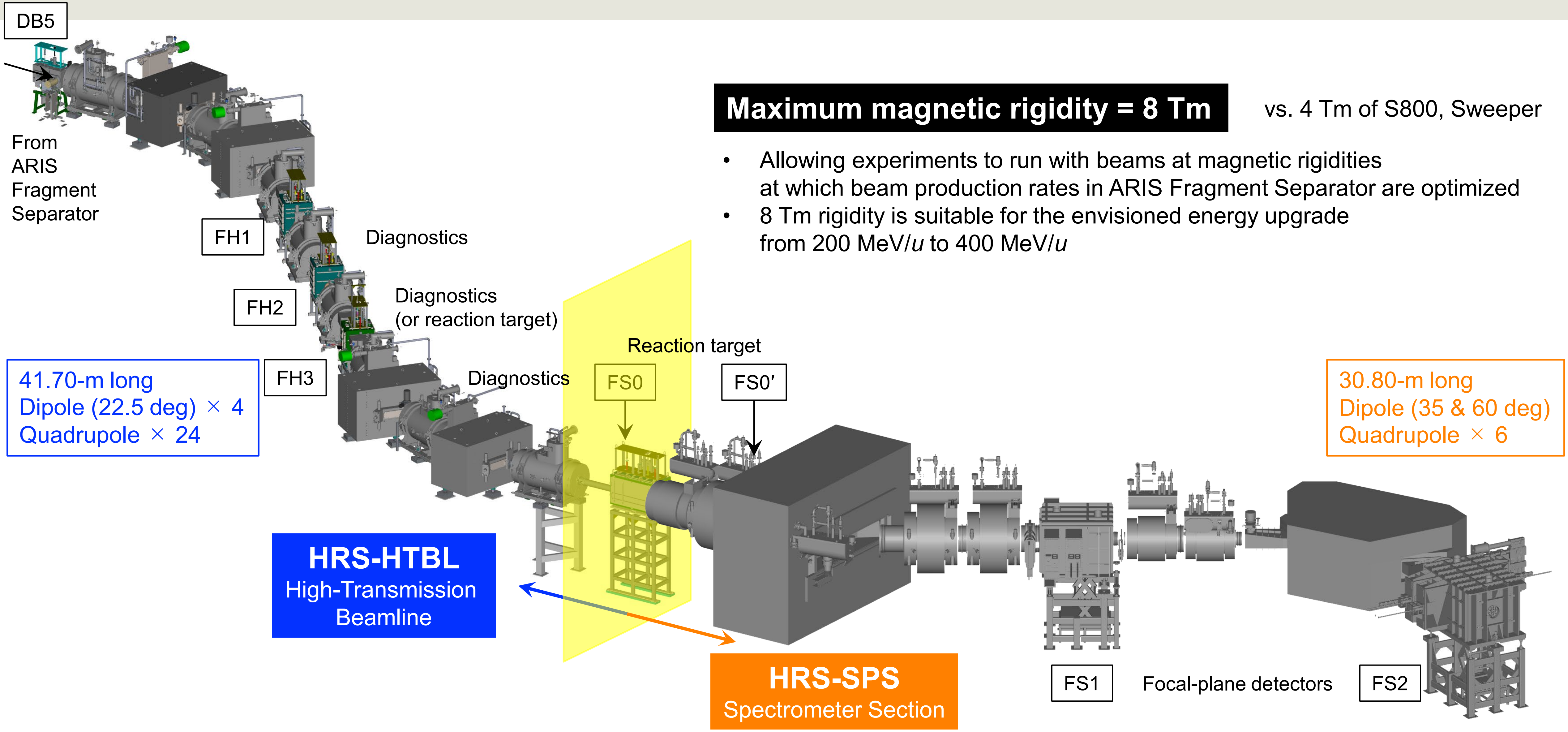
- The High Transmission Beam Line (HTBL) transports beams of interest to target stations at FS0 or FS0’
- The Spectrometer Section (SPS) analyzes the fission products - ancillary detectors such as GRETA and MoNA-LISA can be used for photon and neutron detection, respectively



Overview of HRS Consisting of HRS-HTBL & HRS-SPS

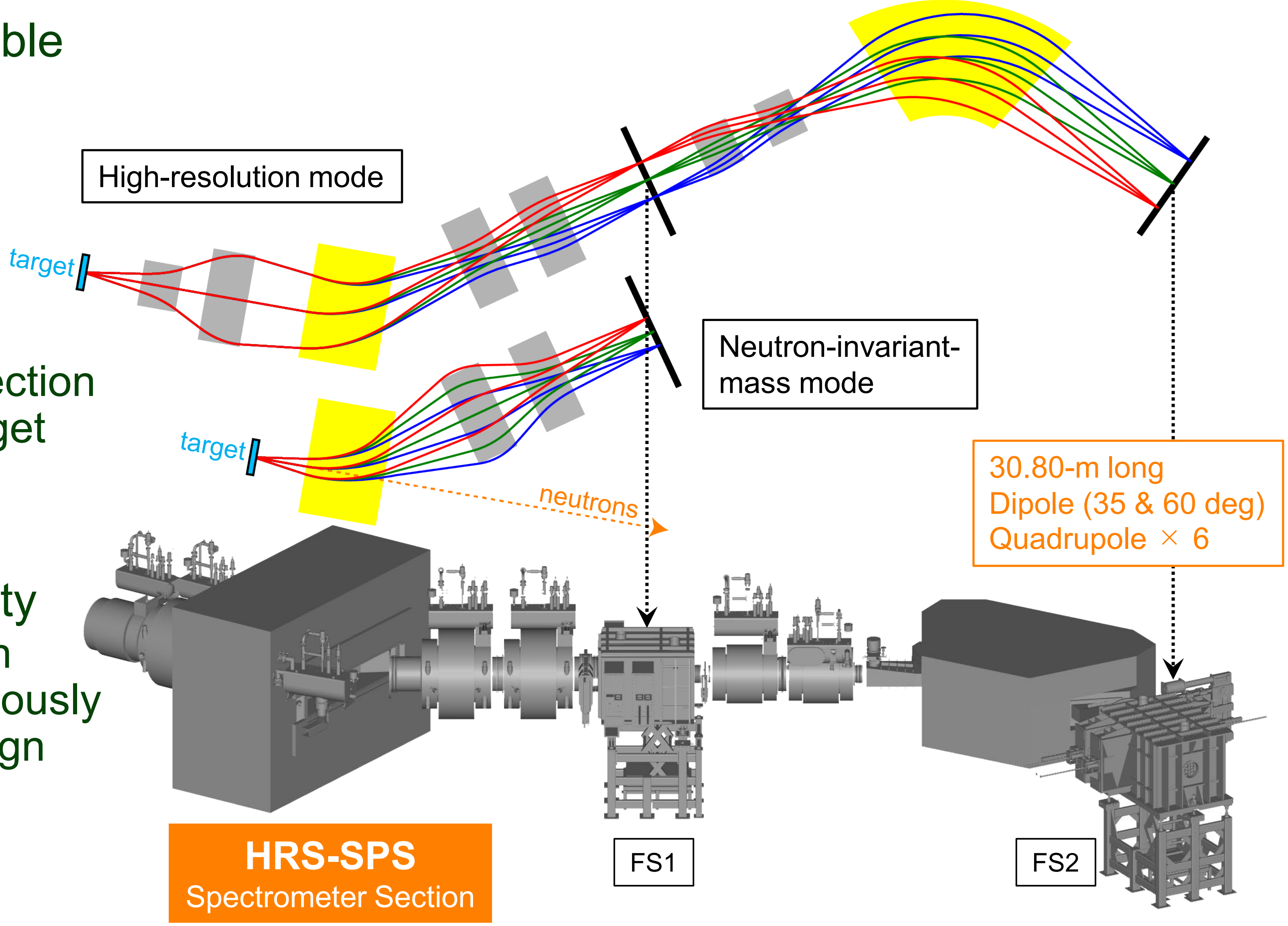
Maximum magnetic rigidity = 8 Tm vs. 4 Tm of S800, Sweeper

- Allowing experiments to run with beams at magnetic rigidities at which beam production rates in ARIS Fragment Separator are optimized
- 8 Tm rigidity is suitable for the envisioned energy upgrade from 200 MeV/*u* to 400 MeV/*u*



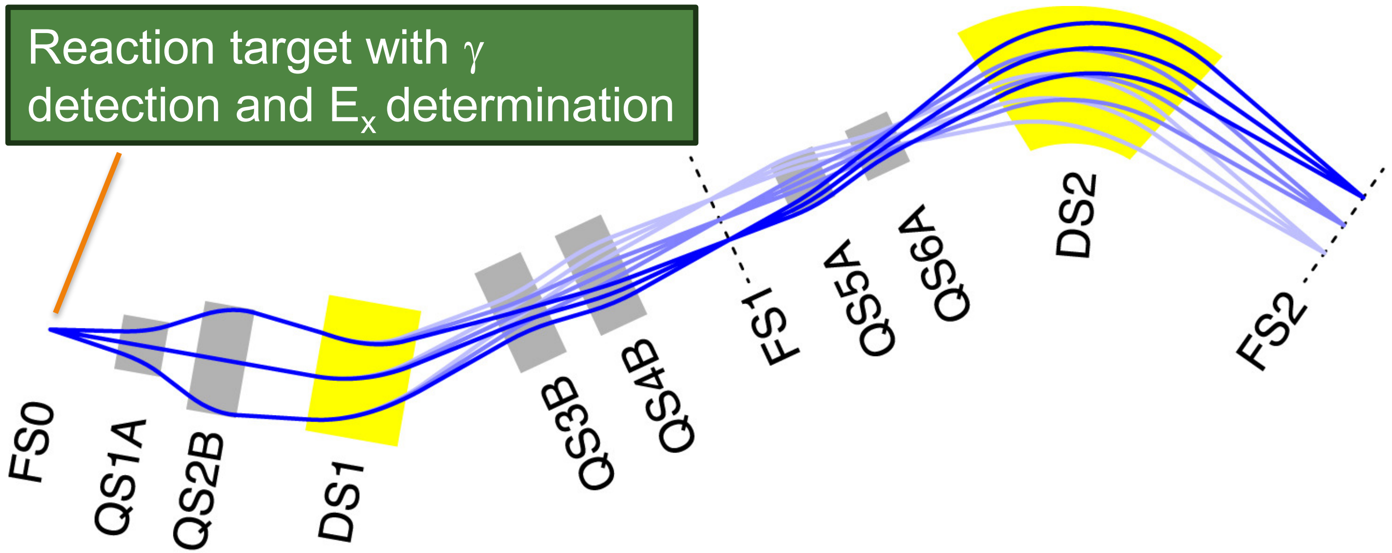
Multiple Operational Modes of HRS-SPS Facilitates Various Science Programs under Optimal Conditions

- Multiple operational modes available in a single hardware setup
  - Lattice layout is optimized for **high-resolution mode** in which the majority of experiments will run
  - **Neutron-invariant-mass mode** is specialized for invariant-mass spectroscopy with fast neutron detection at forward angles, with reaction target placed in front of the first dipole
- Interface with auxiliary detectors is coordinated with user community
  - Input from users (organized through the HRS Working Group) is continuously sought to ensure that the HRS design accommodates user program and facilitates detector installation



Fission Studies in the High Resolution Mode

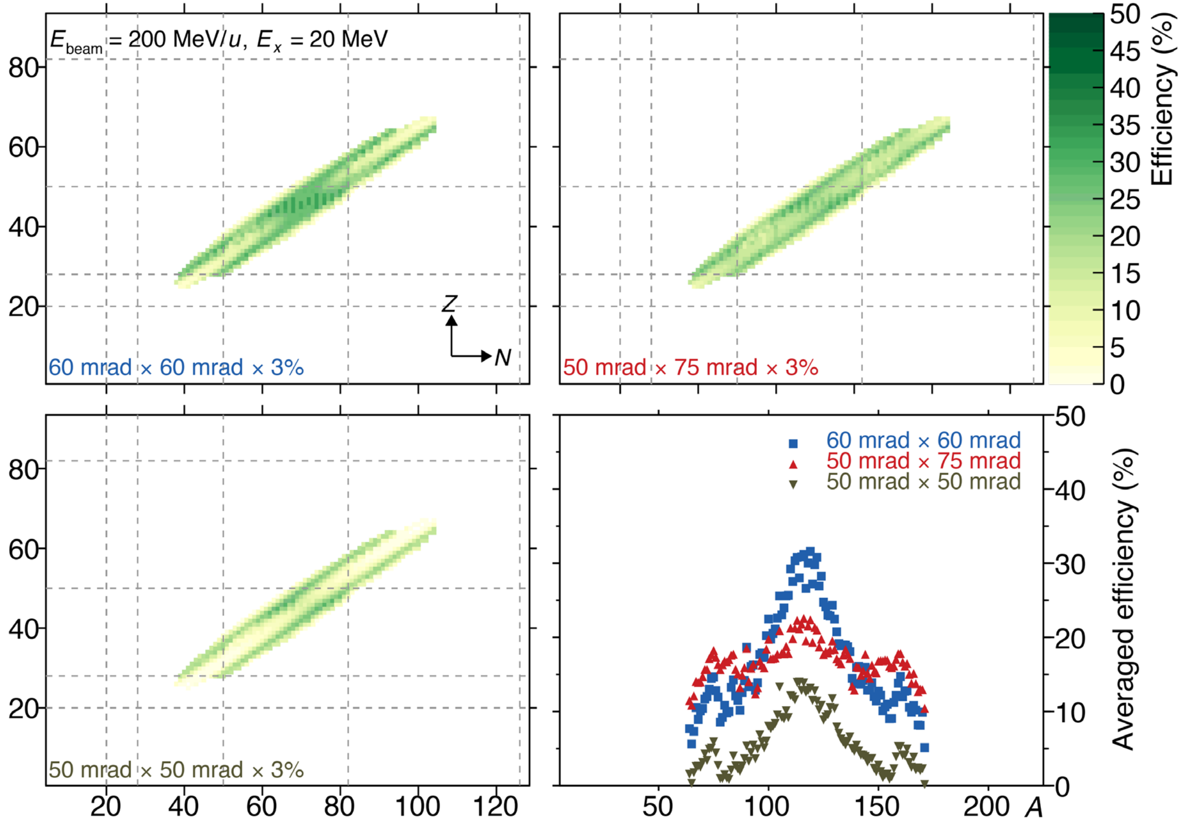
- Reaction target at FS0; different reactions can be used, including those that enable determination of excitation energy
- Full SPS is used to analyze the fission product(s)
- In-flight γ detection possible at FS0 using e.g. GRETA
- Limited acceptance for measuring in-flight neutrons from fission in e.g. MoNA-LISA
- Sufficiently large angular and momentum acceptances required for the detection of both fission fragments



Excitation energies can be determined through two-body kinematics using a suitable reaction, e.g. (d,p), (p,n) etc. Requires additional detection system at the target

Detection Efficiency Studies for Fission Pairs at the HRS

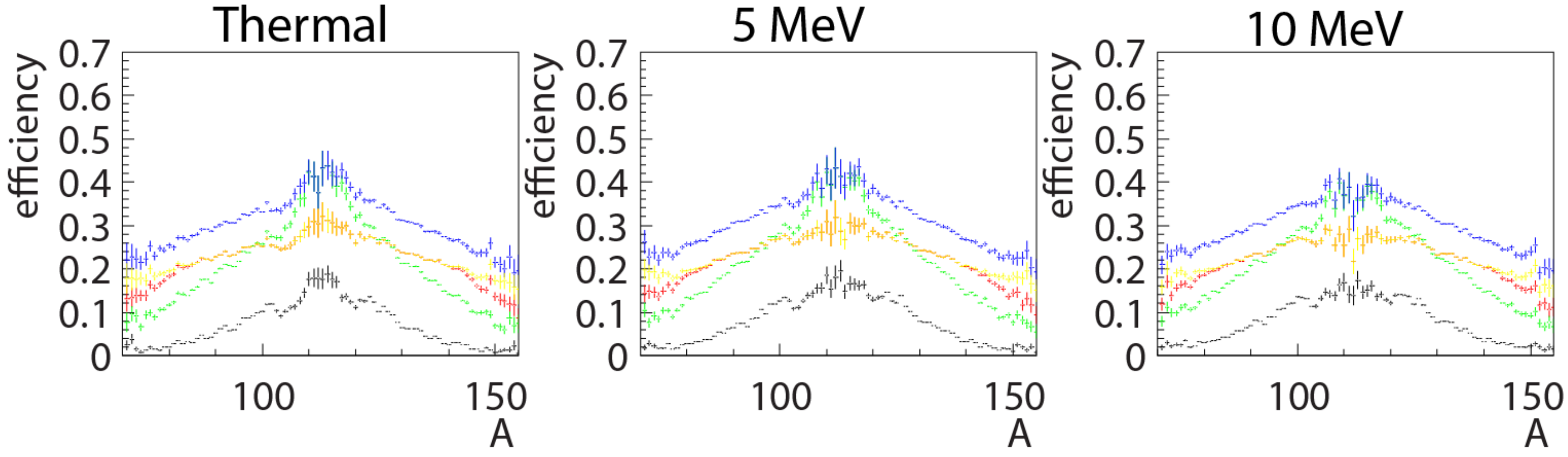
- The efficiency of detecting both fragments in the SPS was simulated using different methods
- Initial studies were performed in LISE++* - example: ^{238}U fission at 200 MeV/u at E_x=20 MeV for momentum acceptance of ±3%
- At an angular acceptance of ±50 x ±50 mrad (10 msr), the efficiency for detecting both fission fragments is compromised
- At an engular acceptance of ±50 x ±75 mrad or ±60 x ±60 mrad (~15 msr) decent efficiency for both fission fragments is achieved
- Asymmetric angular acceptance benefits even efficiency distribution



* O.B.Tarasov et al., NIM B 541 (2023) 4

Detection Efficiency Studies for Fission Pairs at the HRS

- Second set of studies were performed with inputs based on the GFMC code* provided by Amy Lovell (LANL)
- Fission of ^{240}Pu at 200 MeV/u (and 400 MeV/u), excitation energies of ~0 MeV (thermal), 5 MeV, and 10 MeV



-50 mrad < θ_x <50 mrad
-50 mrad < θ_y <50 mrad

-50 mrad < θ_x <50 mrad
-75 mrad < θ_y <75 mrad

-60 mrad < θ_x <60 mrad
-60 mrad < θ_y <60 mrad

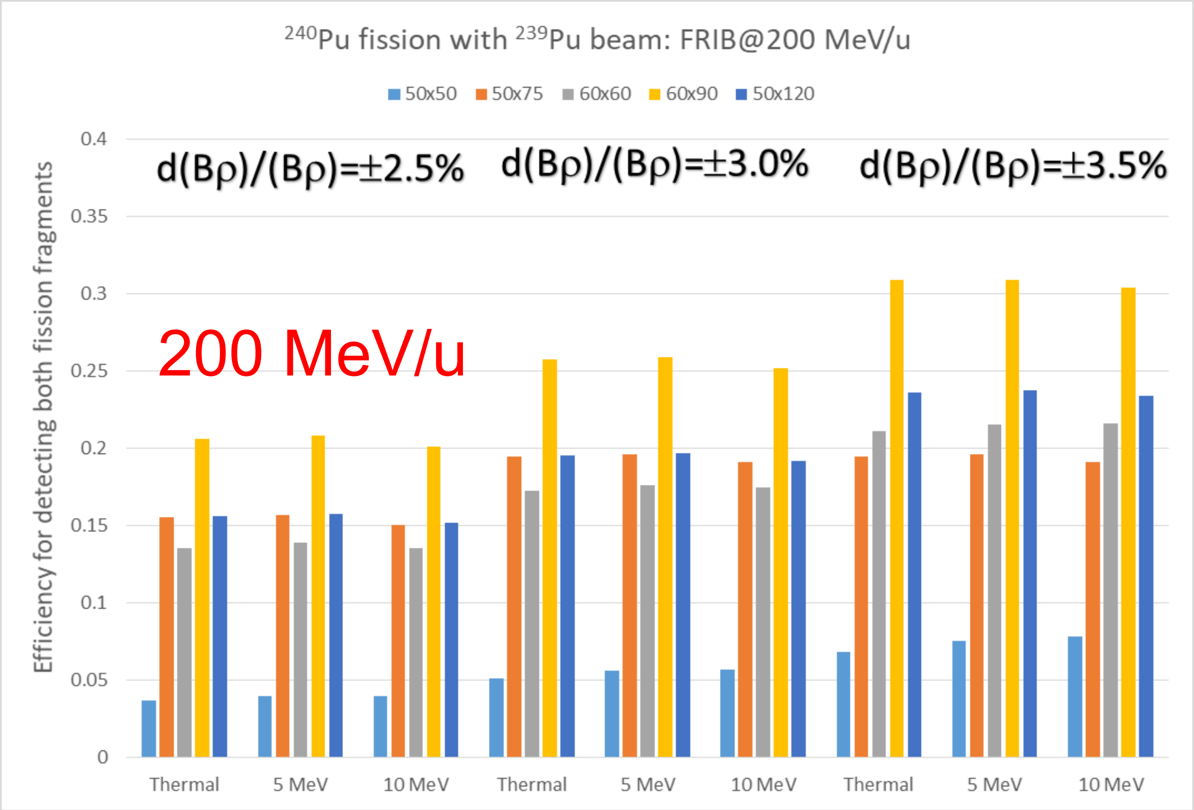
-60 mrad < θ_x <60 mrad
-90 mrad < θ_y <90 mrad

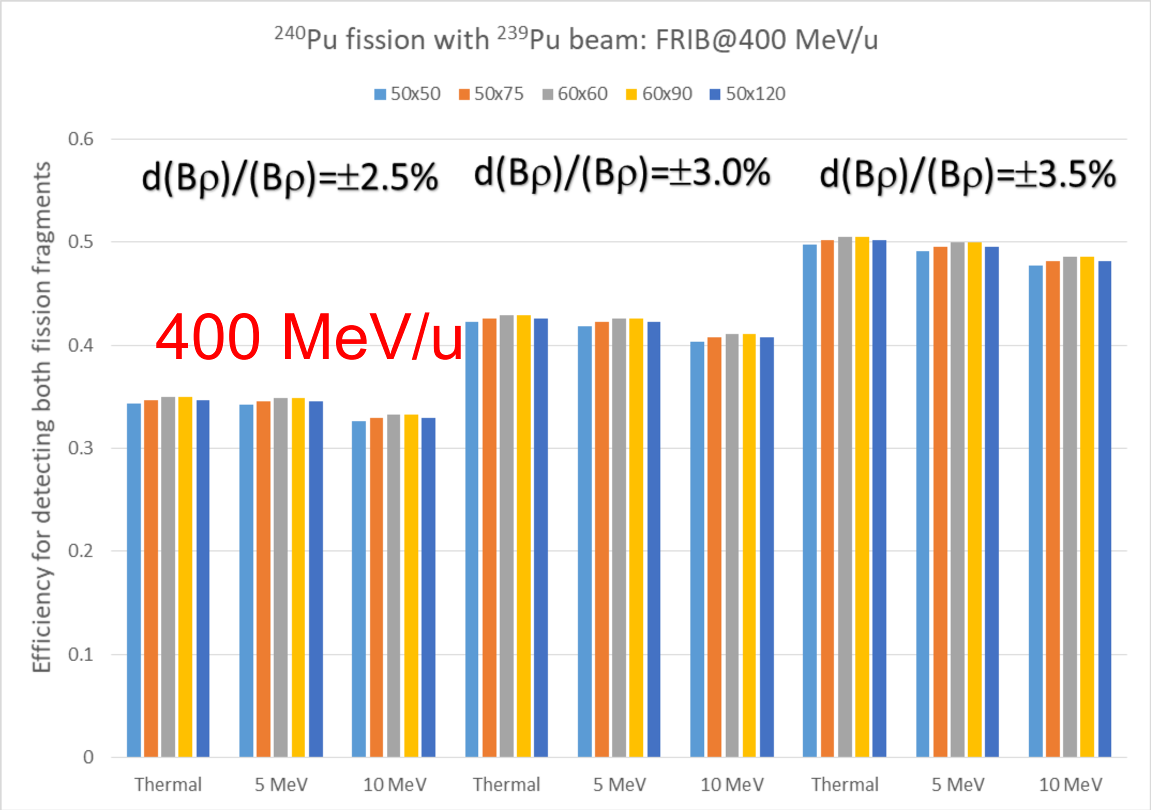
-50 mrad < θ_x <50 mrad
-120 mrad < θ_y <120 mrad

*Patrick Talou, Toshihiko Kawano, Ionel Stetcu, Physics Procedia 47, 39 (2013)

Effects of Angular and Momentum Acceptances

- At 200 MeVu (FRIB), angular acceptance plays an important role in the detection efficiency of fission pairs
- At 400 MeVu (FRIB400 Upgrade), the momentum acceptance constrains the pair-detection efficiency (full fission cone in acceptance) – efficiency about 2x higher than at 200 MeV/u





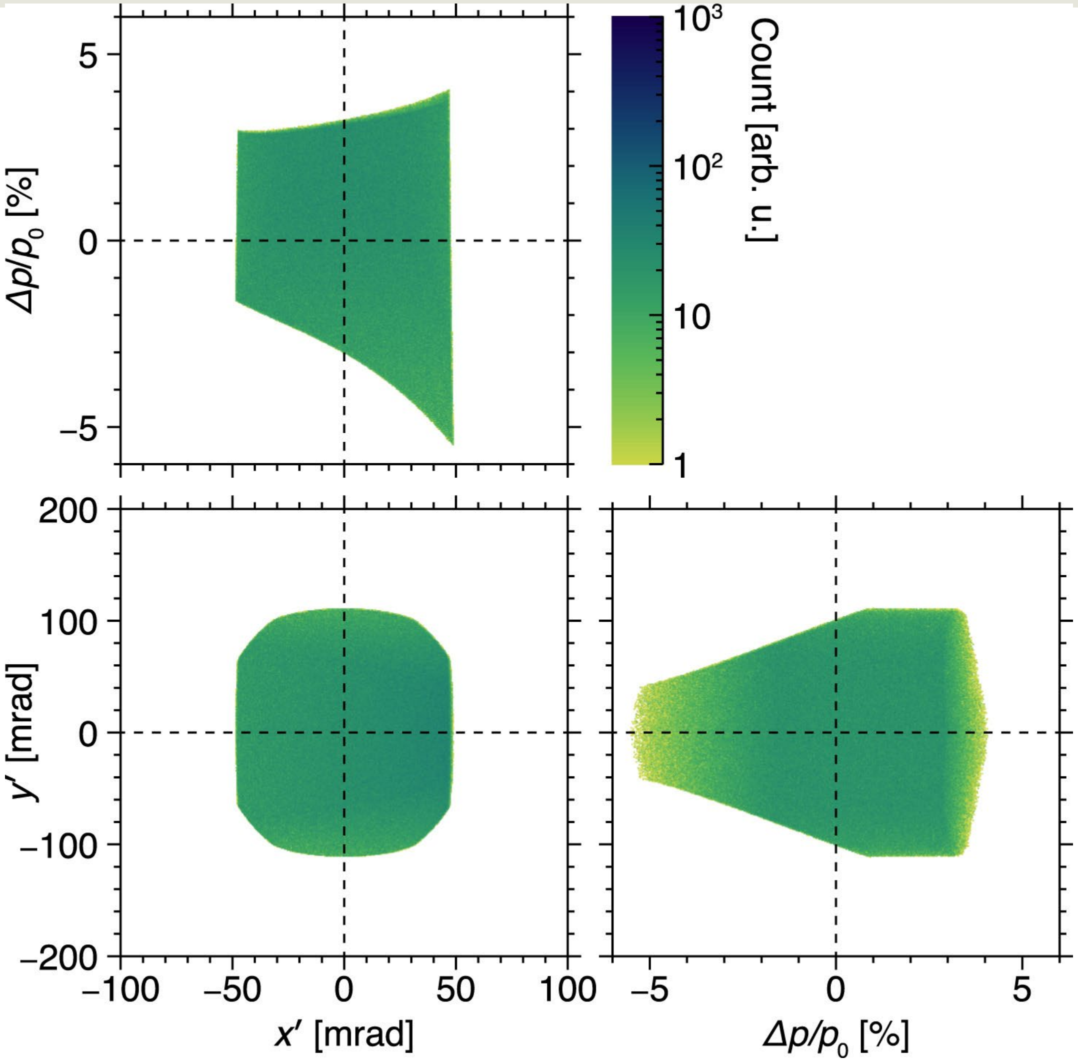
HRS-SPS Acceptance Requirements

- Requirements were determined on the broad science program envisioned for the HRS
- Fission studies key for constraining the solid angle of the spectrometer and the momentum acceptance

Requirements	High-resolution
Maximum mass number	238
Mass resolving power (FWHM)	400
Charge resolving power (FWHM)	156
Time-of-flight resolution (FWHM) (ps)	150
Flight path for charged particles (m)	25
Momentum resolving power (FWHM)	1500
Spectrometer solid angle (msr)	**15**
Angular resolution (mrad)	5
Space around target (cm)	123
Momentum acceptance (δ*p*/*p* in %)	**±2.5**
Neutron solid angle (msr)	-
Gap for Time Projection Chamber	-
Neutron flight-path length (m)	-
Unreacted beam rejection	yes
Maximum magnetic rigidity (Tm)	8

HRS High Resolution Mode Meets Requirements

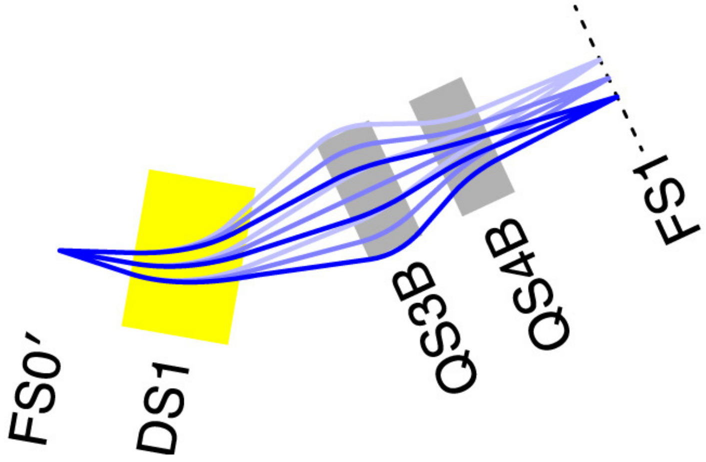
- Momentum acceptance dp/p: ~±3%
- Dispersive angle acceptance: ±50 mrad
- Non-dispersive angle acceptance: ~ ±75 mrad
- Solid angle covered: 15 msr



Fission Studies in the Invariant Mass Mode

- Reaction target at FS0'; different reactions can be used, including those that enable determination of excitation energy
- Part of SPS is used to analyze the fission product(s)
- In-flight γ detection possible at FS0 using e.g. GRETA
- Large acceptance for measuring in-flight neutrons from fission in e.g. MoNA-LISA
- Angular acceptance compromised, but large momentum acceptance

(b) Neutron-invariant-mass mode



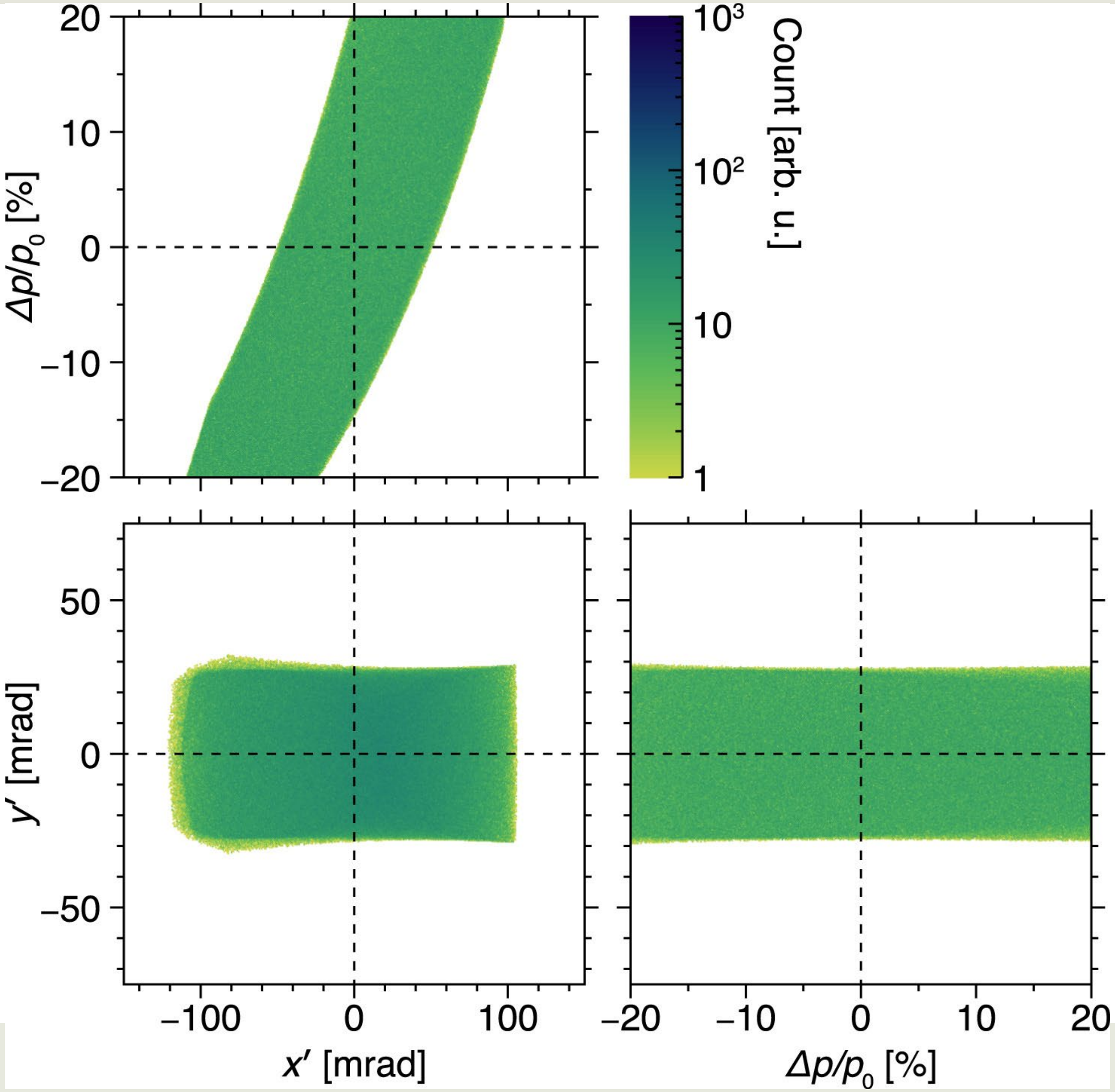
HRS-SPS Parameters for Neutron Invariant Mass Mode

- Not constrained by fission studies at 200 MeV/u, but strong opportunities for fission studies in which only one fission fragment needs to be detected and momentum acceptance and/or neutron detection are desired
- At 400 MeV/u, in principle the detection of both fission fragments, photons, and neutrons is possible with good efficiency

Requirements	Neutron invariant-mass
Maximum mass number	132
Mass resolving power (FWHM)	220
Charge resolving power (FWHM)	85
Time-of-flight resolution (FWHM) (ps)	150
Flight path for charged particles (m)	11
Momentum resolving power (FWHM)	290
Spectrometer solid angle (msr)	**10**
Angular resolution (mrad)	5
Space around target (cm)	90
Momentum acceptance ($\delta p/p$ in %)	**±5**
Neutron solid angle (msr)	32
Gap for Time Projection Chamber	60
Neutron flight-path length (m)	15
Unreacted beam rejection	yes
Maximum magnetic rigidity (Tm)	8

HRS Invariant Mass Mode Provides Complementary Opportunities for Fission Studies

- Momentum acceptance dp/p: ~±5%
- Dispersive angle acceptance: ±100 mrad
- Non-dispersive angle acceptance: ~ ±25 mrad
- Solid angle covered: 10 msr



FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

Summary

- The High Rigidity Spectrometer (HRS) provides unique opportunities for in-flight fission studies
- The HRS High Resolution Mode enables the detection of both fission fragments with sufficient efficiency for detailed correlation studies
- It is possible to determine the excitation energy by using a suitable direct reaction
- The HRS Invariant Mass Mode enables the detection of in-flight neutrons and has a large momentum acceptance for the detection of fission fragments
- Both modes support the simultaneous detection of photons emitted in the fission process
- The FRIB400 energy upgrade significantly increases the detection efficiency for fission pairs and makes it possible to perform experiments in which both fission fragments, neutrons, and photons can be detected simultaneously

Functional Requirements for HRS-HTBL

- Three main objectives of HTBL have been identified
  - **Transmit** rare-isotope beams at the magnetic rigidities at which the production rates in Fragment Separator are maximum
  - **Minimize** transmission losses between Fragment Separator & Spectrometer Section
  - **Transmit** beams to Spectrometer Section for physics experiments with appropriate ion-optical properties & **characterize** beams when necessary

Maximum rigidity	8 Tm
Minimum beam transport efficiency	95% in achromatic beam transport mode
Available beam-transport modes	Achromatic & dispersion-matched modes that deliver beams to the Spectrometer Section with properties appropriate for achieving the scientific program of the HRS
Minimum time-of-flight path length for ToF-$B\rho$ mass measurements	90 meters when combined with the FRIB Fragment Separator & the Spectrometer Section of the HRS
Beam tracking capabilities	Ability to determine the momentum (with a resolving power of at least 1,500) & angle (with a resolution of better than 5 mrad) at the HRS-SPS reaction target by using tracking stations in the HTBL
Rare isotope separation	Ability to insert a Radio-Frequency Fragment Separator with a length of 2.2 m as well as associated steering magnets

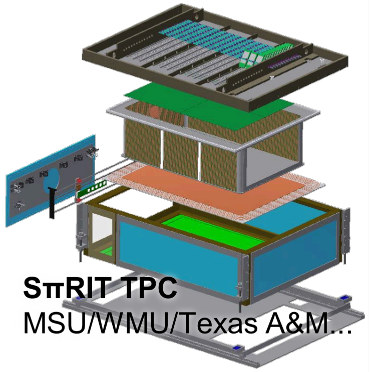
Functional Requirements for HRS-SPS

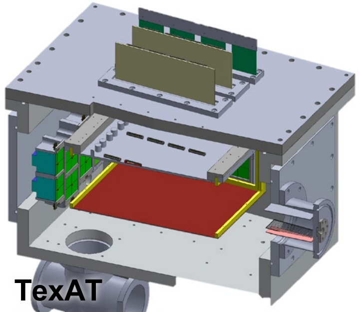
- Three basic operation modes have been identified
  - Three operation modes are realized in a single hardware setup
  - Interface with auxiliary detectors has been discussed and coordinated with collaborators

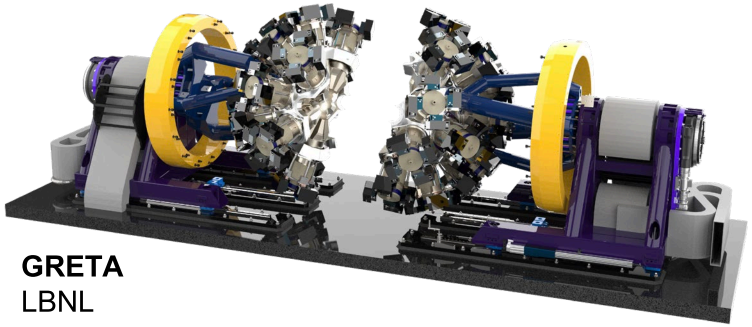
		High-resolution mode	Neutron-invariant-mass mode	ToF-$B\rho$ mass-measurement mode
Maximum mass		238	132	238
Mass resolving power		400	220	10000
Charge resolving power		156	85	156
Time-of-flight resolution	[ps]	150	150	30
Charged-particle flight path	[m]	25	11	90
Momentum resolving power		1500	290	>10000
Spectrometer solid angle	[msr]	15	10	3
Angular resolution	[mrad]	5	5	–
Space around target	[cm]	123	90	N/A
Momentum acceptance	[%]	±2.5	±5	±0.5
Neutron solid angle	[msr]	–	32	–
Maximum neutron flight path	[m]	–	15	–
Gap for Time Projection Chamber	[cm]	–	60	–
Unreacted beam rejection		Yes	Yes	N/A
Maximum magnetic rigidity	[Tm]	8	8	7

HRS Accommodates Various Auxiliary Detectors Developed by User Community to Meet Scientific Objectives of FRIB

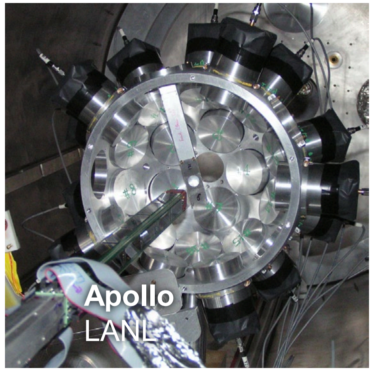

AT-TPC
MSU, LBNL, ND, TRIUMF…


SπRIT TPC
MSU/WMU/Texas A&M…

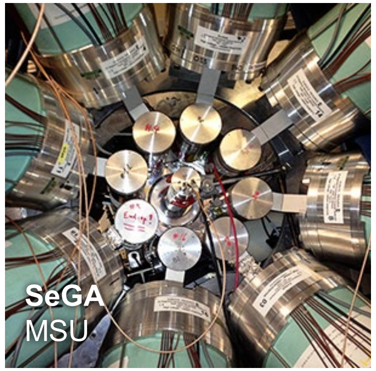

TexAT
Texas A&M

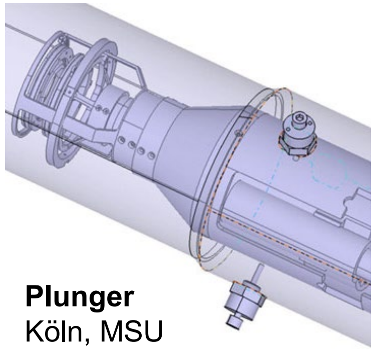

GRETA
LBNL


ORRUBA
Rutgers, ORNL


Apollo
LANL


LENDA – MSU
VANDLE – UT
LH_2 target – Ursinus


SeGA
MSU


Plunger
Köln, MSU


MoNA-LISA
MoNA-LISA Collaboration

HAGRiD
Rutgers, UT, ORNL


HiRA
MSU, Wash U, Indiana U,WMU


CAESAR
MSU