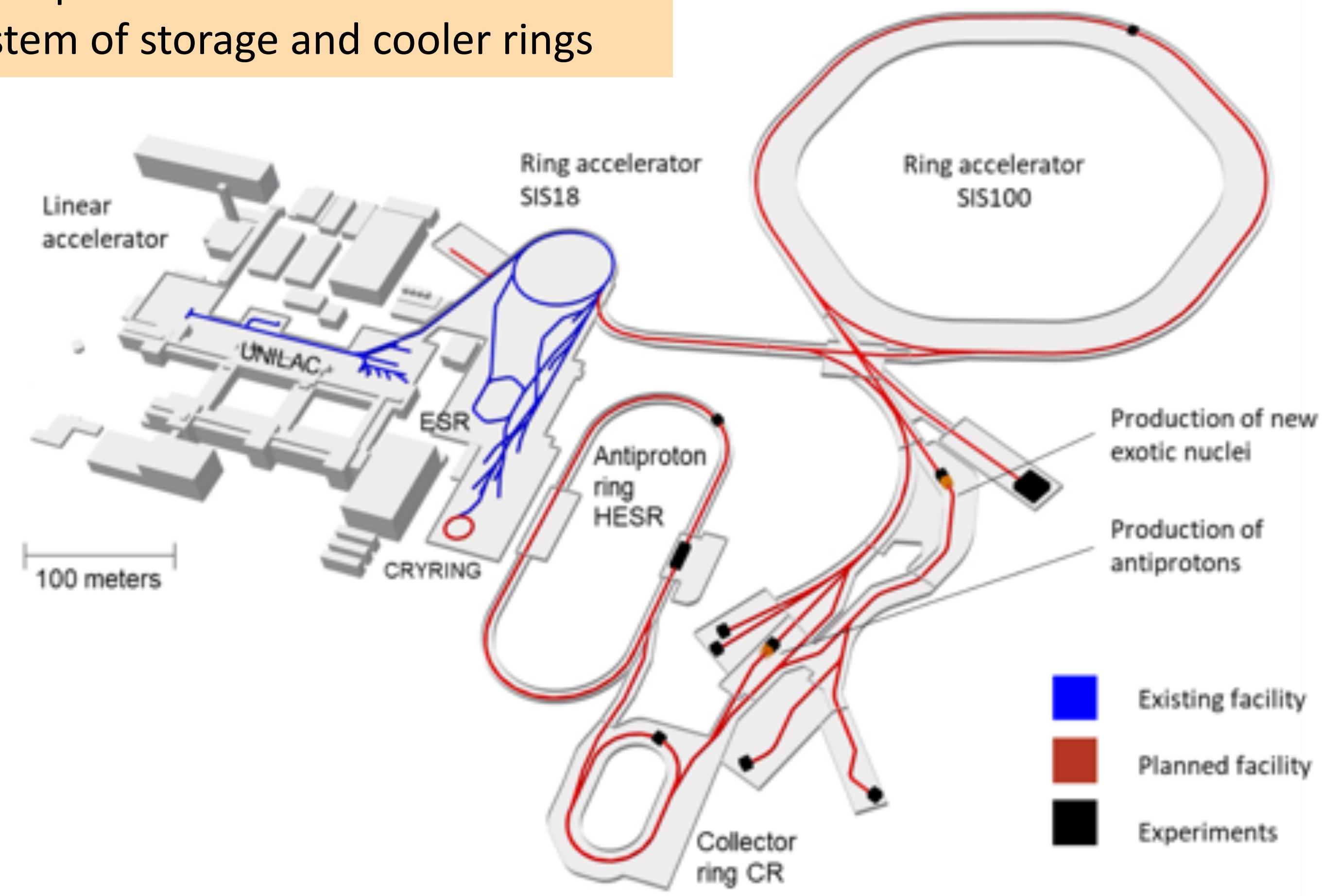
Nuclear Physics Research at GSI/FAIR: Precision experiments with stored and cooled exotic nuclei

Yuri A. Litvinov

Meeting of the Nuclear Physics Division Board of the EPS
30 September - 01 October 2019, GSI and University of Frankfurt, Germany

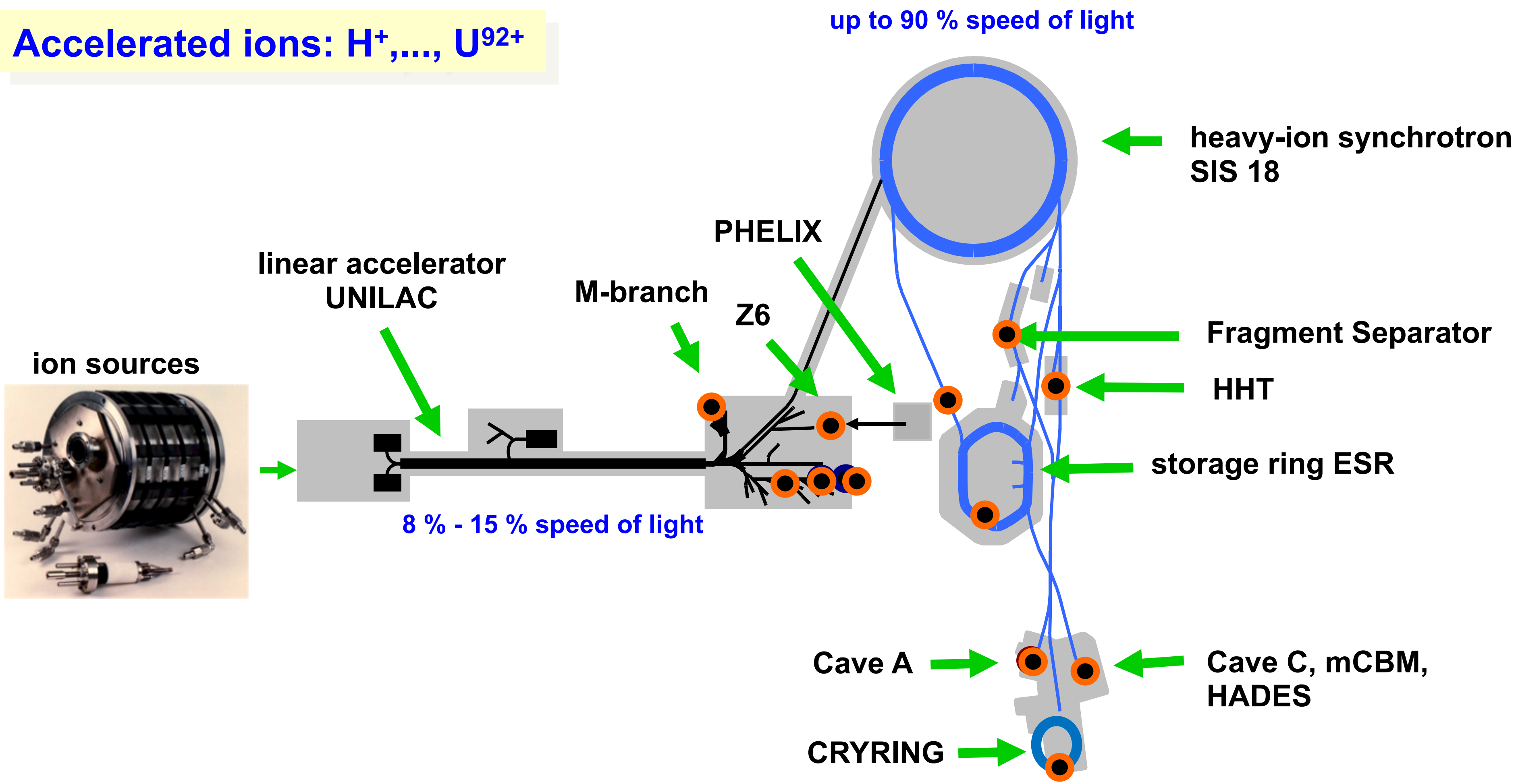
GSI and FAIR Facilities

- **Intensity gain: x 100 – 1000**
- 10 x energy (comp. to GSI)
- **Antimatter:** antiproton beams
- **Precision:** System of storage and cooler rings



Experimental Facilities available for FAIR Phase-0

Accelerated ions: H^{+},..., U^{92+}



Physics at Storage Rings

Storage rings stay for:

Single-particle sensitivity

Broad-band measurements

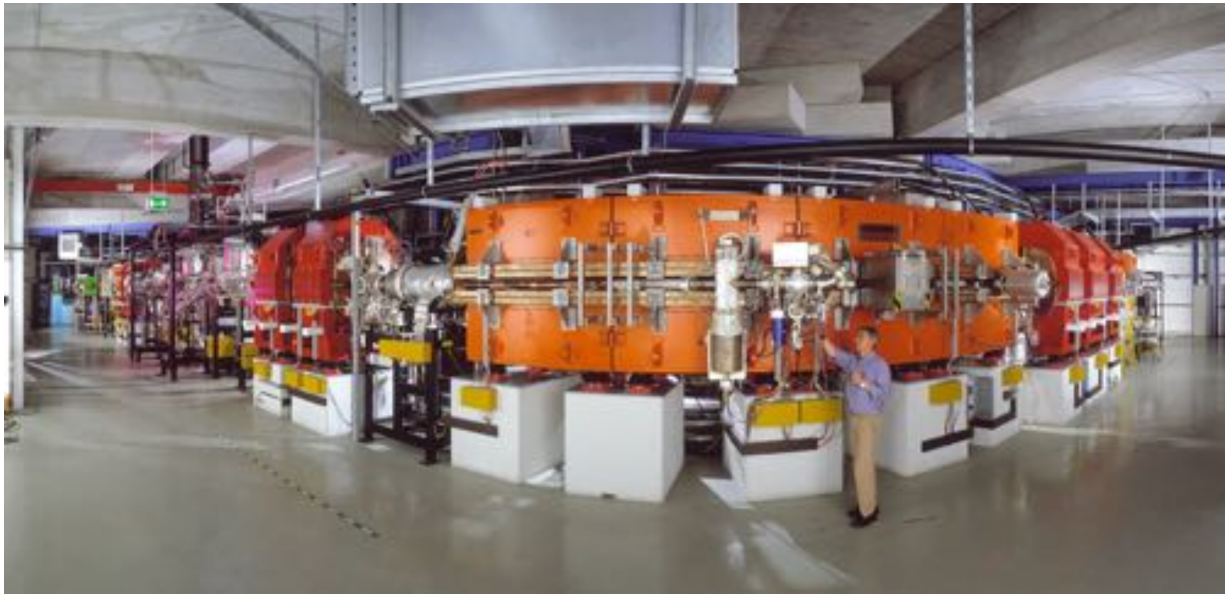
High atomic charge states

High resolving power

Why storage rings?

- Storage - efficient use of rare species
- Cooling - high quality beams
- Recirculation - high luminocities though thin targets
- Removing of contaminants
- Ultra-high vacuum – preserving atomic charge state
- Laser-ion interaction
- Various gaseous internal targets, electrons, (neutrons)
- High detection efficiencies for recoils

Storage ring facilities at GSI



Experimental Storage Ring (ESR)

In operation since 1990
Circumference = 108.3 m
Vacuum = 10^{-10}—10^{-12} mbar
Electron, stochastic cooling
Energy range = 4 – 400 MeV/u
Slow and fast extraction

CRYRING
(transported from Stockholm University)

Planned start of operation (stable ions) – 2016
Planned start of operation (exotic nuclei) – 2020
Circumference = 54.15 m
Vacuum = 10^{-11}—10^{-12} mbar
Electron cooling
Energy range = ~0.1 – 15 MeV/u
Slow and fast extraction

Physics with Storage Rings

Nuclear Physics

Nuclear structure through transfer reactions

Long-lived isomeric states

Atomic effects on nuclear half-lives

Half-life measurements of ^{7}Be

Nuclear effects on atomic decay rates

Exotic decay modes (NEEC/NEET, unbound states, …)

Di-electronic recombination on exotic nuclei

Purification of secondary beams from contaminants

Nuclear magnetic moments

Neutron–induced reactions

Capture reactions for p-process

….

Atomic Physics

Precision x-ray spectroscopy

Super-Critical fields

Electron-Ion collisions

Atomic lifetimes

Nuclear effects on atomic decay rates

Photoionization

Di-electronic recombination on exotic nuclei

Electron spectroscopy / electron scattering

Atom/Molecule fragmentation

Ion-molecule interactions

Laser induced recombination

…..

PROPOSALS SUBMITTED TO G-PAC IN 2017

E131	CRYRING	A	Z>54, Be-like	Slowing down, E-cooling, Vacuum	27
E138	CRYRING	A	U91+	Slowing down, E-cooling	39
E121	ESR	A	206Pb->205Tl81+	FRS, Stacking, E-cooling, Gas-Jet	21
E122	ESR	B	208Pb->fragments	FRS, S-cooling, E-cooling	
E123	ESR	B	238U	E-cooling, Drift-tubes	
E124	ESR	B	238U89+, 91+	E-cooling, Gas-Jet, E-spectrometer	
E125	ESR	A-	238U89+, 91+	Slowing down, E-cooling, Gas-Jet	48
E126	ESR	B	238U88+	Slowing down, E-cooling, Gas-Jet	
E127	ESR	A	Z~50	Slowing down, E-cooling, Gas-Jet, Vacuum	15
E128	ESR	A	209Bi82+, 80+	(Stacking), E-cooling, Lasers, Drift tubes	10
E130	HITRAP	A	209Bi82+, 80+	Slowing down, (Stacking), E-cooling	10
E132	ESR	A	132Xe	Slowing down, E-cooling, Gas-Jet	48
E133	ESR	B	Z>54	E-cooling, Gas-Jet	
E136	ESR	B	12C3+	E-cooling, Lasers	
E135	ESR	A-	84Kr32+	E-cooling, Lasers	21
E137	ESR-C. A	A	238U89+	E-cooling, Extraction to Cave-A	18
S461	CRYRING	A-	40Ar->30P15+	FRS, Slowing down, E-cooling	21
				TOTAL	278

Bound-State Beta Decay of ^{205}Tl Nuclei

Proposal for an experiment to be conducted at FRS/ESR

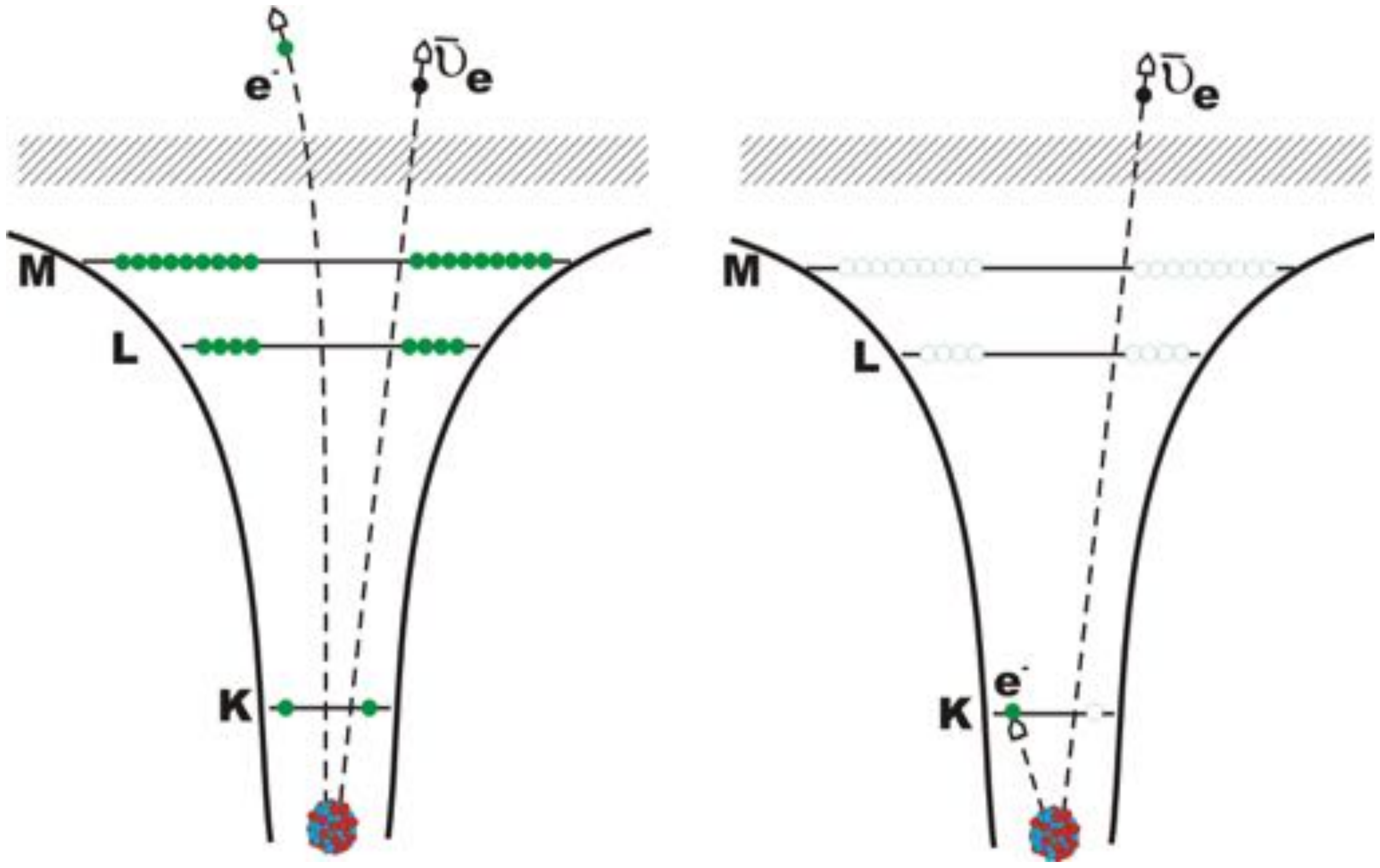
Measurement of the bound-state beta decay of bare ^{205}Tl ions

Updated from previously accepted proposal E100

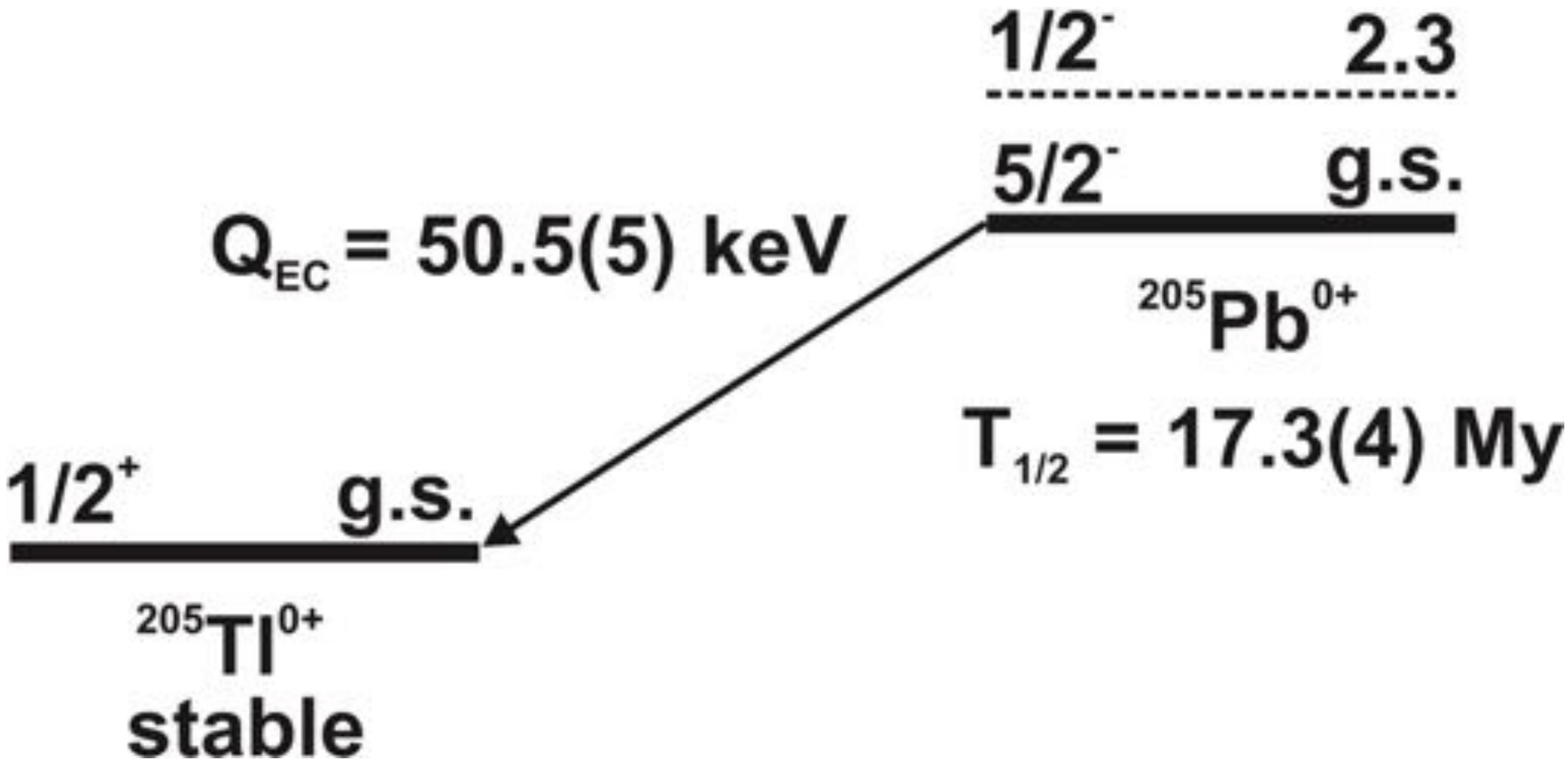
For the LOREX, NucCAR, SPARC and ILIMA Collaborations

*Regarding the proposal "Measurement of the bound-state beta decay of bare ^{205}Tl ions" (Proposal E121), the G-PAC recommends this proposal with **highest priority (A)** and that **21 shifts of main beam time** be allocated for this measurement.*

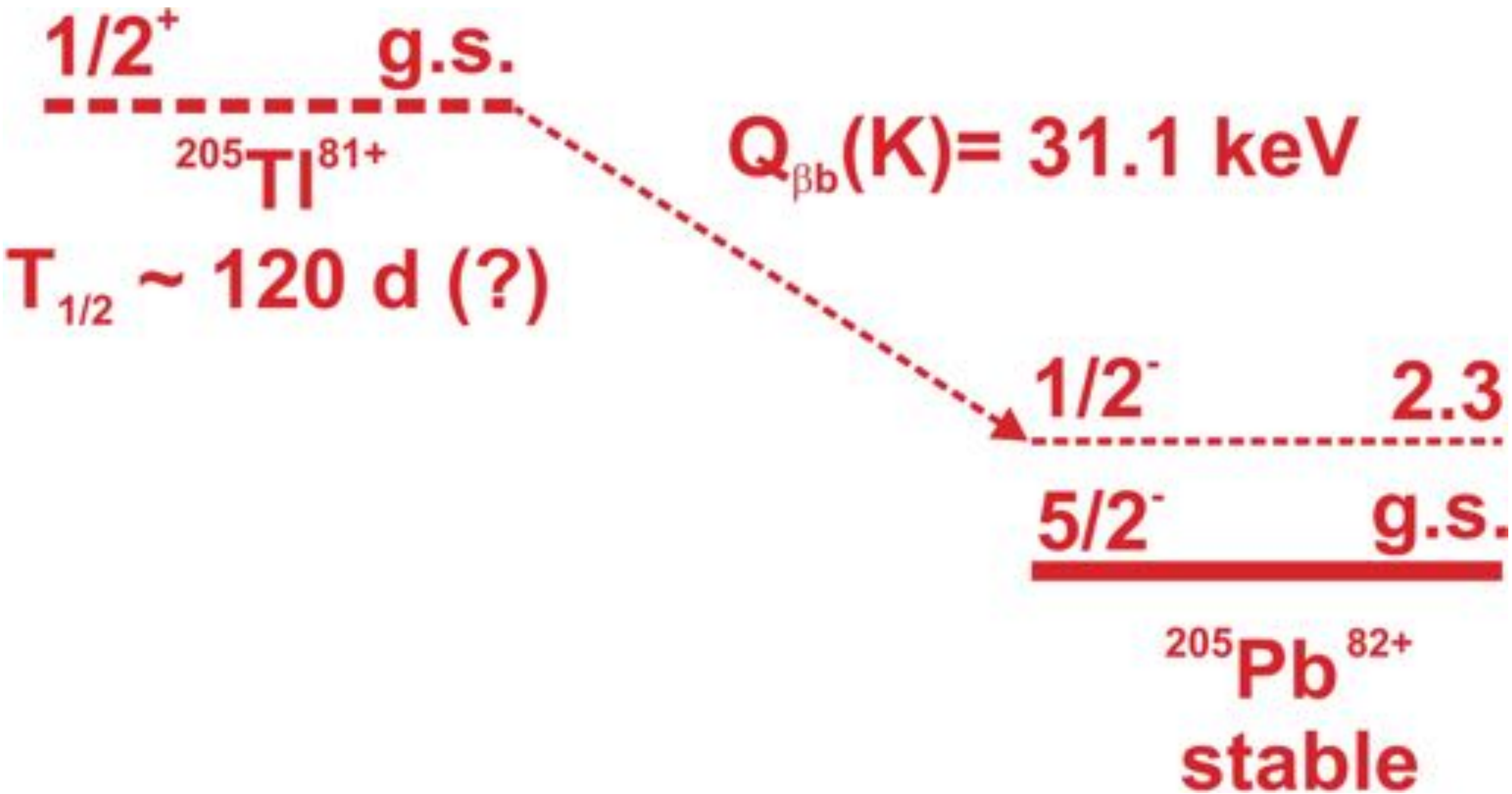
Bound-State β-decay



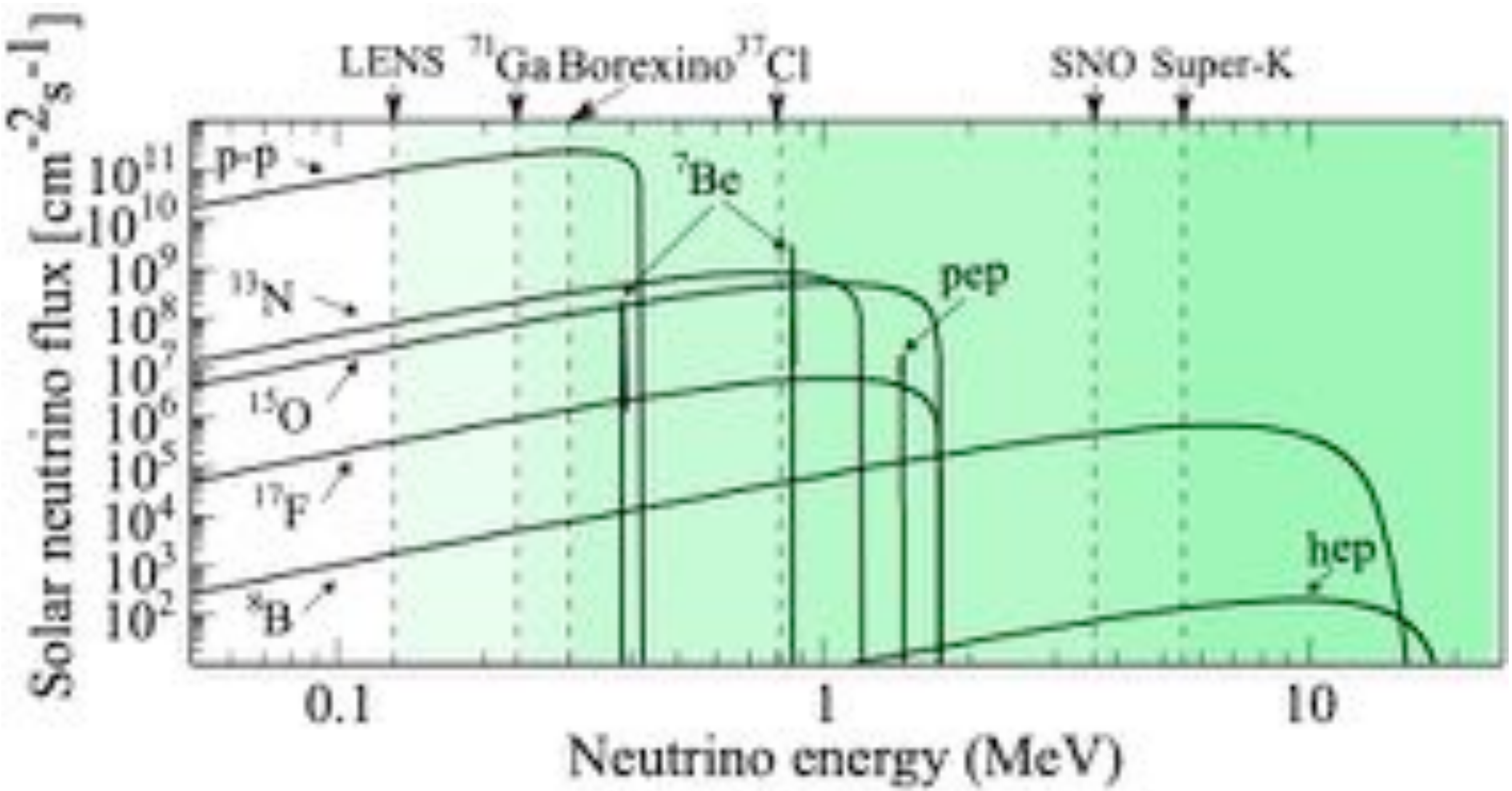
Bound-State Beta Decay of ^{205}Tl Nuclei



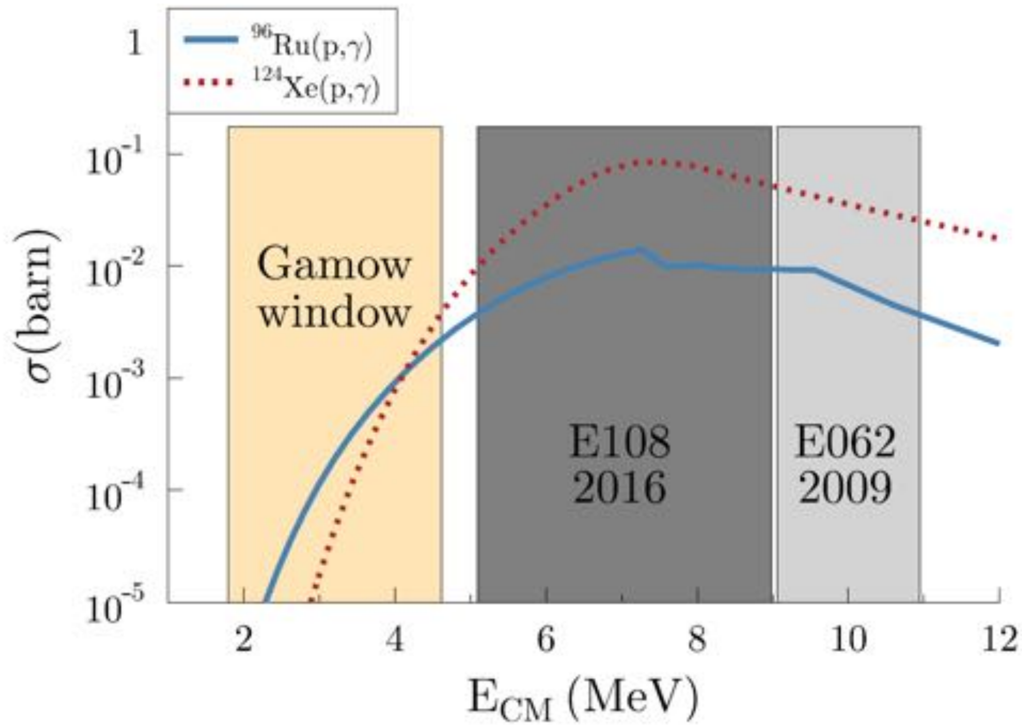
Bound-State Beta Decay of ^{205}Tl Nuclei



Solar Neutrino Flux



Proton Capture Reaction Measurements



E127 R. Reifarth et al.

NucAR

*Regarding the proposal "Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process" (Proposal E127), the G-PAC recommends this proposal with **highest priority (A)** and that **15 shifts of main beam time** be allocated for this measurement.*

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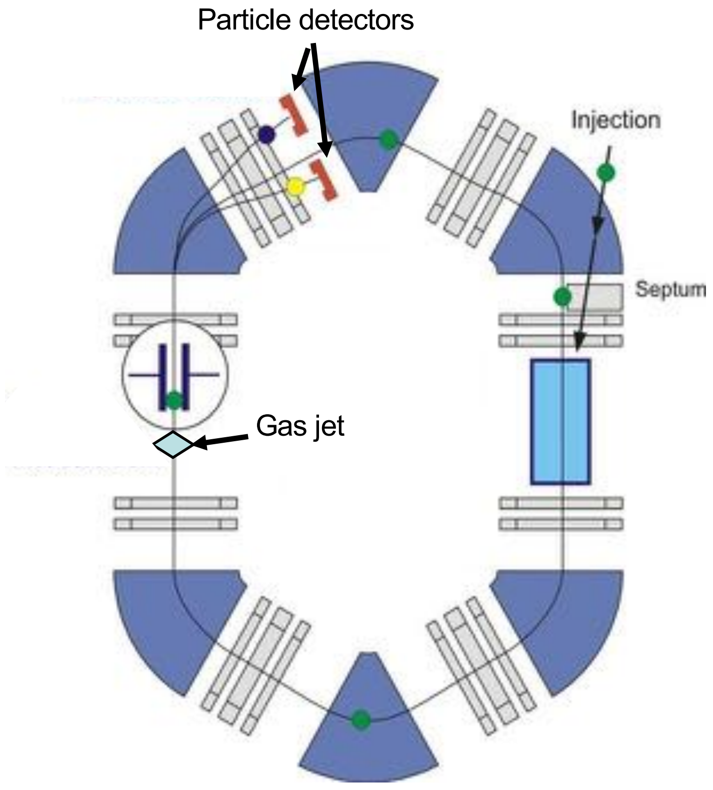
Nuclear reaction studies in a storage ring



ESR

High revolution frequency

→ high luminosity even with thin targets

Detection of ions via in-ring particle detectors

→ low background, high efficiency

Well-known charge-exchange rates

→ in-situ luminosity monitor

Ultra-thin windowless gas targets

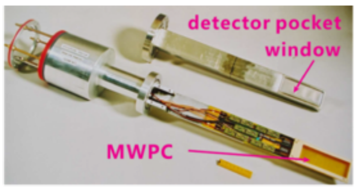
→ excellent resolution

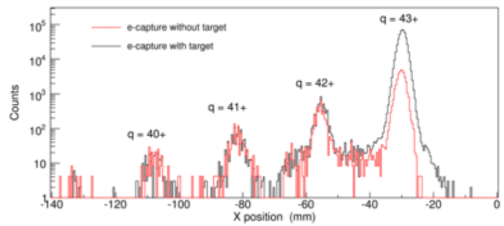
Applicable to radioactive nuclei

Normalization of Nuclear Cross Sections

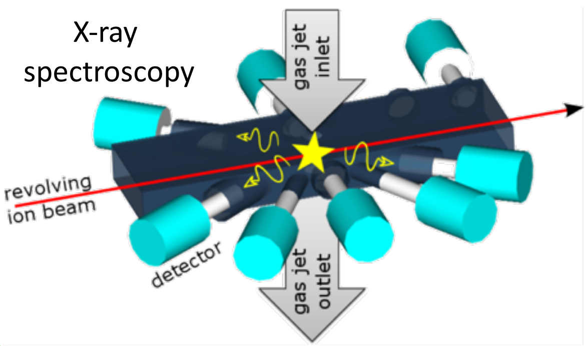
total e^- capture rate [NRC + REC]

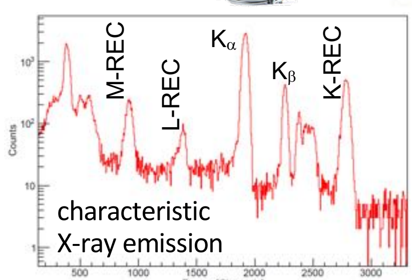
measured by particle detection

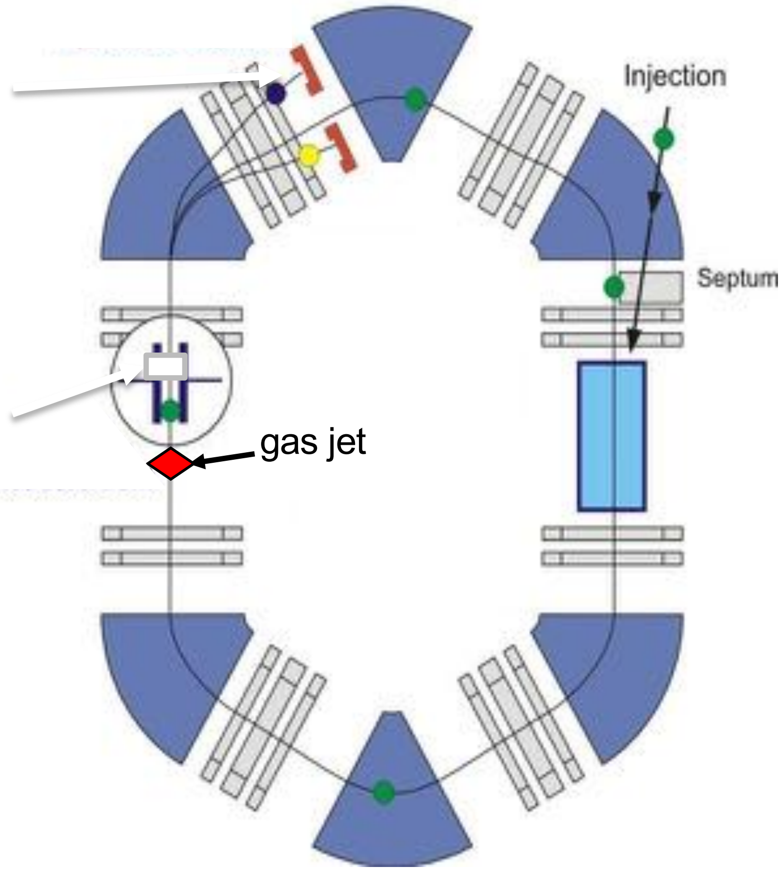




radiative e^- capture rate [REC]

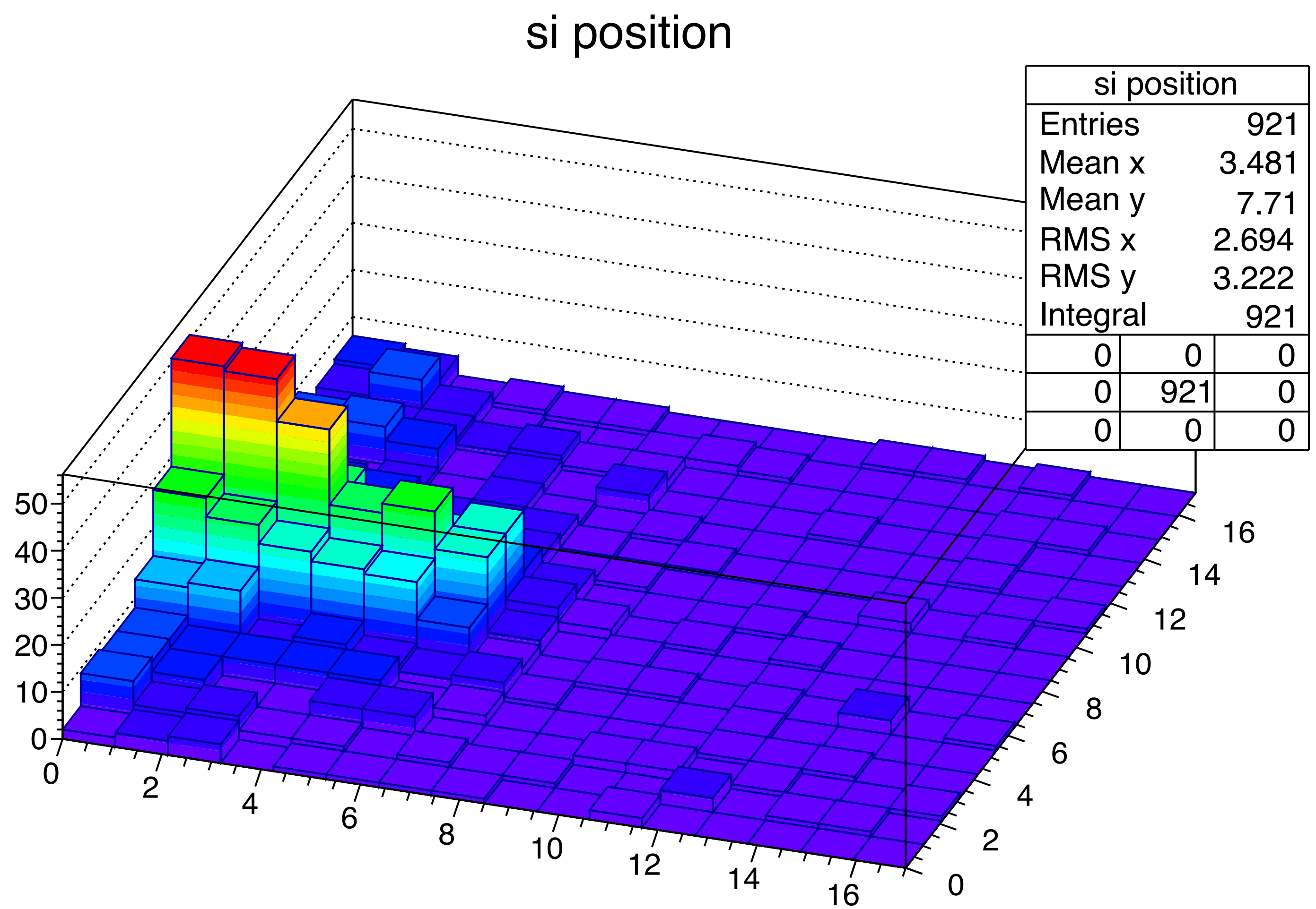




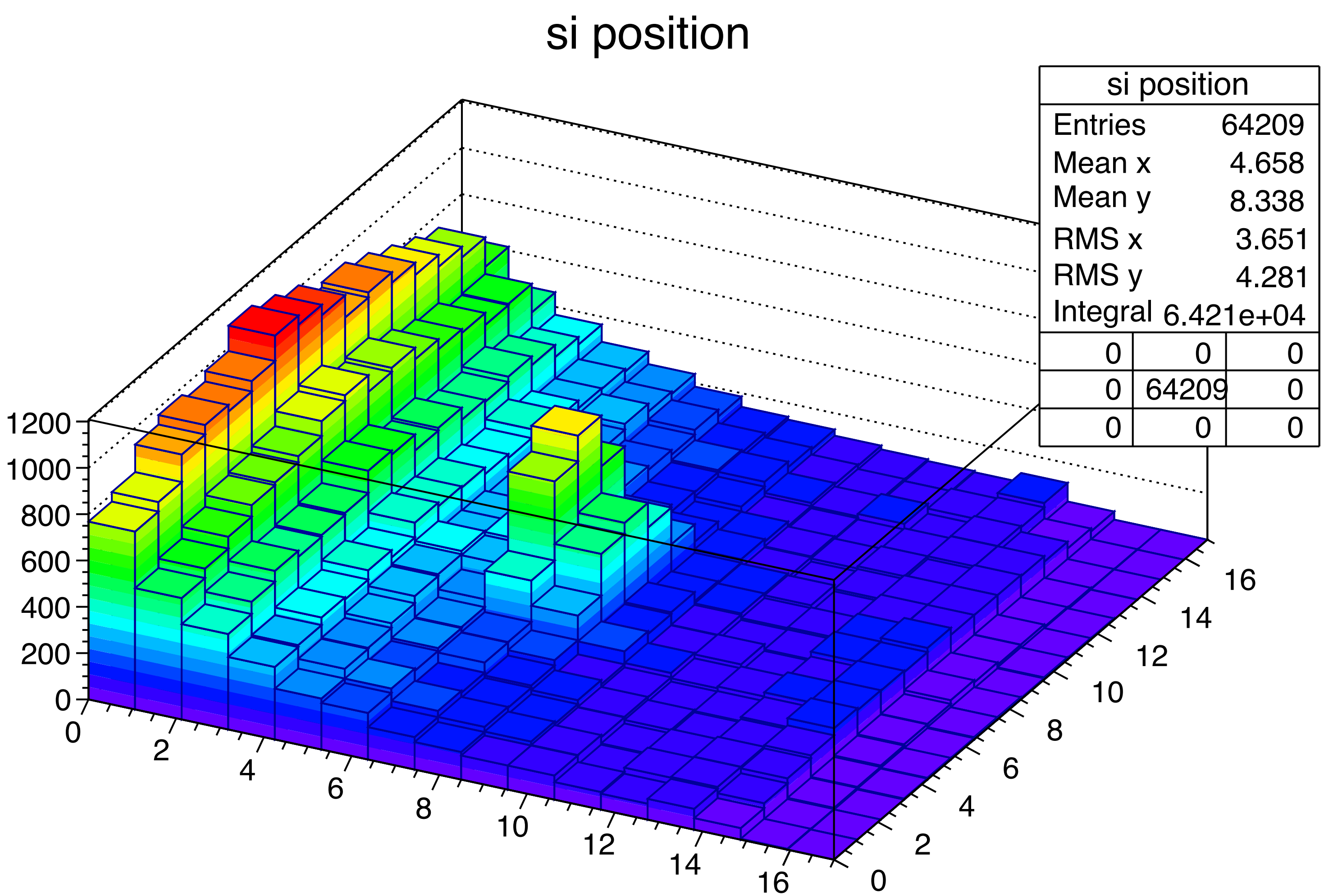


Courtesy Jan Glorius

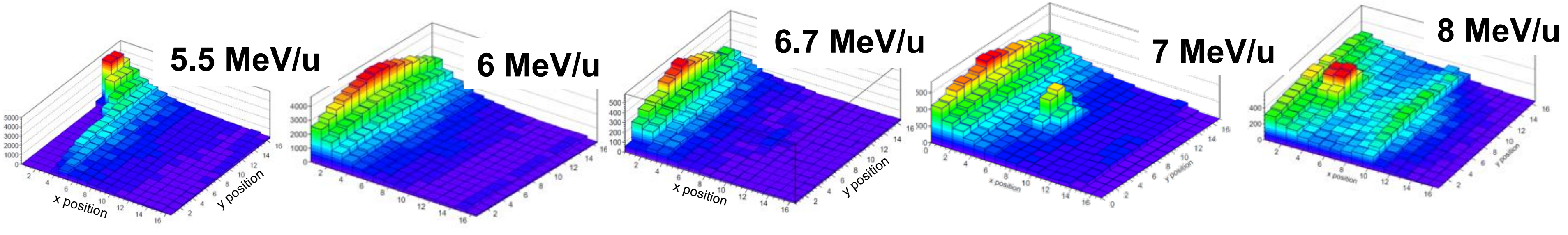
$^{124}Xe(p,g)^{125}Cs$ Experiment at the ESR

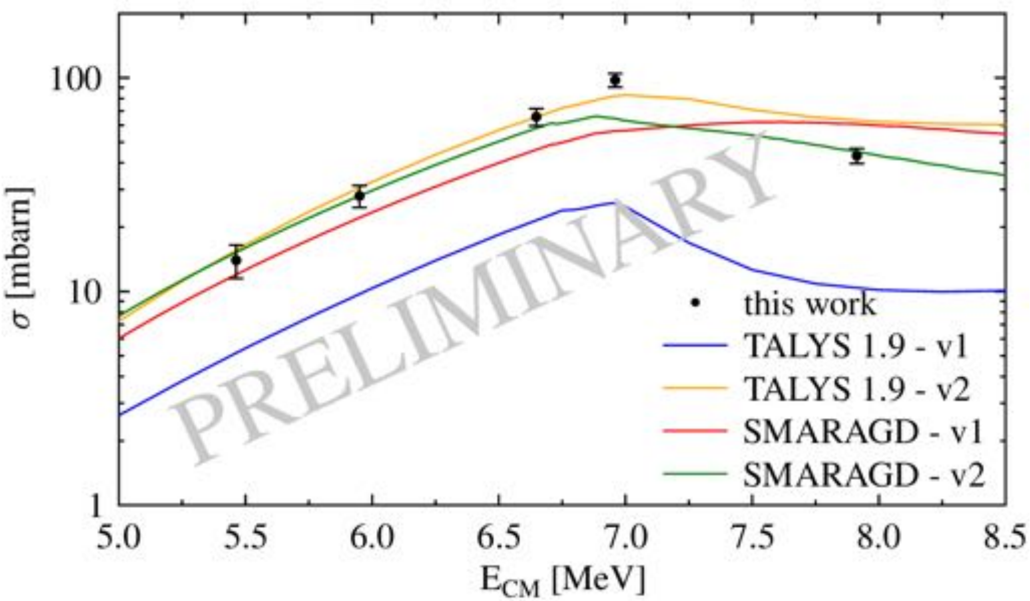


$^{124}Xe(p,g)^{125}Cs$ Experiment at the ESR



$^{124}Xe(p,\gamma)$ - Results





PHYSICAL REVIEW LETTERS **122,** 092701 (2019)

Approaching the Gamow Window with Stored Ions:
Direct Measurement of $^{124}Xe(p,\gamma)$ in the ESR Storage Ri

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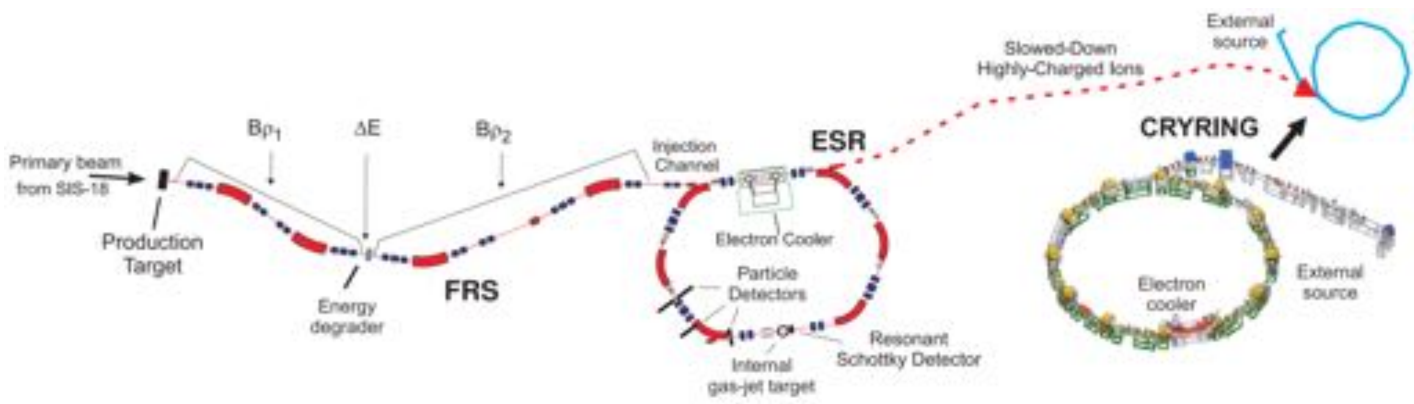
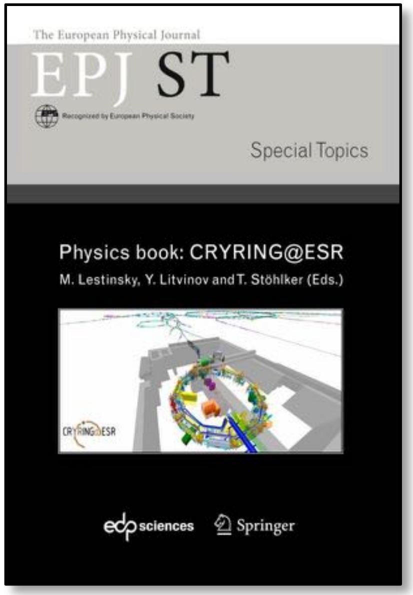
Courtesy Jan Glorius

HELMHOLTZ GSI

The CRYRING facility

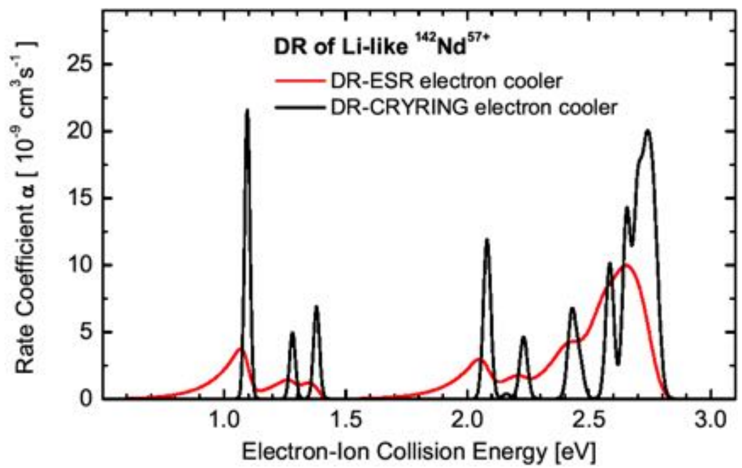


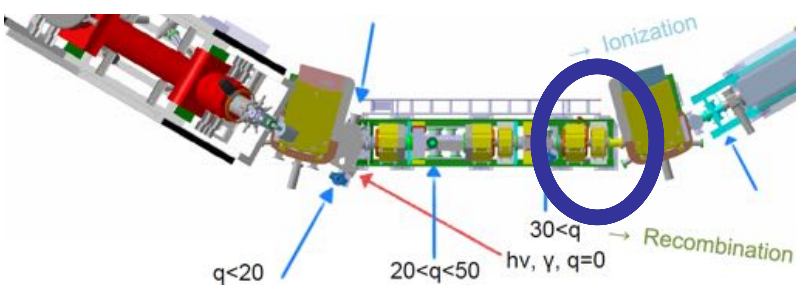


- CRYRING is a dedicated low-energy storage ring
  - all GSI beams available between ~100 keV/u and ~15 MeV/u
  - longer beam lifetimes for highly charged ions at low energies
- first commissioning phase is finished
- CRYRING is the ideal machine for astrophysical reaction studies

E131: Precision collision spectroscopy of Be-like ions at the electron cooler

Technical requirements:





- Be-like ions from ESR with Z ≥ 54 and I = 0 (e.g. $^{132}Xe^{54+}$, $^{142}Nd^{56+}$, $^{208}Pb^{78+}$, $^{238}U^{88+}$) .
- Highest possible energy in CRYRING to minimize electron capture from residual gas.
- Number of stored ions in CRYRING > 10^4.
- Ion-beam diagnostics (current transformer, beam profile monitor, Schottky analysis).
- Cold electron beam (expansion factor 100).
- Control of electron and ion beam positions in order to be able to achieve coaxial beams of electrons and ions in the electron cooler.
- Flexible programming control of high-voltage amplifier at electron cooler.
- Movable single-particle detector with 100% detection efficiency at position “30<q”.
- Hardware timing signals for data acquisition such as “injection”, “start of voltage ramp”, and “new voltage”.

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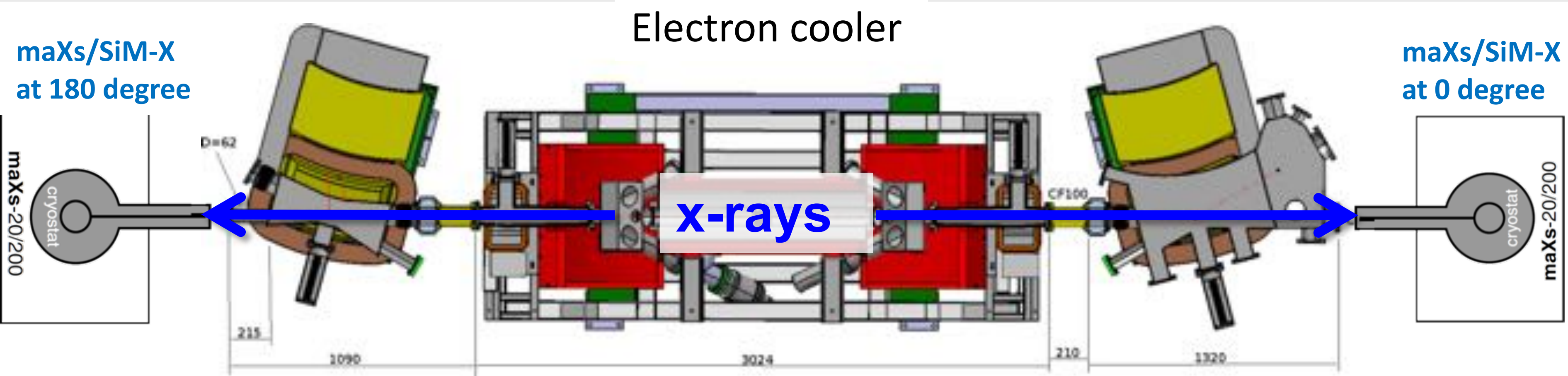
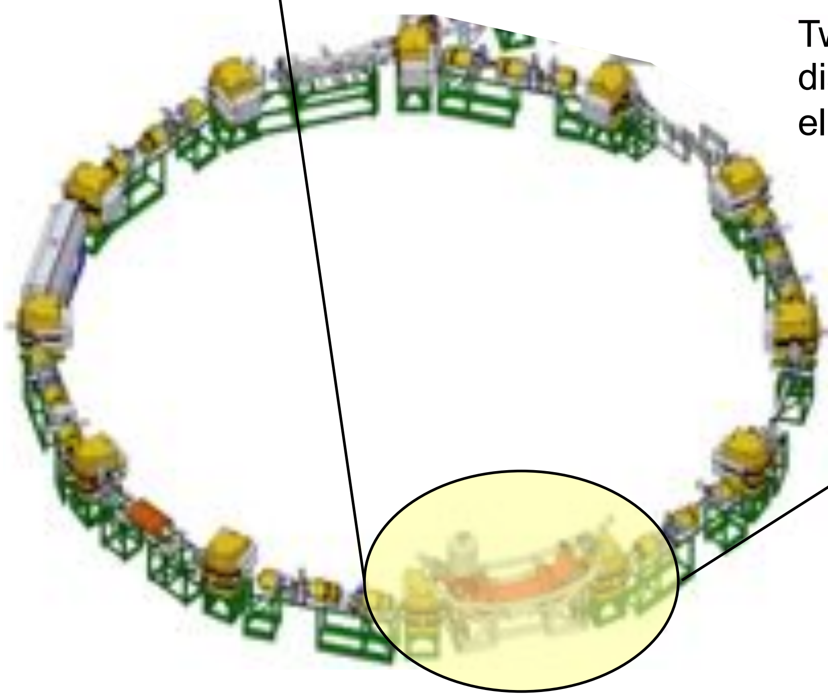
E138: 1s Lamb Shift in U^{91+}





Two microcalorimeters, each at a distance of roughly 3 m from the electron cooler region.

Basic parameters

Active area: 1 cm^2

FWHM @ 60 keV
30 to 50 eV

Absorption eff.@ 100 keV
50% to 75%

total efficiency
0.5×10^{-6}

Operation temperature
50 mK

FAIR Storage Rings

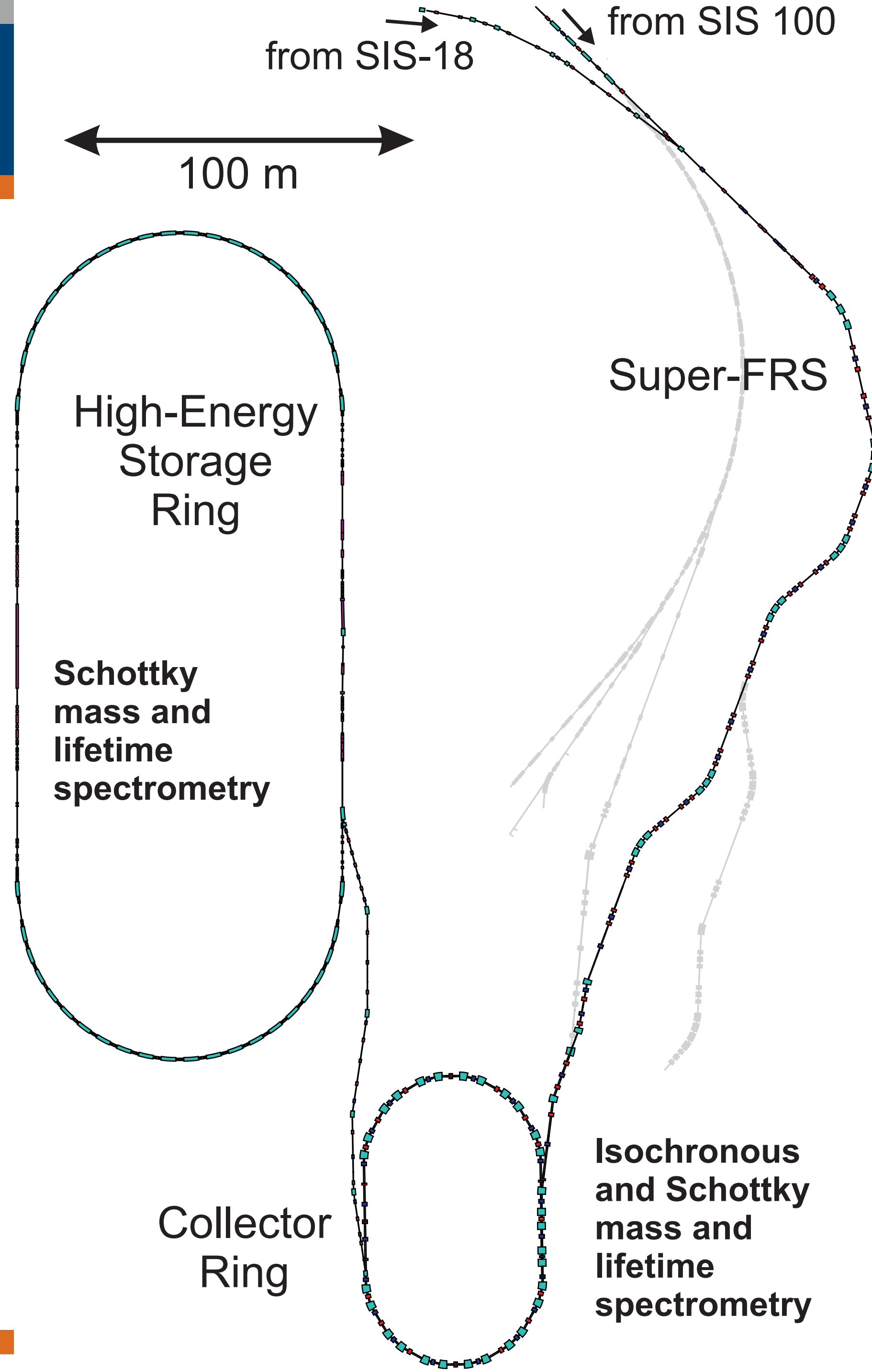
NUSTAR

ILIMA Isomeric Beams, Lifetimes and Masses

EXL Exotic nuclei studied in light-ion induced reactions at the NESR storage ring Experiment

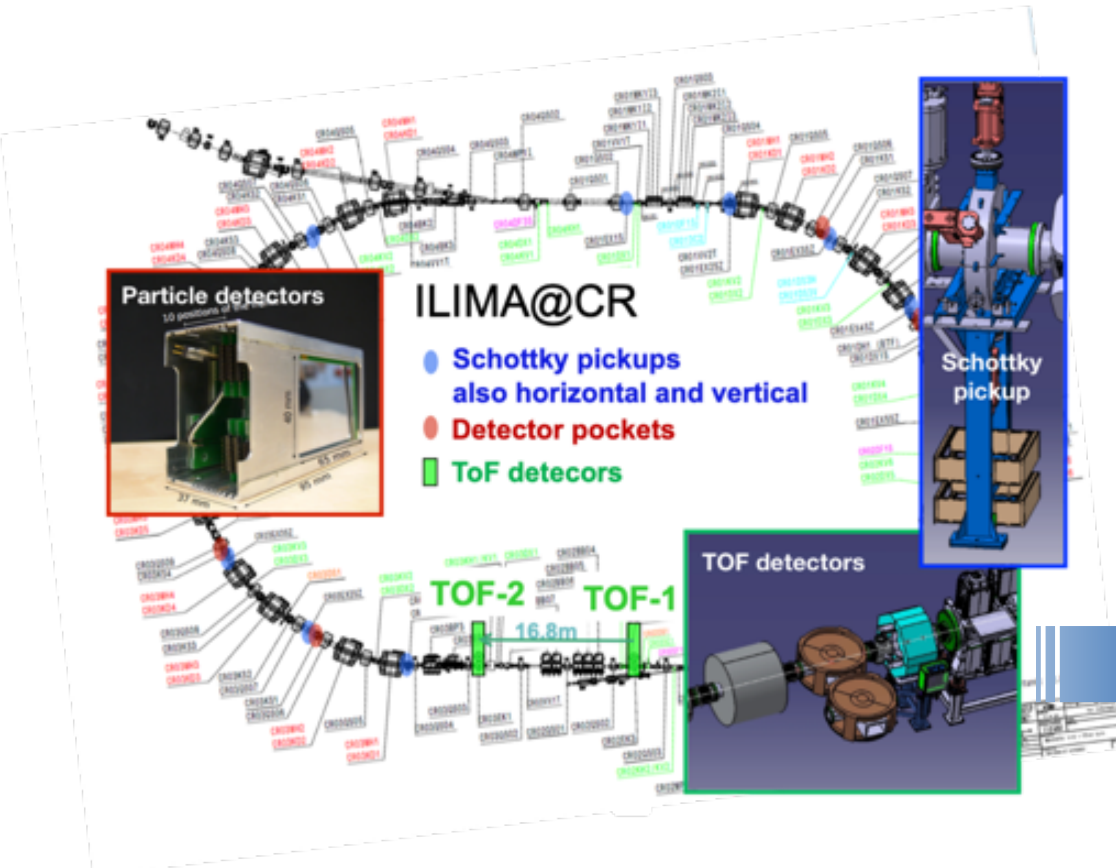
SPARC

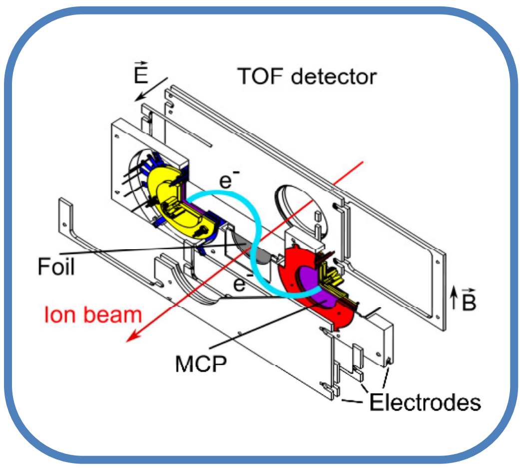
PANDA



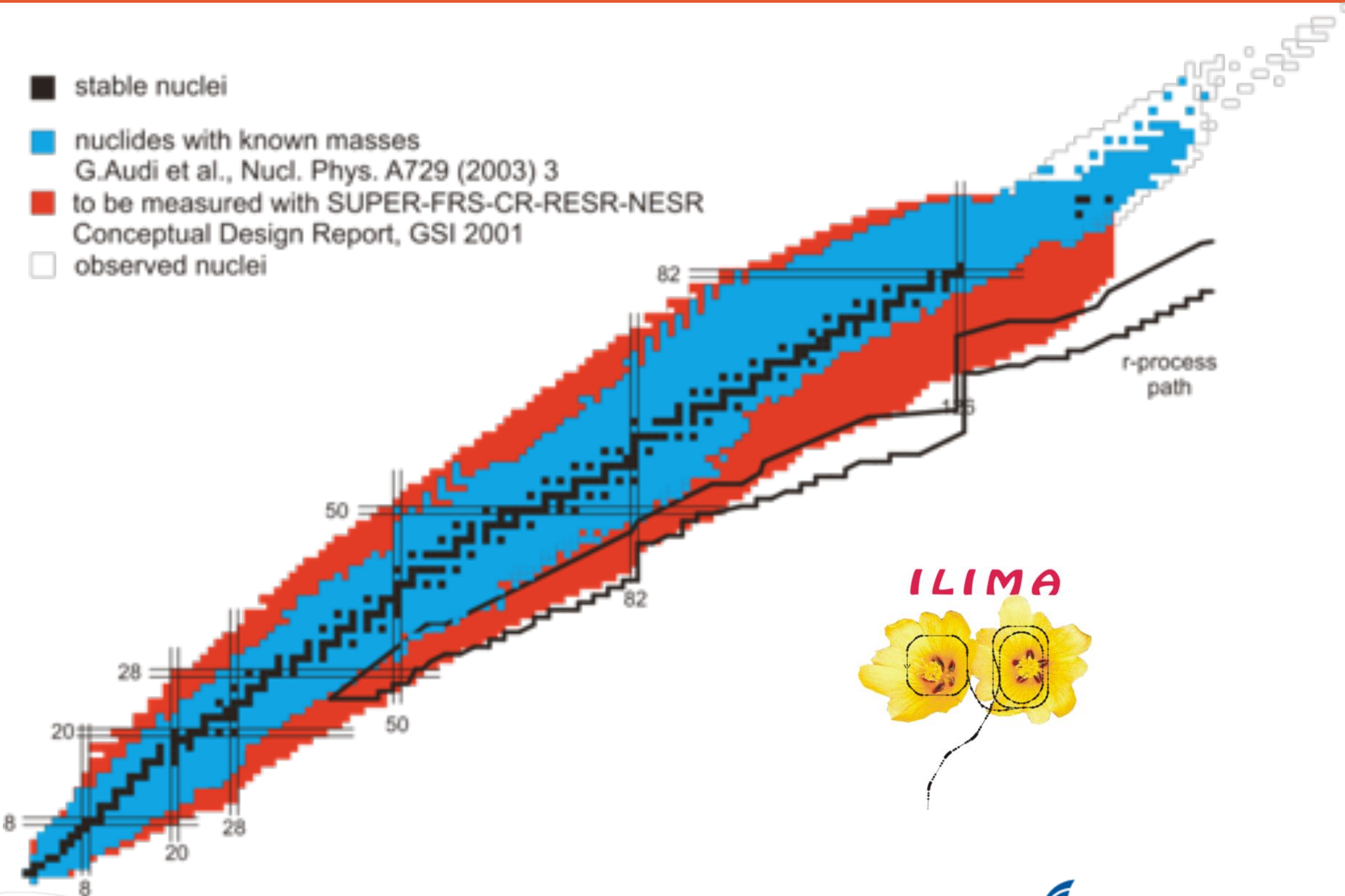
ILIMA in Collector Ring

Isochronous Mass Spectrometry
- Time of Flight Detectors
- Ultra-sensitive non-destructive Schottky detectors

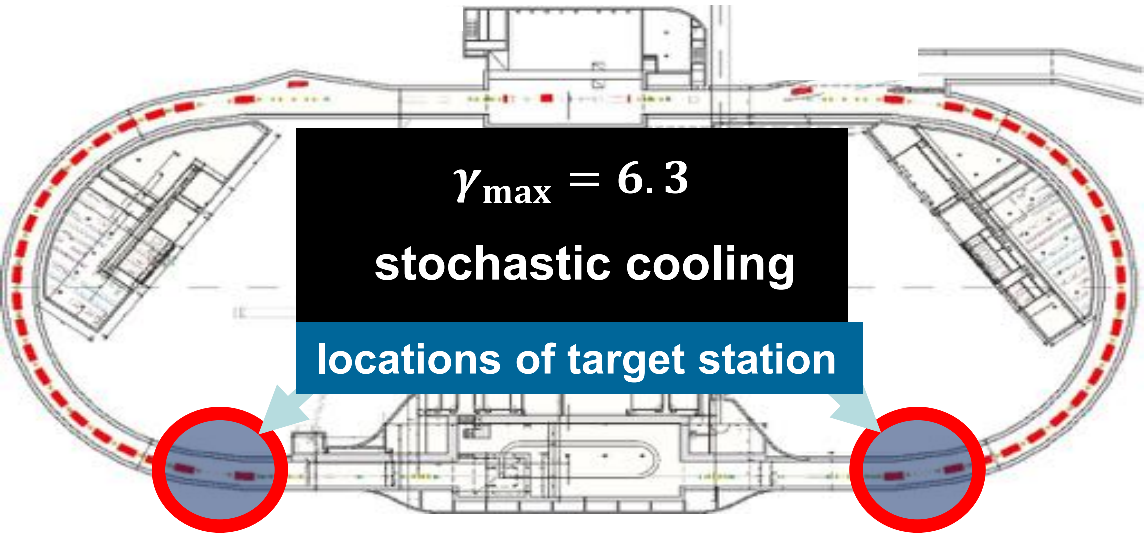


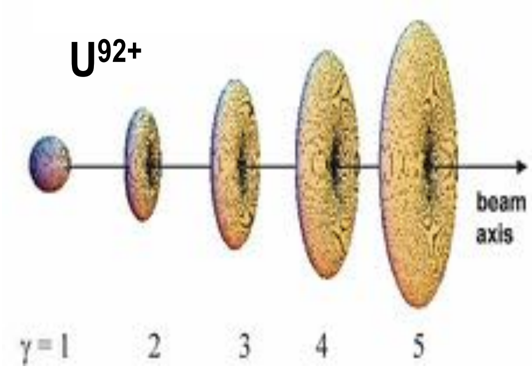


ILIMA: Masses and Lifetimes



FAIR Phase-1: SPARC@HESR





2 TDRs approved in 2016

- species: p, pbar, HCI, RIB
- circumference 574 m
- injection energy 740 MeV/u
- $B\rho$ = 50 Tm
- for U^{92+}: 4.937 GeV/u
- γ_{MAX}=6.30; β_{MAX}=0.987
- momentum (energy) range
  1.5 to 15 GeV/c (0.8-14.1 GeV)
- stochastic cooling / e-cooling

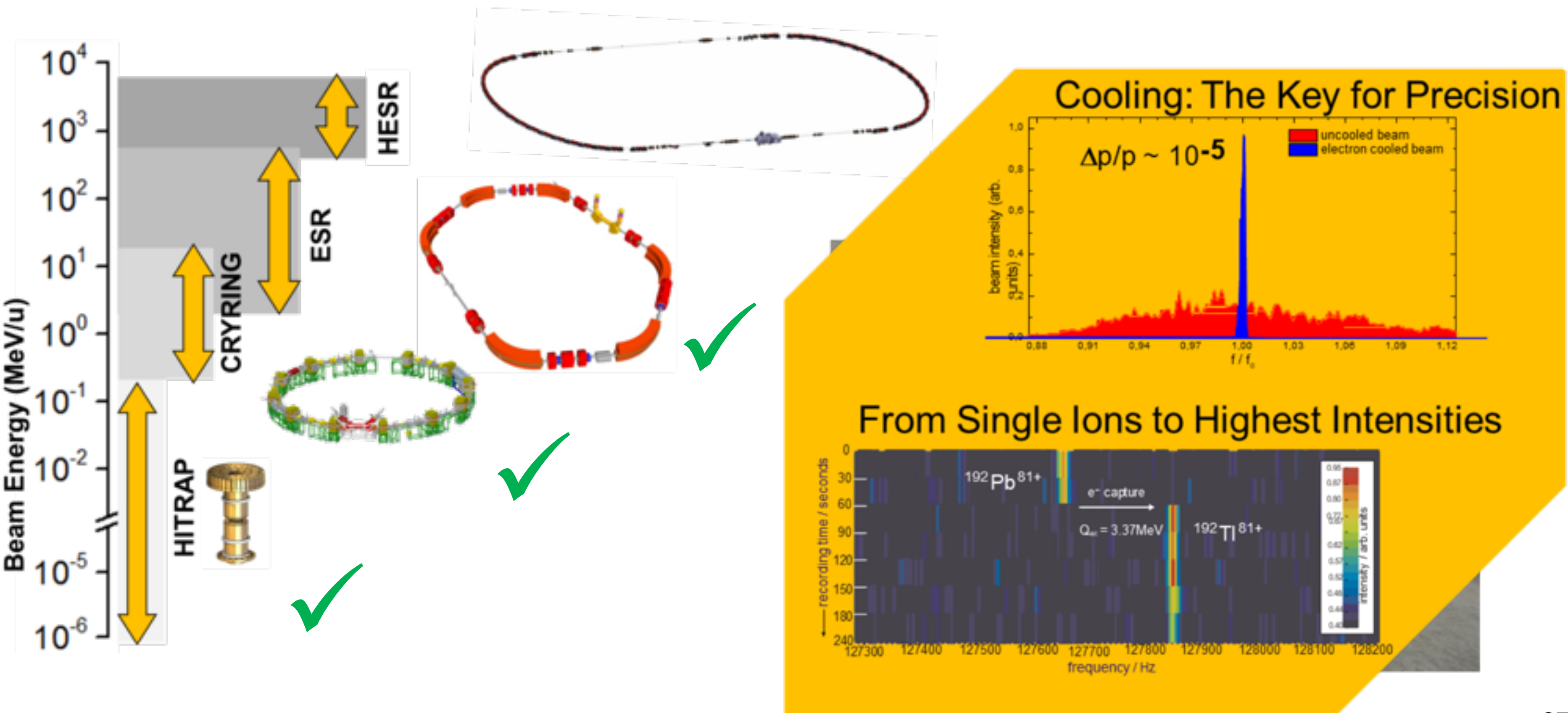
Ion Beam Facilities / Trapping & Storage

Worldwide Unique

Stored and Cooled

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

From Rest to Relativistic Energies (up to 4.9 GeV/u)

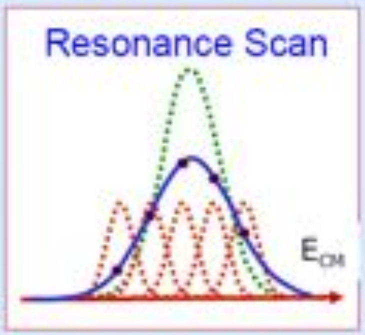


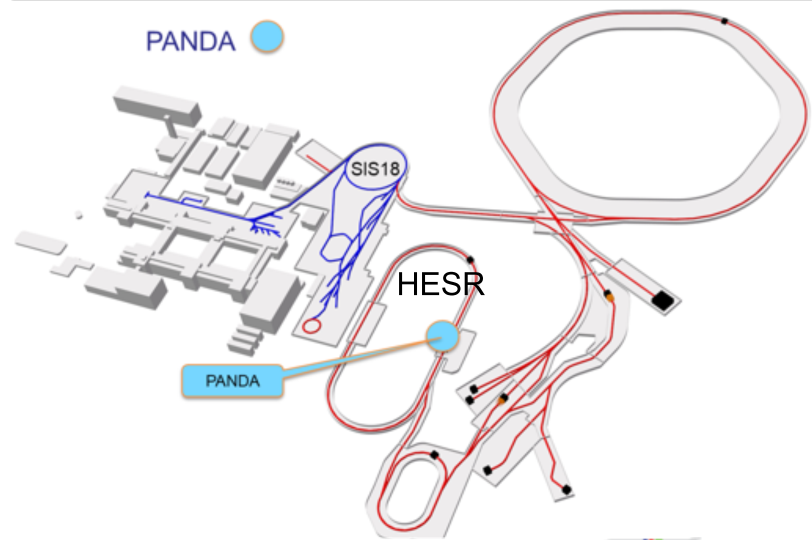
HESR Parameters

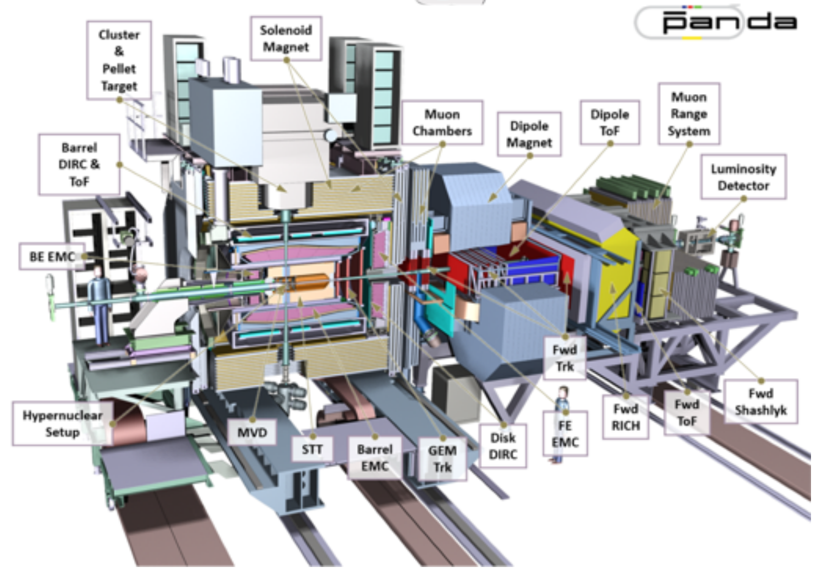
- Storage ring for internal target
- Initially also used for accumulation
- Injection of $\bar{p}$ at 3.7 GeV/c
- Slow synchrotron (1.5-15 GeV/c)
- Luminosity up to L~ 2×10^{32} $cm^{-2}s^{-1}$

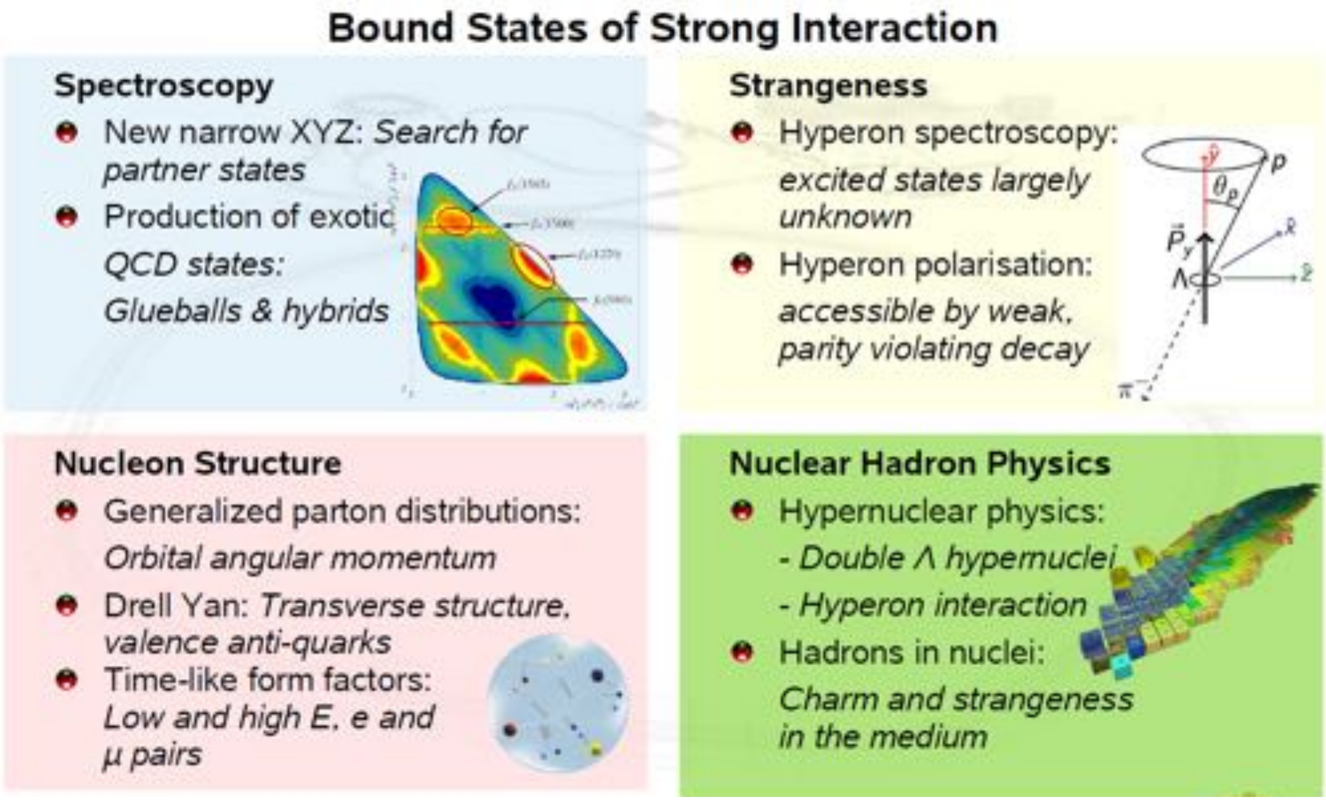
Mode	High luminosity (HL)	High resolution (HR)
$\Delta p/p$	$\sim10^{-4}$	$\sim4\times10^{-5}$
L ($cm^{-2}s^{-1}$)	2×10^{32}	2×10^{31}
Stored $\bar{p}$	10^{11}	10^{10}

- Stochastic & electron cooling
- Resolution ~50 keV
- Tune E_{CM} to probe resonance
- Get precise m and Γ









NUPECC Report

The combination of PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world.

Thank you for your attention!