APPA@FAIR

SPARC — Stored Particles Atomic Physics Research Collaboration

From Basic Science to Applications

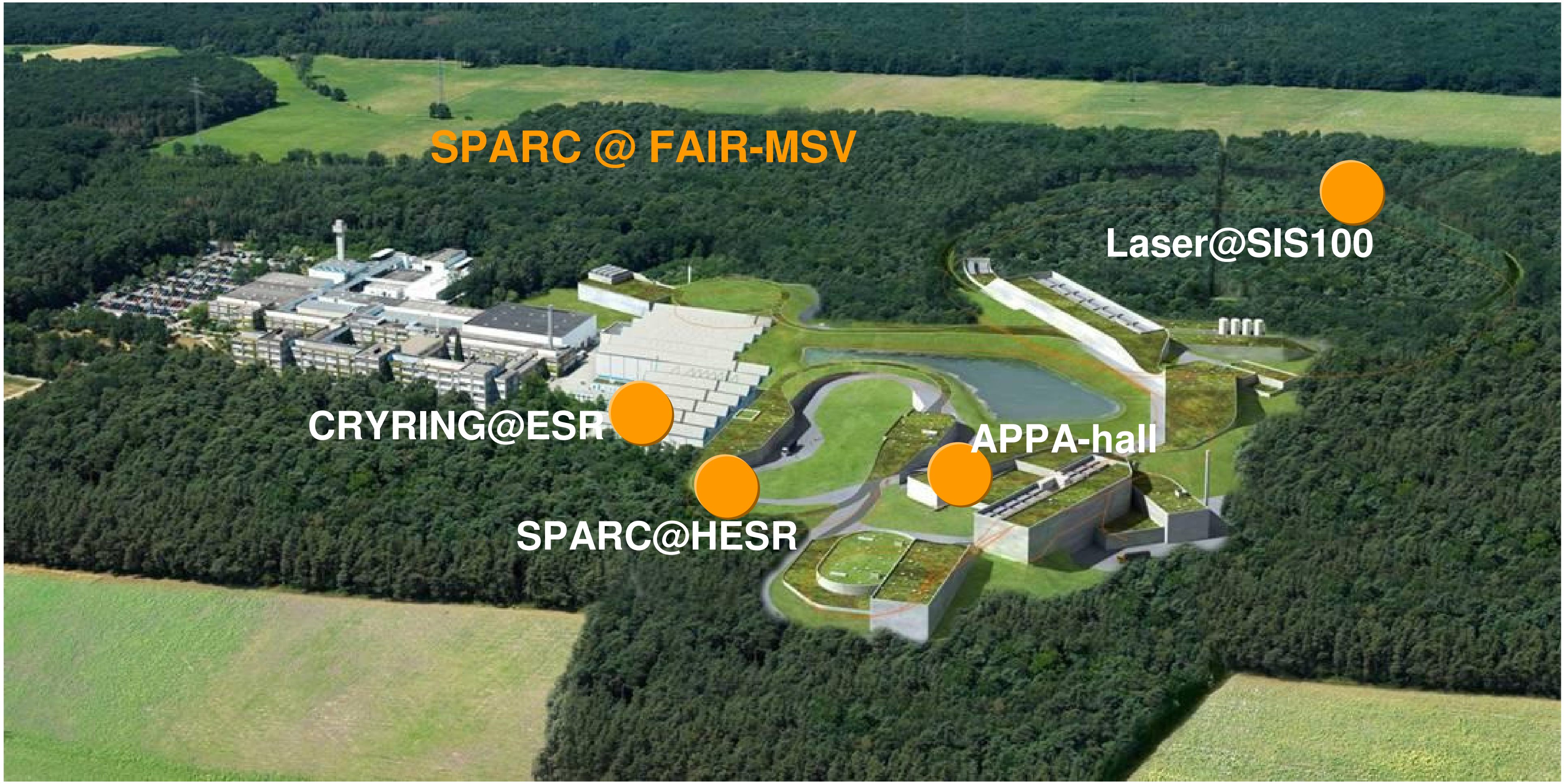
SPARC — Stored Particles Atomic Physics Research Collaboration | FLAIR — Facility for Low-energy Antiproton and Ion Research | HED geHOB | BIO*MAT

Highest Charge States	***Extreme Static Fields***
Relativistic Energies	***Extreme Dynamical Fields and Ultrashort Pulses***
High Intensities	***Very High Energy Densities and Pressures***
High Charge at Low Velocity	***Large Energy Deposition***
Low-Energy Anti-Protons	***Antimatter Research***

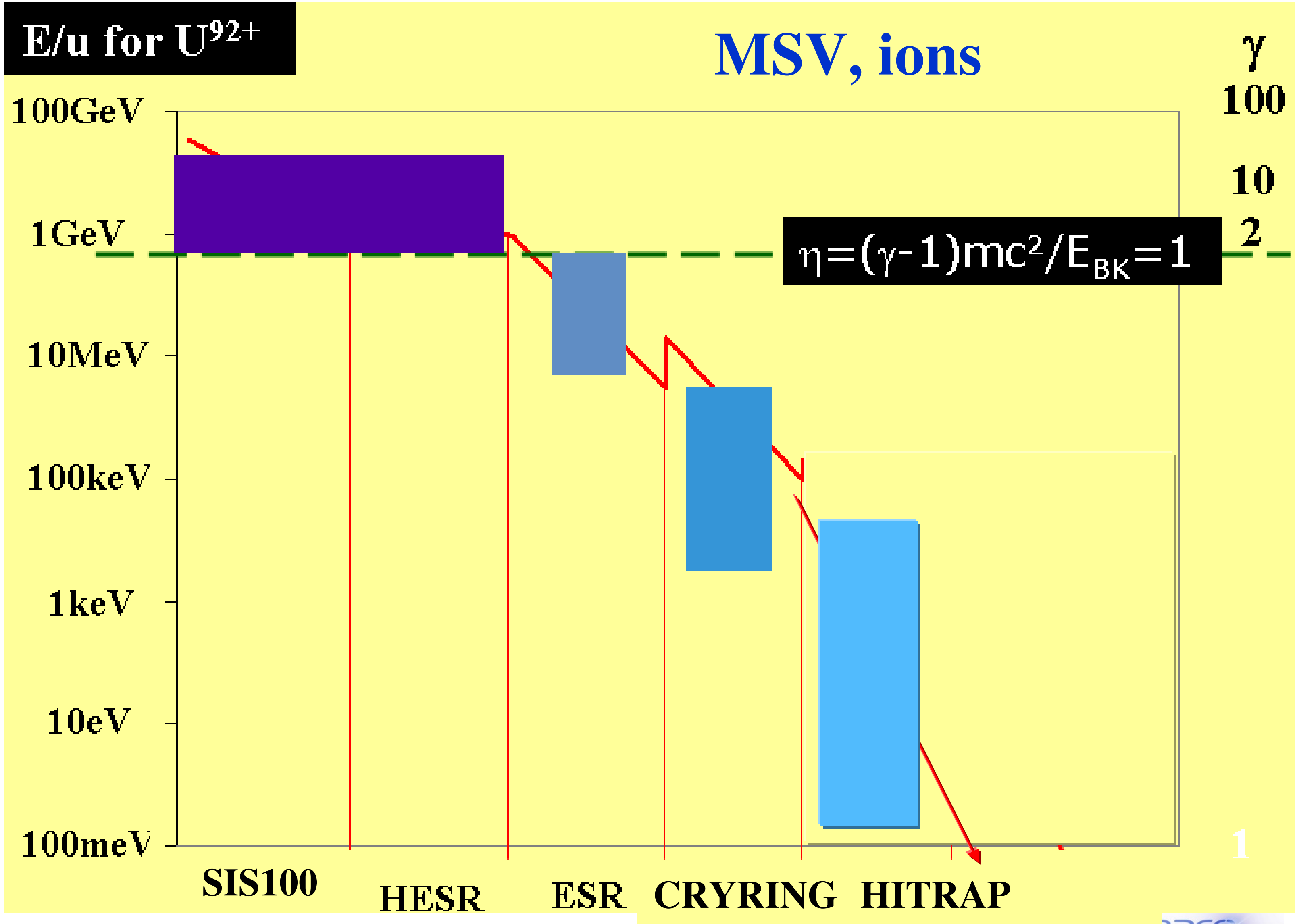
Atomic Physics SPARC & FLAIR (Facility for Low-energy Antiproton and Ion Research)

Reinhold Schuch (for SPARC Collaboration) *FLAIR workshop Heidelberg, 15.-16. 5. 2014*

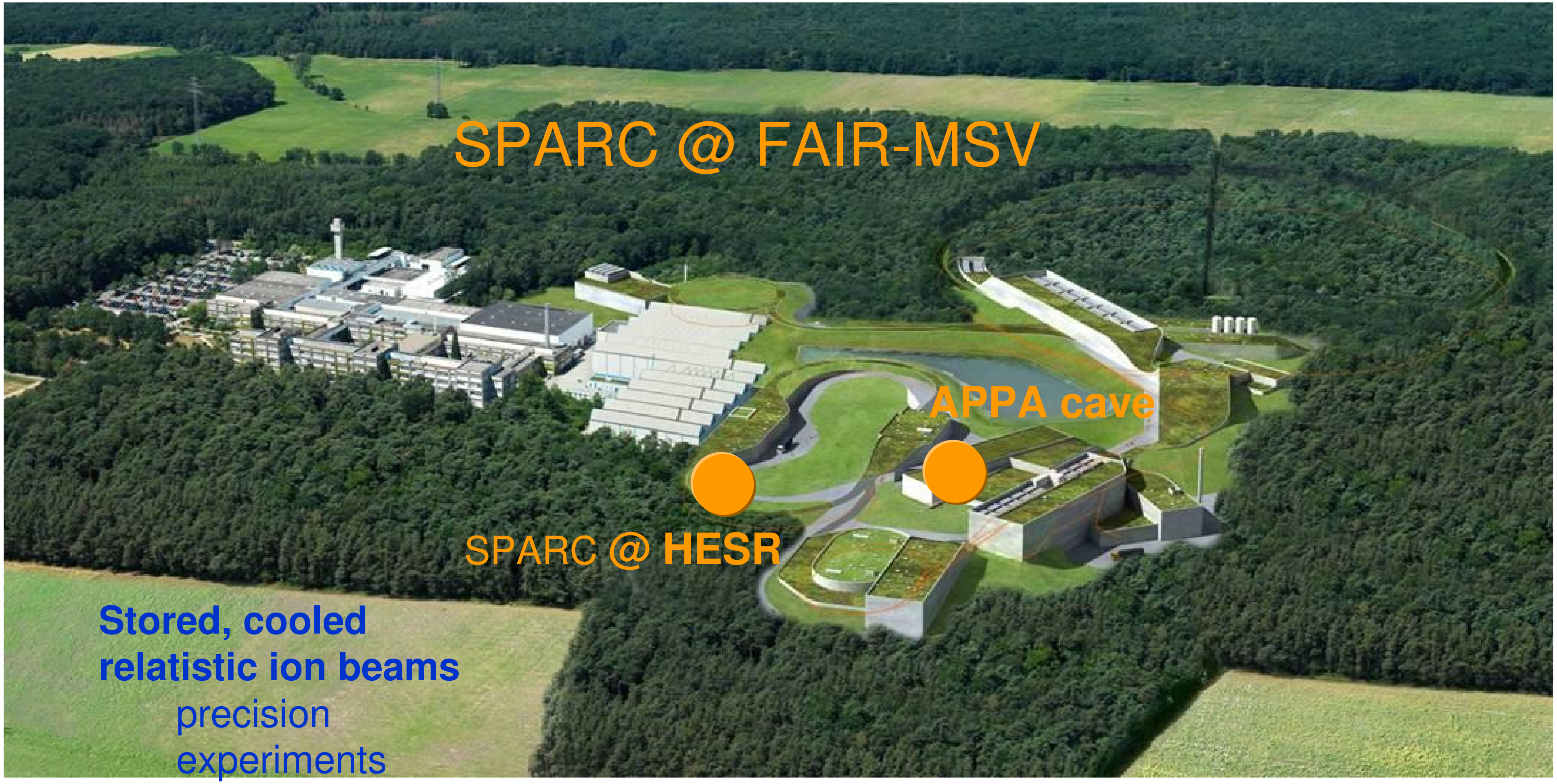
FAIR Modular start version



SPARC Energy range @FAIR

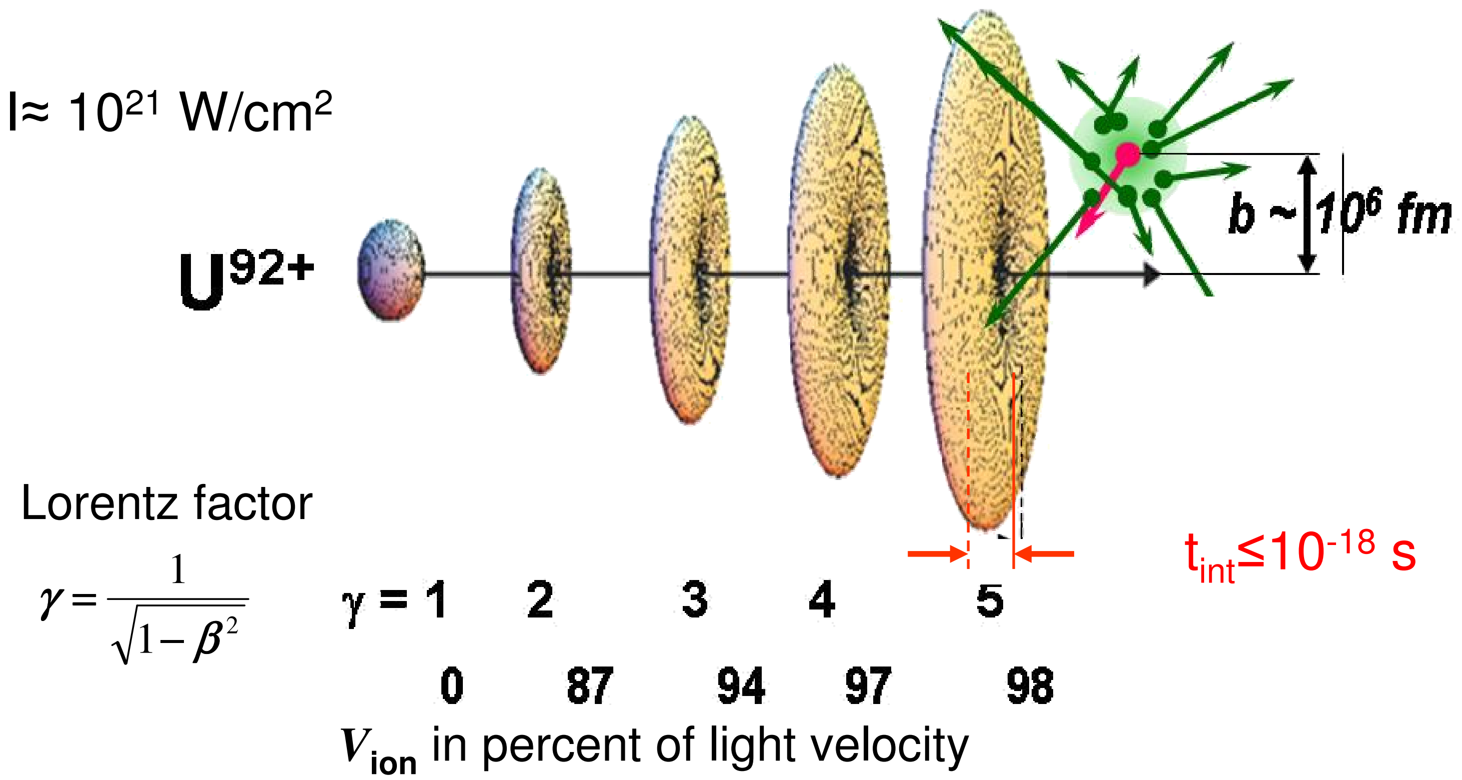


SPARC High Energy experimental areas



Stored, cooled
relatistic ion beams
precision
experiments
at high luminosity

(Ultra) Relativistic highly charged ions

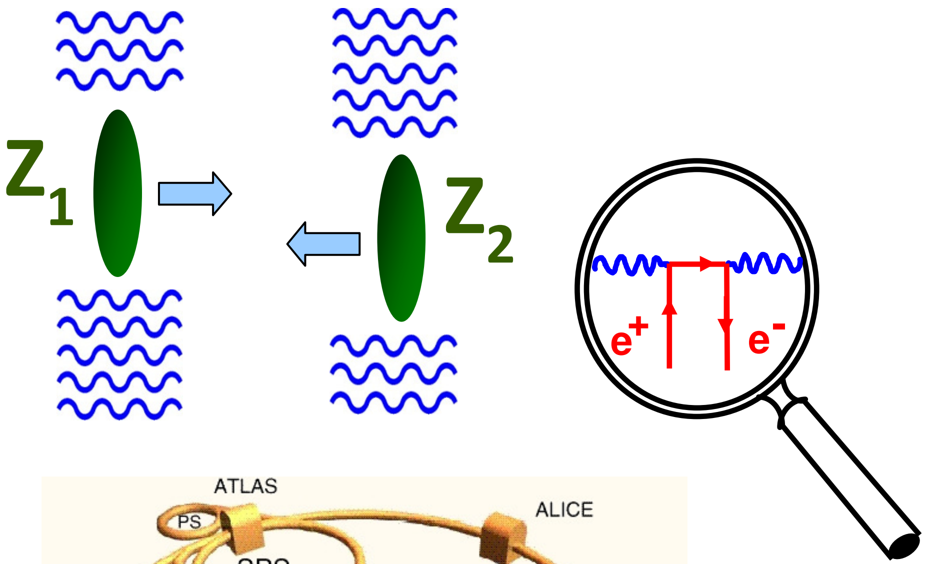


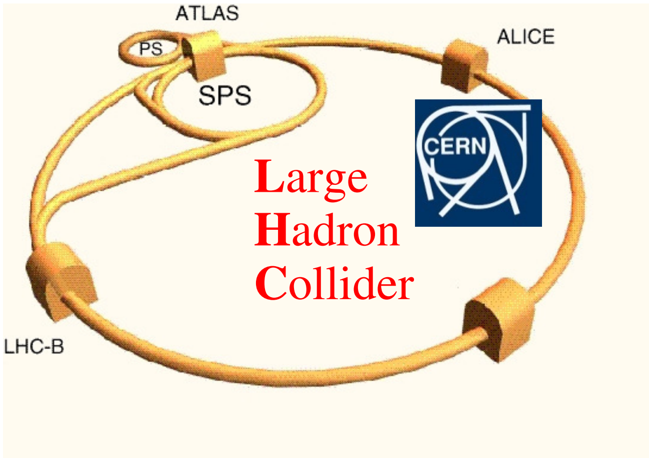
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

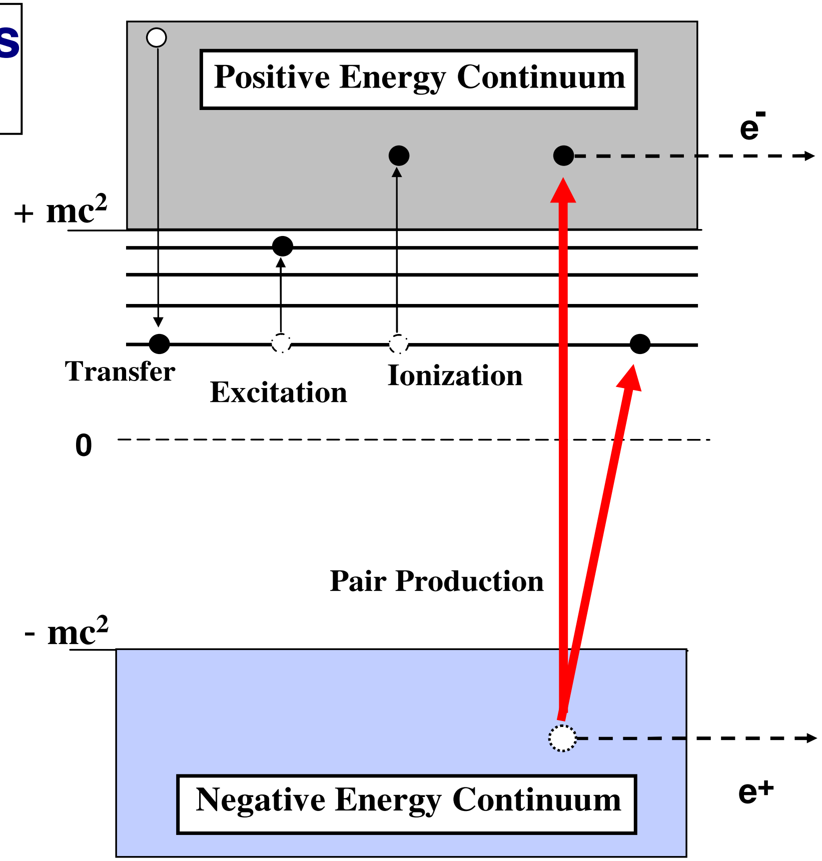
- ***Intense fields → Equivalent photon field created by relativistic ions***
- **Extreme EM fields, ultrashort and almost no momentum transfer. Ideal for tracking the correlated motion of bound electrons**

(Ultra) Relativistic Ion-Atom Collisions

- **Dynamically induced strong fields result in exotic atomic processes**





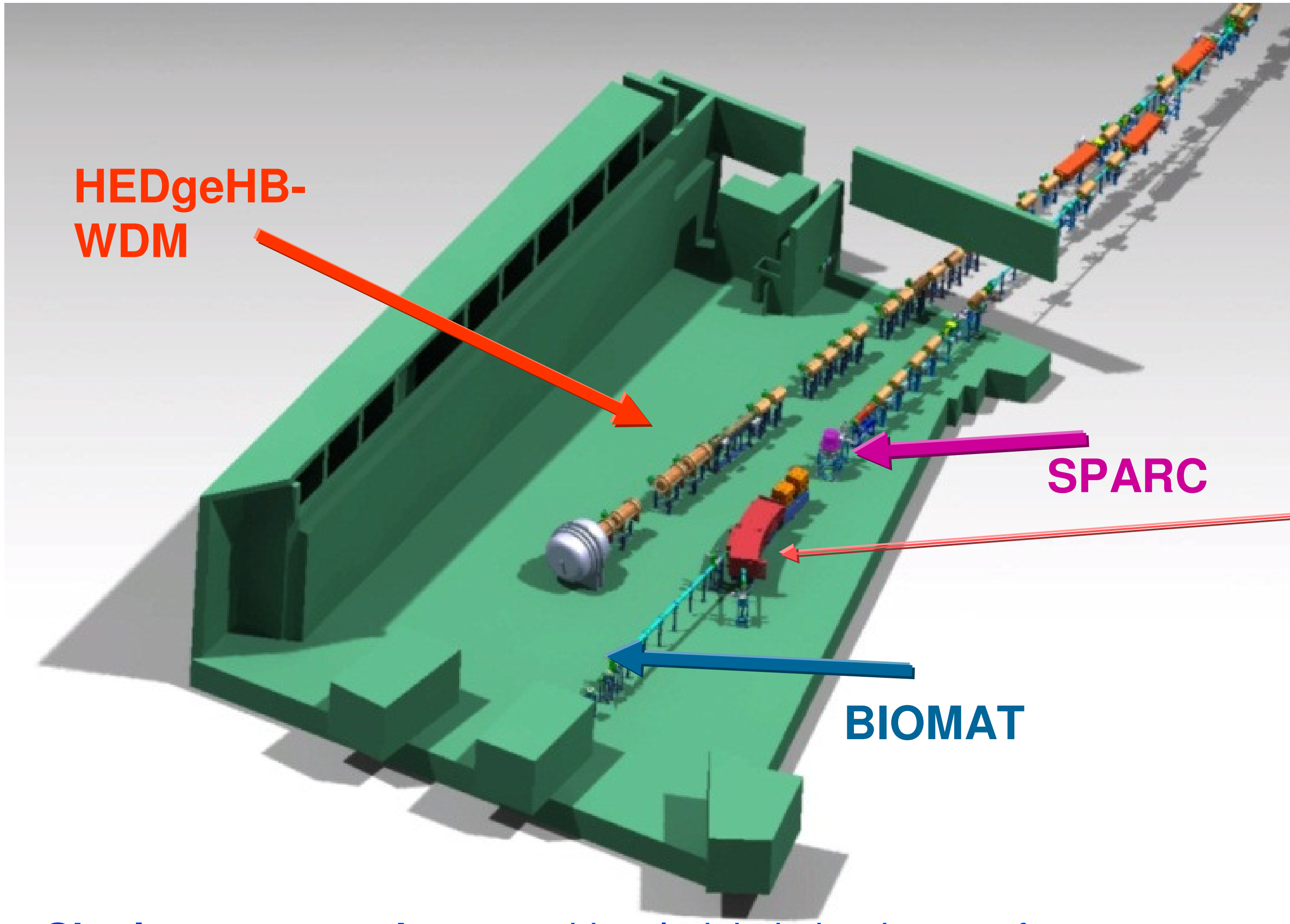


- Bound-free pair production limits the luminosity of the LHC

CERN Courier ***47*** *(2007) 7*

APPA cave: a multipurpose experimental area

…for experiments of all APPA collaborations: **SPARC**, **BIOMAT** and **HEDgeHOB-WDM**



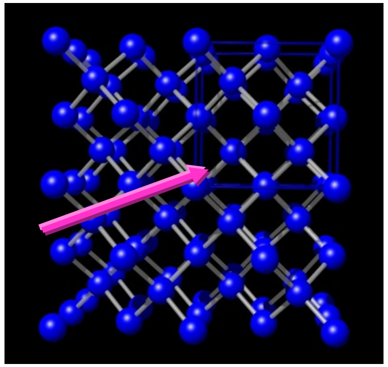
SPARC installations:

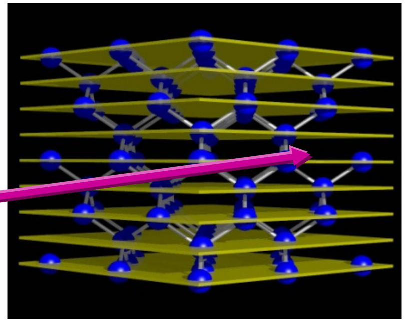
- ✓ a large interaction chamber (1 m diameter) equiped with a high-precision goniometer
- ✓ a charge state separator for ion with Bρ ≤ 18 Tm (E_{ion}≤1 GeV/u for Uranium 92+)
- ✓ Photon detectors: x-ray and gamma
- ✓ Position sensitive ion detector (CVD Diamond-based)

Single-pass experiments with relativistic ion beams from SIS18 and SIS100 : 0.1 GeV ≤ E_{ion} ≤10 GeV pulsed and 'dc' beams

Atomic and nuclear spectroscopy via RCE

<100> axis d= 1.6 Å





<110> axis d= 3.3 Å

Crystal lattice, d ≈ 10^{-10} m

Ion velocity, v: close to c, 10^{8} m/s

$\nu \approx v/d = 10^{18}$ Hz

X-ray range: 5÷20 keV

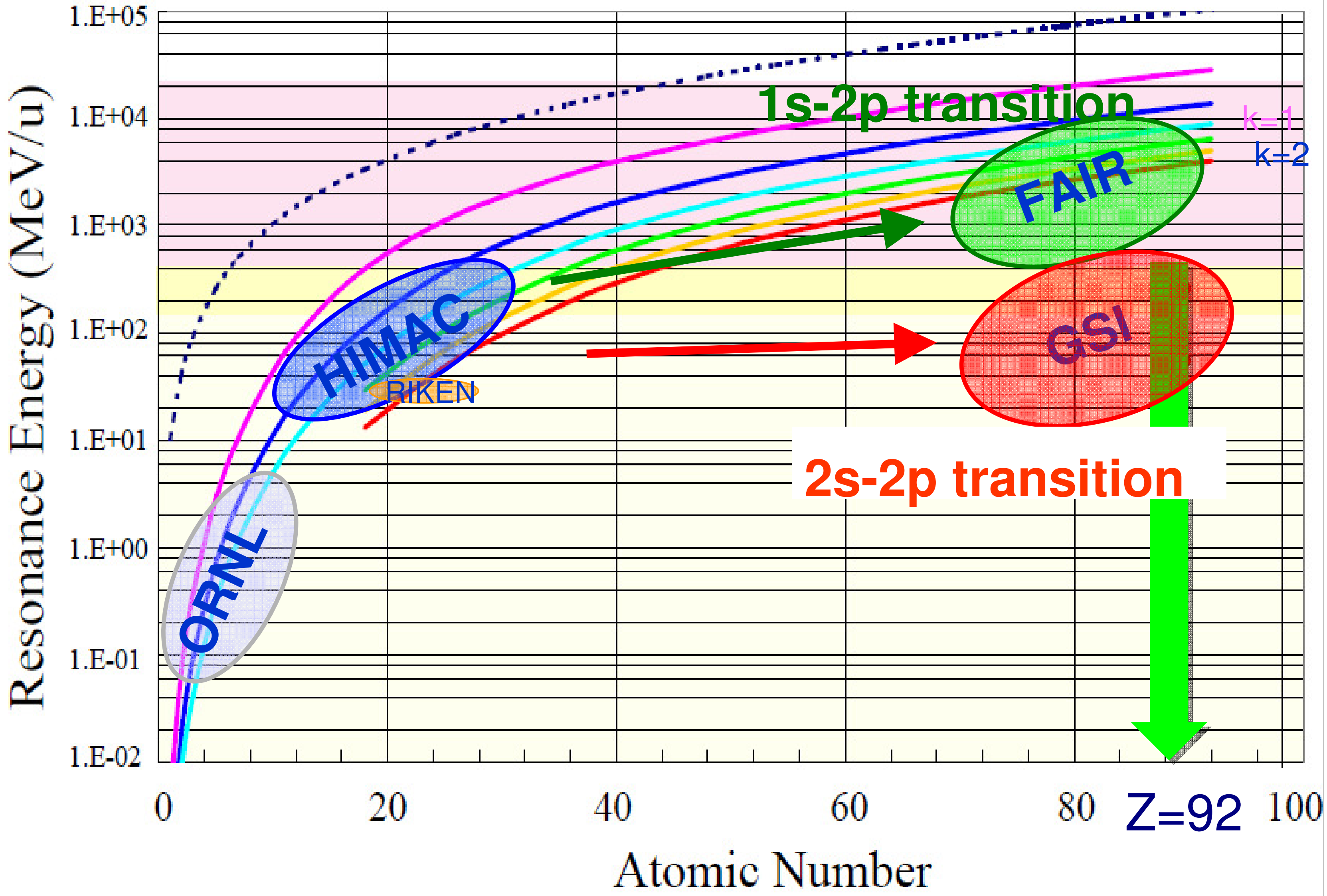
$$E_{trans} = h\nu = h\gamma\langle g . v\rangle \qquad \mathbf{g}_{k,l,m} = k\mathbf{A}^{*} + l\mathbf{B}^{*} + m\mathbf{C}^{*},$$

reciprocal lattice vector

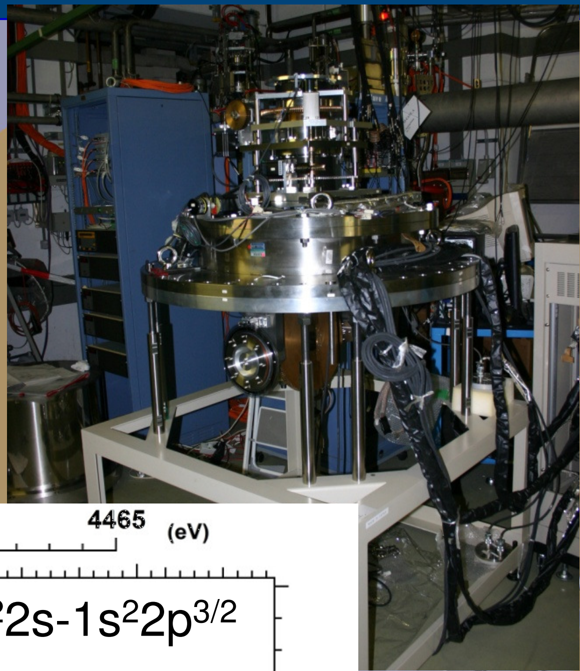
Frequencies of virtual field oscillations

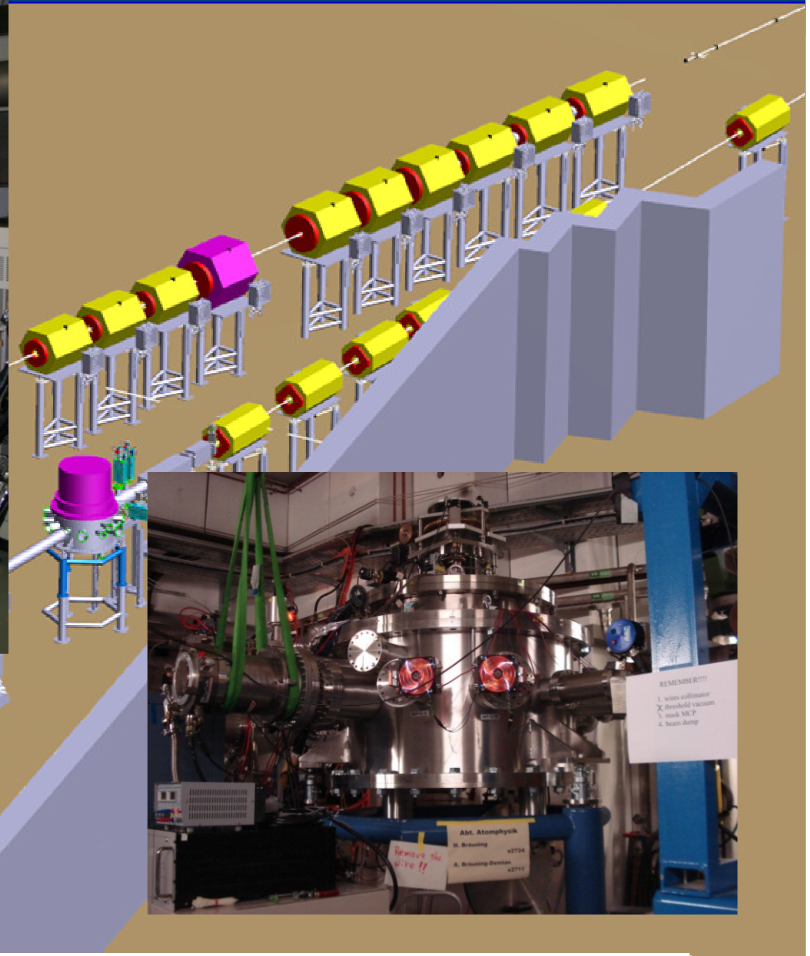
$$\begin{aligned} \nu_{k,l,m}(\theta,\phi) &= \gamma \mathbf{g}_{k,l,m} \cdot \mathbf{v} \\ &= \frac{\gamma v}{\mathbf{d}}\{(\sqrt{2}k\cos\phi + \sqrt{2}m\sin\phi)\cos\theta + l\sin\theta\}, \end{aligned}$$

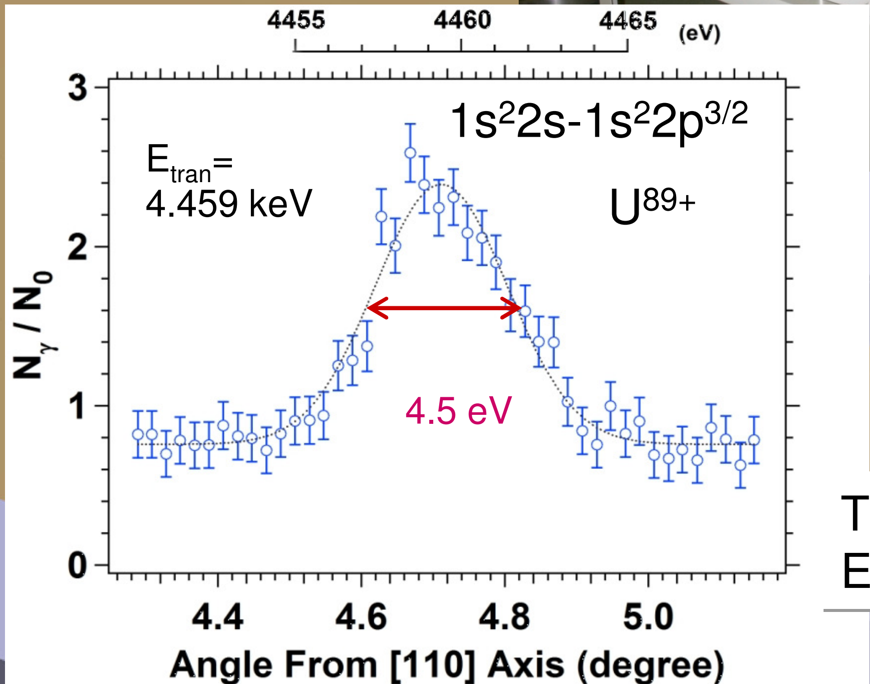
Atomic spectroscopy via RCE



APPA hall setup for RCE experiments



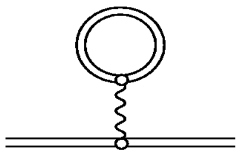


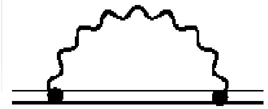


Test experiment performed at SIS 18 and ESR

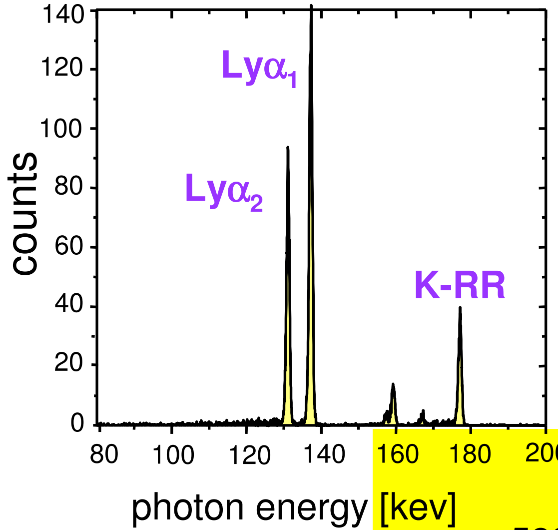
In collaboration with RIKEN and Tokyo University

Test of QED in Strong Field by X-Ray Spectroscopy





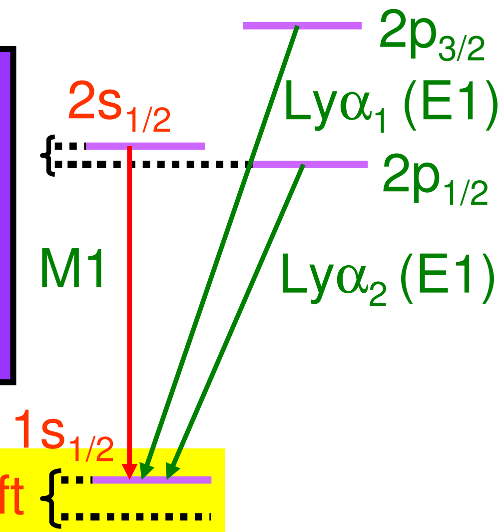
1s-LS in H-like Uranium

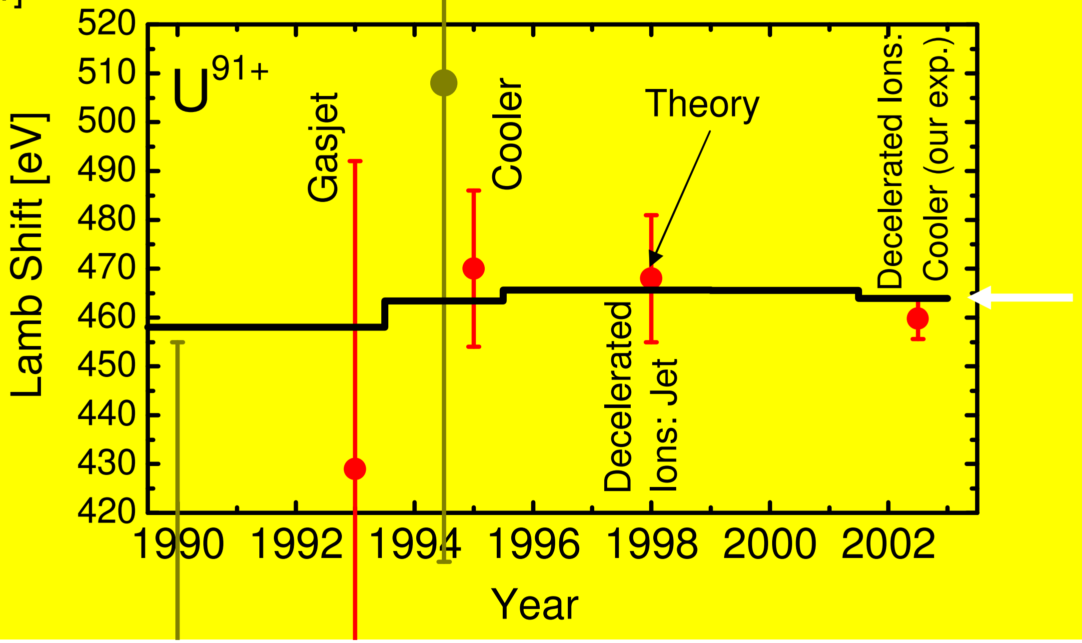


1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV





exp. Stöhlker et al

theor Soff et al.

RCE perspectives with relativistic HCI at FAIR

The ion energy range at SIS100 will permit :

- **1s → 2p** excitations in heavier ions
- **Coulomb excitation of nuclear levels** (this phenomenon was not yet observed due to the non availability of the high energy (~ GeV/u) ion beams. DE $_{fi}$ ~ 100 keV)

Could be done for:

1. stable nuclei: for the 45 KeV level of ^{236}**U** and for the 14.4 keV level of ^{57}**Fe**
2. metastable nuclei with lower level separation (<10 keV) and t > 1 ms

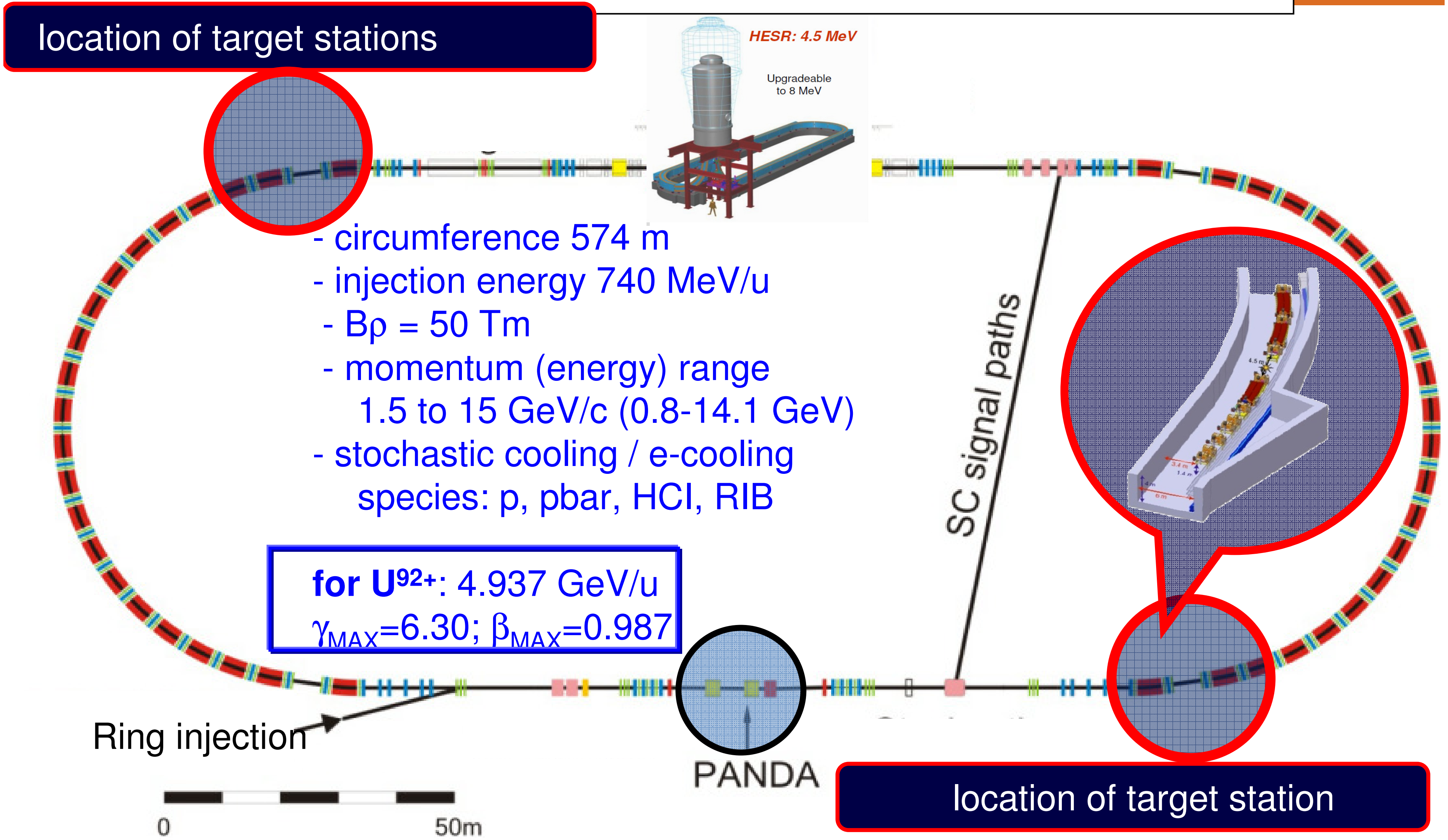
Possibly the Day 1 Experiment

Challenges: ion cooling at relativistic energies

•good emittance

•small divergence ⇒ **RCE in HESR**

SPARC experiments at HESR



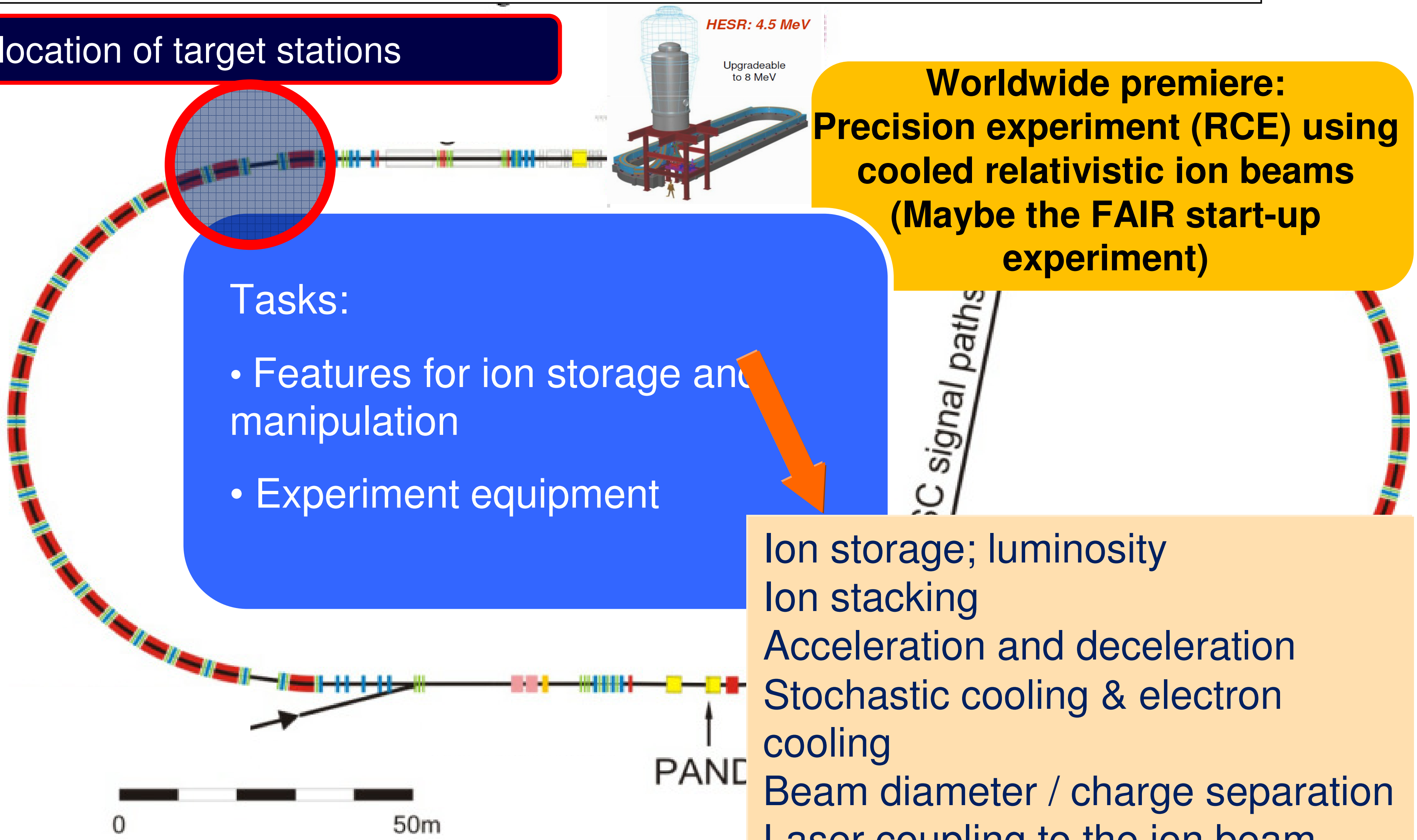
- circumference 574 m
- injection energy 740 MeV/u
- Bρ = 50 Tm
- momentum (energy) range
  1.5 to 15 GeV/c (0.8-14.1 GeV)
- stochastic cooling / e-cooling
  species: p, pbar, HCI, RIB

for U^{92+}: 4.937 GeV/u
γ_{MAX}=6.30; β_{MAX}=0.987

SPARC experiments at HESR

location of target stations

Worldwide premiere: Precision experiment (RCE) using cooled relativistic ion beams (Maybe the FAIR start-up experiment)



Tasks:

- Features for ion storage and manipulation
- Experiment equipment

Ion storage; luminosity
Ion stacking
Acceleration and deceleration
Stochastic cooling & electron cooling
Beam diameter / charge separation
Laser coupling to the ion beam

Other Experiments at (HESR)

pair-production phenomena
- non-perturbation regime ($\alpha Z_1 \approx \alpha Z_2 \approx 1$)
- multiple pairs
- negative continuum dielectronic recombination

radiative processes
- recombination (polarization phenomena etc.)
- photon-photon angular correlation

target ionization
- correlated electron motion – exploring the ultrafast, extremely strong transient fields of relativistic ions

electron impact phenomena
- electron impact excitation and ionization

bound state QED and nuclear parameters
- laser excitation in Li-like ions ($\Delta n = 0$)

laser Interaction at high γ
- test of special relativity
- laser cooling
- laser assisted pair creation

fundamental physics
- PNC effects in high-Z ions

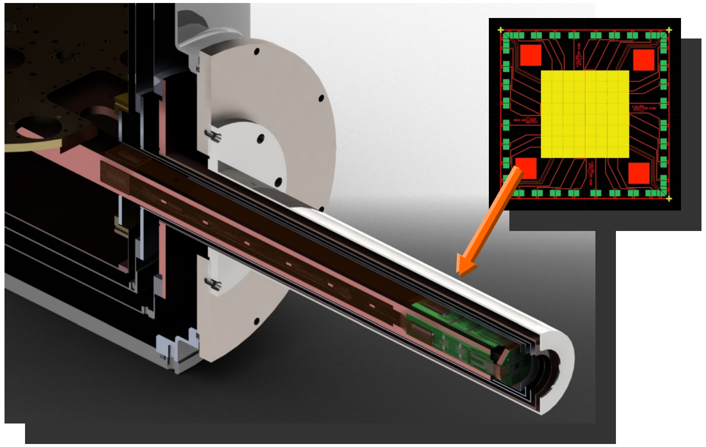
SPARC instrumentation at HESR

Dense internal targets:
electron-, gasjet-, fiber-targets (!)

R. Grisenti et al., Frankfurt U.

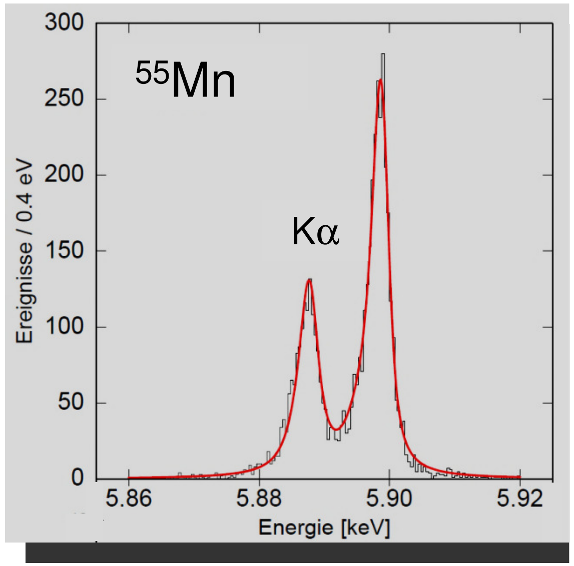
Photon detectors

maXs: micro-calorimeter arrays for hi-res x-ray spectroscopy



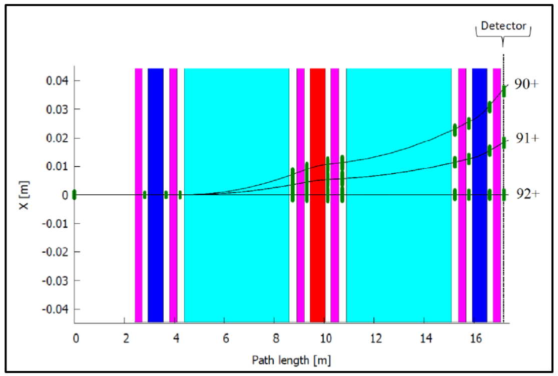
C. Enss, A. Fleischmann, Heidelberg U.

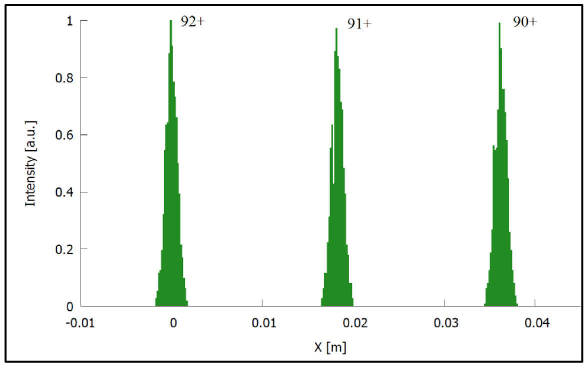
ΔE_{FWHM} **= 1.6 eV** @ 0..6 keV



Ion detectors

O. Kovalenko, Heidelberg U.



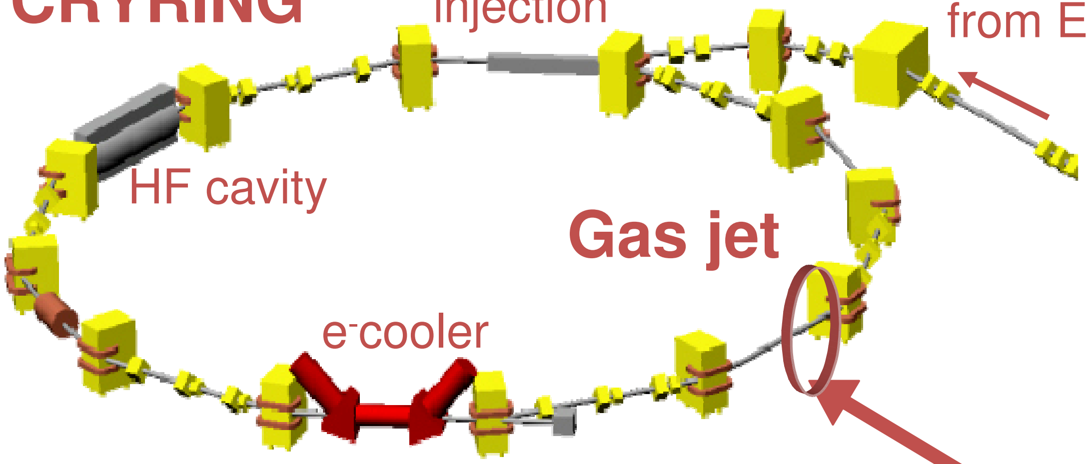


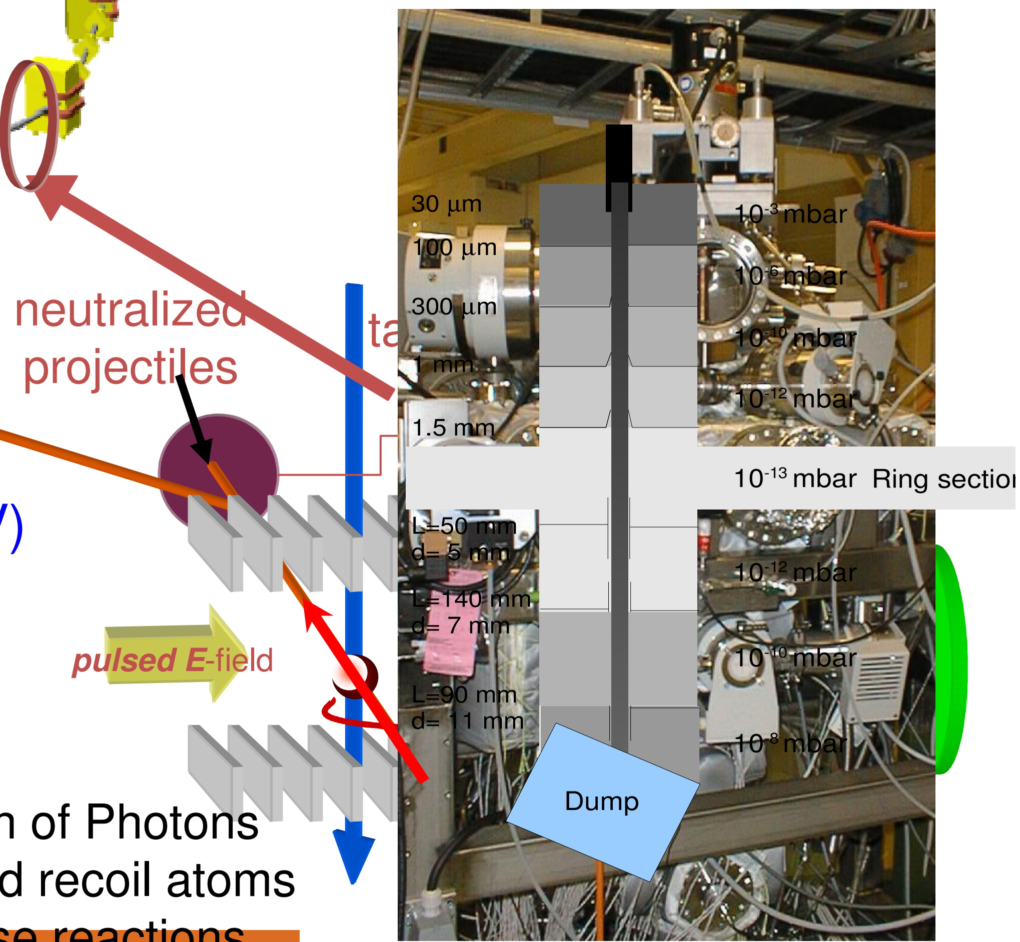
CRYRING

Low Energy Heavy Ion & Antiproton Experiments

- unique experimental capabilities for ion and antimatter research
- commissioning in 2015
- FAIR test facility (stand alone mode)
- development platform of experimental equipment

Spectroscopy at Gasjet of CRYRING





→Intense and narrow ion beam
→Cooled beam diameter ~ 1 mm
→Gas jet diameter ~ 1 mm
→Ultra high vacuum ~10^{-12} Torr (UHV)
→Temp T < 1 K

-> Talks by F. Herfurth, D. Fischer

- QED tests: Almost Doppler-free detection of Photons
- Atomic fragmentation: detect electron and recoil atoms
- Low Energy Nuclear Astrophysics: Inverse reactions

CRYRING@ESR: Highly-Charged Ions at Low Energies

- **Spectroscopy for tests of QED**
  - High-precision x-ray spectroscopy
    - 1s-Lamb-Shift
    - Two-Electron-QED
  - Recoil ion momentum spectroscopy
    - Highly-excited stated
  - Laser spectroscopy
  - Recombination spectroscopy with high resolution
- **Atomic collisions**
  - Sub-femtosecond correlated dynamics
  - Unexplored regime: strong perturbation Q/v
- **Nuclear Physics at low-energies**
  - exotic nuclear decay modes
  - astrophysical reactions

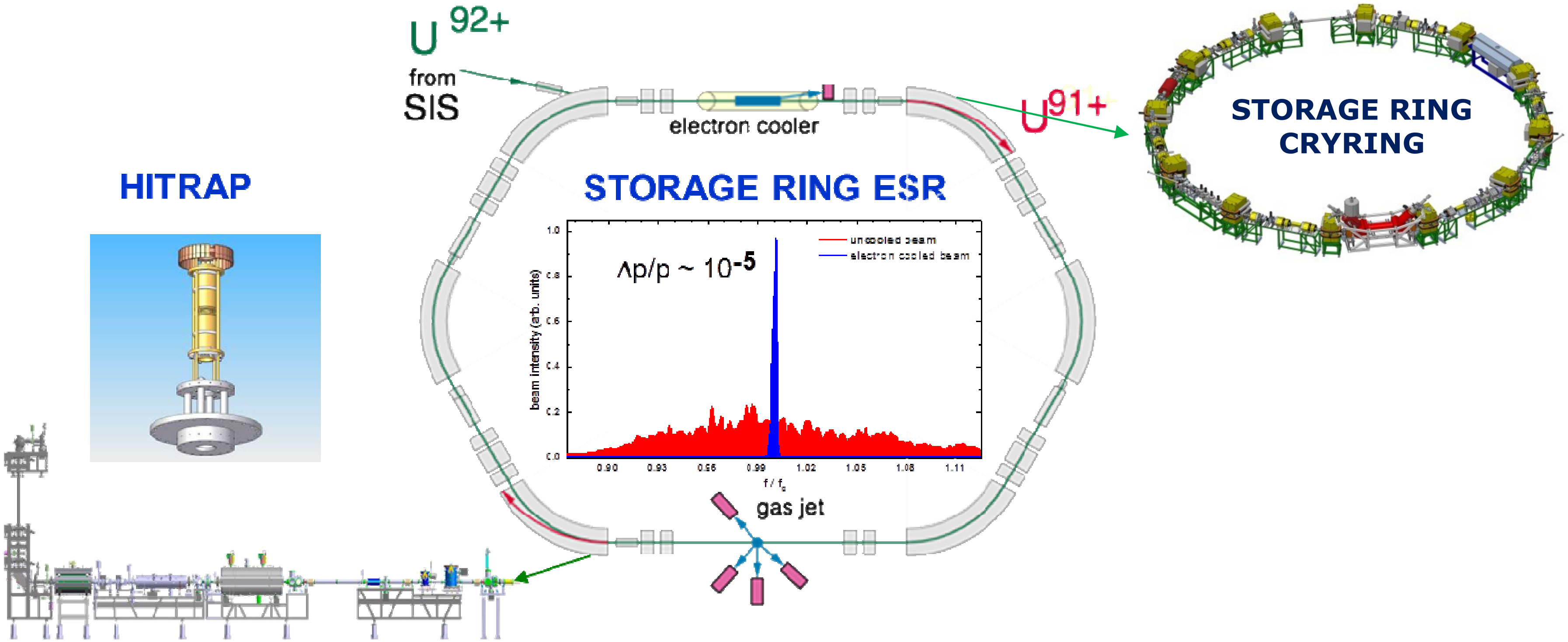
Features@Cryring

- Low-energy and spread, intense high charge ion beams
- Electron cooling with adiabatic expansion 1meV energy spread
- Extremely good vacuum 10^{-12} mb
- High-luminosity for in-ring experiments
- Very fast deceleration 7 T/s
- Internal jet and electron targets
- Slow extraction

(CRYRING & HITRAP)@ESR ➡ FLAIR @ ESR

Slow, heavy, highly charged Ions … stored and always well controlled

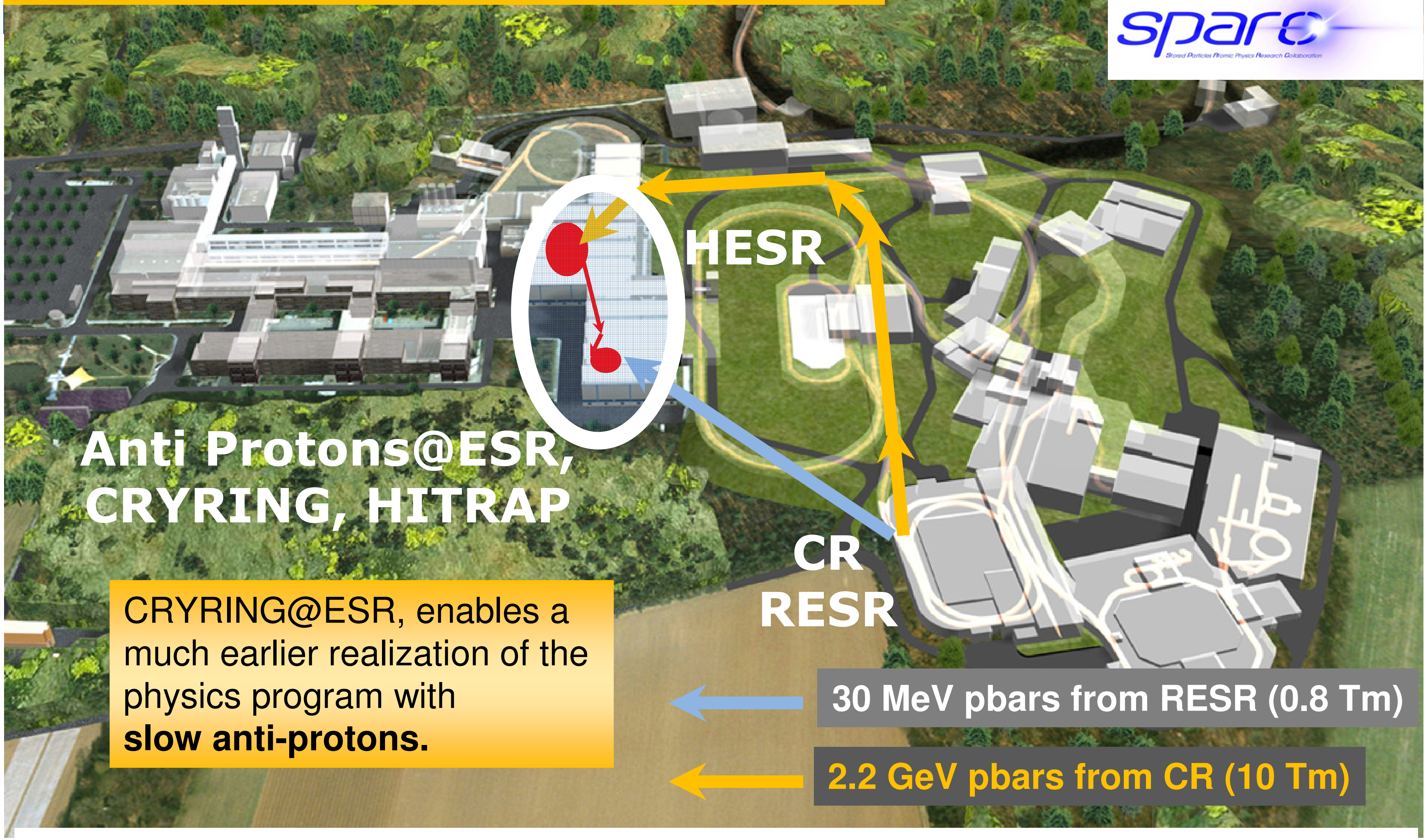
- Energy range between 10 MeV/u <u>to 0.1MeV/u, to sub eV</u>
- 10^5 to 10^7 heavy, highly charged ions like U^{91+}
- Low energy antiprotons in the future



Modularized Start Version of FAIR and beyond

FLAIR
Facility for Low-energy Antiproton and Ion Research

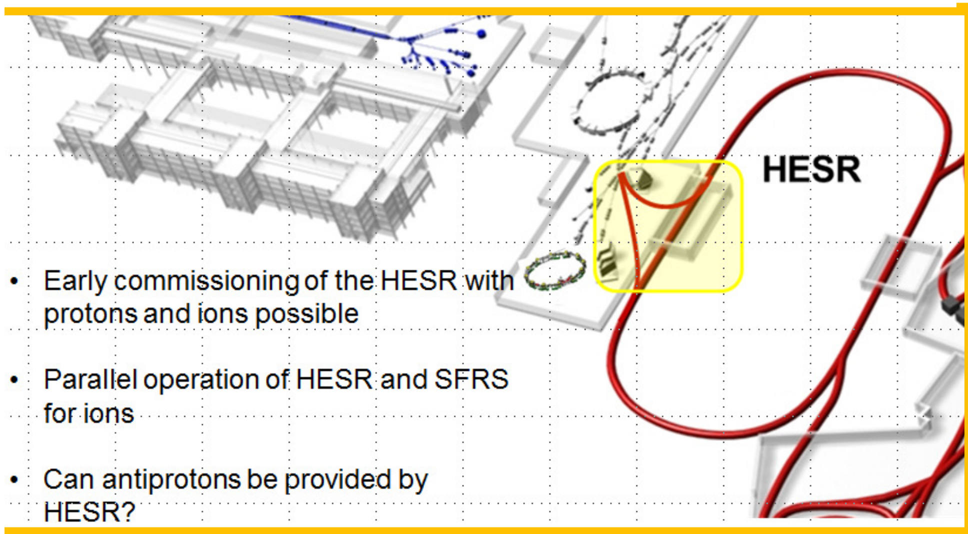
sparc
Stored Particles Atomic Physics Research Collaboration

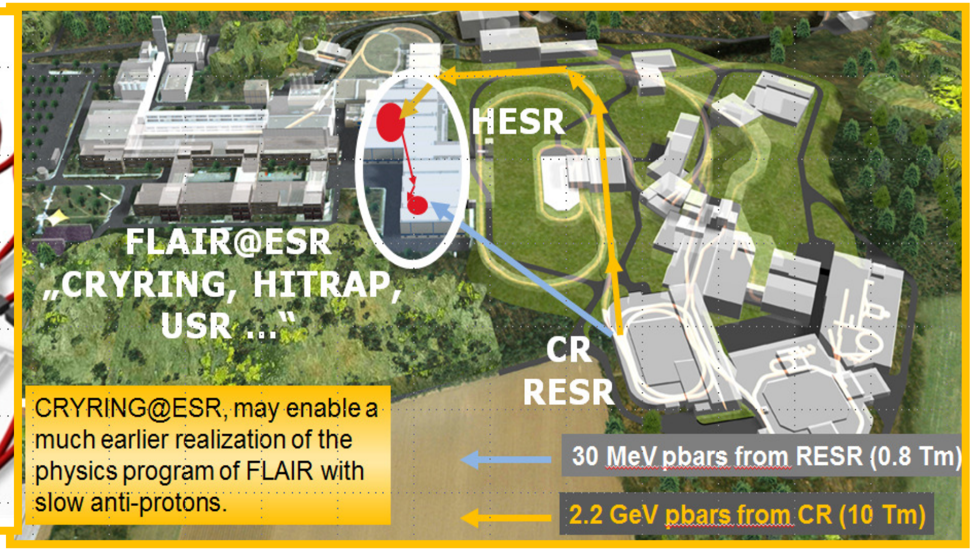


A dedicated Storage Ring Task Force

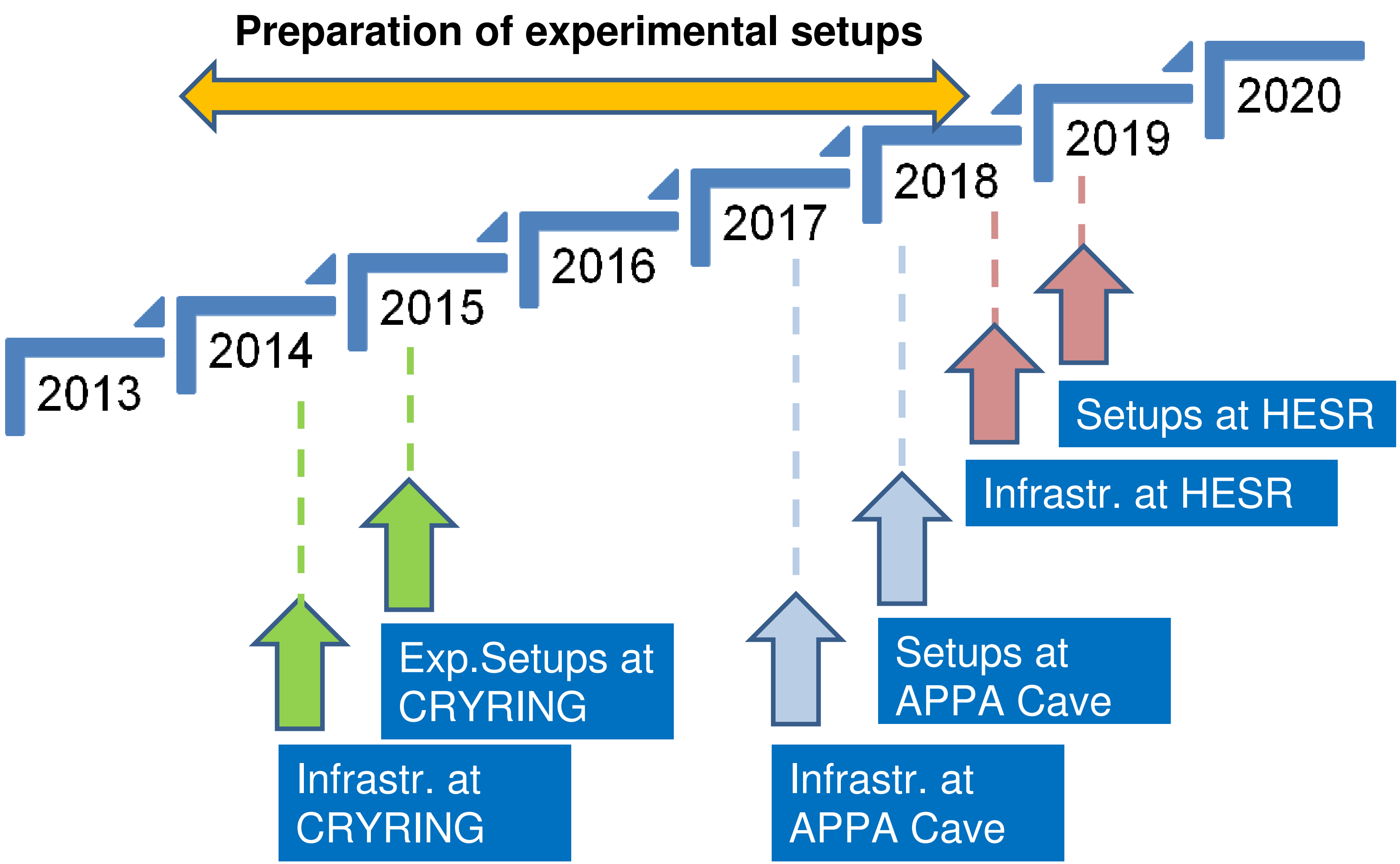
A dedicated Storage Ring Task Force (SRTF) has been formed (October 2013) to investigate possible of option of storage experiments within the MSV of FAIR:

•transfer line between stable and exotic ions from CR to ESR
•transfer of ions to the HESR
•transfer line for pbars from CR to ESR to CRYRING





Timeline: Installation of SPARC setups



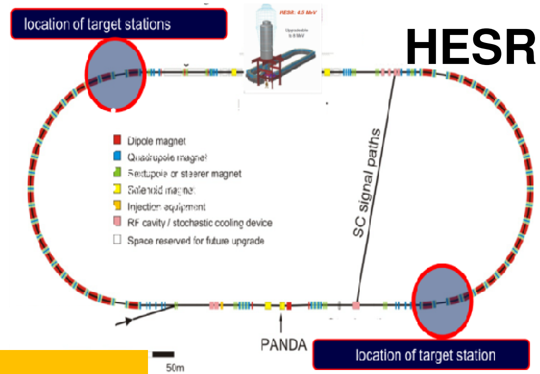
TDRs and Reports of the SPARC & FLAIR Collaborations

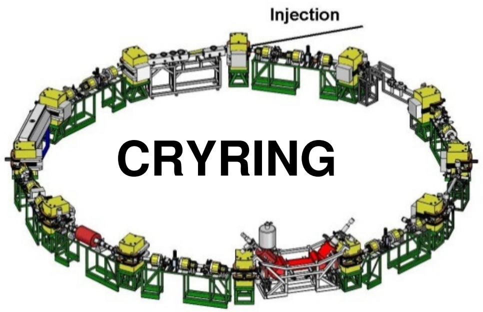
LSR: Technical Design Report

CRYRING@ESR: A study group report

TDR: Internal target station

SPARC experiments at HESR: A feasibility study





TDRs in preparation (2014)

- e^+e^- - spectrometer
- micro-calorimeter
- polarimeters/read-out electronics
- laser infrastructure SIS100
- experiment infrastructure HESR
- experiment infrastructure CRYRING
- channeling @ APPA cave/HESR

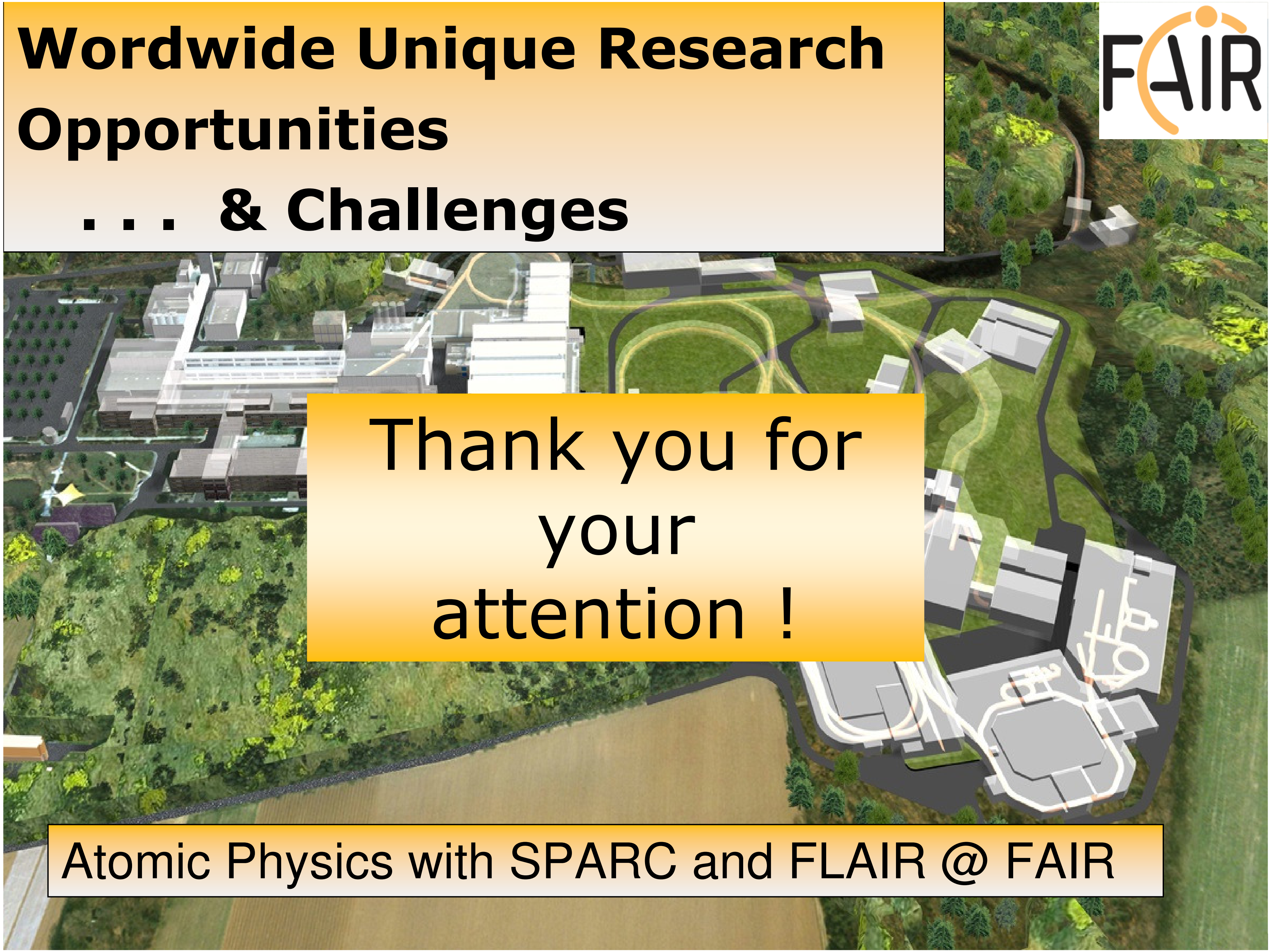
experiment infrastructure APPA cave (together HEDgeHOB und BIOMAT)

SPARC @ FAIR: Summary

- Modularized start version had initially a very significant impact on physics program, timelines, and working packages for SPARC (even more for FLAIR).
- SPARC made a strong move in compensating for this by CRYRING and HESR
- We are now able to contribute significantly to the **Day 1** experiments at FAIR (with CRYING, HESR).
- The instrumentation technologies applied by SPARC are currently progressing very rapidly (e.g. laser, traps, x-ray detectors...).
- Initiatives were started to make RIB and anti-protons available early in the low energy cooler rings and traps.
- Support and financies are needed for these developments

Wordwide Unique Research Opportunities

. . . & Challenges



Thank you for your attention !

Atomic Physics with SPARC and FLAIR @ FAIR