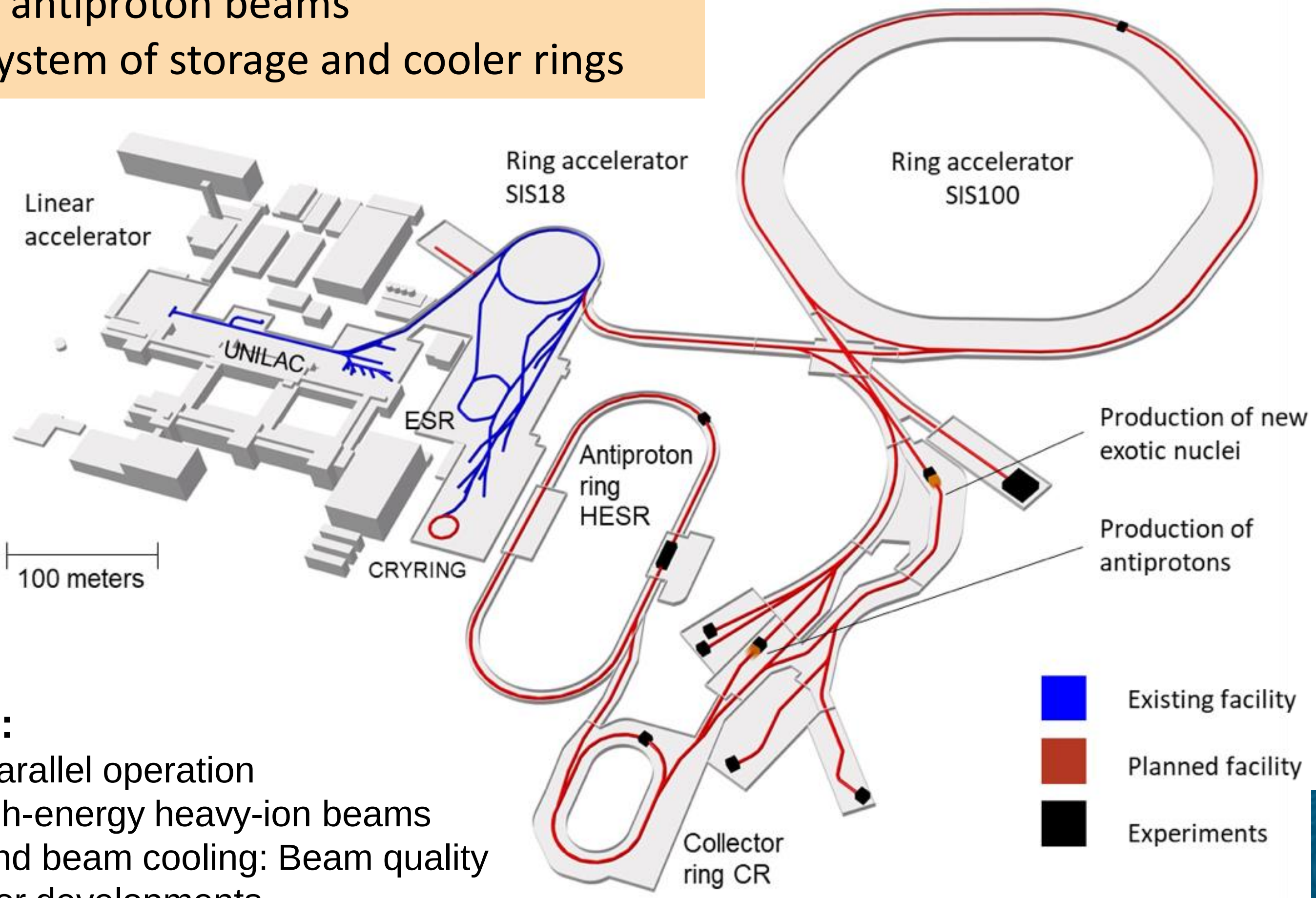
Meeting of the Nuclear Physics
Division Board of the EPS

News from GSI/FAIR/Super-FRS

Haik Simon
Subproject Super-FRS

FAIR – The Facility

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

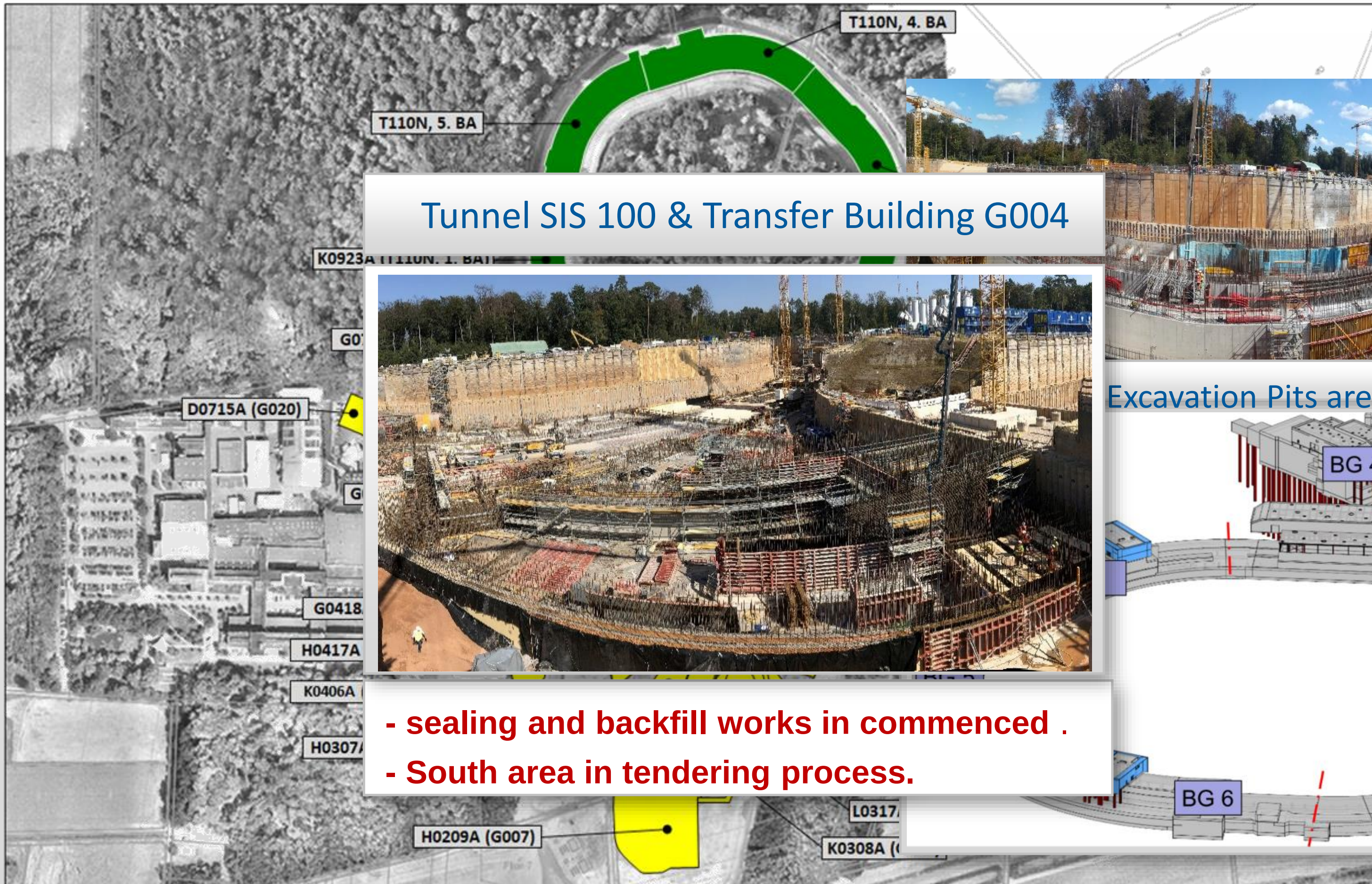


Unique features:

- Flexibility and parallel operation
- **Intense** and high-energy heavy-ion beams
- Storage rings and beam cooling: Beam quality
- Major accelerator developments

FAIR: Status of Civil Construction

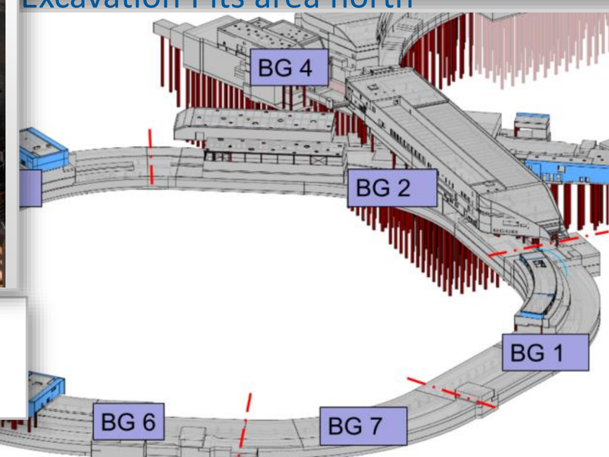
FAIR Site & Buildings



Tunnel SIS 100 & Transfer Building G004

- sealing and backfill works in commenced .
- South area in tendering process.

Excavation Pits area north



FAIR: Status of Civil Construction

- See videos via

  www.gsi.de/en/researchaccelerators/fair/fair_civil_construction/photos_and_videos.htm

Bird‘s view
19 May 2019

Status of FAIR: Accelerators: construction / procurement progress

>50% SIS100 sc dipoles manufactured at BNG, shipped to GSI and accepted

SIS100 quadrupole units shipped from JINR to BNG for integration into FOS module

All 51 HEBT vacuum chambers of batch 1 delivered (BINP, Russia)

The series production of RF – debunchers

All HESR Dipoles are produced in Jülich and about to be delivered to FAIR

Delivery of 1st 6 series Power Converter from India, (ECIL, India)

Status of FAIR: Accelerators: construction / procurement progress

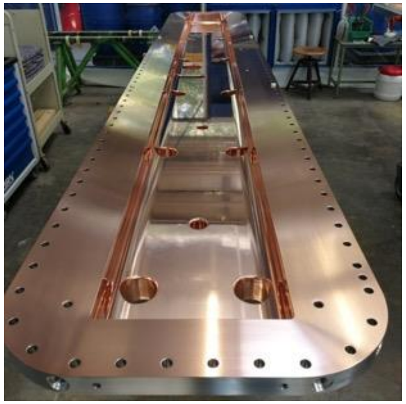
Two FoS vacuum chambers for the quadrupole doublet modules of the SIS100 arrived from China. They will be installed by the integrator in the quadrupole units

First-of-Series of the Super-FRS short SC Multiplet arrived in February 2019 at CERN test facility for execution of the Site Acceptance Test

First HESR Stochatic cooling pick-up and kicker in operation at COSY

Successfully First-of-Series FAT for the Super-FRS short SC Multiplet took place in Italy at January 2019

Copper plating and first tests of the RFQ accelerator cavity for the pLinac have been completed and match specifications



Three new MA acceleration cavities installed and commissioned with beam

Evolution of the FAIR/NUSTAR program

- **Phase 0 (2018-202x)**
  - R&D and experiments to be carried out with present facilities, e.g., GSI and external, with FAIR/NUSTAR equipment (basic set-ups)
- **Phase 1 (from 2024/25)**
  - Core detectors and subsystems completed (Day-1 configuration)
  - First measurements with FAIR/Super-FRS beams

➢ **Carry out "Day-1 experiments" with highest visibility and within the FAIR MSV**

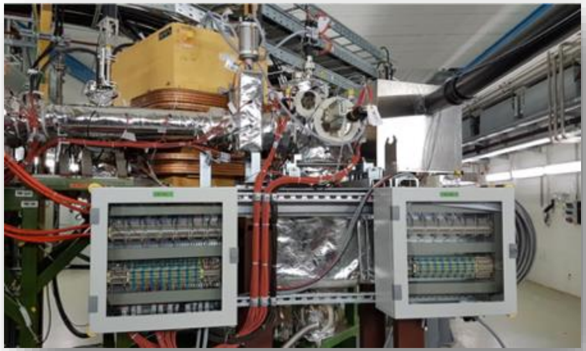
- **Phase 2**
  - FAIR evolving towards full power
  - Completion of all experiments within MSV

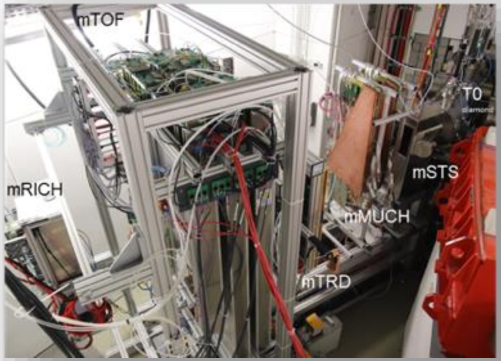
➢ **Essentially the full program of MSV can be performed**

- **Phase 3**
  - Moderate projects, which have been initiated on the way (outside MSV) can be included (e.g. experiments related to return line for rings)
- **Phase 4**
  - Major new investments and upgrades for all experiments.

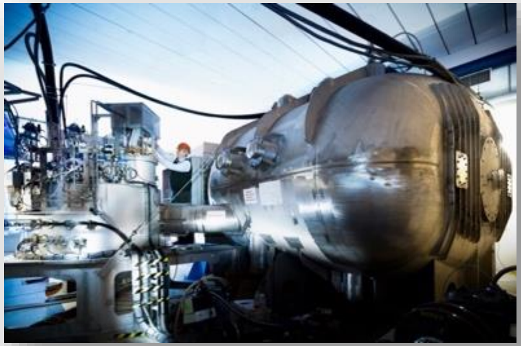
FAIR Experiments: A few Highlights from Phase-0

- APPA: CRYRING commissioning (own sources). Laser spectroscopy setup for APPA-SPARC





- CBM: mini-CBM completed first test beam campaign (prototypes of CBM detectors + distributed DAQ)

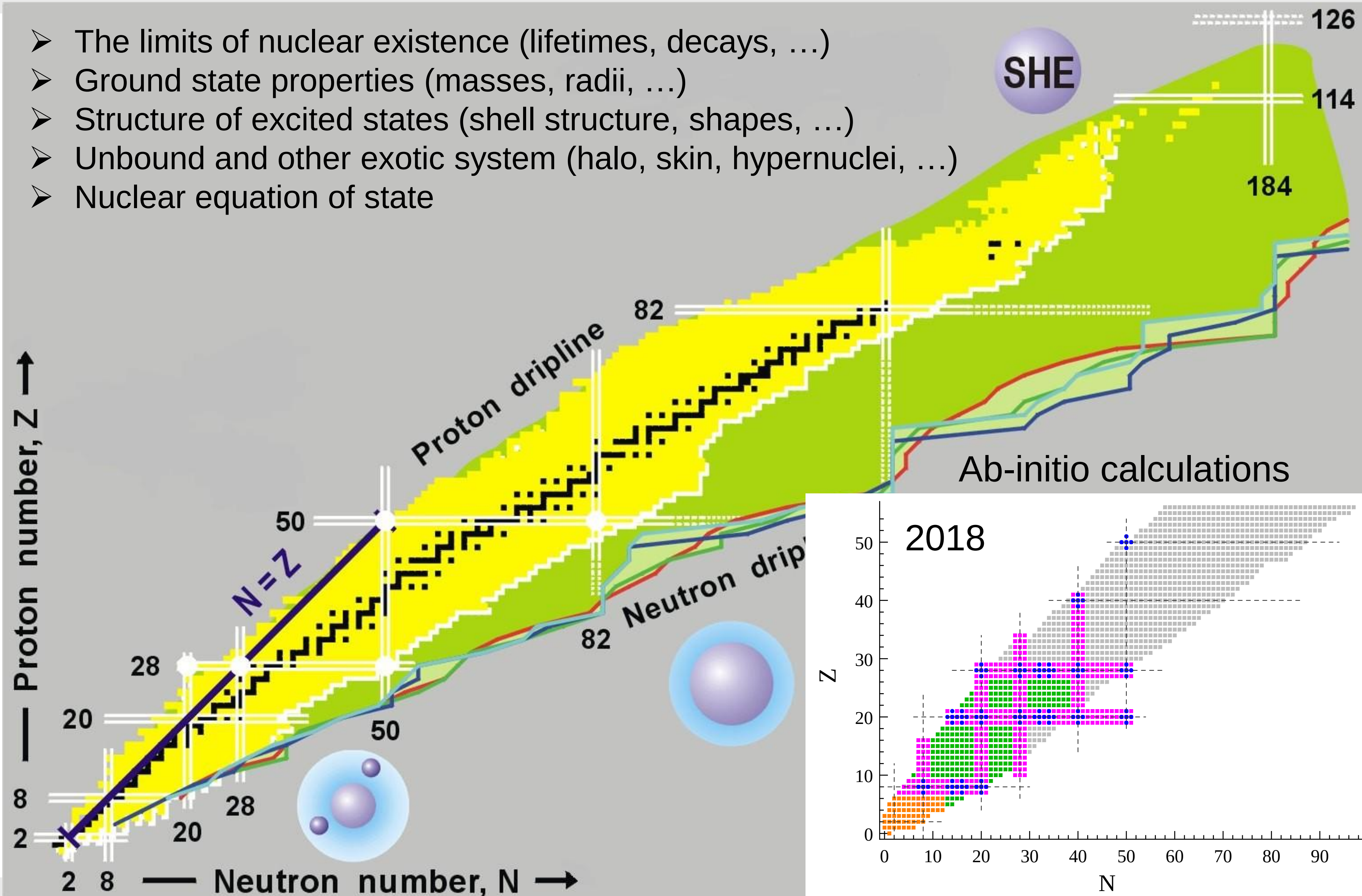


- NUSTAR: R³B: First Experiments with the GLAD magnet

- PANDA: Cluster jet target operated successfully at FZJ

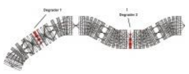
NUclear STructure Astrophysics and Reactions

- The limits of nuclear existence (lifetimes, decays, …)
- Ground state properties (masses, radii, …)
- Structure of excited states (shell structure, shapes, …)
- Unbound and other exotic system (halo, skin, hypernuclei, …)
- Nuclear equation of state

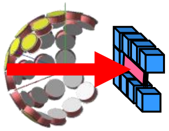


NUSTAR experiments

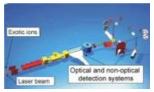
Super-FRS



HISPEC/ DESPEC

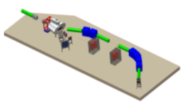


LASPEC

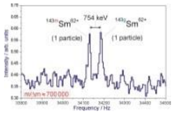


MATS

R3B

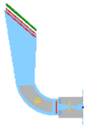


ILIMA



SHE

ELISE



EXL

	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	ground state and isomers μs...s			resonance width, decay up to 100ns	bare ions, ms…years	μs...days		
Matter radii	interaction x-section				interaction cross sections				matter densitiy distribution
Charge radii	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ-ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range & tensor correlations	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromagnetic transition strength	quadrupole moments	halo structure	dipole response, fission	changes in deformation		electromagnetic transition strength	monopole resonance
EoS					polarizability, neutron skin			neutron skin	neutron skin, compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon resonances	rare and exotic e.m. and particle decays			n-rich hypernuclei	exotic decay modes			

NUSTAR Phase 0 program (2019-20)

Approved SIS/FRS experiments (without SHE)

FRS and detector commissioning/development (eng. beam time)

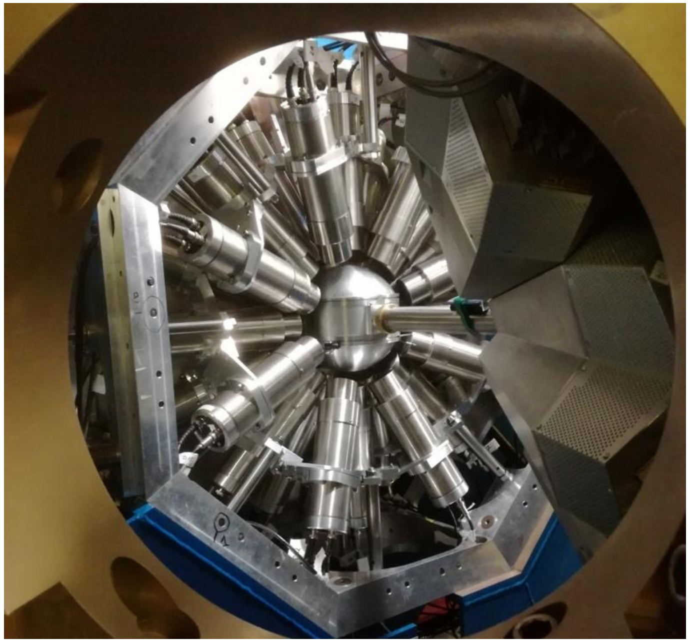
E121	Measurement of the bound-state beta decay of bare ^{205}Tl ions
E127	Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process
S465	Dipole response of the drip-line nuclei ^{6}He and ^{22,24}O
S442	Study of multi-neutron configurations in atomic nuclei towards the drip line
S467	Single-particle structure of neutron-rich Ca isotopes: shell evolution along Z=20
S455	Fission investigated with relativistic-radioactive beams and the advanced SOFIA@R3B setup
S447	Studies of the d+p signal and lifetime of the $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS
S474	Detector tests with the prototype of the CSC for the Super-FRS and direct mass measurements of neutron-deficient nuclides below ^{100}Sn
S468	Search for new neutron-rich isotopes and exploratory studies in the element range from terbium to rhenium
S452	The Oblate-Prolate Shape Transition around A~190
S460	Investigation of 220-A-230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation
S450	Study of N=126 nuclei: isomeric and beta decays in ^{202}Os and ^{203}Ir

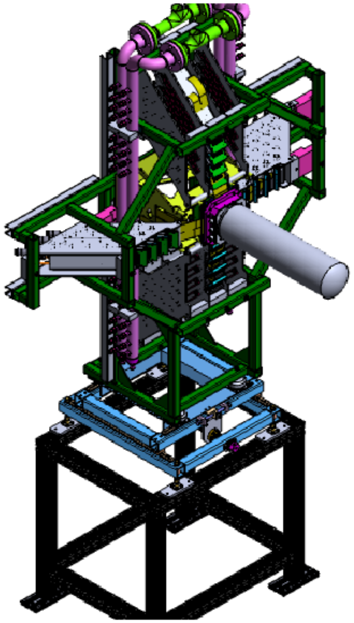
DESPEC Super FRS R3B EXL ILIMA

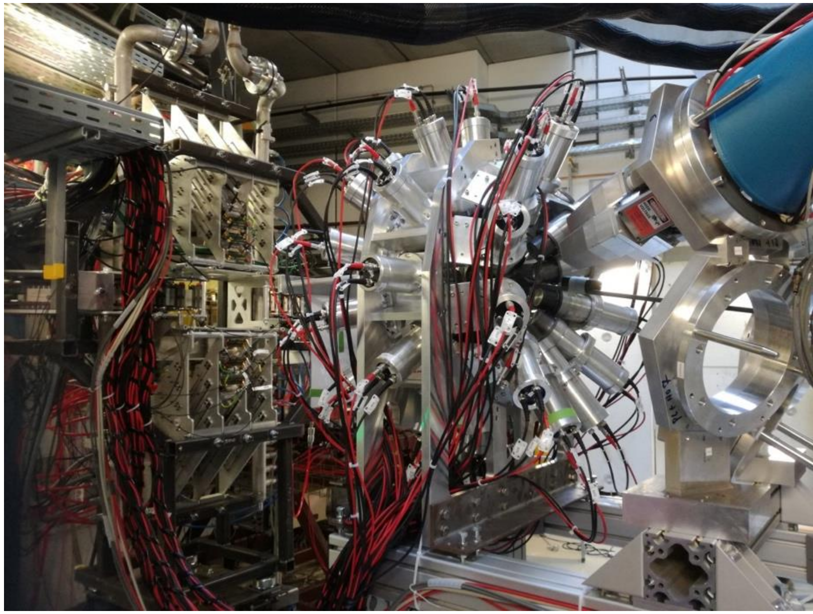
Spectroscopy & lifetimes of neutron-rich nuclei close to N=126

FATIMA fast-timing array - ready for experiments (S452, S460 & S468)

FATIMA & AGATA at GANIL | *AIDA* | *DEGAS & FATIMA (2019-20)*



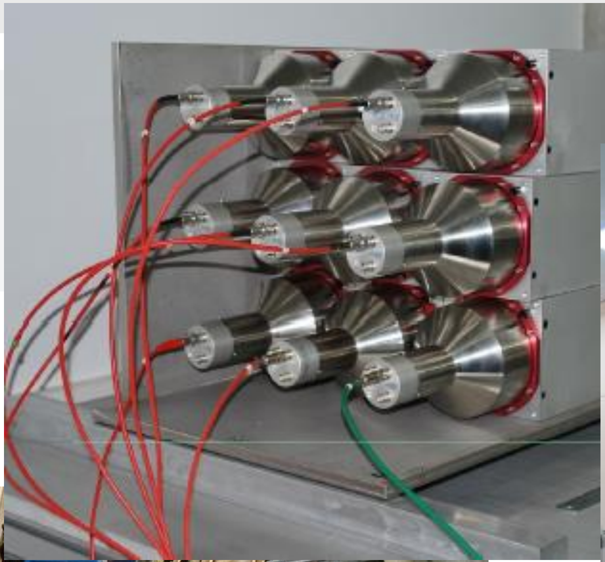


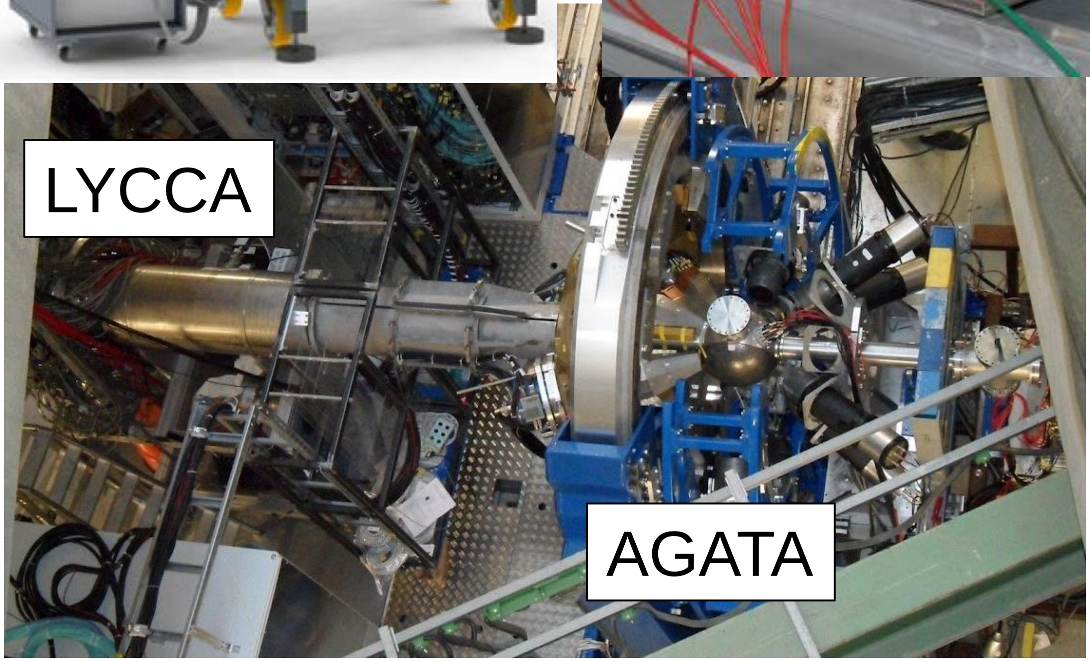


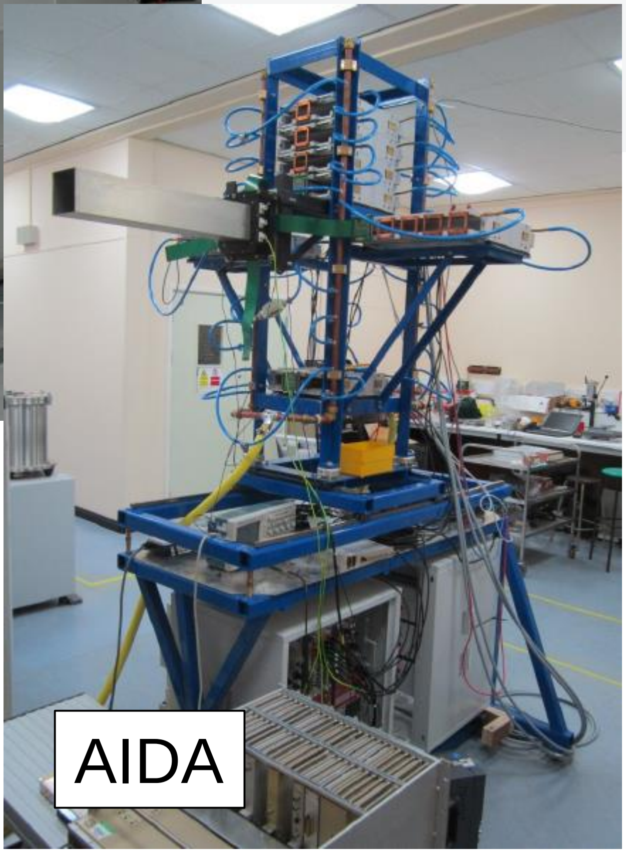
AGATA+VAMOS+FATIMA

AIDA implantation and decay detector
(1/3 of full size available in 2018)
Commissioned in RIKEN, Japan

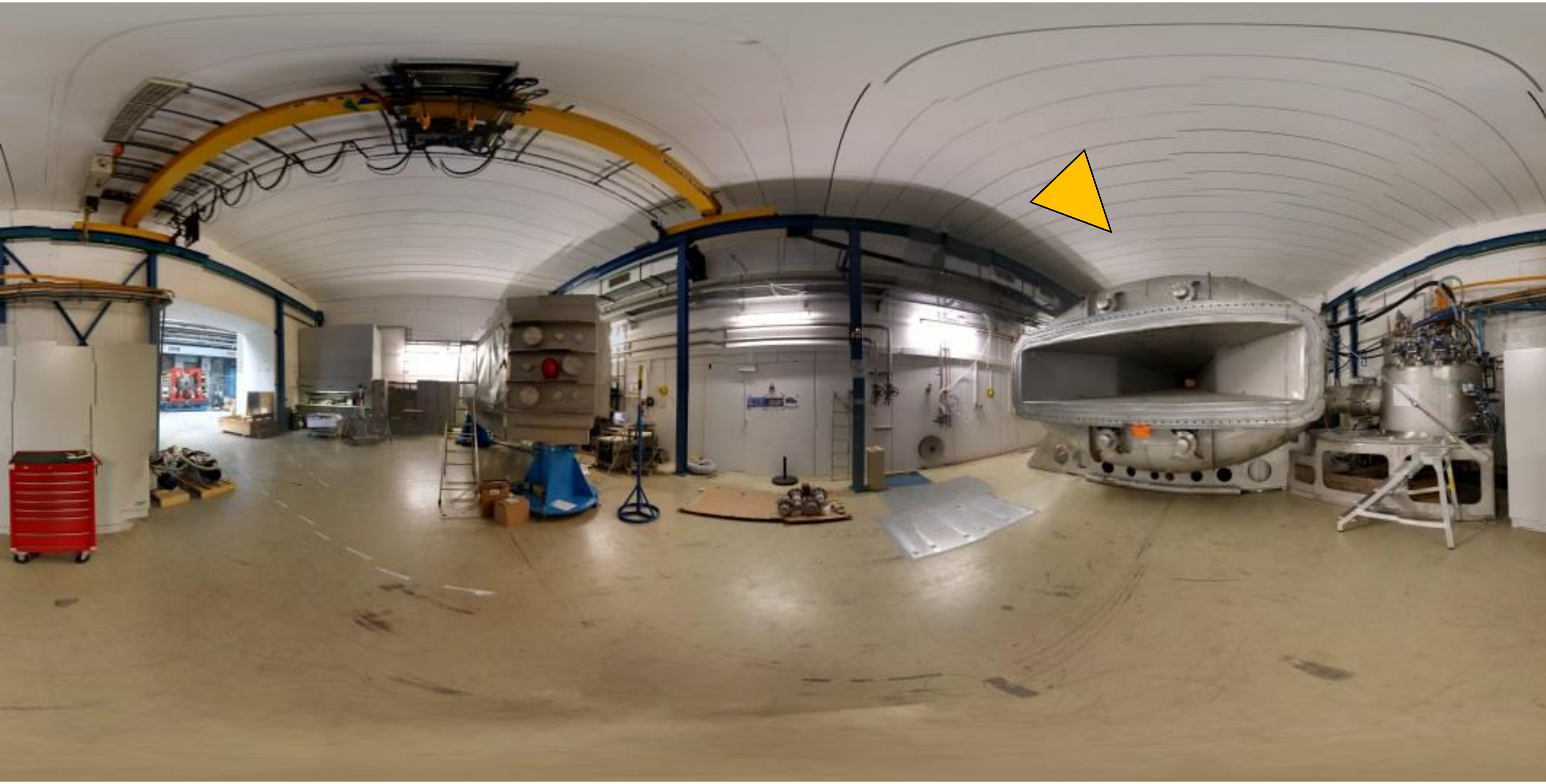
DeSpec Instrumentation ready for operation







R³B: Starting point 2016



R3B set up progress

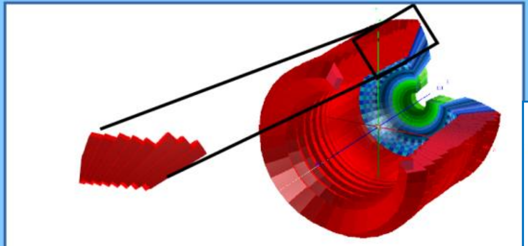
L3T (DSSSD,delayed) ➔
AMS up to 8 systems
18 det.ladders (6+12)
Strip pich 50μm
912 ASICS 116736 channels

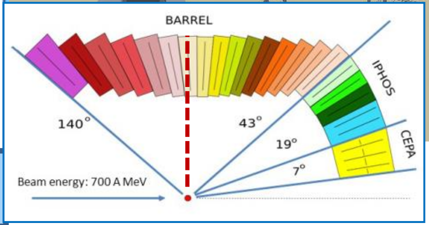
NeuLAND

8/12 (30) double planes + frame
1600/2400 (6000) el. channels & HV

GLAD & LH2 target station

Advanced tracking system
PSPs, MUSIC,
plastic ToF (ΔE and position via ToT)
fibre detector trackers
(partly in vacuum, with electronics)





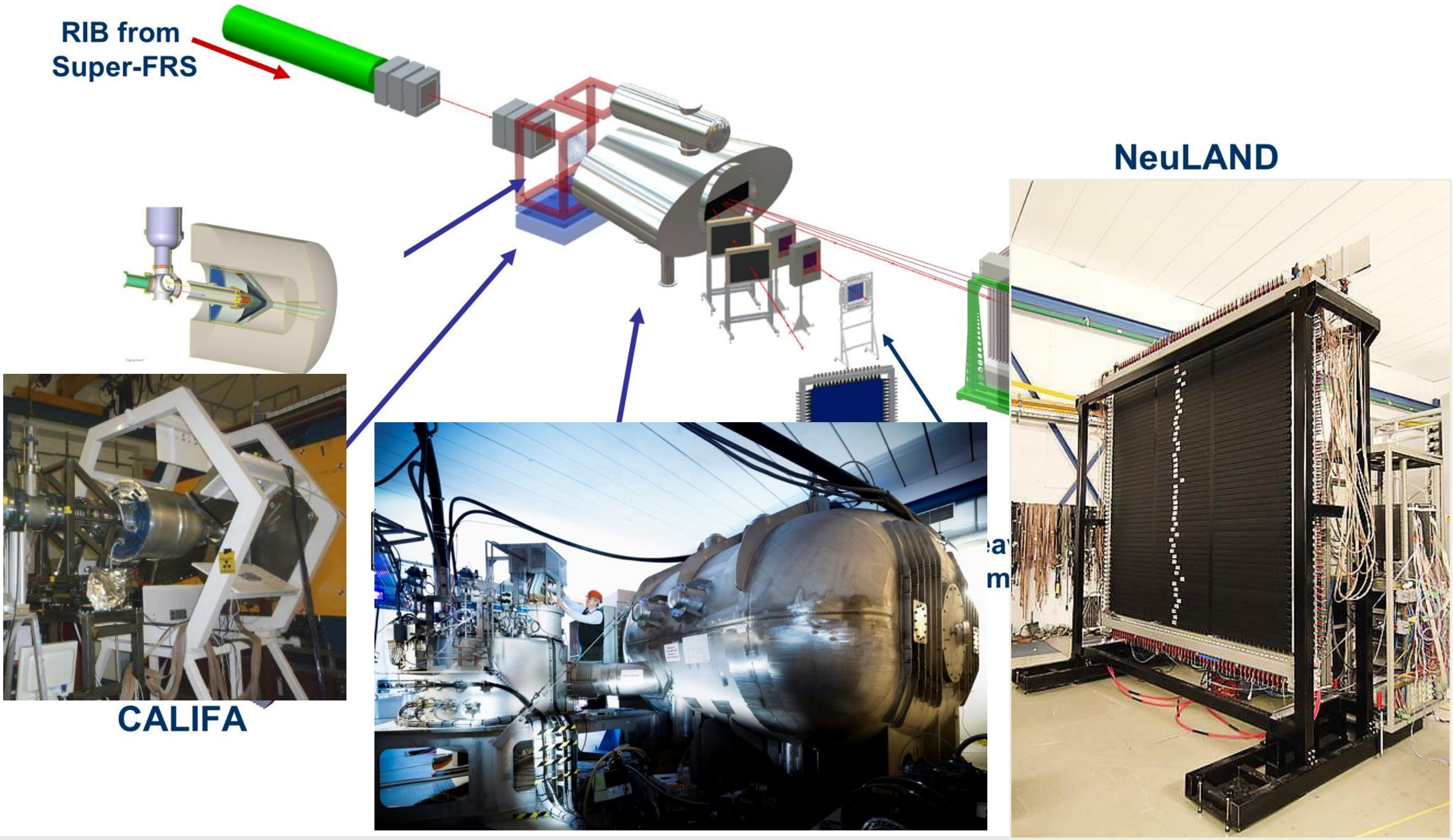
Califa (forw. Barrel)

- Barrel (red) – 1952 CsI(Tl) Crystals
- Endcap – 608 Crystals
  - iPhos (blue) – CsI(Tl)
  - CEPA (green) – $LaBr_3$ & $LaCl_3$
- 2560 crystals in total

DAQ & Controls (NUSTAR DAQ / EPICS)
Simulation-Analysis (UCESB/R³BRoot)

R3B instrumentation ready for operation

Reaction studies with relativistic radioactive beams

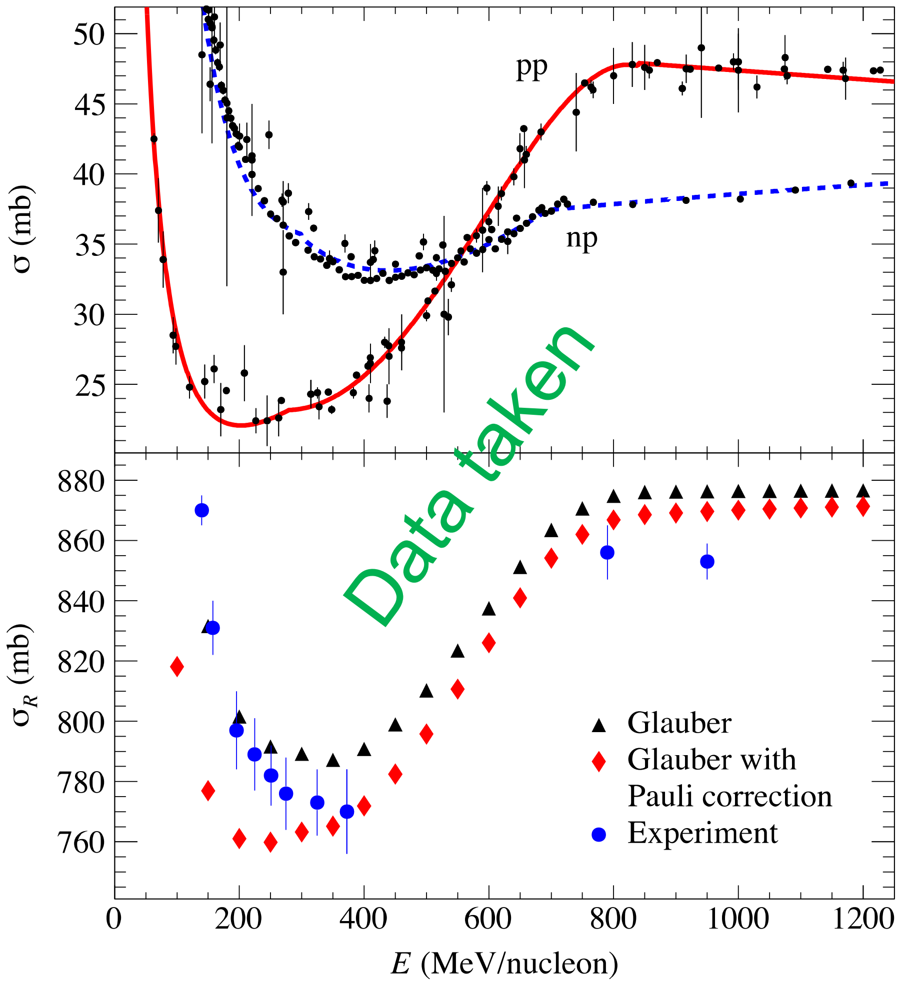


Start of Experiments 20190220

Stable Beam Experiments 2019

S473: Test of Eikonal reaction theory

T. Aumann et al.



Test with energy dependence of ^{12}C + ^{12}C total reaction cross section

Parameter-free Eikonal prediction overestimates cross sections

Expected deviations due to:
1) In-medium effects: Pauli blocking
2) Fermi motion
3) Higher-order
4) Collective excitations

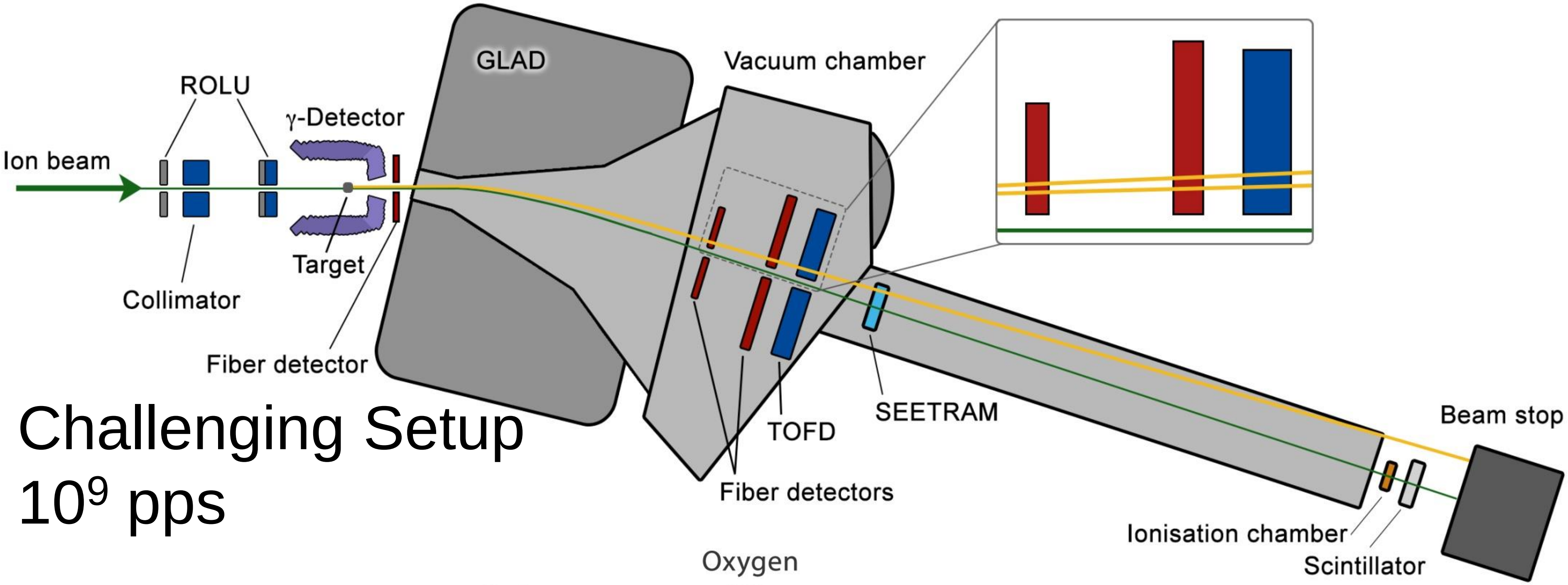
Taking into account Pauli blocking:
C.A. Bertulani, C. De Conti, PRC 81 (2010)
Higher-energy data point overestimated by ≈2%

Theoretical improvements needed

But:
only three data points in the range 0.4 to 1.2 GeV/u
→ Precise data needed incl. energy dependence

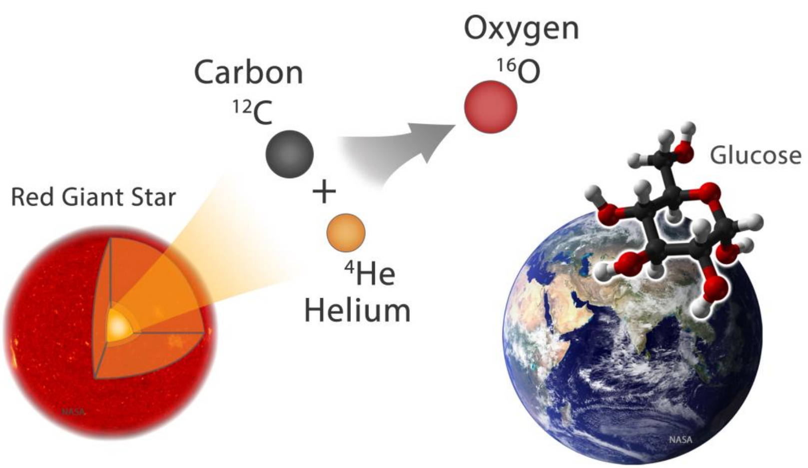
Stable Beam Experiments 2019

S454 Astrophysics $^{16}O(\gamma,\alpha)^{12}C$



Challenging Setup

10^9 pps



K. Göbel, M. Heil, R. Reifarth et al.

S454 – achievements

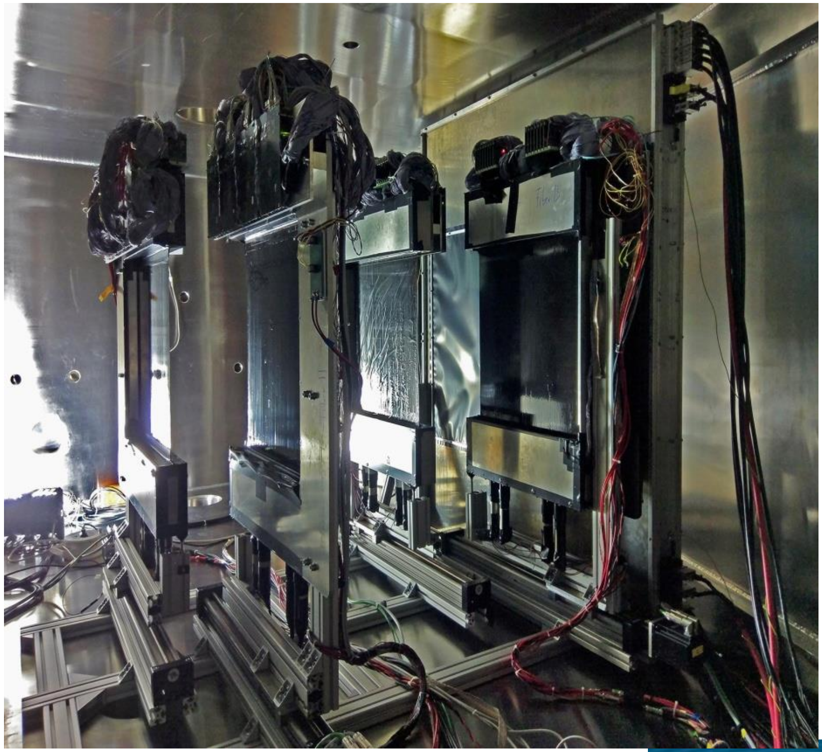
- Coulomb dissociation of ^{16}O on ^{208}Pb

$$^{16}\mathbf{O} + {}^{208}Pb \rightarrow {}^{4}He + {}^{12}C + {}^{208}Pb \quad (CD)$$

- Advantages:
  - high intensity of ^{16}O (stable) beam
  - large number of virtual photons
  - large (γ,α) cross section

- Direct comparison to direct measurements using E1 data, proof of principle via R-Matrix decomposition. CD studies with E1/E2, proof of principle.

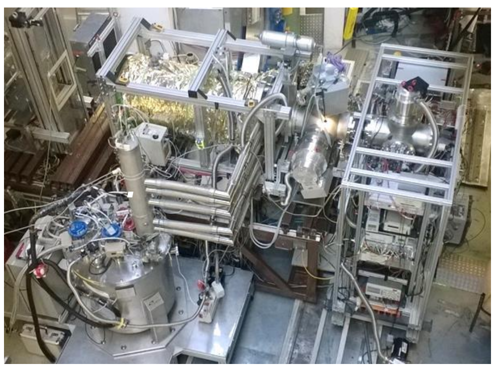
- High speed (several MHz) tracking with two particles, first results already available.



High-resolution spectrometer experiments at the border line of nuclear, atomic and hadron physics

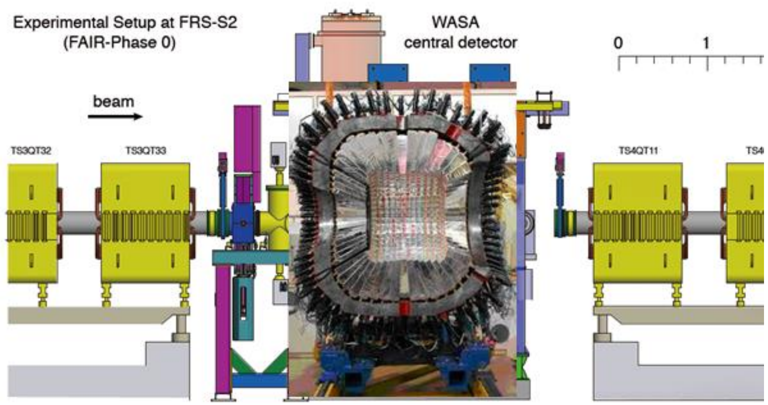
(Super-)FRS as multiple-stage magnetic system (separator, analyser, spectrometer, energy buncher) combined with ancillary detectors, e.g. with:

FRS Ion Catcher

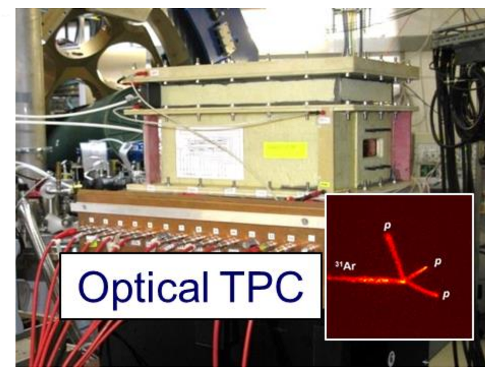


→ Cryogenic Stopping Cell

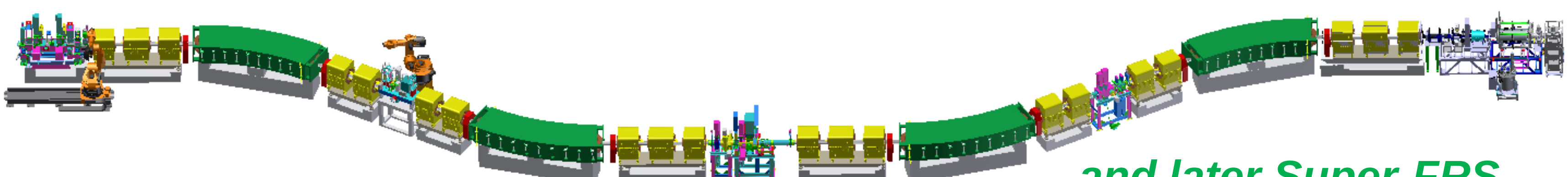
WASA



EXPERT

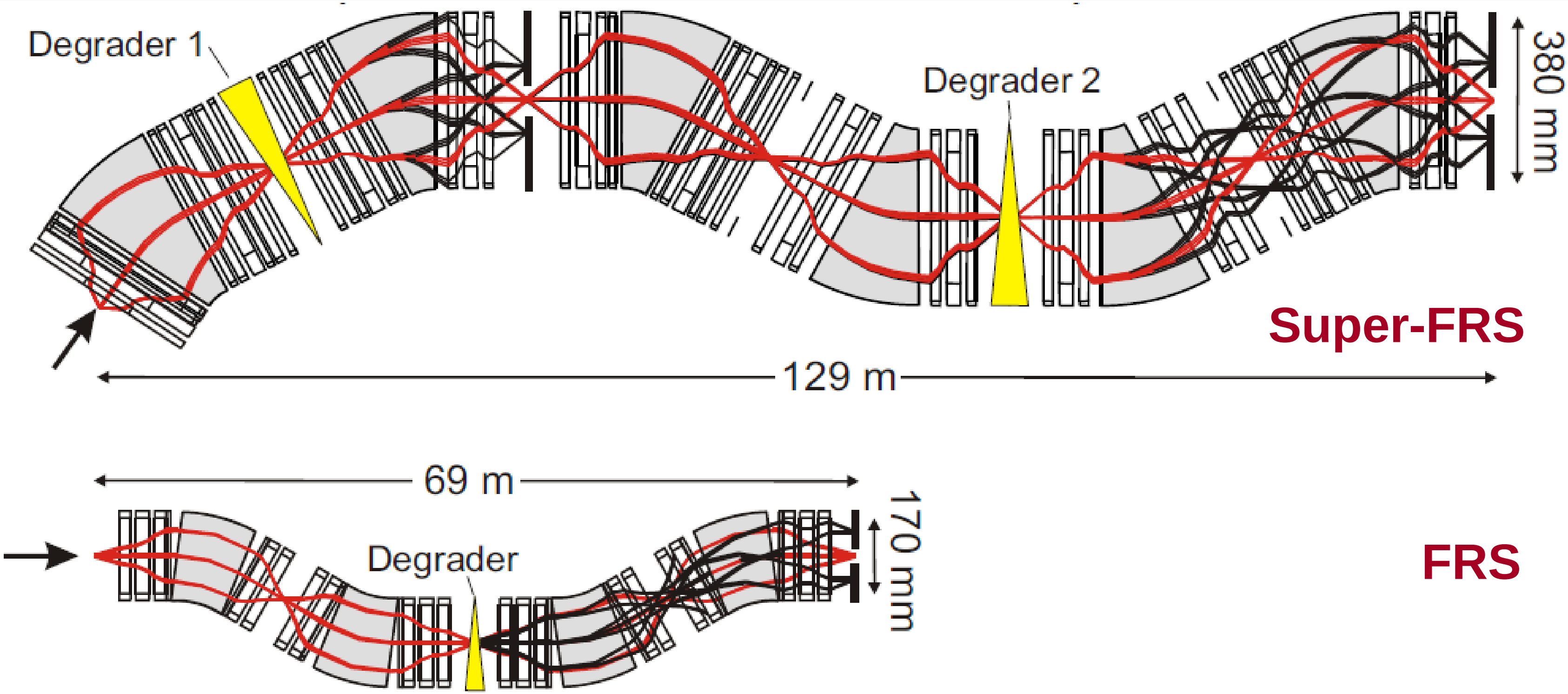


at FRS...



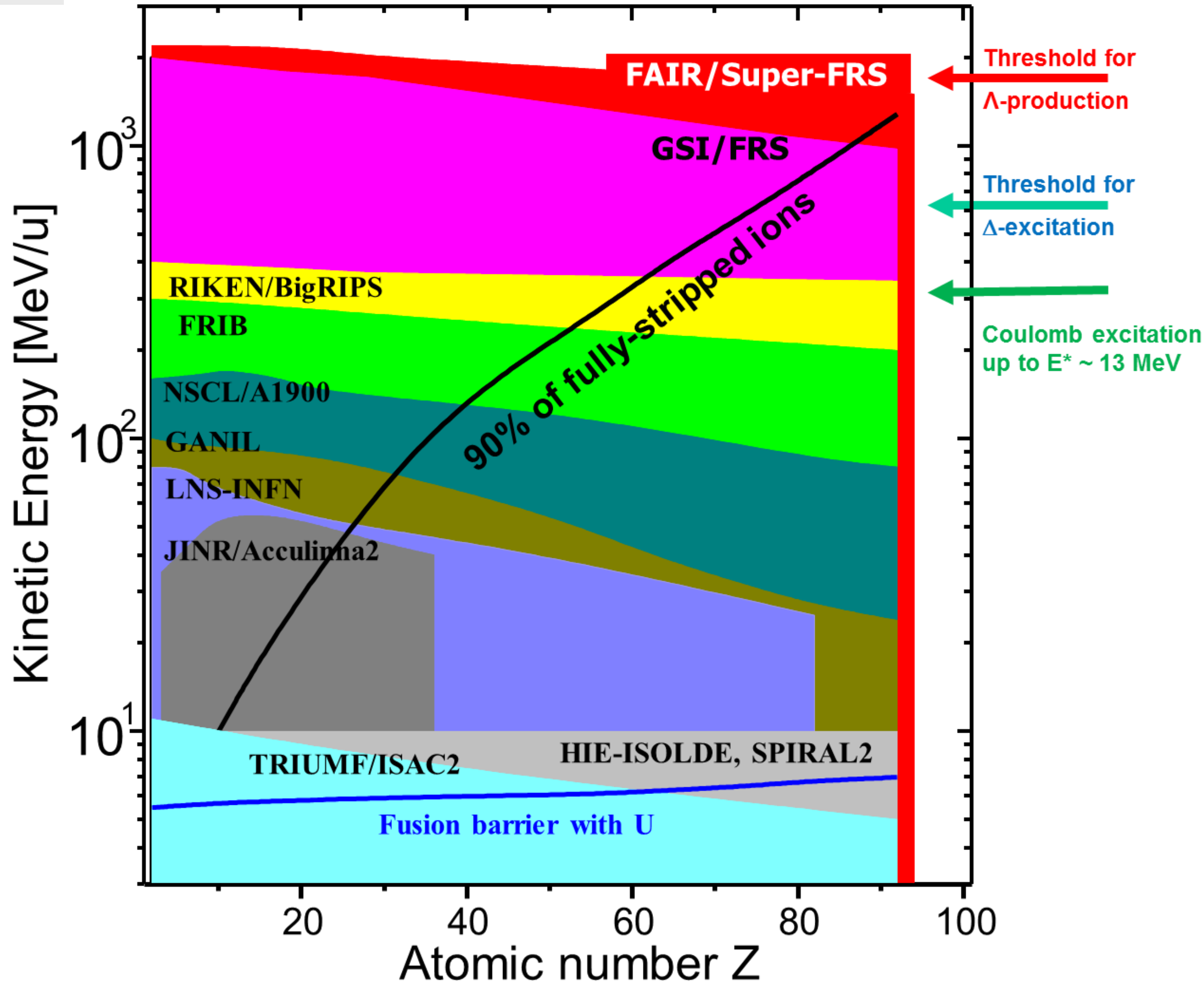
...and later Super-FRS

GSI FRS → FAIR Super-FRS



	$B\rho_{max}$	$\Delta p/p$	$\Delta\Phi_x$, $\Delta\Phi_y$	resolving power
FRS	18 Tm	1.0 %	± 13, ±13 mrad	1500
Super-FRS	20 Tm	2.5 %	±40, ±20 mrad	1500

Twofold increase of secondary beam intensity



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acceptance
of a versatile
n optics and
ention

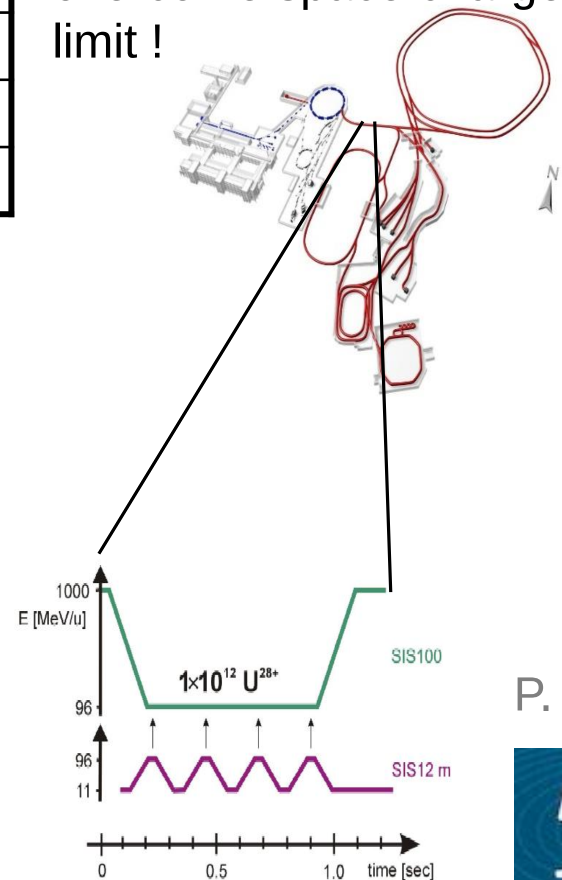
Injector chain developments:
Beam Parameters SIS18/SIS100

SIS18	Protons	Uranium
Number of ions per cycle	5×10^{12}	1.5×10^{11}
Initial beam energy	70 MeV	11 MeV/u
Ramp rate	10 T/s	10 T/s
Final beam energy	4.5 GeV	200 MeV/u
Repetition frequency	2.7 Hz	2.7 Hz

SIS100	Protons	Uranium
Number of injections	4	4
Number of ions per cycle	2.5×10^{13} ppp	5×10^{11}
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz

... and all other ion species

Lower charge state to overcome space charge limit !

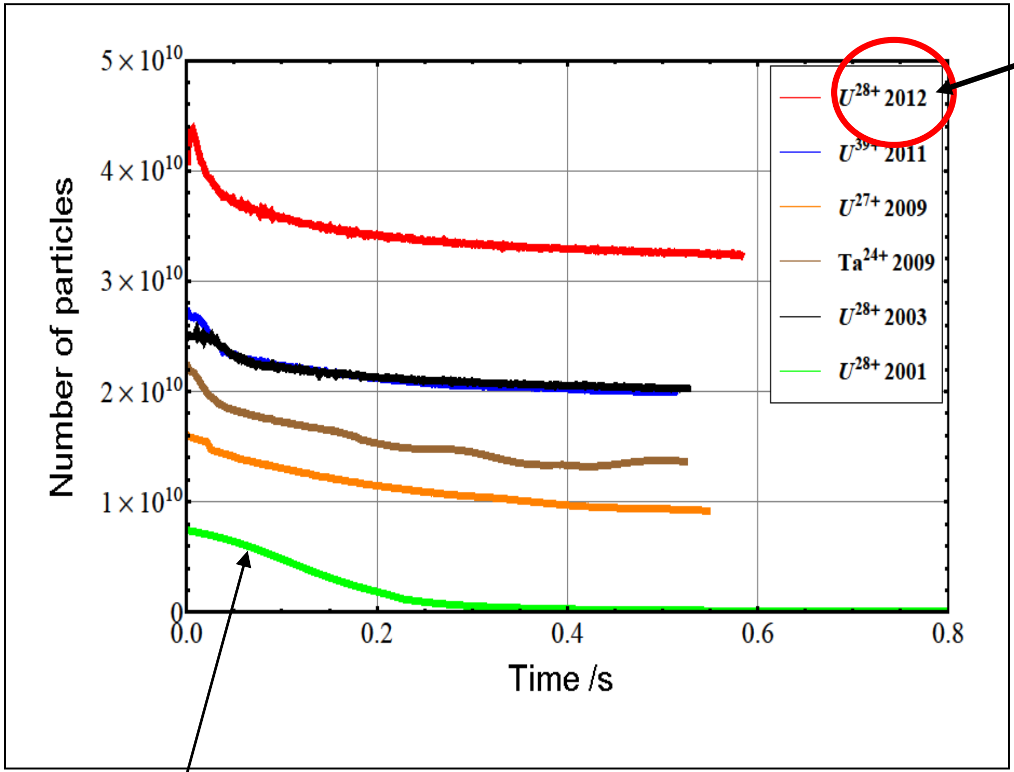


P. Spiller

U^{28+} - Beam Intensity

World record intensity for intermediate charge state heavy ions.

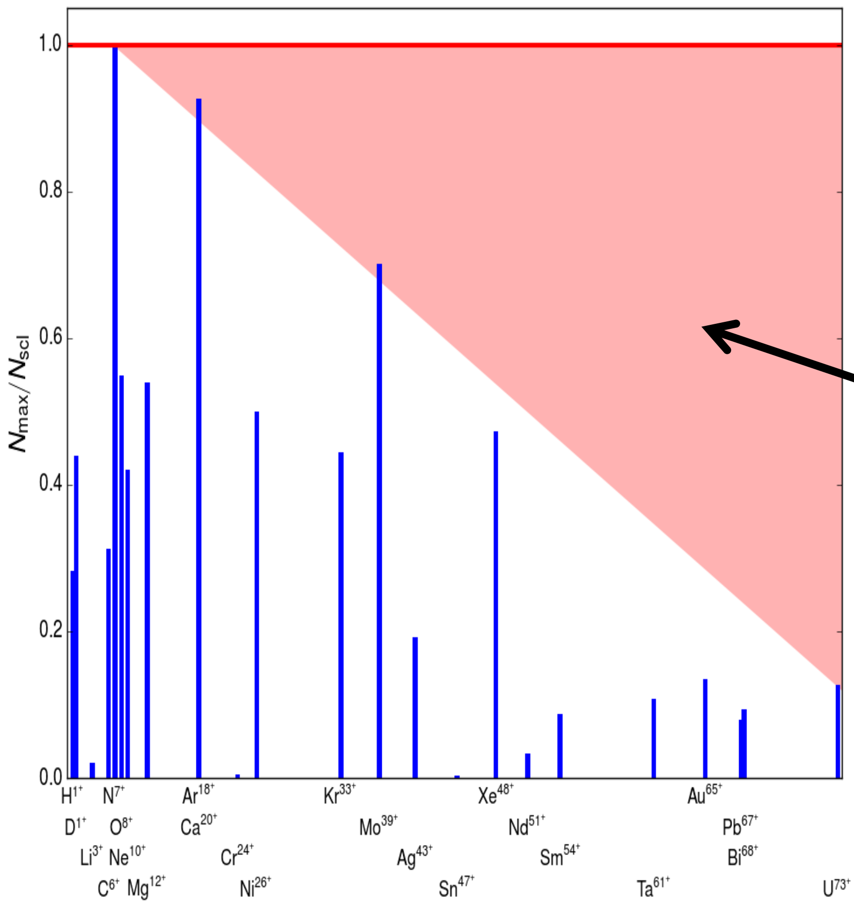
The feasibility of high intensity beams of intermediate charge state heavy ions has been demonstrated.



2001 FAIR conceptual design report (FAIR proposal)

P. Spiller

Currently obtained Peak Intensities versus Space Charge Limit



Space charge limit for different specied

Further performance gain with improved UNILAC beam intensity & quality

P. Spiller

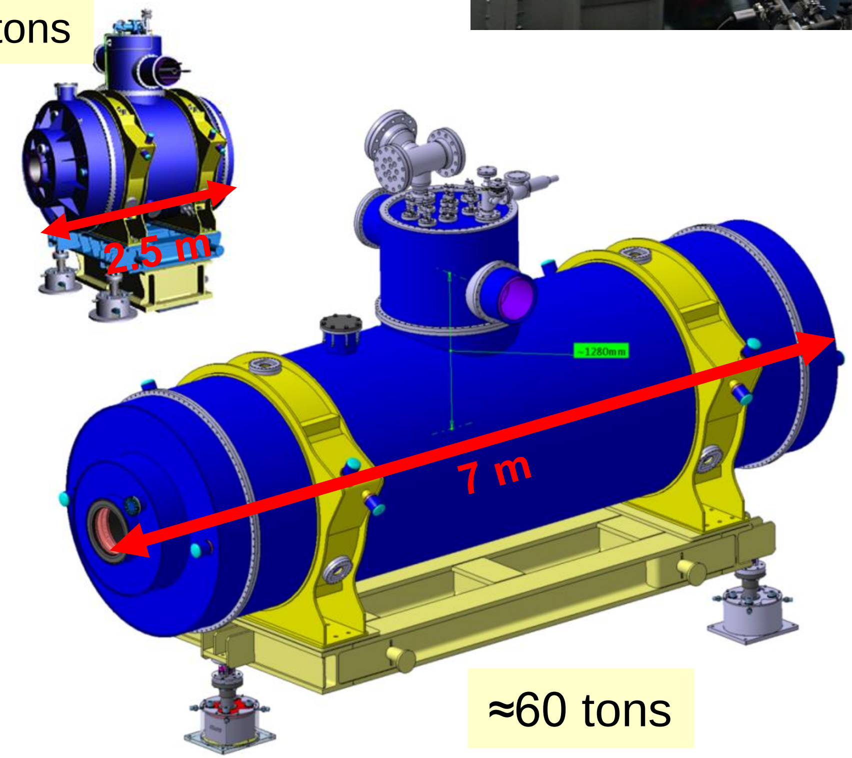
SIS18 upgrade programme and UNILAC improvements will be carried out within Phase-0 programme (engineering beam time)

Big items govern schedule:
Ex.: Superconducting Multiplets

Scope:

- 8 short multiplets
  - QS configuration
- 25 long multiplets
  - Quadrupol triplet

≈25 tons



≈60 tons

Schedule FoS SC multiplets

- ✓ Contract closed **07/2015** (ASG, Genova)
- ✓ Design phase for SM and LM done
  - ✓ FDR 12/16
  - ✓ PRR SM 07/17
  - ✓ PRR LM 12/17
- **Construction phase for FoS running**
  - ✓ FAT FoS SM 01/19
  - **shipment to CERN**
  - **Installation @ CERN**

    SAT FoS SM Q4/20

Distributed testing infrastructure for FAIR's superconducting magnets

GSI: Series test facility for the SIS100 s.c. dipole magnets, string test, current leads and local cryogenics components.

CERN: Test facility completed for the Super-FRS s.c. dipoles and multipletts

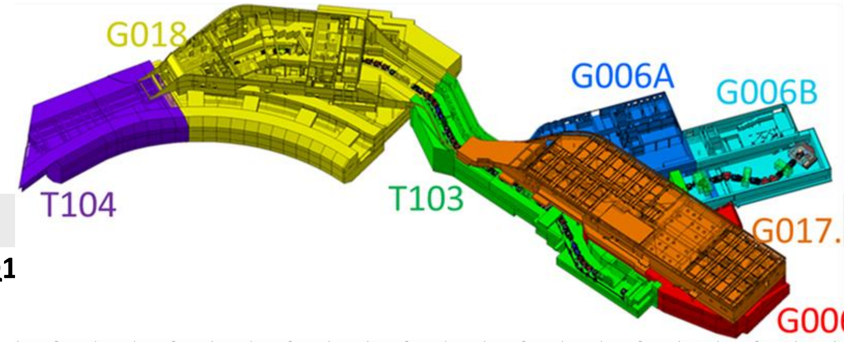
INFN: Test facility in Salerno for testing the series of SIS100 quadrupole modules

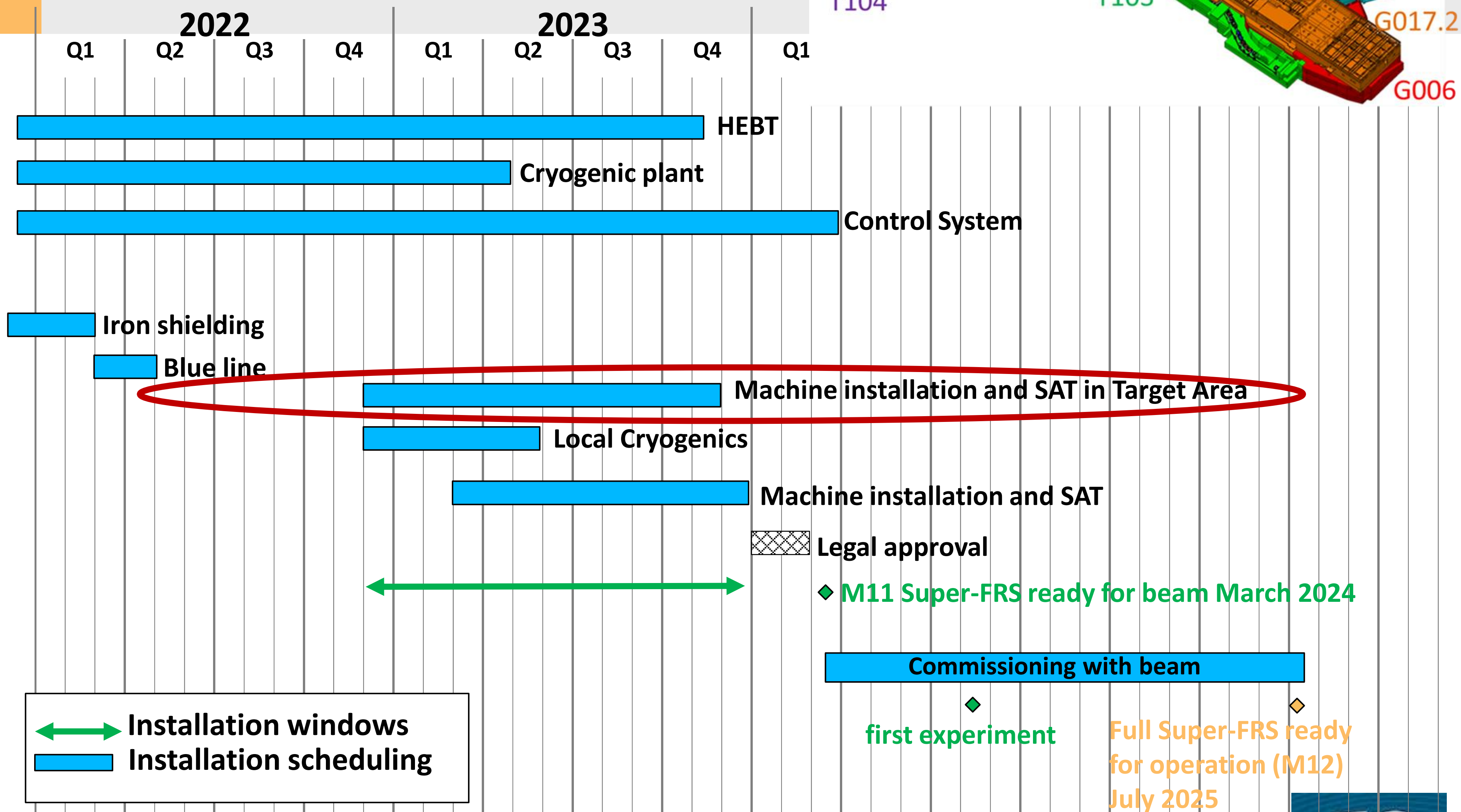
JINR, Series test facility in Dubna for testing of the series of SIS100 s.c. quadrupole units

Sc Magnet testing @ CERN

- Determines delivery schedule!
- Operation: Kick off (3 benches) 02/2019 & 07/2019

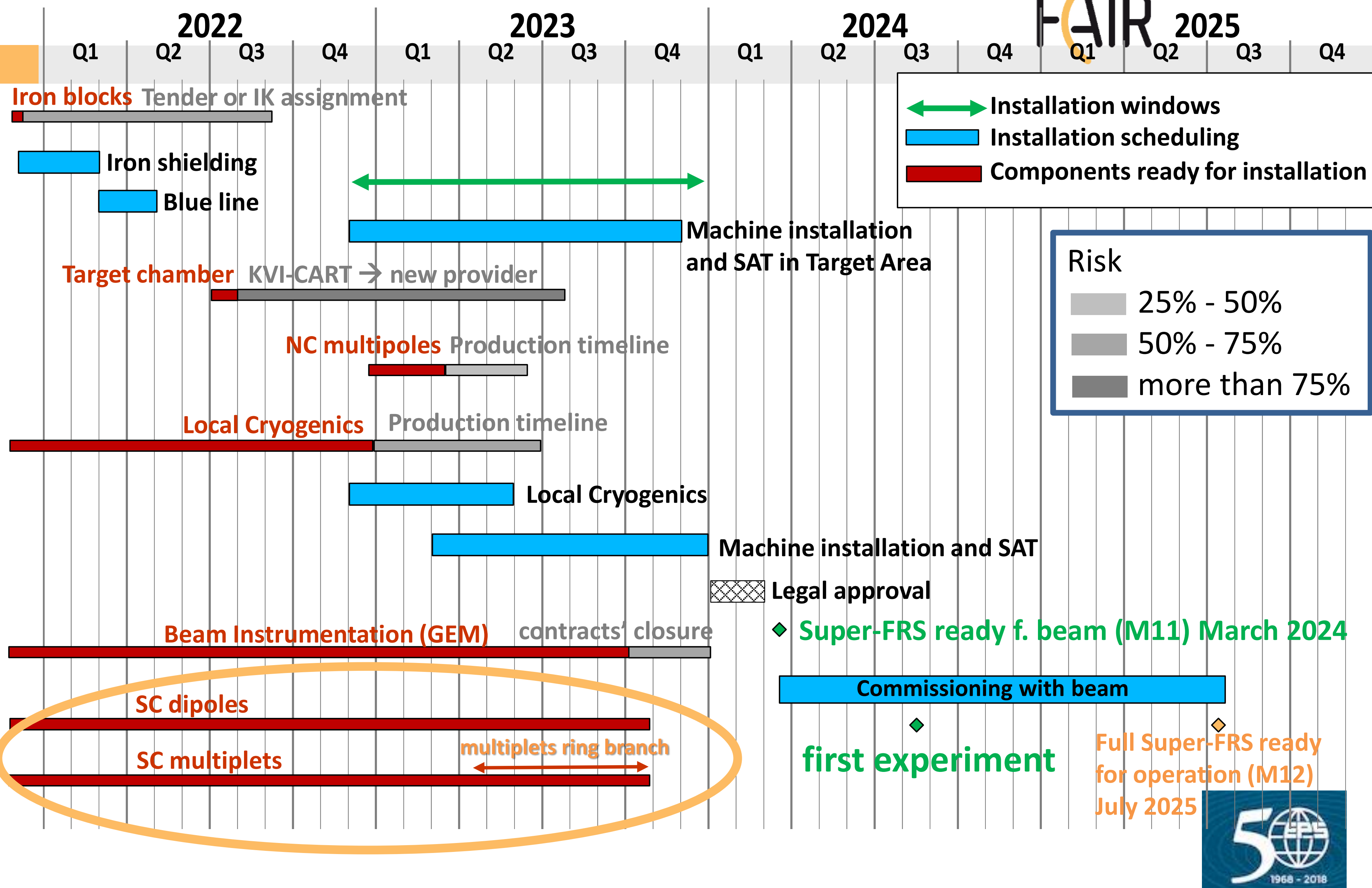
Installation plan based on LCM (for G018)



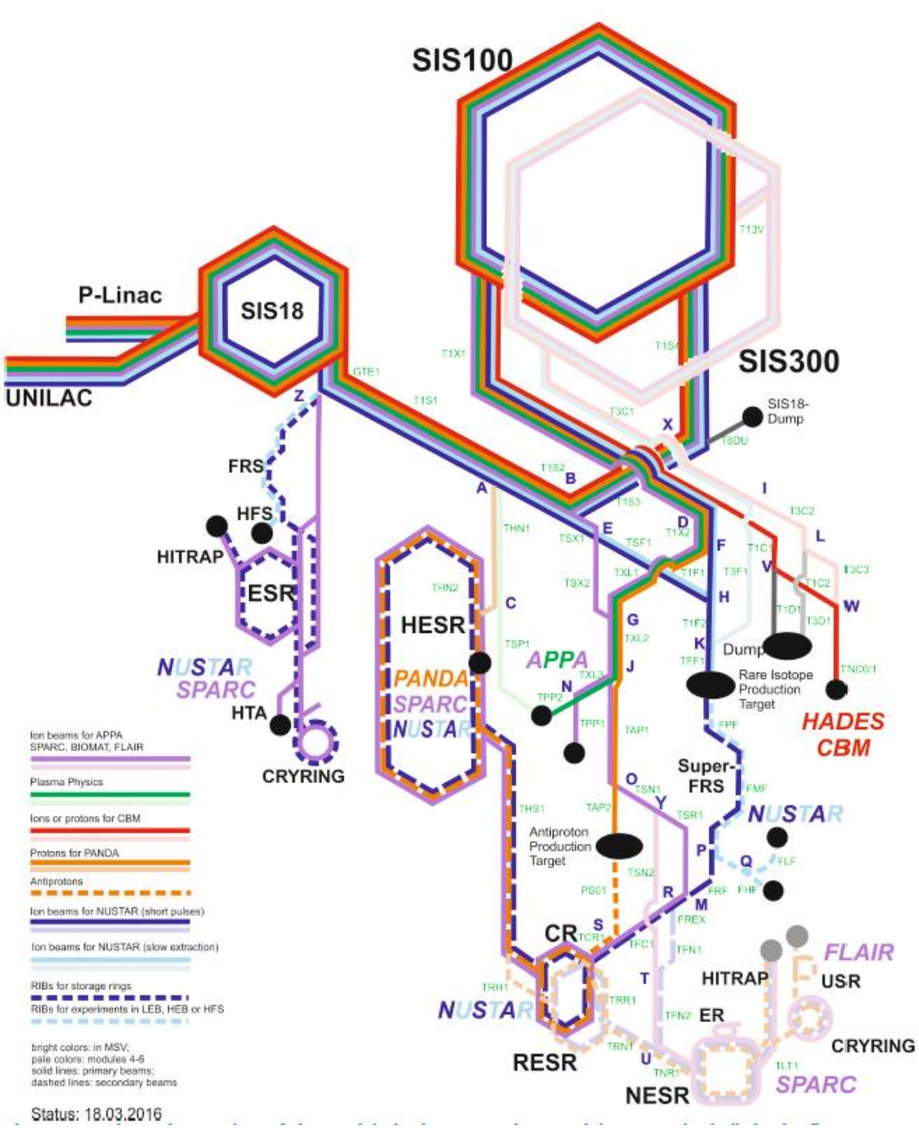


Building & Installation process interspersed

Installation plan based on LCM (+ risk analysis)



Phase-1 start-up scenarios and implications for day-1



NUSTAR start-up scenario

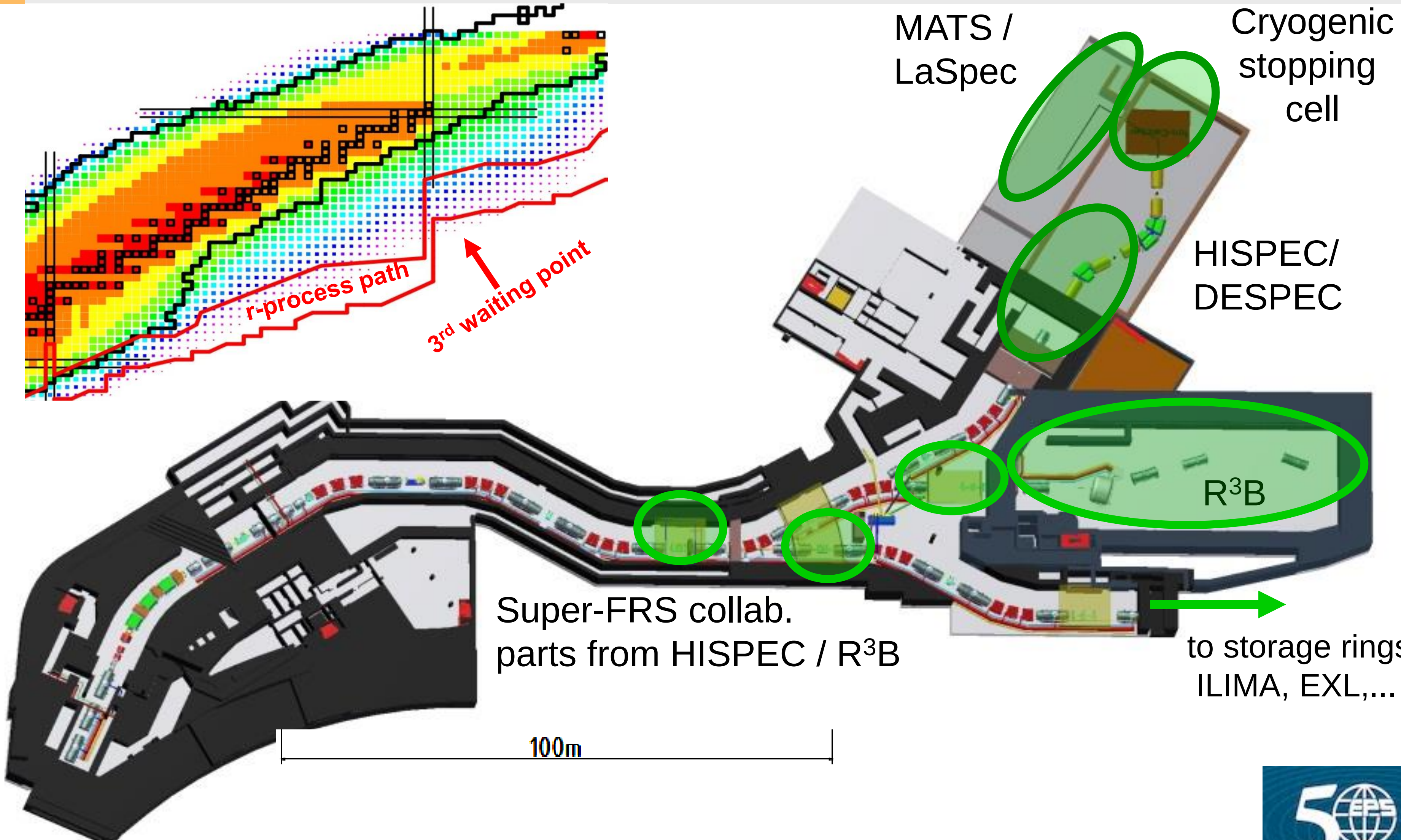
for an advanced start of FAIR Phase-1

1. Stage
requires
UNILAC + SIS18 + Super-FRS

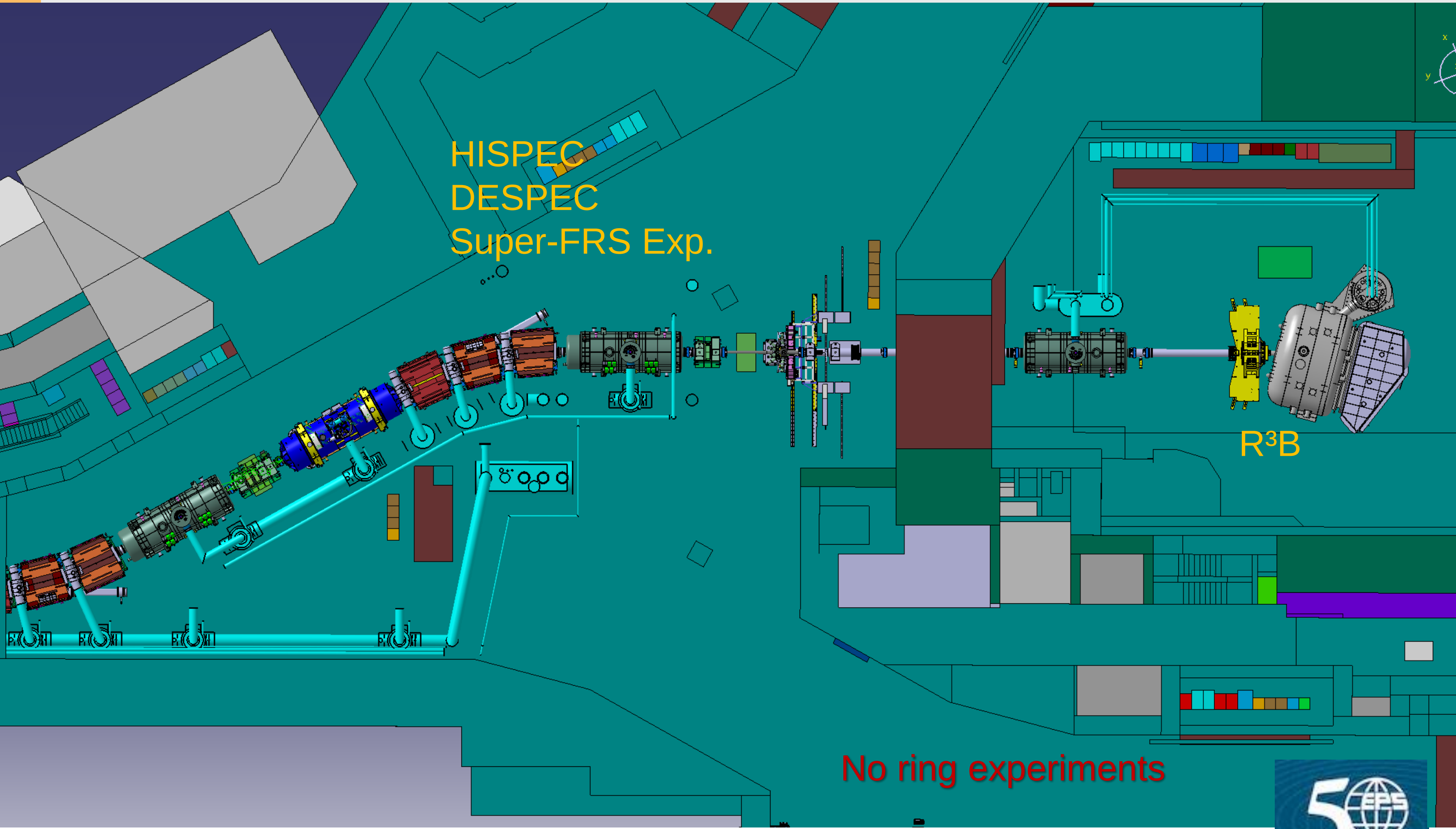
realisation:
complete installation, followed by stepwise commissioning

first physics experiments in stages
1. Intermediate S-FRS focal planes
2. HEB
3. LEB
Covers thematically about 70% of Day-1 Physics

Super-FRS & NUSTAR facility



First stage:
-High energy branch (γ-setup @ FHF1) + R3B/GLAD



Most Experiments possible at least in start versions

Second stage:
-(HEB (R3B/GLAD) + γ-setup @ FRF3

Improved performance for HISPEC/DESPEC experiment

Commissioning

- Basic tests are performed during installation and SATBa
- Cooling for the whole facility takes 1-2 months
- A commissioning period of 4 month is foreseen after the beam becomes available
- Pilot beam will be used to check the basic functionality of the separator
- In conjunction with ramping up the performance first physics experiments can be envisaged
- Based on BigRIPS startup experience

History of RIBF commissioning

Dec. 28th , 2006

First Beam $^{27}Al^{10+}$ 345 MeV/u at RIBF-SRC

Winter break at the facility !

March, 2007

12th $^{86}Kr^{31+}$ beam at 345 MeV/u several pnA.

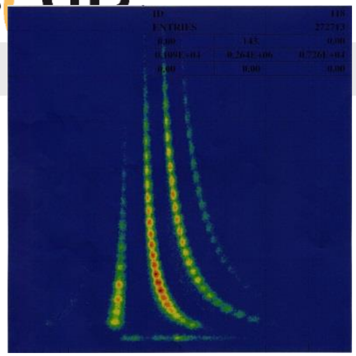
13th First production of RI beams with ^{86}Kr beam

23rd First successful acceleration of $^{238}U^{86+}$ beam at 345 MeV/u and 0.002 pnA

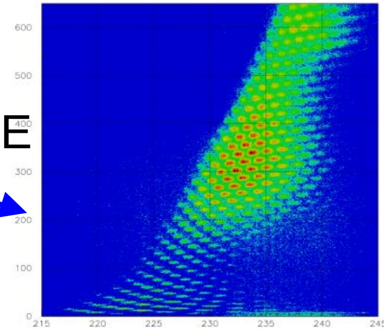
27th First production of RI beams with ^{238}U beam

TOF

ΔE



ΔE



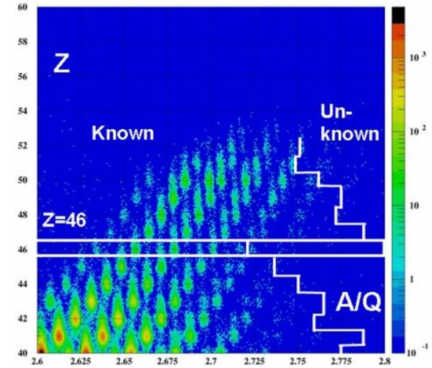
May-June, 2007 (without ZDS)

with ^{238}U beam at 345 MeV/u and 0.02 pnA max (~1x10^8 pps)

May 16th-23th BigRIPS commissioning experiment

May 24th – June 3rd Search for new isotopes

End of June(a few days) detector testing

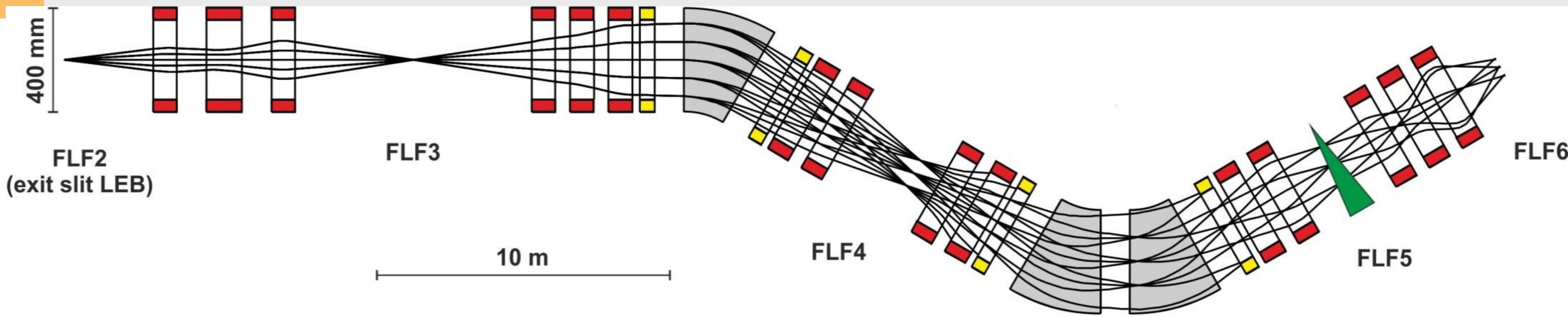


Nov. 2007 acceleration test with ^{86}Kr beams, 30 pnA

T. Kubo RIKEN / Separator Expert Meeting

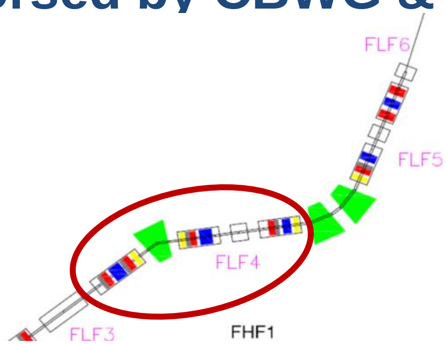
Few months from pilot beams to first experiments!

Low Energy buncher – LEB spectrometer
new S-shape layout (using standard multiplet magnets)



- **The energy buncher at the low energy branch allows to fill the cryogenic stopping cell serving the low energy experiments MATS and LASPEC**

Indian in-kind has been returned, potential interest of France on dipoles, multiplets shall be procured within existing contract with ASG.
Endorsed by CBWG & Project Review.



Design for dipoles still to be done
magnets are last in testing sequence
➔ Installation of the spectrometer for the LEB starts in 2025.

Summary

- FAIR project is entering production phase
- Building construction in full flow
- Machine and experiments follow
- Enable many optimizations through phase-0 (experimental) programme
- Many components already available as prototypes to be tested
- Super-FRS as key instrument for NUSTAR can be ready for operation in 2025
- Time schedule: ambitious but realistic
- Allows for early experiments in Q4/2024-Q1/2025
- Risk profile in regards to machine is governed by production schedules and remaining contracting (commercial and in-kind partners)
- Staged installation of Super-FRS allowing for early experiments in case time schedule risks materialize
- Schedule driven by manufacturing and delivery of components

Thank you for your attention.