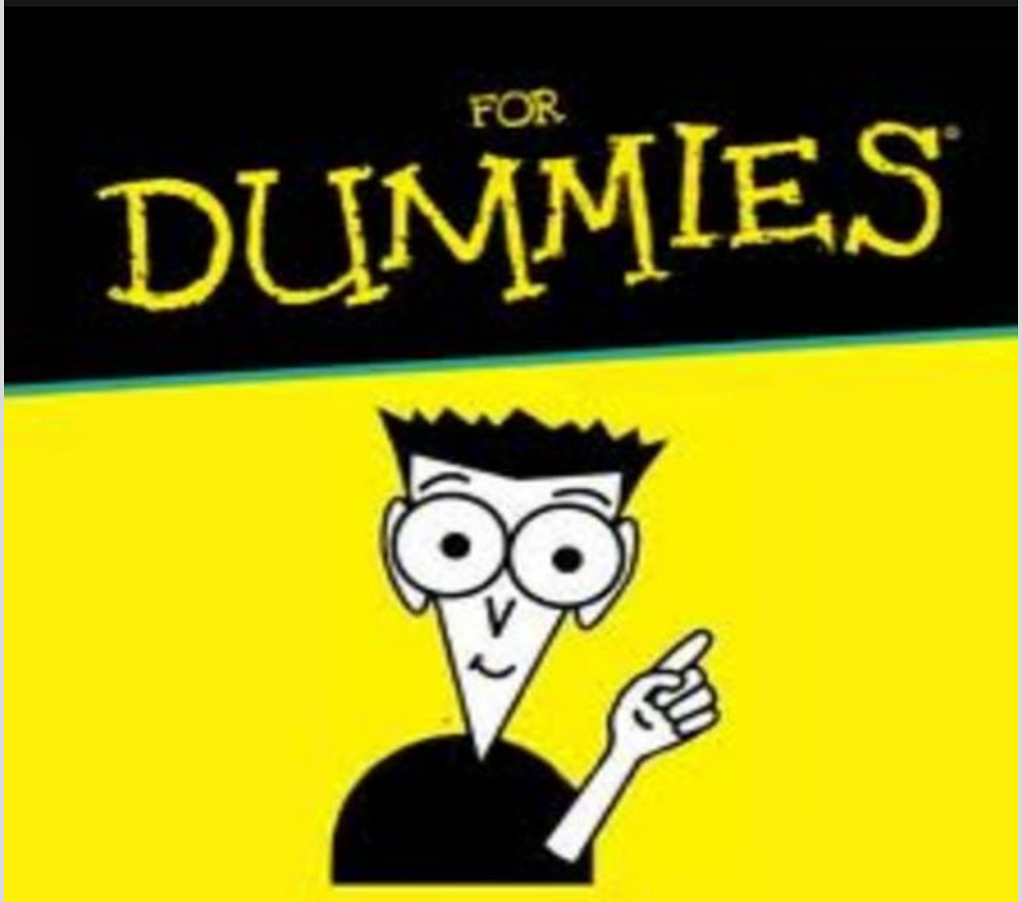
The FAIR project at GSI

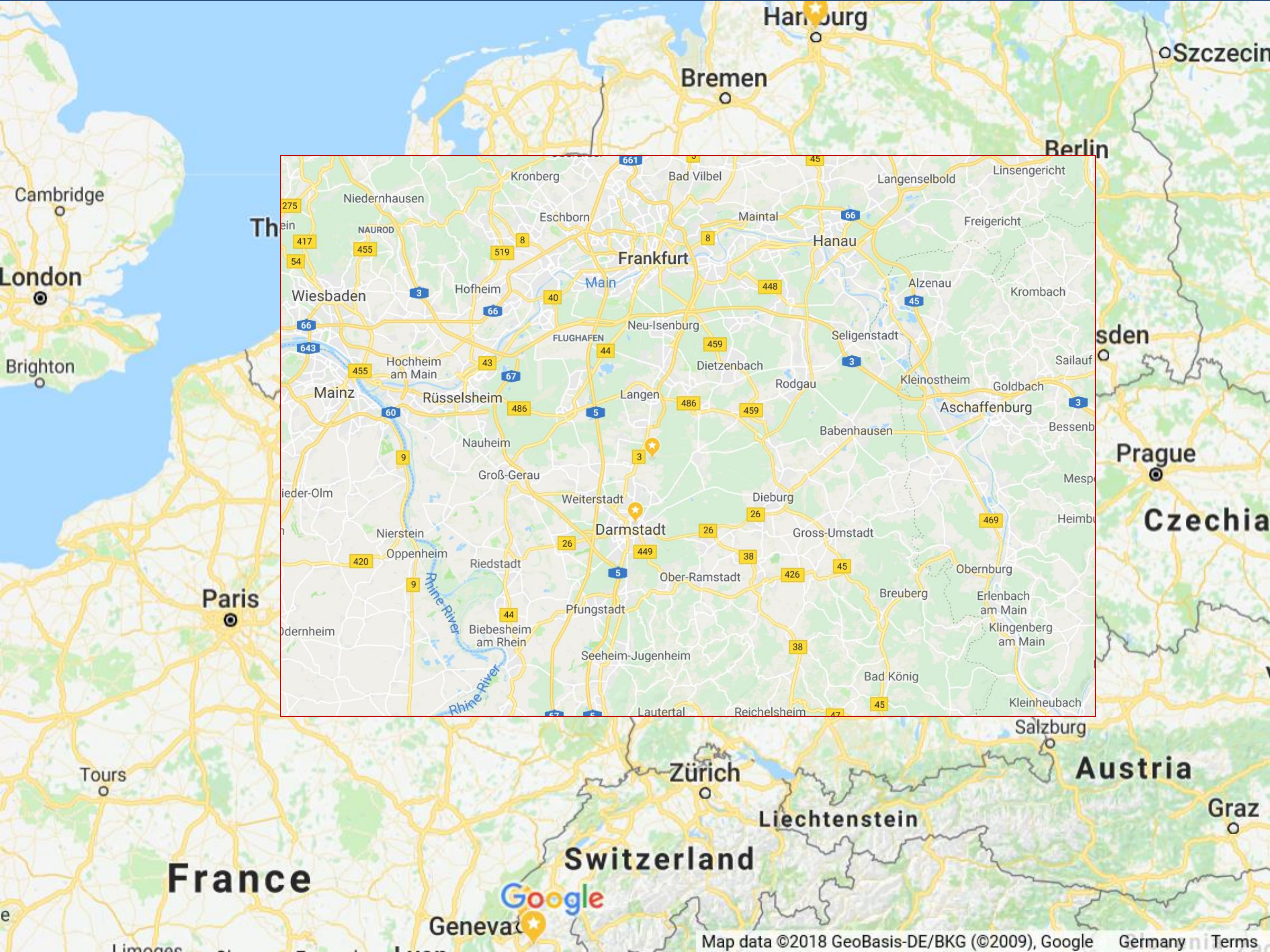
Rüdiger Schmidt 8 January 2018

Slides thanks to E.J.Cho, I.Koop, H.Müller, D.Prasuhn, P.Spiller, R.Steinhagen, P.Szwangruber, M.Winkler, H.Weick and others

FAIR



From a Dummie


Hamburg
Szczecin
Bremen
Berlin
Cambridge
London
Brighton
Paris
Tours
France
Prague
Czechia
Salzburg
Austria
Graz
Zürich
Liechtenstein
Switzerland
Geneva
Kronberg
Bad Vilbel
Langenselbold
Linsengericht
Niedernhausen
Eschborn
Maintal
Freigericht
Hanau
Frankfurt
Main
Wiesbaden
Hofheim
Alzenau
Krombach
Neu-Isenburg
Seligenstadt
FLUGHAFEN
Dietzenbach
Sailauf
Hochheim am Main
Rodgau
Kleinostheim
Goldbach
Mainz
Rüsselsheim
Langen
Aschaffenburg
Babenhausen
Nauheim
Groß-Gerau
Weiterstadt
Dieburg
Darmstadt
Gross-Umstadt
Nierstein
Oppenheim
Riedstadt
Ober-Ramstadt
Obernburg
Breuberg
Erlenbach am Main
Pfungstadt
Biebesheim am Rhein
Klingenberg am Main
Seeheim-Jugenheim
Bad König
Kleinheubach
Rhine River
Lautertal
Reichelsheim
Google
Map data ©2018 GeoBasis-DE/BKG (©2009), Google
Germany
Terms

FAIR construction site - Darmstadt


ERN Bâtiment 180
CERN Bâtiment 30
Route Arago
Route Arago
Route Jentschke
Route Fermi
Route Gregory
Route Cockcroft
Route Cockcroft
Route A Einstein
Route Ruth Fiord
Chemin du Tonkin
C5
D984F
D984F
France
Schweiz
France
Schweiz
France
Schweiz
France
Schweiz
Complexe sportif
de Maisonnex
CERN IdeaSqua
Conseil Européen pour
la Recherche Nucléaire
CERN Post Office
Hôtel du CERN
Google
Imagery ©2018 Google, Map data ©2018 Google Germany

GSI Helmholtz Centre for Heavy Ion Research

Basic and applied research in physics and related natural science disciplines. Main fields of study include

- Plasma physics
- Atomic physics
- Nuclear structure and reactions research
- Biophysics and medical research

Main tools are heavy ion accelerator facilities:

- UNILAC, the Universal Linear Accelerator (energy of 2 - 11.4 MeV per nucleon), commissioned in 1975
- SIS 18, the heavy-ion synchrotron (0.010 - 2 GeV/u), 1990
- ESR, the experimental storage ring (0.005 - 0.5 GeV/u), 1990

Medical applications

Use of heavy ion beams for cancer treatment (from 1997)

- Instead of using X-ray radiation, carbon ions are used to irradiate the patient.
- The technique allows tumours which are close to vital organs to be treated, which is not possible with X-rays. This is due to the fact that the Bragg peak of carbon ions is much sharper than the peak of X-ray photons.
- A facility based on this technology, called Heidelberger Ionenstrahl-Therapiezentrum (HIT), built at the University of Heidelberg Medical Centre began treating patients in November 2009

Other installations

- Two high-energy lasers, the nhelix (Nanosecond High Energy Laser for Heavy Ion Experiments) and the Phelix (Petawatt High Energy Laser for Heavy Ion Experiments)
- FRagment Separator (FRS) – (1990) produces and separates different beams of (usually) radioactive ions.
  - Beam accelerated by UNILAC and SIS18 impinging on a production target.
  - From the target, many fragments are produced. The secondary beam is produced by magnetic selection of the ions.
- Experimental Storage Ring (ESR) in which large numbers of highly charged radioactive ions can be stored for extended periods of time. This facility provides the means to make precise measurements of their decay modes. The discovery of a mysterious new phenomenon is known as the GSI anomaly.

GSI History

- **1969** Foundation of Gesellschaft für Schwerionenforschung mbH
- **1975** First experiments with linear accelerator UNILAC
- **1981** until **2010** Discovery of six new chemical elements and their official recognisation by IUPAC in the Periodic Table of the Elements: Bohrium, Hassium, Meitnerium, Darmstadtium, Röntgenium, Copernicium
- **1990** Commissioning of the ring accelerator SIS-18 and the storage ring ESR
- **1997** First patient treatment with carbon ions at GSI therapy facility
- **2003** Green light for the new accelerator facility FAIR
- **2007** FAIR Start Event – official start of the project
- **2008** Commissioning of the PHELIX laser system
- **2009** Opening of the Heidelberg Ion-Beam Therapy Center (HIT)
- **2010** Foundation of FAIR GmbH, GSI holds a share of 75 percent

GSI Facts

- Employees of GSI and FAIR: 1,400 employees
- Scientific users of the FAIR facility: 3000 researchers from 50 countries
- Total cost of FAIR: 1,262 million Euro plus 95 million Euro site-related costs, thus overall cost frame 1,357 million Euro (price level of 2005 respectively)
- FAIR is in principle a company ……

FAIR
Facility for Antiproton and Ion Research in Europe GmbH

Partners

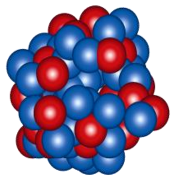
Partner States

- DE - Germany
- FI - Finland
- FR - France
- IN - India
- PL - Poland
- RO - Romania
- RU - Russia
- SE - Sweden
- SI - Slovenia
- UK - United Kingdom

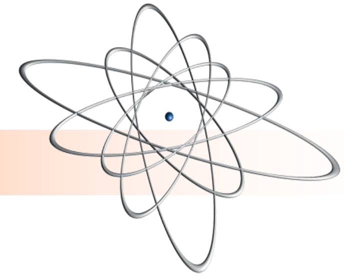
Main Physics Programme

Nuclear Physics & Physics with Hadrons

- Nuclear Reaction from lowest to highest Energies
- Super-heavy Elements
- Compressed Baryonic Matter
- Anti-matter Research
- new: PANDA (QCD)



Atomic Physics

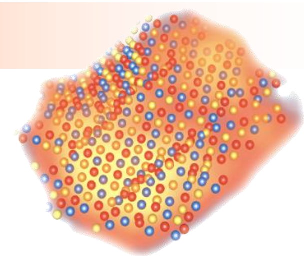


- Atomic Interactions
- Precision Spectroscopy of highly charged Ions

Bio-Physics and Bio-Medical Applications

- Radiobiological effects of ions
- Cancer therapy with ion-beams

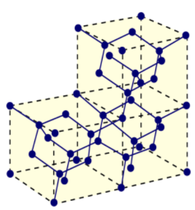
Plasma Physics



- Hot dense Plasmas
- Ion-Plasma Interactions

Material Science

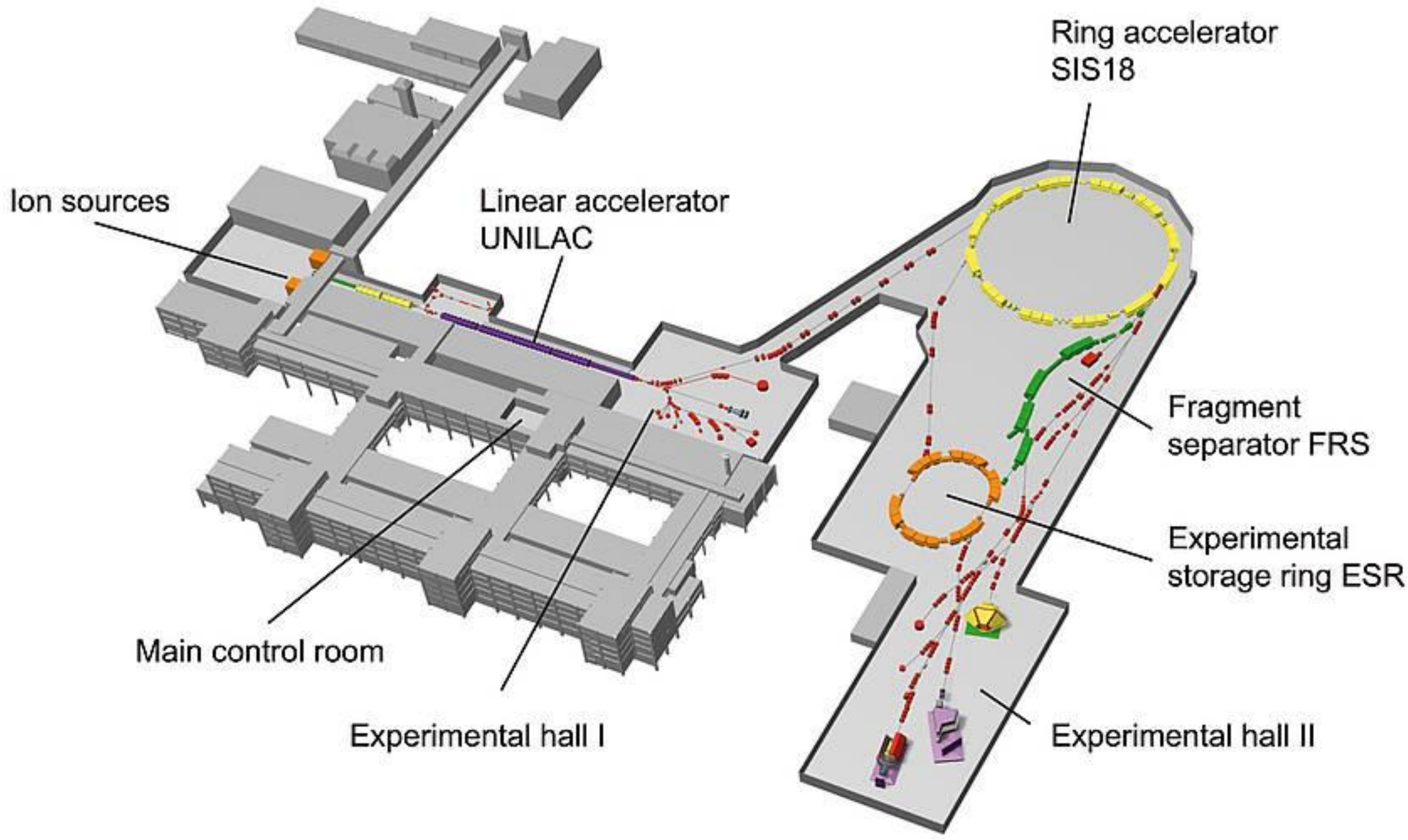
- Ion-Condensed-Matter Interactions
- Nano-structures using ion-beams



Accelerator Technology

- Linear accelerators
- Synchrotrons and Storage Rings

Existing GSI accelerator complex

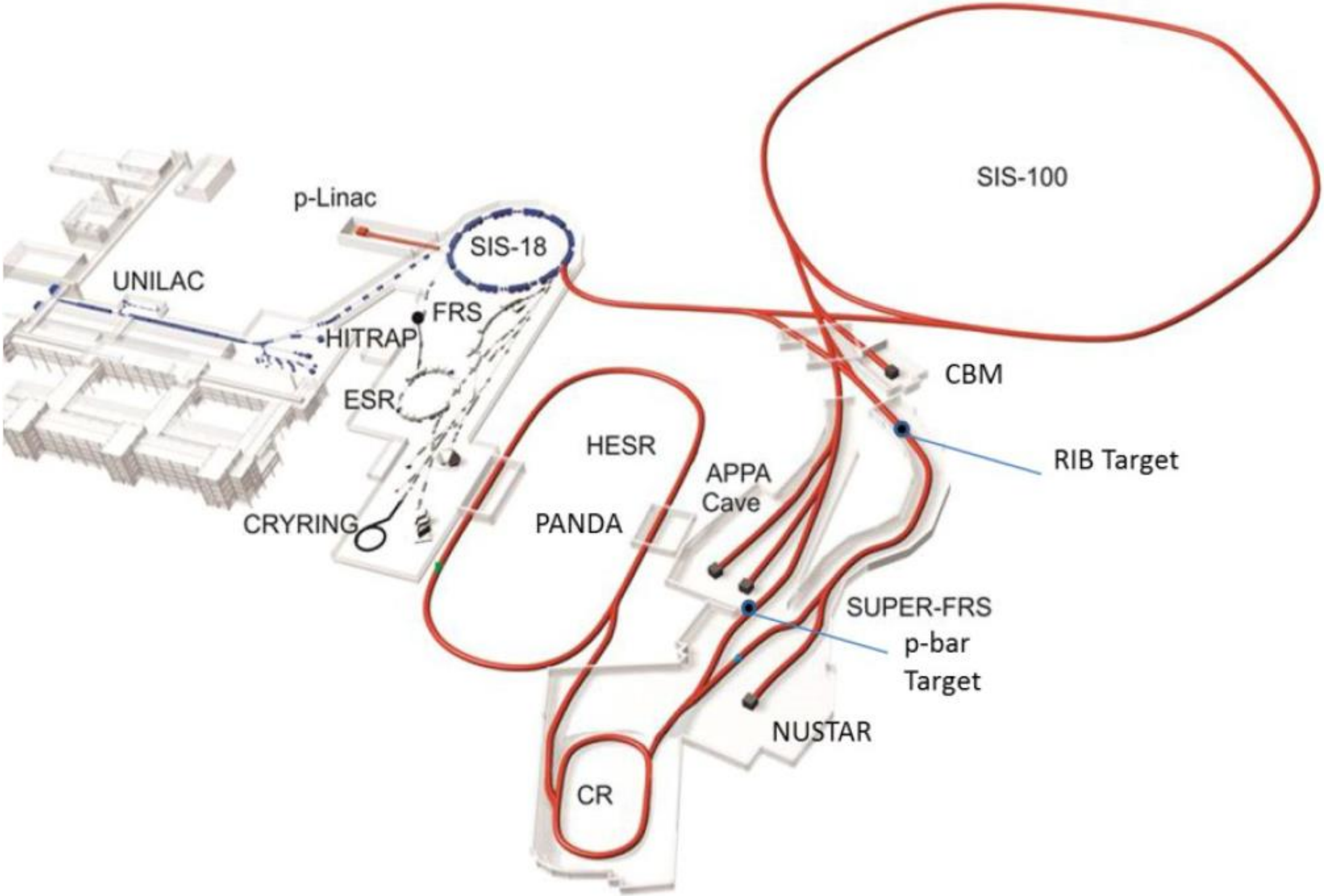


New FAIR accelerator complex

- UNILAC – Linear accelerator for ions and protons
- P-LINAC - Linear accelerator for protons
- SIS 18 - Synchroton accelerating protons and ions
- SIS 100 – Synchroton accelerating protons and ions
- SuperFRS –Super Fragment Separator
- CR – cooler ring
- HESR – High Energy Storage Ring
- HEBT - High Energy Beam Transport

- Antiproton production target at SIS 100
- Ion production target at SIS 100

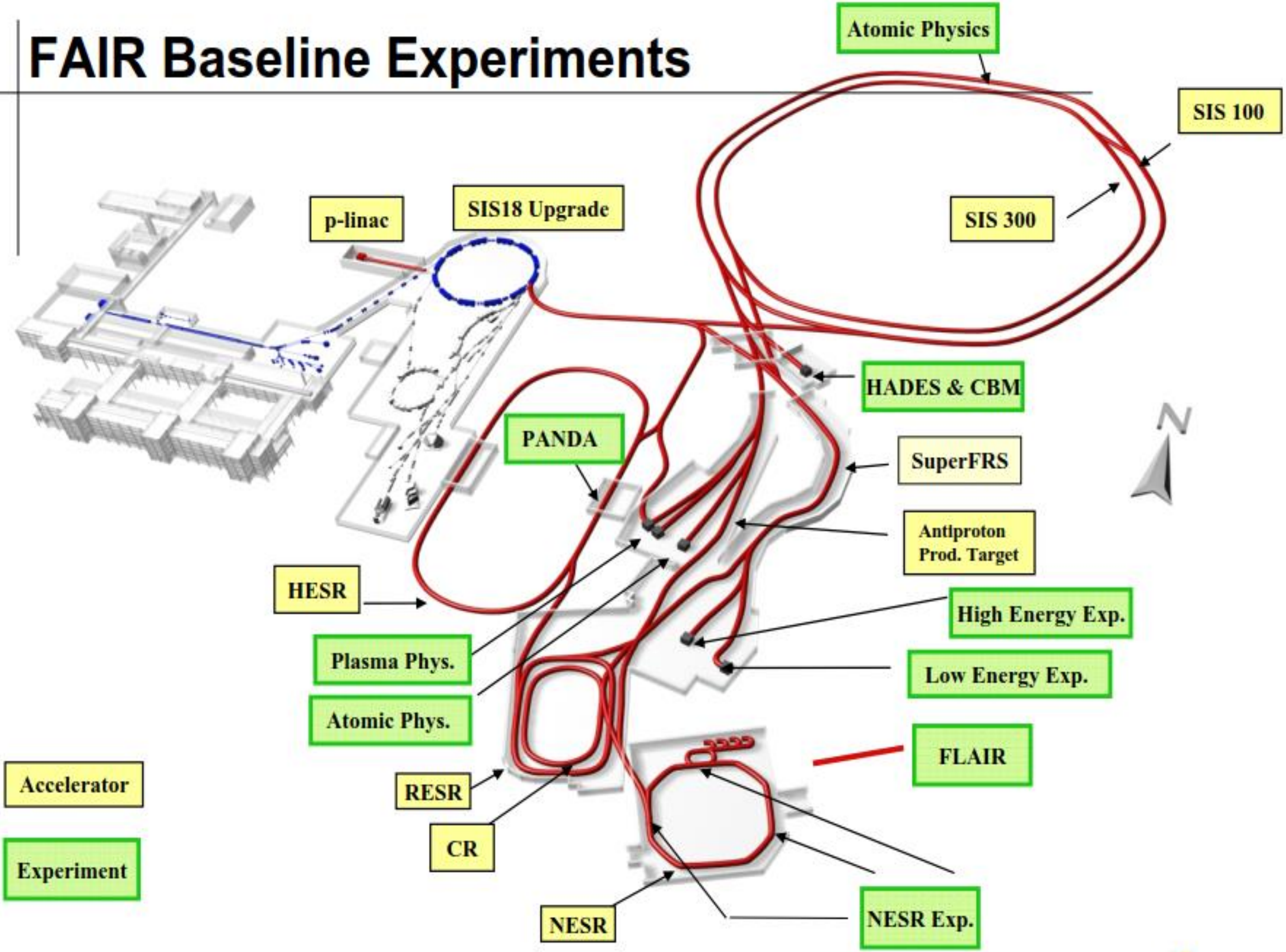
Layout


p-Linac
SIS-18
UNILAC
FRS
HITRAP
ESR
CRYRING
SIS-100
CBM
RIB Target
HESR
APPA
Cave
PANDA
SUPER-FRS
p-bar
Target
NUSTAR
CR

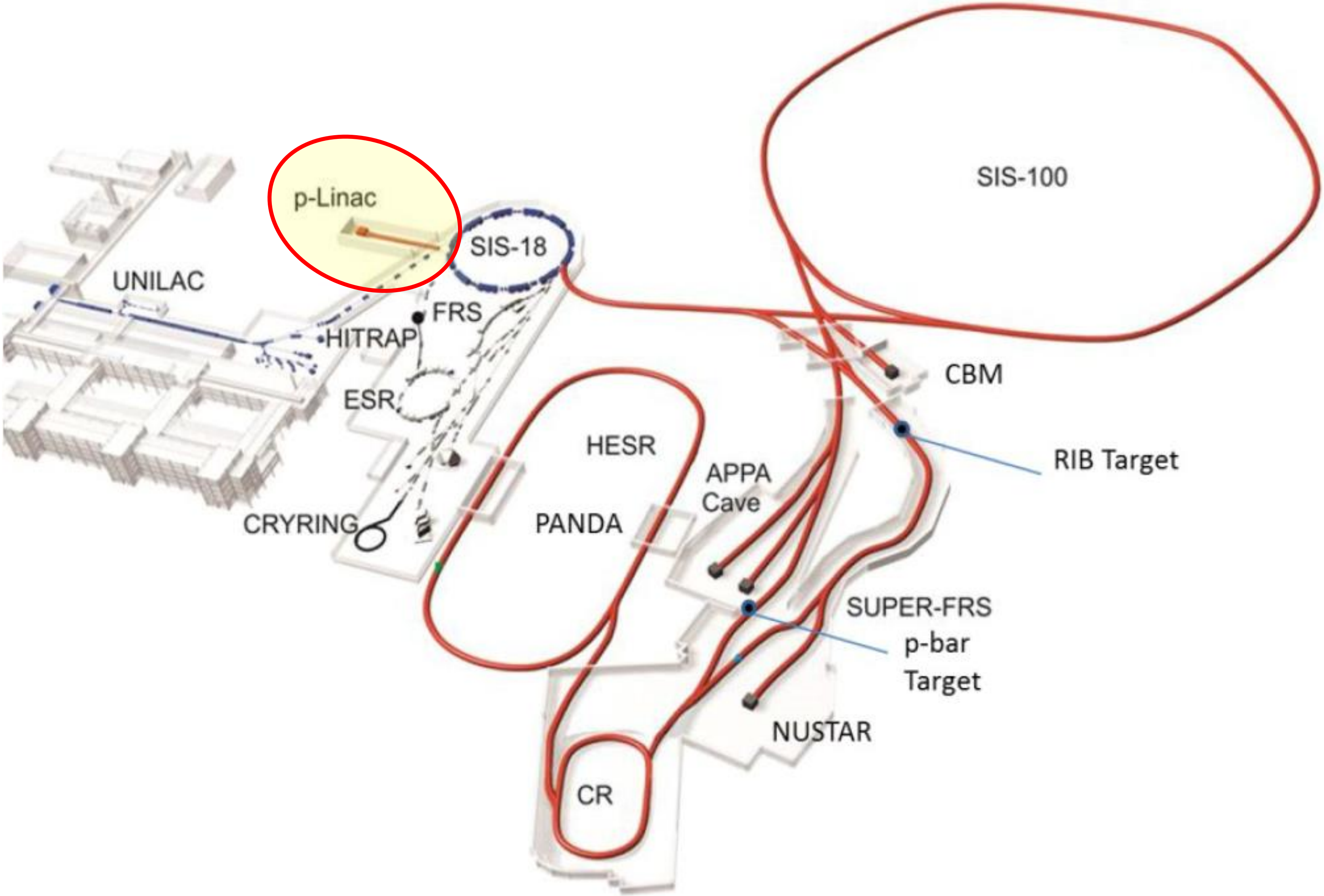
FAIR experiments

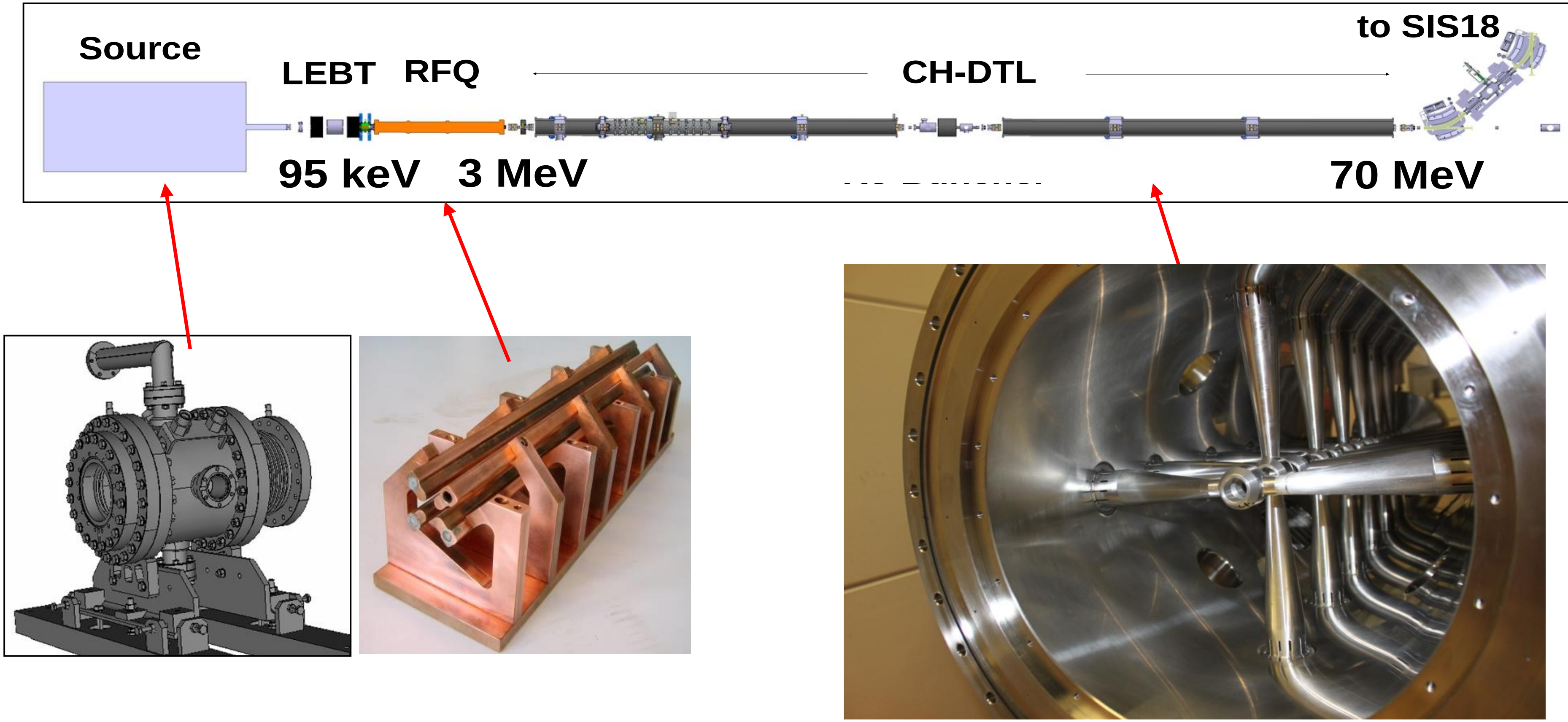
- **NUSTAR**: 2×10^{11}/pulse U^{28+} @ 400-1500 MeV/u
  bunch compression to 70 ns
  highest gain factors for exotic nuclear beams
- **CBM**: Heavy-ion beam intensities of 10^{10} particles/s
  @ 11 (34@SIS300) GeV/u for U^{92+}
- **PANDA**: pbar in wide momentum range (1.5 - 15 GeV/c)
  High luminosity and high momentum resolution
- **FLAIR**: Cooled antiprotons in the 20 keV range
- **SPARC**: Cooled and high brilliance beams of rare isotopes
- **Plasma Physics**: High intensity beams, bunch compression to 70 ns

FAIR Baseline Experiments



GSI


p-Linac
SIS-18
UNILAC
FRS
HITRAP
ESR
CRYRING
SIS-100
CBM
RIB Target
HESR
APPA
Cave
PANDA
SUPER-FRS
p-bar
Target
NUSTAR
CR



- ECR proton source & LEBT
- 4-rod RFQ, 325.224 MHz
- 6 accelerating cavities, 35 mA beam current
- 5 MW of beam loading (peak), 710 W (average)
- 11 MW of total rf-power (peak), 1600 W (average)

FAIR Ring Accelerator Parameters

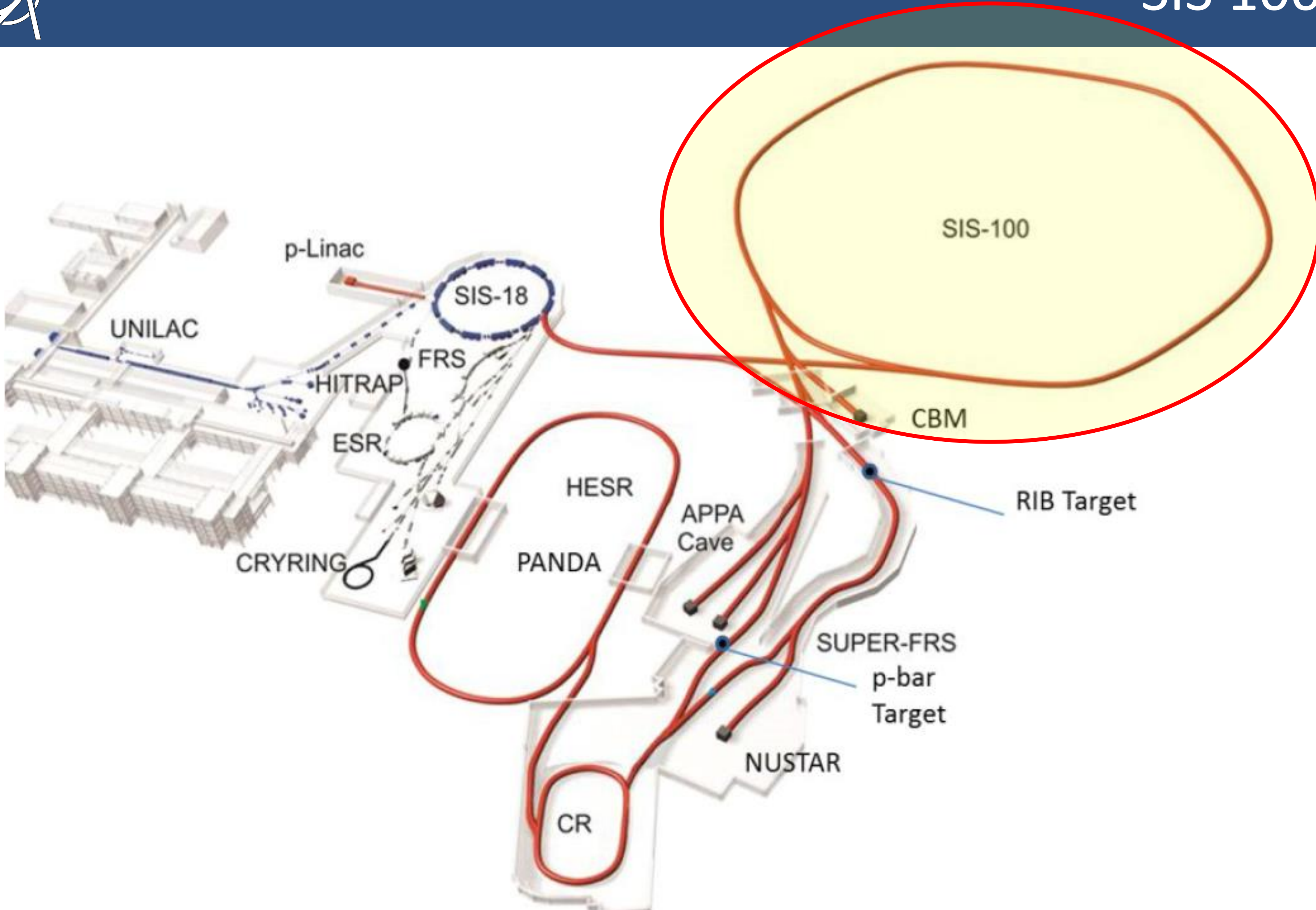
	SIS18	SIS100	CR	HESR
Circumference [m]	216	1083	215	575
Max. beam magnetic rigidity [Tm]	18	100	13	50
Injection energy of protons or anti protons [GeV]	0.07	4	3	3
Final energy of protons or antiprotons [GeV]	4	29	3	14
Injection energy of heavy ions [GeV/u]	0.0114	0.2	0.74	0.74
Final energy of heavy ions U(28+) [GeV/u]	0.2	2.7		
Final energy of heavy ions U(/73+/92+) [GeV/u]	1	11	0.74 (92+)	0.2-4.9 (92+)
Max. beam intensity for protons or antiprotons /cycle	$5*10^{12}$	$2*10^{13}$	10^{8}	10^{10}
Max. beam intensity of ^{238}U-ions /cycle	$1.5*10^{11}$	$5*10^{11}$	10^{8}	10^{8}
Required static vacuum pressure [mbar]	$< 10^{-11}$	$<5*10^{-12}$	$<10^{-9}$	$<10^{-9}$

LHC = ~24000

Main FAIR challenges:

- Control of highest proton and (unprecedented) uranium ion intensities
- Excellent XHV vacuum conditions
- Very fast cycling in SIS100 (4 T/s)

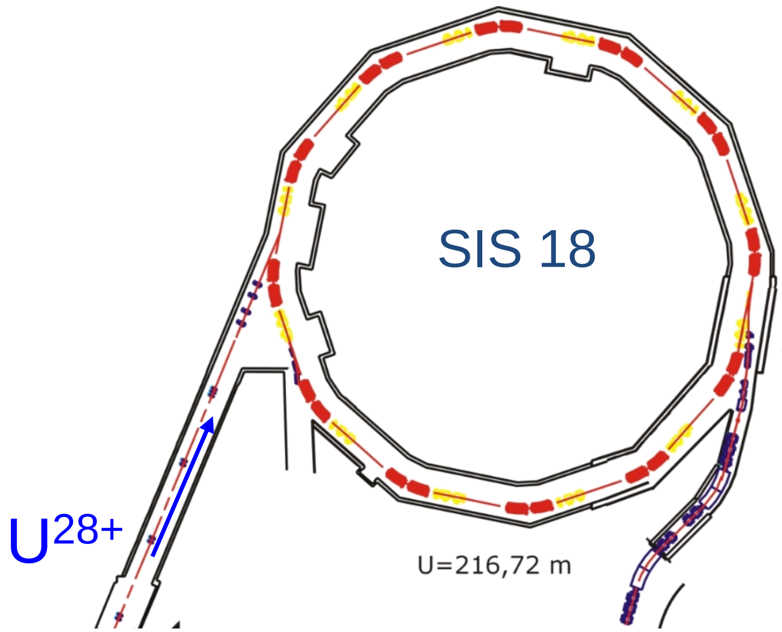
SIS 100



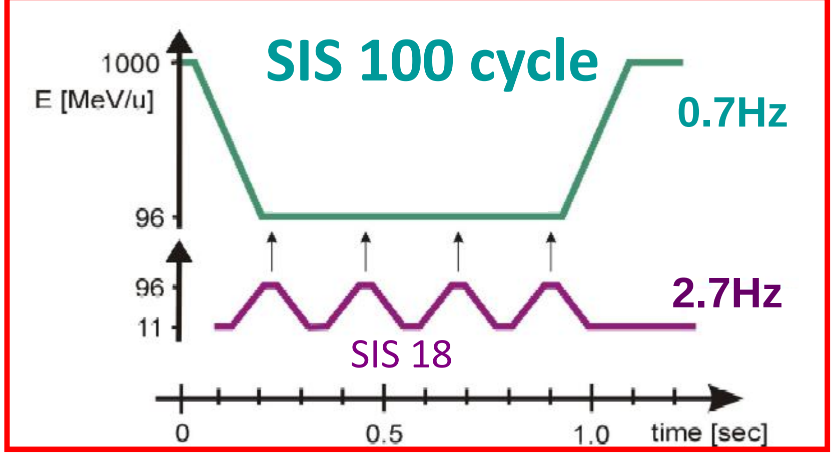
SIS-100
p-Linac
SIS-18
UNILAC
FRS
HITRAP
ESR
CBM
HESR
RIB Target
APPA
Cave
CRYRING
PANDA
SUPER-FRS
p-bar
Target
NUSTAR
CR

- Accelerating high intensity ion beams
- Accelerating high intensity proton beams
- Slow extraction
- Fast extraction
- Bunch manipulations
- Very fast cycle

- Injection from SIS18
- Superconducting magnets
- Challenging vacuum

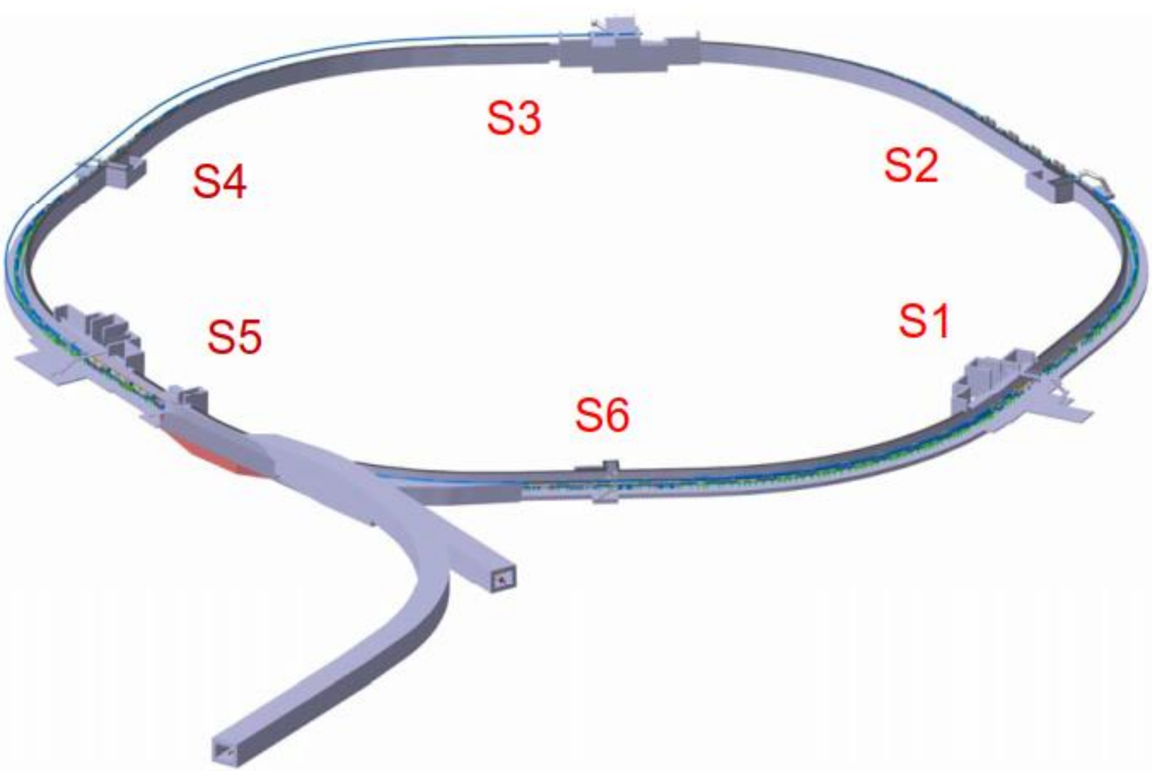


To exceed the existing space charge limits in SIS18 and to reach the desired intensities in SIS100, the charge state of Uranium beams had to be lowered from the presently used charge state 73 down to charge state 28



Sixfold Symmetry

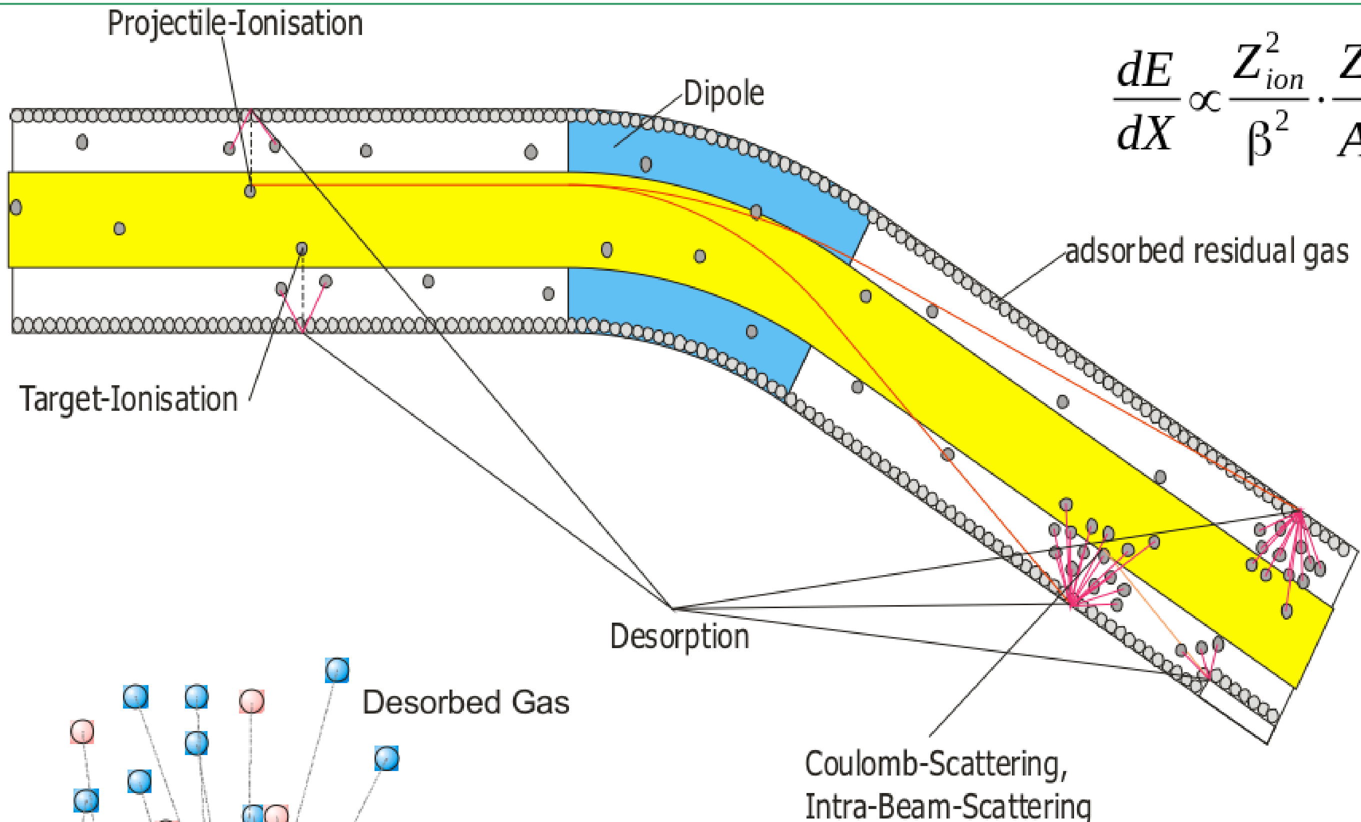
- Sufficiently long and number of straight sections
- Reasonable line density in resonance diagram
- Good geometrical matching to the overall topology



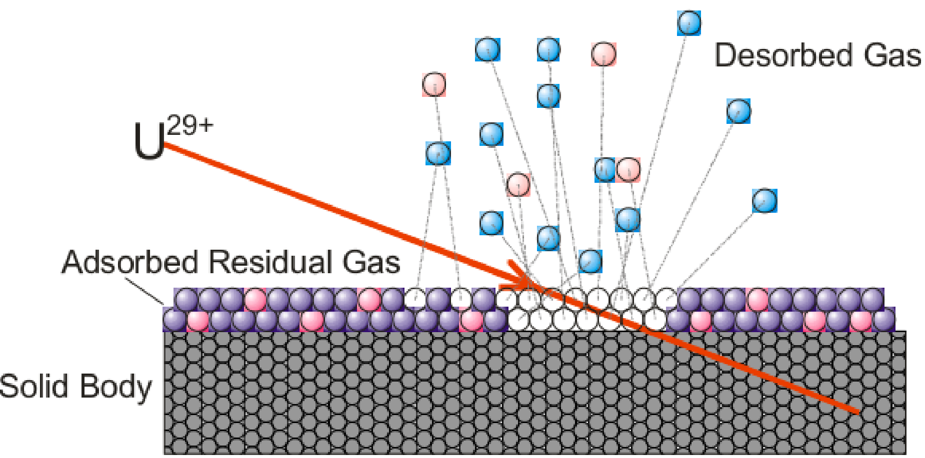
S1: ~~Transfer to SIS300~~
S2: Rf Acceleration (Ferrite loaded)
S3: Rf Acceleration (Ferrite loaded)
S4: Rf Compression (MA loaded)
S5: Extraction Systems (slow and fast)
S6: Injection System plus RF Acceleration and Barrier Bucket

The SIS100 technical subsystems define the length of the straight sections of both synchrotrons

Dynamic Vacuum Pressure



$$\frac{dE}{dX} \propto \frac{Z_{ion}^2}{\beta^2} \cdot \frac{Z_{gas}^*}{A_{gas}^*}$$

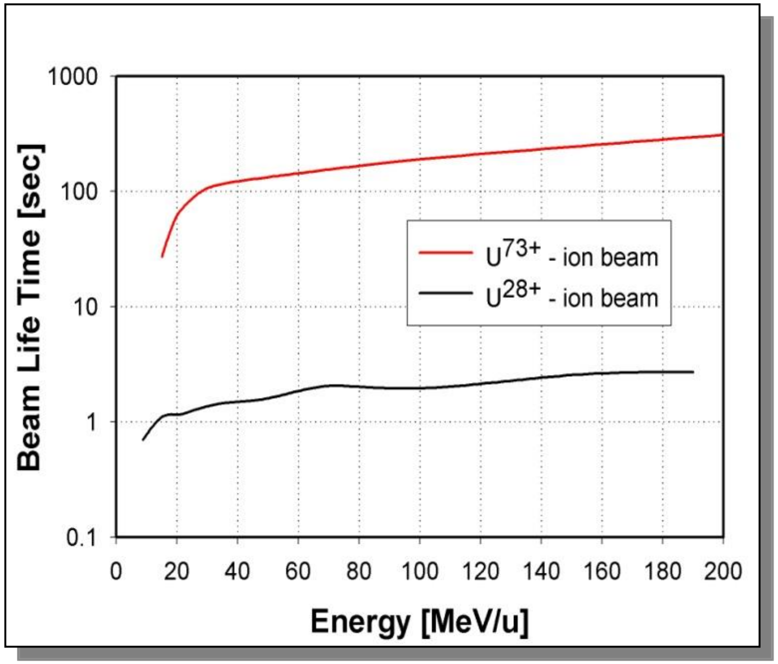


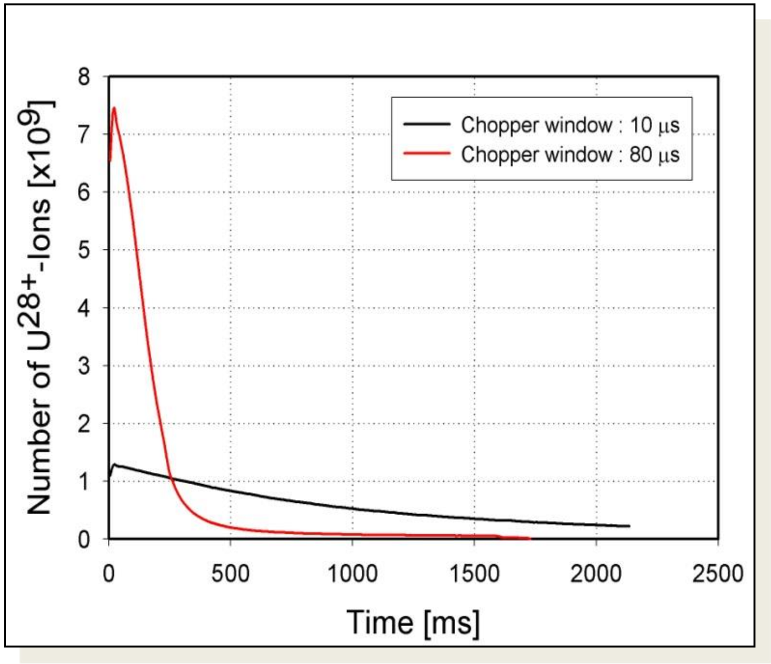
Dynamic pressure:

$$\frac{dP}{dt} = \frac{P - P_0}{\tau_p} + \alpha\, \eta_{loss}\, NP$$

H. Kollmus et al., J. Vac. Sci.(2009)

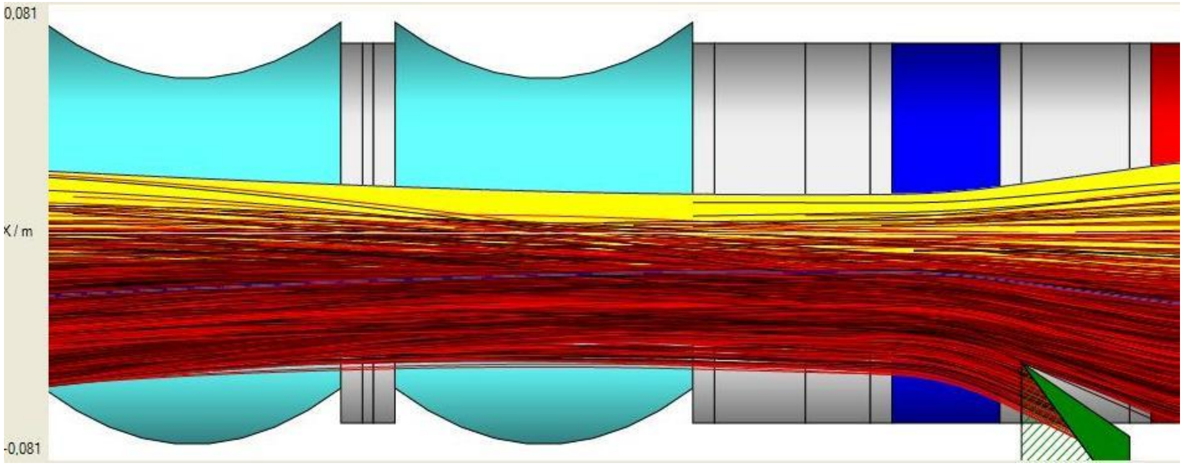
Ionisation and Dynamic Vacuum





- Lifetime of U28+ is significantly lower than of U73+
- Lifetime of U28+ depends strongly on residual gas pressure and composition

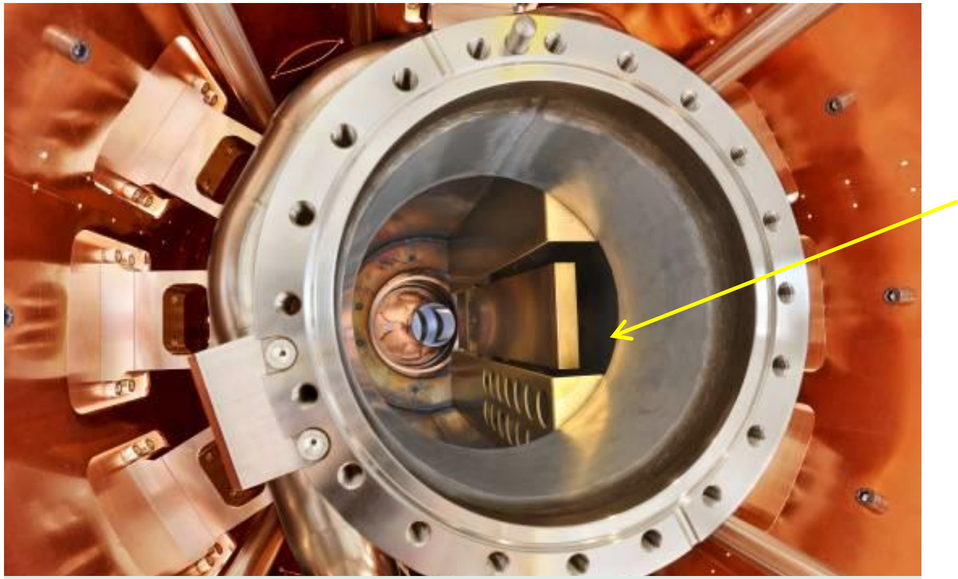
- Ion induced gas desorption (multiplication of 10000) increases the local pressure
- Beam loss increases with intensity (dynamics vacuum, vacuum instability)



- U29+ loss positions are peaked by design at cryo - aborbers (collimators)
- Doublet focusing structure

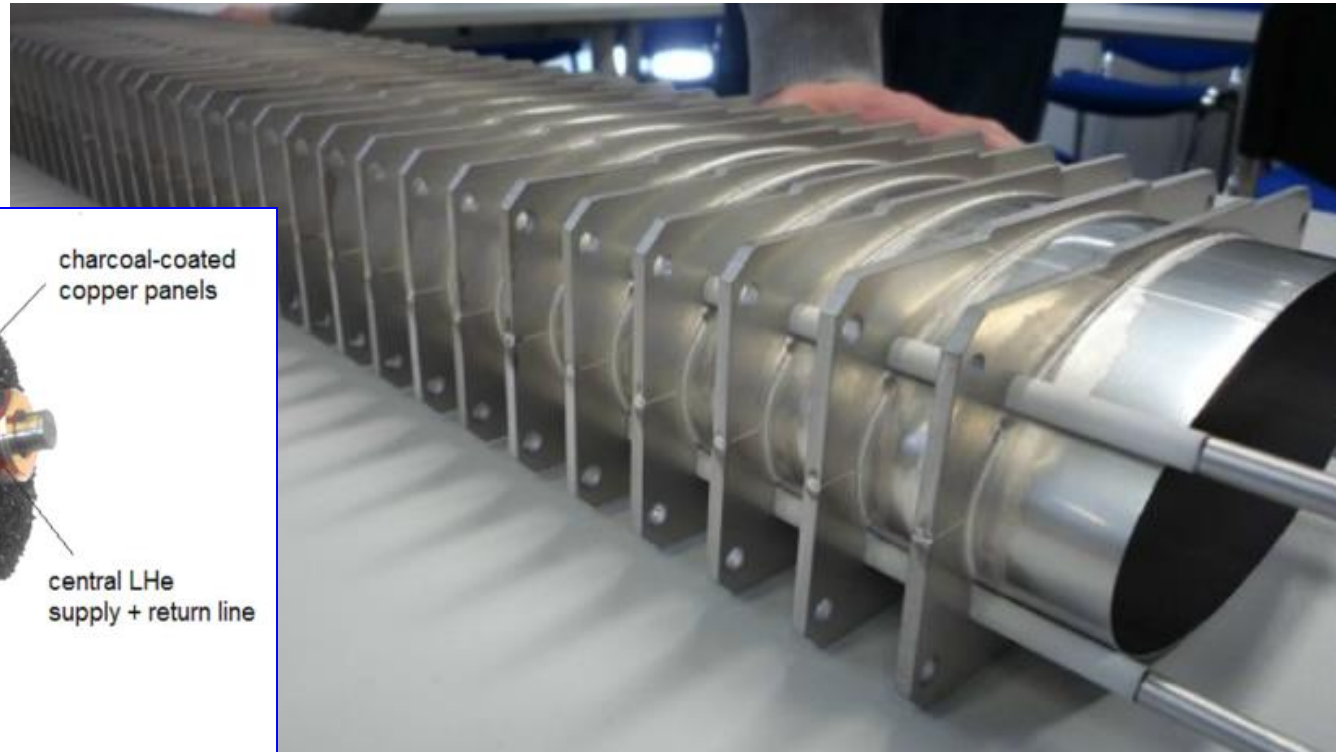
Dynamic vacuum requires huge pumping speed:

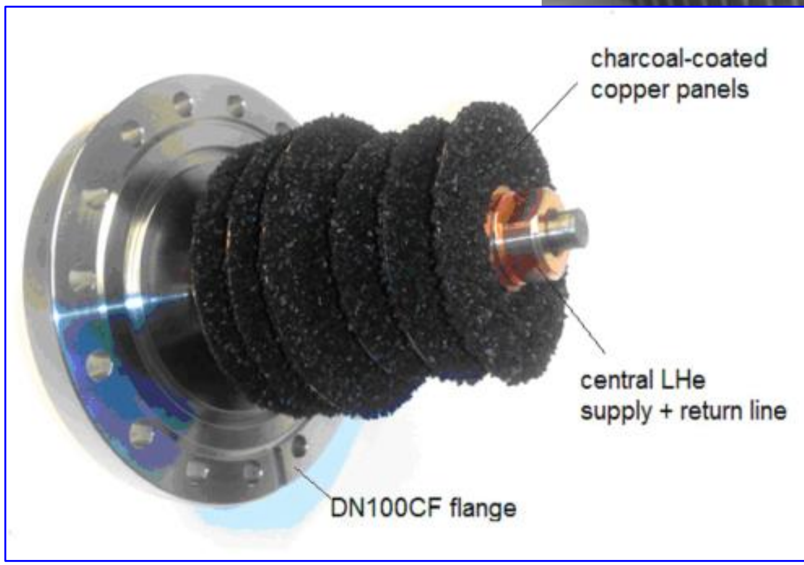
- Cryogenic vacuum chambers, principal reason why SIS100 is cold → super-conducting magnets
- NEG-coating of most warm vacuum chambers



Ion catcher (at 50 K) in secondary chamber with enhanced pumping, confines most desorbed gases

Vacuum chamber





- Thin wall to avoid heating and field distortions by Eddy currents
- Must be cooled to below 15 K, to capture all gases – done by helium cooling tubes
- Mechanical stability required (reinforcement)
- Design parameters not fully achieved

SIS100 versus LHC

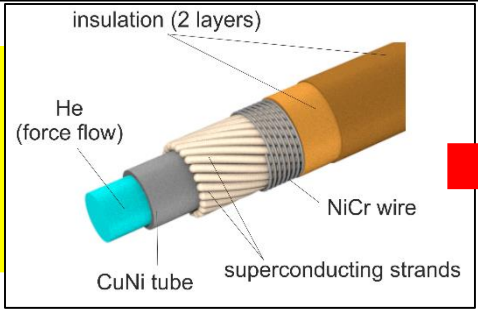
Parameters of superconducting dipole circuit of LHC and SIS100

Machine	LHC	SIS100
Number of magnets	154/circuit	108
Number of power converters	1/circuit	2
Nominal current (kA)	11.85	13.1
Nominal ramp rate (A/s)	10	28000
Total inductance of the circuit (mH)	$154 \times 2 \times 51 =$ $= 15.7 \times 10^3$	$108 \times 0.55 =$ $= 59.4$
Inductive voltage at cycling (V) per twin dipole / overall in the circuit	$1/ \approx 160$	$15.4/ \approx 1660$
Energy extraction system	$2 \times R_d$ per circuit	12 $6 \times R_d$
Cold by–pass	cold diode per twin dipole	none
Quench back heaters	on each coil	none

SIS100 is a fast cycling machine with extremely high ramp rate!

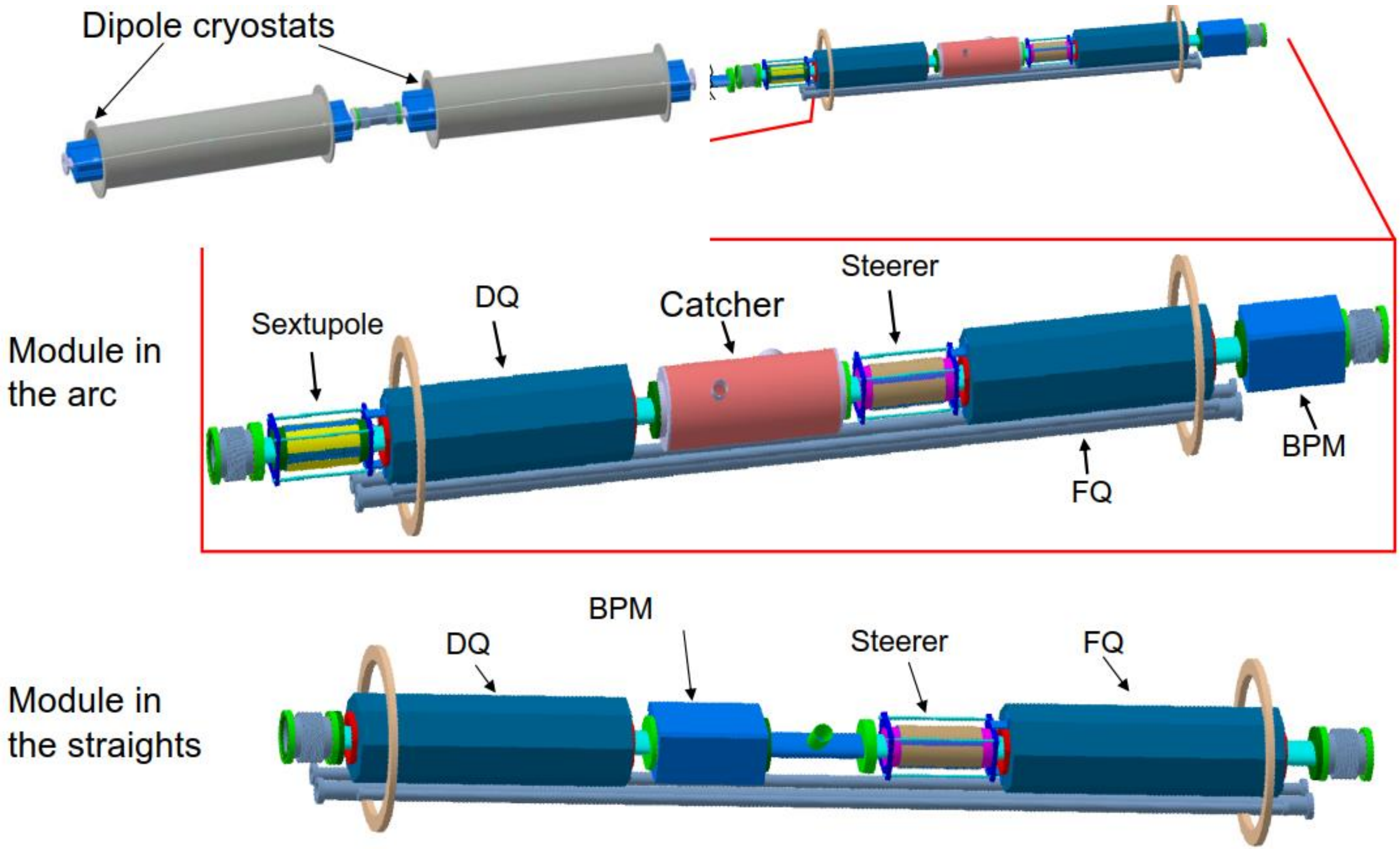
Protection system of SIS100 considers only extraction resistors (no heaters)

SIS100: low AC loss superconducting cable (Nuclotron type), NbTi/CuMn

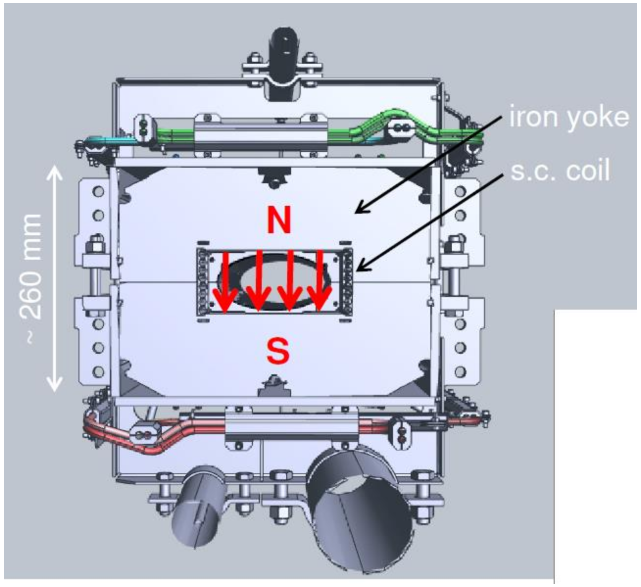


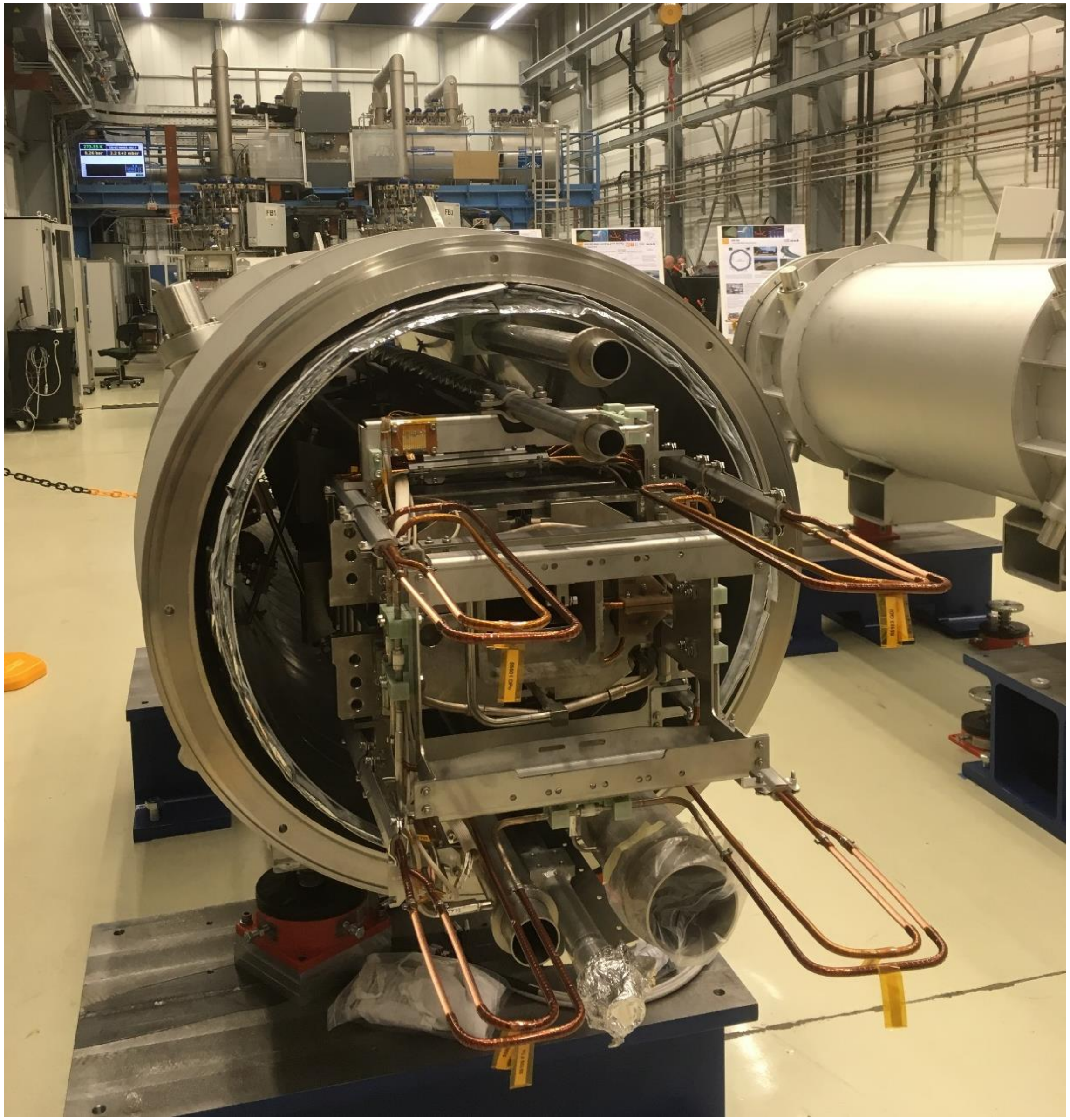
Quench back effect is not expected! If a single magnet quenches, other magnet will not quench due to high d*i*/d*t* at current dumping (very low probability).

Principle Cell Layout

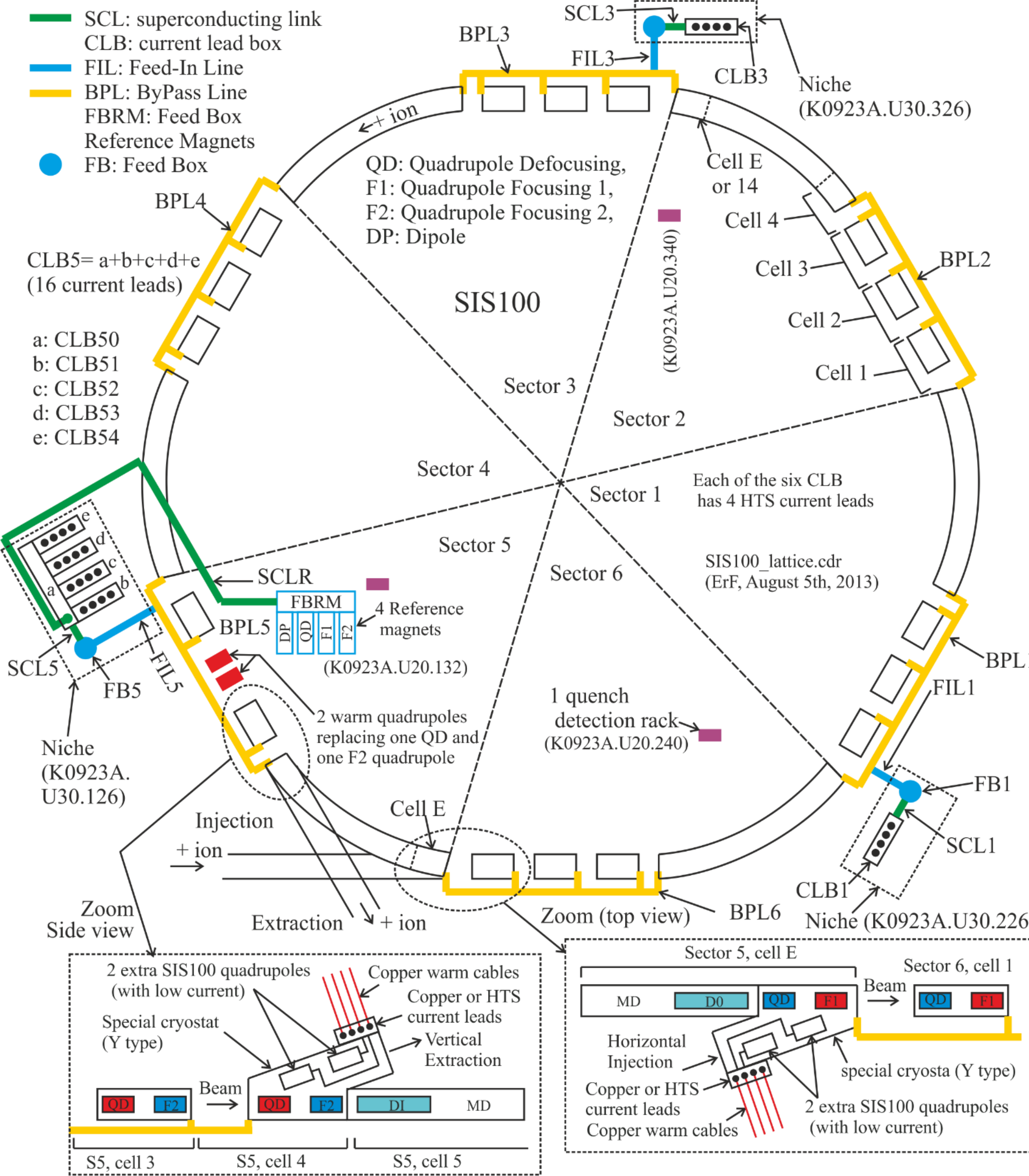


Superconducting dipole magnet SIS100

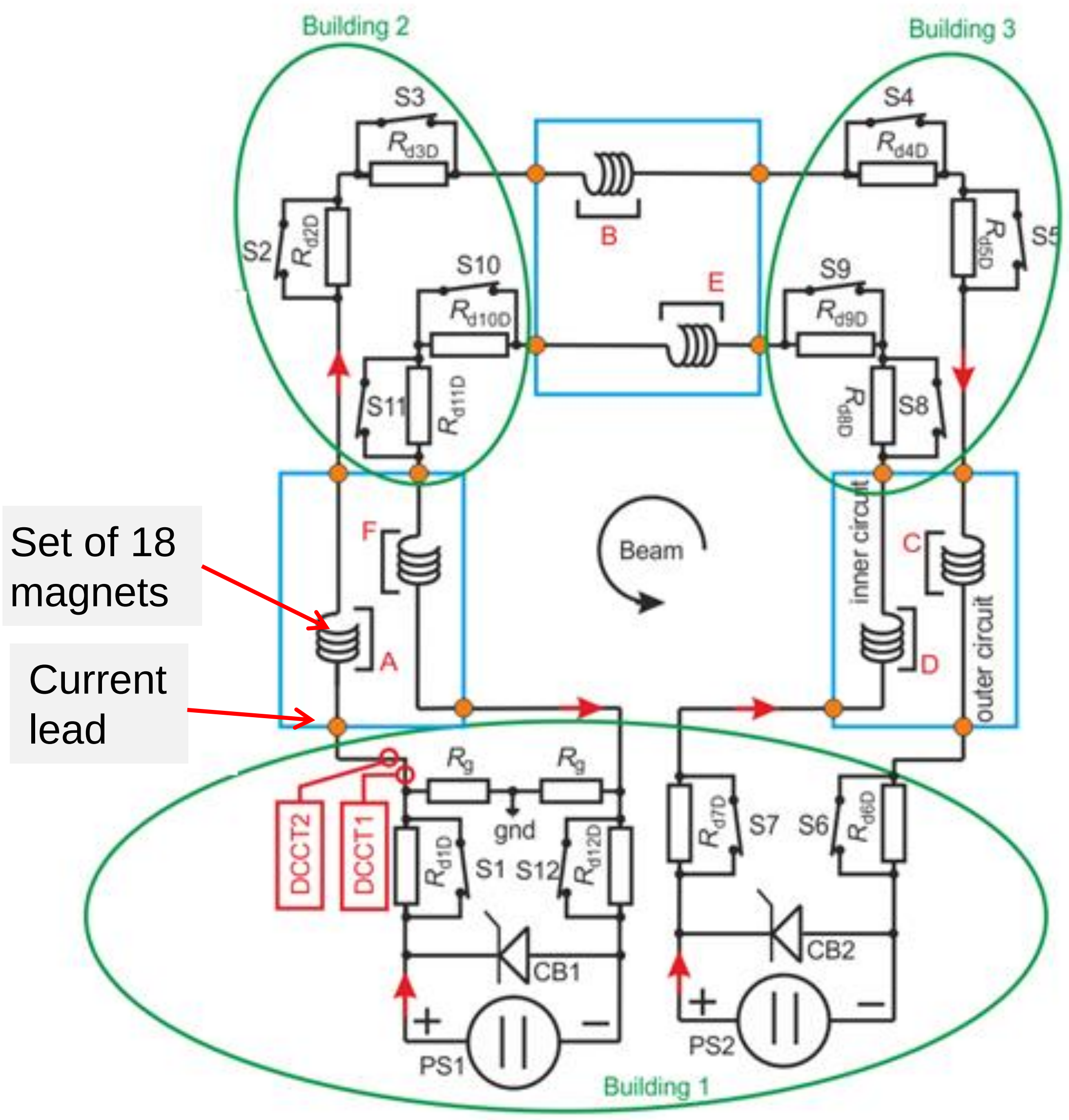




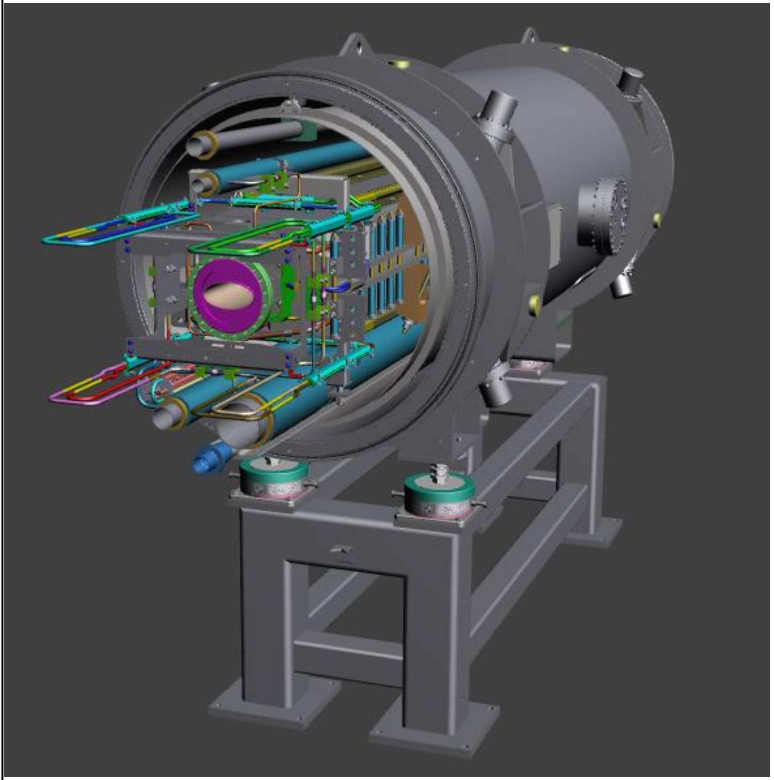
SIS 100 layout



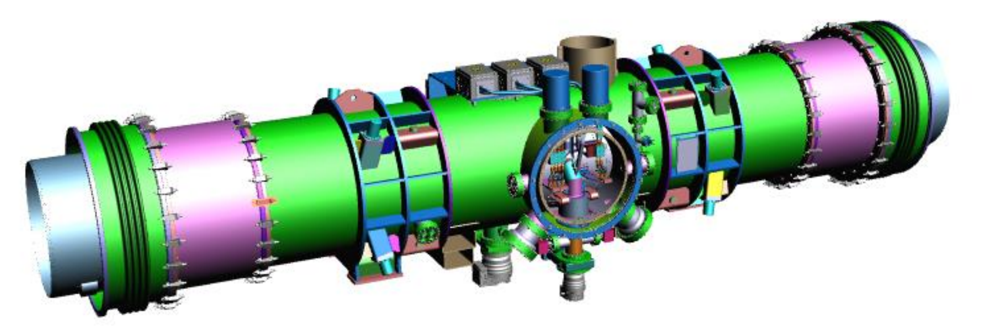
SIS100 Dipole Circuit



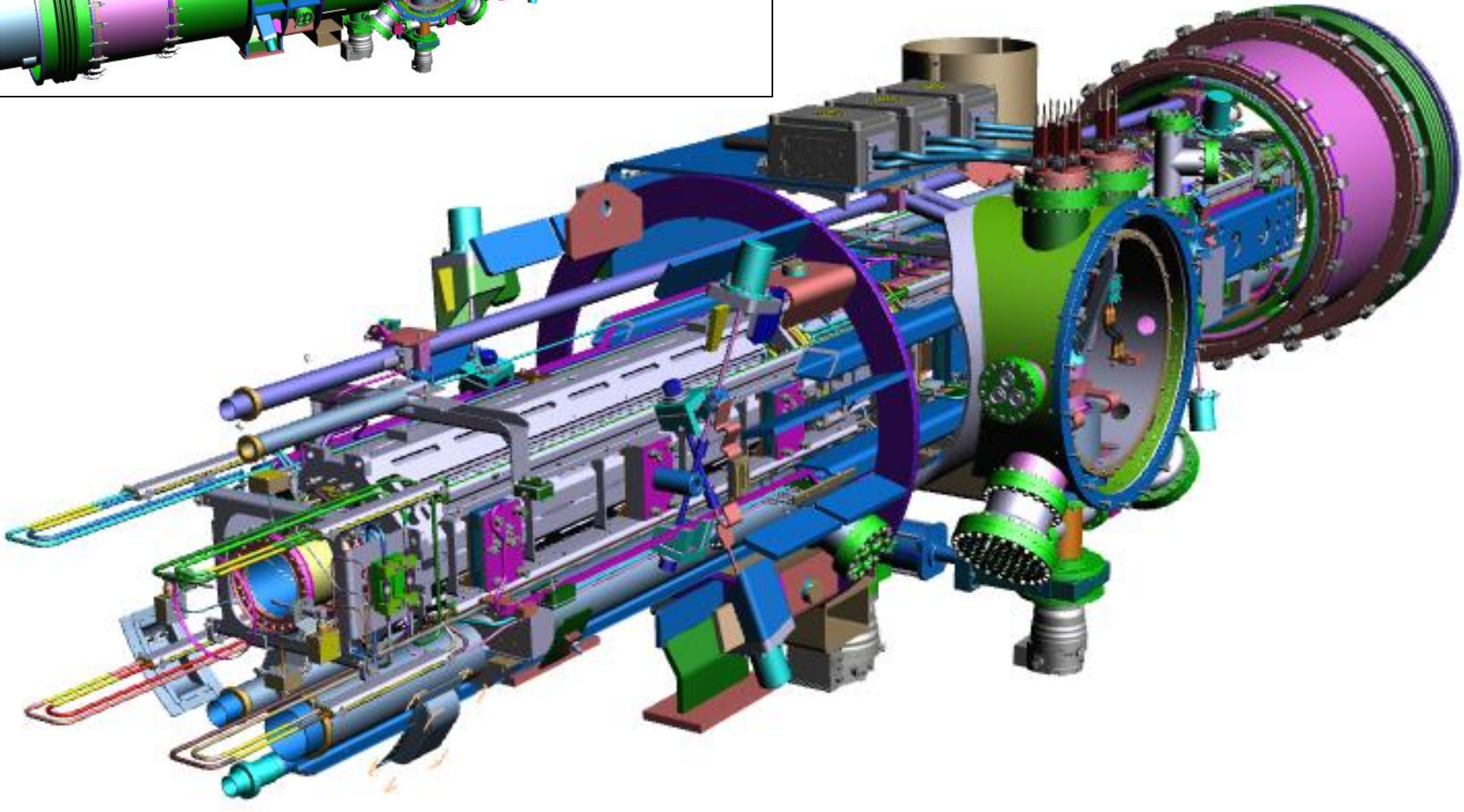
*I*n = 13.2 kA
108 magnet connected in series
12 energy extraction resistors (67 mΩ, 5%)
IGBT DC circuit breakers

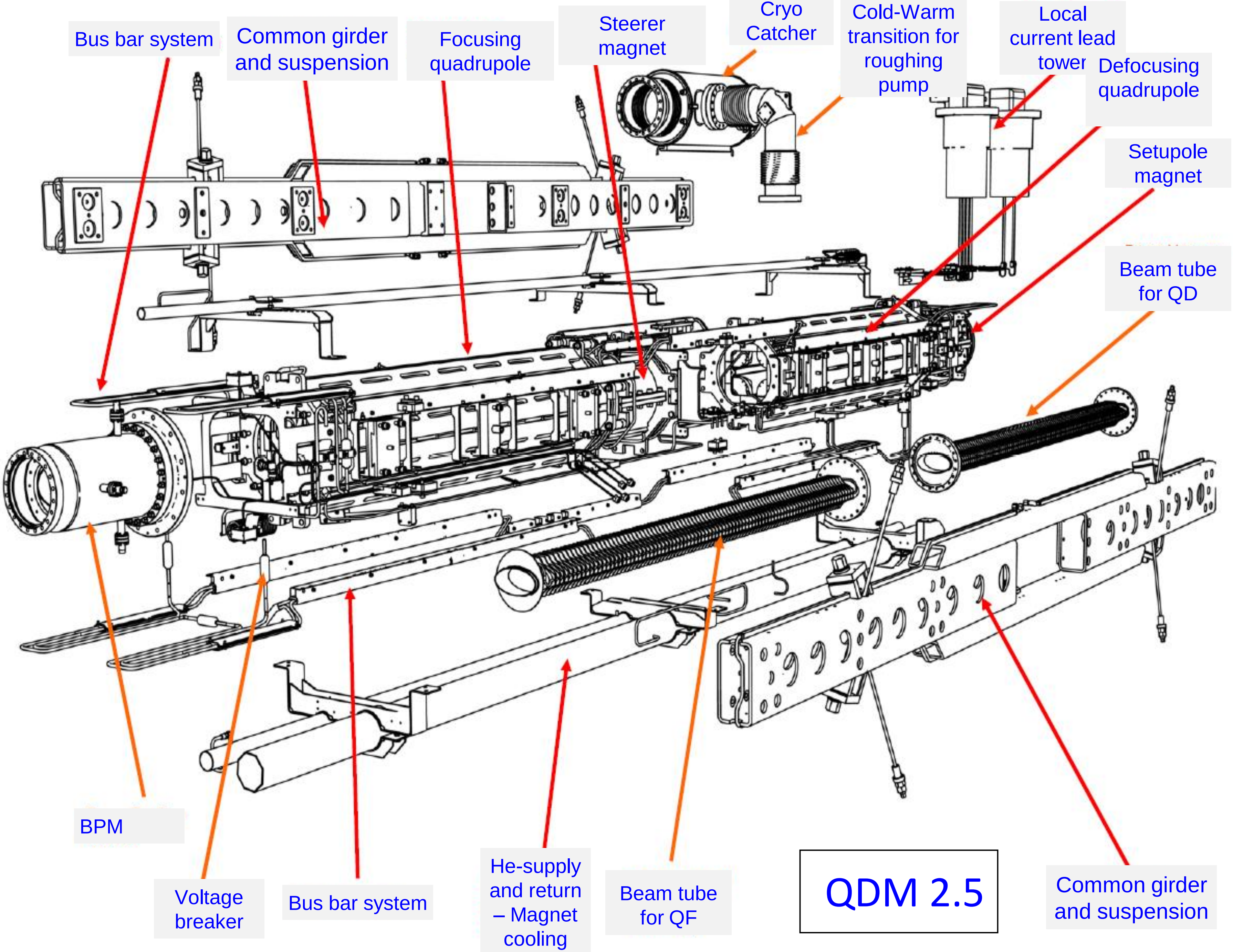


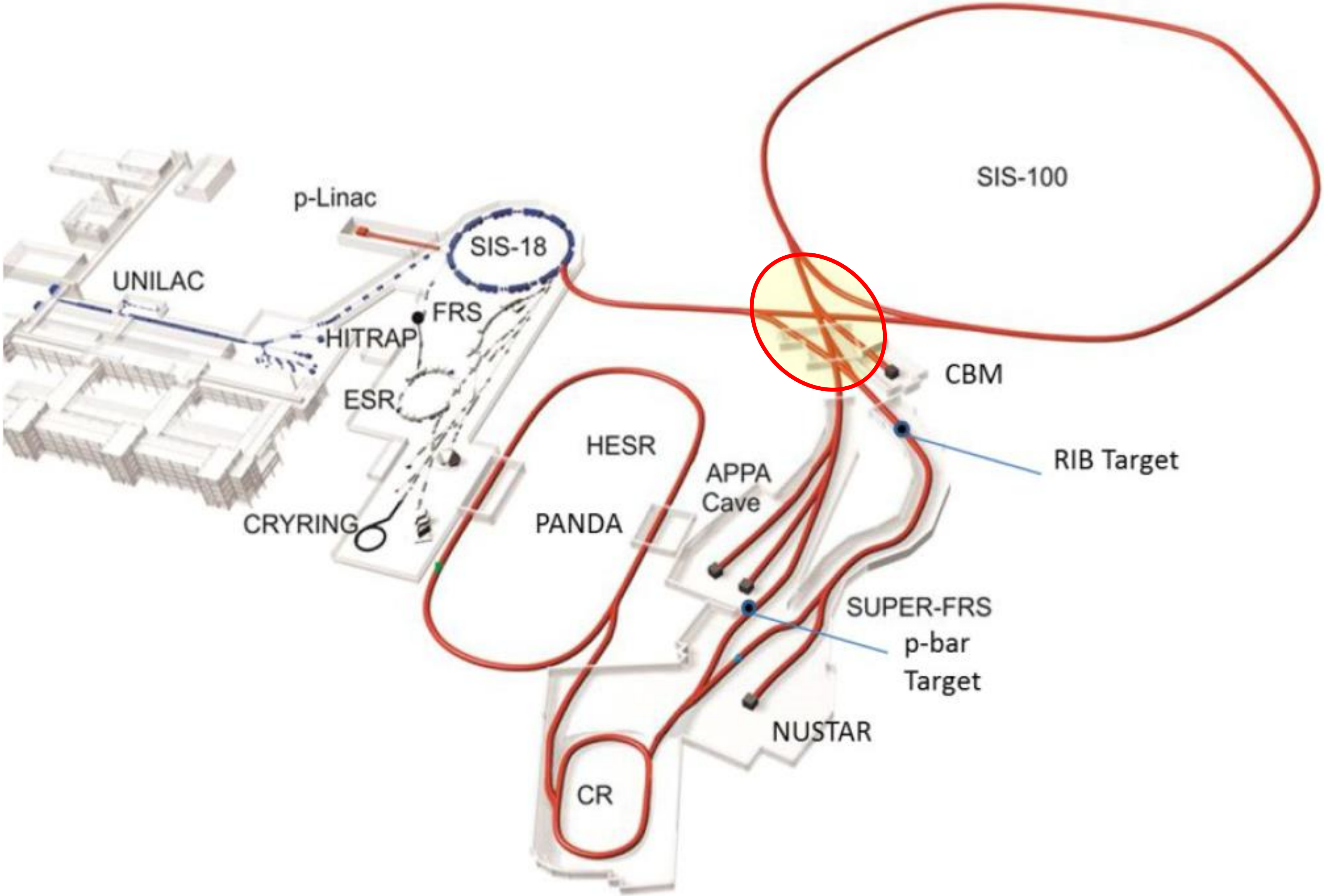
Quadrupole Doublet Module (QDM)



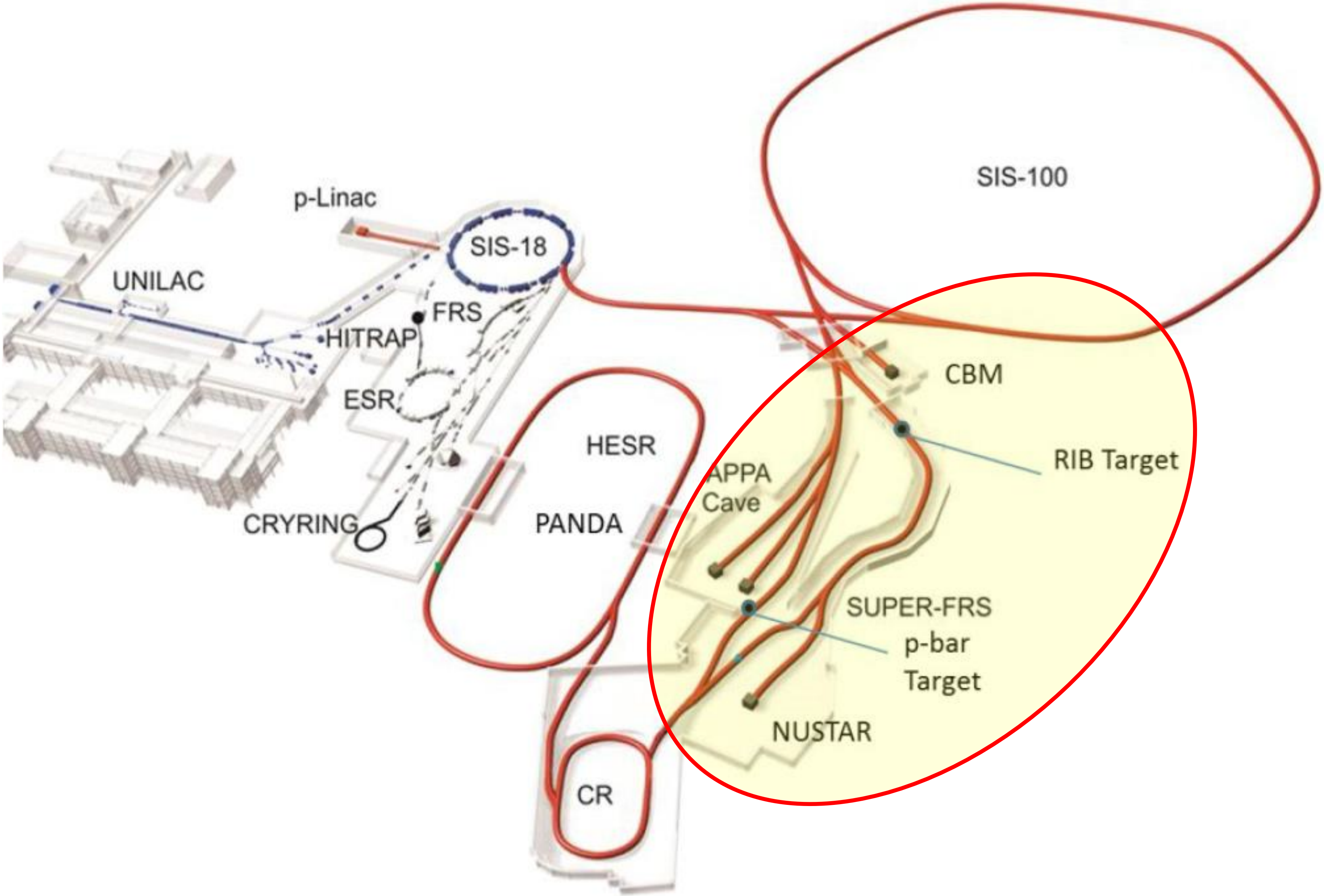
QDM: QD + F1 or F2 + corrector magnets + local current leads and other devices (e.g. collimator, BPM, etc.)




Bus bar system
Common girder and suspension
Focusing quadrupole
Steerer magnet
Cryo Catcher
Cold-Warm transition for roughing pump
Local current lead tower
Defocusing quadrupole
Setupole magnet
Beam tube for QD
BPM
Voltage breaker
Bus bar system
He-supply and return – Magnet cooling
Beam tube for QF
QDM 2.5
Common girder and suspension

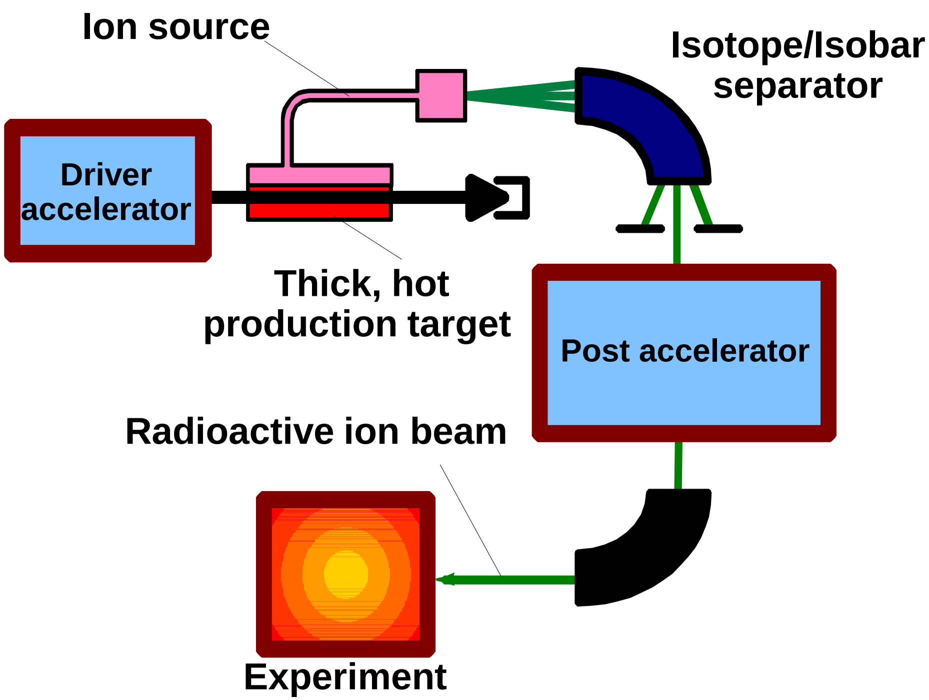

p-Linac
SIS-18
UNILAC
FRS
HITRAP
ESR
CRYRING
SIS-100
CBM
RIB Target
HESR
APPA
Cave
PANDA
SUPER-FRS
p-bar
Target
NUSTAR
CR

The ‘High Five’ (Dallas)
2002 → 2005


SIS-100
p-Linac
SIS-18
UNILAC
FRS
HITRAP
ESR
CBM
RIB Target
HESR
APPA
Cave
PANDA
CRYRING
SUPER-FRS
p-bar
Target
NUSTAR
CR

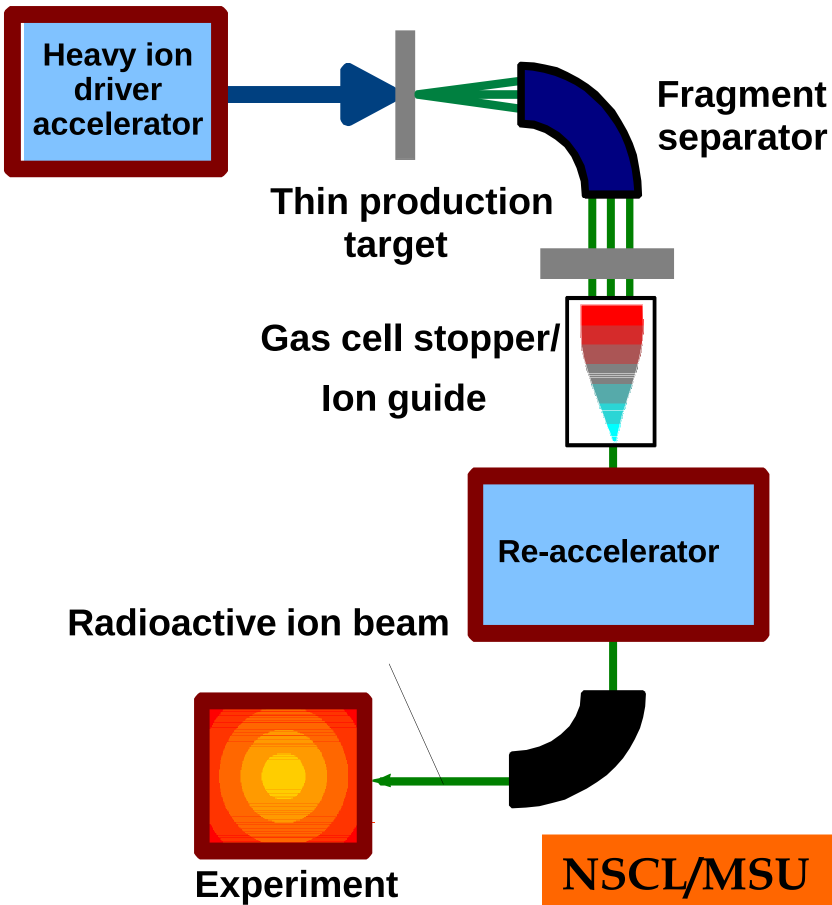
How to produce rare radioactive isotopes

ISOL

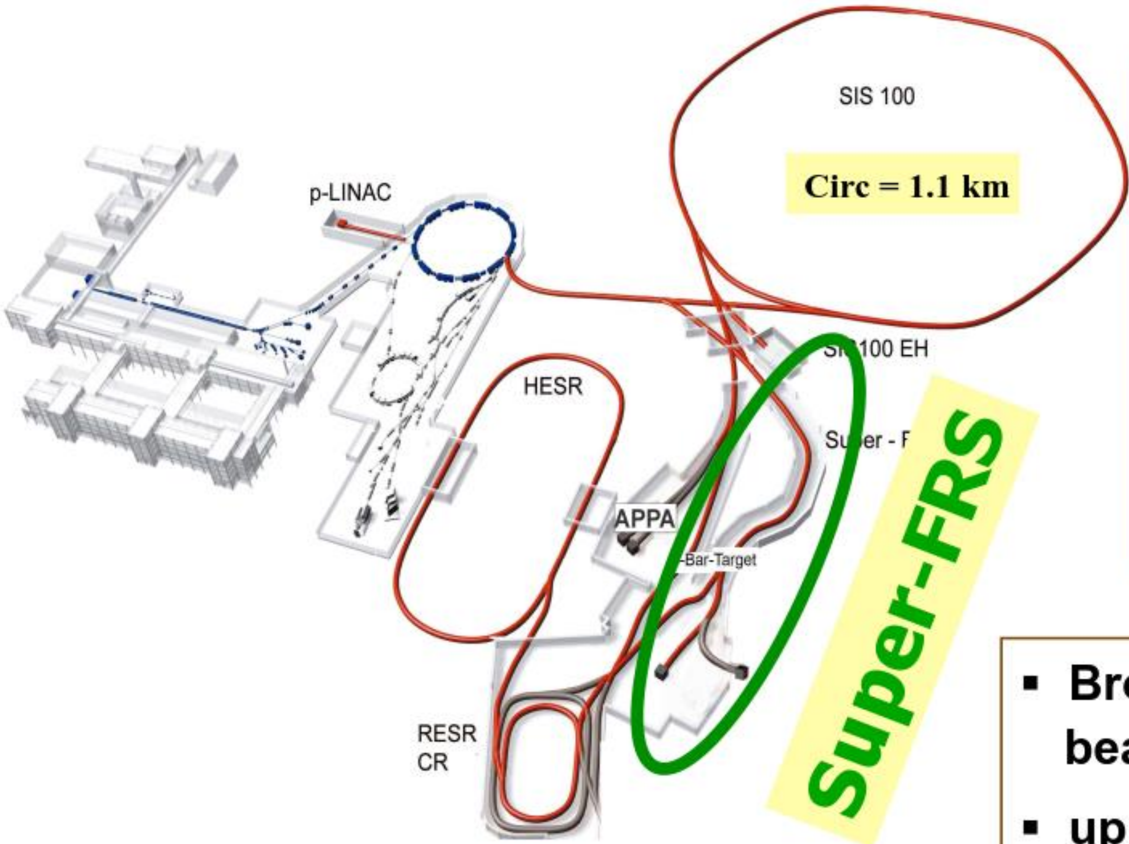


ISOLDE (CERN)
TRIUMF
GANIL

Projectile Fragmentation (PF) and stopped beams



NSCL/MSU
GSI, RIKEN



Primary Beams

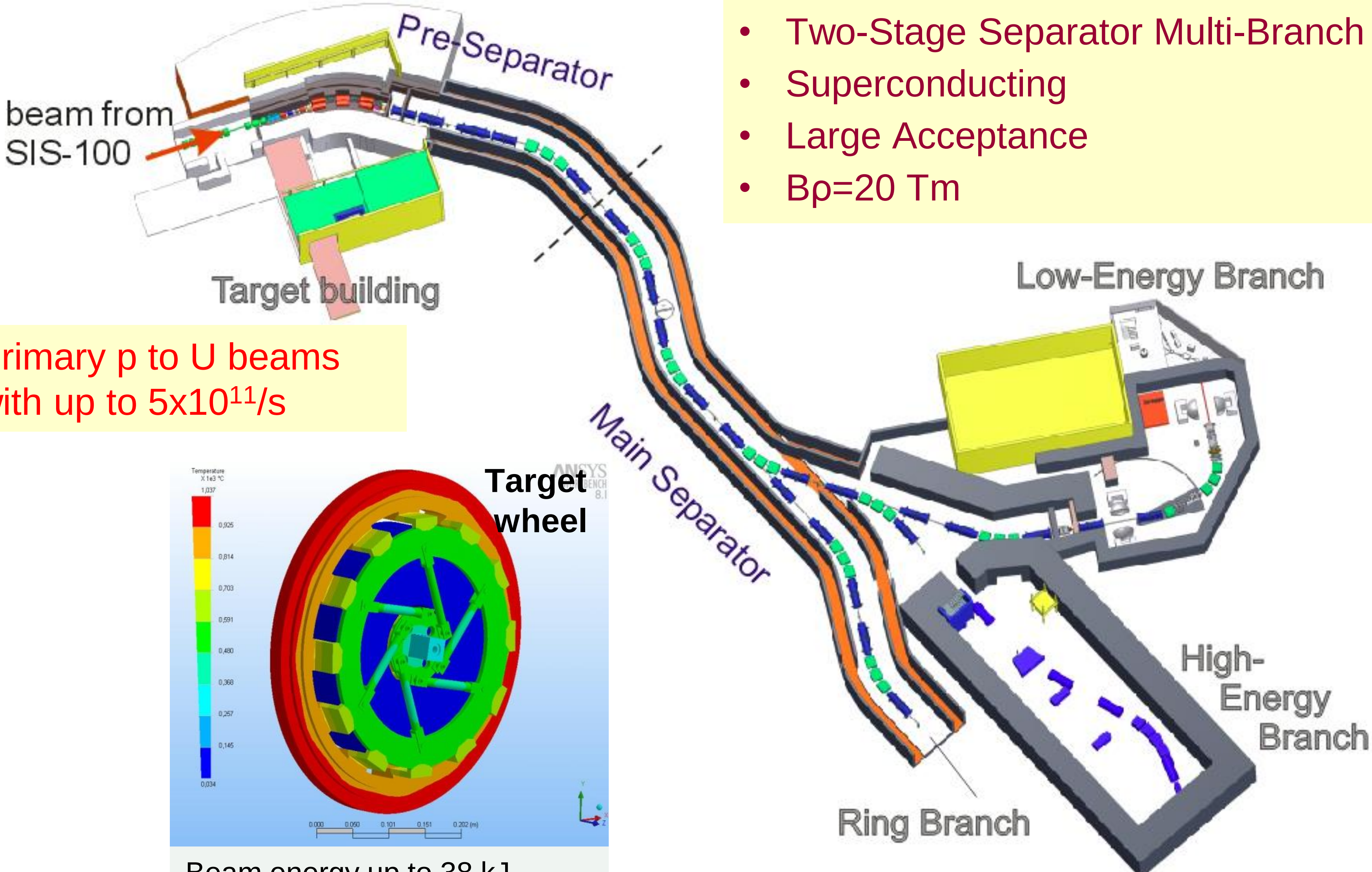
- $3 \cdot 10^{11}$ $^{238}U^{28+}$/s (Slow extr.) @ 1.5 GeV/u
- $4 \cdot 10^{11}$ $^{238}U^{28+}$ (pulsed) @ 1 GeV/u
- factor 100 in intensity over present

Secondary Beams

- Broad range of radioactive beams up to 1.5 GeV/u
- up to factor 10 000 in intensity over present

Rare Ion Beam Separator Super FRS

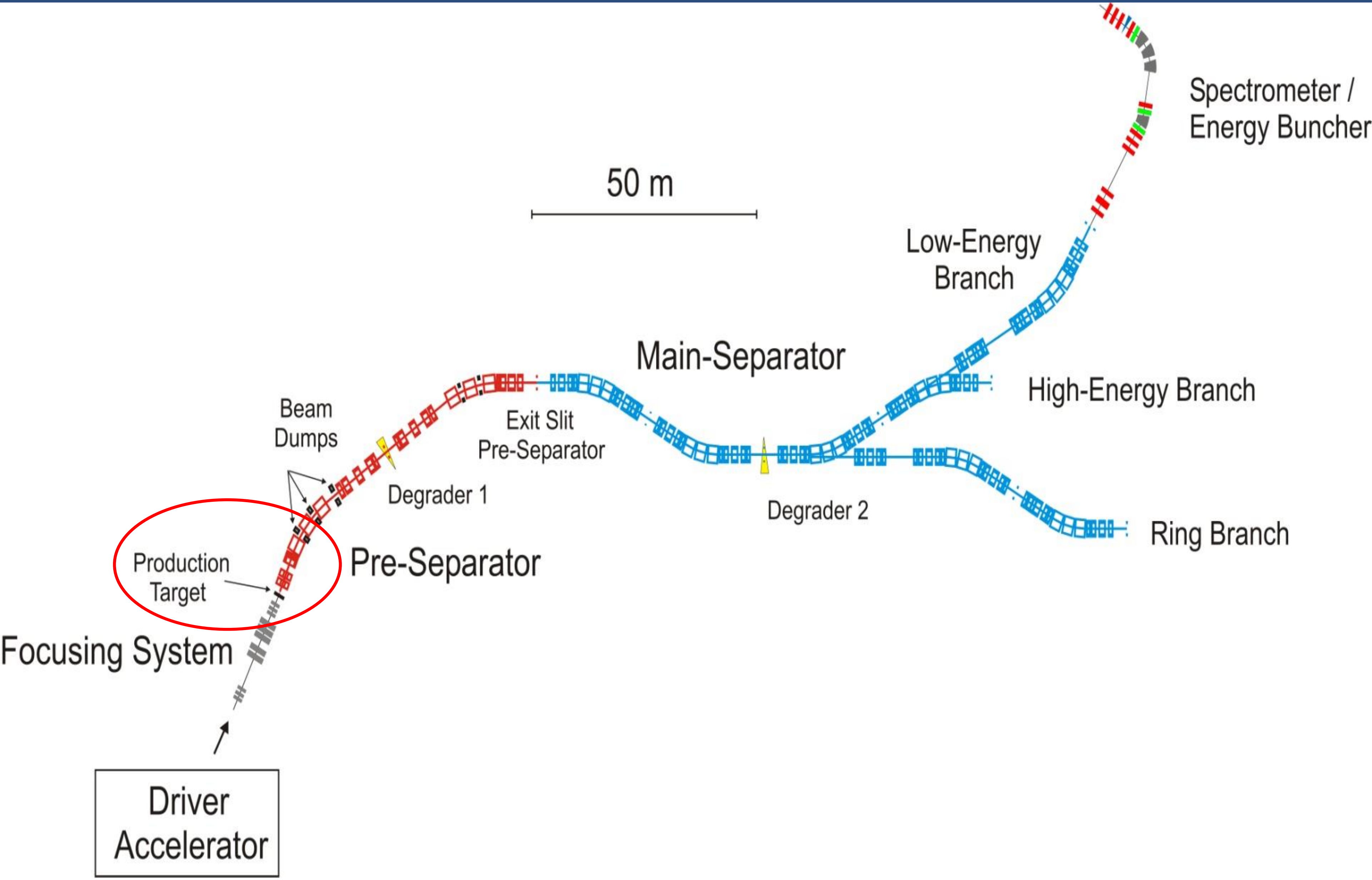
- Two-Stage Separator Multi-Branch
- Superconducting
- Large Acceptance
- Bρ=20 Tm

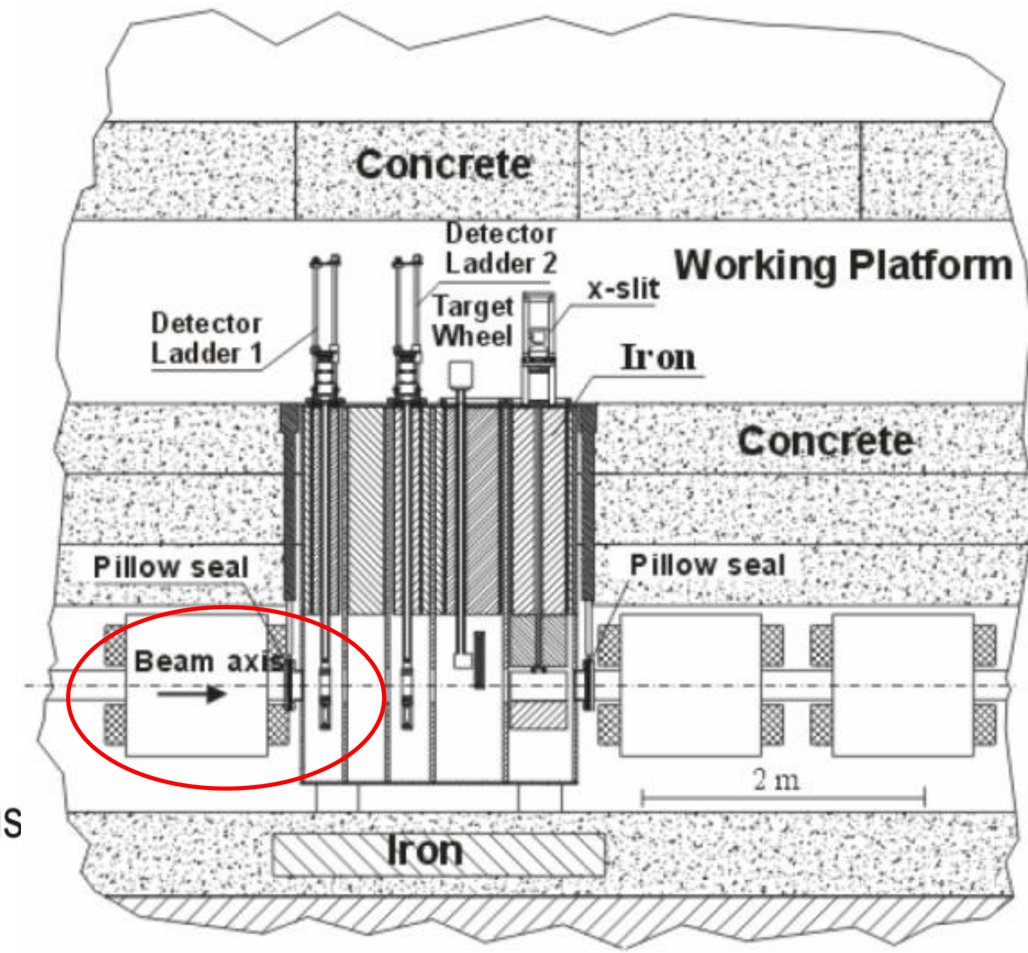


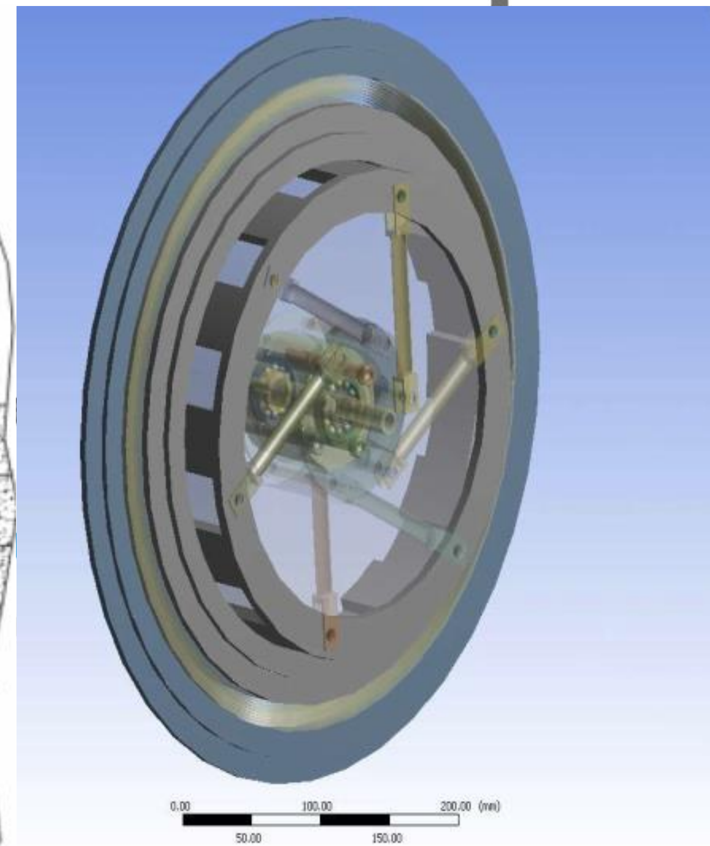
Primary p to U beams with up to $5x10^{11}$/s

Beam energy up to 38 kJ
i.e. 200 GW peak power

Super FRS components



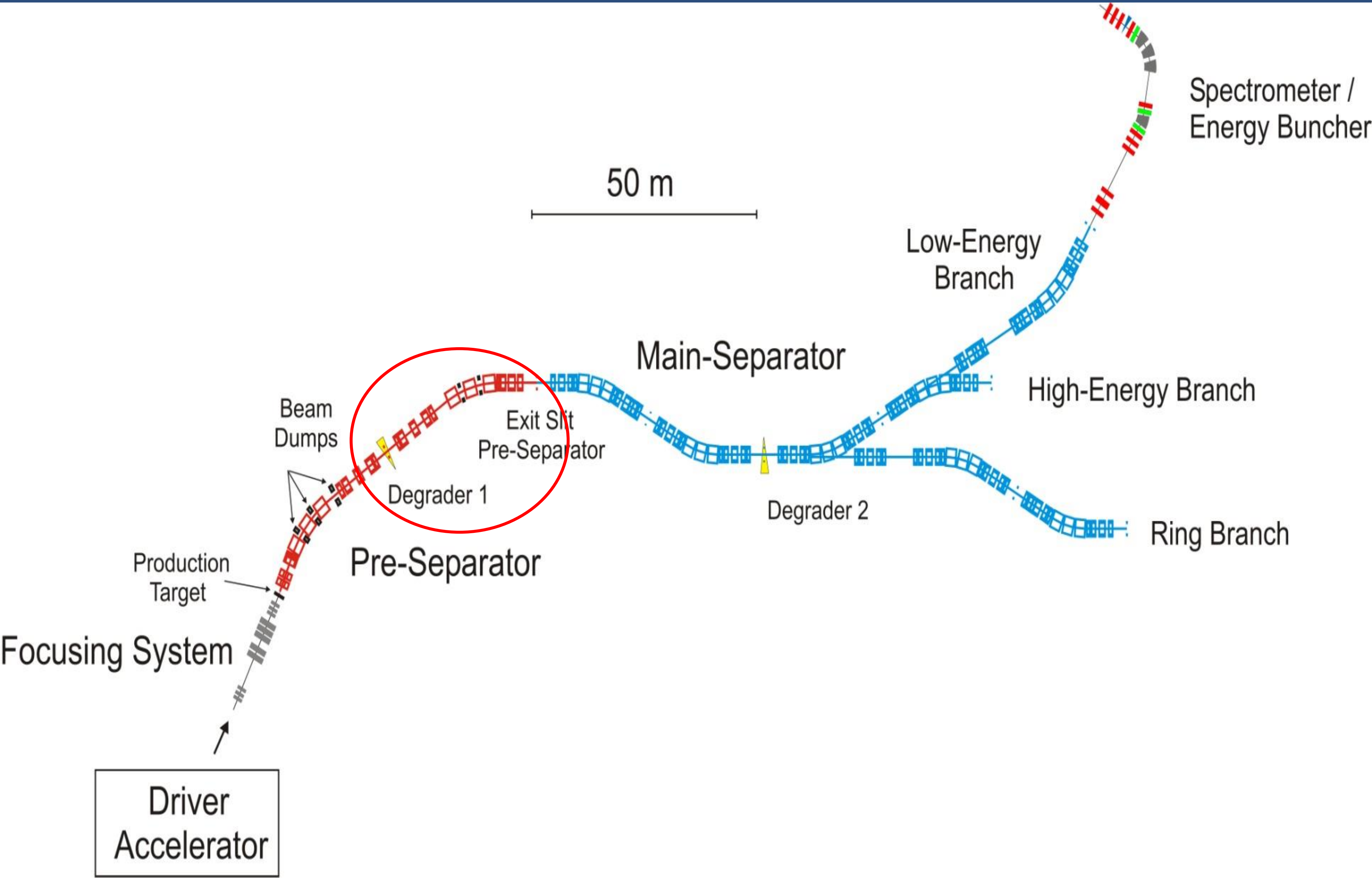




ter /
ncher

Focus

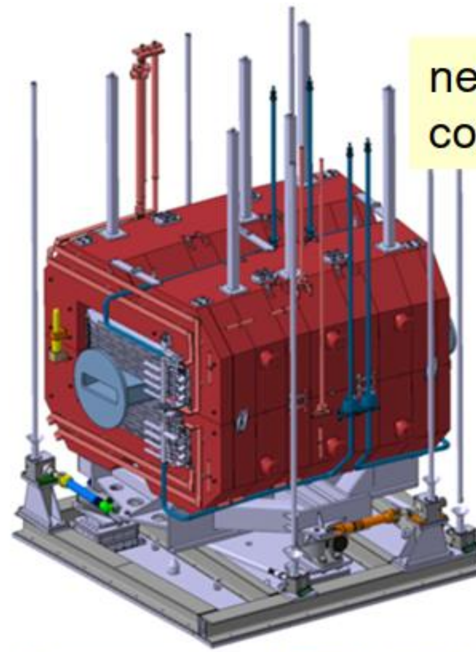
Driver
Accelerator



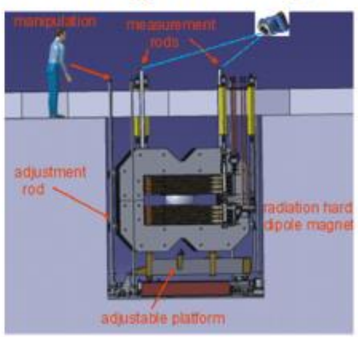
Spectrometer /
Energy Buncher
50 m
Low-Energy
Branch
Main-Separator
High-Energy Branch
Beam
Dumps
Exit Slit
Pre-Separator
Degrader 1
Degrader 2
Ring Branch
Production
Target
Pre-Separator
Focusing System
Driver
Accelerator

Radiation resistant magnets

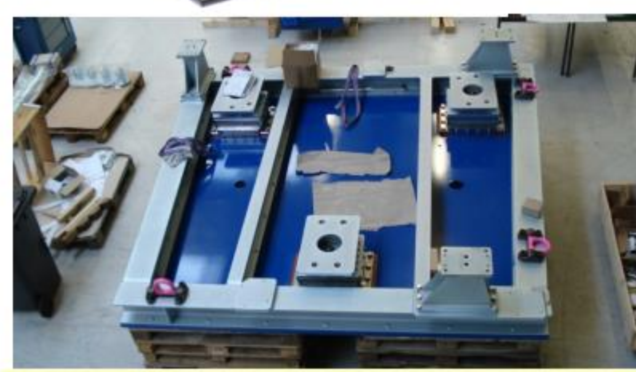
- Magnets located in the target area
- Normal conducting magnets using MIC cable
- 3 dipole units, 3 quadrupoles, 2 sextupoles
- Test on existing prototype dipole:
  - ✓ Heating test done (>95% of Q into water)
  - ✓ New current and water connectors successfully tested
  - ➢ Construction of modified remote alignment is running.
  - ➢ Repetition of alignment test at present
  - ➢ Finalizing specification
- Tendering of magnets via FAIR (Q3/2016)



new media connection

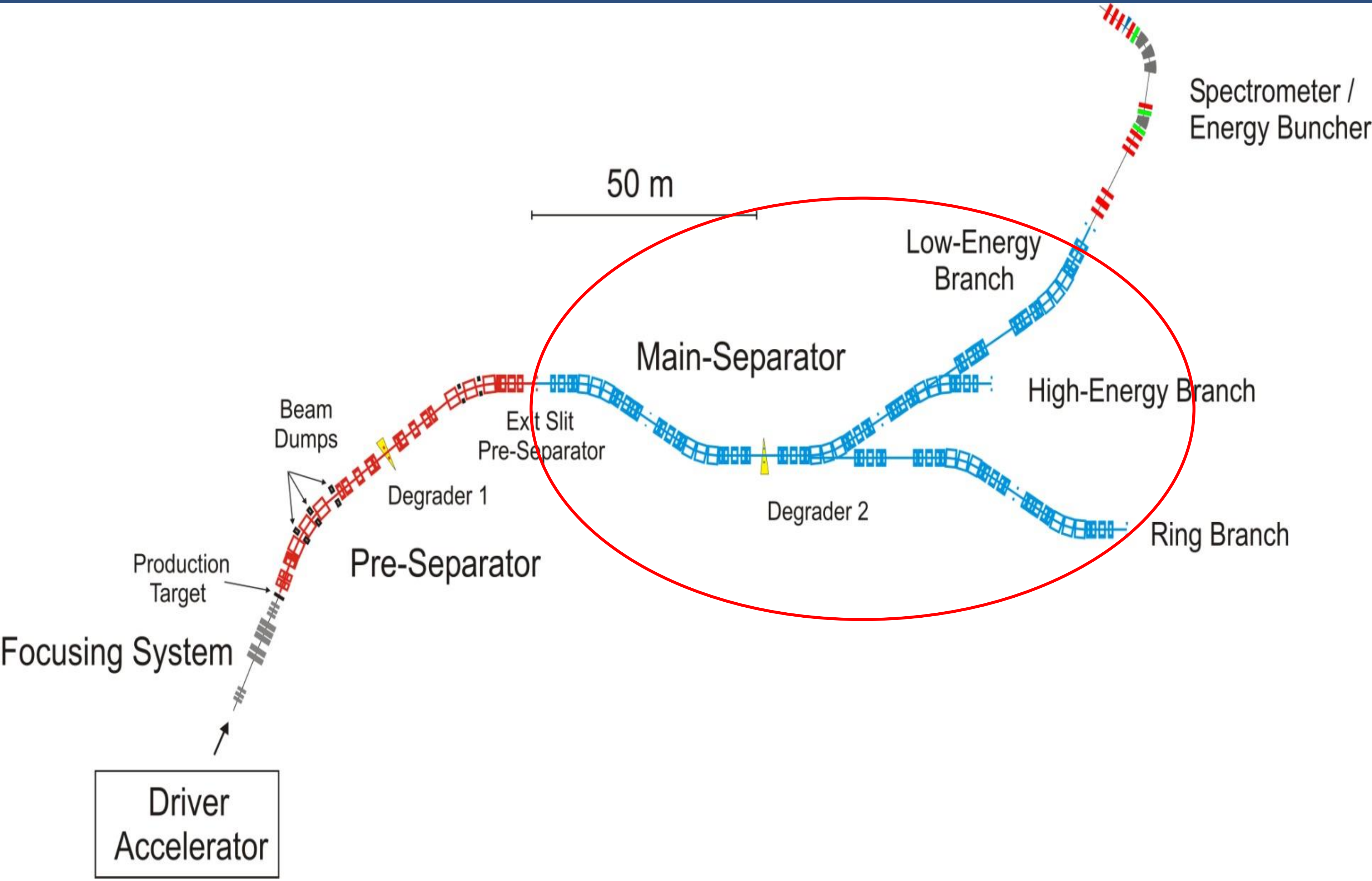


heat test: encased dipole



construction of new lubricants-free support structure

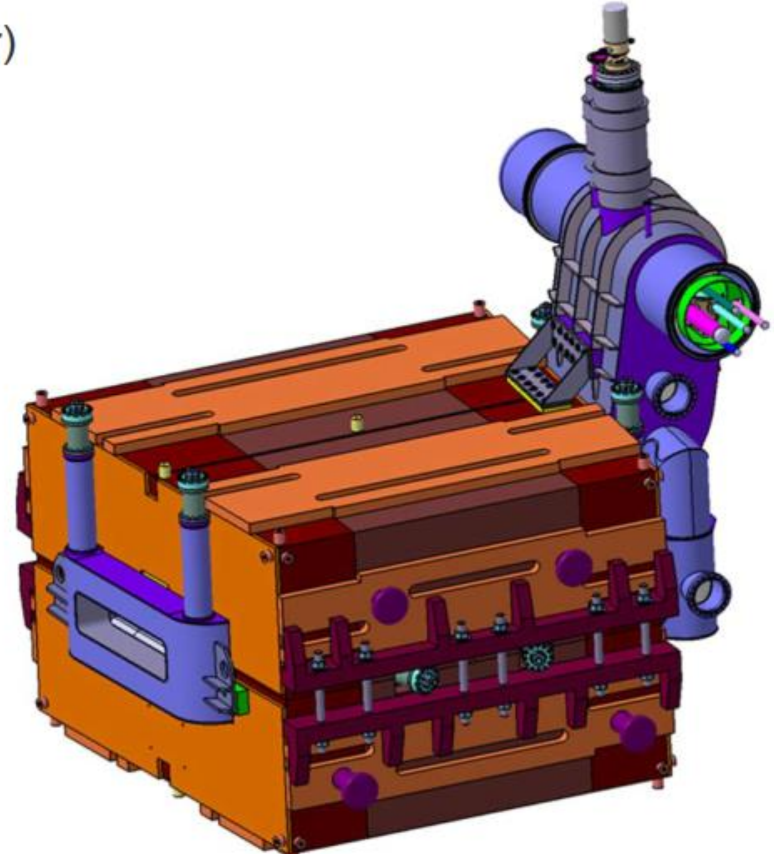
GSI Helmholtzzentrum für Schwerionenforschung GmbH M. Winkler / Super-FRS Statu


Spectrometer /
Energy Buncher
50 m
Low-Energy
Branch
Main-Separator
High-Energy Branch
Beam
Dumps
Exit Slit
Pre-Separator
Degrader 1
Degrader 2
Ring Branch
Production
Target
Pre-Separator
Focusing System
Driver
Accelerator

Standard superconducting dipole magnets

- Based on the succesfully tested prototype by FAIR China Group (Lanzhou, Hefei, Beijing), a redesign is done by Irfu/CEA, Saclay concerning
  - bending angle
  - cryostat mechanics (design pressure 20 bar)
  - coil support system
  - branching dipoles

Prototype from FAIR China Group in 2014



Design by Irfu/CEA, Saclay, 2017

Eun Jung Cho/ Super-FRS magnet design and production 11/01/2017 7

Superconducting multiplets

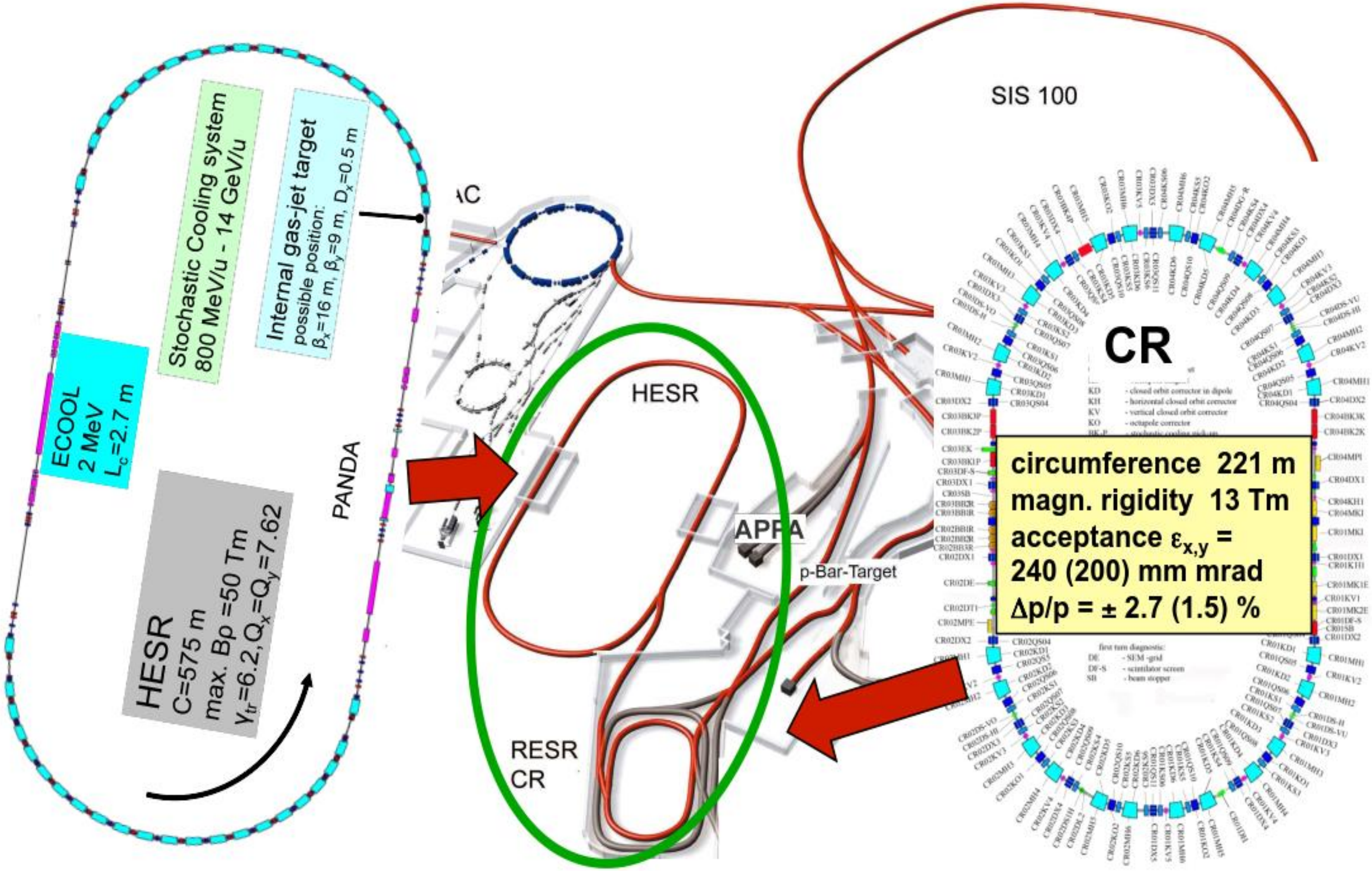
- 25 long multiplets (mainly MS)
  - ➢ Quadrupol triplet
- 8 short multiplets (PS)
  - ➢ QS configuration
- include corrector elements & steerer

- iron dominated, cold iron (≈40 tons)
- common helium bath, LHe ≈ 1.300 l
- warm beam pipe
- per magnet 1 pair of current leads
- max. current <300A for all magnets

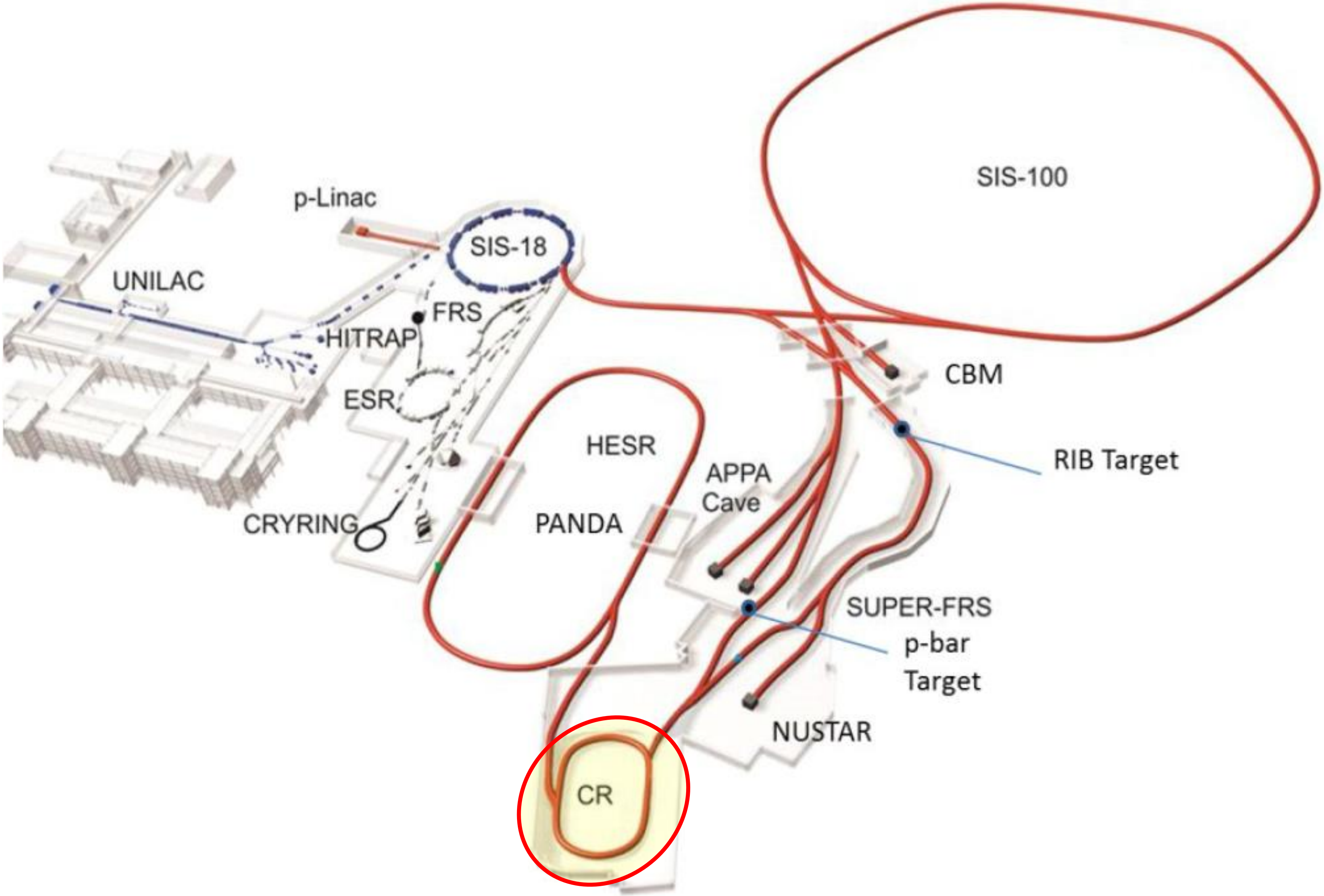
✓ Contract award July 1st, 2015
  - ➢ Winning company: ASG Genoa
  - ➢ Contract volume ≈50 M€

✓ Kick-off: July 15, 2015

Preliminary ASG Modell, May 2016


Stochastic Cooling system
800 MeV/u - 14 GeV/u
Internal gas-jet target
possible position:
β_x=16 m, β_y=9 m, D_x=0.5 m
ECOOL
2 MeV
L_c=2.7 m
PANDA
HESR
C=575 m
max. Bρ =50 Tm
γ_{tr}=6.2,Q_x=Q_y=7.62
SIS 100
HESR
APPA
p-Bar-Target
RESR
CR
CR
circumference 221 m
magn. rigidity 13 Tm
acceptance $\varepsilon_{x,y}$ =
240 (200) mm mrad
Δp/p = ± 2.7 (1.5) %

Cooler Ring CR (Novosibirsk)

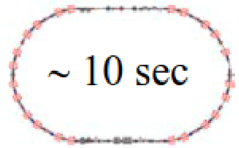


1. Cooling of antiproton beam, Pbar

From pbar separator, E = 3 GeV

$\varepsilon_{\perp} = 240$ mm mrad
$\Delta p/p = \pm 3$ %

→



→

$\varepsilon_{\perp} \leq 5$ mm mrad
$\Delta p/p \leq \pm 0.05$ %

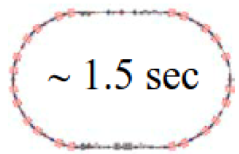
→ to the HESR

2. Cooling of secondary beams of radioactive ions, RIB

From Super-FRS, E = 740 MeV/u

$\varepsilon_{\perp} = 200$ mm mrad
$\Delta p/p = \pm 1.5$ %

→



→

$\varepsilon_{\perp} \leq 0.5$ mm mrad
$\Delta p/p \leq \pm 0.025$ %

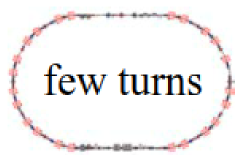
→ to the HESR

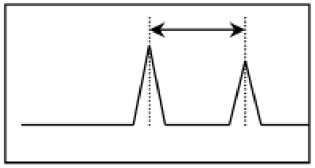
3. Mass spectrometer of radioactive ions (TOF), ISO

From Super-FRS, E = 400-800 MeV/u

$\varepsilon_{\perp} = 100$ mm mrad
$\Delta p/p = 1$ %

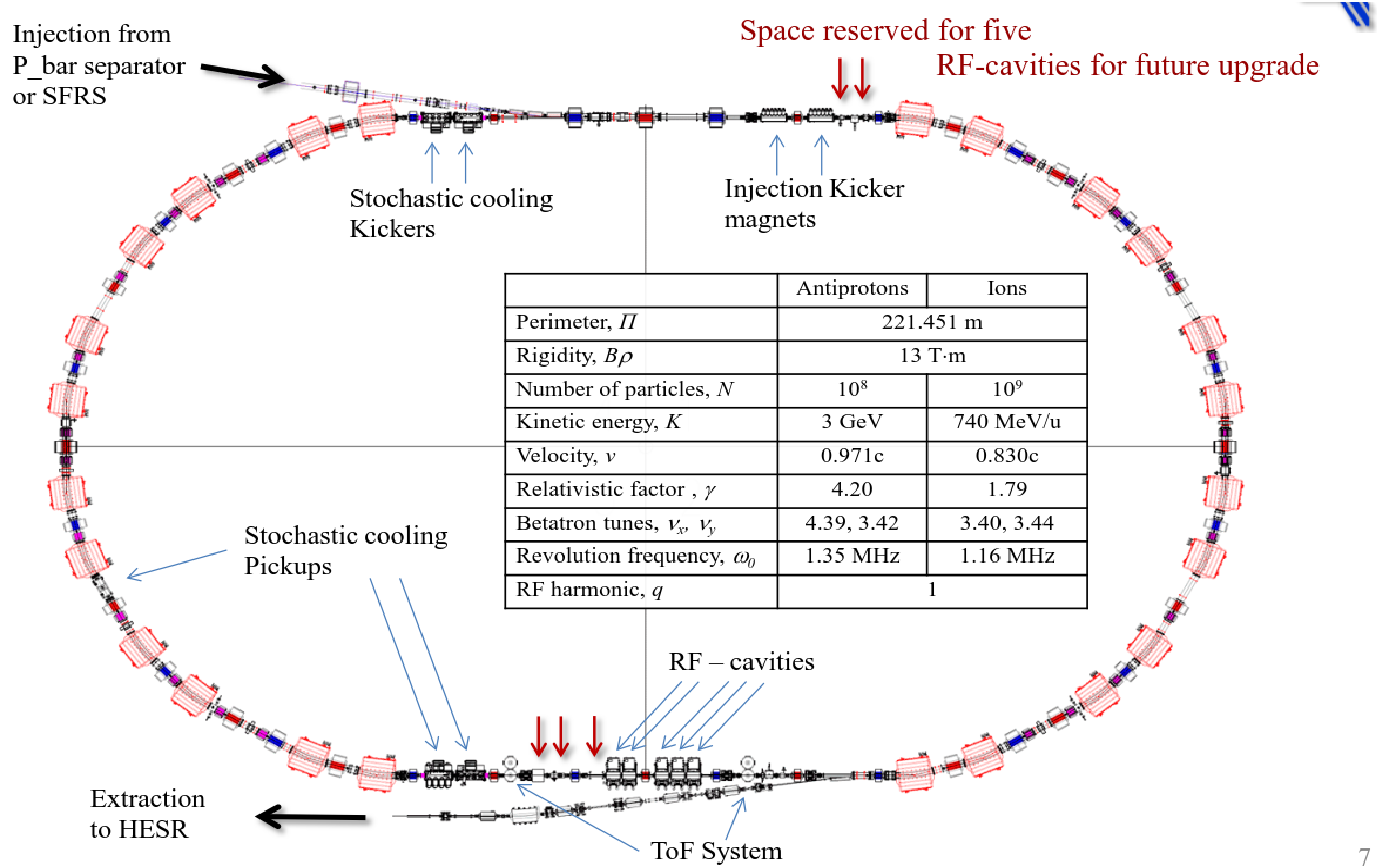
→





$$\frac{\Delta m}{m} = \gamma_{tr}^2 \frac{\Delta f}{f}$$

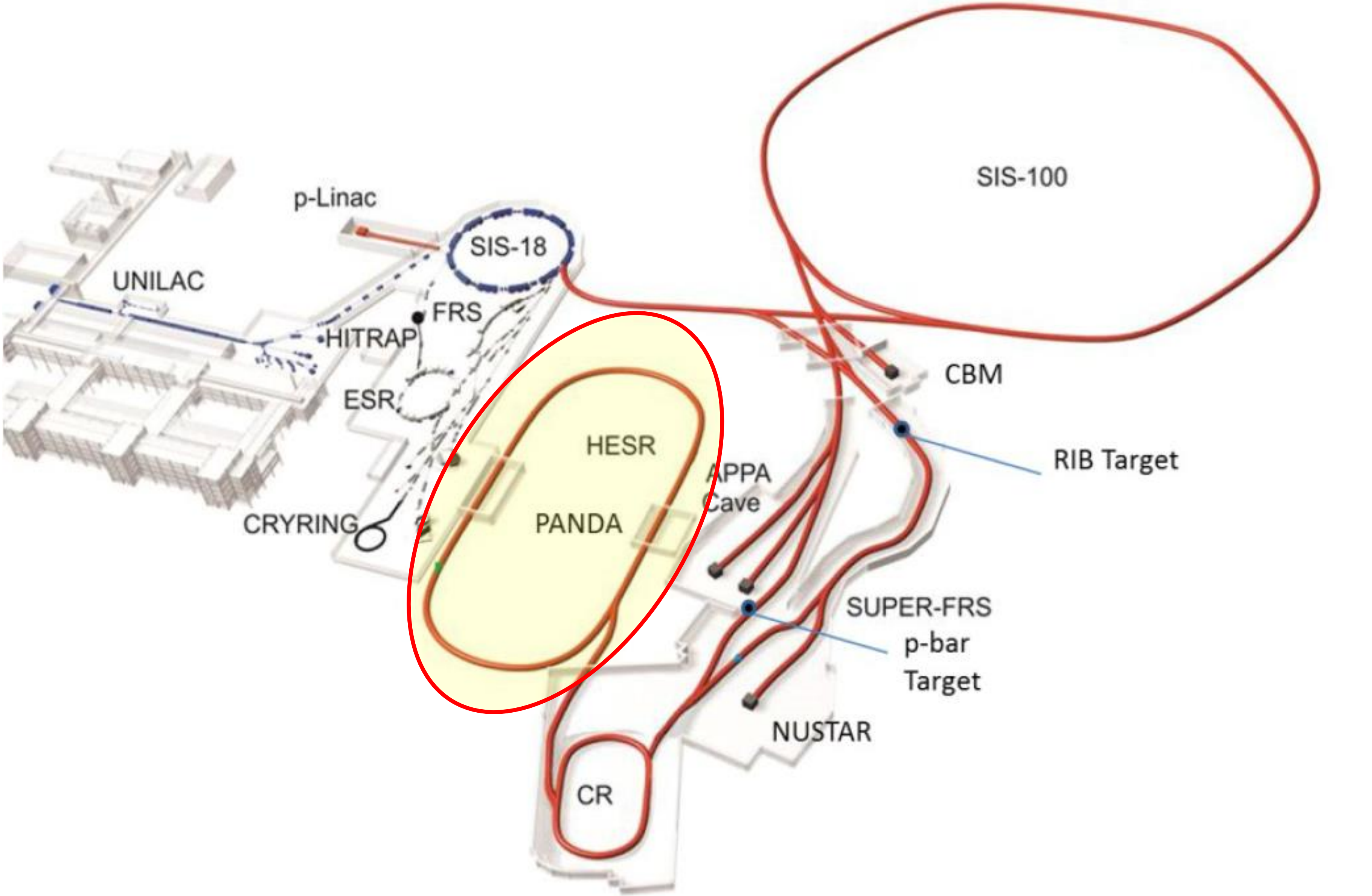
CR ring layout

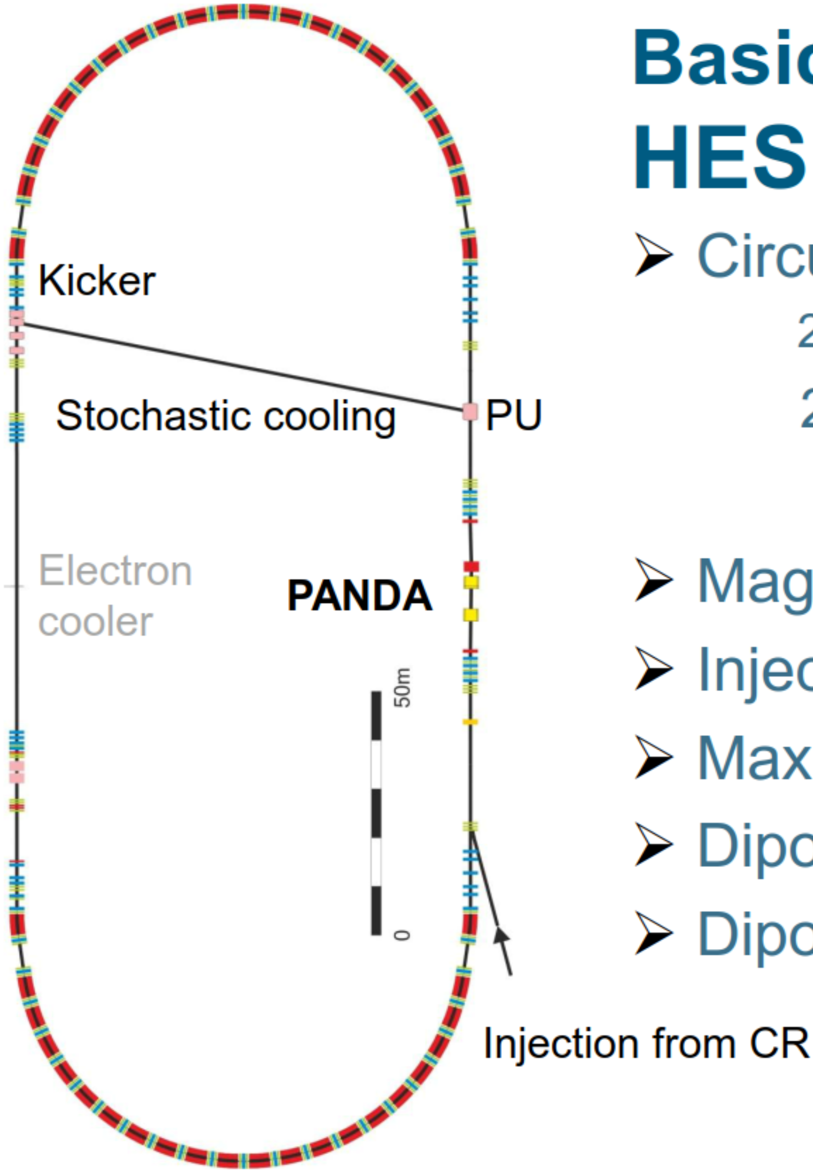


	Antiprotons	Ions
Perimeter, Π	221.451 m	
Rigidity, $B\rho$	13 T·m	
Number of particles, N	10^8	10^9
Kinetic energy, K	3 GeV	740 MeV/u
Velocity, v	0.971c	0.830c
Relativistic factor , γ	4.20	1.79
Betatron tunes, ν_x, ν_y	4.39, 3.42	3.40, 3.44
Revolution frequency, ω_0	1.35 MHz	1.16 MHz
RF harmonic, q	1	

7

High Energy Storge Ring HESR (Jülich)





Basic Data of HESR

- Circumference 574 m
  - 2 arcs of 155 m
  - 2 straight sections of 132 m
- Magnetic rigidity: 5 – 50 Tm
- Injection from CR at 13 Tm
- Maximum dipole field: 1.7 T
- Dipole field at injection: 0.4 T
- Dipole field ramp: 0.025 T/s

- Operating with antiprotons
- Operating with heavy ions

Remarks

- FAIR is one of the largest research projects worldwide, an extremely interesting and challenging accelerator project
- GSI faces rather tough challenges to build FAIR
- Apart from FAIR construction, the existing accelerators need substantial upgrade / replacements
- CERN contributes in several areas, controls, magnet testing, …

- As it has been experiences with SSC in the US – the accelerator community has a large interest in the success of FAIR


R.Heuer and B.Sharkov, 2010

Material used

- SIS 100: P.Spiller, MAC01, MAC14
- HESR: D.Prashuhn, MAC14
- CR: I.Koop, D.Shwartz, MAC15
- Super FRS: H.Müller, E.J.Cho, MAC15, MAC18
- FAIR: D.Krämer, MAC1

- Movie: C.Omet, P.Spiller