Collector Ring at FAIR. Status and Plans

Oleksiy Dolinskyy

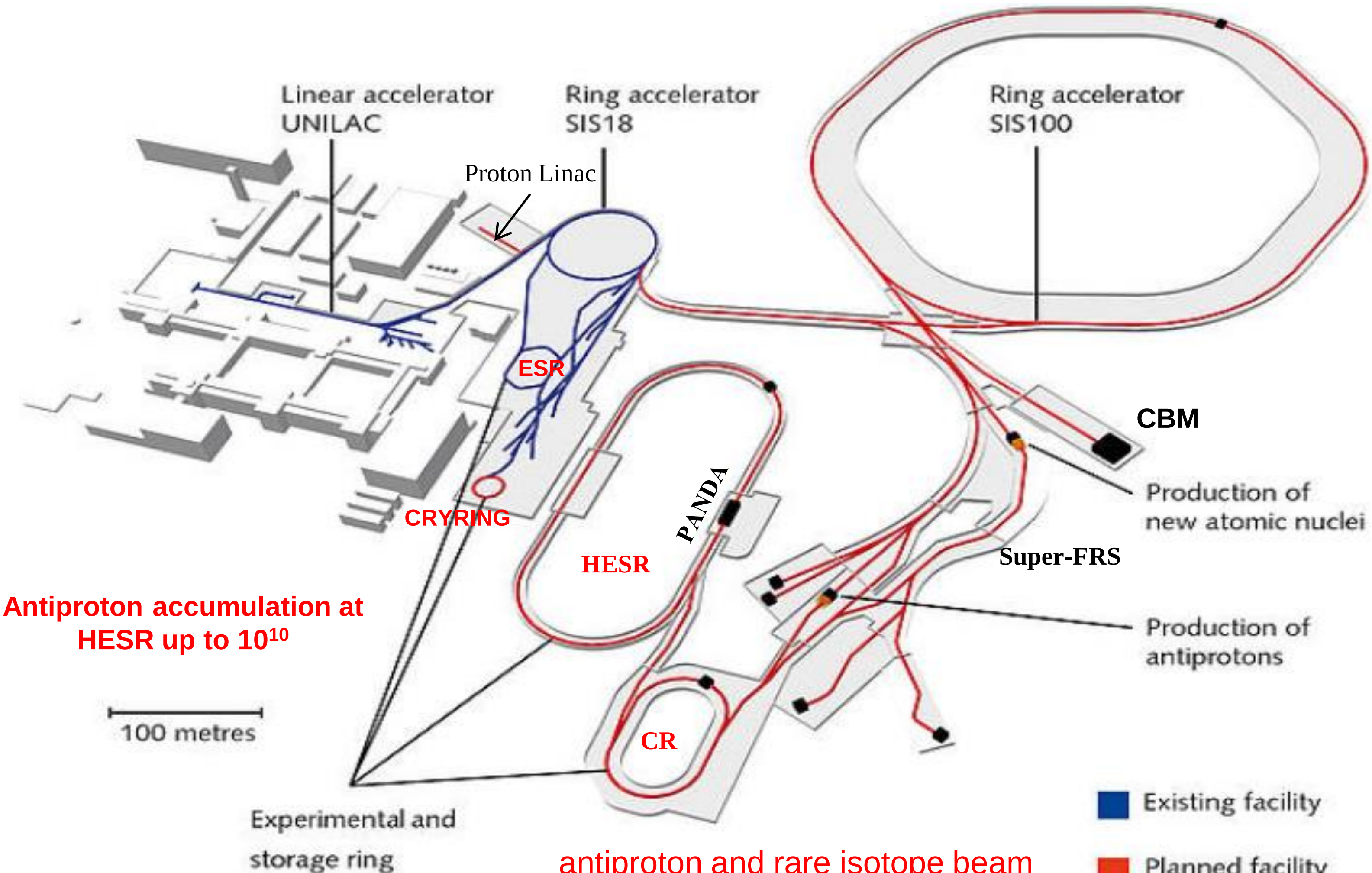
Extreme Storage Rings Workshop 2022.

February 1, 2022

Outline

- ***CR Performances***
- ***RF debuncher***
- ***Stochastic Cooling system***
- ***Magnets***
- ***CR as a mass spectrometer***
- ***Civil construction***

FAIR facility



Antiproton accumulation at HESR up to 10^{10}

antiproton and rare isotope beam cooling at CR:
In-ring experiments. $N=10^8$

CR features

- **Fast cooling of antiproton and heavy ion beams**
- **Nuclear physics experiments with a high precision of measurements**
- **Operation at magnetic rigidity of 13 Tm.** B_{max}=+1.6 T,
- B_{min}=-1.6 T (polarity change 60 s)
- **Flexible optics to meet requirements of Stochastic cooling and in-ring experiments**
- **Large acceptance provides operation of beam with a momentum spread up to 6% and emittances up to 240 mm* mrad**

Tasks of the CR

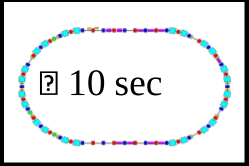
Cooling of antiproton beams

From antiproton separator

$\varepsilon_{\perp} = 240$ mm mrad

$\Delta p/p = 6$ %

CR →



$\varepsilon_{\perp} \leq 5$ mm mrad

$\Delta p/p \leq 0.1$ %

→ to the HESR

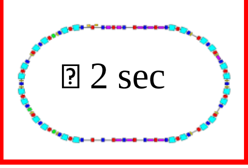
Cooling of secondary beams of radioactive ions

From Super-FRS

$\varepsilon_{\perp} = 200$ mm mrad

$\Delta p/p = 3$ %

CR →



$\varepsilon_{\perp} \leq 0.5$ mm mrad

$\Delta p/p \leq 0.05$ %

→ to the HESR (RESR)

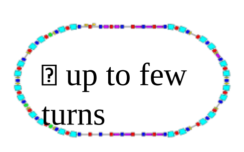
Mass spectrometry of radioactive ions

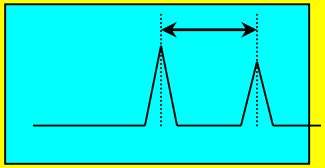
From Super-FRS

$\varepsilon_{\perp} = 100$ mm mrad

$\Delta p/p = 1$ %

CR →



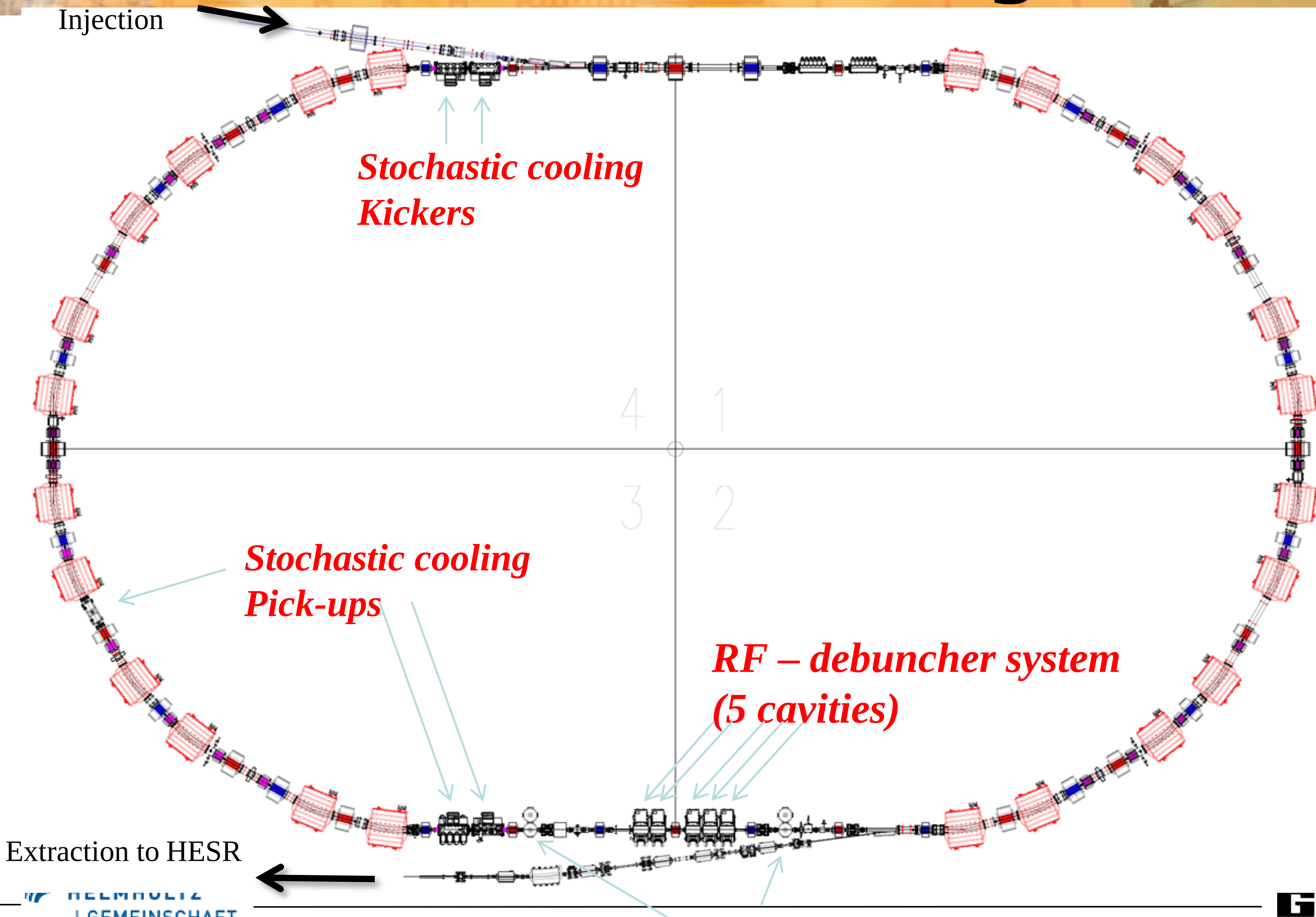


$$\frac{\Delta m}{m} = \gamma_{tr}^{2} \frac{\Delta f}{f}$$

Basic CR parameters

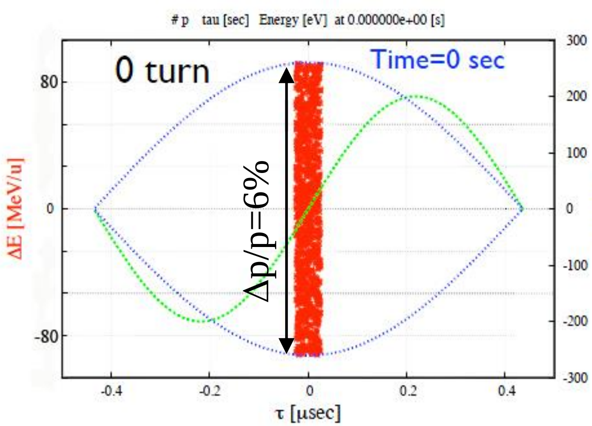
Circumference	m	221.45		
Max. magnetic rigidity	Tm	13		
		Anti-protons	Rare isotopes	Isochronous mode
Max. number of particles		10^8	10^8	$1\text{-}10^8$
Kinetic energy	MeV/u	3000	740	790
Velocity, β	v/c	0.971	0.83	0.84
Lorentz, γ		4.2	1.79	1.84
Transition energy, γ_{tr}		3.85	2.82	1.43-1.84
Frequency slip factor , η		-0.011, 0.014	0.176	0
Betatron tunes , Q_h / Q_v		4.39 / 3.42	4.28 / 3.44	3.4 / 4.44
Revolution frequency	MHz	1.315	1.124	1.137
Bunch length at injection	ns	50	50	50
Bunch length at extraction	ns	300-500	200-700	no extraction
Beam injection		fast single turn, full aperture		
Beam extraction		fast single turn		no extraction
Average vacuum	mbar	3×10^{-9}		

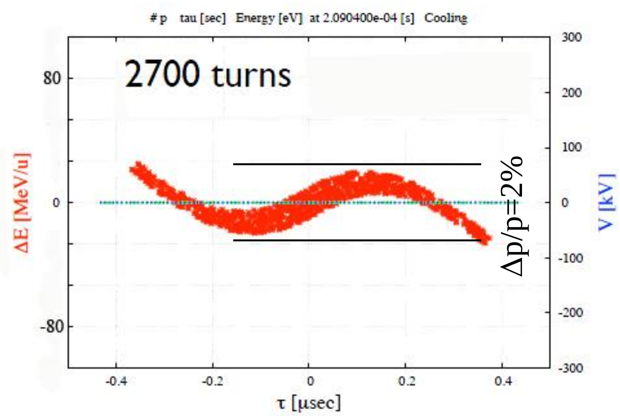
Key components for beam cooling



RF debuncher system

By bunch rotation the momentum spread is reduced by factor 3
P-bars (from 6% to less than 2%)
RIBs (from 3% to less then 1 %)



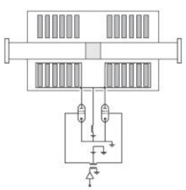


$$\gamma_{tr} = \gamma_{tr}(\delta p/p)$$

Preliminary sketch of cavity/amplifier

Length (flange to flange): 1m
Width: 850mm
Total height: 2100mm

Total voltage (5 cavities)	**200 kV**
Peak voltage per cavity	**40 kV**
Peak dissipation per valve	393 kW
Peak dissipation per valve into ring cores	648 kW
Peak power per valve	1040 kW



- Two inductively loaded coaxial quarter wave length resonators operating on a common gap
- Six ring cores per cavity half (total of 12)
- Forced air cooling of cavity
- Change of resonance frequency by means of variable capacitors
- Inductive coupling of amplifier to cavity
- Push-pull amplifier consisting of two tetrodes

Existing SIS18 bunch compression cavity. The design of the CR DB will be very similar to this cavity.

RF debuncher system

- Series production of 5 RF-debuncher systems completed
- They have been delivered to GSI in 2019
- SAT of all system takes place at GSI

RF cavity and its Power Supply at GSI test hall

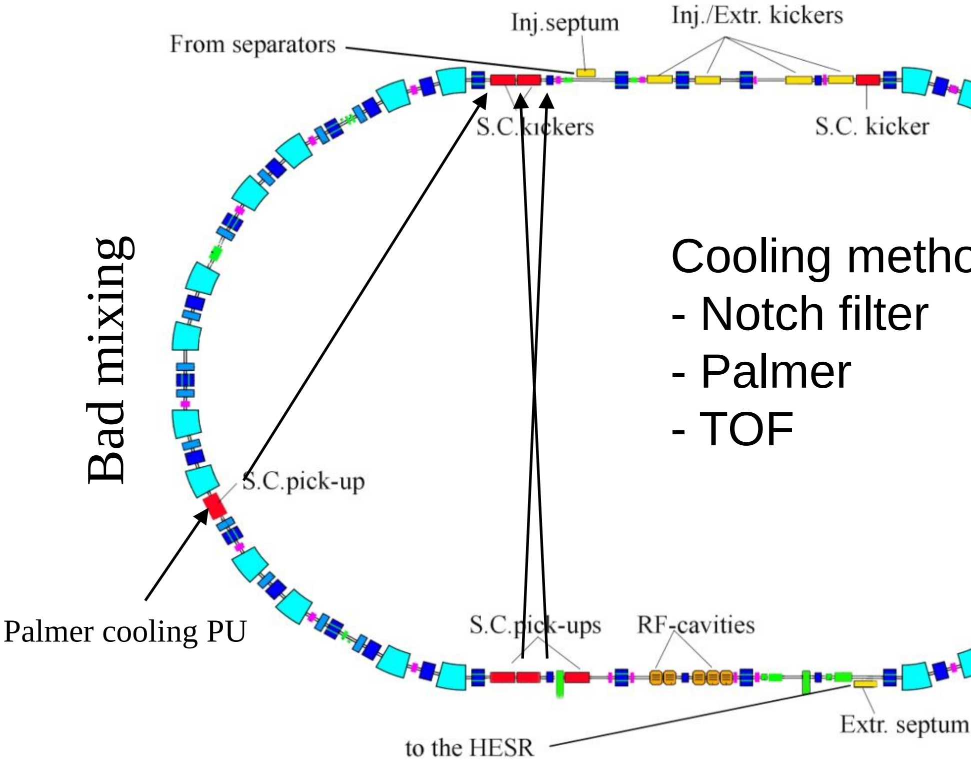
- EMC/EMI effects have to be carefully studied

- Some technical corrections are needed to improve reliability

- A long term of collaboration with companies is ongoing

Stochastic cooling

The ring is designed to have a required η parameter both for antiproton and RI beams. Optics and positions of PU and KI are optimized to have required phase advances between all pairs of PU-KI.



Bad mixing

Cooling methods:
- Notch filter
- Palmer
- TOF

Good mixing

η=-0.011 for pbar
η=+0.014 for pbar
η=+0.177 for RIB

Pickup tanks (1-2 GHz)
Kicker tanks (1-2 GHz)
Palmer Pickup tanks

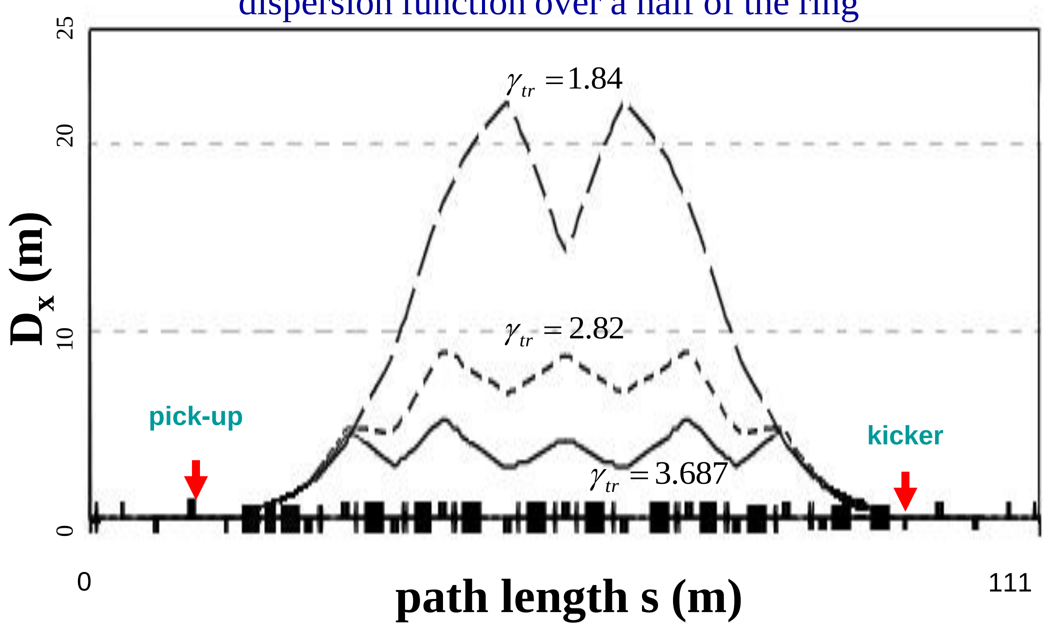
Phase advance PU-KI

$$\Delta\mu_{x\ or\ y} = (2n+1)\frac{\pi}{2}$$

CR Optics
Dispersion function

The ring lattice should be adjustable to different slip factors (gamma-tr).

dispersion function over a half of the ring



Antiproton mode (η=–0.011)

RIB mode (η=0.186)

Isochronous mode (η=0)

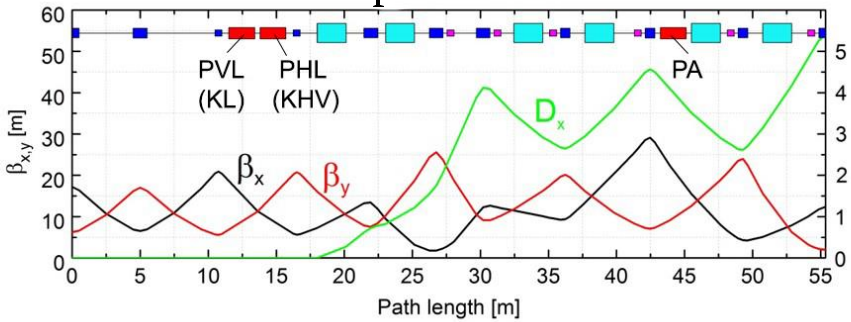
γ_{tr}=1.84, 1.67, 1.43

* Phase advance between pick-ups and kickers for stochastic cooling is $\Delta\mu_{x,y} = \frac{\pi}{2}(2n+1)$

* There are 13 independent power supplies for quadrupole magnets

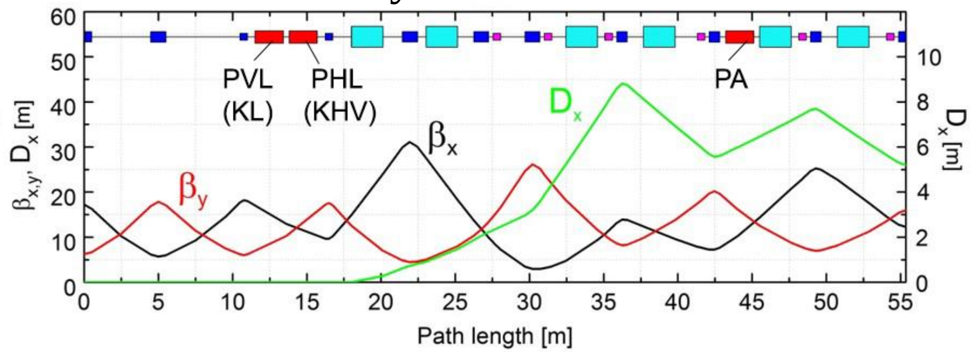
CR optics

Antiproton mode



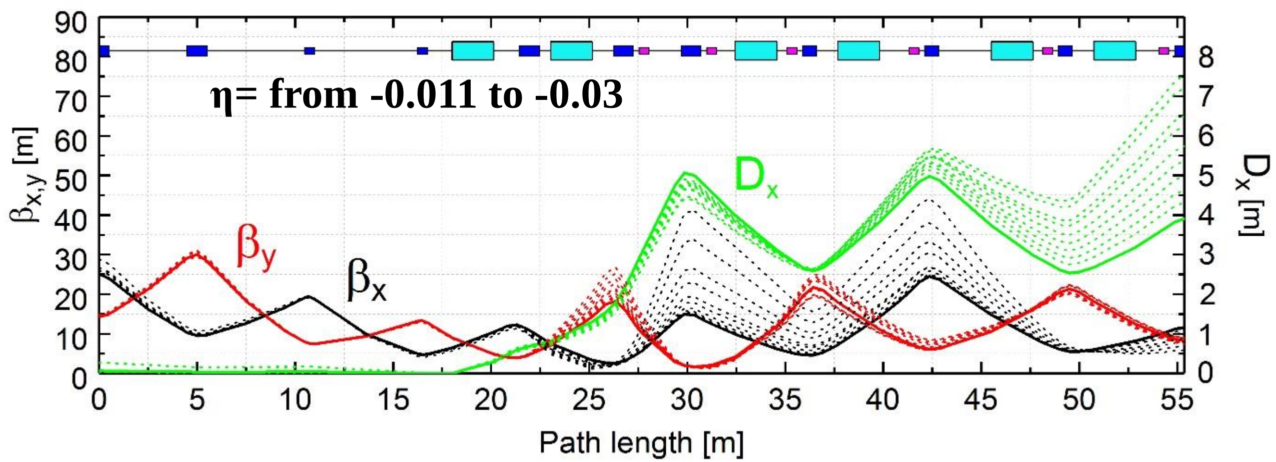
RF, SC Pick-Up and SC Kicker at D=0

Heavy ion mode



Palmer Pick - Up

Dynamic variation of the momentum slip factor during cooling process to increace SC efficiency



13 families of
Quadrupole PC
Ramp rate 5.1 T/m

One has to keep phase advances

$$\Delta\mu_{x\ or\ y} = (2n+1)\frac{\pi}{2}$$

Stochastic cooling

After bunch rotation Stochastic cooling is applied to reduce both the beam emittance and momentum spread, which is required by HESR for further accumulation

Antiproton beam

Momentum spread: 2% → 0.1%
Emittance: 240 → 5 mm*mrad
Cooling time: 10 s

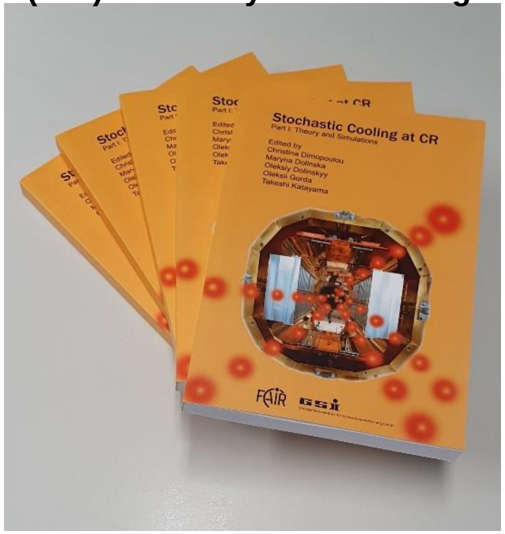
Heavy ions

Momentum spread: 1 % → 0.05 %
Emittance from: 200 → 0.5 mm*mrad
Cooling time: 2 s

The SC system is under construction at GSI by C.Dimopoulou's team

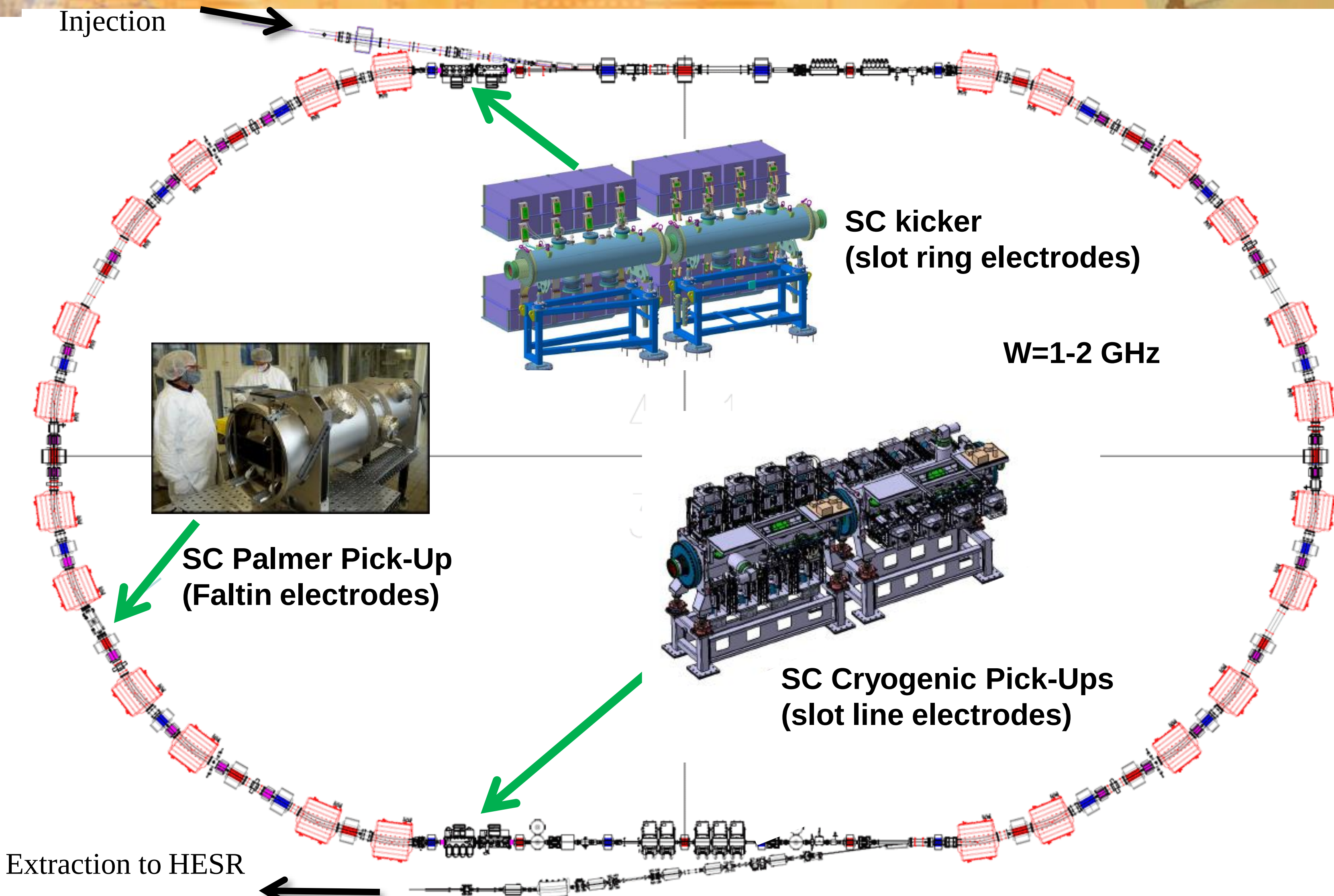
Fritz Nolden is the father of SC system at CR

Stochastic cooling theory and simulations for CR were developed over many years by: F.Nolden (GSI), D.Möhl (CERN), L.Thorndahl (CERN), T.Katayama (Japan), C.Dimopoulou (GSI), C.Peschke (GSI), M.Steck (GSI), M.Dolinska (GSI) and many other colleagues.



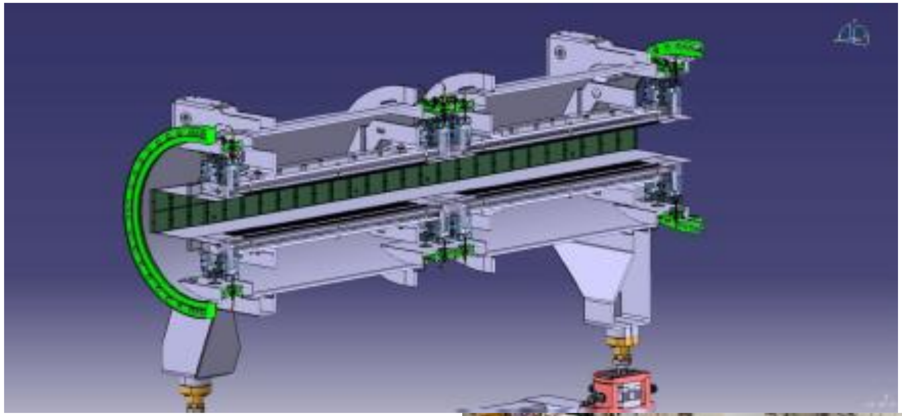
Hand Book „Stochastic Cooling at CR"

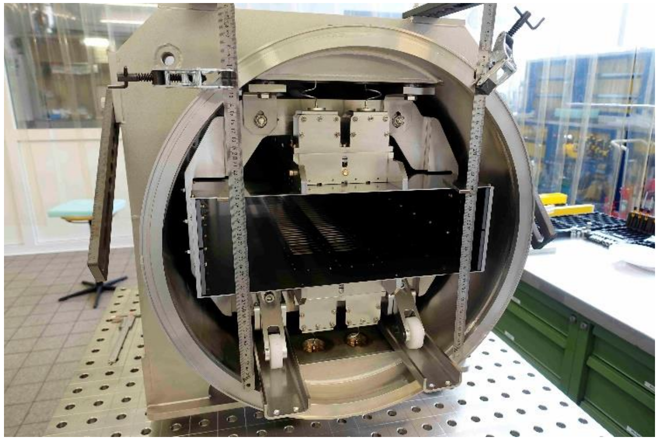
Stochastic Cooling system

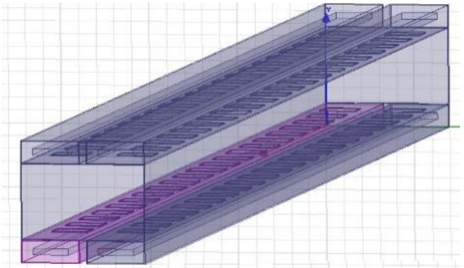


Palmer Pick-Up for Stochastic pre-cooling of heavy ions

Engineering at GSI
Manufacturing has been done at GSI + external company in 2020.



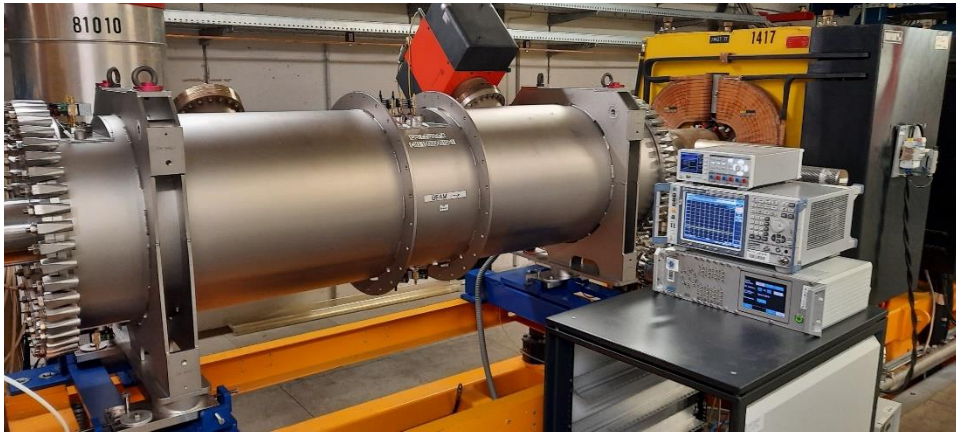


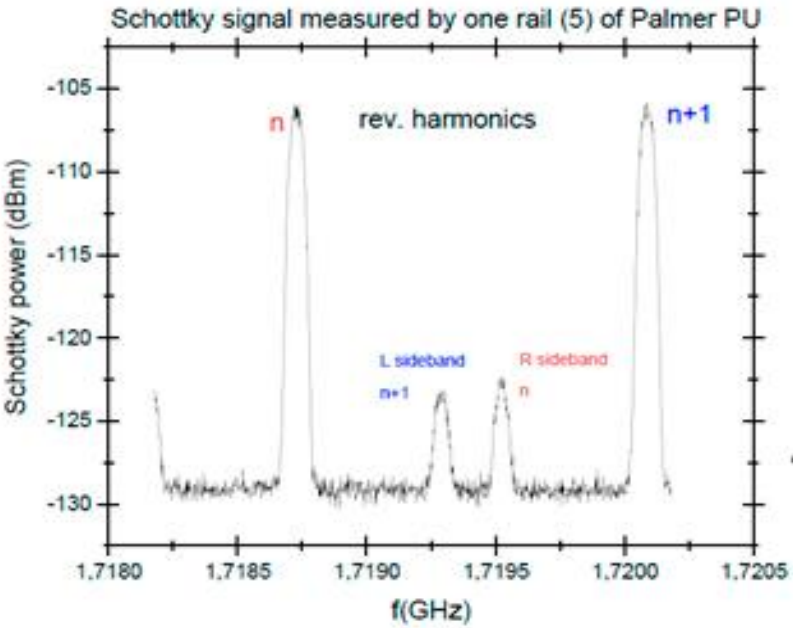


Faltin electrodes

Palmer Pick-Up for Stochastic pre-cooling of heavy ions

Test with proton beam at COSY (FZJ) in 2021



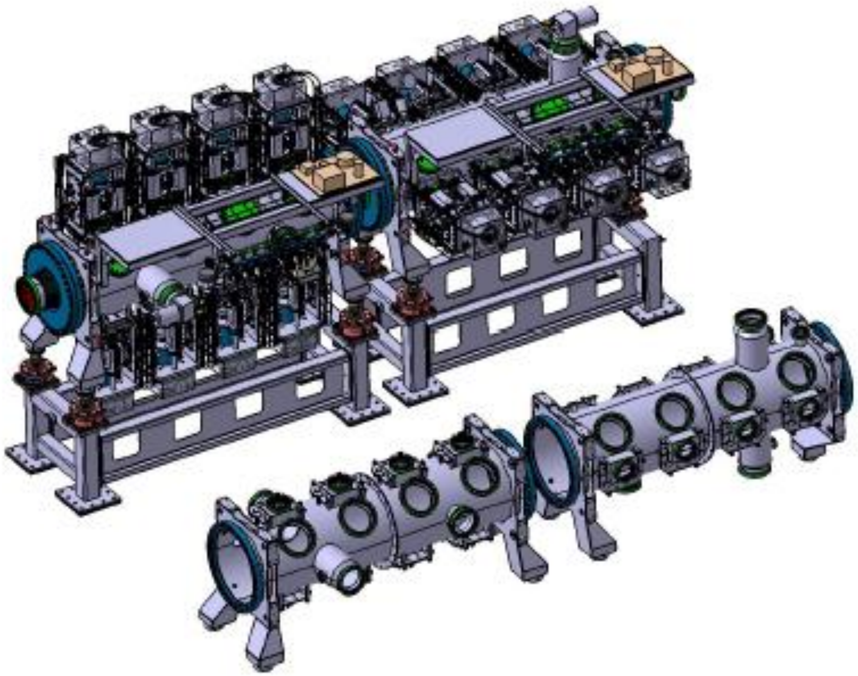


all Faltin electrodes deliver good signals at characteristic beam frequencies (rev. harmonics + vertical betatron)

coasting beam, v=0.83 c
Proton beam N=1.8 x 10^{10}

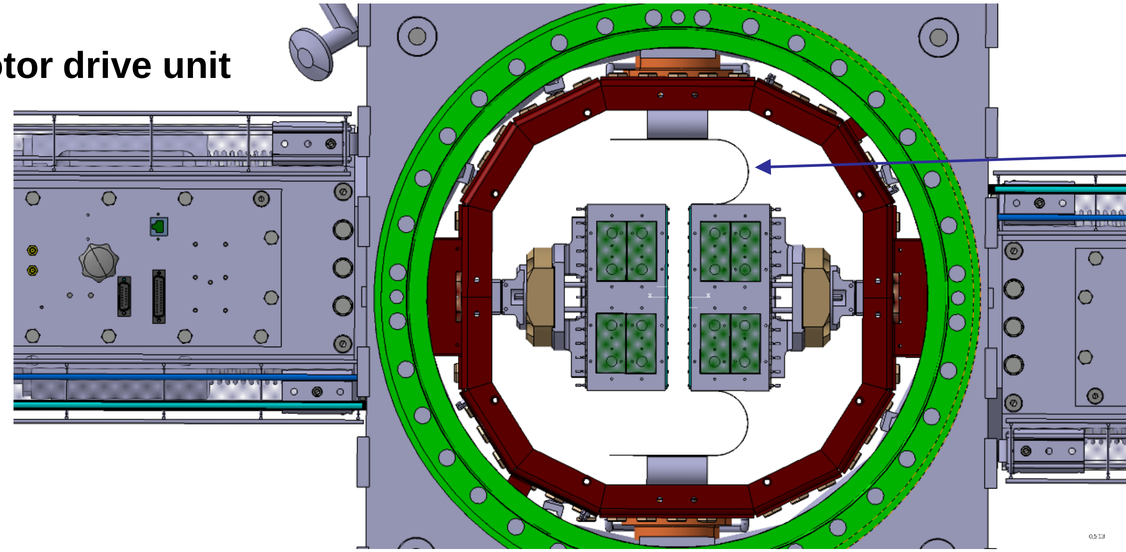
Cryogenic Pick-Up for Stochastic cooling of all ions

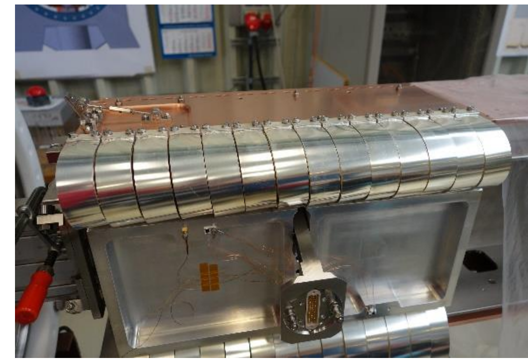
- Engineering done at GSI
- 2 vacuum tanks has been manufactured in 2021.
- Delivery Q1/2022



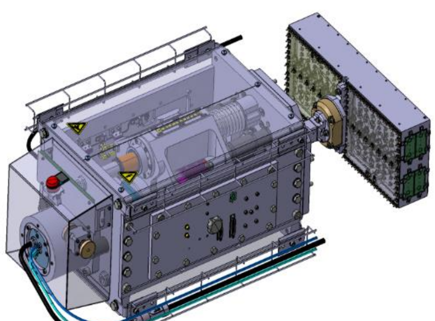
Cryogenic Pick-Up for Stochastic cooling

Motor drive unit





~3500 CuBe plunging foils and their Ag/Cu holders (incl. spares)



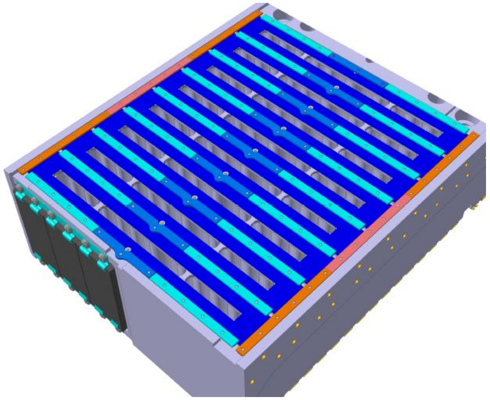
design of motor drive unit with electrode module

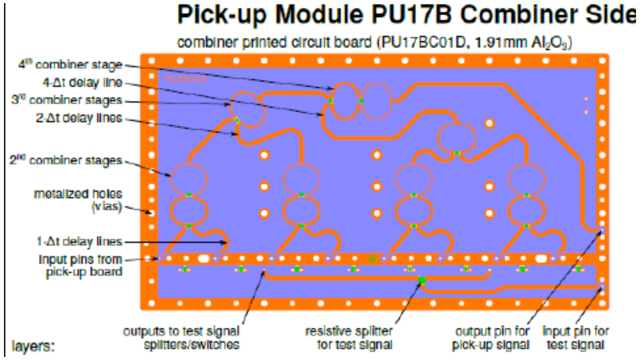
16 Motor Drive Units: ready, pre-assembled in house; stored

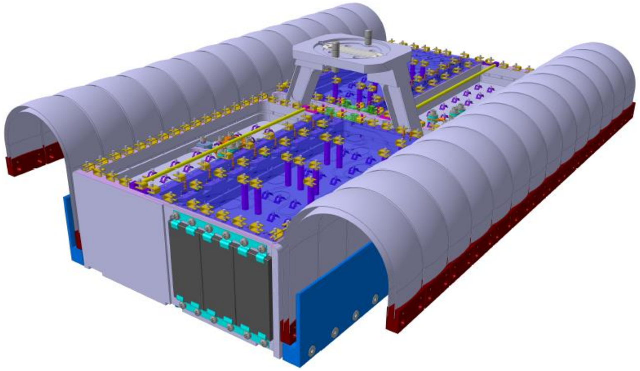
Cryogenic Pick-Up for Stochastic cooling of all ions

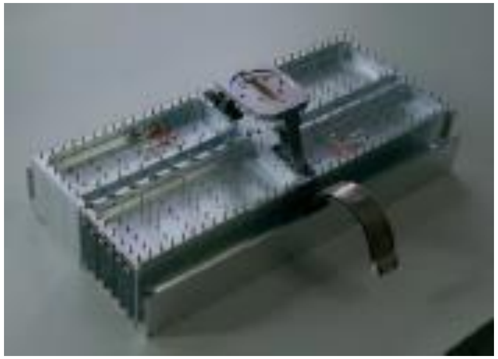
Slotline Electrode Module

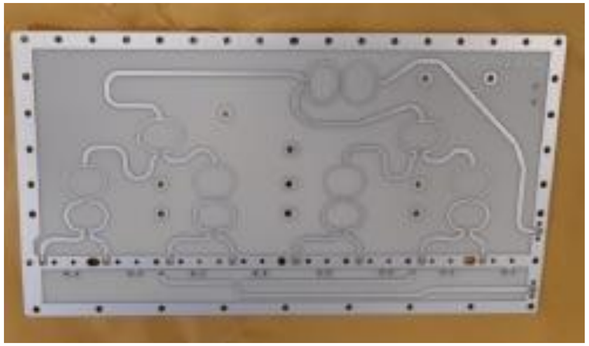
- Engineering at GSI
- Manufacturing at GSI + external
- Delivery to GSI Q3/2023







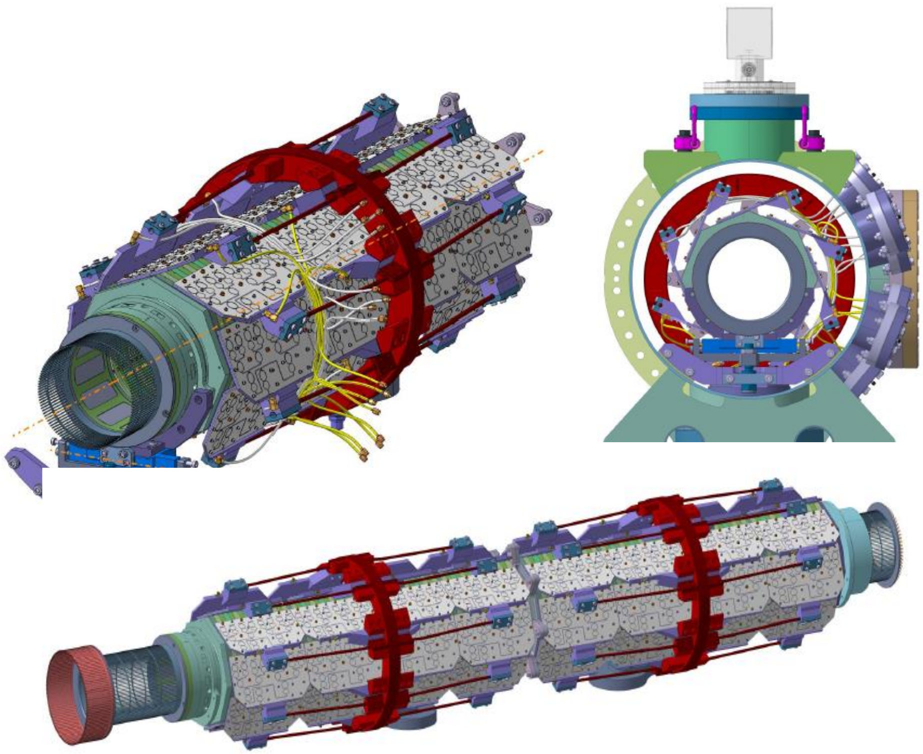




Stochastic Cooling Kicker

- electrodes= slot-rings 1-2 GHz;
- 140 mm aperture
- one tank transverse (Hor/Ver);
- one tank longitudinal cooling

- Decision to adapt the well-proven FZJ kicker concept
- Engineering at FZJ
- 2 vacuum tanks will be manufactured at FZJ
- Delivery to GSI Q4/2024



CR Kicker design done at FZJ

HESR Kicker module

CR Beam dynamic study

Dynamic aperture

Field quality

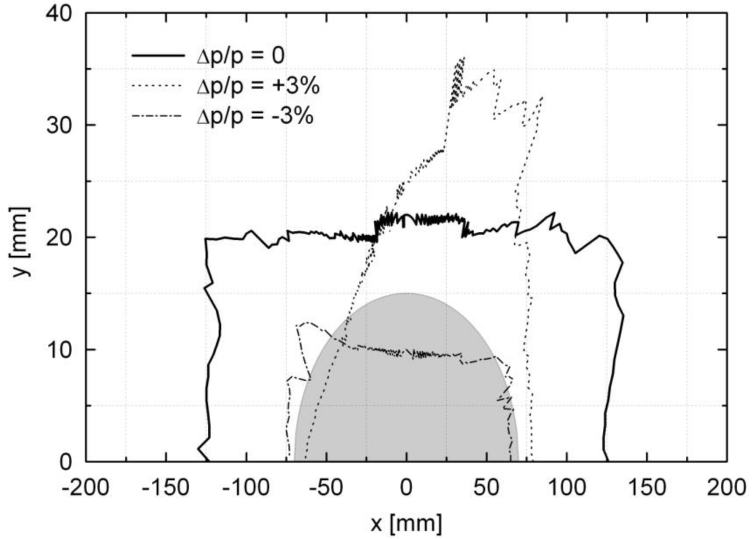
dipole magnet $dB/B = \pm 1*10^{-4}$

quadrupole magnet $dQ/Q = \pm 5*10^{-4}$

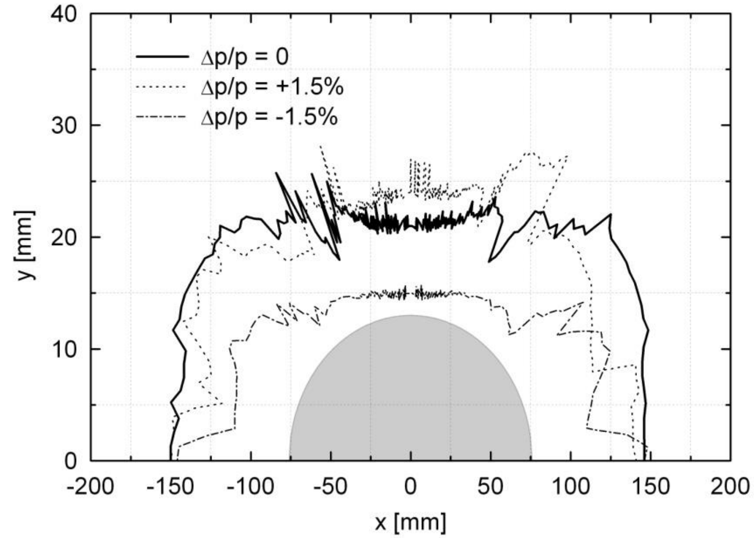
Dynamic aperture with field imperfection up 9th order

Fringe field effect of quadrupole magnets is included

antiproton optics

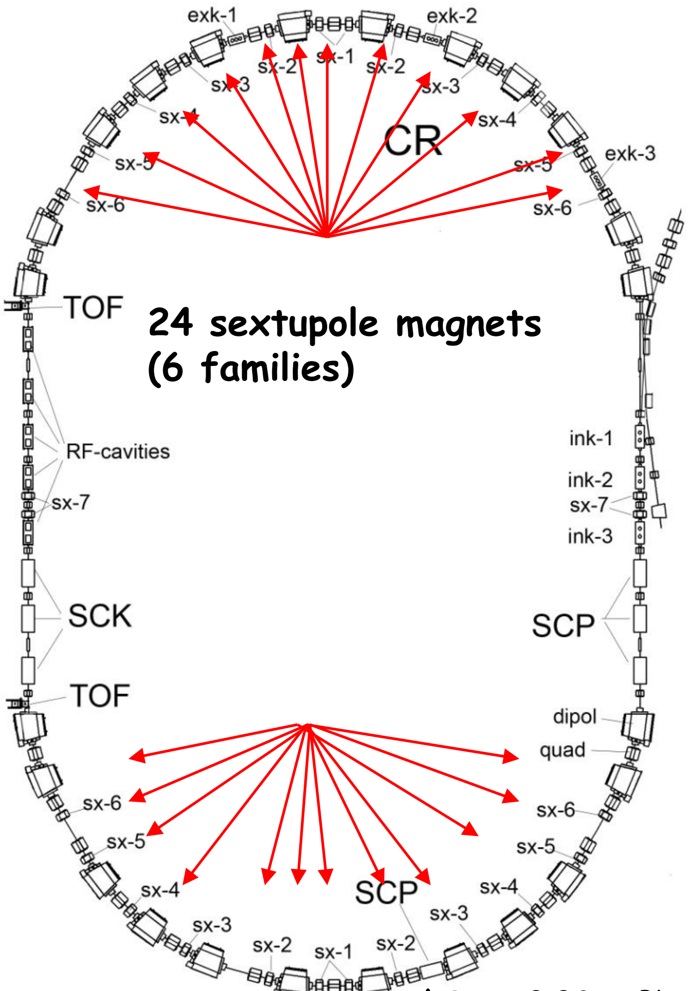


heavy ion optics



Beam dynamic study

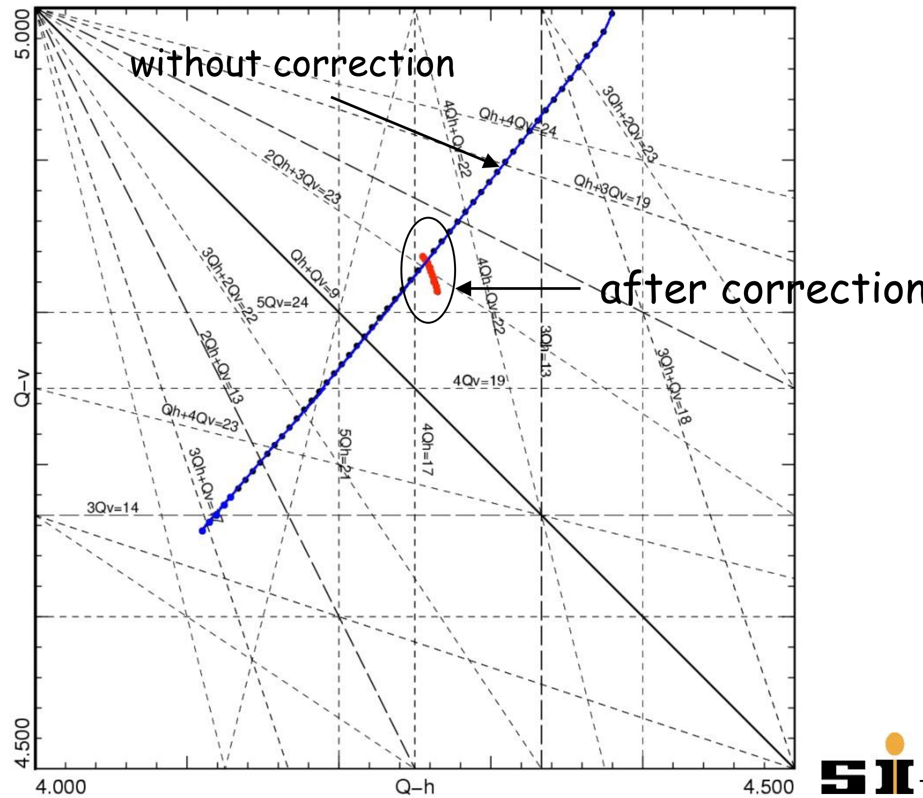
Nonlinear correction



$\Delta Q_{h,v} \approx 0.02$ in Pbar mode
$\Delta Q_{h,v} \approx 0.02$ in RIB mode

24 sextupole magnets (6 families) are needed for :
* Chromaticity correction
* Control of the dispersion function
* Avoiding synchrobetatron coupling

12 octupole correctors (3 families)
for minimizing of the fringe field effect of quadrupoles
in the isochronous mode operation



CR ring systems

BINP (Novosibirsk, Russia): design, engineering, manufacturing, testing, installation, commissioning without beam

- Dipole magnets
- Quadrupole magnets
- Sextupole magnets
- Steerers and correction coils
- Vacuum system
- Power converters
- Diagnostic elements
- Inj./ext. kicker
- Inj./ext. septa

Contract with BINP for production of major part of CR components has been signed in 2018

CR Dipole magnet

- Engineering and Manufacturing at BINP (Russia)
- First of Series delivered to GSI in 2021
- SAT is planned in Q2/2022

Main Parameters	
Good field region	**380 x 140 mm^2**
Required field quality at B_{max}=1.6 T	**± 1 x 10^{-4}**
Required field quality at B = 0.8 T	**± 2.5 x 10^{-4}**
bending angle	**15°**
pole gap	**170 mm**
bending radius:	**8.125 m**
max. current	**1400 A**
Weight	**60 t**
Embedded coils for horizontal steering	**± 3 mrad**

measured field inhomogeneity

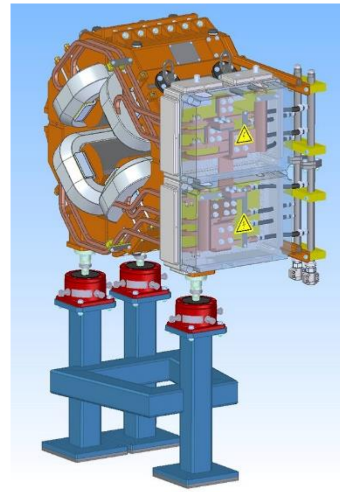
HELMHOLTZ GEMEINSCHAFT

GSI

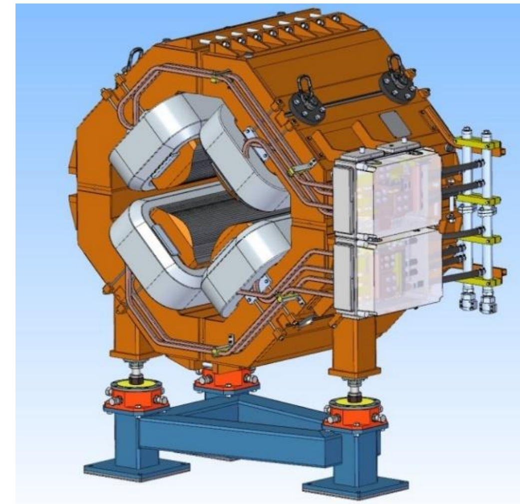
Quadrupole Magnets

Wide and narrow quadrupole magnets:

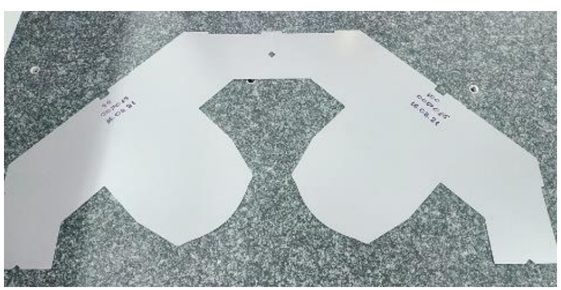
- **Design done by BINP**
- **Materials procurement ongoing**
- **Production workshop at BINP is preparing tools for manufacturing**



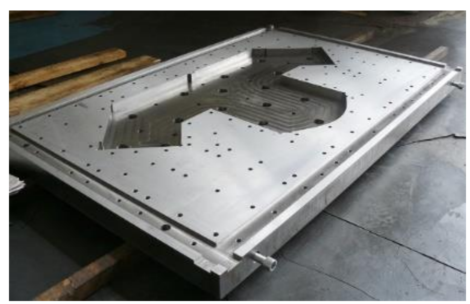
narrow quadrupole

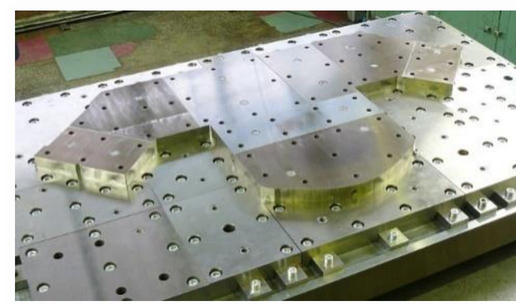


wide quadrupole



Narrow quadrupole test laminas stamped

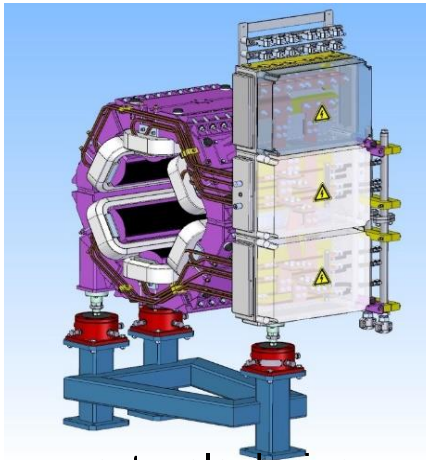




Wide quadrupole stamping tooling assembly

CR Magnets

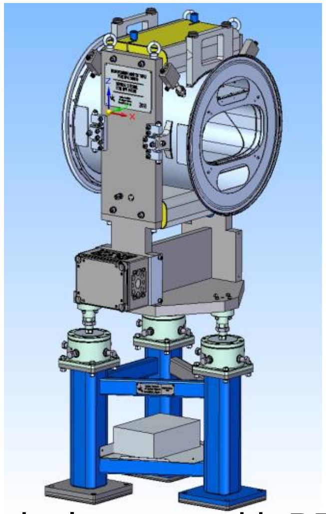
Sextupole magnte:
- Design done,
- Tooling are ready;
- FoS sextupole magnet is expected in Q1/2022



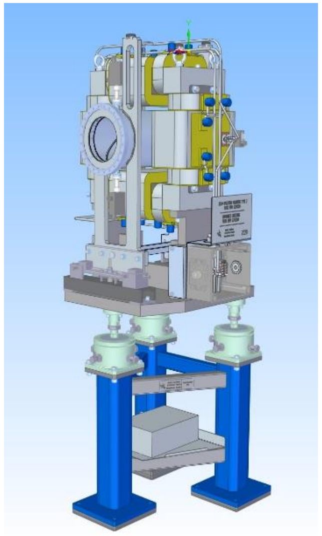
sextupole design

test laminas of sextupole

Steerer with BMP:
- Design done
- Prototype of BPM and Steerer is under test.



Vertical steerer with BPM



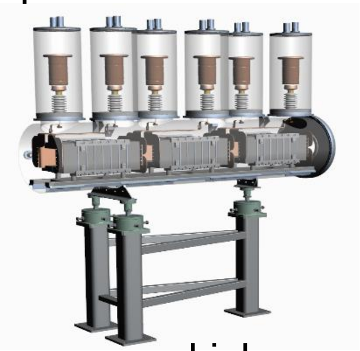
Narrow aperture steerer

CR components

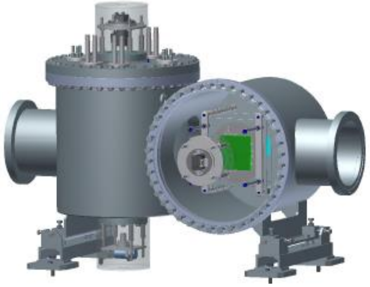
Engineering design , procurement of materials, prototypes, test, series manufacturing at BINP are ongoing

- **Power converters for all magnets**
- **Kicker magnet**
- **Injection extraction magnets**
- **Diagnostic: BPM, Scrapers, Stoppers, RGM, Scintilator screen**
- **Vacuum system**


power converter


kicker

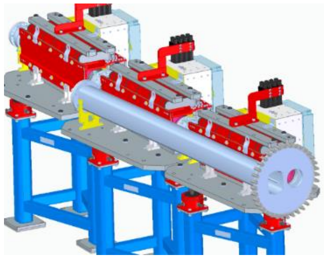

Vacuum chamber


RGM


BPM


scintilator screen

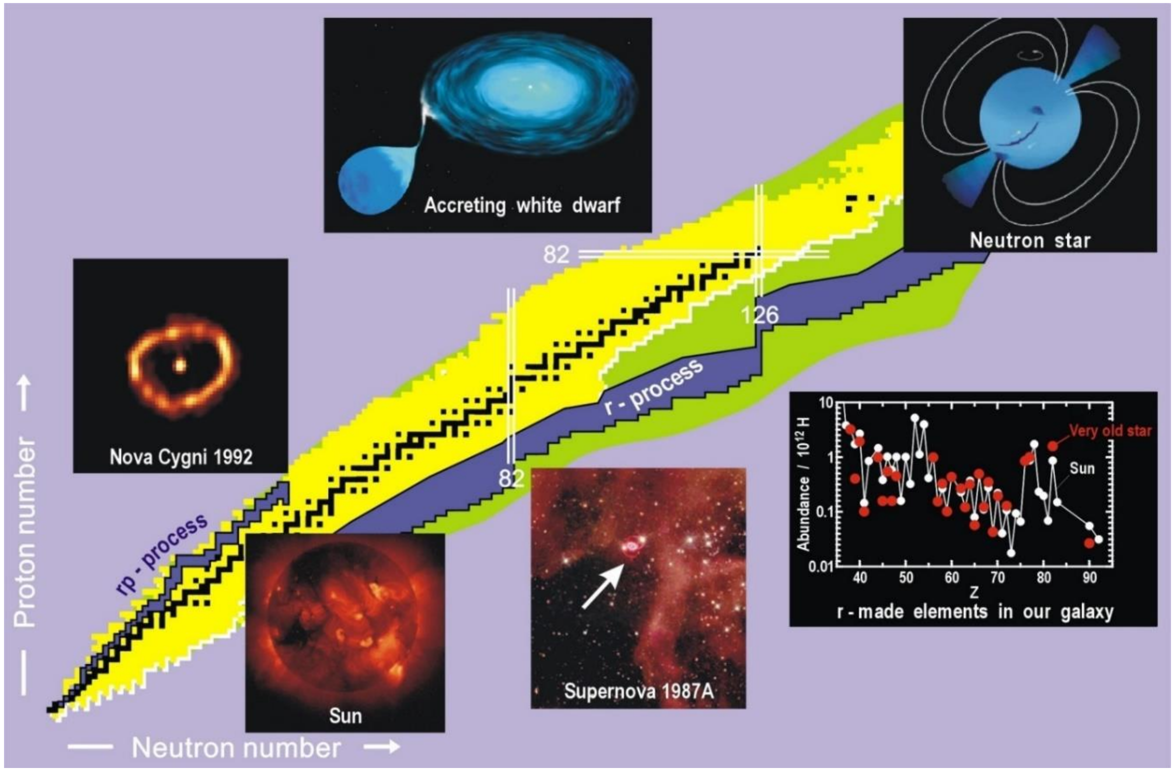

screaper


septa

ILIMA experiments at FAIR

ILIMA =Isomeres, LIfetimes and MAsses

- Total binding energies
- Nuclear decay modes
- Separation energies
- Driplines
- Pairing correlations
- Deformations
- Shell closures
- Reaction Q-values
- Testing and improving nuclear theories
    - Path ways of nucleosynthesis
    - Mass measurements of rare isotopes



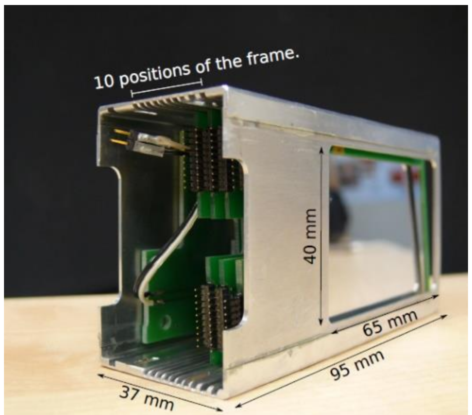
For experiments at CR many detectors are planned to be istalled: Pocker detectors; Schotky resonators; Time of Flight detectors

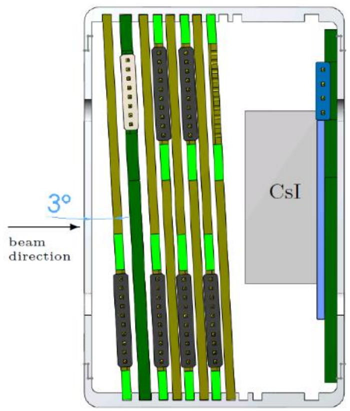
HELMHOLTZ GEMEINSCHAFT

GSI

Silicon Heavy Ion Detector

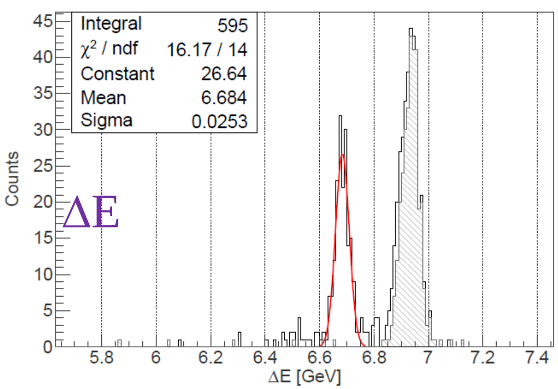
Measurements of β-decay half-lives for determination of the pathways of nucleosynthesis processes

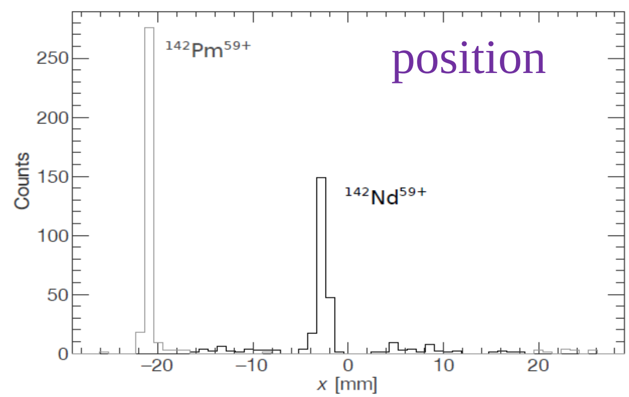




- -Silicon pad detectors (x6)
- -Double sided silicon strip detector (x1)
- -Passive absorber (x1)
- -CsI scintillator coupled to silicon photodiode

β^+ decay: ^{142}Pm^{60+} → ^{142}Nd^{59+}, electron capture ^{142}Pm^{59+}





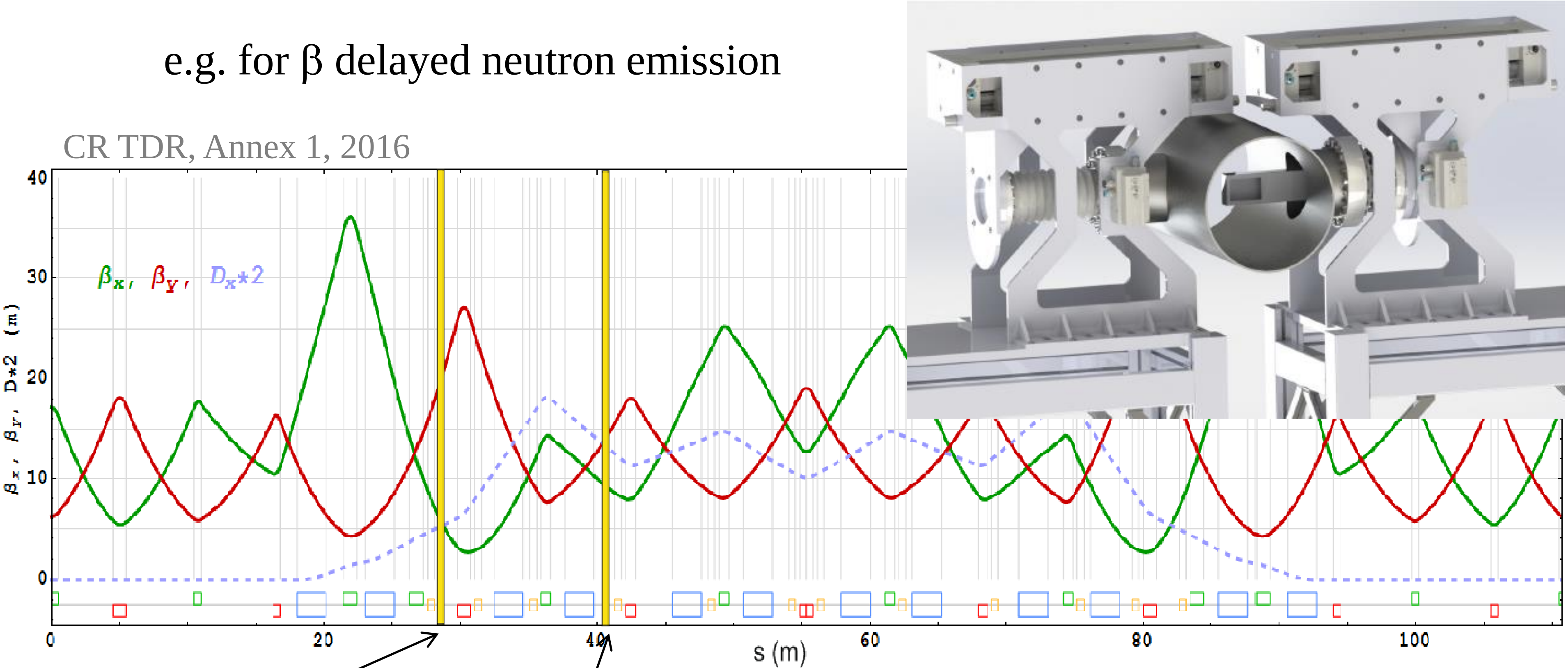
Ali Najafi et al.
NIM A836 (2016) 1.

S/DSSD stack for ΔE, x
active area 40mm x 60mm
with CsI calorimeter +
Si photo diode to identity
Z and A by ΔE, E.

Detector Pockets

e.g. for β delayed neutron emission

CR TDR, Annex 1, 2016



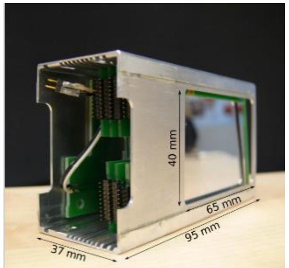
Δx = -72 mm
for Z=50, m=132

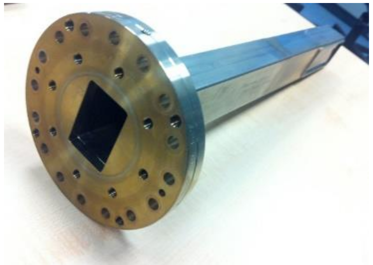
Δx = -130 mm
for Z=82, m=126

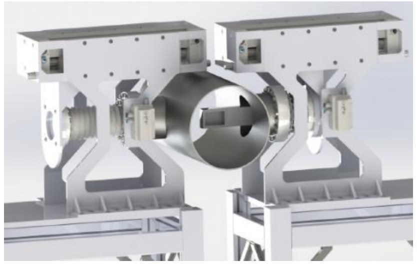
cooled beam (ε_x = 1 mm mrad)
➔ x-width = 2.2 – 3.2 mm

pocket out during injection
→ fast drive with servo motor

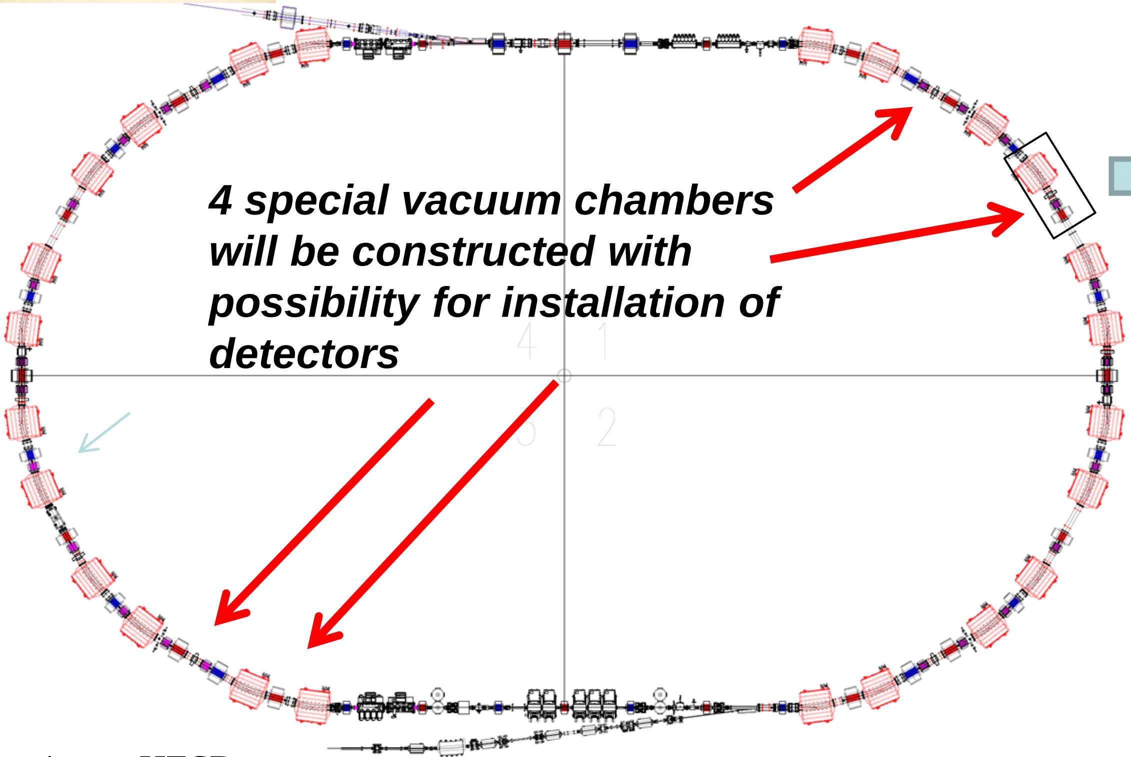
Position of detectors at CR

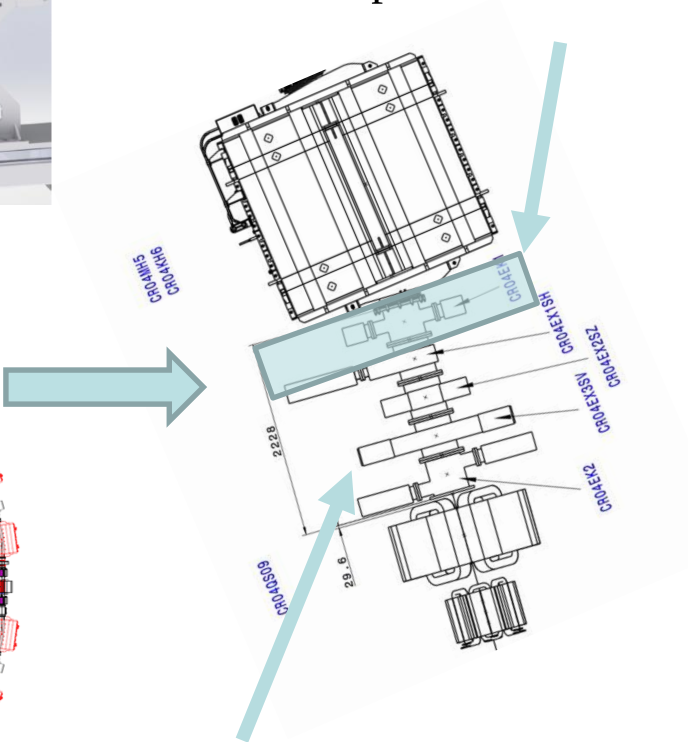






pocket detector





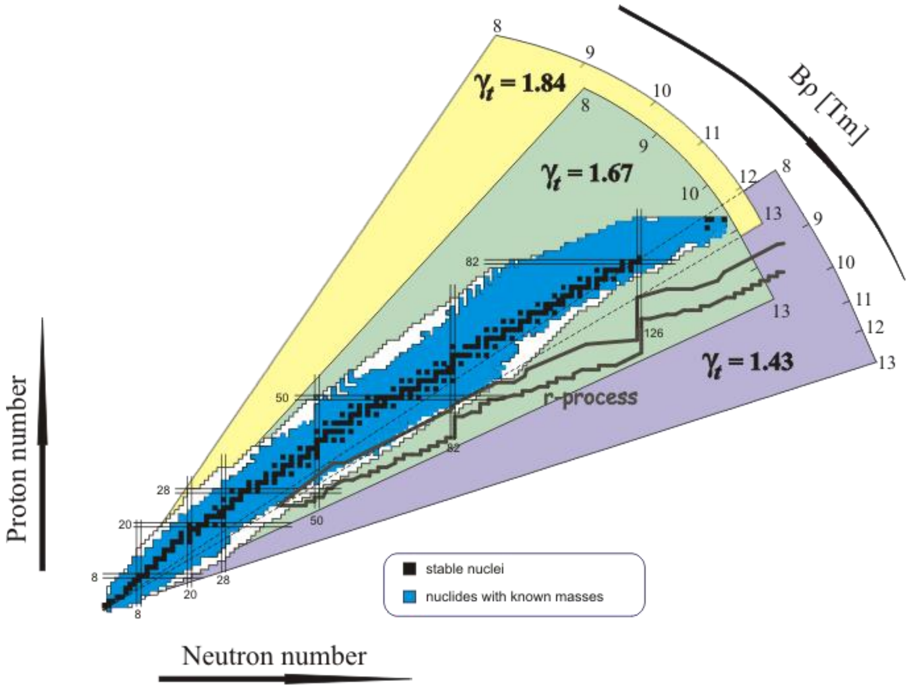
Schottky resonator

Extraction to HESR

CR as a mass spectrometer

To determine the r-process, rapid neutron capture process, that occurs in core-collapse supernovae one have to measure masses of neutron-rich exotic nuclei.

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta(m/q)}{m/q} + \left(1 - \frac{\gamma^2}{\gamma_{tr}^2}\right)\frac{\Delta v}{v} + \left(\frac{\delta f}{f}\right)_{error}$$



TOF mass measurements

Isochronous mode ($\gamma_{tr} = \gamma$) for fast mass measurements.

$$\gamma_t = \gamma = 1.84\ (E = 782.5\ MeV/u)$$
$$\gamma_t = \gamma = 1.67\ (E = 624.1\ MeV/u)$$
$$\gamma_t = \gamma = 1.43\ (E = 400.5\ MeV/u)$$

Isochronous Mass Spectrometry (IMS) is one and only quick and sensitive enough technique for mass measurements of large number of extremely short exotic nuclei with high accuracy ($\Delta m/m \sim 10^{-6}$)

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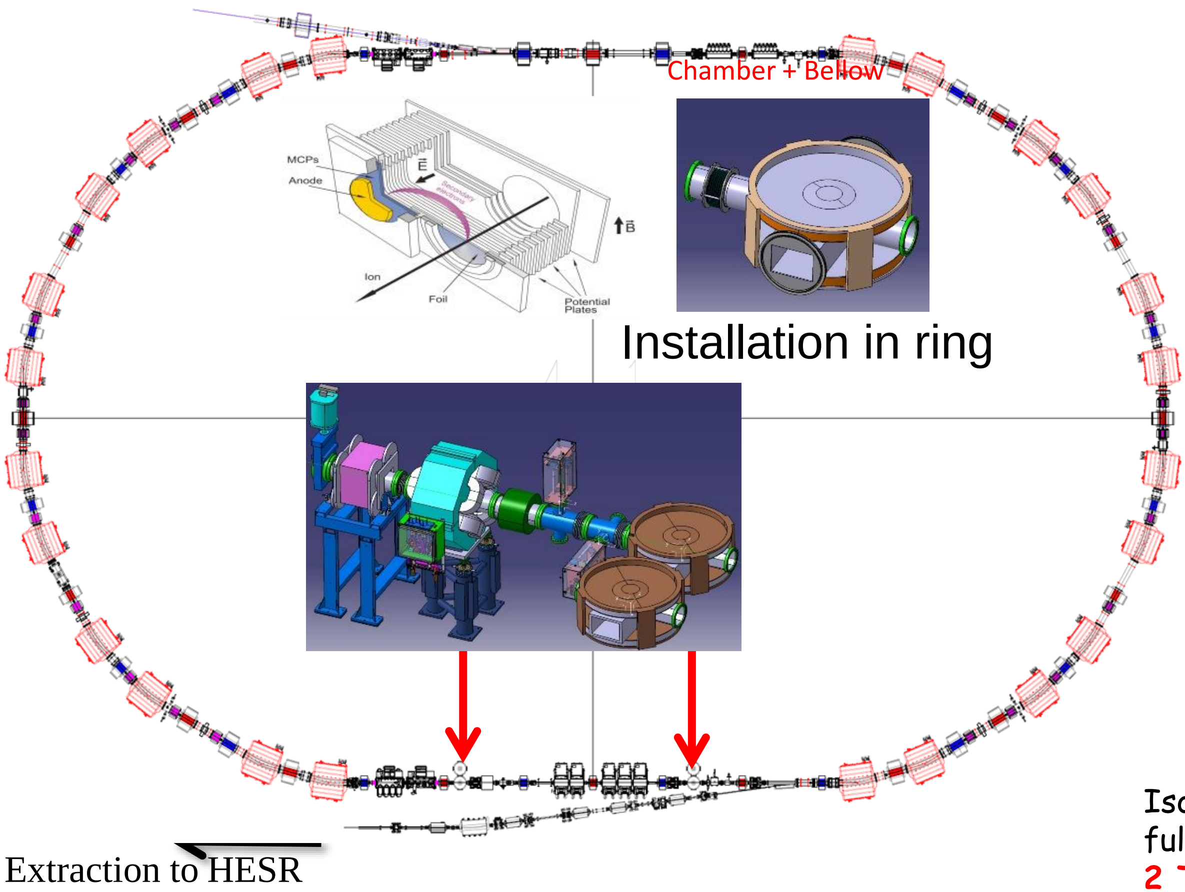
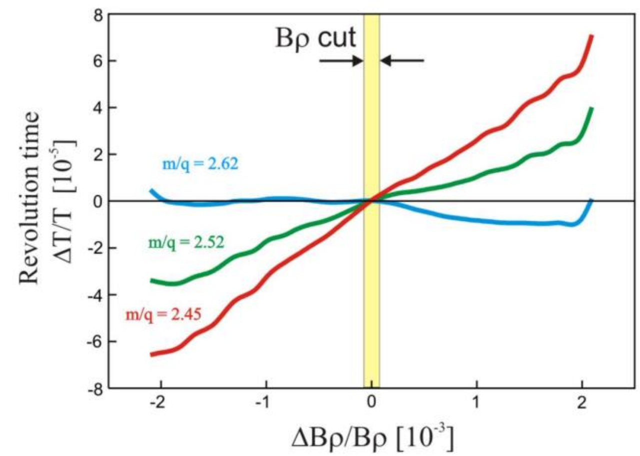
TOF detectors





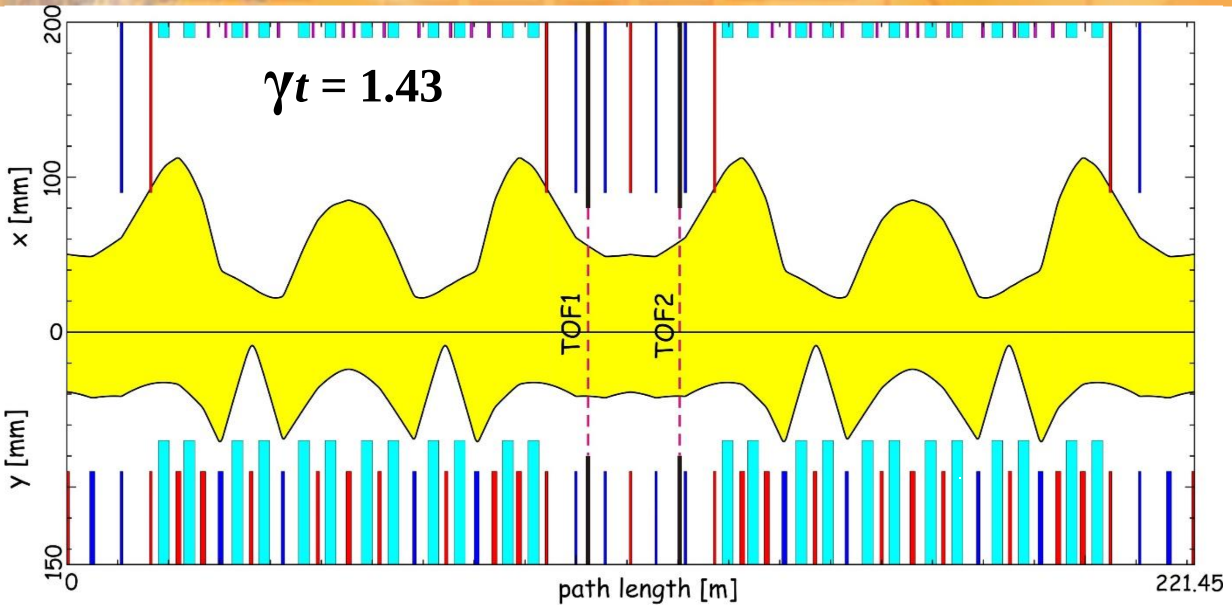
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta(m/q)}{m/q} + \left(1-\frac{\gamma^2}{\gamma_{tr}^2}\right)\frac{\Delta v}{v} + \left(\frac{\delta f}{f}\right)_{error}$$

$$\gamma_{tr} = \gamma_{tr}(\delta p/p)$$

$$\gamma_{tr}(\delta p/p) \neq \gamma$$

Isochronous conditions are no ideal for full momentum spread area.
2 TOF detectors are used for velocity measurement as a function of m/q

Isochronous optics for TOF measurements



$\varepsilon_x = \varepsilon_y$=100 mm mrad

Δ*p/p* ±0.2%

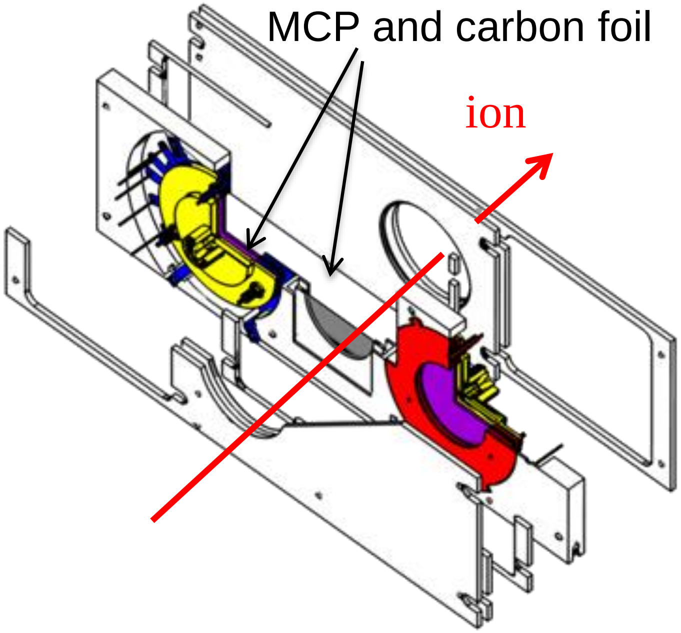
ΔL (TOF) = 18 m

***x/y* (TOF1) = 56/42 mm**

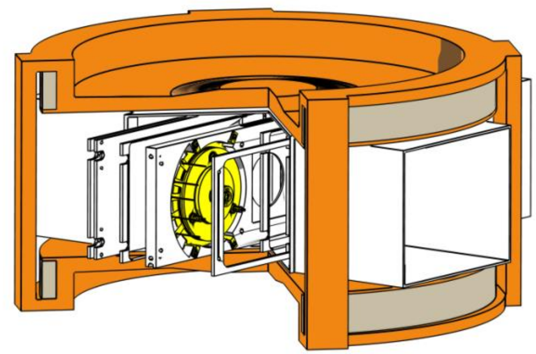
***x/y* (TOF2) = 59/42 mm**

D_{max}=47 m,
=0 at the straight sections.

TOF Detector System for CR



Isochronous electron transport by crossed E, B fields.



yoke diameter 900mm
magnet hom. dB/B = 10^{-3}

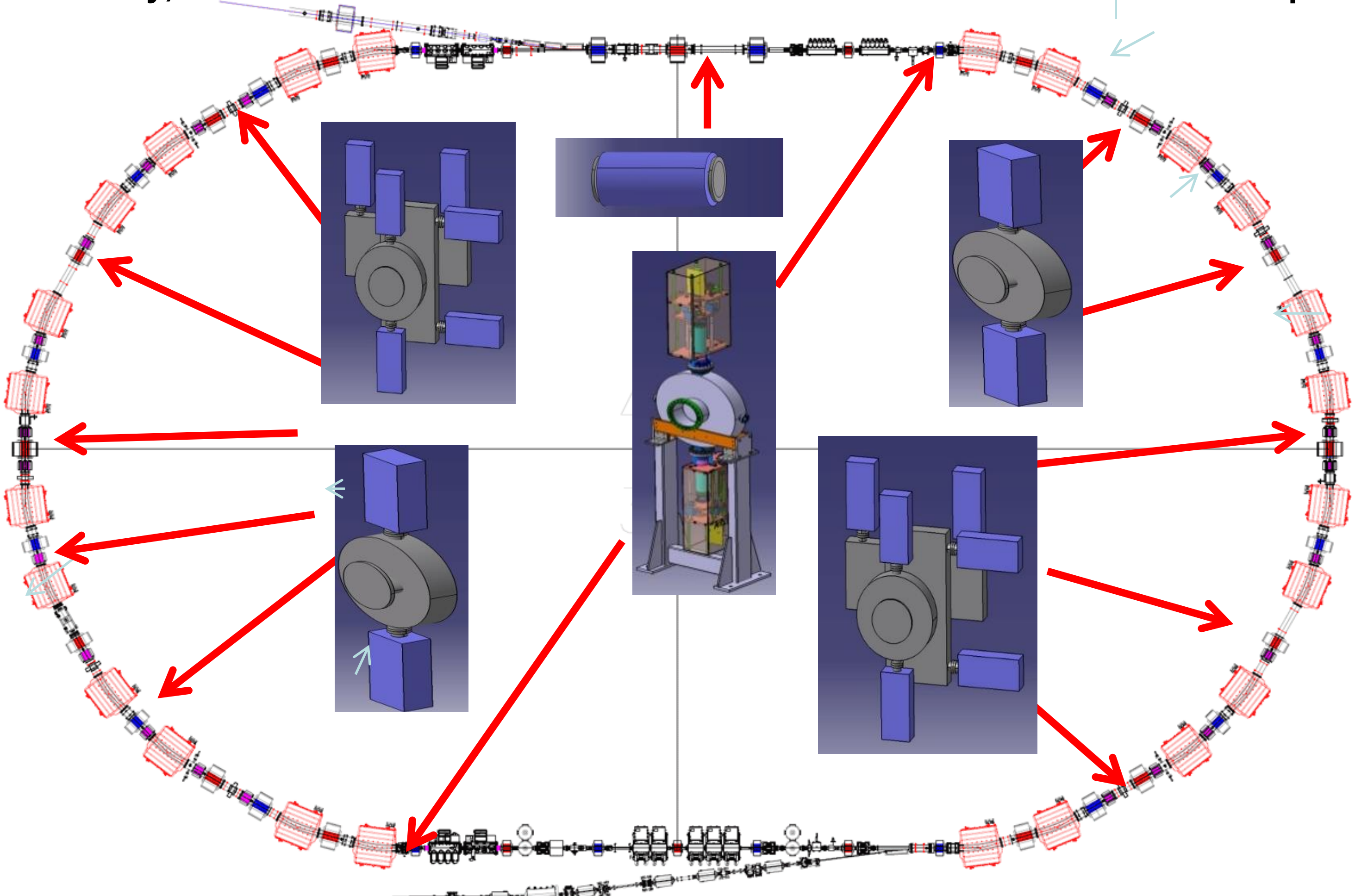
Electron transport efficiency ≈ 98%
Timing accuracy ≈ 35 ps

- **Active area d=80mm wanted, accepted emittance (x * y) scales with d^4 !**
- **Simulations + Tests for detector show even better timing than ESR detector**

M. Diwisch thesis, University Giessen 2014, N. Kuzminchuk et al., NIM B 821, 160

Schottky resonators

Schottky resonators are planned for measurements of radioactive decay, electron capture decay, for mass measurements in both in normal and isochronous mode operation.



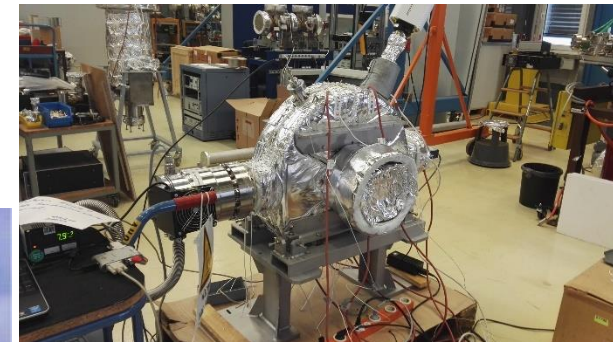
There will be 13 resonators in the CR ring.

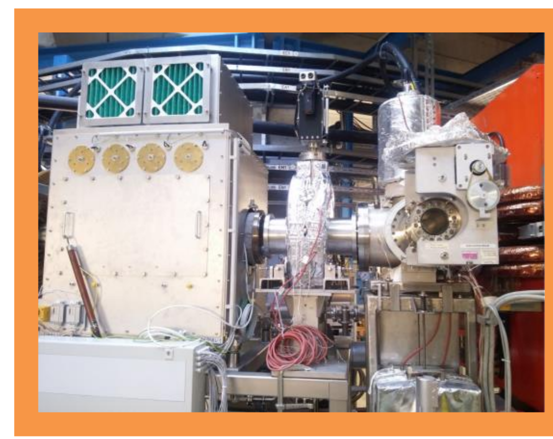
4 types of resonators for measurement of longitudinal and transverse Schottky signals

It will also be useful for diagnostics of antiprotons with high sensitivity, stochastic cooling process.

Schottky resonators

One type of resonator:
A prototype has been designed and manufactured at GSI.
Test at ESR/ GSI has been done.

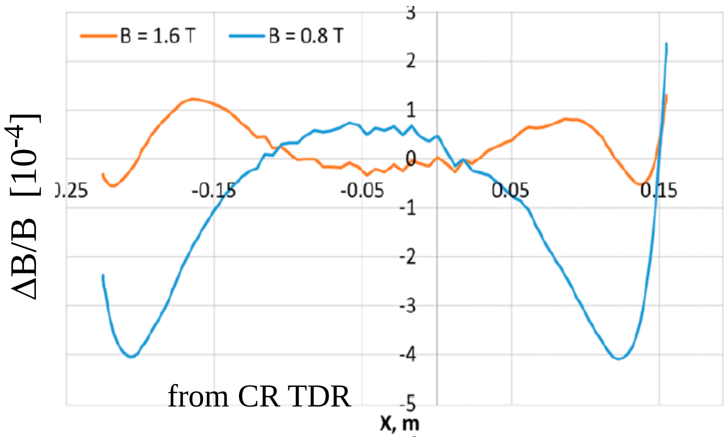


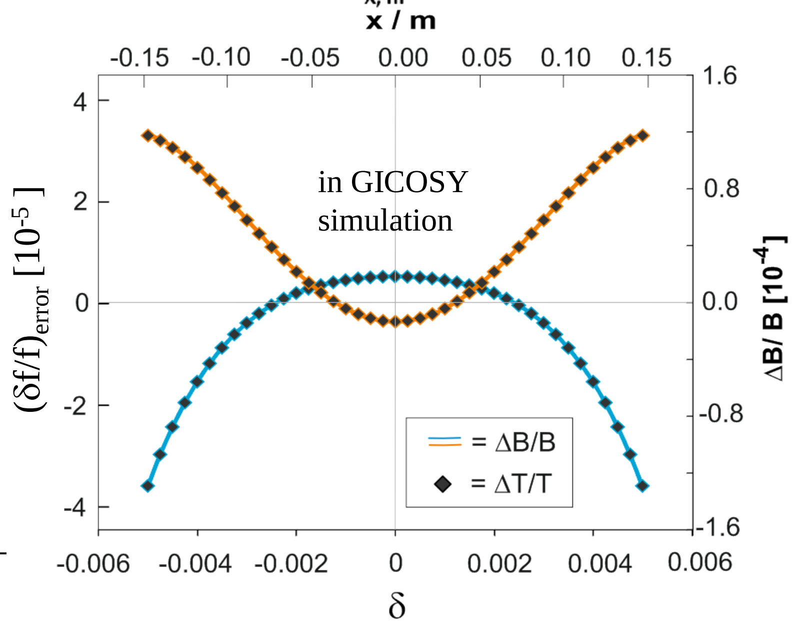


Precision of mass measurements

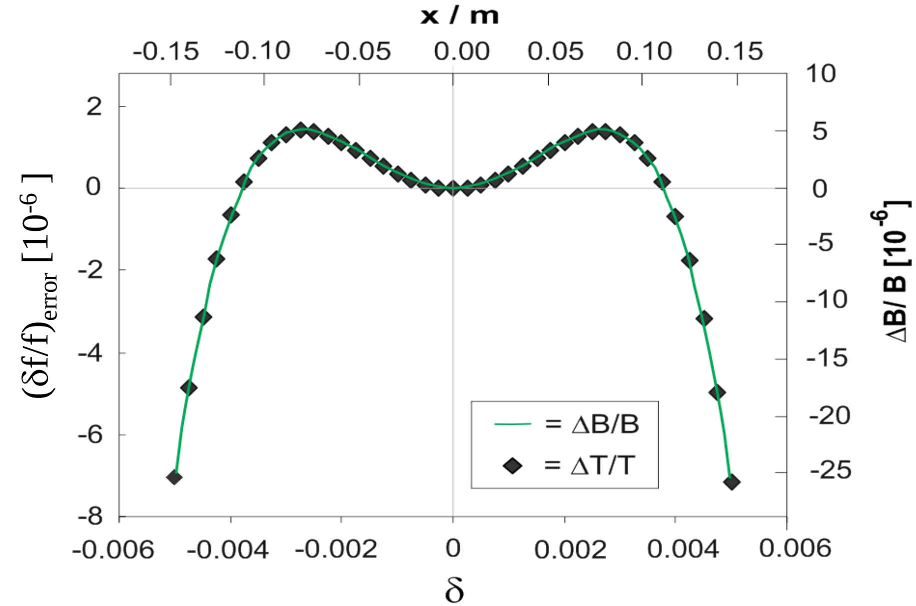
Sextupoles, octupoles are foreseen, but also a 4th order corrector is needed.

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta m}{m} + \frac{\Delta f}{f}_{error}$$





With full correction

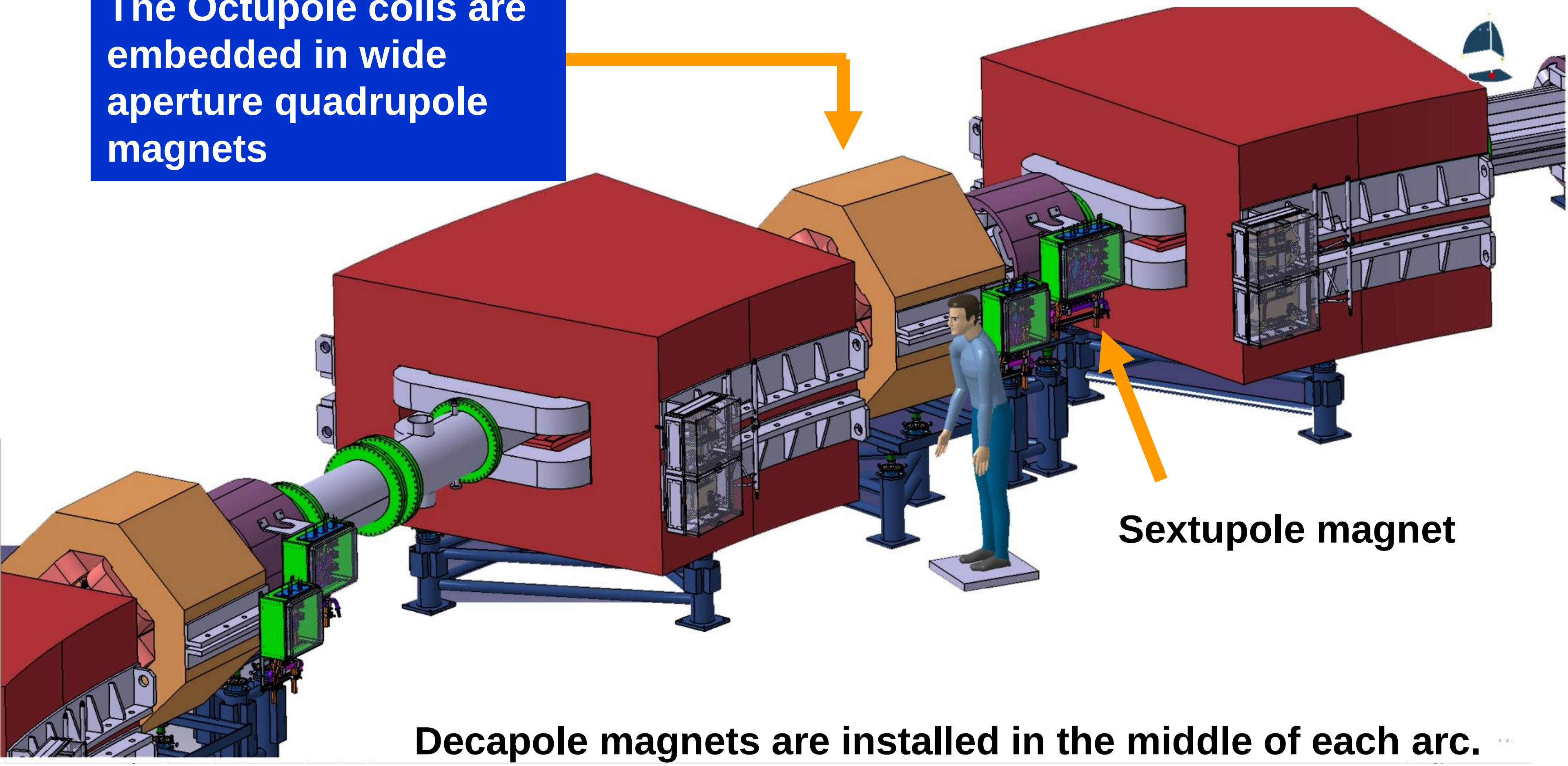


Decapole Corrector **$B^{(4)}L = 80\ Tm/m^4$**

Current ripple δI/I of power converter for dipole magnets should be not larger as 10^{-6}

GSI

CR magnets

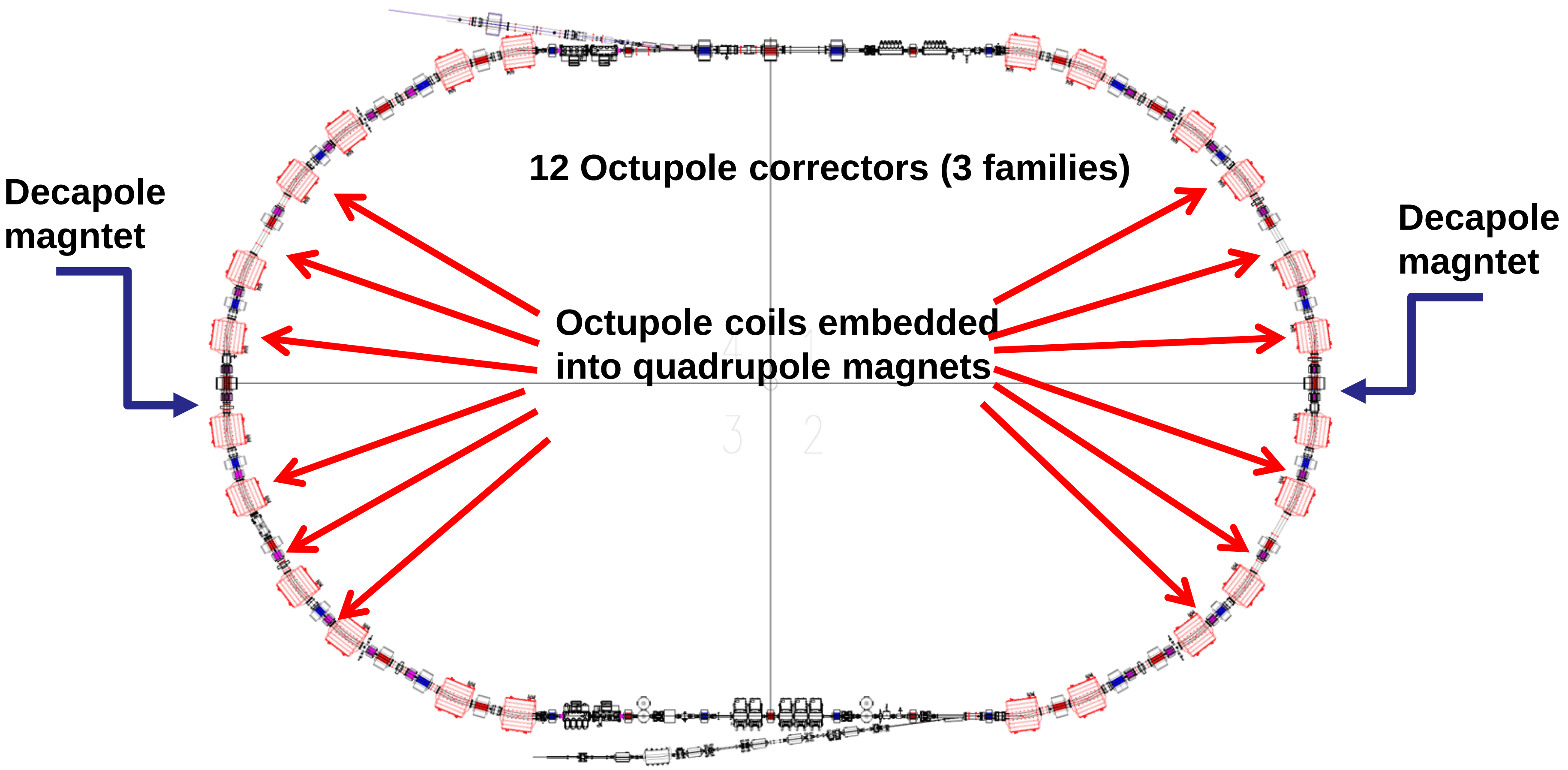


The Octupole coils are embedded in wide aperture quadrupole magnets

Sextupole magnet

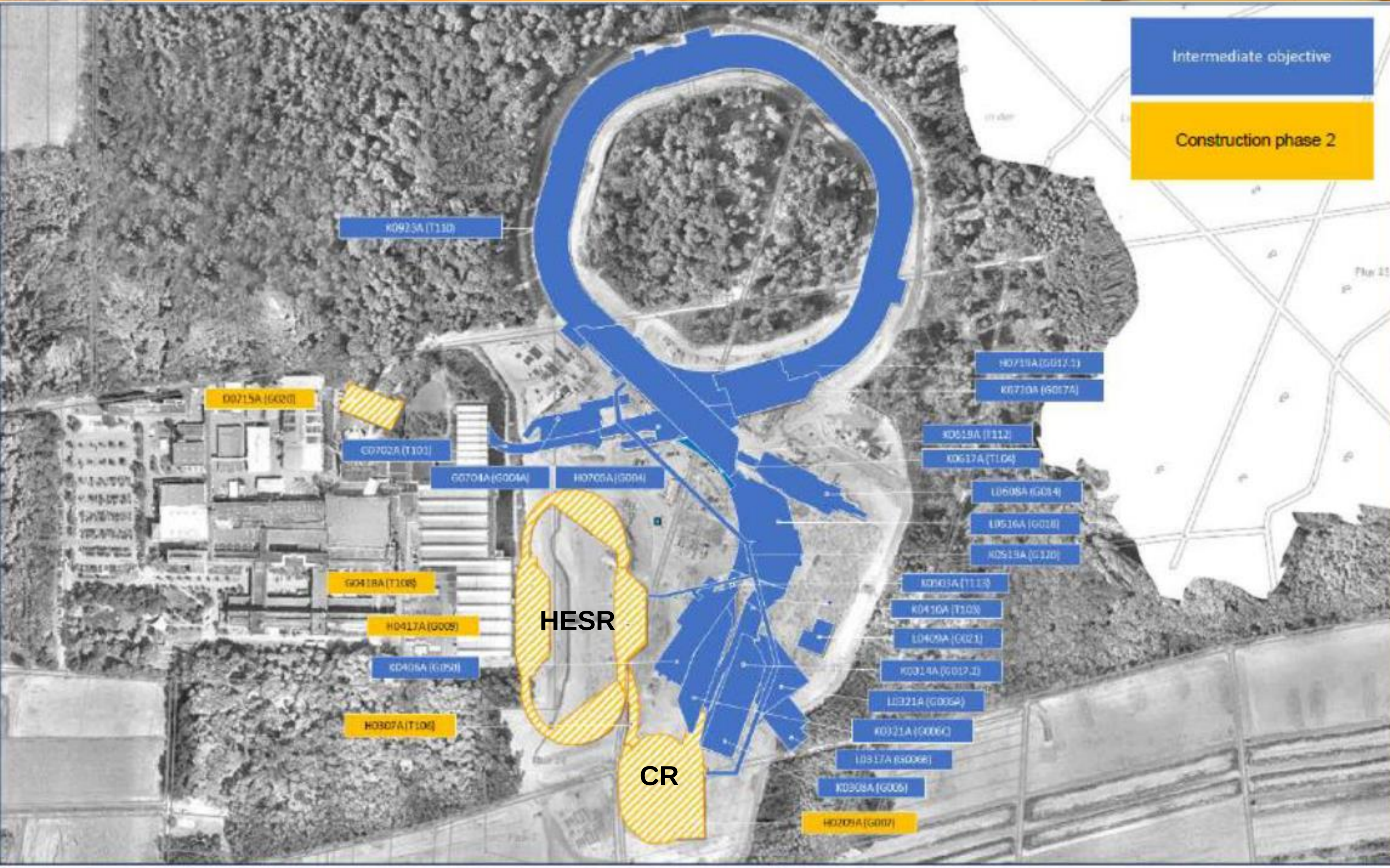
Decapole magnets are installed in the middle of each arc.

non linear correction

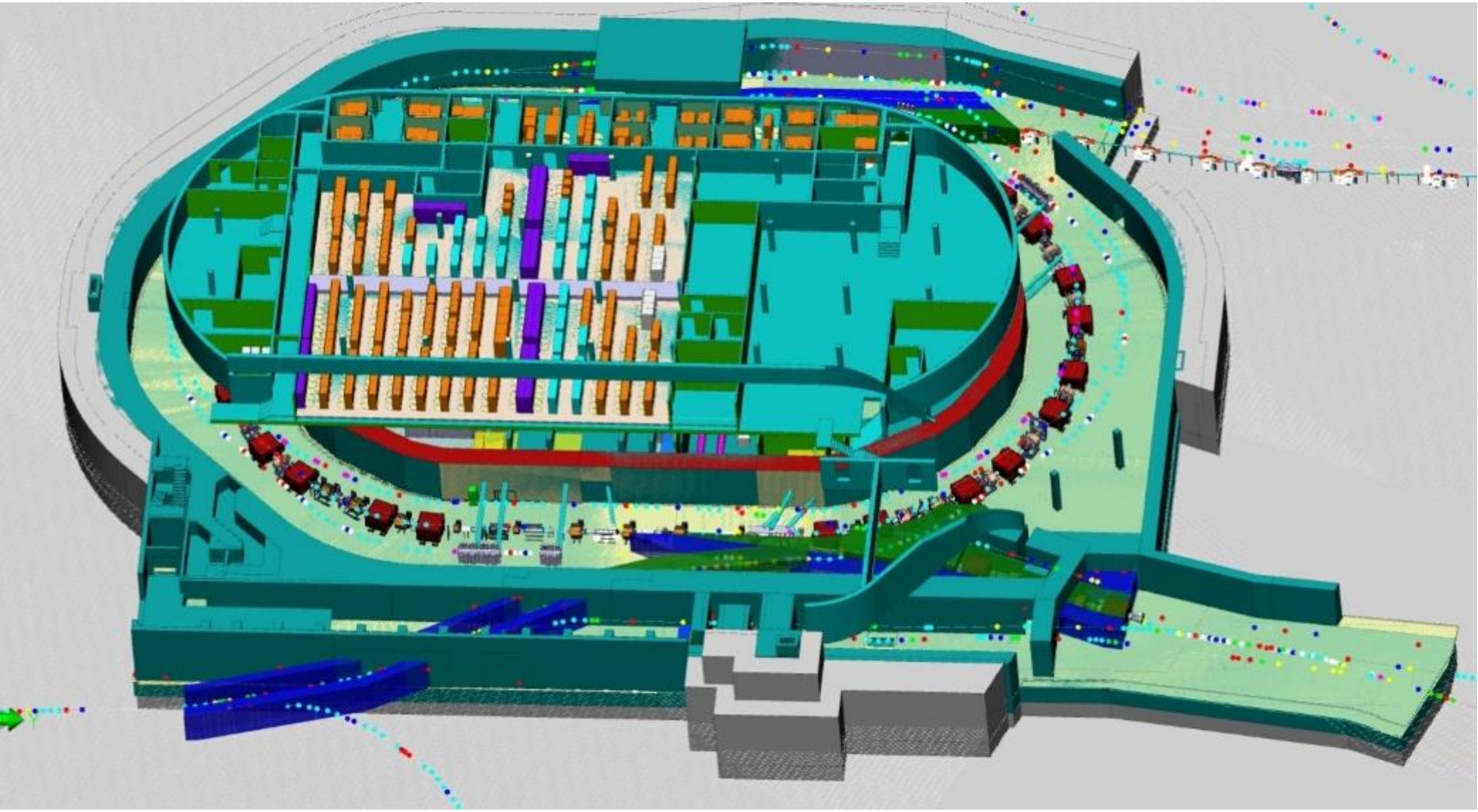


FAIR CIVIL CONSTRUCTION

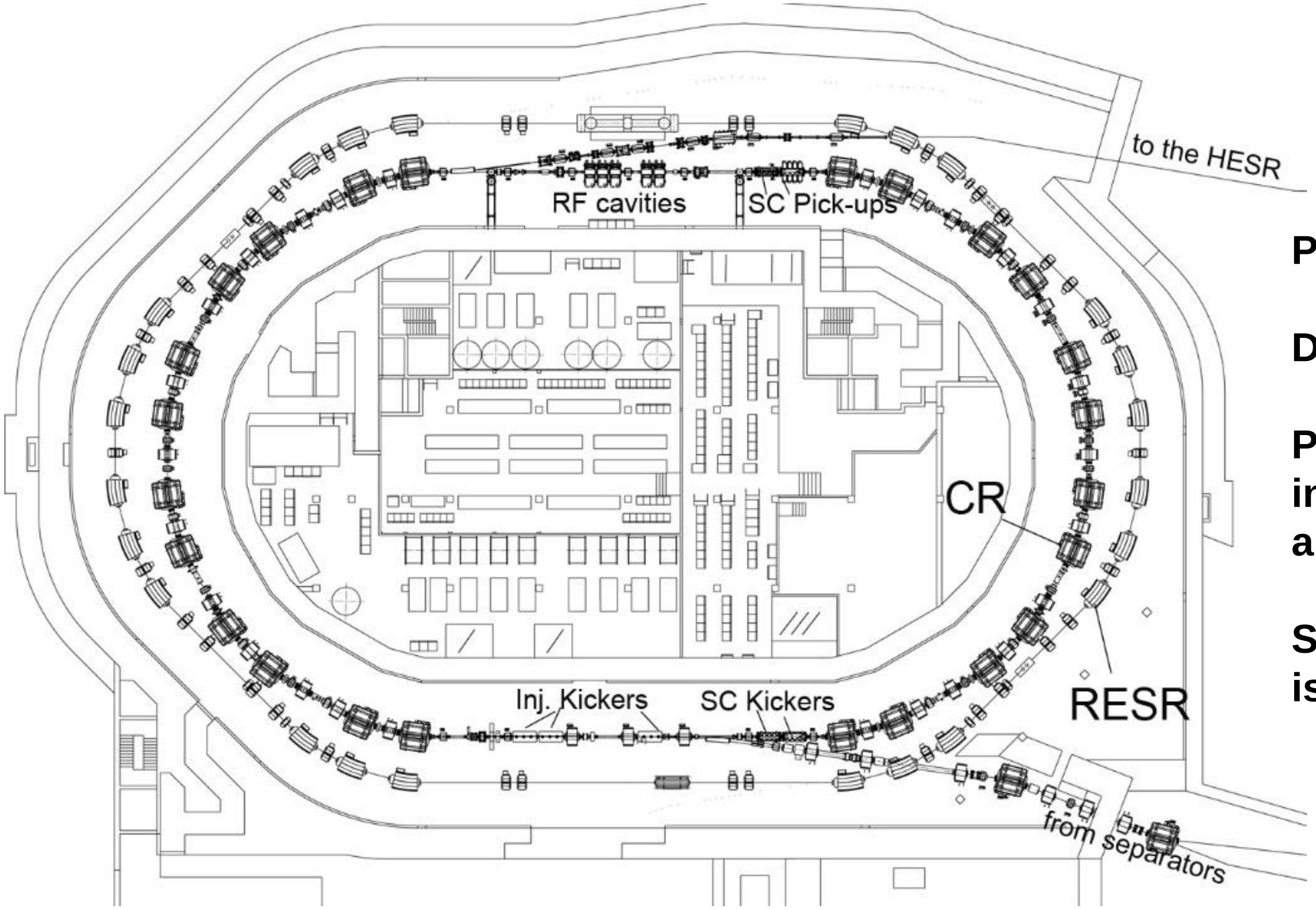
FAIR CIVIL CONSTRUCTION



Building for CR and RESR



Building for CR and RESR



Present status:

Design of building done

Planning of technical infrastructure and cable takes place.

Start of construction is planned in 2023

Conclusion

- CR will provide cooling of secondary beams with a high efficiency
- In-ring experiments can be done with a high precision
- Technical design of all CR systems has been finished.
- The RF debuncher system has been completed by 100 %
- The SC Palmer Pick-Up has been constructed and tested
- Many accelerator components are under serial production
- It is planned to finish production of all accelerate systems by 2025
- Ring assembling is planned in 2025-2026
- Commissioning in 2026 -2027
- Start operation 2027

FAIR – Facility for Antiproton and Ion Research
GSI Helmholtzzentrum für Schwerionenforschung