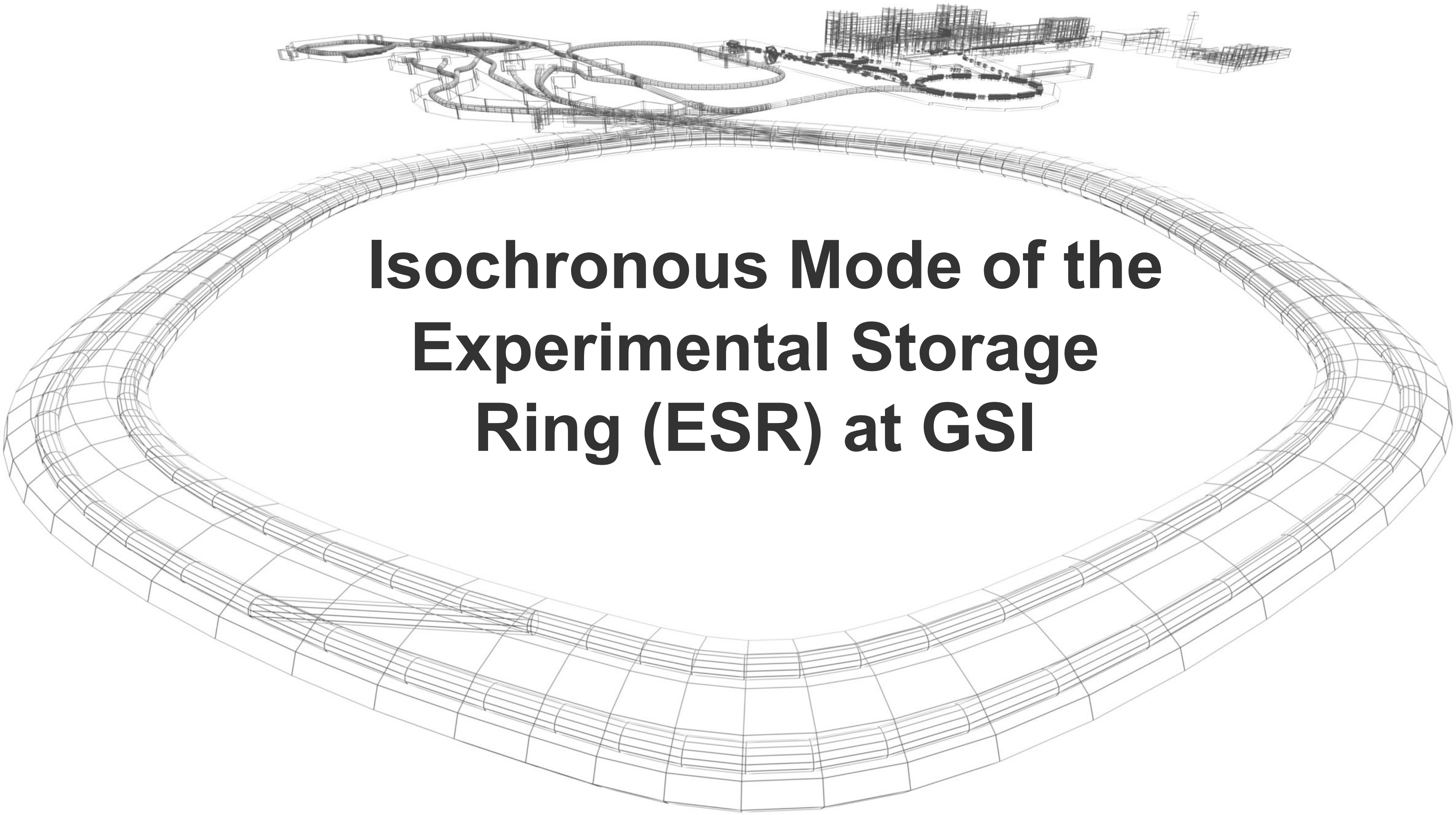
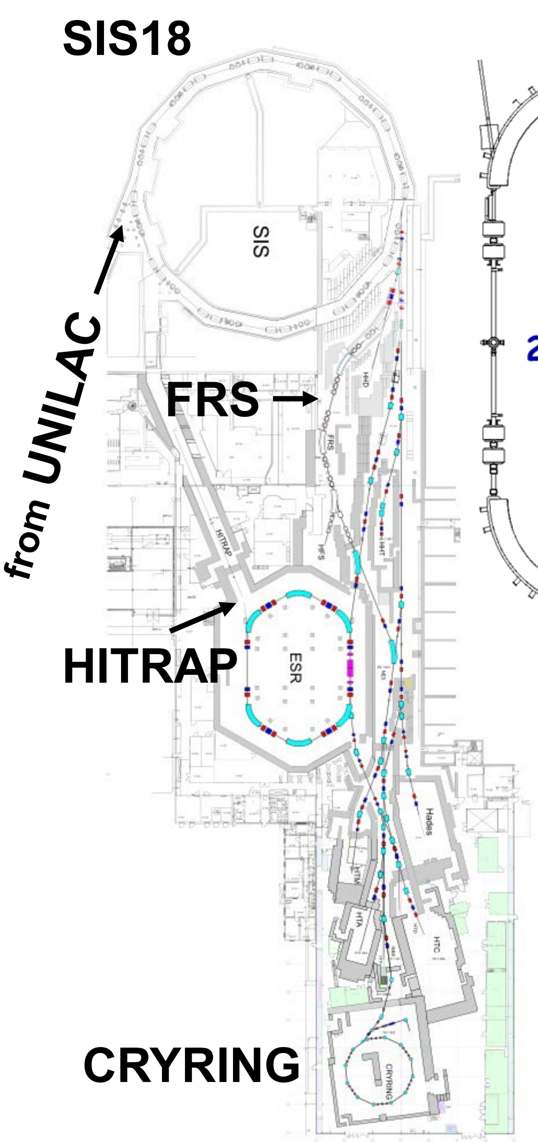
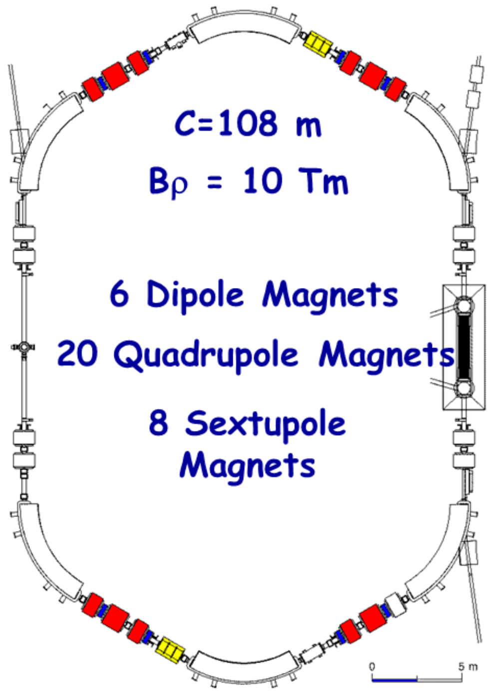


Isochronous Mode of the Experimental Storage Ring (ESR) at GSI

Accelerator Facility at GSI





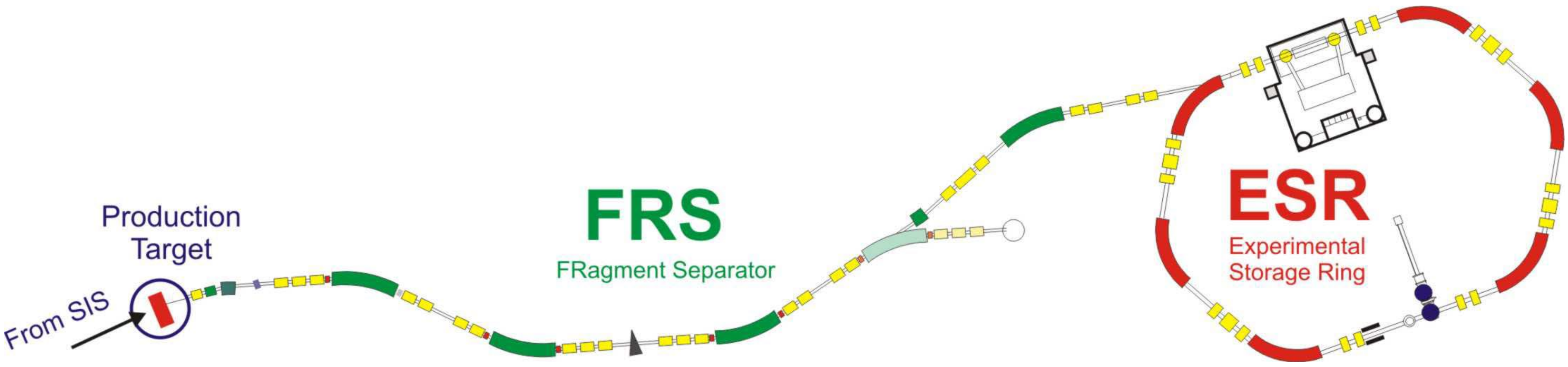
The stable primary beams are accelerated by The linear accelerator UNILAC to an energy Of 11.4 MeV/u and then by synchrotron SIS18 to energies 100-1000 MeV/u.

The secondary beams can be produced via Fission or fragmentation of primary beams in a production target and separated in flight either by the FRagment Separator (FRS) or in the straight transfer line from SIS18 to the ESR and then injected in the ring.

The ESR is the core instrument for unique physics experiments. The ESR is operated for accumulation, storage, cooling and Deceleration of heavy ion beams in the energy range from 4 – 400 MeV/u.

Decelerated highly charged ions can be used either for in-ring experiments or can be fast extracted to the low energy ring CRYRING (extraction energy of 10 MeV/u) or to the Heavy Ion TRAP facility (HITRAP) (extraction energy of 4 MeV/u).

Production and Separation of Exotic Nuclei



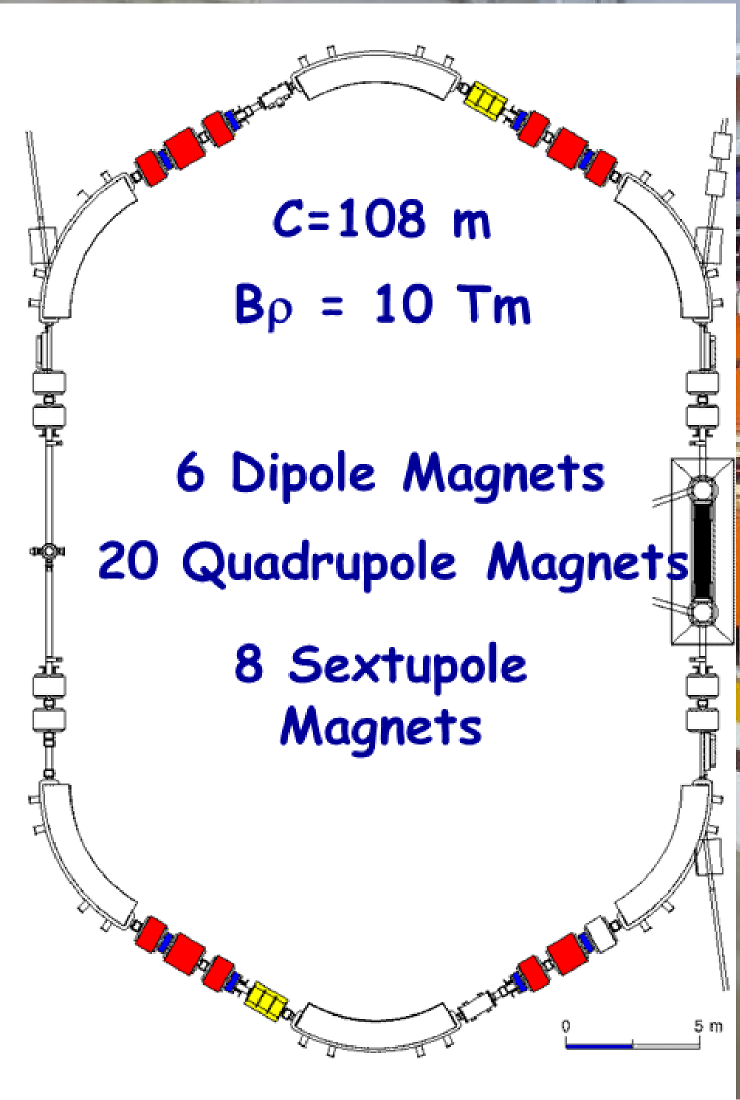
Primary beams @ 400-1000 MeV/u

Highly-Charged Ions (0, 1, 2 … bound electrons)

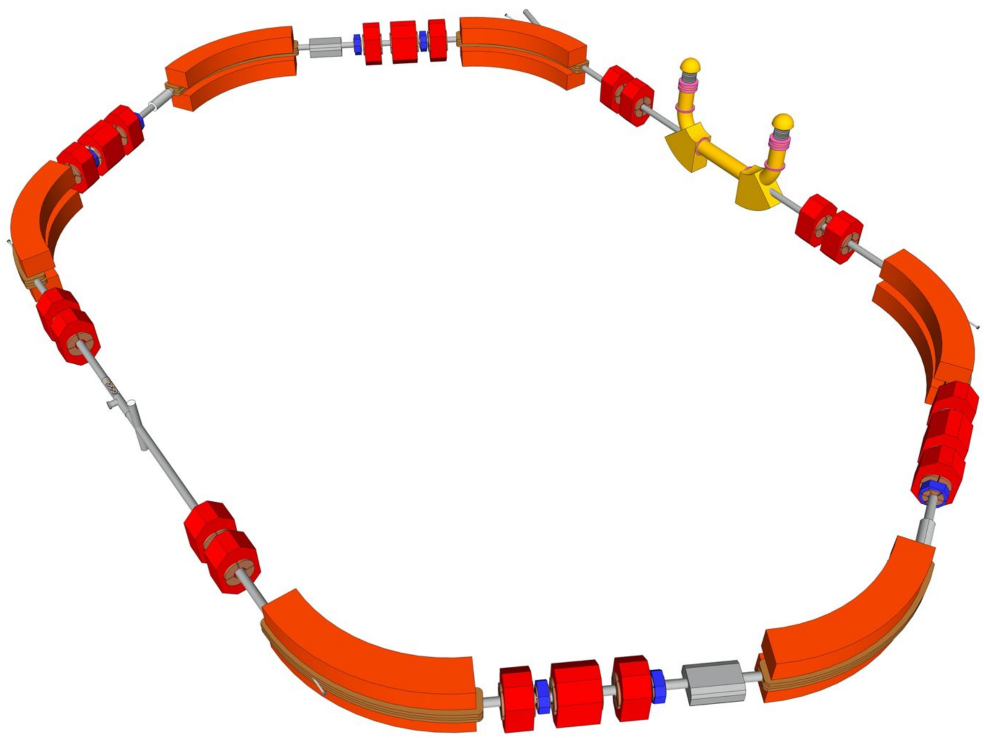
In-Flight separation within ~ 150 ns

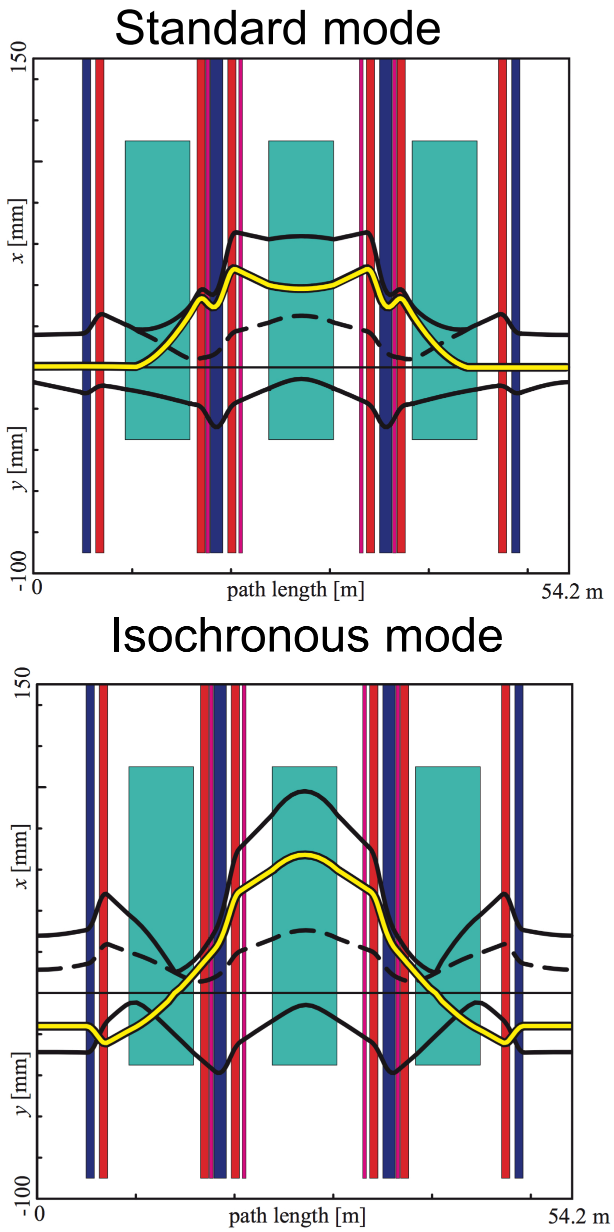
Cocktail or mono-isotopic beams

The Experimental Storage Ring ESR at GSI



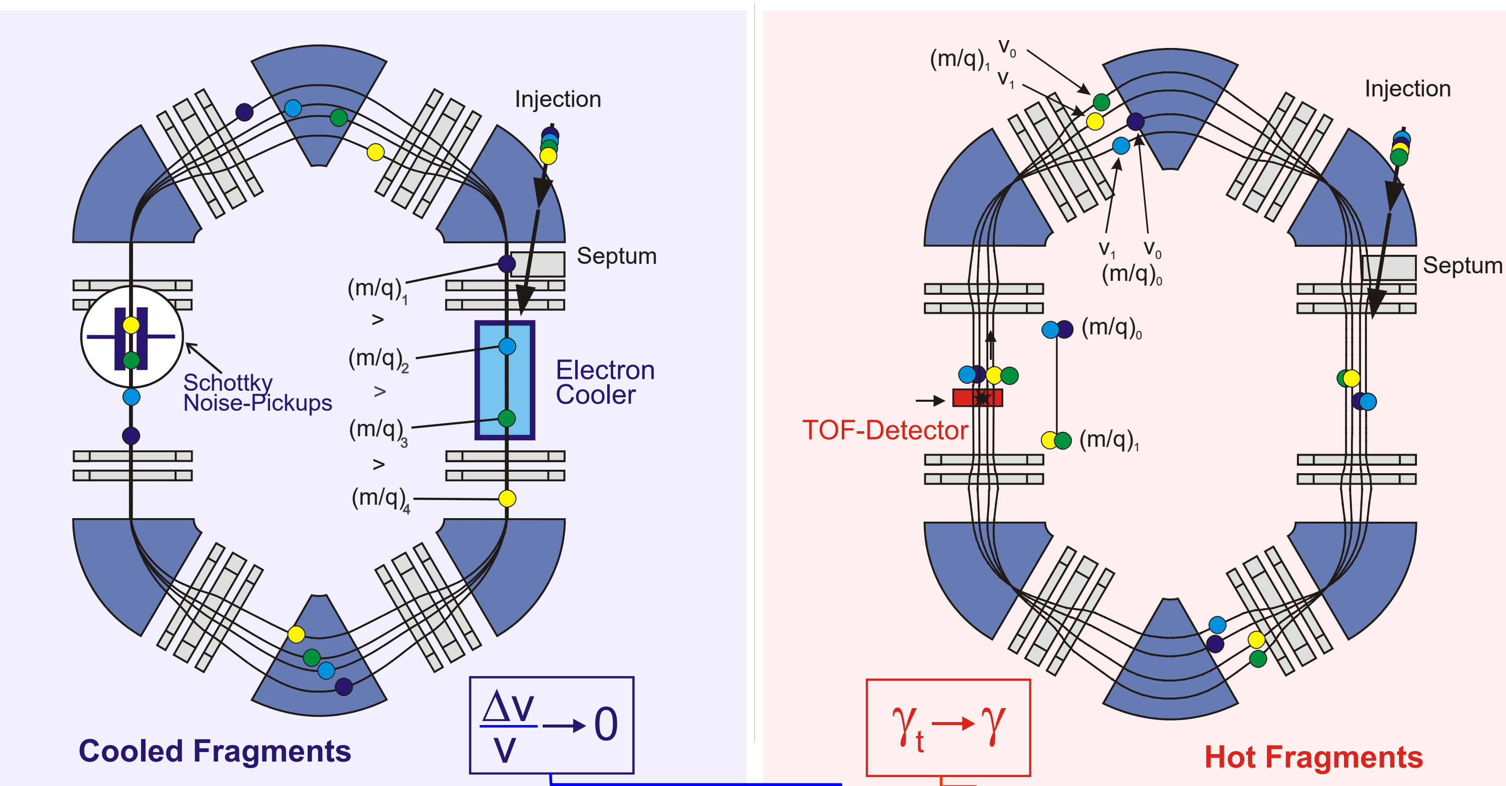
ESR Operational Modes





Large dispersion function in the arcs and negative in the straight sections. It limits momentum acceptance and makes injection difficult.

SCHOTTKY MASS SPECTROMETRY — ISOCHRONOUS MASS SPECTROMETRY

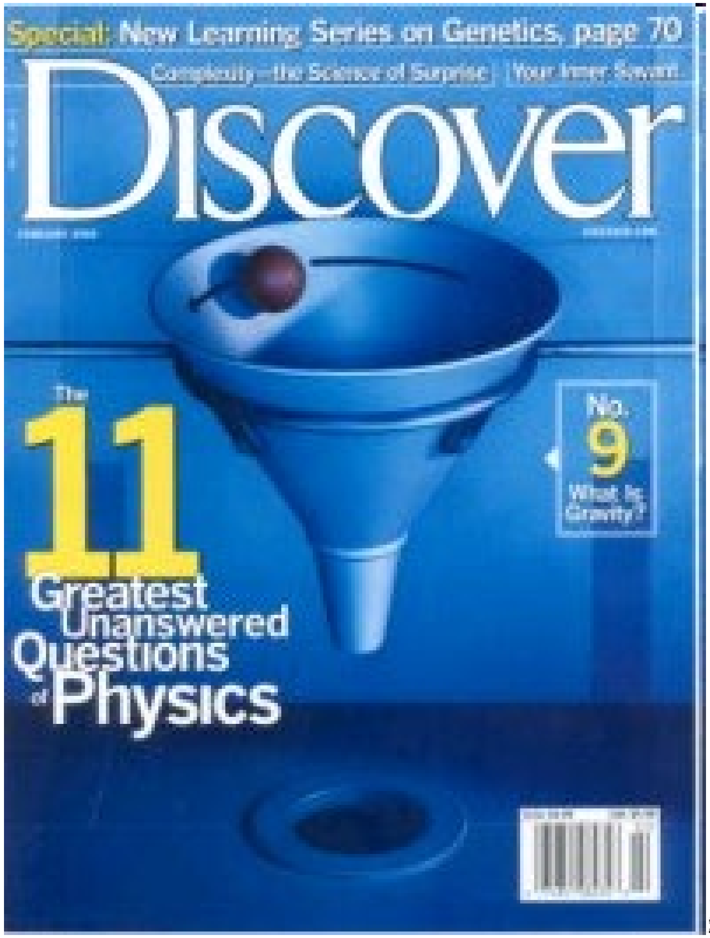


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

In the isochronous mode all particles with the same m/q but different velocities will travel around the ring with equal revolution times, which can be measured with TOF-detector.

Cooling needs time. In order to measure masses of short-lived exotic nuclei with half-lives down to a few tens *μ*s the measurements with only the isochronous mode is possible.

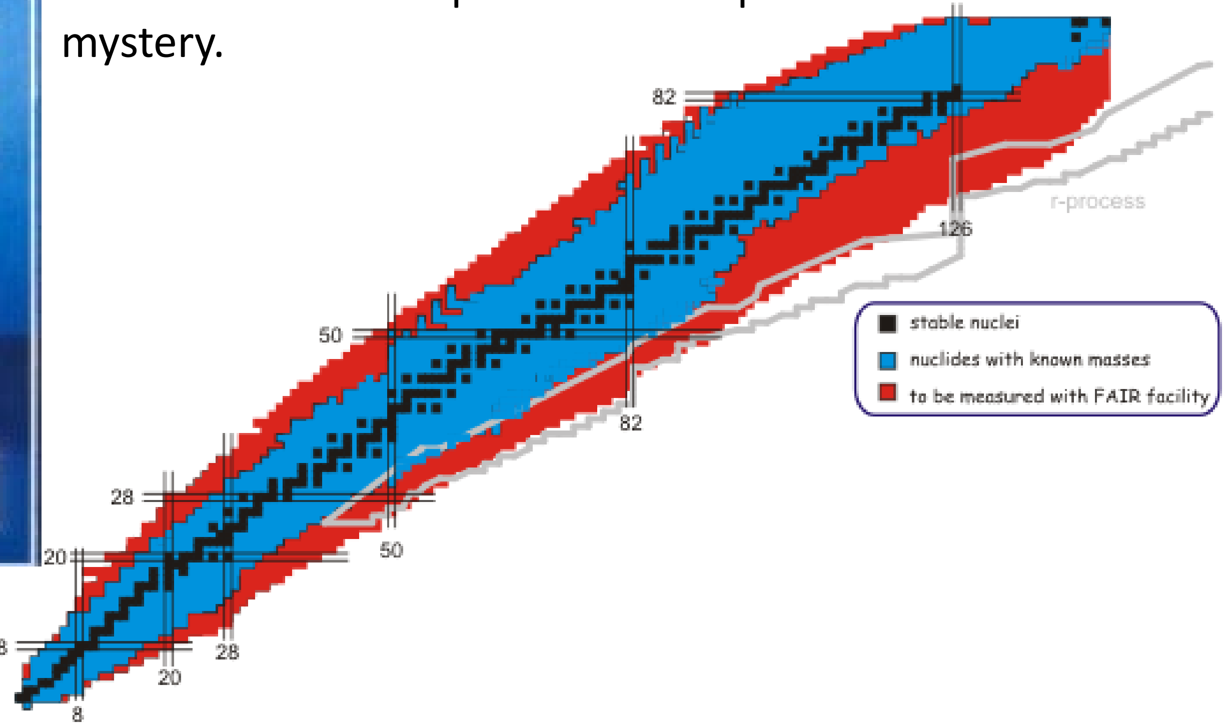
Why do we need to know masses?



Question numer 3 is:

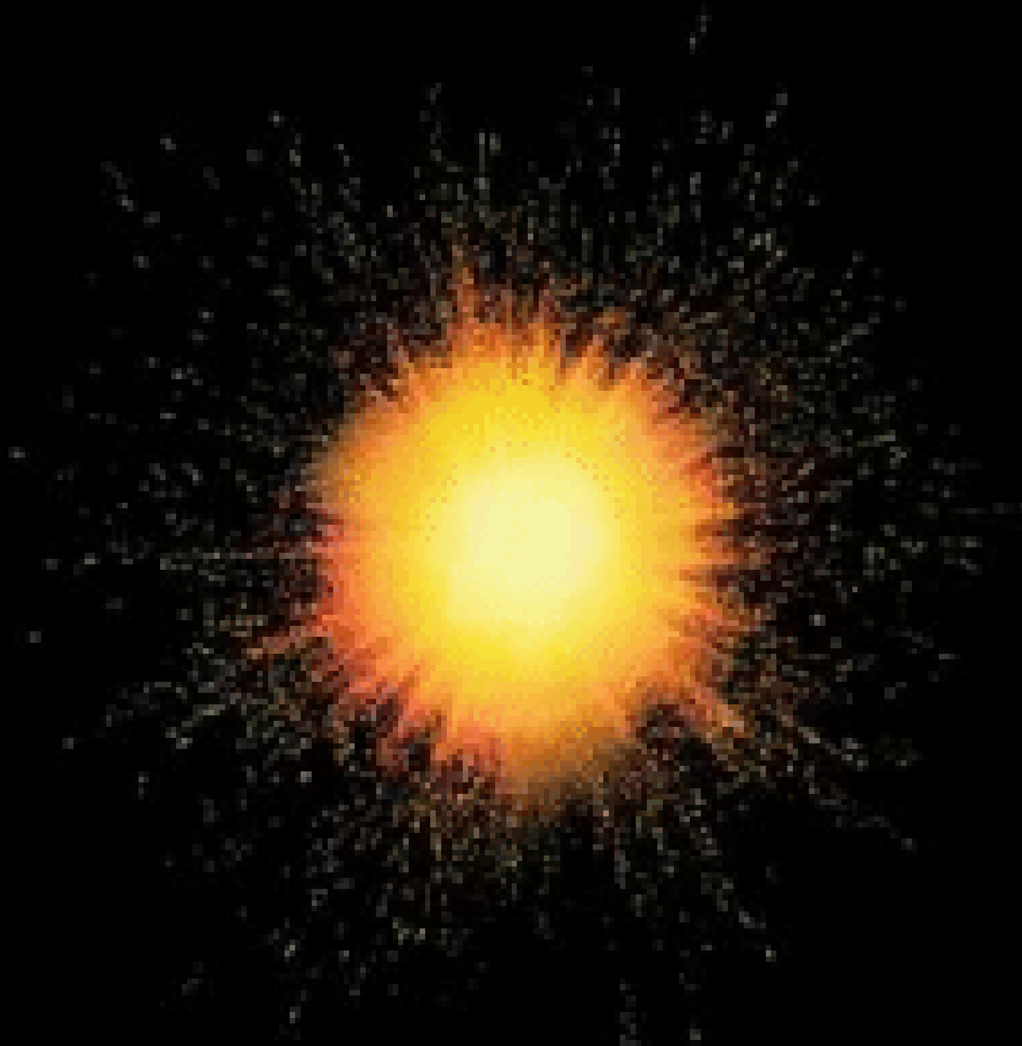
How were the heavy elements from iron to uranium made in Universe?

The rapid neutron capture process (r-process) is a possible scenario of their creation. And the sites where the r-process take place are a mystery.



The mass of very neutron-rich nuclei is a key quantity for revealing the origin of heavy elements. To measure them with required high accuracy (10^{-6}) is a great challenge.

Nucleosynthesis after Big Bang: only He and Li are produced



No stable masses with
A = 5 and A = 8

Decreasing density and temperature

Deuterons mostly destroyed by photodissociation

Credits to Y. Litvinov

Are Supernovae IIa the sites of the r-process??

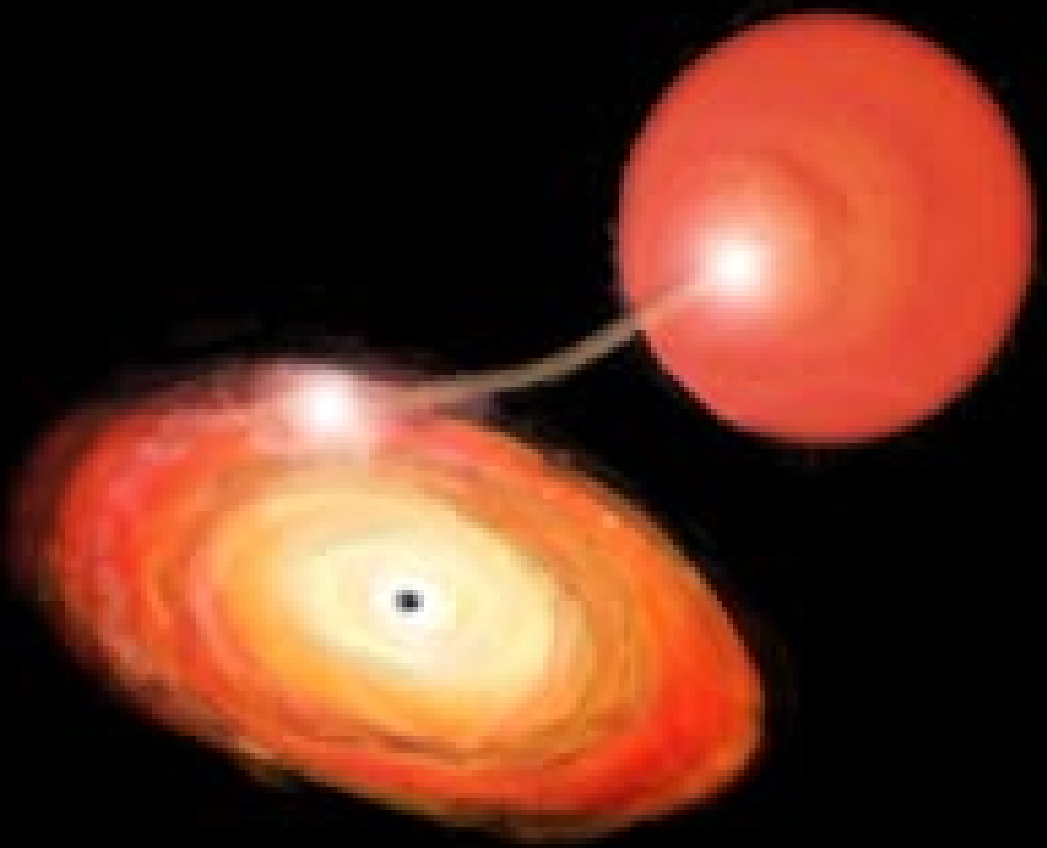
A possible scenario:

Supernovae IIa provide in the second of their outbreak a huge neutron flux creating a plenty of **unstable neutron-rich nuclei**

that decay by a **chain of beta decays** towards the valley of stability

Credits to Y. Litvinov

The rp (rapid proton capture) -process



In binary systems **white dwarfs** are accreting mass from its compagnon, leading to explosive hydrogen burning

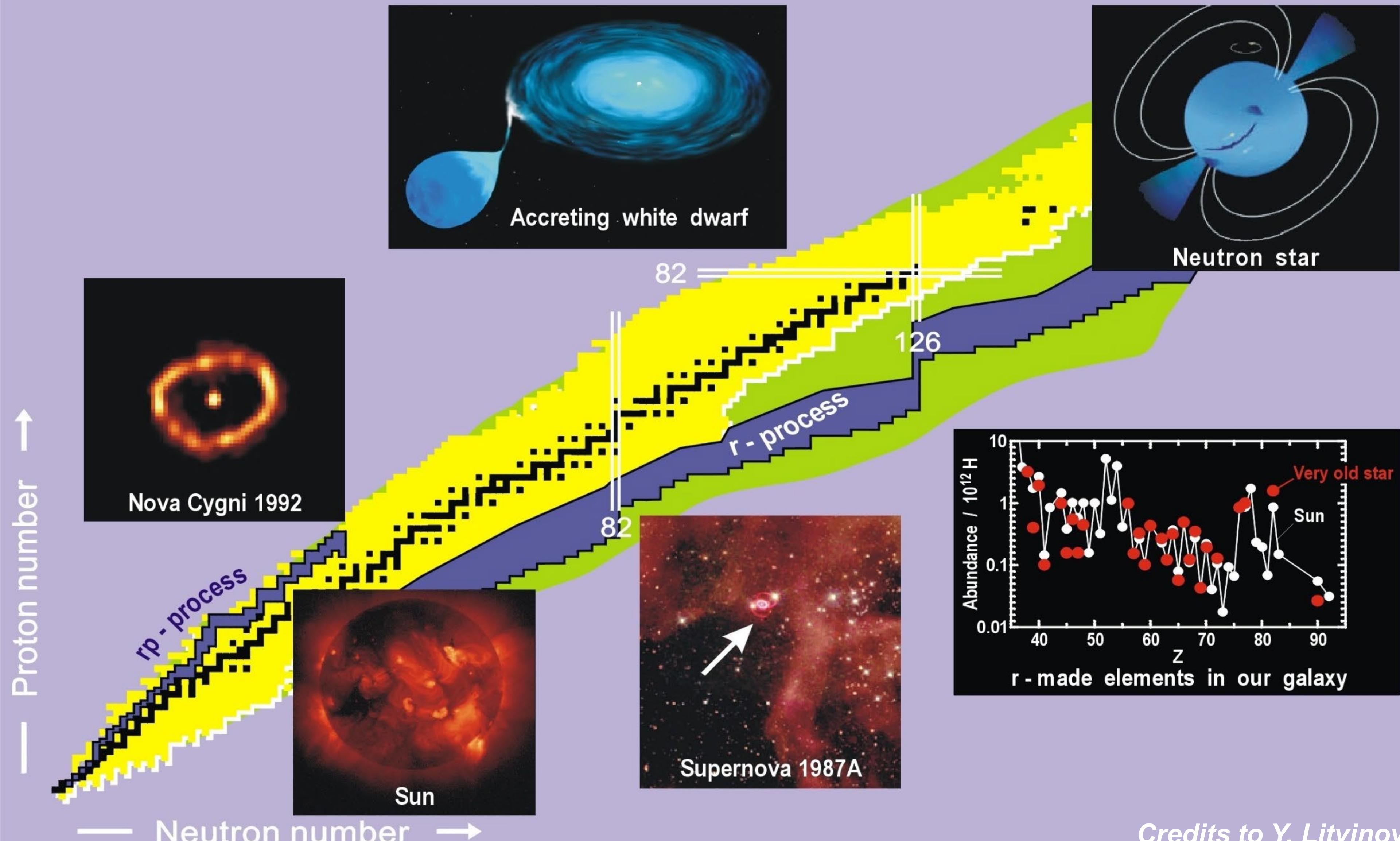
→ **Novae**

mass accretion of a **neutron star** leads to

→ **X ray bursts**

Credits to Y. Litvinov

The r (rapid neutron capture) –process creates about 50% of nuclei; its site is still unknown



Credits to Y. Litvinov

To measure: Ground state properties of exotic nuclei:

masses and β-decay half-lives

masses determine the pathways of s-, rp- and r-processes

β half-lives the accumulated abundances

Requirements for the measurement instruments:

1. Sensitivity and quickness
2. Large acceptance
3. High accuracy for mass measurements
4. Calibration masses → lower energy

Solution: Isochronous Mode

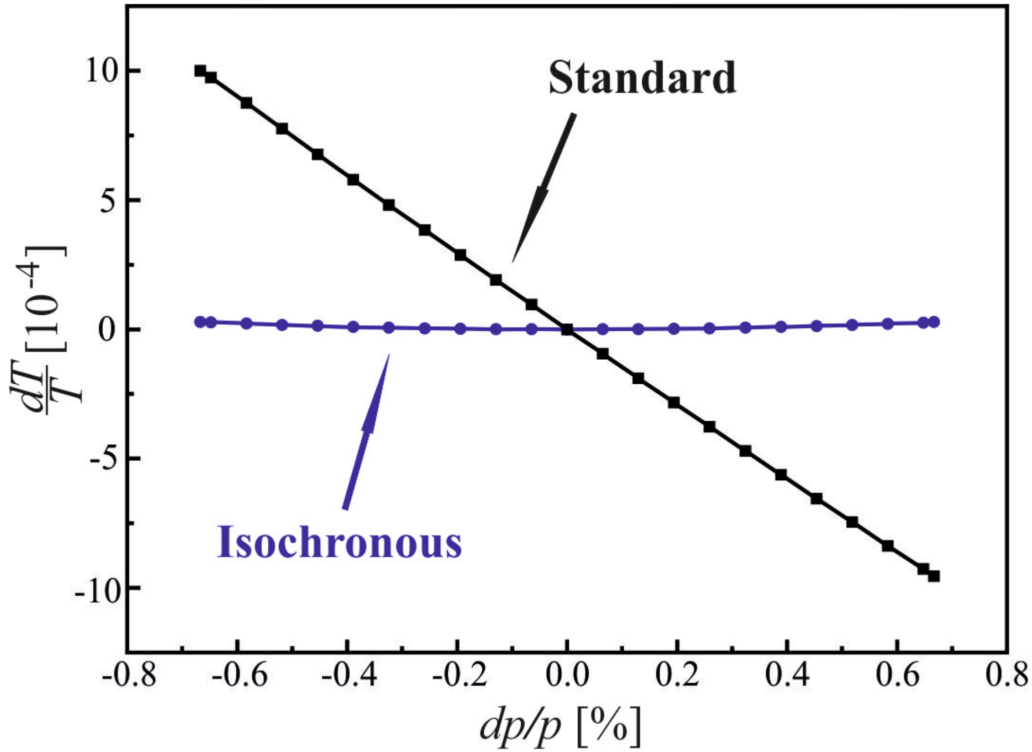
How to make isochronous optics?

1. Revolution frequency difference (or revolution time) of two particles with different *m/q* ratio circulating in the ring can be written as:

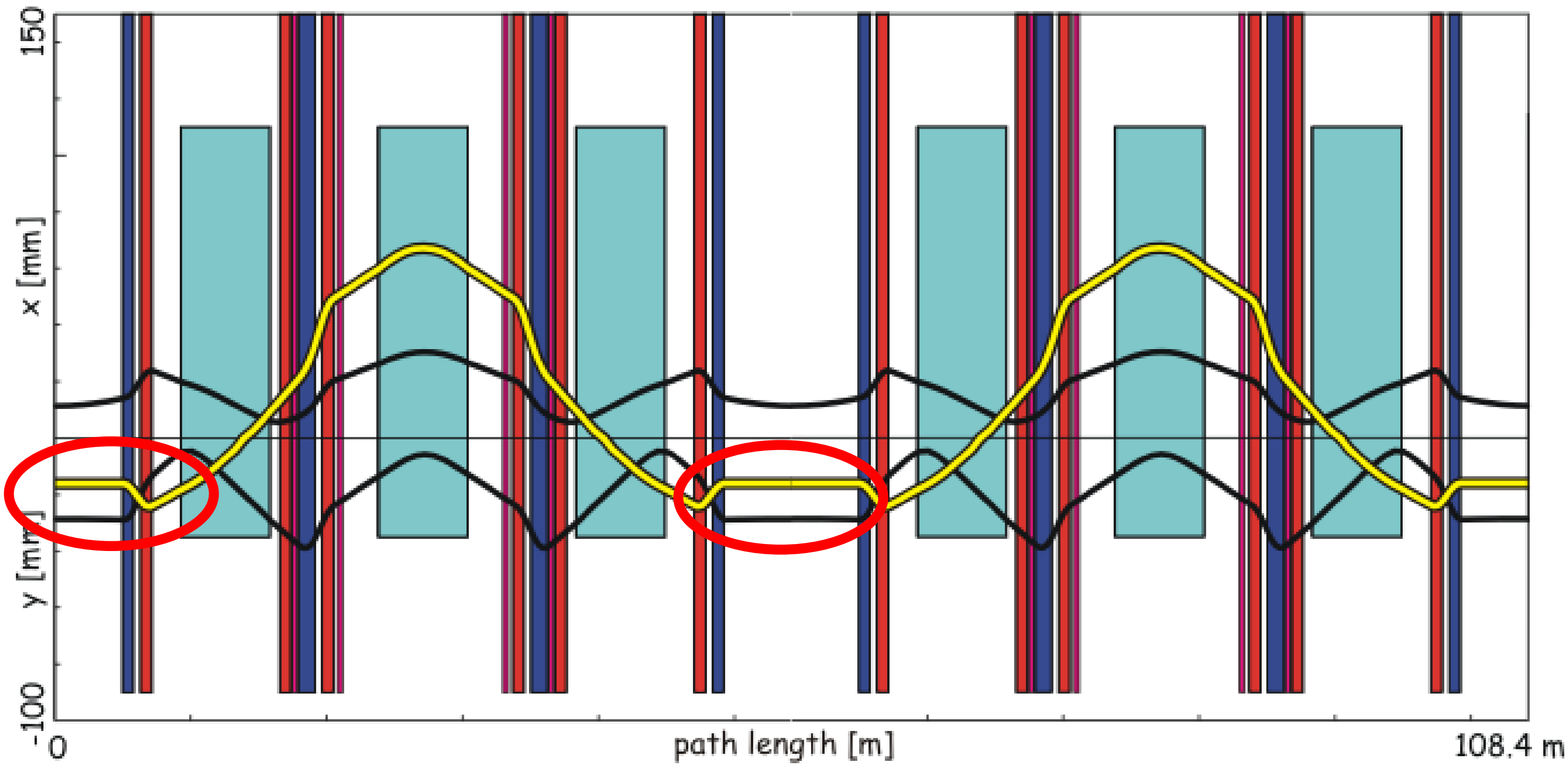
$$\frac{\Delta f}{f} = -\frac{\Delta T}{T} = -\frac{1}{\gamma_t^2} \cdot \frac{\Delta(m/q)}{m/q} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$

2. Transition energy γ_t is: $\frac{1}{\gamma_t^2} \sim \oint D(s)ds$

One has to calculate quadrupole setting in such a way that $\gamma = \gamma_t$



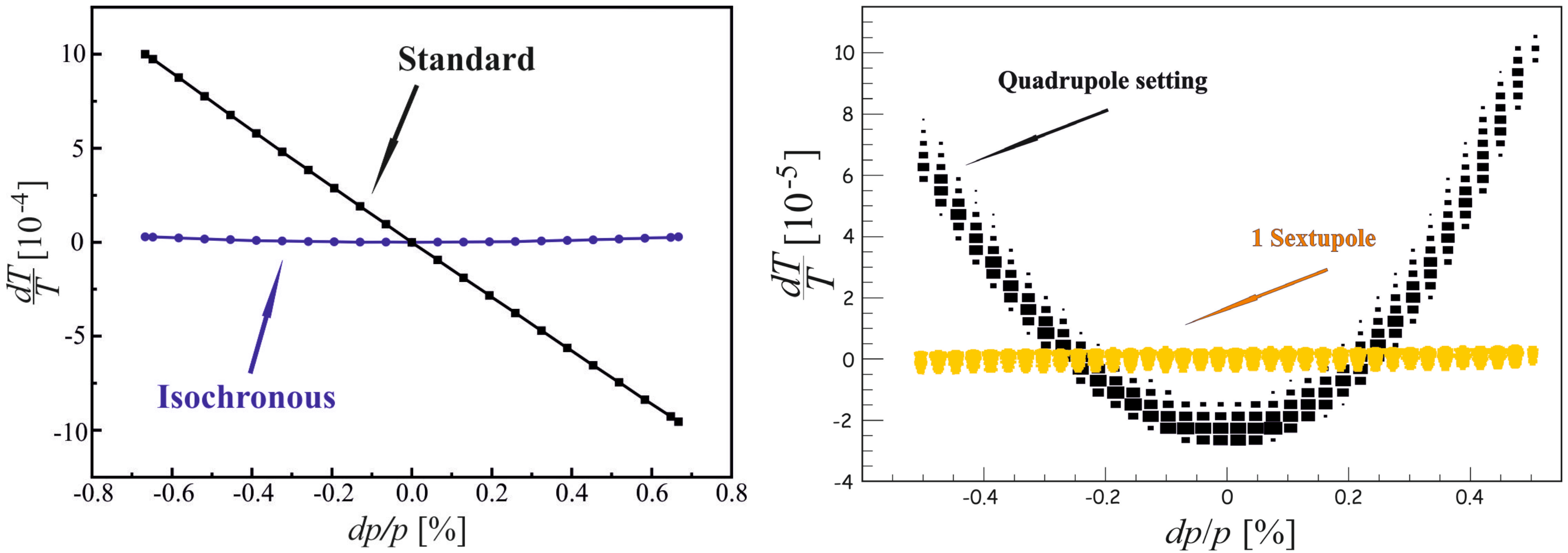
Present Isochronous Mode of the ESR



This isochronous mode is characterized by a large negative dispersion function (-7 m) in the straight sections.

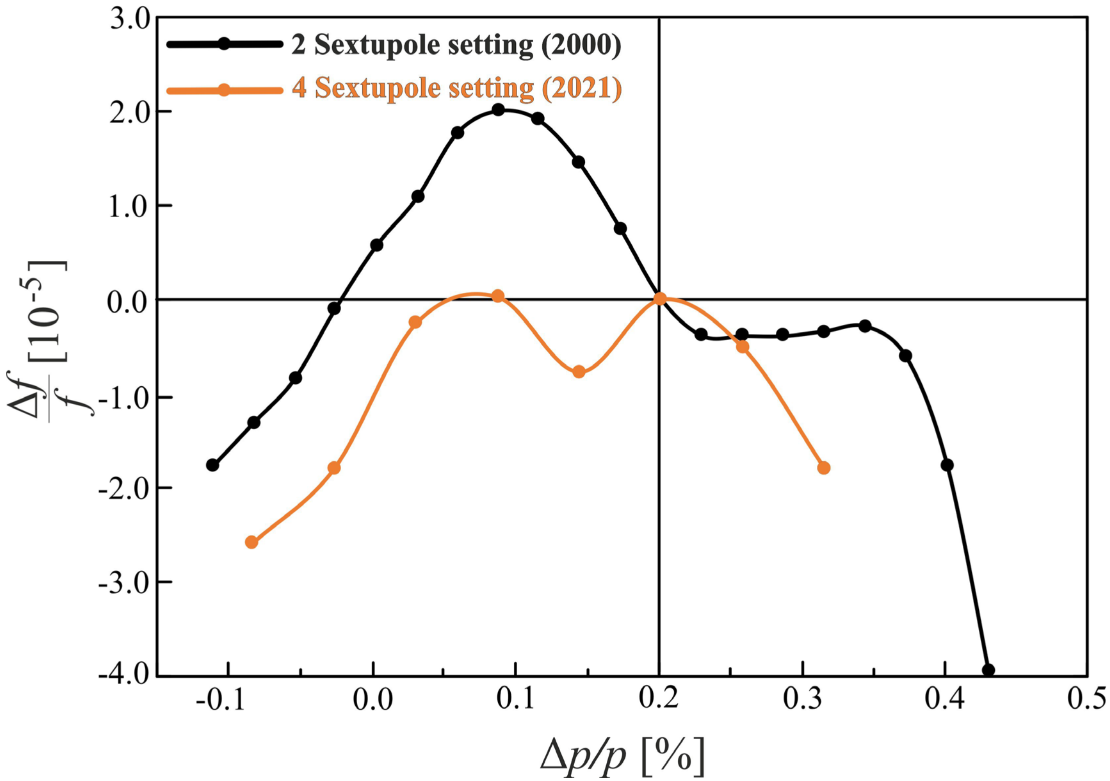
Isochronicity or Cooler Curve (Sextupole Correction)

However, the quadrupole isochronous setting is not enough to get necessary time resiolution. We need to use sextupole correction (second-order effect)



Simulations show, that only one sextupole family is enough to correct second-order isochronicity. However, the ESR is nonlinear machine and it is hard to perform flat isochronicity curve.

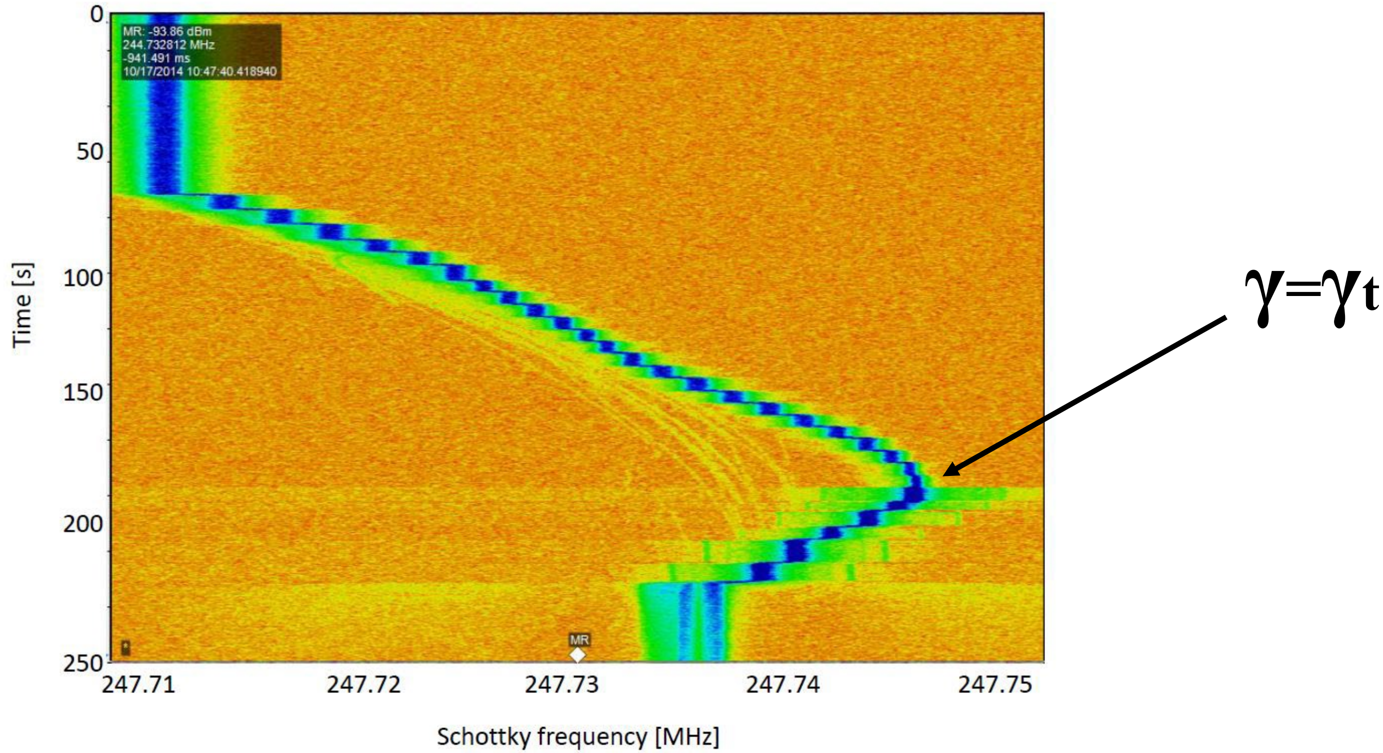
Present Experimental Isochronicity Curves of the ESR (2021)



The energy of a stored beam is changed by applying the electron cooler voltage and corresponding revolution frequency shift is recorded.

One can see the stron high-order nonlinear effects which cannot be corrected with sextupoles but the nonlinear tails can ne cut by applying scrapers in dispersive plane of the separator or the ring.

Direct Measurement of the transition point

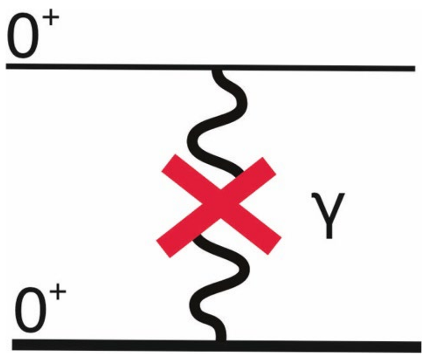


The revolution frequency change of the beam during the incremental increasing the electron cooler energy. The latter was changed every 5 s. in 50 eV. It gives the momentum acceptance range of [-0.08; 0.38]%.

Search for nuclear two-photon-decay

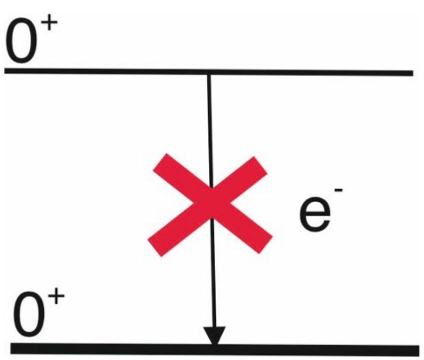
On May an July 2021 the experiment for the search of nuclear-photon decay using isochronous ESR has been performed for the first time.

Short motivation:



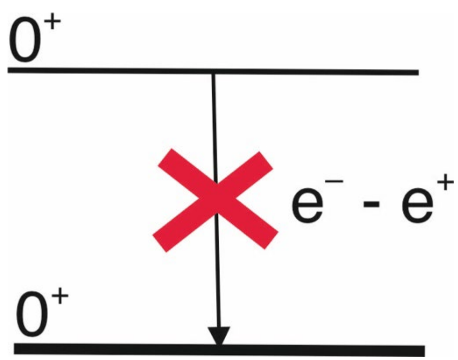
Single photon de-excitation is forbidden

fully-stripped ions

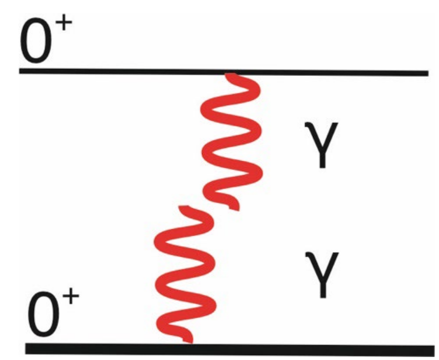


conversion electron

$E_x(0^+)<1.022$ MeV



electron-positron pair

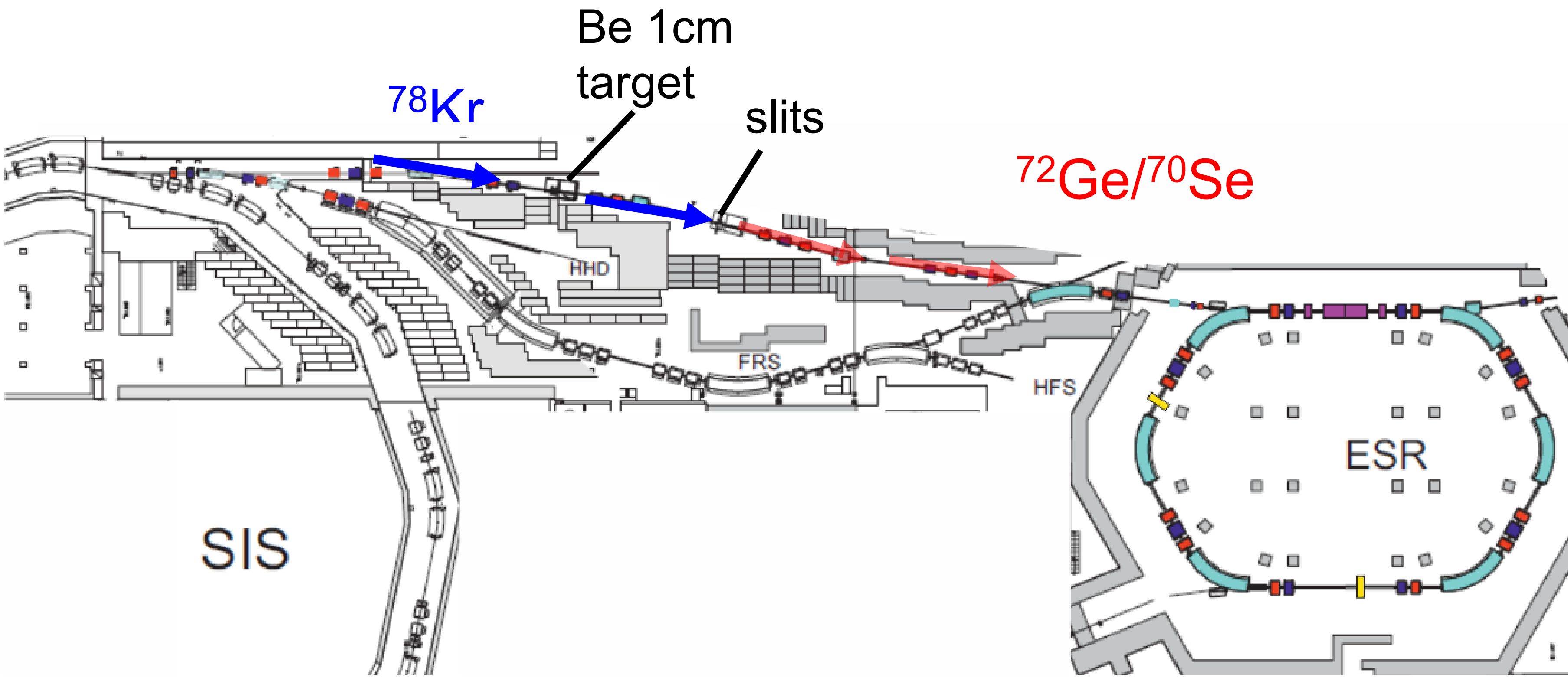


two-photon emission

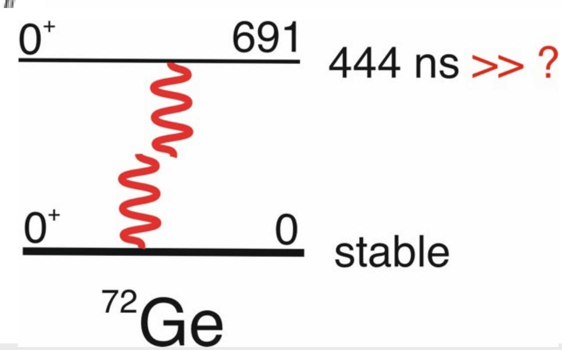
Credits to W. Korten and Y. Litvinov

Experimental Setup

78Kr Beam with an energy of 370 MeV/u hits the beryllium target. Nuclei of interest are Selected with slits and injected in the ESR. For this experiment SIS18-TE-ESR was used.



1) Verify the method

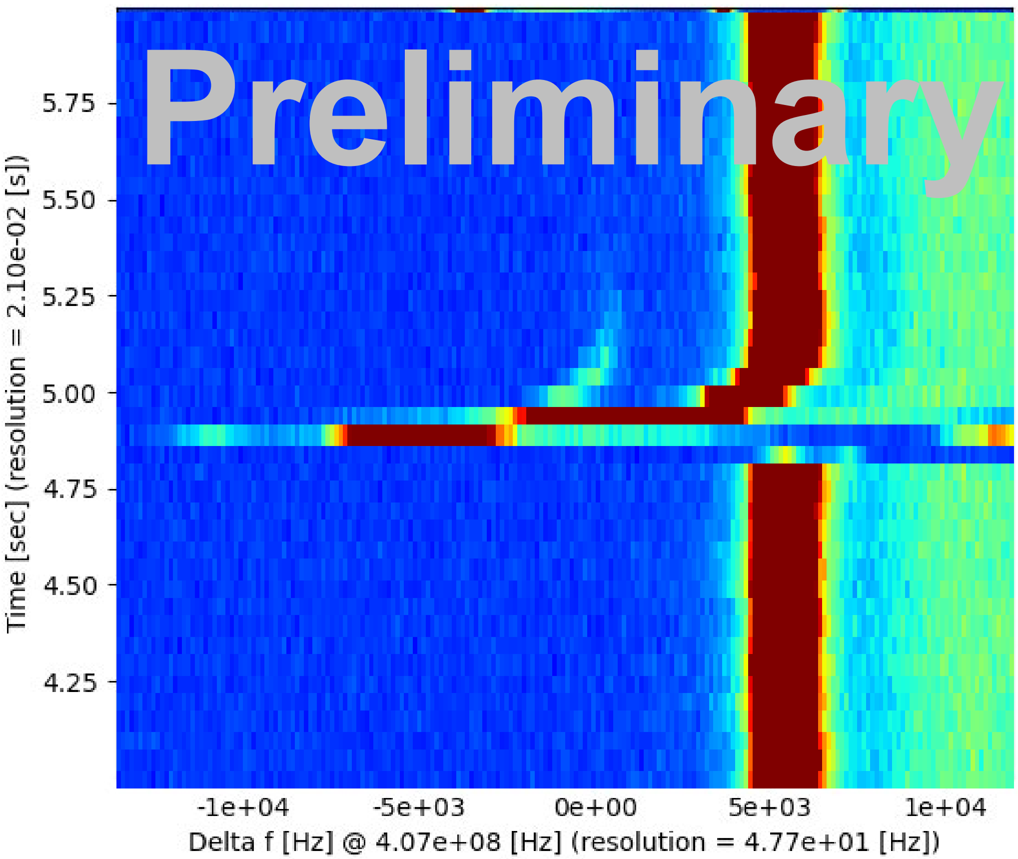


2) Observe 0^+ decay in $\boxed{^{70}\text{Se}}$

Credits to W. Korten and Y. Litvinov

Two-photon decay of ^{72}Ge

Superposition of 84 events



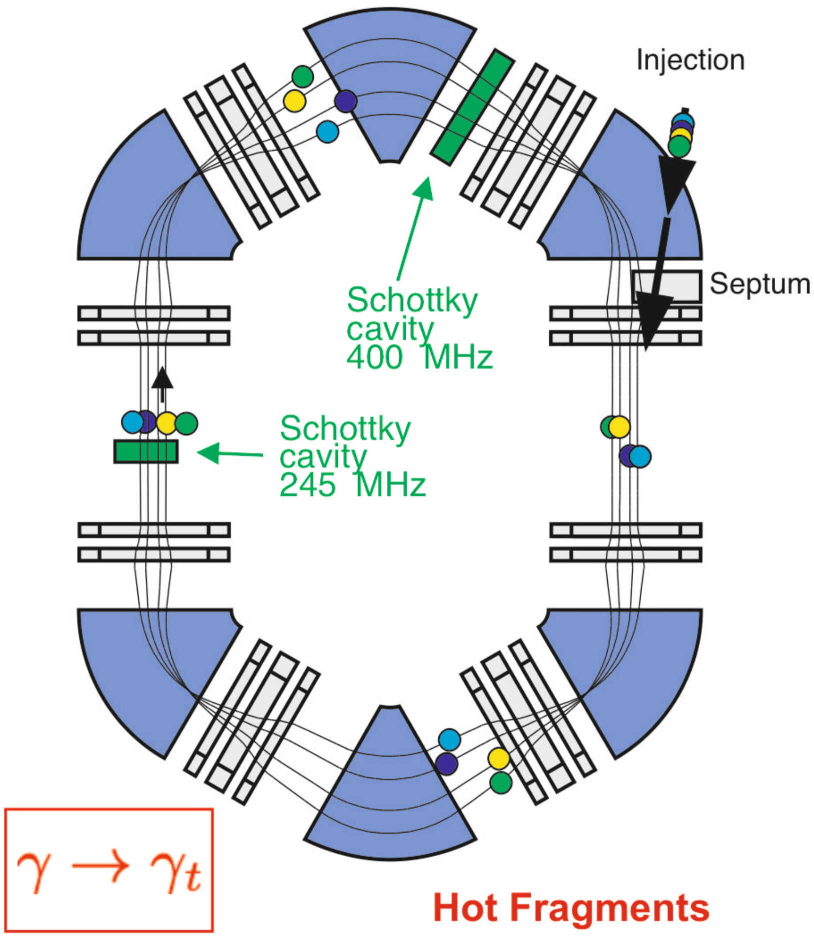
- Two-photon decay in ^{72}Ge was successfully observed. Data analysis ongoing. Lifetime is well below 100 ms

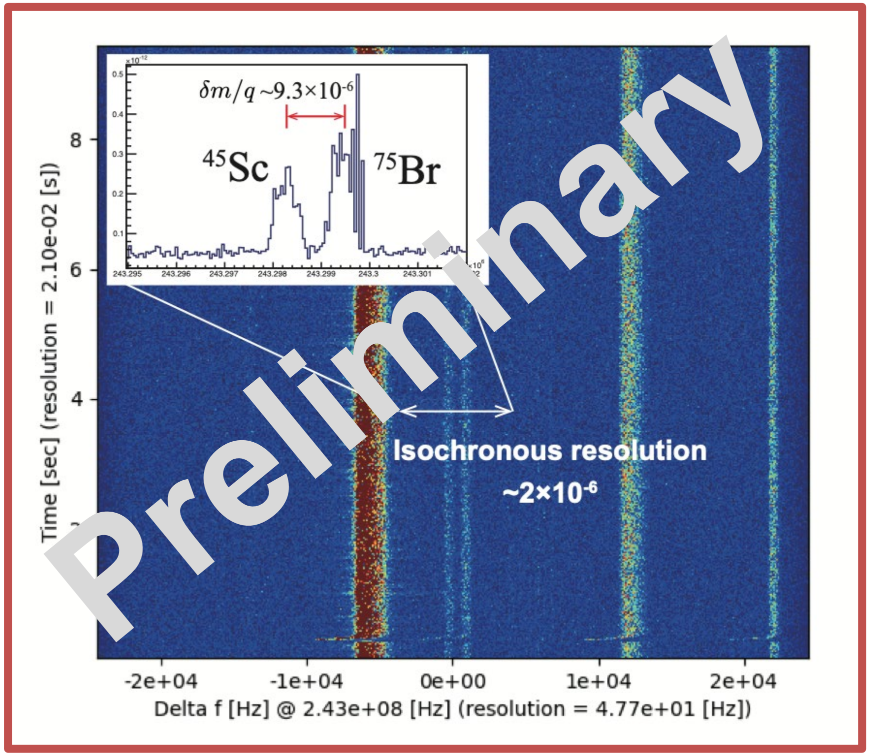
- Two-photon decay in ^{70}Se was not seen online. Data analysis ongoing.

Credits to W. Korten and Y. Litvinov

Combined Isochronous and Schottky Mass Spectroscopy at the ESR

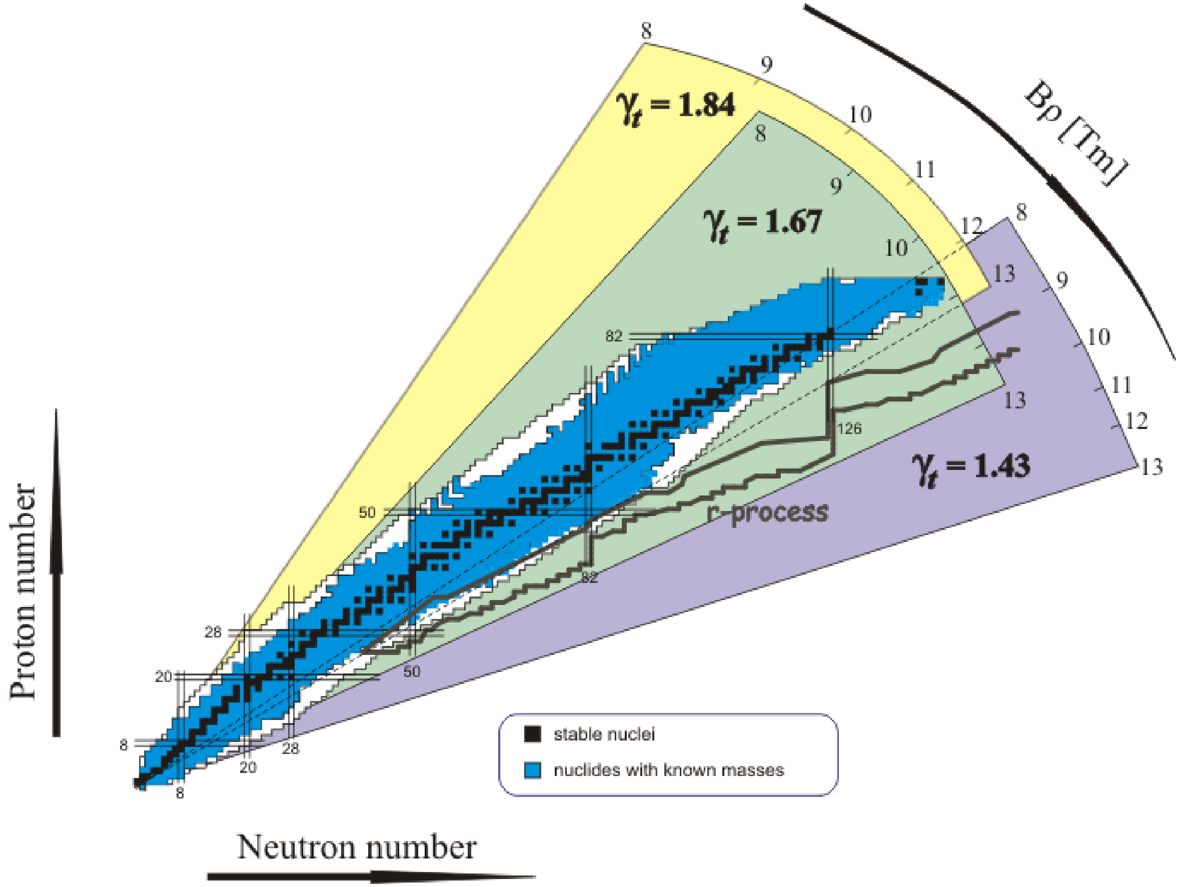
High mass resolving power was achieved in combined Isochronous + Schottky mass Spectrometry, which enables simultaneous mass and lifetime measurements on the rarest nuclides. Preliminary results show observation of low-lying isomeric state in ^{70}Br.

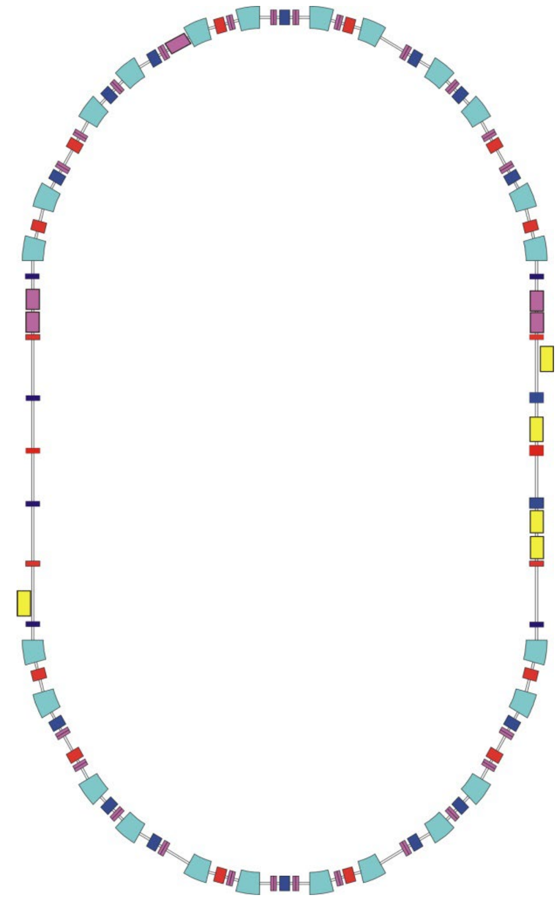




Credits to W. Korten and Y. Litvinov

Collector Ring (CR) at FAIR



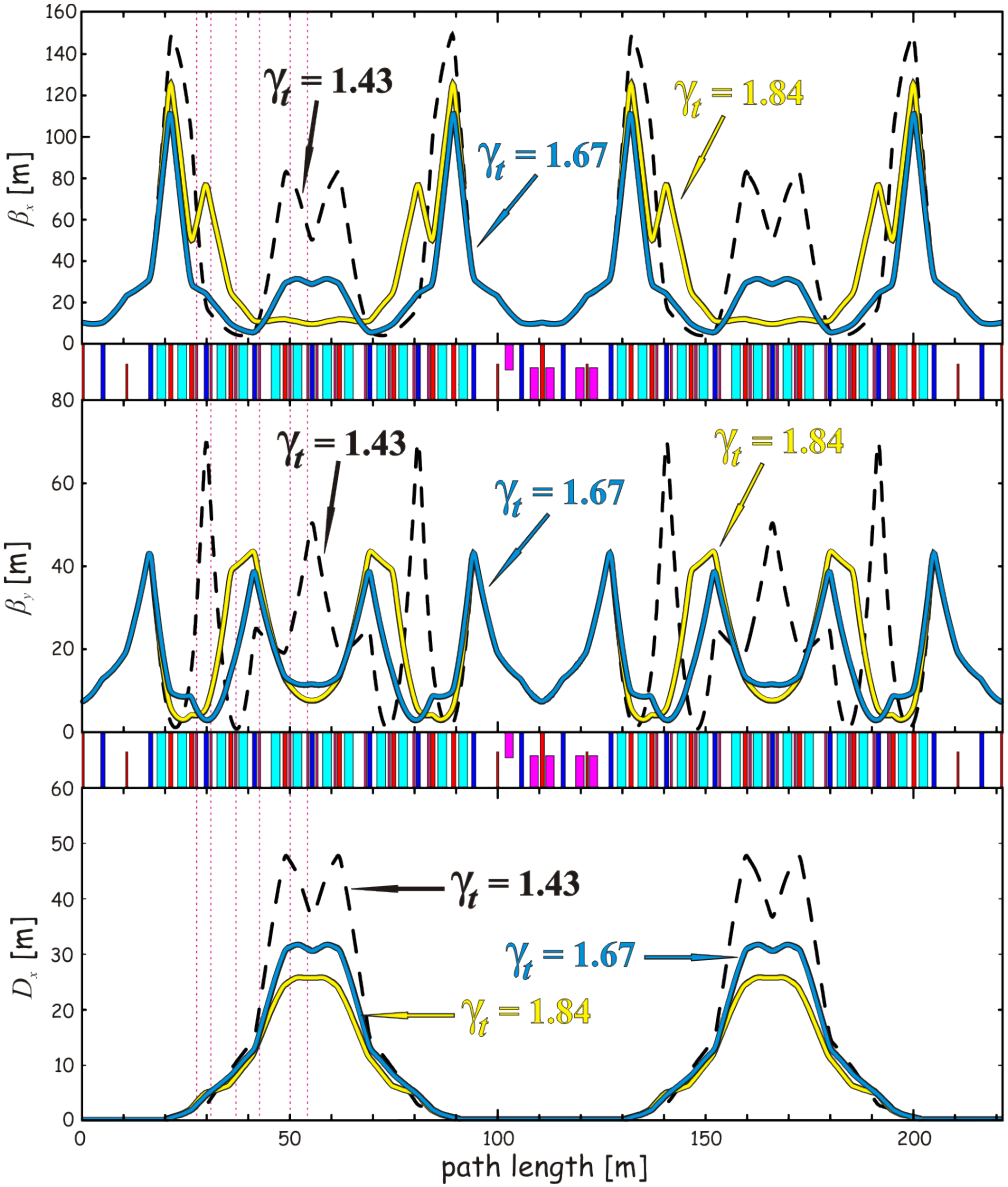


1. $\gamma_t = \gamma = 1.84$ ($E = 782.5\ MeV/u$)

2. $\gamma_t = \gamma = 1.67$ ($E = 624.1\ MeV/u$)

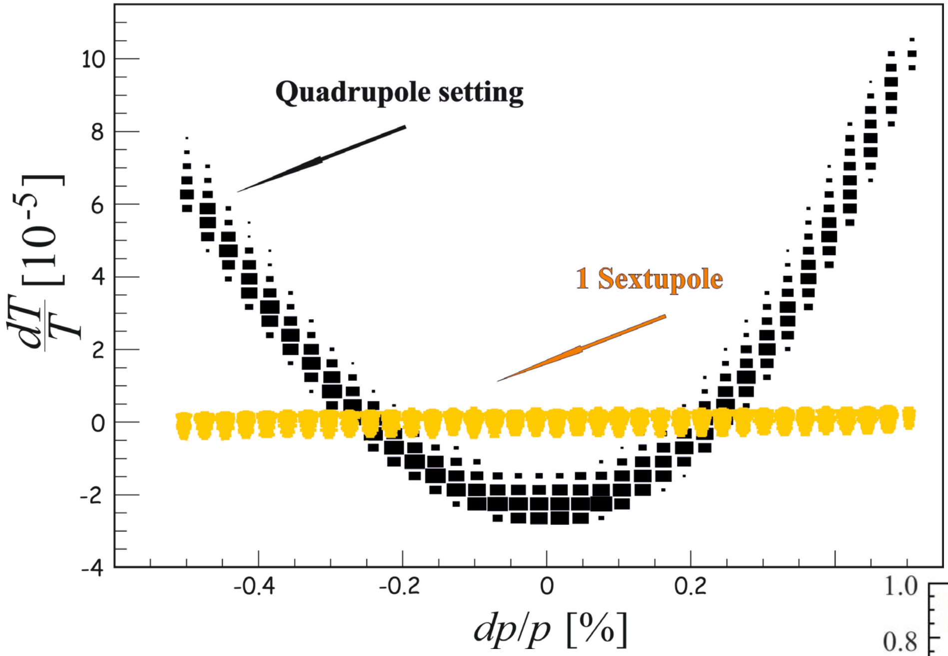
3. $\gamma_t = \gamma = 1.43$ ($E = 400.5\ MeV/u$)

Beam Functions

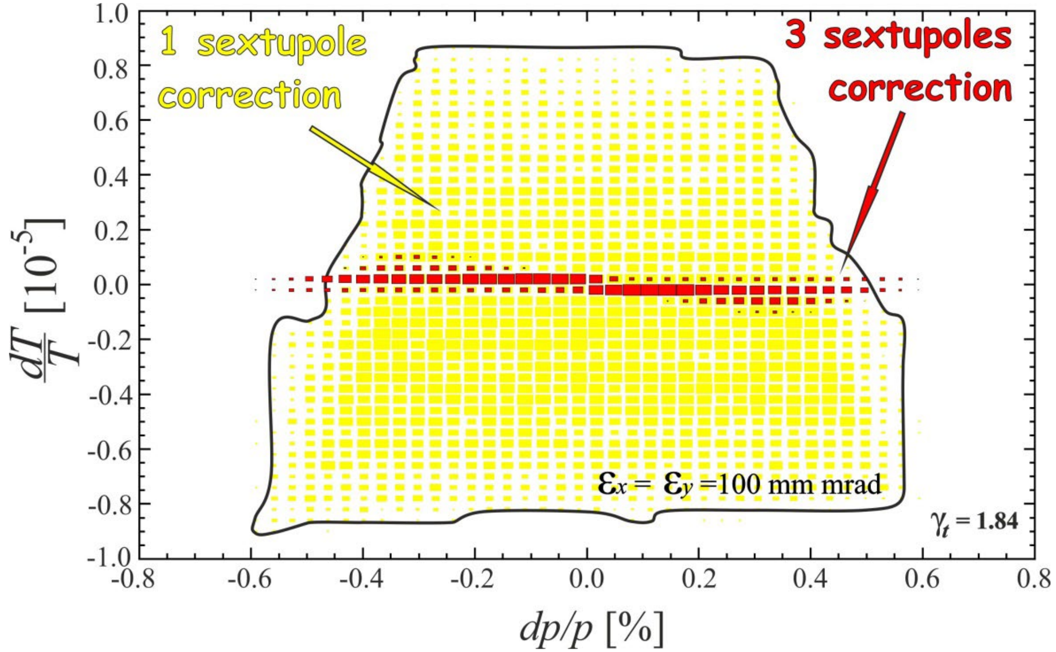


γ_t		1.43	1.67	1.84
Q_x		2.28	2.15	1.93
Q_y		4.62	3.19	3.29
$\Delta p/p$	%	$\pm$ 0.2	$\pm$ 0.4	$\pm$ 0.6
$\varepsilon_x, \varepsilon_y$	mm mrad	100	100	100
$\lvert k_{quads.}^{max} \rvert$	[T/m]	4.02	2.58	2.96
$\lvert k_{sex.}^{max} \rvert$	[T/m^2]	1.6	1.0	0.6

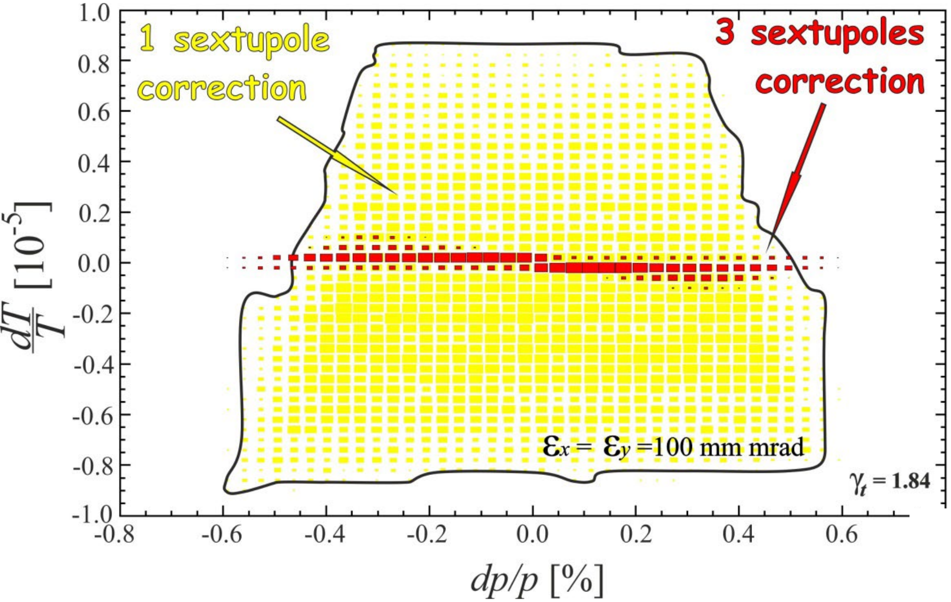
Emittance influence

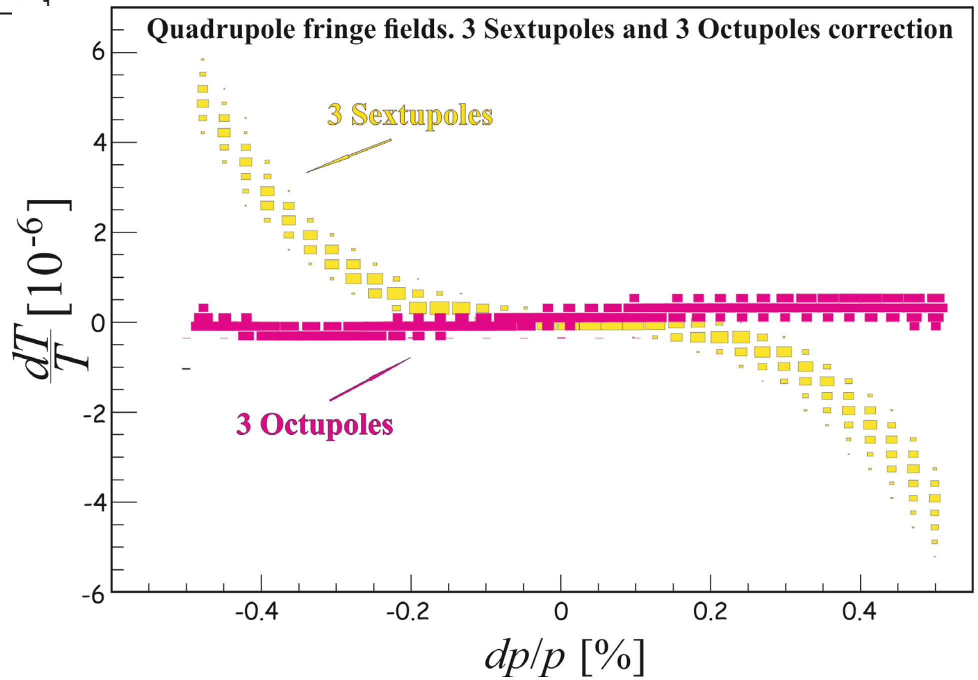


Monte-Carlo simulation



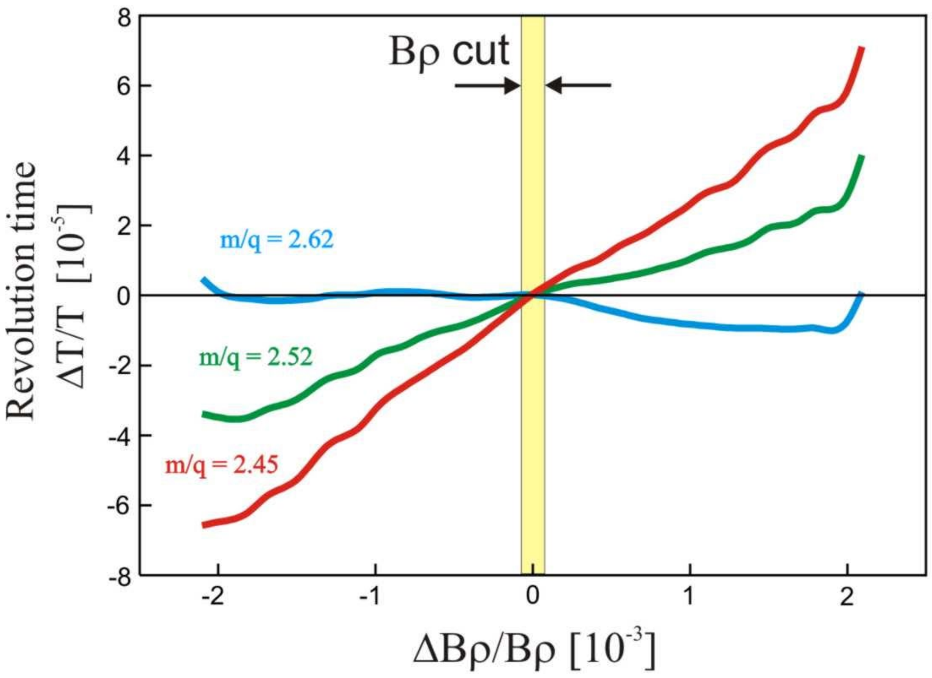
Octupole Correction

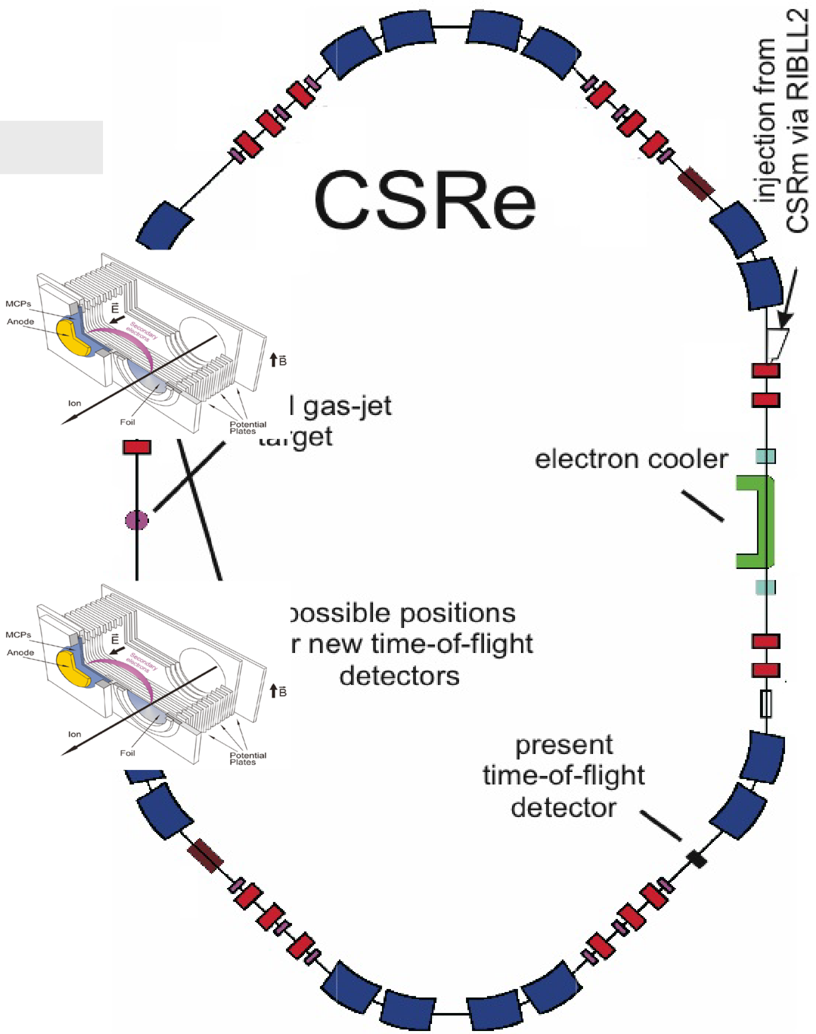




2 TOF Detectors

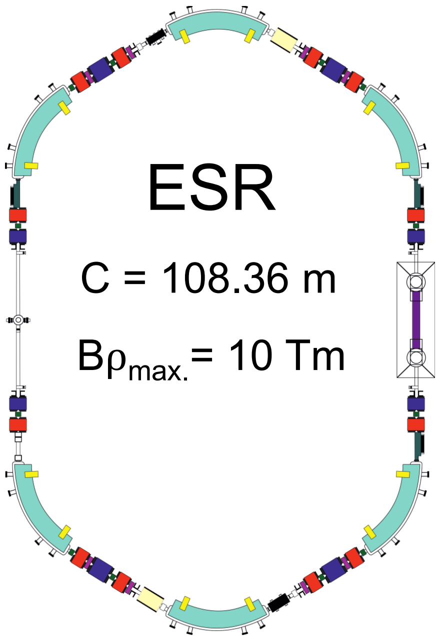
ESR experimental isochronicity curves

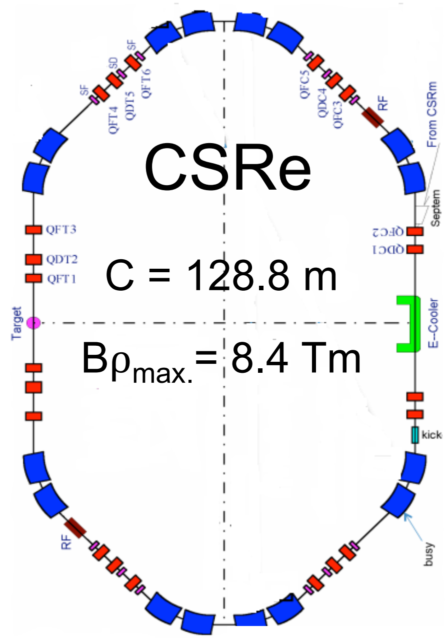


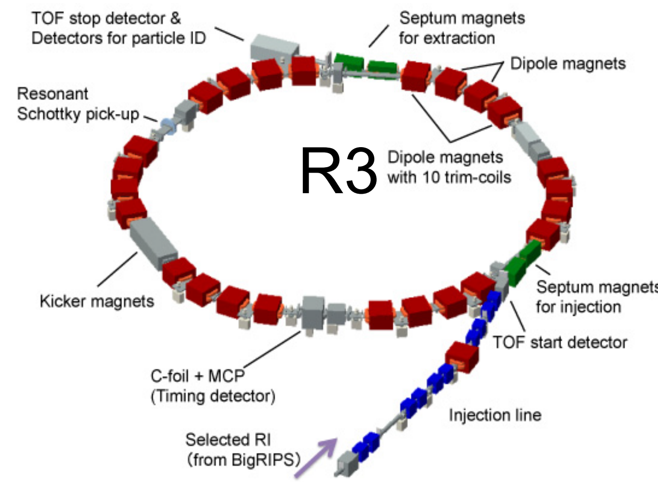


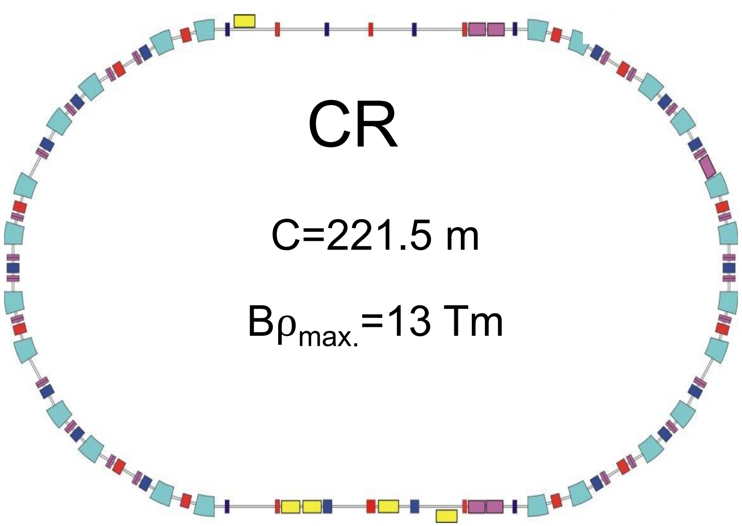
Good isochronous conditions are fulfilled only in a small range.
One has to reduce momentum acceptance!
or use 2 TOF detectors for velocity measurement!

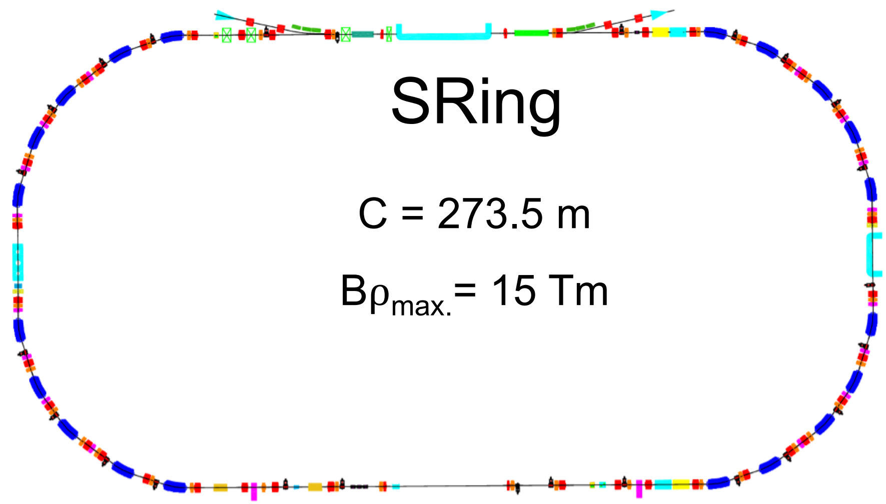
Isochronous Rings in the world











Thank You for Your Attention