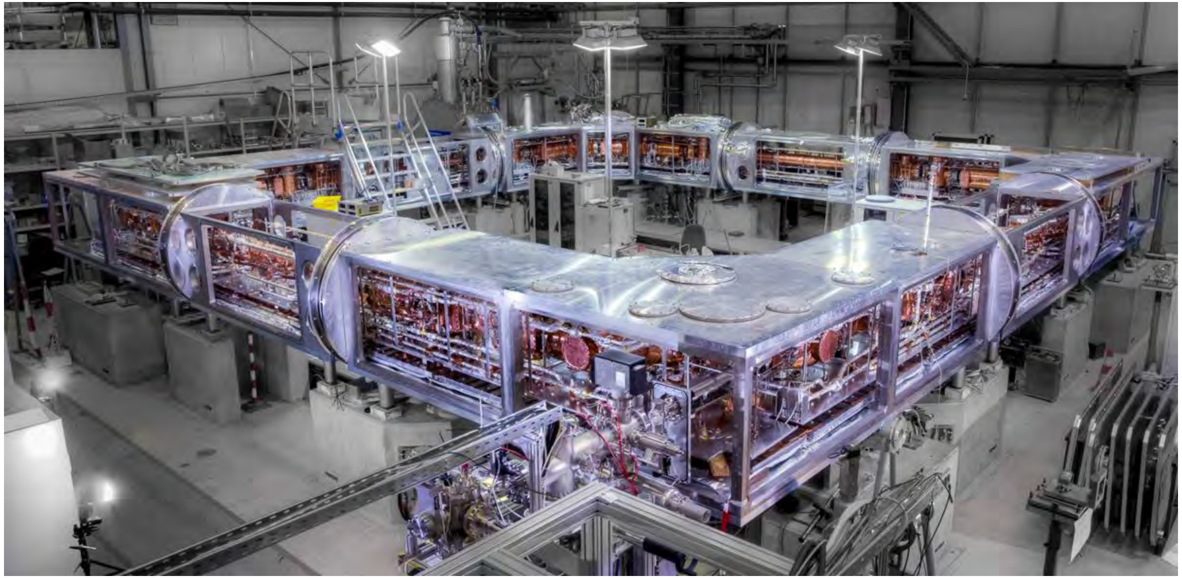
Isochronous mass spectrometry and beam purification methods in an electrostatic storage ring



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NUSTAR Meeting 2022

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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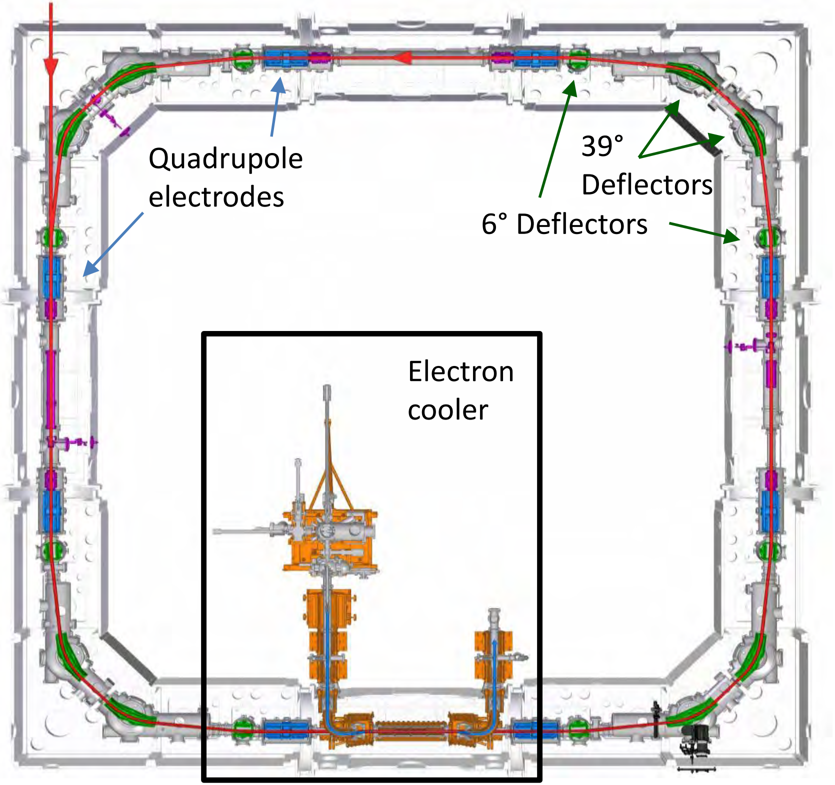
Electrostatic Cryogenic Storage Ring (CSR)

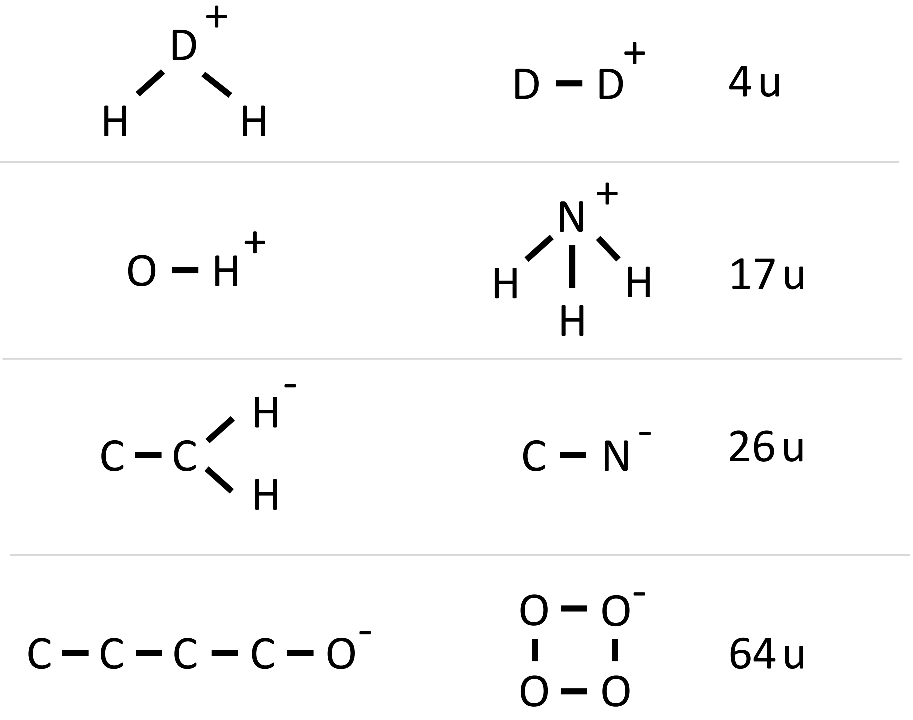
- Fully electrostatic
- Beam energies: (20 – 300) keV
- Cryogenic operation: T<10 K, $\rho < 1000\ cm^{-3}$
- Mostly astro-physically relevant collision experiments: molecular ions + photons/e-/atoms



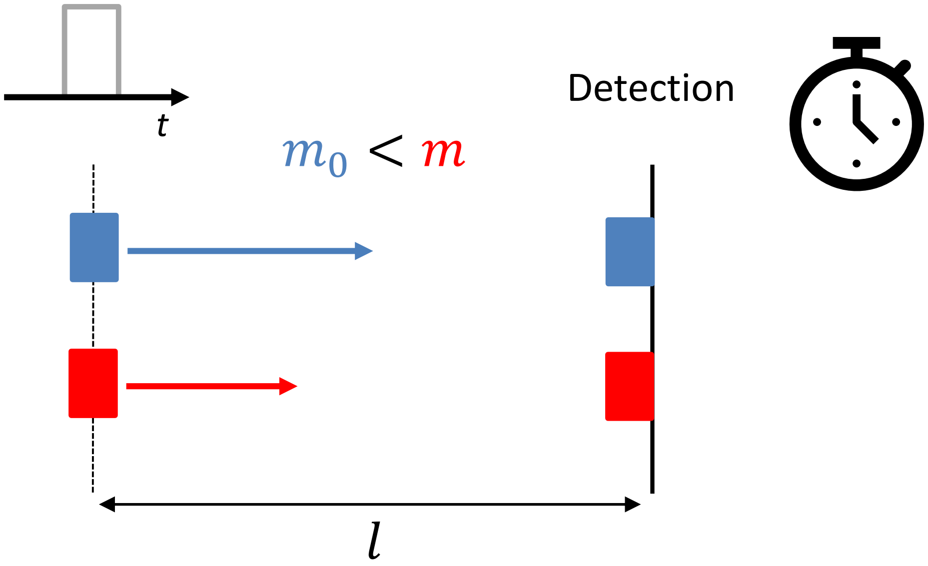
Contamination: Molecular isobars

- Molecules with same integer mass
- $\frac{\Delta m}{m} \approx 10^{-5}$
- Mass independent storage inside CSR
- Beam cleaning before injection difficult

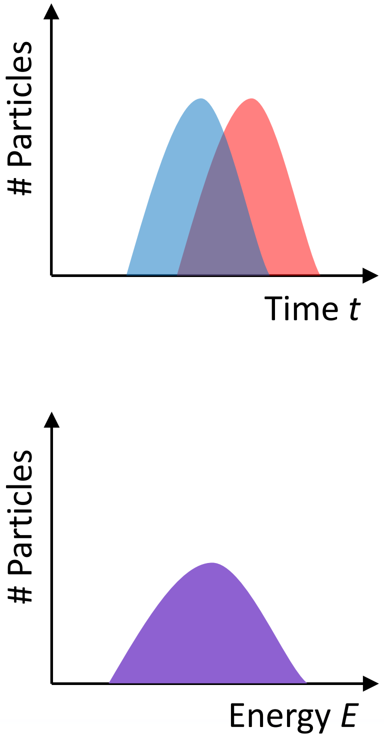
-> Identification and removal inside CSR



Time-of-Flight (ToF) mass measurements



$$E = \frac{1}{2} m v^2 \longrightarrow m = m_0 \frac{t^2}{t_0^2}$$



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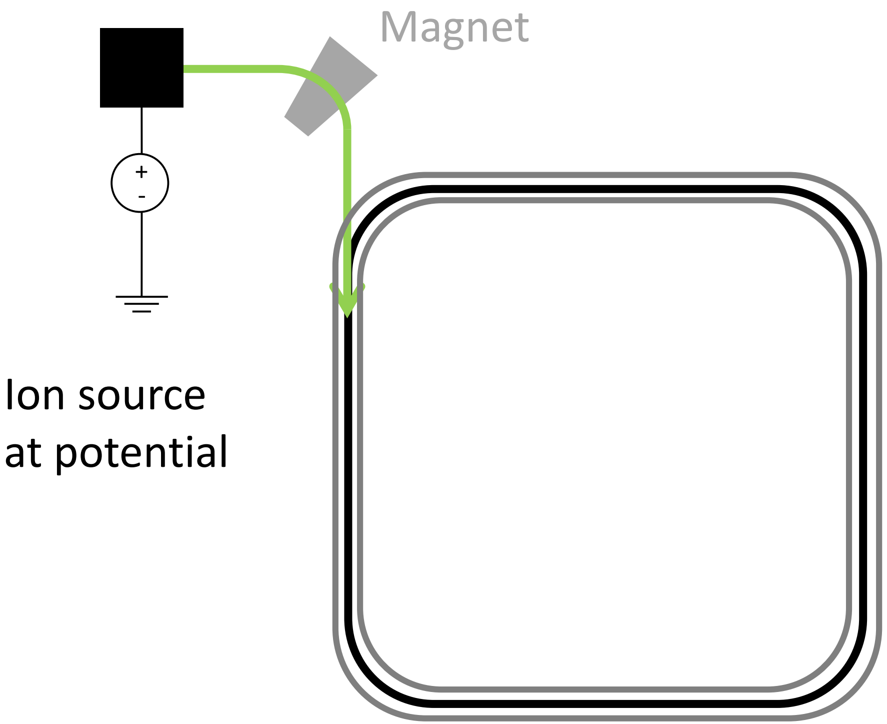
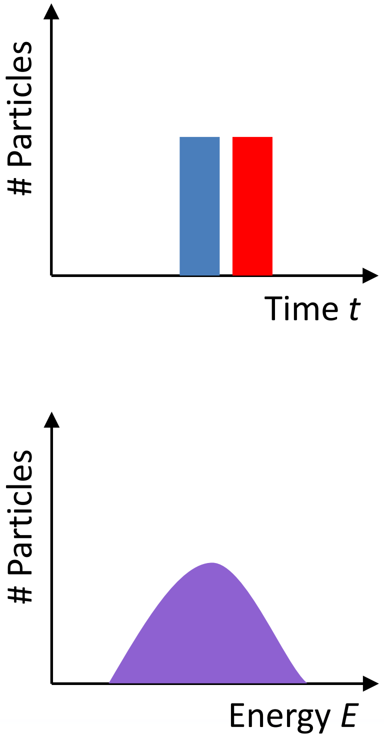




Isochronous condition

- Revolution time only depend on mass
- Slip factor η

$$\eta = \frac{\Delta f/f}{\Delta p/p}$$

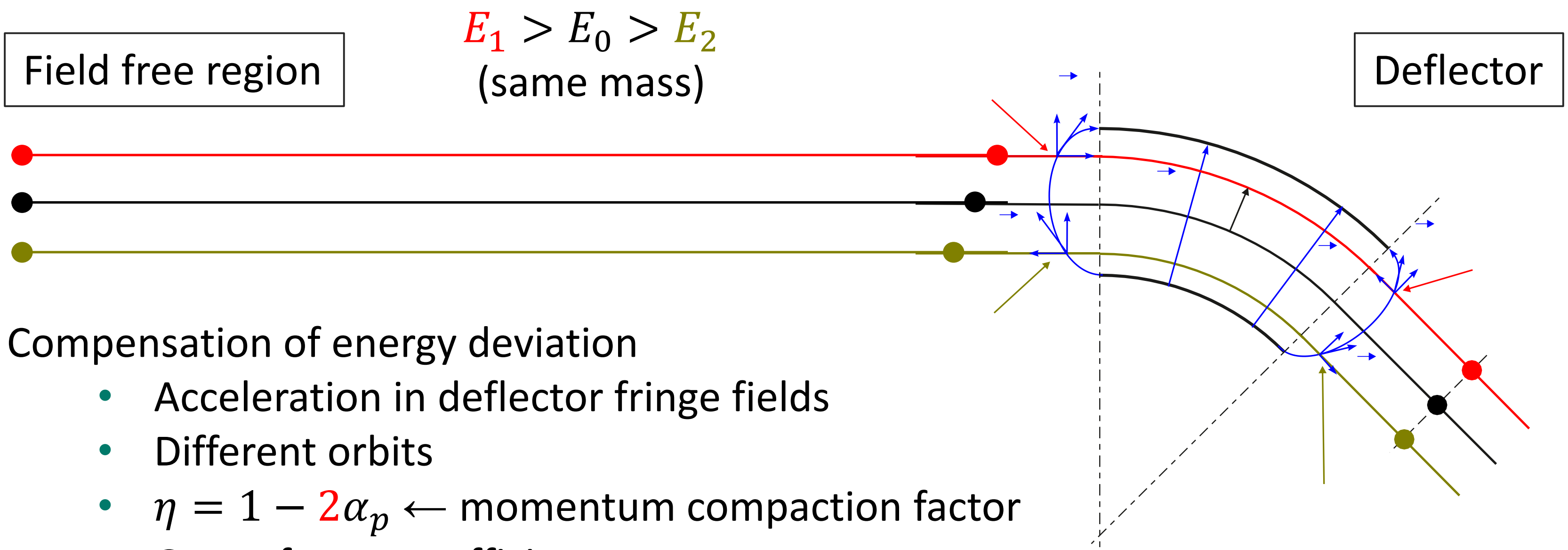
- T dependence on ΔE (1st order)
- Isochronous condition $\eta = 0$

$$\frac{\Delta T}{T_0} = \frac{1}{2}\frac{\Delta(m/Q)}{m_0/Q_0} - \frac{\eta}{2}\frac{\Delta(E/Q)}{E_0/Q_0}$$

- T only dependent on m

Isochronous mass measurements: $$\frac{f_0}{f} = \frac{T}{T_0} = \sqrt{\frac{m/Q}{m_0/Q_0}}$$

Realization of isochronous condition



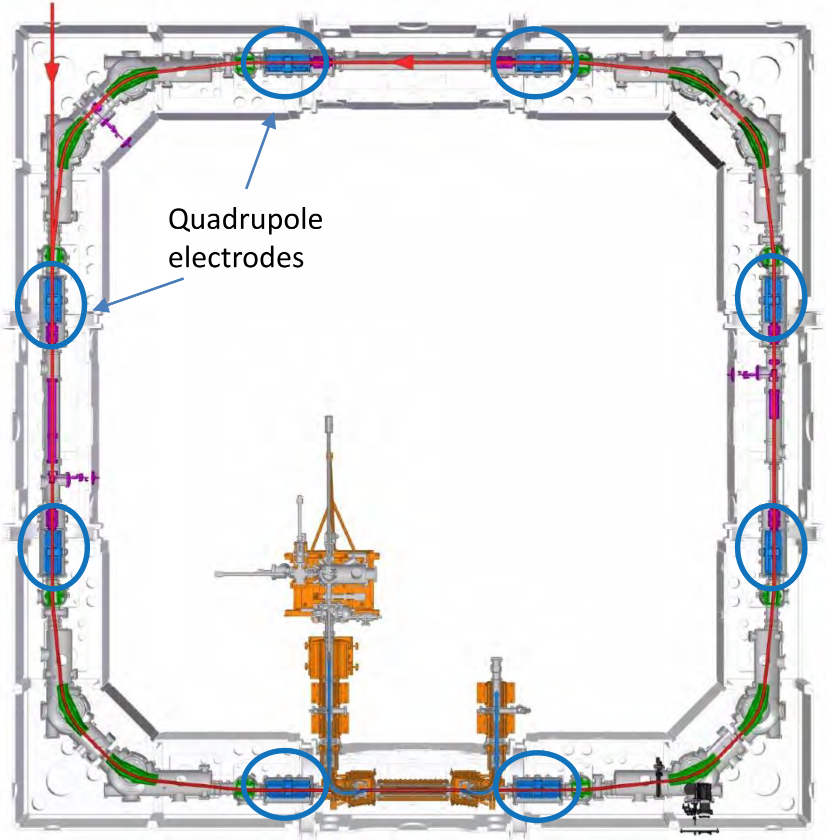
Compensation of energy deviation

- Acceleration in deflector fringe fields
- Different orbits
- $\eta = 1 - 2\alpha_p \leftarrow$ momentum compaction factor
- One reference sufficient
- Simultaneous storage not necessary

$$T_1 = T_0 = T_2$$

Different modes of CSR

- 16 quadrupoles shape the ion beam
- Can be grouped together in “families”
- Different modes available at CSR
    1. “**Standard mode**”(long lifetimes)
    2. “**Isochronous mode**”
       (mass measurements)
- Influence betatron oscillations
- Determine dispersion function



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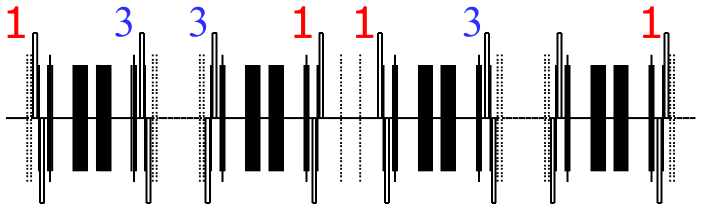
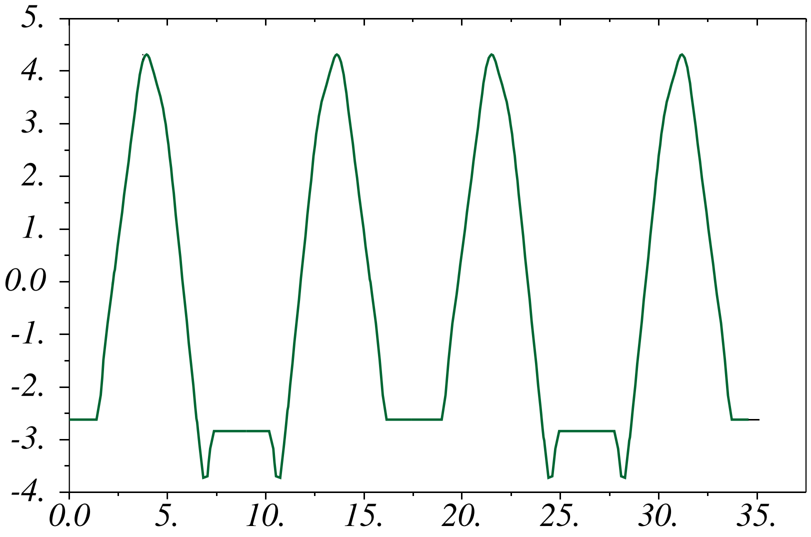


CSR with 4 Quadrupole families

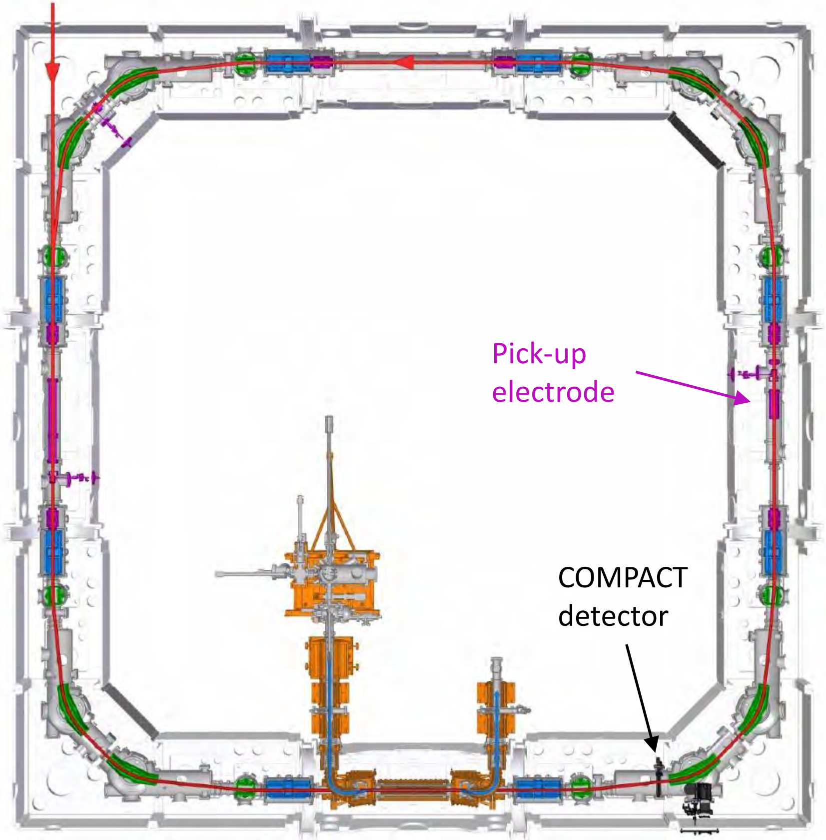


Diagnostics for mass measurements at CSR

- Frequency measurement
  - Pick-up electrode

- Time-of-Flight method (ToF)
  - Single particle detector

$$\frac{f_0}{f} = \frac{T}{T_0} = \sqrt{\frac{m/Q}{m_0/Q_0}}$$



Beam parameters

- Beam energy: 150 keV
- Room temperature
- $p \approx 10^{-11}$ mbar

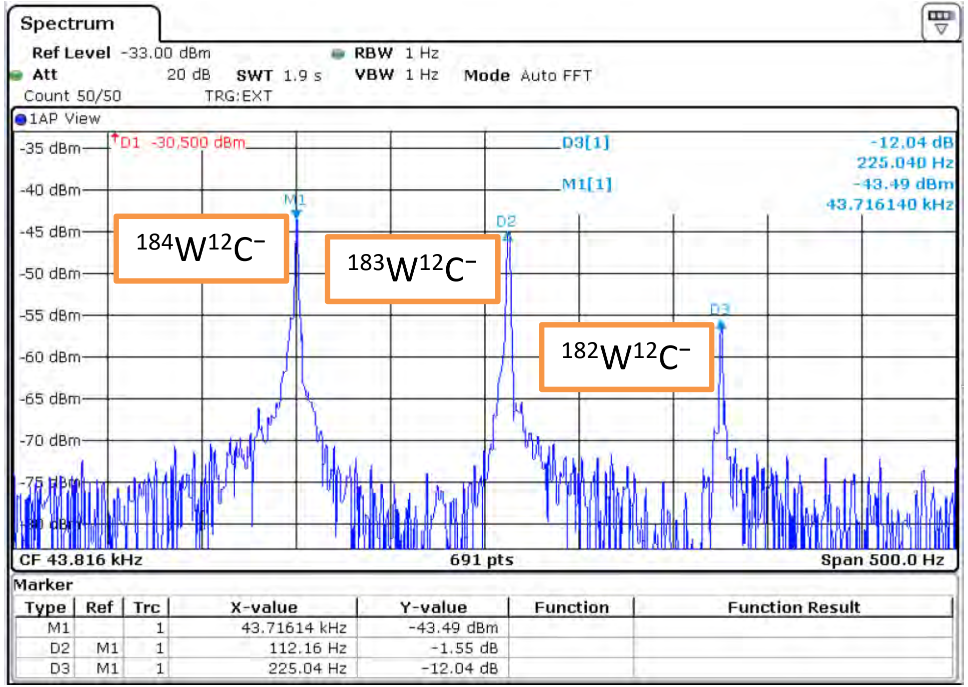
- Isotopes of WC^{-}
- Production in sputter source
- Different integers masses inside CSR

A (u)	Isotope
194	$^{182}W^{12}C^{-}$
195	$^{183}W^{12}C^{-}$
196	$^{184}W^{12}C^{-}$

Frequency measurement

- Measurement of 4th harmonic
- Three masses visible
- 1 Hz resolution of spectrum analyzer
- $^{184}W^{12}C^{-}$ used as reference

Ion	m_{ex}	$\frac{m_{ex} - m_{theo}}{m_{ex}}$
$^{183}W^{12}C^{-}$	194.95127 u	2.58×10^{-6}
$^{182}W^{12}C^{-}$	193.94988 u	5.81×10^{-6}

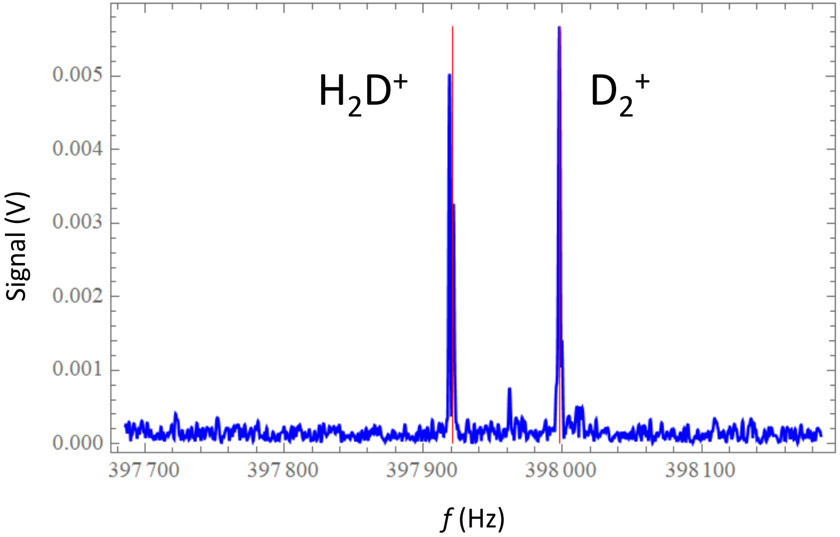


Frequency measurement: Molecular isobars

Molecule	**Theo. mass (u)**
H_2D^+	4.02920
D_2^+	4.02765

Measured mass for D_2^+: 4.02766 u

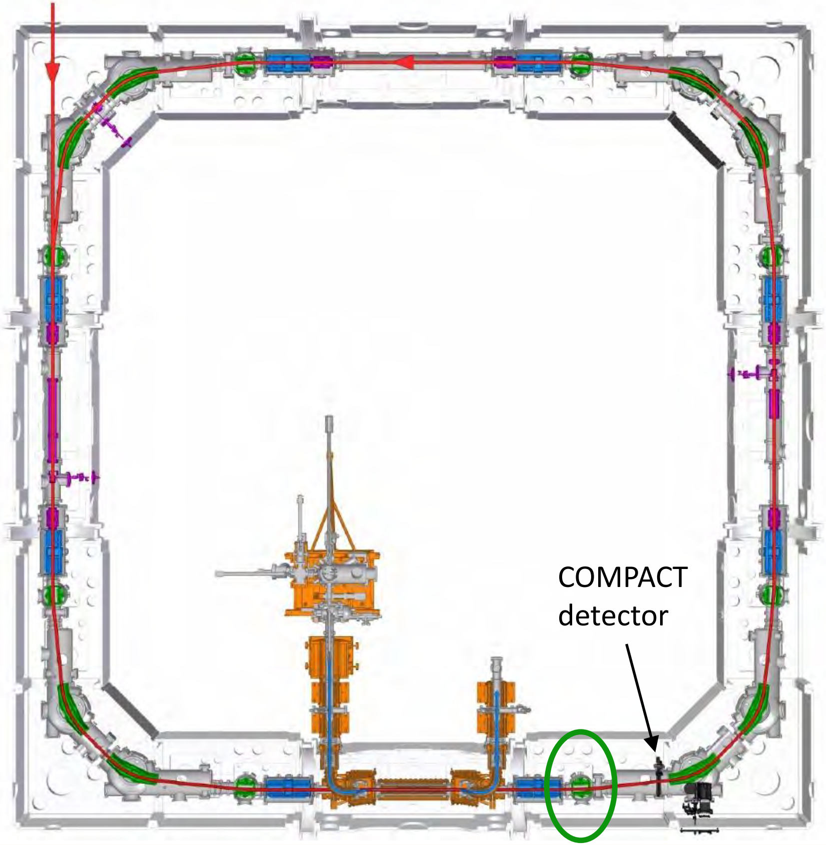
$$\frac{\Delta m}{m} = 2.5 \times 10^{-6}$$



Detector measurement

Movable detector

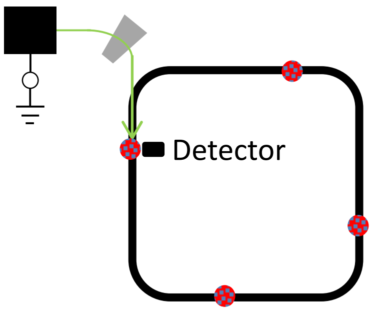
1. Neutral position
   - Collects neutral fragments
   - Residual gas collisions
2. Halo position
   - At the edge of beam
   - Collects ions with large betatron oscillations

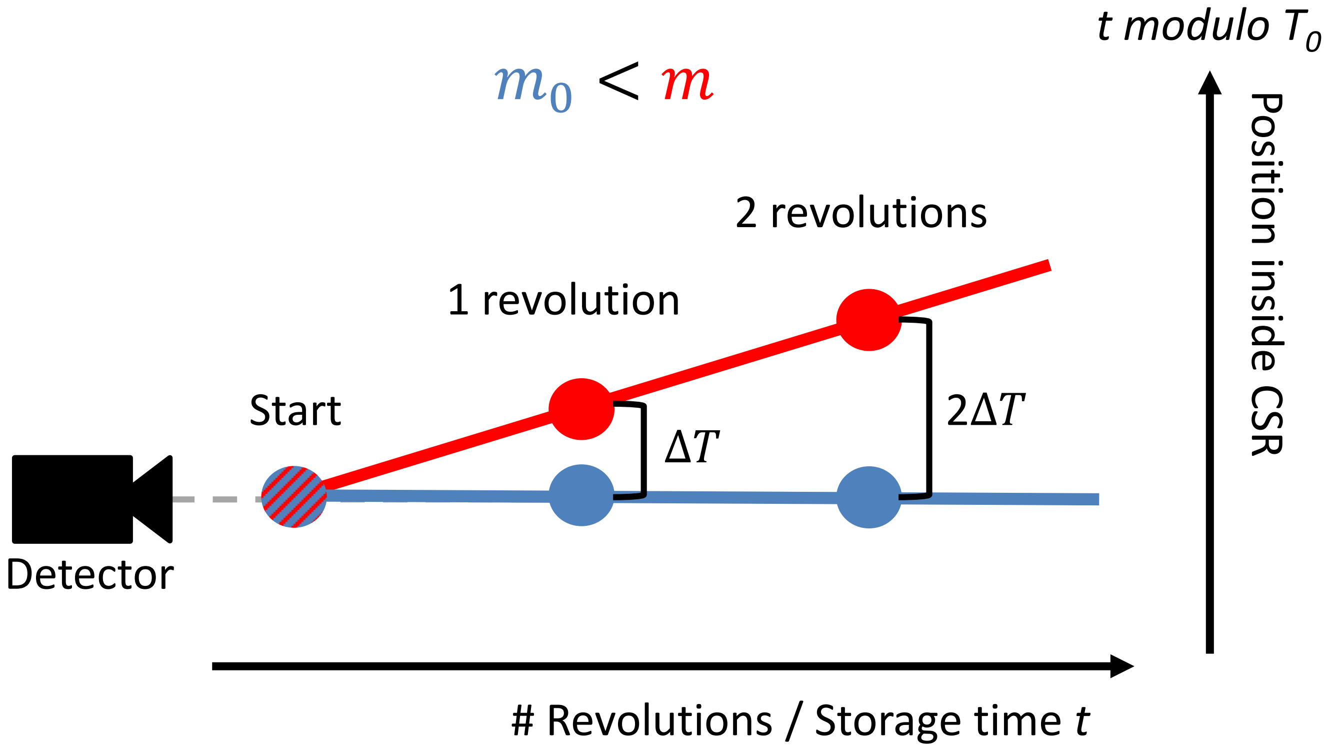


Analysis of the ToF measurement

For constant *Q*:

$$\frac{\Delta T}{T_0} = \frac{\Delta\sqrt{m}}{\sqrt{m_0}}$$





ToF spectrum

Reference:
$^{184}W^{12}C^-$

- $^{183}W^{12}C^-$
- $^{182}W^{12}C^-$
- $^{197}Au^-$

For constant *Q*:

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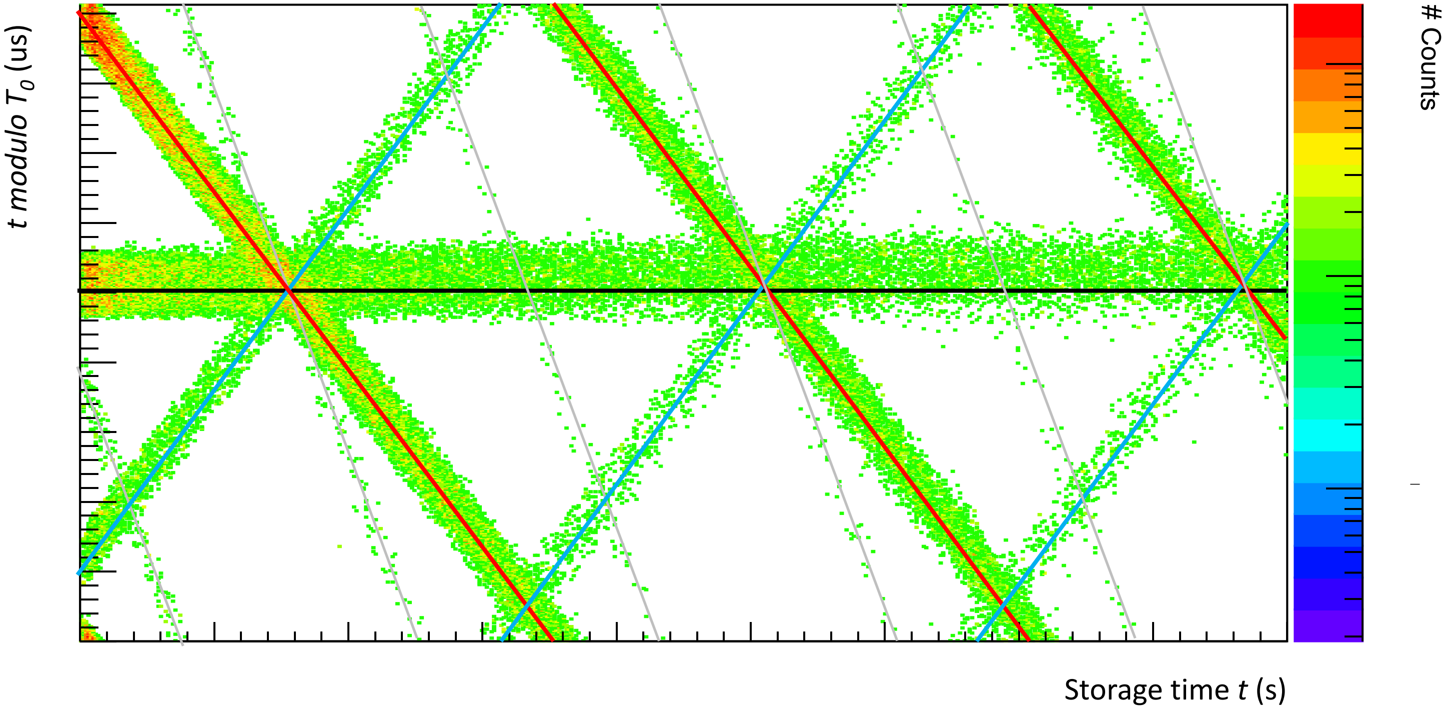
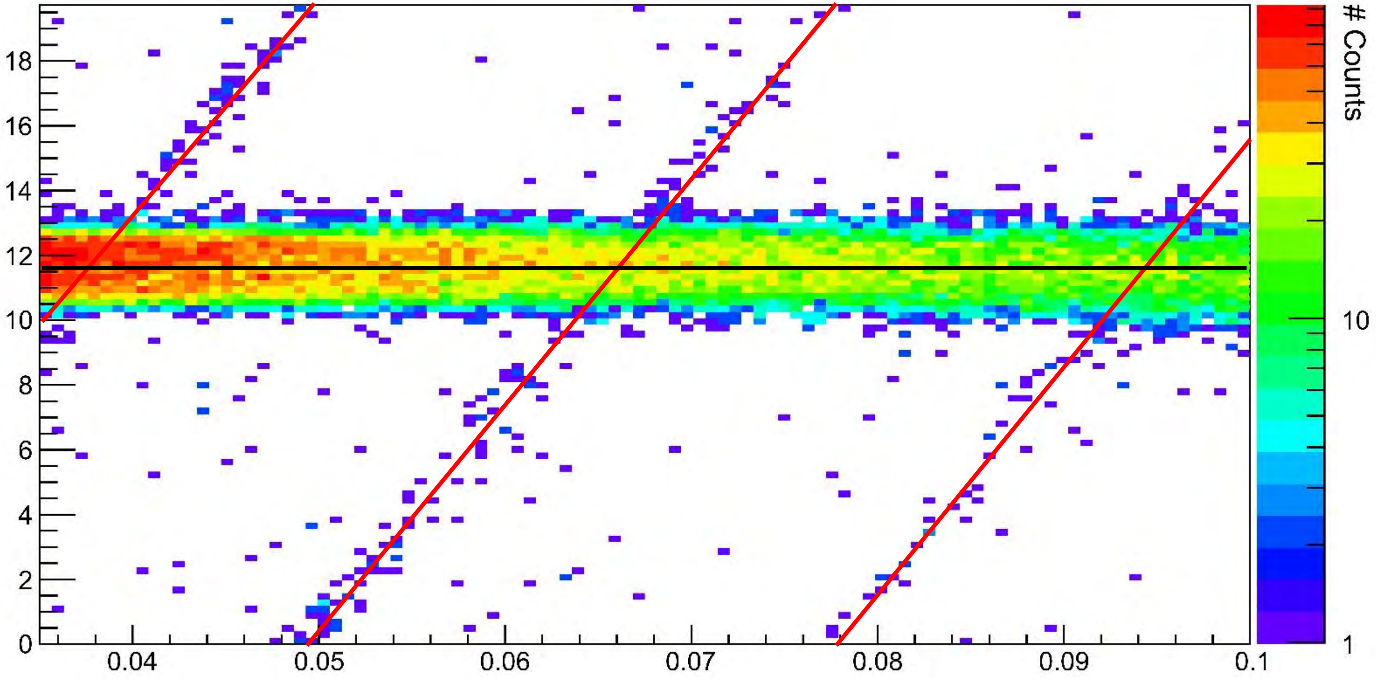


ToF spectrum: Molecular isobars

$^{16}OH^+$	**17.0022 u**
$^{14}NH_3^+$	+0.0238 u

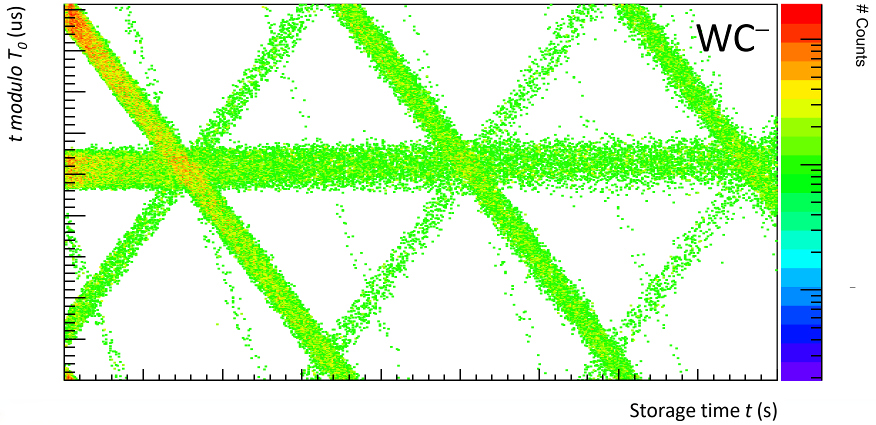
Contamination sensitivity:
1 : 46 000

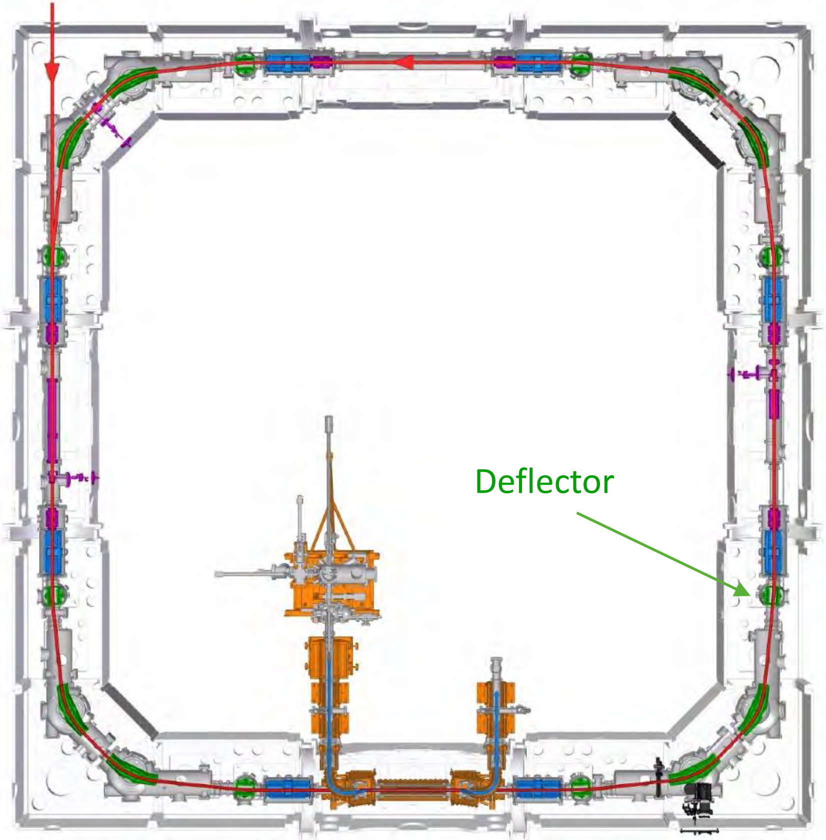


Beam purification

Purification: Deflector kick

- Different species separately bunched
- Separation between bunches oscillates with storage time
- Fast switch at one deflector
- Apply kick to push bunches on unstable trajectories





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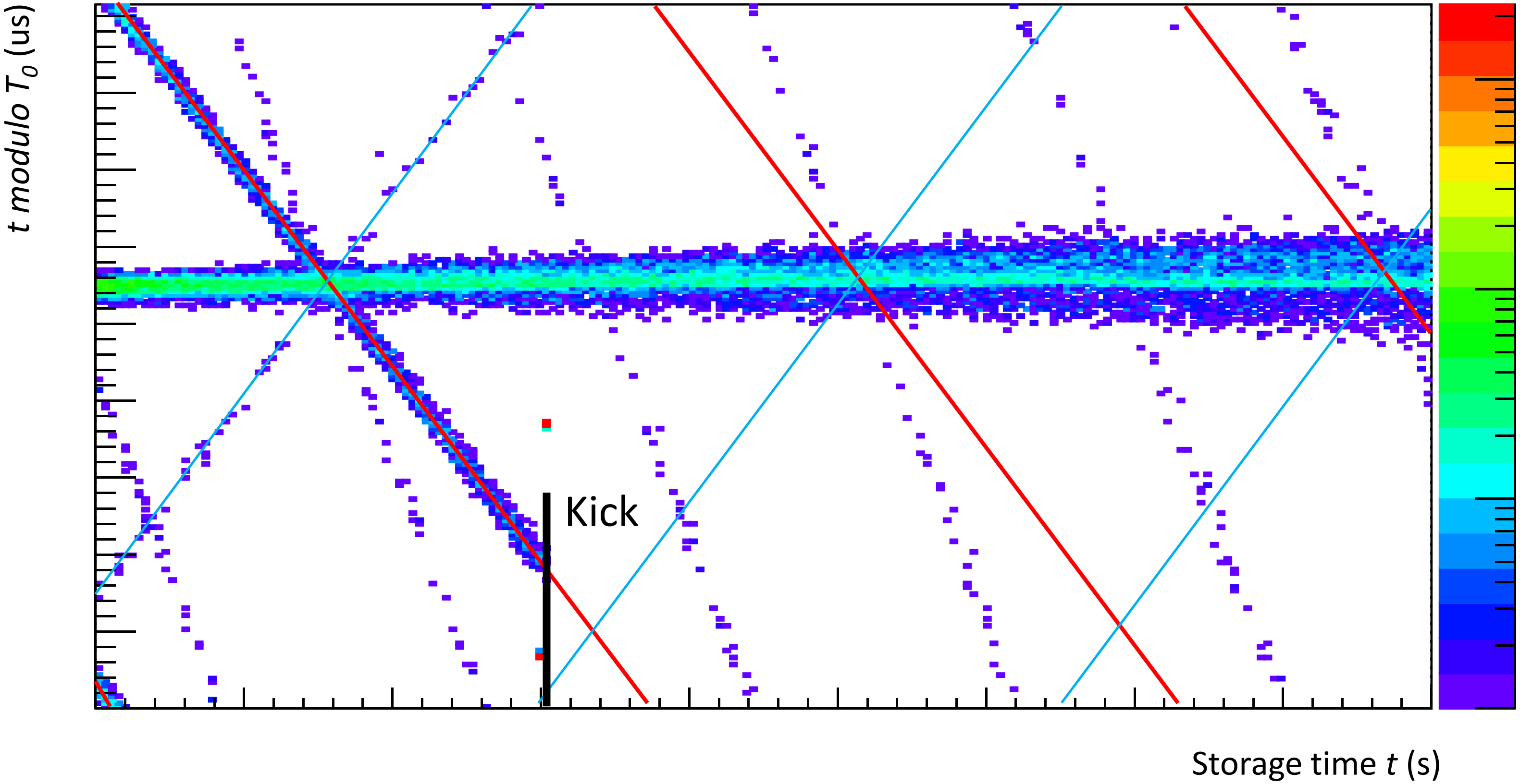
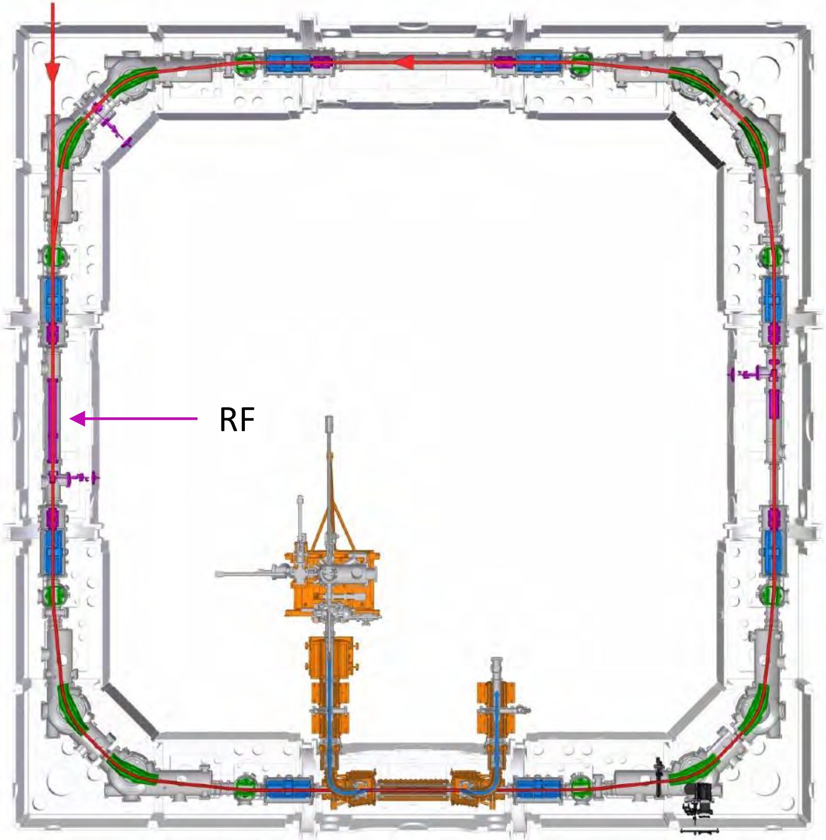


RF - Excitation

- Oscillating potential on drift tube
- Modification of the ions' velocity
- $f_{RF} \approx n \cdot f_{rev}$:

1. Non-isochronous operation: bunching of the ions
2. Isochronous operation: excitation out of ring acceptance



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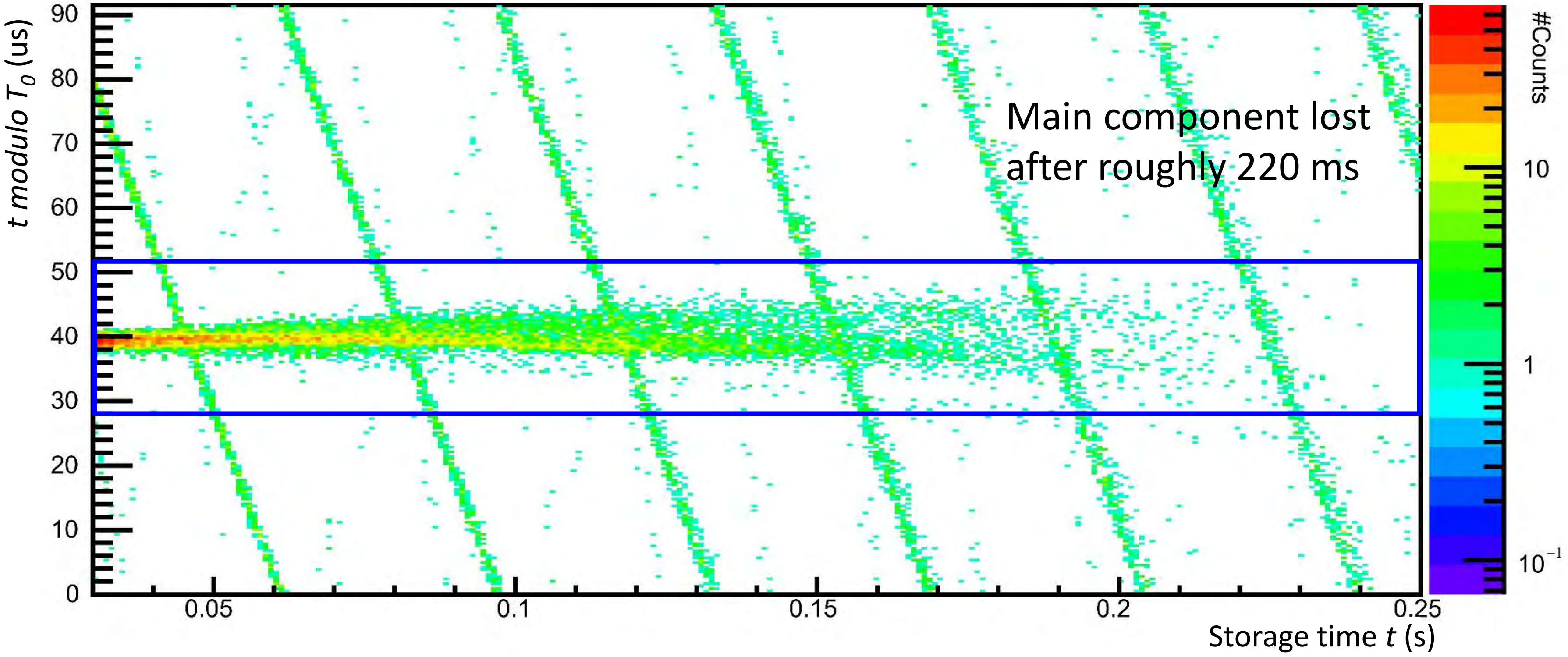
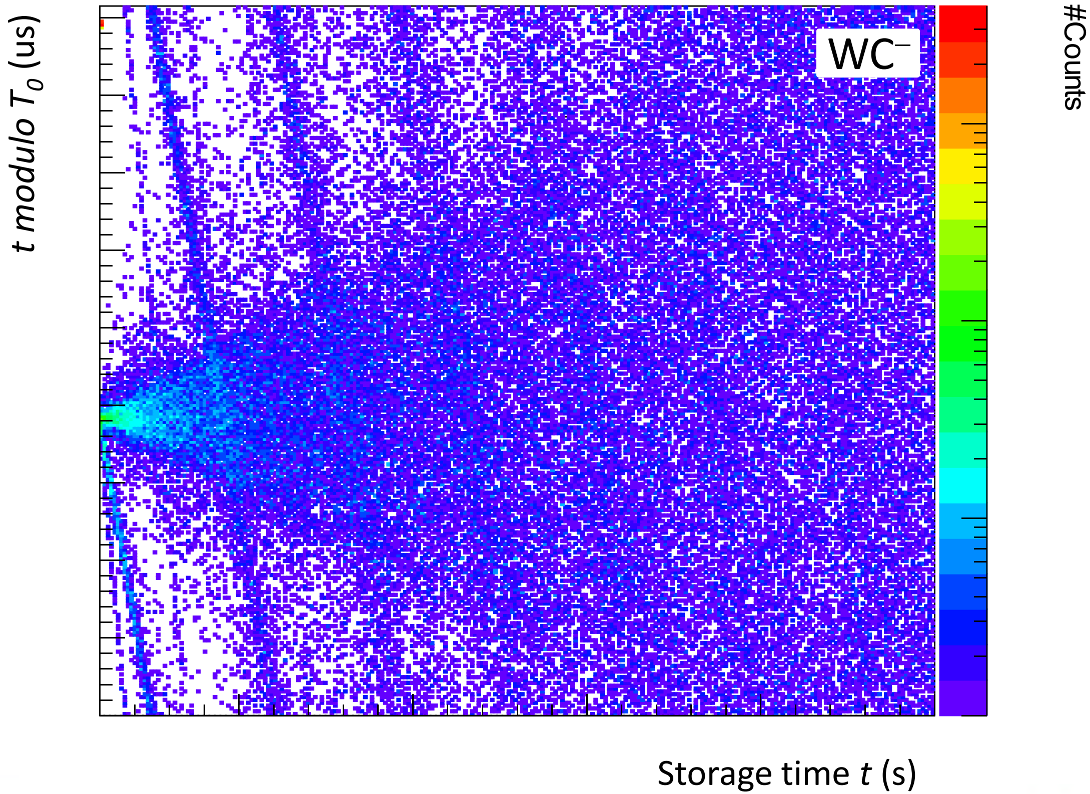


The “standard mode” of CSR

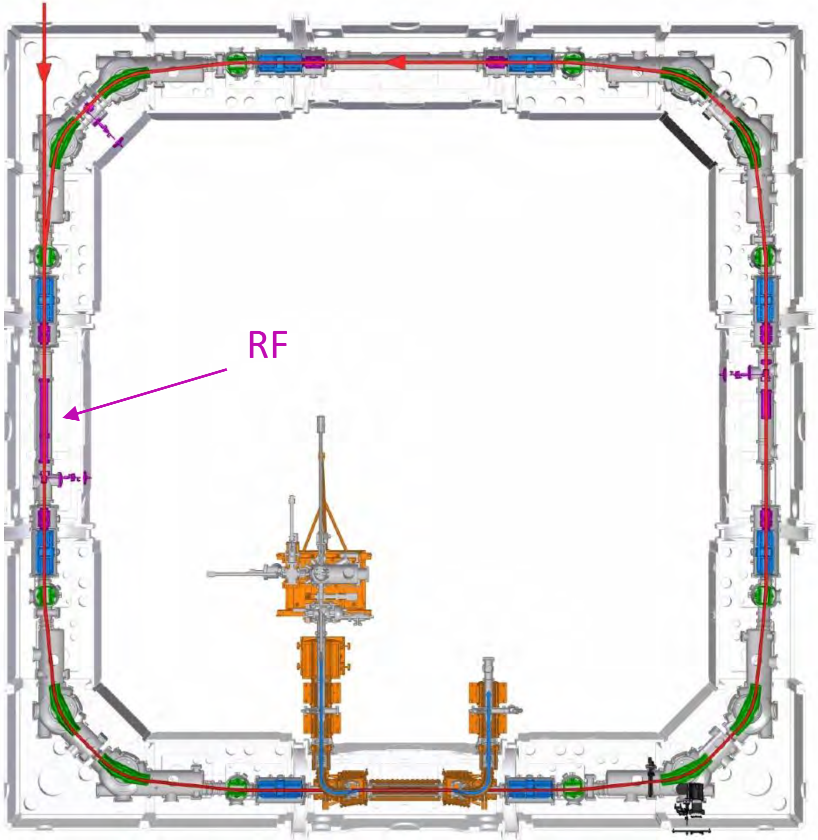
- Main research field at CSR: Molecular astrophysics
- Requires very long beam lifetimes (10^3 s)
- Experiments performed in so-called “standard mode”
- Isochronous operation for diagnostics
- Fast de-bunching during “standard mode”



Standard mode: De-bunching suppression through RF

- Oscillating potential on drift tube
- Modification of the ions' velocity
- $f_{RF} \approx n \cdot f_{rev}$:

1. Non-isochronous operation: bunching of the ions



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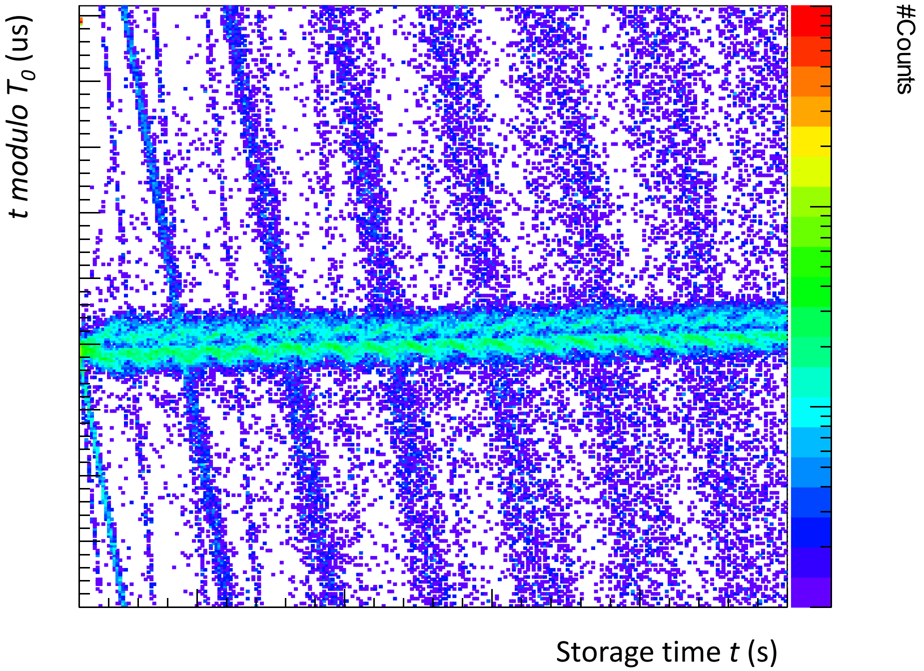
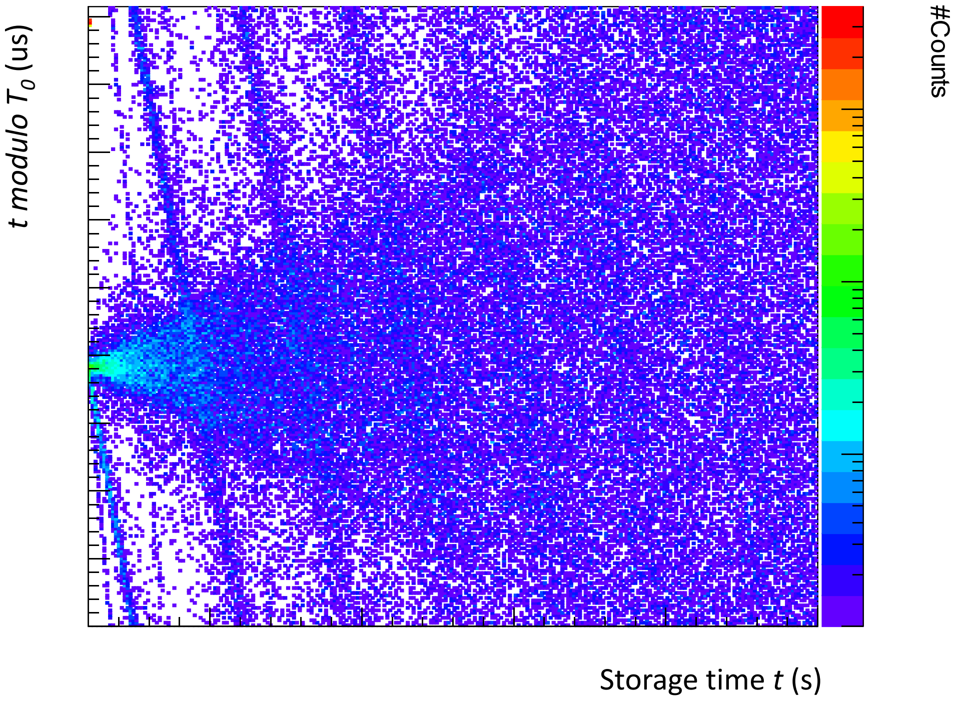


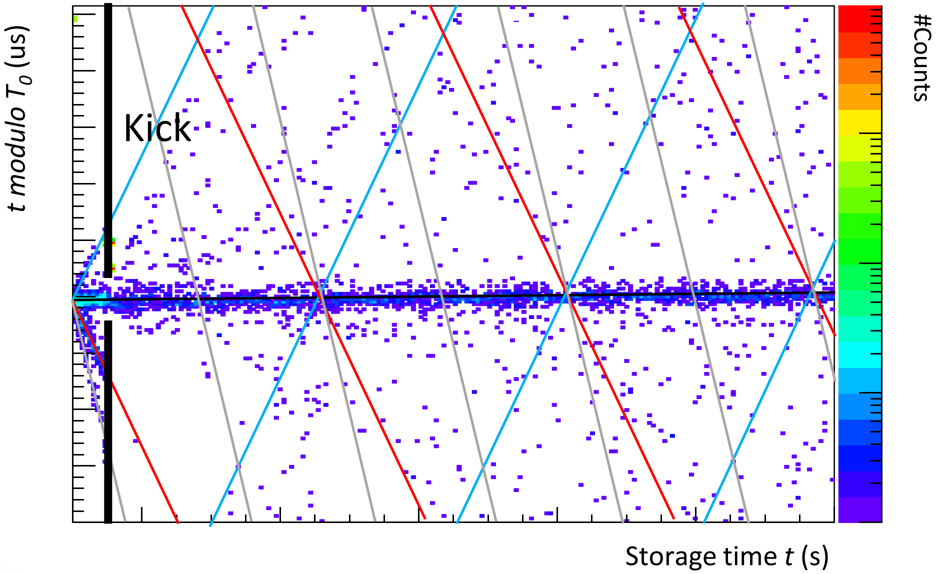
With RF

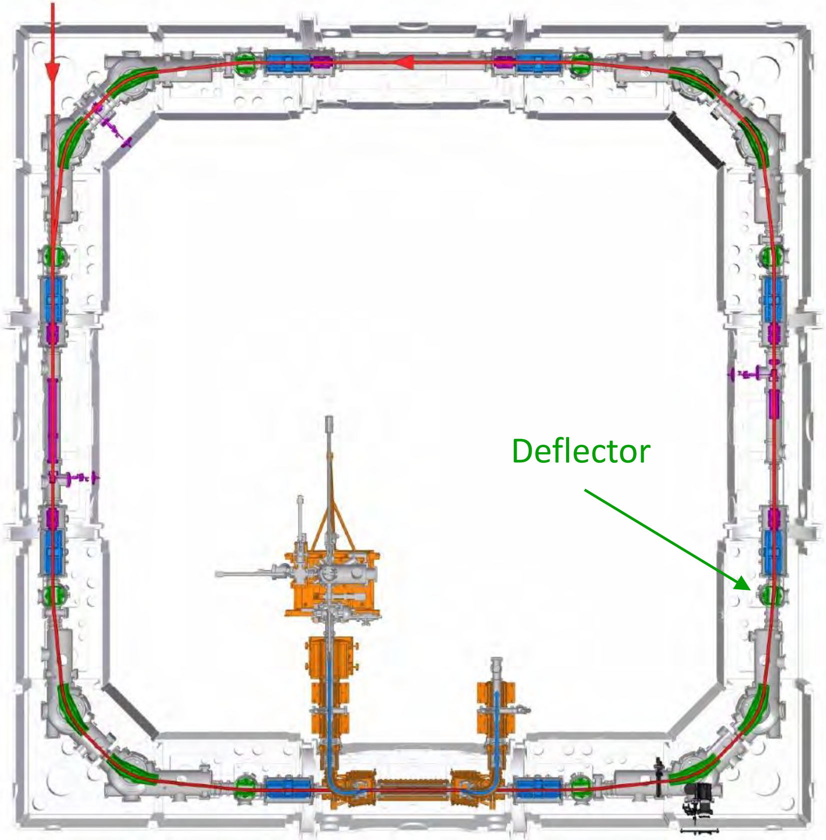


Without RF

Standard mode: Deflector kick

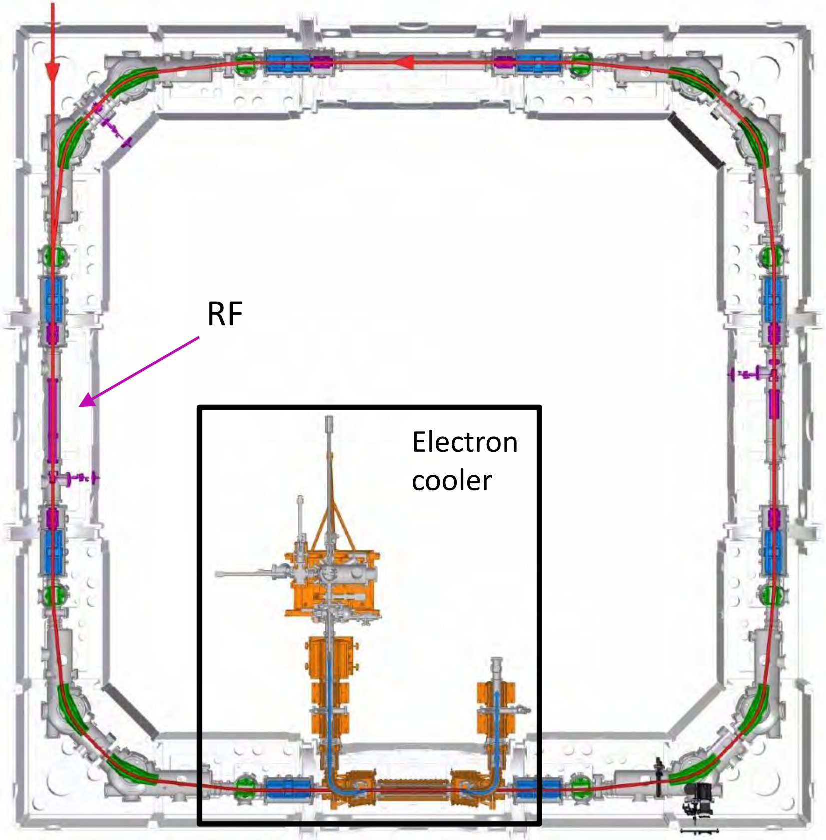
- Fast switch at one horizontal deflector
- Apply kick to push bunches on unstable trajectories





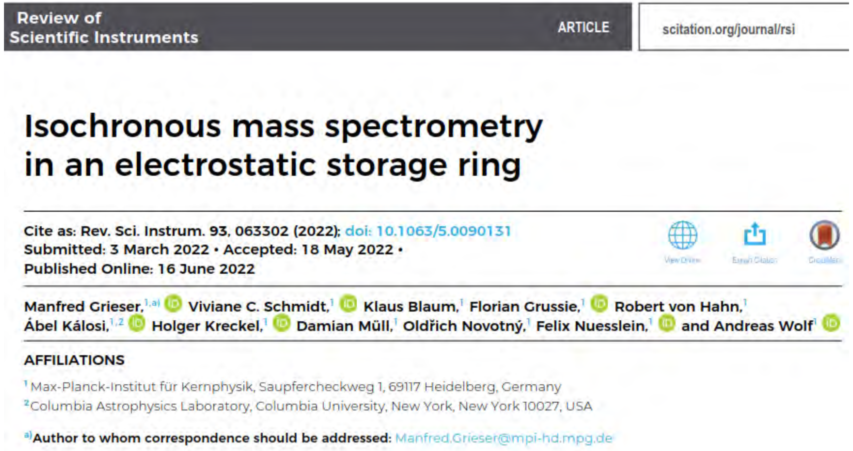
Standard mode: Cleaning methods under development

- Energy modification out of ring acceptance
  1. Using the RF
     - Modification of RF-frequency during bunching
  2. Using the Electron cooler
     - Modification of the electron velocity during cooling



Summary and Outlook

- First isochronous operation of an electrostatic storage ring
  - $\frac{\Delta m}{m} < 10^{-5}$
  - Sensitivity for relative fractions down to 0.02%
- Beam purification methods at CSR
  - Deflector kick
  - RF excitation
  - Also methods for non-isochronous operation



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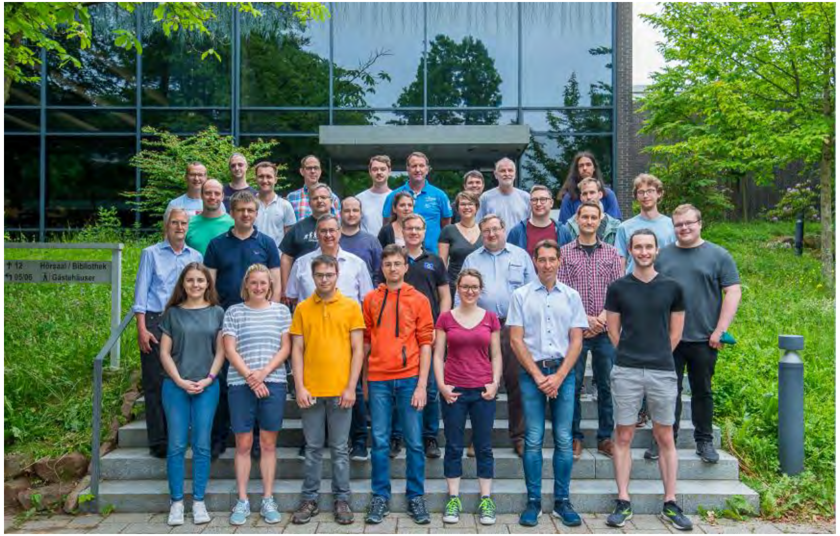

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