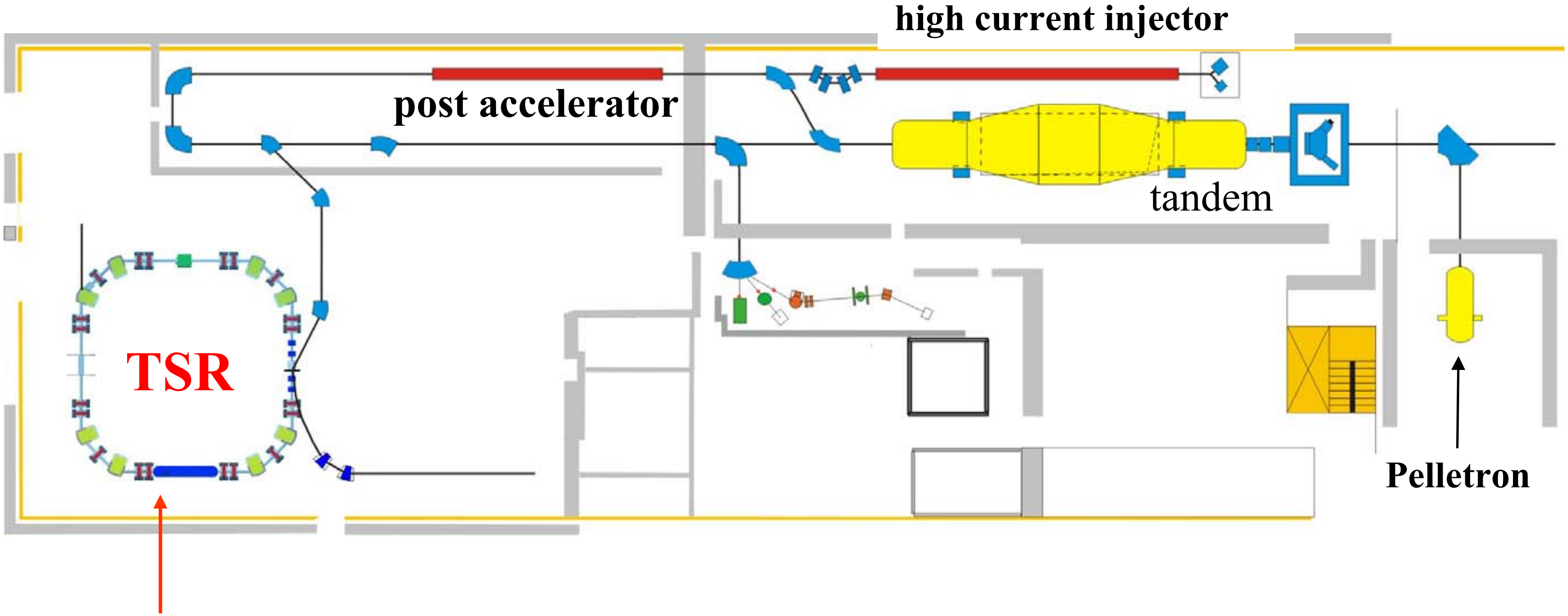
MG1

Acceleration, Deceleration and Bunching of Stored Cooled Ion Beams at the TSR, Heidelberg

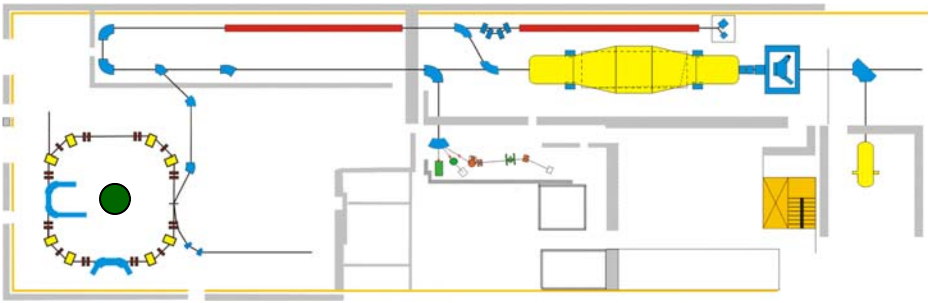
Manfred Grieser

Accelerator facility at MPI-K Heidelberg

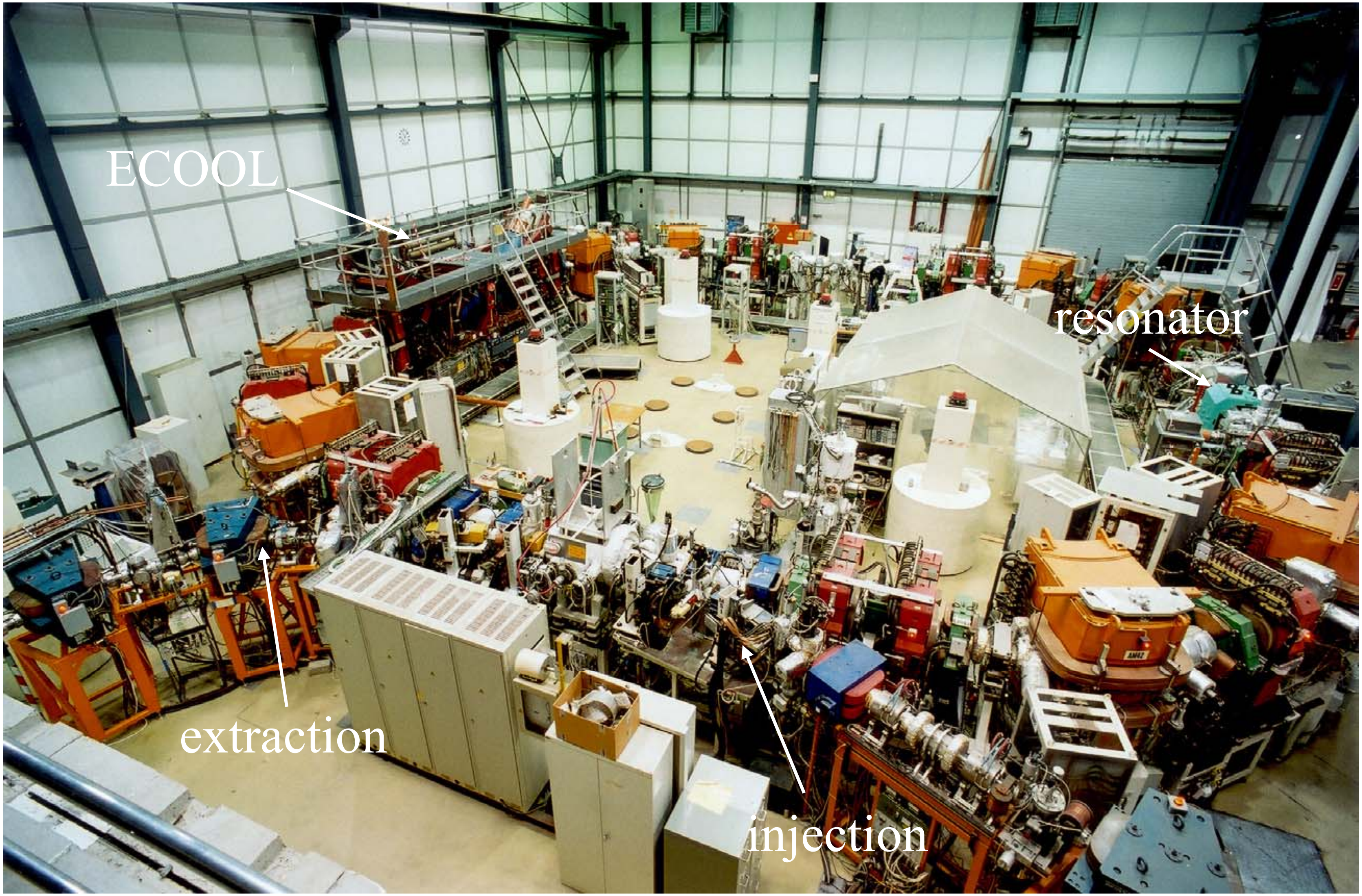


heavy ion cooler storage ring TSR

HIAT 09, 9. June 2009

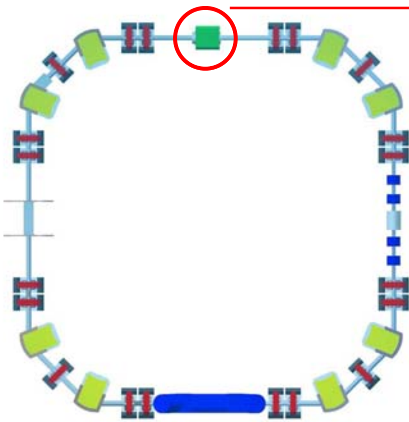


The heavy ion storage ring TSR



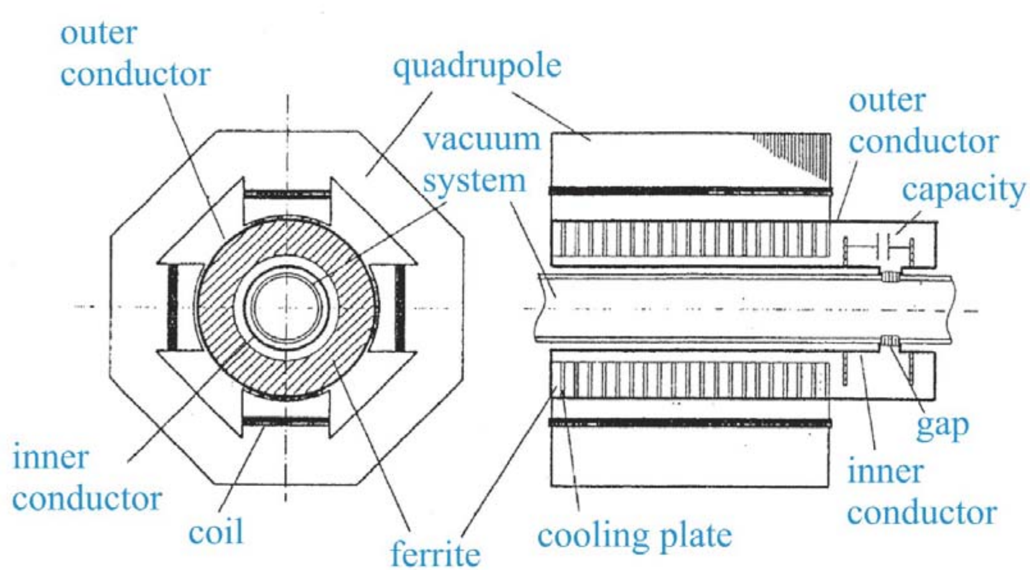
RF acceleration and deceleration

RF resonator



frequency range: 0.5-7 MHz
only with magnetization:
factor ≈ 7 I_{mag}=0-150 A
rf voltage: max 5 kV
rf power: max 10 kW
ferrite: Philips FXC 8C12
ferrite size: 498x270x25 mm^3
number of ferrites: 20
cooling: 21 water cooled Cu disks

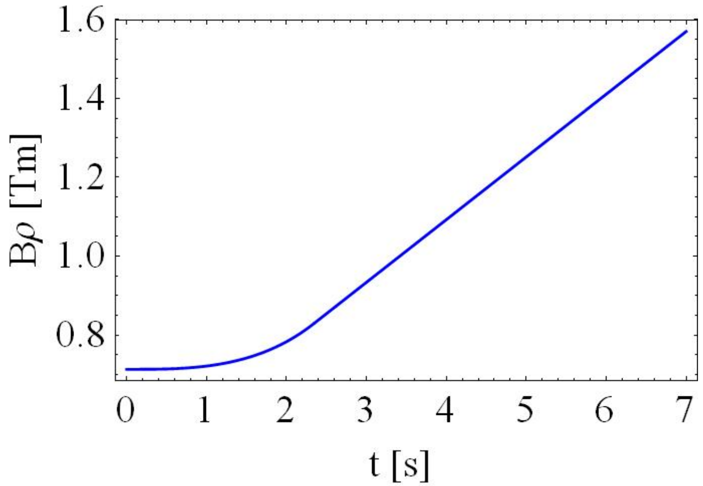
quadrupole
- magnetization of the ferrites
- decoupling of rf field and magnetization field



Acceleration tests with $^{12}C^{6+}$ ions

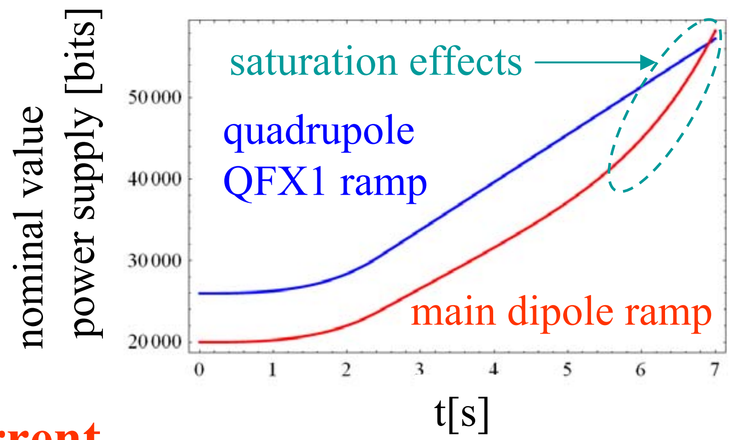
energy E= 73.3 MeV→ 362 MeV ⇔ $B \cdot \rho = 0.71$ Tm → **1.57 Tm**

rigidity



⇒

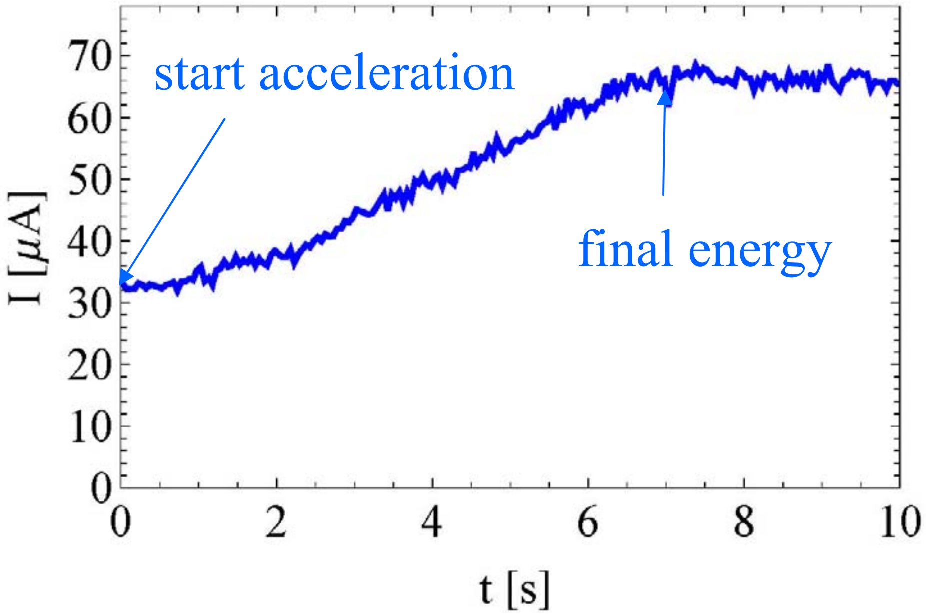
nominal value power supplies



ion current

ion current

$$I = Q \cdot N \cdot f_0$$



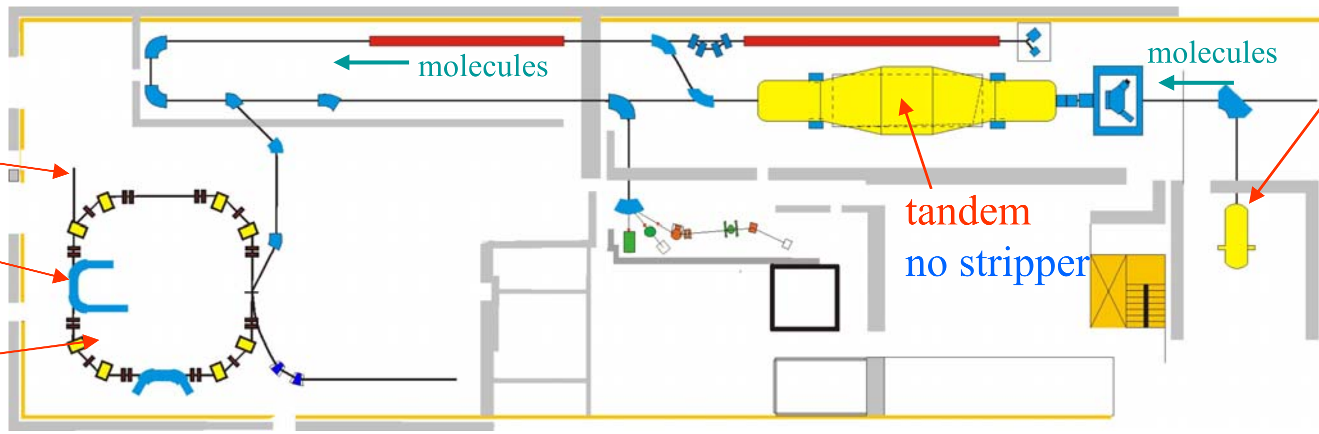
efficiency

$$\eta = \frac{N_{final}}{N_{start}}$$

η=98 %

MG2

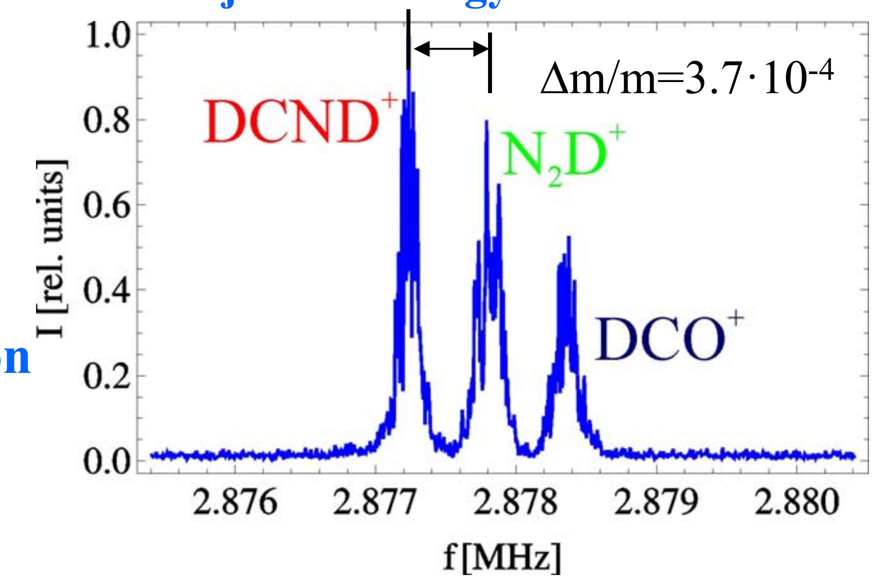
Mass selective acceleration at the heavy ion storage ring TSR



ion source produces several heavy **molecular ion species** with relative mass differences of $\Delta m/m = 3.7 \cdot 10^{-4}$ (DCND+,N2D+) .

with mass selective acceleration
separation of the right molecular ion species, for example $DCND^+$

Schottky spectrum at injection energy E=2 MeV

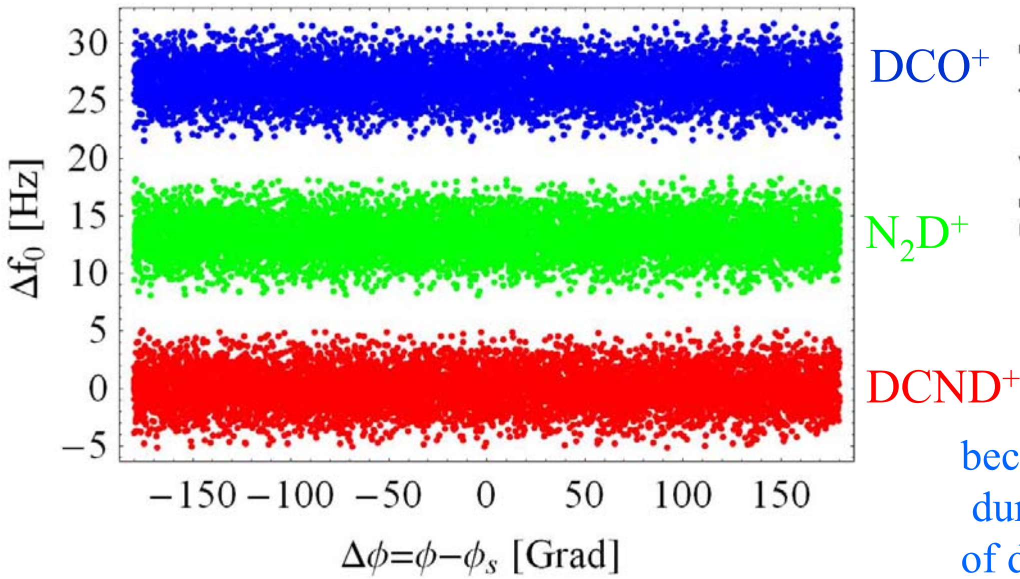


relation between ion mass and Schottky frequency for constant energy:

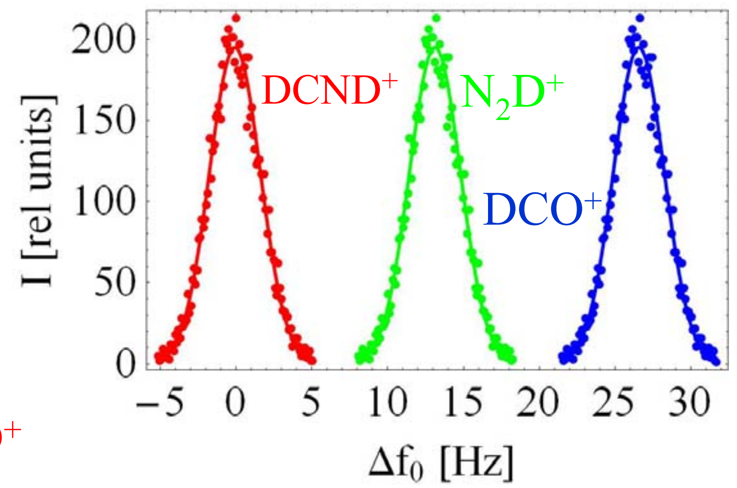
$$\frac{\Delta f}{f} = -\frac{1}{2}\frac{\Delta m}{m}(1+\alpha)$$

Description of the mass selective acceleration in the longitudinal phase space

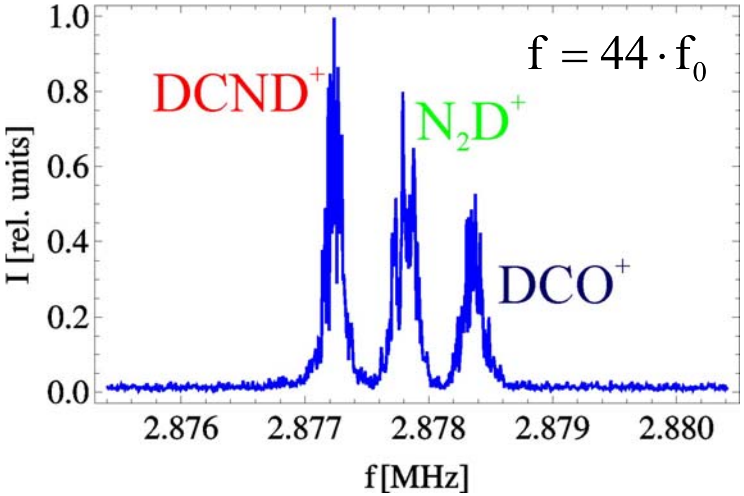
longitudinal phase space after injection



energy distribution



because relative intensity height changes during the beam time, intensities of different ion species was assumed to be the same in the simulation σ=120 eV



phase space coordinates

$\Delta f_0 = f_0 - f_{0,s}$ $\Delta\phi = \phi - \phi_s$

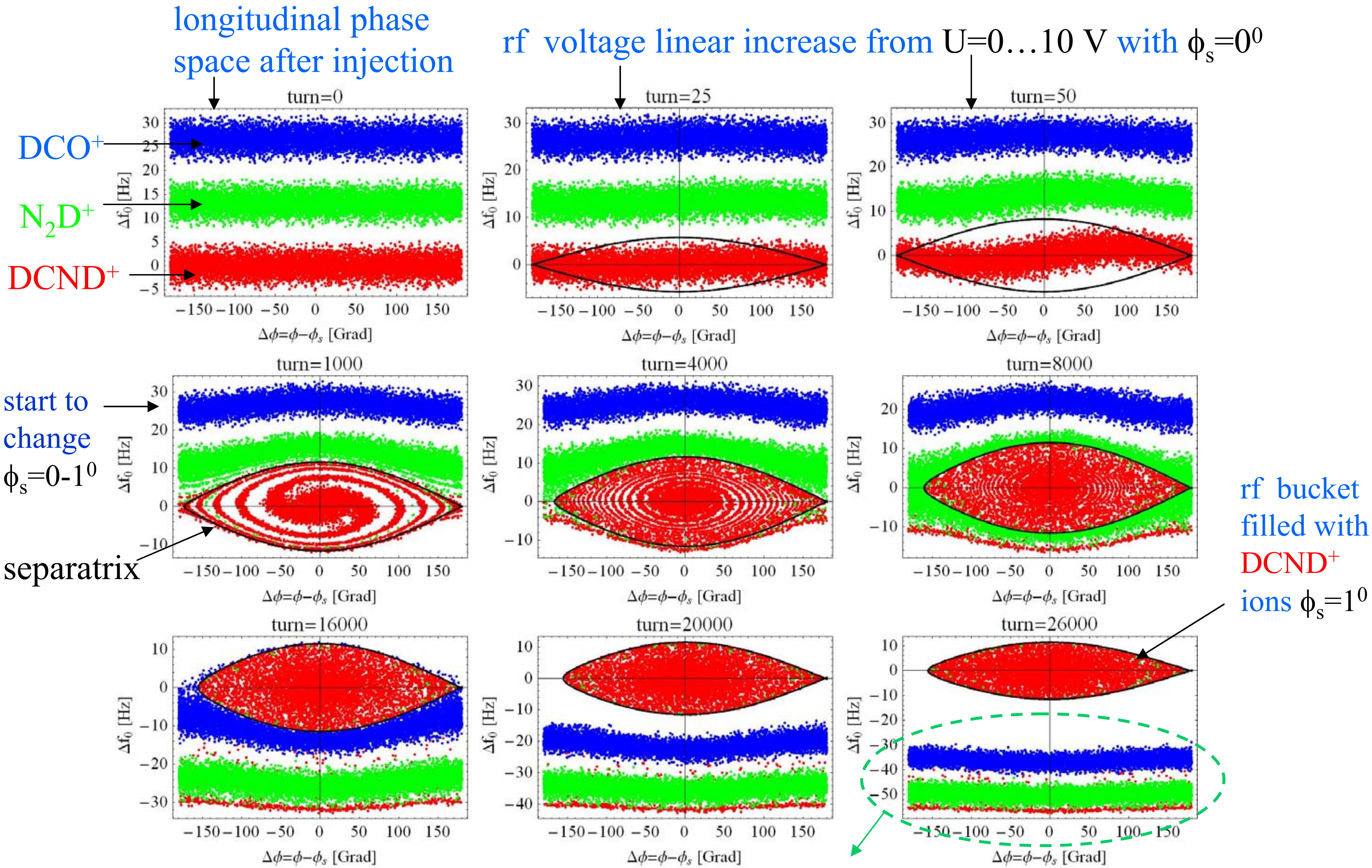
f_0 - ion revolution,

$f_{0,s}$ – revolution frequency of synchronous particle

ϕ- rf phase when ion reaches the rf gap

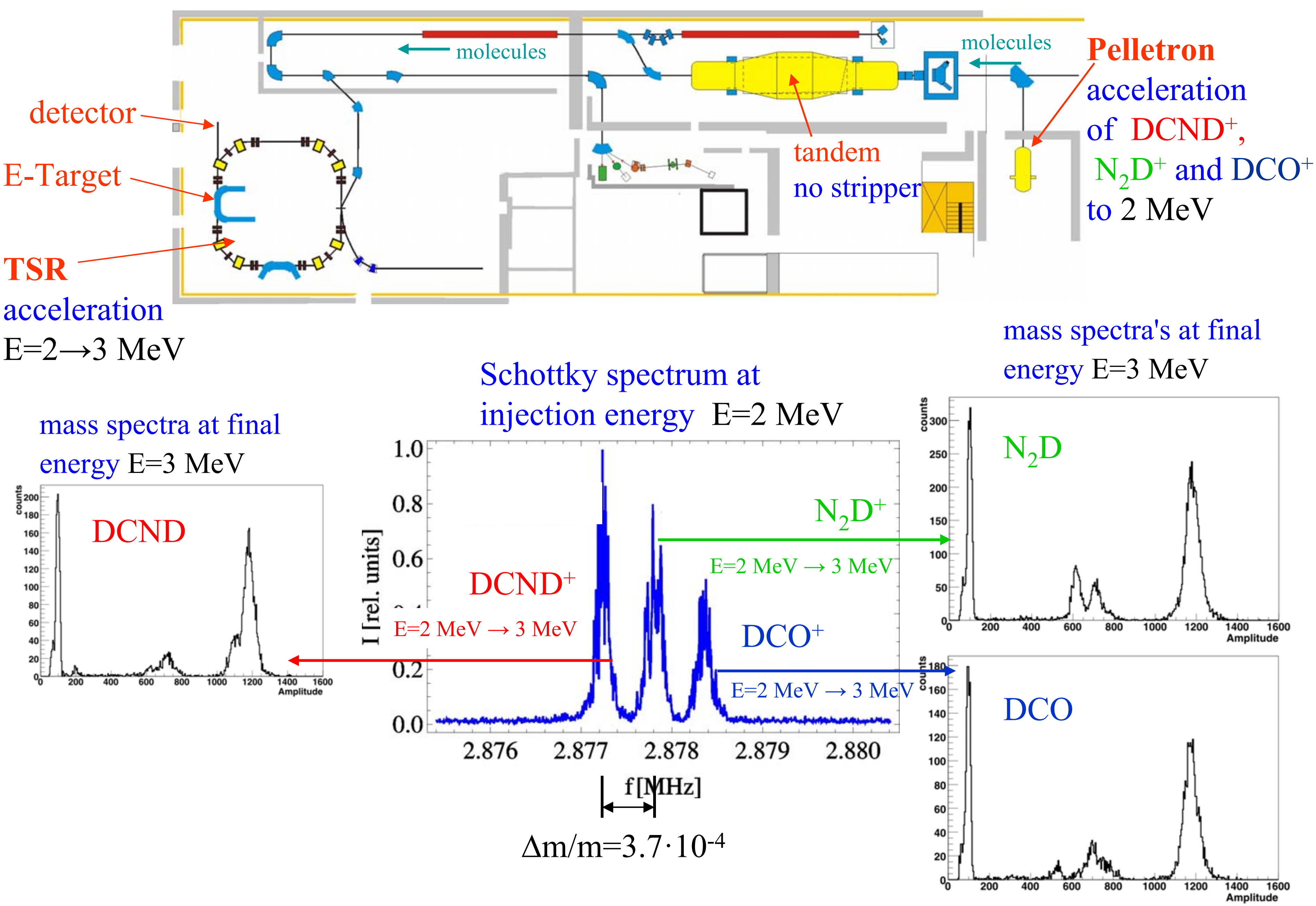
ϕ_s - rf phase of the synchronous particle

Simulation of mass selective acceleration

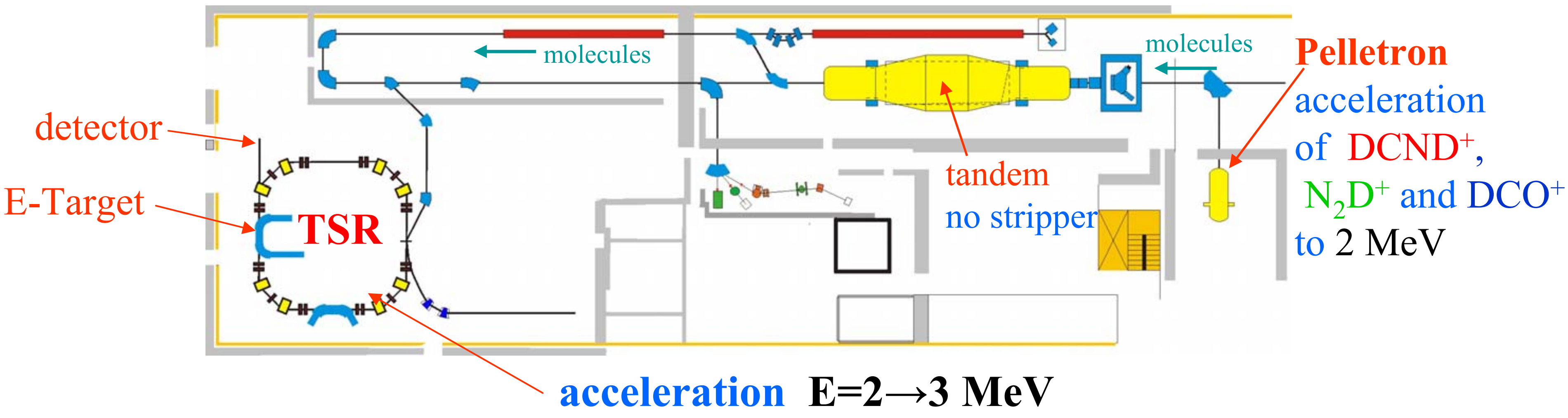


ions outside the bucket will hit the vacuum chamber, during acceleration of DCND+ and are lost

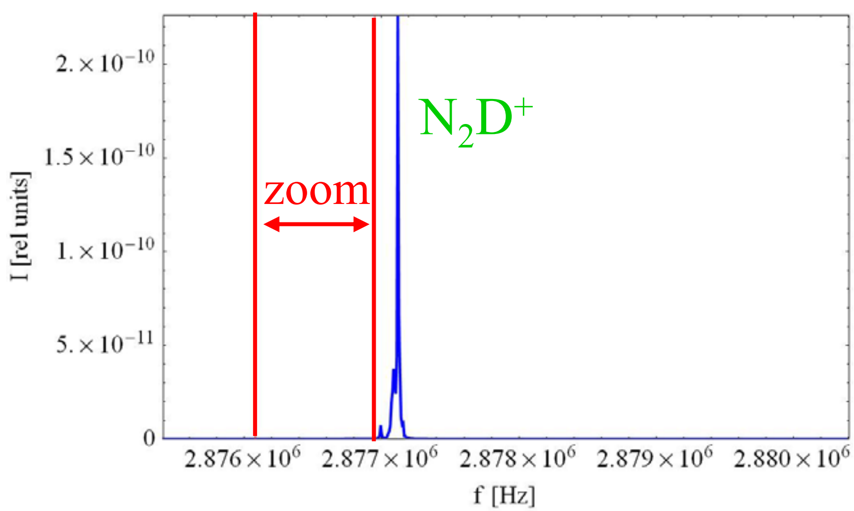
Mass selective RF acceleration at the heavy ion storage ring TSR



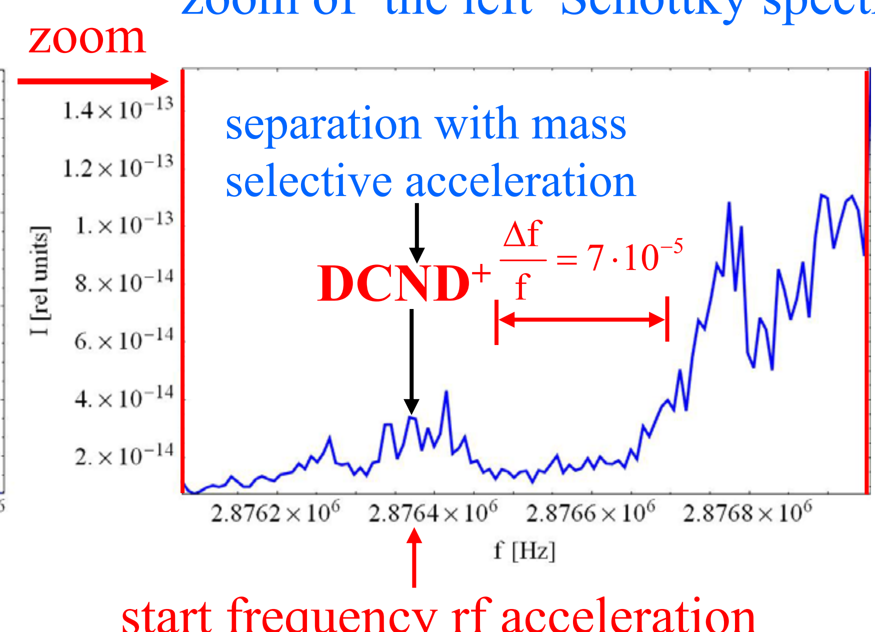
Mass selective RF acceleration at the heavy ion storage ring TSR



Schottky spectrum at injection energy E=2 MeV



zoom of the left Schottky spectrum

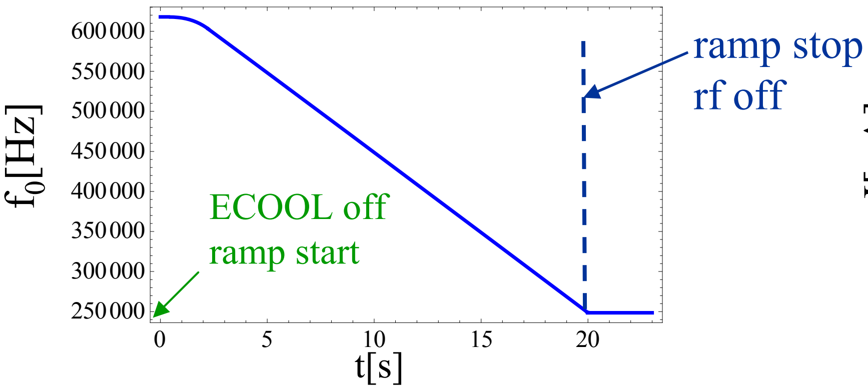


Deceleration tests with $^{12}C^{6+}$ ions

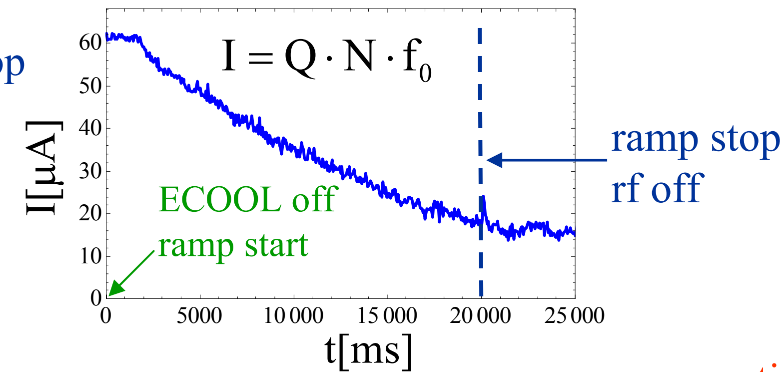
provide highly charged ions at low energies

energy E= 73.3 MeV→ 11.8 MeV (1MeV/u) ⇔ B·ρ = 0.71 Tm → 0.28 Tm

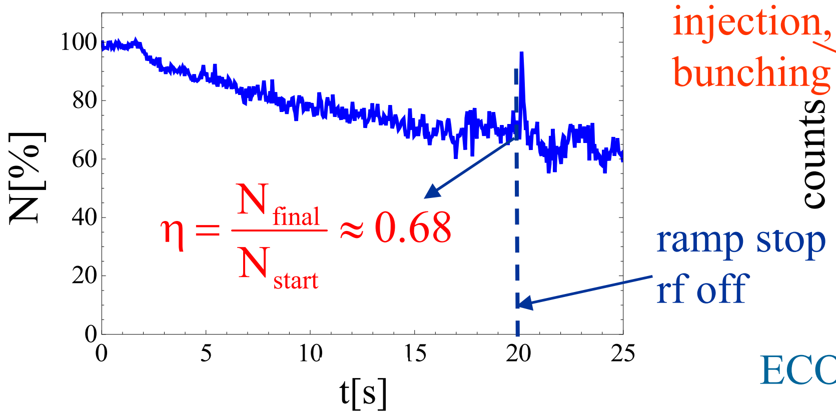
revolution frequency



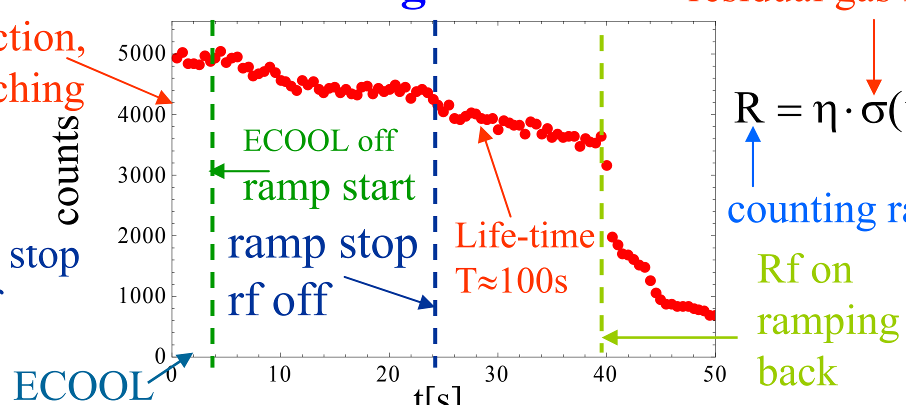
ion current



number of ions



counting rate BPM



cross section for residual gas ionization

$$R = \eta \cdot \sigma(v) v \cdot n \cdot N$$

counting rate

Rf on ramping back

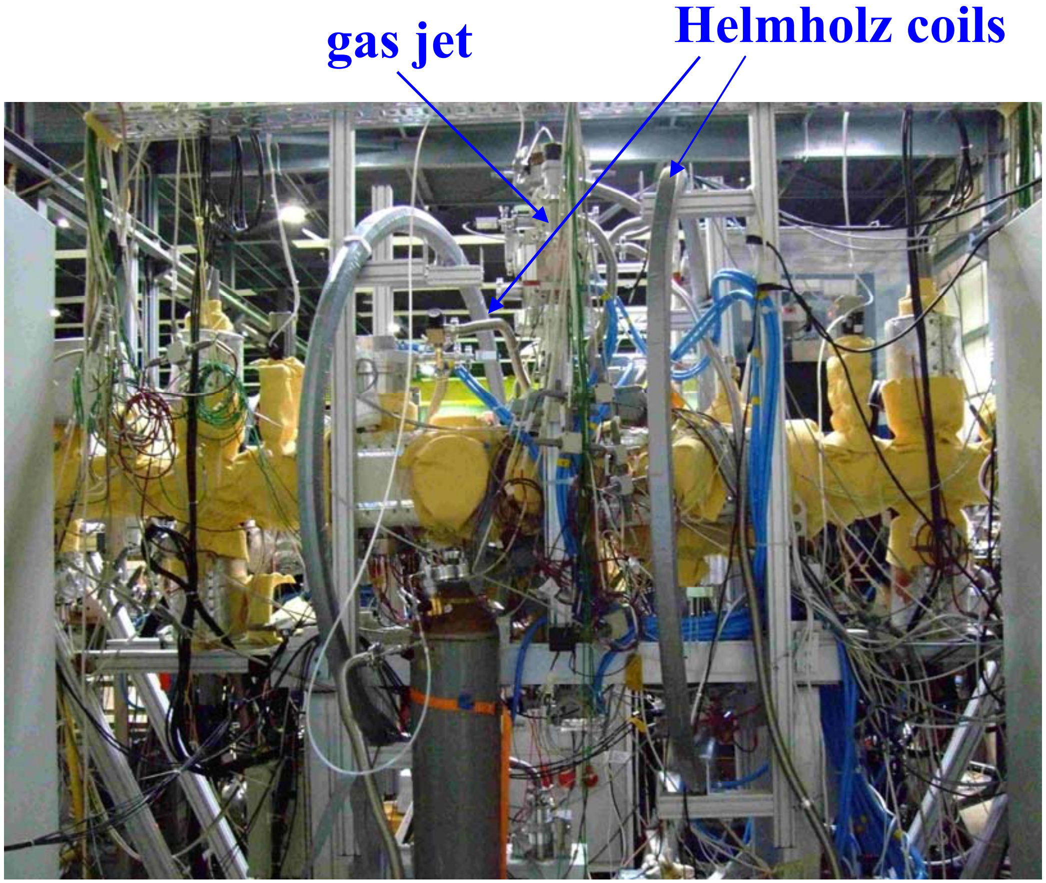
bunch length increase during deceleration process ⇒ particle loss

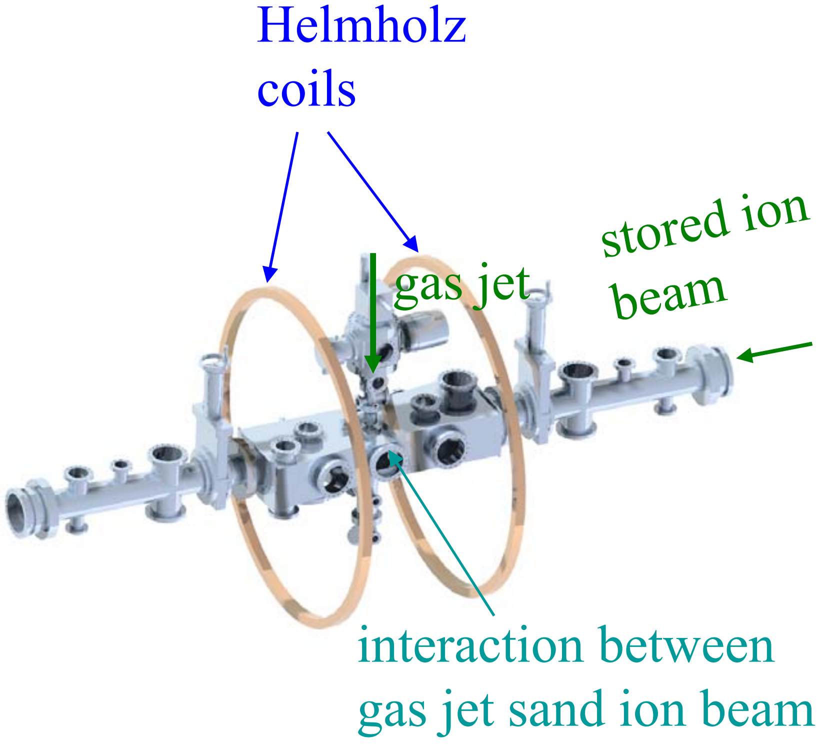
⇒ **electron cooling at injection necessary to get short initial bunches**

TSR experiments with a reaction microscope

reaction microscope

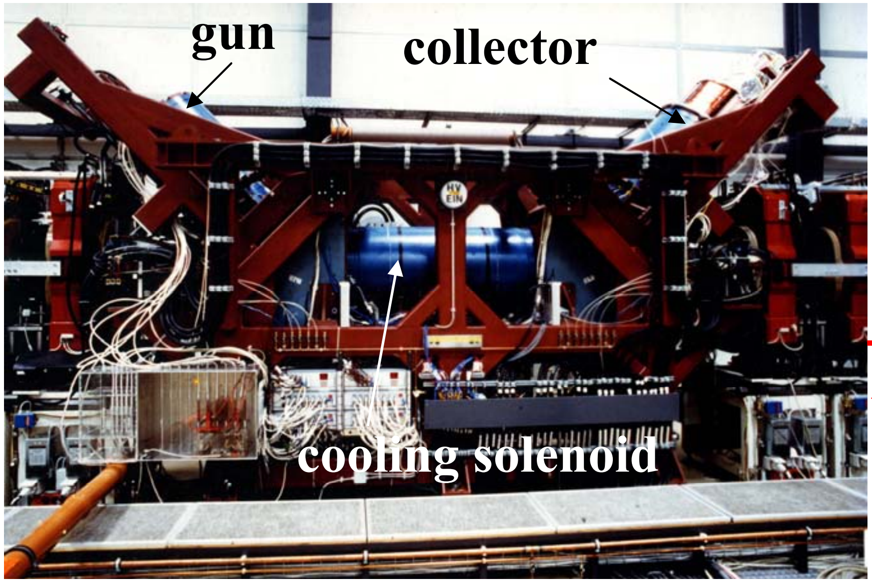
tool to measure the dynamic of charge transfer/ionization processes between a stored ion beam and an neutral beam

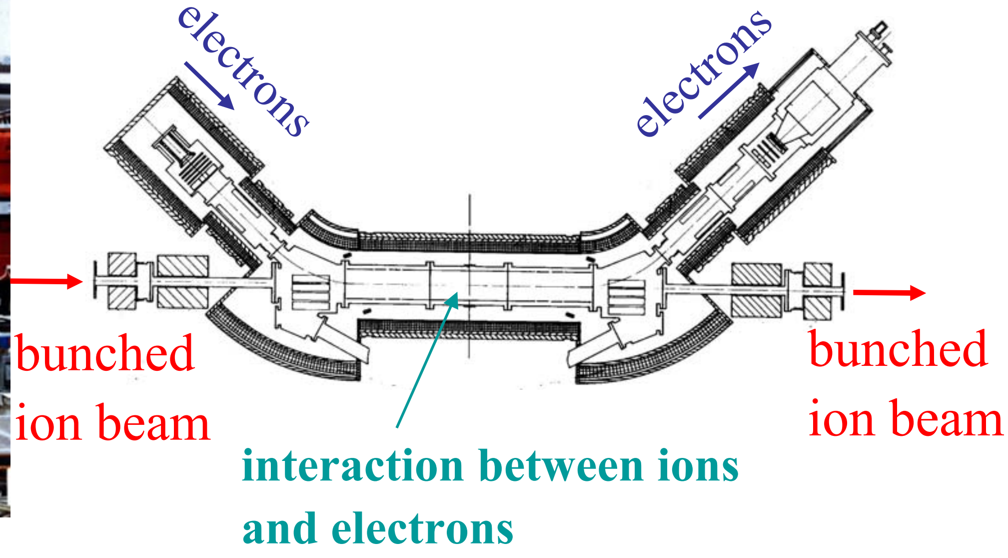




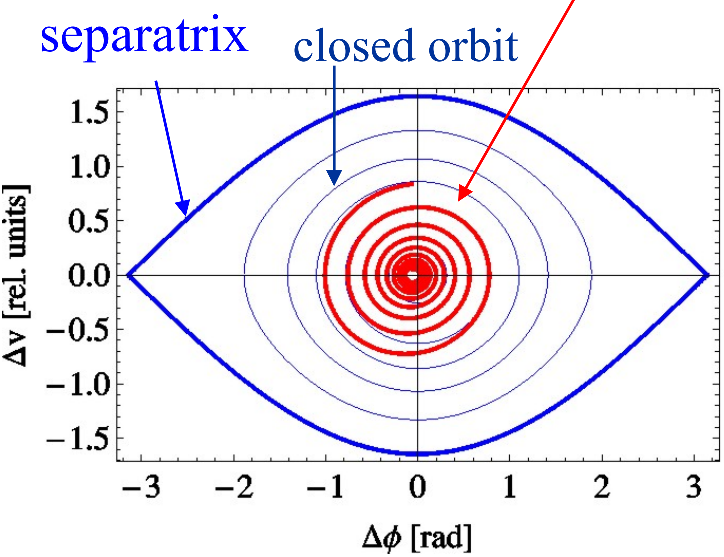
for some experiments **very short ion bunches are required**

Bunch length compression with electron cooling

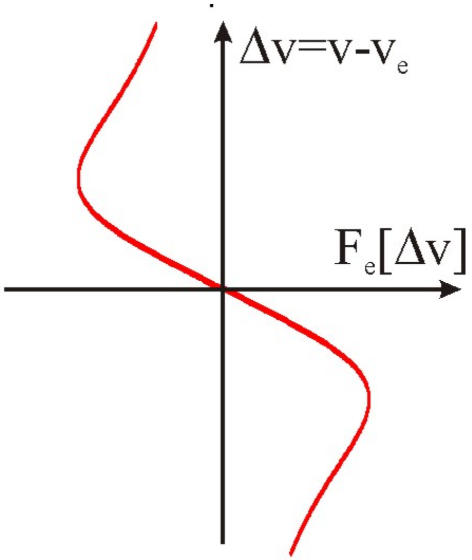




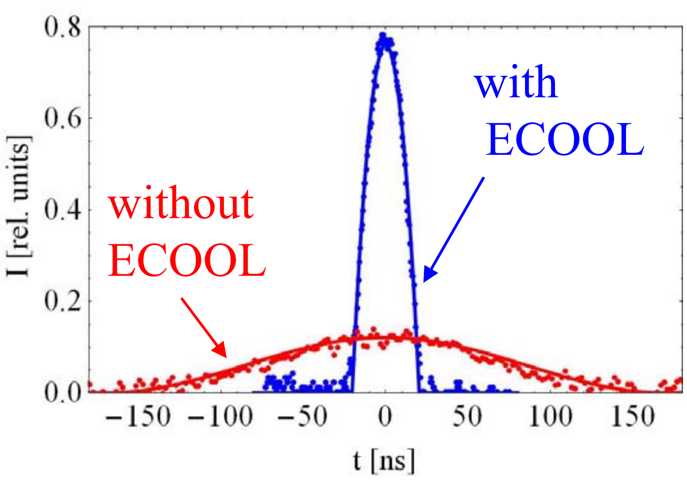
longitudinal phase space
damping of synchrotron oscillation



cooling force

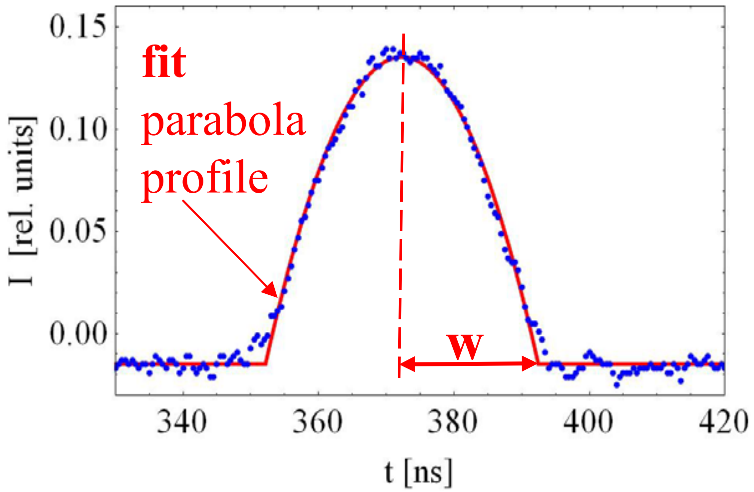


bunch profiles



Measured bunch profile with electron cooling

measured bunch profile



beam

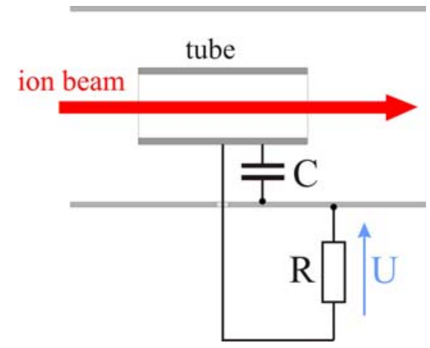
$^{12}C^{6+}$ E=50 MeV

I = 45 μA

U=795 V

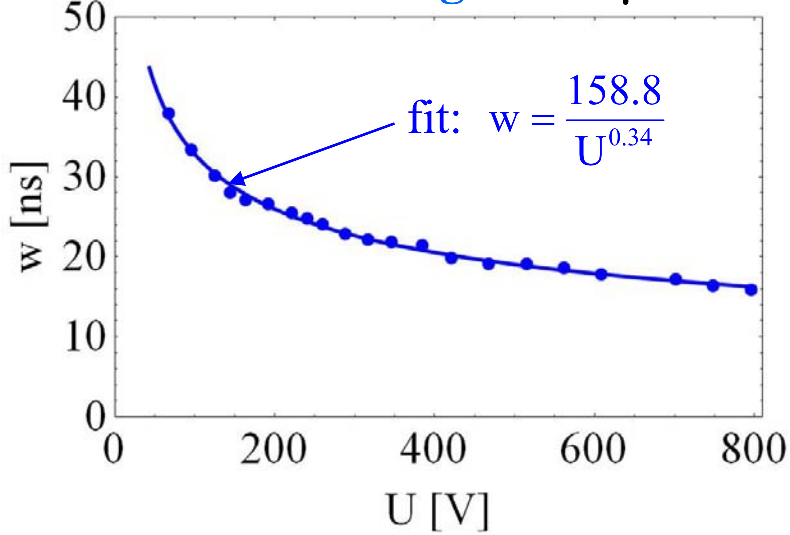
W = 20 ns

measurement with capacitive pick up

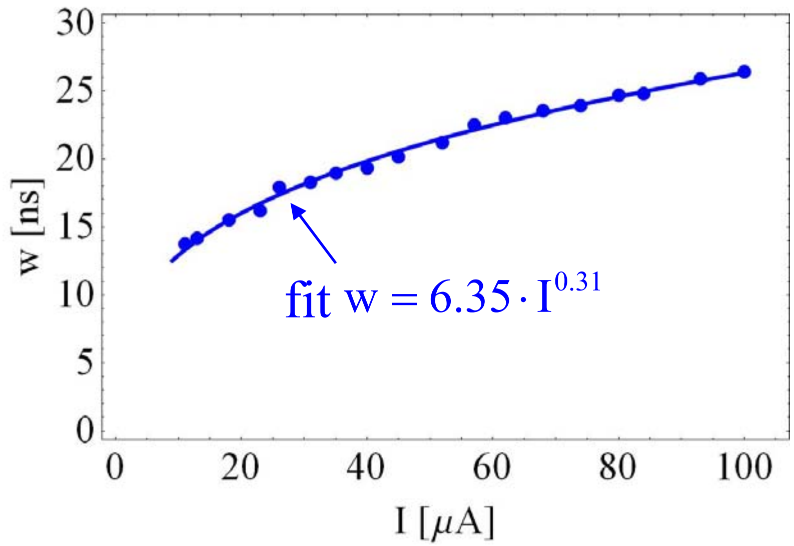


for R→∞: **U~I**

bunch length as a function of resonator voltage I=20 μA

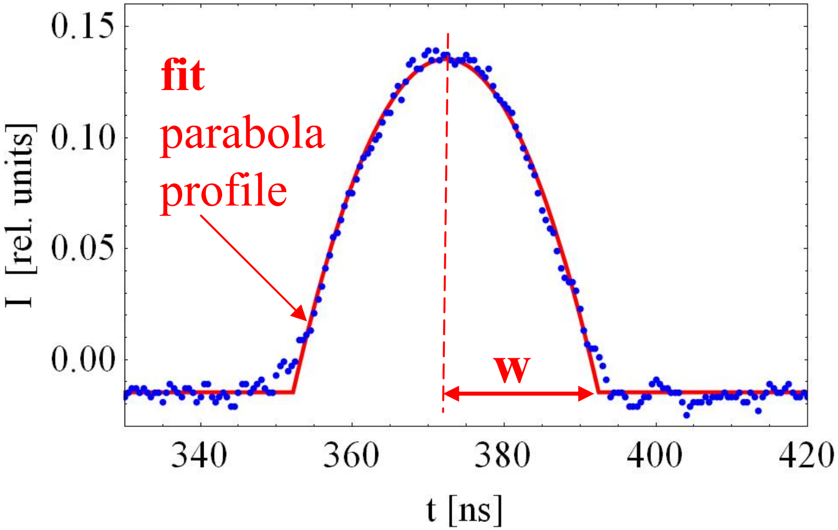


bunch length as a function of intensity U=795 V



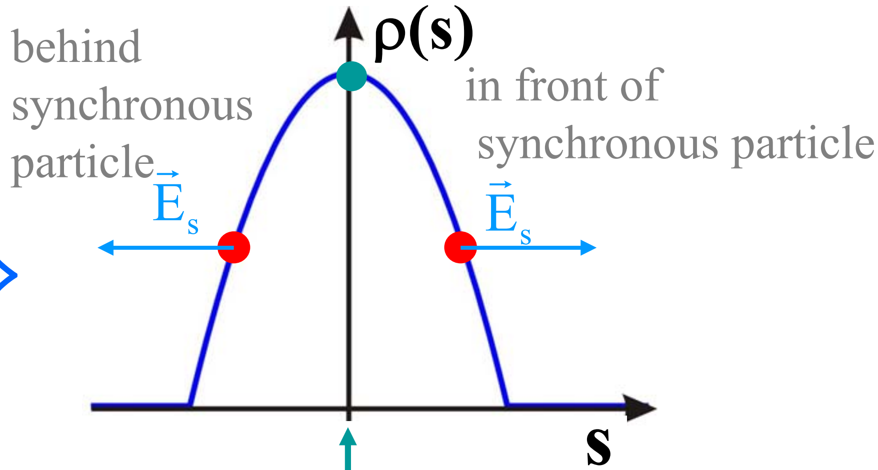
Space charge limitation of bunch length

bunch profile with electron cooling



$\Rightarrow$

space charge ion bunch



effective acceleration voltage:

$$U_{eff}(\Delta\phi) = U \cdot \sin(\Delta\phi + \phi_s) + U_s(\Delta\phi)$$

with $U_s(\Delta\phi) = E_s(\Delta\phi) \cdot C_0$ C_0 - circumference

space charge limit

at $\eta = \frac{\Delta f / f}{\Delta p / p} > 0$ $\mathbf{U_{eff}(\Delta\phi) = 0}$ $\Rightarrow$

$\phi_s = 0^0$

beam width at space charge limit

$$w = C_0 \frac{\sqrt[3]{3(1 + 2\ln(\frac{R}{r}))\, I}}{\sqrt[3]{2^4 \pi^2 c^4 \varepsilon_0 \gamma^2 h^2 \beta^4 U}}$$

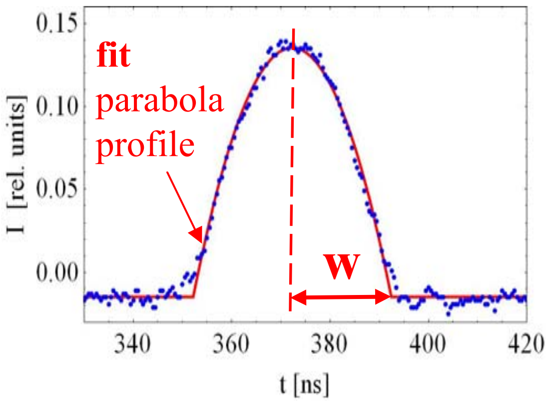
parabola profile

Space charge limitation comparison theory and measurements

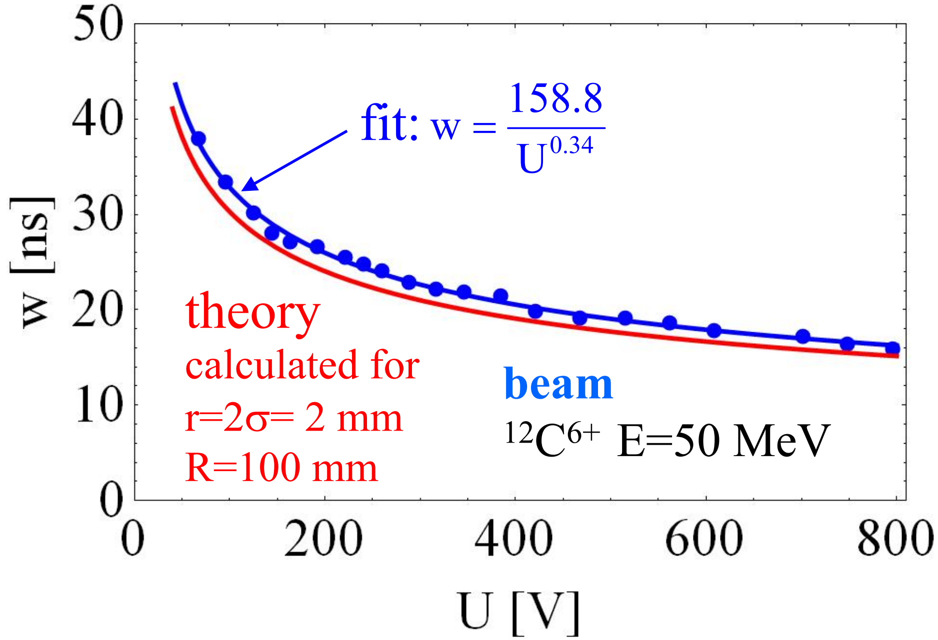
space charge limit:
parabola profile

$$w = C_0 \frac{\sqrt[3]{3\left(1+2\ln\left(\frac{R}{r}\right)\right) I}}{\sqrt[3]{2^4 \pi^2 c^4 \varepsilon_0 \gamma^2 h^2 \beta^4 U}}$$

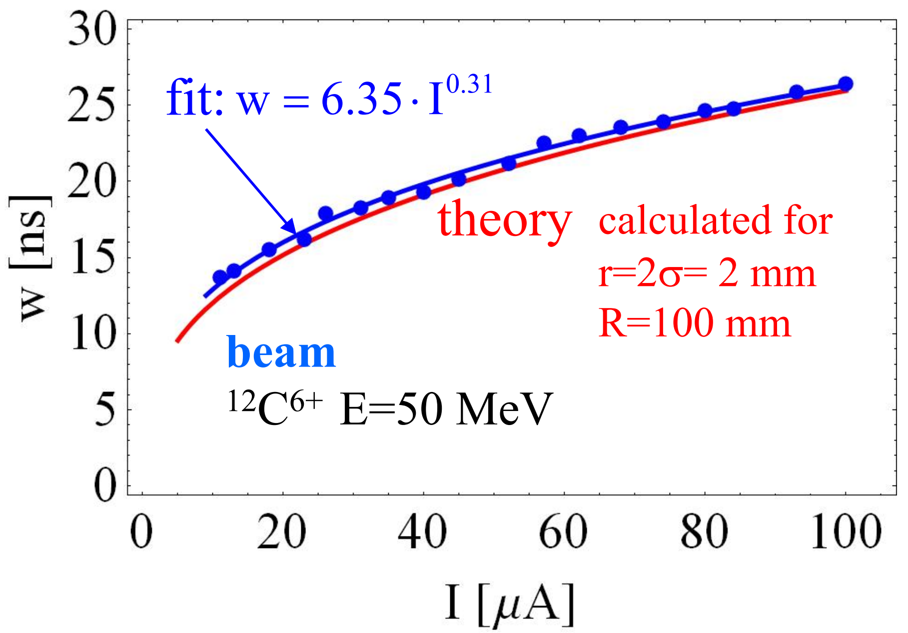
I – intensity, U - resonator voltage



bunch length as a function of resonator voltage U I=20 μA



bunch length as a function of intensity I U=795 V

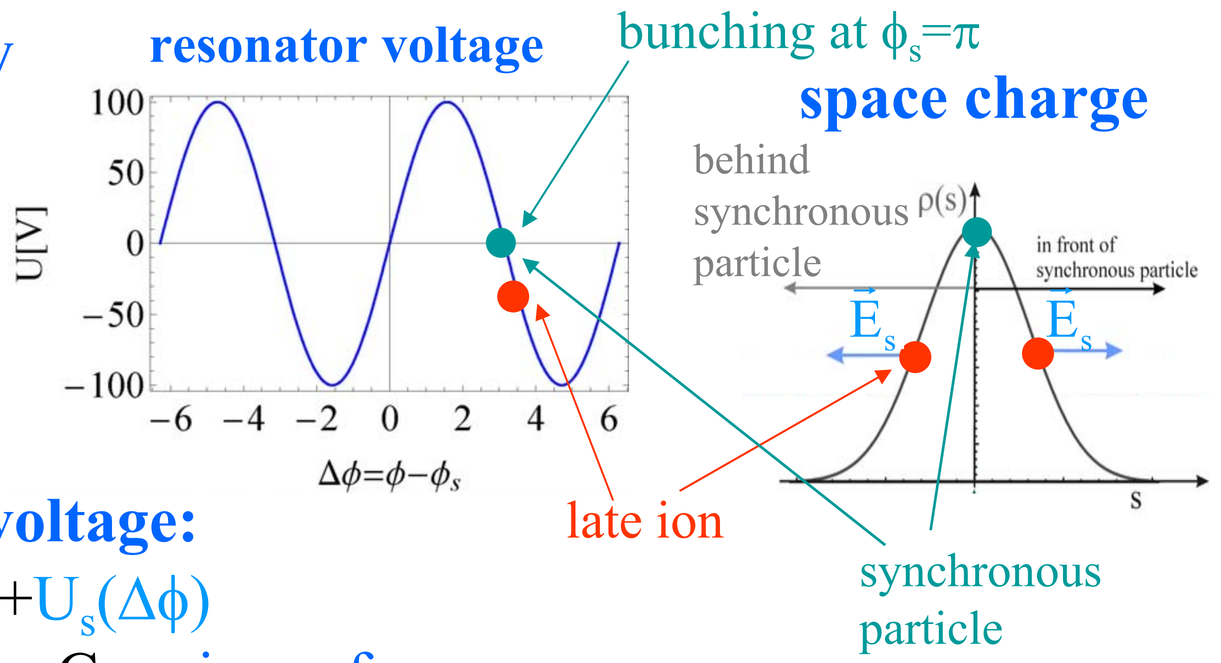


Operation of the storage ring at η<0 ring

f- revolution frequency

p- momentum

at $\eta = \dfrac{\Delta f / f}{\Delta p / p} < 0$



effective acceleration voltage:

$U_{eff}(\Delta\phi)=U\cdot \sin(\Delta\phi+\phi_s)+U_s(\Delta\phi)$

with $U_s(\Delta\phi)=E_s(\Delta\phi)\cdot C_0$ C_0 - circumference

at $\eta = \dfrac{\Delta f / f}{\Delta p / p} < 0$

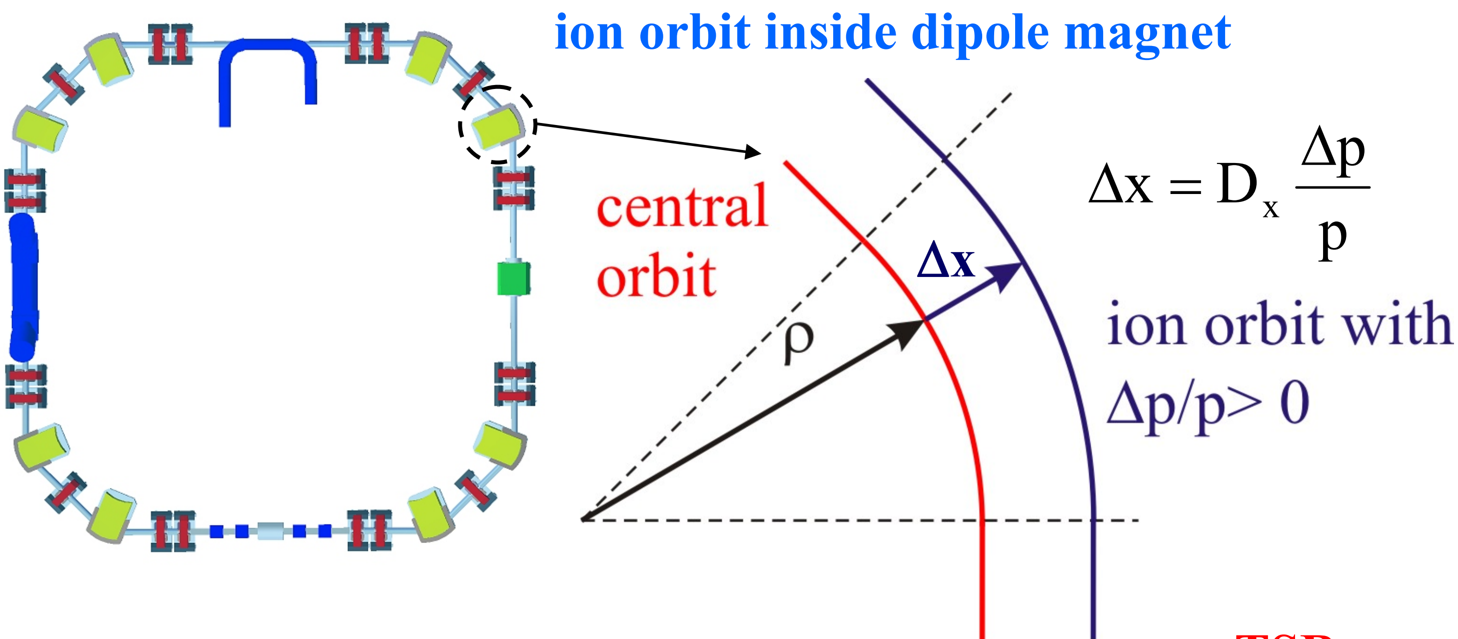
space charge voltage $U_s(\Delta\phi)$ doesn't compensate resonator voltage $U\cdot \sin(\Delta\phi+\pi)$,

no space charge limit at η<0 !!!!

⇒operation of the storage ring at η<0
to achieve smaller bunch length

The slip factor η of a storage ring

To get the η parameter negative the **orbit length of ions with positive momentum deviation has to increased** by increasing the dispersion $D_x(s)$ inside the dipole magnets



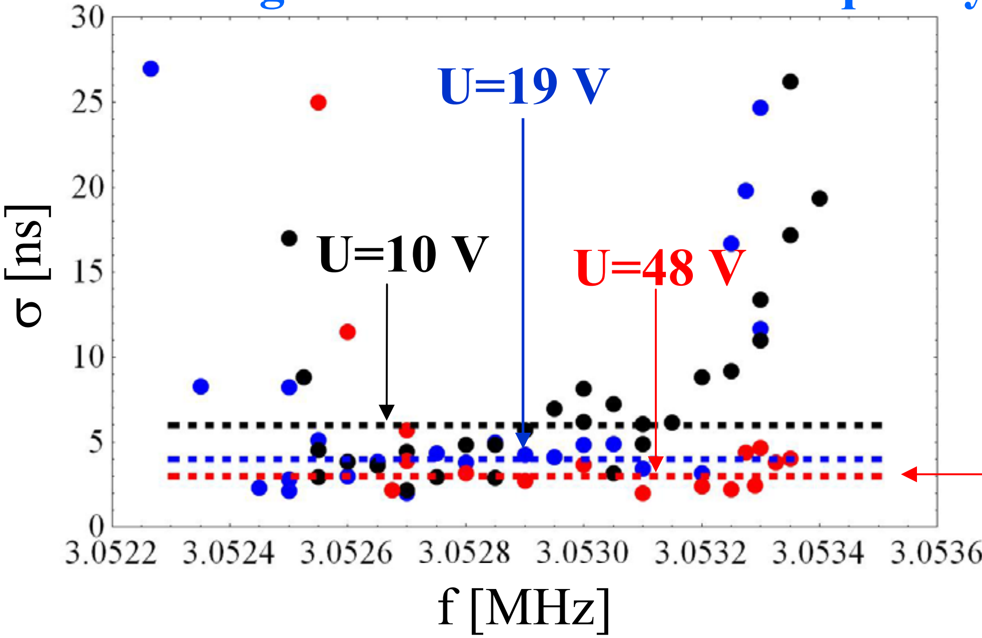
increasing of the orbit length degreases revolution frequency

$$\eta = \frac{\Delta f / f}{\Delta p / p} = \frac{1}{\gamma^2} - \alpha \quad \text{with} \quad \alpha = \frac{\Delta C_0 / C_0}{\Delta p / p} = \frac{\oint \frac{D_x(s)}{\rho(s)} ds}{C_0}$$

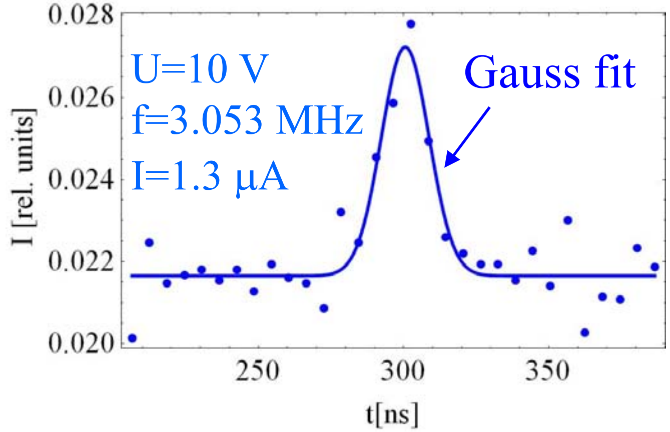
TSR
α=1.57
⇔ dipole: $\overline{D}_x = 13.8$ m
for
$^{12}C^{6+}$ E=50 MeV
η=-0.57

Measured bunch length at η=-0.57

bunch length as a function of rf frequency



measured profile



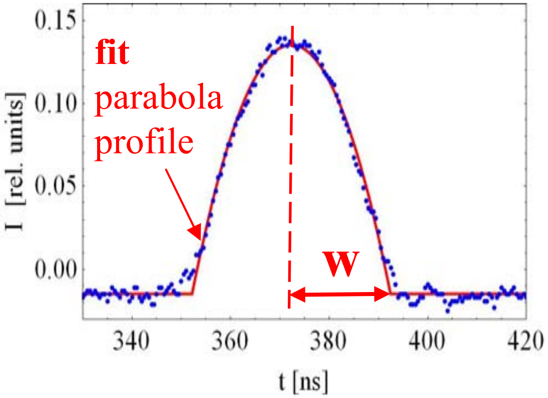
σ ≈ 3 ns

I ≈ 0.5-1.5 μA

beam
$^{12}C^{6+}$ E=50 MeV
h=6

comparison to the standard mode η=0.9

for $^{12}C^{6+}$ E=50 MeV and h=6 : $w(ns) = 62.115 \cdot \frac{I(\mu A)^{0.31}}{U(V)^{0.34}}$



a corresponding Gaussian distribution having the **same half width**: $\sigma_{cor} = 0.6 \cdot w$

⇒ for I=0.5 μA , U = 48 V : $\boldsymbol{\sigma_{cor} = 8}$ **ns**

⇒shorter bunch length (<u>factor 2.7</u>) are archived at η<0 for the same U an I compared to the standard mode with η>0