Cooling Activities at the TSR Storage Ring

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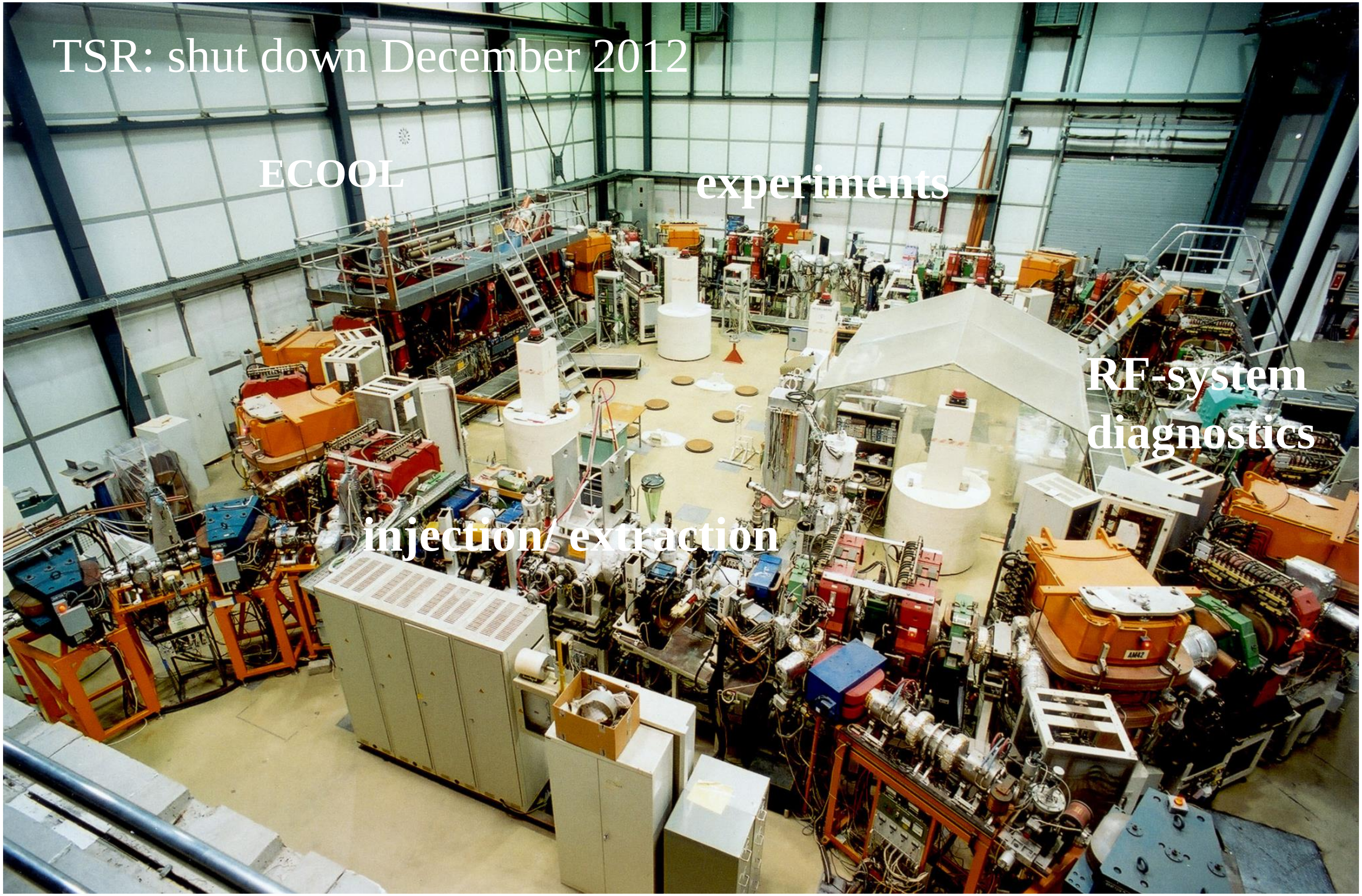
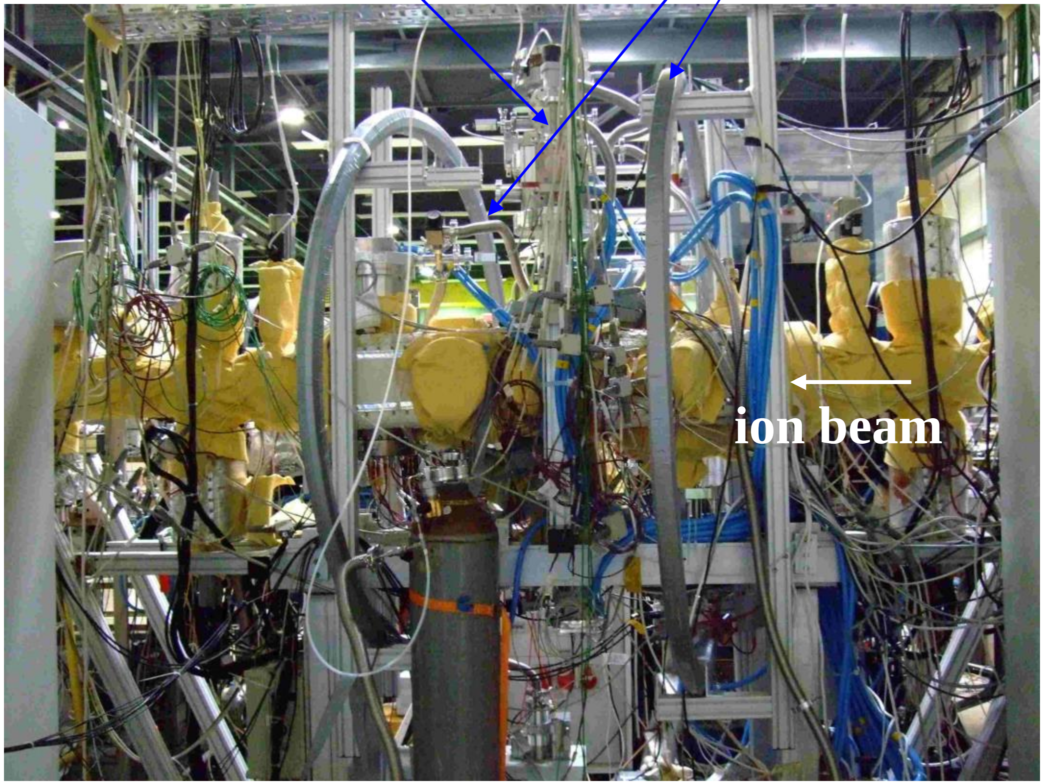
The TSR Storage Ring

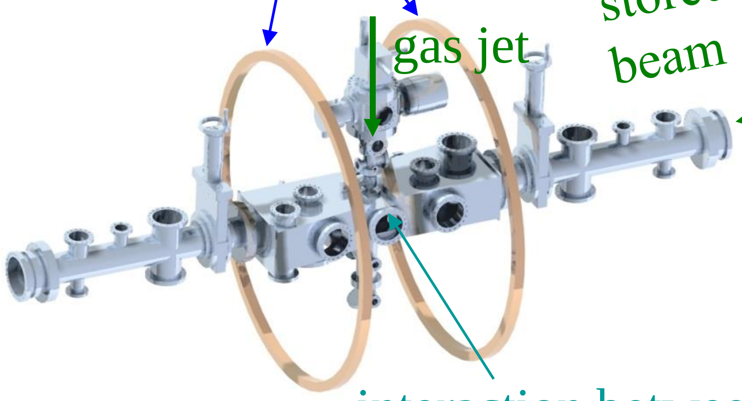


TSR experiments with a reaction microscope

reaction microscope

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

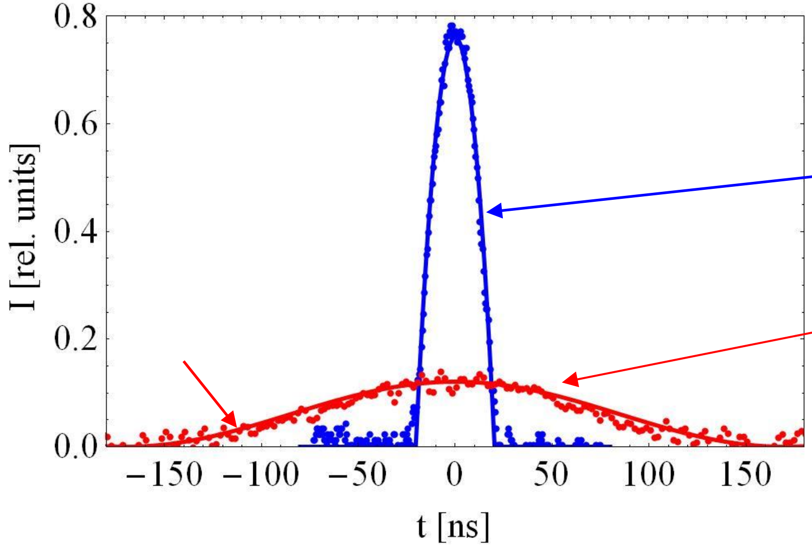




for some experiments **very short ion bunches are required**

⇒ investigation of short bunch creation at the TSR

Bunch length compression with electron cooling

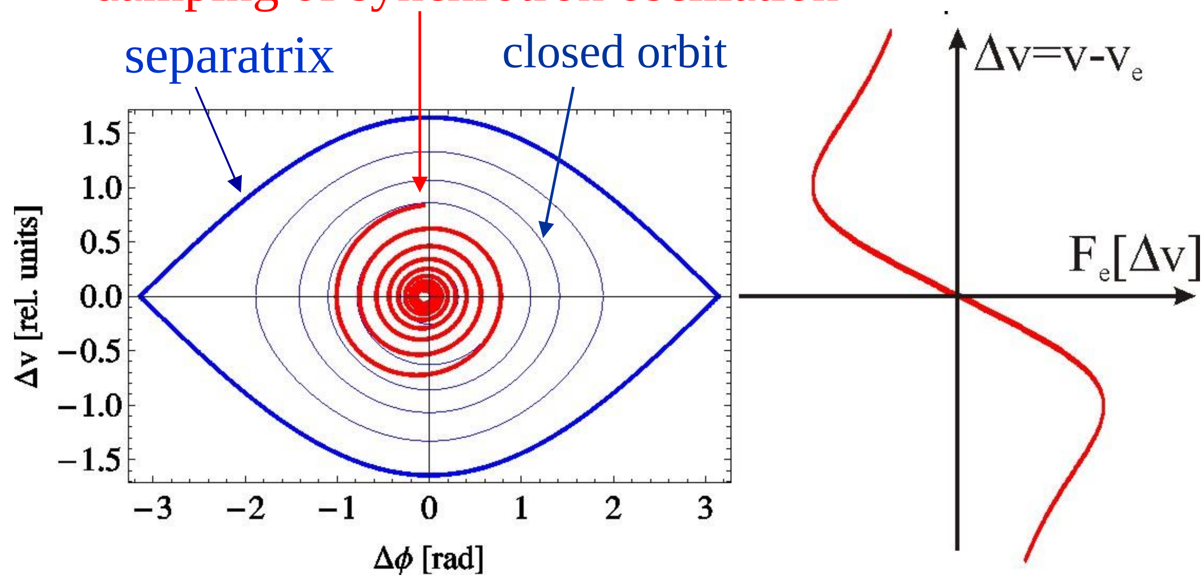


bunch profile before electron cooling

bunch profile before electron cooling

longitudinal phase space

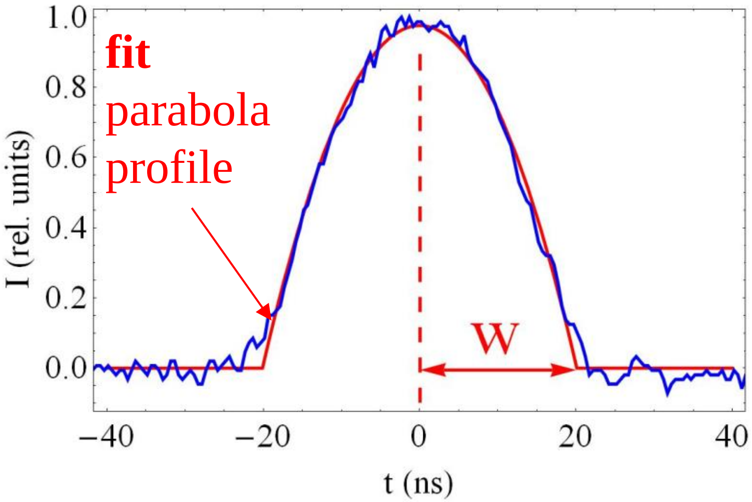
damping of synchrotron oscillation



electron cooling force

Measured bunch profile with electron cooling

measured bunch profile



beam

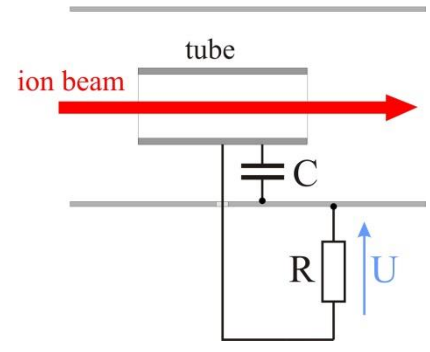
$^{12}C^{6+}$ E=50 MeV

I = 45 μA

U=795 V

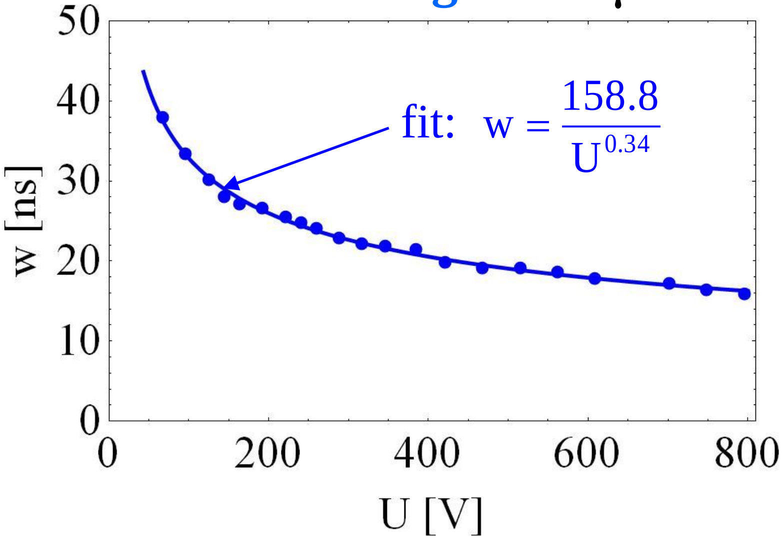
W = 20 ns

measurement with capacitive pick up

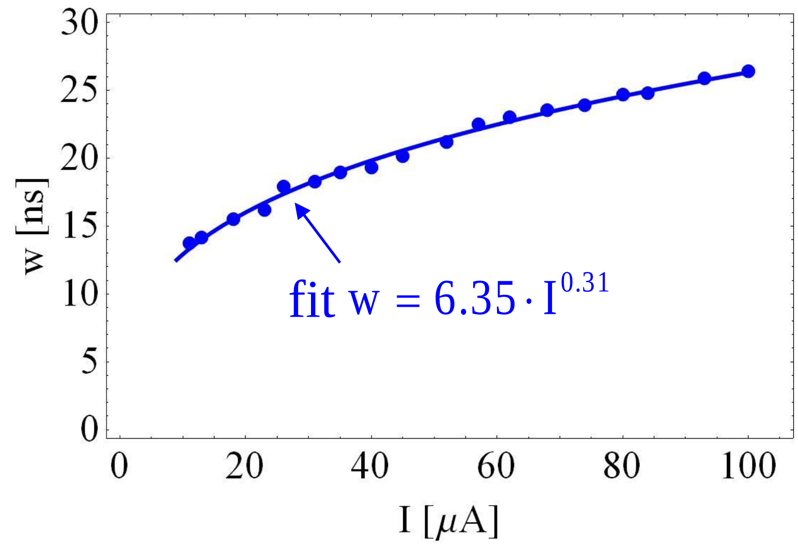


for R→∞: **U~I**

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

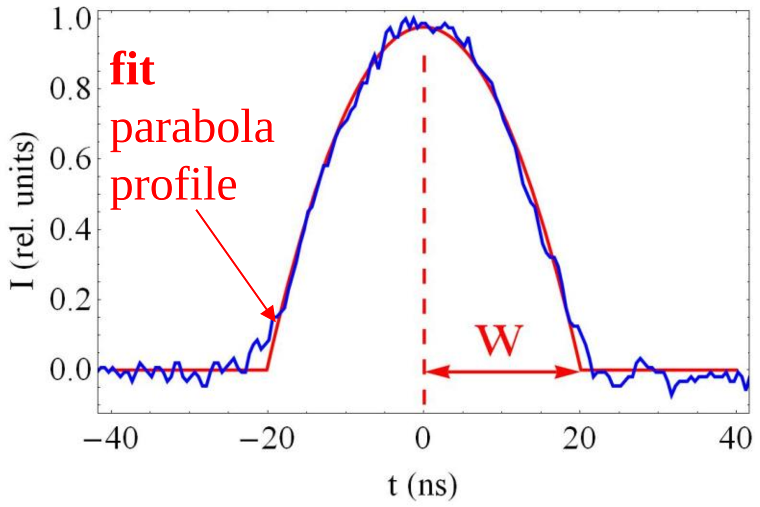


bunch length as a function of intensity **U=795 V**

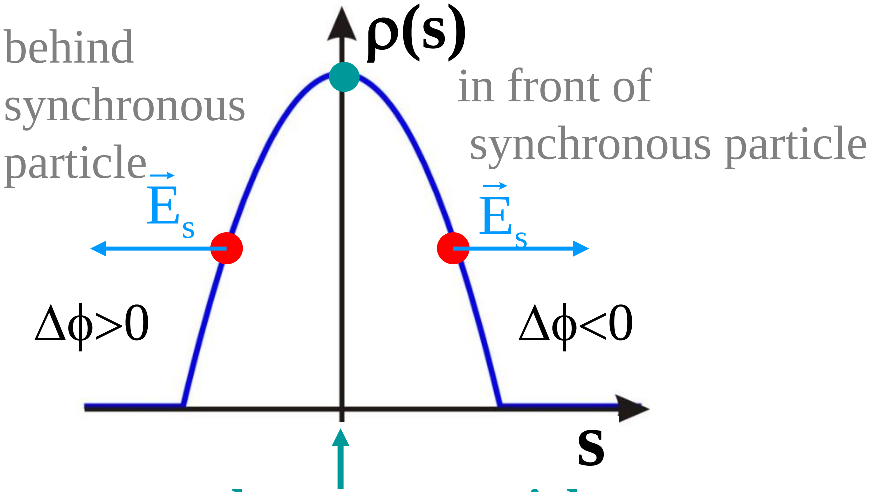


Space charge limitation of bunch length

bunch profile with electron cooling



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

beam width at space charge limit

space charge limit

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

$\phi_s = 0^0$

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

parabola profile

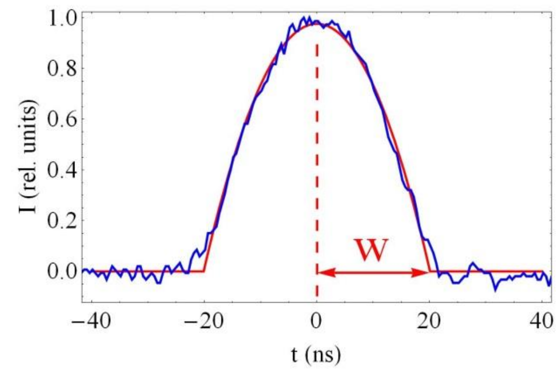
parabola profile: only distribution to compensate the synchrotron motion of each ion

Space charge limitation comparison theory and measurements

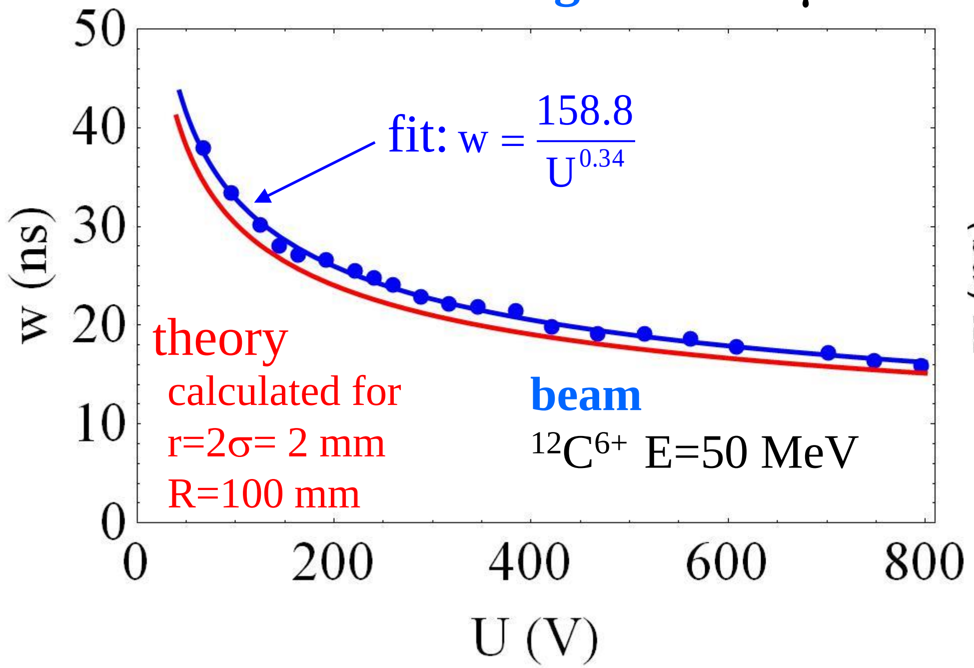
space charge limit:
parabola profile

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

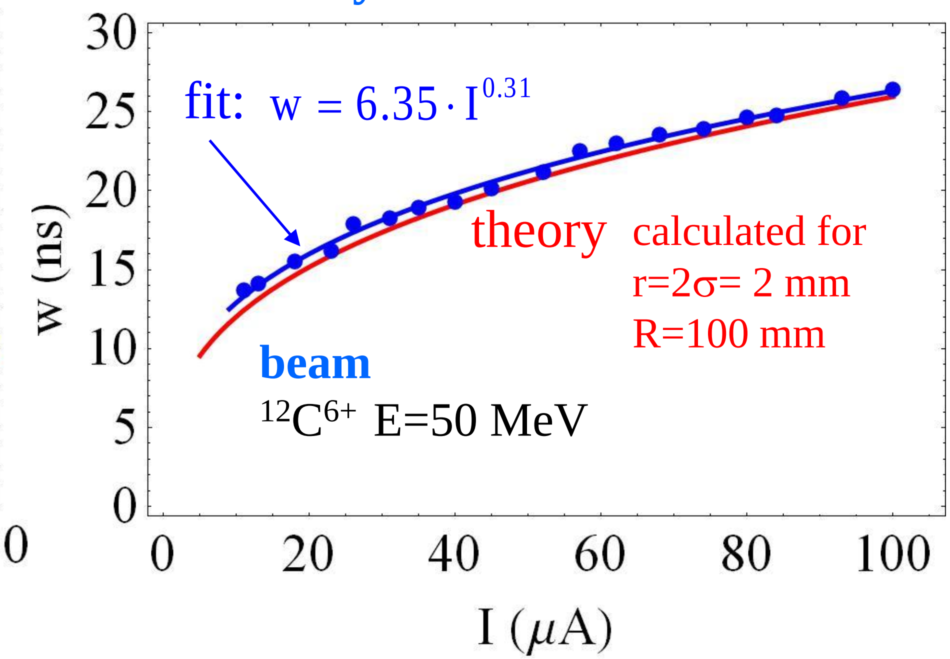
I – intensity, U - resonator voltage



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



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

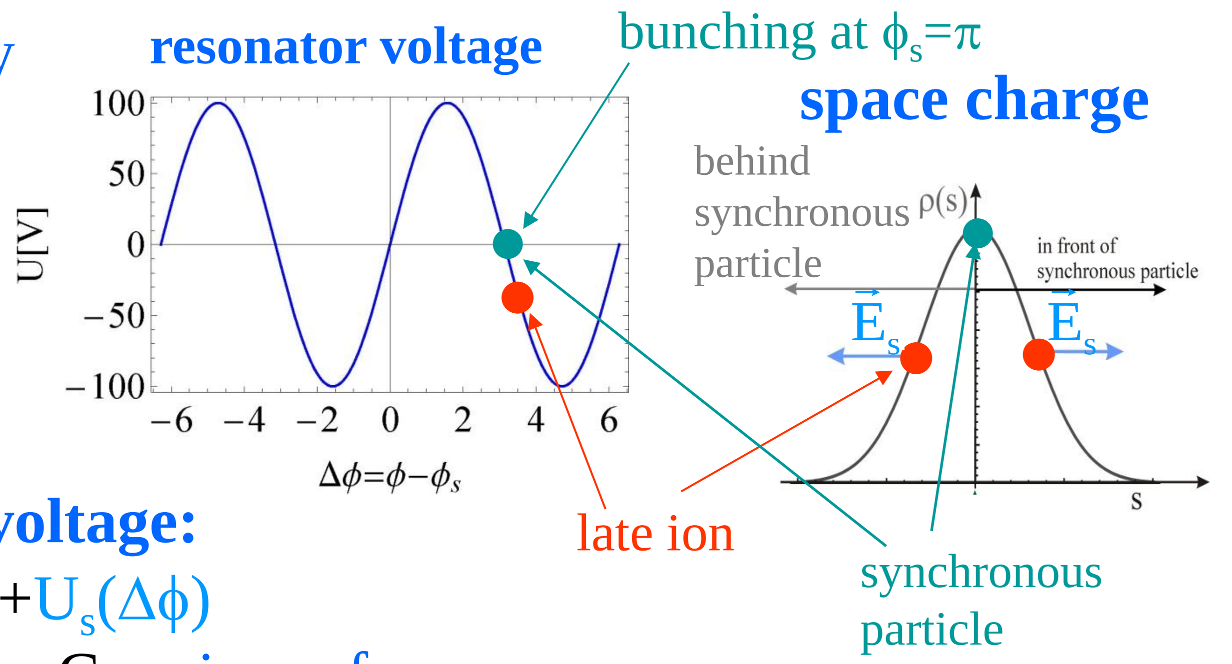


Operation of the storage ring at η<0 ring

f- revolution frequency

p- momentum

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



effective acceleration voltage:

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

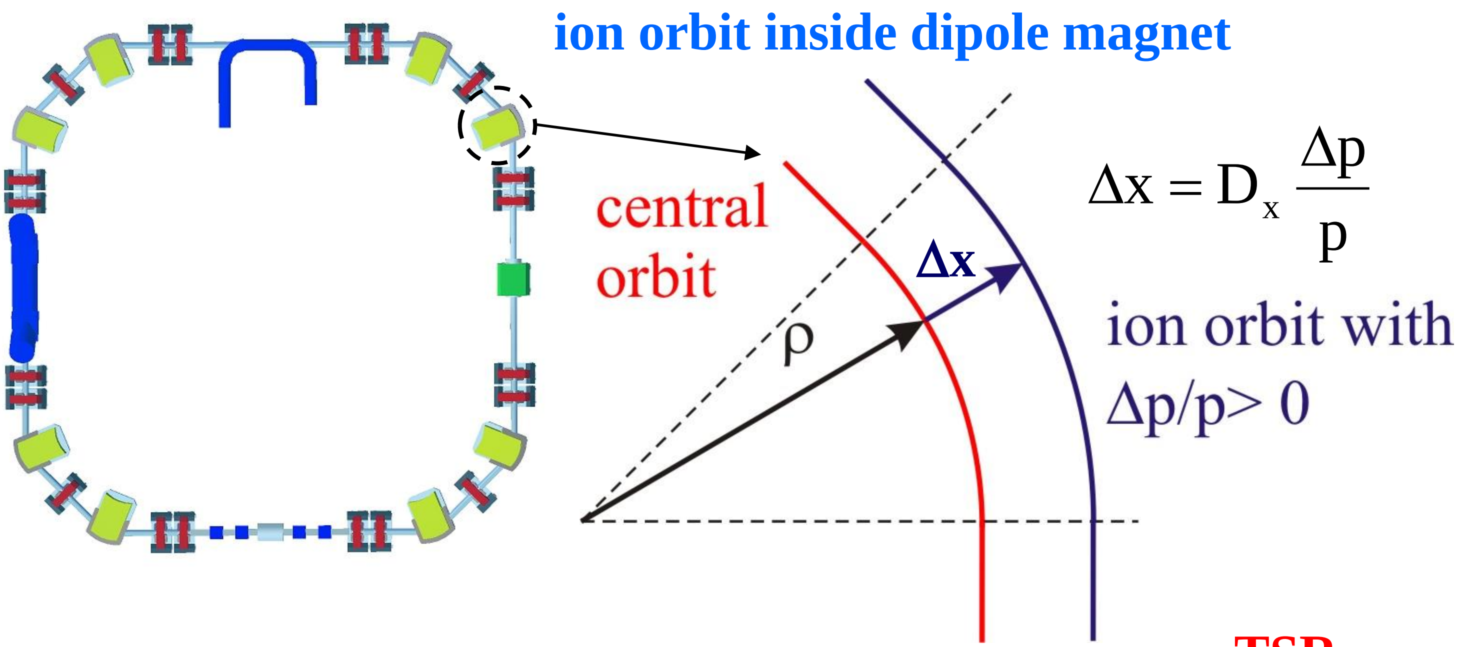
with $U_s(\Delta\phi)=E_s(\Delta\phi)\cdot C_0$ C_0 - circumference

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



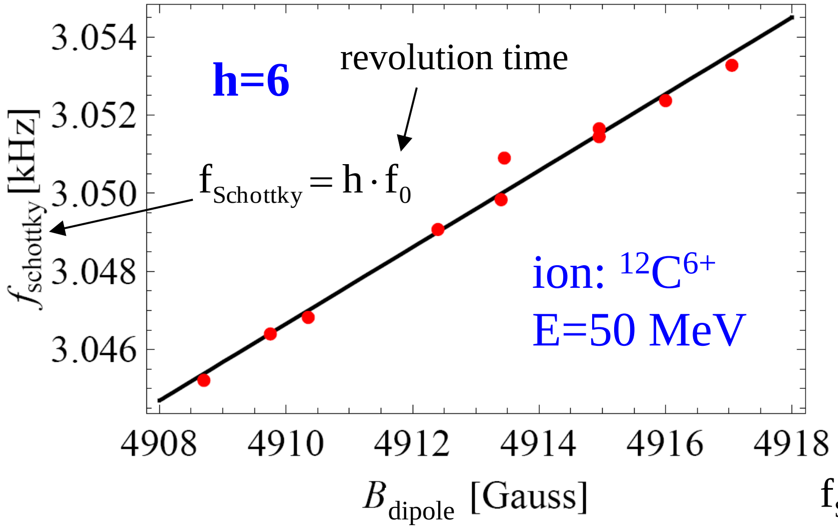
increasing of the orbit length degreases revolution frequency

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

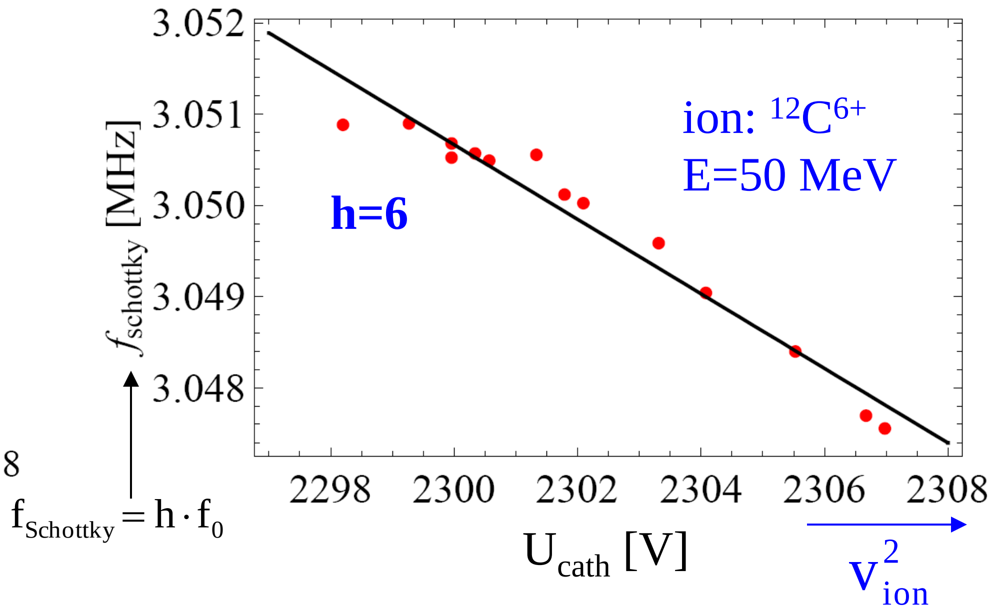
TSR
α=1.58
⇔ dipole: $\overline{D}_x = 14$ m
for
$^{12}C^{6+}$ E=50 MeV
η=-0.59

The slip factor of the TSR at negative η

Schottky frequency as a function of the magnetic field (main dipole)



Schottky frequency as a function of cathode voltage



measurement of γ_{tr}

$$\alpha = \frac{\Delta C / C}{\Delta p / p} = \frac{\Delta f_{Schottky} / f_{Schottky}}{\Delta B / B} \Rightarrow \alpha = 1.58$$

ion velocity constant — main dipole field

$$\Rightarrow \quad \eta = \frac{1}{\gamma^2} - \alpha = -0.59$$

average dispersion in the main dipole magnets

$\langle D_x \rangle = 14$ m

cathode voltage increases ion velocity

faster ion lower revolution frequency

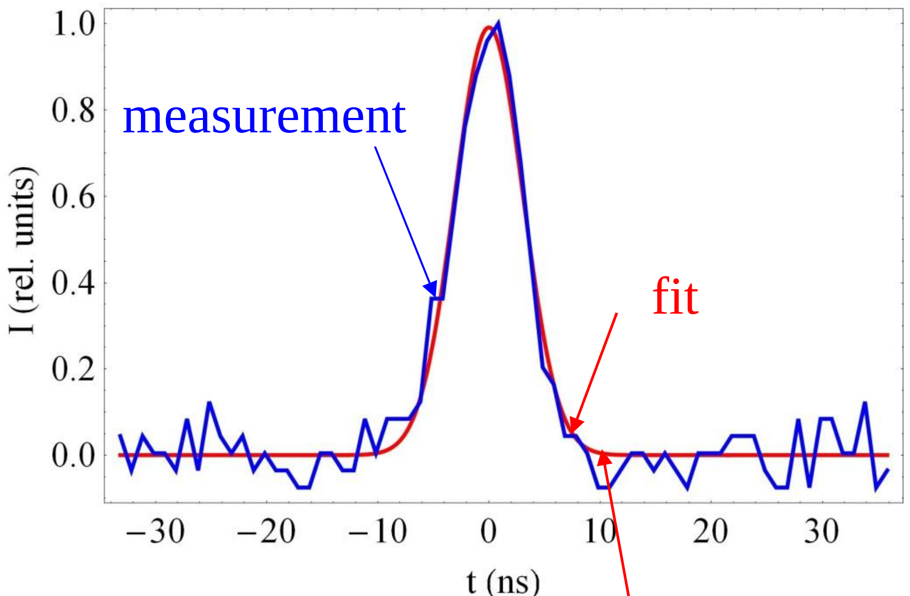
η is negative !!!

$$\eta = \frac{\Delta f_0 / f_0}{\Delta p / p} \approx 2 \cdot \frac{U_{cath}}{f_0} \frac{\Delta f_0}{\Delta U_{cath}} = -0.62$$

Electron cooled bunches at negative and positive η

slip factor: $\eta = \frac{\Delta f / f}{\Delta p / p}$ **beam:** $^{12}C^{6+}$ E=50 MeV

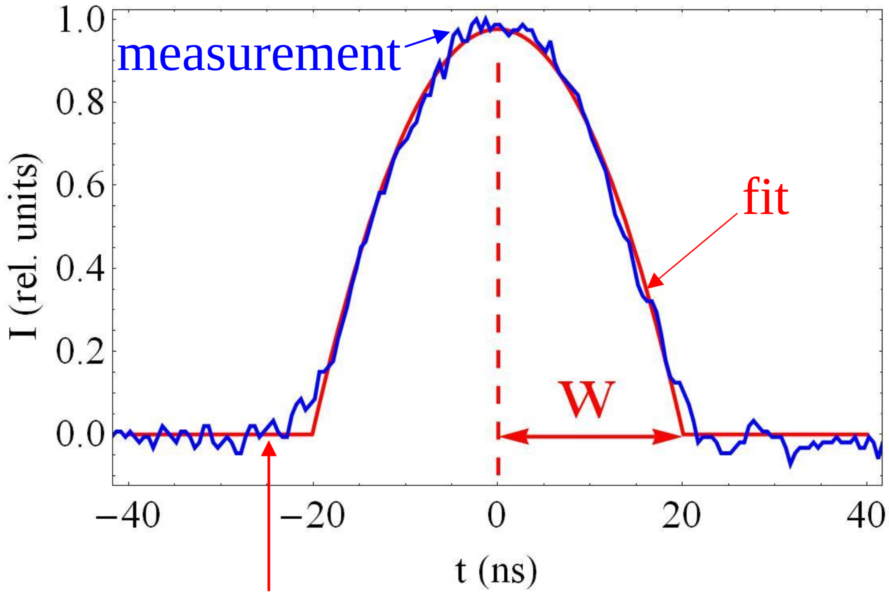
bunch length measured at η=-0.59



Gaussian distribution

I=2.9 μA
U=651 V

bunch length measured at standard mode η= 0.91



Parabola distribution

I= 45 μA
U=795 V

comparison: corresponding Gaussian bunch length σ* with same half width as parabola distribution: $\sigma^* = \frac{w}{2\sqrt{\ln(2)}} = 0.6 \cdot w$

Measured bunch length at η=-0.59

Comparison of measured bunch length at η=-0.59 and at the TSR standard-mode (η=0.91)

$U_0[V]$	$I_0[\mu A]$	$\sigma_{\eta<0}$ [ns]	σ^* [ns]	$\frac{\sigma^*}{\sigma_{\eta<0}}$
51	5.8	4.73	16.39	3.47
102	4.4	3.87	11.97	3.09
204	3.6	3.71	8.95	2.41
409	3.7	3.47	7.18	2.07
651	2.9	3.03	5.71	1.88

η=-0.59

corresponding bunch length at η=.91 with same half width:

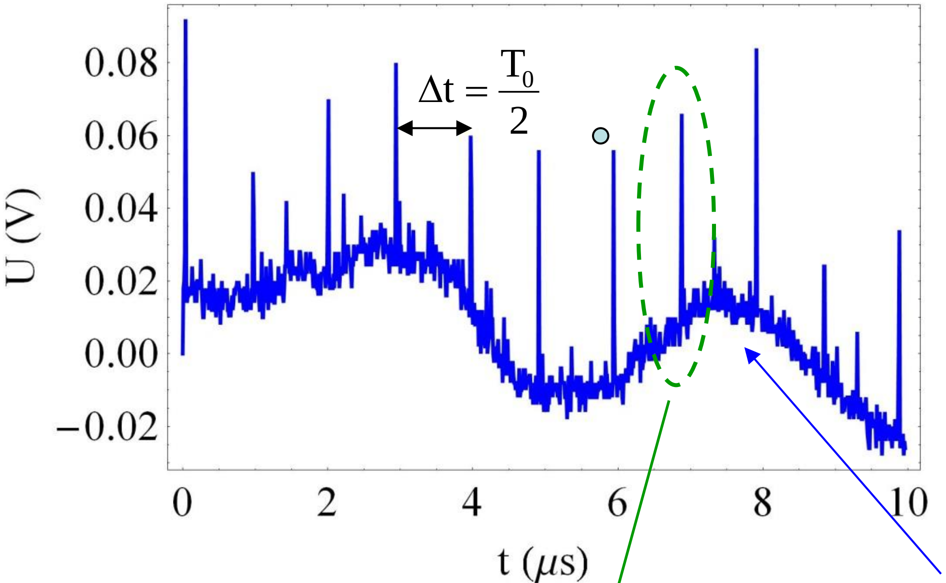
$$\sigma^* = 0.6 \cdot w$$

⇒ shorter bunch length (factor ≈ 2-3.5) are archived at η<0 for the same U an I compared to the standard mode with η>0

Self Bunching at $\eta<0$

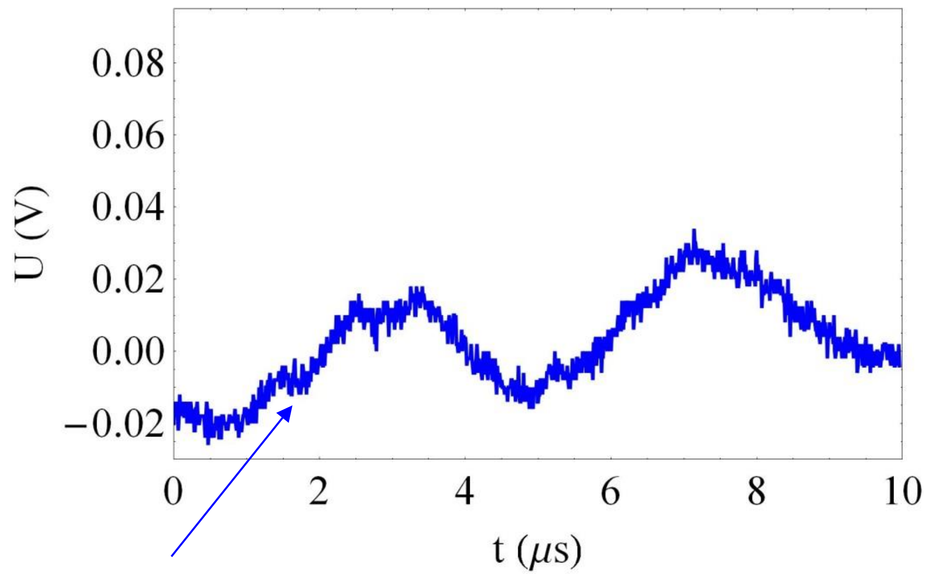
pick-up voltage

with beam, without rf U0=0, ECOOL on

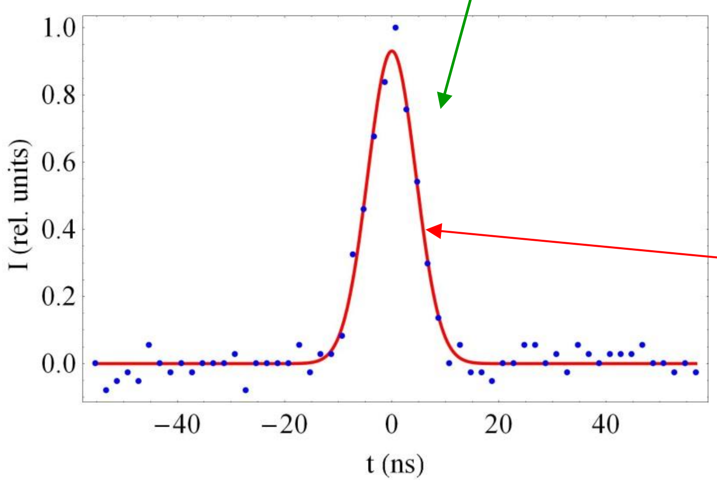


pick-up voltage

without beam, without rf, ECOOL on



disturbance



$I \approx 2\mu A$

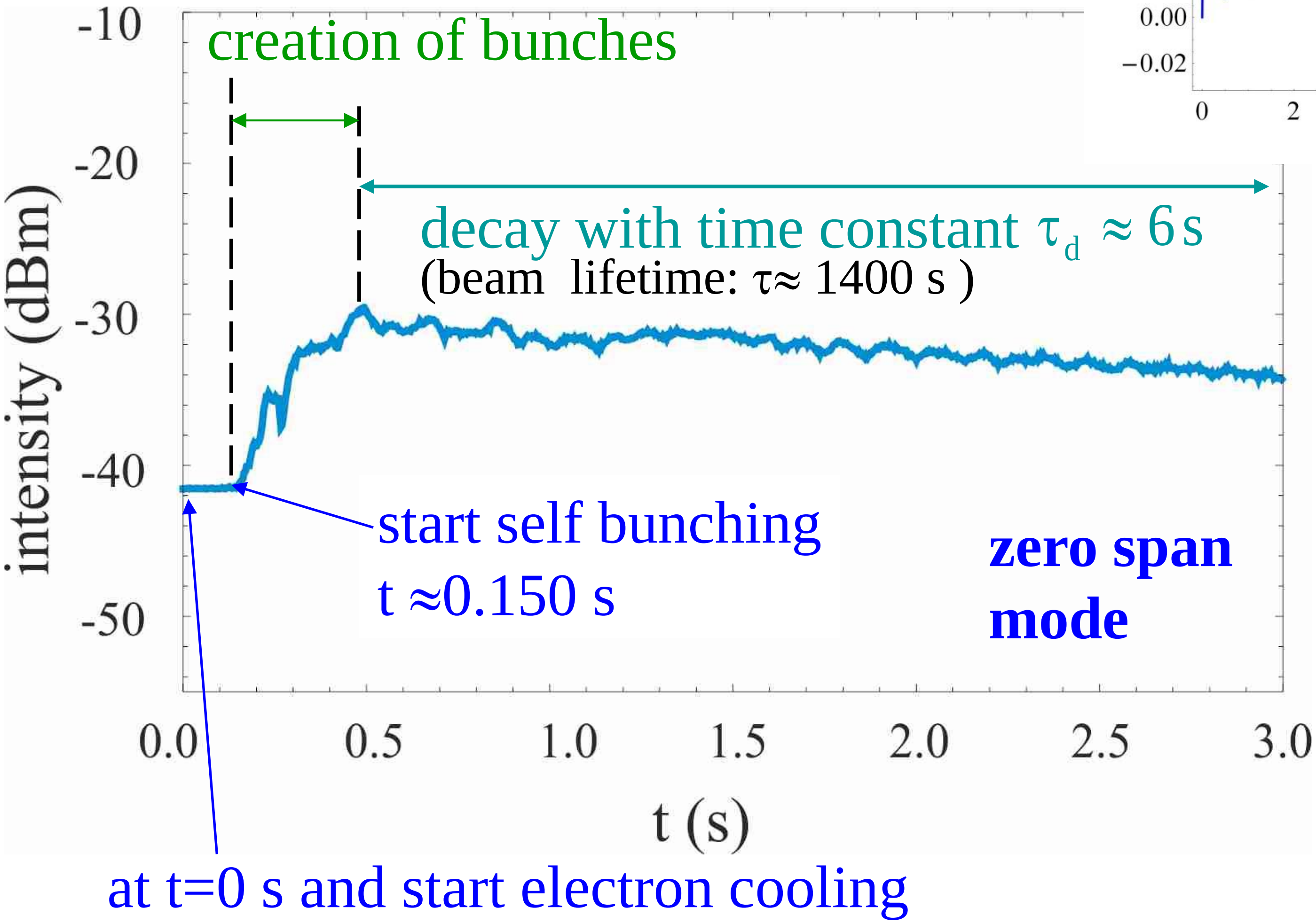
$\sigma = 4.5$ ns

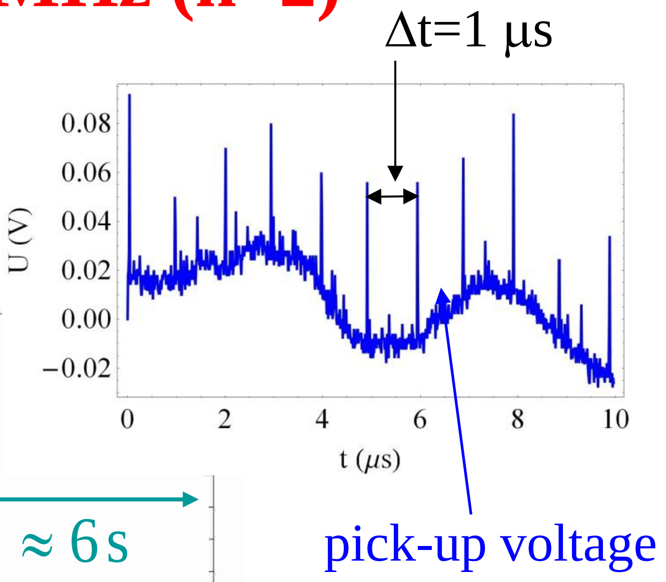
Gaussian Fit

beam: $^{12}C^{6+}$

E=50 MeV

Pick-up signal meaured at f=1 MHz (h=2) as a function of time



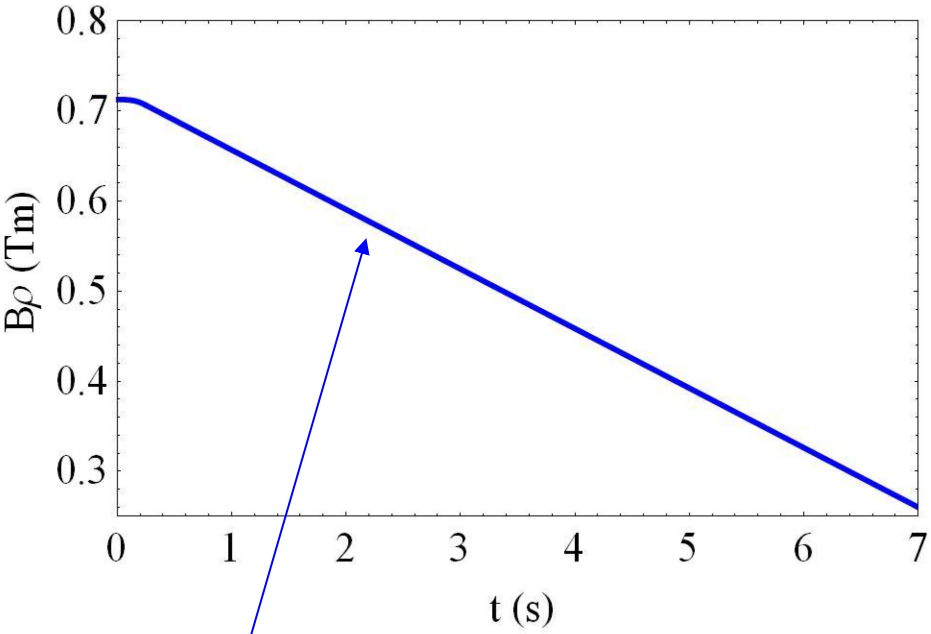


Deceleration of ion beams

demand of highly charged ions at low velocities for experiments with a reaction microscope

Example: deceleration of $^{12}C^{6+}$ ions: energy: 73.3 MeV → 9.7 MeV
B·ρ: 0.71 Tm → 0.26 Tm

beam rigidity as a function of time



declaration cycle:

increase of bunch length and beam size

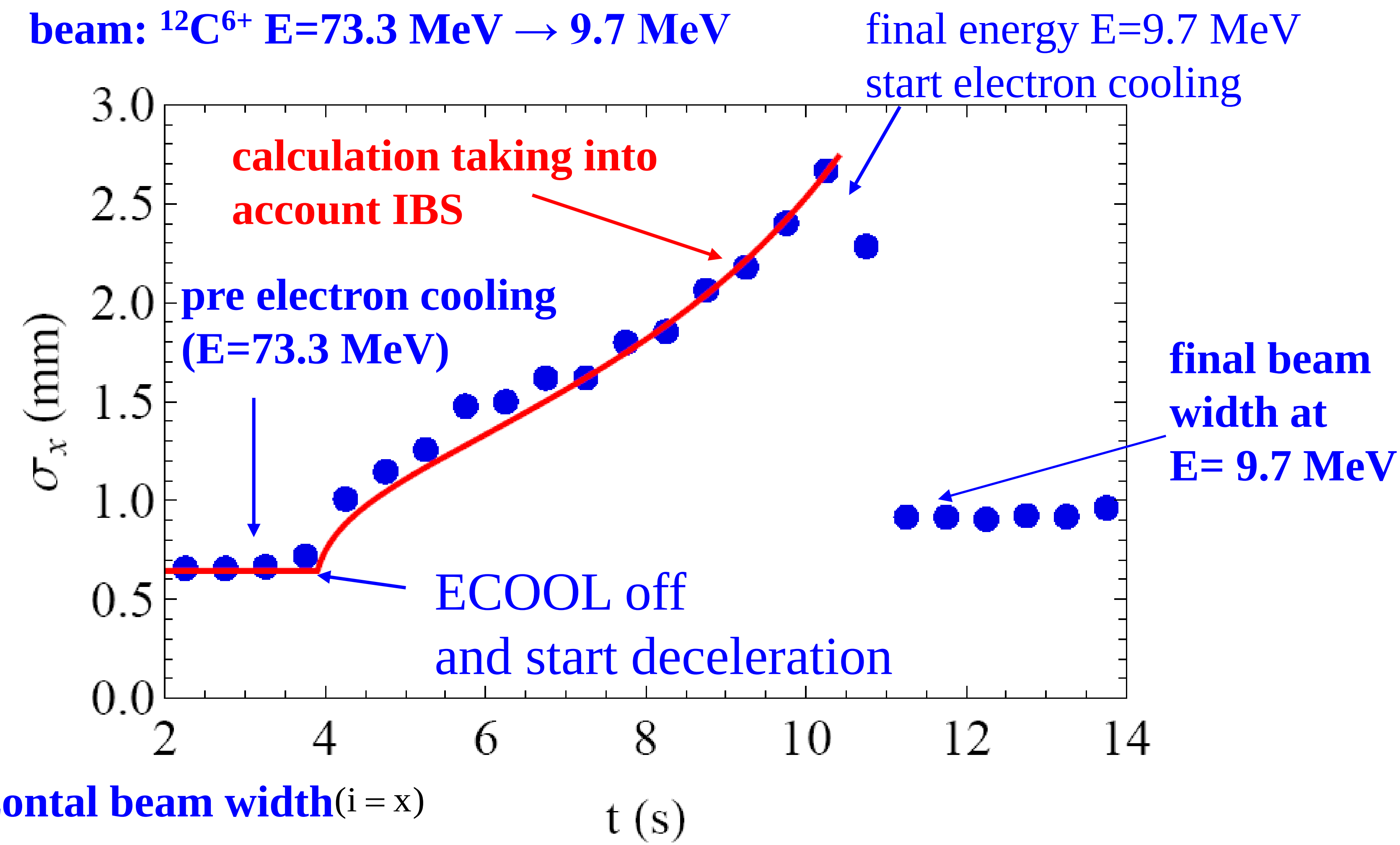
⇒ **two electron cooling steps:**

1. after injection before ramping
2. at the final energy to provide good beam quality for the experiment

almost linear decrease of beam rigidity and beam velocity

Horizontal beam σ_x beam width during deceleration

beam: $^{12}C^{6+}$ E=73.3 MeV → 9.7 MeV



horizontal beam width (i = x)

$$\sigma_i(t) = \left(\sigma_{i,0}^{\gamma} + \frac{\gamma \tilde{D}_i \left(\beta_0^{1-\kappa} - \beta(t)^{1-\kappa}\right)}{\alpha(\kappa - 1)}\right)^{\frac{1}{\gamma}} \sqrt{\frac{\beta_0}{\beta(t)}}$$ with $\beta(t) = \beta_0 + \alpha t$ and $\alpha = (\beta_f - \beta_0)/T$

heating term: $\tilde{D}_i \propto N \frac{q^4}{A^2}$

κ=3 γ= 5.9 (bunched beams)

IBS studies with $^{12}C^{6+}$ ions at the initial energy of 73.3 MeV

IBS rates: $$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = c_i \frac{q^4}{A^2}\frac{N}{\beta^3}\frac{1}{\varepsilon_x \varepsilon_y \Delta p/p \cdot h \cdot l_{eff}}$$ i=x,y,Δp/p

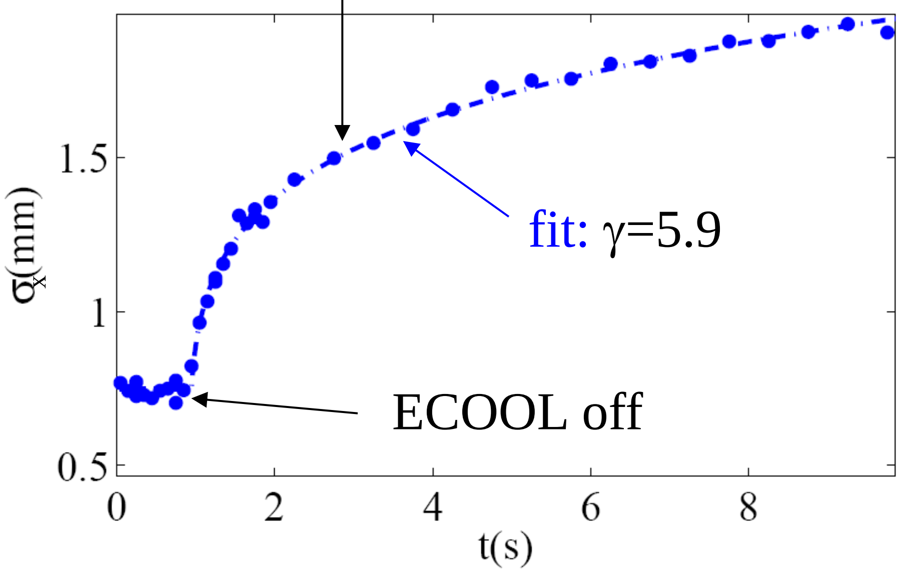
if in the IBS process starting from the equilibrium between cooling and IBS:

$\sigma_x \sim \sigma_y \sim \Delta p/p \sim l_{eff}$ ← effective bunch length

then we get: $$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = \frac{1}{\beta^\kappa}\frac{\tilde{D}_i}{\sigma_i^\gamma}$$ for a bunched beam, where γ≈6, κ≈3 $\tilde{D}_i \sim \frac{q^4}{A^2}\frac{N}{h}$

solution for ß is constant: $$\sigma_i(t) = \left(\sigma_{i,0}^\gamma + \gamma \frac{\tilde{D}_i}{\beta^\kappa} t\right)^{\frac{1}{\gamma}}$$

horizontal beam width



IBS measurement at TSR

E=73.3 MeV

bunching at h=6

I=50 μA

Beam width during deceleration

beam with due to IBS at a constant velocity: $\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = \frac{1}{\beta^{\kappa}}\frac{\tilde{D}_i}{\sigma_i^{\gamma}}$

$\tilde{D}_i \sim \frac{q^4}{A^2}\frac{N}{h}$

determined at initial energy for particle number N

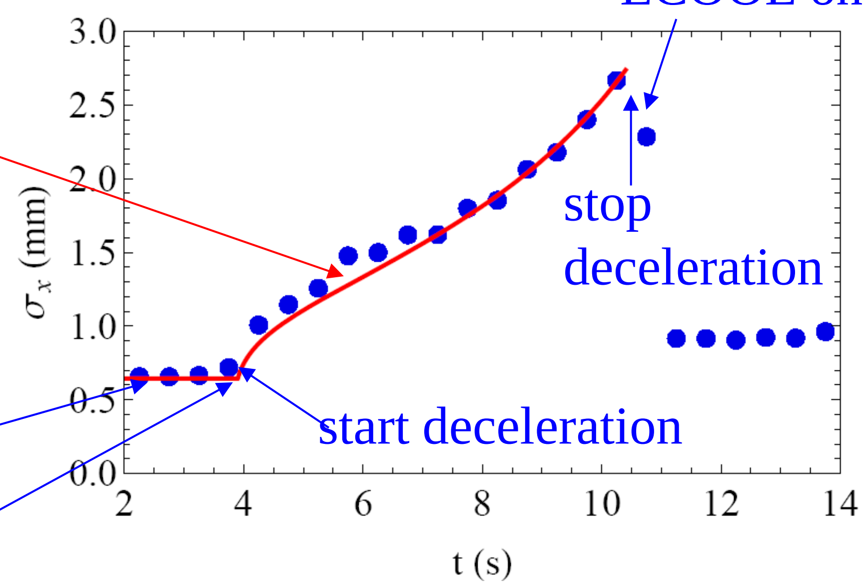
in the deceleration process: $\beta(t) = ß_0 + \alpha \cdot t$ $\quad ß_0$ initial velocity

$\Rightarrow$ beam width during deceleration:

$$\sigma_i(t) = \sqrt{\frac{\beta_0}{\beta(t)}}\left(\sigma_{i,0}^{\gamma} + \frac{\gamma \tilde{D}_i(\beta_0^{1-\kappa} - \beta(t)^{1-\kappa})}{\alpha(\kappa - 1)}\right)^{\frac{1}{\gamma}}$$

$\kappa \approx 3$

change of the beam size due to Lioville



calculated beam width during deceleration with κ=3

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