Overview of the Heavy Ion Storage Ring TSR

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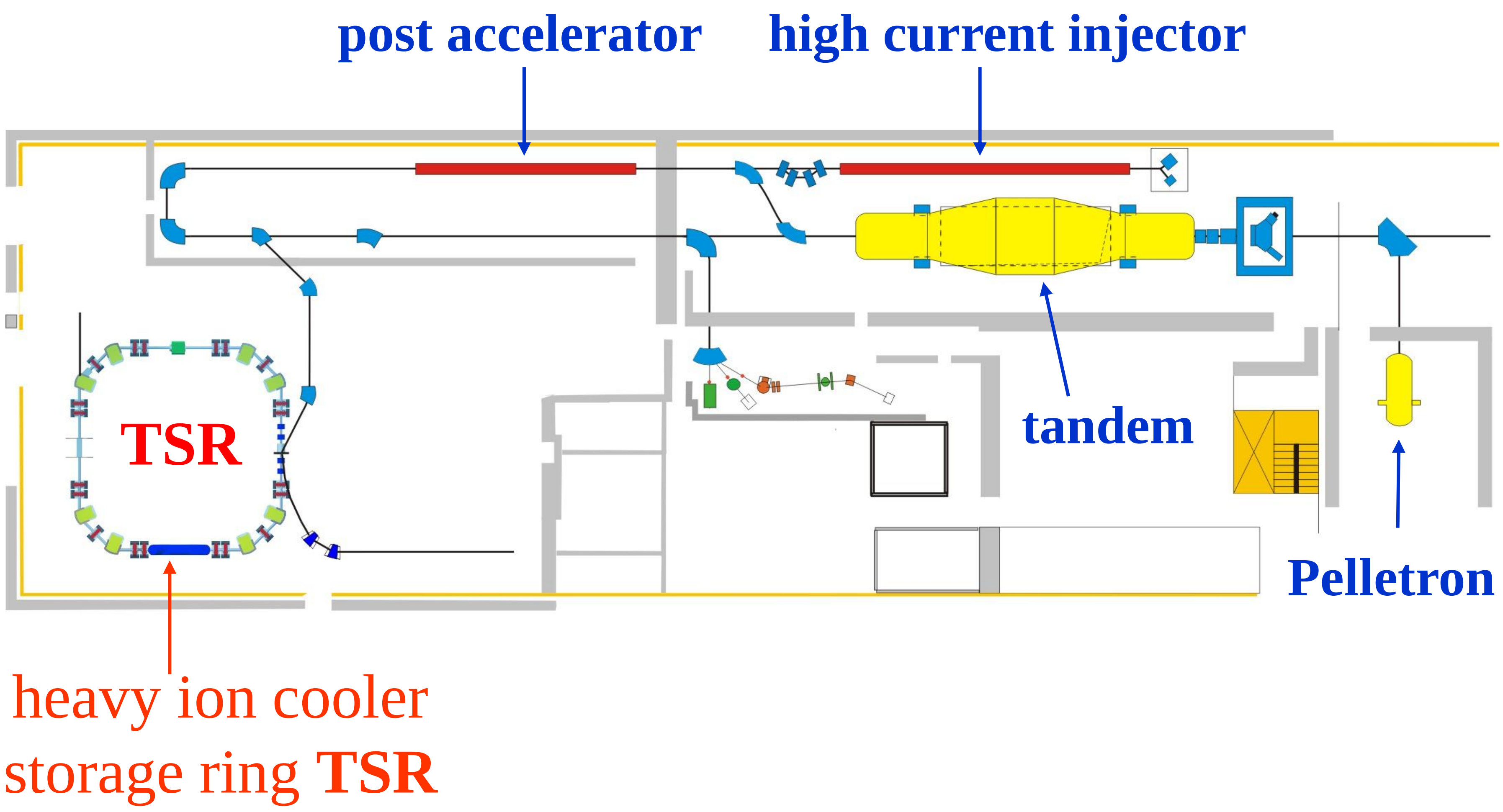
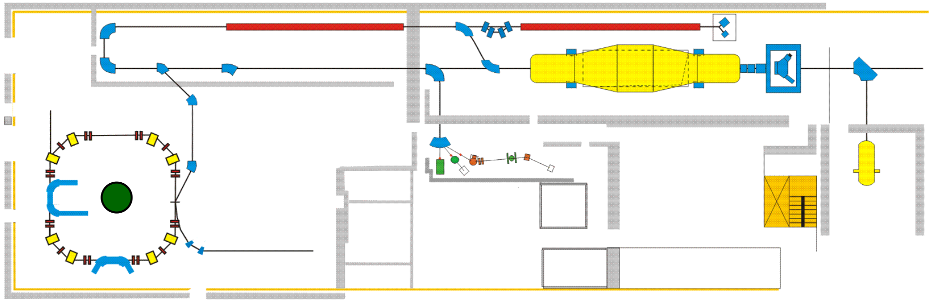
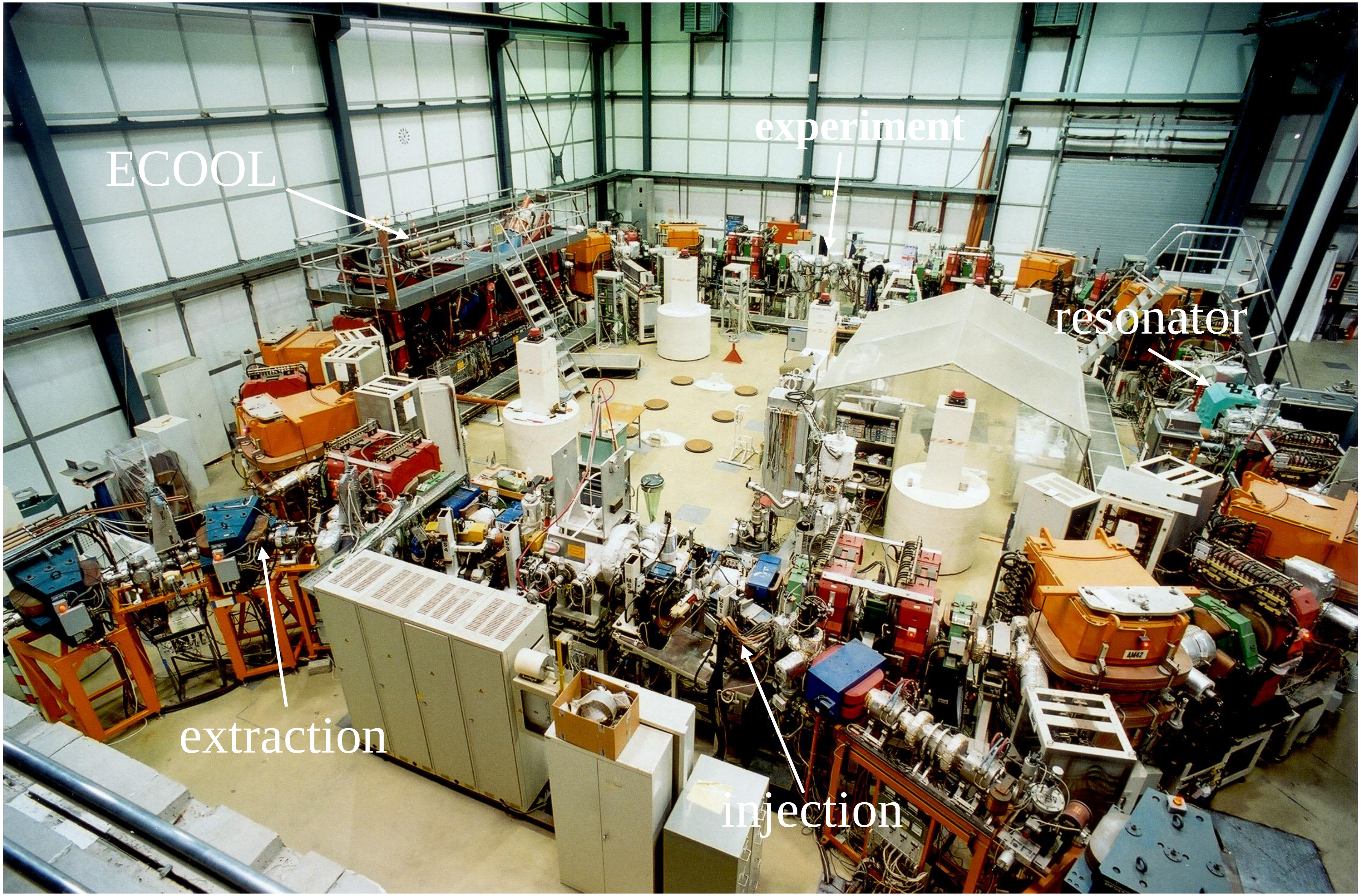
TSR@ISOLDE Workshop, CERN, 29-30 October 2012

The accelerator facilities at MPIK





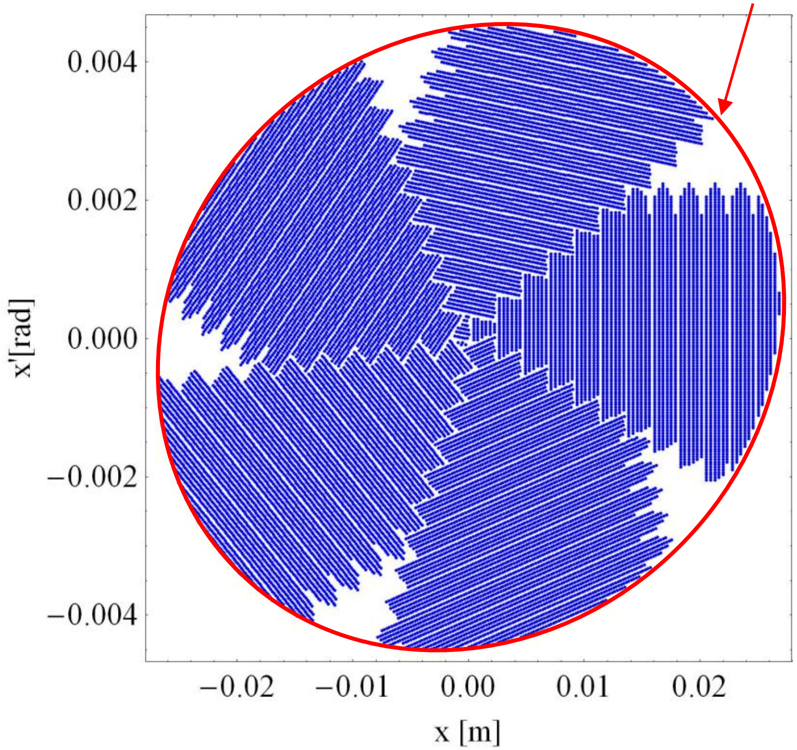
The heavy ion storage ring TSR



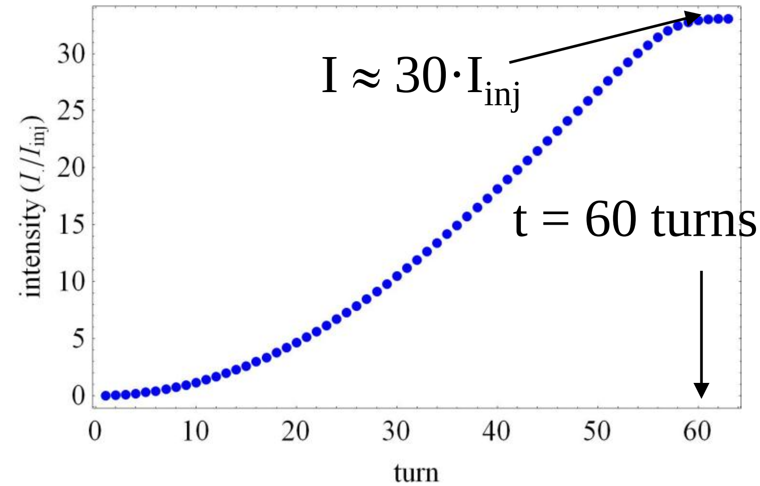
Multiturn injection at TSR@Isolde

transverse phase space

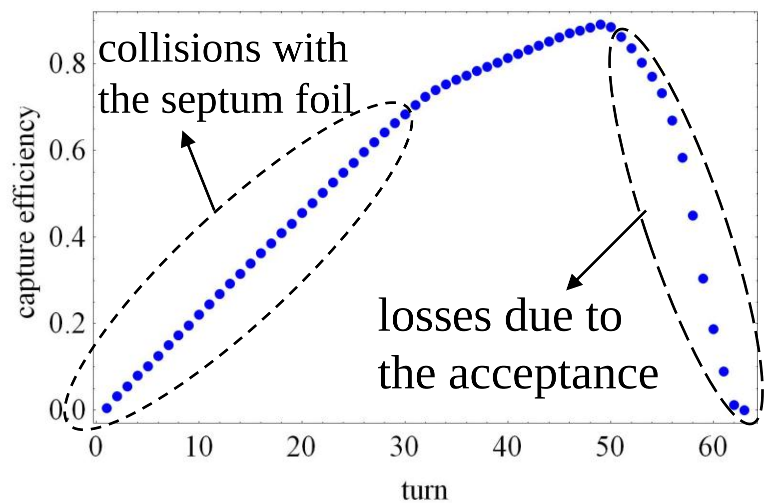
acceptance
A=120 mm·mrad



intensity increase



capture efficiency



Q_x=2.8
ε= 4
mm·mrad

Hie Isolde beam typically emittance at 10 MeV/u

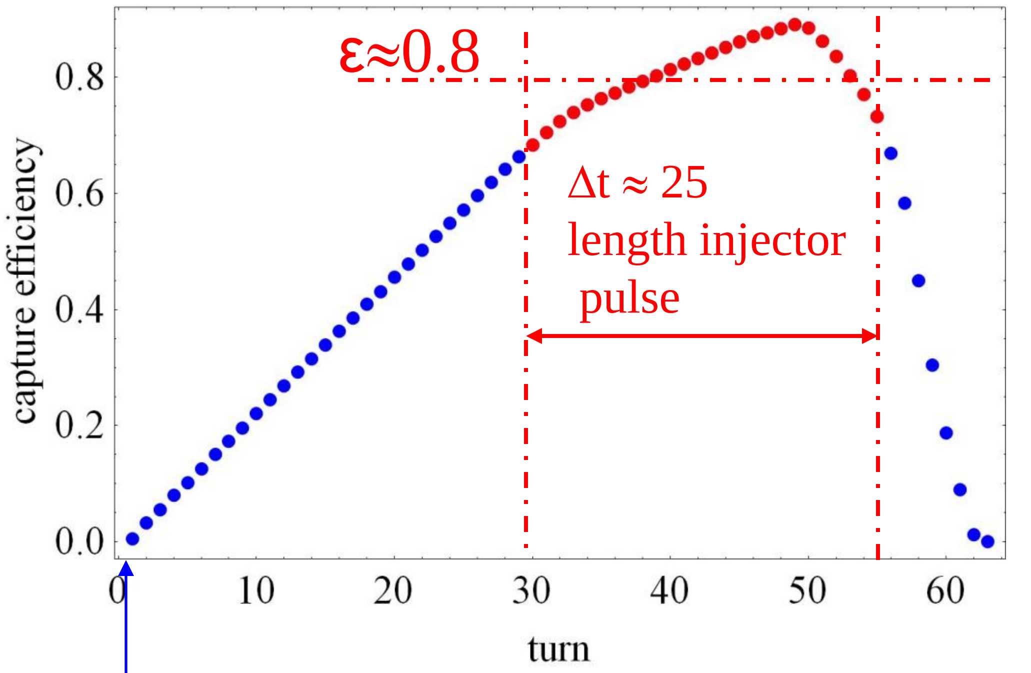
intensity increase:

$I \approx 30 \cdot I_{inj}$

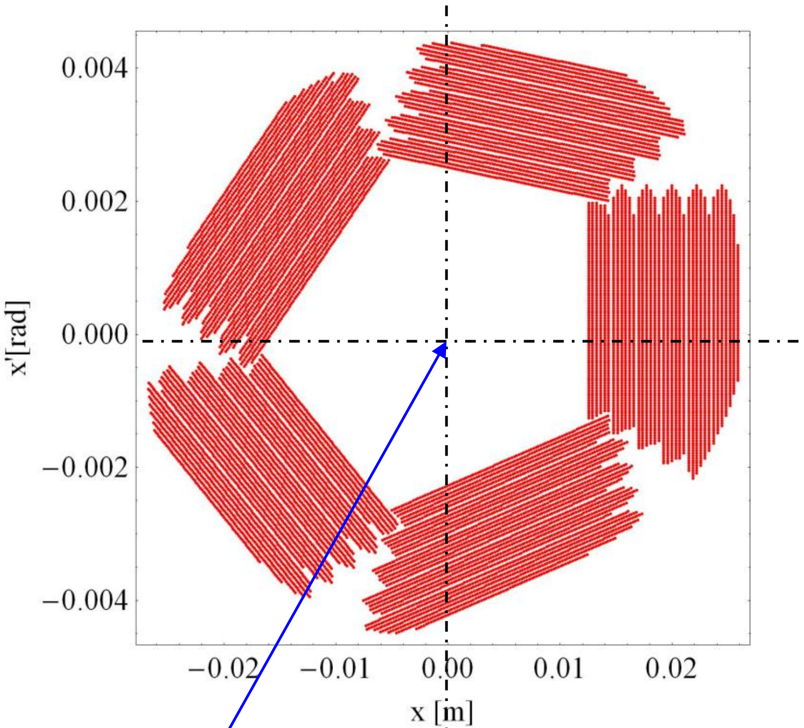
efficiency

≈ 0.5 for injector beam with pulse length t≈60 turns

Multiturn injection at TSR@Isolde



transverse phase space



closed orbit at
the septum foil

$\Delta t \approx 25$ turns
typically ≈ 30 μs (10 MeV/u)

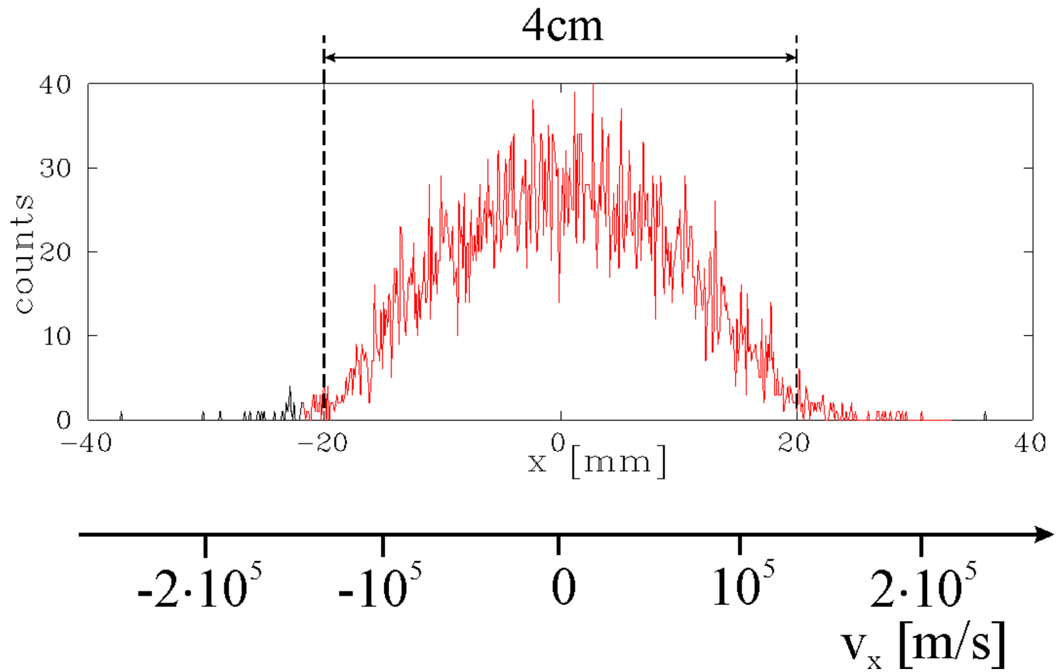
closed orbit

$\varepsilon = 4$ mm·mrad
$Q_x = 2.8$

if $\Delta t \leq 25$ turns $\Rightarrow \approx 80$ % of the injected ions can be captured

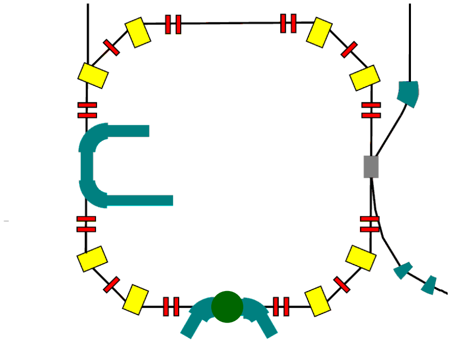
Beam profile after multi turn injection

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

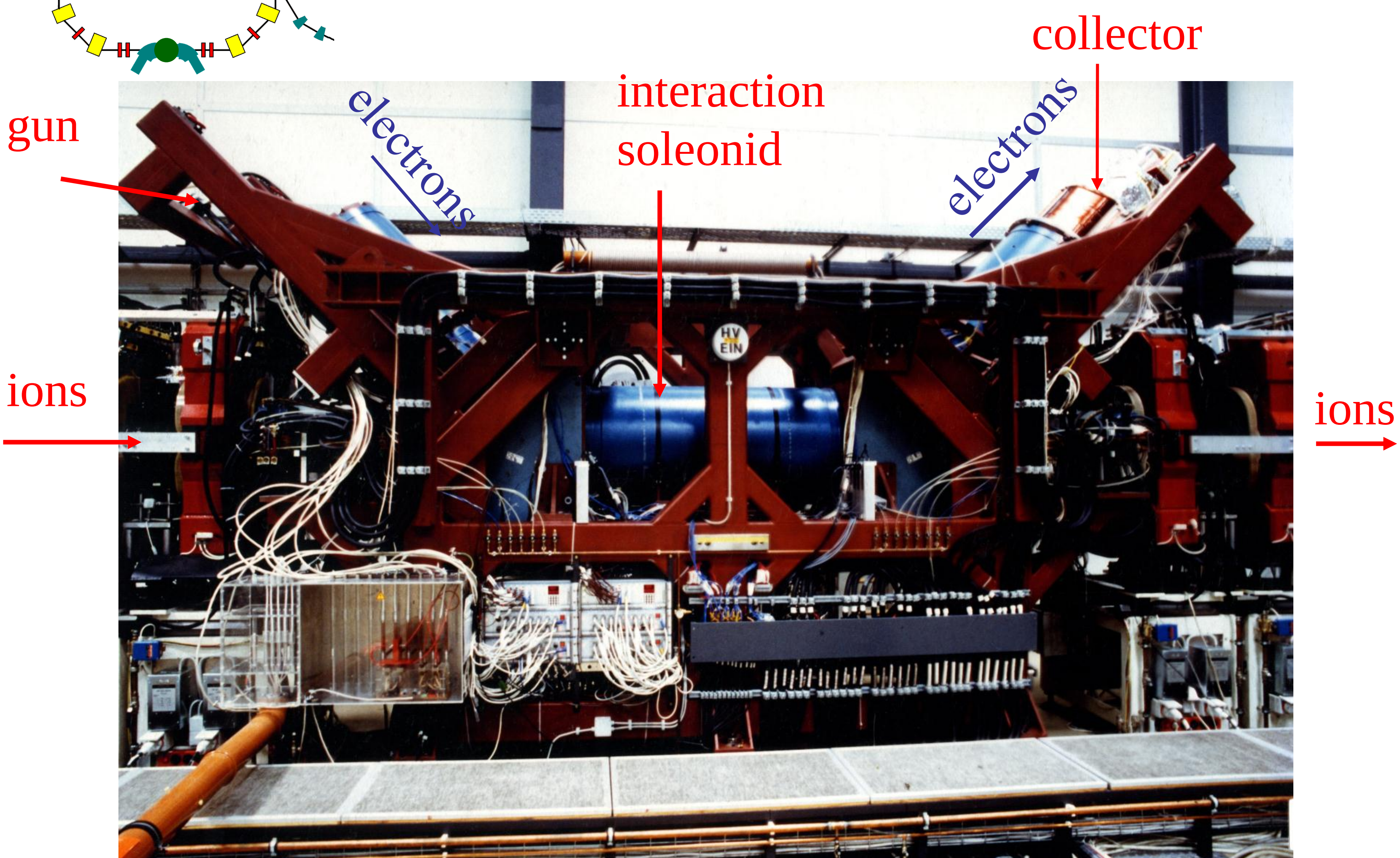


velocity distribution $$n(v_x) = \frac{N}{\sqrt{2\pi}\sigma_{v_x}} e^{-\frac{1}{2}\frac{v_x^2}{\sigma_{v_x}^2}}$$ $$\sigma_{v_x} \approx 6 \cdot 10^4 \, m/s$$

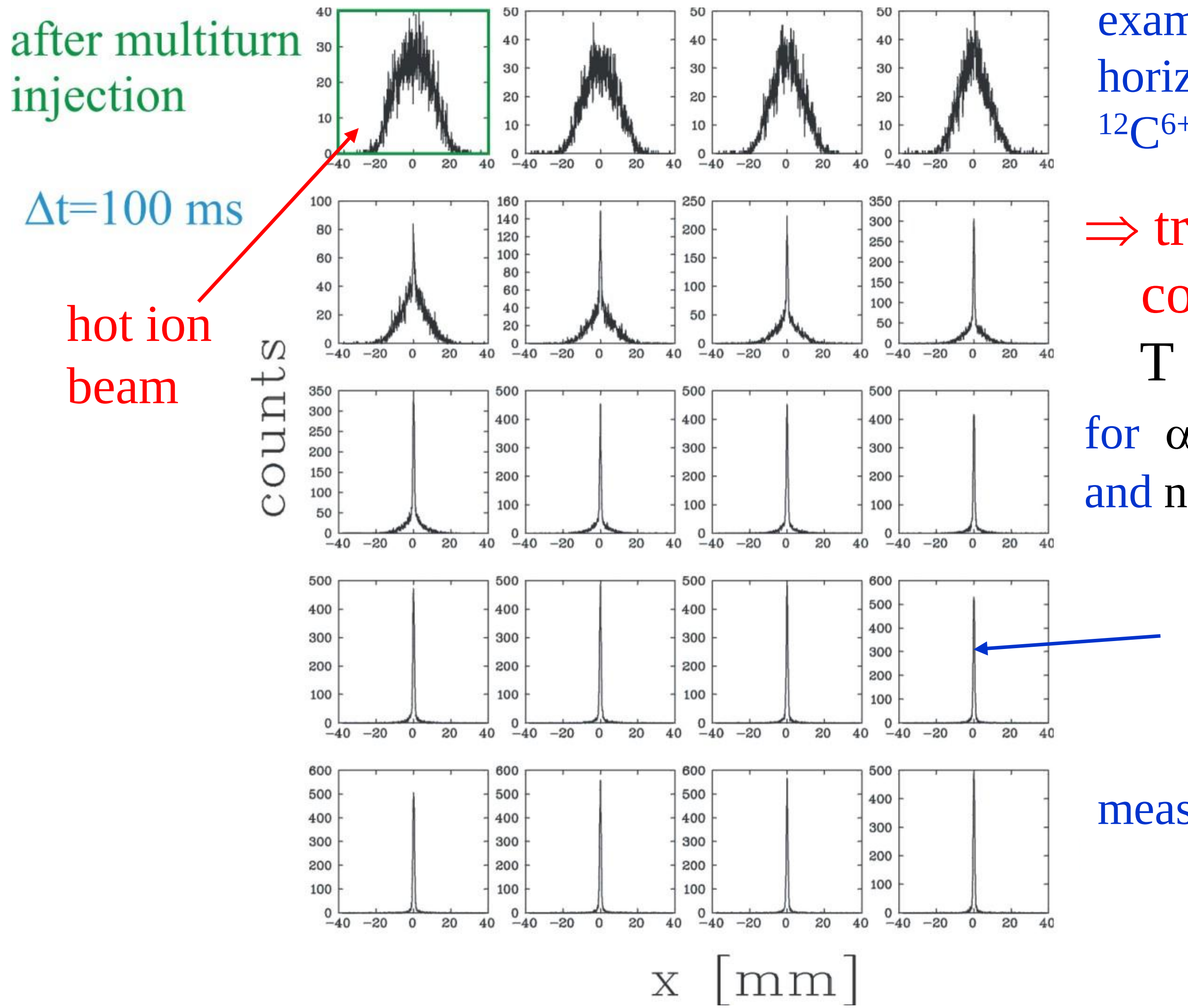
beam temperature: σ_{v_x} with $$\frac{1}{2} k \cdot T = \frac{1}{2} m \cdot \sigma_{v_x}^2 \quad \Rightarrow \mathbf{T \approx 5 \cdot 10^6 \, K}$$



The electron cooler



Transverse electron cooling



example
horizontal beam profile
$^{12}C^{6+}$ (E=73.3 MeV)

$\Rightarrow$ transverse cooling time:

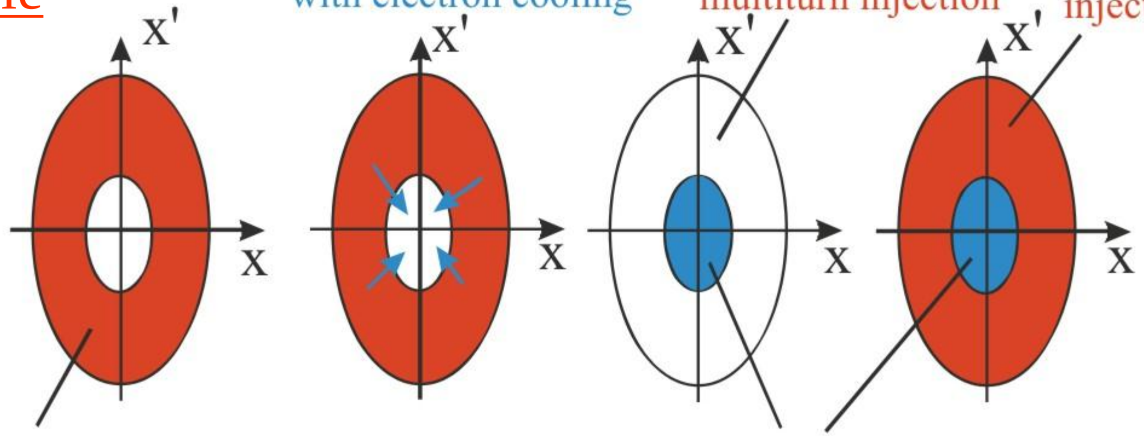
$T \approx 1s$

for α_{ex}= 7.7
and $n_e=1.53\cdot10^7$ 1/cm^3

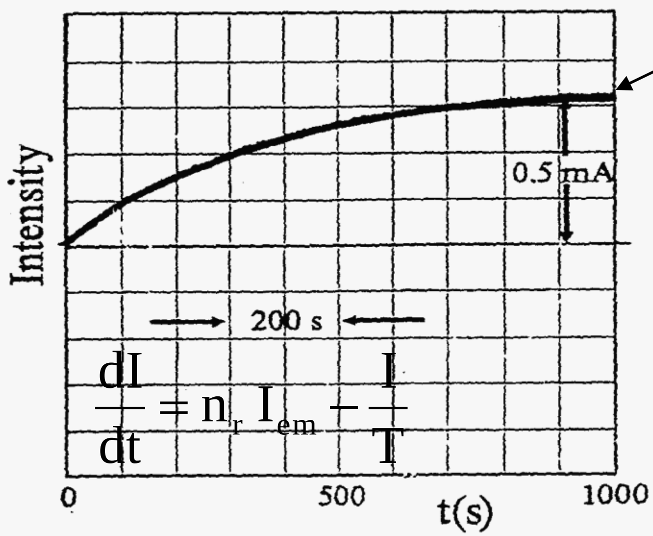
measuring time: 2s

ECOOL Stacking

principle



measured I(t) for $^{35}Cl^{17+}$ ions



$$\frac{dI}{dt} = n_r I_{em} - \frac{I}{T}$$

equilibrium intensity I_0

$$I_0 = n_r \cdot T \cdot M_{eff} \cdot I_{inj}$$

$$n_r = \begin{cases} 1/T_{cool} & T_{cool} > 0.2s \\ 5\ 1/s & T_{cool} \le 0.2s \end{cases}$$

I_{em} effective intensity increase with multiturn injection

I_{inj}-Injector intensity

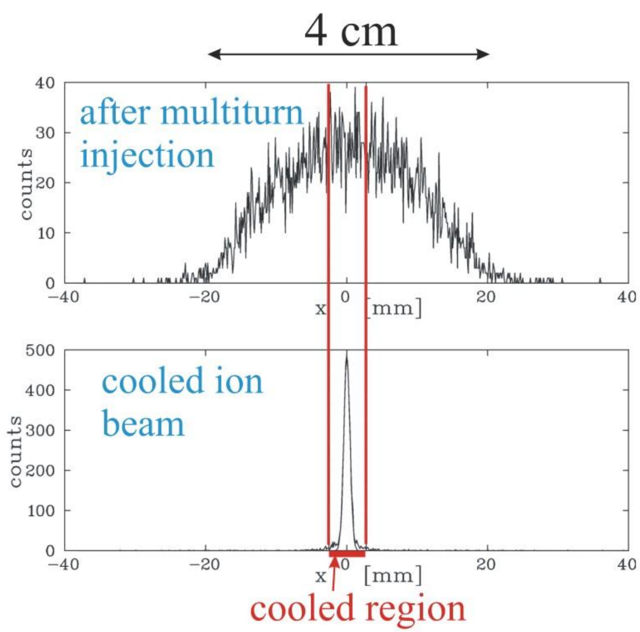
M_{eff}- effective intensity multiplication factor : $M_{eff} = \frac{I_{em}}{I_{inj}}$

T- beam lifetime

n_r-injection rate

T_{cool}- electron cooling time

Cooling time T_{cool} of a multiturn injected ion beam



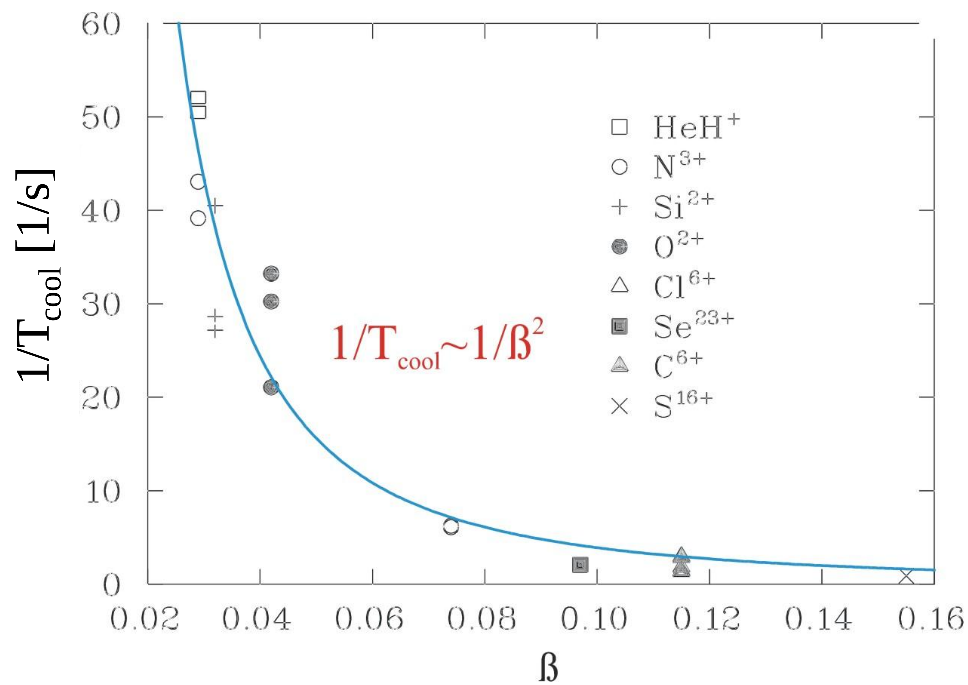
definition of transverse cooling time

The cooling time is the time it takes to cool 80% of the particles outside the cooled region into the marked region

$$T_{cool} \approx const \cdot \frac{A\,ß^2}{q^2\, n_e} \quad (0.03<ß<0.16)$$

inverse cooling time $1/T_{cool}$ as a function of ß

normalized to q^2/A and $n_e=10^8\ cm^{-3}$



$\Rightarrow$ for $\alpha_{ex}=9.6$ and per =1 µperv

$$T_{cool} \approx \frac{A}{q^2} \cdot 3s \quad \text{because} \quad n_e \propto \beta^2$$

Beam life-time T for some ions

60 h

Ion	Energy [MeV]	Pressure [10^{-11} mbar]	cooled [s]	uncooled [s]	cooled [s]	expl.	uncooled [s]	expl
p	21	4	220000		180000	REC		
HD^+	2	7		5				DIS
$^{7}Li^{+}$	13	6		48	41	ST	41	ST
$^{9}Be^{+}$	7	6	16	16	12	ST	12	ST
$^{12}C^{6+}$	73	6	7470		5519	REC	5630	MS
$^{28}Si^{14+}$	115	6	540	260	424	CAP	493	CAP
$^{32}S^{16+}$	196	5	450		554	REC	1200	CAP
$^{35}Cl^{15+}$	157	6	366		306	CAP	375	CAP
$^{35}Cl^{17+}$	202	6	318	366	402	REC	735	CAP
$^{56}Fe^{22+}$	250	5	77		90	REC	278	CAP
$^{58}Ni^{25+}$	342	5	60		89	REC	374	CAP
$^{63}Cu^{26+}$	510	6	122		166	REC	622	CAP
$^{74}Ge^{28+}$	365	5	45		59	REC	162	CAP
$^{80}Se^{25+}$	480	5	204		179	REC	384	CAP
$^{197}Au^{51+}$	710	5	23	51				

Intensities for a few ions achieved with ECOOL stacking

Ion	E [MeV]	life time[s]	Intensity [μA]
p	21	220000	1000
$^{16}O^{8+}$	98		750
$^{12}C^{6+}$	73	1700	1000
$^{32}S^{16+}$	195	450	1500
$^{35}Cl^{17+}$	293	318	1000
$^{45}Sc^{18+}$	178		380
$^{56}Fe^{22+}$	250	77	70
$^{56}Fe^{23+}$	260	74	128
$^{58}Ni^{25+}$	342	60	600
$^{63}Cu^{25+}$	290	49	280
$^{63}Cu^{26+}$	510	122	100
$^{74}Ge^{28+}$	365	45	110
$^{80}Se^{25+}$	480	204	100
$^{80}Se^{31+}$	506	50	<1
$^{197}Au^{50+}$	695	3	3

I≈1 mA → (between $^{35}Cl^{17+}$ and $^{45}Sc^{18+}$)

inchoherent tune shift limit

$N \approx 4000$ $^{32}S^{16+}$

$$N = \frac{I_0}{I_{inj}} = M \cdot \varepsilon_m \cdot n_r \cdot T$$

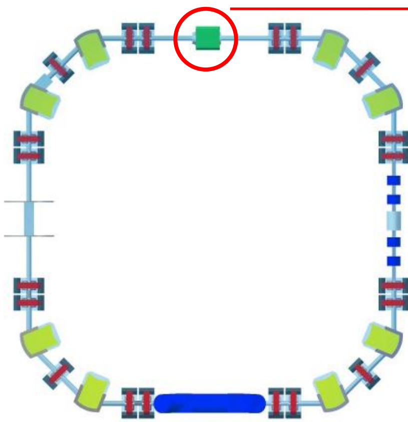
$$n_r = \begin{cases} 1/T_{cool} & T_{cool} > 0.2s \\ 5\,1/s & T_{cool} \le 0.2s \end{cases}$$

$$\varepsilon_m = \begin{cases} 0.8 & n_r = 1/T_{cool} \\ 1 & n_r < 1/T_{cool} \end{cases}$$

I_0 equilibrium intensity
I_{inj} injected intensity
T- life time
T_{cool} cooling time of a multiturn injected ion beam
M intensity multiplication factor multiturn injection
ECOOL Stacking $M \le 10$

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

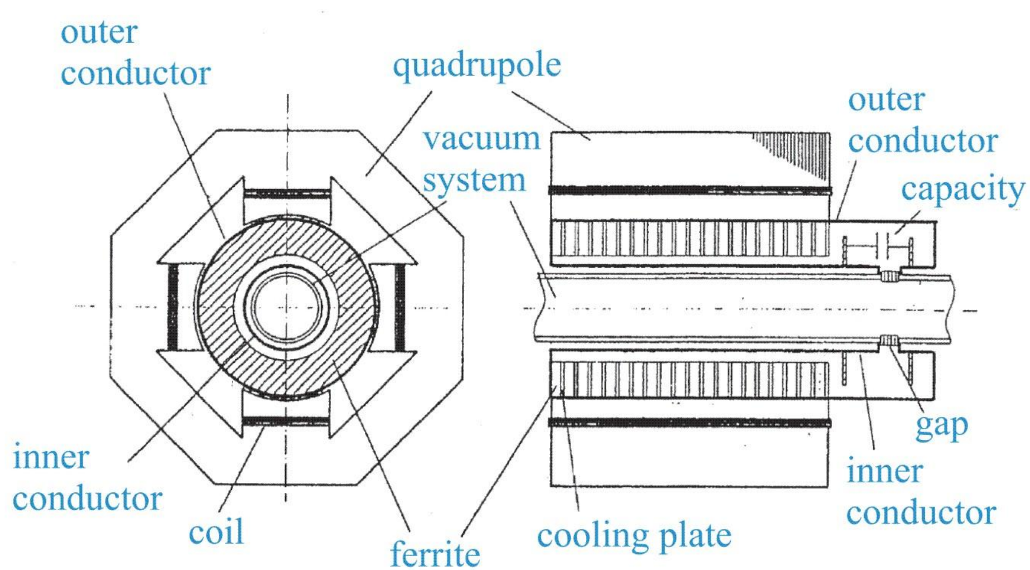
ferrite size: 498x270x25 mm^3

number of ferrites: 20

cooling: 21 water cooled Cu disks

quadrupole

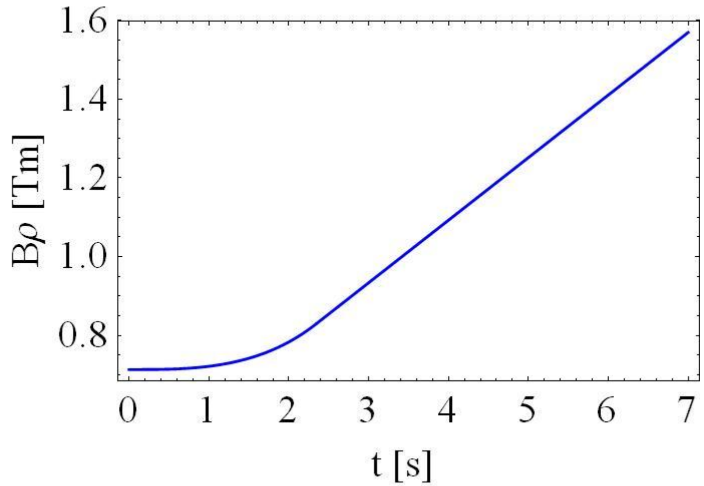
- magnetization of the ferrites
- decoupling of rf field and magnetization field



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

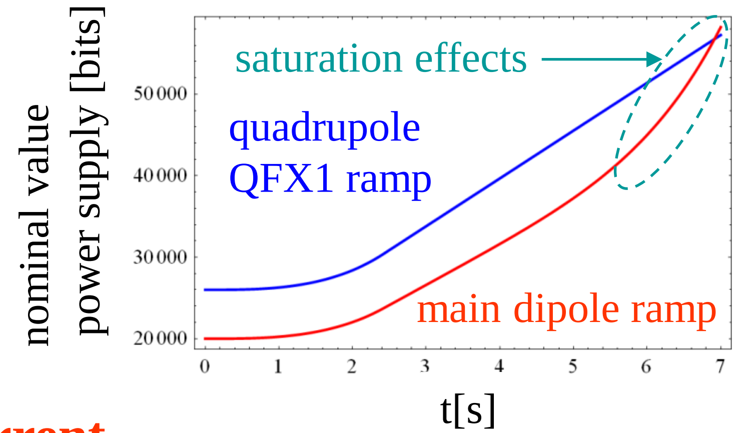
energy E= 73.3 MeV → 362 MeV ⇔ B·ρ = 0.71 Tm → **1.57 Tm**

rigidity



⇒

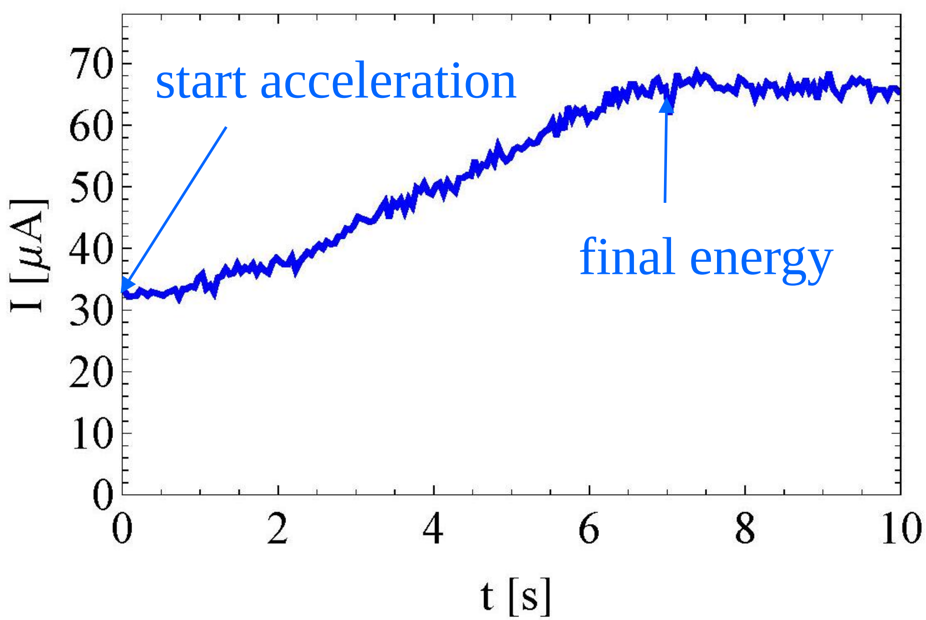
nominal value power supplies



ion current

ion current

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

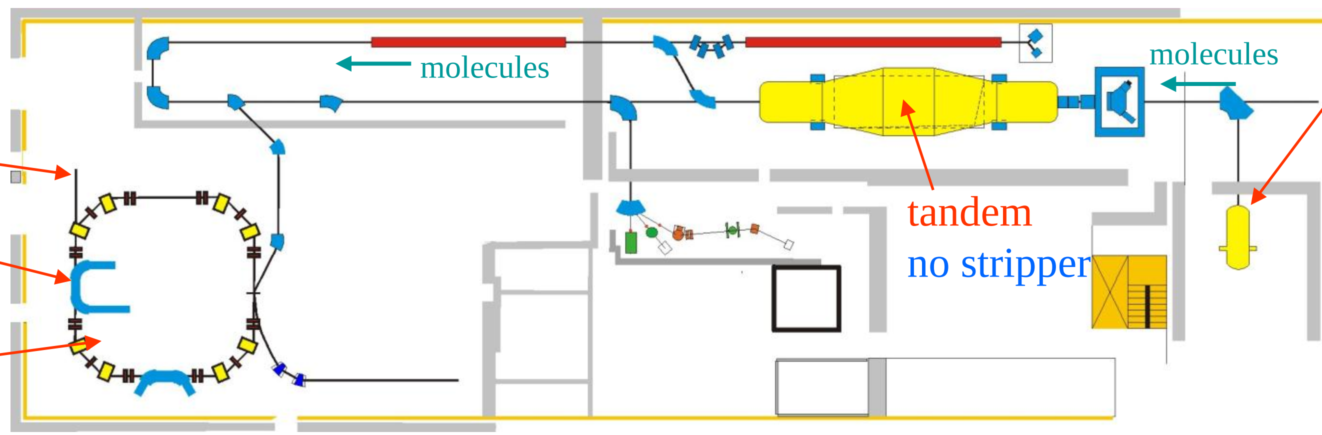


efficiency

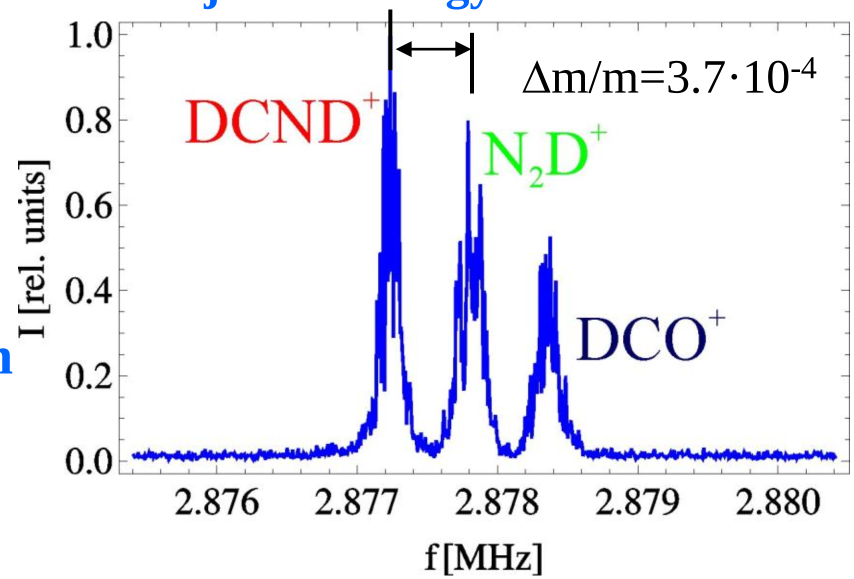
$$\eta = \frac{N_{final}}{N_{start}}$$

η=98 %

Mass selective acceleration at the heavy ion storage ring TSR



Schottky spectrum at injection energy E=2 MeV



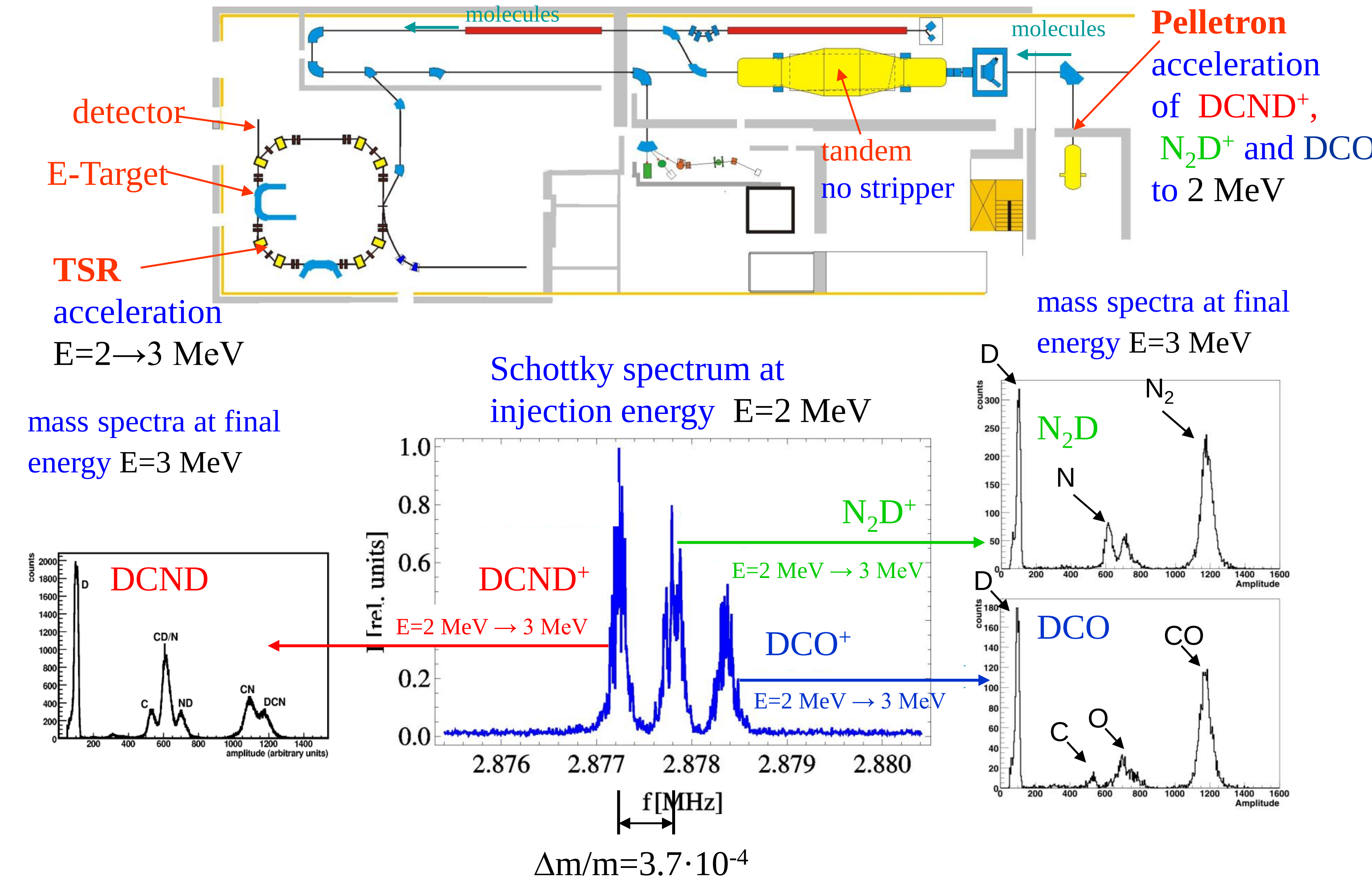
ion source produces several heavy **molecular ion species** with relative mass differences of $\Delta m/m=3.7\cdot10^{-4}$ ($DCND^+$, N_2D^+) .

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

relation between ion mass and Schottky frequency for constant energy:

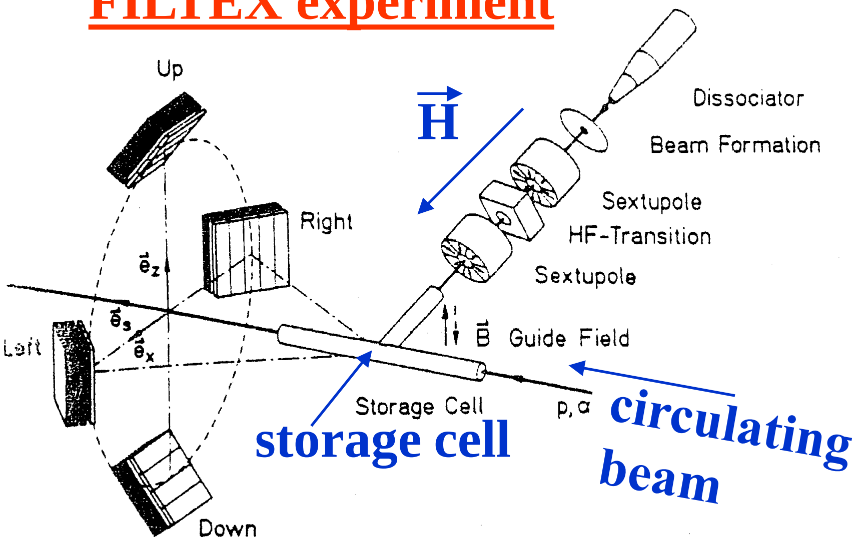
$$\frac{\Delta f}{f} = -\frac{1}{2}\frac{\Delta m}{m}(1+\alpha)$$

Mass selective RF acceleration at the heavy ion storage ring TSR

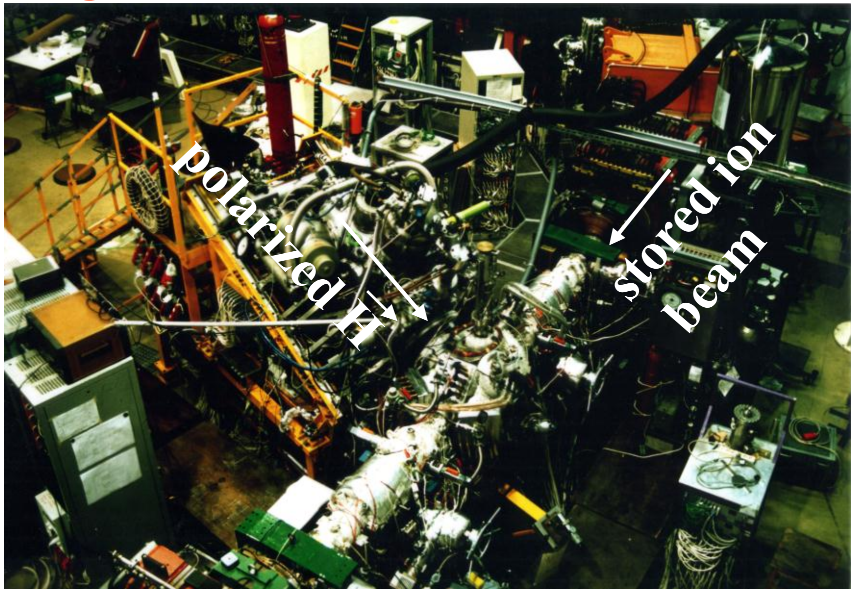


Internal target experiments at the TSR

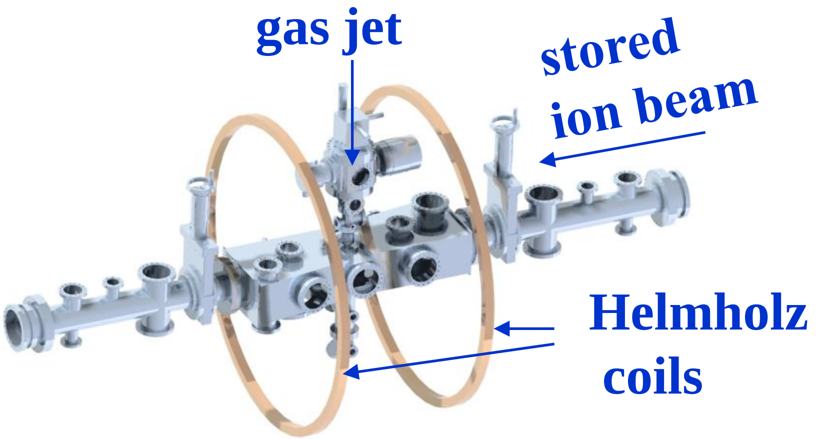
FILTEX experiment

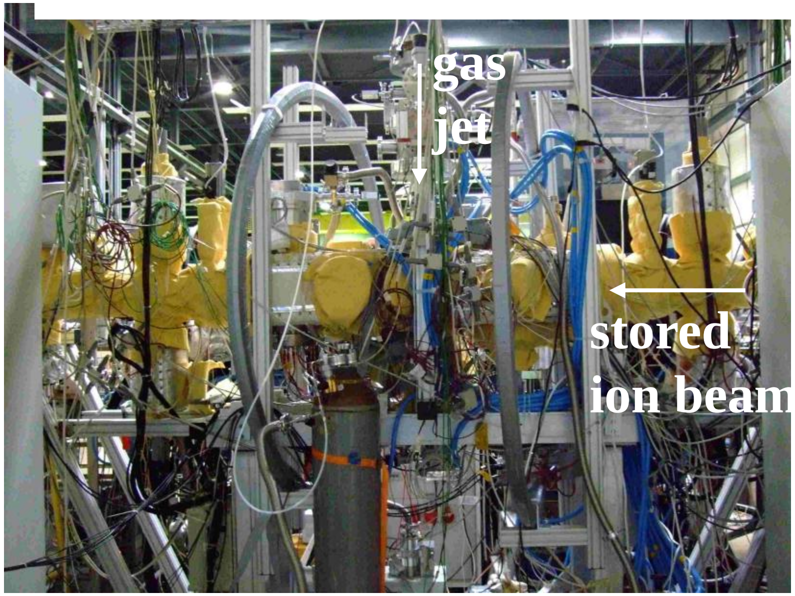


target thickness: $5 \cdot 10^{13}$ atoms/cm^2



Reaction microscope





Lifetimes due to interaction with a internal targets

Calculated ion lifetime for target thickness:
$5 \cdot 10^{13}$ atoms/cm^2

Ion	Energy [MeV]	target	τ_{sc} [s]	τ_{cap} [s]
$^{12}C^{6+}$	73	H_2	1847	4340
$^{12}C^{6+}$	73	He	461	236
$^{12}C^{6+}$	73	N_2	38	1.2
$^{12}C^{6+}$	73	Ar	6	0.055
$^{35}Cl^{17+}$	293	H_2	3200	302
$^{35}Cl^{17+}$	293	He	790	16
$^{35}Cl^{17+}$	293	N_2	64	0.086
$^{35}Cl^{17+}$	293	Ar	10	0.0095

⇒ possible targets: H_2, He

Filtex experiment
storage cell
target thickness
hydrogen
$5.6 \cdot 10^{13}$ H/cm^2

23 MeV protons
τ= 60 minutes
27 MeV He^{2+}
τ=38 minutes

lifetime determined by single scattering

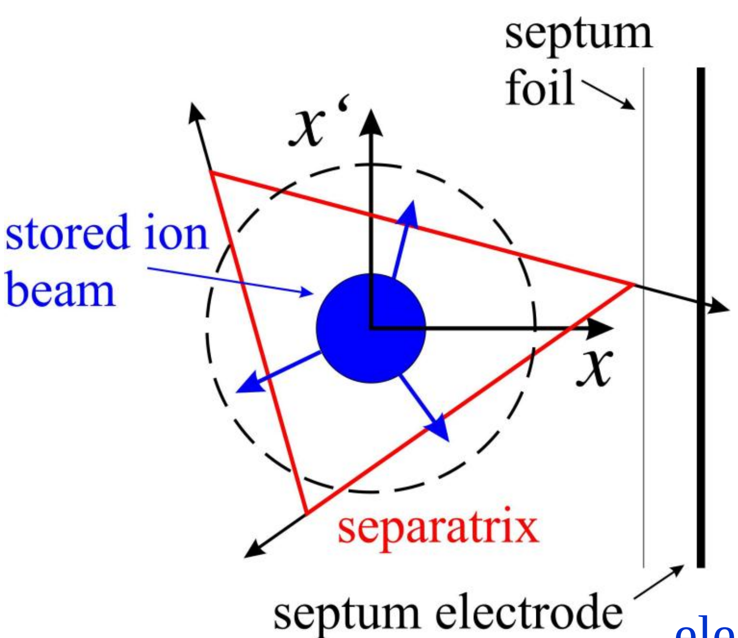
calculated lifetime for p and He^{2+} about factor two higher

Slow extraction

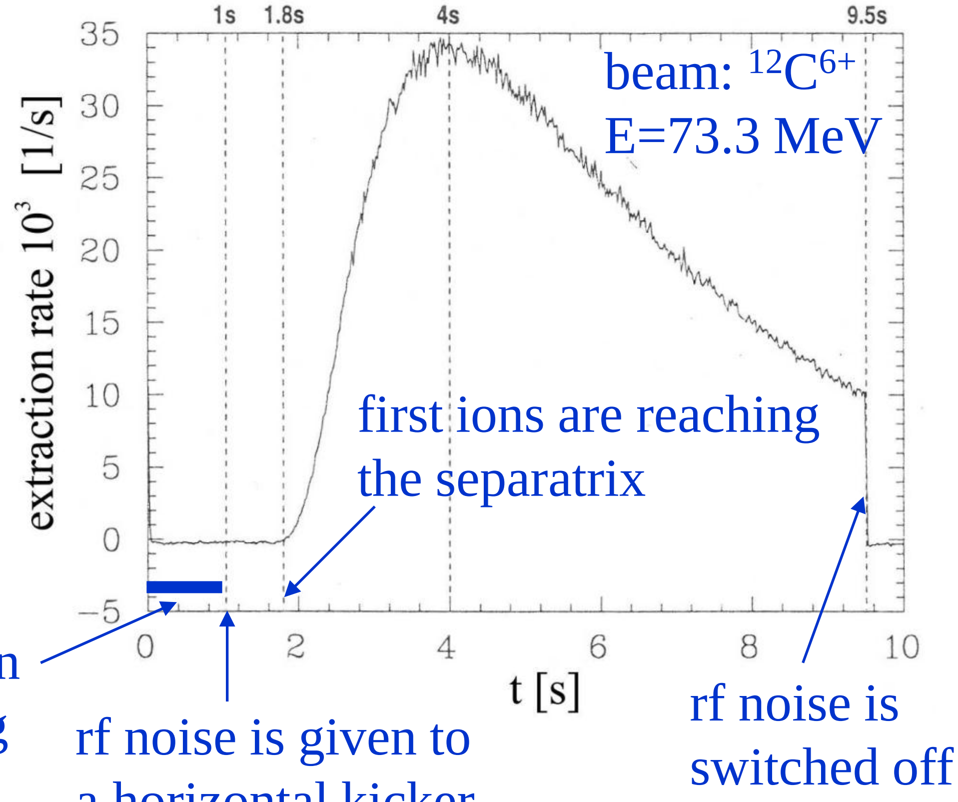
slow extraction process

- ion beam is cooled with electron cooling
- horizontal working point is shifted close to the third order resonance: $Q_x \rightarrow 2.66\ldots$
- rf noise is given to a horizontal kicker to blow up the horizontal phase space

extraction scheme



extraction rate

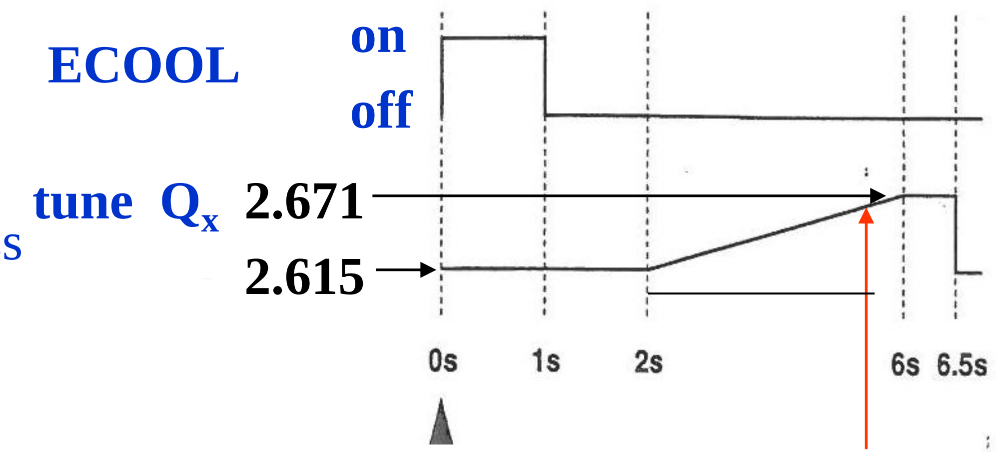


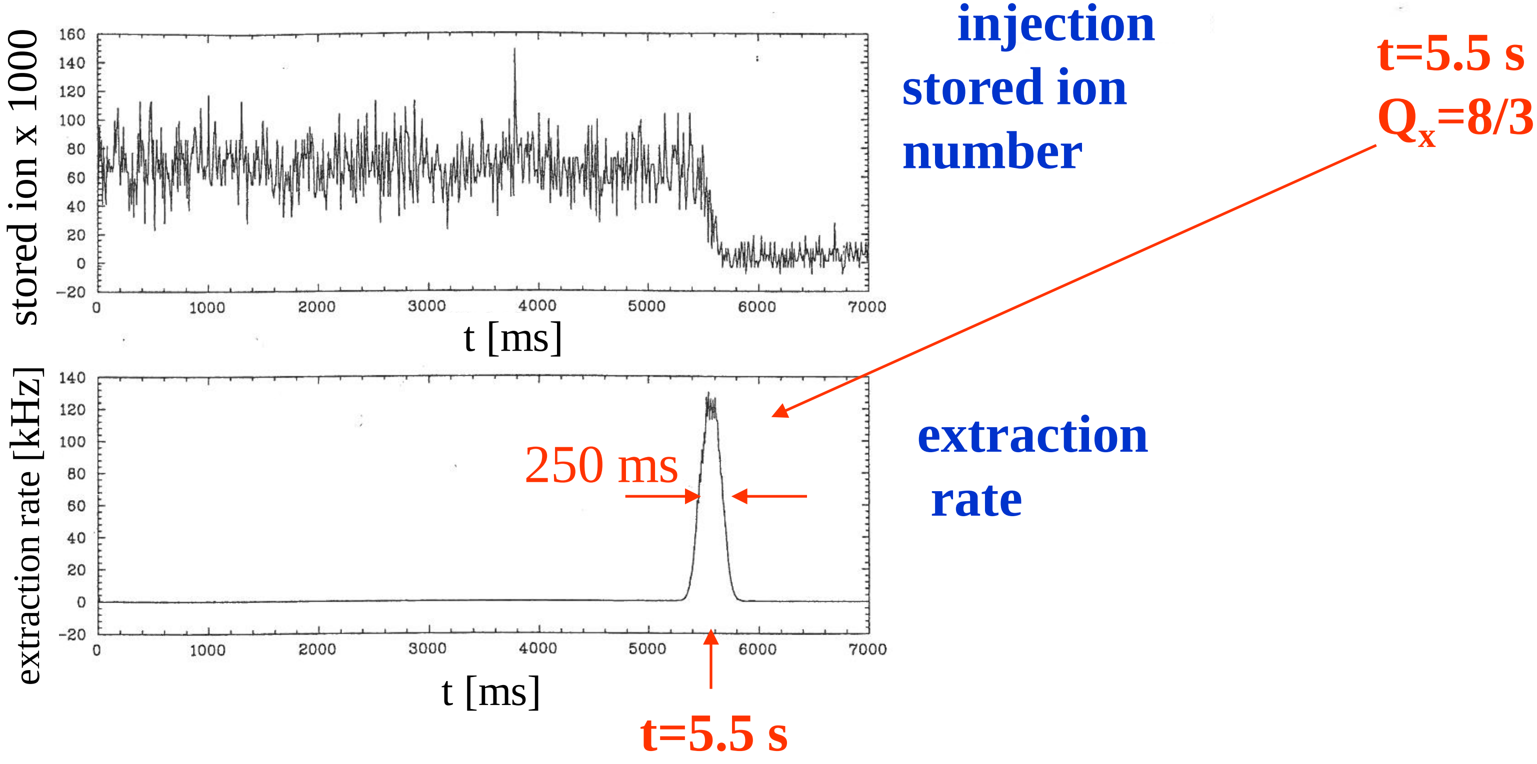
efficiency:
without electron pre-cooling: ≈ 27 %
with electron pre-cooling: ≈85 %

Slow Extraction Classical Method

timing scheme:

- injection at Q_x=2.615
- electron cooling
- change of quadruple strength to cross the third order resonance: Q_x=8/3

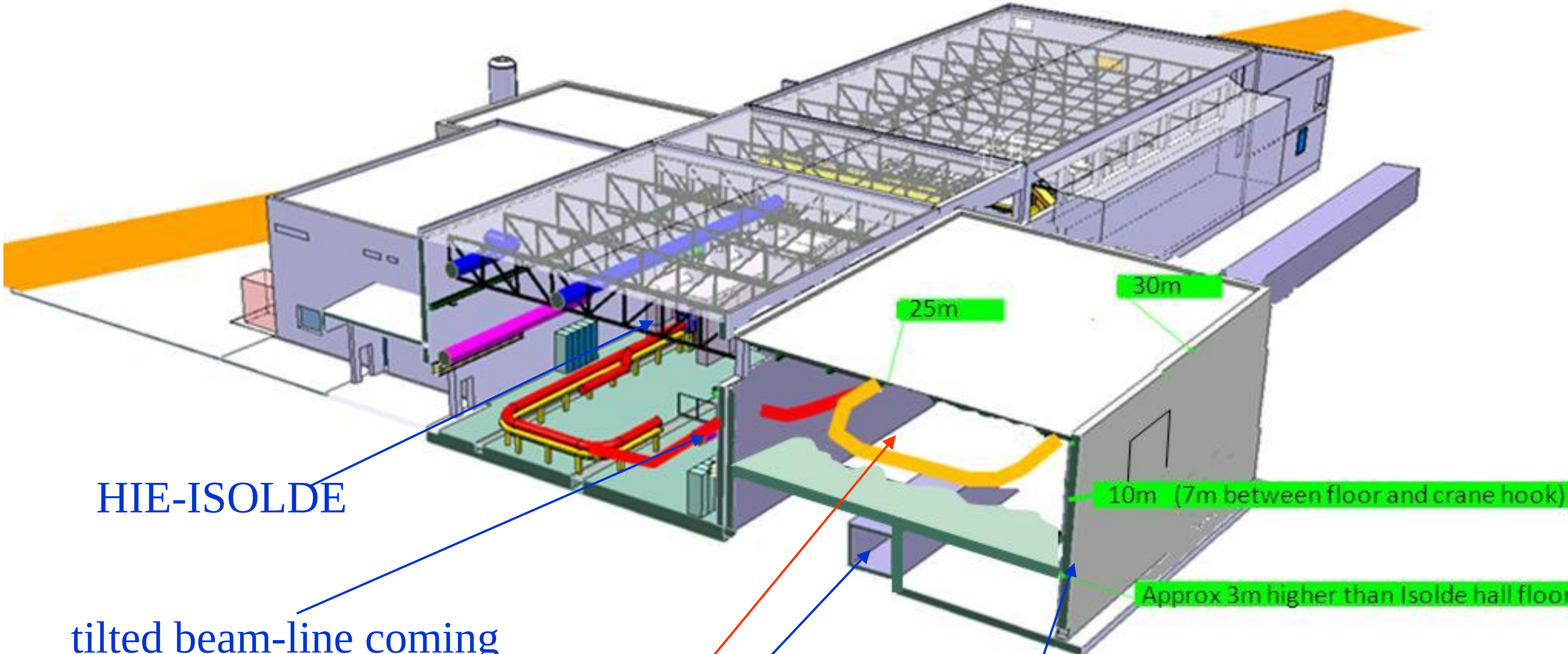




Status of the TSR ring

- TSR is routinely used at MPI up to the end of 2012
- end of 2012: shut down of the whole accelerator facility at MPIK, including TSR
- TSR will kept at MPI until TSR can be reassembled at ISOLDE (scheduled 2015)
- between 2013-2015 some modification at the TSR can be done to fulfill the requirements from CERN
- in 2015: disassembly and reassembly by specialists from MPIK and CERN,ISOLDE
- commissioning of the TSR at ISOLDE can be done in a joined effort with experts from MPIK and CERN,ISOLDE

TSR @ HIE-ISOLDE



HIE-ISOLDE

tilted beam-line coming
from the HIE-ISOLDE machine.

possible TSR installation
above the CERN cable-tunnel.
(E. Siesling)

TSR@HIE-ISOLDE building

Technical Design Report

Storage Ring at Hie-Isolde

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(Eds.)

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