# Feasibility of experiments at TSR@ISOLDE from the accelerator point of view

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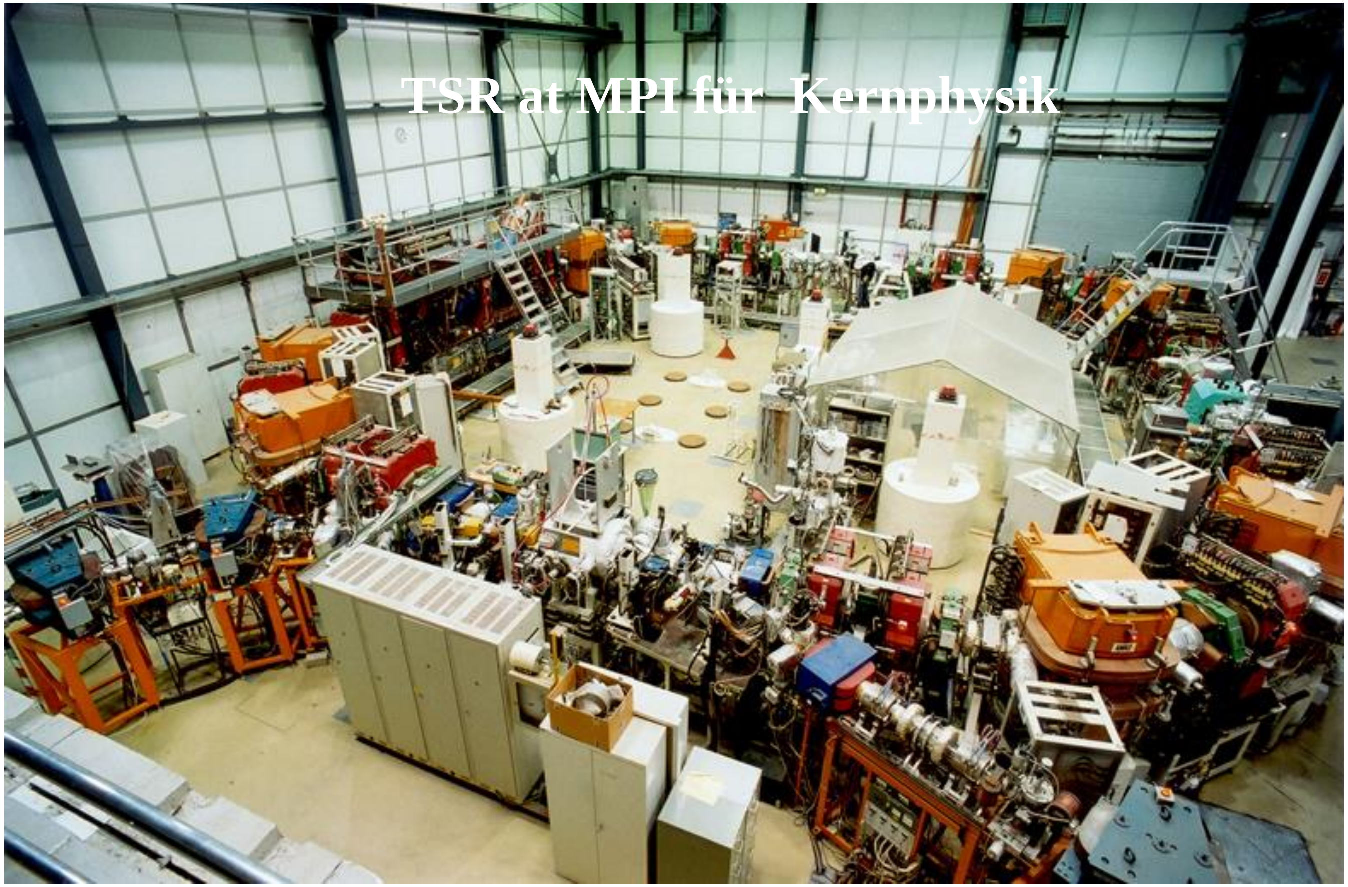
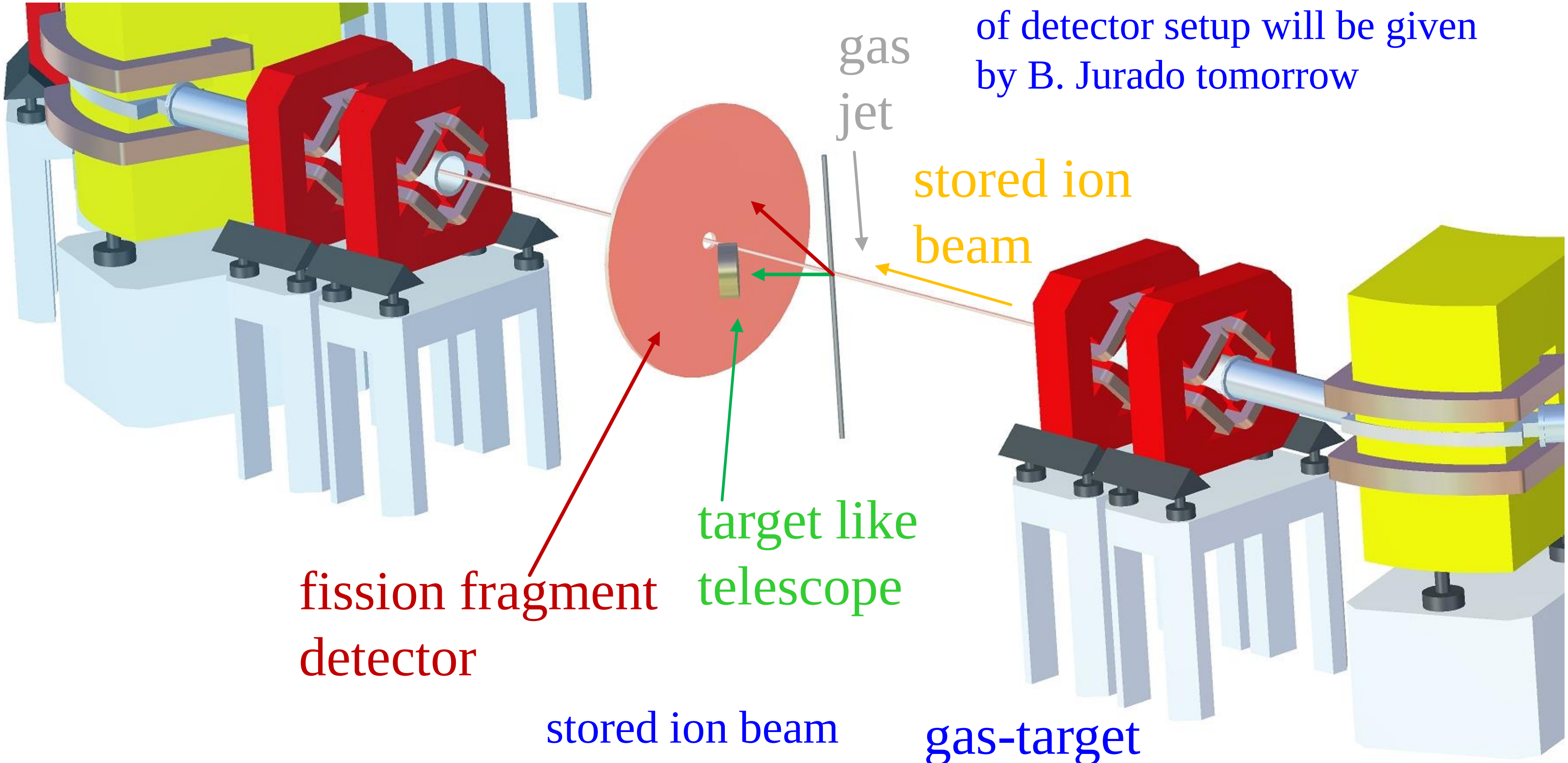


TSR@ISOLDE workshop, CERN, 27th -28th April 2015

# Fission Experiment at TSR@ISOLDE

Transfer induced fission experiments proposed by **Beatriz Jurado**

physics motivation and explanation
of detector setup will be given
by B. Jurado tomorrow



gas jet

stored ion beam

target like telescope

fission fragment detector

stored ion beam

gas-target

proof of principle experiment: $^{232}\text{Th}+^{3}\text{He}$

# Lifetime modification due to gas target

intensity multiplication factor

$$\frac{1}{\tau} = \frac{1}{\tau_v} + \frac{1}{\tau_t}$$

life time due to target density

$$\tau_t = \frac{1}{\sigma_{cap} \cdot n_t \cdot f_0}$$

life-time due to electron capture in the cooler and residual gas interactions

target thickness $n_t$:

$$n_t = \int n \cdot ds$$

n- target density

$f_0$-revolution frequency

## main loss process in the target: electron capture

Schlachter formulae:

$$\tilde{\sigma} = \frac{1.1\cdot10^{-8}}{\tilde{E}^{4.8}}(1-e^{-0.037\tilde{E}})\cdot(1-e^{-2.44\,10^{-5}\tilde{E}^{2.6}})$$

$$\tilde{E} = \frac{E/A}{Z_{gas}^{1.25}q^{0.7}} \qquad \sigma_{cap} = M\cdot\frac{\tilde{\sigma}\cdot q^{0.5}}{Z_{gas}^{1.8}}$$

cross section in 1/cm$^2$

remark

for $H_2$ target M=2

He target M=1

E projectile energy in keV, A mass number, $Z_{gas}$-target atomic number, q ion charge

At TSR energies: $\sigma_{cap} = 1.1\cdot10^{-8}\frac{q^{3.9}Z_{gas}^{4.2}}{(E/A)^{4.8}}[cm^2]$

# Target Life time and optimum charge state

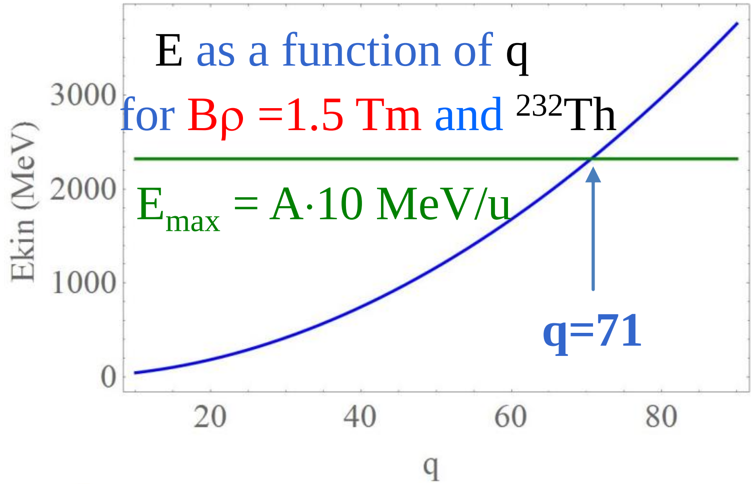
beam life time determined by electron capture in the target

At TSR energies: $\sigma_{cap} = 1.1\cdot 10^{-8}\,\dfrac{q^{3.9} Z_{gas}^{4.2}}{(E/A)^{4.8}}\,[cm^2]$ E in keV

maximum beam rigidity: $B\rho = \dfrac{p}{Q}$ =1.5 Tm

p- ion momentum

$Q=q\cdot e_0$ ion charge

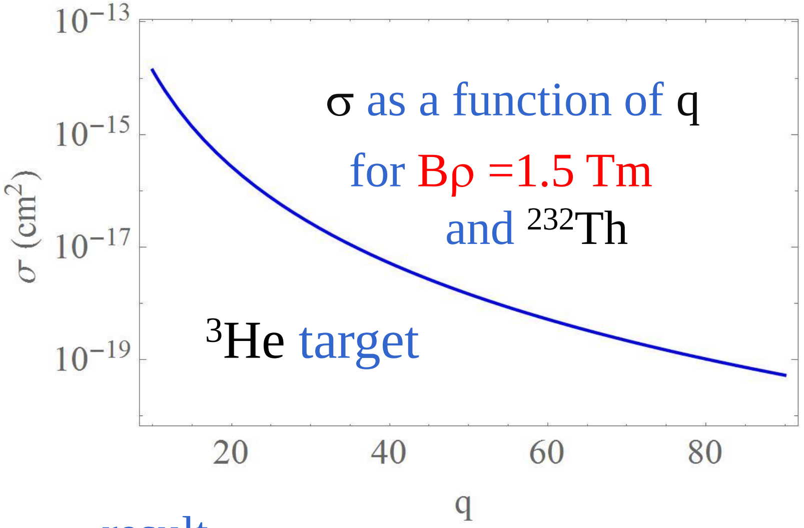


E as a function of q

for Bρ =1.5 Tm and $^{232}$Th

$E_{max} = A\cdot 10$ MeV/u

**q=71**

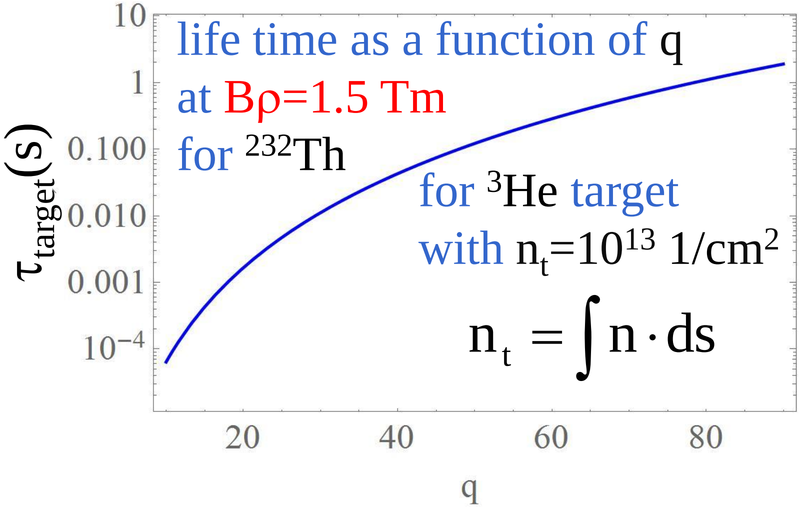


σ as a function of q

for Bρ =1.5 Tm

and $^{232}$Th

$^3$He target



life time as a function of q

at Bρ=1.5 Tm

for $^{232}$Th

for $^3$He target

with $n_t=10^{13}$ 1/cm$^2$

$$n_t = \int n\cdot ds$$

result

E= 2320 MeV

⇒ for Bρ=1.5 Tm: **q=71**

for target thickness $n_t=10^{13}$ 1/cm$^2$

$\tau_{target}$= 0.75 s (**He** target)

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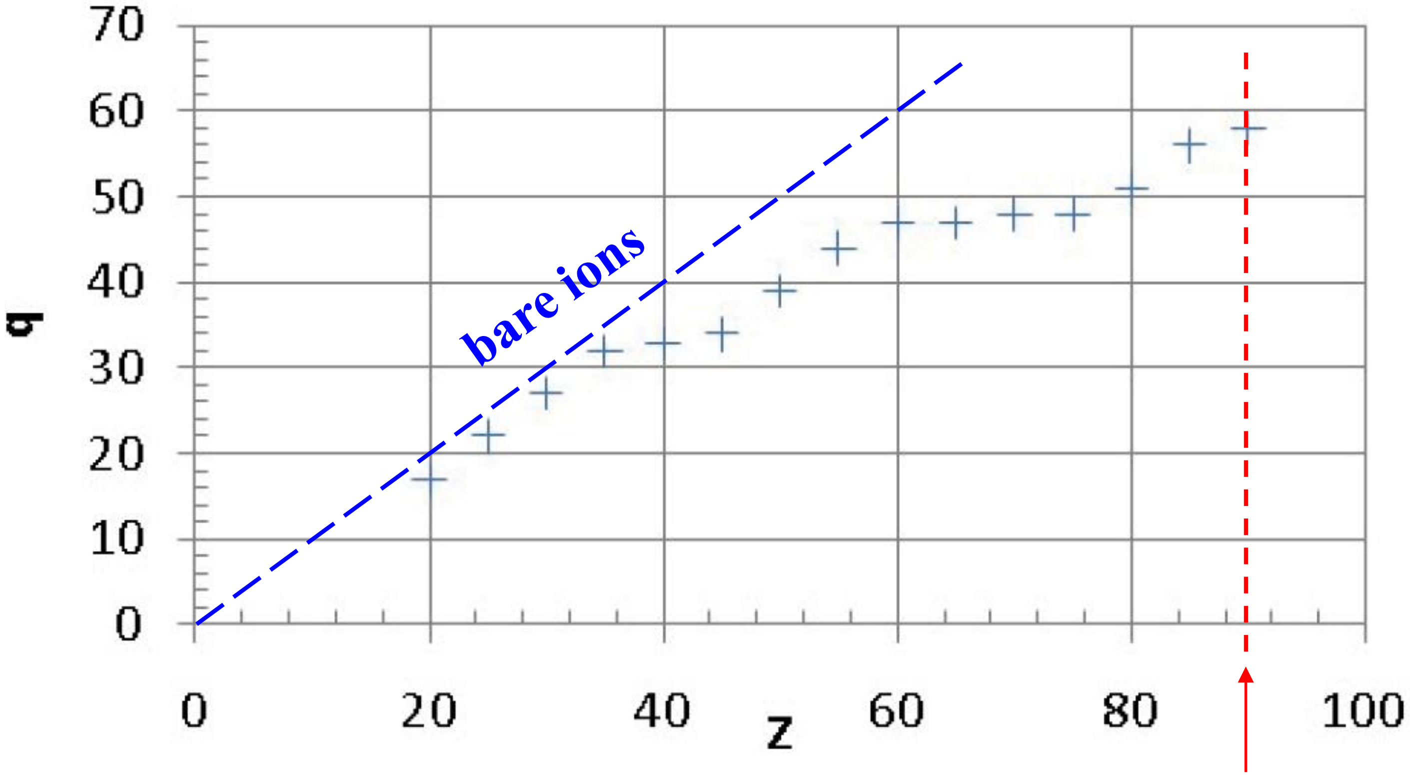
remark: $\sigma_{cap} \propto Z_{gas}^{4.2}$

$$\tau_{target,H_2} = 18.4\,\tau_{target,He}$$

# Charge State in REXEBIS

Estimated attainable charge states in REXEBIS as a function of ion Z
(ref. TSR@ISOLDE TDR)



Z=90
(Thorium)

**Stripping of Th ions at 2320 MeV (10 MeV/u) :**

carbon foil: equilibrium charge state: **72** close to **q=71** (calculated with LISE 9.10.62)

# Upgrade of REXEBIS

A new EBIS, producing much higher charge states is under investigation at CERN

Design parameters HIE-ISOLDE / TSR@ISOLDE breeder

| | Charge breeder | REXEBIS |
|---|---|---|
| Electron energy [keV] | 150 | 5 |
| Electron current [A] | 2-5* | 0.2 |
| Electron current density [A/cm$^2$] | 1-2x10$^4$ | 100 |
| Trap pressure (mbar) | ~10$^{-11}$ | ~10$^{-11}$ |
| Ion-ion cooling needed | YES | NO |
| Extraction time (us) | <30 | >50 |

new TSR@Isolde charge breeder

With the new TSR@Isolde charge breeder bare ions up to Z=60 should be possible

Much more details about this project was given by Fredrik Wenander during the last TSR@ISOLDE 2014 workshop at CERN

# Lifetime of $^{232}Th^{71+}$ with E=2320 MeV in the TSR

$B\rho$=1.5 Tm

**target:** for target (He) thickness $n_t=10^{13}$ 1/cm$^2$ : $\tau_{target}$= 0.75 s
for target (He) thickness $n_t=10^{12}$ 1/cm$^2$ : $\tau_{target}$= 7.5 s

**vacuum life times** for p=$5\cdot10^{-11}$ mbar:

electron capture: $\tau_{cap}$=100 s
multiple scattering: $\tau_{ms} > 10^6$ s
stripping: neglect able

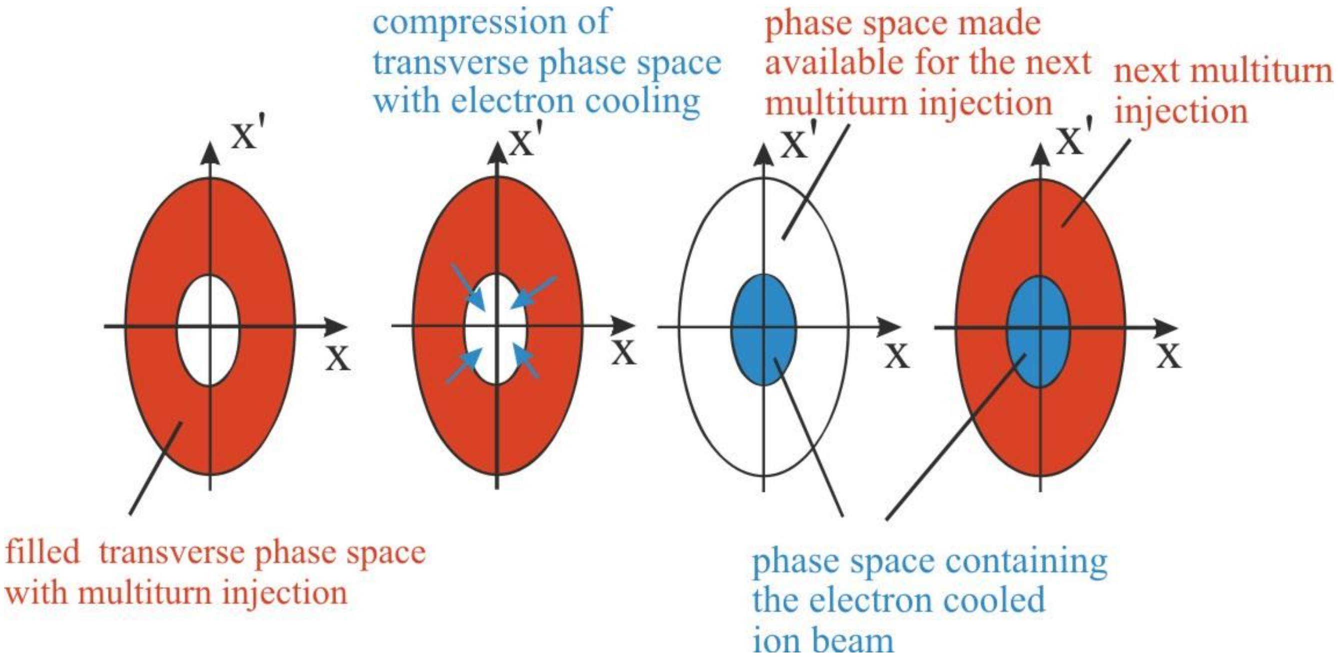
ECOOL maximum possible electron current: $I_e$=0.43 A, $\alpha_{ex}$=9.3: $\tau_{REC}$= 4 s
reduced electron current: $I_e$=0.1A, $\alpha_{ex}$=9.3: $\tau_{REC}$= 16 s

total life time $\tau$: $\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$ $\tau_i$- life time of loss processes

for very high target densities ($n_t > 5\cdot10^{12}$ 1/cm$^2$): $\tau \approx \tau_{target}$

# $^{232}$Th$^{71+}$ injection: electron stacking

## ECOOL stacking scheme:



compression of transverse phase space with electron cooling

phase space made available for the next multiturn injection

next multiturn injection

filled transverse phase space with multiturn injection

phase space containing the electron cooled ion beam

injection rate $n_r$: determined by electron cooling time $\tau_{ECOOL}$:

$$n_r \approx \frac{1}{T_{ECOOL}} \qquad \tau_{ECOOL} \approx 3s \frac{I_{e\,max}}{I_e}\frac{A}{q^2}$$

for $0.03 < ß < 0.16$

but $n_r \leq 5\ 1/s$

| $I_e/I_{emax}$ | $\tau_{ECOOL}$ (s) | $n_r$ (1/s) |
|---|---|---|
| 1 | 0.14 | 5 |
| 0.25 | 0.56 | 1.8 |

where: A-ion mass
q-ion charge
$I_e$- electron current
$I_{e\,max}$ –maximum possible electron current

# Space charge limit due to inchoherent tune

maximum possible stored ion number: $$N = \frac{A}{q^2} \frac{2\pi}{r_p} \cdot B \cdot \beta^2 \cdot \gamma^3 \cdot \varepsilon \cdot (-\Delta Q)$$

$-\Delta Q$ - possible incoherent tune shift TSR: $-\Delta Q \approx 0.065-0.1$ for $B=1$

with $I = q \cdot e_0 \cdot N \cdot f_0$ and $\varepsilon \propto \left( \frac{q^4}{A^2} \frac{N}{\lambda_{Cool}} \frac{1}{\beta^3} \right)^{0.44}$ $\lambda_{cool} \propto n_e \frac{q^2}{A}$ $n_e \propto \beta^2$ ($\alpha_{ex}$=const)

intensity limit: $I = \mathrm{const} \frac{(A^{19} \cdot E^9)^{1/28}}{q}$ const is calculated from the $^{12}C^{6+}$ data:

| Ionm | E [MeV] | Intensity [μA] | calculation I[μA] |
|---|---|---|---|
| p | 21 | 1000 | 740 |
| $^{16}O^{8+}$ | 98 | 750 | 1000 |
| $^{12}C^{6+}$ | 73 | 1000 | 1000 |
| $^{32}S^{16+}$ | 195 | 1500 | 999 |
| $^{35}Cl^{17+}$ | 293 | 1000 | 1130 |

stability limit incoherent tune shift $I \approx 1$ mA

space charge limit: $^{232}Th^{71+}$ (E=10·232 MeV) : I= 1.9 mA ⇔ **N= 2 ·10$^8$**

# Luminosity

definition of luminosity:

$$L(t) = \frac{R(t)}{\sigma}$$

R(t)-reaction rate

$\sigma$- cross-section

$$R(t) = N(t) \cdot f_0 \cdot \sigma \cdot n_t(t)$$

$$\Rightarrow L(t) = N(t) \cdot f_0 \cdot n_t(t)$$

N(t)-number of stored particles

$f_0$-revolution frequency

$n_t$-target thickness

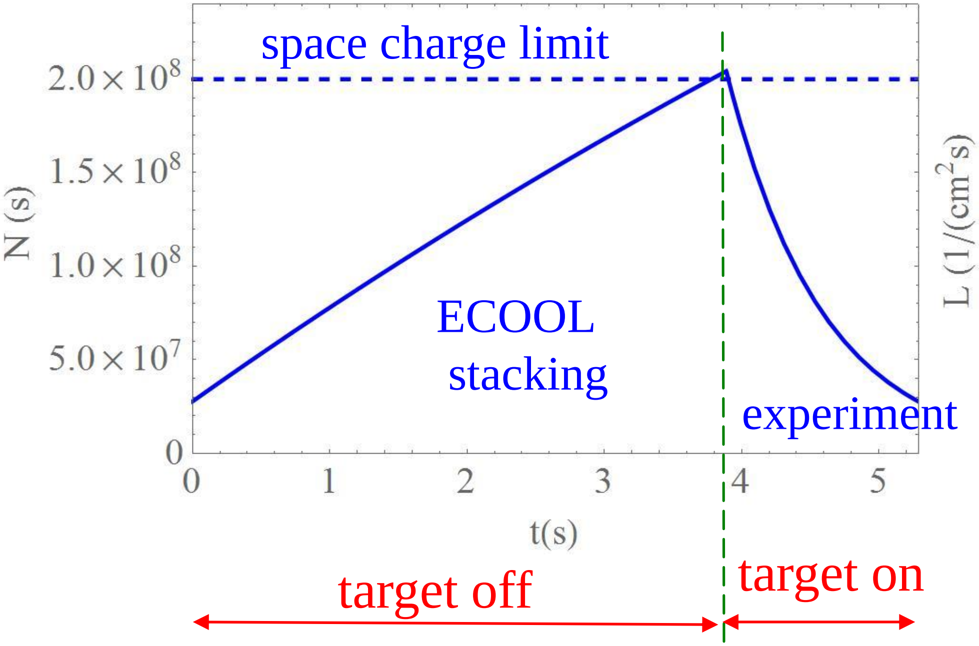
$$n_t = \int n \cdot ds$$ n-target density

remark: -due to possible switching of the target, owing to better lifetimes and lower $^3$He (very expensive) consumption, target thickness $n_t$ depends on time

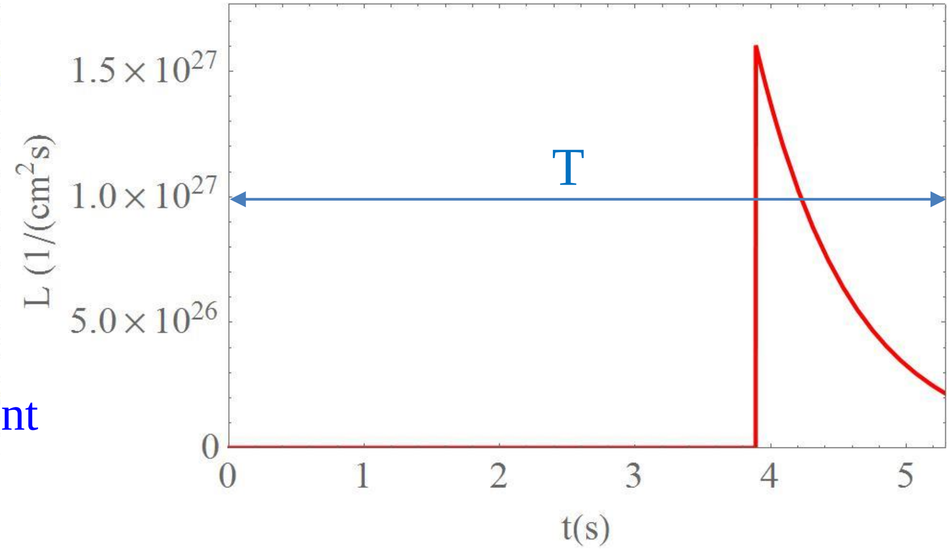
- a strong variation of the particle number N(t) may occur due to separated injection (intensity increase) and experiment (intensity decrease) cycle

# Ion Number and Luminosity

## periodical change of N(t)



## periodical change of luminosity



life time: $\tau_1$=14 s

7 multi turn injections with $N_i=3\cdot10^7$ ions and $n_r$ =1.8 1/s

life time: $\tau_2$=0.7 s

measuring time per period:

$2\cdot\tau_2$

$n_t=10^{13}$ 1/cm²

**average luminosity:**

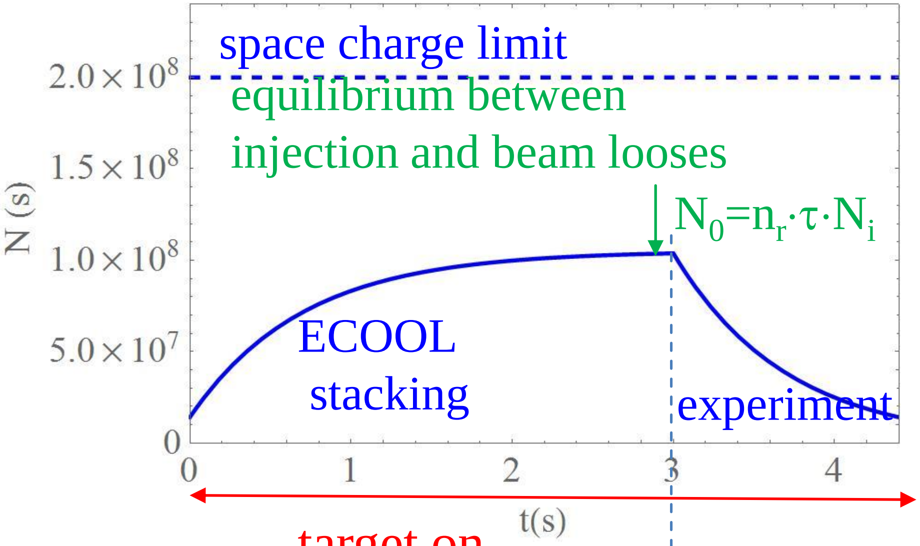
$$\overline{L} = \frac{1}{T}\int_0^T L(t)\,dt$$

$$\overline{L} = 1.8\cdot10^{26}\,1/(\text{cm}^2\text{s})$$

for $^{232}\text{Th}^{71+}$ beam E=2320 MeV
($f_0$=0.786 MHz)

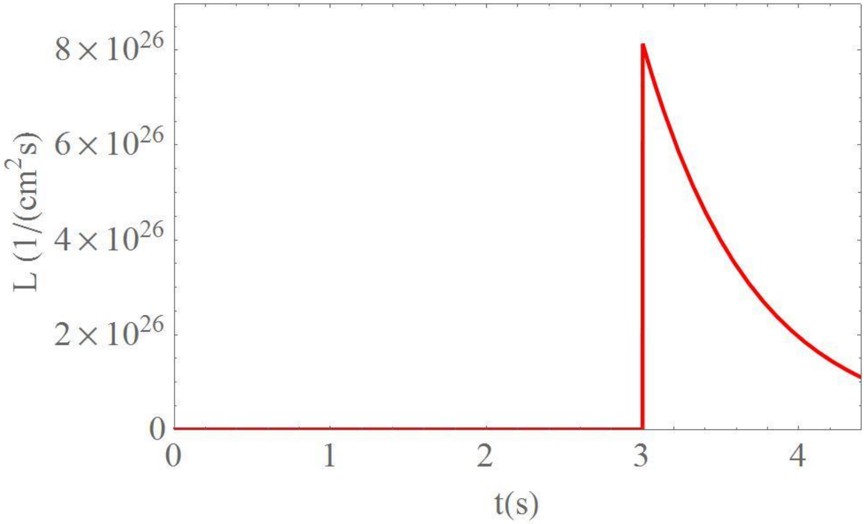
# Ion Number and Luminosity

**periodical change of N(t)**



target on

**periodical change of luminosity**



life time: $\tau_1$=0.7 s

with $N_i=3\cdot10^7$ ions
and drastically increased
electron current:
$I_e$=0.28-0.43 A
injection rate: $n_r$ =5 1/s

maximum possible $\mathbf{n_r}$

$n_t=10^{13}$ 1/cm²

life time: $\tau_2$=0.7 s
measuring time
per period:
$2\cdot\tau_2$

**average luminosity:**

$$\overline{L}=\frac{1}{T}\int_0^T L(t)\,dt$$

$$\overline{L}=1.1\cdot10^{26}\,1/(\mathrm{cm}^2\mathrm{s})$$

for $^{232}\mathrm{Th}^{71+}$ beam E=2320 MeV
($f_0$=0.786 MHz)

# Luminosity at continues injection and measurement

particle number N(t):

$$\frac{dN(t)}{dt} = n_r N_i - \frac{N(t)}{\tau}$$

$N_i$-injected particle number per injection

$n_r$- injection rate

$\tau$- total lifetime

for high target densities the beam lifetime is very short and determined by the target lifetime $\tau_t$. In the equilibrium: $dN(t)/dt = 0$

stored number of ions $N_0$ ($N_0 \leq N_s$ ):

$$N_0 = n_r \, \tau \, N_i$$

$N_0$ - equilibrium particle number

$N_s$ -space charge limit

with: $\tau \approx \tau_t = \dfrac{const}{n_t}$ and const=$0.75 \cdot 10^{13}$ s/cm$^2$

(E=2320 MeV $^{232}Th^{71+}$ and He target)

$n_t$-target thickness11

It follows for the luminosity L:

$$L = \frac{R}{\sigma} = N_0 f_0 n_t = n_r \underset{\uparrow}{\tau} n_t N_i f_0 \approx n_r N_i f_0 \, const$$

$$\tau \propto \frac{1}{n_t}$$

**and independent of the target thickness !**

($n_t > 5 \cdot 10^{12}$ 1/cm$^2$)

example:

$f_0$=0.786 MHz

$N_i$= 3 $\cdot 10^7$

$n_{r,max}$=5 1/s

He target

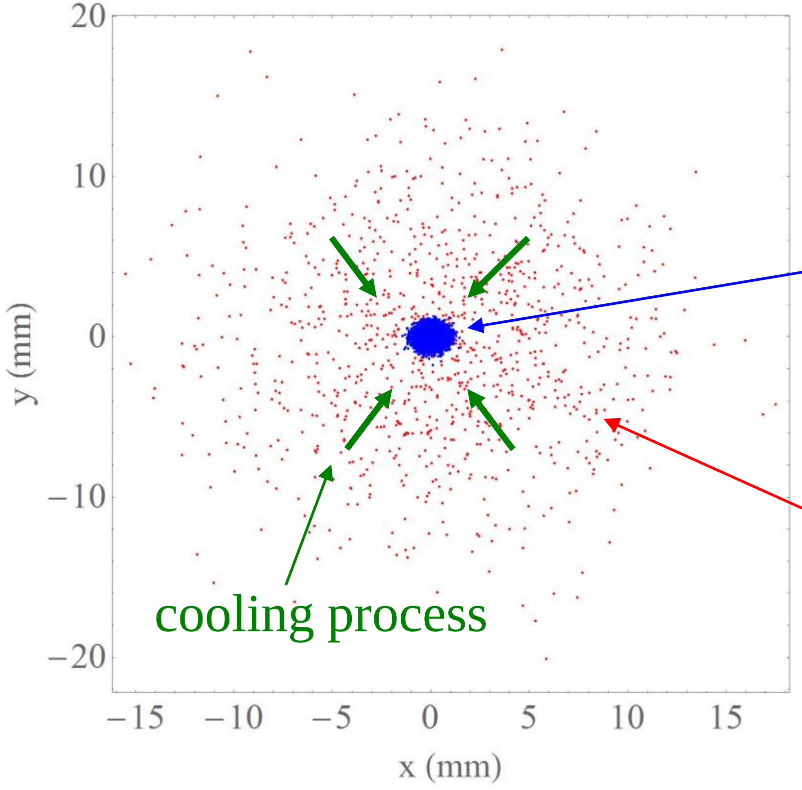
$\Rightarrow$ $L \approx 9 \cdot 10^{26}$ 1/(s$\cdot$cm$^2$)

$$L_{H_2} \approx 18 \cdot L_{He}$$

stacking to the space charge limit requires $N_i$ =6 $\cdot 10^7$ and results in $L \approx 1.8 \cdot 10^{27}$ 1/(s$\cdot$cm$^2$) (He-target) maximum possible luminosity

# Halo formation during ECOOL stacking

**beam at the target location**



cooling process

very dense **stack** with cooled ion beam

**halo:** hot injected ion beam, which is cooled down until next injection proceed

ratio of number of ions in halo $N_{halo}$ and stack $N_{stack}$

$$\frac{N_{halo}}{N_{stack}} \le \frac{1}{n_r \tau} \propto \frac{n_t}{n_r}$$

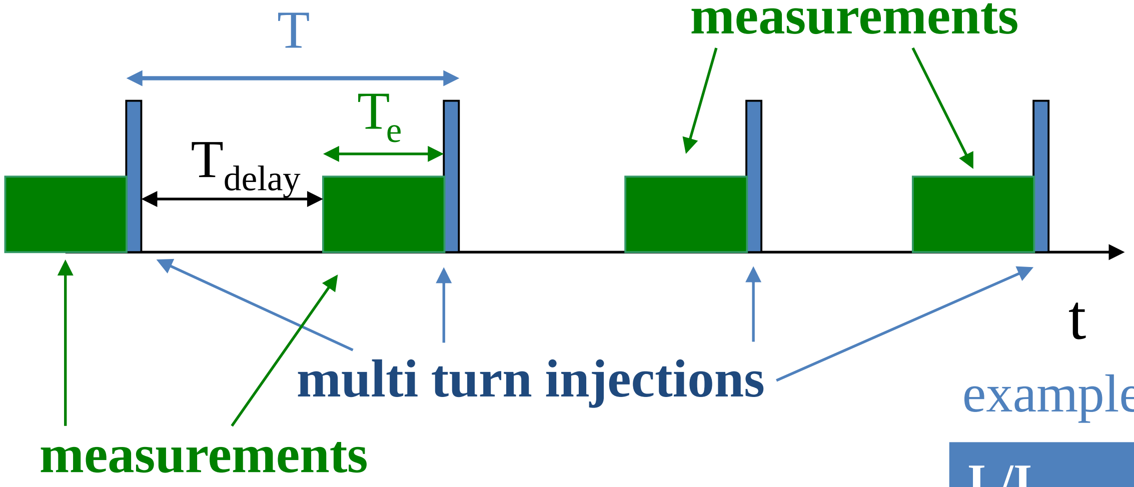
← target thickness

← repetition rate of multi turn injection

# Minimization of the halo size during measurement

-measurement starts after a certain delay $T_{delay}$ after injection and ends before the next multi-turn injection takes place

**timing scheme**



T

$T_e$

$T_{delay}$

**measurements**

t

**multi turn injections**

**measurements**

optimum

$T_{delay} \approx \tau_{ECOOL}$

**advantage:**

-halo: size significant reduction

number of particle significant reduction

-almost constant beam current and counting rate

-no switching of gas jet

**disadvantage:**

-luminosity reduction by factor: $T_e/T$

example for $^{232}Th^{71+}$ (E=2320 MeV)

| $I_e/I_{emax}$ | $\tau_{ECOOL}$ (s) | $n_r$ (1/s) |
|---|---|---|
| 1 | 0.14 | 5 |

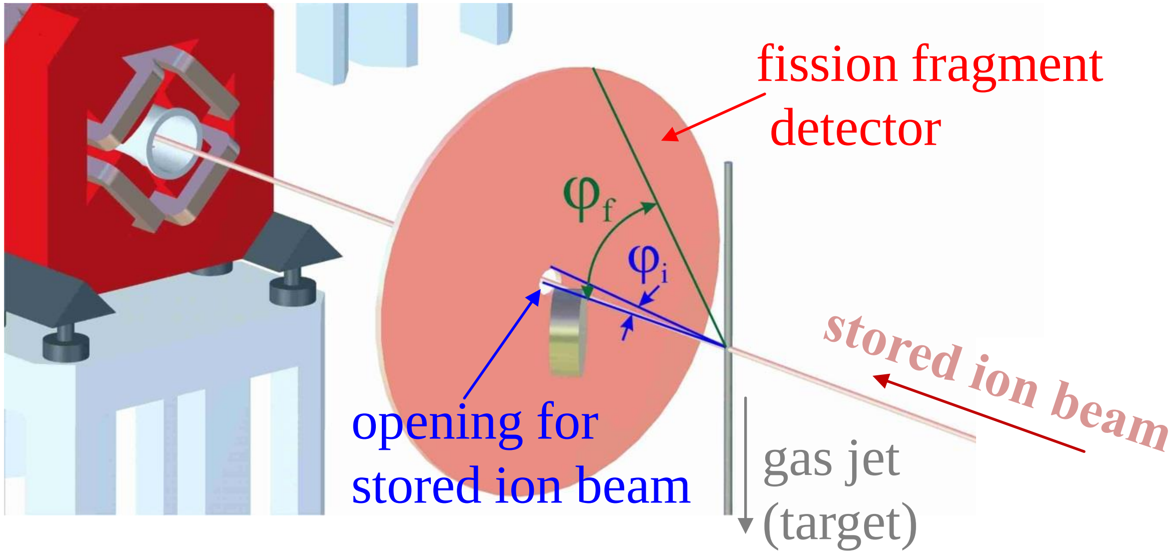
electron current: $I_{e\ max}$=0.43 A

T=0.2 s

**electron beam power**:

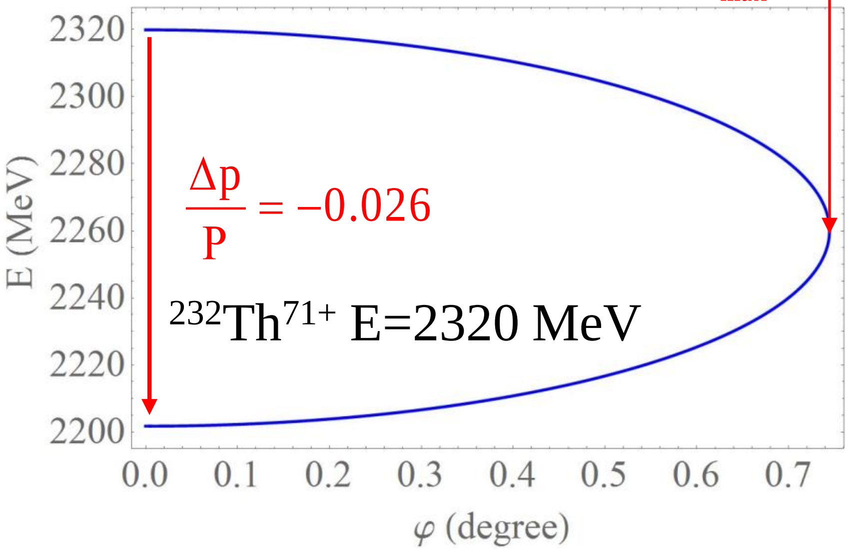
0.43 A·0.5860 kV= 2.5 kW

# Background by Coulomb scattering in the target



energy scatter angle relation of Rutherford scattered Th ions

$\varphi_{max} = 13\,\mathrm{mrad}$



$\frac{\Delta p}{P} = -0.026$

$^{232}\mathrm{Th}^{71+}$ E=2320 MeV

$\varphi_{max} < \varphi_i$

- directly after scattering ion will pass the fission fragment detector, but

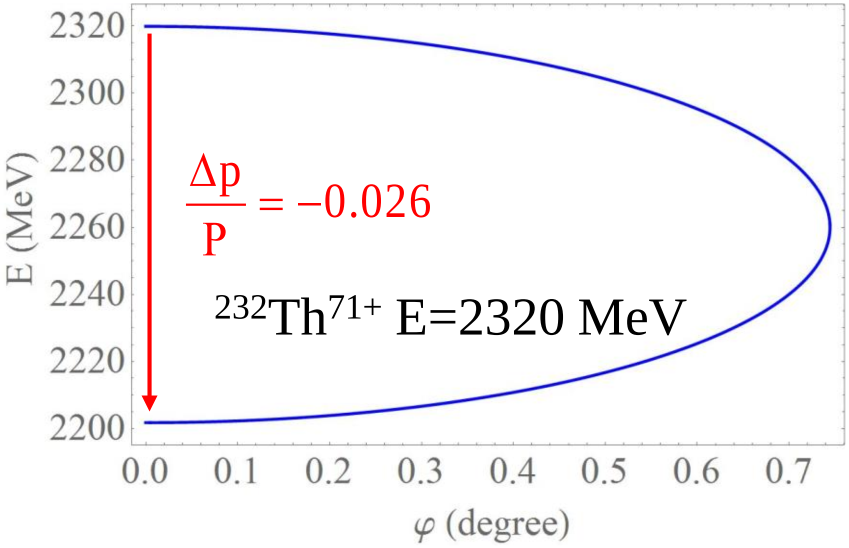
$\varphi_{max} > \varphi_{acc} \leftarrow$ acceptance angle of the TSR

due to the small detection angle of scatted fission fragments, the fission fragment detector may determine the ring acceptance

⇒collision of scattered ions after a few turns with fission detector

# Background by Coulomb scattering in the target

energy scatter angle relation of Rutherford
scattered Th ions



-further there is a momentum shift of the scattered Th ions of up to -2.6%

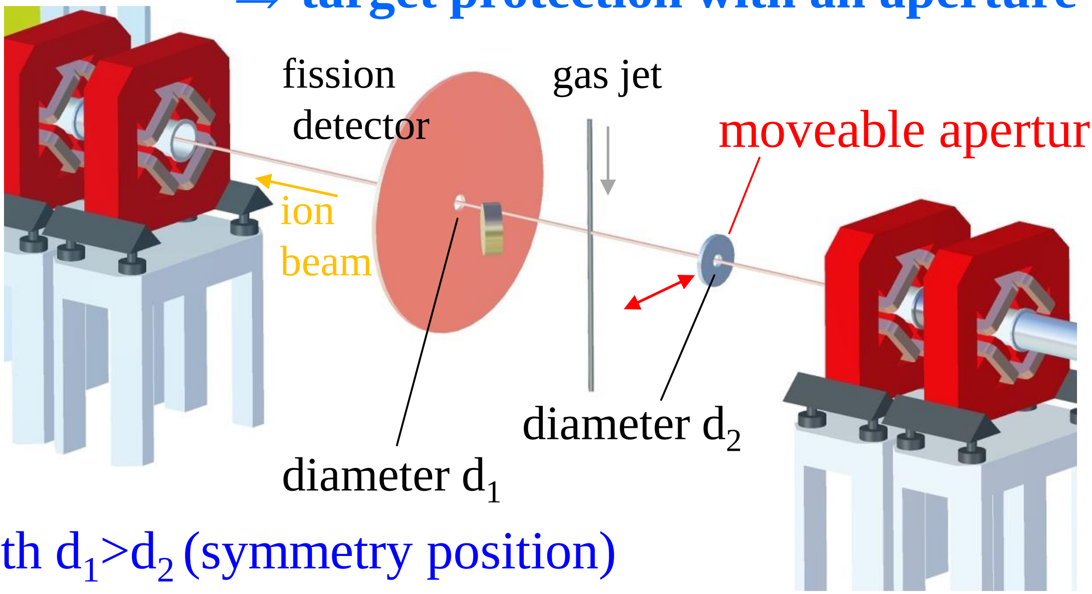
⇒ closed orbit shift by

$$\Delta x = D\frac{\Delta p}{p}$$ D- dispersion in the target area

leading to an increaseof the betatron oscillation around the new closed orbit

⇒ possible collision with the fission target after a few turns

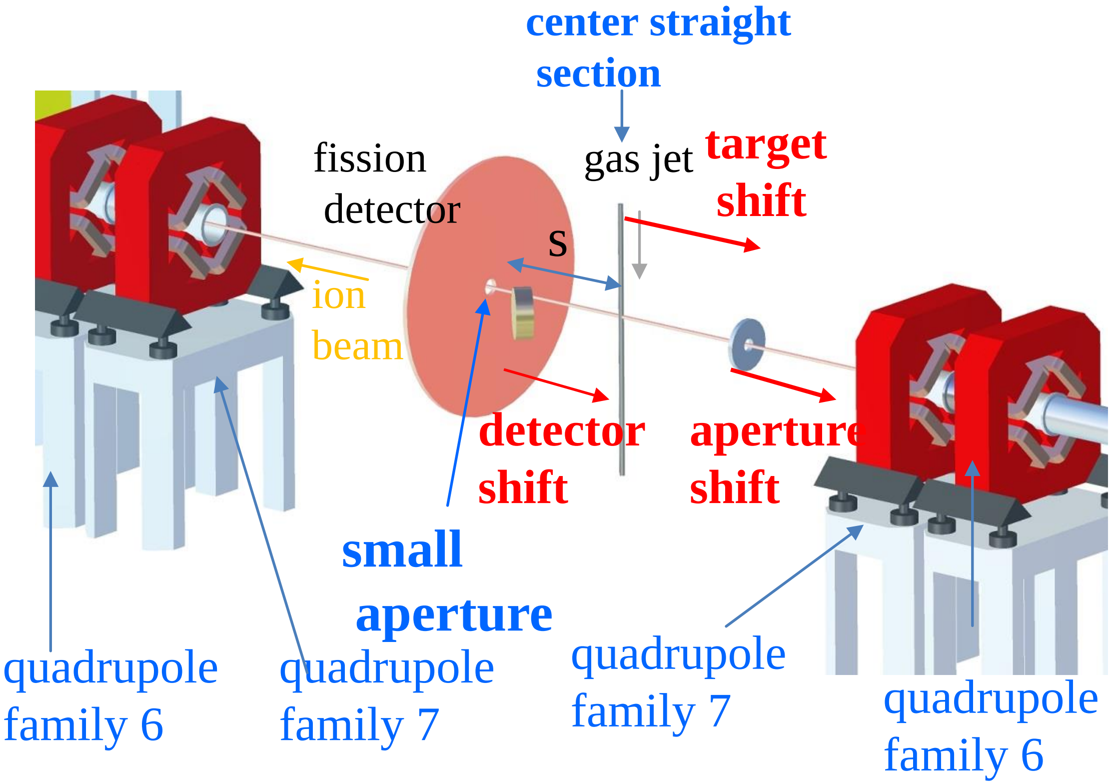
⇒ **target protection with an aperture or scraper**



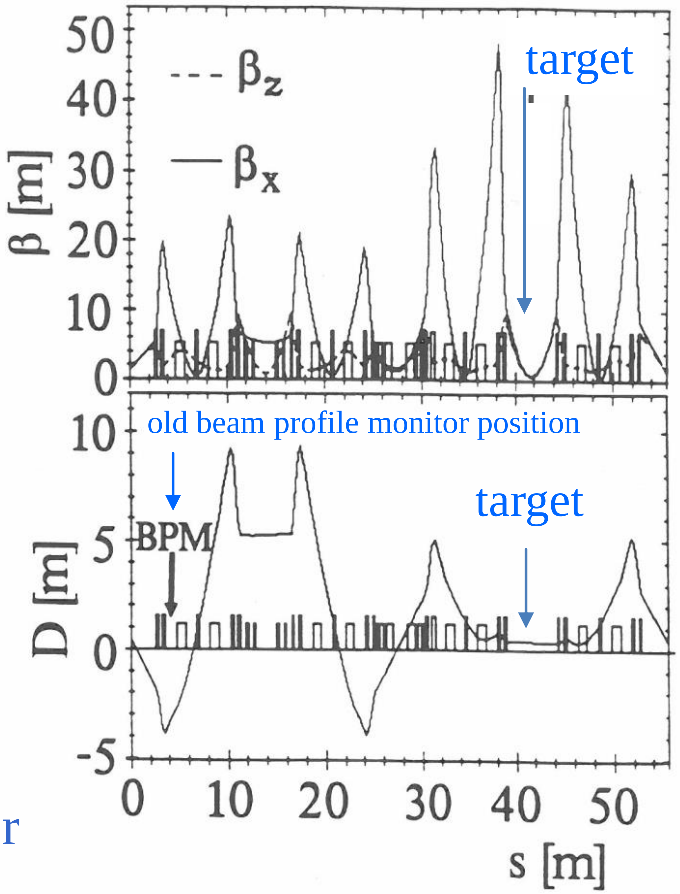
with $d_1 > d_2$ (symmetry position)

remark:
aperture protect
also detectors against
Injected ion beam

# Low Beta Mode ?



## Low Beta TSR Mode



In the low beta mode the number of quadrupole family is increased from 5 to 7,creating a small beta functions in the center of a straight section and increasing rapidly with s:

$$\beta(s) = ß_0 + \frac{s^2}{\beta_0}$$

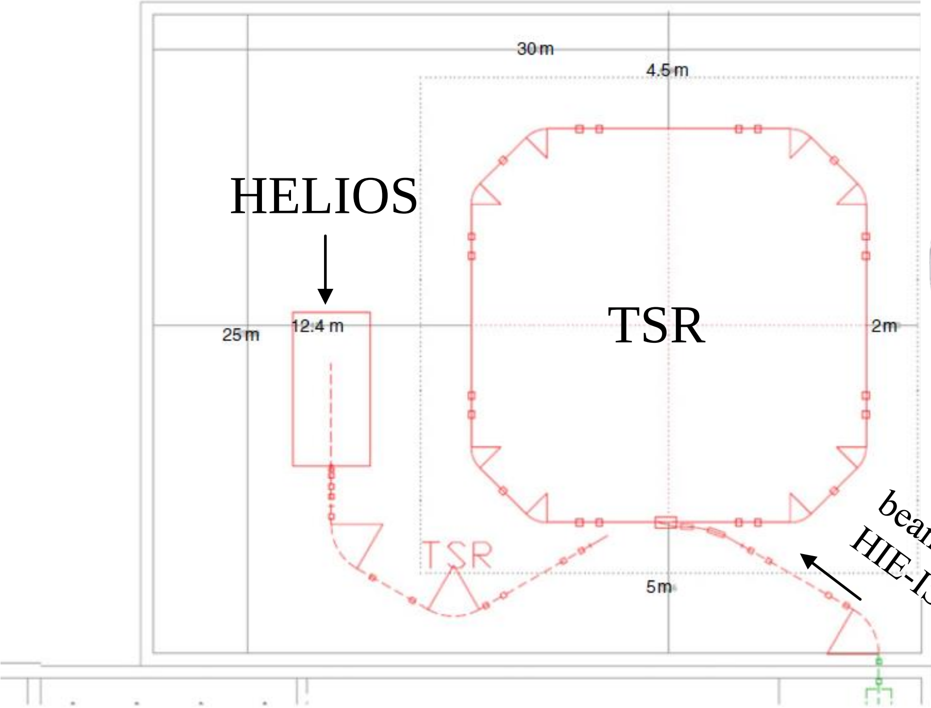
$ß_0$ beta function in the center

To benefit from the low beta mode fission detector has to be in the center of the straight section ⇒shift of the detectors towards center of straight section ⇒ required shift of the gas target downstream to the beam direction

# Cold ion beams for external spectrometer HELIOS

information about HELIOS spectrometer was given in the talk by Sean J Freemann at last TSR@ISOLDE workshop 2014 and will be given by Robert Page, tomorrow

possible location of HELIOS spectrometer

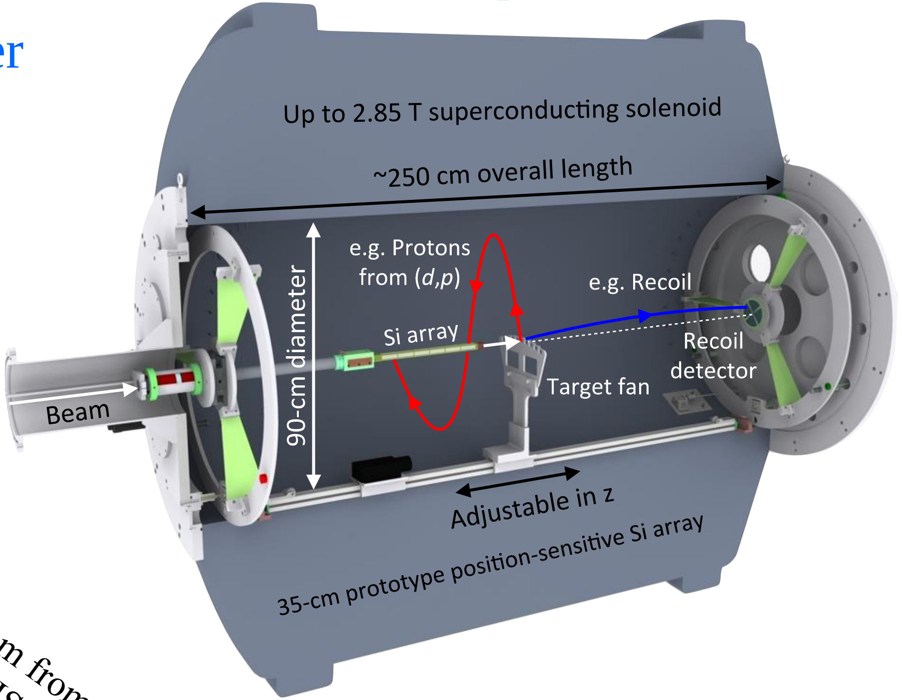


HELIOS

TSR

beam from HIE-ISOLDE

HELIOS spectrometer

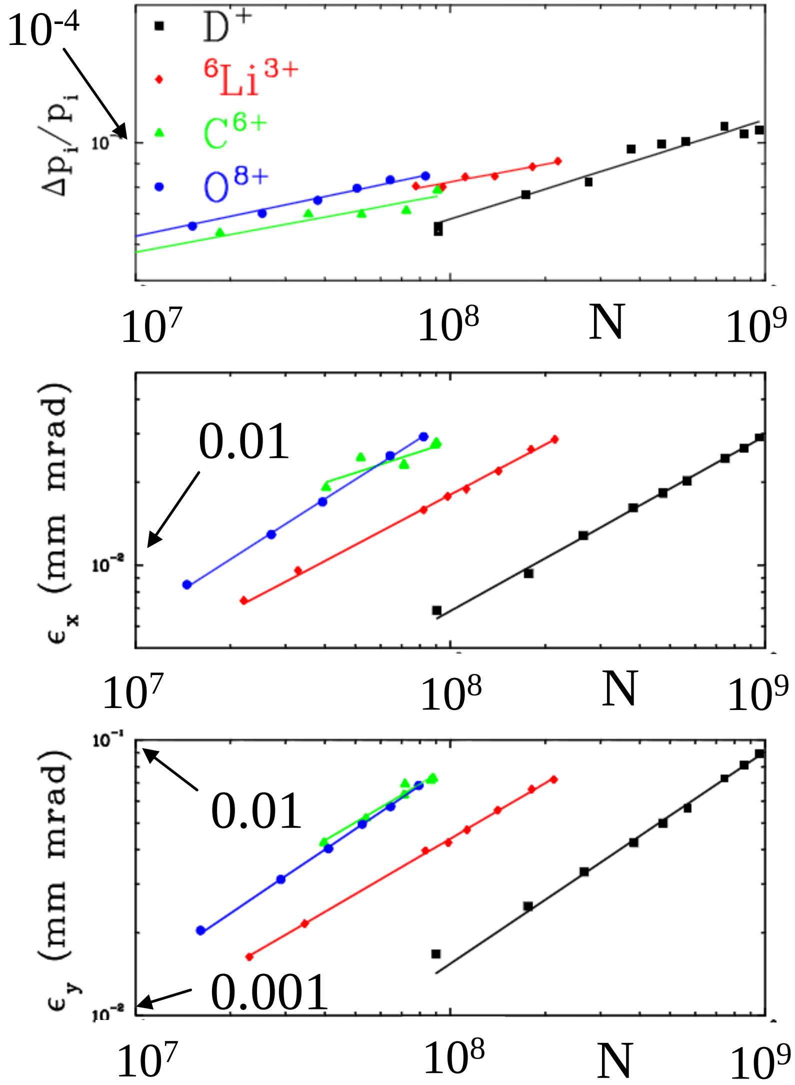


picture from talk of Sean J Freemann, TSR@ISOLDE 2014 workshop

beam requirement: transverse emittance ≤ 0.01 mm·mrad
FWHM energy spread ≈0.025%

Peter Butler, technical note, June 12 2014

# Emittance and momentum spread of an electron cooled ion beam



equilibrium emittances and momentum spread of cooled ion beams as a function of particle number for the ion species: $D^+$, $^6Li^{3+}$, $^{12}C^{6+}$ and $^{16}O^{8+}$

($n_e = 8\cdot 10^6$ cm$^{-3}$, Bcool=418 Gauss, $\beta$=0.11)

**definition of emittances:**

horizontal and vertical emittance is defined by the $\sigma$ values of the horizontal and vertical beam size:

$$\varepsilon_{x,y} = \frac{\sigma^2_{x,y}}{\beta_{x,y}}$$

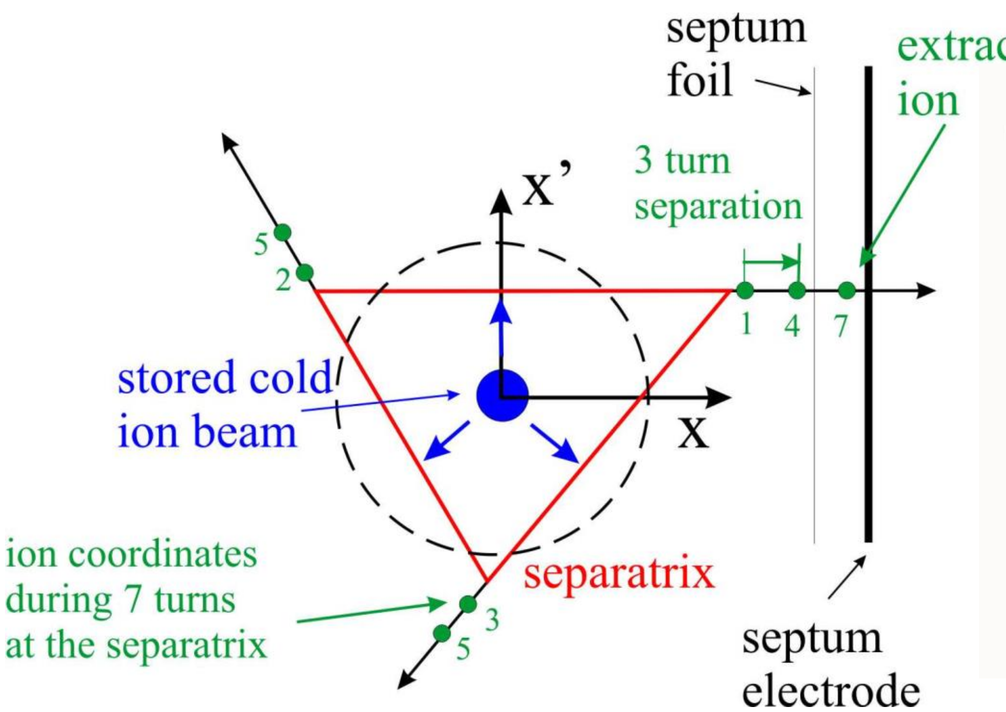
momentum spread:

momentum spread is rms value:

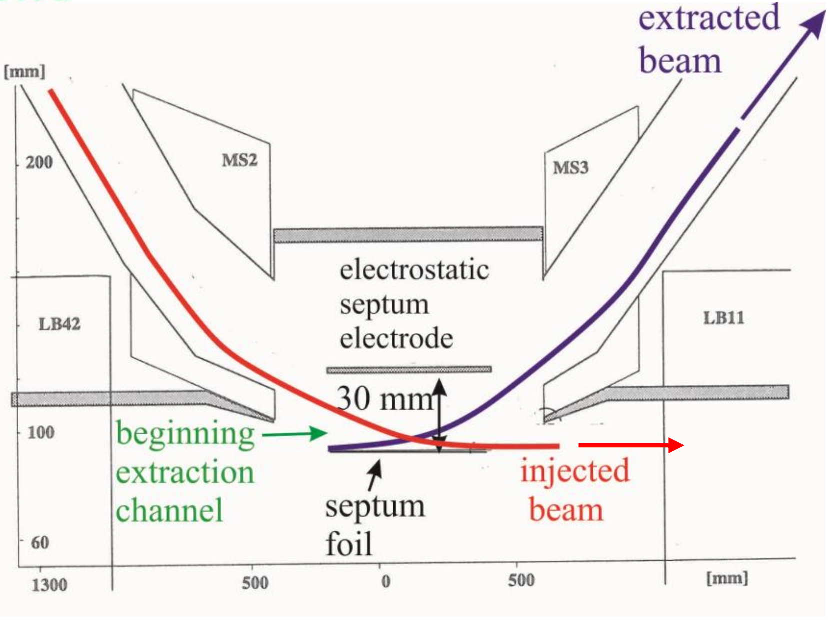
$$\frac{\Delta p_i}{p_i} = \frac{\Delta p_{rms}}{p_i} = \frac{1}{2}\frac{\Delta E_{rms}}{E} \Rightarrow \frac{\Delta E_{rms}}{E} = 0.01 - 0.02\%$$

# Slow Extraction at the TSR

## horizontal phase space



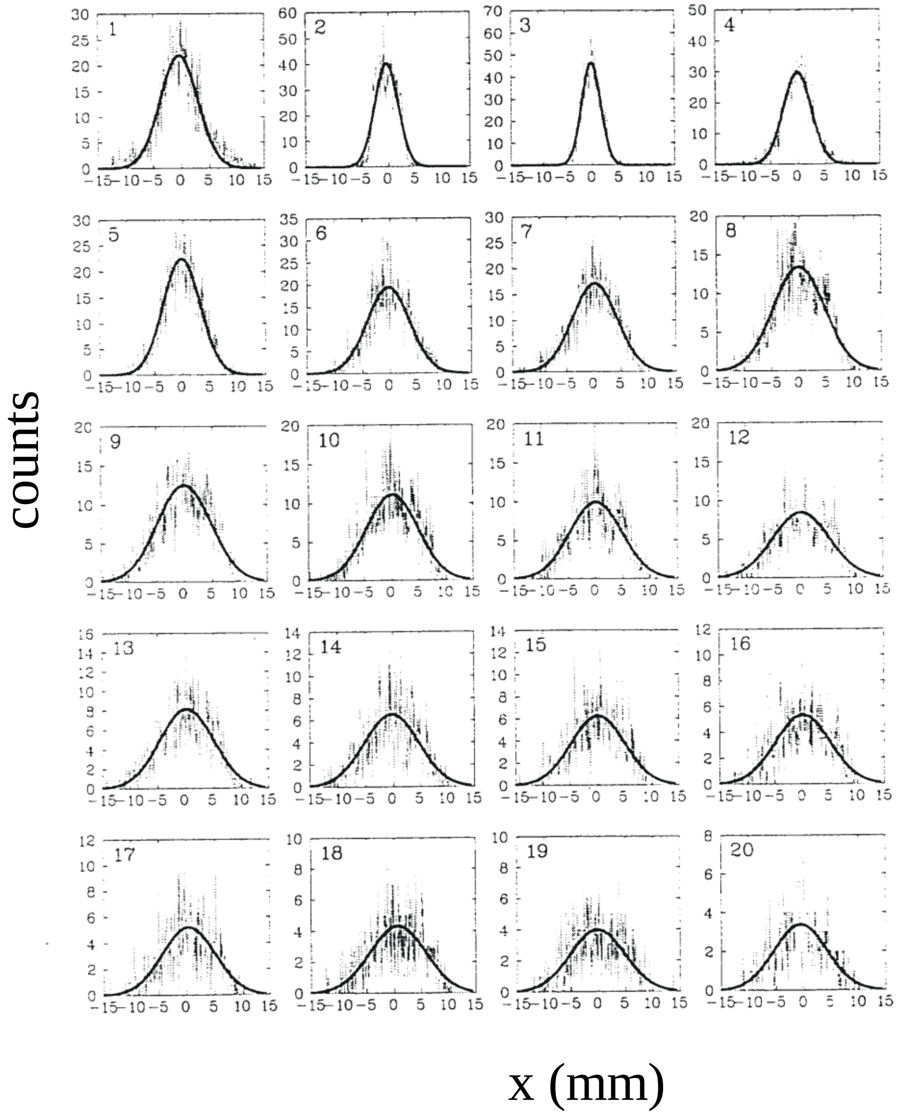
## electrostatic septum for injection and extraction

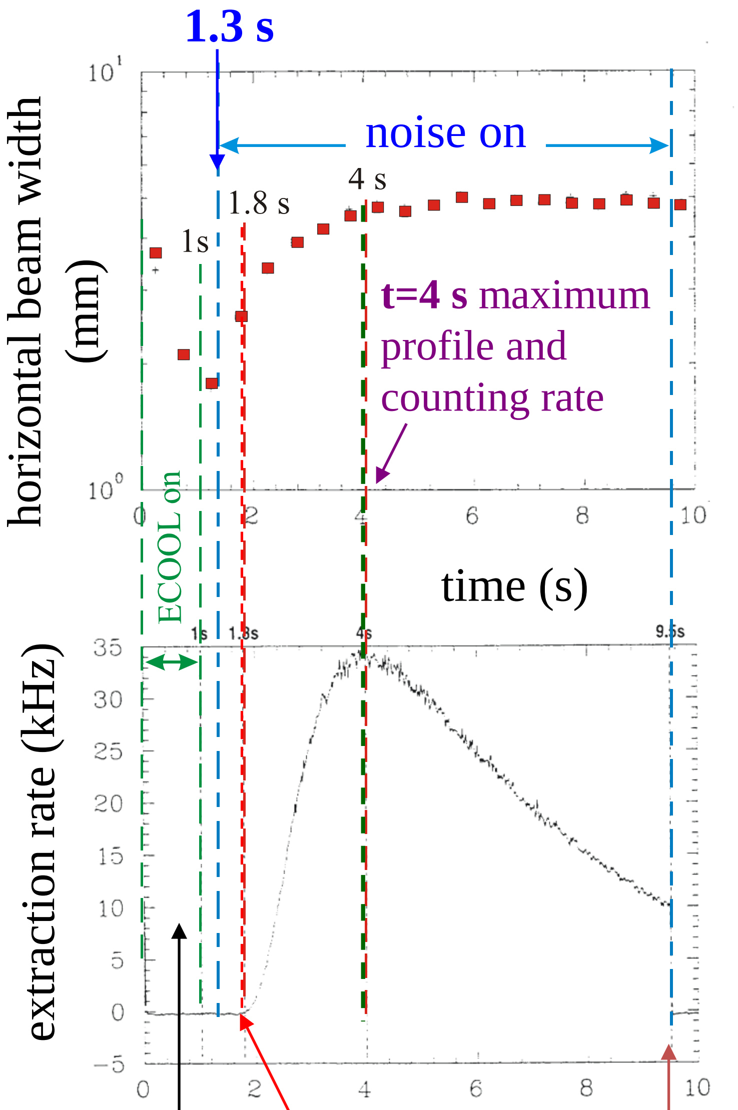


- working point shifted close to a third order resonance $Q_x=2.6666\ldots$
- third order resonance is exited by one or two sextupoles
- creating a separatrix around the stored ion beam
- inside the separatrix ions can be stored stable
- if ions reaches the separatix ions are moving along the separatrix towards the electrostatic septum foil, jumping into the field of the septum and are extracted
- excitation of betatron motion inside the separatrix is done by rf noise given to a kicker where the ECOOL has to be off
- with the noise level the extraction rate can be affected

# Extraction experiment with $^{12}C^{6+}$ E=73.3 MeV ions

Development of the horizontal beam profile





**1.3 s**

noise on

**t=4 s** maximum profile and counting rate

ECOOL on for **1s**

**1.8 s** the first ions are reaching the separatrix

noise off

# Measured emittance of the slow extracted beam

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

**Measured emittances of the slow extracted beam :**

number of injected ions: N= 2.7 $10^5$ (I=0.15 μA)

horizontally: $\varepsilon_{x,2\sigma}$= 1±0.2 mm·mrad ⇒ $\varepsilon_{x,\sigma}$=0.25±0.05 mm·mrad

vertically: $\varepsilon_{y,2\sigma}$=1.1±0.1 mm·mrad ⇒ $\varepsilon_{y,\sigma}$= 0.275±0.025 mm·mrad

stored ion beam: $\varepsilon_{y,\sigma}$= 0.245±0.019 mm·mrad

emittance definition: $\varepsilon_\sigma = \frac{\sigma^2}{\beta} = \varepsilon_{rms}$ $\quad \varepsilon_{2\sigma} = \frac{(2\sigma)^2}{\beta}$

**momentum spread of slow extracted beam:**

was not measured

**cooled stored beam without extraction**

$N=4\cdot10^7$

$\varepsilon_{x,\sigma}$= 0.02 mm·mrad

$\varepsilon_{y,\sigma}$= 0.04 mm·mrad

measured for

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

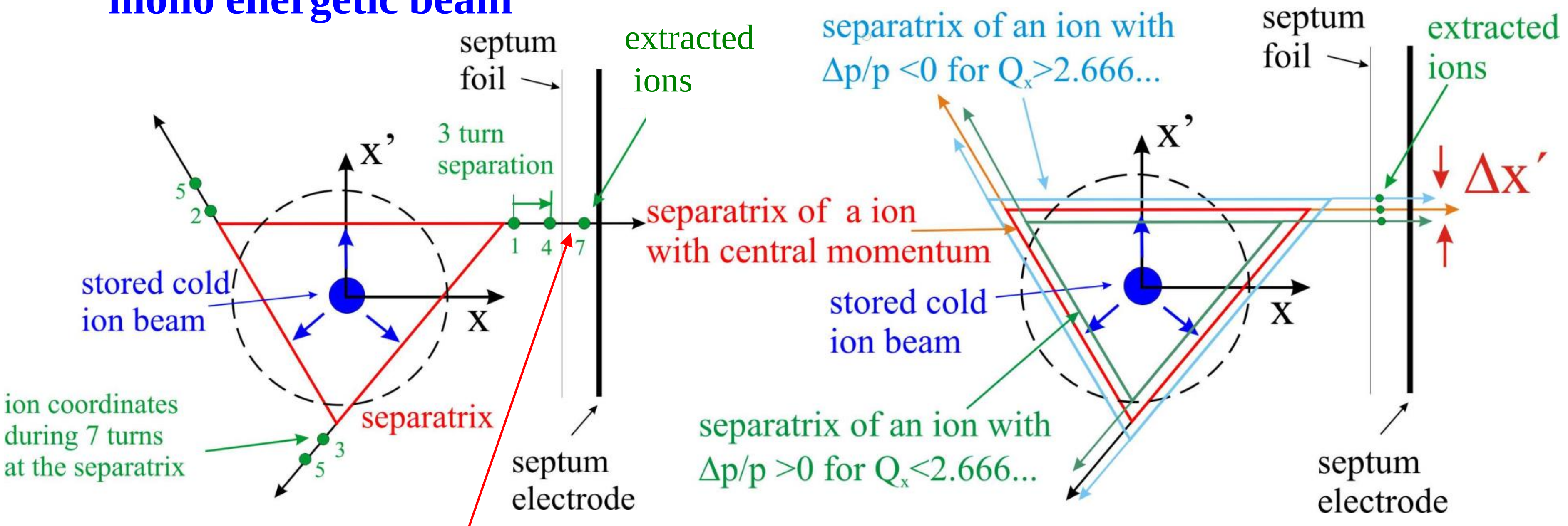
and $n_e=8\cdot10^6$ cm$^{-3}$

# Horizontal emittance of extracted beam

horizontal emittance of slow extracted beam is determined by the extraction method and momentum spread $\Delta p/p$

**mono energetic beam**

**beam with momentum spread**



ions are extracted along a straight line in the transverse phase space

$\Rightarrow \varepsilon = 0$ !

(for simplification the dispersion at the septum: D=0 m, D\`=0).

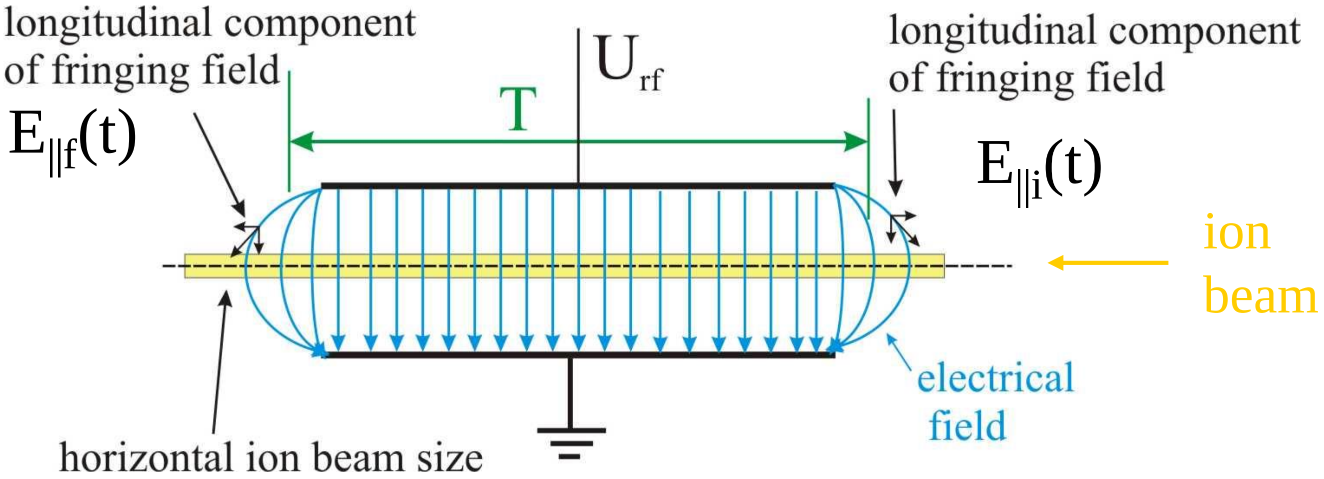
$\Rightarrow$ divergence $\Delta x'$ of extracted beam horizontal beam size $\Delta x$ is given by the three turn separation at septum position with $\Delta x' > 0 \Rightarrow \varepsilon > 0$

---

Hardt condition D'<0 for D>0 m (D-dispersion at septum) to suppress $\Delta x$\` cannot full filed

# Momentum spread

momentum spread of stored ion beam is affected by the rf noise field given to the kicker, used to increase the betatron amplitude during extraction



If the flight time to the kicker integer number of rf period $1/f_{rf}$

$$T = m\cdot T_{rf} = m\cdot 1/f_{rf} \Rightarrow E_{\parallel f}(t+mT_{rf}) + E_{\parallel i}(t) = 0$$

fringing field almost no effect to momentum spread !!

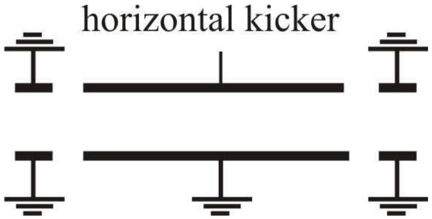
$$f_{rf} = f_0(n\pm q)$$

T- flight time through the kicker ,$f_{rf}$ -center frequency of rf noise, $f_0$-revolution frequency, n,m- integer number, q- non integer part of the tune $q\approx 0.66$,$C_0$- circumference, L- kicker length

⇒new extraction kicker working at relatively high frequencies $\approx C_0/L\cdot f_0$

⇒ condition

$$n\pm q = m\frac{C_0}{L} = \frac{C_0}{L} \quad \text{for } m=1$$



# Intra Beam Scattering (IBS) effects

-reduction of the longitudinal heating effects may reduce the momentum spread and improves the horizontal emittance of the extracted beam.

-But there is an increase of the horizontal, vertical and the momentum spread in the TSR due to IBS:

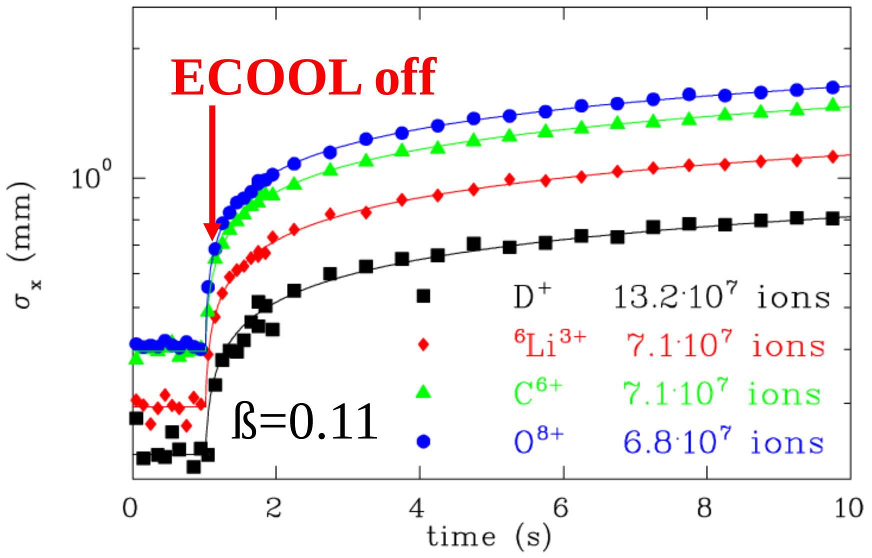
for the slow extraction process electron cooling has to switch off

⇒ blow up of the horizontal, vertical and momentum spread by IBS in the ring

-horizontal emittance of extracted beam not influenced by IBS, because it is determined by the slow extraction process

- but vertical emittance and the momentum spread of extracted beam are affected by IBS

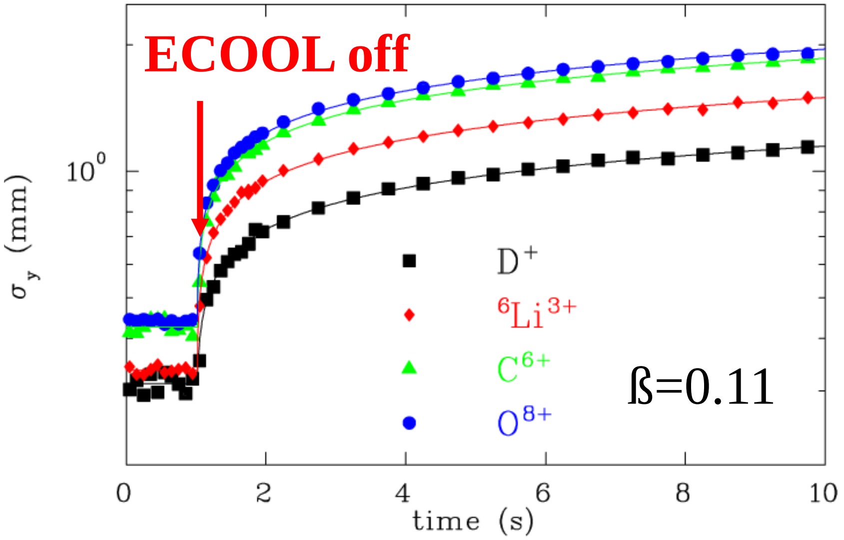
**horizontal beam width**



ECOOL off

ß=0.11

**vertical beam width**



ECOOL off

ß=0.11

# Modifying the slow extraction scheme

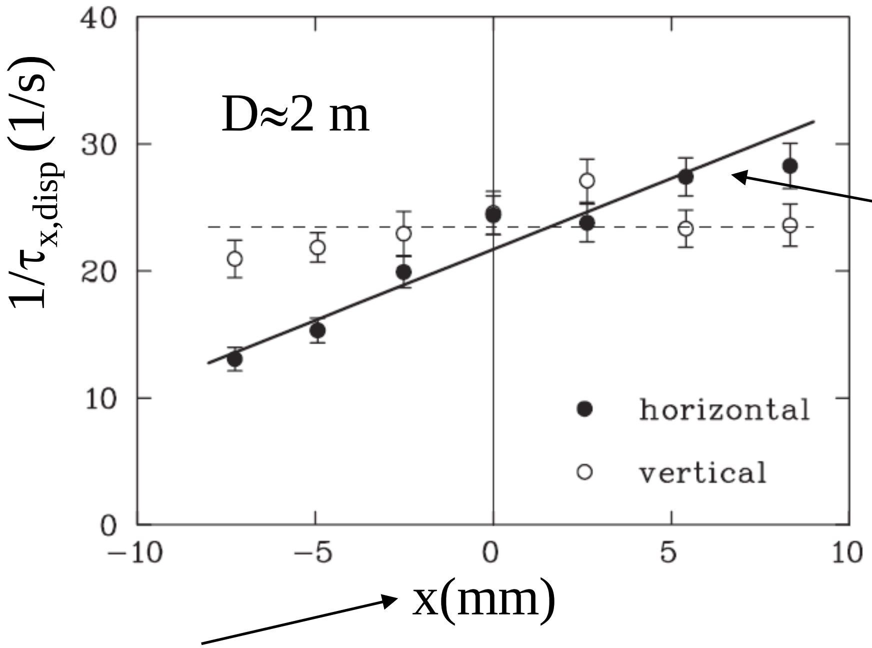
-electron **cooling has to be permanent on** to cool the vertical and longitudinal degree of freedom during the extraction process

-increase the horizontal rf noise level to overcome electron cooling force

-this process can be supported by **dispersive electron cooling** where the horizontal cooling force are transferred in the longitudinal degree of freedom, or opposite .

**horizontal and vertical cooling rate**

measured with 73 MeV $^{12}C^{6+}$



horizontal position of the ion beam to the center of electron beam

**Dispersive electron cooling** is realized by using an horizontal gradient in the horizontal cooling force realized by shifting the electron beam and applying dispersion in the electron cooler

$$\frac{1}{\tau_{x,disp}} = \frac{1}{\tau_{x,0}} + \eta_c \frac{\alpha_D D}{p_0} \alpha_\parallel \cdot x$$

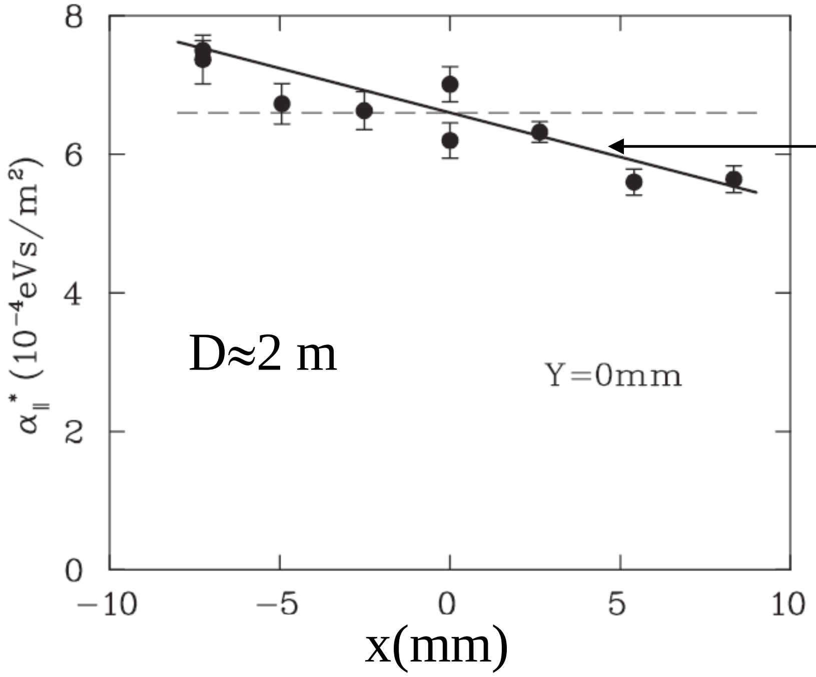
$$\alpha_D = e^2 n_e / (4\varepsilon_0 m_e v_0)$$

$$n_e = 8 \cdot 10^6\,\mathrm{cm}^{-3} << n_{e,max} = 5.6 \cdot 10^7\,\mathrm{cm}^{-3}$$

⇒switching off horizontal cooling and horizontal heating with the electron beam should be possible !! ⇒ noise reduction transferred to the horizontal kicker

# Dispersive electron cooling, longitudinal cooling force

Longitudinal friction coefficient $\alpha_{\|}^{*}=-\frac{\partial F_{\|}(v_{\|})}{\partial v_{\|}}$



$F_{\|}(v_{\|})$- longitudinal cooling force

$$\alpha_{\|}^{*}=\alpha_{\|}\cdot(1-2\cdot\alpha_{D}D/v_{0}\cdot x)$$

$$n_{e}=8\cdot10^{6}\,cm^{-3} << n_{e,max}=5.6\cdot10^{7}\,cm^{-3}$$

Transverse cooling force is transferred to longitudinal cooling by dispersive electron cooling

$\alpha_{\|}+\alpha_{x}+\alpha_{y}$=constant

transfer of cooling force

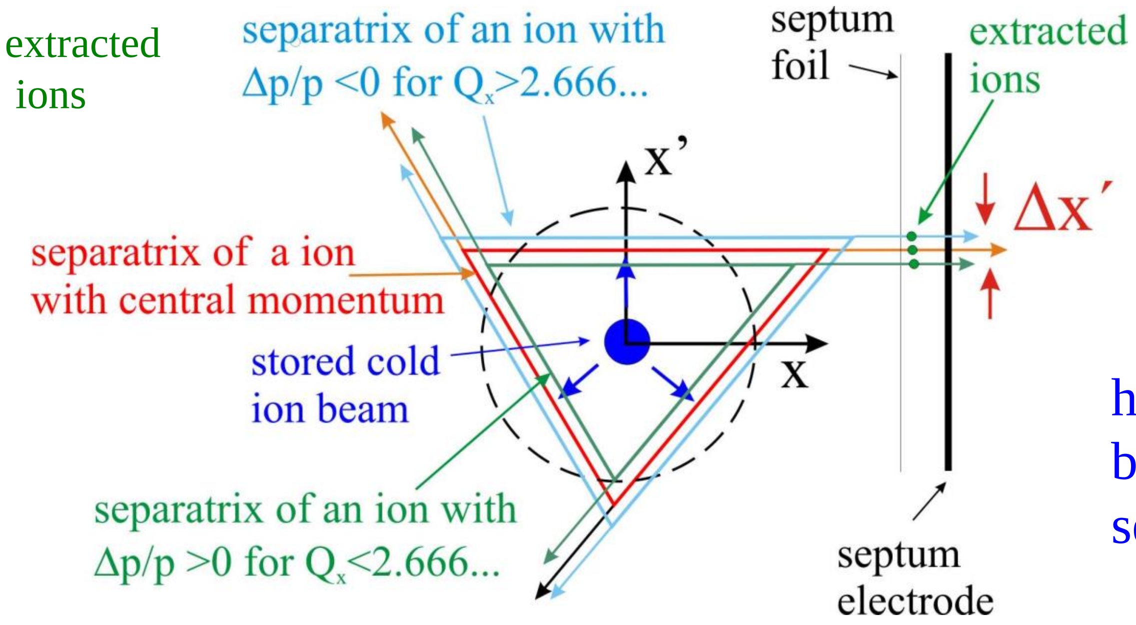
vertical cooling force remains constant

Active vertical and improved longitudinal ($\alpha_{\|}\rightarrow0$ or $\alpha_{\|}<0$ ) electron cooling during the slow extraction process !

Enhanced active longitudinal electron cooling will reduce the horizontal emittance of the slow extracted beam significantly !

# Horizontal emittance of slow extracted beams

horizontal emittance of slow extracted beam is determined by the extraction method and momentum spread $\Delta p/p$



compression of $\Delta x'$ with active and improved longitudinal electron cooling
$\Rightarrow$**significant reduction of the horizontal beam emittance !**

horizontal beam size $\Delta x$ is given by the three turn separation at septum position

(for simplification the dispersion at the septum: D=0 m, D`=0,
this condition is approximately fulfilled at the TSR if dispersive electron cooling is applied).

-This slow extraction scheme combined with dispersive electron cooling is not tested so far !!!

---

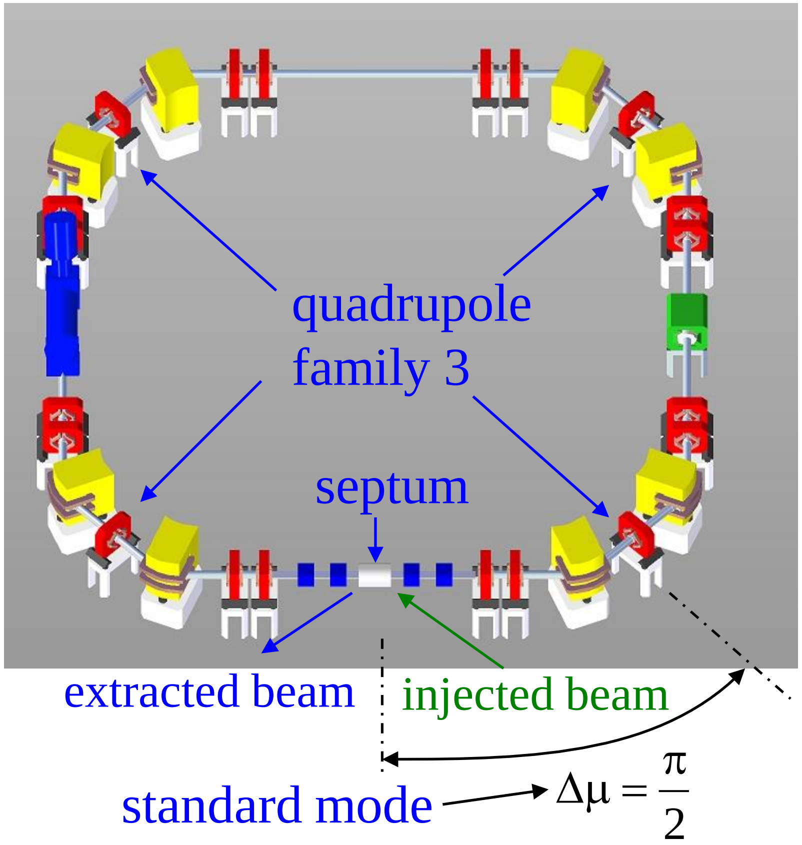
Alternatively **fast extraction** can be used to extract an cold ion beam

# Fast extraction at the TSR

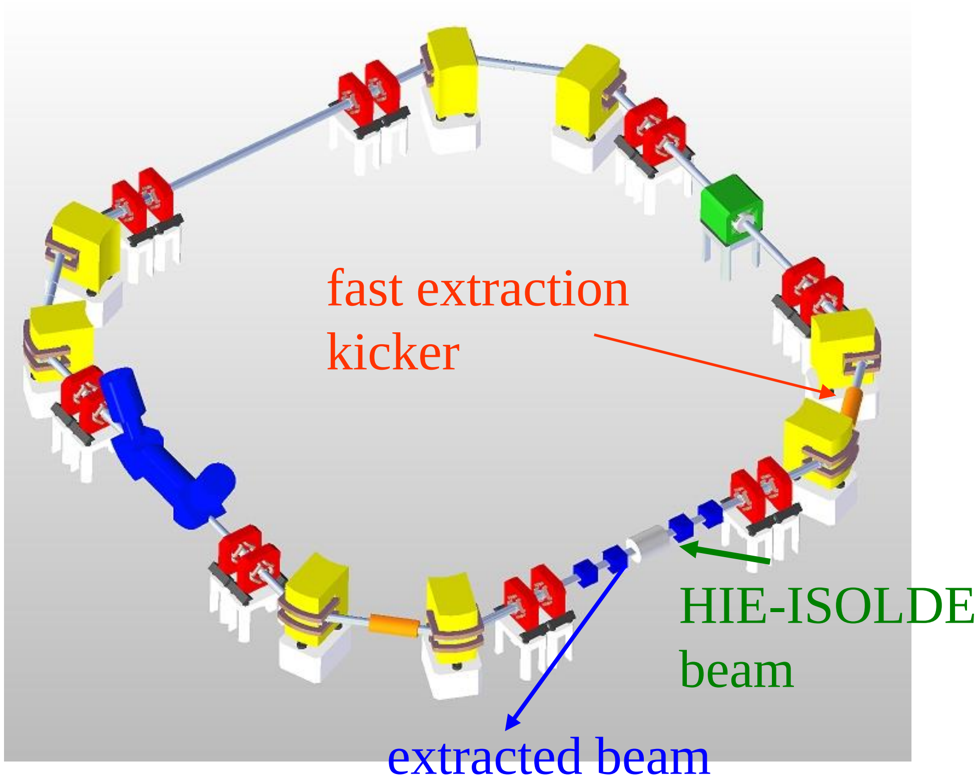
For fast extraction the phase advance between kicker and electrostatic septum:

$$\Delta\mu_x = \int_{\text{kicker}}^{\text{septum}} \frac{1}{\beta_x} ds = \frac{\pi}{2}$$

**location of fast extraction kicker**



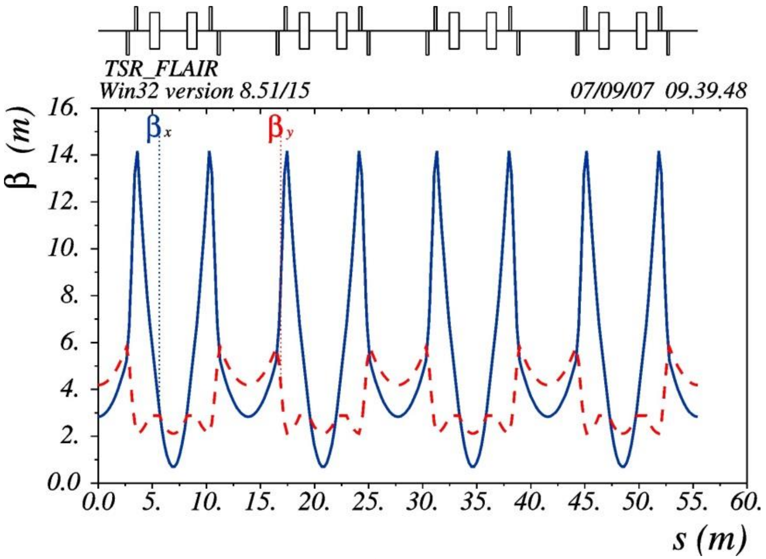
-extraction kicker huge device
- dimensions only very roughly known
-worst case: removing quadrupole family 3 to provide enough space for the kicker



# TSR lattice with four quadrupole families

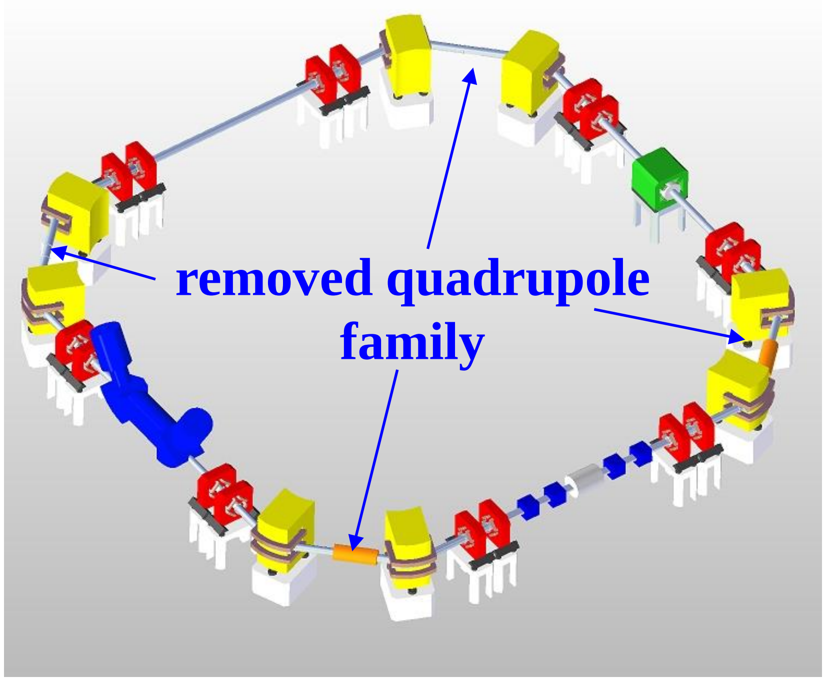
ß function

**Standard Mode**



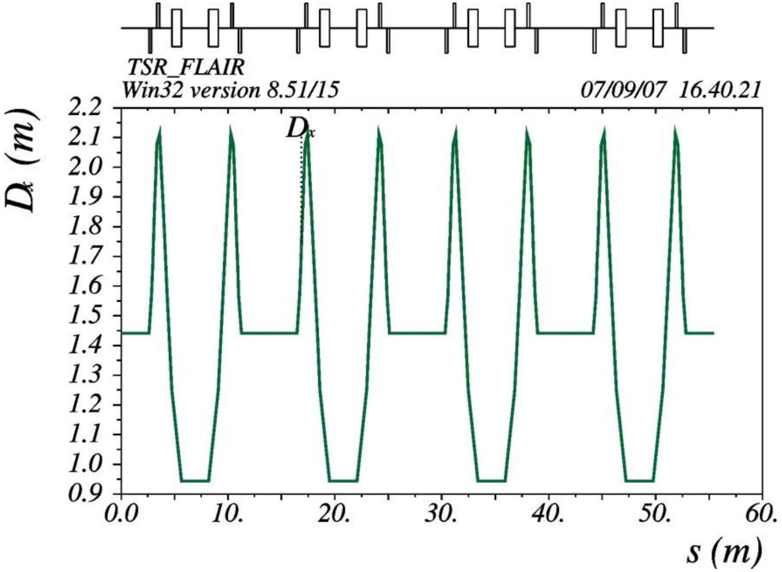
**SP=4**

$Q_x$=2.84
$Q_y$=2.91



**removed quadrupole family**

dispersion function



# Fast Extraction

septum deflection angle α=40 mrad

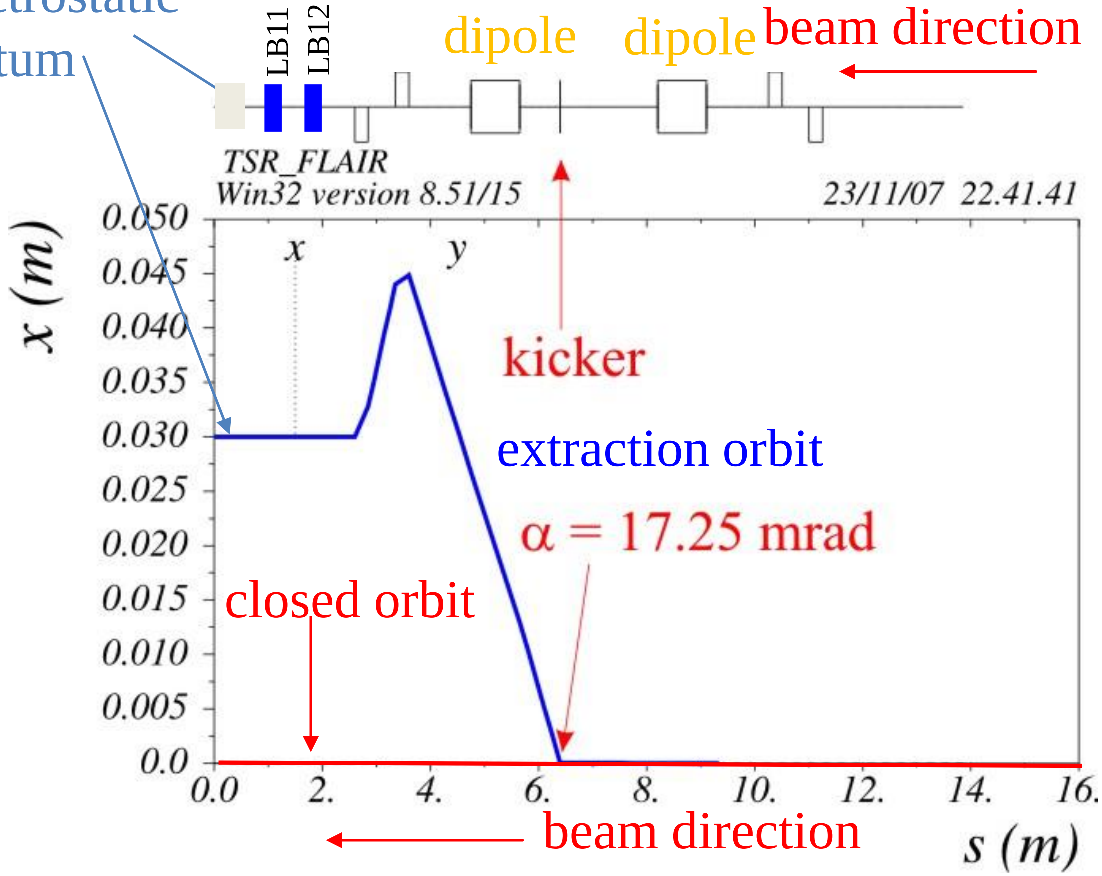
electrostatic septum

dipoles

dipole

dipole

beam direction



kicker

extraction orbit

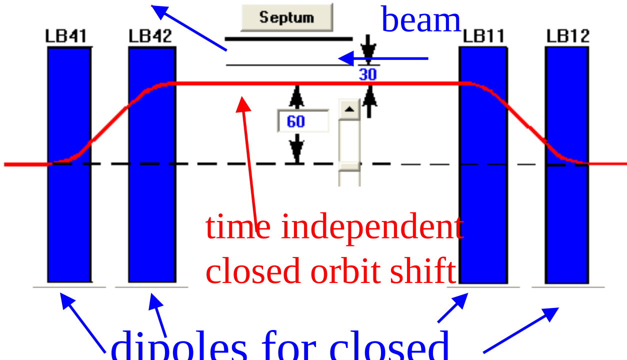
α = 17.25 mrad

closed orbit

beam direction

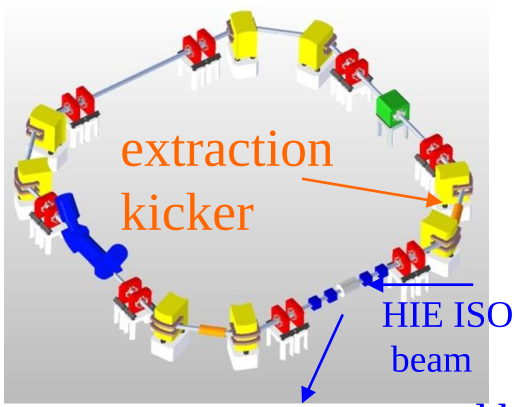
to experiment

extracted beam



time independent closed orbit shift

dipoles for closed orbit shift



extraction kicker

HIE ISOLDE beam

extracted bean

- For fast extraction the closed orbit is shifted permanently towards the electrostatic septum by about 60 mm
- a fast kicker deflect the ion beam by around 17 mrad. Leading to a beam deflection of 30 mm at the location of electrostatic septum, therefore the total beam deflection in front of the septum is 30+60mm=90 mm
- In the electrostatic septum the extracted ion beam is deflected by about 40 mrad and transferred to the experiments

# Fast extraction kicker specifications

## fast kicker specification for a rough cost estimation from CERN

maximum beam rigidity: 1.5 Tm
deflection angle: about 20 mrad
response time (from B=0T to 0.9 $B_{max}$): about 200 ns (roughly), preferable 100 ns
maximum length of the kicker: below 1 m (if possible)
(to avoid removing of quadrupole family 3)
kicker chamber (inside): horizontal width of at least 100 mm, 200 mm (preferable)
vertical height: ≥ 55 mm

remark: kicker has switching time, defined by the respond time
coasting beam: causes movement of the extracted beam
to avoid movement → bunching + ECOOL → increasing of emittance and momentum spread

## kicker specification requirements fulfills:

-two modules of the **LEIR/CERN** extraction kicker
-fast injection kicker for **ELENA/CERN** (roughly)
**remark:** fast ELENA injection kicker can be used also as an extraction kicker fulfilling our demand for an 20 mrad deflection angle at $B\rho$=1.5 Tm,
but the field quality of the horizontal field is less than expected

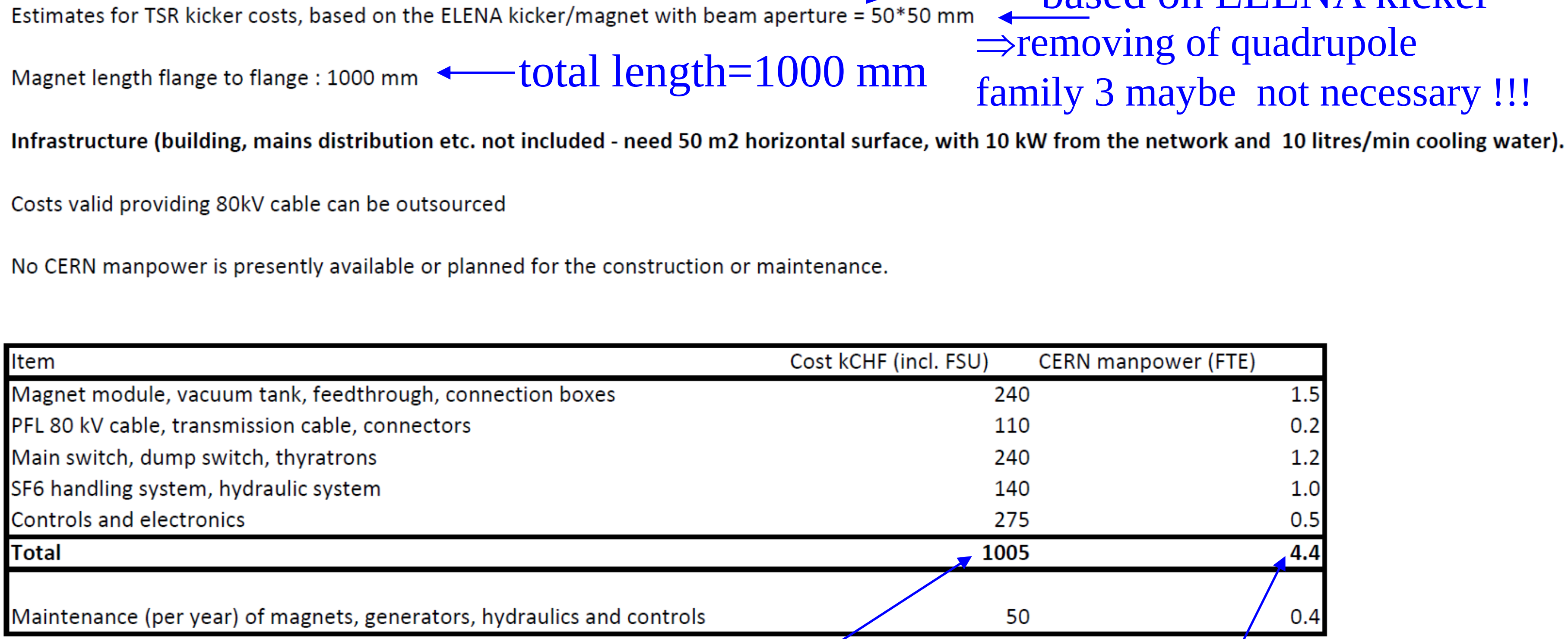
# Rough cost estimation for the extraction kicker

very rough cost estimation from **Brennan Goddard** and **TE-ABT group/CERN** from 14. April 2015

can increased to 100x55 mm

based on ELENA kicker
⇒removing of quadrupole family 3 maybe not necessary !!!

total length=1000 mm



Estimates for TSR kicker costs, based on the ELENA kicker/magnet with beam aperture = 50*50 mm

Magnet length flange to flange : 1000 mm

**Infrastructure (building, mains distribution etc. not included - need 50 m2 horizontal surface, with 10 kW from the network and 10 litres/min cooling water).**

Costs valid providing 80kV cable can be outsourced

No CERN manpower is presently available or planned for the construction or maintenance.

| Item | Cost kCHF (incl. FSU) | CERN manpower (FTE) |
|---|---|---|
| Magnet module, vacuum tank, feedthrough, connection boxes | 240 | 1.5 |
| PFL 80 kV cable, transmission cable, connectors | 110 | 0.2 |
| Main switch, dump switch, thyratrons | 240 | 1.2 |
| SF6 handling system, hydraulic system | 140 | 1.0 |
| Controls and electronics | 275 | 0.5 |
| **Total** | **1005** | **4.4** |
| | | |
| Maintenance (per year) of magnets, generators, hydraulics and controls | 50 | 0.4 |

total cost: 1005 kCHF     CERN manpower: 4.4 FTE

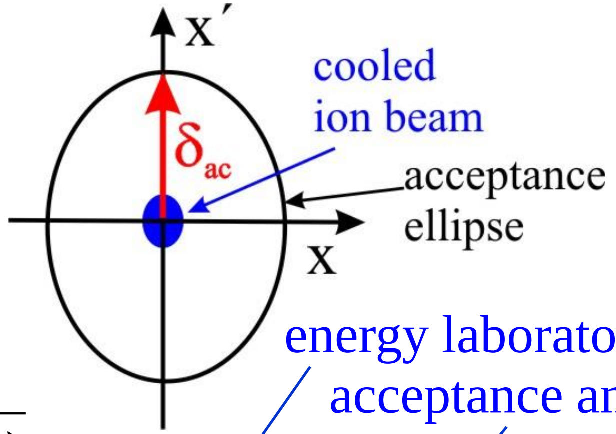
Maintenance of magnets, generators etc. : 50 kCHF per year

# Acknowledgement

Peter Butler, University of Liverpool, Liverpool
Brennan Goddard, CERN, Geneva
Beatriz Jurado, CENBG, Gradignan
Shabab Sanjari, GSI, Darmstadt
Luc Sermeus, CERN, Geneva
Fredrik Wenander, CERN, Geneva

# back-up

# Single scateing in gas targets



-CMS System Rutherford scattering:

$$\frac{d\sigma}{d\Omega}=\frac{1}{4}\left(\frac{q\cdot Z\cdot e^2}{4\cdot\pi\cdot\varepsilon_0\cdot 2\cdot E_s}\right)^2\frac{1}{\sin^4(\Theta/2)}$$

energy laboratory system

acceptance angle laboratory system

$$E_s=\frac{m_t}{m+m_t}E$$

$$\tan(\delta_{ac})=\frac{\sin(\varphi_{ac})}{\cos(\varphi_{ac})+\frac{m_t}{m}}$$

⇒ cross section for particle loss

$$\sigma_{sc}=\int_{\varphi_{ac}}^{\pi}\frac{d\sigma}{d\Omega}\cdot 2\pi\sin(\Theta)d\Theta=\frac{e^4\cdot q^2\cdot Z^2}{64\cdot\pi\cdot\varepsilon_0^2\cdot E_s^2}\cot^2(\frac{\varphi_{ac}}{2})$$

acceptance angle
CMS system

$$\delta_{ac}\approx 5\,\text{mrad}$$

⇒ life-time

$$T_{sc}=\frac{1}{\sigma_{sc}\cdot n_t\cdot f_0}$$

$^{232}$Th$^{71+}$ E=2320 MeV and $^{3}$He target with $n_t=10^{13}$ 1/cm$^2$:

$T_{sc}\approx$ 14000 s (negligible)

# ECOOL stacking with $^{12}C^{6+}$ ions (E=73.3 MeV) at the TSR

## Intensity increase during ECCOL stacking

$$\frac{dI(t)}{dt} = n_r I_m - \frac{I(t)}{\tau}$$

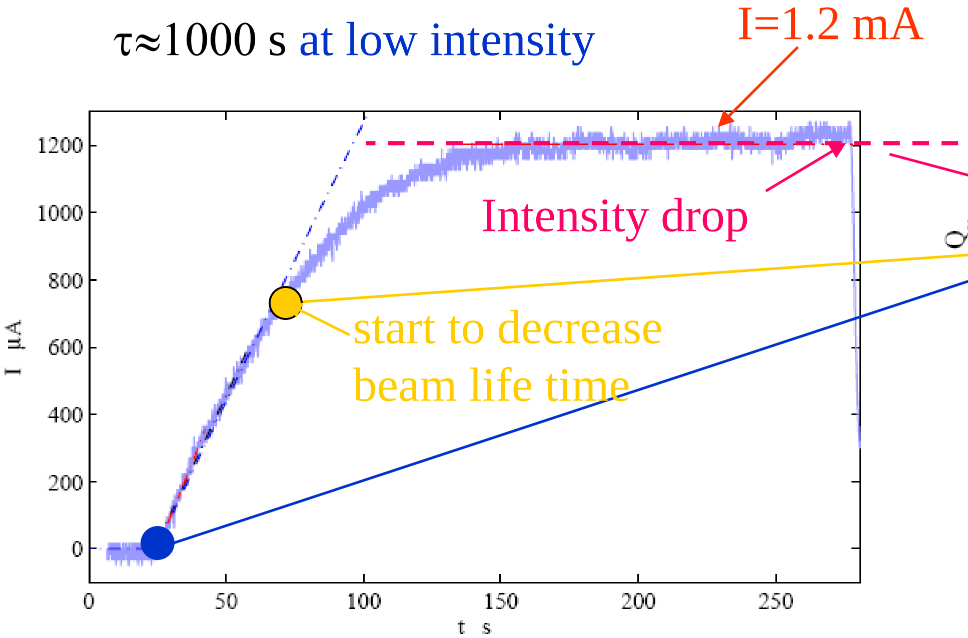
I(t)-stored intensity

$I_m$-intensity stored with a multi turn injection

$n_r$ injection rate

τ beam life time

τ≈1000 s at low intensity

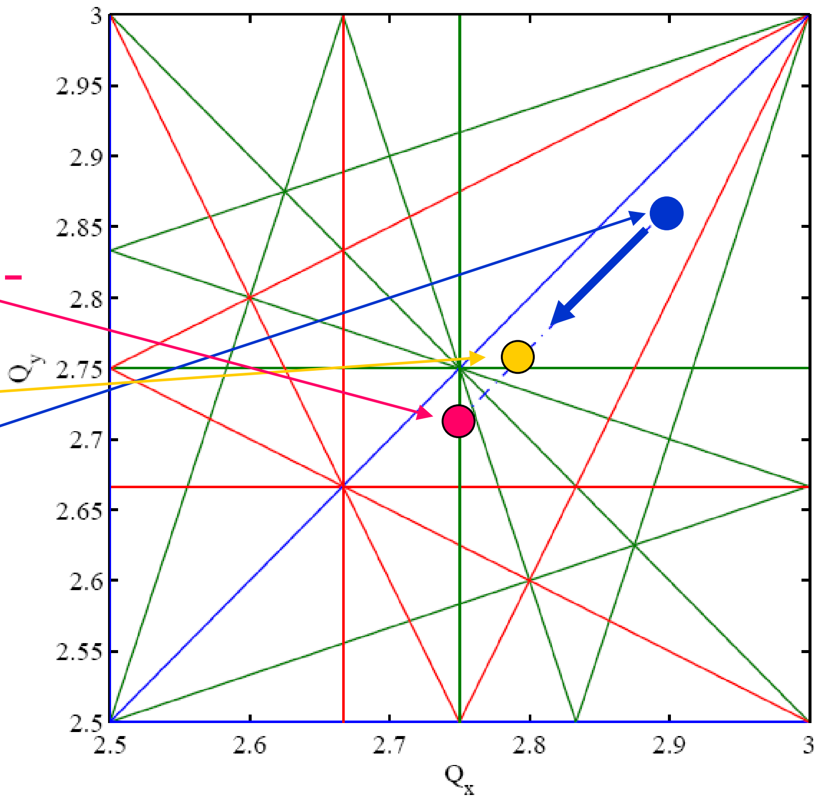


I=1.2 mA

Intensity drop

start to decrease beam life time

### working diagram



fourth order resonance Q=2.75 should be avoided !

possible incoherent tune shift without reducing beam life time: $\Delta Q \approx 0.1$

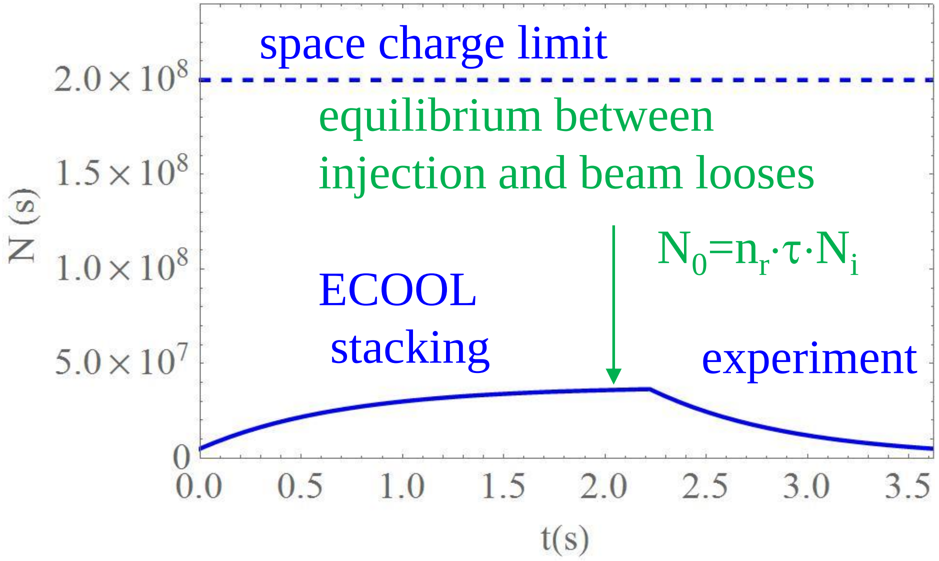
$Q_x$=2.75

🟩 fourth order resonances

🟥 third order resonance

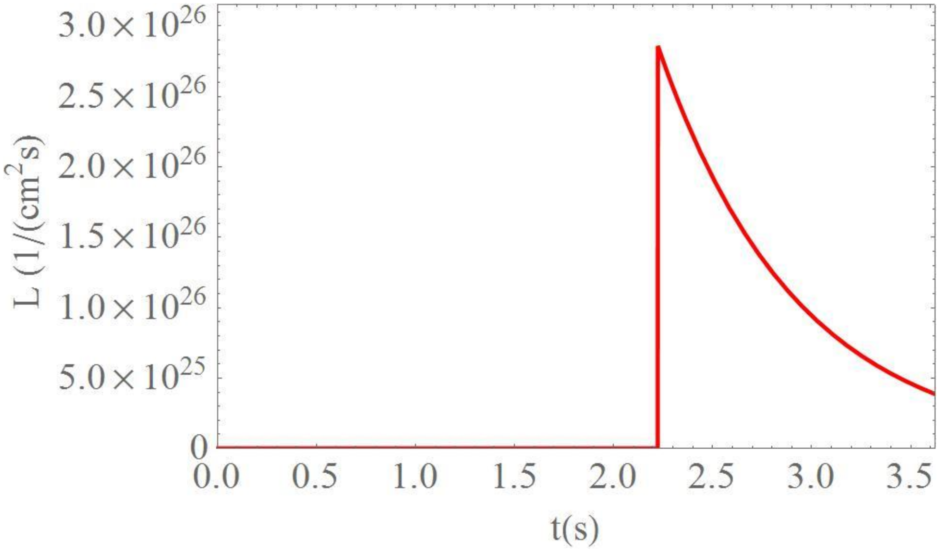
# Ion Number and Luminosity

**periodical change of N(t)**



target on

**periodical change of luminosity**



life time: $\tau_1$=0.7 s

4 multi turn injections
with $N_i = 3 \cdot 10^7$ ions
and $n_r = 1.8$ 1/s

life time: $\tau_2$=0.7 s

measuring time
per period:
$2 \cdot \tau_2$

$n_t = 10^{13}$ 1/cm²

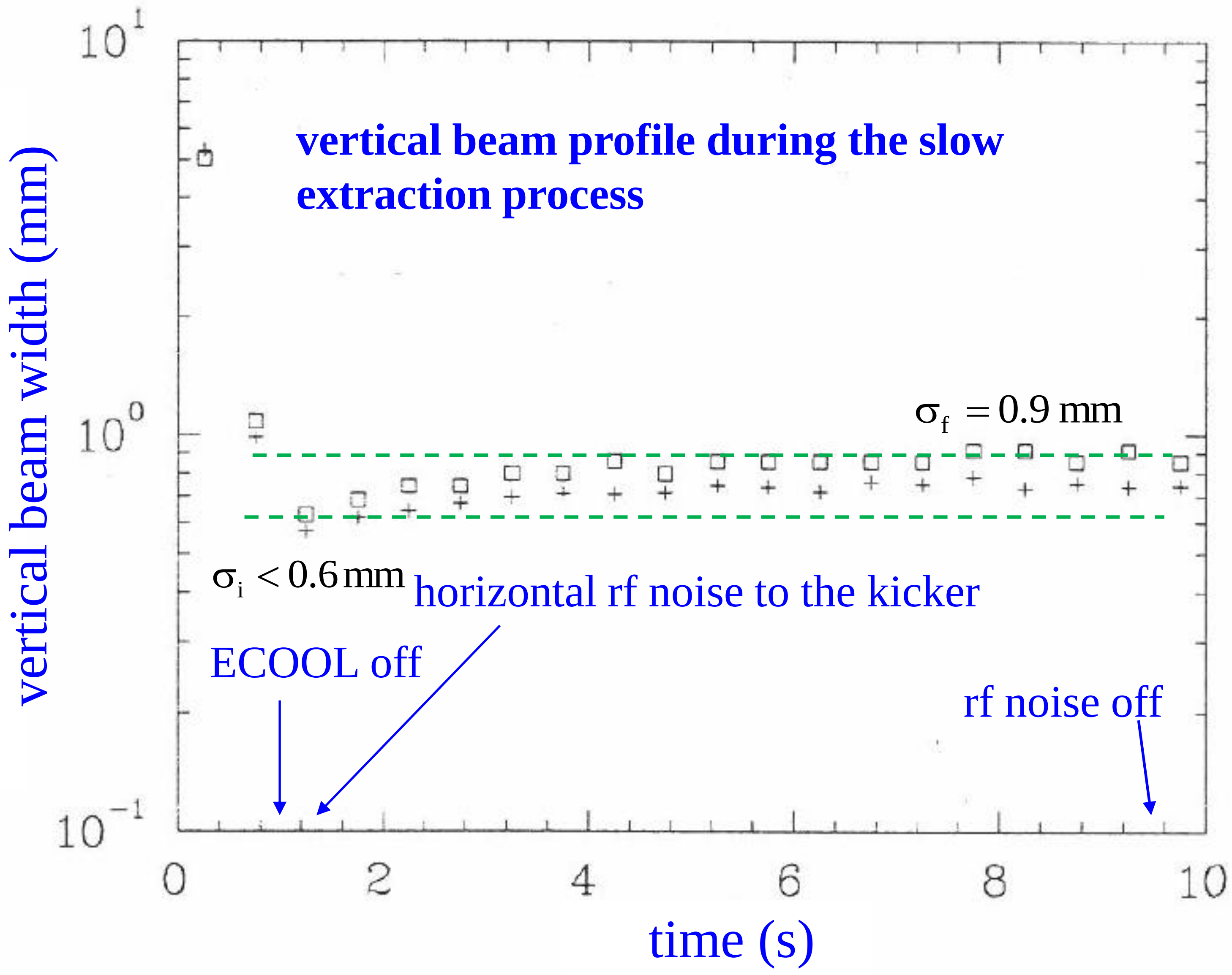
**average luminosity:**

$$\overline{L} = \frac{1}{T}\int_0^T L(t)\,dt$$

$$\overline{L} = 4.8 \cdot 10^{25}\, 1/(\mathrm{cm}^2 \mathrm{s})$$

for $^{232}\mathrm{Th}^{71+}$ beam E=2320 MeV
($f_0$=0.786 MHz)

# Time development of the vertical beam profile



**vertical beam profile during the slow extraction process**

$\sigma_f = 0.9\,\mathrm{mm}$

$\sigma_i < 0.6\,\mathrm{mm}$

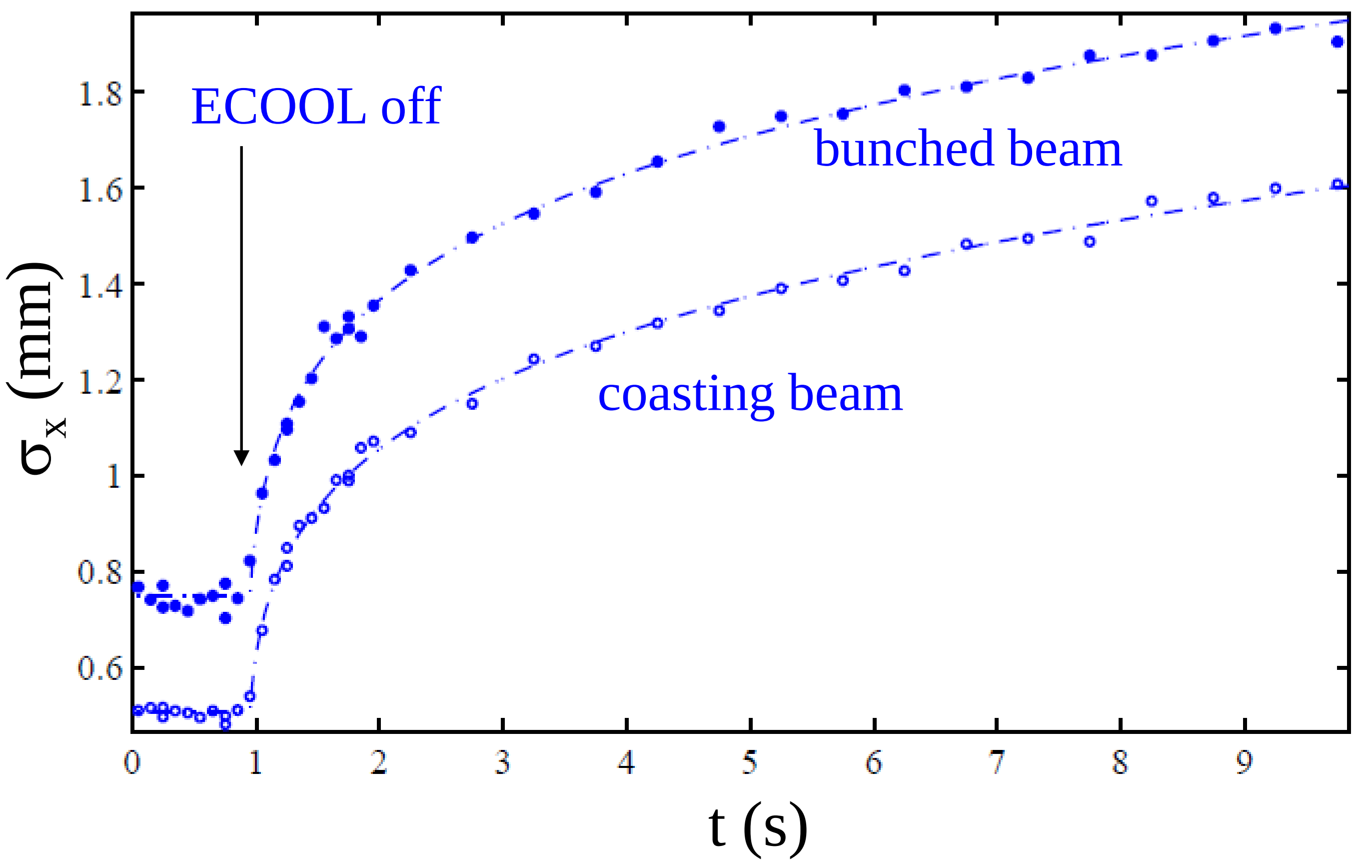
horizontal rf noise to the kicker

ECOOL off

rf noise off

# Comparison of bunched and coasting beams

**horizontal beam profile**



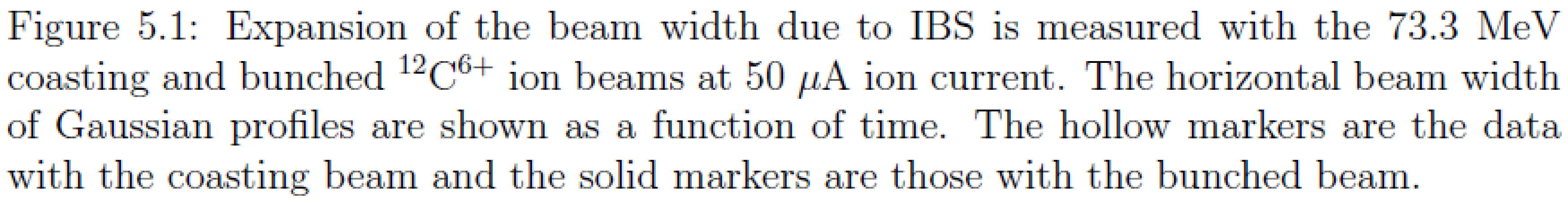
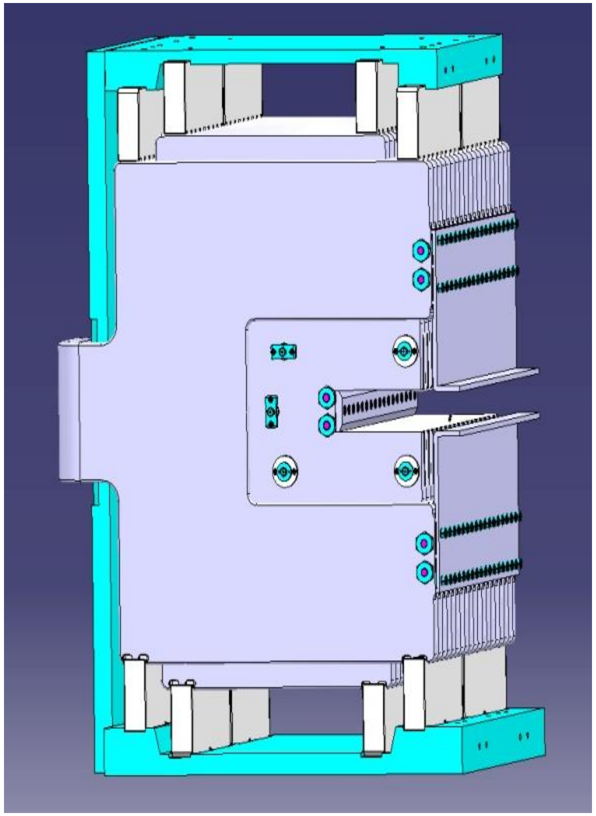


Figure 5.1: Expansion of the beam width due to IBS is measured with the 73.3 MeV coasting and bunched $^{12}C^{6+}$ ion beams at 50 $\mu$A ion current. The horizontal beam width of Gaussian profiles are shown as a function of time. The hollow markers are the data with the coasting beam and the solid markers are those with the bunched beam.

# Elena Injection kicker →TSR fast extraction kicker ?

- Existing (1986), from AA ring
- Magnet installed into new vacuum tank to be bakeable upt 300 deg in situ
- HV power converter recuperated from AAC
- PFL (SF6, 15 Ohm, 40kV) discharged by fast thyratron switches
- Terminated by matched resistor
- Pulse length can be adjusted with a dump thyratron
- Polarity reversal by swapping HV in/out cables in magnet connection box



slide from Wolfgang Bartmann (CERN), ELENA review CERN,15-16 October 2013

# ELENA Injection kicker parameters

slide from Wolfgang Bartmann (CERN), ELENA review CERN,15-16 October 2013

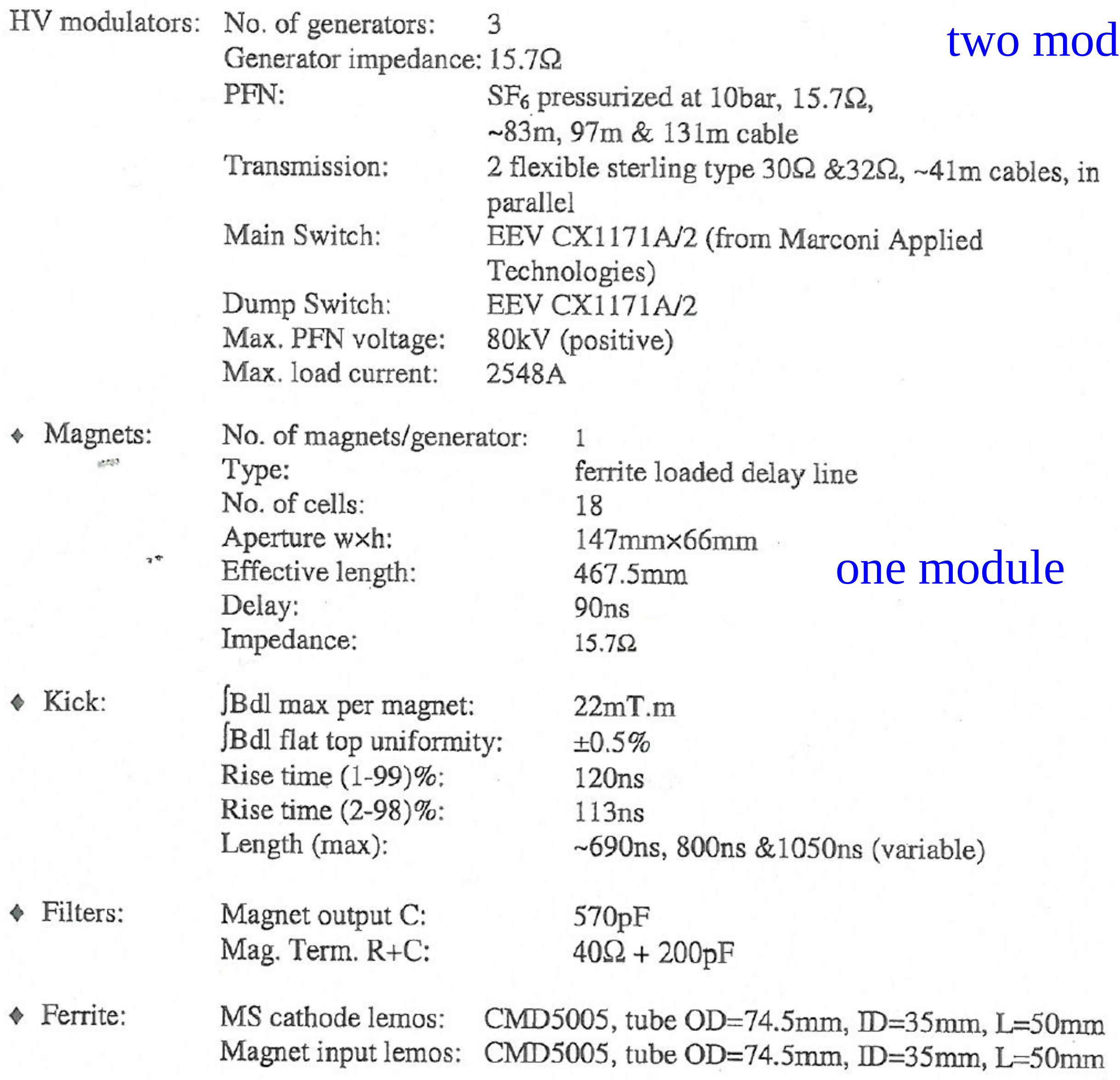
| **Injection kicker magnet data** | **Unit** | |
|---|---|---|
| **Required angle @5.3 MeV** | mrad | **84** |
| **Effective magnetic length** | mm | **432** |
| **Maximum B.l** | mT.m | **31.36** |
| **Rise/Fall time (2-98) %** | ns | **200** |
| **Flat top (max)** | ns | **~600** |
| **Aperture w × h** | mm × mm | **110 × 45** |
| **Good field region, h × v (nominal ± 1 %)** | mm × mm | **72 × 36** |
| **Magnet impedance** | Ω | **15** |
| **Magnet transit time** | ns | **106.2** |
| **Magnet termination** | Ω | **15** |
| **Maximum magnet current/voltage** | kA/kV | **2600/40** |
| **B max** | mT | **72.6** |
| **Remnant B.l max** | µT.m | **75** |

too small

too small

# LEIR extraction kicker

from PIL/LEIR design report, C.Carli, M. Chanel, S. Maury



| | | |
|---|---|---|
| HV modulators: | No. of generators: | 3 |
| | Generator impedance: | 15.7Ω |
| | PFN: | $SF_6$ pressurized at 10bar, 15.7Ω,<br>~83m, 97m & 131m cable |
| | Transmission: | 2 flexible sterling type 30Ω &32Ω, ~41m cables, in parallel |
| | Main Switch: | EEV CX1171A/2 (from Marconi Applied Technologies) |
| | Dump Switch: | EEV CX1171A/2 |
| | Max. PFN voltage: | 80kV (positive) |
| | Max. load current: | 2548A |
| ◆ Magnets: | No. of magnets/generator: | 1 |
| | Type: | ferrite loaded delay line |
| | No. of cells: | 18 |
| | Aperture w×h: | 147mm×66mm |
| | Effective length: | 467.5mm |
| | Delay: | 90ns |
| | Impedance: | 15.7Ω |
| ◆ Kick: | ∫Bdl max per magnet: | 22mT.m |
| | ∫Bdl flat top uniformity: | ±0.5% |
| | Rise time (1-99)%: | 120ns |
| | Rise time (2-98)%: | 113ns |
| | Length (max): | ~690ns, 800ns &1050ns (variable) |
| ◆ Filters: | Magnet output C: | 570pF |
| | Mag. Term. R+C: | 40Ω + 200pF |
| ◆ Ferrite: | MS cathode lemos: | CMD5005, tube OD=74.5mm, ID=35mm, L=50mm |
| | Magnet input lemos: | CMD5005, tube OD=74.5mm, ID=35mm, L=50mm |

two modules are required

one module