Pièges à ions

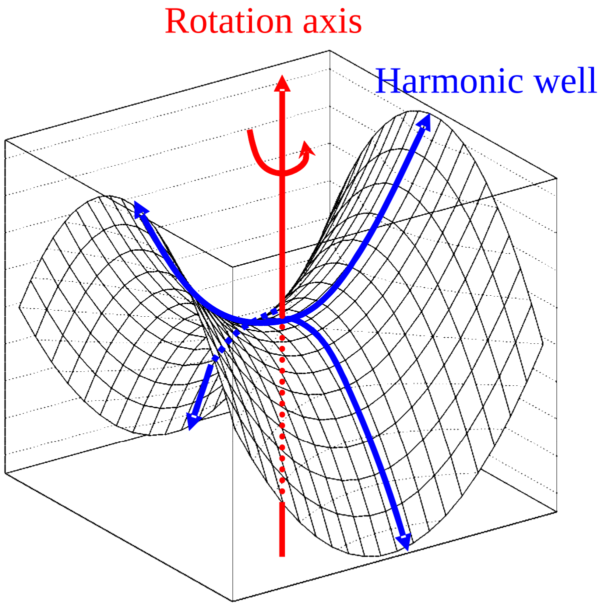
Ecole Joliot-Curie
Physique nucléaire instrumentale
22-27 Septembre 2008
Seignosse

P. Delahaye

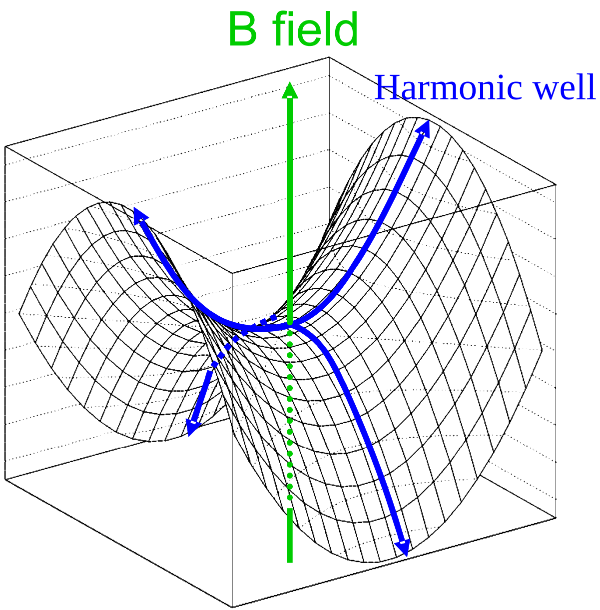
Bref Historique

- Piégeage d’ions
  - Loi de Laplace

$$\Delta\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0$$



Piège de Paul

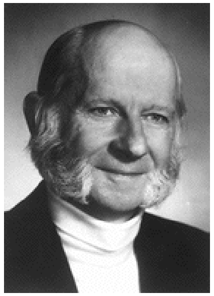


Piège de Penning

Frans Michel
Penning

1930’s: Penning gauges
+J.R. Pierce 1940’s: Penning trap for electrons

Paul traps as
Mass spectrometers
Late 1950’s



« Penning trap »

W. Paul

H. Dehmelt

Nobel Prize 1989

With N. F. Ramsey

for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

"for the development of the ion trap technique"

Modes de fonctionnement

- Piège de Paul

Potentiel quadrupôlaire

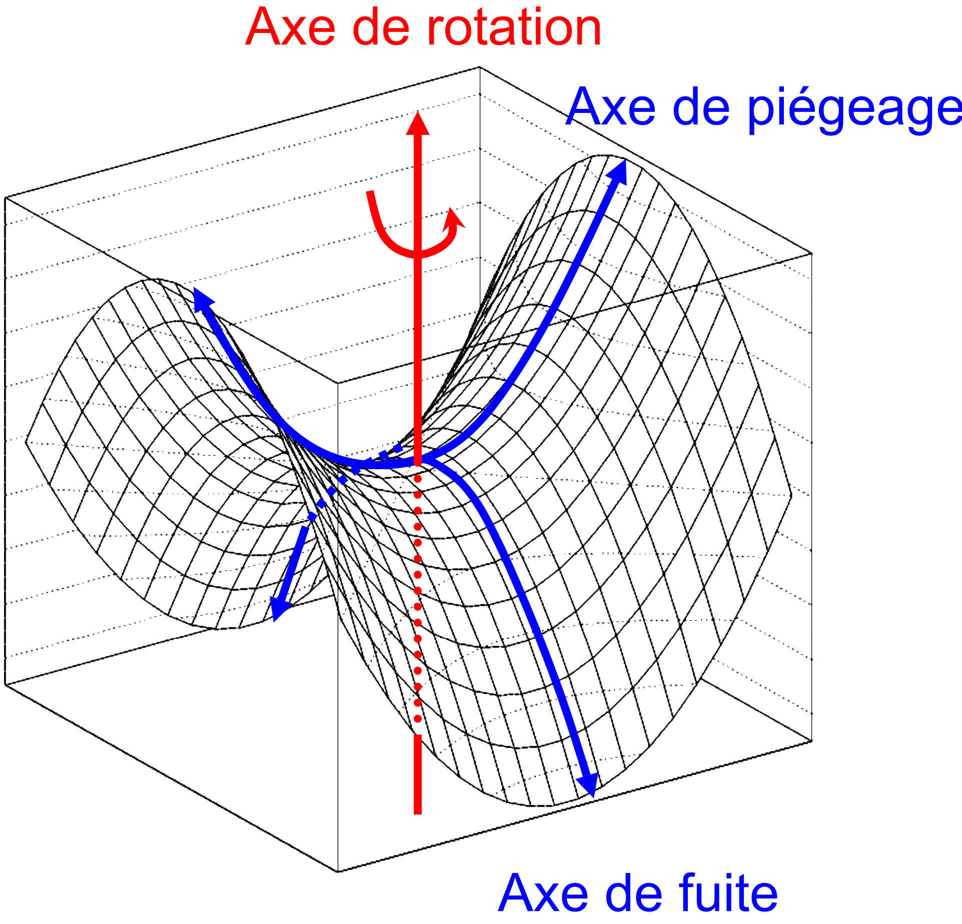
$$\phi(x,y) = \frac{V_0}{2}\left(\frac{x^2 - y^2}{r_0^2}\right)$$

$$\phi(x,y) = V\cos(\Omega t)\,\frac{x^2 - y^2}{2r_0^2}$$

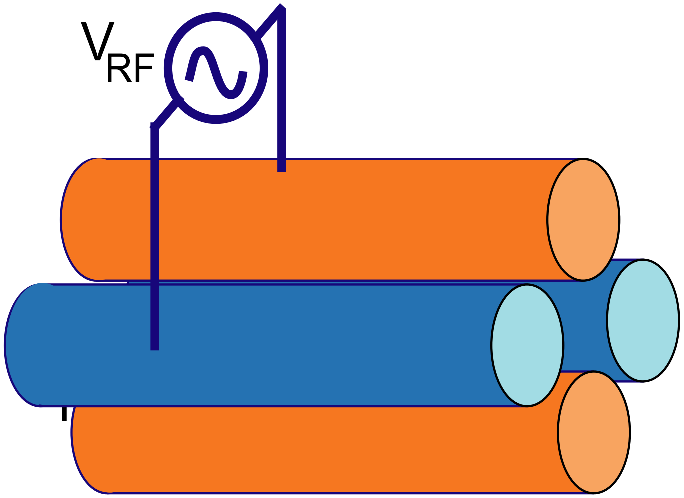
Paramètre de Matthieu q_Z

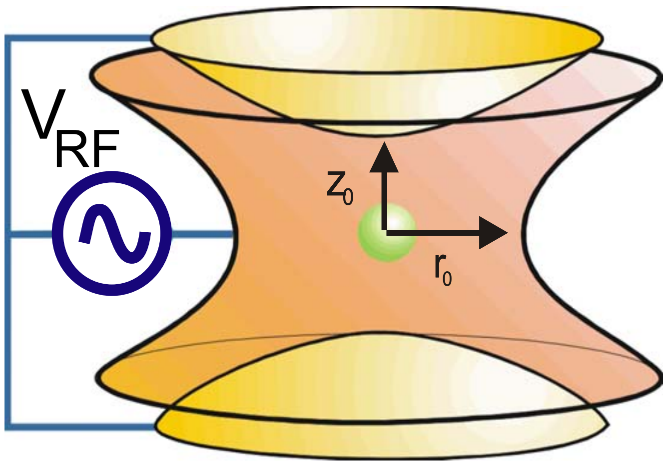
$$q_z = \frac{4qV}{m r_0^2 \Omega^2}$$

$q_z \in [0.;0.908]$



Pièges de Paul linéaires (RFQ) ou 3D





Equations de Matthieu

Piège linéaire ou RFQ

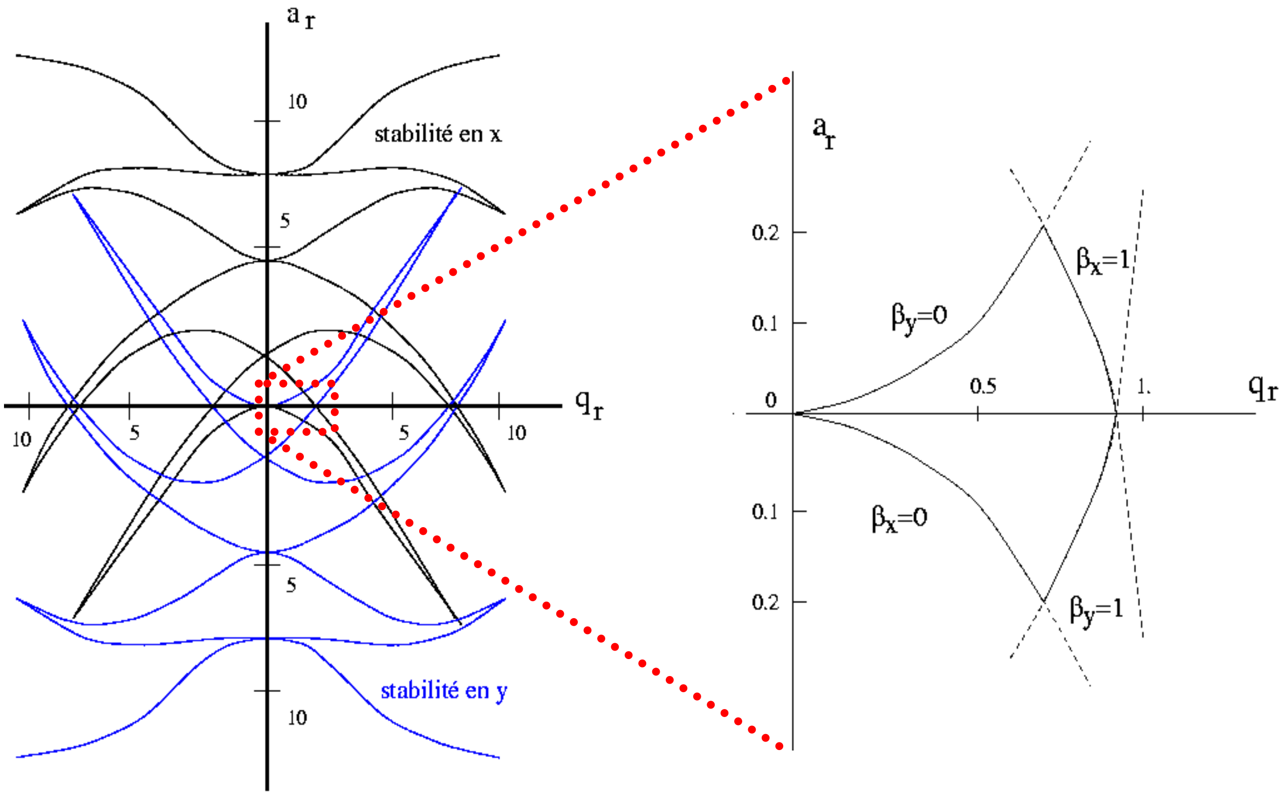
$$m\frac{d^2x}{dt^2} = -q(U - V\cos(\Omega t))\frac{x}{r_0^2}$$

$$m\frac{d^2y}{dt^2} = q(U - V\cos(\Omega t))\frac{y}{r_0^2}$$

$$a_r = \frac{4qU}{mr_0^2\Omega^2};\ q_r = \frac{2qV}{mr_0^2\Omega^2}\ et\ \zeta = \frac{\Omega t}{2}$$

$$\frac{d^2x}{d\zeta^2} + (a_r - 2q_r\cos 2\zeta)x = 0$$

$$\frac{d^2y}{d\zeta^2} - (a_r - 2q_r\cos 2\zeta)y = 0$$



$$u(\zeta) = \alpha' \sum_{n=-\infty}^{n=+\infty} C_{2n} e^{(2n\pm\beta)i\zeta} + \alpha'' \sum_{n=-\infty}^{n=+\infty} C_{2n} e^{-(2n\pm\beta)i\zeta}$$

$a_r=0$ $\longrightarrow$ $q_r \in [0.;0.908]$

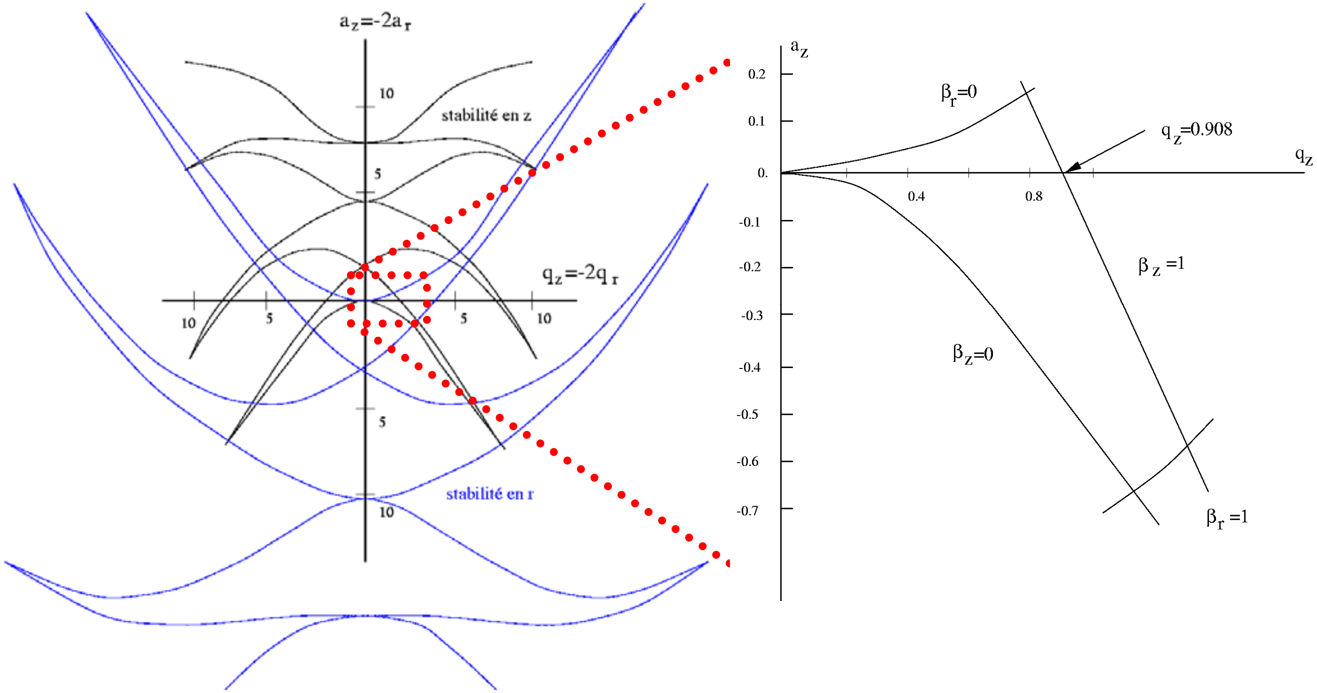
Diagrammes de stabilité (3D)

Équations de Matthieu

$$\frac{d^2r}{d\zeta^2} + (a_r - 2q_r \cos 2\zeta)r = 0$$

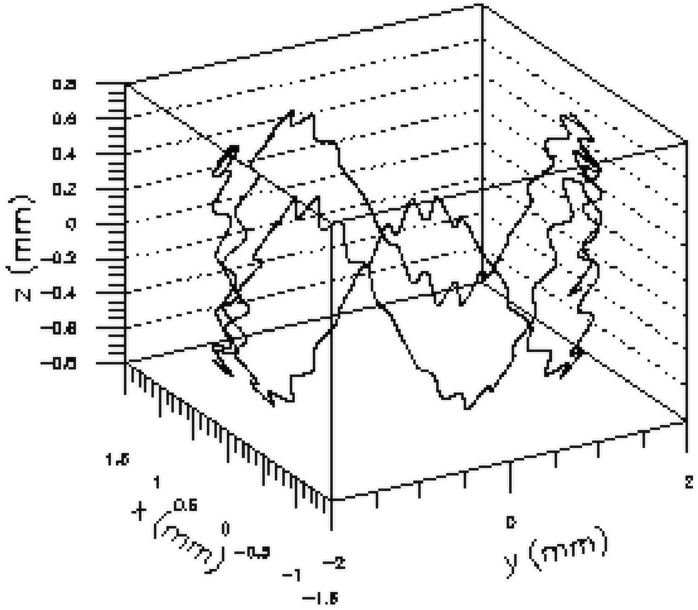
$$\frac{d^2z}{d\zeta^2} + (a_z - 2q_z \cos 2\zeta)z = 0$$

$a_z=-2a_r$
$q_z=-2q_r$

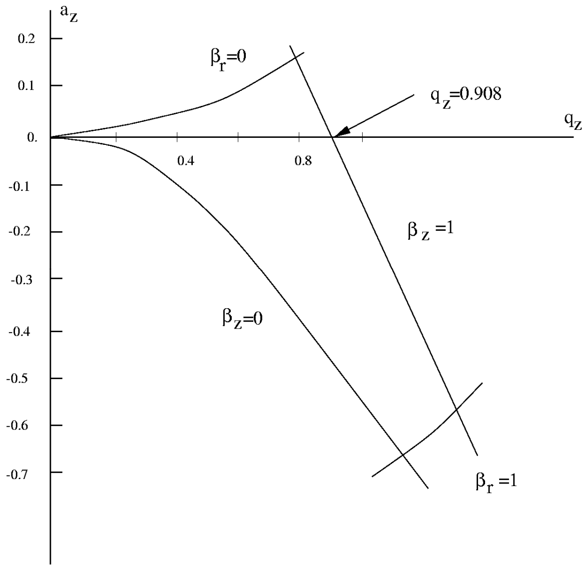


$a_z=0 \longrightarrow q_z \in [0.;0.908]$

Micromotion et mouvement séculaire



Stability diagram



Micromotion $\omega_\mu=(1-\beta/2)\bullet\Omega$

Secular motion $\omega_M=\beta\Omega/2$

with $\beta_z \approx \frac{q_z}{\sqrt{2}} = \frac{2\sqrt{2}qV}{mr_0^2\Omega^2}$

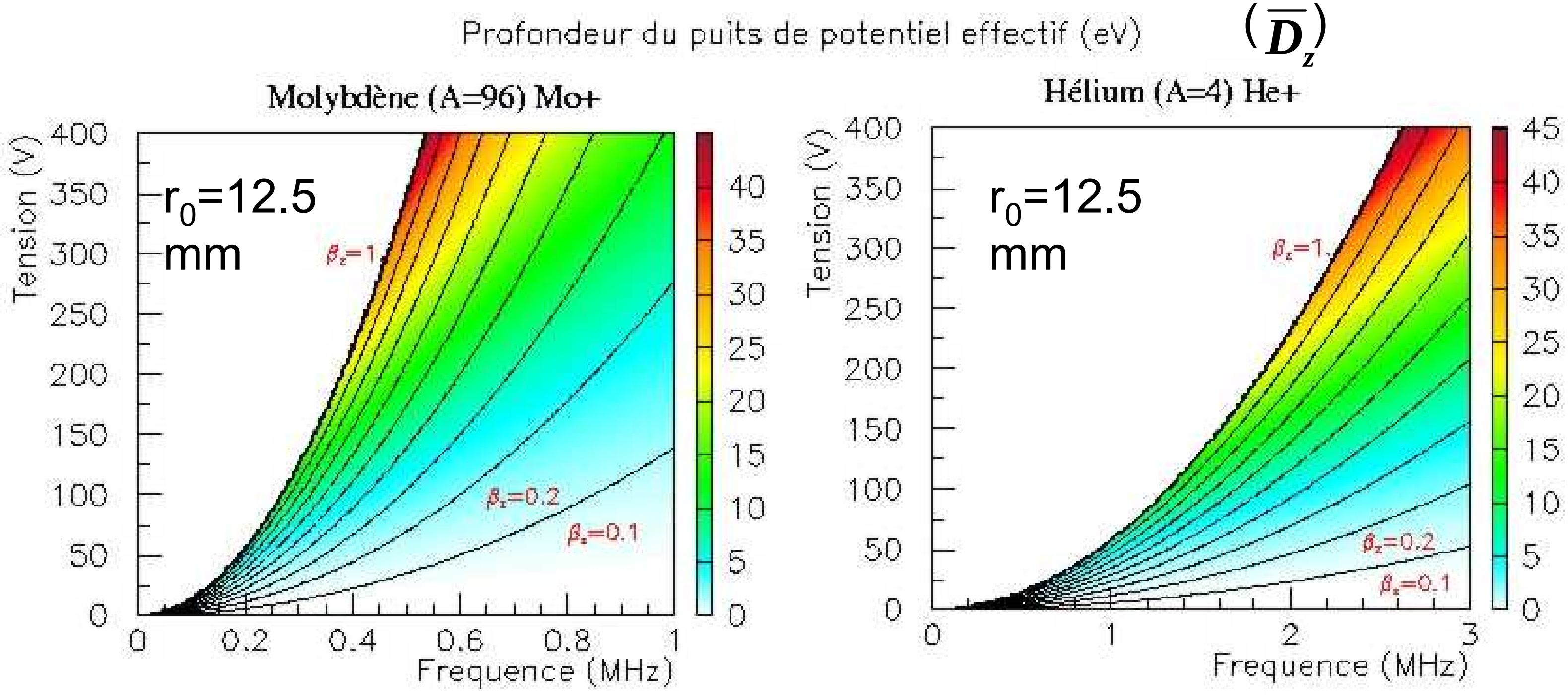
$$a_r = \frac{4qU}{mr_0^2\Omega^2};\ q_r = \frac{2qV}{mr_0^2\Omega^2}$$

Matthieu parameters

Modèle du potentiel effectif

$$\bar{D}_z = \frac{qV^2}{4mz_0^2\Omega^2} = \frac{mz_0^2\Omega^2q_z^2}{16q}$$

$$\bar{D}_r = \frac{qV^2}{4mr_0^2\Omega^2} = \frac{\bar{D}_z}{2}$$



Profondeur du puits de potentiel effectif (eV) $(\bar{D}_z)$

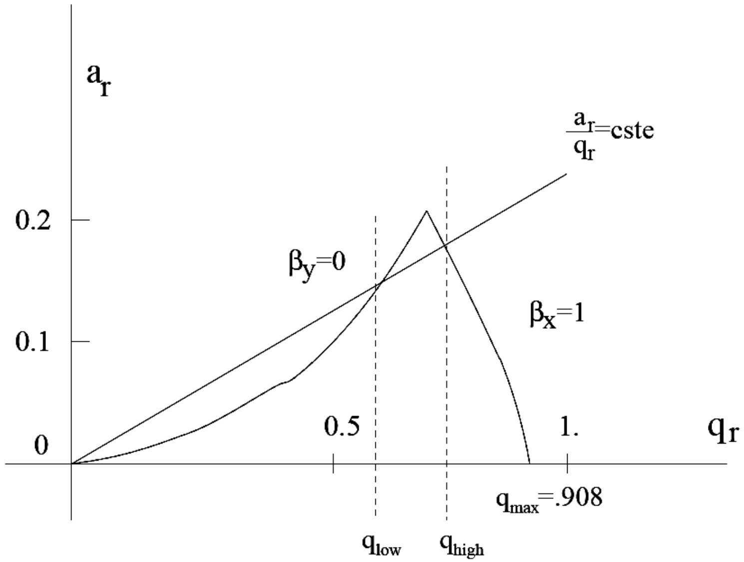
Molybdène (A=96) Mo+

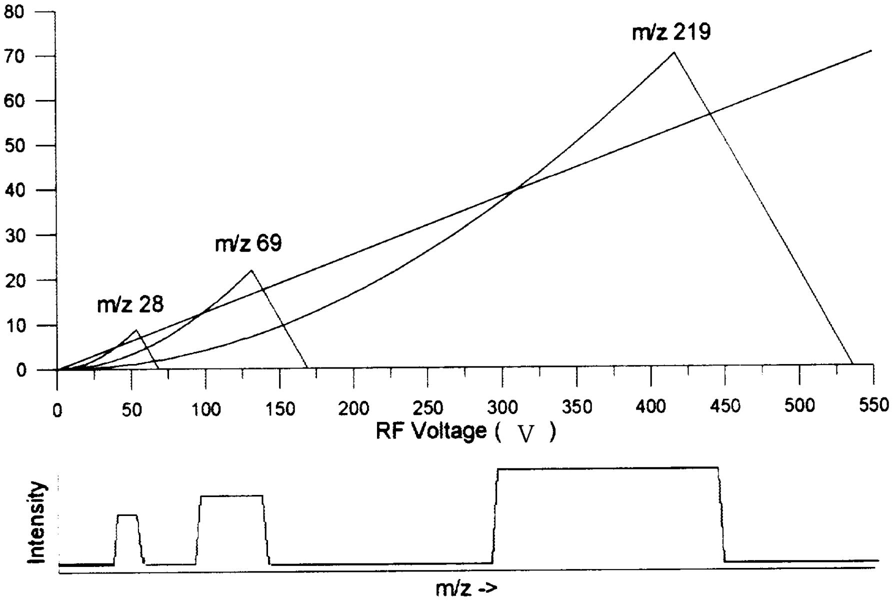
r_0=12.5 mm

Hélium (A=4) He+

r_0=12.5 mm

Application en spectromètre de masse

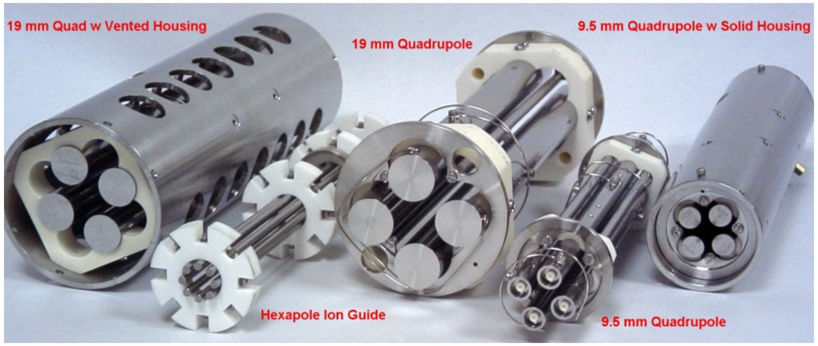


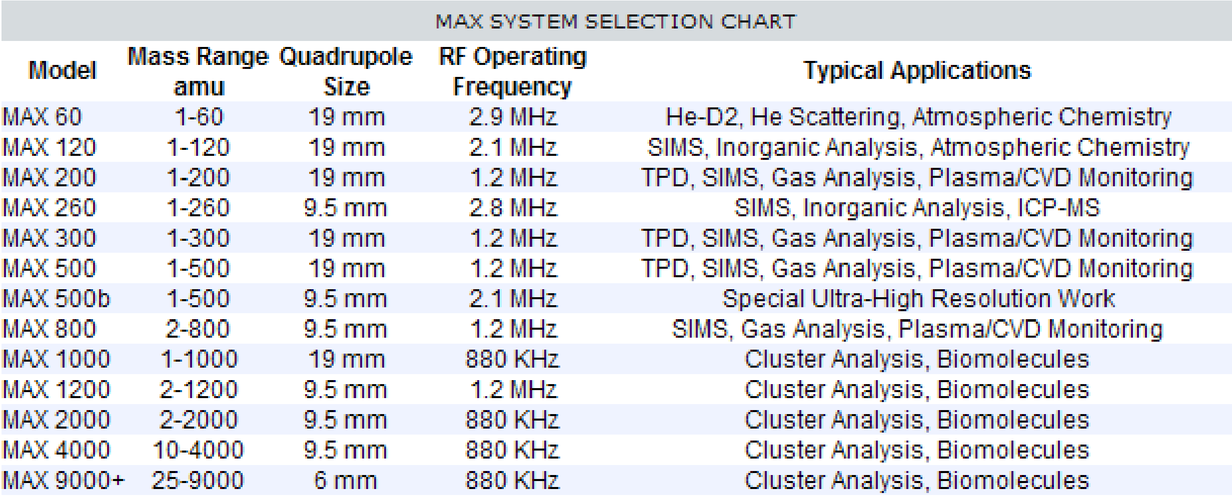


a_r/q_r=U/V=cste

Spectromètres commerciaux

Extraits du catalogue en ligne de EXTREL http://www.extrel.com





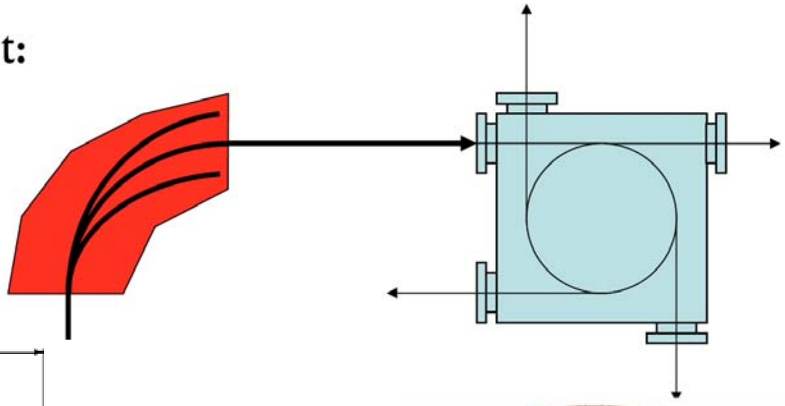
MAX SYSTEM SELECTION CHART

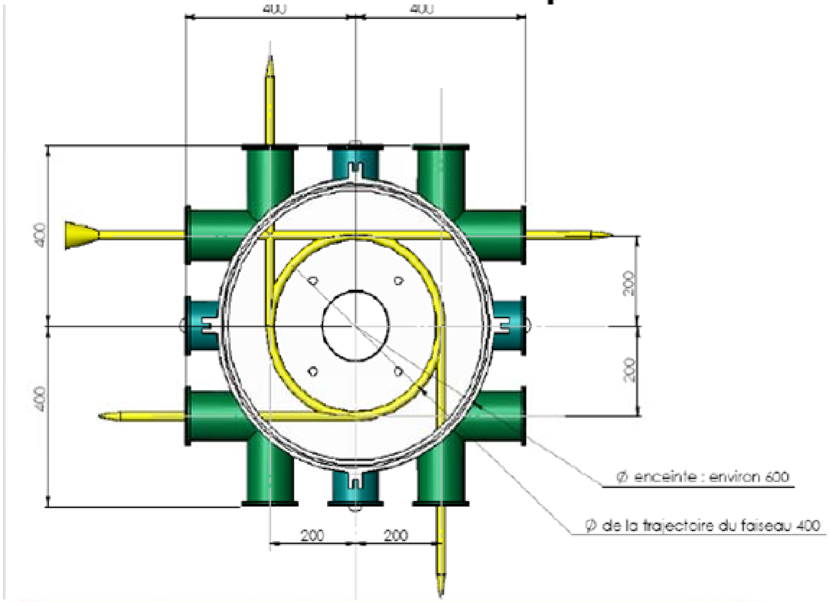
Model	Mass Range amu	Quadrupole Size	RF Operating Frequency	Typical Applications
MAX 60	1-60	19 mm	2.9 MHz	He-D2, He Scattering, Atmospheric Chemistry
MAX 120	1-120	19 mm	2.1 MHz	SIMS, Inorganic Analysis, Atmospheric Chemistry
MAX 200	1-200	19 mm	1.2 MHz	TPD, SIMS, Gas Analysis, Plasma/CVD Monitoring
MAX 260	1-260	9.5 mm	2.8 MHz	SIMS, Inorganic Analysis, ICP-MS
MAX 300	1-300	19 mm	1.2 MHz	TPD, SIMS, Gas Analysis, Plasma/CVD Monitoring
MAX 500	1-500	19 mm	1.2 MHz	TPD, SIMS, Gas Analysis, Plasma/CVD Monitoring
MAX 500b	1-500	9.5 mm	2.1 MHz	Special Ultra-High Resolution Work
MAX 800	2-800	9.5 mm	1.2 MHz	SIMS, Gas Analysis, Plasma/CVD Monitoring
MAX 1000	1-1000	19 mm	880 KHz	Cluster Analysis, Biomolecules
MAX 1200	2-1200	9.5 mm	1.2 MHz	Cluster Analysis, Biomolecules
MAX 2000	2-2000	9.5 mm	880 KHz	Cluster Analysis, Biomolecules
MAX 4000	10-4000	9.5 mm	880 KHz	Cluster Analysis, Biomolecules
MAX 9000+	25-9000	6 mm	880 KHz	Cluster Analysis, Biomolecules

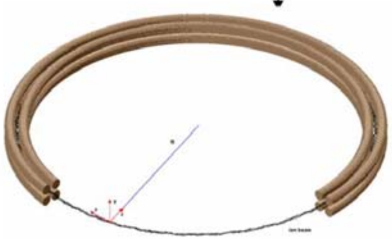
Ion Circus

The Ion Circus concept:

transport
bunching
separation
cooling







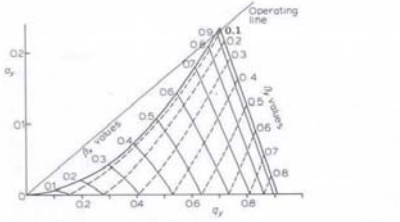
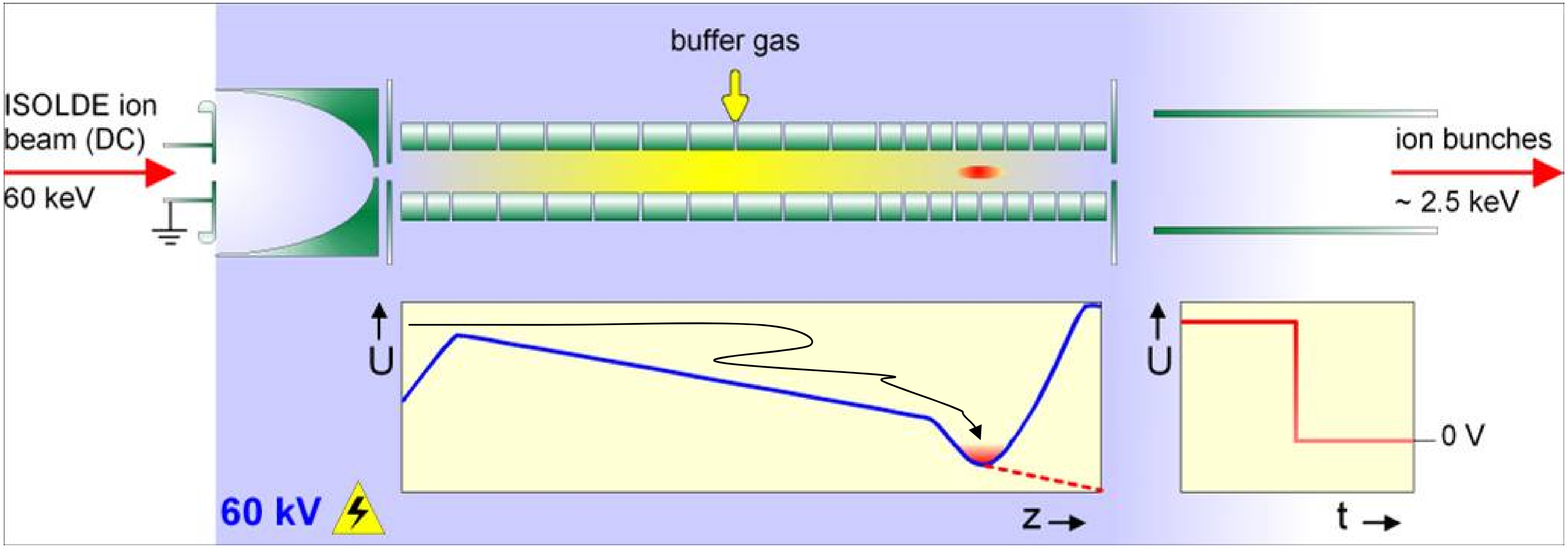


Fig. 2.10. The lower stability region normally used in mass filter lines for the x and y directions and a typical operating line.

D. Lunney and E. Minaya-Ramirez, CSNSM Orsay

Refroidissement par « buffer gas cooling »



- Piège de Paul linéaire (comme pour QMS)
- Segmentation des electrodes

- Buffer gas ^{4}He

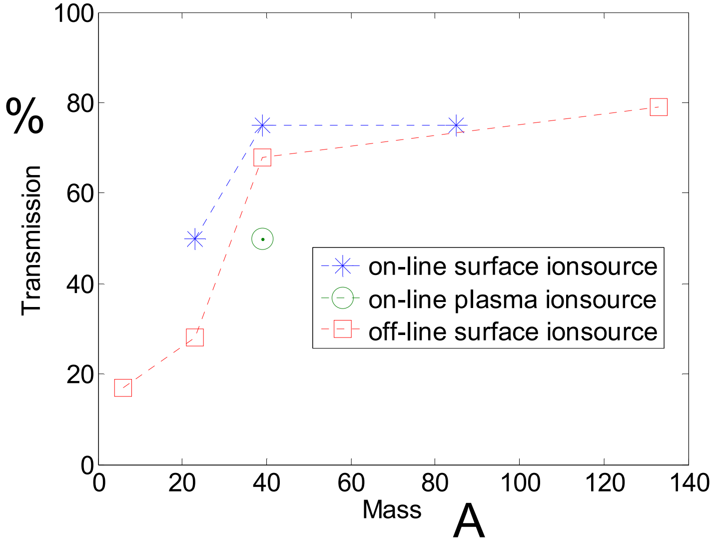
Confinement radial

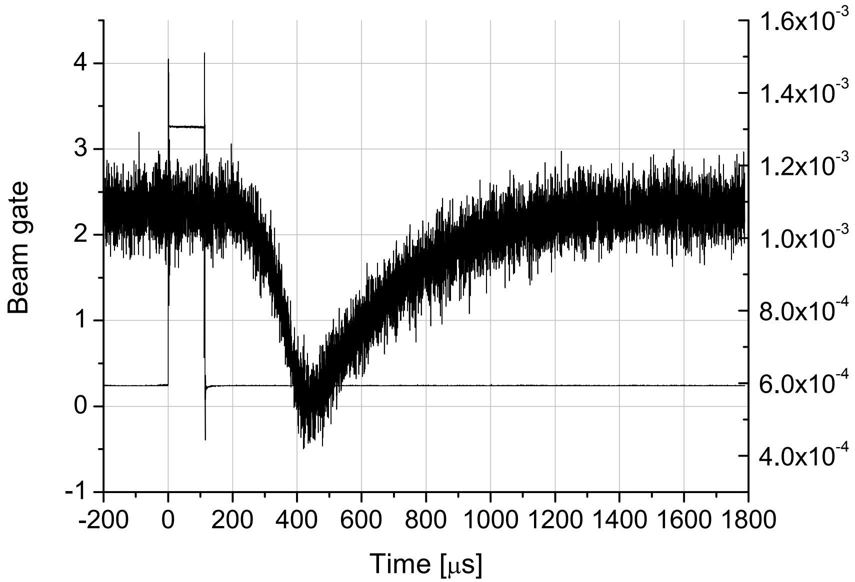
Piègeage et regroupement « bunching » ou simple drift par gradient linéaire

Refroidissement par collision

Performances optimales

ISCOOL, ISOLDE 2007





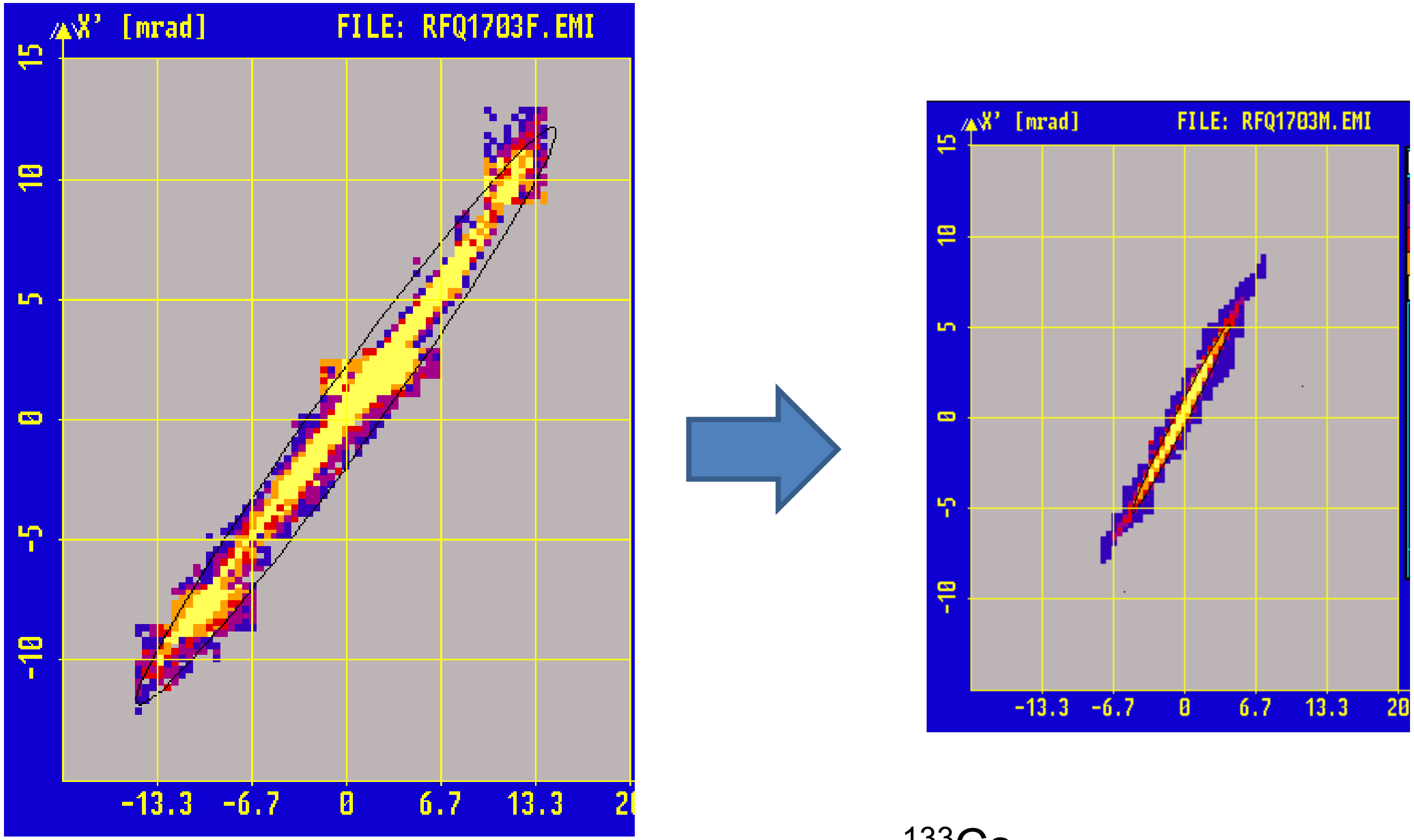
Masses légères: pertes par « RF heating »

500 μs drift time

Damping time: $\tau=T/T_0$🕐P_0/P 🕐 K_0 🕐 M/q

^{39}K: 100μs

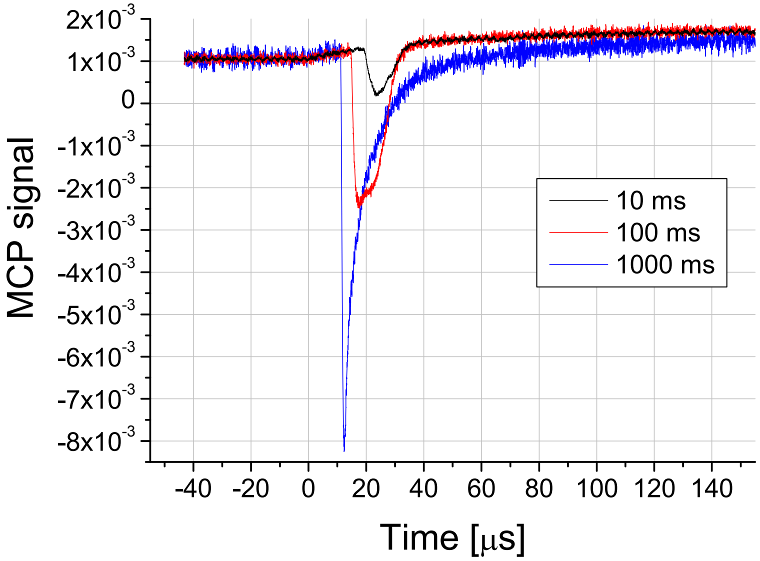
Refroidissement en mode continu

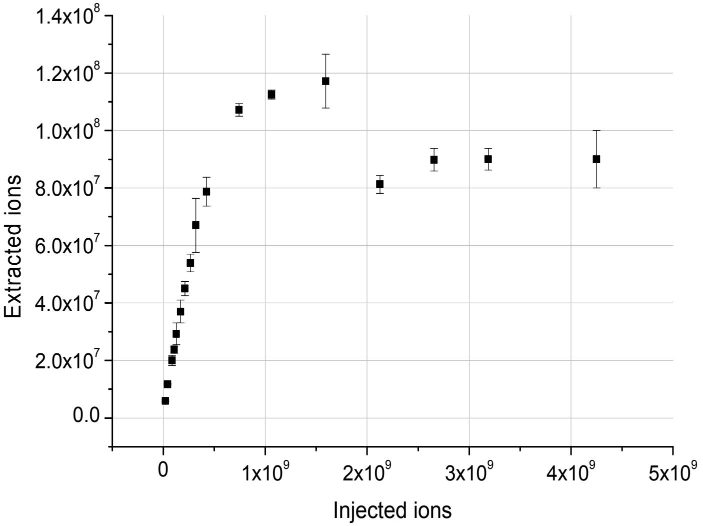


^{133}Cs

Réduction d 'émittance d'un facteur > 10

Mode « bunching »





^{39}K,

Collection time=10 ms–1 sec

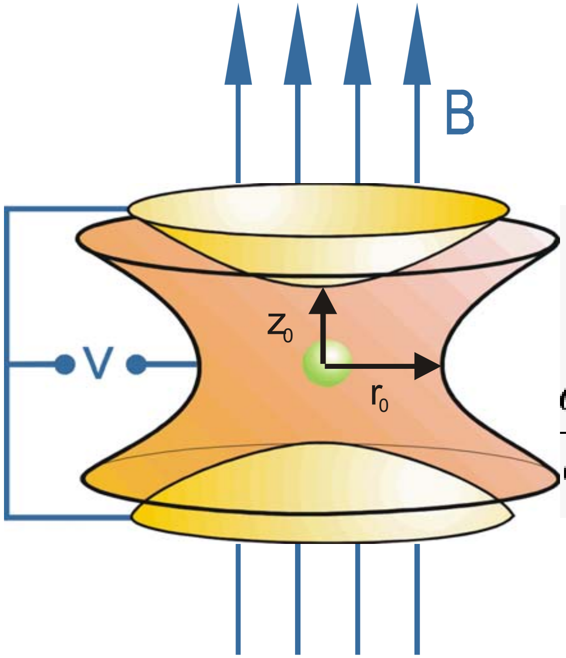
Extraction time 150 us

ISCOOL, ISOLDE WS 2007

Principe de fonctionnement

Piège de Penning

Piège de Penning



$$\phi(x,y,z) = \frac{U}{2r_0^2}(2z^2 - x^2 - y^2)$$

Mouvement en z: osc. harmonique

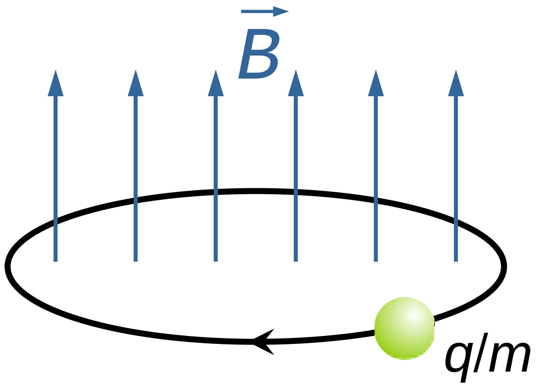
$$\omega_{0z} = \sqrt{\frac{2qU}{mr_0^2}}$$

$$\frac{d^2x}{dt^2} = \omega_c\frac{dy}{dt} + \frac{\omega^2}{\ }$$

$$\frac{d^2y}{dt^2} = -\omega_c\frac{dx}{dt} + \frac{\omega}{2}y$$

Equations du mouvement radial couplées

Mouvements cyclotrons et magnétron

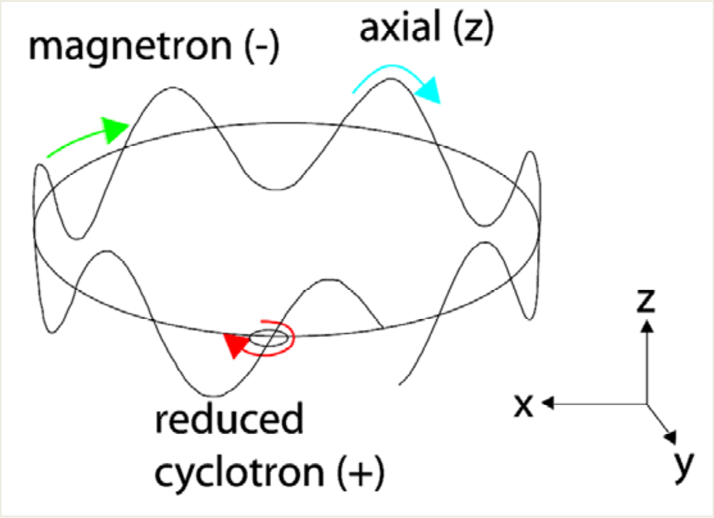


$$\omega_c = \frac{q}{m}\cdot B = 2\pi\cdot f_c$$

2 fréquences propres

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



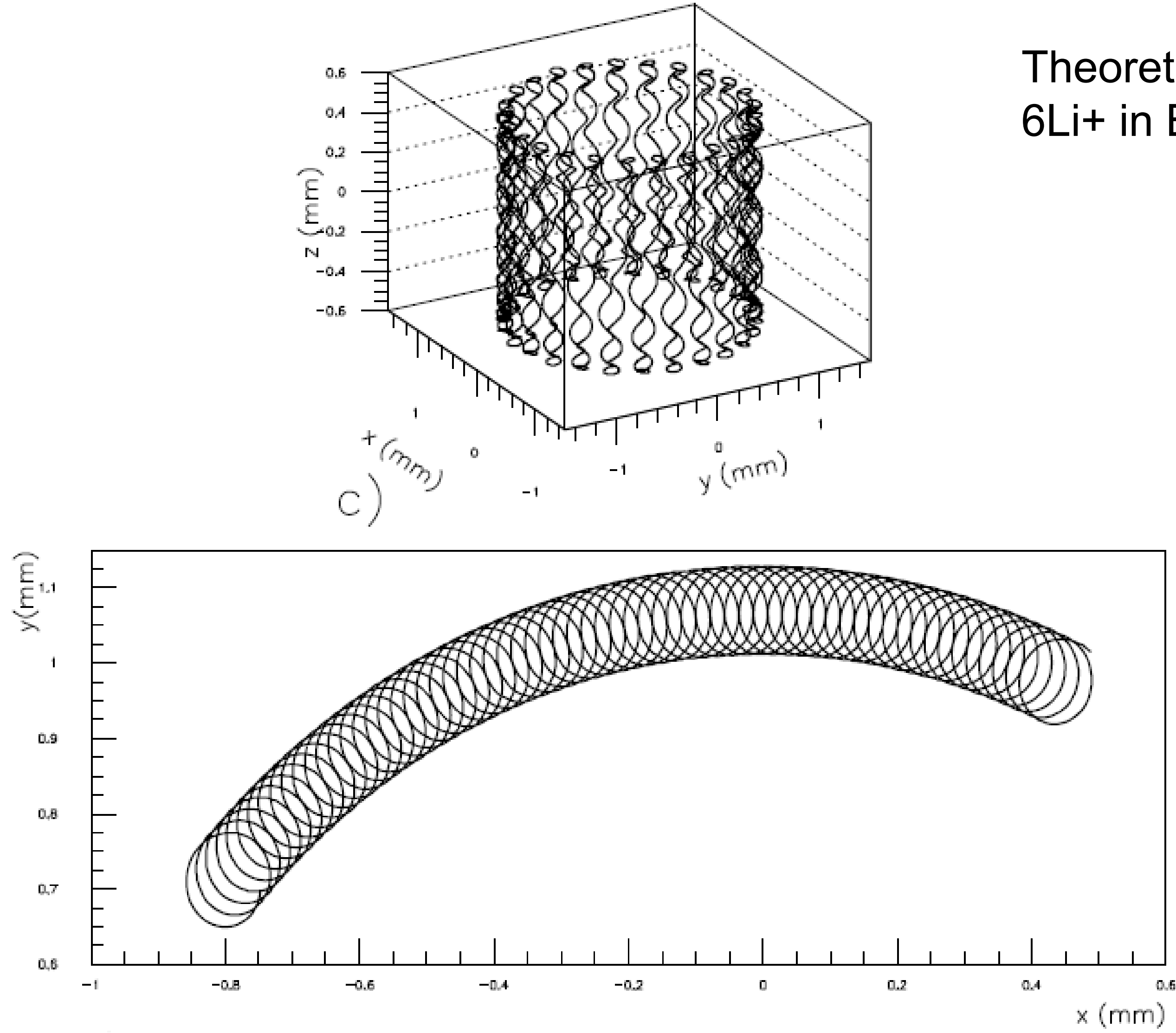
$$\omega_+ + \omega_- = \omega_c$$

$$\omega_+ \approx \omega_c >> \omega_-$$

A=100, q=1, B=6T

- $f_+ \approx 1$ MHz
- $f_- \approx 1$ kHz

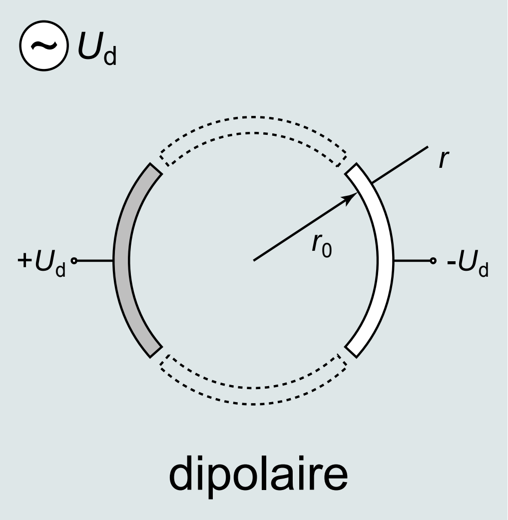
Trajectoire



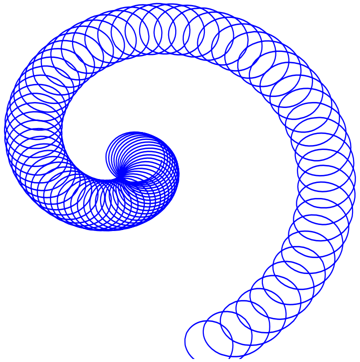
Theoretical example:
6Li+ in B=1T V0=8V

Excitation des mouvements propres

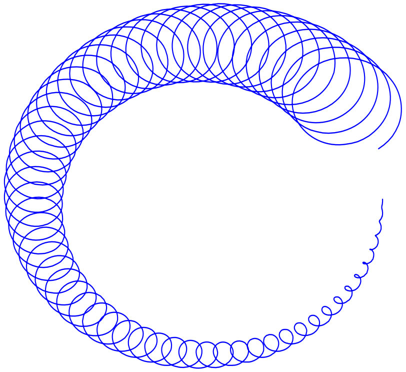
- Excitations dipolaires
  - Magnetron $\blacklozenge_-$
  - Cyclotron $\blacklozenge_+$



Magnetron excitation: ρ_-

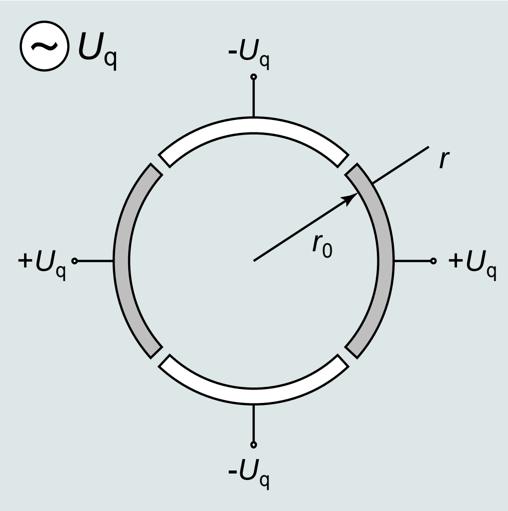


Cyclotron excitation: ρ_+



Excitation quadrupolaire $\blacklozenge_c$

- Excitation quadrupolaire $\blacklozenge_c$
  - – $\blacklozenge_c = \blacklozenge_+ + \blacklozenge_-$ couplage des 2 mouvements
  - – Conversion du mouvement magnétron en mouvement cyclotron et vice - versa

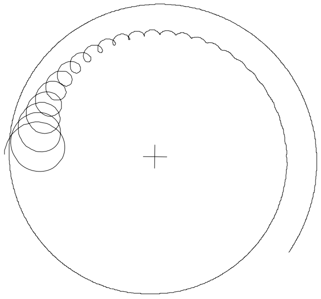


quadrupolaire

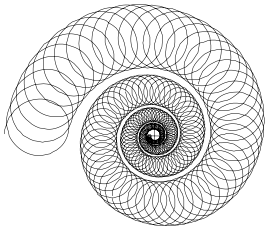
Techniques de refroidissement

- Buffer gas cooling

Gaz tampon ^{4}He
Sans excitation



Gaz tampon
Excitation quadrupolaire à $\blacklozenge_c$



force de friction $F = -\delta\, m\, v$

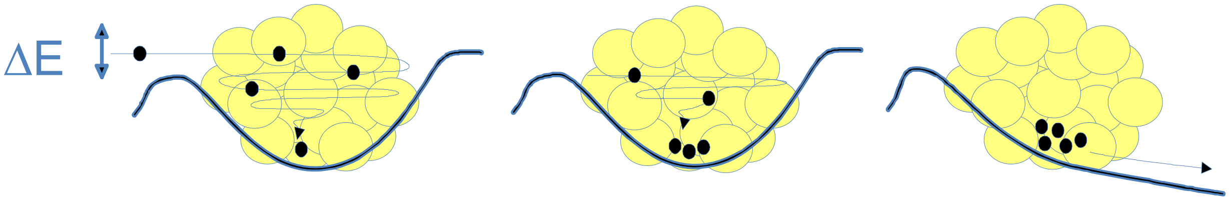
$\Rightarrow r(t) \approx r(0)\, e\, -\delta/2\, t$

exemple Na^+ 10^{-4} mbar Ne: δ **$= 400\ s^{-1}$**

$\tau_{refroidissement} \approx 20$ ms

Couplage des mouvements
magnétron et cyclotron

Sideband Cooling

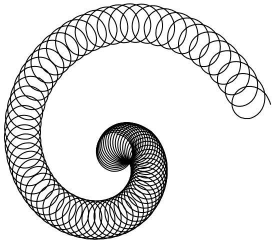


Accumulation | Refroidissement | Éjection

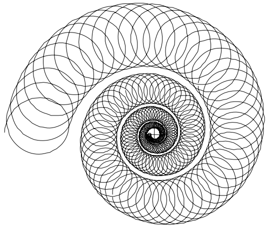
Mode pulsé
Obligatoire!

Méthode de refroidissement sélective en masse

- Excitation magnétron dipolaire
  - Décentre les ions



- Excitation cyclotron quadrupolaire
  - Recentre les ions $\omega_{rf}=\omega_c=qB/m$

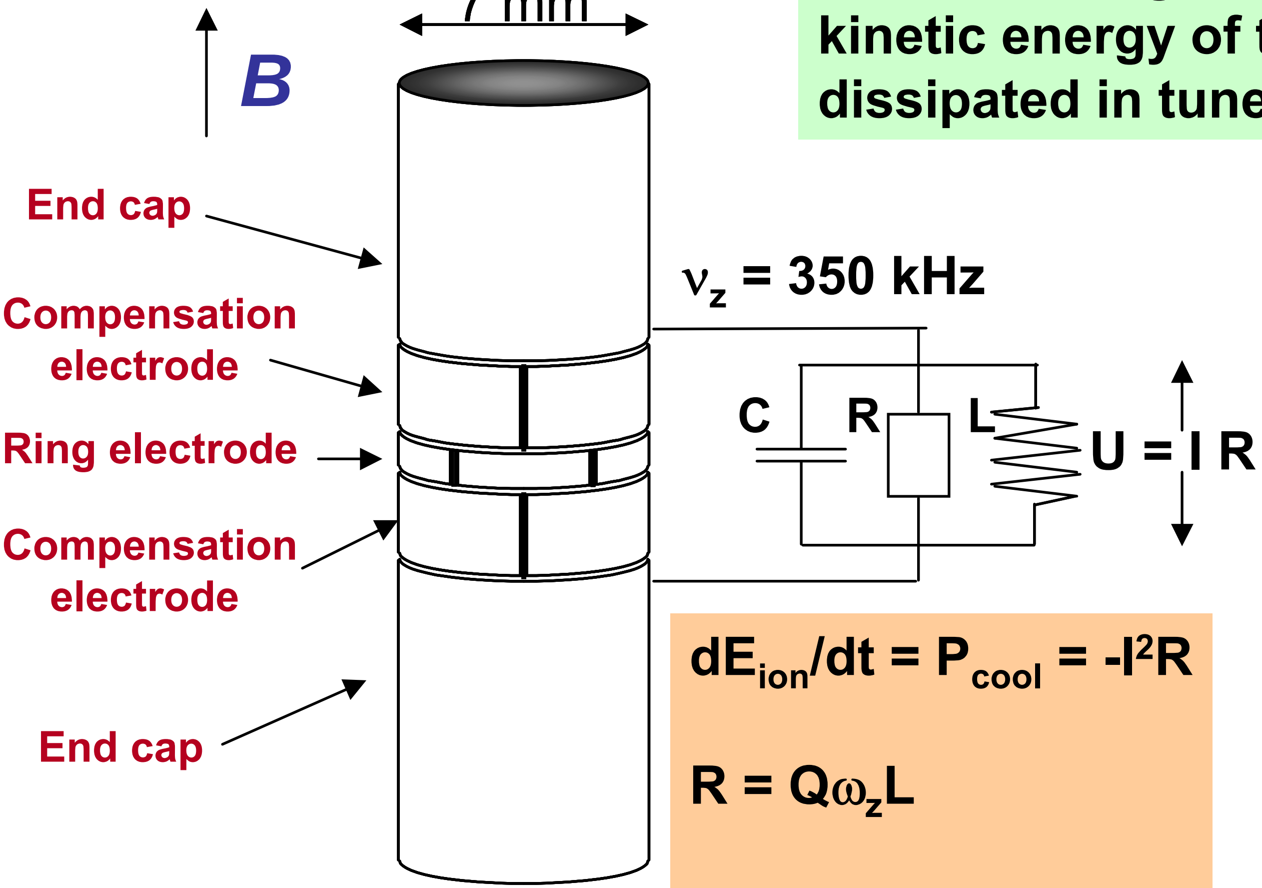


Relative accuracy:

$(\delta m/m)$ ✍ 10^{-5}

Resistive cooling

induced image currents:
kinetic energy of trapped ions is dissipated in tuned circuit (T = 4 K)

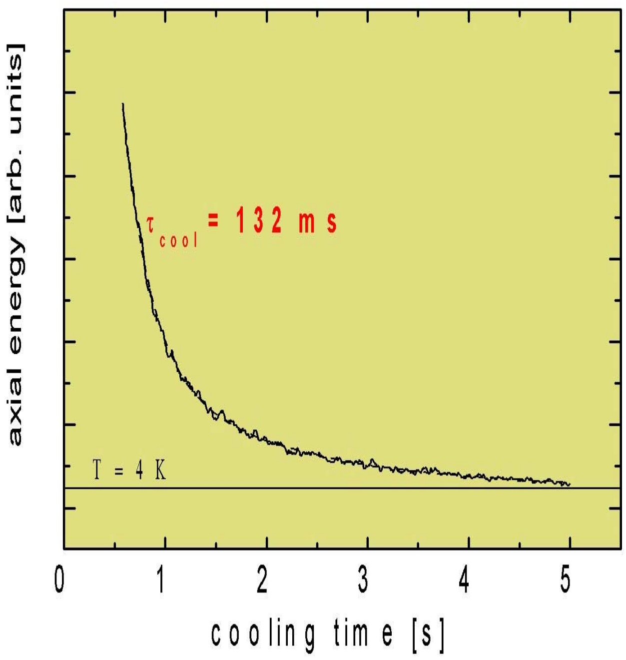


$dE_{ion}/dt = P_{cool} = -I^2R$

$R = Q\omega_z L$

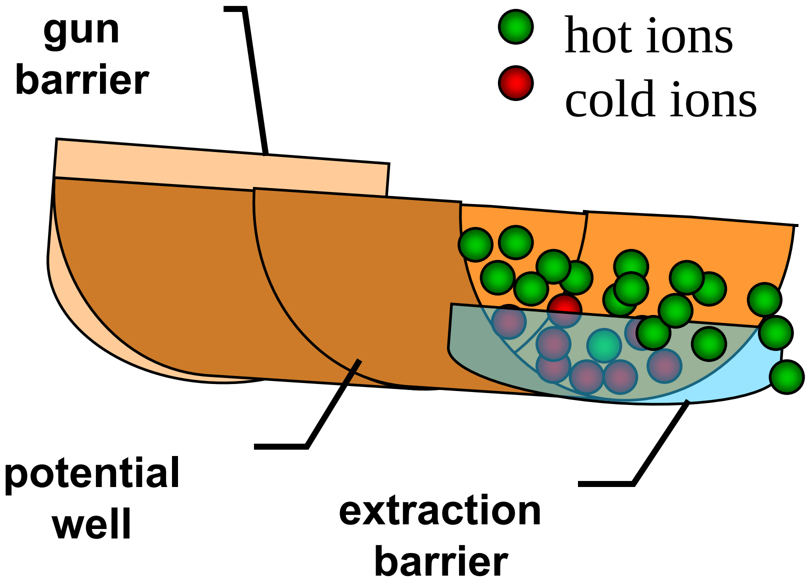
$\Rightarrow$? τ_{cool}

Resistive Cooling of $^{12}C^{5+}$ to 4 K



Refroidissement évaporatif

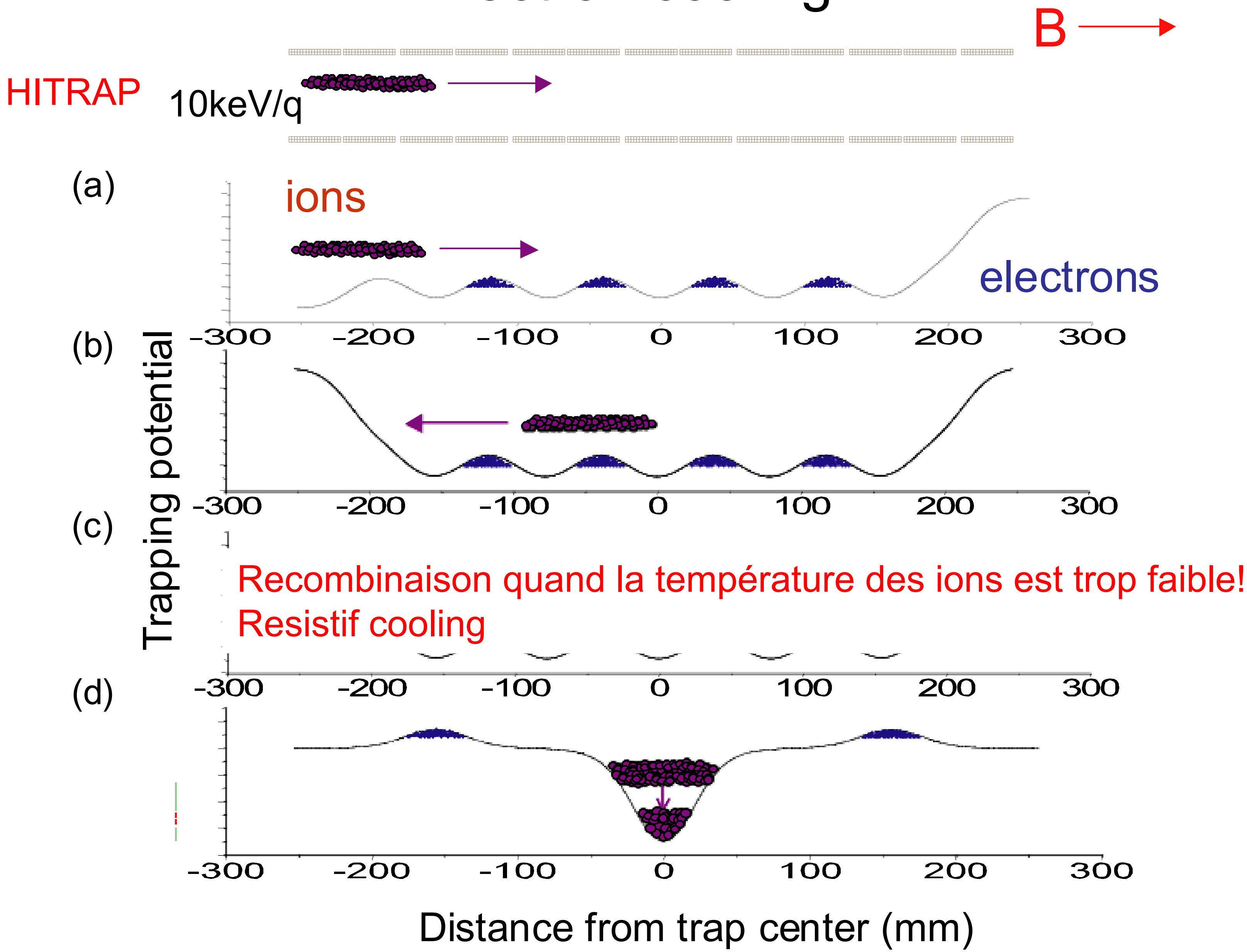
Ions lourds dans un bain d’ions de masses légères



Les ions légers et chauds sont extraits en diminuant la barrière de potentiel

Surtout utilisés pour les sources EBIS
Peu efficace pour les pièges Penning

Electron cooling



Recombinaison quand la température des ions est trop faible!

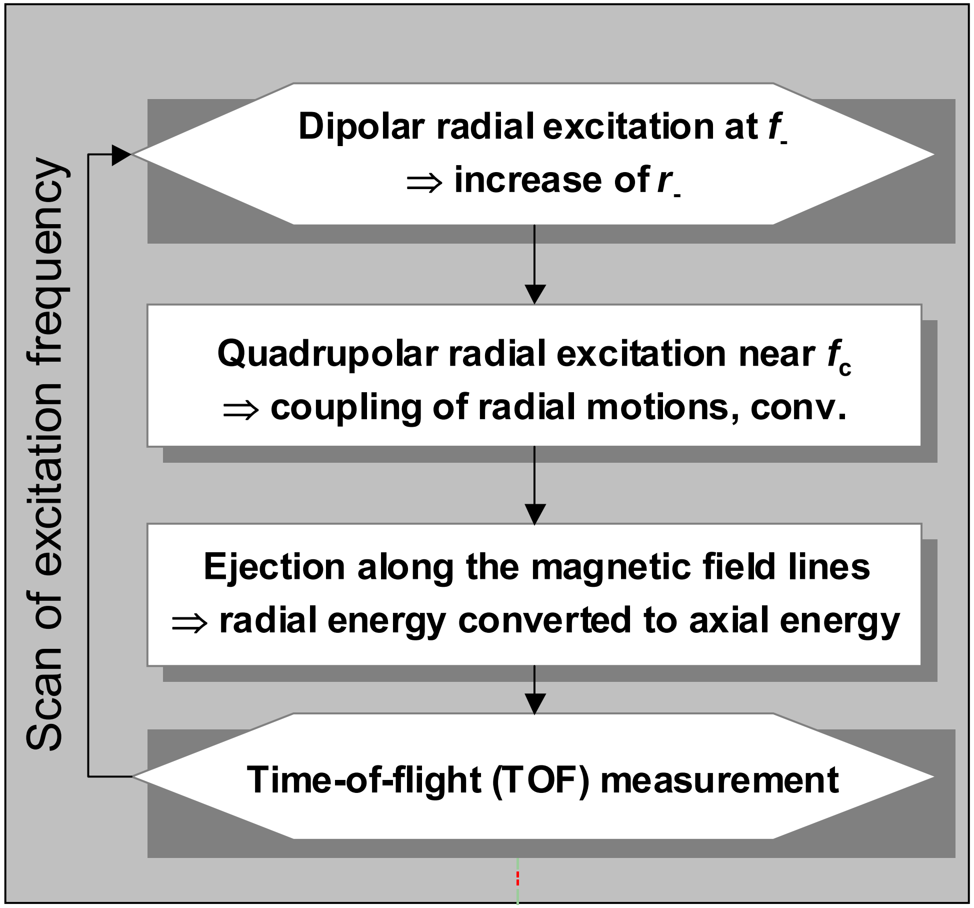
Resistif cooling

Techniques de mesure des fréquences propres

- Time of flight
- Charge induite

◆ c

Time-of-flight resonance technique

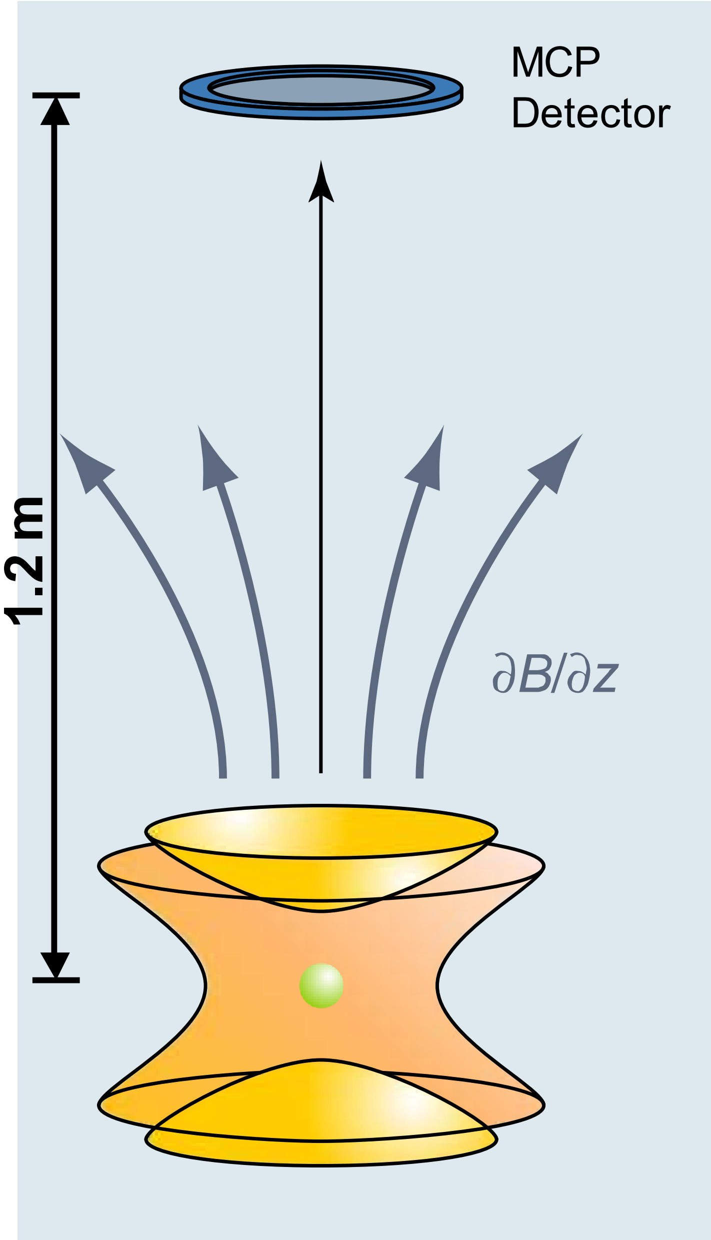


Dipolar radial excitation at f_-
⇒ increase of r_-

Quadrupolar radial excitation near f_c
⇒ coupling of radial motions, conv.

Ejection along the magnetic field lines
⇒ radial energy converted to axial energy

Time-of-flight (TOF) measurement



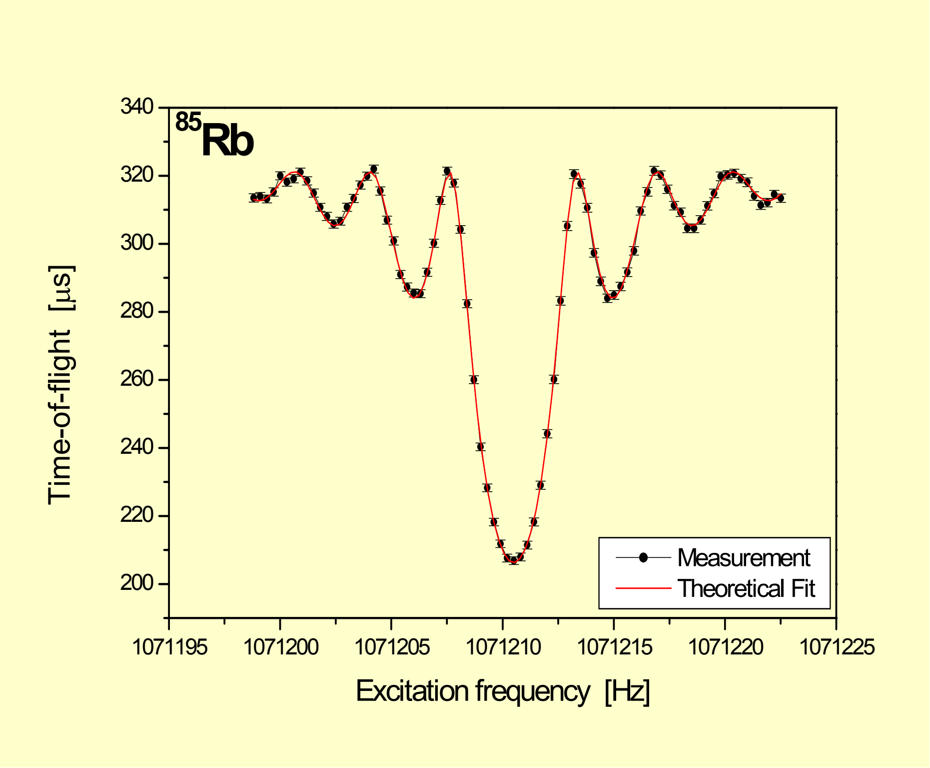
Resolving power: $R = f_{exc} T_{exc}$

Spectre de temps de vol

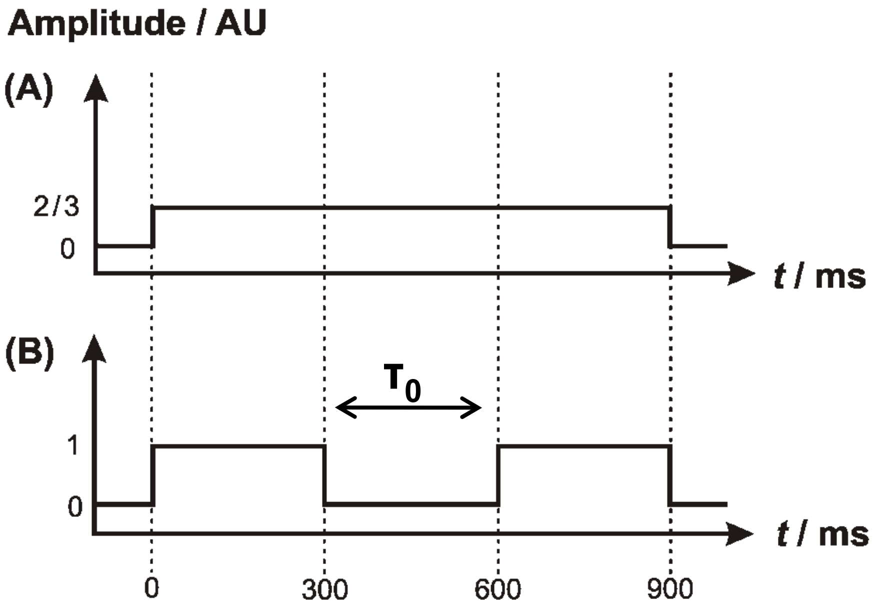
- Excitation pendant une porte $\Delta t=T_{exc}$
  - Transformée de Fourier sinc(ω), largeur 1/Texc
  - Temps de vol minimal $\omega=\omega$ quand la conversion est
  - $R=\omega/\delta\omega=f_{exc}\sphericalangle T$

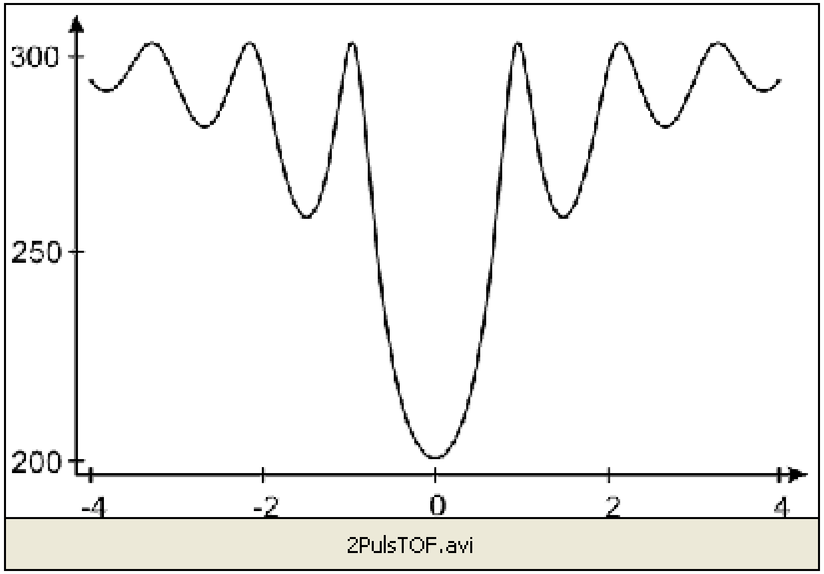
Relative accuracy:

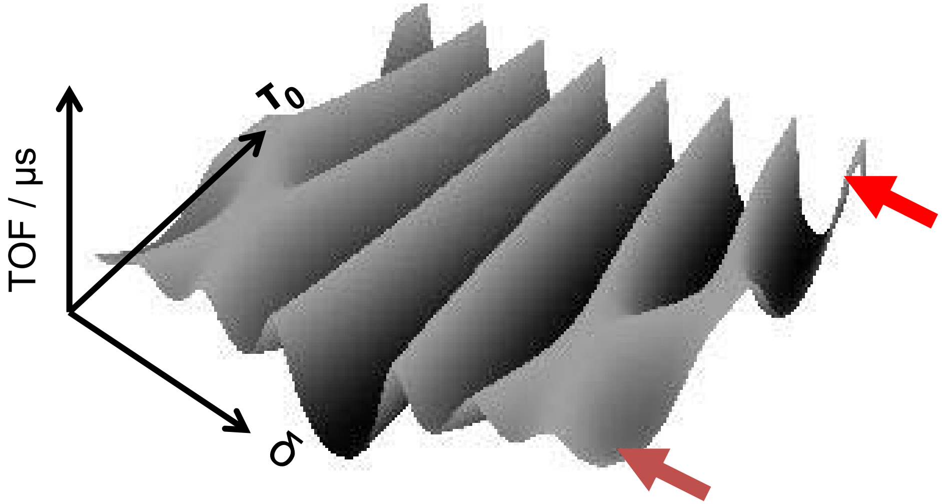
$(\delta m/m) \leq 10^{-7}$

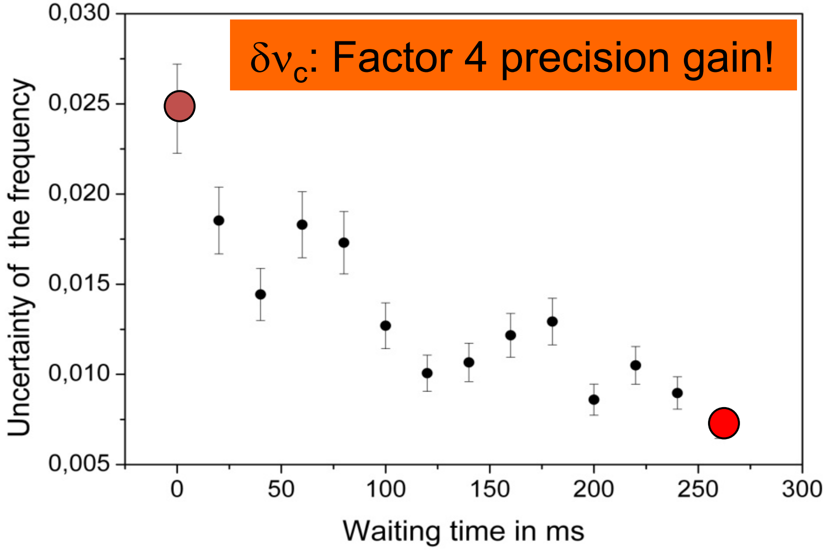


Excitation Ramsey





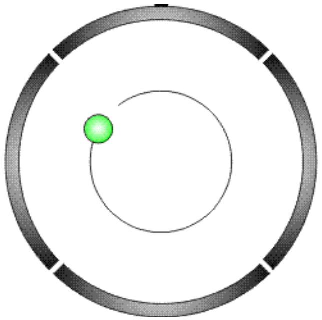




$\delta\nu_c$: Factor 4 precision gain!

. **George** *et al.*, Int. J. Mass Spectrom., (2006).

Charge induite



ion signal

mass/frequency spectrum

Amplitude

very small signal ~fA

„FT-ICR“

Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

Operation of traps and electronics at **cryogenic** (4 K) temperature.

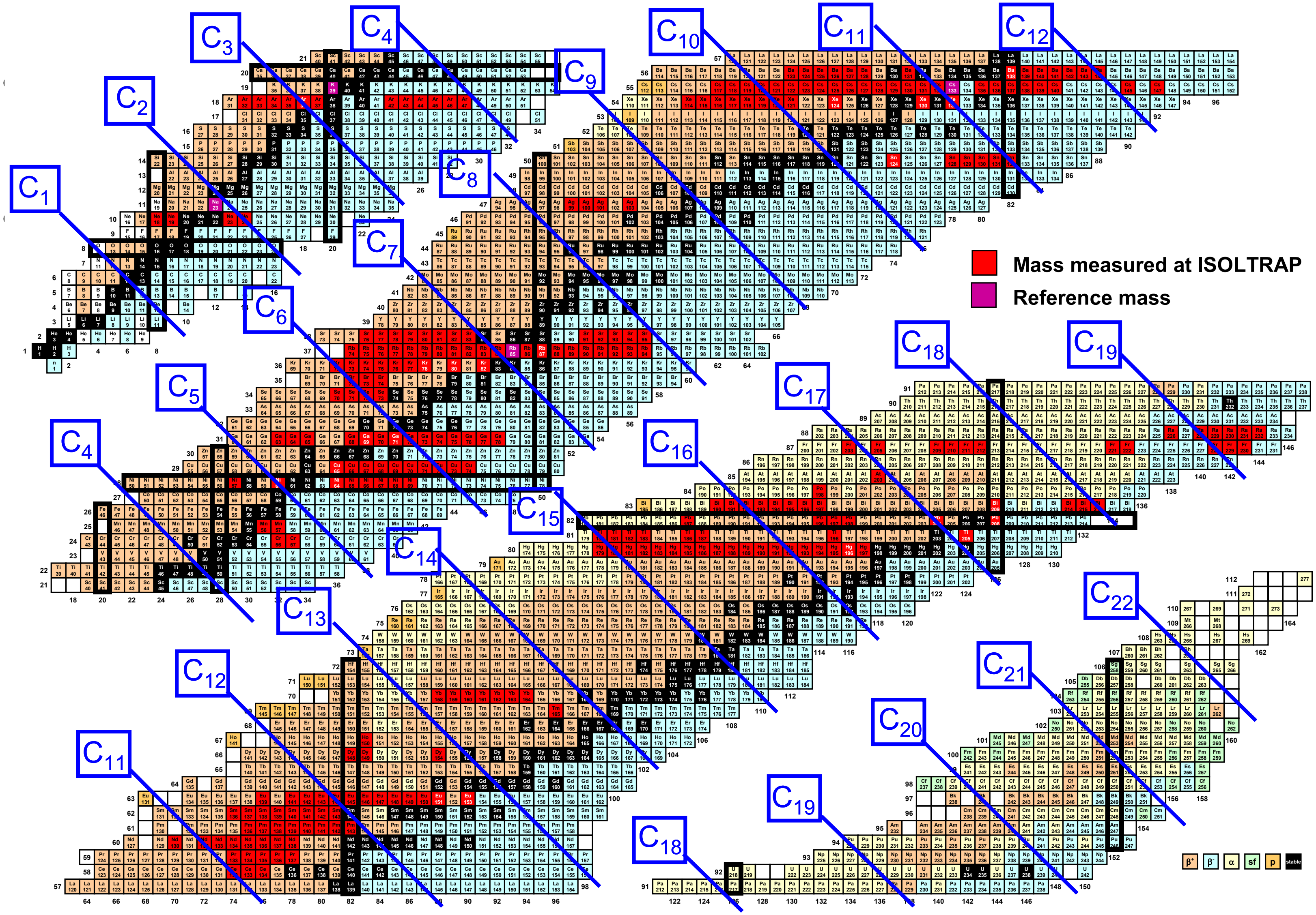
- – Mass measurements on heavy and superheavy rare elements (SHIPTRAP)
- – Fast identification and effective use of stored ions
- –Ultra high-precision mass measurements on long-lived/stable ions

C. Weber, PhD thesis, University of Heidelberg (2004) and C. Weber *et al*., Eur. Phys. J A 25, 65 (2005)

Klaus.blaum@mpi-hd.mpg.de

Mesure de masse

Carbon clusters



🟥 **Mass measured at ISOLTRAP**

🟪 **Reference mass**

S

Manipulation de faisceaux d'ions radioactifs

- Faisceaux ISOL (Isotopes Separation On Line) et faisceaux in-flight

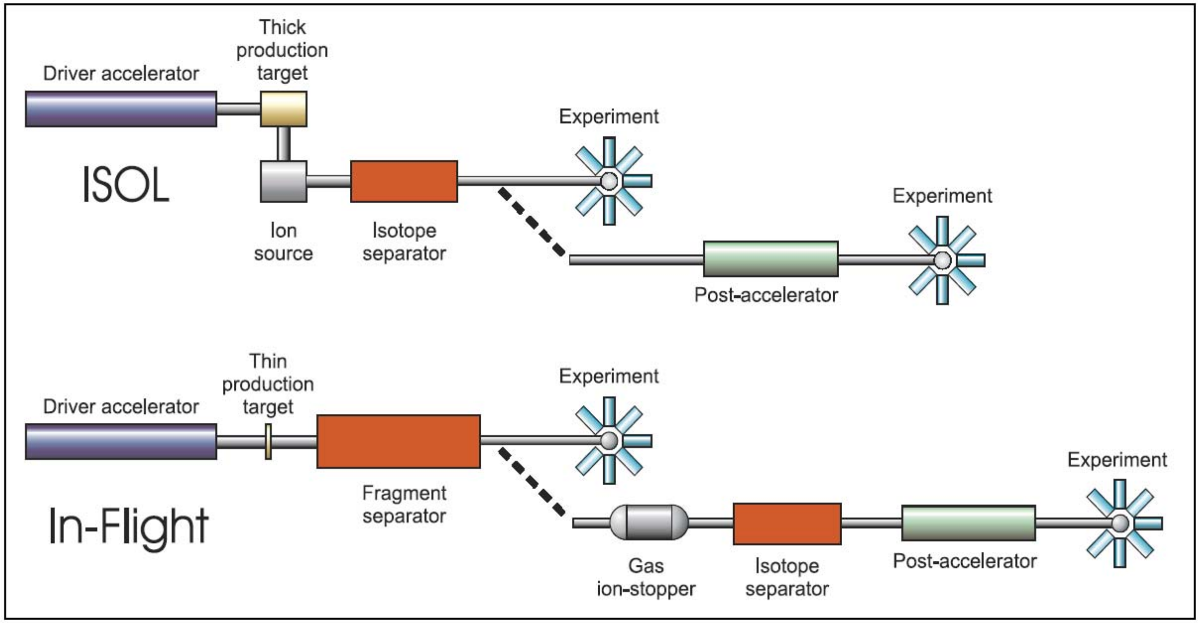


Fig 3.1: Comparison between the ISOL and In-Flight methods of producing radioactive ion beams. Post-acceleration is possible in either case.

From the EURISOL report

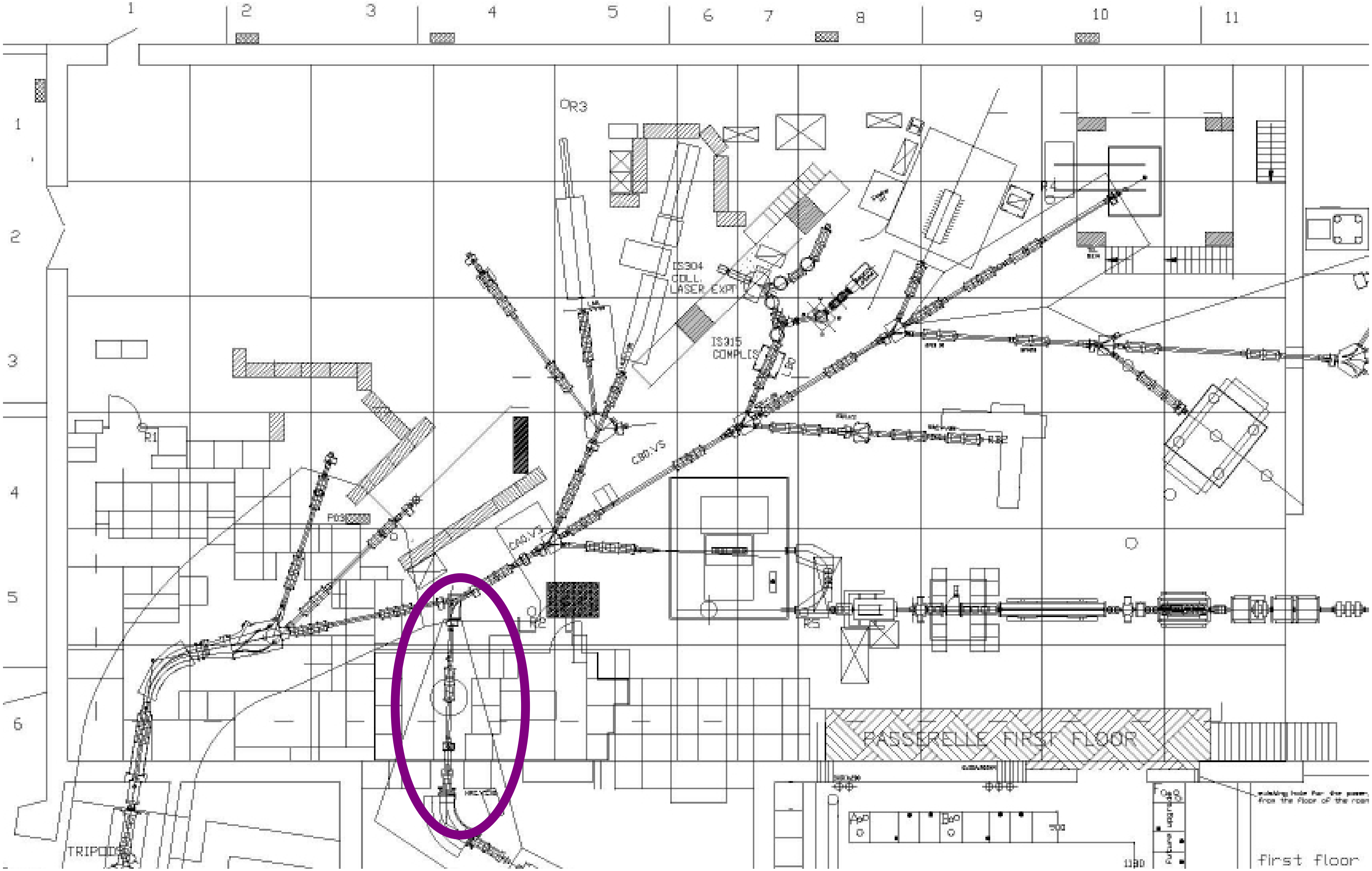
ISOLDE, GANIL/SPIRAL, TRIUMF, …

GSI (FAIR project), MSU, ANL…

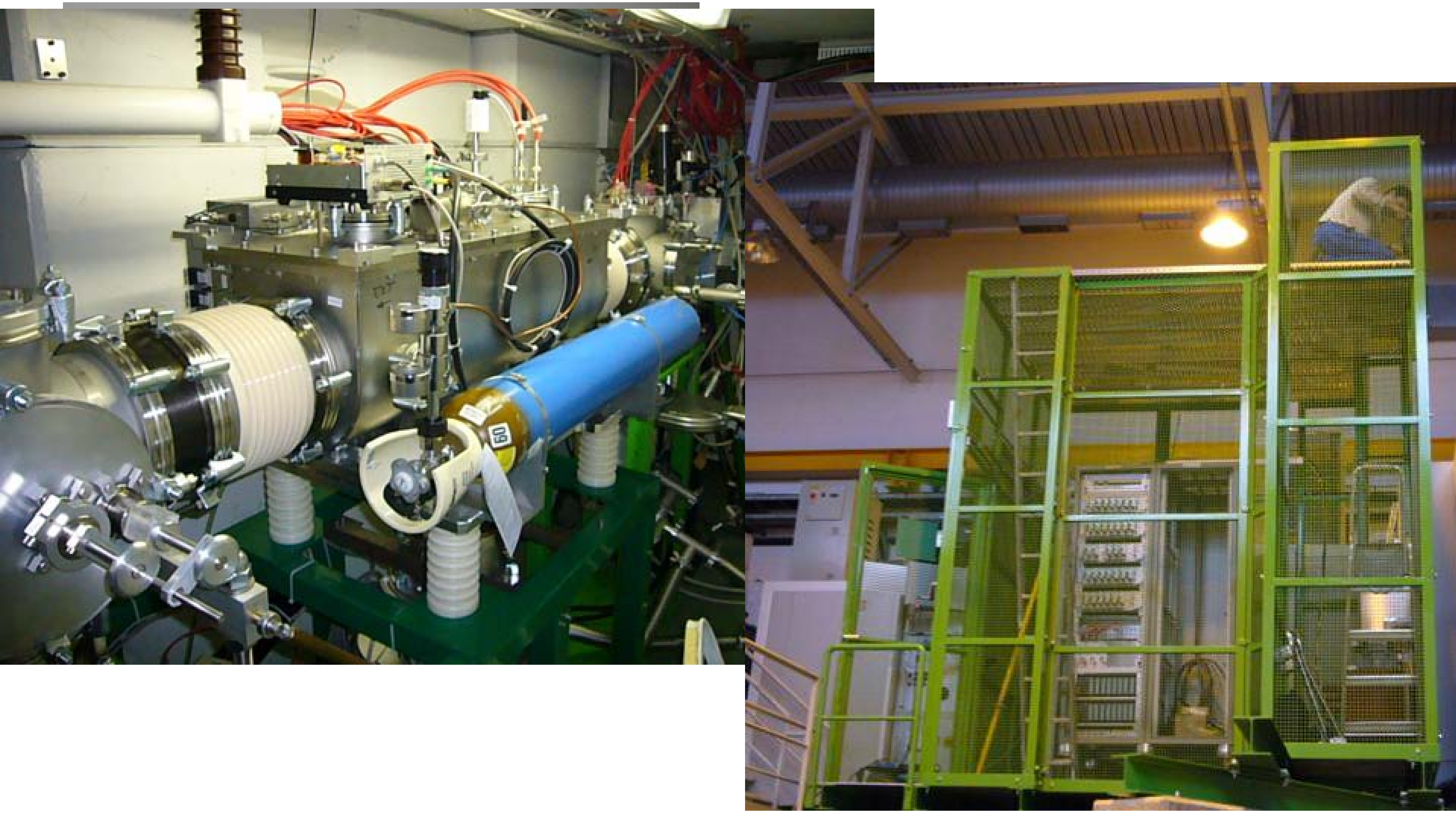
Faisceaux ISOL

- RFQ coolers
  - Réduction d'émittance du faisceau et bunching (10:1)
  - Temps record de refroidissement (<1ms)
  - De plus en plus populaires – ISCOOL desservant plusieurs lignes expérimentales, SHIRAC en développement au GANIL
  - Limites de capacité en mode bunching

ISCOOL à ISOLDE

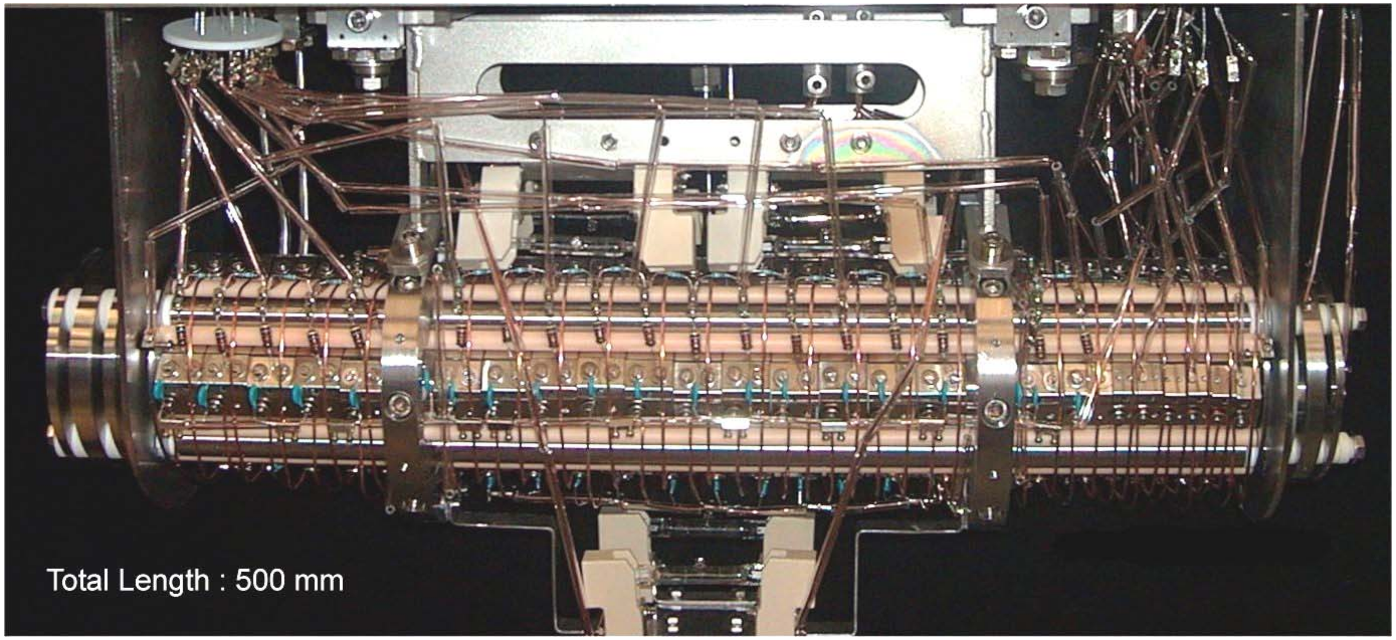


Installation ISCOOL



RFQ cooler $1^{\text{ère}}$ génération

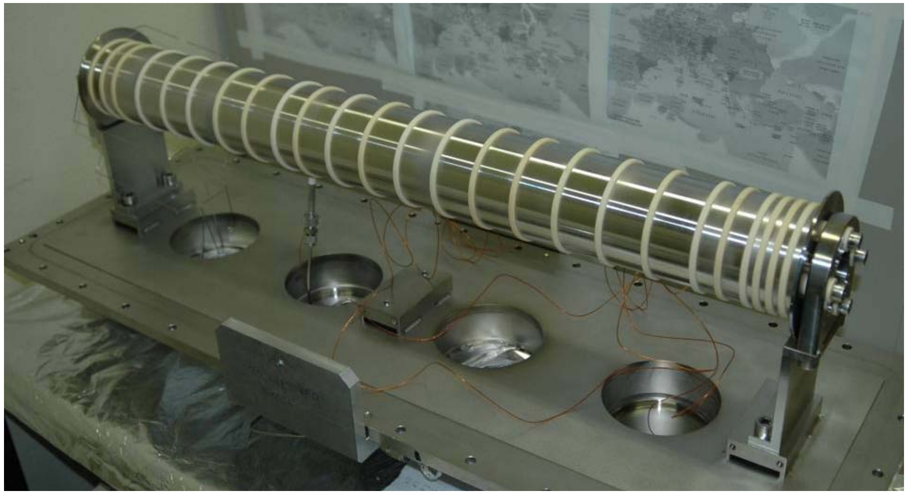
LPCTRAP setup



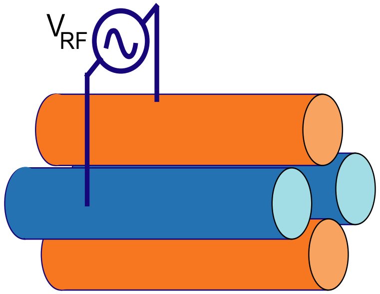
Réduction d'émittance: 80 π.mm.mrad à 40keV -> 10 π.mm.mrad à 100 eV
Réduction de l'espace de phase du faisceau ~1600 en 1 ms
Énergies thermiques 0.025 eV
Efficacité de piégeage: <50%

Limitations en charge d'espace: 10^5 ions par paquet

ISCOOL: 2ème génération



- Anneaux pour les tensions DC suivant l'axe de piégeage
- Puissance RF 400Vpp à 1MHz
- Dimensions significativement plus grandes r0=20mm

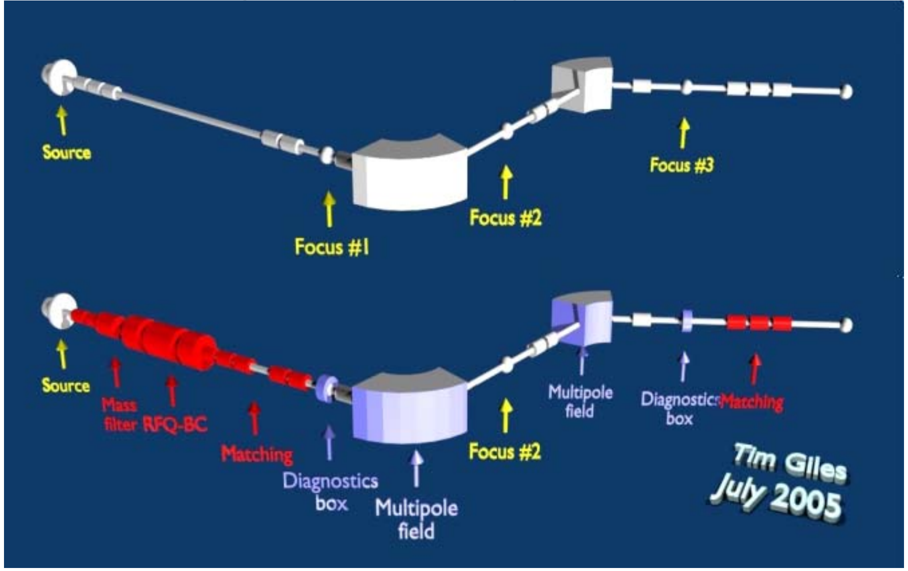


Transmission optimales >70% pour m>=40

Space charge limits: 10^8/bunch
Mode CW: >>100nA

Séparation en masse

- Association avec un séparateur de masse
  - Réduction d'émittance améliore la résolution
    - Meilleure séparation de faisceaux fins
    - Meilleure homogénéité du champ magnétique le long de la trajectoire des ions



ISOLDE HRS upgrade
Tim Giles CERN AB-OP

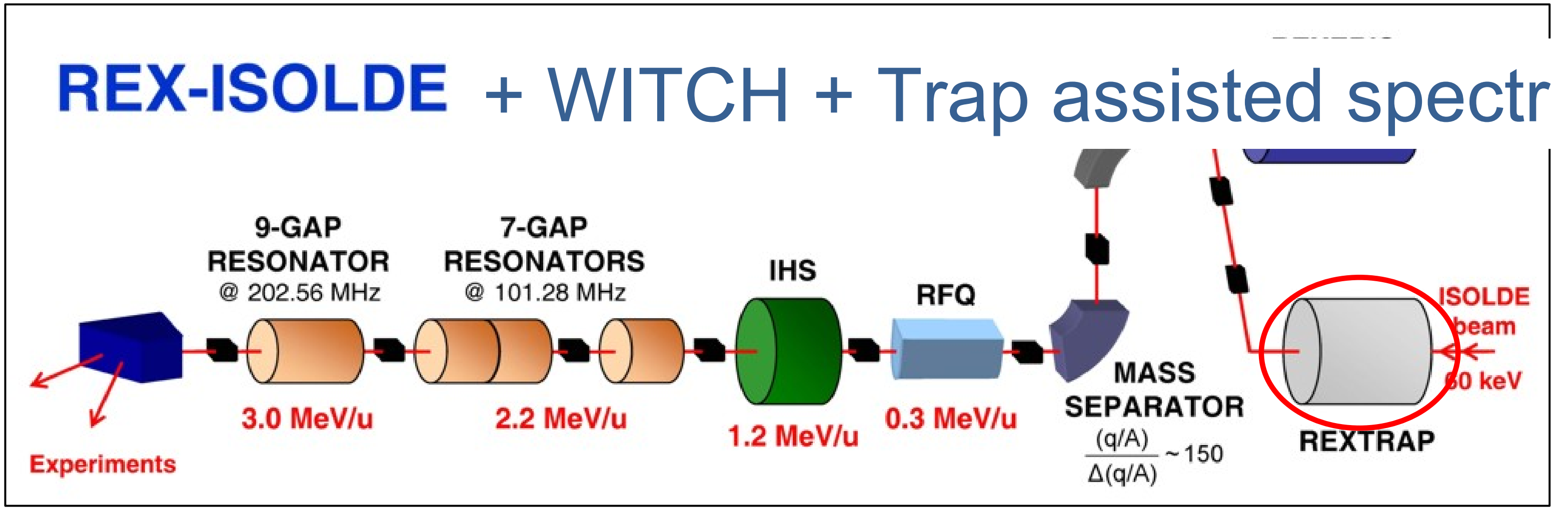
$R=m/\delta m \sim 4000$ in best cases
Upgrade
$R \sim 10{,}000$

High acceptance 100%
Ultra-fast separation

Penning traps

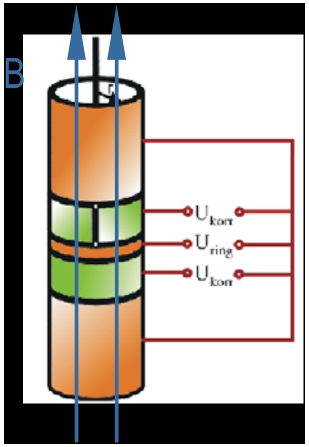
- Penning traps comme refroidisseurs regroupeurs
  - Non end-user experiment: REXTRAP à ISOLDE, selection de masse en développement
  - Trap assisted spectroscopy à JYFLTRAP, en développement auprès des spectromètres de masse
  - Possibilités de sélection en masse
  - Temps de cooling/ sélection en masse incompressibles (de 20 ms à 1s)
  - Limites de capacités

REXTRAP



+ WITCH + Trap assisted spectroscopy

Refroidissement et regroupement

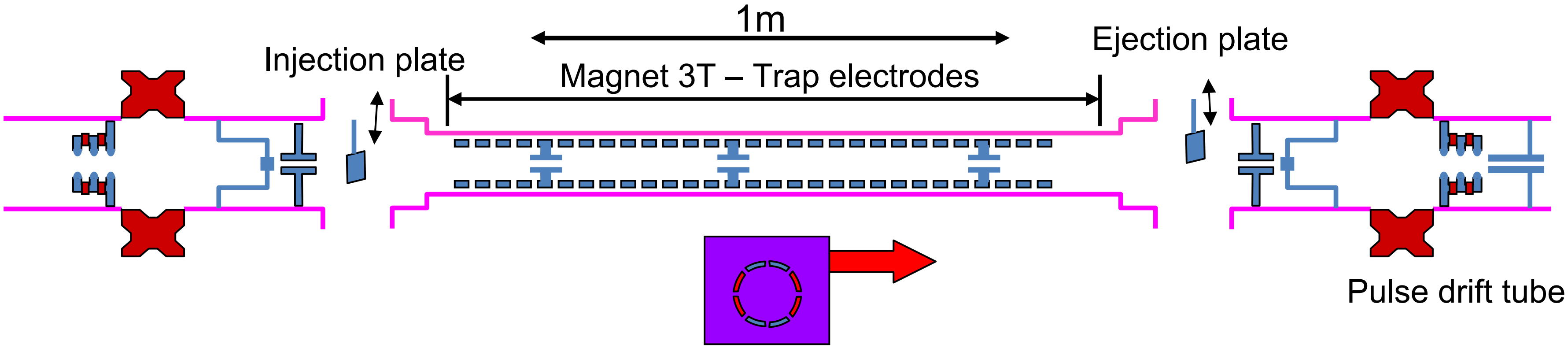


Superconducting magnet
3T

P_{Ne} ~10^{-4} mbar in the trapping area

Performances de REXTRAP

- Le piège Penning le plus large pour la physique nucléaire



1m

Injection plate

Magnet 3T – Trap electrodes

Ejection plate

Pulse drift tube

Center electrodes

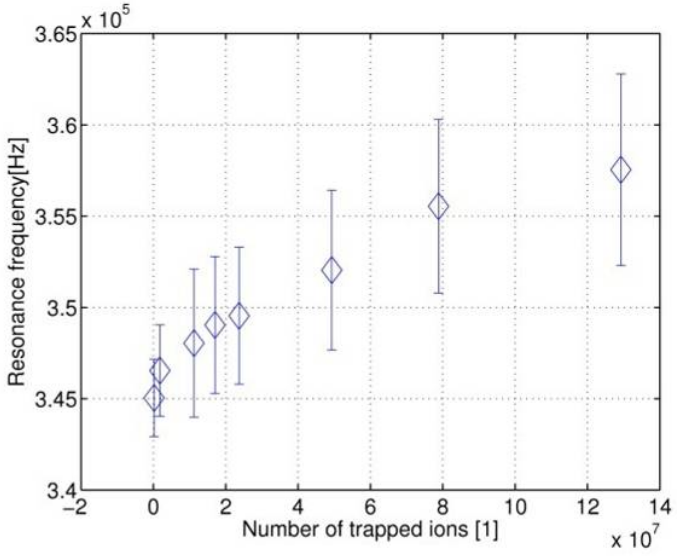
breeding time (A/q < 4.5)	20 ms
beam intensities	$< 10^9$ /s
ions in one charge state	< 30%
injection efficiency into EBIS	>80%
efficiency REXTRAP	50%

P. Schmidt et al,
Nucl. Phys. A
701(2002)550

Un piège très large de grande capacité
Limitations de charge d'espace 10^8 ions/ cycle

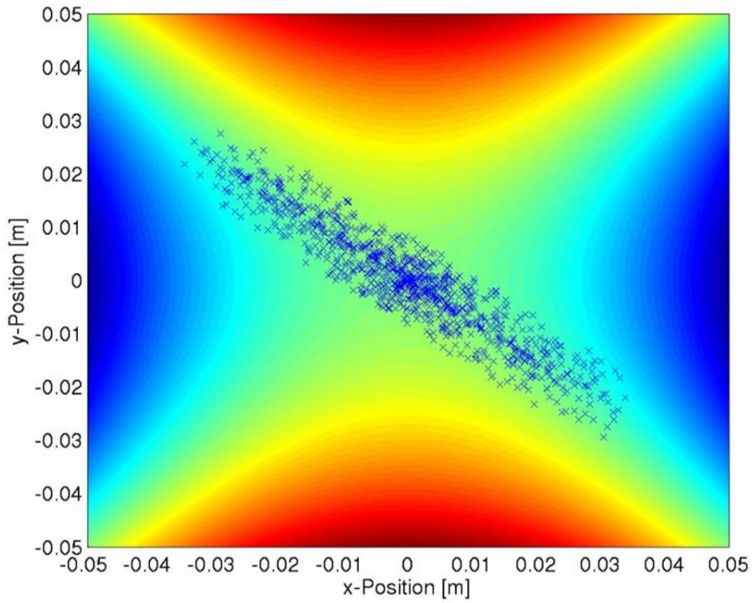
Tests de sélection en masse

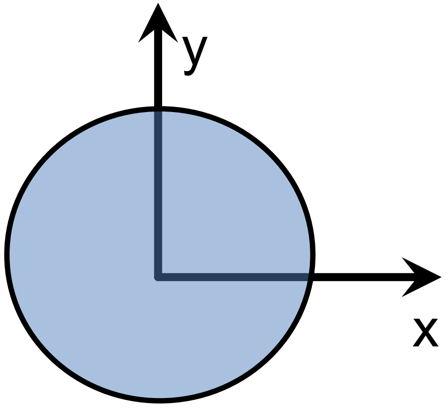
Pb de charge d’espace!!



Observed resonance frequency shift and
broadening as function of the number of ions

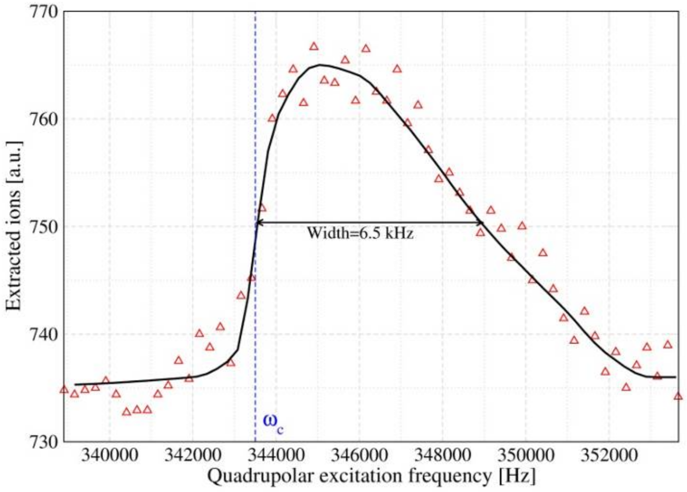
D. Beck et al, Hyp. Int. **132**(2001)469



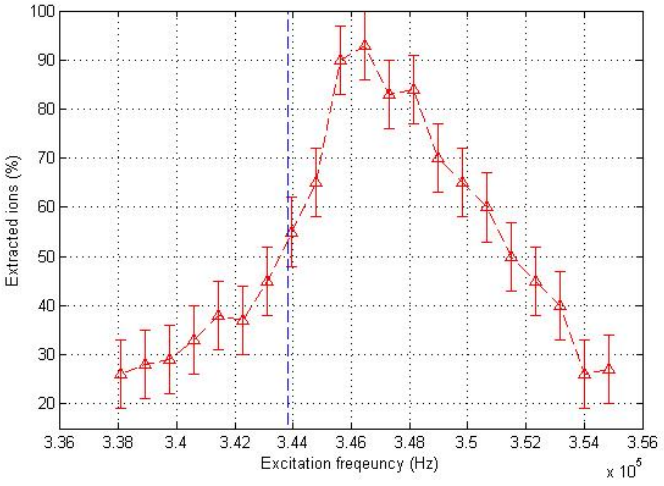


Diploma thesis Sven Sturm

Simulations vs experiments

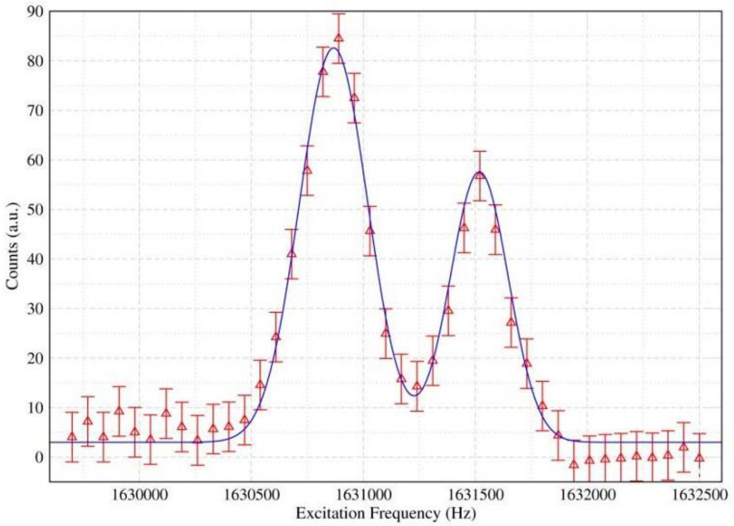


Measured resonance with 5 10^{6} ^{133}Cs ions in Rextrap

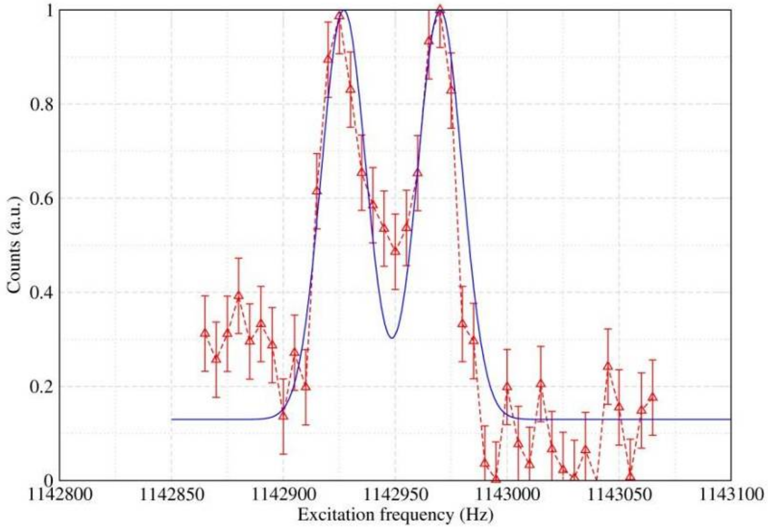


Simulated resonance with 1 10^{7} ^{133}Cs ions, normalised to Rextrap magnetic field

Tests de séparation en ligne

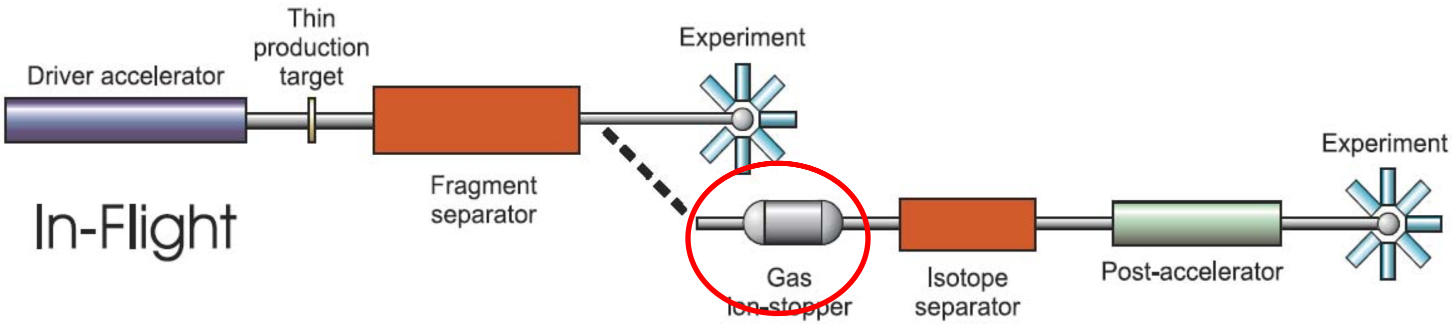


Resolving 2pA N_2 (lower frequency) and 1.5pA CO, both mass 28 (Error bars derived from statistical fluctuations)



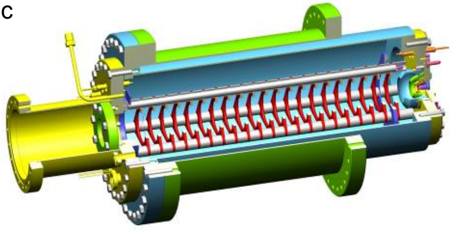
Resolving approx. 0.8pA ^{40}K (lower frequency) and 0.8pA ^{40}Ca (Errror bars derived from statistical fluctuations) Resolving Power~4.5 10^4

Faisceaux in-flight



Gas stopping of fast projectile fragments

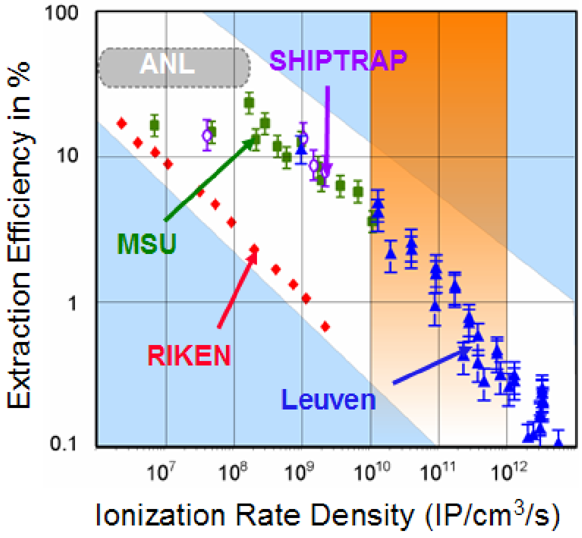
- **Study of gas stopping of fast beams (>50 MeV/u) in linear gas cells**
  - –**NSCL** (high-pressure gas cell) : **90 - 150 MeV/u** Si, P, Ca, S, Ge, As, Se, Br
    NIM A540(2005)245, NIM A522(2004)212,
    NIM A531(2004)416, Nucl. Phys. A746(2004)655c
  - –**RIKEN** (low-pressure gas cell) : 50 -70 MeV/u Li, Be
    Rev. Sci. Instr. 76(2005)103503,
    NIM A532(2004)40, NIM B204(2003)570
  - –**GSI** (low-pressure ANL gas catcher): 280 MeV/u Cr



- **Linear gas cells work:**
  NSCL first to start experimental program with stopped fast beams (LEBIT):
  Penning trap mass measurements of rare isotopes from projectile fragmentation
  Since summer 2005: ^{33}Si, ^{29}P, ^{34}P, ^{37}Ca, ^{38}Ca, ^{40}S, ^{41}S, ^{42}S, ^{43}S, ^{44}S, ^{63}Ga, ^{64}Ga, ^{64}Ge, ^{65}Ge, ^{66}Ge, ^{66}As, ^{67}As, ^{68}As, ^{80}As, ^{68}Se, ^{69}Se, ^{70}Se, ^{81}Se, ^{81m}Se, ^{70m}Br, ^{71}Br

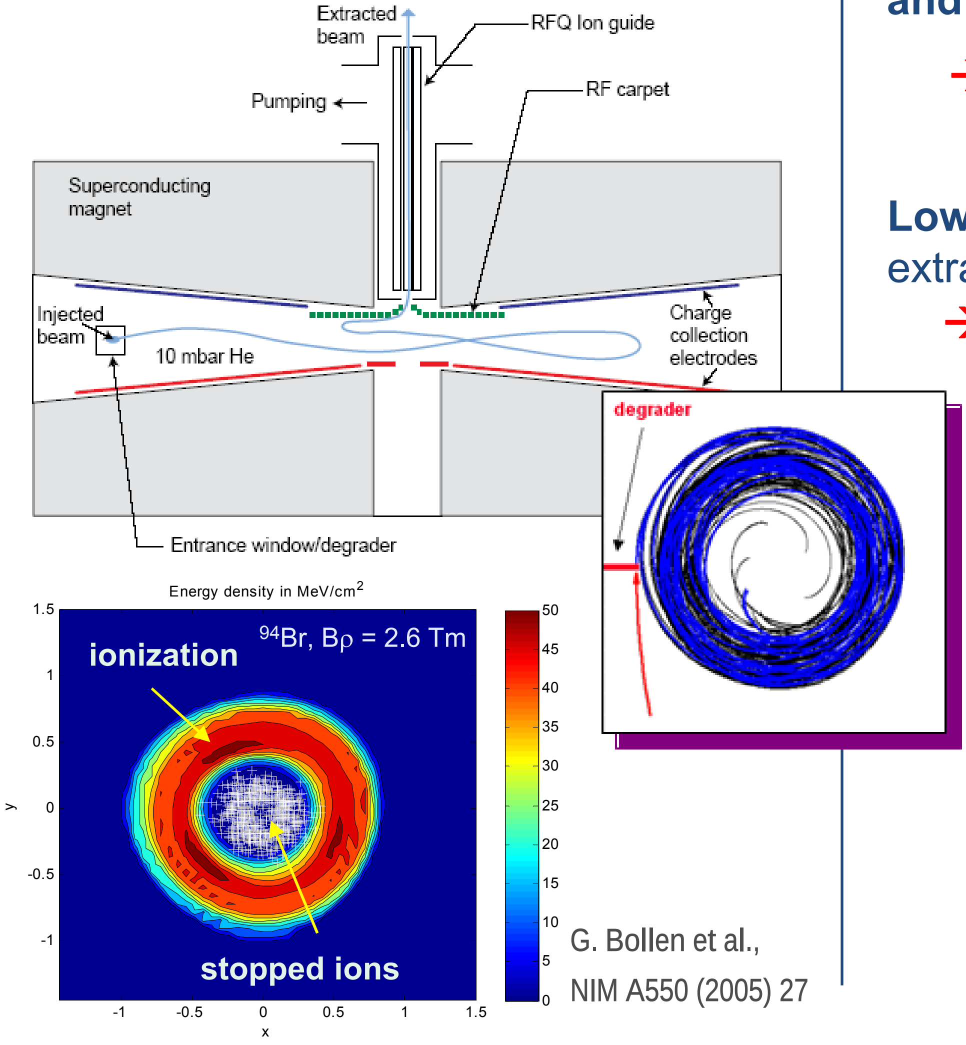
- **Linear gas cells have limitations!**
  - ➢ Rate-dependent extraction efficiencies limit experimental opportunities
  - ➢ Average extraction times of about 100 ms do not match advantages of in-flight production

Ionization rate density is critical parameter →



An advanced concept - the cyclotron gas stopper

Gas-filled focusing cyclotron magnet + RF guiding techniques



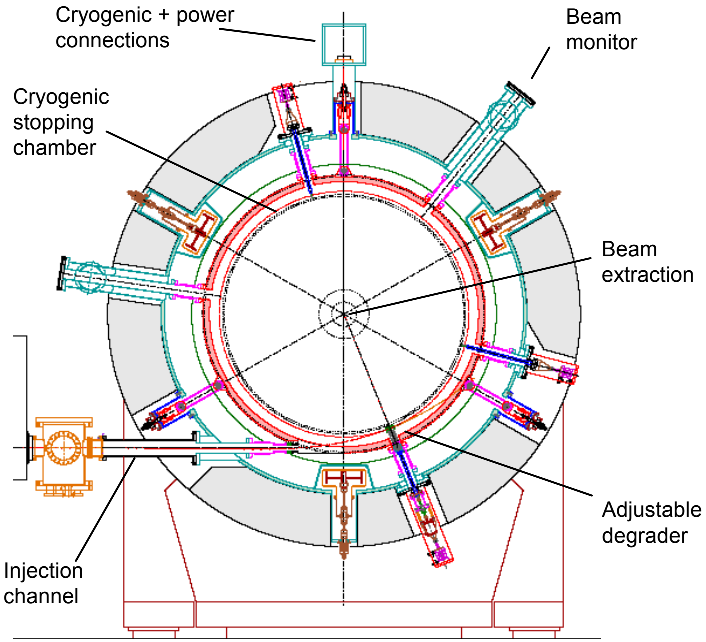
G. Bollen et al., NIM A550 (2005) 27

Separation of stopped-ion distribution and region of maximum ionization

→ **Beam rate capability > 10^8/s for 100 MeV/u fragments**

Low pressure (10 mbar typical) + short extraction path

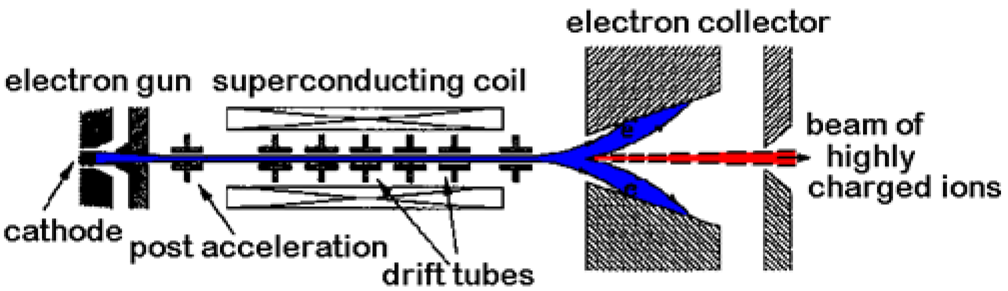
→ **Extraction times < 10 ms**



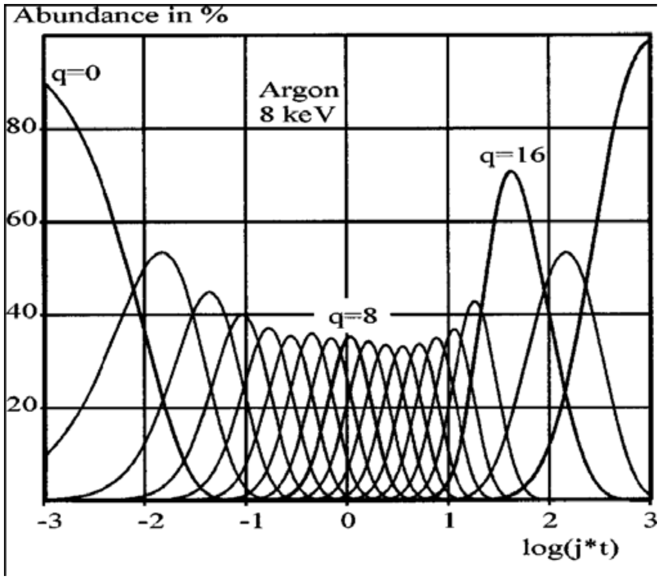
- **Concept fulfills requirements of next generation facility**
- **Full scale system under design at MSU – will be used at ISF**

Pièges électromagnétiques au sens large

- Sources EBIS
  - Penning trap + electron beam!



E. D. Donets, V. I. Ilyushchenko and V. A. Alpert, JINR-P7-4124, 1968
E. D. Donets, Rev. Sci. Instrum. **69**(1998)614



Etat de charge moyen

$\bar{q} \sim \log(j.\tau)$

Capacité de charges élementaires

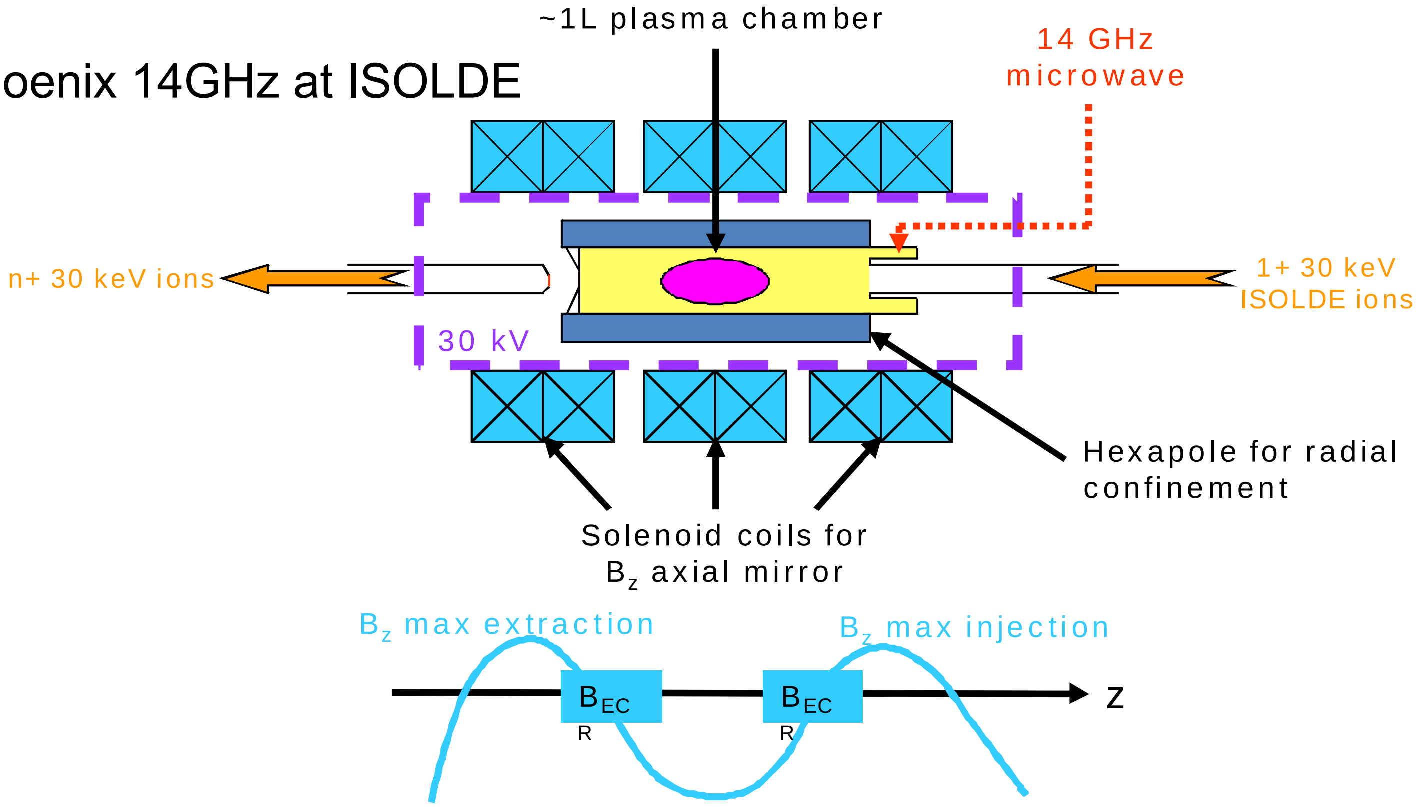
$Q=3.36\ 10^{11} L.I_e/E^{-1/2}$

Contrôle de l'état de charge

Régime essentiellement pulsé

Sources ECR

Phoenix 14GHz at ISOLDE

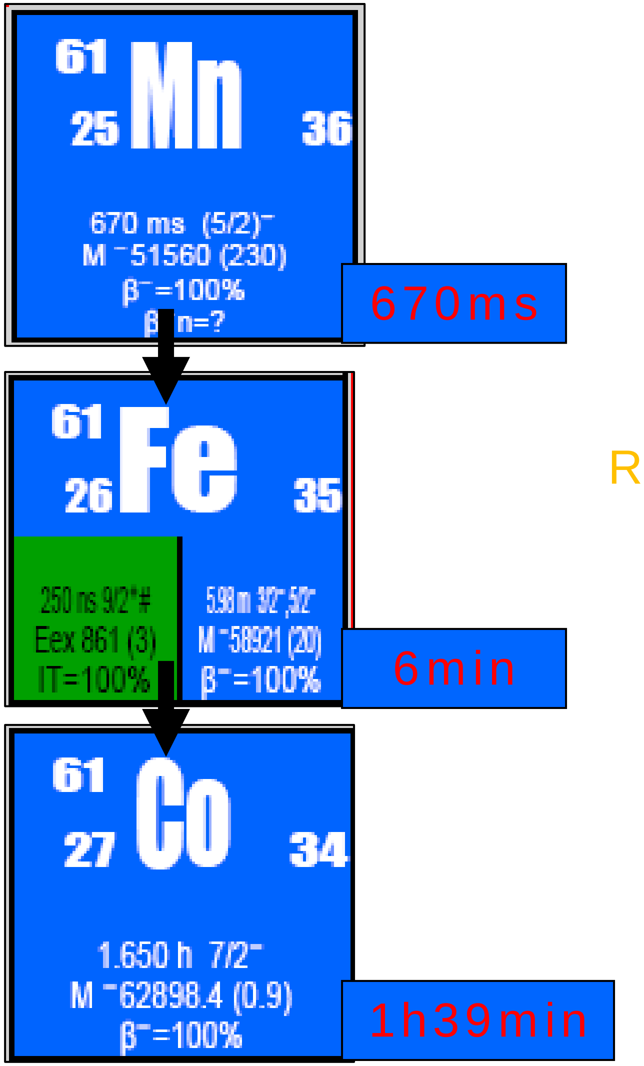


R. Geller, *Electron Cyclotron Resonance Ion Source and ECR plasmas*, IOP, Bristol, UK, 1996.

$f_{RF}=qB_{ECR}/m$ $n_e \sim f^2_{RF}$

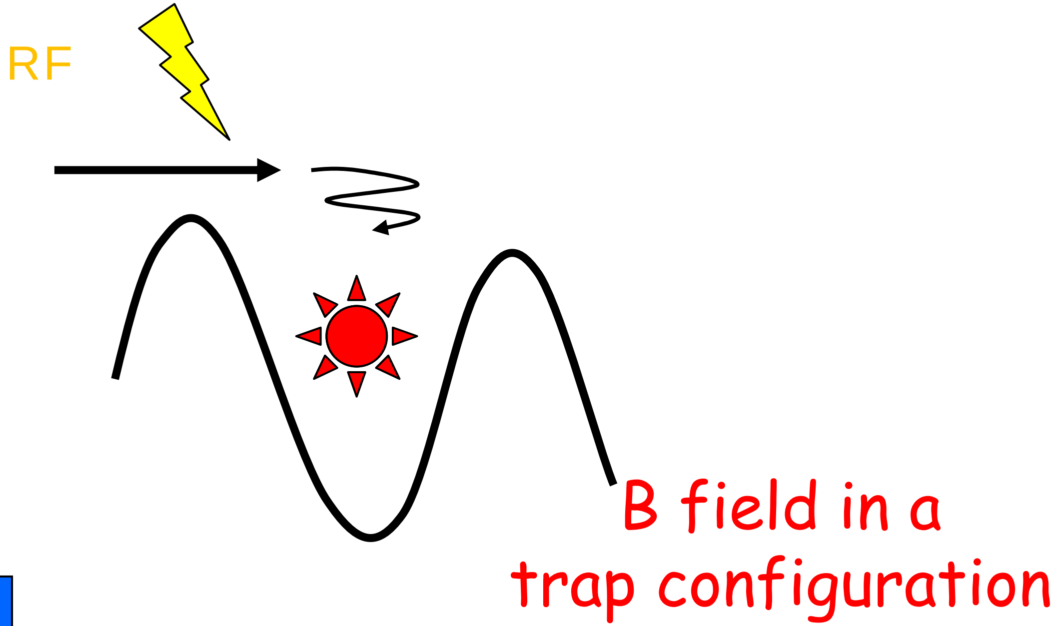
Régime naturellement continu, peut être pulsé

Charge breeding of daughter nuclides



Measurement cycle:

1. ECR plasma is on
2. ^{61}Mn injected into the ECR



Pièges à ions

Ecole Joliot-Curie
Physique nucléaire instrumentale
22-27 Septembre 2008
Seignosse

P. Delahaye

Applications des pièges électromagnétiques à la physique nucléaire et des interactions fondamentales

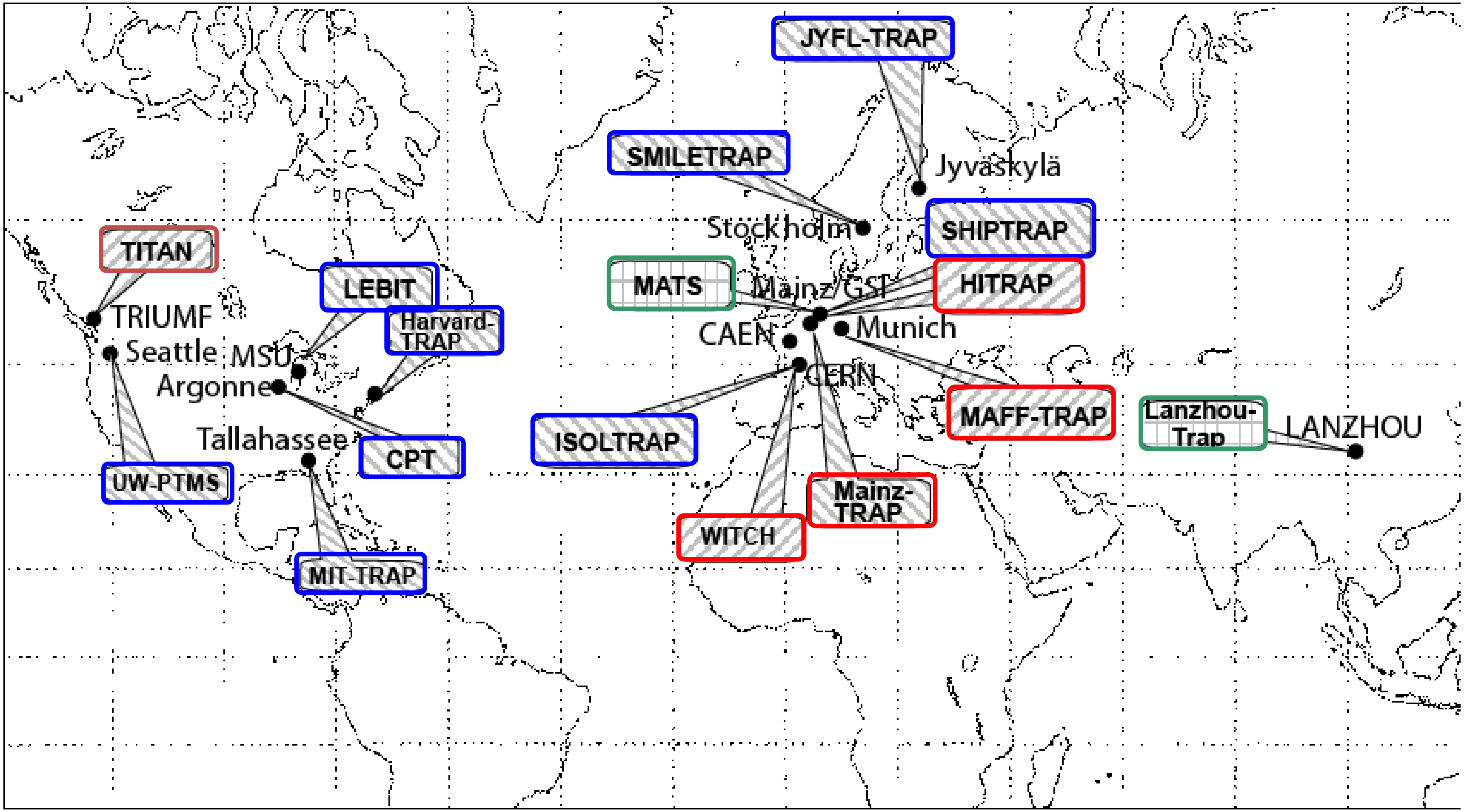
- Penning trap mass spectrometry
- Etude de la désintégration β
- Spectroscopie collinéaire laser
- Antihydrogène et CPT

Requirements for mass spectrometry

K. B., Phys. Rep. 425, 1-78 (2006)	$\delta m/m$
General physics & chemistry	$\lesssim 10^{-5}$
Nuclear structure physics - separation of isobars	$\lesssim 10^{-6}$
Astrophysics - separation of isomers	$\lesssim 10^{-6}$
Weak interaction studies	$\lesssim 10^{-8}$
Metrology - fundamental constants	$\lesssim 10^{-9}$
CPT tests	$\lesssim 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\lesssim 10^{-11}$

Klaus.blaum@mpi-hd.mpg.de

Facilities for mass spectrometry



operating facilities

facilities under construction or test

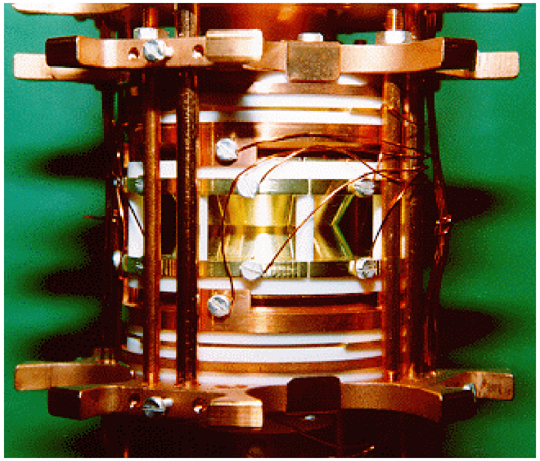
planned facilities

Klaus.blaum@mpi-hd.mpg.de

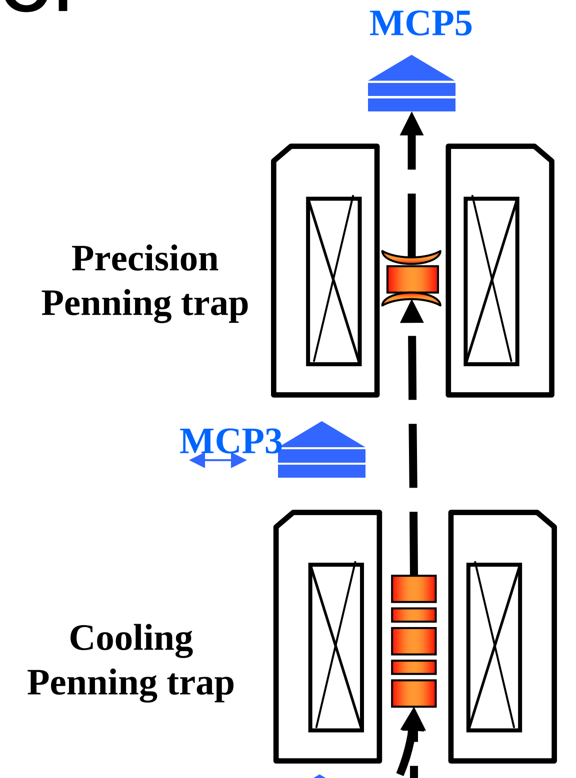
K.B., Phys. Rep. 425, 1 (2006)

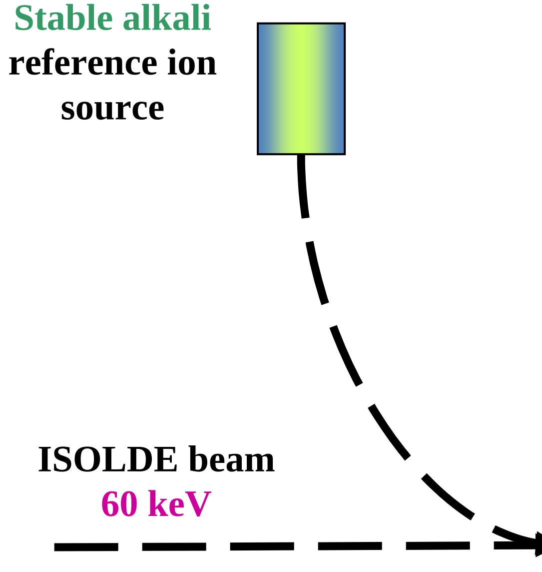
The ISOLTRAP mass spectrometer

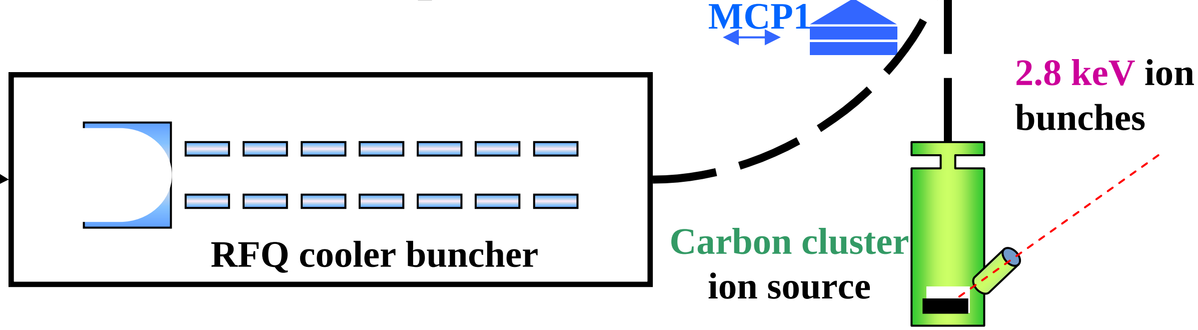
Precision measurement of $\omega_c = qB/m$



Precision trap







Structure nucléaire

$$S_{2n}=B(N,Z)-B(N-2,Z)$$

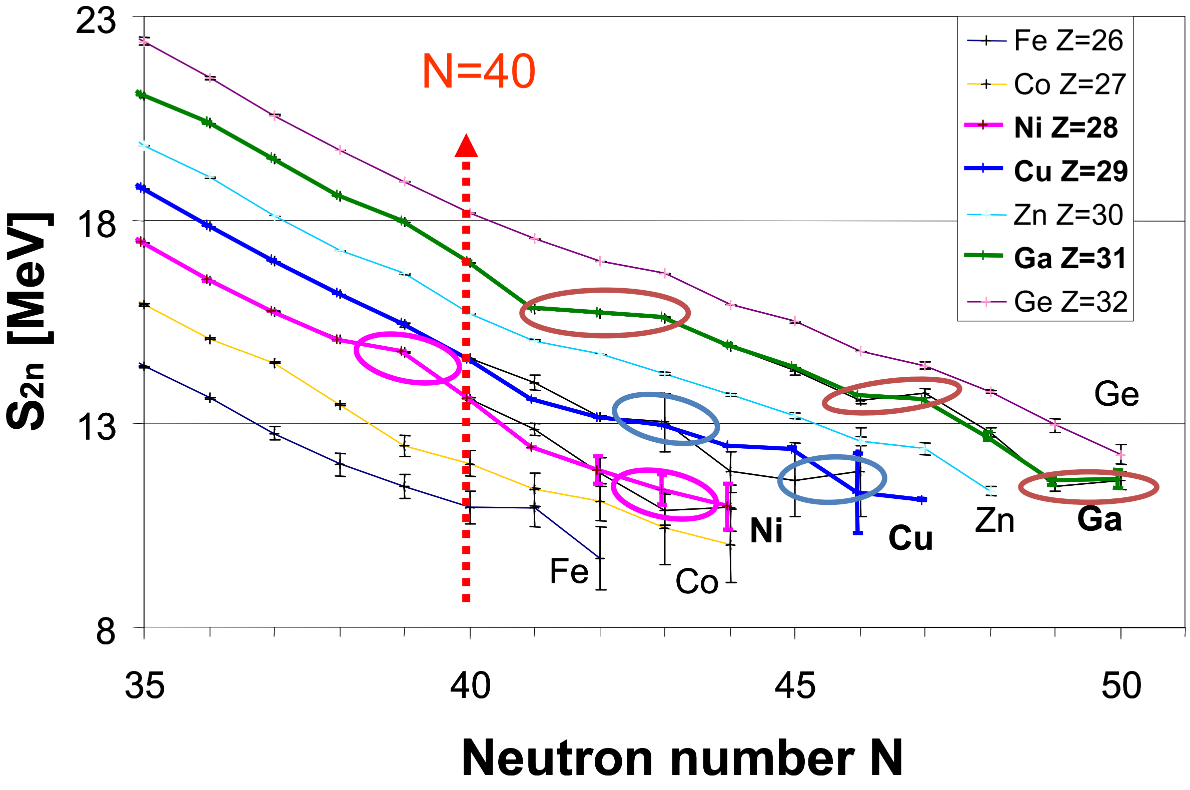
$S2n=B(N,Z)-B(N-2,Z)$

N = 50 shell closure

Deformation

Inspection de la surface de masse

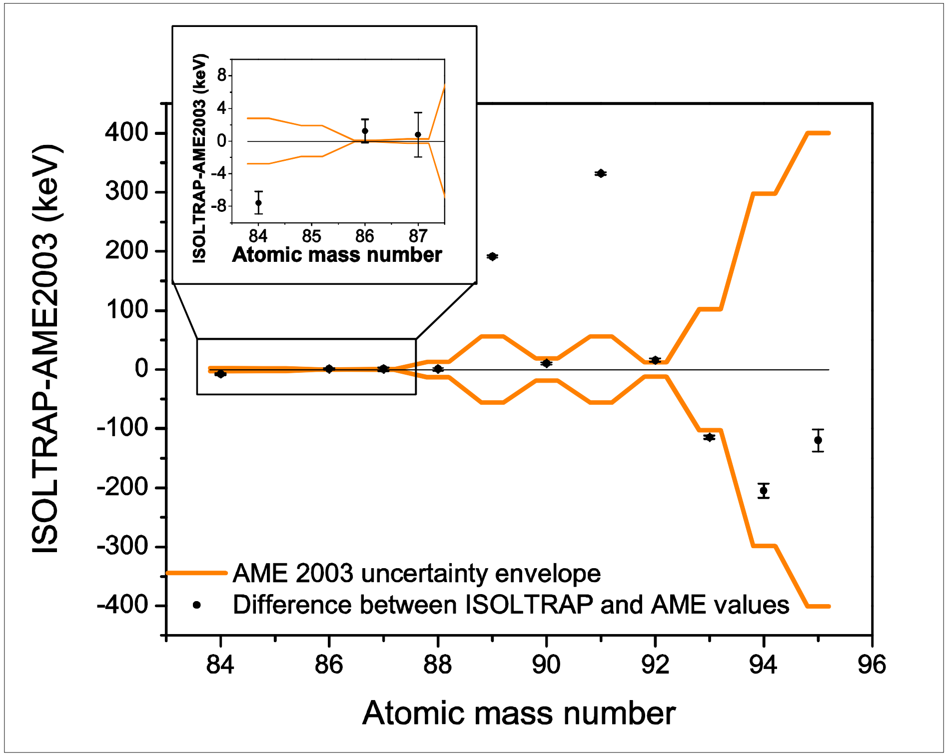
Mid-shell effects around N=40

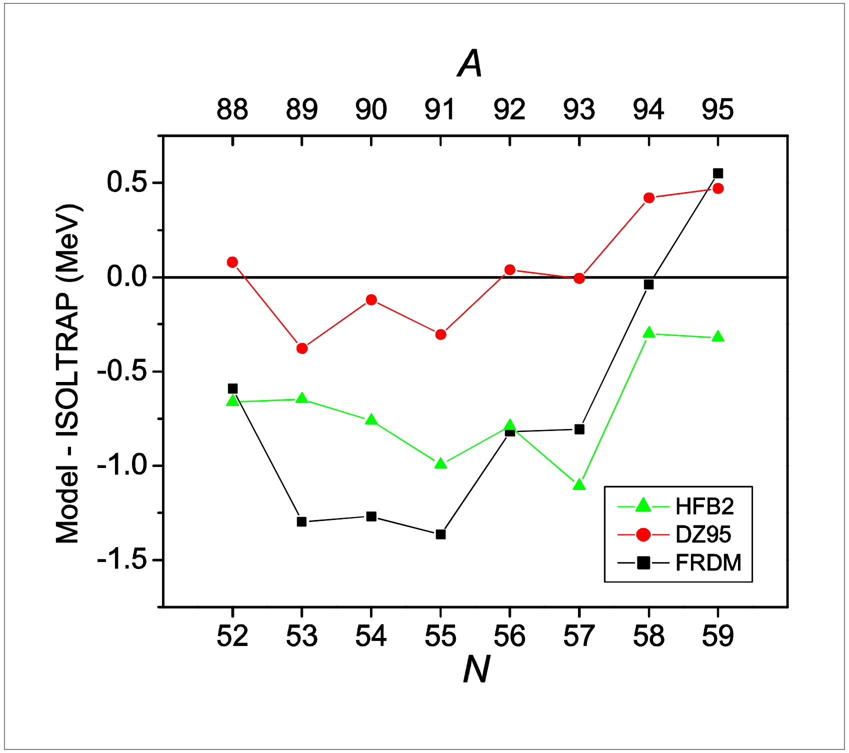


Cu,Ga, Ni isotopic chains measured – Céline Guénault et al, Phys. Rev. C **75**, 04430

Test des modèles de masse

- Exemple: $^{88-95}$Kr mass measurements





Astrophysique nucléaire

- Nucleosynthesis in stars

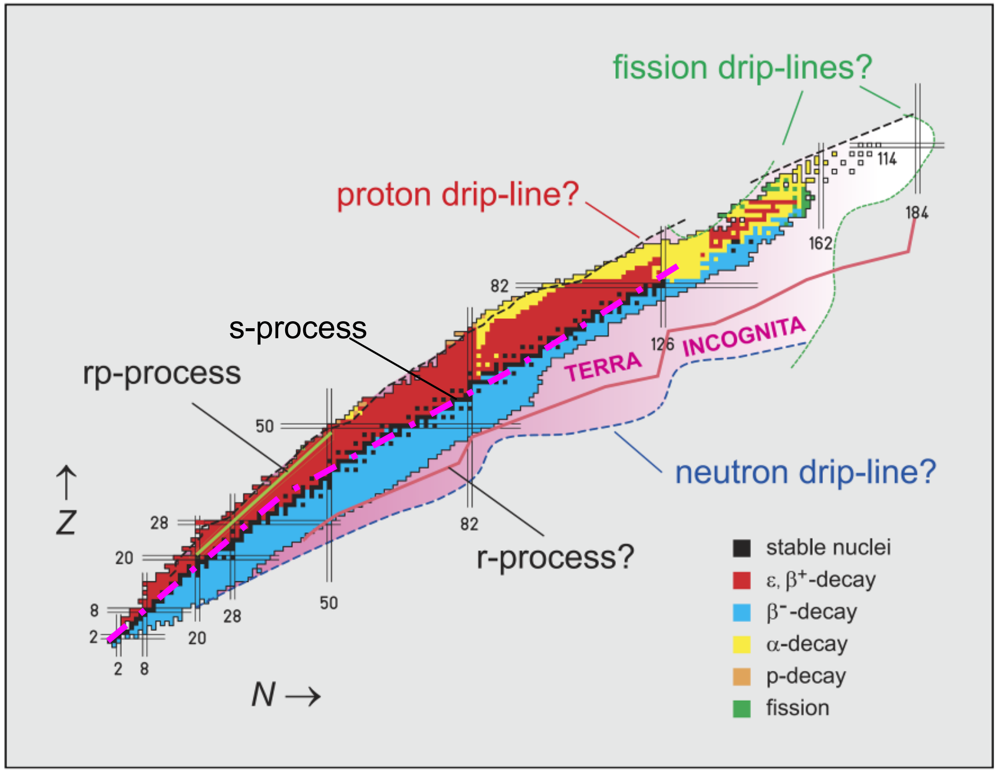
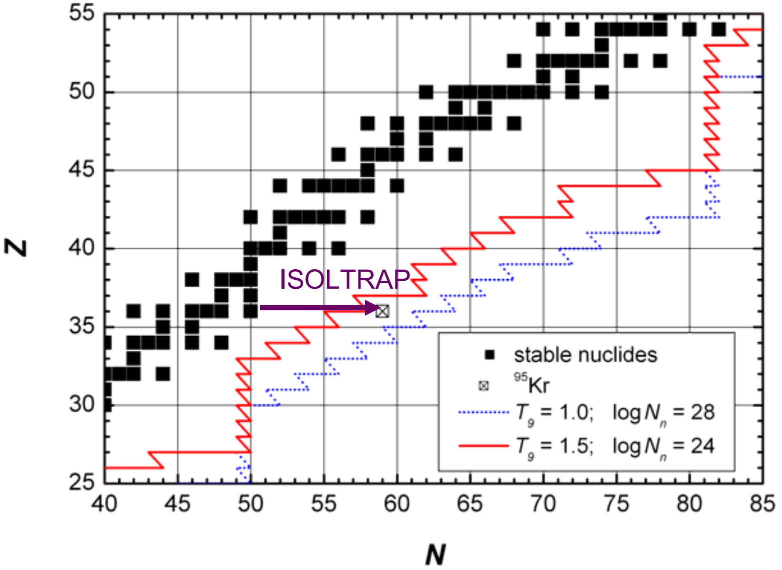


Fig. 2.1: Map of the nuclear landscape.

From the EURISOL report

s and r processes are responsible for the formation of Heavy elements m> 56

Neutron capture / Neutron emission Beta decay competition



CVC et unitarité de la matrice CKM

- CVC L’interaction vectorielle n’est pas influencée par le milieu nucléaire
- Unitarité de la matrice CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\mathrm{ud}}^2 = \frac{G_{\mathrm{V}}^2}{G_{\mathrm{A}}^2}$$

  - Contribution au test d’unitarité de la première ligne de la matrice CKM au travers de G_V

Masses et l’unitarité de CKM / test de CVC

Superallowed β transitions: $0^+ \to 0^+$

- Comparative half-life $ft = \dfrac{K}{\langle M_\mathrm{V}\rangle^2 G_\mathrm{V}^2}$

K – Product of fund. constants

G_V – Vector coupling constant

$\langle M_V \rangle$ - Nuclear matrix element

- corrected *ft* $\mathcal{F}t \equiv ft(1+\delta_\mathrm{R})(1-\delta_\mathrm{C}) = \dfrac{K}{2G_\mathrm{V}^2(1+\Delta_\mathrm{R}^\mathrm{V})}$

Is constant in the CVC hypothesis

δ_R radiative correction

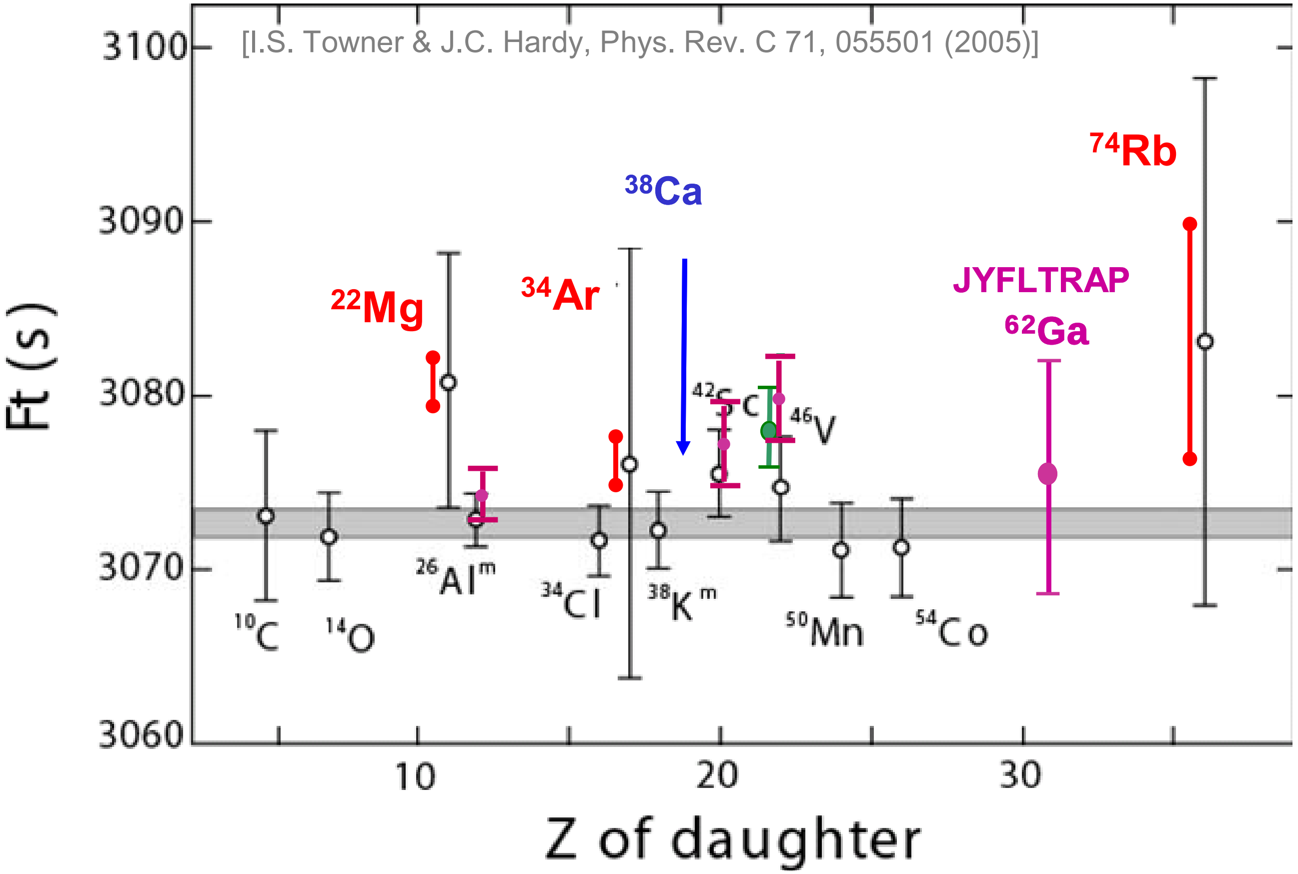
δ_C isospin symmetry-breaking correction

Δ_R^V nucleus independent radiative correction

$$Ft = Ft(Q, T_{1/2}, R, P_{EC}, \delta_R, \delta_C)$$

$f \sim Q^5$

Mesures de masses



ISOLTRAP: Mg-22, Al-26, Ar-34, Ca-38, Rb-74

F. Herfurth *et al*., Eur. Phys. J. A 15, 17 (2002)
A. Kellerbauer *et al*., Phys. Rev. Lett.93, 072502 (2004)
M. Mukherjee *et al*., Phys. Rev. Lett. 93, 150801 (2004)
S. George et al. Phys. Rev. Lett. 98, 162501 (2007)

LEBIT: Ca-38

G. Bollen et al., Phys. Rev. Lett. 96 (2006) 152501

JYFL-TRAP: Al-26m, Sc-42, Ga-62

T. Eronen et al., Phys. Rev. Lett. 97 (2006) 232501
T. Eronen et al., Phys. Lett. B 636 (2006) 191
B. Hyland et al., Phys. Rev. Lett. 97(2006) 102501

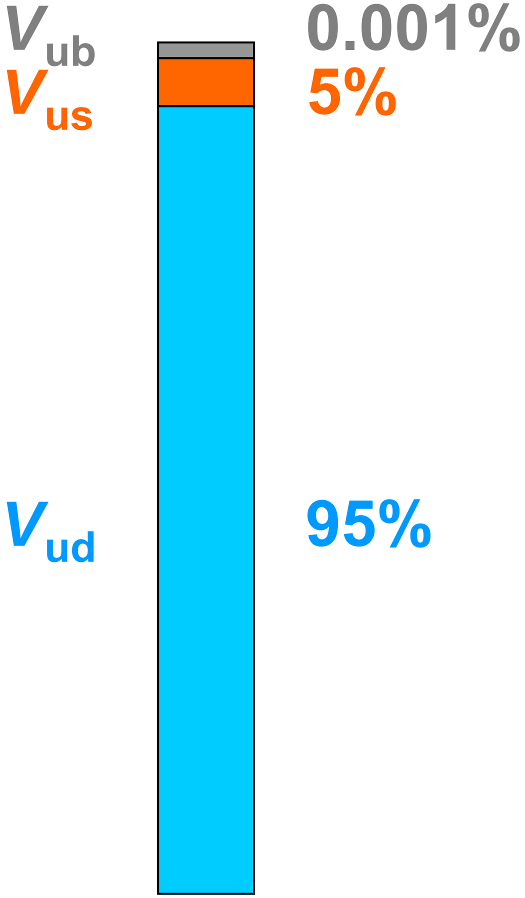
CPT: Mg-22, V-46

G. Savard et al., Phys. Rev. Lett. 95, 102501 (2005)
Phys. Rec. C 70, 042501(R) (2004)

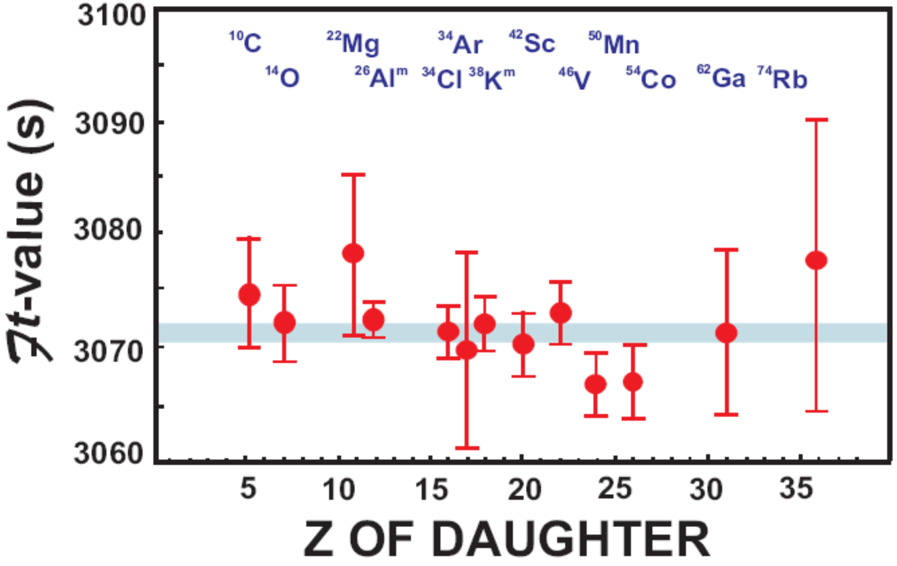
Klaus.blaum@mpi-hd.mpg.de

Problème de non-unitarité résolu

Unitarity contribution:



Statut actuel (Hardy 2008):



V_{ud} (nuclear β-decay) = 0.9742(3)

V_{us} (kaon-decay) = 0.2256(18)

V_{ub} (B meson decay) = 0.0037(5)

$$\left|V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 = 1{,}0000\,(10)$$

Klaus.blaum@mpi-hd.mpg.de

Etude de l’interaction faible

- Mesure du paramètre de corrélation angulaire $\beta-\nu$
- Spectroscopie des transitions Fermi pures
- Atomes polarisés

The β–ν angular correlation in nuclear β decay

- Test of the V-A theory
- Sensitive to exotic interactions S,T

- Pure Fermi transitions

$$a_F = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

V-A $a_F=1$

Adelberger et al. (1999)

^{32}Ar

$$a_F = 0.9989 \pm 0.0065$$

$|\frac{C_S}{C_V}| \leq 0.06$ & $|\frac{C'_S}{C_V}| \leq 0.08$ if $|C_V| = |C'_V|$

- Pure Gamow Teller transitions

$$a_{GT} = \frac{1}{3}\frac{|C_T|^2 + |C'_T|^2 - |C_A|^2 - |C'_A|^2}{|C_T|^2 + |C'_T|^2 + |C_A|^2 + |C'_A|^2}$$

V-A $a_{GT}=-1/3$

Johnson et al. (1963!)

^{6}He

$$a_{GT} = -.3343 \pm .0030$$

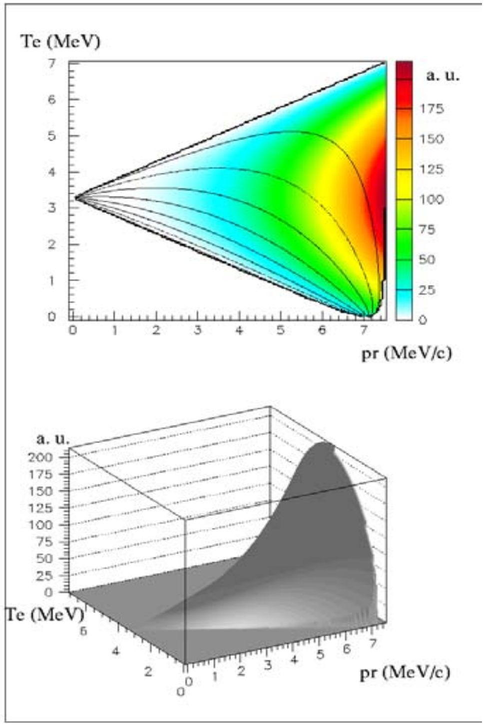
$|\frac{C_T}{C_A}| \leq 0.13$ & $|\frac{C'_T}{C_A}| \leq 0.13$ if $|C_A| = |C'_A|$

The β-ν angular correlation in nuclear β decay

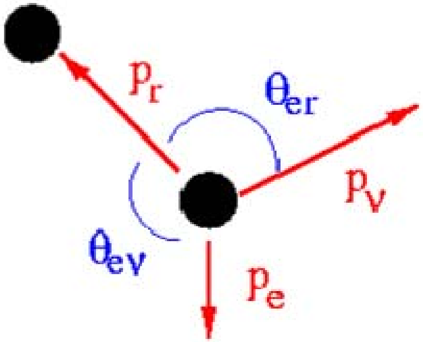
β decay spectrum

$$N(E_e,\Omega_{e\nu})dE_e d\Omega_{e\nu} = F(\pm Z, E_e)N_0(E_e)\left(1 + b\frac{m}{E_e} + \overset{\downarrow}{a}\,\frac{\vec{p_e}\vec{p_\nu}}{E_e E_\nu}\right)dE_e d\Omega_{e\nu}$$

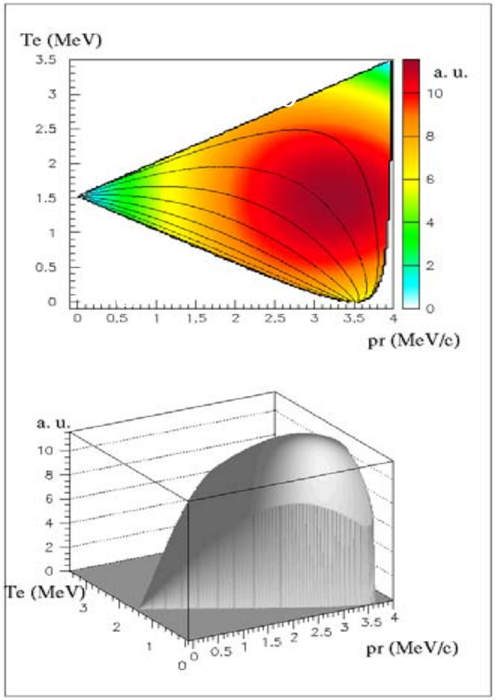
- Fermi transition (ΔJ=0)
- Gamow-Teller transition (ΔJ=0±1)



$^{46}\mathrm{V}$

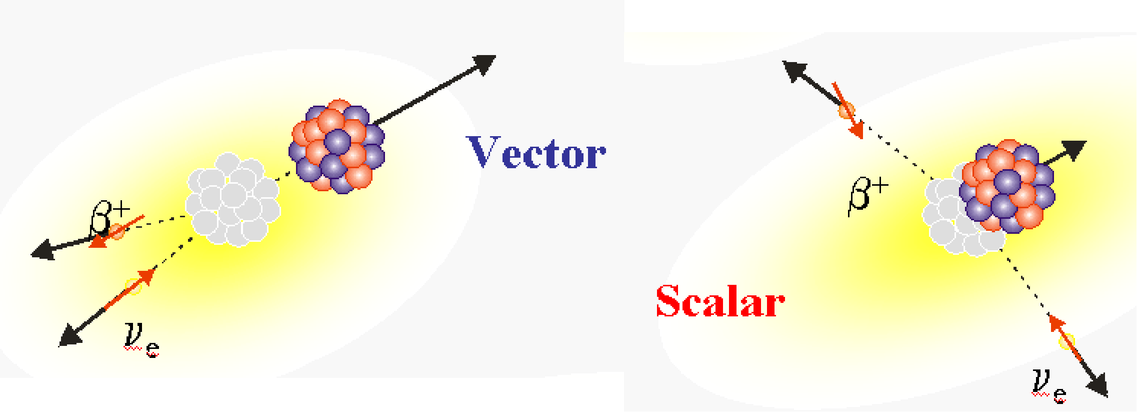


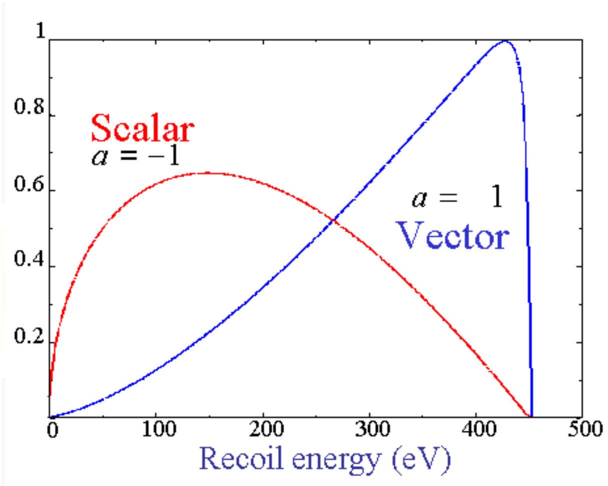
$^{6}\mathrm{He}$

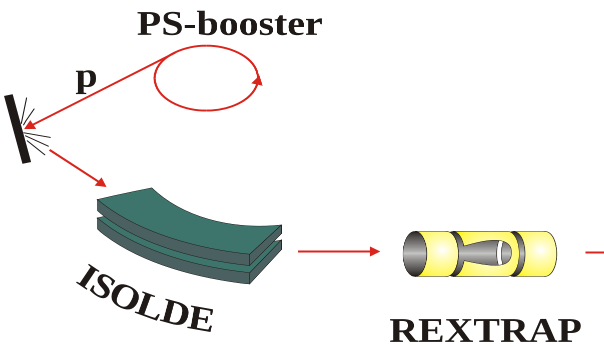


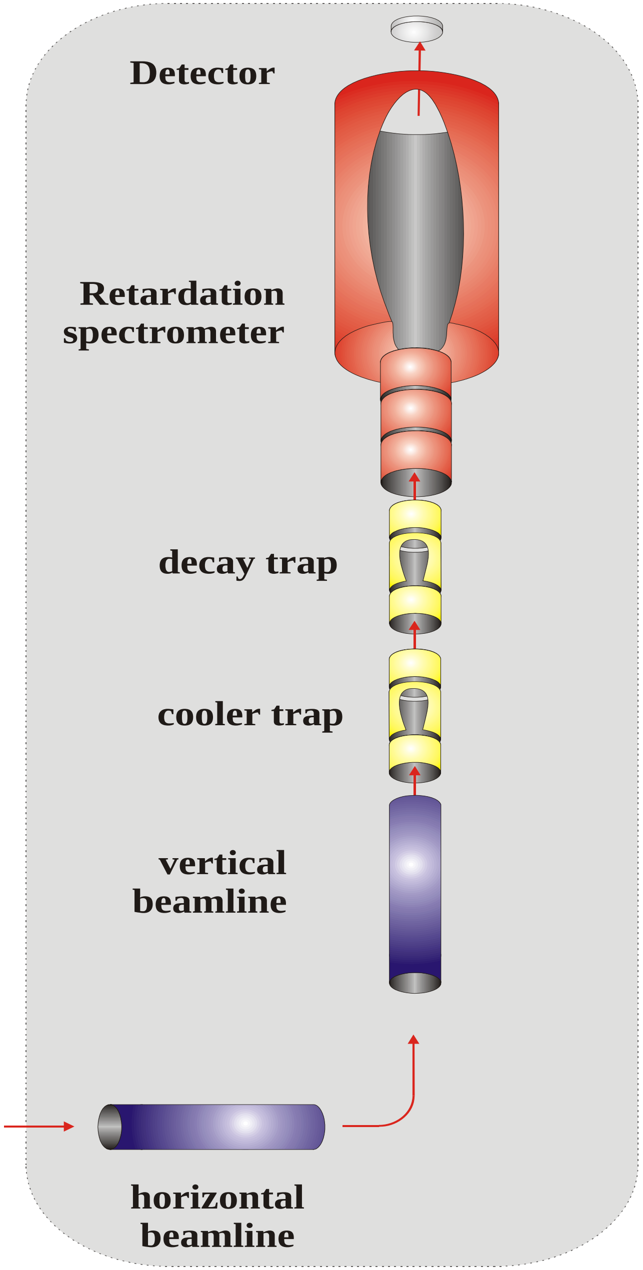
WITCH experiment at ISOLDE/CERN

K.U.Leuven, Univ. Munster, ISOLDE-CERN,
GSI, NPI Rez-Prague



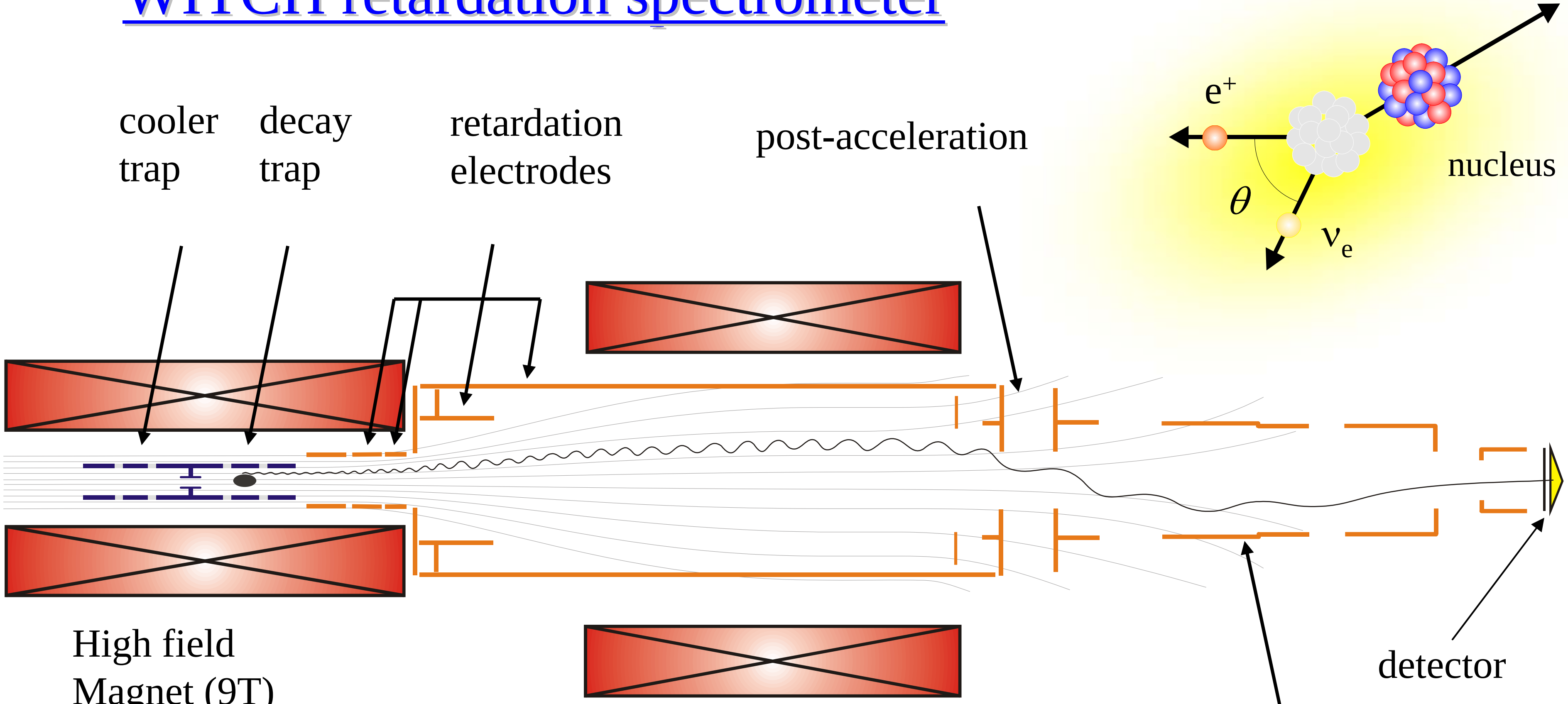






M. Beck et al, Nucl. Instr. Meth. A503 (2003) 567

WITCH retardation spectrometer



cooler trap

decay trap

retardation electrodes

post-acceleration

e^+

nucleus

θ

ν_e

High field Magnet (9T)

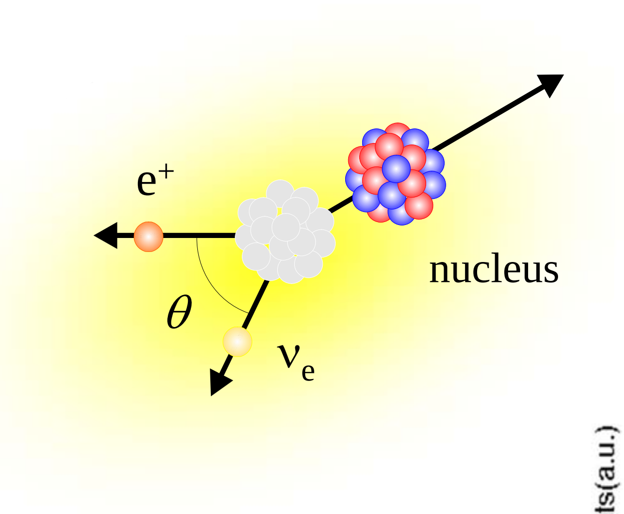
Low field Magnet (0.1T)

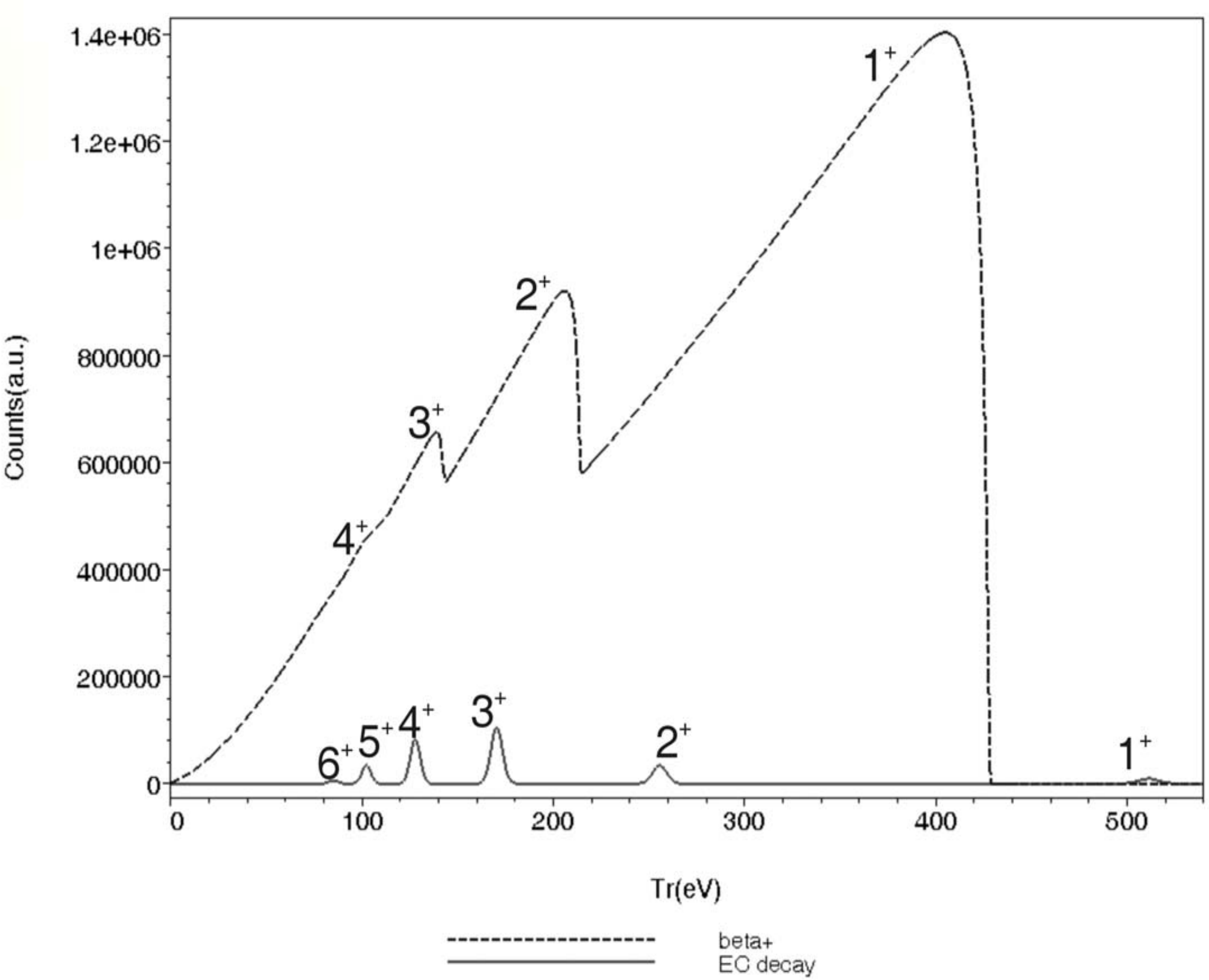
detector

einzellens

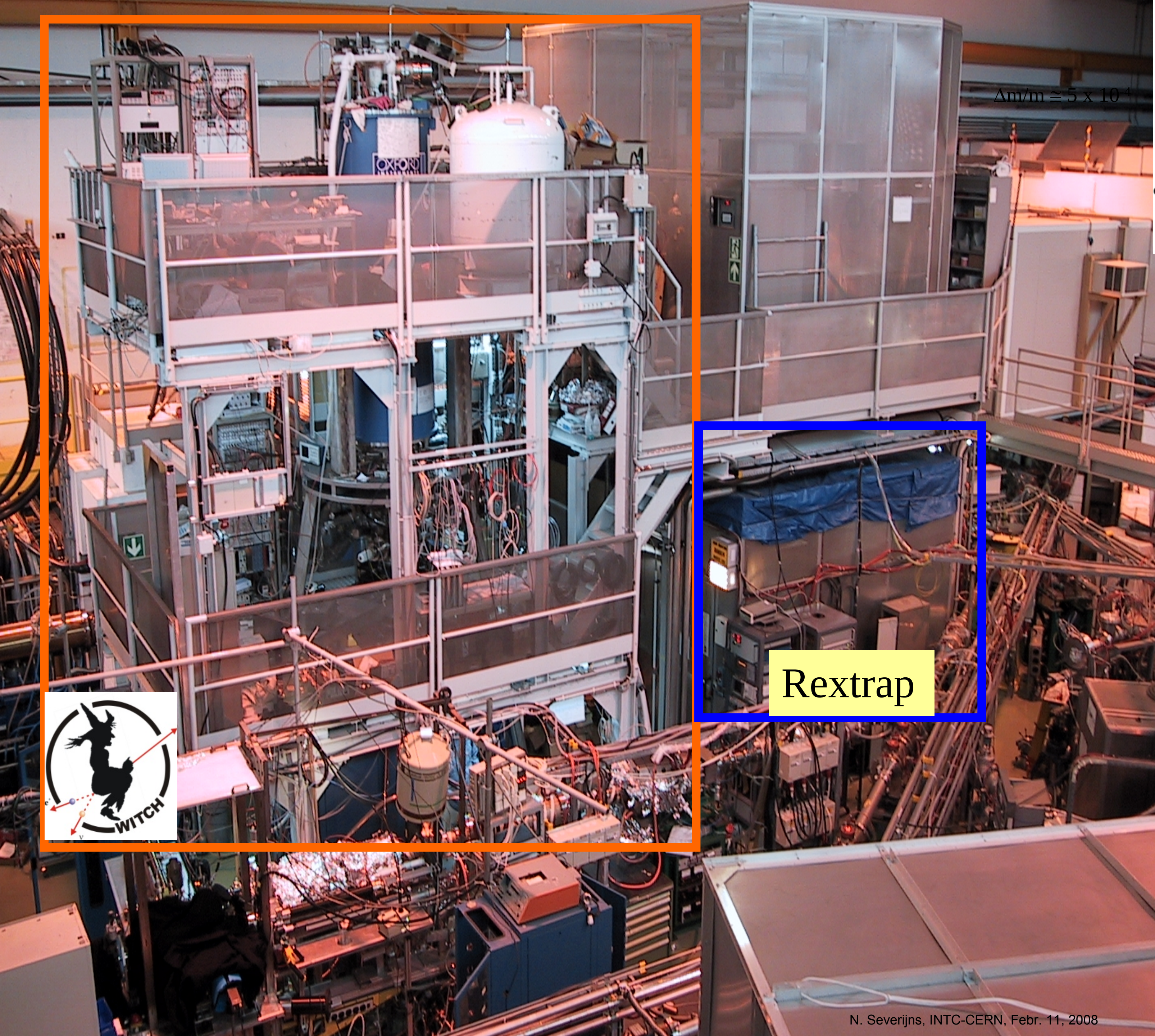
⇨ Energy conversion

$$\frac{E_{\perp 1}^{kin}}{E_{\perp 0}^{kin}} = \frac{B_1}{B_0} = \frac{0.1T}{9T} = 1.1\%$$





Simulated recoil energy spectrum for the decay of ^{38m}K



$\Delta m/m \cong 5 \times 10^{-4}$


decay trap (20 cm)

cooler Trap (20 cm)

Efficiencies

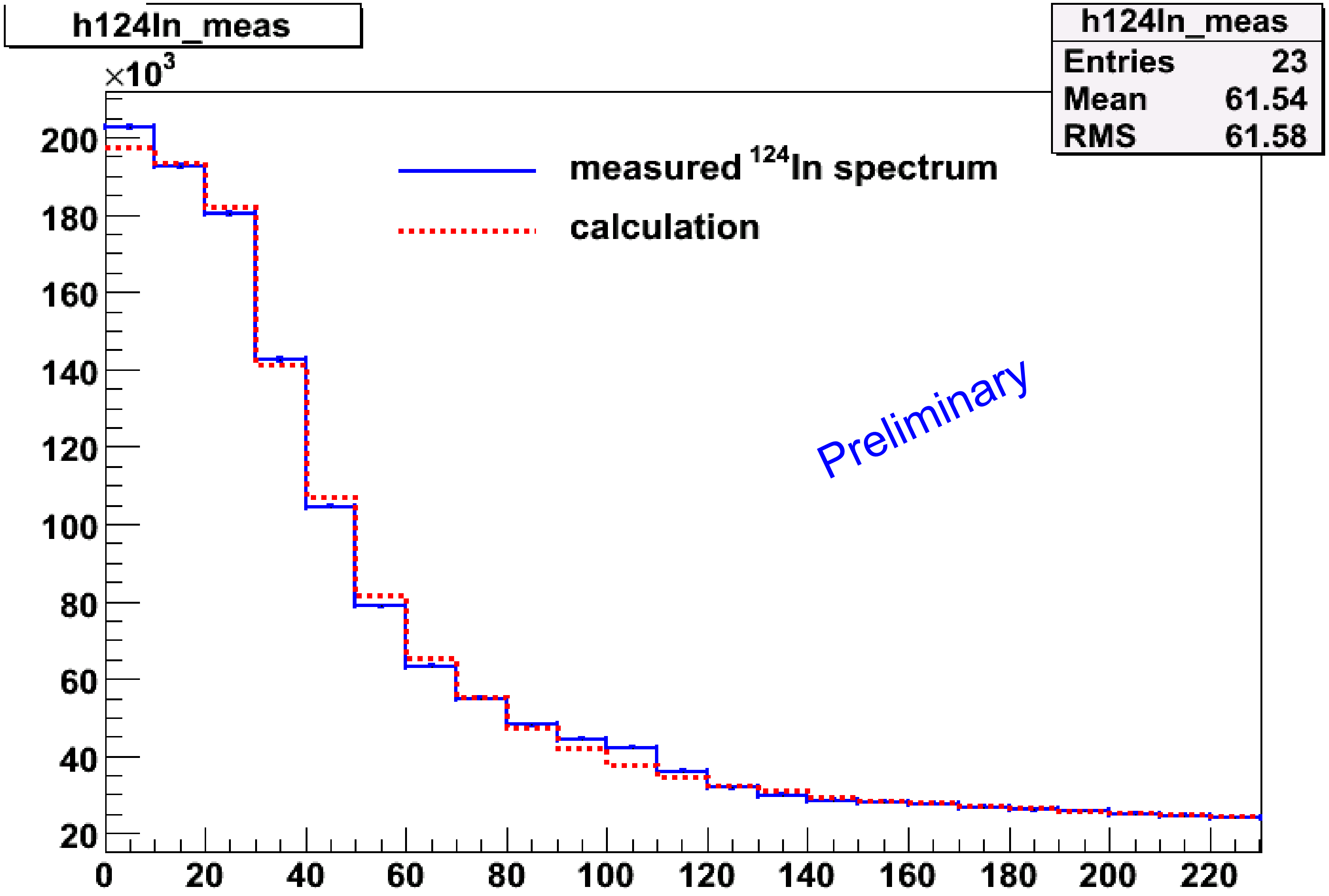
Description	**‘ideal set-up’**	**Best achieved yet**
		2004 - now
Beamline transfer + pulse-down	50%	~ 80%
Injection into B-field, $\varepsilon_{\text{injection}}$	100%	20%
Cooler trap efficiency	100%	~ 45%
Transfer between traps	100%	~ 80%
Storage in the decay trap	100%	100%
Fraction of ions leaving the decay trap	~ 40%	not yet studied
Shake-off to lowest charge state	10% [c]	not yet studied
Transmission through spectrometer	100%	~ 100% (*prelim*.)
MCP efficiency, ε_{MCP}	60%	52.3(3)% [a]
Total efficiency	**~ 1%** [c]	**0.1%** [b, c]

[a] Lienard et al., NIM A 551 (2005) 375.

[b] improved by factor of ≈**150** in comparison with 2004

[c] for β^+ decay (1^+ charge state); for β^- decay (2^+ charge state) these numbers are about **10 times larger**

First recoil spectrum - 124In



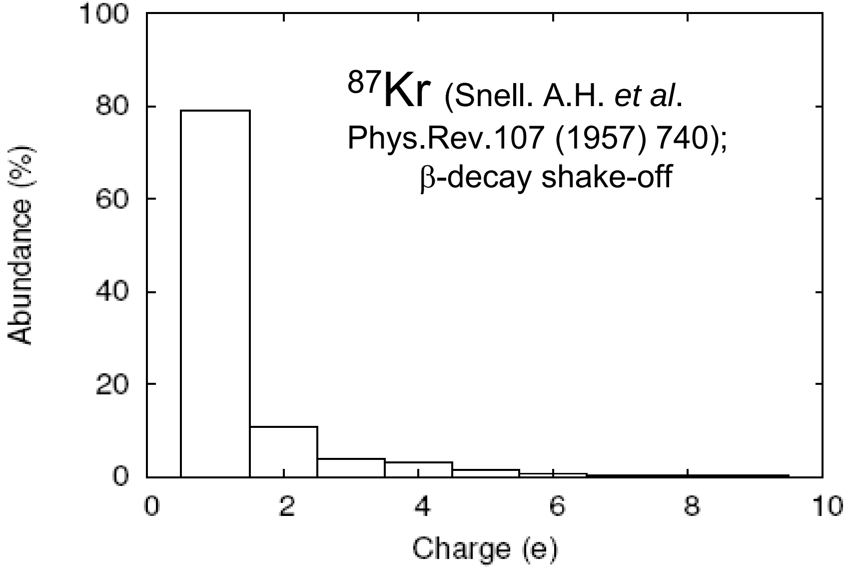
Mixed beam:

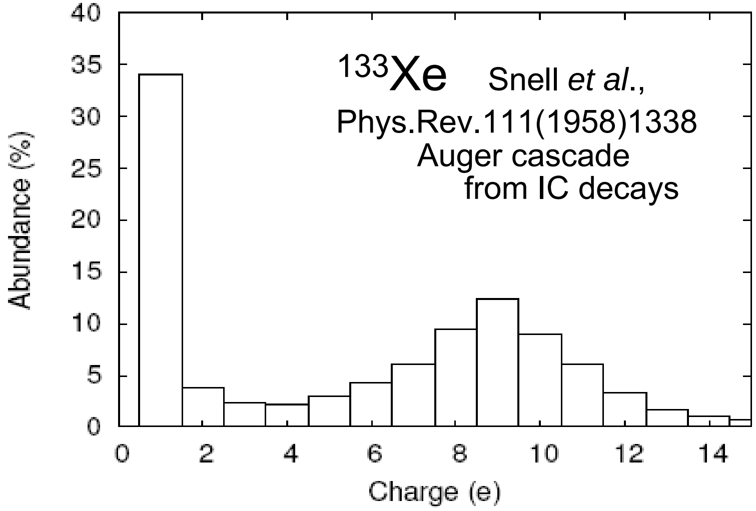
^{124g}In: R_{end}= 204 eV

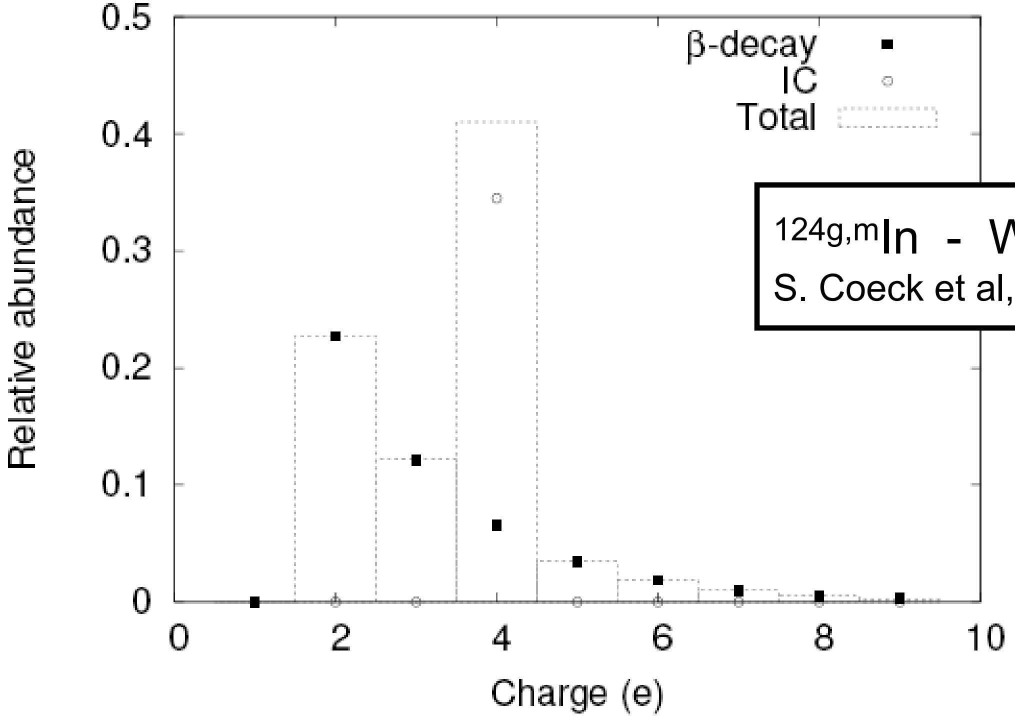
^{124m}In: R_{end}= 83 eV

T_{meas} (eff.) = 500 cycles x 2.3 s = 1150 s

Recoil charge state distribution


^{87}Kr (Snell. A.H. *et al.* Phys.Rev.107 (1957) 740); β-decay shake-off


^{133}Xe Snell *et al.*, Phys.Rev.111(1958)1338 Auger cascade from IC decays



^{124g,m}In - WITCH

S. Coeck et al, to be published

Status and prospects:
- further improvements ongoing
- physics candidate ^{35}Ar

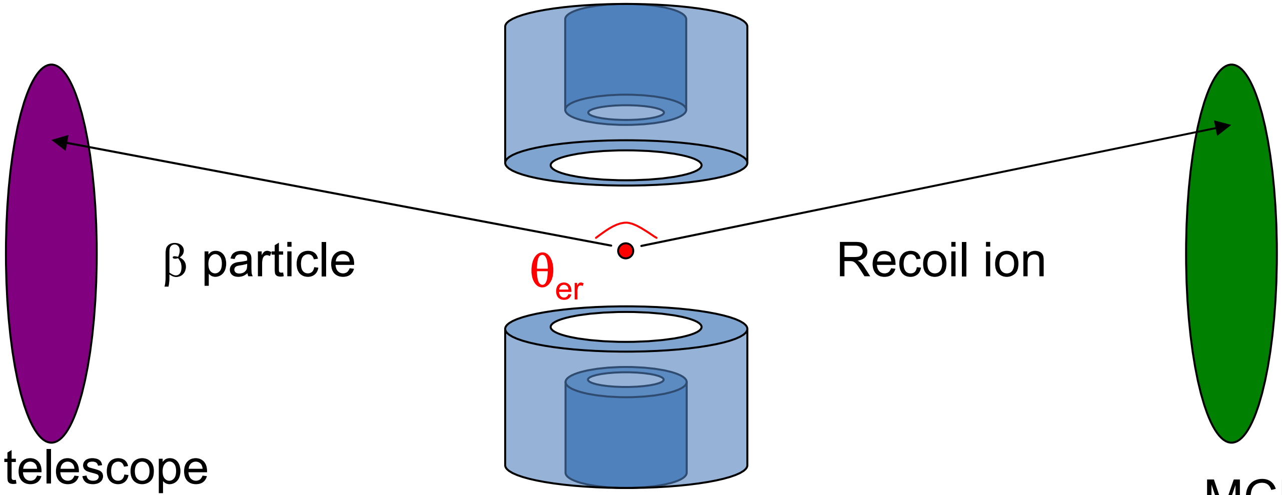
LPCTRAP:
Piège de Paul transparent

LPCTRAP collaboration, at GANIL

- Transparent Paul trap, UHV

- Ions confined in the middle of the device, nearly at rest

- In coincidence detection of the electron and the recoil ion



E_β, t_{start}

β particle

θ_{er}

Recoil ion

t_{stop}

Beta telescope
Silicone stripped detector
+ Scintillator

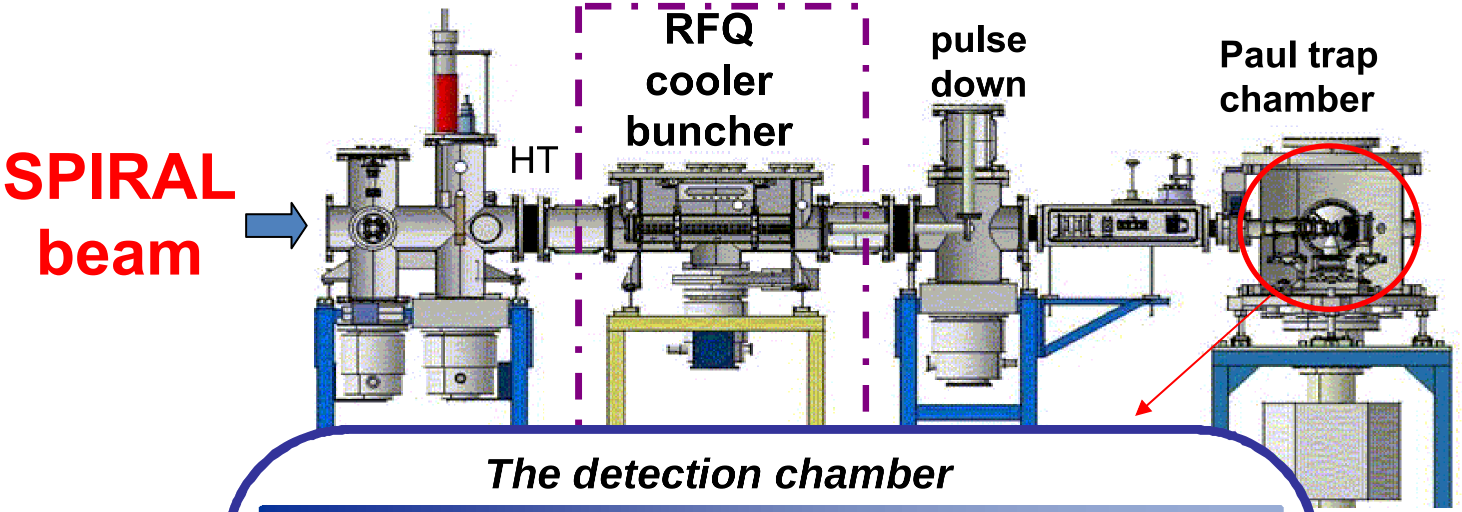
MCP
Delay lines anode

In coincidence measurement of:

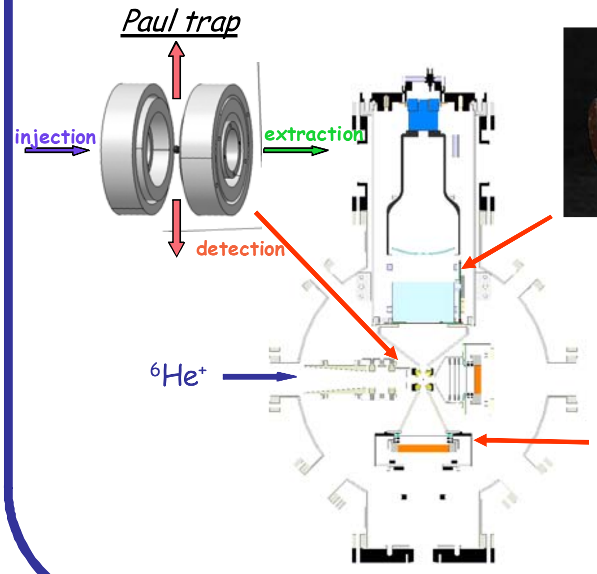
- the time of flight of the recoil ion t_R
- the beta particle energy E_β
- the angle between these two particles θ_{er}

Pierre Delahaye et al.,
Hyp. Int. 132(2001)479

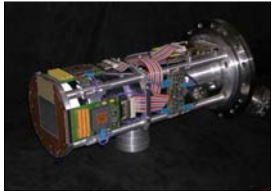
Setup experimental



The detection chamber

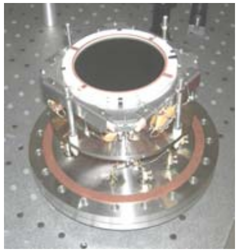


β telescope



- DSSSD
  60 x 60 mm x 300 μm
  1 mm spatial resolution
- Plastic scintillator
  σ_E 10 % at 1 MeV
  σ_T < 200 ps

MCP detector



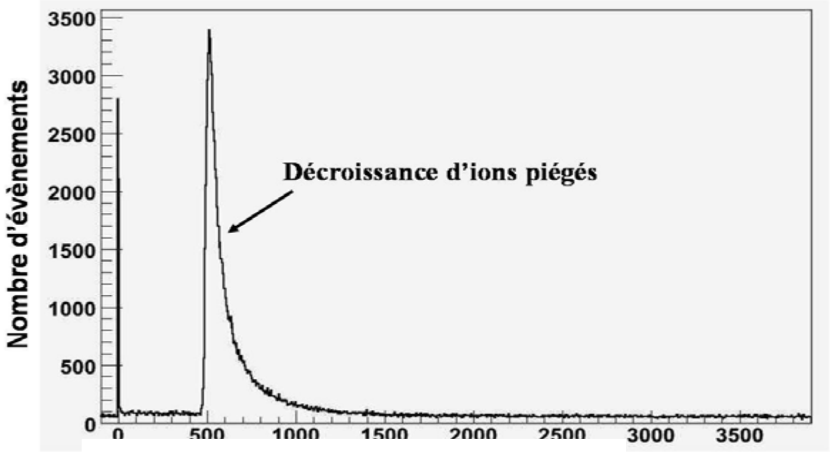
- MCP
  Active Ø 80 mm
  σ_T < 200 ps
- Delay lines
  σ_x,σ_y < 200 μm

E. Liénard et al. *NIMA 551,375 (2005)*

Résultats préliminaires

- Juillet 2006 : 1 semaine de temps de faisceau à GANIL avec ~10 pA 10 keV $^{6}He^{+}$

Spectre de temps de vol expérimental



~700 ions piégés
0.3 – 0.8 coincidences/s
~100 000 coincidences

a_{GT} with 1.5% relative uncertainty (statistical)

- 2007 : Optimisation du setup:
  - -> alignement des détecteurs (Δp ~ 1/10 mm)
  - -> Transmission (x40)
  - -> Nouvelle MCP orthogonale à l'axe du faisceau et des détecteurs
  - ->Analyse préliminaire des résultats et des effets systématiques

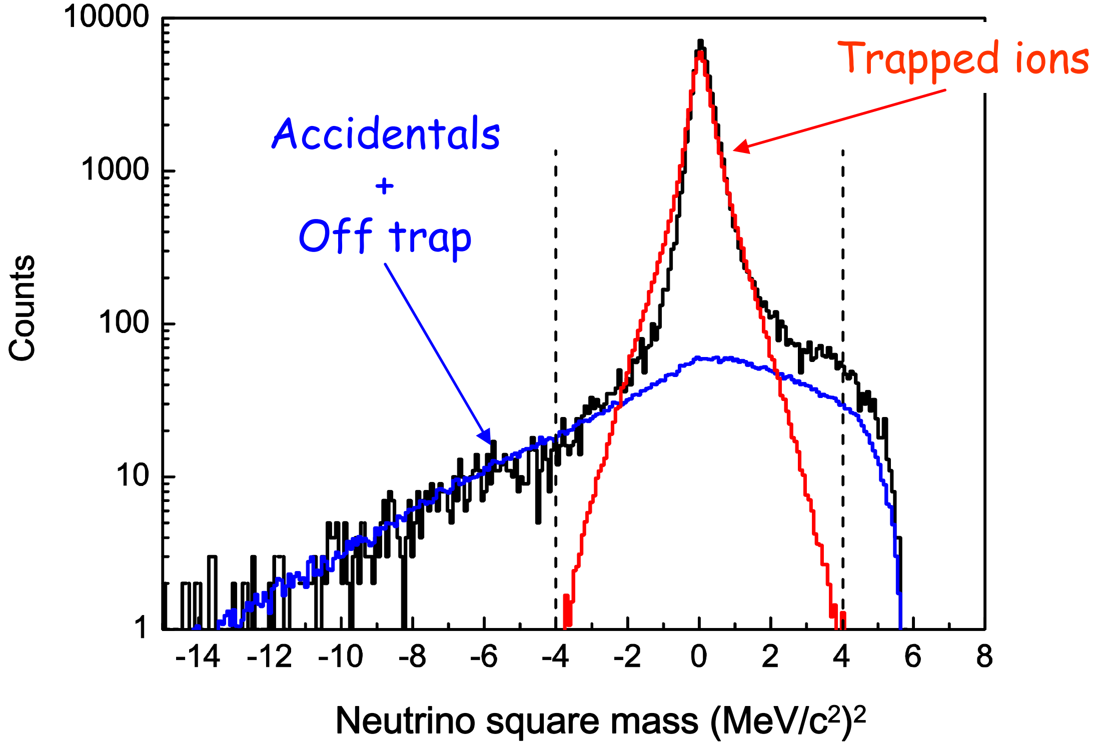
Effets systématiques par la reconstruction de M_ν

Momentum conservation -> p_ν

Energy conservation -> E_ν

Neutrino mass reconstruction

$$\boxed{M_\nu^2 = E_\nu^2 - p_\nu^2}$$



$$\sigma_{M_\nu^2} \approx 0.42\ MeV^2 c^4$$

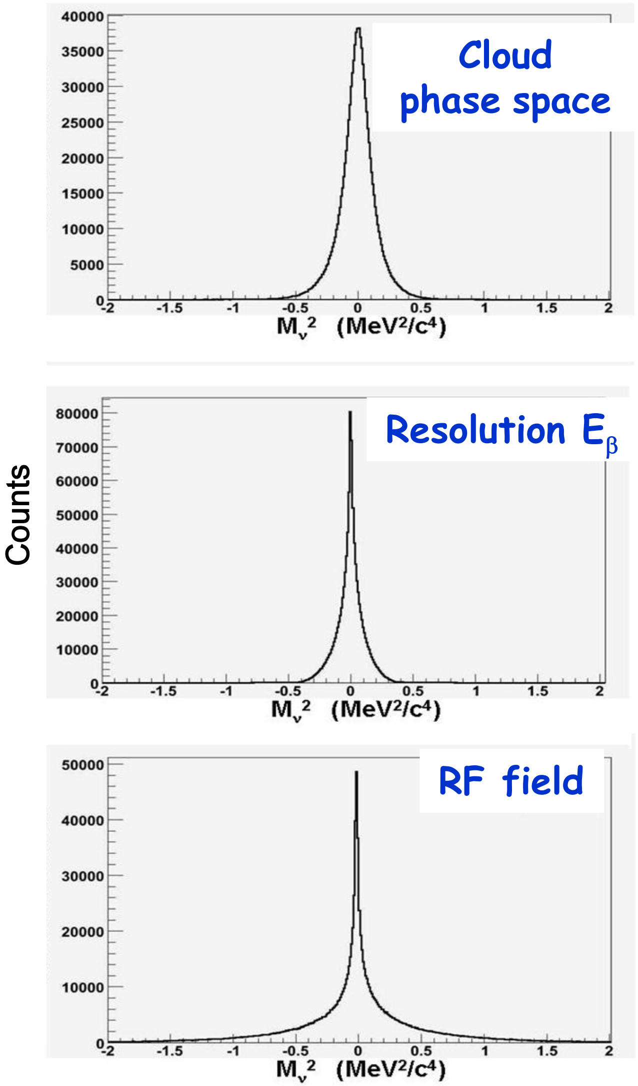
(experimental resolution)

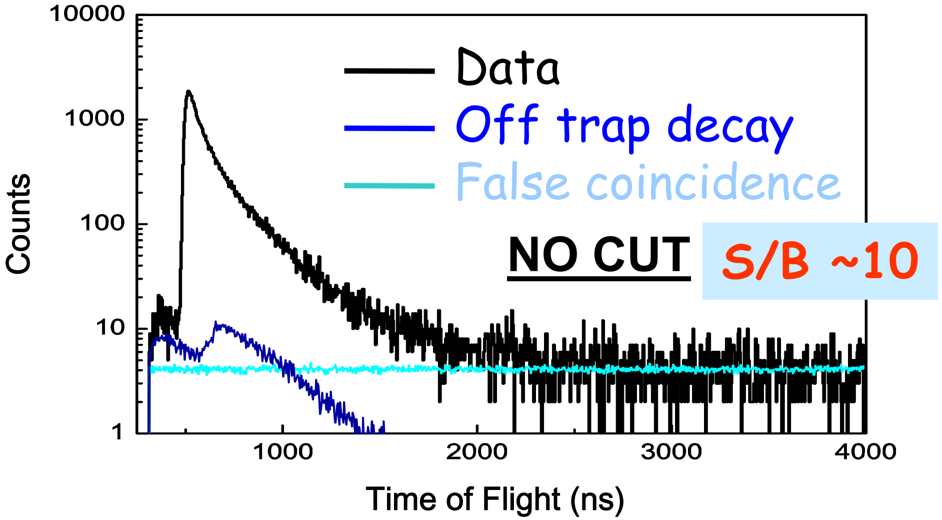
Kinematic cut

$$\left| M_\nu^2 \right| < 3 \times \sigma_{M_\nu^2}$$

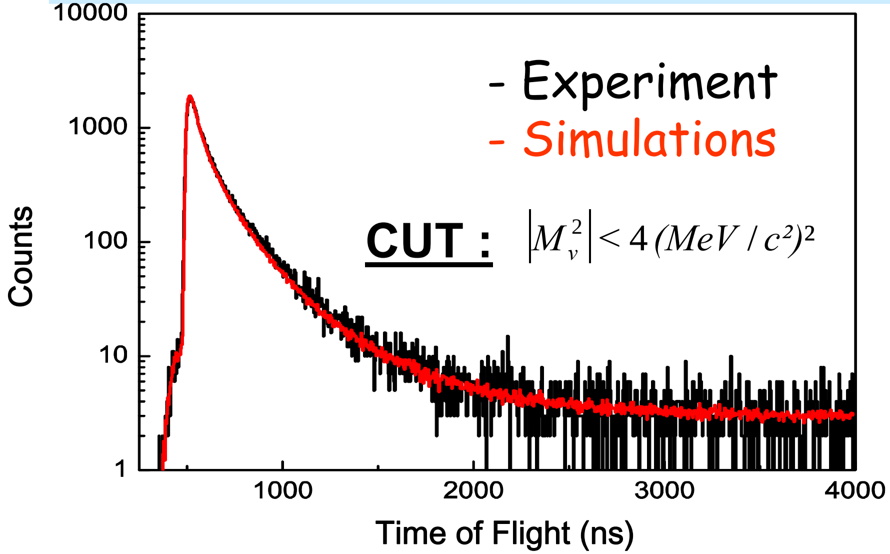
Signal/noise ~100

Simulations des effets systématiques





Main systematic effects identified !!!



Autres effets systématiques

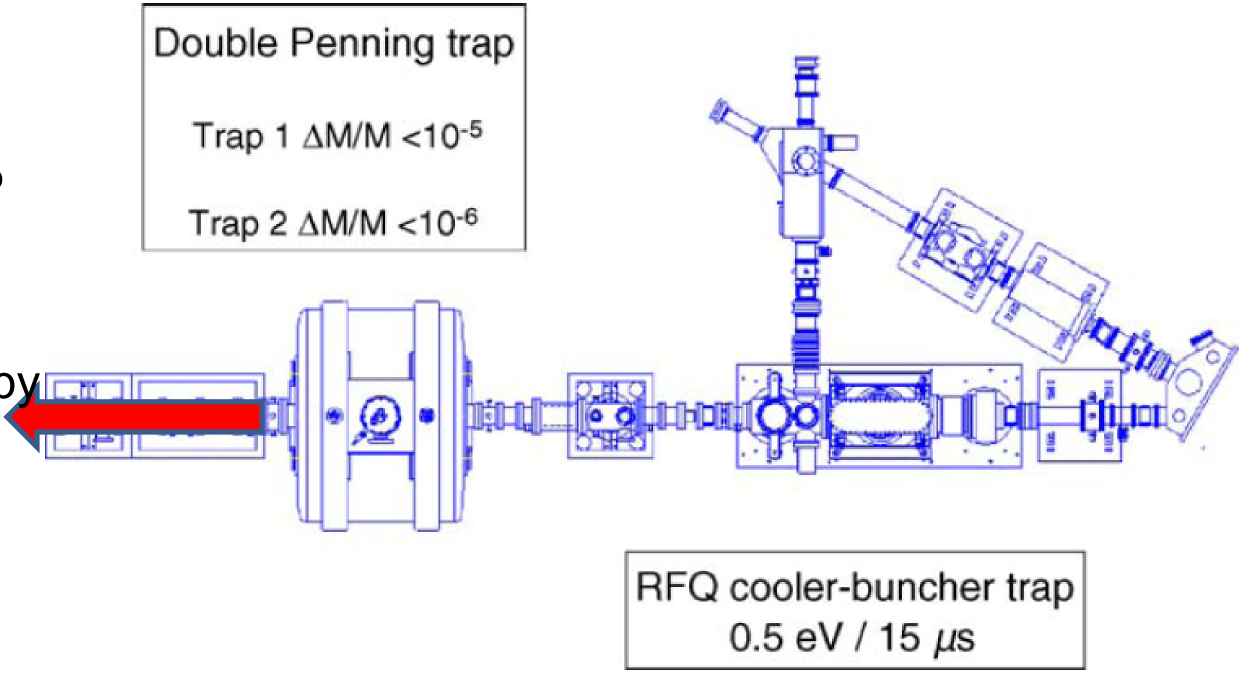
- Diffusion des β sur les détecteurs & structures
  - Influence sur le spectre d'energie et les positions des β
  - Simulation GEANT 4 en cours
- Shake off $Li^{2+} \rightarrow Li^{3+} + e^-$
  - Effets des potentiels RF et de postacceleration pour les ions Li^{3+} $P_{ionization} = 0.02338 + 0.4118 \times 10^{-4} \times E_{recoil}(keV)$
    (Z. Patyk, Soltan Institute for Nuclear Studie, Warsaw)
  - Estimation:
  - Mesure en ligne

Spectroscopie des transitions Fermi pures

$$Ft = Ft(Q, T_{1/2}, R, P_{EC}, \delta_R, \delta_C)$$

Temps de vie et branching ratio (cf presentation J. Souin)

JYFLTRAP



Double Penning trap

Trap 1 $\Delta M/M < 10^{-5}$

Trap 2 $\Delta M/M < 10^{-6}$

RFQ cooler-buncher trap
0.5 eV / 15 μs

Trap assisted spectroscopy
T1/2 ^{62}Ga, ^{26}Si, ^{42}Ti
Purification ^{62}Cu, ^{26m}Al

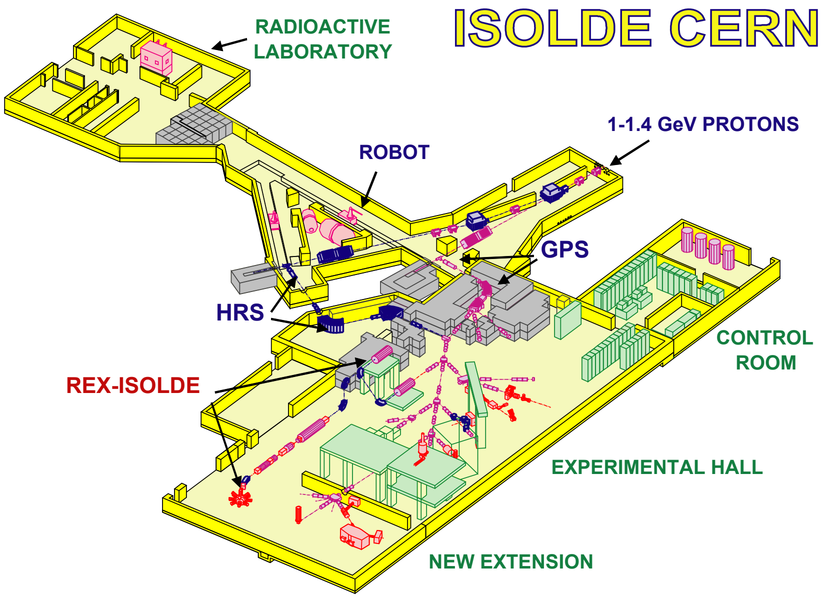
Mesure du temps de vie du ^{38}Ca

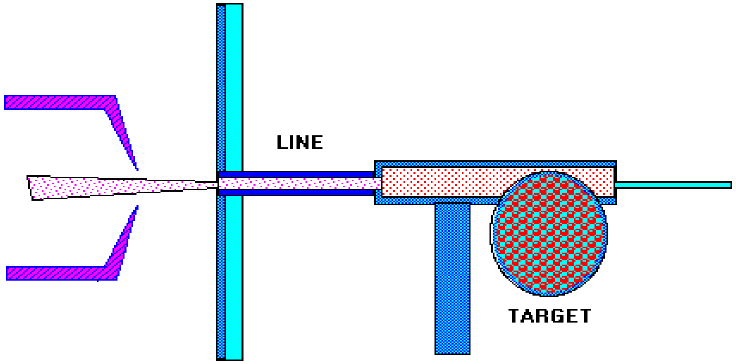
CENBG

ISOLDE CERN

- Elimination du ^{38}K: formation de faisceau moléculaire de ^{38}CaF

^{38}CaF^{+} production and separation





1.4 GeV protons on a Ti foils targ
W ionizer and CF4 leak
Fluorination~70%

Refroidissement, bunching et sélection

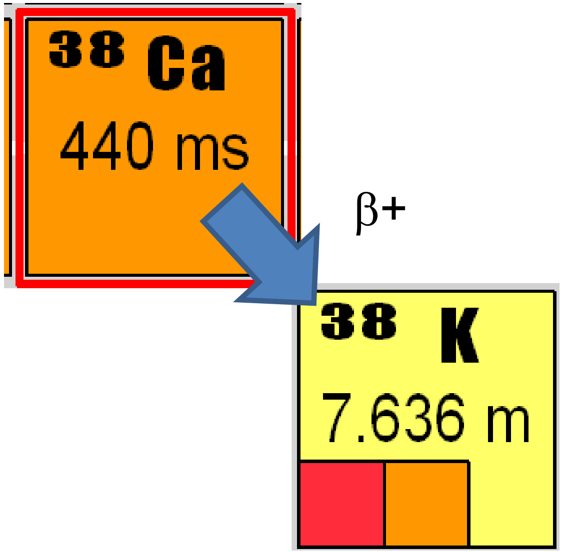
Injection dans REXTRAP ^{38}CaF^{+}

- Refroidissement et bunching

Référence en temps pour la mesure de $T_{1/2}$

- Selection de la masse 57 par temps de vol

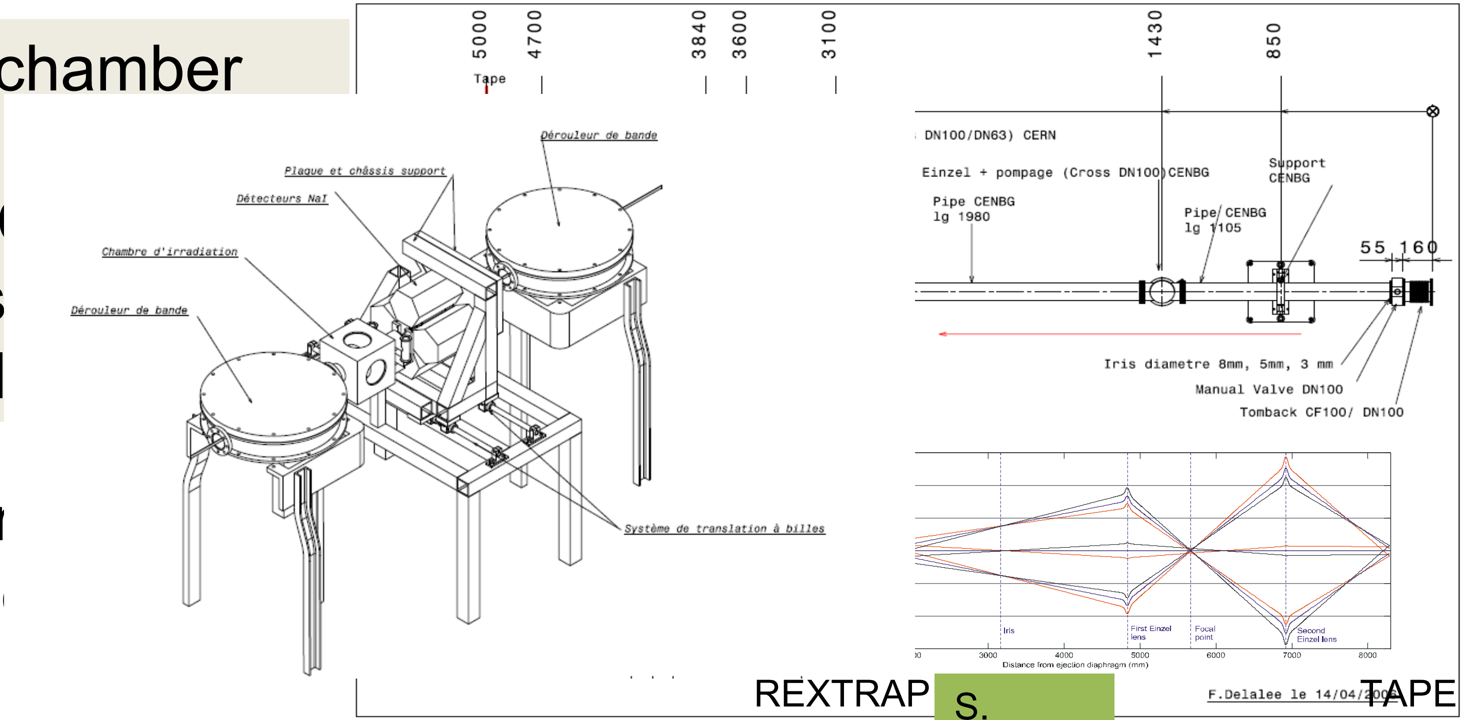
Suppression 38K^{+}



Dispositif experimental

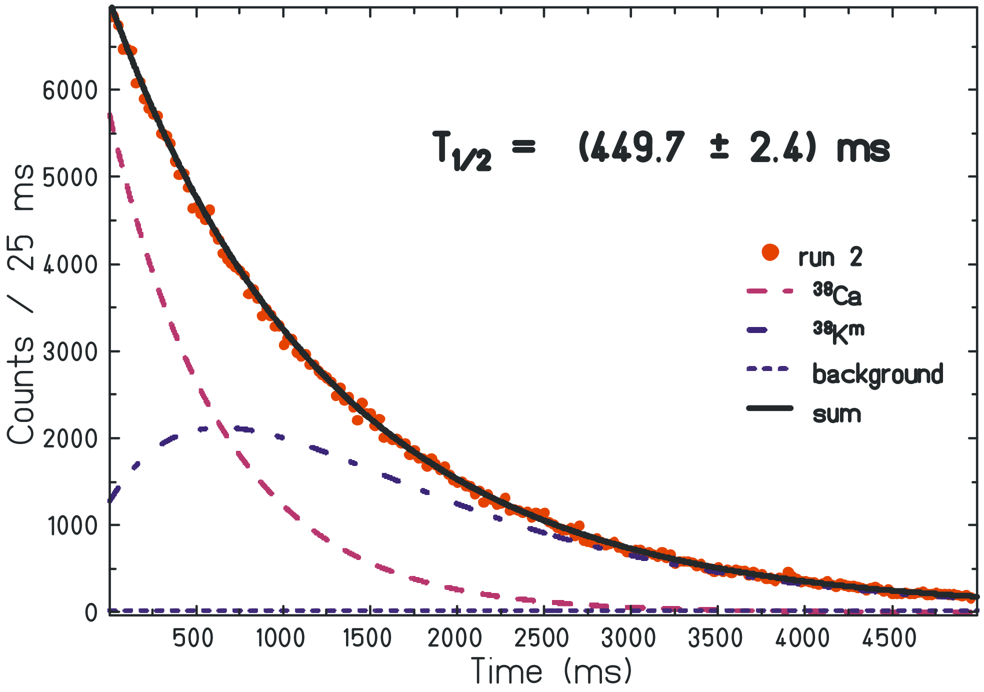
- Implantation chamber
- Tape
- Gas counter(
- NaI detectors
- Plastic scintill

Ultra-pure bu
of ^{38}CaF^{+} inje
onto the tape



S.
Sturm

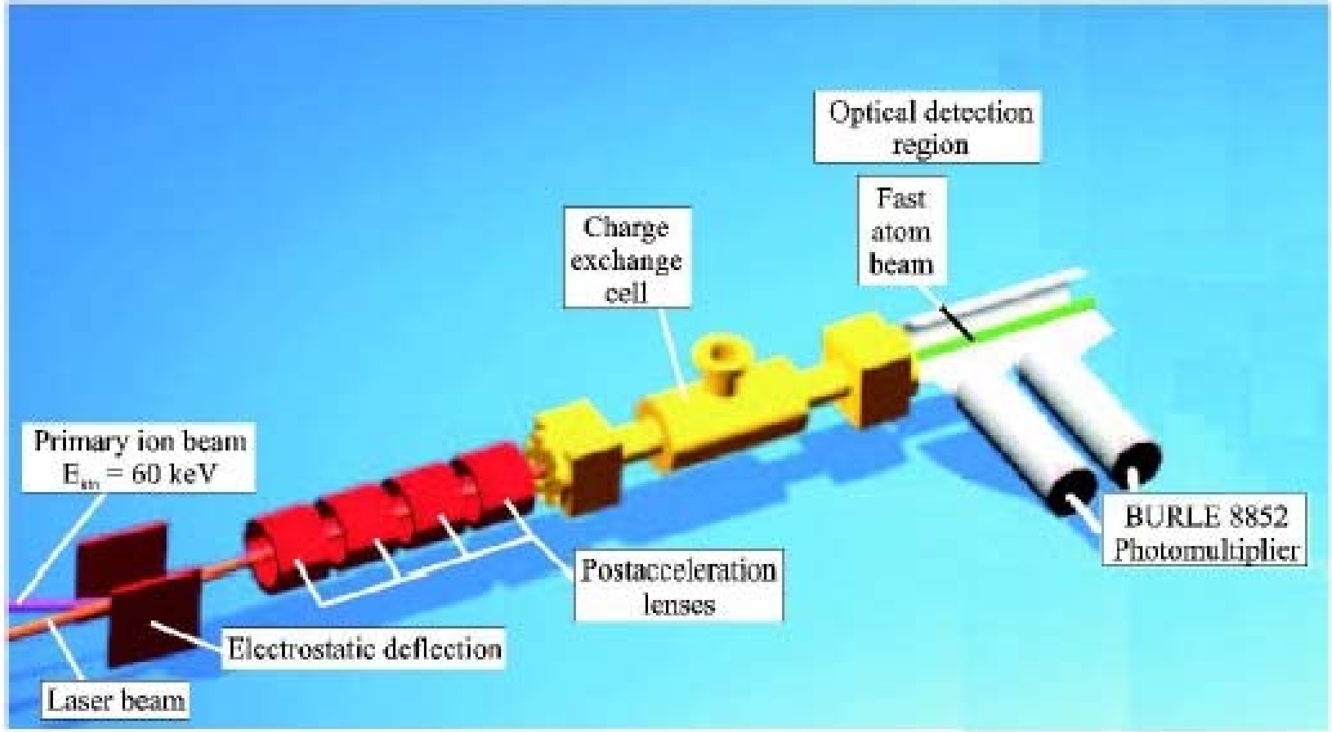
Spectre de temps de vie typique



En cours d’analyse

Spectroscopie laser colinéaire des ions radioactifs

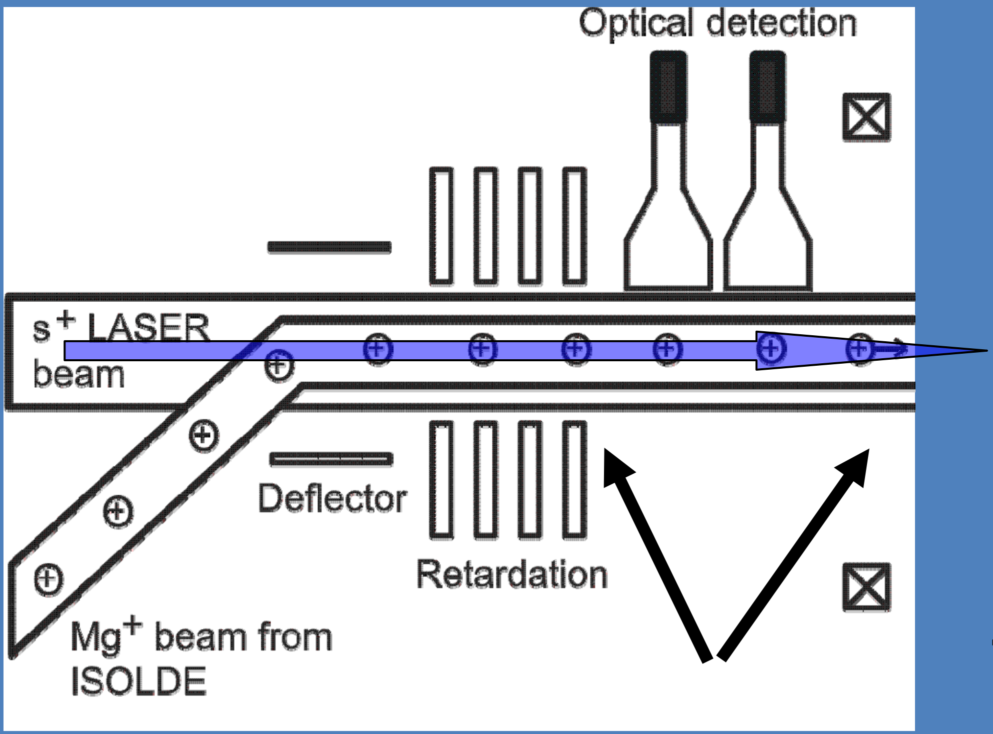
- COLLAPS: Mesure des rayons de charge, moments nucléaires et spins par spectroscopie colinéaire et β-NMR



Avantage des faisceaux refroidis et pulsés

Current limiting factors for laser spectroscopy

- **Background of scattered laser light detected by PMT ~2000/s.**
- **Detection efficiency within the light collection region.**
- **Broadening of lineshape due to voltage ripples.**



K. Flanagan COLLAPS collaboration

Within the light collection region the ion beam should have zero divergence (parallel beam)

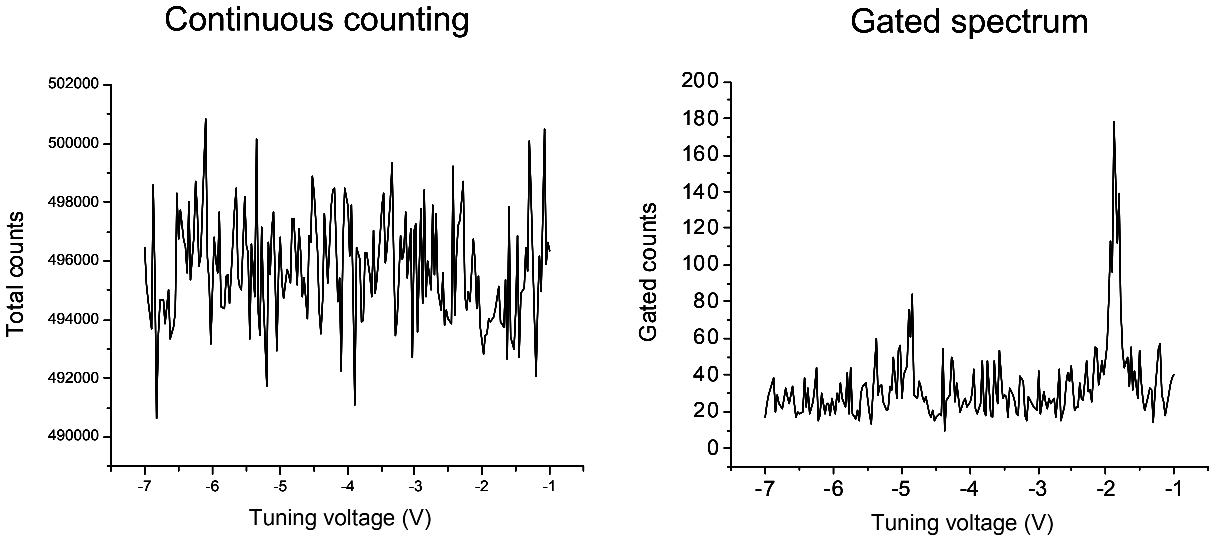
Currently the minimum ion beam diameter reached is ~6mm

In order to maximize the detection efficiency good overlap between laser and ion beams is necessary

This results in a high background level from scattered light

Résultats préliminaires ISCOOL+COLLAPS

- Réduction d’un facteur >10^4 du bruit de fond


Continuous counting

Gated spectrum

46K, gated on 12µs window

Antihydrogène et tests de CPT au CERN

- La matière et l’antimatière sont-elles symétriques? Tests de CPT
- Production d’antihydrogène dans 2 expériences: ATRAP et ATHENA (ALPHA)
- But ultime: spectroscopie de la transition 1s 2s

ATHENA
Production d'antihydrogène

Antiproton capture trap

Deceleration and capture of antiprotons

Penning trap in 3-T field at 15 K

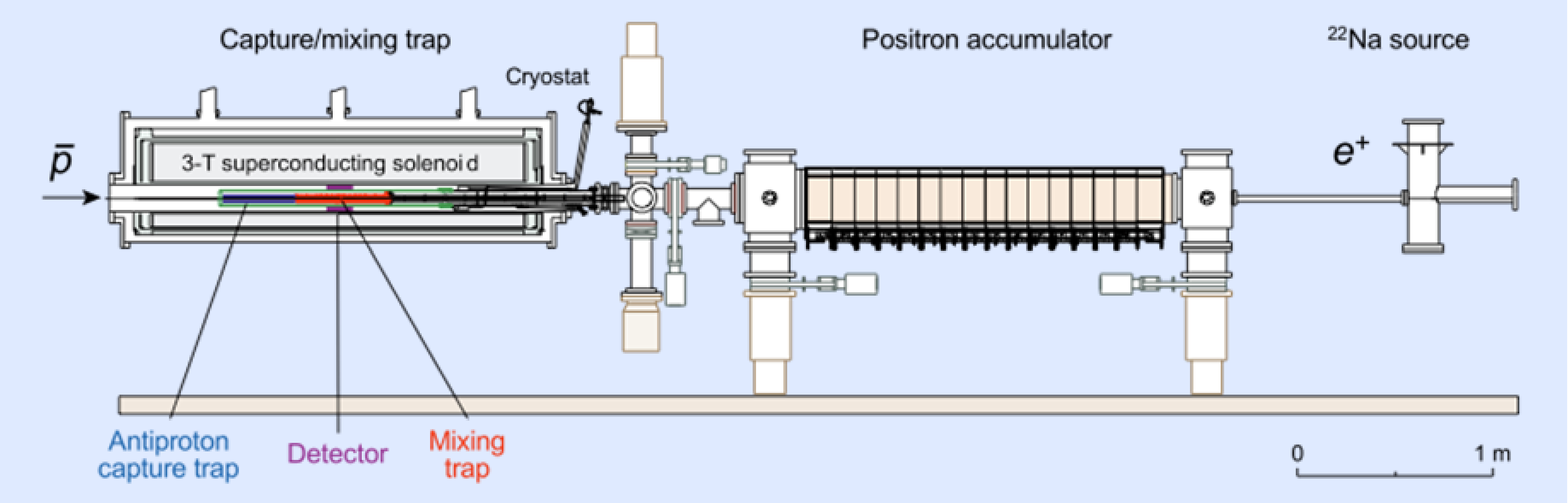
Cooling and accumulation in e^- plasma

^{22}Na source

Positron production via $^{22}Na(\beta^+)^{22}Ne$ at 5.5 K

Positron accumulator

Penning trap in 0.14-T field at 300 K



Mixing trap

Antihydrogen production

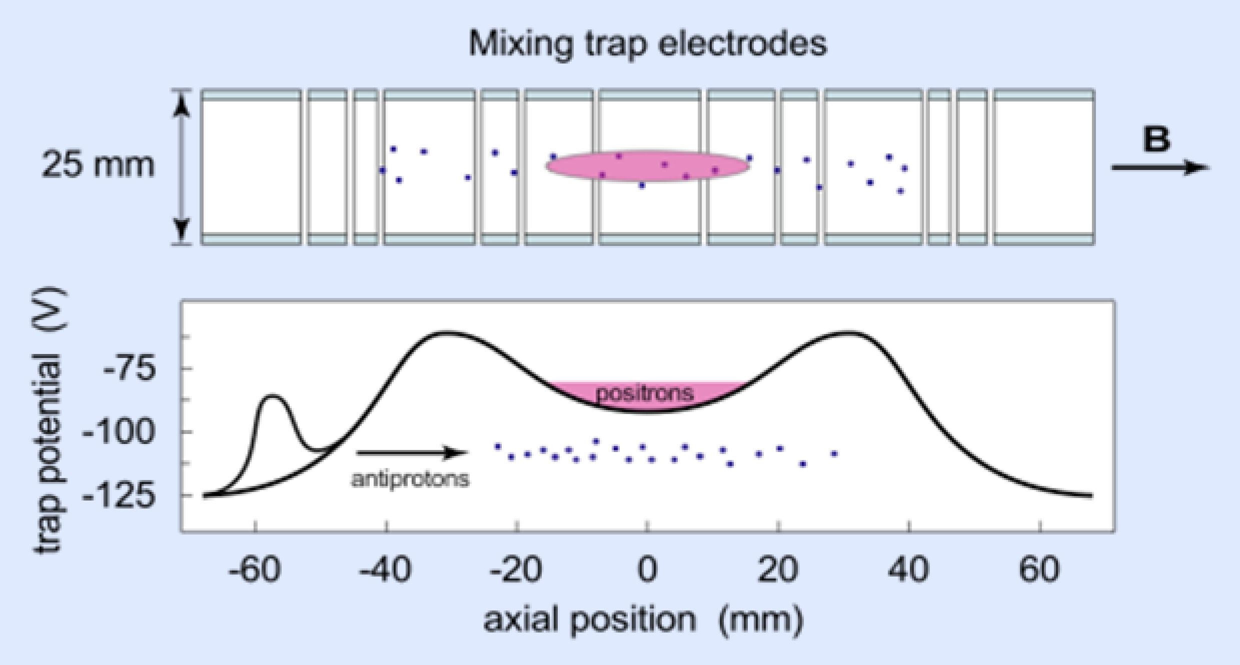
Nested Penning trap in 3-T field at 15 K

Detector

By courtesy of M. Doser

[M. Amoretti et al. NIM A 518 (2004)]

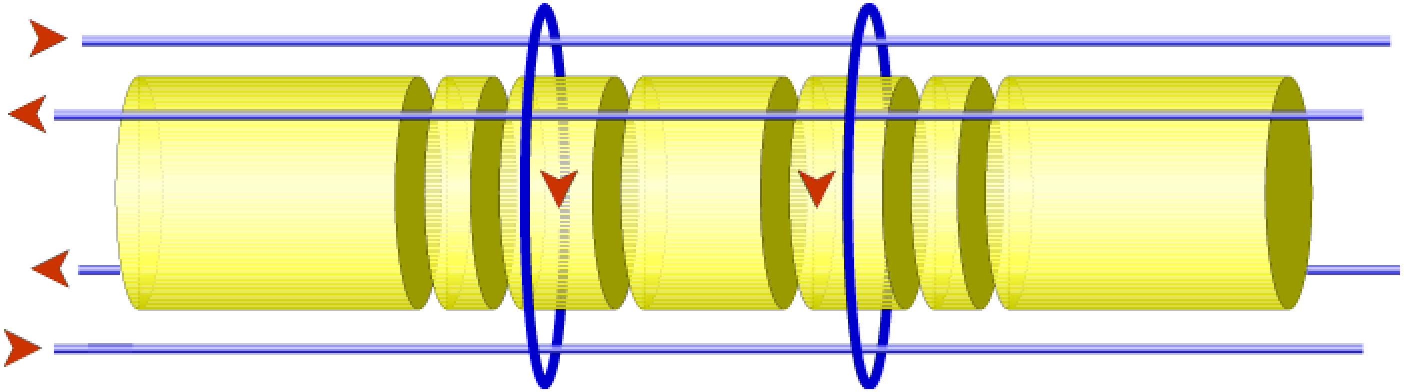
Mixing trap



- Refroidissement des antiprotons interagissant avec les positrons
- Refroidissement des positrons par rayonnement synchrotrons

Alpha – le futur d'ATHENA

- Un piège de type « Ioffe-Pritchard » pour les atomes d'antihydrogène
  - Piégeage des atomes grâce à leur moment magnétique



Tests de QED

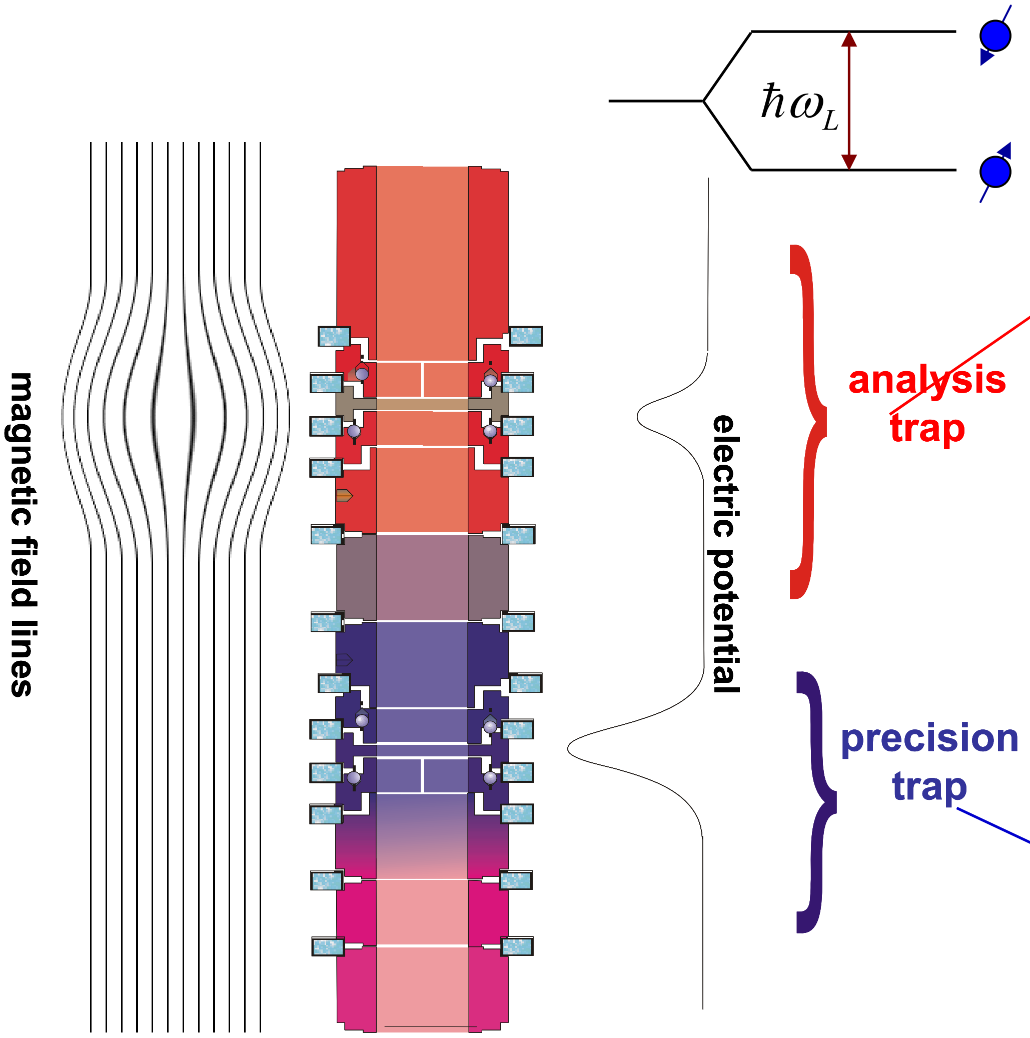
- Mesure du facteur gyromagnétique pour les ions « hydrogen-like »

$$\vec{\mu} = g_J \frac{|q|}{2\,m} \hbar \vec{J}$$

relation entre le dipole magnétique et le moment angulaire

Lepton libre: g_s = *g*-factor du spin

Meas. principle for highly-charged ions



Zeeman splitting in the spin eigenstates → Larmor frequency

$$\omega_L = \frac{2\mu \cdot B}{\hbar} = g\,\frac{e}{2m_e}\,B$$

$$\Downarrow$$

$$g = 2\,\frac{\omega_L}{\omega_c}\,\frac{m_e/e}{m_{ion}/q_{ion}}$$

$$\Uparrow$$

$$\omega_c = \frac{q_{ion}}{m_{ion}}\,B$$

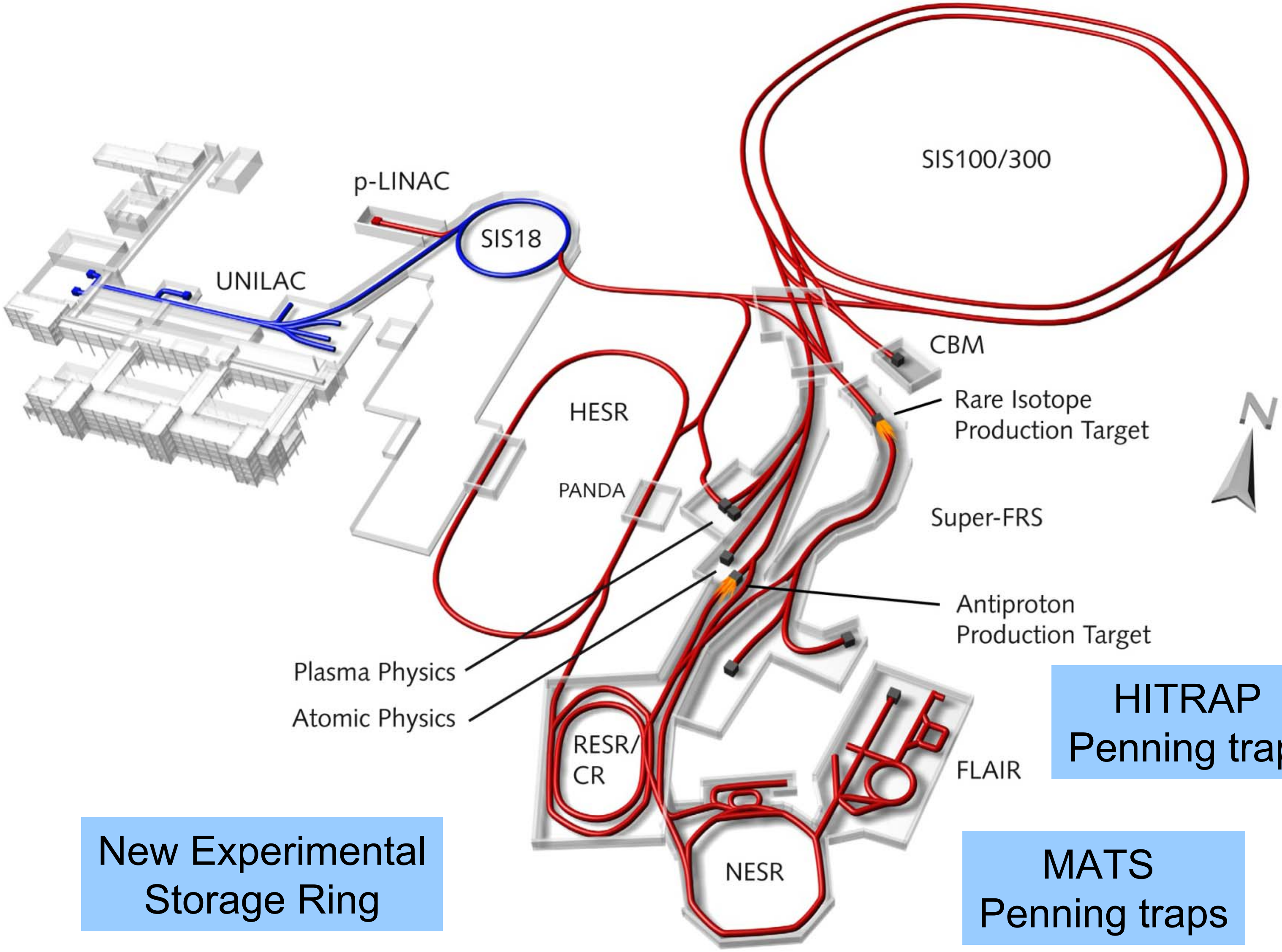
Eigenmotions of the particle → cyclotron frequency

We aim for $\delta g/g < 10^{-9}$.

Installations futures

- HITRAP et MATS à GSI/FAIR
- DESIR à GANIL
- EURISOL

Future Penning trap facilities at FAIR



HITRAP Penning traps

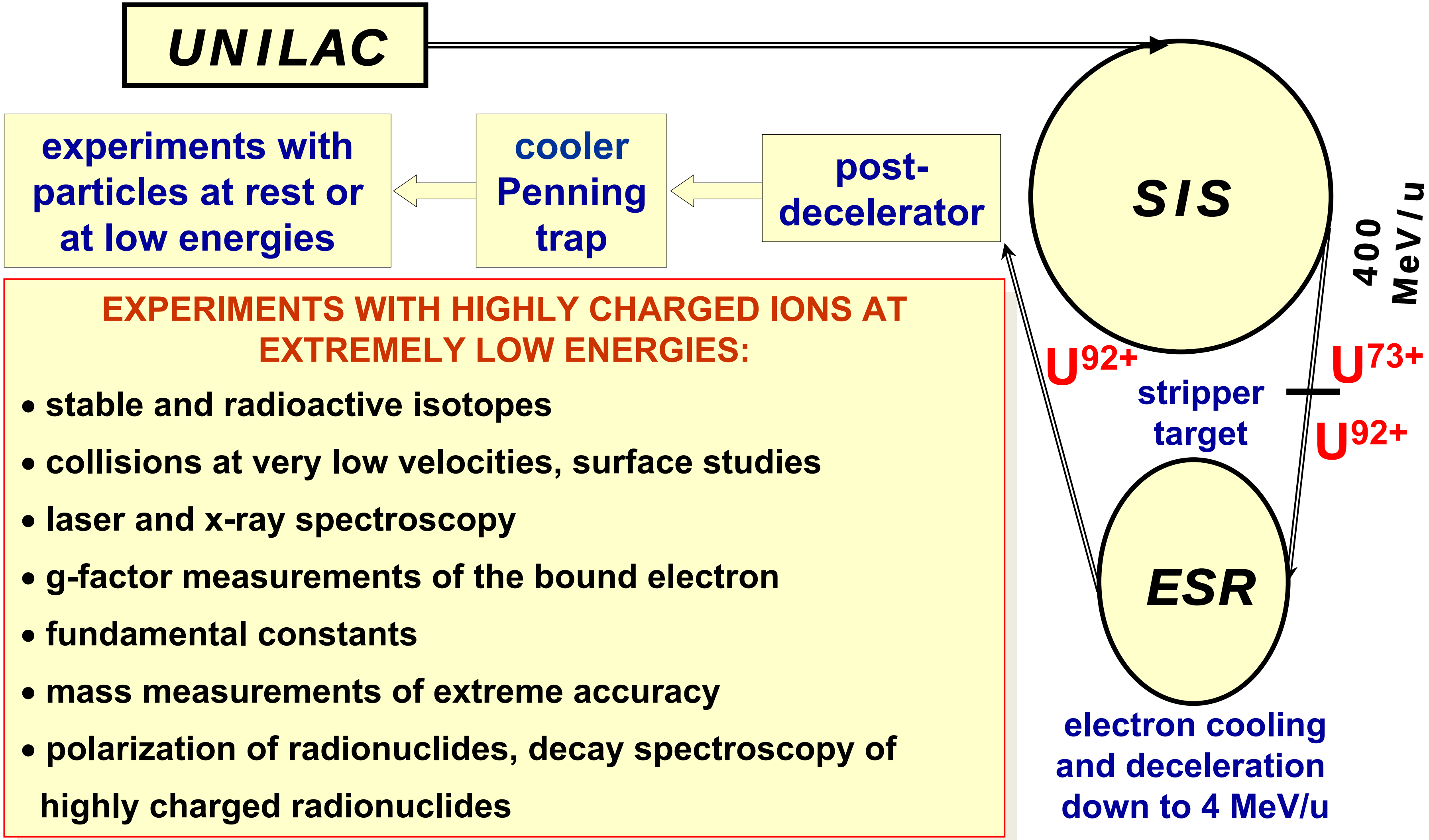
MATS Penning traps

New Experimental Storage Ring

Klaus.blau hd.mpg.de

The HITRAP Project for Highly Charged Ions
GSI Darmstadt

Courtesy of W. Quint and the HITRAP collaboration



EXPERIMENTS WITH HIGHLY CHARGED IONS AT EXTREMELY LOW ENERGIES:

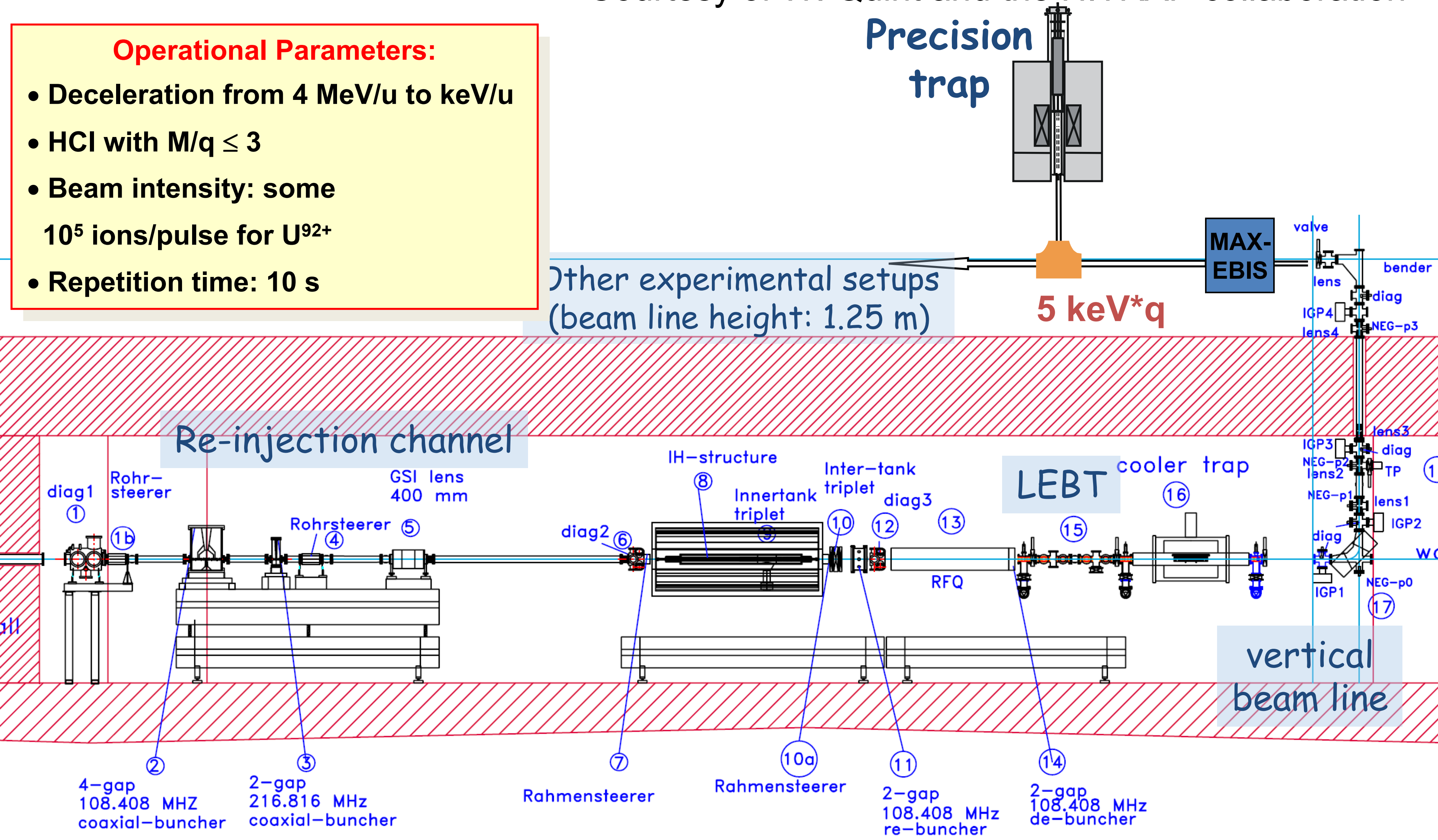
- stable and radioactive isotopes
- collisions at very low velocities, surface studies
- laser and x-ray spectroscopy
- g-factor measurements of the bound electron
- fundamental constants
- mass measurements of extreme accuracy
- polarization of radionuclides, decay spectroscopy of highly charged radionuclides

HITRAP at the Experimental Storage Ring ESR

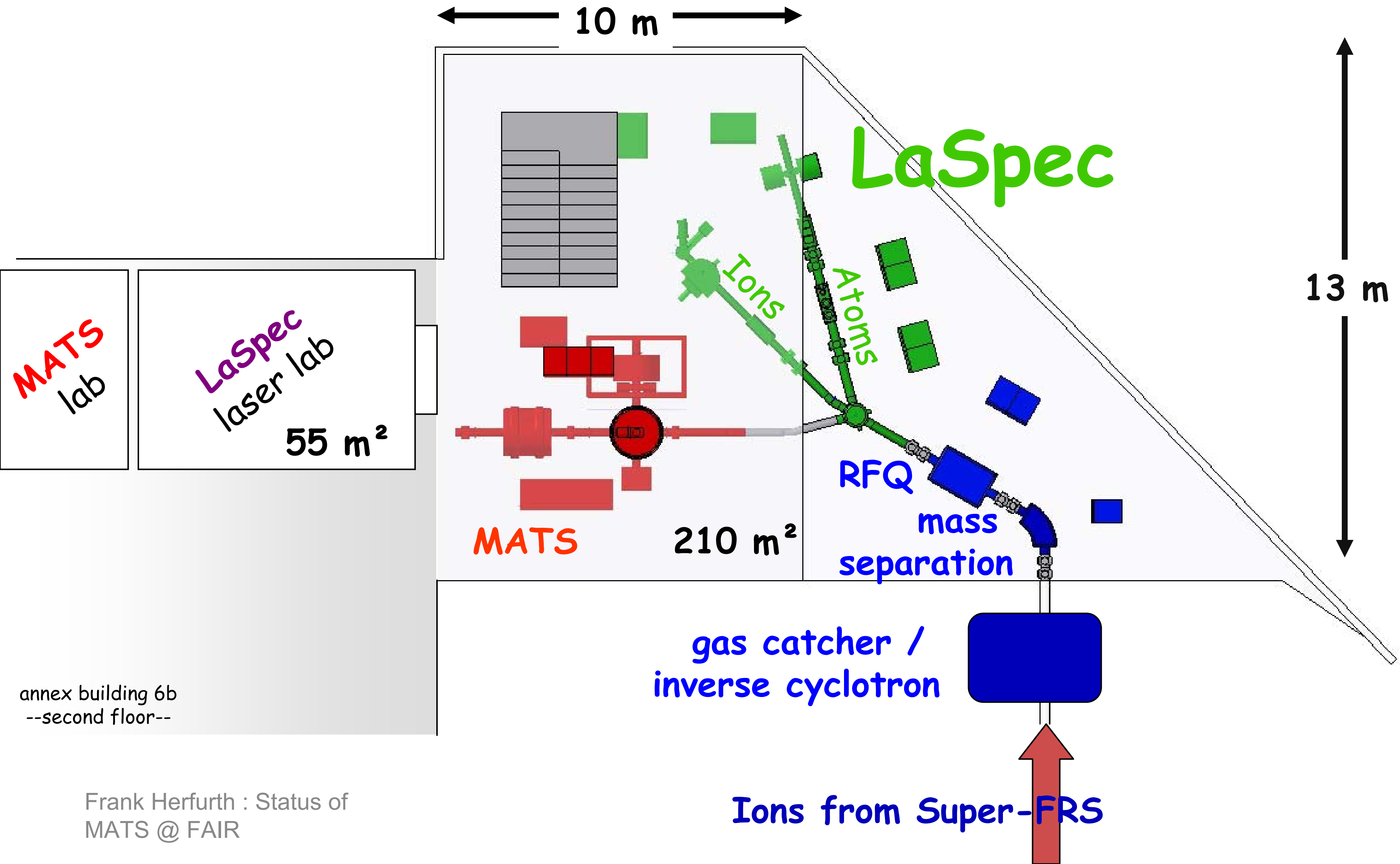
Courtesy of W. Quint and the HITRAP collaboration

Operational Parameters:

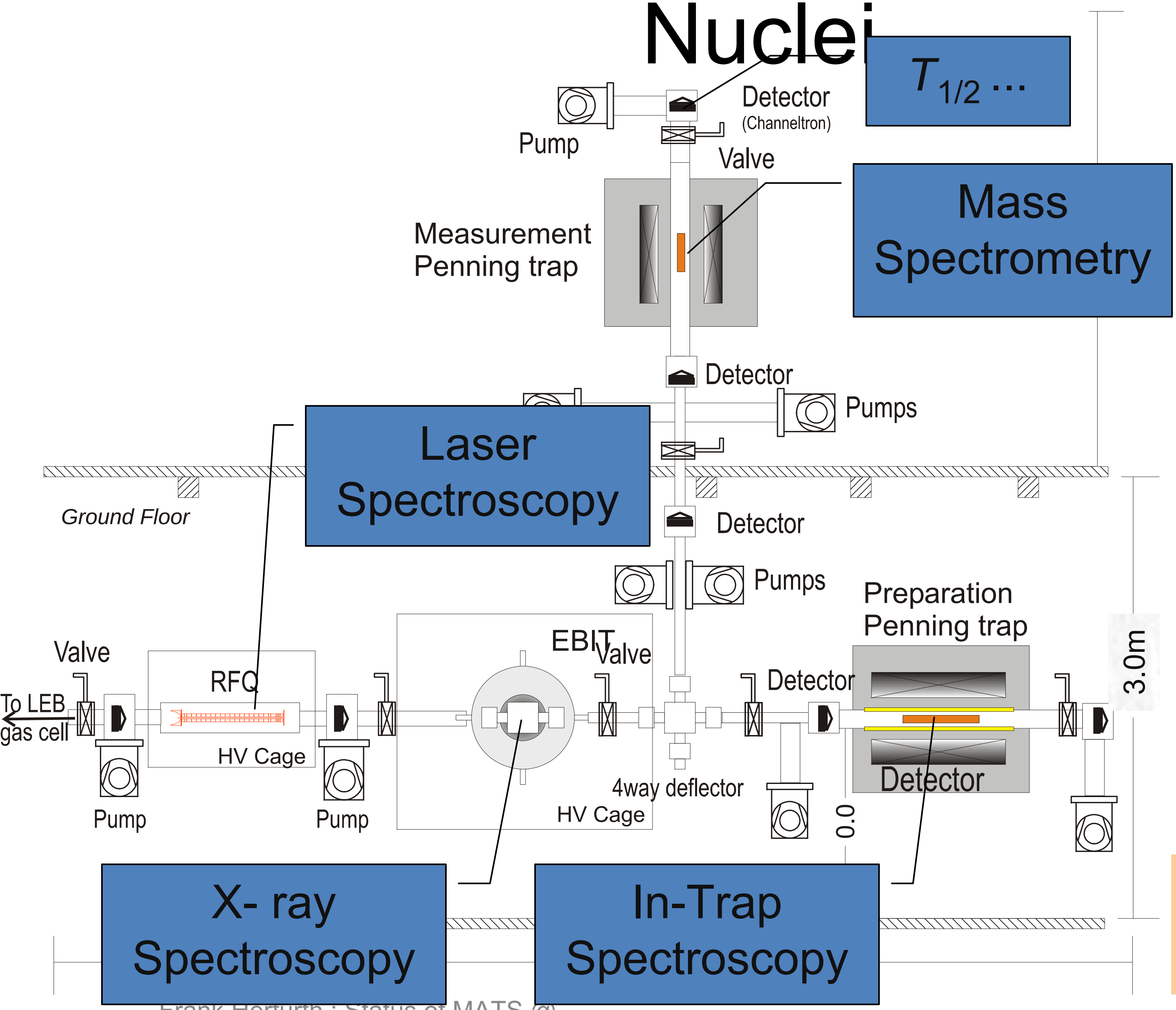
- **Deceleration from 4 MeV/u to keV/u**
- **HCI with M/q ≤ 3**
- **Beam intensity: some 10^5 ions/pulse for U^{92+}**
- **Repetition time: 10 s**



MATS – Setup:


10 m
13 m
LaSpec
Ions
Atoms
MATS lab
LaSpec laser lab
55 m²
MATS
210 m²
RFQ
mass separation
gas catcher / inverse cyclotron
Ions from Super-FRS
annex building 6b
--second floor--

MATS – Experiments with Exotic Nuclei



$T_{1/2}$ …

Mass Spectrometry

Laser Spectroscopy

X- ray Spectroscopy

In-Trap Spectroscopy

Detectors:
- FT-ICR
- TOF-ICR
- Si(Li) electron

Precision trap:
mass measurements

Cooler trap:
beam preparation & spectroscopy

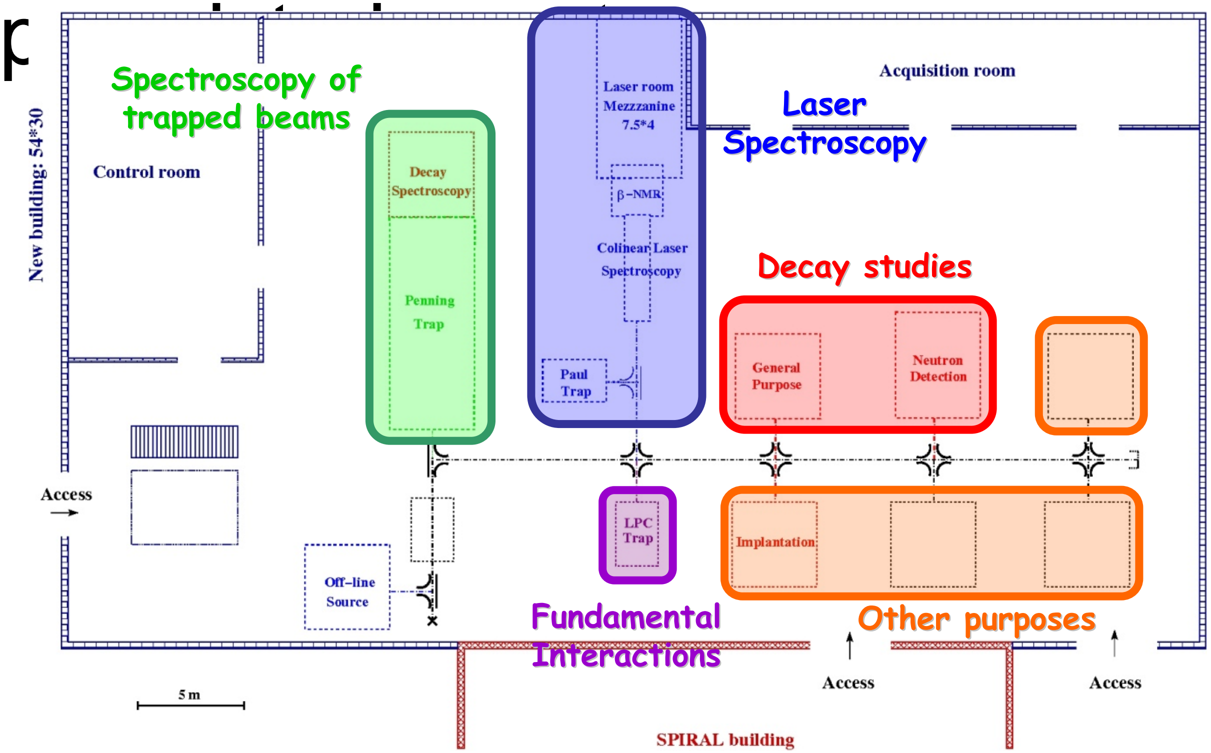
Magn. deflector:
q/m separation

EBIT:
charge breeding

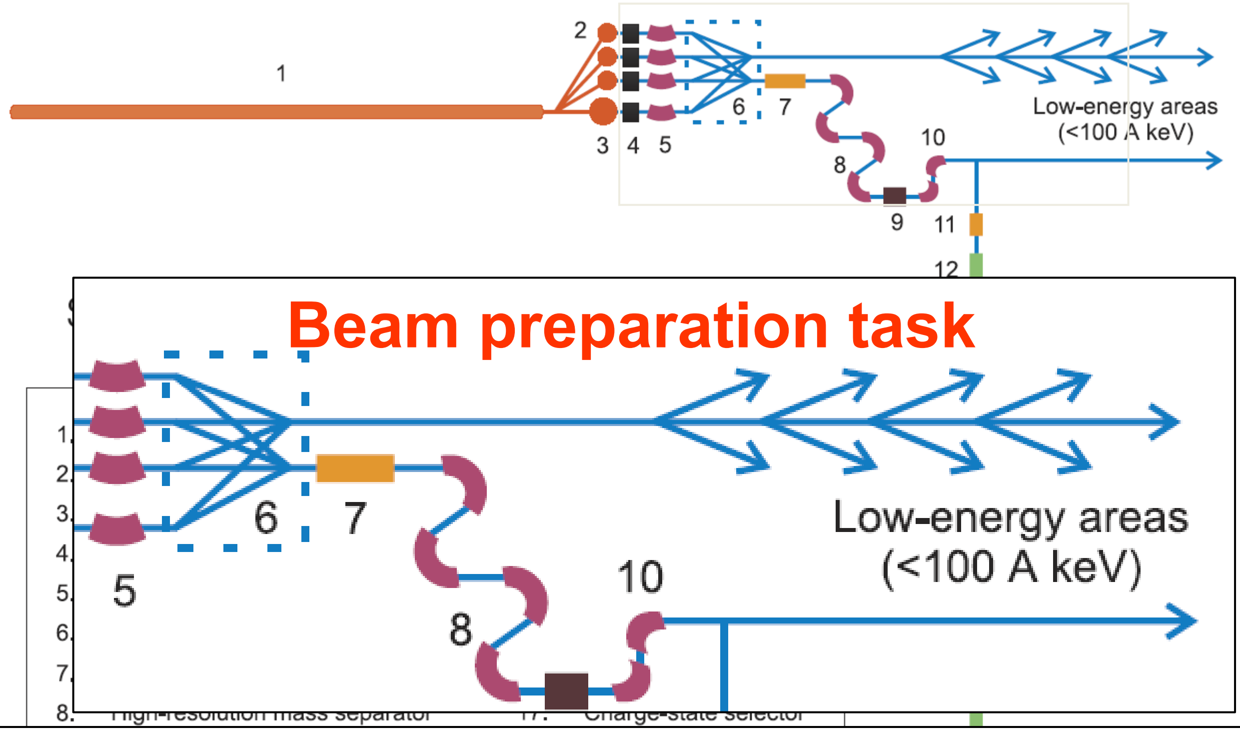
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

DESIR à GANIL

- Faisceaux radioactifs de SPIRAL-2 et de S3
- Trap



EURISOL



Dévelopement de techniques de manipulation de faisceaux d'ions radioactifs

Refroidisseurs haute intensités
Sources multichargées
Méthodes de séparation

Merci de votre attention!

UN GRAND MERCI
à Nathal Severijns pour les transparents de WITCH,
Klaus Blaum pour la documentation sur MATS et les tests de QED
et Xavier Flechard pour LPCTRAP