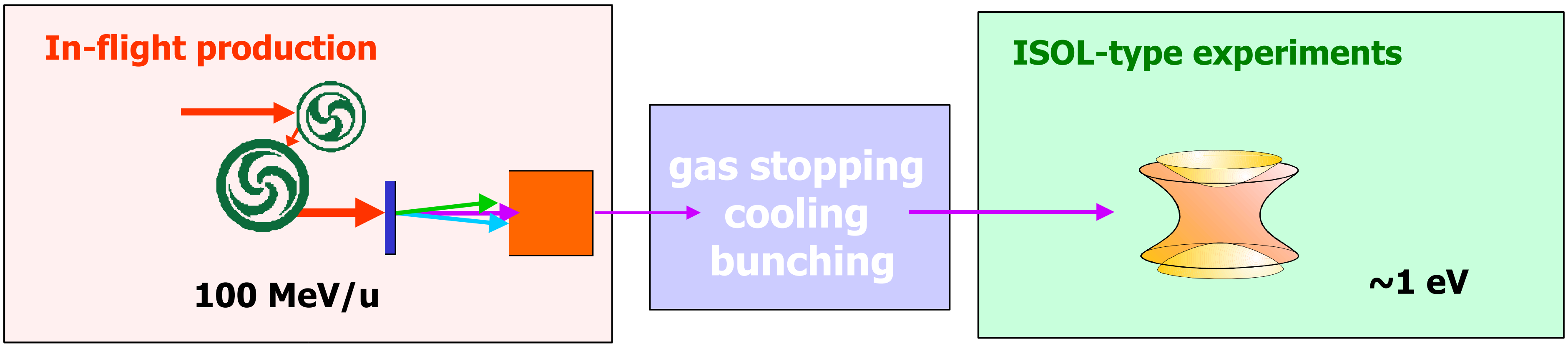
Simulations & more from LEBIT

Low-Energy Beam and Ion Trap Project



Coupled Cyclotron Facility
National Superconducting
Cyclotron Laboratory
Michigan State University

The LEBIT team:

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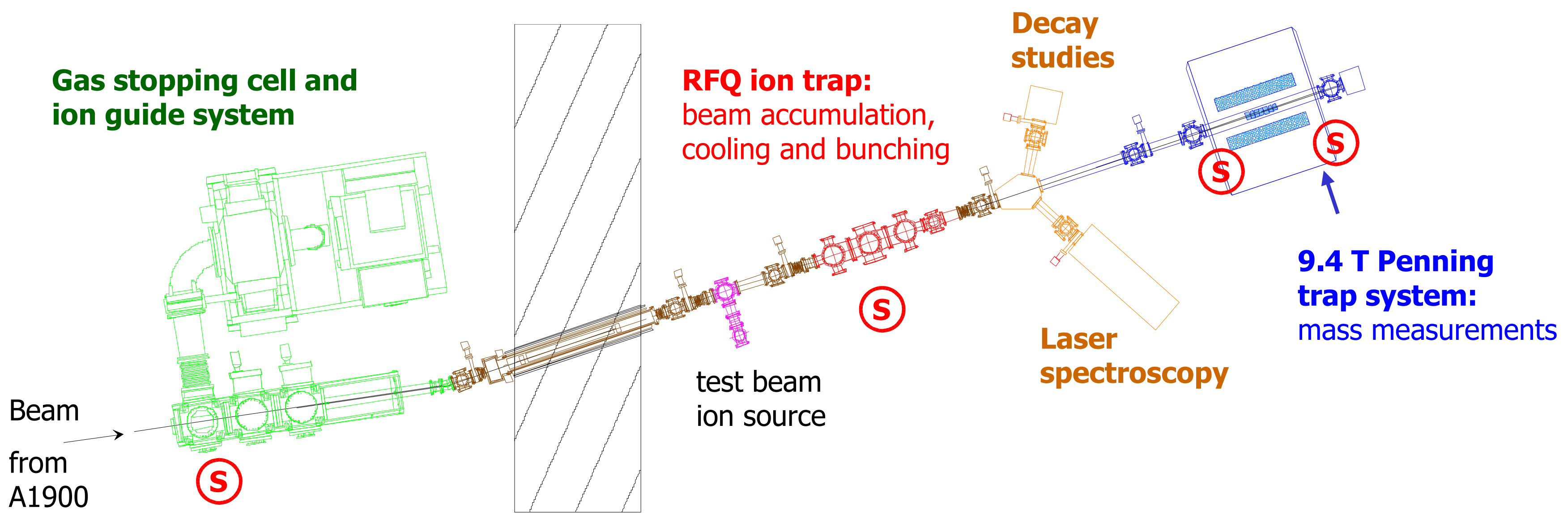
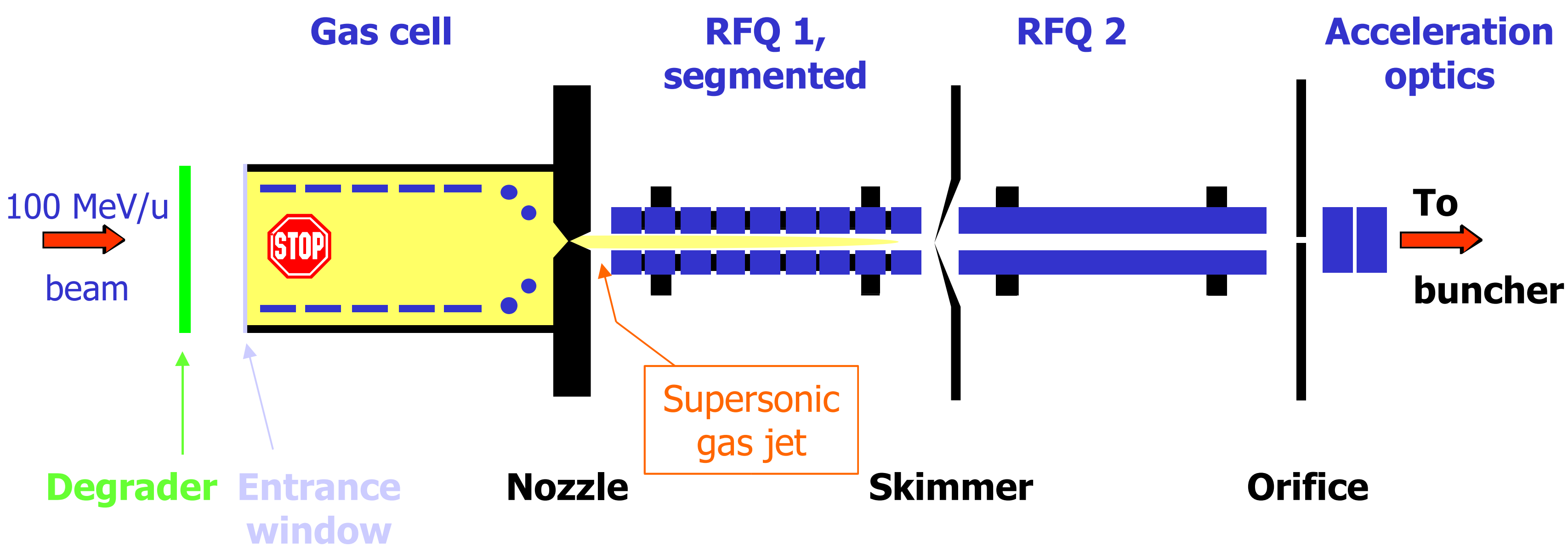
SCS, GSI Tele-Trap-Workshop 11/04

LEBIT - a facility for Low-Energy Beam and Ion Trap experiments

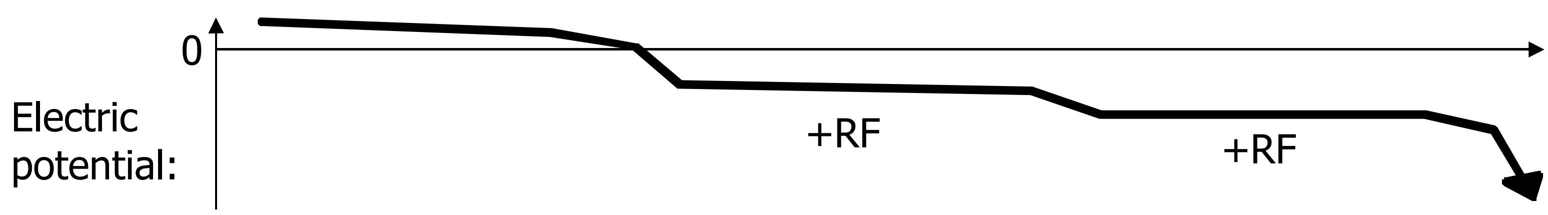


- Gas cell - stops fragment beams: E ~ 100 MeV/u ⇒ 5keV, DC
- Beam cooling and Bunching
- Experiments - Penning trap mass spectrometry, laser spectroscopy, decay studies

Gas stopping cell and ion guide system: overview

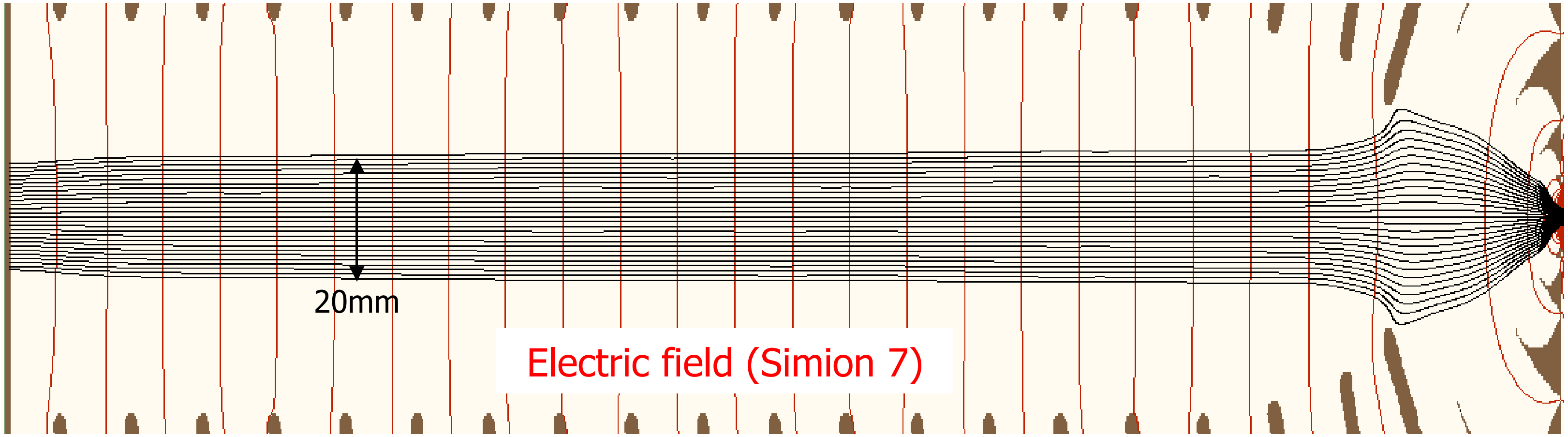


Pressure (He): ~1 bar — down to 0.1 mbar — ~10^{-4} mbar — < 10^{-6} mbar



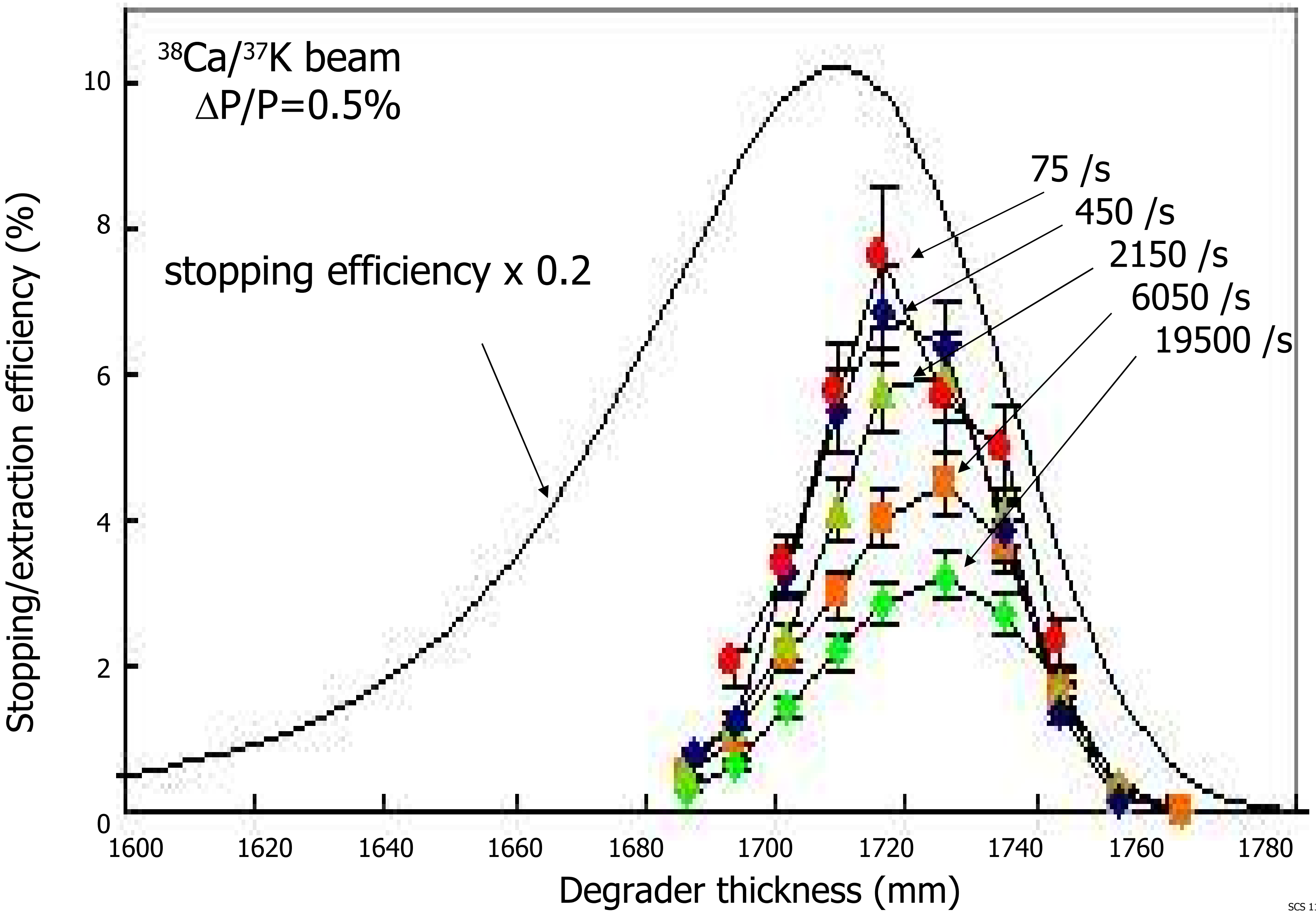
Ion extraction from the gas cell, flower power

Simulation: Electric field + gas flow (VarJet) -> ε=1



But there is space charge … and lots of it !!!

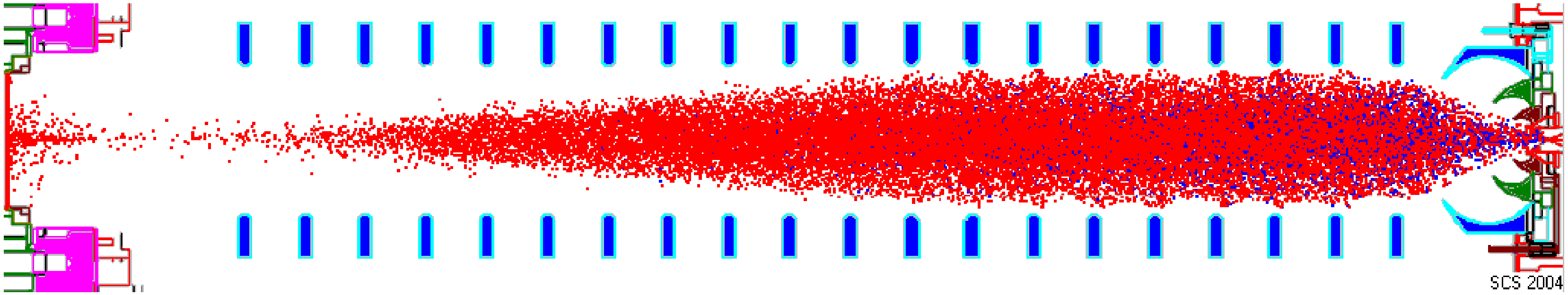
Some results of extraction measurements



Ion extraction from the gas cell, space charge at work

NSCL

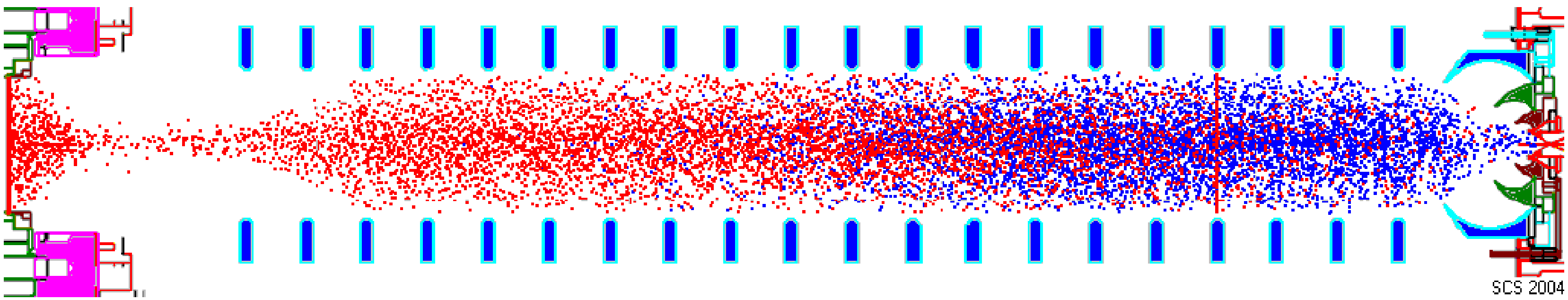
r=1e3/s



ε_{fr}=76%

ε_{gas}=23%

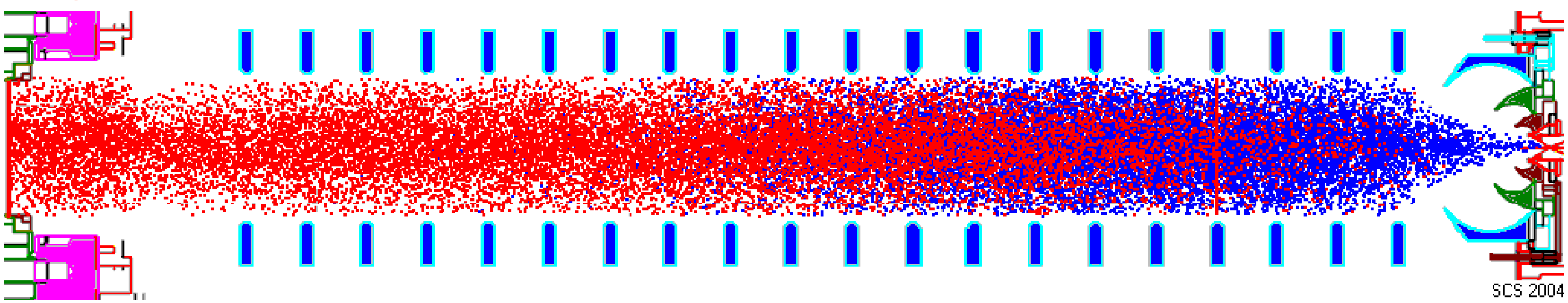
r=1e5/s



ε_{fr}=21%

ε_{gas}=1.2%

r=1e7/s

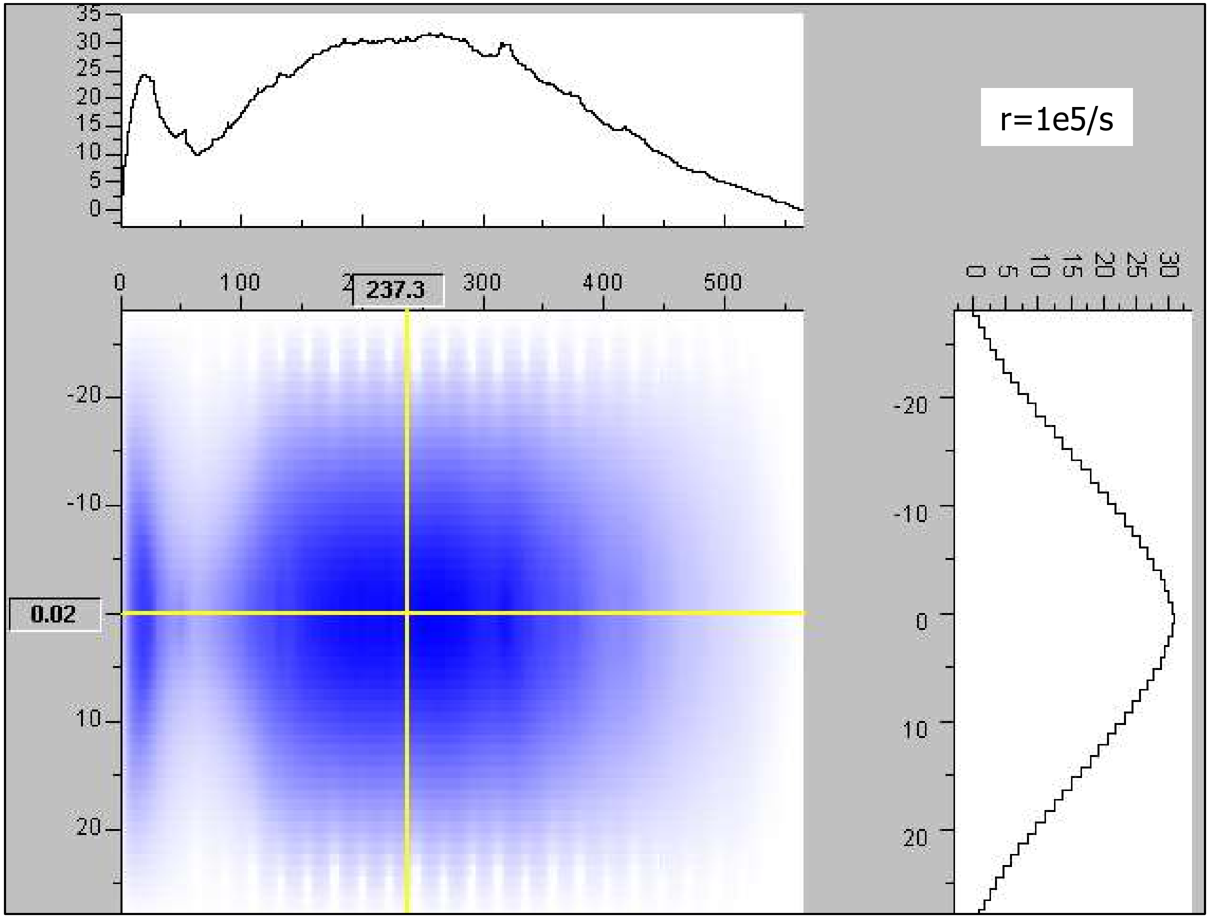


ε_{fr}=1.2%

ε_{gas}=2e-5

U_{Ring1}=1300V, U_{Ring2}=1600V, U_{Ring21}:1025V – ^{40}Ca

Ion extraction from the gas cell, space charge & potential

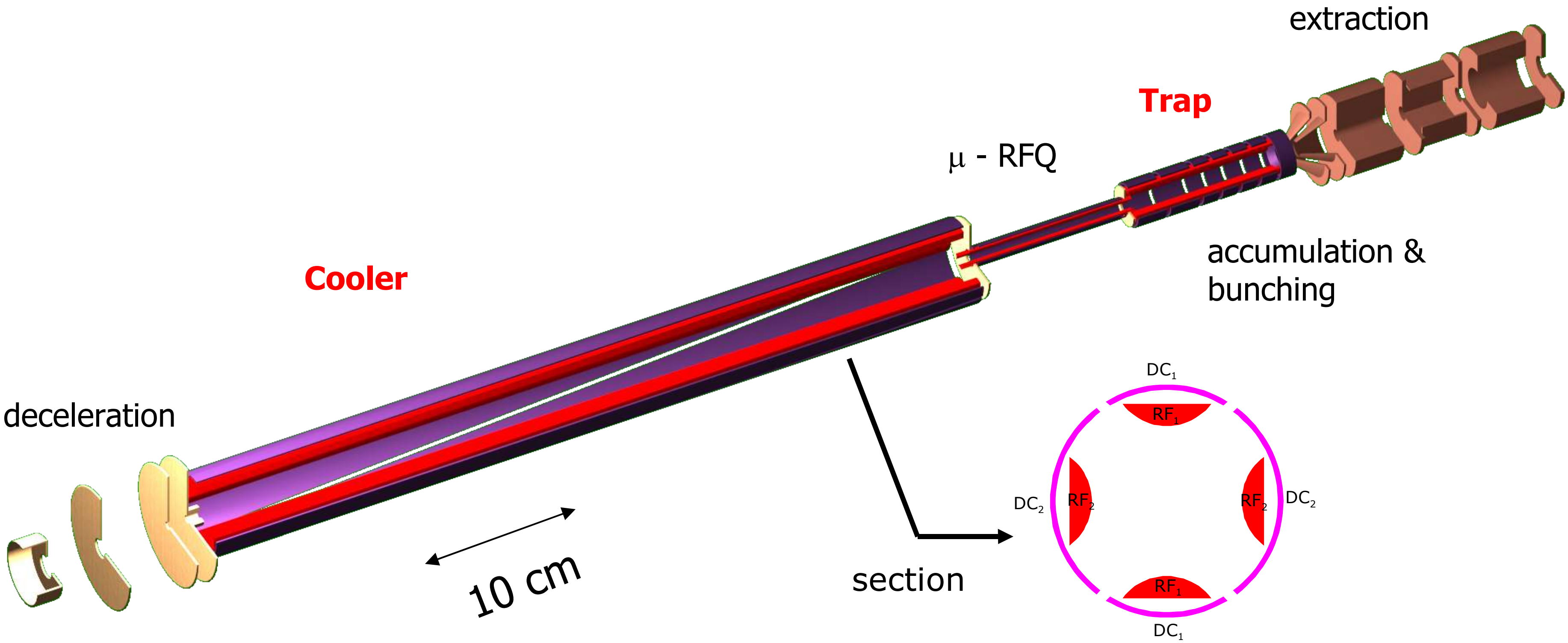


- PIC code:
  FAST! ~10min – 10kions
- Handles He^+, Ca+ and even e^-
- ⇒ Efficiency
- ⇒ Where ions get lost
- ⇒ Extraction time

- Work in progress !

U_{Ring1}=1300V, U_{Ring2}=1600V, U_{Ring21}:1025V – ^{40}Ca

The LEBIT cooler & buncher



Features:

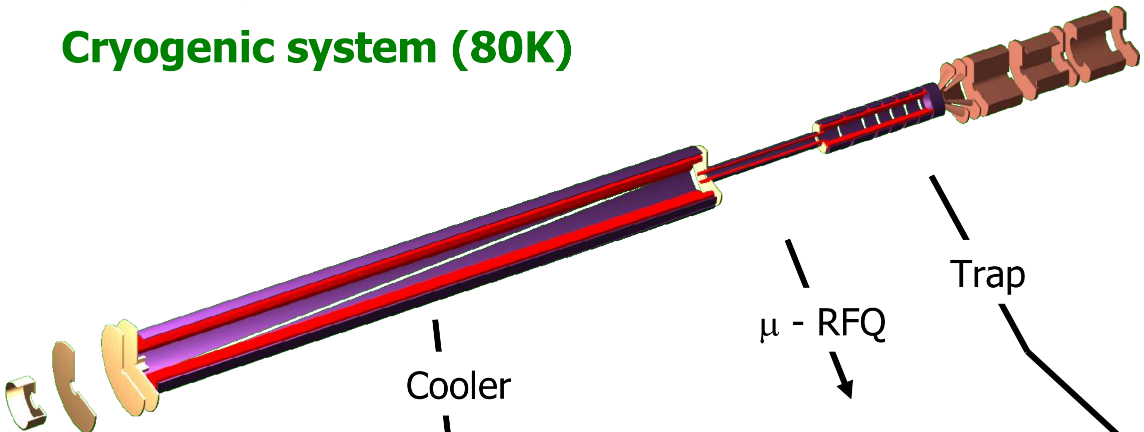
Two-stage system	• high-pressure cooling (~0.1mbar) low-pressure trapping & bunching ($<10^{-3}$ mbar)
Wedge-type electrodes	• no segmentation (except for DC in trap section)
Cryogenic system	• N_2-cooled, clean, no charge-exchange very low emittance, high efficiency

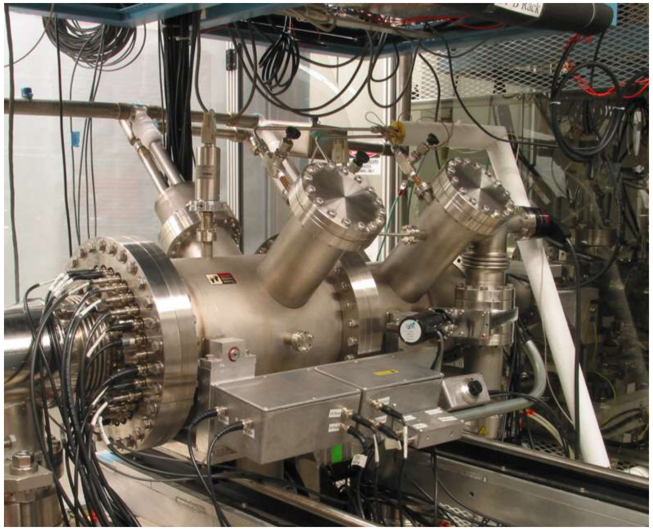
The LEBIT cooler & buncher - setup

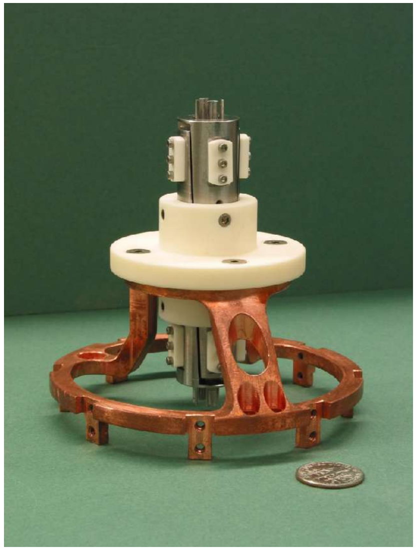
2-stage electrode concept

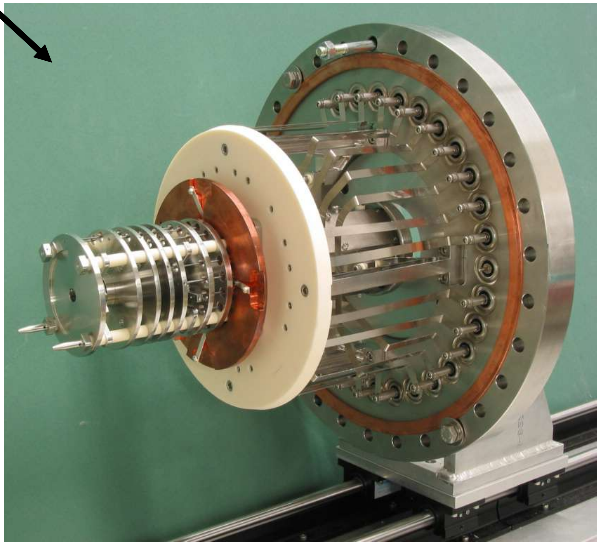
Multistage pumping

Cryogenic system (80K)







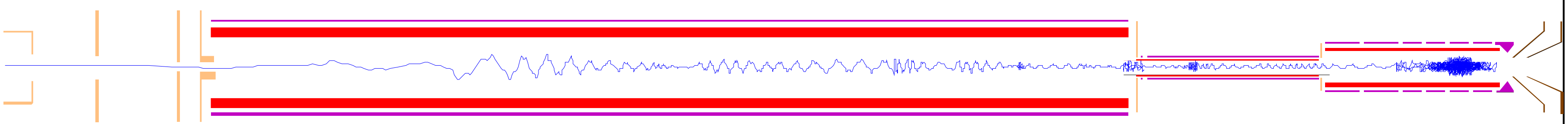


The LEBIT ion accumulator & buncher for LEBIT, simulations

- Simulation of complete transfer process
- ^{23}Na, ^{133}Cs (realistic potential scattering), ^{200}XX
- T = 80 K, 300 K

Trapping process

$^{23}Na^{+}$ / He

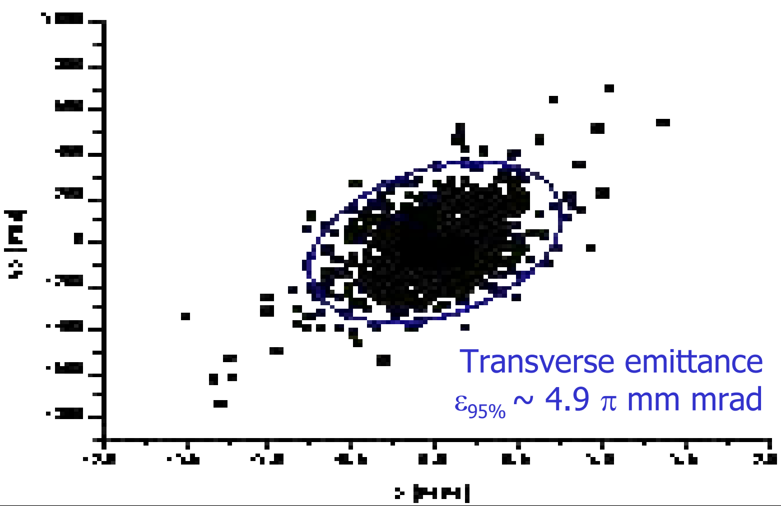


$p_{He}=5 \cdot 10^{-2}$ mbar

$p_{He}=2 \cdot 10^{-3}$ mbar

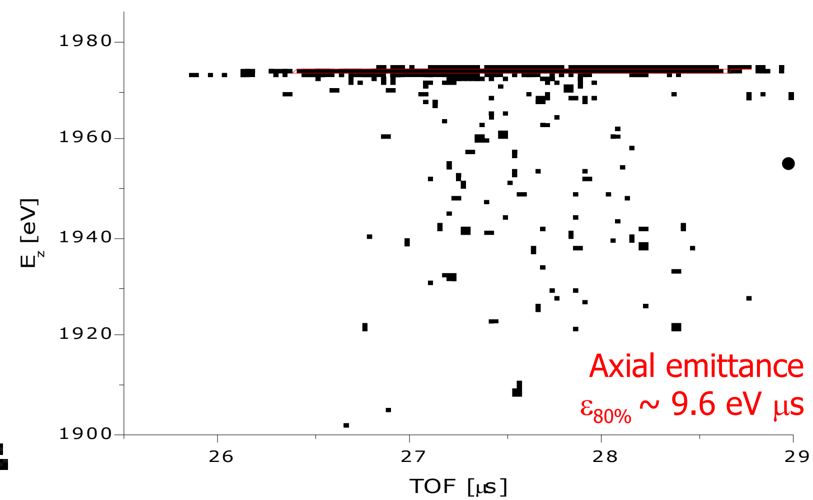
Properties of ejected ions, 2 keV

Cs+/He, T = 80 K, p = 4e-4 mbar



Transverse emittance

$\varepsilon_{95\%} \sim 4.9\ \pi$ mm mrad



Axial emittance

$\varepsilon_{80\%} \sim 9.6$ eV µs

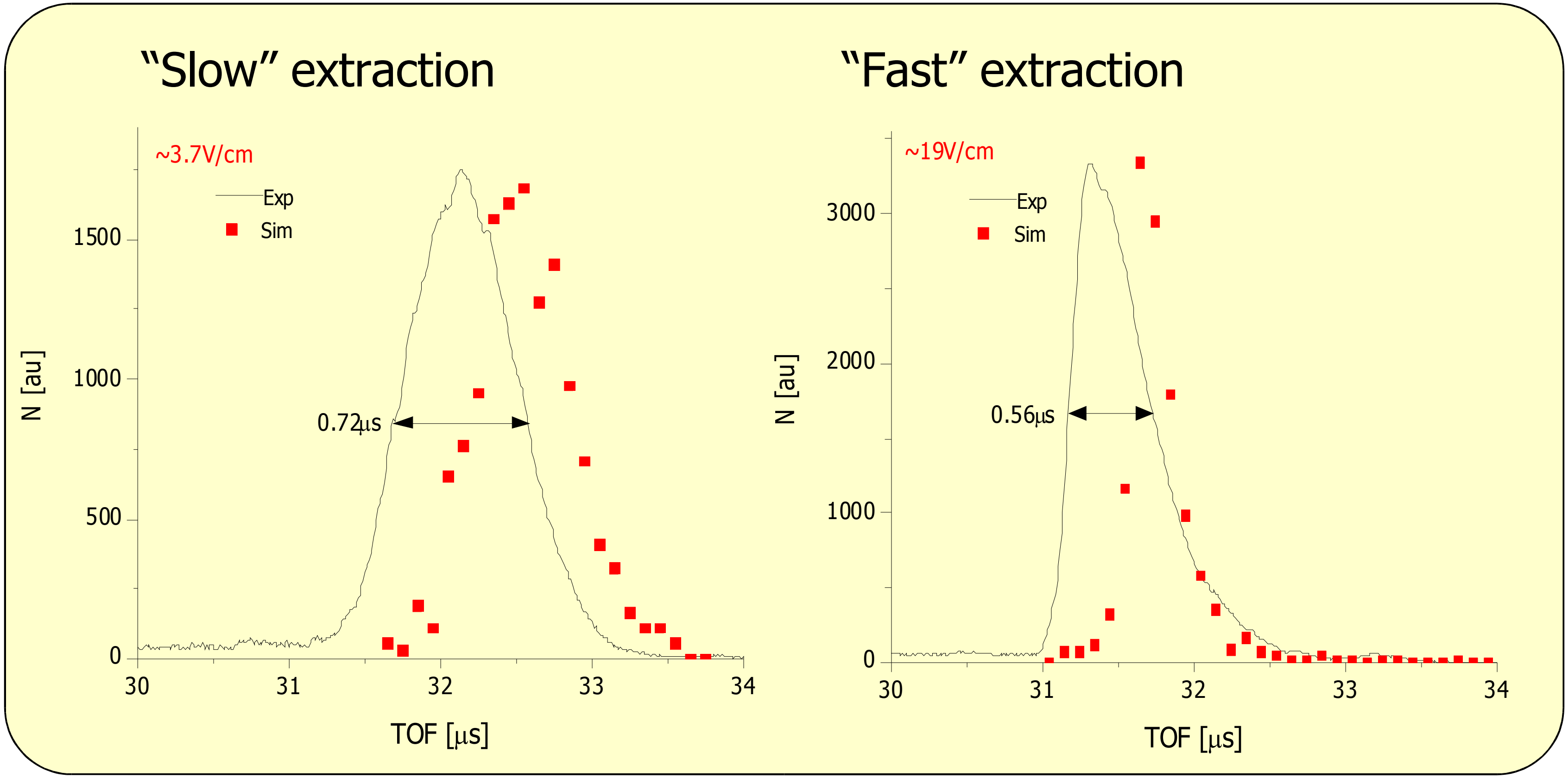
- total eff.(80K)

  ~ 100%

Pulsed mode operation

NSCL

Time-of-flight distributions, measured with an MCP detector.



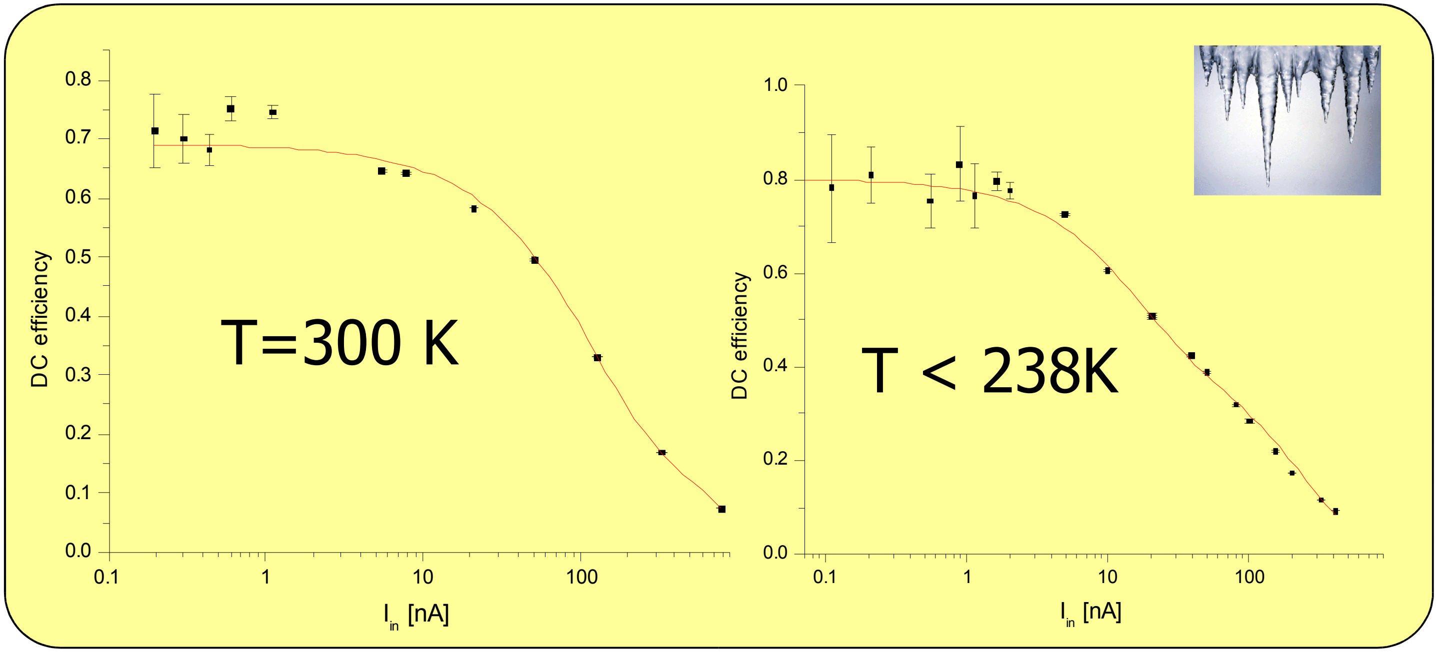
… with cooling times ~ 20ms

The LEBIT cooler & buncher: efficiency

Pulsed mode:

Total efficiency (with Penning trap):
ε > 10-15% (not corrected for MCP detector efficiency)

DC mode: Transmission efficiency vs. beam current:



RIA R&D proposal submitted to DOE:
High intensity beam cooling for better isobar separation

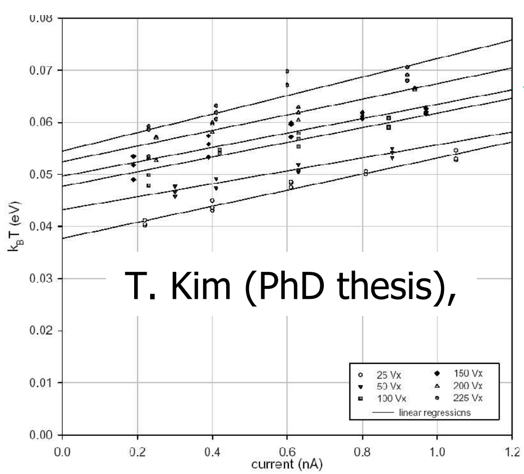
Experiment | Simulations

T. Kim, R.B Moore, McGill, Montreal

Beam size as a function of beam current ⇒ beam temperature assuming no space charge

r_0 = 7 mm, Cs^+/N_2, p = 8·10^{-2} mbar

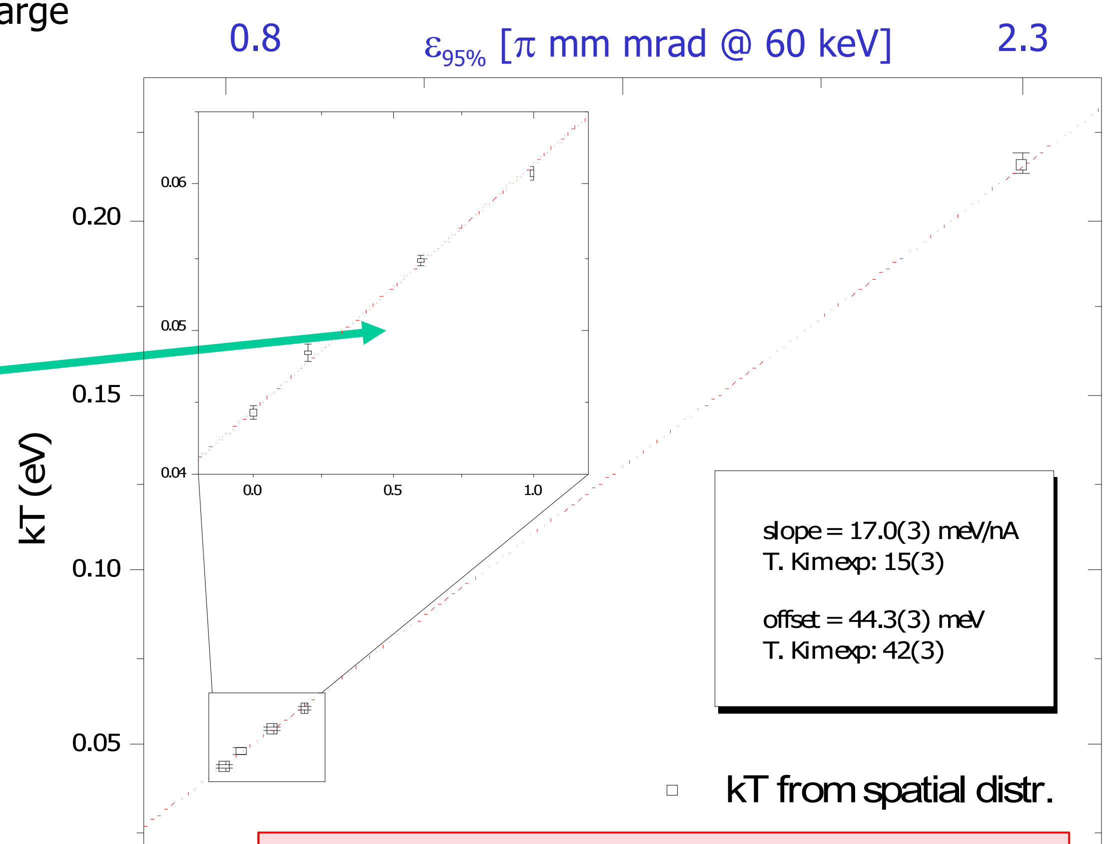
U_{RF} = 300 V, f_{RF} = 0.7 MHz, E = 1 V/m



Agreement for spatial distribution (0 - 1.2 nA) & slow rise of beam temperature

"Mean field"-code: (FH & SCS)

RF + Buffer gas collisions + Coulomb interaction



1μA simulation:
U_{RF} = 15 kV, f_{RF} = 5 MHz, E = 10 V/m
$\varepsilon_{95\%}$ ≈ 3 π mm mrad @ 60 keV

"Mean field" vs. PIC code

MD simulations not very efficient for space charge calculations

Mean field:

Electric field **E** = quadrupole field $\mathbf{E}_{RFQ}$

↓

Define initial coordinates of ions

→

Run ions through RFQ using **E**

→

Solve 1d Poisson-eqn for $\mathbf{E}_{ions}$: $1/r \, d/dr(r \, E_r) = -\rho/\varepsilon_0$

→

$\mathbf{E}=\mathbf{E}_{RFQ}+\mathbf{E}_{ions}$

→ (back to Define initial coordinates of ions)

10ms

N=15

Typical CPU-time: hours

Particle in cell:

Define initial coordinates of ions

↓

Calculate charge density matrix ρ_{ij}

→

Solve $\Delta\Phi=-\rho/\varepsilon_0$ on 2d grid with FFT methods

CPU:~8ms!!!

→

Integrate eqns of motions ("Leapfrog")

→

Collisions ? Loss ? Refill ?

→ (back to Calculate charge density matrix)

$0.1\mu s$

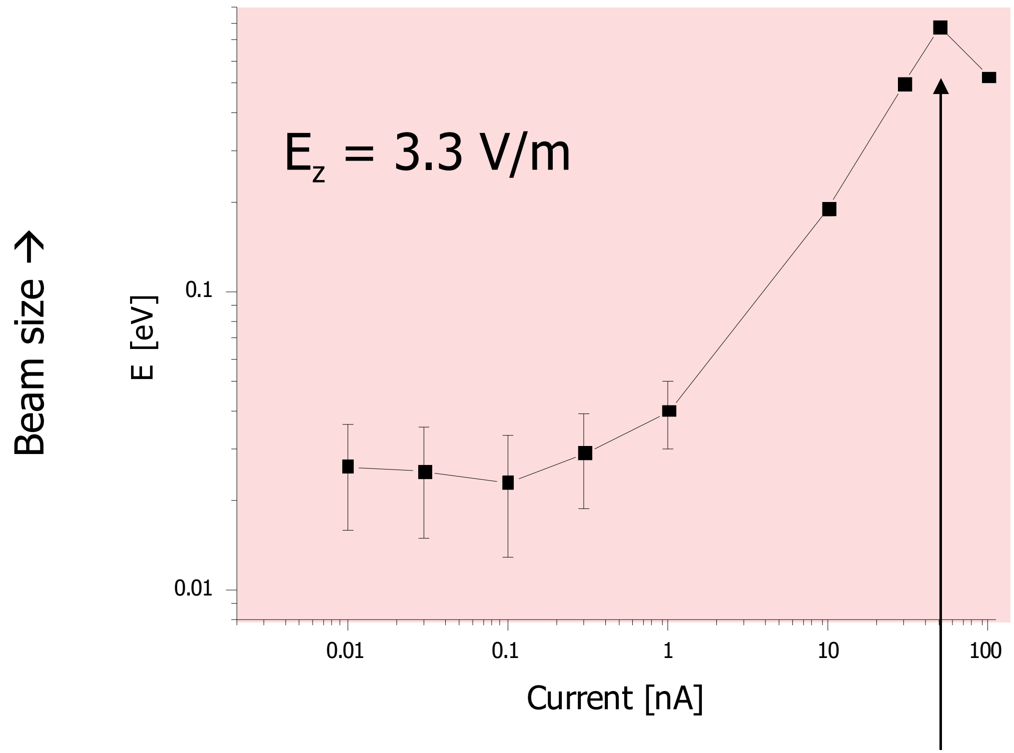
$N=10^5$

Typical CPU-time, 10k ions: 10min

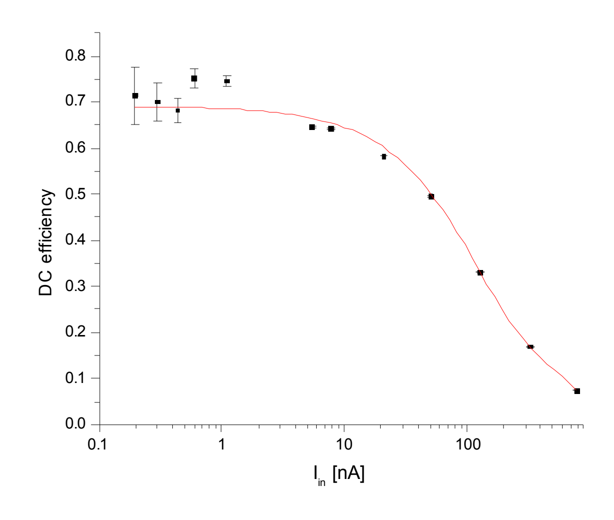
Method: D.W.Mitchell, R.D.Smith: IJMS Ion Proc 165 (1997) 271

The LEBIT miniature RFQ: space charge "heating"

Beam size as a function of beam current
$\Rightarrow$ beam temperature



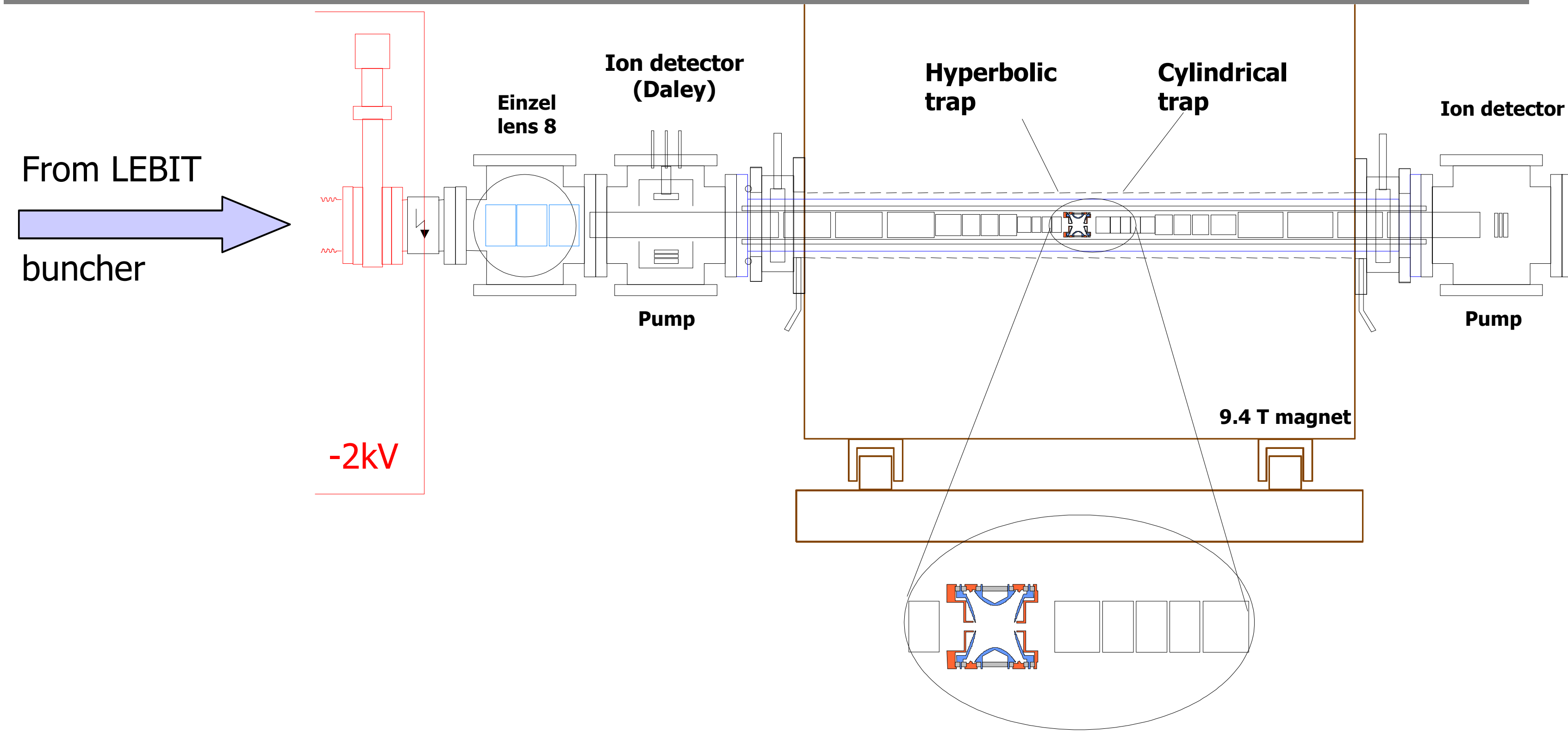
Losses start here
- agrees with experiment!



- Code will yield:
  - emittance
  - efficiency …

- Fast & promising !
- Work in progress !!

The 9.4 T Penning trap mass spectrometer



Features:

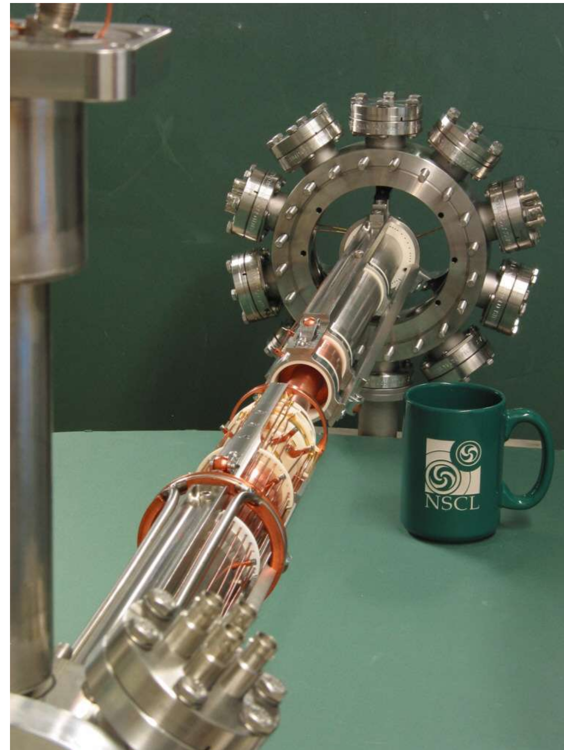
9.4 T magnet	• shielded and compensated (ambient fields!)
Hyperbolic trap	• mass measurements via determination of cyclotron frequency $\omega_c = (q/m) \cdot B$
Cylindrical trap	• ion parking, decay studies
Cold traps at 80K	• improved vacuum
Backwards TOF detection	• free access to traps

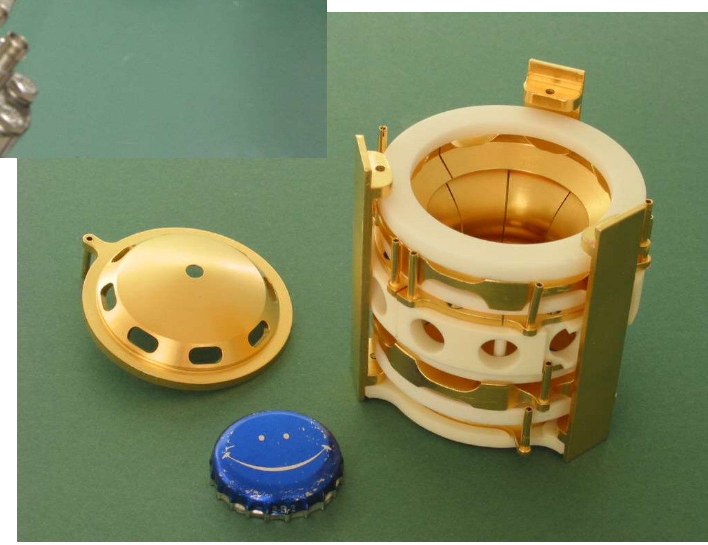
Why 9.4T ?

$\delta m/m \approx c \cdot R^{-1} \cdot N^{-1/2}$

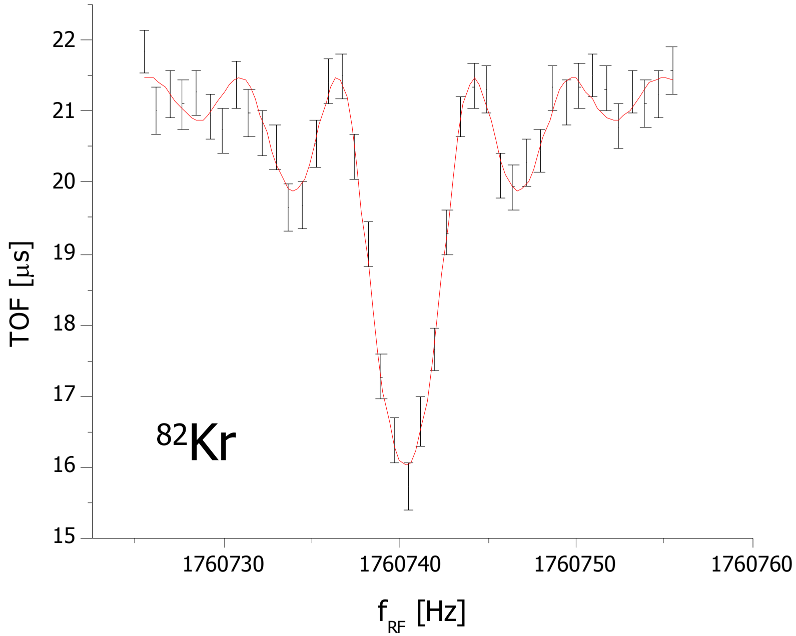
$\Rightarrow$ Same $\delta m/m$ in half the time compared to 6T systems

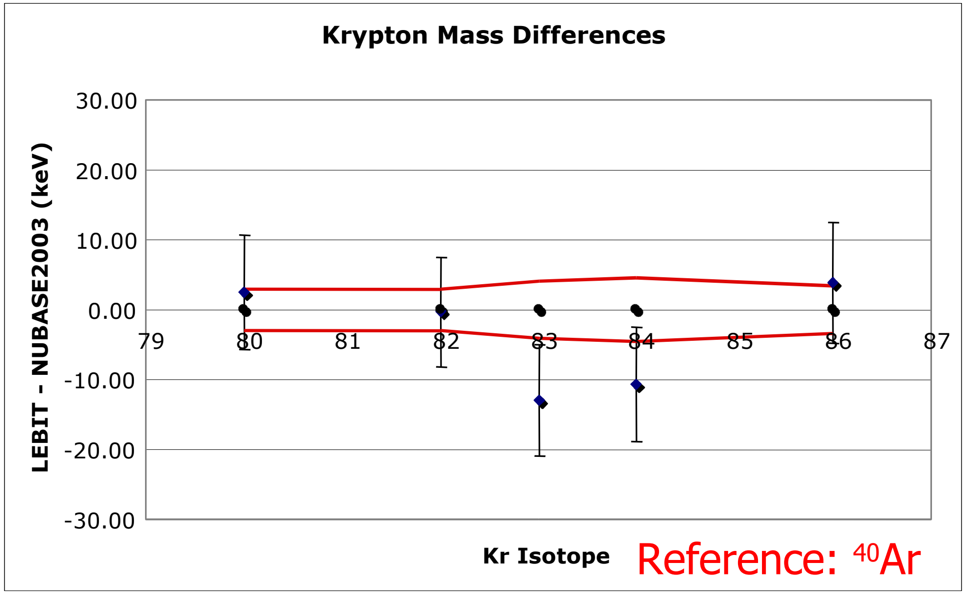
The LEBIT 9.4 T Penning trap system





Test Measurement with Stable Krypton Isotopes





- $R = \nu/\Delta\nu \sim \nu \cdot T_{exc} \sim 4 \cdot 10^5$

  $R_{max} \sim 2.5 \cdot 10^6$

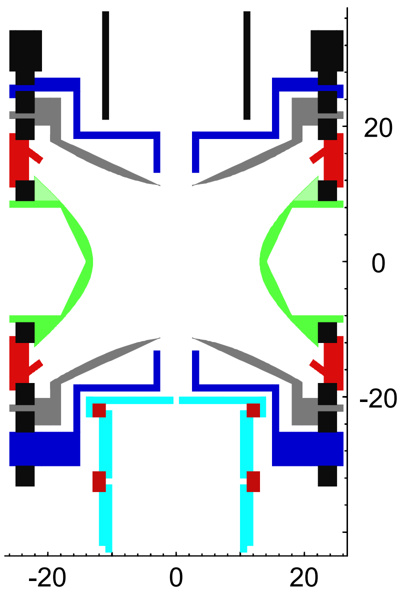
- $\delta m/m_{stat} \sim 4 \cdot 10^{-8}$

- Average relative mass difference: $5 \cdot 10^{-8}$
- Mass dependent systematic effects: $< 2 \cdot 10^{-9}$/amu

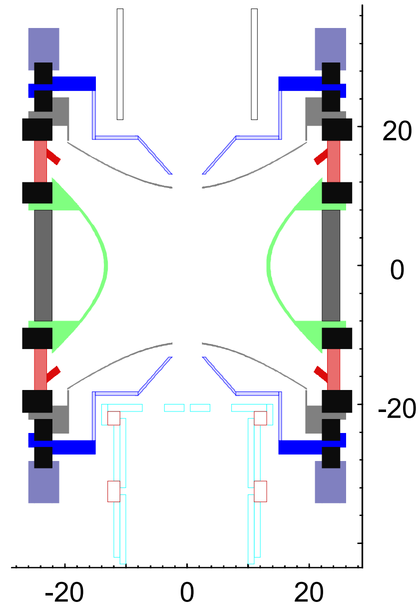
Rare isotope measurements soon

The LEBIT Penning trap – B-Field

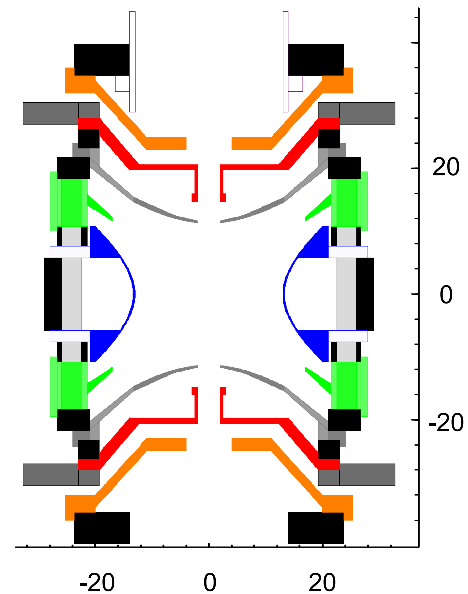
ISOLTRAP

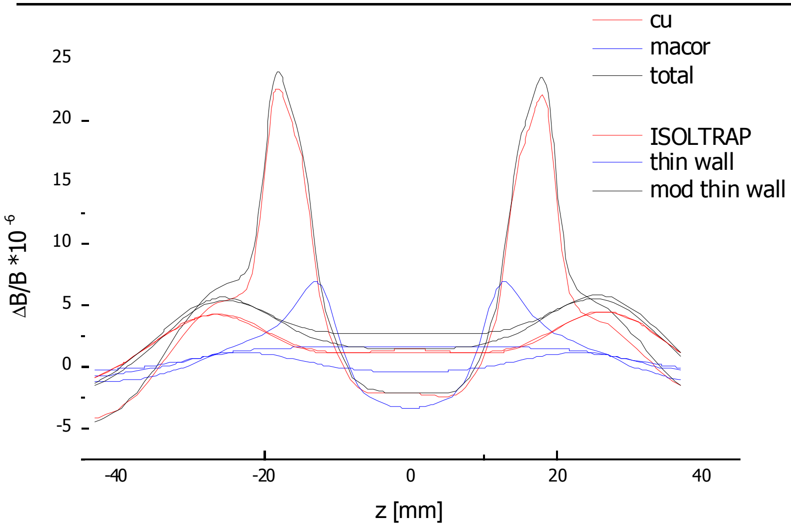


"Thin" wall #1

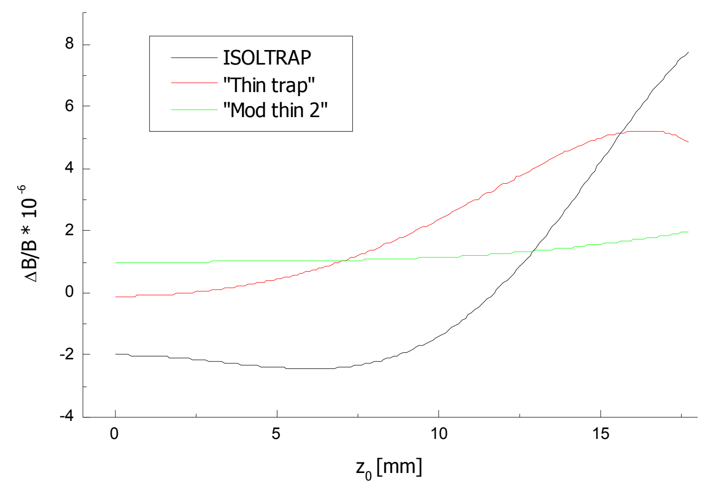


"Mod. thin wall #2"





Deviation of B-field on z-axis introduced by material



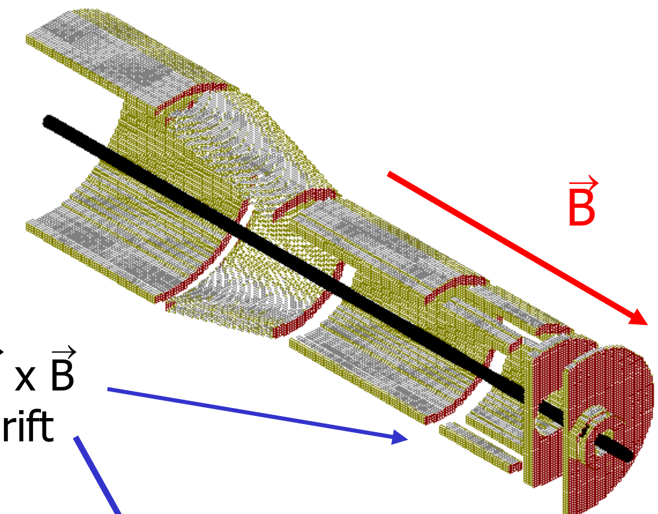
Avg B-field felt by a particle with amplitude z_o

The LEBIT Penning trap – Lorentz steerer for magnetron preparation

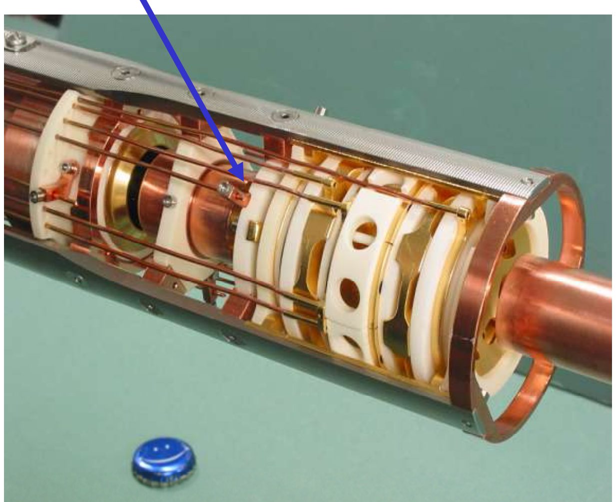
True cyclotron frequency detection needs magnetron motion

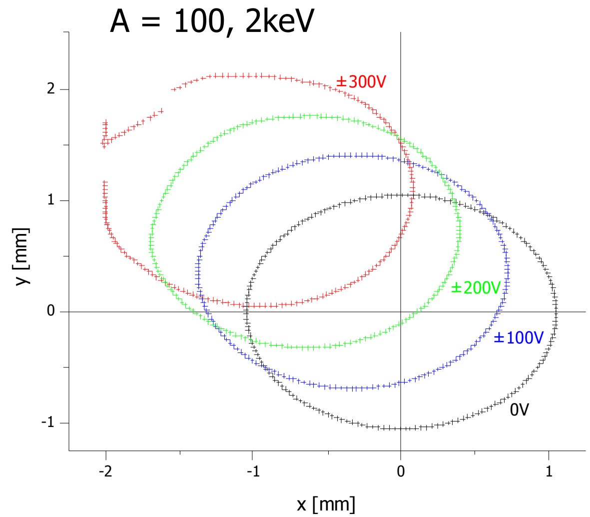
"Lorentz"-deflector:

Avoids time-consuming magnetron excitation !
No phase-locking required

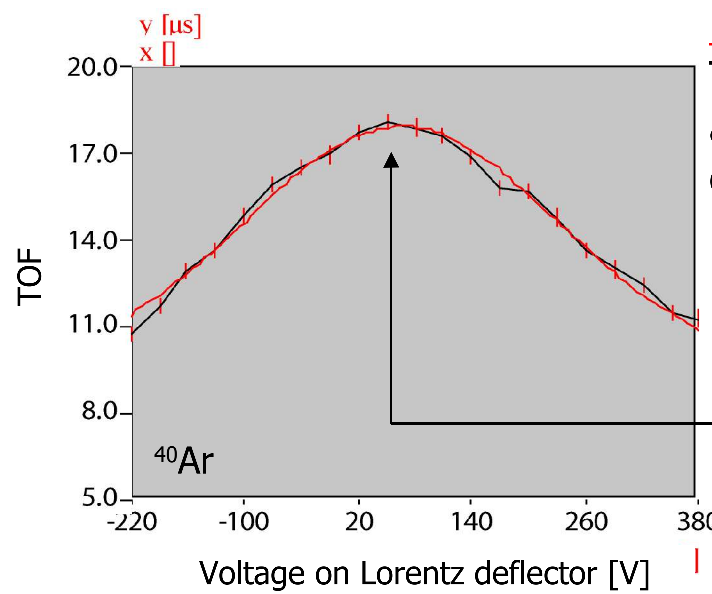


$\vec{E} \times \vec{B}$ drift





<u>Simulation:</u>
Trapped ions having passed the Lorentz steerer. Deflection of beam increases until at ±300 V ions begin to hit the endcaps



<u>Experiment:</u>
TOF recorded after conversion of magnetron into cyclotron motion:

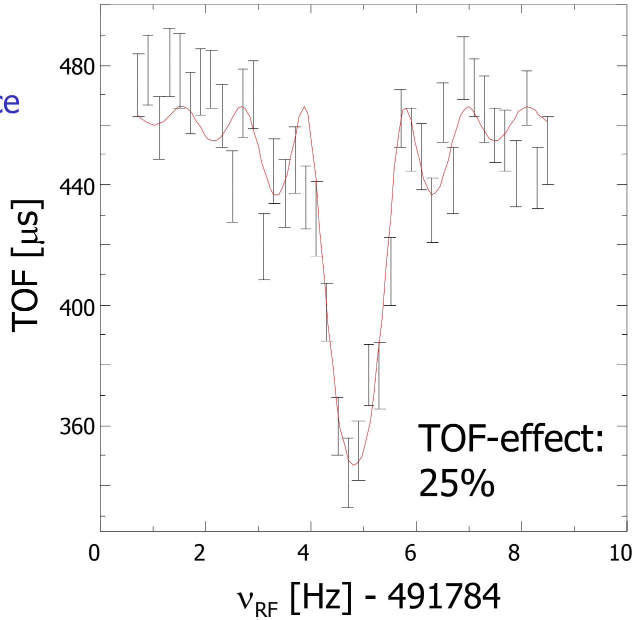
Injection of ions with smallest $\langle\rho_-\rangle$

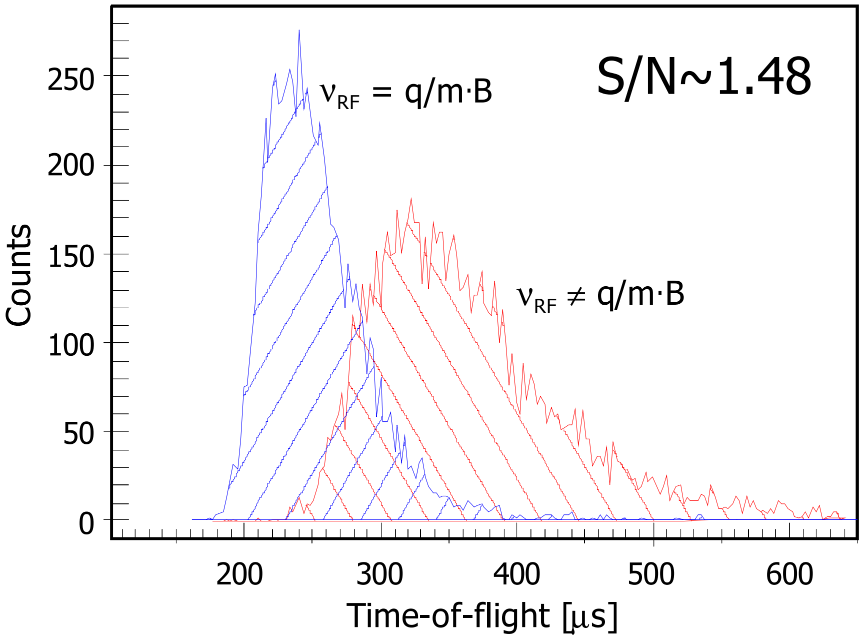
The LEBIT Penning trap – TOF detection / Signal-to-noise #1

Can we improve on the signal-to-noise ratio ?

$$S/N = (\overline{TOF_2}-\overline{TOF_1}) / \sqrt{(\sigma_1^2+\sigma_2^2)}$$

Measured ISOLTRAP TOF-resonance and spectra



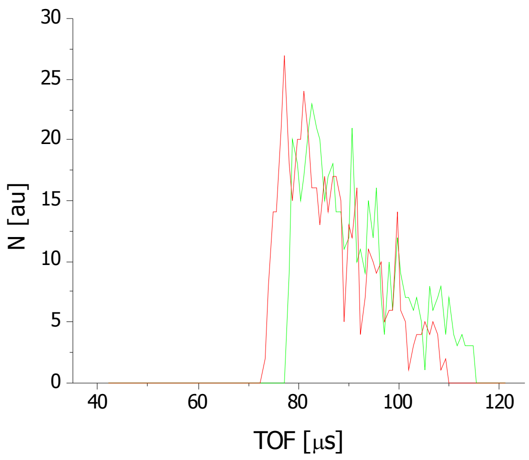


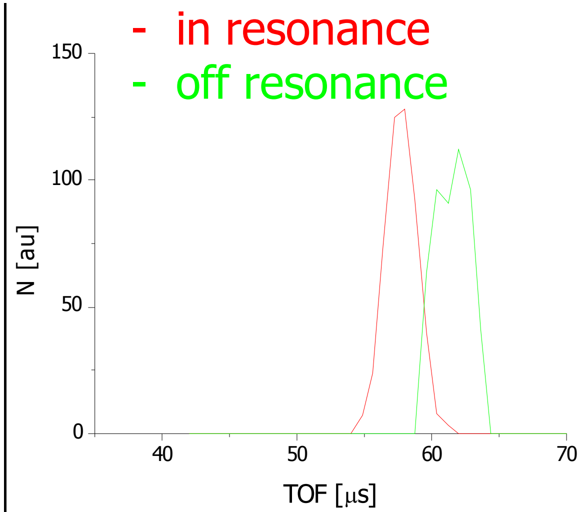
Yes! Optimize layout & voltages… LEBIT ejection optics:

The LEBIT Penning trap – TOF detection / Signal-to-noise #2

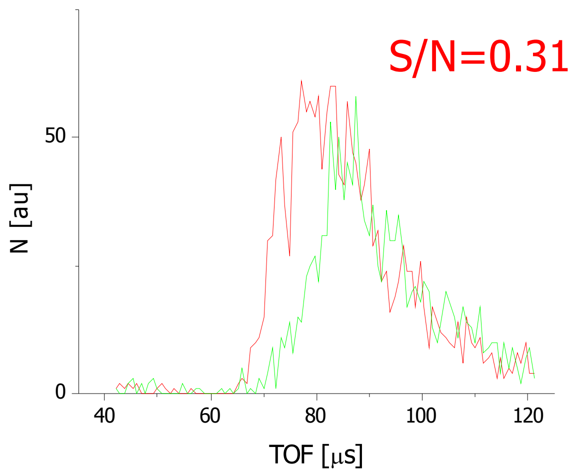
NSCL

Simulations

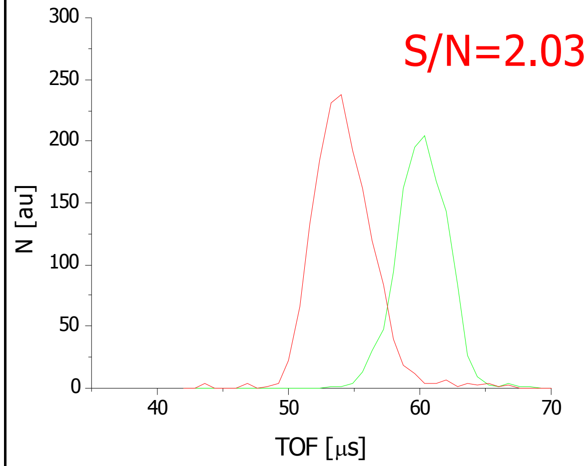




Experiment:



Drift #1: -10V



Drift #1: -70V

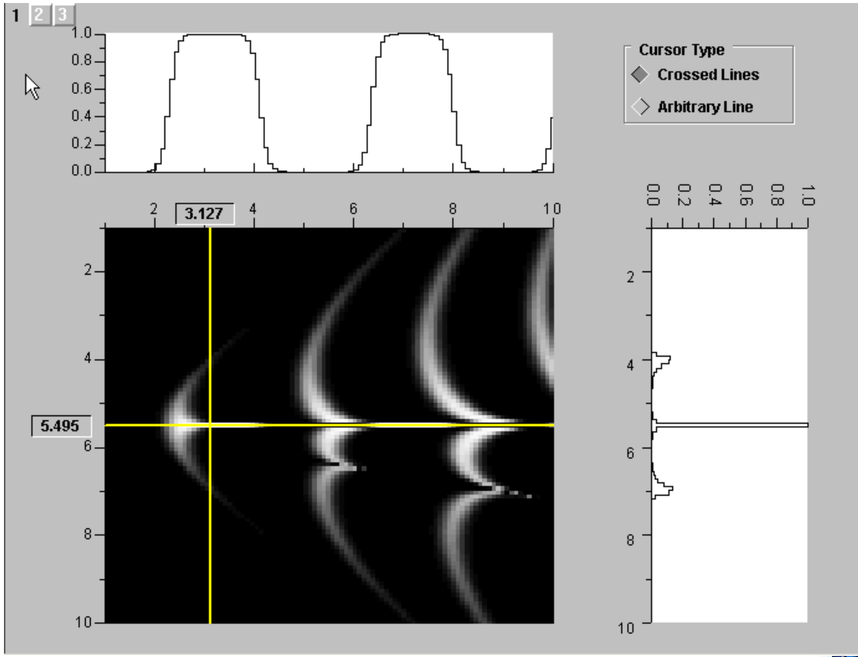
- ^{84}Kr
- Initial radial distribution: ρ_{-} = 0.75 mm, σ=0.3 mm
- Initial axial distribution: ±6 mm (rectangular)
- 500 ions simulated

- Work in progress !

Octupole excitation at $2\omega_c$

Ideal conditions $\rho_+ = 0$, $\rho_- = 1$, $\phi_- = 0$, $\phi_+ = 17^o$, $T_{rf} = const$

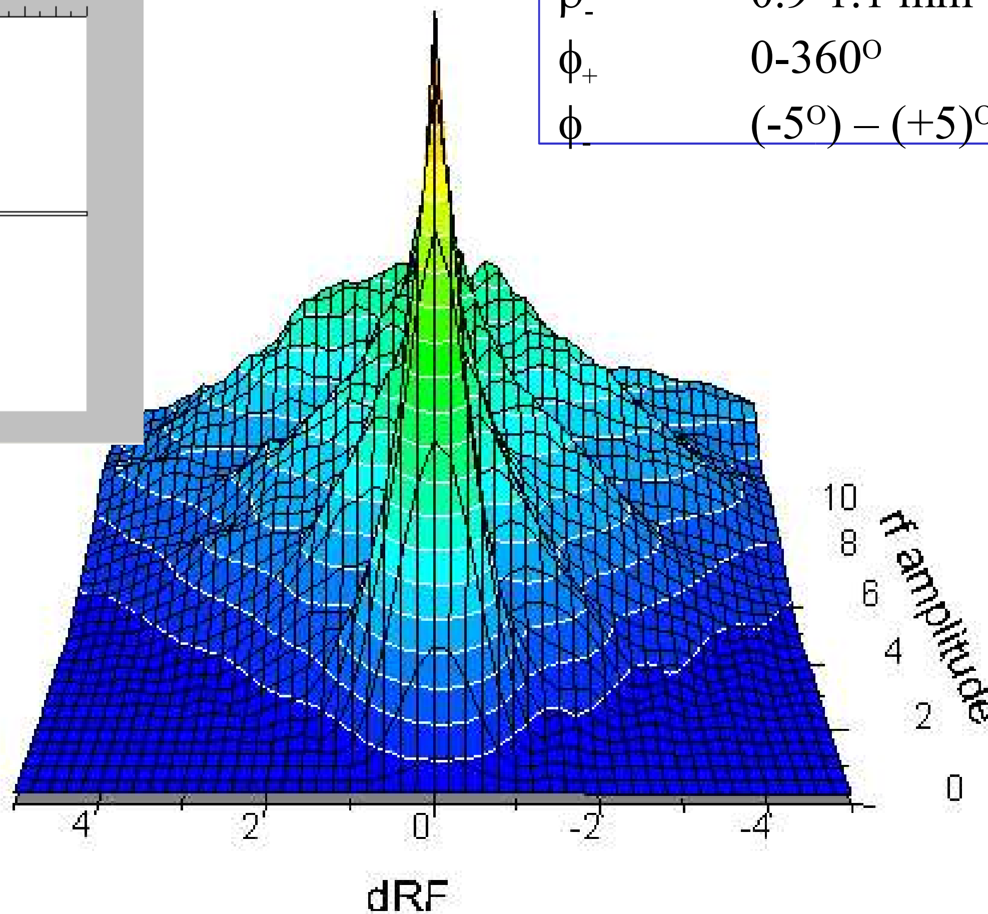
detuning $\Delta\nu_{RF}$



RF amplitude A_{RF}

Realistic resonance profile

ρ_+	0-0.2 mm
ρ_-	0.9-1.1 mm
ϕ_+	0-360^o
ϕ_-	$(-5^o) - (+5)^o$



Experimental studies needed

Summary

LEBIT – is in commissioning phase – rare isotope mass measurements soon

Simulations have played a very important role in LEBIT design and still do:

- Latest development: PIC code
  - gas cell optimization
  - high intensity beam cooling
  - other possible applications : space charge effects in RFQ and Penning traps

- Octupole excitations - analytical description desirable – experiments needed