Stopping of Energetic Radioactive Ions Using Cyclotron Principles

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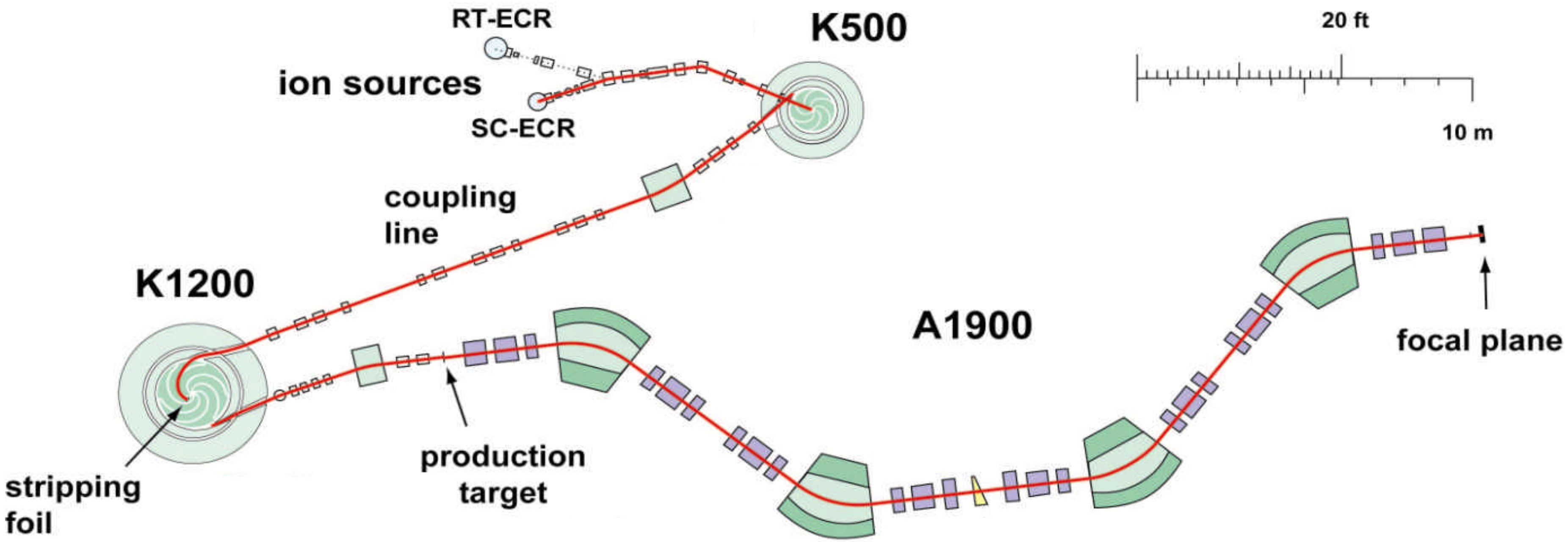
Questions to answer

- Why do we need to stop the ions?
- What is the present technology?
- What are the weak points of the present technology?
- What is the cycstopper?
- Where are we in the understanding of the device?
- Where do we go from here?

Radioactive ions are produced by projectile fragmentation

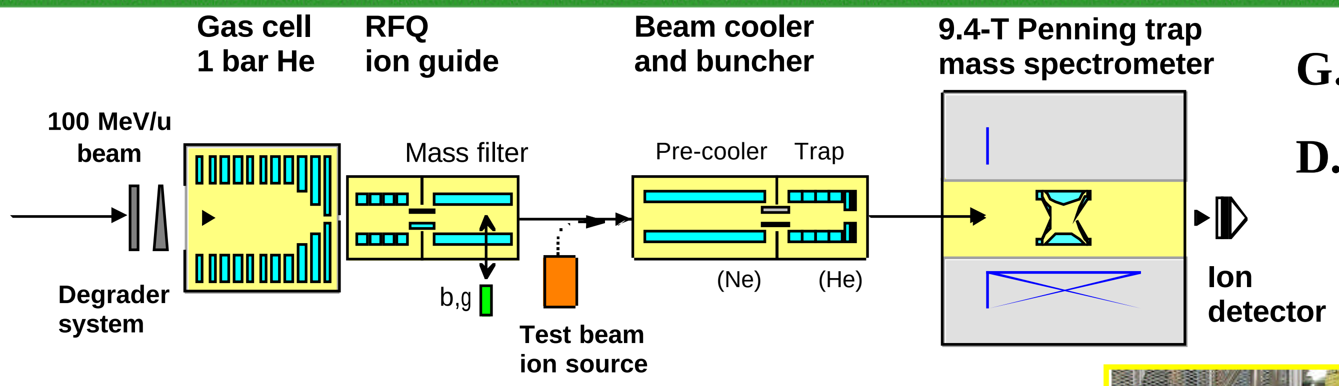


Why do we need to stop the ions?

- Atomic masses measurements
  - Highest precision with ions at rest in Penning traps.
  - Masses of rare isotopes are important for nuclear structure studies (evolution of shell structure), nuclear astrophysics (element synthesis via the r process and the rp process), and test of fundamental interactions and symmetries.
- Atomic (Laser) Spectroscopy
  - Nuclear charge radii (nuclear deformation) and nuclear moments
  - Experiments with polarized beams (moments, fundamental tests)
- Reacceleration
  - Reactions of interest to nuclear astrophysics
  - Safe Coulomb excitation and transfer reactions (nuclear structure)

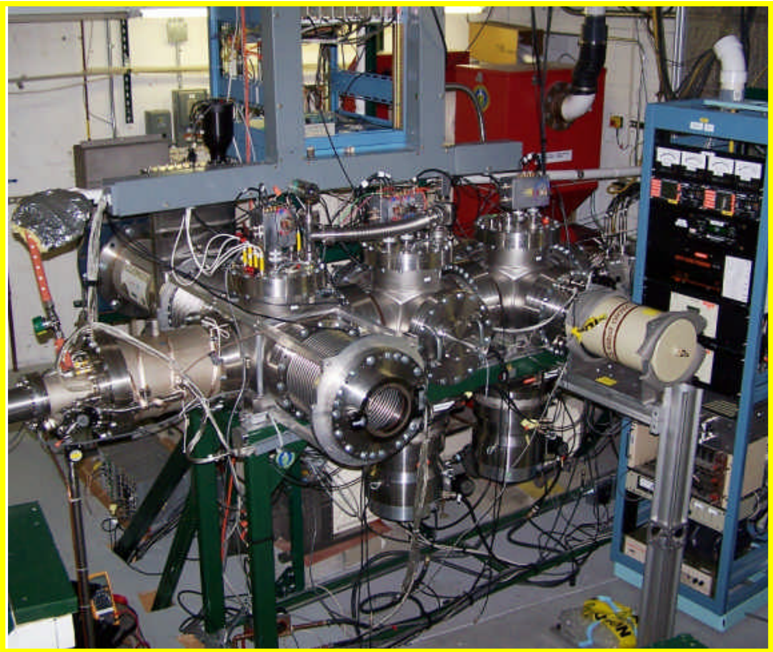
Low Energy Beam and Ion Trap Facility LEBIT

100 MeV/u → 1 eV

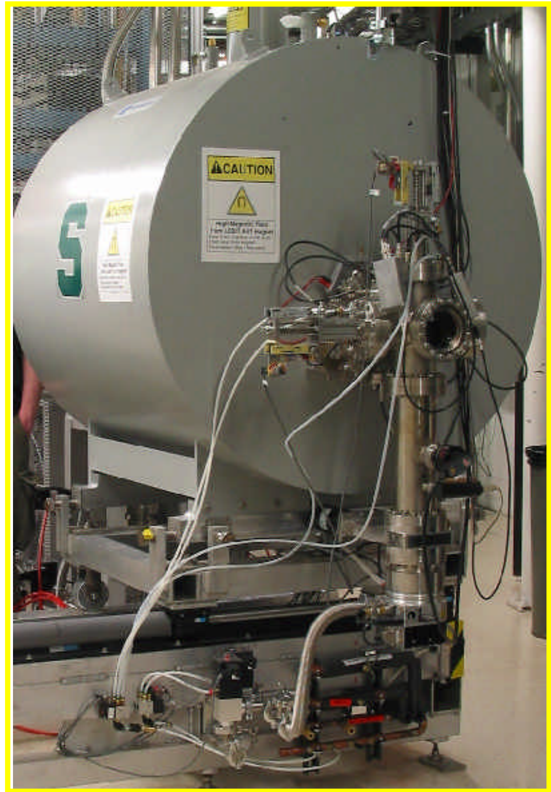


G. Bollen-

D. Morrissey



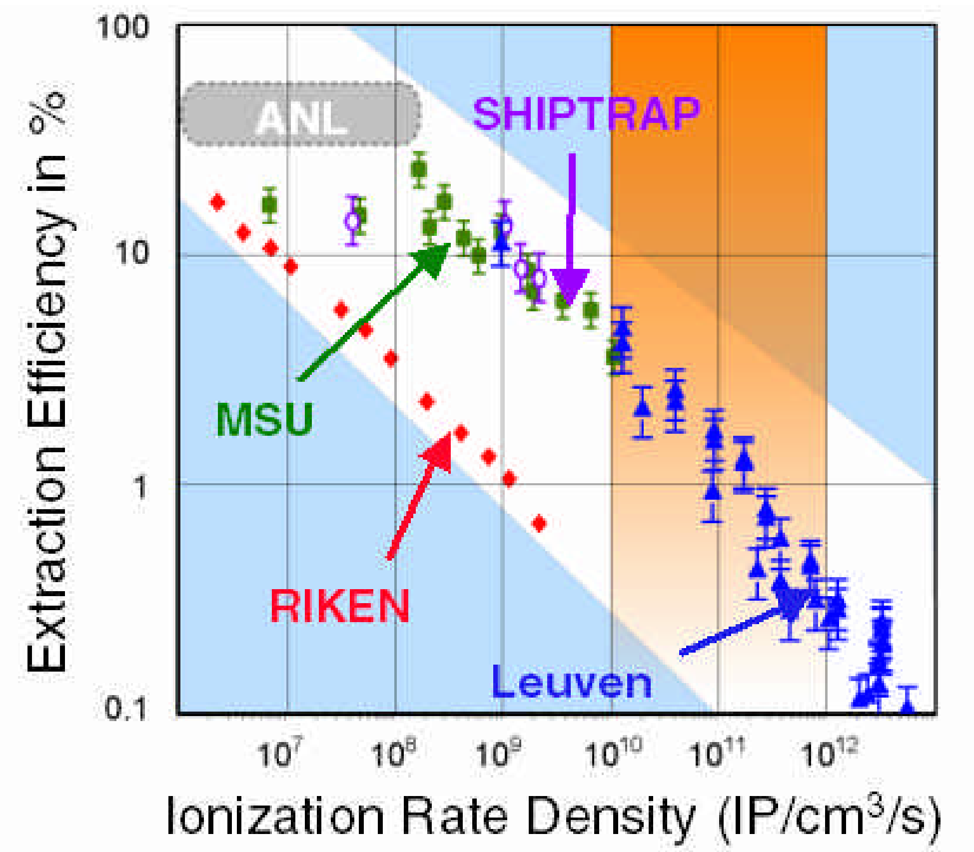
Masses of >30 rare isotopes measured since 2005: Si, P, S, Ca, Fe, Co, Ga, Ge, Se, As, Br



What is the present technology?

- **Linear gas cell combines:**
  - **A production method based on the in-flight fragment separator**
  - **Stops fragments in a helium gas cell and extracts them with guiding electric fields**
  - **Short extraction times (a few milliseconds) compared to ISOL, but lower emittance and more accurate energy beams than simple fragmentation**

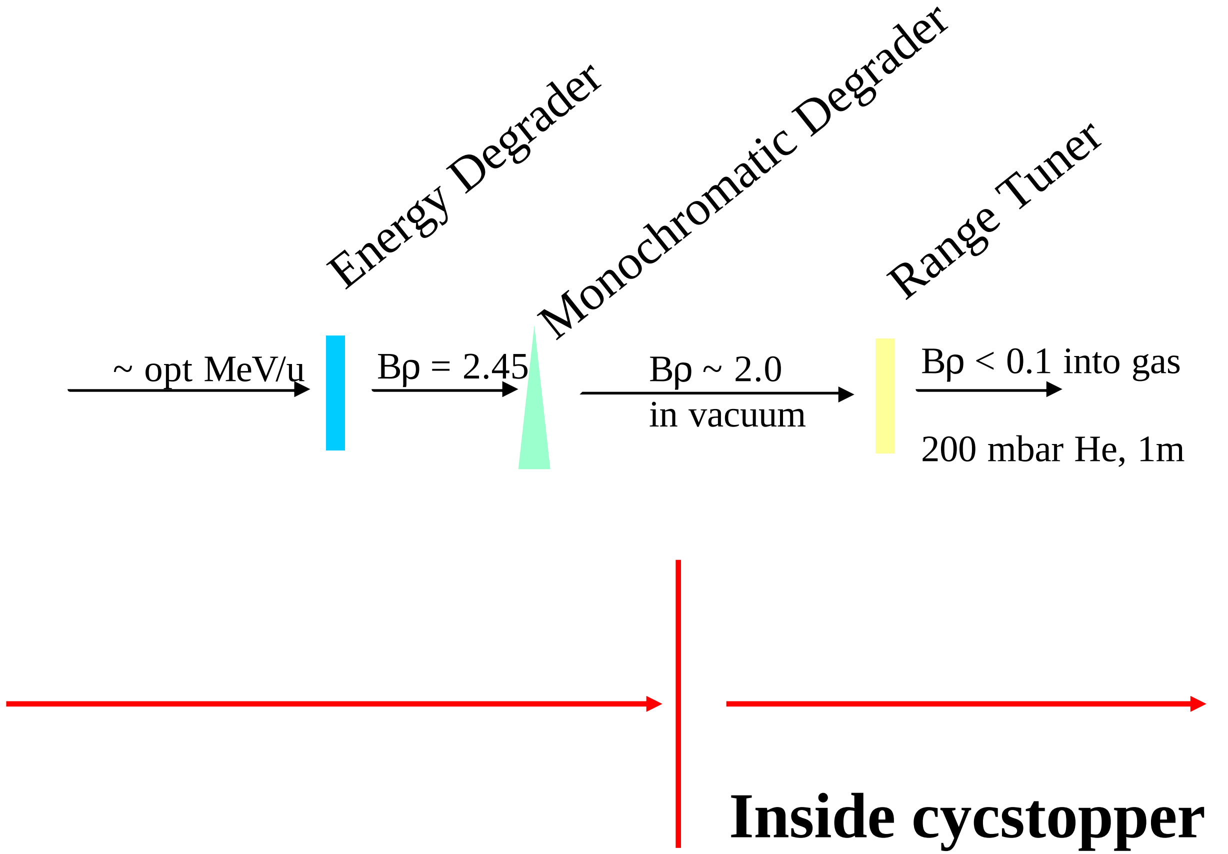
Limitations of the linear gas cells



D. Morrissey, NSCL

- Intensity-dependent extraction efficiencies limit reach far from stability
  - Very large cells (>2m) impractical
  - RF walls/carpets can help - require cryogenic operation
- Extraction times of ≈ 100 ms do not match advantages of fast RIB production
  - Practically independent from gas cell size

Linear Gas Cell 200 mbar He, 1m long



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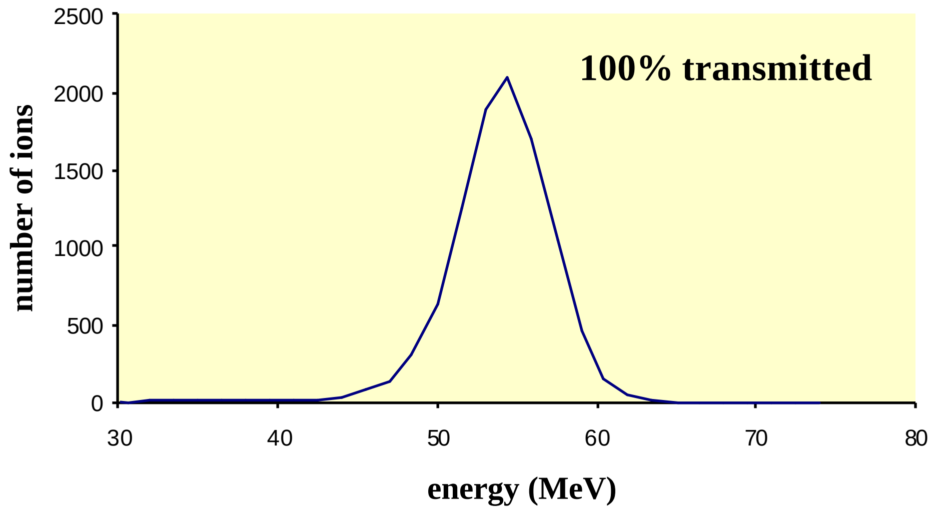
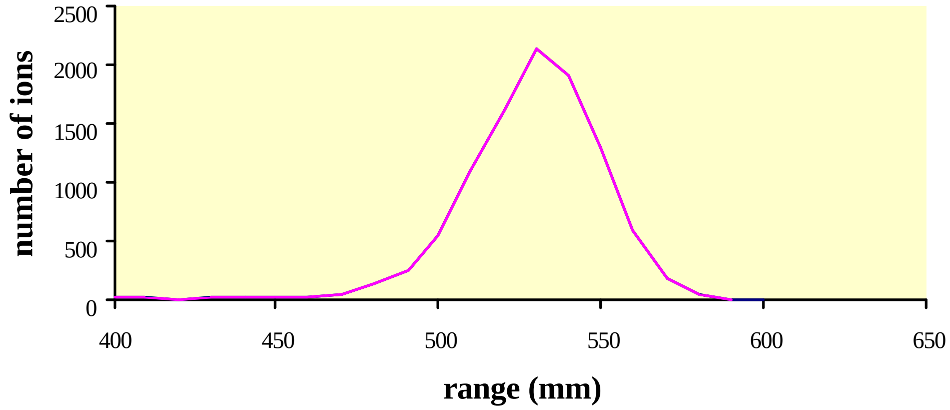
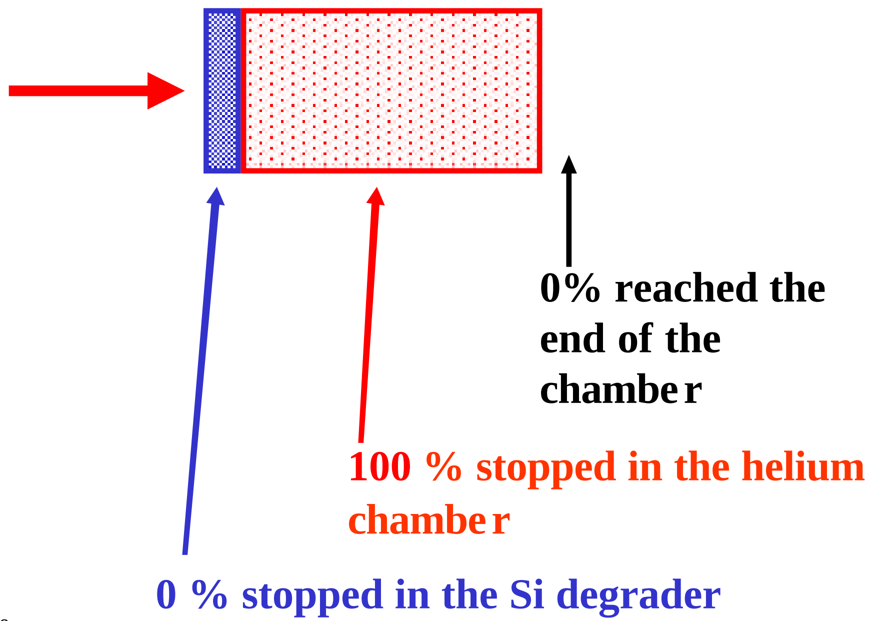
Heavy ions have good stopping characteristics

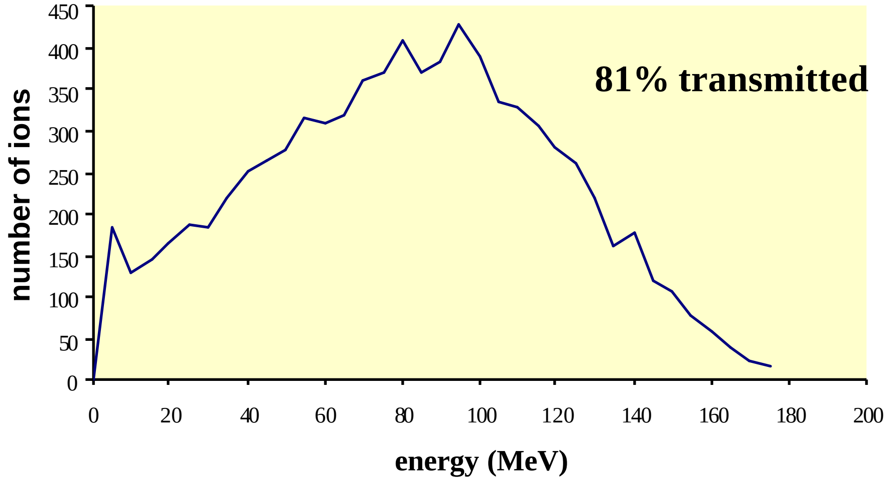


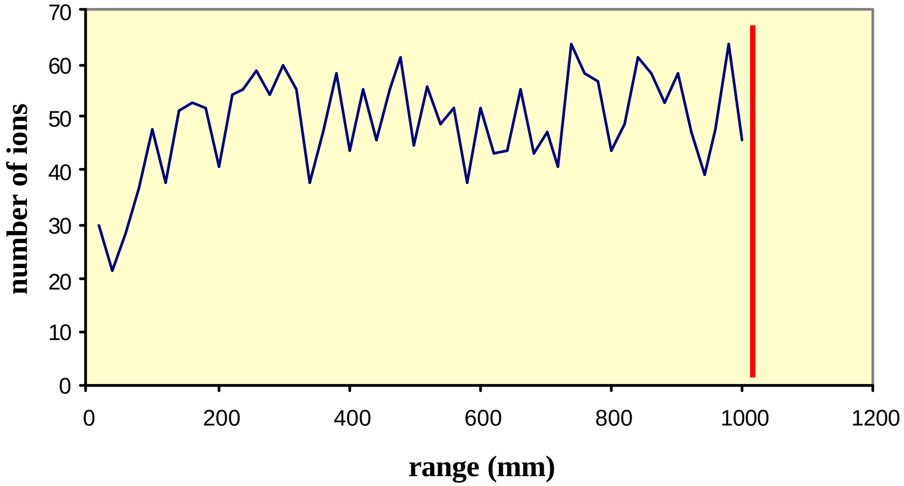


10000 ions ^{150}I slowed down in Si before entering a 1 m long helium linear cell at 200 mbar.



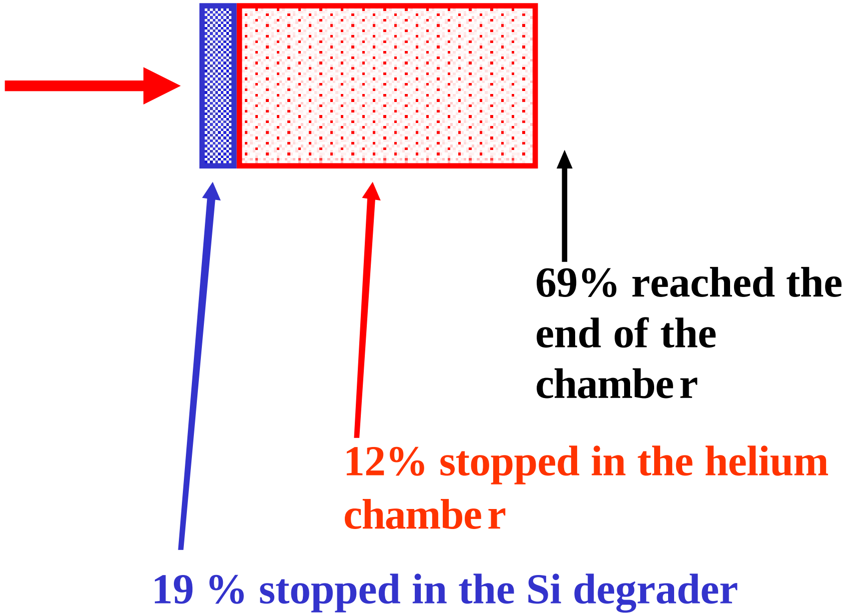
Ligth ions have a long range





20000 ions ^{14}O slowed down in Si before entering a 1 m long helium linear cell at 200 mbar.

- Light beams important for re-accelerated beam program (astrophysics)
- Large range straggling



Why use Helium as the stopping medium?

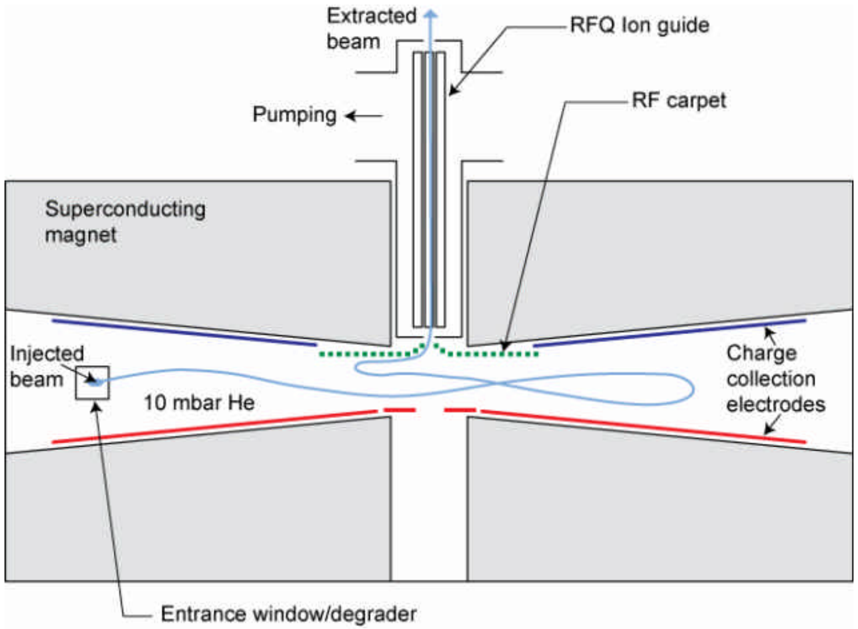
- Helium has a high ionization potential and helps to keep the ions singly charged.
- The purity of the helium is crucial to avoid the formation of heavy molecules that would be extracted with the ions of interest but in much larger numbers.

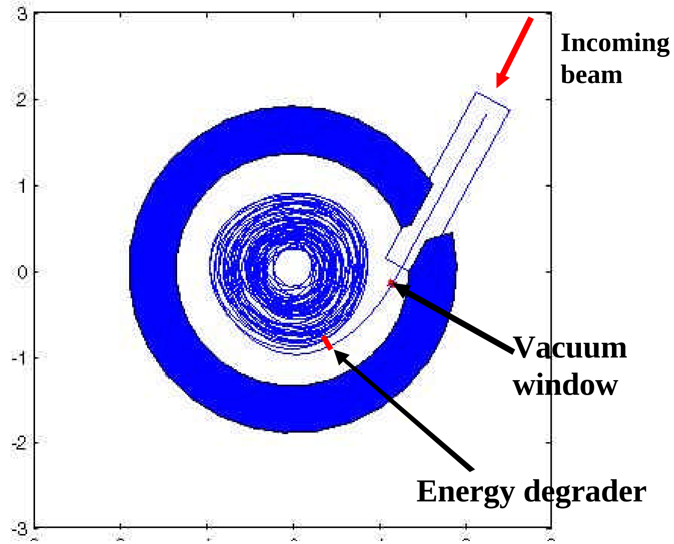
Origins of the cycstopper

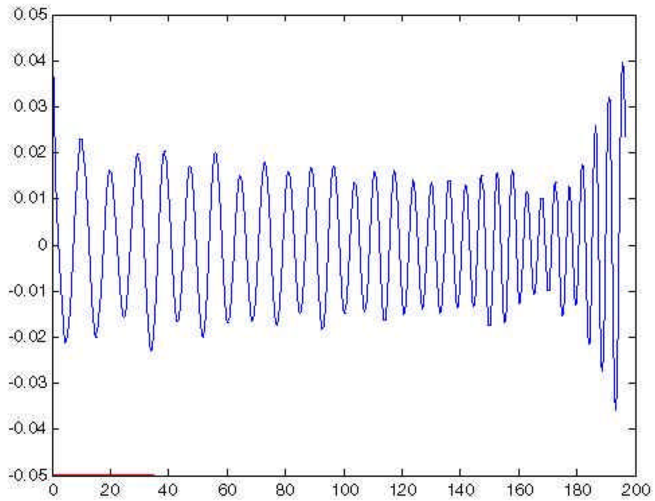
- Originally proposed to decelerate antiprotons available from the LEAR ring at CERN [1]
- Similar concept proposed to slow down radioactive ion beams introducing an "RF carpet" to transport the ions and extract them[2]
- Concept extended to mitigate the space charge degradation of the extraction efficiency for intense heavy ion beams in linear gas cells[3]

- (1) J. Eades and L. M. Simons, NIM A 278 (1989) 368.
- (2) I. Katayama et al., Hyperfine Interactions 115 (1998) 165.
- (3) G. Bollen et al., NIM A 550 (2005) 27.

Basic concepts of the cycstopper

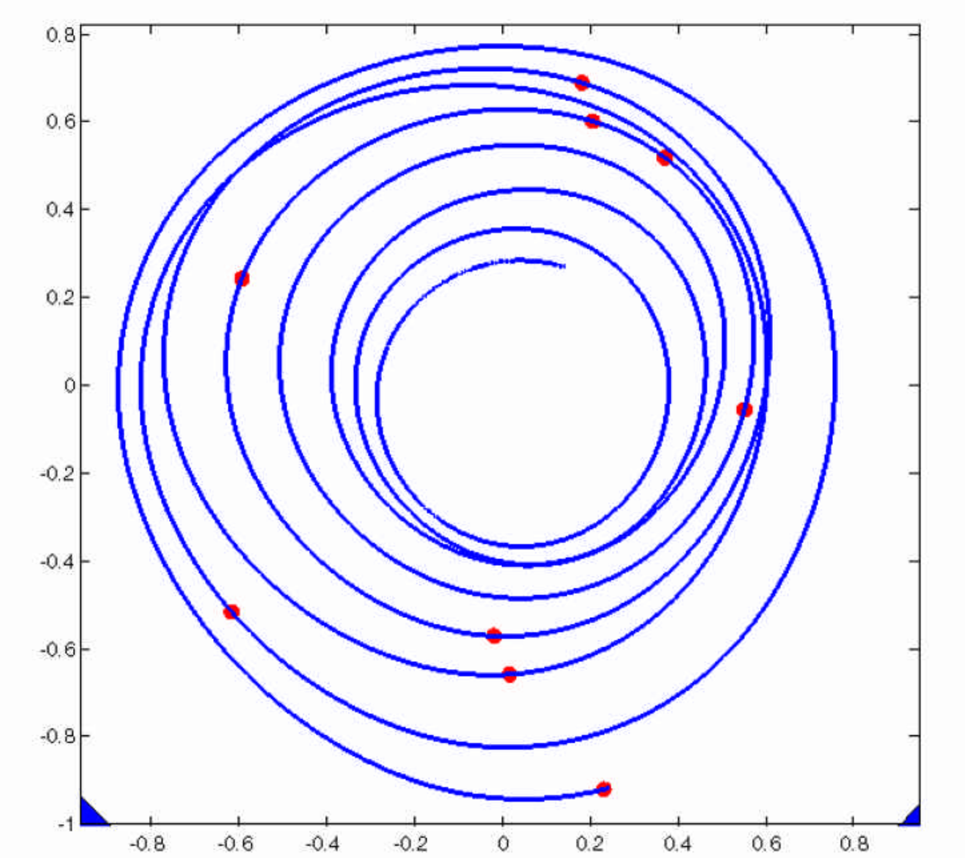


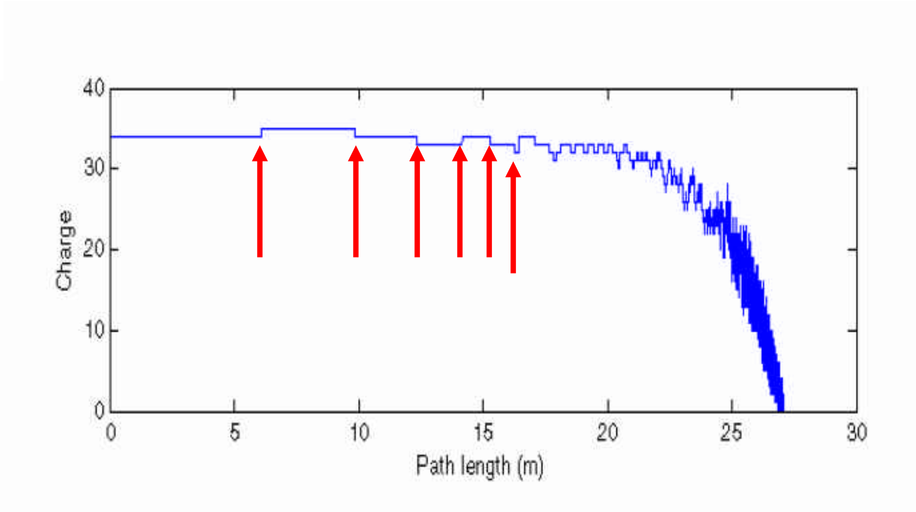




The helium interacts with the incoming ion, slowing it down. The energy is transferred to the helium ions, ionizing them. The axial electric field moves the ions toward the upper collecting plates, and the electrons toward the lower plates. The radioactive ions stop near the center where the RF carpet prevents them from striking the surface and guides them toward the axial hole.

Off-center orbits



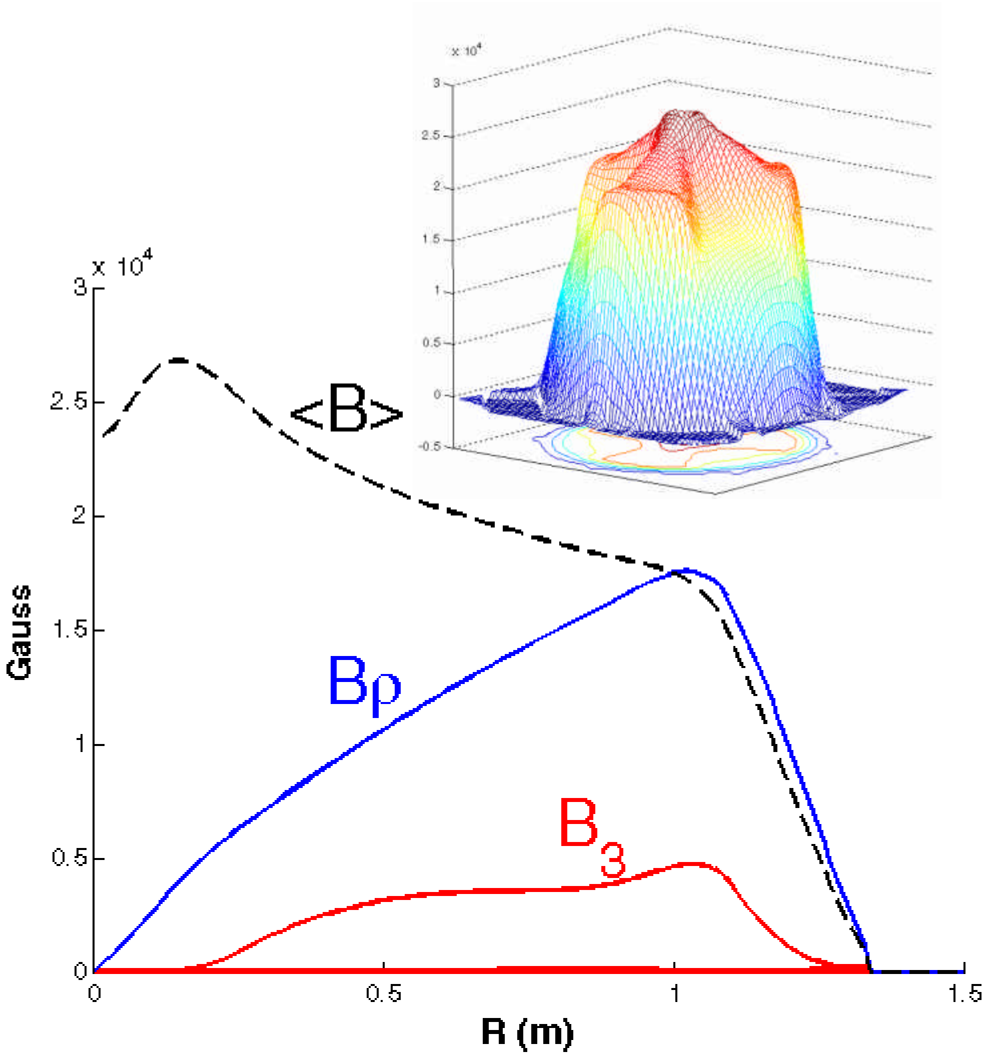


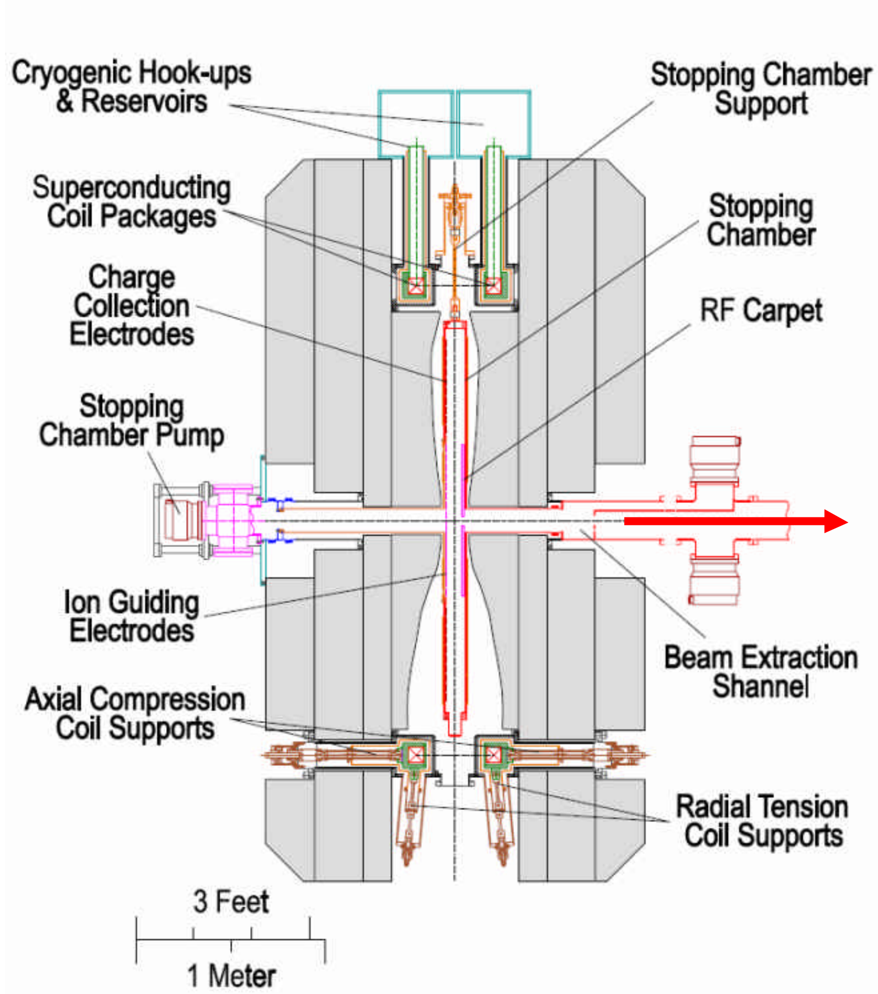
The sudden changes in charge state force the orbit to change centers of curvature suddenly, becoming off-centered.

Special care should be taken to avoid the $n_r=2n_z$ resonance given the large centering errors.

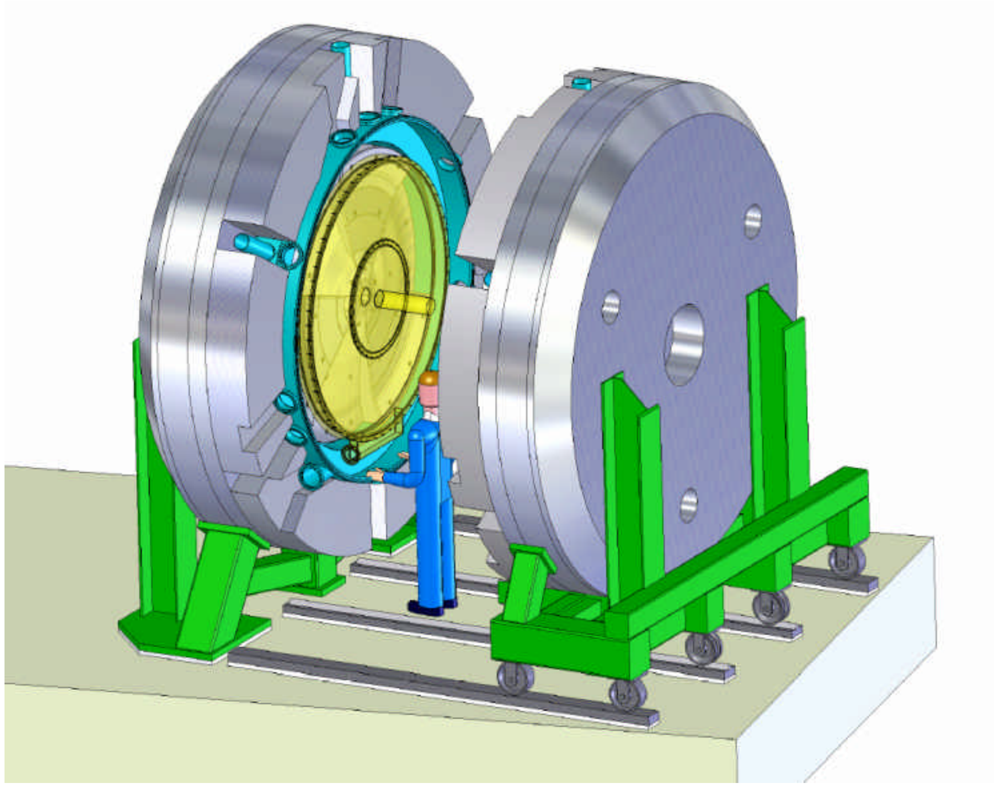
^{79}Br at 100 mbar

Magnetic field

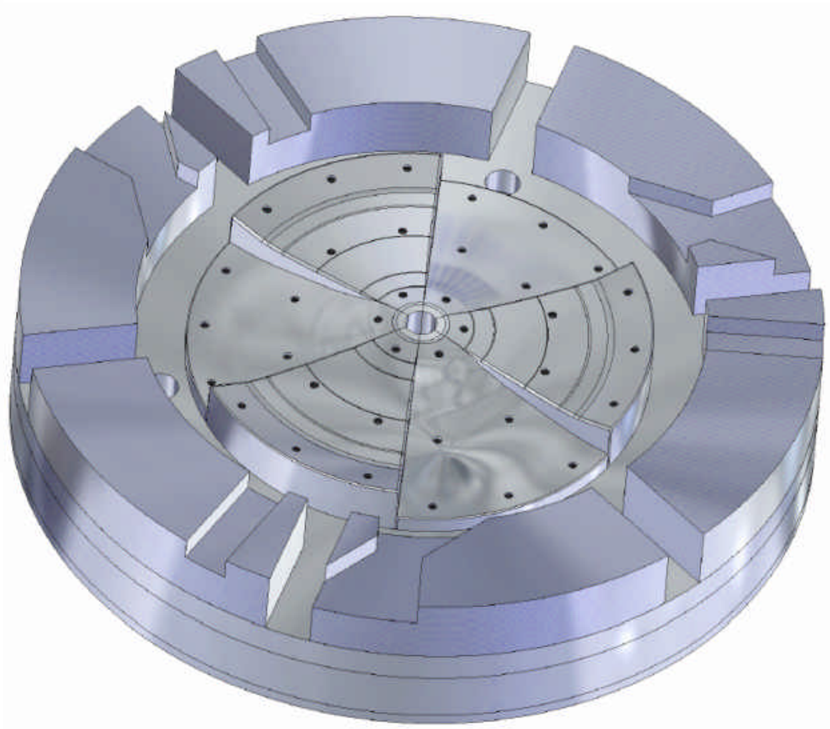




Conceptual design

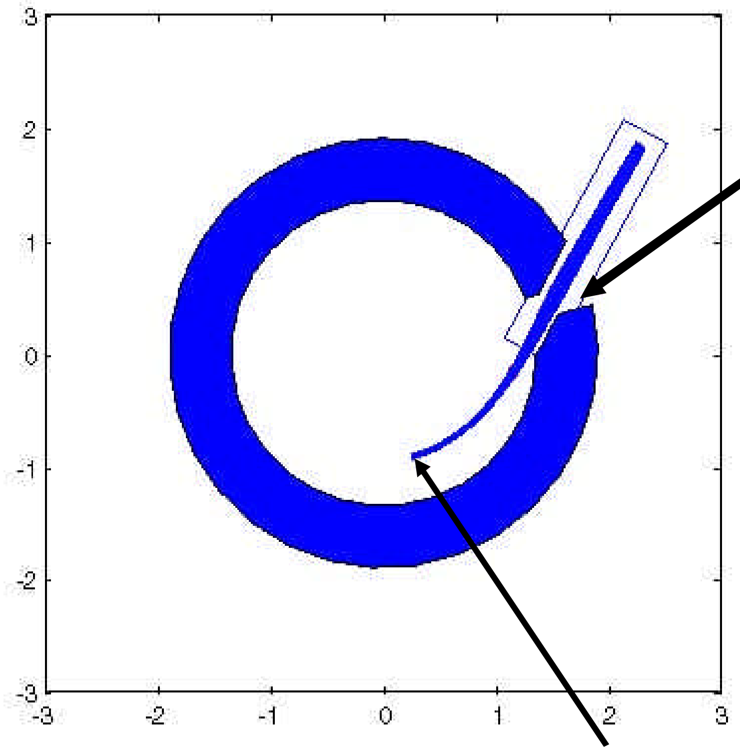


The median plane is vertical. The half of the magnet with the injection and extraction systems remains stationary. The other half moves away to have access to the vacuum chamber.



NSCL

Focusing in the return yoke

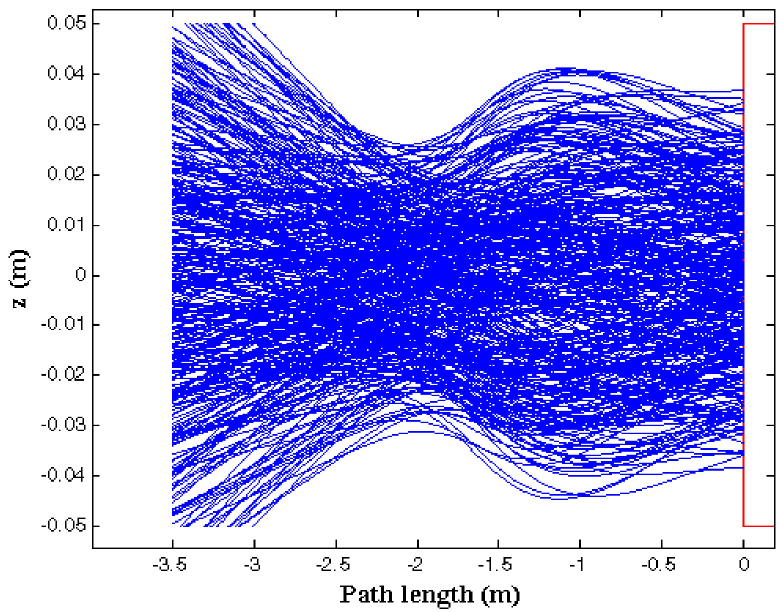


Degrader

A 5 T/m gradient magnet is placed in the return yoke to compensate the defocusing in the fringe field.

e_x = **565** p **mm mrad**

e_z = **1131** p **mm mrad**



Simulations

- **Two codes have been developed in parallel with the possibility of using different formulations for the various effects.**
- **We include**
  - **Magnetic and electric fields**
    - Obtained from 3D TOSCA models
  - **Energy loss in the vacuum window and internal degrader**
    - Calculated using ATIMA [(1)]
  - **Energy loss in helium**
    - Interpolated in tables from SRT (SRIM , Ziegler and Biersack) [(2)]
  - **Energy loss straggling**
    - Empirical formulas [(3)]
  - **Charge exchange**
    - Cross sections generated from several sources
  - **Small angle scattering**
    - Using either Sigmund small angle multiple scattering distributions [(4)] or single scattering after Amsel [(5)]

(1) Rozet NIMB 107 (1996) 67. (2) www.srim.org. (3) Chu Phys.Rev. A 13(1976)2057 and Yang NIM B61 (1991) 149. (4) Sigmund NIM 119 (1974) 541. (5) Amsel NIMB 201 (2003) 325

Range of Br in Helium at 100 mbar

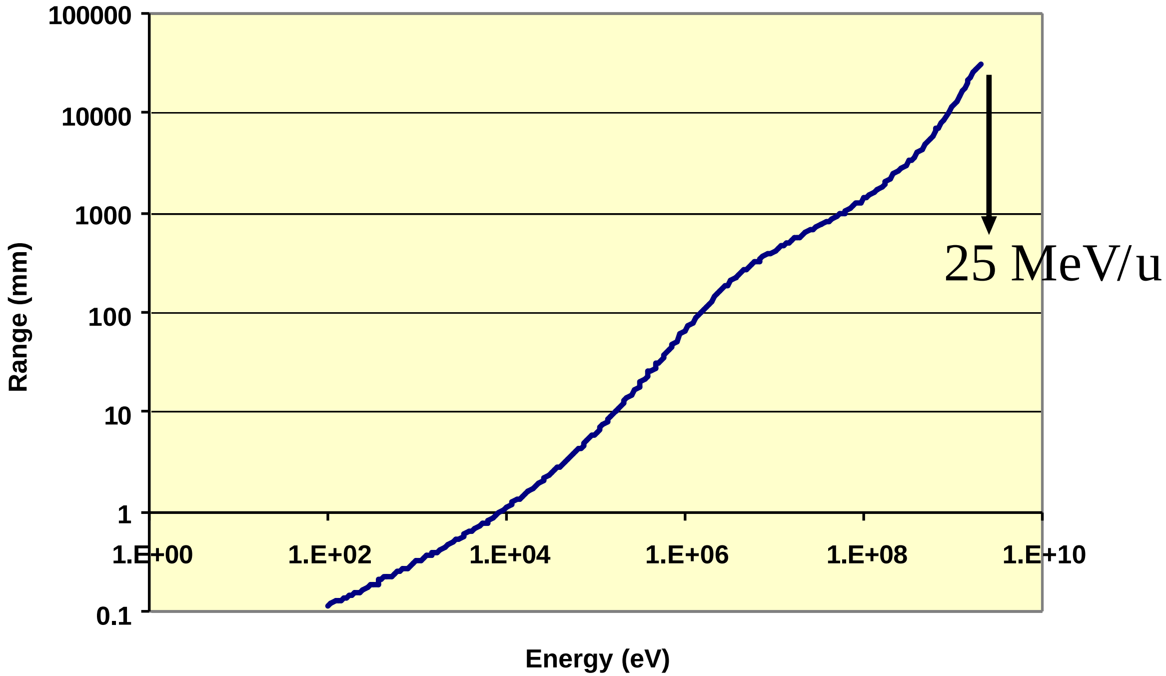
^{79}Br in 100 mbar He

The motion of the ions is followed until the energy is ~ 100 eV. The range at this energy is about 0.1 mm.

At this point we switch the calculation to include the space charge effects and assume “terminal velocity “ for the ions, based on the ion mobility:

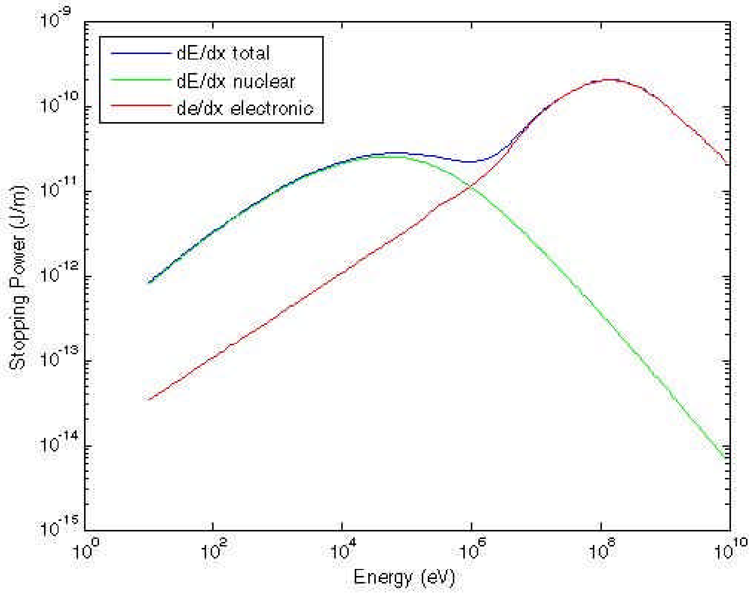
$$v_d = KE$$

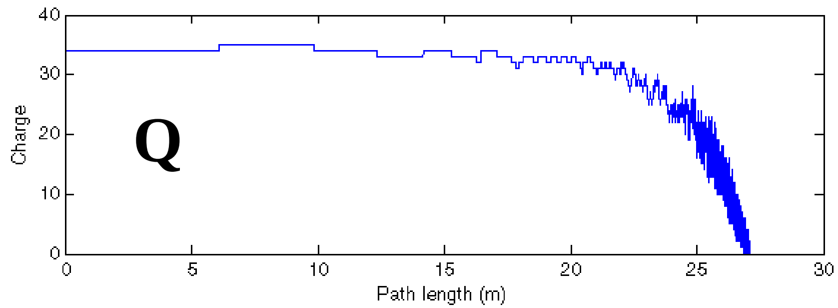
SRIM calculation

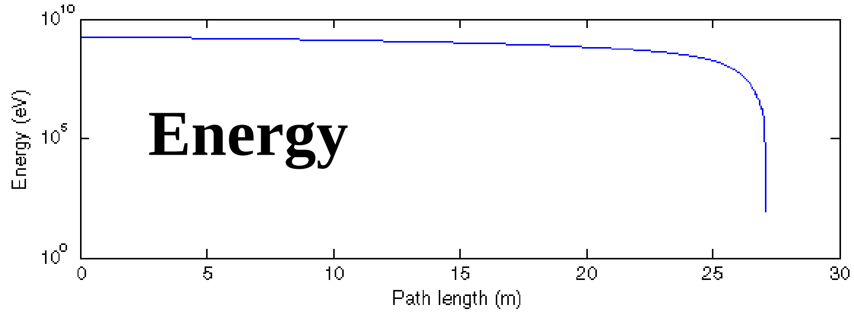


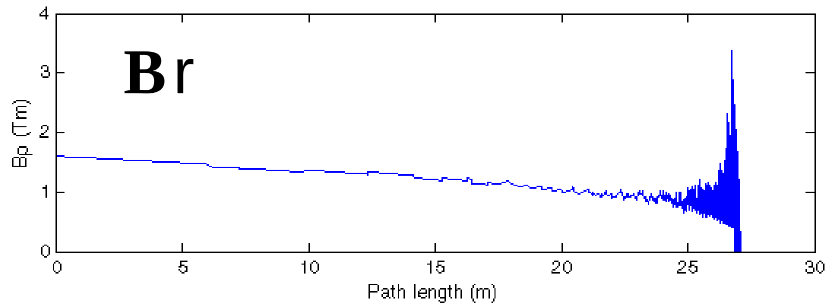
For energies below 1 MeV the range is just a few centimeters.

79Br in 100 mbar Helium









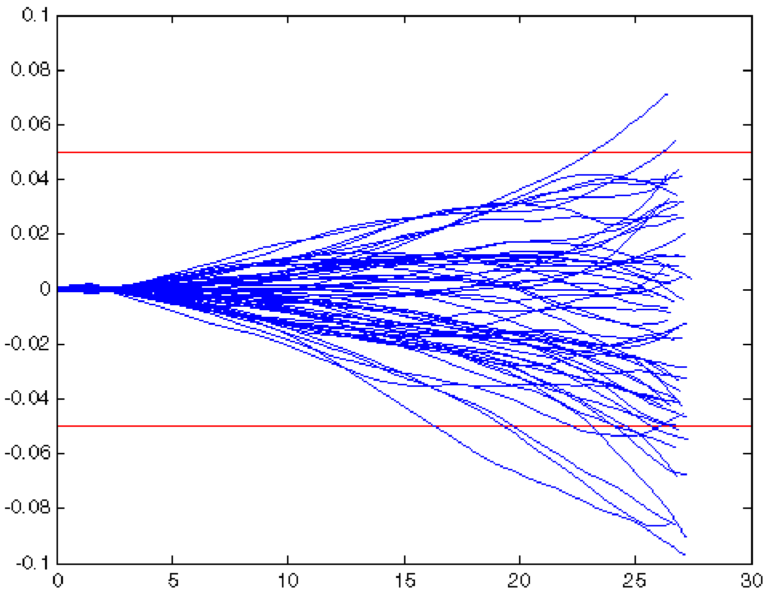
Energy loss is treated as a continuous effect. Calculated with SRT (SRIM).

The integration step is smaller than the mfp for charge exchange. The ion charge keeps decreasing while slowing down.

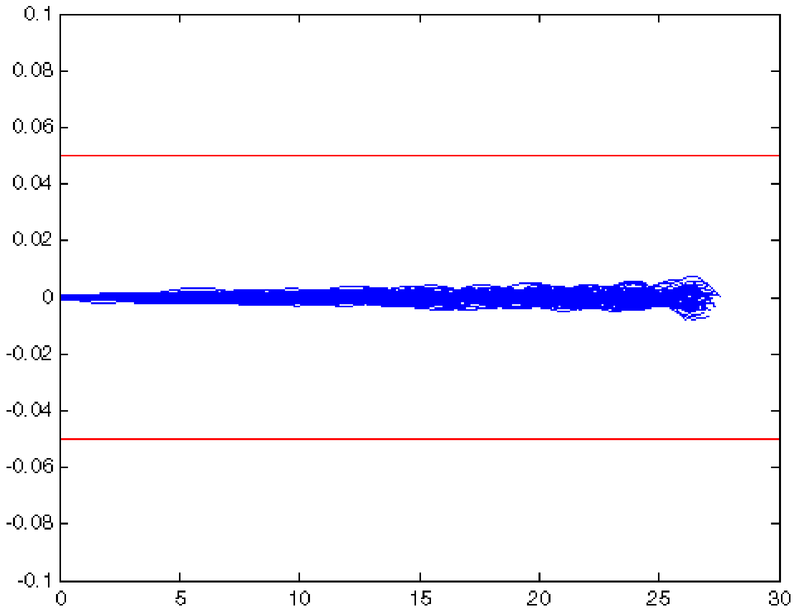
Magnetic focusing in the cycstopper

The magnetic field gradient helps to keep the beam focused in the axial direction. Z vs. path length (m)

^{79}Br in 100 mbar Helium (1π mm mrad in both directions)

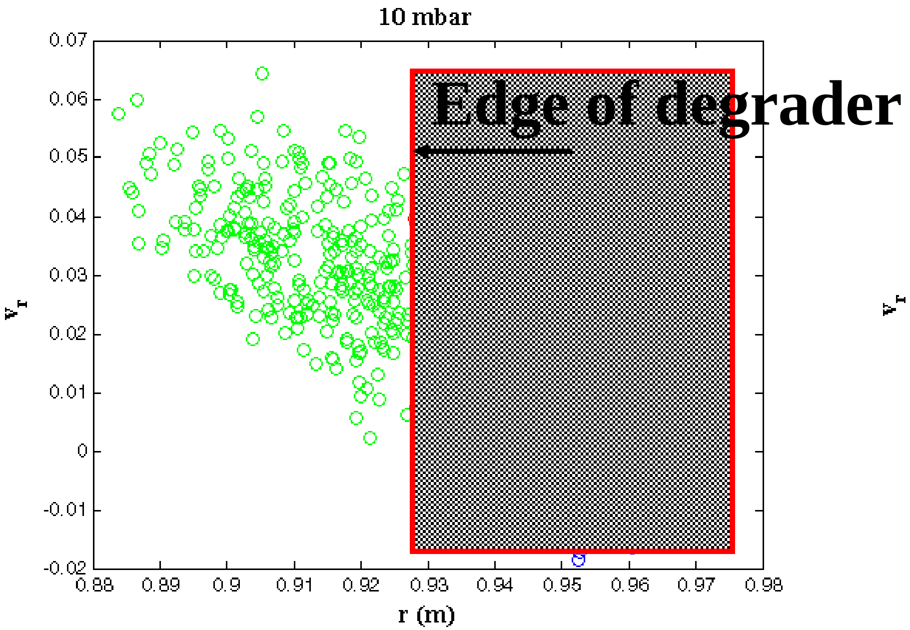


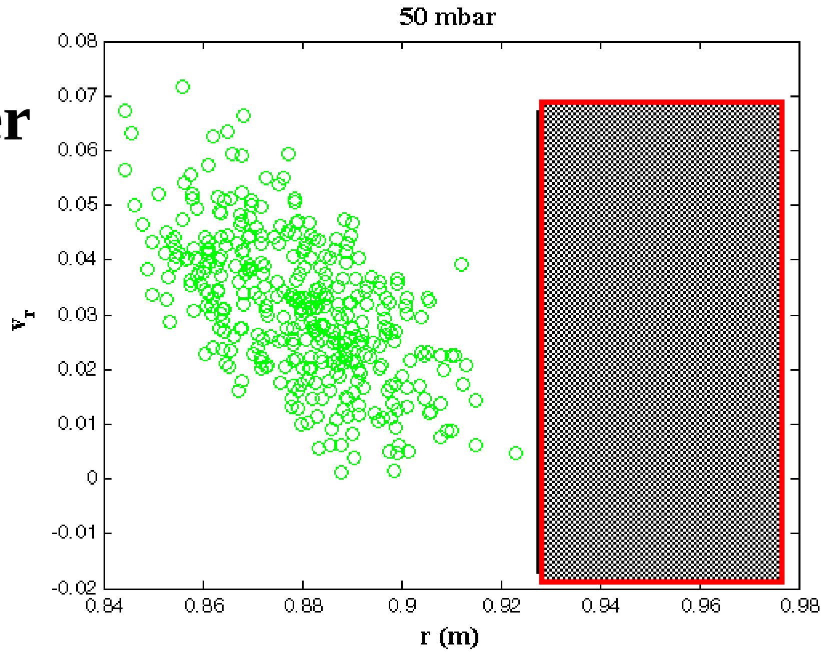
linear gas cell



cycstopper

Higher pressures help to clear the degrader

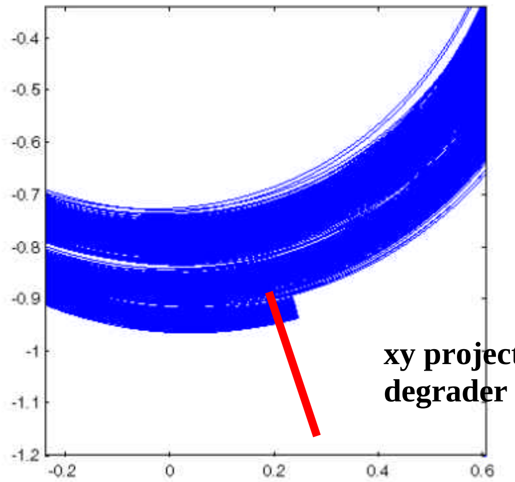




The degrader thickness is determined to change the beam $B\rho$ from 2.6 to 1.6 Tm for all beams.

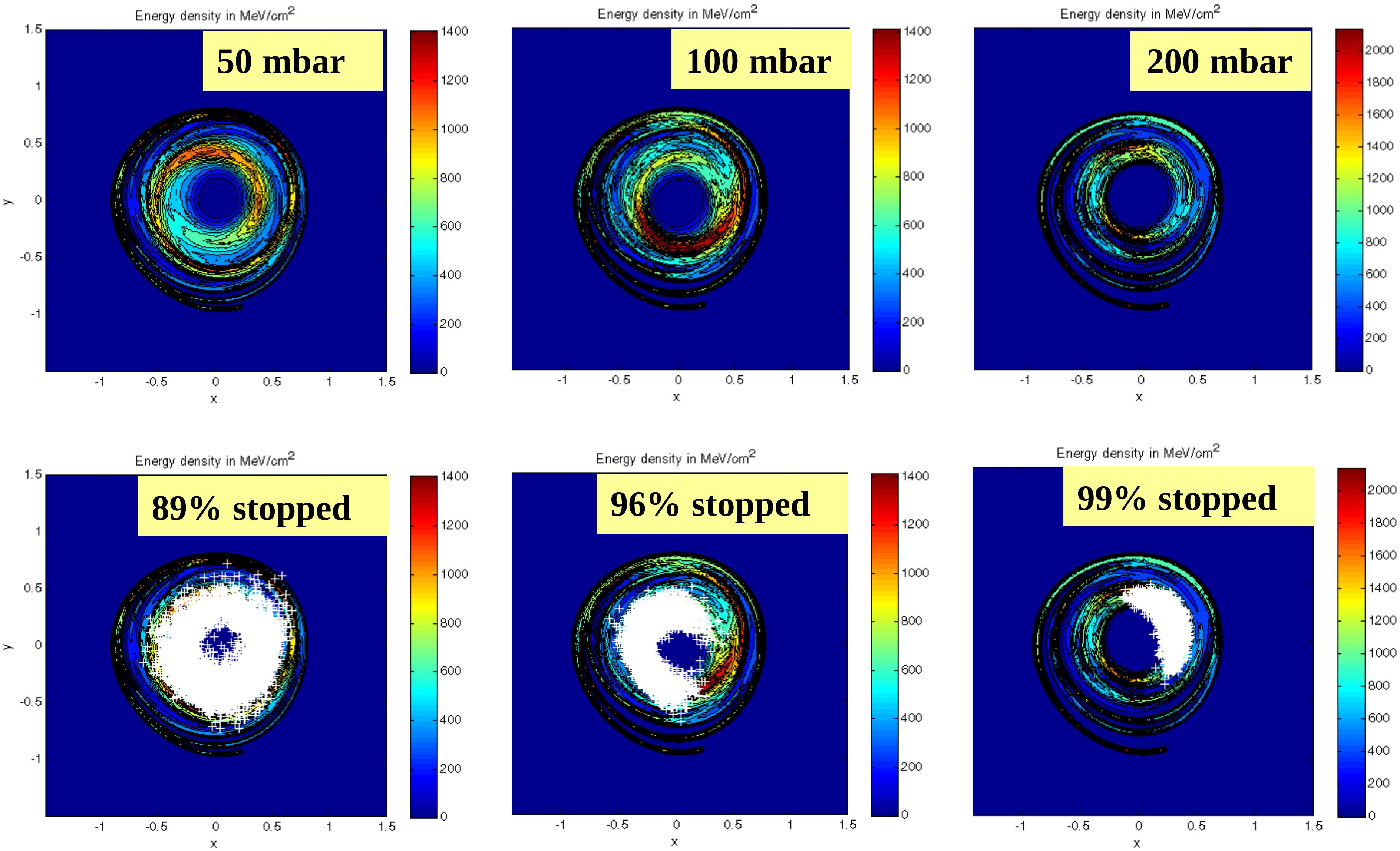
For lower pressures the slowed down beam partially hits the degrader a second time and is lost (red points). Higher pressures induce higher energy loss.

^{79}Br $\epsilon_x = 565\pi$ and $\epsilon_z = 1131\pi$ mm mrad

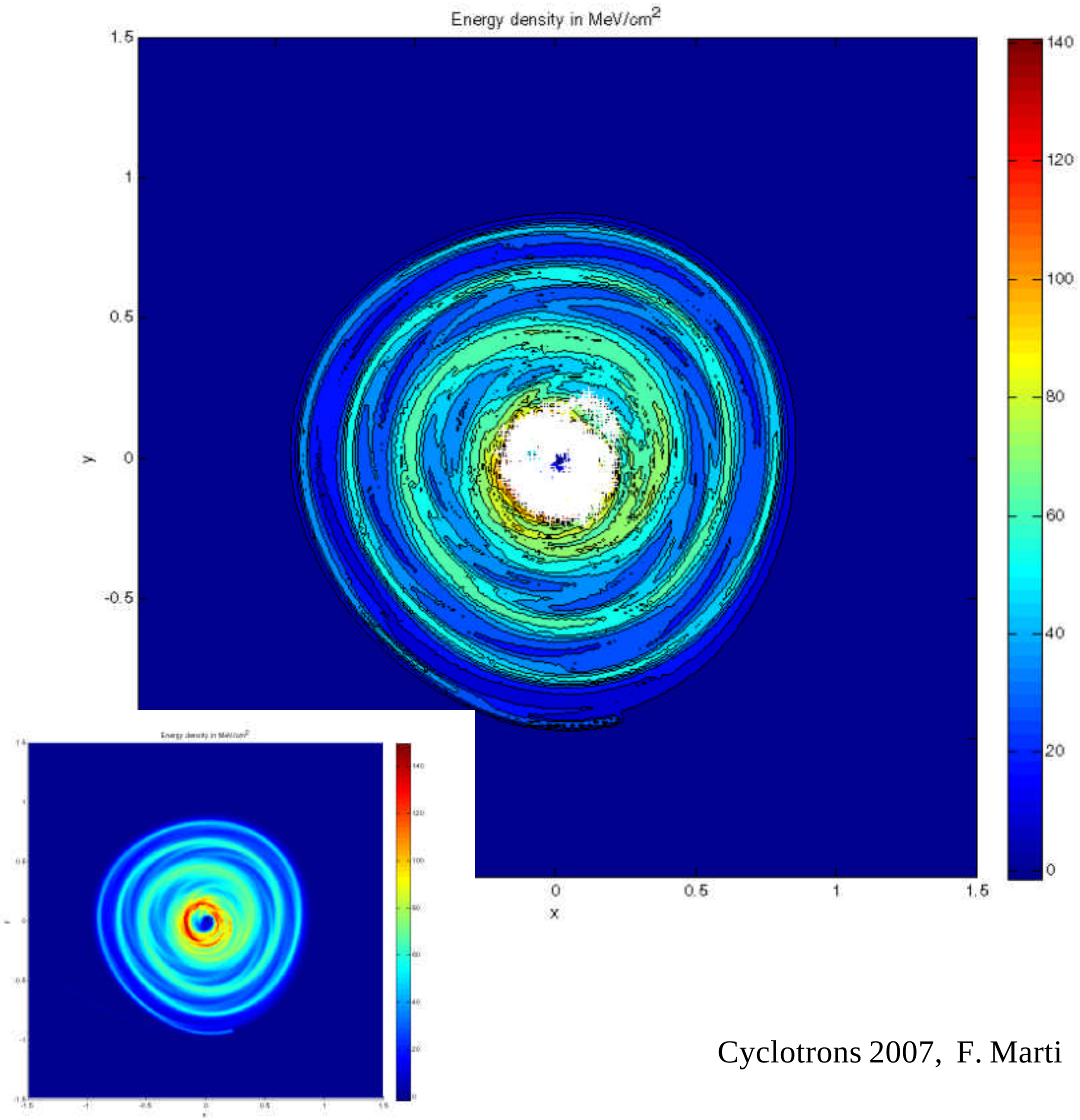


xy projection of degrader area.

Stopping as a function of pressure (^{79}Br 6656 ions)



^{14}O in the cycstopper (200 mbar)



e_x=570 p mm mrad

e_z=1700 p mm mrad

60% stopped in chamber

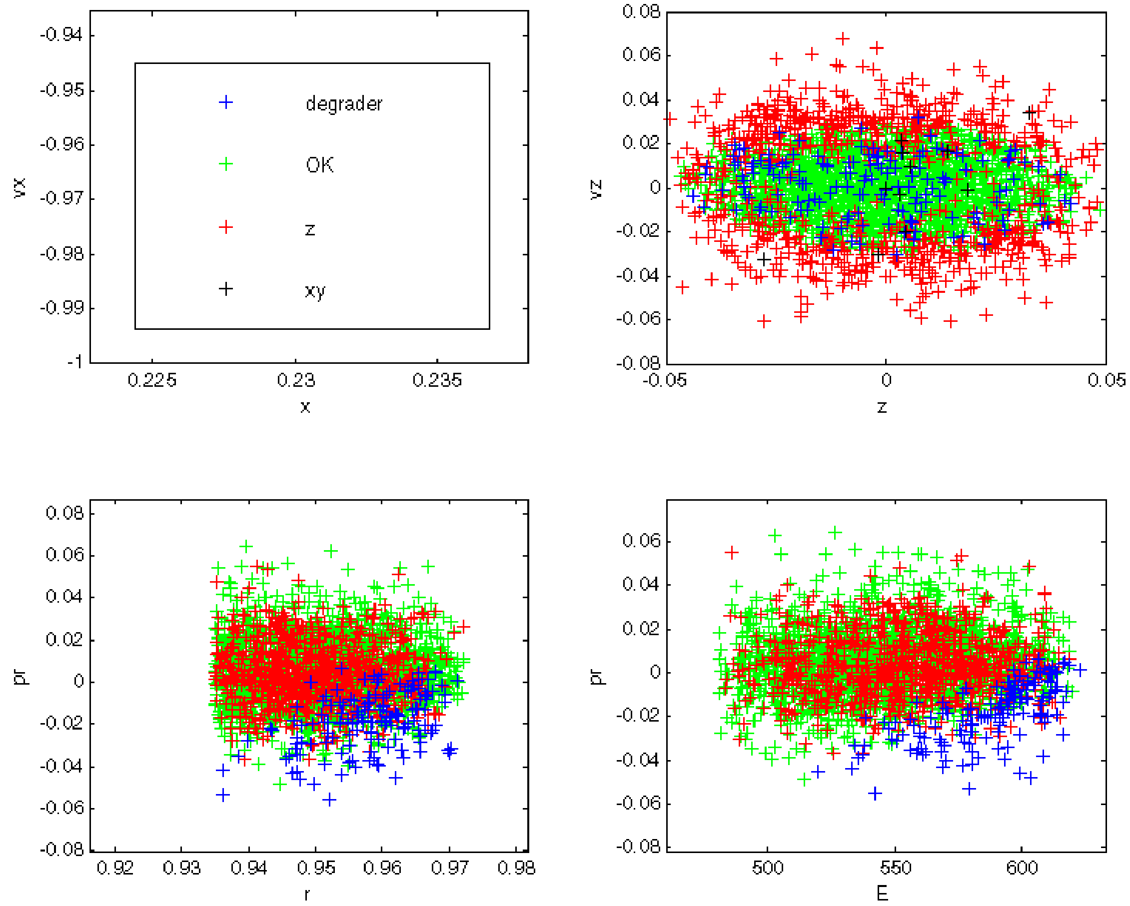
30% lost due to emittance and small angle scattering

5% hit degrader a second time

5% miss degrader

The distance from the stopped ions to the axial exit channel is small, decreasing the delay in extracting the short lived ions.

^{14}O in the cycstopper, lost ions position at degrader



p_z vs. z

p_r vs. r

p_r vs. E

RF carpet

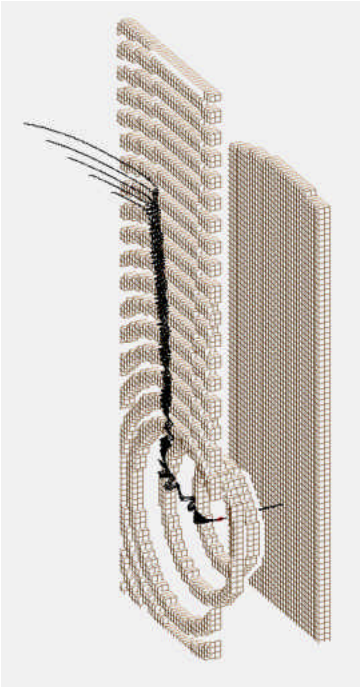


Fig. 12. Typical ion trajectories in the two layer rf-carpet as determined by microscopic particle simulation for ^{8}Li ions in 90 Torr He gas. The rf voltage between neighboring electrode rings is 190 V at 26 MHz. The superimposed dc field at the surface of the nozzle carpet and the upper carpet are 8 and 10 V/cm, respectively.

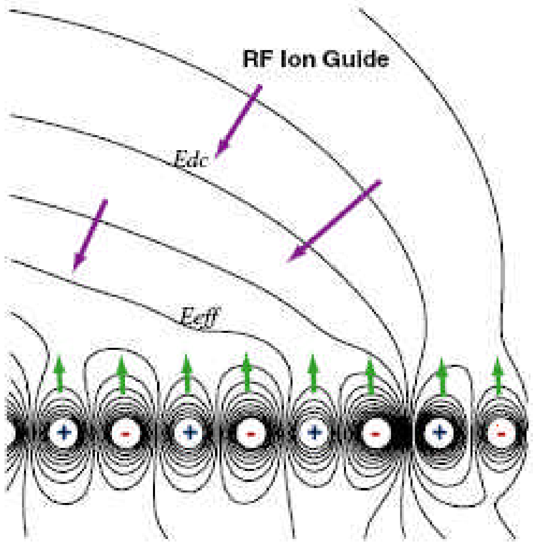
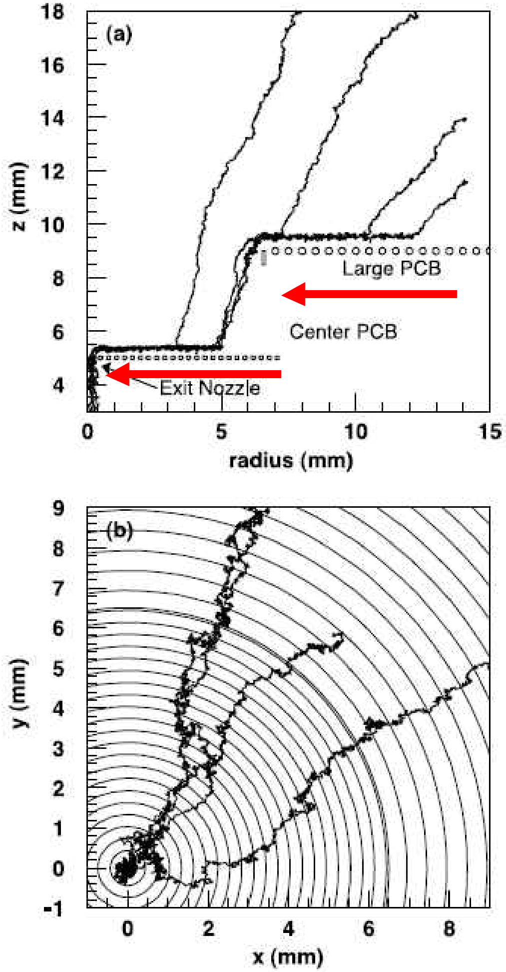


Fig. 3. Superposition of RF-barrier field (E_{eff}) and DC field (E_{DC}) to form RF-carpet. Ions in high-pressure gas are pulled by E_{DC} while E_{eff} keeps ions away from the electrodes.

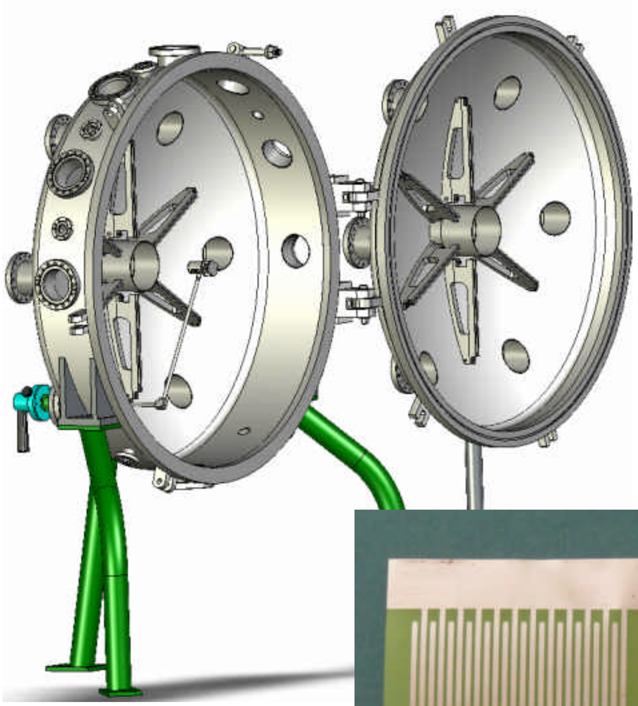


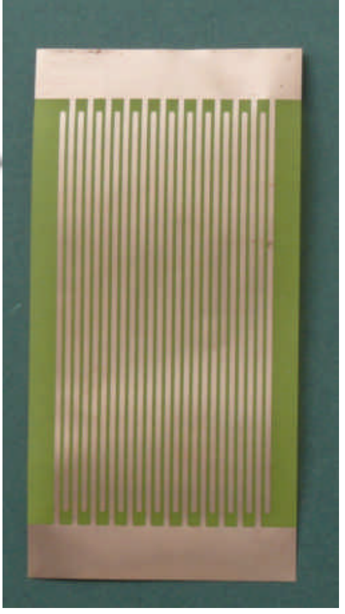
Cyclotrons 2007, F. Marti

Wada et al., NIMB 204 (2003) 570

Wada et al., NIMA 532 (2004) 40

RF carpet test stand and space charge

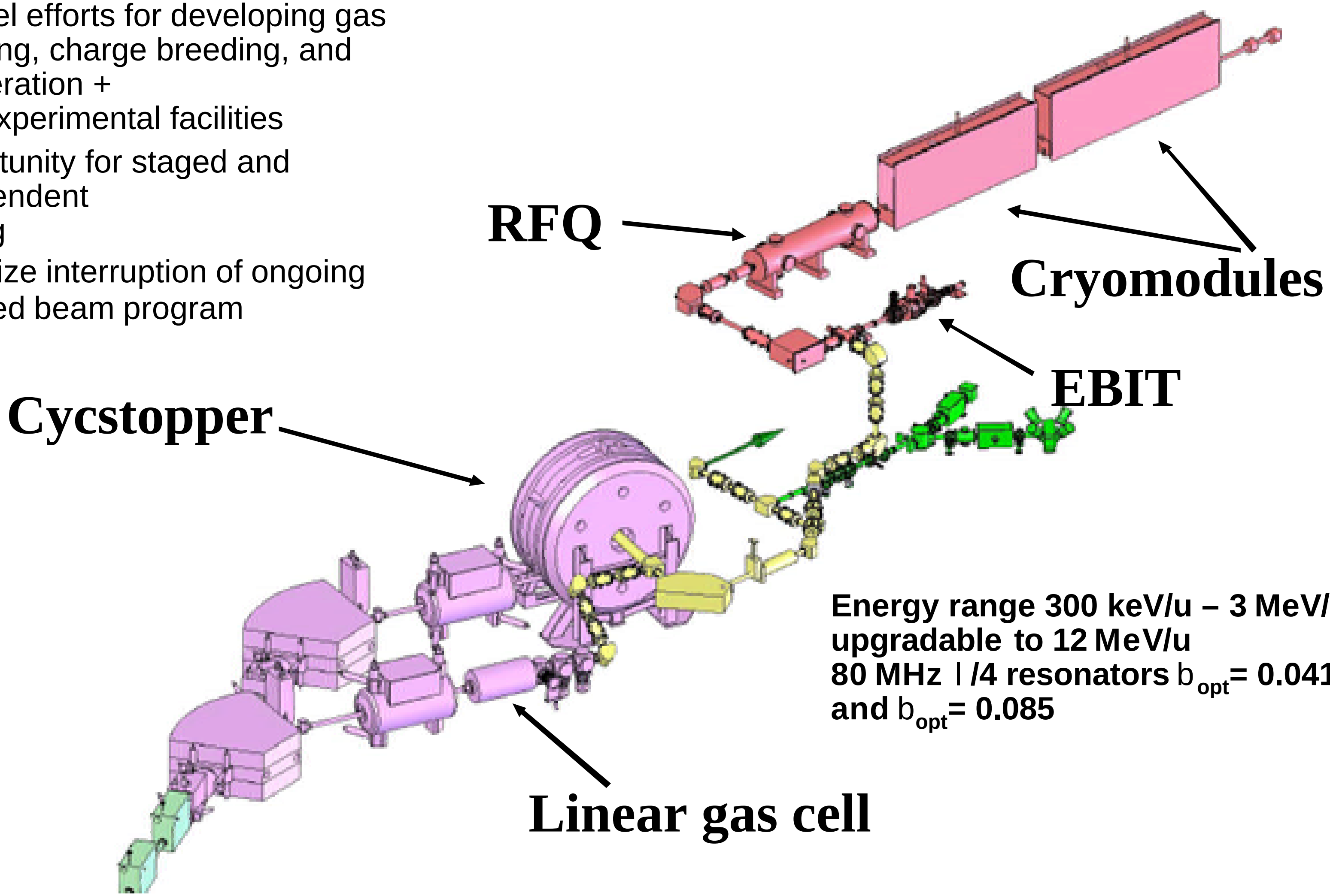




- Study of ion extraction with RF carpet systems
  - Simulations including space charge. Determine the limits on charge collection.
  - Dedicated test stand (funded by DOE)

Low energy beams at the NSCL

- Parallel efforts for developing gas stopping, charge breeding, and acceleration +
  new experimental facilities
- Opportunity for staged and independent
  testing
- Minimize interruption of ongoing stopped beam program



Energy range 300 keV/u – 3 MeV/u, upgradable to 12 MeV/u
80 MHz l /4 resonators b_{opt}= 0.041 and b_{opt}= 0.085

Post-accelerator status

The EBIT is being designed

RFQ is being designed. The contract has been awarded to A. Schempp (Frankfurt). Delivery expected in 18 months.

We are testing the prototype of the low b srf quarter wave cavity. The high b cavity has been prototyped as well as the cryomodule design. Will begin soon the production of the two types of cavities.

Ion mobility in helium

The motion of the ions in the helium bath is characterized by the drift velocity equation:

$$v_d = KE$$

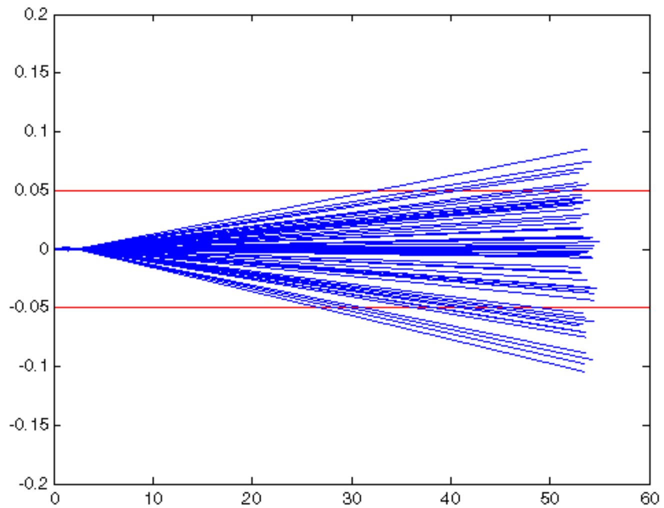
where v_d is the drift velocity, K the ion mobility and E the applied electric field. The mobility is related to the reduced mobility K_o (at standard pressure and temperature) by:

$$K = K_o \frac{T(^oK)}{273.16} \frac{1000}{p(mbar)}$$

In helium $K_o \sim 20$ cm^2/(Vs), and typical $E = 10$ V/cm

McDaniel and Mason, "The mobility and diffusion of ions in gases", Wiley, (1973).

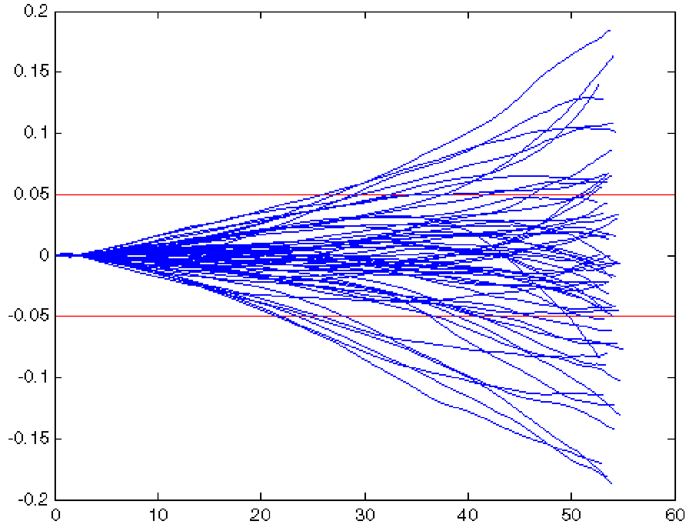
Effect of multiple scattering in a small emittance beam



Z vs. path length

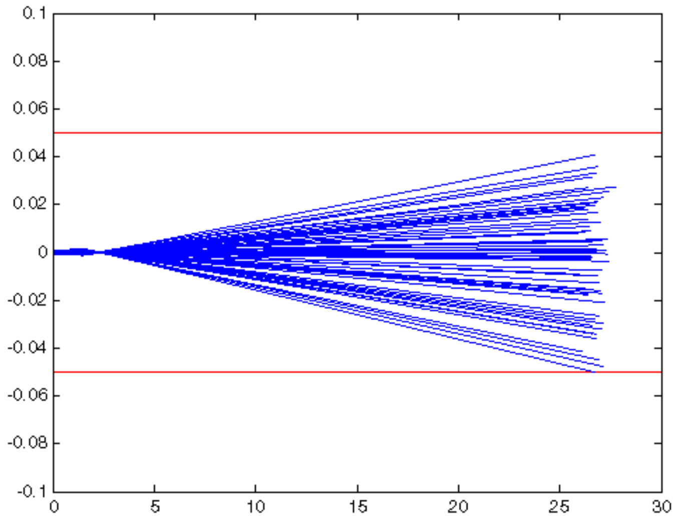
Linear gas cell, 1p mm mrad in both directions

50 mbar



No multiple scattering

With multiple scattering



100 mbar