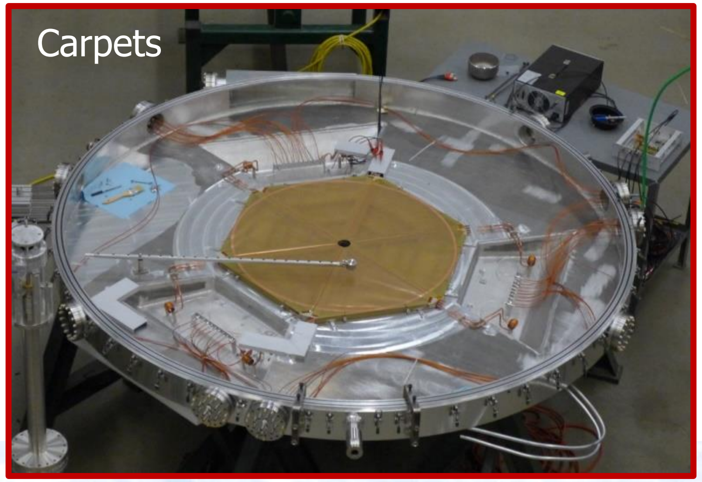
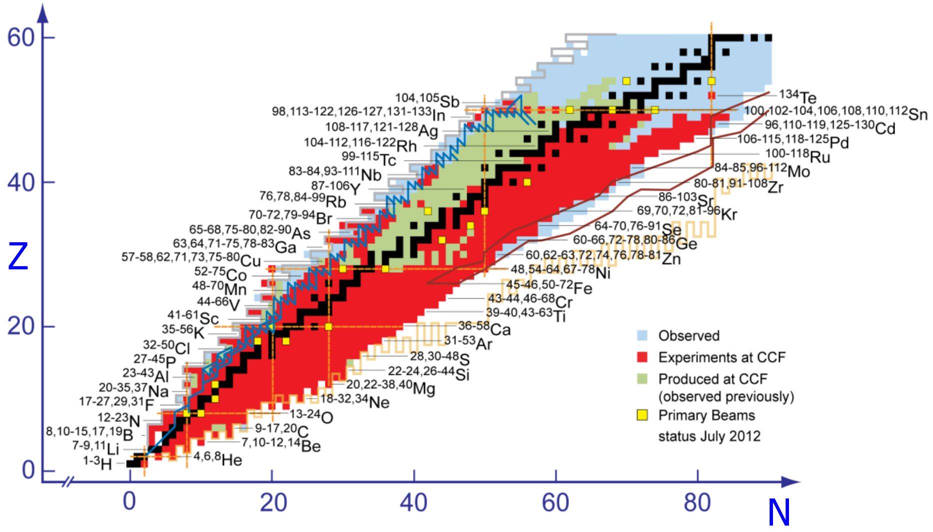
Offline tests with the NSCL Cyclotron Gas Stopper

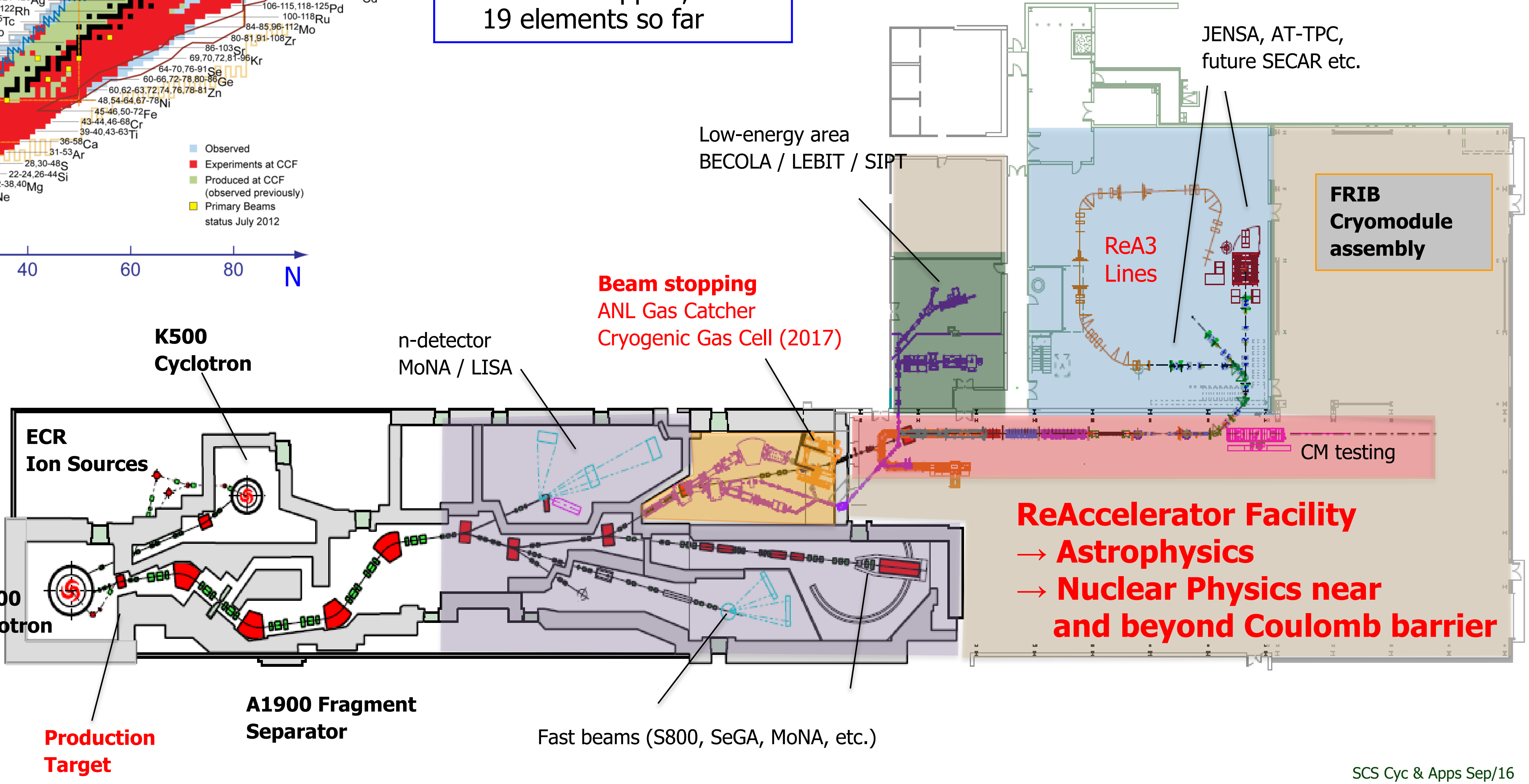
- *Why we want it*
- *What it is*
- *Status: Offline tests, Low-energy transport*
- *Outlook*



NSCL: User facility, RIB production by projectile fragmentation and fission



> 1000 RIBs made
> 900 RIBs to experiments
> 25 RIBs 'stopped',
19 elements so far

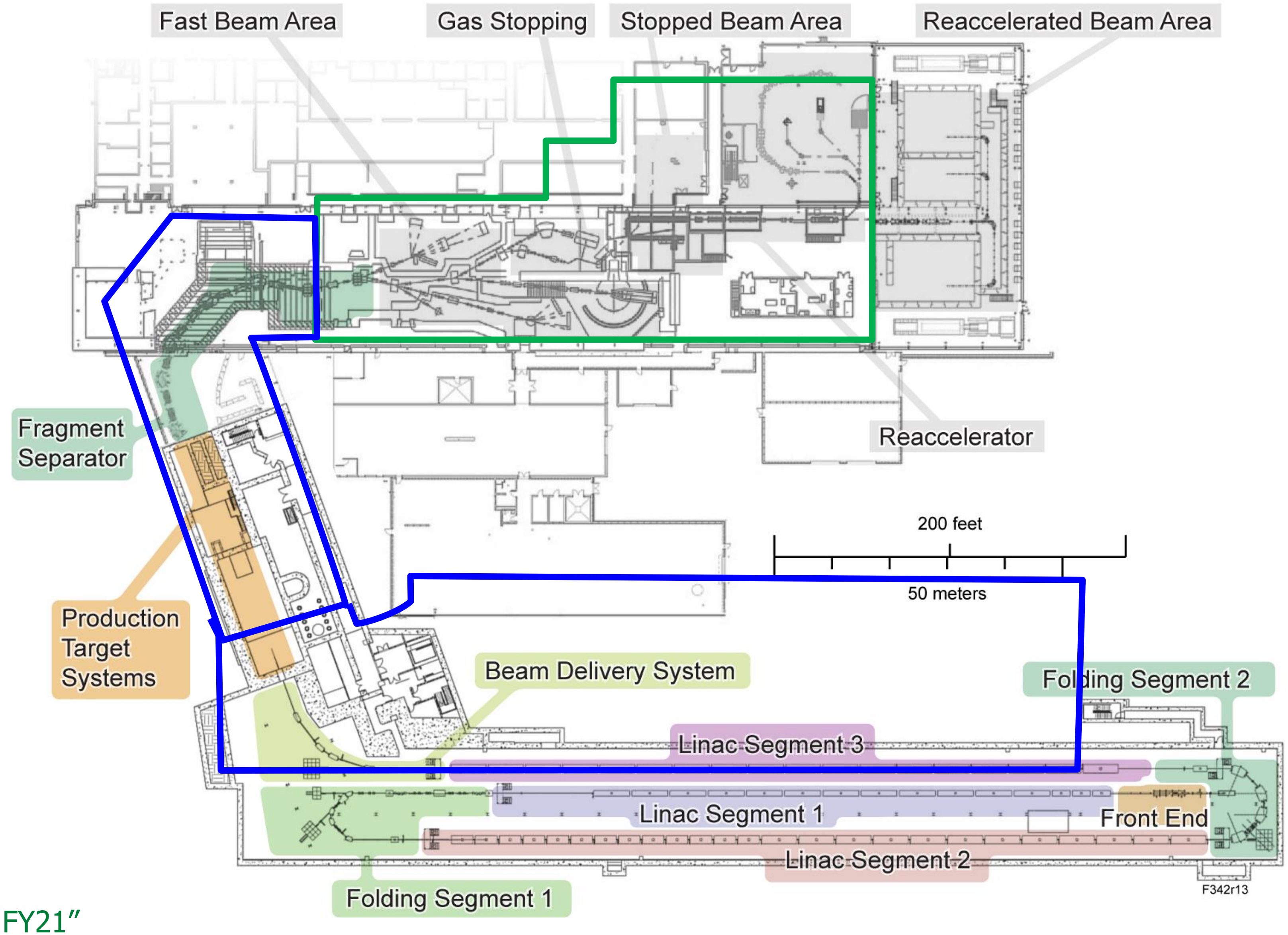


NSCL integrated into FRIB - Facility for Rare Isotope Beams

- NSCL cyclotrons → FRIB LINAC
  In-flight RIB production,
  primary beams:
  up to 400 kW, 200 MeV/u U

  → More than 1000 new isotopes at useful rates
  → High fraction of reaccelerated beams projected at 1e6 to 1e8/s

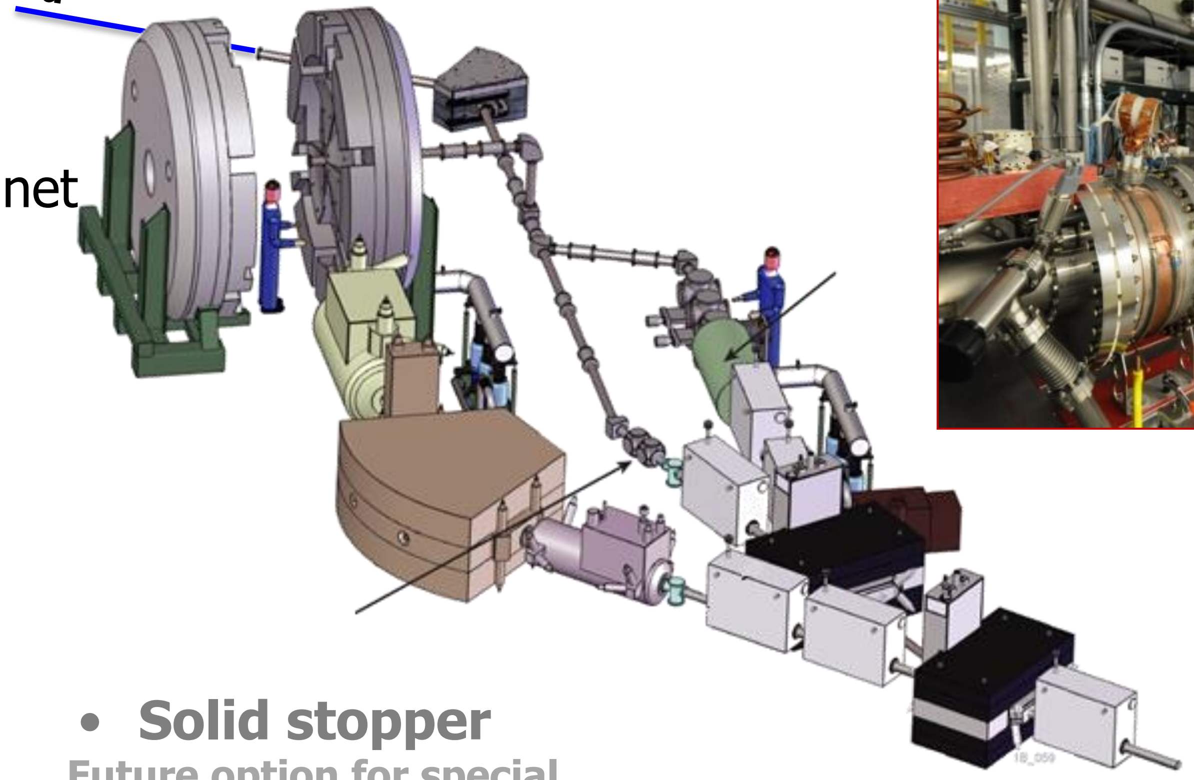
- Large demand for light reaccelerated beams
- But … need to stop them first!



Project on track,
"Managed for early completion in FY21"

NSCL beam stopping options

Complementary stopper options:



Cyclotron stopper
- Cyclotron-type magnet
- Low-pressure + RF ion guiding

→ ***Light ions***

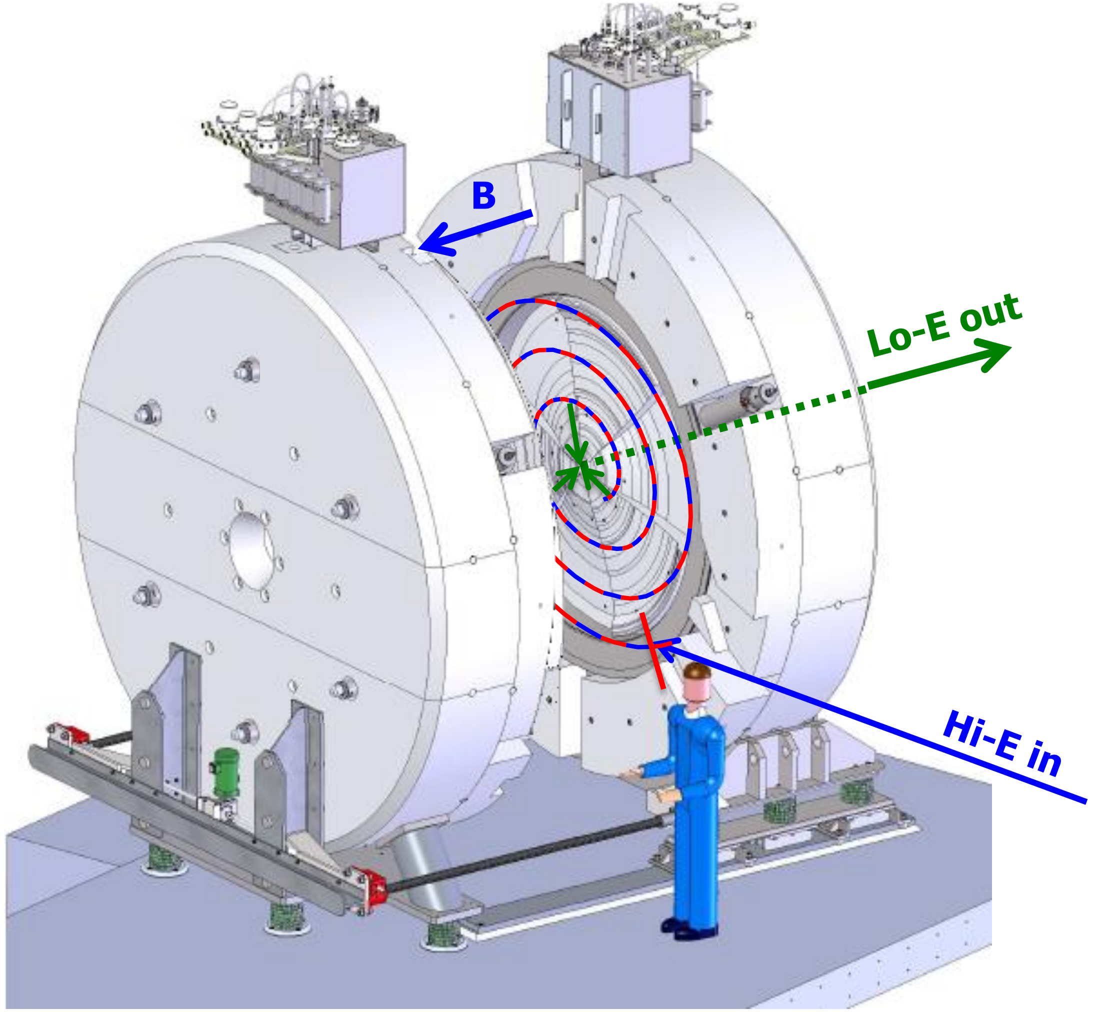
Linear gas stopper (v2/v3)
- Low-pressure with RF carpets / wires
- ANL gas cell (>2009) / Cryogenic gas cell: ACGS

Elements stopped so far:
C, O, Na, Cl, Ca, Si, P, S, Fe, Co, Ga, Ge, As, Se, Br

- **Solid stopper**

Future option for special elements and very high beam rates
Example: ^{15}O, I >10^{10}/s

Cyclotron stopper – the idea



1 Confine:

- **Magnetic field, <2.6 T**
  - 'wind up' trajectory in central chamber
    → confinement in radial direction
  - Cyclotron-type **sector field**:
    → axial focusing

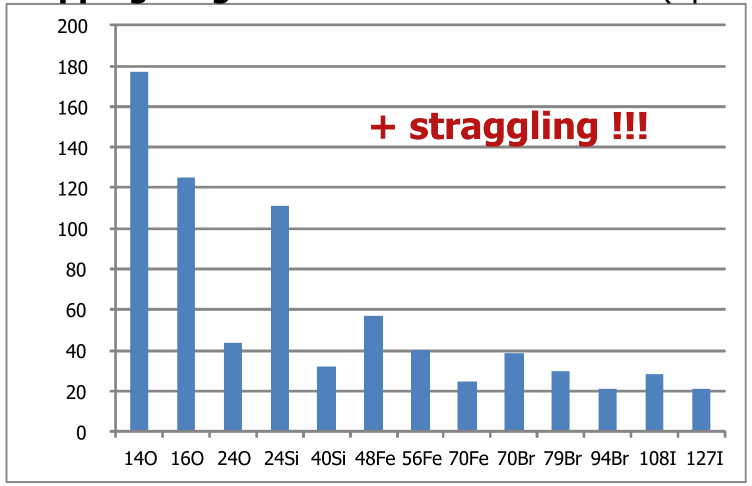
2 Thermalize:

- **Low-pressure gas in cryogenic chamber**
  ions lose energy, spiral towards center

3 Extract:

- Use **HF/RF ion guiding techniques**
  to move thermalized ions to center and out within a few 10 ms

Stopping range for ions into 100mbar of He (Bρ =1.6 Tm)



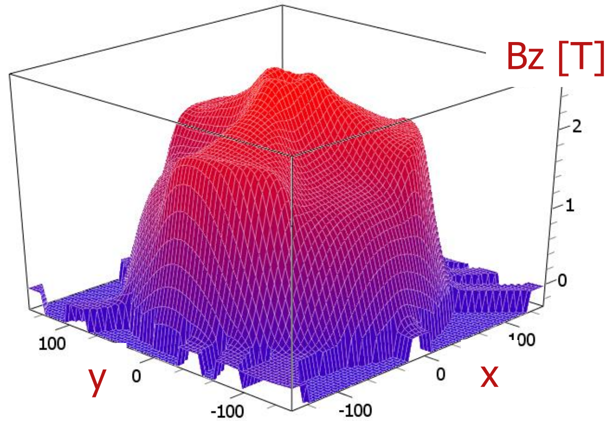
Origins:

- Decelerate antiprotons: J. Eades and L. M. Simons, NIM A 278 (1989) 368
- Proposal to stop lighter ions: I. Katayama et al., HI 115 (1998) 165
- Also: Inverse c. for μ cooling: T. Hart, Proc Cyc'13, MO3PB01

NSCL-Cyc-stopper:

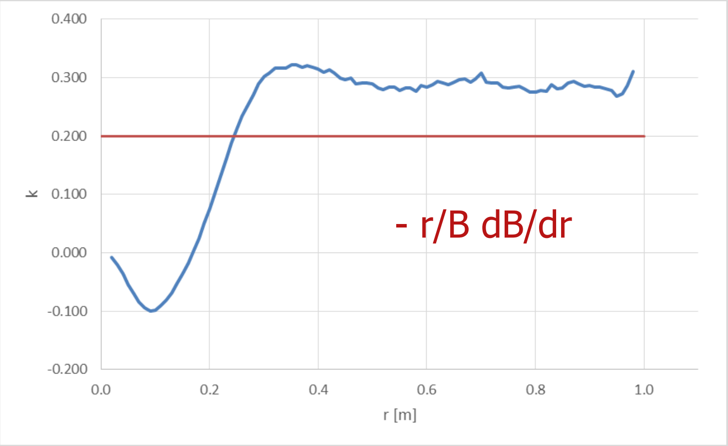
- Bollen et al. NIM A550 (2005) 27, NIM B266 (2008) 4442,
- Guenaut et al HI 173(2006)35 … SCS et al NIM B376(2016)256

MC-type stopping calculations



(S. Chouhan, v20)

Field index



Code includes:

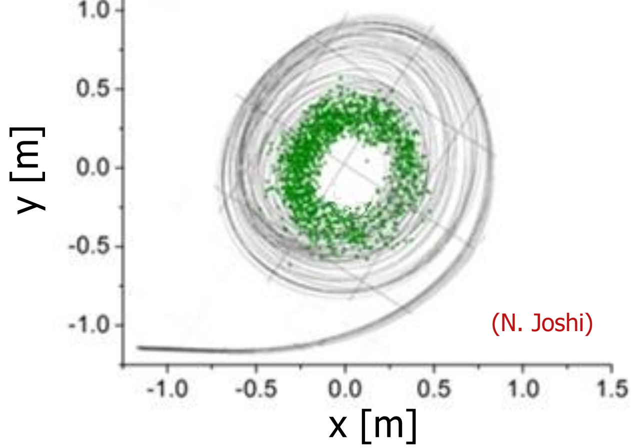
- Ion motion
- Energy loss at degrader: ATIMA
- Energy loss by collisions with buffer gas: SRIM, stopping and range tables
- Charge exchange:
  - hi-energy: ETACHA,
  - lo-energy: combination of formula
  - interpolate between extremes
- Small-angle-scattering (Amsel‘s framework)
- **Magnetic field** (TOSCA 3d)
  ~20 iterations: #sectors, size, gap, ...

(C. Guenaut, C. Campbell, N. Joshi)

Cases:

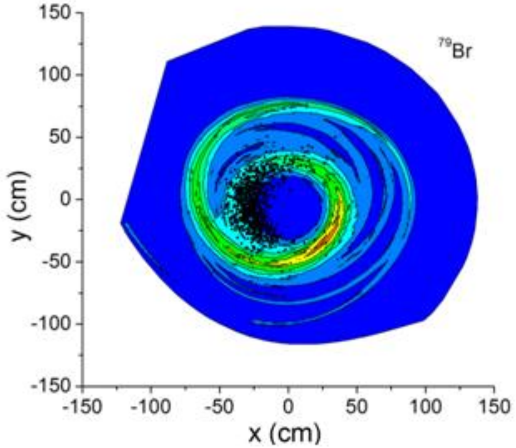
^{9}Li, $^{14,\mathbf{24}}$**O**, ^{17,31}F, $^{24,\mathbf{40}}$**Si**, ^{56,70}Fe, $^{70,\mathbf{79}}$**Br**, ^{127}I

^{79}Br trajectory and stopped-ion distribution



(N. Joshi)

Stopped ion distribution separated from ionization density
→ **Reduced effect from space charge**



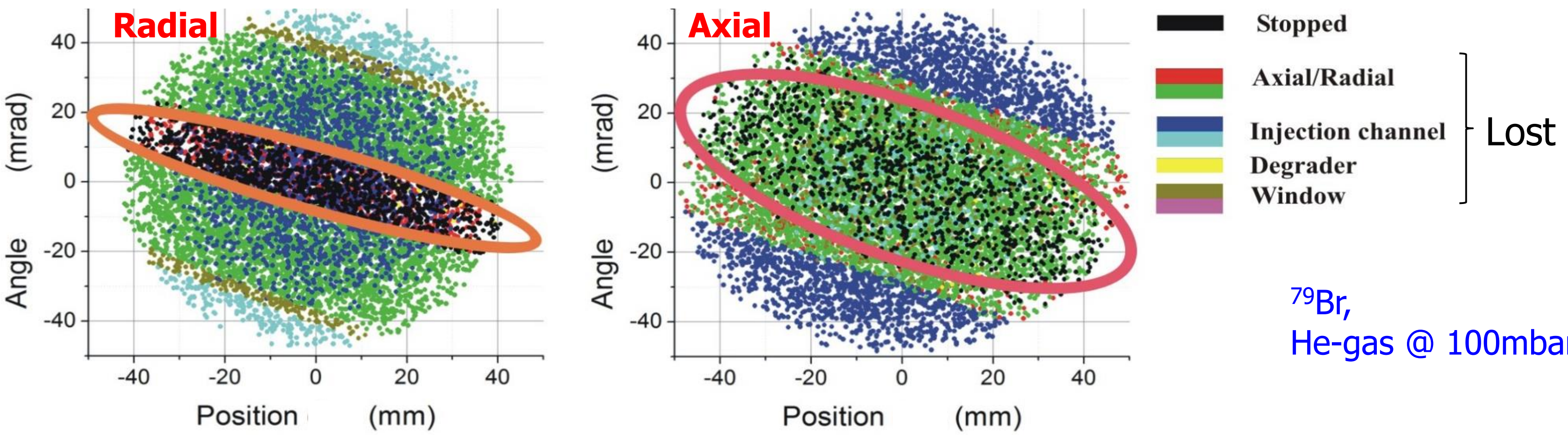
Etacha: Rozet NIMB 107 (1996) 67
Schlachter: PR A27 (1983) 3372
Amsel: NIMB 201 (2003) 325

SRIM: srim.org
Schiwietz: NIM B 175 (2001) 125

B-field:
S. Chouhan: Proc. PAC07 … EUCAS'13

Calculated stopping efficiency

Acceptance of device, calculated from large 4d-input distribution

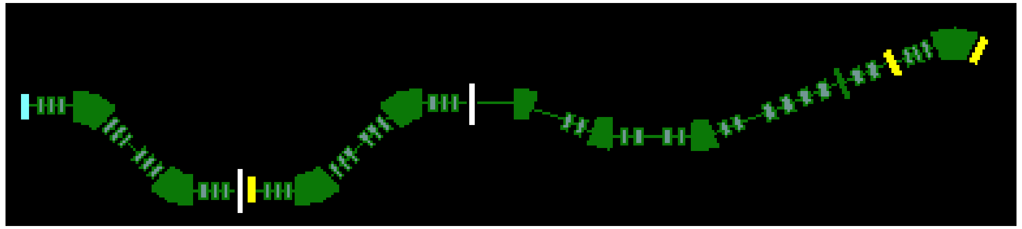


^{79}Br,
He-gas @ 100mbar

Ion	Radial *Acceptance* CycStop	Radial *Emittance* LISE++	Axial *Acceptance* CycStop	Axial *Emittance* LISE++	Efficiency
79Br	897	227	1190	424	98.1%
56Fe	740	153	1165	419	96.9%
40Si	853	336	1187	1098	86.5%
24O	707	1550	1179	1038	64.9%

N. Joshi et al.,
Proc. IPAC2012, TUPPR087

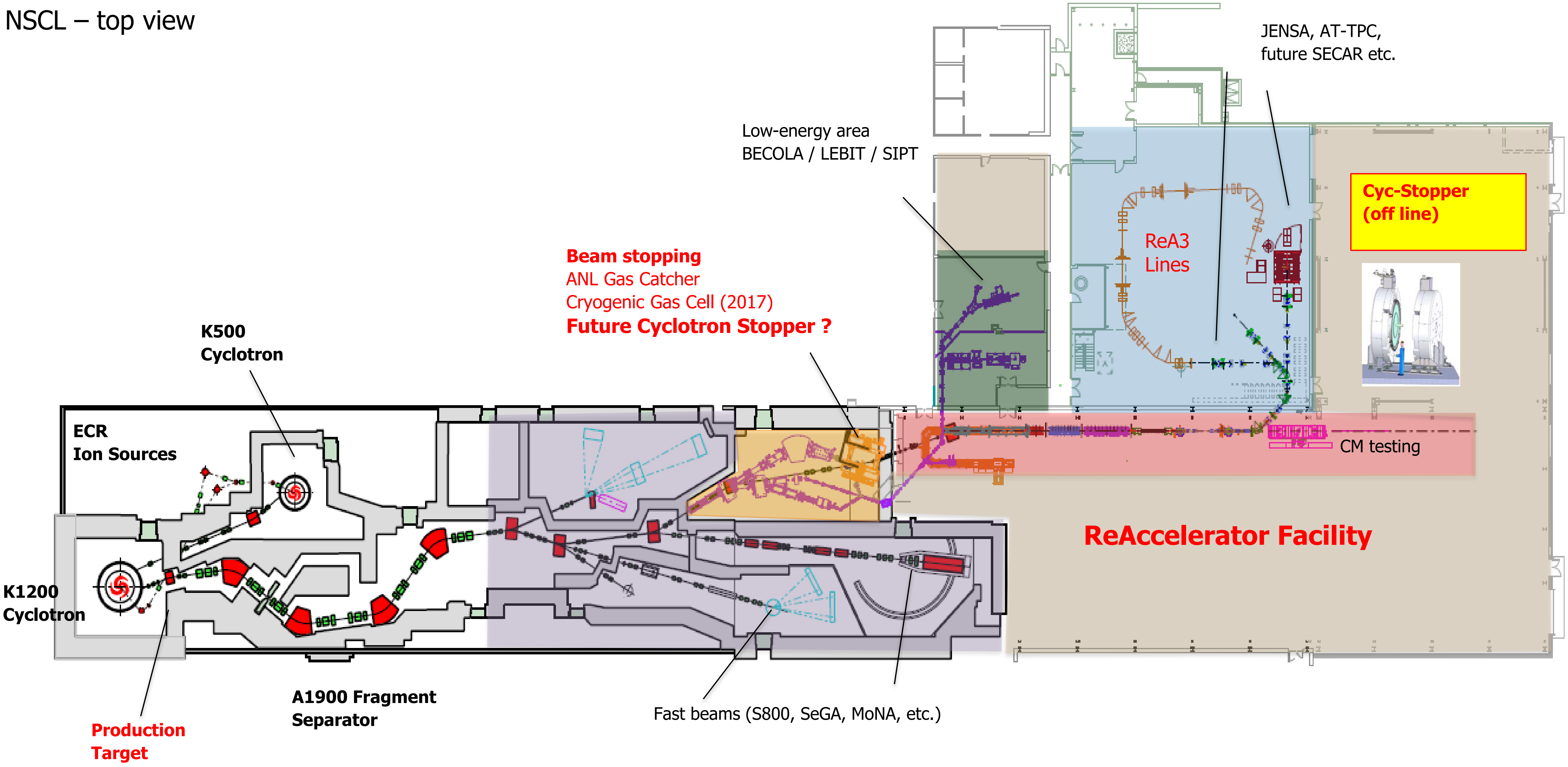
→ High acceptance (~**700-1000 π mm rad**)
→ High stopping efficiency
→ Stopping area r<0.5m



LISE++ output phase spaces, transport matched to stopped-ion distributions above

The cyclotron stopper – location

NSCL – top view

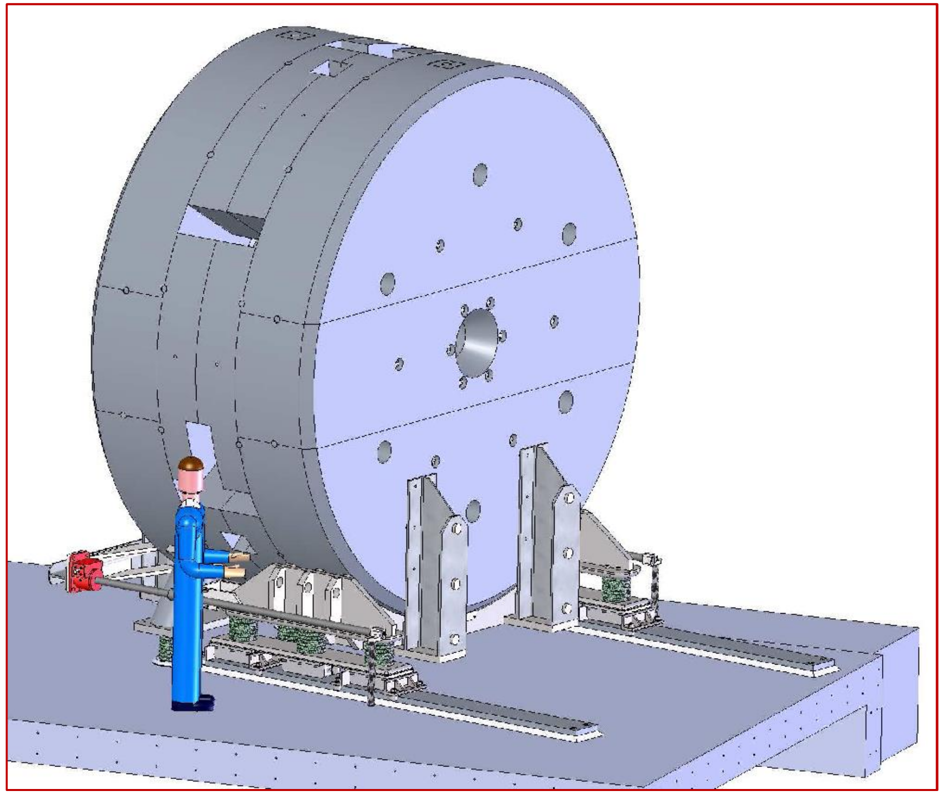


The magnet

Warm iron superconducting cyclotron dipole

2 superconducting coils, iron dominated	
Magnetic field (max)	2.6 T
Sectored, 3hills / 3valleys, k =	-0.28
Diameter	4 m
Injection radius	0.95 m
Axial gap	180 mm
Beam rigidity	2.6 Tm → 1.6 Tm
Weight	165 tons
Cyclotron-type RF	N/A - Wrong talk!

Installed in offline testing area



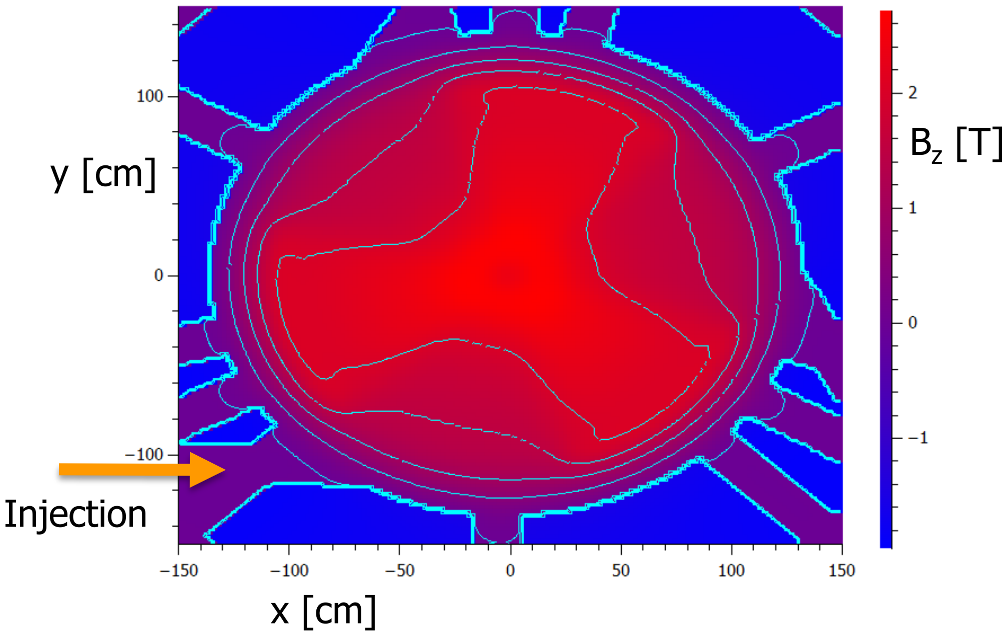
60kV operation!

One half moveable
for access to cryogenic stopping chamber

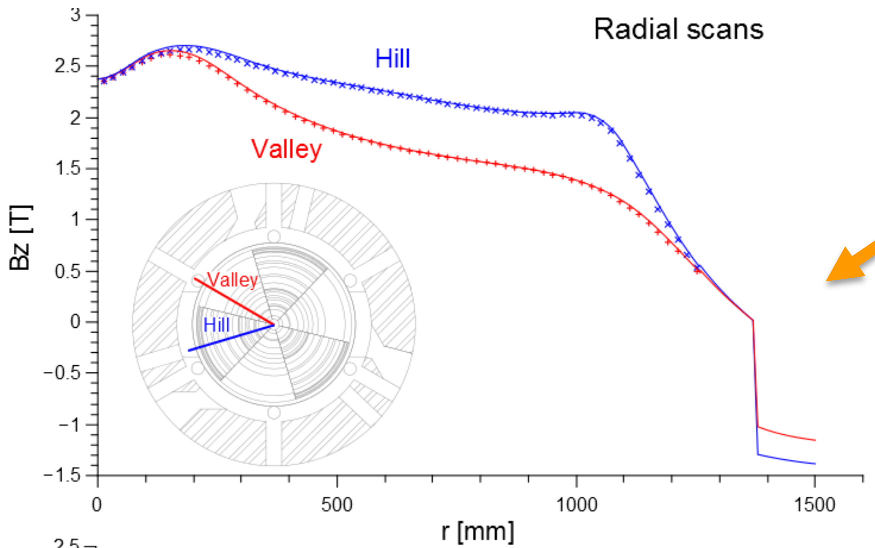
S. Chouhan et al. IEEE Trans on applied SC 23 (2013) 4101805
S. Chouhan et al. Journal of Physics: CS 507 (2014) 032010
M.A. Green et al. Proc. 6th IPAC, 2015 WEPTY061
M.A. Green et al. Proc. Int. Conf. Magnet Tech. 2PoBA_13, 14

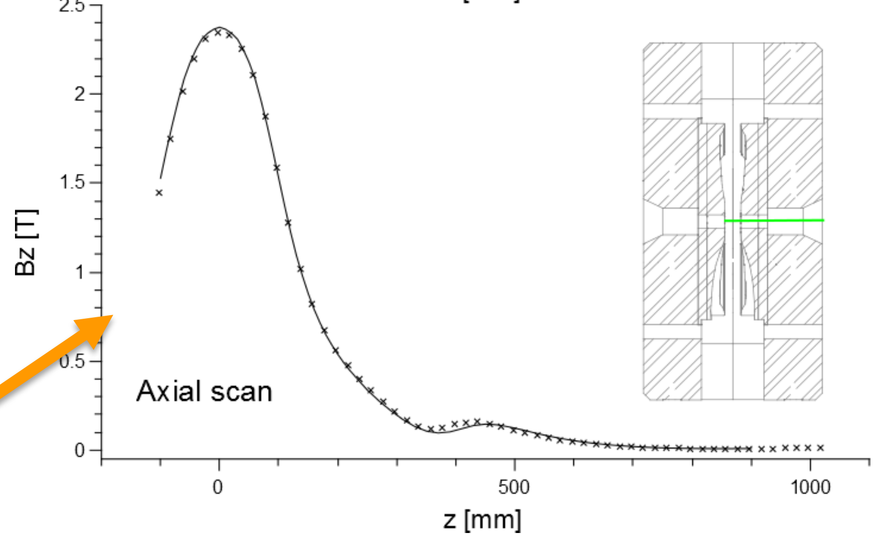
Magnet test

Calculated field B_z ,
in mid-plane



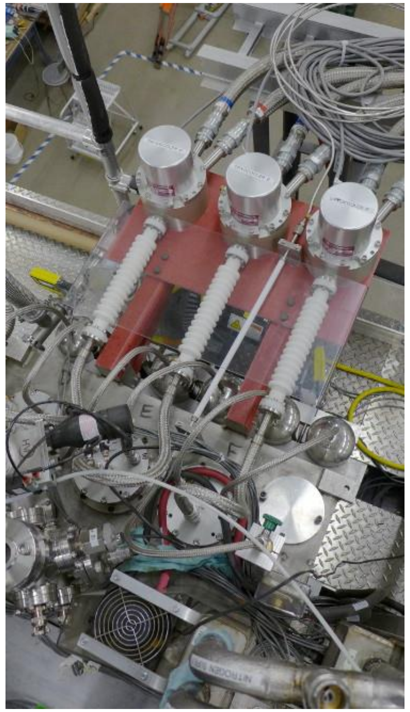
- Energized to nominal field at 180A / 2.6T max
- Measured profiles agree with expectations
  → Critical for efficient stopping!





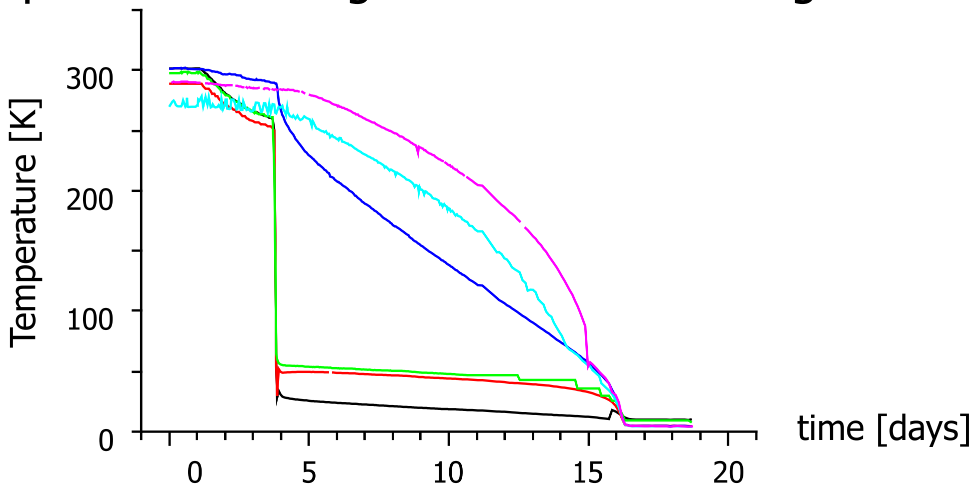
Cryostats, cool-down

"Moving-side" cryostat being installed

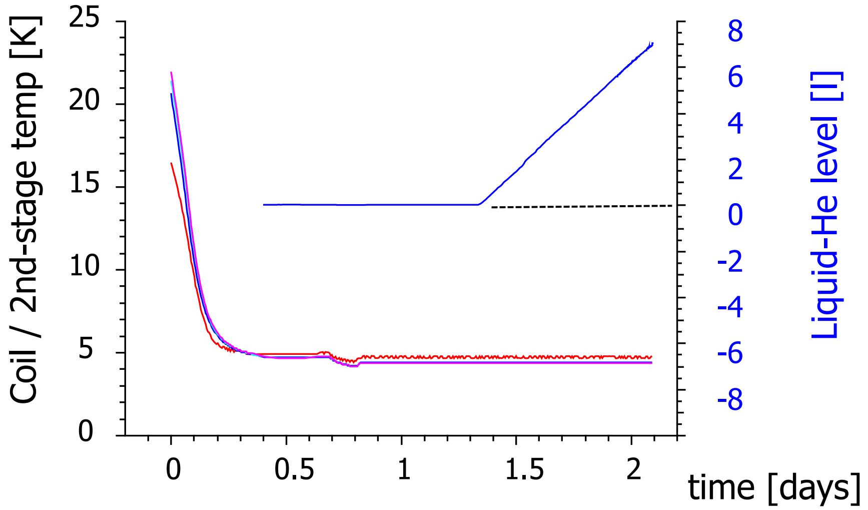


3 of the 6 cold heads
with HV insulators

Temperatures during cool-down on rolling side



T and He-level at end of cool-down: Making liquid



Two separate cryostats:

- LN cooling + 6 two-stage cold heads total
- Make and maintain L-He inventory from gas

→ No external liquid helium needed (HV!)

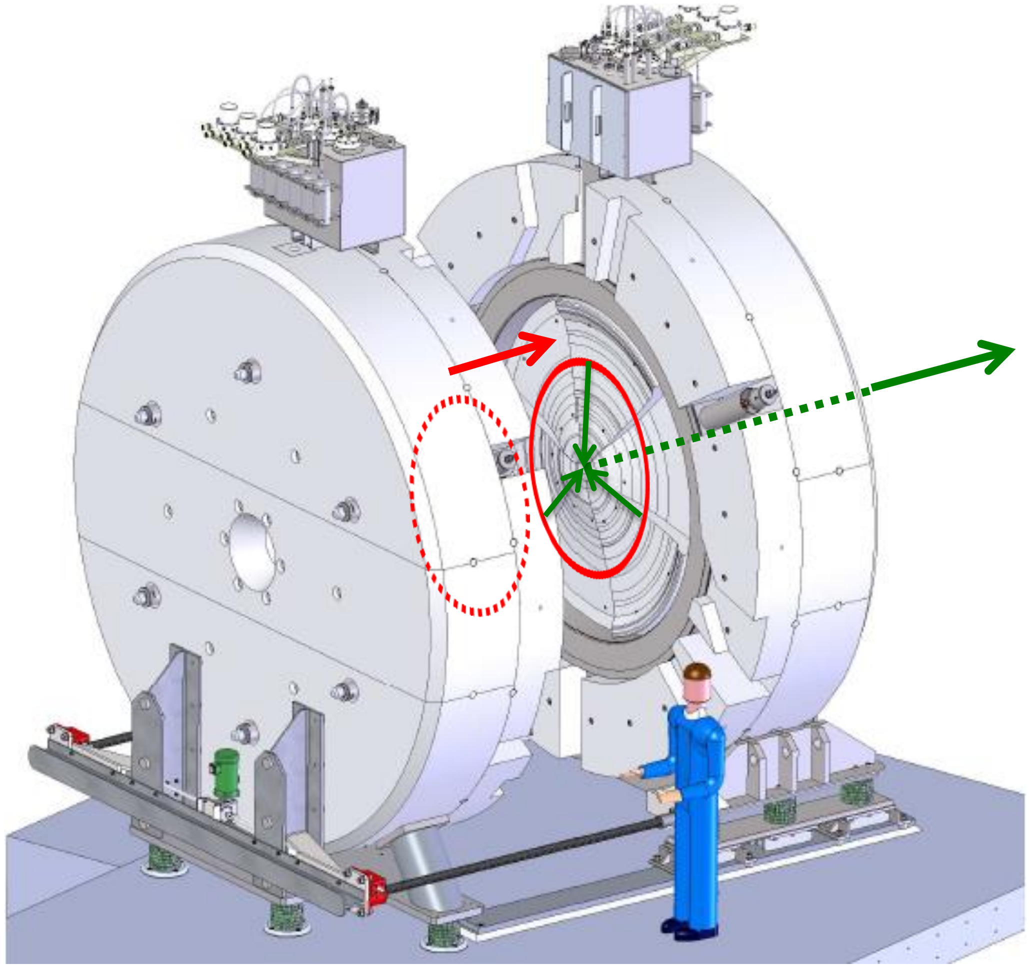
→ ~2 weeks cool and make liquid

→ Quench recovery: Two days – tested.

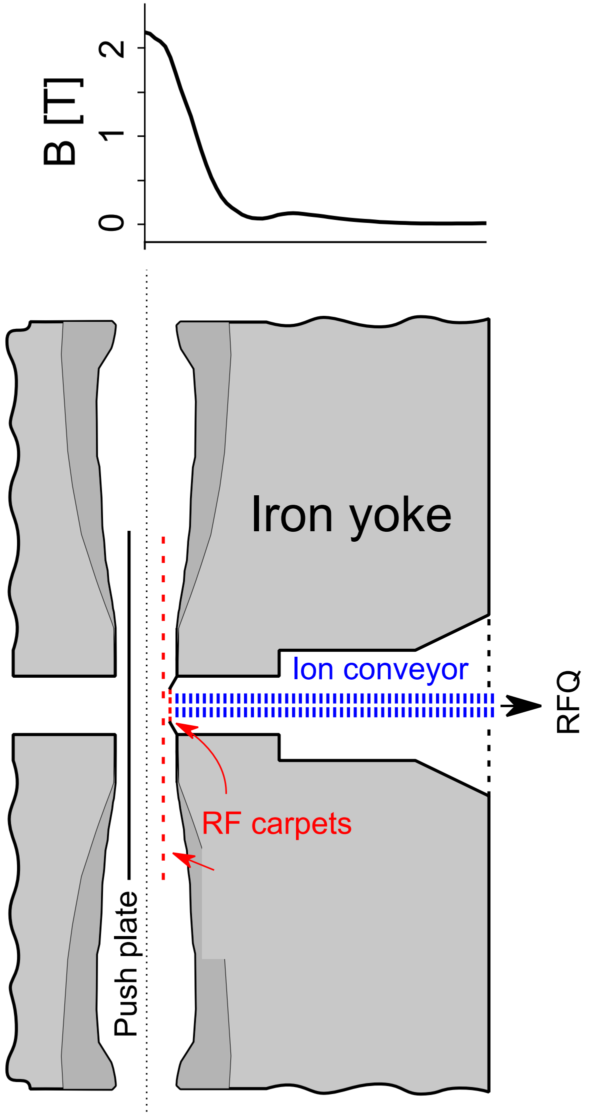
More on cryogenics:
M.A. Green et al. Proc. IPAC'15, WEPTY061
+ IEEE Trans. Applied SC 26 2016 4103104

Fast ion extraction

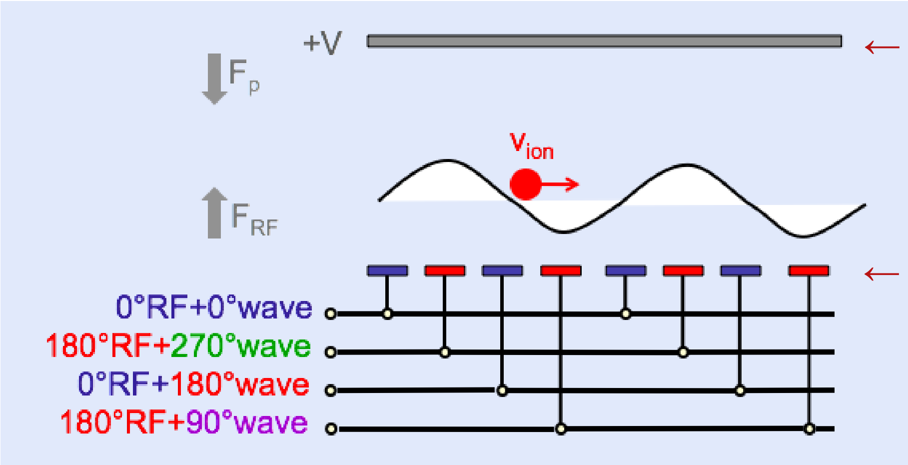
Ion transport to center:
- Large **RF ion carpet**, ~1m diameter
- ~ 100 mbar He (at RT)



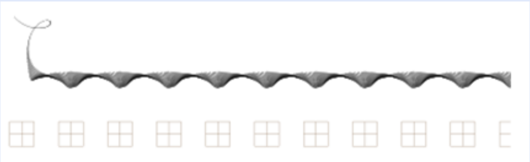
Ion extraction through axial hole on fixed side:
- **Ion conveyor**
- + Differential pumping: ~5 mbar

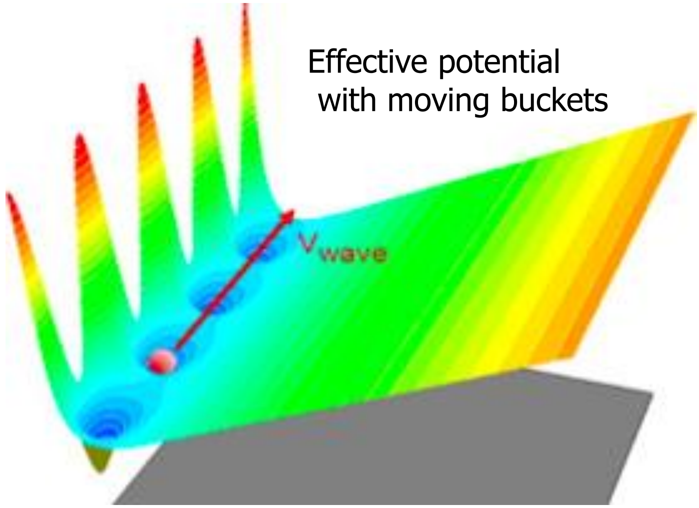


'Surfing' RF carpet:
- Push field: move ions to carpet
- Electrode stripes with RF: keep ions above carpet
- **Low-frequency electric wave** moves ions along carpet



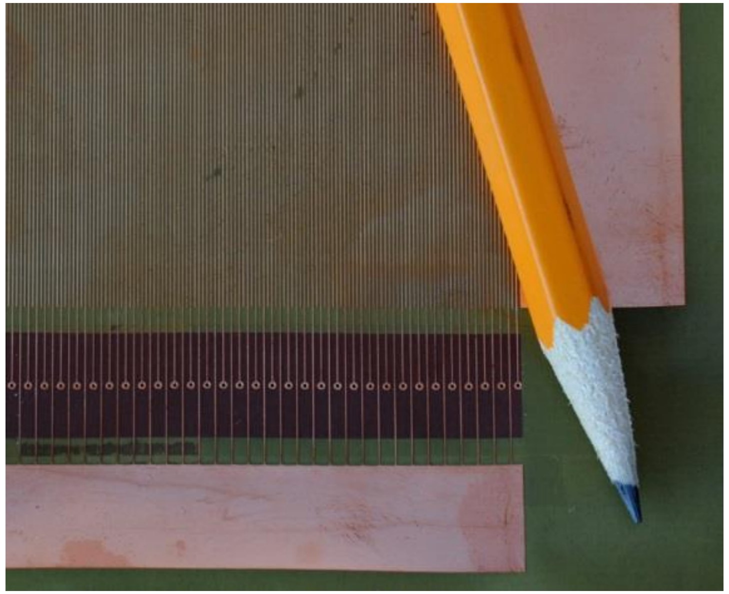
Trajectory:





"Highly damped LINAC"

Sample carpet, used for 'speed tests'



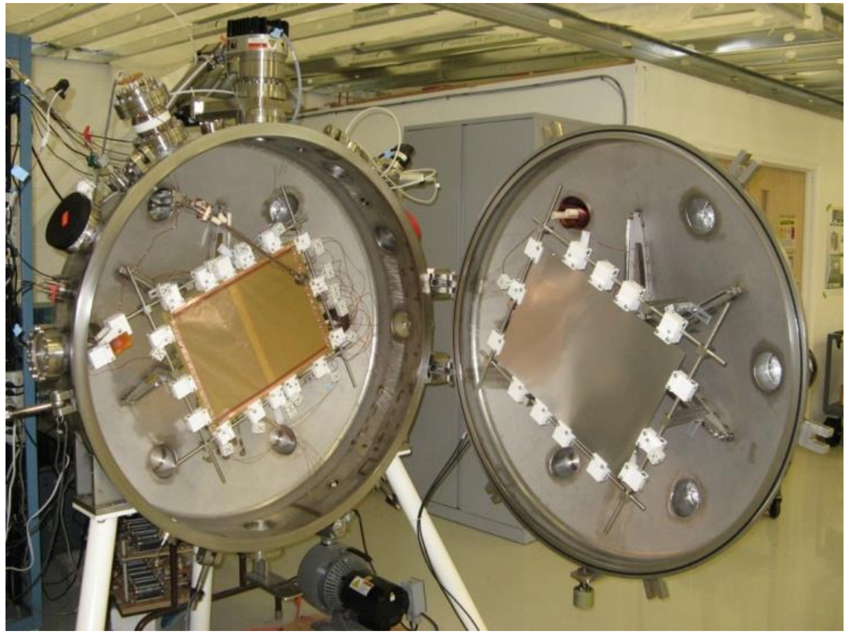
G. Bollen, IJMS 299 (2011),131
SCS, IJMS 299 (2011),71
M. Brodeur et al., IJMS 336 (2013) 53
A. Gehring, NIM B376(2016)221

Proof of principal: large linear carpet tests

Tests with large surfing carpets:

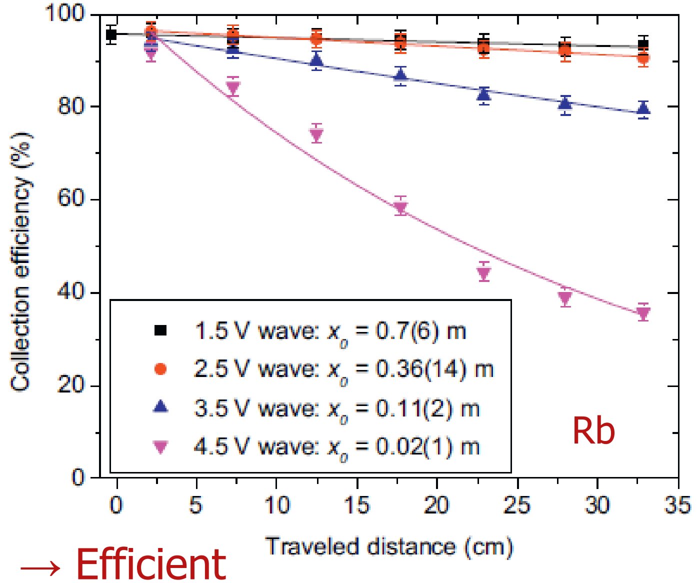
- 41cm long, pitch 0.375mm

Test stand with large rectangular carpet



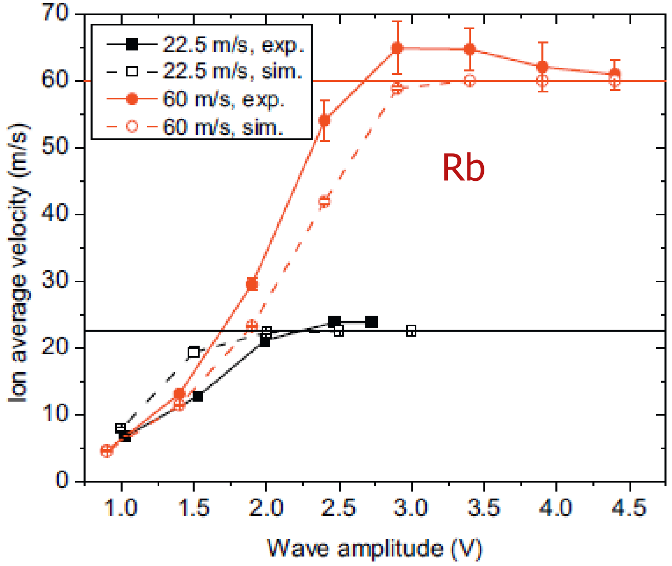
More systematic studies on parameter space:
M. Brodeur et al. IJMS 336 (2013) 53

Transmission:



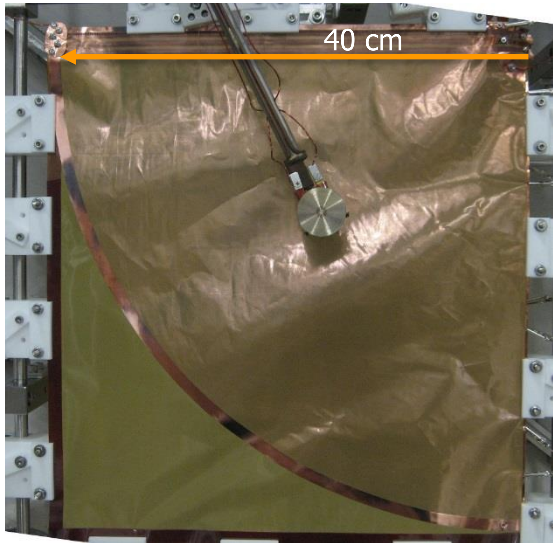
→ Efficient

Speed:



→ fast: up to wave speed = lock-mode

Towards cyc-stopper geometry: ¼ circle



- Pitch: 0.375mm
- Split in two RF areas
  due to large capacitance
- Transport / speed tests:
  K^+ ions, RF: 8.5MHz, $65V_{0p}$

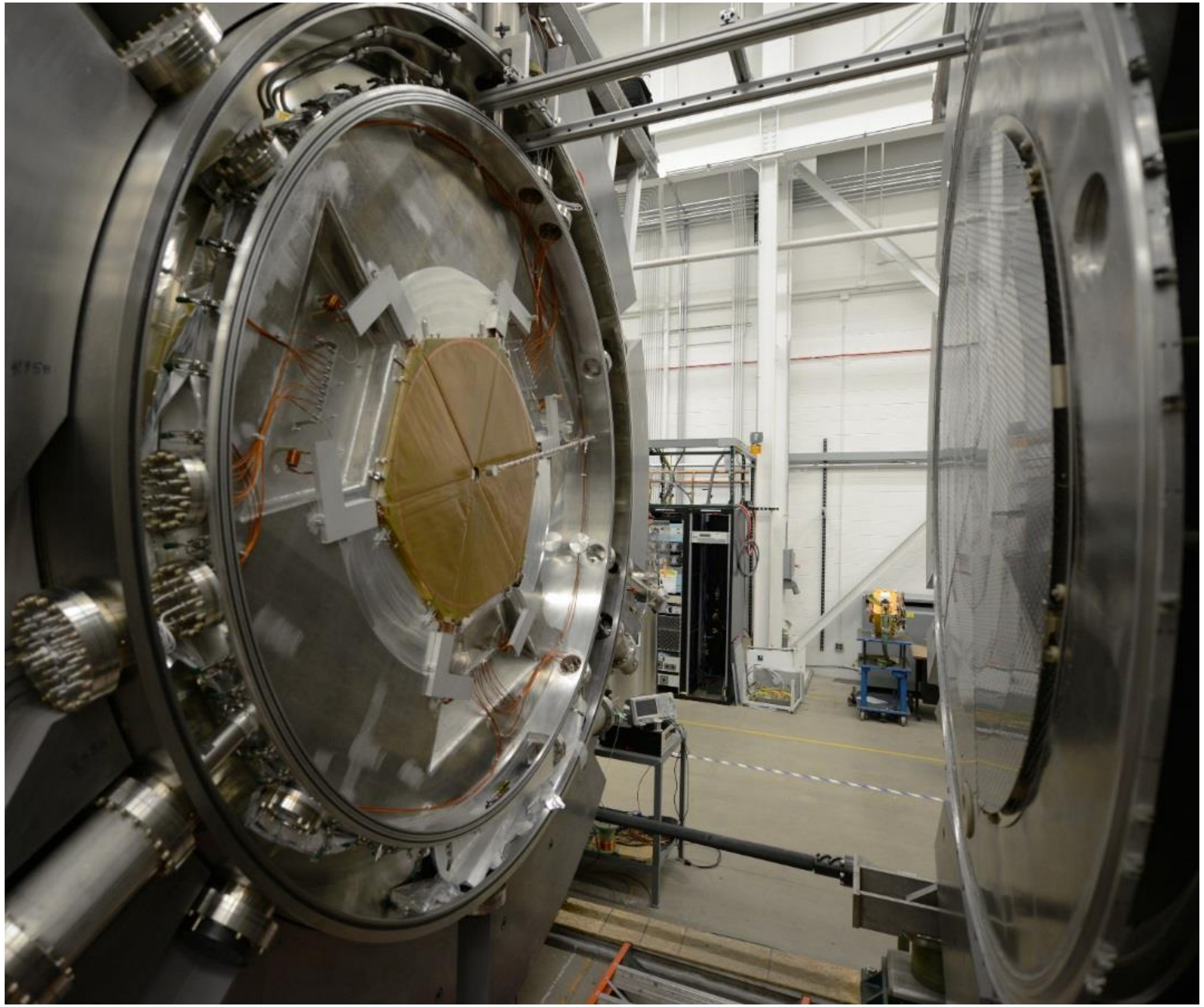
→ Efficient transport
at up to 60 m/s at 80 mbar

The real deal

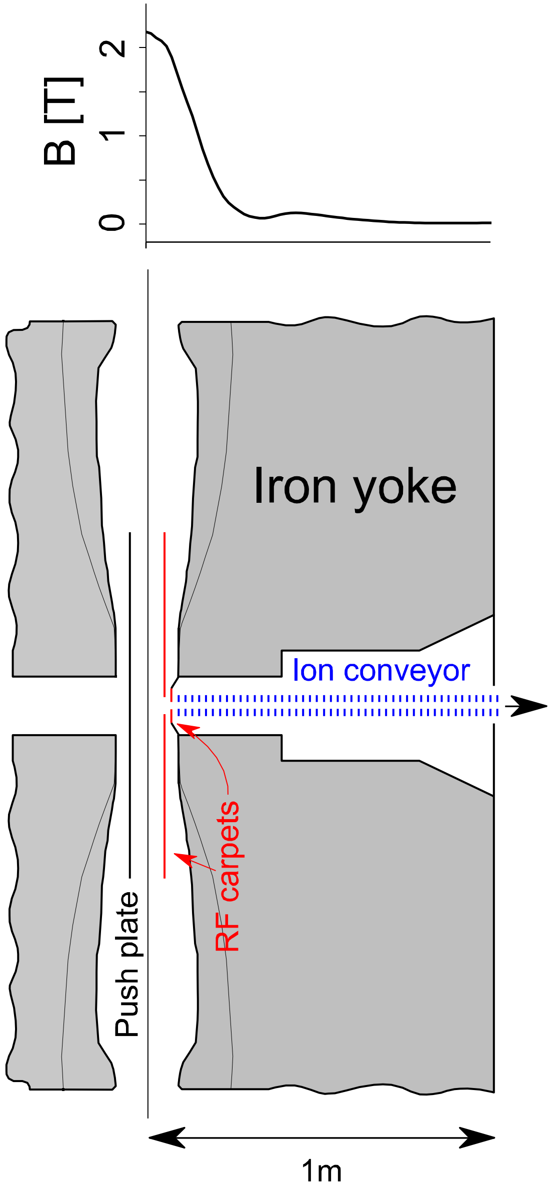
Carpets:
- 6 segments, pitch ~0.47 mm,
  Kapton backed, radius: 42cm.
- 6 'vacuum-compatible' RF resonant circuits
- 3 pockets fit in pole valleys,
  → RF circuits accessible, but hidden from hi-energy beam
- HF: a few 10kHz, a few V
- RF load: 4 nF each
- RF/HF cabling: Kapton isolated
- Support structure: PEEK
- Push field: segmented plate on lid

RF tests:
- Two carpets set up: 7.5 / 8.4 MHz
- At ~60Vpp, need about 16-20W per carpet.

Ion tests:
- Use degrader drive to move ion source across carpet
- To start ... after this conference!

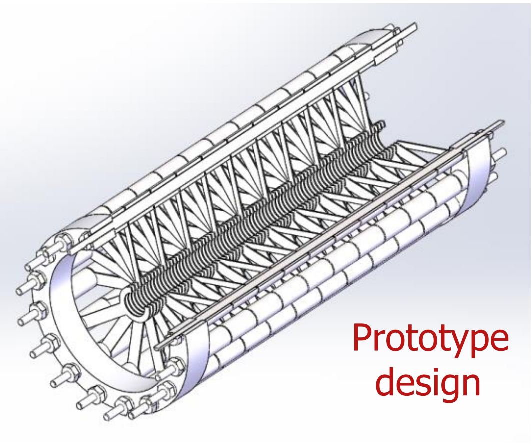


Try a conveyor

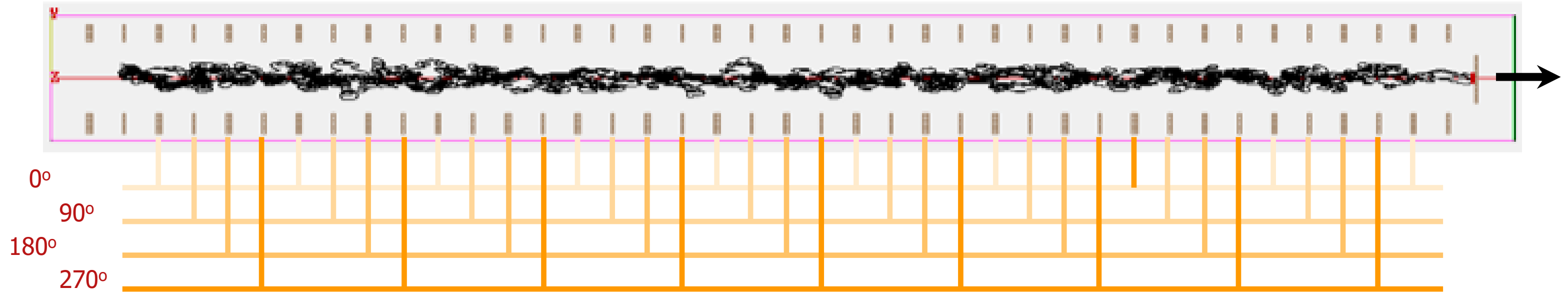


Setup: A (long) stack of ring electrodes
Drive: Periodic voltage on each segment shifted by some phase – **same as surfing carpet without RF**

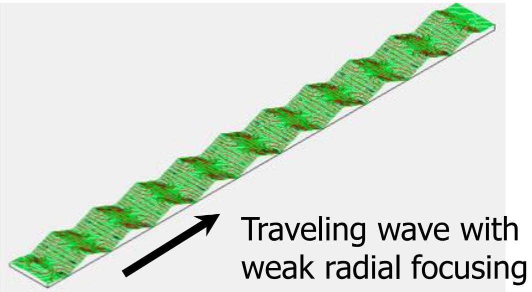
→ Axial transport by surfing
→ Radial focusing by inhomogeneous field
→ Expected to work in B-field



Slip-mode motion, not locked at wave speed



Besides dimensions and # of phases,
three key parameters: pressure, voltage, frequency

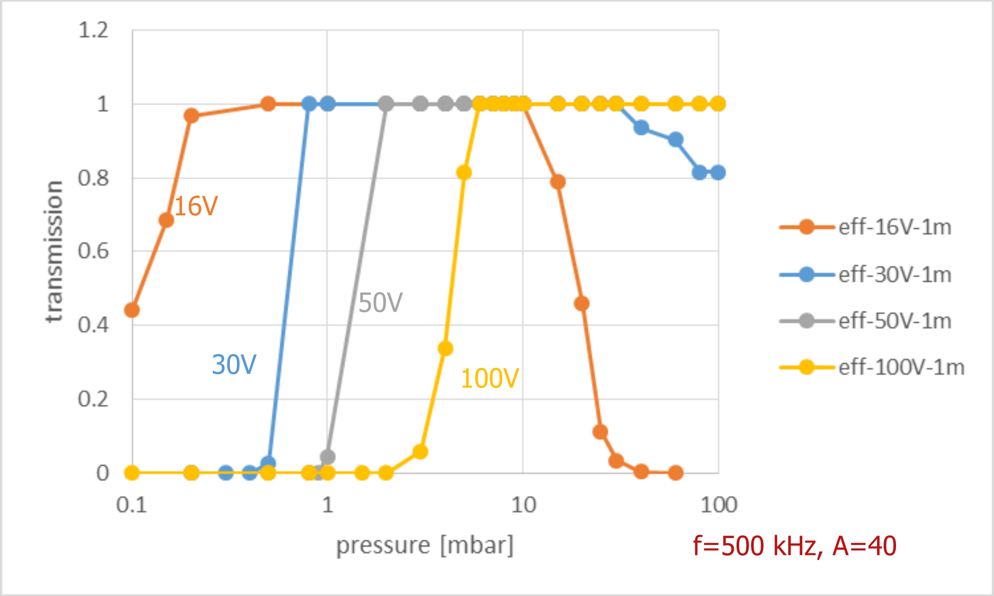


Not a new idea, used for analytical chemistry before
See e.g. **Colburn et al., Physics Procedia 1(2008) 51**

Conveyor simulations: *efficient and fast*

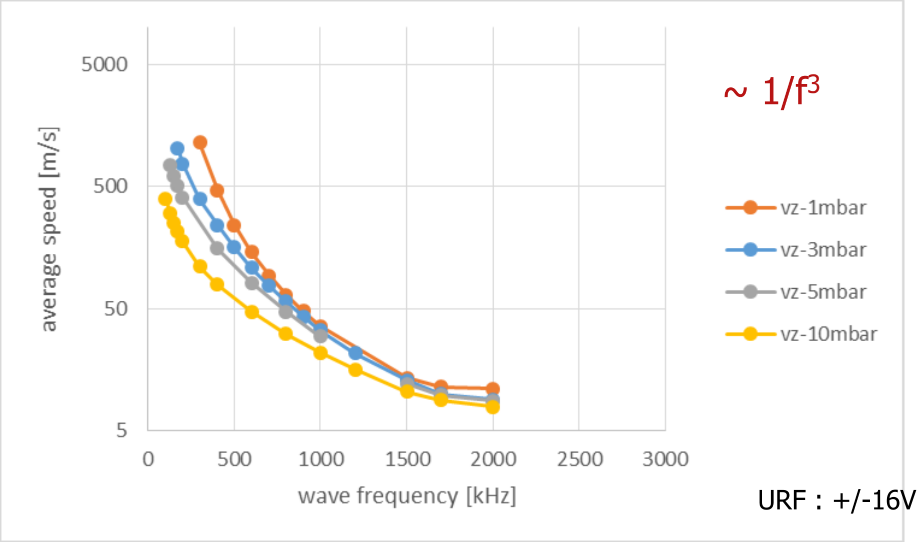
Simulations:
- 8 electrodes-per-period: wave-field better defined, better transmission
- Geometry: ~2 mm spacing, ~10mm opening
- Square-wave drive → Easy to change frequency

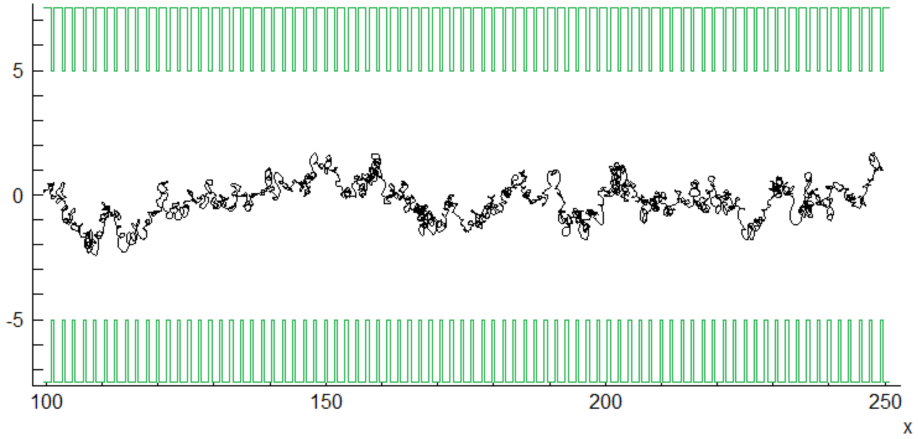
Transmission vs pressure / amplitude



→ Efficient transport +
→ Transport times of a few ms feasible

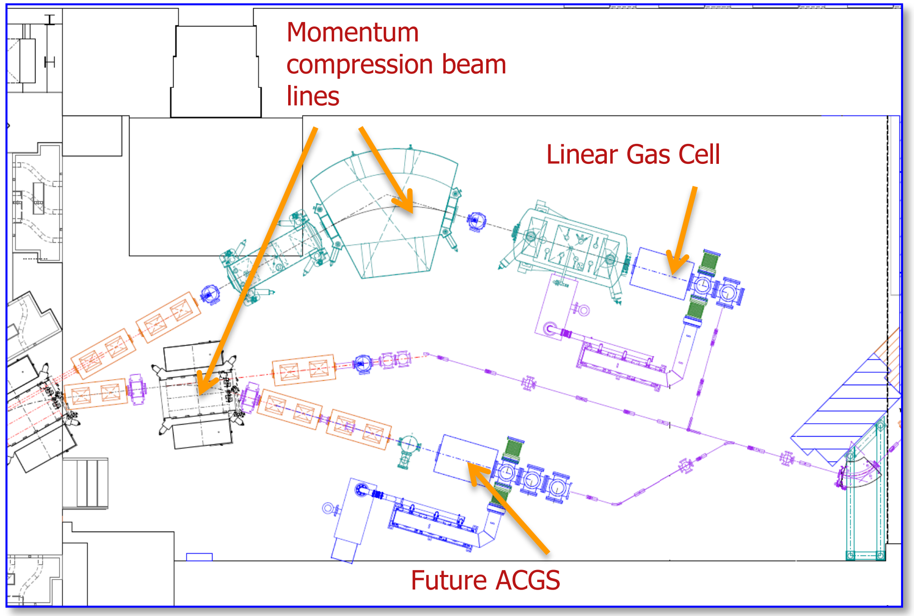
Average velocity:
<v> vs wave frequency / pressure



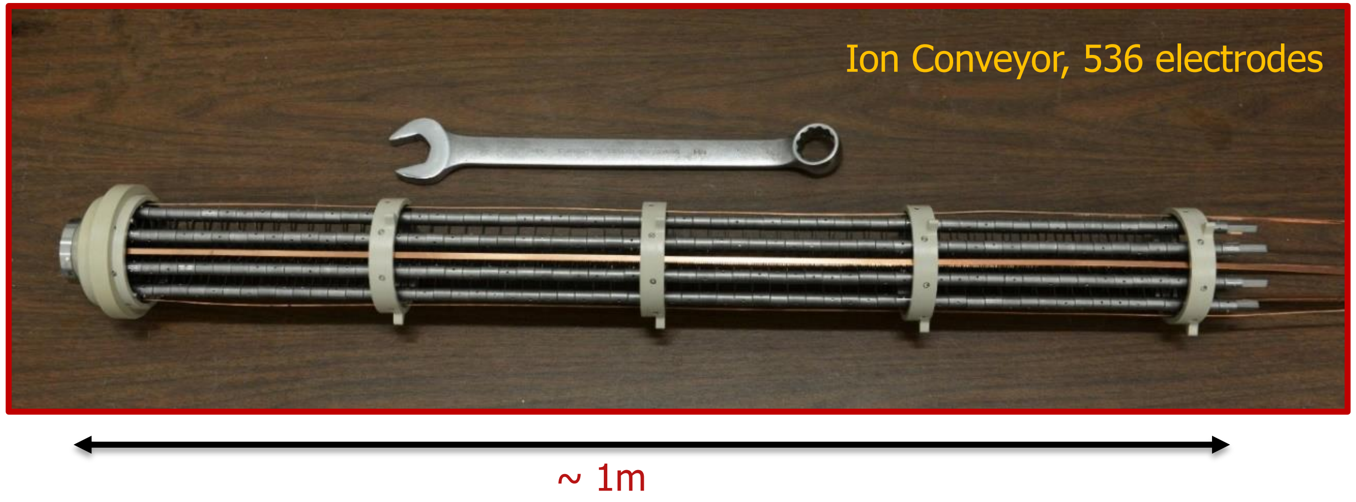


Demo trajectory : $^{40}Ar^{+}$, 500kHz, U_{RF} 16V, p=3mbar

Full-size conveyor test stand



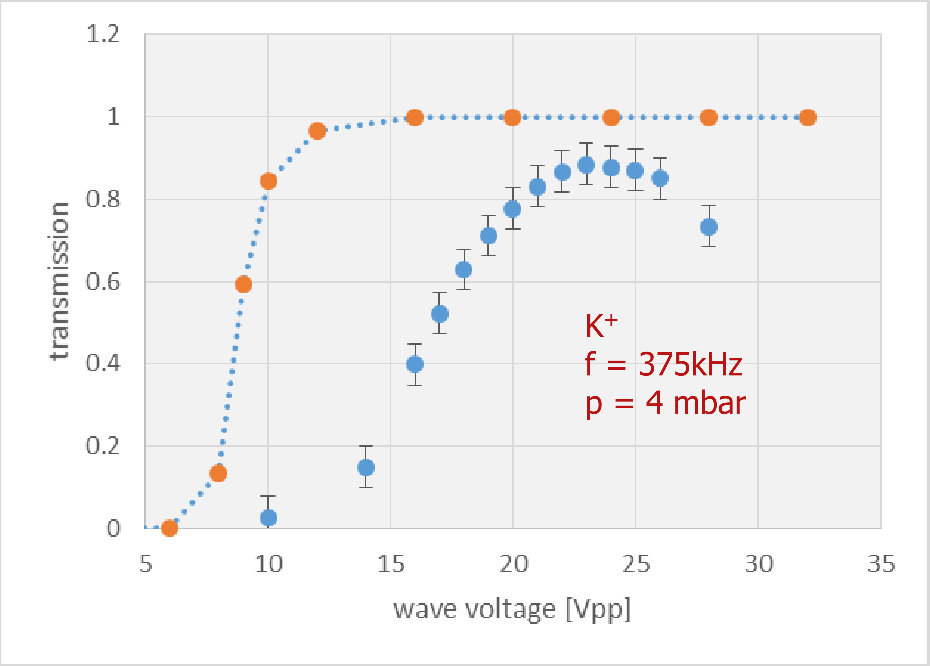
Advantages:
- **Pumping infrastructure to test differential pumping**
- mass separator



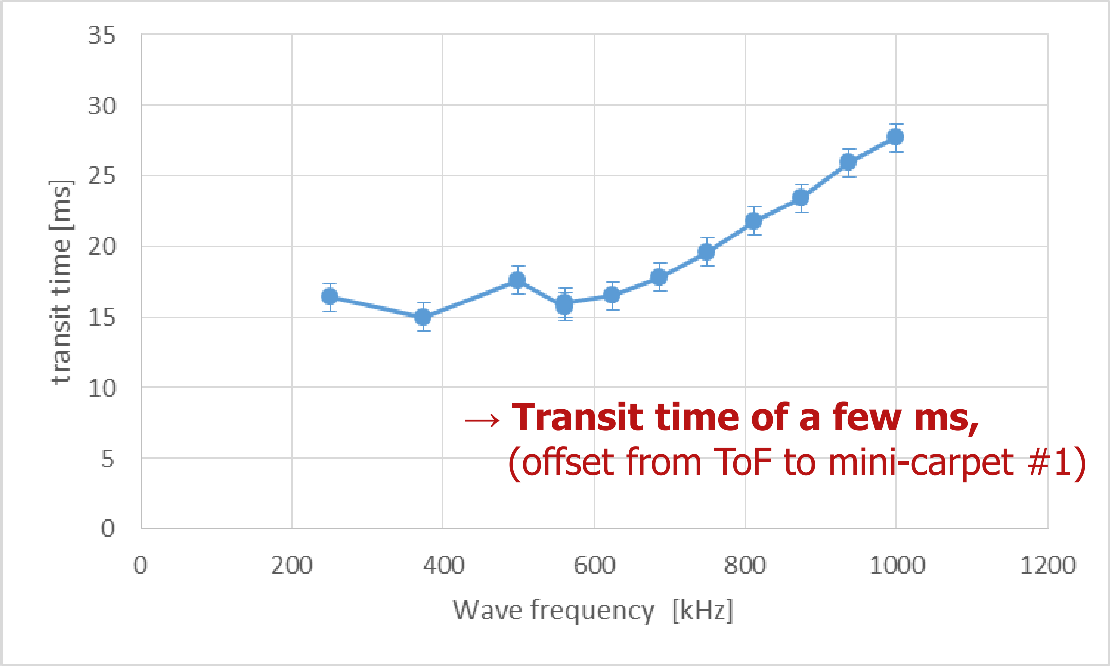
At either end:
Mini-surfing carpets for differential pumping

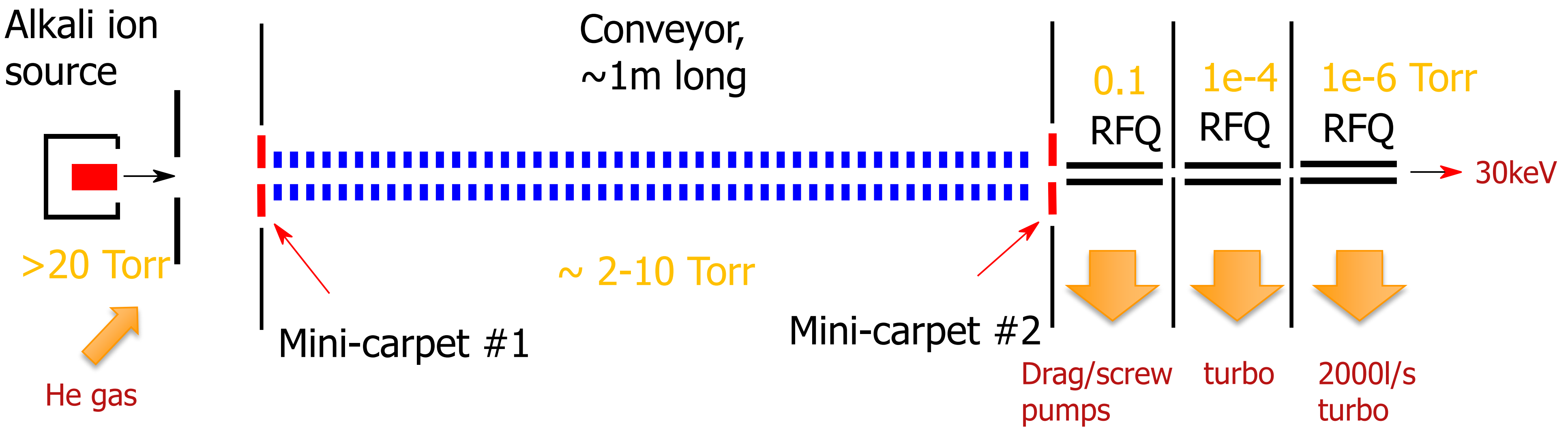
Recent tests with ion conveyor

Transmission vs wave amplitude



Transit time of pulsed beam vs wave frequency





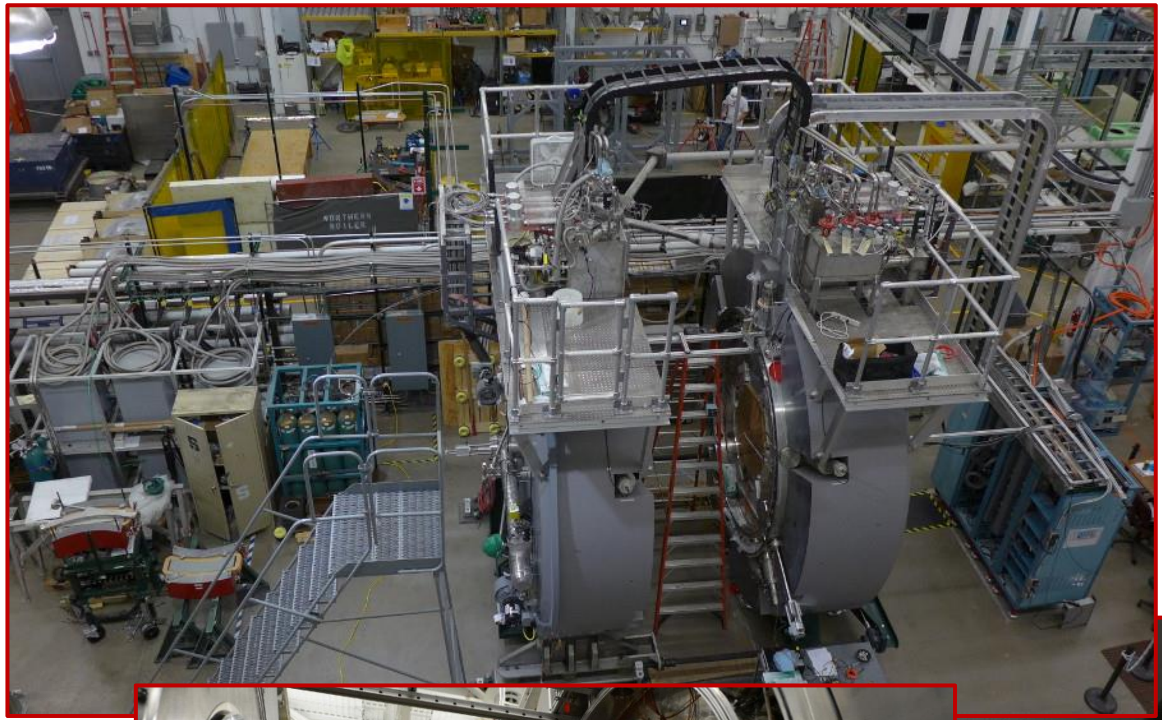
Tested with Rb, K, Na.
Generally: 1st carpet: T = 100%
Conveyor: 80%. Total > ~2/3

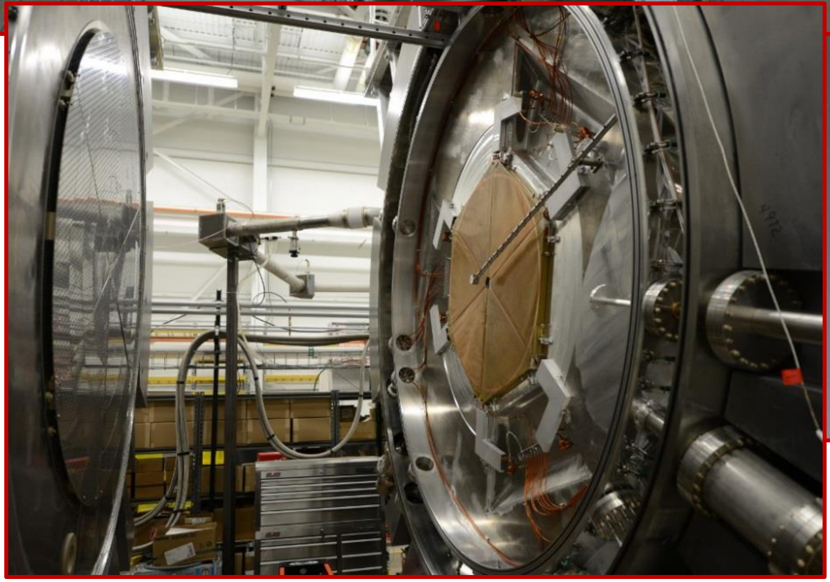
To be continued in cyclotron stopper !

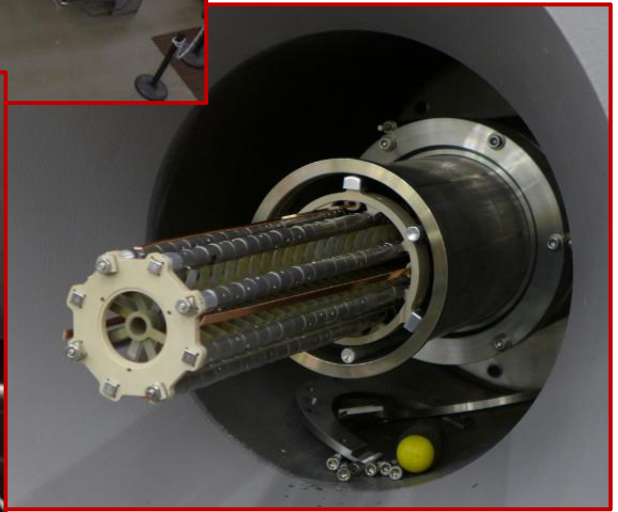
Status

Magnet:
- tested to full field

Stopped-ion transport:
- stopping chamber in place,
initial pressure tests at RT passed
- 90^{o} prototype RF carpets tested
- 60^{o} RF carpets: Electronics working
- Conveyor: Offline tests promising
- Carpet + conveyor installed







Thanks for listening!

Next:
- Test ion transport with magnetic field
- Cool chamber with LN

Move to dedicated vault: 2018 ?

G. Bollen, M. Brodeur, M. Gehring, K. Lund,
N. Joshi, C. Magsig, D. J. Morrissey,
J. Ottarson, SCS, S. Chouhan, J. DeKamp,
J. Ottarson, A. Villari, A. Zeller
… and many more!

MICHIGAN STATE UNIVERSITY
NSF Cyclotron stopper grant
PHY-09-58726, PHY-11-02511