Production, transport and laser trapping of radioactive francium beams for the study of fundamental interactions

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Fundamental interactions and symmetries can be tested efficiently on trapped atoms

These searches of new physics beyond the Standard Model are complementary to those at high energy

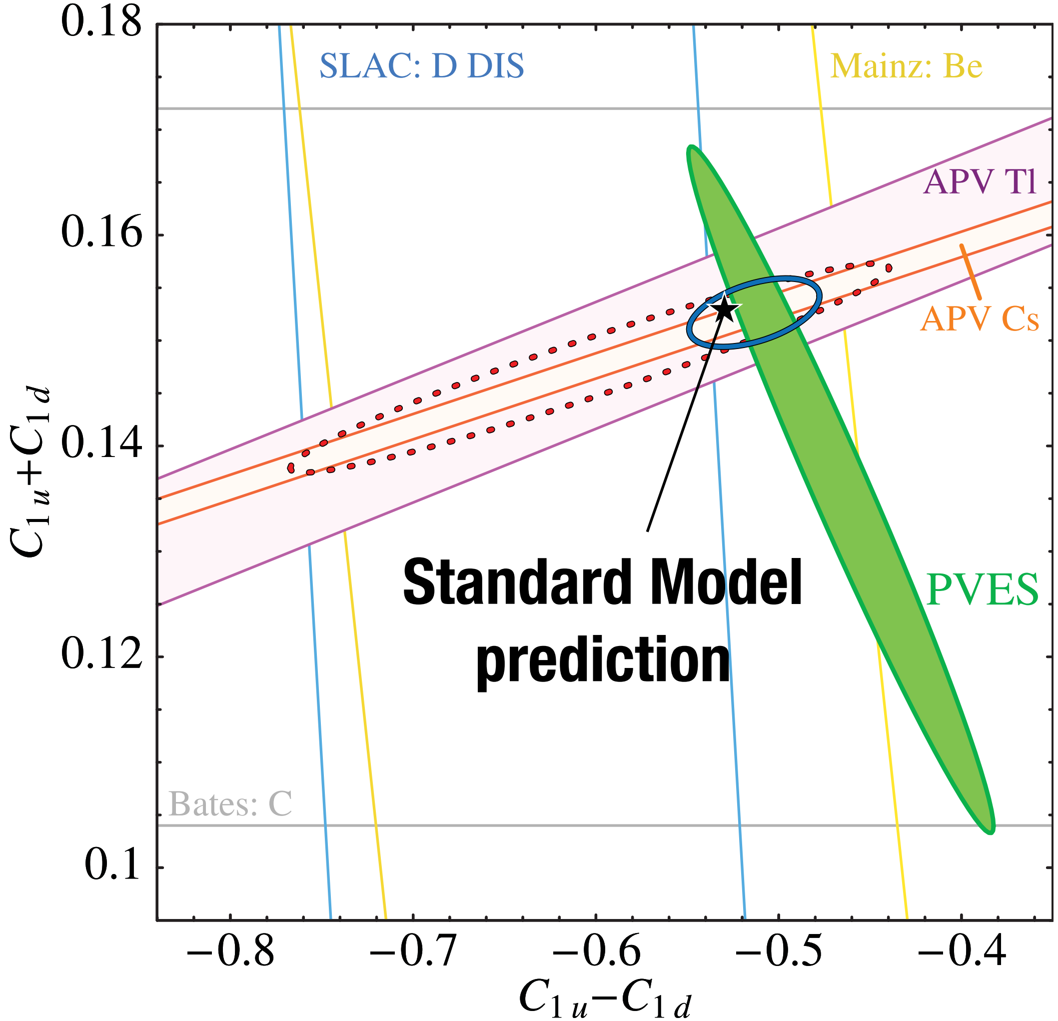
Two main lines of research:

Atomic parity violation (APV) tests weak force at low momentum transfers: electron-nucleon interaction parameterized by weak charge; nucleon-nucleon through the anapole moment (difficult to access otherwise)

Search of permanent electric dipole moments (EDMs) of electrons, nucleons and atoms

Review: Ginges and Flambaum, Phys. Rep. 397, 63 (2004)

Atomic parity violation is complementary to parity-violating electron scattering (PVES) in determining the effective weak couplings of the quarks



New physics constrained to above 1-5 TeV mass scale

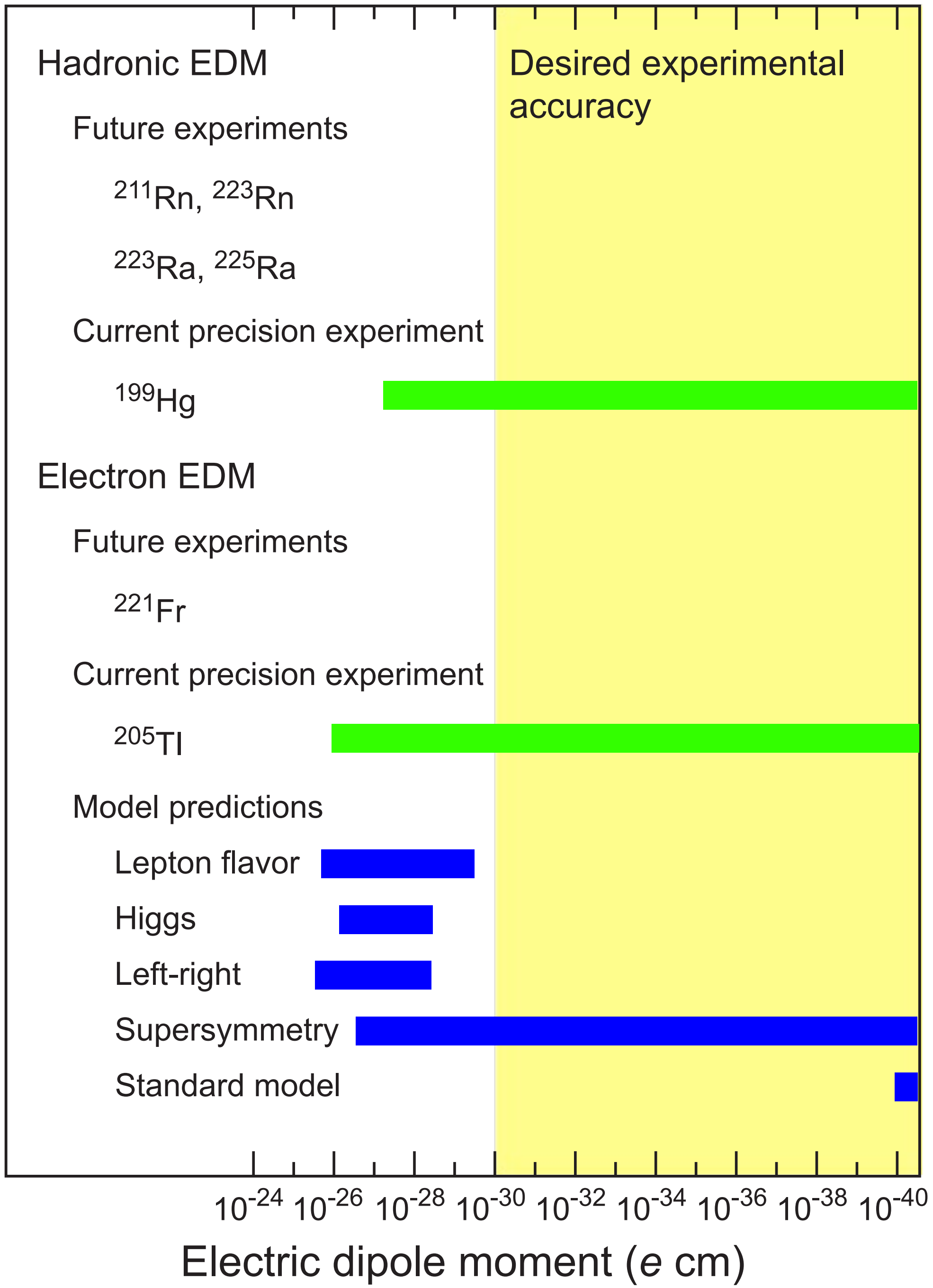
Recent analysis: Young et al., Phys. Rev. Lett. 99, 122003 (2007)

Electric dipole moments (EDMs) are related to violations of time-reversal (T) symmetry

Assuming CPT is conserved, EDMs can shed light on the nature of CP violation

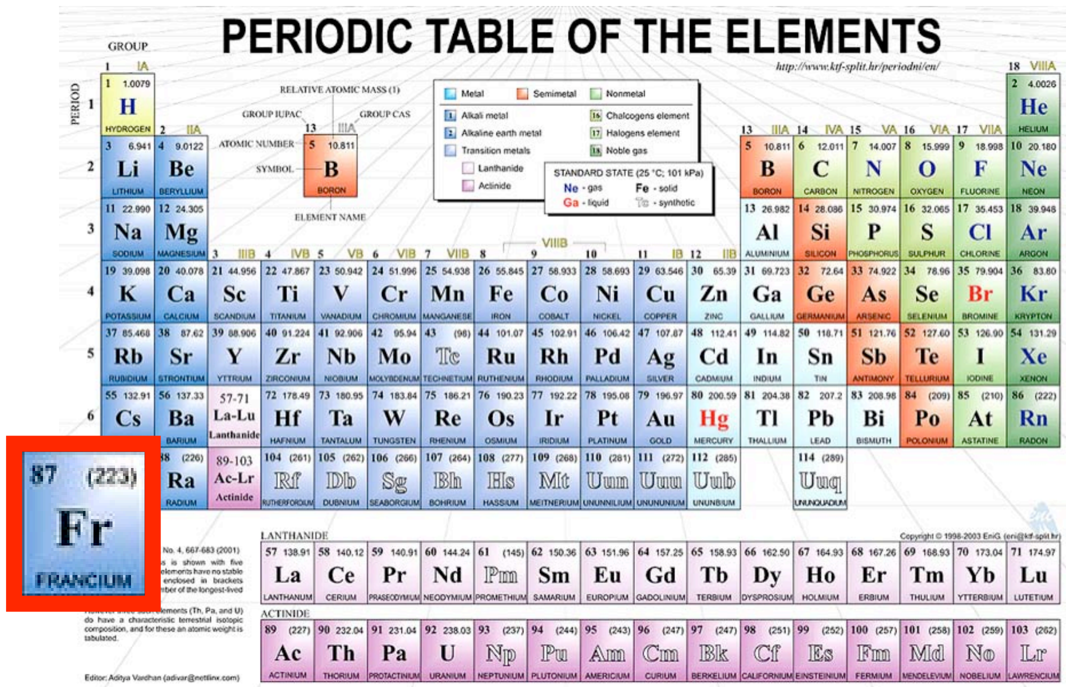
Detection of EDMs near the current experimental limits would unambiguously imply new physics

[N. Fortson, P. Sandars, and S. Barr Phys. Today, June 2003]



Francium is one of the best candidates for APV and EDM measurements

Heaviest alkali metal:
large nucleus and
simple atomic structure



Enhancement of APV (~Z^3) and EDM (electron x 10^3) effects

Several isotopes with relatively long lifetimes (~minutes) to reduce systematics

No stable isotopes,
but scarcity partly compensated by **accumulation in traps**

Several groups are pursuing physics with trapped francium atoms

SUNY Stony Brook, USA
- pioneered Fr traps
- extensive spectroscopy
- moving to TRIUMF

[Gomez, Orozco, and Sprouse, Rep. Prog. Phys. 69, 79 (2006)]

LNL Legnaro, Italy
- status in this talk

JILA Boulder, USA
- vapor cell
- spectroscopy of ^{221}Fr

[Lu et al., Phys. Rev. Lett. 79, 994 (1997)]

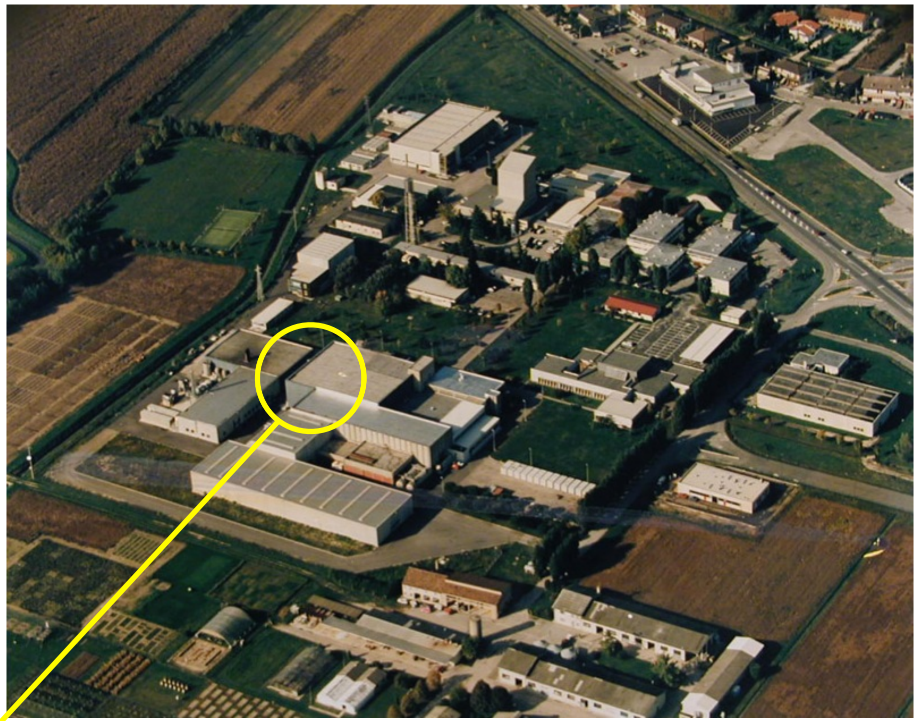
CYRIC / Tohoku University, Japan
- feasibility tests for EDMs
- first beam next spring

[Sakemi, private communication]

Research in this field requires advancements in

francium sources and traps (increase signal)

precision spectroscopy (reduce theoretical uncertainties)



A facility at INFN’s Laboratori Nazionali di Legnaro (LNL)
has been built and commissioned for this purpose

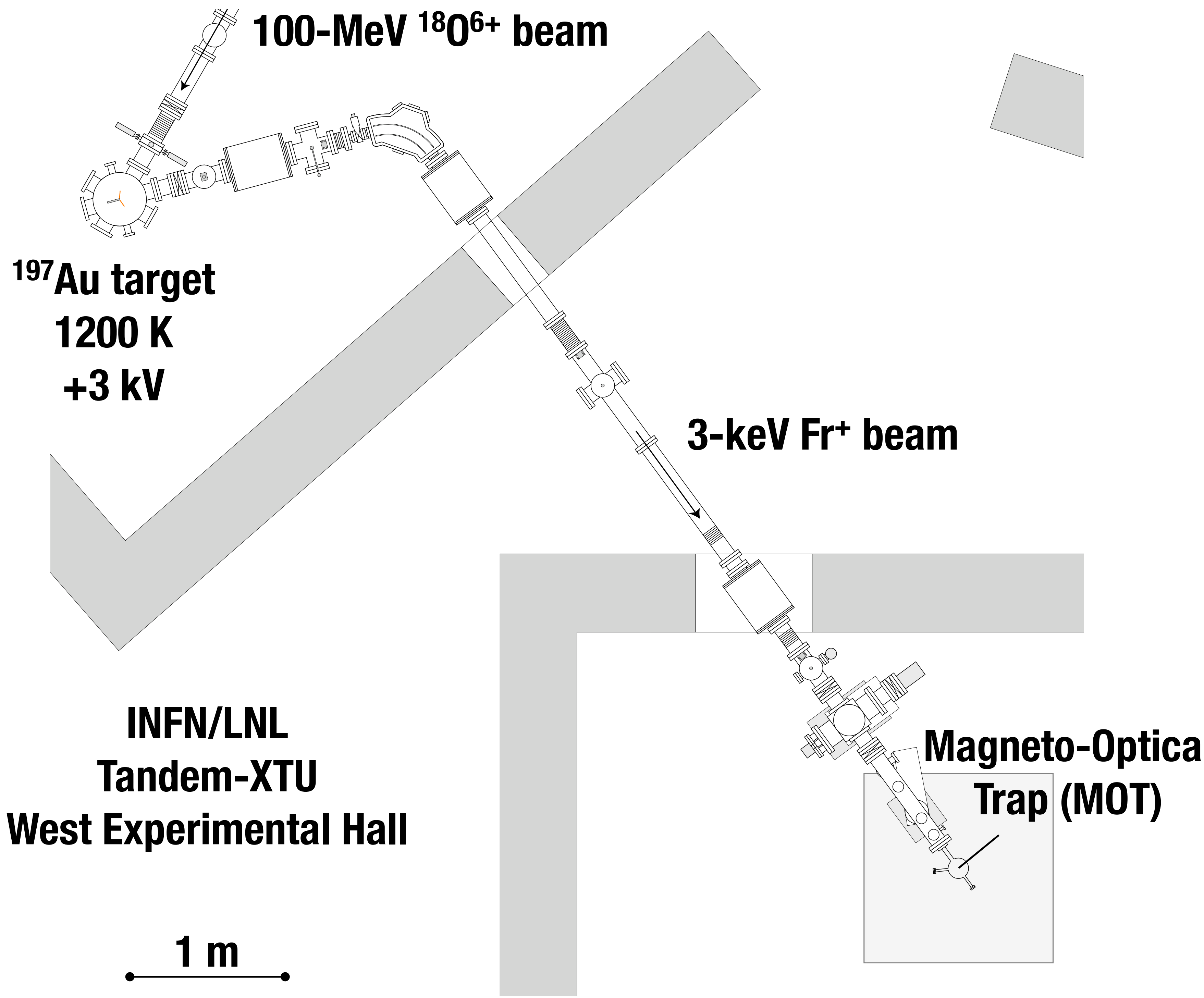
The TRAP-RAD Collaboration at LNL is an interdisciplinary team born to combine expertise in several fields: atomic physics and laser spectroscopy, nuclear physics, particle and accelerator physics.

- S. N. Atutov, R. Calabrese, G. Stancari, L. Tomassetti
  University and INFN Ferrara, Italy

- L. Corradi, A. Dainelli
  INFN Laboratori Nazionali di Legnaro, Italy

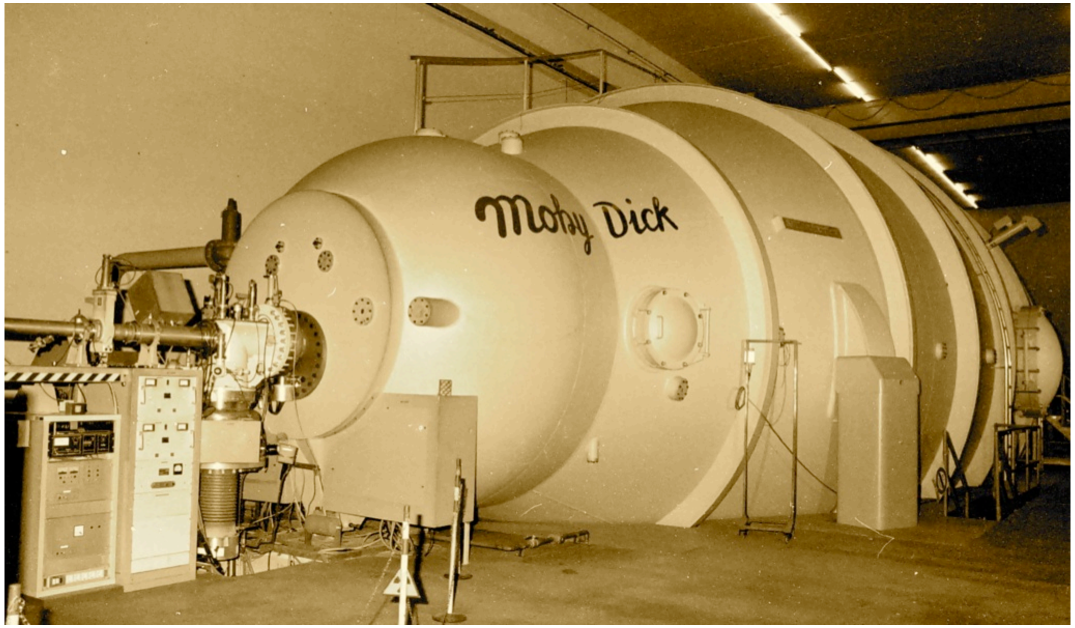
- P. Minguzzi, S. Sanguinetti
  University and INFN Pisa, Italy

- C. de Mauro, A. Khanbekyan, E. Mariotti, L. Moi, S. Veronesi
  University of Siena, Italy



100-MeV 18O6+ beam
197Au target
1200 K
+3 kV
3-keV Fr+ beam
Magneto-Optical
Trap (MOT)
INFN/LNL
Tandem-XTU
West Experimental Hall
1 m

The primary $^{18}O^{6+}$ beam is provided by the Tandem-XTU accelerator at 95–115 MeV



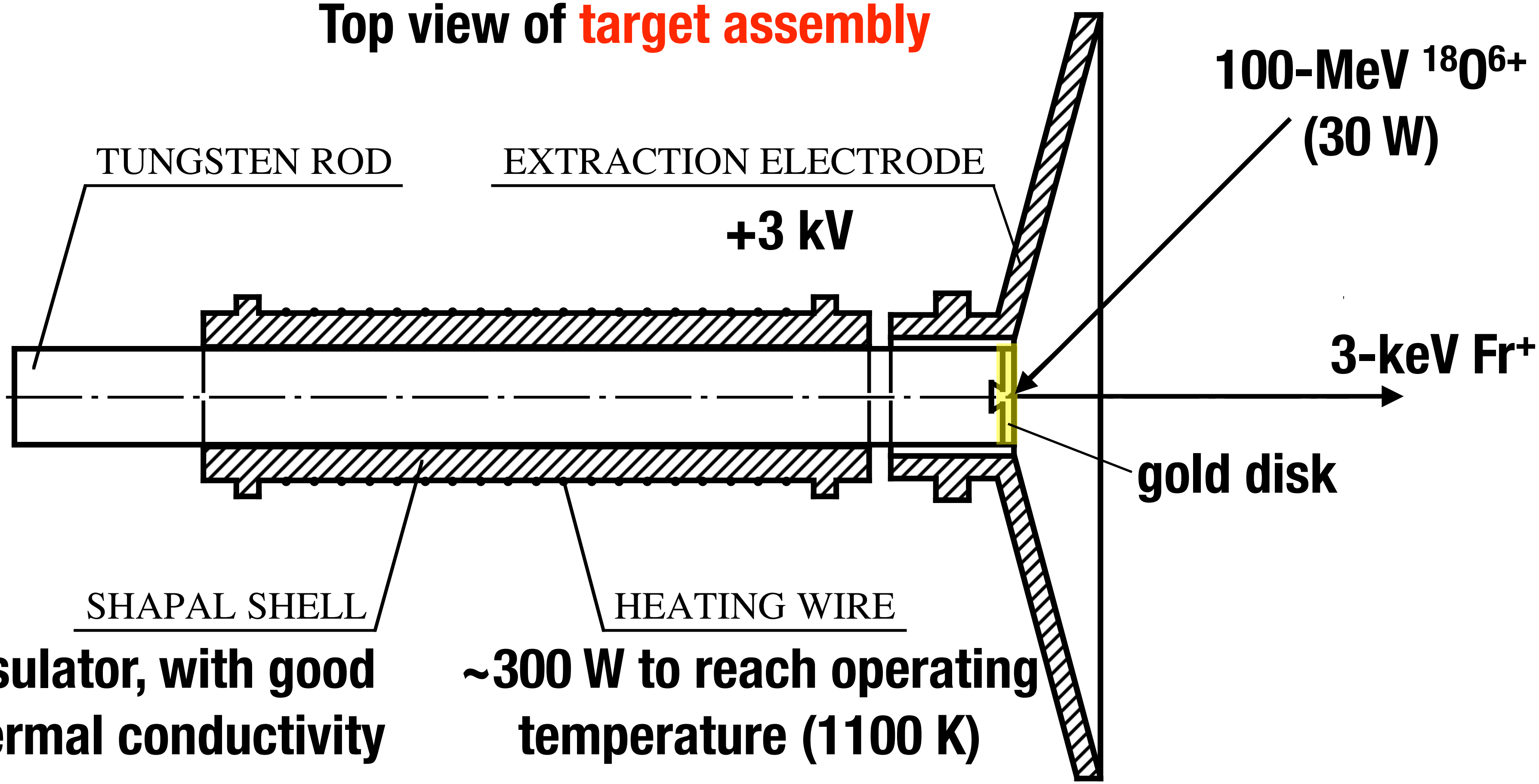
Maximum intensity is 2 x 10^{12} particles/s (2 μA)

About 2 days/month of beam time dedicated to francium production

For production of $^{208-211}$Fr, best combination of projectile/target is ^{18}O on ^{197}Au:

- large fusion-evaporation cross section (~0.1 b)
- large work function of gold (5.1 eV) for surface ionization
- purity, malleability, and high melting point (1337 K) of gold

Top view of target assembly



insulator, with good thermal conductivity

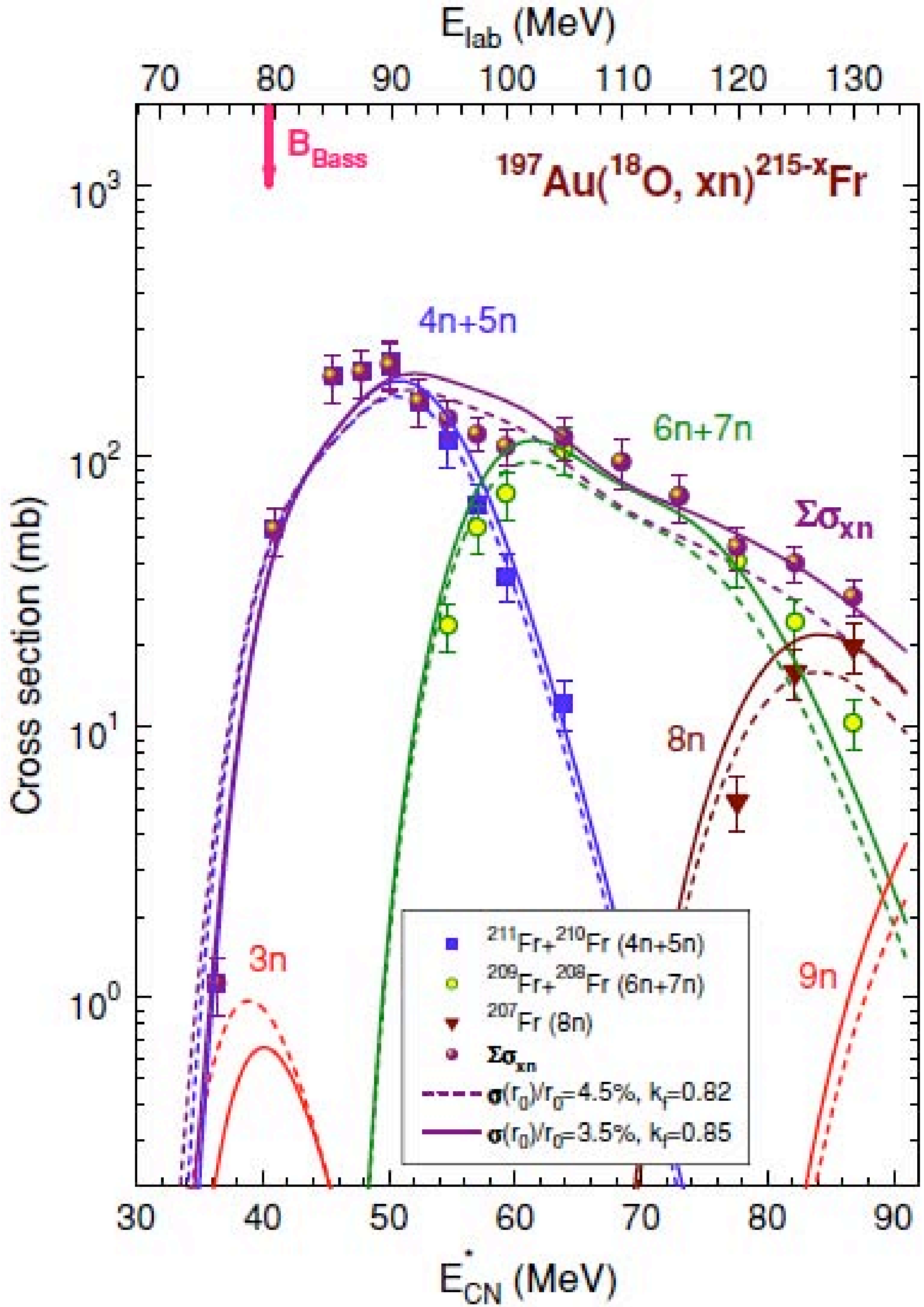
~300 W to reach operating temperature (1100 K)


gold disk
molybdenum
heat shield
extraction
electrode

Experiment concentrates on isotopes that are most abundantly produced:

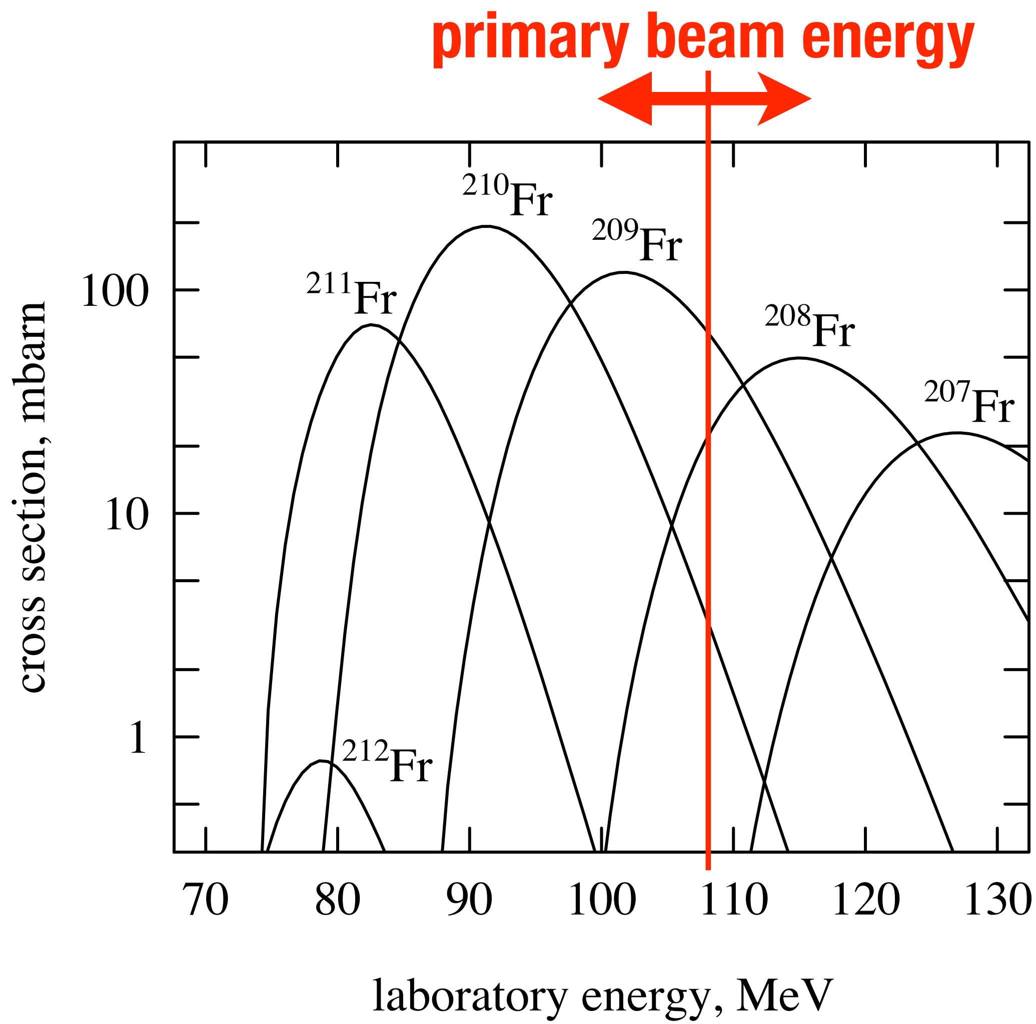
isotope	half life (s)	α fraction (%)	α energy (keV)
^{208}Fr	59.1(3)	90(4)	6641(3)
^{209}Fr	50.0(3)	89(3)	6646(5)
^{210}Fr	191(4)	60(30)	6543(5)
^{211}Fr	186(1)	> 80	6534(5)

Fusion-evaporation cross sections are measured at LNL with PISOLO apparatus (oxygen on thin gold target)



[Corradi et al.,
Phys. Rev. C <u>71</u>, 014609 (2005)]

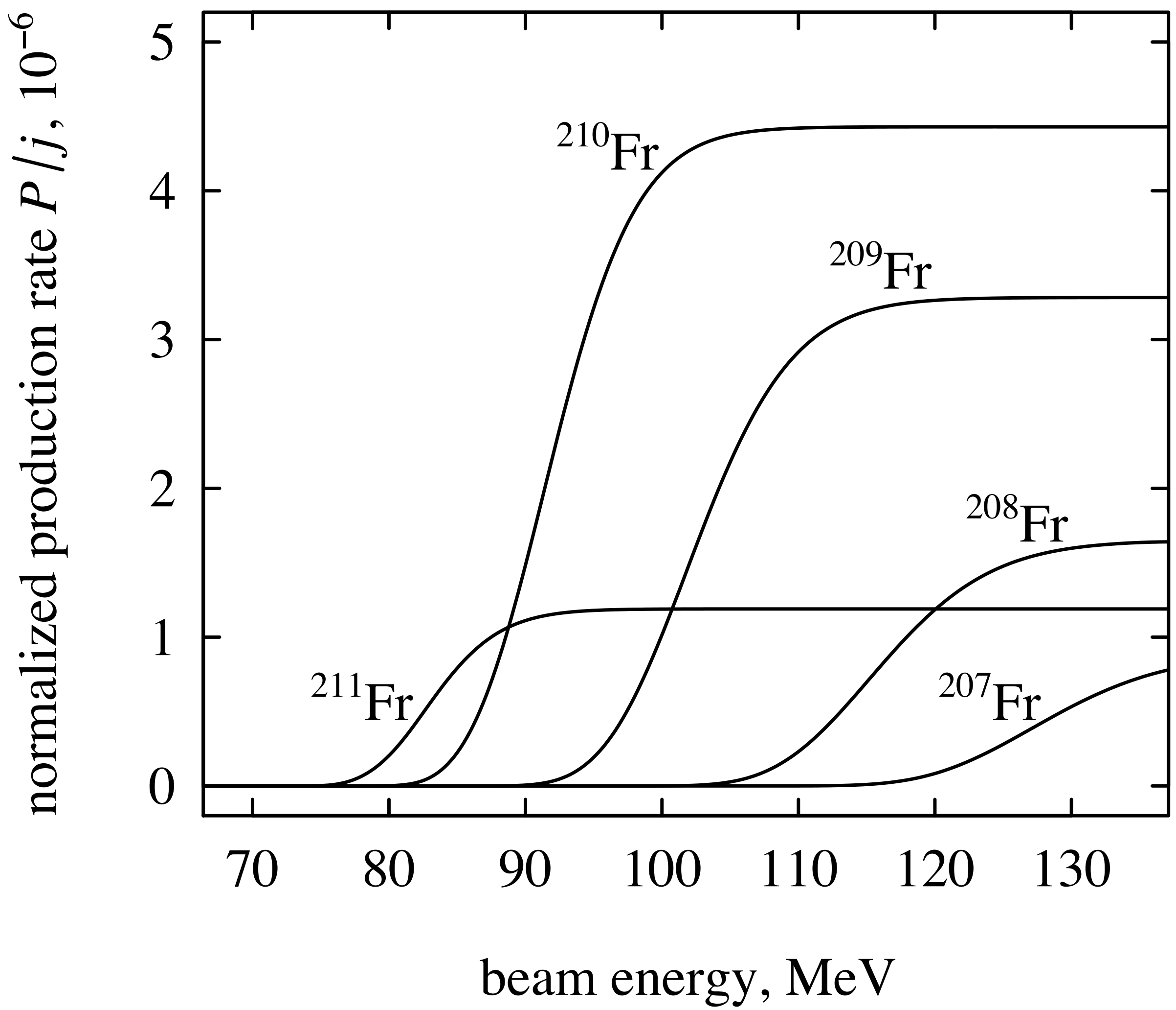
Primary beam energy chosen experimentally as trade-off between integrated cross section and diffusion time



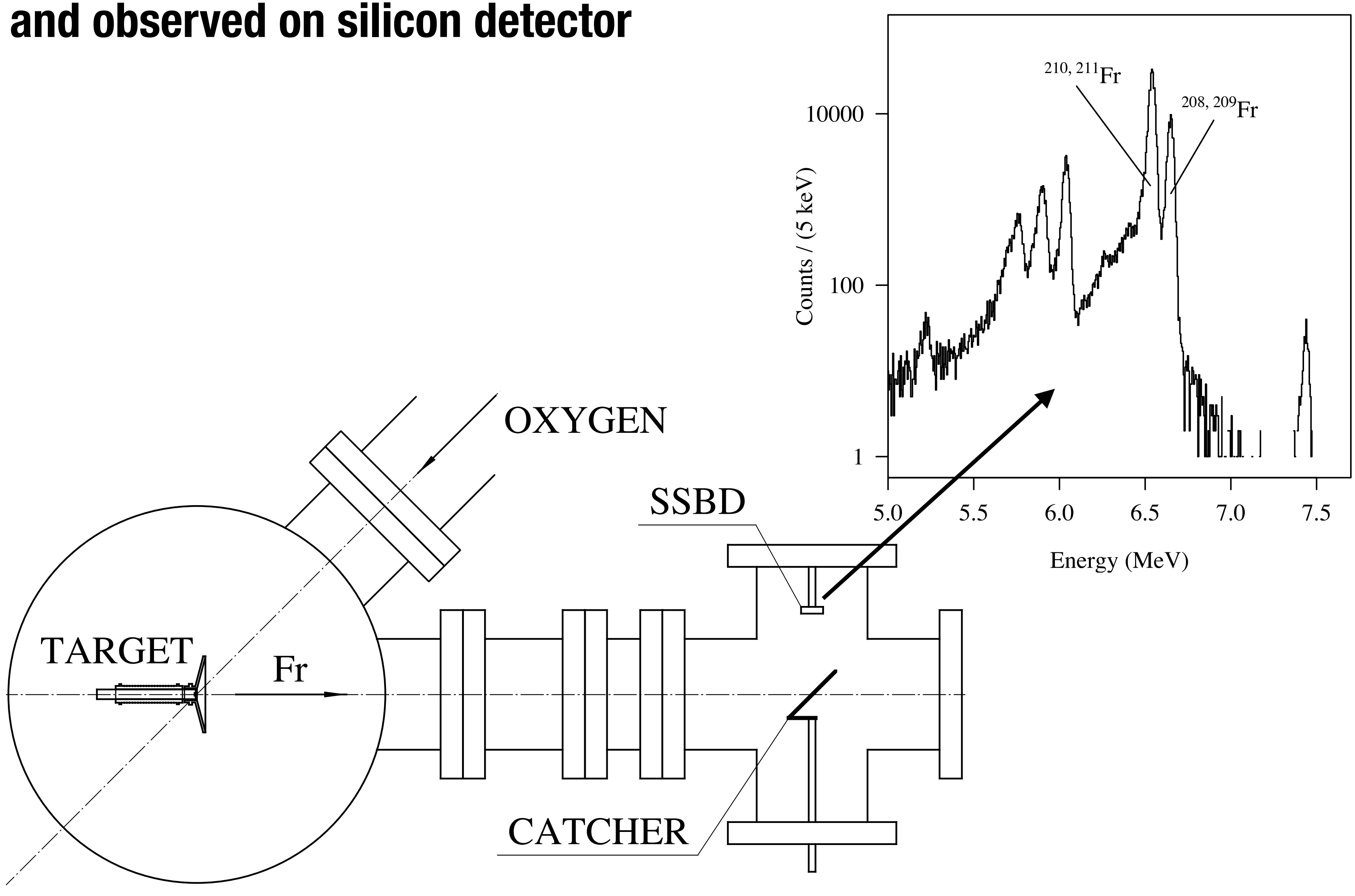
depth in gold (~ 3.5 μm / 10 MeV)

Predicted yields are calculated from integrated cross sections

$$\frac{P}{j} = \int_0^{E_0} \frac{\sigma(E')}{\langle dE/dx \rangle} \frac{N_A}{M} \, dE'$$

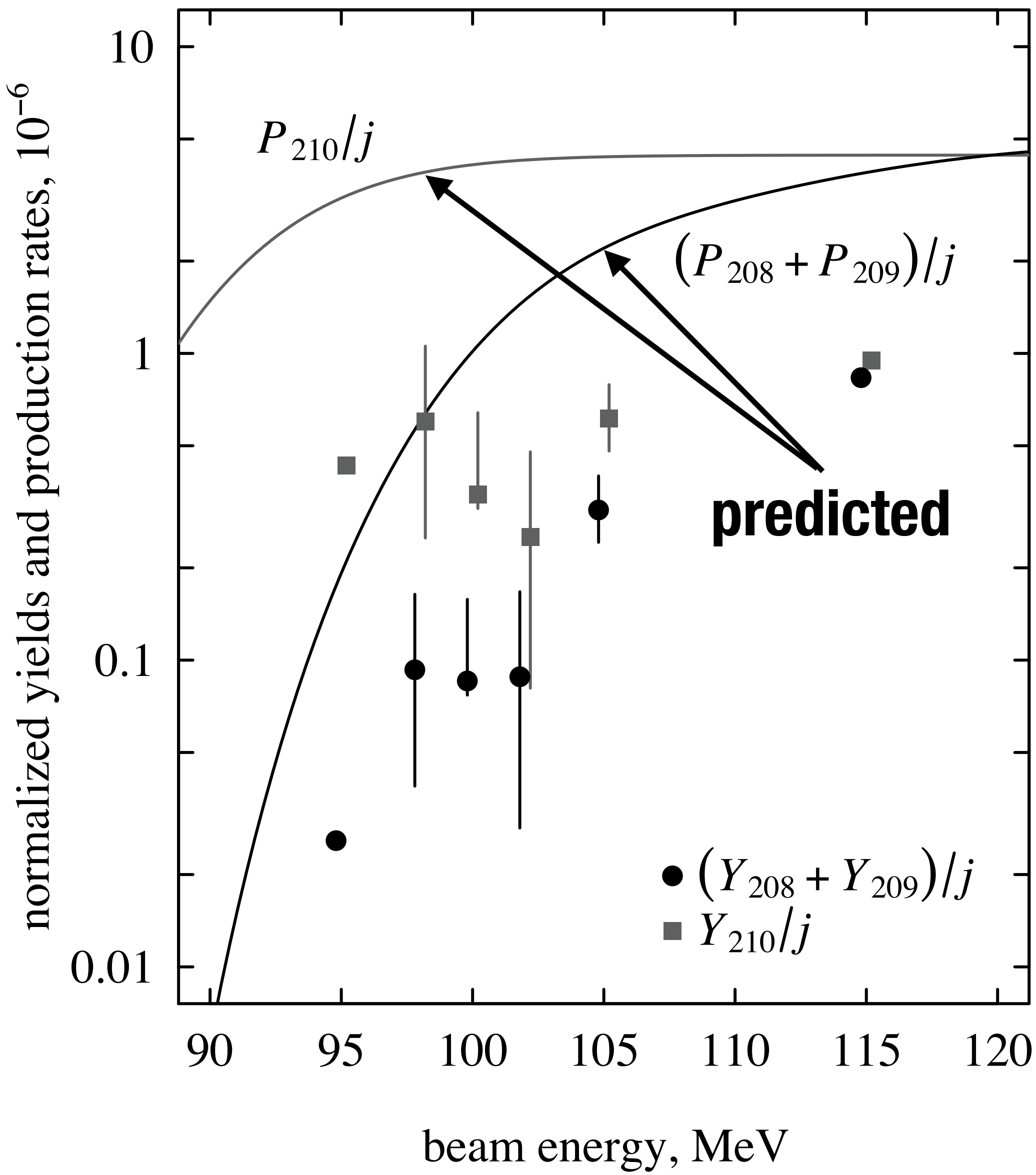


Measured yields from α decays of francium collected on catcher foil and observed on silicon detector



Stancari et al., Nucl. Instrum. Methods A 557, 390 (2006)

Measured yields vs primary beam energy



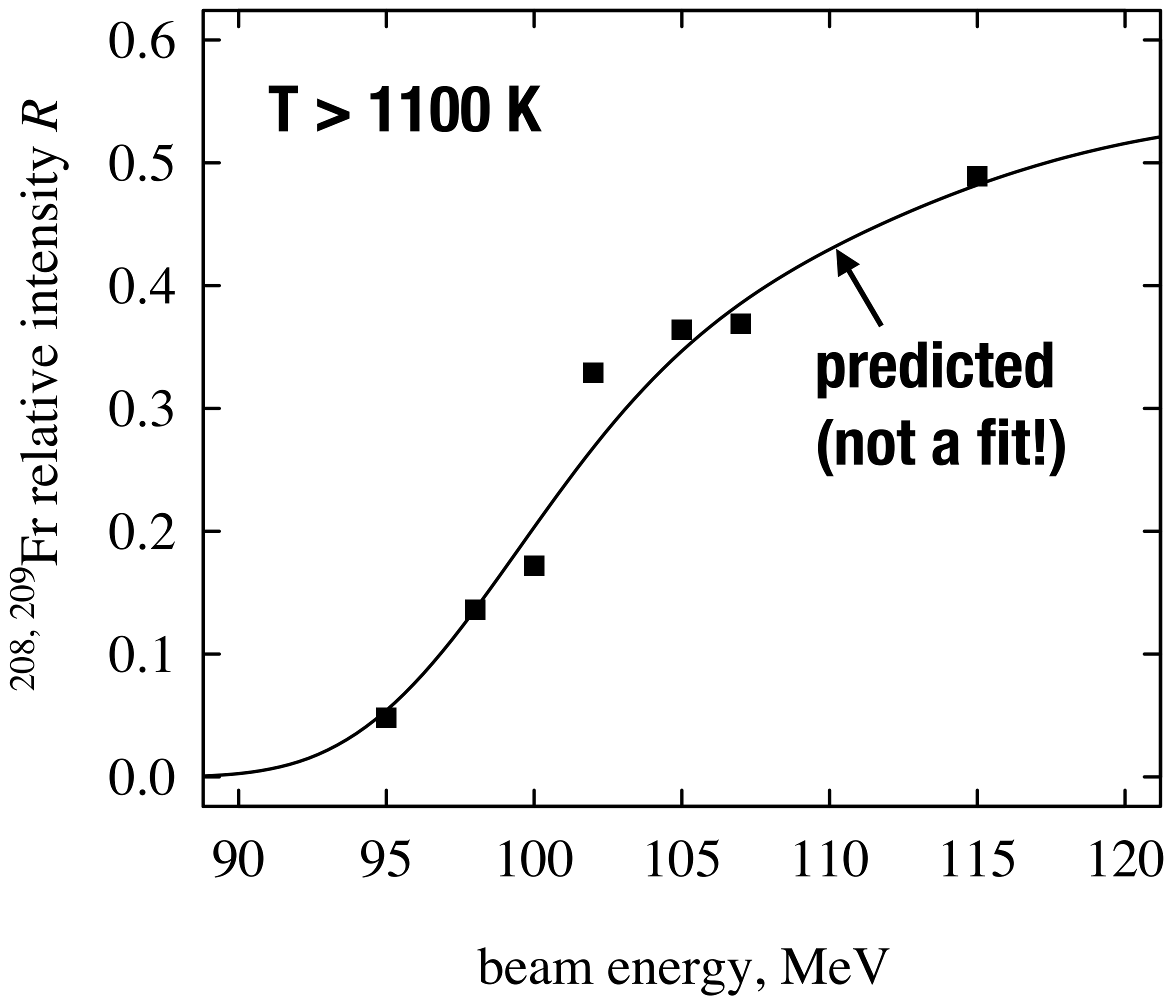
^{210}Fr yields @ 1.5 x 10^{12} ^{18}O/s:
1 x 10^6 ions/s (average)
3 x 10^6 (maximum, near melting)

Efficiency (extracted/produced) is ~15% (40% max)

Sufficient for spectroscopy
Might need ~10^9 for APV
[Sanguinetti et al., Eur. Phys. J. D 25, 3 (2003)]

Yield ratios (208 + 209) / (total) measured vs beam energy and temperature

Atomic and ionic properties (surface desorption, ionization, transport) cancel out



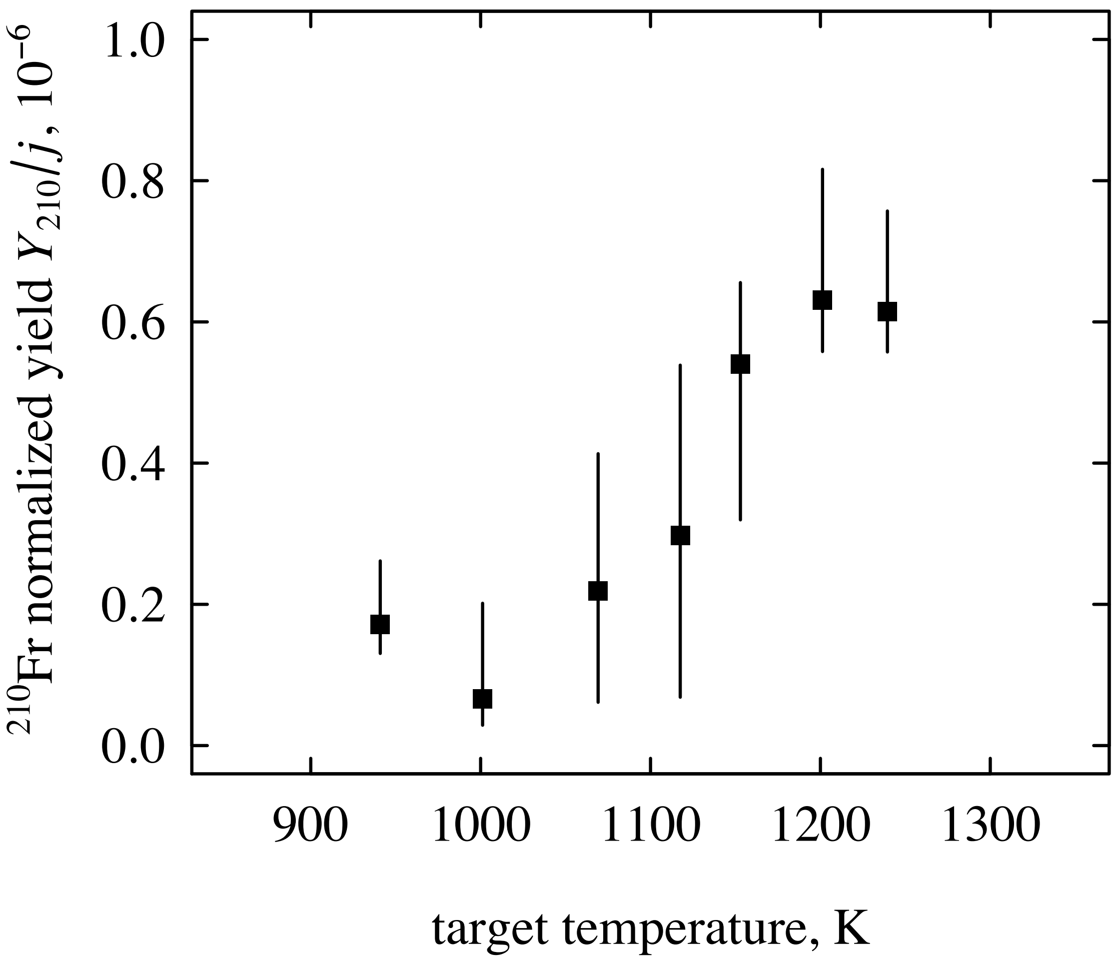
Diffusion process is efficient above 1100 K:

$t_{diffusion} \gg t_{Fr}$

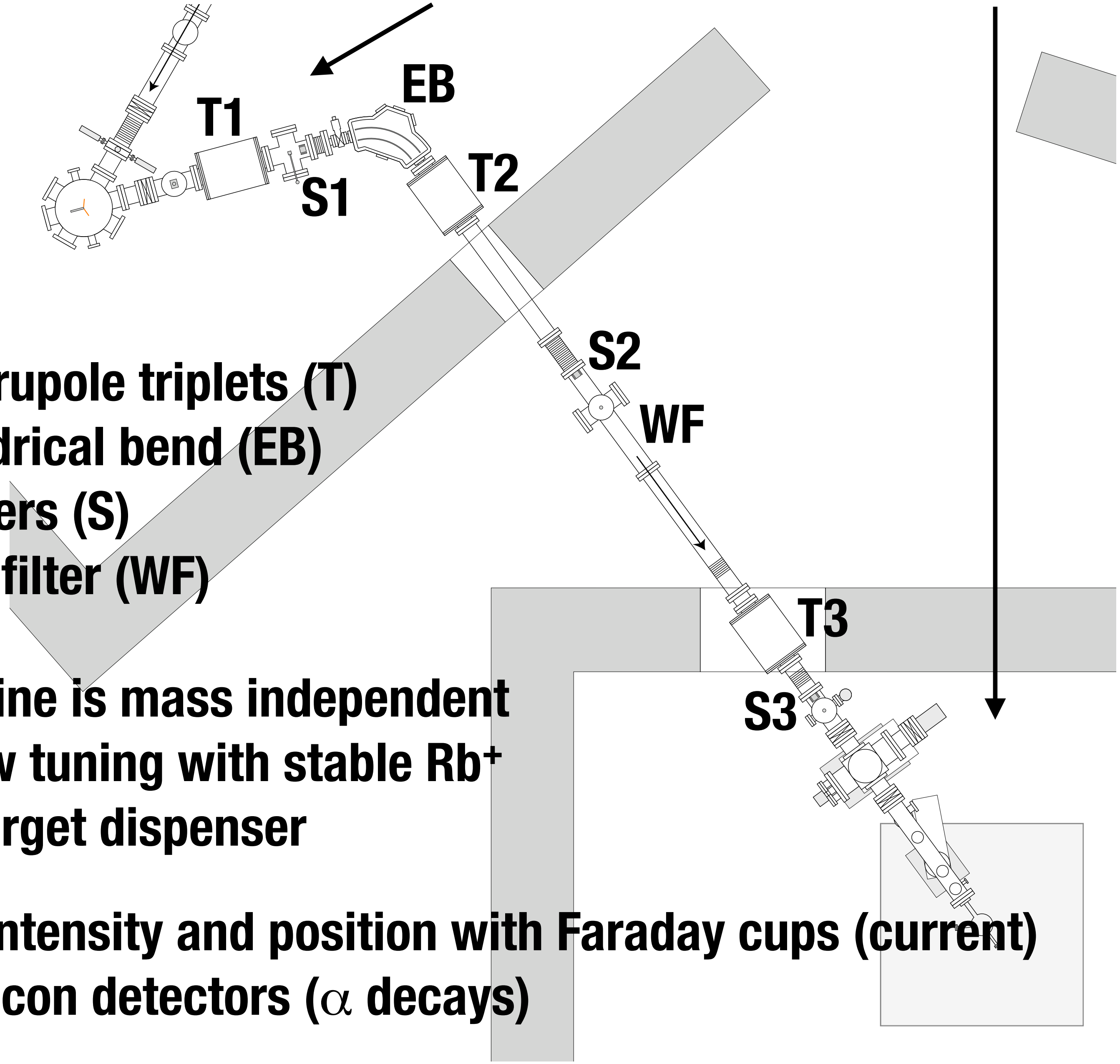
$D \gg 2 \times 10^{-9}\ cm^2/s$

Yields are limited by surface desorption

Measured yields vs temperature



Transport beam line decouples radiation and vacuum of production area from laser trapping laboratory

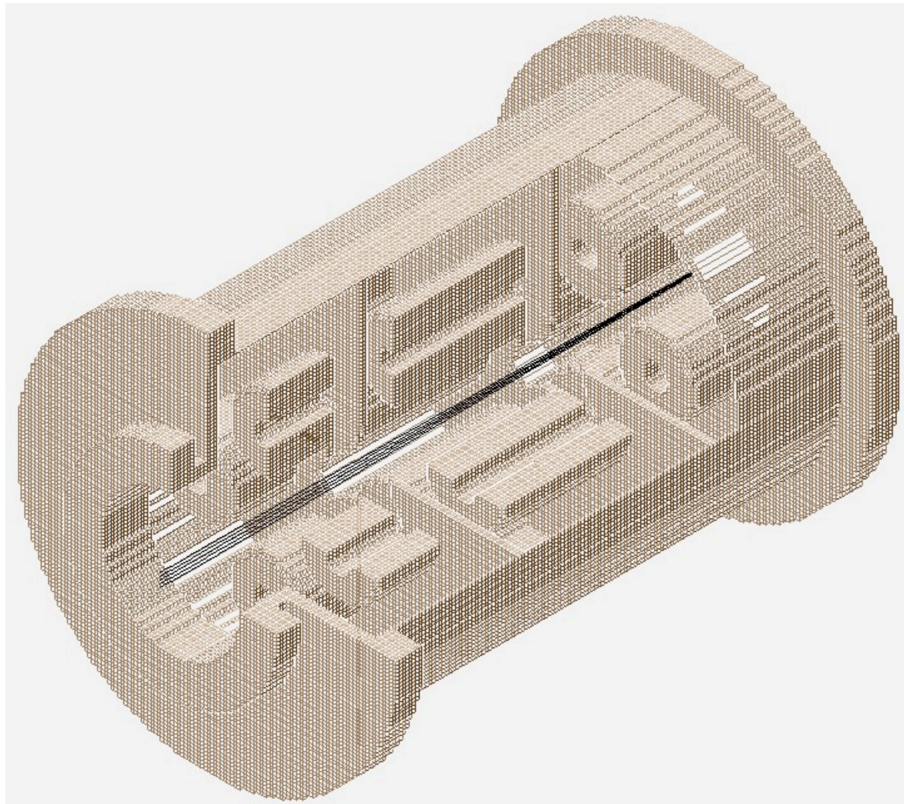


3 quadrupole triplets (T)
1 cylindrical bend (EB)
3 steerers (S)
1 Wien filter (WF)

Beam line is mass independent to allow tuning with stable Rb^+ from target dispenser

Beam intensity and position with Faraday cups (current) and silicon detectors (α decays)

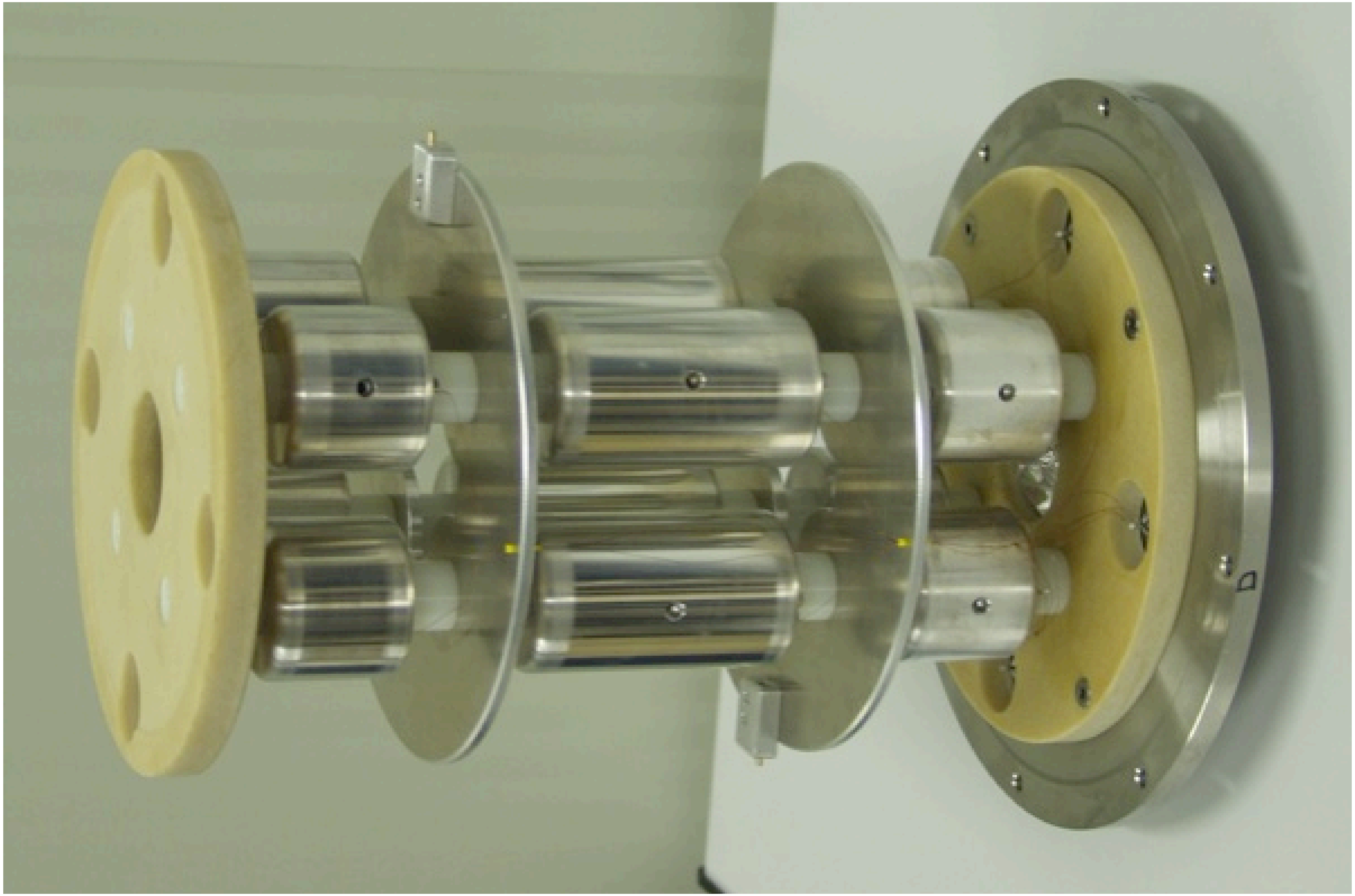
Ion optics of individual elements designed with Simion 3D



design of electrostatic quadrupole triplet

Electrode geometry defined on a discrete grid

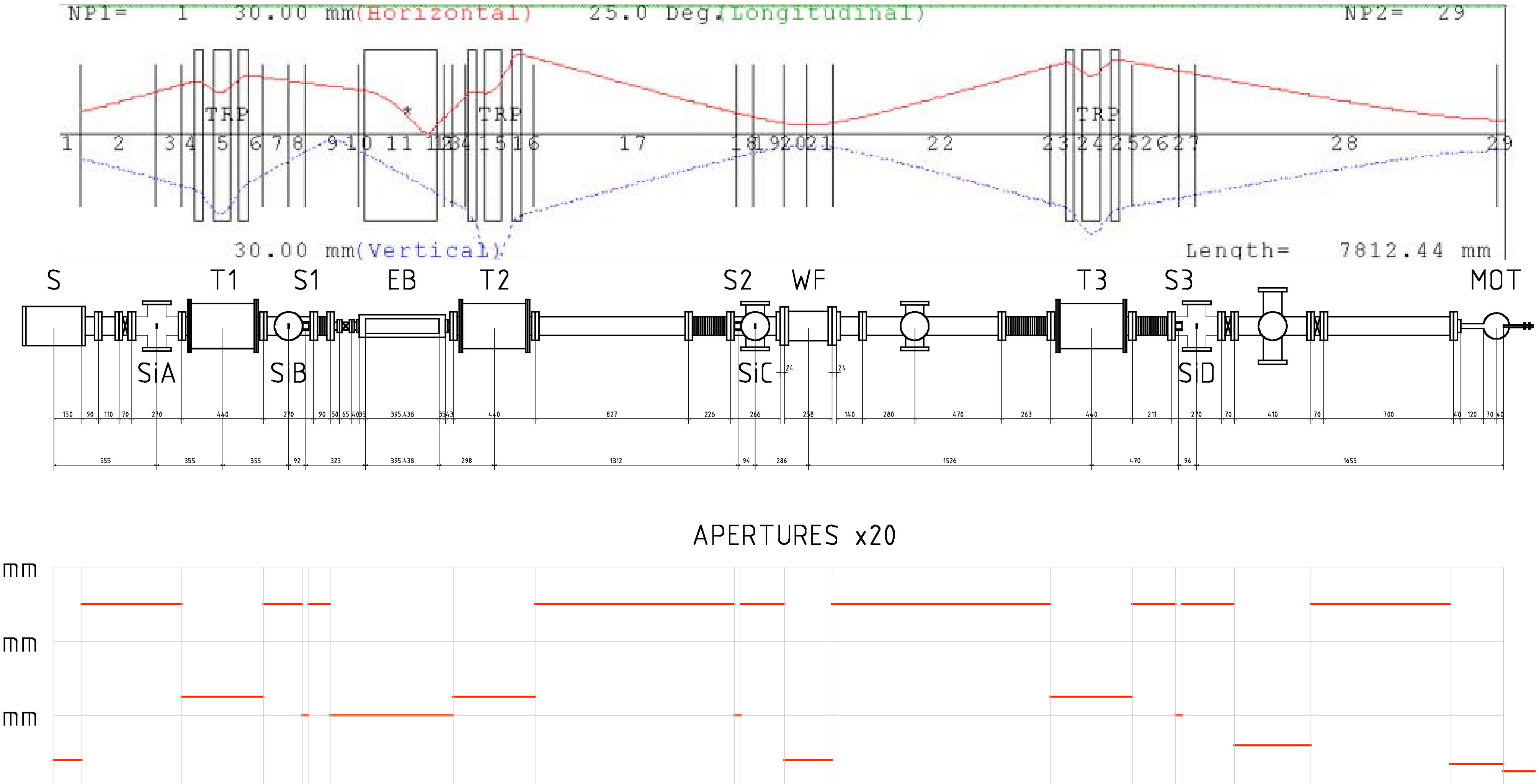
Potentials calculated with relaxation method are used to integrate trajectories



Quadrupole triplet built at LNL

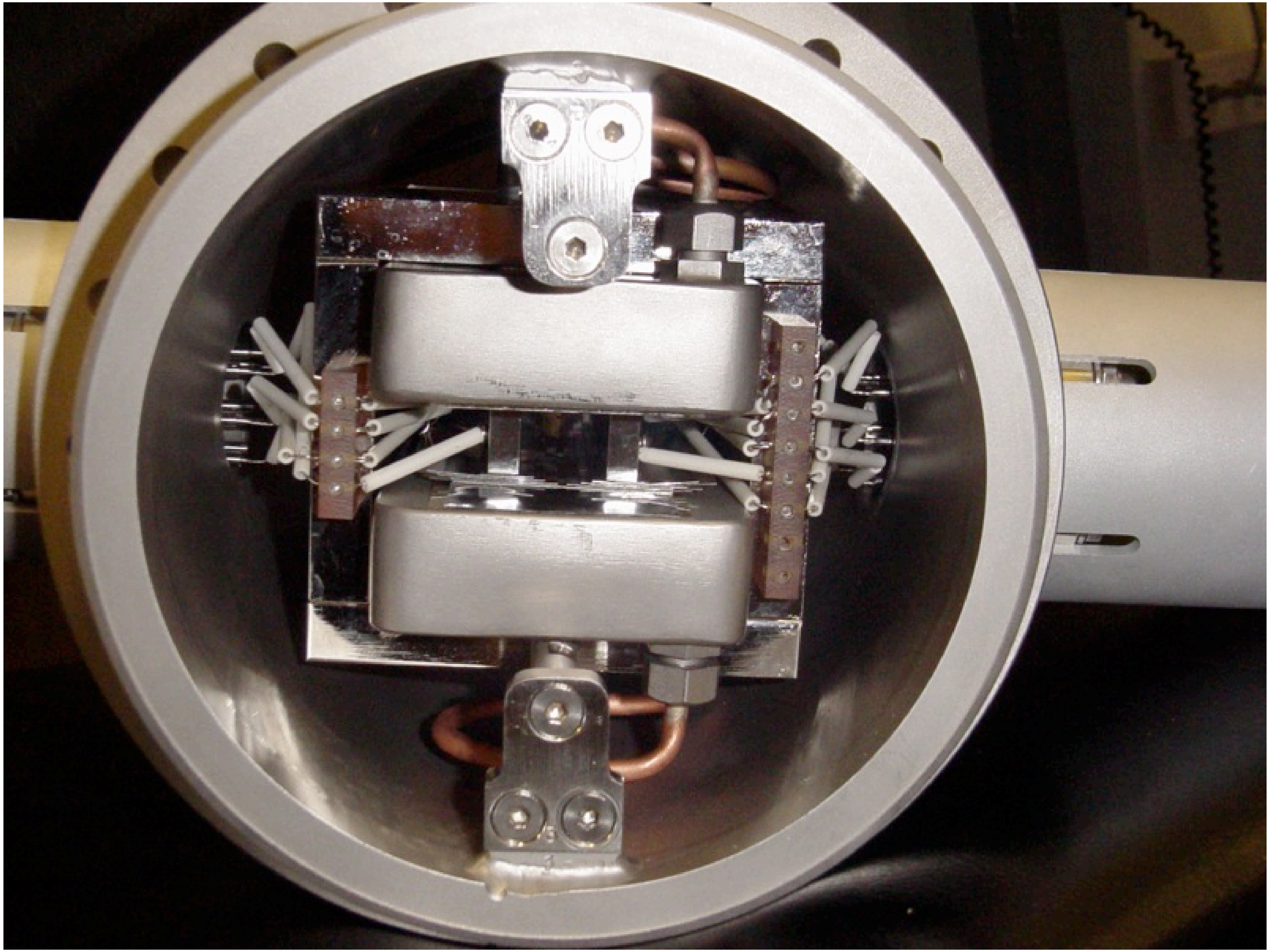
Prism built at LNL

Beam line optics **designed with pencil, paper, and Trace-3D / PBO-Lab, using transfer matrices of individual elements from Simion 3D**



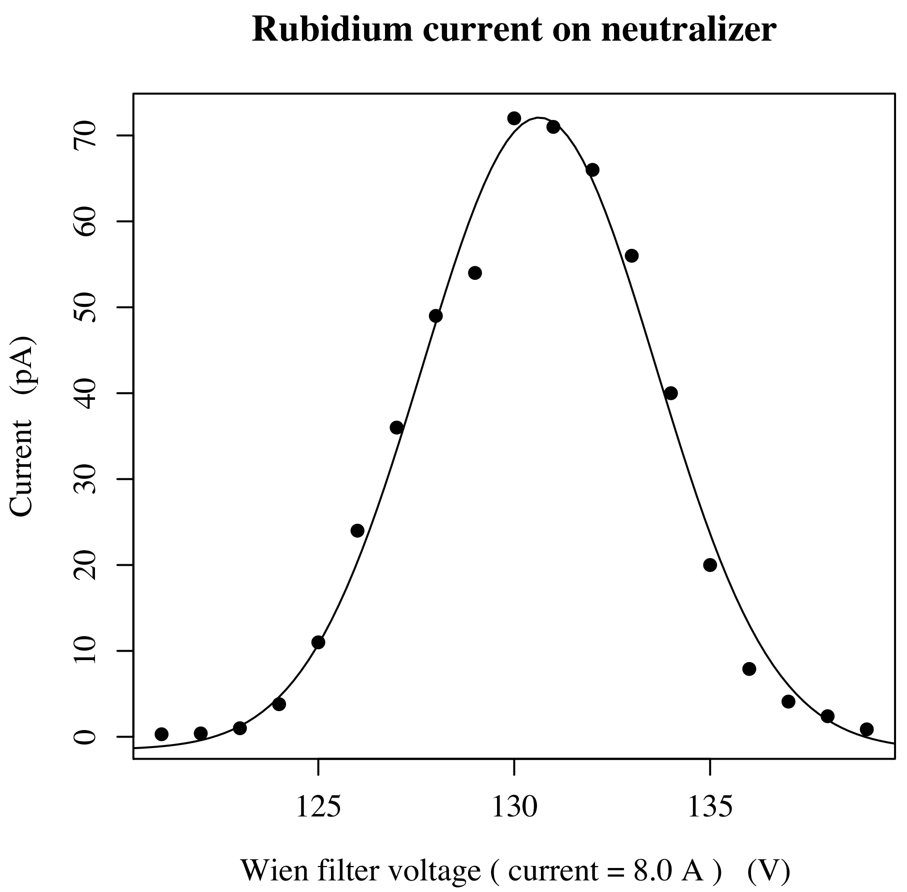
Constraints include layout of experimental hall and acceptance of MOT

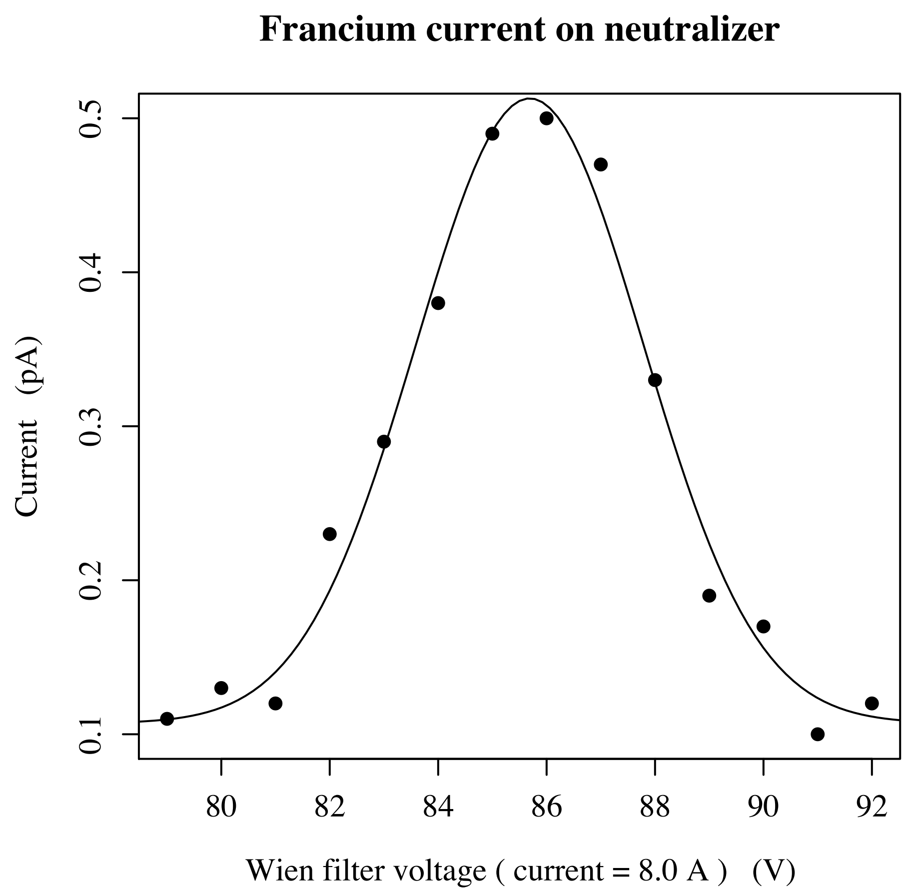
Optimized electrode voltages are within a few % of design values



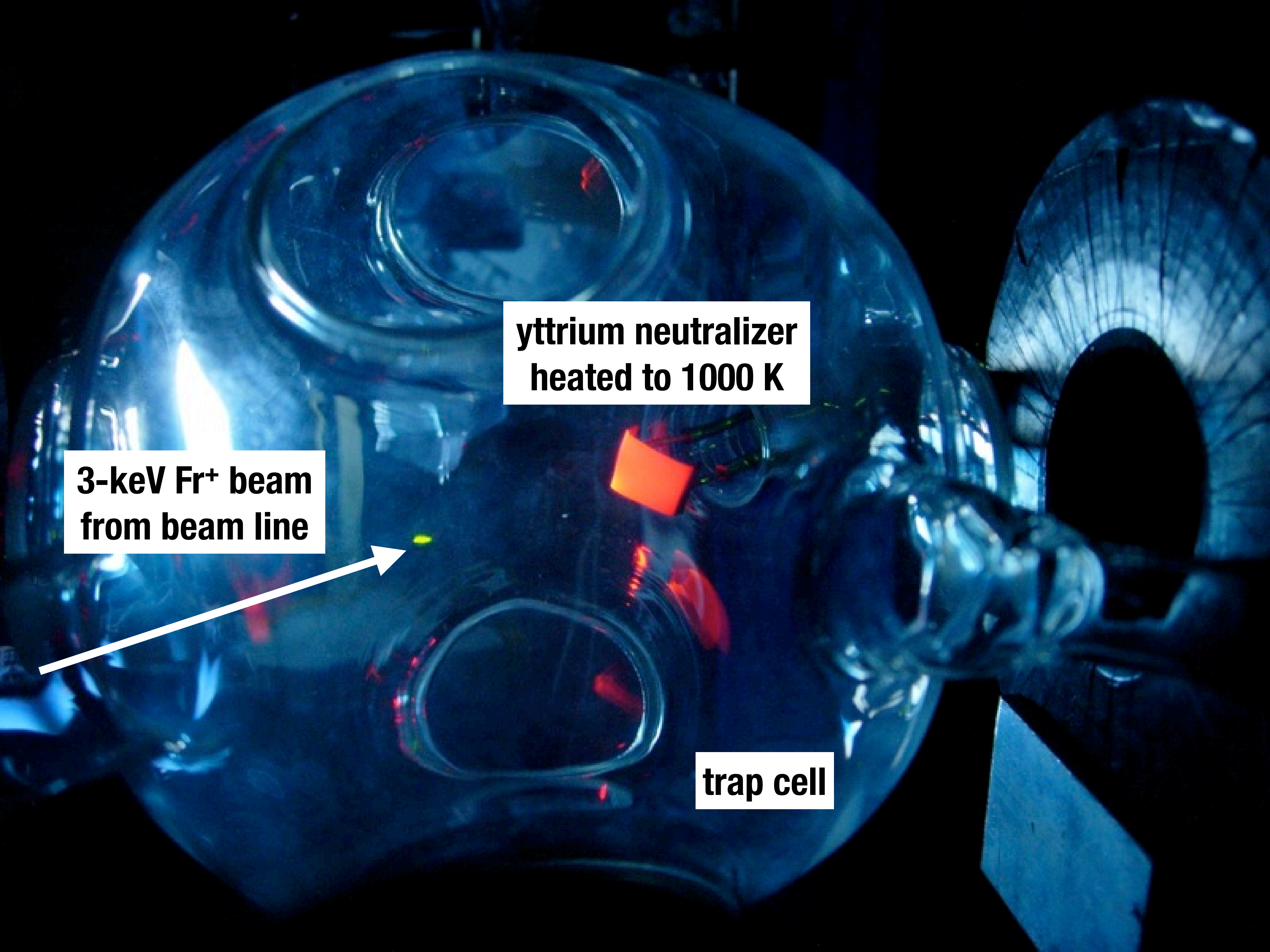
Wien filter from Colutron Research Corp., Boulder, CO

Mass selection is performed with a Wien filter (E x B velocity selector), mainly to suppress thermionic current from hot target





Wien-filter resolution set to $\Delta m/m \sim 20/210$ to accept all Fr isotopes


yttrium neutralizer
heated to 1000 K
3-keV Fr+ beam
from beam line
trap cell

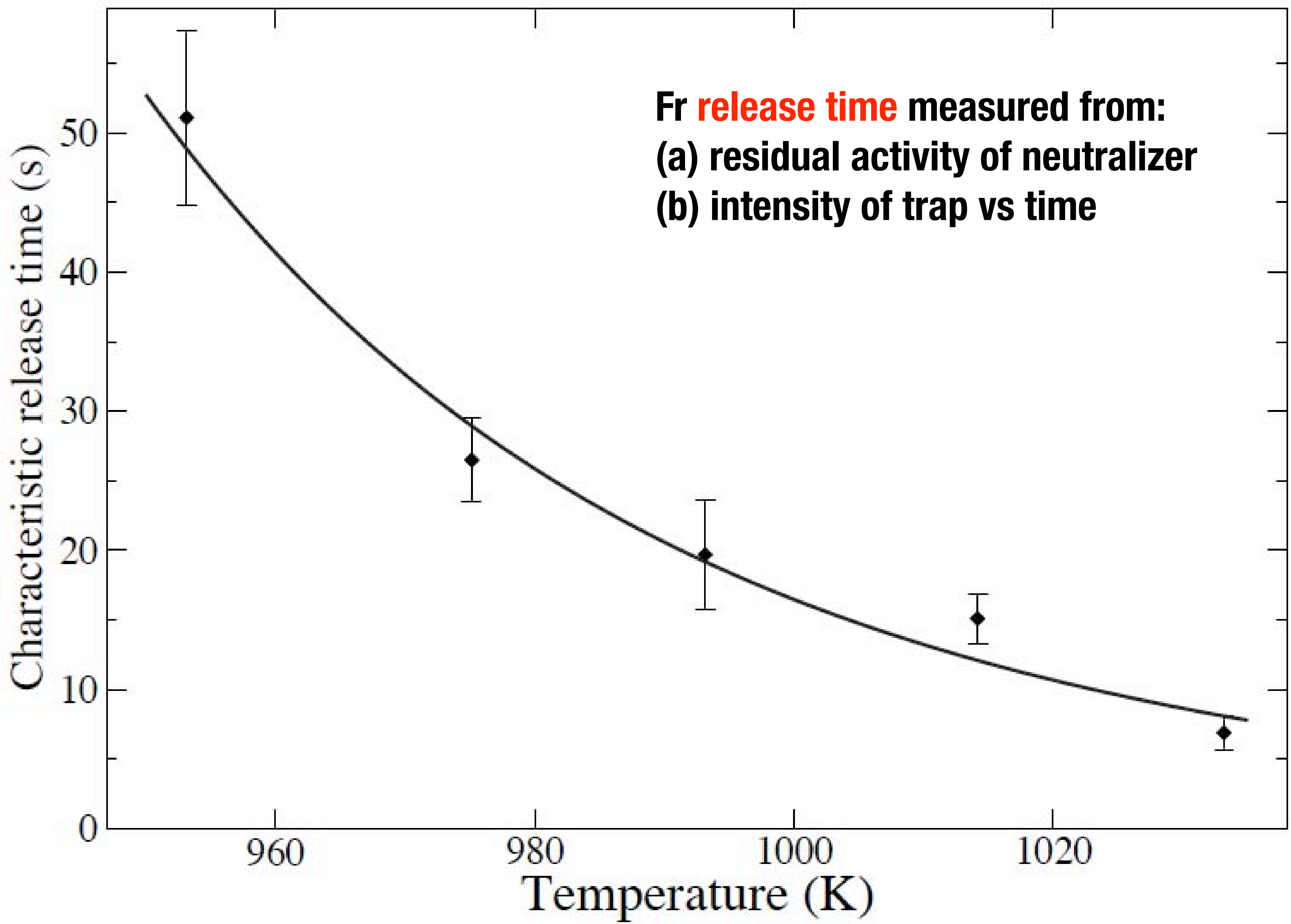
Neutralizer temperature trade-off:

increase Fr diffusion
and desorption

possible damage
of cell coating

Low **work function** of yttrium (3.1 eV) enhances release of neutral francium, whose ionization potential is 4.1 eV

(**range** of 3-keV Fr^+ in Y is 5.1 nm)


Fr release time measured from:
(a) residual activity of neutralizer
(b) intensity of trap vs time
Characteristic release time (s)
Temperature (K)
0
10
20
30
40
50
960
980
1000
1020

The magneto-optical trap (MOT) combines

production of optical molasses by Doppler cooling (deceleration)

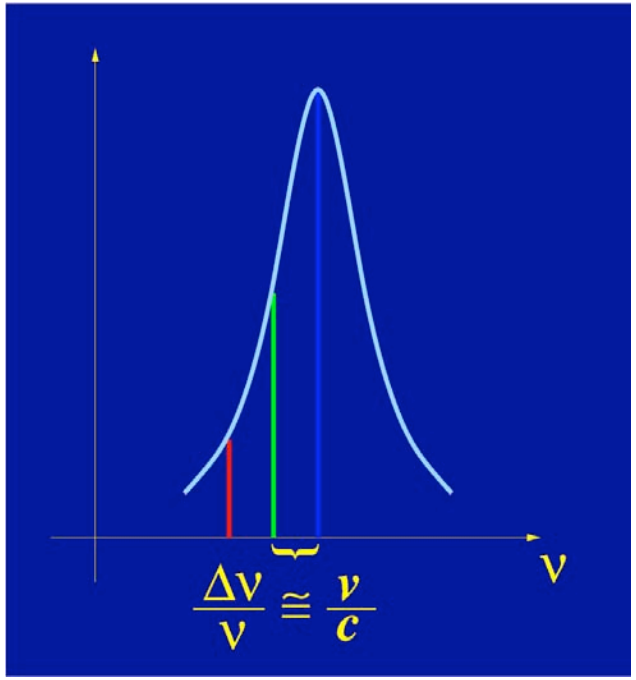
and

position-dependent Zeeman shifts (confinement)

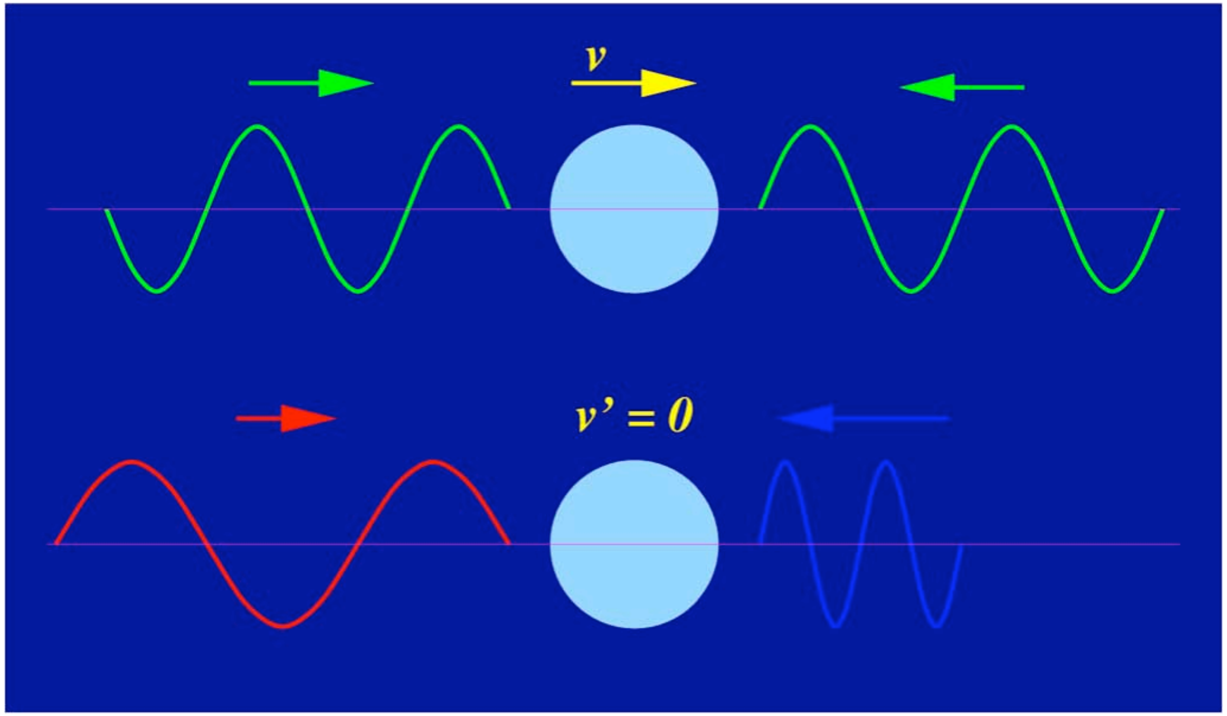
to produce a cold (~mK) cloud of atoms from a vapor

[Raab et al., Phys. Rev. Lett. 59, 2631 (1987)]

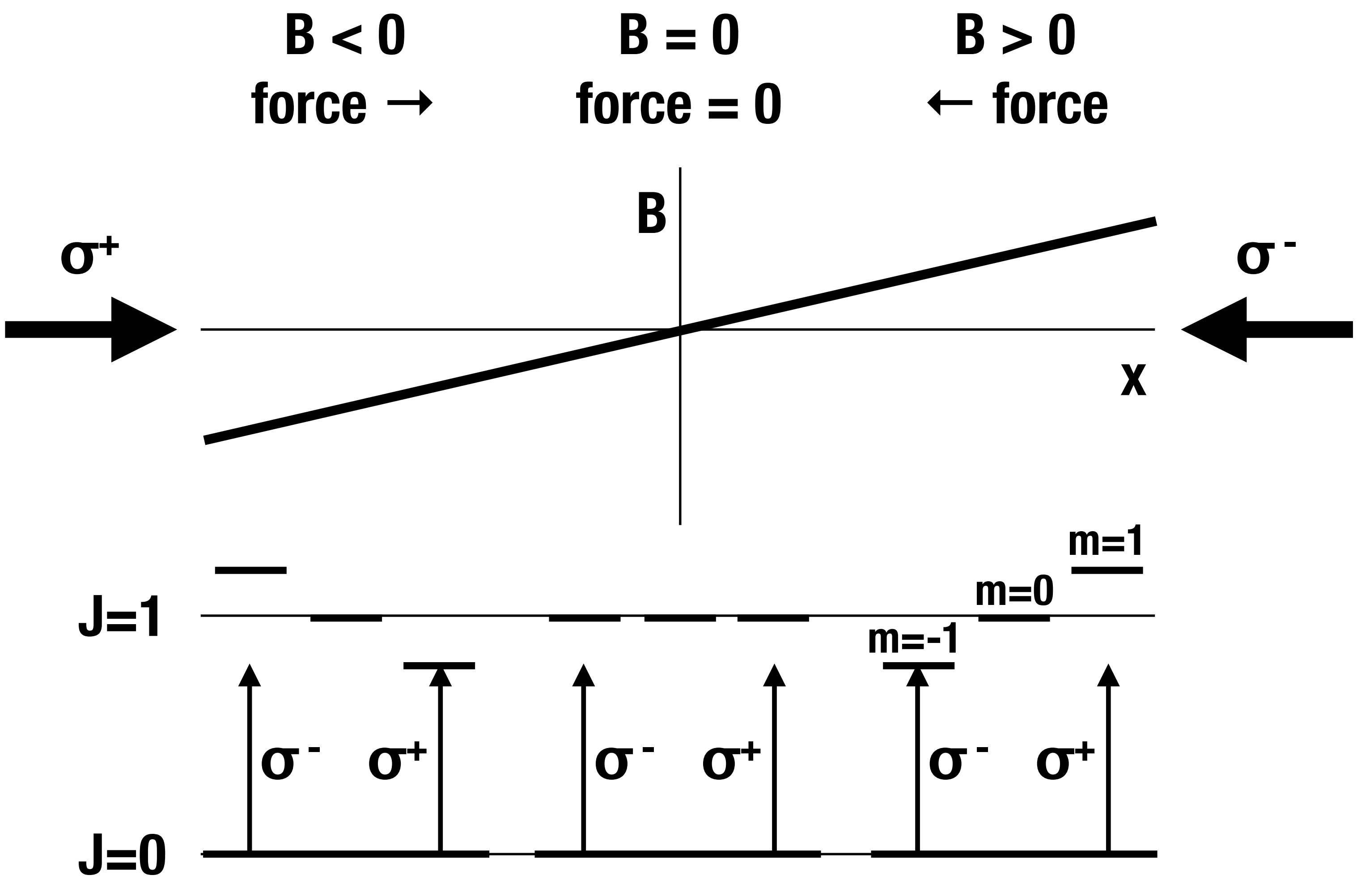
Its main components are
6 orthogonal red-detuned circularly-polarized laser beams and
a constant-gradient magnetic field

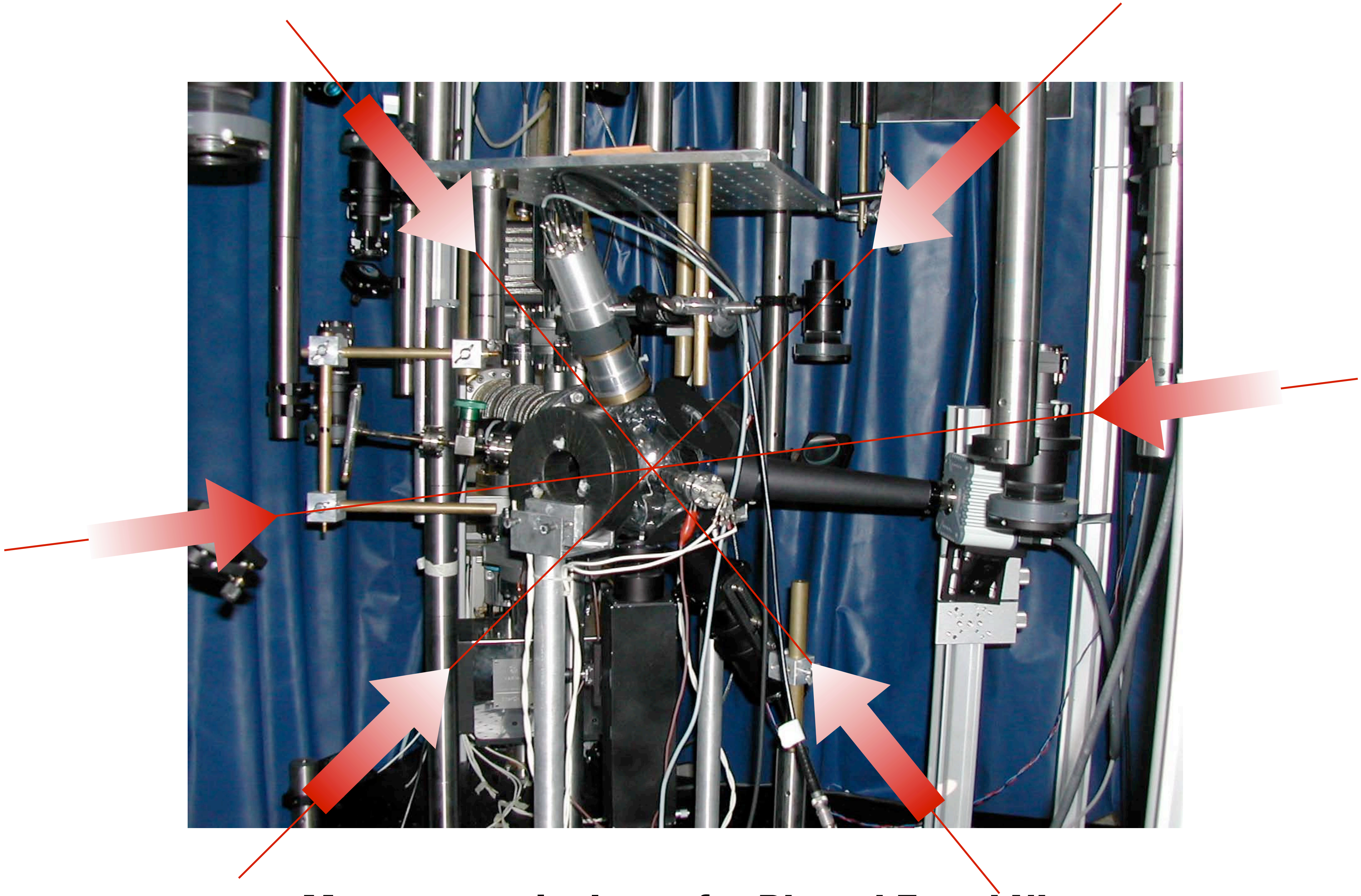


Doppler cooling**: an atom in a red-detuned field feels a viscous force ⇒ “optical molasses”**



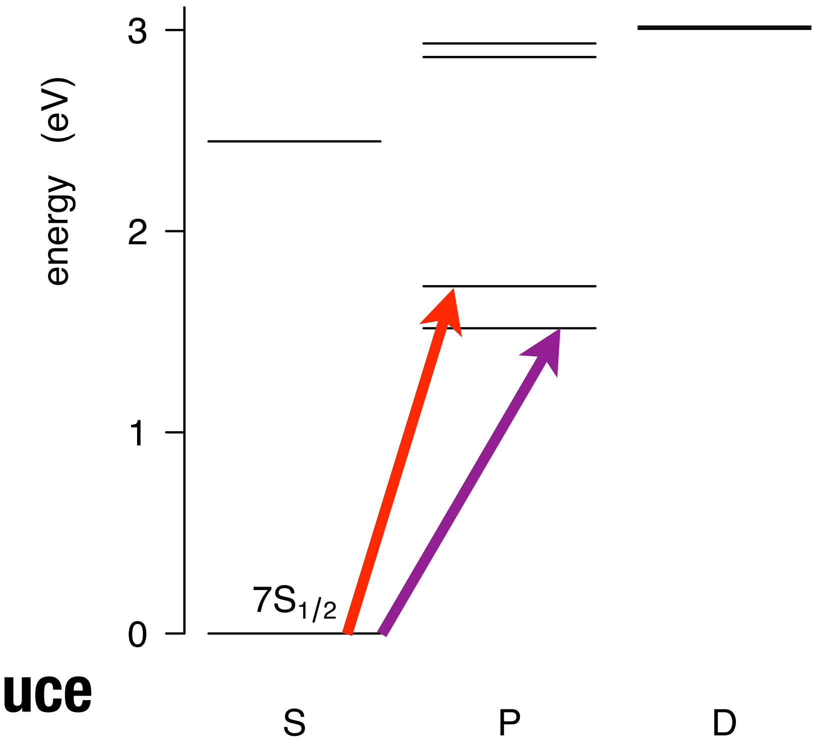
Zeeman-shift confinement: in an inhomogeneous magnetic field, the red-detuned laser beams create a position-dependent confining force if circularly polarized





Magneto-optical trap for Rb and Fr at LNL

Trapping transition is D_2 line at 718 nm, excited with Ti:sapphire laser

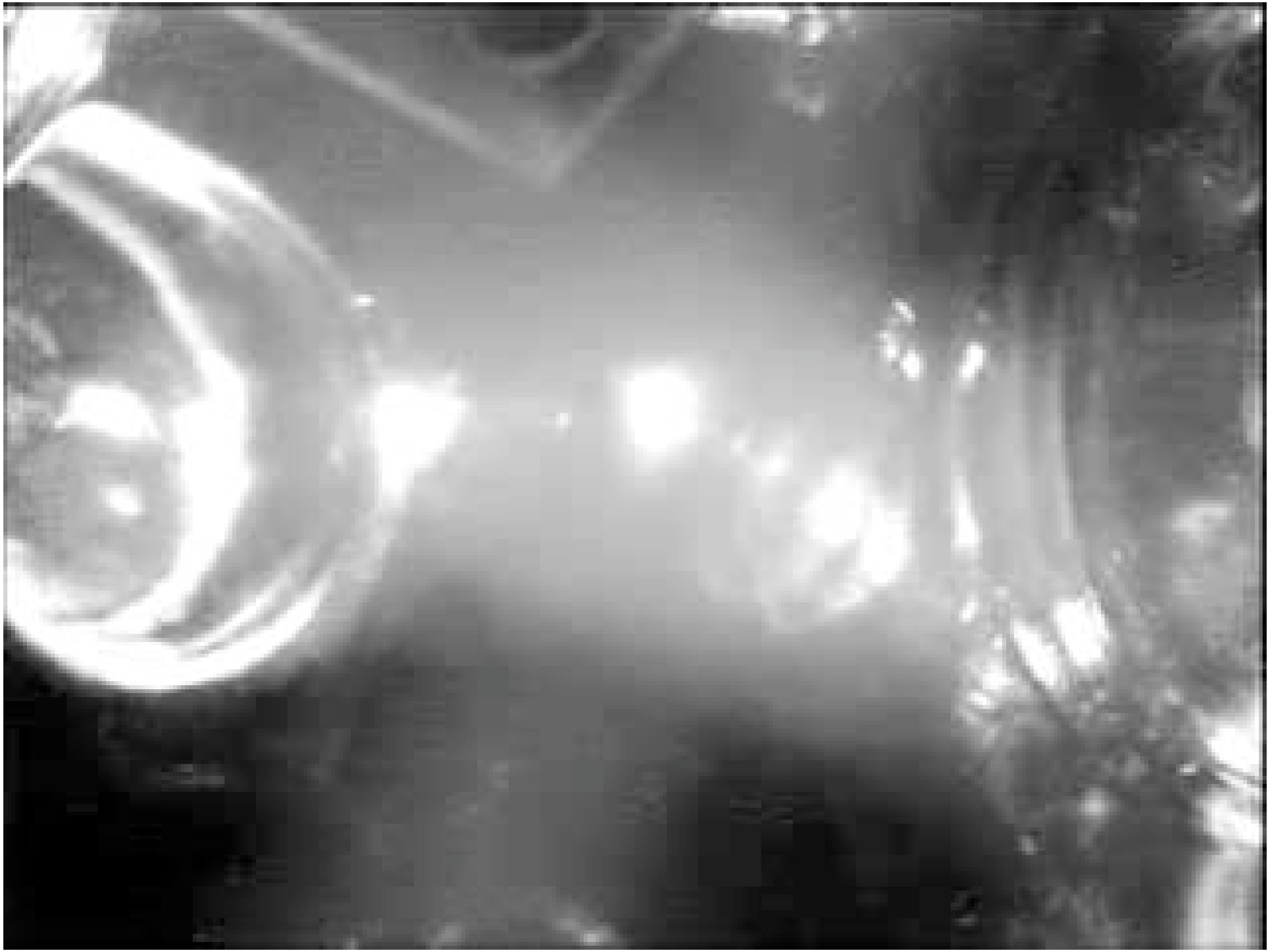


Repumping transition at 817 nm, with diode laser

Laser beam diameter is 4 cm

Pyrex cell walls coated with Dryfilm to reduce adsorption (1 $\rightarrow$ 10^4 bounces)

Typical vacuum in cell is ~10^{-9} mbar



Rubidium trap: response to changing magnetic field and laser frequency

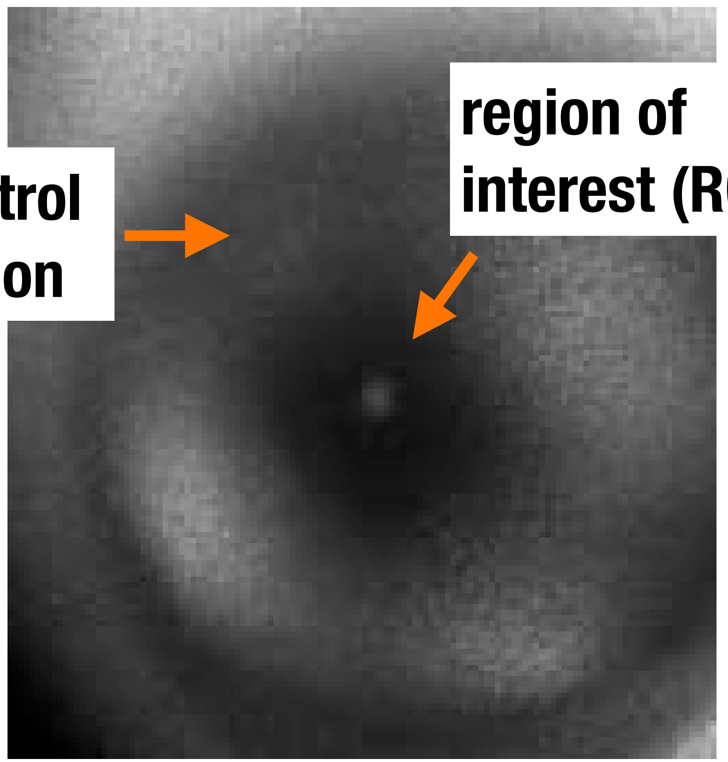
Light detection is challenging:

- small number of atoms
- background from stray light

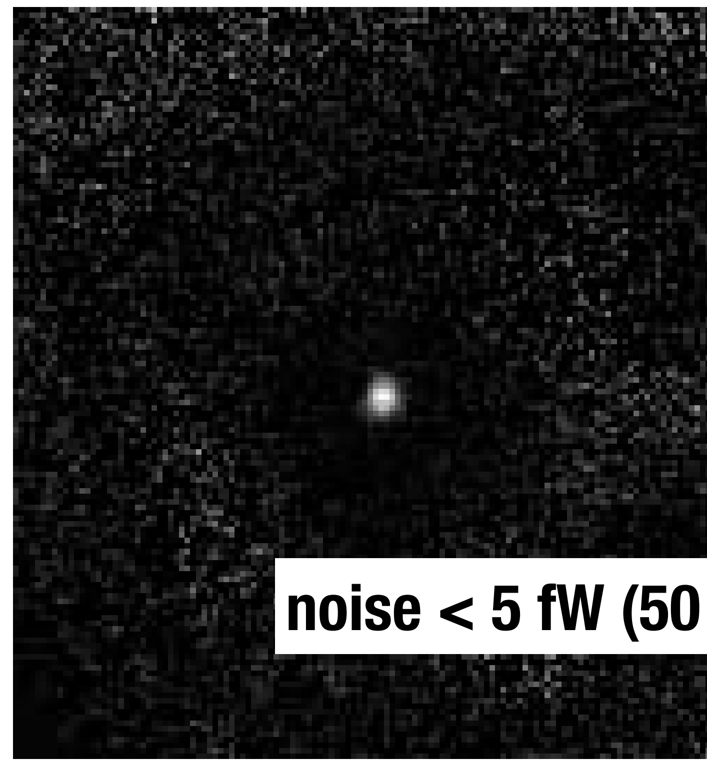
→

- photodiode and lock-in technique
- cooled CCD camera

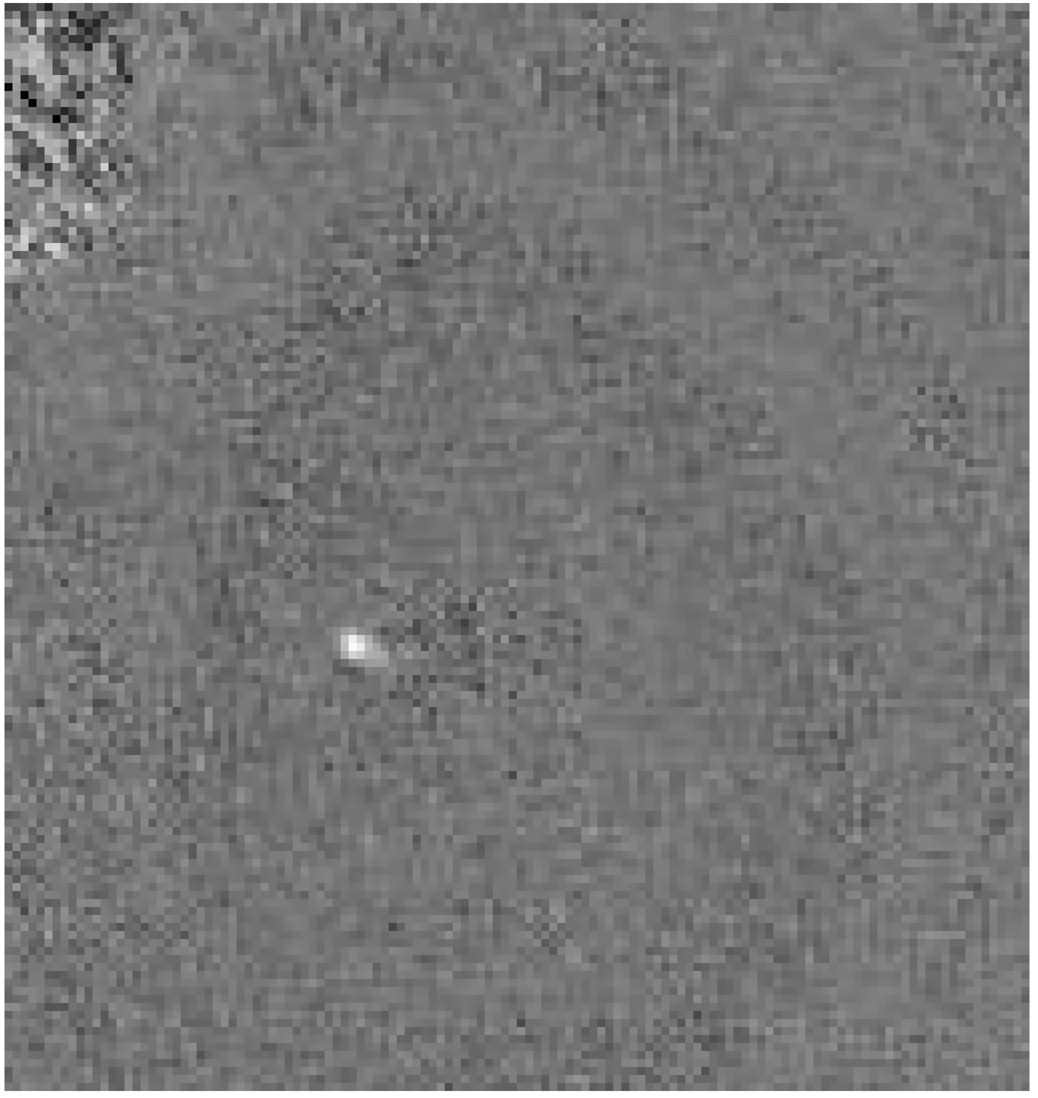
Detection with cooled CCD camera: Rb trap example (500 atoms)



raw image

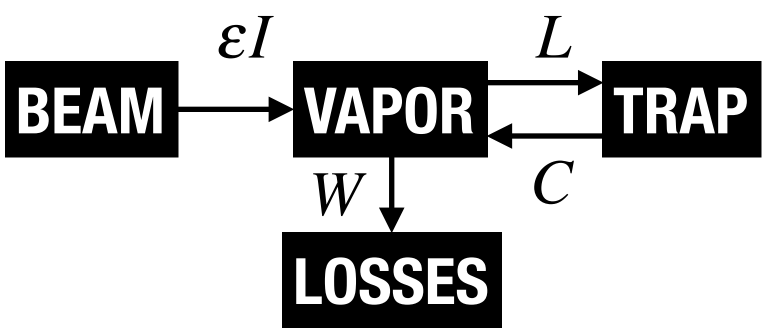


background subtracted



^{210}Fr trap observed!

Trapping efficiency depends on several factors, including cell coating and geometry (through W), vacuum (C), laser power (L), and neutralizer temperature (ε)



trap loading rate

neutralization efficiency

number of trapped atoms

$$N_t = \frac{L\varepsilon}{CW} I$$

incoming ion flux

trap loss rate

vapor cell loss rate

$$\frac{L\varepsilon}{CW} \sim 2 \times 10^{-3}\ \mathrm{s}$$

First results on precision laser spectroscopy of ^{209}Fr, ^{210}Fr and ^{211}Fr have been obtained

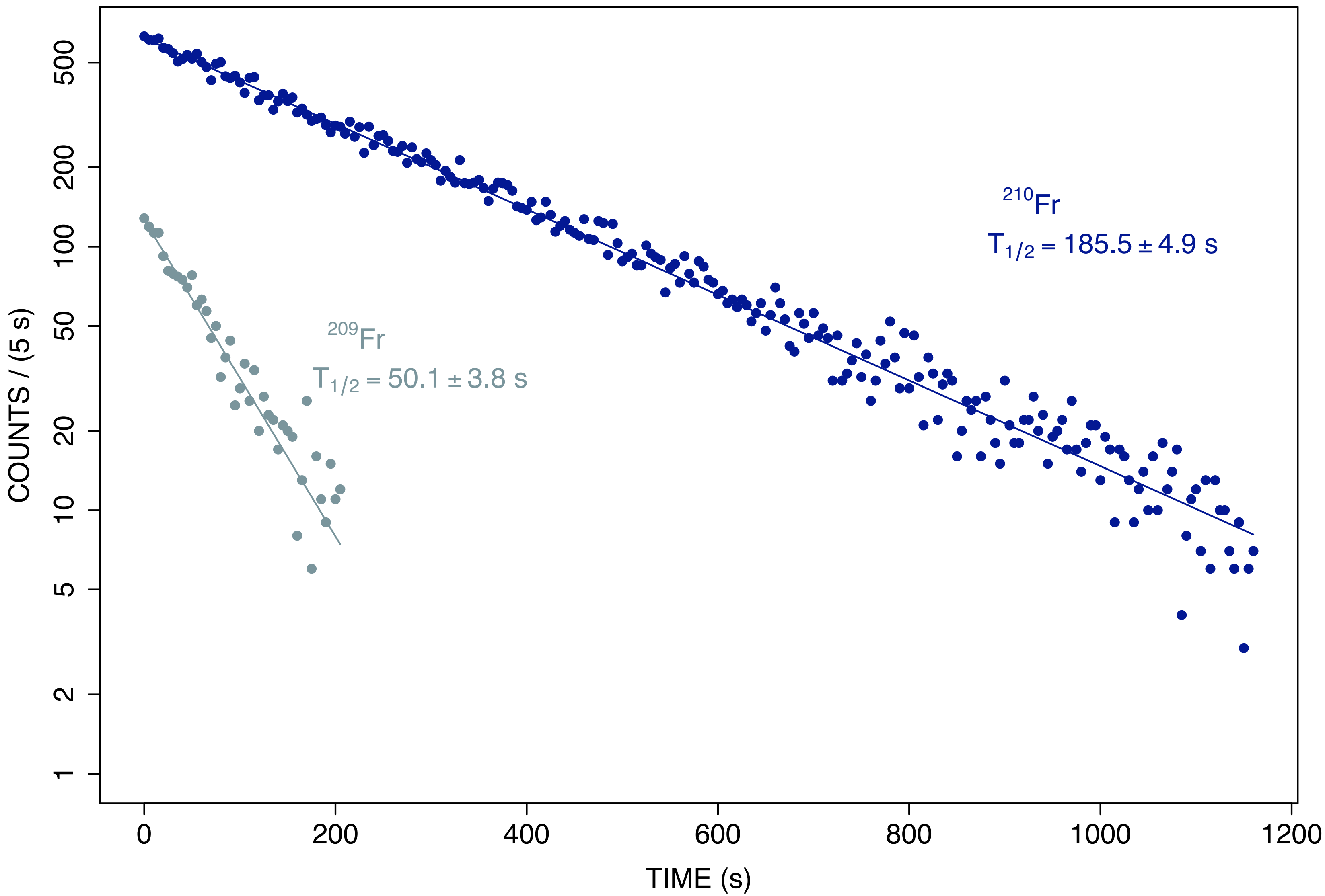
Precision on trapping transitions improved by factor ~20 with confocal Fabry-Perot interferometer calibrated with two-photon Rb transition

^{210}Fr example:

	trap freq. (MHz)	uncertainty (MHz)
LNL (preliminary)	417,412,490	$\boxed{4}$
Stony Brook	417,412,460	90

Atomic spectroscopy necessary to test relativistic many-body calculations. Continue with search of unobserved transitions.

We can easily improve precision on some francium lifetimes



Measurements of atomic parity violation in forbidden transitions to 1% precision will probably require intensities ~10^9 ions/s [Sanguinetti et al., Eur. Phys. J. D 25, 3 (2003)]

Several options are being explored:

. study alternative observables, such as linear Stark shifts [Bouchiat, arXiv:0711.0337v2] with ~10^4 trapped atoms

. duplicate part of apparatus at CERN/ISOLDE

. study feasibility of a recirculating-beam ion source ⟵

Production of secondary beams with standard techniques is usually inefficient (~10^{-6}): most interactions are electromagnetic, not nuclear

One may wish to re-use the primary beam until the desired reaction is obtained: a recirculating-beam ion source

The negative effects of the target on the primary beam need to be compensated

It was recently proposed to produce ^{8}Li and ^{8}B beams (for beta beams, hadron therapy) from a primary beam stored in a small ring with an internal thin target. Ionization cooling could provide reasonable lifetimes. [Rubbia et al., NIM A 568, 475 (2006); Neuffer, NIM A, in press (2007)]

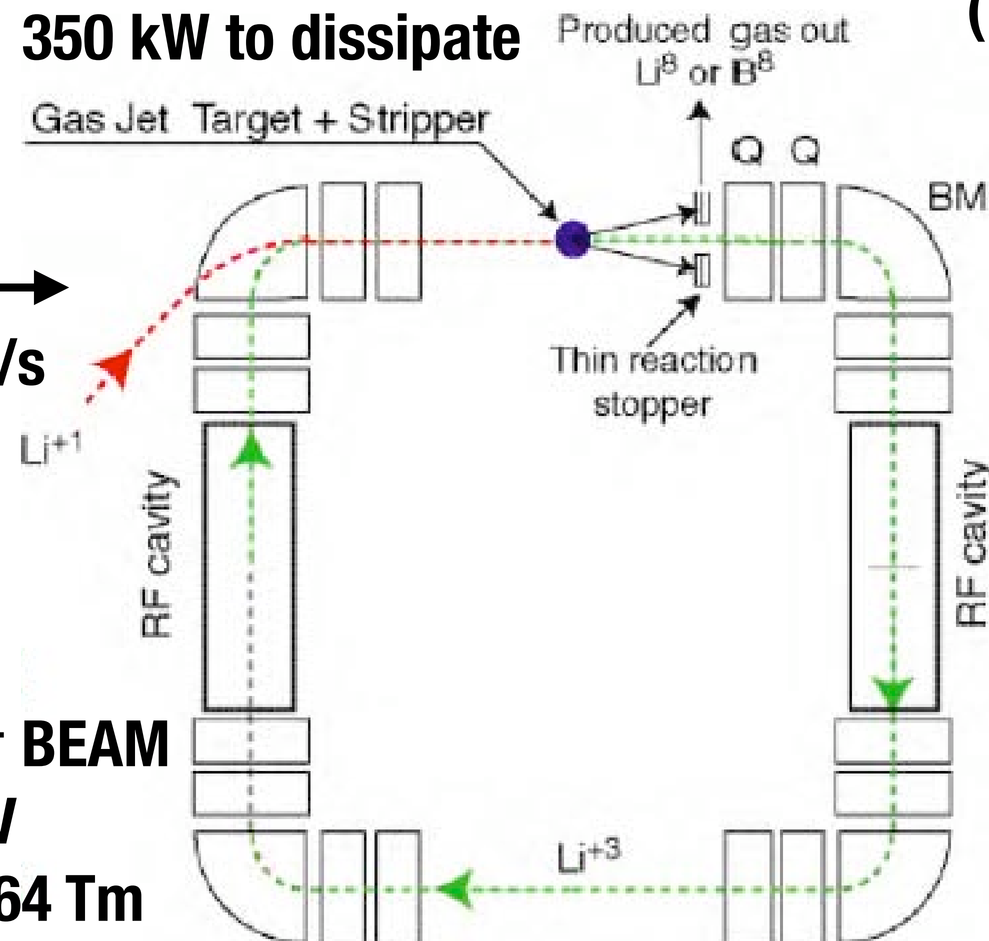
yield: $$Y = \phi_{\text{in}}\, \sigma\, n_{\text{turns}}\, \Delta x / m_{\text{target}}$$

input flux — useful cross section — lifetime (# of turns) — target thickness

D_2 TARGET
$\Delta x = 0.3$ mg/cm^2
$\Delta E = 300$ keV/ion
350 kW to dissipate

→ OUTPUT
10^{14} d(^{7}Li,p)^{8}Li reactions/s
(10^{15} total)

INPUT →
10^{15} ^{7}Li$^+$ ions/s
160 μA



RF BEAM POWER
(300 kV)(3.5 A)/3
= 350 kW

STORED ^{7}Li^{3+} BEAM
25 MeV
(B rho) = 0.64 Tm
lifetime 1.5 ms (10^4 turns)
10^{12} ions, 3.5 A
circumference 4 m

[Rubbia et al., NIM A 568, 475 (2006)]

Could this scheme work for francium?

→ OUTPUT

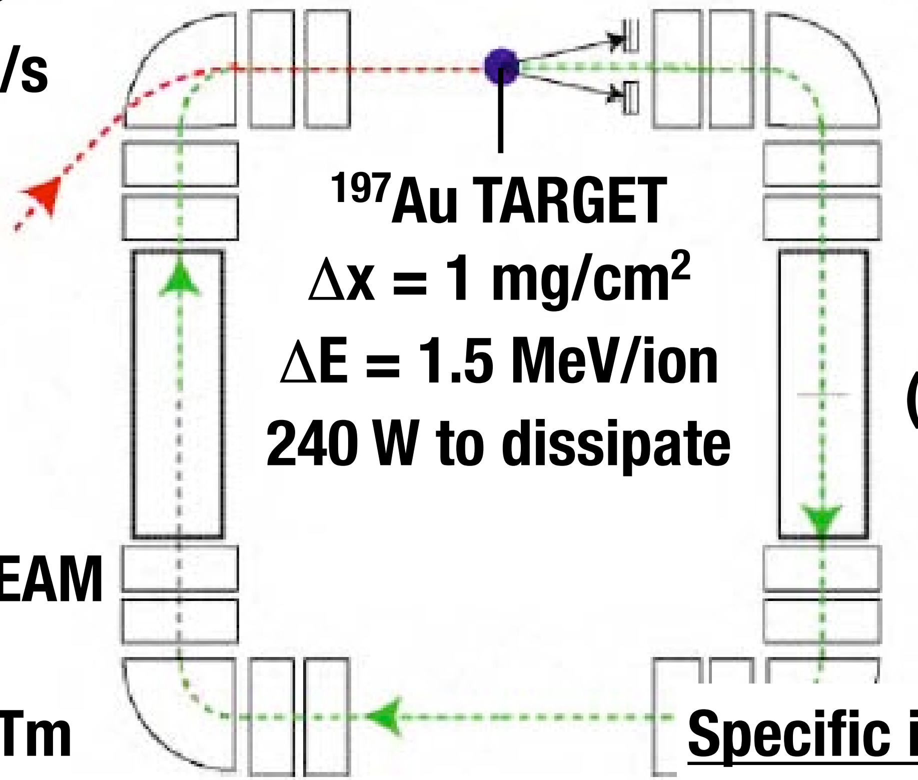
3 x 10^8 $^{197}Au(^{18}O,5n)^{210}Fr$ reactions/s

(6 x 10^8 total)

INPUT →

2 x 10^{12} $^{18}O^{6+}$ ions/s

2 μA



^{197}Au TARGET

Δx = 1 mg/cm^2

ΔE = 1.5 MeV/ion

240 W to dissipate

RF BEAM POWER

(1.5 MV)(1.3 mA)/8

= 240 W

STORED $^{18}O^{8+}$ BEAM

100 MeV

(B rho) = 0.77 Tm

lifetime 0.15 ms (500 turns)

3.1 x 10^8 ions, 1.3 mA

circumference 10 m

<u>Specific issues</u>:

. charge state distributions

. target heating

. extraction

Conclusions

- Francium is one of the best candidates for studying violations of fundamental parity and time-reversal symmetries
- The first European facility for Fr atomic traps has been built and commissioned at LNL (Legnaro, Italy)
- First results on high-precision laser spectroscopy were achieved
- We're looking forward to the next challenging phase of atomic parity-violation measurements in francium

Thank you for your attention!