Search for electron EDM in laser-cooled francium factory

Cyclotron and radioisotope center (CYRIC) Tohoku Univ.

Hirokazu Kawamura

Contents

Collaborators

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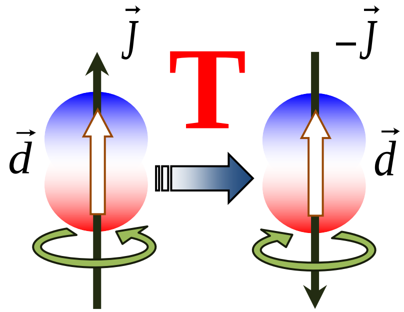
CYRIC; Univ. of Tokyo; TMU; TAT; RCNP; JAEA; Kyoto Univ.; Tohoku Univ.; Kyusyu Univ.;

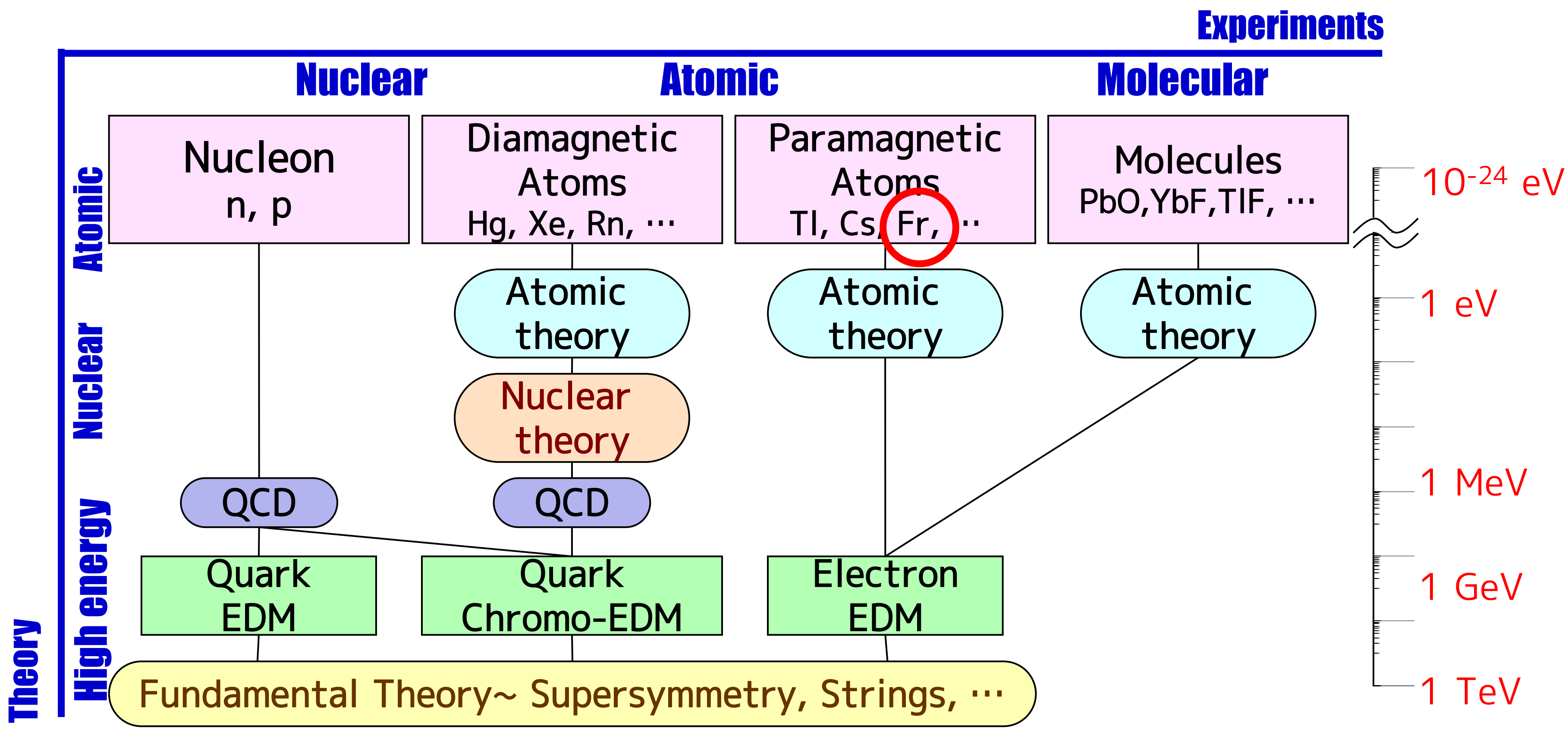
SSP2012 – 5th International Symposium on Symmetries in Subatomic Physics
18-22 June 2012, KVI, Groningen, the Netherlands

Electric Dipole Moment (EDM)



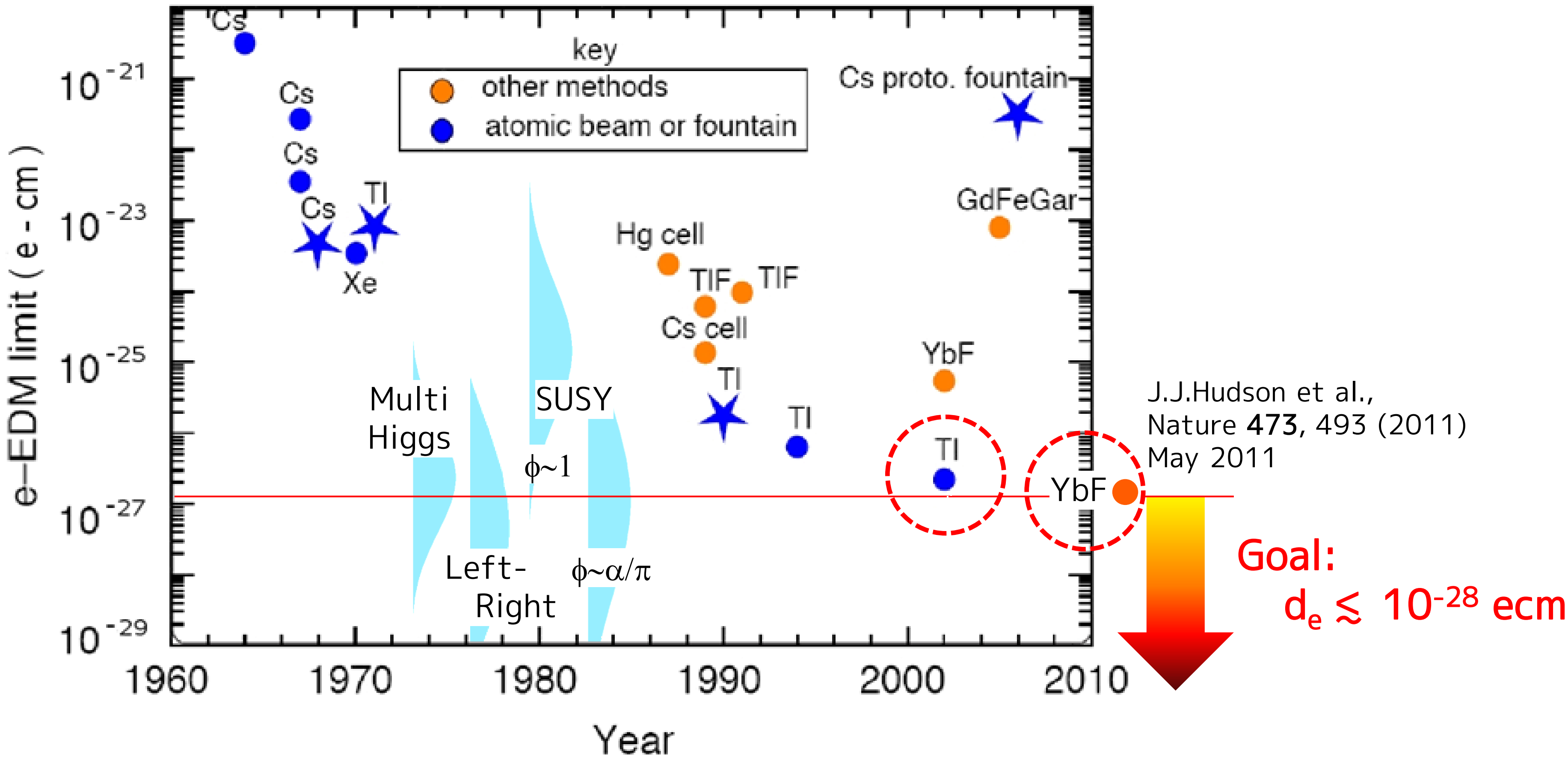
Non-zero EDM = time-reversal symmetry violation

CP-violation



Journey of e-EDM search

An electron EDM can induce a net atomic EDM.
→ The net EDM of a heavy atom can be many times larger than the electron EDM.

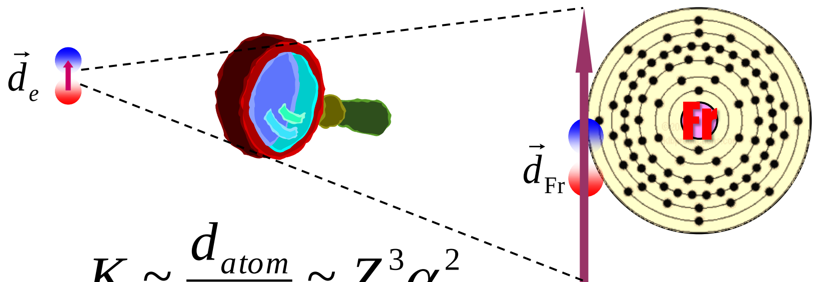


No experimental result of EDM search for cooled/trapped radioactive atoms

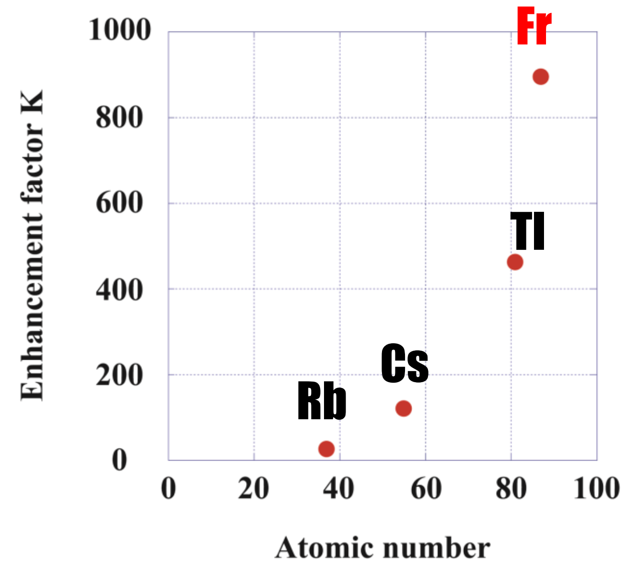
Francium

- **Heaviest alkali metal = Francium :**
  - ⇒simple electronic structure and large nucleus
  - ⇒Enhancement of EDM: Z=87 → $K \sim 10^3$

Enhancement factor:



$$K \sim \frac{d_{atom}}{d_e} \sim Z^3 \alpha^2$$



H.S.Nataraj, B.K.Sahoo, B.P.Das, D.Mukherjee, PRL**106**,200403(2011).
J.Phys.Chem.A**2009**,113,12549.

- No stable isotopes: radioactive atom
  - Several isotopes with long half-life
  - ⇒^{210}Fr =3.2 min, ^{211}Fr =3.1 min, ^{212}Fr =20. min.

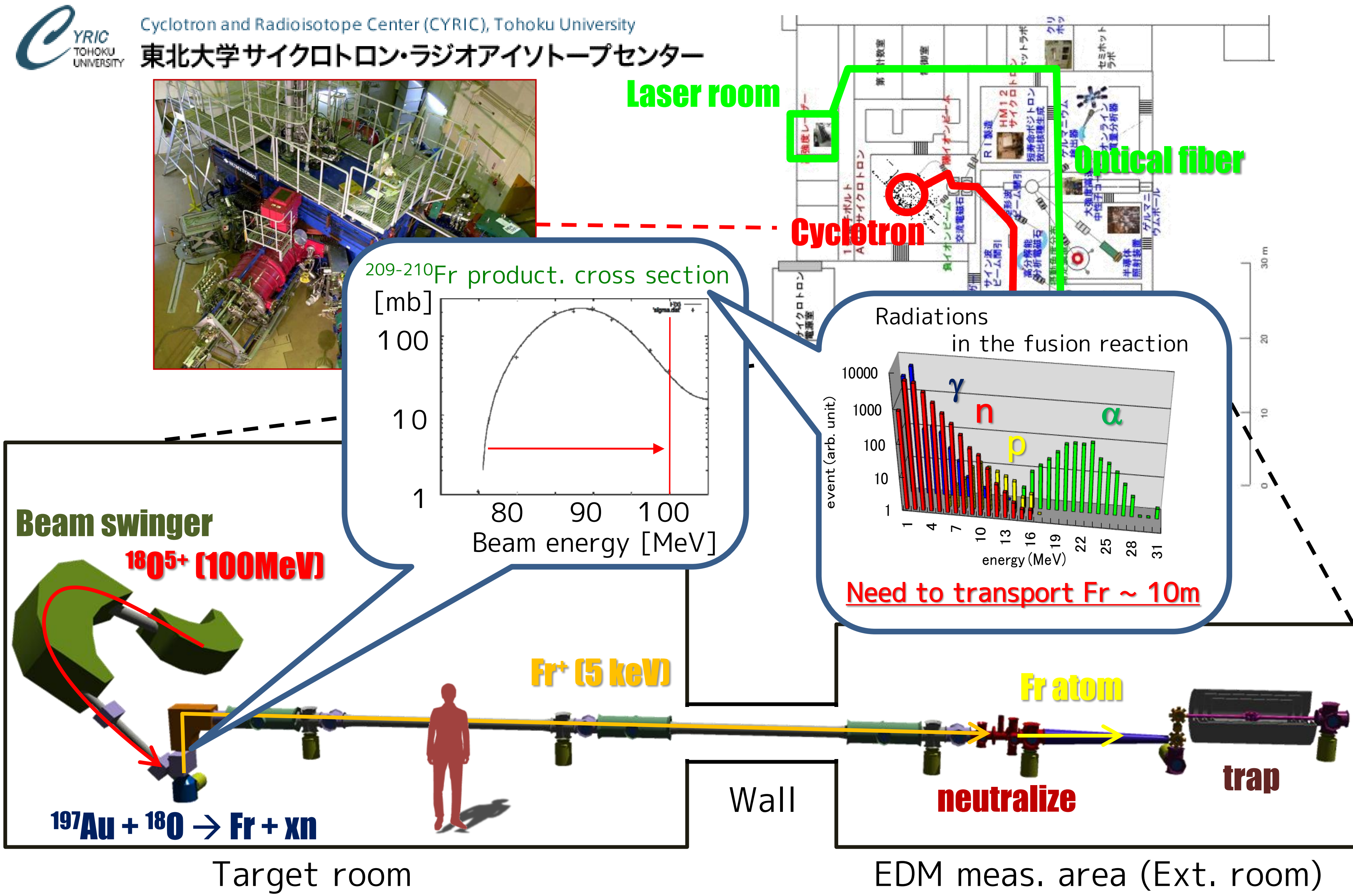
- Laser cooling and trapping techniques: localize atoms
  - ⇒ Reduce systematic errors

International situation of Fr trapping

LNL (Italy), TRIUMF (Canada) → Parity Violation

R. Calabrese et al. **G. Gwinner et al. (talked by L.A.Orozco)**

Laser-cooled francium factory @ CYRIC



Fr^+-ion source ~ Thermal ionizer

Fusion reaction: $^{18}O + ^{197}Au \rightarrow ^{210}Fr + 5n$

Saha-Langmuir equation

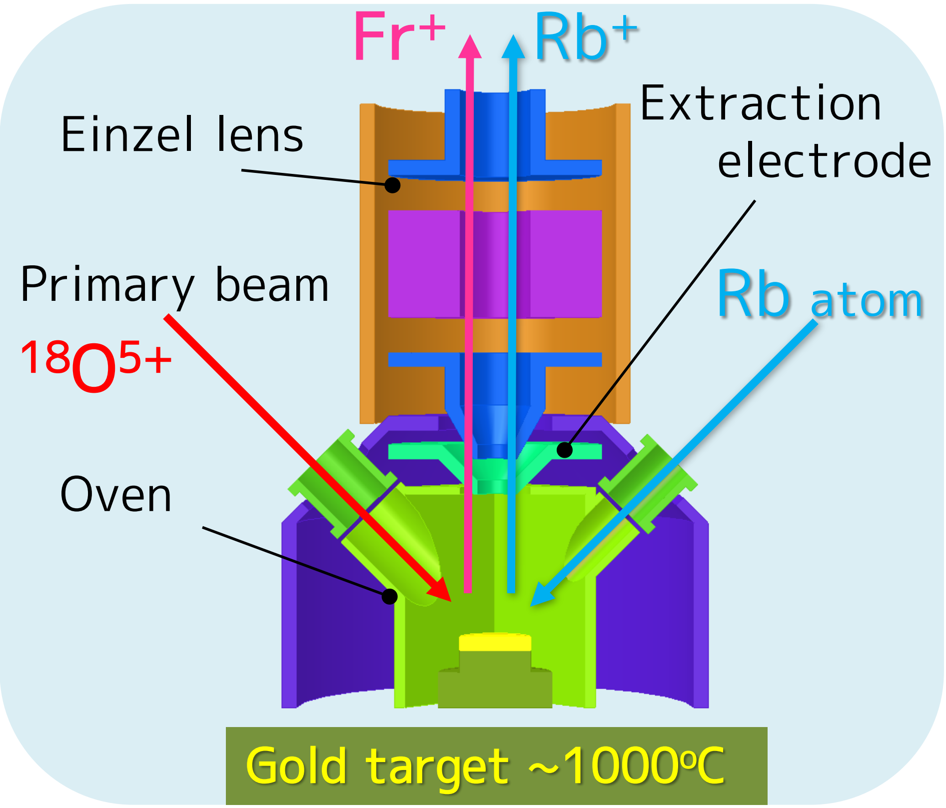
$$\frac{n^+}{n^0} = \frac{1}{2}\exp\left(\frac{E_{WF} - E_{IP}}{kT}\right)$$

Thermal ionization ← $E_{IP}(Fr) < E_{WF}(Au)$

E_{IP} (Ionization potential): Fr 4.0 eV

E_{WF} (work function): Au 5.1 eV

Ions can be extracted by electric fields.



Desorption from high-temperature liquid target

- **Faster diffusion**
- **Convection flow**
- **Clear surface**

➔ Efficient Ion Production

- Available for molten gold.
- Rb beam test w/o cyclotron.

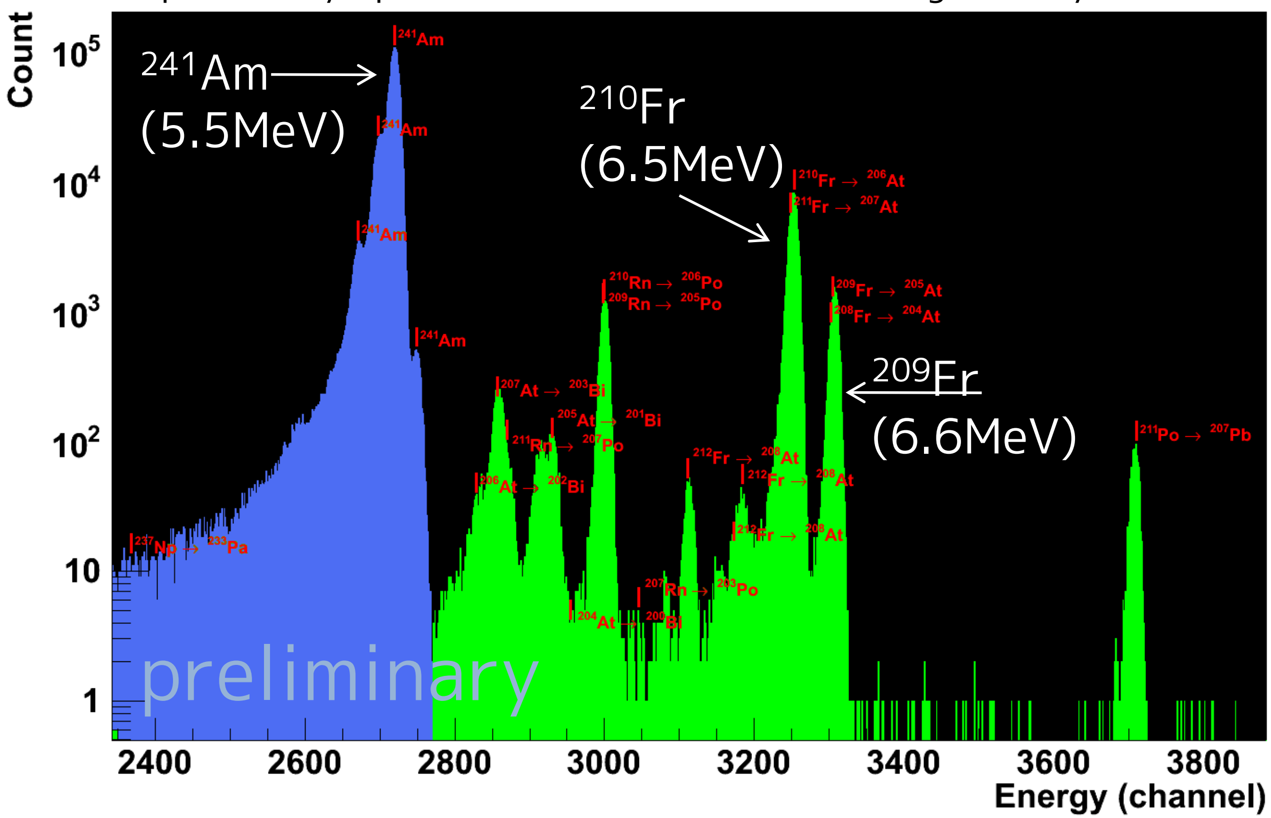
Alpha-decay spectrum from produced Fr

Francium is identified using SSD in Diagnosis system.

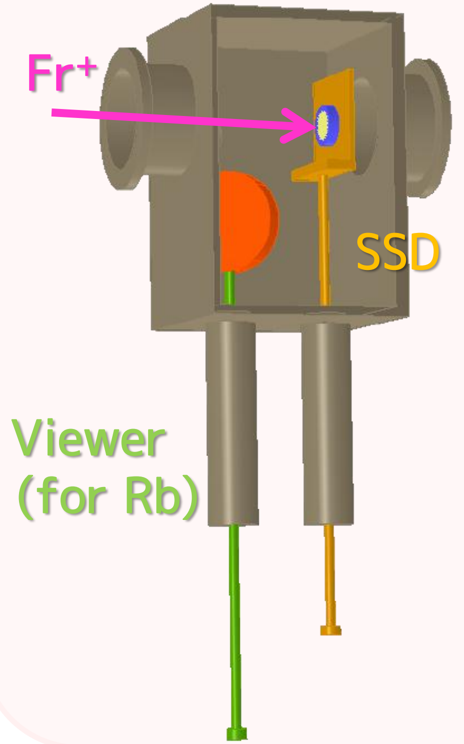
Solid State Detector:
detect alpha particles from unstable nuclei.

Checking source (^{241}Am) placed near SSD
for energy calibration.

Alpha-decay spectrum was obtained at a diagnosis system



Diagnosis system

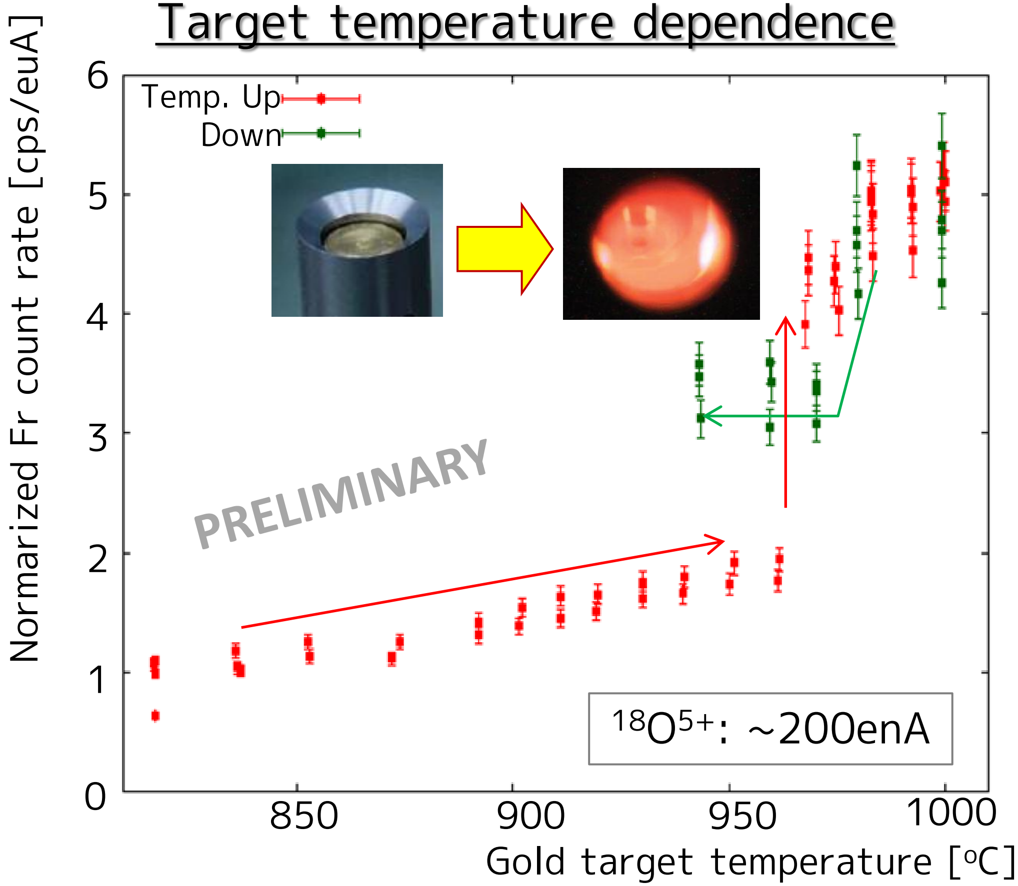


Blue:
originating from ^{241}Am

Green:
originating from $^{208\text{-}212}$Fr
and also daughter nuclei

Status of Fr production

Target temperature dependence

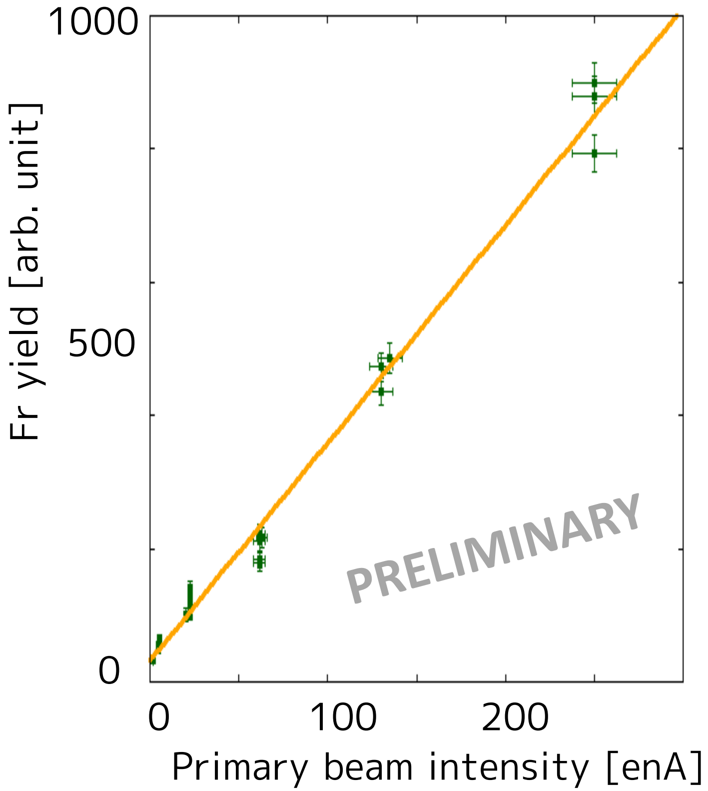


monitored by thermocouple (W/Re5-26) inside target rod

cf: Au melting point = 1064°C.

The target was maintained at melting temperature.
Fr extraction yield was quite stable.

Primary beam dependence



Proportional to primary beam.

More Fr can be expected
when ^{18}O beam gets higher intensity.

Achieved $^{210}Fr^{+}$ yield: ~10^{6} ion/sec @ 0.2eμA → Goal: ~10^{7} ion/sec @ 1 eμA

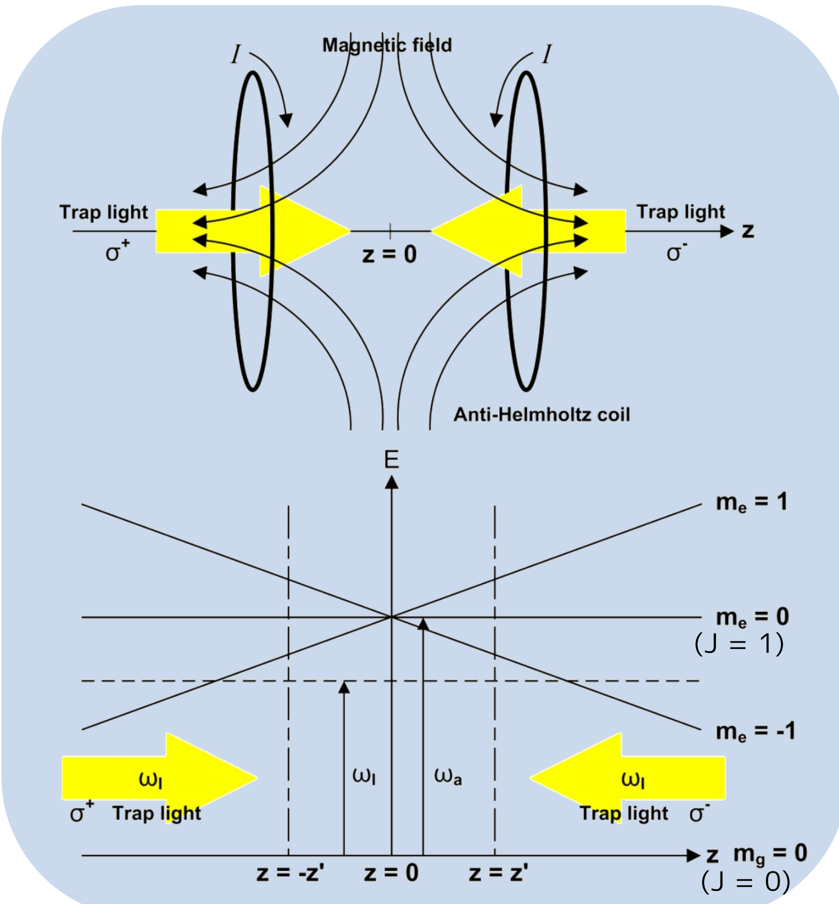
Magneto-optical trap (MOT)

Combination of lasers and magnetic fields to localize and cool neutral atoms.

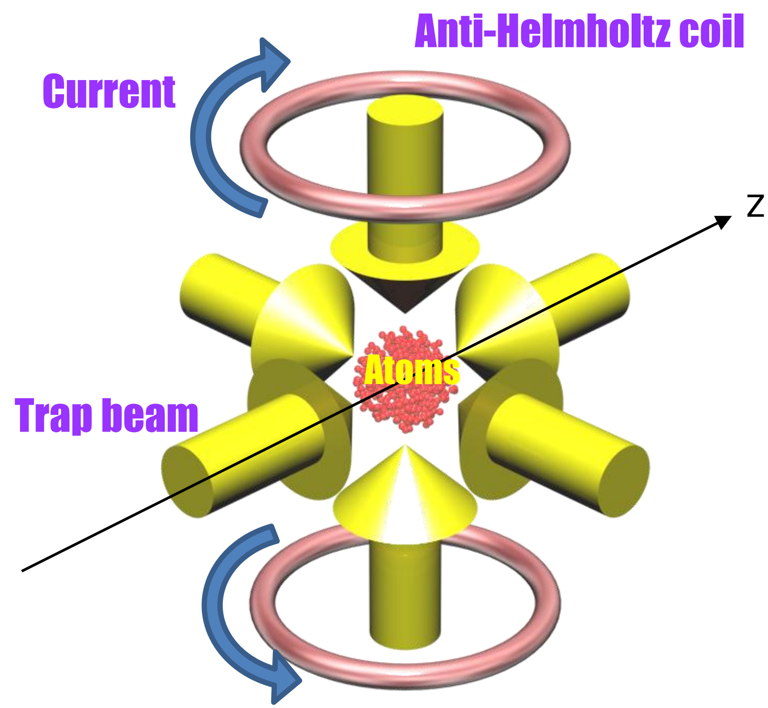
A pair of anti-Helmholtz coils produces the inhomogeneous magnetic field.

2 lasers need to be frequency locked such that they are slightly detuned to red of atomic transitions and stabilized to less than natural linewidth.

→ *Trap and repump laser*

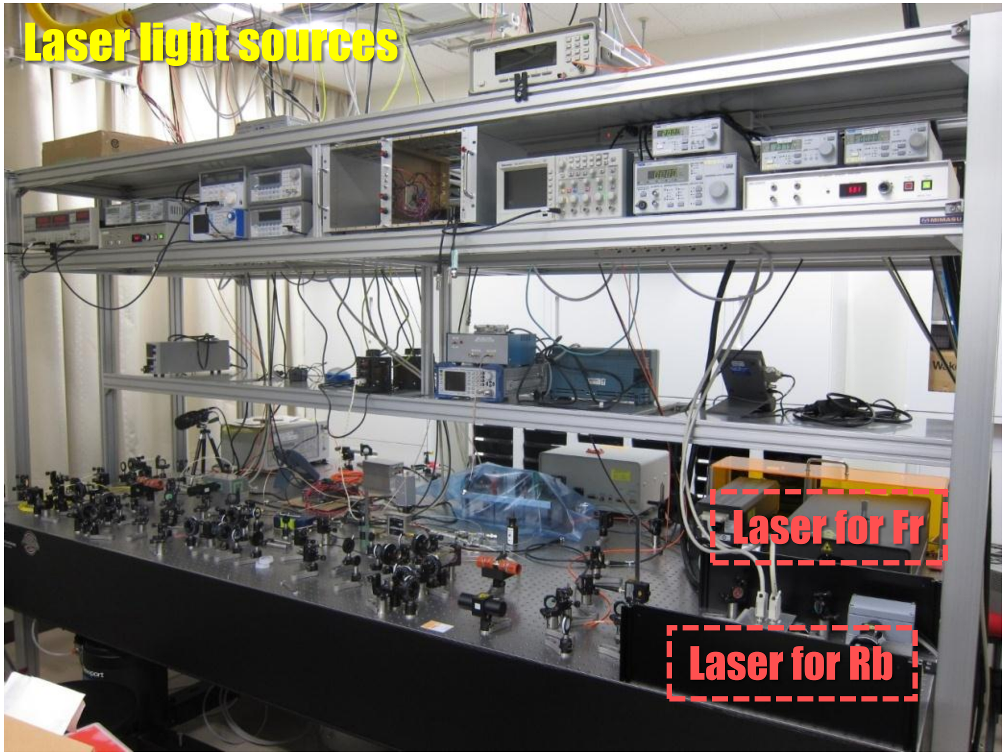


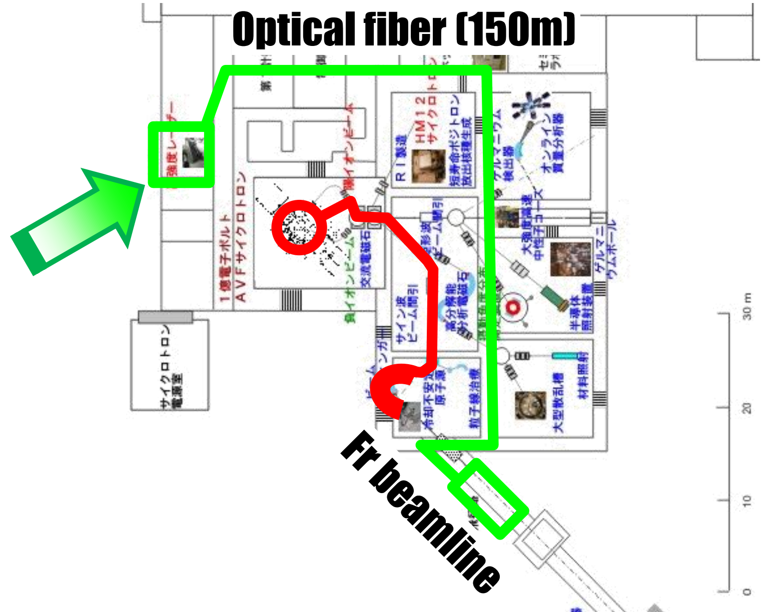
The mechanism of MOT in one dimension.



6 beams are necessary to provide confinement & cooling in 3D.

Laser room





Required laser

●Fr-atom trap

Trapping : 718 nm (Ti:S laser) ~Ready

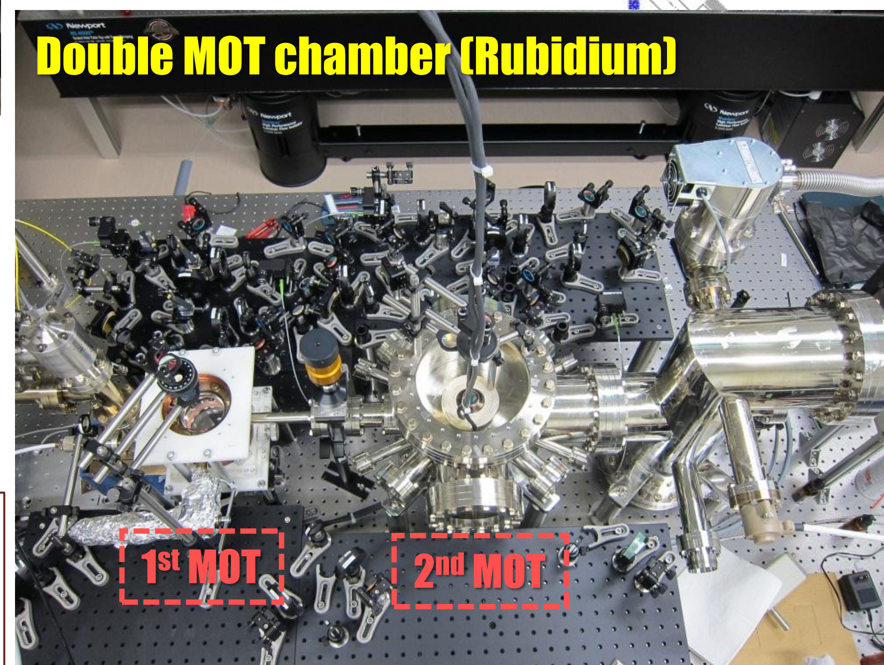
Repumping: 718 nm (custom ECLD) ~Ready

●Rb-atom trap

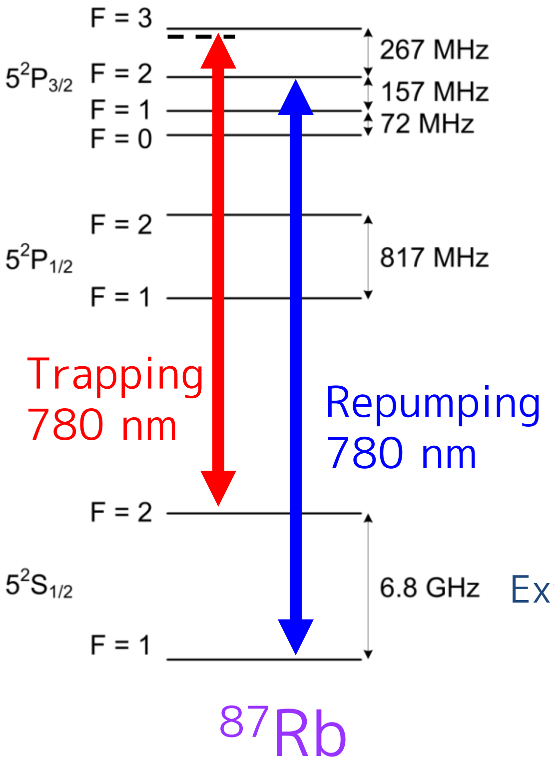
Trapping : 780 nm (ECLD) + Taper amp. ~Ready

Repumping: 780 nm (ECLD) ~Ready

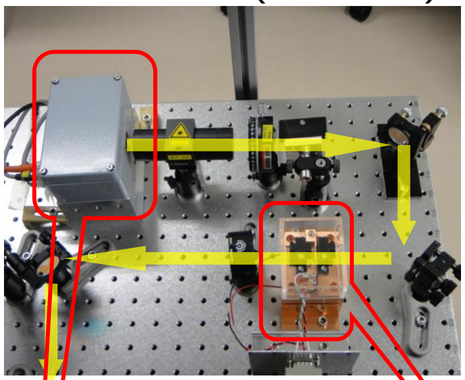
When Fr-MOT experiment is performed, the laser lights are transported from Laser room to Fr beamline.



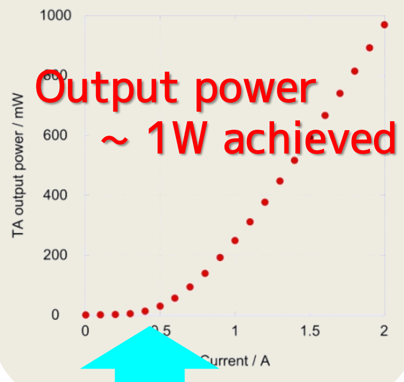
Lasers for Rb MOT



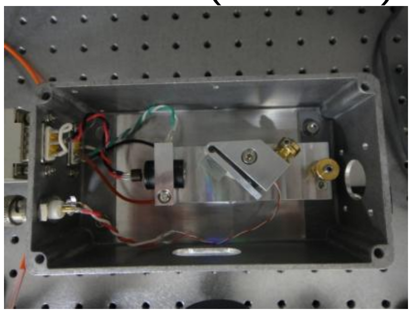
Trapping laser
ECLD (780nm)



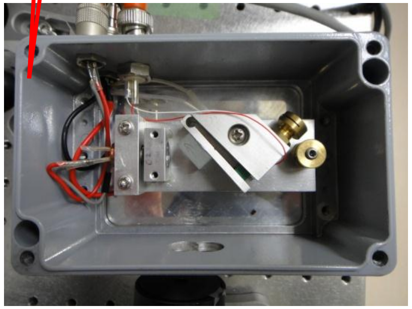
TA output power



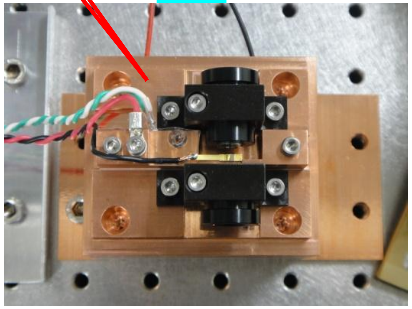
Repumping laser
ECLD (780nm)



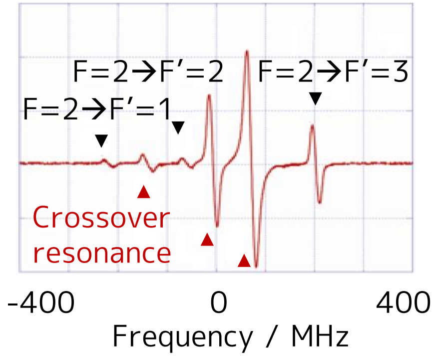
External Cavity Laser Diode



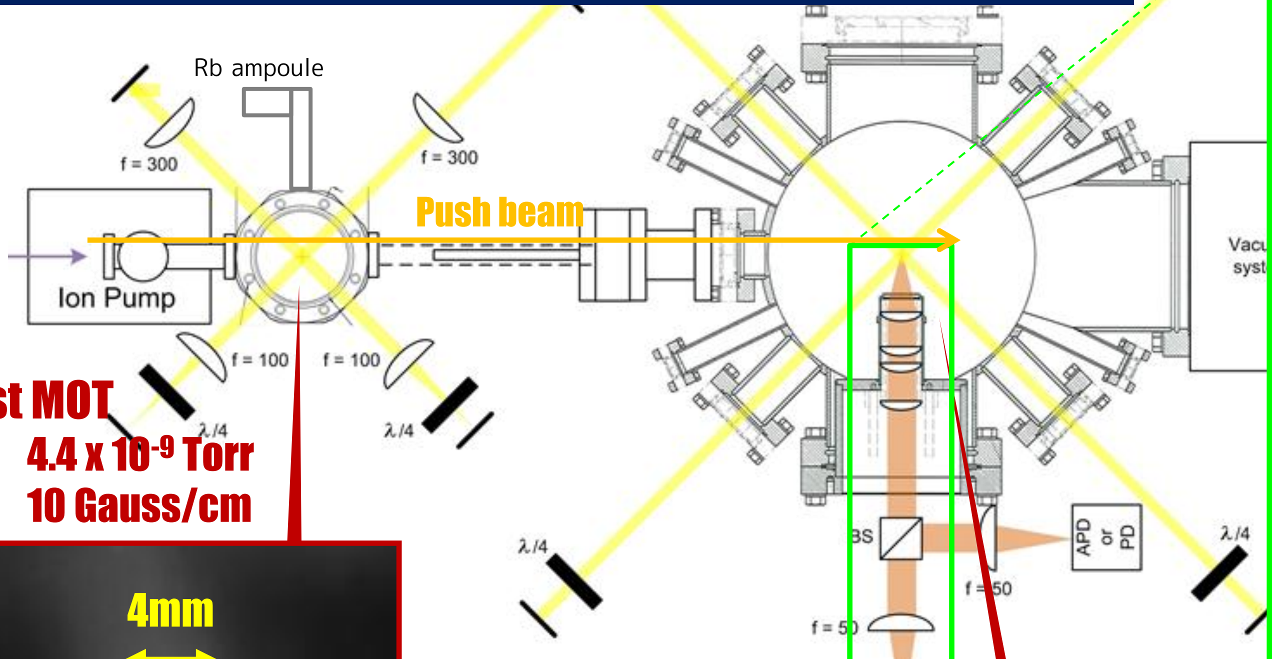
Tapered amplifier



Developed a frequency-stabilization circuit



Rb atoms in MOT

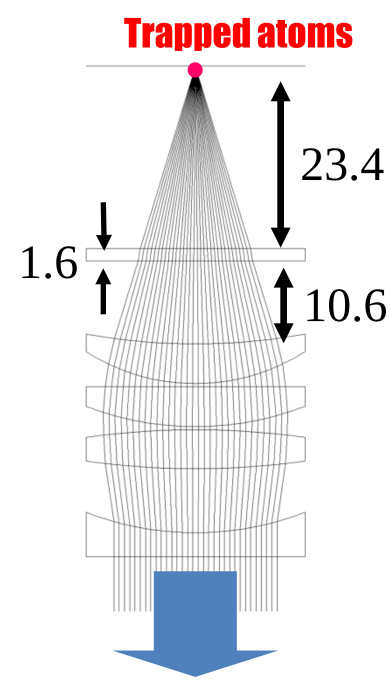


1st MOT
- 4.4 x 10^{-9} Torr
- 10 Gauss/cm

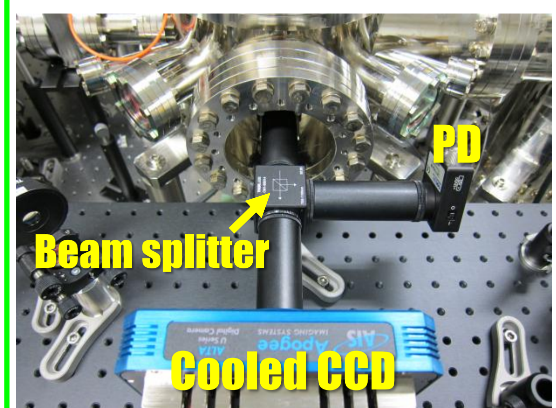
2nd MOT
- 9.7 x 10^{-12} Torr
- 30 Gauss/cm

- Trapping beam power 5 mW
- Repumping beam power 2 mW

Lens system



Detection system

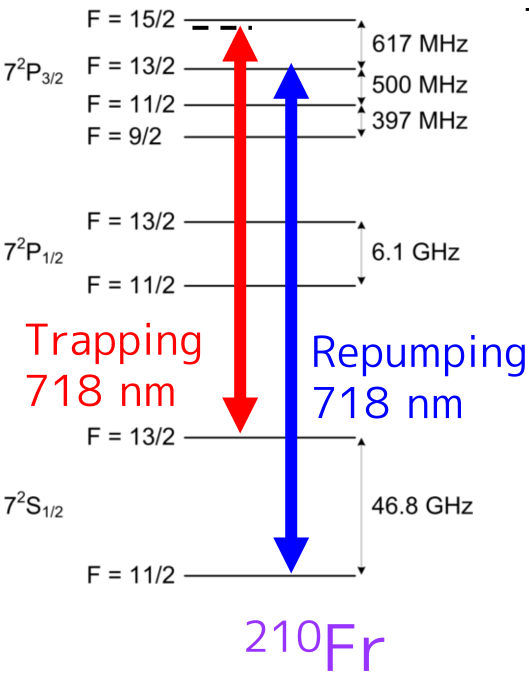


Efficient imaging optics to collect low levels of fluorescence light

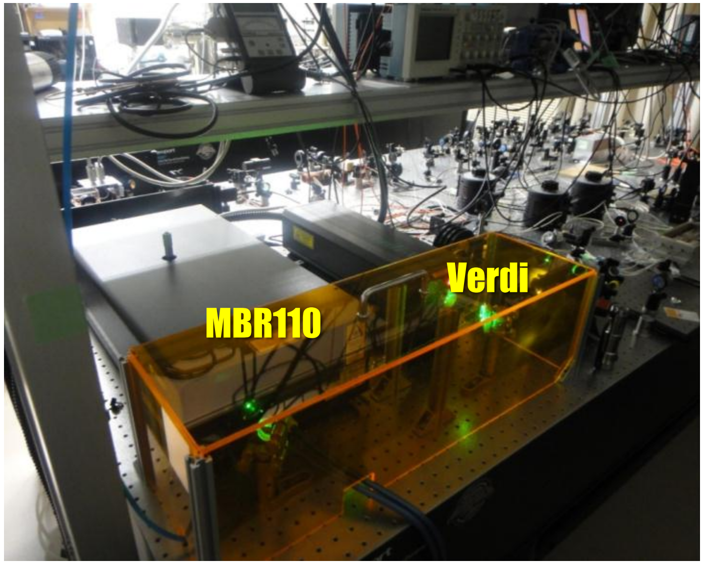
➔ Available to observe a small number of Fr produced by nuclear reaction

➔ Develop a new MOT chamber for Fr

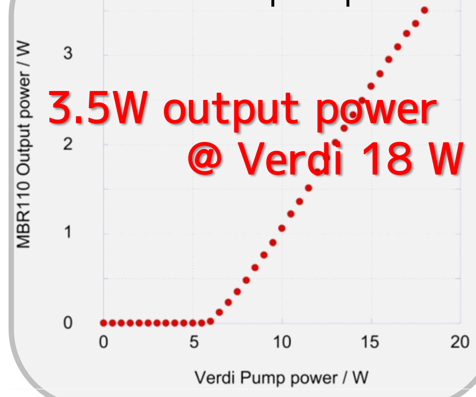
Lasers for Fr MOT



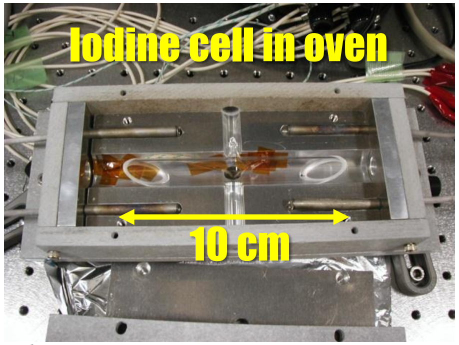
Trapping laser - Ti:S Laser (718 nm)
Coherent Verdi (532 nm) + MBR110

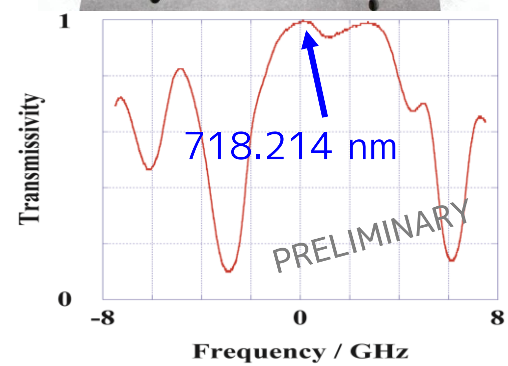


MBR110 output power

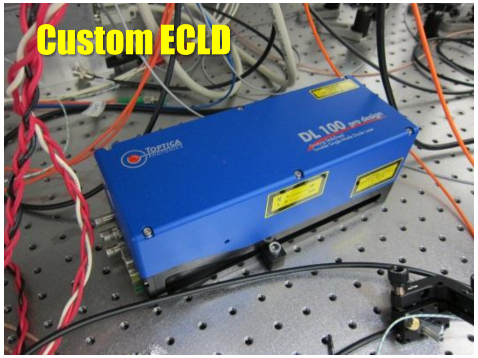


Developing a frequency-stabilization circuit

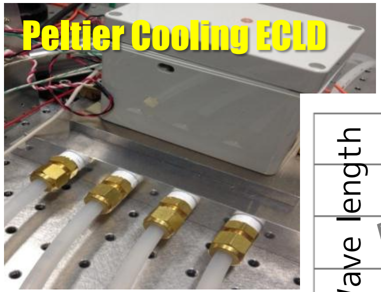




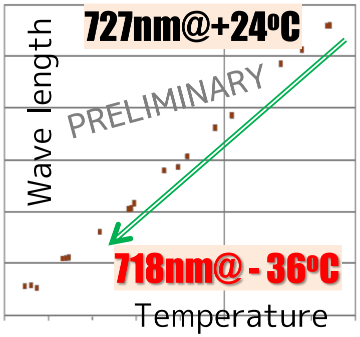
Repumping lasers (718 nm)



Toptica 718nm ECLD
30mW output



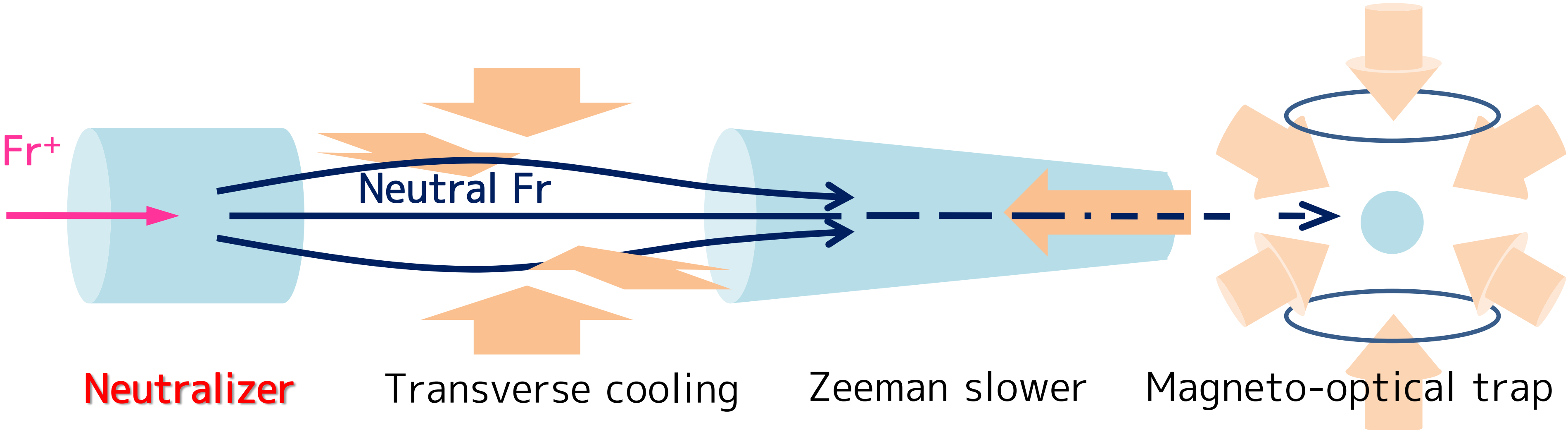
Developing
handmade ECLD
~ 10mW output



Ion to neutral atom converter

Require <u>neutral atoms</u> for laser cooling and EDM measurement.

Francium ion has to be converted to neutral atom.



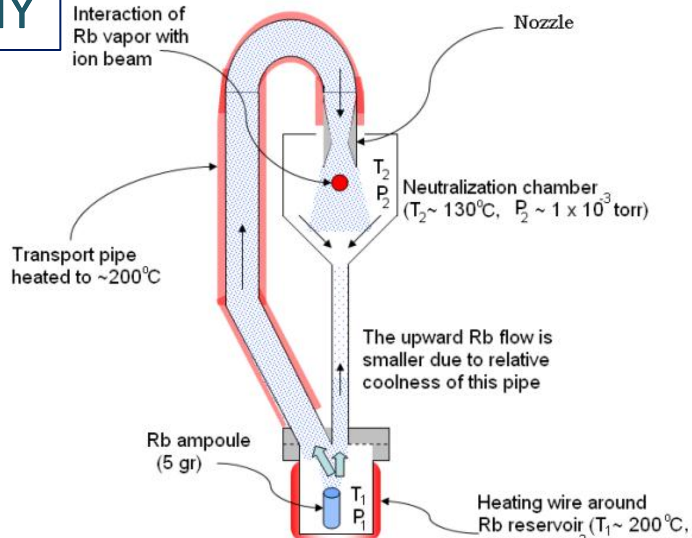
- ◆ Neutralize the positive ion
- ◆ Collimate by transverse cooling
- ◆ Decelerate by Zeeman slowing
- ◆ Finally, trap in MOT chamber

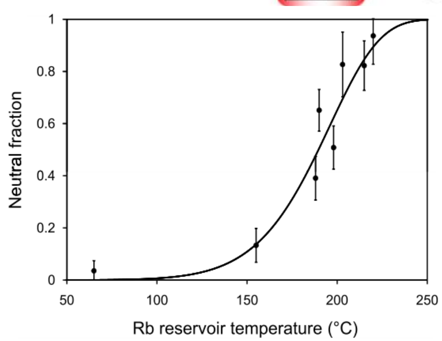
Beam converter is an important device
to couple the ion beam and laser-cooling atom

How to convert ion beam to neutral atom beam

◆Charge-exchange with alkali vapor
- To produce 5 keV atomic beam

@ SUNY

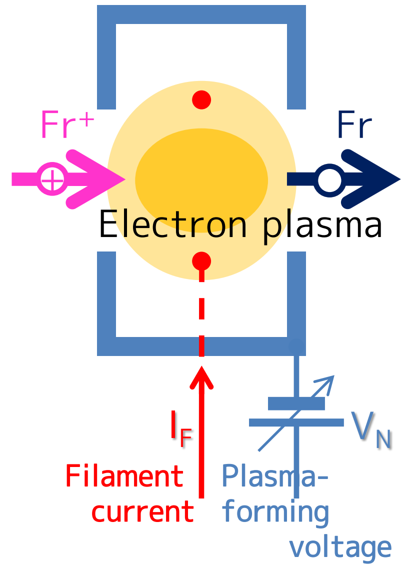


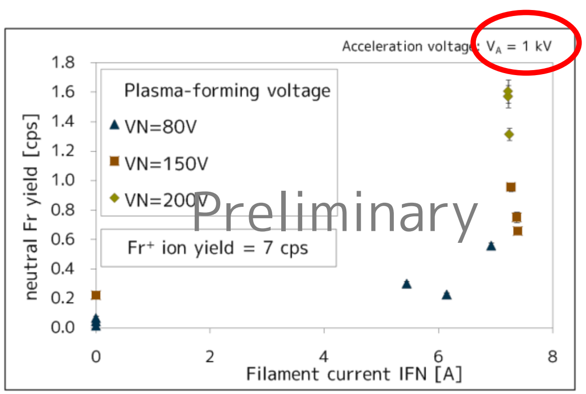


J.F.Sell, K.Gulyuz, G.D.Sprouse, REVIEW OF SCIENTIFIC INSTRUMENTS 80, 123108 (2009)

◆ion-electron recombination process
using electron plasma

@ CYRIC





◆Thermal neutralization on yttrium surface

@ many labratories

- Thermal neutral atom ~ 1000°C → The most general method for MOT

cf. An orthotropic source of thermal atoms @ LBNL

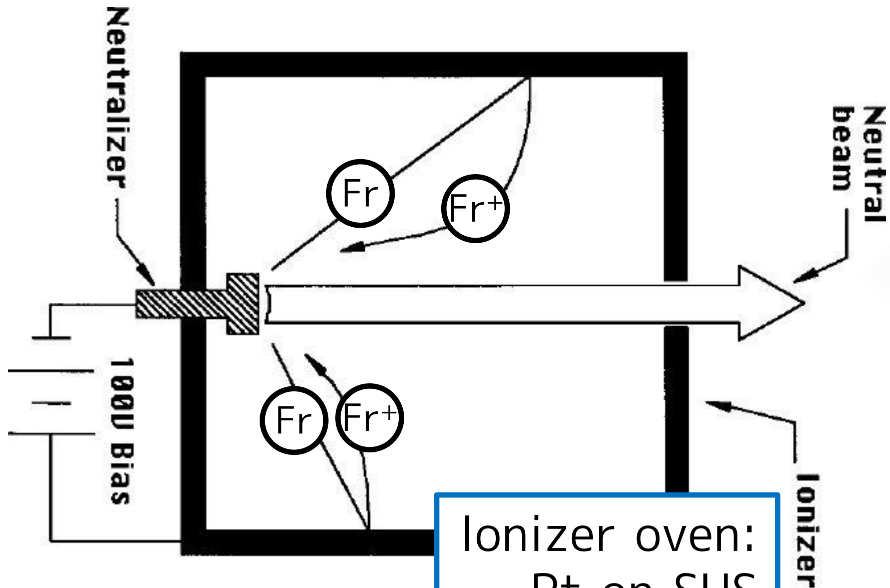
E_{IP} (Ionization potential): **Fr 4.0 eV**

E_{WF} (work function): Y 3.1 eV → Neutralization, Pt 5.6 eV → Ionization

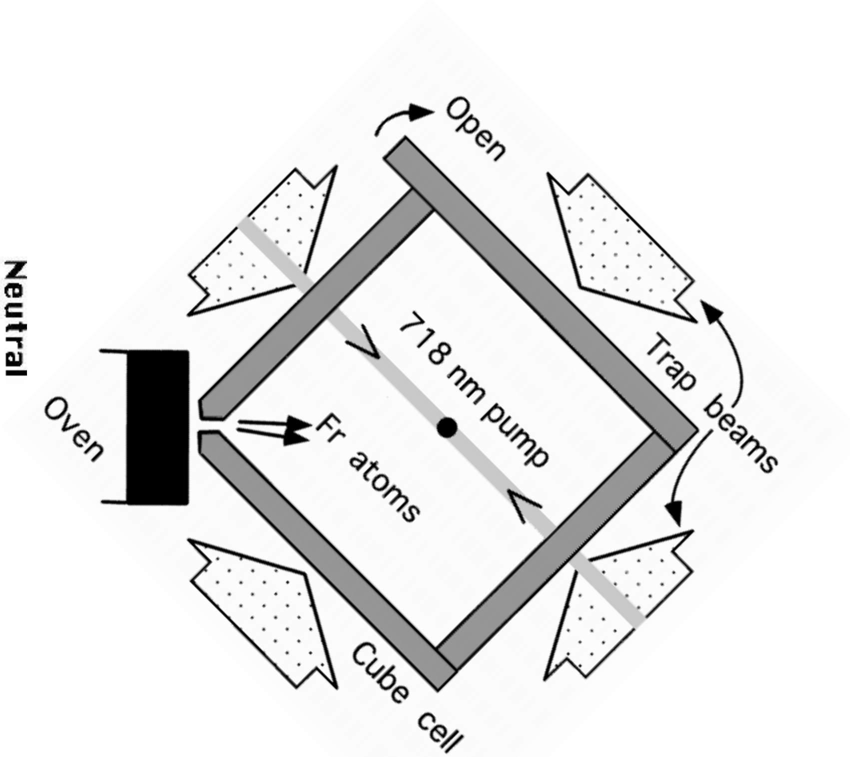
Neutralizer: Yttrium

^{225}Ac in Yttrium

^{225}Ac → ^{221}Fr + α

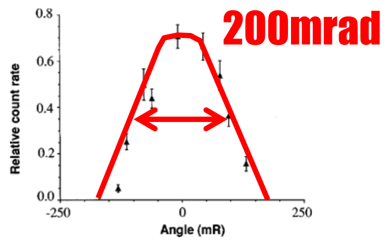


Ionizer oven: Pt on SUS

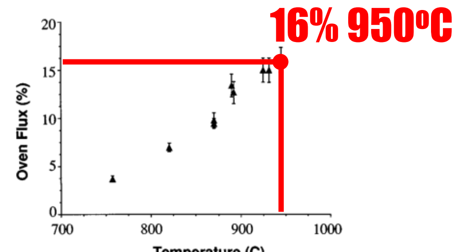


→ **Offline Fr-MOT** Highly efficient collection with orthotropic source

Beam broadening



Conversion efficiency



T. Dinneen et al., Rev.Sci.Instrum.67(3)1996

Z.-T. Lu et al., Phys.Rev.Lett.79(1997)994

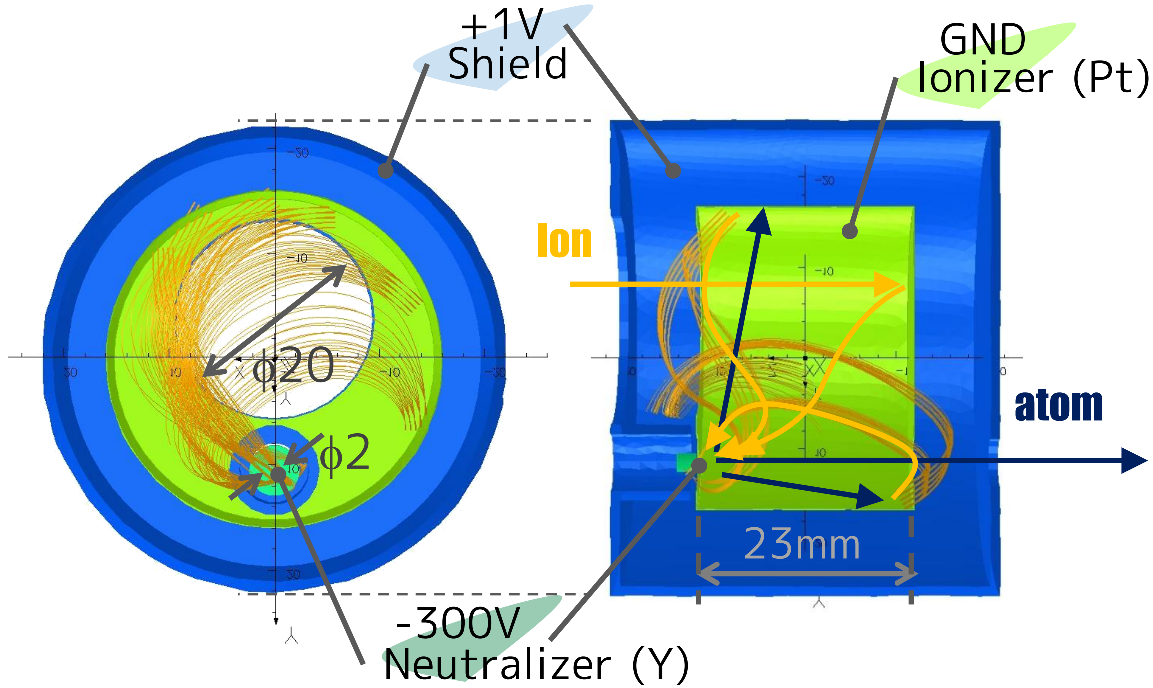
→ Utilize as the ion beam to atomic beam converter

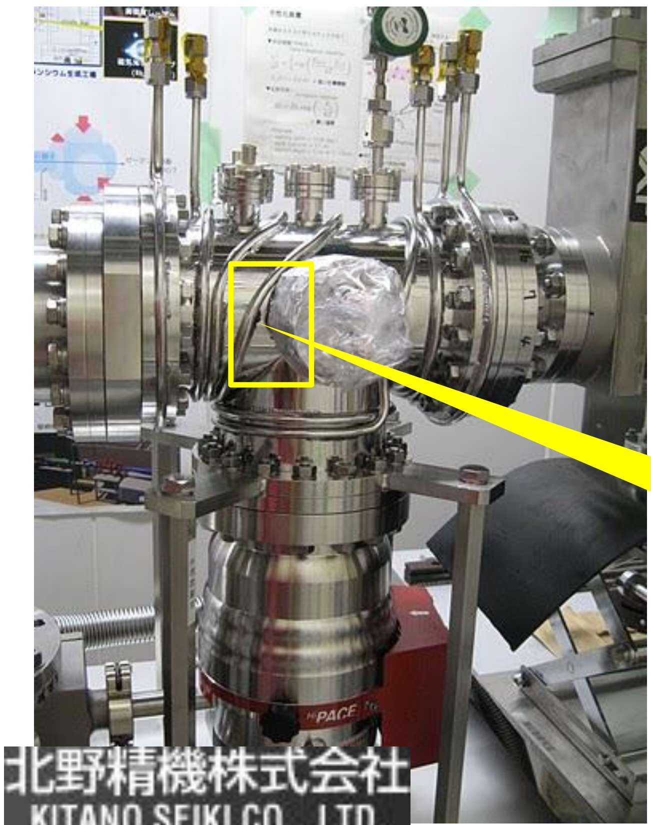
Orthotropic type beam converter @ CYRIC

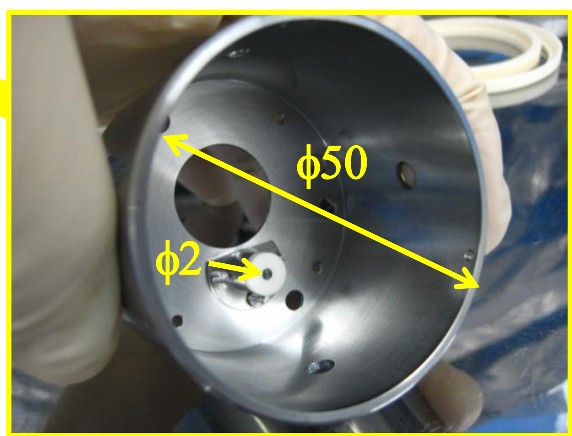
Electric field simulation by OPERA-3d/TOSCA

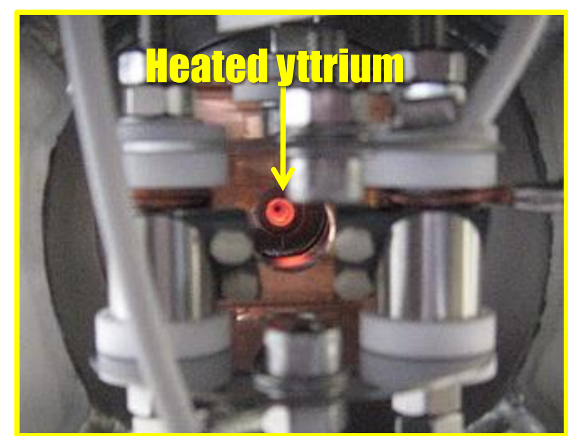
Neutralizer: Y
(T_{melt}=1526°C, E_{WF}=3.1eV)

Ionizer: Pt
(T_{melt}=3825°C, E_{WF}=5.6eV)

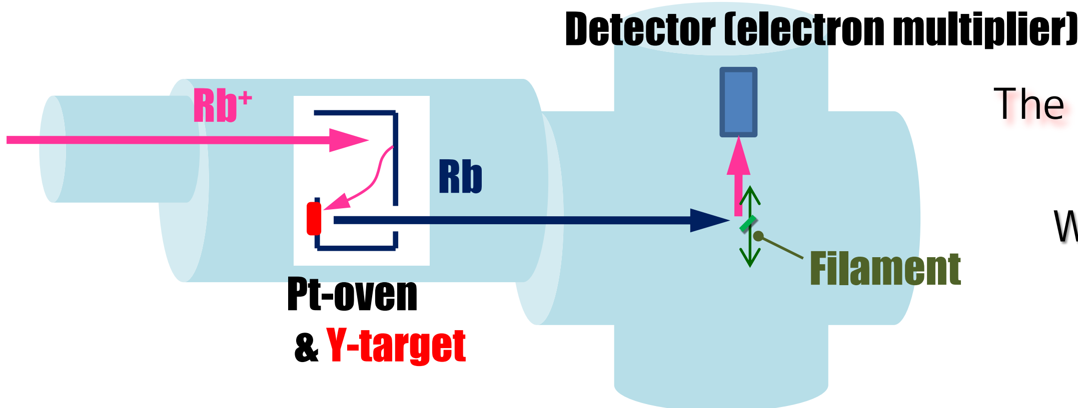








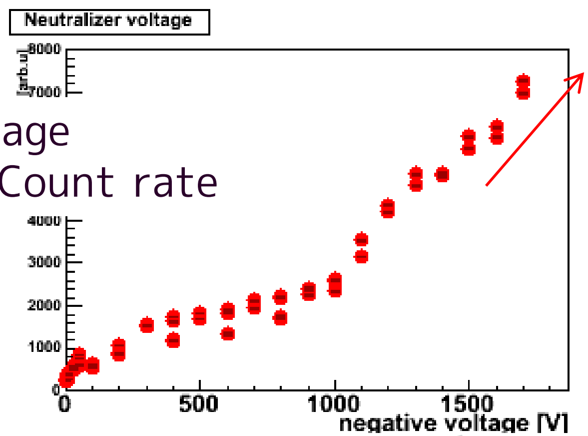
Rb neutralization test results



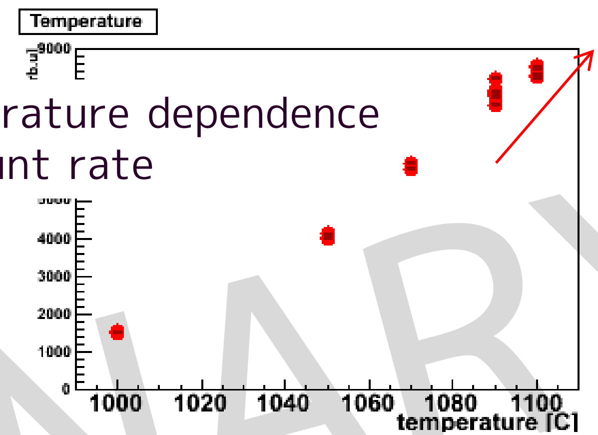
The converter is well-functioning

- Produce a neutral atomic beam.

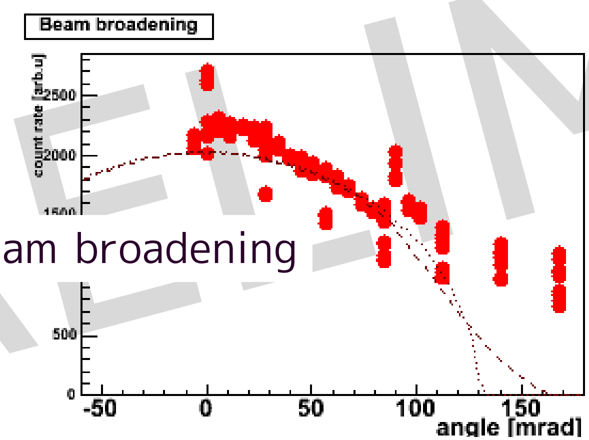
We need more experiments to understand quantitatively.



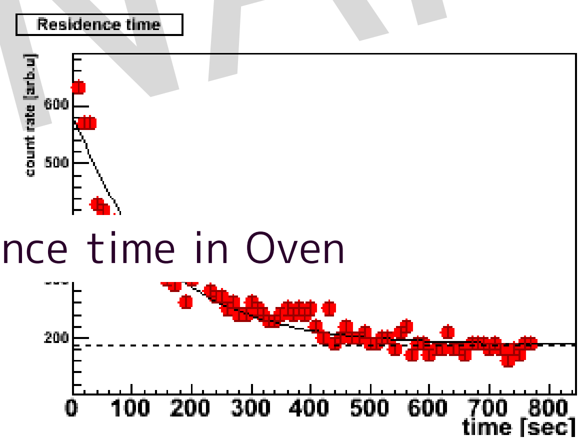
Attracting voltage dependence of Count rate



Temperature dependence of Count rate



Neutralized beam broadening



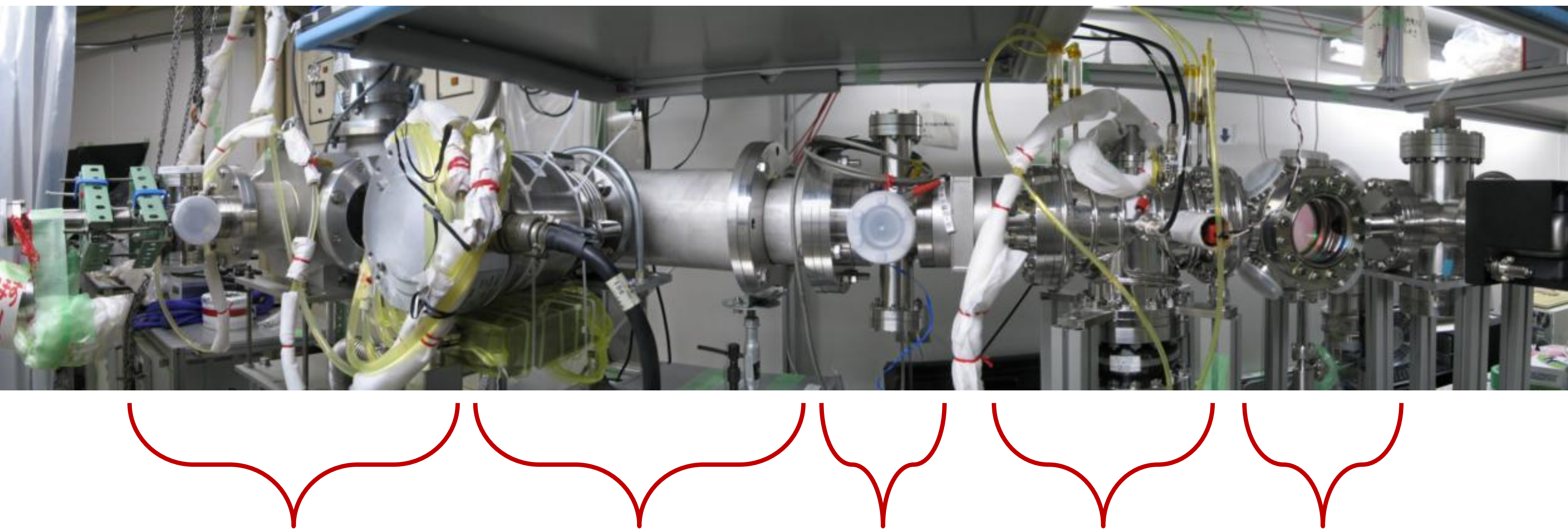
Residence time in Oven

PRELIMINARY

“Mini” Laser-cooled rubidium factory

Test setup for neutralization and MOT

- Rb ion beam ··· Ready
- Ion-atom converter ··· Ready
- Rb MOT (w/ this setup) ··· 1st try in this month

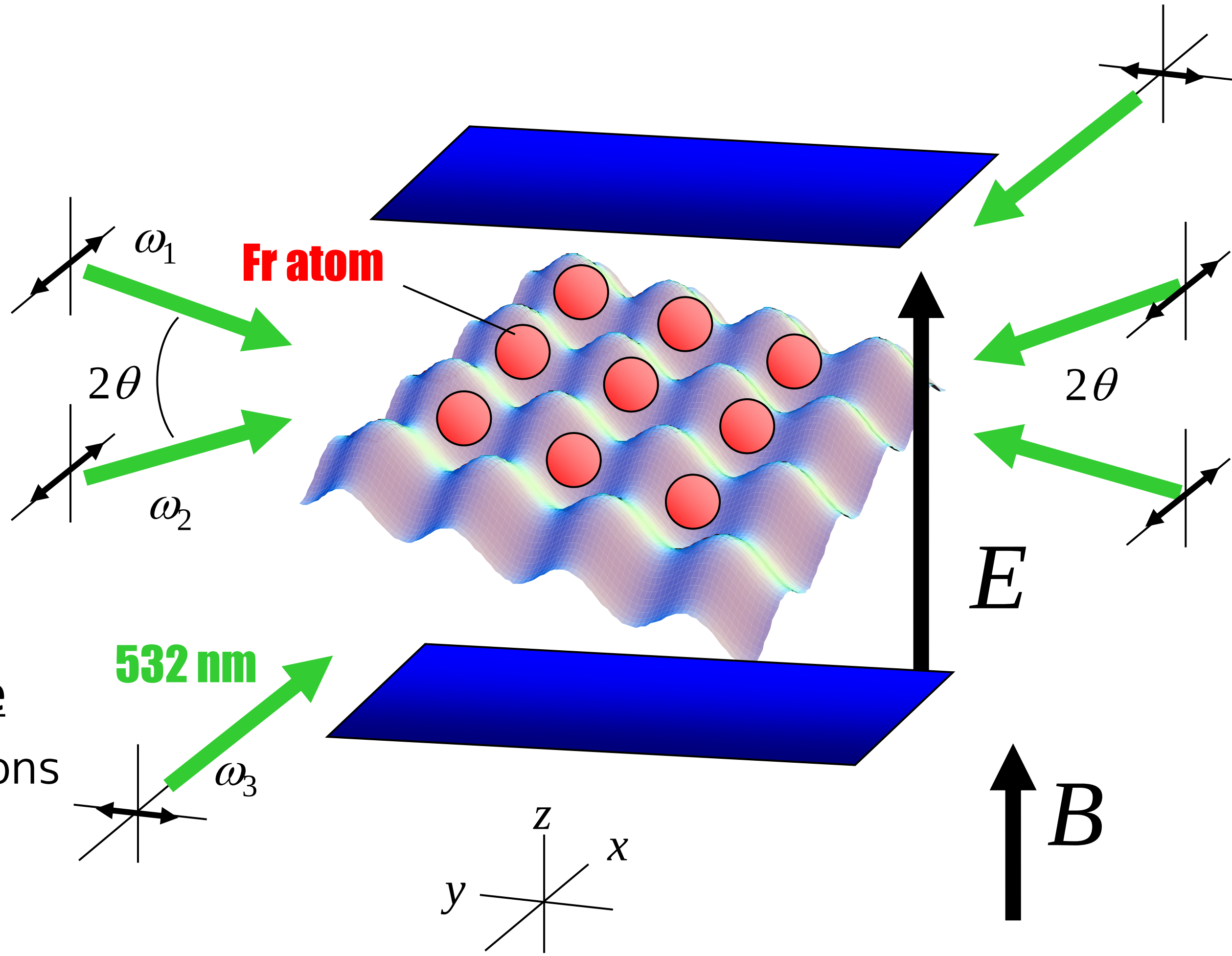


Rb-ion source | Ion-beam focus lens | Diagnosis | Beam converter | MOT

EDM search with optical lattice

<u>Optical lattice</u>

- Formed by interference of counter-propagating beams.
- Creating a spatially periodic polarization pattern.



<u>EDM measurement in lattice</u>

- Suppress atomic collisions
- Long coherence time
- Auxiliary atoms "co-magnetometers"

➔ **High precision EDM search**

cf. Phys.Rev.A 63(2001) 033401
C.Chin, V.Leiber, V.Vuletic, A.J.Kerman, S.Chu

Summary and Outlook

Laser-cooled francium factory for electron-EDM measurement

Francium ion production

Achieved extraction of 10^6 Fr^+/sec
To install new lens system and upgrade primary beam
➔ >10^7 Fr^+/sec

Laser cooling and trapping

Achieved Rb-MOT of 10^8 atoms
Developing light sources for Fr

➔Efficient imaging optics
➔Transverse cooling system
➔Zeeman slower
➔Optical lattice trap

Convert ion to neutral atom

Beginning to develop an orthotropic type converter
➔ >10% conversion efficiency

➔ **Rb-MOT with neutralization of Rb-ion beam**

In 2012, Fr-MOT and design EDM-measuring method
In 2013, 1st Fr-EDM measurement