Search for Permanent Electric Dipole Moments of Francium Atom

Yasuhiro SAKEMI

Research Center for Nuclear Physics (RCNP), Osaka University

For EDM collaboration at RCNP

K.Hatanaka, A.Tamii, S.Morinobu, Y.Shimizu, K.Fujita, Y.Tameshige, H.Matsubara,T.Kaneda (RCNP)

K.Imai, Y.Takahashi, T.Murakami (Kyoto Univ.)

T.Wakasa (Kyushu Univ.), Bhanau P. Das (Indian Institute of Astrophysics)

- **Physics motivation**
- **EDM experiment**
- **Present status of Fr EDM search at RCNP**
- **Summary**

Electron EDM search

↓

Francium atom

↓

Fundamental interaction

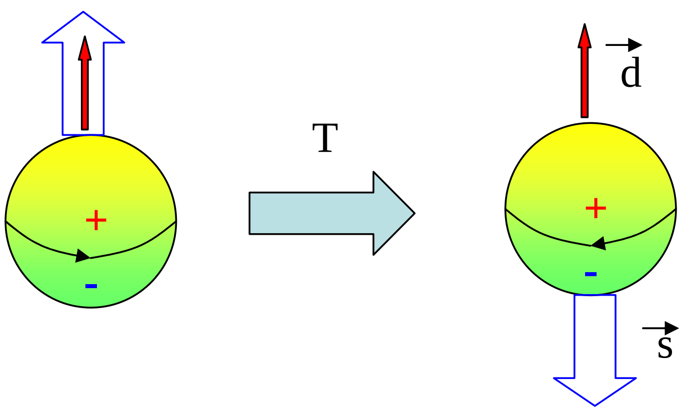
Search for permanent EDM

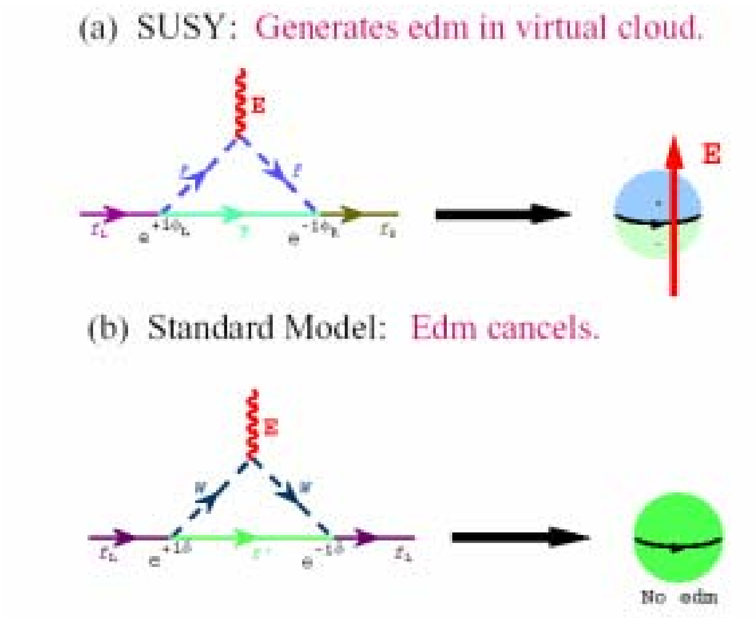
Time Reversal Symmetry ~ Violation ? ~ Test !

CPT ~ invariant in quantum field theory : No evidence of violation

- ✓**T: Time Reversal** ~ **No evidence of violation**
- ✓**CP: violation was found** ~ **K^0, B decay**
- ✓**CPT theorem + CP violation** → **T violation ?**

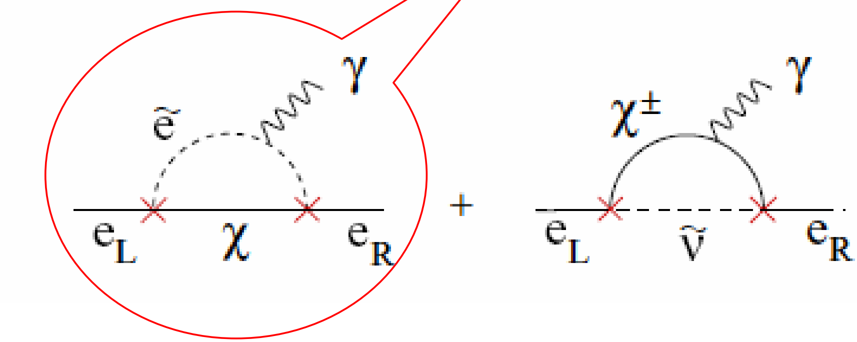
Window to look at Beyond the Standard Model ~ Supersymmetry …





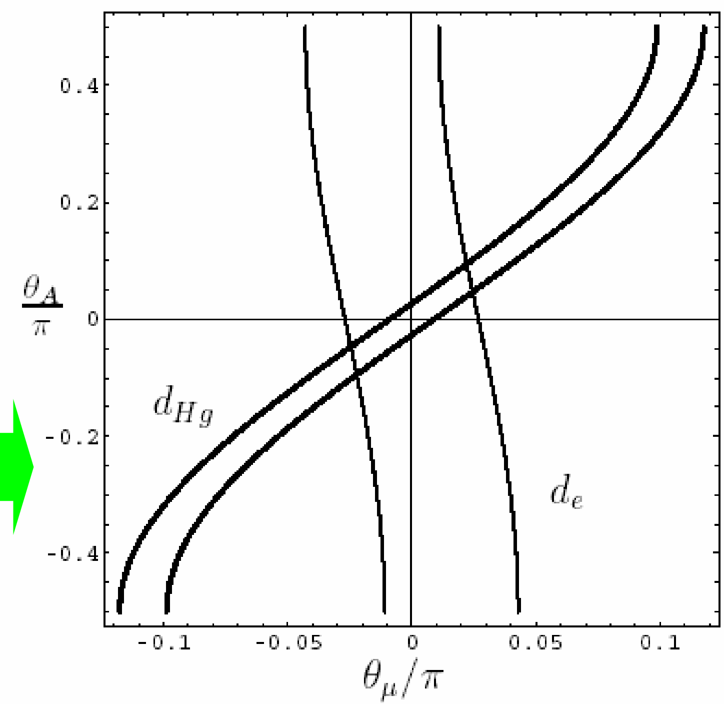
EDM and MSSM

Electron EDM in MSSM $\sim \dfrac{\sin\theta_\mu}{M^2}$ **→ limit to SUSY particle mass and CP-violating phase**



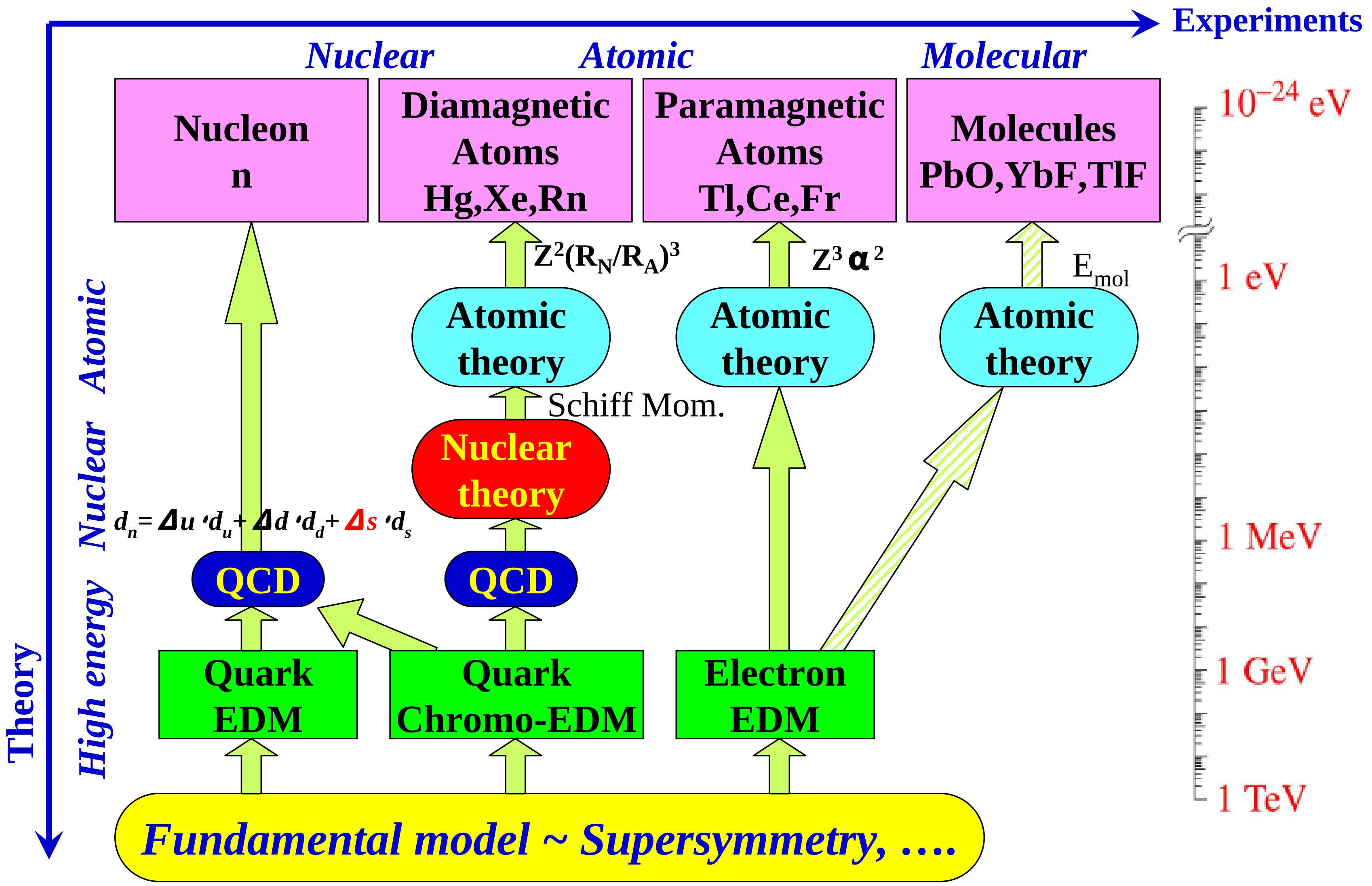
Dominant diagram

M=500 GeV case

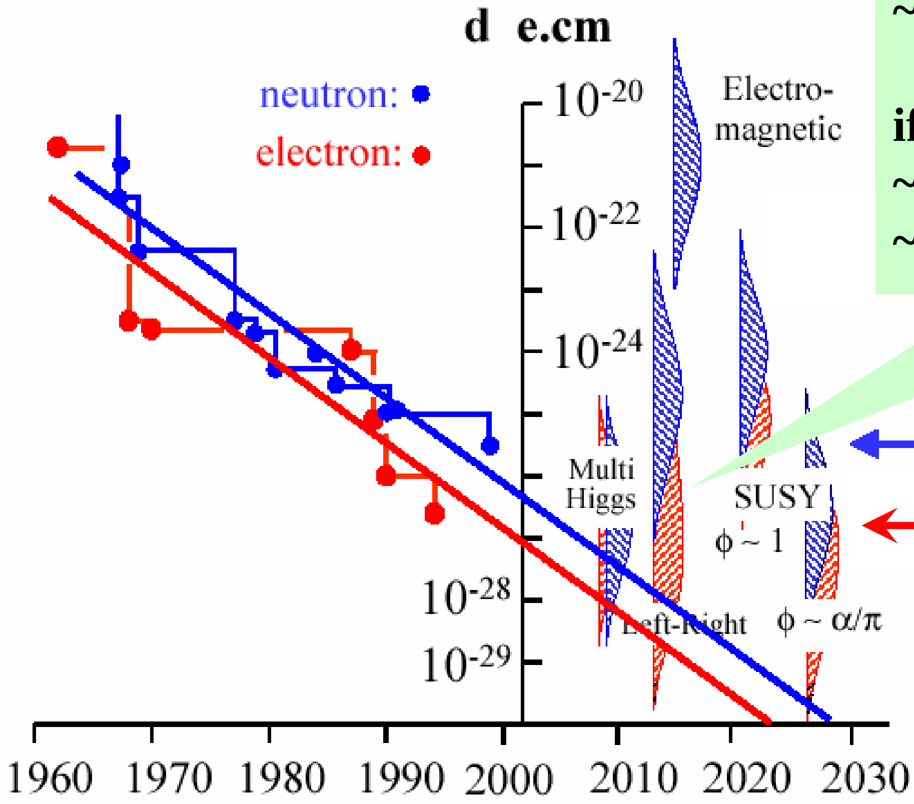


Phase pattern ~ limit the SUSY particle mass

Origin of EDMs



Status of EDM experiments



if EDM is *observed*
~ Beyond the Standard Model

if EDM is *measured*
~ signal of supersymmetry …
~ mechanism of SUSY violation

d(neutron) < 6×10^{-26}

Current limit e-EDM :
$|d_e|<1.5\times10^{-27}$
from E.D.Commins ,^{205}Tl

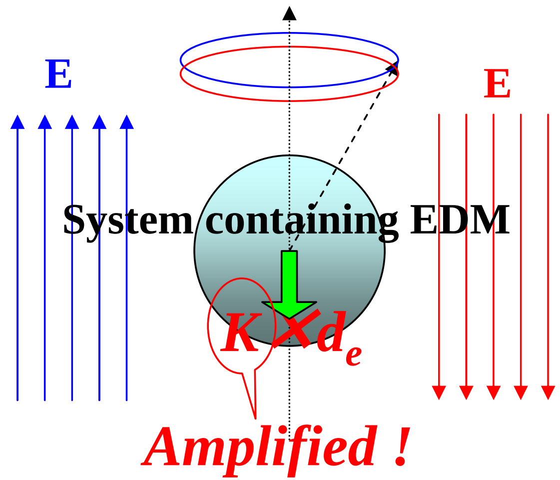
d_e(Standard Model)<10^{-37}

A challenge is set !
$d_e < 10^{-28}$ e ‘cm

EDM limits

Particle	Exp. Limit [10^{-27} *e* cm]	SM [factor to go]	Possible New Physics [factor to go]
e (Tl)	< 1.6	10^{11}	≤ 1
μ	< 1.05 *10^{9}	10^{8}	≤ 200
τ	< 3.1 * 10^{11}	10^{7}	≤ 1700
n	< 63	10^{4}	≤ 60
Tl (odd p)	< 10^{5}	10^{7}	≤ 10^{5}
Hg (odd n)	< 0.21	10^{5}	various

EDM Measurement and Sensitivity



$$h\nu_{\uparrow\uparrow} = 2\mu \cdot B + 2d \cdot E$$

$$h\nu_{\uparrow\downarrow} = 2\mu \cdot B - 2d \cdot E$$

$$\Rightarrow h\Delta\nu = 4d \cdot E$$

Electric dipole moment : d

Sensitivity :

$$\delta d = \frac{h}{2e} \cdot \frac{1}{K} \cdot \frac{1}{E} \cdot \frac{1}{\sqrt{N \cdot \tau \cdot T}}$$

K: Enhancement factor ~ Atom EDM = **Largest ~ Francium**

E : Electric Field ~ Strong, 100 kV/cm = **Laser trap in high vacuum**

N : Number of Particles ~ Many particles ! = **Ion Source + Atom cooling**

τ : Coherence Time (Stored time) ~ Long ! = **Laser trap**

T : Lifetime of Experimentalist ~ Long !

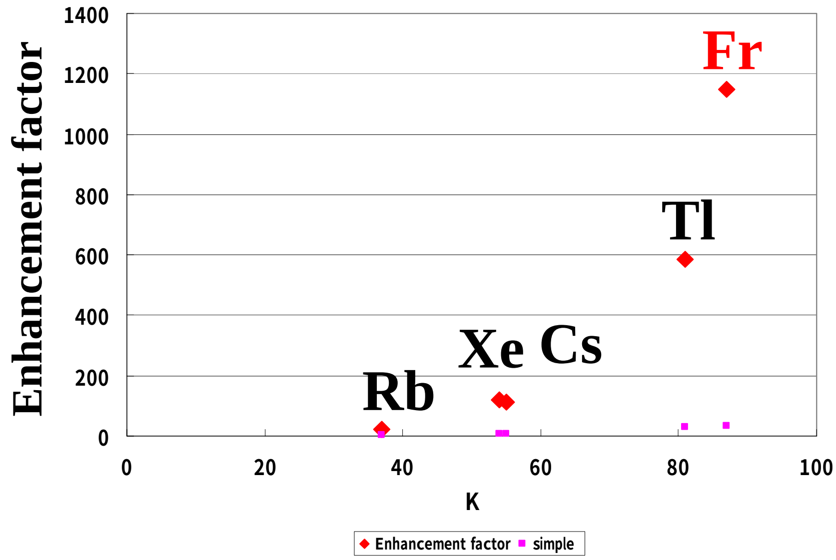
Why Francium traps ?

- **Heaviest Alkali metal ~ Francium :**
  - **⇒simple electronic structure and large nucleus**
  - **⇒Enhancement of EDM ~ largest ! : ^{210}Fr ~ K=1150**
- **Several isotopes with long lifetime > 1 min.**
  - **⇒^{210}Fr =3.2 min., ^{212}Fr =19.3 min.**
- **No stable isotopes, but traps compensate scarcity**
- **Magneto-Optical Trap (MOT) : localize the trapped atoms**
  - **⇒systematic error reduced**
- **Temperature of MOT cloud < mK ~ Doppler-free spectroscopy**

Heavy atoms amplify EDM
~ P.G.H. Sandars, Oxford, 1960s
Enhancement factor:

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

$$\sim |\psi_s(0)|^2 V Z^5 \alpha^2 \frac{e}{a_0^2}$$



Fr trapping experiments

Presented by Dr.Giulio Stancari @ INFN Ferrara at ISOLDE workshop at CERN, Feb.2006

SUNY Stony Brook

pioneered Fr trapping; spectroscopy

moving to TRIUMF

Gomez et al., Rep. Prog. Phys. 69, 79 (2006)

JILA Boulder

vapor cell; spectroscopy of ^{221}Fr

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

Fr from the decay of ^{225}Ac

LNL Legnaro

status in this talk

RCNP Osaka

feasibility tests for EDM

Sakemi, RCNP proposal 2005 (unpublished)

EDM search in the world

Institute	Project	Elements	Trap	Status	Goal
SUNY		^{210}Fr	MOT	Atomic structure	
KVI	TRIuP	Ra (p)	MOT/Penning	First beam	
TRIUMF	TISOL		MOT		
California / LBL		^{205}Tl (e)	Atomic beam	Best limit	$\sim 10^{-27}$
Kyoto		^{171}Yb (p)	MOT+Laser Trap		
Tokyo Tech.		Xe (p)			
RCNP		$^{210-212}$Fr	MOT+Laser Trap	This proposal	$\sim 10^{-28}$

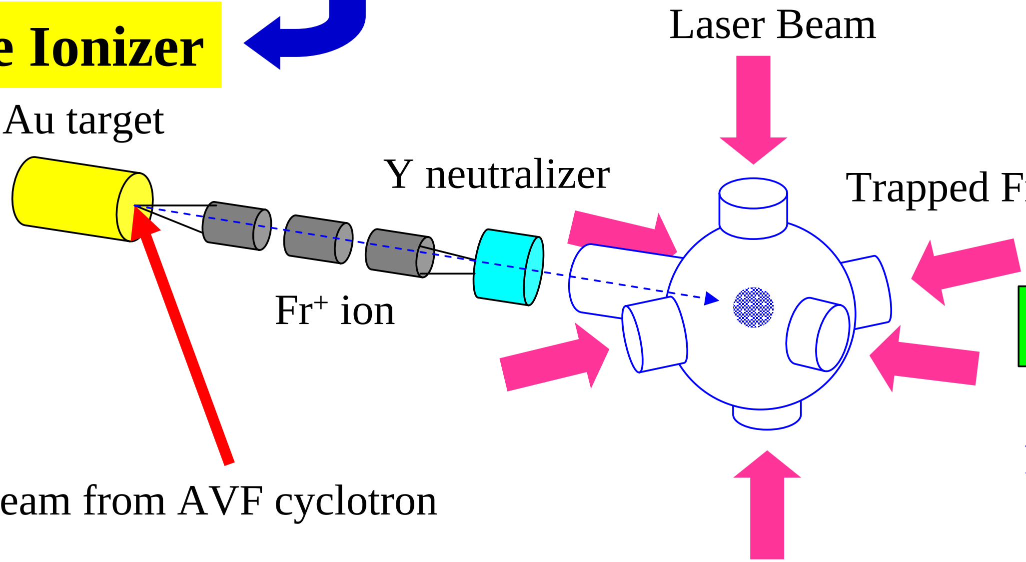
EDM	Elements						
Electron	Rb	Cs	Fe^{3+}	^{129}Xe $^3P_2$	^{205}Tl	**Fr**	Others
Nucleus	^{129}Xe $^1S_0$	Rn	^{199}Hg	Ra	Yb	Dy,Sm,Ba	Others

Experiment

Francium Production with Heavy Ion Fusion Reaction :

$^{197}Au(^{18}O,xn)^{209\text{-}211}Fr$

Surface Ionizer

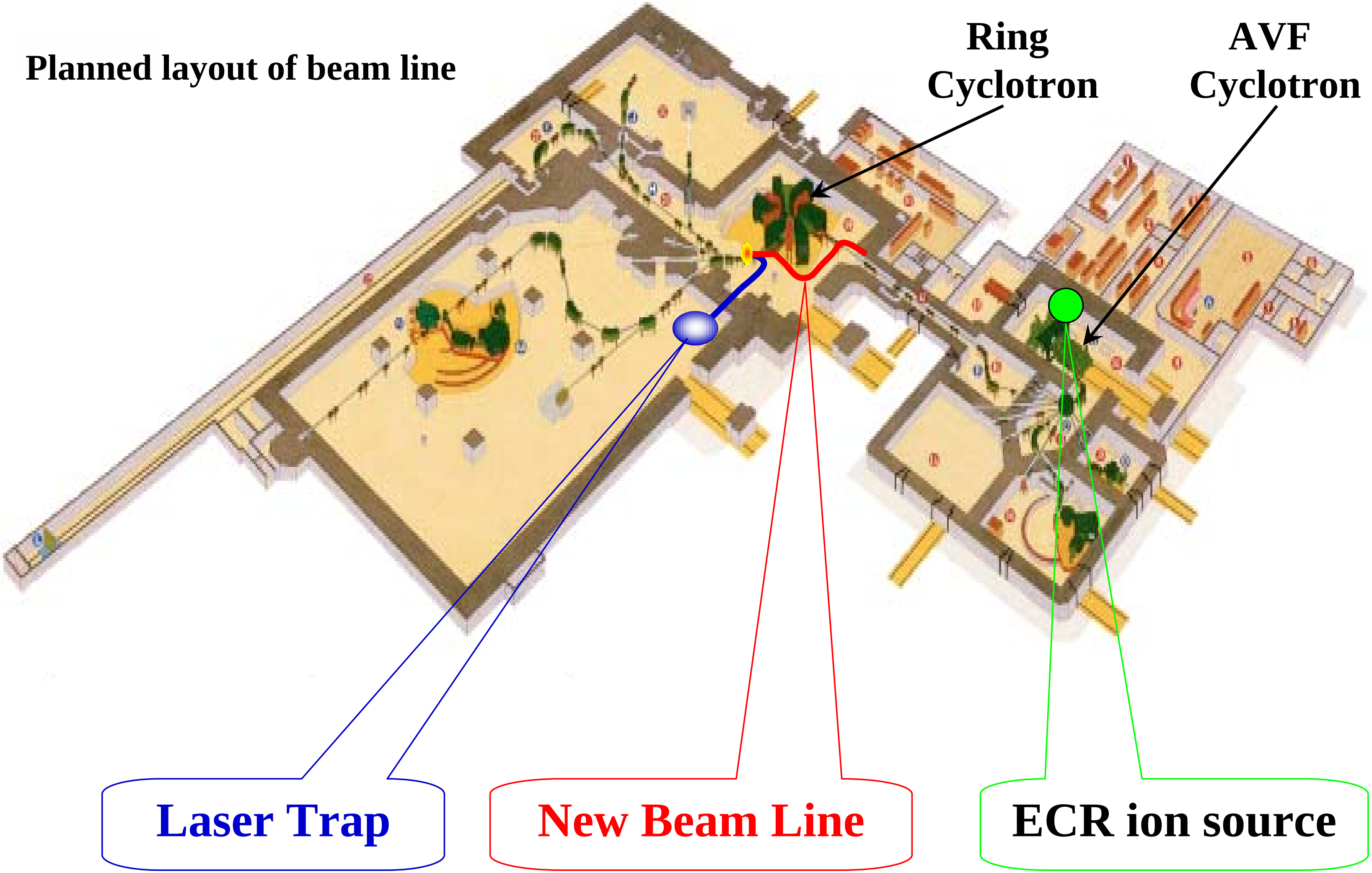


EDM search

Fundamental interaction

High intensity ECR ion source	Magneto-Optical Trap	TRV SUSY…
Nuclear Physics	**Atomic Physics**	**Particle Physics**

Overview at RCNP



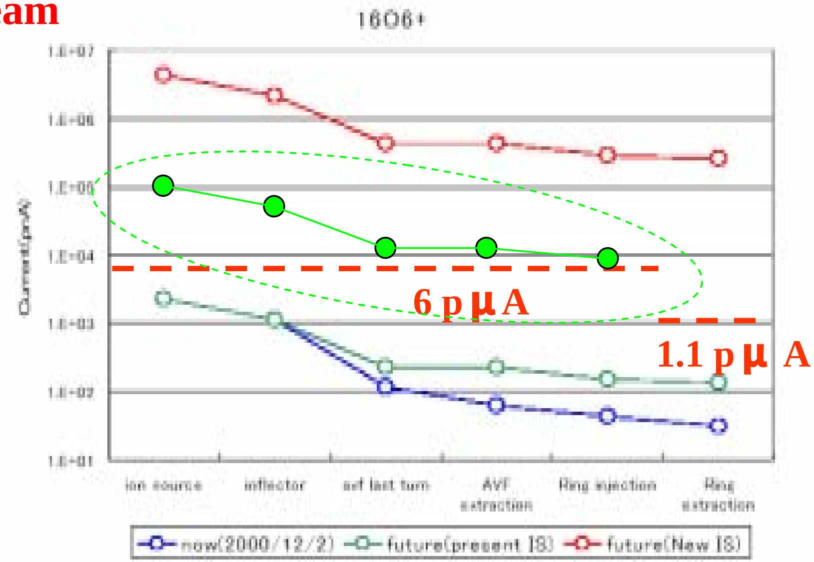
Primary beam

- ~ 100 MeV $^{18}O^{6+}$ beam from AVF cyclotron
- **New ion source : 18GHz Superconducting ECR**
  - ✓For heavy ion and polarized ^{6}Li beam
  - ✓Construction ~ completed soon
  - ✓Operation test ~ will be done next week
  - ✓**Maximum intensity**
    ~ radiation protection limit: 6 puA

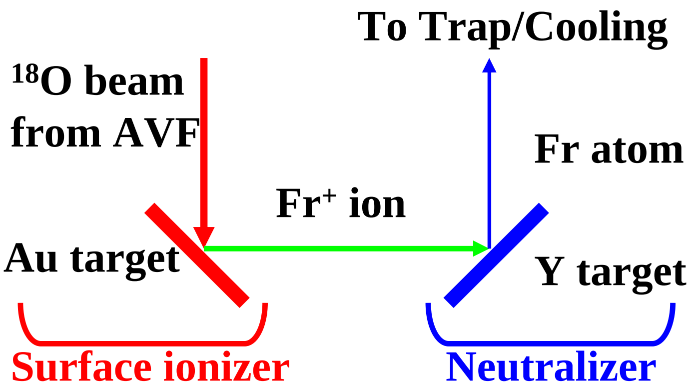
SC ECR ion source

Extracted beam

Beam intensity (expected)



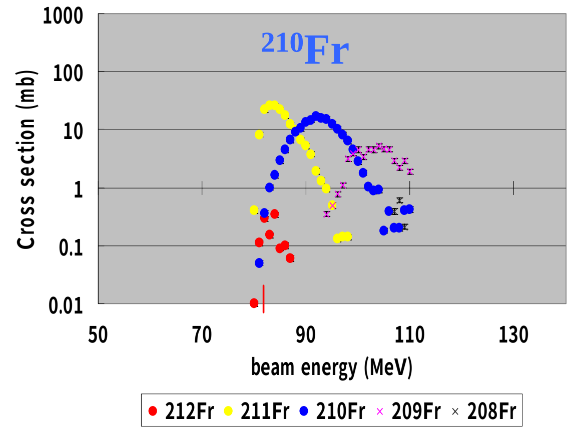
Francium production



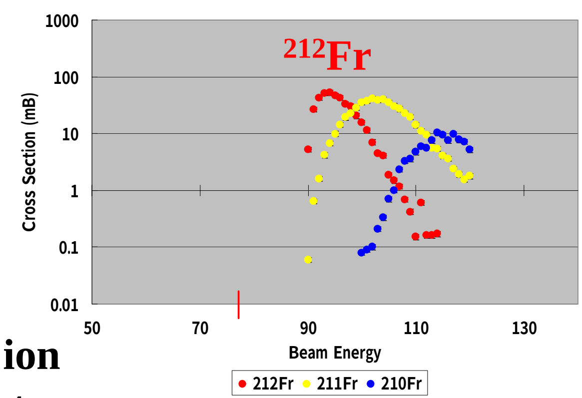
Fusion Reaction :

$^{18/16}\mathrm{O} + {}^{197}\mathrm{Au} \rightarrow {}^{207\text{-}211}\mathrm{Fr} + \mathrm{Xn}$

$^{18}\mathrm{O}+{}^{197}\mathrm{Au}$



$^{19}\mathrm{F}+{}^{198}\mathrm{Pt}$

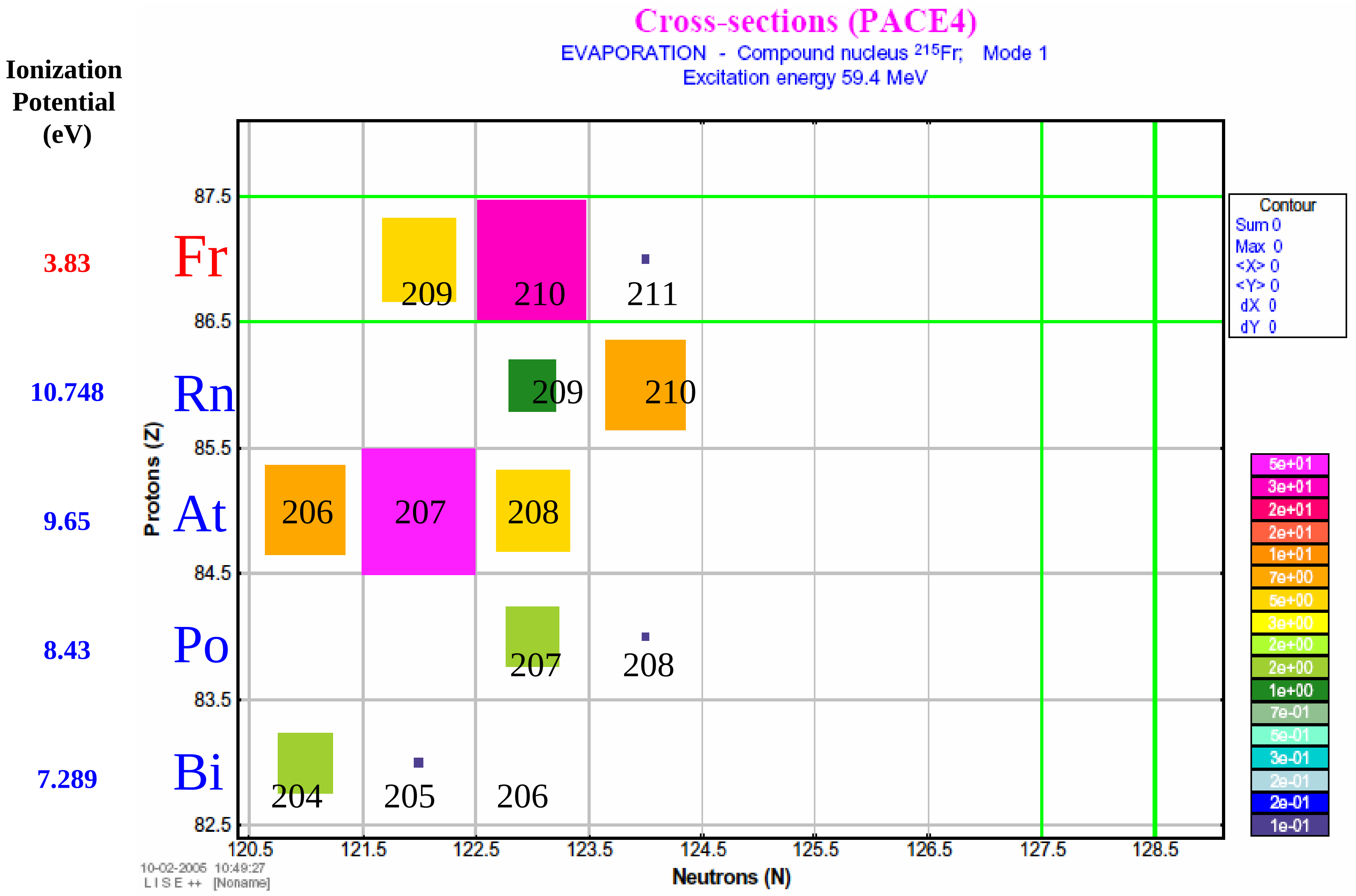


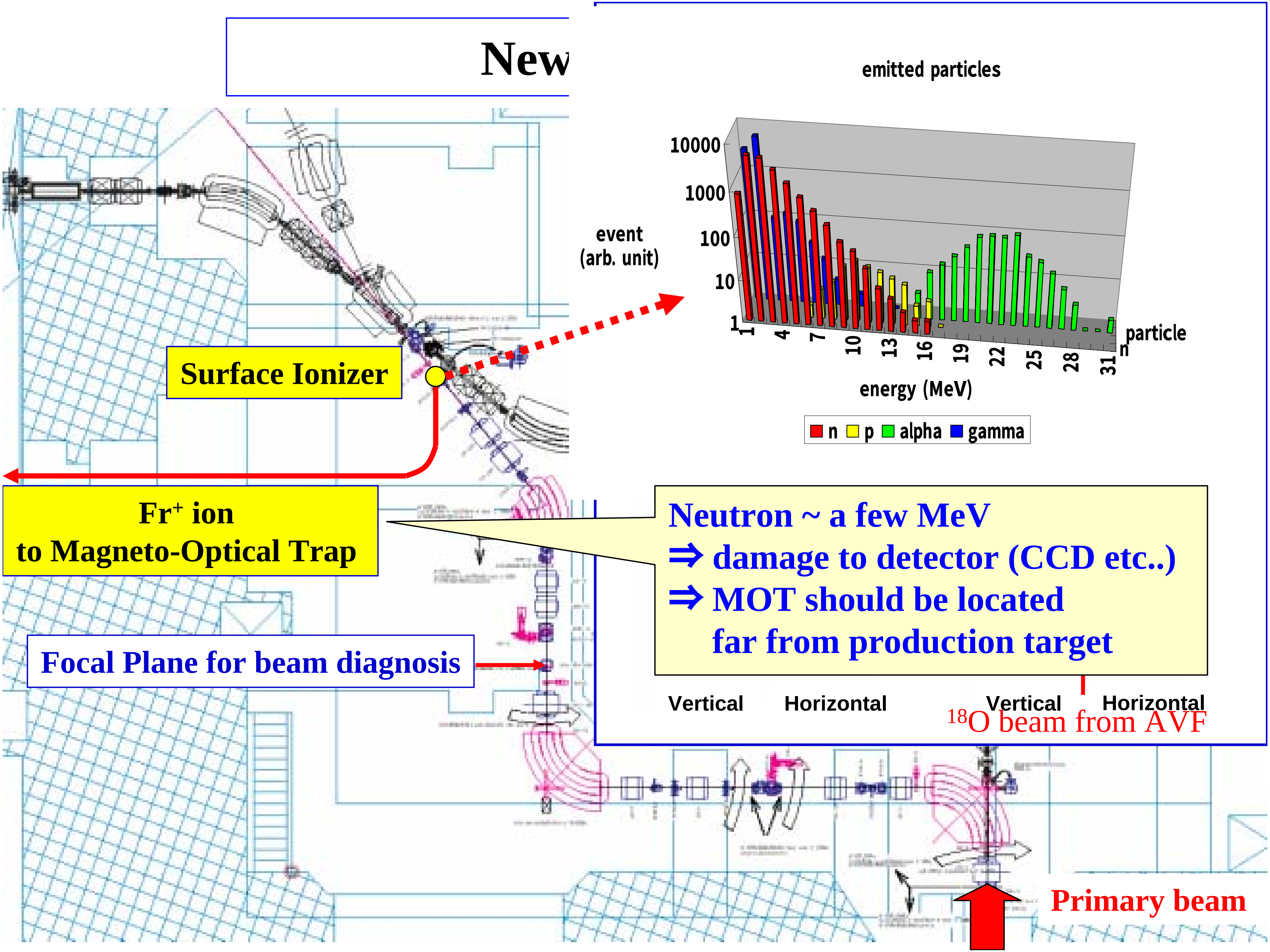
Francium desorbs from the target surface as atoms/ions according to

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

- **Target : Gold (Au) ~ E_{WF}(5.1eV)>E_{IP}(4.1eV) → Fr^+ ion**
- **Target : Yttrium (Y) ~ E_{WF}(3.1eV)<E_{IP}(4.1eV) → Fr atom**

$^{18}O+^{197}Au$

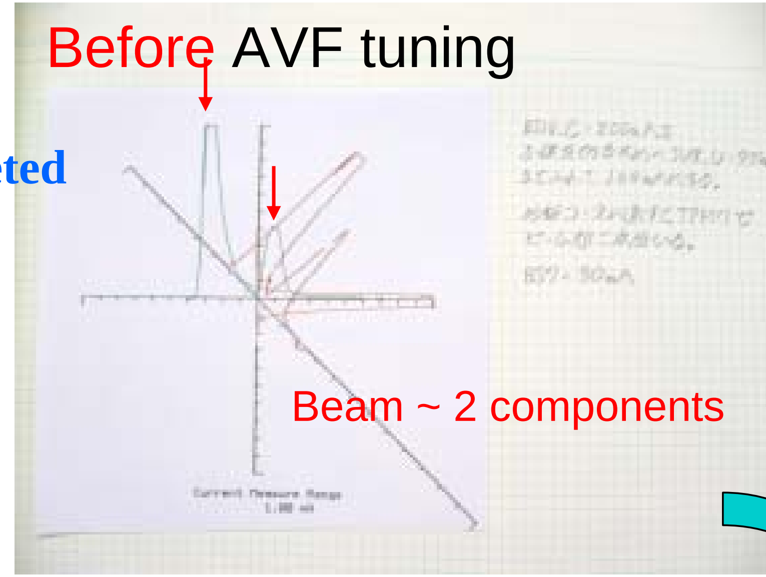

Ionization Potential (eV)
3.83
10.748
9.65
8.43
7.289
Fr
Rn
At
Po
Bi
Cross-sections (PACE4)
EVAPORATION - Compound nucleus 215Fr; Mode 1
Excitation energy 59.4 MeV
87.5
86.5
85.5
84.5
83.5
82.5
Protons (Z)
209
210
211
209
210
206
207
208
207
208
204
205
206
120.5
121.5
122.5
123.5
124.5
125.5
126.5
127.5
128.5
Neutrons (N)
Contour
Sum 0
Max 0
<X> 0
<Y> 0
dX 0
dY 0
5e+01
3e+01
2e+01
2e+01
1e+01
7e+00
5e+00
3e+00
2e+00
2e+00
1e+00
7e-01
5e-01
3e-01
2e-01
2e-01
1e-01
10-02-2006 10:49:27
LISE ++ [Noname]

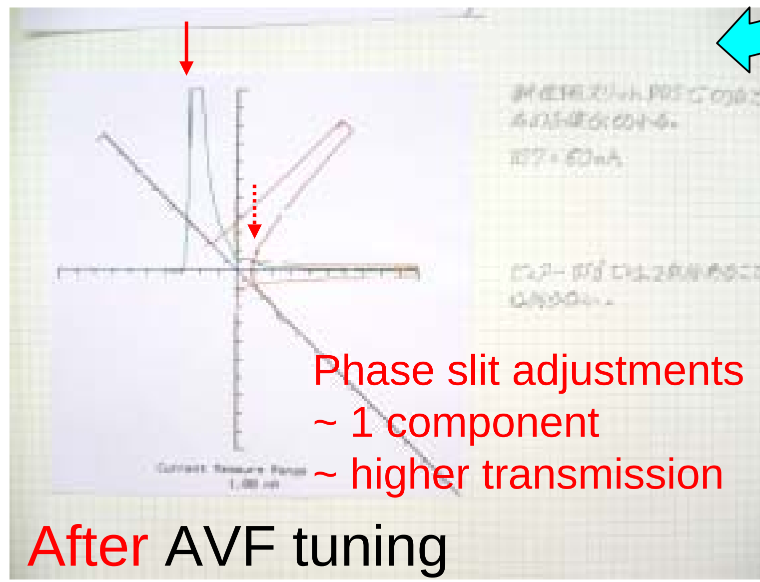

New
emitted particles
event (arb. unit)
10000
1000
100
10
1
1
4
7
10
13
16
19
22
25
28
31
energy (MeV)
particle
n
n
p
alpha
gamma
Surface Ionizer
Fr+ ion
to Magneto-Optical Trap
Neutron ~ a few MeV
⇒ damage to detector (CCD etc..)
⇒ MOT should be located
far from production target
Focal Plane for beam diagnosis
Vertical
Horizontal
Vertical
Horizontal
18O beam from AVF
Primary beam

New Beam Line for EDM search experiment

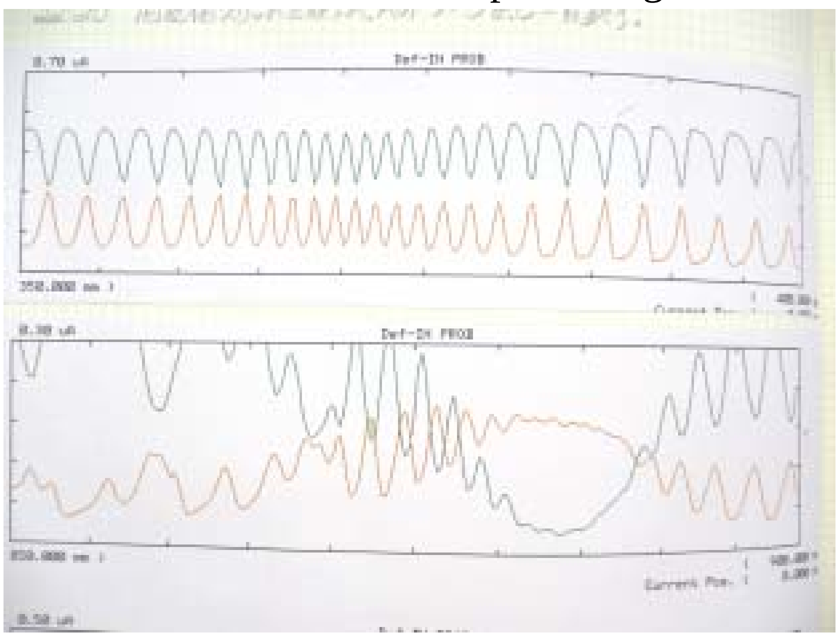
Beam transport and diagnosis with new beam line

- **Construction ~ completed**
- **Transport test with ^{18}O beam ~ completed**
- **Beam diagnosis ~ routinely used**
  for high resolution beam preparation
- **Transmission ~ more than 90 %**
  ~ depend on beam emittance

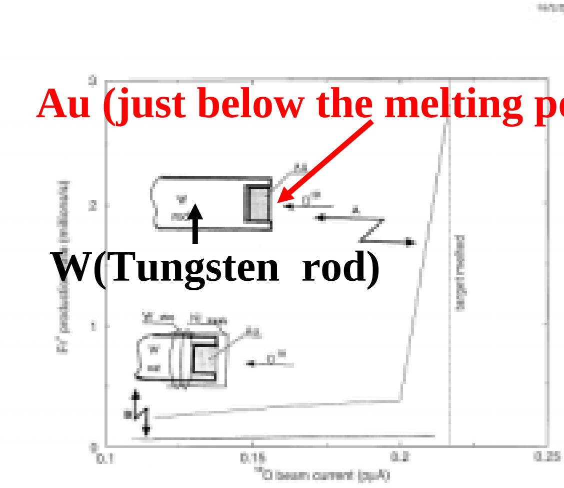




AVF accelerator turn ~ separation good

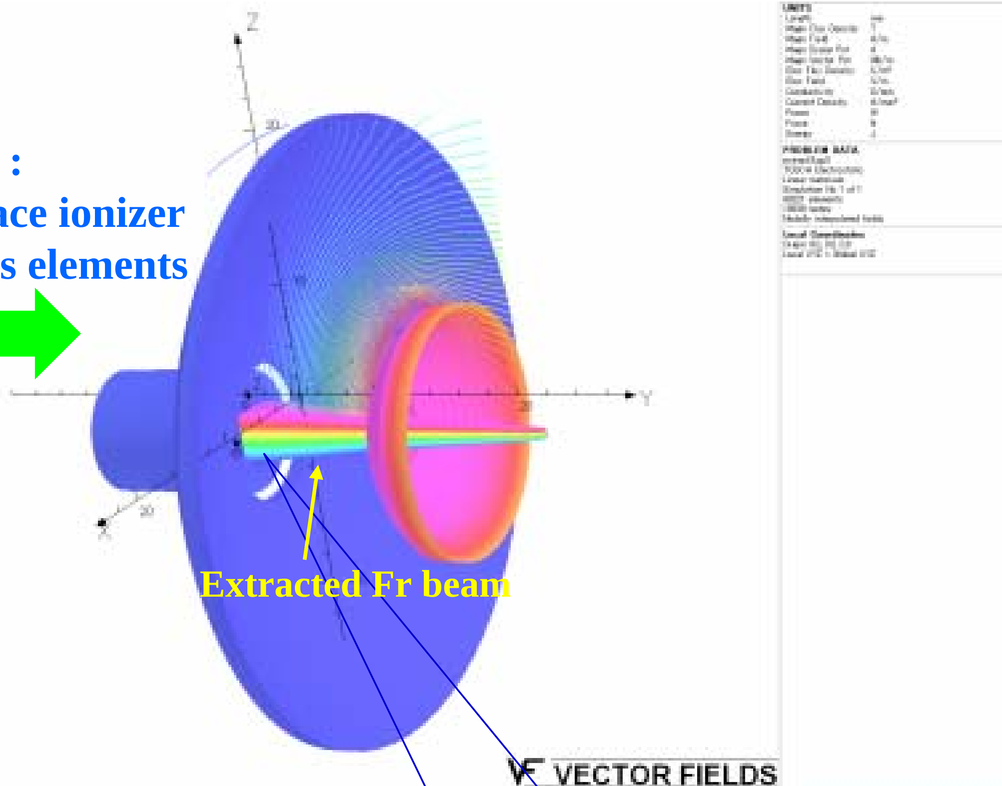


Surface ionizer



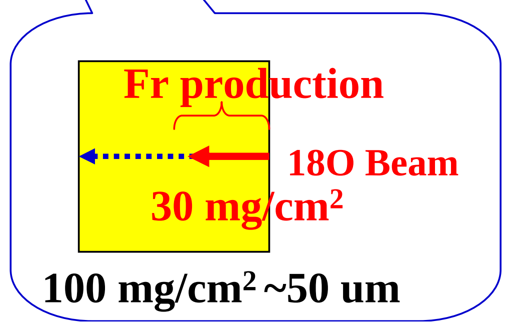
Based on Surface ionizer at SUNY

Design :
Surface ionizer
+ Focus elements

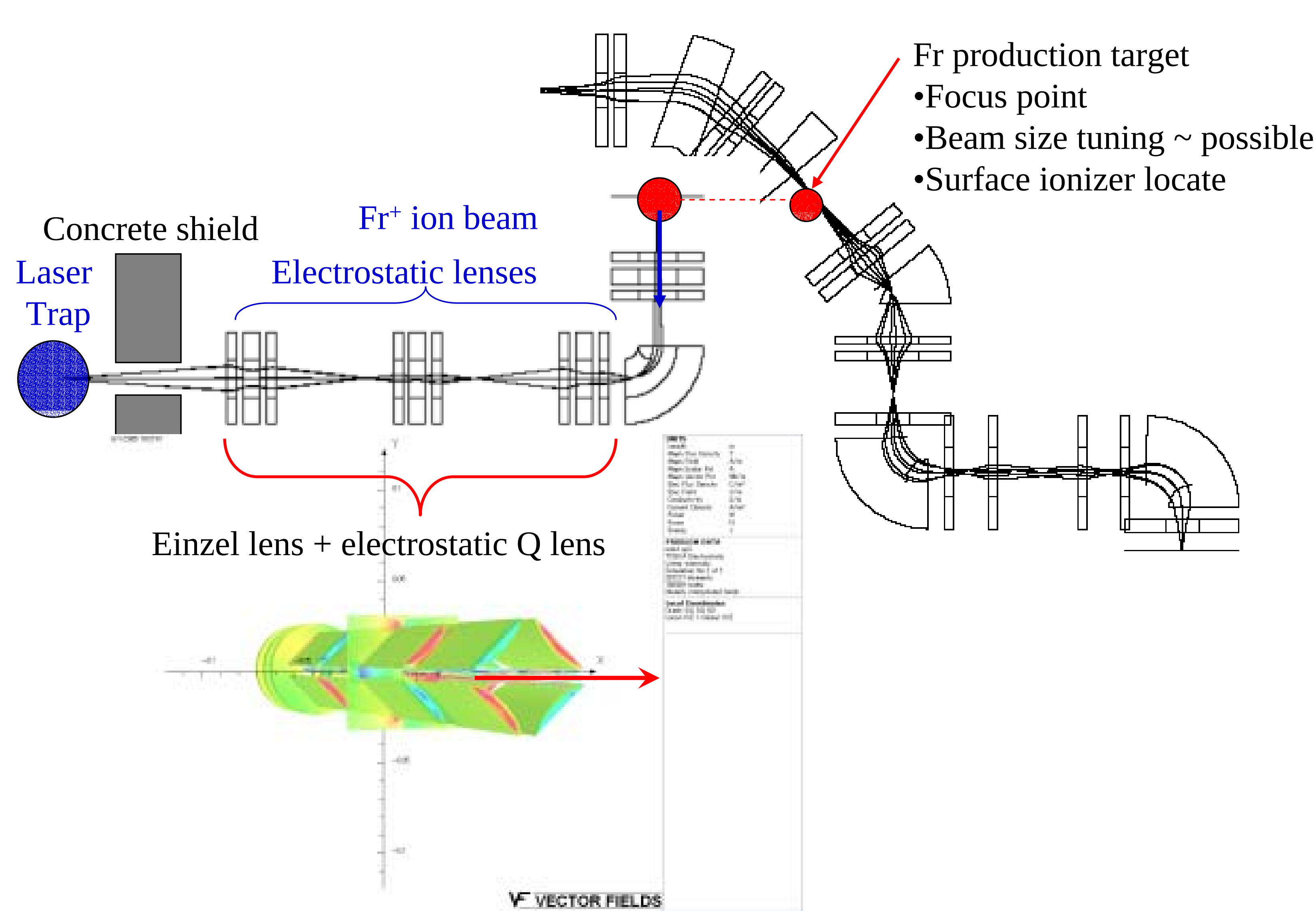


- **^{197}Au disk on W support rod**
- **1200 K for surface ionizer**
- **3 kV to extract Fr^{+} ion**
- **Fusion reaction : $^{197}Au(^{18}O,xn)^{215-x}Fr$**
- **Focusing elements ~ design with 3d field calculation**

Design ~ almost finished
Construction ~ will be completed in this summer

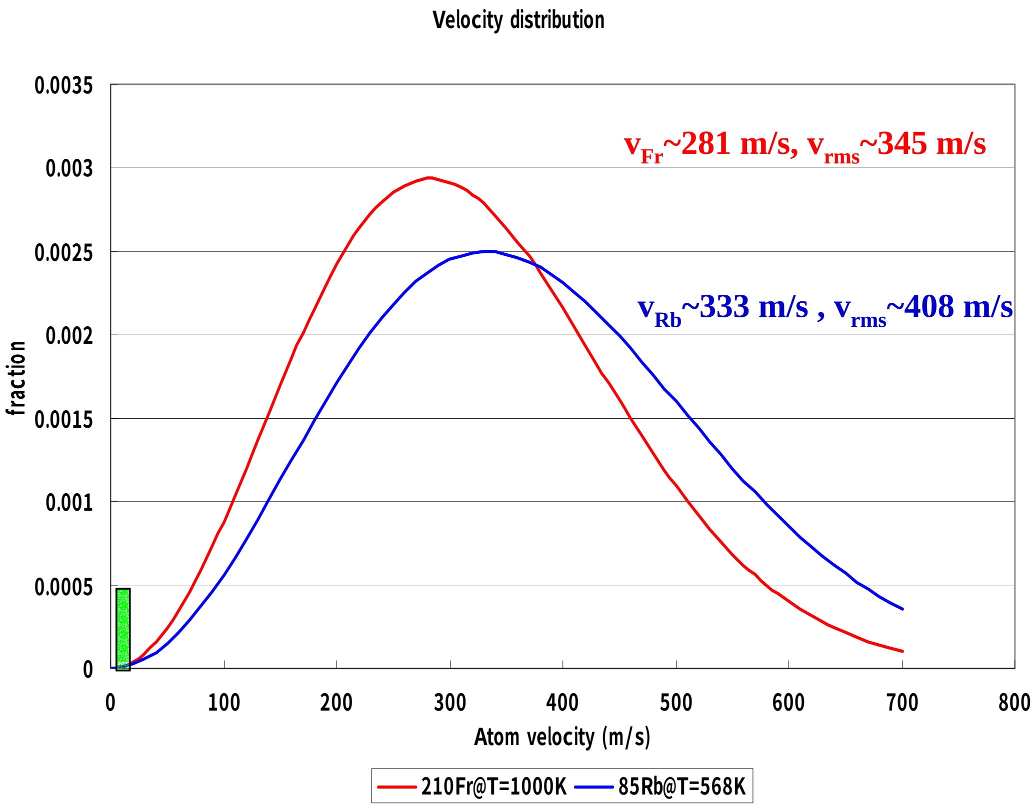


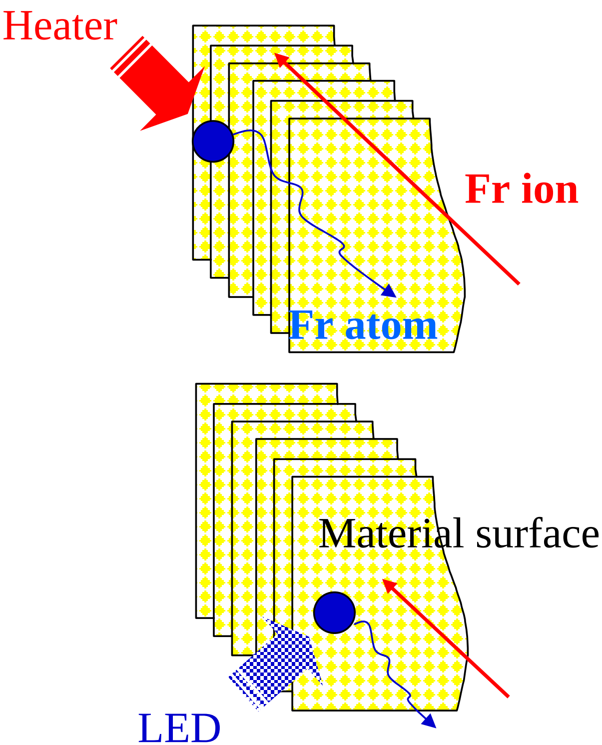
Francium ion transport



Neutralizer

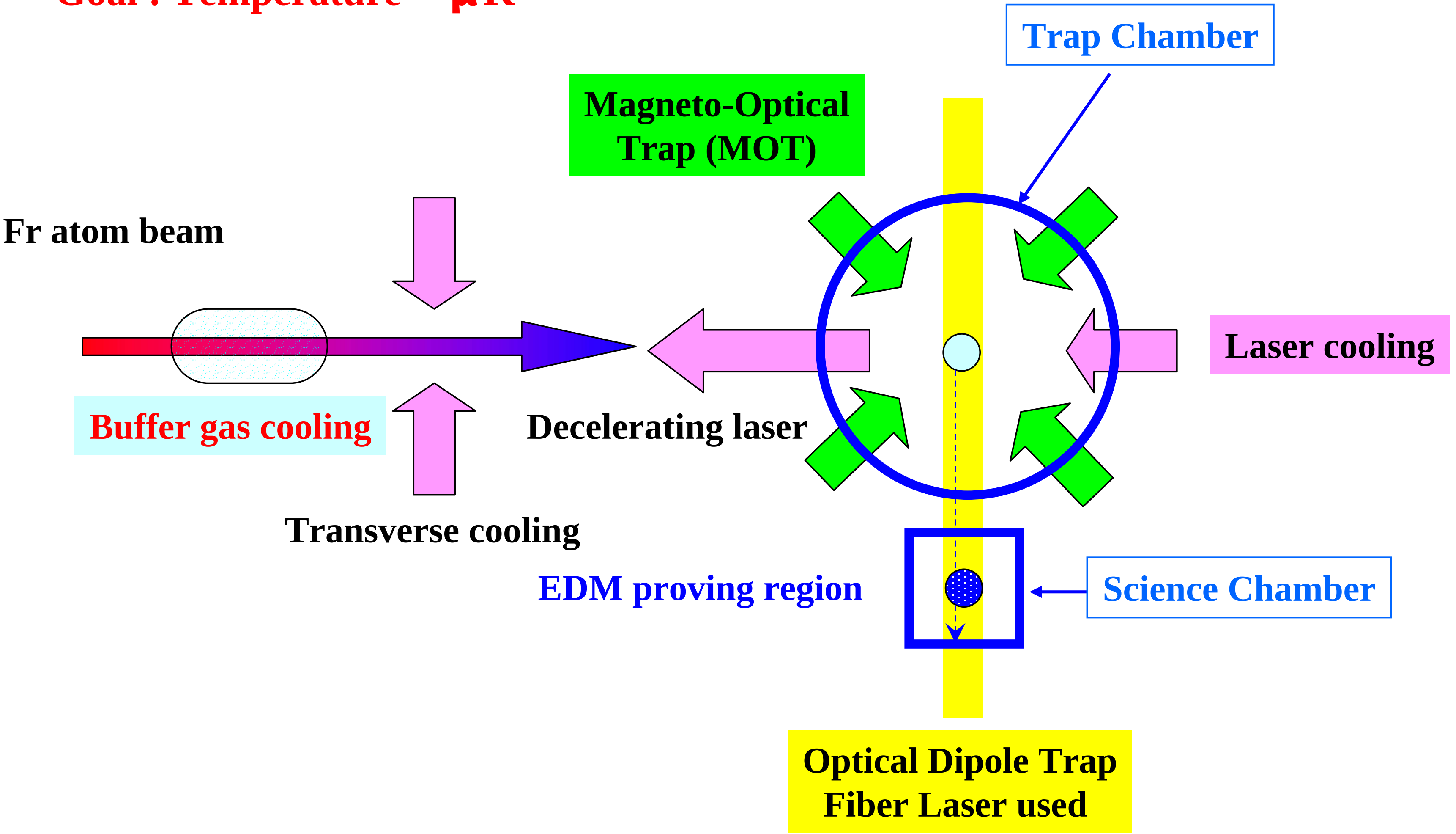
- Oven (Y) temperature : 1000 K ~ heater temperature for Fr atom release
- Capturing velocity of MOT : Vc~1 m/s
- Fraction of trapping atoms : 10^{-4} ~ 10^{-5}
- High trapping efficiency realization ~ need to cool atoms





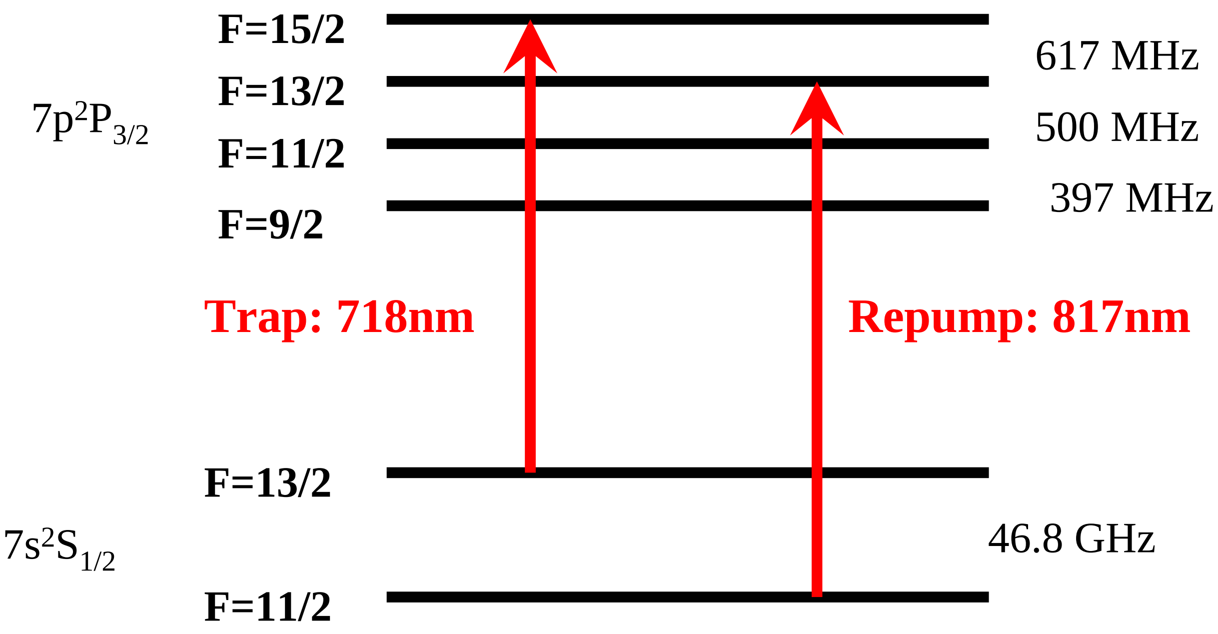
Laser cooling and trapping

Goal : Temperature ~ μK

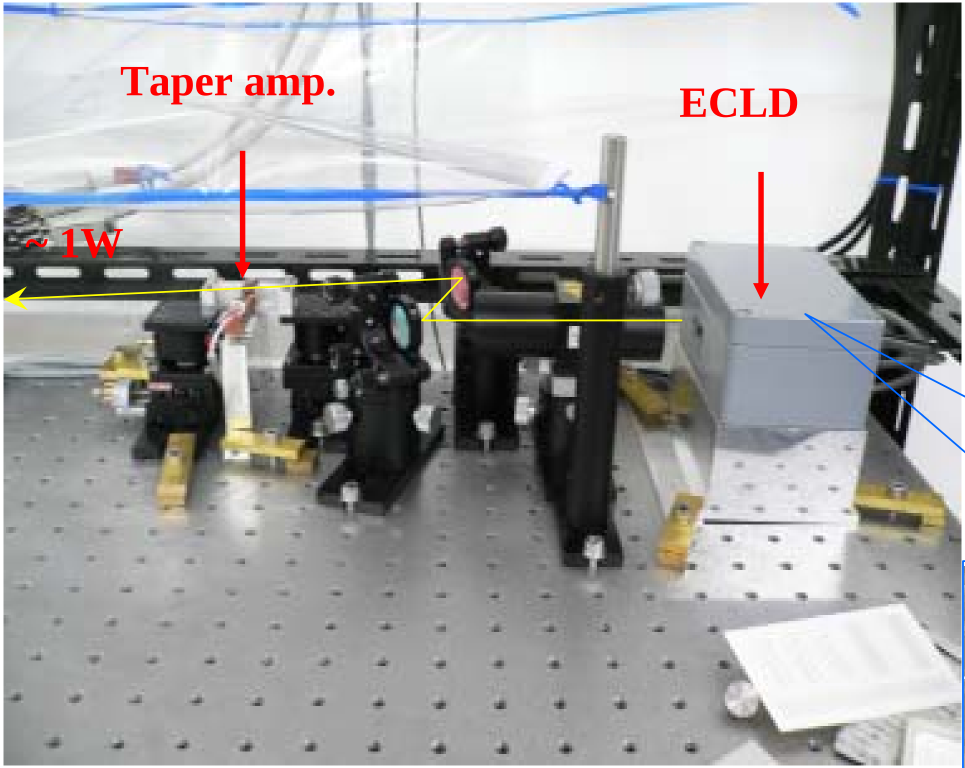


Trap view

- ➢ **Trap laser : 718 nm and 817 nm**
  - ✓ **External Cavity LD (ECLD) + Taper amplifier**
  - ✓ **Fabrication ~ in progress**
- ➢ **Beam diameter ~ 30 mm**
- ➢ **Anti-helmholz coil ~ 10 G/cm**
- ➢ **Pyrex cell with dryfilm coating**
- ➢ **Decouple MOT from target area (radiation and vacuum)**
- ➢ **Laser for Optical Dipole trap : red detuned**
  - ✓ **High power fiber laser used**

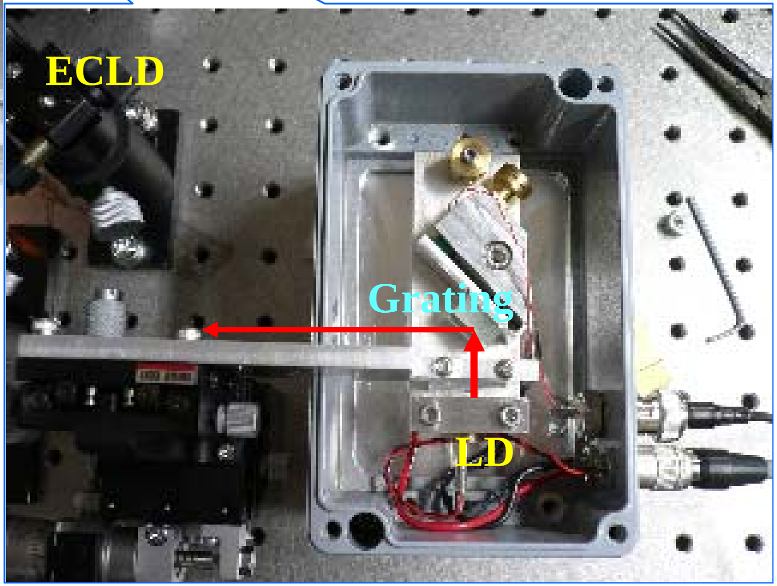


ECLD+Taper amp.



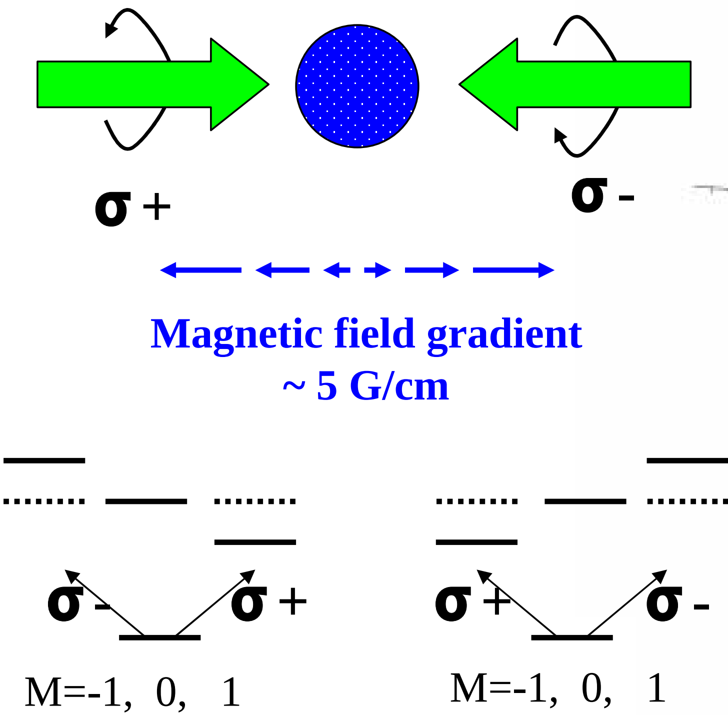
MOPA configuration :
➢Master oscillator ~ ECLD ~ 10 mW
➢Power amplifier ~ Taper amp. ~ 1 W

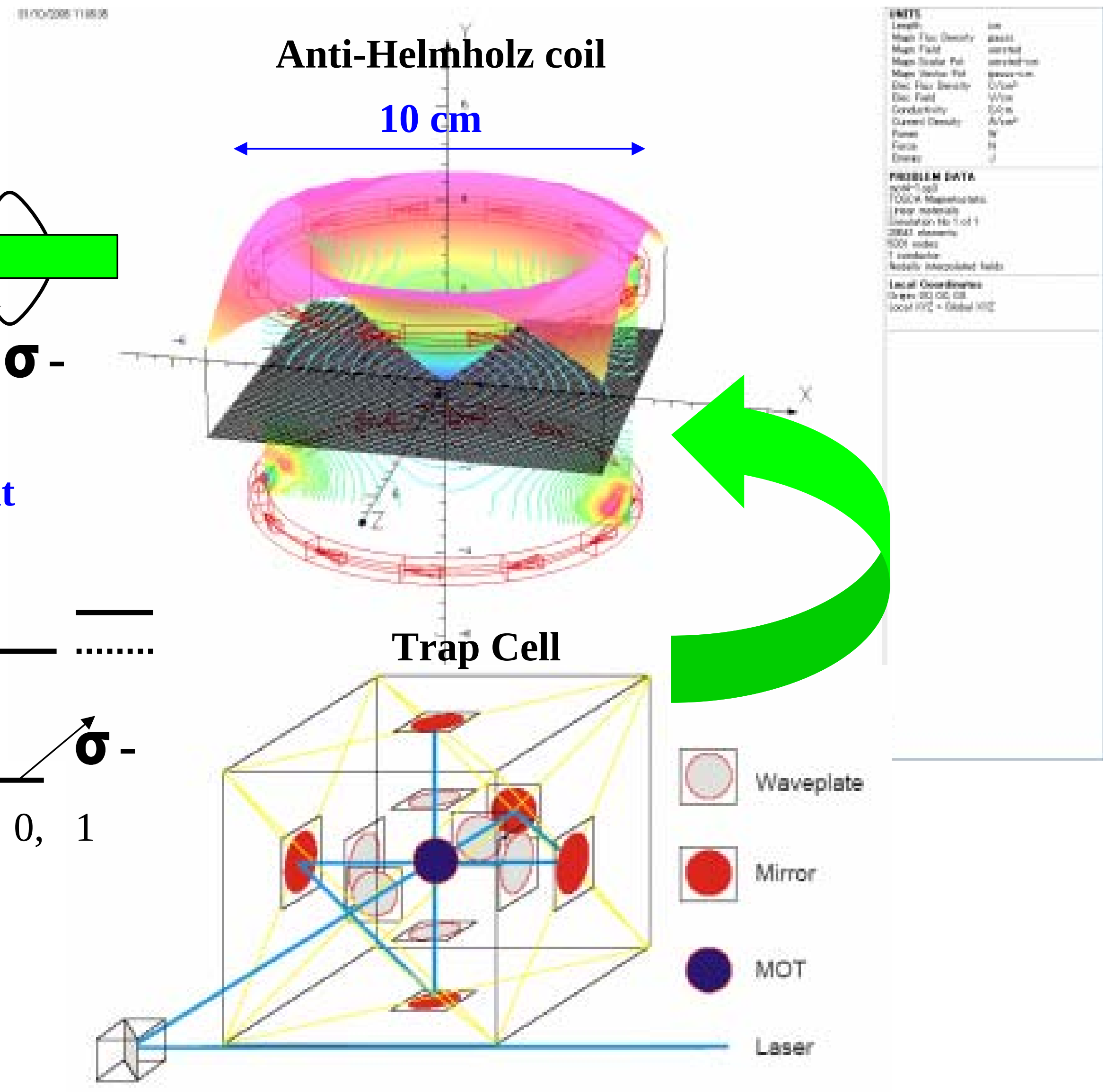
Low cost
Compact



What should be solved !
~ 718 nm Taper amp …

MOT


σ +
σ -
Magnetic field gradient
~ 5 G/cm
σ -
σ +
M=-1, 0, 1
σ +
σ -
M=-1, 0, 1

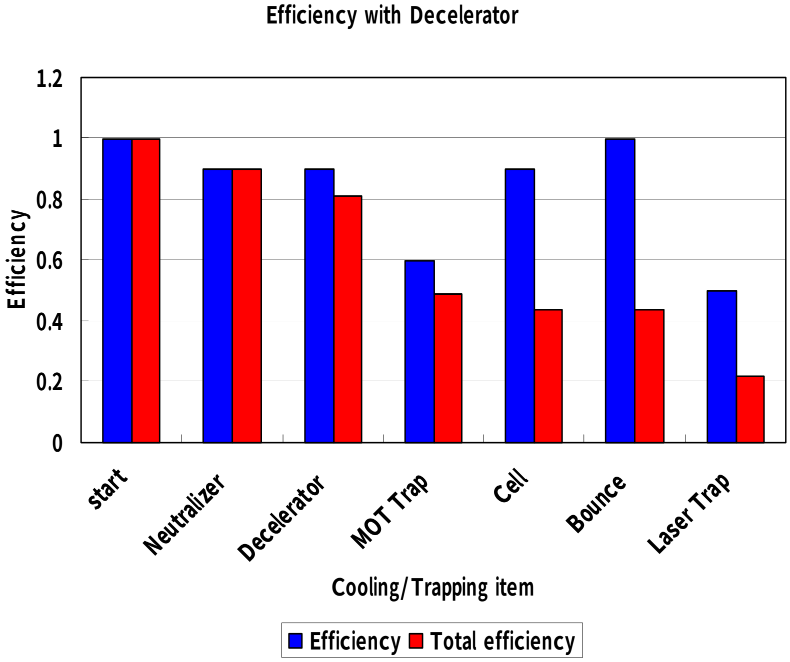

Anti-Helmholz coil
10 cm
Trap Cell
Waveplate
Mirror
MOT
Laser

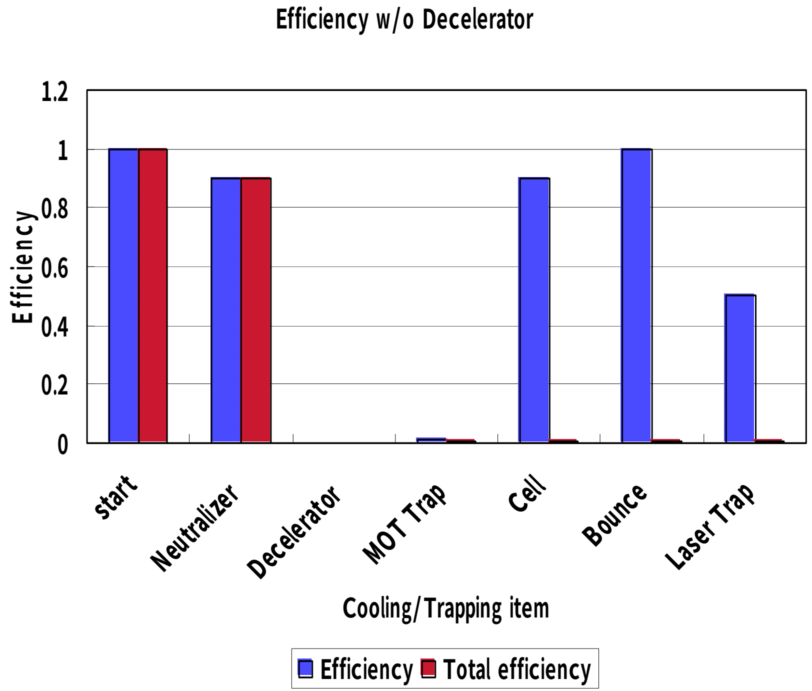
Cooling atoms

Goal : Cooled atom number ~ 10^8 → Trap efficiency : P_{trap} ~ higher !

$$P_{trap} = \eta_n \cdot \varepsilon_D \cdot P_{MOT}(v_c) \cdot \varepsilon_{Laser} = \eta_n \cdot \varepsilon_D \cdot \frac{f_v P_1(v_c)}{1-\left(1-\frac{1}{N_{bounces}}\right)\left[1-f_v P_1(v_c)\right]} \cdot \varepsilon_{Laser}$$

- η_n Neutralizer efficiency : material, LED
- ε_D Decelerator efficiency : Collimation laser
- P_{MOT} MOT efficiency : Decelerator
  - ✓ f_v trap size : Laser size
  - ✓ P_1 trap efficiency : Laser detuning, power
  - ✓ N_{bounce} Bounce : Coating, LED
- ε_{Laser} Laser trap efficiency : Laser power

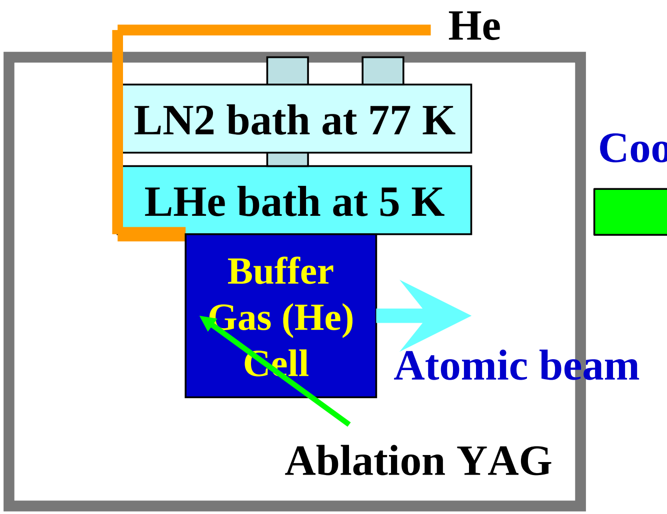


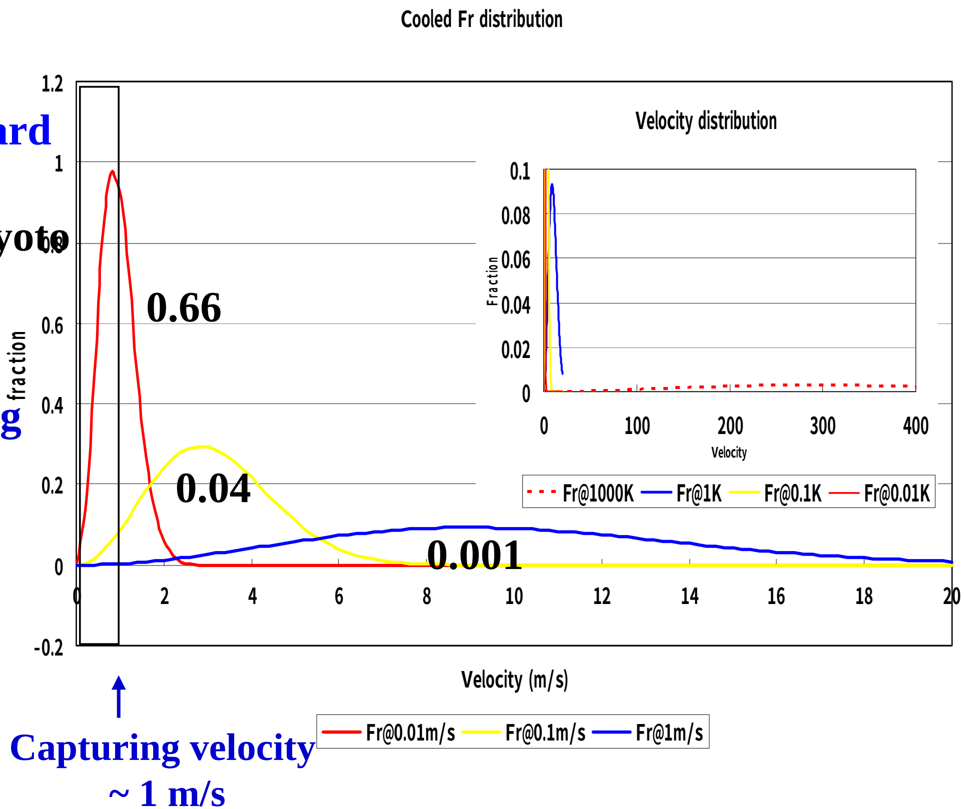


Buffer gas cooling

Buffer gas cooling ~ J.M.Doyle@Harvard

- ➢Apparatus delivered from Harvard
- ➢Started to check the feasibility at Kyoto





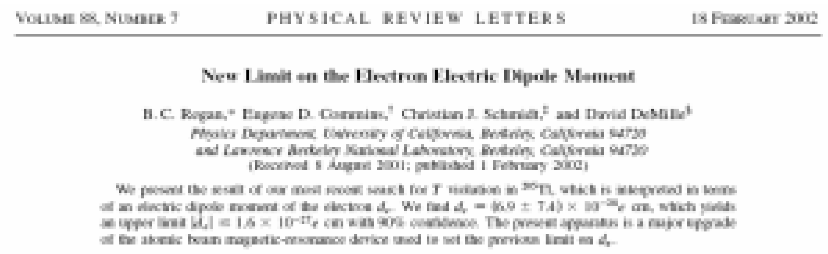
EDM measurement

- Ramsey's method of Separated Oscillatory Fields
  - ~ Atomic beam

- Larmor frequency determination by Faraday Rotation measurement
  - ~ Trapped atom

Ramsey's method

Electron



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New Limit on the Electron Electric Dipole Moment

B. C. Regan,* Eugene D. Commins,† Christian J. Schmidt,‡ and David DeMille§

Physics Department, University of California, Berkeley, California 94720
and Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 8 August 2001; published 1 February 2002)

We present the result of our most recent search for T violation in ^{205}Tl, which is interpreted in terms of an electric dipole moment of the electron d_e. We find $d_e = (6.9 \pm 7.4) \times 10^{-28} e$ cm, which yields an upper limit $|d_e| \le 1.6 \times 10^{-27} e$ cm with 90% confidence. The present apparatus is a major upgrade of the atomic beam magnetic-resonance device used to set the previous limit on d_e.

$$F_+ \propto \frac{1}{2} + d_a \cdot E \cdot t$$

$$F_- \propto \frac{1}{2} - d_a \cdot E \cdot t$$

Laser

RF B-field

RF B-field

Laser

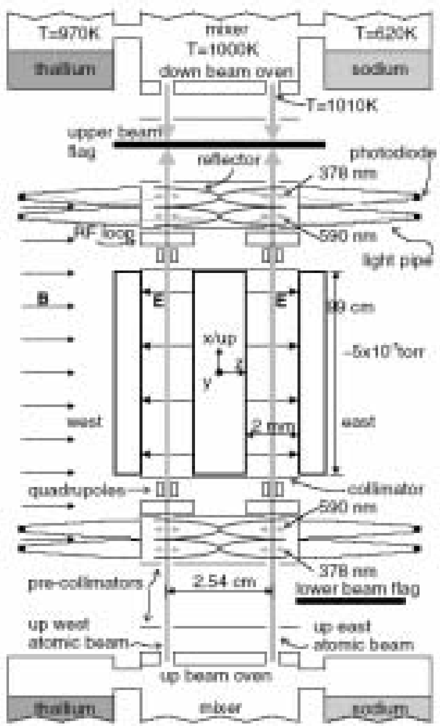
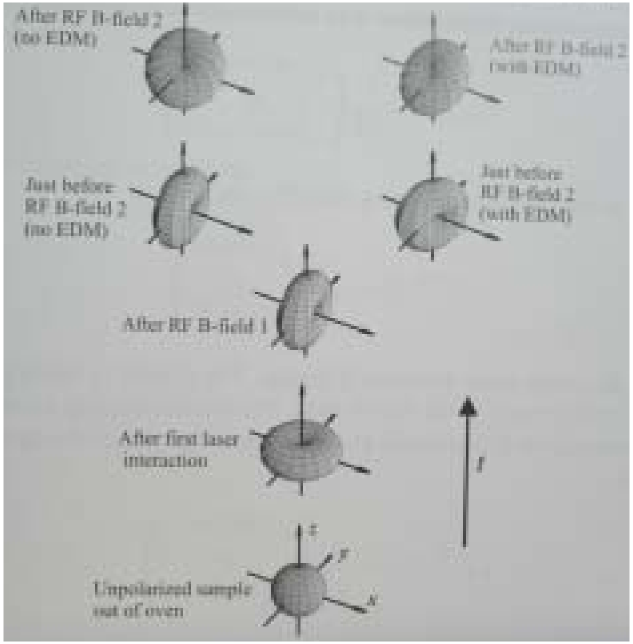
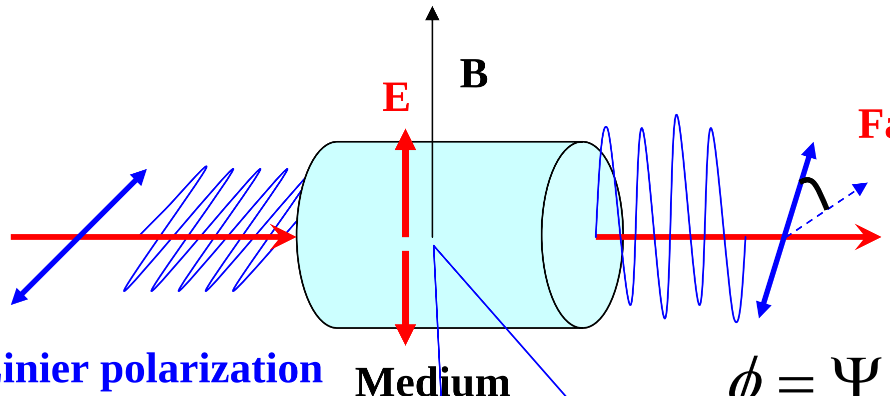


FIG. 1. Schematic diagram of the experiment, not to scale.



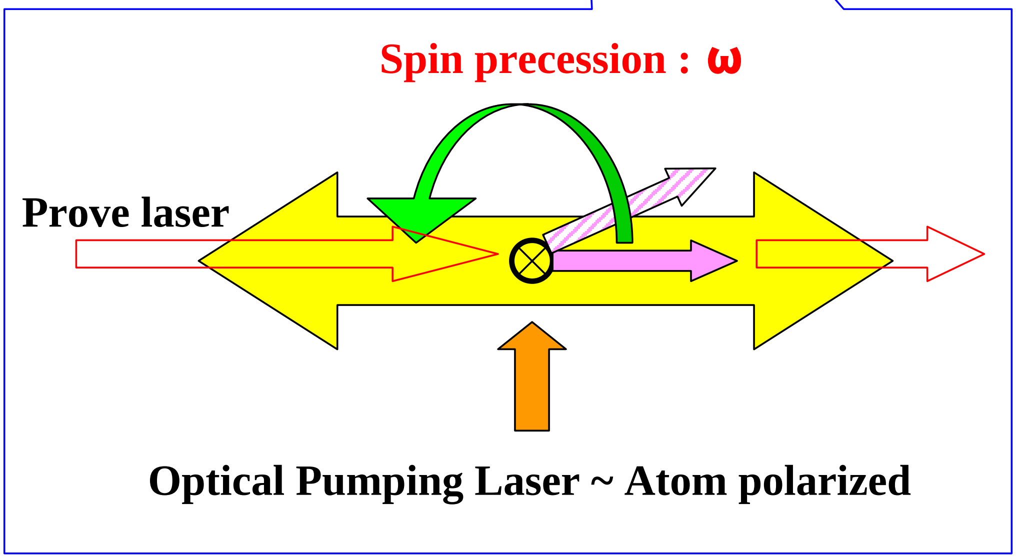
Faraday rotation measurement

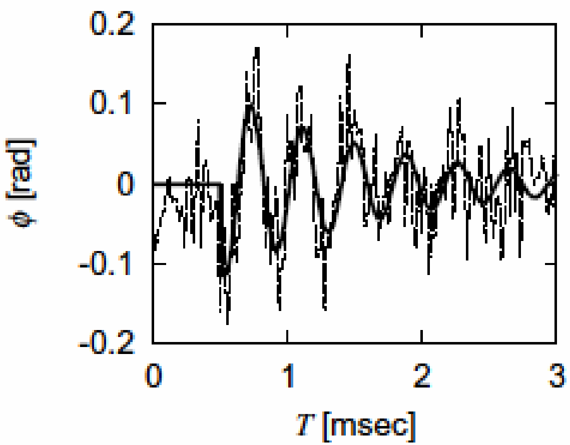


Faraday Rotation angle : ϕ

$$\phi = \Psi \cdot \exp\left(-T/\tau\right) \cdot \sin\left(\omega T + \theta\right)$$

$$\hbar \cdot \Delta\omega = 4 \cdot d_a \cdot E$$





Fr EDM search timeline

To achieve $d_e < 10^{-28}$ e・cm

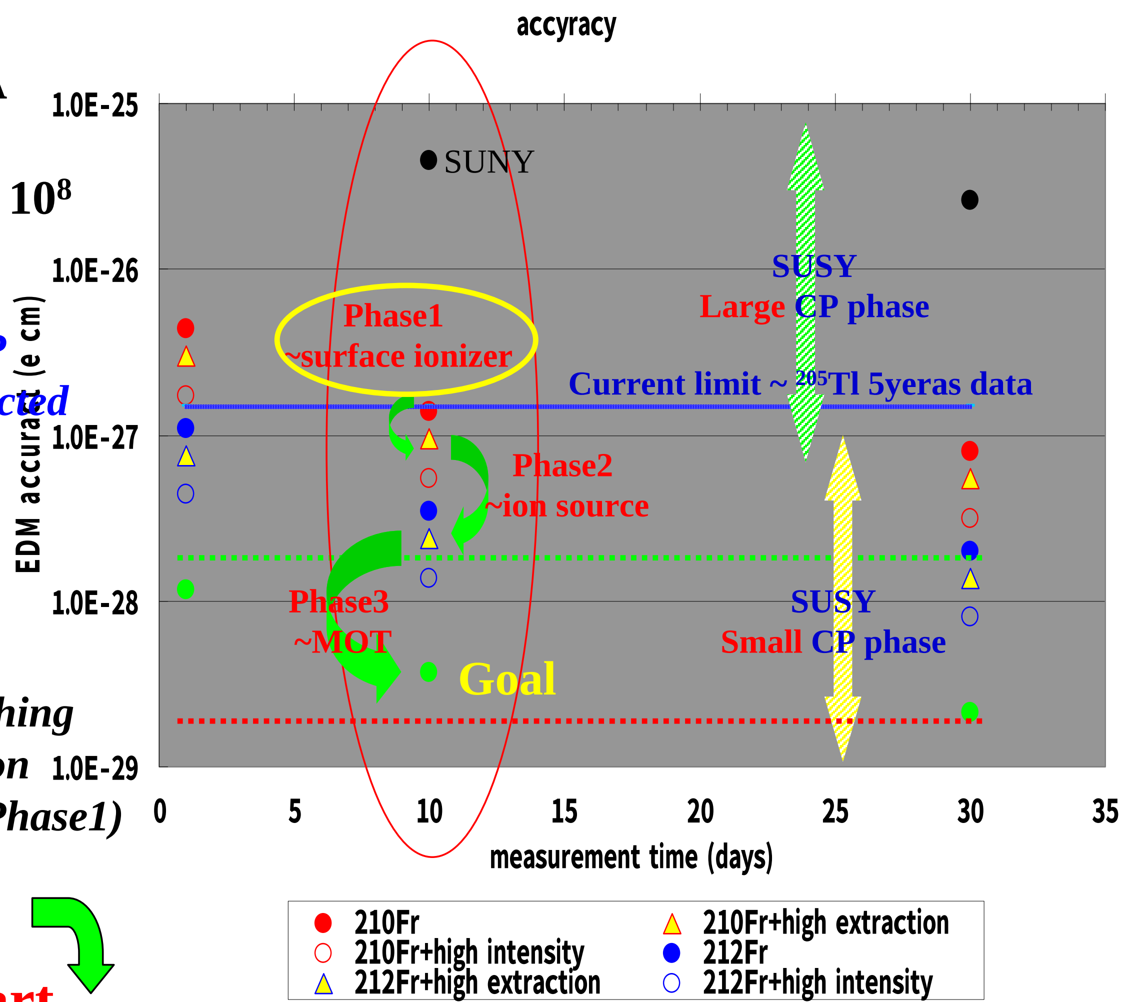
High intensity beam : 6 puA

⇒**SC ECR ion source**

Trapped atom ~ increased : 10^8

⇒**MOT with Cooling**

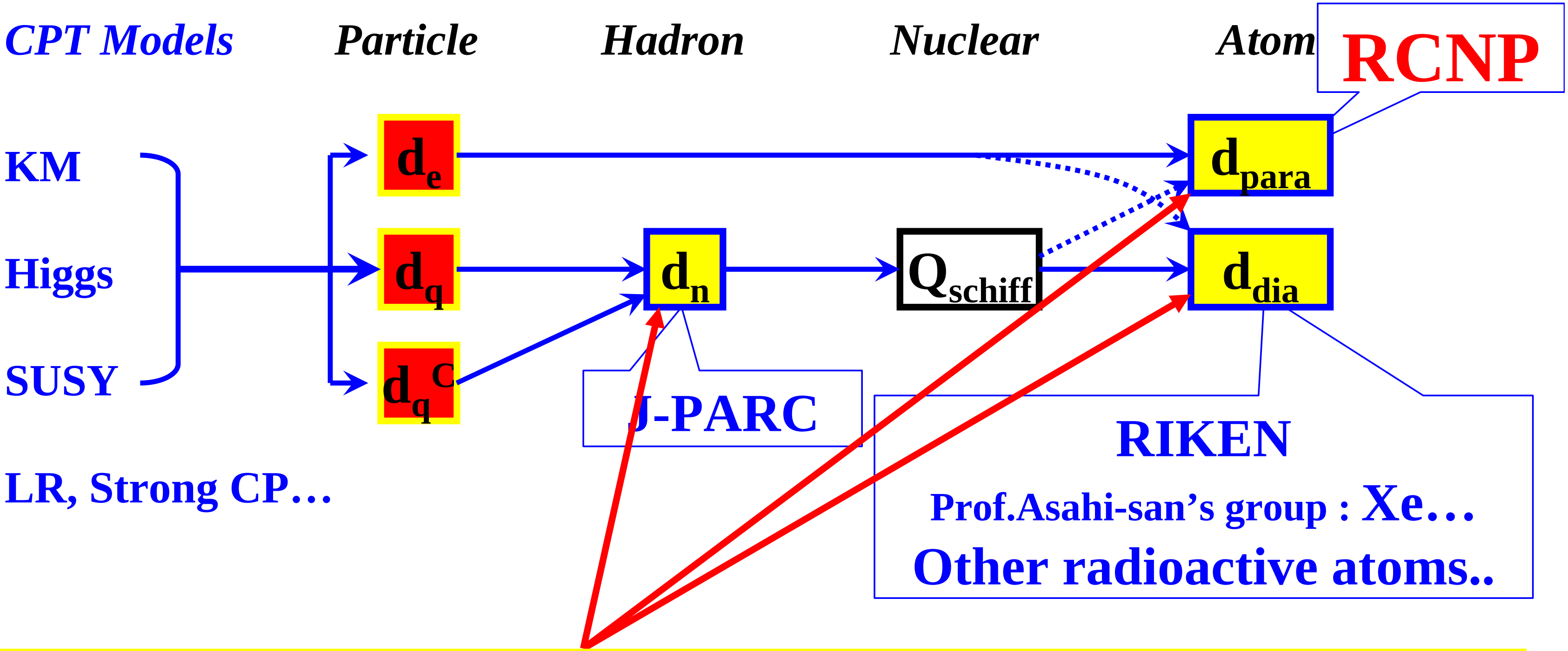
2005	*•Proposed at RCNP* *•Beam line constructed*
2006	*•ECR ion source* *•Surface ionizer* *•MOT ~ ready*
2007	*•Fr production test* *•Atom cooling test*
2008	*•Shakedown everything* *•Fr trap optimization*
2009	*•Test experiment (Phase1)* *•Data taking* *•Phase2,Phase3….*



2007/LHC start

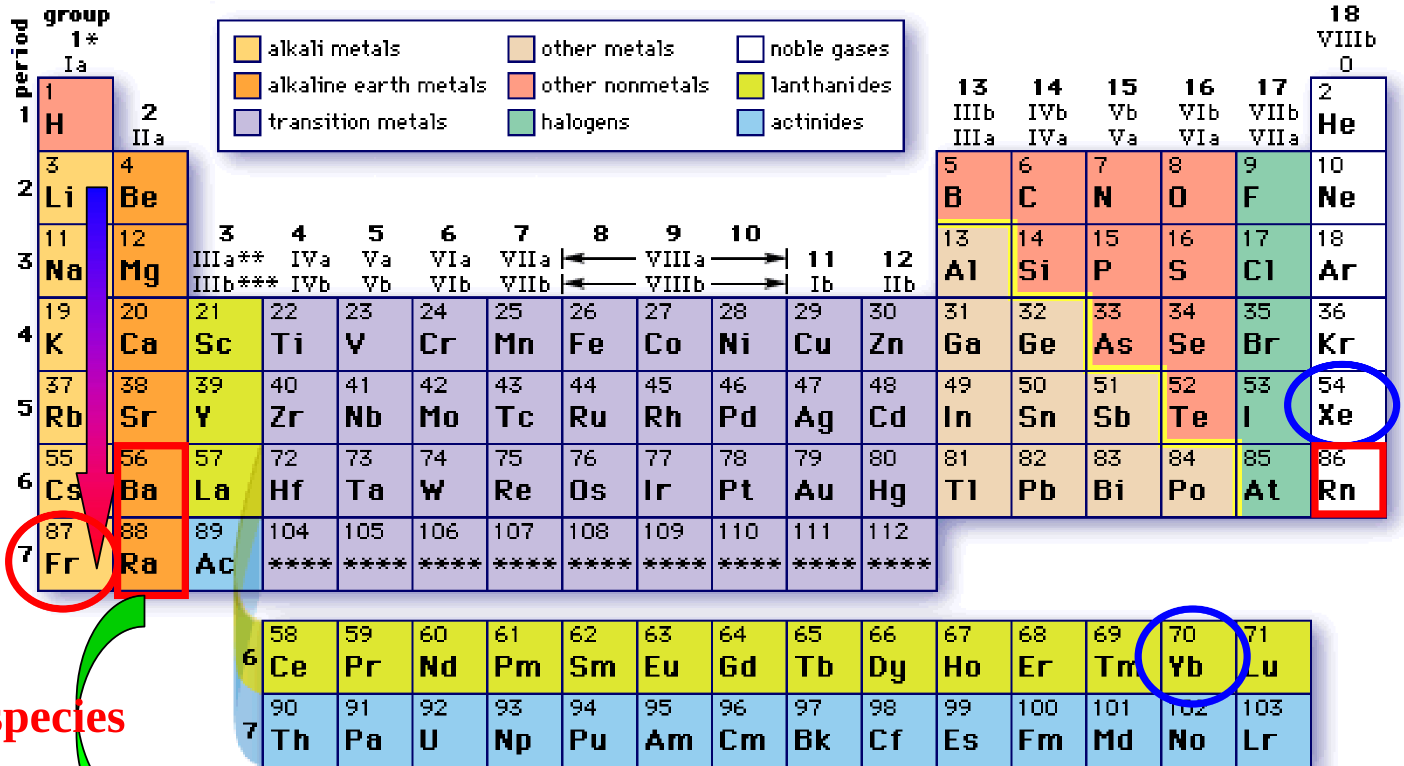
2009/LHC high luminosity

EDM in Japan



One may miss something essential by focusing on ONE EDM only!

Next step



Next species

$^{15}N + ^{205}Ta \rightarrow ^{213}Ra + 7n$

Nuclear EDM with diamagnetic atoms at RIBF@RIKEN

- **High intensity heavy ion beam ~ $^{15}N^{5+}$: 50 MeV/u**
- **Many experts on atomic physics, quantum optics, …**
- **Magnetic separator, RFQ decelerator …**

Detailed study should be done,
But interesting ..

Summary

◆**Permanent EDM search**

- **To find Physics beyond standard model, Supersymmetry, …**
- **Offer a nice way to approach new physics at low energy**

◆**EDM search at RCNP ~ development in progress**

- **In the mean time: experimental apparatus preparation**
- **ECR ion source, beam line, surface ionizer, buffered gas cooling, MOT …**
- **Test experiment ~ should be ready in 2007..**

◆**We need NOT one EDM experiment, BUT MANY experiments needed !**

- **Electron EDM : Paramagnetic atom ~ Fr at RCNP**
- **Nucleus EDM : Diamagnetic atom**
  ~ Xe and extend heavy radioactive atoms at RIBF
- **Lepton Flavor Violation (LFV) planned at PRISM(@J-PARC…)**

$$d_e \sim \sqrt{\frac{Br(\mu \to e\gamma)}{1.2\times10^{-11}}} \times \frac{U_{e3}}{0.1} \cdot \varphi_{CP}$$ **: EDM and LFV ~ correlation**

New approach promise the significant progress to new physics.

Let's just do it together !   Thank you.