# Development of a Polarized $^{6}Li^{3+}$ Ion Source at RCNP

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# Collaboration of the Polarized $^{6}Li^{3+}$ Ion Source Project

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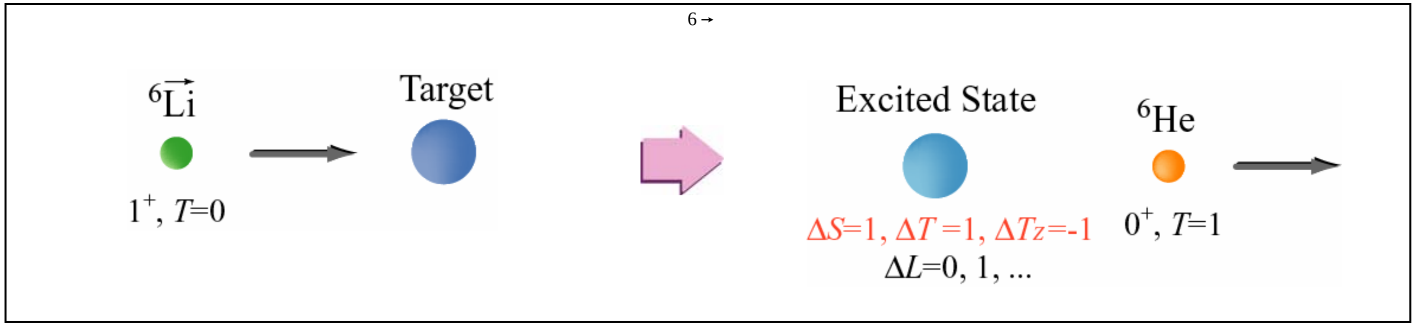
# Motivation

Study of nuclear structures by using polarized $^{6}$Li beam at 100MeV/U.

– Study of spin dipole excitations ($2^-$,$1^-$, and $0^-$), especially $0^-$, via ($^{6}\vec{\mathrm{Li}}$,$^{6}$He) reaction.
  Tensor analyzing power at $0^{\circ}$ is sensitive to J of SD excitations.
– Study of isovector spin-flip excitations via ($^{6}\vec{\mathrm{Li}}$,$^{6}$Li$\gamma$) reaction.




Study of reaction mechanism of composite particles

– elastic scattering, inelastic scattering, ($^{6}\vec{\mathrm{Li}}$, $^{6}$He) Reaction
– diff. cross section and analyzing power

For these purposes, development of a polarized $^{6}Li^{3+}$ ion source is required.

Requirements (or goal):

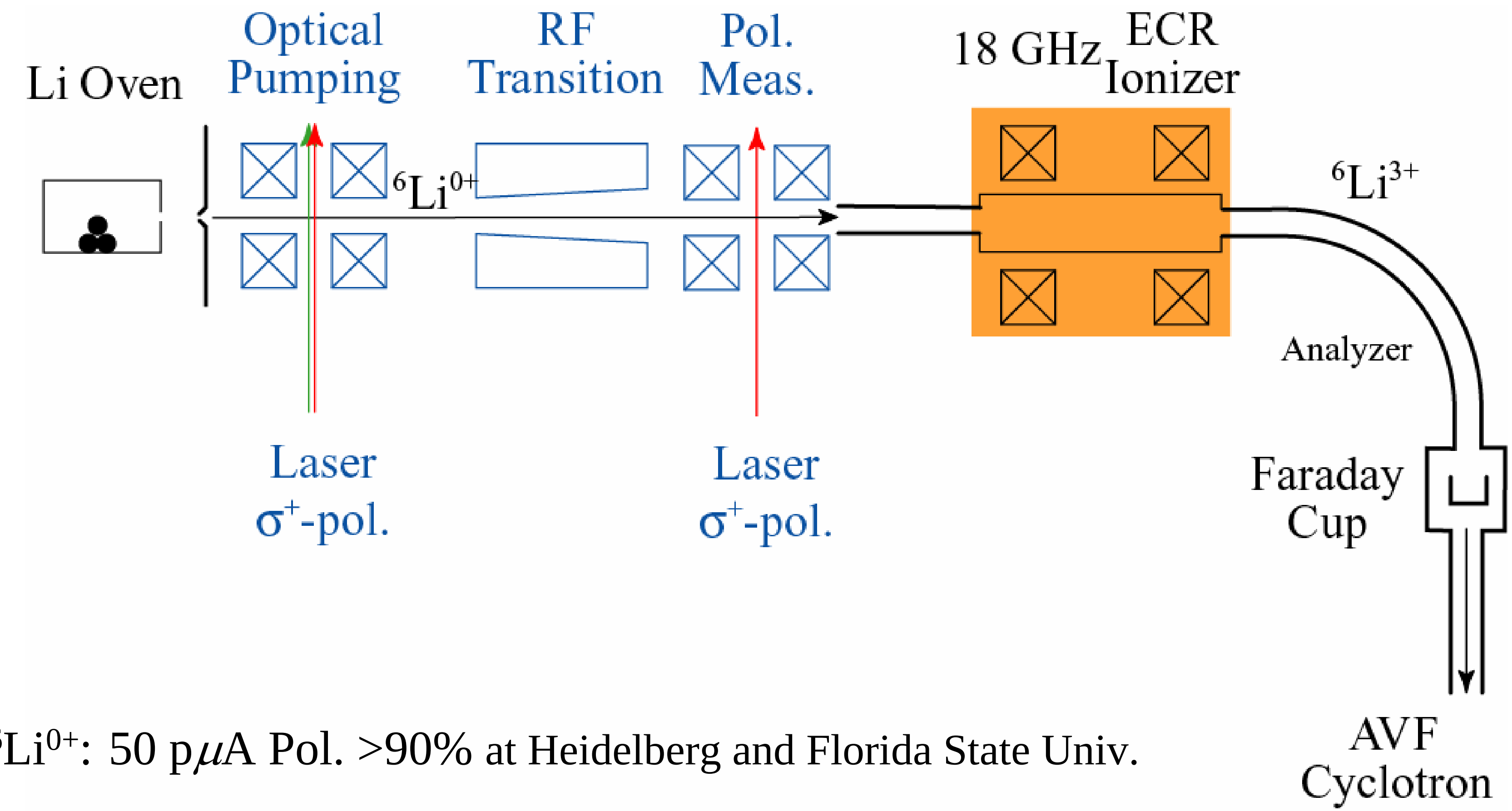
| | |
|---|---|
| Injection energy to AVF cyclotron: | 57 keV (19 kV) |
| Beam intensity: | $\gtrsim$ 10nA on target |
| Beam polarization (ratio to maximum): | $\gtrsim$ 0.7 |

Reduction of depolarization of $^{6}Li$ nuclei in the ionization process is one of the key points of the development.

Feasibility test has been planned.

# Outline of the ion source

# Outline of the polarized $^6$Li ion source ($^6Li^{0+}$ injection to ECR)




$^6Li^{0+}$: 50 p$\mu$A Pol. >90% at Heidelberg and Florida State Univ.

Mean free path of single ionization in ECR plasma is 10-30cm.

$^6Li^{0+} \rightarrow {}^6Li^{1+}$

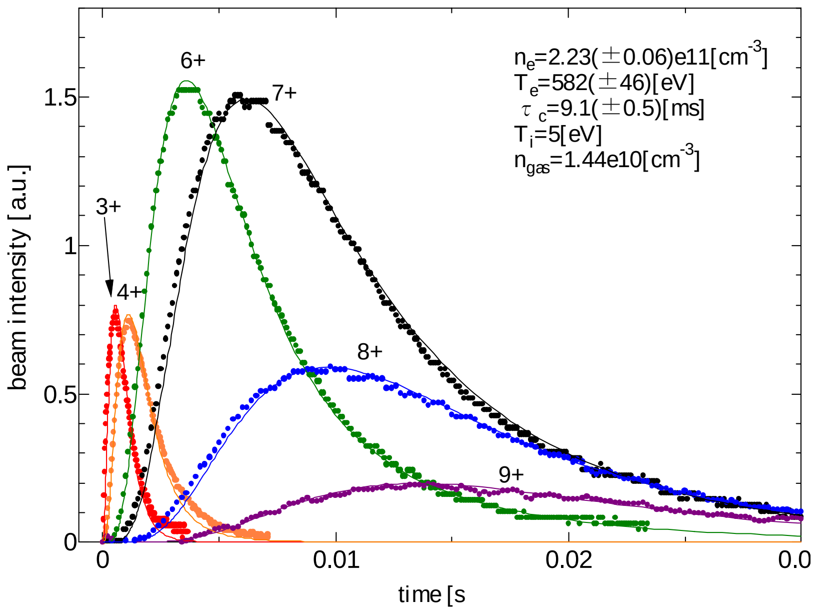
# Simulations

# Assumption of the Plasma Condition

The following plasma condition is assumed according to an empirical study of the laser ablated Al ion intensities from a 14.5 GHz ECR ionizer (SHIVA).

(M. Imanaka, PhD thesis, Univ. of Tsukuba)

| | |
|---|---|
| Buffer Gas: | Oxygen |
| RF Power: | 250 W |
| Neutral Gas Density ($n_{gas}$): | $1.4 \times 10^{10}$ cm$^{-3}$ |
| Electron Density ($n_e$): | $2.2 \times 10^{11}$ cm$^{-3}$ |
| Electron Temperature ($T_e$) : | 580 eV |
| Ion Temperature ($T_i$) : | 5 eV |



# Confinement Time of Ions in the ECR plasma

Form the same study using 14.5GHz SHIVA, confinement time of $^{27}Al^{3+}$ was obtained by fitting the data as (M. Imanaka, PhD thesis, Univ. of Tsukuba)

$$\tau_c(^{27}Al^{3+}) = 2.3\text{msec}$$

By applying the following relation (Shirkov, CERN/PS 94-13)

$$\tau_i \propto i\sqrt{A_i}$$ $i$: charge state, $A_i$: mass

confinement time of $^6$Li ions are

$$\tau_{1+} = 0.3\text{ msec},\ \tau_{2+} = 0.7\text{ msec},\ \tau_{3+} = 1\text{ msec}$$

From our laser ablation experiment by using 18GHz SC-ECR at RIKEN, we obtained

$$\tau_c(^7Li^{2+}) = 0.4\text{ msec}$$

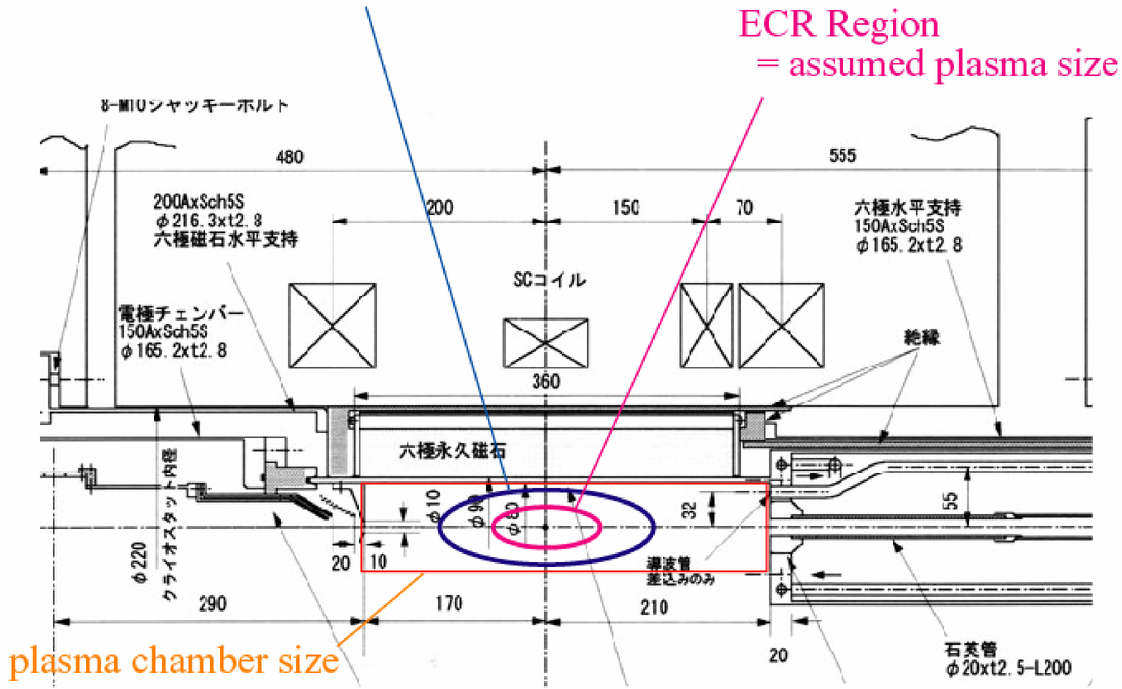
It is more or less consistent with the above values.

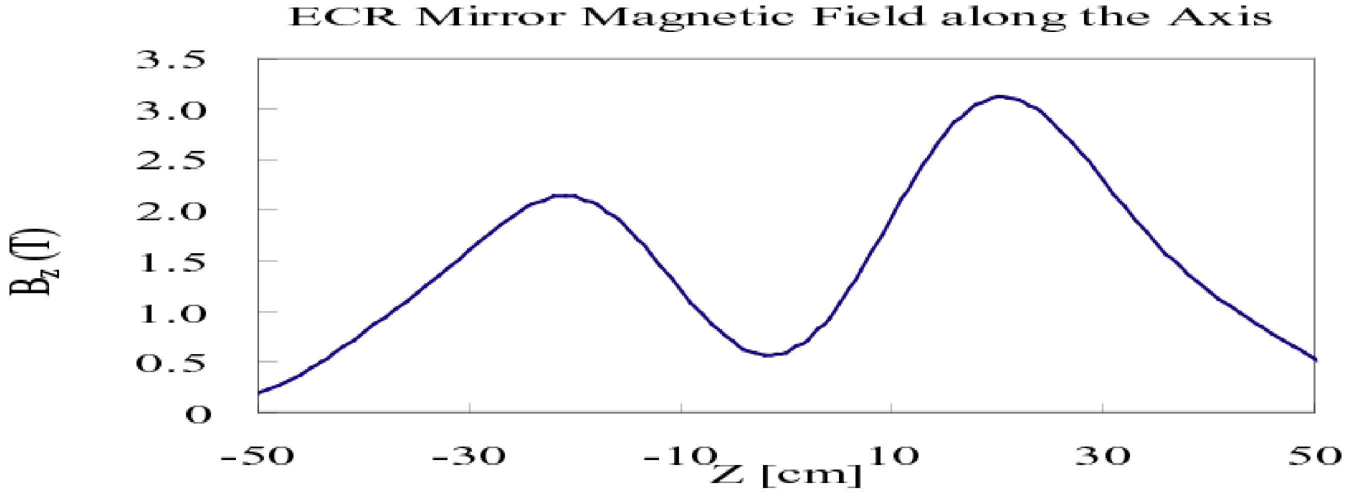
# Assumption of the Plasma Size

Plasma size is not well known.

We conservatively assume that the plasma size is the same as the volume inside of the ECR region.

Two times larger size will be used as an optimistic assumption.



# Critical Magnetic Field

The critical magnetic field for decoupling the hyper-fine interaction between an electron and a nucleus in $^{6}Li^{2+}$ is $B_c$=3kG.

Our SC-ECR has a minimum magnetic field of $B$~ 5kG.

Thus

$$x \equiv \frac{B}{B_c} \geq 1.7$$

$$\bar{x} = 2.1 - 2.5$$

dep. on the assumption

of the plasma size.

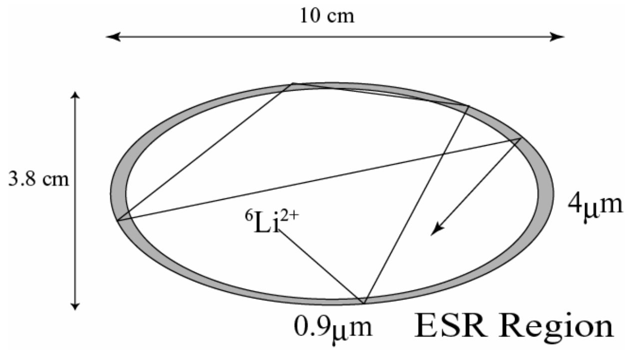
Calc. by H. Okamura

| atom | state | calc. $\nu$ | calc. $B_C$ | exp. $\nu$ | exp. $B_C$ | $\mu_I/\mu_N$ |
|---|---|---|---|---|---|---|
| $^{1}$H | 1$s$ | 1422.586 | 508.204 | 1420.406 | 507.591 | +2.7928 |
| | 2$s$ | 177.823 | 63.525 | 177.557 | 63.450 | |
| $^{2}$H | 1$s$ | 327.564 | 117.019 | 327.384 | 116.842 | +0.8574 |
| | 2$s$ | 40.945 | 14.627 | 40.924 | 14.605 | |
| $^{3}$H | 1$s$ | 1517.387 | 542.071 | 1516.702 | 542.059 | +2.9790 |
| | 2$s$ | 189.673 | 67.759 | 189.594 | 67.759 | |
| $^{3}He^{+}$ | 1$s$ | 8669.430 | 3097.062 | | | −2.1275 |
| | 2$s$ | 1083.679 | 387.133 | | | |
| $^{6}Li^{2+}$ | 1$s$ | 8479.169 | 3029.093 | | | +0.8220 |
| | 2$s$ | 1059.896 | 378.637 | | | |
| | | (MHz) | (Gauss) | (MHz) | (Gauss) | |

# Depolarization caused by the electron spin resonance (ESR) effect on $^6Li^{2+}$ (following the procedure of M. Tanaka *et al.*, NIMA524,46)

If a 250W microwave is fed in a non-resonating cylinder with a diameter of 78mm.

$$u = \frac{W}{\pi r^2 c} = 1.7\times10^{-10}\,\mathrm{J/cm3},\ \ B_1 = \sqrt{\mu_0 u} = 0.15\,\mathrm{Gauss}$$




The thickness of the ESR region is

$$\Delta R = 4.0\,\mu m \quad \text{at } R = 5.0\mathrm{cm}\ \text{(in axial direction)}$$

$$\Delta R = 0.9\,\mu m \quad \text{at } R = 1.9\mathrm{cm}\ \text{(in radial direction)}$$

Plasma size may be larger than the ESR region. We conservative assume this worst case.

The effective thickness averaged over isotropic ion motion and averaged length between the ESR regions are

$$L \cong \frac{4.0+0.9\times2}{3}\times\left(2+\ln\frac{R}{2\Delta R}\right) = 22\,\mu m,\quad \overline{\mathrm{R}} = \frac{5.0+1.9\times2}{3} = 2.9\,cm$$

Spin rotation angle of an electron caused by ESR is, by random-walk approx.

$$\omega = \Delta\omega\times\sqrt{N} = 4.5\times10^{-3}\mathrm{rad}\times\sqrt{180} = 6.0\times10^{-2}\mathrm{rad} = 3.5°$$

Nuclear depolarization is further caused by the hyper-fine coupling between electron and nucleus. Hence depolarization caused by ESR effect is negligibly small.

# Nuclear depolarization caused by inhomogeneous magnetic field ($^6Li^{1+}$ and $^6Li^{3+}$)

The $T_1$ relaxation time is expressed by, Schearer *et al.*, Phys. Rev. 139 (1965) A1398

$$\frac{1}{T_1} = \frac{2}{3}\frac{v^2}{\gamma_I^2 \tau_c H_z^4}\left(\frac{\partial H_y}{\partial y}\right)^2$$

Quantum axis is taken along the direction of the local magnetic field.

For $^6Li^{1+}$ and $^6Li^{3+}$, by putting the following numbers

$$\gamma_I = 3.94\times 10^7 \text{ rad}/s/T$$

$$\tau_c = 1.2\times 10^{-6}\text{ sec}$$

$$v = 1.3\times 10^6\text{ sec}$$

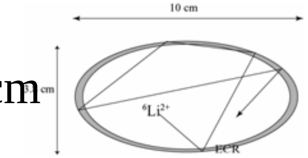
$$\overline{H}_z = 0.70\text{ T}$$

$$\overline{\frac{1}{H_z}\left(\frac{\partial H_y}{\partial y}\right)} = 0.25\text{ rad}/\text{cm}$$

$$\overline{\frac{1}{H_z^4}\left(\frac{\partial H_y}{\partial y}\right)^2} = 0.18\text{ rad}^2\text{cm}^{-2}\text{T}^{-2}$$

10cm

3.8cm




$T_1$ = 9.2 msec

If the plasma size is larger by a factor of 2 (in length)

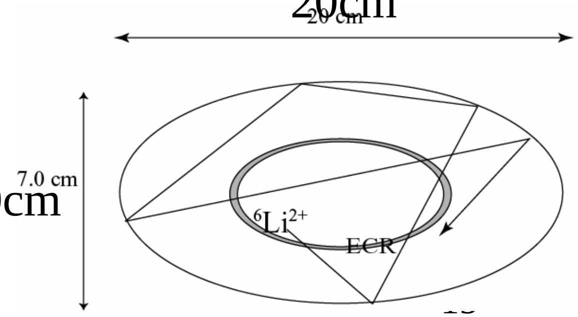
$$\overline{H}_z = 1.1\text{ T}$$

$$\overline{\frac{1}{H_z}\left(\frac{\partial H_y}{\partial y}\right)} = 0.28\text{ rad}/\text{cm}$$

$$\overline{\frac{1}{H_z^4}\left(\frac{\partial H_y}{\partial y}\right)^2} = 0.11\text{ rad}^2\text{cm}^{-2}\text{T}^{-2}$$

20cm

7.0cm




$T_1$ = 15 msec

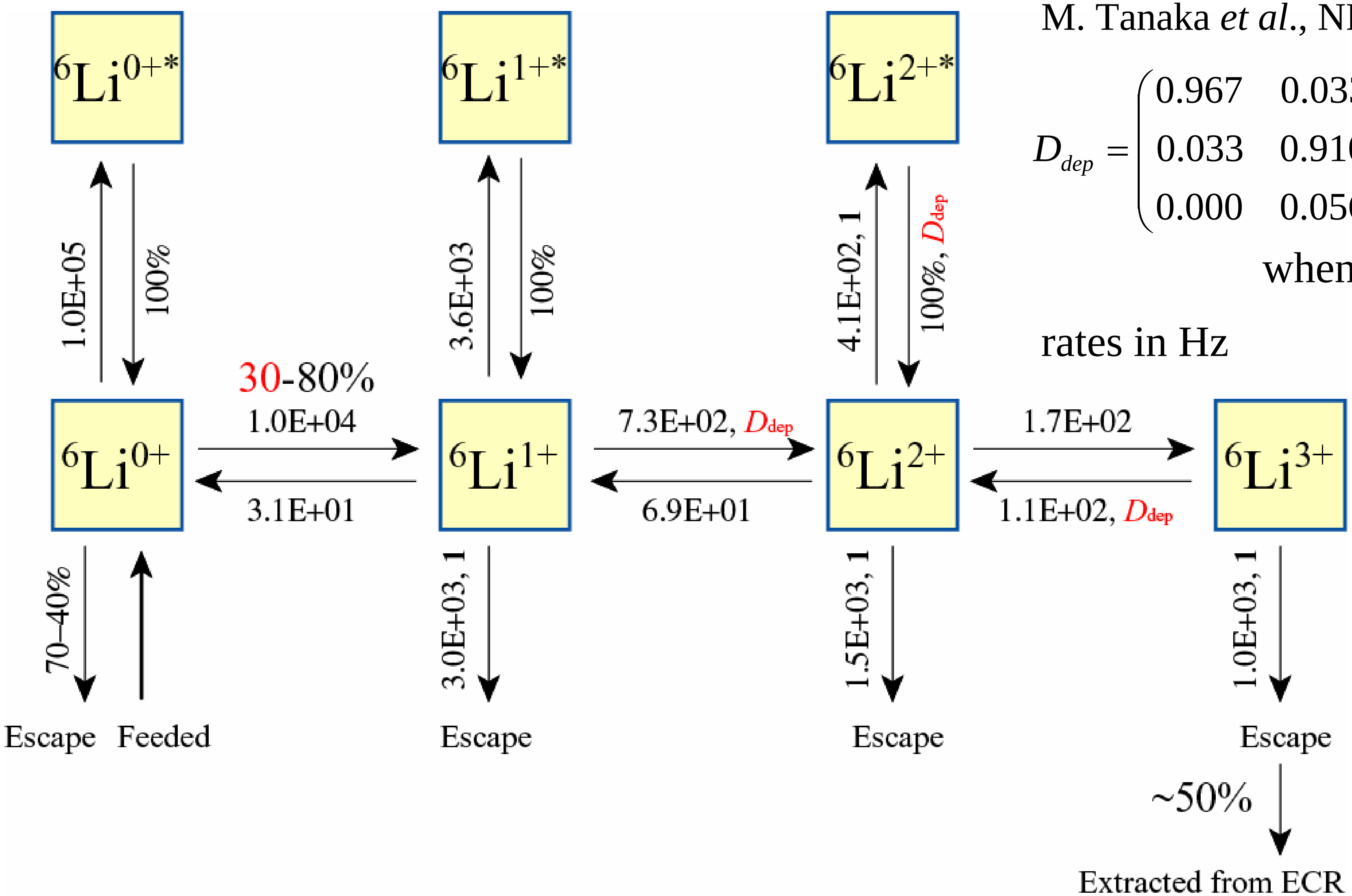
# Reaction Rates and Depolarization in (de-)ionization/(de-)excitation processes in the ECR plasma

following the procedure of
M. Tanaka *et al.*, NPA524, 46.

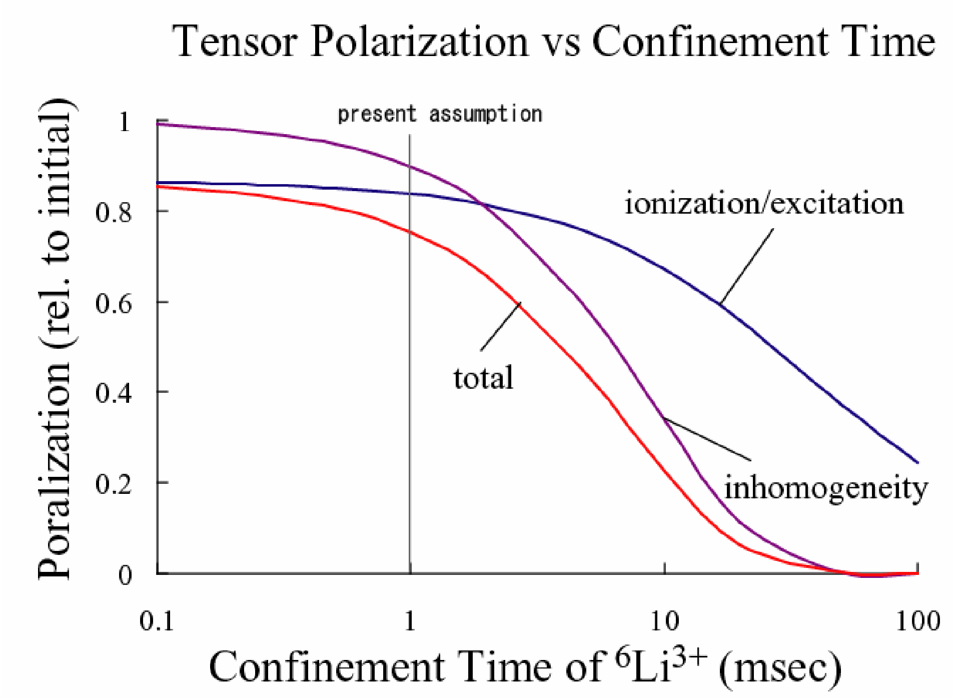
$$D_{dep} = \begin{pmatrix} 0.967 & 0.033 & 0.000 \\ 0.033 & 0.910 & 0.056 \\ 0.000 & 0.056 & 0.944 \end{pmatrix}$$

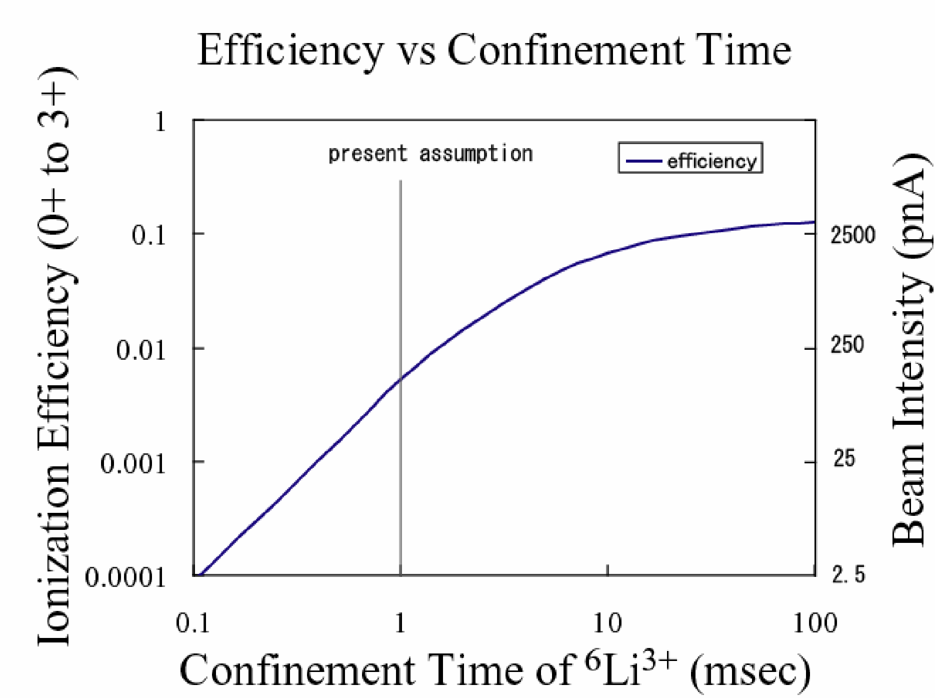
when x=2.1

rates in Hz



# Results of the simulation
# (confinement time dependence)

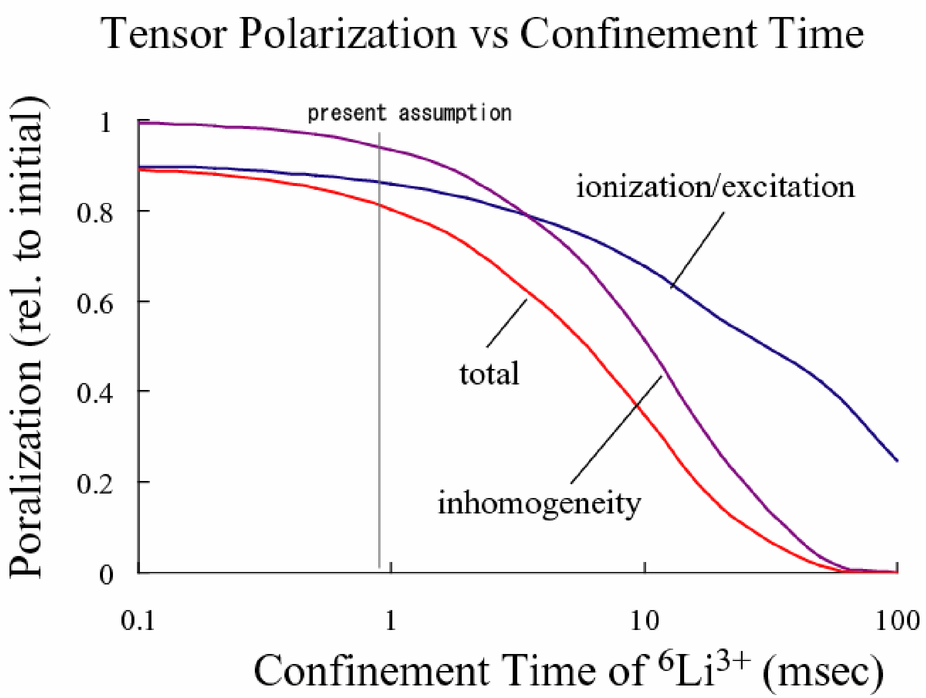


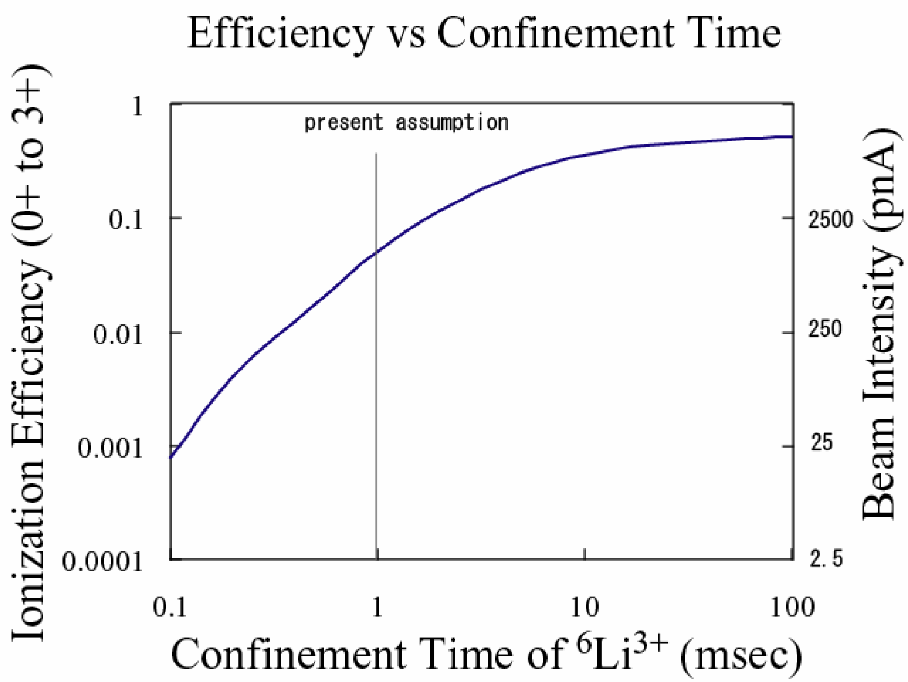




The total depolarization (pol~0.75) is expected to be at acceptable level, while the efficiency (beam intensity) is not high.

The intensity can be improved by increasing the electron density in the ECR plasma and/or improving the Li oven and Laser system.

# Results of the simulation (confinement time dependence) optimistic case

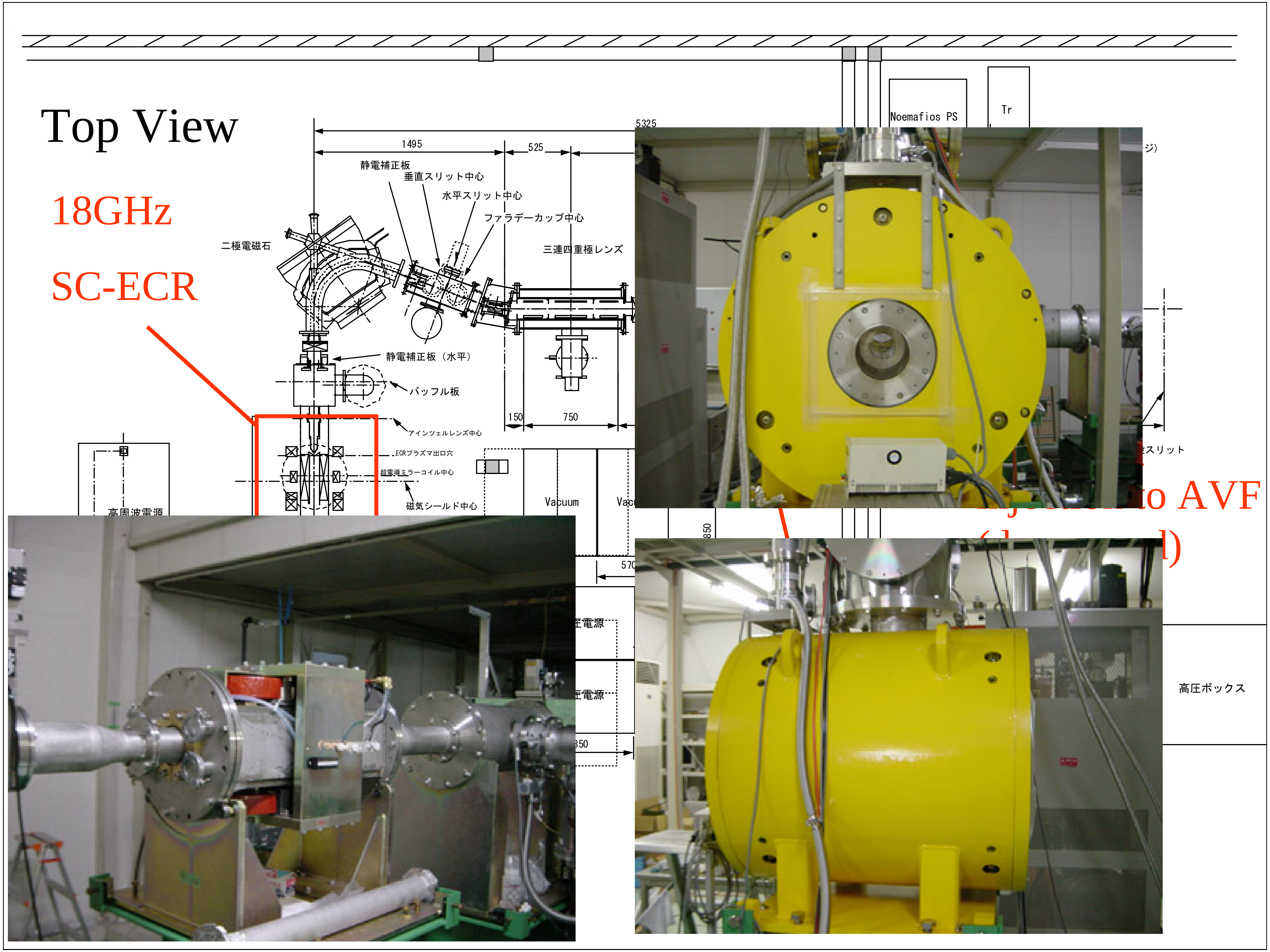



The results much depends on the plasma assumption. If an optimistic assumption is applied, i.e. 2.3 times larger electron density ($5 \times 10^{11}$ $cm^{-3}$) and 2 times larger plasma size, the estimated beam intensity much increases.

Feasibility test experiment is required.

# Present Status (Pictures)


Top View
18GHz
SC-ECR
5325
1495
525
静電補正板
垂直スリット中心
水平スリット中心
ファラデーカップ中心
二極電磁石
三連四重極レンズ
静電補正板（水平）
バッフル板
150
750
アインツェルレンズ中心
ECRプラズマ出口穴
超電導ミラーコイル中心
磁気シールド中心
Noemafios PS
Tr
Vacuum
高圧ボックス

# Summary

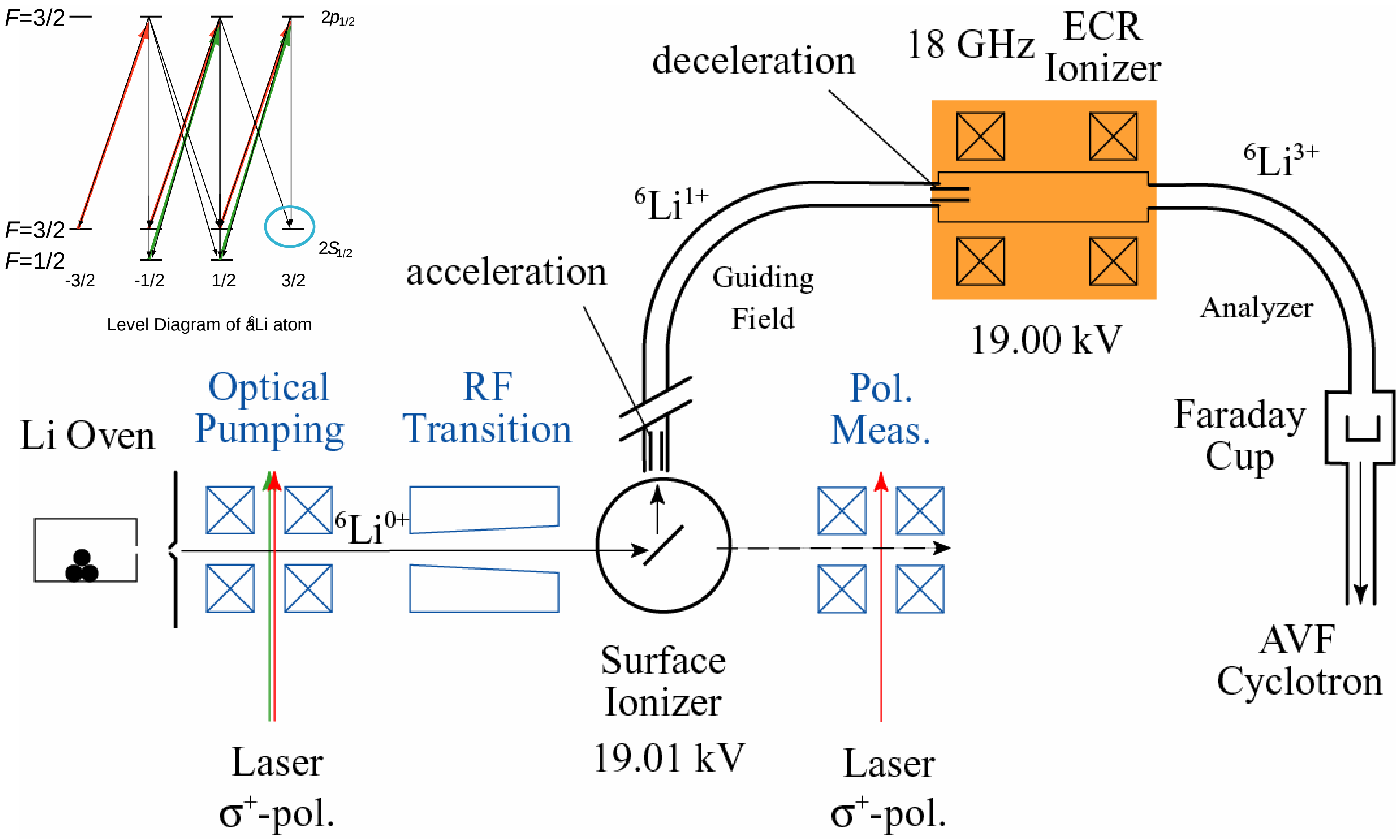
- Simulations have been done about the depolarization and ionization efficiency of a $^{6}Li^{3+}$ ion source by using an ECR ionizer.

- Under an assumption of the plasma condition, the calculated polarization (0.75) is acceptable. The beam intensity is somewhat low (~100 nA) and improvements may be needed.
This method looks hopeful.

- Feasibility test experiment is required for conforming the simulation, and optimizing plasma parameters by tuning magnetic field, RF power, gas density, and extraction geometry.

- Final design and construction is in progress.

# Outline of the polarized $^6Li^{3+}$ ion source (I) ($^6Li^{1+}$ injection to ECR)




$^6Li^{1+}$: 20-30 p$\mu$A Pol. 80-90% at Florida State Univ.

From calculations and simulations

- Emittance of the $^{6}Li^{1+}$ beam from the surface ionizer

  vertical dir.: 300 $\pi$ mmmr

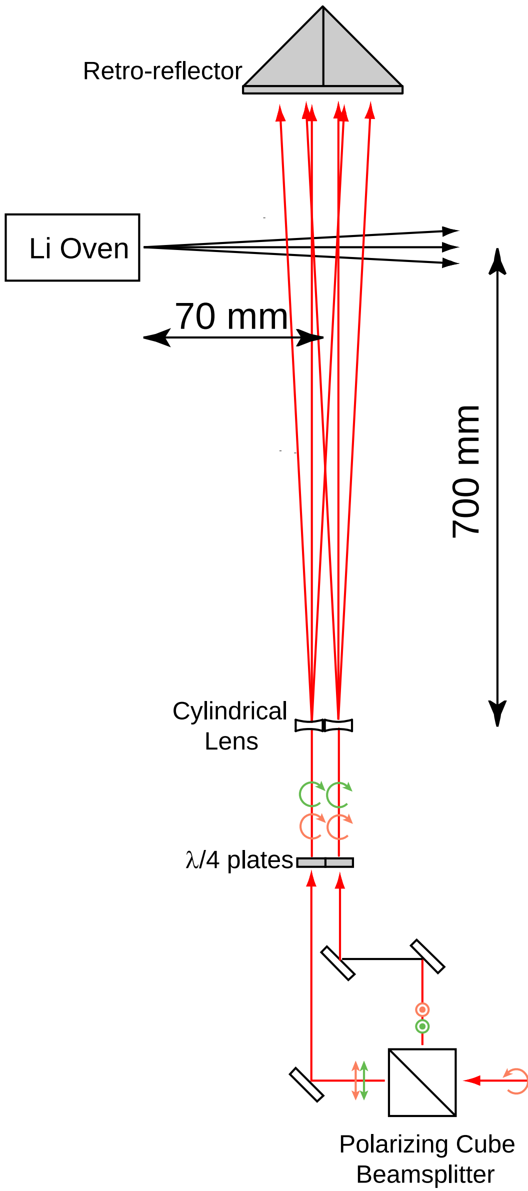
  horizontal dir.: 200 $\pi$ mmmr

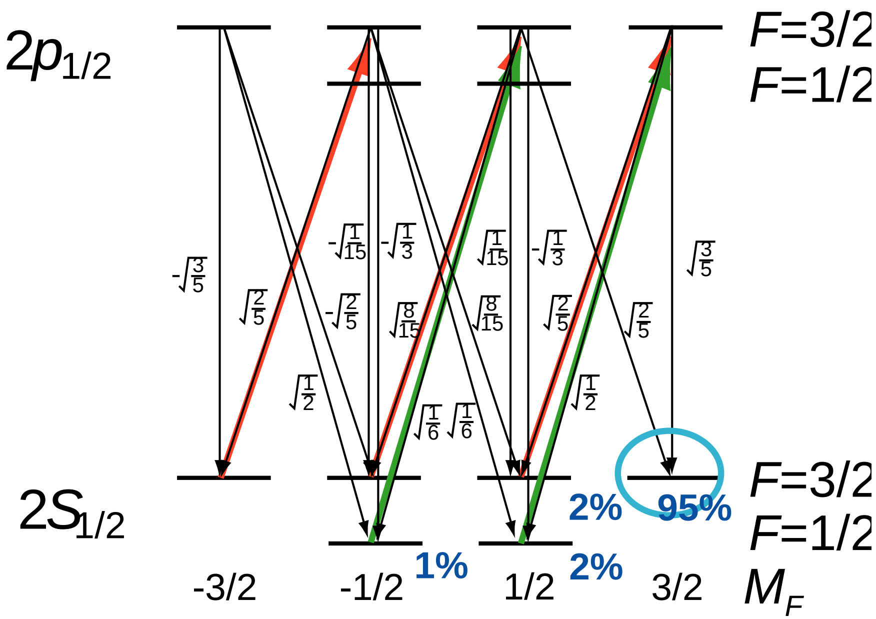
- ~70% of the beam is reflected at the deceleration electric field (19 kV$\rightarrow$10 eV) placed at the entrance of ECR.

- Dense plasma with a thickness of $\gtrsim$50 cm is required to efficiently decrease the energy of 10 eV $^{6}Li^{1+}$ ions and trap them in the plasma.

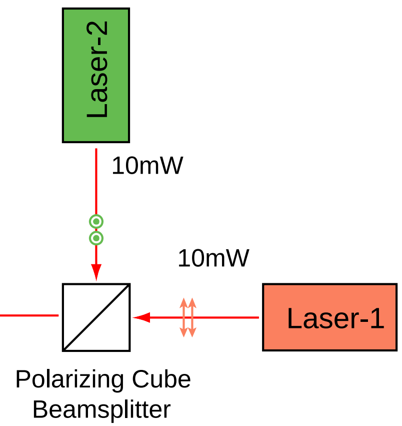
Efficient injection of the $^{6}Li^{1+}$ beam into ECR plasma is not expected in the assumed setup.

# Simulation of the Optical Pumping

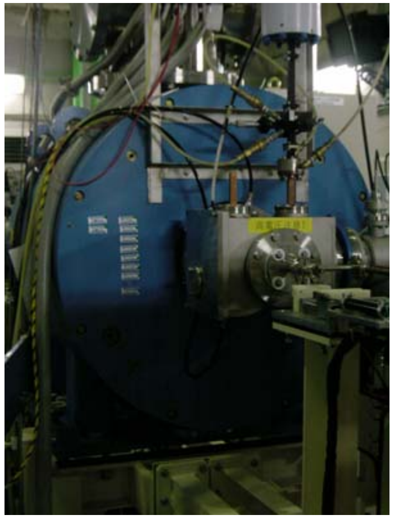



Level Diagram of a $^6$Li atom

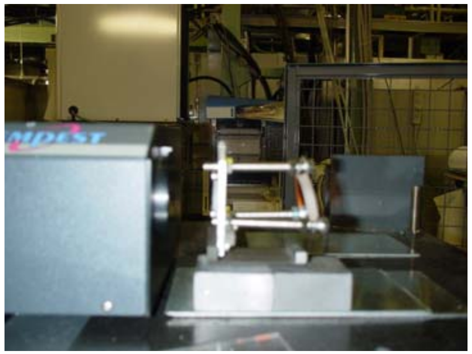


# Study of the Confinement Time of Li ions by the Laser Ablation method



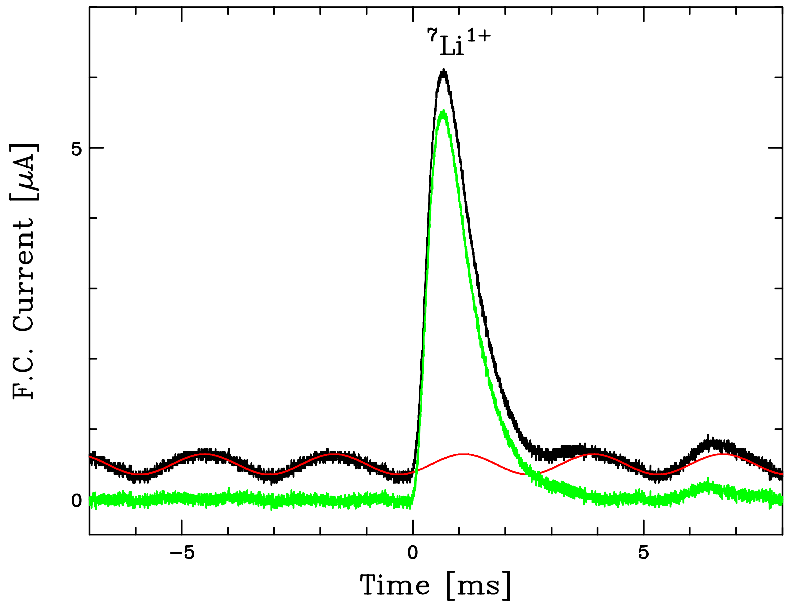
18GHz SC-ECRIS

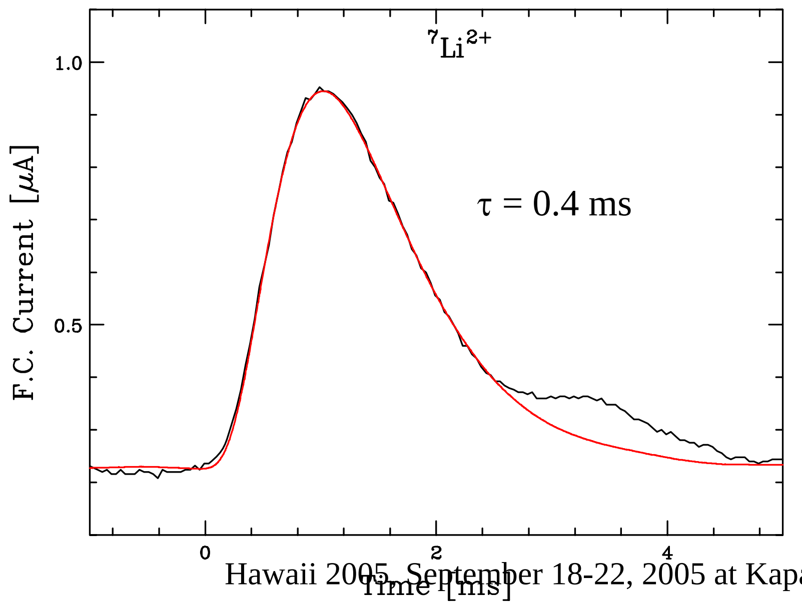
Lens, Mirror and LiF rod



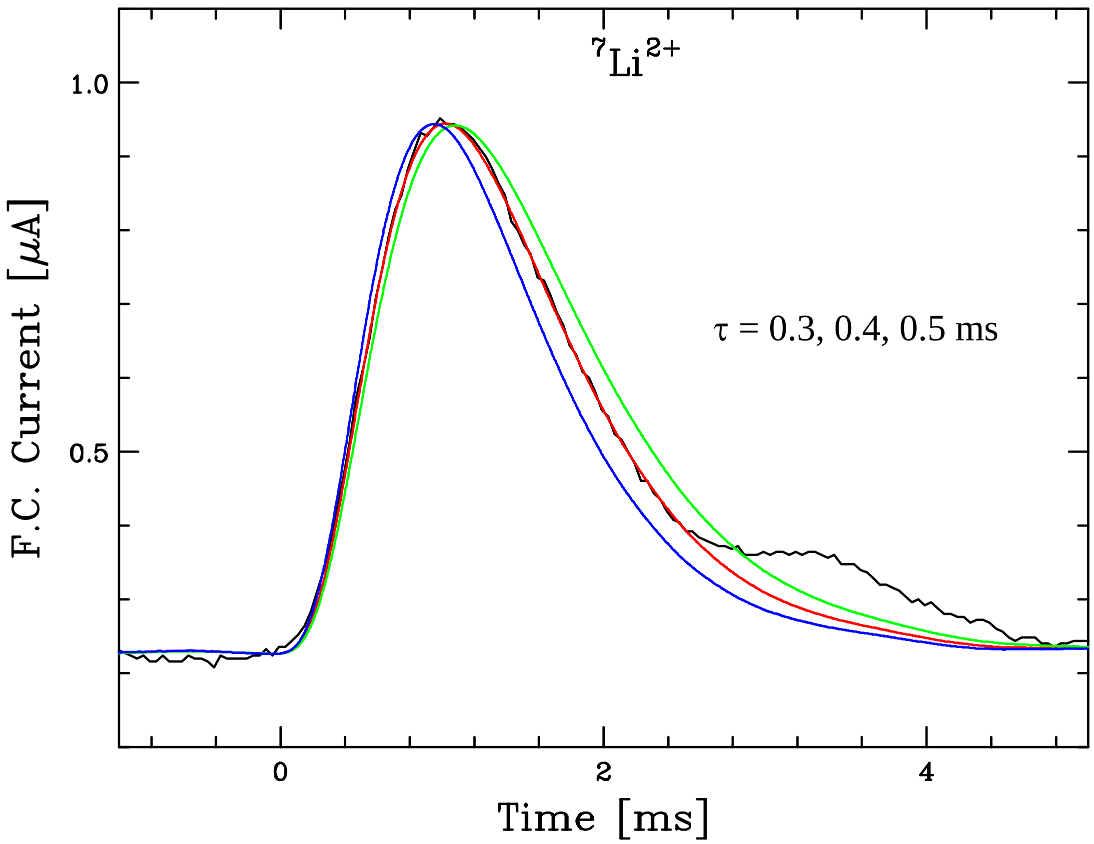
YAG 523nm 5ns
Max 100mJ/pulse

Laser ablation test in atmosphere



# Study of the Confinement Time of Li ions by the Laser Ablation method




Note: the ECRIS operation has not tuned to $^6Li^{3+}$

# Magnetic-Substate Transition Matrix (1/2)

(according to the calc. of 3He by M. Tanaka and Y. Plis)

The wave functions $\Psi_i(t)$ of the electron-nucleus system in a magnetic field system are written as a linear conbination of |IJ> states as

$$\Psi_{\mathrm{I}}(0) = \left|\uparrow +1\right\rangle$$
$$\Psi_{\mathrm{II}}(0) = \sin\beta_+ \left|\uparrow 0\right\rangle + \cos\beta_+ \left|\downarrow +1\right\rangle$$
$$\Psi_{\mathrm{III}}(0) = \sin\beta_- \left|\uparrow -1\right\rangle + \cos\beta_- \left|\downarrow 0\right\rangle$$
$$\Psi_{\mathrm{IV}}(0) = \left|\downarrow -1\right\rangle$$
$$\Psi_{\mathrm{V}}(0) = -\cos\beta_- \left|\uparrow -1\right\rangle + \sin\beta_- \left|\downarrow 0\right\rangle$$
$$\Psi_{\mathrm{VI}}(0) = -\cos\beta_+ \left|\uparrow 0\right\rangle + \sin\beta_+ \left|\downarrow +1\right\rangle$$

$$\sin\beta_\pm \equiv \sqrt{\frac{1}{2}(1+\delta_\pm)} \qquad \cos\beta_\pm \equiv \sqrt{\frac{1}{2}(1-\delta_\pm)}$$

$$\delta_\pm \equiv \frac{\pm\frac{1}{3} + x}{\sqrt{1 \pm \frac{2}{3}x + x^2}}$$

$$x \equiv \frac{B}{B_c} \qquad B_c : \text{critical magnetic field}$$

The time revolution of the | ↓ +1> state is

$$\begin{aligned}
\left|\downarrow +1\right\rangle_t &= \cos\beta_+ \Psi_{\mathrm{II}}(t) + \sin\beta_+ \Psi_{\mathrm{IV}}(t) \\
&= \cos\beta_+ \Psi_{\mathrm{II}}(0)\exp(-iE_{\mathrm{II}}t) + \sin\beta_+ \Psi_{\mathrm{IV}}(0)\exp(-iE_{\mathrm{IV}}t) \\
&= \cos\beta_+ \left(\sin\beta_+ \left|\uparrow 0\right\rangle + \cos\beta_+ \left|\downarrow +1\right\rangle\right)\exp(-iE_{\mathrm{II}}t) \\
&\quad + \sin\beta_+ \left(-\cos\beta_+ \left|\uparrow 0\right\rangle + \sin\beta_+ \left|\downarrow +1\right\rangle\right)\exp(-iE_{\mathrm{IV}}t)
\end{aligned}$$

The probability to find | ↓ +1> and its time average (after sufficient time) is

$$\begin{aligned}
P(t) &= \left|\cos^2\beta_+ \exp(-iE_{\mathrm{II}}t) + \sin^2\beta_+ \exp(-iE_{\mathrm{IV}}t)\right|^2 \\
&= \cos^4\beta_+ + \sin^4\beta_+ + 2\cos^2\beta_+ \sin^2\beta_+ \cos\left((E_{\mathrm{II}} - E_{\mathrm{IV}})t\right)
\end{aligned}$$

$$\overline{P} = \cos^4\beta_+ + \sin^4\beta_+ = \frac{1}{2}(1+\delta_+^2)$$

# Magnetic-Substate Transition Matrix (2/2)

By similar calculations we obtain

$$\begin{pmatrix} |\uparrow +1\rangle' \\ |\uparrow 0\rangle' \\ |\uparrow -1\rangle' \\ |\downarrow -1\rangle' \\ |\downarrow 0\rangle' \\ |\downarrow +1\rangle' \end{pmatrix} = \begin{pmatrix} 1 & & & & & \\ & \frac{1}{2}\left(1+\delta_+^2\right) & & & & \frac{1}{2}\left(1-\delta_+^2\right) \\ & & \frac{1}{2}\left(1+\delta_-^2\right) & & \frac{1}{2}\left(1-\delta_-^2\right) & \\ & & & 1 & & \\ & & \frac{1}{2}\left(1-\delta_-^2\right) & & \frac{1}{2}\left(1+\delta_-^2\right) & \\ & \frac{1}{2}\left(1-\delta_+^2\right) & & & & \frac{1}{2}\left(1+\delta_+^2\right) \end{pmatrix} \begin{pmatrix} |\uparrow +1\rangle \\ |\uparrow 0\rangle \\ |\uparrow -1\rangle \\ |\downarrow -1\rangle \\ |\downarrow 0\rangle \\ |\downarrow +1\rangle \end{pmatrix}$$

We are not interested in the electron spin.

In the case that the orientation of the electron spin is random at $t$=0, by taking the average for the initial state and sum for the final state concerning the electron spin, we obtain

$$\begin{pmatrix} |+1\rangle' \\ |0\rangle' \\ |-1\rangle' \end{pmatrix} = \begin{pmatrix} \frac{1}{4}\left(3+\delta_+^2\right) & \frac{1}{4}\left(1-\delta_+^2\right) & 0 \\ \frac{1}{4}\left(1-\delta_+^2\right) & \frac{1}{4}\left(2+\delta_+^2+\delta_-^2\right) & \frac{1}{4}\left(1-\delta_-^2\right) \\ 0 & \frac{1}{4}\left(1-\delta_-^2\right) & \frac{1}{4}\left(3+\delta_-^2\right) \end{pmatrix} \begin{pmatrix} |+1\rangle \\ |0\rangle \\ |-1\rangle \end{pmatrix}$$

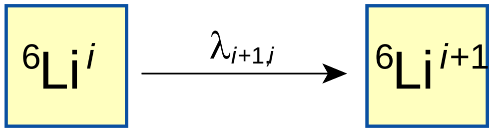
When $x$=5/3, the matrix is

$$D_{\text{dep}} = \begin{pmatrix} 0.955 & 0.045 & 0 \\ 0.045 & 0.871 & 0.083 \\ 0 & 0.083 & 0.917 \end{pmatrix}$$

# Ionization Rate by Electron Impact

## Voronov's empirical fit

G.S. Voronov, Atom. Data and Nucl. Data Tables 65 (1997)1.




$$\chi_{i\to i+1} = \langle \sigma v_e \rangle = A\frac{1+PU^{1/2}}{X+U}U^K e^{-U} \quad [\mathrm{cm^3 s^{-1}}]$$

$$U = \frac{I_i}{T_e}$$

$I_i$: Ionization Energy

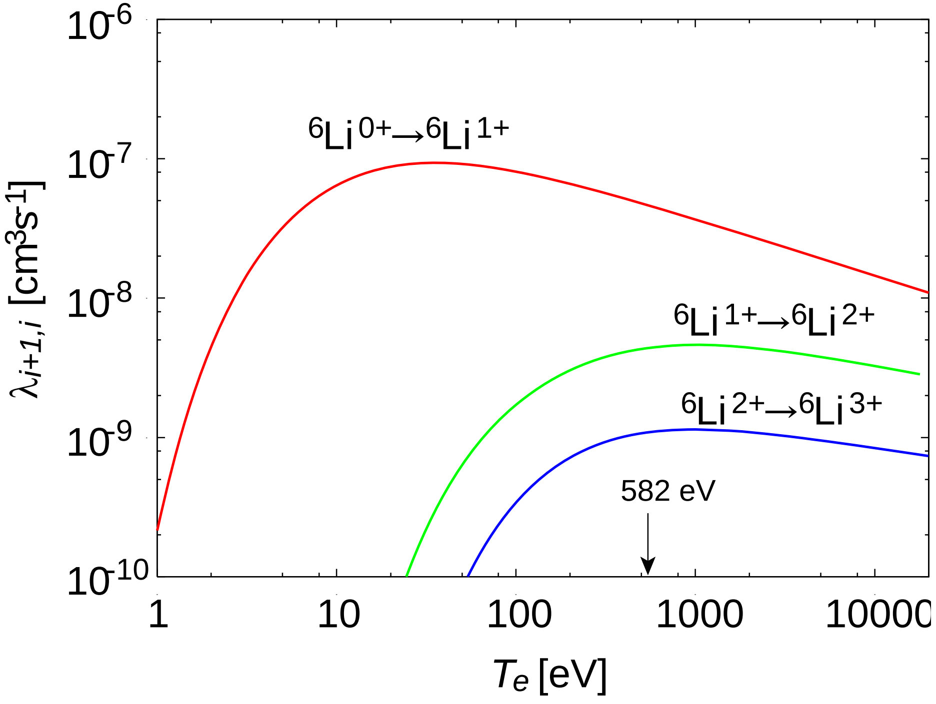
$T_e$: Electron Temperature

$A$, $P$, $X$, $K$: Fitting Parameters

$^6\mathrm{Li}^{0+} \longrightarrow {}^6\mathrm{Li}^{1+}$: $4.52 \times 10^{-8}$ cm$^3$s$^{-1}$
$^6\mathrm{Li}^{1+} \longrightarrow {}^6\mathrm{Li}^{2+}$: $3.26 \times 10^{-9}$ cm$^3$s$^{-1}$
$^6\mathrm{Li}^{2+} \longrightarrow {}^6\mathrm{Li}^{3+}$: $7.53 \times 10^{-10}$ cm$^3$s$^{-1}$

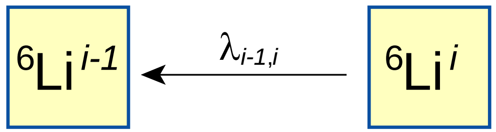
$$\lambda_{i\to i+1} = \chi_{i\to i+1} n_e$$

$n_e$: $2.23 \times 10^{11}$ cm$^{-3}$



# Charge Exchange Reaction Rate with the Neutral Gas

## Muller and Saltzborn Empirical Fit




A. Muller and E. Saltzborn, Phys. Lett. A62 (1977) 391.

$$\sigma = 1.43\times10^{-12} i^{1.17} I_{gas}^{-2.76} \quad [\mathrm{cm}^2]$$

$$\varsigma_{i\to i-1} = \langle \sigma v_i \rangle = 3.15\times10^{-6} i^{1.17} I_{gas}^{-2.76} \sqrt{\frac{T_i}{A_i}} \quad [\mathrm{cm}^3\mathrm{s}^{-1}]$$

$I_{gas}$: Ionization Energy of the Neutral Gas (Oxygen: 13.6 eV)

$T_i$: Ion Temperature (5 eV)

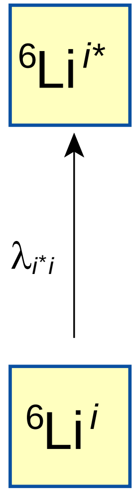
$A_i$: Ion Mass in AMU

$^6Li^{1+} \longrightarrow {}^6Li^{0+}$: $2.14\times10^{-9}$ cm$^3$s$^{-1}$
$^6Li^{2+} \longrightarrow {}^6Li^{1+}$: $4.81\times10^{-9}$ cm$^3$s$^{-1}$
$^6Li^{3+} \longrightarrow {}^6Li^{2+}$: $7.72\times10^{-9}$ cm$^3$s$^{-1}$

$$\lambda_{i\to i-1} = \varsigma_{i\to i-1} n_{gas}$$

$n_{gas}$: $1.44\times10^{10}$ cm$^{-3}$

# Atomic Excitation Rate by Electron Impact (1/2)




$^{6}Li^{0+} \longrightarrow {}^{6}Li^{0+*}$ 2s→2p (including cascade)

D. Leep and A. Gallagher, Phys. Rev. A 10 (1974) 1082.

$\sigma \sim 3.5\pi a_0^2 = 3.1\times10^{-16}$ [cm$^2$] at $T_e \sim 600$ eV

$\sigma v_e = 4.5\times10^{-7}$ [cm$^3$s$^{-1}$] $\lambda_{0\to0*} = \sigma v_e n_e$

a factor of ~10 larger than the ionization rate coefficient

$^{6}Li^{1+} \longrightarrow {}^{6}Li^{1+*}$ 1s→2p

assume that a factor of ~5 larger than the ionization rate coefficient

$\sigma v_e = 1.6\times10^{-8}$ [cm$^3$s$^{-1}$] $\lambda_{1\to1*} = \sigma v_e n_e$

# Atomic Excitation Rate by Electron Impact (2/2)

$^6Li^{2+} \longrightarrow {}^6Li^{2+*}$ 1s→2p

Fisher *et al.*, Phys. Rev. A 55 (1997) 329.

Empirical fit of 1s→2p excitation cross sections of hydrogen-like atoms

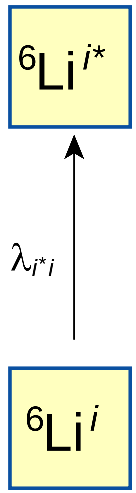
$$\sigma \sim 1.0\pi a_0^2 Z_i^{-4} = 1.1\times10^{-18} \quad [\mathrm{cm}^2]\,\mathrm{at}\,T_e \sim 550\,\mathrm{eV}$$

$$\sigma v_e = 1.6\times10^{-9} \quad [\mathrm{cm}^3\mathrm{s}^{-1}] \quad \lambda_{2\to2*} = \sigma v_e n_e$$

Summing up transitions 1s→2,…,6 and taking the Boltzmann distribution

$$\langle \sigma v_e \rangle = 1.82\times10^{-9} \quad [\mathrm{cm}^3\mathrm{s}^{-1}]$$

a factor of ~2 larger than the ionization rate coefficient



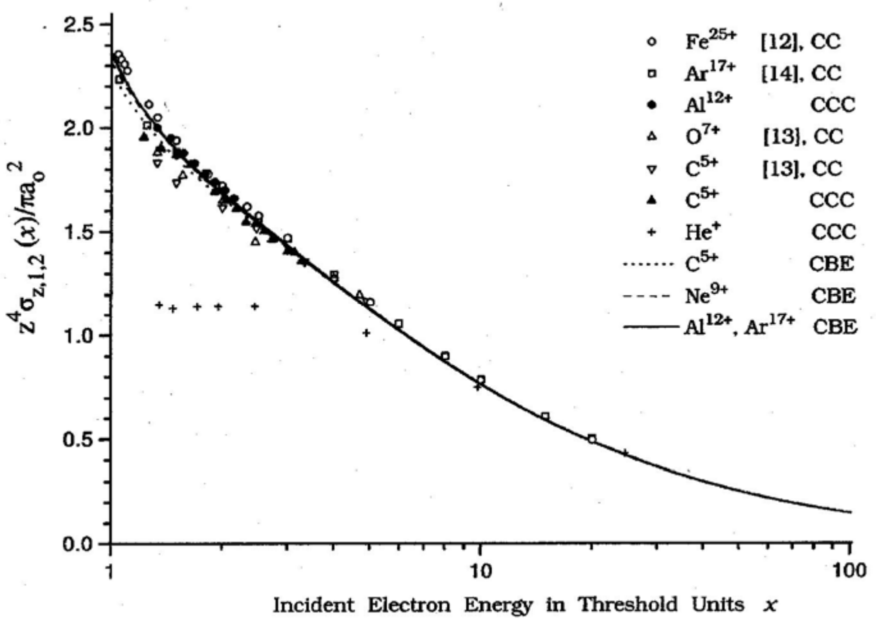




FIG. 3. Cross sections for transition 1→2 in hydrogenlike ions with $z=2$–26.