Spin (re)polarization of Muonium

S. Kamioka

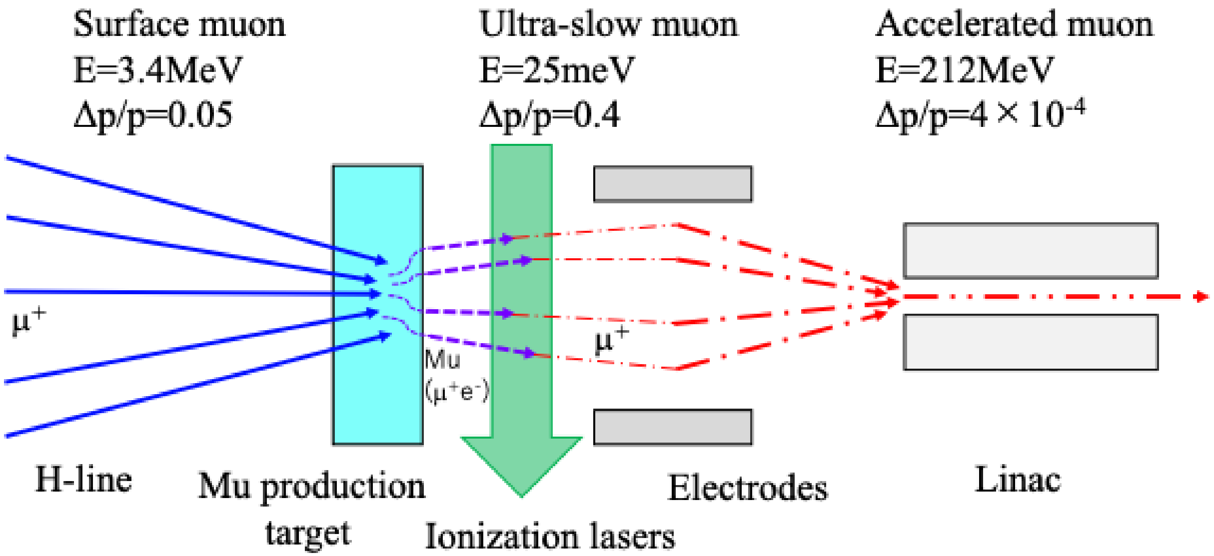
Quick review:
Spin polarization of ultra-slow muon

- Ultra-slow muon (USM): μ^+ source of J-PARC g-2 experiment

✓ Instead of the improvement of beam quality, spin polarization of USM becomes **half times smaller**

➢ $\Delta a_\mu \propto$ **spin polarization**$^{-1} \times N^{-1/2}$

➢ **Increase of the spin polarization** for better sensitivity ??



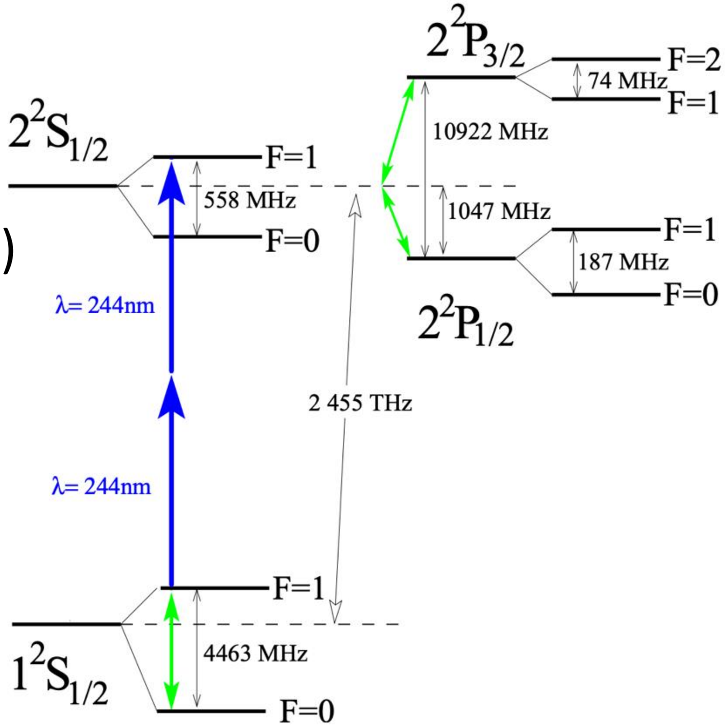
More detail on spin polarization

Assumption

- ✓ Initial μ^+ has 100% spin pol.
- ✓ e^- in Mu target has no spin pol. (↑ and ↓ equally)

Then, when muonium is formed…

- ➢ Half of Mu: $|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\uparrow\rangle$. **This is OK!!**
- ➢ The other half: $|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\downarrow\rangle$
  - ➢ **Not an energy eigenstate**



$|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\downarrow\rangle$ is a super position of $|\boldsymbol{F},\boldsymbol{m}\rangle = |\mathbf{1},\mathbf{0}\rangle$ and $|\boldsymbol{F},\boldsymbol{m}\rangle = |\mathbf{0},\mathbf{0}\rangle$.

→ $|\uparrow\rangle|\downarrow\rangle = \frac{1}{\sqrt{2}}\,|\mathbf{1},\mathbf{0}\rangle + \frac{1}{\sqrt{2}}\,|\mathbf{0},\mathbf{0}\rangle \boldsymbol{e}^{\boldsymbol{i\omega t}}$, where $\omega = 2\pi \times 4.4\ \mathrm{GHz}$

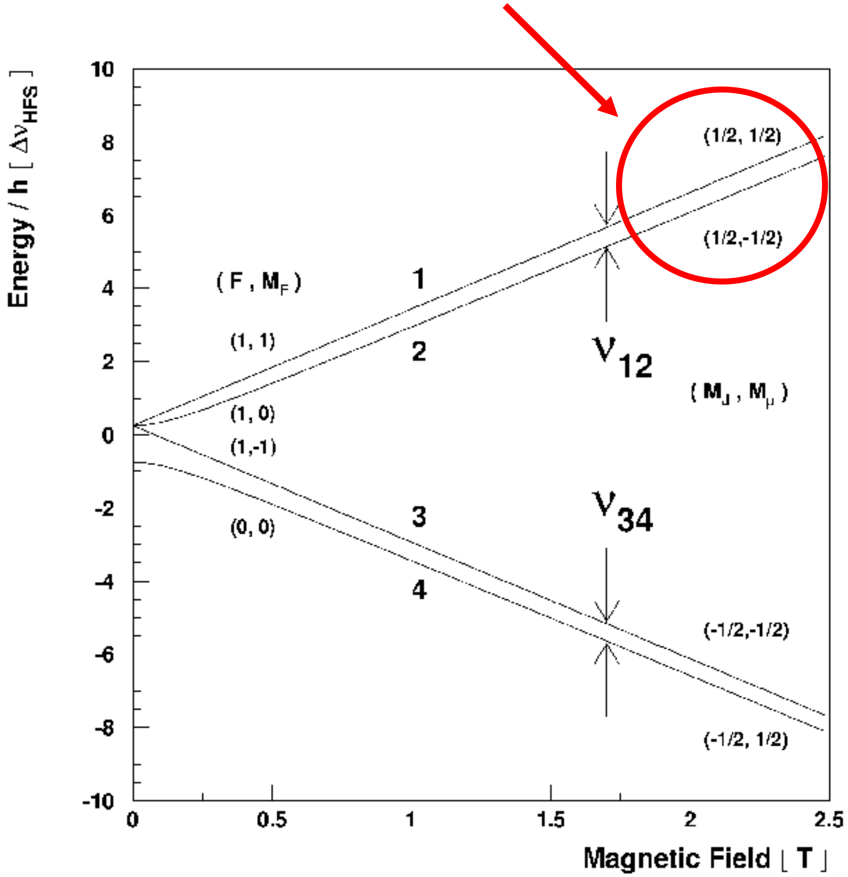
→ $\langle S_\mu^z\rangle = \frac{1}{2}\,\mathbf{cos}(\boldsymbol{\omega t})$ **-> 0 (t>>1/4GHz)**

or $|\uparrow\rangle|\downarrow\rangle$ is euqally popupated to $|\mathbf{1},\mathbf{0}\rangle$ and $|\mathbf{0},\mathbf{0}\rangle$ states

Simple approach? : Magnetic field

- ✓ If $|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\downarrow\rangle$ is an energy eigenstate, it remains unchanged.
- ➢ Zeeman shift of Mu
  - Quenching hyperfine coupling.
  - B=0.2T → Spin pol. of **80%**
- It looks OK, but **beam transport becomes much difficult.**
- ✓ Beam acquires $\mathbf{P_\theta}$
  - **Difficult to be controlled** by a conventional optics
  - **>10 times larger than transverse momentum** of our beam
  - Not today’s main topic. (any idea??)

|F,m> is not an energy eigenstate anymore

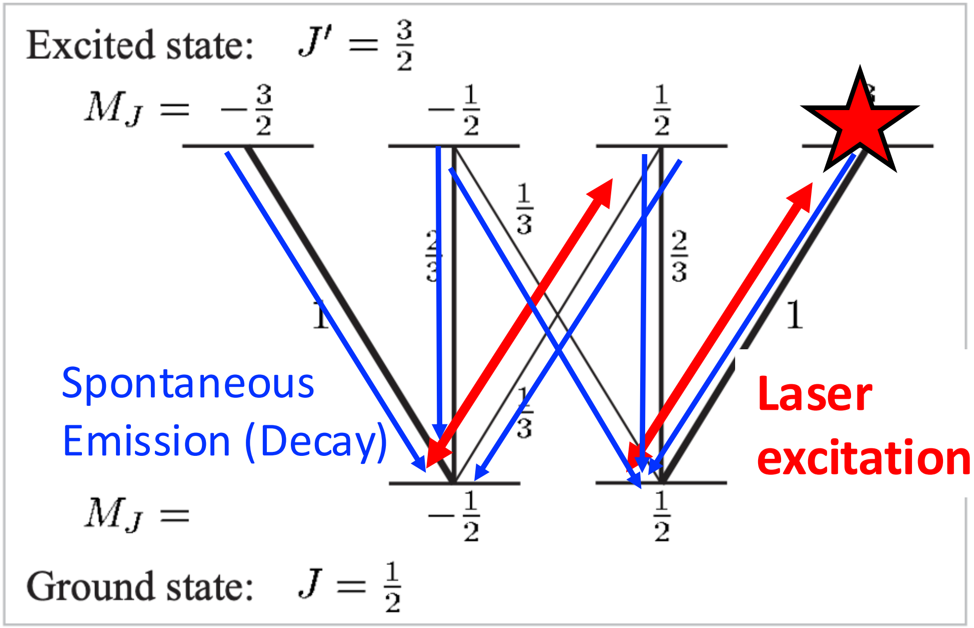


Another approach: optical pumping

- Optical pumping: widely used technique in atomic physics to polarize the electron spin
  - **Consider total angular momentum J: J=L (orbital one) + S (electron spin)**
- Excitation (de-excited) by circularly polarized laser: **$M'_J = M_J+1$**
  - Photon gives angular momentum to orbit.
  - Orbital angular momentum couples to spin: electron spin can be changed

- Spontaneous emission (=decay)
  - Atoms **randomly lose J**
  - ΔM_J =-1,0,1

- By repeating this process many times, the atom is **initialized to a specific spin state**
  - Laser excitation → decay → laser excitation → decay….

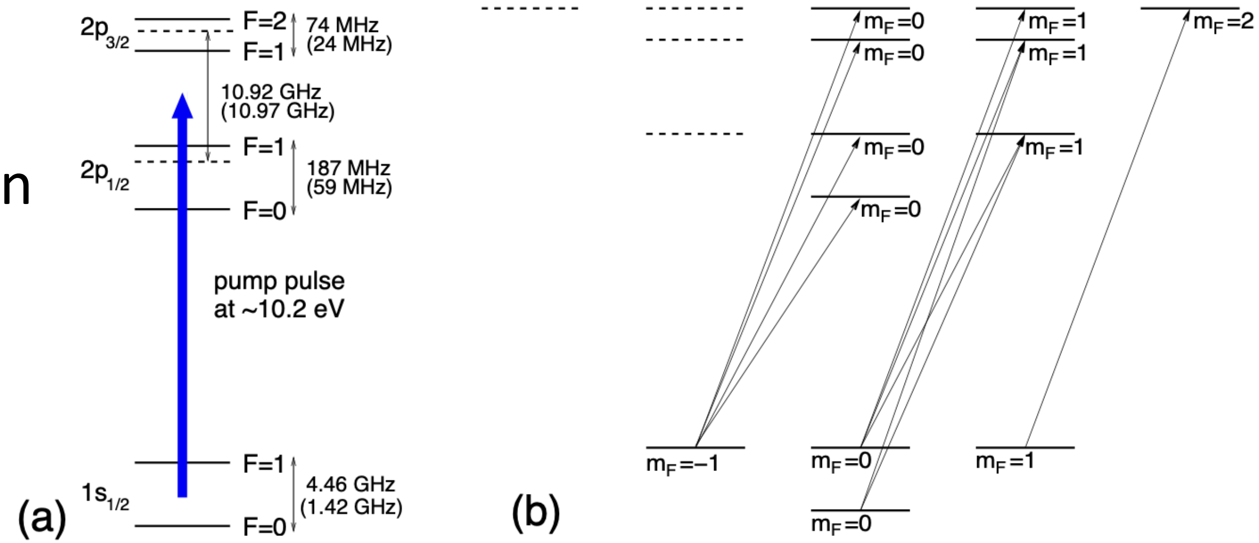


Optical pumping of Mu

- This is a **nuclear spin polarization.**
- Instead of J, let us consider the F (total angular momentum)
  - **F=L (orbital one) + S (electron spin) + I (nuclear or muon spin)**
- Then,
  1. Circular polarized laser gives an orbital angular momentum to atom
  2. Coupling of the Electron spin and orbital angular momentum
  3. **Coupling of the Electron spin and nuclear spin: new step !!**
  4. Decay (1.6ns): random change of the angular momentum: ΔmF=-1,0,1

λ=122nm for transition

Too many eigen state…



Requirement to laser: CW

- In short, we want to repeat excitation and spontaneous emission many times.
- **CW laser is the best.** Saturating the transition & many repetition
  - Too high intensity may introduce unwanted ionization by absorption of multiple 122nm photons. Many repetition is better.
  - **However, no CW @122nm is available. Very short Mu lifetime.**

Mathematics (for those who are intested in):

- Saturation intensity of a transition: $\mathbf{I_s \sim \pi/3\, hc/\lambda^3/\tau}$ $[\mathrm{W/m^2}]$ -> 70 $\mathrm{kW/m^2}$
- Doppler width: **80GHz**
- Natural width: 100MHz

➢ **Required intensity: 80GHz/100MHz × $\mathbf{70kW/m^2 = 6kW/cm^2}$**

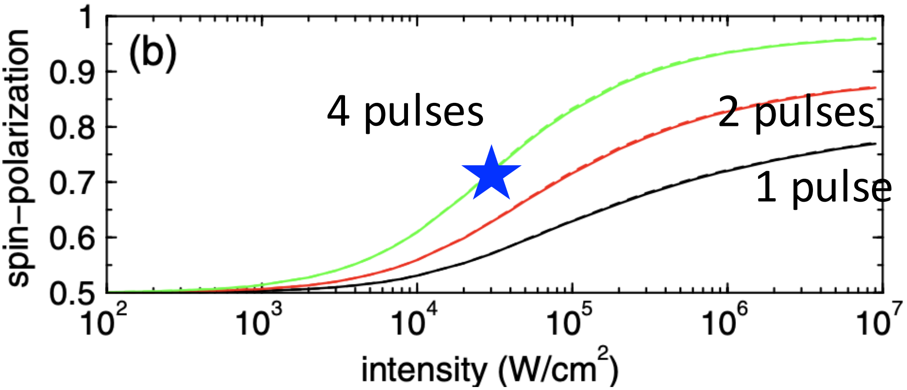
- Spatial spread of Mu: $\mathbf{2cm^2}$

➢ **Required CW power: $\mathbf{2cm^2}$ × $\mathbf{6kW/cm^2}$ = 12kW!!! (established: few μW)**

Optical pumping with train of laser pulse

- Proposal is to use **a pulse train to repeat the process**
  - We are developing **pulsed 122nm light source (2ns, 100μJ).**

- Roughly, required pulse energy is 2ns × 6kW/cm^2 × 2cm^2 × # of pulse
  - O(24)μJ × # of pulse
  - See previous page

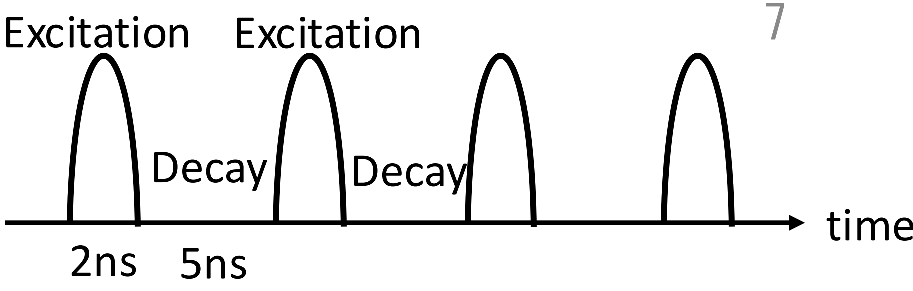


- Previous proposal exists: [link]()

- It is possible to increase spin pol. **to ~75%** by 4 pulses with P=10kW/cm^2
  - **Total energy is 4 × 40μJ**
  - Good benchmark?? (one order more pulse energy is unlikely)

※ This is for a tungsten target. **Please multiply 0.3 to the energy for scaling to SiO$_2$ results**

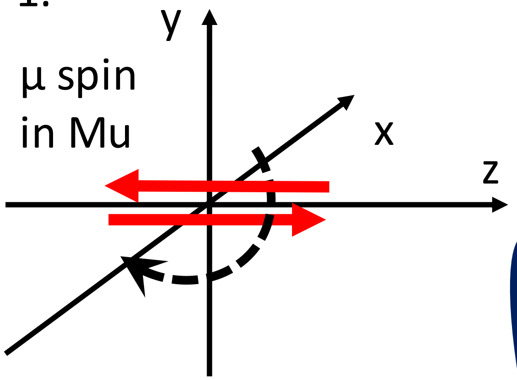
※ Probably, they did not consider multi-ionization by 122nm photons



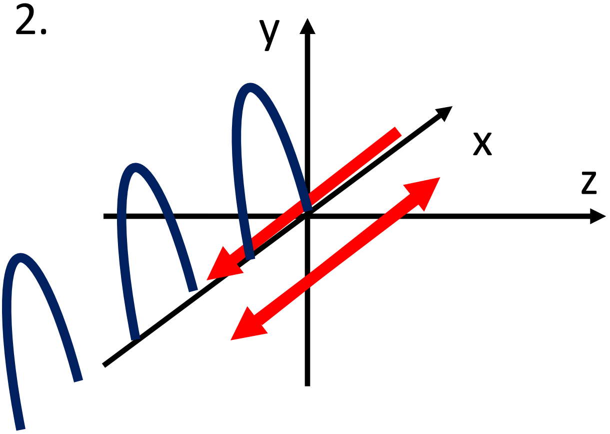
Experimental sequence

1. Rorate the Mu spin to align with the laser direction by B-field
   - Quantization axis: along the laser path.
2. Shoot the 4 lasers to polarize Mu
   - 50%->70-80%?
3. Rorate the Mu spin
   - If you want to choose any specific initial direction of muon.
4. Excite and ionize the Mu
   - Our default scheme. When step3 is skipped, the last pulse of step 2 can be used? (depending on the energy of the pulse)
   - 100μJ for excitation to 2P state and 300mJ for ionization from 2P state

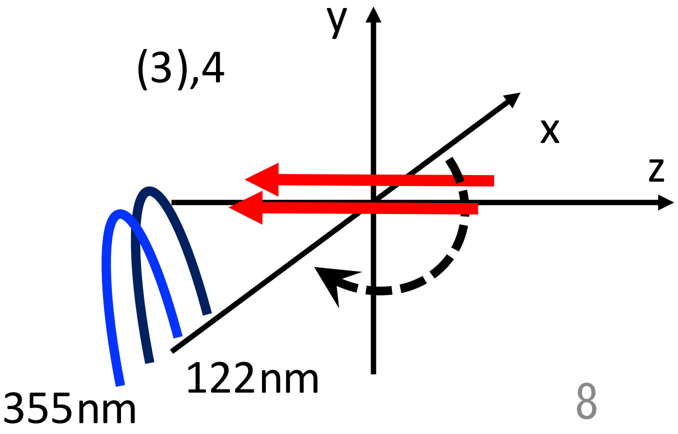
1.



2.



(3),4



Technical challenge(s)

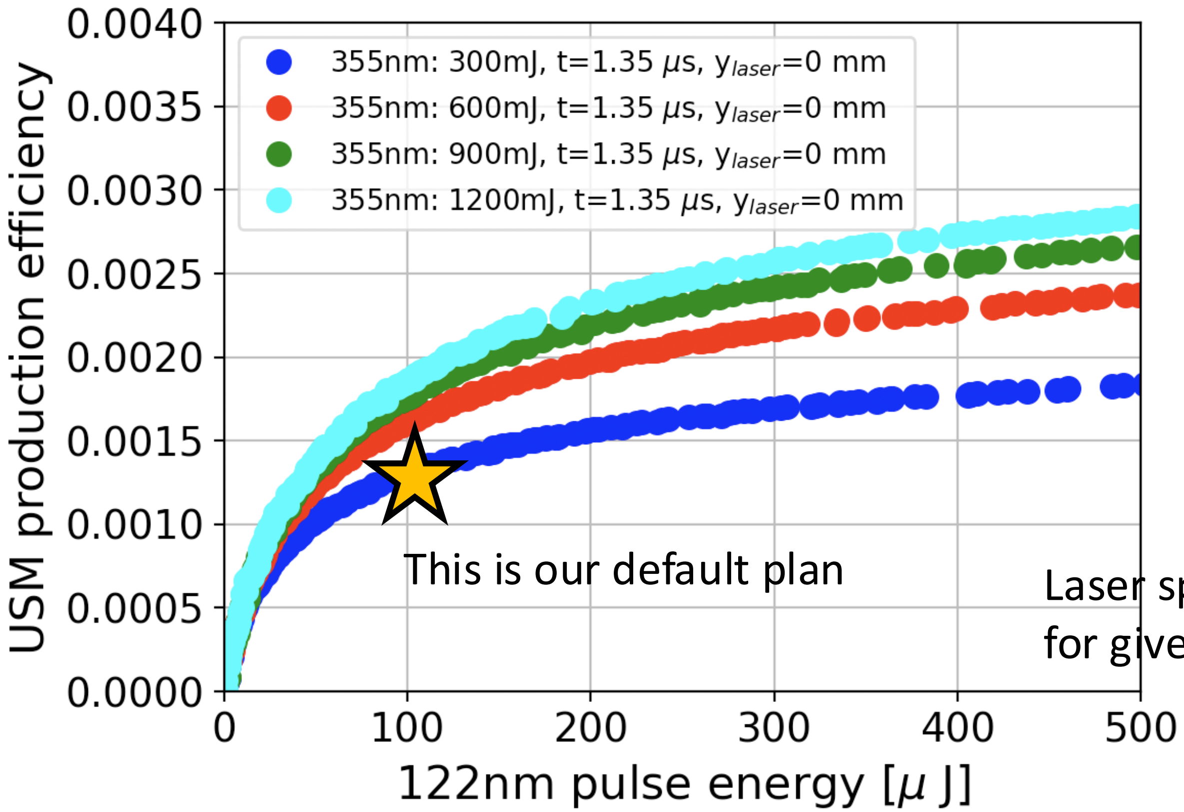
- **Production of circular polarized 122nm radiation**
  - Not demonstrated
  - Vacuum UV (VUV): many materials are not transparent to this wavelength.
  - Waveplate development or direct production ?
- **Evaluation of polarization of 122nm**
  - Relatively the easiest challenge. Frenal reflection+ rotating plate???
- **We need a pulse train**
  - Fast repetition of laser amplifiers with 5ns interval is impossible.
  - Production of one giant incident pulse, then it is split, re-combined to produce a pulse train. We need good design!!
- Concern:
  - Muon spin polarization will be correlated with the initial position.
    - the spin of Mu will be more polarized if Mu is near the center of the laser.
    - Or slower Mu along x-axis will be more polarized.

More pulse energy
for more USM or for more polarization ??

- With this option, we need additional (>100μJ) pulse energy.
- Is it better to use that energy for more ionization ??

✓ **Probably, No.**

  ➢ ×2 USM: >200μJ more 122nm pulse and >600mJ more 355nm



This is our default plan

Transition is saturated with I=O(24)μJ.

With 100μJ, transition is saturated, meaning increase of the energy is less efficient

Laser spot size and position is optimized for given pulse energy

Thank you!

It is not such a simple in fact…

- Extraction of USM from such a B-field results in the increase of $\mathbf{p_\theta}$
  - Considering the conservation of canonical momentum: $P_C = P - eA$
- **$\mathbf{P_\theta(r) = er/2 \times B}$**
  - B=0.2T at the beginning & r=1mm at B=0T -> P_θ = **30keV/c**
  - $P_{transverse}$ of USM is **3keV/c**

- Momentum in theta direction is difficult to be controlled by a usual transport optics…
  - Any good idea??? This is not today's main discussion.

$B \neq 0T$
$P_\theta = 0$

→

$B=0T$
$P_\theta \neq 0$