Study on Bose-Einstein Condensation of Positronium

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APSA
Advanced Photon Science Alliance

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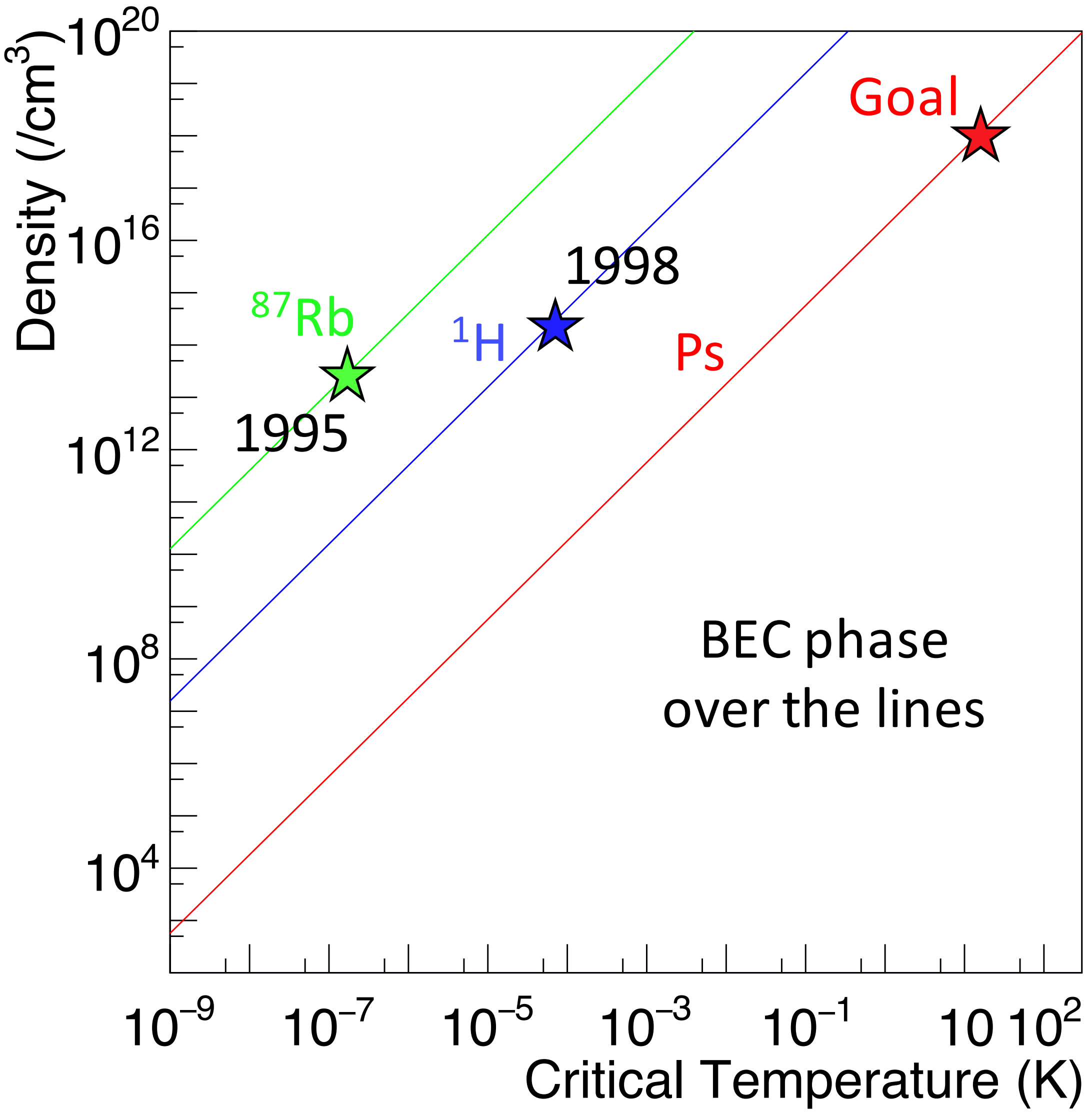
Ps - BEC

- Ps: The lightest atom
  Advantage
  Very high critical temperature of BEC
- e.g.) 14 K @ 10^{18} /cm^3

➢ Ps is the best candidate for the first BEC with anti-matter

Novel applications of Ps - BEC:

- ☐ Precise measurements of anti-matter gravity
- ☐ Realization of 511 keV laser using decaying gamma rays



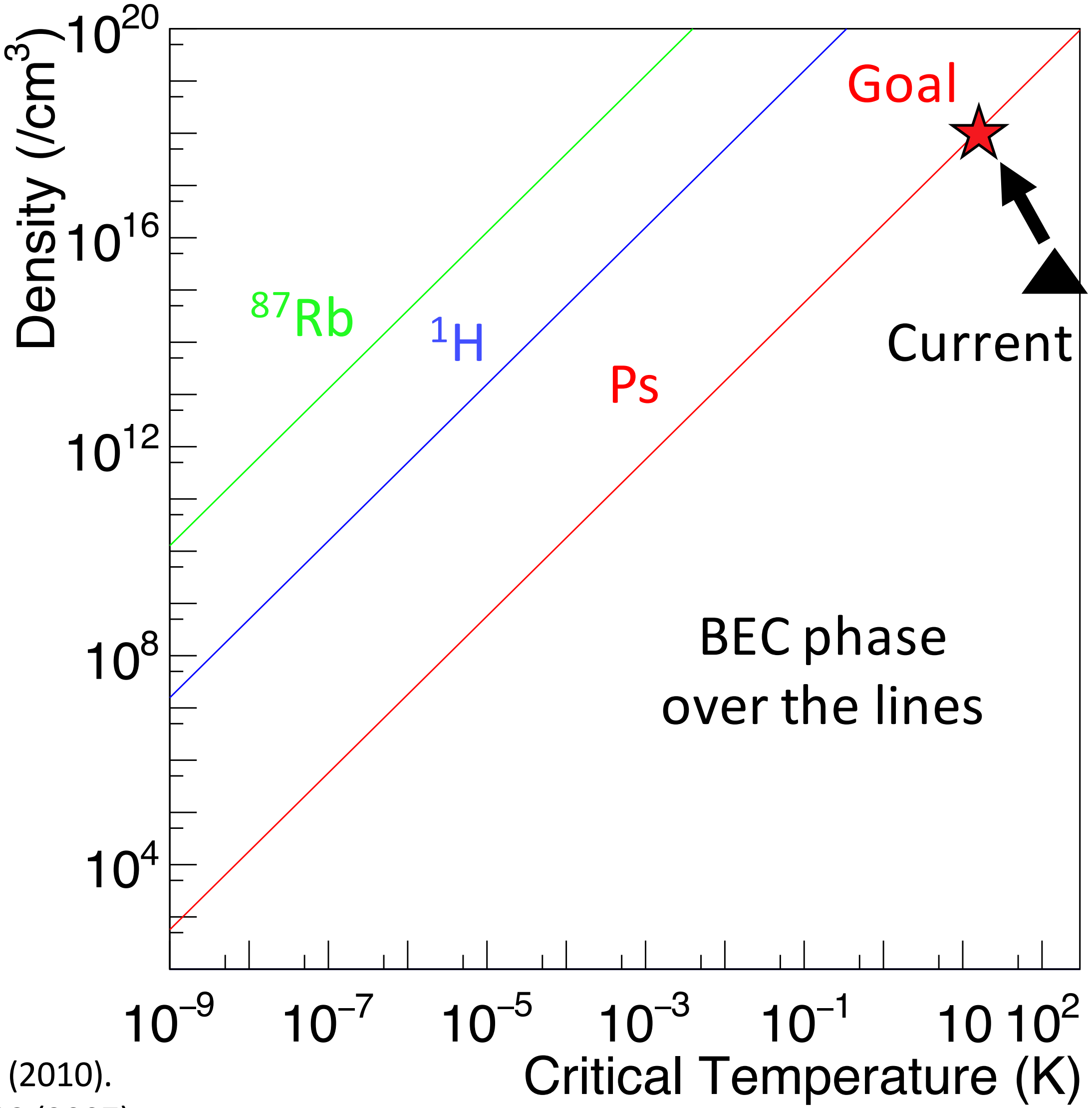
Challenges: High Density and Cooling

- Difficult because of
  Short lifetime as 142 ns

Two Challenges in lifetime
- ☐ High density 10^{18} /cm^3
- ☐ Cooling 10 K

Currently
10^{15} /cm^3 *1, 150 K *2

Both need much improvement!

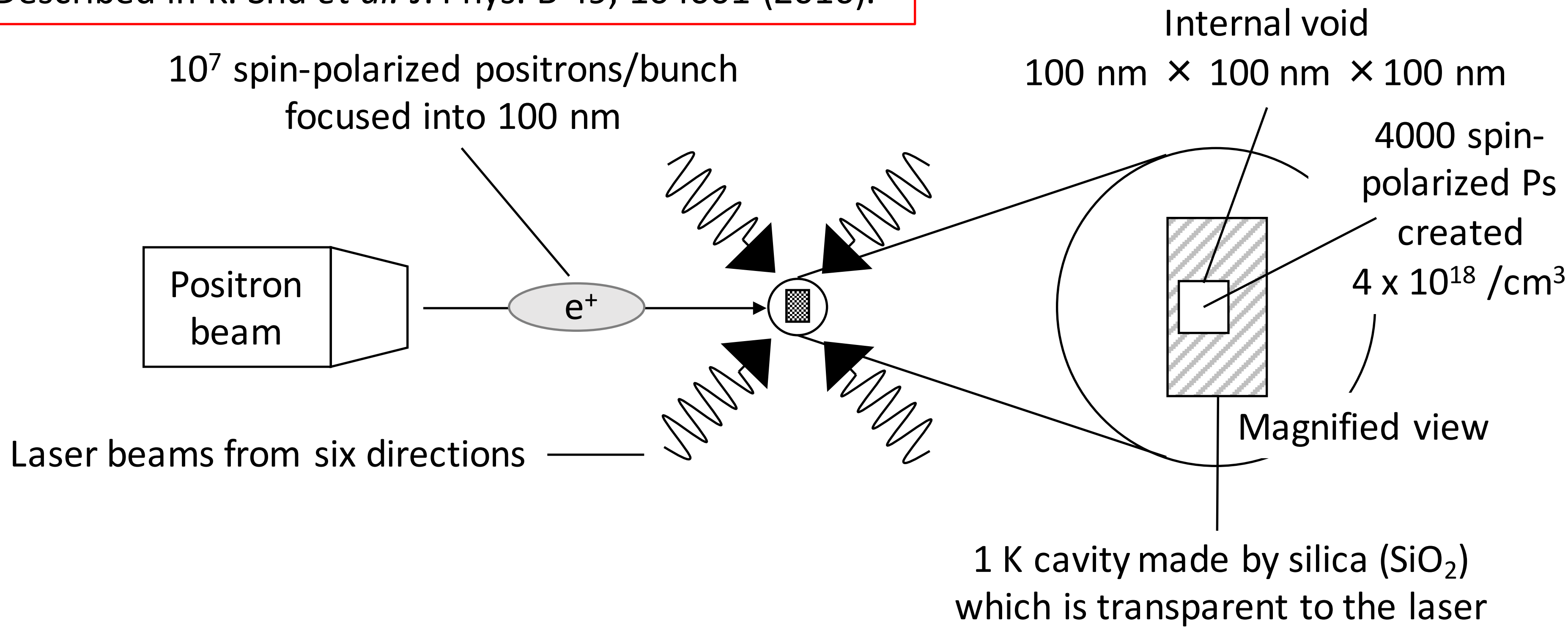


*1 : S. Mariazzi *et al.* Phys. Rev. Lett. 104, 243401 (2010).
*2 : D. B. Cassidy *et al.* physica status solidi 4, 3419 (2007).

Our strategy: Two-Stage Cooling Thermalization and Laser Cooling

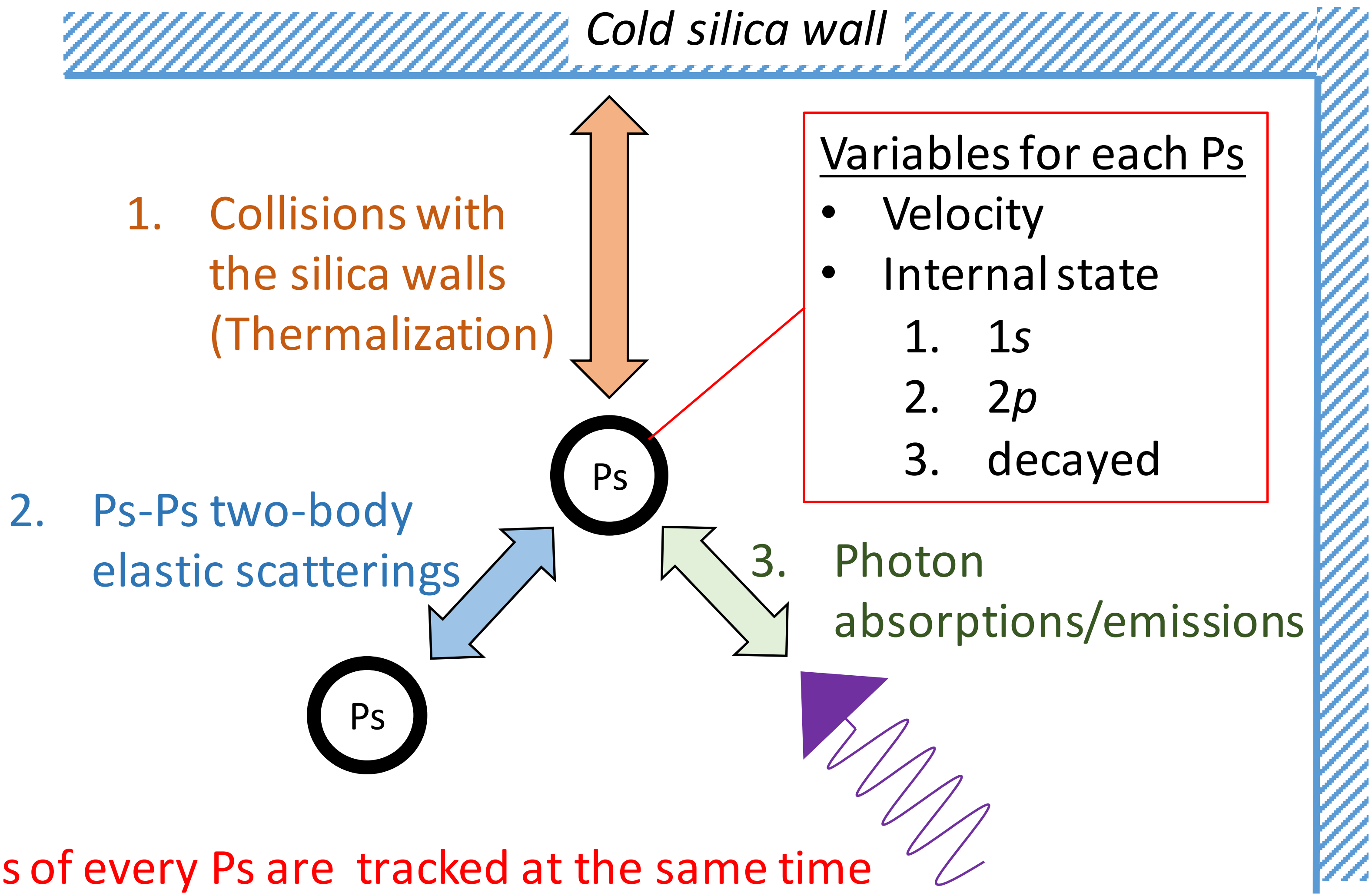
Using two cooling processes: efficient in different Ps temperature region

Described in K. Shu *et al.* J. Phys. B 49, 104001 (2016).



1. Down to 300 K: Energy exchange by collisions with cold silica (thermalization process)
2. Down to 10 K: Laser cooling (Doppler cooling)

Model of the Simulation



- Variables of every Ps are tracked at the same time
- 3 interactions are integrated
- Details are in a poster session by A. Ishida today

Thermalization Model and Parameters

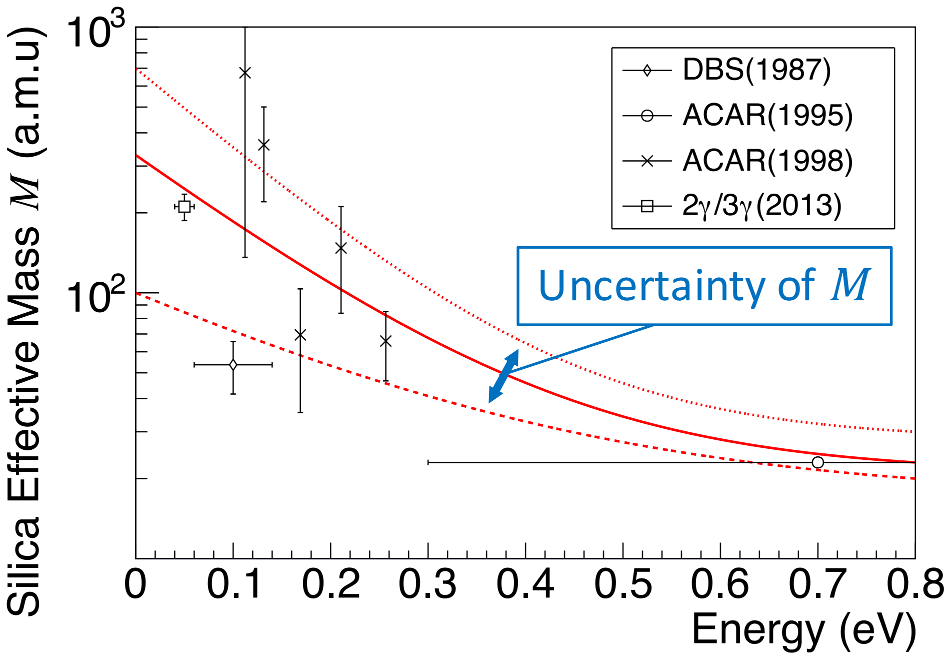
- The classical model by Nagashima et al. ←well-tested for Ps in large pores

  from Y. Nagashima *et al.* Phys. Rev. A, 52, 258(1995)

$$\frac{\mathrm{d}E_{\mathrm{av}}}{\mathrm{d}t} = -\frac{2}{LM}\sqrt{2m_{\mathrm{Ps}}E_{\mathrm{av}}}\left(E_{\mathrm{av}} - \frac{3}{2}k_B T\right)$$

E_{av} : Ps average kinetic energy, m_{Ps} : Ps mass,
L : Mean free path of scatterings,
M : Effective of mass of scatteing bodies,
T : Temperature

M depends on kinetic energy of Ps
Estimated by various experiments



Measured values superimposed

- Estimation of the dependence :

$$M(E) = p_0 + p_1 \exp\left(\frac{E}{p_2}\right)$$

Legends:
DBS(1987): T. Chang *et al.* Phys. Lett. A 126, 189
ACAR (1995): Y. Nagashima *et al.* Phys. Rev. A 52, 258
ACAR (1998): Y. Nagashima *et al.* J. Phys. B 31, 329
2γ/3γ(2013) : K. Shibuya *et al.* Phys. Rev. A 52, 258

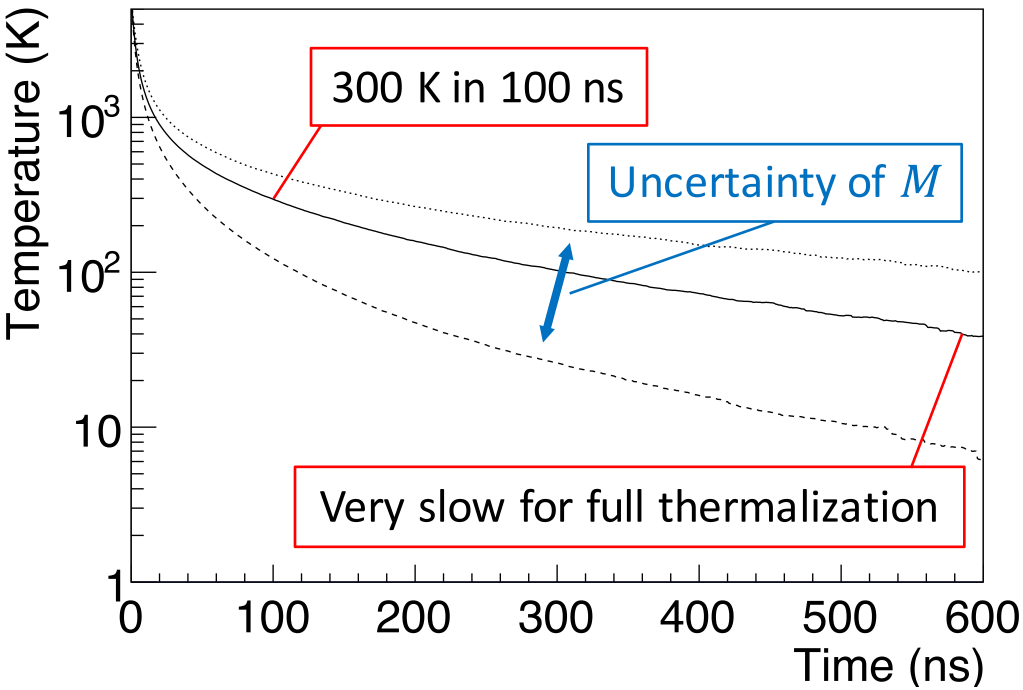
Evaluation of Ps Thermalization

<u>Included</u>

- Classical model with three M estimation
- The two body elastic scatterings

<u>An initial condition</u>

- ➢ Ps initial kinetic energy : 0.8 eV
  from Y. Nagashima *et al.* Phys. Rev. A 52, 258(1995)
- ➢ An initial number of Ps : 4000
- ➢ Silica cavity :
  100 nm x 100 nm x 100 nm, 1K

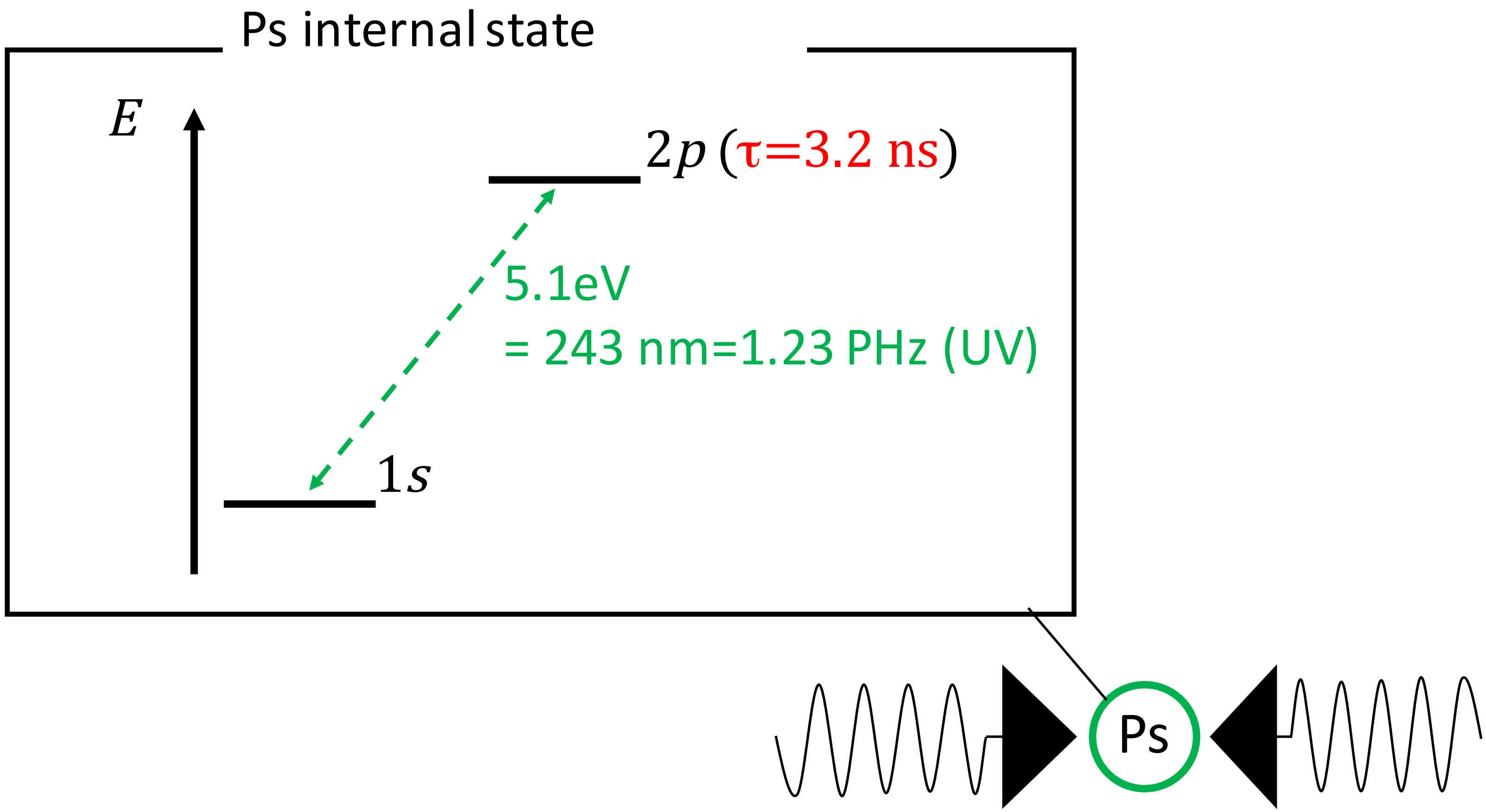


Time evolution of Ps temperature

✓ Precise measurement is necessary

- Cooled to 300 K in 100 ns
- Cooling to 10 K is too slow
- ➢ <u>Laser cooling is important after 300K</u>

Laser cooling of Ps



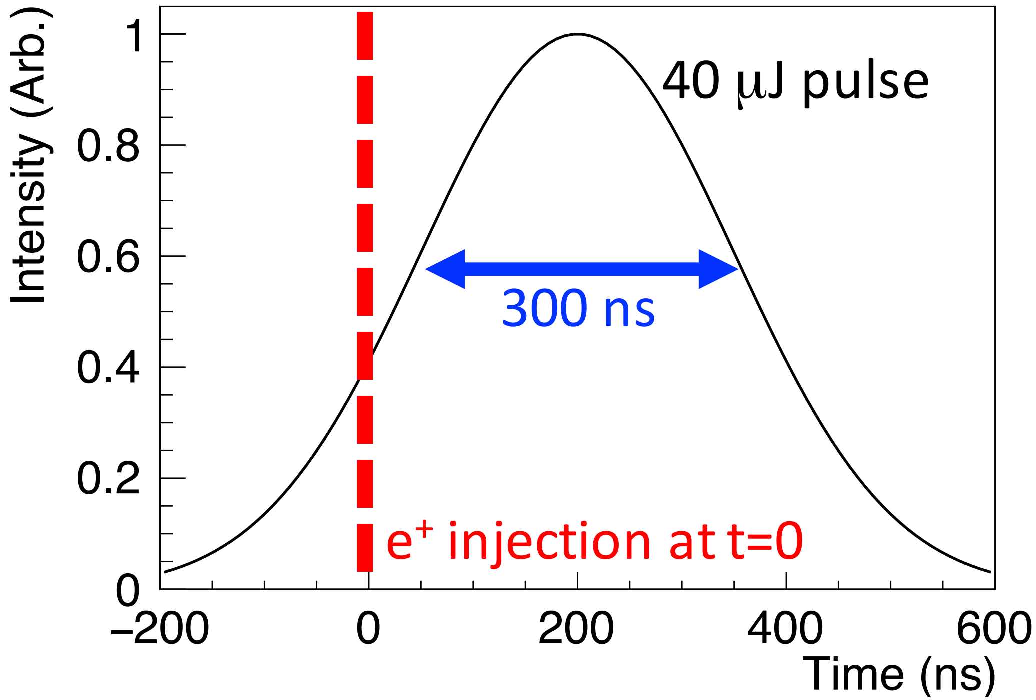
Resonance between 1*s* – 2*p* will be used
Cooled in every 3.2 ns x 2 = 6.4 ns in average

Requirements for the Laser: Long pulse

<u>Two requirements for efficient cooling especially for Ps:</u>

① Long pulse

- Ps cooling takes the order of the lifetime (>100 ns)
- Laser should be pulsed with 300 ns width
  (much longer than usual)
- Pulse energy is 40 μJ to saturate cooling cycle



Laser intensity vs Time

Requirements for the Laser: Broad bandwidth & Frequency shift

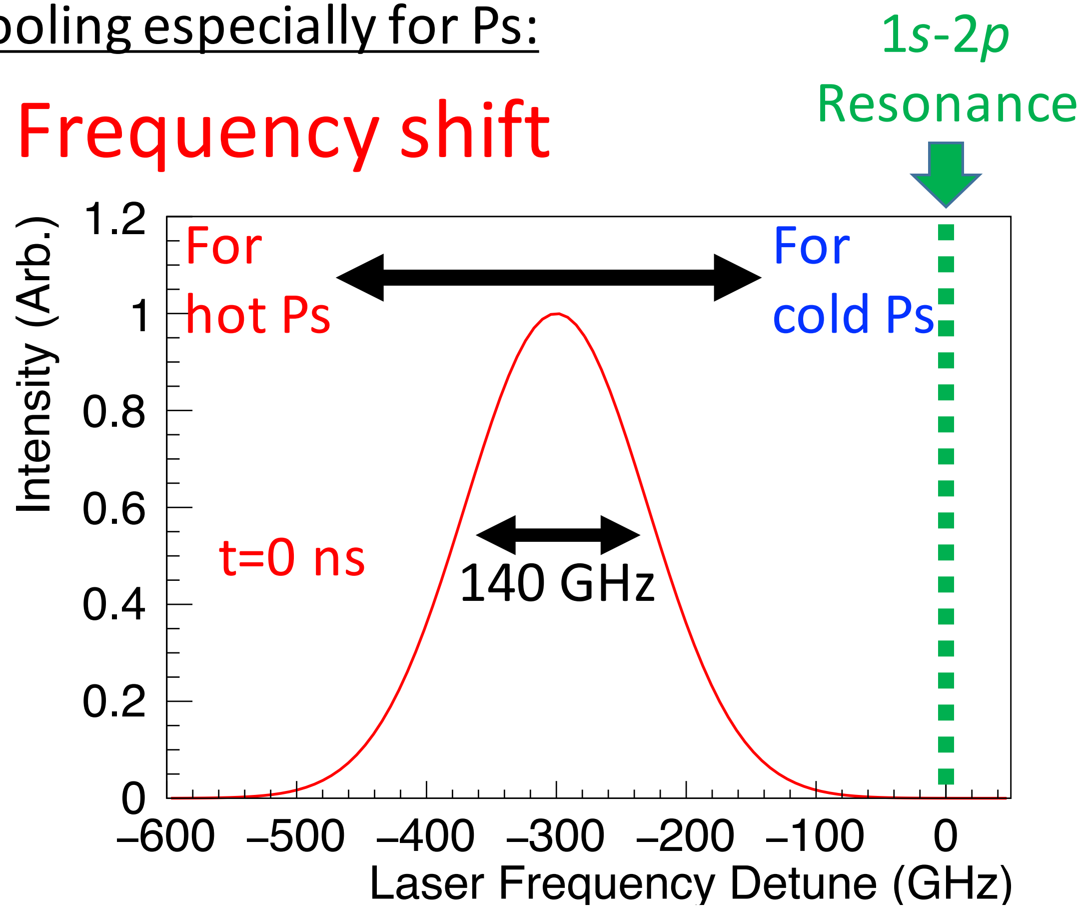
<u>Two requirements for efficient cooling especially for Ps:</u>

② Broad bandwidth & Frequency shift

- Doppler broadening for Ps is quite large because of its light mass
  c.f. 500 GHz at 300 K

<u>Broad bandwidth</u>
To cool Ps with various velocities

<u>Frequency shift</u>
To follow smaller Doppler shift of cold Ps



Frequency Profile of the Cooling Laser

Requirements for the Laser: Broad bandwidth & Frequency shift

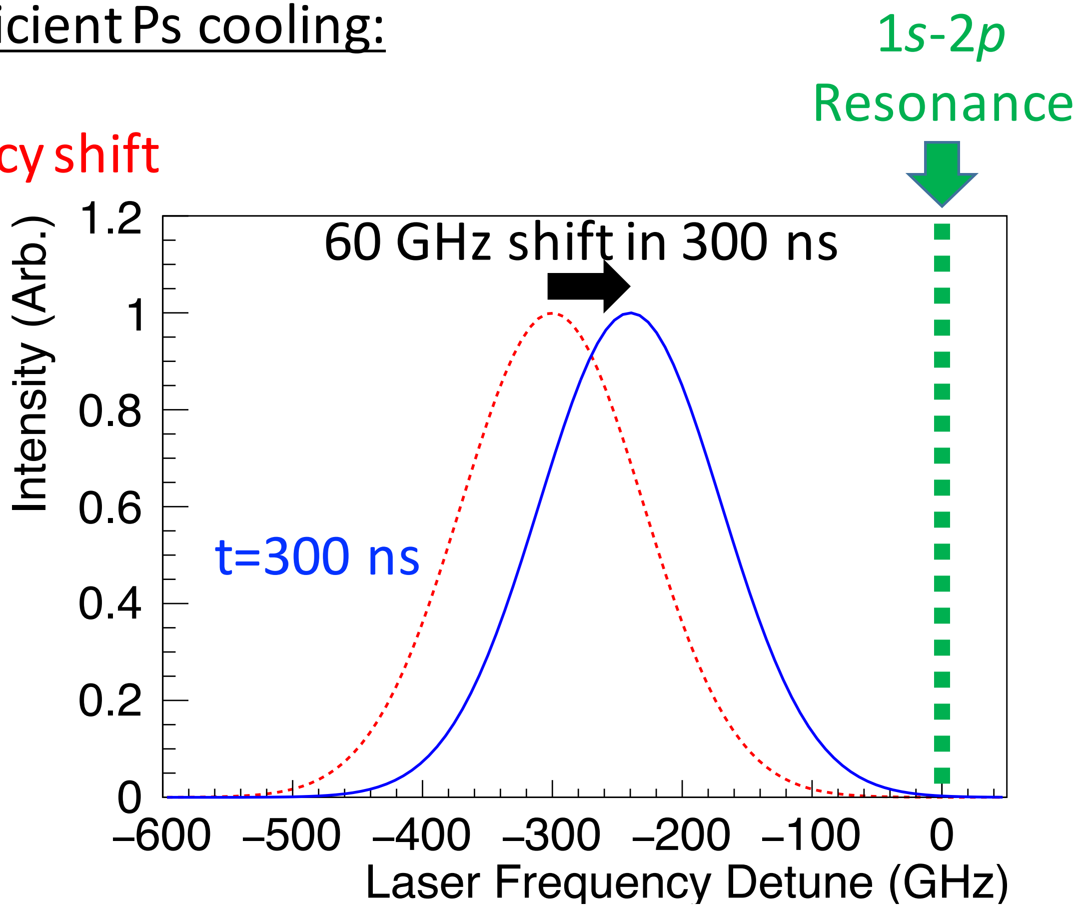
<u>Two special requirements for efficient Ps cooling:</u>

② Broad bandwidth & Frequency shift

- Doppler broadening for Ps is quite large because of its light mass
  c.f. 240 GHz at 300 K

<u>Broad bandwidth</u>
To cool all of Ps with various velocities

<u>Frequency shift</u>
To follow smaller Doppler shift of cooled Ps



Frequency Profile of the Cooling Laser

Laser Specifications

Summary of required specifications

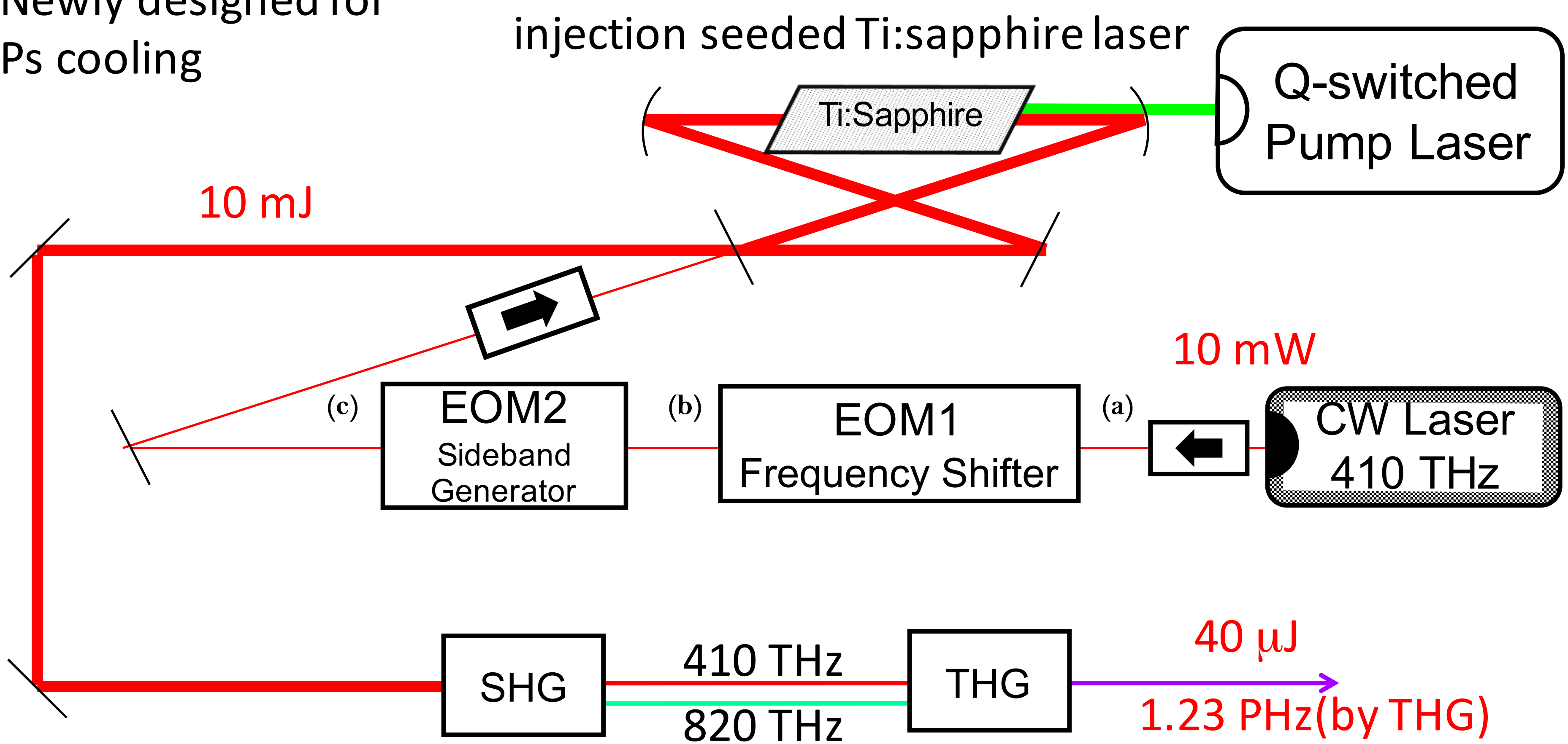
Pulse energy	40 μJ
Center frequency	1.23 PHz - D(t)
Frequency detune (D(t))	D(0 ns)=300 GHz D(300 ns)=240 GHz
Bandwidth (2σ)	140 GHz
Time duration (2σ)	300 ns
Beam waist (2σ)	200 μm

Very special specs!
Especially: fast and well-controlled frequency shifting in pulsed mode

New trial for optics!!!

Design of the Laser System

Newly designed for
Ps cooling



Design of the Laser System

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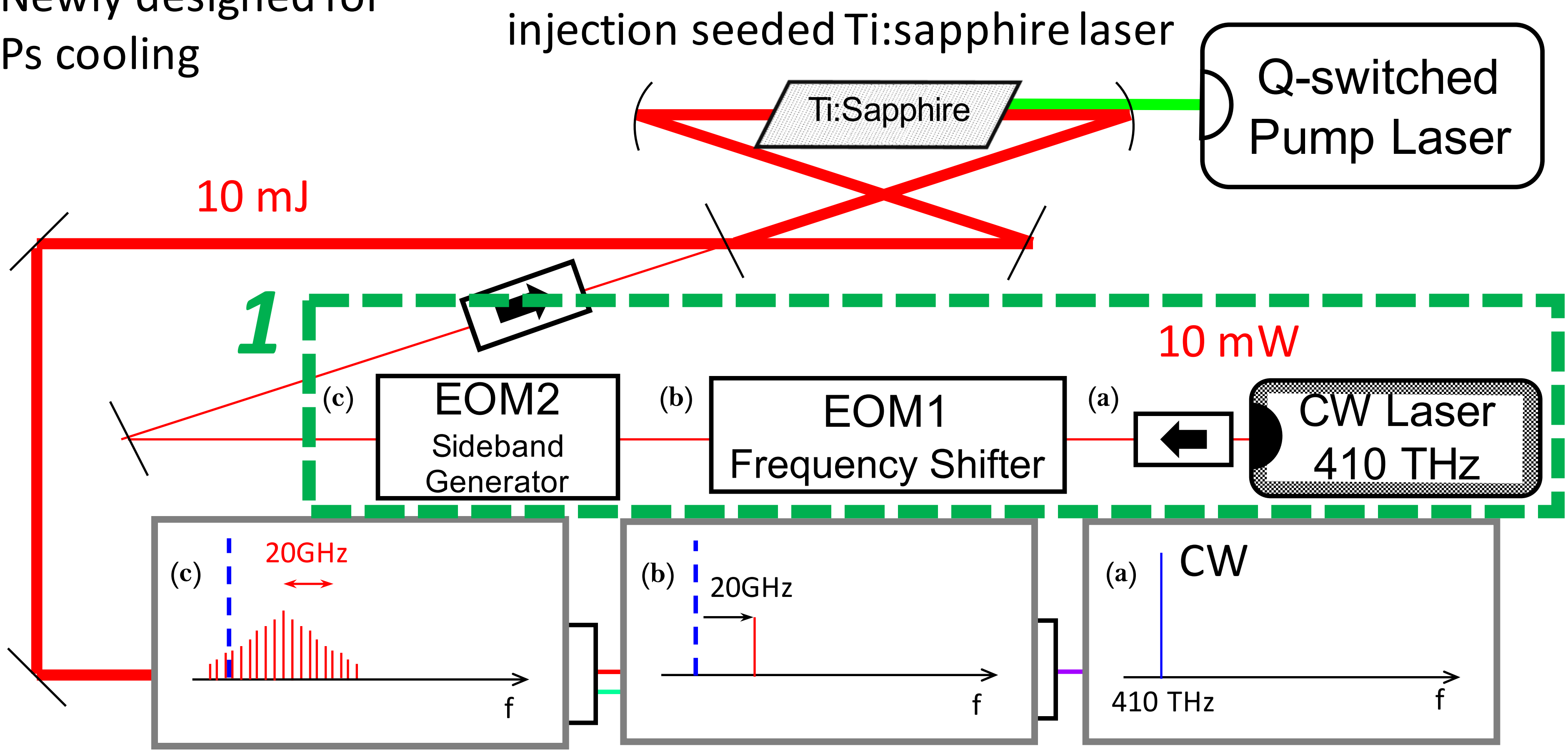


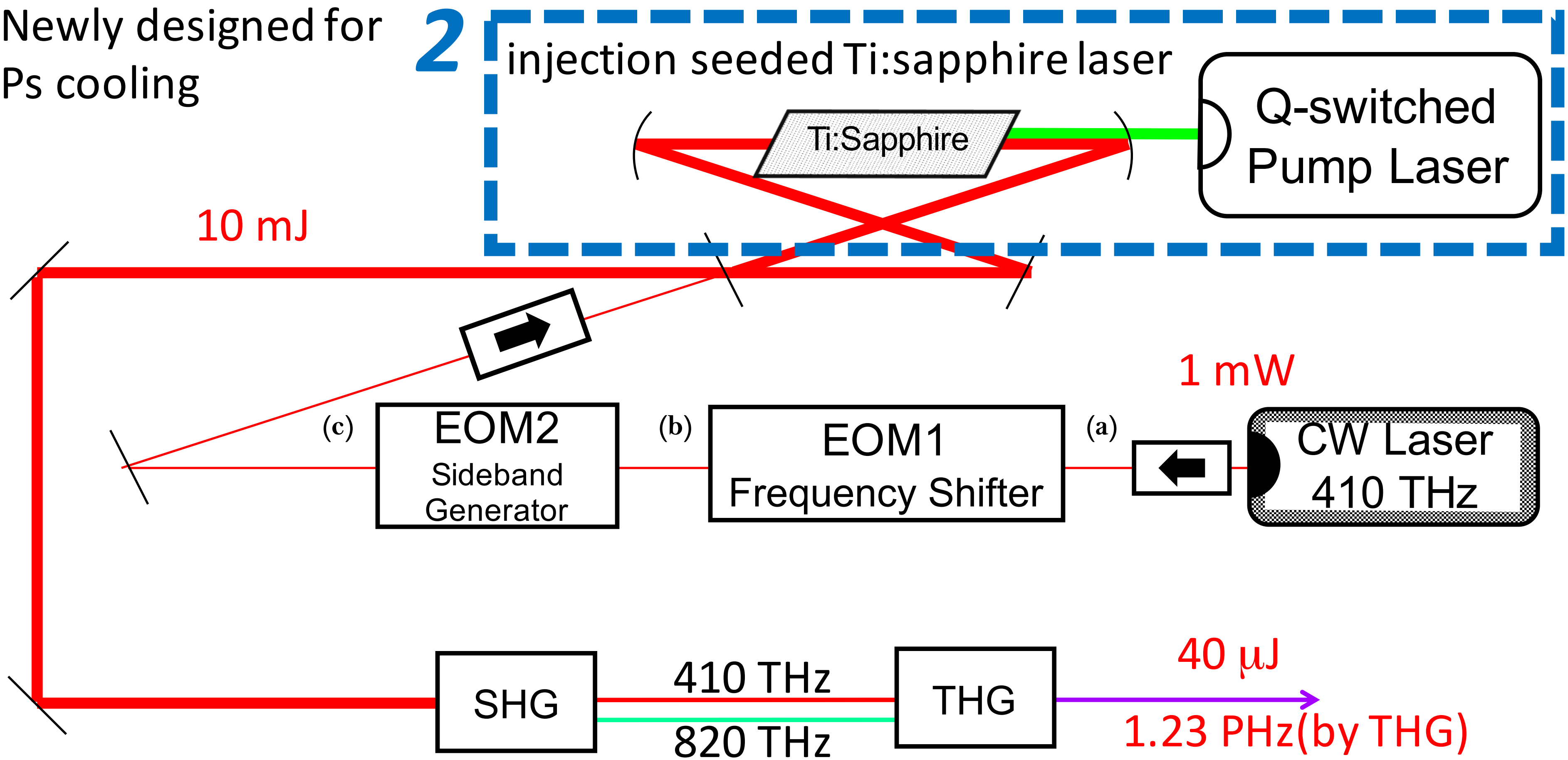
Idea of the design:

1. <u>Controling frequency in Continuous Wave mode with a third frequency</u>

   ☆Both of shifting and broadening are possible by EOMs

Design of the Laser System

Newly designed for Ps cooling



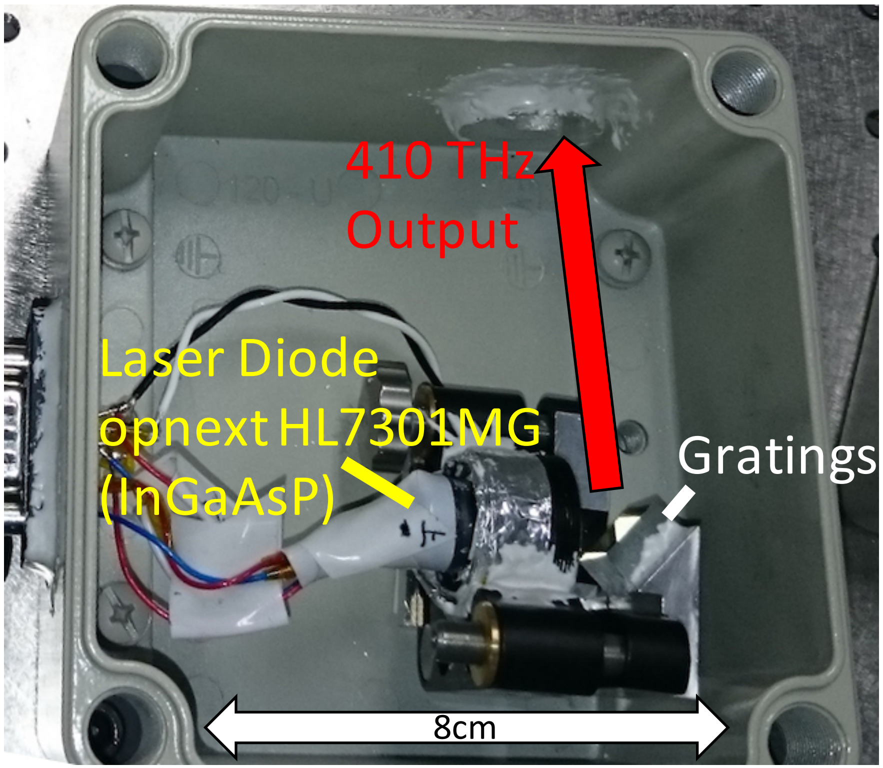
Idea of the design:

2. Seeding the CW laser into Ti:Sapphire to generate pulsed laser

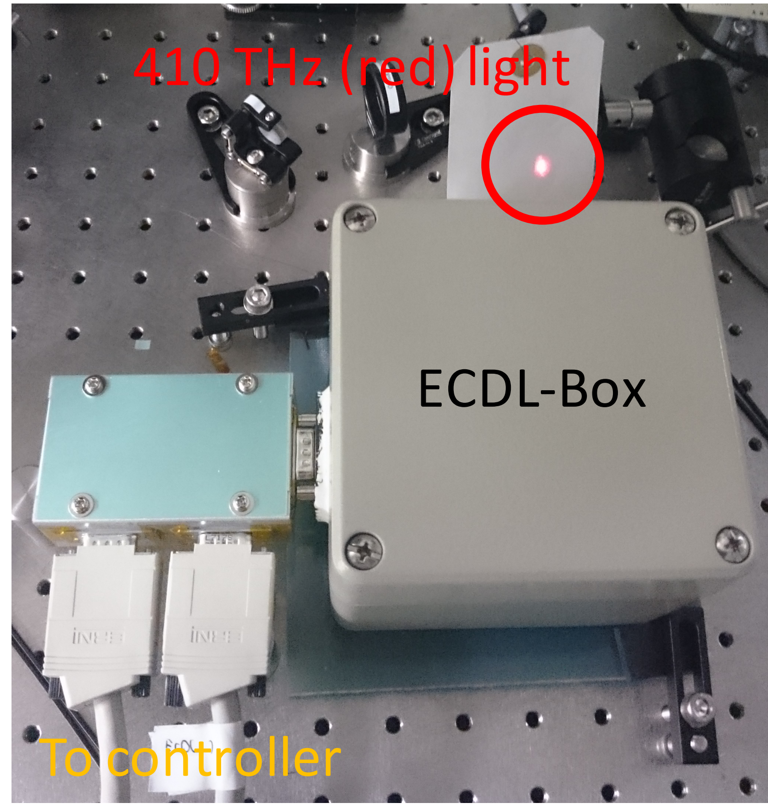
☆ Generate pulsed laser with controlled frequency

Development of the cooling laser

<u>The initial part (CW seed laser)</u>



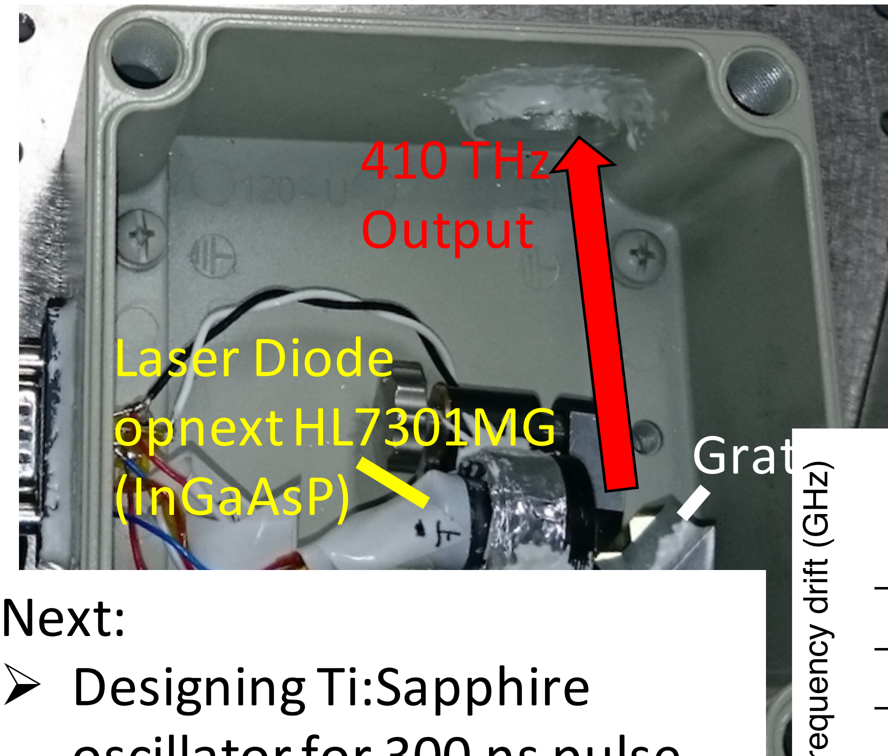
Home-made External Cavity Diode Laser
☆Compact

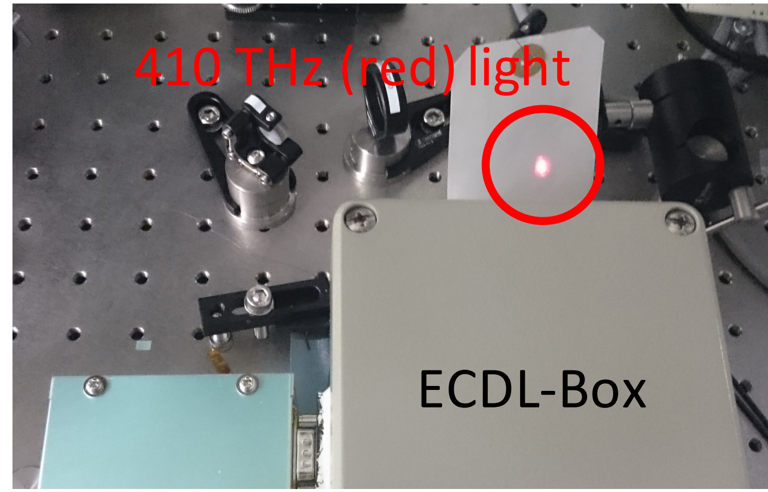


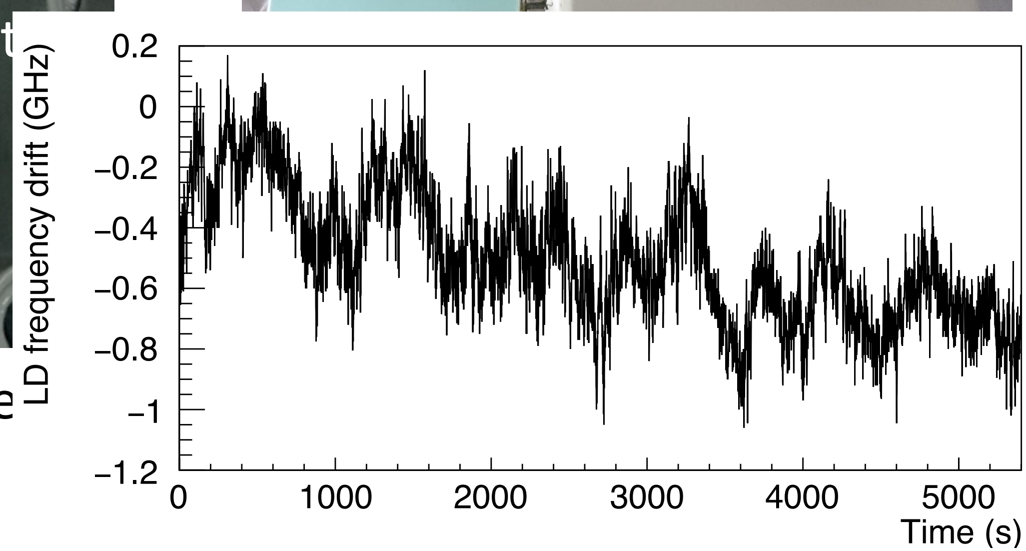
- Oscillating at desired ~410 THz
- Powerful enough (~10 mW)

Development of the cooling laser

<u>The initial part (CW seed laser)</u>







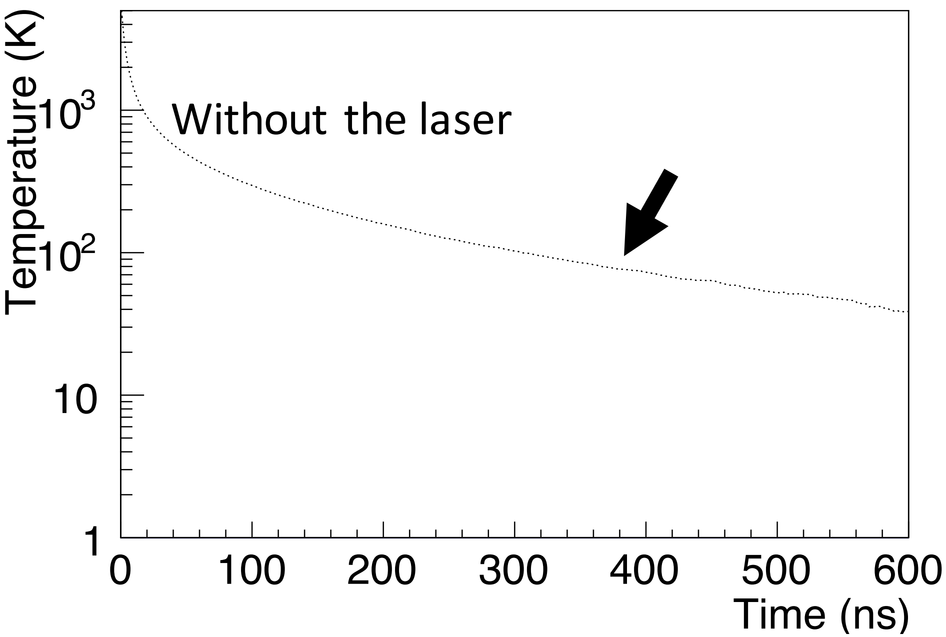
Next:

- ➢ Designing Ti:Sapphire oscillator for 300 ns pulse and injection seeding

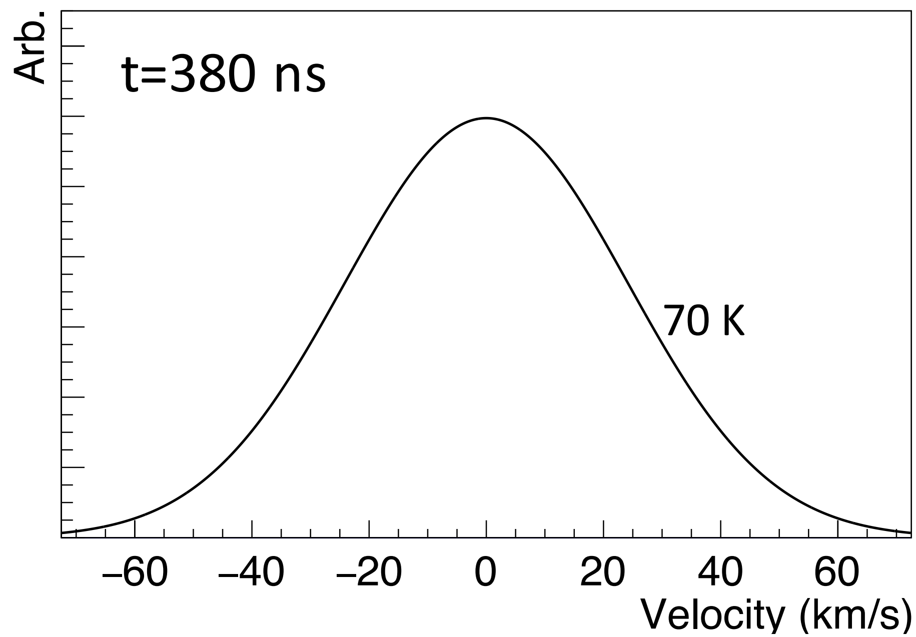
☆Compact

e

Evaluation of the Cooling



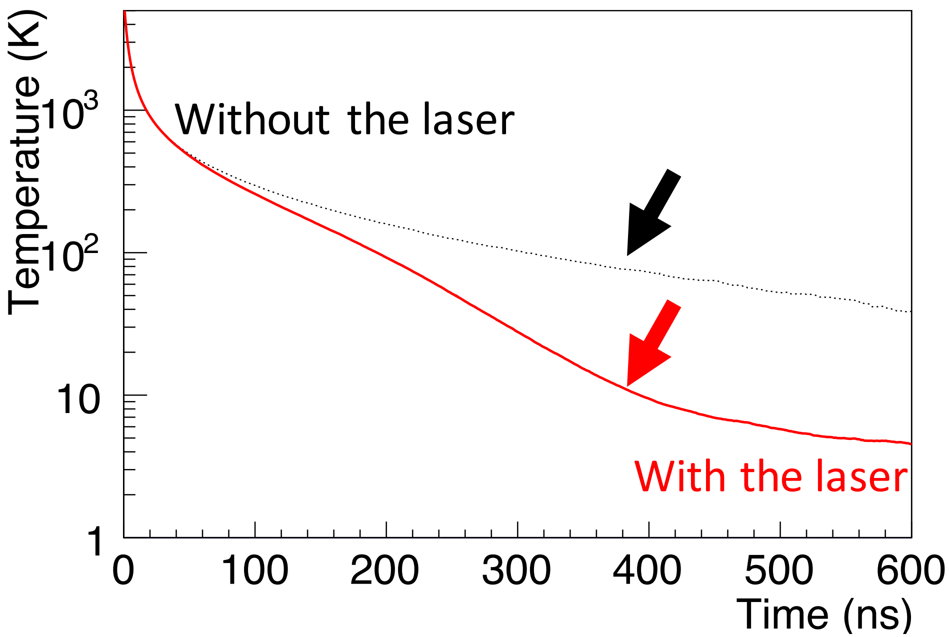
Time evolution of Ps temperature



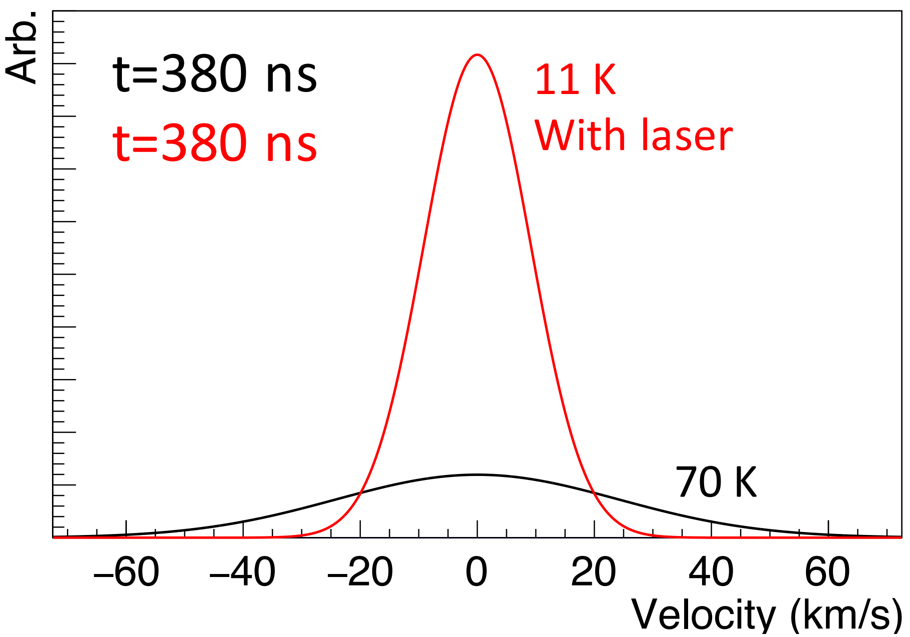
Ps velocity distribution
(Calculated by simulated temperature)

- Without the laser, cooling is too slow (by Best fit estimation of M)

Evaluation of the Cooling



Time evolution of Ps temperature



Ps velocity distribution
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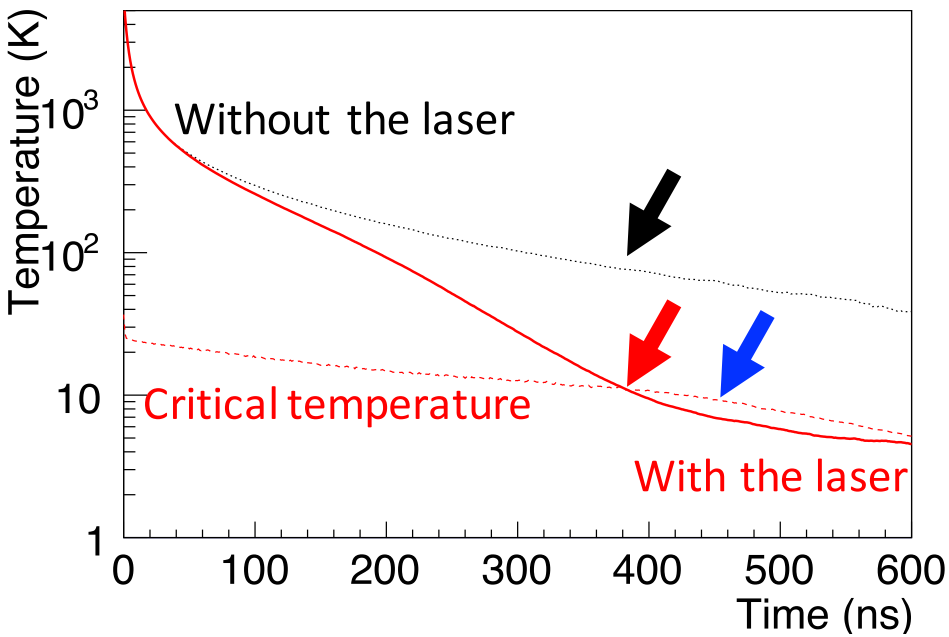
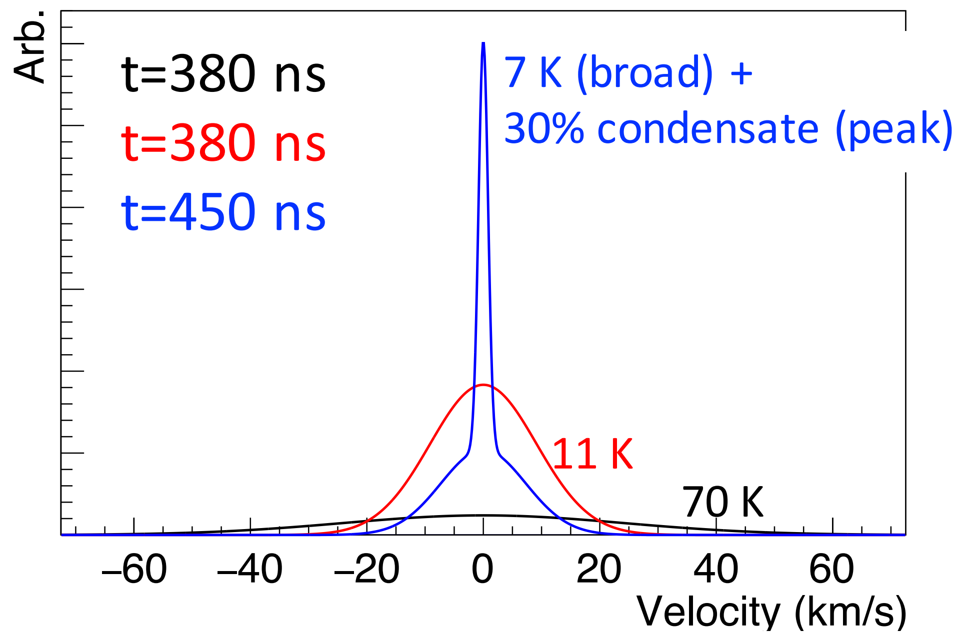
- Without the laser, cooling is too slow (by Best fit estimation of M)
- With the laser, cooling from ~300 K is accelerated

Evaluation of the Cooling



Time evolution of Ps temperature



Ps velocity distribution
(Calculated by simulated temperature)

- Without the laser, cooling is too slow (by Best fit estimation of M)
- With the laser, cooling from ~300 K is accelerated
- Compared with the critical temperature, BEC transition will happen at 400 ns!

Roadmap

1. Precise Ps Doppler spectroscopy (in 2 years)
   - Establishment of a methodology for cold Ps
   - Solving uncertainty of Ps thermalization process with silica

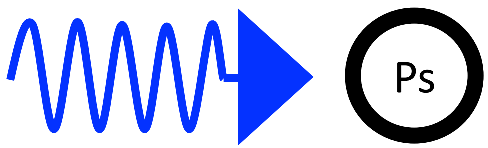
2. Ps laser cooling (in 4 years)
   - Development of the laser system with long pulse, wide bandwidth, frequency shift

3. Developing a dense positron system
   - 10^7 e^+ into 100 nm diameter in a nanoseconds bunch

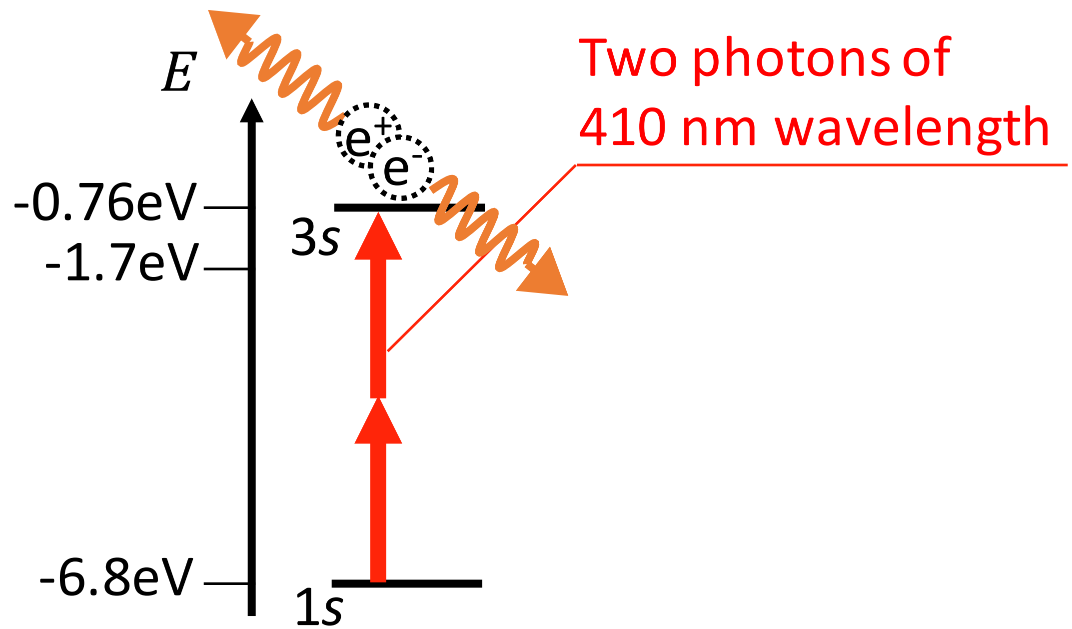
4. Ps BEC
   - Combing all the technologies!

Principle of Doppler-sensitive two-photon spectroscopy of Ps

- Conventional technique is not precise for 10 K Ps or BEC
- We will use Doppler-sensitive two-photon spectroscopy (New for Ps)



410nm pulsed laser



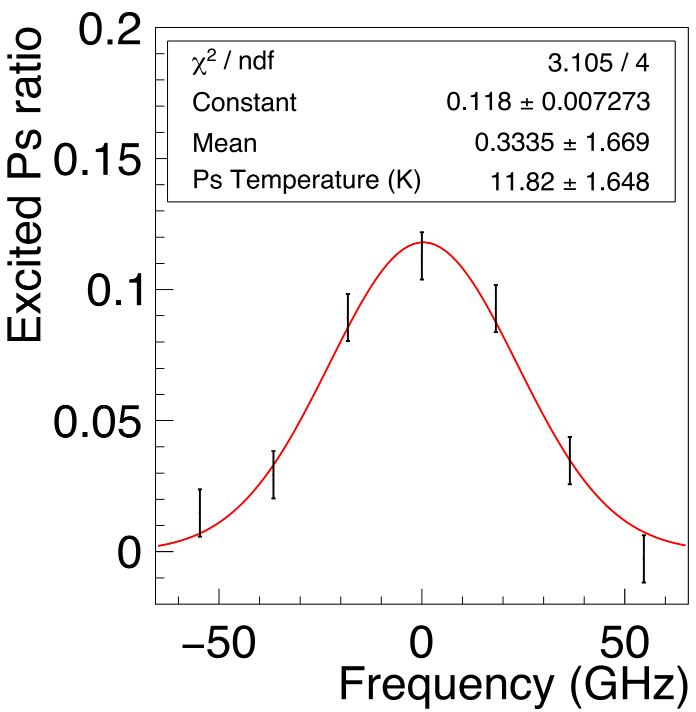
1. Excited to 3*s* by absorbing co-propagating two photons
2. Ionize 3*s*-Ps to free e^+ and e^-
3. The e^+ annihilates into γ-rays

- Doppler effect is doubled because two-photon: sensitive to Ps temperature
- Resonance can be measured via SSPALS
  (D. B. Cassidy *et al.* App. Phys. Lett. 88, 194105(2006))

Laser Requirements for Doppler Spectroscopy

Laser spec. for temperature measurement

Wave length	410 nm
Pulse energy	1 mJ
Time duration	A few ns
Bandwidth (FWHM)	25 GHz
Freq. tunable range	150 GHz
beam waist (2σ)	850 μm
Repetition rate	100 Hz



Expected resonance curve for 10 K Ps with 10^7 Ps in total, at t=300 ns

- ◯ Visible wavelength
- ◯ Easily achievable bandwidth
- ➢ Design of the laser is under study
  (SHG of Ti:Sapphire laser is a promising candidate)

<u>Plan to</u>

- ■ Confirm feasibility of the method
- ■ Measure thermalization process of Ps with cold silica

Goal for Dense Positron

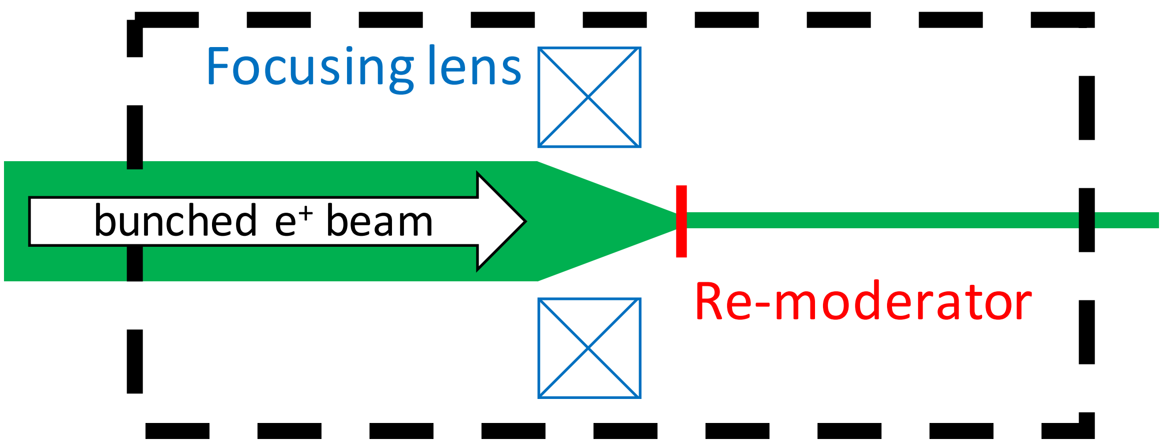
Goal for Ps-BEC

Number of positrons	10^7 e^+/bunch
Beam waist	< 100 nm
Pulse width	< 5 ns
Positron Energy	< 5 keV

Current at AIST microbeam
1 stage brightness-enhancement-system

Number of positrons	10^4 e^+/bunch
Beam waist	25 μm
Pulse width	~ μs
Positron Energy	0.5 ~ 30 keV

Principle of positron focusing (brightness enhancement):



Re-moderated positrons are
- Perpendicular to surface
- Monochromatic Energy
- With focused waist

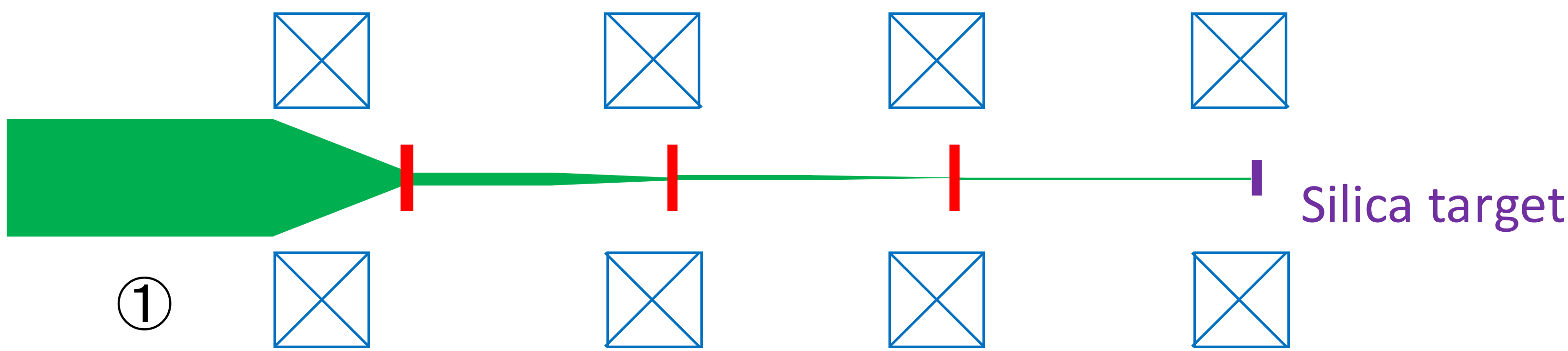
N. Oshima *et al.* J. Appl. Phys. 103, 094916 (2008).

Planned Upgrade of Positron Beam

Two necessary improvements:

	State-of-the-art	Goal
Buncher for spin-polarized positron	10^8 e^+/bunch	$2\text{x}10^9$ e^+/bunch
Beam compression ratio by Focusing lens	1/10	1/20 - 1/30

➡ With 20% re-moderation efficiency, 10^7 e^+ in 100 nm by 3-stage brightness-enhancement-system



n=$2\text{x}10^9$ e^+, ϕ=15 mm ➡ $4\text{x}10^8$ e^+, 750 μm ➡ $8\text{x}10^7$ e^+, 40 μm ➡ $2\text{x}10^7$ e^+, 2 μm ➡ $2\text{x}10^7$ e^+, 100 nm, <u>At target</u>

- Buncher and beam optics are now under detailed consideration

Summary

- We proposed and evaluated a new experimental scheme shown to be possible to realize Ps-BEC by:
  1. Thermalization process with cold silica (down to 300 K)
  2. Laser cooling (down to 10 K)

- The Cooling laser is special for:
  1. Long pulse – 300 ns time duration
  2. Broad bandwidth – 140 GHz
  3. Frequency shift – 60 GHz ← New optics for efficient cooling

  CW seed ECDL is ready

  Next: Ti:Sapphire injection seeding laser including frequency shift

- Several tasks are under detailed study and preparation:
  1. Doppler-enhanced 1*s* - 3*s* spectroscopy using two-photon excitation
  2. Designing a buncher and beam optics for 10^7 spin-polarized e^+/bunch in 100 nm waist by 20 times more e^+ & factor 2 strong focusing