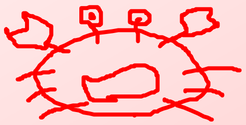


Laboratory Experiments of Induced Compton Scattering: Initial Results

Shuta Tanaka (Aoyama Gakuin U.)
with
Y. Kuramitsu, Y. Fukuda,
R. Yamazaki, Y. Sakawa et al.

Induced Compton Scattering

Various light scattering processes

- Geometric optics limit: $R > \lambda$, R = size of scatterer, λ = light wavelength
- Mie scattering: $R \sim \lambda$
- Rayleigh scattering: $R < \lambda$
- Brillouin scattering: Phonon, ion acoustic wave
- Raman scattering: Plasmon, vibration and/or rotational level of a molecule
- Compton scattering: an electron $\gamma + e \rightarrow \gamma + e$
  - Thomson scattering: classical limit of Compton (h = 0, elastic)
  - Induced Compton scattering: induced counterpart, redshift
  - Nonlinear Compton scattering: multiple photon absorption, blueshift

$$N\gamma + e \rightarrow \gamma + e$$

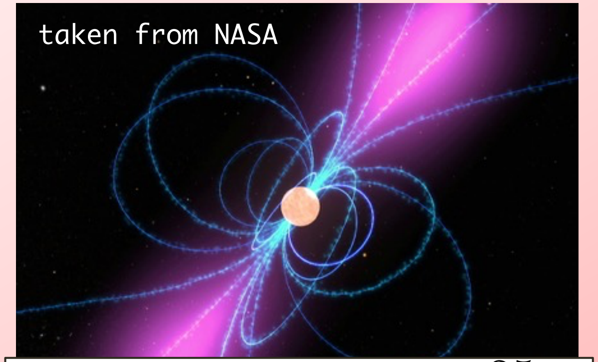
  - Double Compton scattering: photon splitting, redshift

$$\gamma + e \rightarrow 2\gamma + e$$

Induced Compton Scattering (ICS)

Interaction between rarefied plasma & bright radiation important in coherent radiation from PSR&FRB.

- Rarefied plasma ($\lambda < \lambda_D$, $\omega > \omega_{pe}$) e.g., Tanaka&Takahara13PTEP
  - Scattering of photons by an electron
  - Cross section is given by Klein-Nishina formula



$T_b(100\ \mathrm{MHz}) \gtrsim 10^{25} K$

Pulsed radio emission

- Bright radiation ($k_B T_b \gg m_e c^2$)
  - $k_B T_b(\nu) \equiv h\nu\, n_{ph}(\nu) \equiv E/(\Delta t \Delta \nu)$ ⇔ not the same as strength parameter
  - $n_{ph} > 2$ is possible for Boson ⇔ induced process rather than exclusion one! $n_{ph} \sim 10^{27}$ for pulsar!!

$T_b(100\ \mathrm{THz}) \gtrsim 10^{20} K$

Laser facilities

$$\frac{dn_{ph}(\nu)}{dt} \propto n_{ph}(\nu_+)(1 + n_{ph}(\nu)) - n_{ph}(\nu)(1 + n_{ph}(\nu_-))$$

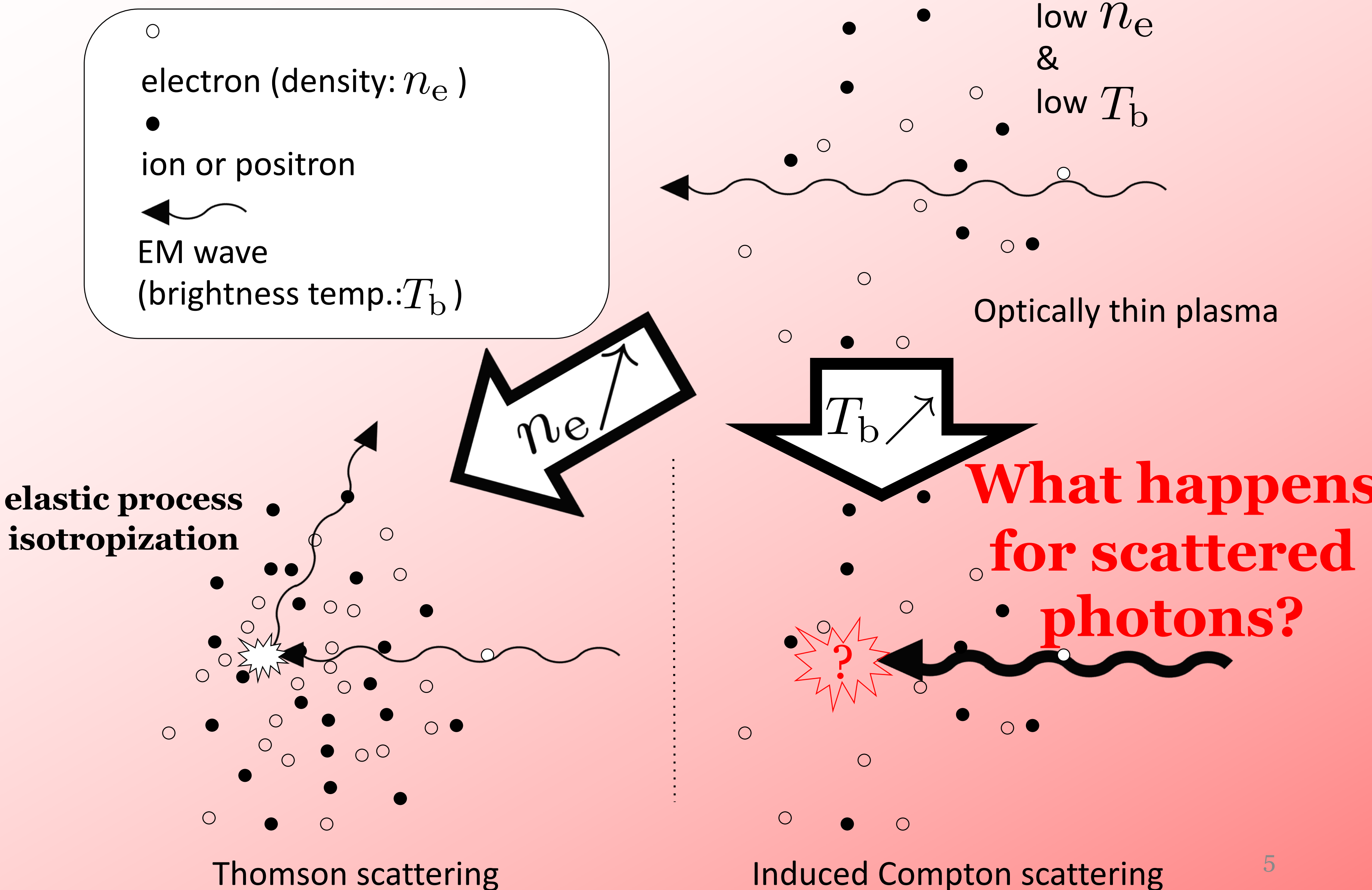
spontaneous + induced terms

$n_{ph}(\nu_+)$

$n_{ph}(\nu)$

$n_{ph}(\nu_-)$

Spontaneous vs. Induced



Description of ICS

Kinetic Equation for Photon

Compton scattering off photons $n_{\rm ph}(\boldsymbol{k})$ by plasmas $f(\boldsymbol{p})$.

$$\left(\frac{\partial}{\partial t} + c\boldsymbol{\Omega}\cdot\boldsymbol{\nabla}\right) n(\boldsymbol{k}) = c n_{\rm pl}\int d^3\boldsymbol{p} f(\boldsymbol{p}) \int d^3\boldsymbol{k}_1$$

$$\times \left[\sigma_{\rm KN}(\boldsymbol{k}_1,\boldsymbol{k},\boldsymbol{p}) n(\boldsymbol{k}_1)(1+\underline{n(\boldsymbol{k})}) - \sigma_{\rm KN}(\boldsymbol{k},\boldsymbol{k}_1,\boldsymbol{p}) n(\boldsymbol{k})(1+\underline{n(\boldsymbol{k}_1)})\right]$$

Boltzmann-Uehling-Uhlenbeck Equation

induced term

no isotropizaiton (Thomson)

$\tau_{\rm T} \approx \sigma_{\rm T} l n_{\rm pl}$

uniform + isotropic + 1st order in hν << $m_e c^2$, $k_B T_e$ << $m_e c^2$

Kompaneets 1957

$$\frac{\partial n(x)}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x} x^4 \left(n(x) + n^2(x) + \frac{\partial n(x)}{\partial x}\right)$$

$$x \equiv \frac{h\nu}{k_{\rm B} T_{\rm pl}},\ y \equiv \frac{k_{\rm B} T_{\rm pl}}{m_{\rm e} c^2} n_{\rm pl}\sigma_{\rm T} c t$$

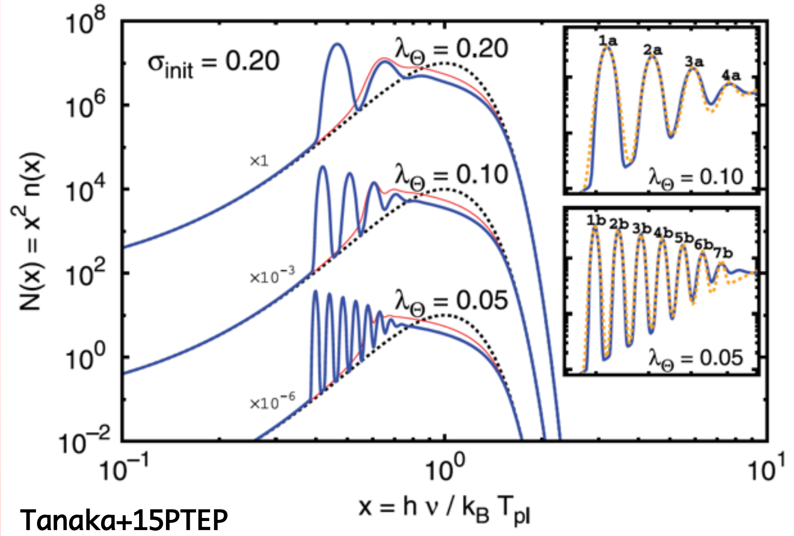
$\tau_{\rm Comp} \approx \tau_{\rm T}\frac{h\nu}{m_{\rm e}c^2}$ Compton recoil

inverse Compton $\tau_{\rm IC} \approx \tau_{\rm T}\frac{k_{\rm B}T_{\rm e}}{m_{\rm e}c^2} \approx y$

induced Compton recoil

$$\tau_{\rm ind} \approx \tau_{\rm Comp} n = \tau_{\rm T}\frac{k_{\rm B}T_{\rm b}(\nu)}{m_{\rm e}c^2}$$

The case for $n_{\rm ph} >> 1$



$$\frac{\partial n}{\partial y} \approx \frac{1}{x^2}\frac{\partial}{\partial x}x^4 n^2$$

$$\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} = 0$$

simple wave

no solution of *y* → ∞

2nd order

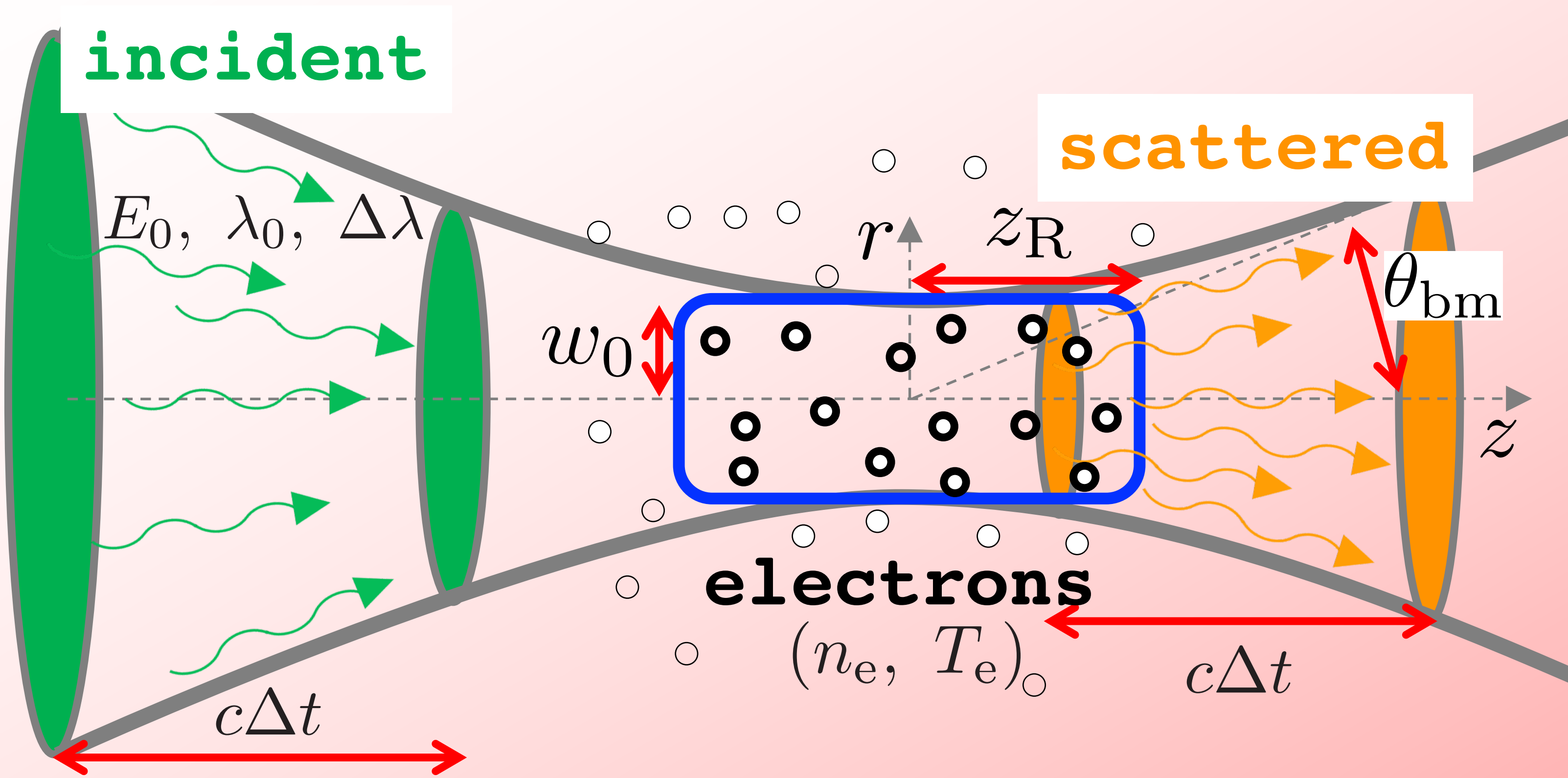
$$\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} + \frac{17\Theta}{5}g\frac{\partial}{\partial x}g = \frac{14\Theta}{5}(xg)\frac{\partial^3}{\partial x^3}(xg)$$

$$\frac{\partial g}{\partial y} - 2g\frac{\partial g}{\partial x} \approx \frac{14\Theta}{5}(xg)\frac{\partial^3}{\partial x^3}(xg)$$

order of $(h\nu)\Theta/(m_e c^2)^2$

$$x = \frac{h\nu}{k_{\rm B}T_{\rm e}},\quad \Theta = \frac{k_{\rm B}T_{\rm e}}{m_{\rm e}c^2},\quad g(x) = x^2 n(x)$$

Solitary structures in spectrum

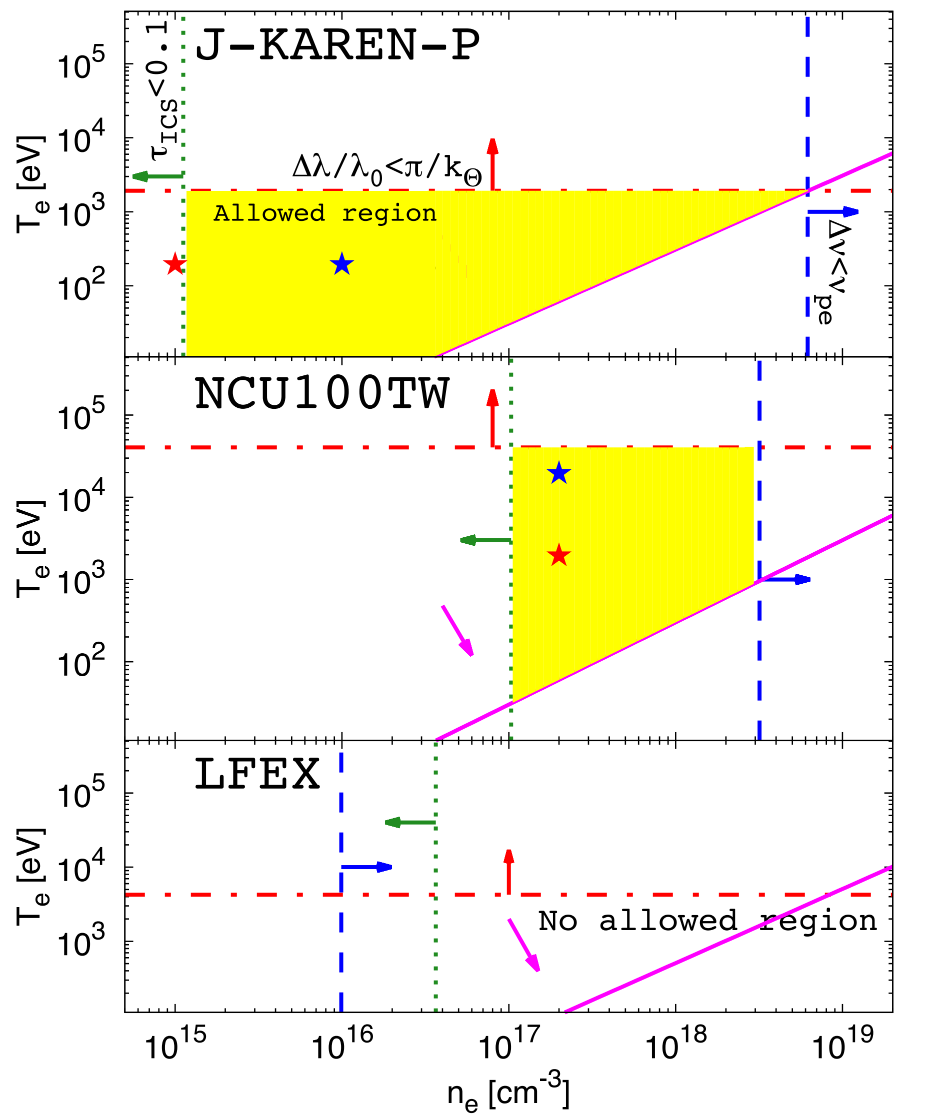


Predictions in Experiments

SJT, Yamazaki, Kuramitsu & Sakawa 2020, PTEP

Laser Facilities

Tanaka+20PTEP



Allowed plasma parameters are found in yellow region.

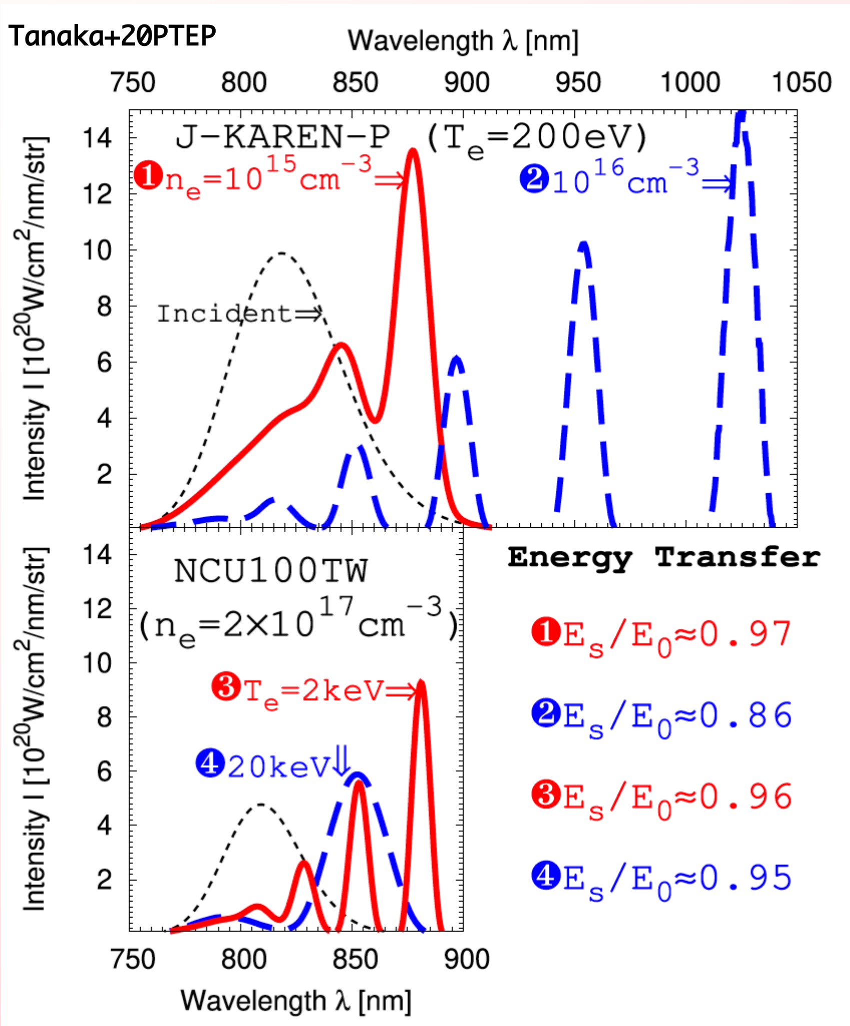
High-power short pulse laser is favored for ICS experiments rather than high (total) energy laser.

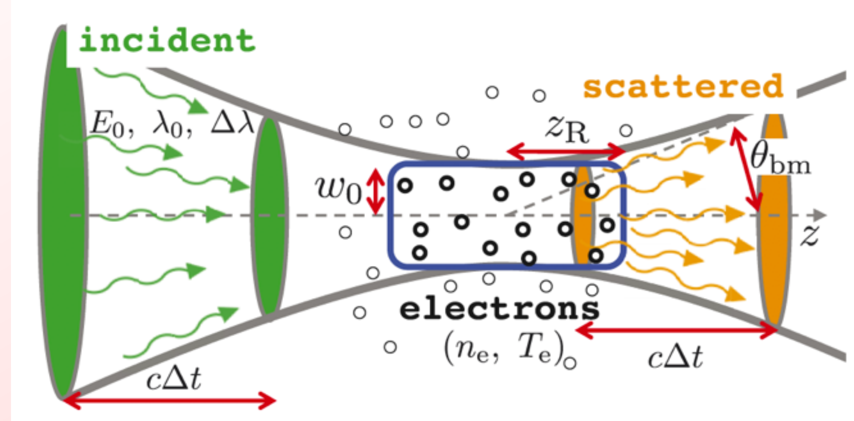
We can draw the same plot for other facilities of the given parameters!

- E: total energy
- Δt: pulse width
- $\Delta \nu$: band width
- w_o: minimum waist
- λ: central wavelength

Predictions

Spectra of transmitted (scattered) light



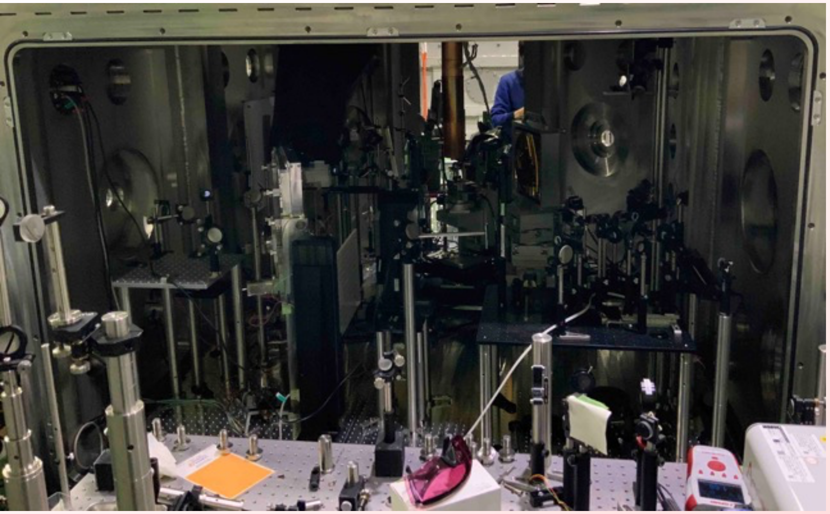


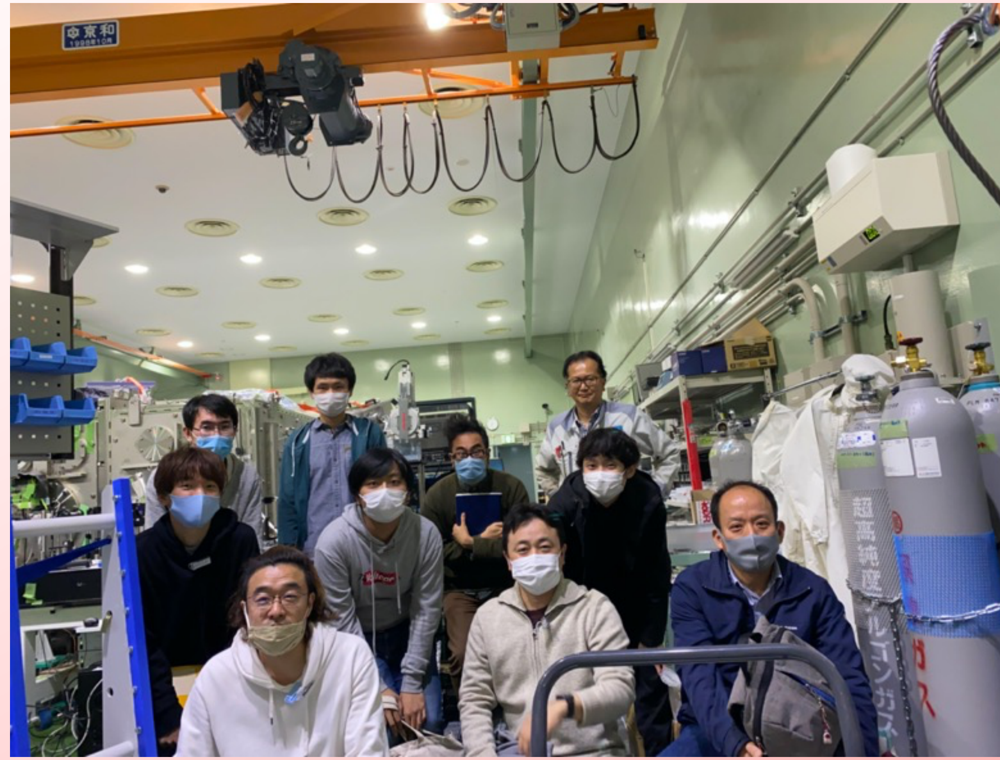
Parameter	J-KAREN-P	NCU100TW	LFEX
E_0 [J]	10	3.3	400
λ_0 [nm]	820	810	1053
$\Delta\lambda$ [nm]	50	35	3.3
Δt [fs]	30	30	1500
w_0 [μm]	0.67	4.3	50
$k_B T_b/m_e c^2$	1.8×10^{14}	8.4×10^{13}	3.6×10^{15}
$\Delta\lambda/\lambda_0$	6.1×10^{-2}	4.3×10^{-2}	3.1×10^{-3}
θ_{bm}	3.9×10^{-1}	6.0×10^{-2}	1.3×10^{-2}
z_R [μm]	1.7	72	1.9×10^3
τ_{ICS}/n_e [cm^3]	9.0×10^{-17}	9.7×10^{-19}	2.7×10^{-18}
$\tau_D/(n_e\Theta)$ [cm^3]	9.0×10^{-18}	2.3×10^{-21}	3.3×10^{-22}
τ_{Th}/n_e[cm^3]	2.3×10^{-28}	9.5×10^{-27}	2.5×10^{-25}

Only $\pi w_0^2\, 2z_R\, n_e \sim 10^4$ electrons at Rayleigh region

They would attain ~ PeV which is rad. reaction limited

$$\frac{dE}{dx} \approx \frac{3}{2}\frac{m_e c^2}{r_e} \approx 2 \times 10^{14}\ \mathrm{MeV/m} = 0.2\ \mathrm{PeV}/\mu\mathrm{m}$$

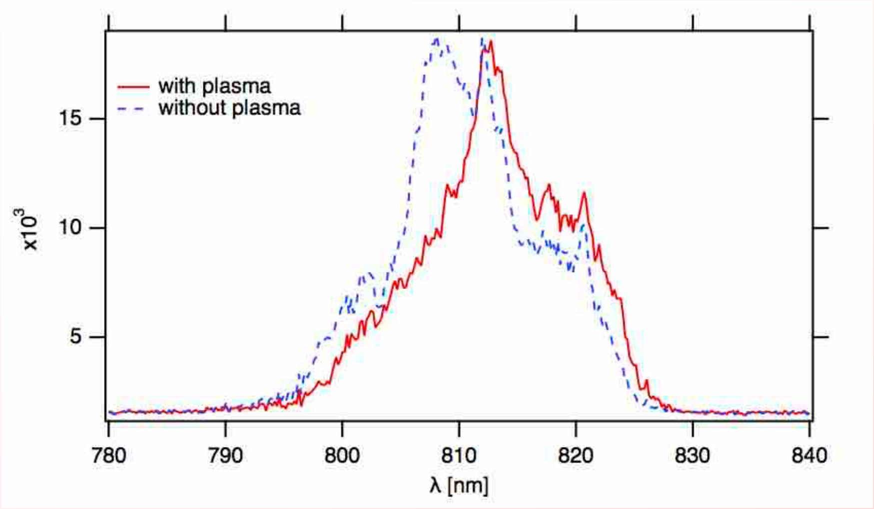


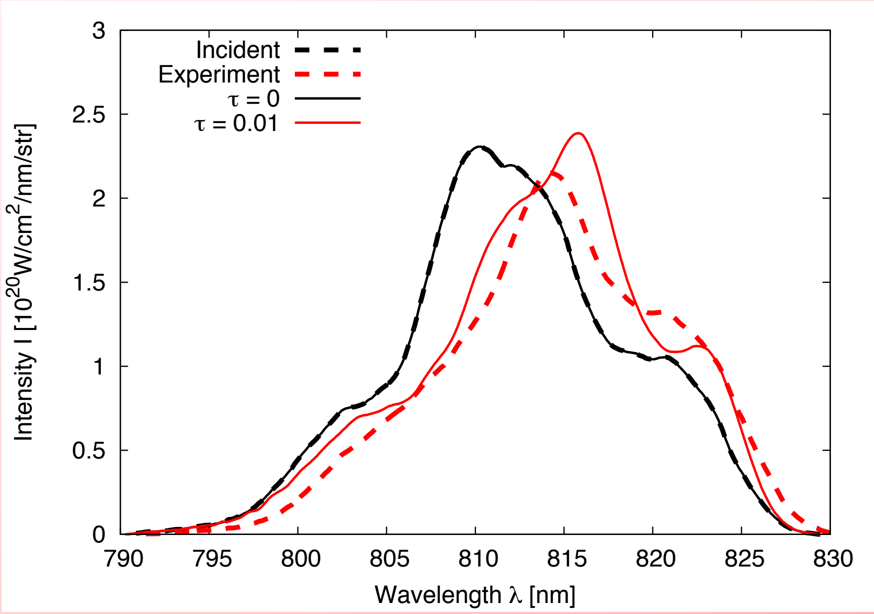


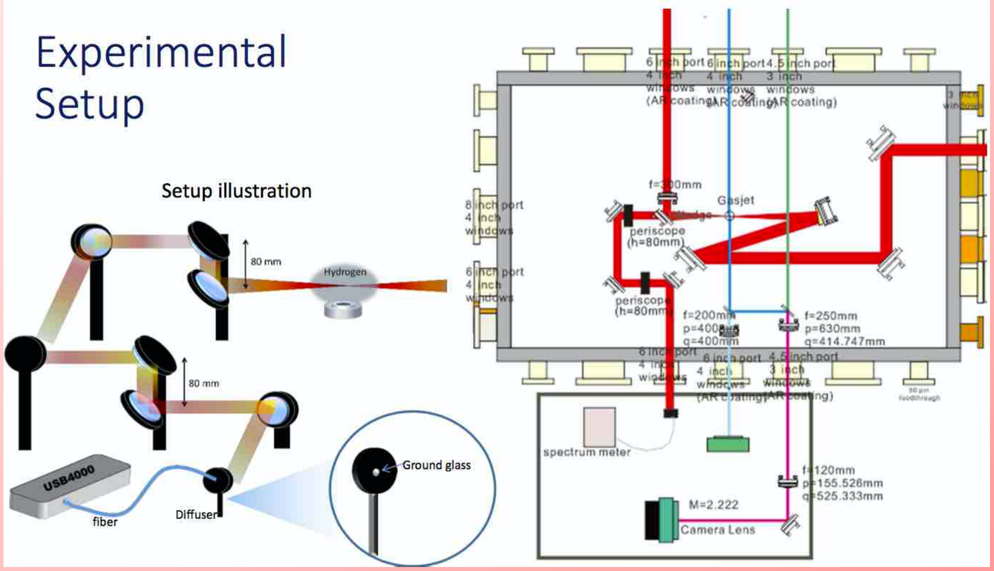
J-KAREN Experiment
2020/12/2, 3

Initial Experiment

July 2017, National Central University @ Taiwan



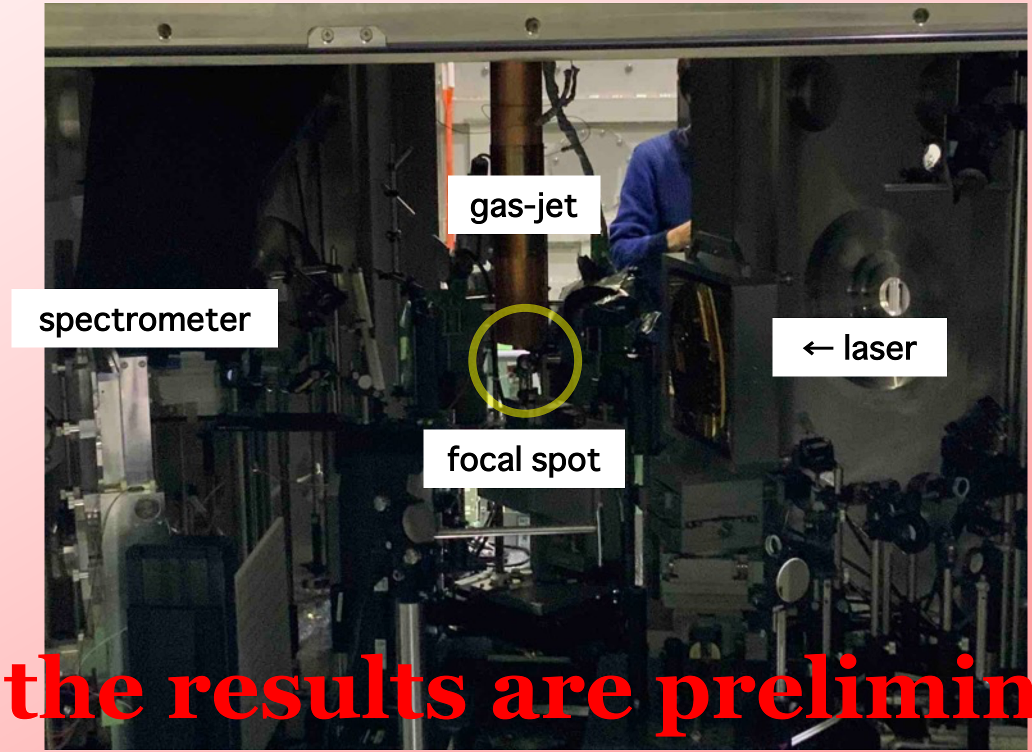




Produced by Kuramitsu-san

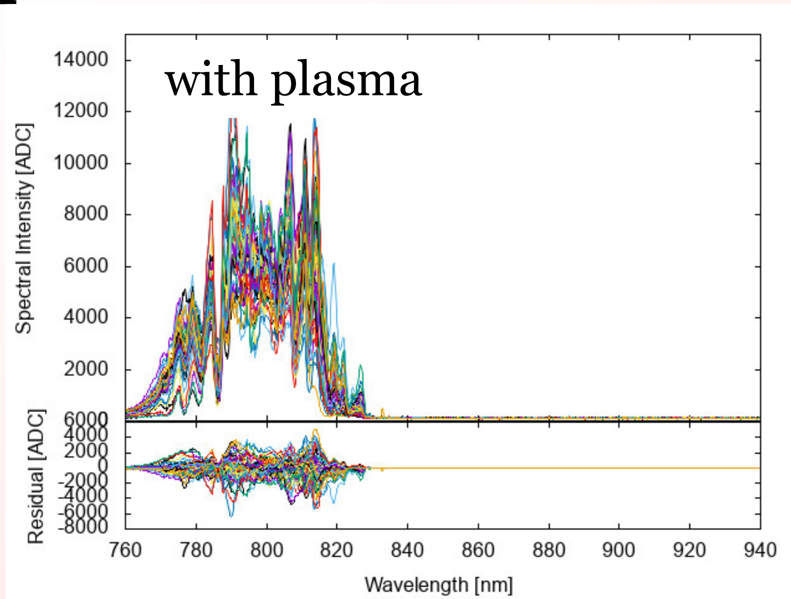
J-KAREN experiment

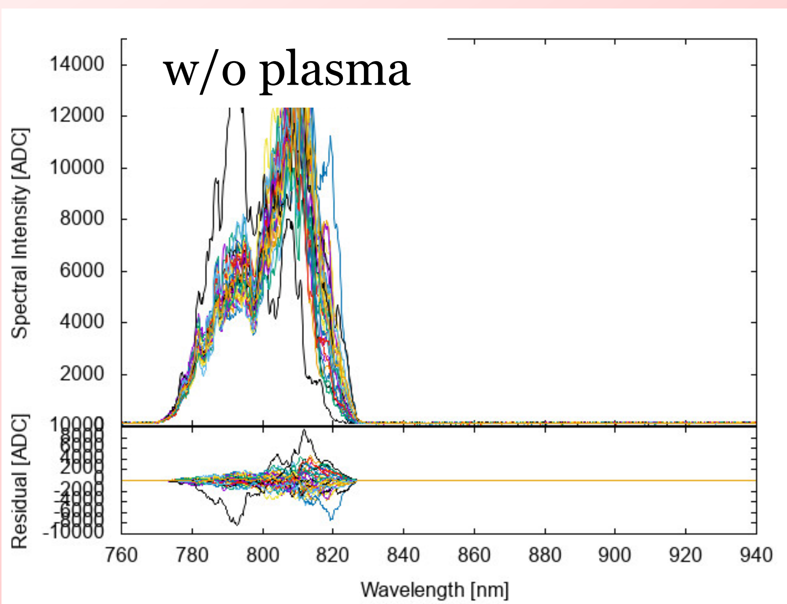
- What do we try to observe?
  - spectrum of scattered light (redshifted compared with incident one)
  - no side- & back-scattering, no change of polarization
  - dependence on electron density (optical depth)
  - dependence on electron temperature
  - acceleration of electrons (radiation reaction limited)

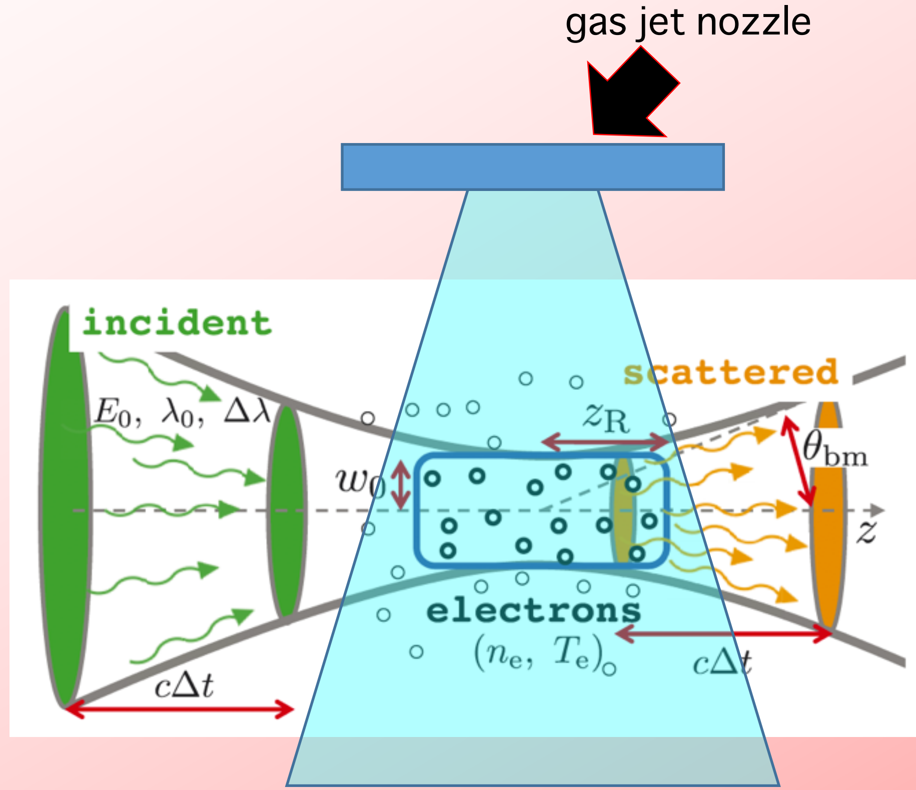


all the results are preliminary

Spectrometer

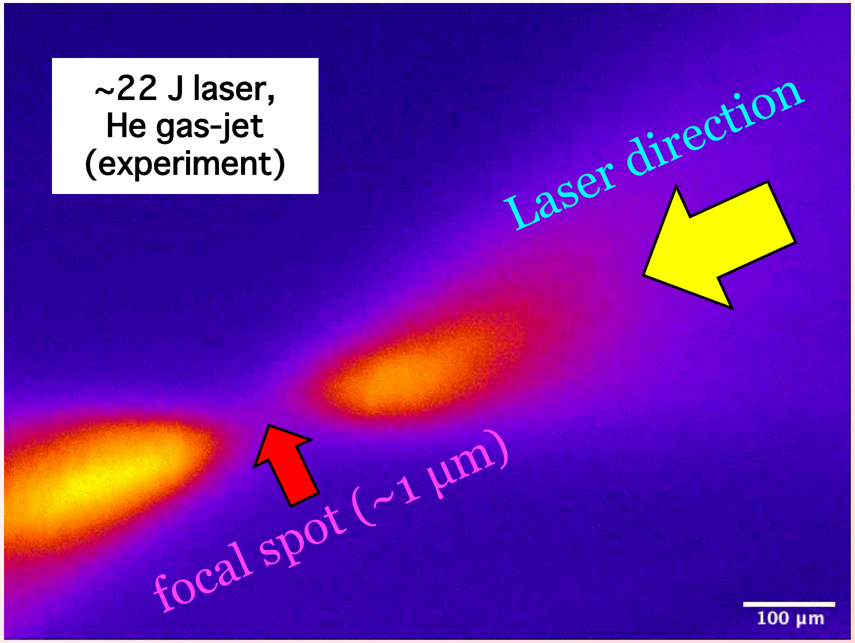


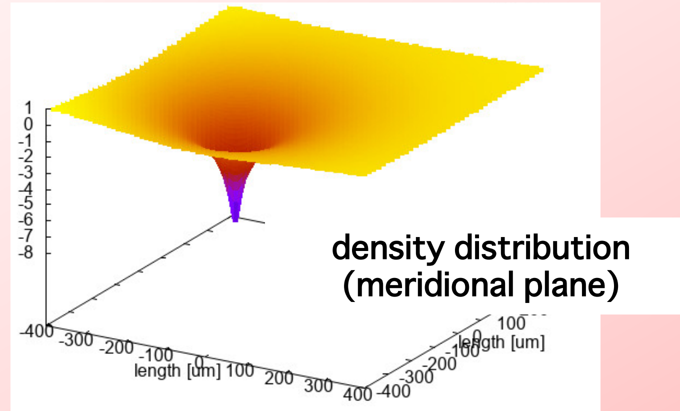


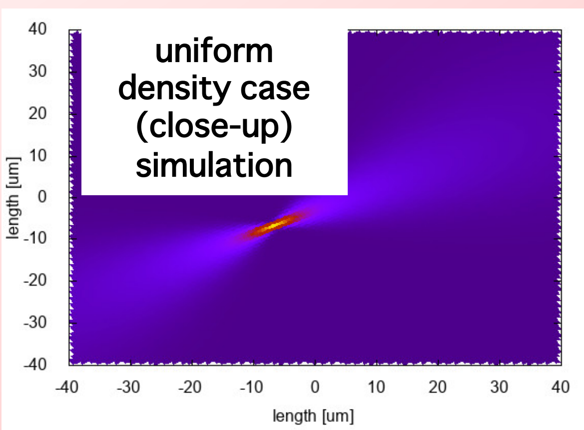


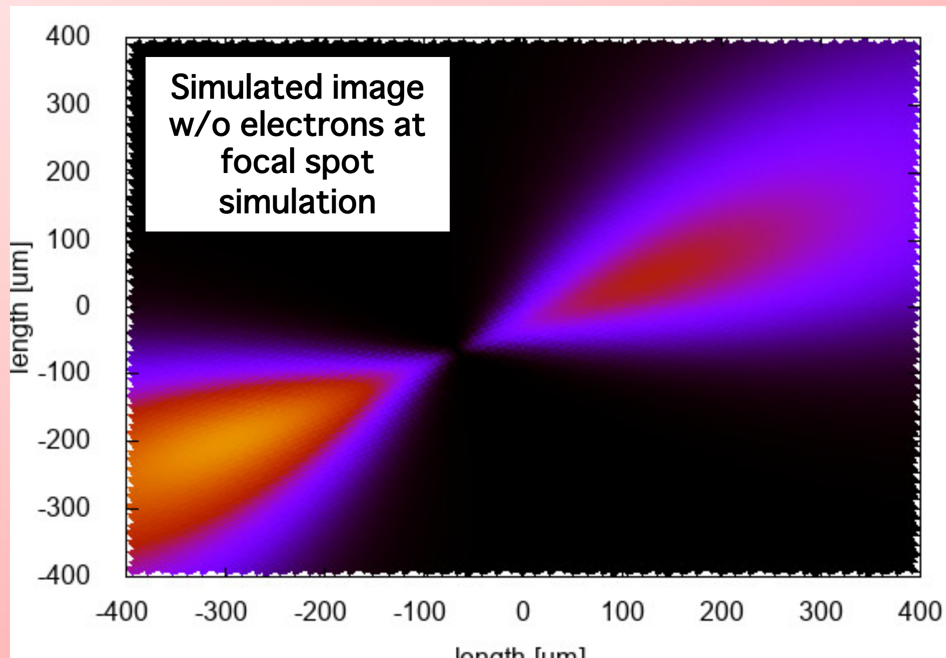
- no redshifted structures found
- scattered and incident spectra are not stable
- analyses on density and laser intensity dependences are on progress.

Imaging (Thomson scattering)









no electron at focal spot?

Summary

- We conducted the laboratory astrophysics experiment of ICS at J-KAREN P laser at KPSI, QST, Japan at Dec. 2020
- ICS signatures can be observed by the recent laser facility.
- Spectrometer: we still do not find the spectral redshift in observed spectra.
- Imaging (Thomson scattering): observed images are consistent with no electron at the focal spot (blown off by radiation pressure?)
- Further experiments are required in order to understand ICS => different experimental set-up? different laser facility (e.g. ELI)?

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