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Highly spin-polarized multi-GeV sub-femtosecond electron beams generated from single-species plasma photocathodes

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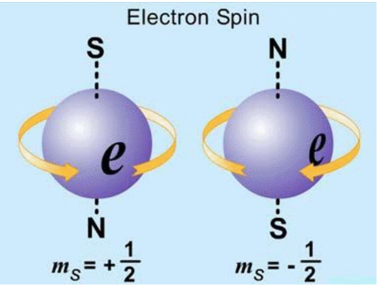
Outline

- Background
- Conventional spin-polarized electron sources
- Our schemes based on ionization injection in a PWFA
  - Xenon + Lithium (SP ~ 31%)
  - Ytterbium (SP ~ 56%)
- Summary

Background

- Spin-polarized electrons are important in high-energy physics
    - colliders
    - parity violation measurement
    - new physics beyond the standard model



- Plasma-based accelerators can shrink the size and cost of future colliders
- **However, there is still no feasible way to generate spin-polarized electrons *in situ* from plasma-based accelerators**

D. Abbott et al. (PEPPo Collaboration), Phys. Rev. Lett. 116, 214801 (2016).

P. L. Anthony et al. (SLAC E158 Collaboration), Phys. Rev. Lett. 92, 181602 (2004).

G. Moortgat-Pick, et.al, Physics Reports 460, 131–243 (2008)

Conventional spin-polarized electron sources

- Self-polarization via Sokolov-Ternov effect
- Photoionization of state selected alkali atoms
- Photoionization: Fano effect
- Electron scattering (Mott)
- Optically pumped He discharge
- Field emission from EuS
- **Photoemission from GaAs**

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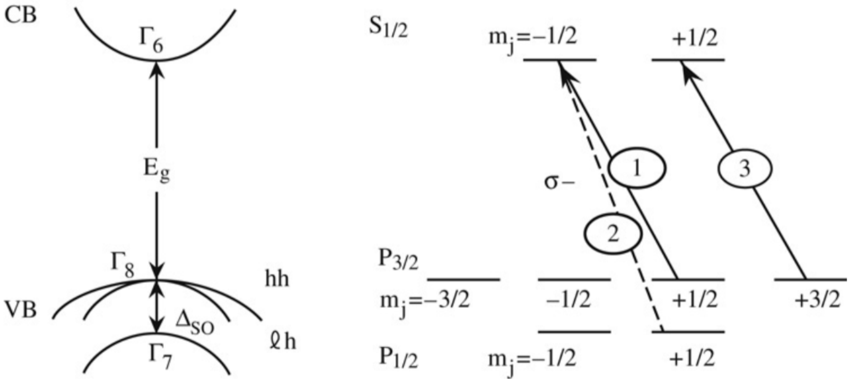
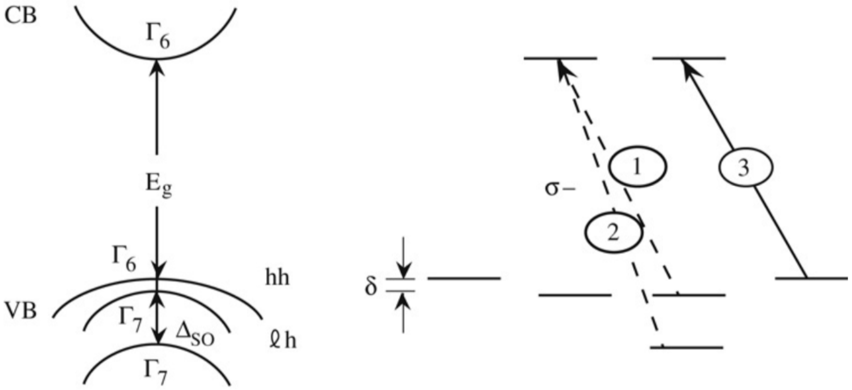
None of them can be directly incorporated into plasma-based accelerators

Photoemission from GaAs

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



(a) GaAs.



(b) GaAsP/GaAs strained-layer.

$P_{max} \sim 50\%$

$P_{max} \sim 100\%$

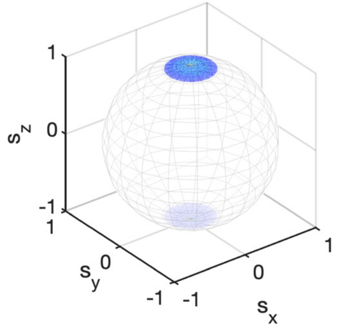
G. Moortgat-Pick, et.al, Physics Reports 460, 131–243 (2008)

Our first scheme: Lithium (5.4 eV) + Xenon (12.1 eV)

- Spin-dependent strong-field ionization by CP lasers (not frequency-sensitive)
- Trapping and acceleration in PWFA

P=32.0%

P=30.7%



Spin selectivity of p-orbitals

$$Xe = [Kr]4d^{10}5s^2\boxed{5p^6}$$

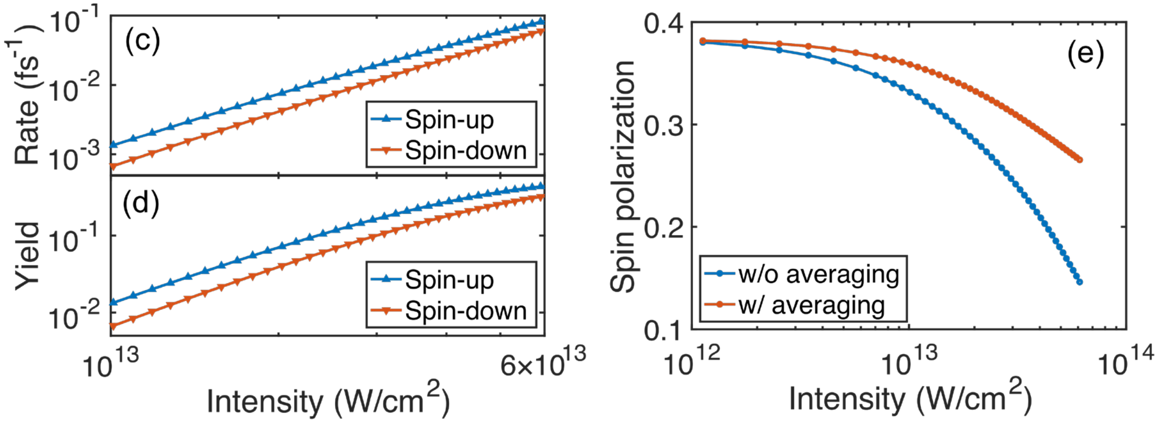
$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$\boxed{\begin{aligned} W_\uparrow &= W_{\frac{3}{2}p^+} + \frac{2}{3}W_{\frac{1}{2}p^-} + \frac{1}{3}W_{\frac{3}{2}p^-} \\ W_\downarrow &= W_{\frac{3}{2}p^-} + \frac{2}{3}W_{\frac{1}{2}p^+} + \frac{1}{3}W_{\frac{3}{2}p^+} \end{aligned}}$$

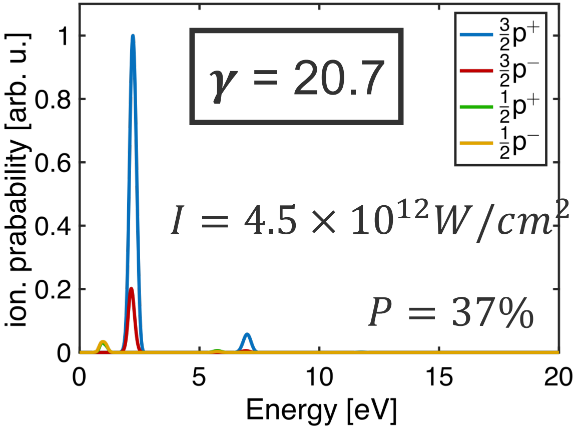
$$P_{max} \simeq \frac{3-1}{3+1} = 50\%$$

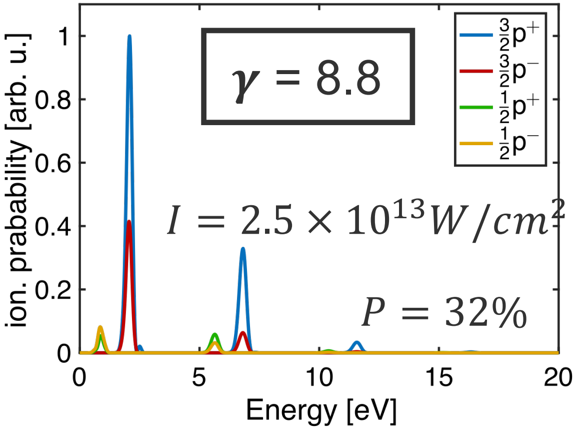
I. Barth, et al., Phys. Rev. A. 87, 013433 (2013)

TDSE results in multi-photon regime (260 nm)

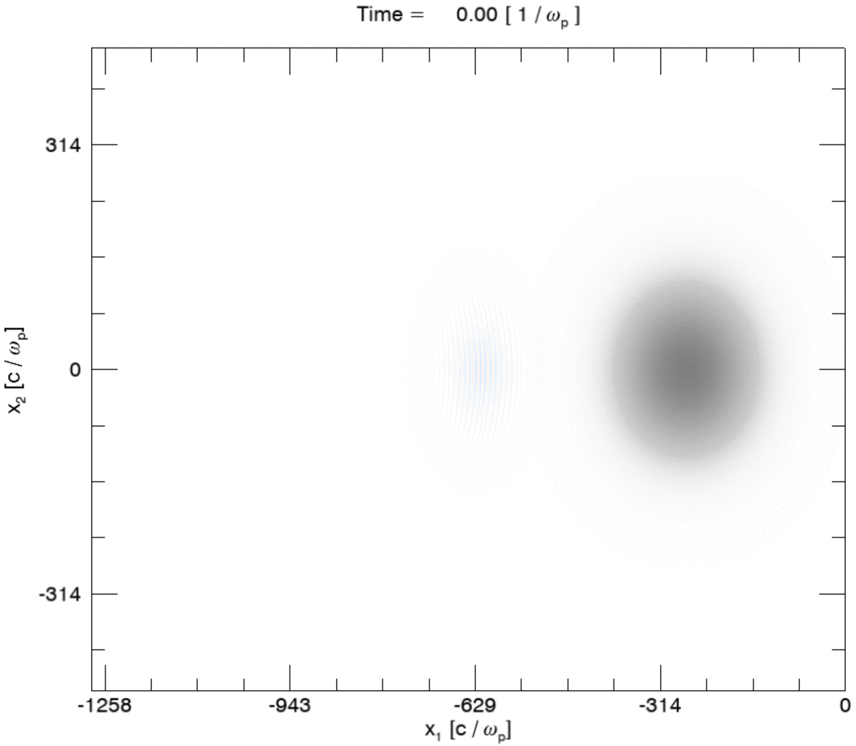


Z. Nie, et al., PRL 126, 054801 (2021)





Evolution of injected electrons



Li density	8.7×10^{16} cm^{-3}	**Laser polarization**	Circular
Xe density	8.7×10^{17} cm^{-3}	**Wavelength**	260 nm
Drive beam energy	10 GeV	**Peak a_0**	7.8×10^{-4}
Drive beam charge	658 pC	**Peak intensity**	2.5×10^{13} W/cm^2
Drive beam σ_r	11.4 μm	**Spot size w_0**	1.5 μm
Drive beam σ_z	11.4 μm	**Pulse duration**	30 fs

Evolution of injected electrons

Z. Nie, et al., PRL 126, 054801 (2021)

OSIRIS **QPAD**

$Q = 3pC$

$I_{peak} = 0.8kA$

$\epsilon_n = 36.6nm$

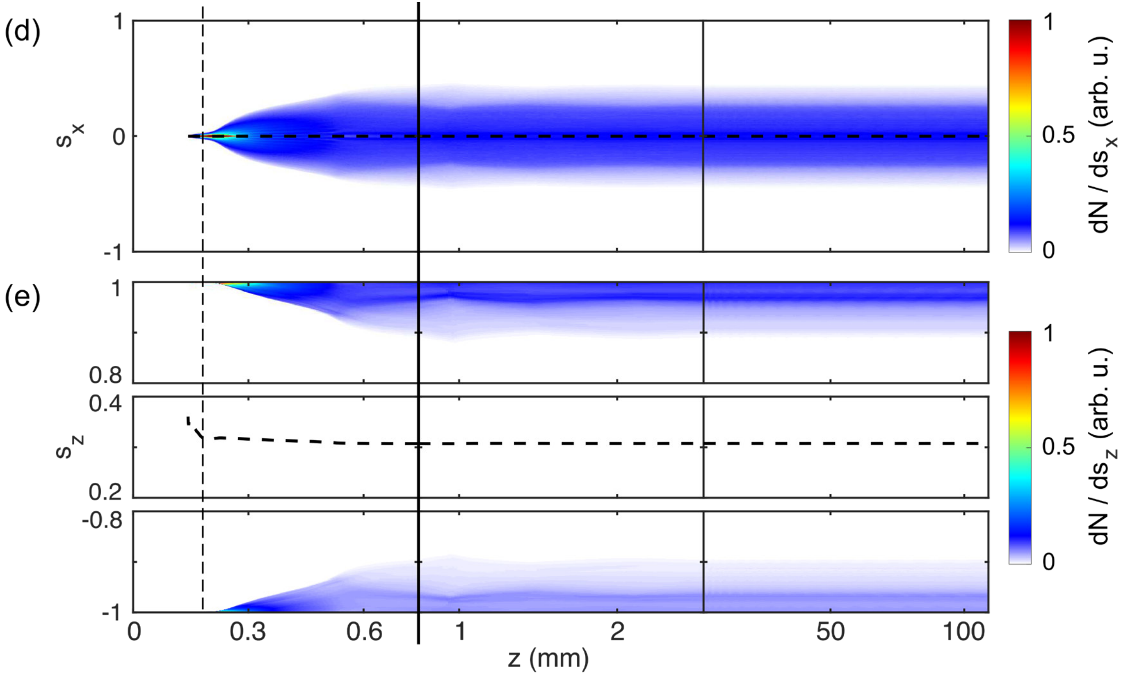
$\langle\gamma_b\rangle = 2.7GeV$

0 0.3 0.6 | 1 2 50 100

z (mm)

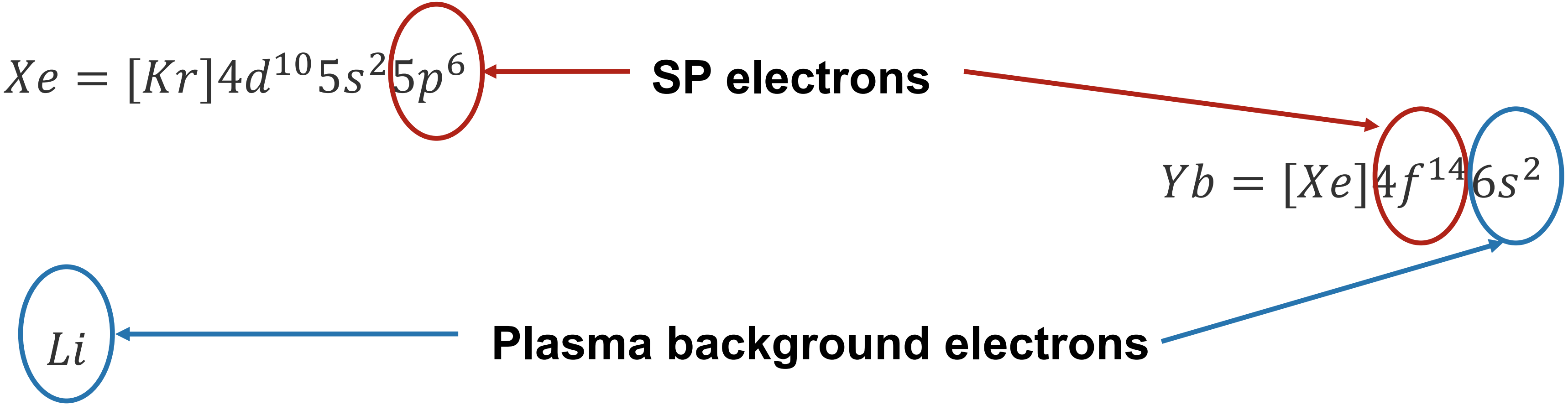
OSIRIS **QPAD**

Z. Nie, et al., PRL 126, 054801 (2021)



$$P = \langle s_z \rangle = 30.7\%$$

Our second scheme:
using Yb instead of Xe + Li



$Xe = [Kr]4d^{10}5s^{2}5p^{6}$

SP electrons

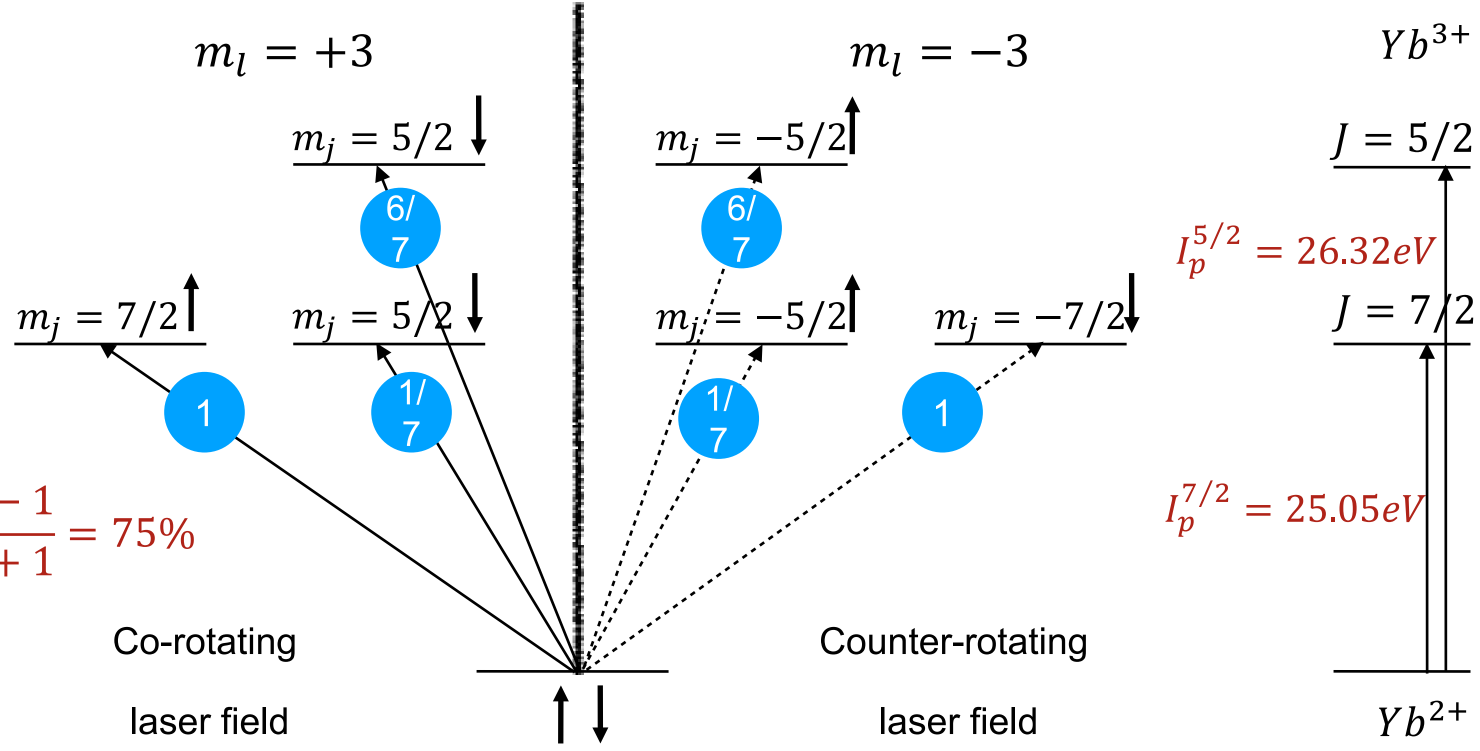
$Yb = [Xe]4f^{14}6s^{2}$

Li

Plasma background electrons

Spin selectivity of f-orbitals

$Yb = [Xe]4f^{14}6s^2$



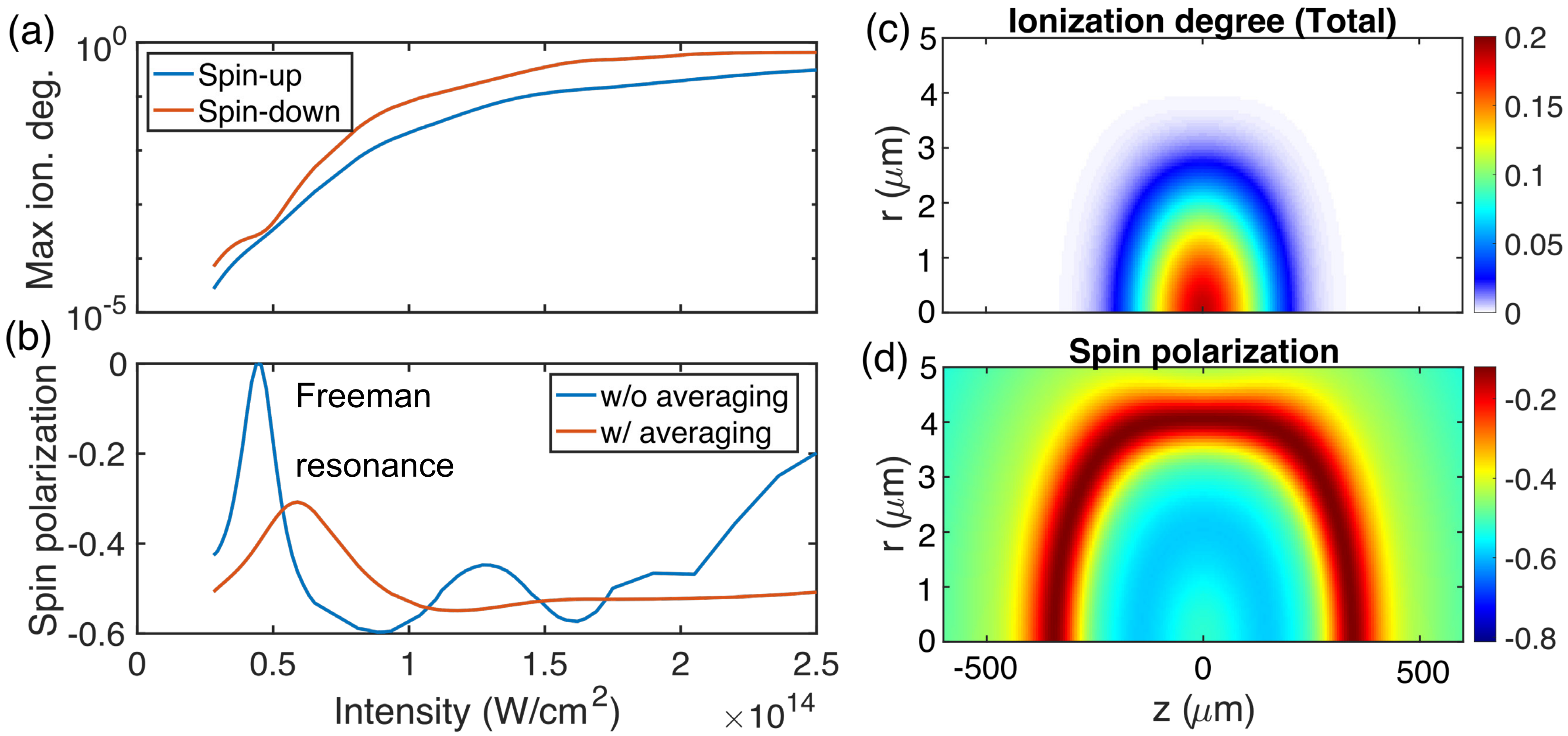
$$P_{max} \simeq \frac{7-1}{7+1} = 75\%$$

J. Kaushal and O. Smirnova, J. Phys. B **51**, 174001 (2018)

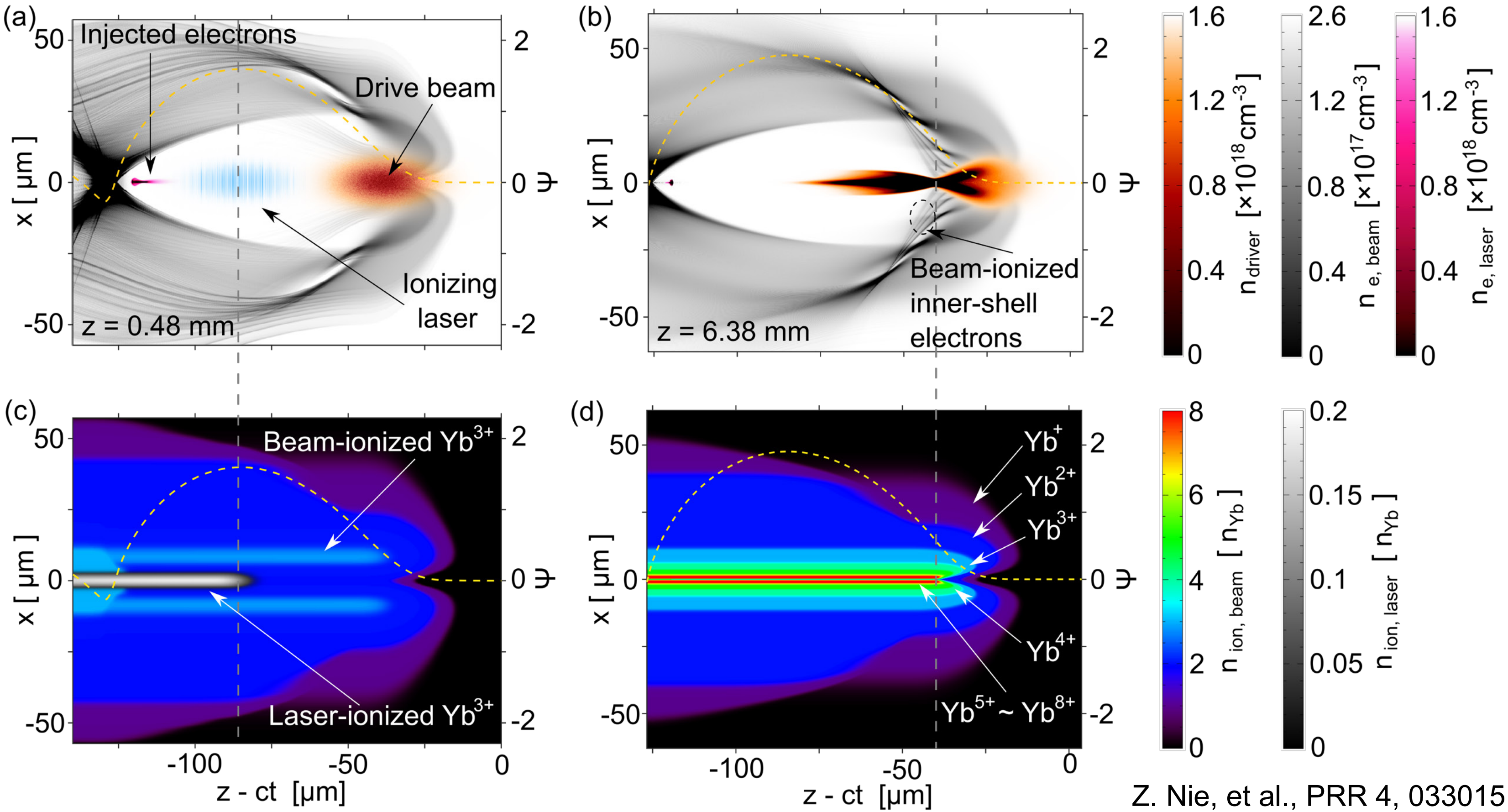
J. Kaushal and O. Smirnova, J. Phys. B **51**, 174003 (2018)

W. C. Martin, R. Zalubas, and L. Hagan, Atomic Energy Levels - the Rare-Earth Elements : (Gaithersburg, MD, 1978).

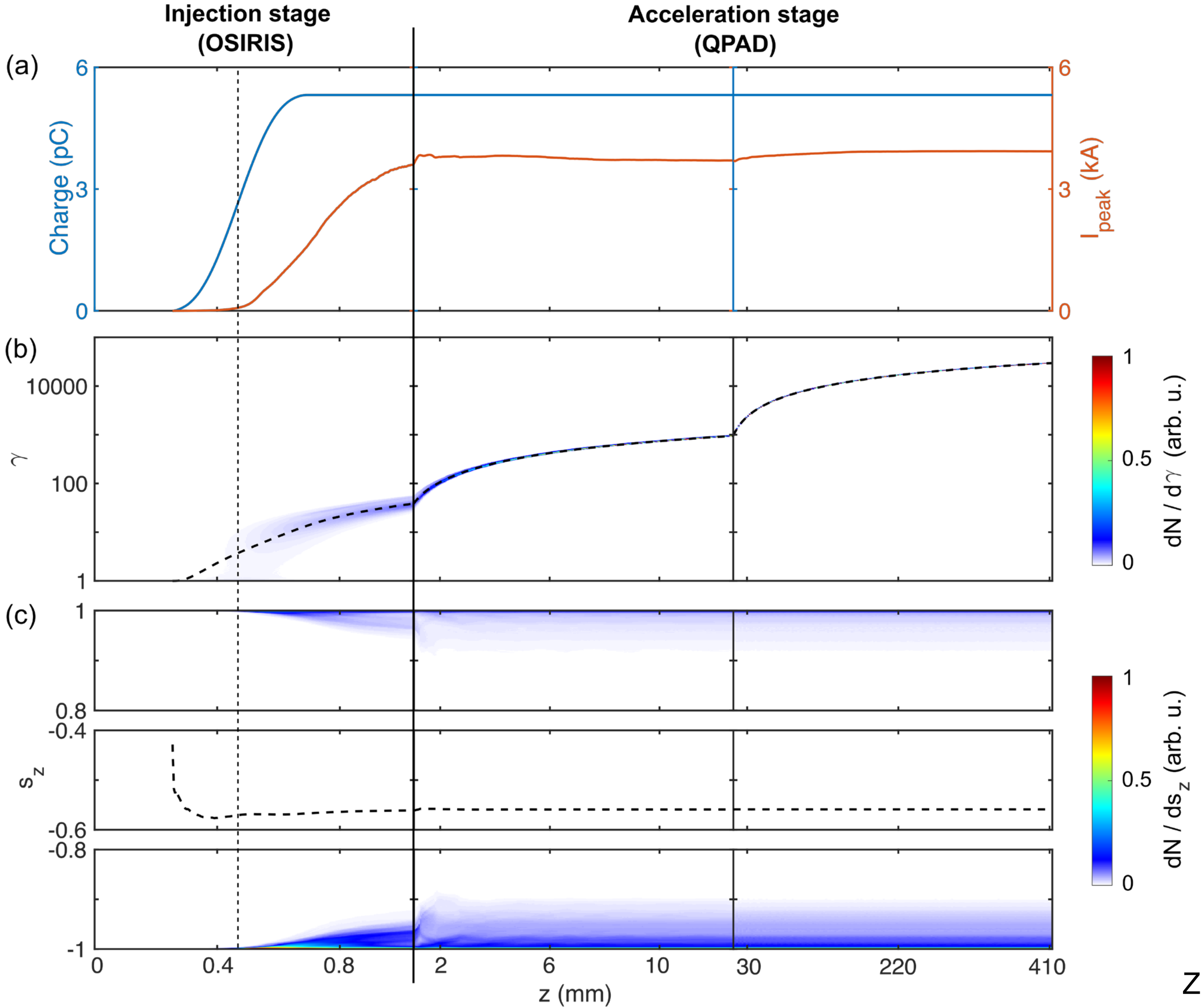
Spin polarization of Yb III



Two snapshots of PIC simulations



Z. Nie, et al., PRR 4, 033015 (2022)



$$P = \langle s_z \rangle = 56\%$$

$$E = 15GeV$$

$$Q = 5.3pC$$

$$I_{peak} = 4kA$$

$$\epsilon_n = 180nm$$

Z. Nie, et al., PRR 4, 033015 (2022)

Summary

- We proposed a new scheme to generate high-energy, low-emittance, high-peak-current, spin-polarized electrons *in situ* by spin-dependent photoionization injection in a PWFA

- We verified such a scheme by TDSE/PIC simulations

- High degree of spin-polarization (56%) is obtained by ionizing f-orbital electrons of Yb