Two-color ionization injection experiment using a CO_2 laser-plasma accelerator at ATF II

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Outline

- Concept of two-color ionization injection: <100 nm normalized transverse emittance
- Example of two-color ionization injection using CO_2 drive laser and $Ti:Al_2O_3$ ionization laser
- Technical/practical considerations: parameter sensitivity
- Prospects for a compact sub-100 nm emittance diagnostic

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Two-Color Laser-Ionization Injection

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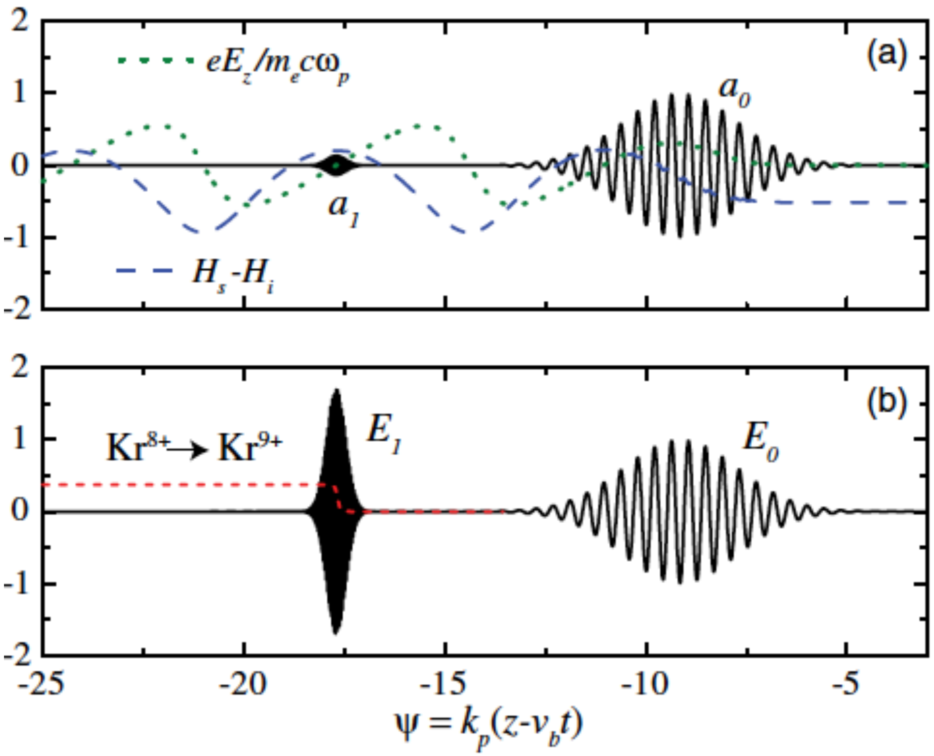


- Laser field: $E = (2\pi m_e c^2/e)\dfrac{a}{\lambda}$
- Ponderomotive force:

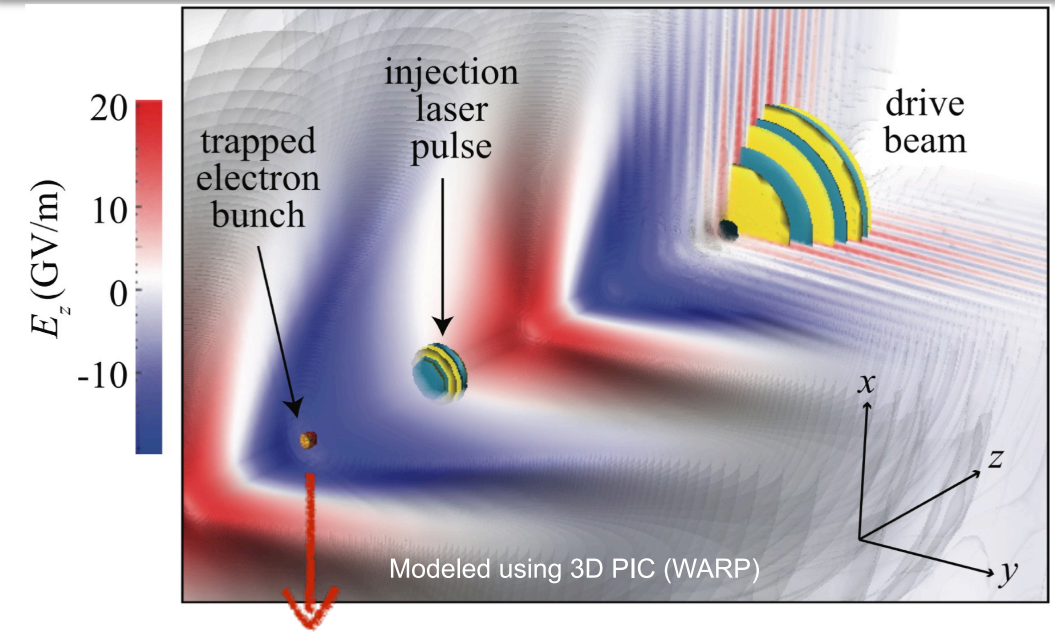
$$F_{\mathrm{PMF}} = m_e c^2 \nabla a^2/2$$

- Ionization rate:

$$w \propto \frac{E_a}{E}\exp\left[-\frac{2}{3}\frac{E_a}{E}\left(\frac{U_{\mathrm{ion}}}{U_{\mathrm{H}}}\right)^{3/2}\right]$$

L.-L. Yu, E. Esarey, et al., SPIE Conf. Proc. (2013)
L.-L.Yu et al., PRL (2014)
Xu et al., PRST-AB (2014)
C. Schroeder et al., PRST-AB (2014)
C. Schroeder et al., SPIE Conf. Proc. (2015)

2-color ionization injection generates beams with ultra-low (tens of nm) transverse emittance

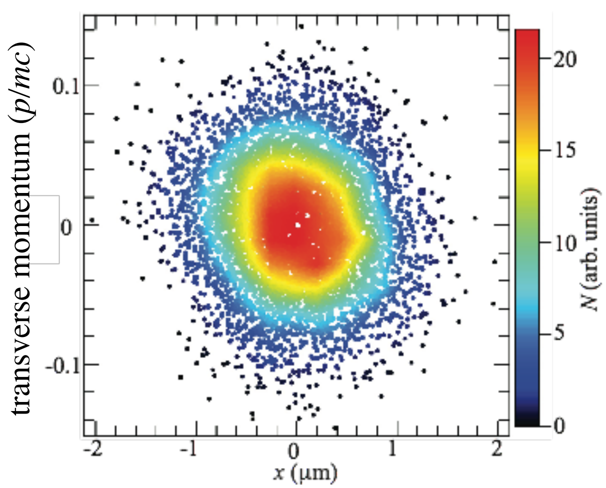


Pump laser pulse (circular-polarization):
a=1.2, 5 um wavelength
92 fs (rms), 36 um spot

Injection laser pulse (linear-polarization):
a=0.1, 0.4 um wavelength
16 fs (rms), 5 um spot

plasma:
Krypton gas, 2x10^{17} cm^{-3}

20 nm emittance



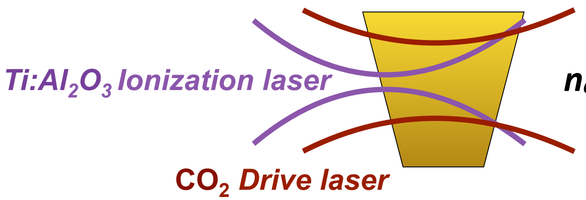
C. Schroeder et al., Phys. Rev. ST Accel. Beams. ***17****, 101301(2014)*

$$\epsilon_n = k_{\beta 0} w_i^2 \left[1 + \frac{2a_i^2}{(k_{\beta 0} w_i)^2}\right] \frac{a_i}{\lambda_i} \left(\frac{3\pi r_e}{4\alpha^4}\right) \left(\frac{U_H}{U_i}\right)^{3/2} = 20 \text{ nm}$$

- Ultra-low (tens of nm) emittance achievable using two-color ionization injection

2-color ionization injection: CO_2 drive laser

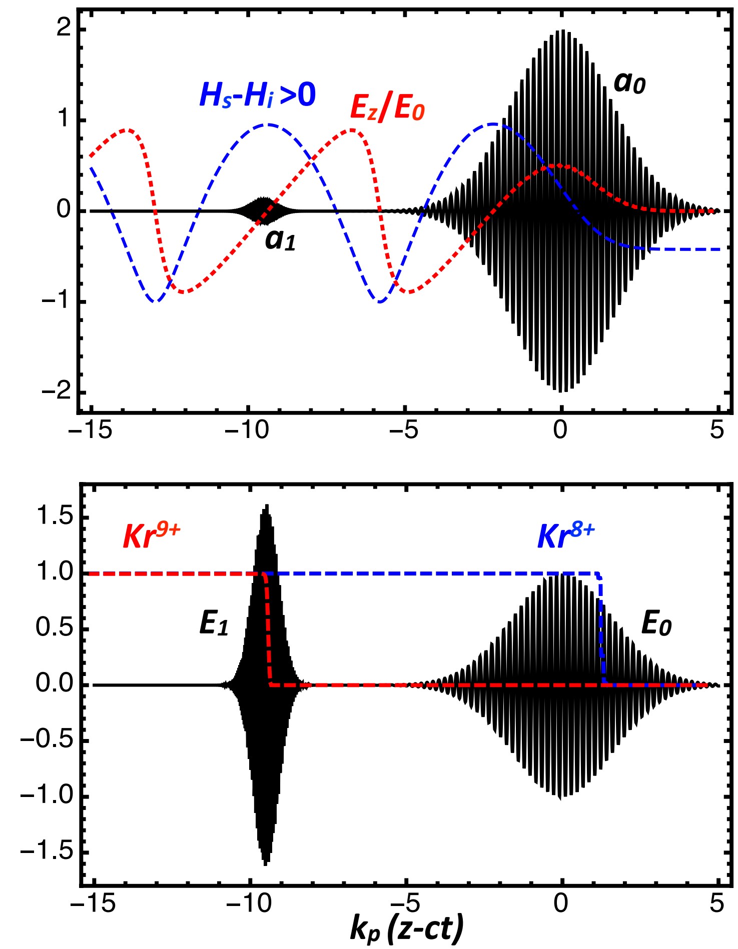
Gas jet: (L~0.5--1 cm) Krypton $n_g = 1.25 \times 10^{15}$ cm^{-3}



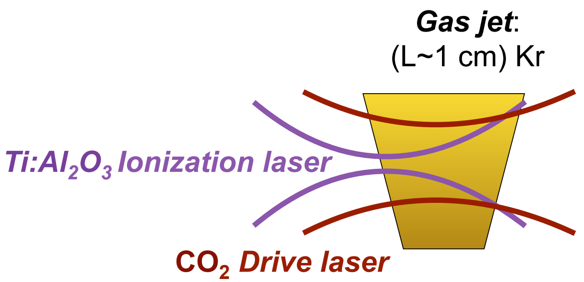
CO_2 pump laser pulse:
a_0=2
10 um wavelength
470 fs (FWHM intensity)
155 um spot (ZR = 7.5 mm)
P=20 TW (P/Pc=1) (linear polarization)
10 J

Soon to be available at BNL - ATF-II
[I Pogorelsky and I. Ben-Zvi, PPCF (2014)]

$Ti:Al_2O_3$ (frequency-doubled)injection laser pulse:
a_1=0.13
0.4 um wavelength
118 fs (FWHM intensity)
20 um spot (ZR = 3 mm)
114 mJ
delay= 1.6 ps



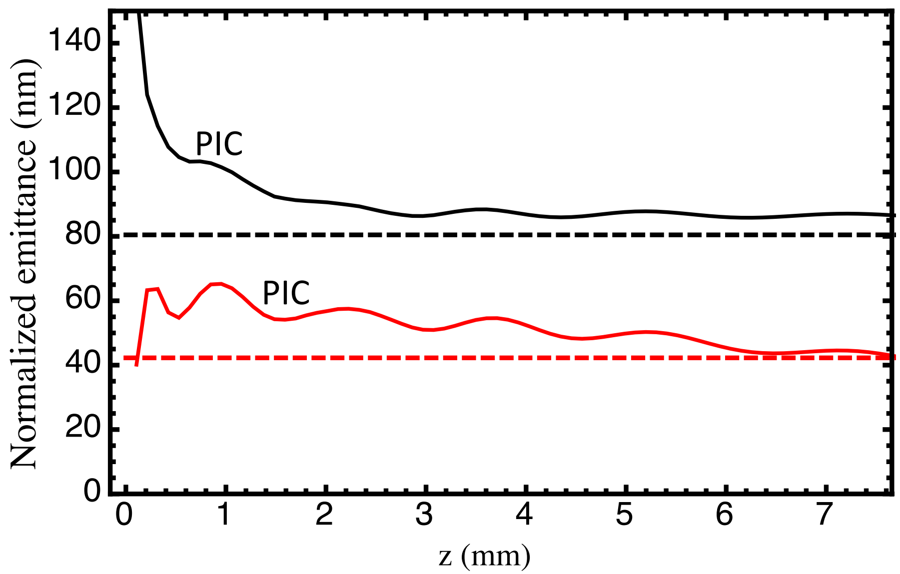
2-color ionization injection: CO_2 drive laser



$n_e = 10^{16}$ cm^{-3}

CO_2 pump laser pulse:
a_0=2
10 um wavelength
470 fs (FWHM intensity)
155 um spot (ZR = 7.5 mm)
10 J

frequency-doubled Ti:Al_2O_3 injection pulse:
a_1=0.13
0.4 um wavelength
118 fs (FWHM intensity)
20 um spot (ZR = 3 mm)
114 mJ



final emittance in laser polarization plane (~ thermal emittance):

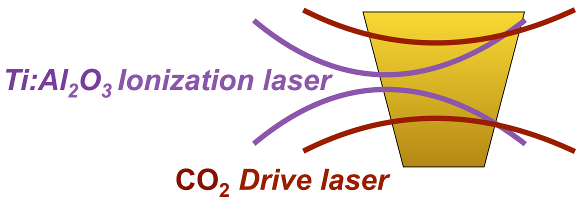
$$\epsilon_{\parallel} = \left[1 + \left(\frac{2a_i}{k_p w_i}\right)^2\right] \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2$$

= 80 nm

final emittance out of laser polarization plane:

$$\epsilon_{\perp} = \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2$$ = 42 nm

2-color ionization injection: CO_2 drive laser



$n_e = 10^{16}$ cm^{-3}

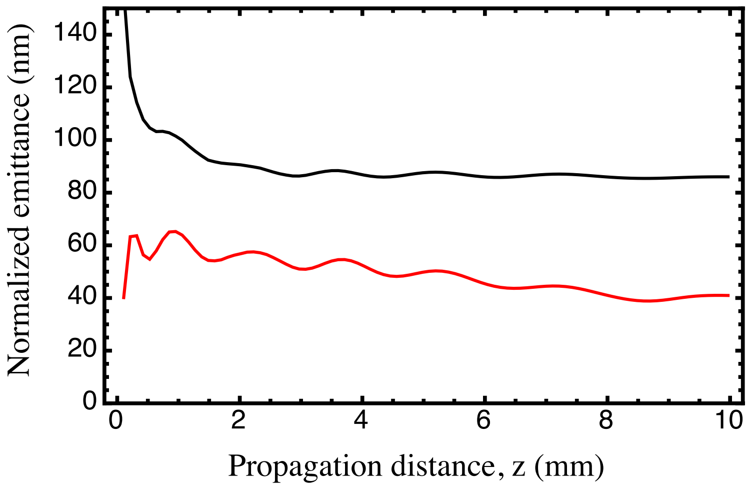
CO_2 pump laser pulse:

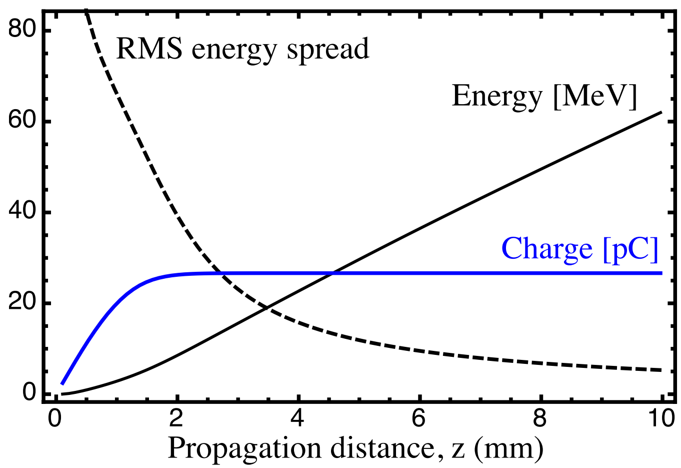
a_0=2
10 um wavelength
470 fs (FWHM intensity)
155 um spot (ZR = 7.5 mm)
P=20 TW (P/Pc=1) (linear polarization)
10 J

Ti:Al_2O_3 (frequency-doubled)injection laser pulse:

a_1=0.13
0.4 um wavelength
118 fs (FWHM intensity)
20 um spot (ZR = 3 mm)
114 mJ
delay= 1.6 ps

PIC simulation





27 pC
62 MeV
5% (rms)
σ_z =0.97μm

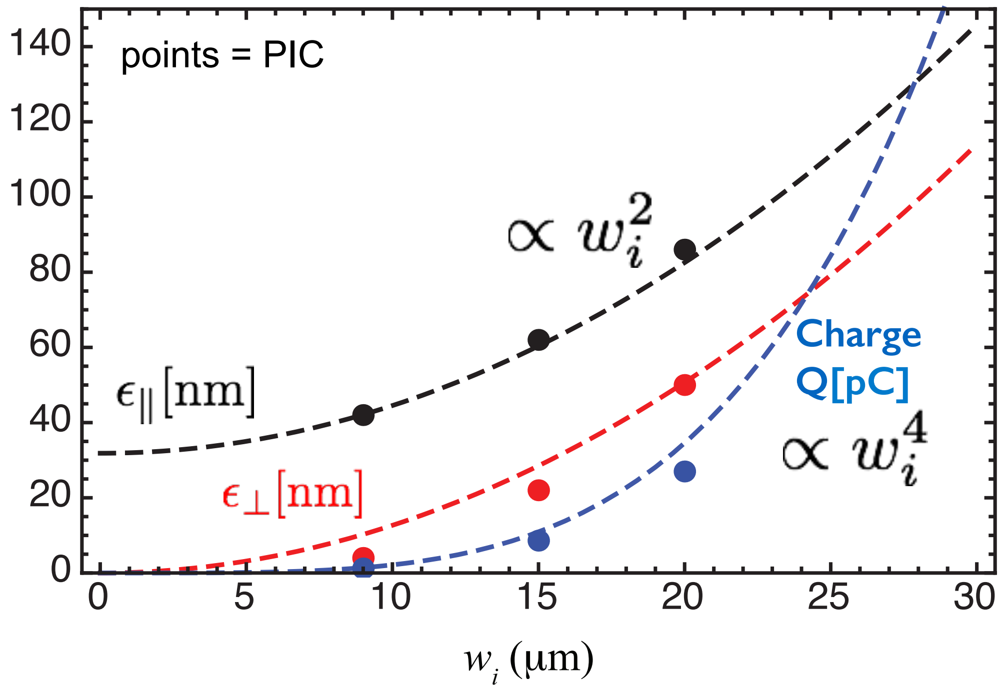
Optimization: charge vs emittance

C. Schroeder et al., PRST-AB (2014)
C. Schroeder et al., SPIE Conf. Proc. (2015)

charge: $Q = eN_t = en_g(\pi w_i^2 \Delta^2) Z_{Ri}$

$$\epsilon_{||} = \left[1 + \left(\frac{2a_i}{k_p w_i}\right)^2\right] \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2$$

$$\epsilon_{\perp} = \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2$$

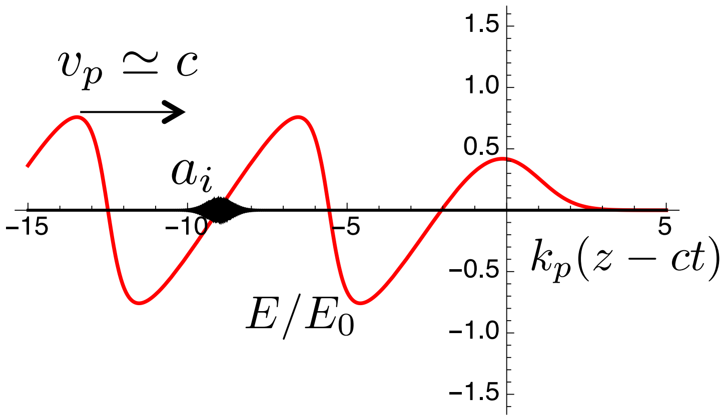


ionization laser spot size (um)

Technical/practical considerations for 2-color ionization injection experiment

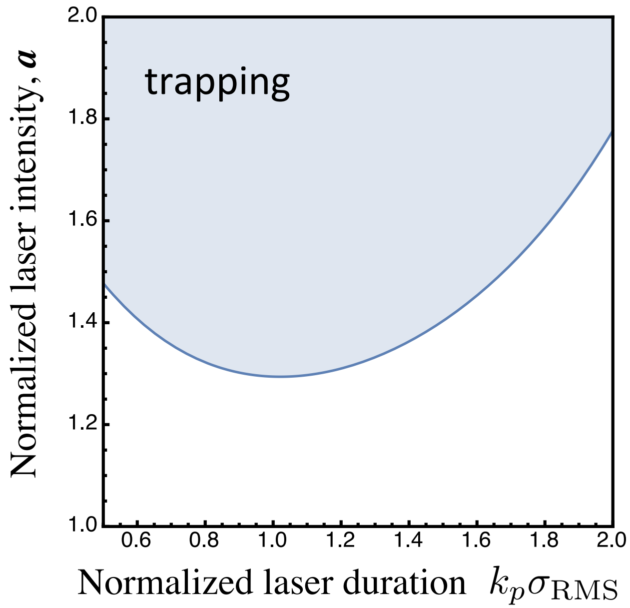
- Sensitivity to plasma wakefield amplitude
  - CO_2 laser driver amplitude and duration
- Sensitivity to timing/jitter between CO_2 and Ti:Al_2O_3 lasers
  - Increased ionization laser duration (energy) relaxes timing requirements
- Performance with ionization laser with 0.8 micron wavelength
- Interaction geometry:
  - co-linearity of lasers
  - required pointing
  - required alignment
- Measurement of <100 nm emittance: single-shot, energy-resolved emittance diagnostic

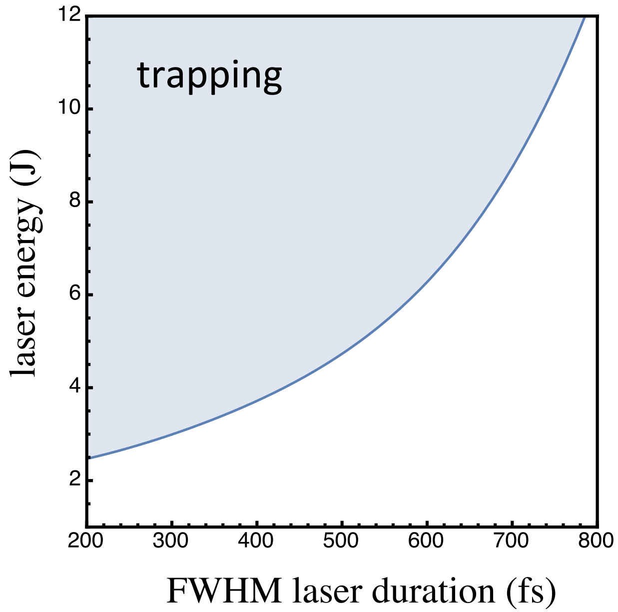
Trapping requires weakly-relativistic wakefields



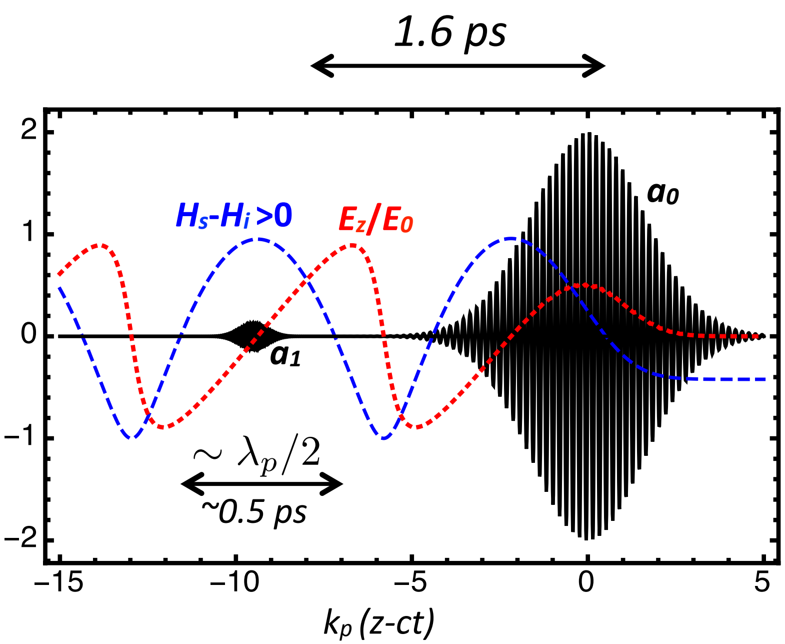
- Wakefield amplitude required to trap:

$$eE/mc\omega_p > \left(\sqrt{5} - 2\right)^{1/2} + \mathcal{O}(\gamma_p^{-1}) \approx 1/2$$





Synchronization and jitter: ~100 fs timing desired



- Operate at 10^{16} cm^{-3} with ~500 fs (FWHM) CO_2 pulse
- ~1.6 ps delay between CO_2 and $Ti:Al_2O_3$
- Trapping wake phases: Δt~500 fs

- Optical synchronization achieved by seeding $Ti:Al_2O_3$ using solid-state front-end of CO_2 amplification chain
- Longer (more energetic) ionization laser can relax timing/delay sensitivity

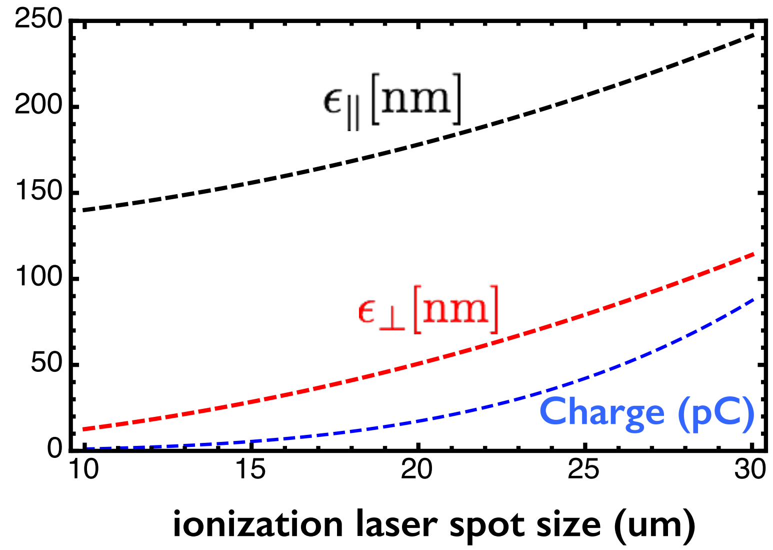
Performance using 0.8-micron ionization pulse: larger emittance in laser-polarization plane

- Efficiency of 2-ω generation (~30-50%) may limit energy in ionization pulse
- For fixed gas: $a_1 = a_0 \frac{\lambda_1}{\lambda_0}$

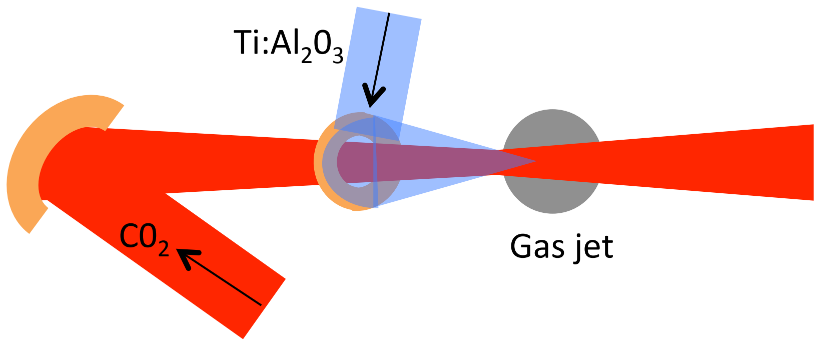
CO_2 pump laser pulse:
a_0=2
10 um wavelength
470 fs (FWHM intensity)
155 um spot (ZR = 7.5 mm)
P=20 TW (P/Pc=1) (linear polarization)
10 J

$Ti{:}Al_2O_3$ injection laser pulse:
a_1=0.26
0.8 um wavelength
118 fs (FWHM intensity)
20 um spot
114 mJ
delay= 1.6 ps

$$\epsilon_n = k_{\beta 0} w_i^2 \left[1 + \frac{2a_i^2}{(k_{\beta 0} w_i)^2} \right] \frac{a_i}{\lambda_i} \left(\frac{3\pi r_e}{4\alpha^4} \right) \left(\frac{U_H}{U_i} \right)^{3/2}$$



Interaction geometry: pointing and alignment tolerances

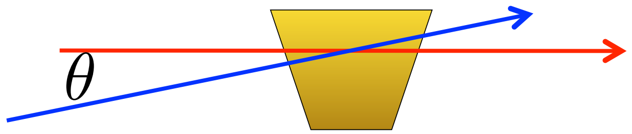


- 90-degree interaction reduces bunch charge: charge = (interaction volume) x (gas density)
  - Co-propagating: (volume) ~ $w^2 Z_R$
  - 90-deg: (volume) ~ w^2 $(T_L c)$

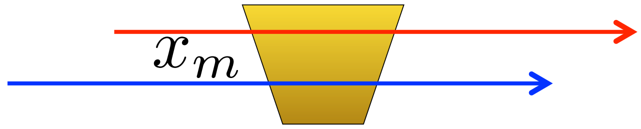
  } charge reduced by ~$(cT_L)/Z_R$

- To avoid injection over larger transverse area (proportionally increasing emittance):
  - Pointing tolerance: $\theta < 1$ mrad for 20 micron spot, 0.4 micron wavelength

$$Z_R \sin\theta < \sigma_x = w\Delta/\sqrt{2}$$



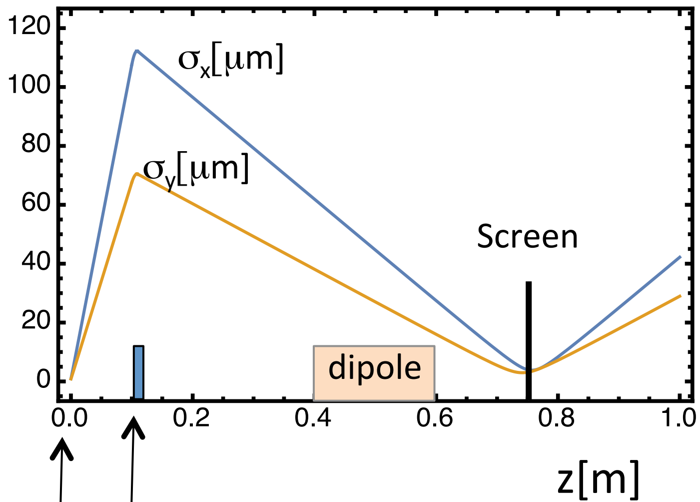
- Alignment tolerances: $x_m < \sigma_x$
  - x_m< 4 um



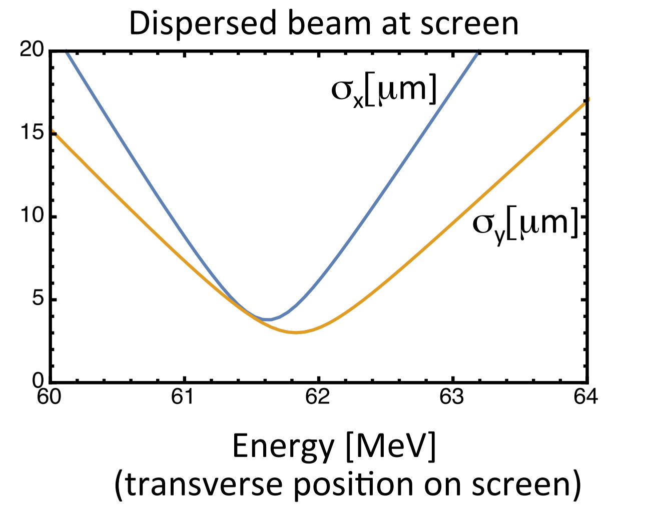
Emittance diagnostic: single-shot, energy-resolved beam size measurement

- Geometric emittance: $\sim 10^{-10}$ m
- Consider lens scan for emittance measurement: $\beta < 1$ m, $\sigma \sim$ few um
- Plasma-based discharge-capillary to provide symmetric, variable, high-field gradient (solenoid) lens

J. van Tilborg et al., PRL (submitted, 2015)



Weingartner et al., PRST-AB (2012)



end of LWFA:
27 pC,
62 MeV,
5% (rms) energy

Discharge-cap lens:
1 cm length, 200 micron radius, 46 A, ~230 T/m

$$\frac{\partial B_\phi}{\partial r} = \frac{\mu_0 I}{2\pi R^2}$$

- measurement requires ~micron resolution at screen
- ½-wave-plate for $Ti:Al_2O_3$ to vary laser polarization and measure x, y-planes

Summary

- Two-color ionization injection using CO_2 drive laser and Ti:Al_2O_3 ionization laser: produces e-beam with tens of nm normalized transverse emittance, tens of pC charge
- Emittance diagnostic: single-shot, energy-resolved measurement of beam size using plasma-based discharge-capillary lens
- ATF-II ideal facility to test concept