ALIC Plans at BELLA

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BELLA Center, LBNL

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~BELLA~

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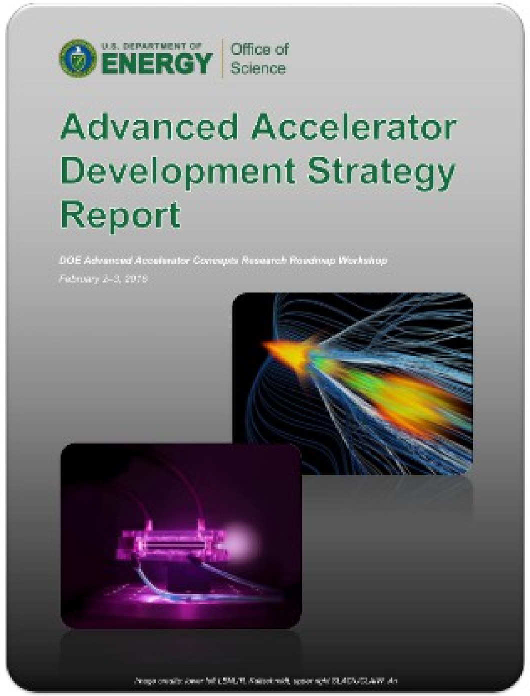
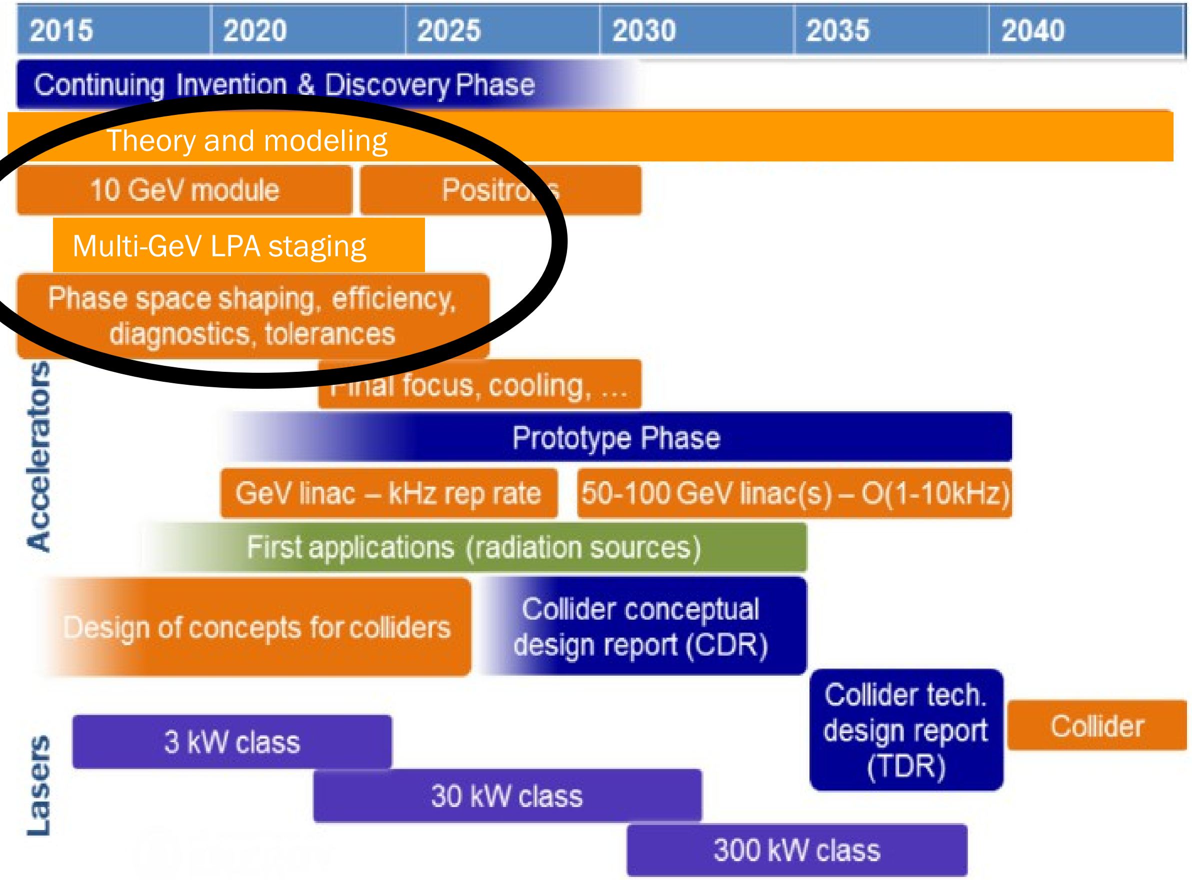
The BELLA activities aim at executing elements of the 2016 U.S. National Advanced Accelerator Development Strategy





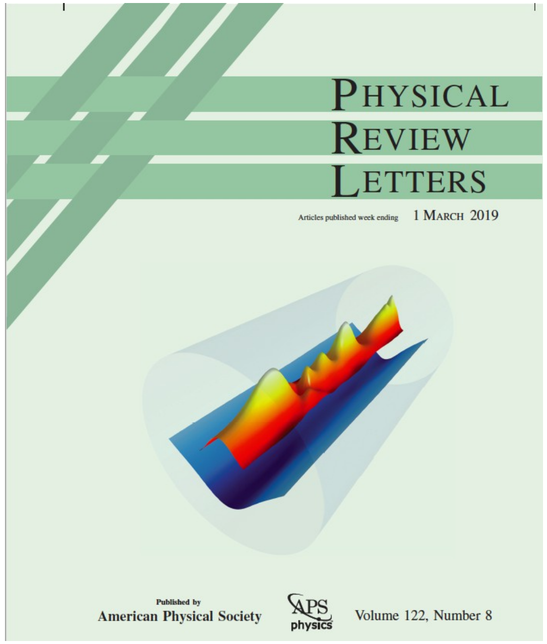
→ sets roadmap for development of technology for an LPA-based TeV collider by 2040-2050

*“**The ten-year R&D goal is to accelerate 100 pC of charge to 10 GeV in a single LPA stage. Accomplishing this requires development of techniques for matched guiding of the laser pulse in the plasma.** […] With the completion of a 10 GeV electron LPA stage, the 10 GeV beam may be employed for electron-positron pair creation and subsequent positron beam capture”*

[tomorrow @ 2.45pm]

*“Critical to the collider application is demonstration of **multi-GeV LPA staging** with independent, equal energy, drive beams.”*

Overview of the presentation



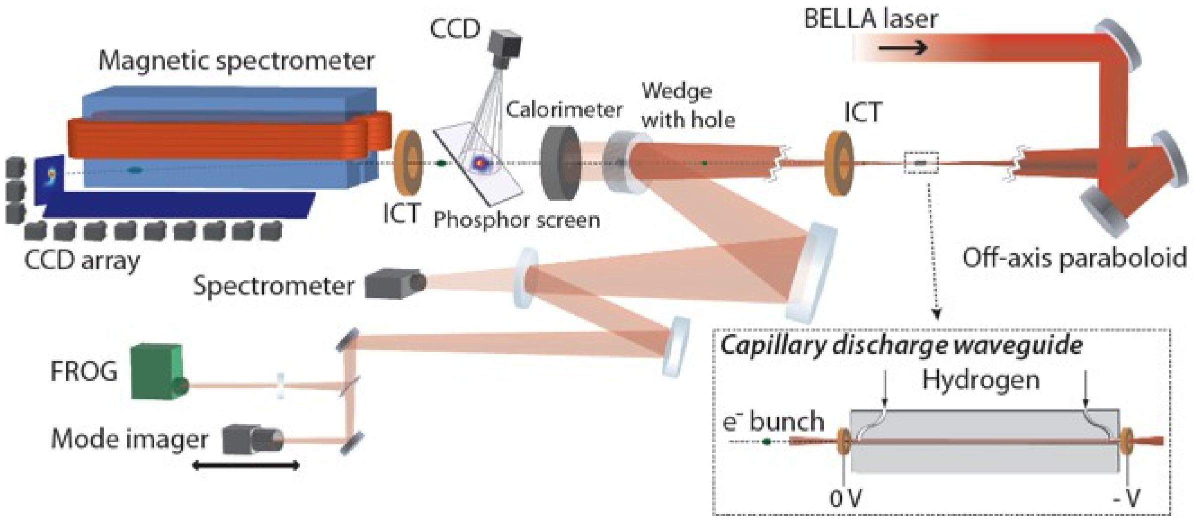
Gonsalves et al., PRL (2019)

- Updates on the path towards a 10 GeV LPA stage
  → guiding of ~PW BELLA laser over a 20 cm plasma w/ laser-heater technique
  → production of electron beams with energy of up to ~8 GeV

- Theoretical/modeling results in support of design activity for a plasma-based collider
  → mitigation of ion motion-induced emittance growth
  → suppression of hosing w/ ion motion
  → energy gain in guided vs unguided LPA stages driven by a laser with a given energy
  → optimal beamloading in quasi-linear and nonlinear LPA stages

- Summary

BELLA laser produces multi-GeV beams with repetition rate up to 1Hz, using single-shot diagnostics for both laser and electron beam



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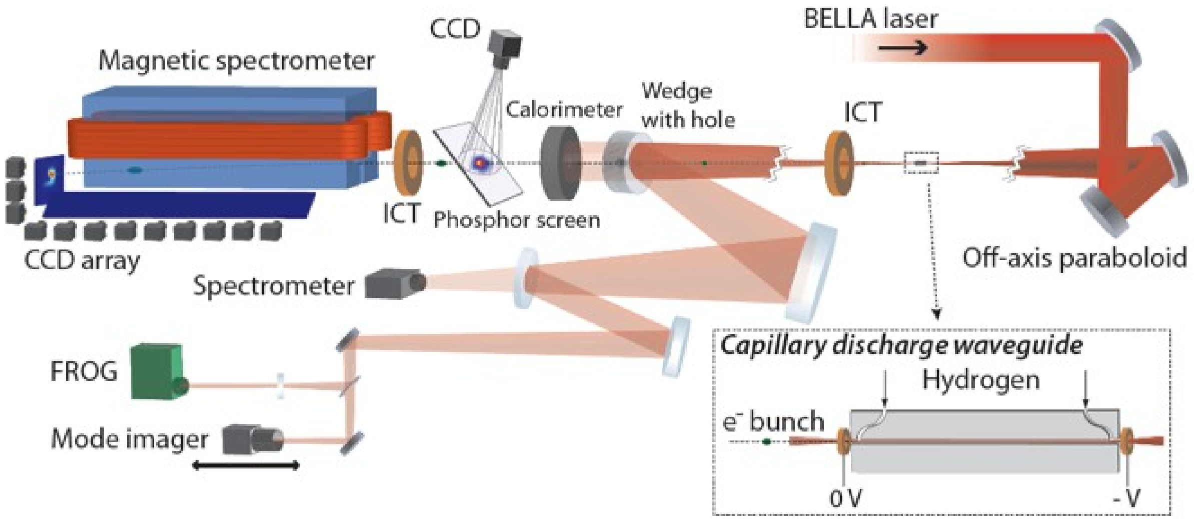
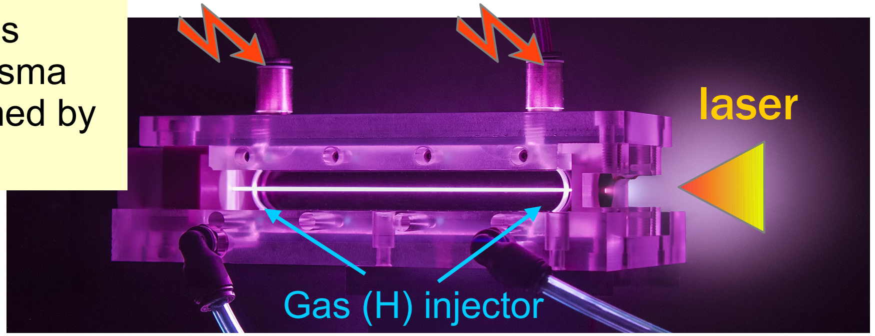


Milchberg *et al.*, POP (1996); Spence & Hooker, PRE (2001); Gonsalves, PRL (2007)

Laser guiding with capillary discharge

- Gas injected near ends
- Discharge creates plasma
- Guiding structure formed by heat conduction



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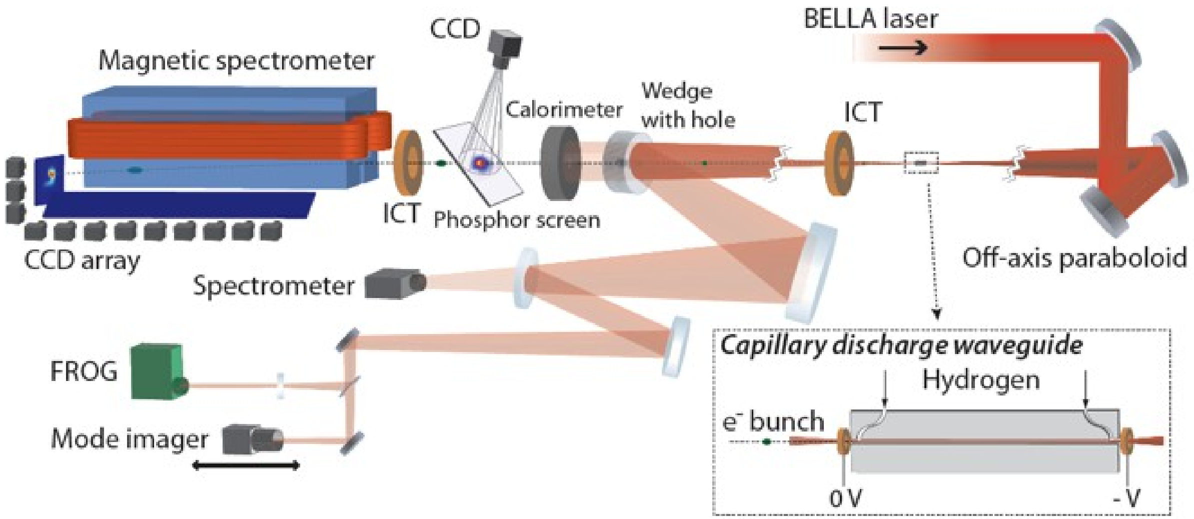

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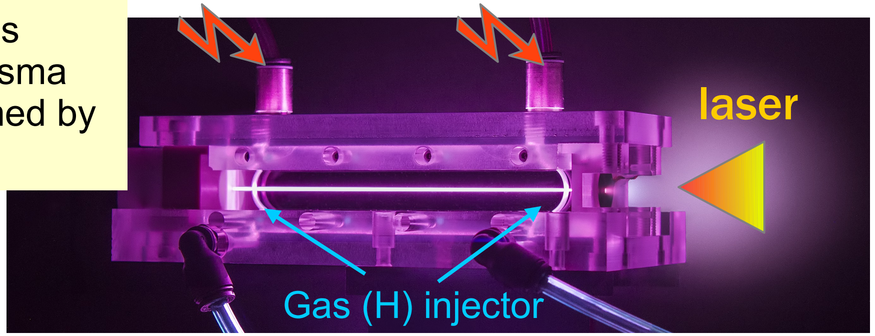
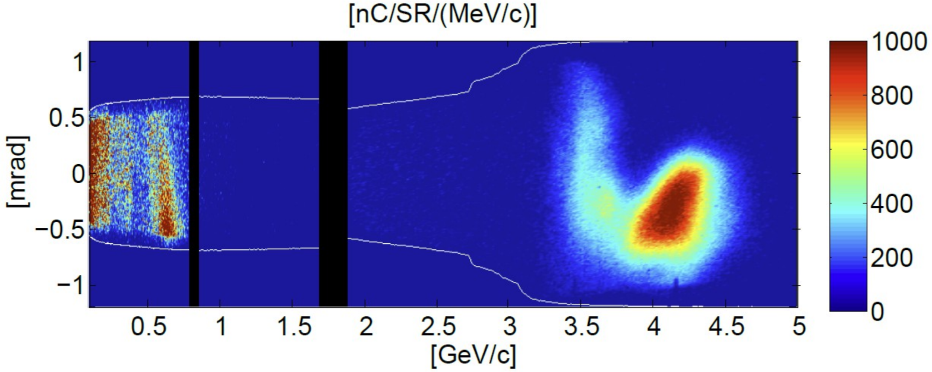


Multi-GeV beams with BELLA in a 9 cm plasma w/ 16 J, 33 fs



- Up to 4.2 GeV ($7x10^{17}$ cm^{-3}), 6 pC
- Stable 2.7 GeV beams ($8.5x10^{17}$ cm^{-3})
- Up to 200 pC ($1.1x10^{18}$ cm^{-3})

Leemans et al., PRL 2014; Gonsalves et al., PoP 2015

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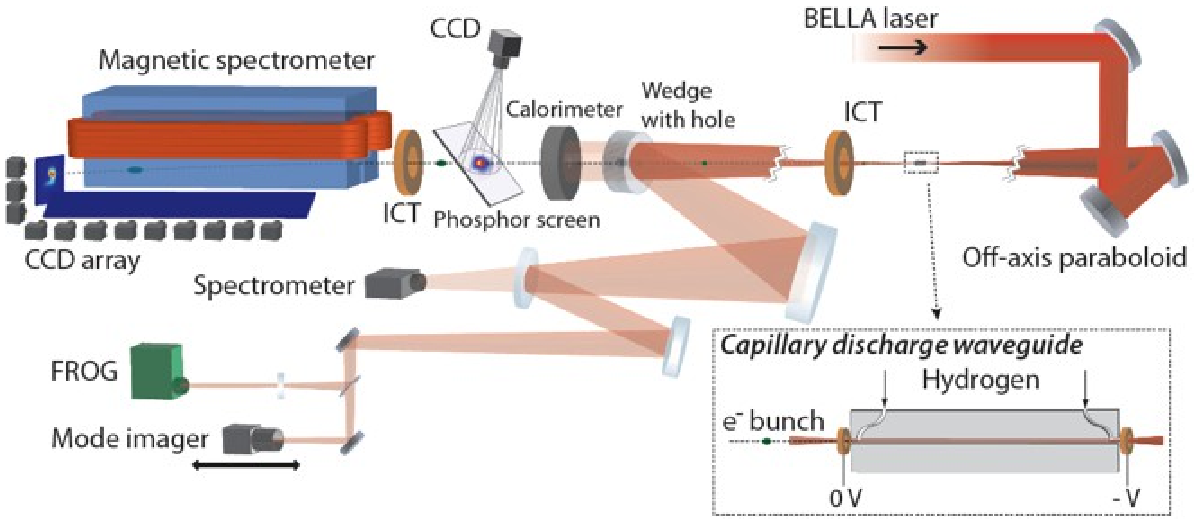

Milchberg *et al.*, POP (1996); Spence & Hooker, PRE (2001); Gonsalves, PRL (2007)

Laser guiding with capillary discharge

- Gas injected near ends
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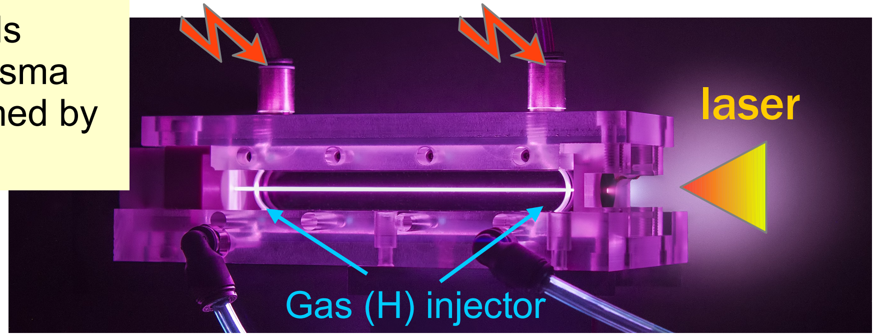

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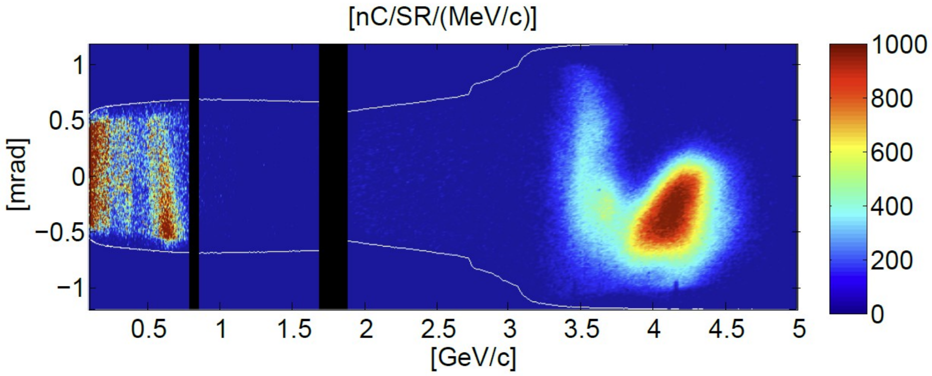

- Up to 4.2 GeV (7×10^{17} cm^{-3}), 6 pC
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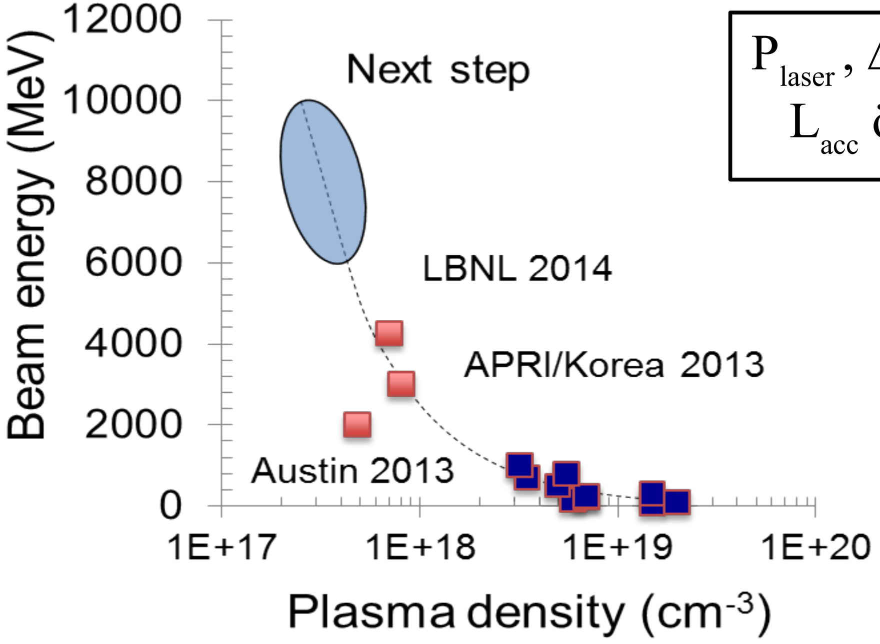
Higher beam energy needs lower density & more power



P_{laser}, $\Delta\gamma \propto n^{-1}$
$L_{acc} \propto n^{-3/2}$

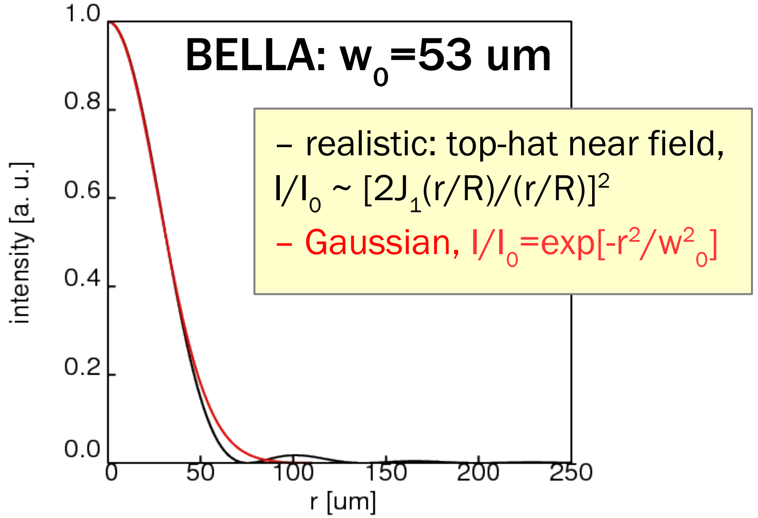
$W \sim 10$ GeV
$n \sim 2.5 \times 10^{17}$ cm^{-3}
$L_{acc} \sim 20 - 30$ cm
$P_{laser} \geq$ PW

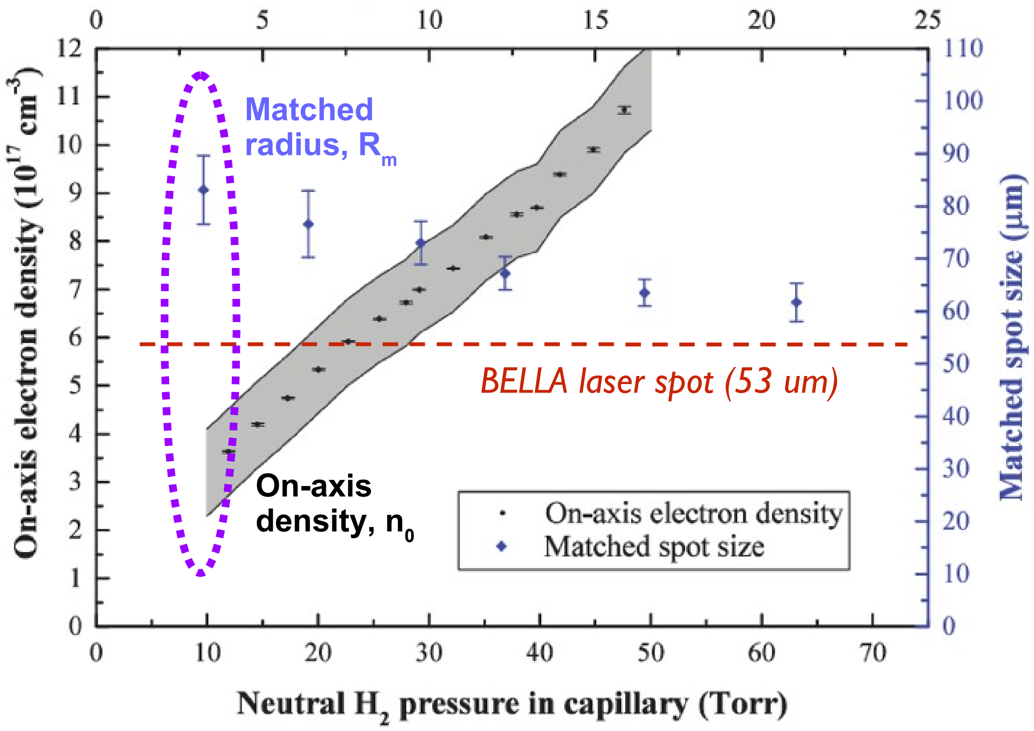
Achieving good guiding over several 10s of cm at low density and for a laser pulse with a realistic transverse laser profile is challenging

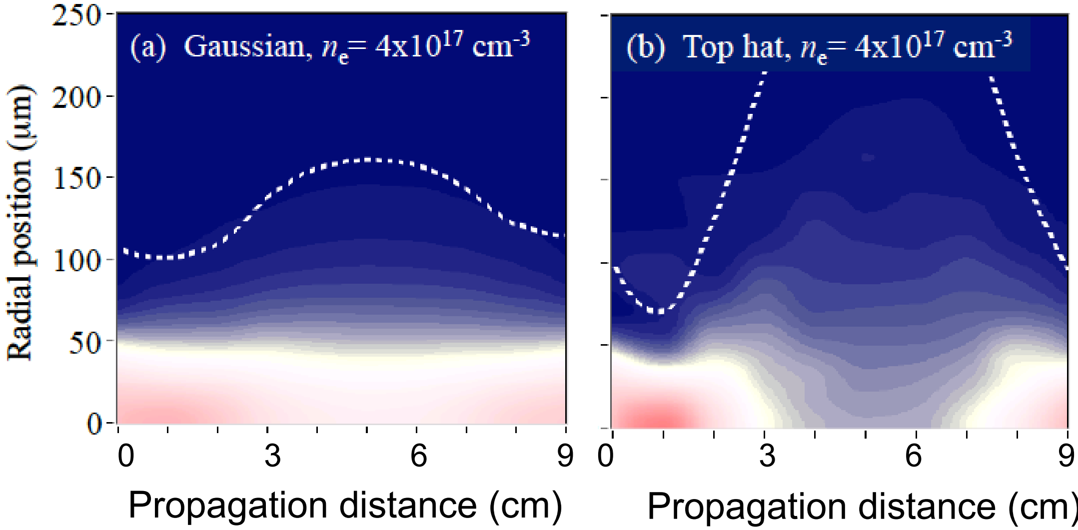
→ Discharge cap generates parabolic density profile (plasma channel): $n(r) = n_0 + \frac{r^2}{\pi r_e R_m^4}$

→ Gaussian laser profile matched if **R_m ≈ laser spot**

→ Realistic (jinc) laser profile (best) matched if **R_m ≈ 0.8 x laser spot**







9 cm cap
n_0=4x10^{17} cm^{-3},
R_m = 80 um

Laser heater technique*, which allows for reduction of matched radius improving guiding at low plasma density, was added to BELLA beamline

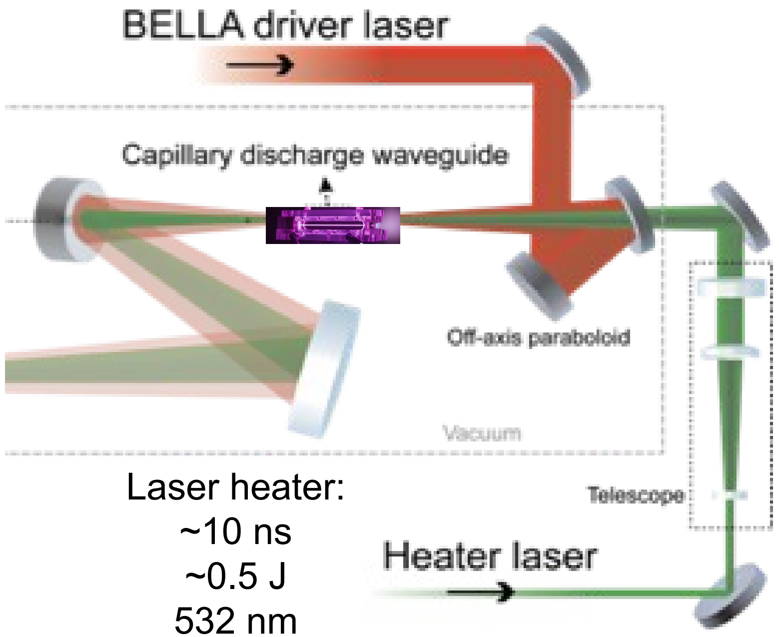
Laser-heater concept:

→ Discharge creates parabolic profile

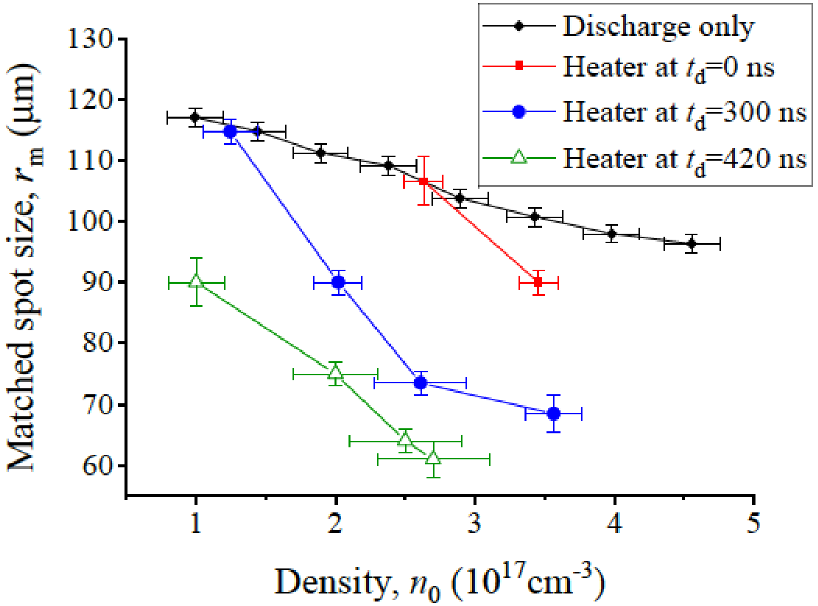
→ Nanosecond (heater) pulse locally heats plasma through **Inverse Bremsstrahlung**

→ Plasma distribution is changed

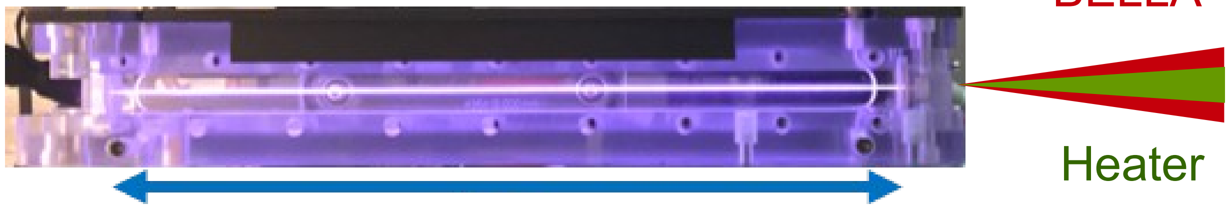
- R_m reduces locally (steeper walls)
- n_0 decreases



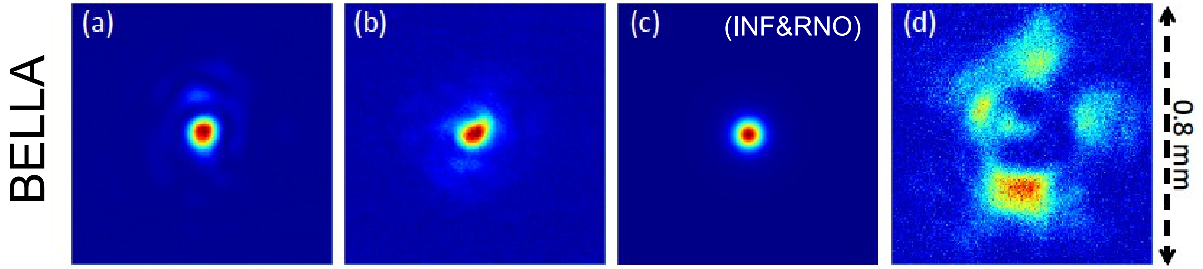
Laser heater:
~10 ns
~0.5 J
532 nm



R_{cap}=400 um



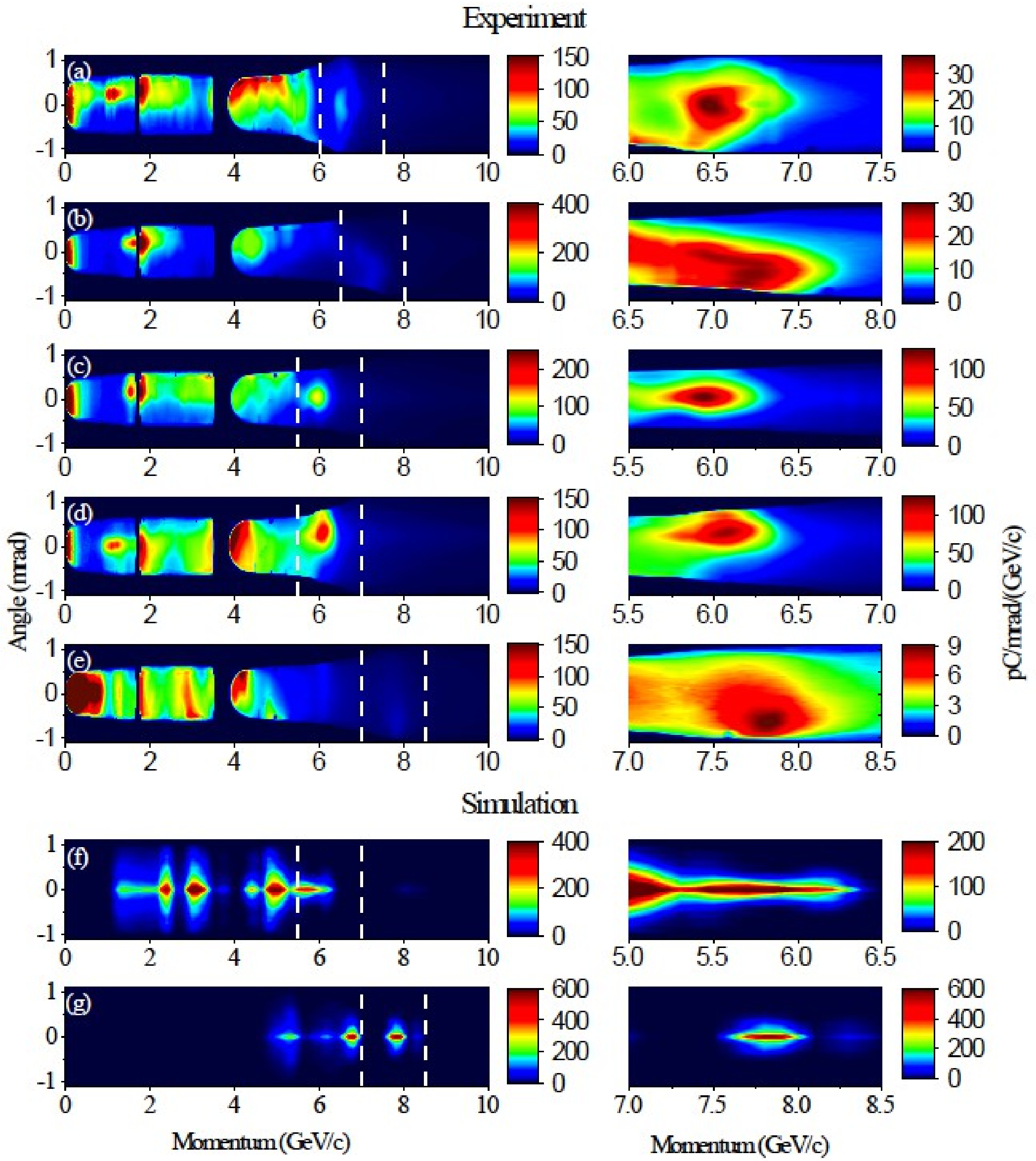
20 cm ≈ 15 $Z_{rayleigh}$



Vacuum focus z=0 cm | Capillary exit z=20 cm (experiment) | Capillary exit z=20 cm (simulation) | Vacuum z=5.4 cm

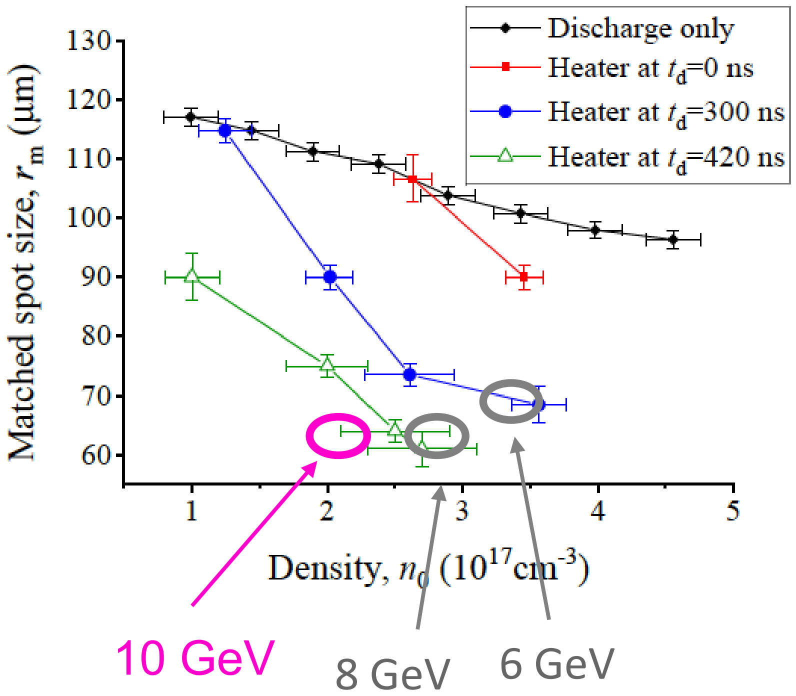
* Bobrova *et al.*, *POP* 2013, *Gonsalves et al., PRL (2019);*

Electron beams with energy up to 7.8 GeV observed for density ~3x10^{17}cm^{-3}, in good agreement with INF&RNO simulations

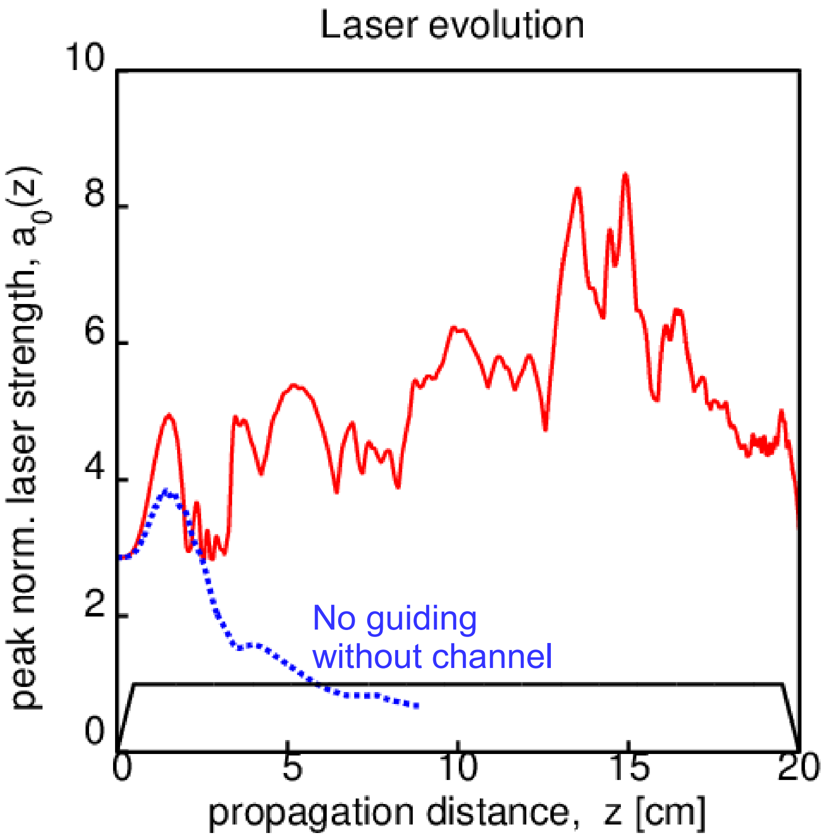


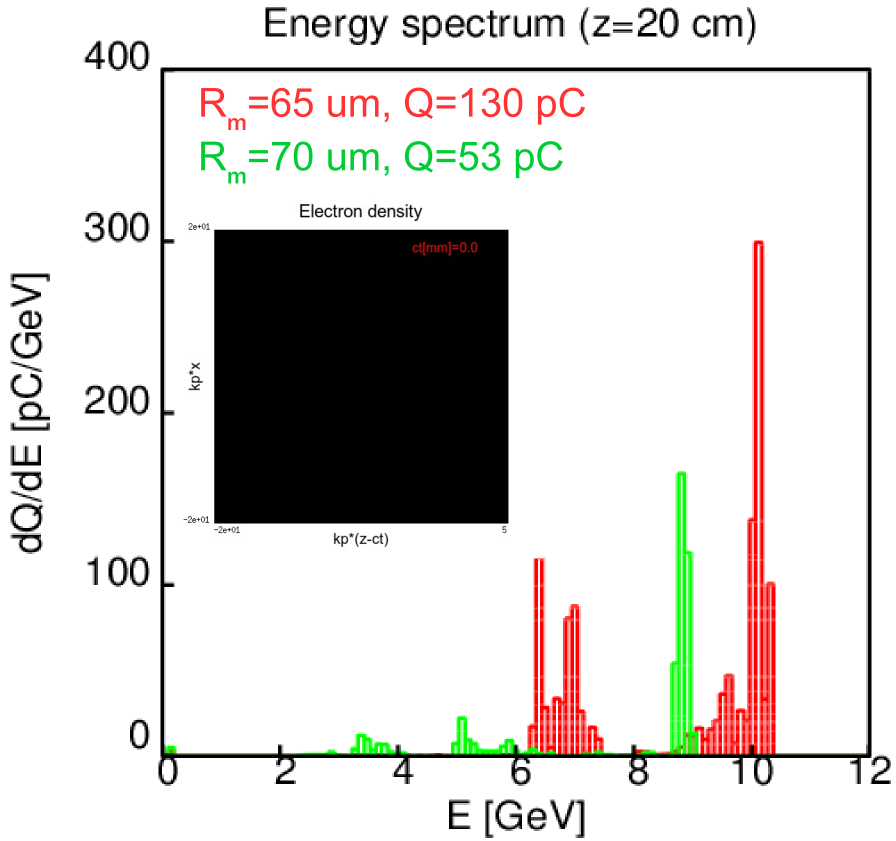
- Non-localized injection produces large energy spread
- Peak at ~7.8 GeV for 2.7x10^{17} cm^{-3} (~6 GeV for 3.4x10^{17} cm^{-3})
- Energy spread in peak ~10% FWHM
- Charge in peak is ~5 pC @ ~7.8 GeV (up to ~62 pC @ ~6 GeV)
- Beam divergence ~0.2 mrad FWHM
- Good good agreement with INF&RNO simulations

INF&RNO simulations show that beams with ~10 GeV are obtainable with optimized heated channel using the full BELLA power



On-axis density: n_0=2.2x10^17/cc (long. uniform), R_m= 65 um
Laser: T_0= 30 fs (exp.), w_0=63 um (jinc), U=39 J





- Final beam properties **sensitive** to laser-plasma parameters
- Use of triggered injection (ionization @ cap entrance) considered to reduce sensitivity to laser-plasma parameters

Space-charge field of high-charge, high-energy, linearly matched bunch in a PA can trigger background ion motion yielding to transverse wake perturbation and emittance growth*

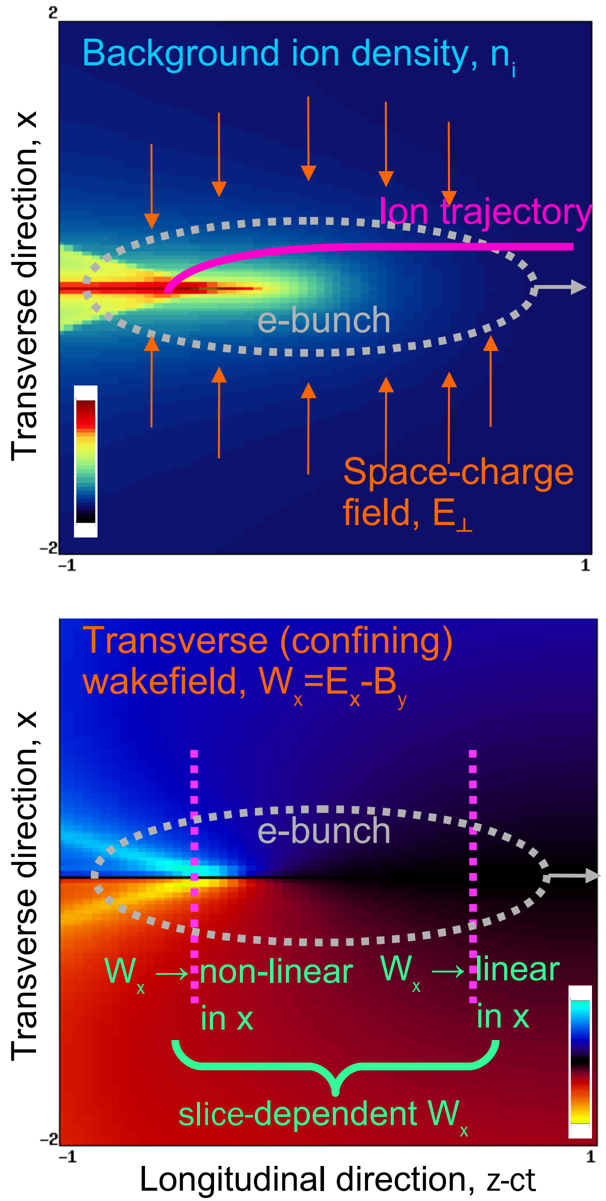
- Emittance preservation achieved via matching bunch size in the linear (unperturbed) confining wake

$$\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\epsilon_n}{k_p}$$

- As γ increases, $\sigma_{x,y}$ adiabatically decrease and n_b increases
  → e-bunch space charge field increases
  → background ions are pulled towards the axis
  → slice-dependent perturb. of transverse wakefield
  → **bunch emittance growth**

Condition for ion motion →

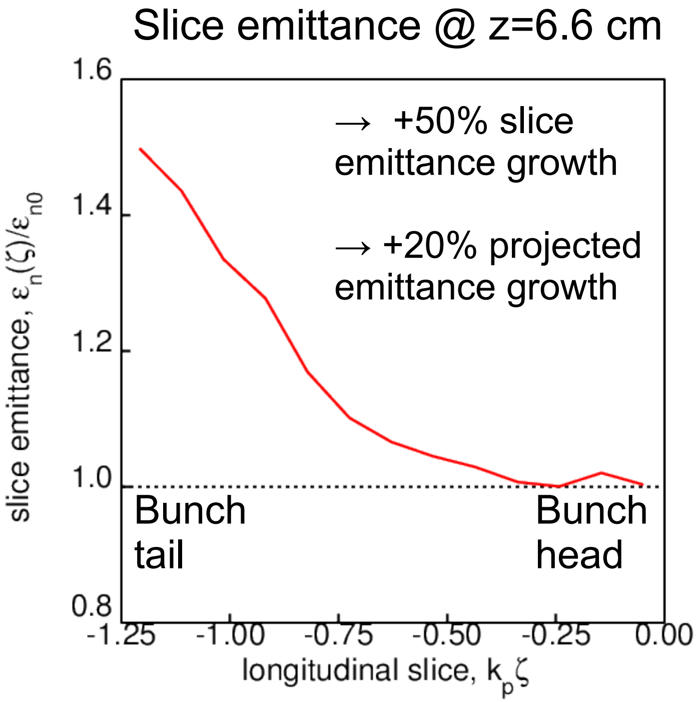
$$\Gamma = Z_i(m/M_i)(n_{b,0}/n_0)(k_pL_b)^2 \gtrsim 1$$



Bunch: E=25 GeV, $\epsilon_{n,0}$=0.6 um, L_b=20 um, $N_b=10^{10}$ → Γ=10

Plasma: $n_0=10^{17}$ cm^{-3} (Hydrogen)

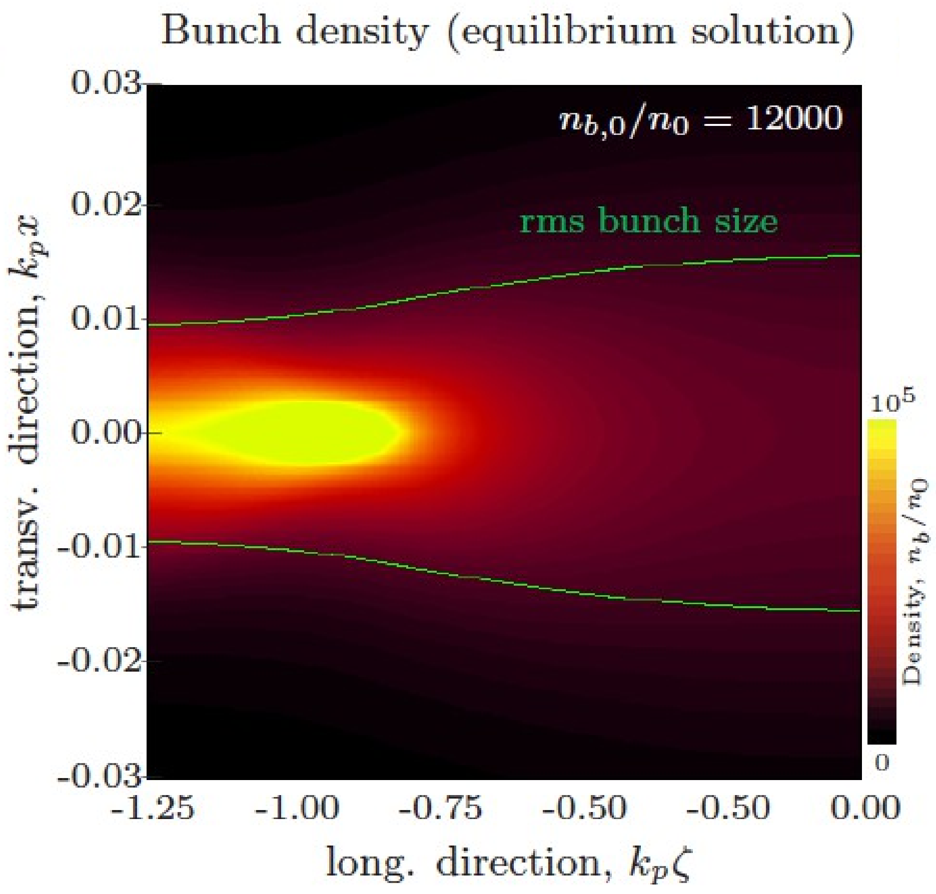
Delahaye *et al.*, IPAC 2014

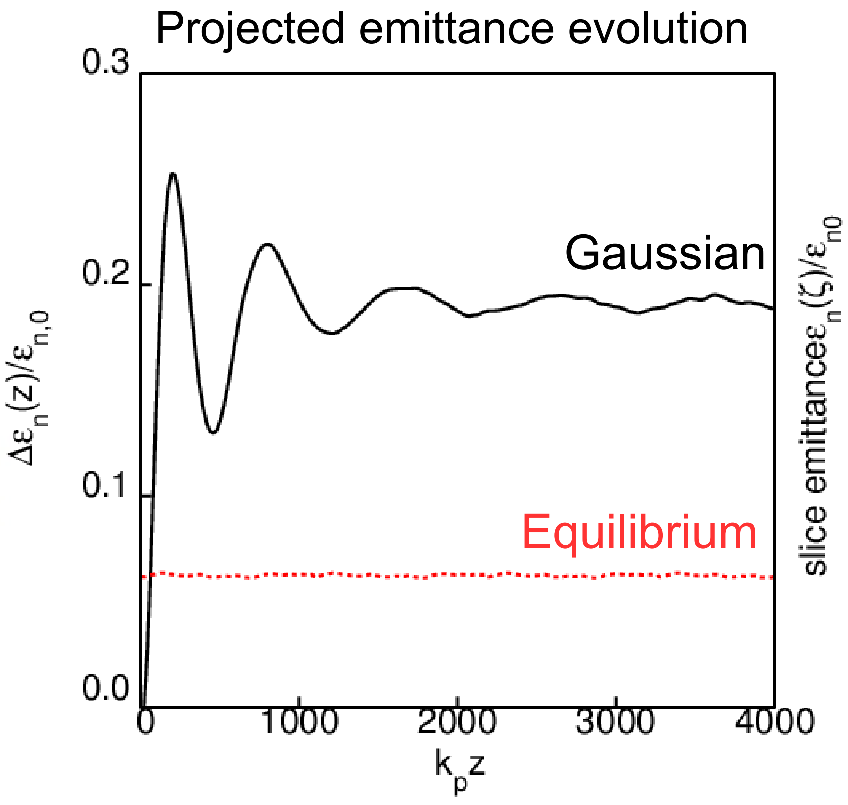


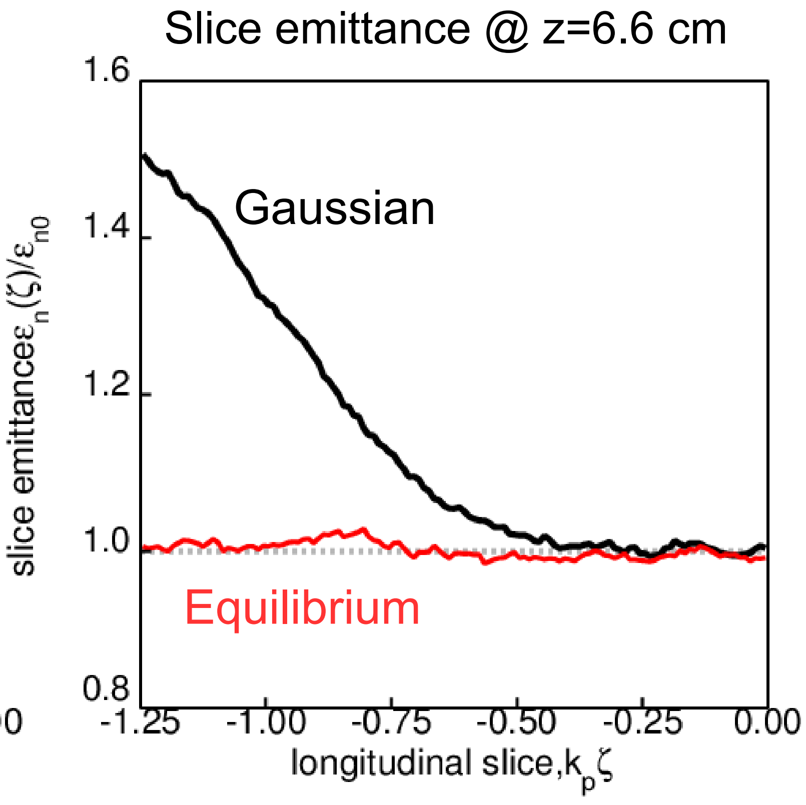
*Rosenzweig et al., PRL (2005); An et al., PRL (2017); Benedetti et al., PRAB (2017)

A class of initial beam distributions with constant slice-by-slice emittance enabling ion motion without emittance growth has been derived*

→ Beam distribution matched to ion-motion-perturbed (nonlinear) focusing forces
→ Requires preparation of initial transverse 4D phase-space (non-Gaussian in space) [approx. Gaussian solution available]
→ Arbitrary longitudinal current distribution







*C. Benedetti et al, "Emittance preservation in plasma-based accelerators with ion motion" PRAB (2017)

Ion-motion-induced betatron frequency spread suppresses hosing instability (emittance growth eliminated by bunch tailoring)

Hosing instability*: resonance between beam centroid oscillations and plasma wakefield which results in emittance growth

→ suppressed by energy chirp (BNS damping) [not desirable for collider application]

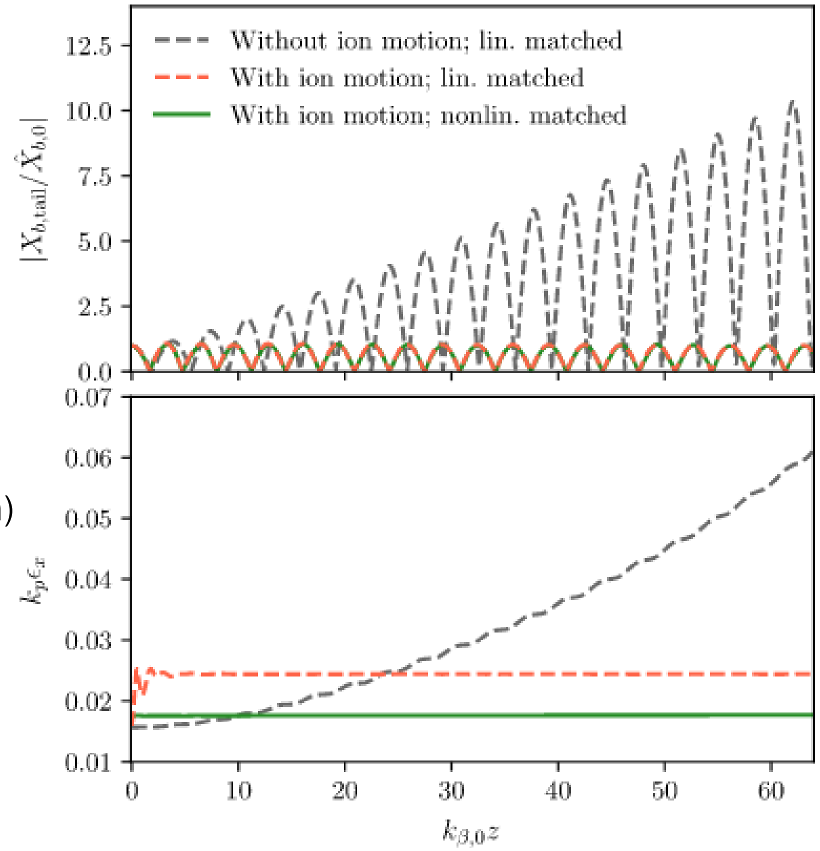
→ in quasi-linear LPA regime the natural head-to-tail spread of focusing force largely suppresses hosing   Lehe et al., PRL (2017)

→ in blowout regime w/ ion motion the ion-motion-induced head-to-tail spread of focusing **suppresses hosing**

Mehrling et al., PRL (2018)

Bunch (collider relevant):
E=25 GeV, $\varepsilon_{n,0}$=0.26 um,
→ $\sigma_{x,0}$=0.17 um
→ init. displacement: $x_0 = \sigma_{x,0}$,
L_b=33.6 um, I_b=(27-17) kA

Plasma: $n_0=10^{17}$ cm^{-3} (Hydrogen)



→ Proper longitudinal and transverse bunch shaping results in acceleration without energy spread growth, without emittance growth (from ion motion), and with hosing mitigated

← hosing, large emittance growth (factor ~10) from hosing

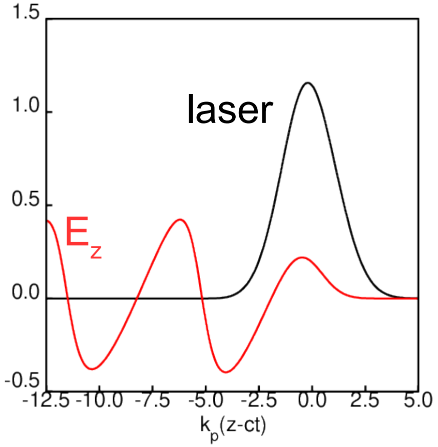
← no hosing, emittance growth (~60%) from ion motion

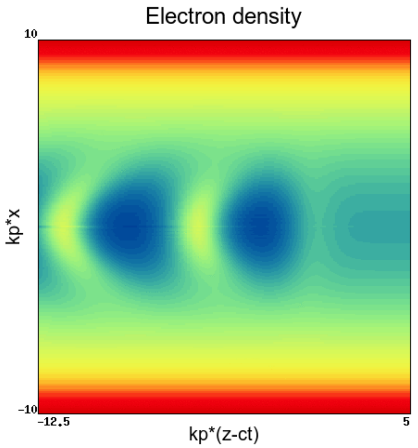
← no hosing + emittance preservation w/ bunch tailoring

*Whittum et al., PRA (1992);Schroeder et al., PRL (1999); Lehe et al., PRL (2017);
Huang et al., PRL (2007); V. Lebedev et al., PRAB (2017); Mehrling et al., Phys. Plasmas (2018)]

Guided and unguided LPAs driven by a laser with given energy operate at different plasma densities

Guided LPA (quasi-linear regime)





Laser driver: a_0~1, $k_p w_0$~ 4-5, $k_p L$~2 (resonant), λ_0=0.8 μm

→ guiding provided by parabolic plasma channel ($P/P_c \leq 1$)

→ accelerating gradient: E_z/E_0 ~ 1

→ density:

$$n_0[\mathrm{cm}^{-3}] \simeq 7.6\times10^{16} a_0^{4/3}(k_p w_0)^{4/3}(k_p L)^{2/3}(U[\mathrm{J}])^{-2/3}$$

(e.g., n_0=2.6x10^{17} cm^{-3} for U=10 J, a_0=1.5, $k_p w_0$= 4, $k_p L$=1.8)

→ accelerating length: $k_p L_{acc}$ ~ n_0^{-1} (dephasing/depletion)

→ energy gain: γ_{bunch} ~ n_0^{-1}

Guided and unguided LPAs driven by a laser with given energy operate at different plasma densities

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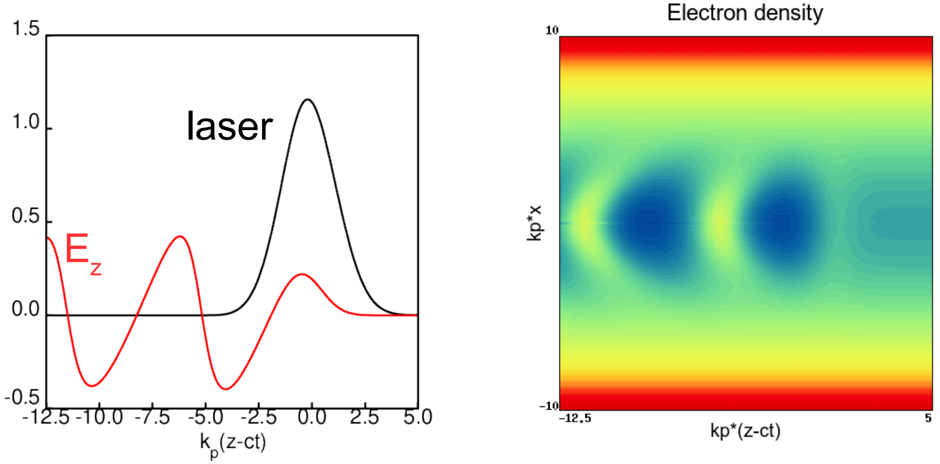


Laser driver: a_0~1, $k_p w_0$~ 4-5, $k_p L$~2 (resonant), λ_0=0.8 μm

→ guiding provided by parabolic plasma channel ($P/P_c \leq 1$)

→ accelerating gradient: $E_z/E_0 \sim 1$

→ density:

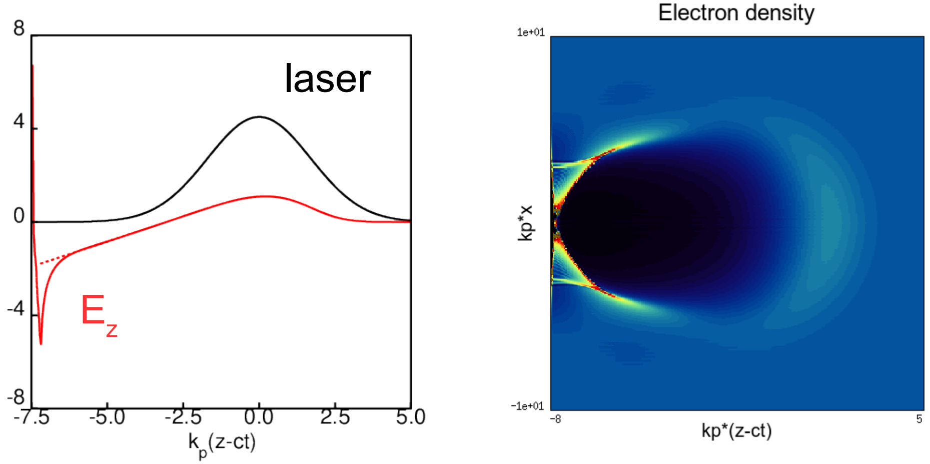
$$n_0[\mathrm{cm}^{-3}] \simeq 7.6 \times 10^{16} a_0^{4/3} (k_p w_0)^{4/3} (k_p L)^{2/3} (U[\mathrm{J}])^{-2/3}$$

(e.g., $n_0=2.6\mathrm{x}10^{17}$ cm^{-3} for U=10 J, a_0=1.5, $k_p w_0$= 4, $k_p L$=1.8)

→ accelerating length: $k_p L_{acc} \sim n_0^{-1}$ (dephasing/depletion)

→ energy gain: $\gamma_{\mathrm{bunch}} \sim n_0^{-1}$

Unguided LPA (nonlinear / bubble regime*)



Laser driver*: a_0=4.5, $k_p w_0=2\sqrt{a_0}$, $L_{fwhm}=(2/3)w_0$, λ_0=0.8 μm

→ self-guiding ($P/P_c \gg 1$)

→ accelerating gradient: $E_z/E_0 > 1$

→ density:

$$n_0[\mathrm{cm}^{-3}] \simeq 2.1 \times 10^{17} a_0^{7/3} (U[\mathrm{J}])^{-2/3}$$

(e.g., $n_0=1.5\mathrm{x}10^{18}$ cm^{-3} for U=10 J, a_0=4.5)

→ accelerating length: $k_p L_{acc} \sim \sqrt{a_0} n_0^{-1}$ (etching=dephasing)

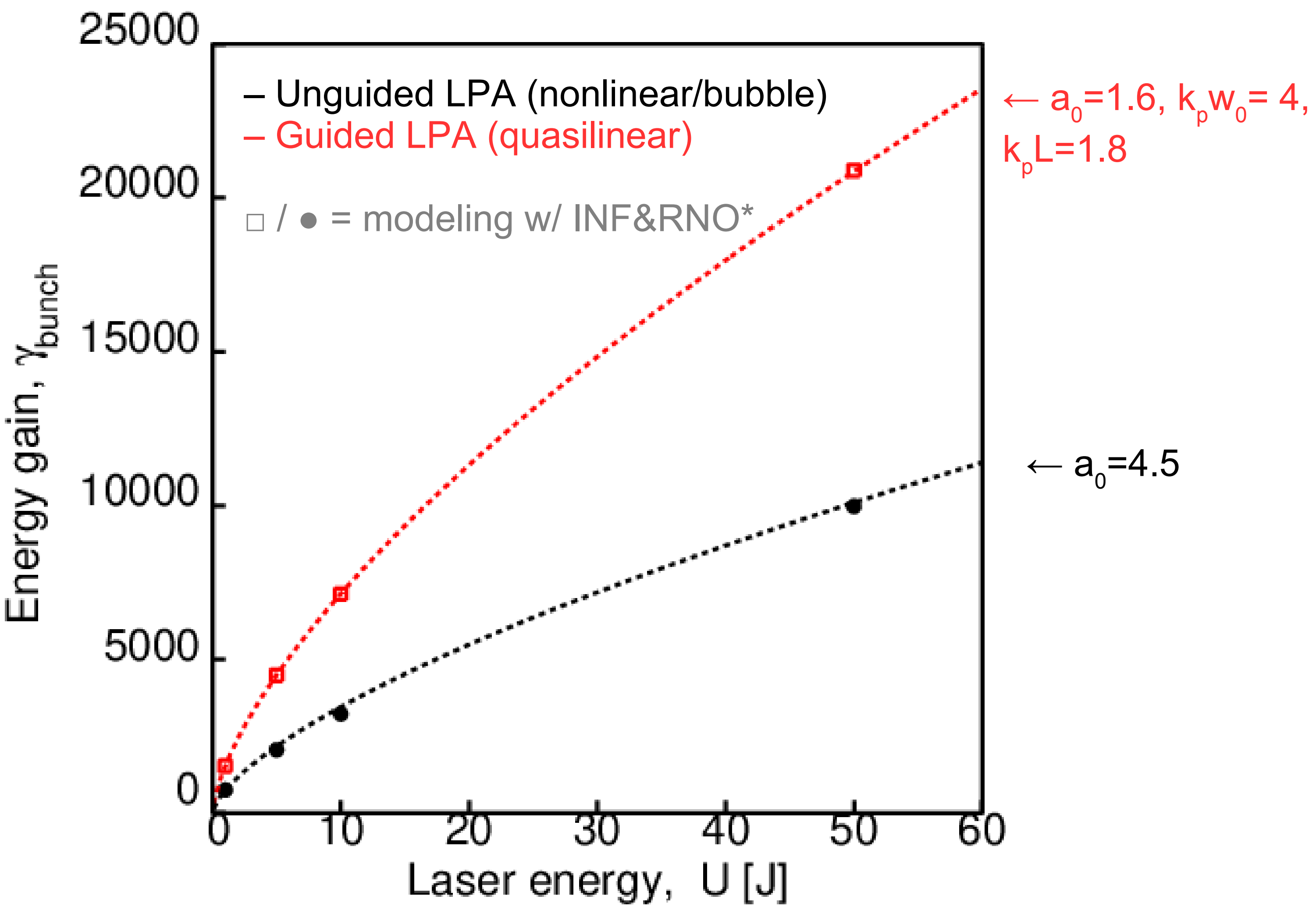
→ energy gain: $\gamma_{\mathrm{bunch}} \sim a_0 n_0^{-1}$

*W. Lu et al., PR ST-AB (2007)

→ Energy gain in guided LPAs **larger** than for unguided LPAs owing to the much lower density of operation (which compensates for the larger gradient available in the nonlinear regime)

For given laser energy the energy gain in guided LPAs is larger than in unguided LPAs

→ Energy gain in guided LPAs is ~2 times larger than in unguided LPAs

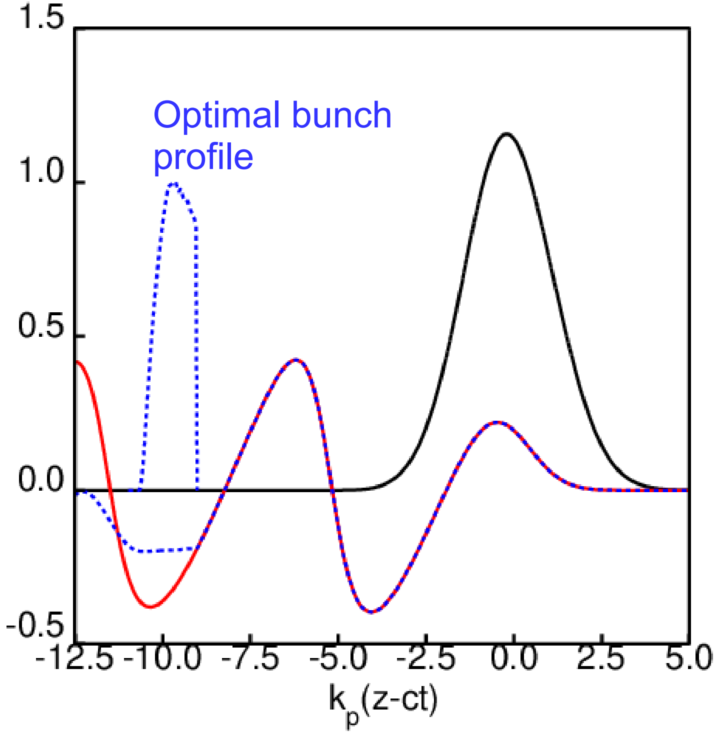


*C. Benedetti et al., AAC (2014), AAC (2016), PPCF (2017)

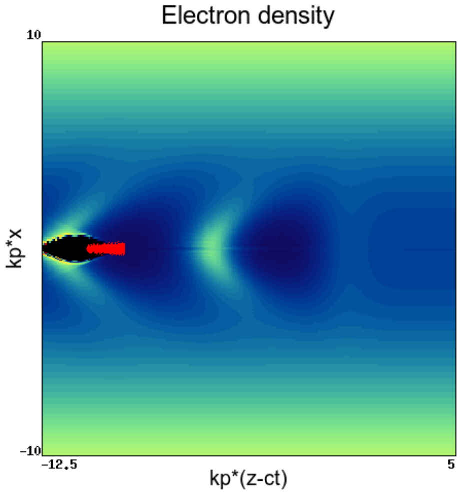
C. Benedetti et al, in preparation

Optimal bunch shape to eliminate wake-induced energy spread calculated in all LPA regimes

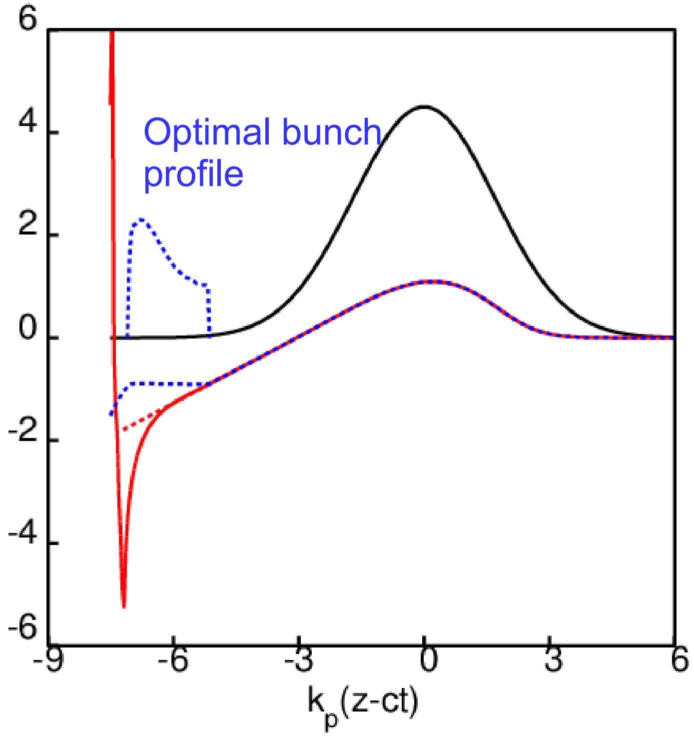
Quasi-linear regime



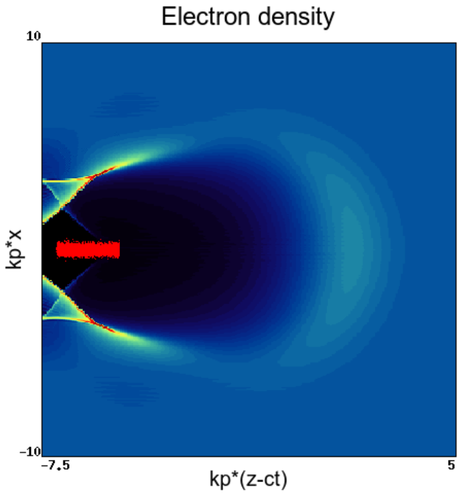
$a_0=1$, $k_p w_0=4$, $k_p L=1.8$



Nonlinear / bubble regime



$a_0=4.5$

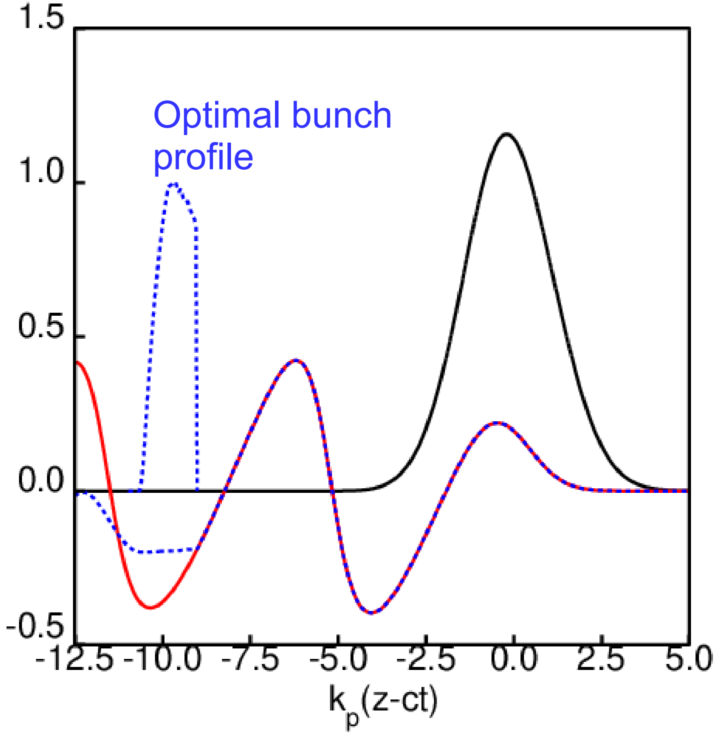


- In the linear limit (i.e., $E_z/E_0 \ll 1$) the optimal current profile is triangular
- In the nonlinear/bubble regime ($a_0=4.5$) the trapezoidal shape predicted by Tzoufras et al. (PRL, 2009) not optimal (laser-driven bubble wake different from blowout)

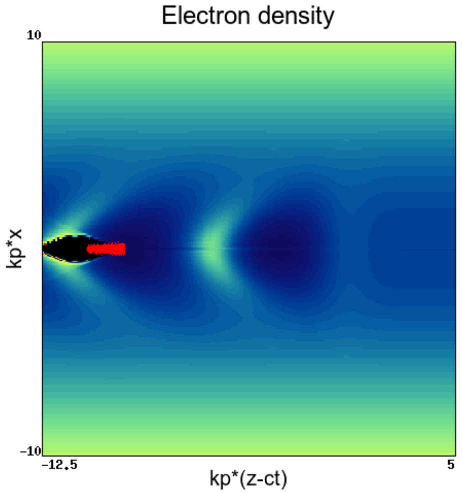
C. Benedetti et al, in preparation

Optimal bunch shape to eliminate wake-induced energy spread calculated in all LPA regimes

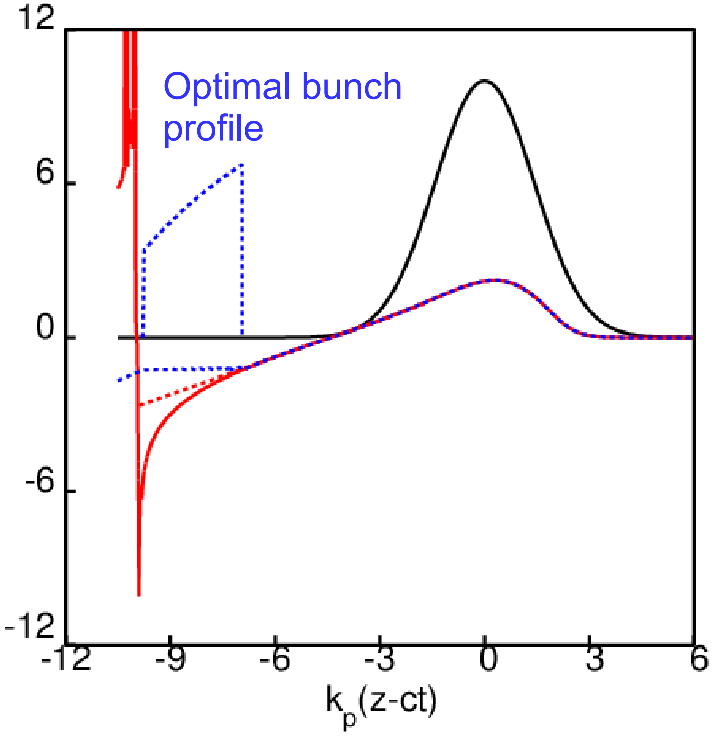
Quasi-linear regime



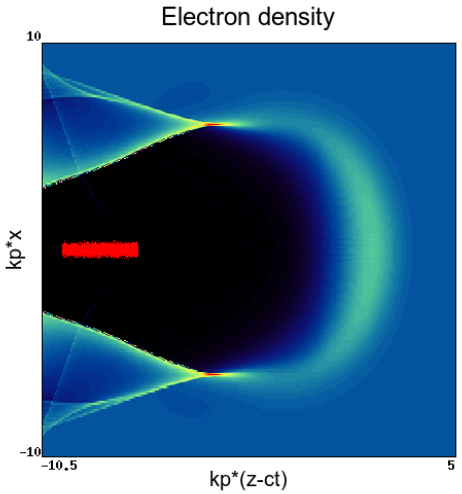
$a_0=1$, $k_p w_0=4$, $k_p L=1.8$



Blowout regime



$a_0=10$



- In the linear limit (i.e., $E_z/E_0 \ll 1$) the optimal current profile is triangular
- In the nonlinear/bubble regime ($a_0=4.5$) the trapezoidal shape predicted by Tzoufras et al. (PRL, 2009) not optimal (laser-driven bubble wake different from blowout)

C. Benedetti et al, in preparation

Summary of ALIC plans @ BELLA

- Guiding of ~PW laser pulse over 20 cm plasma (~15 Rayleigh lengths) achieved with laser-heater technique.

- Quasi-monoenergetic beams with energy up to 7.8 GeV produced. Charge was 5 pC at 7.8 GeV and up to 62 pC in 6 GeV peaks, and typical beam divergence was 0.2 mrad.

- Theory/modeling in support of development of plasma-based collider:
  - strategy to suppress/mitigate emittance degradation from ion motion proposed;
  - strategy to suppress/mitigate hosing that relies on ion motion has been proposed;
  - energy gain in guided vs unguided LPA stages investigated;
  - optimal bunch shape to eliminate wake-induced energy spread calculated in all LPA regimes.

- Other ALIC-relevant activities @ BELLA: [tomorrow @ 2.45pm]
  - Multi-GeV staging experiment planned and project underway (plasma mirror, triggered injections, cap lens, etc.);
  - High-average (kW) power, short-pulse laser development via temporal/spatial/wavelength combining;
  - Experiments for LPA-driven (100 TW) FEL w/ beam phase-space manipulation;
  - Focusing GeV-class electron beams with active plasma lens;
  - Testing thin plasma mirrors from liquid crystal (collaboration with OSU).

Job opportunity

Postdoc position (1 year, renewable) at BELLA to work on theory and modeling of plasma-based acceleration...

Contact me (cbenedetti@lbl.gov) for more info!