Efficient Modeling of Laser-Plasma Accelerators Using the Ponderomotive-Based Code INF&RNO

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Overview of the presentation

- Basic physics of laser-plasma a accelerators (LPAs): LPAs as compact particle accelerators

- Challenges in modeling LPAs over distances ranging from cm to m scales

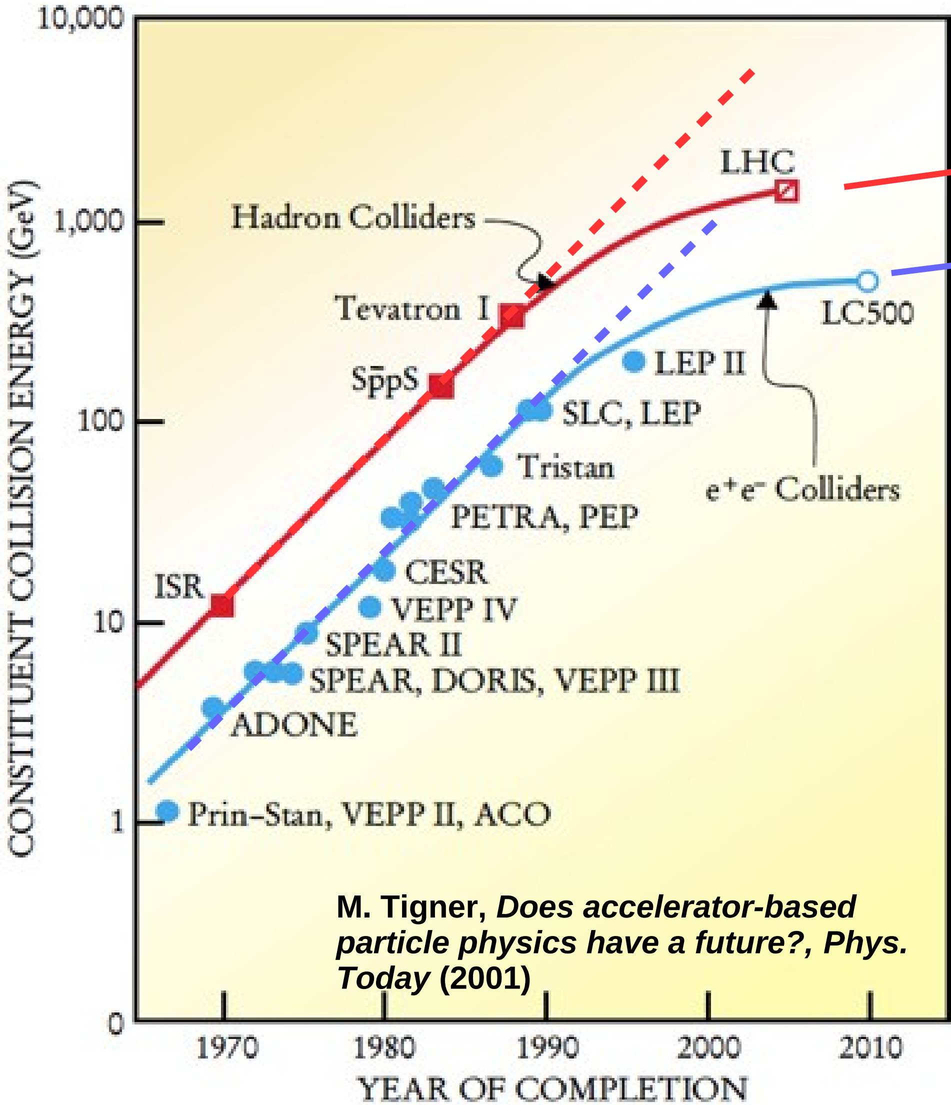
- The code INF&RNO (INtegrated Fluid & paRticle simulatioN cOde)
  - basic equations, numerics, and features of the code

- Numerical modeling of LPAs:
  - modeling present LPA experiments: 4.3 GeV in a 9 cm w/ BELLA (BErkeley Lab Laser Accelerator, 40 J, 30 fs, > 1 PW), using ~15 J laser energy [currently world record!]
  - modeling future LPA experiments: 10 GeV LPA

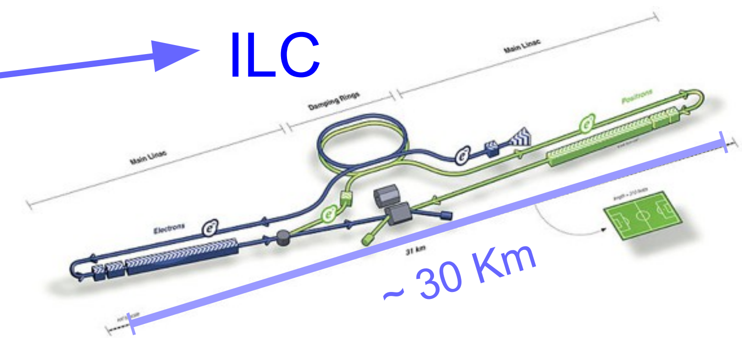
- Conclusions

Advanced accelerator concepts (will be) needed to reach high energy

- "Livingston plot": saturation of accelerator technology:
  - practical limit reached for conventional RF accelerators
  - max acc. gradient ~100 MV/m (limited by material breakdown)



M. Tigner, *Does accelerator-based particle physics have a future?, Phys. Today* (2001)



- Higher energy requires longer machine:
  - facility costs scale with size (and power consumption)
  - TeV machines are desirable
  - 50 MV/m implies 20 km/TeV
  - > 50% cost in main accelerator

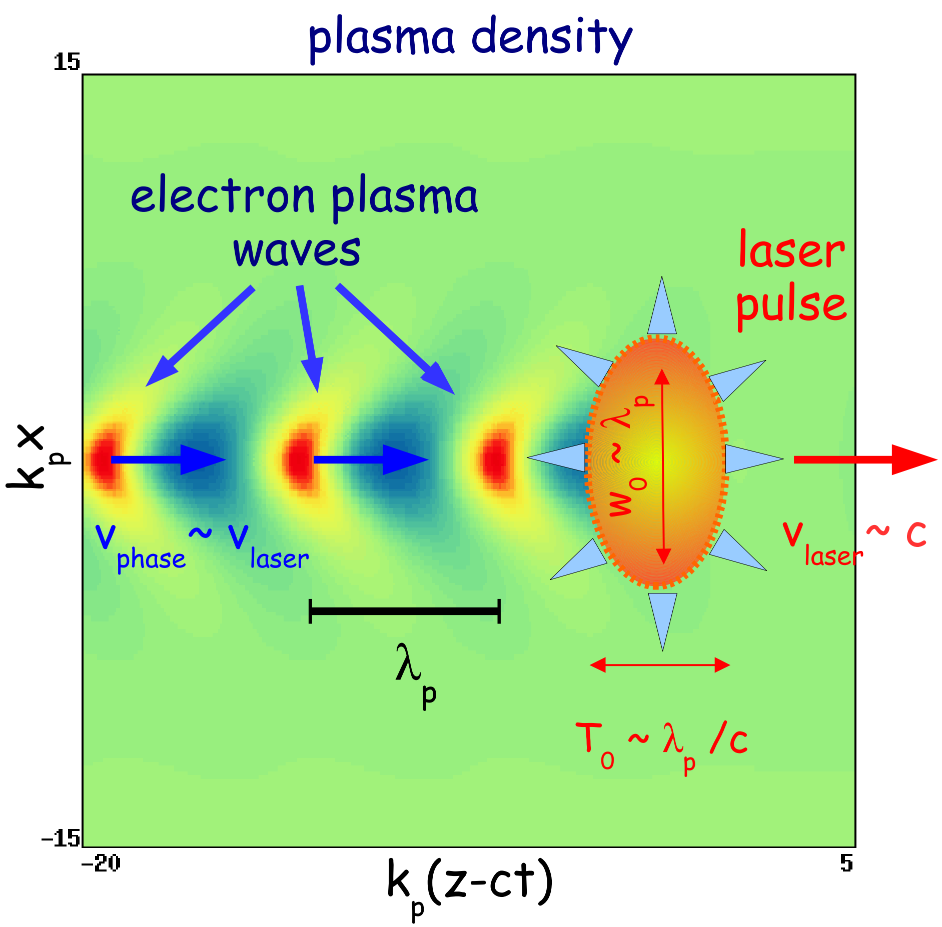
Laser-plasma accelerators*: laser ponderomotive force creates charge separation between electrons and ions

Short and intense laser propagating in a plasma (gas of electrons & ions):

- short □ $T_0 = L_0/c \sim \lambda_p/c$ of tens of fs
- intense □ $a_0 = eA_0^{laser}/mc^2 \approx 8.5 \cdot 10^{-10}\, I_0^{1/2}[\mathrm{W/cm^2}]\, \lambda_0[\mu\mathrm{m}] \sim 1$
  (Ti:Sa laser, $\lambda_0 = 0.8$ um, $I_0 > 10^{18}$ W/cm^2)

Plasma frequency:
$\omega_p = (4\pi n_0 e^2/m)^{1/2}$
□ $k_p = \omega_p/c = 2\pi/\lambda_p$

$\lambda_p \sim n_0^{-1/2} \approx$ 10-100 μm,
for $n_0 \approx 10^{19}$-10^{17} cm^{-3}



Δ = ponderomotive force:
$F_p \sim -\mathrm{grad}(I_{laser})$

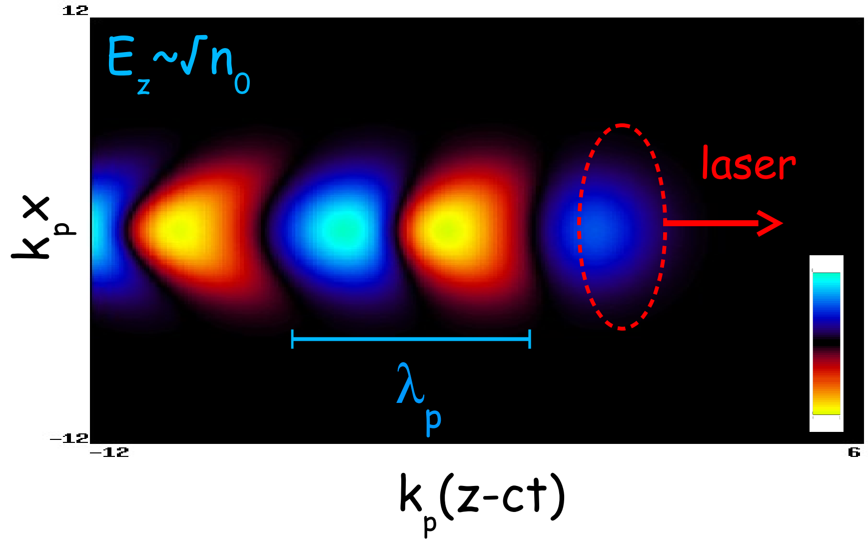
□ F_p displaces electrons (but not the ions) creating charge separation from which EM fields arise

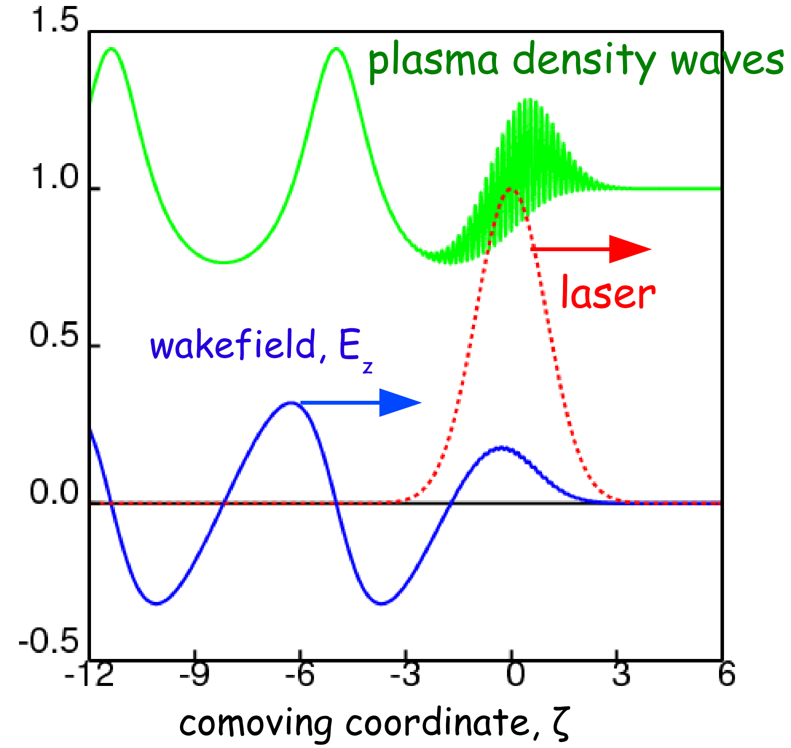
*Esarey *et al.*, Rev. Mod. Phys. (2009)

Laser-plasma accelerators: 1-100 GV/m accelerating gradients

• **<u>Wakefield excitation</u>** due to charge separation: ions at rest VS electrons displaced by ponderomotive force

Map of longitudinal wakefield, E_z



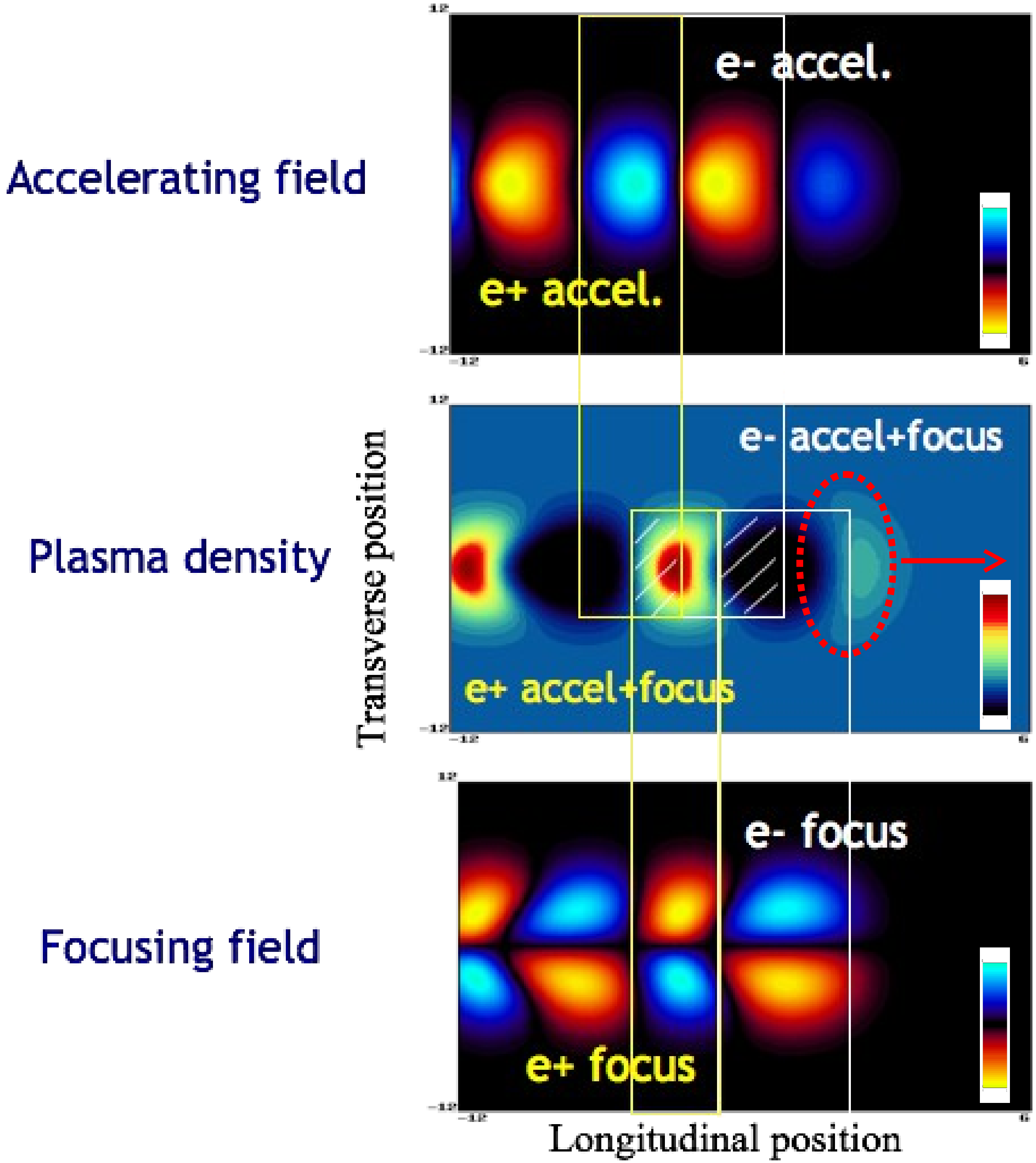


$$E_z \sim mc\omega_p/e \sim 100\ [\mathrm{V/m}] \times (n_0[\mathrm{cm}^{-3}])^{1/2}$$

e.g.: for $n_0 \sim 10^{17}\ \mathrm{cm}^{-3}$, $a_0 \sim 1$ **E_z ~ 30 GV/m**,

~ 10^2-10^3 larger than conventional RF accelerators

Laser-plasma accelerators: laser wake provides focusing for particle beams



- electron and positrons can be accelerated and focused in an LPA

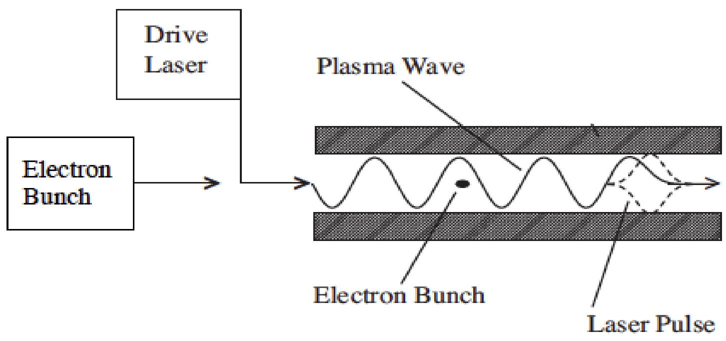
- relative size of focusing and accelerating domains for electrons and positrons depends on laser intensity

- for a_0>>1 the domain for positron focusing shrinks

Electron bunches to be accelerated in an LPA can be obtained from background plasma

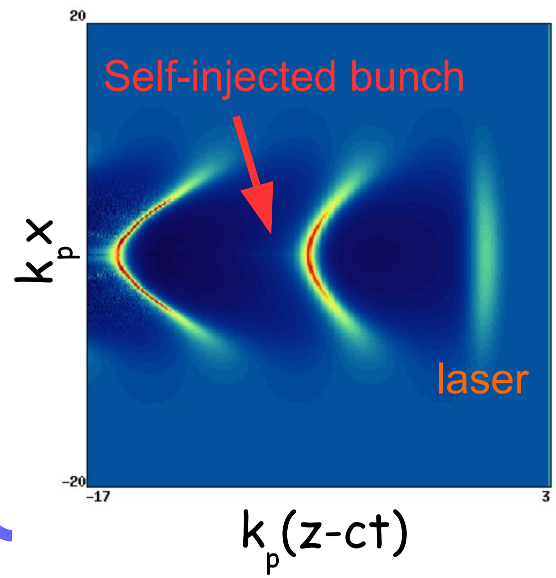
Electron bunch to be accelerated

→ external injection (bunch from a conventional accelerator)



Requires:
- short (~ fs) bunch generation
- precise bunch-laser synchronization

→ trapping of background plasma electrons



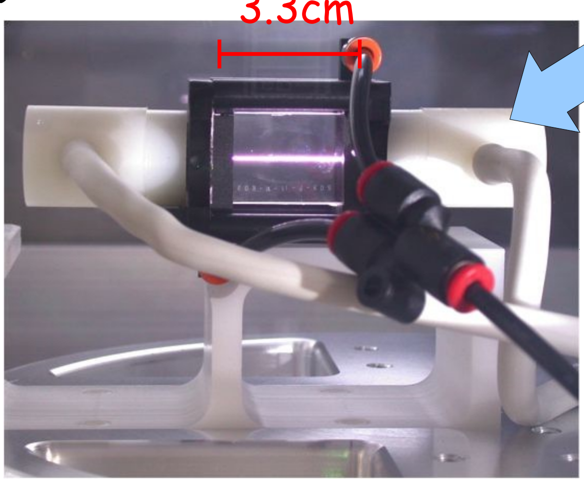
* self-injection (requires high-intensity, high plasma density) → limited control

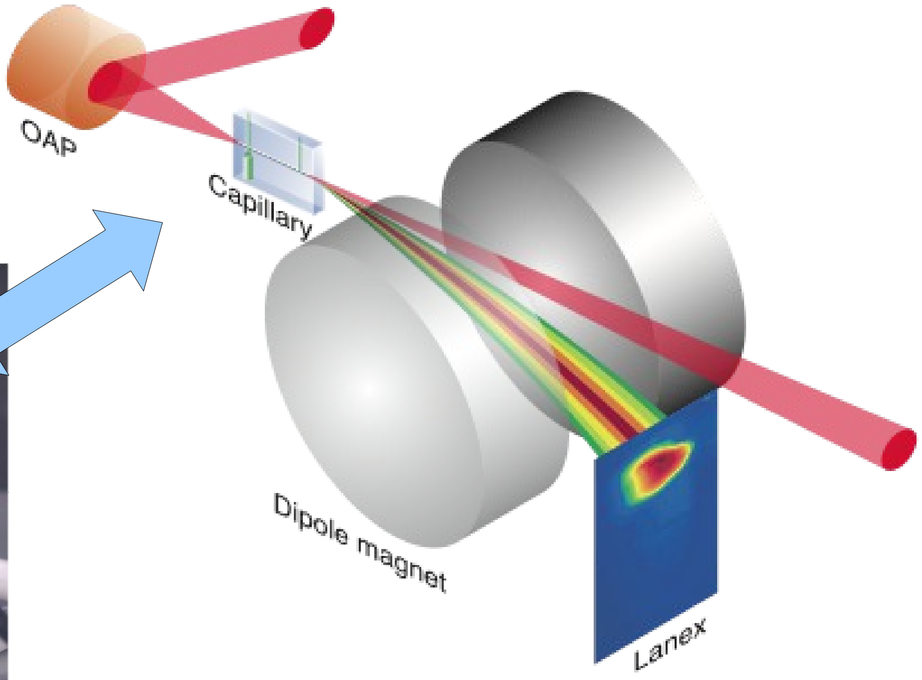
* controlled injection → use laser(s) and/or tailored plasma to manipulate the plasma wave properties and "kick" background electrons inside the accelerating/focusing domain of the wake:

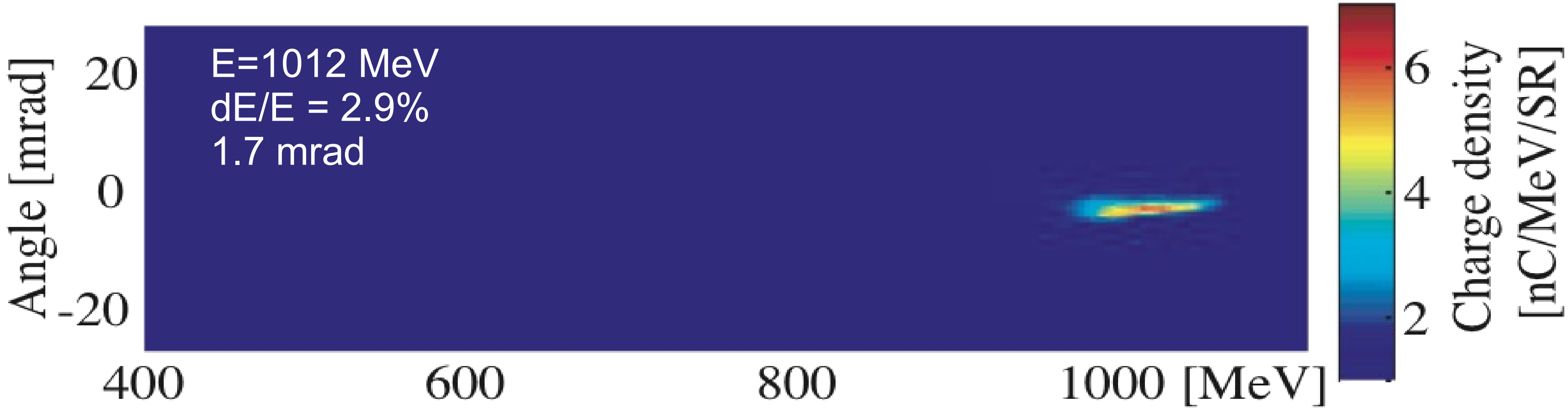
  - laser-triggered injection (e.g., colliding pulse)
  - ionization injection
  - density gradient injection

Example of LPA experiment: 1 GeV high-quality beams from ~3 cm plasma

GeV e-bunch produced from cm-scale plasma (using 1.5 J, 46 fs laser, focused on a **3.3 cm** discharge capillary with a density of 4×10^{18} cm^{-3})*

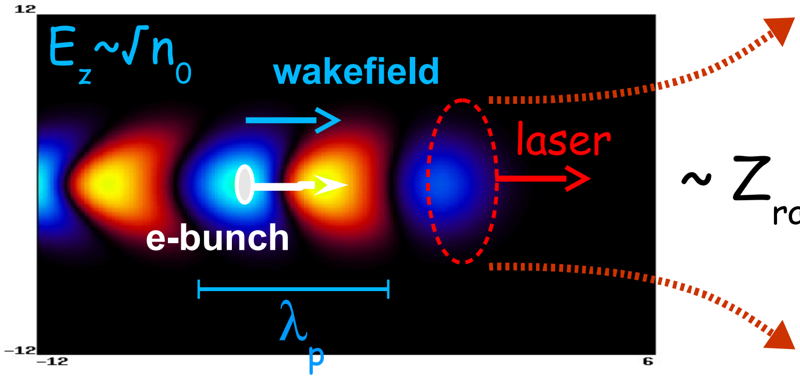




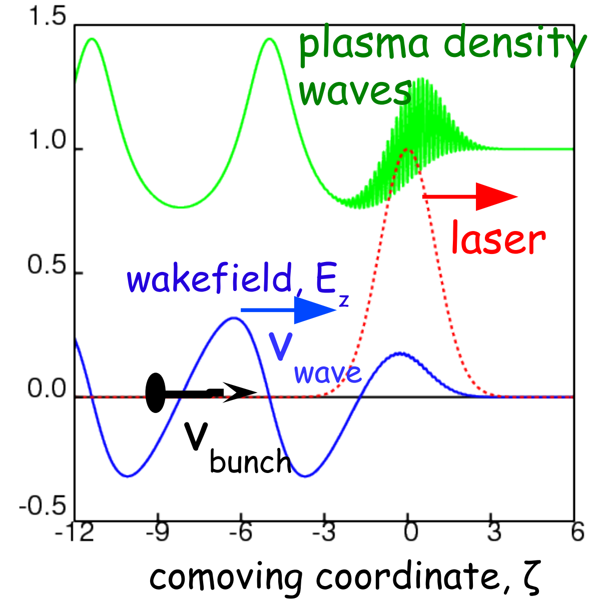


*Leemans *et al.*, Nature Phys. (2006); Nakamura *et al.*, Phys. Plasmas (2007)

Scalings for e-beam energy in LPAs



$\sim Z_{rayleigh} = \pi w_0^2/\lambda_0$



Limits to single stage energy gain:

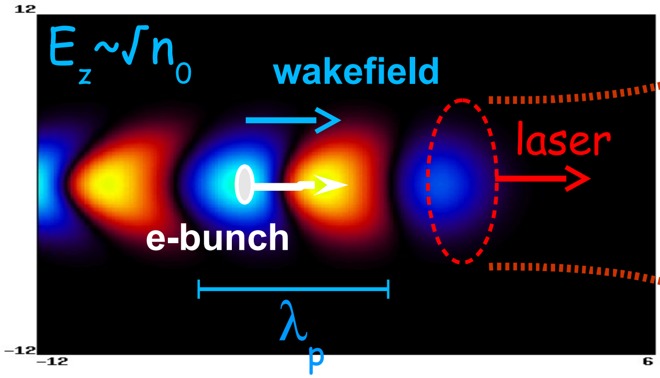
- ✓ laser diffraction (~ Rayleigh range)
  ⇒ mitigated by transverse plasma density tailoring (plasma channel) and/or self-focusing: (self-)guiding of the laser

- ✓ beam-wave dephasing
  $v_{bunch}/c \sim 1$, $v_{wave}/c \sim 1-\lambda_0^2/(2\lambda_p^2)$ ⇒ slippage $L_d \approx \lambda_p c/(v_{bunch}-v_{wave}) \sim n_0^{-3/2}$
  ⇒ mitigated by longitudinal density tailoring

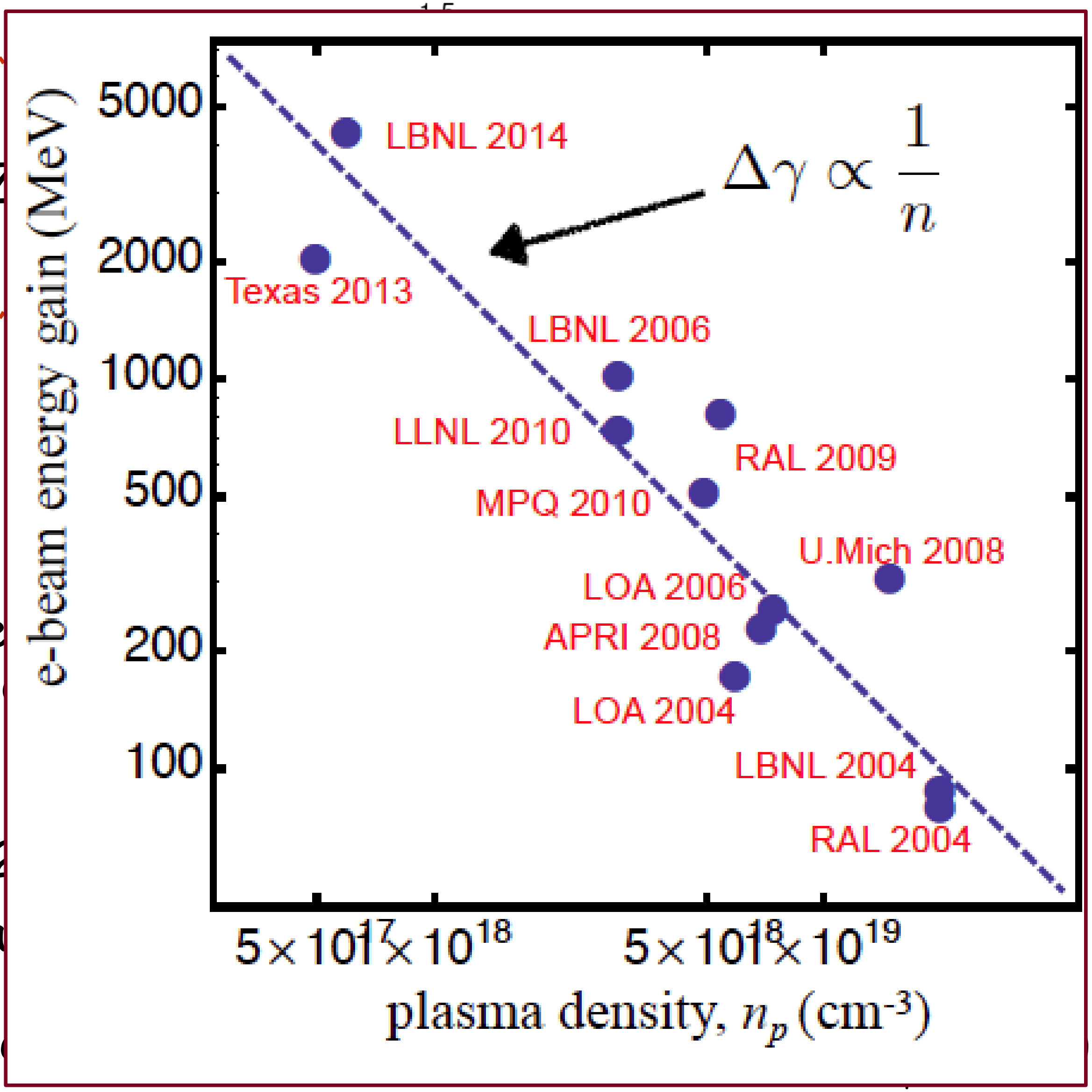
- ✓ laser energy depletion ⇒ energy loss into plasma wave excitation ($L_{pd} \sim n_0^{-3/2}$)

Energy gain (single stage) ~ n_0^{-1} Interaction length (single stage) ~ $n_0^{-3/2}$

Scalings for e-beam energy in LPAs



~ Z



Limits to single stage energy gain:

- laser diffraction (~ Rayleigh
   - mitigated by transverse
  and/or self-focusing: (self-)gui
- beam-wave dephasing
  - $v_{bunch}/c \sim 1$, $v_{wave}/c \sim 1-\lambda_0^2/(2$
   - mitigated by longitudina
- laser energy depletion en

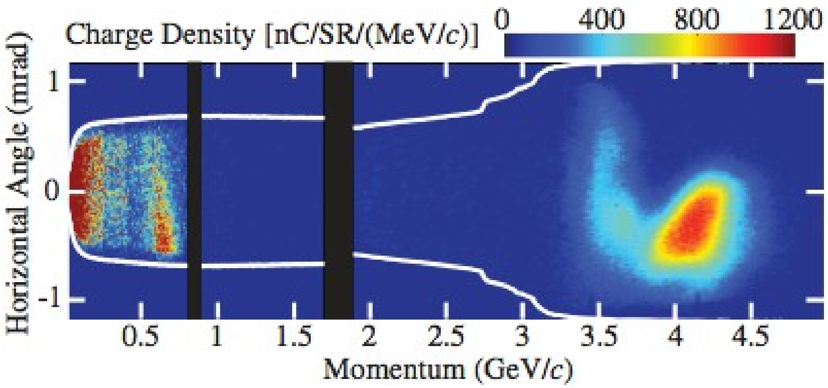
Energy gain (single stage) ~ n_0^{-1} Interaction length (single stage) ~ $n_0^{-3/2}$

BELLA facility (BErkeley Lab Laser Accelerator) aims at reaching 10 GeV

BELLA facility*:

- state-of-the-art PW-laser for accelerator science
  U_{laser}=40 J, T_{laser}=30 fs (> 1 PW), 1 Hz repetition rate
- 10 GeV LPA requires $n_0 \approx 10^{17}$ cm^{-3}, $L_{acc} \approx$ 10-100 cm plasma (depends on LPI regime)

- so far[+], using 16 J, a 4.3 GeV e-beam in a 9 cm plasma (n_0= $7{\cdot}10^{17}$cm^{-3}) has been obtained



*Leemans *et al.*, AAC (2010)
[+] Leemans *et al.*, PRL (2014)

Numerical modeling can help understanding the physics and aid design of future LPAs

Physics of laser-plasma interaction is (highly) nonlinear:

⇒ no (or very few) analytical solutions are available

⇒ fully nonlinear simulation tool is required to help understanding the physics, and aid the design of next generation LPAs, in particular, we need to:

- model laser evolution in the plasma (optimize guiding)
- model 3D wake structure (optimize accelerator)
- model kinetic physics related to particle trapping (optimize injection)
- model details of the dynamics accelerated beam

==> Requires solving Maxwell's equations for electromagnetic fields (laser+wake) coupled with evolution equation for plasma (Vlasov equation)

Particle-In-Cell (PIC)* scheme is a widely adopted modeling tool to study LPAs

PIC scheme
- EM fields (**E**, **B**, **J**) → represented on a (3D) spatial grid
- plasma (electrons, ions) → represented via numerical particles (macroparticles)

Deposit charge/current:
particles → grid,
$(r_k, p_k) \rightarrow \mathbf{J}_{i,j}$

Integration of EM field equations

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla\times\mathbf{E} \qquad \frac{\partial \mathbf{E}}{\partial t} = c\nabla\times\mathbf{B} - 4\pi\mathbf{J}$$

$$\nabla\cdot\mathbf{E} = 4\pi\rho \qquad \nabla\cdot\mathbf{B} = 0$$

Compute force:
interpolation
grid → particles,
$(\mathbf{E},\mathbf{B})_{i,j} \rightarrow \mathbf{E}_k, \mathbf{B}_k$

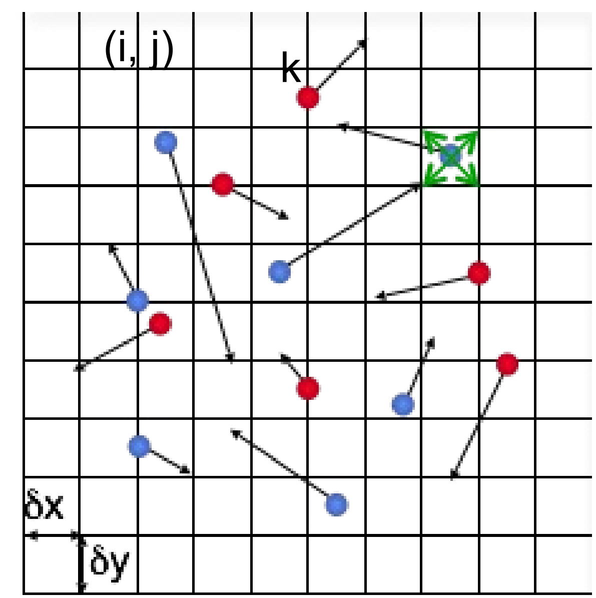
Push particle

$$\begin{cases} \frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i \equiv \frac{\mathbf{p}_i}{m_i\gamma_i}, \\ \frac{d\mathbf{p}_i}{dt} = q_i\left(\mathbf{E}(\mathbf{r}_i,t) + \frac{\mathbf{v}_i}{c}\times\mathbf{B}(\mathbf{r}_i,t)\right) \end{cases}$$

Δt

Initial condition:
laser field & plasma configuration

Spatial grid



*Birdsall, Langdon "*Plasma physics via computer simulations*"

3D full-scale modeling of an LPA over cm to m scales is a challenging task

laser wavelength (λ_0)	~ µm
laser length (L)	~ few tens of µm
plasma wavelength (λ_p)	~10 µm @ 10^{19} cm^{-3} ~30 µm @ 10^{18} cm^{-3} ~100 µm @ 10^{17} cm^{-3}
interaction length (D)	~ mm @ 10^{19} cm^{-3} $\rightarrow$ 100 MeV ~ cm @ 10^{18} cm^{-3} $\rightarrow$ 1 GeV ~ m @ 10^{17} cm^{-3} $\rightarrow$ 10 GeV

Simulation complexity:

$\propto (D/\lambda_0) \times (\lambda_p/\lambda_0)$

$\propto (D/\lambda_0)^{4/3}$ [if D is dephasing length]

3D explicit PIC simulation:

- 10^4-10^5 CPUh for 100 MeV stage
- ~10^6 CPUh for 1 GeV stage
- ~~~10^7 - 10^8 CPUh for 10 GeV stage~~

Ex: Full 3D PIC modeling of 10 GeV LPA

grid: 5000x500^2 ~10^9 points

particles: ~4x10^9 particles (4 ppc)

time steps: ~10^7 iterations

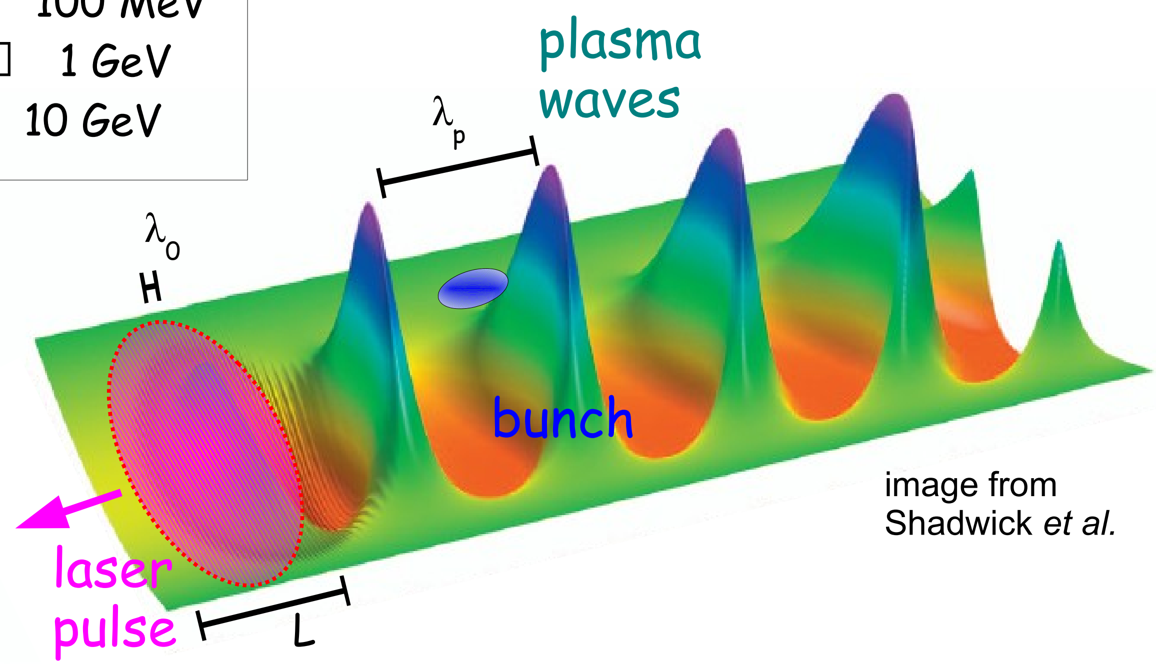


image from Shadwick *et al.*

The INF&RNO framework: motivations

What we need (from the computational point of view):

- run 3D simulations (dimensionality matters!) of cm/m-scale laser-plasma interaction in a reasonable time (a few hours/days)
- perform, for a given problem, different simulations (exploration of the parameter space, optimization, convergence check, etc..)

Reduced Models[#,%,^,&,@,+]
[drawbacks/issues: neglecting some aspects of the physics depending on the particular approximation made]

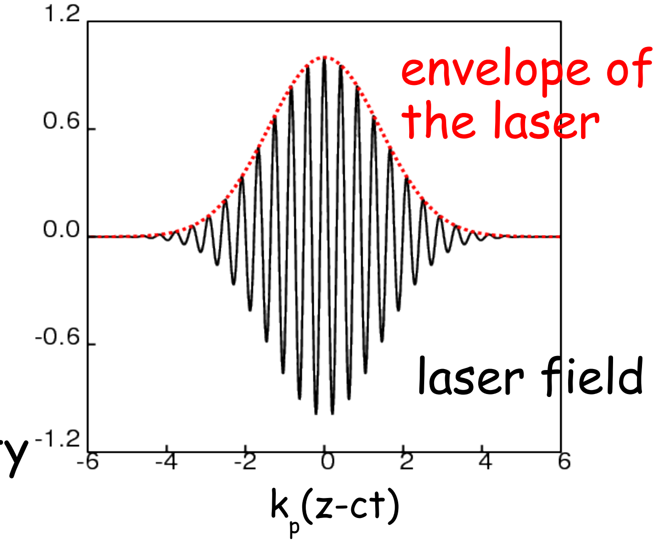
[#] Mora & Antonsen, Phys. Plas. (1997) [WAKE]
[%] Huang, et al., JCP (2006) [QuickPIC]
[^] Lifshitz, et al., JCP (2009) [CALDER-circ]
[&] Cowan, et al., JCP (2011) [VORPAL/envelope]
[@] Benedetti, et al., AAC2010/PAC2011/ICAP2012 [INF&RNO]
[+] Mehrling, et al., PPCF (2014) [HiPACE]

Lorentz Boosted Frame[*,~]
[drawbacks/issues: control of numerical instabilities, self-injection to be investigated, under-resolved physics]

*Vay, PRL (2007)
~S. Martins, Nature Phys. (2010)

INF&RNO* is orders of magnitude faster than conventional PIC codes in modeling LPAs still retaining physical fidelity

INF&RNO ingredients:



- Envelope model for the laser
  - no λ_0
  - axisymmetric
- 2D cylindrical (r-z)
  - self-focusing & diffraction for the laser as in 3D
  - significant reduction of the computational complexity

    ... but only axisymmetric physics
- time-averaged ponderomotive approximation to describe laser-plasma interaction
  - (analytical) averaging over fast oscillations in the laser field
  - scales @ λ_0 are removed from the plasma model # of time steps reduced by $\sim\lambda_p/\lambda_0$
- PIC & (cold) fluid
  - fluid noiseless and accurate for linear/mildly nonlinear regimes
  - integrated modalities (e.g., PIC for injection, fluid acceleration)
  - hybrid simulations (e.g., fluid background + externally injected bunch)
- Moving window
  - computational grid "follows" the laser and the trailing wakefield

* Benedetti *et al.*, Proc. of AAC10; Benedetti *et al.*, Proc. of ICAP12

The *INF&RNO* framework: physical model

The code adopts the "comoving" normalized variables $\xi = k_p(z - ct)$, $\tau = \omega_p t$

- laser pulse (envelope): wave equation

$$a_\perp = \frac{\hat{a}(\xi,r)}{2} e^{i(k_0/k_p)\xi} + c.c. \quad \rightarrow \quad \left(\nabla_\perp^2 + 2i\frac{k_0}{k_p}\frac{\partial}{\partial\tau} + 2\frac{\partial^2}{\partial\xi\partial\tau} - \frac{\partial^2}{\partial\tau^2}\right)\hat{a} = \frac{\delta}{\gamma_{\rm fluid}}\hat{a}$$

- wakefield (fully electromagnetic): Maxwell's equation

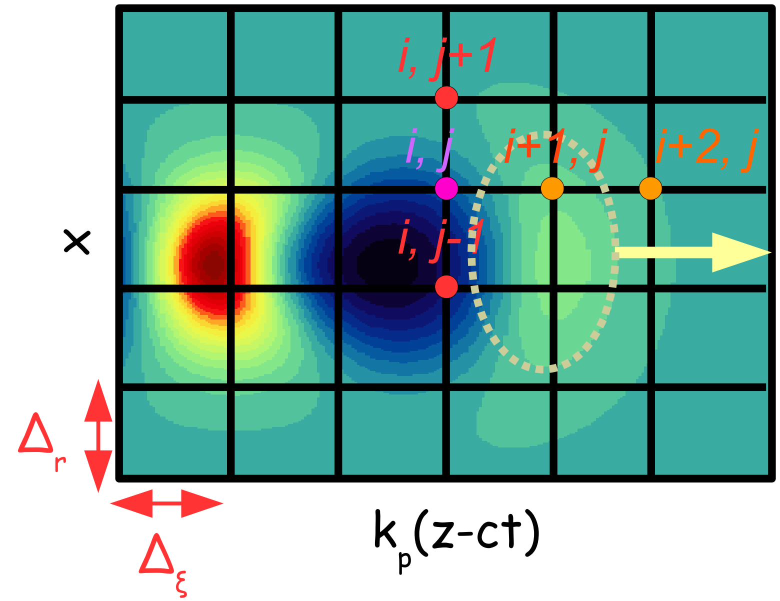
$$\frac{\partial E_r}{\partial\tau} = \frac{\partial(E_r - B_\phi)}{\partial\xi} - J_r \qquad \frac{\partial E_z}{\partial\tau} = \frac{\partial E_z}{\partial\xi} + \frac{1}{r}\frac{\partial(rB_\phi)}{\partial r} - J_z \qquad \frac{\partial B_\phi}{\partial\tau} = -\frac{\partial(E_r - B_\phi)}{\partial\xi} + \frac{\partial E_z}{\partial r}$$

- plasma

$$\text{PIC} \rightarrow \begin{cases} \forall j=1,\dots,N_p \\ \dfrac{d\xi_j}{d\tau} = \beta_{z,j} - 1 \qquad \dfrac{du_{z,j}}{d\tau} = -\dfrac{\partial\gamma_j}{\partial\xi} - E_z - \beta_r B_\phi \\ \dfrac{dr_j}{d\tau} = \beta_{r,j} \qquad \dfrac{du_{r,j}}{d\tau} = -\dfrac{\partial\gamma_j}{\partial r} - E_r + \beta_z B_\phi \\ \gamma_j = \sqrt{1 + |\hat{a}|^2/2 + u_{z,j}^2 + u_{r,j}^2} \end{cases} \qquad \text{fluid} \rightarrow \begin{cases} \dfrac{\partial\delta}{\partial\tau} = \dfrac{\partial\delta}{\partial\xi} - \nabla\cdot\left(\vec{\beta}\delta\right) \\ \dfrac{\partial(\delta u_j)}{\partial\tau} = \dfrac{\partial(\delta u_j)}{\partial\xi} - \nabla\cdot\left(\vec{\beta}\delta u_j\right) + \\ \quad + \delta\left(-(\mathbf{E} + \vec{\beta}\times\mathbf{B}) - \dfrac{1}{2\gamma_{\rm fluid}}\nabla\dfrac{|\hat{a}|^2}{2}\right)_j \\ \gamma_{\rm fluid} = \sqrt{1 + |\hat{a}|^2/2 + u_z^2 + u_r^2} \end{cases}$$

where δ is the density and **J** the current density

The *INF&RNO* framework: numerical aspects



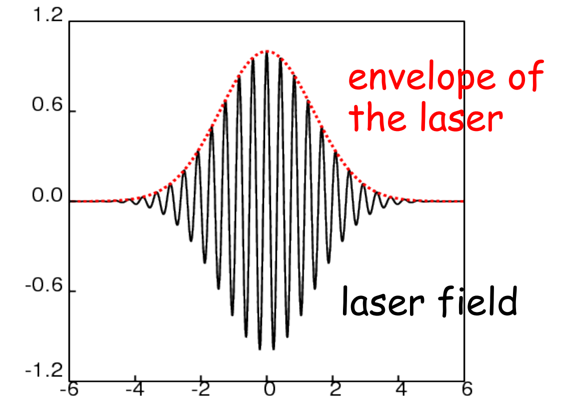
- longitudinal derivatives:
  - 2^{nd} order **upwind** FD scheme*
    - $(\partial_\xi f)_{i,j} = (-3f_{i,j} + 4f_{i+1,j} - f_{i+2,j})\,/2\Delta_\xi$
  - B.C. easy to implement (unidirectional information flux in ξ from R to L)
- transverse (radial) derivatives:
  - 2^{nd} order **centered** FD scheme
    - $(\partial_r f)_{i,j} = (f_{i,j+1} - f_{i,j-1})\,/2\Delta_r$
  - fields are "well behaved" in r=0, (no singularity)
- **RK2** [fluid]/**RK4** [PIC] for time integration of particles/fields
- **quadratic shape** function for force interpolation/current deposition [PIC]
- **digital filtering** for current and/or fields smoothing [PIC]
- **Langdon-Marder** method for charge conservation [PIC]

*Shadwick *et al.*, Phys. Plasmas (2009)

The *INF&RNO* framework: improved laser envelope solver (for LPA problems)/1

- envelope description: $a_{laser} = \hat{a}\, \exp[ik_0(z-ct)]/2 + c.c.$

"slow" "fast"



- $k_0 = 2\pi/\lambda_0$ is the (initial) laser wavenumber;

- In order to accurately describe laser evolution in plasma it is important to correctly model changes in the spectral properties of the laser as the laser depletes

- INF&RNO adopts a 2nd order Crank-Nicholson scheme to evolve $\hat{a}$:

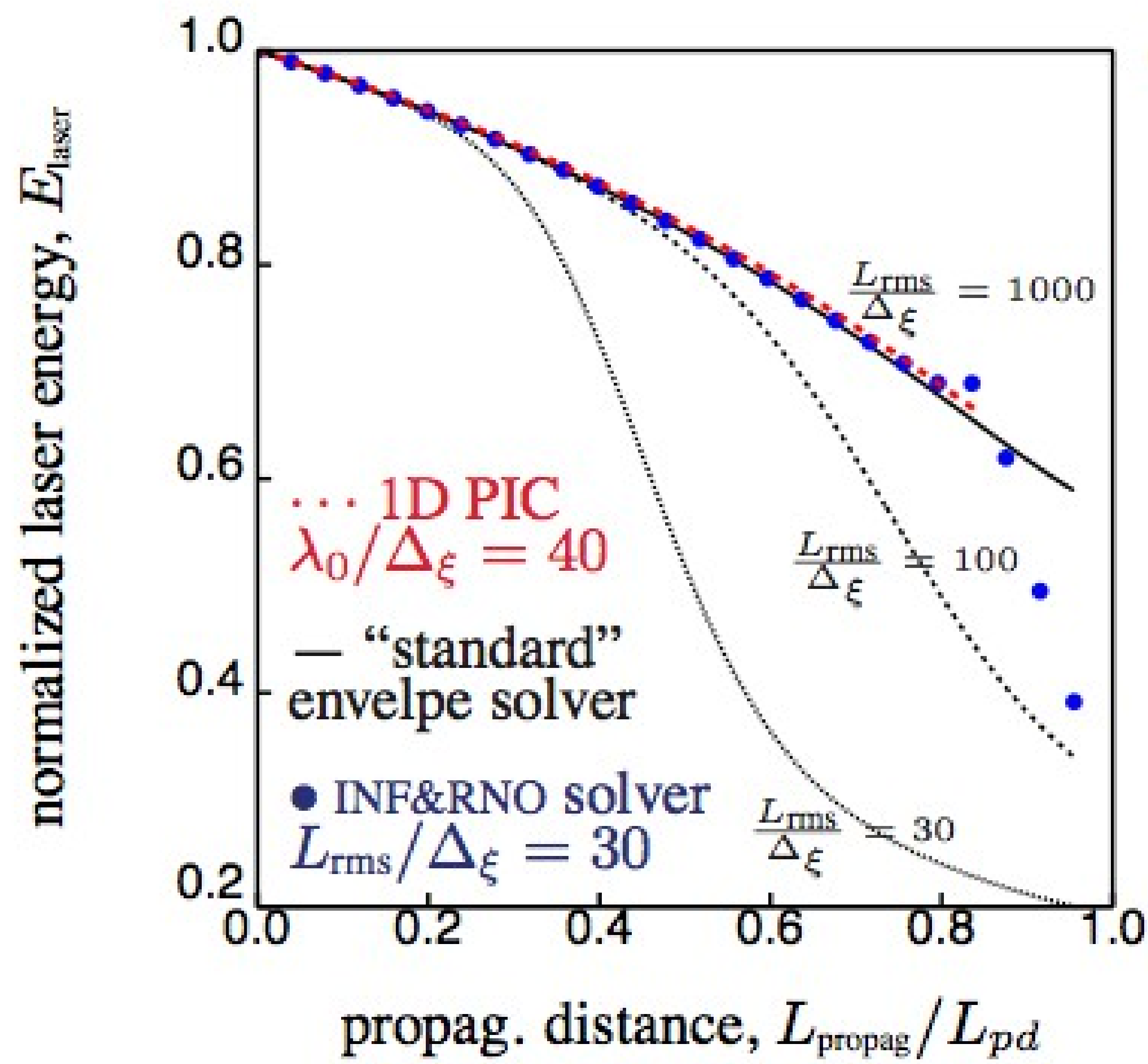
$$-\frac{\hat{a}^{n+1}-2\hat{a}^{n}+\hat{a}^{n-1}}{\Delta_\tau^2}+2\left(i\frac{k_0}{k_p}+\boxed{\frac{\partial}{\partial\xi}}\right)\frac{\hat{a}^{n+1}-\hat{a}^{n-1}}{2\Delta_\tau}=-\nabla_\perp^2\frac{\hat{a}^{n+1}+\hat{a}^{n-1}}{2}+\frac{\delta^n}{\gamma^n_{\text{fluid}}(\hat{a}^n)}\frac{\hat{a}^{n+1}+\hat{a}^{n-1}}{2}$$

- $\partial/\partial\xi$ is computed using a polar representation* for $\hat{a}$, namely $\hat{a}=a\exp(i\theta)$, providing a reliable description of laser evolution even at a relatively low resolution

*Benedetti, *et al.*, Proc. of ICAP2012

The *INF&RNO* framework: improved laser envelope solver (for LPA problems)/2

1D sim.: a_0=1, k_0/k_p=100, L_{rms} = 1 (parameters of interest for a 10 GeV LPA stage)



(L_{pd}=80 cm)

The *INF&RNO* framework: quasi-static solver*

- QS approximation: driver evolves on a time scale >> plasma response

  - **neglect** the $\partial/\partial t$ in wakefields/plasma quantities

for a given
driver configuration
solve
ODE/PDE
for plasma and
wakefield

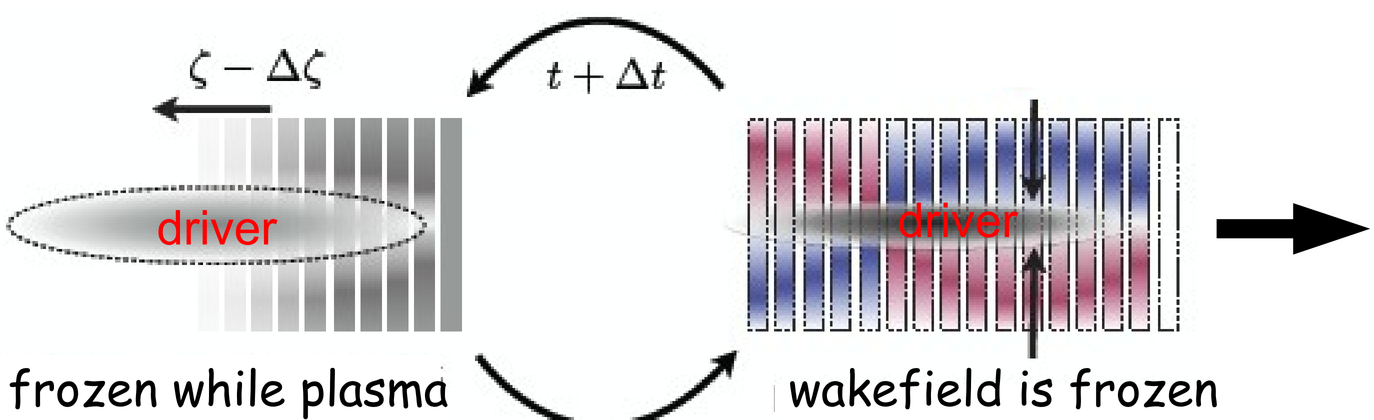
$$\begin{cases} \dfrac{dr}{d\xi} = -\dfrac{u_r}{1+\psi} \\[2ex] \dfrac{du_r}{d\xi} = \dfrac{F_{laser}+\gamma(E_r-B_\phi)}{1+\psi} + B_\phi \\[2ex] \dfrac{d\psi}{d\xi} = \dfrac{u_r}{1+\psi}(E_r-B_\phi) - E_z \\[2ex] \gamma - u_z - \psi = 1 \end{cases}$$

$$\nabla_\perp^2 E_z = \frac{1}{r}\frac{d}{dr}(rJ_r)$$

$$\frac{\partial(E_r-B_\phi)}{d\xi} = J_r$$

$$\frac{1}{r}\frac{d}{dr}(rB_\phi) = J_z - \frac{\partial E_z}{\partial \xi}$$

  - **retain** $\partial/\partial t$ for the driver (laser or particle beam)



driver is frozen while plasma is passed through the driver and wakefields are computed

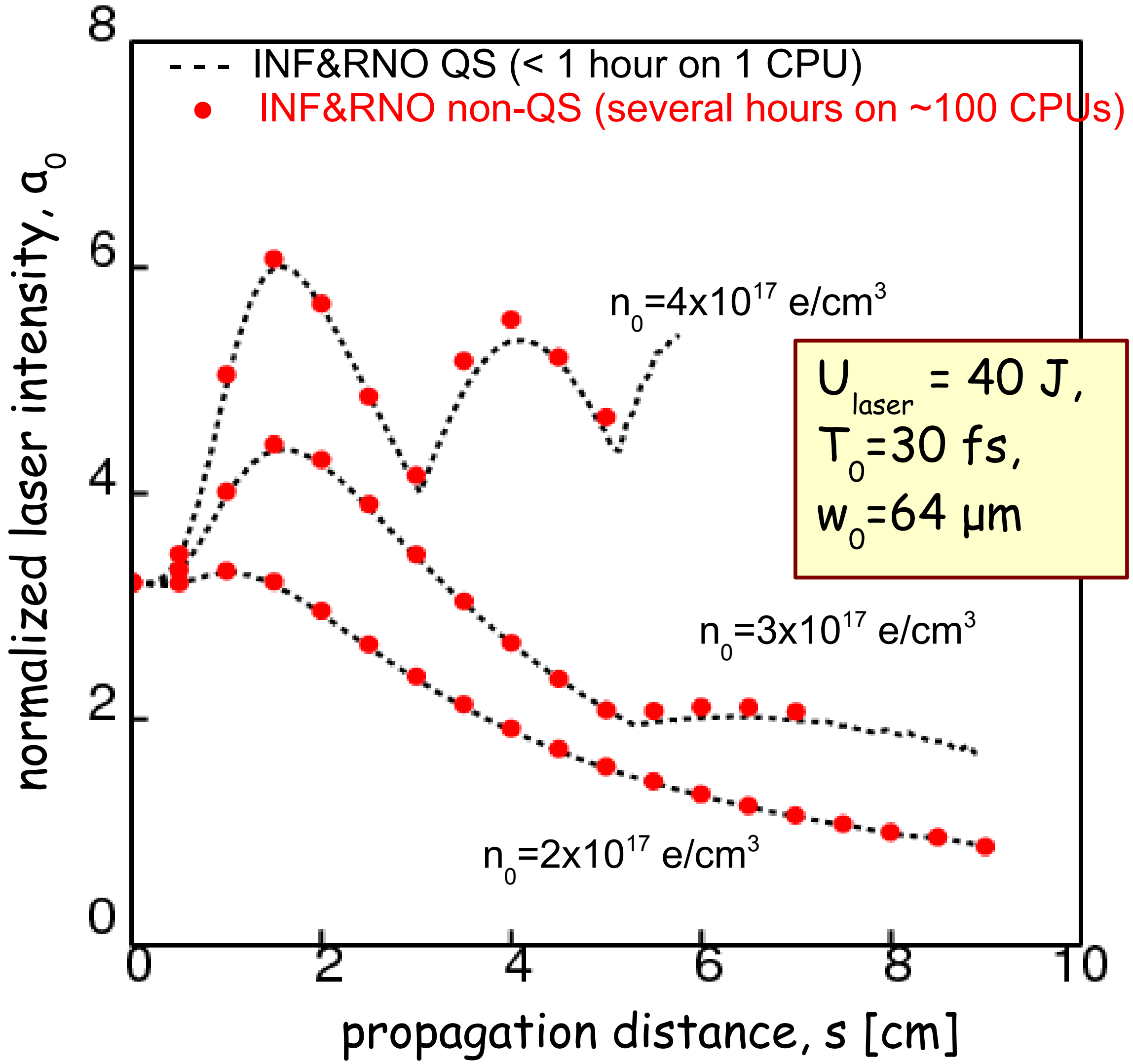
wakefield is frozen while driver is advanced in time

Δt set according to driver evolution (much bigger than conv. PIC)

*Sprangle, *et al.*, PRL (1990)
Mora, Antonsen, Phys. Plas. (1997)
Huang, *et al.*, JCP (2006)
Mehrling, *et al.*, PPCF (2014)

Quasi-static solver allows for significant speed-ups in simulations of underdense plasmas

BELLA laser propagating in uniform plasma (gas-cell)



- Reduction in # of time steps compared to full PIC simulations (laser driver) □ $\sim (\lambda_p/\lambda_0)^2$

- Reduction in # of time steps compared to a PIC code w/ ponderomotive approx (laser driver) □ $\sim\lambda_p/\lambda_0$

- QS solver **cannot** model some aspects of kinetic physics like particle self-injection

The *INF&RNO* framework: Lorentz Boosted Frame* (LBF) modeling/1

• The spatial/temporal scales involved in a LPA simulation DO NOT scale in the same way changing the reference frame

Laboratory Frame	Boosted Lorentz Frame (β_*)
$\lambda_0 \rightarrow$ laser wavelength $\ell \rightarrow$ laser length $L_p \rightarrow$ plasma length $c\Delta t < \Delta z \ll \lambda_0,\ \lambda_0 < \ell \ll L_p$	$\lambda_0' = \gamma_*(1+\beta_*)\,\lambda_0 > \lambda_0$ $\ell' = \gamma_*(1+\beta_*)\,\ell > \ell$ $L_p' = L_p/\gamma_* < L_p$
$\Rightarrow t_{simul} \sim (L_p + \ell)/c$ $\#\,\text{steps} = \frac{t_{simul}}{\Delta t} \propto \frac{L_p}{\lambda_0} \gg 1$ **large** # of steps	$\Rightarrow t'_{simul} \sim (L_p' + \ell')/(c(1+\beta_*))$ $\#\text{steps}' = \frac{t'_{simul}}{\Delta t'} \propto \frac{L_p}{\lambda_0 \gamma_*^2 (1+\beta_*)^2}$ # of steps **reduced** $(1/\gamma_*^2)$

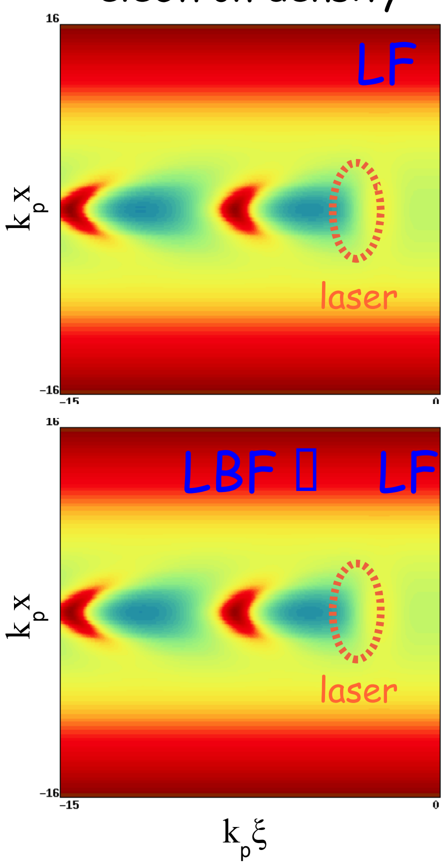
- the LF ***is not*** the optimal frame to run a LPA simulation
- sim. in LBF is shorter (optimal frame is the one of the wake $\gamma_* \sim k_0/k_p$)
- comp. savings ***if*** backwards propagating waves are negligible!
- diagnostic more complicated (LBF ⟹ LF loss of simultaneity)

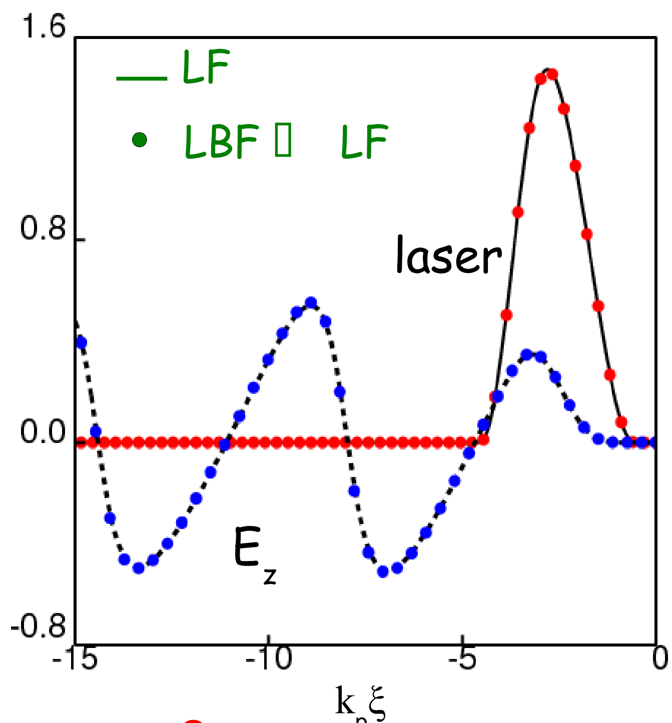
* Vay, PRL (2007); Vay, *et al.*, JCP (2011)

The *INF&RNO* framework: Lorentz Boosted Frame (LBF) modeling/2

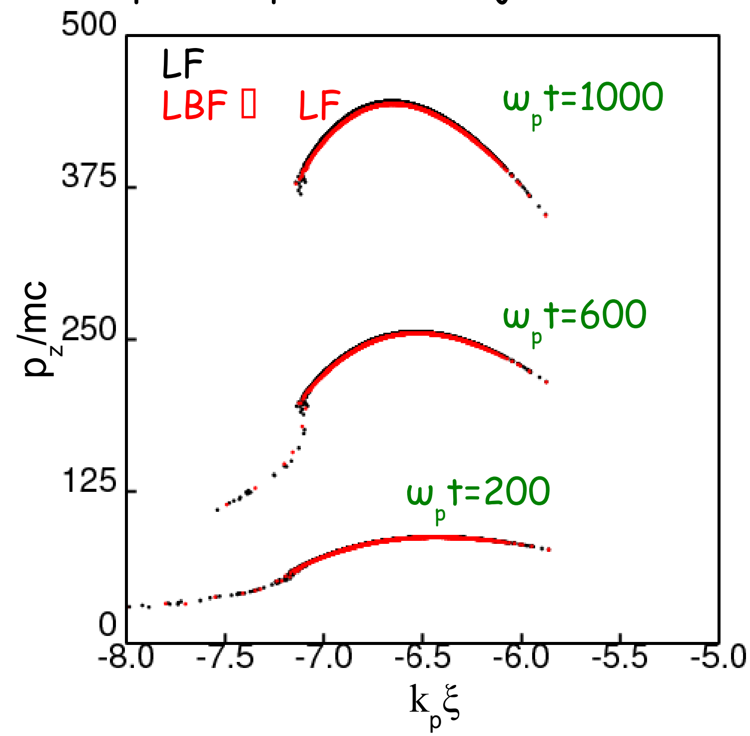
- LBF modeling implemented in INF&RNO/fluid (INF&RNO/PIC underway):
  - ✓ input/output in the Lab frame (swiping plane*, ***transparent*** for the user)
  - ✓ some of the approx. in the envelope model are not Lorentz invariant (limit max γ_{LBF})#

electron density





phase space: ext. injected bunch



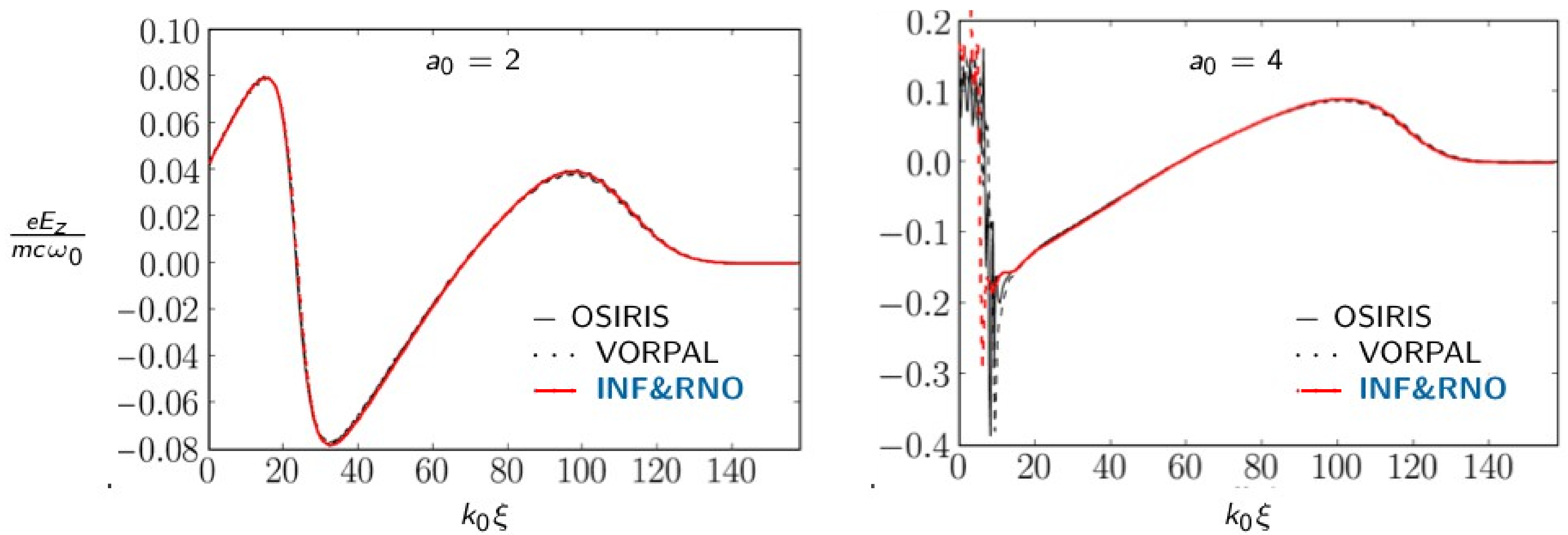
$\gamma_{LBF} = 8$

LF= 16h 47' **VS** LBF=15'

INF&RNO has been benchmarked against other PIC codes used in the laser plasma community*

Comparison with VORPAL[1] and OSIRIS[2]

a_0	$k_p w_0$	k_0/k_p	numerics
2,4	5.7	11.2	$k_p\Delta\xi = 1/30$, $k_p\Delta r = 1/10$, 20ppc, QSF



* Paul *et al.*, Proc. of AAC08 (2008), [1]C. Nieter and J.R. Cary, JCP (2004), [2]R.A. Fonseca *et al.*, ICCS (2002)

Performance of INF&RNO (PIC/fluid)

- code written in C/C++ & parallelized with MPI (1D longitudinal domain decomp.)
  - typically we run on a few 100s to a few 1000s CPUs

- code performance on a MacBookAir laptop (1.7GHz, 8GBRAM, 1600MHz DDR3)

FLUID (RK2)	PIC (RK4)
0.54 μs / (grid point * time step)	0.9 μs / (particle push * time step)

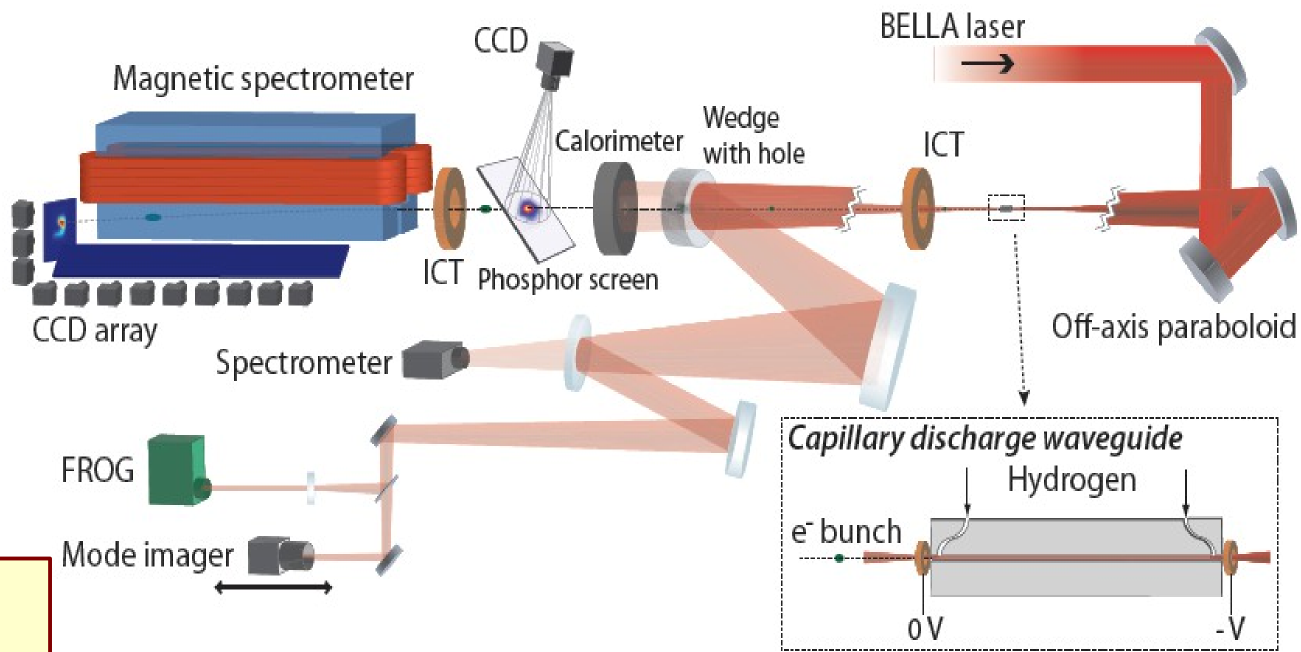
- Examples of simulation cost
  - 100 MeV stage (~10^{19} cm^{-3}, ~ mm) / PIC → **~10^2** CPUh
  - 1 GeV stage (~10^{18} cm^{-3}, ~ cm) / PIC → **~10^3–10^4** CPUh
  - 10 GeV stage quasi-lin. (~10^{17} cm^{-3}, ~m) / FLUID → **~10^3** CPUh
  - 10 GeV stage quasi-lin. (~10^{17} cm^{-3}, ~m) / FLUID + LBF[γ_{LBF}=10] → **~10** CPUh
  - 10 GeV stage bubble (~10^{17} cm^{-3}, ~ 10 cm) / PIC → **~10^4–10^5** CPUh

==> gain between 2 and 5 orders of magnitude in the simulation time compared to "standard" PIC codes

INF&RNO is used to model current BELLA experiments at LBNL

- Modeling of multi-GeV e-beam production from 9 cm-long capillary-discharge-guided sub-PW laser pulses (BELLA) in the self-trapping regime*

Understanding laser evolution (effect of laser mode and background plasma density on laser propagation): limit cap damage & provide "best" wake for acceleration



Interpreting post-interaction laser spectra as an *in situ* density diagnostic: knowledge of density is crucial but difficult

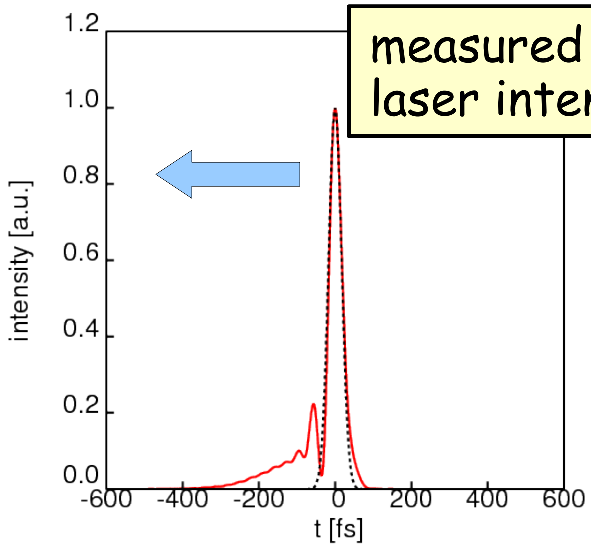
Model e-beam generation & acceleration

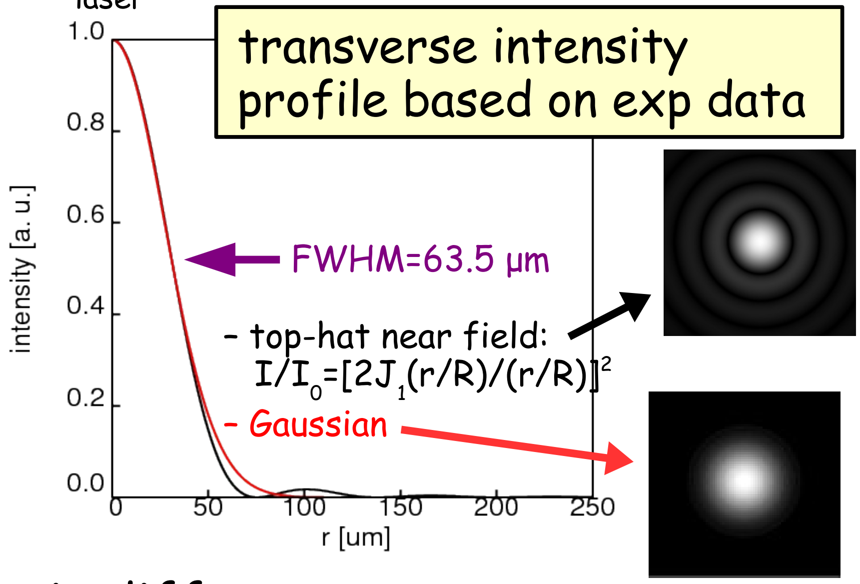
features of INF&RNO allowed to run several simulations for detailed parameters scan at a reasonable computational cost

* Leemans *et al.*, PRL (2014)

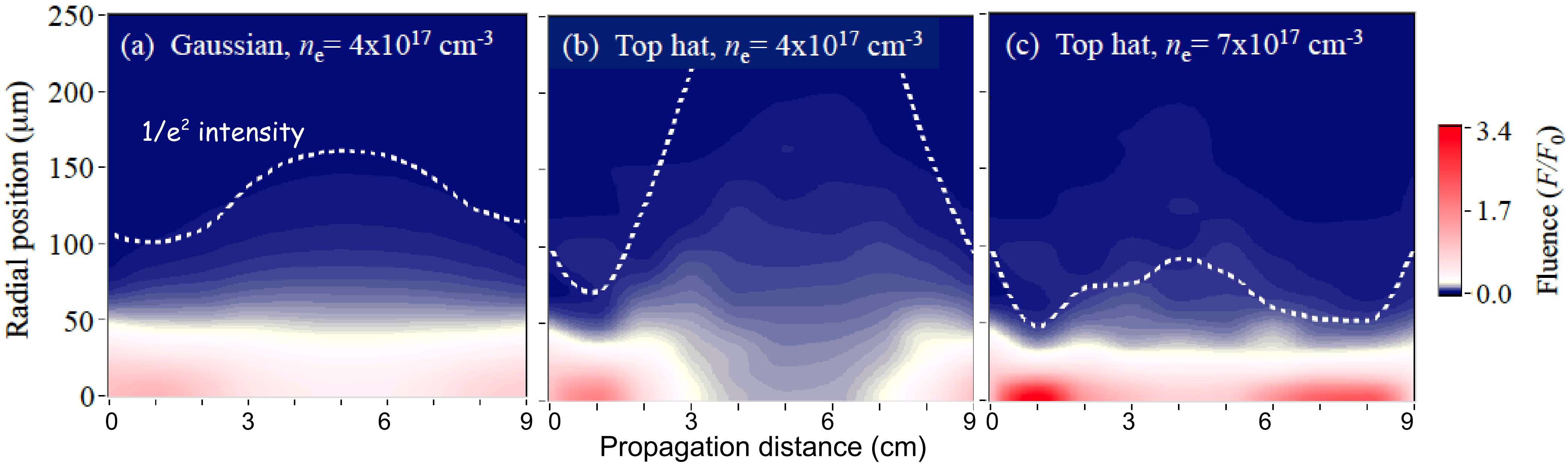
BELLA laser pulse evolution has been characterized studying the effect of transverse laser mode and plasma density profile

- An accurate model of the BELLA laser pulse (U_{laser}=15 J) has been constructed



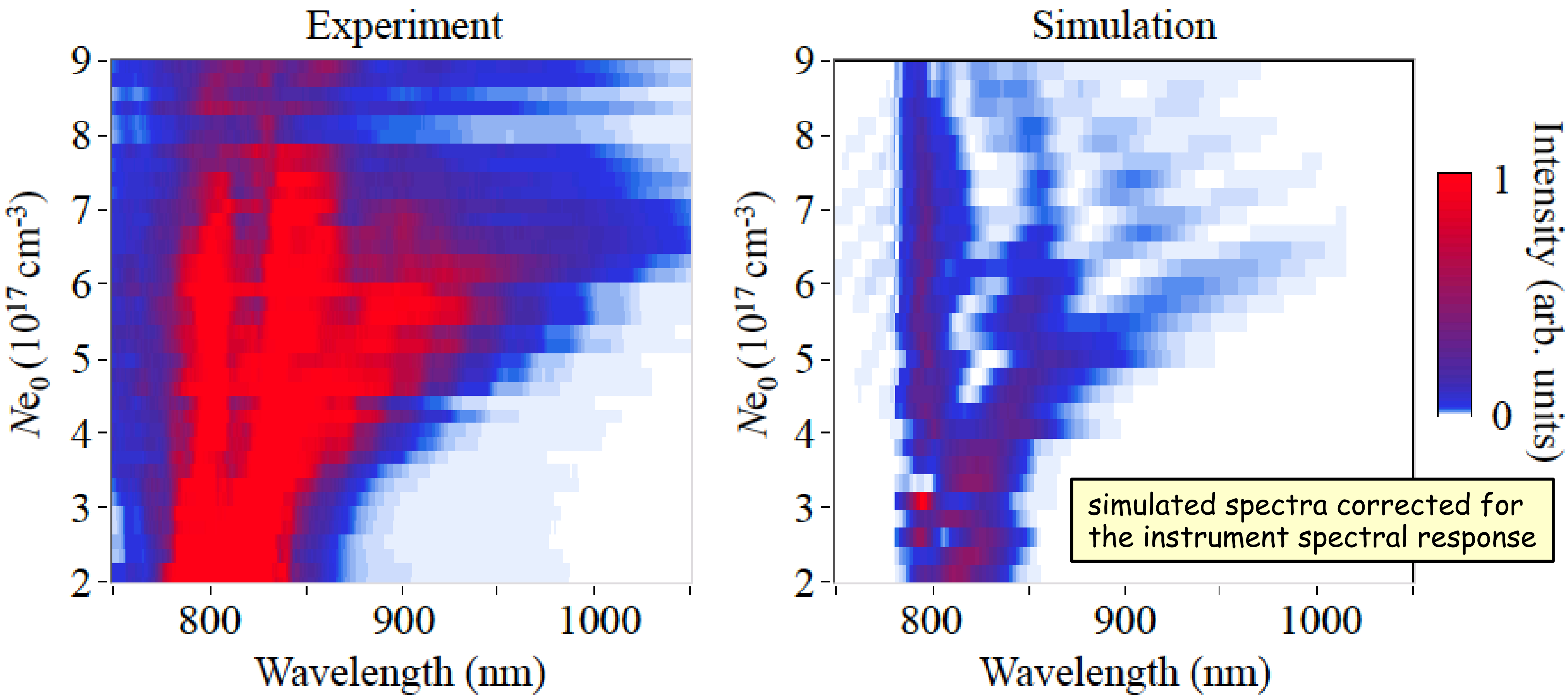


- Propagation in plasma of Gaussian and top-hat is different



Post-interaction laser optical spectra have been used as an independent diagnostic of the on-axis density

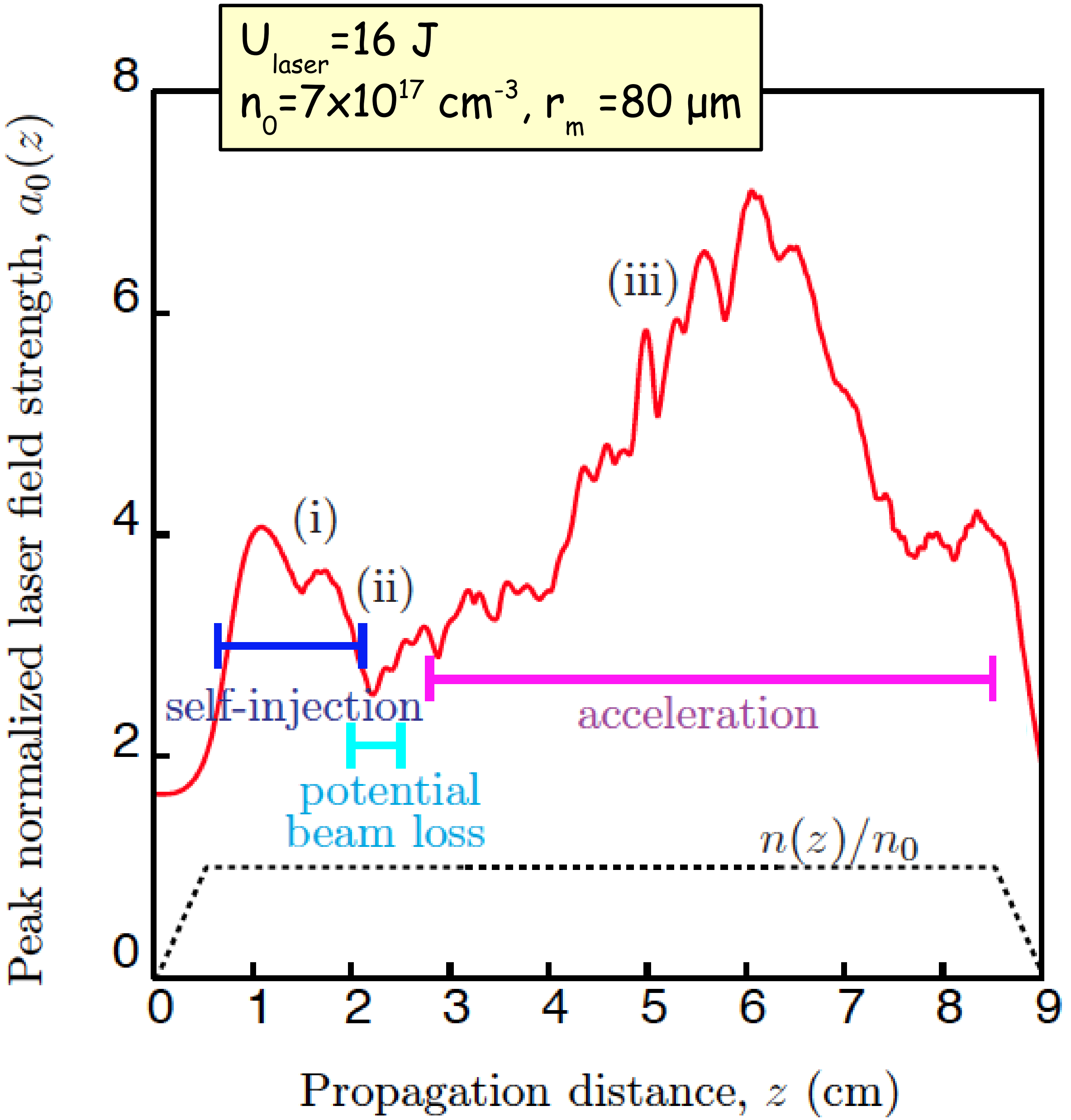
• Comparison between measured and simulated post-interaction (after 9 cm plasma) laser optical spectra (U_{laser}=7.5 J)

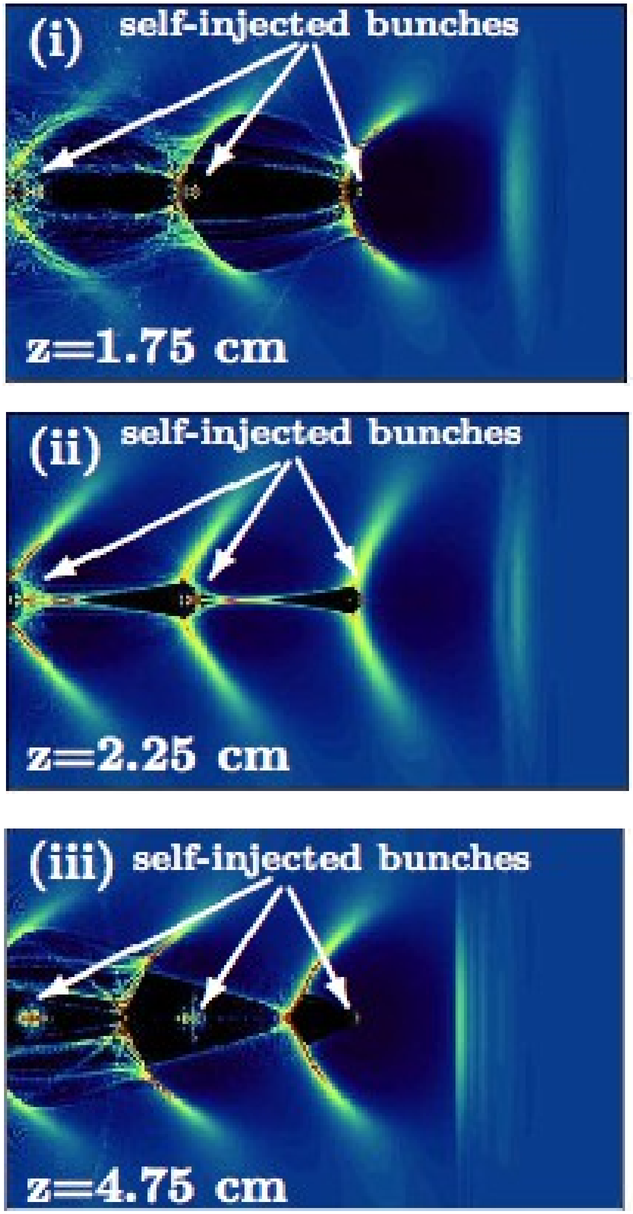


 good agreement between experiment and simulation: independent (*in situ*) diagnostic for the plasma density

Simulation cost: 28 (# sim) x7 CPUh=200 CPUh

INF&RNO full PIC simulation allows for detailed investigation of particle self-injection and acceleration/1



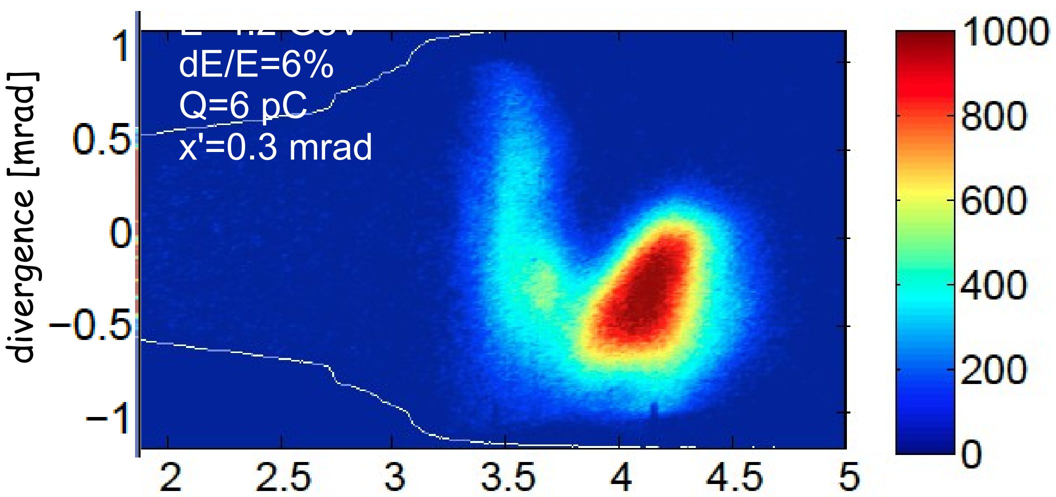


Simulation cost: (1-3) x 10^5 CPUh (gain ~ 1000 compared to full PIC)

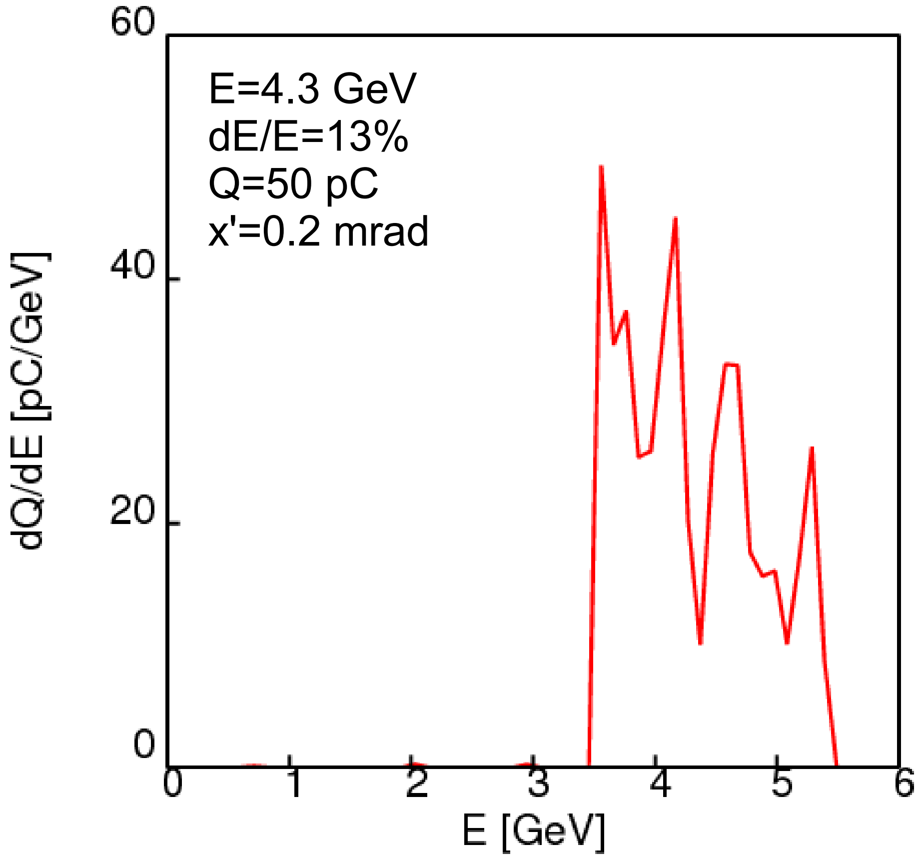
INF&RNO full PIC simulation allows for detailed investigation of particle self-injection and acceleration/2

U_{laser}=16 J
n_0=7x10^{17} cm^{-3}, r_m =80 μm

Measured e-beam spectrum [nC/SR/(MeV/c)]



Simulated energy spectrum



 simulation results for the final e-beam properties in good agreement with experiment

Theory has been used to design different 10 GeV-class scenarios

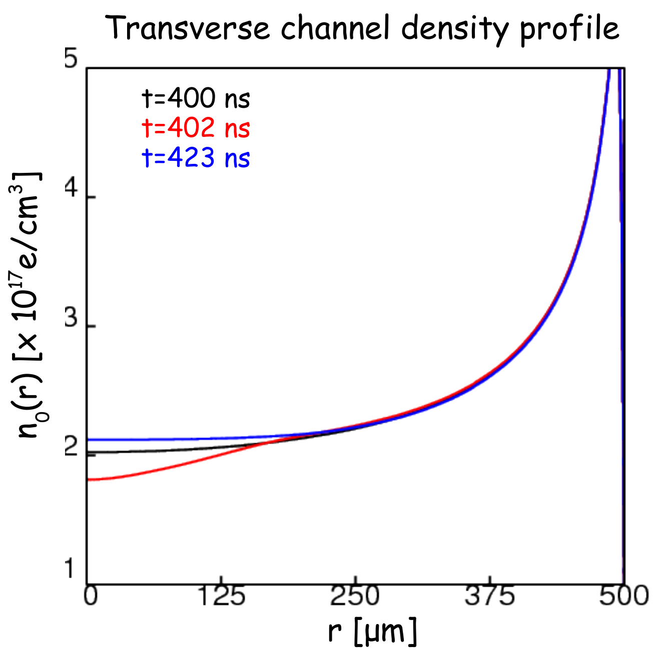
BELLA laser parameters

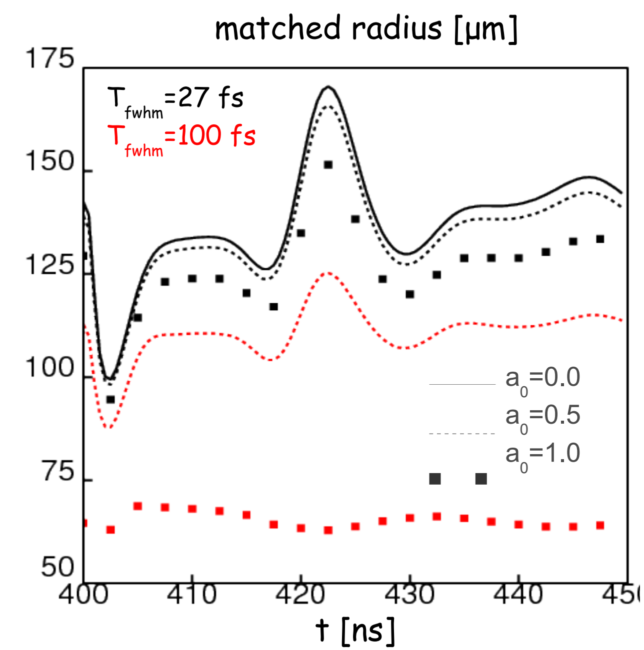
- energy, E_{laser} = 40 J
- pulse length, $T_0 \geq 30$ fs

regimes
- $a_0 > 4$ (T_0=30 fs) **nonlinear (bubble)**
- $a_0 \leq 2$ (T_0=100 fs) **quasi-linear (inj.+accel.)**

Plasma parameters

- on-axis density, n_0 = (1-4) x 10^{17} e/cm^3
- laser guiding through plasma channel (tailored transverse density profile)
  - obtained through MHD sim*
  - optimization laser guiding



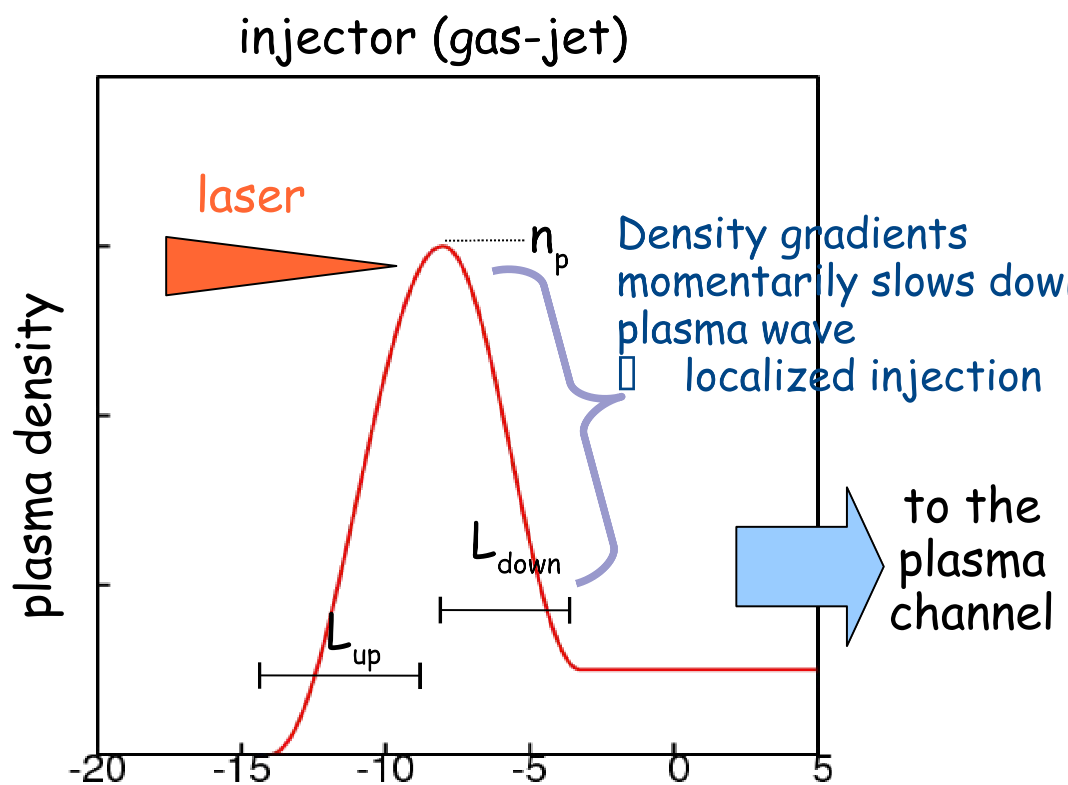


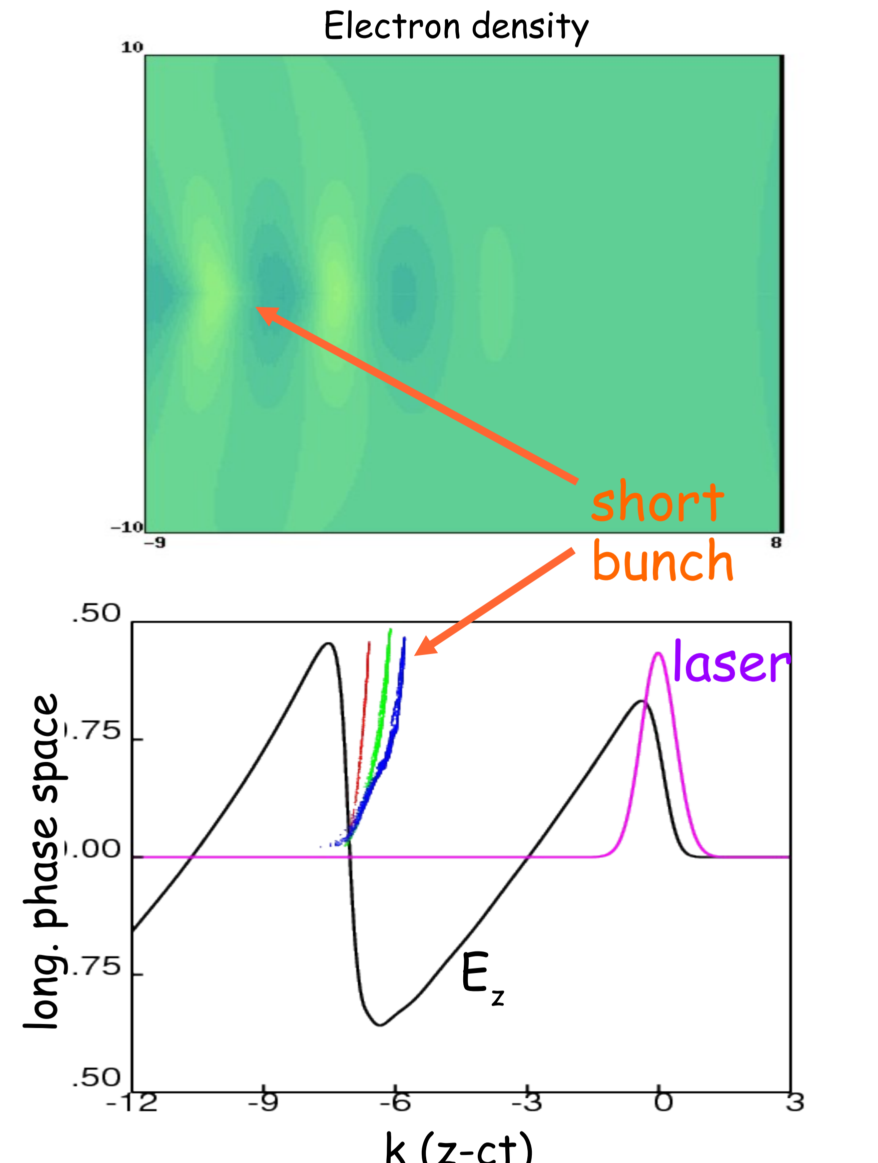
*Bobrova *et al.*, POP (2013)

10 GeV-class stage in the quasi-linear regime: injector + accelerator

$T_{laser} \approx 100$ fs, E=40 J, a_0=1.7, plasma channel $n_0 \approx 2 \times 10^{17}$ e/cm^3 ==> requires triggered injection*

injector (negative density gradient)





$L_{up} \approx L_{down} \approx 100$ µm, $n_p \approx$ (5, 6, 7) x10^{17}e/cm^3

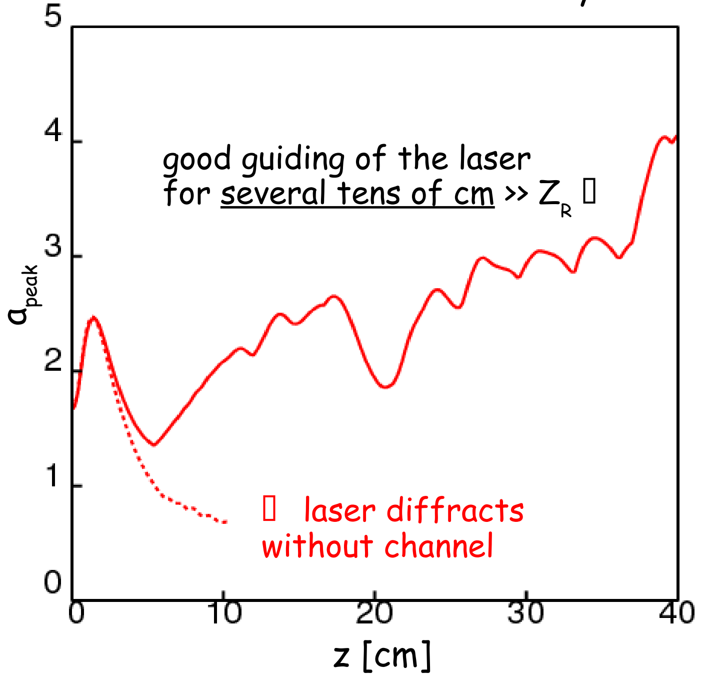
injection phase can be accurately controlled through $\mathbf{n_p}$ and $\mathbf{L_{down}}$

* Gonsalves *et al.*, Nature Phys. (2011)

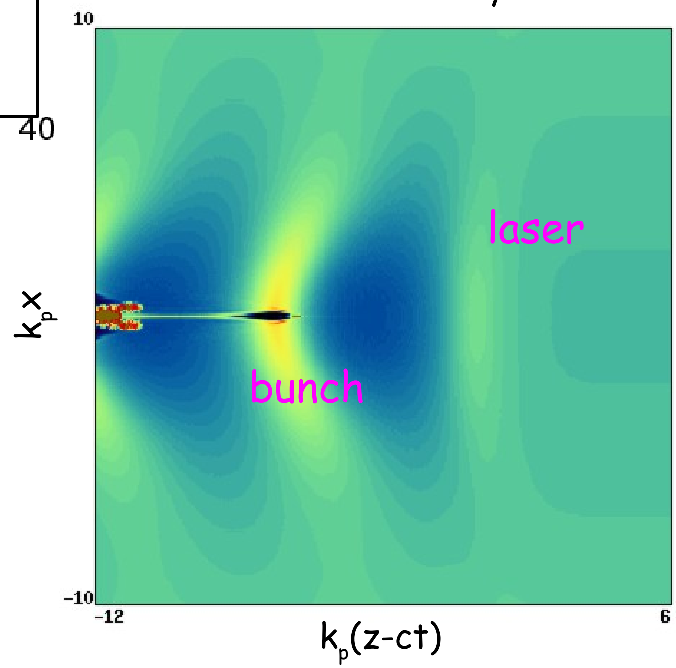
Low energy spread beams produced in 40 cm acceleration length

accelerator (plasma channel)

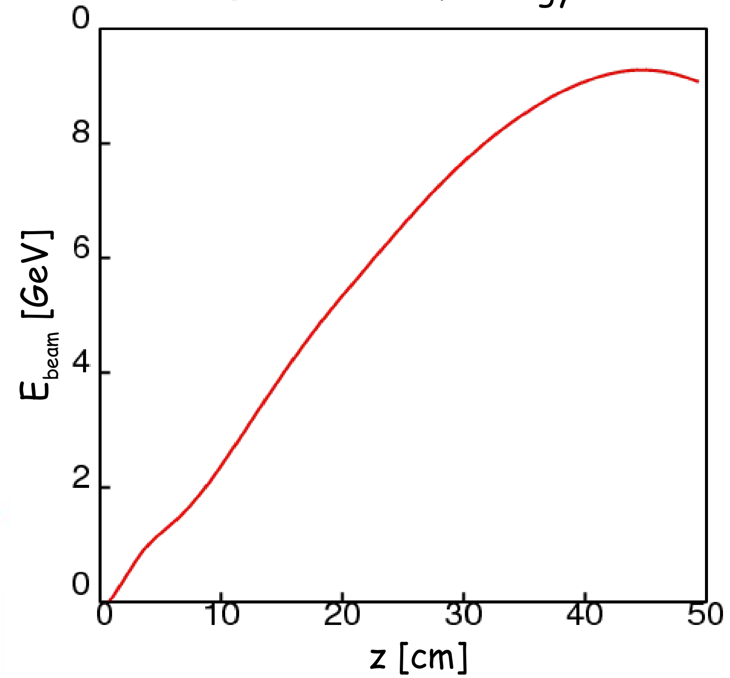
Normalized laser intensity



Electron density



Electron beam energy



Q ~ 10 pC
$E_{average}$ ~ 9.1 GeV
$(dE/E)_{rms}$ ~ 6 %
$(\sigma_z)_{rms}$ ~ 1 µm
$(\sigma_{x'})_{rms}$ ~ 0.15 mrad

Simulation cost: 18 kCPUh (gain ~5000 compared to full PIC)

Conclusions

The INF&RNO computational framework has been presented

- INF&RNO is tailored to LPA problems

- the code is **several orders of magnitude faster compared to "full" PIC**, while still retaining physical fidelity possible to perform large parameters scan at a reasonable computational cost

- **INF&RNO** used to model current (and future) BELLA experiments at LBNL, and to test new ideas

- Simulations are critical to the development of advanced acceleration techniques