Istituto Nazionale
di Fisica Nucleare

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

A review of plasma based beamline elements for advanced beam manipulation

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INFN - Milan


Erice School – Workshop “Trends in Free Electron Laser Physics”, May 17-23 2016

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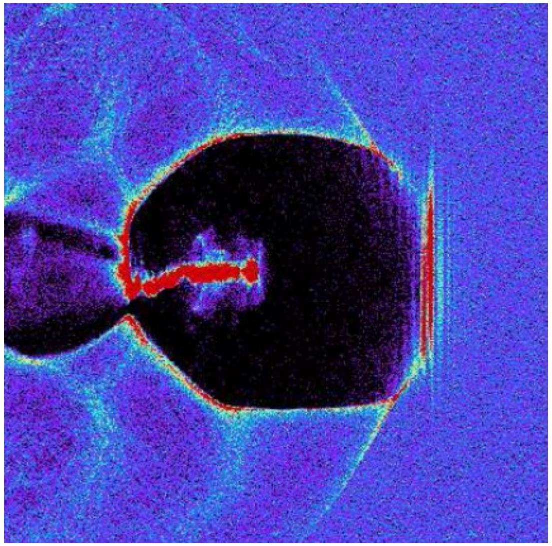
BD issues with plasma beams

Plasma beams properties



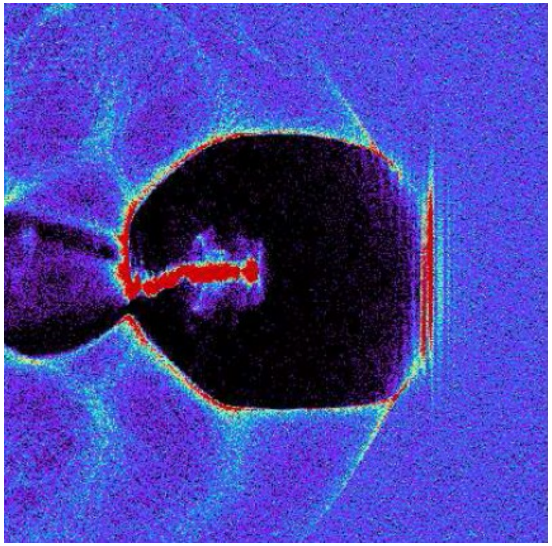
Courtesy: C. Benedetti

Plasma structures (waves) are small:

typical scales are from few tens to few hundreds of microns, depending on plasma density (and wave regime) through

$$\lambda_p[\mu m] \approx \frac{100}{\sqrt{n_0[10^{17}\mathrm{cm}^{-3}]}}$$

Plasma beams properties



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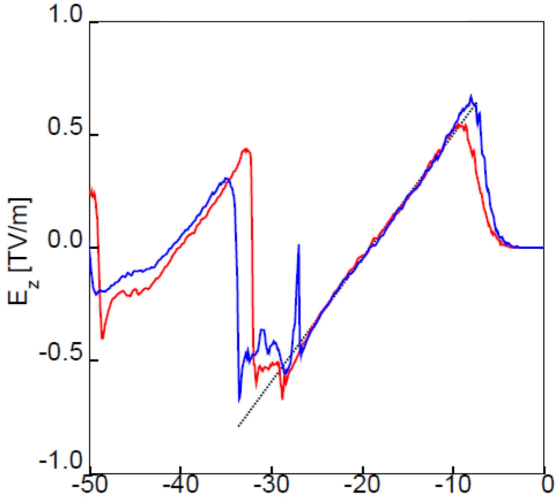
typical values may vary in the range of few to a thousand GV/m

$$E_z^{(\max)}[\mathrm{GV/m}] \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$
$$\partial_r E_r[\mathrm{GV/m/\mu m}] \approx 6 n_0\,[10^{18}\mathrm{cm}^{-3}]$$



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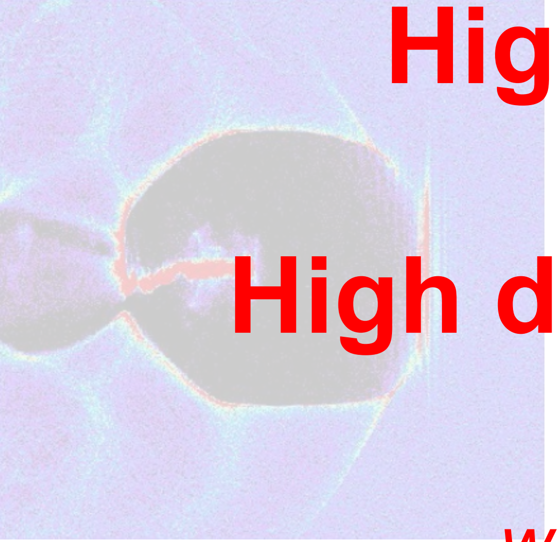

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High energy spread

&

High divergence and tight focusing

… within the plasma channel

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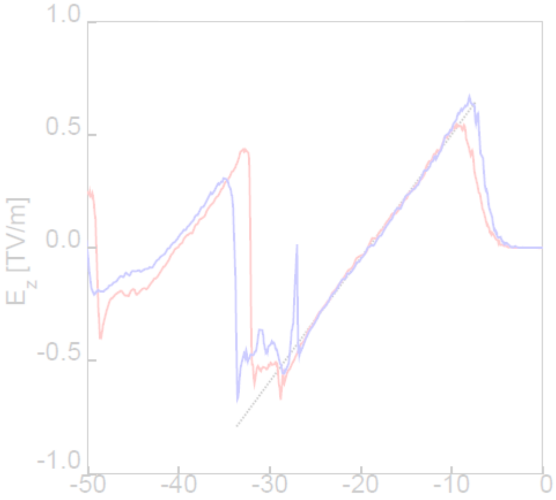

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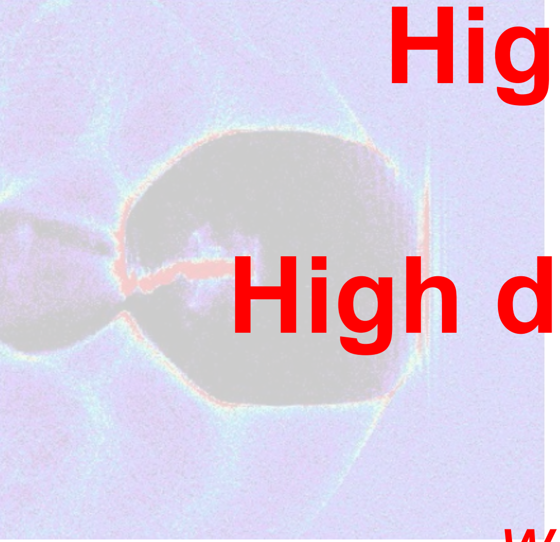

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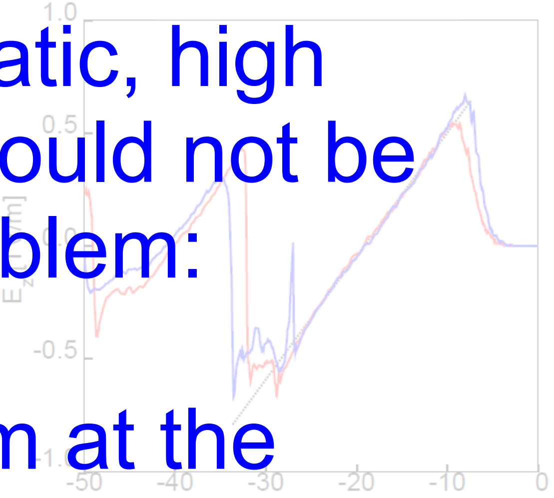
$\partial_r E_r[\mathrm{GV/m/\mu m}] \approx$ [illegible] $n_0[10^{18}\mathrm{cm}^{-3}]$

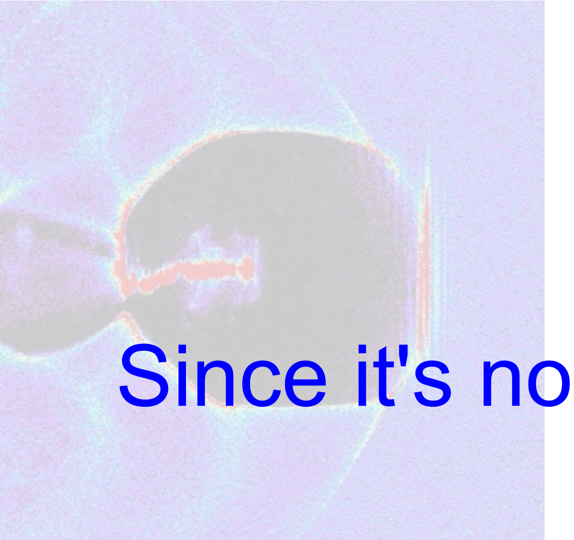
If the bunch was monochromatic, high divergence and tight focusing would not be (at least in principle) a problem:



Courtesy: C. Benedetti

Proper matching of the beam at the (vacuum-)plasma-vacuum interface(s)

Plasma beams properties



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Since it's not, we must be prepared to face the effects of

CHROMATISM

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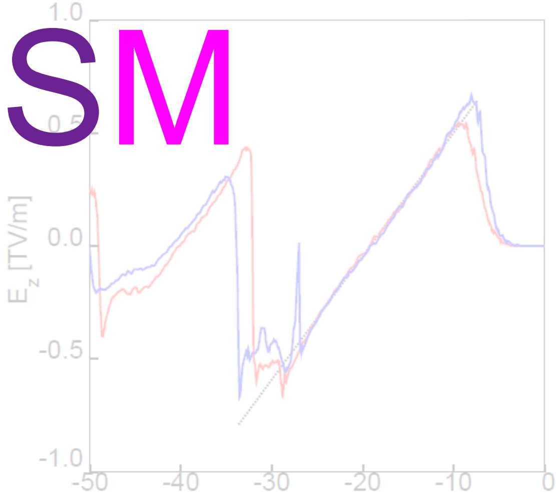


Courtesy: C. Benedetti

Highly chromatic beam transport: RF acceleration vs plasma acceleration

$$\varepsilon_n^2 = <\gamma>^2 \left(\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2\right)$$

General formula

Emittance dominated beam drifting in vacuum

$$\varepsilon_n^2 = <\gamma>^2 \left(s^2 \sigma_E^2 \sigma_{x'}^4 + \varepsilon^2\right)$$

EXAMPLE: RF gun

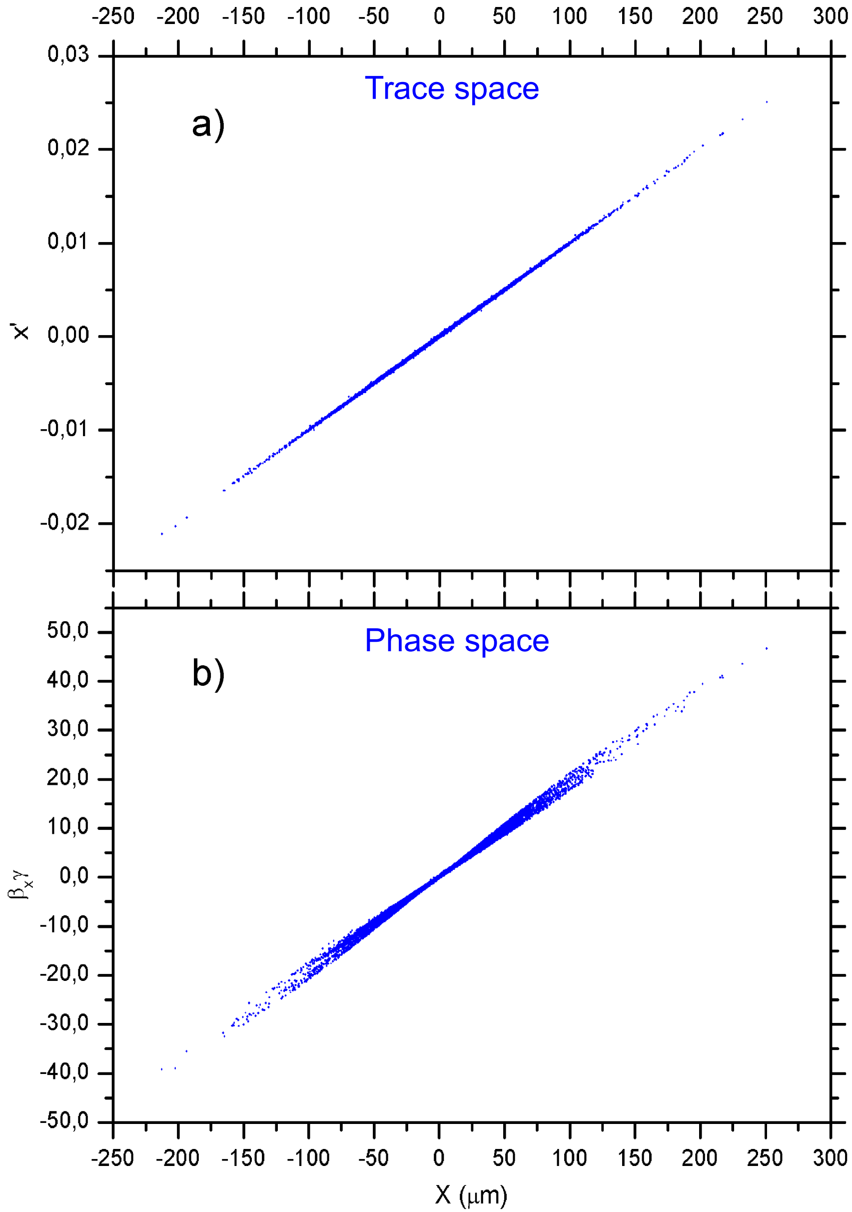
$<\gamma>$	σ_E	σ_x	$\sigma_{x'}$	s	$s\,\sigma_E\sigma_{x'}^2$	$\gamma\varepsilon$	ε_n
12	9×10^{-3}	780 um	1.1×10^{-4}	1 m	10 nm	1.01 um	1.02 um

EXAMPLE: GeV class beam from SELF INJECTION

$<\gamma>$	$\sigma_E^{(0)}$	$\sigma_x^{(0)}$	$\sigma_{x'}^{(0)}$	s	$s\,\sigma_E\sigma_{x'}^2$	$\gamma\varepsilon$	ε_n
1800	6.4×10^{-2}	0.49 um	2.9×10^{-2}	1 m	0.94 mm	2.5 um	~ 1 mm

Highly chromatic beam transport: a closer look

Self-injection beam



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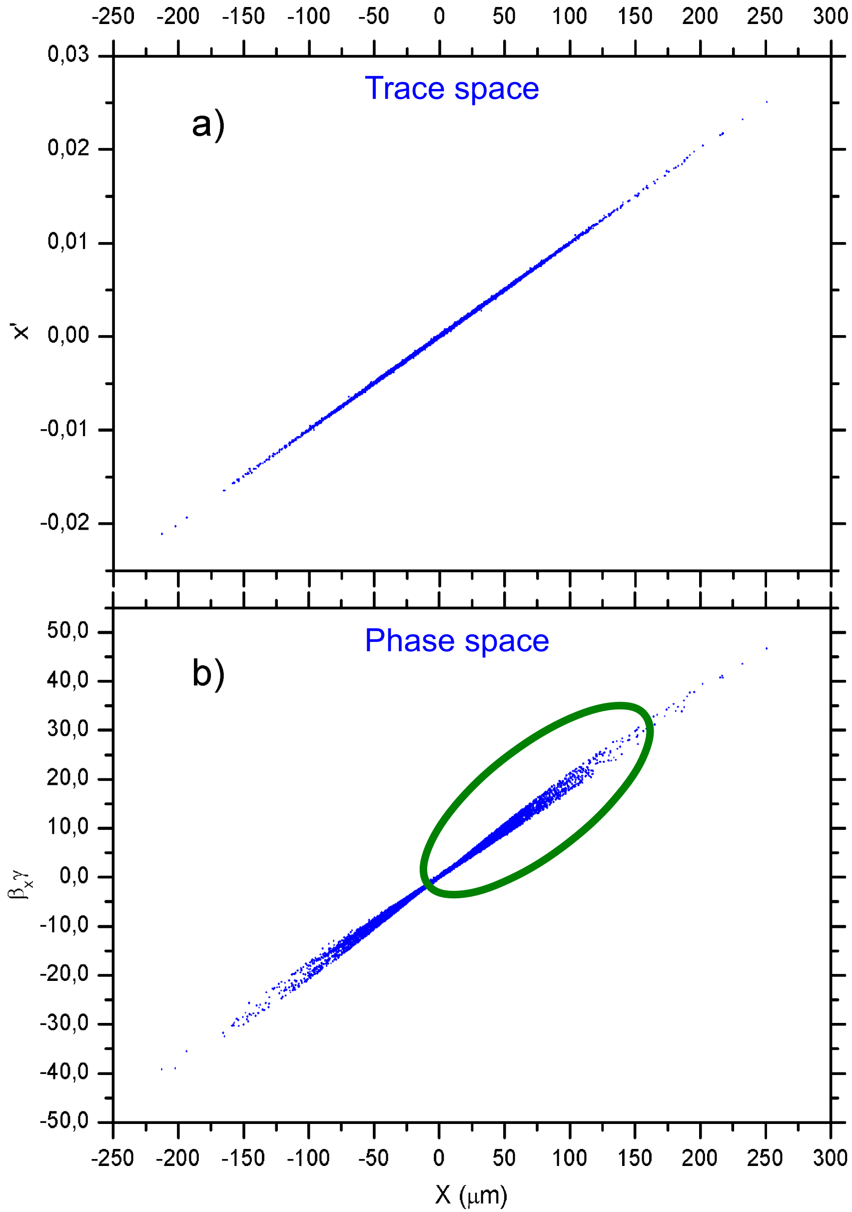

- Transverse PS broadening

Highly chromatic beam transport: a closer look

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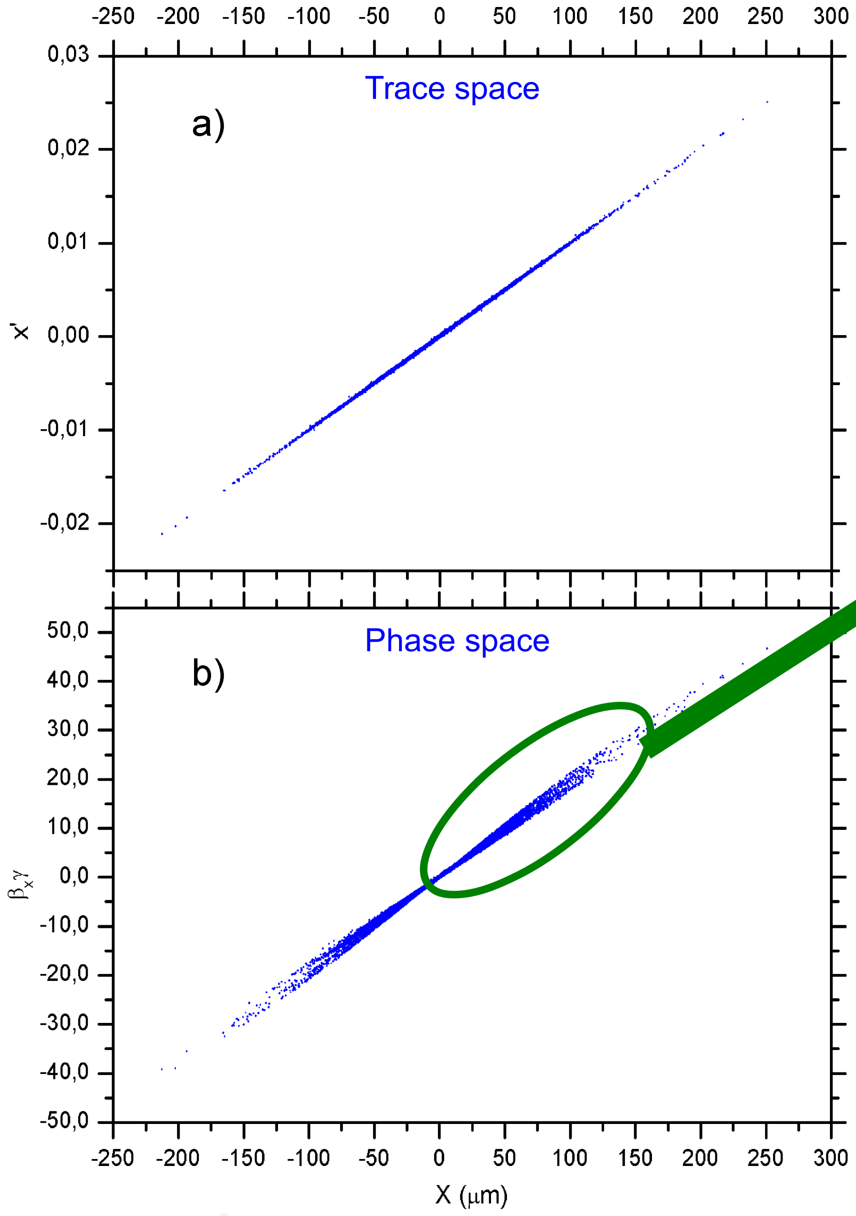
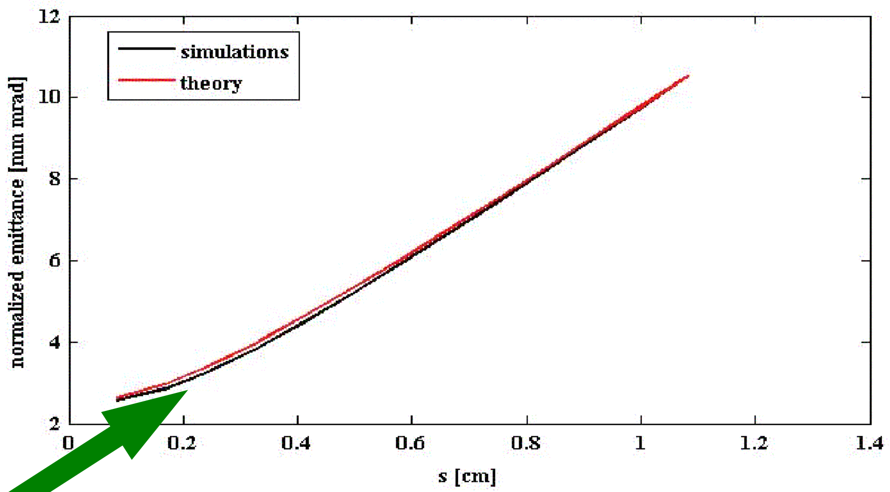
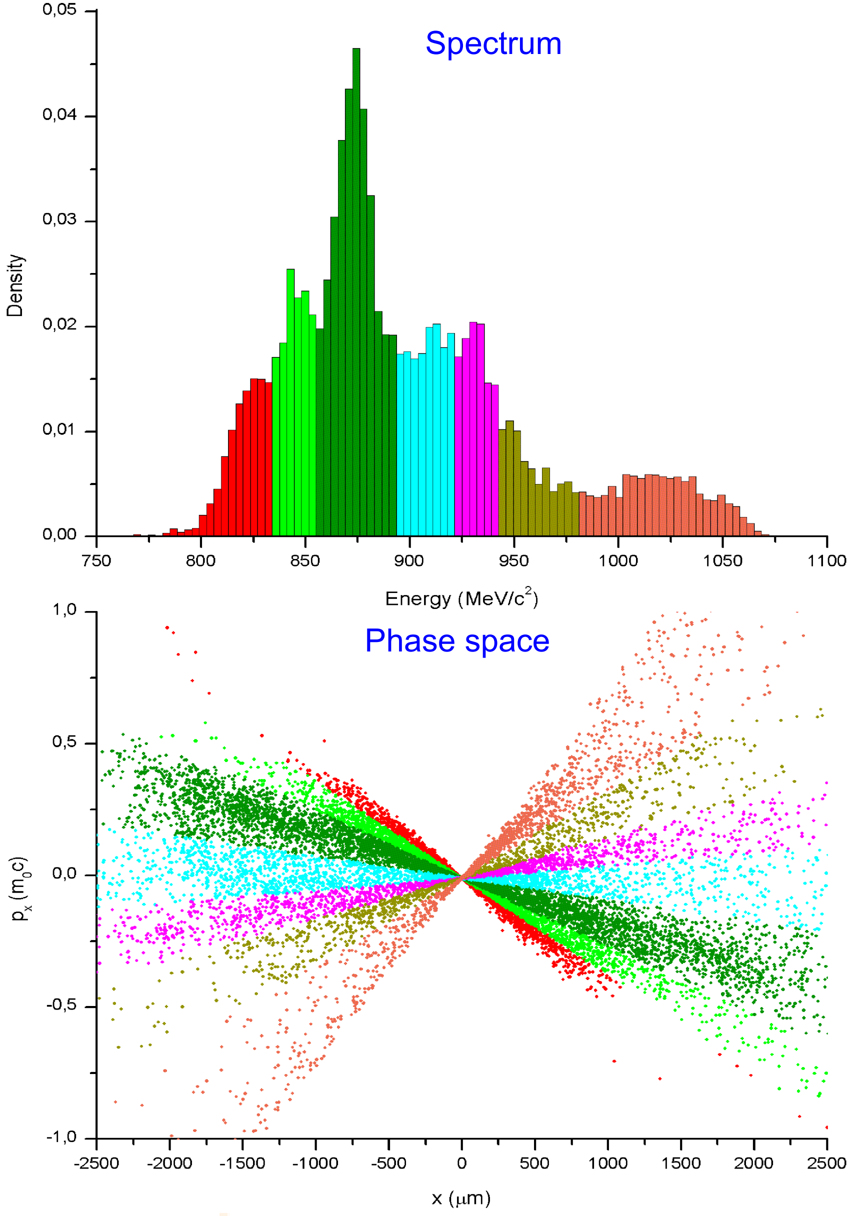


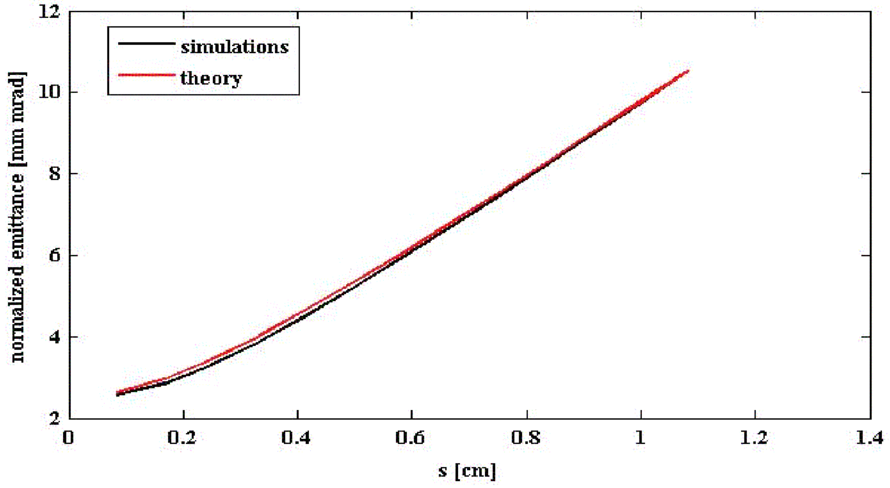


- Transverse PS broadening
- Strong (normalized) emittance dilution

Highly chromatic beam transport: a closer look

Self-injection beam





- Transverse PS broadening
- Strong (normalized) emittance dilution
- Broadening (dilution) is driven by energy spread through betatron frequency spread:

$$\left(\frac{\Delta\omega_b}{\omega_b}\right)^2 \propto \sigma_E^2$$

Highly chromatic beam transport: some bibliography

- K. Floettmann, *Some basic features of beam emittance*, Phys. Rev. STAB **6**, 034202 (2003).
- T. Mehrling *et al.*, *Transverse growth in staged-wakefield acceleration*, Phys. Rev. STAB 15, 111303 (2012).
- P. Antici *et al.*, *Laser-driven electron beamlines generated by coupling laser-plasma sources with conventional transport systems*, J. App. Phys. 112, 044902 (2012).
- M. Migliorati *et al.*, *Intrinsic normalized emittance growth in laser-driven electron accelerators*, Phys. Rev. STAB 16, 011302 (2013).

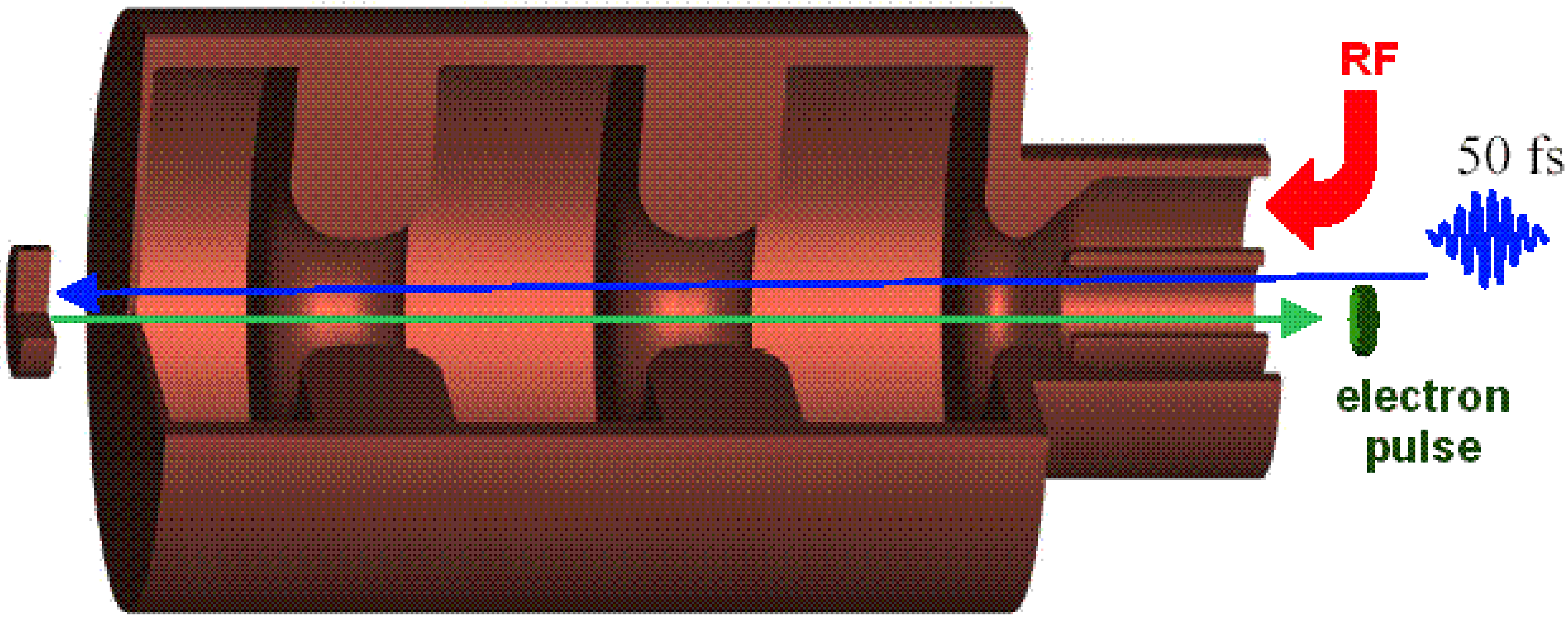
Plasma beams manipulation

Plasma beams manipulations...

- **Control** initial beam parameters at **injection**, for internal injection schemes.
- Eventually **reduce beam length**, for external injection / staging.
- **Inject** beams **into plasma** with the correct size, to avoid emittance dilution in subsequent acceleration, for external injection / staging.
- **Extract** beams **from plasma** realizing a trade-off between size and divergence at constant emittance (adiabatic matching), to avoid propagating highly divergent beams.
- **Control energy spread**, keeping it as low as possible to avoid chromaticity induced emittance dilution.

Injection

- Self-injection.
- Optical injection.
- Density gradient injection.
- Ionization injection.
- Field ionization.
- External injection*.

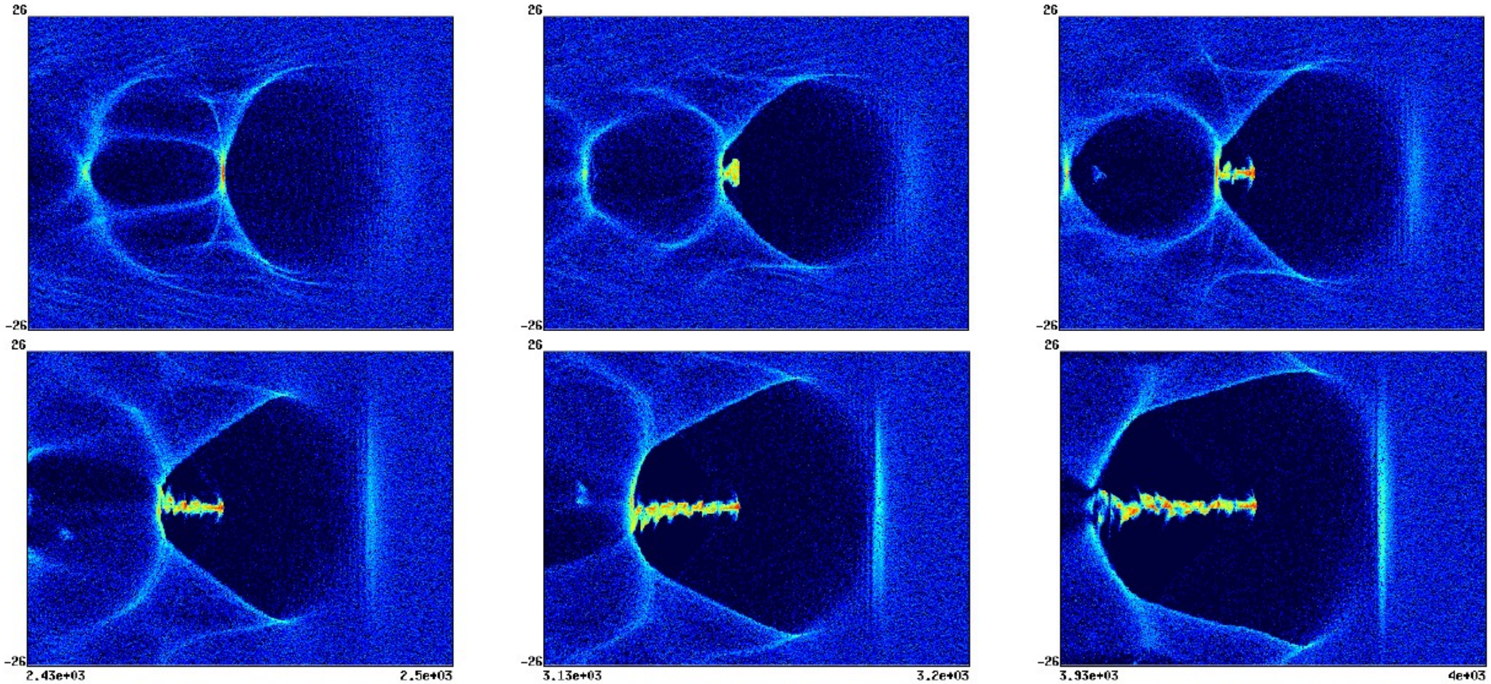


* C.E. Clayton and L. Serafini, IEEE Trans. Plas. Sci. **24**, 400 (1996)
N.E. Andreev, S.V. Kuznetsov, Plas. Phys. Contr. Fus. **45**, 39 (2003)

Self-injection

Relays on wave breaking due to large amplitude fields, plasma wavefronts distortion, forward Raman scattering[1] and other non linear phenomena: very poor control on injected bunches.

$$a_0^2 > \gamma_{\mathrm{p}} \approx \frac{\omega_0}{\omega_{\mathrm{p}}}$$



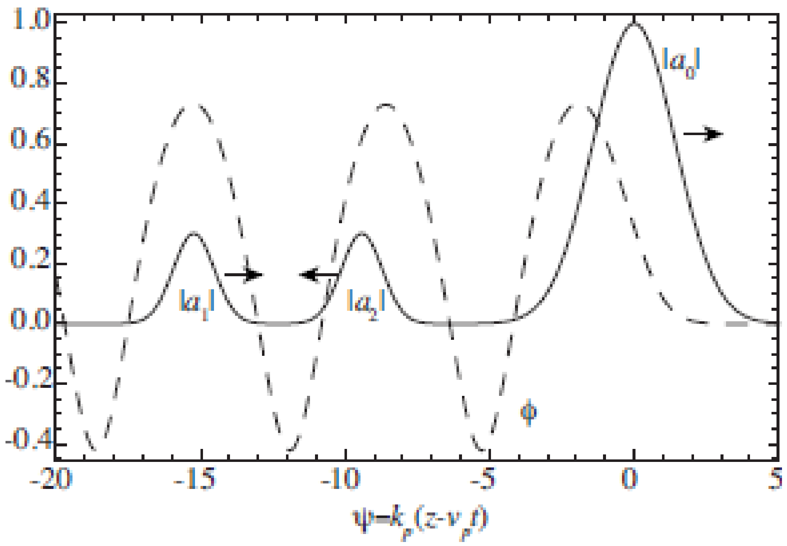
Courtesy: C. Benedetti

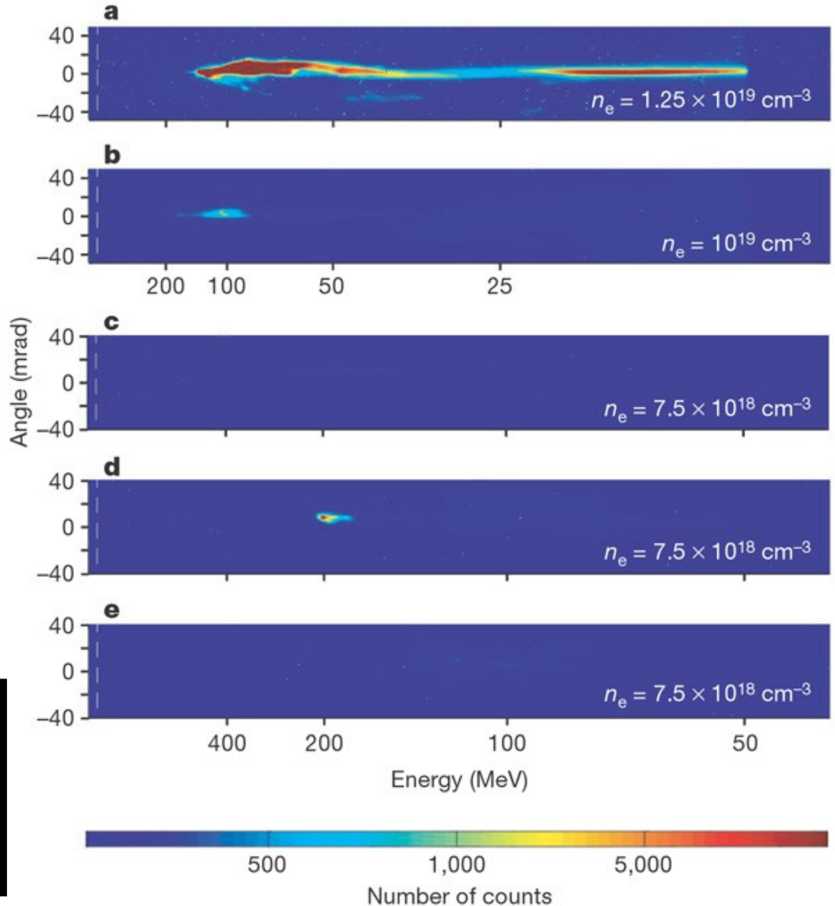
High charge bunches, “easy” to implement. Many experimental results.

[1] Modena, A., Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, and F. N. Walsh, 1995, Nature London **377**, 606.

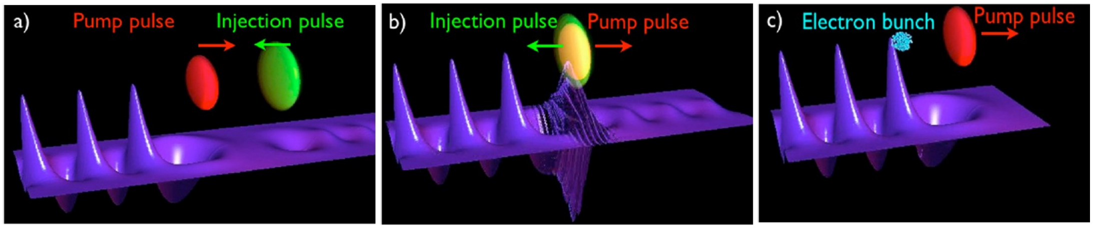
Optical injection: ponderomotive injection and colliding pulses

Two high intensity laser pulses[1] or three resonant lower energy laser pulses[2]: one pulse is the “pump” and drives the plasma wakefield; the others “push” background electrons into the accelerating bucket. Different blends but usually requires a complex experimental setup and a high degree of precision in space and time.





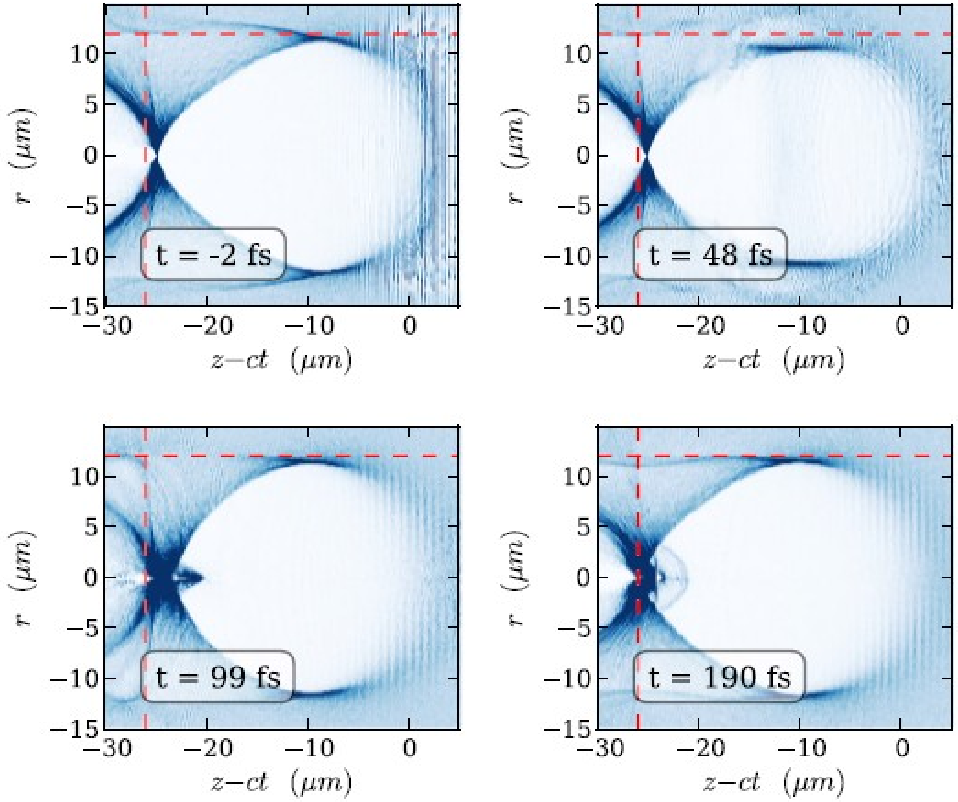
J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, Nature 444, 737 (2006).

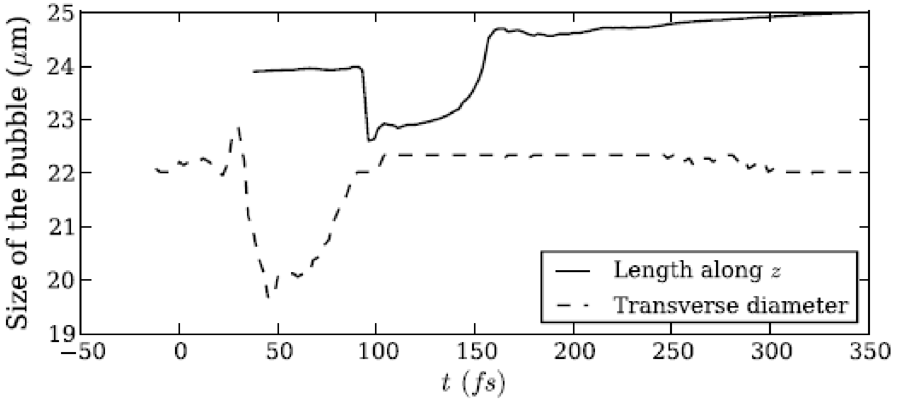


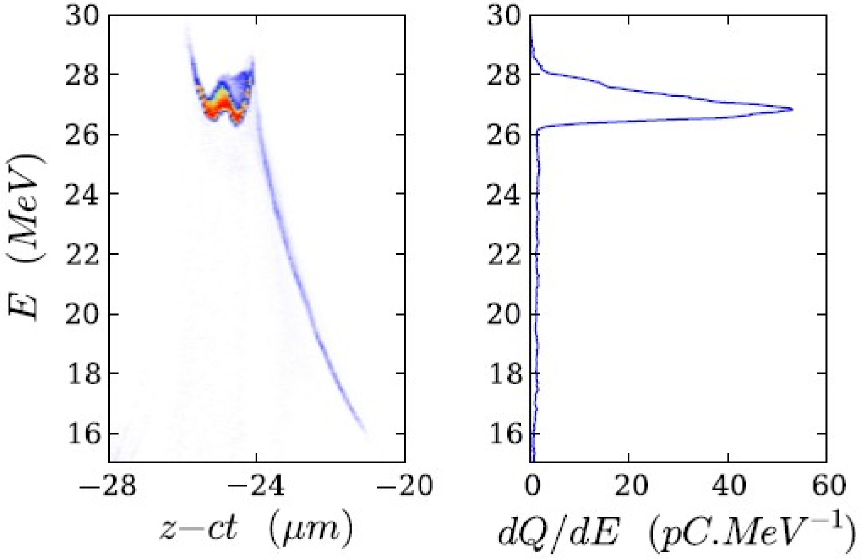
[1] D. Umstadter, J. K. Kim, and E. Dodd, 1996, Phys. Rev. Lett. **76**, 2073.
[2] E. Esarey, A. Ting, R. F. Hubbard, W. P. Leemans, J. Krall, and P. Sprangle, Phys. Rev. Lett. 79, 2682 (1997).

Optical injection: cold injection

The driver laser pulse collides head on with a low intensity injection laser. The bubble is temporarily deformed and a high charge bunch of “cold” electrons is injected when the bubble goes back to its original shape[1].



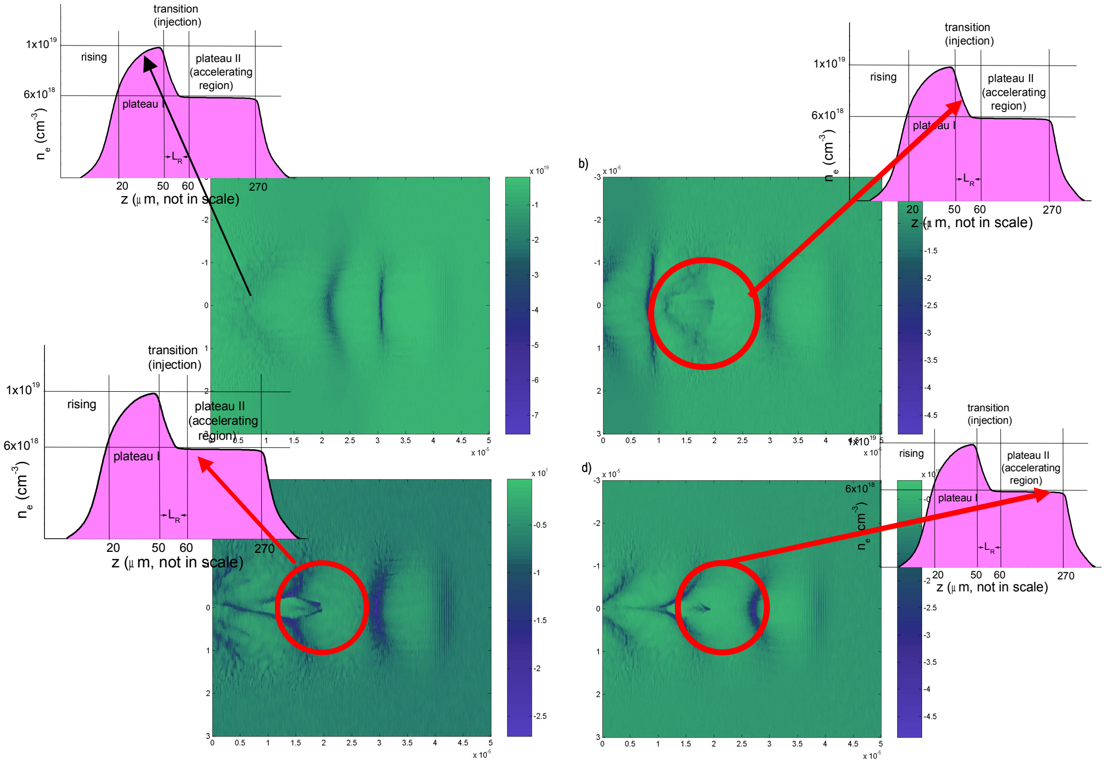




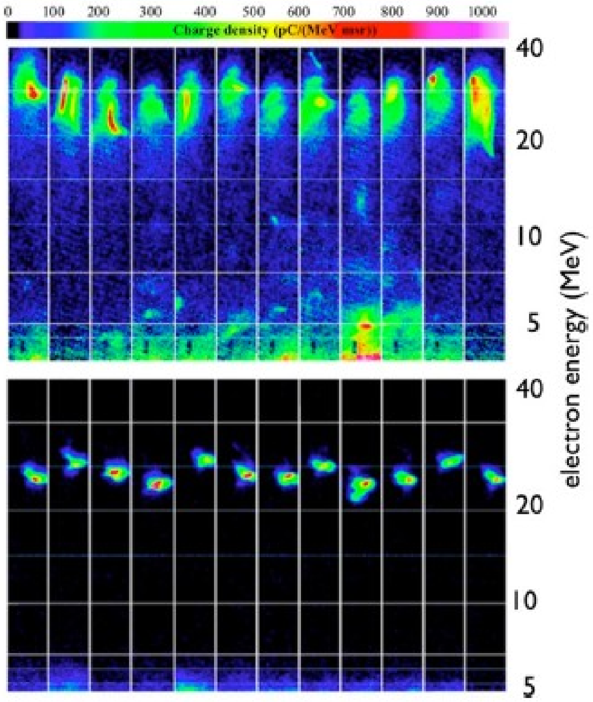
[1] R. Lehe, A. F. Lifschitz, X. Davoine, C. Thaury, and V. Malka, Phys. Rev. Lett. **111**, 085005 (2013)

Density gradient injection

A decreasing plasma density[1] causes the plasma wavelength to increase so that background electrons are enclosed in the larger bubble.



V. Petrillo, L. Serafini and P. Tomassini, Phys. Rev. STAB **11**, 070703 (2008)



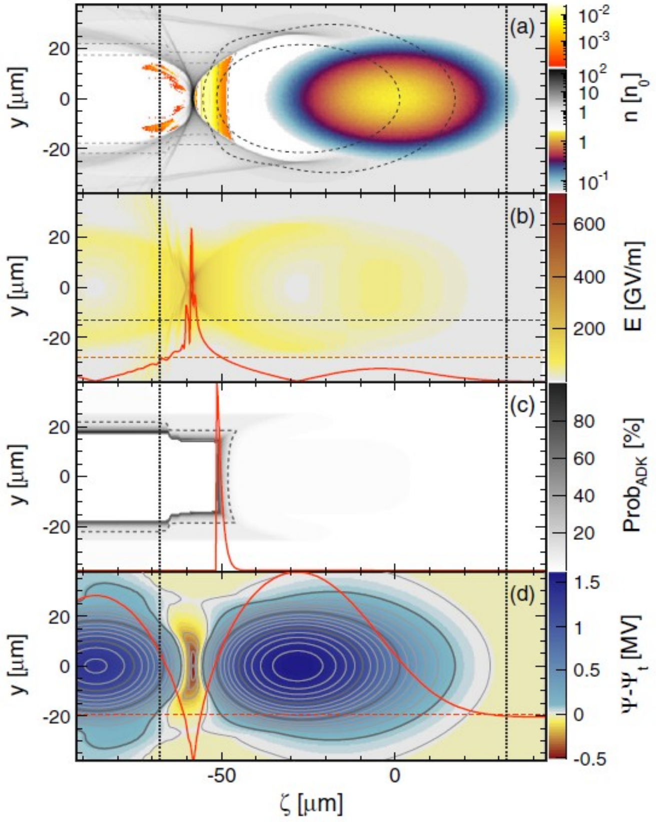
Schmid et al., Phys. Rev. STAB **13**, 091301 (2010).

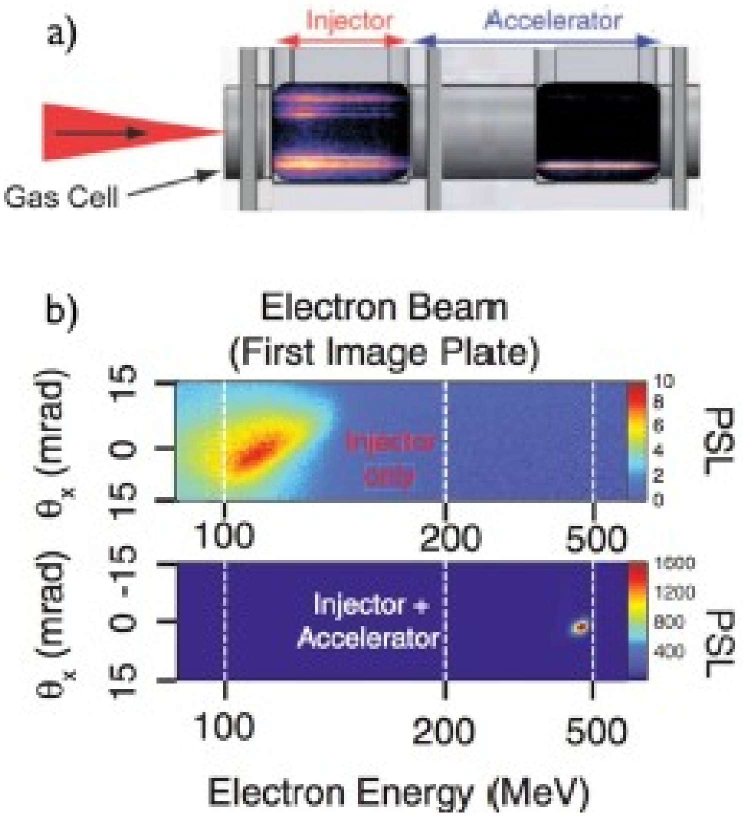
[1] Bulanov, S., N. Naumova, F. Pegoraro, and J. Sakai, 1998, Phys. Rev. E **58**, R5257.

Injection by ionization/1

The plasma is composed by a mixture of gases, with different ionization energies. One is ionized by the wave driver and forms the plasma wave, the other is ionized either by the plasma field[1] or by an injection laser and the ionized electrons form the injected bunch. In LWFA this last technique takes the name of ionization injection[2].

1)



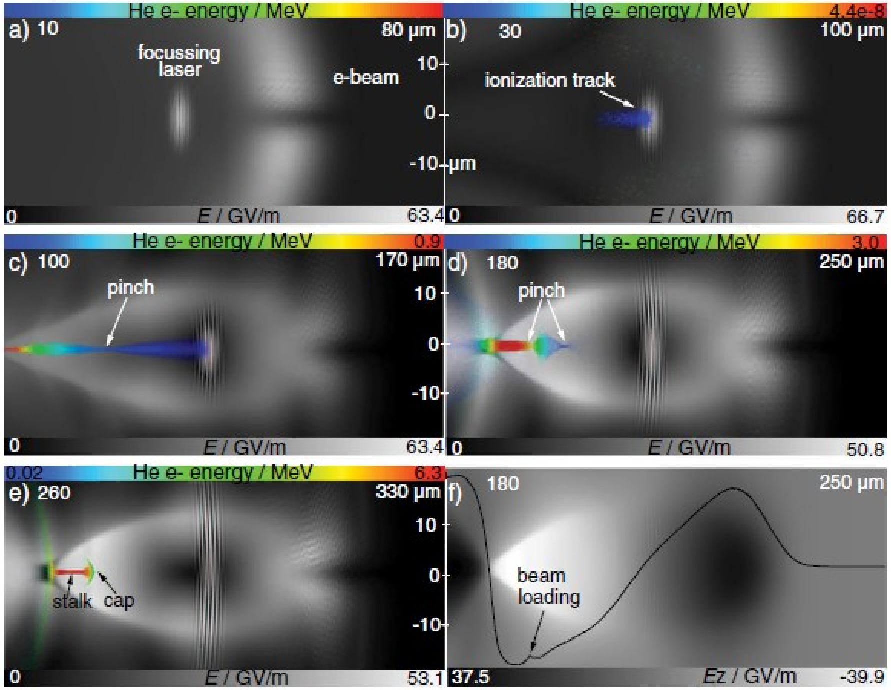


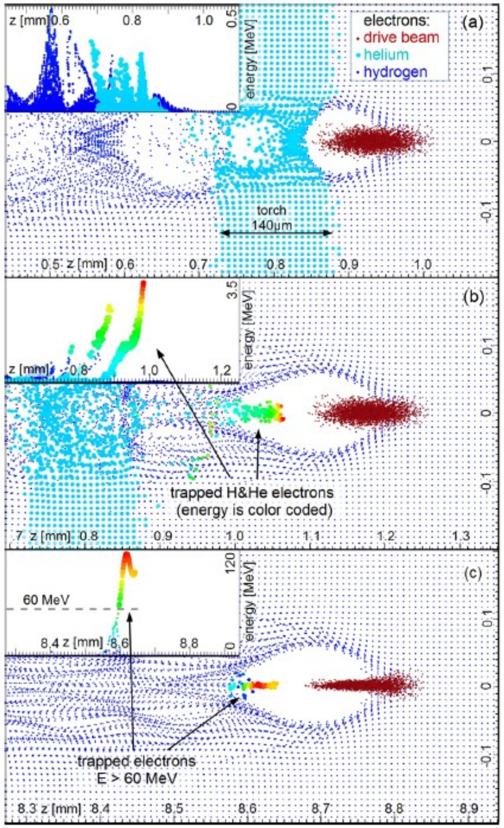
Pollock et al., Phys. Rev. Lett. 107, 045001 (2011).

[1] A. Martinez de la Ossa, J. Grebenyuk, T. Mehrling, L. Schaper, and J. Osterhoff, Phys. Rev. Lett. **111**, 245003 (2013).
[2] E. Oz, et al., Phys. Rev. Lett. **98**, 084801 (2007).

Injection by ionization/2

In PWFA, ionization injection is named Trojan Horse[1]. A rather new mechanism, injection by plasma torch[2], is between ionization injection and density gradient.

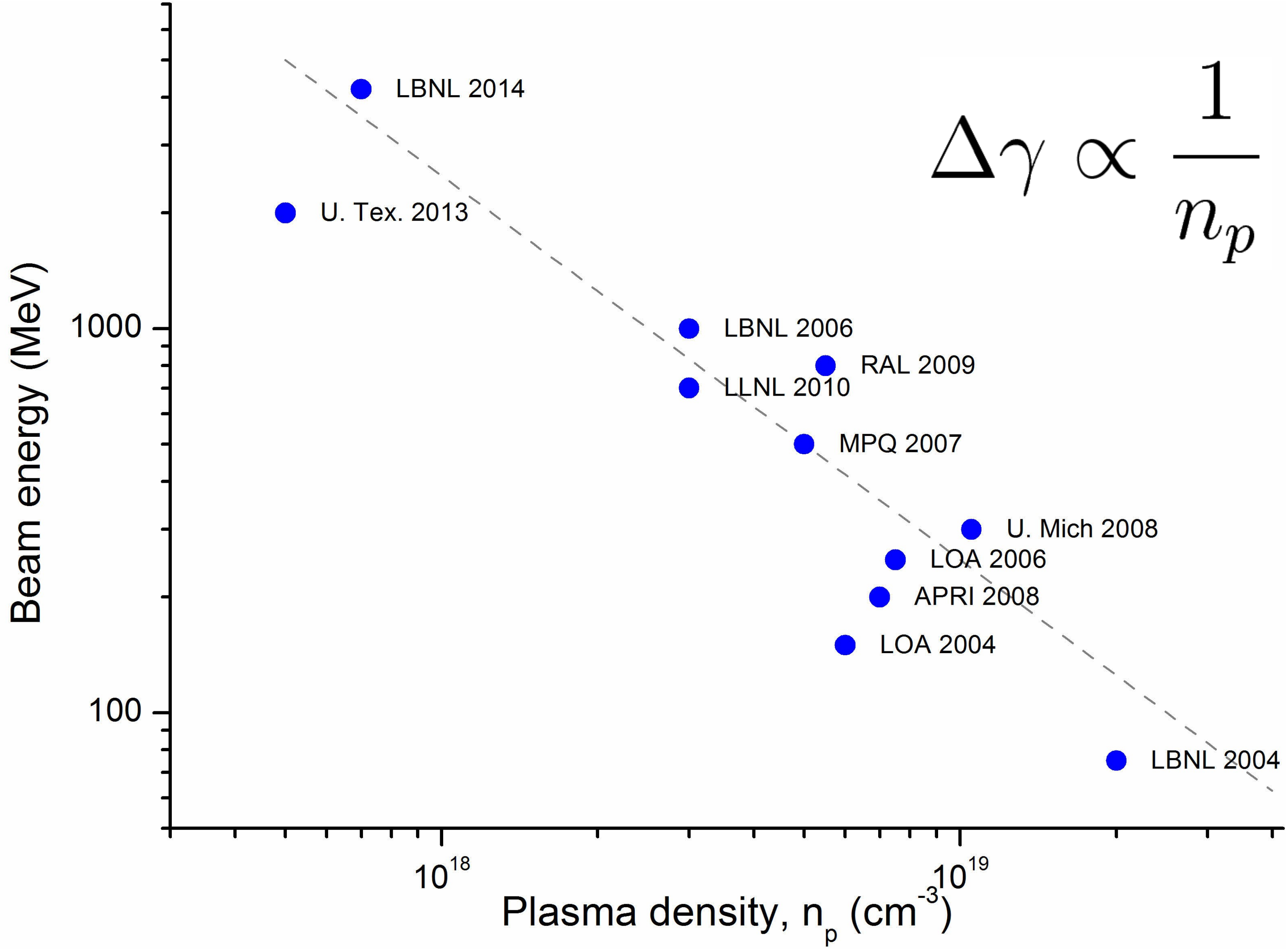




[1] B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler, Phys. Rev. Lett. **108**, 035001 (2012).
[2] G. Wittig, et al., Nuc. Inst. Meth. Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.02.027 (in press).

Acceleration

Plasma density and maximum energy

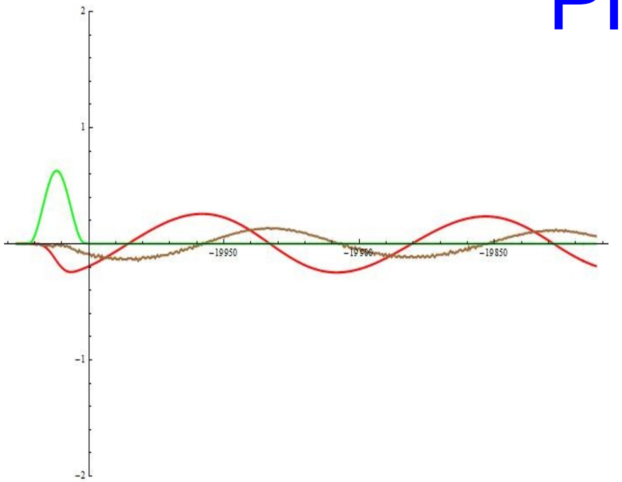


$$\Delta\gamma \propto \frac{1}{n_p}$$

B.A. Shadwick et al., Phys. Plas. **16**, 056704 (2009).

Plasma wave regime

Linear



Easier and more stable but beam loading can dominate the process.
Requires the capability to manage bunches with a charge in the range from hundreds of fC to few pC.

$$a_0 \ll 1$$

$$\alpha = \frac{n_b}{n_0} \ll 1$$

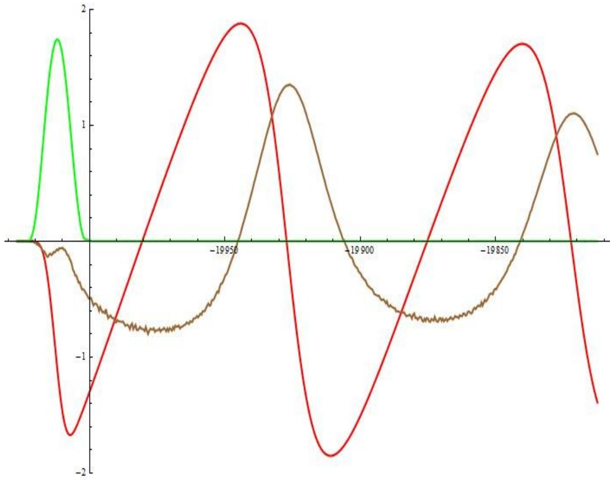
$$\tilde{Q} = Qk_{\mathrm{p}}^3 \ll 1$$

$$a_0 \approx 1$$

$$\alpha \approx 1$$

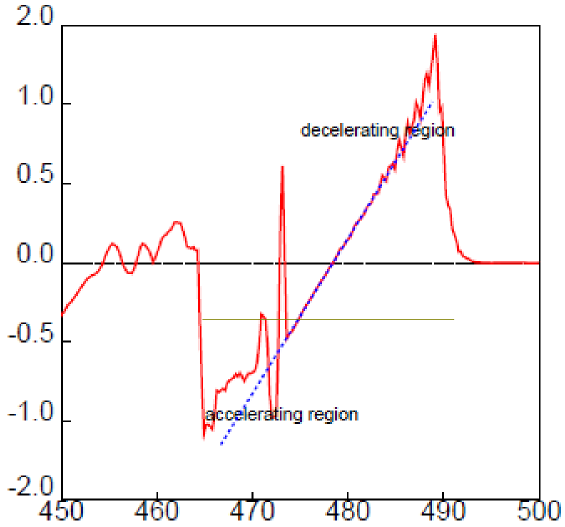
$$\tilde{Q} < 1$$

Quasi-linear



Fields are quite intense so performances can be very interesting.
Beam loading is significant but manageable with bunch charges up to few tens of pC.

Bubble



Courtesy: C. Benedetti

Regime with wider diffusion because of ease in implementation. However, it's the least manageable, due to high sensitivity to jitters.
Extremely intense fields for top performances; beam loading is usually not a problem up to few hundreds of pC.

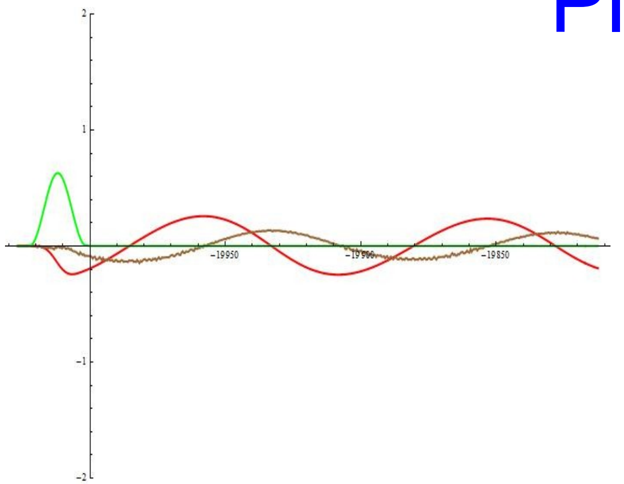
$$a_0 \gg 1$$

$$\alpha > 1$$

$$\tilde{Q} > 1$$

Plasma wave regime

Linear



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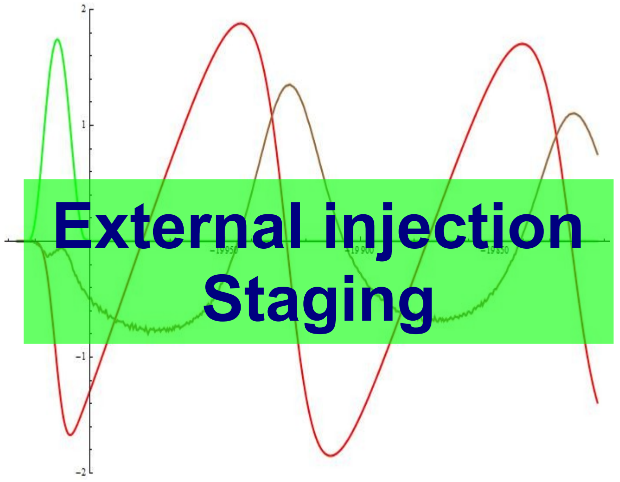

External injection
Staging

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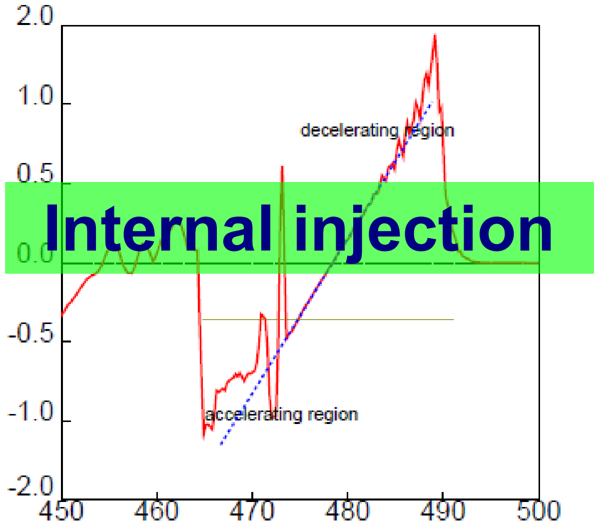
Bubble



Internal injection

Courtesy: C. Benedetti

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$$a_0 \gg 1$$

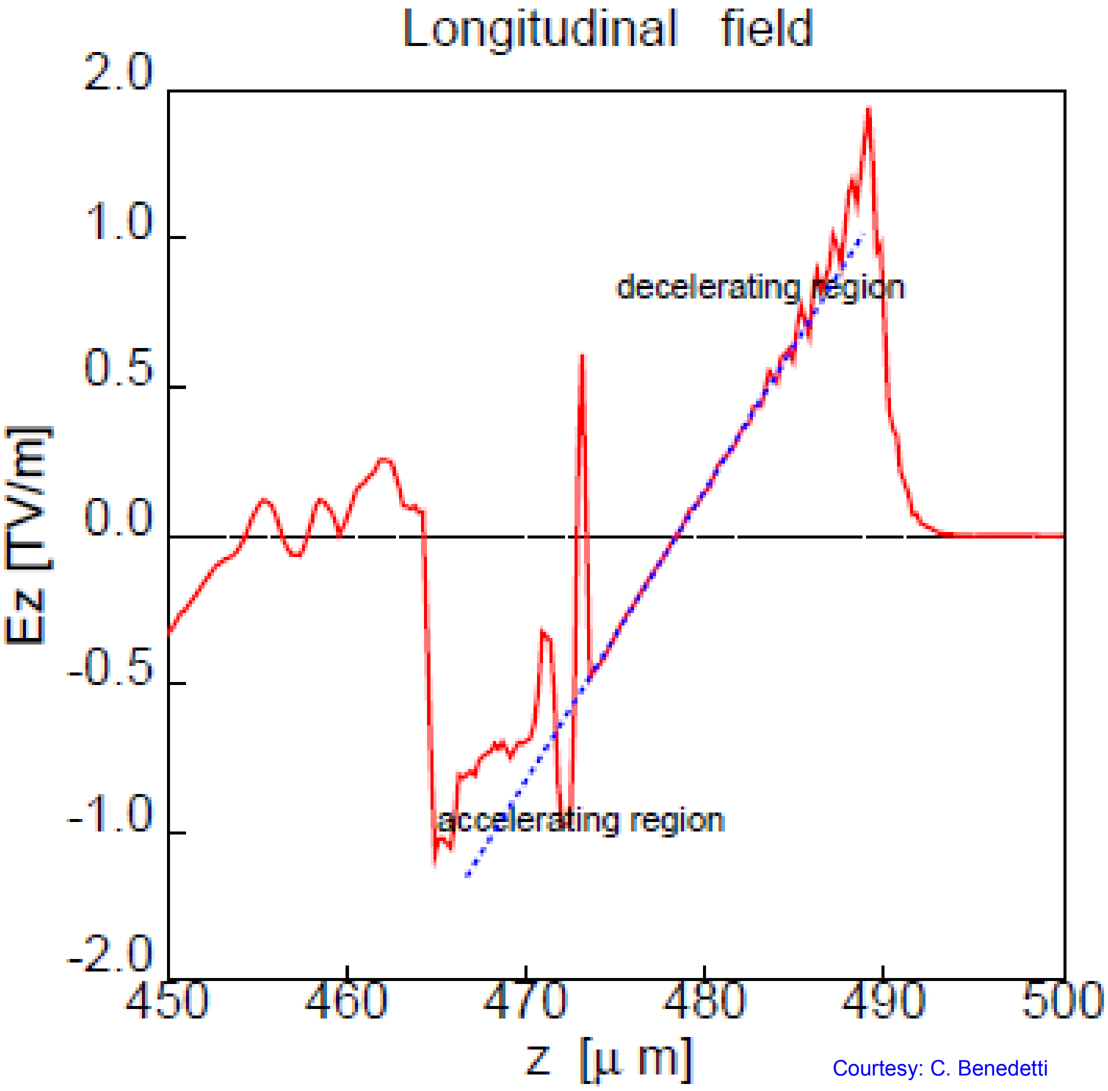
$$\alpha > 1$$

$$\tilde{Q} > 1$$

Beam loading

Beam loading is the perturbation to the plasma fields due to the witness bunch self-fields. Generally speaking:

- Modifies the total fields acting on the witness.
- May reduce acceleration performances.
- May be used for reducing energy spread.
- Depends on witness current.
- Its effects depend on the intensity of plasma fields, hence also on plasma wave regime.
- Requires very fine tuning if used for reducing energy spread.



Courtesy: C. Benedetti

Transverse manipulations and matching

Matching into plasma

It's easy to find matching conditions for bubble regime with negligible beam loading:

$$\sigma_{\mathrm{tr,match}} = \sqrt[4]{\frac{2}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_{\mathrm{p}}}}$$

Typical values are in the order of 0.1 – 1 um.

For a **quasi-linear** plasma wave regime matched spot-sizes have the same order of magnitude. If the plasma driver transverse size is always much larger than the beam size, transverse fields can be considered linear, although they depend on ζ.

In **linear regime** the same considerations on the nature of transverse fields hold true, **but beam loading is usually not negligible**, unless charge is very low.

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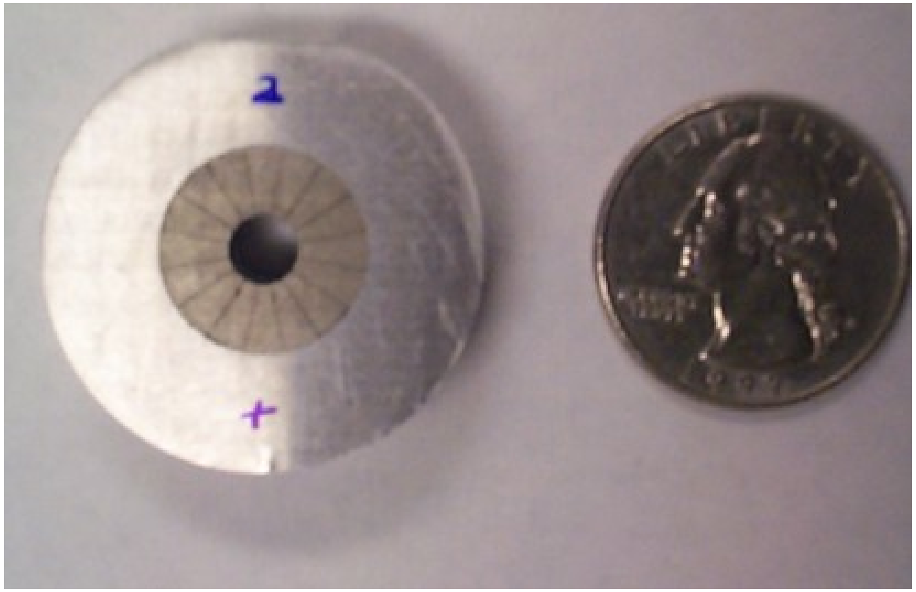
Tight focusing is needed

Matching into/out of plasma/1

More conventional solutions: high performance beam optics like permanent magnet quadrupoles...



...reaching many hundreds of T/m gradients, adequate for energies up to few hundreds MeV.

Matching into/out of plasma/2

Plasma lenses: classification

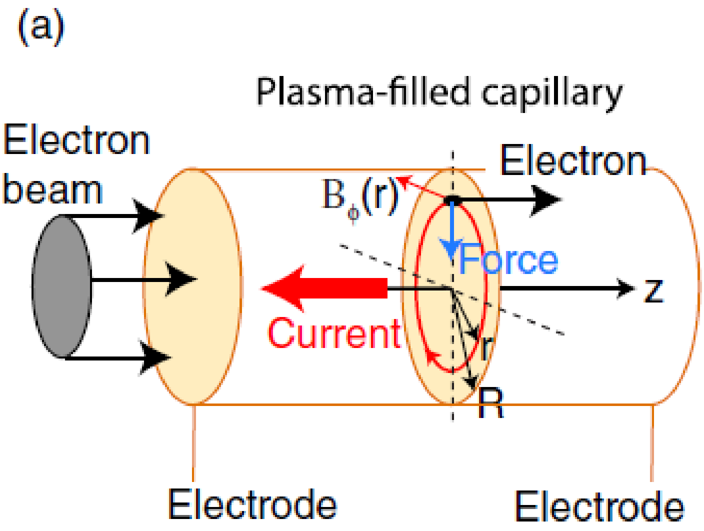
Effectiveness

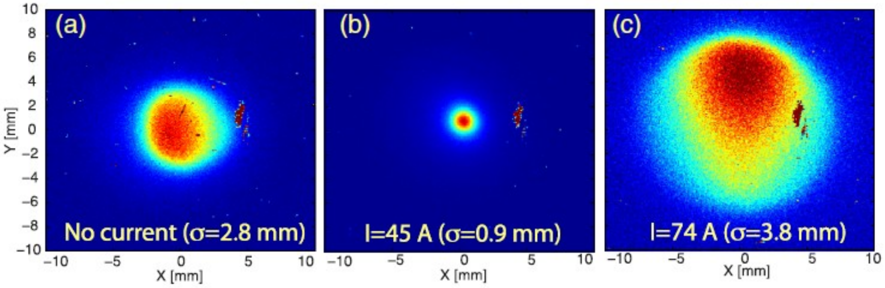
Ease of implementation and operation

	Passive	Active
Stand alone	Gas jets	Discharge
Integrated	Ramps	---

Stand alone, active plasma lens: discharge capillary[1]

The beam goes through a capillary filled with gas, while a current is flowing in the capillary. If some (rather restrictive) conditions are met, the bunch is focused by the azimuthal magnetic field generated by the current density.





[1] J. van Tilborg, et al., Phys. Rev. Lett. **115**, 184802 (2015)

Favourable scaling

$$\partial B_\phi/\partial r = \mu_0 I_0/(2\pi R^2)$$

able to easily reach thousands T/m gradients

Operation conditions:

$$\left(\frac{\sigma_z}{\sigma}\right)^2 J_{\mathrm{beam}} \ll \frac{J_{\mathrm{dis.}}}{2}$$

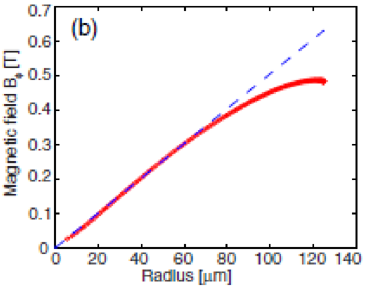
$$k_{\mathrm{p}}\sigma \gg 1$$

$$k_{\mathrm{p}}\sigma_z \ll 1$$

Requires a relatively long drift btw beam source and lens to operate correctly

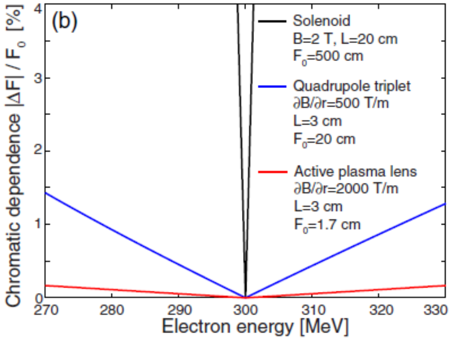
Effective only as a thin lens

Linear focusing field



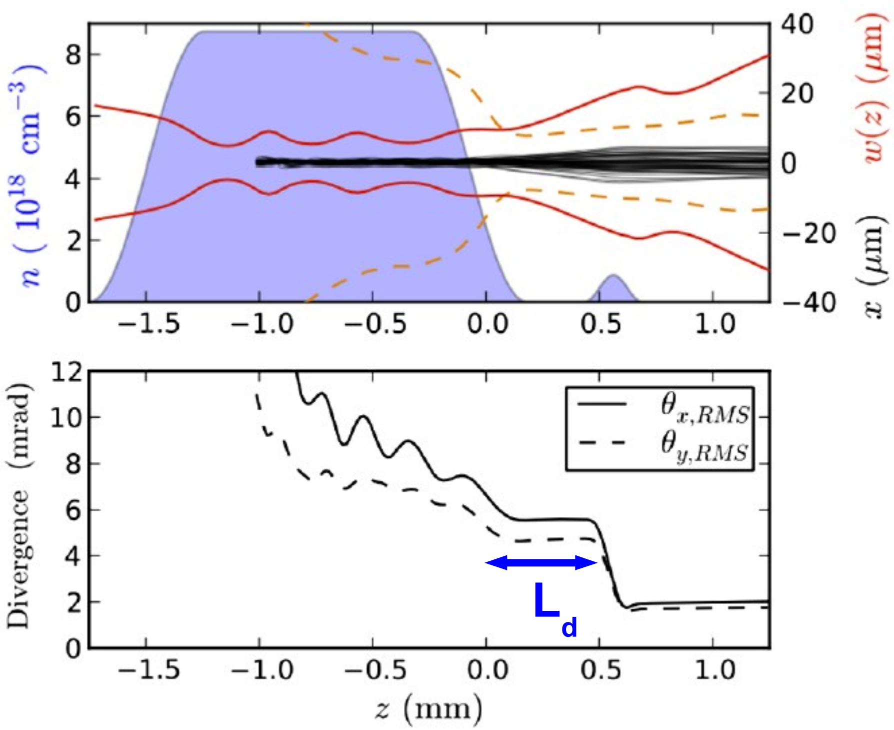
up to half R

Low chromaticity



Stand alone, active plasma lens: gas jet[1]

A gas jet, acting as plasma lens, is powered by an *ad hoc* laser pulse.



Linear, intense focusing

$$F_r = -m_e c^2 k_p^2 r/2$$

Easily tuned for different bunches
Adequate acceptance

Density profile

$$n(z) = \begin{cases} n_1 & \text{for } z < 0 \quad \text{(First jet)} \\ 0 & \text{for } 0 < z < L_\mathrm{d} \quad \text{(Drift space)} \\ n_2 & \text{for } L_\mathrm{d} < z < L_\mathrm{d} + L_2 \quad \text{(Second jet)} \end{cases}$$

Condition for optimal collimation*

$$\langle k_\beta \rangle L_\mathrm{d} \tan(\langle k_\beta \rangle L_2) = 1$$

$$k_\beta = k_p / \sqrt{2\gamma}$$

The only significant source of aberrations is energy spread (chromaticity)

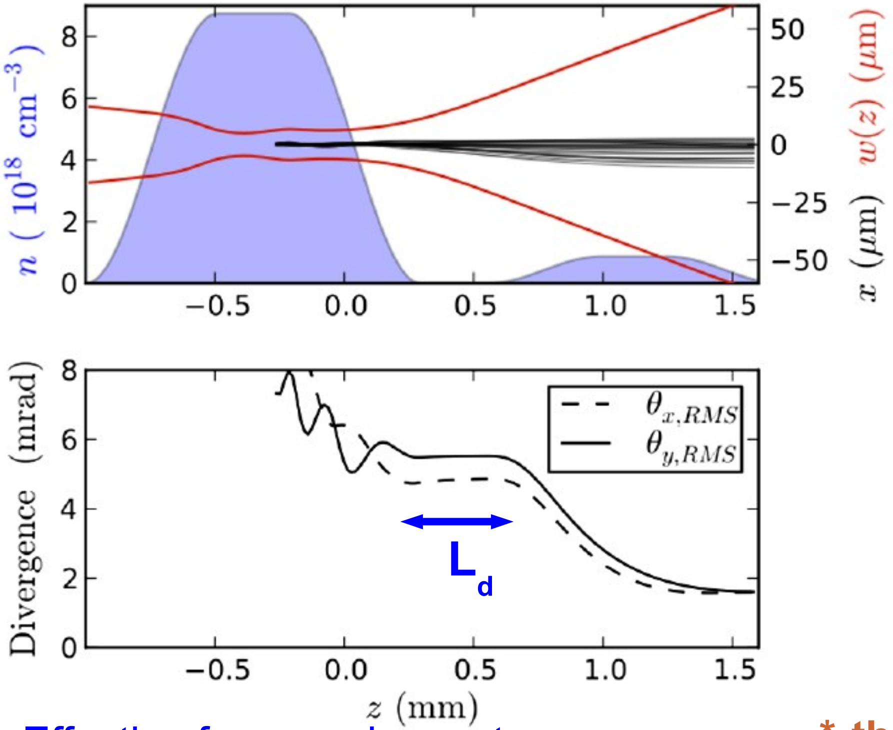
*** this relation was derived assuming a constant emittance during drift.**

Requires two high power lasers to be operated.

[1] R. Lehe, C. Thaury, E. Guillaume, A. Lifschitz, and V. Malka, Phys. Rev. STAB **17**, 121301 (2014)

Stand alone, passive plasma lens: gas jet[1]

A gas jet, acting as plasma lens, is powered by the same laser extracting and accelerating the bunch



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Condition for optimal collimation*

$$\frac{\langle k_\mathrm{foc}\rangle Z_R^2}{L_\mathrm{d} + L_2} \tan\left(\frac{\langle k_\mathrm{foc}\rangle Z_R^2}{L_\mathrm{d}} - \frac{\langle k_\mathrm{foc}\rangle Z_R^2}{L_\mathrm{d} + L_2} \right) = 1$$

$$k_\beta = k_p / \sqrt{2\gamma}$$

Requires only one laser

Effective for energies up to

$$\gamma < \frac{3}{5} \frac{a_0^2 Z_\mathrm{R}^4}{L_\mathrm{d}^2 w_0^2}$$

Easily tuned for different bunches

Adequate acceptance

*** this relation was derived assuming a constant emittance during drift.**

Beam loading may reduce effectiveness.

[1] R. Lehe, C. Thaury, E. Guillaume, A. Lifschitz, and V. Malka, Phys. Rev. STAB **17**, 121301 (2014)

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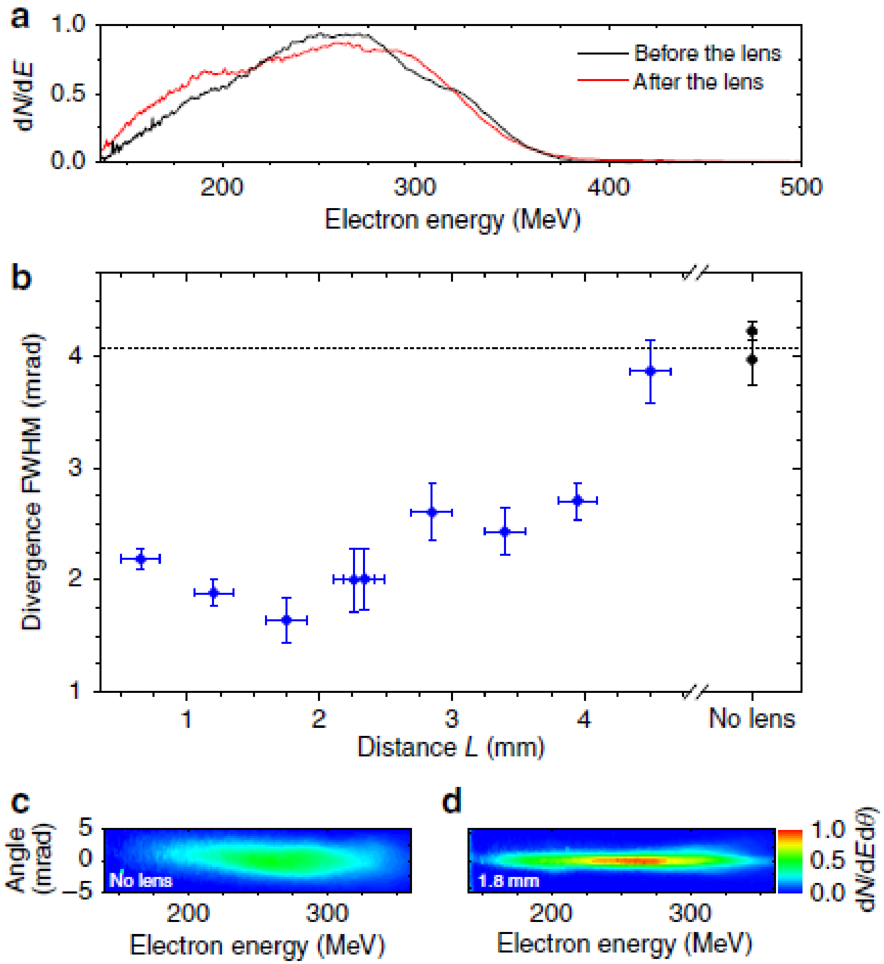
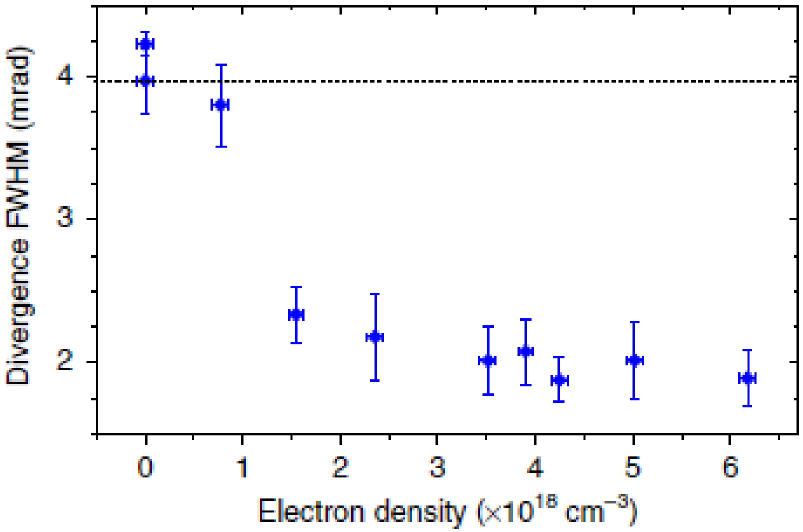
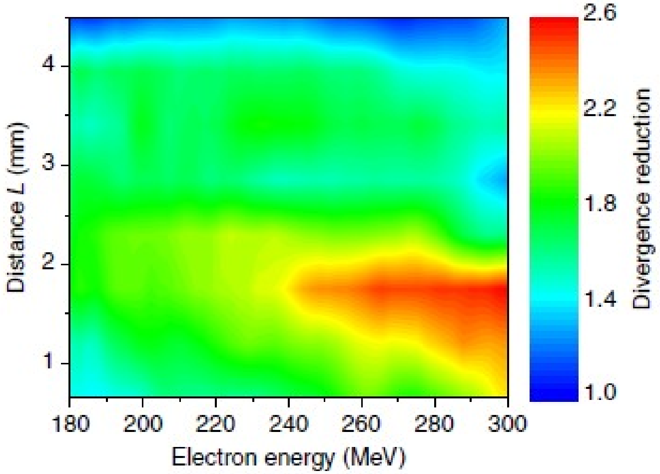






[1] C. Thaury, et al., Nature Comm. **6**, 6860 (2015)

Integrated, passive plasma lens: plasma ramps

A tapering at the end (beginning) of the plasma channel acts as a plasma lens and defocuses (focuses) the bunch performing matching. Moreover, the focusing (defocusing) of the driver helps in performing the process.

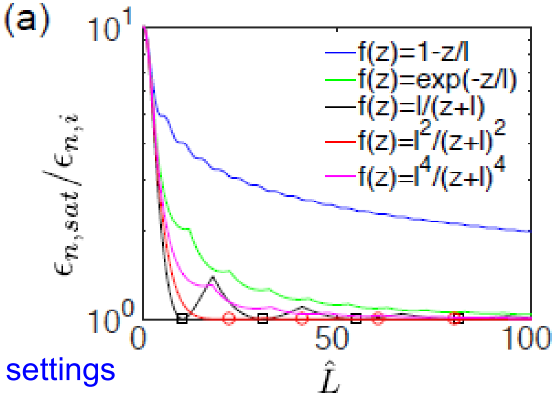
Emittance dilution as a function of initial Twiss parameters, average β in focusing element and betatron phase

$$\epsilon_n = \epsilon_{n,sat}\sqrt{1-\frac{(\gamma_i\beta_F+\beta_i/\beta_F)^2-4}{(\gamma_i\beta_F+\beta_i/\beta_F)^2}\left(\frac{\sin\Delta\Phi}{\Delta\Phi}\right)^2}$$

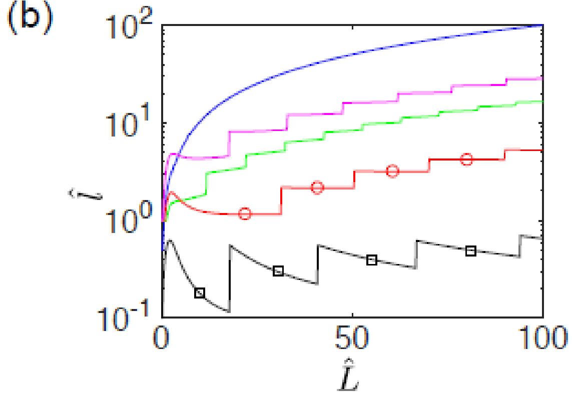
$$\beta_F = \sqrt{\langle\gamma_b\rangle mc/Ge}$$

$$\Phi = \Phi_i + (\sqrt{2\gamma_b}-\sqrt{2\gamma_{b,i}})/E_z$$

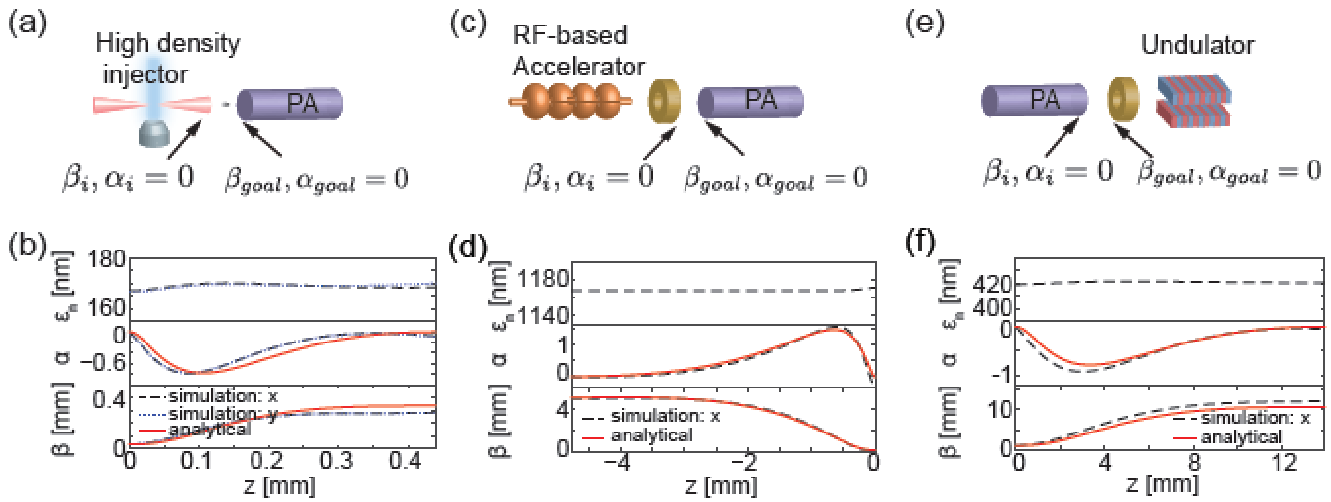
Scan $\epsilon_{sat}/\epsilon_i$ vs ramp length L



Scan ramp scale l vs ramp length of $\epsilon_{sat}/\epsilon_i$ = 1



Application to different settings



Bubble regime (linear focusing)

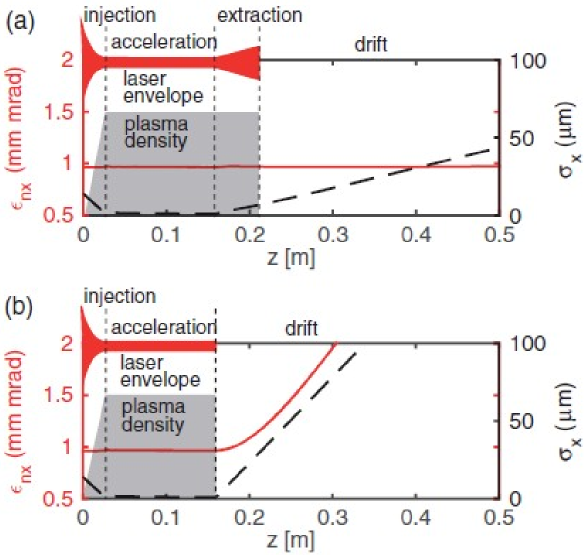
Small beam loading

X. L. Xu, et al., arXiv: 1411.4386v2 [physics.acc-ph] 2015

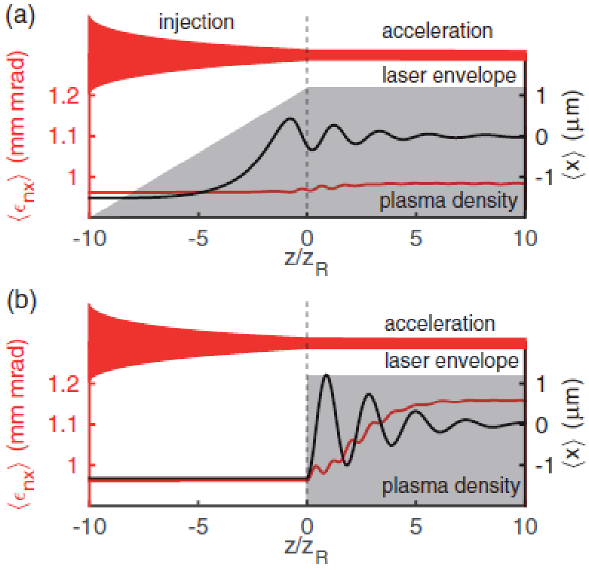
Integrated, passive plasma lens: plasma ramps & driver focusing/defocusing

A tapering at the end (beginning) of the plasma channel acts as a plasma lens and defocuses (focuses) the bunch performing matching. Moreover, the focusing (defocusing) of the driver helps in performing the process.

Emittance conservation and adiabatic focusing/defocusing

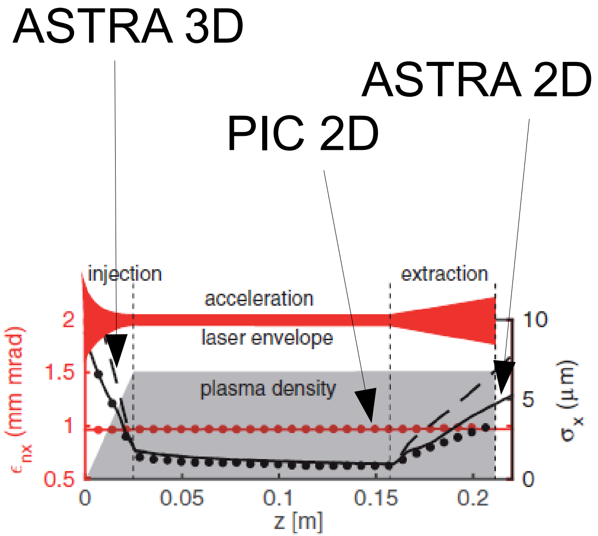


Tolerance to beam position jitters



Optimal focusing strength longitudinal profile

$$K(z) = K_0/(1+gz)^4$$



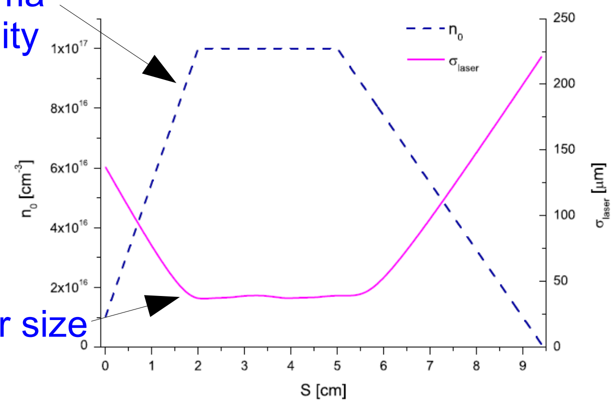
Linear regime

Negligible beam loading

I. Dornmair, K. Floettmann, and A. R. Maier, Phys. Rev. STAB **18**, 041302 (2015)

Integrated, passive plasma lens: plasma ramps & tailored driver focusing/defocusing in hollow capillary

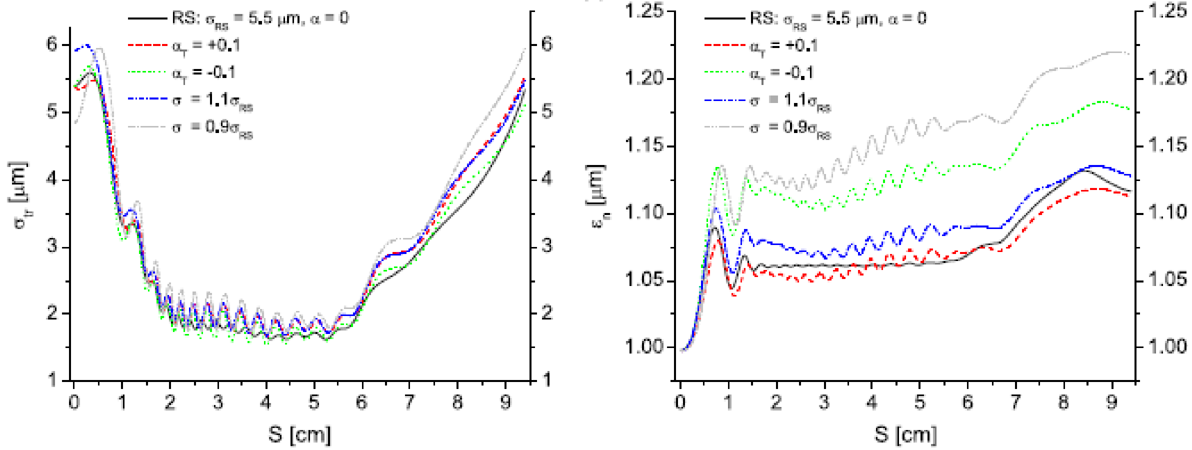
A tapering at the end (beginning) of the plasma channel acts as a plasma lens and defocuses (focuses) the bunch performing matching. Moreover, the focusing (defocusing) of the driver is tailored to help in performing the process.



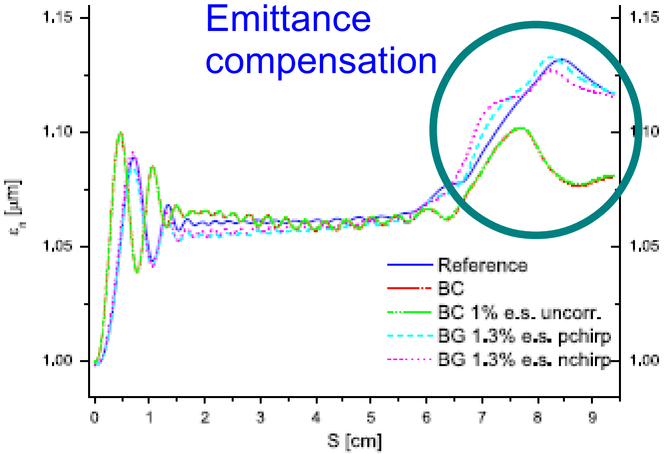
Plasma density

Laser size

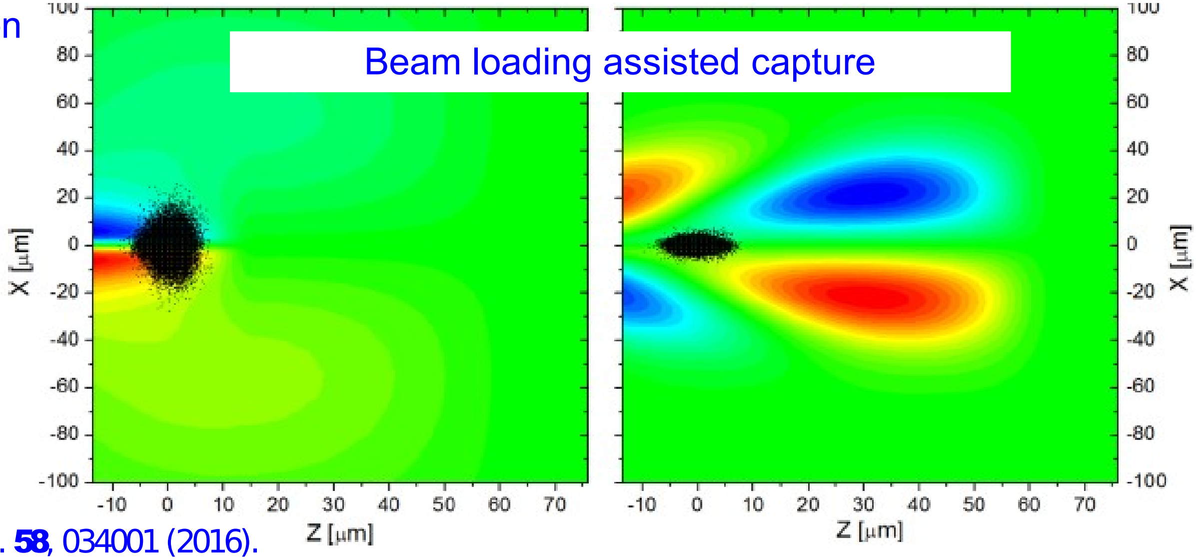
Stability vs injected beam parameters jitters



Stability vs injected beam charge distribution



Emittance compensation



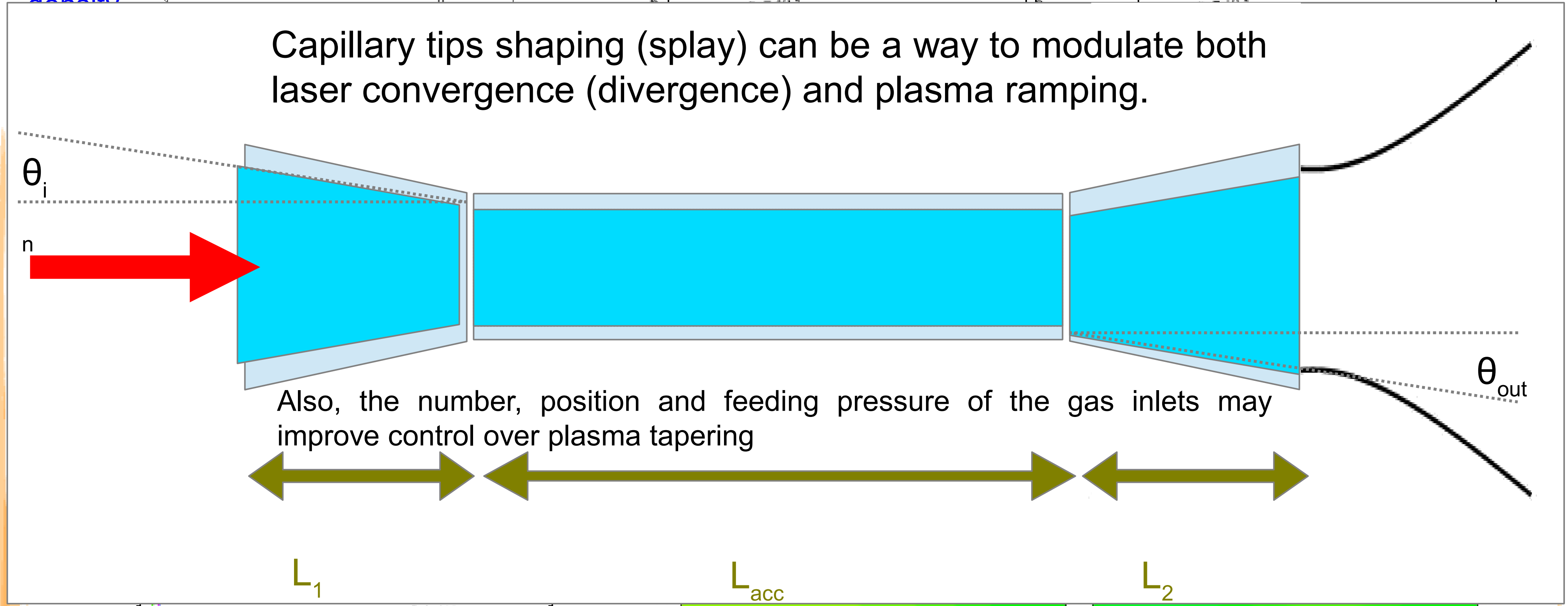
Beam loading assisted capture

P. Tomassini and A.R. Rossi, Plas, Phys. Cont. Fus. **58**, 034001 (2016).
A.R. Rossi, et al., Nuc. Met. Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.02.015 (in press)

Integrated, passive plasma lens: plasma ramps & tailored driver focusing/defocusing

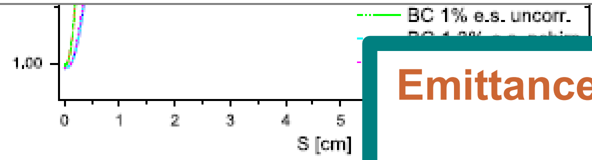
In the raps the regime is linear with dominating beam loading. This working condition allows a beam loading assisted matching. In the acceleration section the regime is quasi-linear and the beam loading negligible.

Plasma density



Capillary tips shaping (splay) can be a way to modulate both laser convergence (divergence) and plasma ramping.

Also, the number, position and feeding pressure of the gas inlets may improve control over plasma tapering

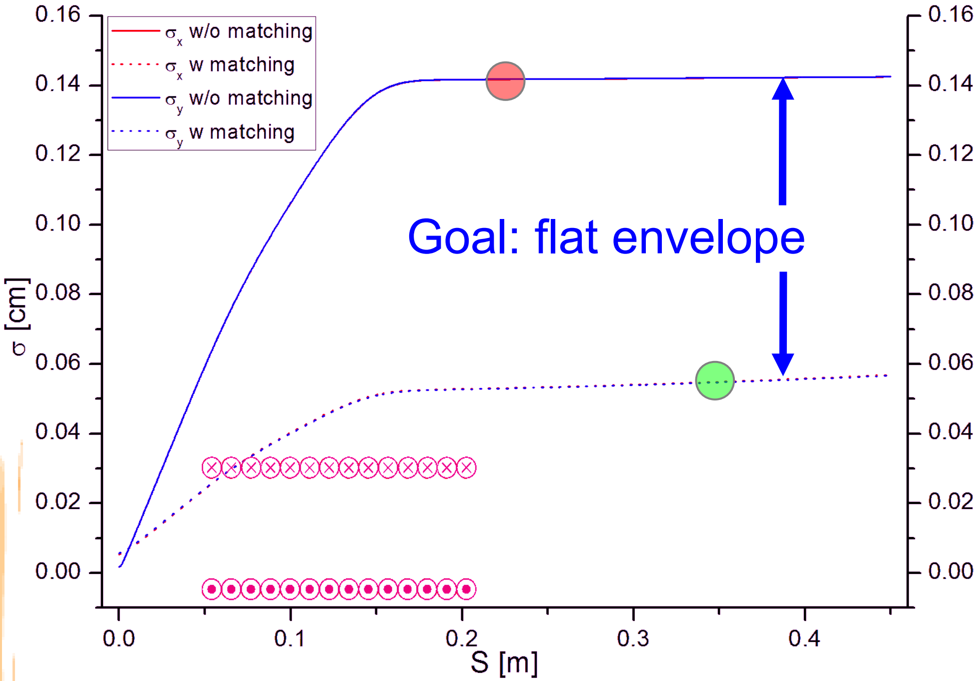


Emittance not completely conserved

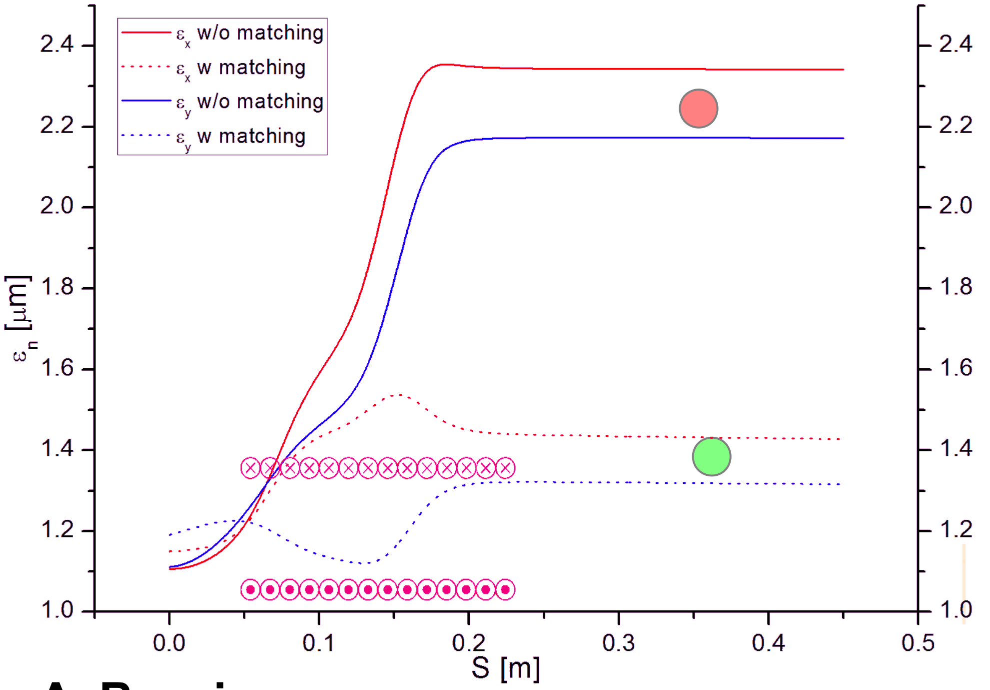
Needs to be confirmed by PIC simulations

P. Tomassini and A.R. Ross
A.R. Rossi, et al., Nuc. Met

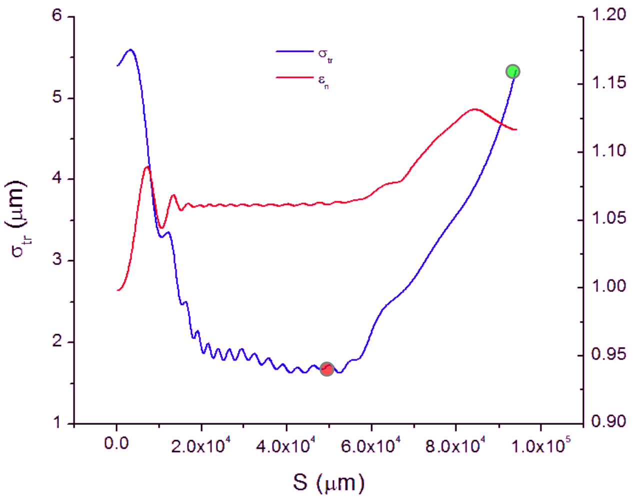
Matching into/out of plasma: is it really necessary?

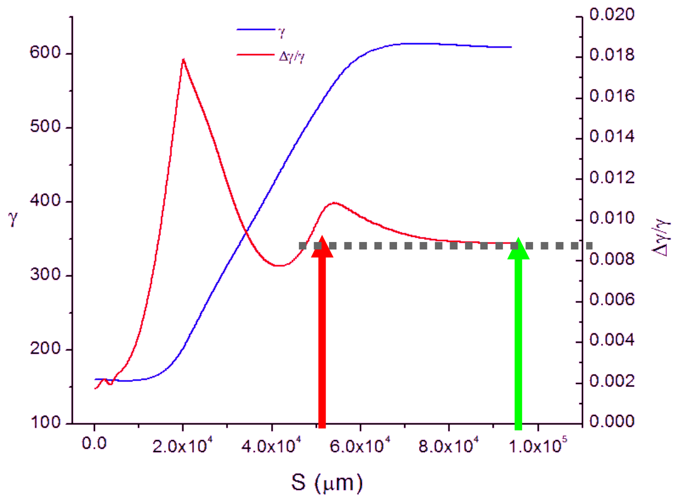


Goal: flat envelope



Simulations by A. Bacci

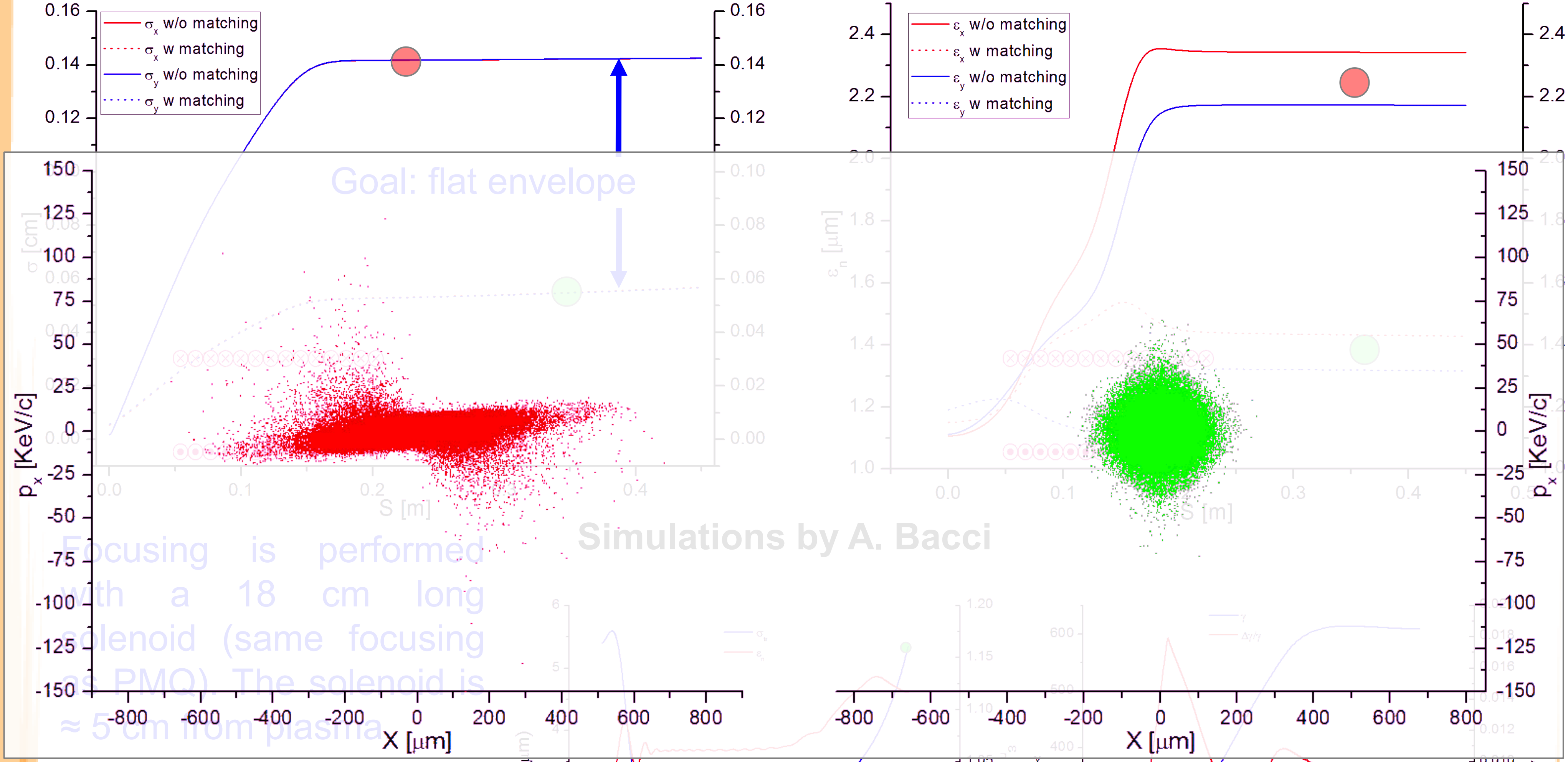




Focusing is performed with a 18 cm long solenoid (same focusing as PMQ). The solenoid is ≈ 5 cm from plasma.

Both beams start with about the same energy spread. The **matched** one behaves in a much better way than the **unmatched**

Matching into/out of plasma: is it really necessary?



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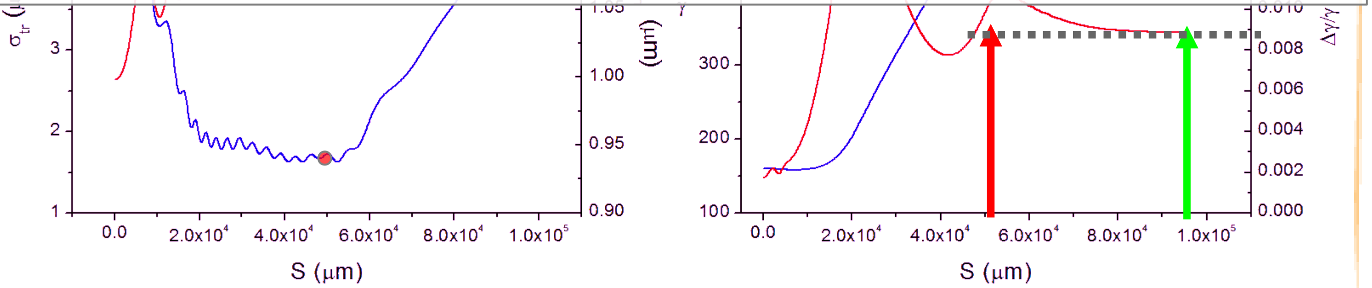

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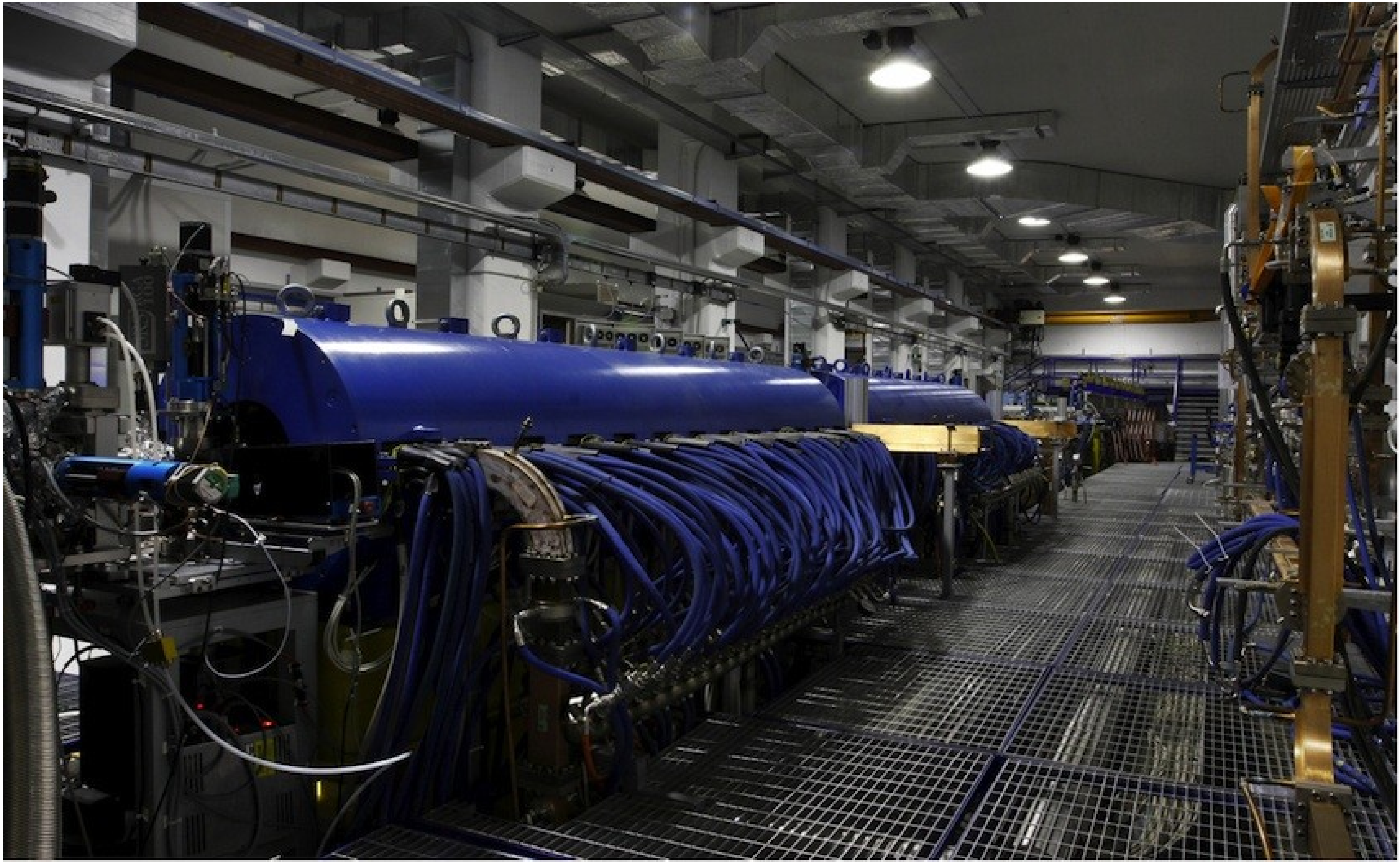
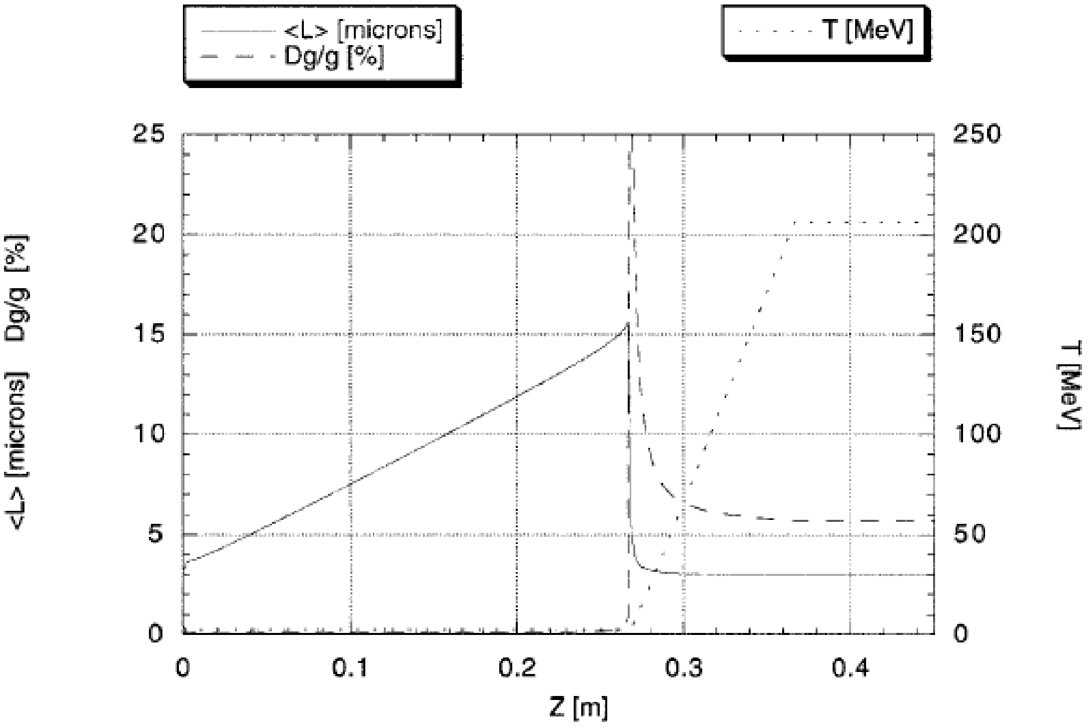
Longitudinal manipulations



Longitudinal compression

Longitudinal compression is possible when a bunch has an energy much lower than the resonant one, i.e. when the witness is (initially) much slower than the plasma wake[1], by velocity bunching[2].



M. Ferrario, T. C. Katsouleas, L. Serafini, and Ilan Ben Zvi, IEEE Trans. Plas. Sci. 28, (2000).

- Linear regime
- No beam loading

Further readings:

- S.V. Kuznetsov and N.E. Andreev, Plas. Phys. Rep. **27**, 372 (2001).
- N.E. Andreev and S.V. Kuznetsov, Plas. Phys. Cont. Fus. **45**, A39 (2003)
- S.V. Kuznetsov, Plas. Phys. Rep. **32**, 282 (2006).
- N.E. Andreev, et al., Nuc. Inst. Meth. Phys. Res. A **653**, 66 (2011).

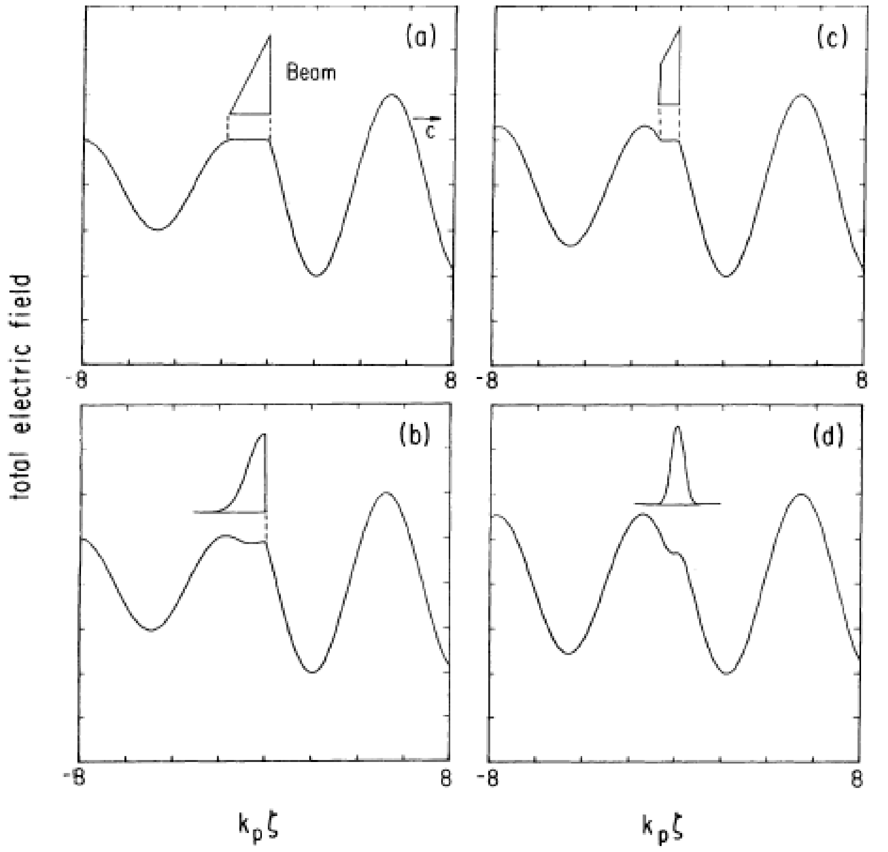
[1] J.L. Bobin, in Proc. of the ECFA-CAS/CEFN-In-2P3-IRF/CEA-EPS Workshop, p. 58 (1987). C.S. Liu and V.K. Tripathi, *Interaction of electromagnetic waves with electron beams and plasmas*, World Scientific, Singapore, 1994.
[2] L. Serafini and M. Ferrario, LNF-00/036, 2000. L. Serafini and M. Ferrario, AIP Conf. Proc. **581**, 87 (2001).

Energy spread control by beam loading

One way to limit energy spread in plasma is to “flatten out” the longitudinal field along the bunch by properly tailoring the beam loading.

Optimal beam profile for linear regime

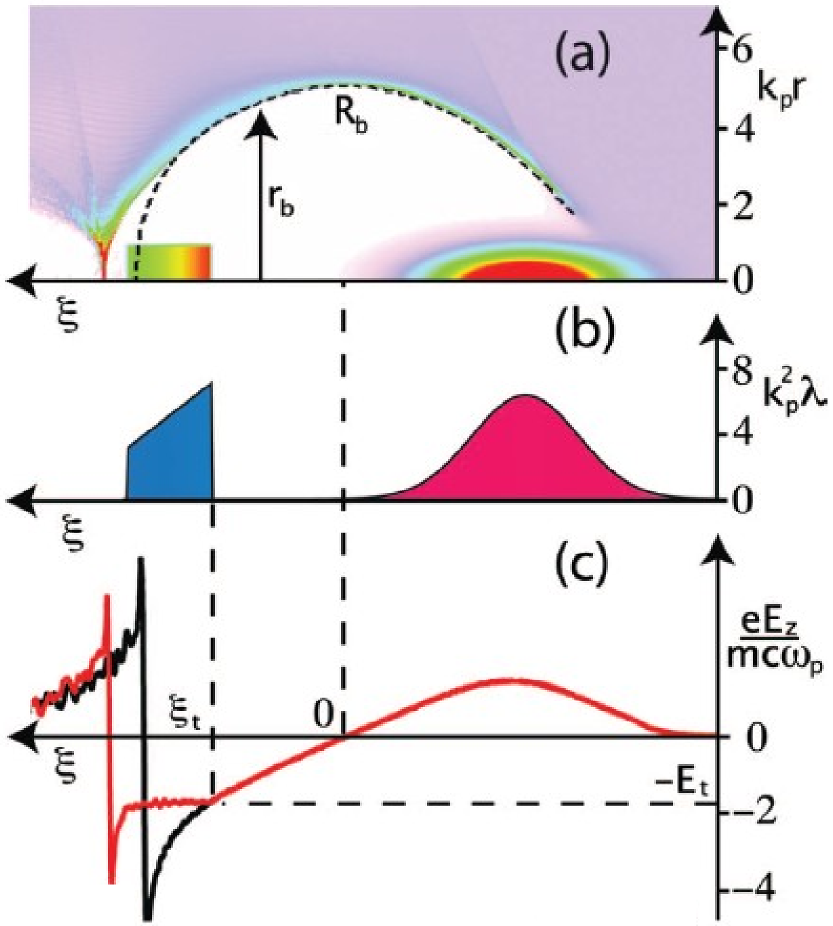
$$\rho_b(\zeta) = -\frac{k_p E_0}{4\pi}\left[(k_p \cos k_p\zeta_0)\zeta + (\sin k_p\zeta_0 - k_p\zeta_0 \cos k_p\zeta_0)\right]$$



T. Katsuleas, S. Wilks, P. Chen, J. M. Dawson and J. J. Su, Particle Accelerators **22**, 81 (1985)

Optimal beam profile for non-linear regime

$$\lambda(\xi) = E_t^2 + \frac{r_b^2}{4} = \frac{R_b^4 + r_t^4}{8r_t^2} - \sqrt{\frac{R_b^4 - r_t^4}{8r_t^2}}(\xi - \xi_t)$$



M. Tzoufras, et al., Phys. Plas. **16**, 056705 (2009)

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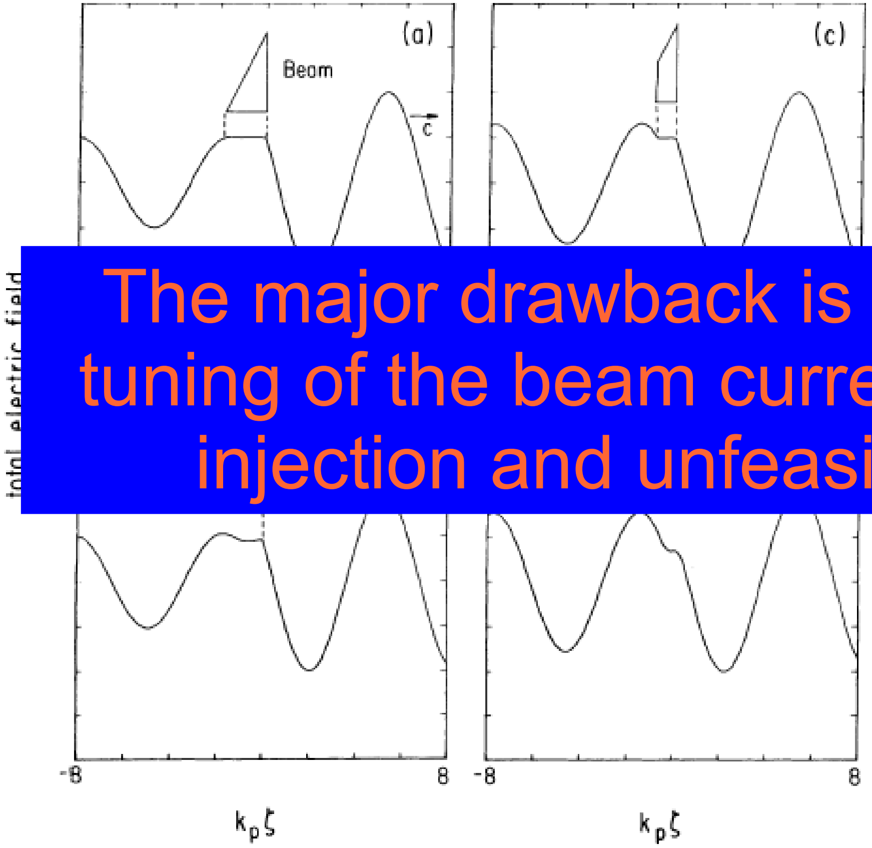

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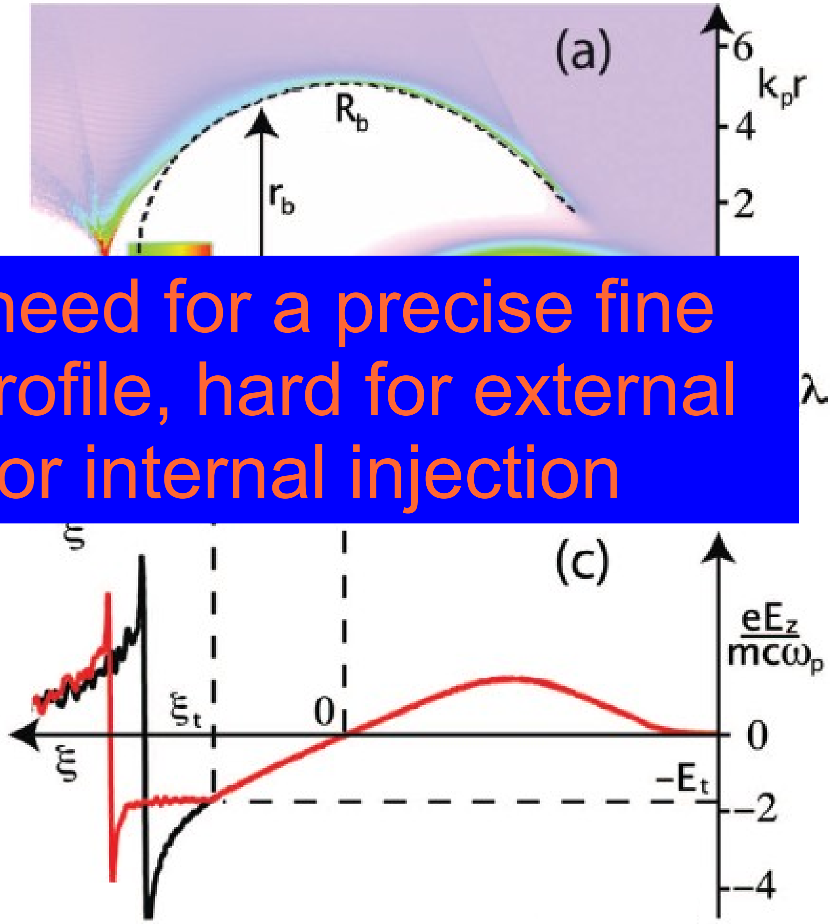

M. Tzoufras, et al., Phys. Plas. **16**, 056705 (2009)

The major drawback is the need for a precise fine tuning of the beam current profile, hard for external injection and unfeasible for internal injection

Energy spread control by hollow plasma channel

Another possibility is to use a hollow plasma channel, which also provides further advantages. The properties of a square well shaped hollow channel have been first studied in

T. C. Chiou, T. Katsouleas, C. Decker, W. B. Mori, J. S. Wurtele, G. Shvets, and J. J. Su, Phys. Plasmas **2**, (1995)

and exploited, in quasi-linear regime, for acceleration in

C. B. Schroeder, E. Esarey, C. Benedetti, and W. Leemans, Phys. Plasmas **20**, 080701 (2013)

We will show the results found in

A. Pukhov, O. Jansen, T. Tueckmantel, J. Thomas, and I. Yu. Kostyukov, Phys. Rev. Lett. **113**, 245003 (2014)

which studies the bubble regime.

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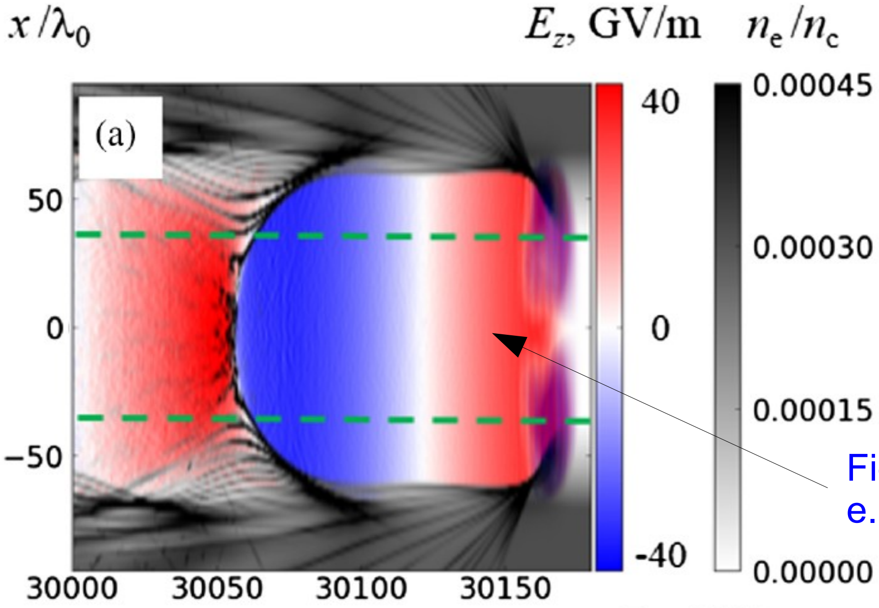
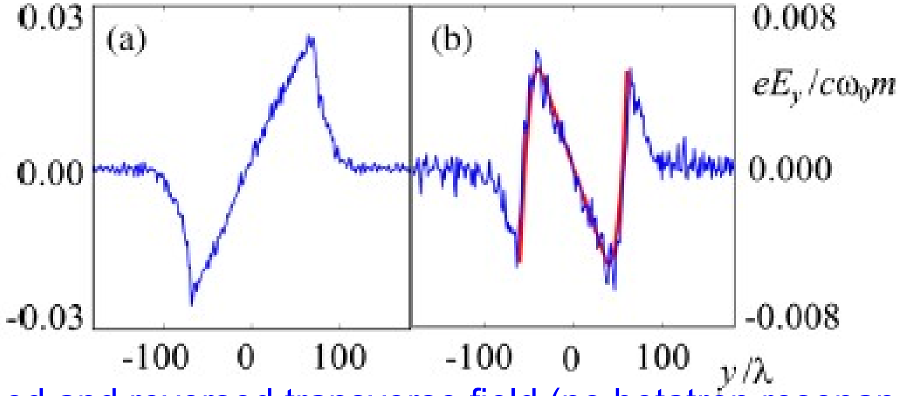
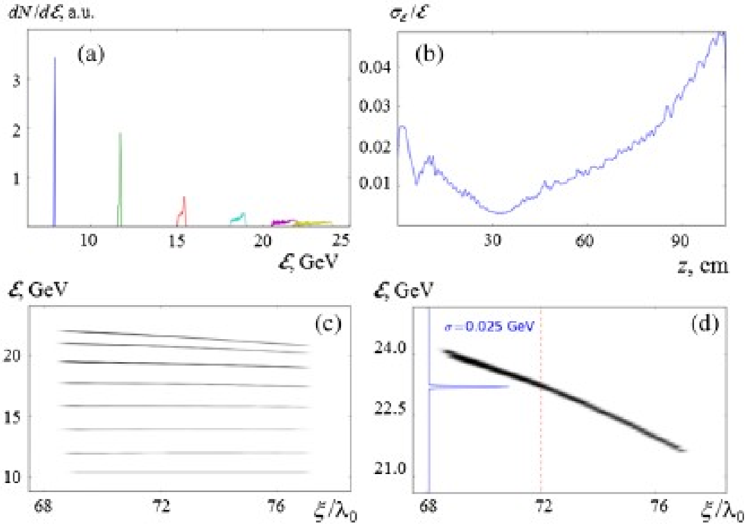
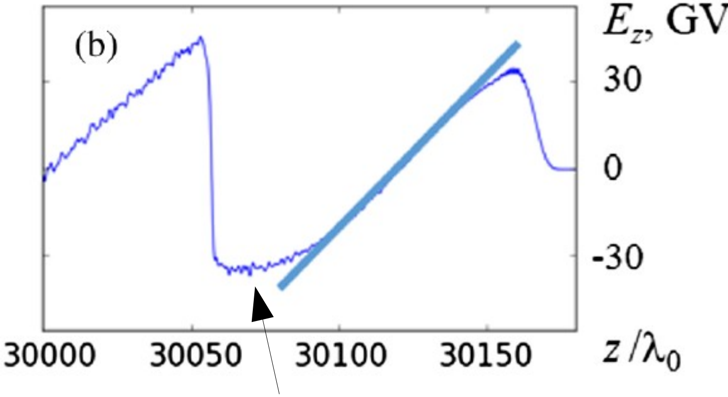




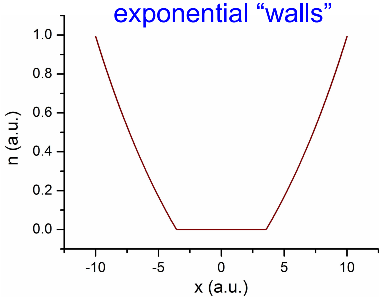
Reduced and reversed transverse field (no betatron resonance)

Fields are purely e.m. near the axis





Hollow channel with exponential “walls”



Small overall and uncorrelated energy spread

Flat longitudinal field

Moreover...

… little or no self injected spurious charge

… possibility to tune depletion and dephasing lengths

[1] A. Pukhov, et al., Phys. Rev. Lett. **113**, 245003 (2014).

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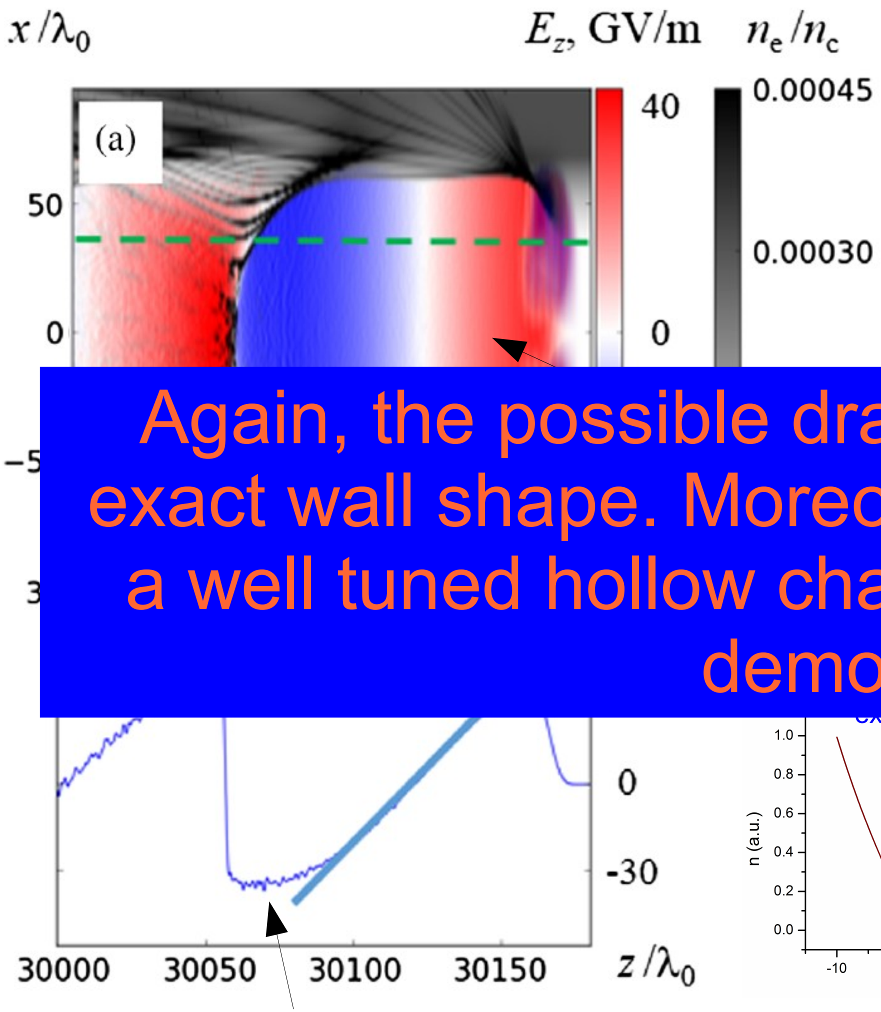
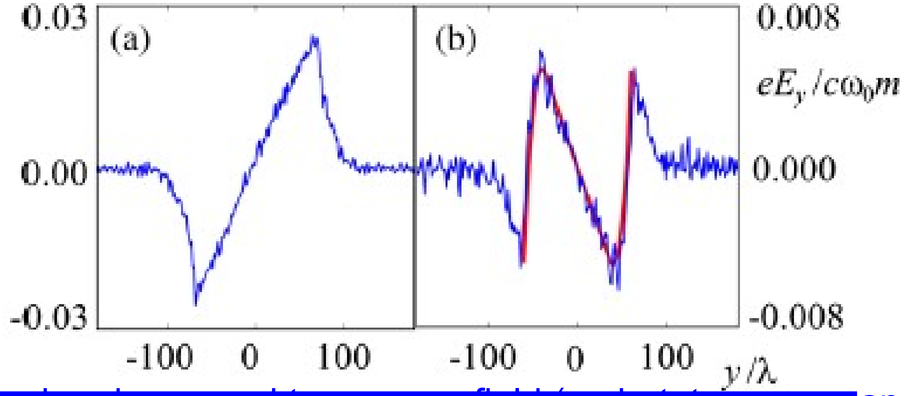
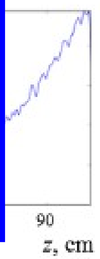
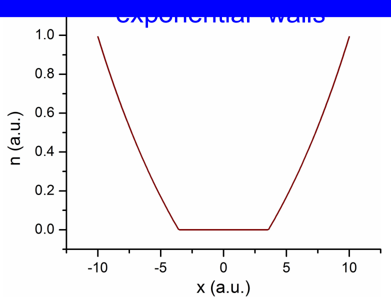


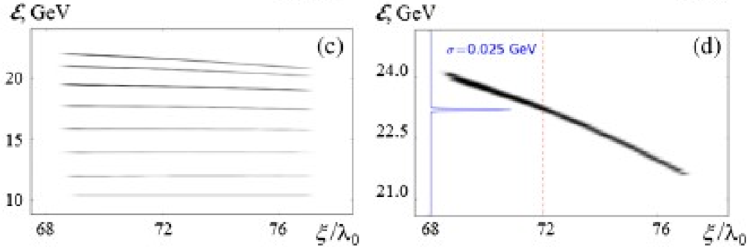


ance)

Again, the possible drawback is sensitivity to the exact wall shape. Moreover the possibility to realize a well tuned hollow channel in a stable way is not demonstrated.







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[1] A. Pukhov, et al., Phys. Rev. Lett. **113**, 245003 (2014).

Moreover...

… little or no self injected spurious charge

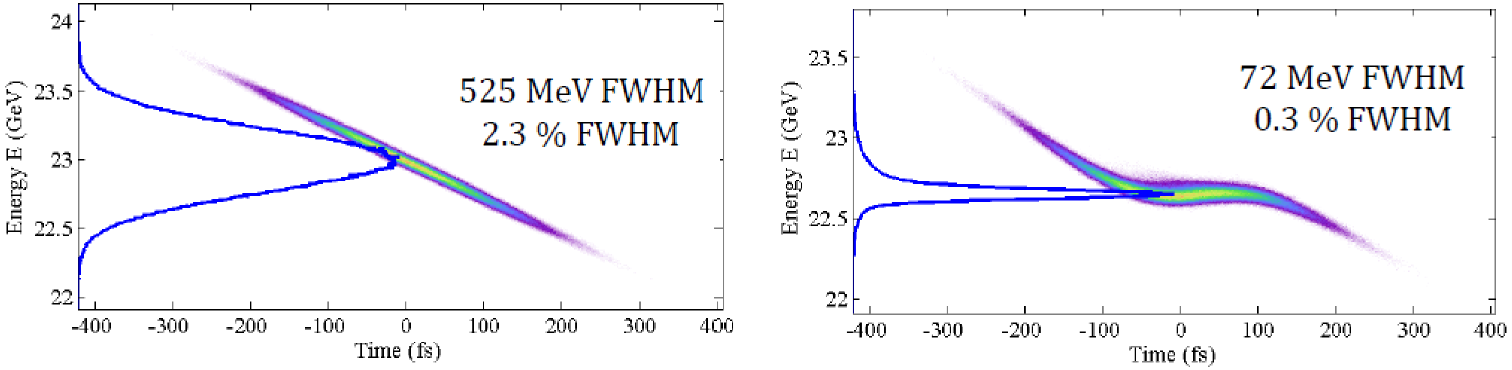
… possibility to tune depletion and dephasing lengths

Energy spread control by plasma dechirper[1]

Following the idea of corrugated pipe dechirper[2], it is possible to arrange plasma density in order to act as a plasma dechirper.

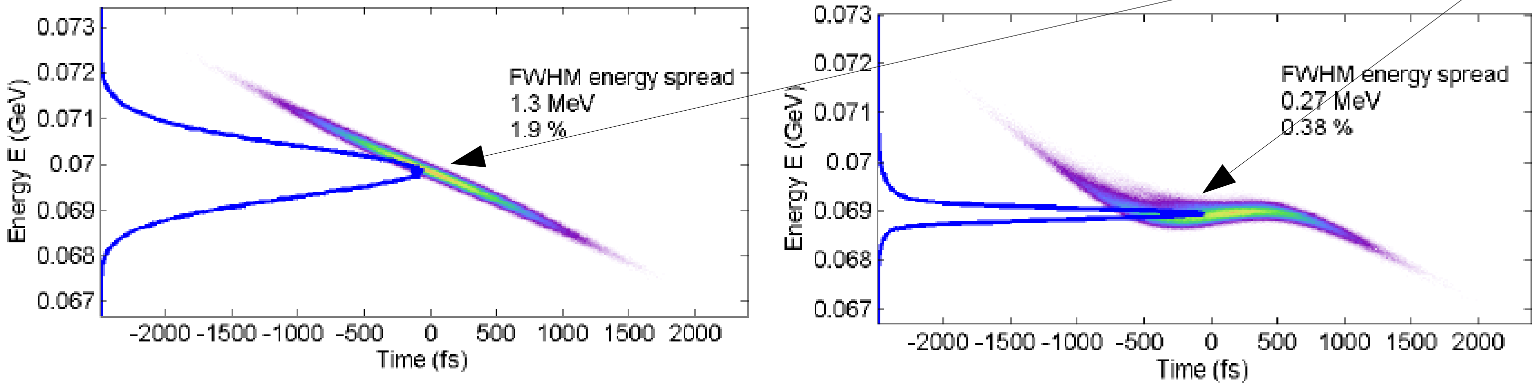
FACET beam parameters

$\sigma_z = 25\ \mu\mathrm{m}, \sigma_{x,y} = 30\ \mu\mathrm{m}, \varepsilon_x = 50\ \mu\mathrm{m}, \varepsilon_y = 5\ \mu\mathrm{m}$, 2 nC, 23 GeV, 1.0 % rms energy spread



ATF beam parameters:

$\sigma_z = 150\ \mu\mathrm{m}, \sigma_{x,y} = 50\ \mu\mathrm{m}, \varepsilon_x = \varepsilon_y = 1\ \mu\mathrm{m}$, 150 pC, 70 MeV, 1.0 % rms energy spread



Works only for positive chirps

Uncorrelated energy spread is (irreversibly) increased

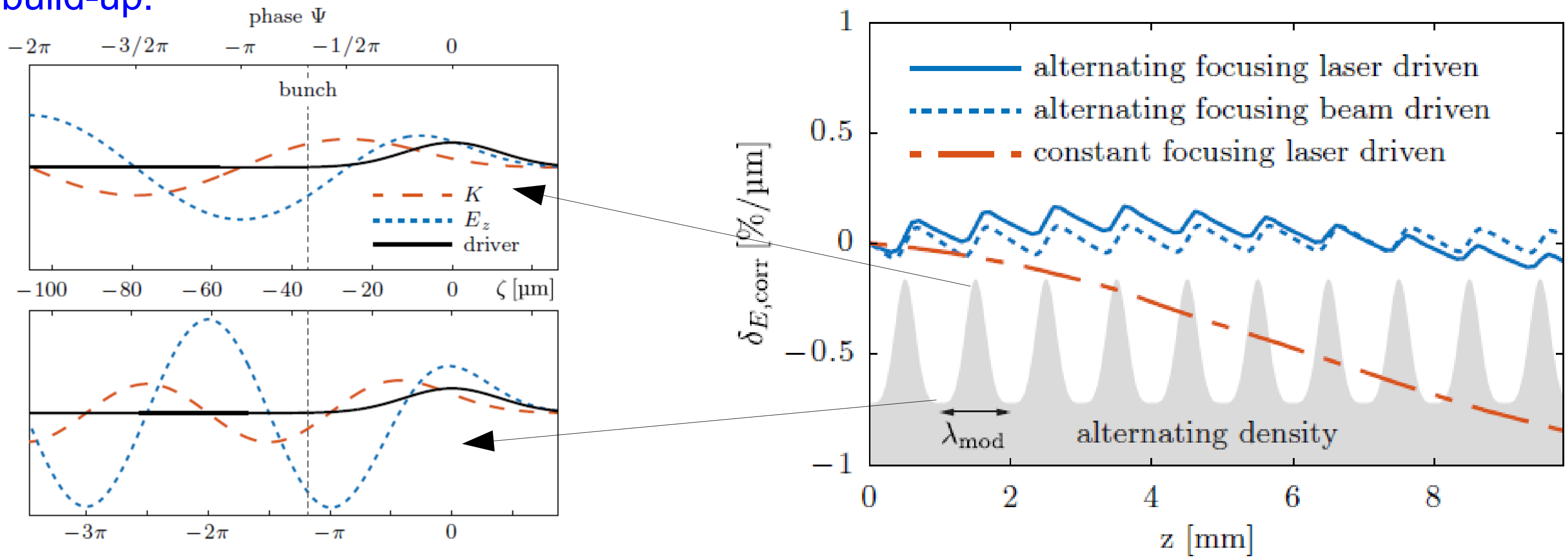
Tuning may still be quite critical

[1] V. Wacker, private communication (2015).

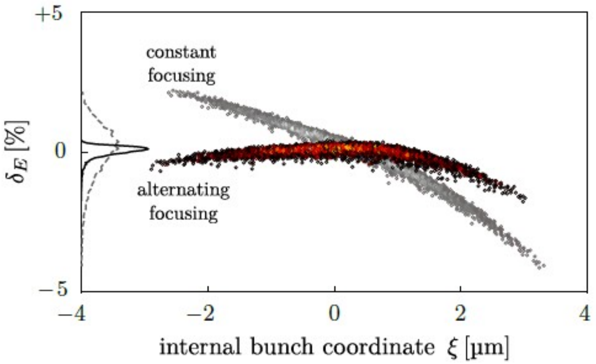
[2] K.L.F. Bane and G. Stupakov, Nuc. Inst. Meth. Phys. Res. **690**, 106 (2012). S. Antipov, et al., Phys. Rev. Lett. **112**, 114801 (2014).

Energy spread control by alternating focusing[1]

In linear and quasi-linear regimes, the focusing strength is zero on crest. For a finite length bunch, however, the tail would be disrupted by defocusing fields. Modulating the plasma density moves the bunch back and forth the accelerating peak keeping it focused and avoiding chirp build-up.



Does not relay on beam loading!



Problematic with bubble regime

Correct tapering critical and seems hard to realize

Emittance conservation (?)

Beam loading (?)

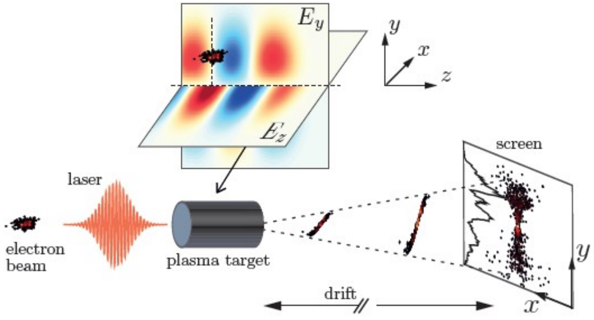
[1] R. Brinkmann, et al., arXiv: 1603.08489v2 [physics.acc-ph] 2016.

Beam streaking

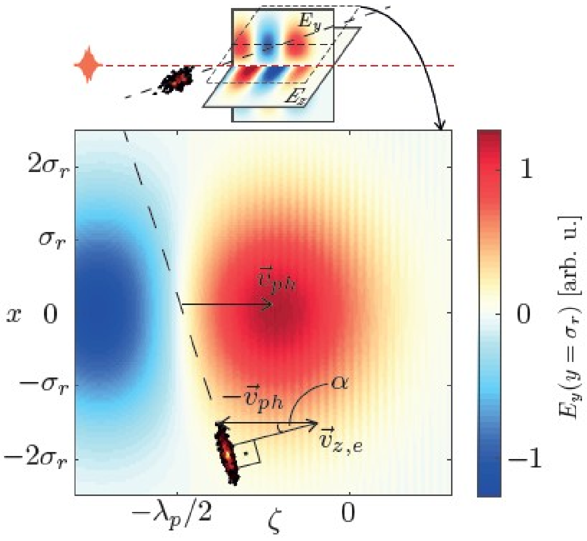
(for longitudinal diagnostics)

Diagnose the longitudinal properties of a plasma beam (ultra short) is hard with conventional methods. A proposal, shows how it is possible to use plasma fields.

Collinear setup

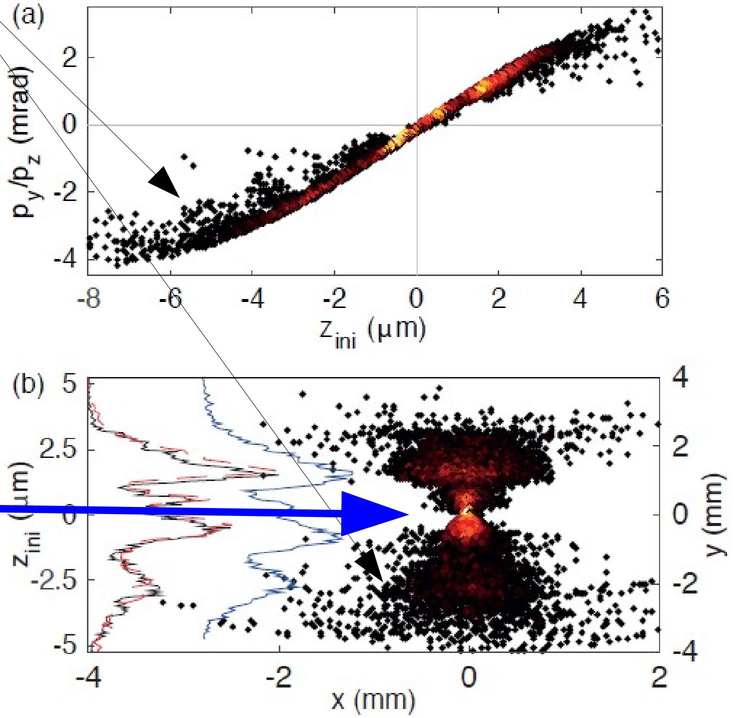


Setup with an angle



Some field non-linearities effects are present

Resolution in the bunch core is below 100 as!

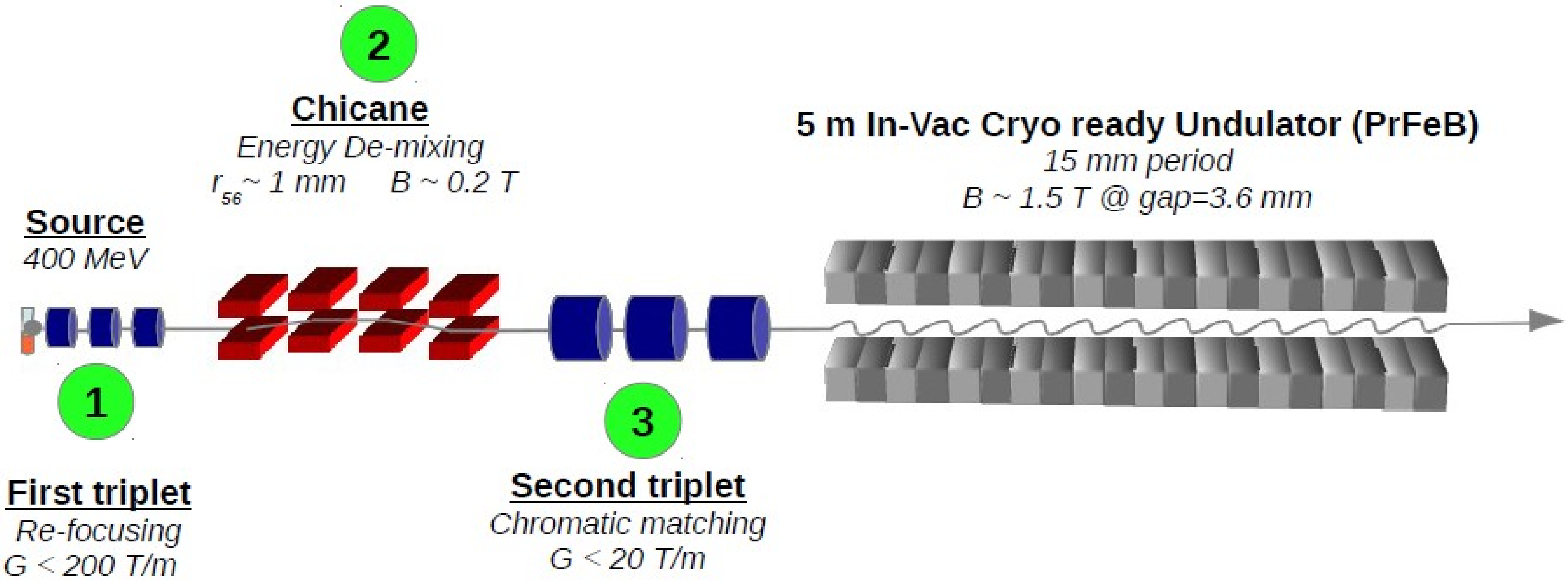


Beam loading may greatly reduce resolution

[1] I. Dornmair, C. B. Schroeder, K. Floettmann, B. Marchetti, and A. R. Maier, arXiv: 1603.02511v1 [physics.acc-ph] 2016.

A (cherry picked) FEL oriented manipulation (not in plasma): chromatic matching[1]

i.e. a possible answer to the question “how could we run an FEL with the plasma beams we can produce right now?”



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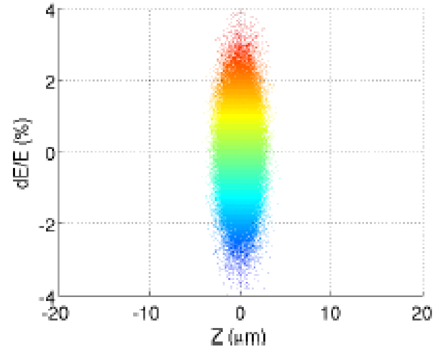
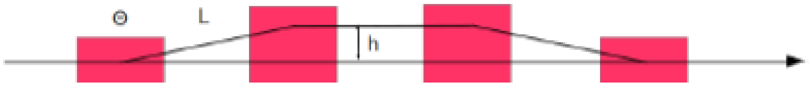
[1] A. Loulergue, M. Labat, C. Evain, C. Benabderrahmane, V. Malka and M.E. Couprie, New J. Phys. **17**, 023028 (2015).

Chromatic matching

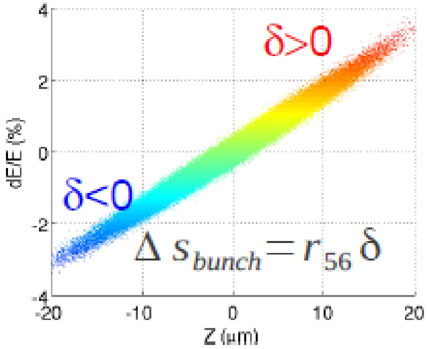
Assume a bunch with high energy spread and divergence. After first focusing use a chicane to stretch the bunch and realize an energy sorting (chirp):

Longitudinal phase space



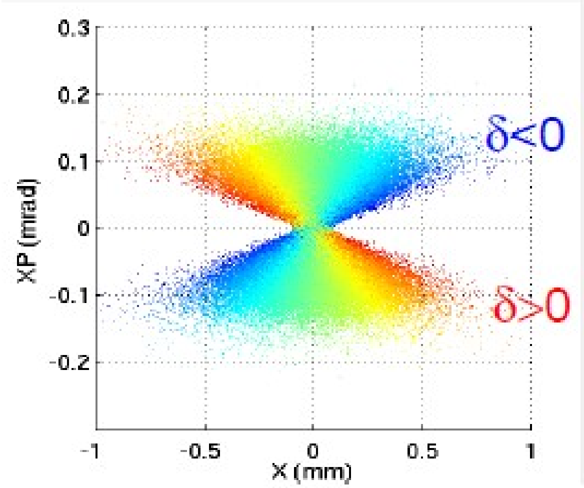


Energy de-mixing Chicane

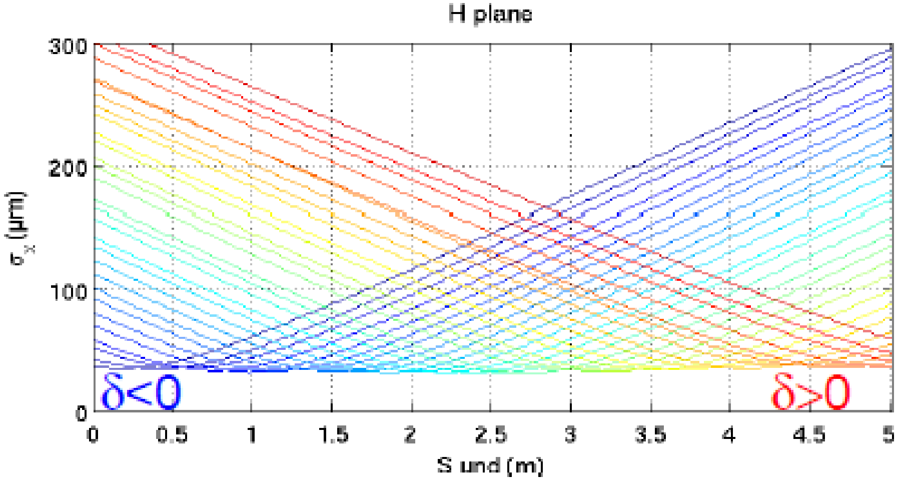


Pictures source: A. Loulergue, LWFA electron beam manipulations for FEL amplification, presented at EAAC 2015.

Transverse phase spaces

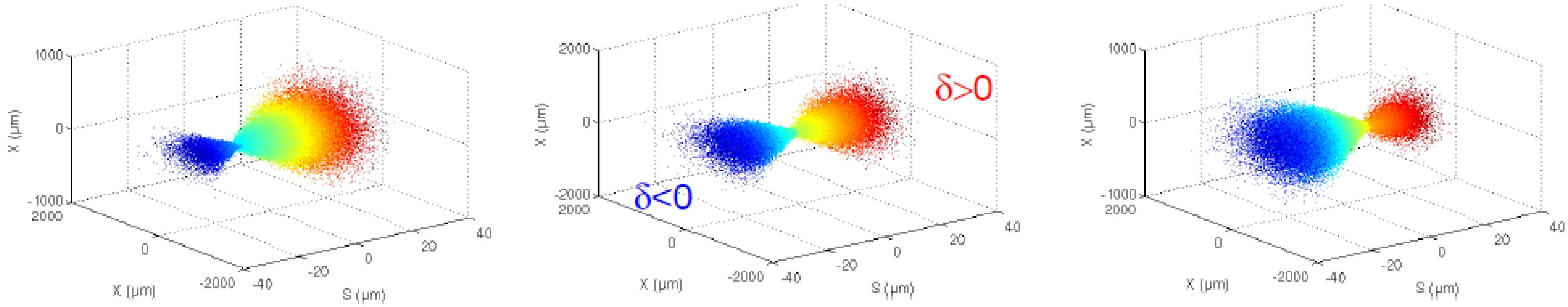


If the beam is focused, each quasi-monochromatic slice will have a waist at a different position.



Chromatic matching

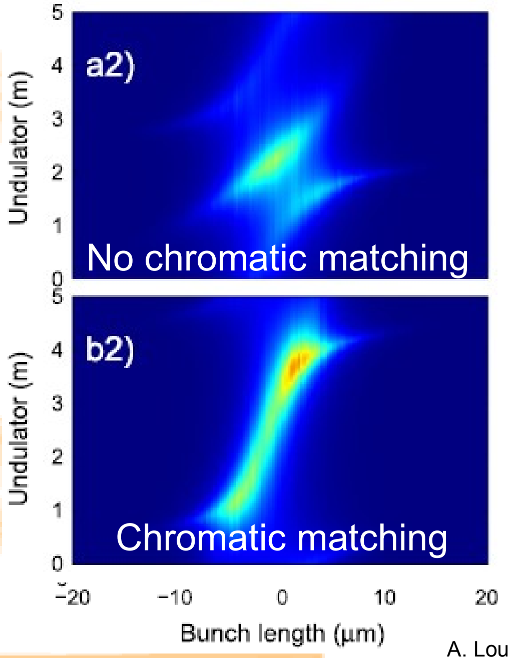
The waist slips along the bunch from the tail to the head...

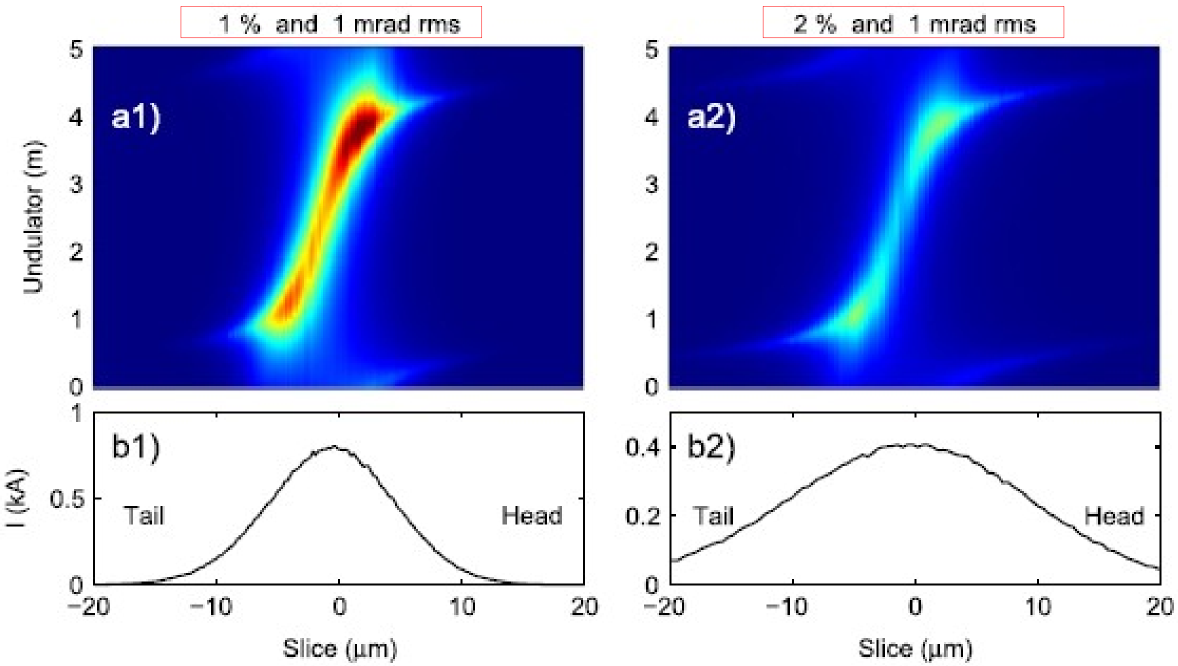


Source: A. Loulergue, LWFA electron beam manipulations for FEL amplification, presented at EAAC 2015.

… pretty much like the FEL radiation ...

… and if they are synchronized …

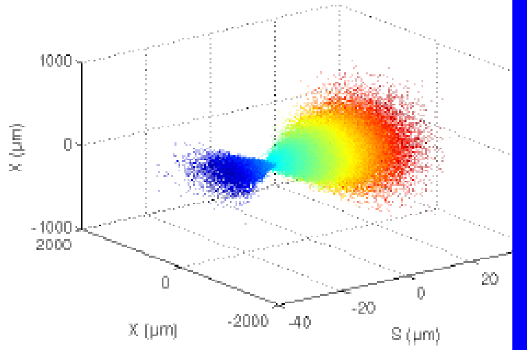


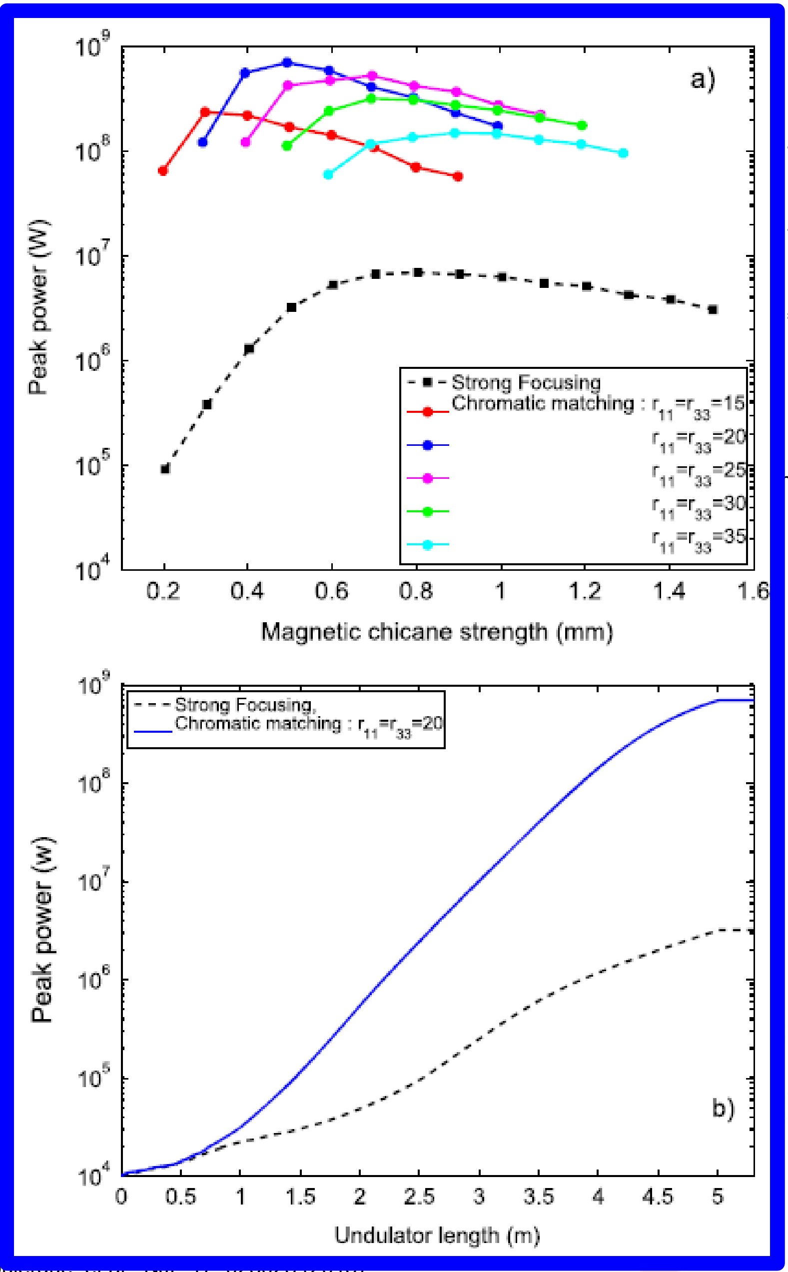


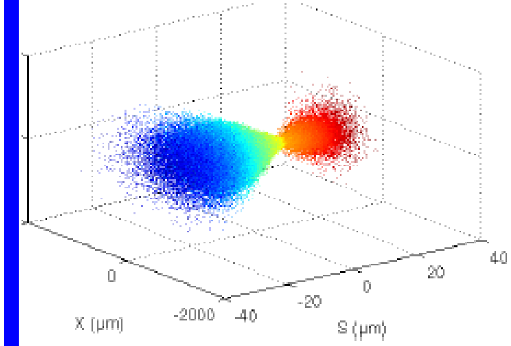
A. Loulergue, et al., NJP 17, 023028 (2015).

Chromatic matching

The waist slips along the bu



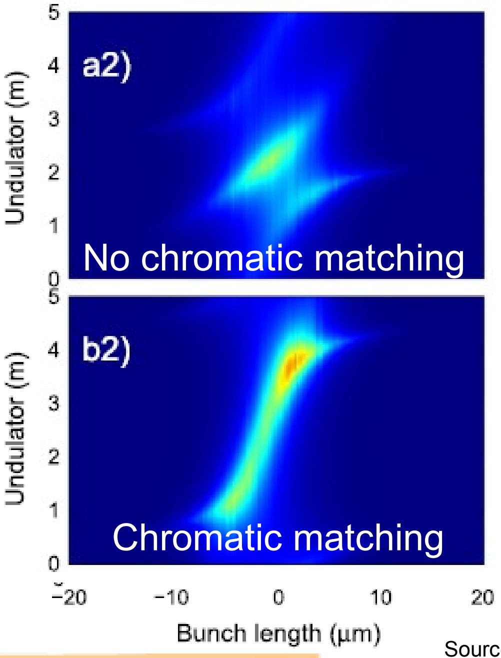


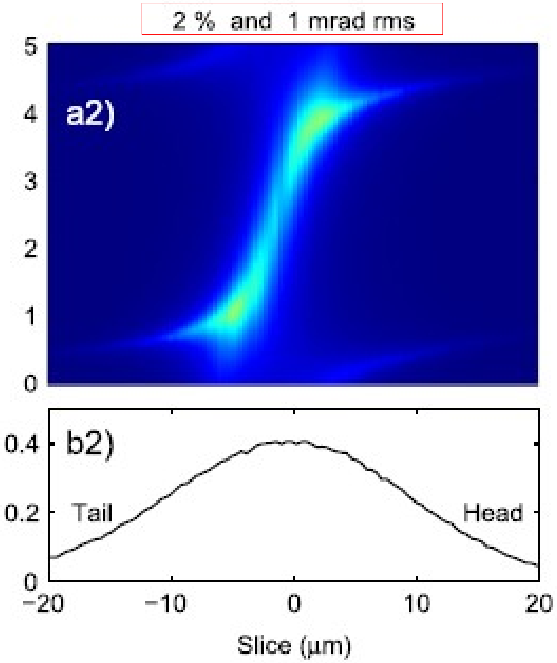


ns for FEL amplification, presented at EAAC 2015.

… pretty much like the FEL

… and if they are synchroni



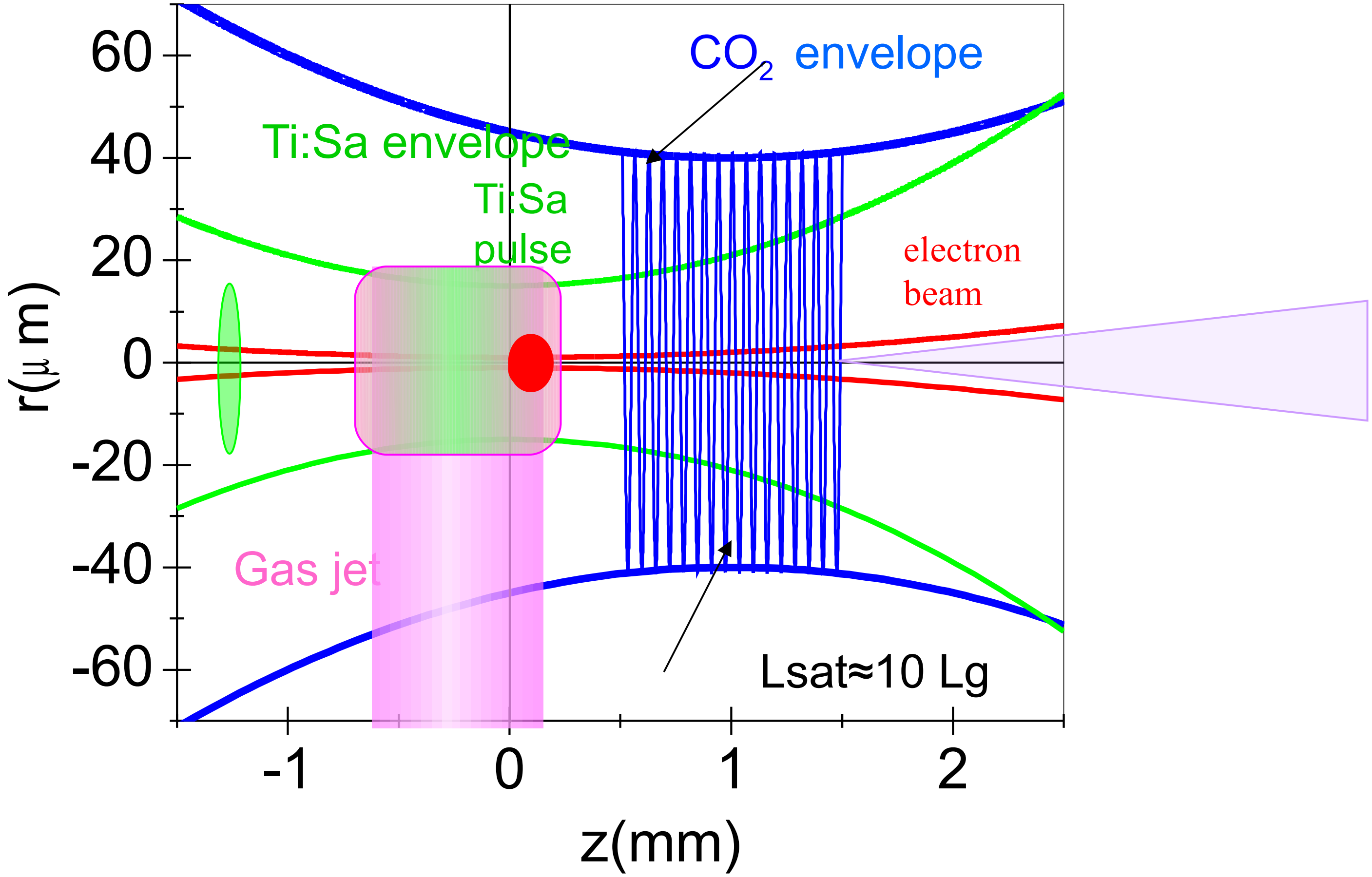


Source: A. Loulergue, et al., NJP 17, 023028 (2015).

Cornerstone application: All Optical FEL

AOFEL in a nutshell

Simply collide a plasma generated beam with an electromagnetic ondulator (laser):

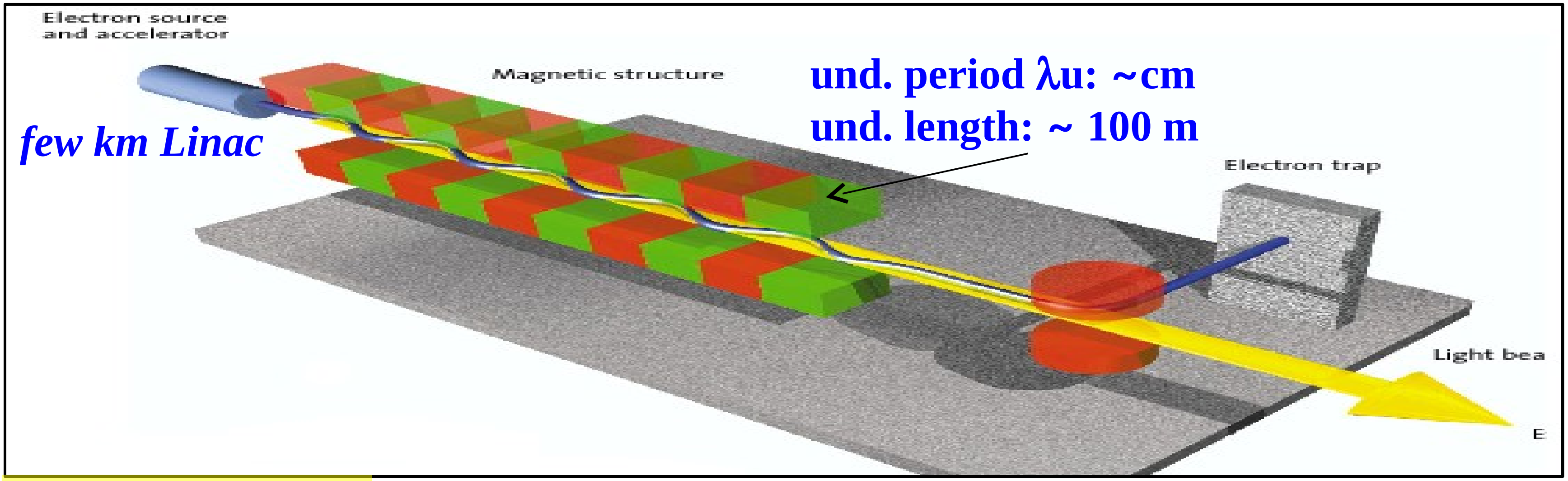


First proposed in V. Petrillo, L. Serafini and P. Tomassini, in Proc. of the 11th European Particle Accelerator Conference, Genova, Italy, 2008.
Studied in A. Bacci, C. Maroli, V. Petrillo, A.R. Rossi, L. Serafini and P. Tomassini, Nuc. Inst. Meth. Phys. Res. A **587**, 388 (2008)
and in V. Petrillo, L. Serafini and P. Tomassini, Phys. Rev. STAB **11**, 070703 (2008)

From FEL to AOFEL:

Scale down linac AND ondulator sizes!

1-25 GeV electrons



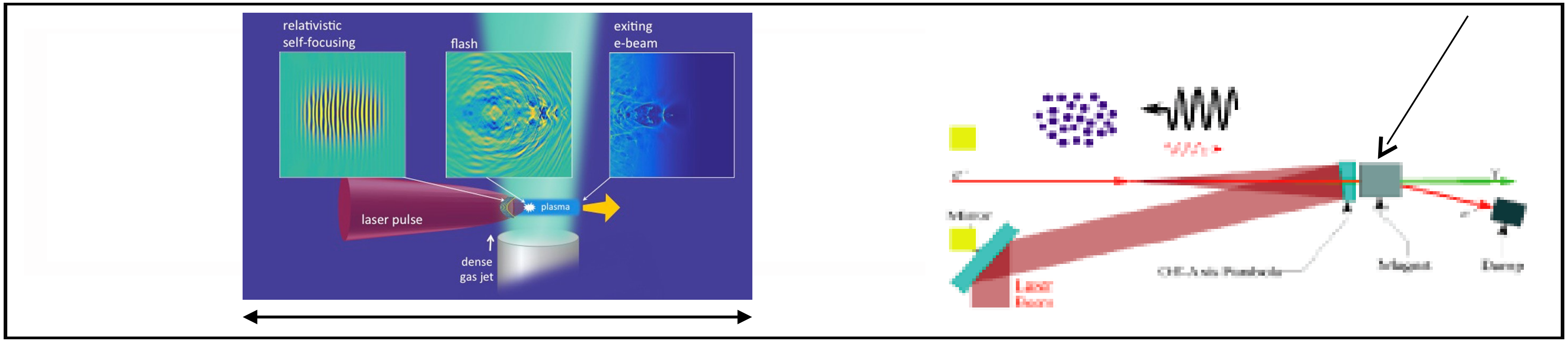
few km Linac

und. period λu: ~cm
und. length: ~ 100 m

100-0.5 Å photons
(0.5 Å   24 KeV)

30-150 MeV electrons

laser λ: ~ 1- 10 μm
interaction area ~ few cm



~ few cm Linac

AOFEL: e.m. undulator

RESONANCE CONDITIONS:

$$\lambda_R = \boxed{\lambda_w} \frac{\left(1 + a_w^2\right)}{2\gamma_0^2}$$

Magnetostatic undulator- FEL

Example : for *λ_R=.1nm, λ_w=2cm and a_w ~ 1*

$\Longrightarrow$ E = 10 GeV

AOFEL: e.m. undulator

RESONANCE CONDITIONS:

$$\lambda_R = \boxed{\lambda_w} \frac{\left(1 + a_w^2\right)}{2\gamma_0^2}$$

Magnetostatic undulator- FEL

Example : for λ_R=.1nm, λ_w=2cm and $a_w \sim 1$

$\Longrightarrow$ E = 10 GeV

$$\lambda_R = \boxed{\lambda_L} \frac{\left(1 + a_0^2/2\right)}{4\gamma_0^2}$$

Electromagnetic undulator

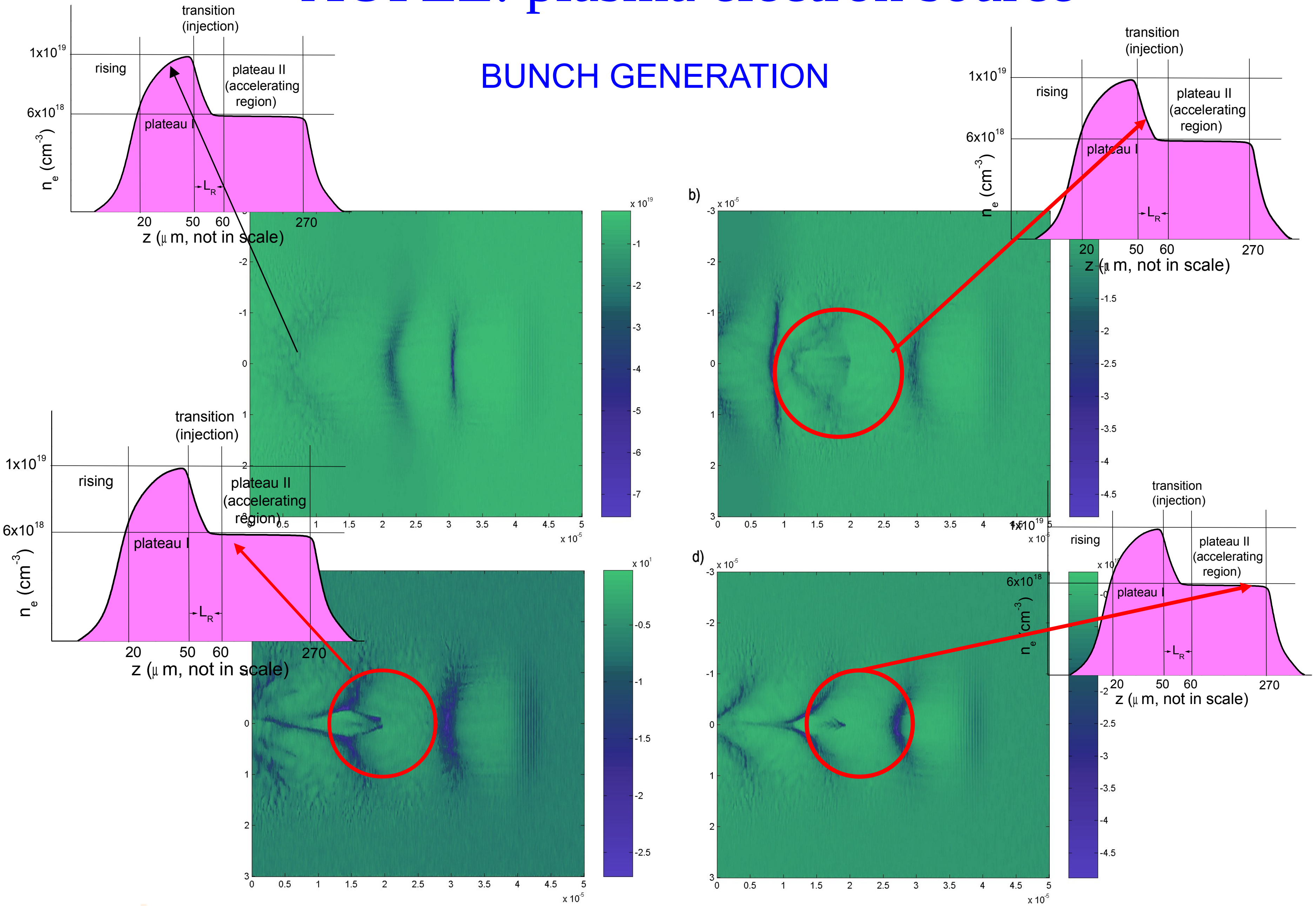
Example : for λ_R=.1nm, λ_L=0.8µm and $a_0 \sim 0.2$*

$\Longrightarrow$ E = 22 MeV

* for many practical reasons, $a_0 \lesssim 1$

AOFEL: plasma electron source

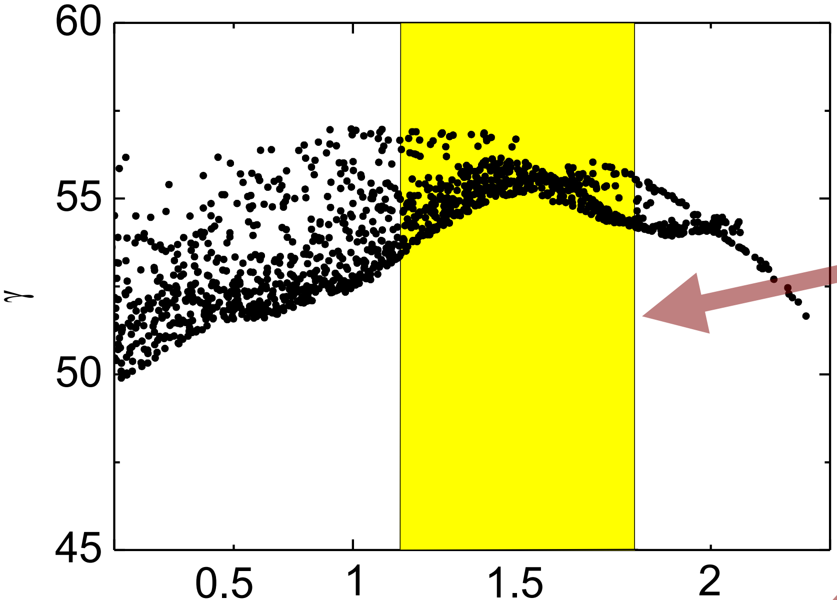
BUNCH GENERATION

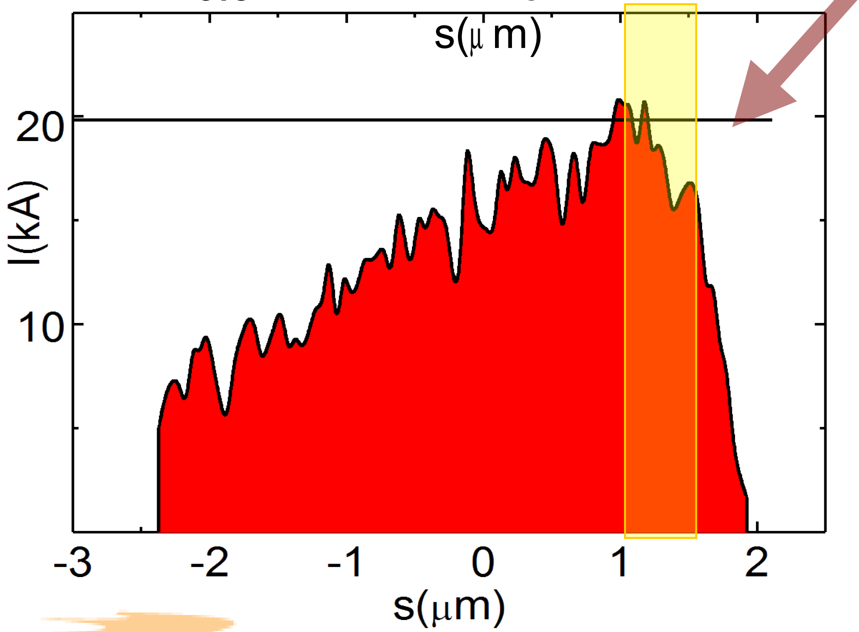


V. Petrillo, L. Serafini and P. Tomassini, Phys. Rev. STAB **11**, 070703 (2008)

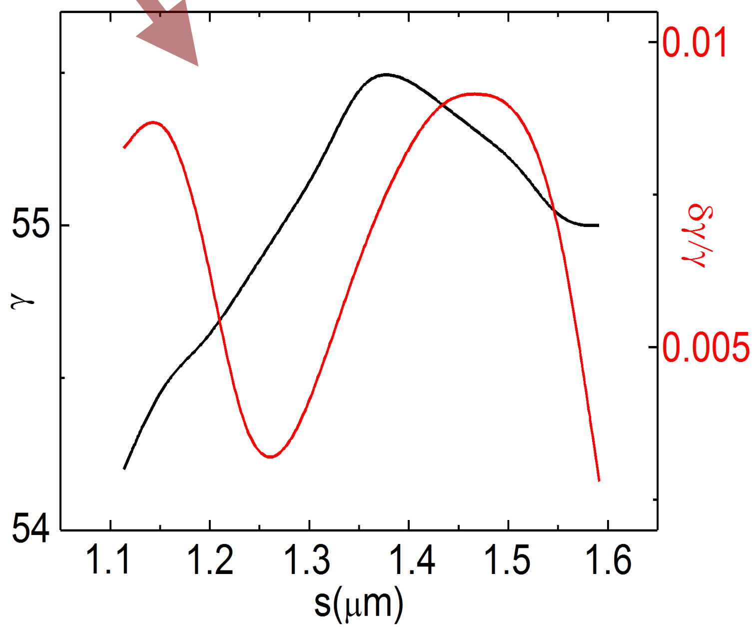
AOFEL: electron bunch

VORPAL results





Best slices: we do not need all the bunch to be perfect for lasing



$<\gamma>=55$

$<E>=27$ MeV

I≈20 kA

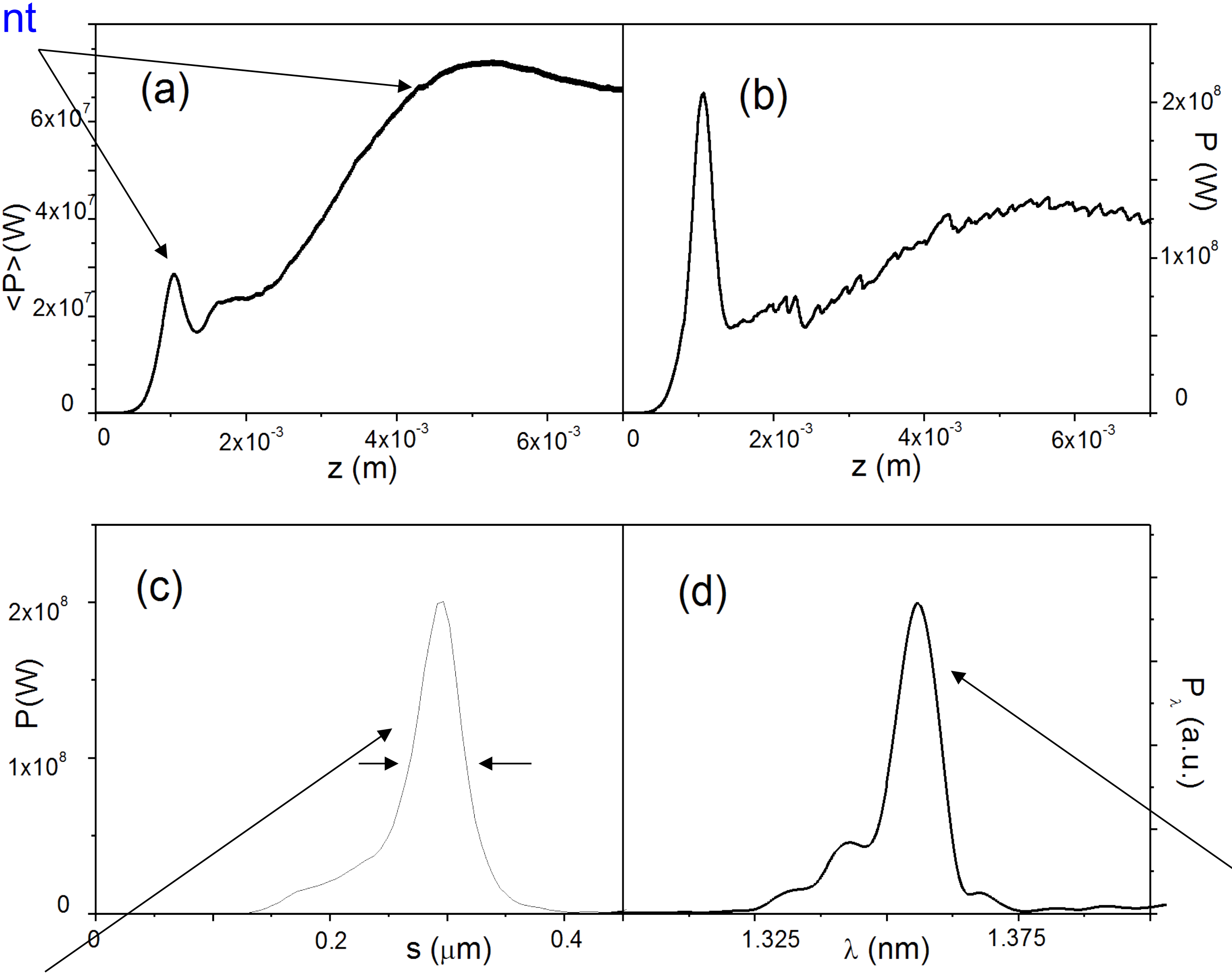
$\varepsilon_x<0.5$ mm mrad

$\Delta E/E\approx 2\ 10^{-3},10$

Q=55 pC

AOFEL: FEL radiation

GENESIS 1.3 results



Superradiant structure

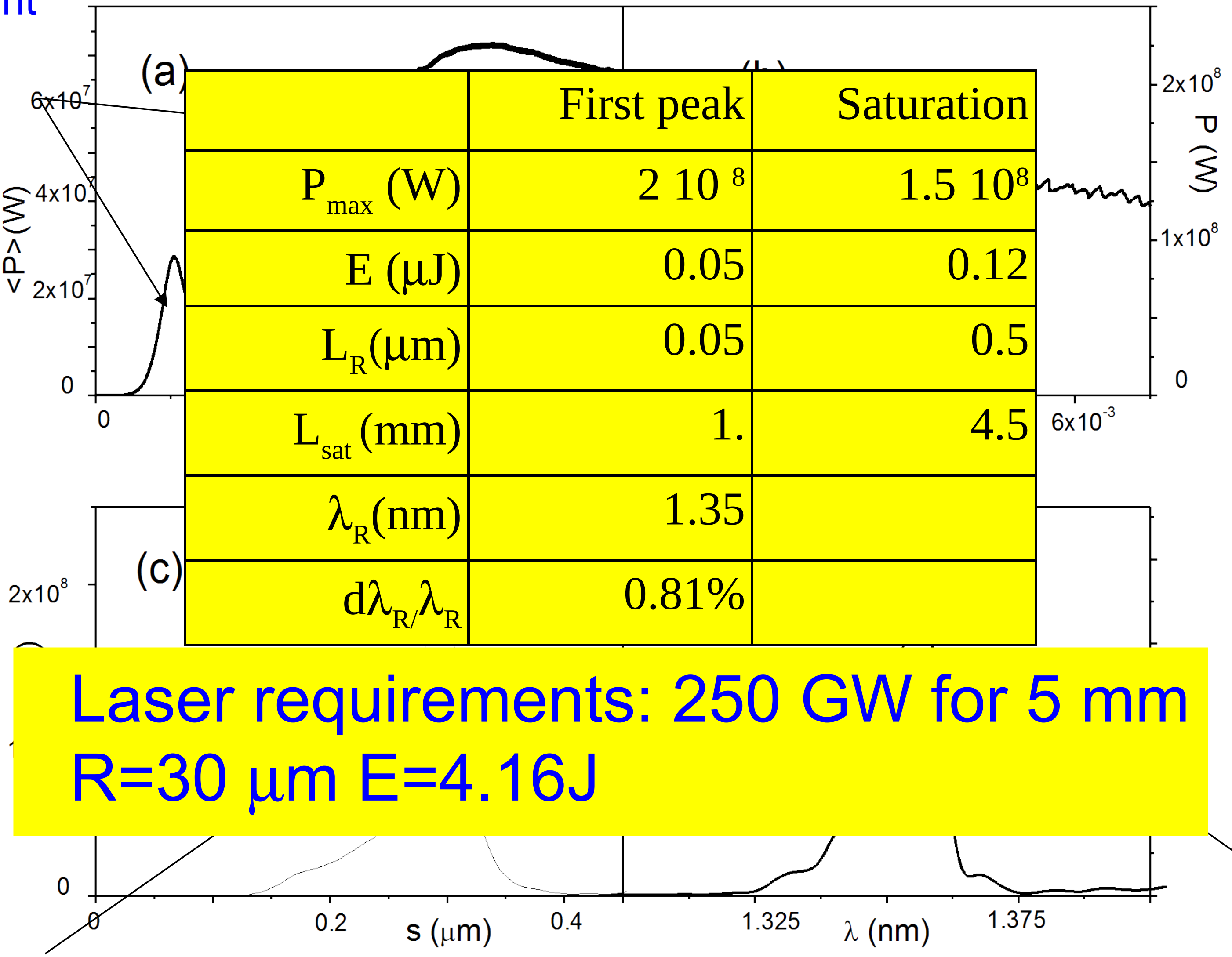
Single spike structure 0.1 µm=330 as

Monochromatic pulse

AOFEL: FEL radiation

GENESIS 1.3 results

Superradiant structure



	First peak	Saturation
P_{max} (W)	$2\ 10^{8}$	$1.5\ 10^{8}$
E (μJ)	0.05	0.12
L_R(μm)	0.05	0.5
L_{sat} (mm)	1.	4.5
λ_R(nm)	1.35	
$d\lambda_{R/}\lambda_R$	0.81%	

Laser requirements: 250 GW for 5 mm R=30 μm E=4.16J

Single spike structure 0.1 μm=330 as

Monochromatic pulse

Conclusion

Conclusion


Beam

~~self~~-control

is the best

super-power

you can have

Thanks for your attention!

Backup Slides

Highly chromatic beam transport: theory

DEF: $\varepsilon_n^2 =< x^2 >< \beta^2\gamma^2 x'^2 > - < x\beta\gamma x' >^2$

DEF: $\sigma_E^2 = \dfrac{< \beta^2\gamma^2 > - < \beta\gamma >^2}{< \gamma >^2}$

DEF: $x' = \dfrac{p_x^i}{< p_z >}$

ASSUME: relativistic electrons (β ~ 1) and no correlation btw *x* and energy

$$\varepsilon_n^2 =< \gamma >^2 \sigma_E^2 < x^2 >< x'^2 > + < \beta\gamma >^2 (< x^2 >< x'^2 > - < xx' >^2)$$

$$\varepsilon_n^2 =< \gamma >^2 \left(\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2\right)$$

Highly chromatic beam transport: theory

$$\varepsilon_n^2 = <\gamma>^2 \left(\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2\right)$$

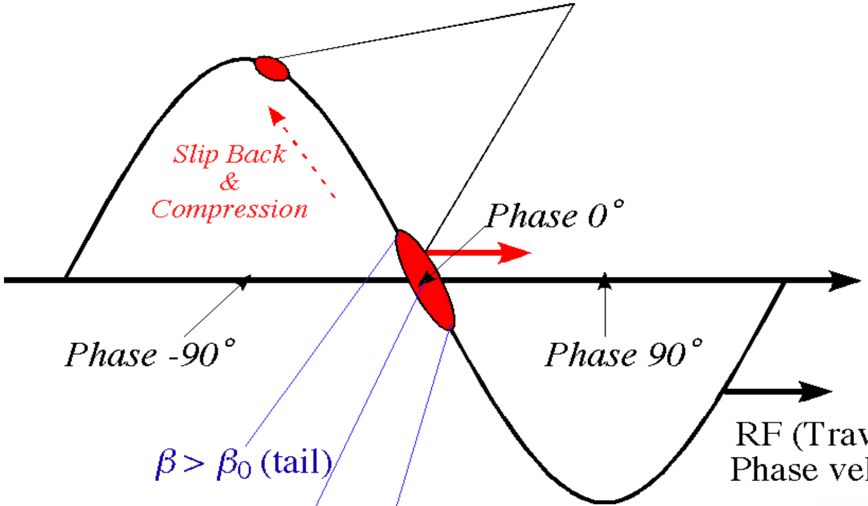
NOTICE: plasma accelerated bunches are usually emittance dominated!

$$\sigma_x(s) = \sqrt{\xcancel{\sigma_0^2} + \xcancel{2\sigma_0\sigma_0'}s + \left(\frac{\varepsilon^2}{\sigma_0^2} + \xcancel{\sigma_0'^2}\right)s^2}$$

Starting from a waist: $\sigma_0' = \left.\frac{d\sigma(s)}{ds}\right|_{s=0} = 0$ and $\varepsilon^2 = \sigma_0^2\sigma_{x'}^2$. After a small drift:

$$\varepsilon_n^2 = <\gamma>^2 \left(s^2 \sigma_E^2 \sigma_{x'}^4 + \varepsilon^2\right)$$

Velocity bunching



Electron Bunch from RF injector
Initial velocity $\beta_0 \sim 0.994$ (4MeV)

Slip Back & Compression

Phase 0°

Phase -90°

Phase 90°

$\beta > \beta_0$ (tail)

$\beta = \beta_0$

$\beta < \beta_0$ (head)

RF (Traveling Wave)
Phase velocity $\beta_{ph} \sim 1$