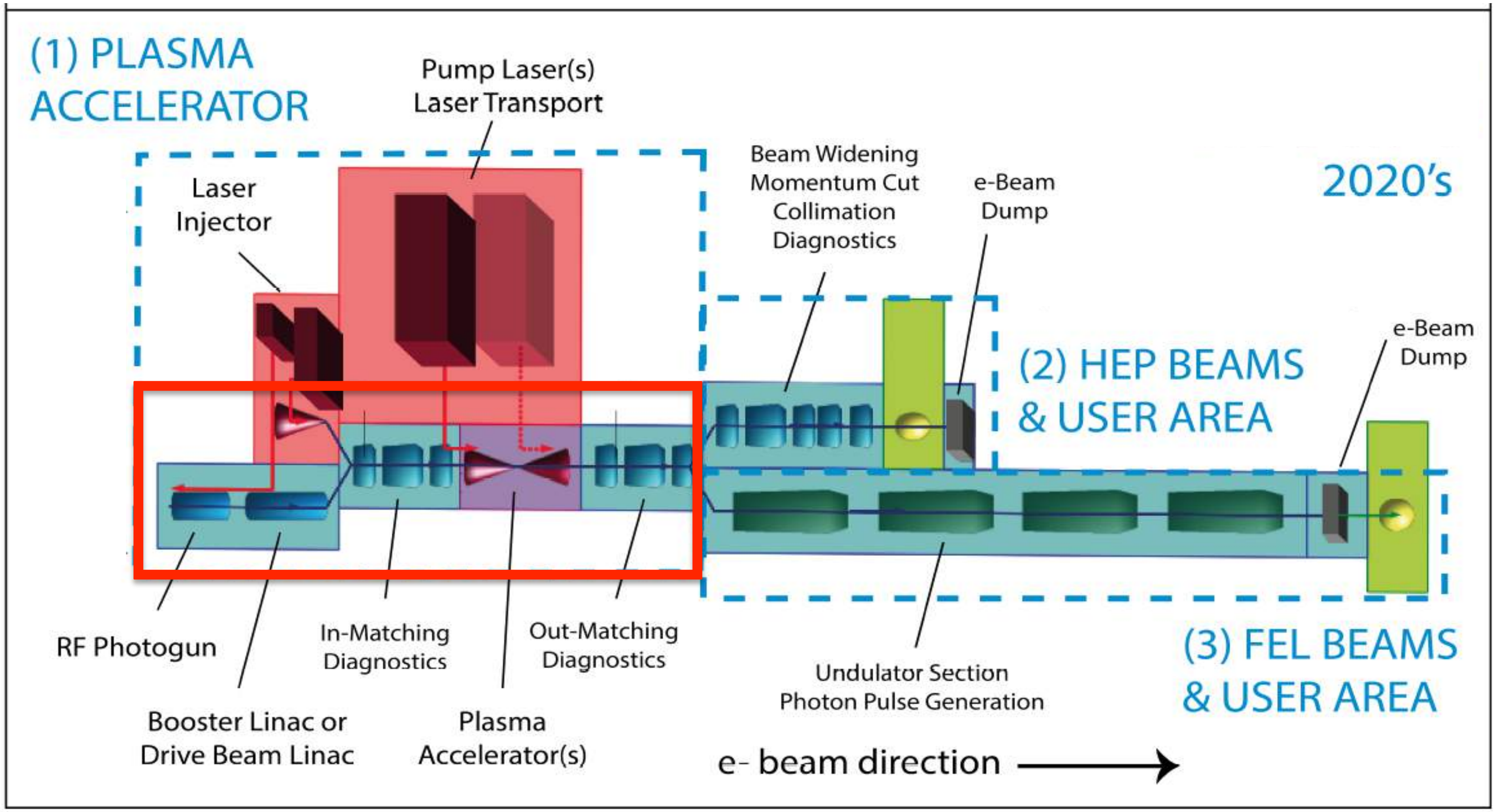
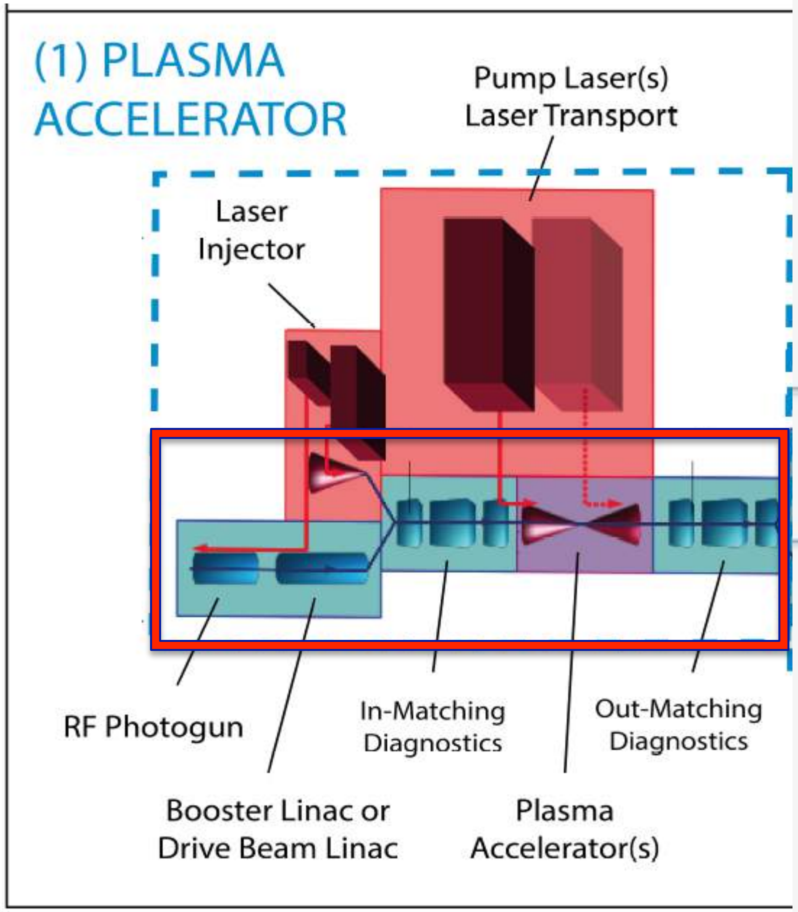
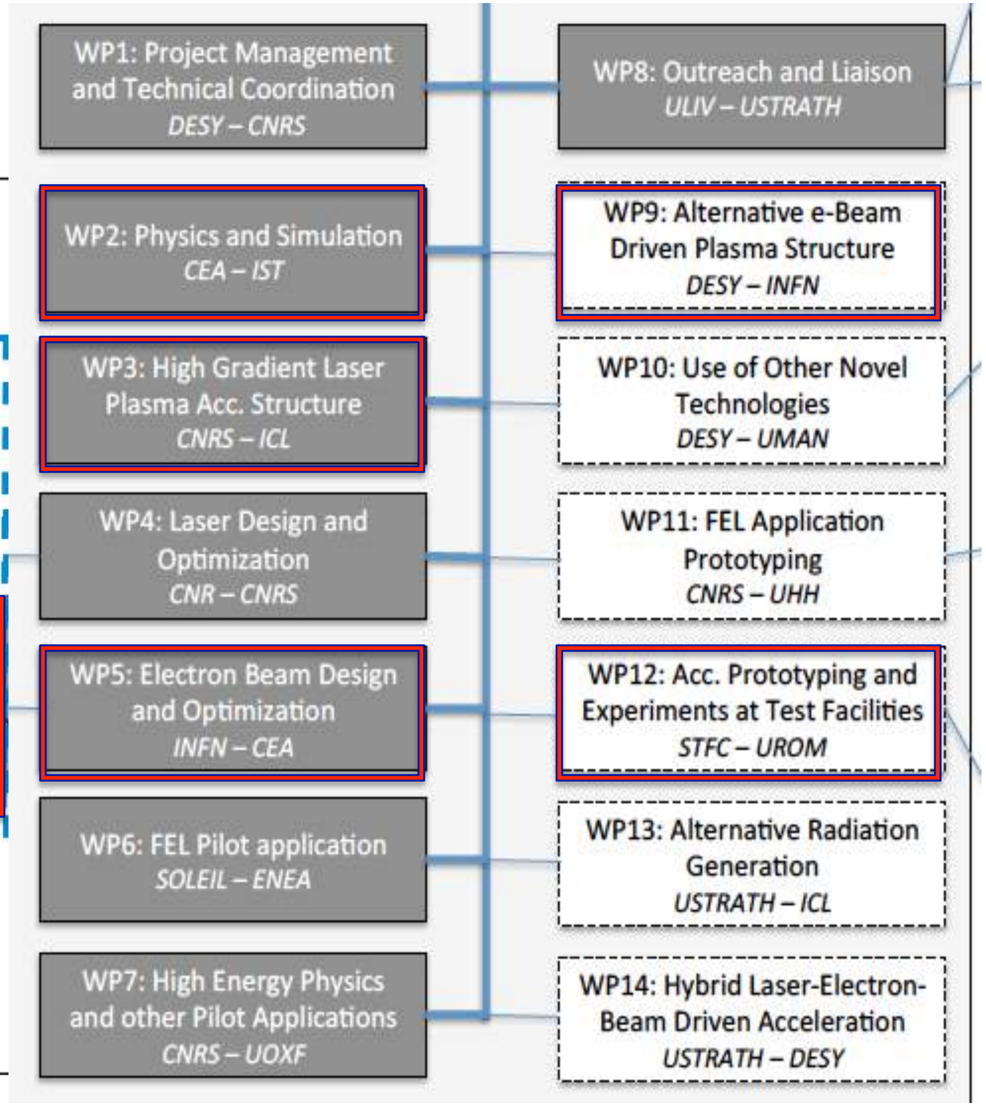
Interfaces: Plasma and Beams

Massimo.Ferrario@LNF.INFN.IT

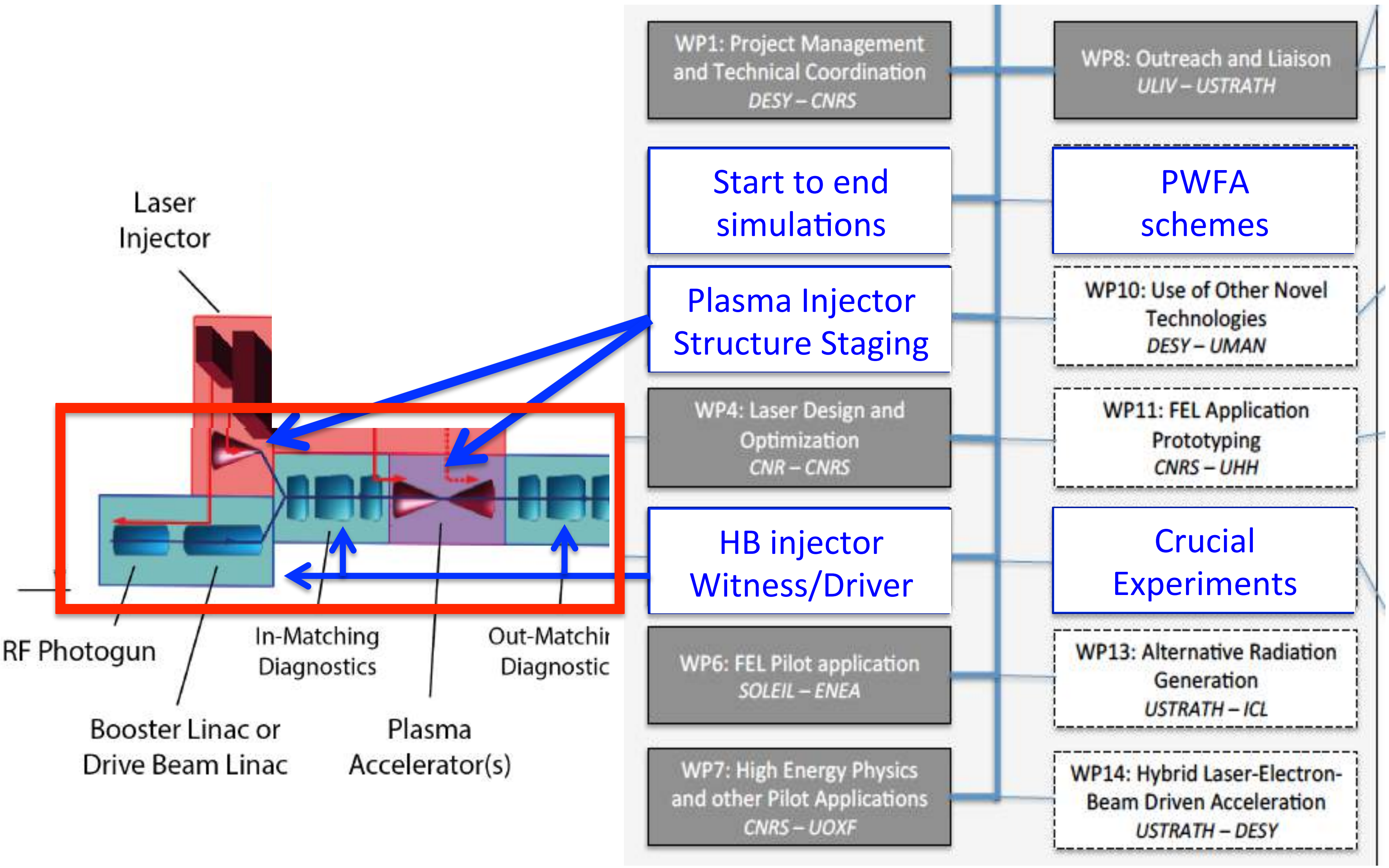


WGs interfaces

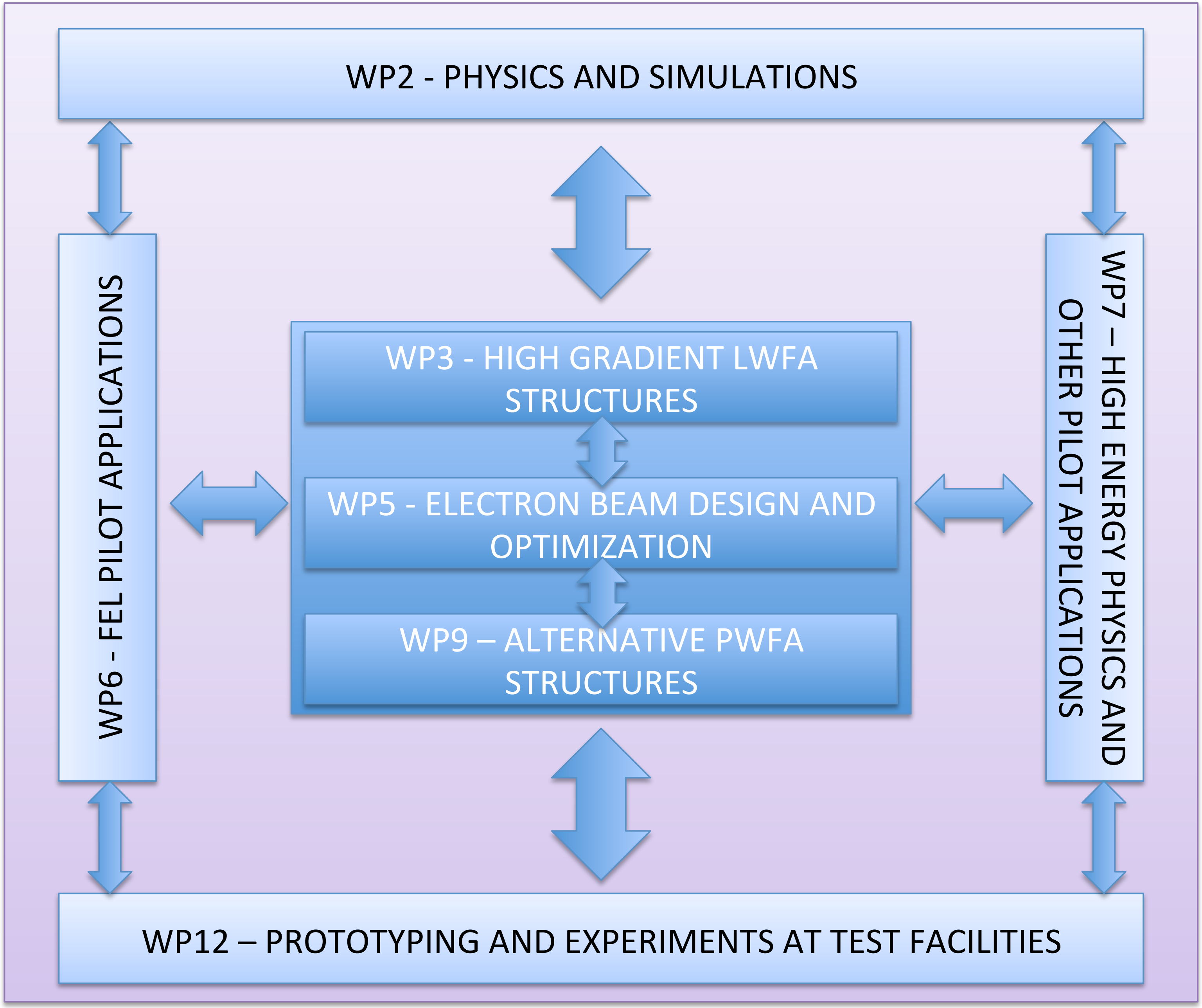




WGs interfaces



Test Facilities


WP2 - PHYSICS AND SIMULATIONS
WP6 - FEL PILOT APPLICATIONS
WP3 - HIGH GRADIENT LWFA STRUCTURES
WP5 - ELECTRON BEAM DESIGN AND OPTIMIZATION
WP9 – ALTERNATIVE PWFA STRUCTURES
WP7 – HIGH ENERGY PHYSICS AND OTHER PILOT APPLICATIONS
WP12 – PROTOTYPING AND EXPERIMENTS AT TEST FACILITIES

SASE FEL at short wavelengths require a very high quality beam

- FEL Parameter

$$\rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

- Exponential growth

$$P(z) = \frac{P_0}{9}\exp\left(\frac{z}{L_G}\right)$$

- Gain Length

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

- Saturation power

$$P_{sat} = \rho P_{beam} \propto N_e^{4/3}$$

- Constraint on emittance

$$\varepsilon_n < \frac{\gamma\lambda_r}{4\pi}$$

- Constraint on energy spread

$$\Delta\gamma/\gamma < \rho$$

- Relative bandwidth

$$\frac{\Delta\omega}{\omega} = \sqrt{\frac{\rho}{N_u}}$$

Normalized emittance and energy spread

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

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

$\langle\gamma\rangle$	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

$\langle\gamma\rangle$	$\sigma_E^{(0)}$	$\sigma_x^{(0)}$	$\sigma_{x'}^{(0)}$	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

References

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- T. Mehrling *et al., Transverse growth in staged-wakefield acceleration*, Phys. Rev. STAB 15, 111303 (2012).
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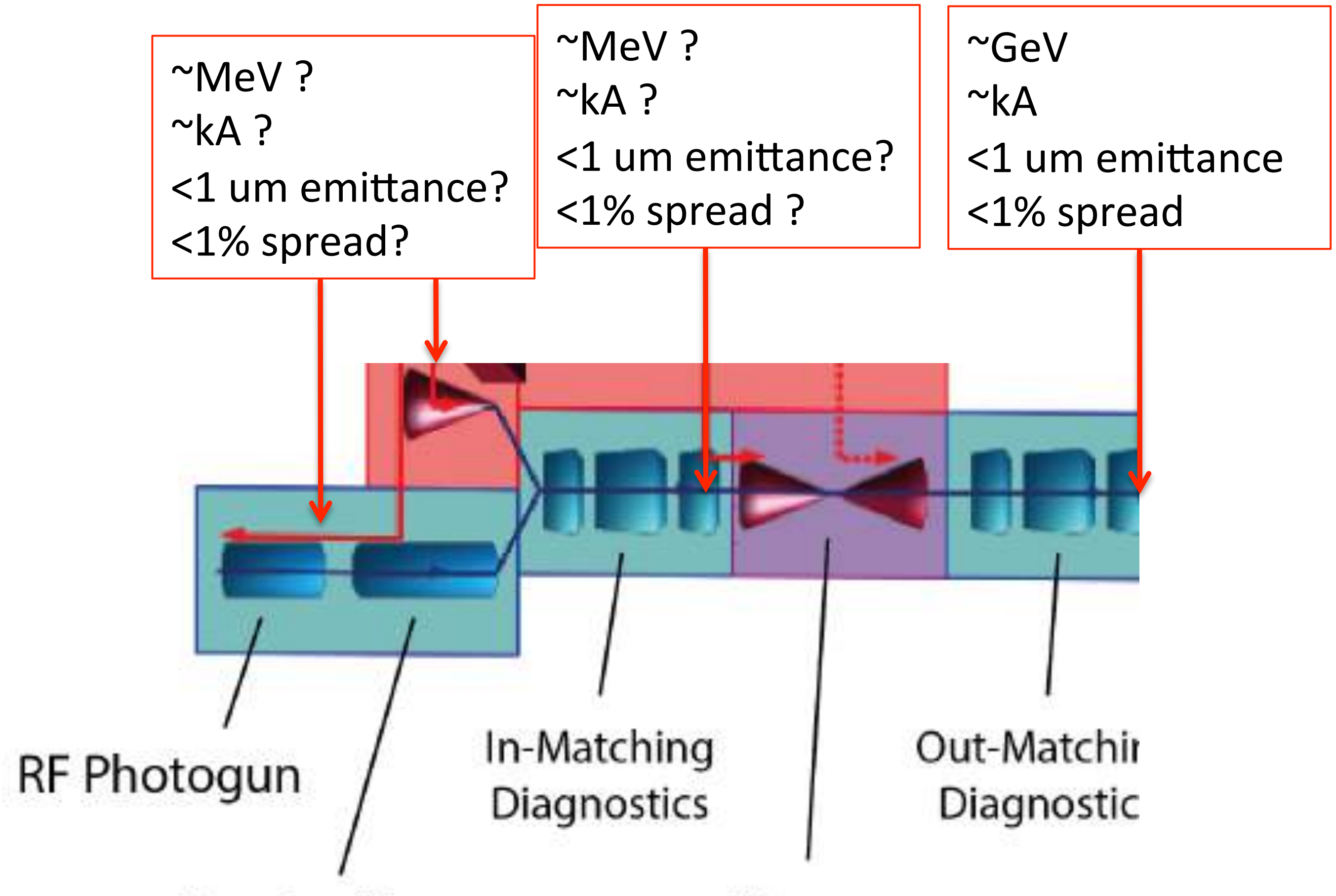
- M. Migliorati *et al., Intrinsic normalized emittance growth in laser-driven electron accelerators*, Phys. Rev. STAB 16, 011302 (2013).

Beam parameters



We need a baseline design supported by start to end simulations

Questions addressed to WPs

- ❑ **Define beam parameters and pulse shaping at injection (internal/external) => wp2+wp3+wp5+wp9**

- ❑ **Verify need of longitudinal Compression => wp2+wp5+wp9**

- ❑ **Transport and Match the beam to the accelerating modules (staging) => wp2+wp3+wp5+wp9+wp12**

- ❑ **Capture the beam at extraction => wp2+wp3+wp5+wp9+wp12**

Questions addressed to WPs

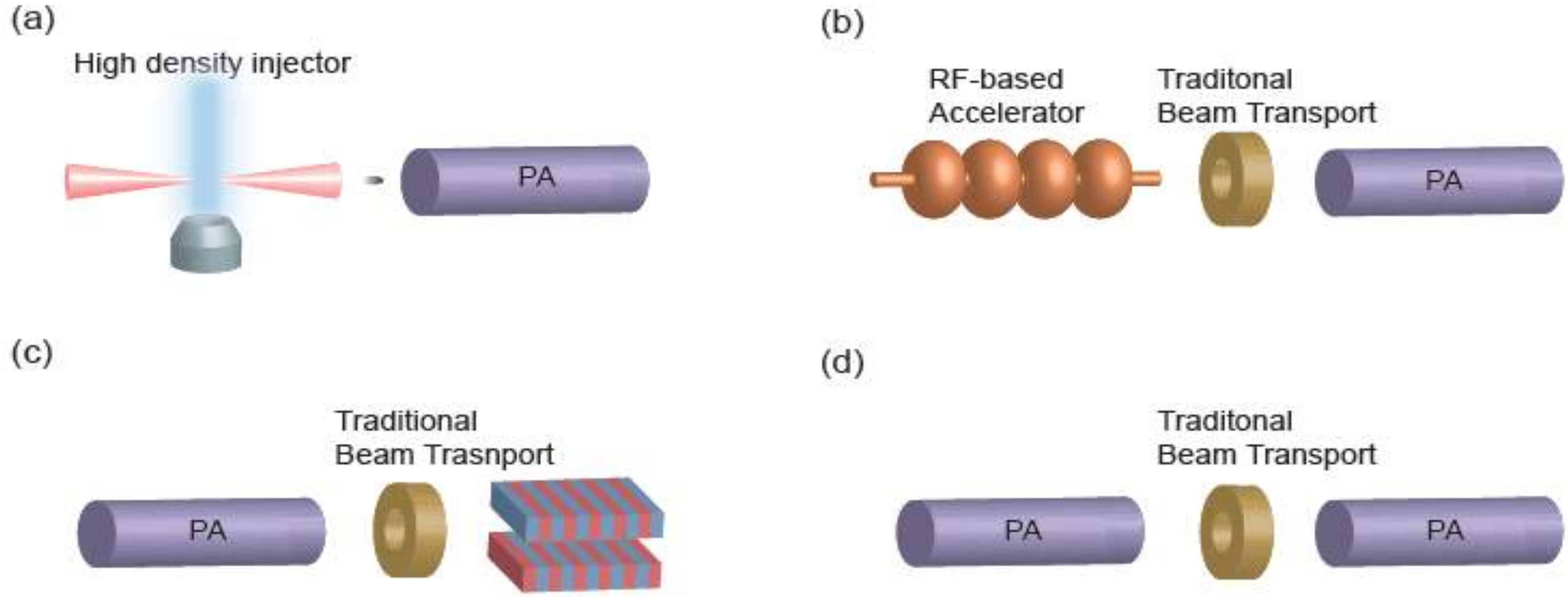
- Energy spread final correction => wp2+wp5+wp12

- Define proper plasma and single shot (non intercepting) beam diagnostics => wp3+wp5

- Provide suitable Synchronization => wp2+wp3+wp5

Coherent phase space matching for staging plasma and traditional accelerator using longitudinally tailored plasma structure

X. L. Xu,[1] Y. P. Wu,[1] C. J. Zhang,[1] F. Li,[1] Y. Wan,[1] J. F. Hua,[1] C.-H. Pai,[1] W. Lu,[1,*] P. Yu,[2] W. An,[2] W. B. Mori,[2] C. Joshi,[2] and M. J. Hogan[3]
[1]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2]*University of Los Angeles, Los Angeles, California 90095, USA*
[3]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
(Dated: November 18, 2014)



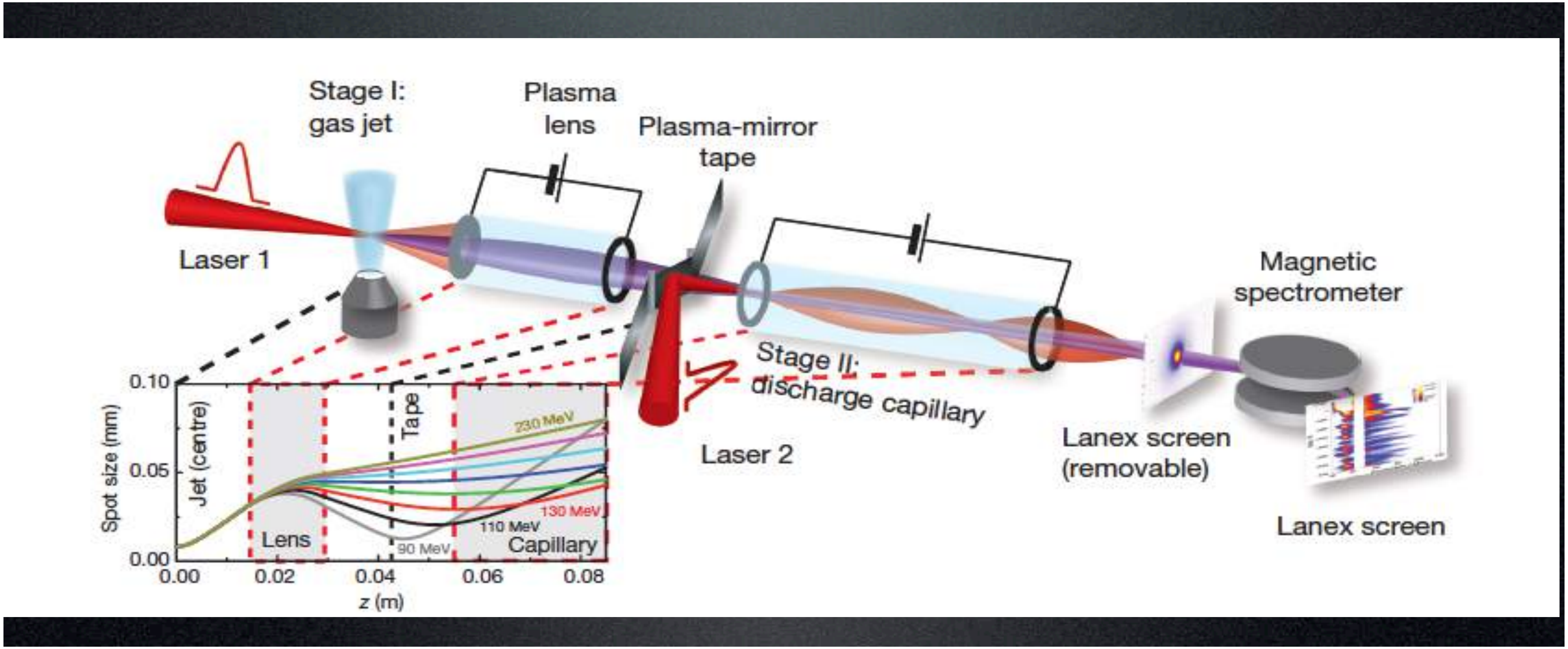
X. L. Xu et al., “Coherent phase space matching for staging plasma and traditional accelerator using longitudinally tailored plasma structure”, arXiv:1411.4386v1

LETTER

doi:10.1038/nature16525

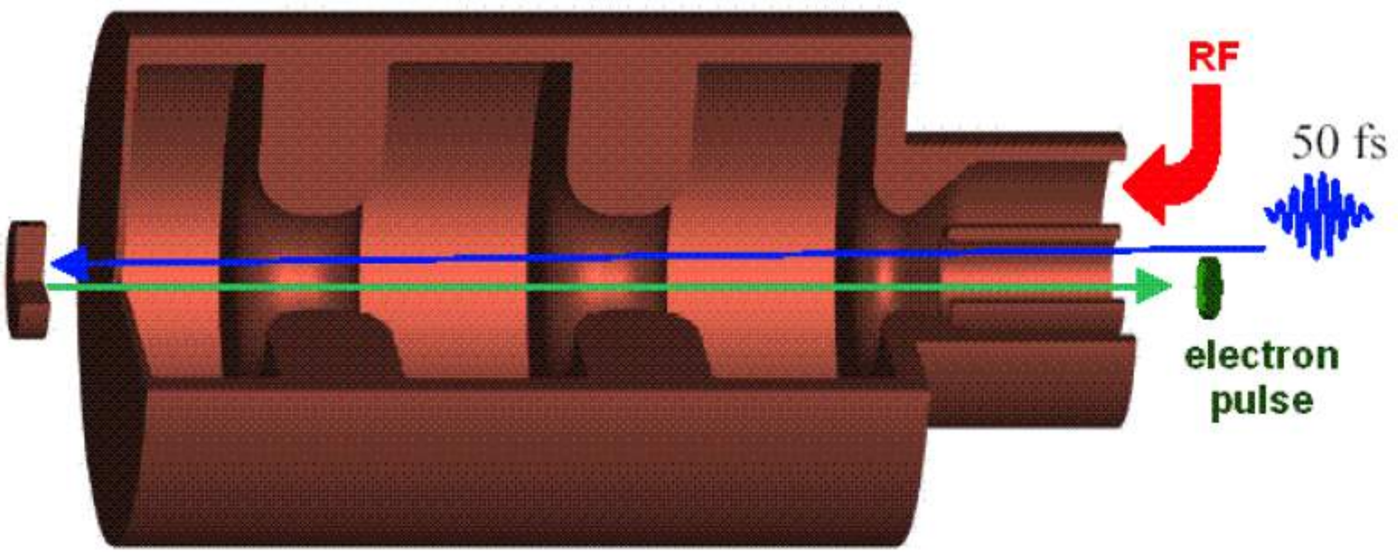
Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



Injection schemes

- 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)

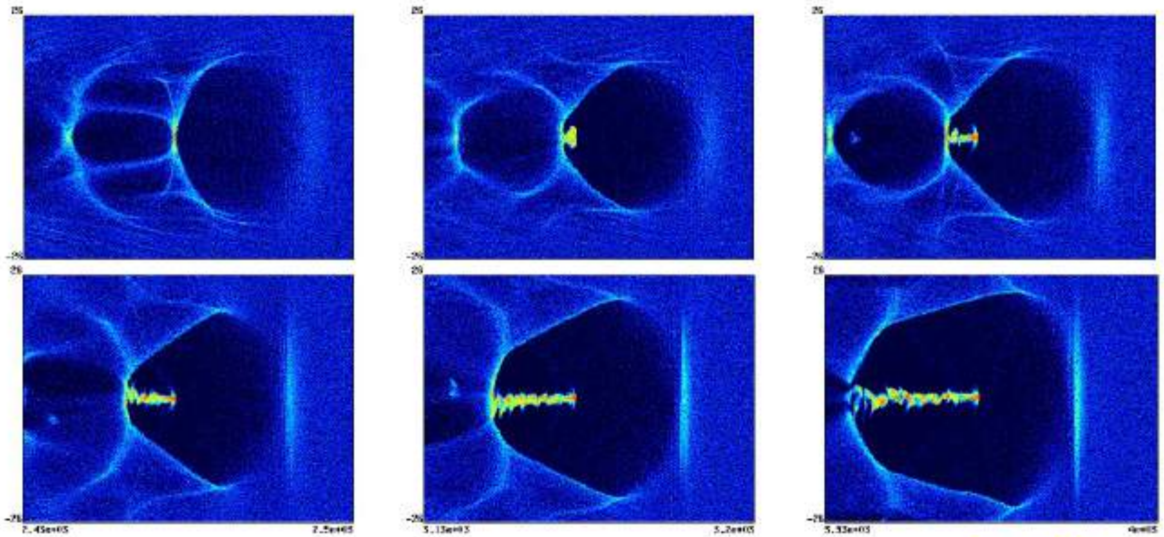
A. R. Rossi, Proc. of Erice workshop "Trends in FEL physics" 2016

Injection schemes

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.

$$a_0^2 > \gamma_p \approx \frac{\omega_0}{\omega_p}$$



Courtesy: C. Benedetti

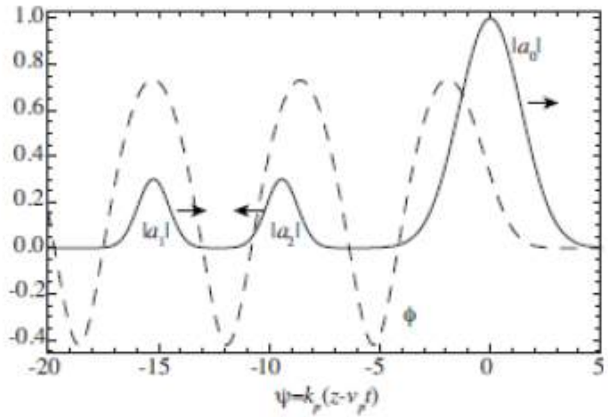
High charge bunches, "easy" to implement. Many experimental results.

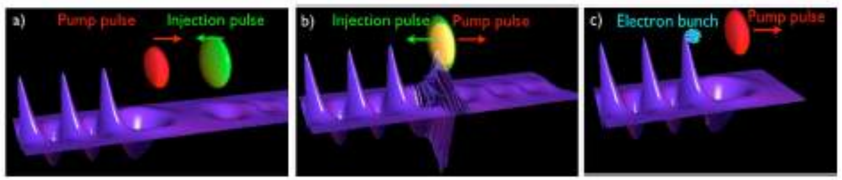
[1] Modena, A., Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, and F. N. Walsh, 1995,

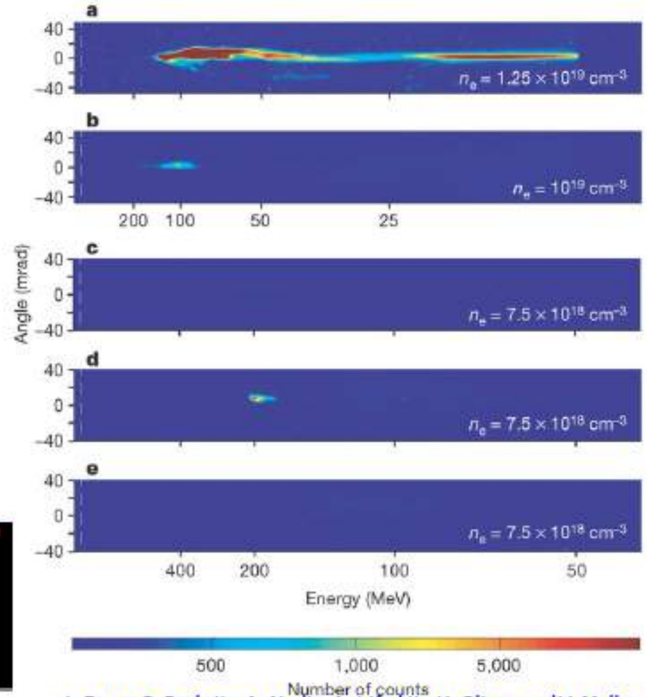
Injection schemes

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.







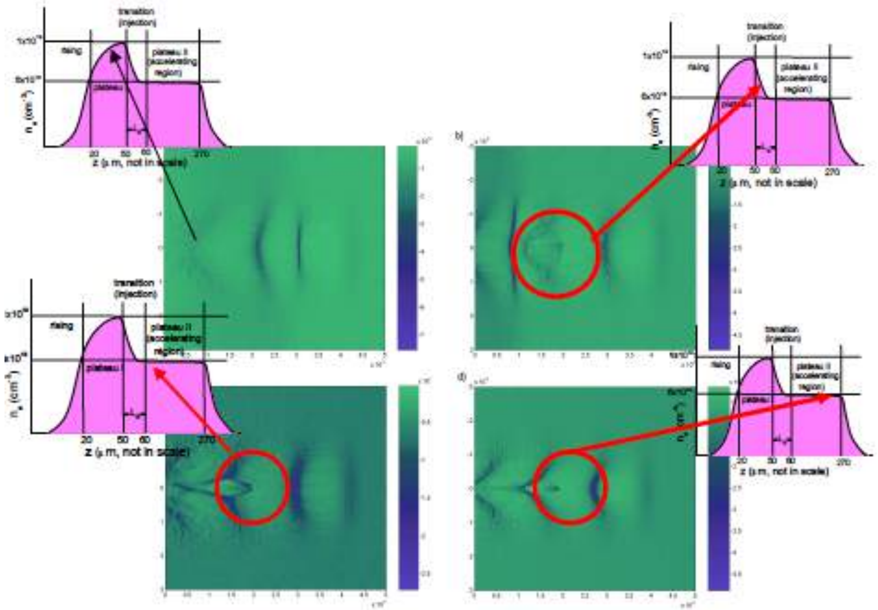
J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, Nature 444, 737 (2006).

[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).

Injection schemes

Density gradient injection

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



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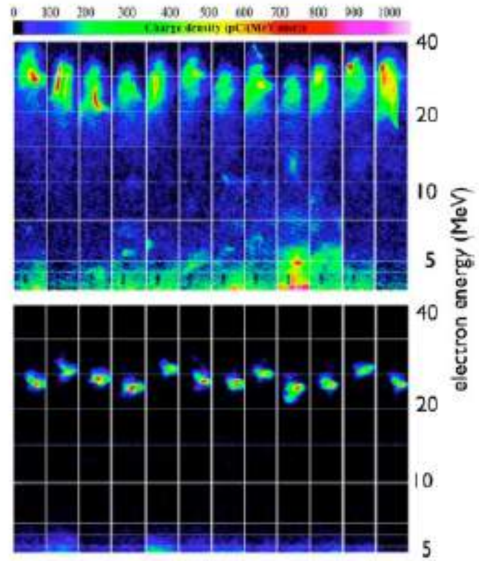

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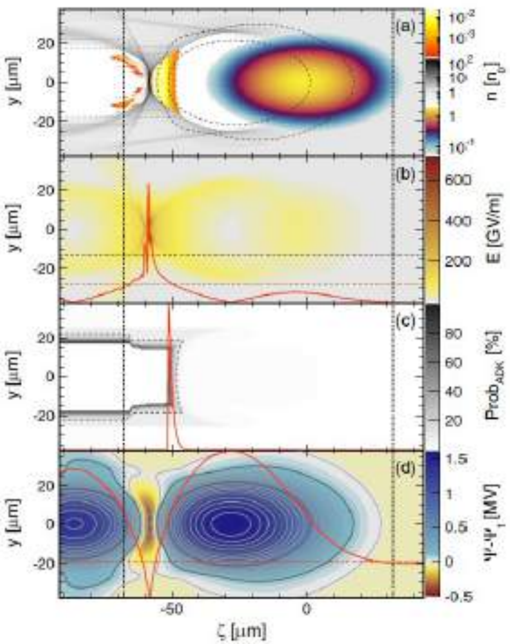
[1] Bulanov, S., N. Naumova, F. Pegoraro, and J. Sakai, 1998, Phys. Rev. E **58**, R5257.

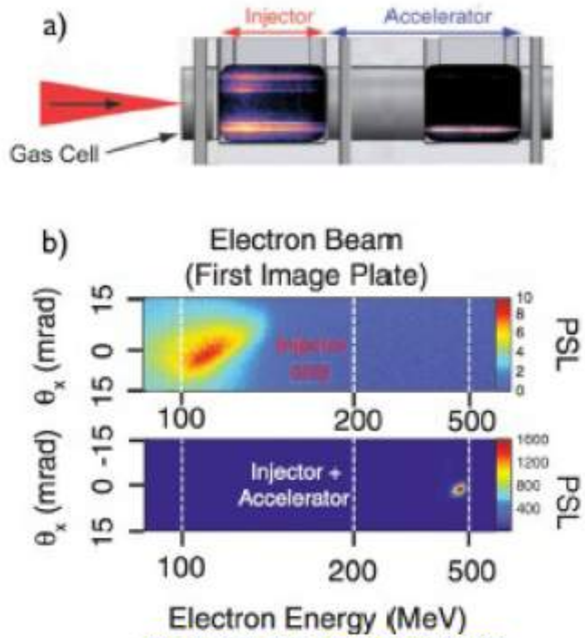
Injection schemes

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).

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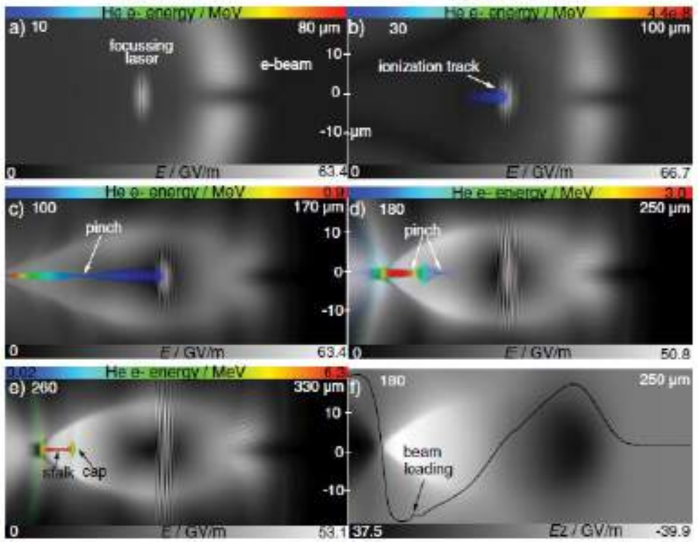
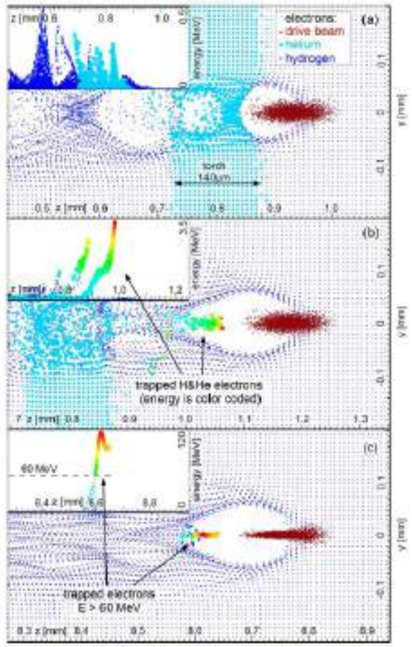
[2] E. Oz, et al., Phys. Rev. Lett. **98**, 084801 (2007).

Injection schemes

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.



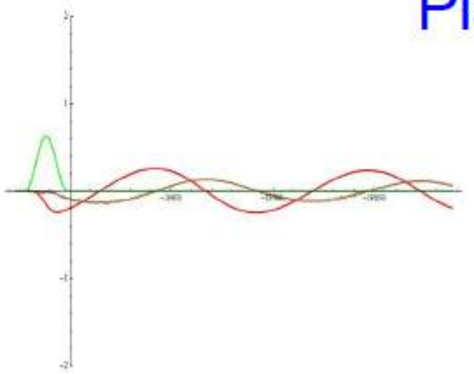


[1] B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler, Phys. Rev. Lett. **108**, 035001 (2012).
[2] G. Wittig, et al., Nuc. Inst. Meth. Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.02.027 (in press).

Acceleration

Plasma wave regime

Linear

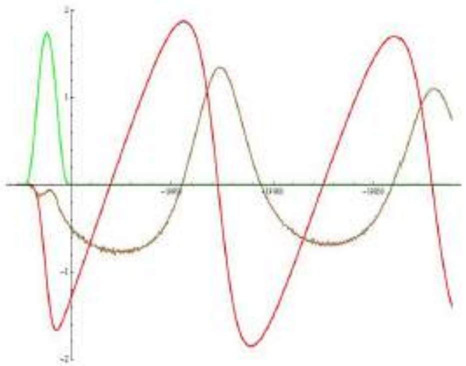


Easier and more stable but beam loading can dominate the process.
Requires the capability to manage bunches with a charge in the range from hundreds of fC to few pC.

$$a_0 \ll 1$$
$$\alpha = \frac{n_b}{n_0} \ll 1$$
$$\tilde{Q} = Qk_p^3 \ll 1$$

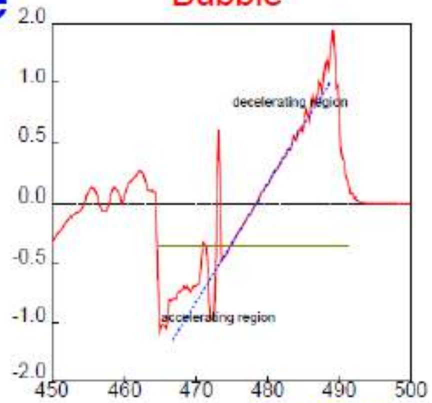
Quasi-linear

$$a_0 \approx 1$$
$$\alpha \approx 1$$
$$\tilde{Q} < 1$$



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.

$$a_0 \gg 1$$
$$\alpha > 1$$
$$\tilde{Q} > 1$$

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.

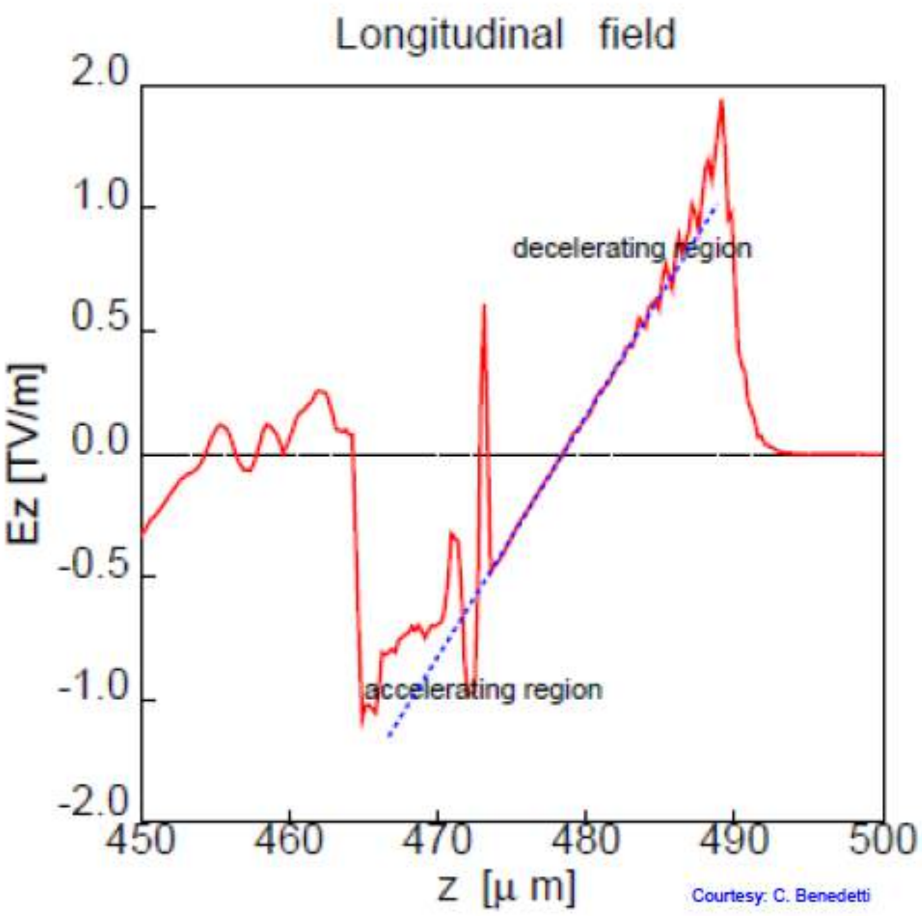
In **linear regime** the same considerations on the nature of transverse fields hold true, **but beam loading is usually not negligible**, unless charge is very low.

Acceleration

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.



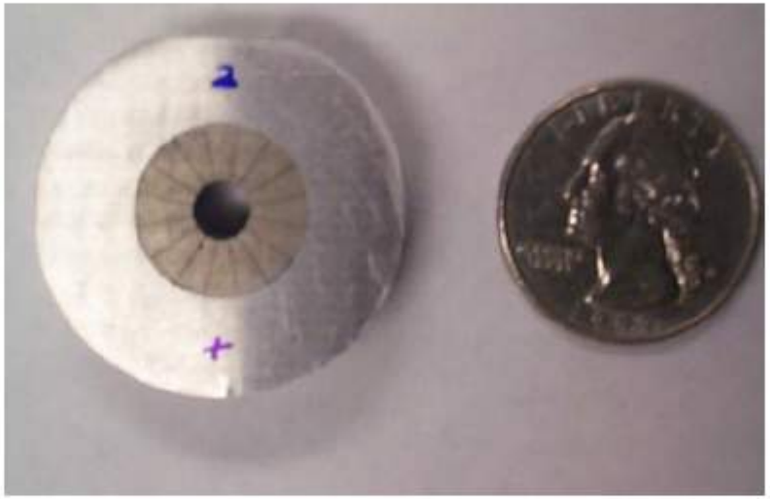
Courtesy: C. Benedetti

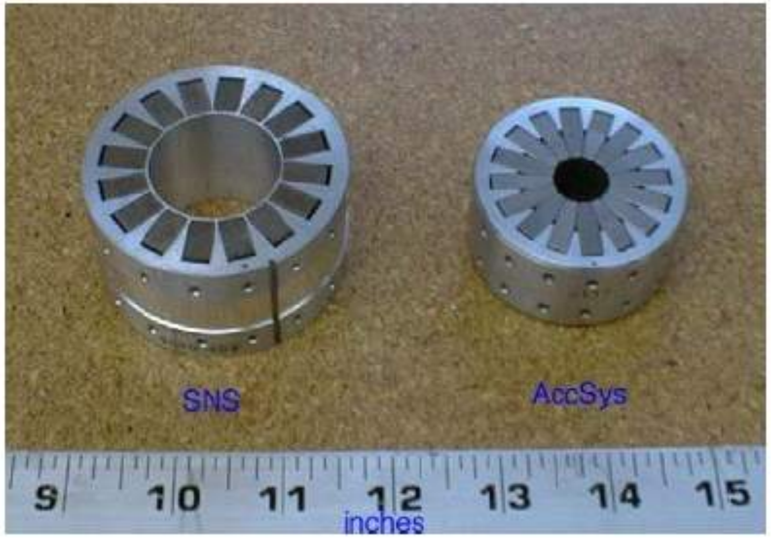
Beam Manipulation

Beam Manipulation

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.

Beam Manipulation

Matching into/out of plasma/2

Plasma lenses: classification

Effectiveness

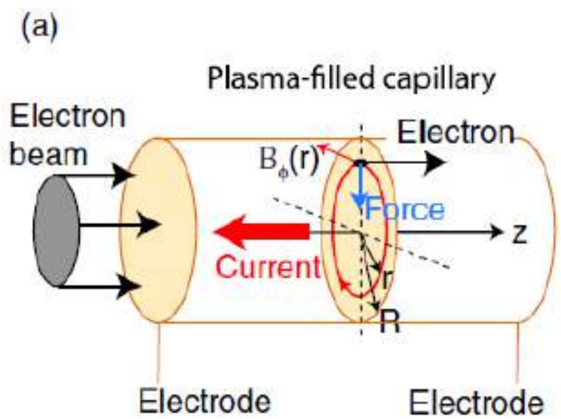
Ease of implementation and operation

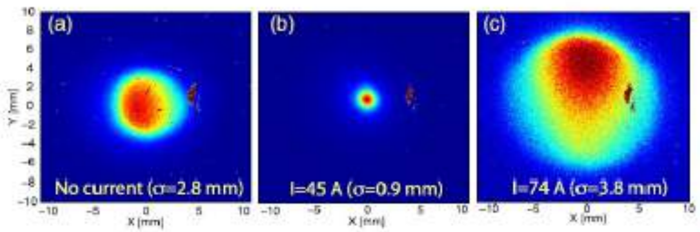
	Passive	Active
Stand alone	Gas jets	Discharge
Integrated	Ramps	---

Beam Manipulation

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.





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:

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

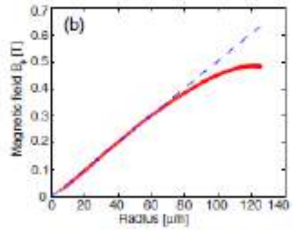
$$k_p \sigma \gg 1$$

$$k_p \sigma_z \ll 1$$

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

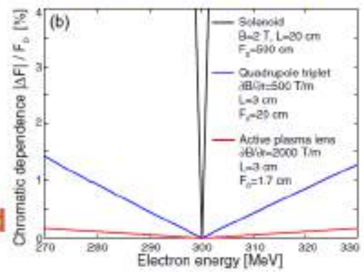
Effective only as a thin lens

Linear focusing field



up to half R

Low chromaticity

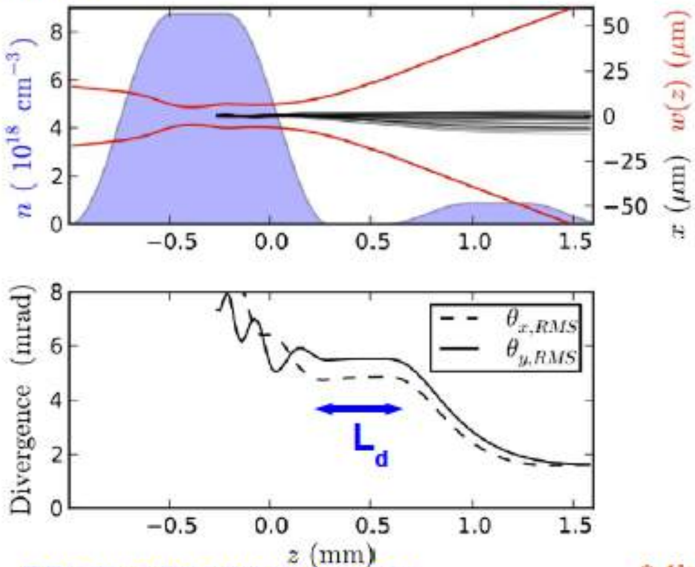


[1] J. van Tilborg, et al., Phys. Rev. Lett. **115**, 184802 (2015)

Beam Manipulation

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



Density profile

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

Condition for optimal collimation*

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

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

Requires only one laser

Effective for energies up to

$$\gamma < \frac{3}{5}\frac{a_0^2 Z_R^4}{L_d^2 w_0^2}$$

Easily tuned for different bunches

Adequate acceptance

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

Beam loading may reduce effectiveness.

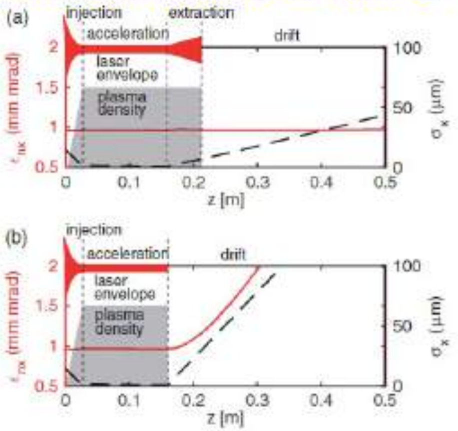
[1] R. Lehe, C. Thaury, E. Guillaume, A. Lifschitz, and V. Malka, Phys. Rev. STAB **17**, 121301 (2014)

Beam Manipulation

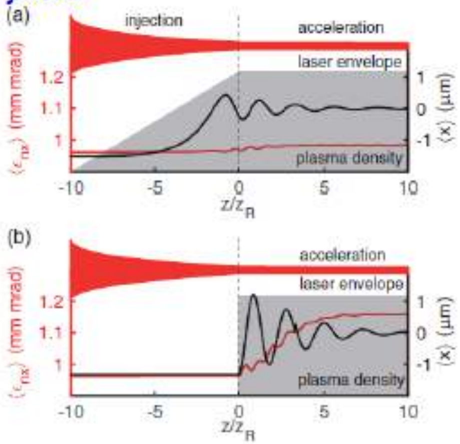
Integrated, passive plasma lens: plasma ramps & driver focusing/defocusing

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

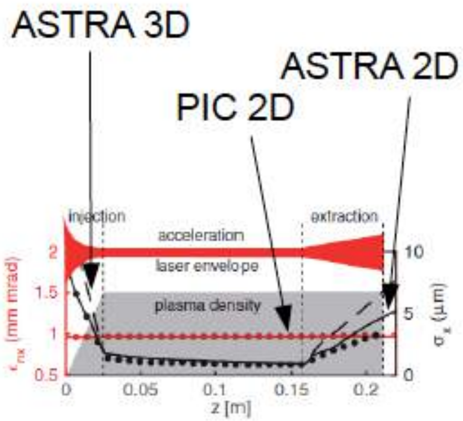


Tolerance to beam position jitters



Optimal focusing strength longitudinal profile

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



Linear regime

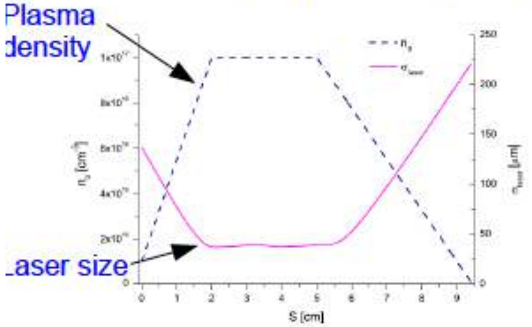
Negligible beam loading

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

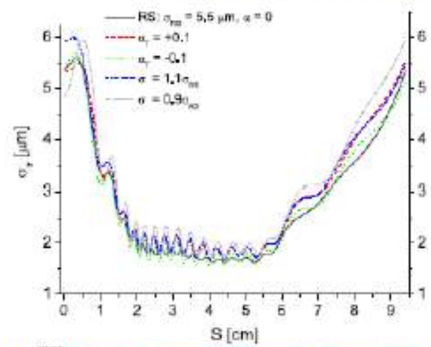
Beam Manipulation

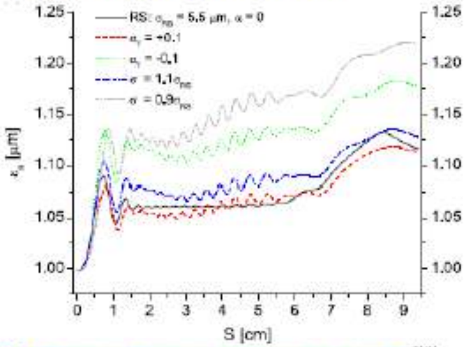
Integrated, passive plasma lens: plasma ramps & tailored driver focusing/defocusing in hollow capillary

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.

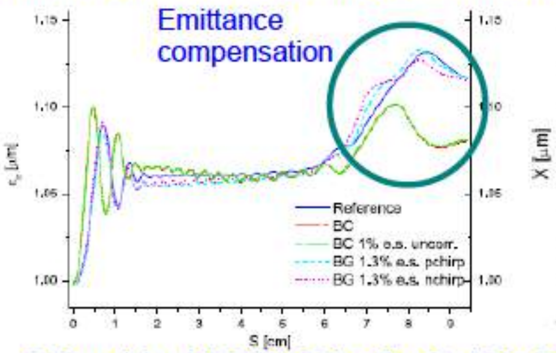


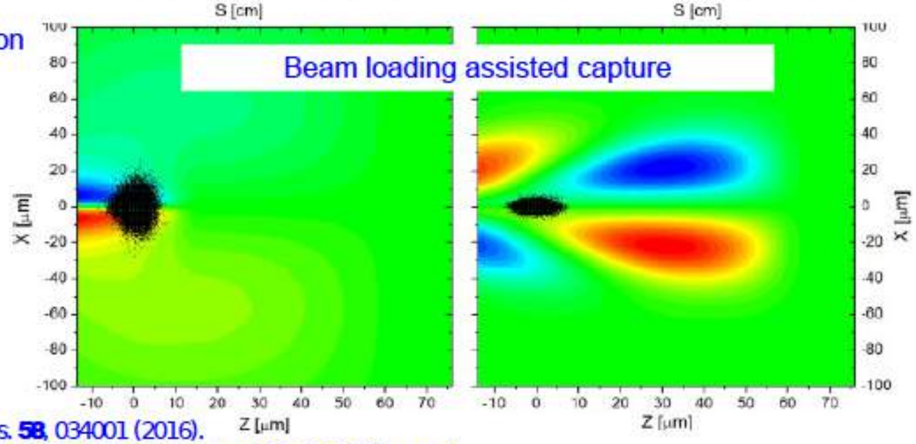
Stability vs injected beam parameters jitters





Stability vs injected beam charge distribution



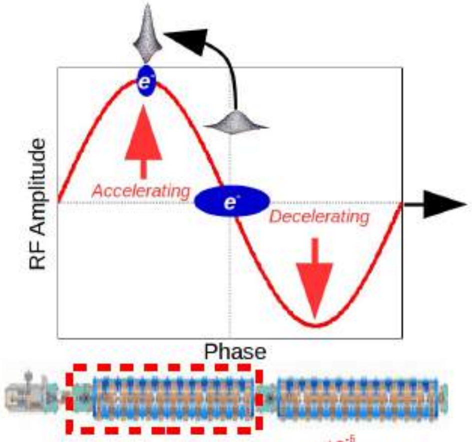


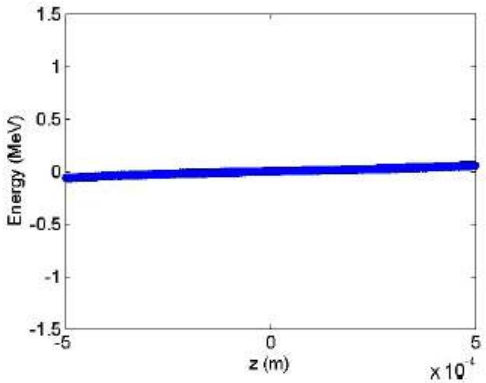
P. Tomassini and A.R. Rossi, Plas. Phys. Cont. Fus. **58**, 034001 (2016).
A.R. Rossi, et al., Nuc. Met. Phys. Res. A, http://dx.doi.org/10.1016/j.nima.2016.02.015 (in press)

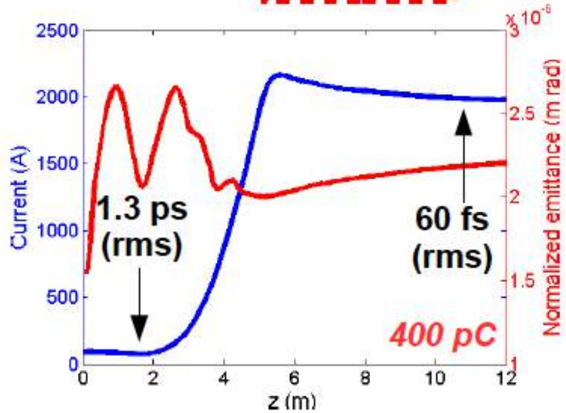
Longitudinal Beam Manipulation

Ultra-short electron beams

- Current demands require high current beams
  - *PWFA-LWFA: high wakefield amplitude (i.e. high driver density), low energy spread (i.e. short witness).*
  - *Advanced radiation sources: high peak currents (FEL), short beams (broadband THz radiation).*
- Velocity bunching @ SPARC_LAB
  - *RF structure embedded in solenoid fields for **emittance compensation***





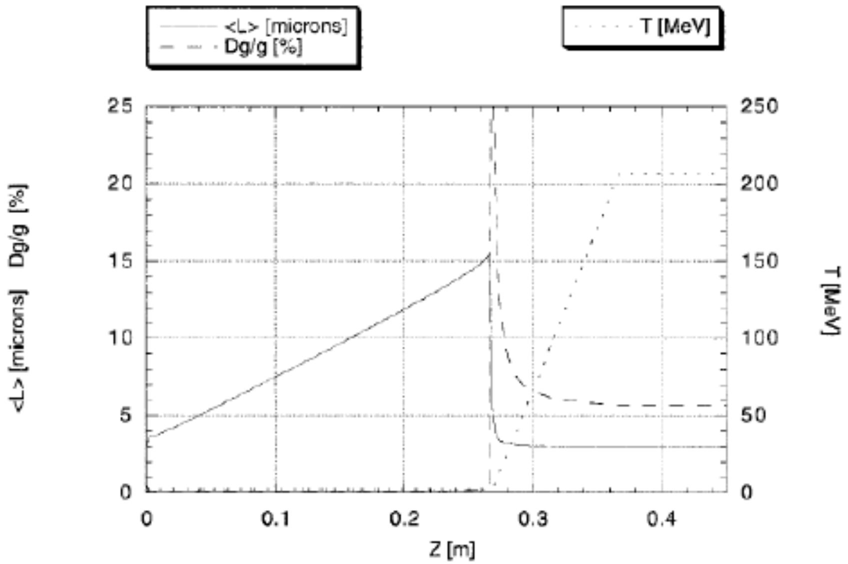


Serafini, L., M. Ferrario. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.
Ferrario, M.et al. "Experimental demonstration of emittance compensation with velocity bunching." PRL 104.5 2010.

Longitudinal Beam Manipulation

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).

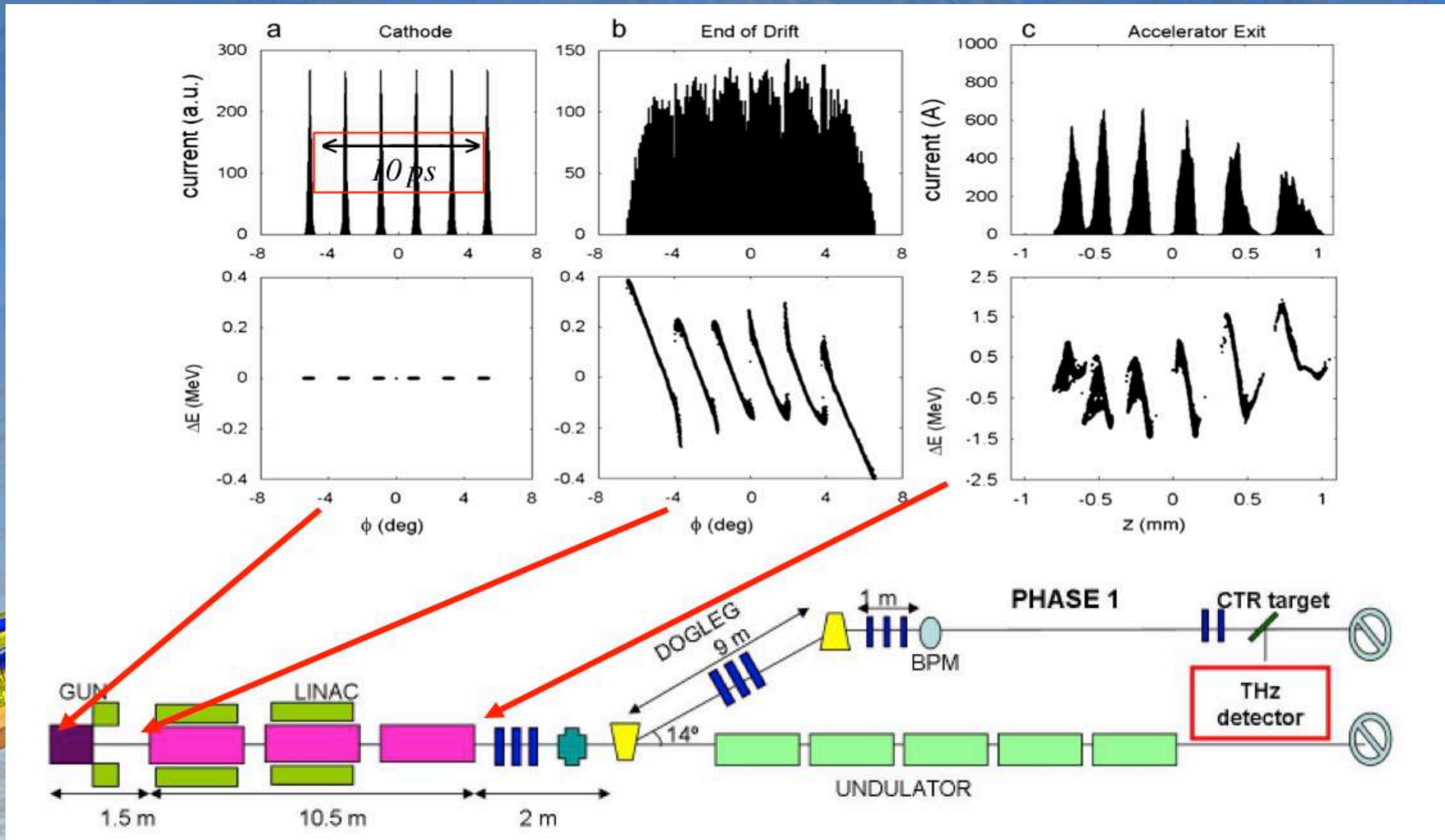
- Linear regime
- No beam loading

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).

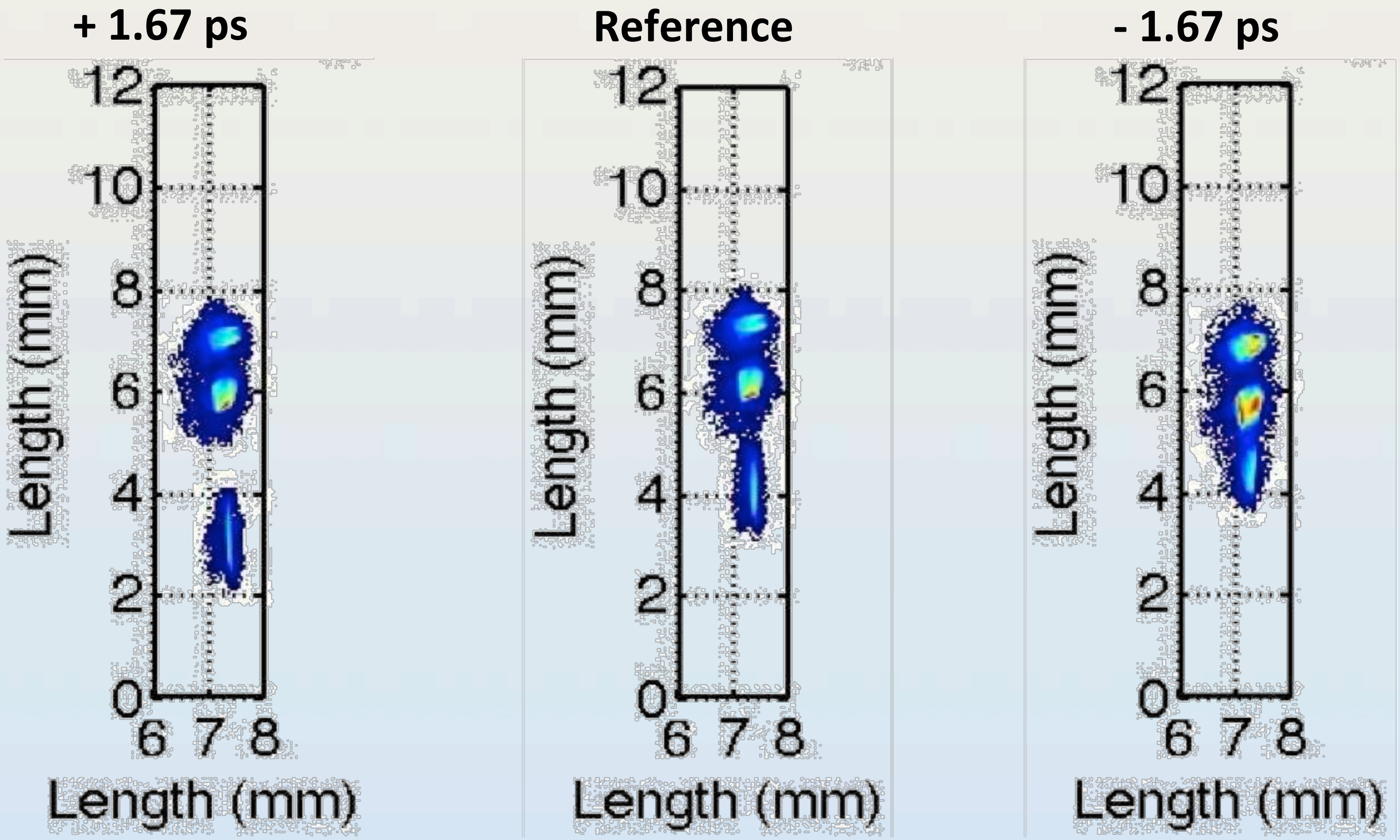
[1] J.L. Bobin, in Proc. of the ECFA-CAS/CEFN-In-2P3-IRF/CEA-EPS Workshop, p. 58 (1987). C.S. Liu and V.K. Tripathi, *Interaction of electromagnetic waves with electron beams and plasmas*, World Scientific, Singapore, 1994.
[2] L. Serafini and M. Ferrario, LNF-00/036, 2000. L. Serafini and M. Ferrario,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

Laser Comb technique: generation of a train of short bunches



- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704. (Low charge regime only)
- M. Ferrario, et al., Int. J. of Mod. Phys. B, 2006 (High charge, Beam Echo)

Three bunches: witness position tuning



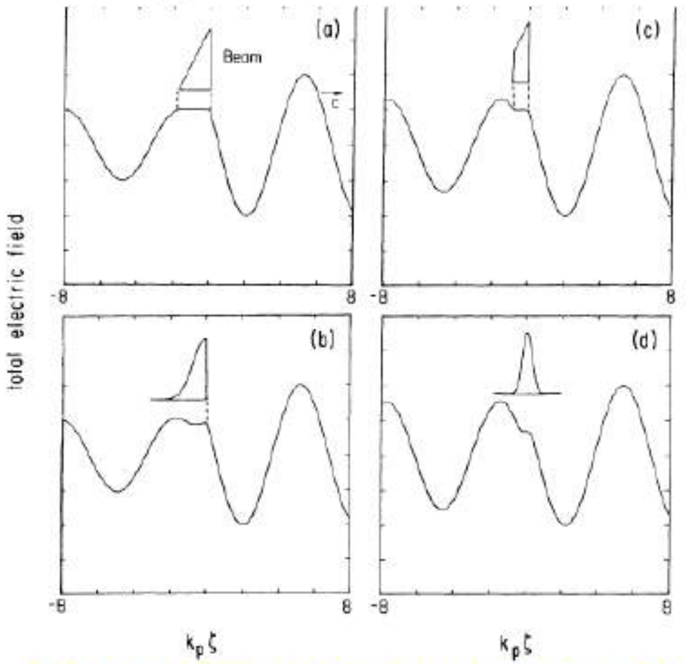
Longitudinal Beam Manipulation

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

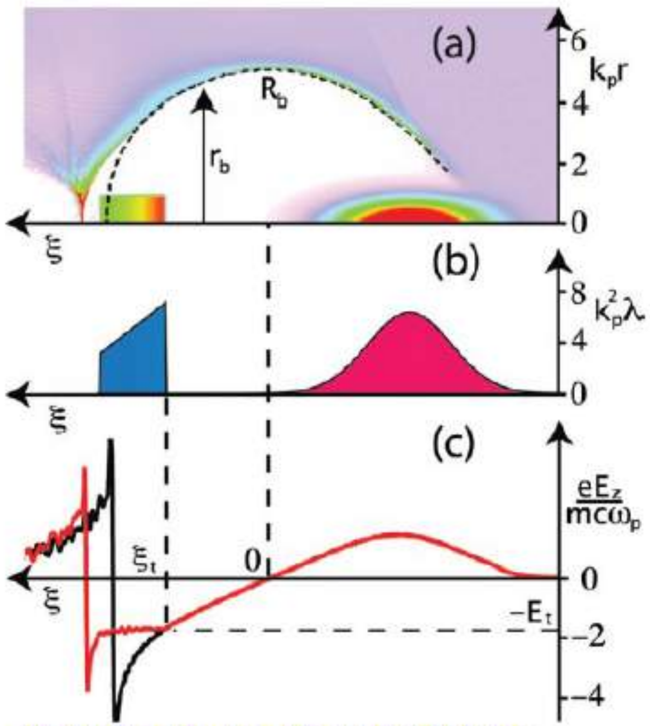
$$\rho_b(\zeta) = -\frac{k_p E_0}{4\pi}[(k_p \cos k_p\zeta_0)\zeta + (\sin k_p\zeta_0 - k_p\zeta_0 \cos k_p\zeta_0)]$$



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)

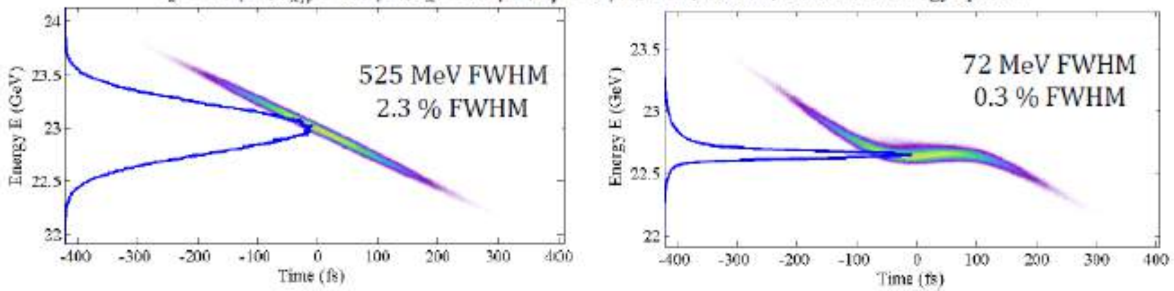
Longitudinal Beam Manipulation

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.

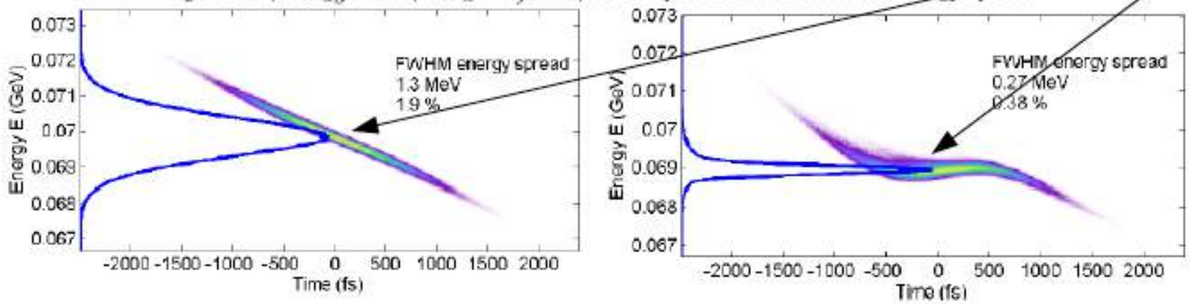
FACET beam parameters

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



ATF beam parameters:

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



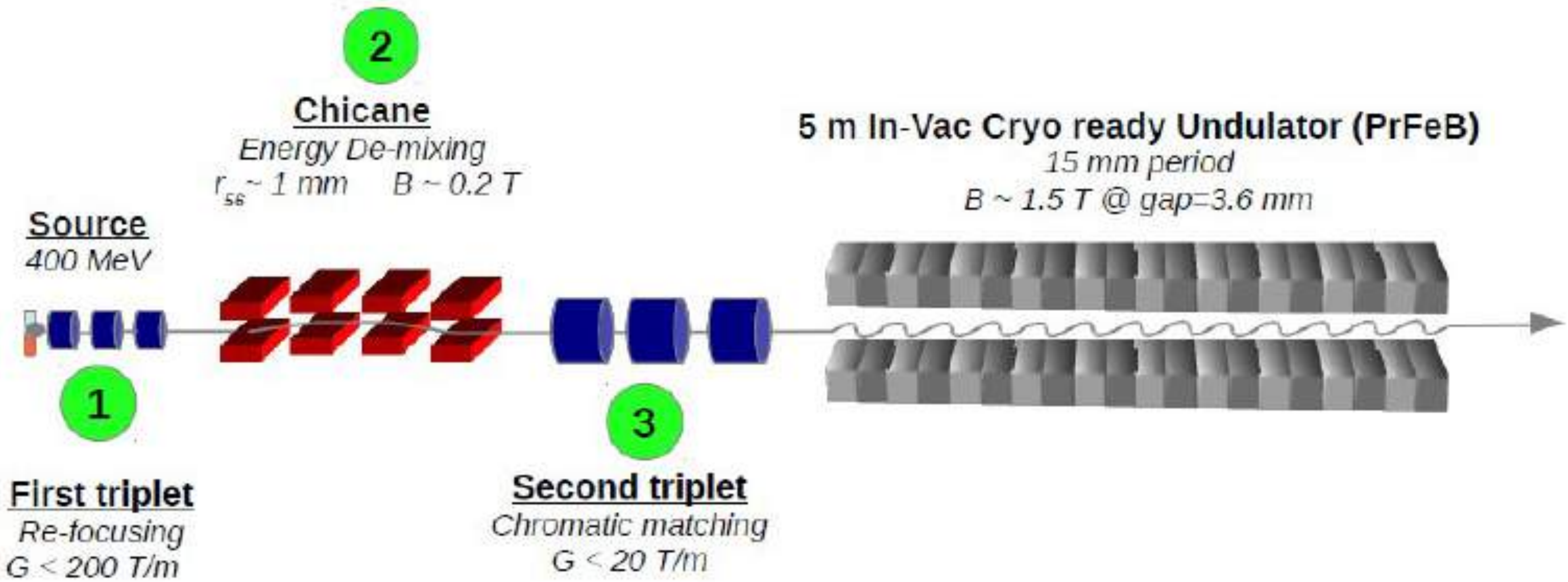
Works only for positive chirps

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).

Chromatic Matching

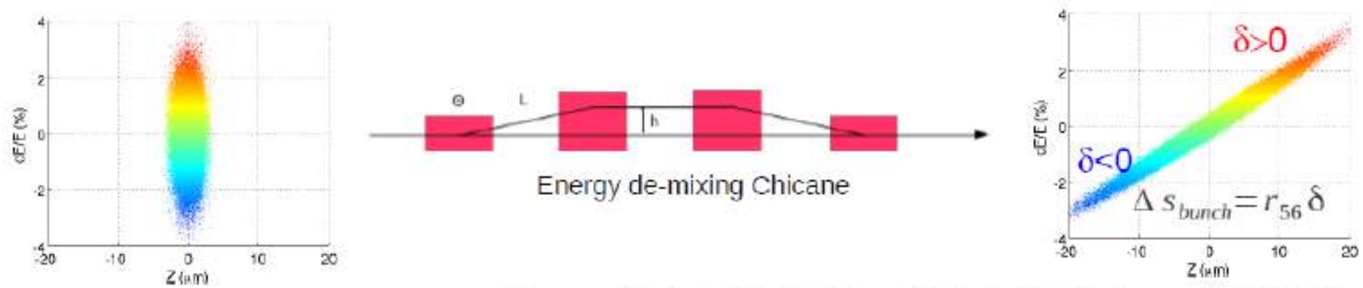


[1] A. Loulergue, M. Labat, C. Evain, C. Benabderrahmane, V. Malka and M.E. Couprie, New J. Phys. **17**, 023028 (2015).

Chromatic Matching

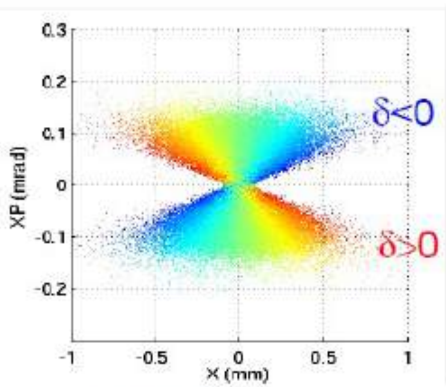
Assume a bunch with high energy spread and divergence. After first focusing use a chicane to stretch the bunch and realize an energy sorting (chirp):

Longitudinal phase space

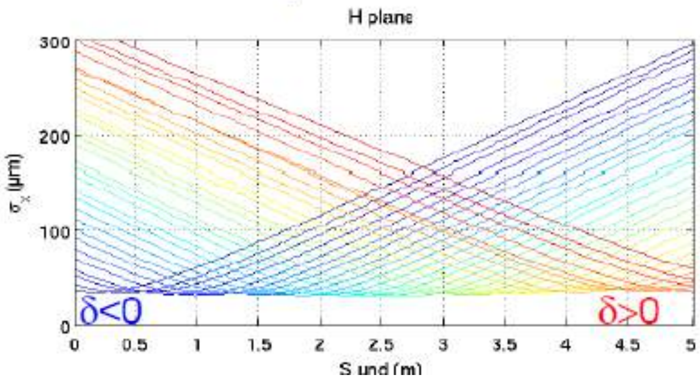


Pictures source: A. Loulergue, LWFA electron beam manipulations for FEL amplification, presented at EAAC 2015.

Transverse phase spaces

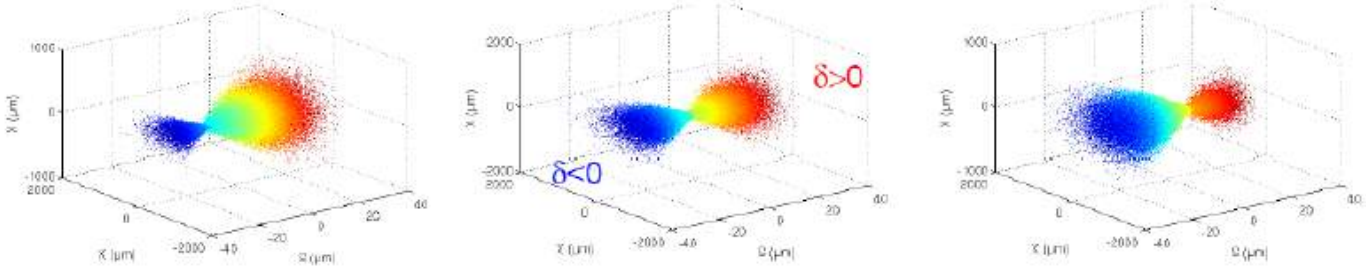


If the beam is focused, each quasi-monochromatic slice will have a waist at a different position.



Chromatic Matching

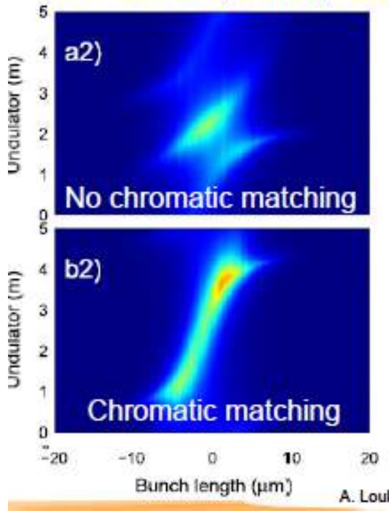
The waist slips along the bunch from the tail to the head...

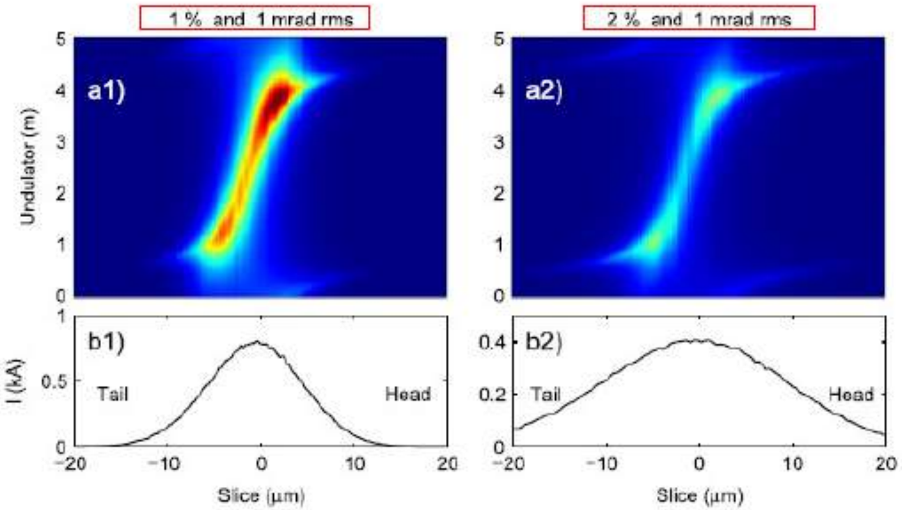


Source: A. Loulergue, LWFA electron beam manipulations for FEL amplification, presented at EAAC 2015.

... pretty much like the FEL radiation ...

... and if they are synchronized ...





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

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