High-Quality LWFA-based electrons sources

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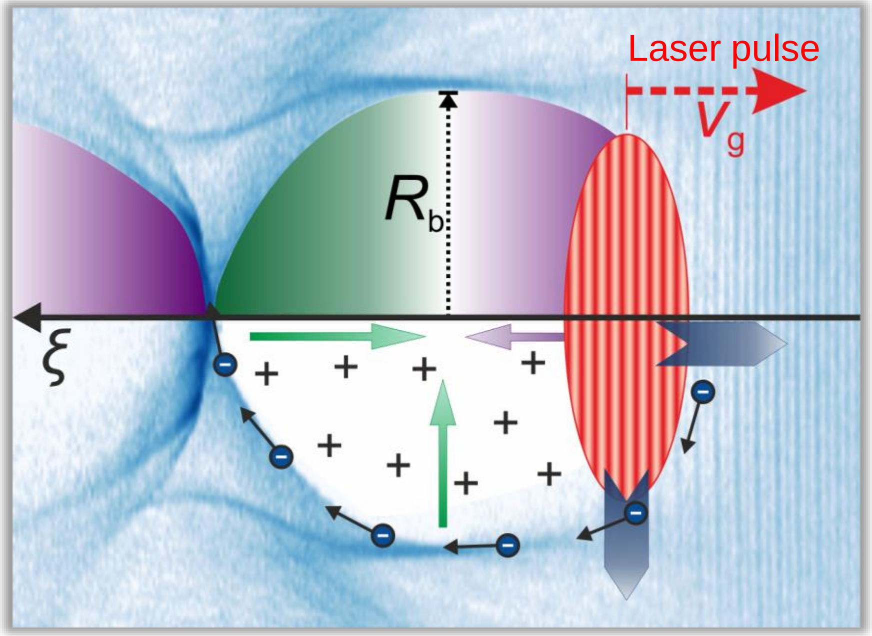
Outline

- **High quality beams**: LWFA vs conventional acceleration
- **Coupled parameters** in LWFA
  - Example case: Improving energy spread with **Beam loading**
- **Injection mechanisms**: crucial for high quality beams
  - Bunch duration
  - Energy spread
- Decoupling injection from acceleration
- Repetition rate & stability
- **Conclusion**

Most LPAs operate in the bubble regime



- Highly nonlinear regime (a_0>2)
  → (I > 8.5 x 10^{18} Wcm^{-2})

$$a_0 \simeq 0.86 \times 10^{-9} \lambda_0[\mu m]\sqrt{I[W\,cm^{-2}]}$$

- High accelerating gradients

$$E_{z,\mathrm{bubble}} \simeq \sqrt{a_0}\,E_0$$

- Wakefield structure and bunch charge balance each other
  - Strong linear **focusing fields**
  - Can contain and accelerate **large charges**
- Accelerating field is **independent of transverse position**
  → reduces energy spread

Pukhov & Meyer-ter-Vehn, Appl. Phys. 74, (2002). Lu *et al.*, PRSTAB 10, (2007), Downer *et* al., Rev. Mod. Phys 90, 035002 (2018).

LWFA: high quality?

- **Strong points** (compared to conv. acc.):

Property	Conventional acc.	Laser wakefield acc.
Acceleration gradient	< 100 MV/m	100s GV/m
Bunch duration	~100 fs – ns range	~few fs
Beam size	> few µm	~few µm at acc. exit
Peak current	few kA	10s kA

Lundh *et al.*, Nat. Phys. (2011)
Heigoldt *et al.*, PRSTAB (2015)
Zhang *et al.*, PRAB (2016)
Köhler *et al.*, NIMA (2016)
Kneip *et al.*, PRSTAB (2012)
Couperus *et al.*, Nat. Comm. (2017)
Li et al., Phys. Plasmas (2017)

- **Work in progress** (compared to conv. acc.):

Property	Conventional acc.	Laser wakefield acc.
Energy spread	<<1%	1 – 100% (typical ~10%)
Divergence	down to µrad	1 mrad (typical ~few mrad)
Beam emittance	< mm mrad	0.1 – 1 mm mrad
Repetition rate (average current)	kHz – MHz	~1 Hz (limited by laser tech.)
Stability	sub-%	1 – 10s %

Wang *et al.*, PRL 124801 (2016)
Rechatin *et al.*, PRL 164801 (2009)
Gallacher *et al.*, Phys. Plasmas (2009)

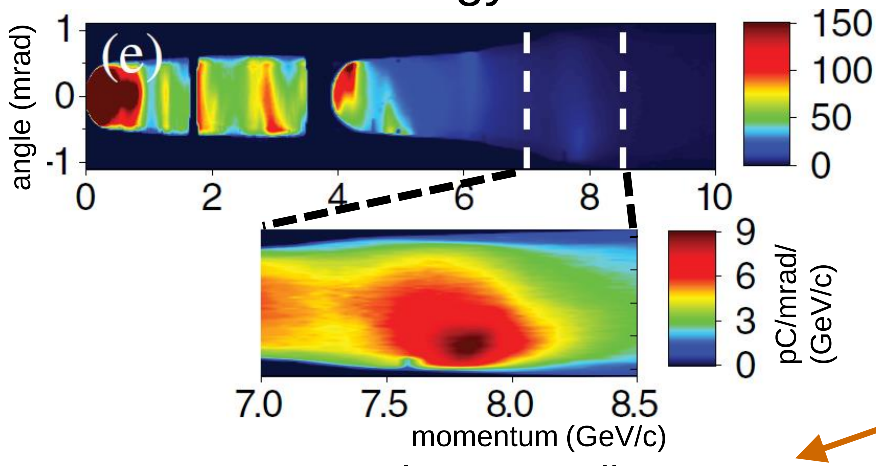
Plateau *et al.*, PRL (2012)
Curcio *et al.*, PRAB (2017)
Barber *et al.*, PRL (2017)

- Laser wakefield acceleration is an attractive scheme, but does not (yet) deliver the same quality electron beams as found in conventional accelerators

M. Downer *et al.*, Rev. Mod. Phys. **90**, 035002

State-of-the-art results

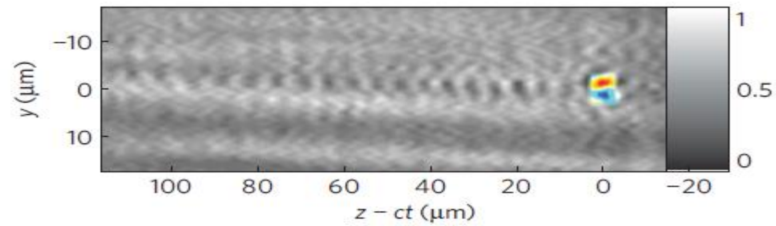
Energy



7.8 GeV, 20 cm plasma medium, 5 pC

Gonsalves *et al.*, Phys. Rev. Lett. 122, 084801 (2019)

Short bunch duration

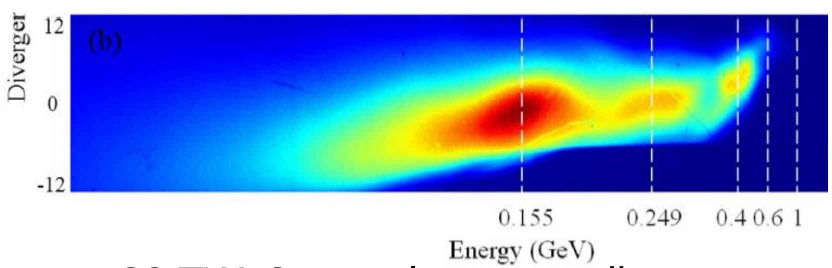


τ_{FWHM} = **5.8 fs**

Buck *et al.*, Nat. Phys. 7, 543(2011)

~1 kA

High charge / peak current



80 TW, 3 mm plasma medium:

620 pC, 30 fs →20 kA

Li *et al.*, Phys. Plasmas 24, 023108 (2017)

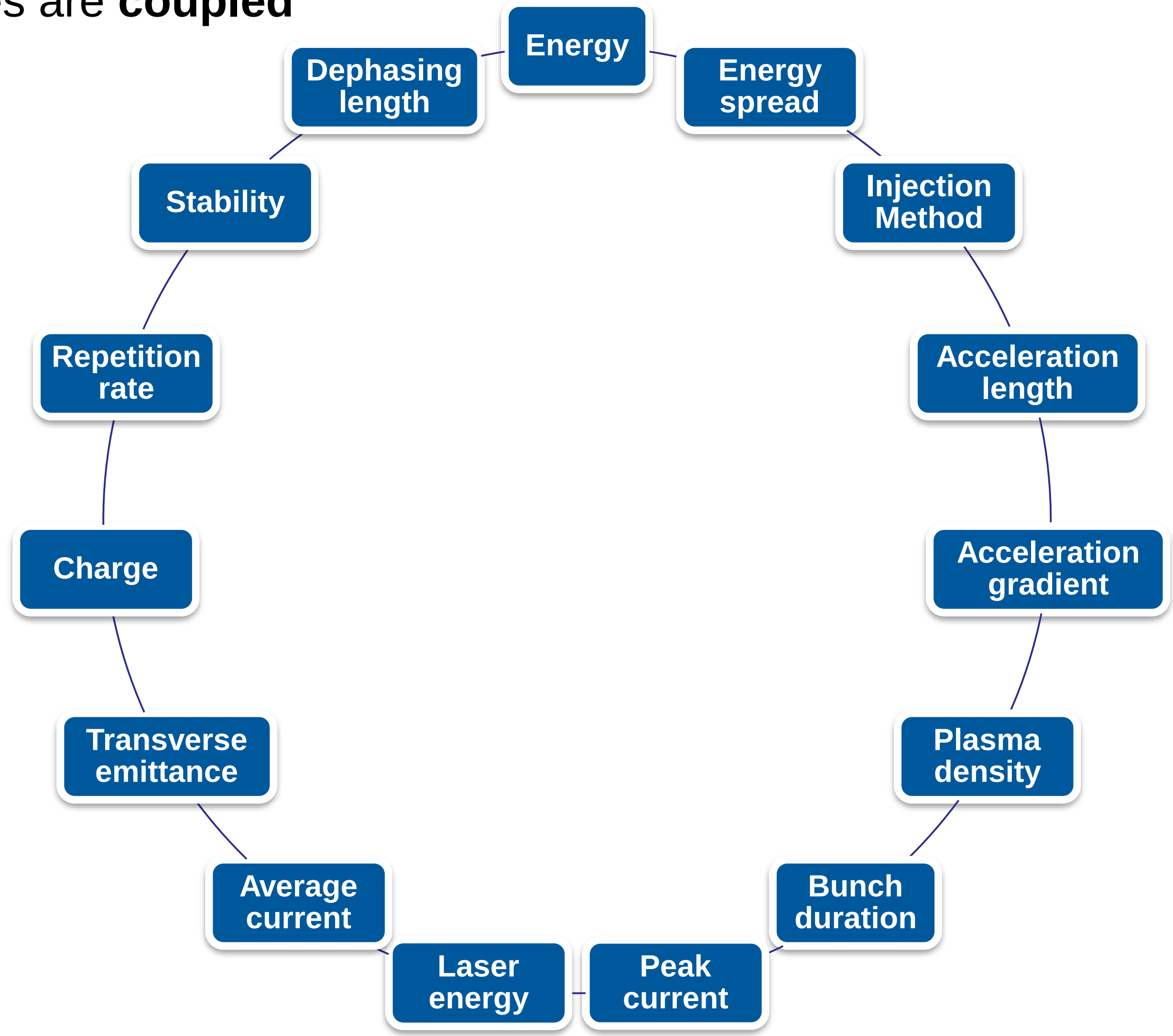
Difficult to optimize all beam parameters at once:

- High energy
- High charge
- Short pulse duration
- Low energy spread

} High peak current

LWFA Electron beam properties

- **Difficult to optimize**: many final beam parameters and/or accelerator properties are **coupled**



LWFA Electron beam properties

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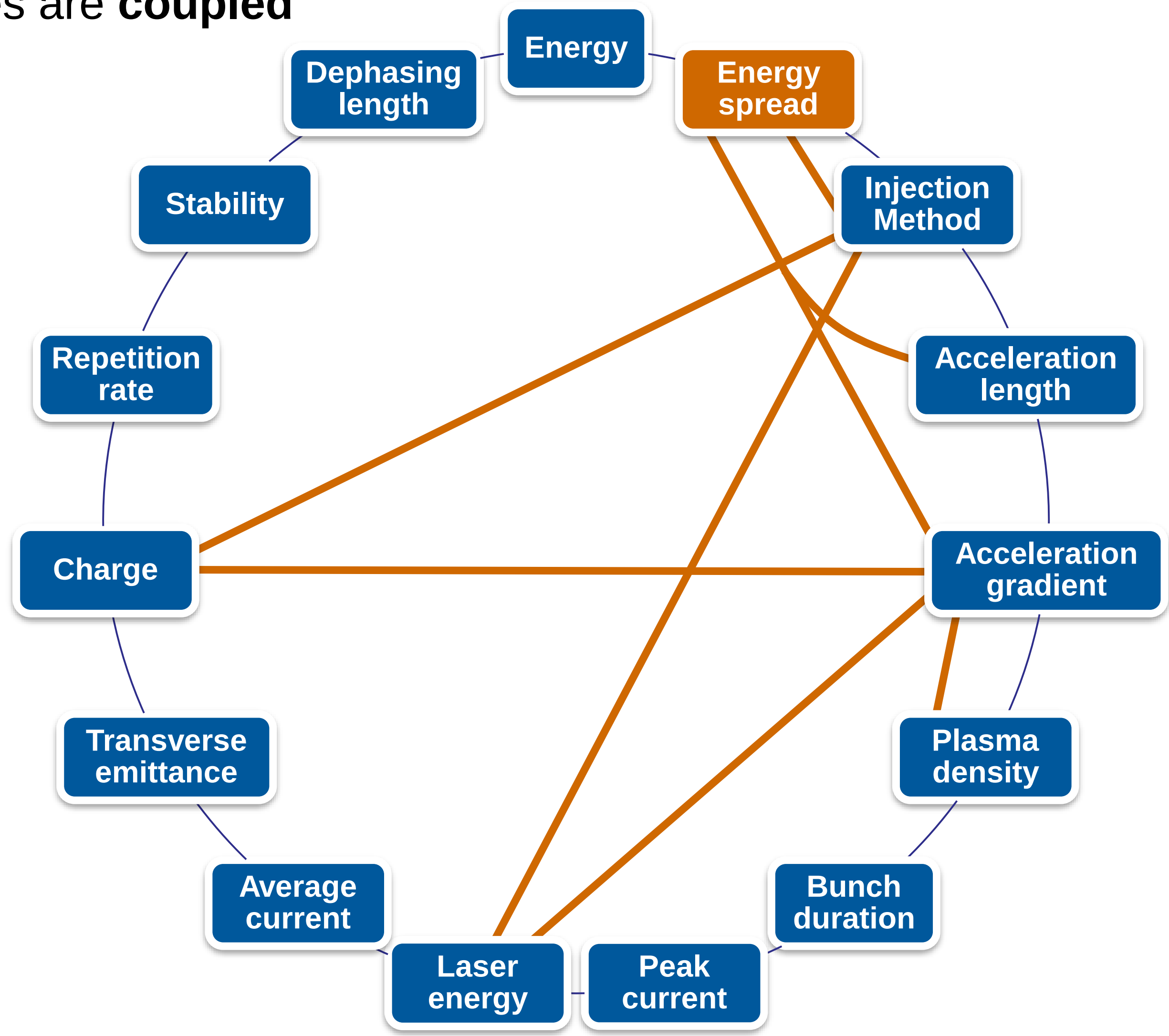

LWFA Electron beam properties

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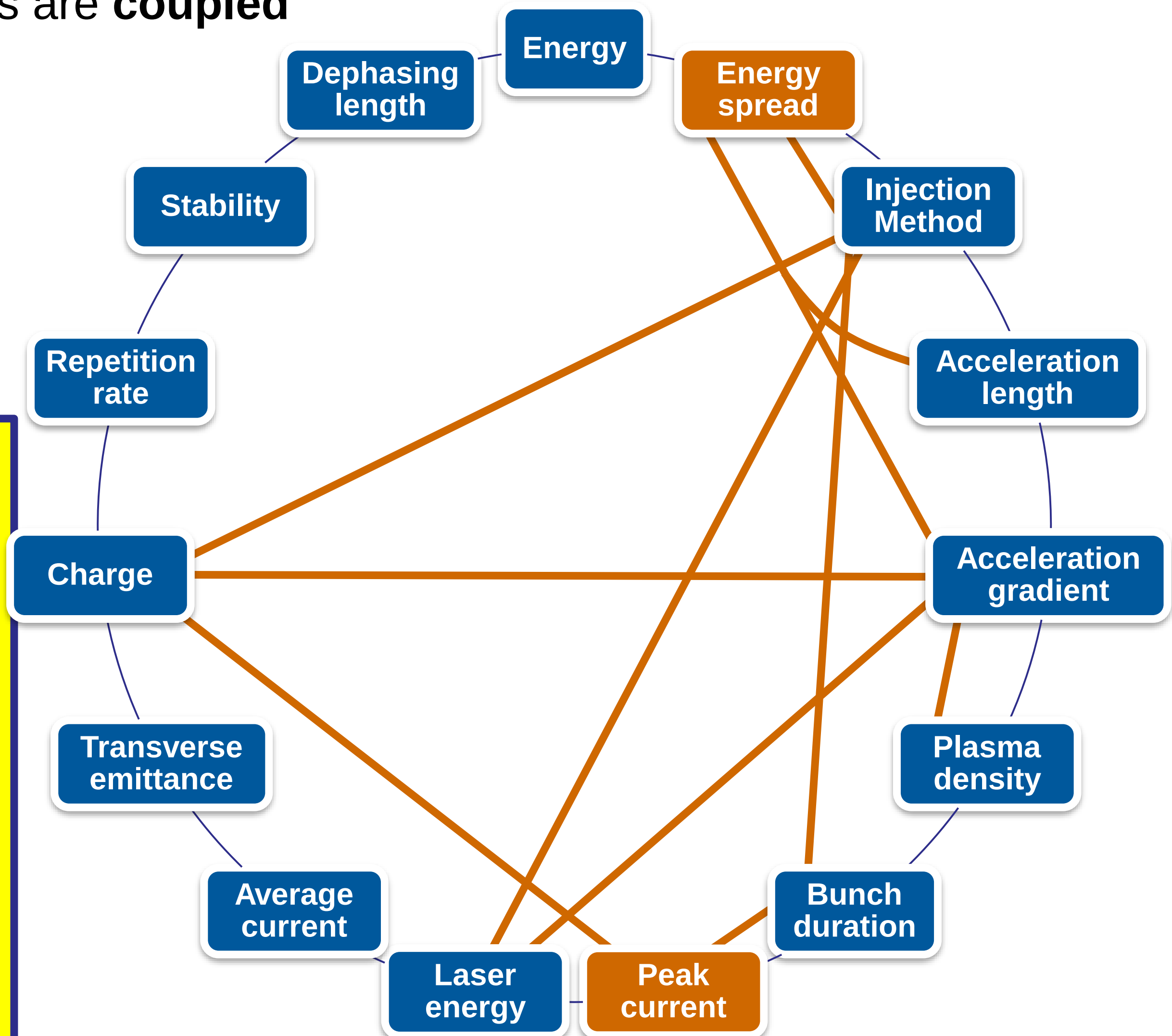
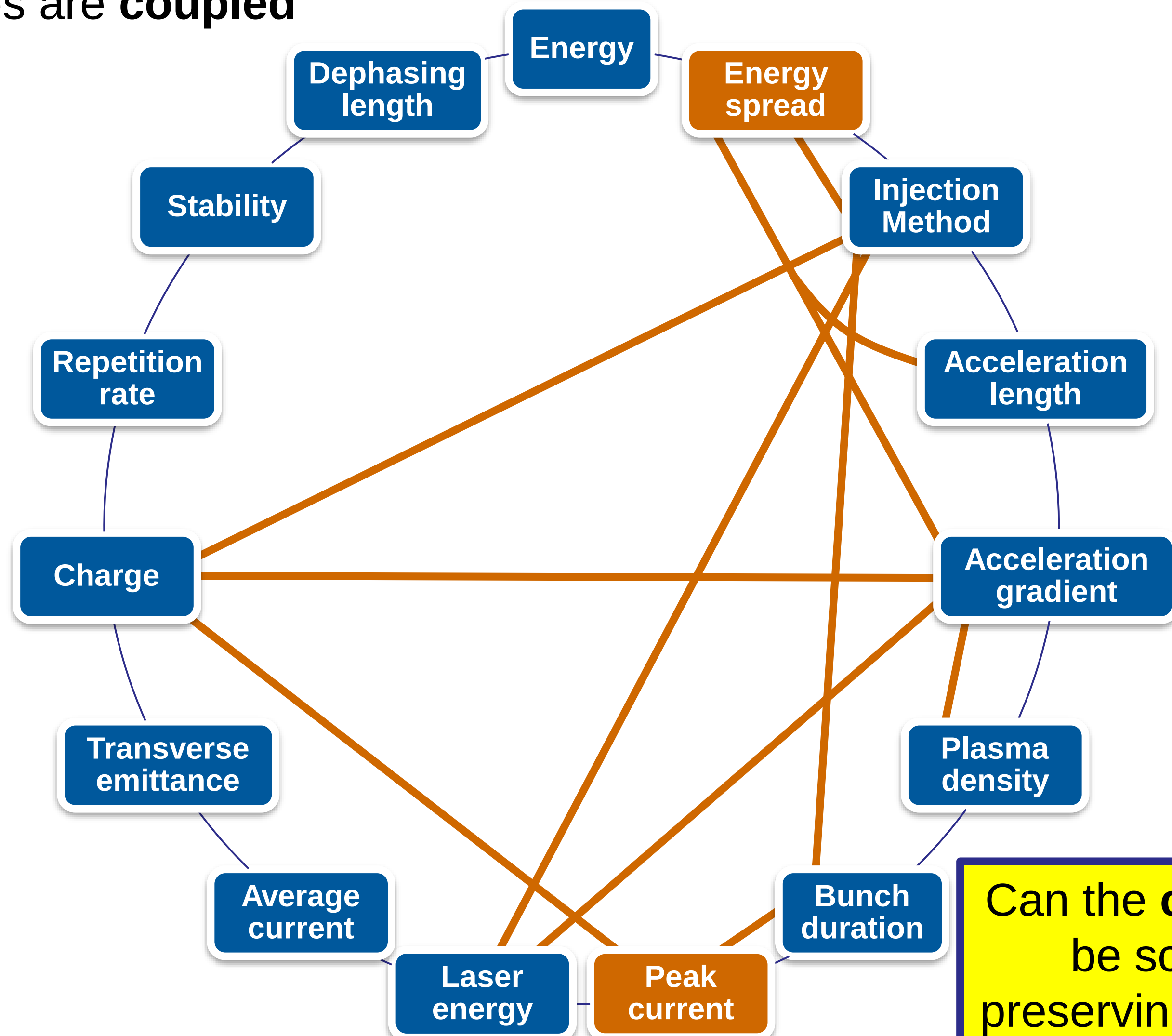


To reach high quality beams: We have to **decouple** beam properties and/or scale key parameters **without deteriorating others**

LWFA Electron beam properties

- **Difficult to optimize**: many final beam parameters and/or accelerator properties are **coupled**



Can the **charge/current** be scaled, while preserving a **low energy spread**?

High charge induces beam loading

- **Self-fields** of bunch **reshape** the accelerating wakefield

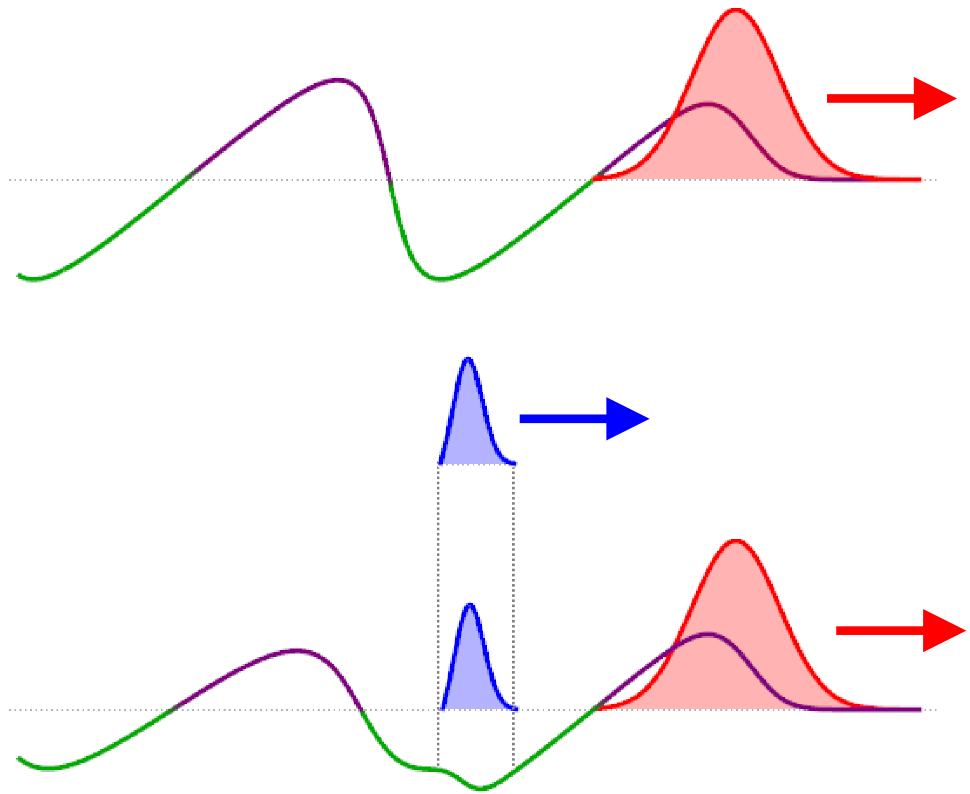
Laser driven acc. field

+

e^- beam self field

=

Beam loading



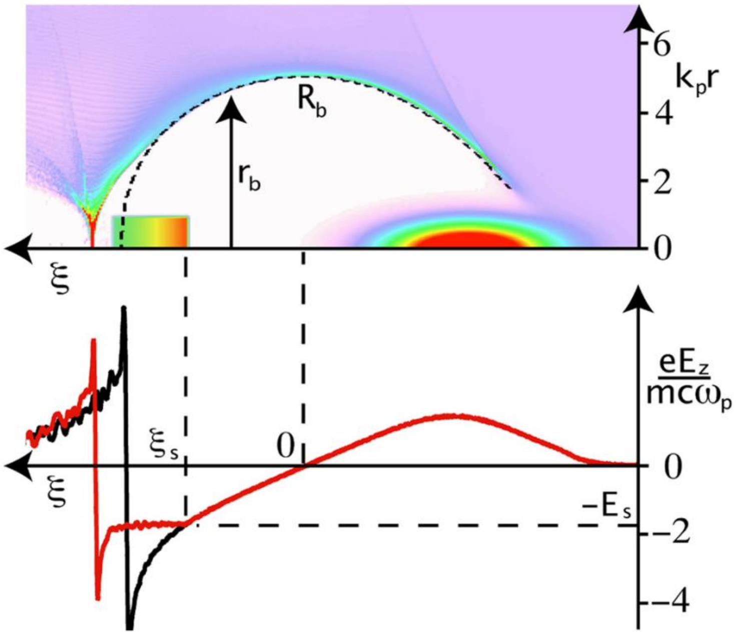
Beam loading effects

- **Reshaping** plasma accelerating structure
- **Reduction** of effective acceleration gradient
- **Degradation** of the final beam quality: maximum energy, energy spread

Rechatin et al., PRL 103, (2009)
Guillaume et al., PRSTAB 18 (2015)
Vafaei-Najafabadi et al., PRL, 112, (2014)

Optimal beam loading

- BUT, one can **optimize** it :
  Injection of an optimum bunch shape in the nonlinear **bubble regime** with a **specific charge Q_s**



- Charge scaling at the **optimum loading condition**

Requires **~0.3 nC** of injected charge at 65 TW laser power

Tzoufras *et al*.,
Phys. Rev. Lett. **101**, 145002 (2008)

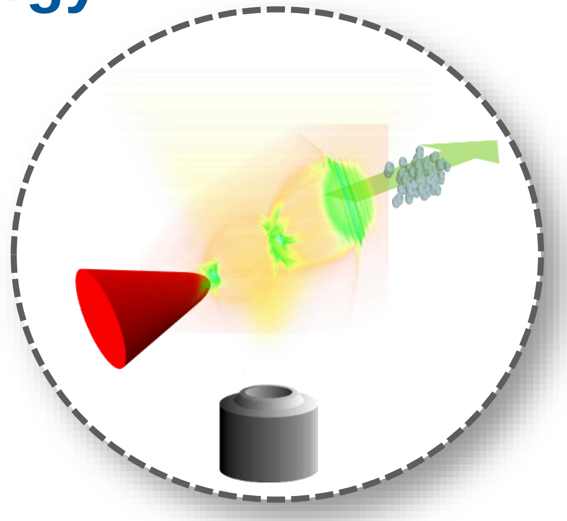
Optimum beam loading

- Accelerating gradient **constant** along the bunch
- No extra addition of energy spread

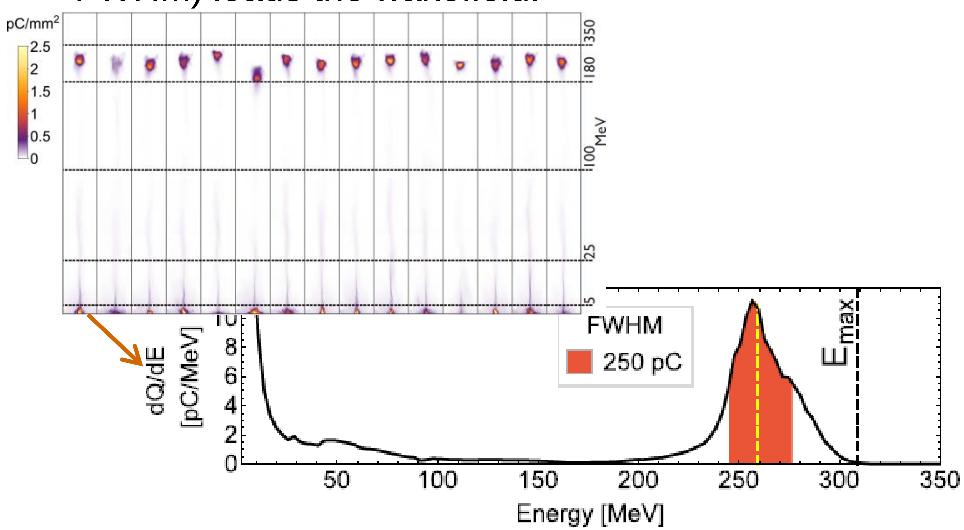
S. van der Meer, CLIC note No. 3 (1985)
Katsouleas et al., Part. Acc. 22 (1987)

Optimal beam loading: minimizing energy spread

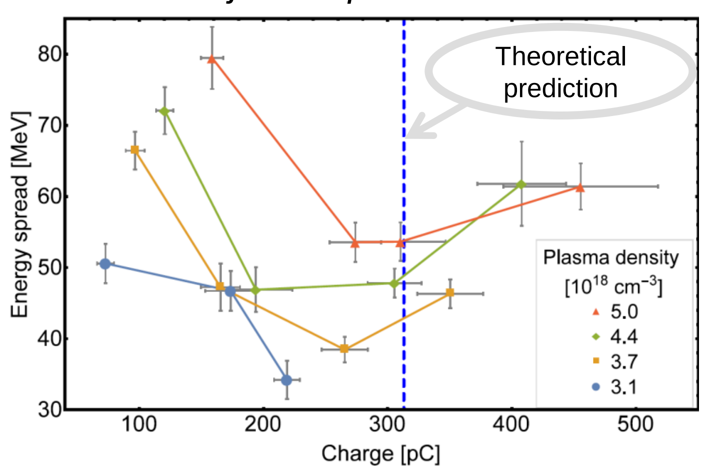
To **minimise energy spread** in a plasma accelerator, the charge has to be increased for **optimal beam loading**



- Controlled injection using self-truncated ionization injection (STII) of a **large charge** (0.1 up to 0.5 nC in FWHM) loads the wakefield.



- Beam loading: At increased charge a **minimum** of energy spread occurs.
  - Here the *acceleration process* no longer increases energy spread.
  - The remaining energy spread originates from the *injection process.*

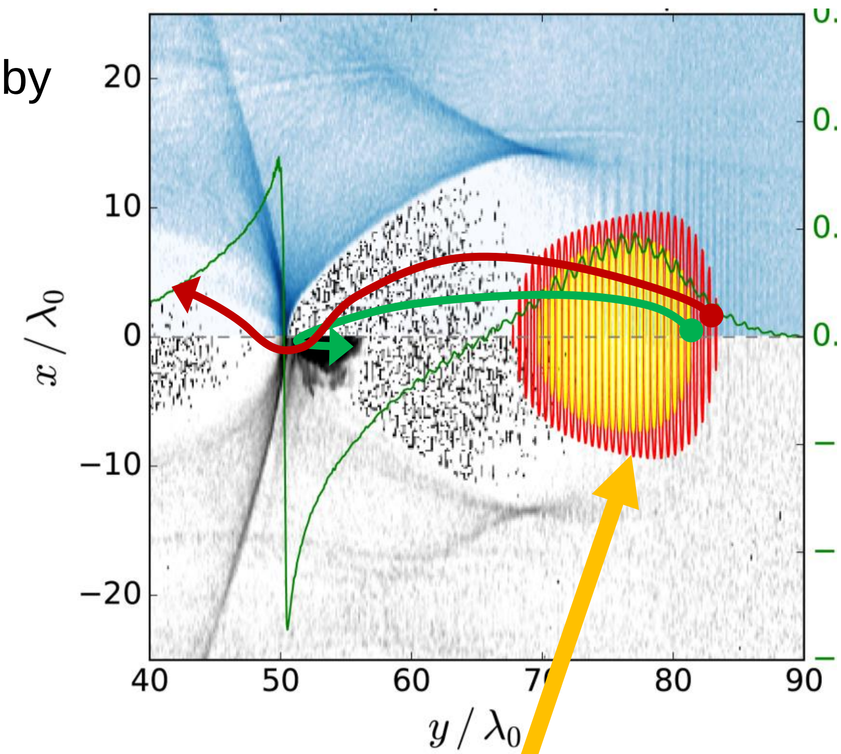


- At the optimal loading condition an **unprecedented high peak current** up to 20 kA at 15% energy spread is reached.

Couperus *et al.* Nat. Commun. 8, 487 (2017)

Ionisation injection

- The accelerating medium is **doped** by a **high-Z** gas
- Choosing the gas and laser energy such that inner shell electrons only ionize at the peak of the laser



Species	Ionisation energy (eV)
He^{1+}	24.6
He^{2+}	54.4
N^{1+}	14.5
N^{2+}	29.6
N^{3+}	47.4
N^{4+}	77.5
N^{5+}	97.9
N^{6+}	552
N^{7+}	667

Ionised only near the laser peak intensity

- Injection volume phase-space constant
- Charge is increased by increasing nitrogen doping

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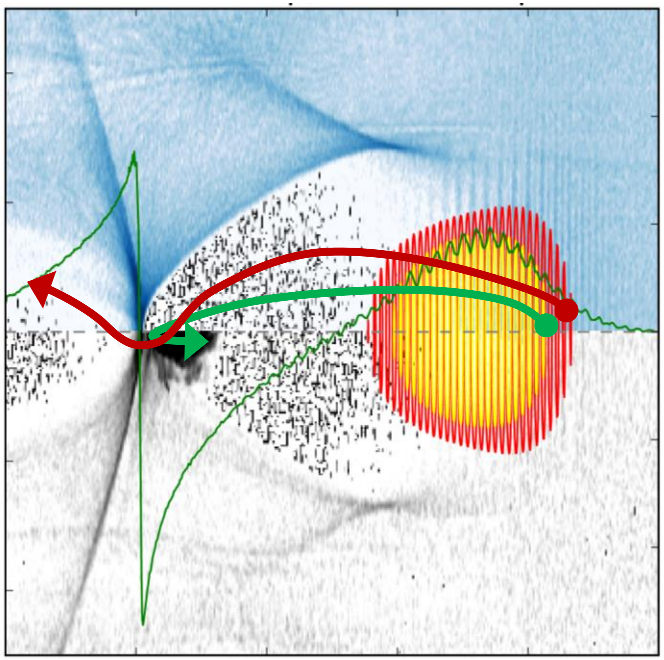
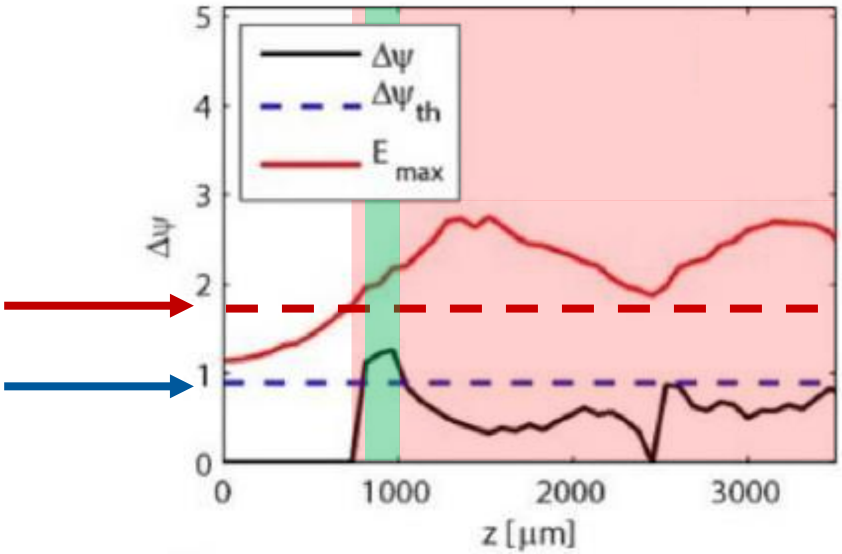
Self-truncated ionisation injection:

Stopping the injection for mono-energetic beams

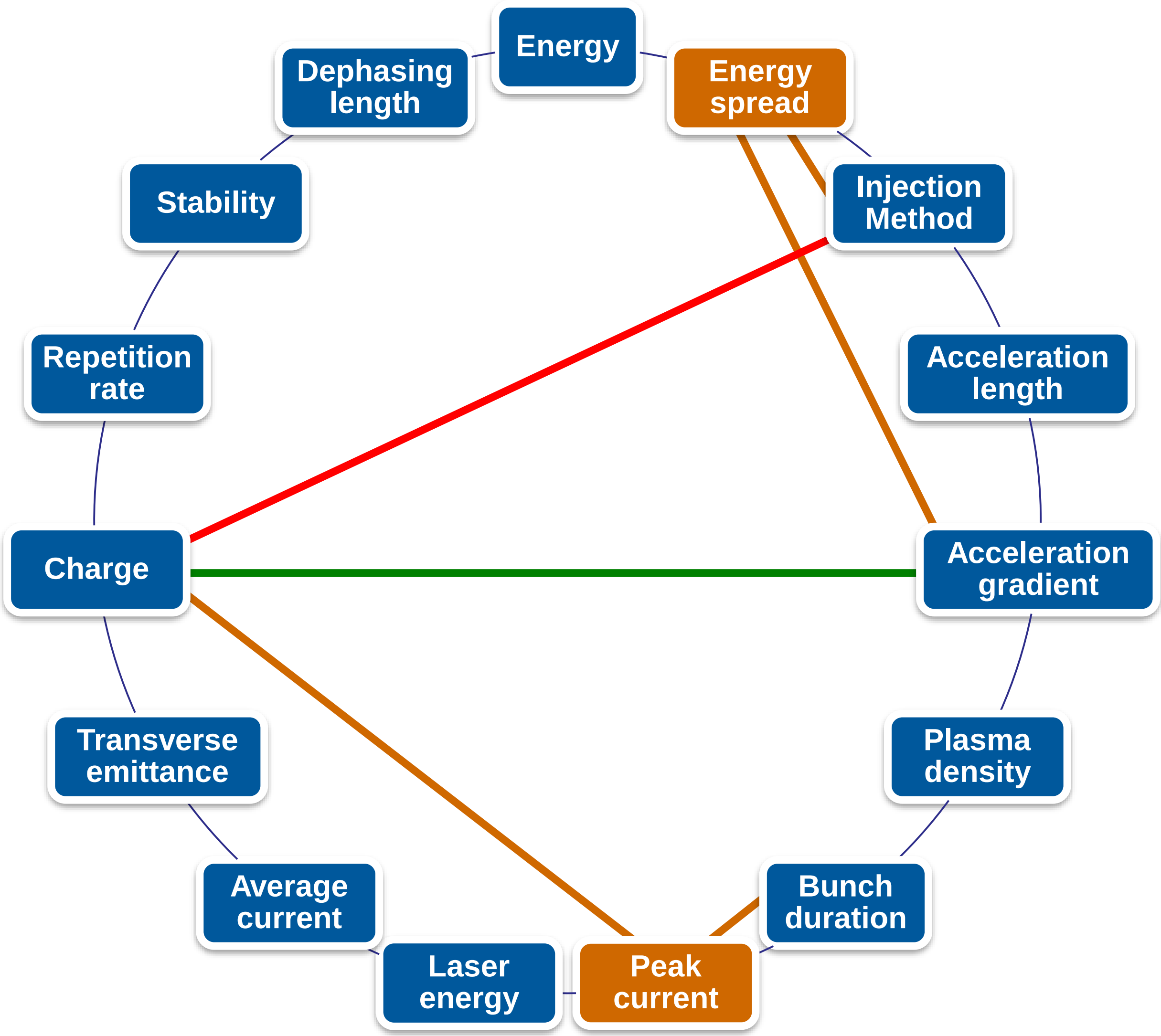
- In order to restrict energy spread from injection, a **limited injection time** is required
- In Self Truncated Ionisation Injection (STII) the **laser driver and wakefield shape evolve** during the interaction such that conditions for injection are fulfilled only in a limited region.
- Injection only when:
  - Laser max energy is high enough for ionisation
  - pseudo-potential difference allows trapping





Zeng *et al.* Phys. Plasmas 21, 030701 (2014), Mirzaie *et al.* Sci. Rep. 5, 14659 (2015)

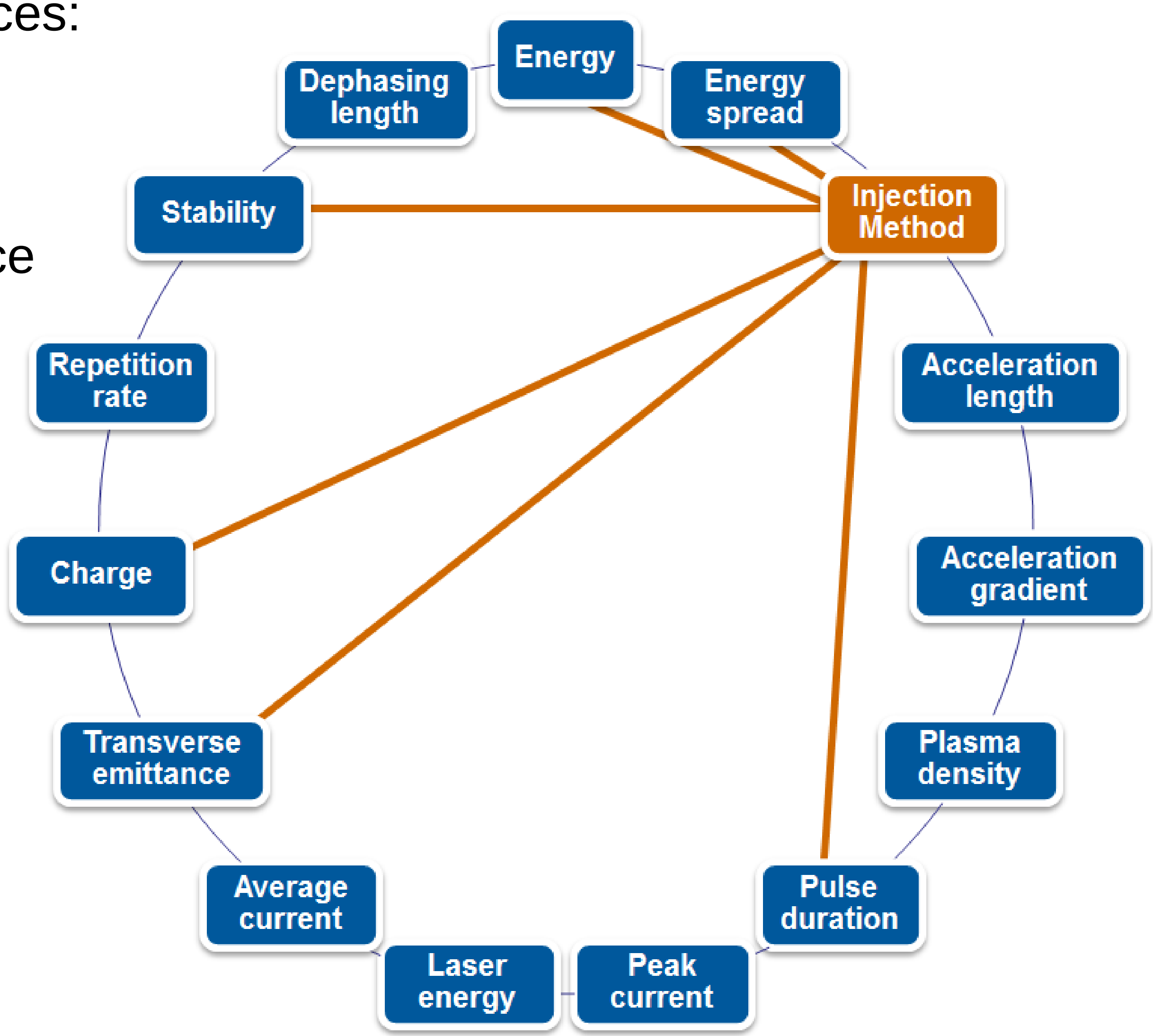
Electron beam properties: Injection



- **Self-truncated ionization injection** is capable to inject high charges, but suffers from relative long injection time and related high energy spread.
  - Injection and acceleration is **coupled**

Injection mechanisms:
crucial for high quality beams

- Controlling the injection is important as this influences:
  - Final energy
  - Energy spread
  - Charge
  - Divergence/emittance
  - Bunch length



Injection: Pulse duration

CTR spectrometer technique to measure bunch durations

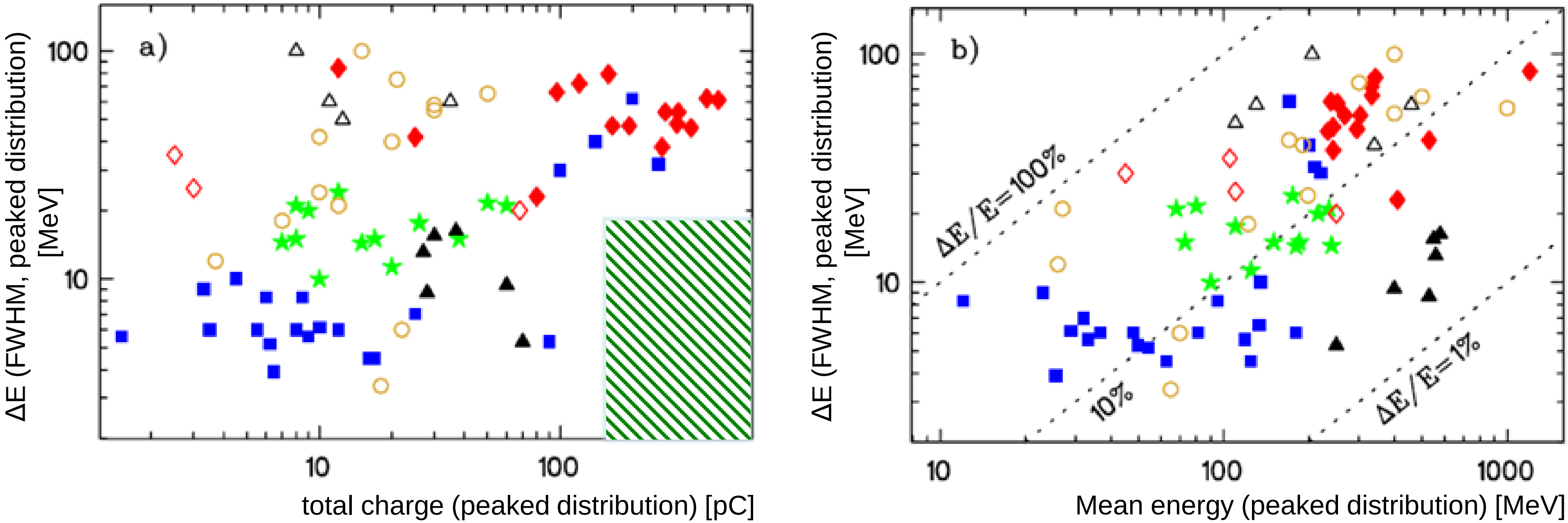
O. Zarini, A. Debus *et al*., in preparation

Self Truncated Ionization injection

Wave-breaking

O. Lundh *et al.*, Nat. Phys. **7**, 219–222 (2011), S.L. Bajlekov *et al.*, PRSTAB **16**, 040701 (2013), T. Maxwell *et al.*, PRL. **111**, 184801 (2013)
M. Heigoldt *et al.*, PRSTAB **18** 121302 (2015), B. Schmidt *et al.*, arXiv:1803.00608 (2018), O. Zarini *et al.*, IEEE AAC (2018)

Injection: Energy spread & Charge

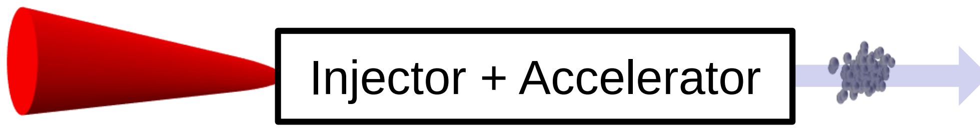


- ○ self injection, samples for reference — J. Osterhoff *et al.*, PRL (2008), S.P.D. Mangles *et al.*, Nat. (2004), J. Faure *et al.*, Nat (2004), W.P. Leemans *et al.*, Nat. Phys. (2006), S. Kneip *et al.* PRL (2009), H.T. Kim *et al.*, PRL (2013)
- ★ colliding pulse injection — J. Faure *et al.*, Nat. (2006), C. Rechatin *et al.*, PRL (2009)
- ■ shock induced injection — K. Schmid *et al.*, PRSTAB (2010), A. Buck *et al.*, PRL (2013), K.K. Swanson *et al.*, PRAB (2017), K. Khrennikov *et al.*, PRL (2015), S. Karsch *et al.*, EAAC unpubl. (2017)
- △ down ramp injection multi stage; ▲ down ramp inj. tailored multi stage — A.J. Gonsalves *et al.*, Nat. Phys. (2011), B.B. Pollock *et al.*, PRL (2011), W.T. Wang *et al.*, PRL (2016)
- ◇ ionization injection — C. McGuffey *et al.*, PRL (2010), C.E. Clayton *et al.*, PRL (2010), Y.F. Li *et al.,* Phys. Plasmas (2017)
- ◆ self truncated ion. inj. — M. Mirzaie *et al.*, Sci. Rep. (2015), J.P. Couperus *et al.*, Nat. Comm. (2017)

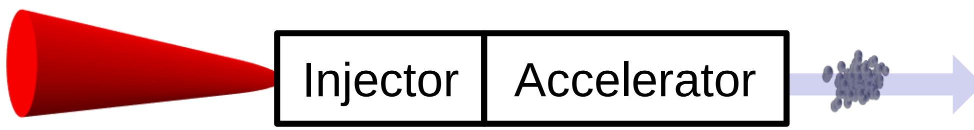
A. Irman *et al.*, Plasma Phys. Control. Fusion **60**, 044015 (2018)

Injection: Coupled parameters with acceleration

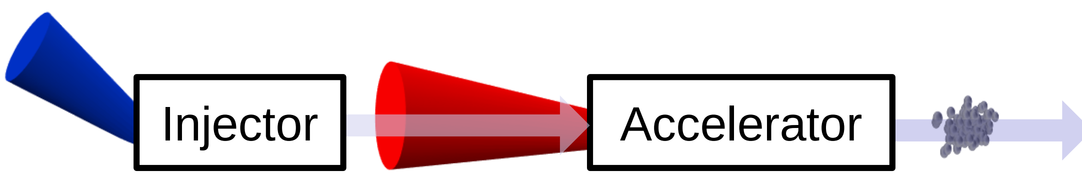
- In Self Truncated Ionisation Injection (STII) & wave-breaking injection the **injector** and **accelerator** are directly coupled



- **Partly decoupling** injector and accelerator gives better control
  - e.g. shock-front injection, colliding pulse injection



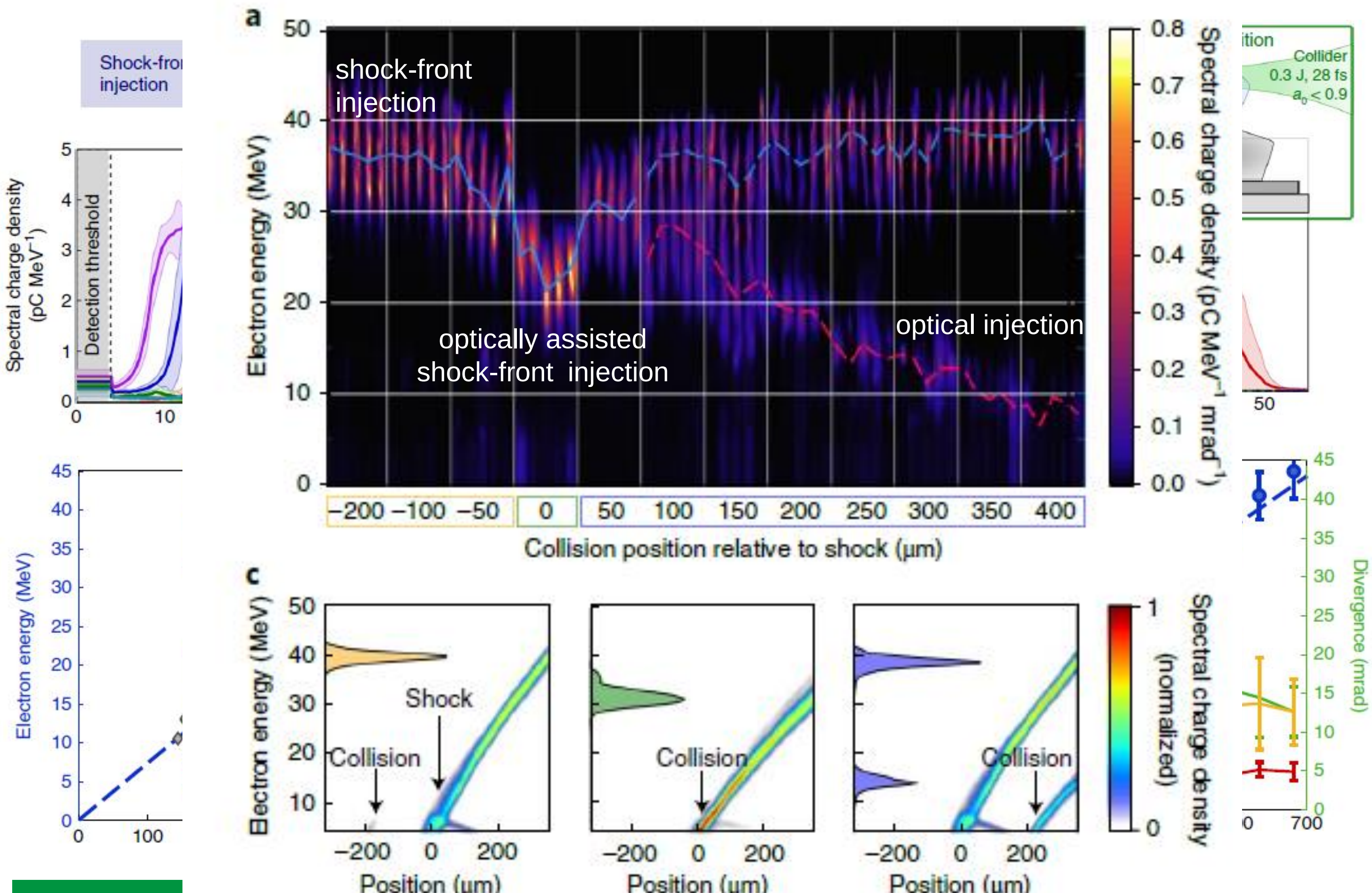
- Ideally we would like to completely separate injection and acceleration parameters
  - e.g. external injection



We still need to inject enough charge to reach the optimal loading condition

Injection: decoupling parameters

- Improved control:
  Shock-front injection + Colliding pulse injection

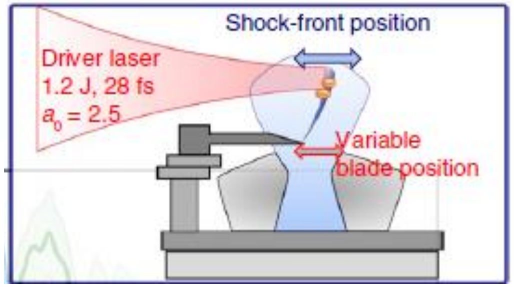


J. Wenz et al., Nat. Photonics (2019)

A. Buck et al., PRL **110**, 185006 (2013), K. Schmid, PRSTAB **13**, 091301 (2010)
K.K Swanson et al, Phys. Rev. Acc. Beams **20**, 051301 (2017). J. Faure et al., Nature **444**, 737-739 (2006)

Injection: decoupling parameters

Shock-front injection



- Stefan Karsch *et al.* (unpublished)

Reaches charge as required for the optimal loading condition!

Stability & Repetition rate

- Talk this morning by Andreas Maier: Reliable laser operation
- Talk this morning by Emily Link: High-average power laser for LWFA
- Current high-power laser systems still suffer from shot-to-shot fluctuations
- Talk yesterday by Lucas Schaper: High-repetition rate plasma sources
  - Heat dissipation from laser/beam driver
  - Plasma perturbations at high-repetition rate

Challenges

In how far can we further improve accelerator stability by improving laser stability?

&

Can we scale to high-repetition rate without sacrificing beam quality

Conclusion

- Laser wakefield accelerators are attractive for their **high accelerating gradient** (compactness), their **inherent short pulse duration** (few fs) and **high peak current** (10s of kA).

- **Coupling** of injector, accelerator and beam parameters makes improving beam quality in laser wakefield accelerators **challenging.**

- Lot of recent progress in beam quality improvement:
  - **Optimal beam loading**: Cancellation of the energy spread contribution from the acceleration process
  - **High peak currents**, even at limited energy spread
  - **Measurement of bunch duration**: sub-fs substructures & influence of different injection schemes
  - **Injection schemes**: decoupling injector from accelerator. Further reducing energy spread & beam divergence/emittance (at high injected charge)
  - **Increased reproducibility & stability**: from acceleration to accelerator.

Thank you for your attention!

HZDR, team electrons:

Arie Irman
Ulrich Schramm
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Alexander Köhler
Omid Zarini
Vincent Chang
Thomas Kurz
Susanne Schöbel