Plasma colliders: efficiency

What is needed, where are we, where do we have to go?

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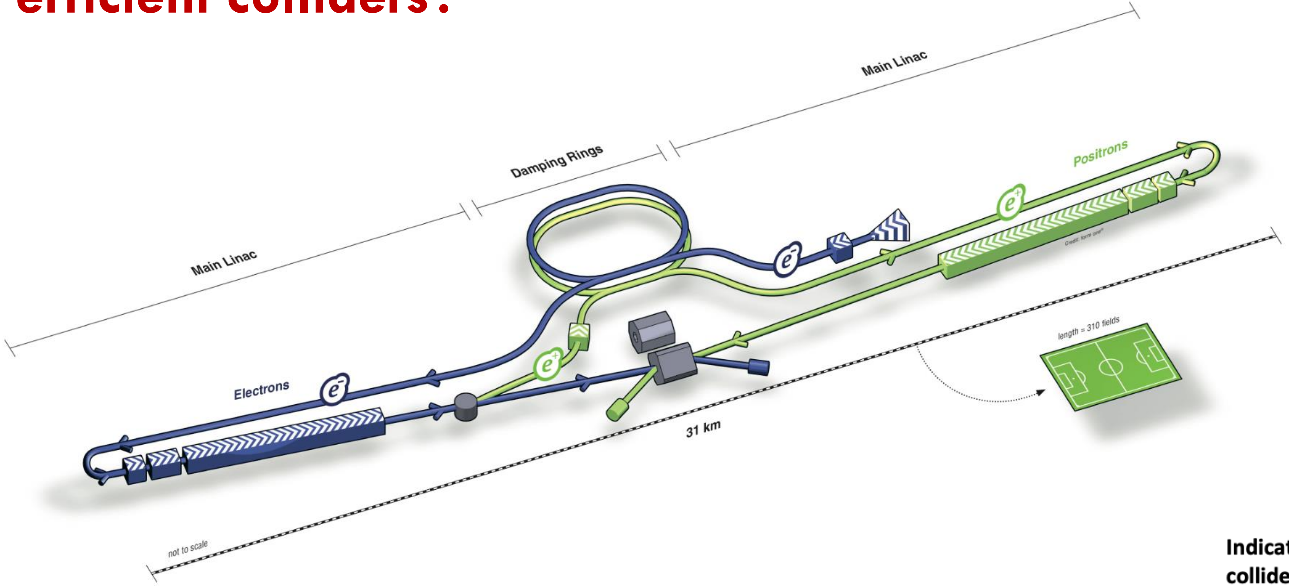
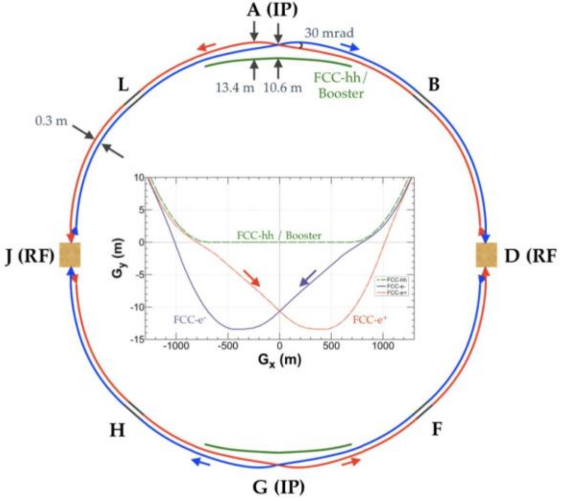
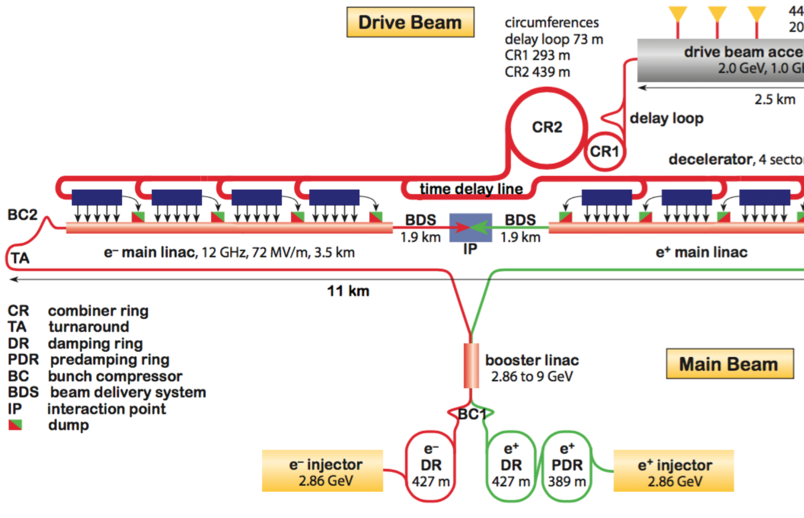
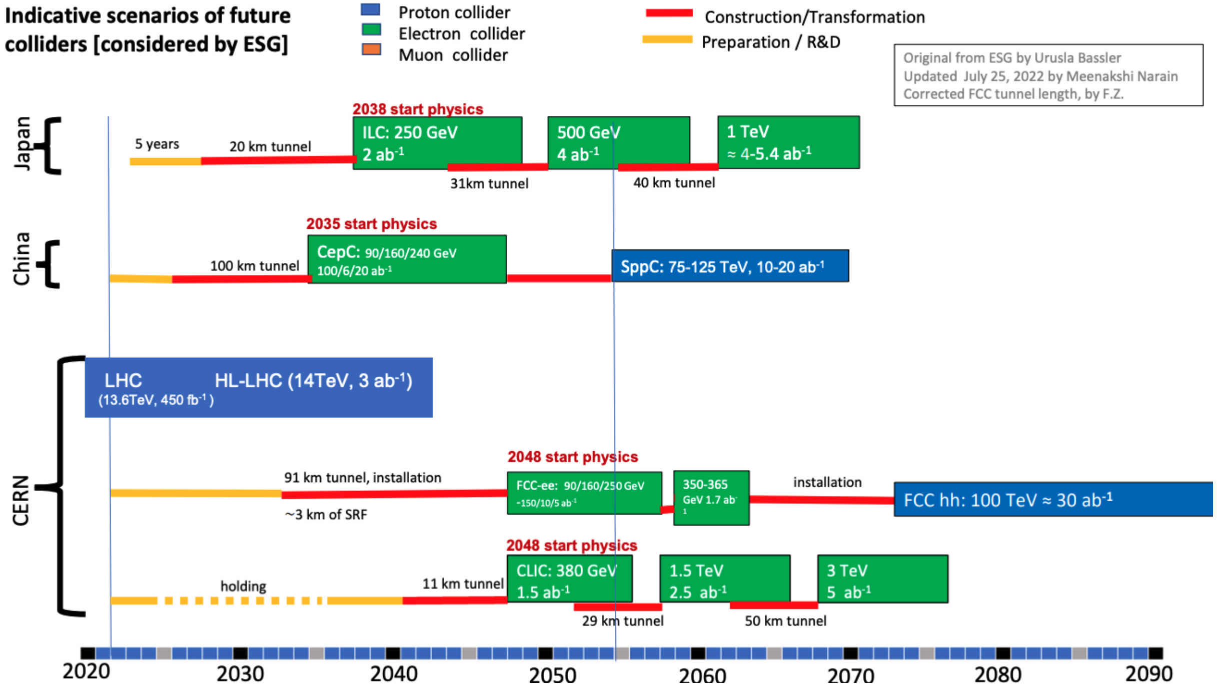
Despite a rich physics program, the current global funding climate makes the realization of the below TeV-scale linear colliders challenging. **Can we provide not only more compact, but more power efficient colliders?**





Schematic of the FCC-ee collider with the details of the crossing schemes at the interaction points.





To be attractive, proposed plasma colliders should **have significant improvement** with respect to the existing projects (ILC, CLIC).

General formula:

$$\mathscr{L} = f_{rep}\frac{N^2 n_b}{4\pi\sigma_x\sigma_y}H_b$$

Rewrite in terms of power :

$$\mathscr{L}/P_{AC} \propto \frac{\eta_{\mathrm{AC}\rightarrow\mathrm{beam}}}{mc^2}\frac{N}{\sigma_x\sigma_y}$$

Taking into account beam strahlung :

$$\mathscr{L}/P_{AC} \propto \frac{\eta_{\mathrm{AC}\rightarrow\mathrm{beam}}}{mc^2}\frac{1}{\sqrt{\sigma_z}\sigma_y}$$

$\sigma_y^2 = \beta_y\,\varepsilon_y$

Possibilities for improvement for a PWFA-LC?

- **footprint (cost)**
- vertical emittance?
- vertical focusing function?
- **wall-plug-to-beam efficiency?**
- Short bunches, but lower limit from beam-beam must be checked (not shown in scaling)?

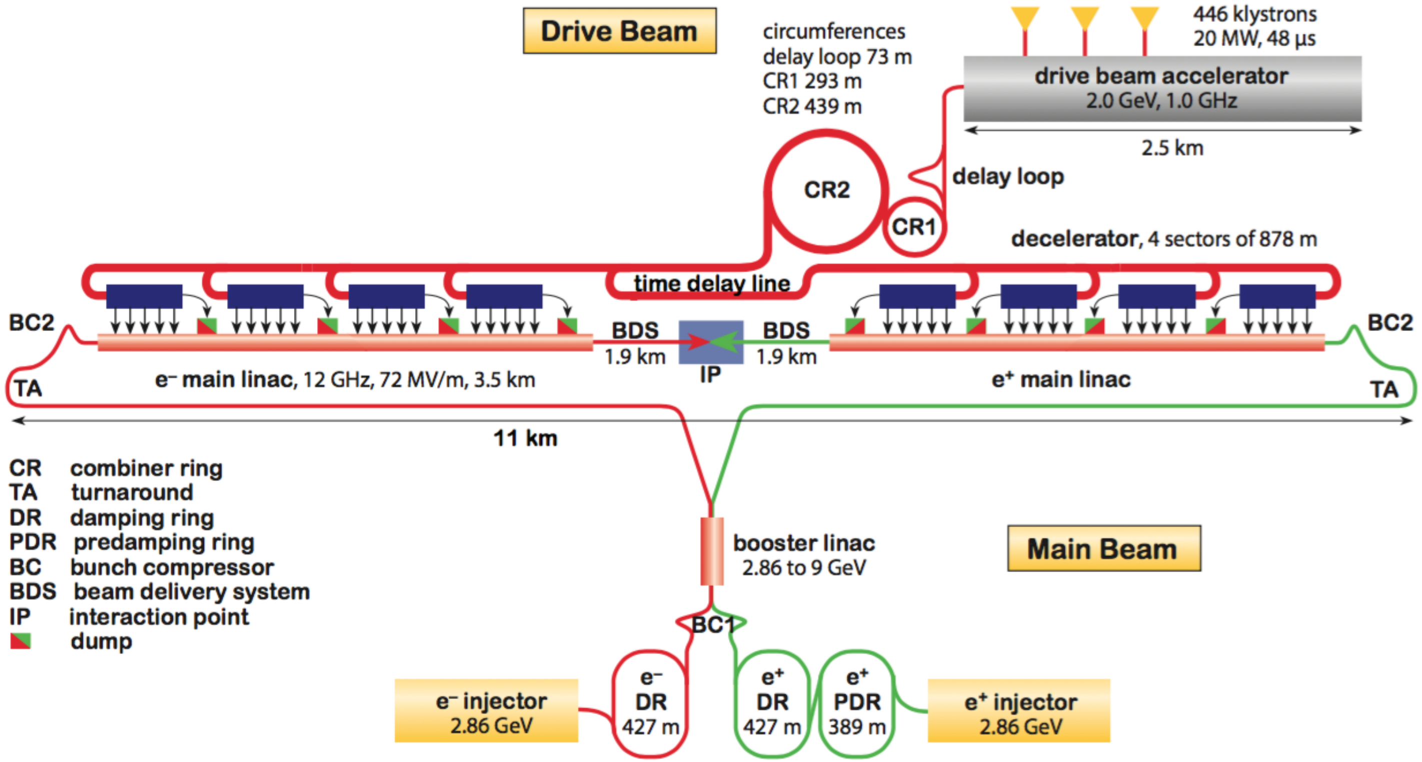
Keep luminosity target!

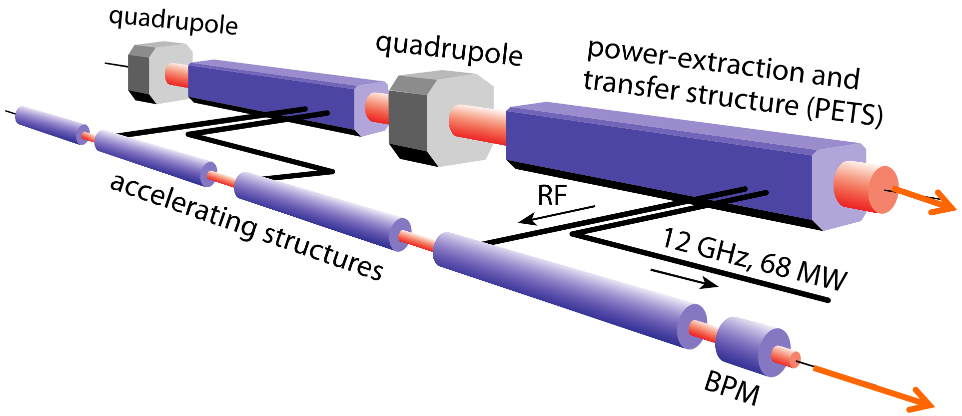
- A collider that costs one O.M less than CLIC/ILC but gives several O.M. less luminosity would likely have limited interest.

Reference project: CLIC

I use CLIC as a reference project for comparison:

- Beam-driven two-beam acceleration scheme, many similarities to PWFA
- Detailed CDR exist, with consistent parameters, all aspects studied
- I know it well, wrote chapters for the CLIC CDR

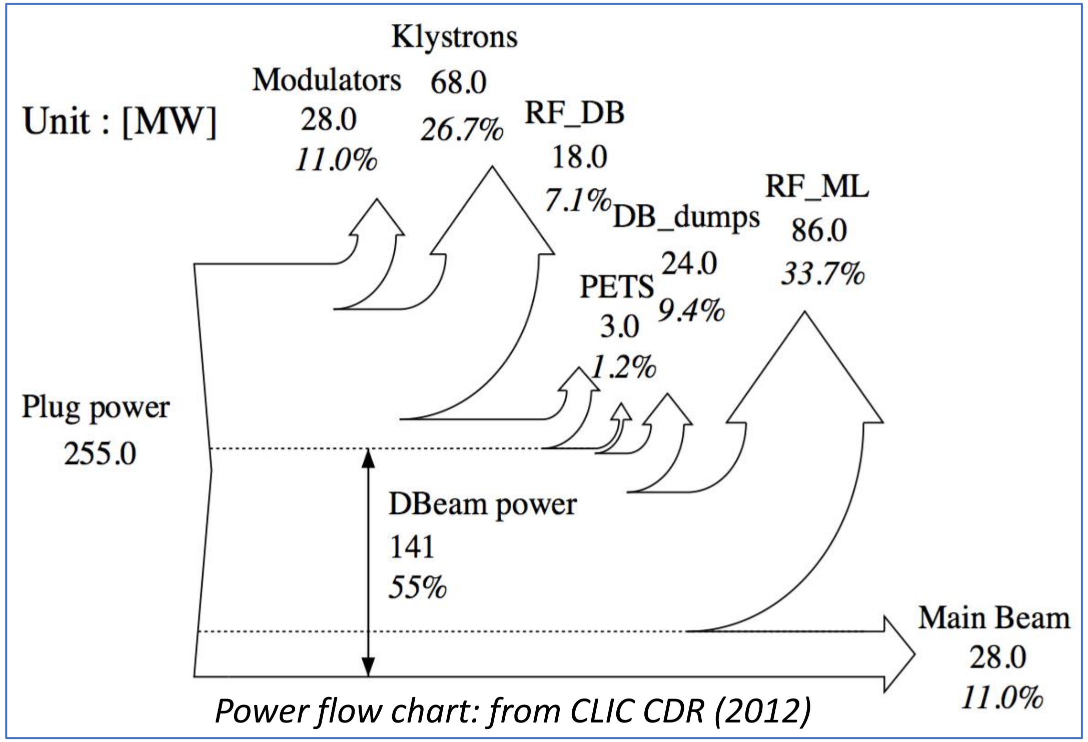




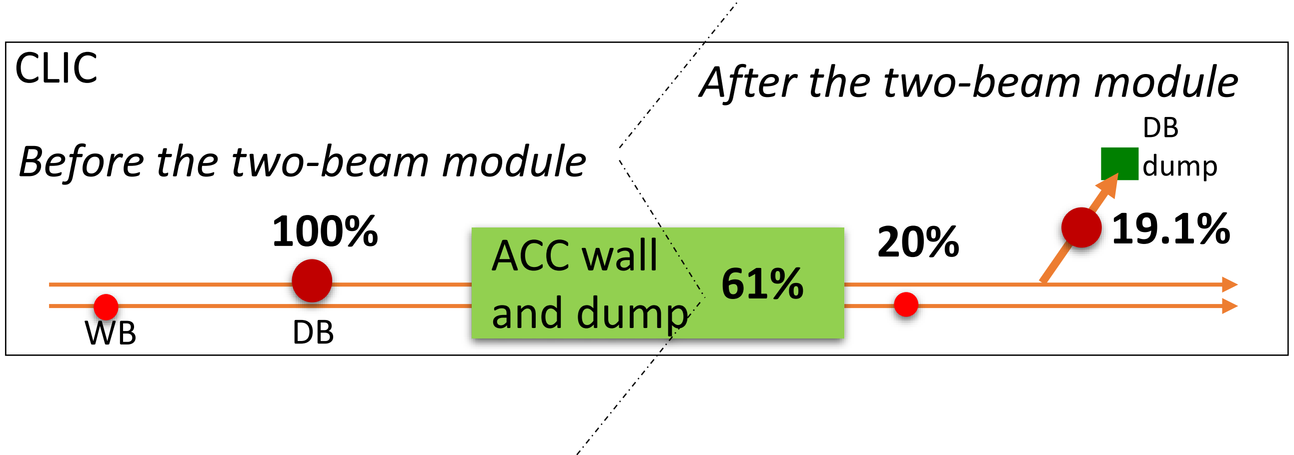
CLIC parameters (3 TeV cm)

gradient 100 MV/m
L = 10
$\mathcal{L} = 10^{34}$ /cm^2/s
$\varepsilon^*_{n,y}$ = 20 nm
σ^*_y = 1 nm
σ^*_z = 44 um
N = 600 pC/e
n_b = 312 @ 2 GHz
f_{rep} = 50 Hz
Efficiencies:

- **AC to DB : 141/255 = 55%**
- DB to rf wake : (28+86)/141 = 81%
- Rf wake to MB : 28/141 = 25%
- -> **DB to MB = 28/141 = 20%**
- -> AC to MB = 28/255 = 11%



Power flow chart: from CLIC CDR (2012)



CLIC

Before the two-beam module

After the two-beam module

100%

ACC wall and dump

61%

20%

DB dump

19.1%

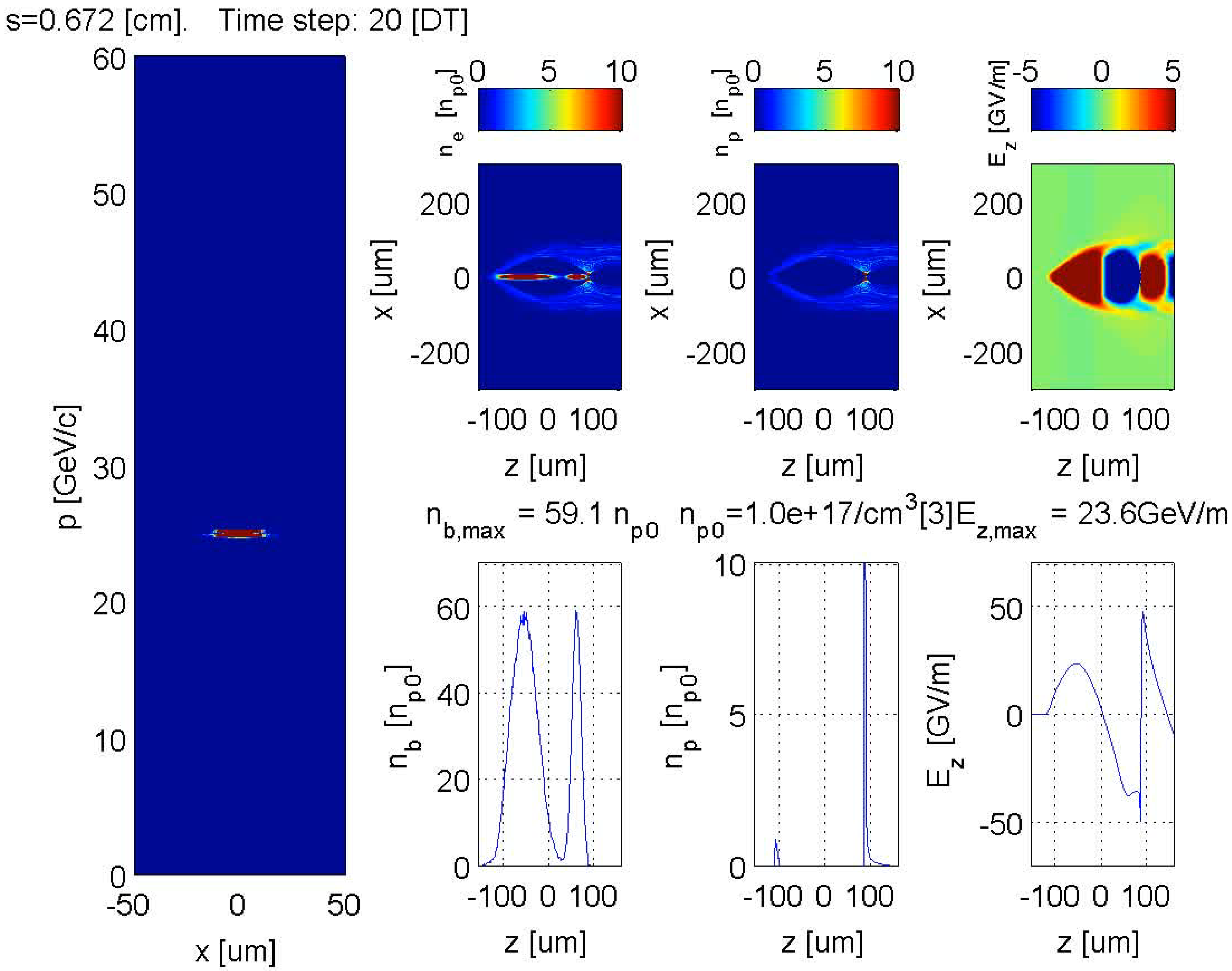
WB

DB

Notes:

- Aux. systems power not shown
- Current efficency numbers improved with respect to CDR

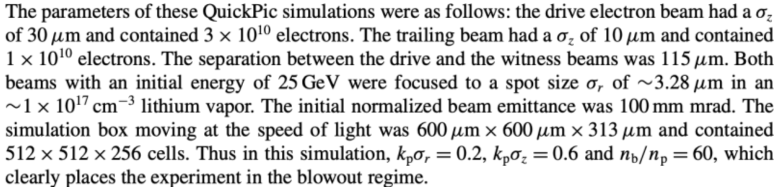
DB-to-wake and wake-to-MB efficiency :



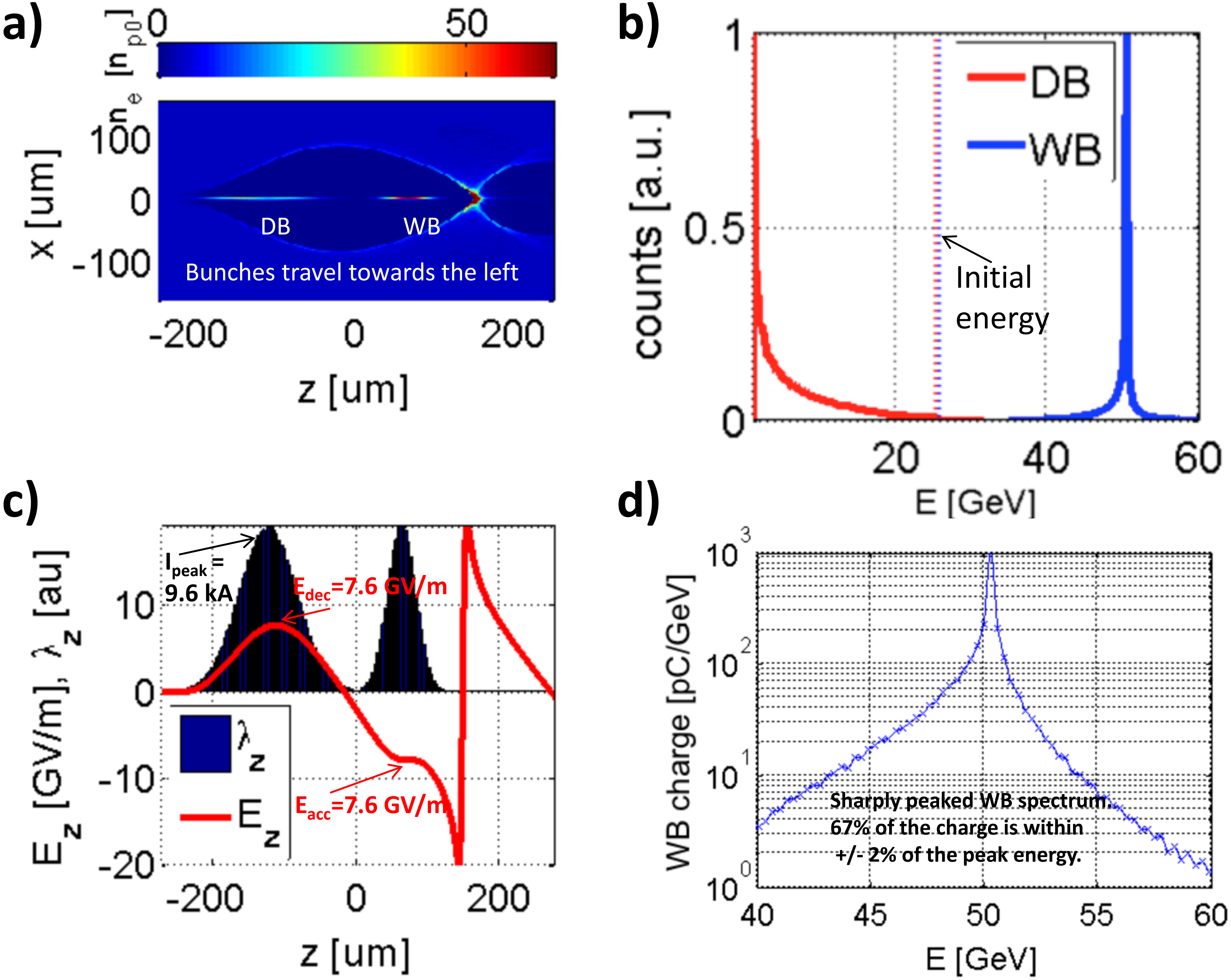
DB to WB efficiency: 50%

Not optimized for efficiency.

Gaussian bunches
with 100 um emittance.


The parameters of these QuickPic simulations were as follows: the drive electron beam had a σ_z of 30 μm and contained 3×10^{10} electrons. The trailing beam had a σ_z of 10 μm and contained 1×10^{10} electrons. The separation between the drive and the witness beams was 115 μm. Both beams with an initial energy of 25 GeV were focused to a spot size σ_r of $\sim$3.28 μm in an $\sim 1 \times 10^{17}\,\mathrm{cm}^{-3}$ lithium vapor. The initial normalized beam emittance was 100 mm mrad. The simulation box moving at the speed of light was 600 μm $\times$ 600 μm $\times$ 313 μm and contained $512 \times 512 \times 256$ cells. Thus in this simulation, $k_p\sigma_r = 0.2$, $k_p\sigma_z = 0.6$ and $n_b/n_p = 60$, which clearly places the experiment in the blowout regime.

Basis for Snowmass 2013 study:
Final energy spectrum
after one stage :



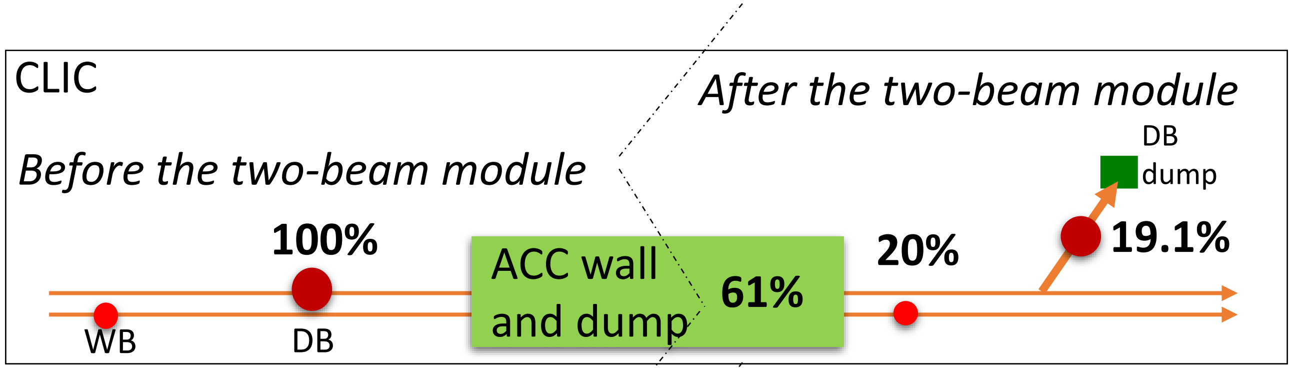
Bunches travel towards the left

Initial energy

Sharply peaked WB spectrum.
67% of the charge is within
+/- 2% of the peak energy.

Opportunity: efficiency

From the 2013 “Snowmass” PWFA-LC concept
(E. Adli, J. P. Delahaye et al.)



CLIC

Before the two-beam module

After the two-beam module

100%

ACC wall and dump

61%

20%

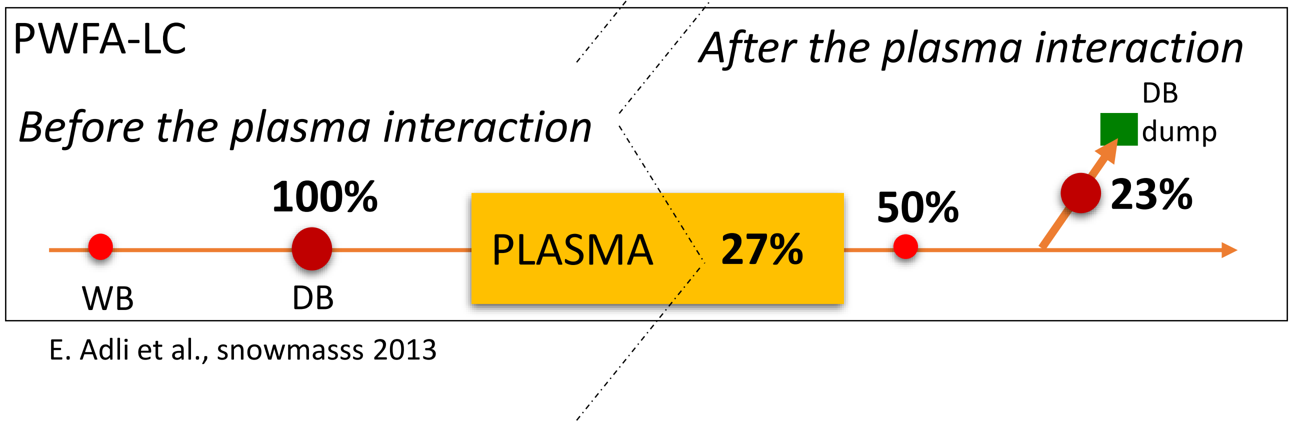
DB dump

19.1%

WB

DB

CLIC CDR



PWFA-LC

Before the plasma interaction

After the plasma interaction

100%

PLASMA

27%

50%

DB dump

23%

WB

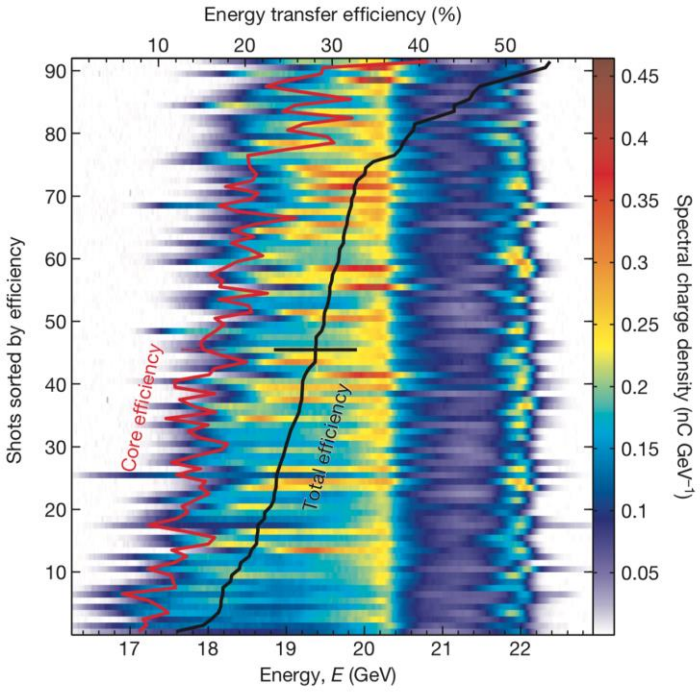
DB

E. Adli et al., snowmasss 2013

Can PWFA beat RF colliders on efficiency?

Improved **efficiency** will reduce operation cost

Experimental status (FACET):
wake to MB > 30%

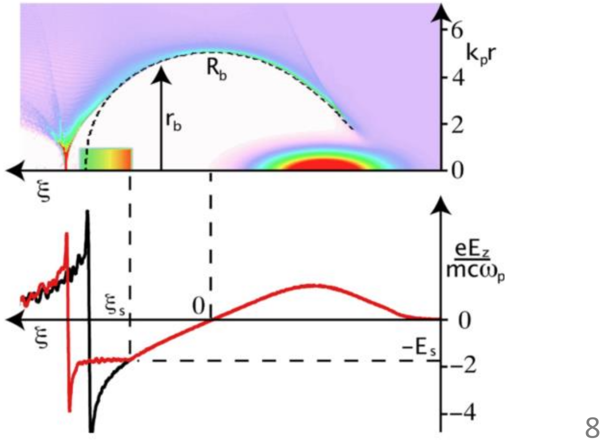


M. Litos, Nature **515**, 92 (2014)

DB-to-wake x wake-to-MB = 0.77 x 0.65 = 0.50

Possibly increased by shaping the DB

Possibly increased by shaping the WB

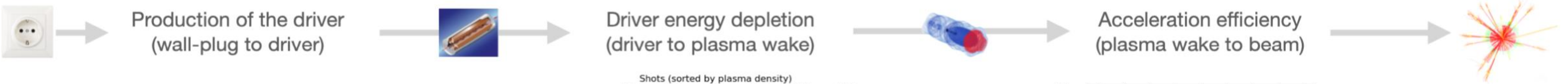


M. Tzoufras, PRL 101, 145002 (2008

DB-to-MB of 90% according to theory and PIC simulations.

PWFA: recent result from DESY

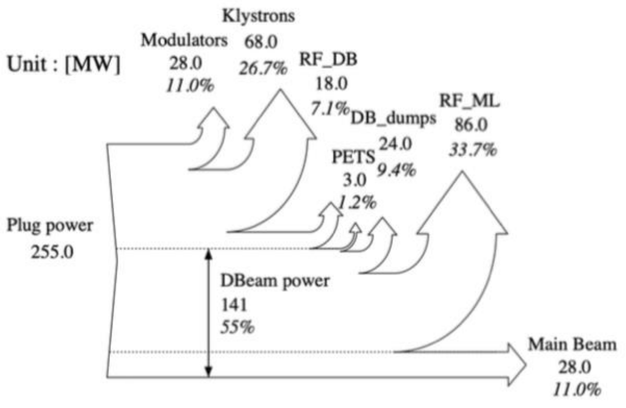
> Three-part efficiency:



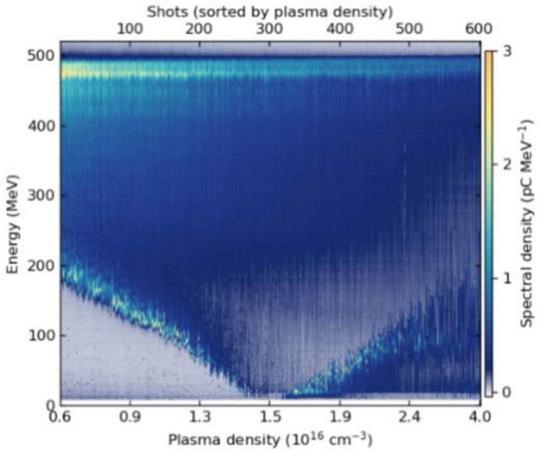
Production of the driver
(wall-plug to driver)

Driver energy depletion
(driver to plasma wake)

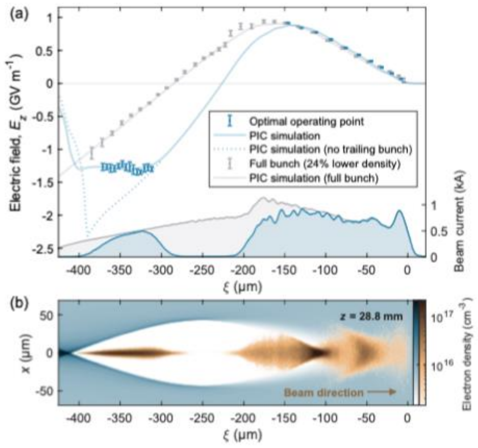
Acceleration efficiency
(plasma wake to beam)



From: CLIC Conceptual Design Report (2012)



From: Peña et al. (manuscript in preparation).



From: Lindstrøm et al., PRL 126, 014801 (2021)

55% predicted for CLIC × ~50% achieved in experiment (up to ~90% in theory) × 42% achieved in experiment (up to ~90% in theory) = *12% if combined (~40% in theory)*

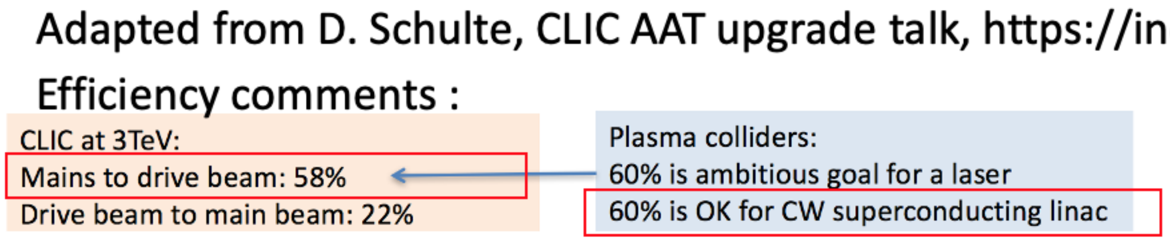
CLIC: AC to DB : 141/255 = 55%
DB to rf wake : (28+86)/141 = 81%
Rf wake to MB : 28/141 = 25%
-> **DB to MB = 28/141 = 20%**
-> AC to MB : 28/255 = 11%

PWFA one-stage, experiement: AC to DB : (n/a)
DB to plasma wake : 50%
Plasma wake to MB : 42%
-> **DB to MB = 21%**
-> AC to MB : (n/a)

PWFA one-stage, simulation: AC to DB : (n/a)
DB to plasma wake : 90%
Plasma wake to MB : 90%
-> **DB to MB = 80%**
-> AC to MB : (n/a)

Efficiency: are we done?

1) Production of driver: we can safely assume about 50-60% . Will anyway be similar for beam-driven RF and beam-driven plasma.



Adapted from D. Schulte, CLIC AAT upgrade talk, https://indico.cern.ch/event/607729/

Efficiency comments :

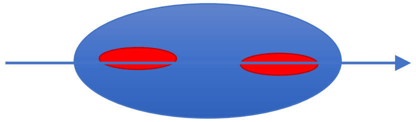
CLIC at 3TeV:
Mains to drive beam: 58%
Drive beam to main beam: 22%

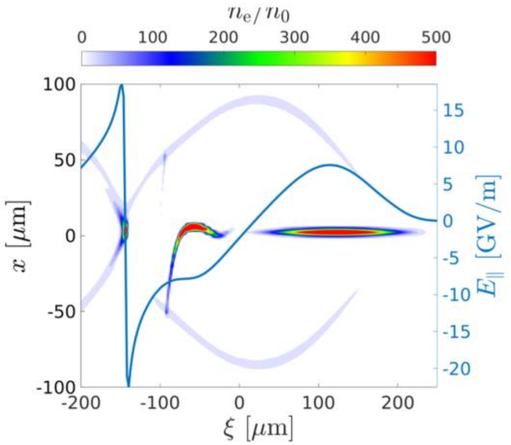
Plasma colliders:
60% is ambitious goal for a laser
60% is OK for CW superconducting linac

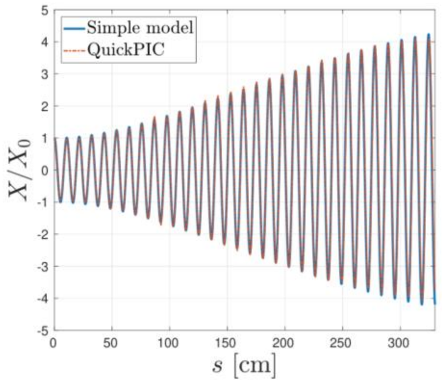
2 + 3) DB to MB: experimentally we have already shown efficenct as good CLIC – for a single stage.

Transverse instabilities: RF colliders vs plasma colliders

Focus lately: witness beam intra-beam wake :

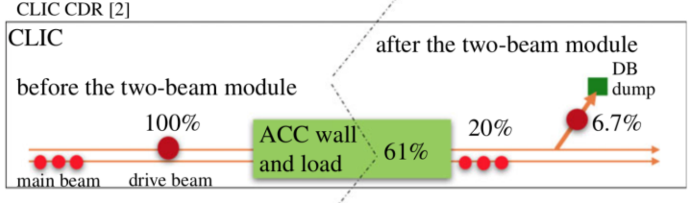






Why are the linear community scrutinizing the main beam single bunch wake?
The single-bunch wake decides how much charge can be loaded into CLIC.

CLIC CDR [2]



CLIC:
Limit for transverse single bunch wake: **100 kV/pC/m/m**
Goal attained by spreading pulse charge into multi-bunch trains. **Limits** the CLIC wake to RF efficiency to ~25%.

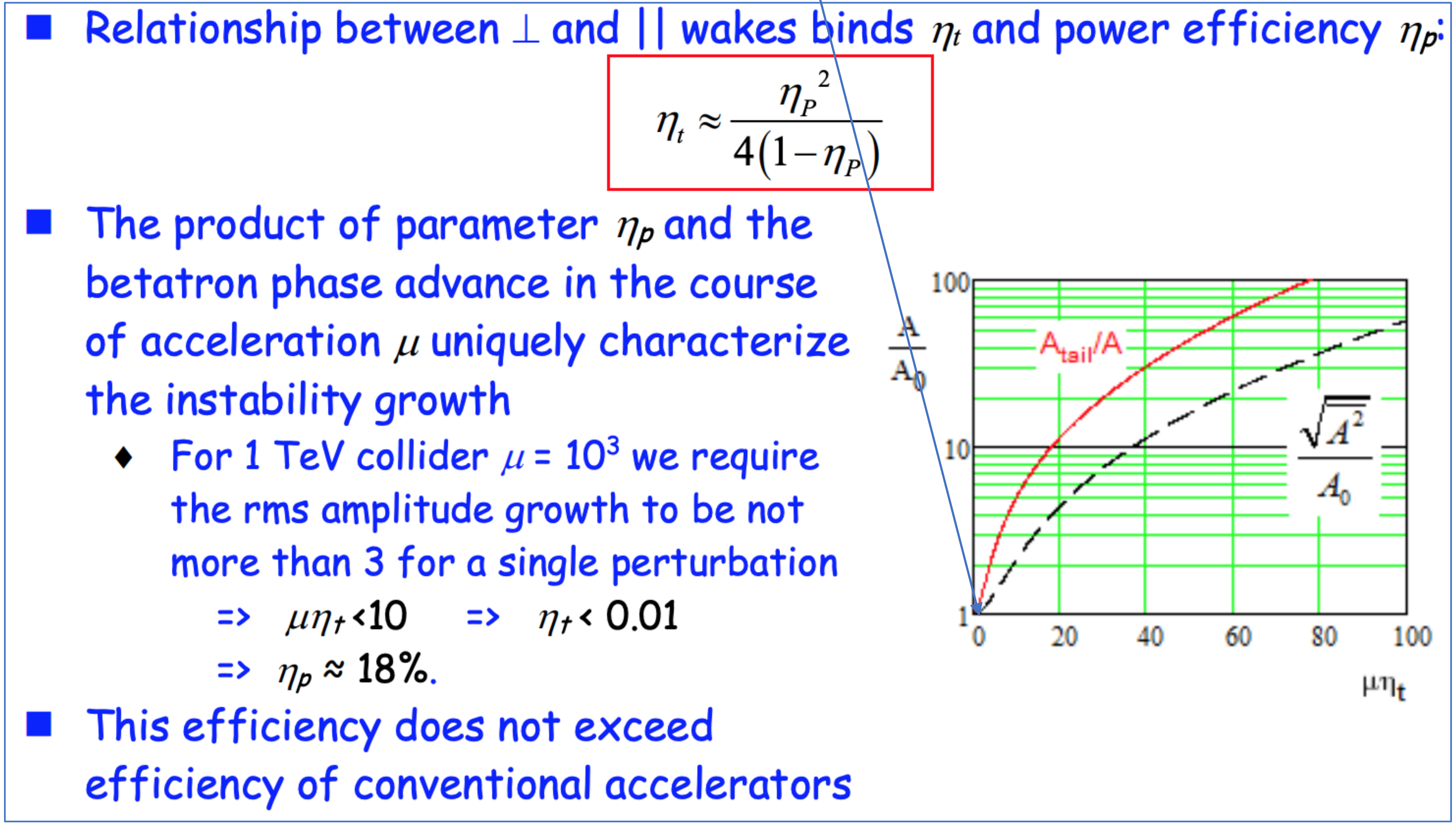
Current plasma collider concepts: **single bunch acceleration**
- disadvantageous with respect to the CLIC multi-bunch scheme

Still an open questions:
- sufficient mitigation of the instability for efficient PWFA single bunch acceleration?
- further studies, including and benchmarking with PIC simulations and experiment needed

To investigate a single stage is not sufficient

Neither in simulation nor experiment.

From Valeri Lebedev, Fermilab



- Relationship between ⊥ and || wakes binds η_t and power efficiency η_p:

$$\boxed{\eta_t \approx \frac{\eta_P{}^2}{4(1-\eta_P)}}$$

- The product of parameter η_p and the betatron phase advance in the course of acceleration μ uniquely characterize the instability growth
  - For 1 TeV collider $\mu = 10^3$ we require the rms amplitude growth to be not more than 3 for a single perturbation

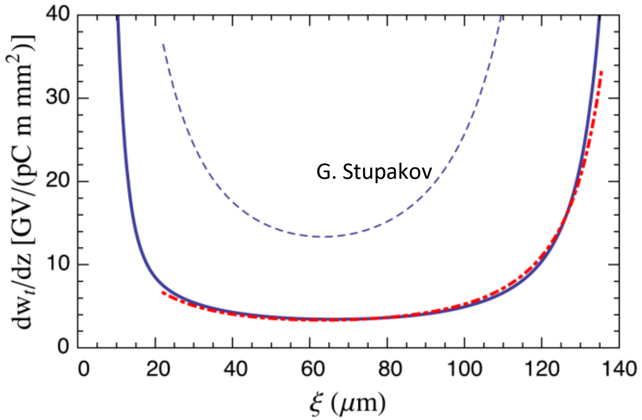
    => $\mu\eta_t < 10$ => $\eta_t < 0.01$

    => $\eta_p \approx 18\%$.
- This efficiency does not exceed efficiency of conventional accelerators

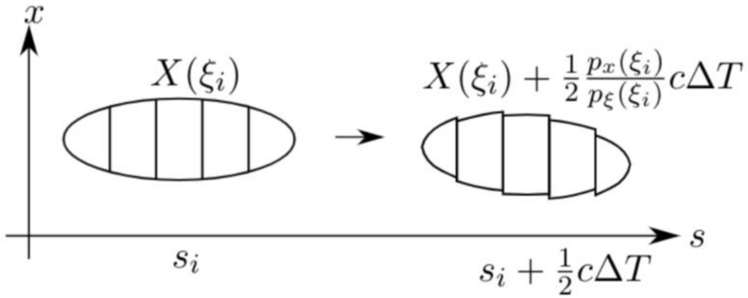
E- blow out regime: can be studied with with simplified models

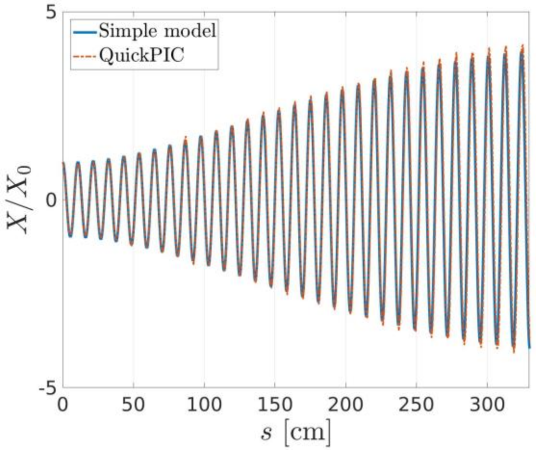
Transverse wakefunctions:

- Fermilab / Gennady Stupakov:
  - $W_\perp(\xi' - \xi, \alpha) = \frac{2}{\pi\varepsilon_0} \frac{\xi' - \xi}{\left(r_\mathrm{b}(\xi') + \alpha k_\mathrm{p}^{-1}\right)^4} \Theta(\xi' - \xi)$
  - $a = r_\mathrm{b}(\xi') + \alpha k_\mathrm{p}^{-1}$ represents an effective structure iris.
  - The electromagnetic fields penetrate into the plasma at depths $\sim k_\mathrm{p}^{-1}$ a numerical coefficient on the order of one.



We have benchmarked the wake function model, combined with simplified quasi-static tracking.

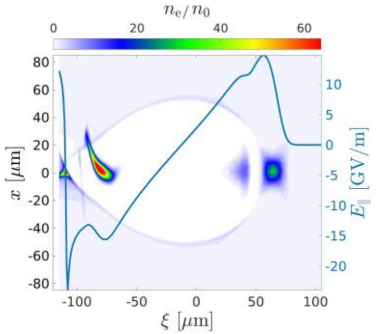




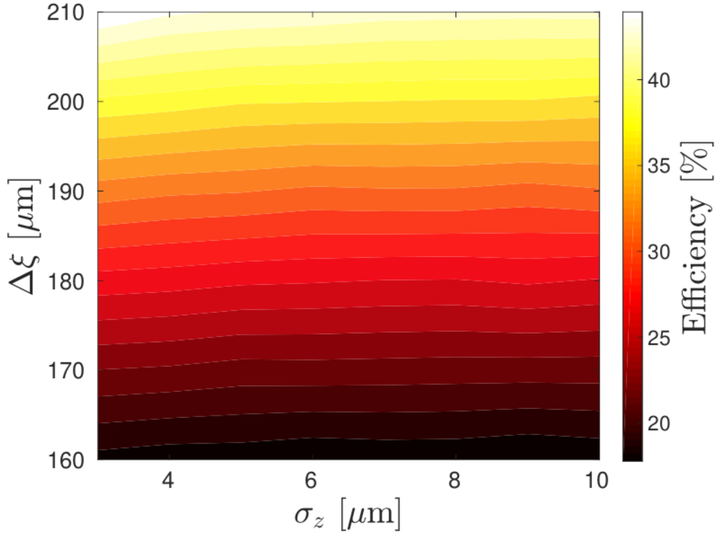
$2\sigma_z$ behind center

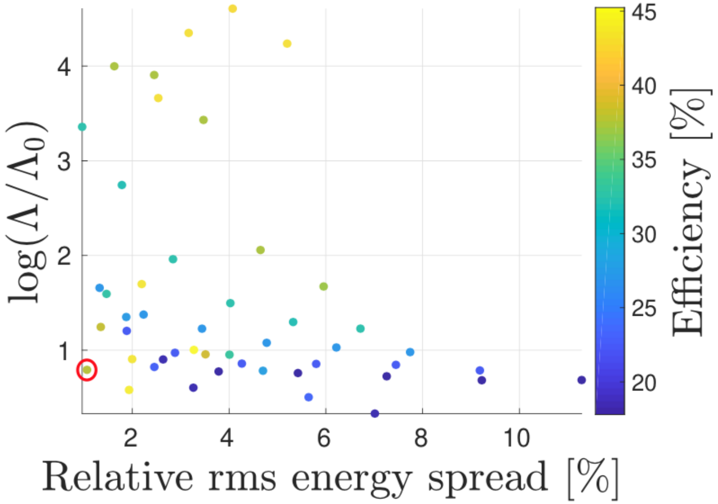
B. Chen, D. Schulte and E. Adli, B 2020 J. Phys.: Conf. Ser. 1596 012057

Optimizing taking instability-efficiency into account: bunch length, charge, damping



Performed by one timestep QuickPIC simulations (negligible computer time), plus tracking with simplified model. 1000s of working points can be in a matter of days.





Working point with acceptable instability and higher luminosity, with respect to Snowmass study.

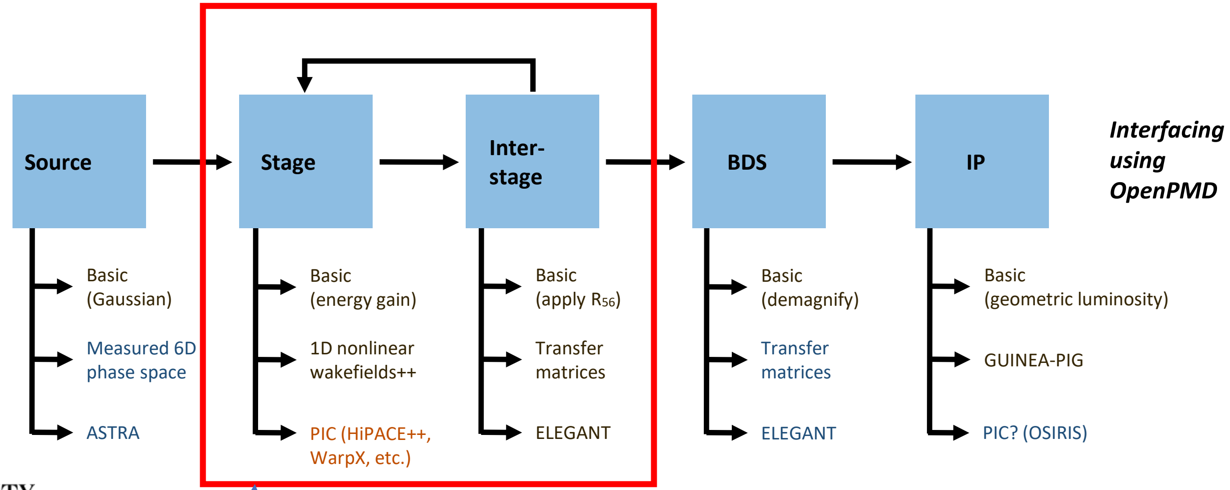
- Bunch length of 5.5 μm (Snowmass: 20 μm)
- Amplification of action of a factor 6 (Snowmass: very large)
- **Energy spread of 1.1%** (Snowmass: 12 %)
- Efficiency of about 37.5 (Snowmass: 50 %)
- **luminosity increase about 1.5**

$$\frac{1}{\sqrt{\sigma_z \sigma_y}}$$

Validity of lum. scaling?
Validity of model?

B. Chen, D. Schulte and E. Adli, B 2020 J. Phys.: Conf. Ser. 1596 012057

Next steps: integrate into our local Oslo framework



Interfacing using OpenPMD

Source → **Stage** → **Inter-stage** → **BDS** → **IP**

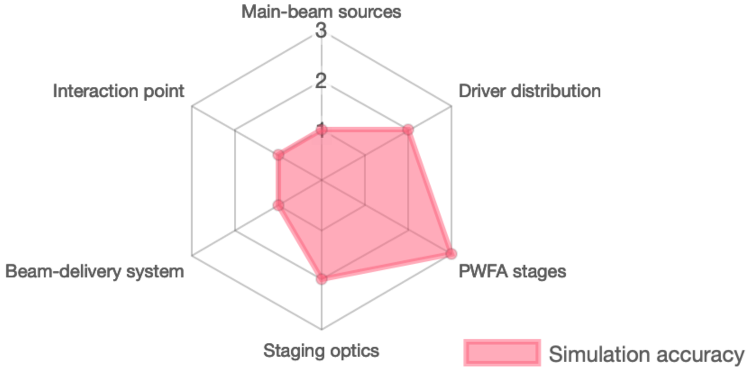
Source
- Basic (Gaussian)
- Measured 6D phase space
- ASTRA

Stage
- Basic (energy gain)
- 1D nonlinear wakefields++
- PIC (HiPACE++, WarpX, etc.)

Inter-stage
- Basic (apply R_{56})
- Transfer matrices
- ELEGANT

BDS
- Basic (demagnify)
- Transfer matrices
- ELEGANT

IP
- Basic (geometric luminosity)
- GUINEA-PIG
- PIC? (OSIRIS)



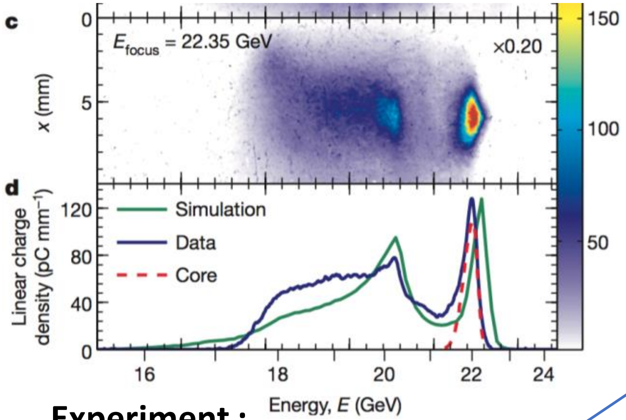
For the efficiency studies: levels of increasing model accuracy:
- No transverse instability modelled (negligible CPU time)
- Fixed amplitude change per cell (negligibe CPU time)
- Wake function + Sliced beam model, as in B. B. Chen et al (seconds)
- Quasi-static PIC code (minutes, hous +)

- Using the Oslo framework, we aim to fully answer the relevance/implications of the Fermilab instability-efficiency relation, for beam-driven e^- linacs. **And get realistic numbers for e- PWFA efficiency.**
- In additon, eventually, experimental verification is needed (work in collaboration with SLAC)

What to take into account for a pre-CDR

Slide from E. Adli, CLIC Novel Accelerator Methods (2017)

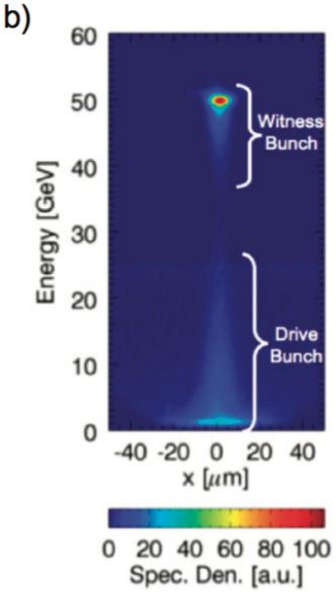
Although experimental progress is impressive, the technology may be far from its ultimate performance. What should a design study take into account when considering feasibility? **One example** from beam-driven two-bunch PWFA :



Experiment :
two-bunch acceleration, 30 wake to DB efficiency. M. Litos et al., Nature **515**, 92–95 (2014)

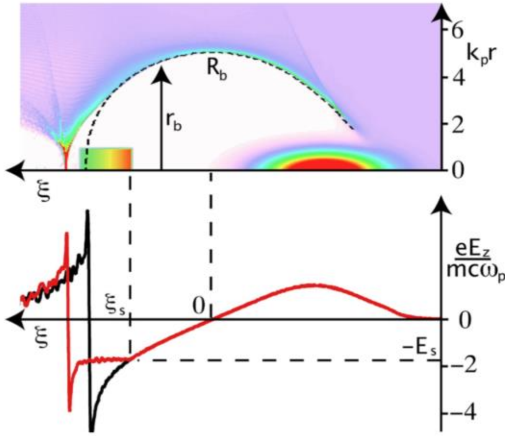
Simulation :

Two-bunch acceleration, almost full DB depletion**, 50% DB to MB efficiency single stage**, emittance preservation at um level, energy spread at %-level. M. Hogan et al., 2010 New J. Phys. **12** 055030 (2010).



Ultimate performance? :

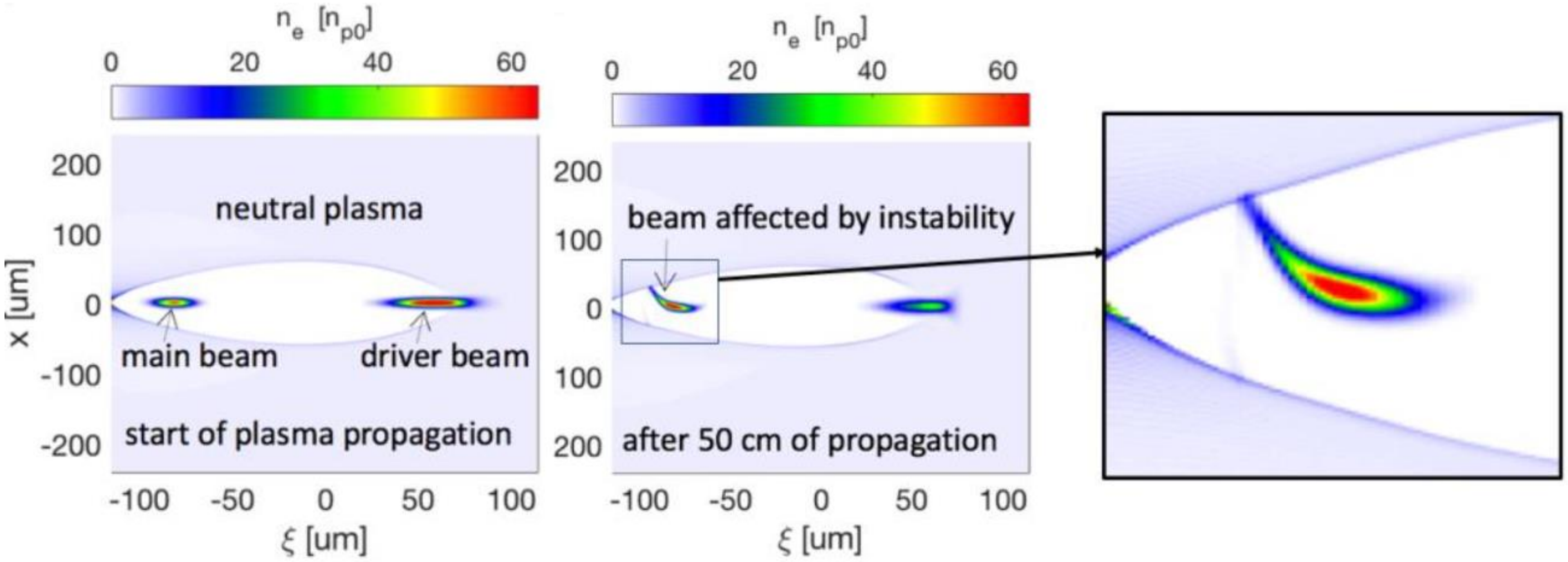
90% efficiency?



Oslo opinion, for the pre-CDR:

- We could and should base ourself on what is possible in simulation today, as long as the assumptions are consistent with technologically feasible plasma drivers and plasma targets.
- It will already hard enough to show a good performance
- The pre-CDR will suggest further technological developments

Experimental challenges – experiments are single stage



Also a challenge for CLIC/ILC :

- can we build CLIC/ILC relying on numerical models? Answer seems to be yes.
- a go ahead for building a plasma collider would likewise not only require experiment progress, but to develop and build up confidence in our simulations and models

Interaction PWFA-LC study and PWFA research

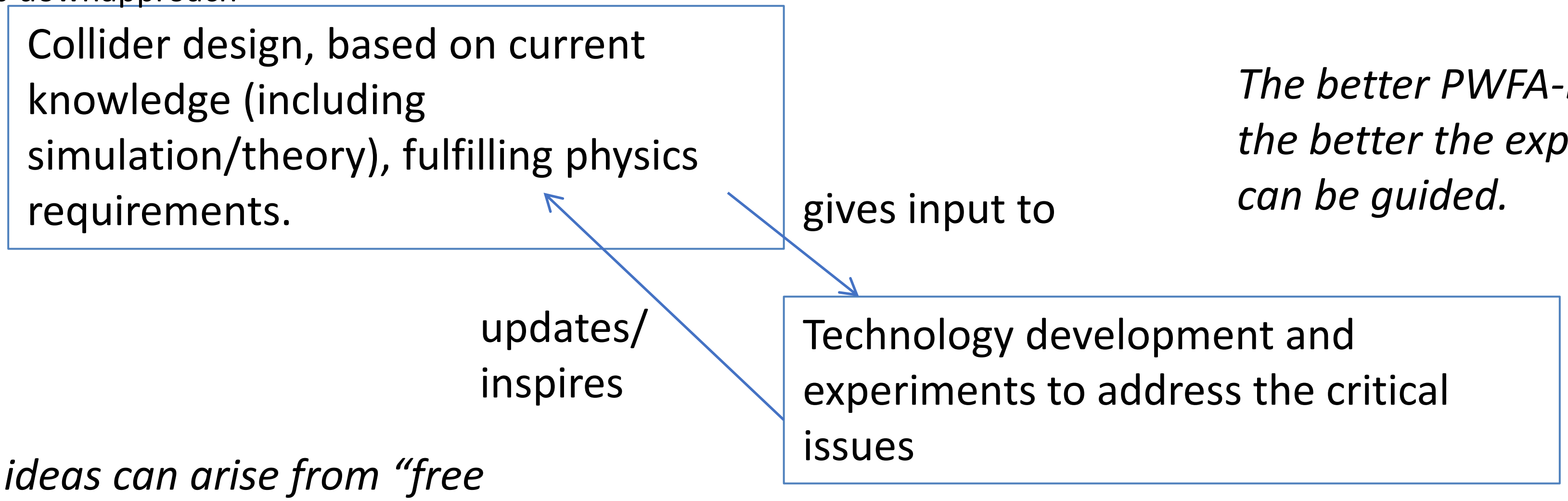
(S. Corde)

$$A = \frac{e^{+}\ \text{research}}{e^{-}\ \text{research}} \ll 1$$

(E. Adli)

$$B = \frac{\text{PWFA collider design}}{\text{PWFA experiments}} \ll 1$$

"Top downapproach" This part is underrepresented in the NAT community.



Collider design, based on current knowledge (including simulation/theory), fulfilling physics requirements.

gives input to

Technology development and experiments to address the critical issues

updates/
inspires

The better PWFA-LC concept exists, the better the experimental studies can be guided.

New ideas can arise from “free experimentation”, and inspire new PWFA-LC concepts

Development not necessary driven by linear collider requirements
"Bottom up approach" – see what comes out of technology

Slide from E. Adli, CLIC Novel Accelerator Methods (2017)

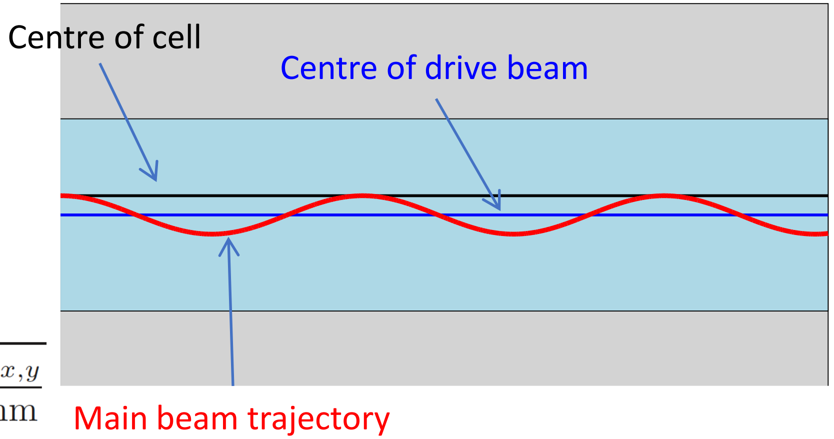
Extra

Transverse tolerances

Independent of instabilities, the very strong focusing of the plasma leads to tight tolerances.

Drive beam center defines center of the focusing

Strong focusing fields gives offset witness beam a kick



$$\sigma_{x,y} \approx 41\,\mathrm{nm}\left(\frac{10^{16}\,\mathrm{cm}^{-3}}{n_0}\frac{\mathrm{GeV}}{E}\right)^{\frac{1}{4}}\sqrt{\frac{\epsilon_{x,y}}{\mathrm{nm}}}$$

Example PWFA:

- ⇒ 2% luminosity loss budget leads to **required jitter stability of 1.4 nm**
- ⇒ Could use phase advance of 2nπ
- ⇒ Or much larger beta-function (lower plasma density) at ends of cells

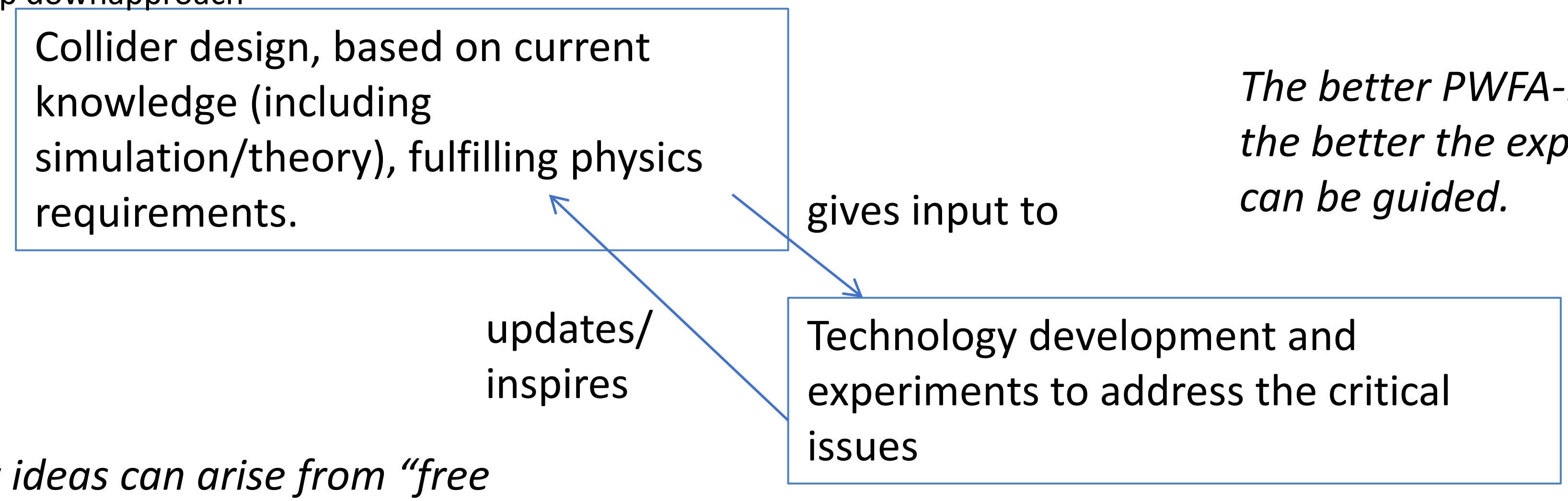
Important to understand tolerances correctly

R&D programme essential on transverse alignment and stabilisation

From CLIC WG on Novel Accelerator Technologies,
D. Schulte (CERN), 2018, *https://indico.cern.ch/event/607729/*

Ideal interaction PWFA-LC study and PWFA research

$$A = \frac{e^+ \text{ research}}{e^- \text{ research}} \ll 1 \quad B = \frac{\text{PWFA collider design}}{\text{PWFA experiments}} \ll 1$$



"Top downapproach"

This part is underrepresented in the NAT community.

Collider design, based on current knowledge (including simulation/theory), fulfilling physics requirements.

gives input to

The better PWFA-LC concept exists, the better the experimental studies can be guided.

updates/
inspires

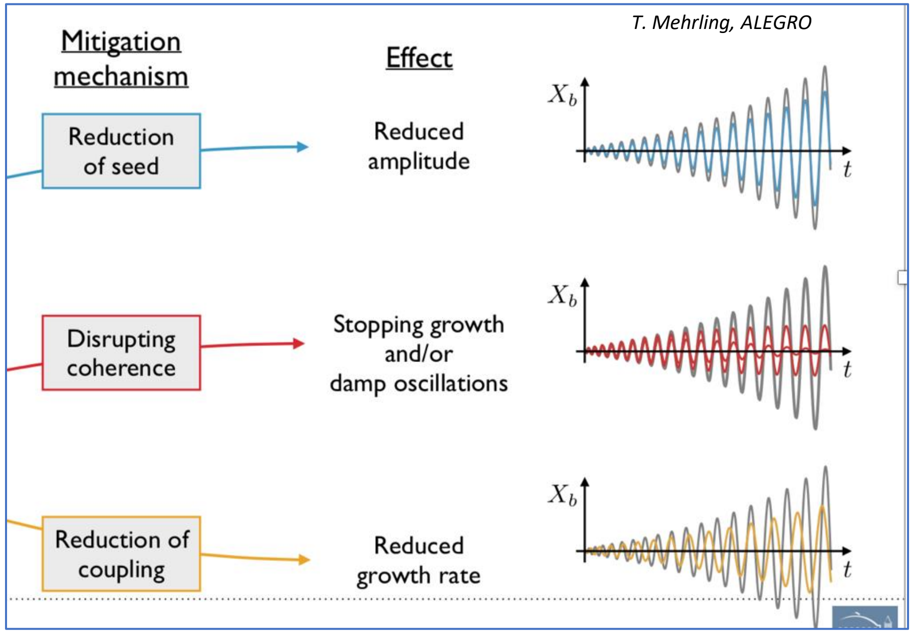
Technology development and experiments to address the critical issues

New ideas can arise from “free experimentation”, and inspire new PWFA-LC concepts

Development not necessary driven by linear collider requirements
"Bottom up approach" – see what comes out of technology

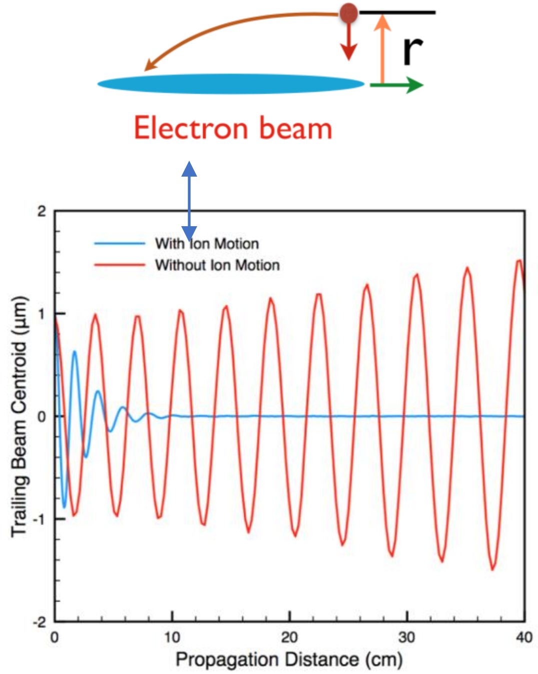
Instabilities, mitigation

Relativist regime
C. Huang et al. PRL
99, 255001 (2007) (UCLA)
(but this mitigation already included in wake model on previous page?)


T. Mehrling, ALEGRO

Mitigation mechanism	Effect
Reduction of seed	Reduced amplitude
Disrupting coherence	Stopping growth and/or damp oscillations
Reduction of coupling	Reduced growth rate

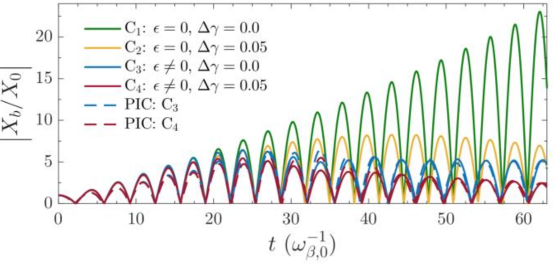
Ion motion: surprising and interesting results from Weiming An



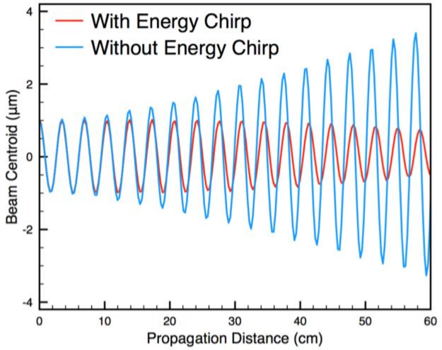
Strong focusing:
Feature of the blow out regime.

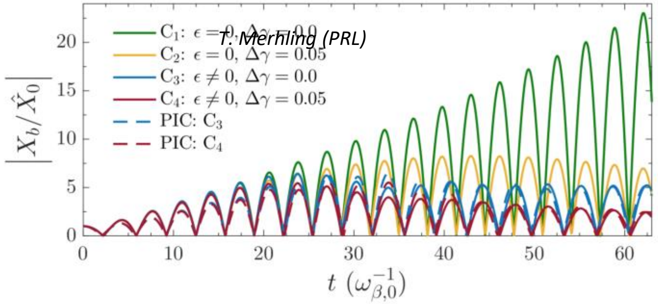
Energy gain and energy spread

Mitigation of seed :
depending on length of ramp : expect factors of few reduction in amplitude.
Growth rate still the same.

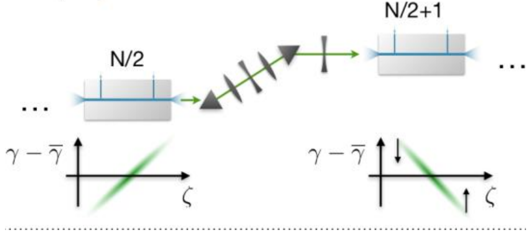


W. An (FACET-II parameters, 10% energy spread)




T. Merhling (PRL)

Clever ideas for high energy spread:



T. Mehrling
C.A. Lindstrøm
- can they be realized in practice in a short, emittance preserving interstage?

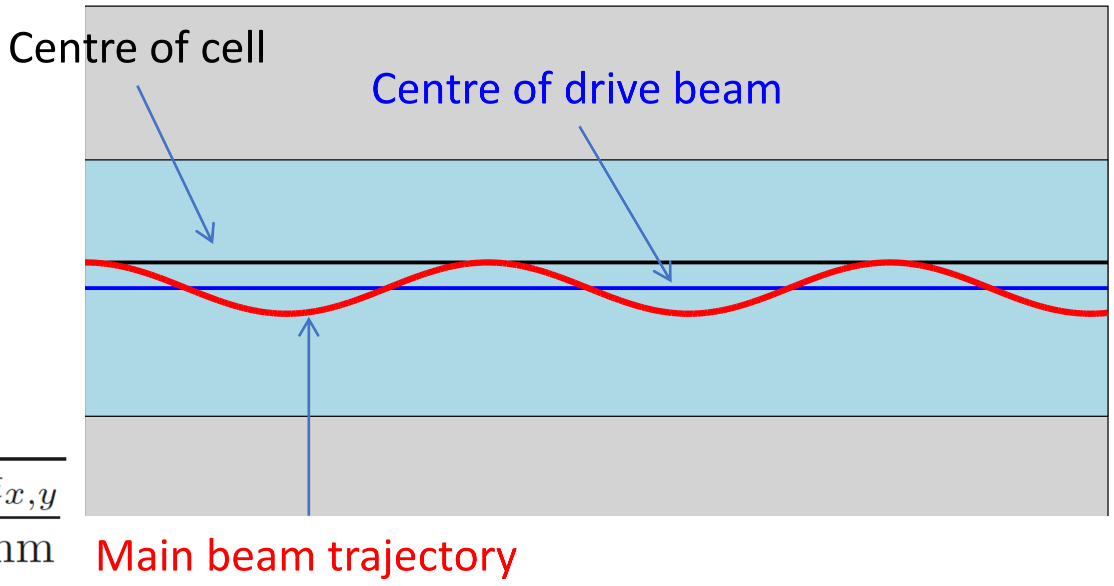
Ideas for mitigation exists.
Lacking: systematic studies of emittance growth through many stages, to verify that suppression is sufficient.

Transverse Tolerance

Adapted from D. Schulte, https://indico.cern.ch/event/607729/

Drive beam center defines center of the focusing

Strong focusing fields gives offset witness beam a kick



$$\sigma_{x,y} \approx 41\,\mathrm{nm}\left(\frac{10^{16}\,\mathrm{cm}^{-3}}{n_0}\frac{\mathrm{GeV}}{E}\right)^{\frac{1}{4}}\sqrt{\frac{\epsilon_{x,y}}{\mathrm{nm}}}$$

Example PWFA:

- $\Rightarrow$ 2% luminosity loss budget leads to **required jitter stability of 1.4 nm**
- $\Rightarrow$ Could use phase advance of 2nπ
- $\Rightarrow$ Or much larger beta-function (lower plasma density) at ends of cells

Important to understand tolerances correctly

R&D programme essential on transverse alignment and stabilisation