Townhall Meeting High Gradient Acceleration Plasma/Laser:

Collider Concepts with Plasma

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Town Hall meeting
The Land of Zoom, March 30, 2021

Scope of talk

- Linear collider projects, ILC and CLIC, **covered by Andrea**
- Linear collider parameters and requirements**, covered by Daniel**
- Progress and plans for PLC technologies, **covered by Jens and Carl**
- This talk:
  - earlier efforts done on how to meet collider requirements with plasma technology (biased towards PWFA)
  - possible future steps towards a Plasma Linear Collider (**PLC**), in terms of design

Very high gradients of plasma accelerators are **well established by now**, focus on the **the luminosity challenge**

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 :

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

Taking into account beam strahlung :

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

$\sigma_y^2 = \beta_y \varepsilon_y$

Possibilities for improvement for a PLC?

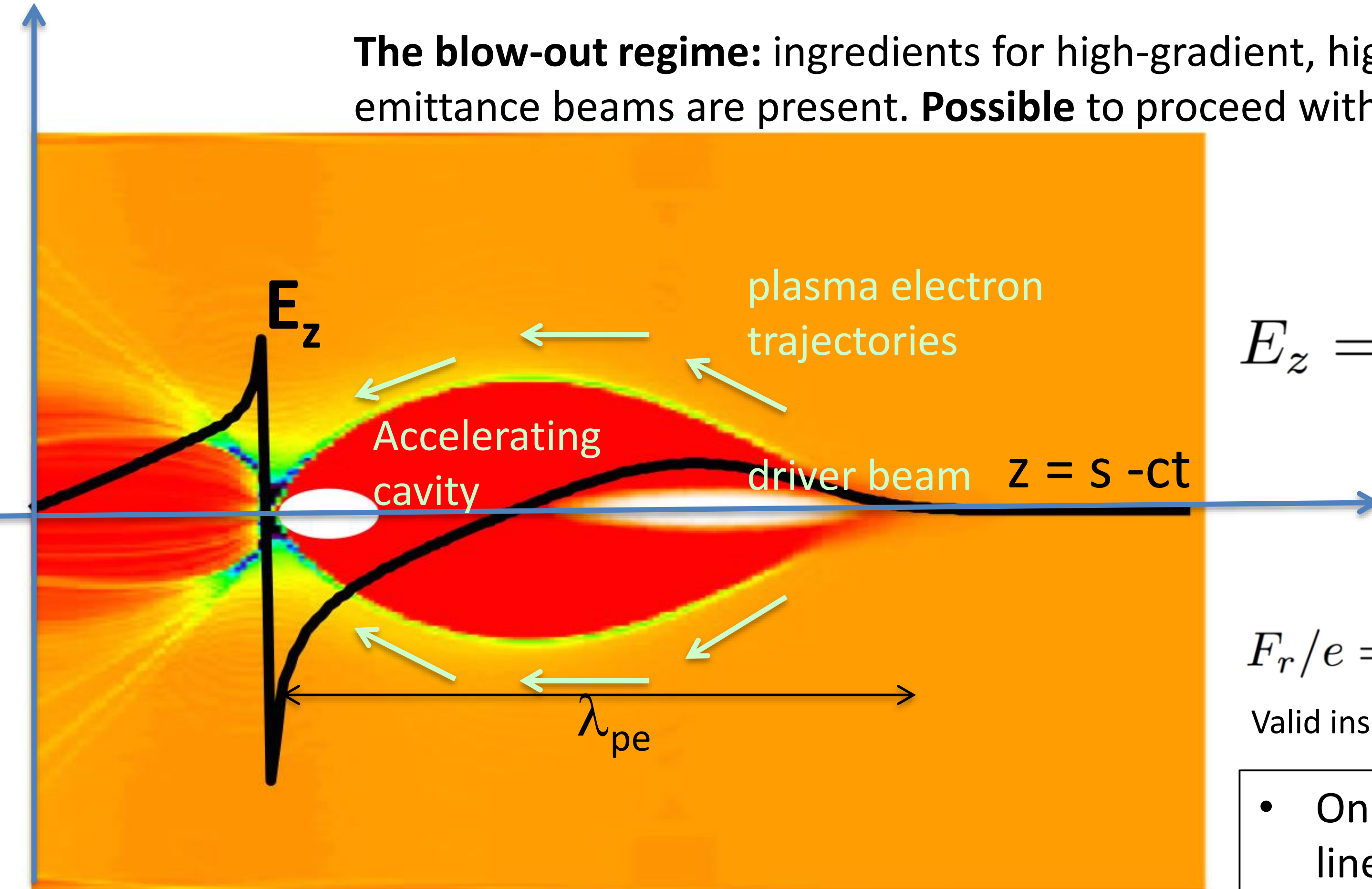
- **footprint (cost)**
- vertical emittance?
- **vertical focusing function?**
- **wall-plug-to-beam efficiency?**
- **Shorter bunches?**

Keep luminosity/power target

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

PWFA status: electron acceleration

The blow-out regime: ingredients for high-gradient, high-efficiency, low emittance beams are present. **Possible** to proceed with design.



$$E_z = \frac{1}{c\epsilon_0}\int_r^\infty dr j_r$$

$$F_r/e = E_r - cB_\phi = \frac{en_0}{2\varepsilon_0}r$$

Valid inside a fully blown-out bubble.

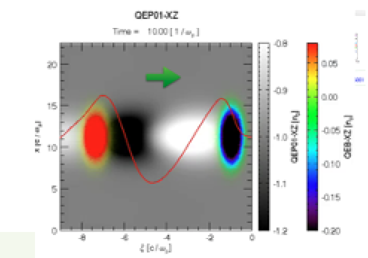
$$\frac{\partial}{\partial r}F_z = 0 \qquad \frac{\partial}{\partial r}F_r = const.$$

$$\frac{\partial}{\partial z}F_z = 0$$ (loaded) $$\frac{\partial}{\partial z}F_r = 0$$

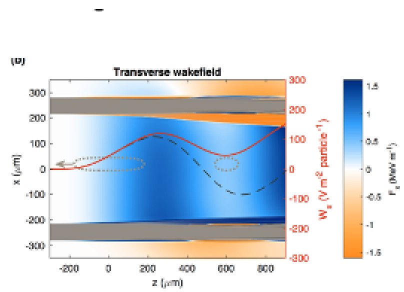
- On paper/simulation, linear collider requirements could possibly be met, for an ideal machine, ideal plasma stage.
- Some open questions on ion motion, ramps

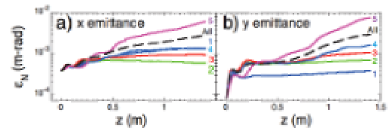
PWFA status: positron acceleration

Progress ...

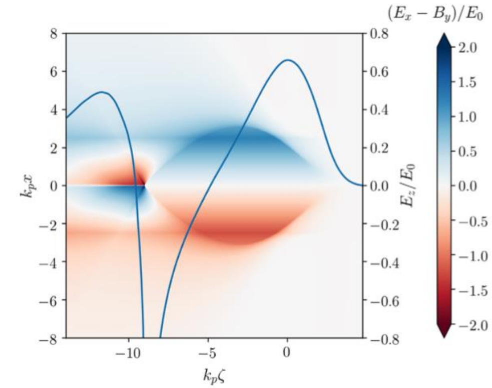


Weiming An | ALEGRO Positron Acceleration in Plasma Mini-Workshop, CERN | February 9 2018





P. Muggli *et al.*, Phys. Rev. Lett 101, 055001 (2008)



S. Diederichs et al., PR AB 22, 081301 (2019)

Quasi-linear plasma wakefield

How to accelerate low emittance beams with high efficiency?

Multi-pulse, energy recovery.

Hollow plasma channels

How to mitigate transverse instabilities?

Position trailing bunch at zero-crossing of transverse wakefield, look for damping mechanisms, flat channels.

Nonlinear plasma wakefield

How to preserve emittance?

Doughnut-shaped wakes, weird trailing bunch shaping, single-stage accelerator, betatron cooling.

Finite radius plasma

New concept,
showing promise for emittance preservation with strong loading.

...but currently, we do not have concepts for positron PWFA with comparable efficiency and beam quality electron PWFA.

How to deal with positrons in PLC design?

- Performance of e+ acceleration in simulations worse than for e- in terms (efficiency, beam quality). Also, not clear which regime is the most promising

- However, unequal e- and e+ bunch charges may still provide interesting luminosity/power

TABLE III. Parameter comparison at 3 TeV collision energy.

Parameter	Unit	$N_{e^+} = N_{e^-}$	$N_{e^+} = 0.5N_{e^-}$	$N_{e^+} = 0.1N_{e^-}$	CLIC
N	10^9	5/5	2.5/5	0.5/5	3.72/3.72
$P_b/(f_r n_b)$	kWs	1.2/1.2	0.60/1.2	0.12/1.2	0.89/0.89
$\mathscr{E}_b$	TeV	1.5	1.5	1.5	1.5
$\mathcal{L}$	$10^{35}\,\mathrm{m}^{-2}\,\mathrm{bx}^{-1}$	1.69	0.69	0.10	0.38
$\mathcal{L}_{0.01}$	$10^{35}\,\mathrm{m}^{-2}\,\mathrm{bx}^{-1}$	0.57	0.30	0.06	0.13

Adapted from https://arxiv.org/pdf/2009.13672.pdf (Chen, Schulte, Adli 2020)

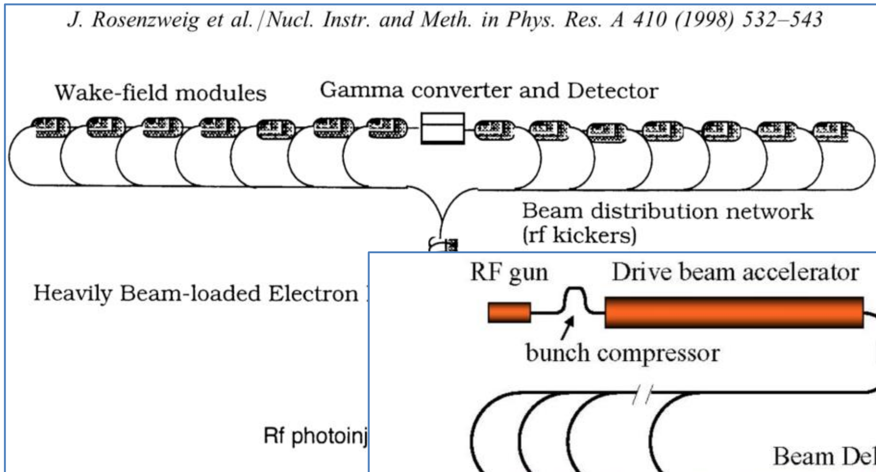
- Studies of the **collider optimisation for unequal bunch charges**: more realistic e- e+ design ?
SNOWMASS21-AF1_AF4-161.pdf

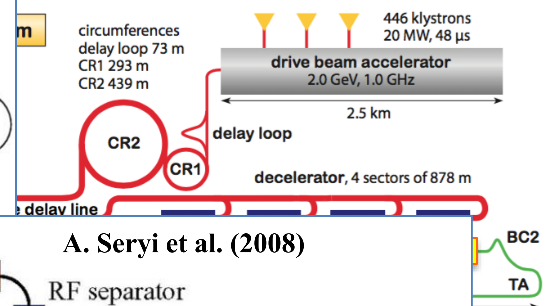
- To advance a collider design using detailed models of positron stages is hard as of know. One possibility to proceed: **assume** an acceleration mechanism similar to that of e- (done in 2009, 2013 concepts). Or, assume similar mechanism with unequal e- and e+ bunch charges (could also originating from unequal efficiency in e- and e+ acceleration).

- Alternatively: focus on **Multi-TeV γγ-collider design** (requires only e- linacs)

PWFA: collider concepts

Linac : linac, the longest and most costly component





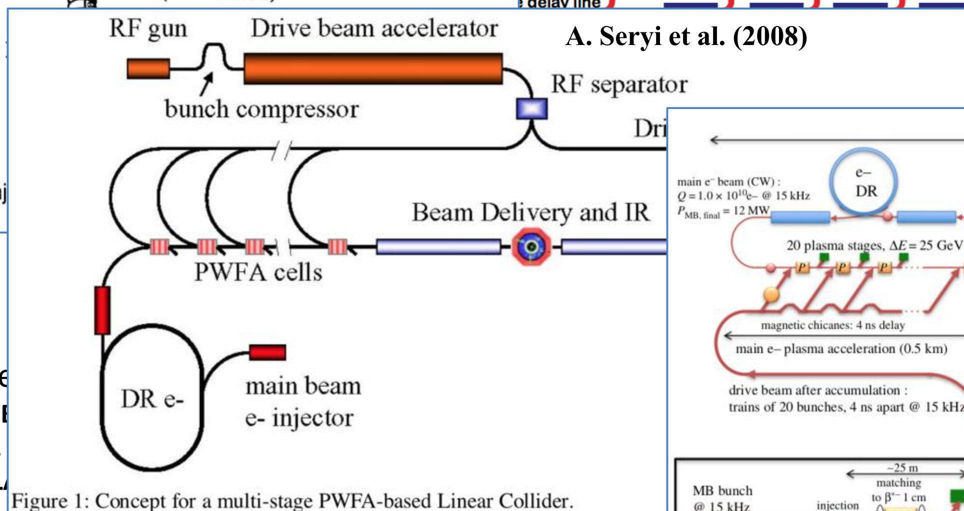
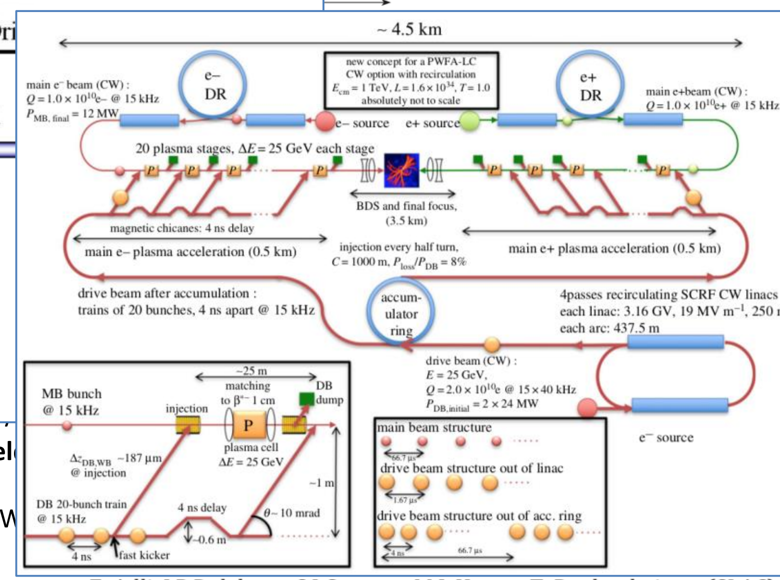


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.



E. Adli, J.P.Delahaye, S.J.Gessner, M.J. Hogan, T. Raubenheimer (SLAC)
W.An, C. Joshi, W.Mori (UCLA) 2013

Some

- **J. E**
- **A.**
  SL
- C.
- **E. Adli, J.P. Delahaye et al., A beam driven plasma-wakefiel**
  PUB-15426
- W. Gai et al., CONSIDERATIONS FOR A DIELECTRIC-BASED TW
- ...

Note: these concepts are far from being machine self-consistent **designs** (put together with very limited funding)

Parameter choices for the 2013 concept

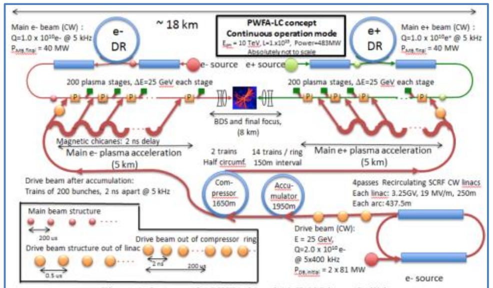


Figure 1: Layout of a PWFA-based 10 TeV Linear Collider

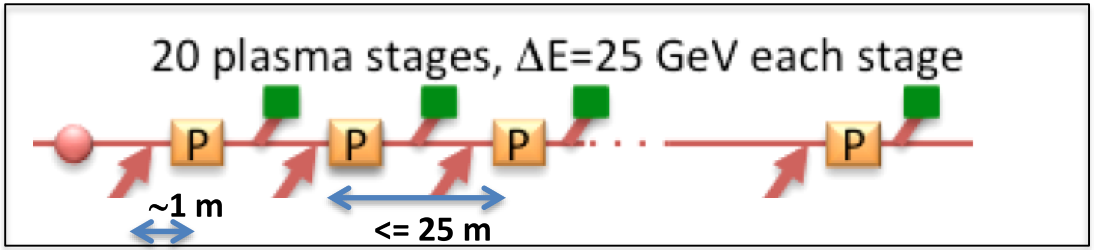
The main beam parameters for the 2013 PLC concept are **assumed to be the ILC main beam parameters**, with some modifications (allows reuse of earlier LC studies):

- Bunch length shortened to fit in plasma
- Charge of 1e10 particles per bunch (1/2 the ILC nominal bunch charge)
- Equal bunch spacing (“CW” collisions)

Other **input** to this concept:

- **1 GeV/m** average gradient along main linac (“CLIC x 10”) with 25 GeV energy gain per plasma stage, **assuming 25 m average stage length**
- High power efficiency
- Minimize plasma density (reduce instabilities, scattering, betatron radiation...)
- Parameter optimization assumes e- drive bunch and e- witness bunch in the **blow out regime, and no ion motion**

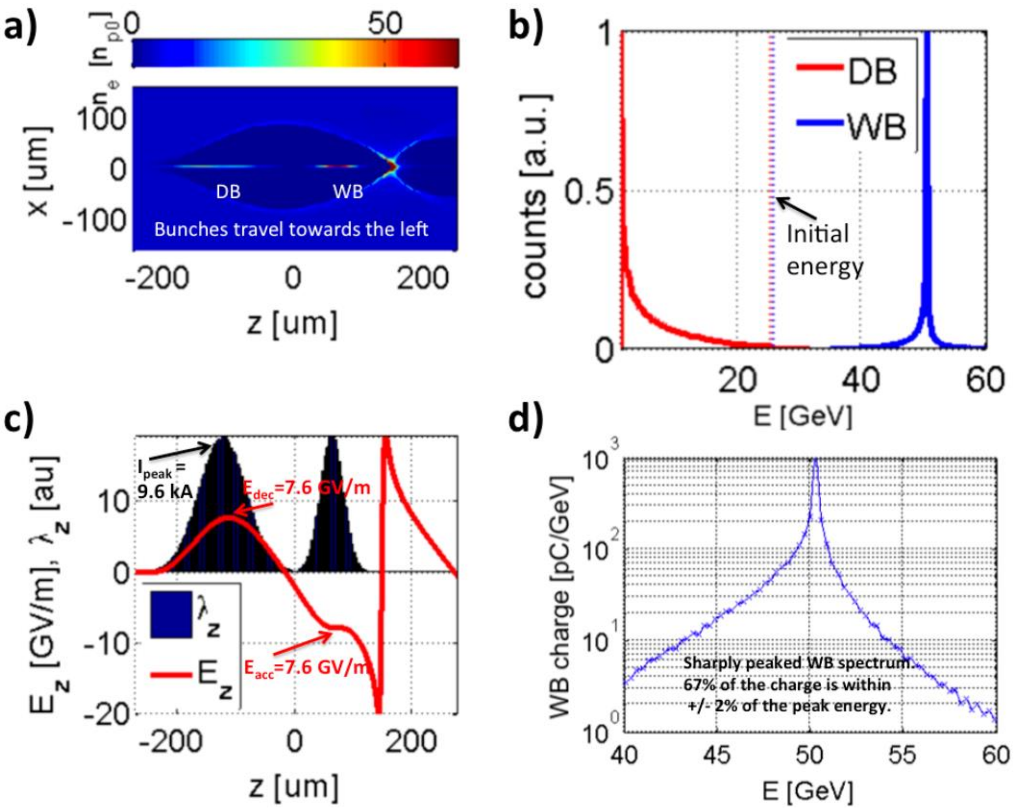
For 1 TeV :

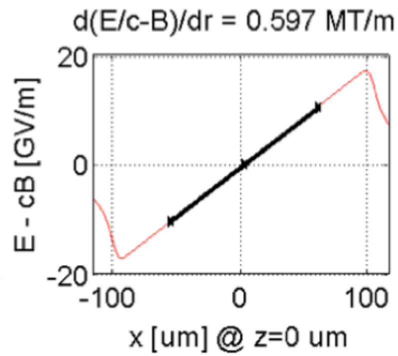


Drive beam parameters : results of plasma optimization process.

Plasma stage optimization

Input constraints: main beam parameters; $Q_{WB}=1\mathrm{x}10^{10}$e, $\Delta\varepsilon$=25 GeV/stage, L_{cell} < few m, keep WB energy spread low, reasonable WB length
Design choice: plasma density $\mathbf{n_0}$, transformer ratio **T**
Drive beams then set : Q_{DB} (charge), $\varepsilon_{0,DB}$ (energy) , Δz_{DW} (DB-WB separation), $\sigma_{z,DB}$, $\sigma_{z,WB}$





With main beam parameters given, plasma density and transformer ratio chosen, the drive bunch parameters are **given** by Q_{DB} x E_{acc} = const., plus the requirement of equal peak current in the drive and witness bunch.

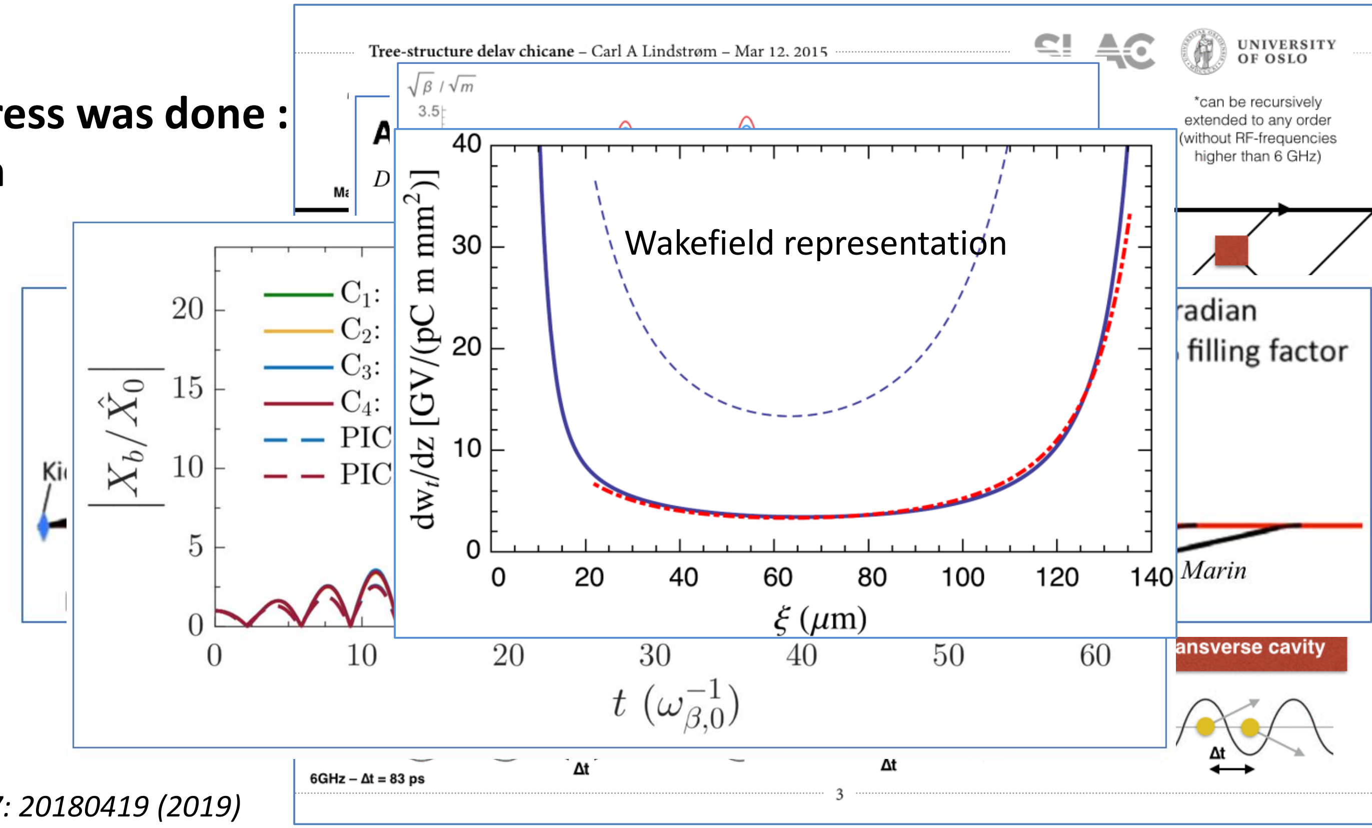
Simulations were performed using QuickPIC (UCLA)
Round beams, normalized emittances of 2 um.

Main point:
several parameters set to reasonable values, not as part of a global optimizatino

The 2013 Snowmass paper was **scrutinized** by the conventional accelerator community (Fermilab, CLIC, ILC), which led to a number of constructive comments, stimulating further work and **progress in a number of areas,** though with limited manpower and little dedicated funding.

A few topics where progress was done :

- drive beam distribution
- drive beam generation
- staging
- plasma lenses
- transverse instabilities
- transverse tolerances



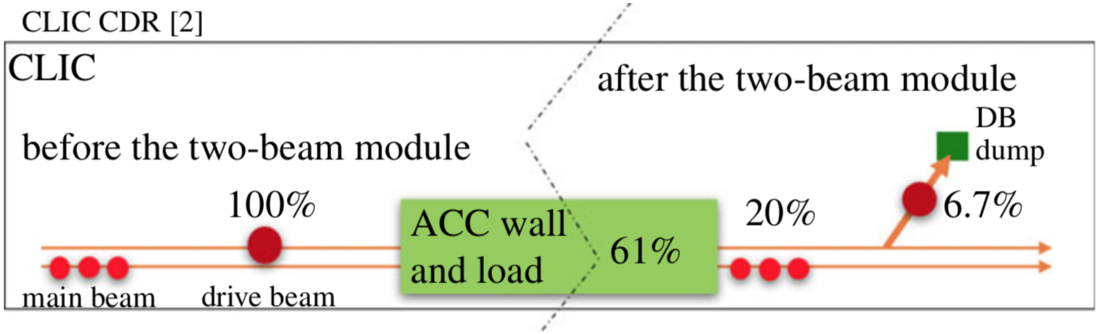
Summarized in
E. Adli, Phil. Trans. R. Soc. A 377: 20180419 (2019)

C.A. Lindstrøm and the SLAC PWFA working group (unpublished)

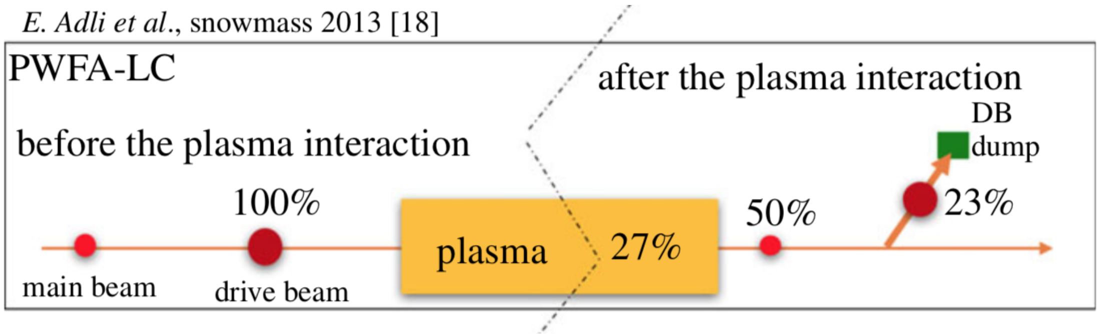
However, no effort made to integrate new results into an overall design -> no global PLC parameters available. Currently no project or lab that is the “keeper of the parameters”.

Opportunity for plasma colliders: efficiency?

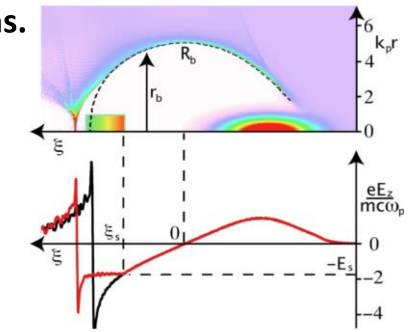
CLIC CDR [2]



E. Adli et al., snowmass 2013 [18]



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



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

Possibly increased by shaping the DB

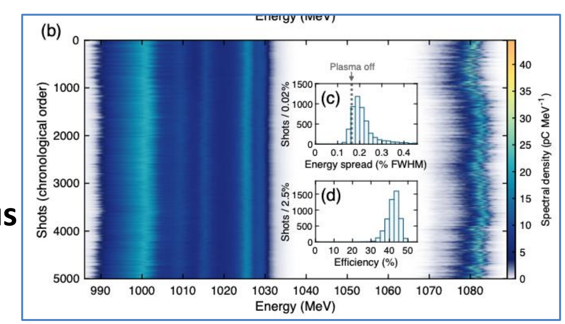
Possibly increased by shaping the MB

Could PWFA even **beat** RF colliders on efficiency?

Improved **efficiency** should reduce operation cost

Related challenge: **instability suppression**

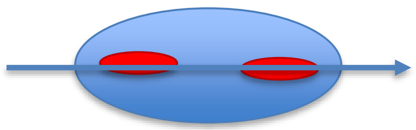
Experimental status (FlashForward): Wake to MB > 40% (simultaneous with 1.3 GV/m, per-mille energy spreads and full charge coupling for 100 pC).

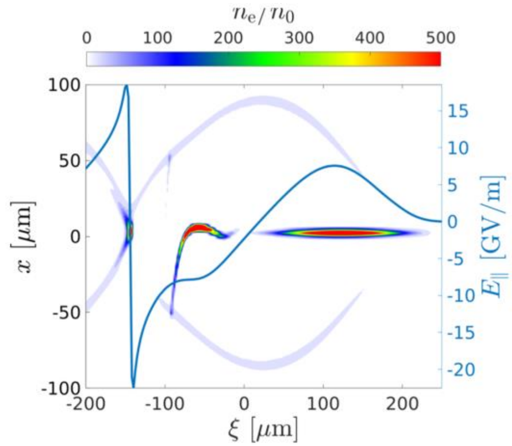


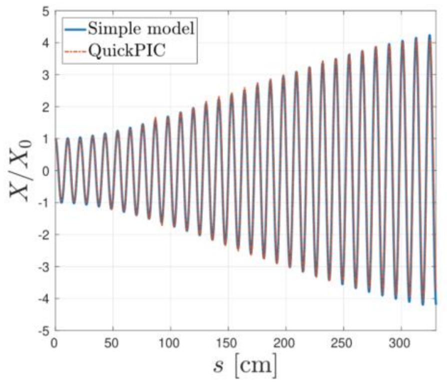
C. A. Lindstrøm et al., PRL 126, 014801 (2021)

Transverse instabilities: RF colliders vs plasma colliders

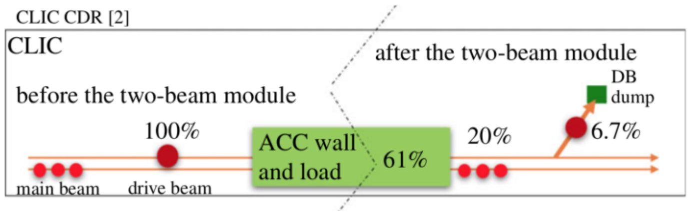
Witness beam intra-beam wake :







The single-bunch wake decides how much charge can be loaded into CLIC. >

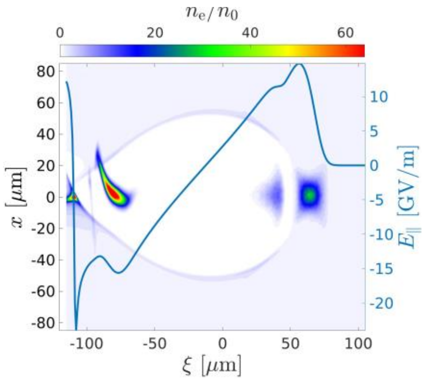


CLIC:
Limit for transverse single bunch wake: **100 kV/pC/m/m**
Goal attained by spreading pulse charge into multi-bunch trains. **Limits** the CLIC RF-to-beam efficiency to ~25%.

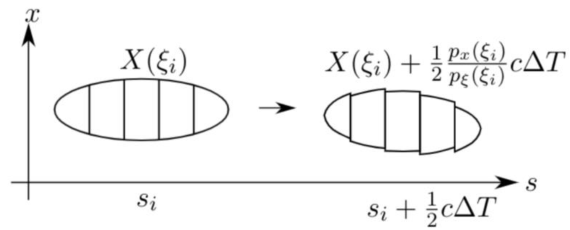
Current plasma collider concepts: **single bunch acceleration**
- may also lose on efficiency if charge needs to be reduced

Questions for PWFA:
- can one achieve sufficient mitigation of the instability for efficient single bunch acceleration?

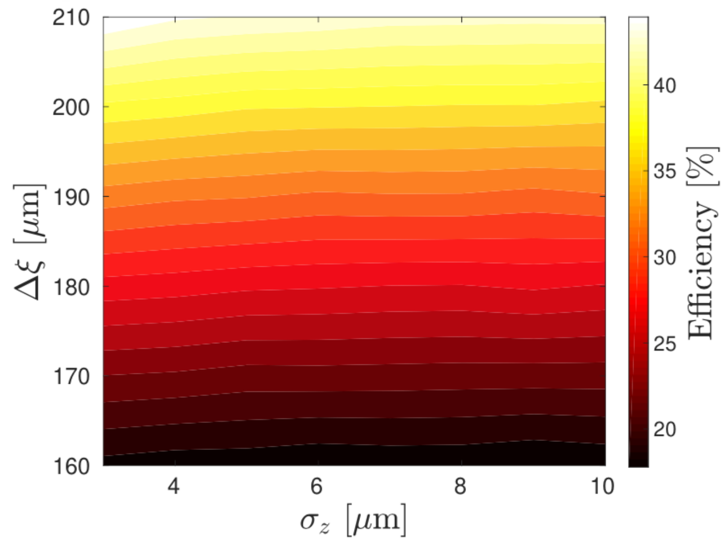
Simplified models (as opposed to PIC) allows **parameter scans**

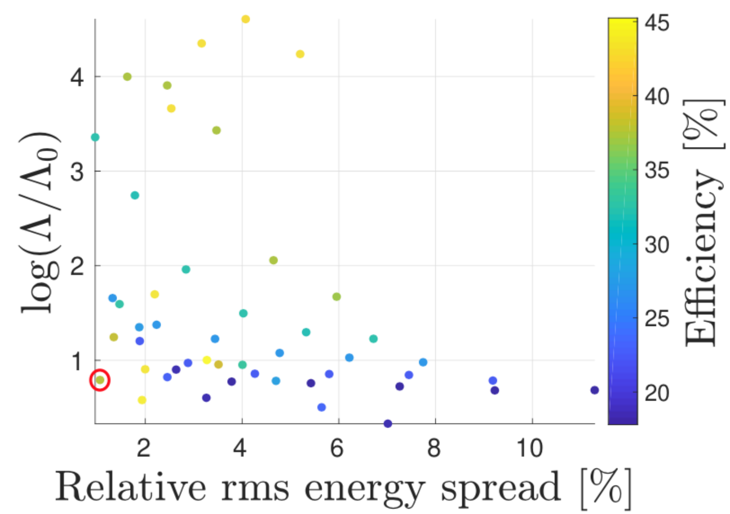


$$W_\perp(\xi'-\xi,\alpha) = \frac{2}{\pi\varepsilon_0} \frac{\xi'-\xi}{\left(r_b(\xi')+\alpha k_p^{-1}\right)^4} \Theta(\xi'-\xi)$$



Performed by one timestep QuickPIC simulations + 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 2013

- 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?

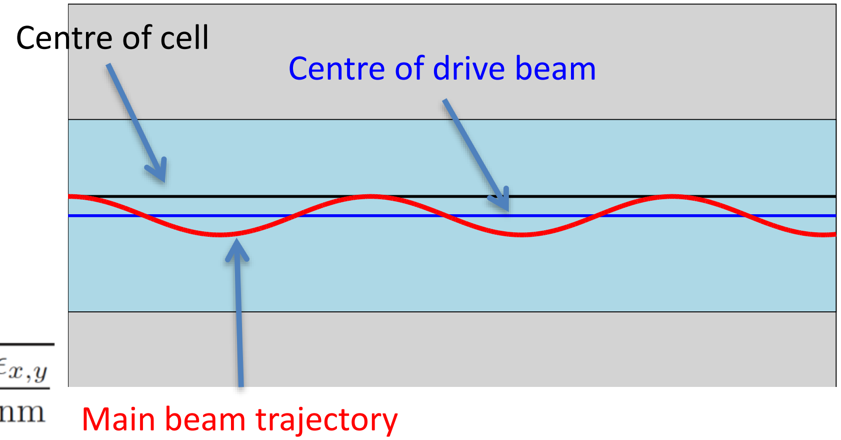
B. Chen, D. Schulte and E. Adli, J. Phys. Conf. Ser., vol. 1596 (2020)
Ben Chen, PhD thesis, U. Oslo (2021)

Transverse tolerances – not only about instabilities

Independent of instabilities, the 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

PLC tolerances must be quantified. Depend on: plasma density, ramping, charge .. (shows again the need for an integrated design)

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

Need for PLC parameters

What should the main PLC parameters be?

- few um or few 100 um bunch length?
- kHz or MHz rep. rate?
- transformer ratio? energy gain per stage?
- Plasmas densities
- few nm alignment tolerances or 100s of nm?

If not known:

- How to established what parameters should demonstrate? How to give time lines for key demonstration facilities (or for a PLC?
- How to compare PLC and RF LC on paper? How can a PLC be considered by a strategy process, if parameters for comparison do not exist?

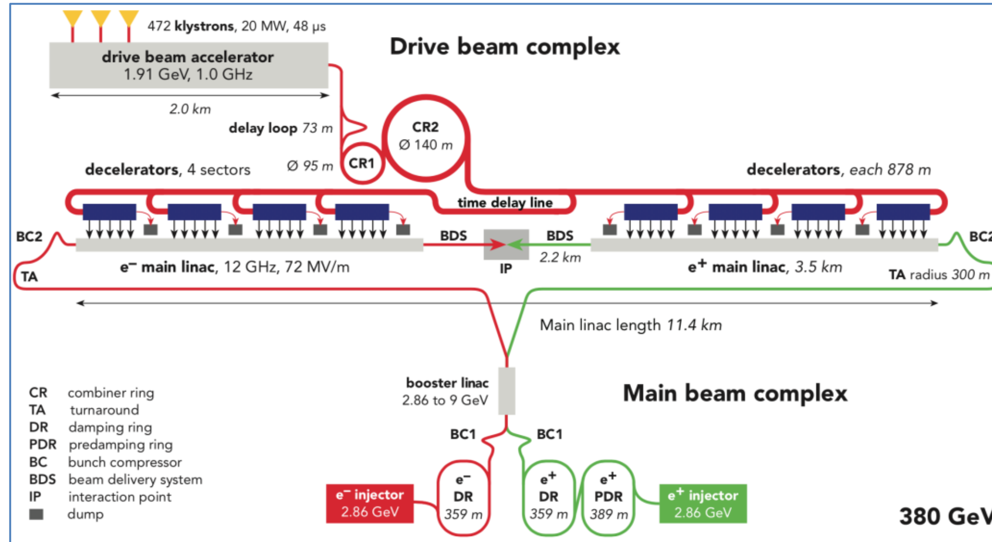
- Therefore, a global integrated design efforts seems important. Snowmass input : SNOWMASS21
- **Resources needed?** CLIC/μcol ~100s of man-years of machine design (could get far by 10s)
- Possble obstacles for getting funding :
  - funding schemes: experiments is ”sexy”, design is not ?
    - possible solution: design kept, driven and partially funded by lab/major project?
  - the positron problem ?
    - for **e-** we do not need to wait for more experimental results to advance design
    - for **e+**: assume a certain performance? Focus on design for γγ?

Other topics that could/should be advances by “paper studies”

- Drive beam generation, distribution and synchronization, including longitudinal tolerances
- Interstaging design (solution could/should be found on paper before defining appropriate experiments)
- Stabilization requirements at IP
- Polarization preservation in plasmas
  - polarization not strictly necessary for collider
- Background from plasma linac
- Heat transfer (20+% of beam power dumped in plasma)
  - high-rep rate experiments important input
- Betatron radiation in plasma (large impact at 10+ TeVs)
- e- emittance preservation with ion motion and high beam loading
- Methods for optimizing main PLC parameters (rep rate, plasma density, transformer ratio)
- For $\gamma\gamma$: studies of round beam, $\gamma\gamma$–IP and physics studies
- For positrons: continue search and quantification of acceleration regimes

Examplle: CLIC cycle:

- design
- feasibility issues
- test facilities



The CLIC Test Facility: designed to demonstrate the CLIC two-beam acceleration scheme and drive beam generation (12 GHz 28 A pulse)

CLIC Feasibility Issues

System	Item	Parameter Issue	Test facility Common with ILC
Two Beam Acceleration	Drive beam generation	100 A peak current / 590 μC total charge 12 GHz bunch repetition freq. & 1 mm bunch length 0.2 degrees phase stability at 12 GHz (0.1 psec) 7.5 10^{-4} intensity stability	CTF3 CTF3/TBL Simulations X-FEL, LCLS
	Beam Driven RF power generation	90% conversion efficiency from drive beam to RF Large drive beam momentum RF pulse shape accuracy < 0.1%	CTF3/TBL Simulatio n s
	Two beam module	Two Beam Acceleration at nominal paramete r s	CTF2&3/TBTS
RF Structures	Accelerating Structures (CAS)	100 MV/m 240 RF pulse length with flat top 160ns breakdown probability/pulse < 3·10-7 /m	CTF2&3 SLAC/NLCTA&NASTA KEK/NEXTE F
	Power Production Structures (PETS)	132 MW total flat-top pulse length 240/160 ns breakdown probability/pulse < 1·10-7 /m On/Off/adjust capability	CTF3 CTF3/TBTS & TBL SLAC/ASTA
Ultra low beam emittance & sizes	Emittance preservation	during generation, acceleration and focusing: Emittances (nm): H= 600, V=5 Absolute blow-up (nm): H=160, V=1 5	ATF, SLS, NSLSII Simulations LCLS, SCSS
	Alignment and stabilisation	Main Linac : 1 nm vert. above 1 Hz BDS: 0.3 nm beam-beam offset	CESRTA A T F 2
Detector	Short interval between bunches	Time stamping: 0.5 nsec bunch interval	Simulatio n s
	Background at high beam collision energy	Beam-Beam background: 3.8 10^{8} coherent/1e5 incoherent e+/e- pairs, Hadrons, High muon flu x	Simulations
Operation and Machine Protection System (MPS)		drive beam power of 72 MW @ 2.4 GeV main beam power of 13 MW @ 1.5 TeV MTBF, MTTR	CTF3 Simulatio n s

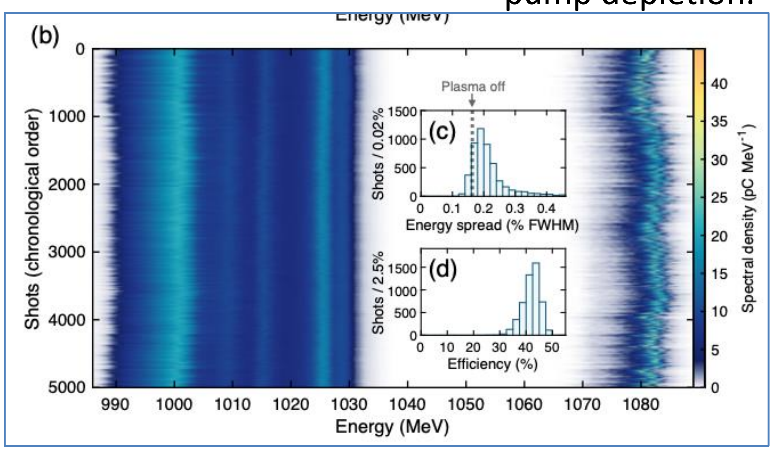
Conclusion

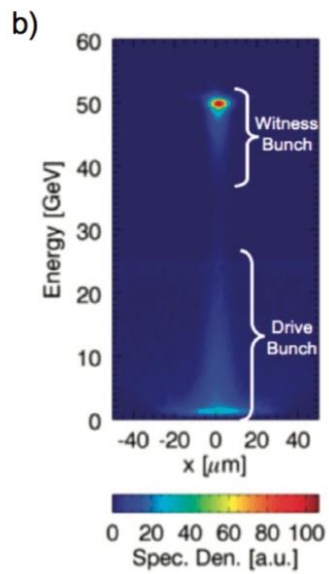
To move towards PLC: a collider parameter “paper” study (not necessary at a CDR level), leading to a consistent global parameters set, and key performance metrics

- needed to understand the promise of a plasma collider, and key parameters
- needed to guide future feasibility demonstrations
- Main input to paper study : performance can be based on theory/simulation, rather than present (non-ideal) experiments. Represents a “a best case”.

Example (FlashFoward)

Experiment :
Few MeV energy gain, far from pump depletion.





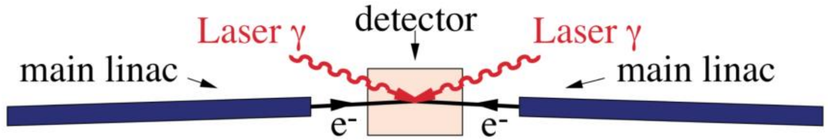
Simulation :
Energy doubling at 25 GV/m and pump depletion

(see also efficiency example)

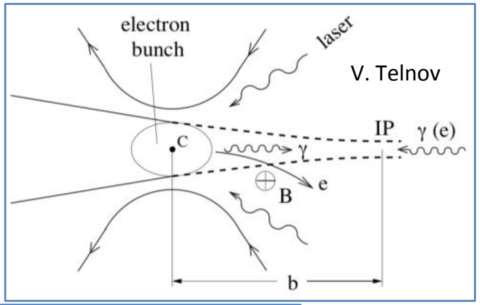
Resources for design: a significant number of man-years. Still **small** compared to cost of on-going and proposed experiments and facilities. Some technology choices should be made.

Extra

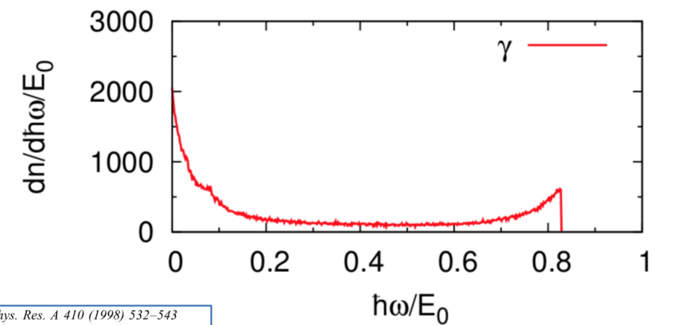
Possible **alternative** to e- e+ collider: **γ–γ collider?**



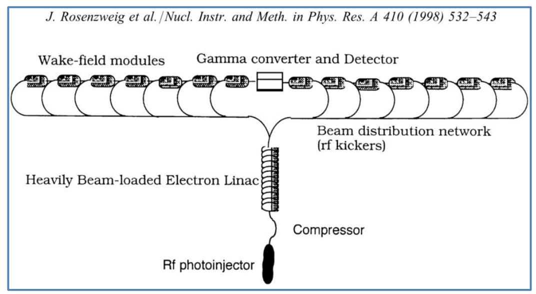
High energy photons are produced by Compton back-scattering off TeV e- beams :



The photon spectra has a peak at about $0.8E_{e-}$



First photon collider proposed at the first workshop on physics at linear collider VLEPP (Novosibirsk, Dec.1980)



Almost 40 year old idea (Telnov and others). The physics case for an γ–γ collider as complement to e- e+ colliders have been studied earlier.

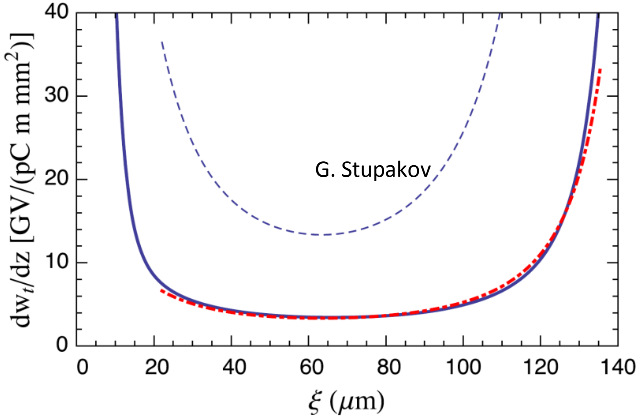
Some recent work (including CLIC study group) shows good physics potential for a **Multi-TeV collider** γγ collider.

Bypasses the positron problem, and allows for a conceptual design of the two e- main linacs.

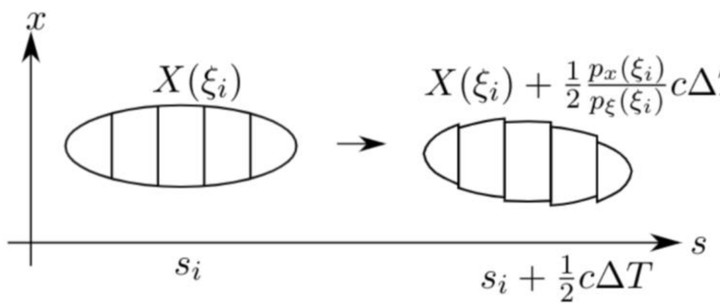
Some recent work on plasma collider parameters (effort level 1 PhD, but **dedicated** to design):

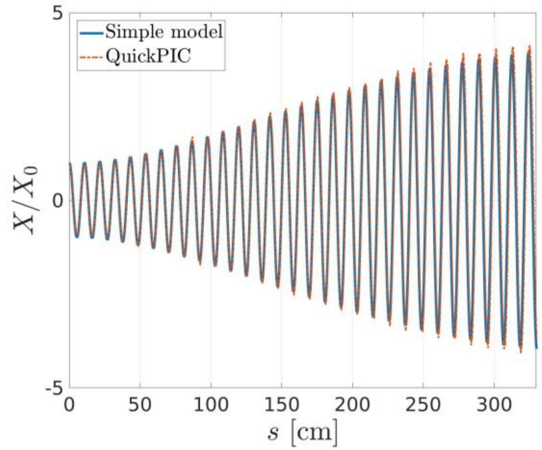
Simplified models: transverse wakefunctions

- 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 $\sim k_\mathrm{p}^{-1}$. α 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, J. Phys. Conf. Ser., vol. 1596 (2020)