Staging in Plasma Accelerators

International School of Particle Accelerators – ERICE 2023

Mark J. Hogan Senior Staff Scientist **FACET and Test Facilities Division Director**

July 31, 2023

Outline

- Why is staging important?
- Challenges and things to consider between stages
- Elements of a complete solution so far considered
- Benefits of having multiple stages
- Staging demonstrations
- Conclusions & Outlook

Note – although this is a school, to cover the topic in one hour, there will not be many derivations. Rather I will highlight topics, give examples of scalings and supply plenty of references to help you get more information and dig deeper

Why Aren't Electrons Accelerated in Circular Machines?

• High energy (multi-GeV) electron beams have many applications in HEP

(Colliders) and Photon Science (X-ray Lasers)

So why don't we just make all accelerators circular?

- A charged particle emits radiation when accelerated.
- The good: allows devices like synchrotron light sources and free electron lasers to work, and can be used to cool beams to make them brighter
- **The bad**: radiating can degrade the beam (especially coherent radiation)
- **The ugly**: power lost per revolution in a circular machine

$$
P_\gamma = \frac{1}{6\pi\varepsilon_0} \frac{q^2 a^2}{c^3} \gamma^4 \; \approx \frac{\gamma^4}{m^2} \quad \blacksquare
$$

SL Ao

low-mass electrons radiate too much!

3

The Scale for a TeV Linear Collider

…and must do it for positrons too!

The Electron Beam Driven Plasma Wakefield Accelerator

- Blow-out when $n_b \gg n_p$
- Large accelerating gradients ~ GeV/m
- Strong ideal focusing ~ MT/m
- Relativistic driver, no de-phasing

$$
E_0 \sim 10 \sqrt{\frac{n_0}{1 \times 10^{16} [\text{cm}^{-3}]}} [\text{GeV/m}]
$$

Accelerating Particles to Accelerating Beams

How much energy do we need?

- $1nC * 1GeV = 1$
- For Higgs ~ 1nC * 250GeV = 250J @ 40kHz for 10MW beam power for Luminosity
- What if XFEL as driver? ~ 1nC * 10GeV = 10J/bunch so need 25 stages
- *• Note: SPS/LHC have 20kJ/300kJ/bunch but long bunches at low rep rate (see AWAKE)***SLAC**

AWAKE Collaboration is Studying Proton Driven PWFA

ARTICLES

IIL 2009: CORRECTED ONLINE: 24 APRIL 2009 | DOI: 10.1038/NPHYS11

AWAKE

Proton-driven plasma-wakefield acceleration

Allen Caldwell^{1*}, Konstantin Lotov^{2,3}, Alexander Pukhov⁴ and Frank Simon^{1,5}

nature

physics

Idea to Harness the Large Stored Energy in Proton Bunches to make High Energy Electrons

Goals of the AWAKE Collaboration:

- \Box >500 GeV e- in single long plasma cell (400m)!
- Requires short proton bunches (100µm vs 10 cm)
- \Box Study physics of self-modulation of long p bunches
- \Box Probe wakefields with externally injected e-
- Study injection dynamics for multi-GeV e-
- \Box Develop long, scalable and uniform plasma cells
- Develop schemes for production and acceleration of short p bunches

HIgh energy…but low rep rate (Luminosity)

For context - what might a plasma based collider look like?

One of the earliest examples:

"Towards a Plasma Wake-field Acceleration-based Linear Collider", J.B. Rosenzweig, et al., Nuclear Instruments and Methods A 410 532 (1998).

Table 1

Nominal drive beam and accelerating module parameters for the plasma wake-field accelerator-based collider shown in Fig. 4

First SLAC Concept Developed with FACET Proposal < 2009 SLAC-PUB-13766 beam, the distance between P cells must be equal to equal half of the distance between mini-trains, i.e. 600 ns/2 or about 90 m. Ω

A CONCEPT OF PLASMA WAKE FIELD ACCELERATION LINEAR COLLIDER (PWFA-LC)* (ANE FIELD ACCELERATION LINEAR interaction point and a practical design for the main beam injector and the drive beam injector and the drive

Andrei Seryi, Mark Hogan, Shilun Pei, Tor Raubenheimer, Peter Tenenbaum (SLAC), Tom rinder Berji, Franc regan, Bindar Fer, For Facebonienner, Feter Fenendalin (BEF18), Font Katsouleas (Duke University), Chengkun Huang, Chan Joshi, Warren Mori (UCLA, California), Patric Muggli (USC, California). T_{max} , can bom, waited bord (CCEA, canorina),

- 'Warm' Drive Linac configurations that yield small energy spreads in the **v** value Dirve Enlac
- 4ns bunch spacing Ins hijnch snacing fo a shaped in profile. The shape
- Many turnarounds viany turnarounds — \cdots a concept of a pwFA-based of a \cdots

 $\mathcal{O}_{\mathcal{A}}$ -LC design consists of a consistence of a consistence beam and 25 GeV electron drive beam and

$H \Delta U$ -PHR-13766 H SLAC-PUB-13766

Alternative Conceptual Layout for TeV PWFA Linear Collider Developed prior to CSS2013

- •Efficient drive beam generation from recirculating superconducting linacs
- •Rapid & Efficient acceleration in meter long plasma cells
- Illustrates R&D challenges for next decade: beam quality, positrons, staging

Figure 1: Layout of a 500 GeV PWFA Linear Collider. Each main bunch is accelerated by 25 GeV in each of ten plasma stages. The plasma is driven by *e*[−] bunches, generated by a SCRF CW recirculating linac, and distributed co-linearly with the main beams.

- 'Cold' Drive Linac
- $\sum_{n=1}^{\infty}$ $\frac{d}{dt}$ • 100 μ s bunch spacing
- that delay chicanes preservation of I \bullet Tricky delay chicanes

E. Adli et al., Proceedings of IPAC2013 $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and a co-linear distribution $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ E. Adli et al., ArXiv 1308.1145 J. P. Delahaye et al., Proceedings of IPAC2014 \mathcal{L} . In addition, there are techTable 1: PWFA-LC parameters for 500 and 3,000 GeV. Parameters are also available for 250 and 1,000 GeV [9].

Wall Plug Power

10

HALHF

A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radiofrequency acceleration

https://arxiv.org/abs/2303.10150 \mathbf{c} hicanes). The positrons enter the beam-delivery system, which is combined with another turn-around, and then enter the system, and then enter the system, and then enter the system of the system of the system of th

Laser-plasma collider concept

Basic concept: Staged laser-plasma accelerators:

- Plasma density scalings indicates operation at $n \sim 10^{17}$ cm⁻³ [high average gradient and low wall plug power]
- Quasi-linear regime (a~1): e+ and e- focusing and acceleration; focusing control
- Staging & laser coupling into plasma channels (for laser guiding):
	- Tens of J laser/energy per stage
	- - *C. B. Schroeder et al., PR ST-AB (2010) C. B. Schroeder et al., NIMA (2016)*

Laser technology development required:

- High luminosity requires high rep-rate lasers (10s kHz)
- Requires development of high average power lasers (100s kW)
- High laser efficiency (~tens of % wall-to-laser)

Rapid Experimental Progress Since Last Snowmass

8 GeV **energy gain** in 20 cm stage using BELLA PW laser 9 GeV in 1.3 m using SLAC beam driver at FACET New: >10 GeV from U. Texas laser

> 42% transfer efficiency with 0.2% energy spread

Proof-of-principle **staging** (~100 MeV energy gain) using laser drivers, high gradient plasma-lenses

Optimized plasma beam loading enables uniform, **high-efficiency** acceleration.

C. A. Lindstrom et al. PRL (2021)

Plasma recovery at high rep-rate

R. D'Arcy et al., Nature (2022)

Driver Technology:

Superconducting XFELs, New laser technology (fibers, Thulium) promise high average power at high efficiency

SLAC

Also: hollow channels for low emittance growth, 0.1 micron emittance

Demonstration 0.5 **GW power**

SWFA structures.

30 29

Outline

• Why is staging important?

- Challenges and things to consider between stages
- Elements of a complete solution so far considered
- Benefits of having multiple stages
- Staging demonstrations
- Conclusions & Outlook

Transverse Forces: Focusing in the Ion Column

- Uniform ion density n_i = initial plasma density n_{e0}
- Focusing is balance between radial E and $v \times B \sim E_r$ CB_{phi}
- Assume $n_b/n_p > 1$ and fully blown-out ion column
	- no plasma return currents within the beam (CFI)
	- In beam frame then no currents to drive B_{phi}
- Focusing then simply obtained from Gauss law for an infinite cylinder (approximation)

$$
\nabla \cdot E = \frac{\rho}{\varepsilon_0} \quad \Rightarrow \quad 2\pi r dz E_r = \frac{\pi r^2 e n_i}{\varepsilon_0} \quad \Rightarrow \quad E_r = \frac{1}{2} \frac{e n_{e0}}{\varepsilon_0} r
$$

- linear in r (ideal lens, no geometric aberration)
- May preserve incoming emittance

Propagation in the Ion Column – Single Electron

• Motion of a single electron in the ion column:

$$
\gamma m \frac{dv_{\perp}}{dt} = F_{\perp} \implies \gamma mc^2 \frac{d^2 r}{dz^2} = e \frac{1}{2} \frac{e n_{e0}}{\epsilon_0} r \implies \frac{d^2 r}{dz^2} = \frac{1}{2 \gamma c^2} \frac{e^2 n_{e0}}{m \epsilon_0} r = \frac{\omega_{pe}^2}{2 \gamma c^2} r = \frac{k_{pe}^2}{2 \gamma} r = k_{\beta}^2 r
$$

• Harmonic motion as long as no energy gain or loss:

$$
\frac{d^2r}{dz^2} = k_\beta^2 r \implies r(z) = r_0 e^{ik_\beta z}
$$

16

• Relativistic electrons though, so will get synchrotron (betatron) radiation

• Particles oscillate at:
$$
k_{\beta}^2 = \frac{k_p^2}{2\gamma}
$$
 or $\omega_{\beta} = \omega_{pe}/\sqrt{2\gamma} \ll \omega_{pe}$

Propagation in the Ion Column for a Beam of Electrons

• Beam evolution described by the envelope equation:

$$
\frac{d^2\sigma}{dz^2} + K\sigma = \frac{\varepsilon^2}{\sigma^3} \quad \text{with} \quad K = \frac{k_p^2}{2\gamma} = k_\beta^2
$$

• No evolution of spot size (sigma) when have matched condition:

$$
\frac{d^2\sigma}{dz^2} = 0 \Rightarrow K = \frac{\varepsilon^2}{\sigma^4} = \frac{1}{\beta^2} \quad \text{or} \quad \beta_{matched} = \frac{\sqrt{2\gamma}}{k_p} = \sqrt{2\gamma} \frac{c}{\omega_p} \qquad \text{recalling} \quad \sigma^2 = \beta \varepsilon
$$

17

• There is a matched beta (n_p dependent) – not a matched spot size (ε_n dependent), e.g. n_p = 10¹⁷, c/w_p = 17 μ m and Beta matched = 1mm (<<L_p!). For ε_n = 1 μ m, E = 1GeV get a matched sigma = $0.7 \mu m$

Measured Plasma Focusing for Matched & Mismatched Beams

• Start with beam evolution in vacuum

$$
\sigma_r(z) = \sigma_{r0} \left(1 + \frac{\varepsilon^2 z^2}{\sigma_0^4} \right)^{1/2} = \sigma_{r0} \left(1 + \frac{\varepsilon^2}{\beta_0^2} \right)^{1/2}
$$

- Increase the density/focusing
	- Can't always measure in plasma
	- Look on profile monitor downstream
	- Sigma(z) at fixed np same as sigma(np) at fixed z

- Focusing orders of magnitude larger than beamline quadrupoles
- Well described by simple model
- Enables high density beam propagation over long distances

Matching and Emittance Preservation rations in the Valid point of \sim are also many other considerations to keep in \mathbb{R}^n <u>designations and cititude</u> growth the final emitted acceleration acceleration acceleration acceleration acceleration acceleration acceler ϵ is a proximately be approximately be approximately be approximately be approximately be approximately be approximately ϵ <u>λ</u>
2004 - Σερατολίτες του Στρατολίτες
2004 - Σερατολίτες του Στρατολίτες του Στρατολίτες του Στρατολίτες του Στρατολίτες του Στρατολίτες του Στρατο Delivering low-emittance beams is of prime importance feservations. In a linear \overline{a} . The luminosity \overline{b}

- Need small emittance for Luminosity in a collider (as low as 0.01 mm-mrad) and/ or for beam brightness in a free electron laser (0.1-1 mm-mrad) \mathbf{L} in $\overline{\mathsf{m}}$ T_{max} is the strict limit. T_{max} sure, T calli blightness in a free electron state and T $\text{E} \left[\text{P} \left(\text{P} \right) \text{E} \left(\text{P} \right) \text{E$
- Need to limit emittance growth in and in between stages to less than above α limit emittance growth in and in $\frac{\alpha}{2}$, $\frac{1}{\alpha}$ $\frac{1}{2}$ discrete to an emitted to be the maximum of $\frac{1}{2}$ discrete $\frac{1}{2}$ energy spread in an above
	- Mismatching bunches with a finite $\Big|$ energy spread leads to emittance $\overline{}$ $\overline{\phantom{$ growth, because the phase space $\epsilon_{\text{sat}} = \frac{1}{2}$ growth, because the phase space
ellipses of different energy slices rotate
 $\frac{\epsilon_{\rm sat}}{\epsilon} = \frac{1}{2} \left((1 + \alpha^2) \frac{p_m}{\beta} + \frac{p}{\beta_m} \right),$ L_s at different rates and coupling drivers of each significant coupling ϵ this contact the prime of pace $\frac{1}{\sqrt{m}} = \frac{1}{2}$ between states in combination with \mathcal{L} in $\mathcal{L$
		- Saturates after a distance L_{sat} and $L_{\text{density 10}}$
		- Avoid emittance growth from mismatch by ensuring that $\beta = \beta_m$ and $\alpha = 0$ 2 $t_{\rm tot}$ (conventional region conventional region conventional region $t_{\rm tot}$ ernittance growth from mismate

 $Gamma$ are the place of a strengtherm $\frac{1}{\sigma}$ and $\frac{1}{\sigma}$ and $\frac{1}{\sigma}$ and $\frac{1}{\sigma}$ and $\frac{1}{\sigma}$ and $\frac{1}{\sigma}$ entrance decomplete (assuming a flatter $\frac{1}{2}$) of details. Equinty to yee, 1 dev, 5% energy spread, 3 mm bet
matched heta is 1 mm resulting in a saturated emit $\mathsf{pha}\ \texttt{-1};$ Complete decoherence occurs after $1/\sigma_{\delta}$ betatron oscillations. e.g. density 10¹⁷/cc, 1 GeV, 3% energy spread, 5 mm beta, alpha -1;

 $\frac{m}{250\%}$ after a decoherence length of 0.2 r Technically, this is also why chromatic is also why chromaticity is also why chromaticity is also why chromaticity is also why chromatic is also why chromatic is also why chromatic is also why chromatic is also why chroma e growth of \ddots is the atoms productions is the δ nerence length of 0.2 m (33 betatron o matched beta is 1 mm, resulting in a saturated emittance growth of
250% after a deceberence length of 0.2 m (23 betatren escillations) 250% after a decoherence length of 0.2 m (33 betatron oscillations).

sung, K. Floettmann, and J. Osterhoff, Transverse emittance
Leocaleration, Phys. Pour Accel, Beause 15, 111200, (2012). μ acceleration, Phys. Nev. Accel. Beams 15, 111505 (2012). growth in staged laser-wakefield acceleration, Phys. Rev. Accel. E T. Mehrling, J. Grebenyuk, F. S. Tsung, K. Floettmann, and J. Osterhoff, Transverse emittance growth in staged laser-wakefield acceleration, Phys. Rev. Accel. Beams 15, 111303 (2012).

Chromaticity & Chromatic Amplitude <u>Communication</u> and \mathcal{R} is the beta function in the lens. To capture and reformed reformed \mathcal{R} natic Amnlitude L, the matrix n usting an integration in an integration of \mathbb{R}^n $Chenomation.$ $Chenomation$ $Chenomation$ $Anonlimit$

- Strong focusing in the plasma results in small beam sizes and $\int_{\mathbb{R}^1}$ is mean sufficient that while $\frac{1}{\mathbb{R}^1}$ from the moniton to confidence care
highly diverging beams **J**uly locasing in the plasma highly diverging beams $\frac{a}{\sqrt{2}}$ and $\frac{a}{\sqrt{2}}$ \bullet Strong focusing in the plasma
- Difficult to capture and refocus United to capture and rerocently remains the beam quality where \mathcal{L} **•** Difficult to capture and refocus $\frac{1}{2}$ $\frac{1}{4}$ without degrading the beam $\frac{2}{x^2}$ and $\frac{2}{x^2}$
- Different energy slices are not all focused in the same way $$ an effect known as chromaticity. $\int_{\frac{1}{2}}^{\frac{1}{2}}$ energy—in this case, the natural divergence of the beam of the is exactly countered by the focusing field such that the beta Advances on the topic were made by Balandin et al. in all focused in the same way $\frac{1}{2}$ $\frac{1}{2}$ an effect known as $\frac{1}{2}$ that any of $\frac{1}{2}$ any $\frac{1}{2}$ any $\frac{1}{2}$ and $\frac{1}{2}$ are a set of $\frac{$
- Defined in terms of the $\frac{1}{6}$ $\frac{5}{6}$ $\frac{50}{1}$ chromatic amplitude which measures (to first order) the combined mismatch of the FIG. 3. Example of emittance grow
A 10 GeV beam with 3% rms energy Twiss parameters α and β, for a relative energy offset δ = $\Delta E/E$ \overline{f} chromatic amplitude which $\frac{0}{0}$ $\overline{35}$ (to in st ord $\frac{1}{2}$ Twiss narameters α and β for a slow article by early 10^{16} cm⁻³ energy offset δ _
2V (∂δ þ fe. \overline{e} energy offset \overline{c} $j = \Delta E/I$ $\sum_{\text{longitudinal distance}}$ measures (to first order) the relative energy offset $\overline{\delta} = \Lambda F/F$ stage, which introduces significant chromatic beam line of the stage.

FIG. 3. Example of emittance growth due to chromaticity. A 10 GeV beam with 3% rms energy spread diverges from a plasma accelerator of density 10^{16} cm⁻³ ($\beta_m \approx 10$ mm). A simple beam optics lens captures and refocuses the beam into the next stage, which introduces significant chromaticity. As a result, the **PRODUCE CITEL BY UITSEL O –** $\Delta E / E$ projected (energy-averaged) emittance increases by more than a factor of 5. factor of 5.

 $\overline{35}$) and the first control of the first control ϵ and $\partial \mu$ $\zeta = \frac{1}{2\pi} \overline{\partial s}$ $W = \sqrt{ }$ $\left(\frac{\partial \alpha}{\partial \delta} - \frac{\alpha}{\beta} \frac{\partial \beta}{\partial \delta}\right)^2 + \left(\frac{1}{\beta} \frac{\partial \beta}{\partial \delta}\right)^2$ $\frac{\partial \beta}{\partial \beta}$ $\partial \delta$ \setminus 2 \pm $\sqrt{1}$ β $\partial \beta$ $\partial \delta$ $\frac{1}{2} \left[\frac{\partial \alpha}{\partial t} - \frac{\alpha}{2} \frac{\partial \beta}{\partial t} \right]^2 + \left(\frac{1}{2} \frac{\partial \beta}{\partial t} \right)^2$ $\overline{}$ $F =$ *L* 2 $W = \beta Kl$ $F = \frac{L}{2} = (Kl)^{-1}$ $\xi =$ 1 2π $\partial \mu$ $\partial \delta$ $\mathcal{L}^{\mathcal{L}}$ \mathcal{C} is a single particle particle, whereas the chromatic particle, \mathcal{C} \mathcal{A}^{2} $\frac{1}{0}$ dKl *F* ∂β ∂δ \overline{I} \equiv \mathbf{K} $\frac{1}{\sqrt{2}}$ $\sum_{i=1}^{n}$ ϵ $\frac{1}{4}$ $\frac{1}{8}$ a L^2 $\Delta \epsilon^2$ $4L^2$ $\frac{1}{2}$ $\beta \approx \frac{1}{\beta}$ and $\beta \approx \frac{1}{\beta}$ and $\frac{1}{\beta^2}$ $\approx \frac{1}{\beta^2}$ L^2 *βm* $\Delta \epsilon^2$ ϵ_0^2 0 $= W^2 \sigma_\delta^2 + \mathcal{O}(\sigma_\delta^4)$ $\Delta \epsilon^2$ ϵ_0^2 \approx 4*L*² *β*2 *m* σ_{δ}^2

> 10GeV, 1016/cc with matched Beta 10mm, $L = 1m$, limit emittance growth to 1% then max $dE/E =$ 0.07% so severe limit if uncorrected th m
าit er : emittance
max dF/F =

carl A. Lindstrøm, Staging of plasma-wakefield accelerators , Phys. Rev. Accel. Beams 24, 014801 (2021). SLAC means and by employing various symmetries, it has not it has not it has not it is it , 014801 (2021) . ϵ

Transverse Misalignments caused by such an offset will gradually increase along the such an offset will gradually increase along the such

- The driver initiates the wake so the main beam need to overlap In the main beam need to overlap $2 \sqrt{p_m}$ staged acceleration is a contract of course, notice is perfect to a stable. The d t ince $r = \frac{1}{2}$ well li $\mathsf{I}_{\mathsf{C}\mathsf{M}}$ a • The driver initiates the wake so well in phase space
- Main beam should be aligned to the driver to a fraction of the $transverse$ beam size and angle $\overbrace{}^{\text{Drift}}$ and \overbrace Idse space
im should be aligned to $\Delta x \ll \sqrt{2\beta_m \epsilon} \Delta x' \ll \sqrt{\epsilon}$ $\frac{31100}{5}$ $\begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ and $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ and $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ • Main beam should be aligned to \overline{a} we \overline{a} and \overline{a} well \overline{a} $\frac{1}{2}$ the driver to a fraction າe
ື່
	- Challenging for small emittance and small betas $\overbrace{a^{x'}}$ Plasma-wakefield accelerators have high-frequency **• Challe** dilu Silidii Detas
- \bullet Similarly to mismatch and dispersion leakage, finite energy spread beams rotate at different rates and smear out the phase space leading to projected emittance growth electromagnetic fields. For stable acceleration, the driver acceleration 001010111
000 boo e at diff

$$
\Delta \epsilon \approx \frac{1}{2} \left(\frac{\Delta x^2}{\beta_m} + \beta_m \Delta x'^2 \right)
$$

#

$$
\Delta x \ll \sqrt{2\beta_m \epsilon} \quad \Delta x' \ll \sqrt{2\epsilon/\beta_m} \quad \text{laser dr}
$$

e.g. for densities with GeV/m e.g. for defisities with dev.
gradients implies <100nm and <5µrad (will be true for laser drivers as well)

R. Assmann et al., Transverse beam dynamics in plasma-based linacs, Nucl. Instrum. Methods Phys. Res., Sect. A 410, 544 (1998).

S. Cheshkov et al., Particle dynamics in multistage wakefield collider, Phys. Rev. Accel. Beams 3, 071301 (2000). D. Schulte, Application of advanced accelerator concepts for colliders, Rev. Accel. Sci. Techol. 09, 209 (2016). C. A. Lindstrøm, E. Adli, J. Pfingstner, E. Marín, and D. Schulte, Transverse tolerances of a multi-stage plasma wakefield accelerator, in Proceedings of IPAC2016, Busan, Korea (JACoW, Geneva, 2016), p. 2561.

Drive Beam Injection and Extraction Drive Beam Injection and Extraction growth. systems.

- Extraction and injection optics should be symmetric (same optics but reverse order) require cancellation of dispersion:
- Either mirror symmetric (C) or rotationally symmetric (S) chicane W is the first-order dispersion. However, $W = \frac{1}{2}$ $\frac{1}{2}$ entries run or symmetric $\left\{0\right\}$
	- C: less total bending, less synchrotron radiation
- S: injection and extraction on opposite sides freeing up space for beam dumps and diverting some containing the space. radiation away from beam distribution and injection systems \bullet Supportion and oxtraction on systems of the state of the systems of the systems of the system of

Some considerations:

- where length, B is the dipole magnetic field is the dipole magnetic field of immite withess, 11, obtitiong uipole gives 10m onset
um combination? • 10GeV drive, infinite witness, 1T, 60cm long dipole gives 1cm offset
- Dipole + septum combination?
- Kickers not fast enough (~1ns rise time)
- TCAV likely won't handle 100% energy spread
• Continuity the necessary spread
- dicturing power beam additions for the drive beam and leads to the drive beam and leads to the drive beam and lea • Caution that need high power beam dumps

Dispersion Cancellation

- Dipoles used for in/out coupling
- Gives a correlation between energy and position = dispersion that intentionally introduces separation between beams of different energy
- Will also disperse single beam with finite energy spread producing projected emittance growth

D'
D'
D

$$
\Delta \epsilon_D \approx \frac{1}{2} \left(\frac{D_x^2}{\beta_m} + \beta_m D_{x'}^2 \right) \sigma_{\delta}^2
$$

x

<u>σ</u>
-
-

Δο

$$
D_x \ll \sqrt{2\epsilon\beta_m}/\sigma_\delta
$$
 and $D_{x'} \ll \sqrt{2\epsilon/\beta_m}/\sigma_\delta$,

nple: 1GeV, 1% dE/E, 1mm-mrad staged between plasma cells of $10^{16}/c$ c requires cancellation of D D to better than 0.16mm and 33mm ad $-$ tough: b Example: 1007, 170 de, 2, 11..... imaged between plasma cells of 10¹⁶/cc requires cancellation of D and D' to better than 0.18mm and 55mrad – tough! Example: 1GeV, 1% dE/E, 1mm-mrad staged between

led with correlated energy spread coupled with correlated chergy spread
can also lead to beam tilt and seed hosing respectively—this can be quite challenging. We should also challenging the correlated energy spread strong dipoles, we may also higher-order to consider the consider to consider the consider \sim • Coupled with correlated energy spread can also lead to beam tilt and seed hosing

Synchrotron Radiation <u>experimental indication</u> need to hit the colliding bunches head on, the multibunch emittance (i.e., averaged over the synchronous management of \sim

- Separating drive and witness beams will likely be done with dipoles p Conorating drive and w \bullet beparating drive and w \bullet Separating drive and witness heams $P_{\text{top}} =$ the accuracy of the accelerator and the position of the positi offset between the acceleration of the drivers—will be derived beam and the deriversity of the driver of the d D. Synchrotron radiation But different in Sec. 2. In Sec. 2 will likely be done with dipoles \sim means that any error in the orbit introduced along that any error introduced along the orbit introduced along \sim \bullet separating drive and withes.
- Synchrotron radiation becomes more important at higher energies divergence in the plasma, respectively. By implication, this more important at higher energies \bullet Synchrotron radiation becomes $\qquad \sigma_{\rm SR} =$ • Synchrotron radiation becomes $\sigma_{\rm CP} = \rho/v$ beam-driven was to the driven when accelerate to the concern acceleration of the state of th hord important at inglict drict gies common can internation to conlow as the nanopole called and nanopole for $\frac{1}{2}$
- Incoherent for long bunches (ISR) e.g. for 10 becoming partially coherent (CSR) as the bunches get shorter as with $\mathbb{E}^{\frac{10}{10}}$ de che canonee geconoreer de mentos.
plasma accelerators $F(x) = \frac{1}{2} \int_0^x e^{ix} dx$ pecoming partially con becoming partially coherent (CSR) is partially coh dedicated cancellation techniques (e.g., in the optics ds the bunches get sho • Incoherent for long bunches (ISR) e.g. for 10GeV as the bunches get shorter as with power duckles along per building per bunch in the proper set of the per building \mathcal{S}
- Represents loss of efficiency, energy spread growth and when coupled with chicanes, intra-bunch correlations may act as seed for beam-driven wakefield accelerator. When accelerating to be staging t only need to be very small at the interaction point, but also be very small at the interaction point, but also \bullet Represents loss of efficiency, toupicu with chicance, correlations may act as seed for $\mathsf{C}\mathsf{H}\mathsf{C}\mathsf{I}\mathsf{B}\mathsf{y}$ spieral growth and writen coupled with chicanes, intra-bunch n.
Depresente less As discussed in Sec. II A, one of the main methods to the main methods to the main methods to the main methods the main $\frac{1}{2}$ separate the driver and the accelerating beam is to disperse

can impose even more stringent alignment tolerances, as r. Carand F. Ding, Three-different effects of conerent synchrotron radiation
by electrons in a bunch compressor, Phys. Rev. Accel. Beams 23, 014402 (2020). Instability in a bunch compressor, Phys Y. Jing and V. N. Litvinenko, Design of a bunch com- pressor with CSR suppression
The achieve bundreds of kA neak current in Proceedings of IPAC2019, n. 382 Y. Cai and Y. Ding, Three-dimensional effects of coherent synchrotron radiation S. Heifets, G. Stupakov, and S. Krinsky, t. Jing and v. N. Eitvillenko, Design of a bunch com- pressor with CSN suppression in A. D. Brynes et al., Characterisation of
SL AC by achieve hundreds of kA peak current, in Proceedings of IPAC2019, p. 382. Fourier an rally hit the same problem as we tried to avoid by using a the radiation would be partially coherent, and the bunch

$$
\begin{array}{ll}\n\text{ess beams} & P_{\text{ISR}} = \frac{e^4}{6\pi\epsilon_0 m^2 c} N\gamma^2 B^2 & P_{\text{CSR}} = NP_{\text{ISR}} \sim N^2 \\
\text{poles} & \sigma_{\text{SR}} = \rho/\gamma^3 = mc/Be\gamma^2 & P_{\text{CSR}} = \frac{\kappa e^2 c}{\epsilon_0} \frac{N^2}{\rho^{2/3} \sigma_z^{4/3}} \\
\text{energies} & \end{array}
$$

 es (lSR) e.g. for 10GeV, 1nC charge, bunch length 10 μ m, 1T magnetic field radiation $\text{L}(\text{CSR})$ is partially coherent and will radiate 0.3% of its energy per meter of dipole
L (CSR) \mathbf{D} compare for 10GeV incoherge bunch length 10nm if magnetic final

f coherent synchrotron radiation S. Heifets, G. Stupakov, and S. Krinsky, Coherent synchrotron radiation for the
Fig. 3. Heifets, G. Stupakov, and S. Krinsky, Coherent synchrotron radiation inconerent synchrotron radiation in the station of study and stations, concreting synchrotron radiation
A D Brance Station of microscope of all characterisation of microbunching instability with 2D and the SD cunnection o com- pressor with CSR suppression (a. D. Brynes et al., Characterisation of microbunching instability with 2D coredings of IPAC2019 in 382 Fourier analysis, Sci. Rep. 10, 5059 (2020).

Isochronicity $\frac{150$ cm or here $\frac{2}{3}$

- Dipole chicanes typically used to compress bunches needed for PWFA ($k_p^* \sigma_z \sim 1$)
- If also use for injection/extraction, need to δ ensure they do not change the bunch length

and the bunch length significantly
- Requirements might be relaxed by adjusting successive chicanes to compress, over compress, compress to compensate for imperfect beam loading and reduce energy spread progen cinence imprit be re
	- For low energy, short beams with large divergence (LWFA), different energies can take different path length in focussing optics

 $\begin{array}{c} 1 \\ 1 \end{array}$ and $\begin{array}{c} 200 \text{MeV} \end{array}$ $\Delta I \approx \frac{1}{2} \sigma^2 I \ll \sigma$ $\sigma = 1$ um $\frac{1}{2}$ stage. Source: $\frac{1}{2}$ $\Delta L \approx$ 1 2

 $L < 37cm$ $E.g. 10^{17}/c$ c $\sigma_{x'}^2 L \ll \sigma_z$ $\sigma_z = 1 \mu m$ Q_{X}^{\prime} - 2.31111 du
L \geq 37cm 200MeV $\sigma_z = 1 \mu m$ ε_n = 1 mm-mrad $\sigma_{x'}$ = 2.3 mrad

Carl A. Lindstrøm, Staging of plasma-wakefield accelerators , Phys. Rev. Accel. Beams 24, 014801 (2021).
25

spread of and bunch length of

Coulomb Scattering

- Need to confine the plasma to the plasma accelerator region with vacuum in the interstage optics in between
- Well established formulas for angular $R_b =$ blowout radius scattering in a neutral vapor ed the part of the part of the thing part of the paper.
- Extend the range of Coulomb $\frac{1}{10}$ interaction to include the effects of traveling through an ion column be found by substituting equations \mathbb{R} into 21 into 21 into 21 into 20, \mathbb{R} $m \left(\frac{m}{2} \right)$
- Negligible for length of total acceleration in low Z materials (need differential pumping) $\sum_{i=1}^{n}$
- Important at higher Z or when beam is

mismatched

N. Kirby et al., Emittance growth from multiple Coulomb scattering in a plasma wakefield accelerator, in Proceedings of the 22nd Particle Accelerator Conference, PAC-2007, Albuquerque, NM (IEEE, New York, 2007), p. 3097.

where x is the electron position coordinate in the x Y. Zhao et al., Modeling of emittance growth due to Coulomb collisions in plasma-based accelerators, Phys. Plasmas 27, 113105 (2020). *k r S ^d ^N ^p ^c* (24)

$$
\Delta \mathcal{E}_N = \sqrt{2} \cdot r_c \cdot S \cdot \left(\sqrt{\gamma_f} - \sqrt{\gamma_i}\right)
$$

$$
S = Q \cdot \left(\ln\left(\frac{R_b}{R_a}\right) + \frac{1.78 \cdot Z \cdot (Z+1)}{Q^2} \cdot \ln\left(\frac{287}{\sqrt{Z}}\right)\right)
$$

- with $\frac{1}{2}$. As an example equation 26 $\frac{1}{2}$. $R_b =$ blowout radius range from atomic radius to blow out radius where extends and the total angles of the R_a = range from atomic radius to blow out radius $radine to blow out radius$ radius to blow out ra
- *dz* $Q =$ *i* θ *n* θ $Q =$ \overline{a} $Q =$ ion charge

² (22)

^N& (23)

the energy of an electron beam initially at 500 GeV
through singly ionized materials with various atomic Normalized emitta
of an electron b *x p n e x dP* Figure 1: Normalized emittance growth from doubling Figure 1: Normalized emittance growth from doubling
the energy of an electron beam initially at 500 GeV numbers.

CONCLUSION

26

[5].

derivative of equation 16.

The next step is to substitute for &

is now important to include not only the energy change 6

matched retains the conditions expressed in equation 15 It can be shown that an accelerating beam that starts

Design of the FACET-II Upstream Differential Pumping System

Multiple scattering not significant as long as gas/plasma is confined to the accelerating cells

- Need differential pumping system to limit scattering as illustrated at FACET-II
- Four stages of differential pumping, separated by conductance limiting apertures
- 1e-9 Torr achievable in each operating state
- Adds additional demands for beam line space between stages

SLAC

Effective or Geographic Gradient

- Plasma cells have fantastic gradients but we can see there are many things to do between stages that require significant space
- 10¹⁷/cc has unloaded gradient of 30GeV/m, but if need 30m to handle the beams in between, effective gradient is back down to 1GeV/m \bullet 10¹⁷/cc has unloaded gradient of 30GeV/m, but if need 30m to handle f

ice is used for
ntz factor.

Energy scaling laws for the high energy regime $(E_m \gg E_d)$. The same lattice is used for all energies, by scaling lengths as $\sqrt{\gamma}$, where γ is the main beam Lorentz factor.

> bending magnetic matrix on dispersion on \mathbf{F} , which sets stringent requirements on \mathbf{F} \blacksquare and \blacksquare and leads to large chromaticity, which must be canceled to avoid $\frac{\sqrt{7}}{1/4\pi}$ distance will get $\frac{2}{\pi}$ s6. \int the system and a linear lattice with \int \int \int \int \int longer at higher \parallel $\frac{42.1}{28.1}$ \parallel \parallel conc_rel requirements. Section maxmax time besiducting $\vert \text{time} \vert$ effective gradient $\begin{array}{c} 0.6666 \overline{0.0} & 7.78 & 15.56 & 23 \end{array}$ checute gradient **Designed by interstage** $S_{const.}$ distance that $S₃$ and $S₄$ and $S₅$ and $S₆$ and $S₇$ and $S₈$ and $S₇$ and $S₈$ and $S₈$ and $S₉$ and $S₉$ and $S₉$ and $S₉$ and Const. energies lowering \int_{0}^{f} affortive gradiant α _{const.} α effective gradient

Fig. 2. Working example for 500 GeV, where 5 dipoles and 8 quadrupoles form a 39 m long C-chicane. Chromaticity is canceled by a linear lattice without sextupoles, however an uncorrected second-order dispersion leads to a 2% emittance growth.

Table 1

C. A. Lindstrøm, E. Adli, J. M. Allen, J. P. Delahaye, M. J. Hogan, C. Joshi, P. Muggli, T. O. Raubenheimer, and V. Yakimenko, Staging optics considerations for a plasma wakefield acceleration linear collider, Nucl. Ins- trum. Methods Phys. Res., Sect. A 829, 224 (2016). J. P. Delandye, M. J. Hogan, C. Joshi, P. Muggii, T. O. Raubennei

Plasma Density Ramps

- Gradually ramp plasma density on either side of the acceleration region
- Increases matched beta before the beam begins to diverge into vacuum $\bigcup_{i=1}^{\infty}$
- Use adiabatic ramps to remain matched – slow change in density s.t. \overline{B} Function \overline{B} and \overline{B} and \overline{B} in \overline{B} and \overline{B} alpha remains \sim 0 throughout the ramp
- Ideal profiles can be calculated analytically or effects can be modeled and increase beta beta beta that a such that and increase beta beta by for measured profiles ϵ_0^2 β_m^2 ϵ_0 ted i.e. typica

K. A. Marsh et al., Beam matching to a plasma wake field accelerator using a ramped density profile at the plasma boundary, in Proceedings of the 21st Particle Accelerator Conference, Knoxville, TN, 2005 (IEEE, Piscataway, NJ, 2005), p. 2702. I. Dornmair et al., Emittance conservation by tailored focusing profiles in a plasma accelerator, Phys. Rev. Accel. Beams 18, 041302 (2015). n0ð1 þ s=lr
Density and lattop density and la βm

 $4L^2$

 σ_{δ}^2

 β_m^2

 \approx

 $\Delta \epsilon^2$

 ϵ_0^2

(β%) close to the start of the entrance ramp. If perfectly matched to the ramp, the beam stays matched throughout the accelerator (β ¼ β^m in the flattop). Finally, the beam is transported through the exit ramp, which reduces the divergence before exiting into energy slices, making the adiabatic ramp quasiachrotherefore, in principle, emittance preserving. Although the focusing force for electrons is exerted by an electric field, we can calculate the equivalent magnetic field gradient (as Er ≡ cB^ϕ for ultrarelativistic particles) ^δ: ð10Þ electron laser (FEL), the lasing power is determined by the 6D brightness [41] i.e. typical ramps are cm to 10's cm and increase beta by ~10 and dropping emittance growth by 100

he 21st Particle Accelerator Phys. Rev. Accel. Beams 22, 041304 (2019).
Notatal accelerator stage at energy and the flatter at energy at energy at each control of the flatter at energy ccelerator using a ramped and R. Ariniello et al., Transverse beam dynamics in a plasma density ramp,

 t_0 Pm

tailored plasma-density profile is relatively straightforward function β% at the entrance or exit of such an adiabatic ^E ^¼ ¹⁰ GeV with plasma density ⁿ ^¼ 1016 cm[−]³ (giving Traditional Accelerator Components Using Longitudinally Tailored Plasma Profiles, Phys. Rev. Lett. 116, 124801 (2016). g riasina anu
i Tailored uniform for all particles inside the wake. sma and $\bm{\mathsf{ored}}$ X.L. Xu et al., Physics of Phase Space Matching for Staging Plasma and

Plasma Lenses ! such that a $\overline{0}$ that a $\overline{0}$ the entire ramp $\overline{0}$! ! ens)
) <u>: אל</u> $t_{\rm max}$ definition of aberration power from Ref. \mathcal{S}

- Two types active or passive $\nabla \cdot E = \frac{\rho}{2} \Rightarrow 2$; _{ð25}
1950 - Andrea Stein, skildar í Sveitar í Sveitar
1950 - Andrea Stein, skildar í Sveitar í Svei Ω active or passive Γ
- Strong focussing in both planes simultaneously \log in both planes are no is the flattop density and local $F = e^B$ is the flattop $2\mathcal{E}_r \equiv c B_\phi$ for ult \bullet Strong focussing in both planes en engrocassing in been planes matic. An example of such a range of such a range \mathcal{L} plasma, the normalized emittance can increase rapidly for a μ ssing in both planes μ \mathbf{u} is \mathbf{v} as a set of \mathbf{v}
- Active: drive large current through plasma to produce large magnetic field \mathbb{P}_{PPL} (next slide) α and α a beta function in the flattop in the flattop α • Active: drive large current through state of such an adiabatic density and leaders and such an adiabatic density and leaders are also such as a su $\begin{array}{c|c} 20.0 \end{array}$ plasma to produce large magnetic field $m_{\rm F}$ is the function in the function in the function in the flattop in the flattop μ $f(x) = \frac{f(x)}{g(x)}$ and $f(x) = \frac{f(x)}{g(x)}$ produce large magnetic field
- **Passive**: utilize focussing from ion example, to asset the control of the significant entirement column (same as for PWFA, ramps etc) characters-scale gap between stages \sim 17.5 • Passive: utilize focussing from ion $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ coron chromatic gap between start groups coop ϵ2
- Laser or beam ionized \bullet Laser or beam ionized m ionizad $\ddot{}$ am ion $\mathsf{U}\mathsf{Z}\mathsf{e}\mathsf{u}$

SLAC

- Head of the drive beam will experience varying focusing as reach full blowout 5 GH IVE DEAIII WIII EXPETIENCE
- Constant focussing for the main beam most realistic conditions, or aliso because ocussing for the main beam
- Stronger than active plasma lens thus the chromatic emittance growth from the passive thromatic emitted \mathbf{r} han active plasma lens

C. E. Doss et al., Laser-ionized, beam-driven, underdense, passive thin plasma lens, Phys. Rev. Accel. Beams 22, 111001 (2019).

ctive or passive

\n
$$
\nabla \cdot E = \frac{\rho}{\varepsilon_0} \implies 2\pi r dz E_r = \frac{\pi r^2 e n_i}{\varepsilon_0} \implies E_r = \frac{1}{2} \frac{e n_{e0}}{\varepsilon_0} r
$$
\ning in both planes

\n
$$
E_r \equiv c B_\phi \text{ for ultrarelativistic particles} \qquad g_{\text{PPL}} = \frac{e n}{2 c \varepsilon_0}
$$

Illustration of two thin plasma lenses used to couple a 10 GeV beam in/out of a 3x10¹⁶/cc plasma source used at FACET-II density ramps of the density ramps of half-width 2.54 cm and peak density ramps of the peak density ramps of t

 $m_0[10^{18}~\mathrm{cm^{-3}}]~\mathrm{MT/m}$

\mathbb{R} lenses \mathbb{R} $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ th planes simultaneously between the control of the **Active: Active current through plasma** letic field $\frac{1}{\frac{1}{\sqrt{1-\frac{1}{\sqrt{$ $10 - 5$ PPL but more than 20 PMQs) solenoids have weak for relativistic electrons and \mathcal{A} for relativistic electrons and \mathcal{A} have, hence, only been applied to energies of \mathbb{R}^n or \mathbb{R} less $\left| \begin{array}{ccc} 1 & i \end{array} \right|$ the strong field gradients of miniature quadrupoles ($\frac{1}{2}$) are promising, and $\frac{1}{2}$ $\frac{$ favorable 1=γ scaling of the focusing strength, but the effective field gradient is strongly reduced when ℓ $\begin{array}{ccc} \begin{array}{ccc} \hline \end{array} & \begin{array}{$ $\mathsf{I}\times\mathsf{I}\qquad\qquad\mathsf{I}\times\mathsf{I}$ lengthere $\overline{}$ with increase chromatic chrom

strength, with \mathcal{L} the electron relativistic Lorentz factor, with \mathcal{L} and \mathcal{L}

- \bullet Ideal focusing requires uniform current density (heat flow effects) carrent achore grical how $\mathbf{w} = \mathbf{w}$ averaged strong, single-element, radially, radially, $\mathbf{w} = \mathbf{w}$ current density (heat flow effects)
- Current limited by z-pinch α is used in the main acceleration. So α ϵ Currant limited by z-pinch \sim current immed by \angle pinent.
	- Beam density limited else get blow-
For cylindrical geometry, from A out and active morphs to passive \bullet Beam density limited else get blow-
- Multiple scattering at higher-z gases and large betas and the same effect can all the same effects of the same effect can all the same effec and longitudinal localities for the candidate for the candidate for the candidate for the candidate for the ca have been demonstrated on international contract on the second on $\frac{1}{2}$ viditiple scattering at inglier-2 gase.
.

J. van Tilborg et al., Active Plasma Lensing for Relativistic Laser-Plasma-SLAC Accelerated Electron Beams, Phys. Rev. Lett. 115, 184802 (2015).

Example APL comparison for 300MeV beam provides cm-scale focal length and reduced chromatic dependance vs solenoid, PMQ triplet

z

experience a different lens strength than the electrons in the electrons in the electrons in the electrons in

For cylindrical geometry, from Ampere's Law: FOI Cymrundai geometr y, nom Ampere's Law.

$$
g_{\rm APL} = \frac{\mu_0 I}{2\pi R^2}
$$
 I.e. for R=500µm, I=500A, g=400T/m

Endstries and Environment Companies (1996).
Free Active Plasma Lens, Phys. Rev. Lett. 121, 194801 (2018). Livistic Laser-Plasifia-
184802 (2015). The Mortius Plasma Lonses Phys. Pov. Lott. 121, 174801 (2018) Active-Plasma Lenses, Phys. Rev. Lett. 121, 174801 (2018) \overline{C} A lindstram at al. Emittance Preservation in an \overline{C} $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are obtained behology if it for the field $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ C. A. Lindstrøm et al., Emittance Preservation in an Aberration-Free Active Plasma Lens, Phys. Nev. Lett. 121, 194601 (2016).
R. Pompili et al., Focusing of High-Brightness Electron Beams with

Plasma Lenses wakefield the experiments (Value 2013). The experiments (Value 2013) have reported no plasma \mathbb{R} active plasma lens focusing gradient (using Eq. 8) as well as well as the maximum focusing gradient within the
The bunch caused by plasma lens maximum focusing gradient within the bunch caused by plasma lens maximum focus wakefield distortion, consistent with expectation. However, a dedicated passive plasma lensing experiment (INFN F

SLAC

• Compact geometry for catching beam near exit of plasma stage but limiting aberrations in the lens places restrictions on the maximum beam density \bullet Compact geometry for catering beam near exit or plasma stage but immung

FIG. 5. (a) Minimum beam size required in an active plasma lens to have negligible distortion, i.e. when the gradient from plasma wakefields is 3% or less of the active plasma lens gradient, and (b) the corresponding active plasma lens gradient given this size. Note that the capillary diameter is constrained to 10 times the beam size, such that a smaller beam size gives a larger gradient (Eq. 8), but that this lens diameter is constrained to be at least 250 μ m. The parameter space is divided in two parts, where lower (left) and higher (right) plasma densities allow smaller beam sizes, respectively. A typical discharge current of 1 kA is used, but smaller beam sizes can be tolerated if this current is increased. Collider parameters from Table II are indicated as colored circles.

Outline

- Why is staging important?
- Challenges and things to consider between stages
- Elements of a complete solution so far considered
- Benefits of having multiple stages
- Staging demonstrations
- Conclusions & Outlook

Interstage Requirements are Similar to Final Focus Systems

- Strong focussing and chromatic correction are desired to properly inject and extract the beam from the plasma
- Traditional FF designs (search literature for P. Raimondi, A. Seryi, G. White…)
	- Chromaticity is compensated in dedicated chromatic correction sections (CCX and CCY)
	- Sextupoles in high dispersion and high beta regions
	- Geometric aberrations generated by the sextuples are cancelled using -I transform between them
	- FFTB@SLAC was >200m at 50GeV
- Local chromaticity correction schemes reduce length and have been studied at ATF2@KEK and designs for 500m @500GeV
- Apochromatic focusing is a lesser-known alternative approach, whereby chromatic errors of Twiss parameters are corrected without the use of bends and sextupoles

Apochromatic Correction

• Inspired by camera lenses, add additional lenses and tune so that multiple colors are in focus additional lenses and tune so tha

SLAC

FIG. 4. Example A: PWFA staging optics, both using quadrupoles (a) and plasma lenses (b). Plots show $\sqrt{\beta}$ (proportional to rms beam size) vs beam line axis s, and chromatic dependence of $\alpha(\delta)$ and $\beta(\delta)$ vs offset δ . Both solutions capture a 100 GeV beam exiting a plasma (with density ramps) matched to $\beta_0 = 32.5$ cm and refocuses it back to 32.5 cm, with a 1 m drift space at the start and end for injection and extraction of drive beams. Solution (a) is a first-order apochromatic lattice using 8 quadrupoles with field gradient 160 T/m are placed antisymmetrically (mirrored with polarity switched), whereas solution (b) is a third-order apochromatic lattice using 7 discharge capillary plasma lenses [18] with field gradient 3000 T/m placed symmetrically. Transporting a beam with 1% rms energy spread leads to a projected emittance growth of 0.96% in lattice (a), and 0.000004% in lattice (b). Note the different δ -scales in the two chromatic dependence plots.

constraints at the halfway point:

B. W. Montague and F. Ruggiero, Apochromatic focusing for linear colliders, CLIC Note No. 37, CERN, Geneva, 1987. optical axis s for a 3-color apochromat. Plot (b) shows transverse C. A. Lindstrøm et al., Design of general apochromatic drift-quadrupole beam lines, Phys. Rev. Accel. Beams 19, 071002 (2016) The section staging optics must match to and from β⁰ ¼ 32.5 cm. $\overline{}$ for $\overline{}$ for $\overline{}$ and $\overline{}$ both the zeroth th X_N , Geneva, 1987.

considerations, discussed in Ref. [2]. Here we simply discussed in Ref. [2]. Here we simply discussed in Ref. [

Apochromatic Transport with Transversely Tapered Plasma Lens

> **Transversely tapered plasma lenses (APL/PPL)** 0

- $>$ *Disperse the bunch into the PL with a dipole, match* the focusing of each energy with a transverse taper.
- > **Local chromaticity correction*** (used in final focus systems) ** Raimondi & Seryi, Phys. Rev. Lett. 86, 3779 (2001)*
- > Simple in/out-coupling of laser and beam drivers.
- > Large, dispersed beams in the plasma lenses \Rightarrow minimal wakefield-distortion in APLs.

SLAC

Carl A. Lindstrøm | European Strategy Town-hall Meeting | 21 May 2021 | Twitter: @FForwardDESY | Web: forward.desy.de| **Page 4** Slide (and concept) courtesy of Carl Lindstrøm 36

Outline

- Why is staging important?
- Challenges and things to consider between stages
- Elements of a complete solution so far considered
- Benefits of having multiple stages
- Staging demonstrations
- Conclusions & Outlook

Synchronization

- Plasmas are high-field and highfrequency accelerators
- The driver initiates the wake so the main beam needs to be synched to the driver to a small fraction of the wakefield period f_{w}

gradient of the state of the sta
The state of the st

• Random timing jitter Δt will produce energy jitter

 ΔE_z E_z $\approx \omega \Delta t$.

e.g. to remain within 1% energy bandwidth at $10^{17}/c$ c ($1/\omega_p$ = 177fs) would need to synchronize main beam to driver to better
Above 26, YEELs now down to 2126s as this is ence acceleration and acceleration at the state of the state of the state of the stage of t state of the art than 2fs. XFELs now down to \sim 10fs so this is

Self-correction for Stability and Energy Spread Damping $\mathcal{L} = \mathcal{L} = \mathcal$

We repeated the simulations using Gaussian bunches

- Beam loading (Energy, energy spread) sensitive to longitudinal shape and location
- Magnetic chicanes provide energy dependent path length
- Possibility for feedback mechanism

- > **Introduce a small compression** between stages (magnetic chicane; *R*56) $\frac{1}{2}$ betweek i.e. ϵ and ϵ $>$ introduce a sinal center is at a distance \sim
- $>$ (1) Synchrotron oscillations of the centroid \Rightarrow **phase stability.** $\sum_{i=1}^{n} a_i$
- $>$ (2) Feedback between beam loading and shape of current profile ⇒ **automatic wakefield flattening** (optimal beam loading). \geq (\angle) reequack being \sim constraints that we start we start we start we start we start that we start that \sim
- > Self-correcting long. phase space: Damps energy spread and energy offset $>$ den-correcting iong.
- $>$ Robust mechanism: specific wakefield regime or exact R_{56} not critical. \sim No. De-Figure No. Defense \sim

Current (kA)

Charge density (nC/μm/%)

Self-correction for Stability and Energy Spread Damping Rel. energy (%) 10 15 $l: L, l \neq m$ **d** Γ $l \neq m \neq n$ $\frac{1}{\sqrt{2}}$ -50 25 Longitudinal position, $\frac{1}{2}$ \mathbf{p} *b* (kA) *Initial profile* <u>- Sta</u> $\frac{1}{2}$ *Final profile* <u>and</u> ability and

Preprint: Lindstrøm, arXiv:2104.14460 (2021) 5 0

- > No need for ultra-precise shaping of current profiles. 0 C
Z
- > Improved synchronization tolerances by several orders to magnitude. o
n
- $>$ (Strong beam loading \Rightarrow natural high efficiency.)

SLAC

- > Implication: **Staging** *not only* **relevant to high energies**
	- > Also beneficial for small-scale plasma accelerators.

- > More R&D required to investigate…
	- > …the coupling to the transverse phase space.
	- > …the effect of CSR, betatron radiation, etc.

Some Nice Movies to Illustrate What is Happening

SLAC

41

Outline

- Why is staging important?
- Challenges and things to consider between stages
- Elements of a complete solution so far considered
- Benefits of having multiple stages
- Staging demonstrations
- Conclusions & Outlook

The Next Steps: Staging

A proof-of-principle demonstration of staging was performed at LBNL in 2016.

BELLA is well-positioned to demonstrate GeV-scale staging with the existing facility.

AWA plans a 0.5-GeV demo followed by a 3-GeV fully-featured module.

Ask to P5: Upgrade AWA facility for 0.5 GeV demonstrator.

FACET-II can study beam transport in and out of a single stage.

Future Request: Facility for demonstrating two or more PWFA stages.

Note to P5: PWFA Staging experiment may be possible at C³ Demo facility.

GeV-scale staging schematic

SWFA 0.5 GeV Staging Demo C. Jing and G. Ha, JINST (2022)

Laser-gated multistage plasma accelerator A. Knetsch et al. arXiv:2210.02263

BELLA Center houses multiple laser facilities addressing laser, accelerator, and light source R&D and applications

BELLA Center Houses a 1Hz Repetition Rate Petawatt Laser for LPA Science

Multi-GeV staging: a key next step on the LPA collider roadmap

• Staging at ∼100MeV using 30TW (BELLA TREX laser) in 2016, but low capture efficiency

S. Steinke PoP **23**, 056705 (2016); B. H. Shaw, PoP **23**, 063117 (2016); J. van Tilborg, PRL **115**, 184802 (2015); S. Steinke, Nature **530**, 190 (2016)

• BELLA PW laser will be used to investigate multi-GeV staging with high efficiency

BELLA PW Facility Layout before 2BL installation

BELLA 2nd bemline (2BL) adds additional laser pulse to the target chamber for the next generation of laser accelerator experiments

2BL enables experiments on multi-GeV staging with high efficiency

- **Injector** to produce electron bunch.
- **LPA 1** driven by 1BL pulse producing quality electron bunch (GeV-energies, ΔE/E < 10%, divergence < 2 mrad).
- Active plasma lens to refocus electron beam.
- **Plasma mirror** to couple in 2BL pulse.
- **LPA 2** driven by 2BL pulse.

Conclusion & Outlook

- Staging will be needed for collider applications of PWFA/LWFA
- Community making steady progress understanding and optimizing individual stages
- Only one staging experiment performed to date
- Next few years will see more
- A complete staging solution is challenging
- …but a great opportunity for smart young people to have an impact
- e.g. the many new and interesting ideas highlighted here from Carl Lindstrøm
- U. Oslo team is developing a workflow to model staging for HALHF concept in preparation for next European Strategy
- Ideas will inform designs for next generation facilities and demonstrations

Questions?

