TOLERANCES FOR PLASMA WAKEFIELD ACCELERATION DRIVERS

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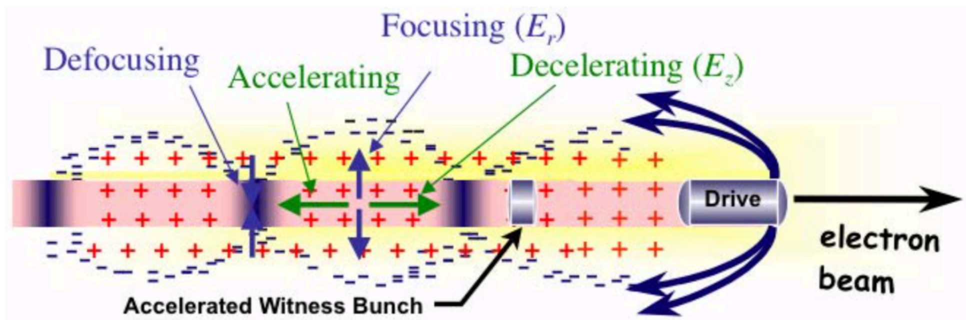
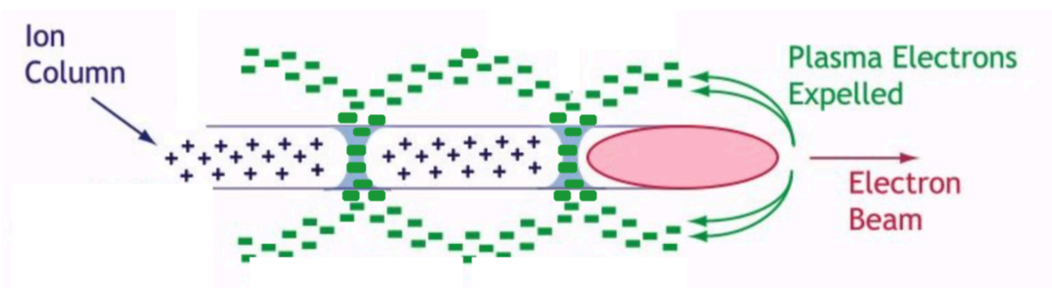
Overview: Beam Driven Plasma Wakefield Accelerator





(Courtesy M. Hogan)

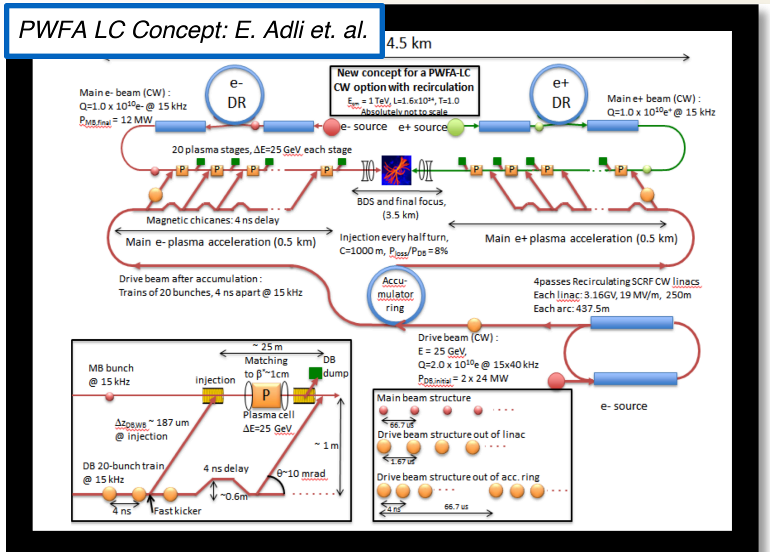
- Accelerating field/gradient scales as $n_e^{1/2}$
- Typical: $n_e \sim 10^{17}$ cm^{-3}, $\lambda_p \sim 100\mu$m, G>MT/m, E>10 GV/m
- Witness beam experiences strong focusing force
- Approximation from Gauss law for infinite cylinder:

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

Consider two-beam (electron), co-linear plasma-based accelerator in "Blow-out" regime ($n_b/n_p >> 1$)

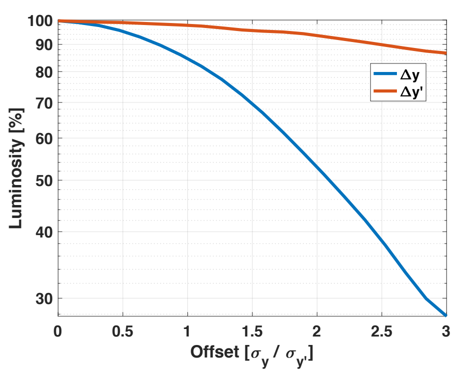
Overview: Jitter Tolerances for a Linear Collider

PWFA LC Concept: E. Adli et. al.



- Consider centroid jitter tolerance (position and angle) of drive beam with respect to witness bunch for a beam-driven plasma accelerator
- Geometric emittance mismatch between drive and witness bunches => tight tolerances on drive beam stability

Beam-Beam Simulation with GUINEA-PIG (e+e-)



σ^* ~ 200 x 1 nm
$\gamma\varepsilon$ ~ 10,000 x 35 nm-rad

Drive Beam $\gamma\varepsilon$ ~ few 1,000 nm-rad @ 25 GeV
vs. "Witness" beam @ multi-TeV

- Collision tolerances looser in angle phase
- For 1% luminosity stability:
  0.1σ (POS), <u>0.3σ (ANG)</u>

Tolerance for vertical collisions at a Multi-TeV linear collider considered to be at 30% of focused beam size

Jitter Model in PWFA Plasma Channel

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- Incoming witness bunch on reference orbit gains random jitter component due to incoming drive beam jitter
- Large (>1 MT) focusing forces due to plasma channel formed by drive beam cause witness bunch to oscillate around drive beam path in plasma channel

M= liner ramp coefficient applied to matched plasma β
N= drive beam jitter normalized by rms beam size

$$\beta_{d,w} = \sqrt{2\gamma_{d,w}}\frac{c}{\omega_p}$$

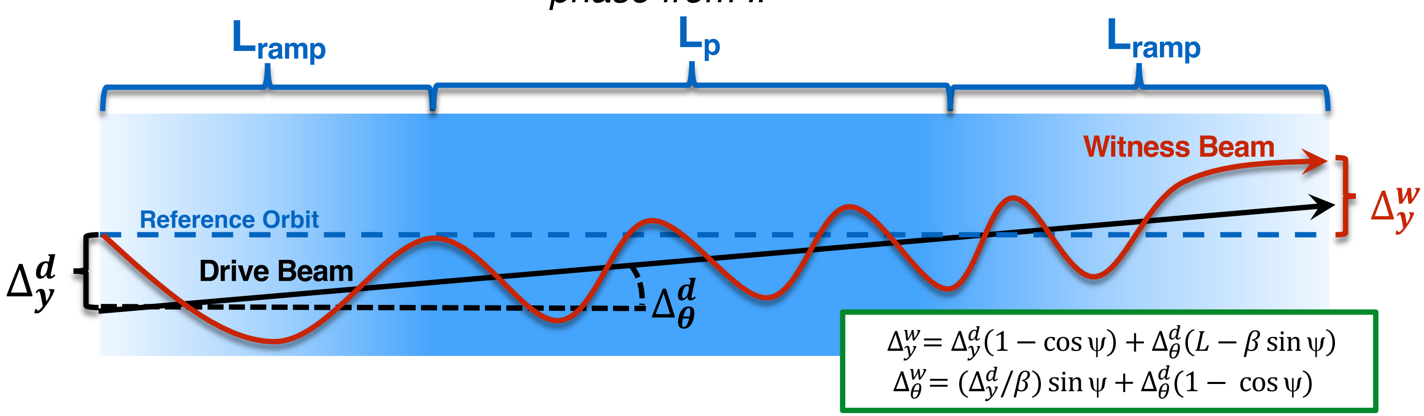
$$\omega_p = \left(\frac{e^2 n_p}{\varepsilon_0 m_e}\right) \approx 5.6E4.\sqrt{n_p(cc)}$$

$$\Delta_y^w = \Delta_\theta^d . L \qquad \Delta_y^w / \sigma_y^w = \frac{\Delta_\theta^d . L}{\sqrt{\varepsilon_y^w \beta_w M}}$$

$$\left(\frac{\Delta_y^w}{\sigma_y^w}\right)^2 = \frac{L^2 N^2 \varepsilon_y^d / (\beta_d M)}{\varepsilon_y^w \beta_w M}$$

$$\left(\frac{\Delta_\theta^w}{\sigma_\theta^w}\right)^2 = 0$$

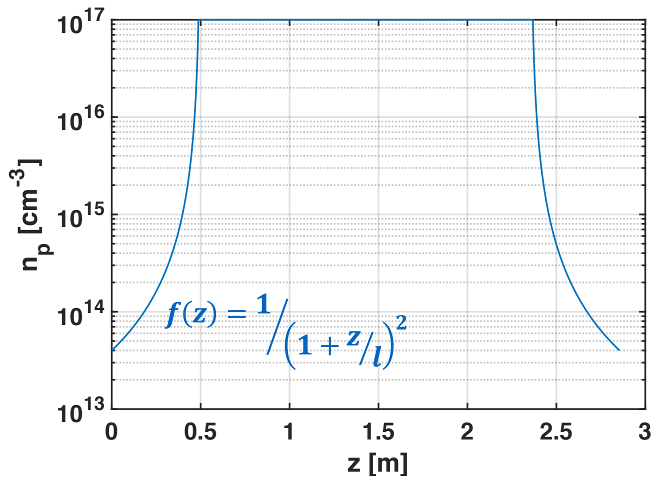
- *Choose phase advance in plasma which produces jitter only in position phase (ψ=2nπ)*
- *Arrange for optics such that PWFA exit nπ/2 out of phase from IP*



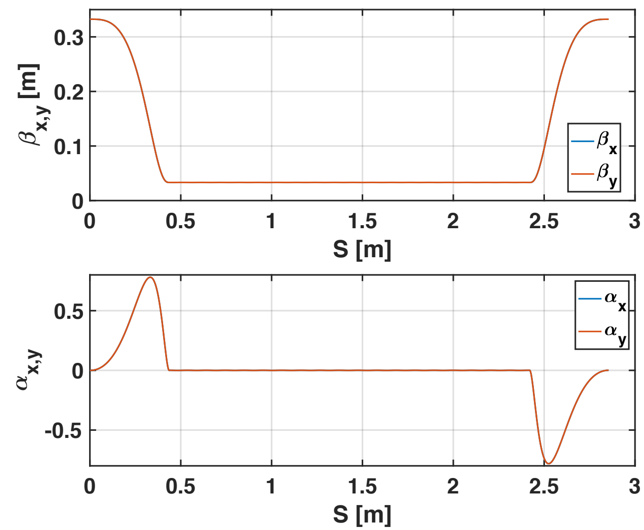
$$\Delta_y^w = \Delta_y^d(1-\cos\psi) + \Delta_\theta^d(L - \beta\sin\psi)$$
$$\Delta_\theta^w = (\Delta_y^d/\beta)\sin\psi + \Delta_\theta^d(1-\cos\psi)$$

Consider simple linear model of jitter transference from drive to witness beam based on plasma channel defined by drive beam + beta matching ramps

Beam Dynamics Model for Witness Bunch Propagation Through PWFA



$$l = \beta_{p0}\sqrt{\left[\frac{(N+1)\pi}{\ln \beta_{\text{goal}}/\beta_i}\right]^2 + \frac{1}{4}}, \qquad \frac{L}{l} = \left(\frac{\beta_{\text{goal}}}{\beta_i} - 1\right), \quad \text{where} \quad N = 0, 1, 2, \ldots$$



- Use 2m plasma channel length
- Taper length and profile to match input/output beam according to optimal formula based on desired beta ramp:

X.Xu et. al. PRL 116, 124801 (2016)

- Sliced plasma lens model for tracking:

$$E_r = \frac{1}{2}\frac{e n_{e0}}{\varepsilon_0} r$$

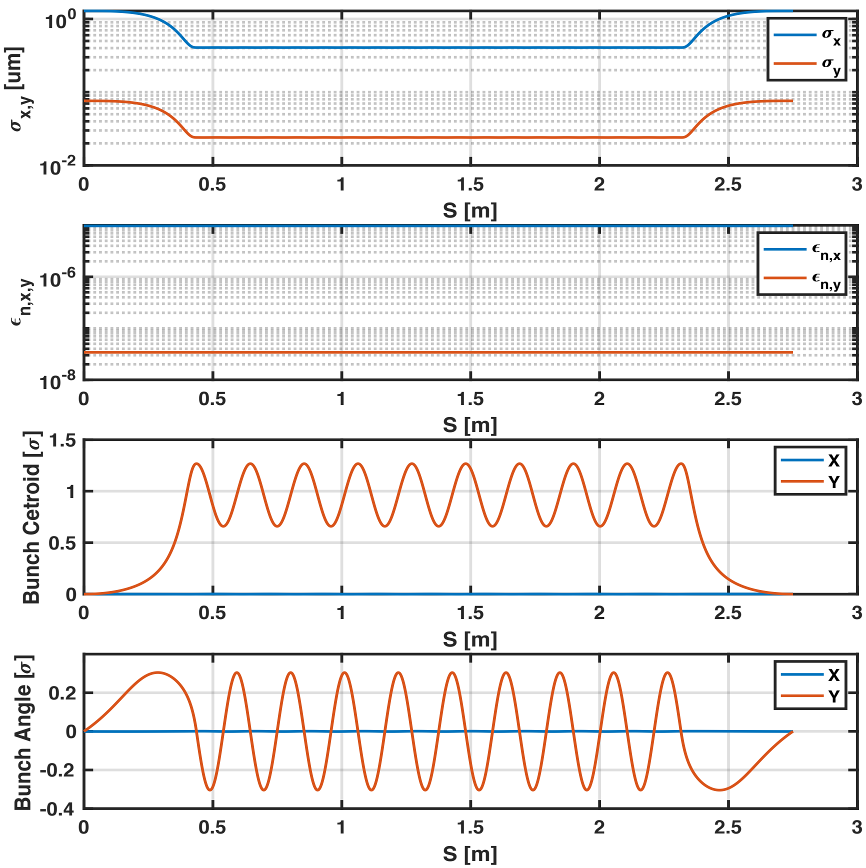
$$g = {}^{E_r}\!/_{rc} \quad \text{(T/m)} \qquad K_q = {}^{g}\!/_{B\rho}$$

Construct sliced tracking model of plasma channel to test simple model

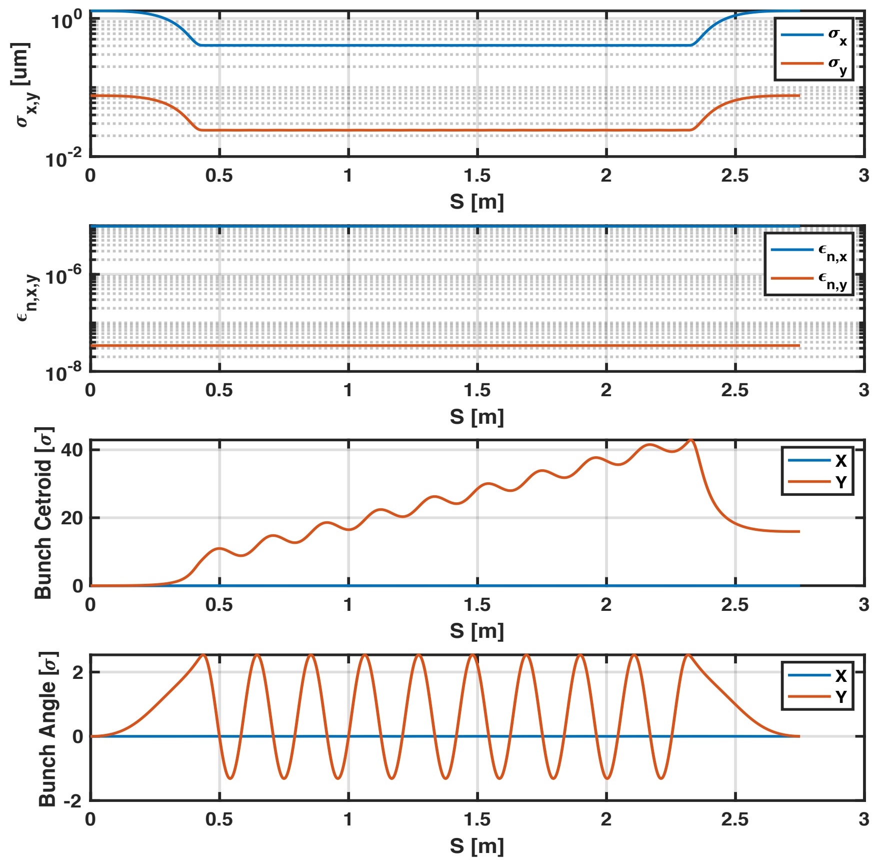
Tracking Example - LC

E_w = 1 TeV ; $\varepsilon^{w}_{x,y}$ = 10, 0.035 µm-rad ; L_p = 2m ; M=10
E_d = 25 GeV; $\varepsilon^{d}_{x,y}$ = 5, 5 µm-rad

$\Delta y_d = 0.01\sigma$



$\Delta\theta_d = 0.01\sigma$

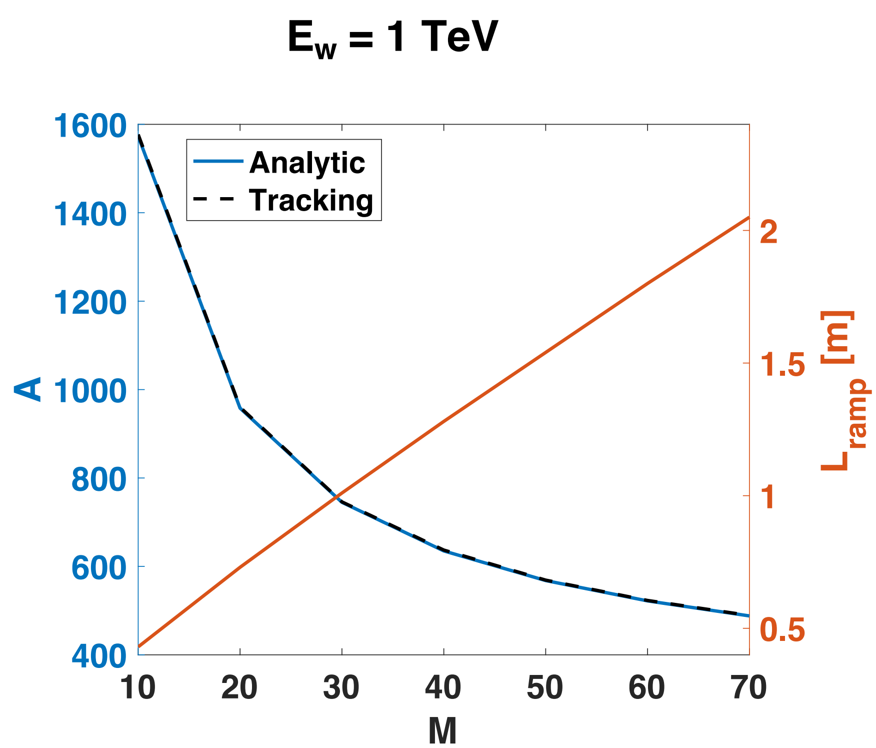


Tracking misaligned beam through sliced model behaves qualitatively as expected

Jitter Amplification vs. Plasma Ramp

- PWFA acts as jitter amplifier of drive beam jitter to witness beam jitter (relative to rms beam sizes)
- Drive beam jitter tolerance for a single plasma cell is:
  witness beam tolerance / *A*
- Amplification factor reduced by use of plasma ramp to increase incoming / outgoing matched beta function
  - Effectiveness limited by physical limitations to length

Jitter amplification factor: $$A = \frac{\Delta y_w / \sigma_{y,w}}{\Delta y_d / \sigma_{y,d}}$$

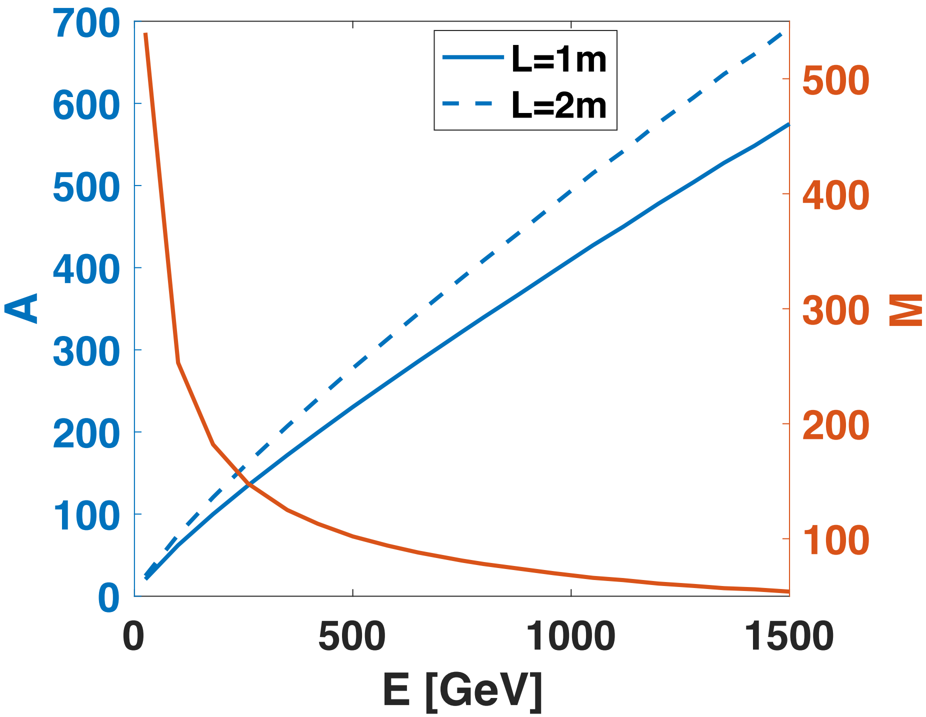


Jitter amplification improves with beta ramp length and tracking agrees perfectly with simple analytical expression

Jitter Amplification vs. Witness Energy

- Assume fixed physical beta ramp length (2m):
  - max M (β/β_p) factor drops (and amplification factor increases) with witness beam energy
- Assess LC jitter tolerance by: *(for n PWFA stages [25:1500] GeV)*

$$A_{LC}^2 = \sum_{i=1}^{n} A_i^2$$



Jitter amplification per PWFA cell becomes worse at higher witness beam energies
Overall jitter amplification from squared sum of each stage

LC PWFA Jitter Tolerance

- Assume 20 x 25 GeV PWFA stages for 1 TeV LC (E_w 25 -> 500 GeV)
  E_d = 25 GeV ; $\varepsilon_{n,d}$ = 5 μm-rad
- Jitter requirement on witness at IP < 0.3σ:
  - L_p = 2m: $\boxed{N_d < 3.8\text{E-}4\ \sigma}$
  - L_p = 1m: $\boxed{N_d < 4.6\text{E-}4\ \sigma}$
- For E_{cm} = 3 TeV LC:
  - L_p = 2m: $\boxed{N_d < 9.0\text{E-}5\ \sigma}$
  - L_p = 1m: $\boxed{N_d < 1.1\text{E-}4\ \sigma}$

Model predicts requirement of 0.01% beam size stability for drive beam
(for 3 TeV collider to deliver witness beam stable to 30%)

Expected Jitter Levels from Existing Facilities?

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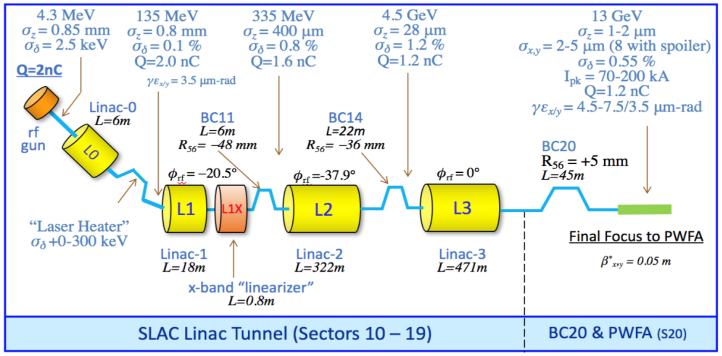
FACET-II @ SLAC



Jitter @ PWFA Entrance

Nominal -> Upgraded

- $\Delta_x / \sigma_x = 0.69 \rightarrow 0.36$
- $\Delta_y / \sigma_y = 0.2 \rightarrow 0.015$

Monte Carlo Simulation Parameters

Property	Unit	FACET	Upgraded
Source Charge Fluctuation	%	1	0.1
Source Electron Position Fluctuation (laser spot jitter on cathode)	% $\sigma_{x,y}$	3	3
Initial Electron Laser Timing Error	fs	200	10
L1 Phase Jitter	degS	0.1	0.01
L2/L3 Phase Jitter	degS	0.25	0.01
L0P Phase Jitter	degS	0.1	0.01
L1 Amplitude Jitter	%	0.1	0.01
L2/L3/L0P Amplitude Jitter	%	0.25	0.01
BC0 & BC11 Magnet Strength Jitter	dB/B	1e-5	1e-6
BC14 & BC20 Magnet Strength Jitter	dB/B	1e-4	1e-6
L1/L2/L3/S20 Magnet Vibration (x/y), rms	μm	1.5/0.5	0.02/0.02
e- injector Magnet Vibration (x&y), rms	μm	0.1	0.02

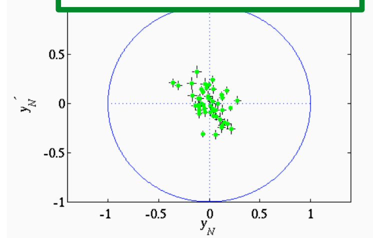
Upgraded: Engineering estimates of max performance given unlimited R&D scope (assuming no technology breakthroughs)

Beam Parameter	Symbol	Unit	Design	rms Jitter: FACET	rms Jitter: Upgraded
Horizontal position	x	μm	0	5.5	0.36
Vertical position	y	μm	0	1.6	0.12
Horizontal angle	x'	μrad	0	103	8.0
Vertical angle	y'	μrad	0	8.6	4.5
Arrival time	t	fs	0	103	6.7
Horizontal rms beam size	σ_x	μm	8	1.4	0.13
Vertical rms beam size	σ_y	μm	8	0.05	0.02
rms Bunch length	σ_z	μm	1	2.5	0.13
Peak current	I_{pk}	kA	70	20.9	4.4

FELs

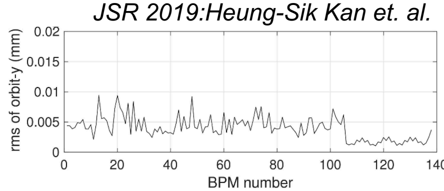
FEL 2008: F Decker et. al.

LCLS (2008) Δ_y / σ_y ~10%



PAL-XFEL (2019) Δ_y / σ_y ~10%

JSR 2019:Heung-Sik Kan et. al.



Many existing Linac-based accelerators exhibit ~10% beam size jitter
FACET-II I_{pk} >> FEL's: expect ~20% y jitter, or down to 1.5% with cost-no-object upgrades

What Limits Performance? SC Driver Example

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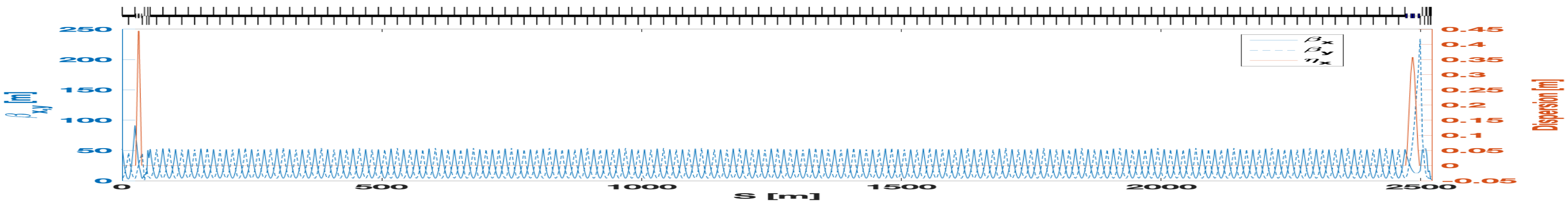
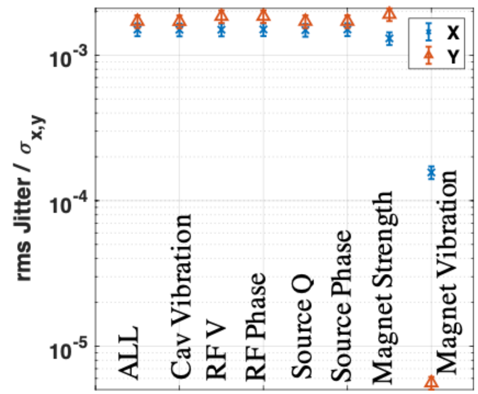
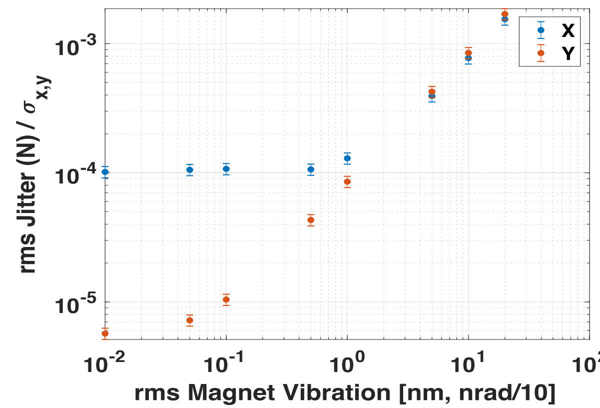


Parameter	Symbol	Value
Injector energy	E_i	135 MeV
RF Frequency	f_{rf}	1.3 GHz
Injector emittance	$\varepsilon^i_{x,y}$	5.0 μm-rad
Injector rms Bunch Length	$\sigma_{z,i}$	1.0 mm
Injector rms energy spread	δ_E/E	1.2 %
Bunch charge	Q_b	3.2 nC
Final Energy	E_f	25.0 GeV
Final rms Energy Spread	δ_E/E	1.5 %
Final rms Bunch Length	$\sigma_{z,f}$	11.3 μm
Final Transverse Size	$\sigma_{x,y}$	20 μm
Final Peak Current	I_{pk}	30 kA
Driver linac length	L	2.5 km
Average beta function	β	30 m





- Simplified 2-stage L-band Linac & compressor
- Using jitter parameters from before, dominant source is vibration of magnets
  - Need <1nm stability (>f_{rep}) (at least for FFS magnets)
- Ignores complexities due to recirculating linacs, accumulator ring, delay system, PWFA injection, PWFA internal tolerances etc…

In simplified driver linac, nm-scale magnet vibration tolerances dominate witness jitter

Summary

- For a beam-driven PWFA accelerating structure, the incoming drive beam acts as a jitter amplifier for the witness beam due to a large mismatch in geometric emittance
- To achieve a 0.3σ beam stability requirement for a LC application, the drive beam jitter tolerance is **~1E-4σ** (for a 3 TeV collider)
- Compared with an existing PWFA driver facility (FACET), tolerances are **2000X** tighter than currently achieved and **150X** higher than achievable through upgrades to the existing accelerator with known technology.
- Considering simplified purpose-designed SC Linac + BC, jitter tolerance may be met but needs <nm magnet stability for key magnets
  - *CLIC R&D shows this could be feasible*
  - *Omits many complications of real drive beam accelerator complex*
- Outlined case for 2-bunch PWFA concept but also applies to laser-driven case

Driver accelerator system for PWFA acceleration stages requires tolerances on beam stability >100X existing facilities