FCC-ee Pre-injector Complex Studies

Brendan O'Shea / Lead Scientist / Advances Accelerator Research Department Head
On behalf of S. Bettoni, P. Craievich and A. Latina
2024 FACET-II PAC & User Meeting

SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University
U.S. DEPARTMENT OF ENERGY

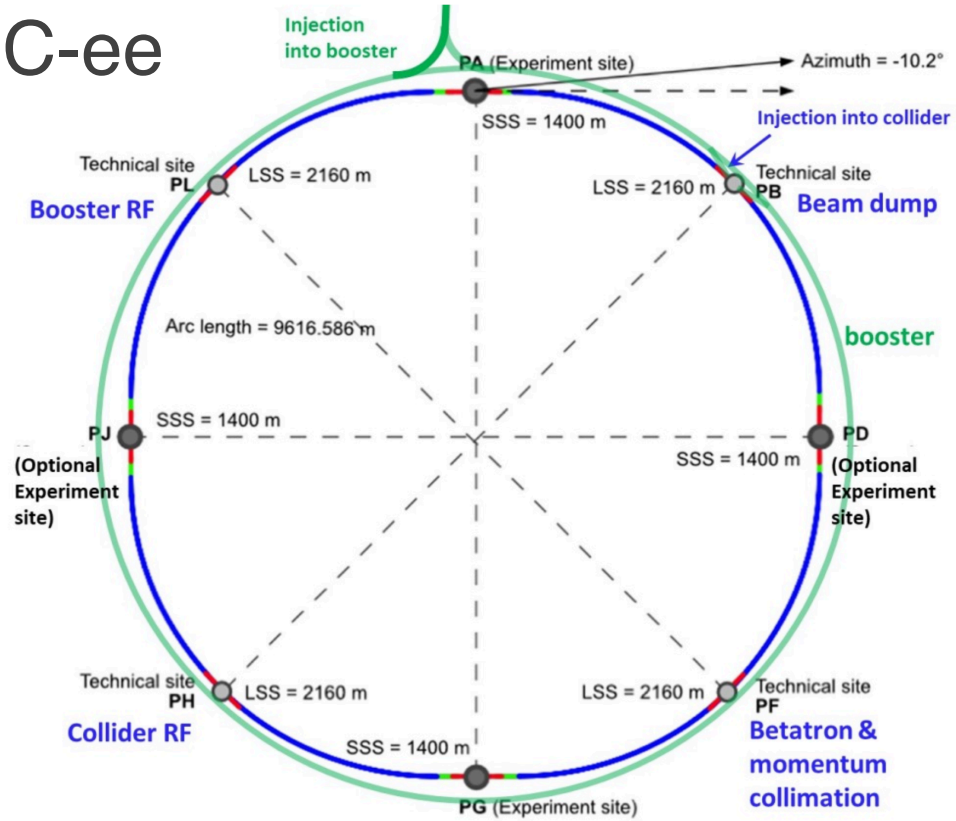
[1]F. Zimmermann, FCC Week 2024

FCC-ee Higgs Factory

Exploring the Quantum Universe

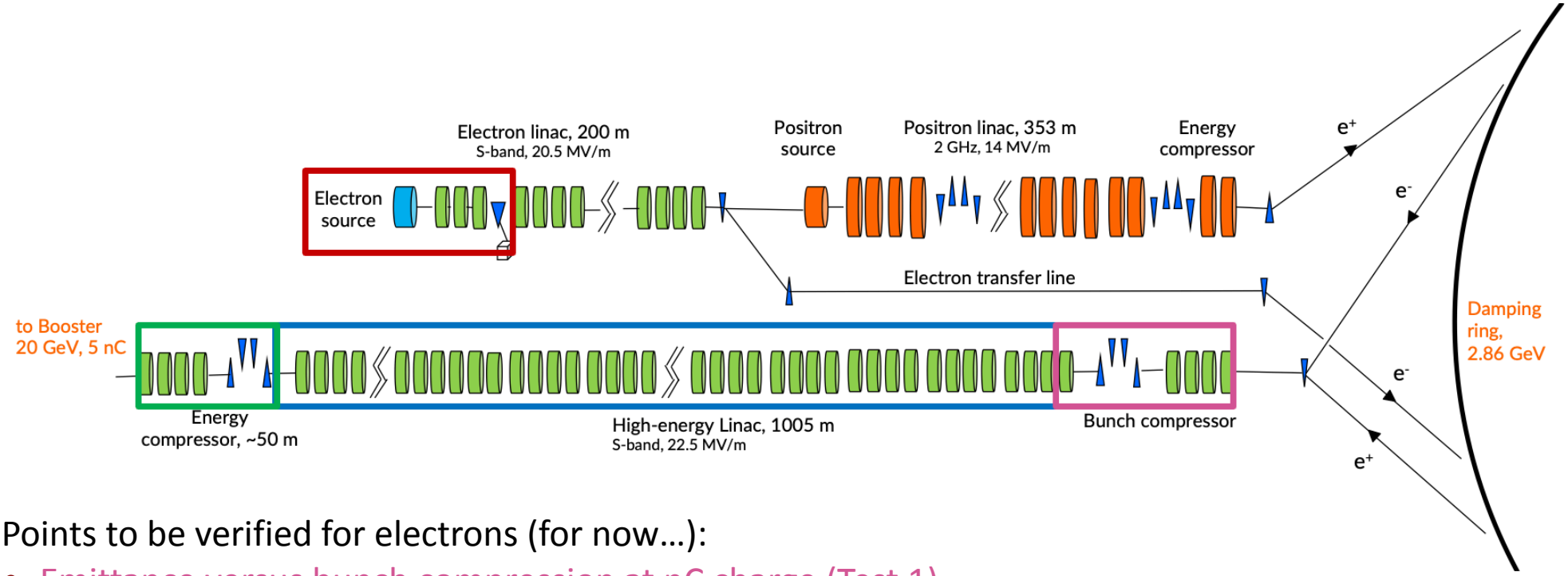
Recommendation 2c:
"An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies."

FCC-ee



FCC-ee is aligned with P5 recommendation for an offshore Higgs factory

FCC-ee Pre-injector



Points to be verified for electrons (for now…):

- Emittance versus bunch compression at nC charge (Test 1)
- Transverse jitter amplification and damping (Test 2)
- Bunch generation for top-up injection: charge scan from 0 to 5 nC (Test 3)
- Test of energy compressor (Bonus)

FACET-II in unique position to test feasibility of FCC-ee design

[1] Phinney, Nan. "SLC final performance and lessons." arXiv preprint physics/0010008 (2000).
[2] Funakoshi, Y., et al. Journal of Instrumentation 19.02 (2024): T02003.
[3] P. Emma, SLAC-TN-05-042
[4] S. Bettoni, C3 Workshop

History of high-charge beams

- Experience at SuperKEKB:
  - Emittance is 6x higher at half the charge
  - Overall luminosity is ~8% design value [2]
- SLC achieved 80% design charge, made up luminosity with optics improvements [1]
- LCLS operational experience lead to charge reduction [3]

FCC-ee Pre-injector

FCC-ee Pre-injector
HE Linac (2.86-20 GeV)

N_bins	Δε (mm.mrad)	ε (mm.mrad)
8	**0.6**	**1.6**
9	0.6	1.6
10	0.6	1.6
12	0.6	1.6

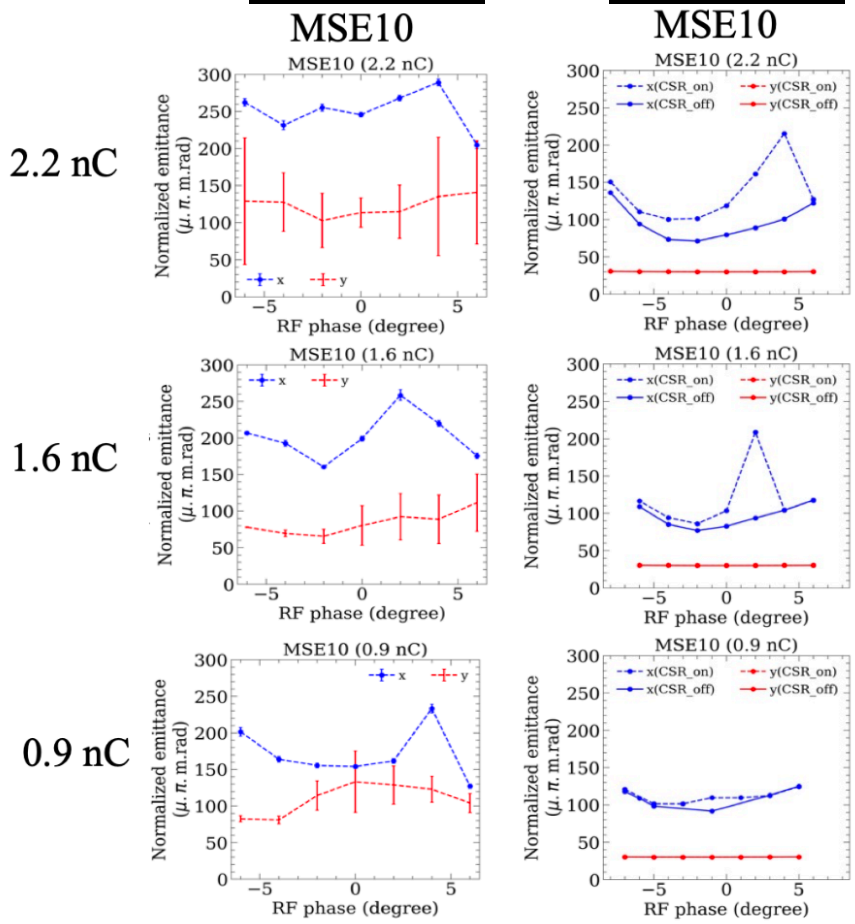
a/λ = 0.12

FCC-ee Pre-injector Booster Injection Parameters

Parameter	Value	Unit
Norm. emittance (x, y) (rms)	<(2,20)	mm.mrad
Bunch length (rms)	~4	mm
Energy spread (rms)	0.1-0.15	%
Transverse jitter	1	sigma
Number of bunches	4	
Bunch spacing	25	ns
Charge variation	100	%

SuperKEKB

Measured **Simulated**

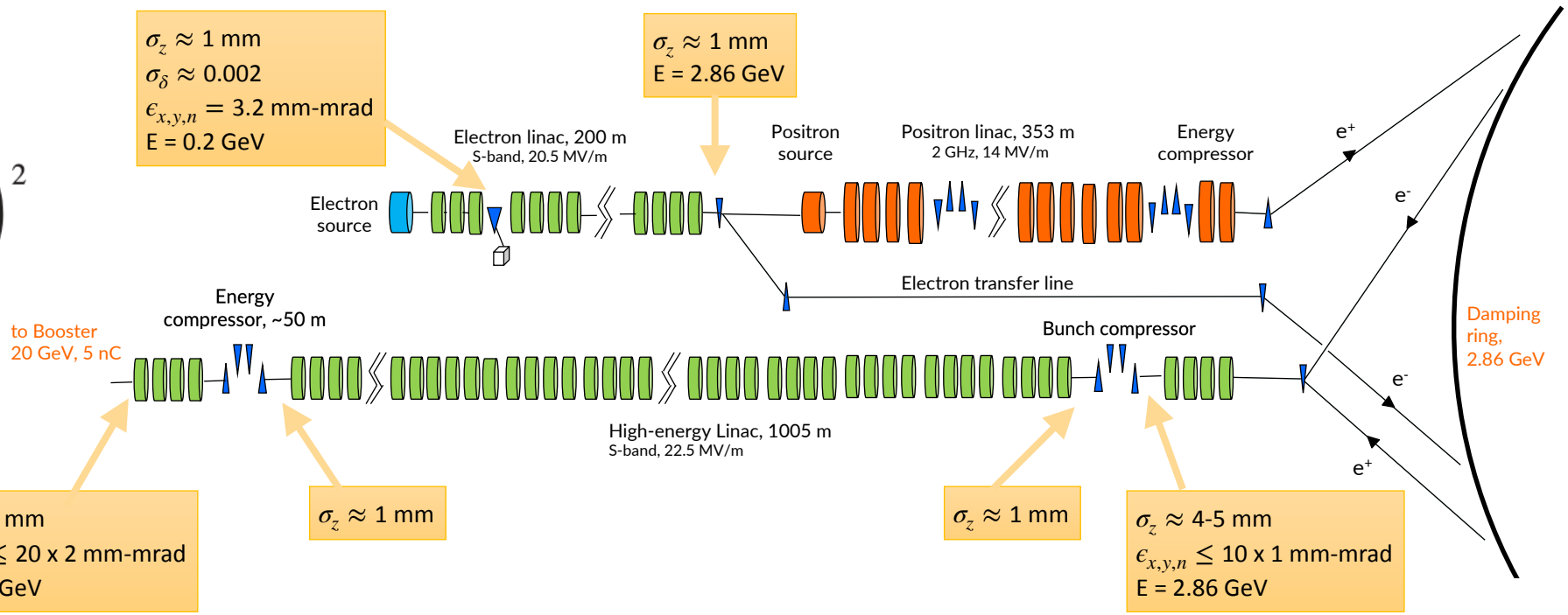


High charge beams have been challenging at times

Emittance growth + bunch compression (Test 1)

$$\Delta\epsilon_N^{(s)} \approx 7.5\times10^{-3}\frac{\beta_x}{\gamma}\left(\frac{r_e N_b L_B^2}{\rho^{5/3}\sigma_z^{4/3}}\right)^2$$

$$\Delta\epsilon_N^{(x)} \approx \frac{(-3+2\sqrt{3})\beta_x}{24\pi\gamma}\left(\frac{\Lambda r_e N_b L_B}{\rho\sigma_z}\right)^2$$



- Norm. emittance out of the damping ring is expected to be 10 x 1 mm-mrad (H x V)
- Booster ring expects <= 20 x 2 mm-mrad

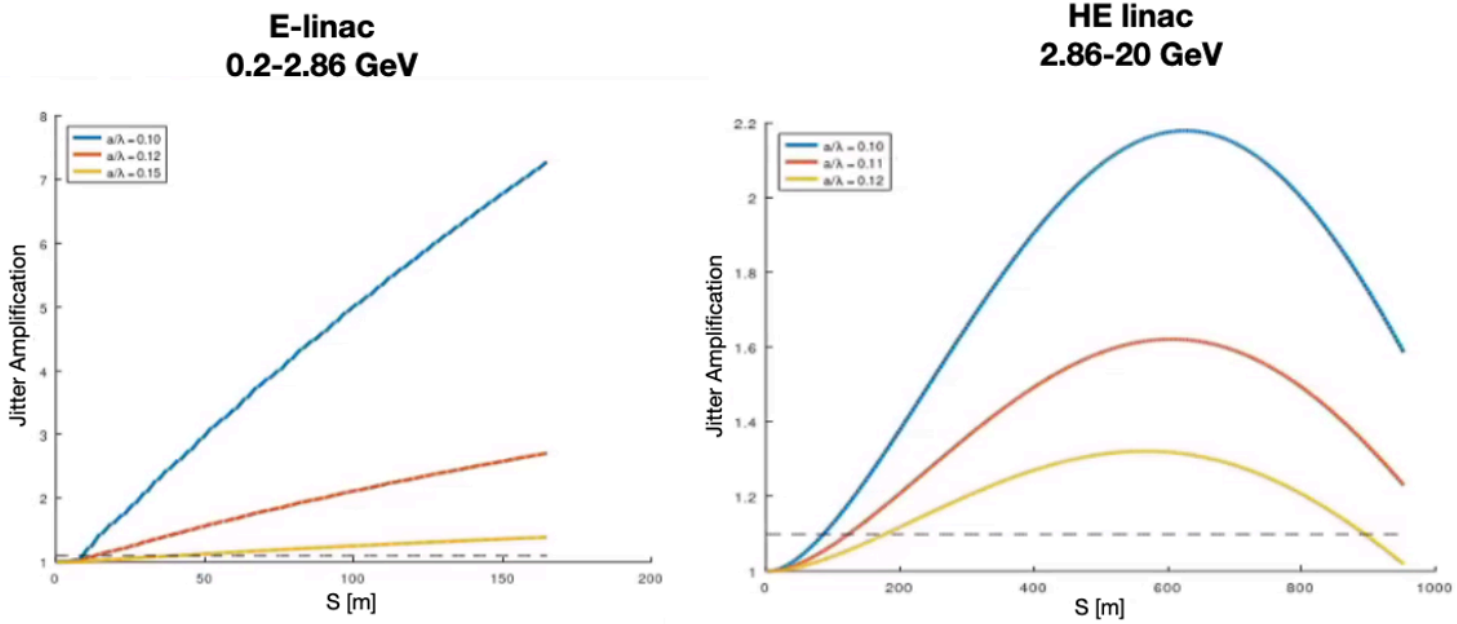
- Estimated emittance growth due to static effects:
  - misalignments is 60%
  - bunch compression (at 5 nC) is 20%

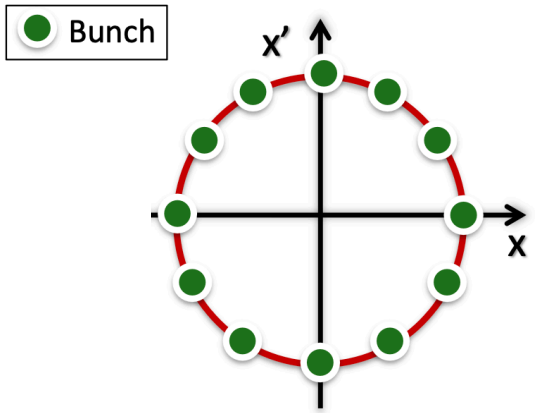
Emittance growth models have to be benchmarked to ensure FCC-ee performance

Jitter Amplification (Test 2)

- Jitter Amplification (JA) simulations fulfill pre-injector requirements with a margin of 30% - validation necessary
- JA depends on short+long range wakefields
- Observed damping mechanism along linac

Test between BC11 and BC14





Jitter amplification computation:

- Single bunches distributed on a circle (in 10 degrees step size) injected to the line with different (x,x')
- Computed the area in the initial beam transverse phase space → A_0
- Computed the area in the final beam transverse phase space → A_F
- Jitter amplification, JA, is defined as the ratio of the areas → A_F / A_0

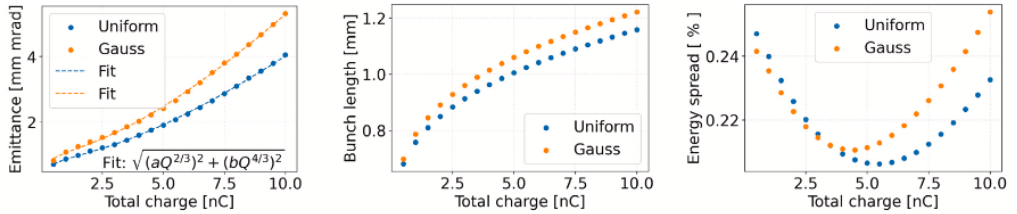
$$JA = \frac{A_F}{A_0}$$

Long-range wakefield models developed for FCC-ee simulations will be tested

Z. Vostrel and S. Doebert. "Design of an electron source for the FCC-ee with top-up injection capability." NIMA 1063 (2024): 169261.

Photoinjector performance when varying charge (Test 3)

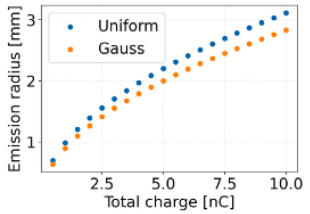
- FACET-II Injector has produced up to 4.2 nC, with sufficient energy overheard to reach 5 nC
- Photoinjector simulations were used to seed inputs into linac simulations
- Initially investigate charge scaling with energy and beam size using existing methods, fill in a few points
- Redesign beam paths on S10 laser table to include SLM and Pockels cell, install Summer 2025
  - Run at 10 Hz, fill in plot



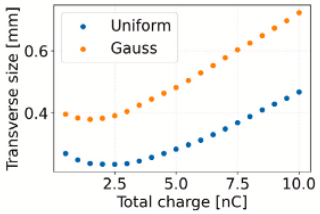
(a) Rms normalized transverse emittance.

(b) Rms bunch length.

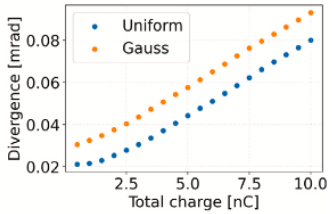
(c) Rms energy spread.



(d) Emission radius.



(e) Rms transverse beam size.



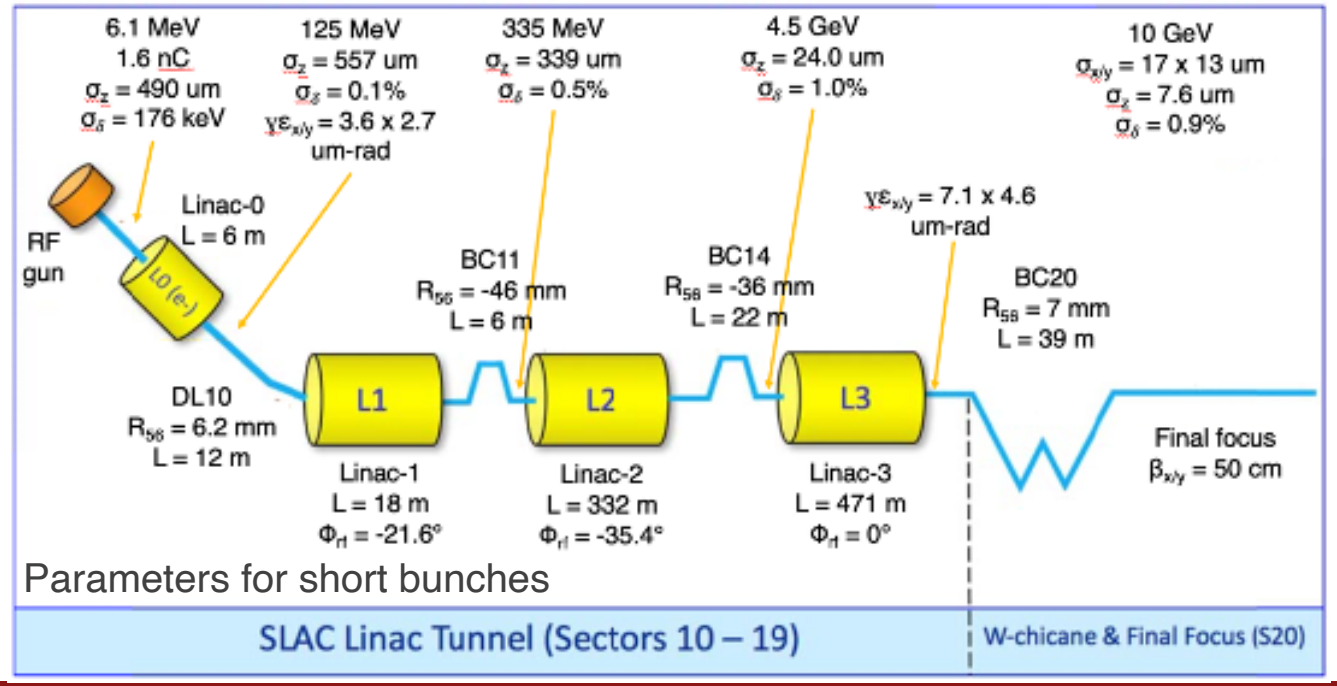
(f) Rms beam divergence.

Bunch parameter	Simulation	Target
Transverse emittance	3.14 mm.mrad (rms) Assumed 3.2 mm.mrad (rms)	< 4 mm.mrad
Bunch length	0.96 mm (rms)	1 mm
Final energy	190 MeV	200 MeV
Energy spread	0.2% (390 keV)	< 0.5 %
Bunch charge	5 nC	5 nC

FACET-II can demonstrate FCC-ee photoinjector performance

FACET-II parameters

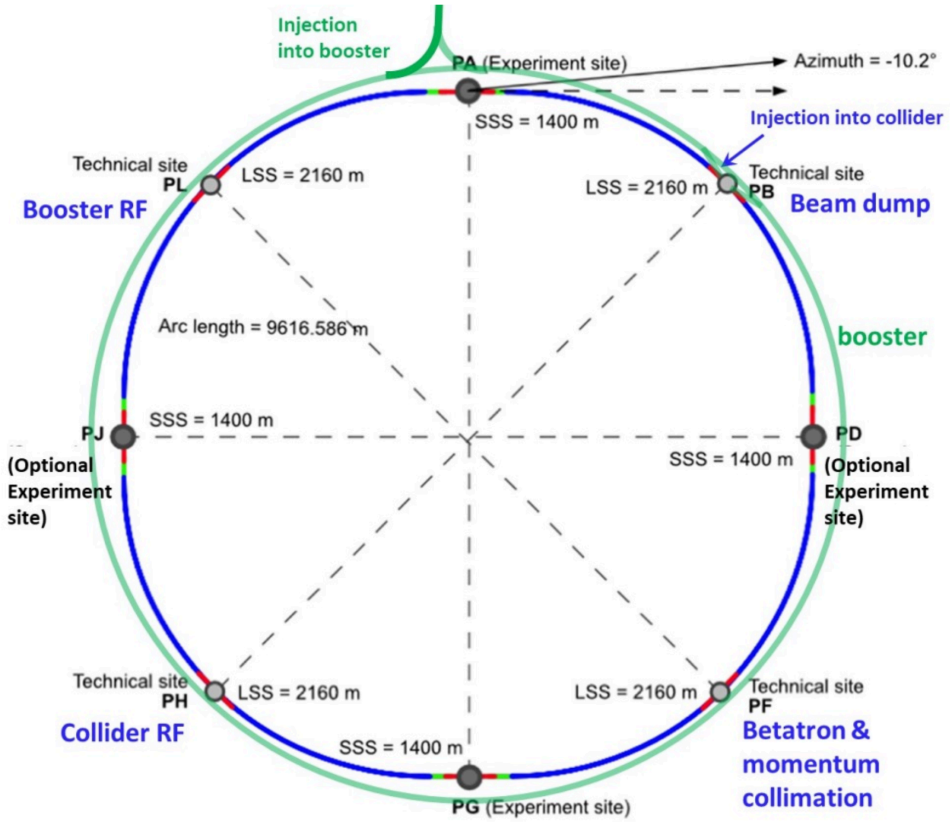
- For emittance growth measurements (Test 1) can reach parameters by changing RF parameters
  - Reverse phase in L1 and L2 to decompress beam to 1 mm FWHM
  - Adjusting laser using existing knobs can get us 2x in laser pulse length, potentially more
- Charge variation measurements (Test 3)
  - Photoinjector previously run at 4.2 nC
  - Start by using existing mechanical methods to adjust energy and beam size
  - Upgrade to 100 Hz compatible methods: spatial light modulator and Pockels cell
- Jitter Amplification (Test 2)
  - Single bunch measurements possible without modification
  - Multibunch would require installation of 25 or 50 ns delay



Most proposed measurements possible with simple machine adjustments

Conclusion

- The design of the FCC-ee pre-injector is a combination of many individually well understood methods
- Previous experience shows that models and simulations are most of the story, but not all
- Validation of parameters at the system level is necessary for project of the size of FCC-ee



Validate system level models in this experimental campaign

Thank You!