Accelerator Configurations and Upgrades

FACET-II

Facility for Advanced Accelerator Experimental Tests

FACET-II PAC Meeting 2022

Glen White / Lead Scientist / AD-ARD Beam Physics

October 25, 2022

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

Outline

Accelerator configurations designed to meet science needs of user programs

Start-to-end tracking simulations with current machine configuration

Minimum # of configurations for ease of accelerator operations:

1. "Clean" single bunch: low energy-spread, low peak-current
   - e.g. **E320 -> requires high energy for γ-boost of photons & low-backgrounds for sensitive measurements of low-energy tails of detected signals**
2. Highly compressed single bunch: high energy-spread, high peak-current (<~80kA)
   - e.g. **E305 -> require v. high fields from bunch to drive instabilities in high-density plasmas, solid targets etc.**
3. 2-bunch for PWFA experiments
   - e.g. **E300 -> High peak-current drive + high-quality witness bunch tailored for optimal beam loading**

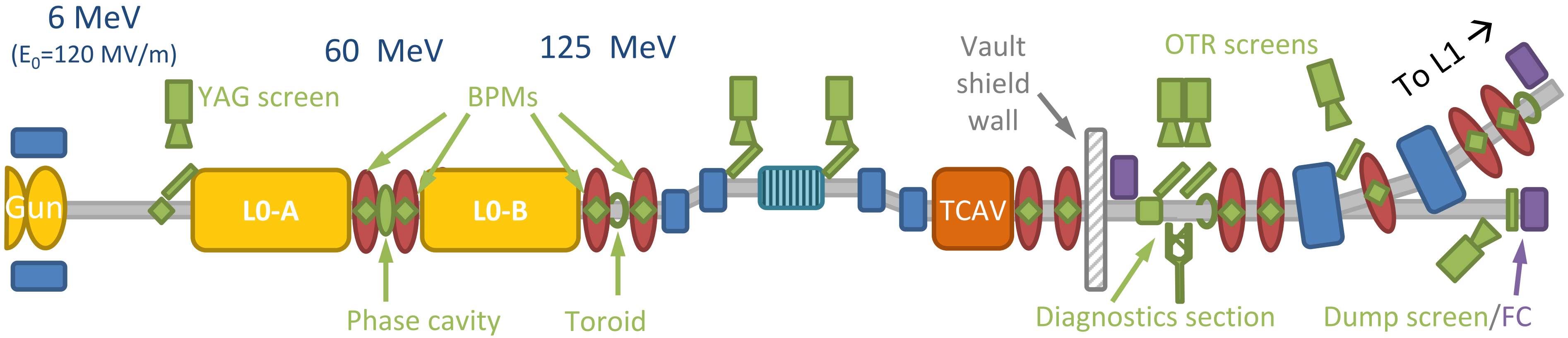
Considered modifications to electron accelerator baseline design

1. Can we get a notch collimator simulation that looks good to tease while we wait for two-bunch mode from gun?
2. Upgrade of final stage BC20 compression chicane?
3. Injector laser heater for increased longitudinal stability, bunch length control & μ-bunching suppression

Some operational experience:

- Injector
- Linac emittances
- Sector 20 transverse bunch size & length

Electron Injector Design & Operational Parameters

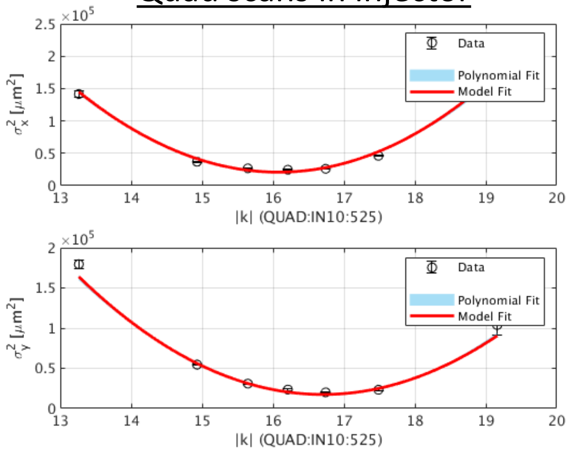


Parameter	Single Bunch	2 Bunch		Operation
		Driver Pulse	Witness Pulse	
Gun rf Phase (deg)	10	15		30
Laser spot Gaussian rms width pre-cut [mm]	5.0	4.5		
Cut radius on transverse laser spot [mm] (initial dist. X2 rms)	2.68	2.68		2.75
Laser pulse length (FWHM) [ps]	7.0	7.0	4.0	3.8
L0-B phase w.r.t. $\delta_{E,min}$ (deg)	0	-9		0
Gun Solenoid Int. Field Strength [kG.m]	0.38	0.48		0.39

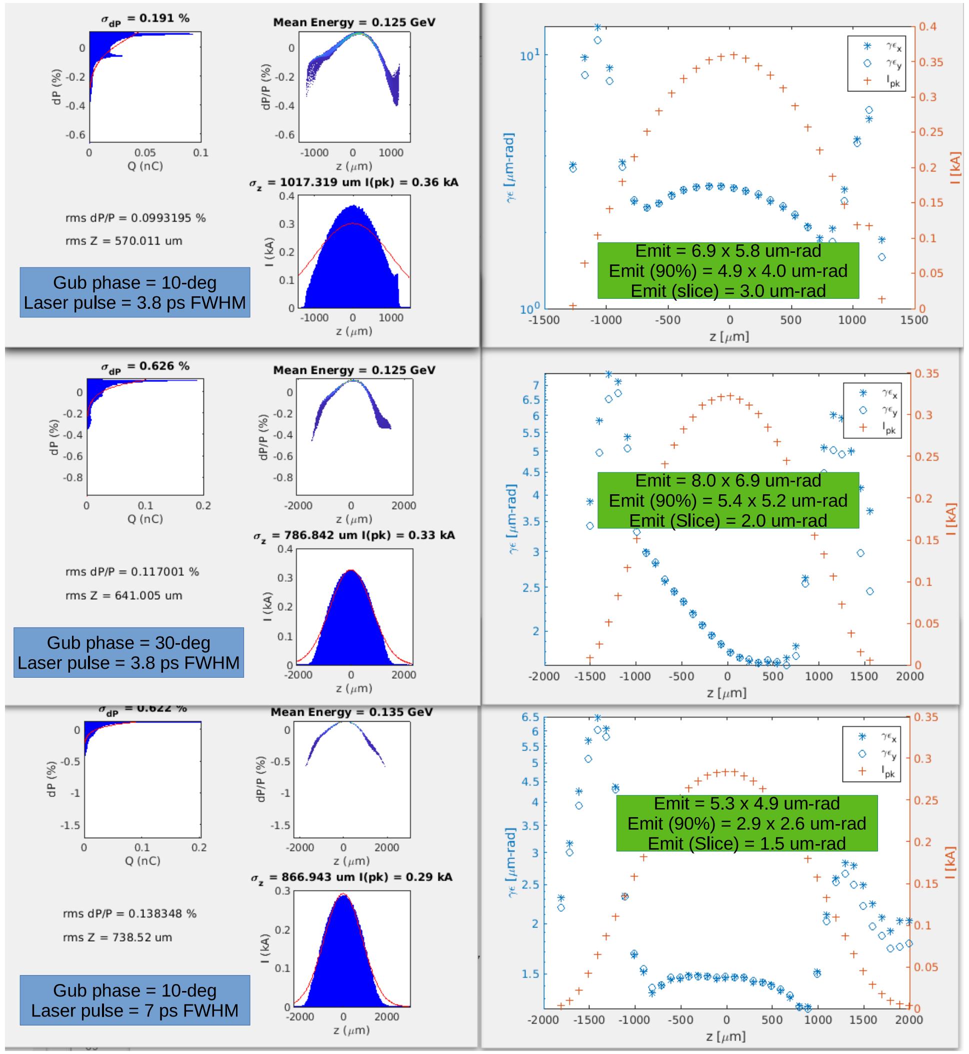
Injector operating well, but with shorter than designed laser pulse on cathode

Beam Parameters into L1

<u>Quad scans in injector</u>



GPT Tracking Simulations →

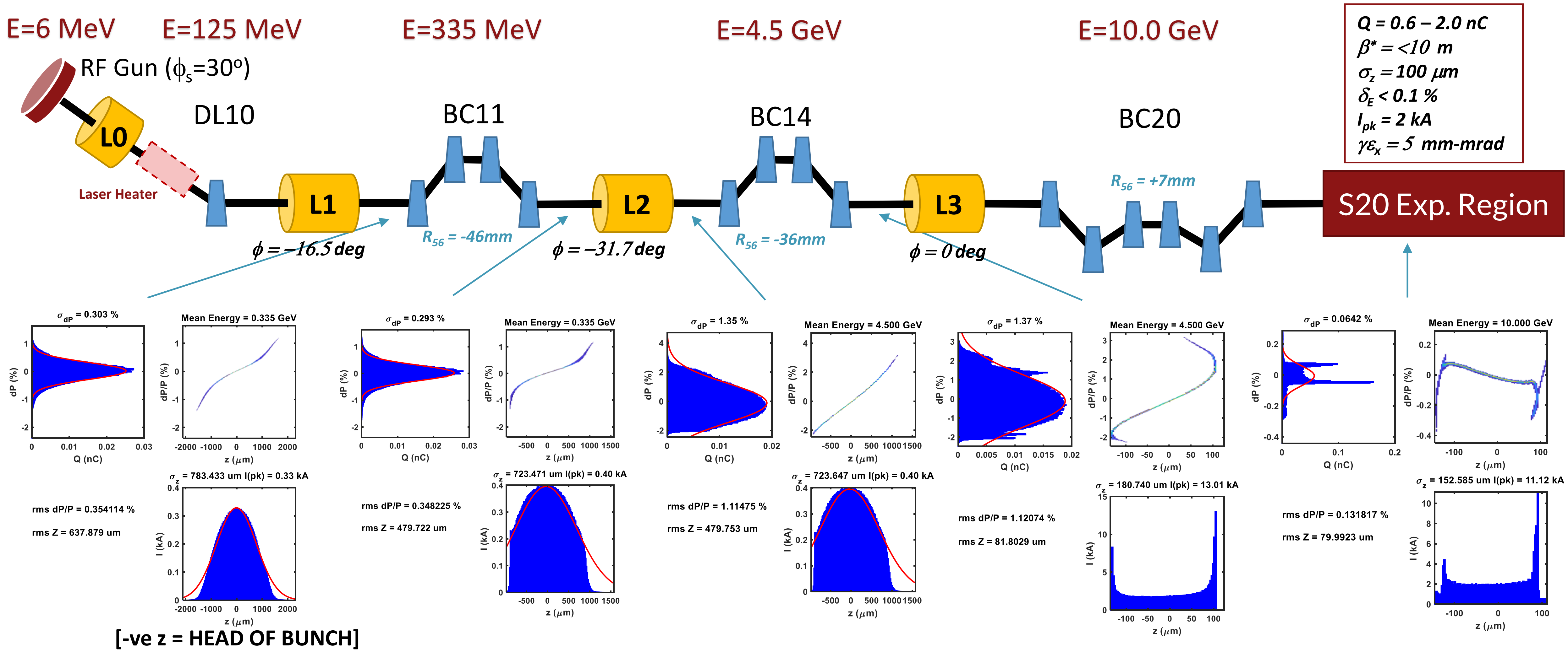


- Operation close to design achieved for short test
  - 2nC, 10-degree Schottky phase (shorter laser pulse)
- Expected emittance measured in injector
- 7ps FWHM laser pulse needed to realize optimal emittance & desired longitudinal profile in Linac

Parameter	FACET-II TDR	Double-Pulse Option		Operation (typical)	Operation 8/21/2022
		Driver Pulse	Witness Pulse	$\phi_s=30^0$	$\phi_s=10^0$
Bunch Charge [nC]	2.0	1.6	0.5	1.6	2.0
Transverse Emittance (90%) [μm-rad]	3.0	3.1	2.3	4.5-5.5	4.9 x 5.2
Peak Current [A]	290	270	180	?	?
Bunch Length (rms) [μm]	736	608	277	?	?
Bunch separation [mm]	--	2.18			

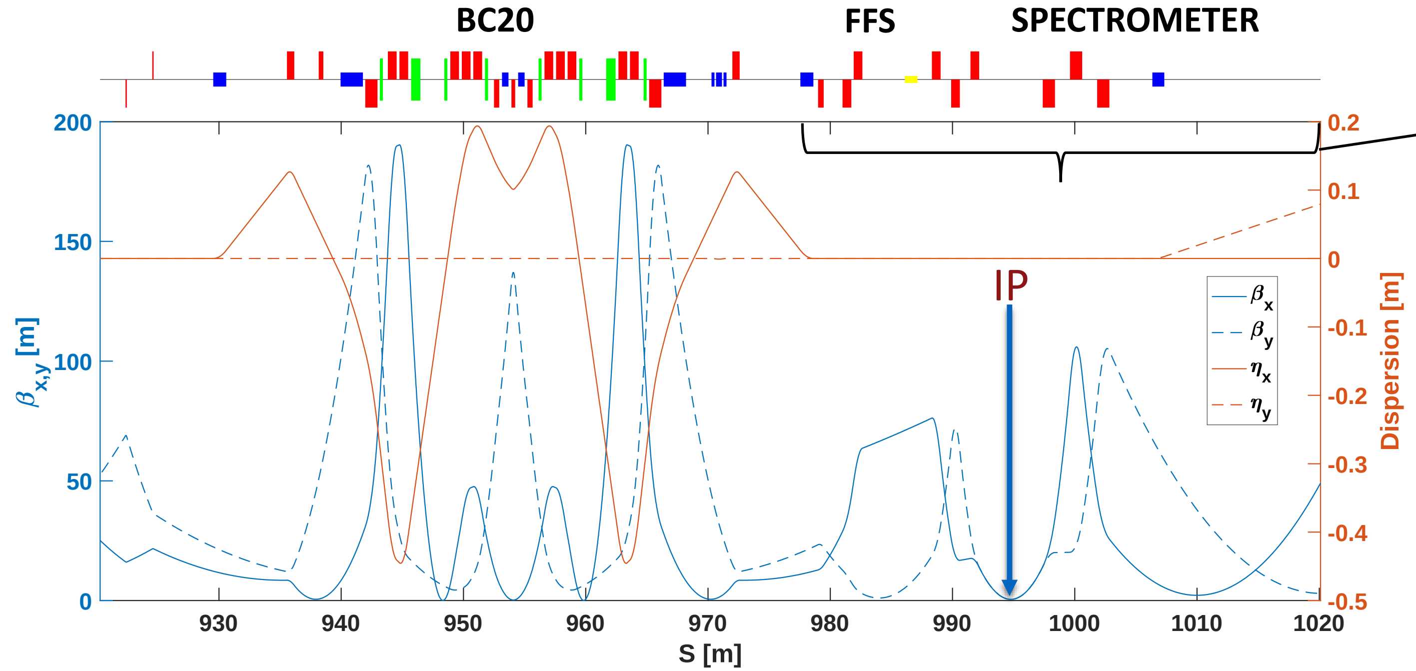
Injector emittance matches design expectations, longitudinal still to be measured

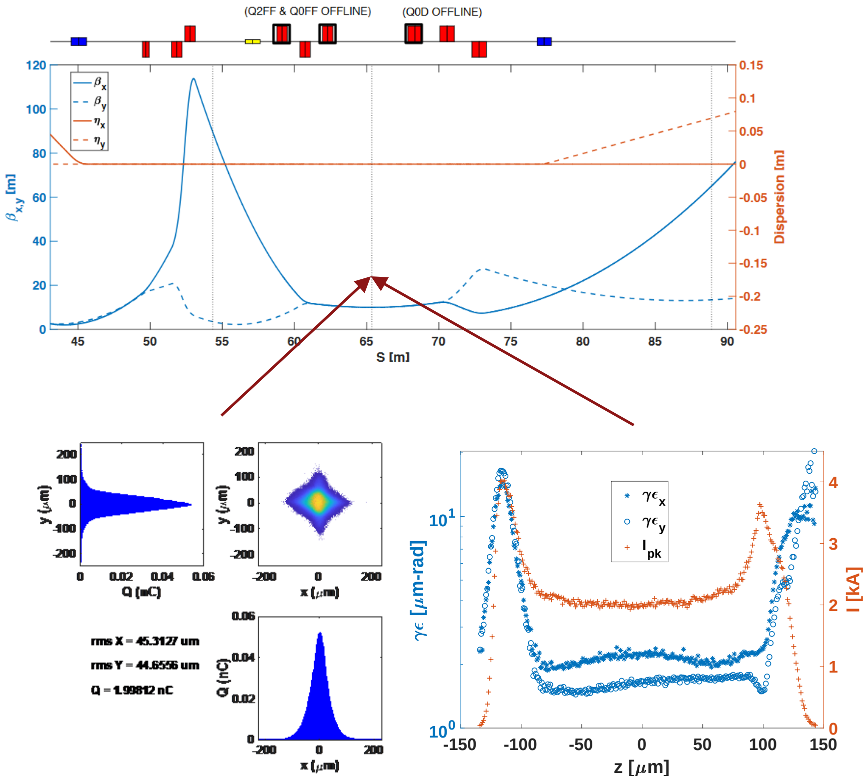
1) Single Bunch "Clean" (Low E-Spread) Design Configuration



Low-compression, low final E-spread, good emittance preservation configuration

1) Sector 20 & Transverse Particle Tracking Results



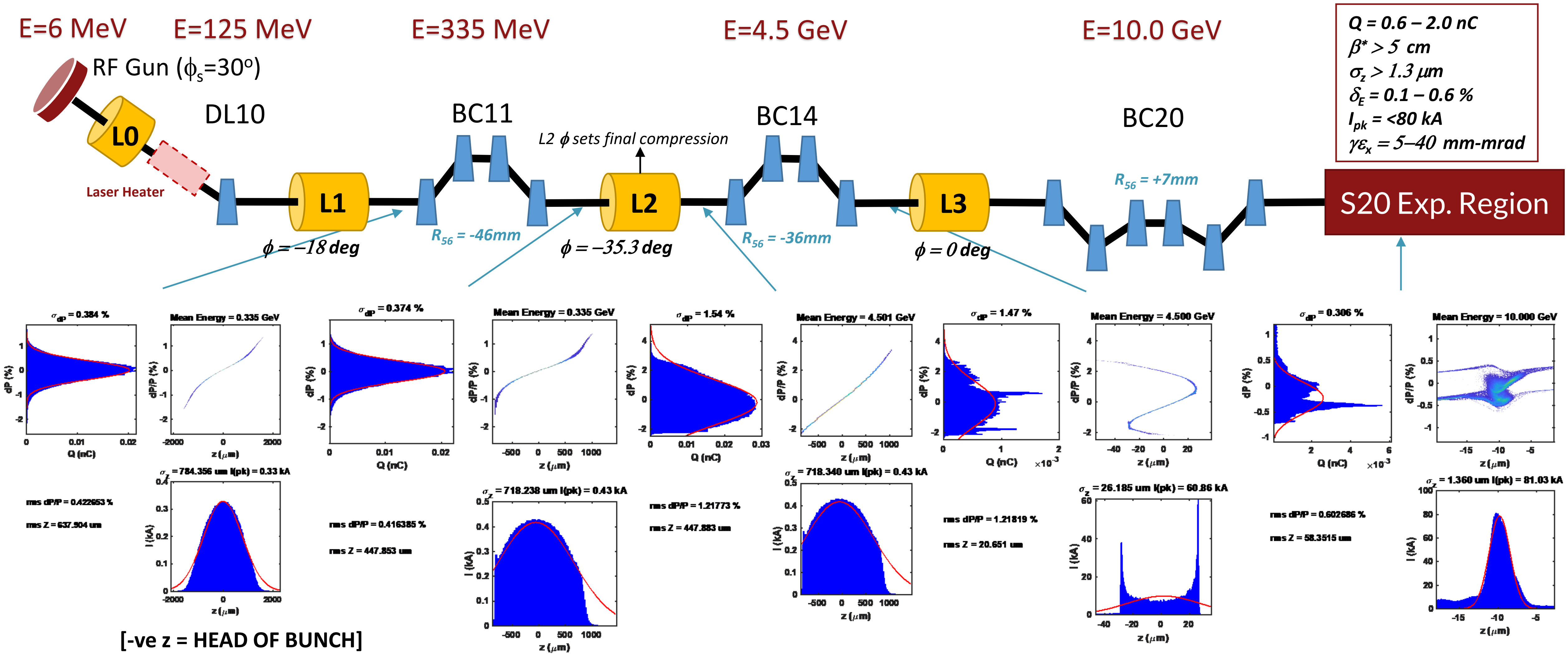


E320 Configuration with β^*=10m

- Current FACET-II Sector 20 layout, matched for R56=+7mm, β^*=50cm
- 3 families of sextupoles matched to minimize T566, & ε_x
- FFS quads (5 families of magnet) matched for round beams at IP
- R56 matching range = [-10:+10] mm
- β^* matching range > 5 cm

Sector 20 contains existing "W" chicane from FACET, new FFS & spectrometer magnets to handle round-beams

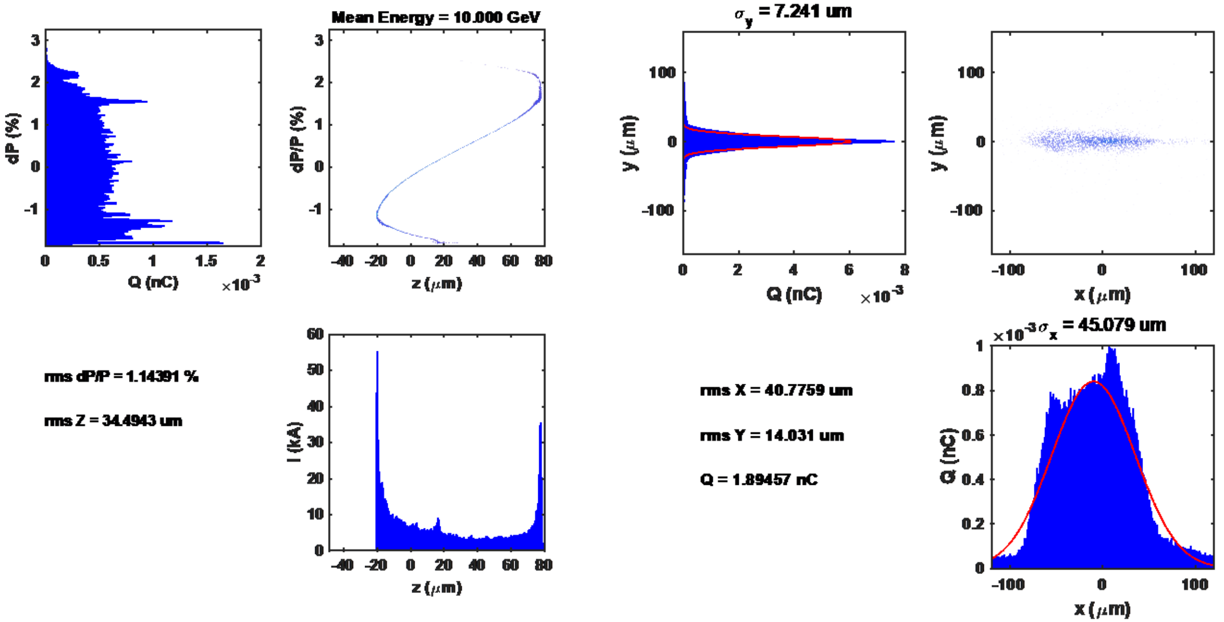
2) Single-Bunch Max-Compression Design Configuration

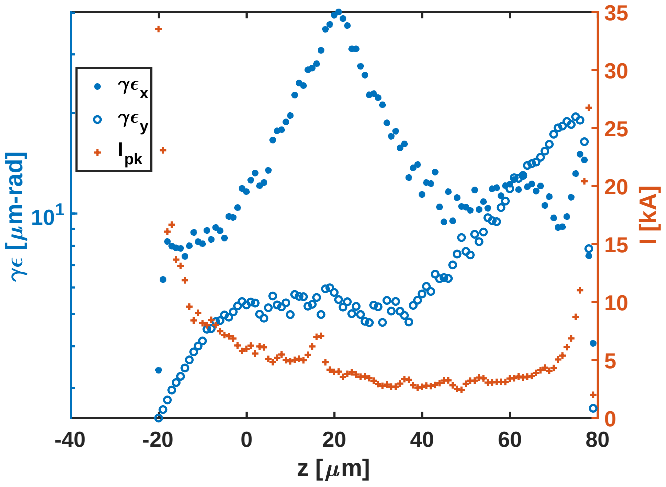


[-ve z = HEAD OF BUNCH]

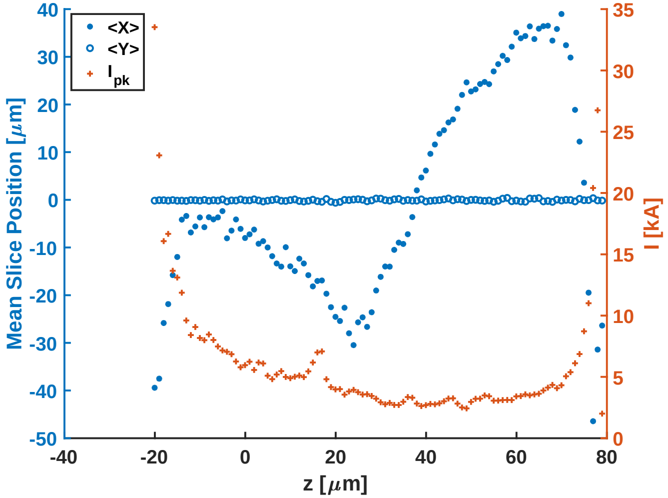
Parameters for high-peak current in S20 with 3.8ps source laser pulse

2) High Compression Simulation using Run 1 Parameters



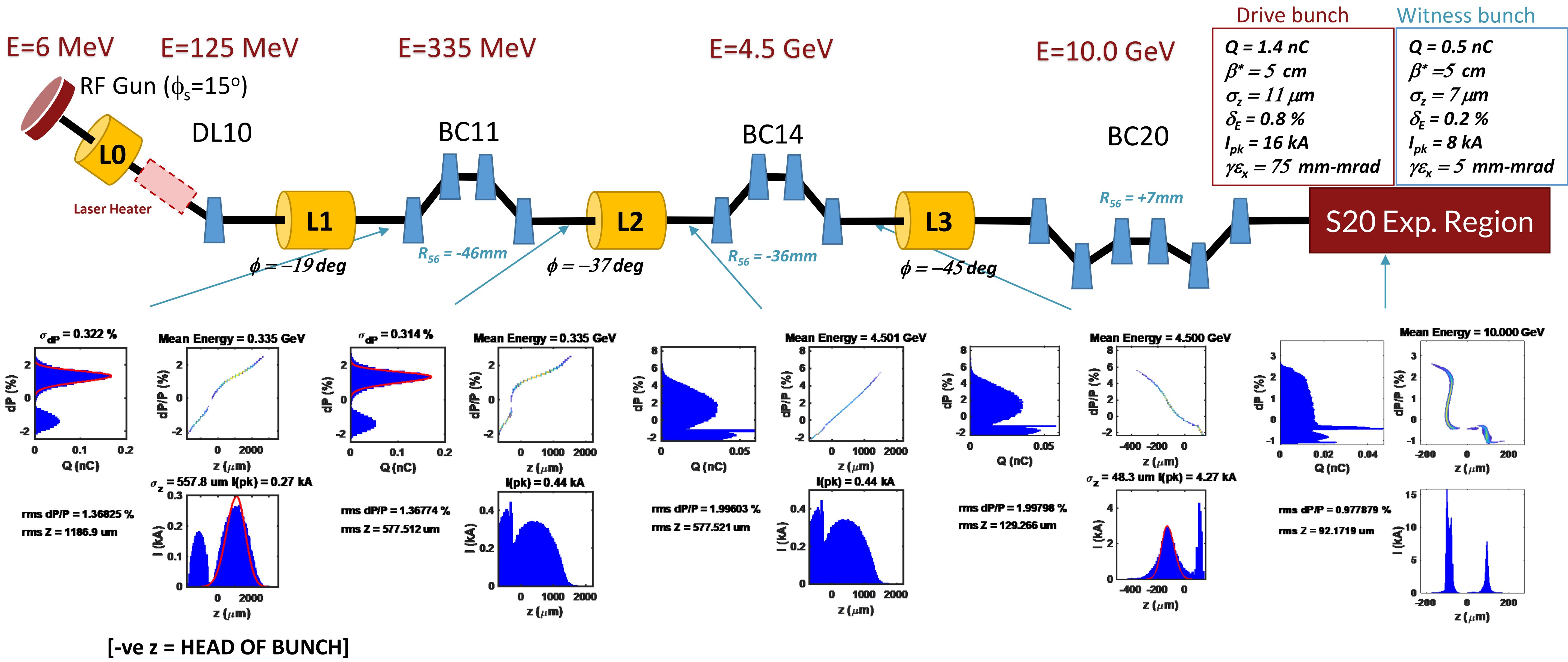


- $\phi_{L1} = -20.5^0$, $\phi_{L2} = -41^0$
- Over-compression in BC20 leads to large horizontal emittance growth: large x:y beam size ratio (not usually seen in practice)
- CSR generates longitudinal position-dependent kicks according to charge as beam traverses BC20



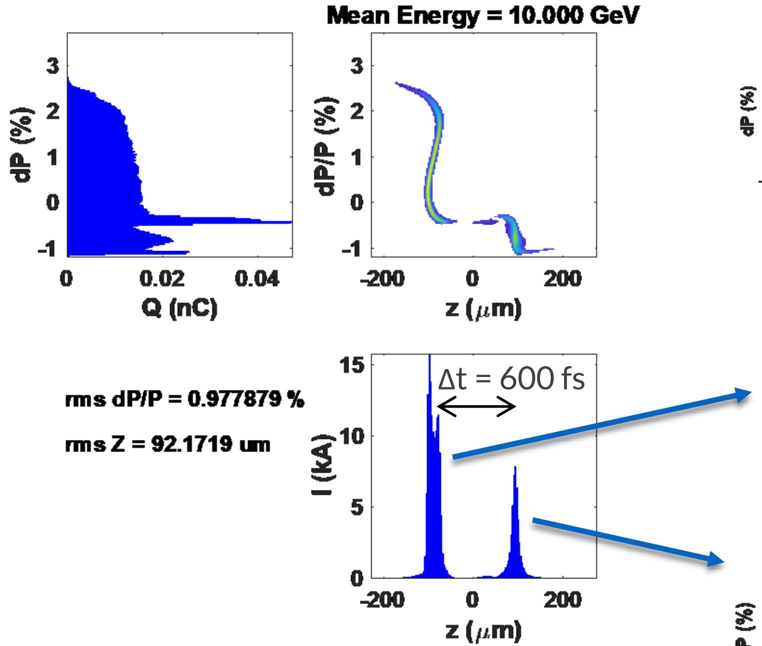
Bunch compression : bend-plane emittance growth tradeoff due to CSR effects

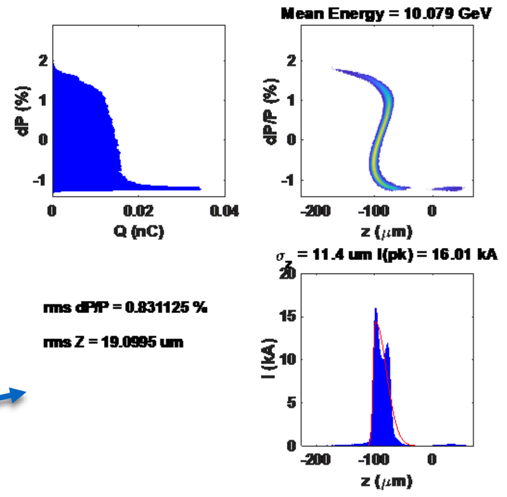
3) Two-Bunch Design Configuration

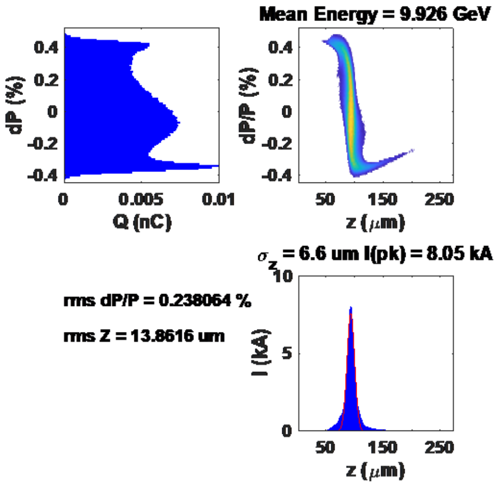


Double-pulsed laser on RF Gun generates drive+witness pulse with 3:1 charge ratio, 2:1 I_{pk}

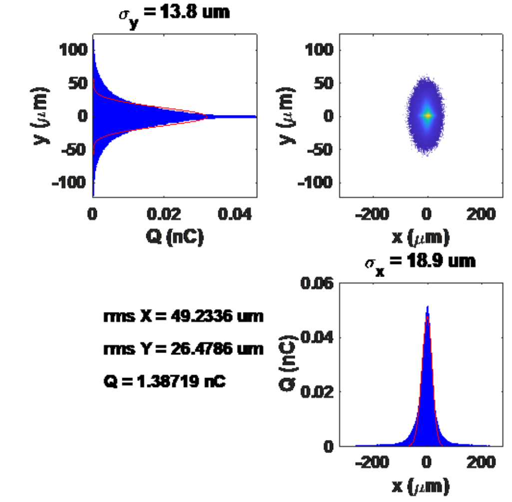
3) Two-Bunch Particle Distributions @ IP







Drive Bunch

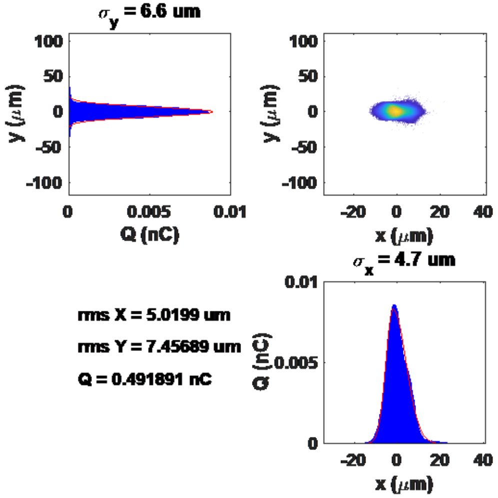


$\gamma\varepsilon$ = 73 x 35 μm-rad

β^* longitudinal waist offset due to energy difference

$\Delta W_{x,y}$ = 22.8, 17.3 cm

Witness Bunch

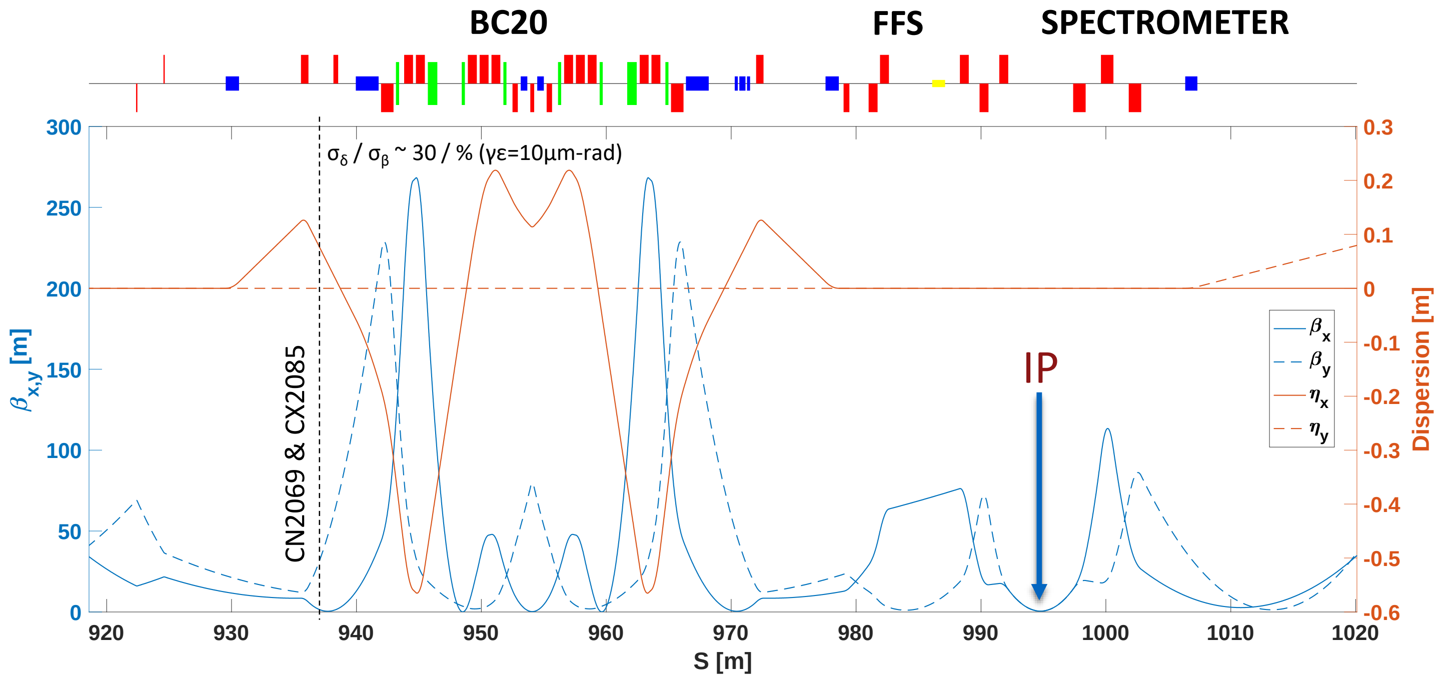


$\gamma\varepsilon$ = 4.5 x 2.6 μm-rad

- Can make use of BC20 "notch" collimator to help separate bunches
- 150 MeV energy difference between drive & witness generates different beam dynamics
- Trade-offs exist e.g. bunch spacing vs. transverse quality: iterating with experimental groups to optimize

High-quality witness bunch generated, driven by higher charge drive beam at requisite longitudinal spacing

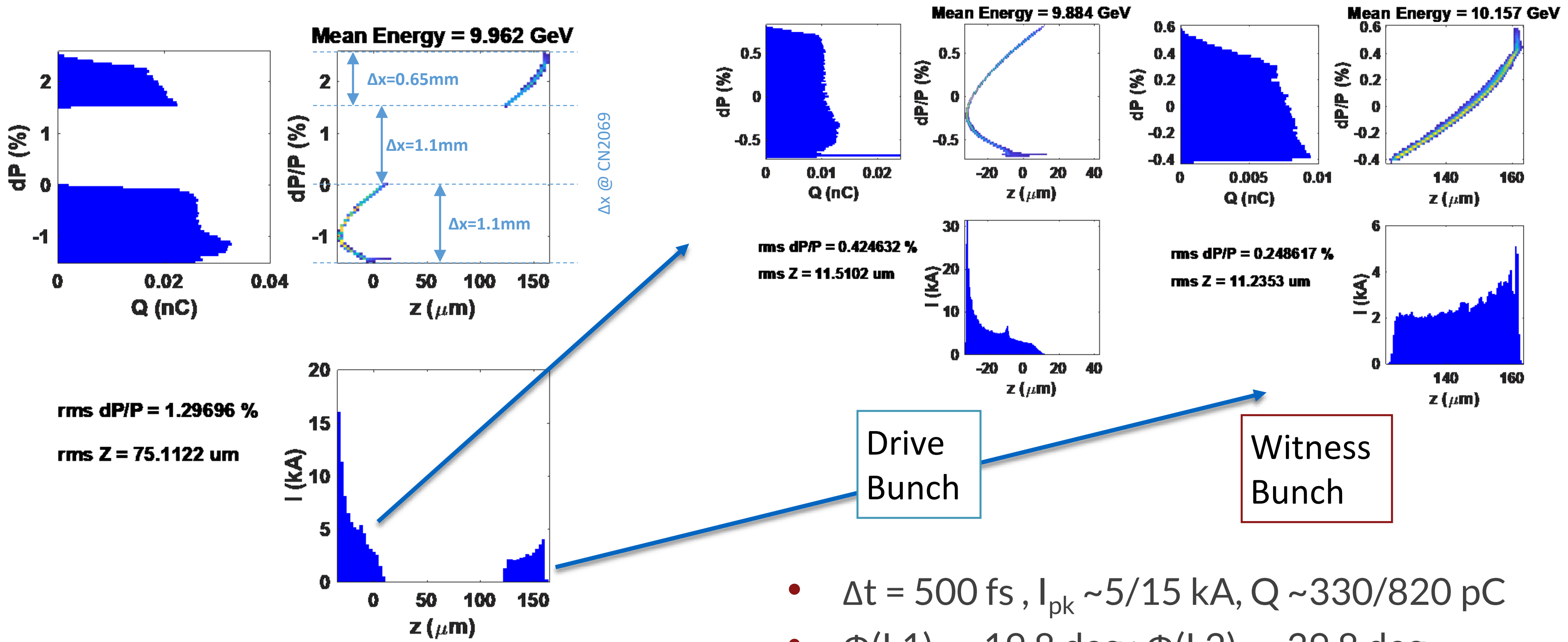
Alternate 2-Bunch Setup using BC20 Notch & Jaw Collimators



- Whilst we commission double-bunch injector setup, use tested notched 2-bunch setup from FACET-I experience
- Compared with FACET-I, smaller head-tail energy spread: re-configure for larger R56 in BC20
  - Optics re-matched for R56=+10 mm
  - Adjust L1 & L2 rf phases to fine-tune 2-bunch results
- Use notch & jaw collimators as indicated to generate 2-bunch profile

Option to use FACET-I mechanism for 2-bunch operations with modifications to BC20 optics

Alternate 2-bunch Configuration Particle Tracking

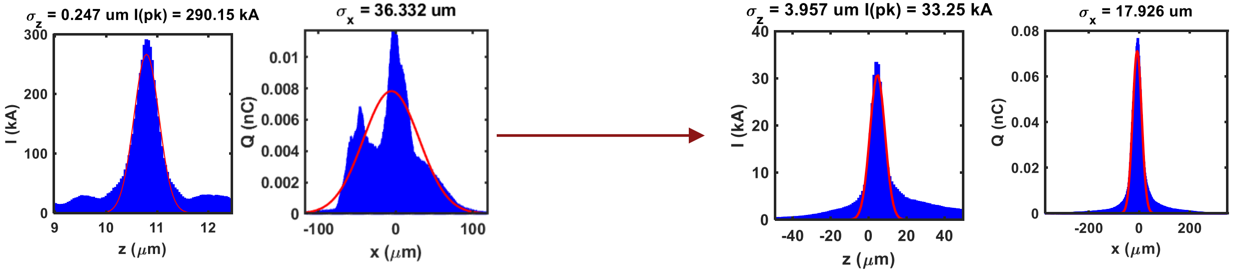


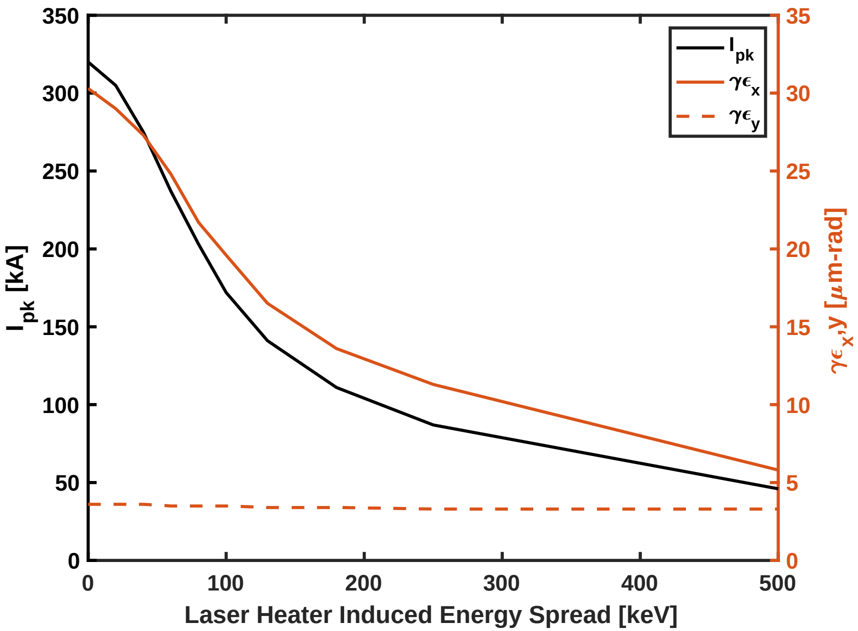
- Δt = 500 fs , I_{pk} ~5/15 kA, Q ~330/820 pC
- Φ(L1) = -19.8 deg ; Φ(L2) = -39.8 deg
- Can trade: >I_{pk} for < Δt by adjusting Φ (L1&L2)

Notched configuration enables quick start of PWFA 2–bunch experiments

Laser Heater

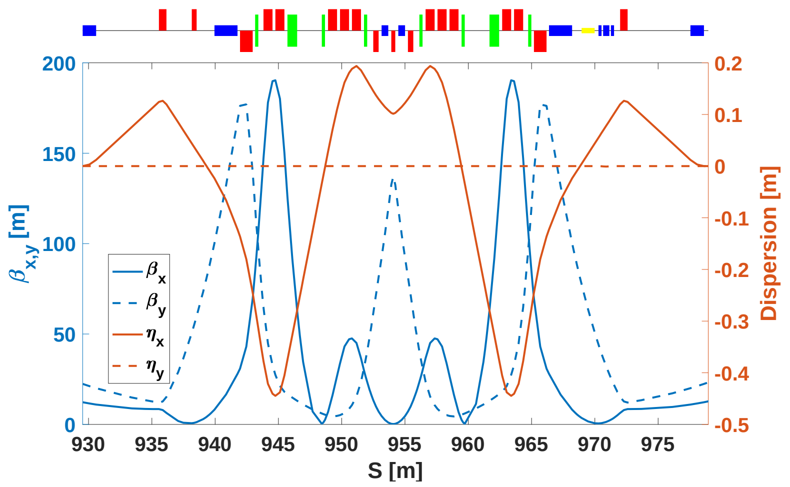
- Laser heater used to increase incoherent energy spread in injector
- Consider 0->500 keV heating
- Enables orthogonal control of final energy spread
  - Minimizes accelerator tuning for different final bunch lengths
- Provides trade-off between final peak current and horizontal emittance
- Final beam profiles become more Gaussian
- Suppresses micro-bunching and coherent emission by putting a cap on max peak current possible

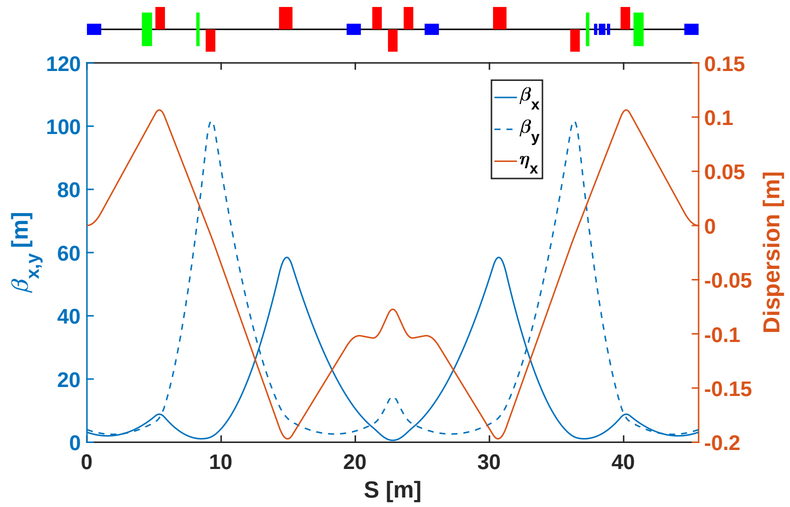




Injector laser heater can be used for bunch length control and μ-bunching suppression

BC20 Chicane Upgrade





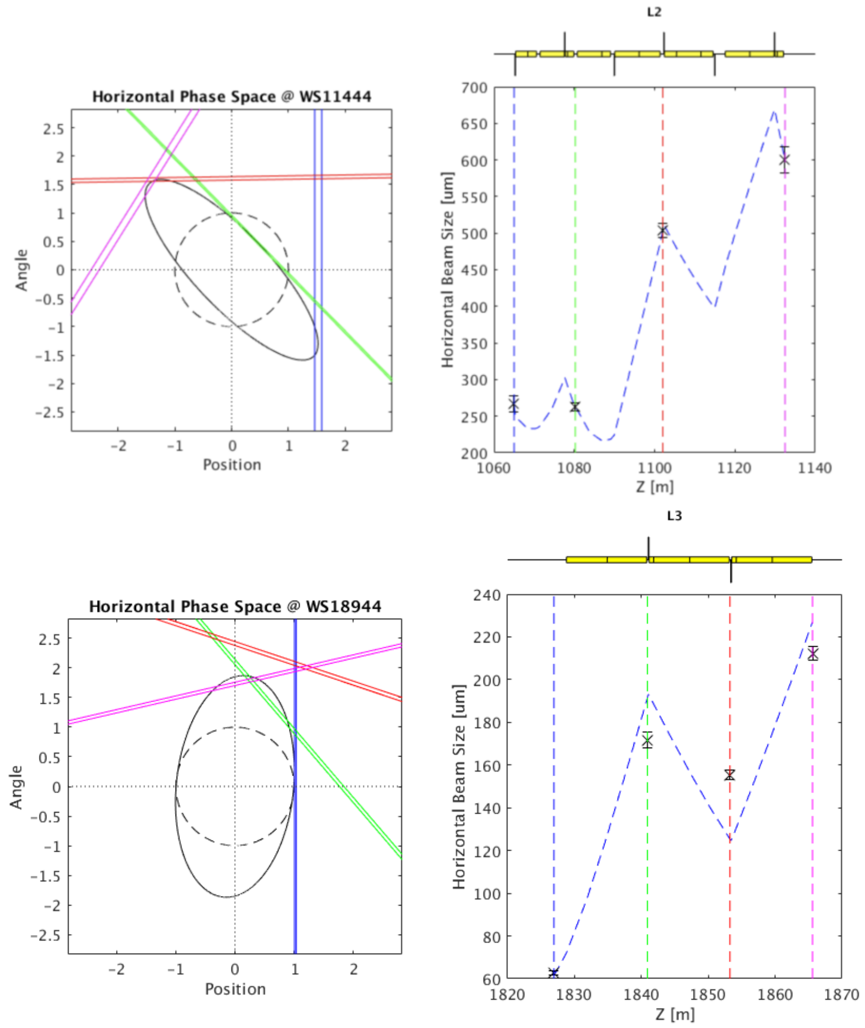
- New BC20E layout, re-using subset of existing magnets
  - uses reduced magnet count => easier operations
  - lower chromatic aberrations, better beam quality / lower losses @ high energy spread
  - compression range R56 = 0 -> 5mm
    OK for FACET-II parameters
    NB: no 2-bunch notch operation option
  - 3.5m shorter z length -> more FFS space

	W-Chicane	New BC20E
R56	-10 - +10 mm	0 - +5 mm
Magnet count	18 quads 6 bends 6 sextupoles	9 quads 4 bends 4 sextupoles
z length	49.1 m	45.6 m
β(max) @ R56=5mm	190 m	100 m
ε_x @ δ_E = 1.2 % **Sextupoles OFF** **Sextupoles Opt.**	 400 um-rad 15 um-rad	 60 um-rad 15 um-rad

New BC20 expected to ease operational complexity and provide more space for upstream S20 experiments

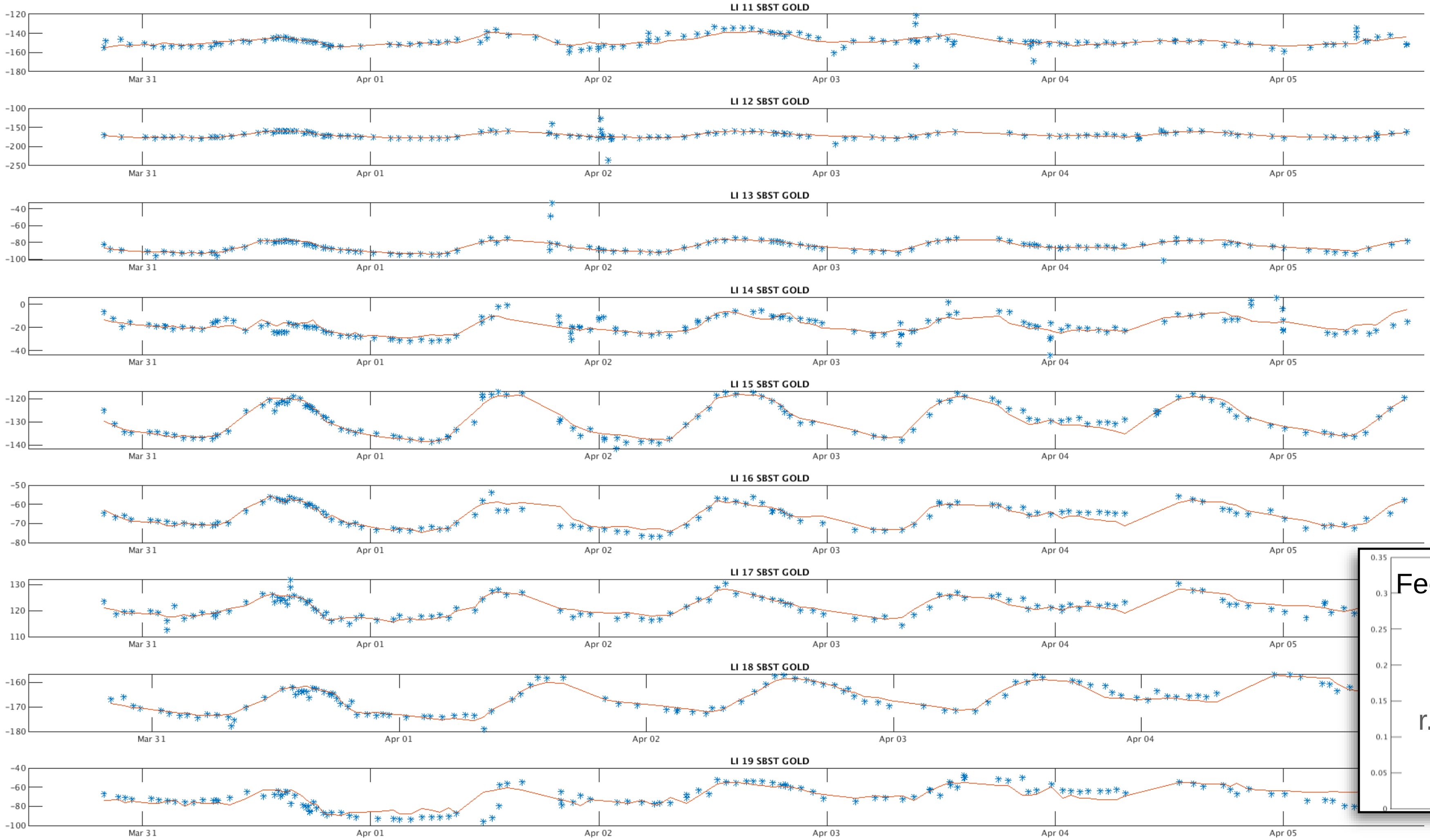
Linac Operational Measurements

- Measurements taken 8/7/2022
  - Multi-wire (4 wirescanners)
- L2 *(LI11/12)*
  - $\gamma\varepsilon_x$ = 8.2 µm-rad, BMAG = 1.1
  - $\gamma\varepsilon_y$ = 4.5 µm-rad, BMAG = 1.9
- L3 *(LI18/19)*
  - $\gamma\varepsilon_x$ = 12.6 µm-rad, BMAG = 1.2
  - $\gamma\varepsilon_y$ = 8.8 µm-rad, BMAG = 1.4
- Operational issues affecting emittance & stability
  - Fast orbit excursions during wirescans
    - Improvements to control system links to SCP over downtime to enable jitter-subtraction
  - Extreme sensitivity to orbit in L1 / beginning of L2
    - MD studies scheduled to further investigate
  - Diurnal variation in klystron phases (see next slide)

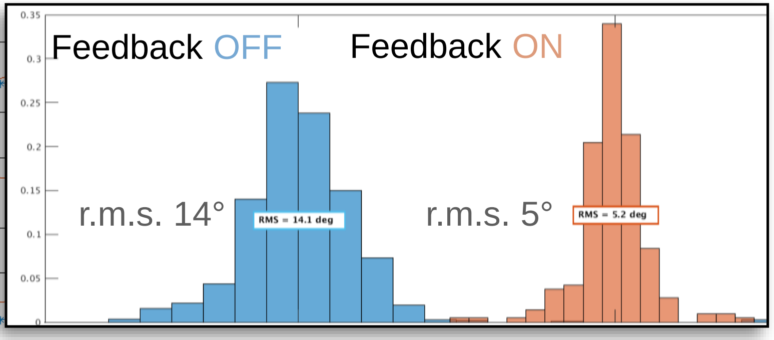


Emittance growth in Linac (L1-L3) typically 2X-3X after tuning

Klystron Sub-Booster Phase feedback (MDL compensation)



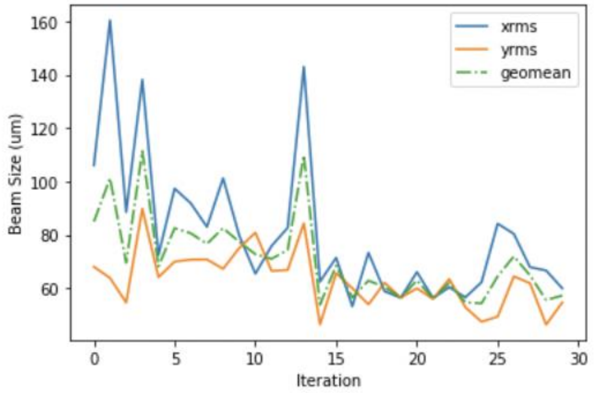
- Compensate for temp & pressure changes affecting main drive line RF distribution
- Blue= phase scan measurements
- Red= NN feedforward model
- Operationally, still see 10's degree phase jumps
  - Investigations ongoing…



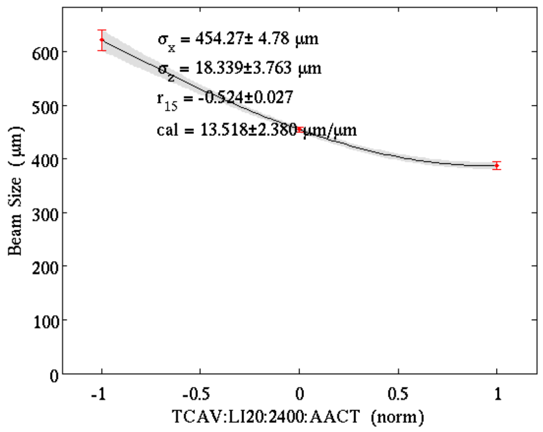
Efforts ongoing to address phase stability in Linac

Sector 20 Operational Measurements

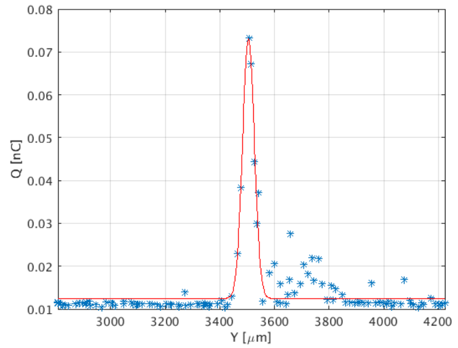
- Measurements taken 8/7/2022 (wirescanner), 8/4/2022 (XTCAV)
- Wire-scanner measurements (IPWS1) with $\beta^* = 0.5$ m
  - **$\sigma_x^* = 23.2\ \mu m$**
  - **$\sigma_y^* = 21.5\ \mu m$**
  - **$\sigma_z = 18.3\ \mu m$**
- Wire breakage
  - ongoing problem due to high charge density
- Similar sensitivity to dispersion leakage seen in FACET
  - Use sextupole movers in BC20 to control
- First checkout of "ML tuning"
  - Bayesian optimization tool applied to Sextupole mover system for S1 & S2 sextupoles (L & R)



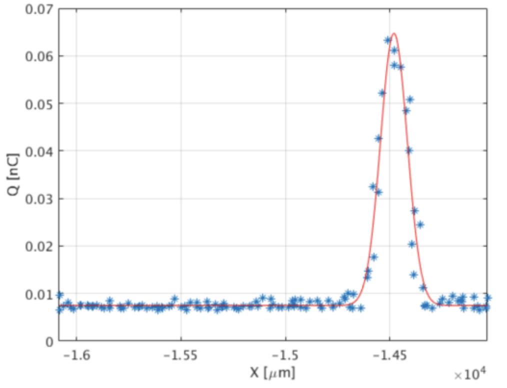
TCAV bunch length on CAMR:LI20:107 04-Aug-2022 16:34:34:30 Asymmetric



Scan showing signs of broken wires on card



Newly fixed card



Efforts ongoing to address phase stability in Linac

Summary

- 3 primary accelerator configurations
  - 3-stage Linac compression with variable 3rd stage compression & real-time configurable FFS
    1. Low Espread, high beam quality
    2. Single pulse, high-compression (tunable)
    3. Double-pulse for drive-witness bunch configuration used by plasma acceleration programs
       - Either double-pulsed from RF gun or "notched" using BC20 collimators
  - Performance assessed using start-to-end tracking simulations
- Operational measurements in first run
  - Delivered normalized emittance into S20 < 20 μm-rad @ 1.6 nC
  - Transverse bunch size ~20 x 20 μm in S20 with σ_z<20 μm
  - Work required on stability and repeatability
- Upgrades considered for improved performance
  - Laser heater chicane in injector for bunch length control and μ-bunching suppression
  - BC20 upgrade using fewer quadrupole and bending magnets for easier operational management

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Questions?

FACET-II DOE Operations Review

June 14-15, 2022

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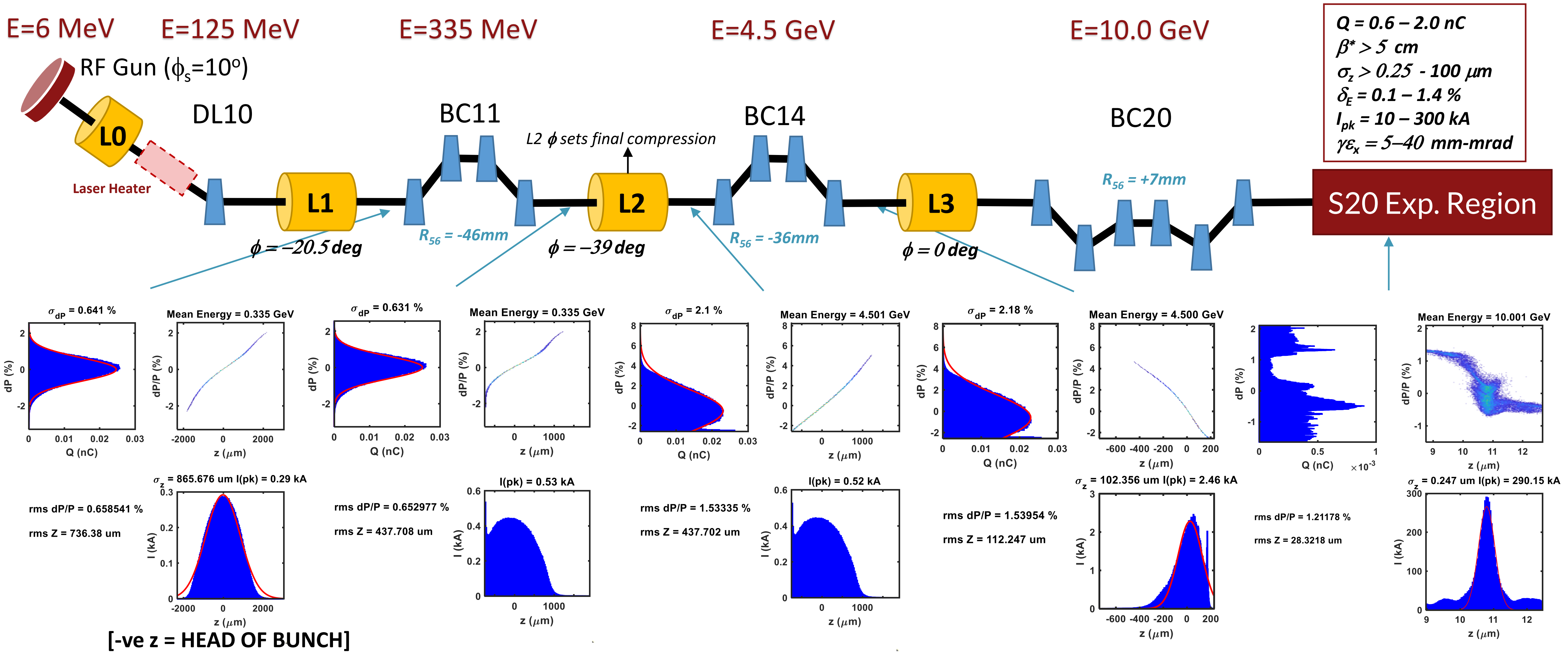
Backup Slides

FACET-II DOE Operations Review

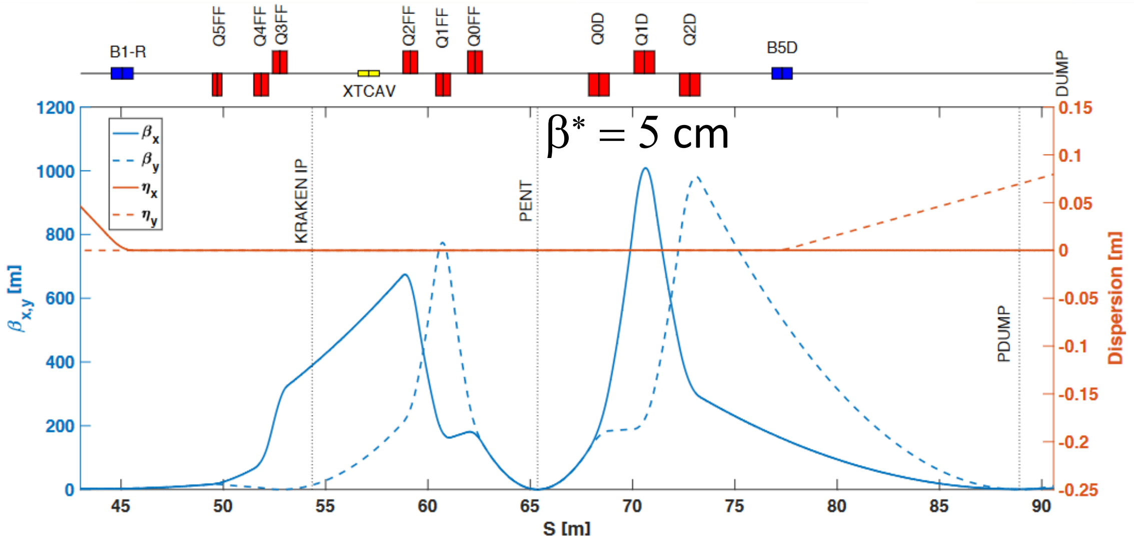
June 14-15, 2022

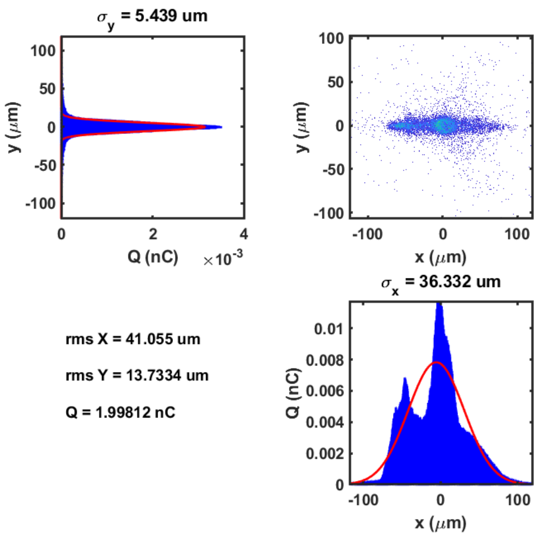
2) Single-Bunch Max-Compression Design Configuration (Original design for RF gun laser pulse duration and Schottky Phase)

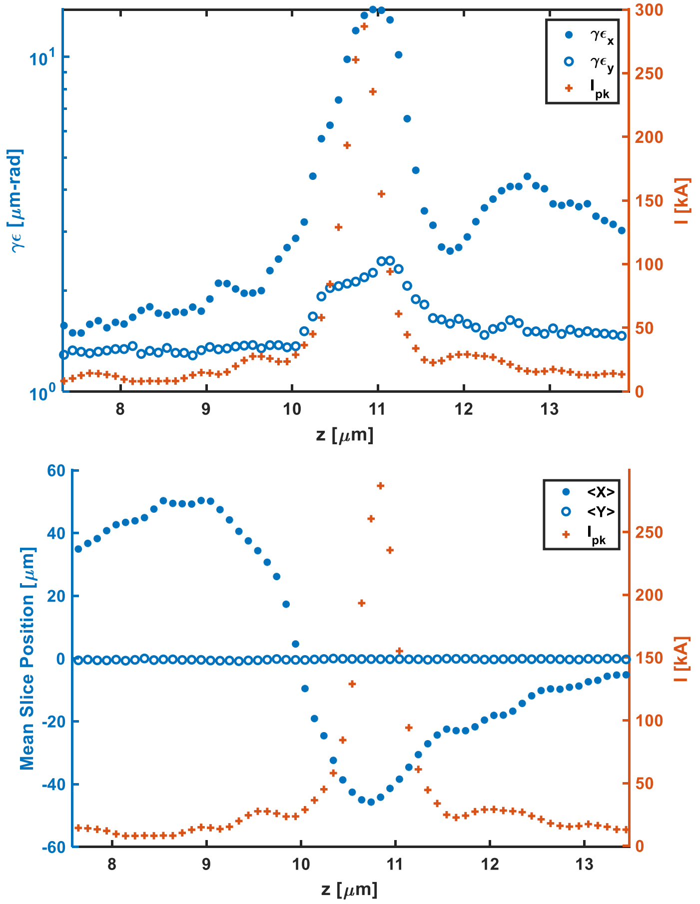


Over-compress bunch in BC14 for high-energy-spread, high-peak current requirements in S20

2) Transverse Particle Distribution @ IP (Max Compression-Original design for RF gun laser pulse duration and Schottky Phase)







- Horizontal emittance varies ~5-40 mm-mrad for bunch lengths 100 -> 0.25 um due to CSR effects in BC20
- CSR generates longitudinal position-dependent kicks according to charge as beam traverses BC20

Bunch compression : bend-plane emittance growth tradeoff due to CSR effects
Communication with experimental groups to understand optimal configuration in each case