FACET-II
Facility for Advanced Accelerator Experimental Tests

FACET-II Design, Parameters and Capabilities

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Overview

Machine design overview

- Electron systems
  - Injector, Linac & Bunch compressors, Sector 20
- Positron systems
  - Source, return lines, damping ring, Linac injection

Operation modes

- Single-bunch, multi-bunch, e-, e+, e- & e+, collimated
- Independent witness bunch injector

Achievable beam parameters

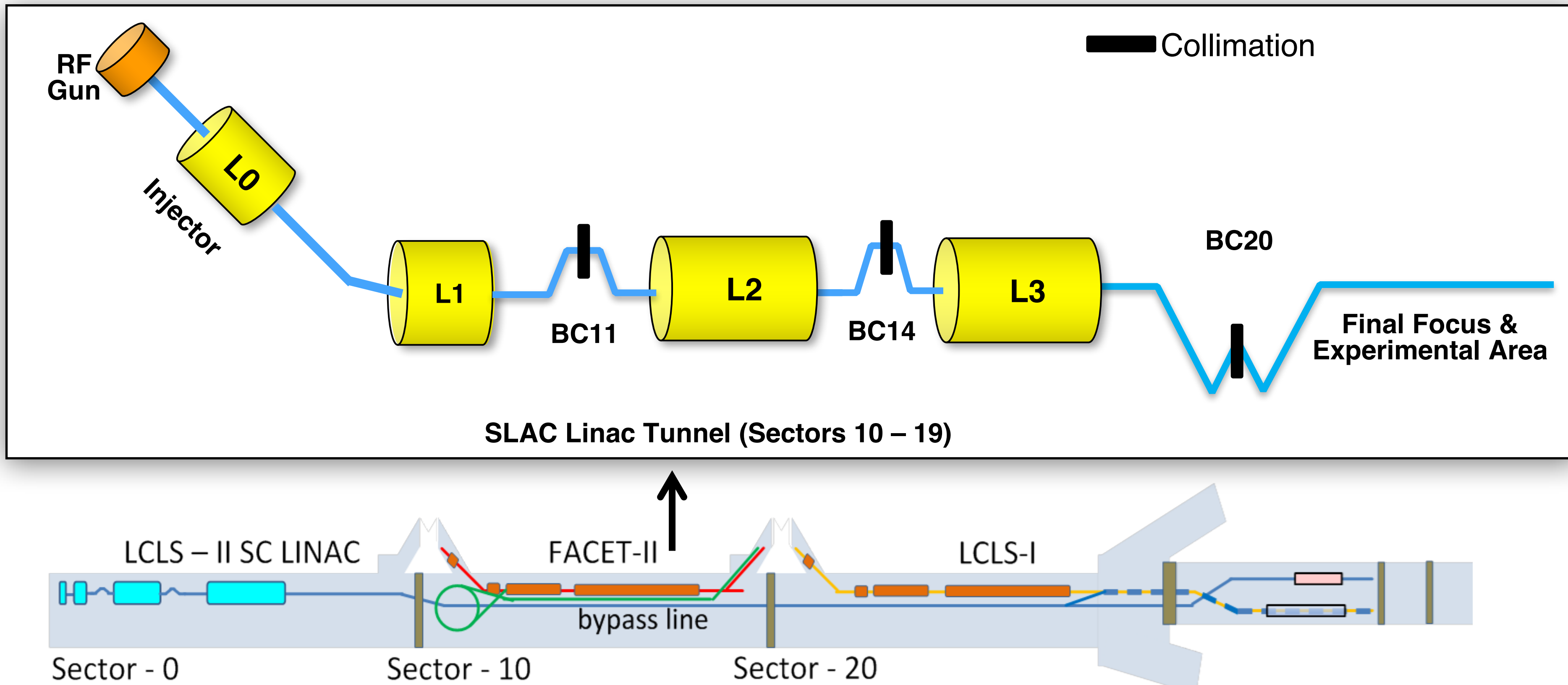
- KPP’s
- Transverse emittance, peak current and charge range and tradeoffs
- Extreme I_{pk} and other exotic options

Design capabilities discussed here -> see later talk for stability analysis

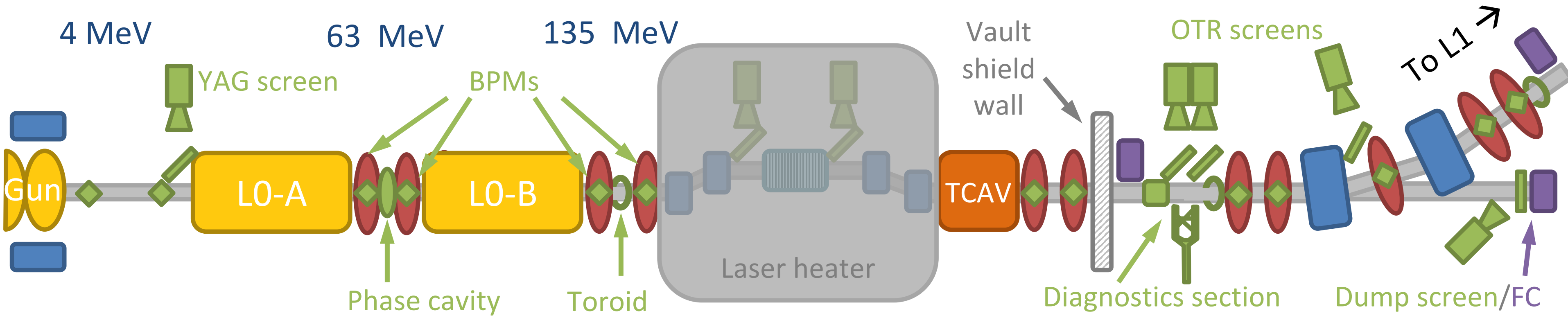
Machine Design

FACET-II Electron Systems (Stage-I)

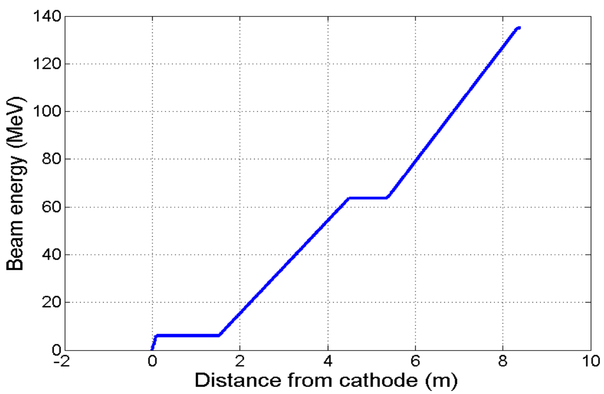
- Injector
- Bunch compressors in Sector 11 (BC11) and Sector 14 (BC14)
- Beam diagnostics
- Sector 20 initially untouched, ideas for improvements later



Electron Injector



- RF Gun, E_0=90-120MV/m
- L0 accelerates to **135 MeV**
- *LH chicane – off project, space reserved*
- 35^0 bend into main linac L1 @ Sector 11
- Q < 5 nC, <300 A peak current
- Design: $\gamma\varepsilon_x$ = **3 μm-rad** @ **2 nC**, **240 A**
- Emittance compensation design using IMPACT-T
- Beam distribution from IMPACT-T simulation used to assess FACET-II performance in tracking model



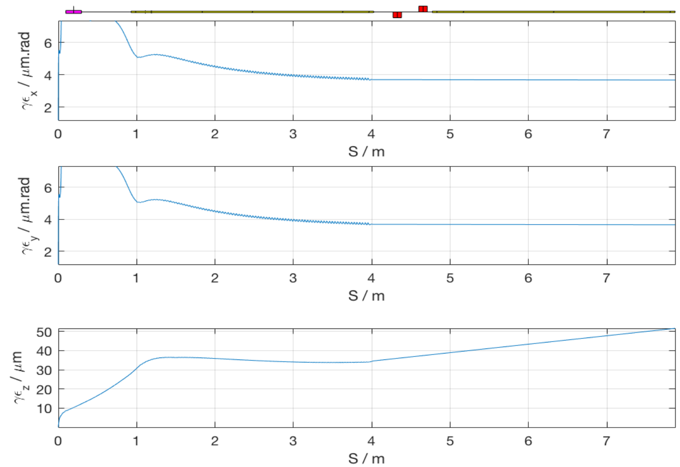
Design of the Injector Complex up to BC11 based on LCLS Sector 20 injector

Electron Injector Optimization & Simulation

SLAC

Parameter	Symbol	Unit	Req.	Tracking Simulation Results			
				Orion	Orion + LH	LCLS	LCLS + LH
Peak current at injector exit	I_{pk}	kA	-	0.24	0.24	0.36	0.33
Peak current at Sector 20 IP	I_{pk}	kA	>10	70	36	95	56
Bunch length after injector (rms)	σ_z	µm	-	838	839	617	618
Bunch length at Sector 20 IP (core rms)	σ_z	µm	<20	1.8	4.3	1.5	2.8
Transverse emittance after injector (90%)	$\gamma\varepsilon_{x,y}$	µm-rad	-	2.9	2.9	3.0	3.0
Transverse emittance into Sector 19 (90%)	$\gamma\varepsilon_{x,y}$	µm-rad	<20	3.9	3.3	4.0	3.5
Tranverse beam size at Sector 20 IP (core rms)	σ_x,σ_y	µm	<20	17.7, 12.2	16.1, 11.9	17.5, 9.8	16.5, 9.9

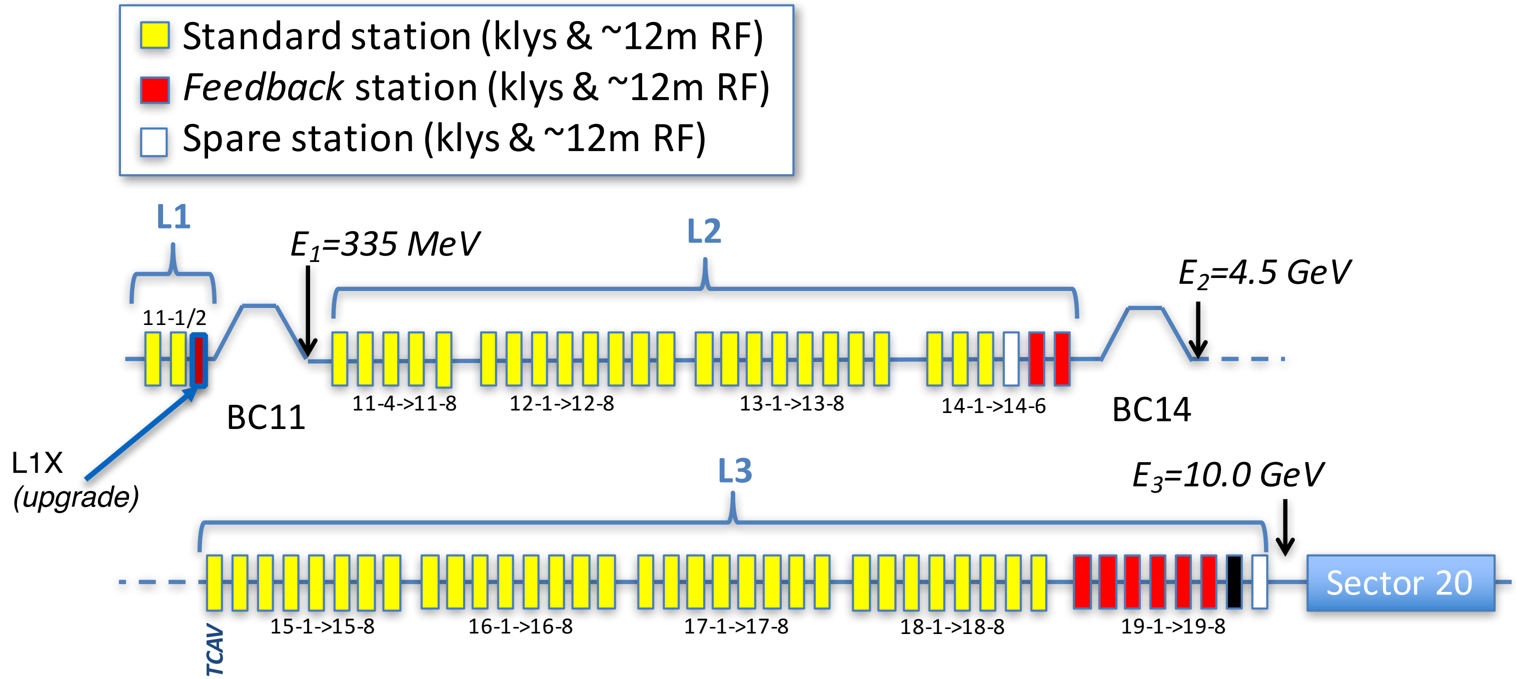
LH = "laser heater"



- ε-compensation optimization & tracking with IMPACT-T & Lucretia
- Optimize:
  - Gun Sol
  - Gun RF phase
  - Cathode-L0a drift
  - 2nd solenoid

All options meet KPP requirements
Increased longitudinal brightness possible with LCLS gun

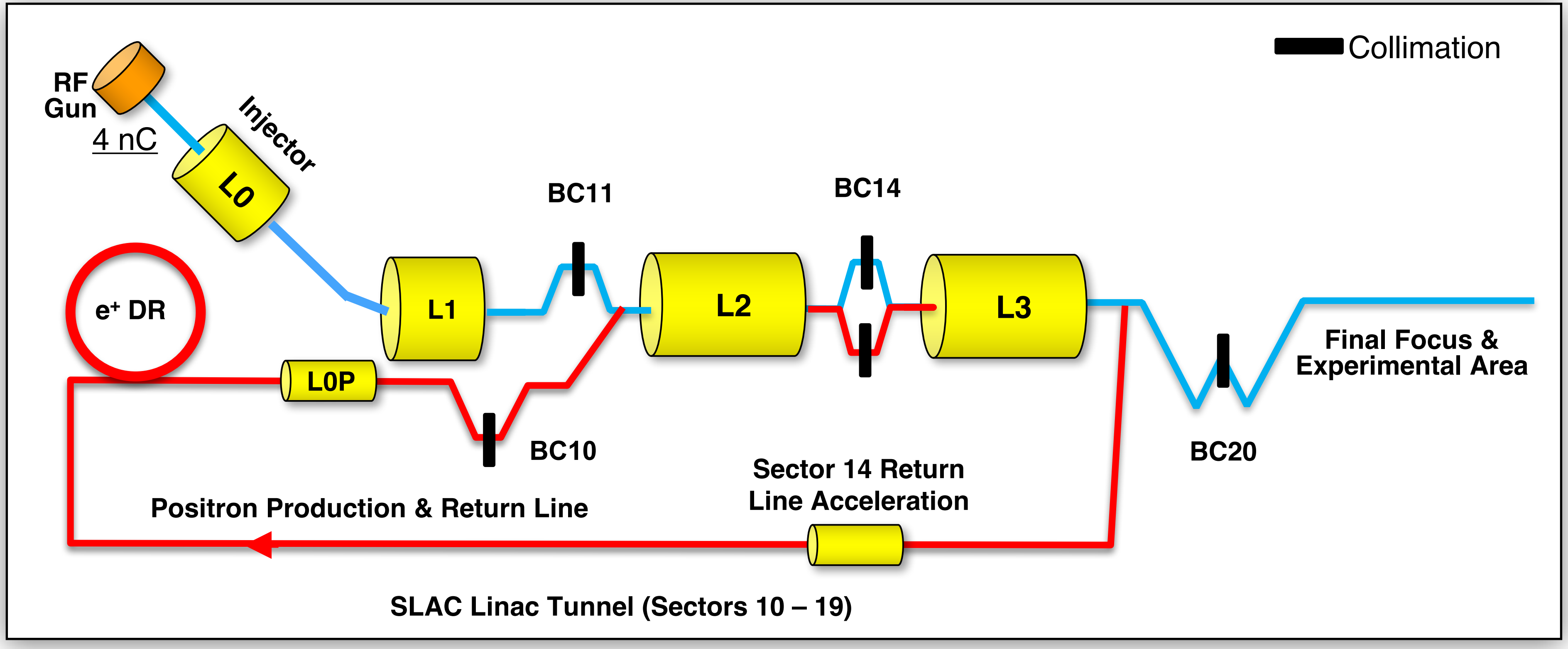
Main Linac Layout & Bunch Compressors



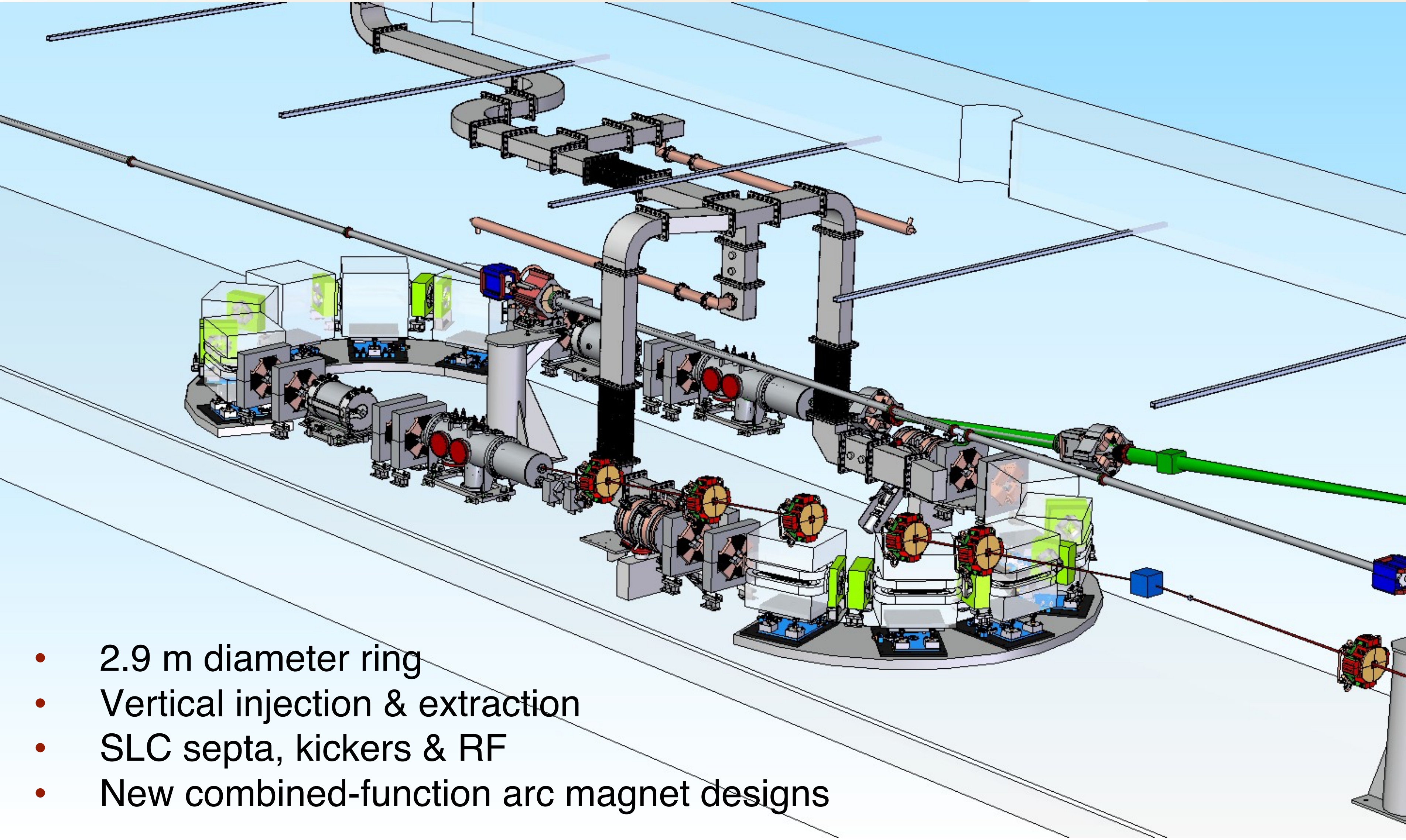
- Sector 20 operations 4.0-13.5 GeV possible (10 GeV design)
- Feedback and TCAV diagnostics stations included in design
- Beyond-baseline parameters shown may include x-band 4th harmonic linearizing structure (L1X) to improve linearity of chirp

FACET-II Positron Systems (Stage-II)

- Existing target in S19 & return lines, truncated in S10
- New return-line booster for 200->335 MeV in S14
- New horizontal & vertical return-line doglegs for DR injection
- DR & DR extraction and pre-compression in S10

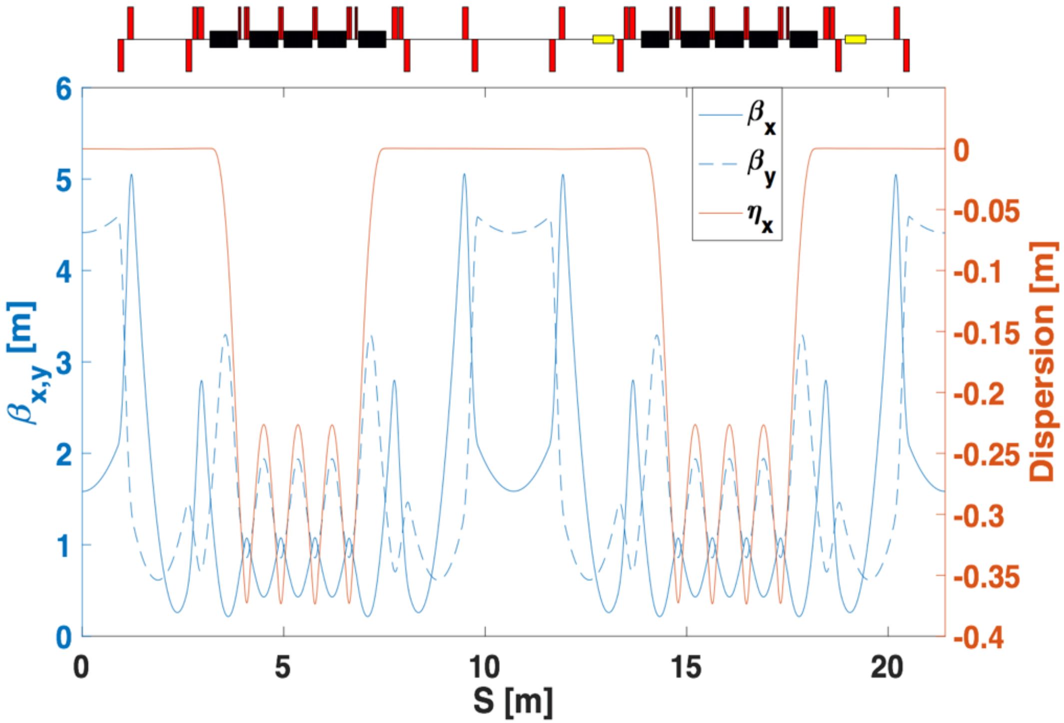


Positron Damping Ring in Sector 10



- 2.9 m diameter ring
- Vertical injection & extraction
- SLC septa, kickers & RF
- New combined-function arc magnet designs

Positron Damping Ring Design Overview



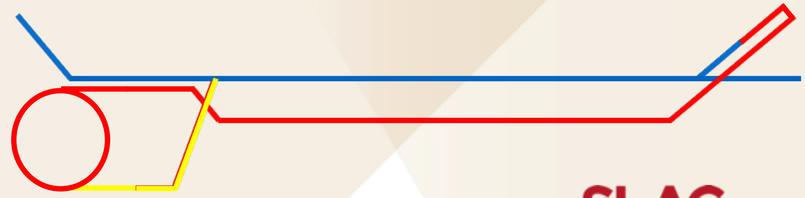
Parameter	Value
Energy, E [MeV]	335.0
Bunch Charge, Q [nC]	1.0
Beam Current, I [mA]	14.0
Circumference, C [m]	21.41
Arc Bend Radius, ρ [m^{-1}]	0.78
RF Energy Acceptance, A [%]	2.9-4.1
Tune, ν_a, ν_b	4.588, 2.570
Emittance, $\gamma\epsilon_{a,b}$ [μm-rad]	5.5-5.8
Bunch length, σ_z [mm]	3.0-3.9
Energy spread, σ_δ [%]	0.048-0.062
Mom. compaction, α_p	0.0525
Damping partition, J_x, J_y, J_z	2.15,1.0,0.85
Damping time, τ_a, τ_b, τ_c [ms]	16.9, 36.4, 43.0
Natural Chromaticity, ξ_{a0}, ξ_{b0}	-6.5, -4.4
Chromaticity, ξ_a, ξ_b	+1, +1
Syn. Energy loss / turn, U_0 [keV]	1.362
RF voltage, V_{RF} [MV]	1.1-2.2
RF frequency, f_{RF} [MHz]	714.0
Harmonic Number [n]	51
Synchrotron Tune	0.037 (521.9 kHZ, 26.8 turns)

1 nC @ 5 Hz

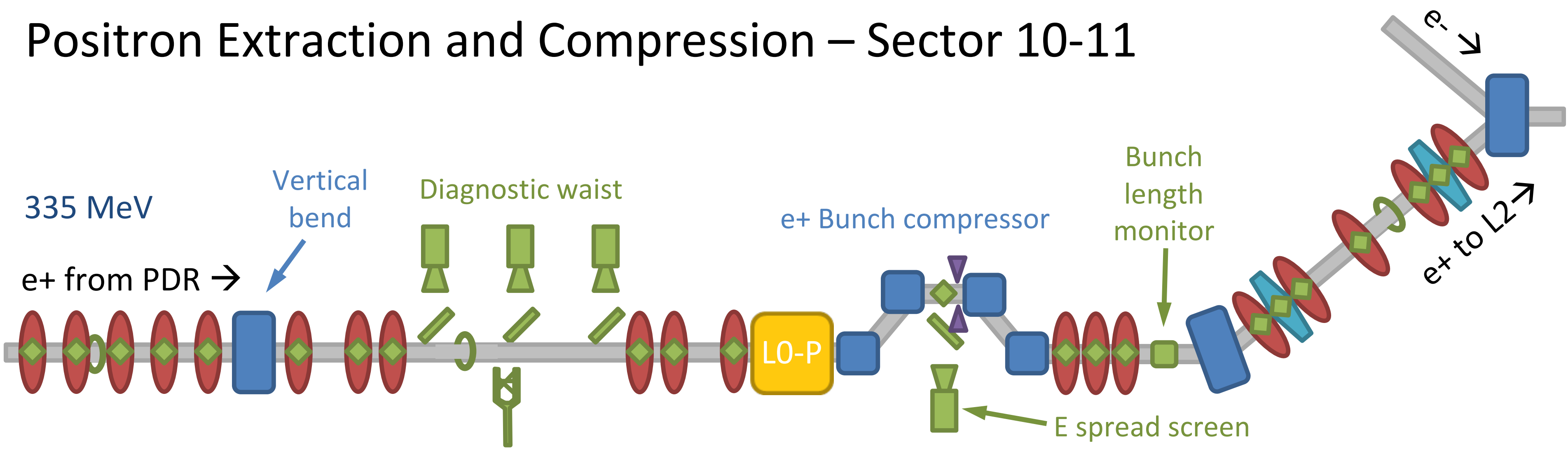
- σ_z = 3.9 mm, σ_δ = 0.062 %
- $\gamma\varepsilon_t$ = 5.5 μm-rad (fully coupled, defined by IBS)

DR designed, incuding collective effects

Positron Transport Lines:
Ring to Linac



Positron Extraction and Compression – Sector 10-11



New Beamline Designed to Extract Positrons from DR, Diagnose & Condition for Linac

PARAMETERS & CAPABILITIES

Operating Modes

Single Bunch [Baseline]

- e^- | e^+ (parameters of single bunch tracked to IP)

Collimated Single Bunch [Baseline]

- e^- | e^+ (as above, using collimator jaws to optimize I_{pk} / Q / ε)

Notched Beam [Baseline]

- e^- | e^+ (FACET-like operations)

Shaped Injector Pulse [Upgrade]

- e^- (controlled, shaped laser pulse from e^- injector laser)

2 Bunch [Upgrade]

- e^- + e^+ (“Stage III” option – simultaneous delivery @ IP)

Max I_{pk} [Upgrade]

- e^- (Re-imagined BC20 and FFS layout for max compression)

FACET-II Key Performance Parameters

Description of Scope	*Units*	*Threshold KPP*	*Objective KPP*
Beam Energy	*[GeV]*	*9*	*10*
Bunch Charge (e-/e+)	*[nC]*	*0.1/0.1*	*2/1*
Normalized Emittance in S19 (e-/e+)	*[μm-rad]*	*50/50*	*20/20*
Bunch Length (e-/e+)	*[μm]*	*100/100*	*20/20*

Threshold KPPs

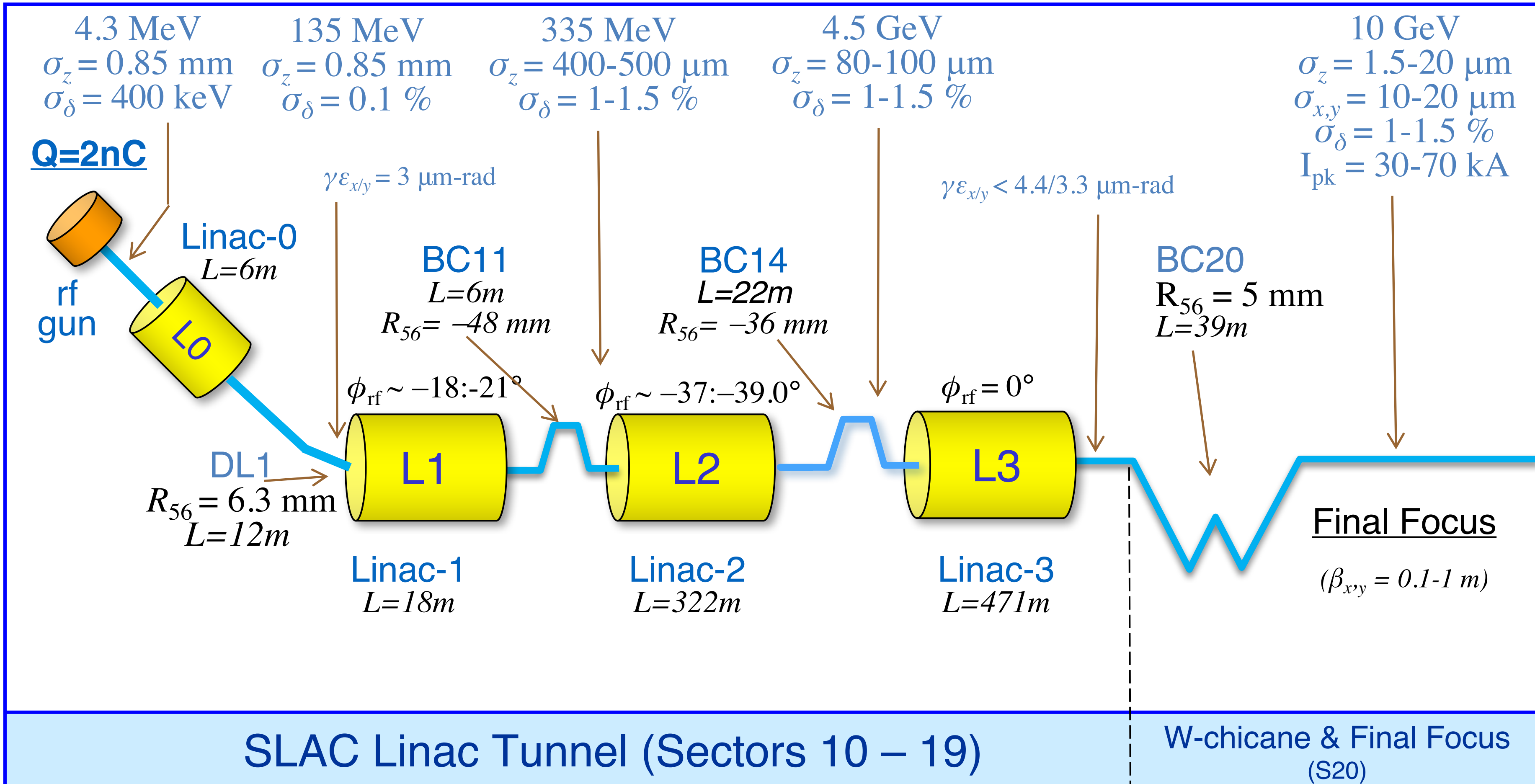
- Minimum parameters against which the project's performance is measured when complete

Objective KPPs

- Desired operating parameters which may be achieved during steady operation

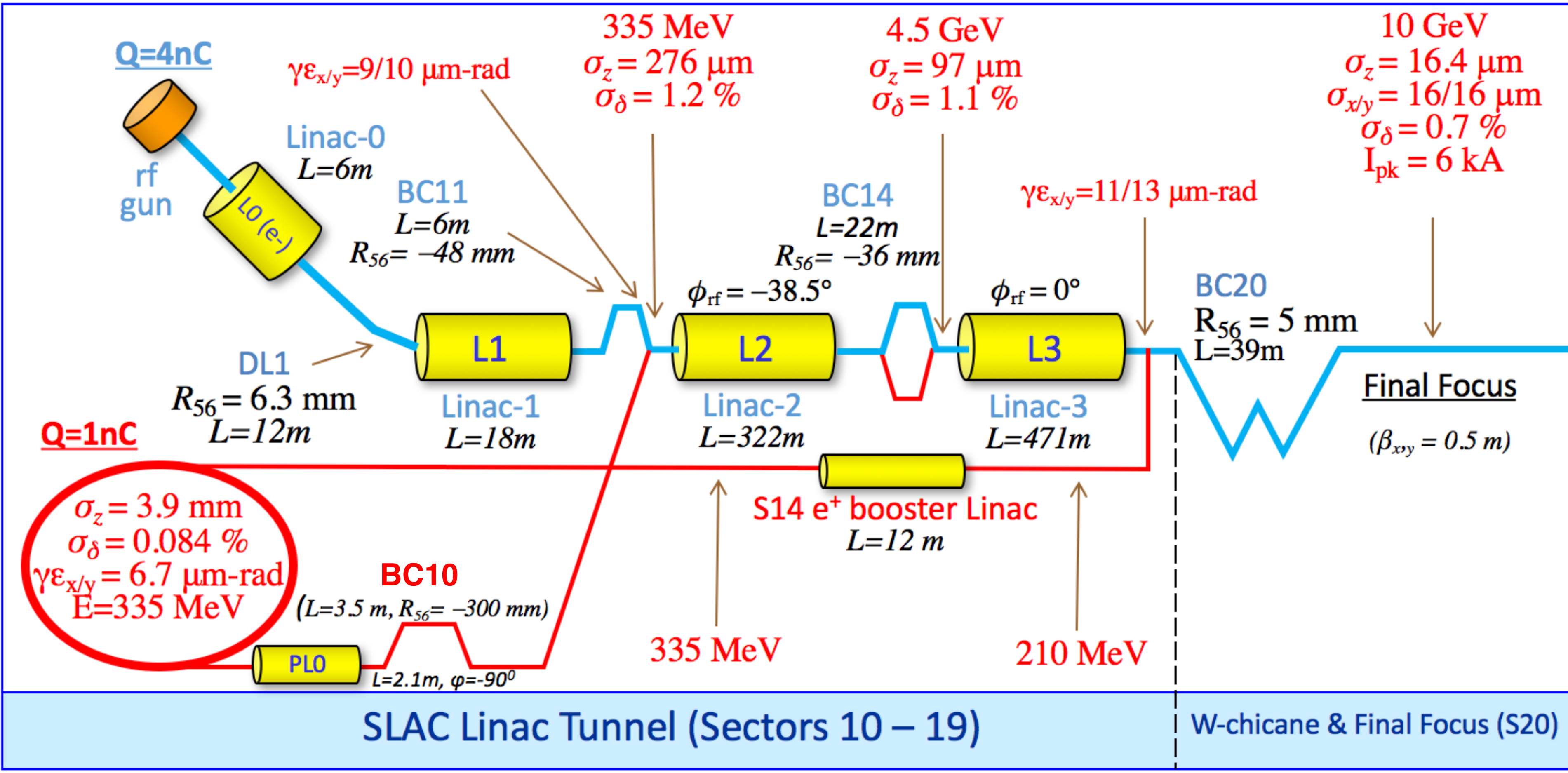
Baseline design allows for objective key performance parameters specified by science program

Baseline FACET-II Electron Single-Bunch Design Parameters



Compression scheme : verified with tracking simulations

Baseline FACET-II Positron Parameters



Compression scheme designed to satisfy objective KPP, verified with tracking simulations

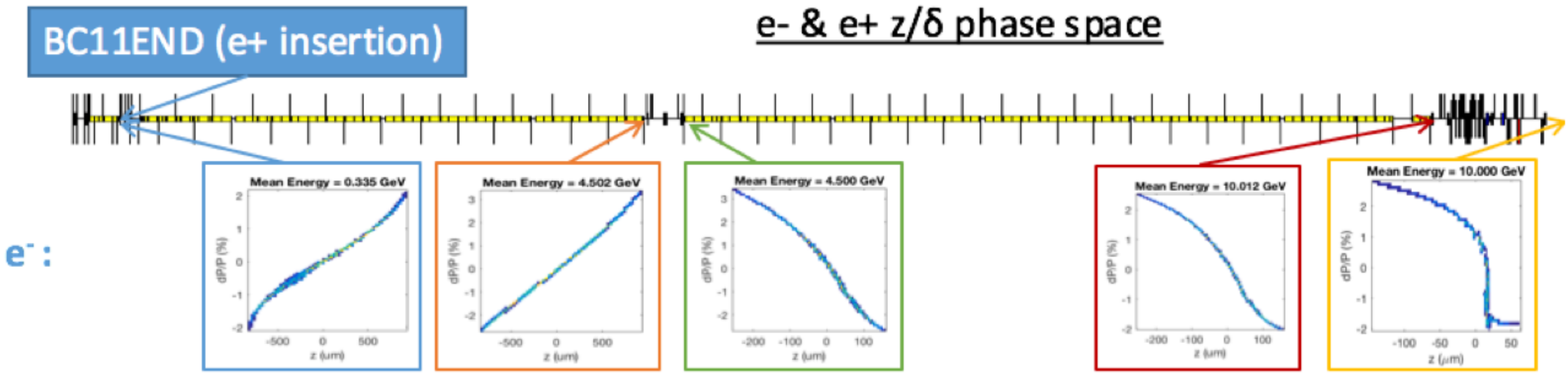
Particle Design and Tracking Simulation

6D start-end particle tracking using ***IMPACT-T*** and ***Lucretia***

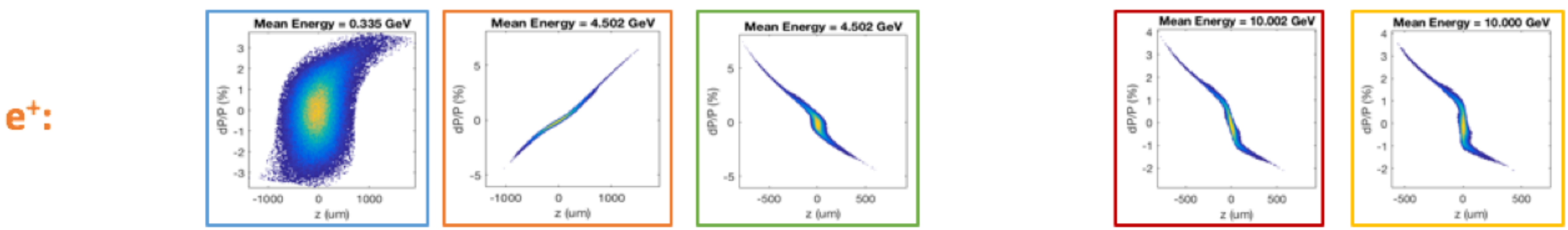
- ***IMPACT-T*** used for injector tracking, including 3-D space charge
  - Tool used for LCLS/LCLS-II
- ***Lucretia***: Matlab-based toolbox for electron beam design and beam dynamics modeling of single-pass beamlines
  - Benchmarked against other tracking engines in context of Linear Collider design and FACET
    - Elegant, PLACET, MADX/PTC, Liar, BMAD, LiTrack
  - Tracking includes effects of ISR, CSR, longitudinal and transverse wakes in structures, longitudinal space charge
  - Treatment of error sources
    - Magnetic fields, element offsets, RF errors

Design and simulation of FACET-II using well tested simulation tools

Example FACET-II Longitudinal Compression Profile



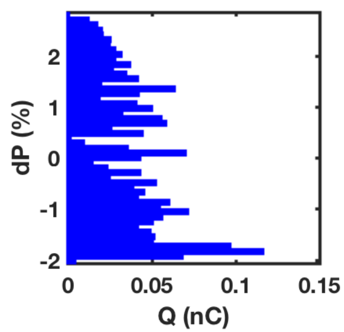
σ_z (um) / I_{pk} (kA)	468 / 0.5	468 / 0.5	96/ 4.9		96 / 4.9	1.8 / 72
δ_E (%)	0.8	1.6	1.6		1.3	1.4

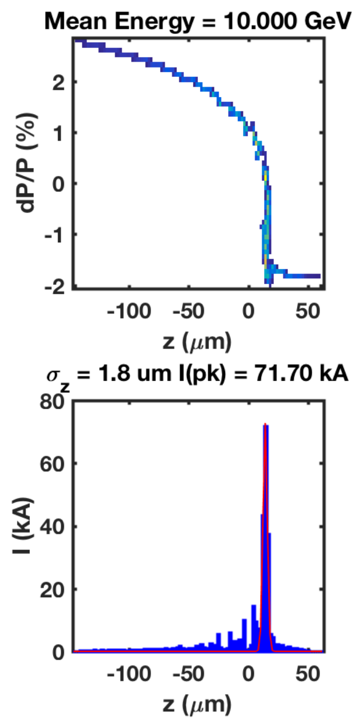


σ_z (um) / I_{pk} (kA)	276 / 0.4	276 / 0.4	97 / 2.5		97 / 2.5	16 / 6
δ_E (%)	1.2	1.1	1.1		0.7	0.7

Start-End Tracking
Longitudinal Phase Space at IP

Electron

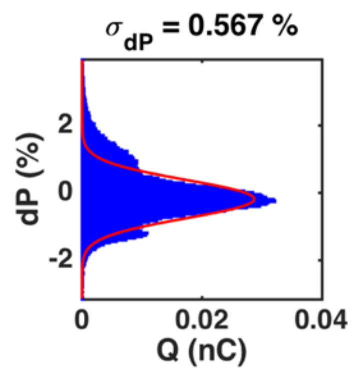


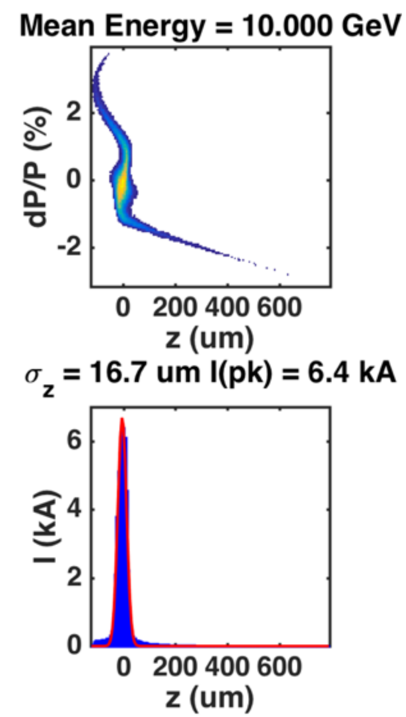


rms dP/P = 1.35713 %

rms Z = 31.497 um

Positron





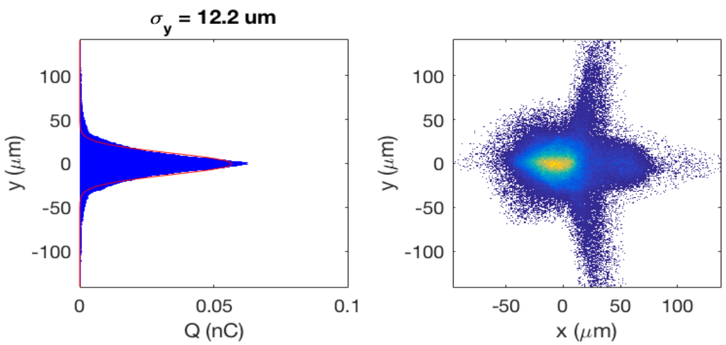
rms dP/P = 0.832536 %

rms Z = 37.4579 um

Design core bunch length **<20um** for both electrons and positrons achieved

Start-End Tracking
Transverse Dimensions at IP

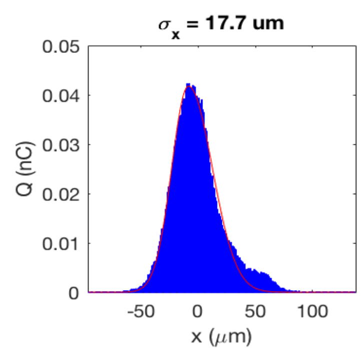
Electron



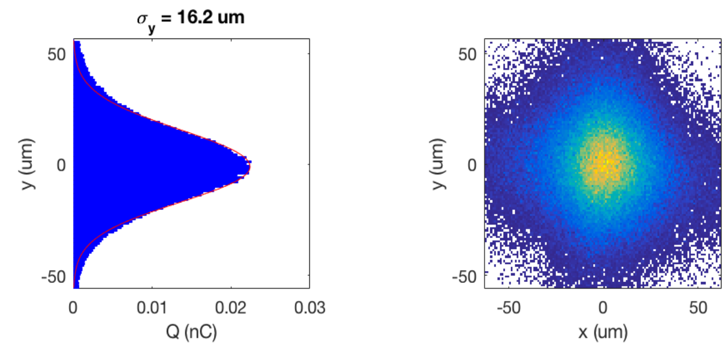
rms X = 22.9454 um

rms Y = 23.4171 um

Q = 2 nC



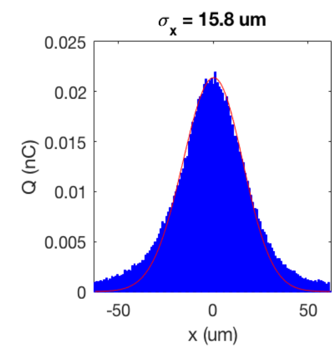
Positron



rms X = 20.7197 um

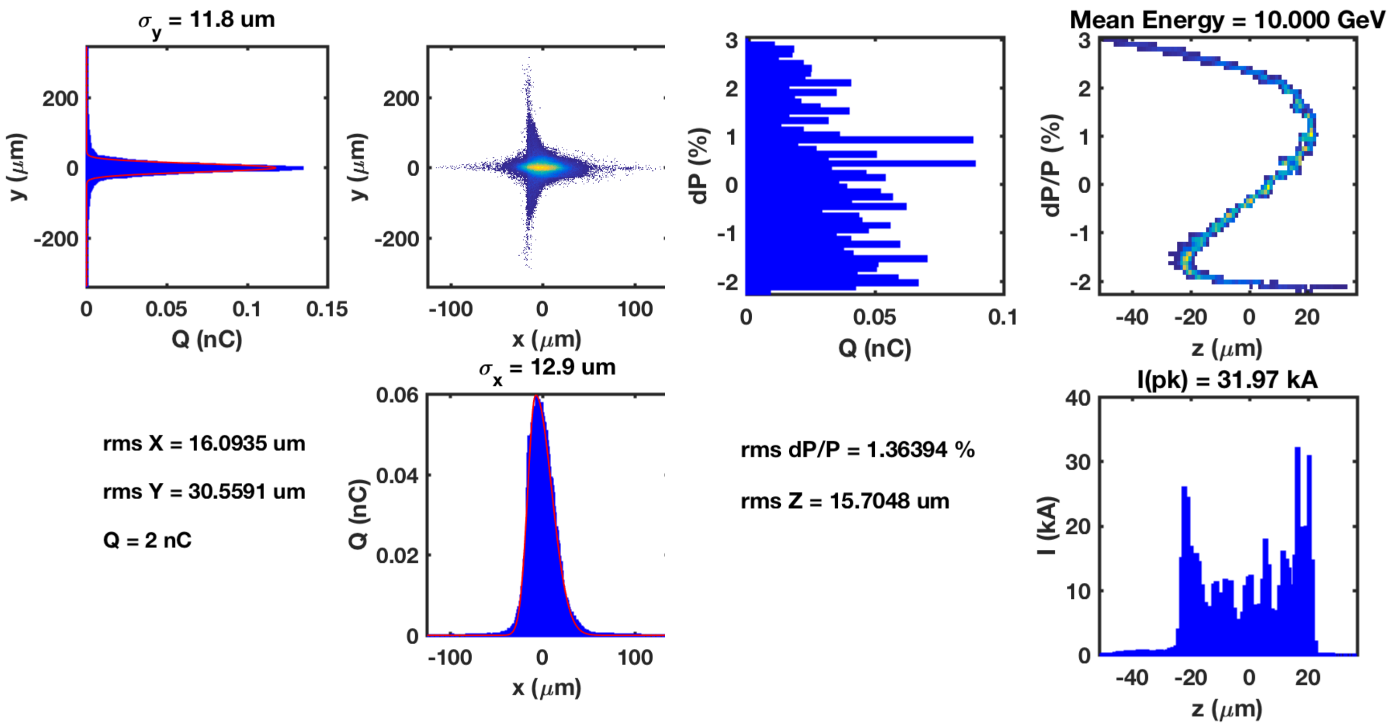
rms Y = 18.5521 um

Q = 0.999995 nC



Meets typical E200 requirements for $\sigma_{x,y} < 20$ μm

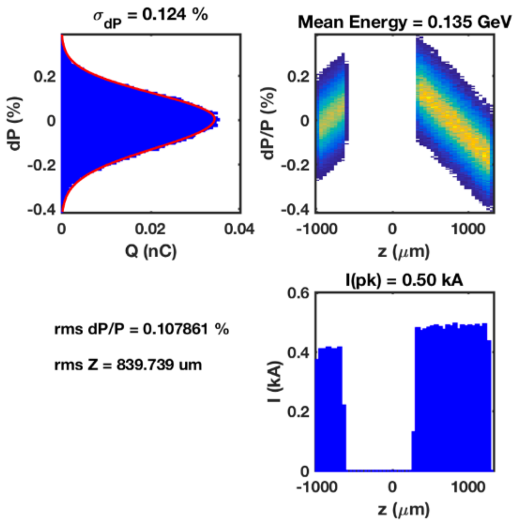
Manipulation of Electron Bunch @ IP Using Linac Phasing



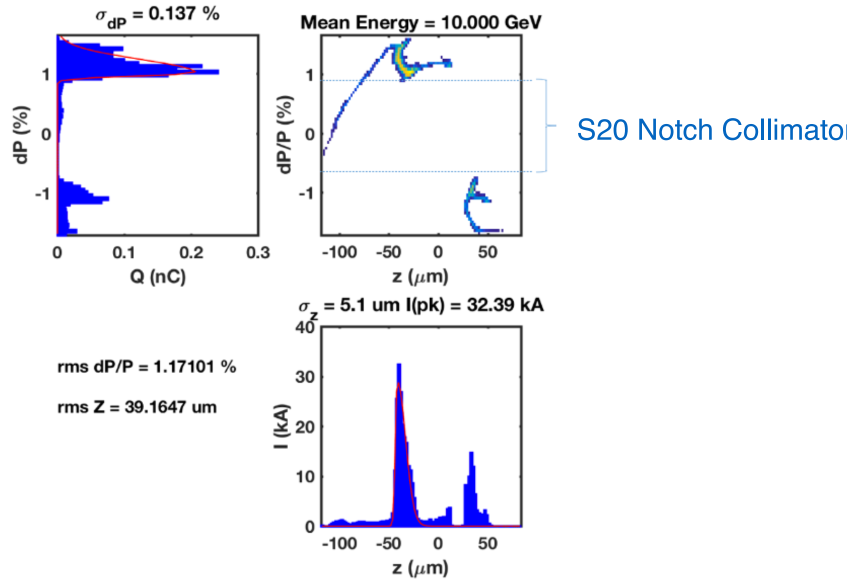
- Spread out longitudinal profile with current peaks at head & tail
- Somewhat suitable configuration for ”2-bunch notch profiles” for plasma experiments
- Difficult to fine-tune drive/witness bunch parameters
  - Need additional parameters: manipulation of injector profiles…

Shaped Injector Pulse to Deliver 2-Bunch Notched Beam in S20

@ Injector



@ S20 IP



Property	Drive Bunch	Witness Bunch
Q / nC	1.6	0.5
δ_E / E (% uncorrel.)	0.08	0.08
Shape	Top-hat, ramp	Top-hat, ramp
Ramp Time / µs	10	10
L / mm	1.0	0.375
<Ez> r_{correl}	-0.45	0.4
dz / mm	1.62	

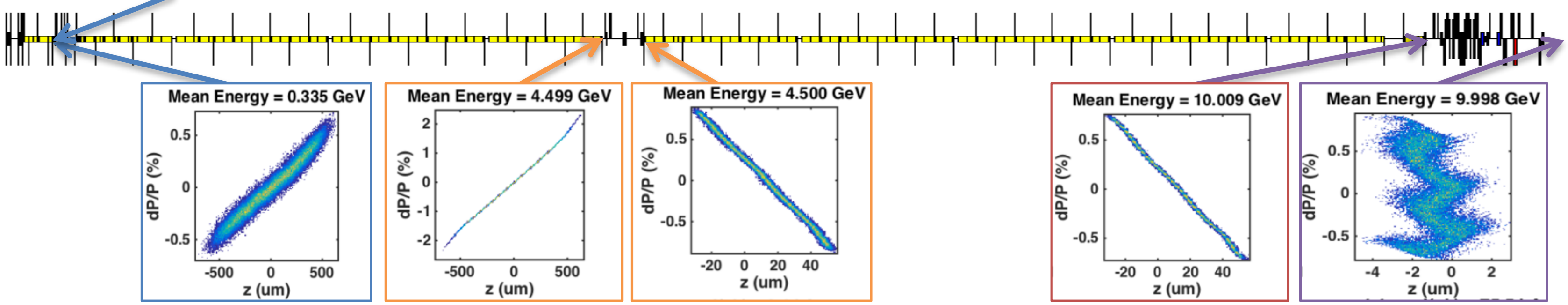
Parameter @ IP	No COLL		S20 Notch COLL	
	Drive	Witness	Drive	Witness
Q / nC	1.6	0.5	1.5	0.5
δ_E / E (% rms)	0.24	0.24	0.16	0.25
I_{pk} / kA	32	16	34	16
$\gamma\varepsilon_y$ / µm-rad	3.4	3.2	3.3	3.2
$\gamma\varepsilon_x$ / µm-rad	6.4	7.8	5.6	7.8
$\gamma\varepsilon_x$ / µm-rad (90%)	5.7	6.1	5.1	6.1

Example Compression with Collimation (2nC e+ source, e- x-band linearizer & LH) 2-bunch

BC1END (e+ insertion)

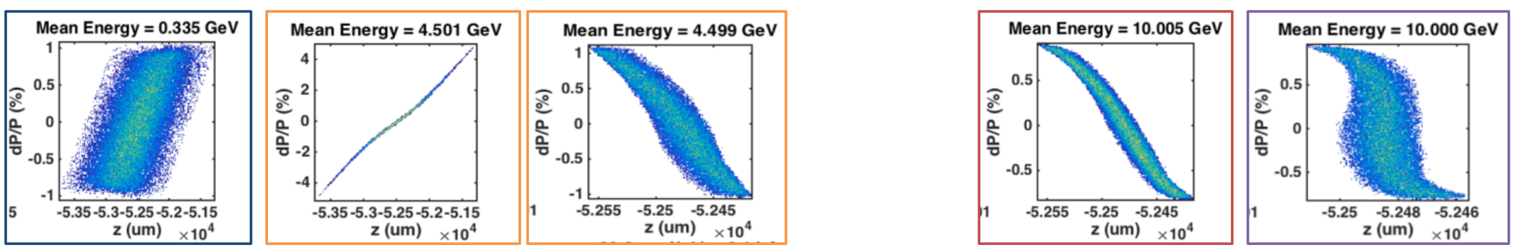
e- & e+ z/δ phase space

e^- :



σ_z (um) / I_{pk} (kA)	287 / 0.4	287 / 0.4	24 / 3.4		24 / 3.8	1 / 76
δ_E (%) / Q (nC)	0.3 / 1.2	0.9 / 1.2	0.5 / 0.7		0.4 / 0.7	0.4 / 0.7

e^+:

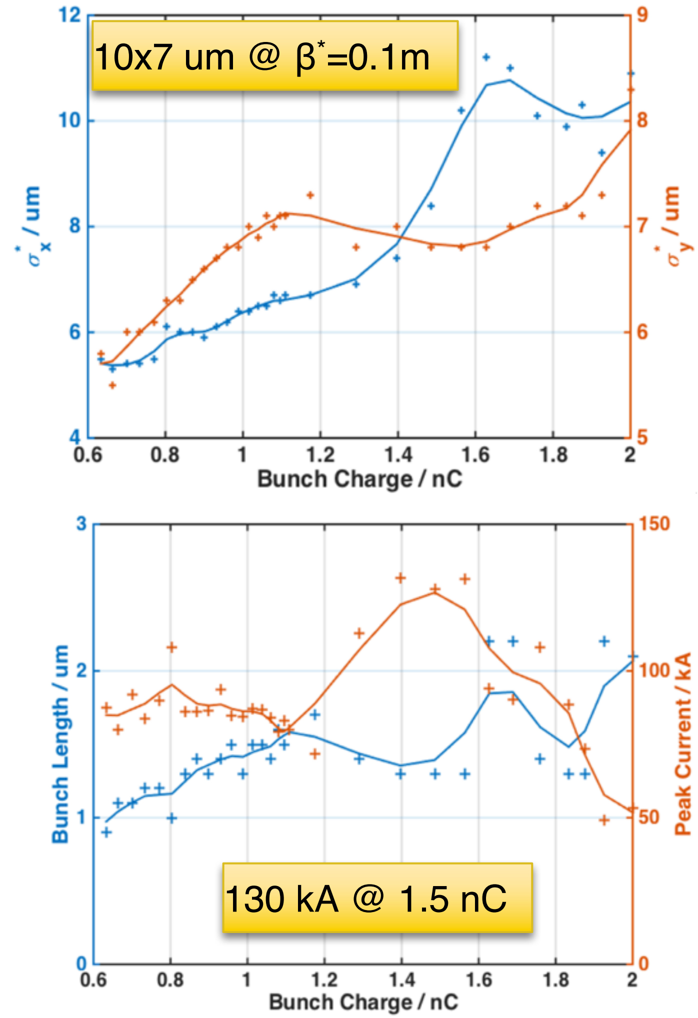


σ_z (um)/ I_{pk}(kA)	350 / 0.4	350 / 0.4	29 / 3.1		29 / 3.1	7.4 / 12.1
δ_E (%) / Q (nC)	0.5 / 1.2	1.2 / 1.2	0.6 / 0.6		0.5 / 0.6	0.5 / 0.6

Tracked longitudinal phase space from BC11, simultaneously for electrons and positrons

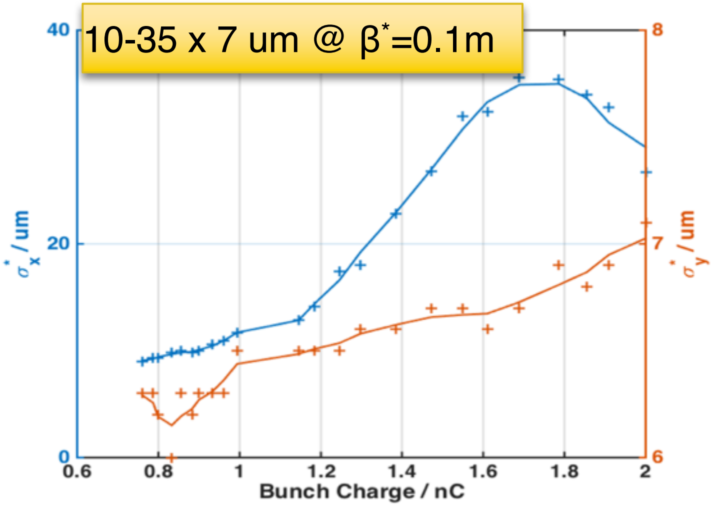
Configuration Options with Collimation - Electrons

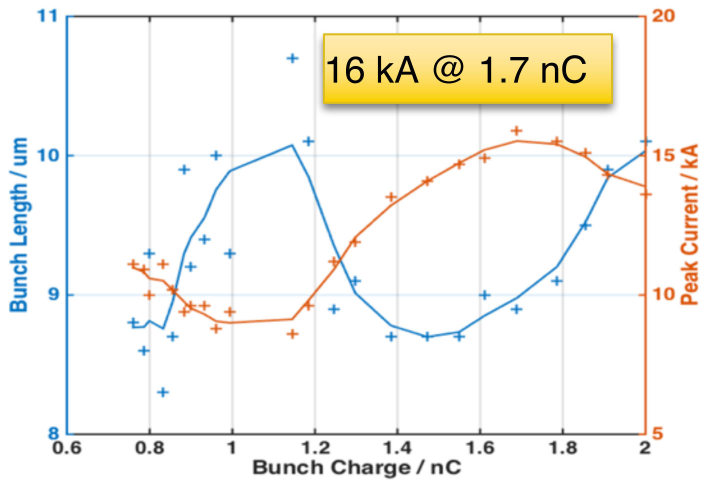
- Electron compression configuration tailored for high peak current
- Compression settings:
  - BC11, BC14, BC20 collimators
  - L1S phase
  - L1X amplitude
  - BC20 R_{56}
- Requires x-band linearizer
- Trade-offs
  - Final charge
  - Final transverse emittance
  - Stability of delivered beam



Configuration Options with Collimation - Positrons

- Positron compression configuration tailored for high peak current
- Compression settings:
  - BC10, BC14, BC20 collimators
  - L0P amplitude
  - BC20 R_{56}
- Trade-offs
  - Final charge
  - Final transverse emittance
  - Stability of delivered beam





BC20 Re-design

Current BC20E ("W-chicane")

- Many magnets, large beta functions : difficult beam alignment with large energy spread
- Experience difficulties with alignment and aberrations / optics control

BC20E is known from simulations to be limiting factor for max peak current performance due to CSR

- Re-design BC20E with fewer bend magnets and fewer quads

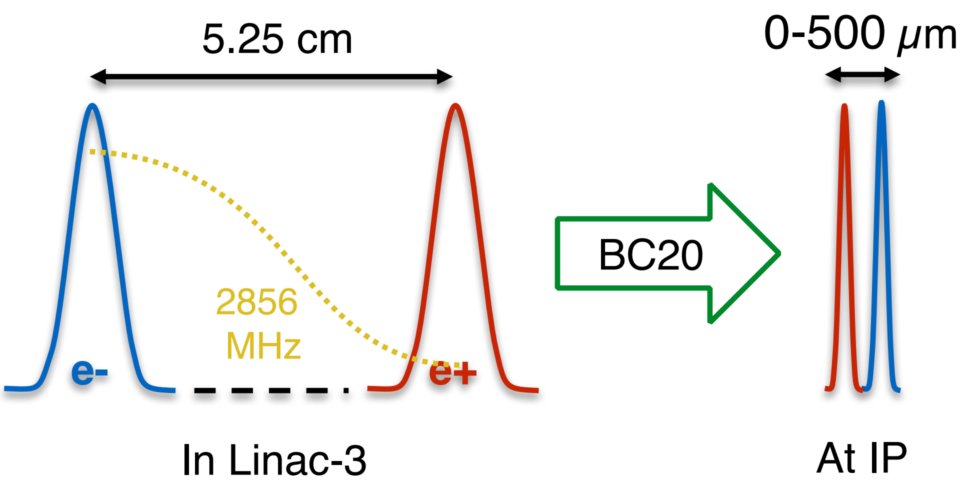
For future simultaneous e-, e+ ops: need positron arm (BC20P)

- Make use of magnets recovered from W-chicane

BC20 Requirements

SLAC

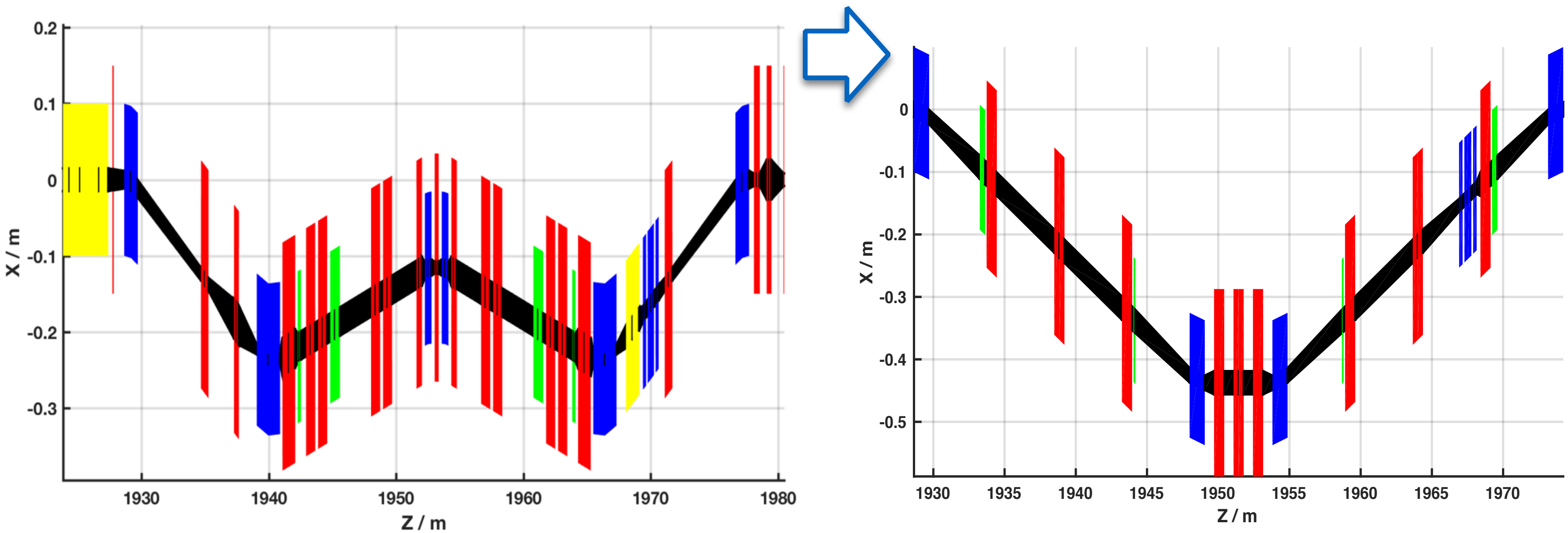
- Deliver KPP electron and positron beams
- Simultaneous solution for e- and e+ (e+ arm with 5.25 cm path length difference)
- R_{56} adjustable in range 0-5 mm
- Relative e-, e+ spacing adjustability
- Small β in chicanes (FACET experience)
- Minimized chromaticity, 2nd order dispersion at IP
- Maximize peak current throughput (minimize CSR emittance growth)



Sector 20 system provides: final bunch compression, transverse focusing at experimental IP, Inversion of e+ / e- time ordering

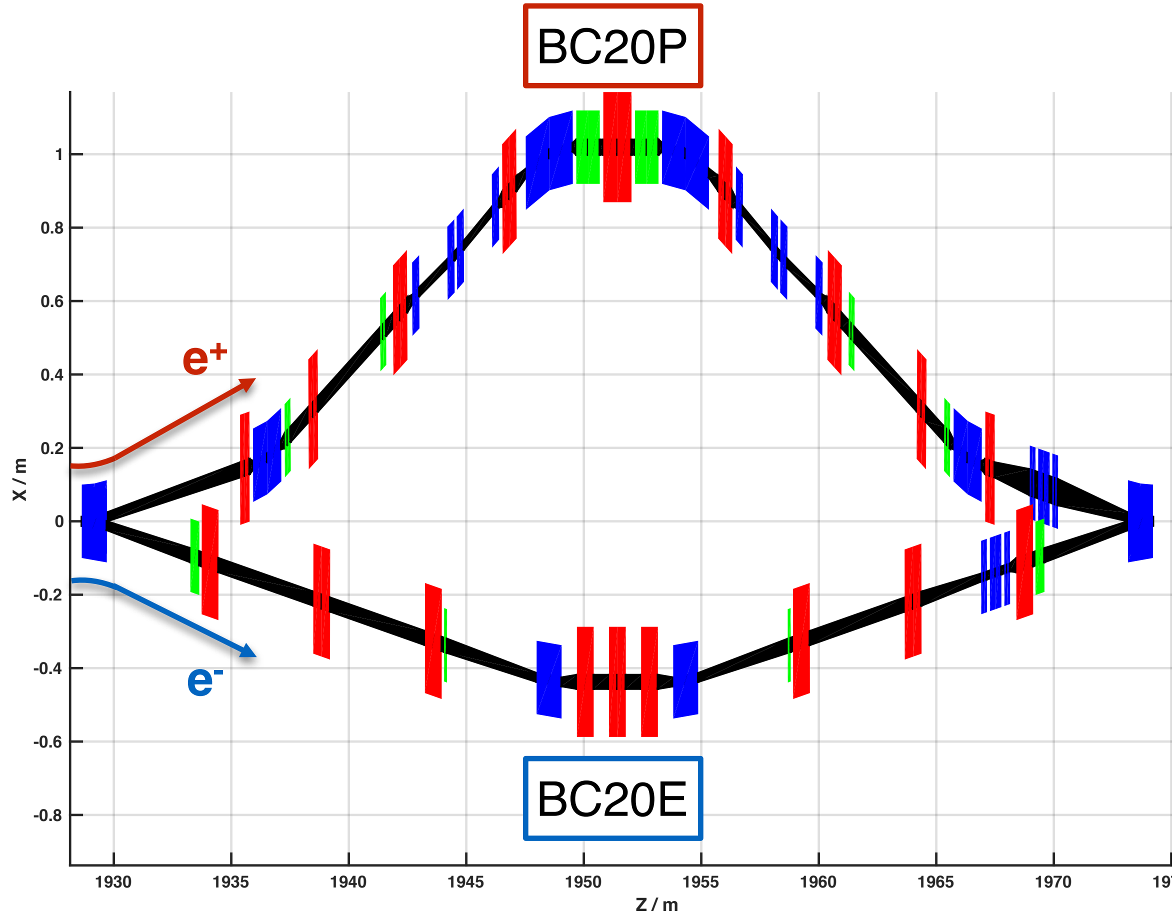
BC20E Re-Design

- Reduced magnet count
- Few bends, simpler design -> less CSR emittance degradation
- Shorter by 3.5 m : allows to move TCAV after B1



BC20E Re-designed for simpler operation and better performance

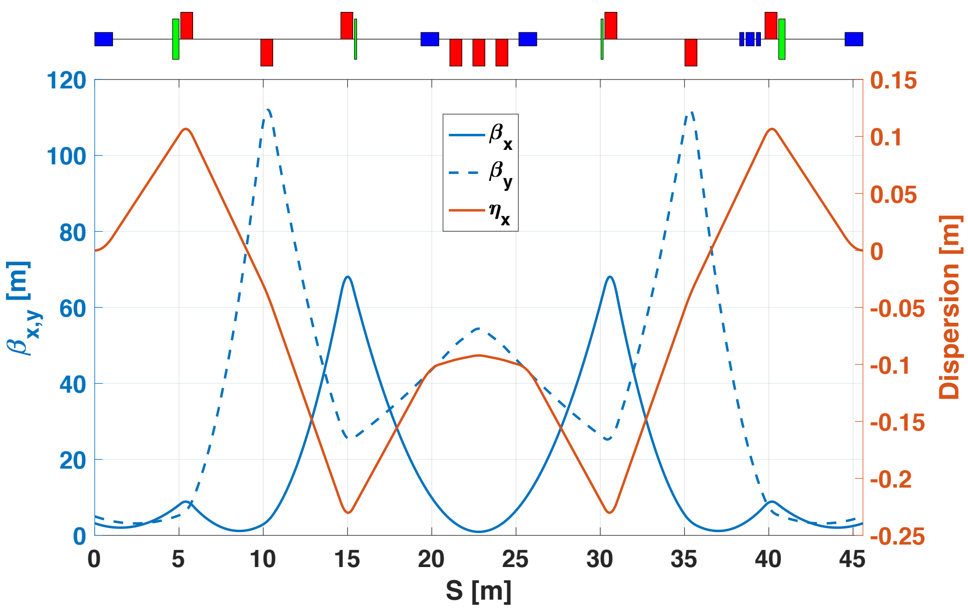
New BC20 Layout (Stage-III)



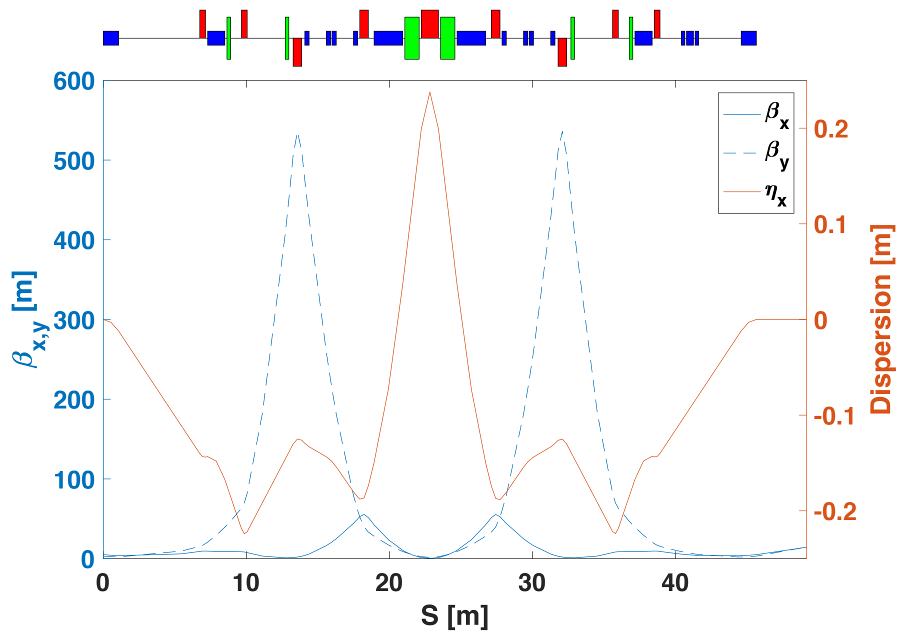
BC20P similar to previous design, shortened in z, re-matched to maintain correct path difference

New BC20E/P Optics (R_{56} = 5mm)

BC20E

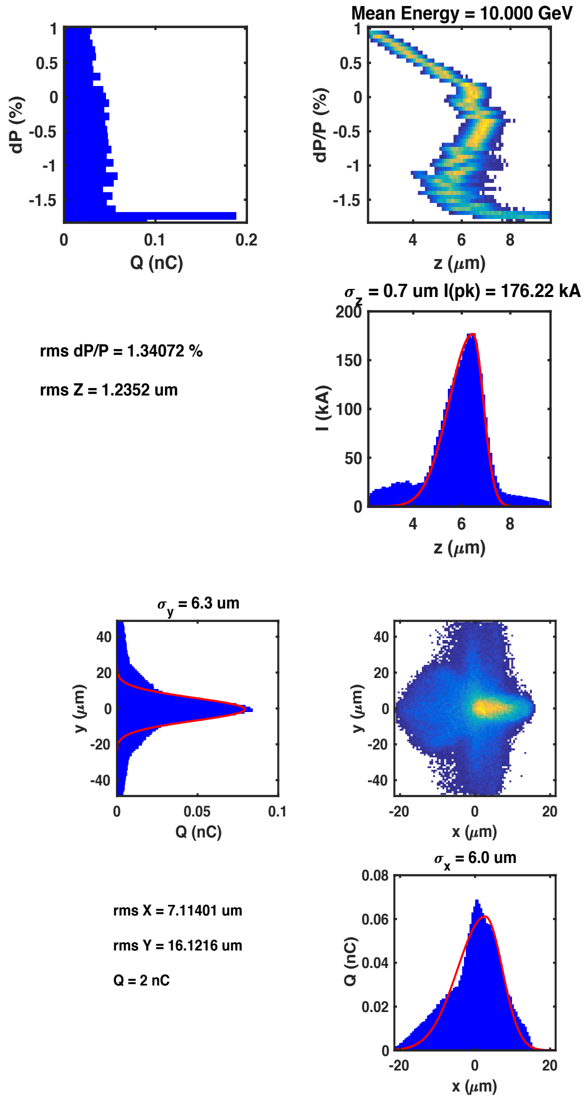


BC20P



Optics design meeting BC20 requirements

Improved Electron Beam Quality with New BC20E



Original "W-chicane":

- I_{pk} (max) = 70 kA, $\gamma\varepsilon$ = 13 µm-rad

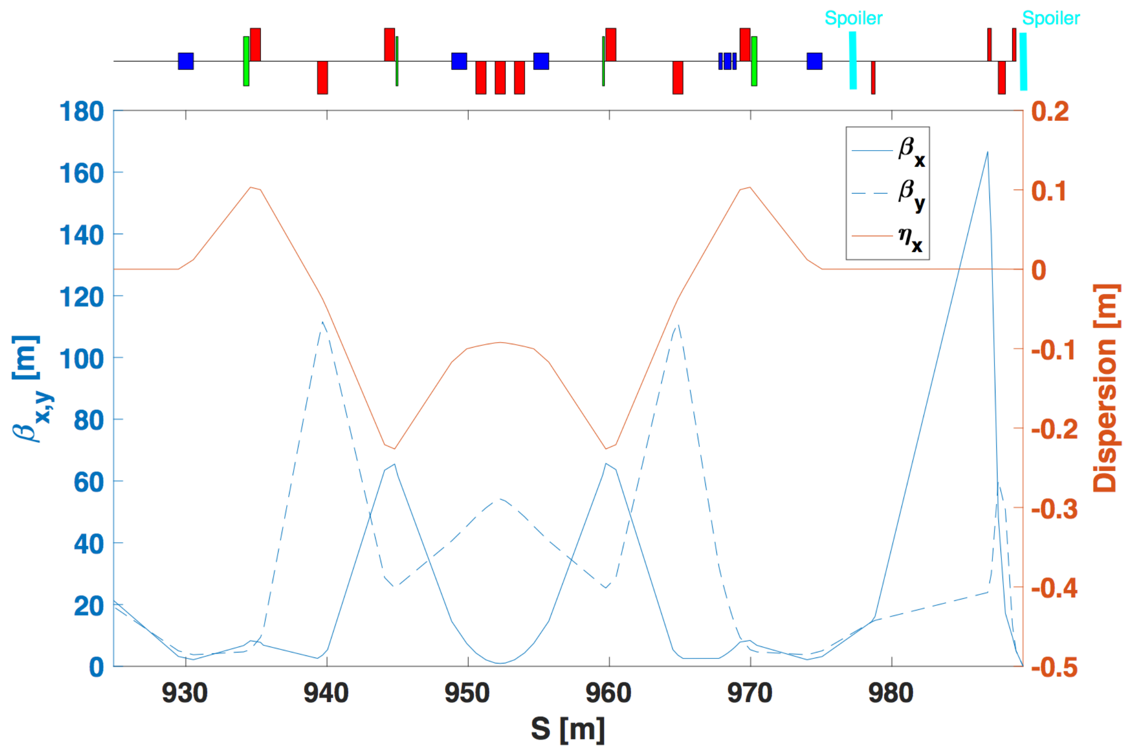
Re-designed BC20E:

- I_{pk} (max) = 176 kA, $\gamma\varepsilon$ = 7 µm-rad

Particle tracking demonstrates improved longitudinal and transverse beam quality @ S20 IP with increased peak current capability

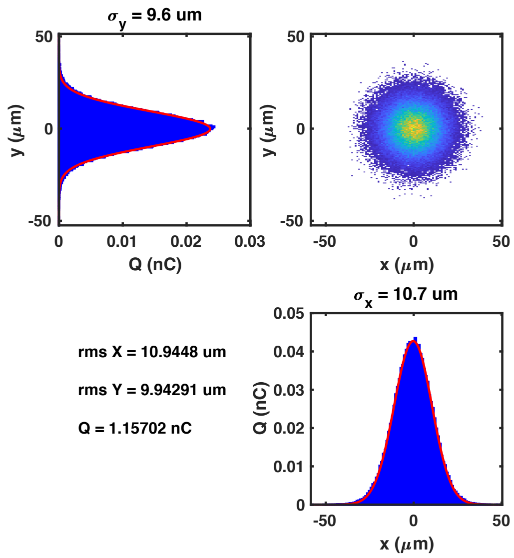
Further Performance Improvements
- Upgraded FFS

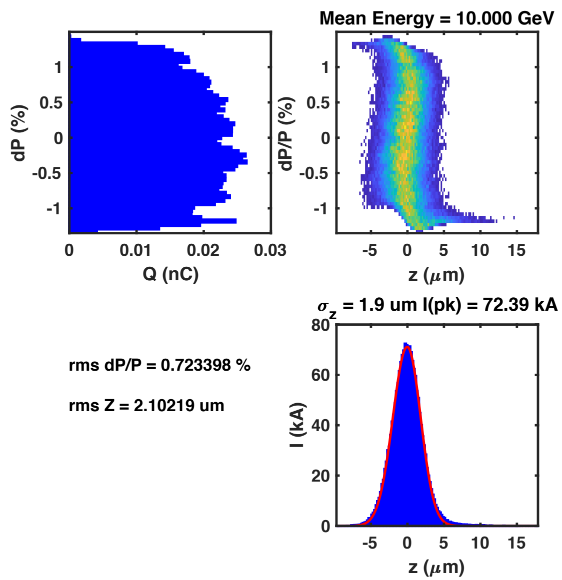
- Injector laser heater + L1X
  - δ_E 50 – 300 keV rms
- Collimation (2 -> 1.2 nC) in BC11 & BC14
- Simplified FFS, $\beta^* > 5$ cm
- Spoilers to symmetrize transverse profile @ IP
- σ_x = 4 – 10 µm
- $\gamma\varepsilon_x$ = 7 – 22 µm-rad
- I_{pk} = 70 – 300 kA



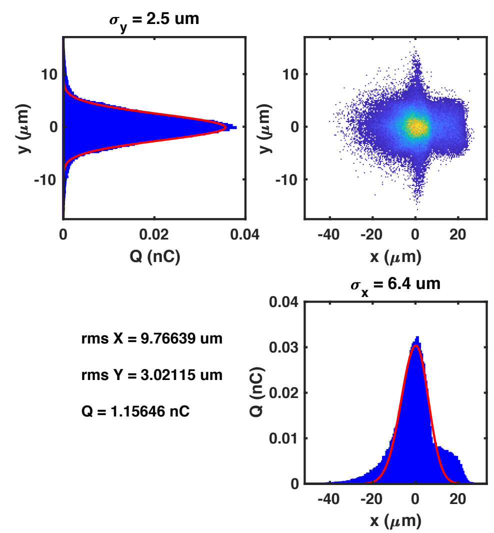
Beam Tracking with Upgraded FFS

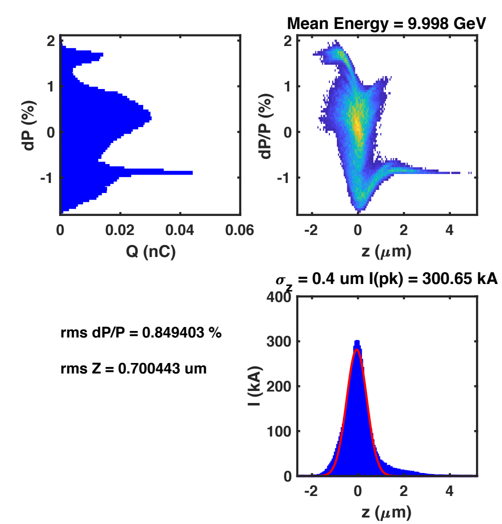
LH = 300 keV
+FFS Spoilers





LH = 50 keV

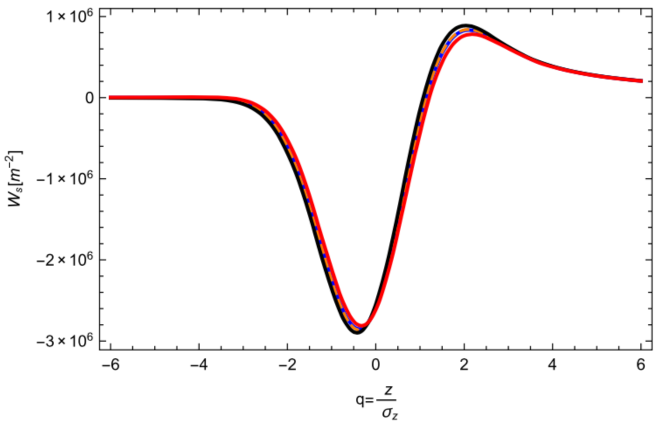




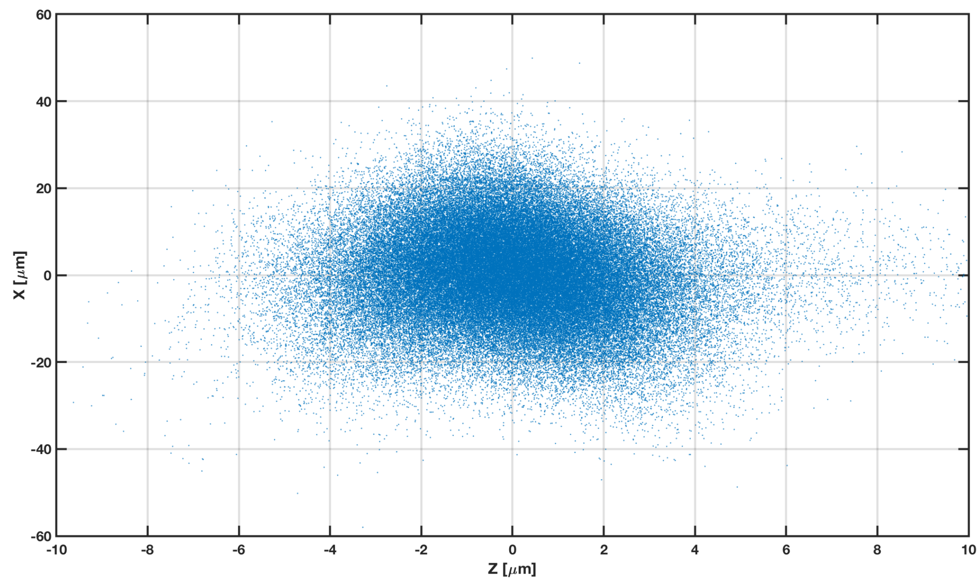
Beam Quality

- Small correlations still present in beam even with spoiler option
- x-z correlations due to CSR
  - Improvement requires “zig-zag” chicane design with active CSR compensation

CSR Wake Potential



Tracked Macro Particle Distribution in x-z plane



Path-Length Adjustability

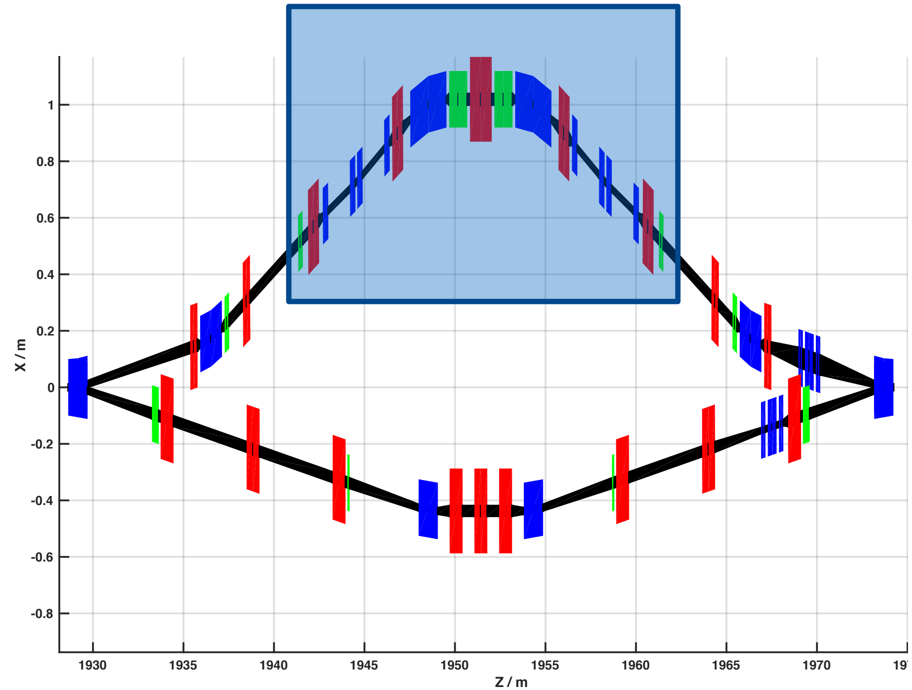
Coarse and fine adjustment controls:

Δz 0 - 500 µm

- Infrequently used- re-tuning required after adjustment
- B3 Δθ = 18.6 mrad (for 500 µm)
- Move Q5, S3E/L to orbit (54 mm)
- Correct angle with Q5 Δx=-21 mm

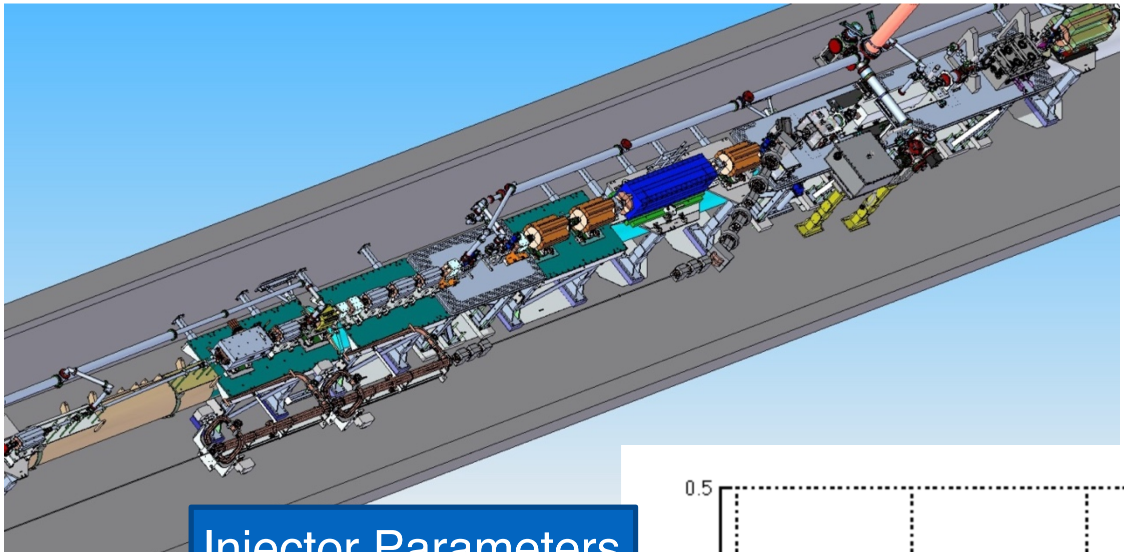
Δz +/- 100 µm

- Continuously adjustable with minimal impact on other delivered beam parameters
- 2 X 4-bend chicanes
- θ = 6.45 mrad (0 - 9.14) = +/- 100 µm



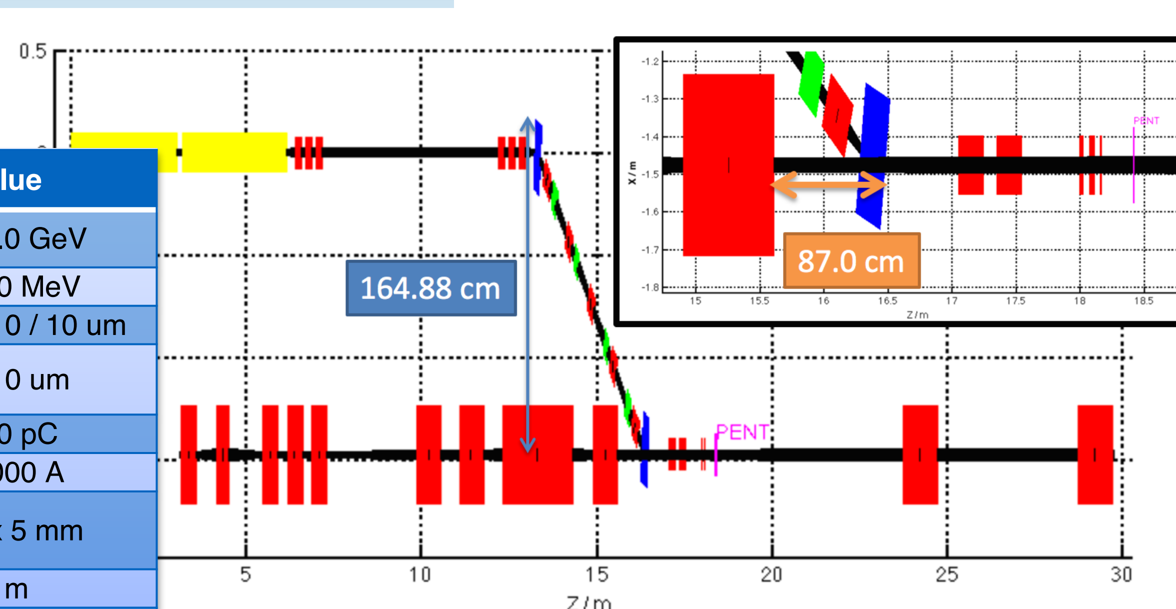
Path length adjustability within BC20P meets requirements

Independent Electron Witness Bunch Injector @ S20



Source Parameters

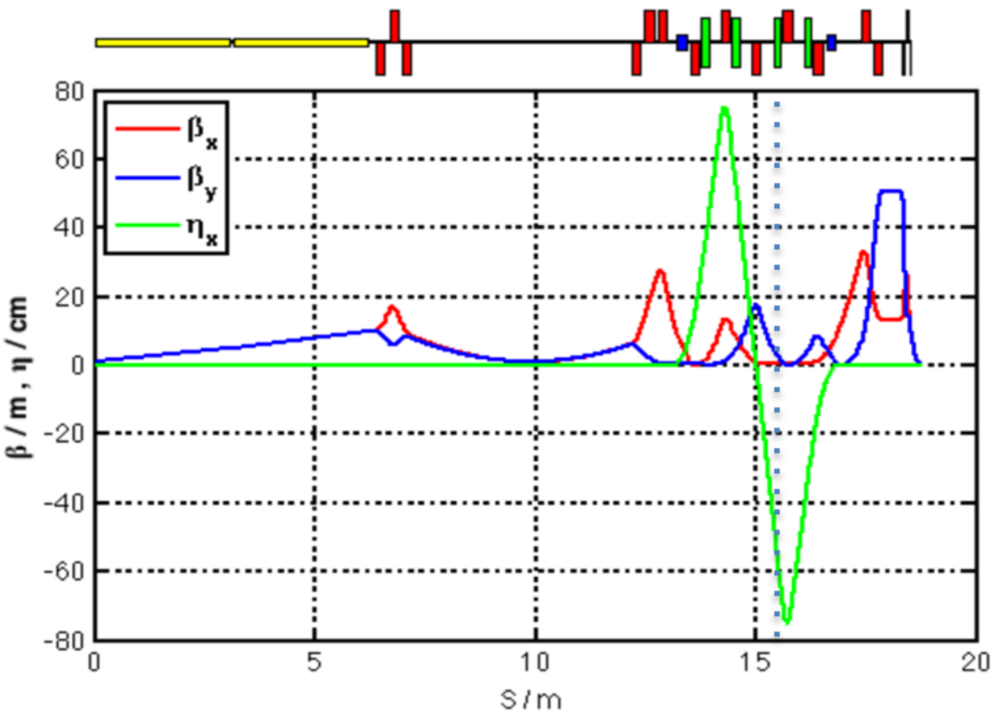
Parameter	Symbol	Value
Initial Bunch Charge	Q_i	350 pC
Normalized Transverse emittance	$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	1 / 1 um.rad
FWHM Bunch Length	Δt_b	1.0 ps
Peak Bunch Current	I_{pk}	300 A

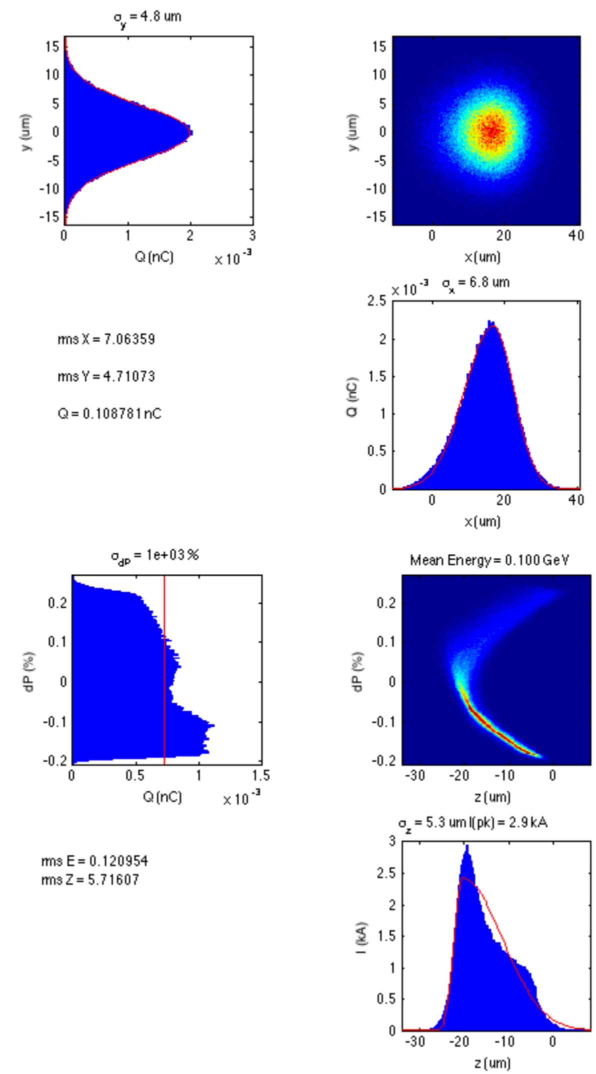


Injector Parameters

Parameter	Symbol	Value
Drive Beam Energy	E_d	10.0 GeV
Witness Bunch Final Energy	E_w	100 MeV
rms Transverse Final Spot Size	σ_x / σ_y	< 10 / 10 um
rms Longitudinal Final Bunch Length	σ_z	< 10 um
Final Bunch Charge	Q_f	100 pC
Final Peak Current	I_{pk}	3,000 A
Final Beta Functions	β_x / β_y	5 x 5 mm
System Length	s	18 m
Injection Bend Angle	Φ	25.78 degrees

Simulated Witness Injector Bunch





Parameter Summary

SLAC

- Summary of high peak current for various configuration options summarized below

Configuration	I^*_{pk} [kA]		σ^*_z [μm]		σ^*_x [μm]		$\gamma\varepsilon^*_x$ [μm-rad]		Q [nC]		
	e-	e+	e-	e+	e-	e+	e-	e+	e-	e+	
Baseline (single or 2-bunch)	70	6	2	17	18	16	13	10	2	1	
2-bunch (2nC posi+LH+L1X+COLL)	130	12	1.8	8	11	10	20	20	1.7	0.7	
Notched (Drive, Witness) +LH	32,16	--	5	--	10, 10	--	6, 8	--	1.5, 0.5	--	10 GeV
BC20 Upgrade	176	--	0.8	--	6	--	7	--	2	--	
BC20+FFS Upgrade +L1X+COLL	300	--	0.4	--	8	--	22	--	1.2	--	
Witness Bunch Injector	3	--	5	--	7	--	1.9	--	0.1	--	100 MeV

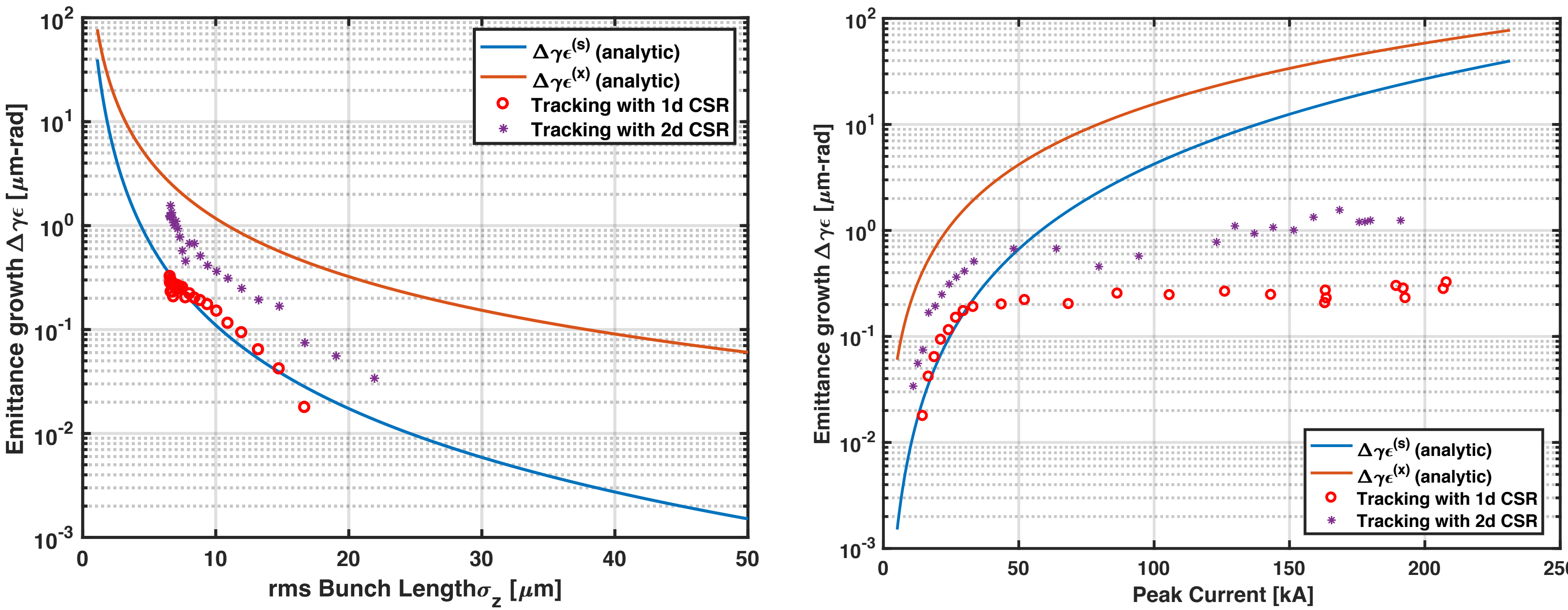
*LH = needs laser heater in injector, L1X = needs x-band harmonic cavity in L1, COLL = utilizes collimation in BC11 & BC14

Backup Slides

BC20E Compression Performance – 2D CSR

$$\Delta\varepsilon_N^{(s)} \approx 7.5\times10^{-3}\frac{\tilde{\beta}_x}{\gamma}\left(\frac{r_e N_b L_B^2}{\rho^{5/3}\sigma_z^{4/3}}\right)^2 \qquad \Delta\varepsilon_N^{(x)} \approx \frac{(-3+2\sqrt{3})}{24\pi}\frac{\tilde{\beta}_x}{\gamma}\left(\frac{\Lambda r_e N_b L_b}{\rho\sigma_z}\right)^2 \qquad \Lambda = ln\left[\frac{(\rho\sigma_z^2)^{2/3}}{\sigma_x^2}\left(1+\frac{\sigma_x}{\sigma_z}\right)\right]$$

[Y. Cai: PR-AB 20, 064402 (2017)]



- Transverse component of CSR wake important for FACET-II @ high I_{pk}
- Newly added feature in Lucretia to perform 2D CSR calculation: only included for Upgraded parameters
  - Fractional impact on results smaller for high-compression cases