FACET·II

Facility for Advanced Accelerator Experimental Tests

FACET-II Diagnostics Overview

FACET-II Science Workshop
October 17 – 21, 2017

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Diagnostics & Controls

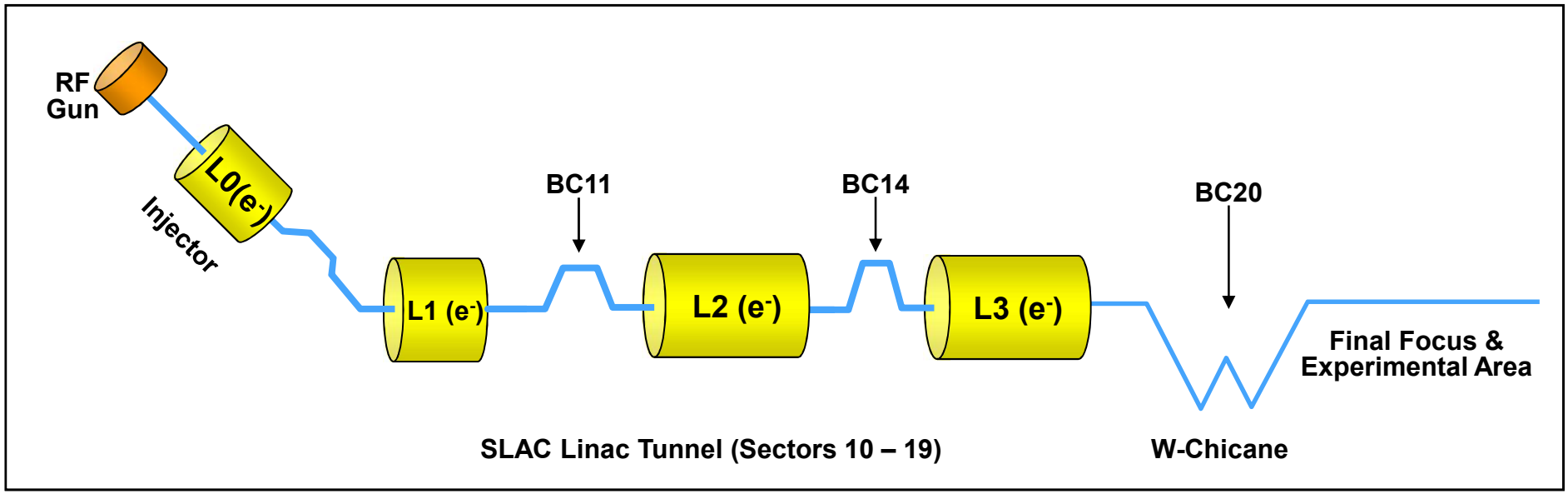
U.S. DEPARTMENT OF ENERGY

Office of Science

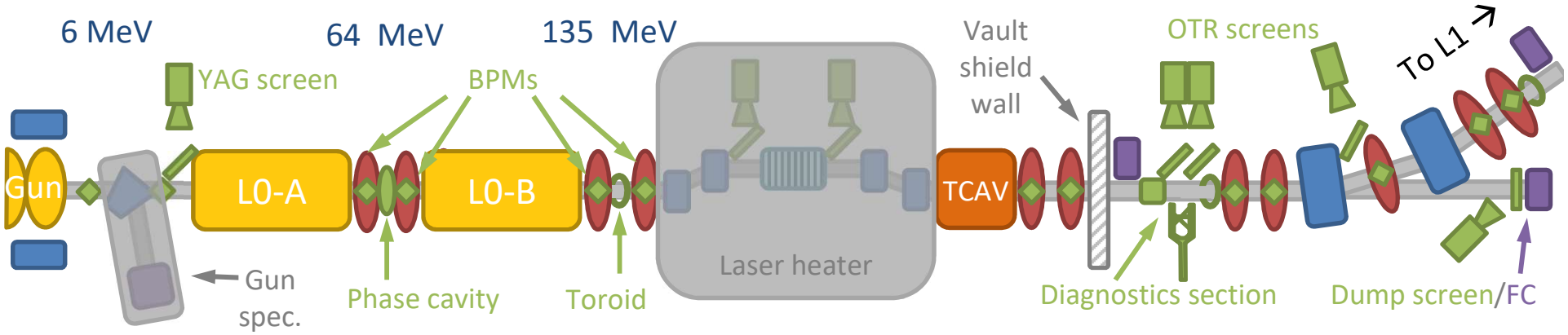
SLAC NATIONAL ACCELERATOR LABORATORY

FACET-II Stage 1 FY17-19

- **Goal:** Deliver compressed electron beam from S10 to experiments in S20
- **Major upgrade:** Electron beam photoinjector in Sector 10
- **Scope:** Injector, shielding wall in S10, bunch compressors in S11 (BC11) and S14 (BC14), beam diagnostics

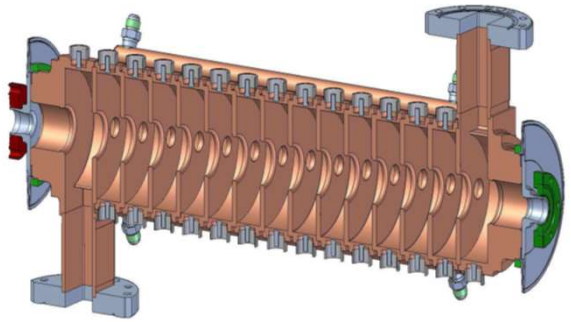


FACET-II Diagnostics
Injector e- Diagnostics Overview



Provide to linac a beam of known:

- Charge
- Arrival time
- Bunch length & distribution
- Energy, energy spread & distribution
- Transverse emittance (projected and sliced)

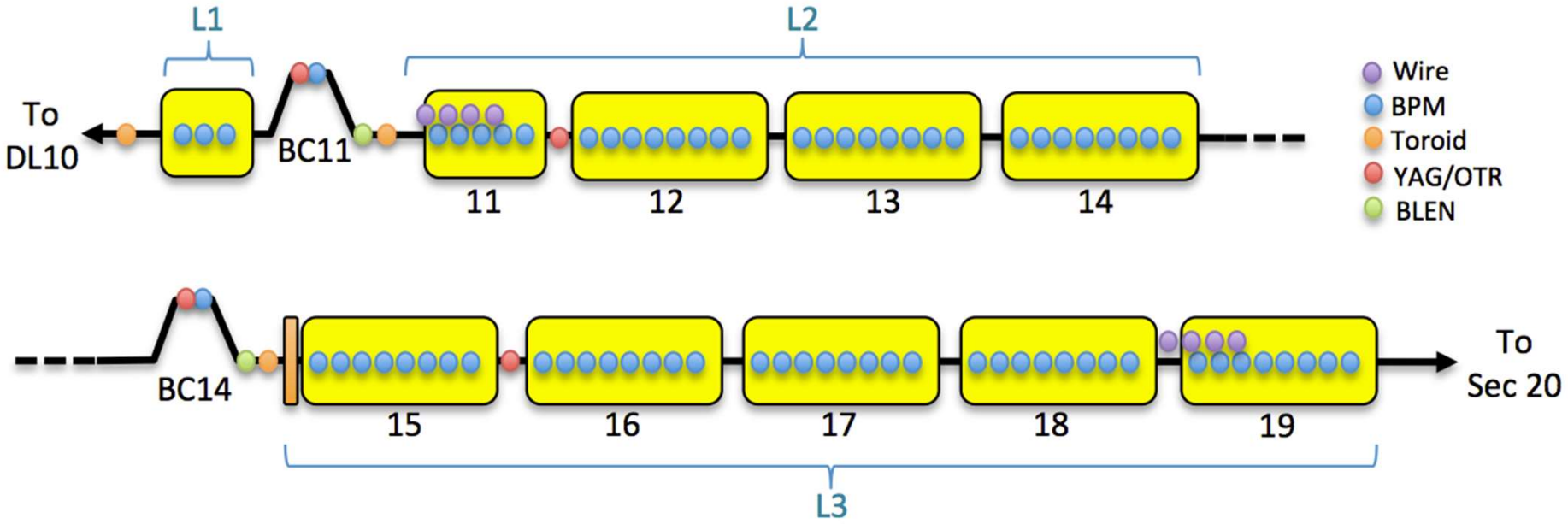


S-band TCAV

- 1.4 MV crest deflection
- 2 MW from klystron 10-5

The most useful LCLS injector diagnostics are reproduced for the FACET-II injector

FACET-II Diagnostics
Linac and Bunch Compressors



- 70 BPMs and 4 wire scanners exist and in use at FACET
- BC11 and BC14 have all-new diagnostics
- TCAV after BC14
- 9-foot instrumentation girders between sectors

Linac diagnostics will mostly be reused in place or repurposed from FACET

FACET-II Diagnostics
Linac L1, BC11 and BC14 Overview

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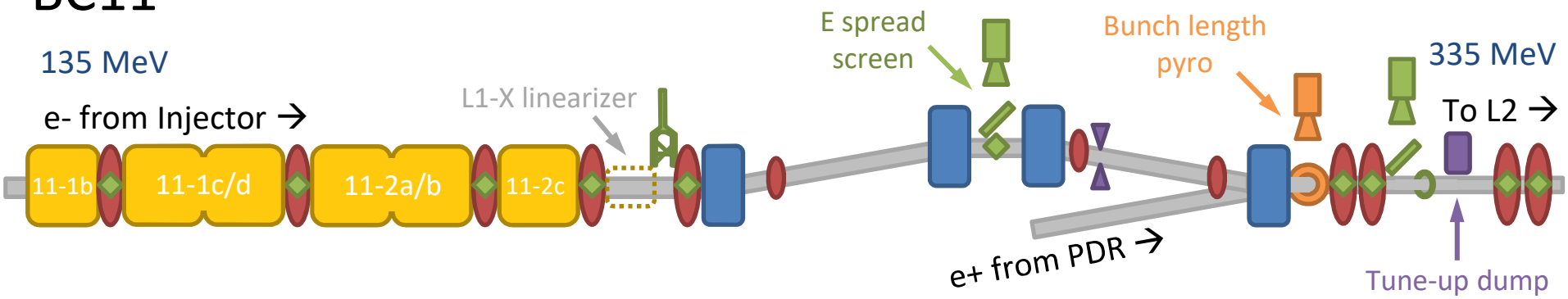
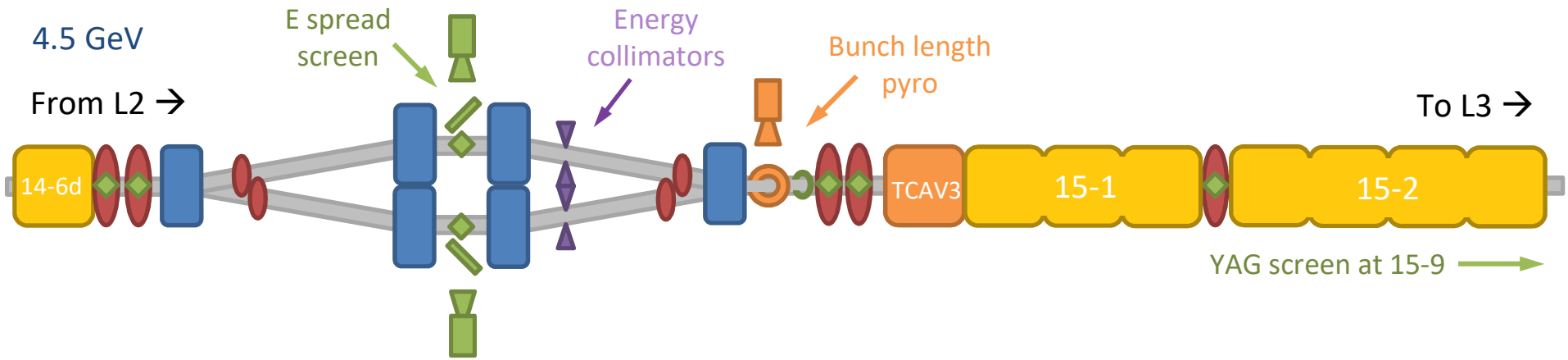
BC11

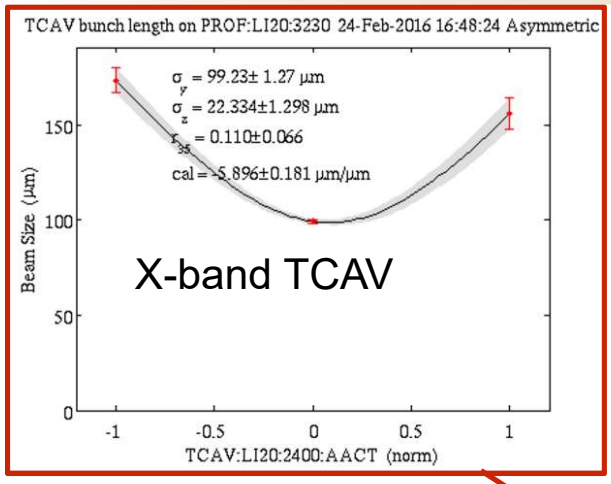


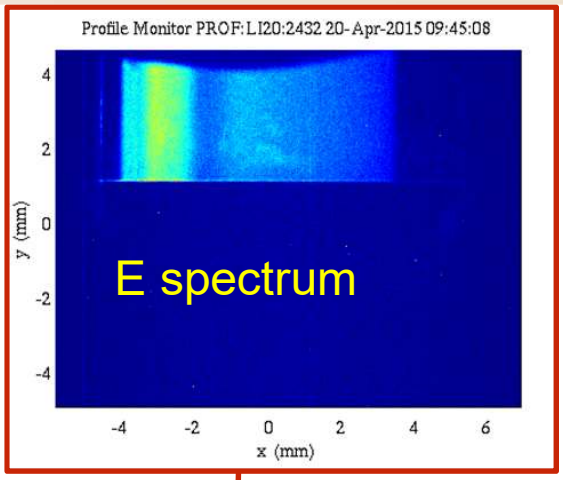
BC14

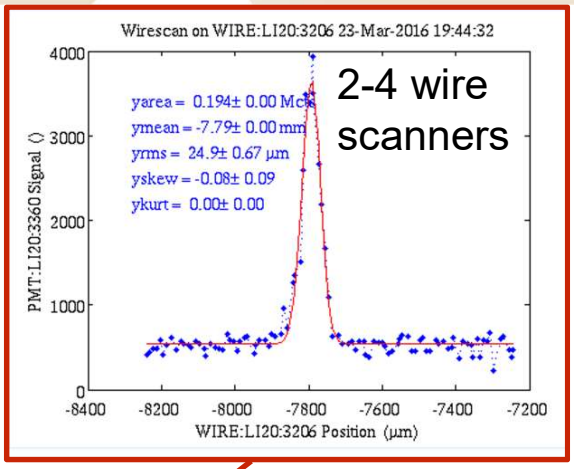


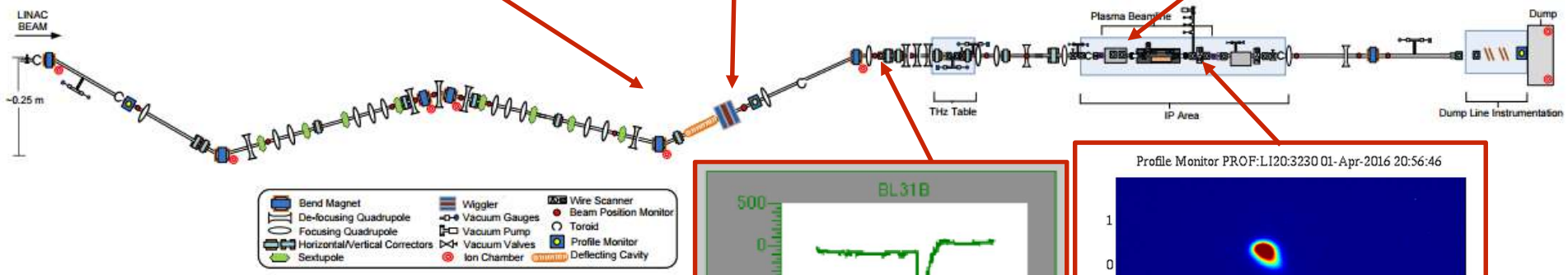
Bunch compressors have longitudinal phase space diagnostics

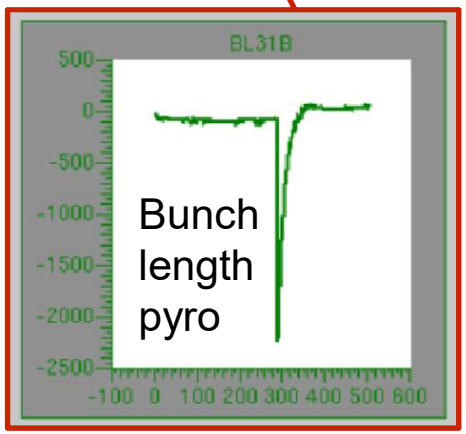
Key BC20 / FACET Existing Diagnostics

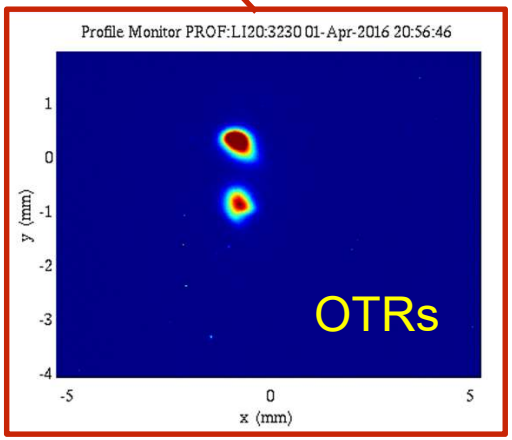












W chicane and IP area diagnostics all new for FACET.

FACET-II Stage 1
Diagnostics Overview

SLAC

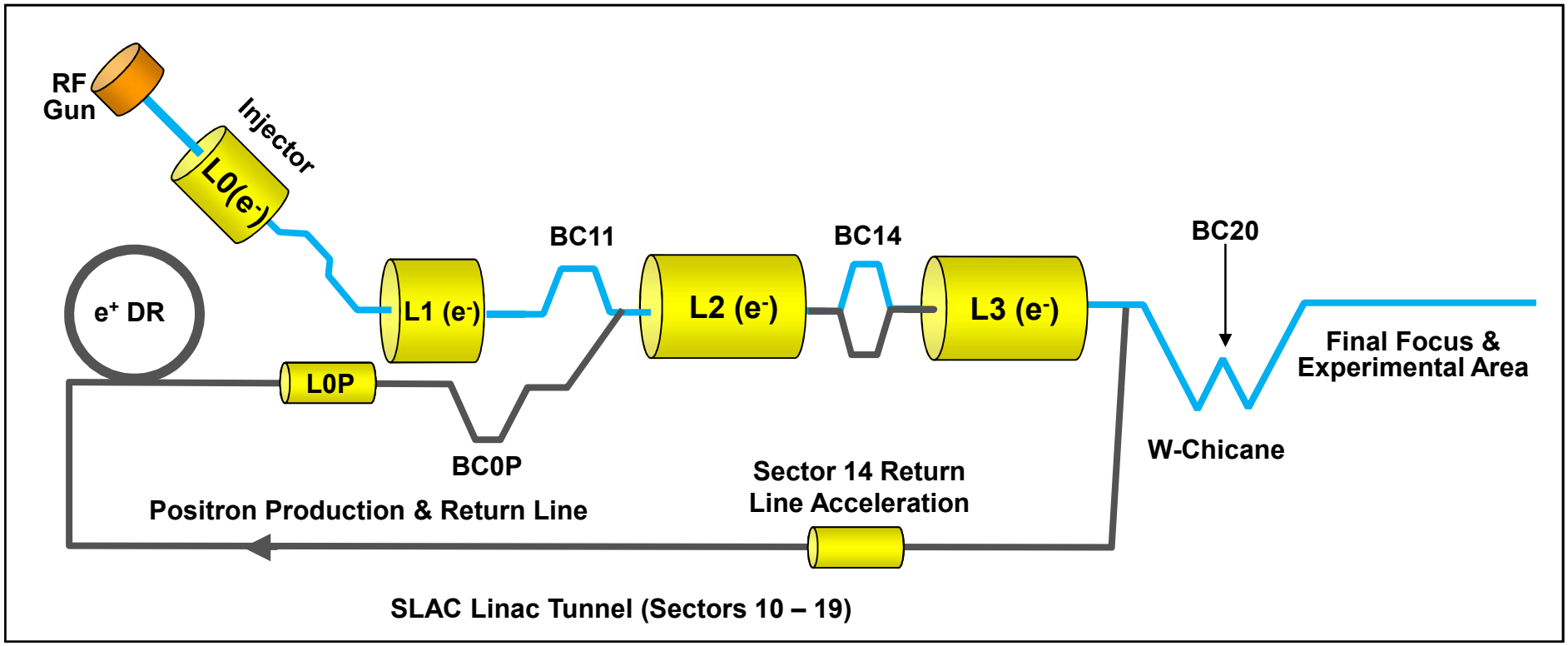
Standard e- beam diagnostics (existing and new)

	Injector	L1 & BC11	BC14	L2 & L3	BC20 & IP	Total (Stage 1)
BPM	12	6 + 3	4 + 2	66	19	**112**
Toroid	3	1	1		5	**10**
Wire scanner	1	1		4 + 4	2	**12**
Profile monitor	5	2	2	1	8	**18**
TCAV	1 S		1 S		1 X	**3**
Bunch Length	1	1	1		1	**4**
Collimator		1	2	2	1	**6**

FACET-II re-uses existing FACET e- beam diagnostics where possible

FACET-II Stage 2 FY17-20

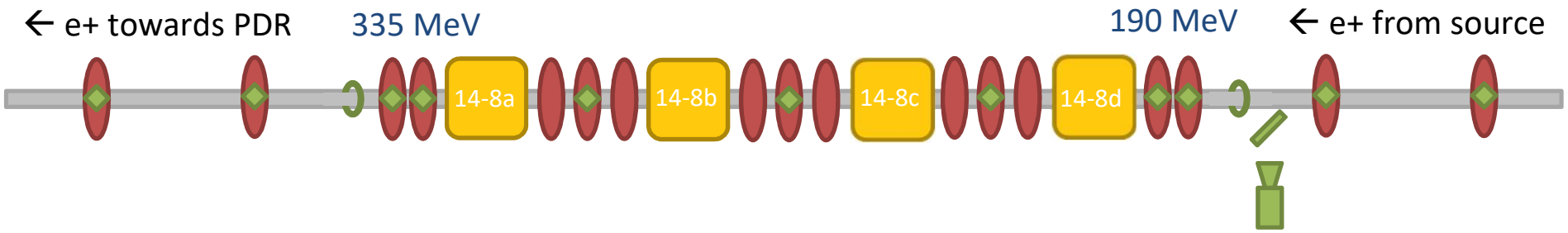
- **Goal:** Deliver compressed electron beam from S10 to experiments in S20
- **Major upgrade:** Positron damping ring
- **Scope:** Damping ring, positron bunch compressor & return line



FACET-II Diagnostics
Positron Transport Lines Overview

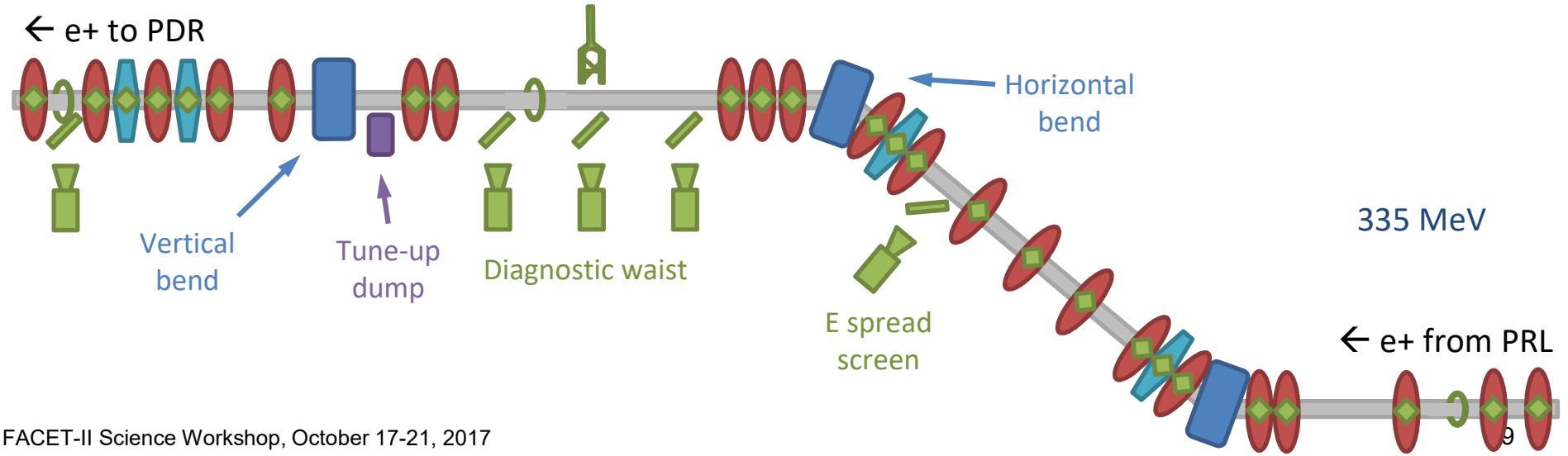
SLAC

Positron Return Line – Sector 14



Diagnostics for e+ return system optimize transmission and ring capture

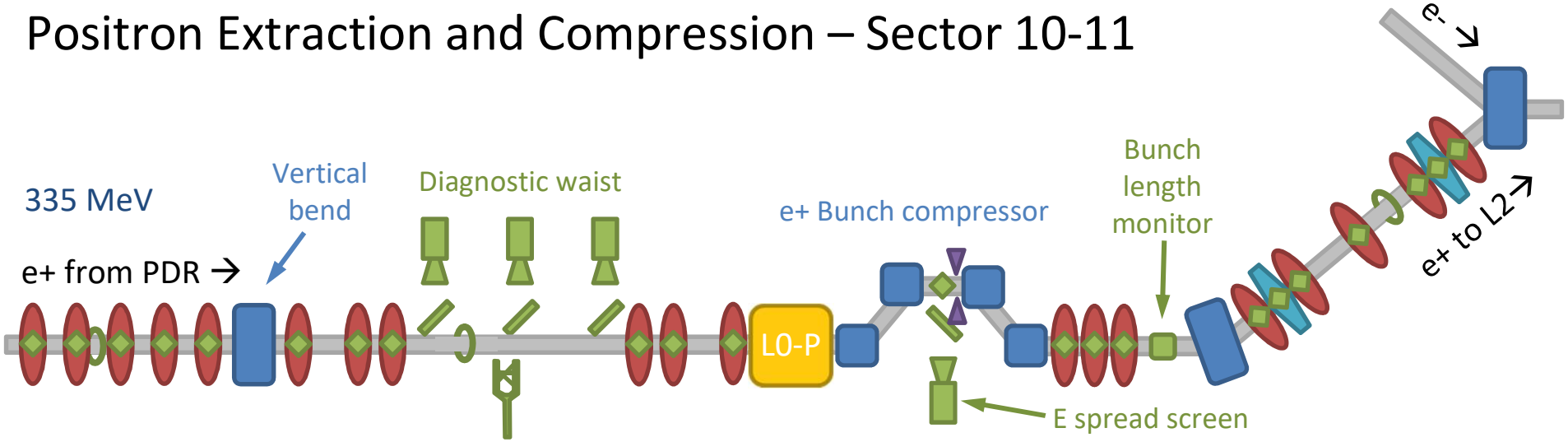
Positron Return Line – Sector 10



FACET-II Diagnostics
Positron Transport Lines Overview

SLAC

Positron Extraction and Compression – Sector 10-11



Provide to linac a beam of known:

- Charge
- Energy, energy spread & distribution
- Transverse emittance (projected)
- Bunch length

PEC diagnostics characterize positron beam before injection into linac at BC11

FACET-II Stage 2
Diagnostics Overview

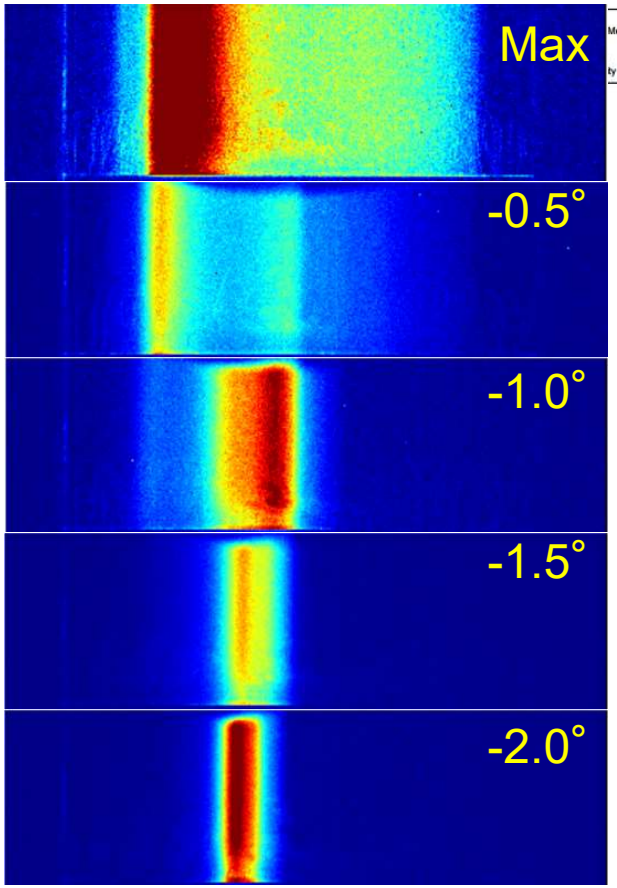
SLAC

Standard e+ beam diagnostics (existing and new)

	e+ source	e+ Return Line	Damping Ring	e+ Extraction	Stage 2 Total	Project Total
BPM	46	62 + 35	28	22	193	**305**
Toroid	5	3 + 2		3	**13**	**23**
Wire scanner		1		1	**2**	**14**
Profile monitor	4 + 1	2 + 5		5	**17**	**18**
TCAV					**0**	**3**
Bunch Length				1	**1**	**5**
Collimator	1			1	**2**	**8**

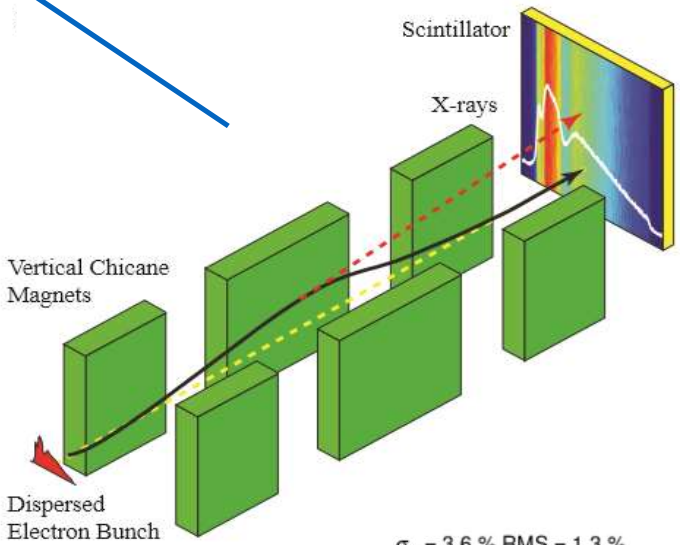
FACET-II re-uses existing FACET e+ beam diagnostics where possible

SYAG wiggler stripe spectrometer



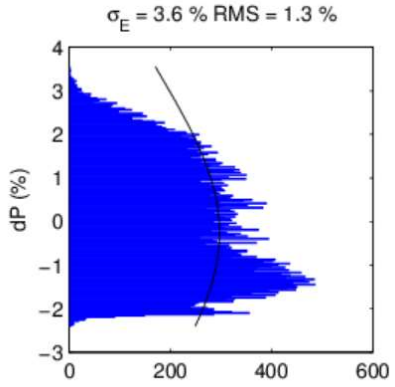
Chirp scan, detuned compression →

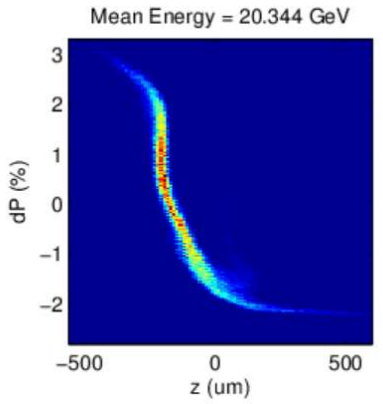
Higher energy →



Always-on, non-invasive energy spectrum measurement

SLAC-PUB-16310





FACET-II Diagnostics
Beam Position Monitor Processors

SLAC

Linac, BC11, BC14, e+ source, e+ return

CAMAC 605/972

SLC,1983

Hybrid mixer

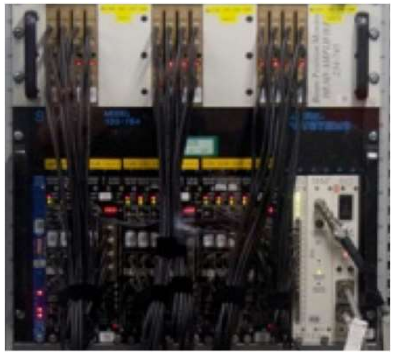
3x self-triggering track-and-hold

10-bit gated ADC

50 μm precision

~800 pC min.

BC20 + IP



CAMAC NiTnH

FFTB, 1991

Preamp/stretcher

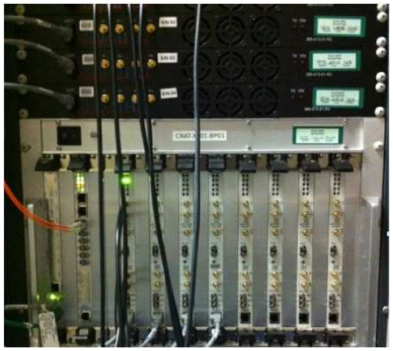
2x self-triggering track-and-hold

16-bit latching ADC

< 5 μm precision

~100 pC min.

FACET IP



VME XTA BPM

LCLS/XTA, 2008

4x 140 MHz BP filter + 4x preamp

~100 MHz 12-bit digitizer

< 5 μm precision

~10 pC min.

e- Injector

μTCA BPM

LCLS-II (Cu), 2013

4x 300 MHz BP filter + 4x preamp

~100 MHz 16-bit digitizer

< 5 μm precision

~10 pC min.

BPMs are the primary diagnostic for monitoring, feedback and tuning

FACET-II Diagnostics
Relative Bunch Length Monitors

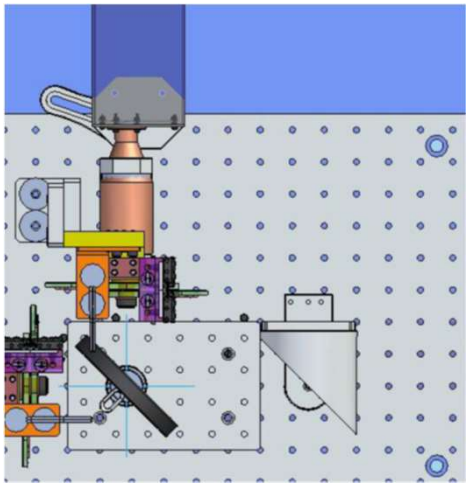
SLAC

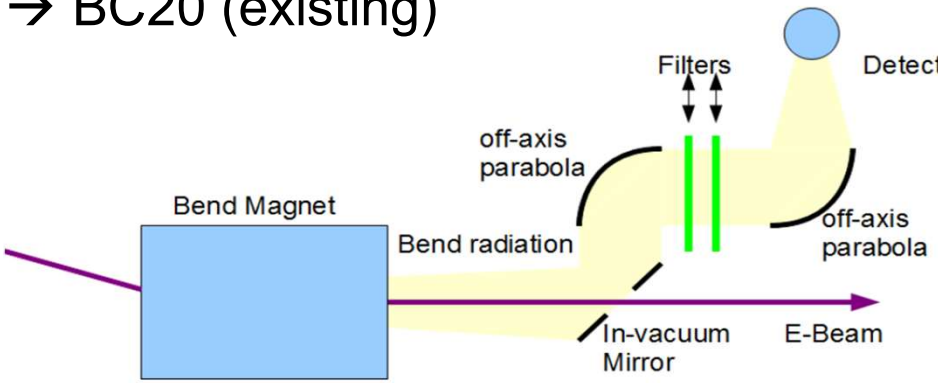
Coherent edge radiation monitor

- Mirror + pyrometer
- f > 300 GHz
- I_{pk} > 300 A

→ BC11, BC14

→ BC20 (existing)





Wall gap monitor

- Ceramic gap + diode
- f < 300 GHz
- I_{pk} < 300 A

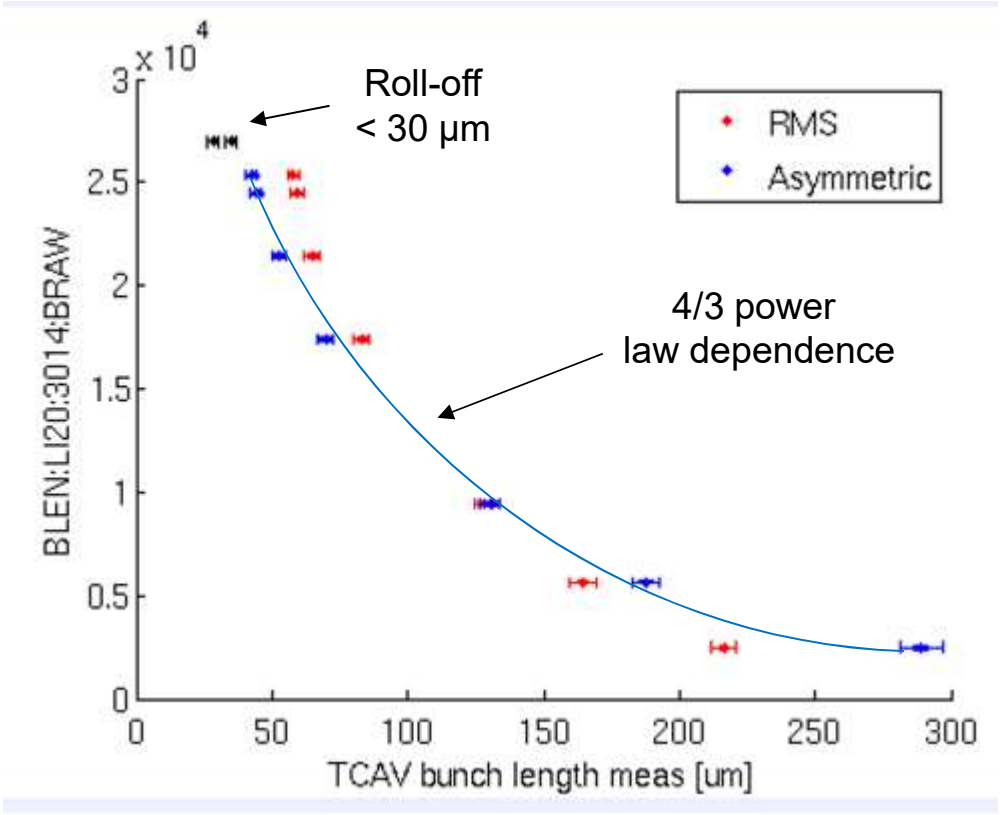
→ Injector, e+ system

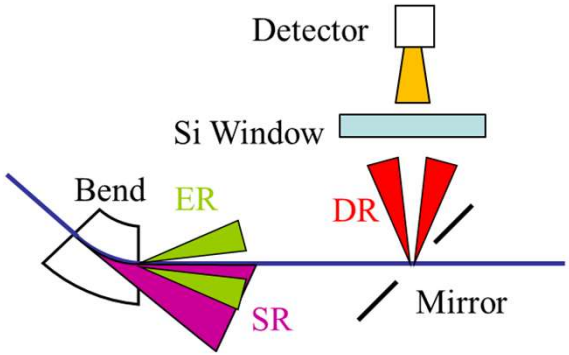
Non-destructive, pulse-by-pulse bunch length monitoring, but need TCAV calibration

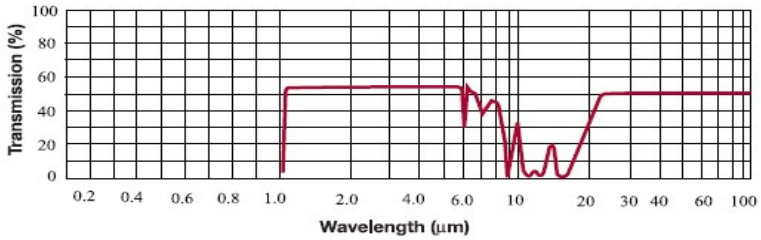
Bunch Length Monitors

Pyroelectric bunch length monitor modeled after LCLS BC1/BC2.

Relative diagnostic, works well for finding and maintaining peak compression.

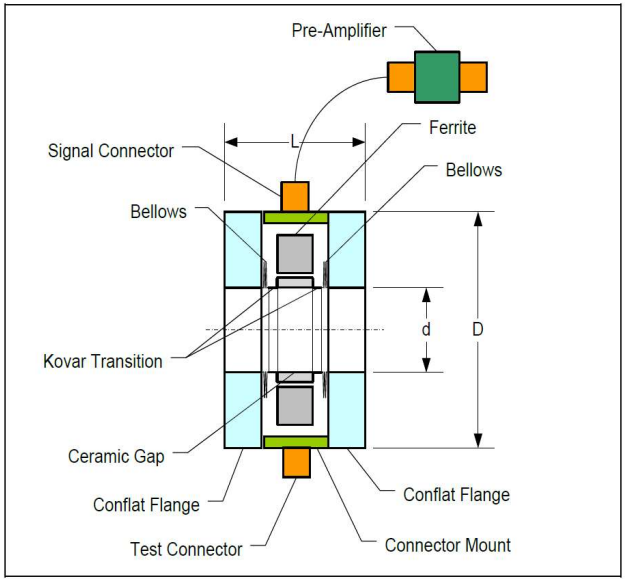


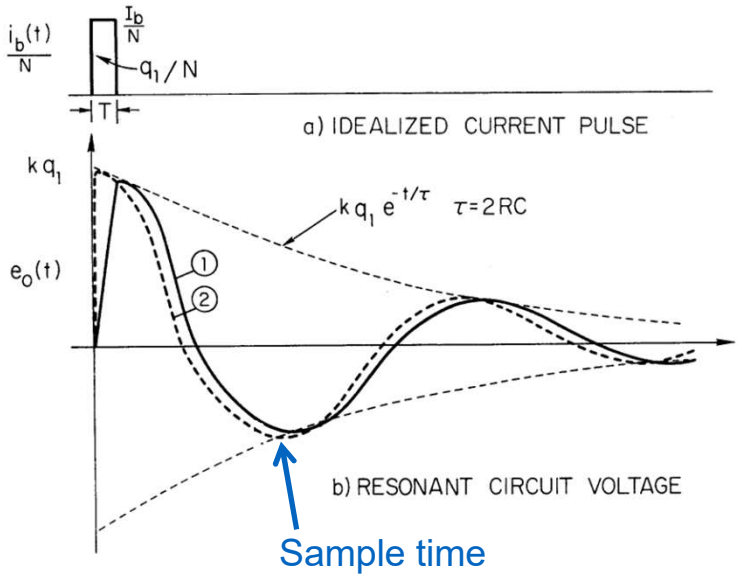




FACET-II Diagnostics
Toroid Beam Charge Monitors

Resonant toroid current transformers with calibration winding





Typically:

- 8-turn signal
- 1-turn calib.
- f ~ 50 kHz

CAMAC TCM module + SLAC preamplifier – used at FACET

- Rectifier to S&H circuit to 10-bit gated ADC
- ~ 5% absolute accuracy and precision at 3 nC

LCLS upgrade: low-noise preamp + twinax cable + 12-bit VME ADC

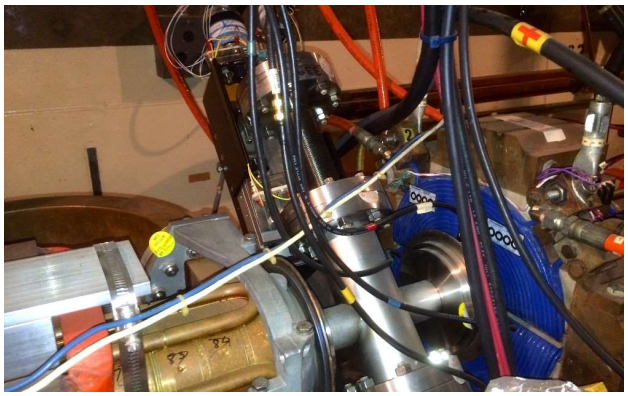
- <1 % accuracy, <0.2% noise at 150 pC

Toroids in FACET-II monitor total beam charge at boundaries of functional areas

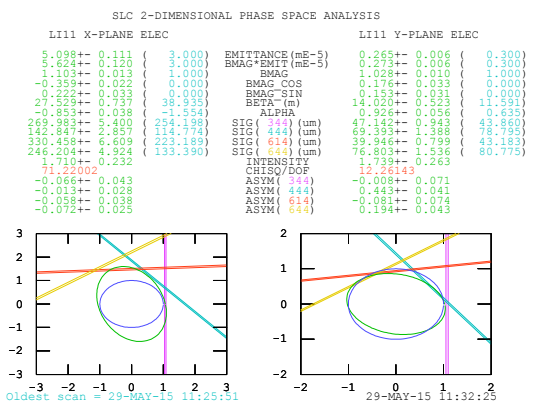
FACET-II Diagnostics
Linac Emittance Measurement

Location	Sector	Energy [GeV]	σ_x (μm)	σ_y (μm)	# of wire scanners	# existing
After BC11	Sector 11	0.335 – 1.0	145-215	110-215	4	4
End of L3	Sector 19	9.0 – 10.0	35-57	38-56	4	1

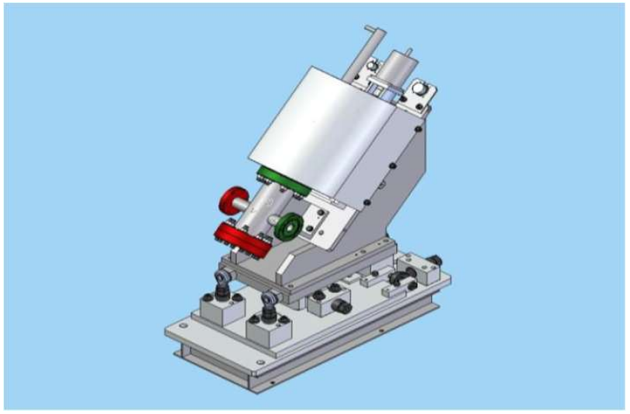
- Relocate wire scanners from Sectors 1 & 2 to FACET-II linac
- Replace standard 10-foot RF structures with modified 9.4-foot sections



Sector 2 wire scanner



4-wire ε measurement



Wire scanner design

Wire scanners characterize emittance preservation across linac-BC system

FACET-II Diagnostics
Guidelines behind diagnostic choices

BPM in every focusing magnet + key dispersive locations

Toroids upstream/downstream of every transport line + BC

At each BC:

TCAV + relative BLM

Energy spread screen/wire, BPM, collimator pair

Multi-profile emittance measurement brackets linac

→ Wire scanners after BC11, before BC20

x-y magnet mover at every sextupole

FACET·II
Facility for Advanced Accelerator Experimental Tests

Questions

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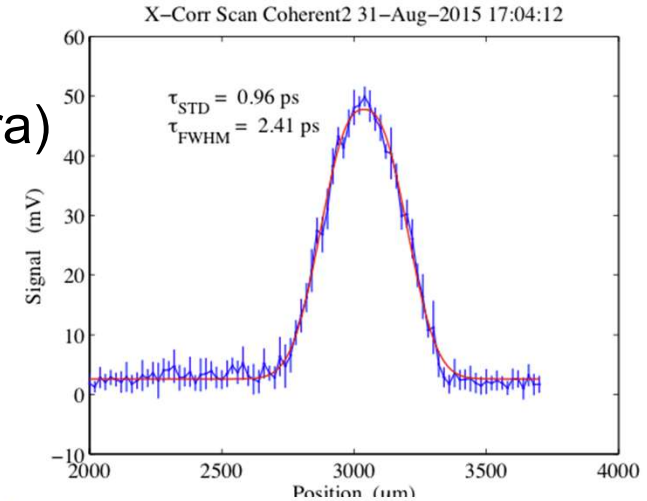
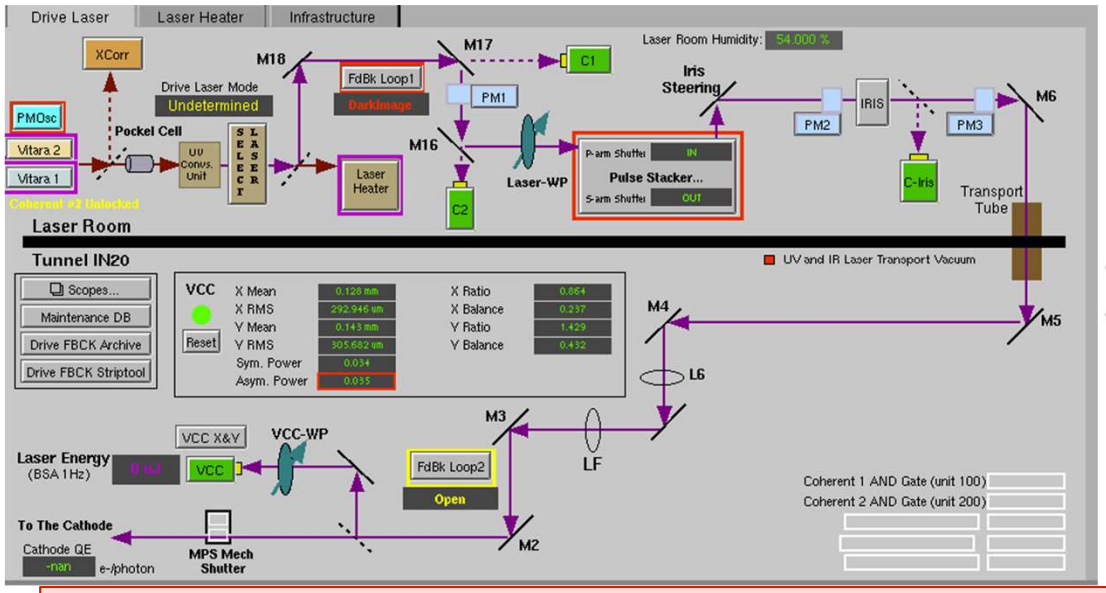
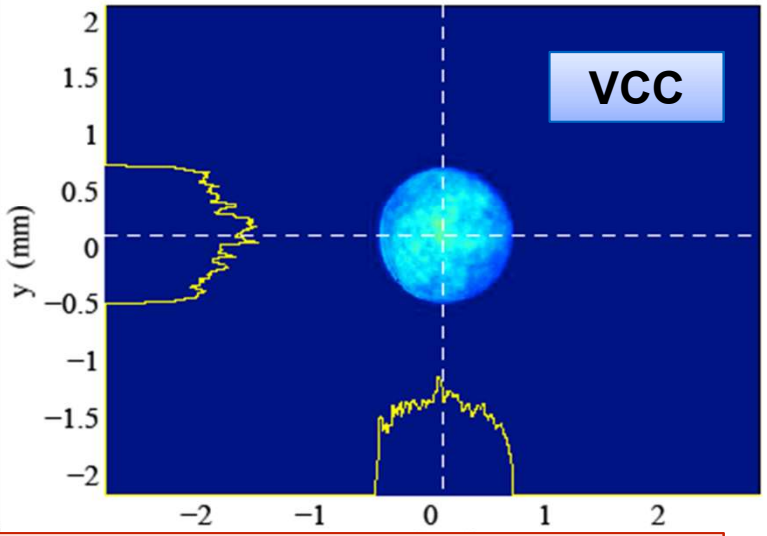
FACET-II Diagnostics
UV Drive Laser and IR Heater Laser

Key LCLS drive laser diagnostics:

- Transverse distribution (virtual cathode camera)
- Pulse length (cross correlator)
- Transport cameras → steering feedback
- Beam charge → intensity feedback, QE monitoring

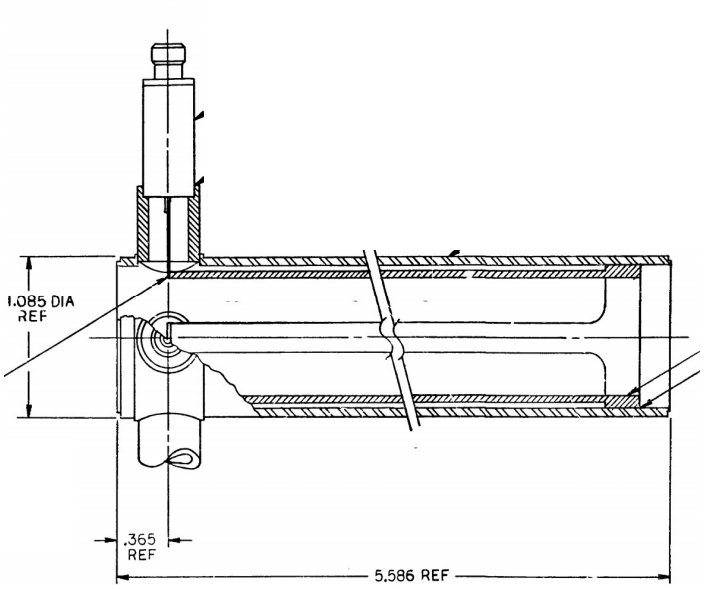


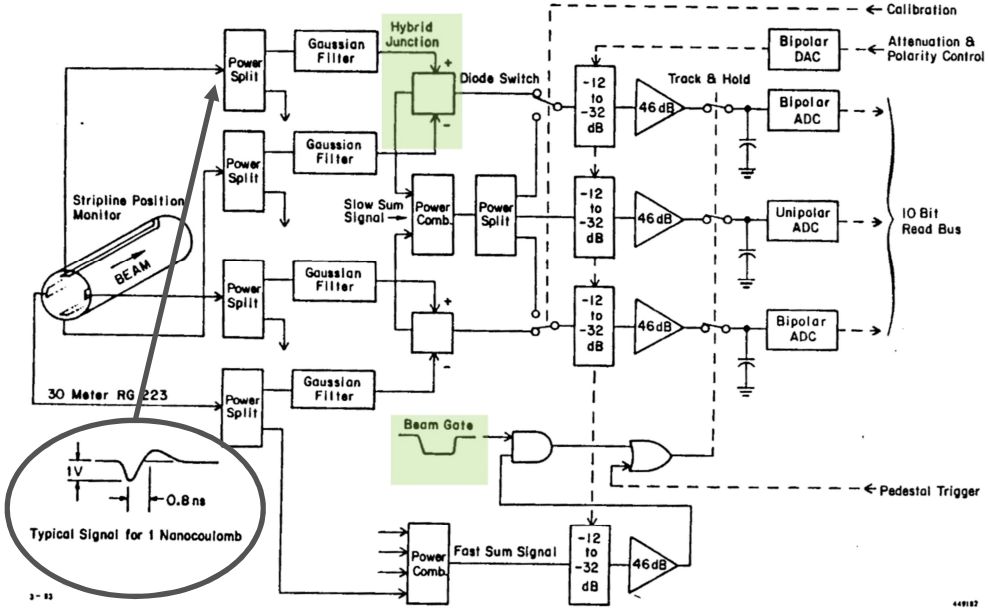


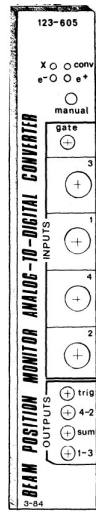


Laser diagnostics reflect ongoing development and current practices at LCLS

Existing Linac BPMs







CAMAC 605

Existing linac CAMAC BPM processors date from SLC

- 70 BPMs in FACET-II linac – 8 per sector
- Broadband, external gate – can resolve bunches 60 ns apart

Existing BPMs are sufficient for interlaced e- / e+, but not co-accelerated beams

FACET-II Diagnostics
YAG/OTR Profile Monitors

Ce:YAG scintillator crystal

Al/Ti OTR foil

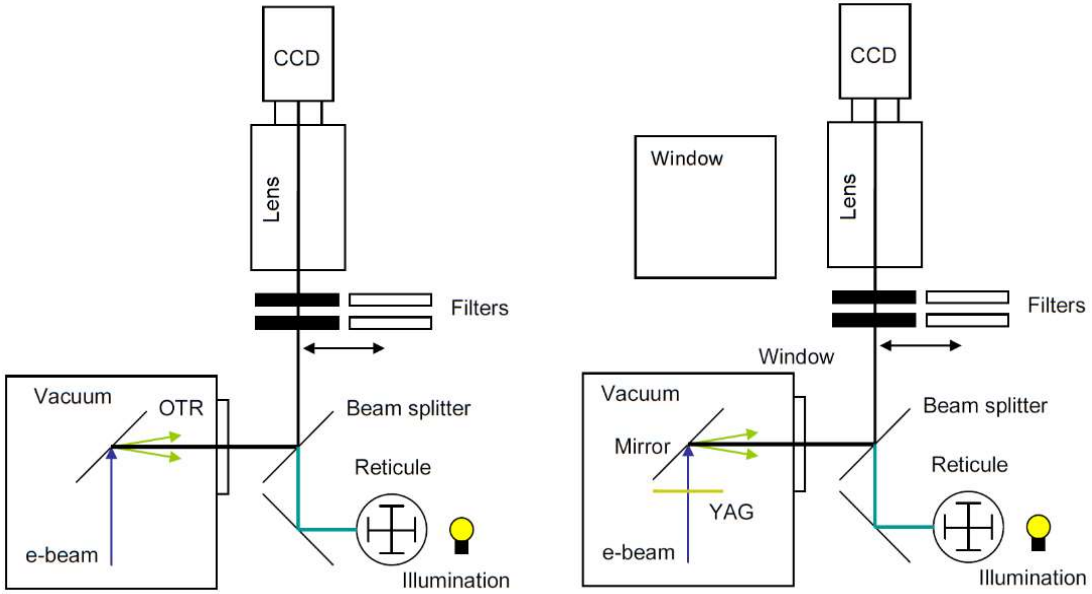
Phosphor

- Transverse profile/emittance measurements
- Energy spread (BCs)
- Bunch length (TCAVs)

YAG: low E, dispersed beam

OTR: high E, focused beam

→ COTR is a problem for compressed bunches

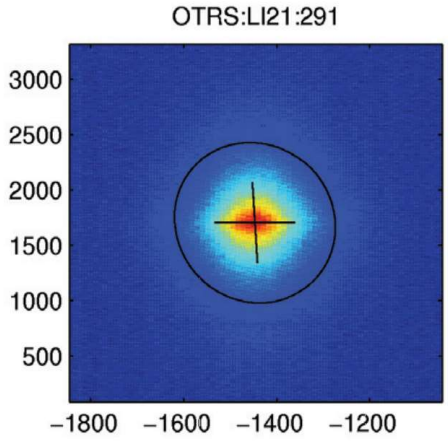


Profile monitors are most efficient and intuitive transverse diagnostic available

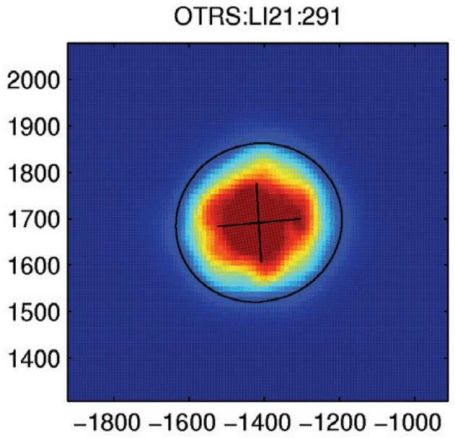
FACET-II Diagnostics
COTR from compressed bunches - LCLS

SLAC

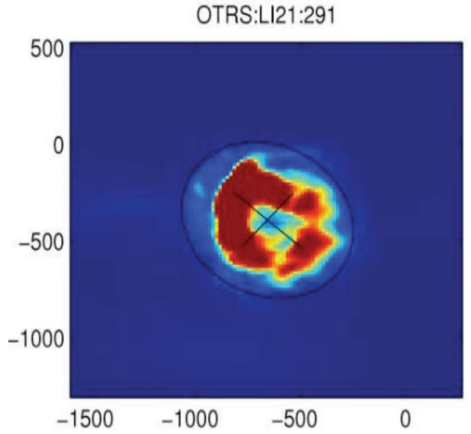
- Upstream foil inserted
- Microbunching spoiled
- Incoherent OTR only



- Nominal compression
- Microbunching present
- Coherent OTR



- Max compression
- Microbunching enhanced
- Strong COTR



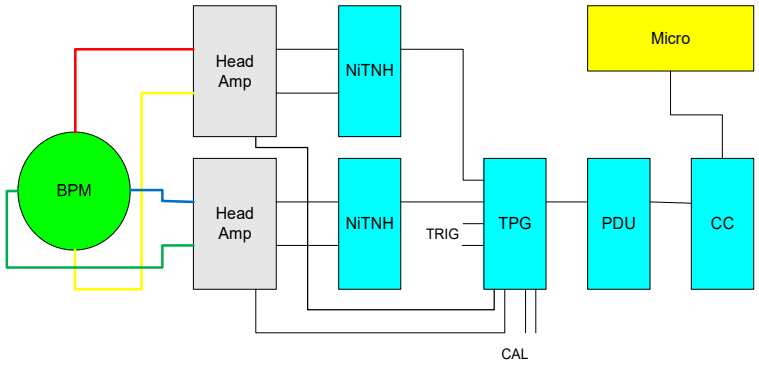
- Microbunched structure at optical wavelengths → coherent OTR emission
- Ways to mitigate this effect for YAG screens: screen tilt, fast camera gating
- Dispersed beams, e.g. E-spread or TCAV screens

Strong COTR from compressed bunches → use wire scanners after BC11 for focused beams

BC20 Diagnostics Controls

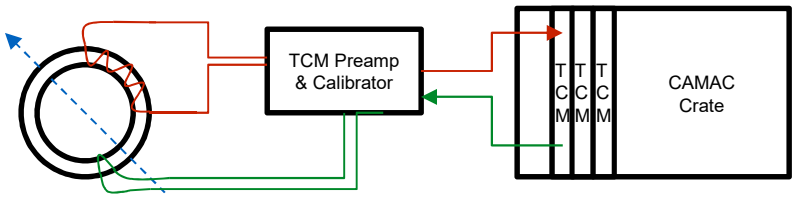
BPMs: 21 FFTB "NiTnH" CAMAC processors in FACET

- 24 in BC20E + BC20P + FFS
- Add 6 modules to existing crates



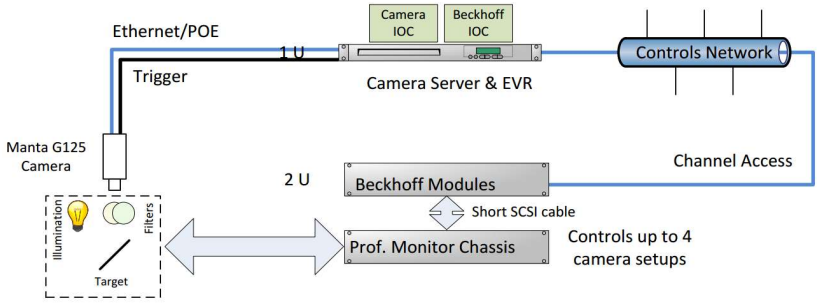
Toroids: 5 TCM CAMAC modules

- Add 2 modules to existing crates



YAG screen:

- Add camera & POE to spare camera server channel

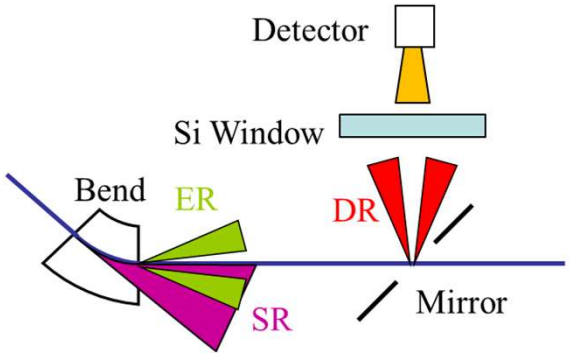


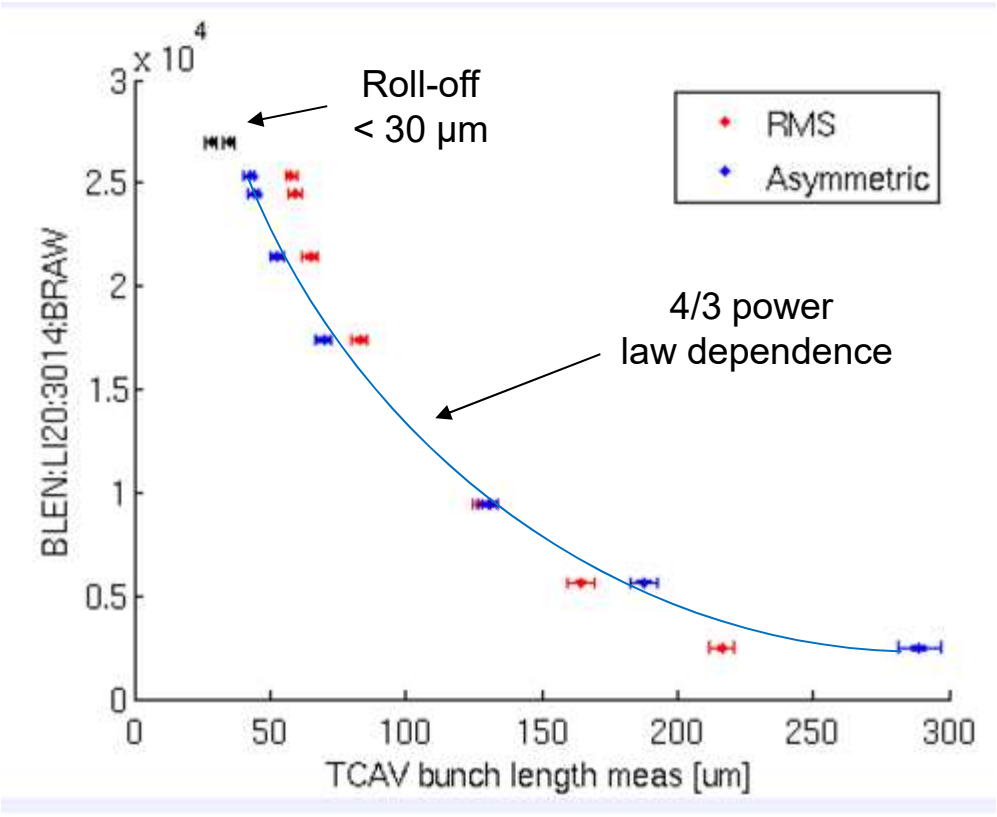
Use existing controls for diagnostics - add channels and run cable if necessary

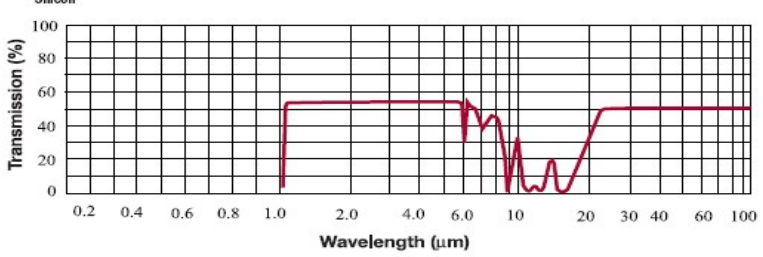
Bunch Length Monitors

Pyroelectric bunch length monitor modeled after LCLS BC1/BC2.

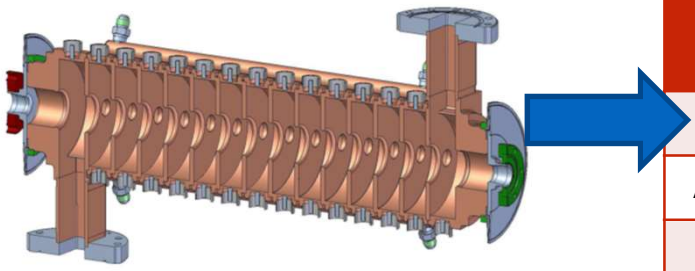
Relative diagnostic, works well for finding and maintaining peak compression.





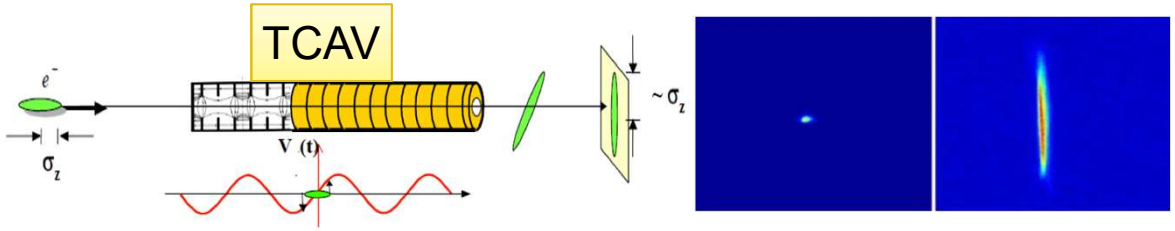


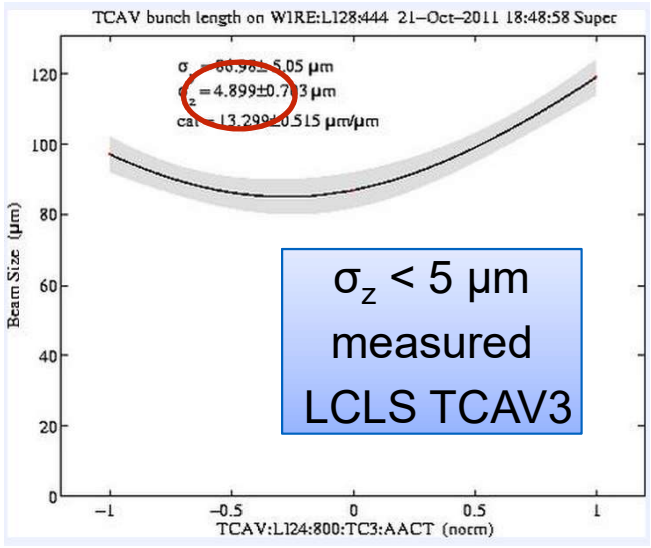
FACET-II Diagnostics
Transverse RF Deflecting Cavities (TCAV)



Injector 55cm S-band TCAV
Designed for LCLS-II

Location	Name	Length [m]	f_{RF} [MHz]	σ_z [μm]	Screen
Injector	TCAV0	0.55	2856	800	OTR04
After BC14	TCAV3	2.4	2856	30	15-9
End BC20	XTCAVE	0.5	11424	1	IP2B

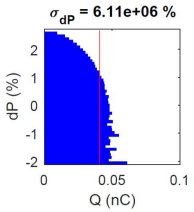


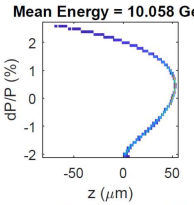


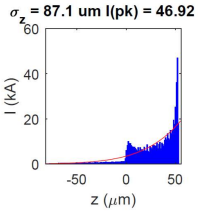
- TCAVs put y-z correlation on beam.
- Measure bunch length with downstream profile monitor or wire scanner.
- Self-calibrating (f_{RF} well known)

TCAVs before/after linac, BC14 for measurement of bunch length & distribution

XTCAV horizontal at dump



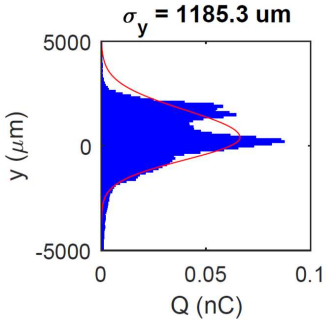


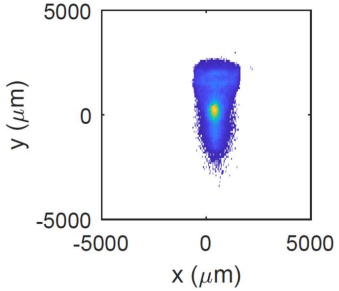


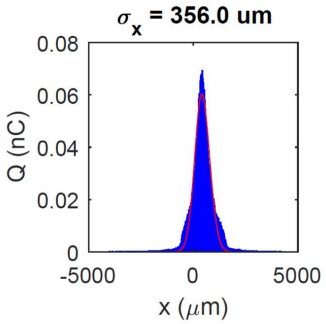
rms dP/P = 1.26285 %

rms Z = 22.8317 um

Dump, TCAV off





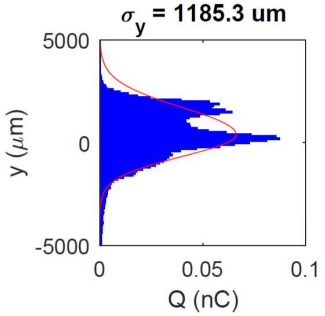


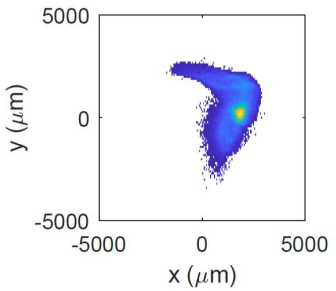
rms X = 553.256 um

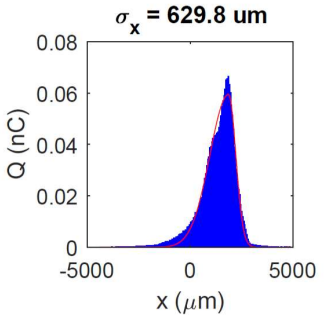
rms Y = 1459.84 um

Q = 1.99719 nC

Dump, TCAV on







rms X = 833.529 um

rms Y = 1459.75 um

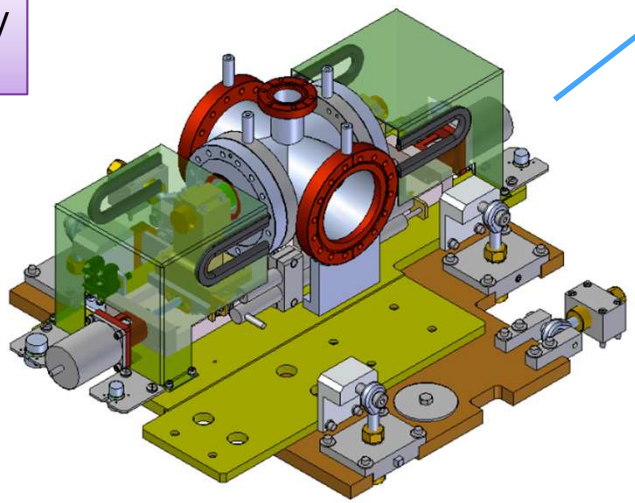
Q = 1.99713 nC

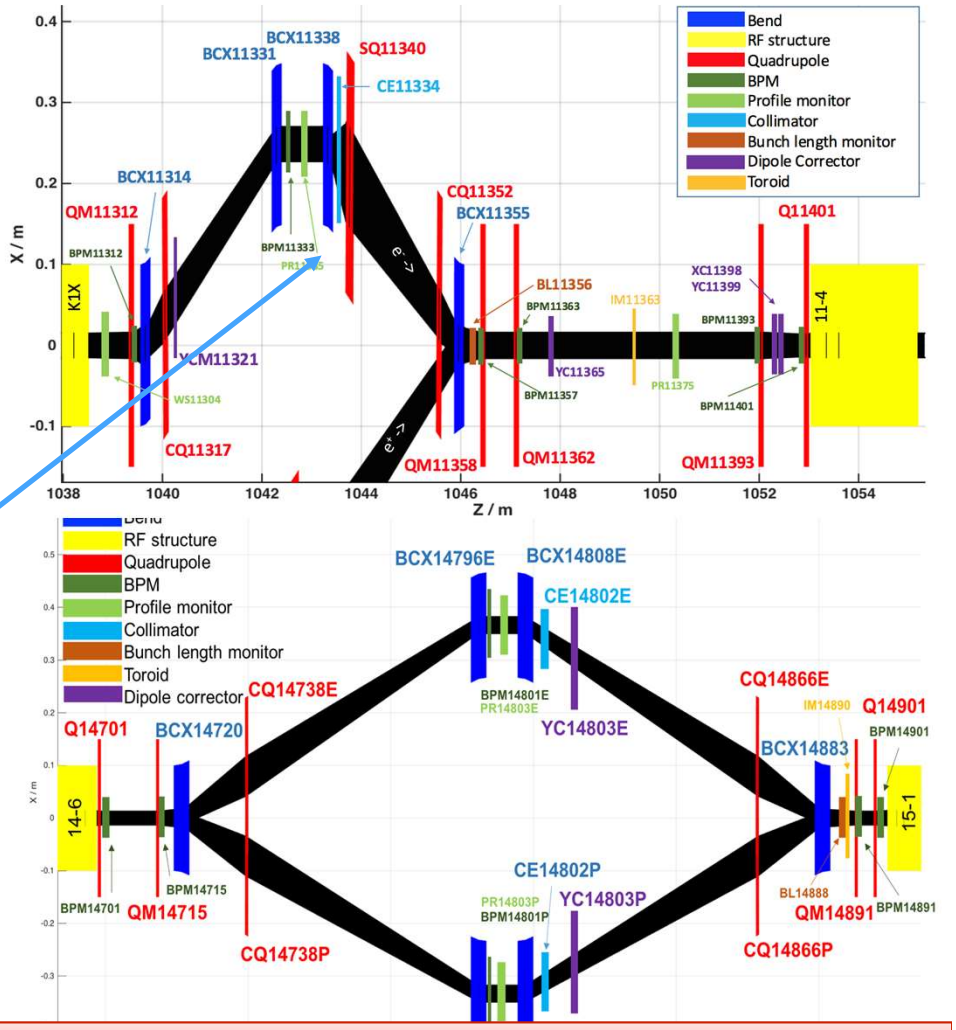
FACET-II Diagnostics
BC11 / BC14 Collimation

2-jaw energy collimation in each bunch compressor:

- Beam quality / tails
- Potential high I_{pk} mode (horn cutting)

BC11 Energy Collimator





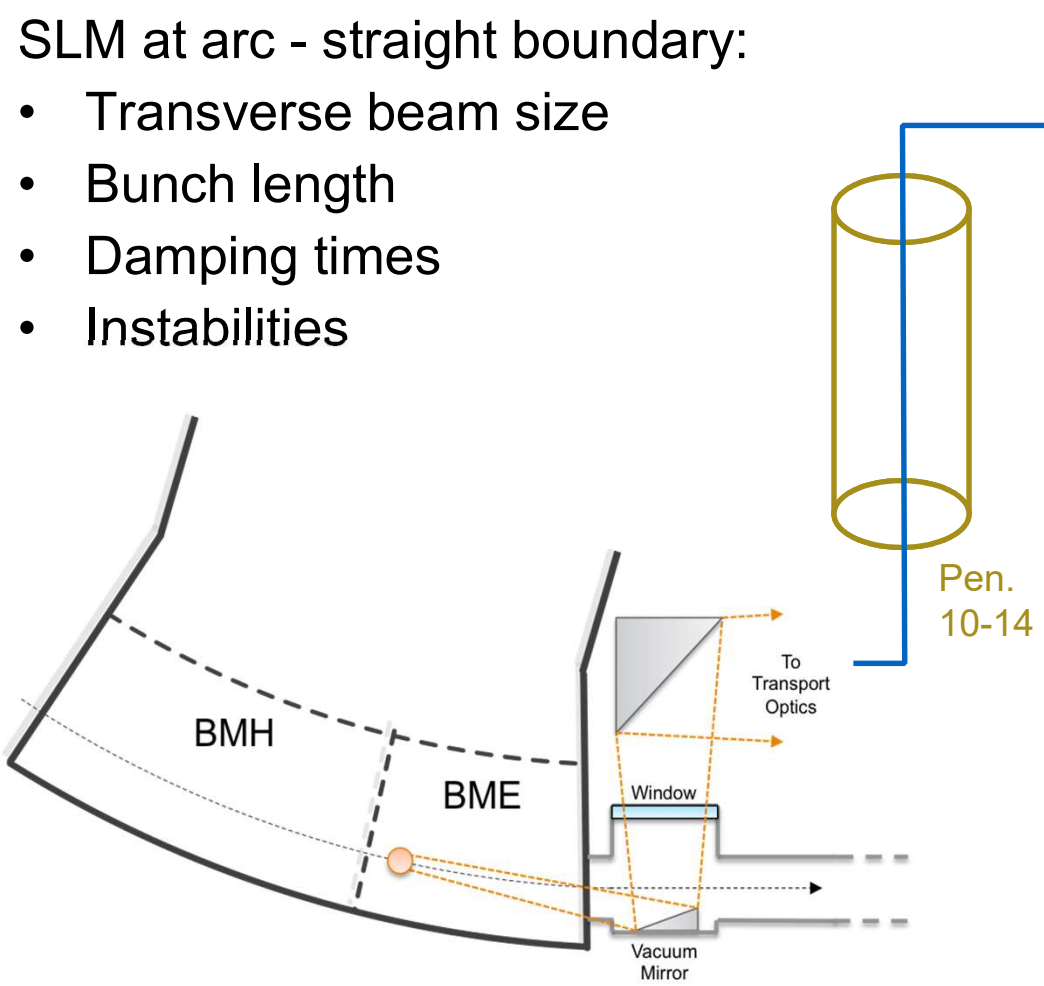
Collimation in bunch compressors gives additional control of longitudinal distribution

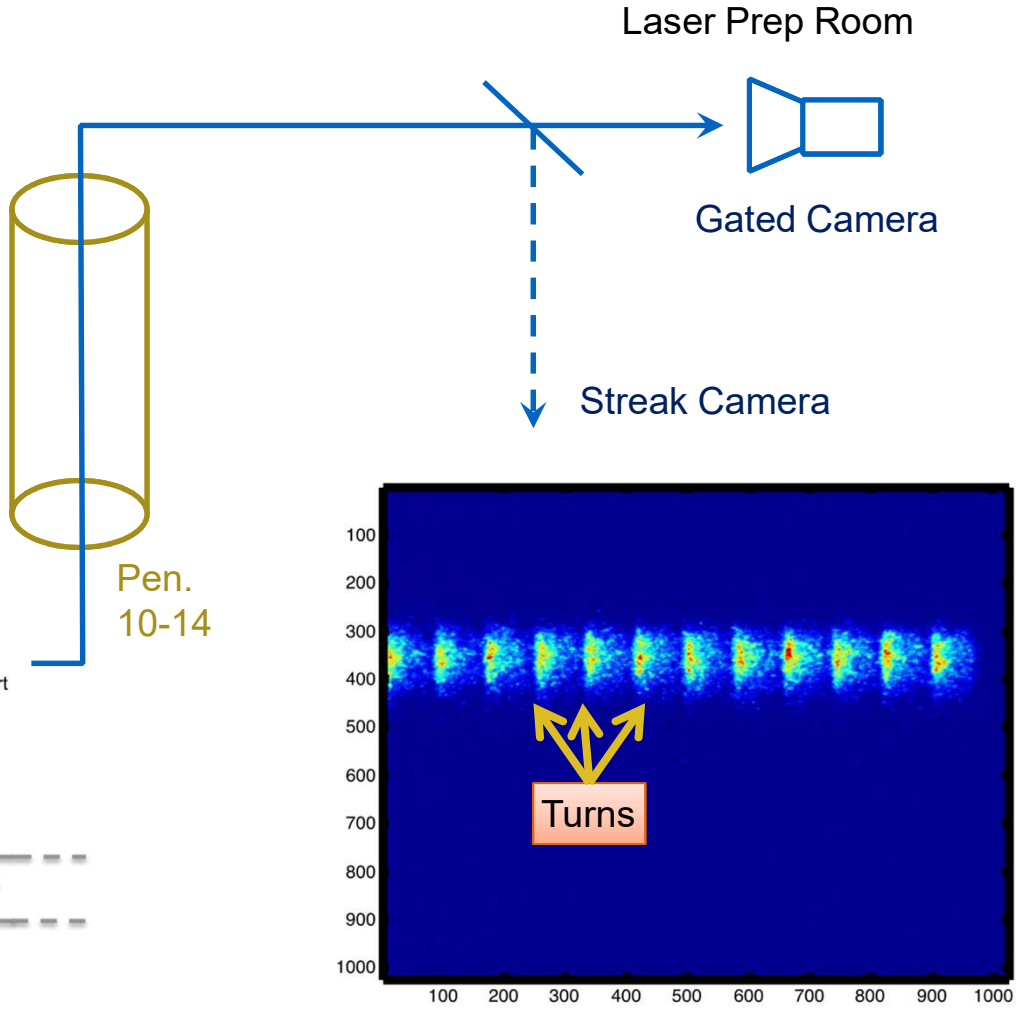
FACET-II Diagnostics
Synchrotron Light Monitor

SLAC

SLM at arc - straight boundary:

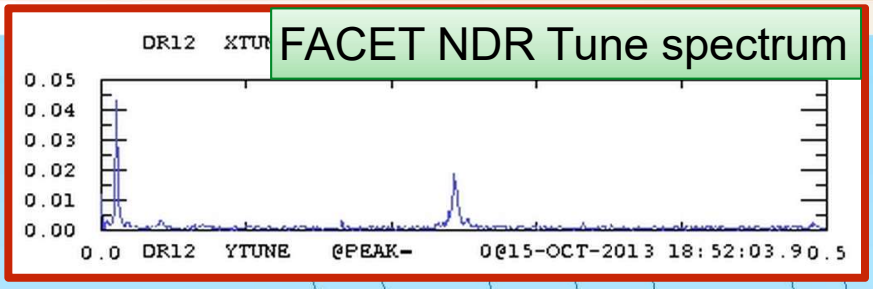
- Transverse beam size
- Bunch length
- Damping times
- Instabilities



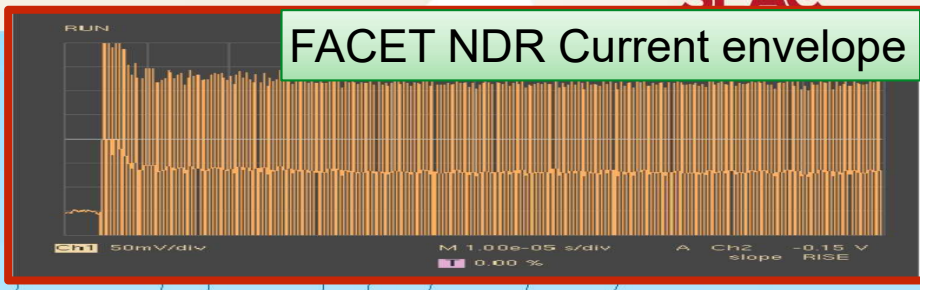


Synchrotron light monitor for transverse/longitudinal study of stored beam

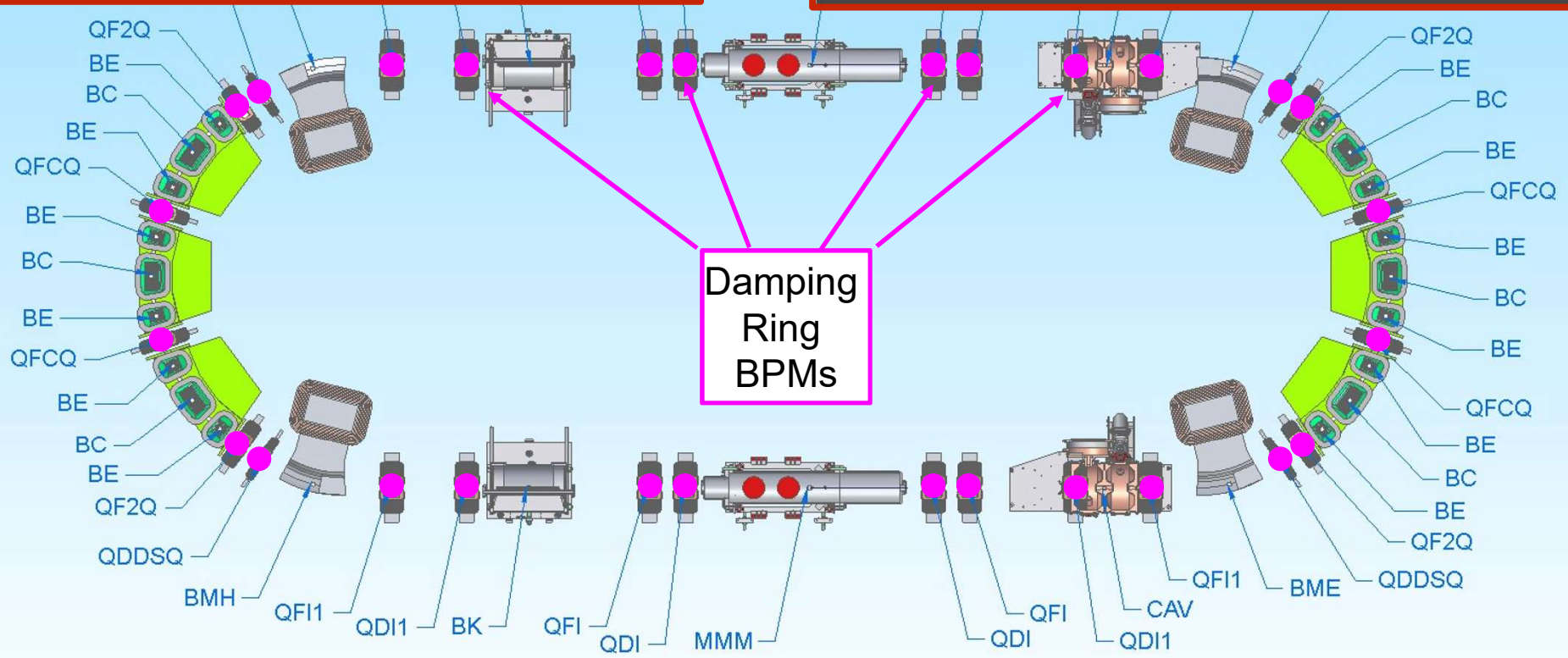
FACET-II Diagnostics
Positron Damping Ring - BPMs



FACET NDR Tune spectrum

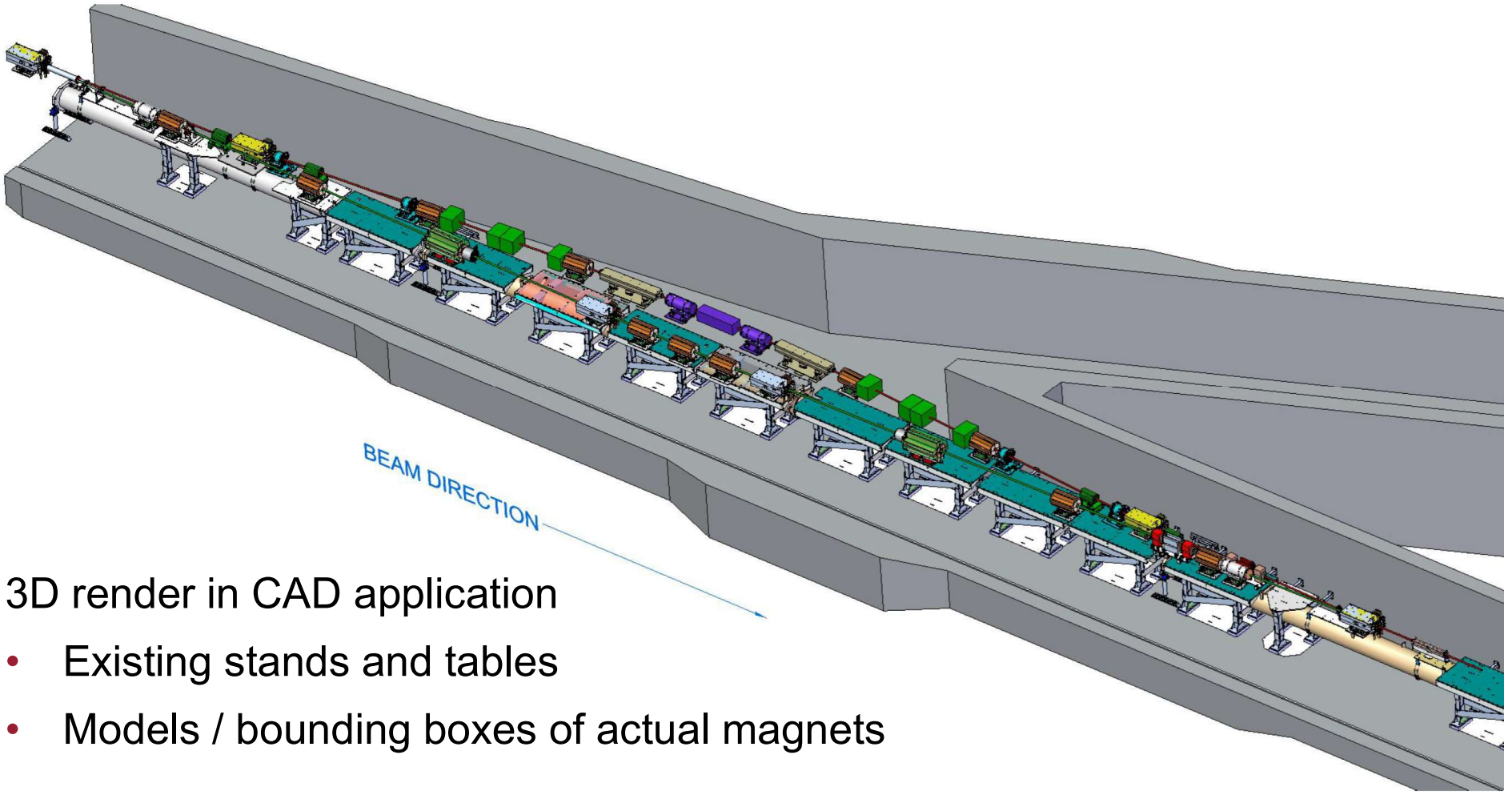


FACET NDR Current envelope



Tune monitor and envelope current monitor are derived from BPM signals

BC20 Stage 3 Beamline Layout

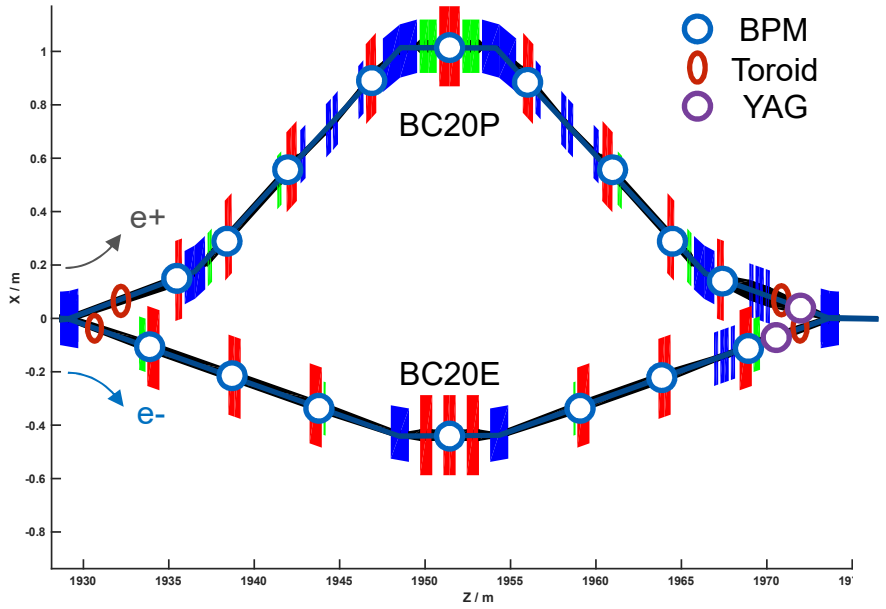


3D render in CAD application

- Existing stands and tables
- Models / bounding boxes of actual magnets

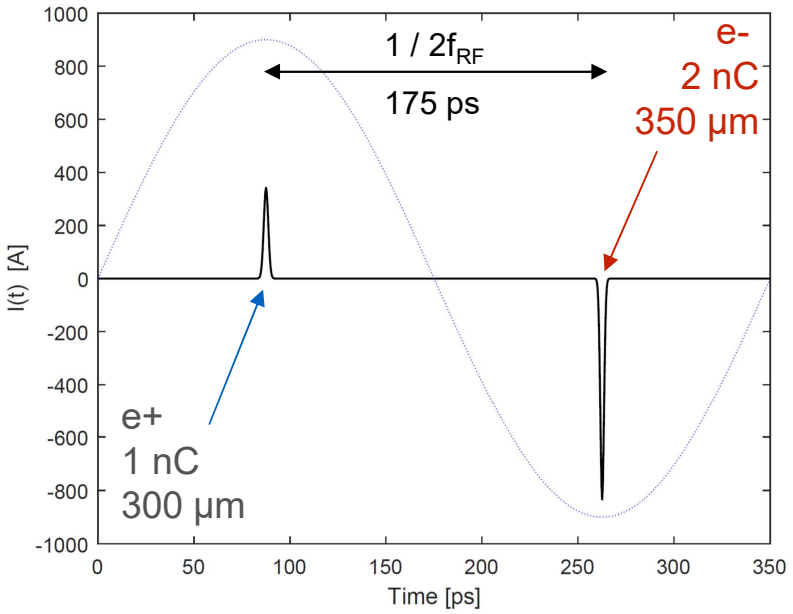
BC20 Diagnostics

- X-ray stripe (Wiggler + YAG) energy spectrum measurement
- Resonant toroid BCM at entrance and exit of chicane
- Stripline BPM near each focusing element
- TCAV relocated downstream to common line

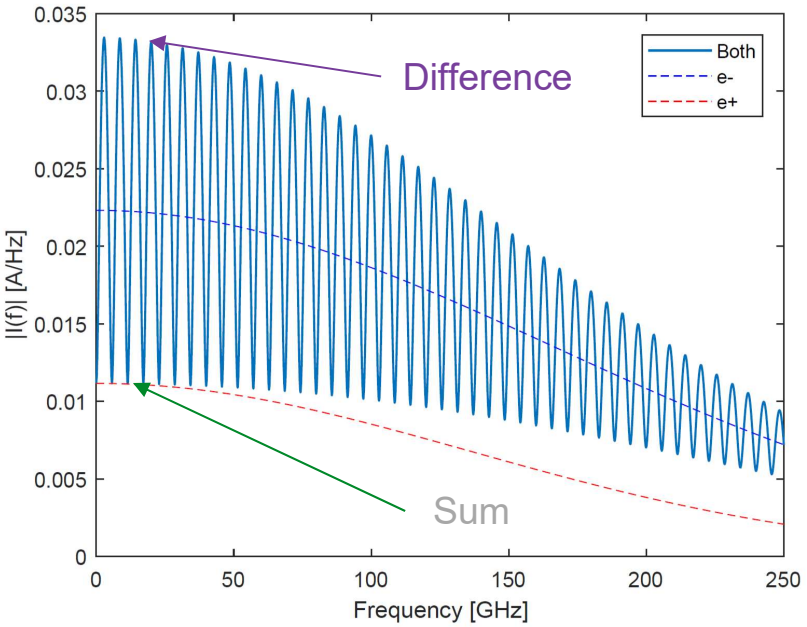


Beamline diagnostic devices are largely re-used from FACET chicane

2-Bunch BPM Design



DFT



Signal on electrode:

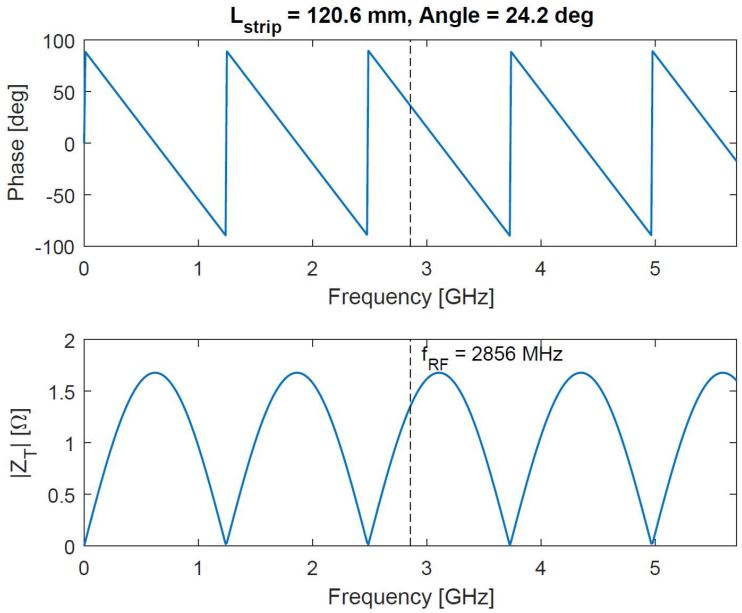
- Proportional to I_{beam}, x_{beam}
- Normalize to bunch length monitor

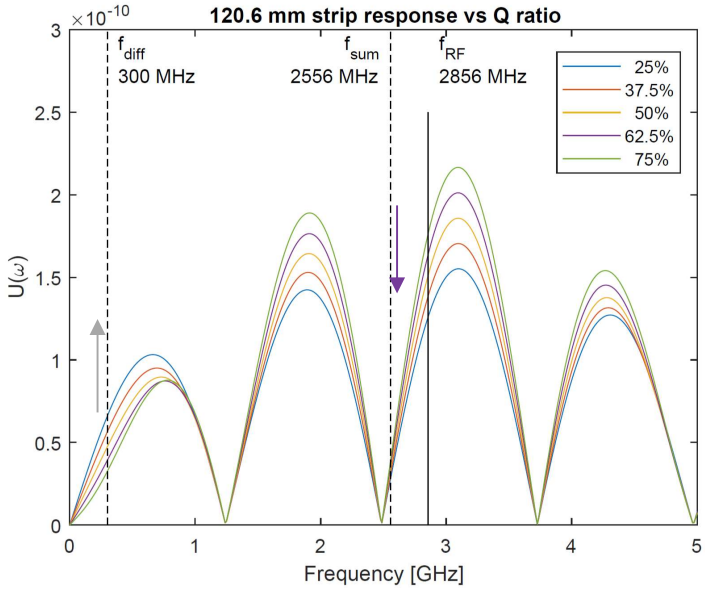
$$x^+ = \frac{1}{I^+ S_x}\left(\frac{R^+ - L^+}{R^+ + L^+}\right) \quad x^- = \frac{1}{I^- S_x}\left(\frac{R^- - L^-}{R^- + L^-}\right)$$

$$x_E = x^+ + x^- \qquad x_P = x^+ - x^-$$

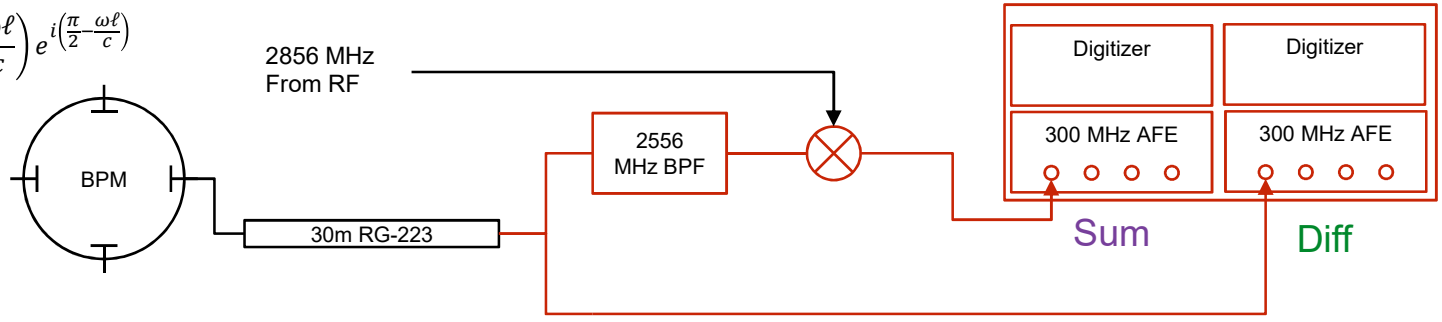
Mix stripline signals with reference RF to resolve 2-bunch orbit in linac

2-Bunch BPM Design



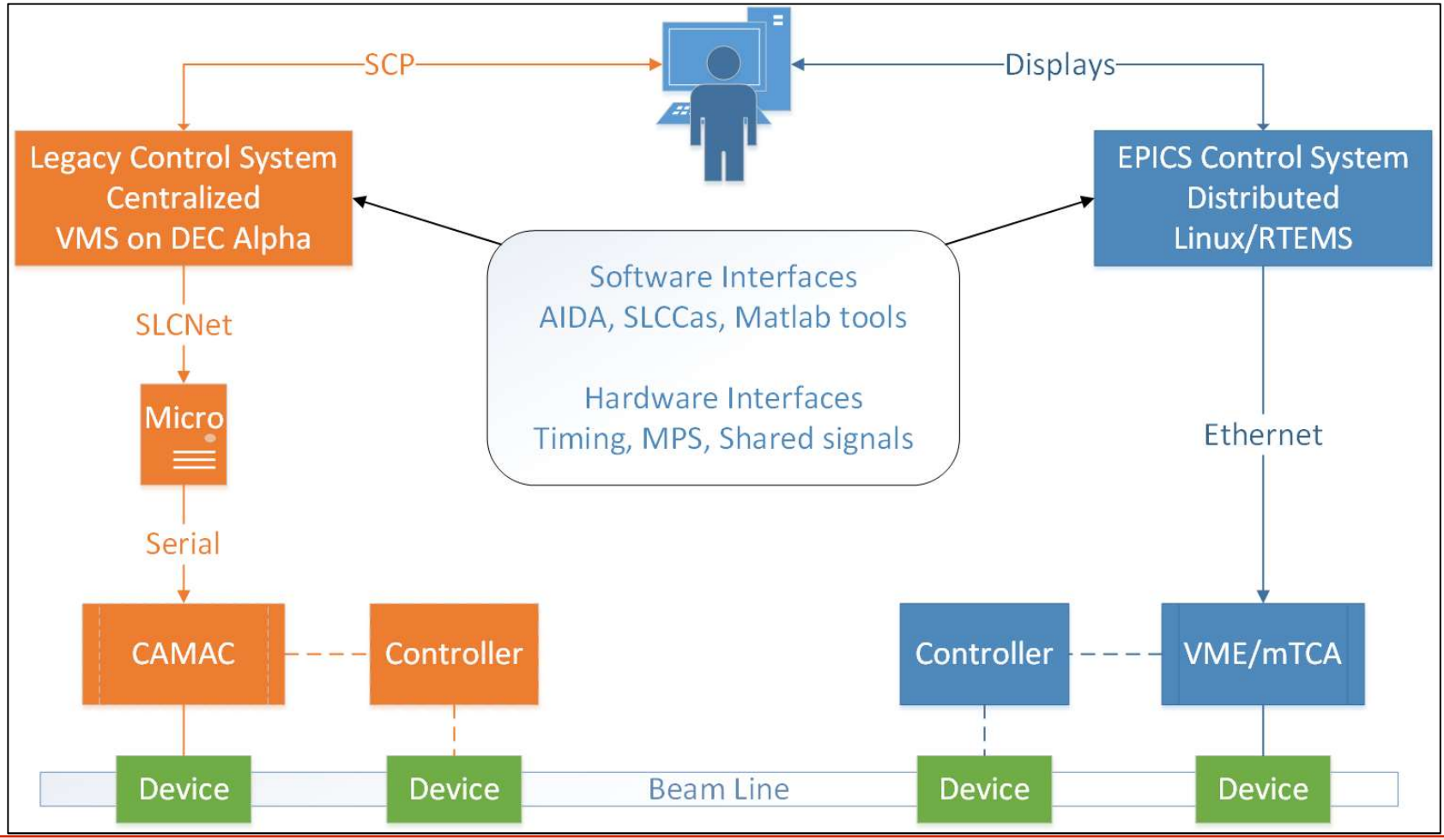


$$Z(\omega) = Z_0 \frac{\alpha}{4\pi} \sin\left(\frac{\omega \ell}{c}\right) e^{i\left(\frac{\pi}{2} - \frac{\omega \ell}{c}\right)}$$



2-bunch resolution < 100 μm using LCLS/LCLS-II electronics

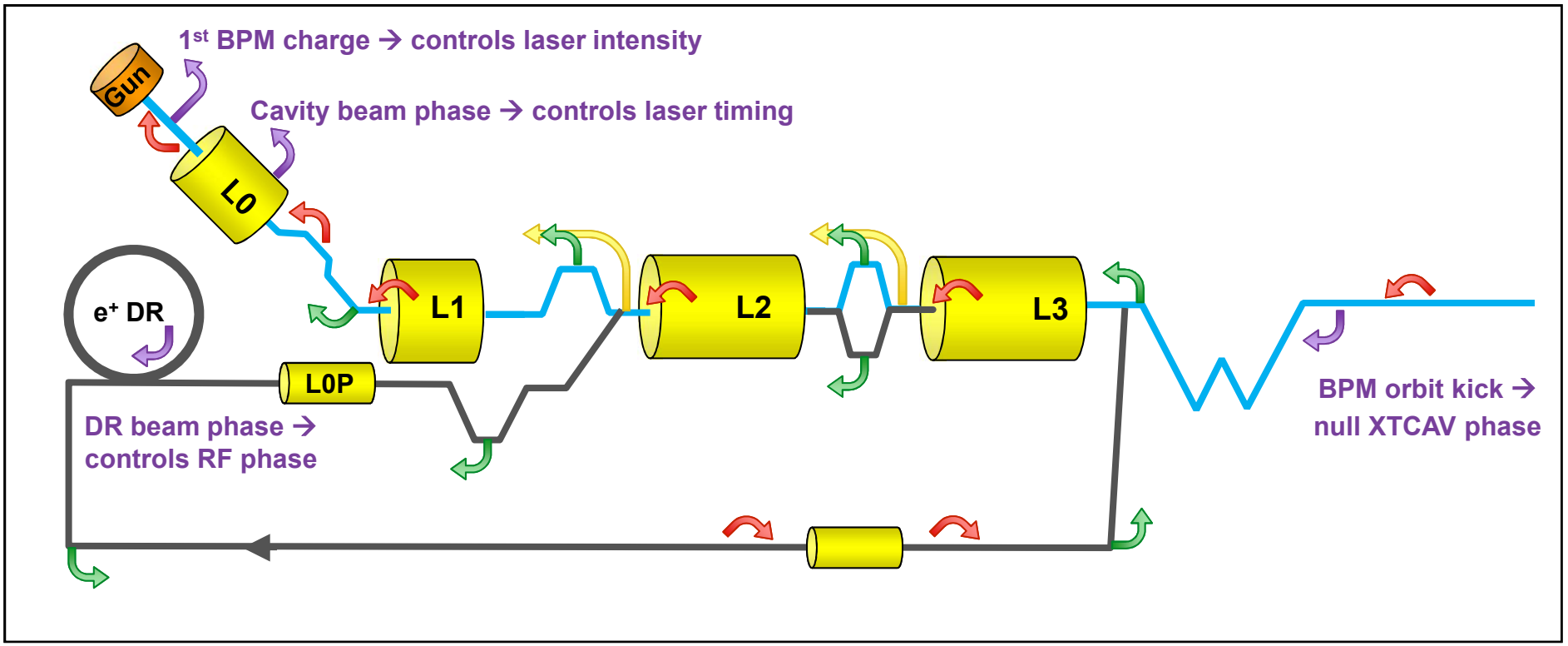
FACET-II Diagnostics Overview
Hybrid Control System Architecture



FACET-II employs a mixture of legacy and modern controls with tools developed for FACET and LCLS to pass data back and forth

Software
Energy and Orbit Stabilization Feedbacks

Matlab/python scripts regulate beam parameters at individual key locations:
Energy and bunch length : upstream RF phase & amplitude
Orbit feedback : use 4 upstream correctors, stabilize [x x' y y']

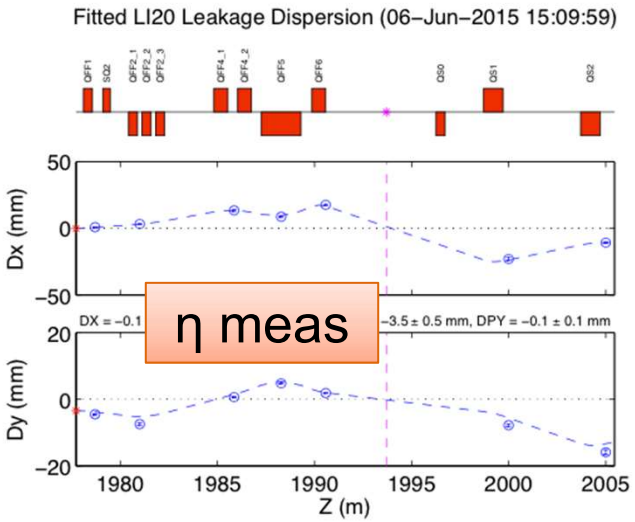


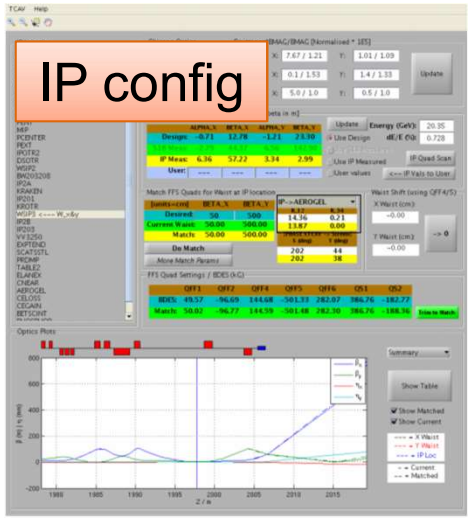
Simple feedbacks at key locations stabilize drift on 5-10 second time scale

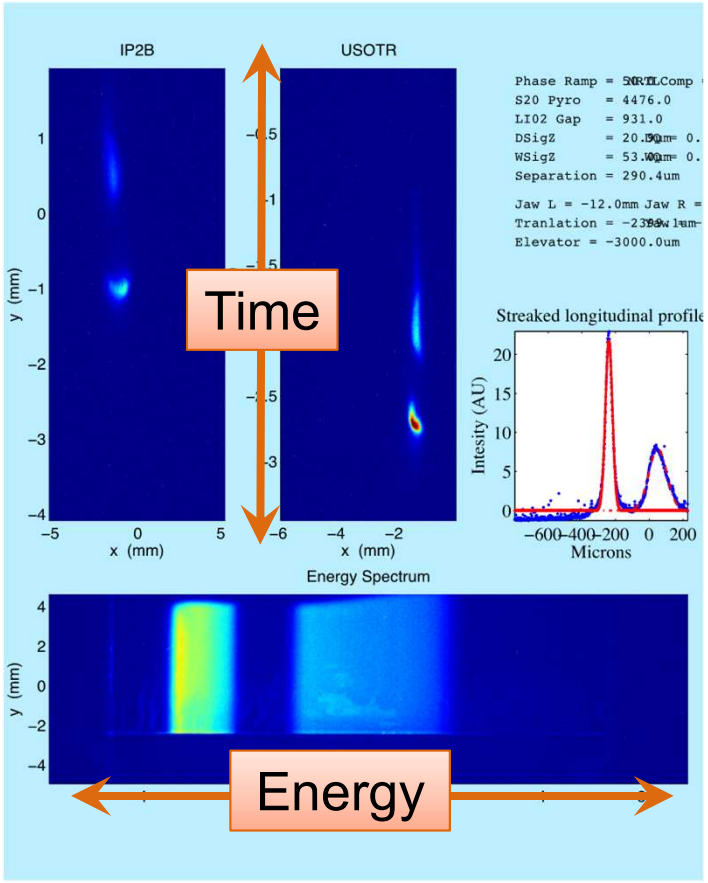
Software
Physics HLAs for Measurement and Tuning

Software developed for FACET (and LCLS) automates many standard tuning and setup tasks:

- Troubleshooting – correlation plot, jitter
- Characterization – profile monitor, wire scans, emittance, bunch length
- Corrections – dispersion, matching, phase scans
- Configuration changes – IP config, longitudinal setup







Matlab physics applications provide online analysis tools and iterative correction for fast, interactive tuning

FACET-II Diagnostics
Recovered components from Sector 0-10

SLAC

Beamline components:

13 wire scanners

40 stripline BPMs (PRL)

13 toroids (various)

24 ion chambers

5 profile monitors (PRL)

1 gap BLM

1 faraday cup

4 stoppers – tune-up dump

2 2-jaw collimators

2 fixed collimators

Controls hardware:

116 CAMAC crates

79 CAMAC PDU/STB (timing)

13 FIDO (timing)

119 CAMAC DAC (magnet)

179 CAMAC SAM (magnet, analog)

140 CAMAC 605 BPM

97 CAMAC 972 BPM

30 CAMAC TCM (toroid)

Linac Low-level RF – L1S

PAC & PAD:

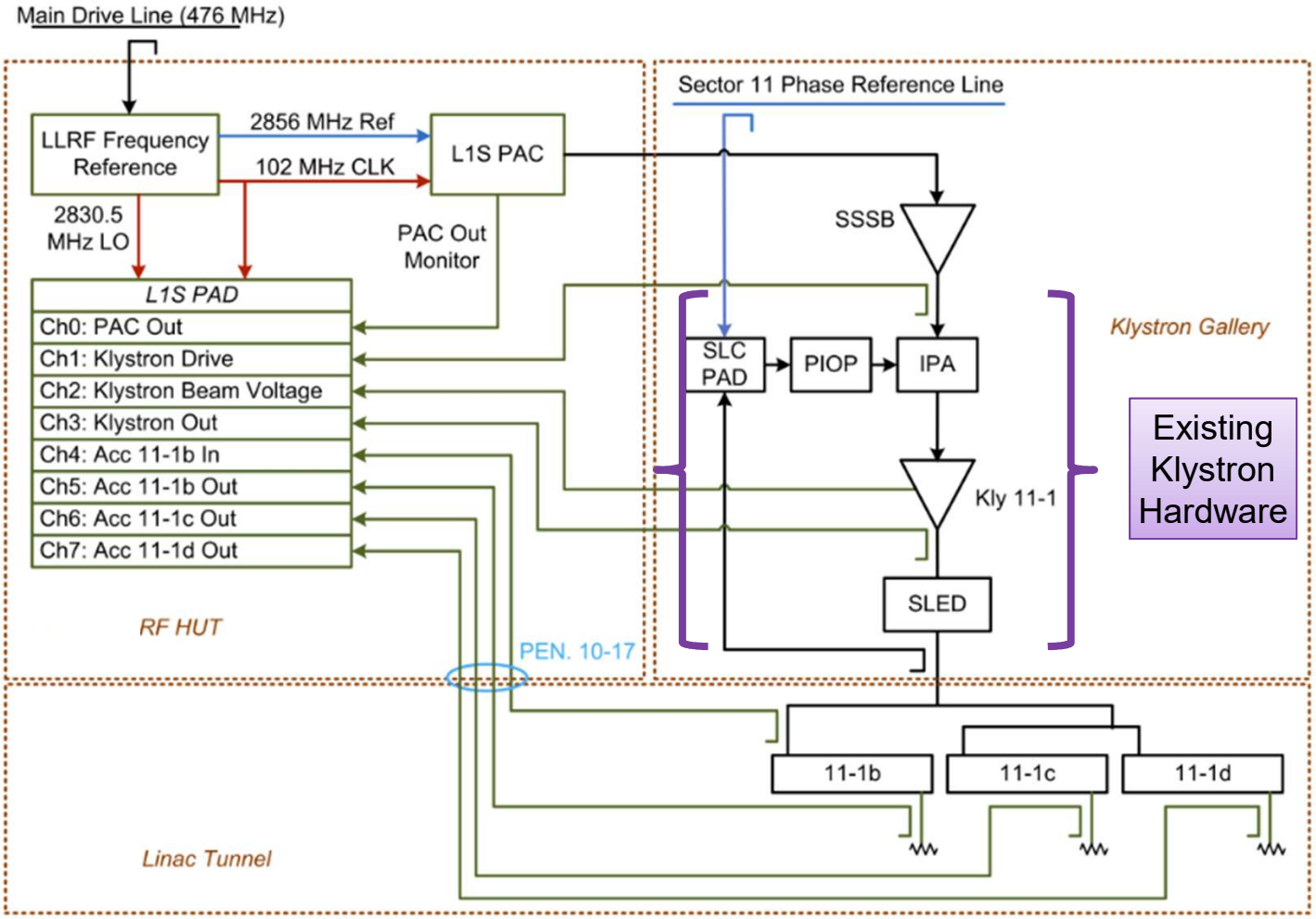
- Phase & Amplitude Controller/Detector
- Feedback in IOC

Linac has installations at:

- L1S (2 stations)
- L1X linearizer
- TCAVs (2 stations)

PAC only installations:

- L2 phase reference
- L2 energy feedback
- L3 energy feedback



PAC/PAD LLRF control and feedback wraps around existing RF hardware