Injector Physics Design

John Schmerge

LCLS-II SLAC Director's Review

30 August-1 September, 2016

Outline

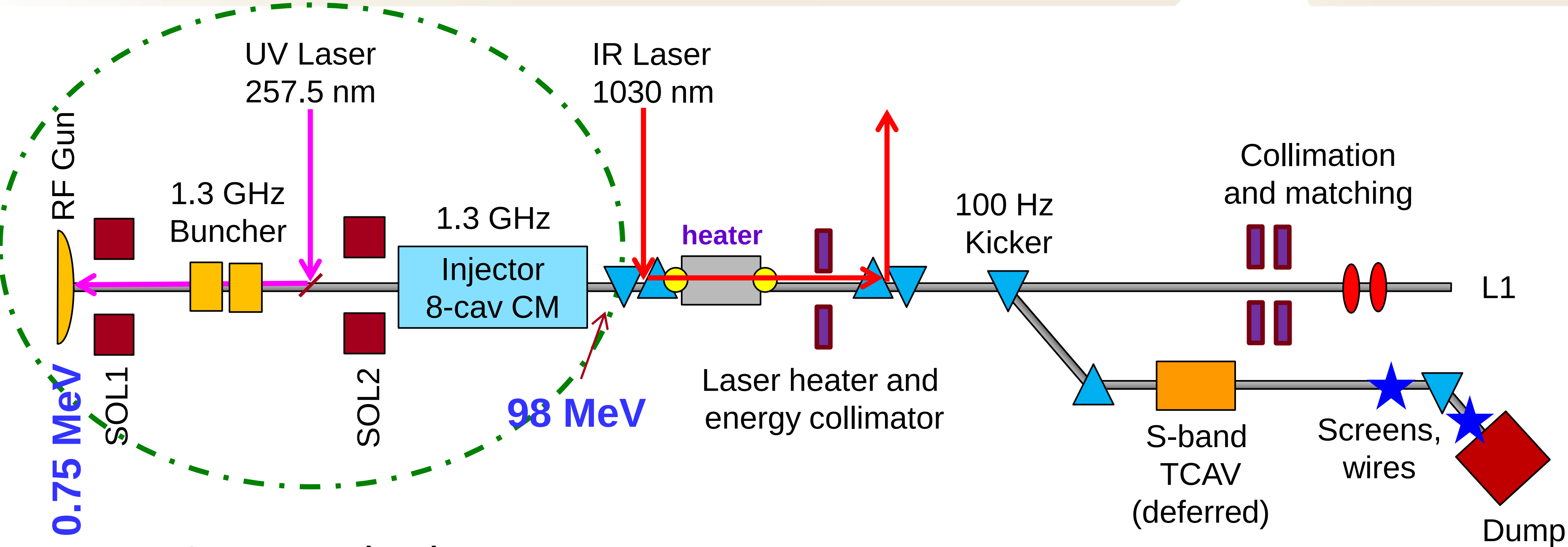
- Injector Overview
- Injector Design
  - Beamline layout optimization
  - Beam with temporal laser modulation
  - RF coupler correction
  - Wakefield effect
  - RF jitter requirement
- Commissioning

Injector baseline parameters

Parameter	nominal	range
Electron Energy at gun exit (keV)	750	500 - 800
Electron Energy (MeV)	98	90 - 120
Bunch Charge (pC)	**100**	**10 - 300**
Bunch Repetition Rate (MHz)	0.62	0 - 0.93
Dark e^- current (nA)	0	0 - 400
Peak e^- current (A)	12	4 - 50
Average e^- current (mA)	0.062	0.0 - 0.3
Normalized slice emittance (rms, μm, 95%)	**0.4**	**0.2 - 0.6**
Bunch length (rms, mm)	1	0.3-2
Slice energy spread (rms, keV)	1	1-5
Cathode quantum efficiency (%)	2	0.5 - 10
Laser Energy at cathode (μJ)	0.02	0.0 - 0.3

LCLSII-2.2-PR-0084-R0

CW (1MHz) injector baseline schematic



- Cs_2Te cathode
- UV/IR lasers for cathode/laser heater
- 185.7 MHz NC RF gun
- NC 1.3 GHz 2-cell buncher
- SC 1.3 GHz 8-cavity CM
- 2 emittance compensating solenoids with quad correctors
- BPM Diagnostics

LCLSII-2.2-PR-0084-R0

Cs_2Te cathode

- Demonstrated performances at APEX
  - low thermal emittance (0.8 μm/mm)
  - High QE (5-10%)
  - long lifetime (>14 days)
  - < 1ps response
  - < 1nA of low dark current (LCLS-II spec <0.4 μA at 100 MeV)
- Cathodes provided by LBNL/INFN for commissioning
- SLAC to fabricate cathodes for long term operations

Lasers

- Two identical 50 W lasers for photocathode and laser heater
  - 50W IR laser (50 μJ/pulse, 2 ps, 1 MHz) is commercially available
  - Includes oscillator, stretcher, pulse slicer, amplifier, and compressor
  - Award of contract in August 2016

- SLAC laser group will design and build
  - Synchronization system
  - UV conversion
  - Pulse stacker for UV
  - Pulse stretcher for laser heater
  - Spatial shaping
  - Imaging and transport systems
  - Diagnostics and controls

LCLSII-2.2-PR-0086
LCLSII-2.2-PR-0085
FDR was June 2016

RF Gun and Buncher

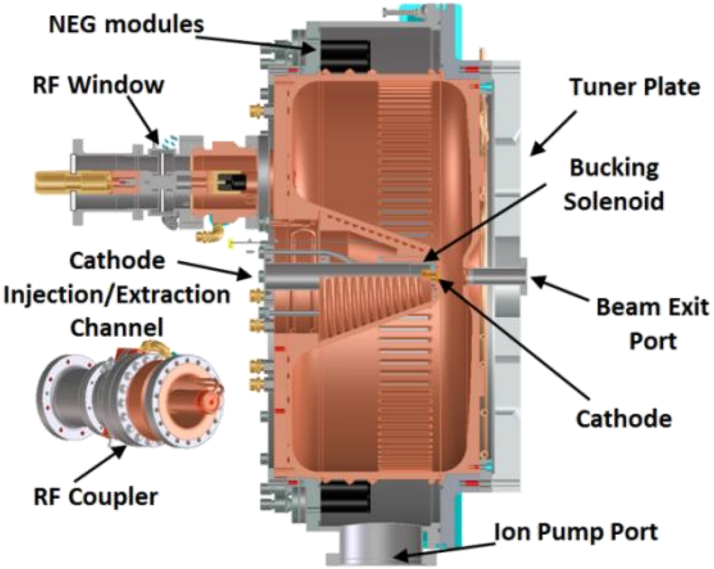
- 186 MHz CW NC Gun
  - ~19.5MV/m on cathode (80KW)
  - 750keV energy gain

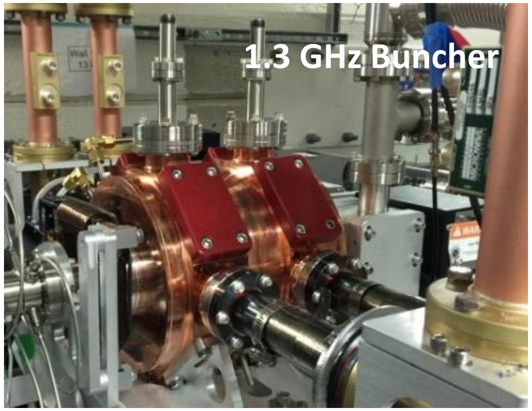
  LCLSII-2.3-PR-0166-R0

- 1.3 GHz CW NC buncher
  - 4 rf feeds with 2.5 kW/feed
  - 3X compression

  LCLSII-2.3-PR-0167-R0

- Performance of both described in APEX experience talk





CM, Solenoids and BPMs

- 1.3GHz, 8 9-cell cavities standard CM
  - 1 HOM coupler upstream and 1 downstream
  - 1 power coupler downstream
  - 1st cavity ~8MV/m
  - 2nd and 3rd cavity <2-3MV/m for emittance compensation
  - 95 MeV energy at the injector exit
- Two NC solenoids before and after the buncher
  - One pair of weak normal & skew quads per solenoid for correction of field perturbations

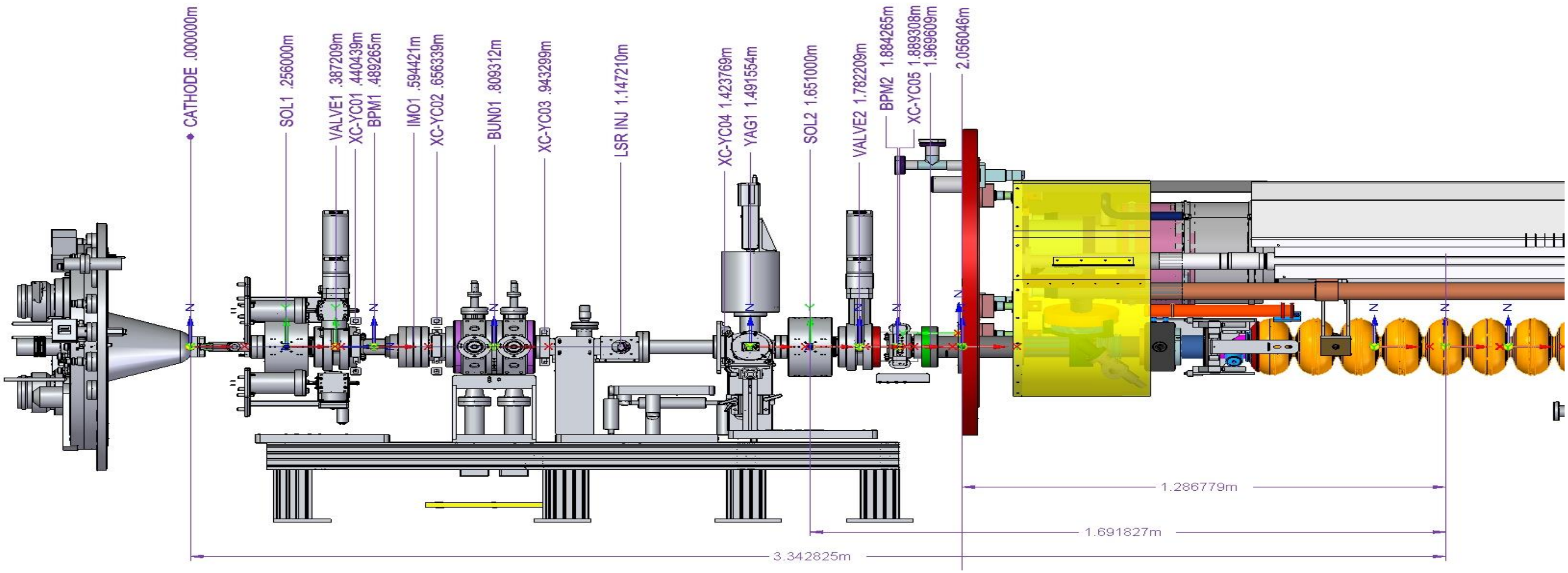
LCLSII-2.3-PR-0165

- Two stripline BPMs (1pC and 30µm res specification)

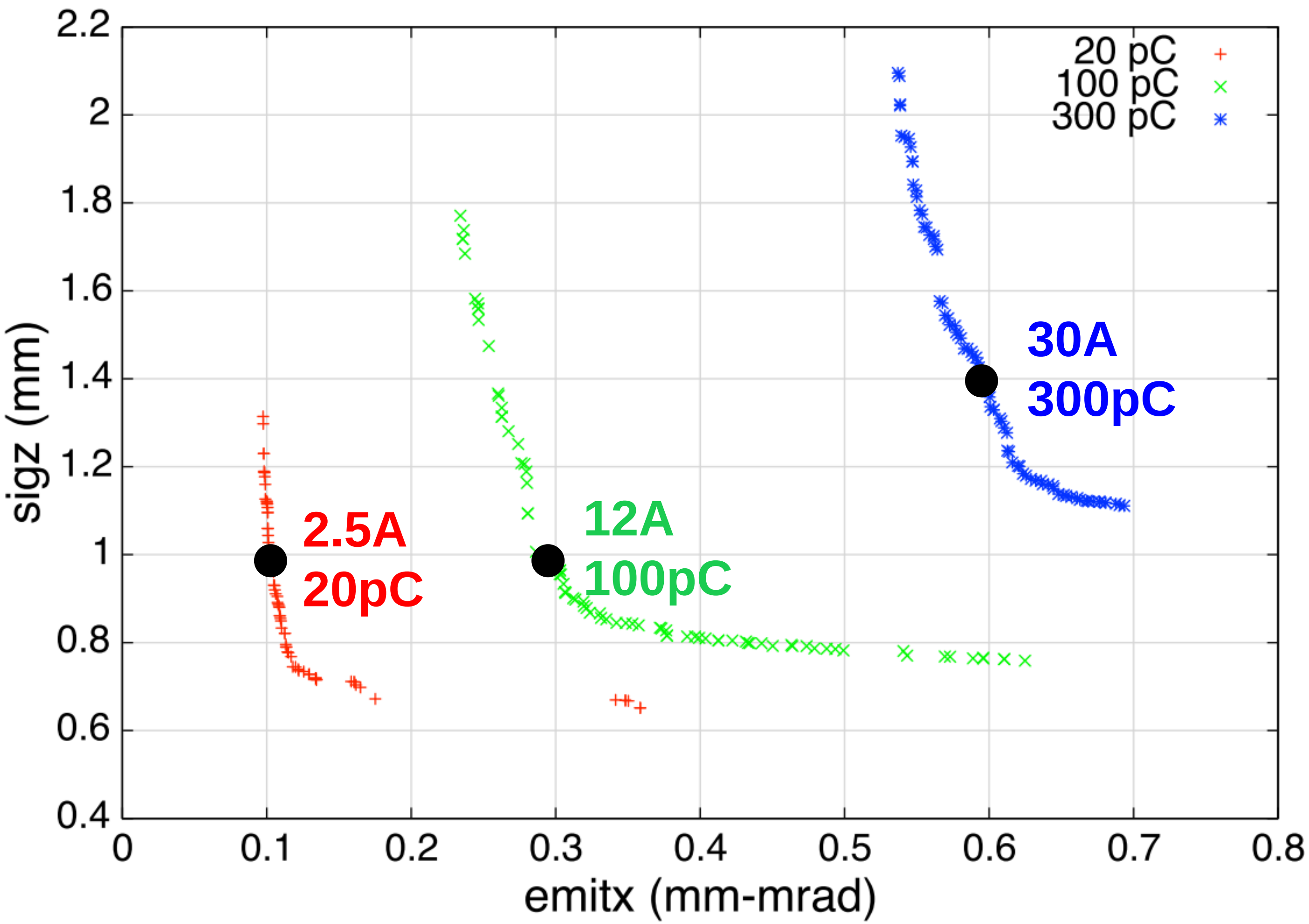
LCLSII-2.4-PR-0136

Optimized injector layout

- 2013 layout (CDR): NGLS design
- 2014 layout: added 50cm with non-standard CM endcap
- 2015 layout: added another 21cm with standard endcap
- Final layout: new shorter solenoid, BPM with larger aperture, modified drift between SOL2 and CM, and moved SOL1 closer to cathode



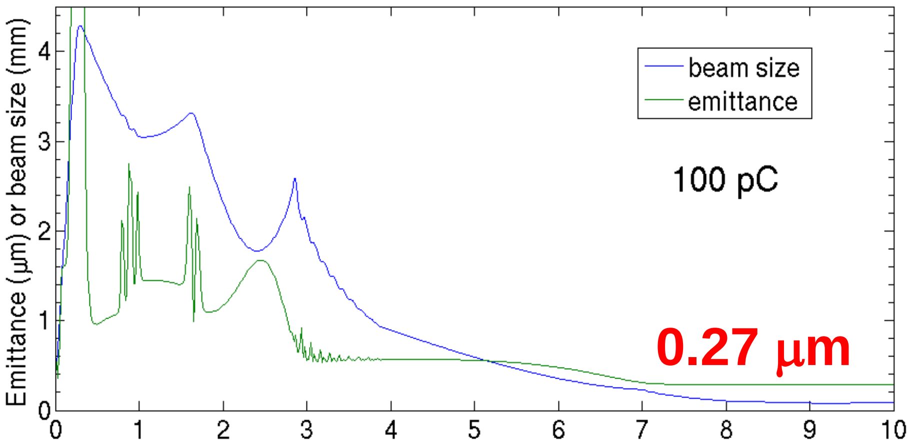
Final layout: emittance vs. bunch length

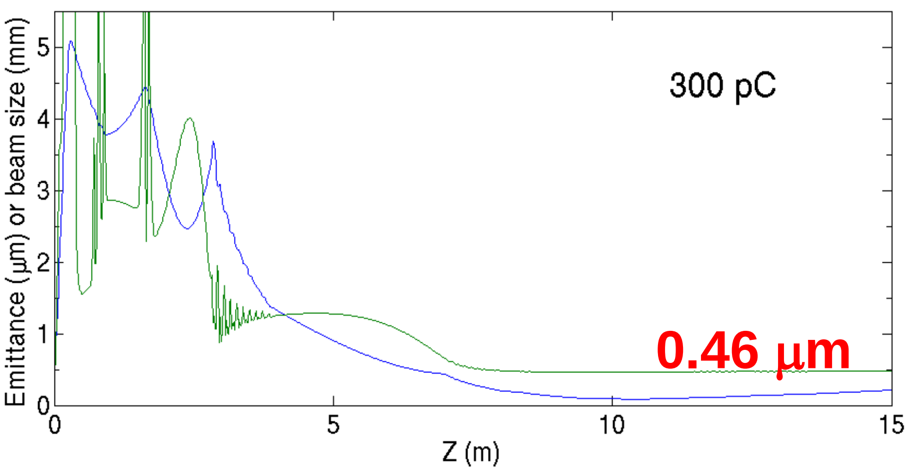


Mitchell, LBNL

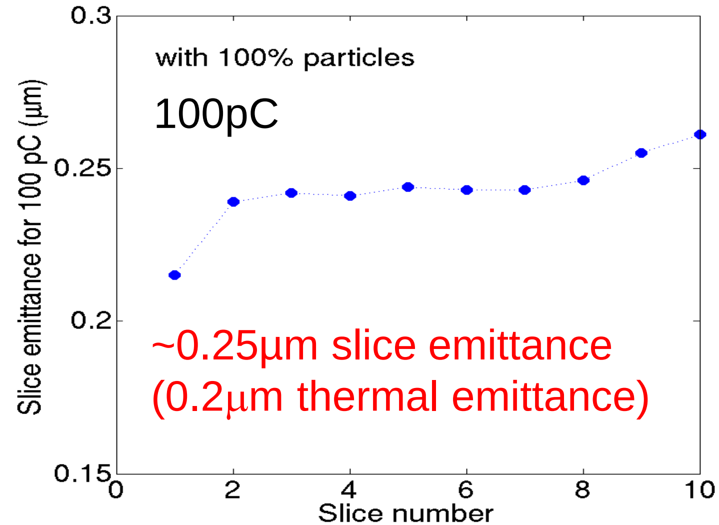
Final layout: emittance

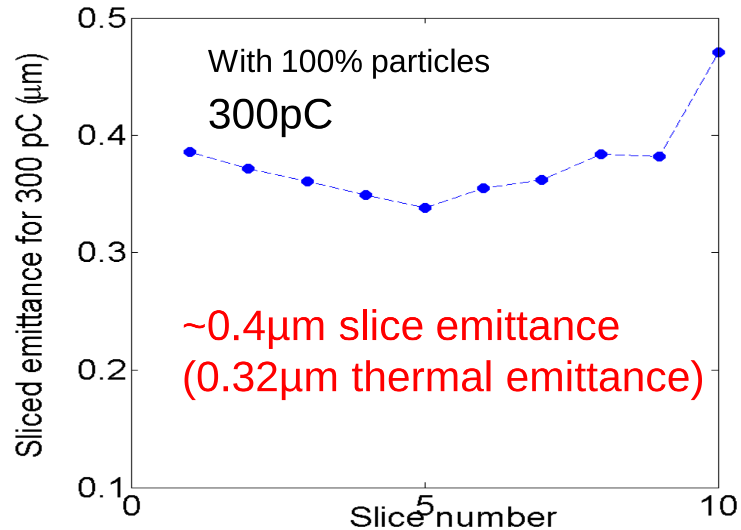
W/ Astra code



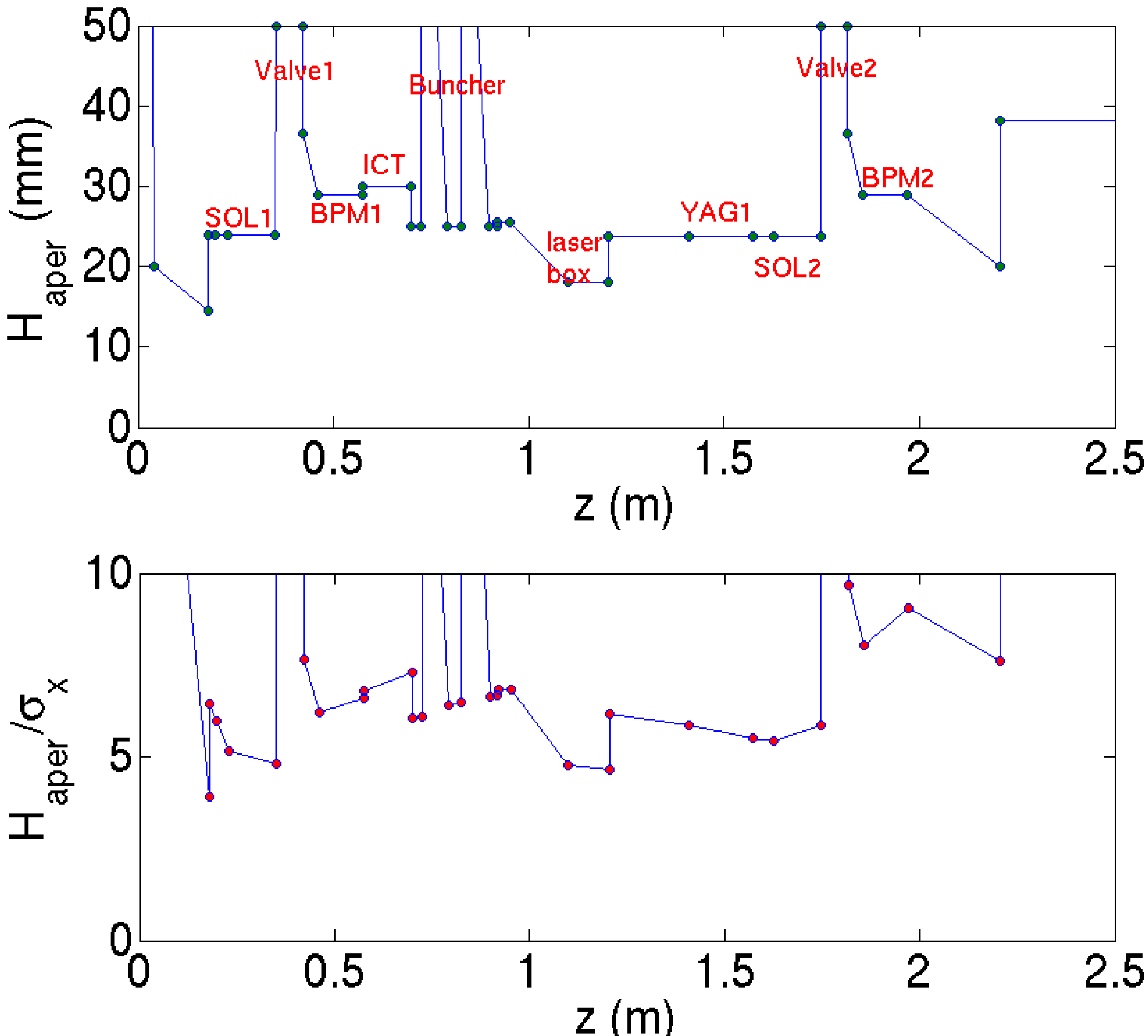


Assumes thermal emittance 1μm/mm





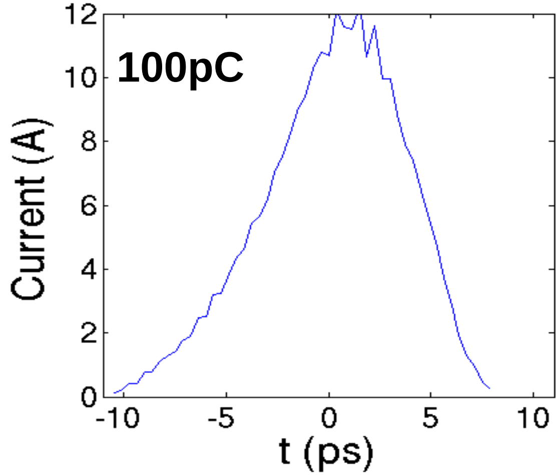
Final layout apertures

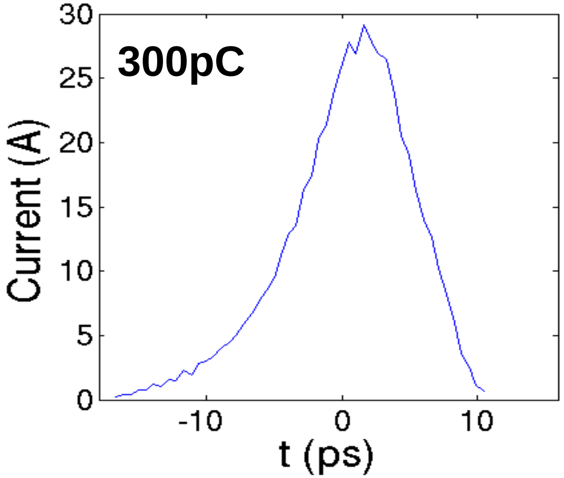


- SOL/BPM aperture increased 50%
- Laser box aperture increased 60%
- Increased the ratio of the half aperture to rms beam-size from 2.5 to 4

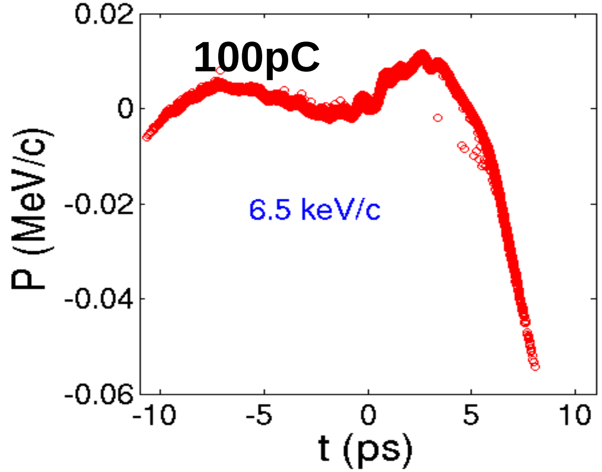
Final layout: longitudinal beam

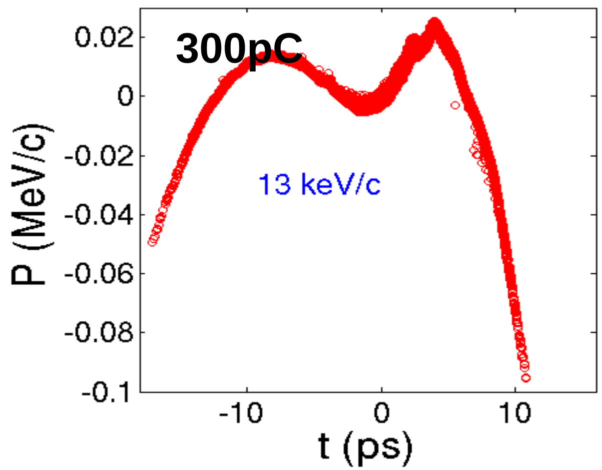
Current @95MeV



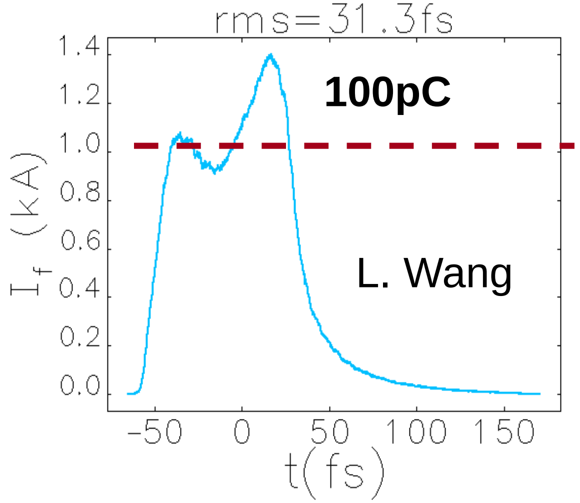


Nonlinear δE @95MeV



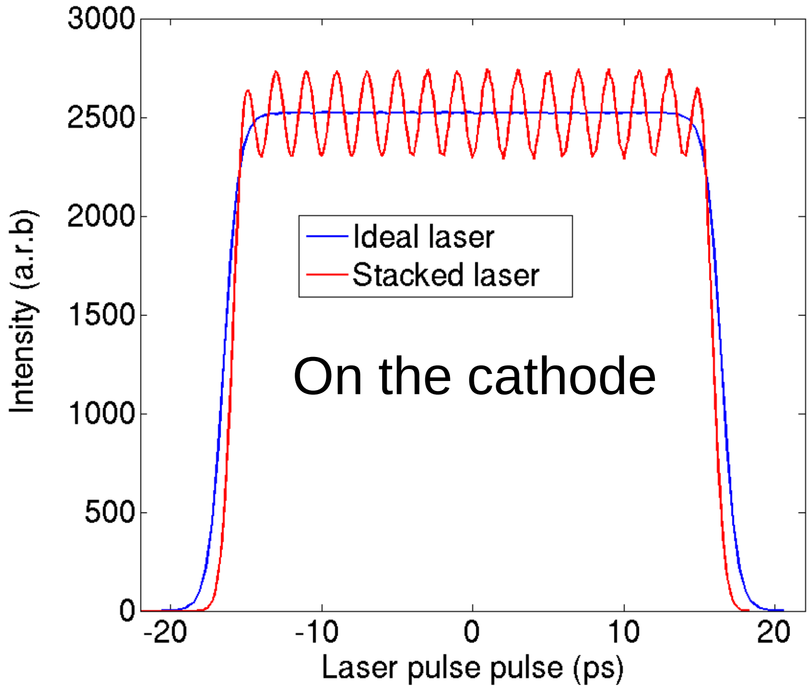


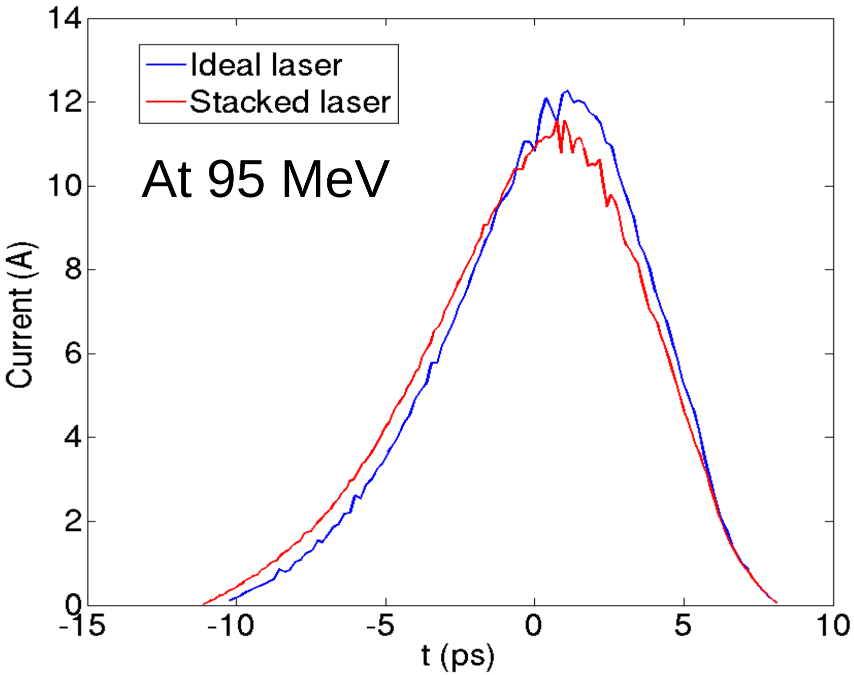
Beam current @4GeV



Elegant code tracking including wake, CSR and LSC with new injector beam (100pC)

With more realistic temporal laser (100 pC)



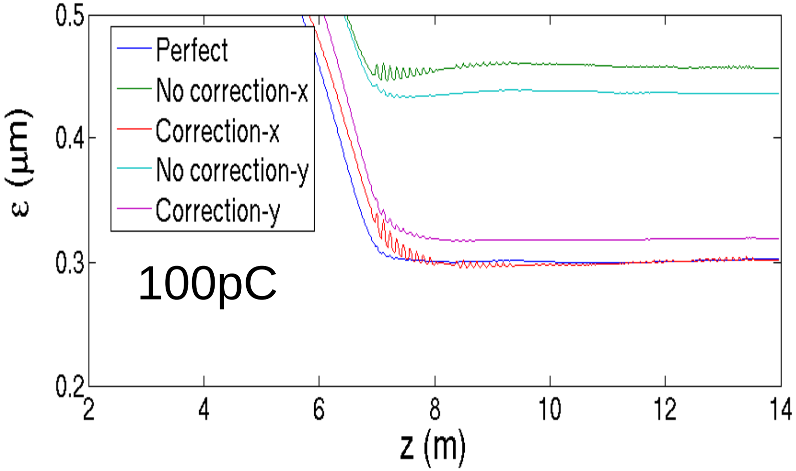


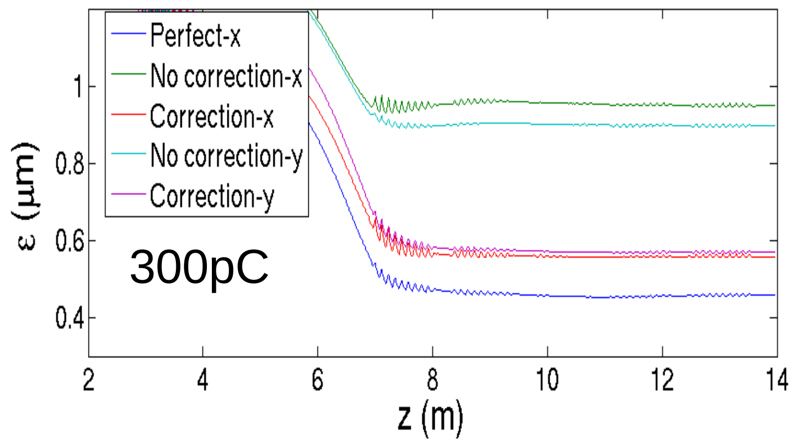
16-32 laser pulses (4-5 BBO crystals) will be stacked to generate 30-60 ps long pulse

- Emittance increases 0.3%
- High order (>2) δE reduces 2%
- Current profile looks similar

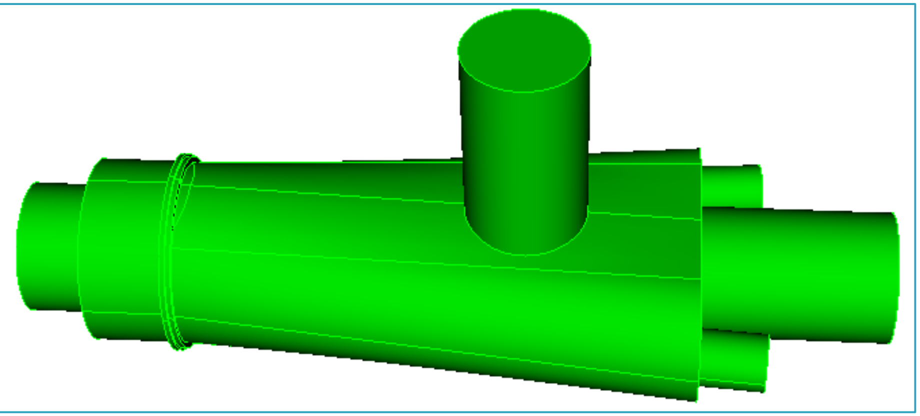
HOM coupler beam perturbation correction

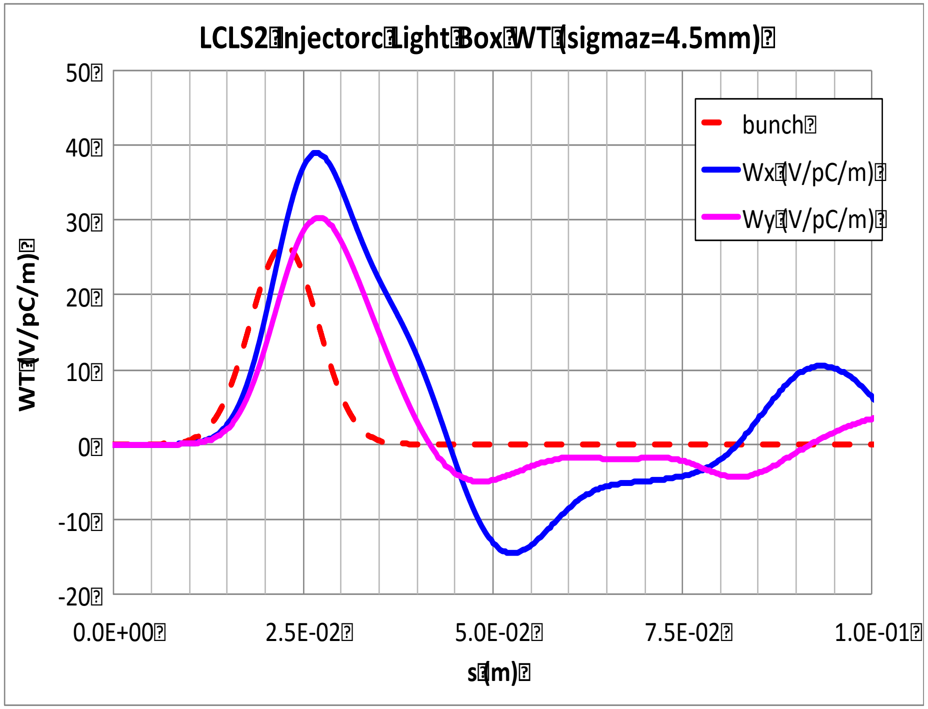
- Emittance growth is dominated by the spatial varying HOM field perturbation for short bunches
- The effect can be effectively corrected with one pair of normal and skew quads
  - <5Gs at SOL2
  - Almost fully corrected for 100pC
  - About 20% emittance growth after the correction for 300pC





Wakefield effect – laser box (worst case)





Z. Li

- Beam parameters:
  - Charge = 300 pC
  - Energy = 865 keV
  - $\sigma_z = 4.5$ mm
  - Transverse offset 2mm
- Emittance growth <5% for the very conservative 2mm beam offset

RF stability requirements

	Jitter	Arrival time (fs)
Laser timing	80 fs	48
Gun phase	0.04°	32
Gun amplitude	0.01%	45
Buncher phase	0.015°	43
Buncher amplitude	0.03%	12
Cav1 phase	0.05°	20
Cav1 amplitude	0.03%	17
Total arrival time jitter at 95 MeV (4 GeV- after x100 compression)	-	90 (<1)

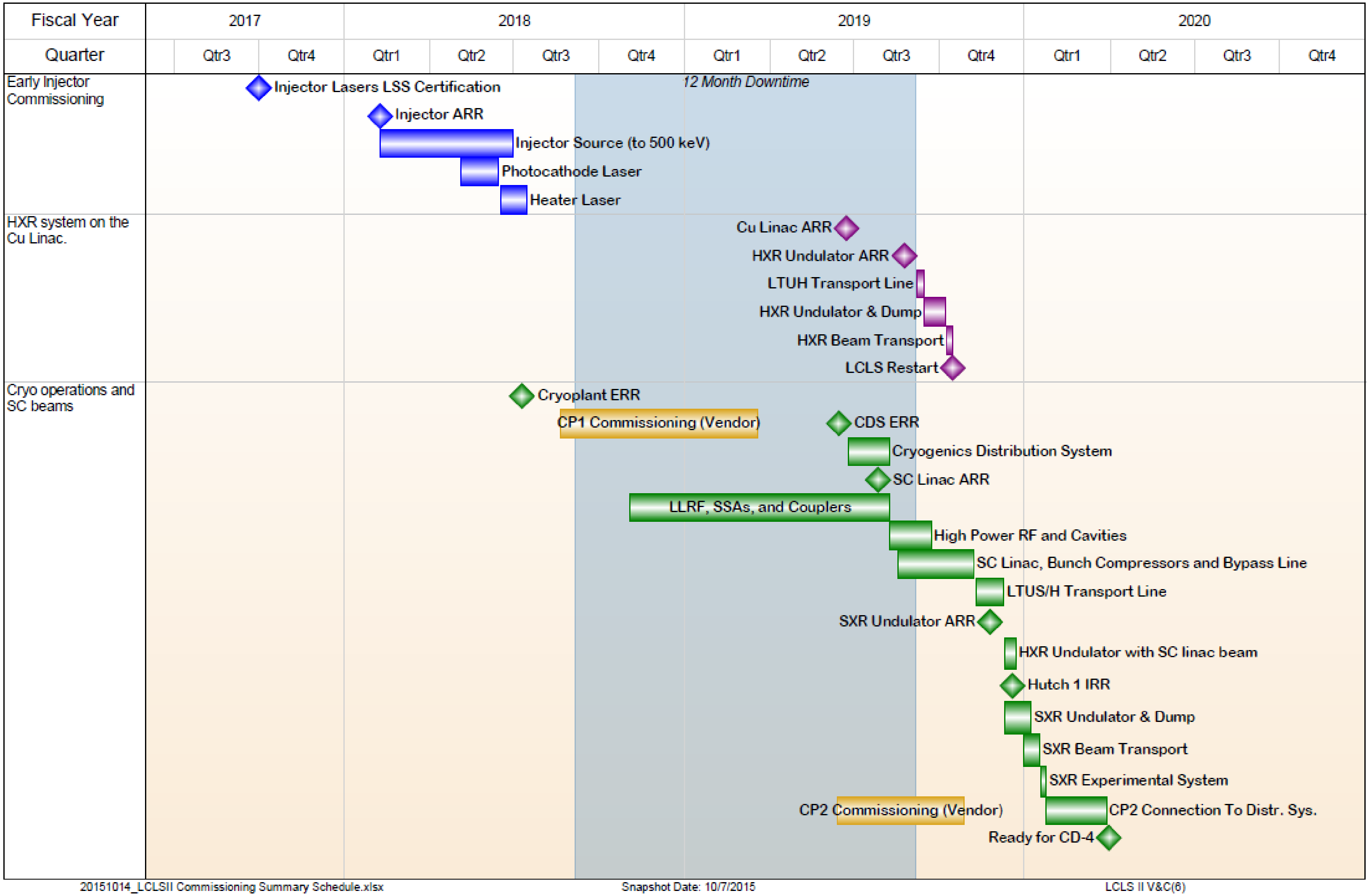
Transverse alignment requirements

- Extensive simulations with Astra code show relaxed alignment requirements:
  - Alignment laser position on cathode <100μm for <2% of ε-growth
  - Solenoid alignment <0.5mm or 2mrad for <2.5% of ε-growth
  - Buncher alignment <1mm or 2mrad for <3% ε-growth
  - CM01 alignment <0.6mm or 0.5mrad for <1% ε-growth

Injector Commissioning Plan

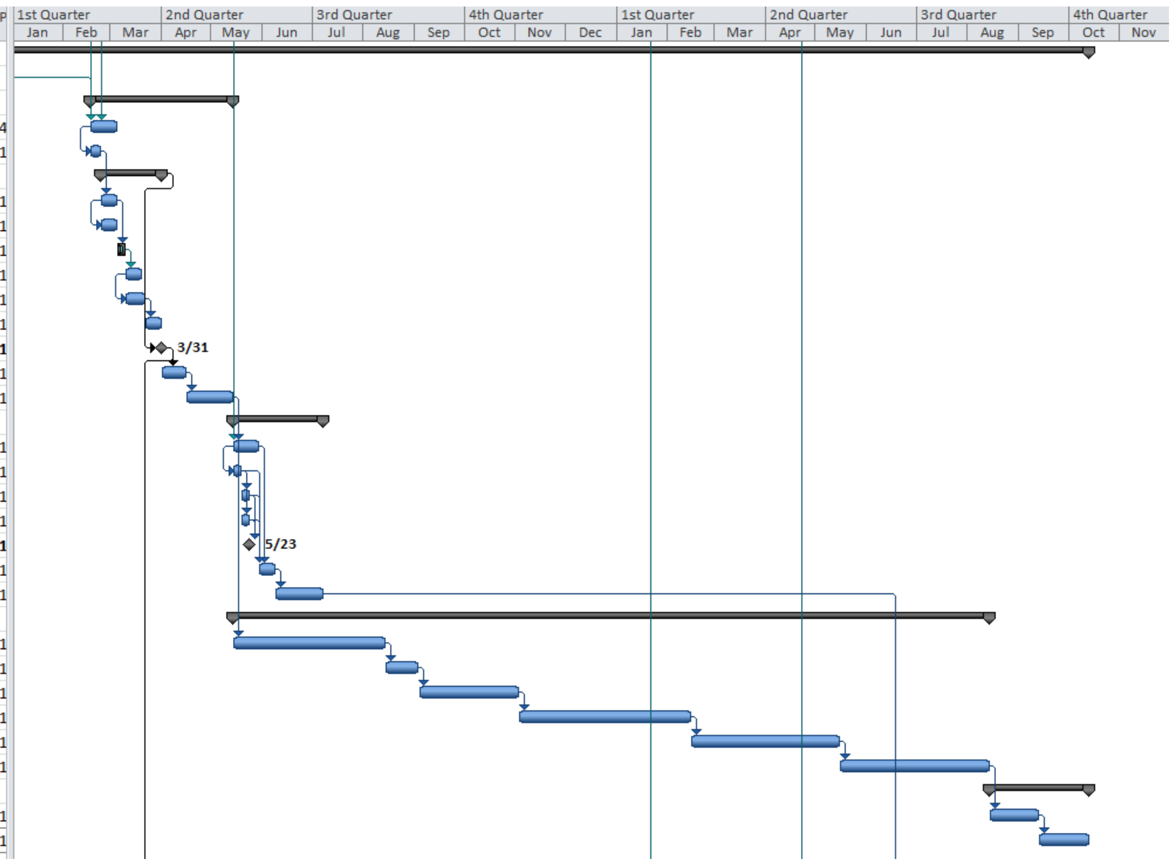
- SLAC injector group actively participates in APEX commissioning efforts
  - 20 pC measurements in early 2016
  - 100 pC measurements soon
  - Testing/developing tuning strategies/codes
- LCLS-II Injector Source (< 1 MeV) Commissioning
  - Fall 2017 RF processing begins
  - Winter 2018 laser commissioning
  - Spring 2018 commissioning 1-MeV electron beamline
    - Charge, QE, QE life time, and thermal emittance
    - Beam based calibration for the laser, buncher phases, and gun/buncher amplitudes
    - Beam energy and BBA
- Full Injector (100 MeV) Commissioning June 2019
  - CMs are cold and operational
  - 10 Hz beam into diagnostic line

Commissioning Schedule



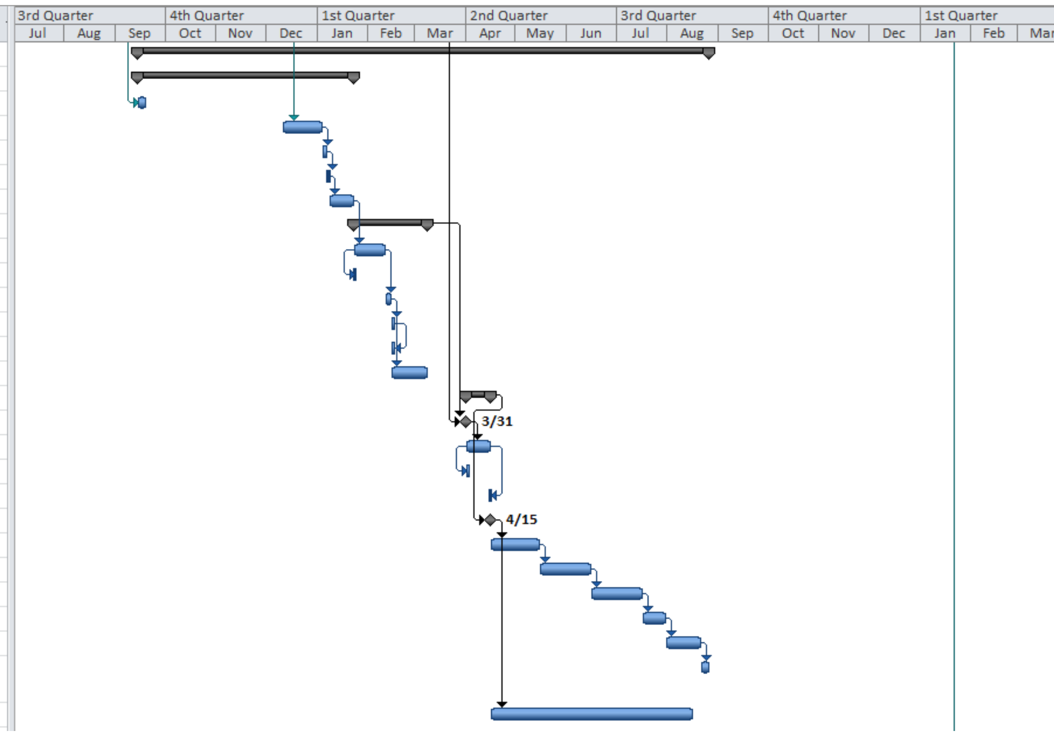
Detailed Injector Laser Schedule

	Task Name	Duration	Start	Finish	P
108	**Injector Lasers**	**736 days**	**Tue 7/18/17**	**Sat 10/12/19**	
109	LSS Certification	1 day	Tue 7/18/17	Tue 7/18/17	
110	**Drive Laser**	**85 days**	**Sat 2/17/18**	**Sun 5/13/18**	
111	Laser Synchronization	15 days	Sat 2/17/18	Sun 3/4/18	4
112	IR Pulse-train	5 days	Sat 2/17/18	Thu 2/22/18	1
113	**UV**	**37 days**	**Fri 2/23/18**	**Sat 3/31/18**	
114	UV Pulse-train	10 days	Fri 2/23/18	Sun 3/4/18	1
115	UV optical table prep at gun	10 days	Fri 2/23/18	Sun 3/4/18	1
116	UV Transport Line	5 days	Mon 3/5/18	Fri 3/9/18	1
117	UV Spatial Shaping	10 days	Sat 3/10/18	Mon 3/19/18	1
118	UV Temporal Shaping	12 days	Sat 3/10/18	Wed 3/21/18	1
119	UV optical table setup at gun	10 days	Thu 3/22/18	Sat 3/31/18	1
120	**DRIVE LASER TTO**	**0 days**	**Sat 3/31/18**	**Sat 3/31/18**	**1**
121	Diagnostics/EPICS/Controls	15 days	Sun 4/1/18	Sun 4/15/18	1
122	Laser Characterization	28 days	Mon 4/16/18	Sun 5/13/18	1
123	**Heater Laser**	**53 days**	**Mon 5/14/18**	**Sat 7/7/18**	
124	Laser Synchronization	15 days	Mon 5/14/18	Tue 5/29/18	1
125	IR Pulse-train	5 days	Mon 5/14/18	Fri 5/18/18	1
126	Temporal Shaping	5 days	Sat 5/19/18	Wed 5/23/18	1
127	IR Transport	5 days	Sat 5/19/18	Wed 5/23/18	1
128	**HEATER LASER TTO**	**0 days**	**Wed 5/23/18**	**Wed 5/23/18**	**1**
129	Diagnostics/EPICS/Controls	10 days	Wed 5/30/18	Fri 6/8/18	1
130	Laser Characterization	28 days	Sat 6/9/18	Sat 7/7/18	1
131	**Optimize Drive/Heater Laser**	**440 days**	**Mon 5/14/18**	**Tue 8/13/19**	
132	Environmental stability	90 days	Mon 5/14/18	Mon 8/13/18	1
133	Spatial Profile	20 days	Tue 8/14/18	Sun 9/2/18	1
134	Temporal Profile	60 days	Tue 9/4/18	Fri 11/2/18	1
135	Beam pointing stabilization	90 days	Sat 11/3/18	Thu 2/14/19	1
136	Rep Rate flexibility	90 days	Fri 2/15/19	Wed 5/15/19	1
137	Pulse energy	90 days	Thu 5/16/19	Tue 8/13/19	1
138	**Spare Laser**	**60 days**	**Wed 8/14/19**	**Sat 10/12/19**	
139	Commission spare laser	30 days	Wed 8/14/19	Thu 9/12/19	1
140	Commission hot swaps	30 days	Fri 9/13/19	Sat 10/12/19	1



Detailed Injector Source Schedule

	Task Name	Duration	Start	Finish	Predecessors
142	**Injector Source**	**297 days**	**Thu 9/14/17**	**Sat 8/25/18**	
143	**Pre-Beam**	**85 days**	**Thu 9/14/17**	**Mon 1/22/18**	
144	ARR	3 days	Thu 9/14/17	Mon 9/18/17	7FS-60 days
145	Pre-Beam Checkout	7 days	Mon 12/11/17	Wed 1/3/18	7
146	PPS/BCS Certification	3 days	Thu 1/4/18	Sat 1/6/18	145
147	LLRF/SSA	1 day	Sun 1/7/18	Sun 1/7/18	146
148	Gun/buncher Processing	14 days	Mon 1/8/18	Mon 1/22/18	147
149	**Dark Current Characterization**	**44 days**	**Tue 1/23/18**	**Thu 3/8/18**	
150	Dark Current I	19 days	Tue 1/23/18	Sat 2/10/18	148
151	Survey	1 day	Tue 1/23/18	Tue 1/23/18	150SS
152	Install Collimator	4 days	Sun 2/11/18	Wed 2/14/18	150
153	Controls Checkout	2 days	Thu 2/15/18	Fri 2/16/18	152
154	BL Components Operational	2 days	Thu 2/15/18	Fri 2/16/18	153FF
155	Dark Current II	21 days	Thu 2/15/18	Thu 3/8/18	152
156	**Initial Photo-Beam**	**15 days**	**Sat 3/31/18**	**Sun 4/15/18**	
157	**First Photoelectrons**	**0 days**	**Sat 3/31/18**	**Sat 3/31/18**	**149,120**
158	Low Energy E-beam	15 days	Sun 4/1/18	Sun 4/15/18	157
159	MPS/BCS checkout	2 days	Sun 4/1/18	Mon 4/2/18	158SS
160	Survey	1 day	Sun 4/15/18	Sun 4/15/18	158FF
161	**INJECTOR TTO**	**0 days**	**Sun 4/15/18**	**Sun 4/15/18**	**156**
162	Cathode characterization	30 days	Mon 4/16/18	Tue 5/15/18	161
163	E-beam alignment	30 days	Wed 5/16/18	Fri 6/15/18	162
164	E-beam optimization	30 days	Sat 6/16/18	Mon 7/16/18	163
165	CW RF thermal management	14 days	Tue 7/17/18	Mon 7/30/18	164
166	Dark Current III	21 days	Tue 7/31/18	Mon 8/20/18	165
167	Remove temporary dump/diagnostics	5 days	Tue 8/21/18	Sat 8/25/18	166
168	Infant mortality	120 days	Mon 4/16/18	Wed 8/15/18	161

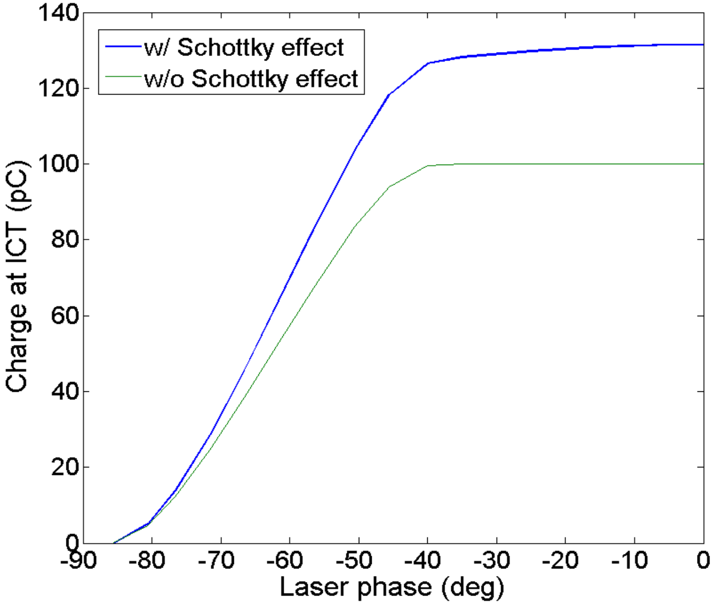


Summary

- Injector beamline is well optimized
  - Exit emittance is close to the thermal emittance
- Imperfections from laser, RF couplers, wakefields, jitter and alignment have been evaluated and/or mitigated.
- Started to prepare for early commissioning in FY18
  - SLAC team has actively participated in the APEX commissioning
  - Beam tuning (RF phase/amplitude calibration and BBA) procedure is developed
  - Will develop the related HLA software

Early commissioning (1MeV)

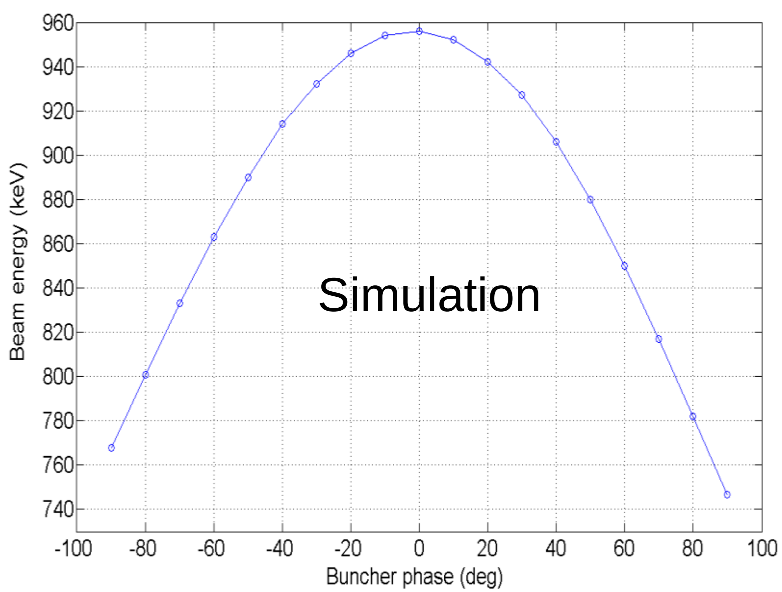
- No energy spectrometer is available for the RF gun/buncher phase/amplitude calibration and energy measurement
  - But keep space for future adding a dipole
- Have to use existing devices (ICT, YAG screen, BPMs, correctors and solenoids) for:
  - Calibration of the gun/buncher phase and amplitude
  - Beam energy measurements
- Laser phase calibration
  - Gun phase is fixed, similar to LCLS1
  - Scan the charge (w/ ICT) vs. laser phase to determine zero-crossing laser phase w.r.t. RF

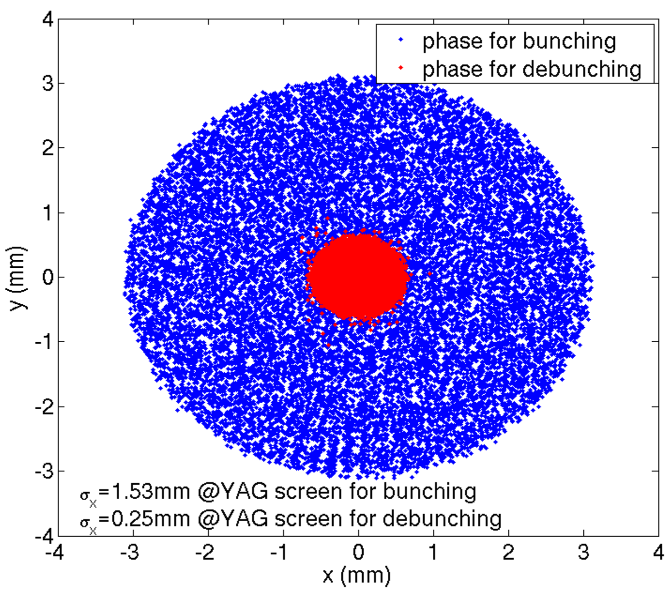


Phase calibration

Buncher phase calibration for zero-crossing phase:

- Beam energy with buncher's zero-crossing phase ≈ gun energy
  ⇒ zero-crossing phase determined
- Zero-crossing bunching: larger beam size at YAG screen
- Zero-crossing debunching: smaller beam size at YAG

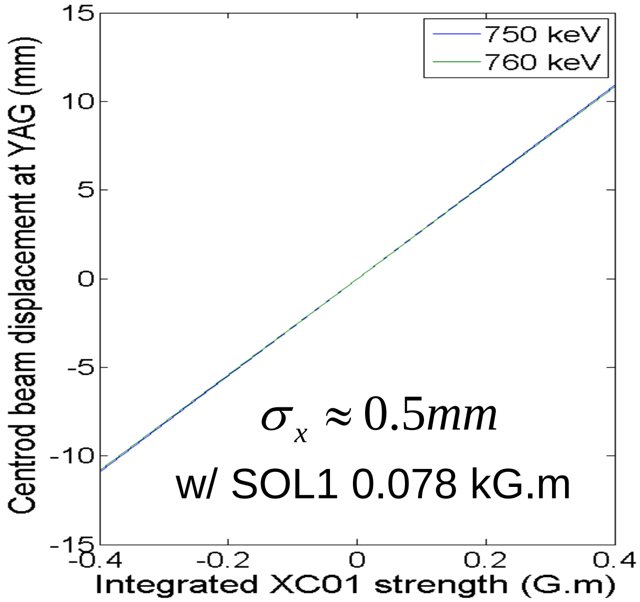


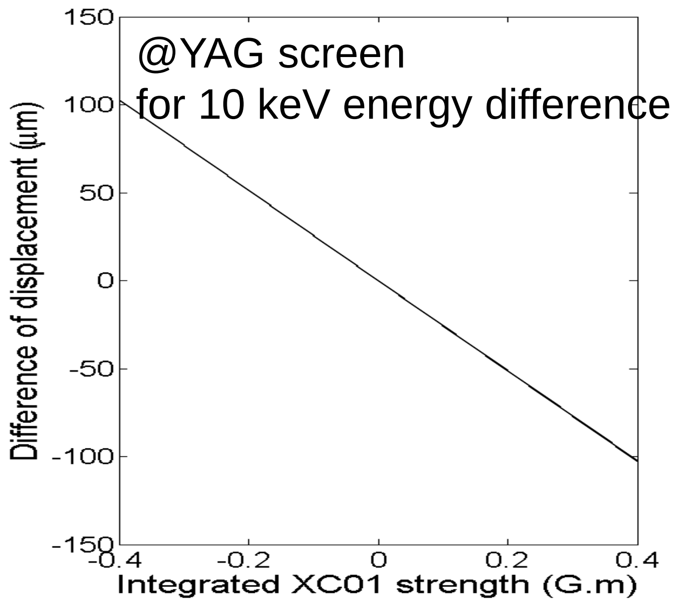


RF amplitude calibration

Gun & buncher amplitude is calibrated with the beam energy measurement:

- Using a weak corrector: measure the slope of x-offset at YAG screen/BPM2 vs. a corrector strength ⇒ may resolve ~10keV energy
- And/or using a solenoid





BBA for cathode

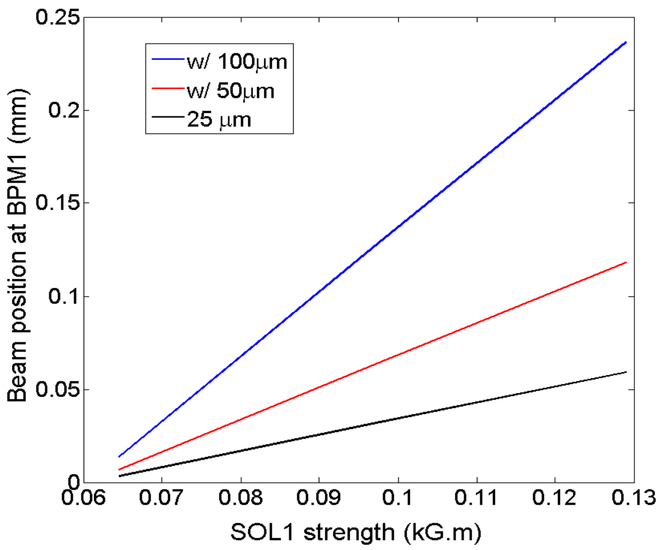
Alignment for laser position on cathode:

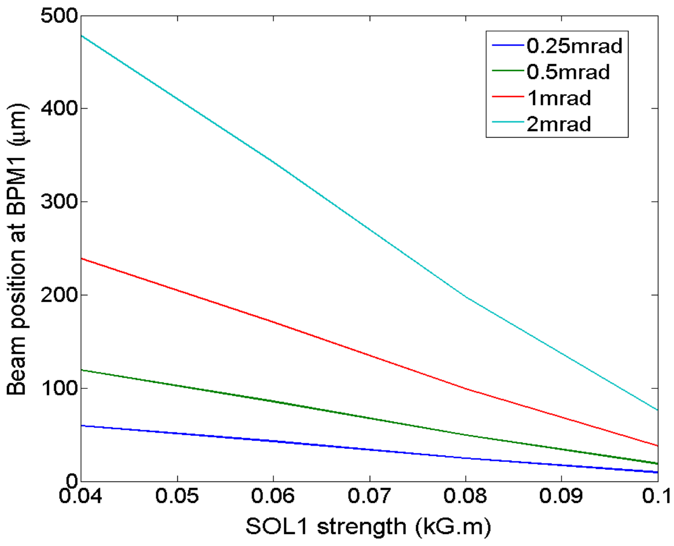
- Cathode plug is aligned well with the gun
- Usually only central 5mm of the cathode center is doped with Cs for electron emission
- QE mapping $\Rightarrow$ boundary of the central 5mm $\Rightarrow$ cathode center
- Can align <100μm according to APEX experience
  - Emittance growth <2%

BBA for solenoid

Using the solenoid matrix, offset at the entrance of the solenoid can be estimated via measuring beam offset at BPM or YAG screen

- Can be aligned < 50 μm and <0.5mrad
- Emittance growth negligible





BBA for buncher

- Set buncher to debunching zero-crossing
  - Eliminated the effect of dispersion due to the stray fields (zero-crossing)
  - Smaller beam size (extra focusing from debunching phase)
- Turn on SOL1 and adjust its strength to focus the beam at YAG
- Correct the offset using pairs of correctors xc01/02 measuring difference of centroid beam at YAG for buncher on/off
  - <100μm emittance growth negligible