Initial X-Band Photoinjector Performance at SLAC

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History

• 20 years of development of X-Band technology at SLAC
  mature technology for high gradient field
  ~100MV/m for accelerating structure (against 25MV/m for S-Band)
  ~200MV/m for RF gun (against 120MV/m for S-Band )

• Success of LCLS and its RF photoinjector
  1.6 cell S-Band RF e-gun from SLAC/BNL/UCLA/APS

• X-Band photoinjector
  • Compact FELs
    180 m long, 2fs, 20GW, 6GeV based on 10pC, no linearizer
    PRST-AB ,15, 030703 (2012) Y.Sun et al.
  • Compact Inverse Compton scattering (ICS) source
    RF components delivered to LLNL
  • Source for Ultra-Fast Electron Diffraction
X-Band Gun

• Originally developed for UC Davies (2001-2005)

• Improved 5.5 cell version “Mark0”
  (racetrack coupling cell)

• Design revisited in 2010 by SLAC/LLNL

• 5.6 cell version “Mark1”
  (mode separation increased, elliptical irises, 5.6)

• “Mark0” tested at XTA

<table>
<thead>
<tr>
<th>TABLE I. Mark 1 rf gun parameters.</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Unloaded quality factor</td>
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<tr>
<td>First cell length</td>
</tr>
<tr>
<td>Coupler type</td>
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<tr>
<td>Iris shape</td>
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<tr>
<td>Mode separation</td>
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<td>Cathode material</td>
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<td>Cathode peak field</td>
</tr>
<tr>
<td>Final kinetic energy</td>
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</table>
X-Band Test Area (XTA) installed in NLCTA tunnel at SLAC

YAG/OTR

Transverse deflector

70 MeV high brightness beam soon to be 100 MeV
~1.8m from cathode

spectrometer

6.7 m

XTA located in NLCTA at SLAC
X-Band Test Area (XTA) operational since summer 2012

Single RF source powers both RF devices
High power phase shifters

Linac
Gun + Solenoid

Laser Injection chamber + YAG + FC

Laser Compressor (IR) Tripler

X-band Test Area (XTA) operational since summer 2012
XTA turn-on

- 1st beam ~ 18 months after project started
  - X-Band RF station/ distribution available
  - NLCTA Tunnel / infrastructure in place
  - Imported LCLS control system & applications
- July 30th: 1st photo-ebeam out of gun
- Aug. 3rd: acceleration to 50 MeV in linac as measured in spectrometer after linac

Solenoid from 155A to 175A in 5 steps

Spectrometer ΔT ~ 3 pulses

BBA for finding cathode center
X-Band vs S-Band: smaller bunch lengths

Bunch length 3-4 times shorter than from S-Band gun (both at low and high charge)

X-Band, 11.424 GHz, with 200 MV/m
S-Band  2.856 GHz with 120 MV/m

Beta of 0.5 reached in 3 times shorter distance

Field over the first 3 mm
AVDRA simulations results (after multi-parameter optimization)

<table>
<thead>
<tr>
<th>Q [pC]</th>
<th>$\varepsilon_{x,95%}$ [mm-mrad]</th>
<th>$\sigma_1$ [mm]</th>
<th>$B_{peak} = Q/\sigma_1/\varepsilon^2$</th>
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<th>$B_{peak} = Q/\sigma_1/\varepsilon^2$</th>
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</tbody>
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High $E_{RF,cathode}$ to beat surface self-field and reach smaller $r_{laser}$ and thus smaller $\varepsilon_\perp$

High $dE_\perp/dt$ for short bunches

$r_{laser} > \sqrt{\frac{Q\varepsilon_o}{\pi E_{RF,cathode}}}$
Experimental Results

- e-beam out of gun $E \sim 7.5$MeV ($V_{RF,peak} \sim 200$MV/m)
- dark current acceptable
- e-beam at 70 MeV after 1.05 m linac
- charge up to 40pC, QE just in 1e-5 range
- bunch length measured $\sim 250$ fs rms for 20pC
- energy spread rms 15 keV at 70 MeV (15 pC)
- emittances < 3 mm-mrad (but very preliminary optimization)
- jitter reduction
  - Laser PLL noise reduced from 350-500 fs rms or more down to 70 fs rms
- Path to emittance minimization
RF Distribution

~30MW out of klystron (can run 50 MW)
RF compression ~ X 4
125 MW out of SLED line, ~ 150 ns
Attenuation 25%
Distribute (3/4, 1/4) to (Linac, gun)
High Power phase shifters [110 deg ]

August 2012: 17.5 MW in gun ~ 209 MV/m
Oct-Nov run: ~170MV/m
Feb-March: ~ 200 MV/m
Dark Current level acceptable

August-2012: 17.5 MW in gun ~ 209 MV/m
Dark Current ~ 180pC

13% Dark Current fluctuations <->
Pwr fluctuations at ~1% level
RF conditioning 24/7
Dark current slightly decreased
Adjusted relative power in gun for ~ 200MV/m
Dark Current acceptable

Dark current visible on spectrometer YAG screen at 70 MeV for $dT \sim 200$ ms

$dT \sim 200$ ms

(ie 13 pulses, high gain)

$dT \sim$ few ms

(single pulse)

Photo-e beam

Dark current not visible

$Q \sim 8$ pC
Charge vs Phase ("Schottky scan")

- \( E_{rf} \approx 178 \text{ MV/m} \)
- Span \( \approx 90 \text{ deg} \)
- Dark Current \( \approx 20 \text{ pC} \)

"Reconditioned" for higher field

- \( E_{rf} \approx 200 \text{ MV/m} \)
- Span \( \approx 120 \text{ deg} \)
- Dark Current 120 pC
QE in the low $10^{-5}$

- Low QE in Oct-Dec
  $E_{UV} \sim 50$ micro-J, $\sim 20$ pC
  $QE \sim 2 \times 10^{-6}$

- January:
  - IR pulse from 40fs to 200fs
  - higher $E_{rf}$ (200MV/m)

- February:
  $E_{UV} \sim 10$ micro-J, 30 pC
  $QE = 1.9 \times 10^{-5}$

- March
  $QE = 3 \times 10^{-6}$
  $E_{UV} \sim 60$ micro-J, $\sim 40$ pC
  But multiple laser pulses (3 observed on photodiode)

From Faraday cup signal
Gun Energy measurement

No space for spectrometer
Centroid vs steerer (d, Bl)
\( \sim 7 \pm 0.3 \text{ MeV} \)

Simulations

Measurements
Challenge no-1: timing stability shot-to-shot

1 deg X-Band = 250 fs

- Major source of noise = Oscillator Phase Lock Loop (PLL)
- Replaced internal loop (80MHz) by external PID control of piezo (using # 2856MHz)
- Noise reduced from ~500fs rms (2deg X-Band rms) to 70 fs rms
- In operation since late February

- Other contributions:
  - Modulator HV: 175 ppm (i.e. $d\Phi \sim 0.6$ deg rms, $dV/V \sim 3\times10^{-4}$)
  - Contribution from LLRF still under investigation

rms energy spread $< 15$ keV $\sim 2.1\times10^{-4}$

As expected from Simulations 😊
Challenge no-2: Alignment /Steering

Beam Based Alignment (BBA) on cathode

Electric center of gun

\[ x_c = f(\Phi_{rf}) \]

Solenoid center

\[ x_c = f(B_{sol}) \]

\[ \Delta x = 0.5 \text{ mm on cathode} \]

Measure \( \Delta y \sim 1.1 \text{mm} \)

Tolerances

ASTRA simulations

Baseline \( \varepsilon_x=0.6/\varepsilon_y=0.6 \)

\( \Delta x = 0.5 \text{ mm laser on cathode} \)

\( \varepsilon_x=0.6/\varepsilon_y=1.2 \)

\( \Delta x = 0.5 \text{ mm solenoid} \)

\( \varepsilon_x=0.6/\varepsilon_y=1.1 \)

Much less forgiving than S-Band

Measurements

Simulations F.Fu, GPT
Emittance

~2.7 mm-mrad at 10 pC on YAG screen

LCLS tools developed by H.Loos and others are in place for automated emittance optimization
Scan of phase, solenoid, steering

Slice emittance possible with TCAV (but not performed yet)

Observed light on OTR screen, with emittance ~3.5 mm-mrad at 30 pC
But light level low so integrated ~ 10 pulses
Challenges of emittance minimization

- Slow drift laser-to-RF phase by 5 deg ~ 1 minute scale feedback detecting e-beam in X-Band cavity w.r.t RF phase
- Better steering on cathode (<200 microns) Transport Model of laser for final steering
- Drift IR at end of transport drifts (depending on time of day) Slow feedback from MessTechnik
- Steering through linac: orbit correction needs at least 20 pC for BPM Cavity BPM have been built but not installed

- Known issue Bz field non-zero on cathode

\[ \varepsilon [mm \text{ } \text{mrad}] = 0.3Bz [mT] \sigma [mm]^2 \]

ASTRA simulations Baseline \( \varepsilon_x=0.6/\varepsilon_y=0.6 \)

\[ Bz = 0 \text{ displaced by 1 mm} \]

\( \varepsilon_x=1.1, \varepsilon_y=1.1 \)
Emittance

Optimized emittance $\varepsilon_{95}$
$\varepsilon_x = 0.26/\varepsilon_y = 0.26$
- Linac located at 0.55m
- Perfect “everything”

Reality:
- XTA linac at 0.8 m
- Bz offset 1mm $\Rightarrow$ 0.6/0.6
- Laser offset 0.5 mm $\Rightarrow$ 0.65/0.4
- Solenoid 0.5 mm $\Rightarrow$ 0.43/0.56
- Gaussian longer $\Rightarrow$ 0.73/0.73

Combination
- Gaussian longer, $r = 1.2$ mm
Bz offset 1 mm, laser offset 0.5
1.0/1.7 !!!

Much less forgiving than S-Band
Bunch length measurements – 250 fs rms at 20pC

X-Band transverse deflector (TCAV)
Good measurements despite large phase jitter/drift

TCAV on, calibration phase -> pixel
TCAV on

250 fs rms at 20 pC

As expected from Simulations 😊

Operation of TCAV limited to 1 week so far
No slice emittance so far
Future development:
ICE-X (Inverse Compton Experiment at X-Band)

Flux of $>10^7 \gamma/s$ of 0.1 ~ 2 MeV photons with $B>10^9 (\gamma/s/mm^2/mrad^2/0.1\%)$

- Narrow bandwidth achieved with high brightness beam and long-pulse laser interaction $\rightarrow$ reasonable beam and laser parameters
  - Commercially available 10 Hz, 3J, 3ns, YAG pump laser with 30 um laser waist ($I_0 \sim 1x10^{14} \text{ W/cm}^2$)
  - 5 cm e$^-$ beta, 250 pC, $\gamma\varepsilon < 0.4 \text{ mm-mrad}$

- Stable beam and laser $\rightarrow$ simpler operating conditions

Upgrades to increase flux & brightness by $>1000$

- Upgrade laser to 120 Hz
- Operate with multibunch train (30 bunches / rf pulse)
Future Development: Ultrafast Electron Diffraction (UED) with X-Band

Step 1:
Long pulse: transverse deflector resolution < 5fs

Step 2:
Short intense single pulses (with compressor)
8 pC, rms < 20 fs, ε = 0.4 mm-mrad

Step 3: compressor as close to the gun 1.6kA with 8pC
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- Alignment: G.Gassner, …
- Many other people (F.Wang, A.Benwell, B.McKee, J.Tice, bldg 33 team, Juan Cruz, C.Hudspeth, …)
Summary

- Successful operation of 200MV/m 5.5 cell X-Band gun
- 250 fs rms, 20 pC bunch measured at 70 MeV
- QE low but not extremely low
  - Need to suppress multiple pulses before quoting QE numbers
  - Plans to do cathode cleaning
- Emittance numbers still large
  - On a path to minization
- Low energy spread \(2 \times 10^{-4}\)
- 70MeV e-beam (soon to be 100 MeV) out of 1.5 m long
- Dark current ok even for few pC operation
- Tolerances/alignment challenging
END PRESENTATION