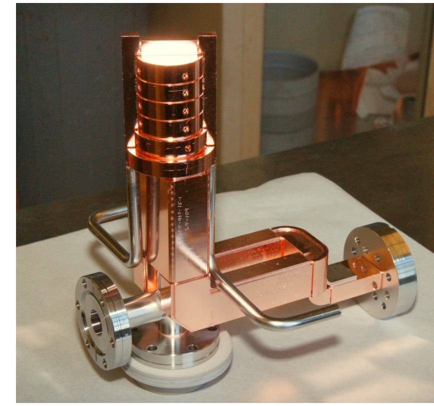
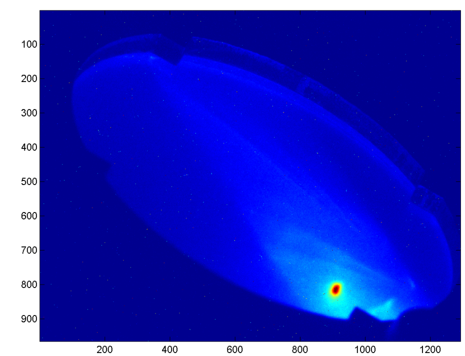


Performance of a First Generation X-Band Photoelectron RF gun

C.Limborg-Deprey, SLAC

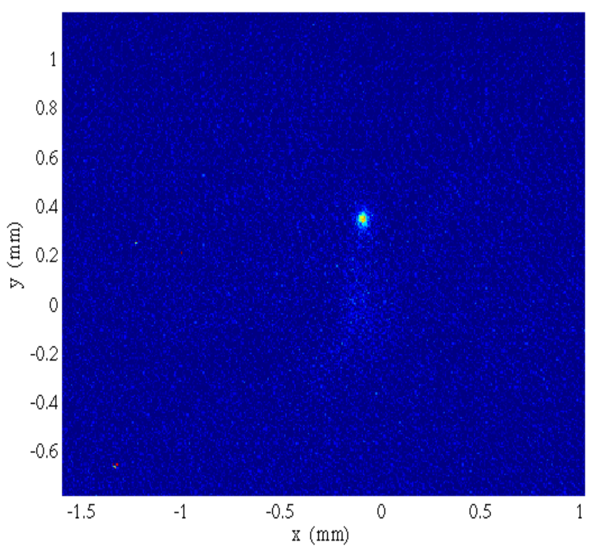


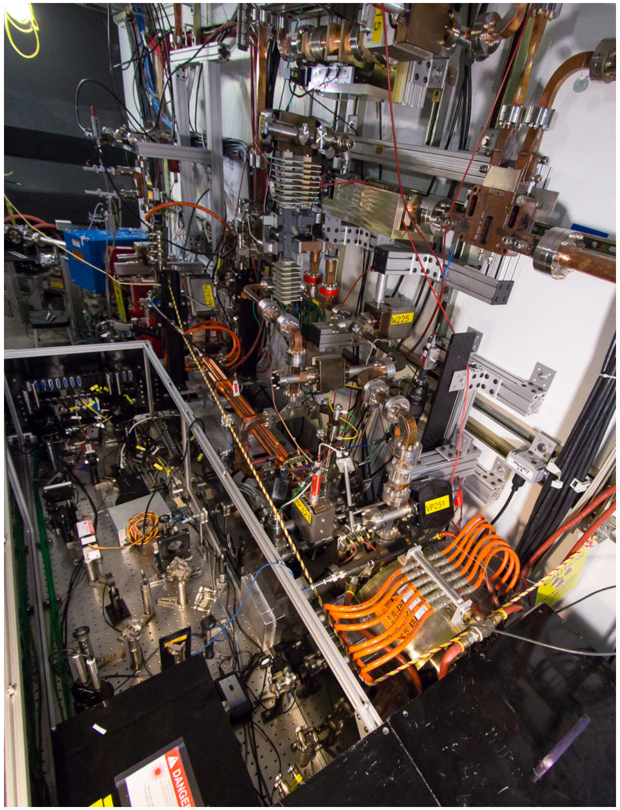
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Motivations for an X-Band photoinjector
- Performance of a 1st generation gun
- R&D in X-Band components
- Other X-Band projects





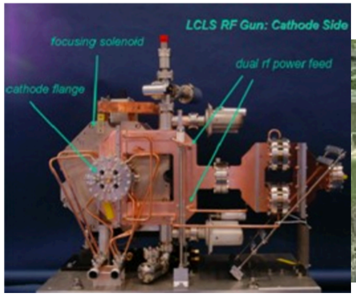
A Brief History
Towards an X-Band Photoinjector

- **X-Band accelerators developed originally for the Next Linear Collider (NLC)** ~ 25 years ago
  - 100 MV/m vs 25 MV/m at S-Band
  - X-Band development post NLC
    - High gradient R&D
    - Linearizers and deflectors

- **High brightness photoinjectors developed for pulsed FELs** for ~ 20 years

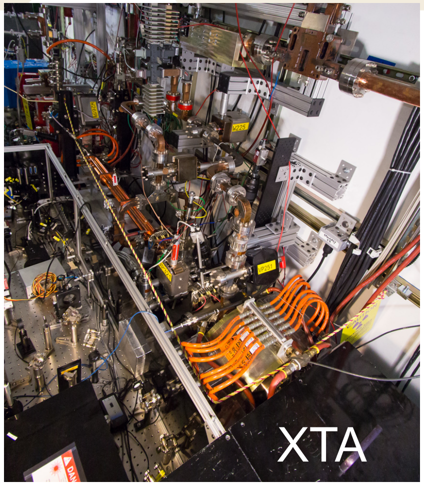
  Success of LCLS S-Band gun at 120 MV/m

  Would an X-Band gun 200 MV/m do better ?



Towards X-Band accelerators based light sources

- **Construction of an all X-Band injector the X-Band Test Area (XTA) at SLAC**
  Calculations show increase 10X in brightness



- **Design Compact X-Band FEL**
  180-m with X-Ray 2fs, 20GW, 10keV
  Sun.Y, *PRST-AB,* Vol 15, 030703, 2012

- **Compact machine for an Inverse-Compton-Scattering(ICS) γ-Ray source for LLNL**
  X-Band system provided by SLAC

History of X-Band Gun

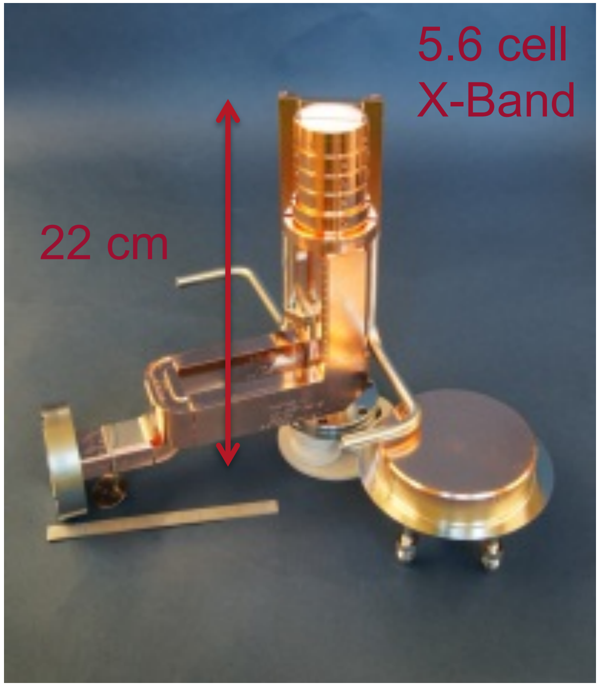
- **Originally developed for UC Davis (2001-2005)**
  for Inverse Compton Scattering source for X-Ray
  A.E. Vlieks, et al. SLAC-PUB-11689, 2006

- **Improved 5.5 cell version "Mark0" (2004)**
  racetrack coupling cell

- **Design revisited by SLAC/LLNL (2010)**
  5.6 cell version "Mark1"
  Mode separation increased, elliptical irises
  R.Marsh et al. PRST-AB 15,102001, 2012

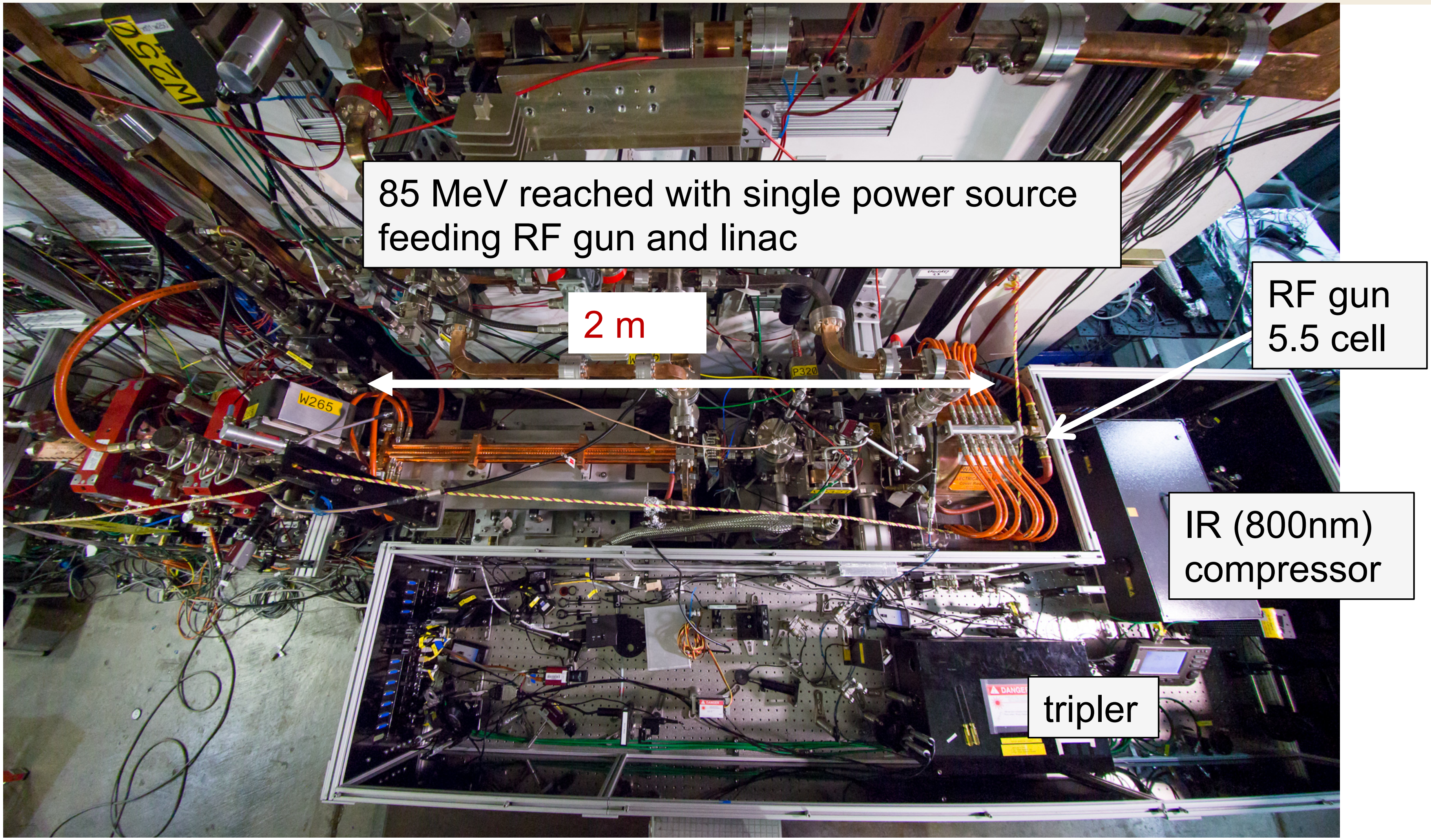
- **"Mark0" installed at XTA (2012)**
  for debugging purposes

- **"Mark1" installed at LLNL (2014)**



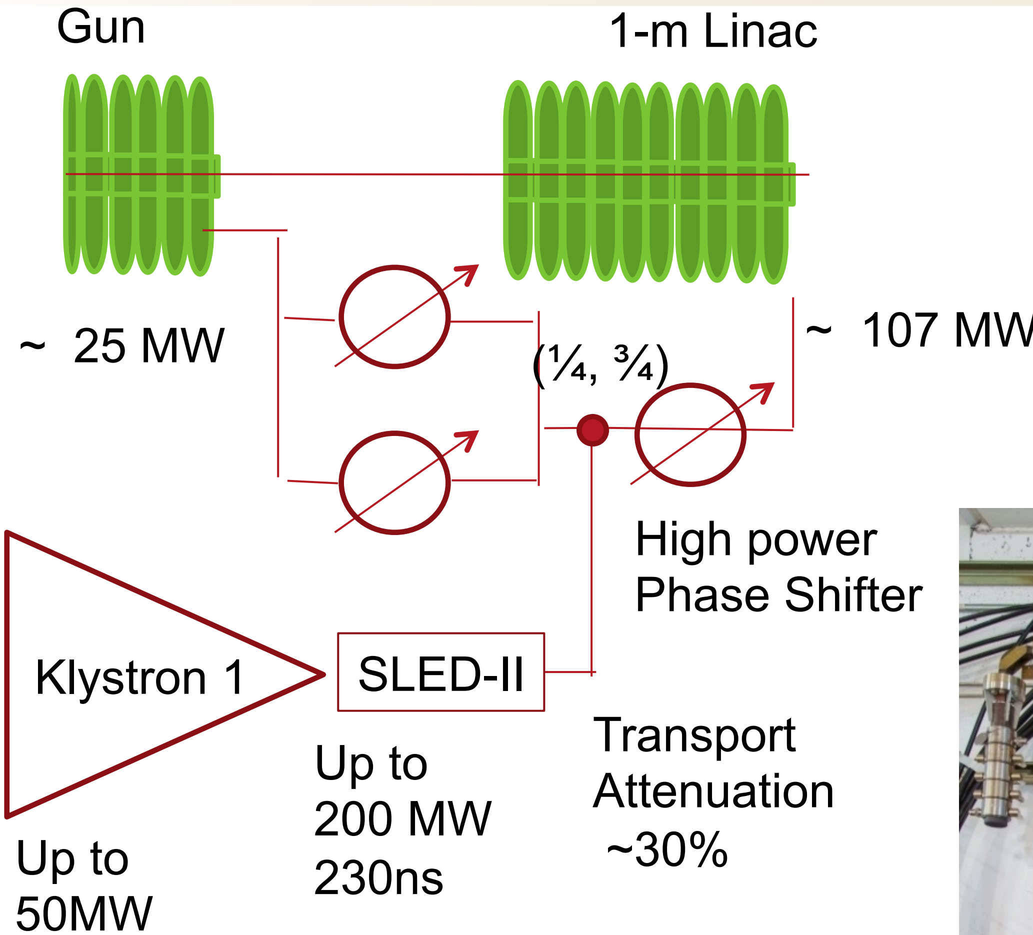
A few RF features
- 11.424 GHz
- Filling time τ = 70 ns
- Dual feed, with racetrack
- Requires 17 MW for 200 MV/m

X-Band-Test Area (XTA)
Very compact 85 MeV e-beam accelerator: 2-m long

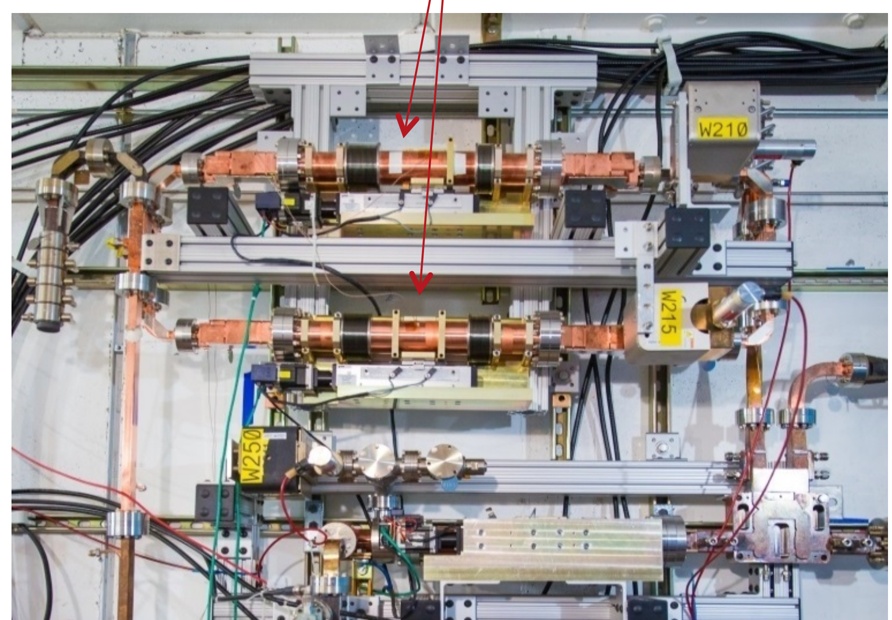


RF Distribution

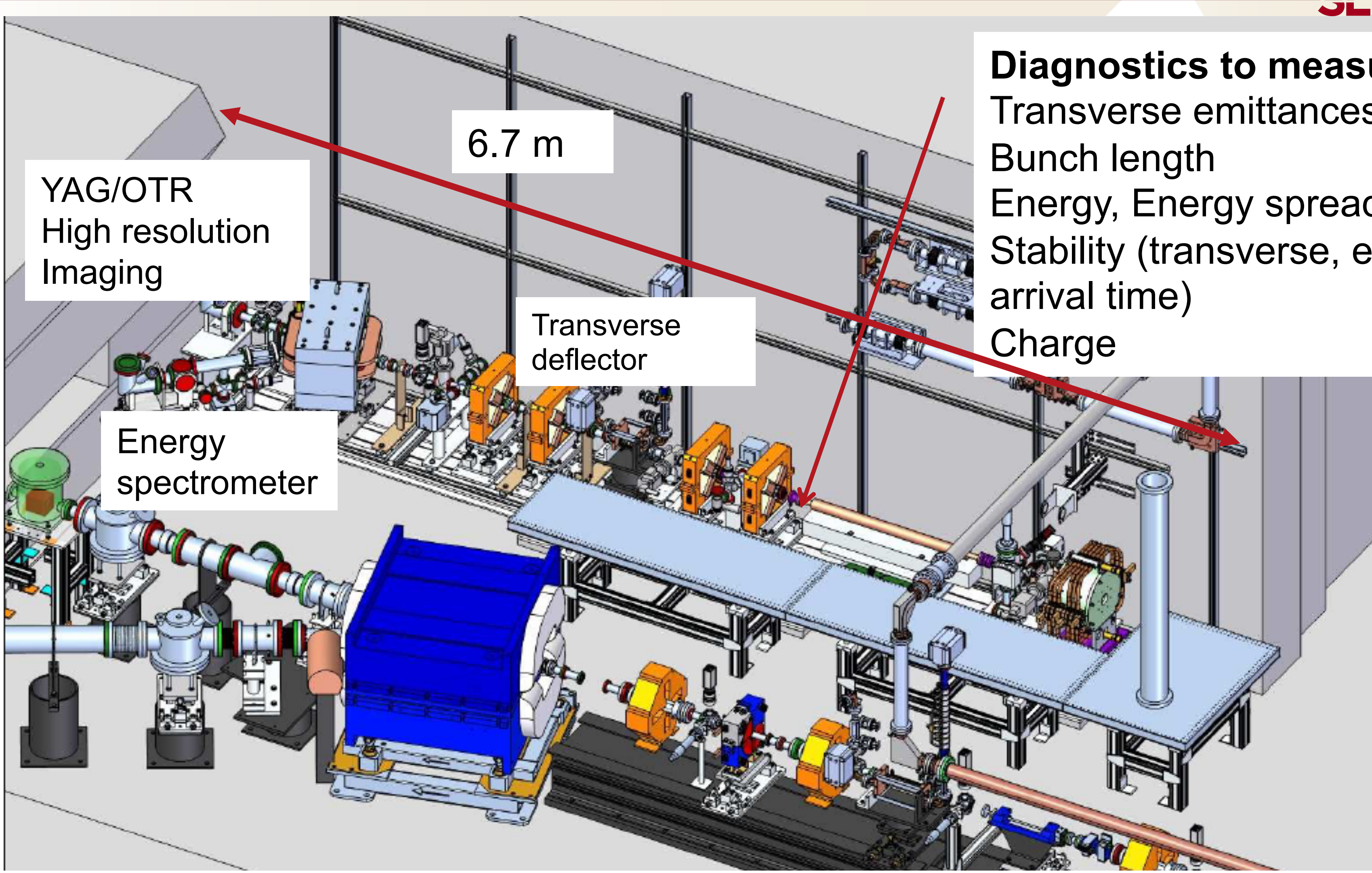
SLAC



Phase Shifters



X-Band Test Area (XTA)
Equipped with 6D diagnostics



Diagnostics to measure
Transverse emittances
Bunch length
Energy, Energy spread
Stability (transverse, energy, arrival time)
Charge

Next Linear Collider Test Accelerator (NLCTA) tunnel, SLAC

X-Band Gun Outperforms an S-Band gun Due to Higher Gradient Cathode Field

- **Smaller transverse emittance**

  Smaller spot size on cathode as high E_{acc} overcomes $E_{pull} = \frac{\sigma}{\varepsilon_o} = \frac{Q}{\pi r^2 \varepsilon_o}$

  Still wins despite $\varepsilon_{thermal}$ increased with field

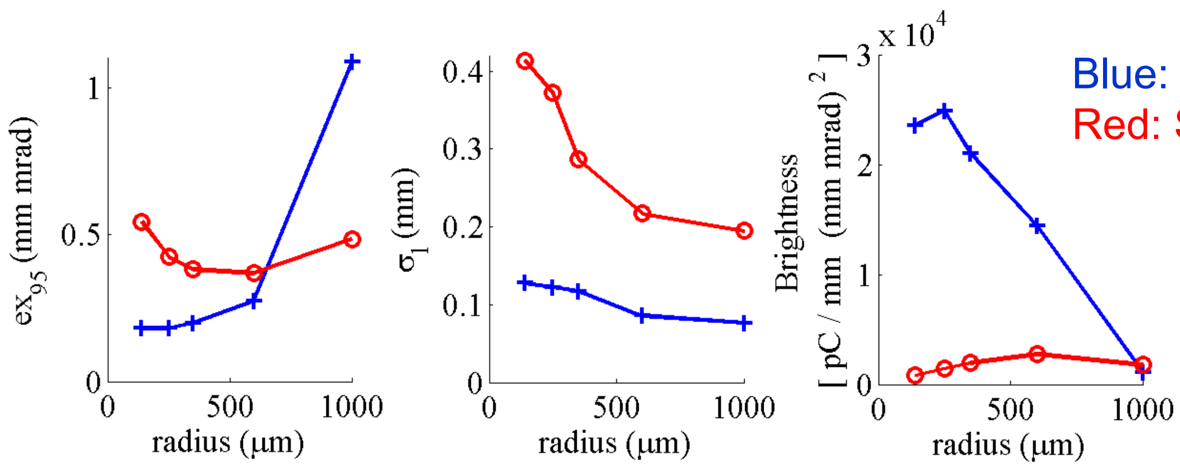
- **Much shorter bunches**

  Ultra-relativisitic ($\gamma_{lorentz}$ ~ 2) e-beam in less than 2 mm (versus 3mm)

  Fights space charge earlier

- **Higher peak brightness**

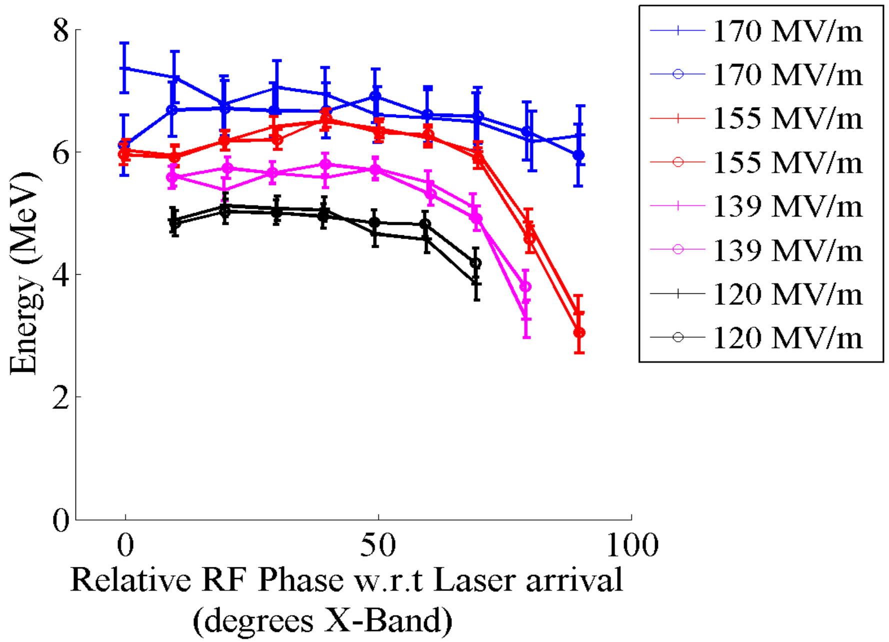
  Calculations show X10 compared to S-Band at 100 pC

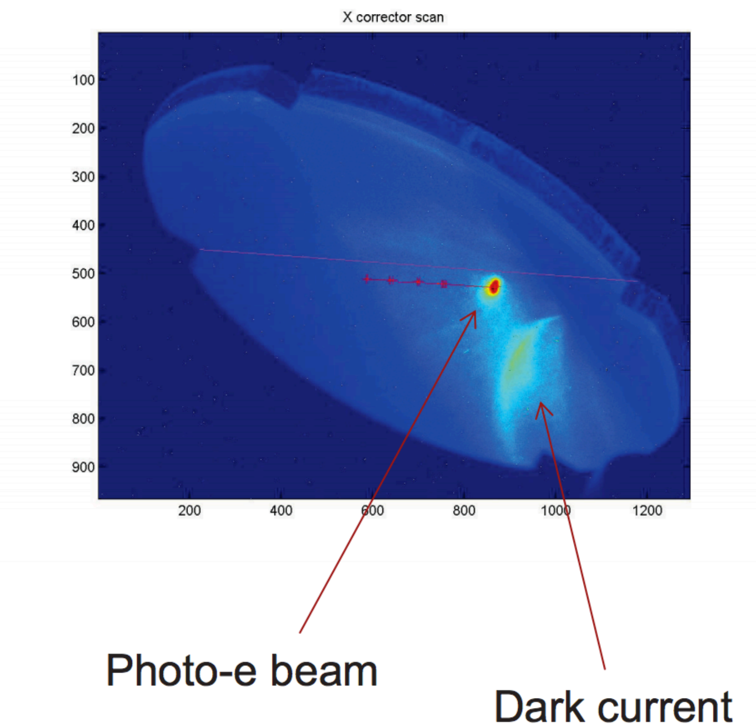


C.Limborg et al.
PRAB 19,053401(2016)

High Gradient Field On Cathode
Experimental Verification With Spectrometer

Dipole corrector used as "spectrometer"
e-beam position on YAG vs corrector strength

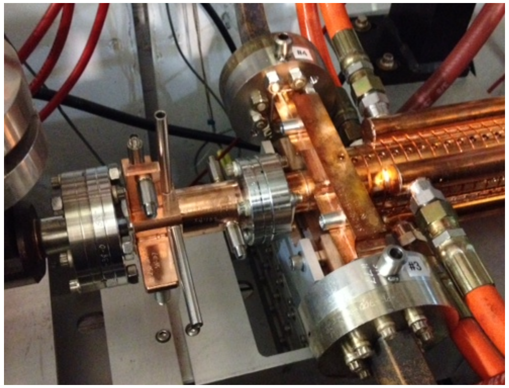


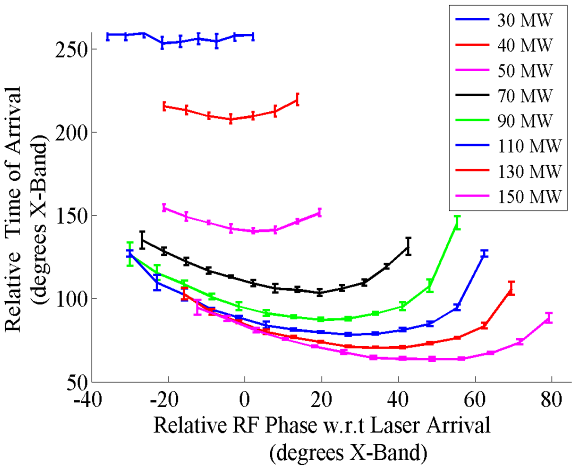


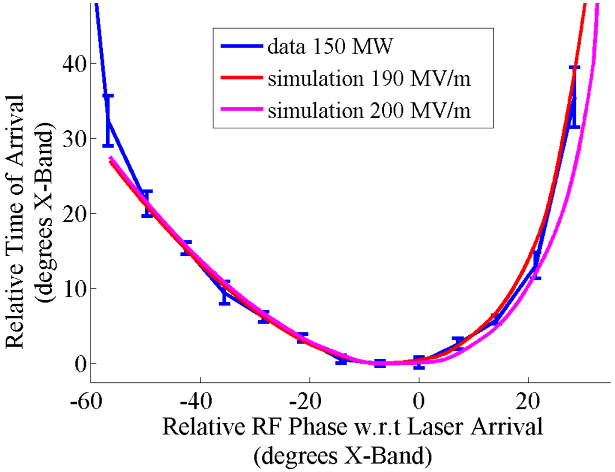
Measurement limited by dark current on YAG screen

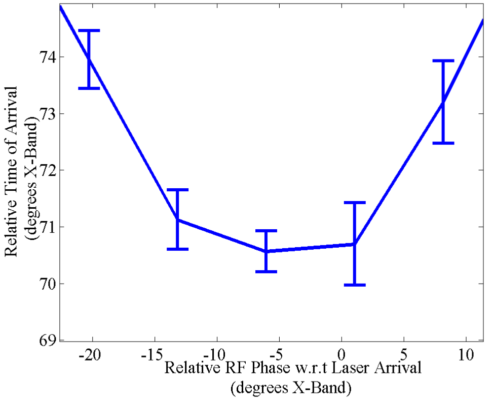
Arrival time ("time-of-flight") using phase measurement in a monopole cavity of a monopole + dipole X-Band BPM (XBPM)

Chose 12.85 GHz cavity frequency to filter dark current signal at 11.424 GHz









Arrival time jitter rms < 125 fs (50 sample points)

C.Limborg et al. PRAB 19,053401(2016)

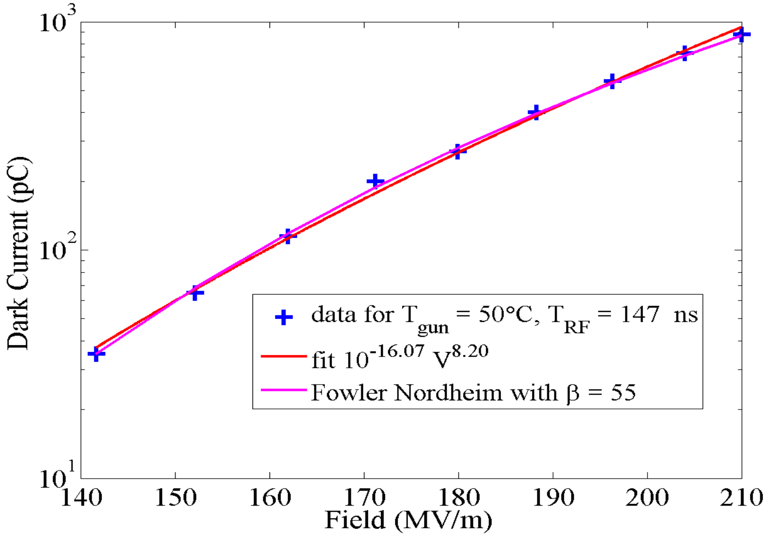
Dark Current Large But Not a Problem

- **Dark current at high gradient fields**

  Few hundreds of pC

  Fit Fowler-Nordheim equa. with $\beta = 55$

  RF pulse used typically shorter (110 ns)

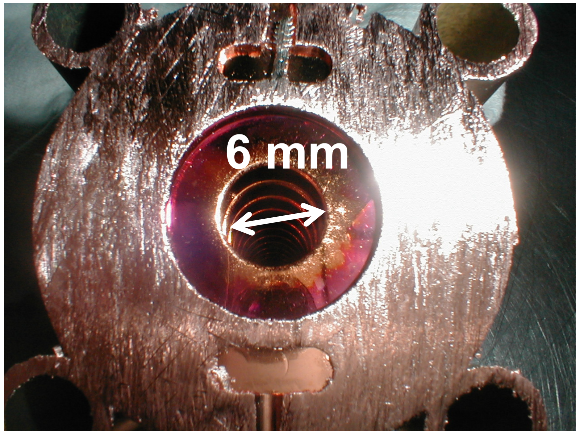


- **Collimated out by 6 mm linac aperture**

  example : 180 MV/m

  $Q_{dark\ current}$ = 300pC but

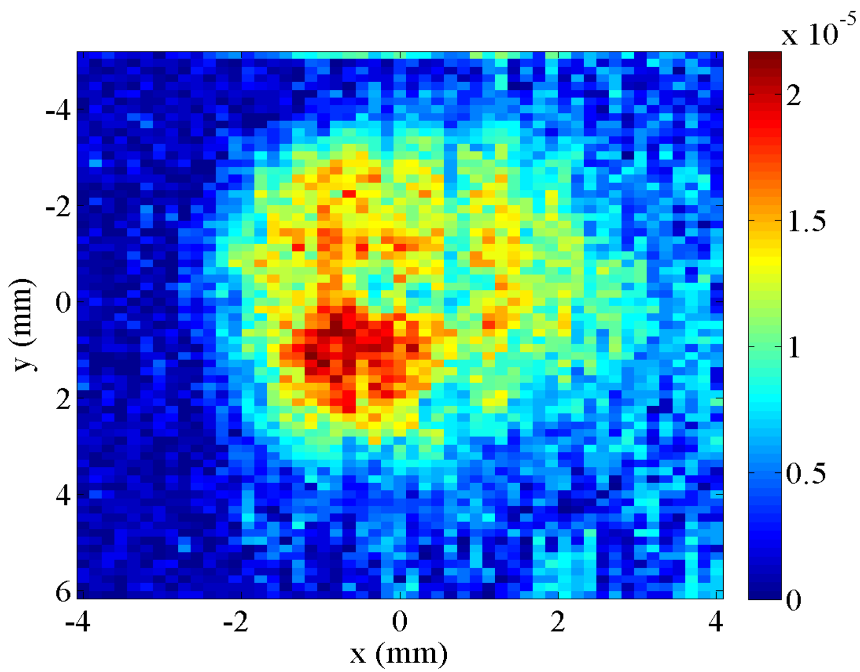
  < 20 pC accelerated to 85 MeV



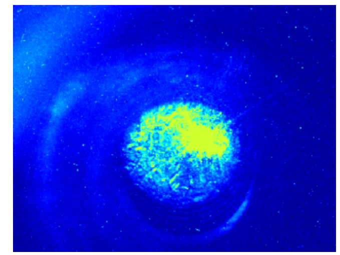
- **Much lower dark current on Mark-1 (LLNL)**

QE Relatively Low ~ 2.10^{-5}
Cathode Damaged (Non-Demountable)

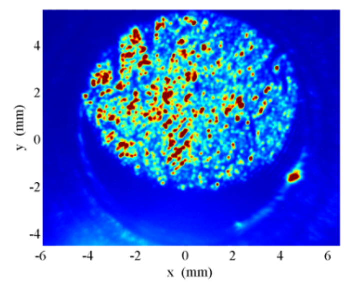
Emission (QE) map



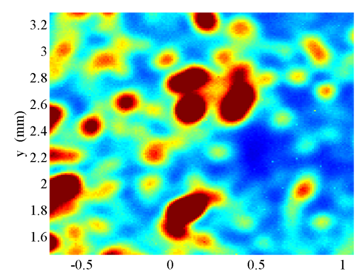
Cathode surface
Observed with visible light



2012
After RF
But before laser



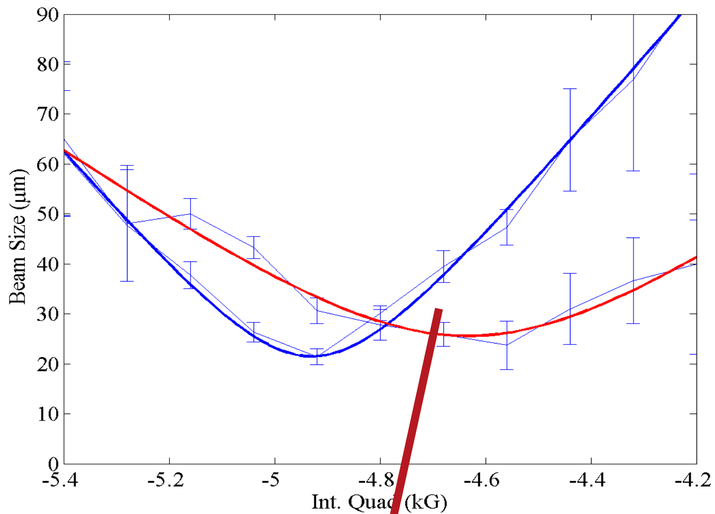
2014
After commissioning

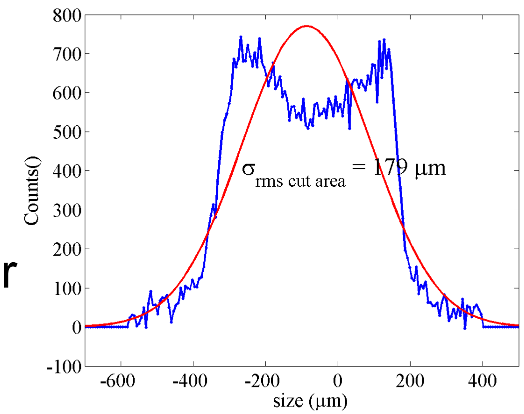


2014
Irregular emission properties
at ~ 100 μm scale

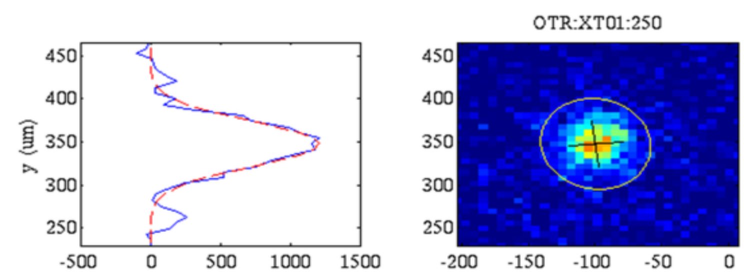
Emittances Not as Good as Predicted: Likely a Consequence of Cathode Damage

Poor $\varepsilon_{thermal}$ (mm-mrad / rms mm) for spots > 1 mm
as large as 3.0 for very large spots (> 1.5 mm)
but ~ 0.9 in some sweet areas with spots < 1 mm

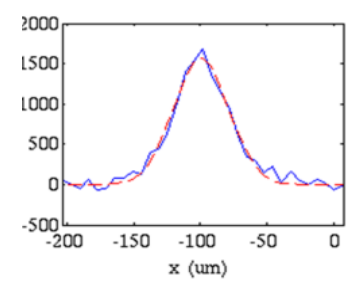




Double emitter visible here



Small sizes
10 pC
σ_x = 20 µm
σ_y = 26 µm

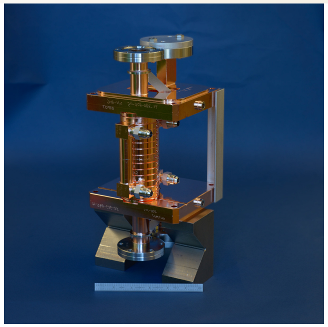


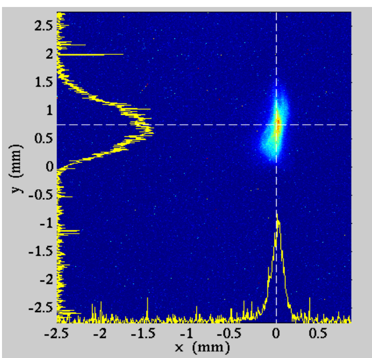
Q (pC)	5 pC	10 pC	30 pC	100 pC
ε_{95} (mm-mrad)	0.22(*)	0.32/0.28	0.47/0.43	0.7

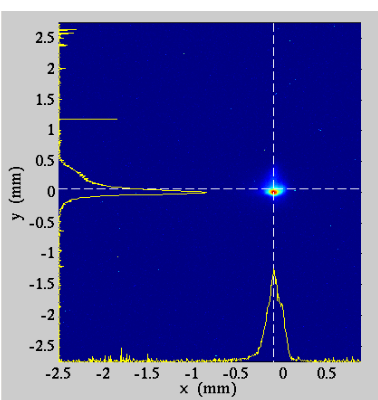
(*) after deconvolving by system resolution

Experimental Confirmation of Small Bunch Lengths
Record 300 A Peak Bunch Currents

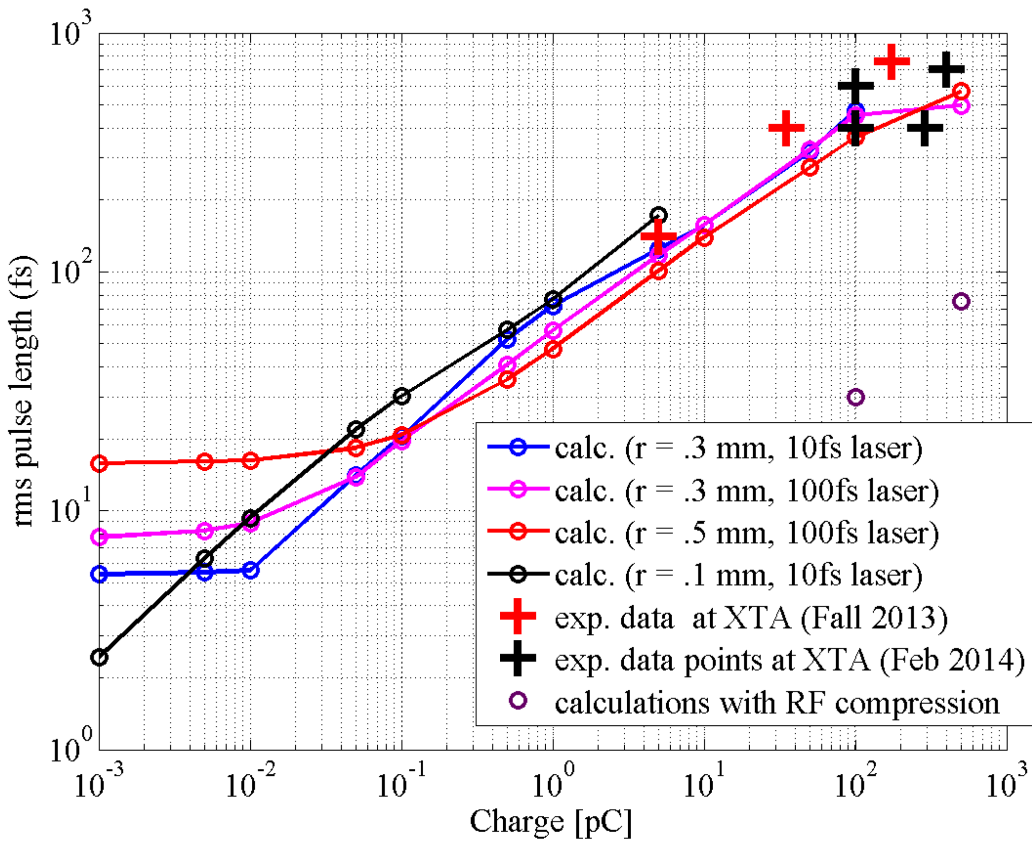
SLAC







Bunch length measured with X-Band transverse deflector powered with another RF station
Resolution of ~ 10 fs

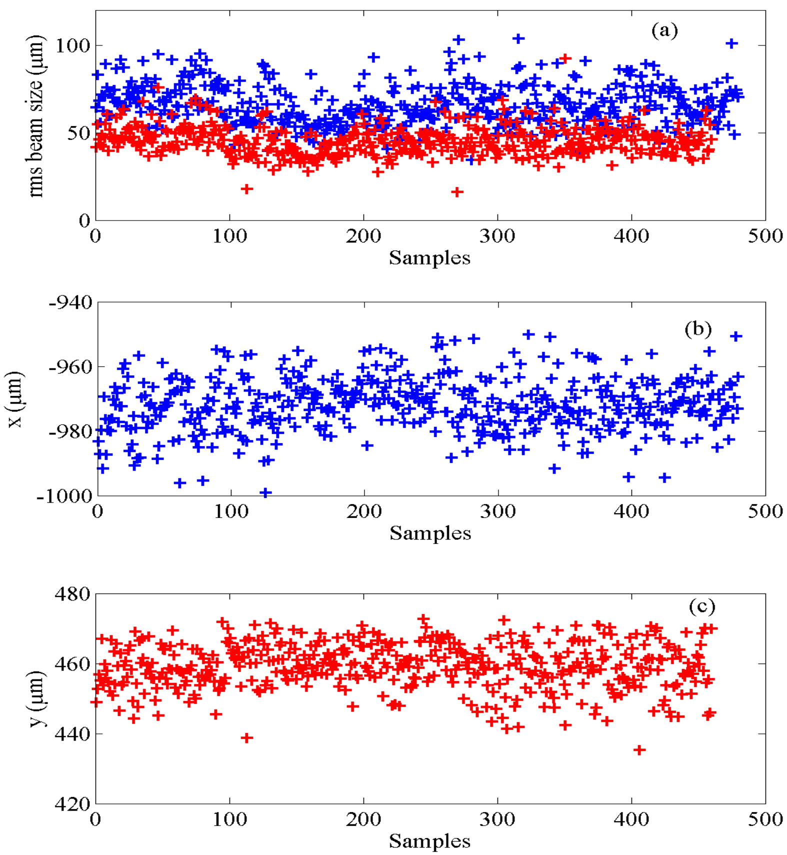


476 fs
at 270 pC
(300A)

Transverse Stability: Dominated by RF Power Jitter, Not Laser Position Jitter

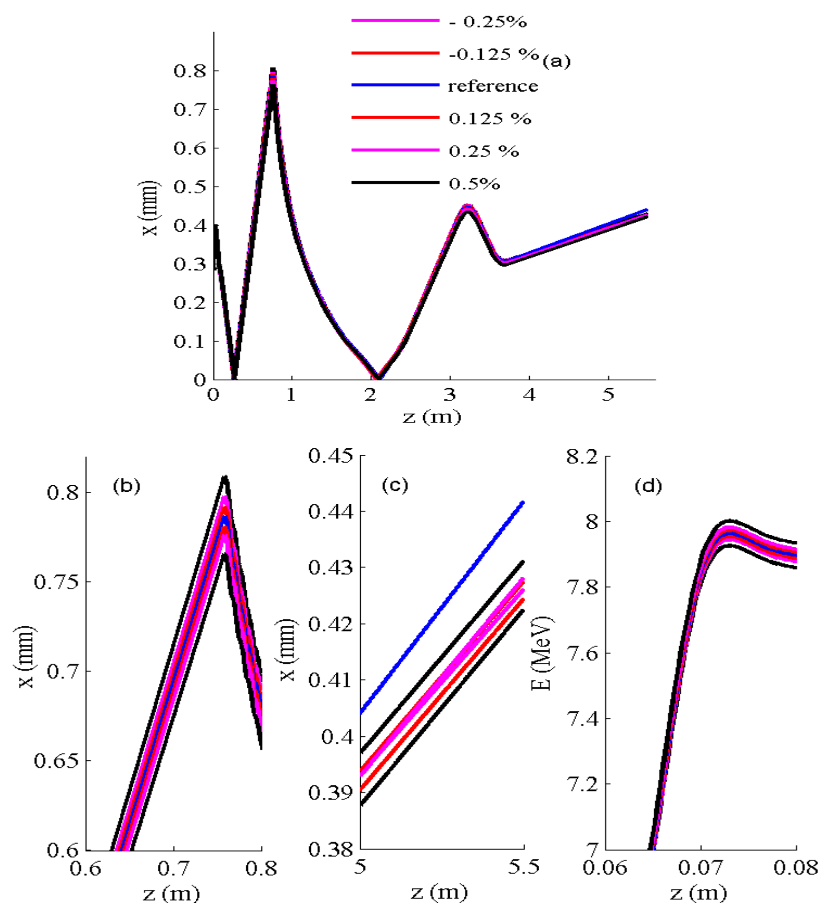
Experimental data

8.2 μm (H) , 6.5 μm (V) over 500 shots
ie 12.4% and 14.4 % of rms beam sizes



Simulations

$(\Delta V/V)_{rf,\ gun} \sim 10^{-3}$
$x_{\text{offset, laser}} = 300\ \mu m$
} $\Delta x = 20\ \mu m$



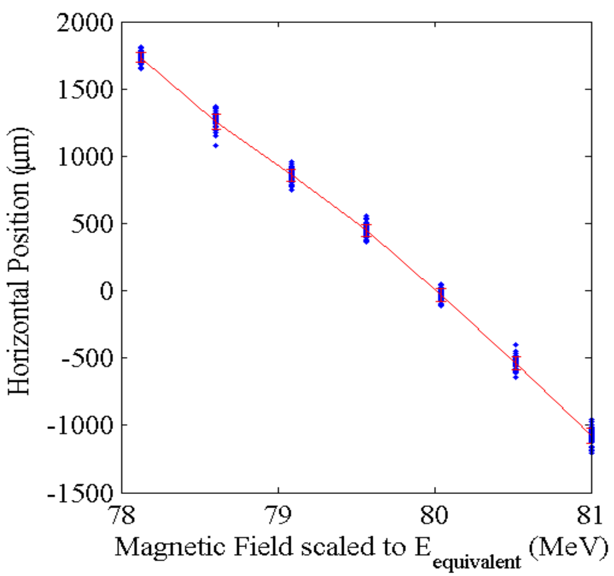
Energy Stability: Dominated by Modulator Voltage Jitter

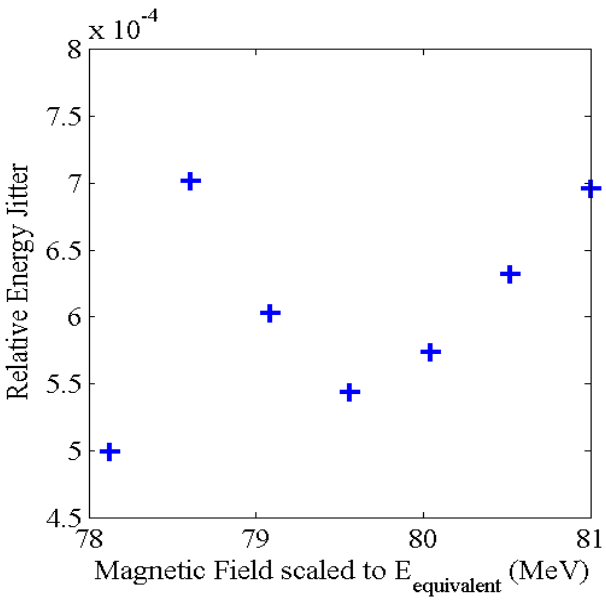
- Dominated by modulator HV

  175 ppm produces dΦ ~ 0.6 deg rms, dV_{rf} / V_{rf} ~ 3.10^{-4} rms

- Jitter always < 10^{-3} (even as low as a few 10^{-4} during quiet times)

  compared to energy spread 15 keV ~ 2.10^{-4}





Achievements

- Good Beam Quality for 1st Generation “Debugging” Gun
  - 1pC to 1.2nC reliably up to 85 MeV
  - Bunch lengths consistent with expected values
    - Peak current of 300 A for 300 pC bunches
    - 120 fs bunch length for 5pC
  - Emittance larger on Mark-0 but good on LLNL Mark-1
    - 0.7 mm-mrad transverse emittance at 100 pC / 100 A
    - 0.2 mm-mrad at 5 pC
    - Thermal emittance 0.9 mm-mrad per rms mm on sweet spots
  - QE low at 2.10^{-5}

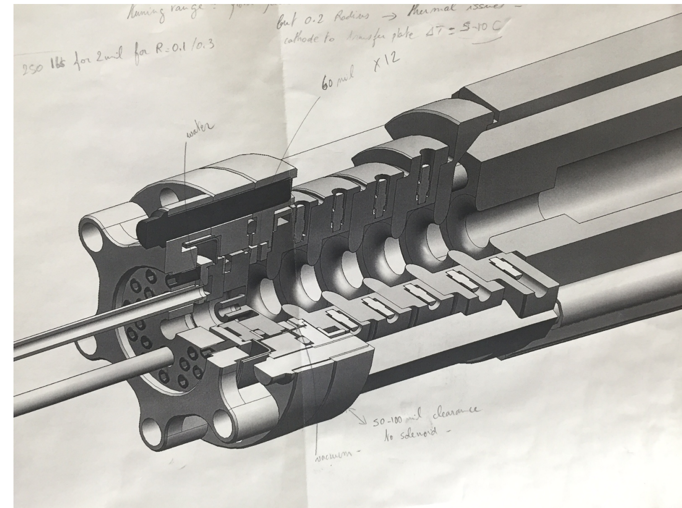
Mark-1 results at LLNL
0.3 mm-mrad at 80 pC
R.Marsh THPOW026

- Measured , analyzed and understood stability limits
  - Energy stability < 10^{-3}
  - Transverse stability < 15% beam size for sizes ~ 40 μm
  - Timing stability w.r.t. laser < 125 fs

Recommendations

To improve performance, we would

- Use demountable cathode gun
- Improve RF breakdown detection to limit damage
- Improve protection against high fluence laser pulses (both mechanical and software)
- For application requiring < 5 μm stability , work to get a 50 ppm modulator



Concept for a demountable 5.5 cell gun design

Would like to explore

- 3.5 cell gun (fewer modes, relaxed solenoid, helps laser injection)

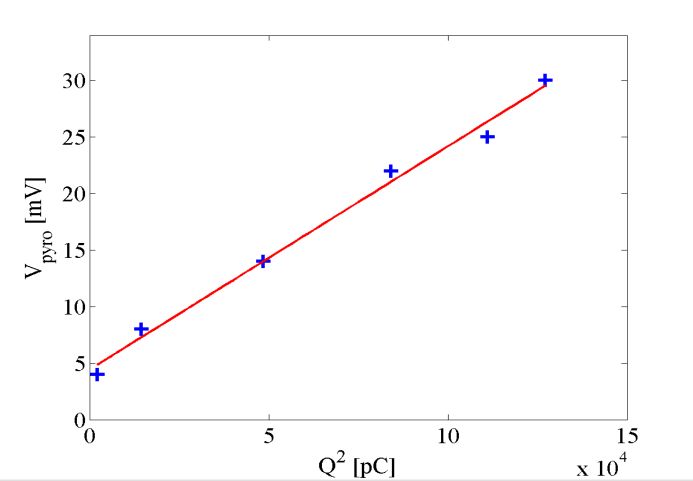
Other Studies at XTA

SLAC

Emission of coherent THz radiation from OTR

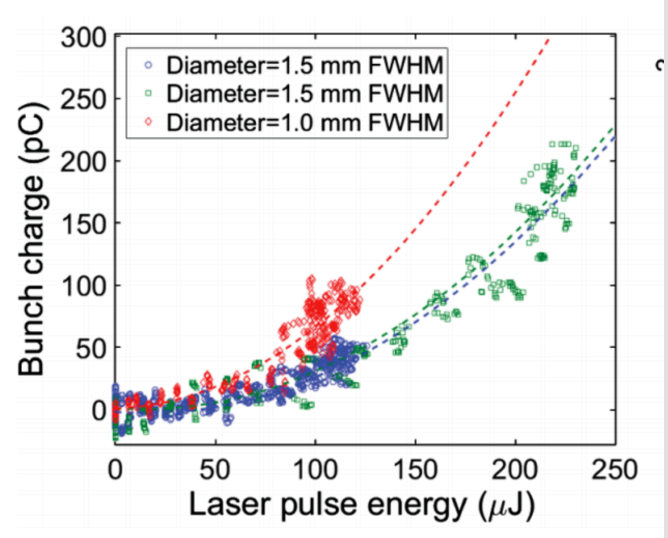
- Energy varies in Q^2
- Pulse energy ~ 4μJ

Confirmed indirectly 300A



2-Photon Photoemission with blue laser (400 nm)

- Q scales with E_{laser} ^2
- QE higher for 400 nm laser than for 266 nm for > 300 GW/cm^2

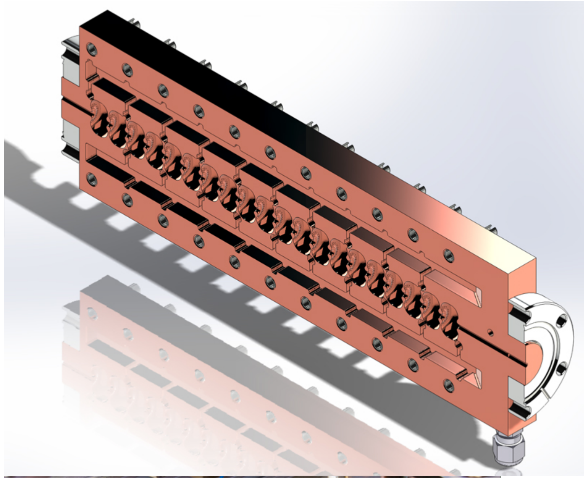


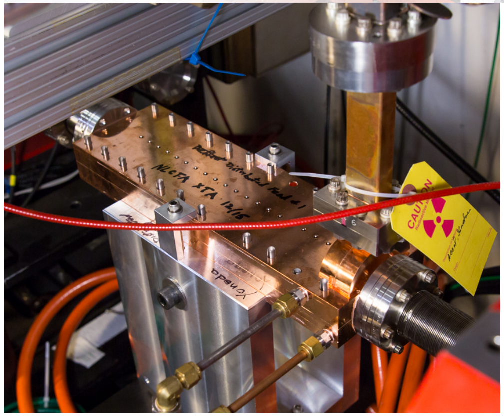
H.Li, PRAB 19, 023401 (2016)

Verification of Energy Gain
Very High Gradient, High Impedance RF Structures

TS06 structure
Only 2 pieces machined and brazed

High Z: 156 MOhms/m,
Aperture 2.7 mm
16 MW -> 25MeV gain (~98MV/m)
As verified with e-beam at XTA
To be conditioned to 32 MeV
(25MW, ~121 MV/m)

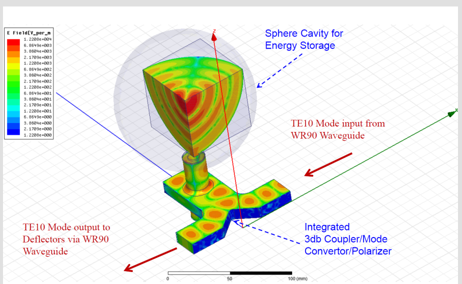




-> XTA now 115 MeV compact machine with high brightness e-beam

Towards a very compact injector
Compact RF Compressor / Klystrino

Compact SLED

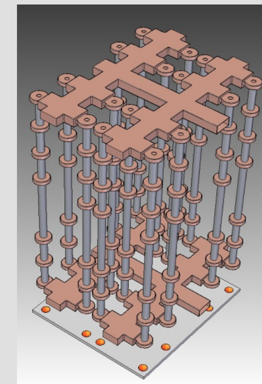


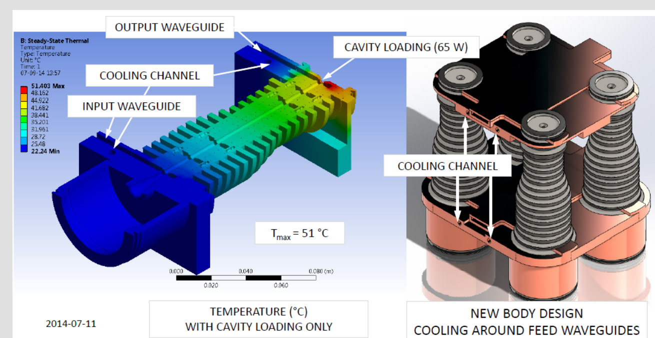
X4 demonstrated
100 ns ramp 300 MW and 150 MW

MOOCA01 ”R&D of a Super-compact SLED System at SLAC”, Juwen W. Wang, SLAC

“Klystrino”

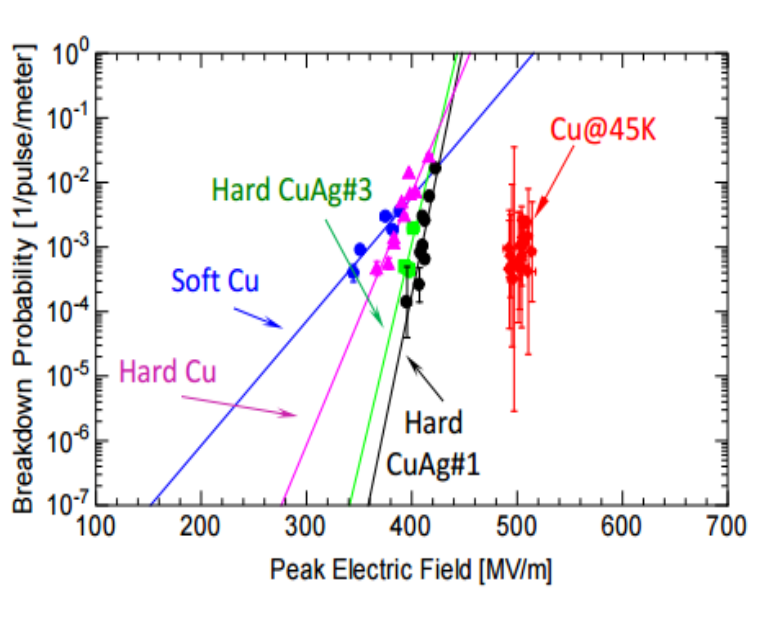
mini-tubes in parallel
power combiner
60kV PS (no oil)
focusing with PM
16 -> 5MW





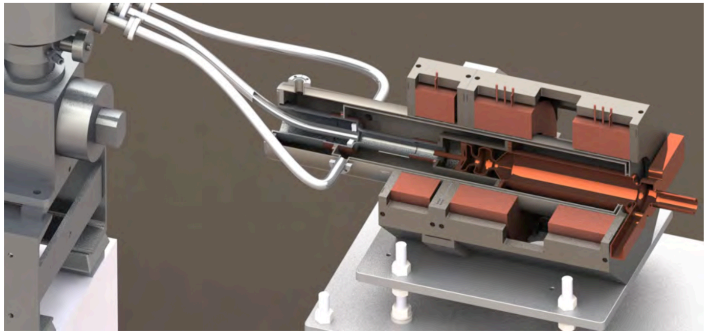
R&D Towards Even Higher Gradients

Cryo-cooled operation of copper cavities
-> 500 MV/m surface field



X-Band data
Courtesy S.Tantawi, V.Dolgashev

Cryo-cooled S-Band gun with
250 MV/m peak field



SLAC/UCLA collaboration
J.Rosenzweig et al,
Submitted Phys. Review Applied
March 2016-
http://arxiv.org/abs/1603.01657

Compact machines
Inverse Compton Scattering

LLNL (Existing)

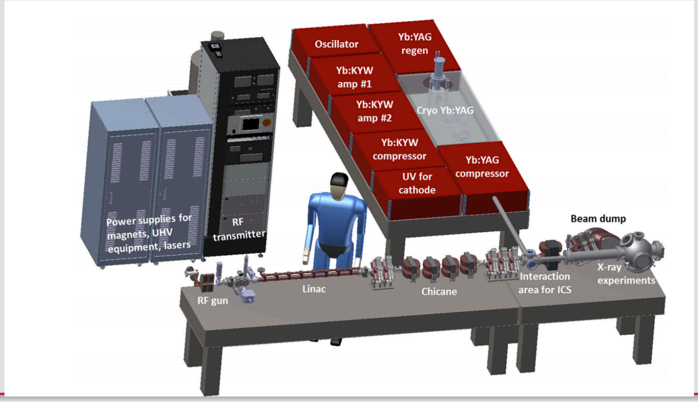
Based on SLAC X-Band technology

Producing 35 keV (2015)

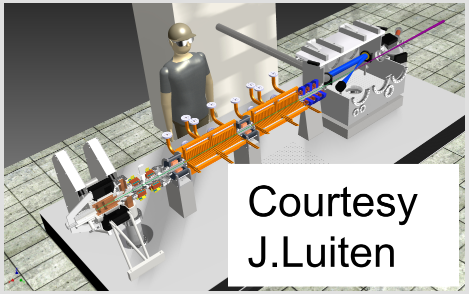
On track for 200 keV (later 2016)

MIT ASU machine 9.3 GHz
Coherent X-Ray from ICS
(planned for 2017)

W.Graves et al PRST-AB
17, 120701 (2014)



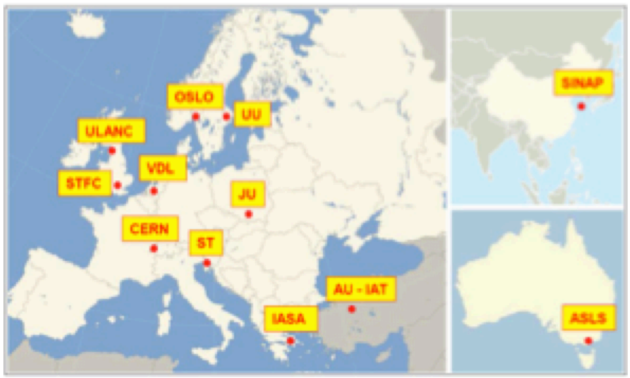
Eindhoven U.
VDL-ETG
12 GHz
(Initiated)



X-Band FEL Collaboration

The XbFEL Collaboration

The XbFEL Collaboration is an initiative among several International Laboratories aimed at promoting the development of X-band technology for the construction of the next generation FEL-based photon sources.



http://xbandfel.web.cern.ch/

ST	*Elettra - Sincrotrone Trieste, Italy.*
CERN	*CERN Geneva, Switzerland.*
JU	*Jagiellonian University, Krakow, Poland.*
STFC	*Daresbury Laboratory Cockcroft Institute, Daresbury, UK*
SINAP	*Shangai Institute of Applied Physics, Shanghai, China.*
VDL	*VDL ETG T&D B.V., Eindhoven, Netherlands.*
OSLO	*University of Oslo, Norway.*
IASA	*National Technical University of Athens, Greece.*
UU	*Uppsala University, Uppsala, Sweden.*
ASLS	*Australian Synchrotron, Clayton, Australia.*
UA-IAT	*Institute of Accelerator Technologies, Ankara, Turkey.*
ULANC	*Lancaster University, Lancaster, UK.*

June 21st face-to-face meeting at CERN

https://indico.cern.ch/event/521539

- *new funding opportunities (Horizon2020, Work Programme 2016-2017);*
- *extend collaboration to new partners.*

See also "Design Optimization of an X-band based FEL", this Conference MOPOW036

Courtesy G.D'Auria

CONCLUSIONS

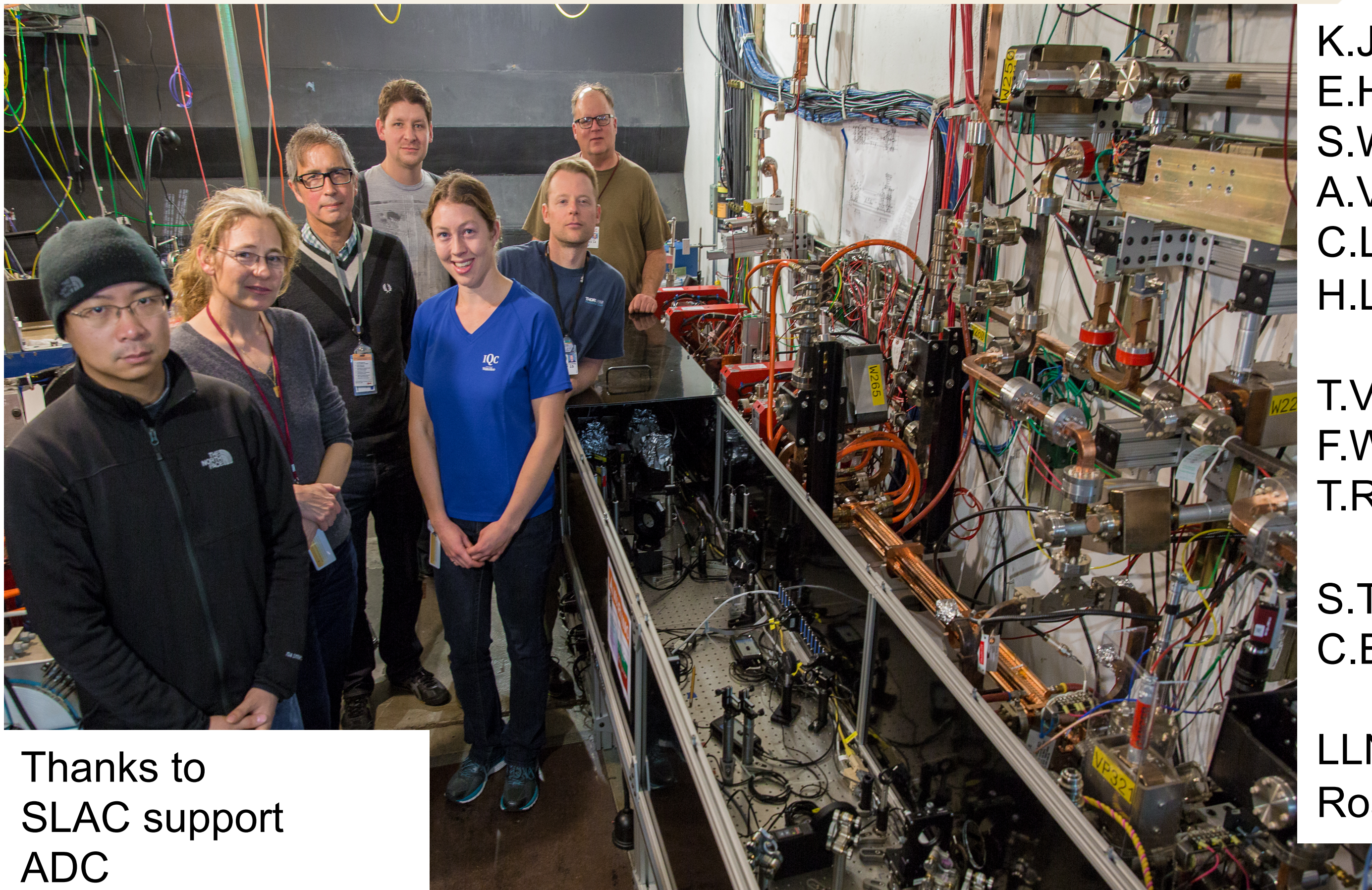
- Mark-0 gun at XTA delivers pC to 1.2 nC reliably

  with brightness equivalent to that of S-Band gun

  even with cathode damage
- Expected increase in brightness X10

  Achieved on Mark-1 at LLNL
- Recommend to design demountable cathode gun for R&D
- On the path to make systems very compact including power source
- Several ICS/FELs projects based on X-Band technology

Team, collaborators, acknowledgements



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