SLAC X-band Technology R&D

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DOE Briefing
June 11th, 2010
Introduction

• Overall ARD strategy
• ILC Program
• X-band program
  – Compact XFEL and other applications
  – Status and development needs
  – Proposed X-band technology & industrialization program
• Issues:
  – LC-X / ALC versus X-band rf
  – Rf technology development and stewardship
  – SLAC’s interface to rf industry
Primary Challenges for Accelerator R&D

1. Beam brightness and control → peak luminosity and radiation source brightness
   - Beam brightness → cost of radiation source; Users also becoming increasingly interested in flexibility of sources

2. Beam energy → energy reach or radiation wavelength
   - Critical problem for HEP requiring new cost-effective concepts
   - Novel concepts will enable new applications elsewhere as well

3. Beam power → average luminosity or brightness
   - High power beams needed in many applications although not always clear how to best utilize; energy efficiency becoming important

- Cost-effective approaches are needed across the field
- Paths to educate and attract more people to field
SLAC Accelerator R&D Strategic Plan

Five main objectives of ARD plan:

1. Maintain world-leading XFEL program with innovation and new concepts
2. Be the world-leader in high power rf systems and high gradient rf linacs
3. Be a world-leader in advanced accelerator R&D with focus on e+/e-
4. Support ongoing accelerator-based laboratory program
5. Have a renowned accelerator education program

<table>
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Support Science
Ongoing SLAC ILC Program

- Core elements of SLAC ILC program:
  - L-band rf development: Marx v1/v2 and DTI, couplers & rf distribution
  - High availability electronics and LC accelerator physics
  - MDI program and the ATF2 test facility

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SLAC ILC funding | 11815 | 9676 | 8017 | 4880 | 4330 | 2280 |

Covered with ARRA funding

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Why X-band Technology Program?  
(Broad Applicability and Core Capability)

- High gradient linacs are needed across the Office of Science
  - Normal conducting linacs are mainstay of many state-of-the-art projects due to lower cost, higher gradients and reduced complexity
  - High frequency linacs offer potential for higher brightness beams because high gradient fields allow better beam control
  - Niche applications include: rf linearizers for bunch compression, rf undulators for rapid (polarization) control, rf deflectors for high resolution phase space measurement, medical/industrial linacs, …
  - Could support low-cost compact linear collider as a step toward CLIC

- SLAC is the world leader in normal conducting linac design and rf systems
  - Core capability at SLAC not duplicated elsewhere in world
  - SLAC groups consulted for many challenging projects
X-band RF System Status

• X-band rf provides capability for 100 MV/m gradient
  – S-band is limited to about ~20 MV/m (SLAC is ~17 MV/m)
  – C-band is limited to about ~35 MV/m

• 2nd generation technology has been largely developed
  – 200+ M$ linear collider R&D effort from 1980’s → 2004
  – Extensive array of rf components have been developed
  – Rf power sources are main limitation

• NLC program ended without development of commercial suppliers or large-scale demonstration
  – Limited ‘penetration’ into accelerator community: linearizers and rf deflectors (C-band approach was quite different)
  – Significant interest in technology but need suppliers
X-Band & the XFEL opportunity

- Exciting science promise of XFELs being demonstrated now by LCLS
  - User demand is growing rapidly and first experiments look very promising
  - Number of XFEL’s is likely to continue to grow (e.g., normal conducting linacs being considered in Korea and China).

- With the low bunch charge being considered for future XFEL’s, X-band technology affords a low cost, compact means of generating multi-GeV, low emittance bunches.
  - Gradients of 70-100 MV/m possible vs ~ 20 MV/m at S-Band and ~ 35 MV/m at C-Band

- To expand X-band use, need to have components industrialized and a small demonstration accelerator built, similar to the 150 MeV C-band linac at Spring-8 in Japan where they have done light source studies.
Early science promise from LCLS

Photosystem-1 nanocrystal injected with water microjet
Early science promise from LCLS

Wide-angle scatter

Small-angle scatter
Applications Example: High Gain FELs

Current High-Gain FEL Projects (January 2008)

<table>
<thead>
<tr>
<th>Institution</th>
<th>BNL</th>
<th>DESY</th>
<th>SLAC</th>
<th>Elettra</th>
<th>Spring8</th>
<th>DESY</th>
<th>INFN</th>
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<th>SINAP</th>
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<td>Concept, Injector built</td>
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<td>Approved concept, Injector test facility (ITF)</td>
<td>Concept approval in 2010?</td>
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</table>

5. http://www.xfel.spring8.or.jp/
7. http://www.sparx.it/

- Comparable number of normal and super-conducting FEL sources
- High gradient needed in many cases due to compact site limitations
- To date, NCRF technology has been simpler and cheaper to implement (at least for small scale applications)
Why X-band Technology R&D? (High Power X-Band Applications)

- Compact linacs 100’s of MeV to many GeV linacs
  - SPARX 1-2 GeV X-Band linac for their FEL
  - LLNL 250 MeV linac for gamma-ray production
  - SLAC 600 MeV energy ‘dither’ linacs for LCLS II
  - LANL 6-20 GeV linac for an XFEL source to probe proton-matter interactions
  - SLAC study of a 6 GeV Linac for a Compact XFEL (CXFEL) source

- CLIC structure development

- Energy Linearizer for bunch compression
  - Single Structure: in use at LCLS, planned for BNL, PSI, Fermi/Trieste and SPARX/Frascati

- Deflecting cavity for longitudinal phase space diagnostics
CERN/CLIC X-band Test-Stand
(Under Construction)
Precision 250 MeV X-band Linac for MeV-Class Compton Scattering Light Source


LLNL, Livermore, CA 94550, U.S.A.


SLAC National Accelerator Lab, Stanford, CA 94025, U.S.A.
MEGa-ray 250 MeV X-band Linac
Existing RF Distribution Hardware

High Power RF Components

RF Vacuum Flanges and gasket

Pump-out

RF LOAD

Circular Guide Phase Shifter

Magic H Hybrid @ 600 MW, 1.435" height

H-hybrid Phase/Attenuator

Movable Short at circular ends

outputs
X-band Cost Optimization

- Working to improve cost estimates for X-band linacs
  - New engineer working on costing and cost optimization
- Expectation is X-band is ~50% cost of S-band and ~30% cost of L-band
  - Gather recent costing data from other projects
- X-band ~10M$ / GeV including tunnel
  - Assuming finished tunnel cost 25 k$/m, AC power + cooling power 2.5 $/Watt, and modulator efficiency 70%, klystron efficiency 55%
### Compact X-ray FEL (CXFEL)

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<th>Parameter</th>
<th>Symbol</th>
<th>$LCLS$</th>
<th>CXFEL</th>
<th>Unit</th>
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<td>250</td>
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<td>0.7</td>
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X-band Linac Driven Compact X-ray FEL

- Use LCLS injector beam distribution and H60 structure ($a/\lambda=0.18$) after BC1
- Transverse wakes have small impact due to short low charge bunches $\rightarrow$ tolerances of 1 mm rms
- Possible to operate in multibunch mode to feed undulator farm $\rightarrow$ effective rep rate of few kHz

LCLS-like injector
- $L \sim 50$ m
- $250$ pC, $\gamma\varepsilon_{x,y} \approx 0.4 \mu$m

X-band main linac+BC2
- $G \sim 70$ MV/m, $L \sim 150$ m

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Layout of Linac RF Unit
(All Existing Hardware)

- 50 MW XL4 Klystrons
- 400 kV Solid State Induction Modulator
- 12 m Dual-Mode SLED-II
- Utility Tunnel
- Linac Tunnel
- Nine T53 Structures (a/λ = 13%) or Six H60 Structures (a/λ = 18%)

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XL4 Klystron Issues

- Breakdown events that damage the output structure
- Lifetime limitation that are not understood
- An ac $\rightarrow$ rf efficiency of 45% and a solenoid efficiency of 50%

9 events occurred during 17 hrs running at 50 MW with 1.44 us pulse width
- Damage was observed

1. Autopsy klystron output sections; check for pulse tearing in current XL4s and build versions to test to destruction.
2. Power output section with rf to see if similar limits are found and compare to models from High Gradient program
3. Based on above, pursue (1) higher power, shorter pulse sources or (2) lower power multi-beam configurations
4. Examine use of SC solenoids vs PPM magnets
The X-band Technology Program
(A proposal to OHEP)

1. Develop conventional rf source for high gradient acceleration
   – 100 MV/m in X-band structures requires ~ 250 MW/m rf power
   – Present XL4 klystron spec’ed at 50 MW but has breakdown problems
   – Support research towards next-generation rf sources and distribution
   – Provides the complement to the High Gradient Struct. Collaboration

2. Industrialize klystron and other components in US industry
   – Main limitation to adoption of X-band technology is lack of industrial suppliers

3. Build 500 MeV X-band demonstration (2 rf units)
   – Demonstrate the fundamental technology for broad application across the Office of Science
   • Next step could be to construct 3 GeV demonstration
     – Expect engagement of a user group to support such activity
Klystron R&D Program

- Klystron development program proceeds in three iterations with industrialization in parallel
  1. Use XL4 to understand klystron limitations
     - Understand breakdown rate and lifetime limitations
  2. Optimize design for maximum sustainable power (XM-serries)
  3. Optimize focusing and output structure for high efficiency (XO-series)

- Each iteration will require building multiple klystrons
- Parallel Rf source research program on novel concepts
  - Maintain pipeline of new ideas
- Klystron R&D program is ~12M$
RF Component Industrialization

Presently SLAC is building:
- 5-XL5 (12 GHz) klystrons for CERN, PSI and Trieste
- 3-XL4 (11.424 GHz) klystrons for LLNL and BNL
- 2-XL4 klystrons for NLCTA operations at SLAC
- SLAC Klystron Department can produce ~1 tube every two months

Availability of the klystron is perceived as major limitation of X-band technology
- Critical to engage industry in klystron program as soon as possible

Other components:
- Pulse compression systems only require conventional machining
- Fermilab industrialized early X-band structures rapidly in 2002
- Modulators are already produced commercially

Industrialization program is ~10M$
Workshop with ~45 people attending from labs and industry: CPI, L3, Thales, Radiabeam, ScandiNova, DTI, INFN, KEK, CERN, CEA, LANL, LLNL, Tsinghua, UWis

- Clear need for much closer interaction with industry
  SLAC has much to offer and much to gain
Summary

- The 15 year, ~200 M$ development of X-band technology for a linear collider produced a suite of robust, high power components.
- Most hardware EXISTS.
  - The XL4 klystron (developed in 1992) is ~20% efficient and has limited reliability → develop new option.
- X-band technology affords a low cost, compact means of generating multi-GeV, low emittance bunches.
- To facilitate X-band use, components must be industrialized and a small demonstration accelerator built.
- X-band technology program would:
  - Enable compact low-cost linacs across the Office of Science
  - Strengthen SLAC role with rf industry and help bridge ‘the valley of death’
  - Maintain SLAC’s core competency in high power rf, a resource for the nation
- Could develop a complete proposal on fall timescale
Backup
Objective #1: World-leading XFEL program

- LCLS is world’s 1\textsuperscript{st} x-ray FEL
  - New sources under construction (Spring-8, DESY XFEL, …)
- XFEL and NGLS are designed to have higher beam power
  - Maintain LCLS advantage with flexibility, beam control and brightness

- Five strategic efforts aimed at XFEL objective
  - Strong beam and FEL theory effort
  - Improved high brightness injectors \& LCLS-II and upgrades
  - Development of novel beam handling and seeding techniques
  - High resolution diagnostics, timing and synchronization techniques
  - Development of high gradient and high rep rate FEL drivers
High Brightness Injector Program
Three Parallel Experimental Efforts

Cathode Test Facility
ASTA Facility
Photocathode R&D aimed at understanding LCLS lifetime and damage issues

LCLS-II Injector Incremental upgrade of LCLS-I with opportunity for R&D during commissioning

Injector R&D Program NLCTA Facility
Simulation and experimental program aimed at significant improvement in brightness

ASTA Facility
Est rf gun modifications before installation in LCLS-I or II

Longer term R&D aimed at high brightness cathodes with lower thermal ε (coatings, smoothness, new materials)

Construction in ~2014 and commissioning in ~2015

1) Design studies on rf gun design, CSR micro-bunching and cathodes
2) Rf gun development and testing at NLCTA in 2011
3) NLCTA R&D on injector beam physics
Rf Gun Development

- X-band rf gun has potential to enable compact linacs
  - Compact single-frequency linac compared with lower rf frequency
  - Higher brightness with ~ 3x higher peak currents for similar $\varepsilon$
  - Lower emittance at low charge (@thermal emittance dominated)
- Construct rf gun test stand in NLCTA and Cathode Test Area in ASTA

Rf Gun Development Diagram

- Rf Gun Test Stand
  - Quad triplet with steering magnets and BPMs
  - Accelerator Structure
  - Profile Monitor
  - Laser Ports
  - Steering Magnets
  - Bunch Charge Monitor
  - Gate valve
  - Input Waveguide (1 of 2)
  - Gate Valve Flange
  - Ceramic Window
  - Power Splitter
  - Water Cooling
  - Cathode
  - Pump-out Port

Rf Gun Test Beam Line

Rf Gun Detail
Objective #2: World-leading High Power Rf & Linacs

- High power linacs are critical element for most accelerators
  - Significant opportunities for further improvements
  - Technology to advance SLAC and world-wide program
- Normal conducting RF historical SLAC strength
  - Extensive infrastructure and expertise to support program
  - Developed infrastructure/technology for SCRF rf power systems
- Strategic efforts aimed at high power rf and linacs
  - Maintain excellent research program with transition into development
  - Pursue collaborations on X-band technology
  - Industrialize existing X-band rf components and demonstrate capability
  - Establish technology to support high gradient linac development
  - Expand SCRF power source R&D to support ERL and/or CW linac
X-band RF Development & Demonstration

- X-band rf provides capability for 100 MV/m gradient
  - S-band is about ~20 MV/m (SLAC is ~17 MV/m)
  - C-band is about ~35 MV/m
- 2\textsuperscript{nd} generation technology has been largely developed
  - 100+ M$ linear collider R&D effort from 1980’s 2004
- NLC program ended without development of commercial suppliers or large-scale demonstration
  - Limited ‘penetration’ into accelerator community: linearizers and rf deflectors (C-band approach was quite different)
  - Significant interest in technology but need suppliers
- Pursuing 3 opportunities at present: LLNL 250 MeV MEGa-ray linac, LCLS 600 MeV energy dither, 500 MeV LC X-band demonstration
Objective #3: World-leading Advanced Accelerator R&D

- Advanced accelerator R&D has transformational potential
  - SLAC has strong programs with different risks and timescales

- Strategic efforts aimed at AARD objective
  - Maintain leading experimental program in AARD
    - Use key facilities at ATF2, NLCTA, FACET, ASTA, CTF, …
  - High gradient beam-driven concepts
    - Plasma wakefield, dielectric wakefield, microwave two-beam acceleration
  - Direct laser acceleration
    - Focused program on innovative technology: accelerator-on-a-chip
  - High gradient microwave acceleration
    - Research near development that can impact the field
  - Beam physics
    - Key leadership in innovative beam manipulation and FEL physics
Plasma Acceleration has demonstrated 1000x the gradient of present acceleration techniques

- 50 GV/m in SLAC experiments
  - Accelerated beam to 84 GeV
  - Potential use for linear colliders and radiation sources
- FACET facility will be used to develop useful technique
Update on FACET
Facility for Advanced aCcelerator Experimental Tests at SLAC

- FACET: Test facility focused on plasma wakefield studies
- Made significant progress with construction
  - Nan Phinney, Jose Chan and John Sheppard taken over leadership
  - DOE CD2/3 review went well
  - Expect to start beam commissioning in May 2011
  - Project completion (CD4) is scheduled for February, 2012

- First FACET Users Meeting March 18-19, 2010
  - 40 participants (UCLA, ANL, BNL, LBL, Euclid Techlabs, USC, UT)
  - Working groups on: Plasma, Dielectrics, Crystals, Materials
  - Presented status and received feedback on requirements for experimental region and support
  - Plans started for proposal review – 1st submission this summer
Direct Laser Acceleration (E-163 Experiment)
Accelerator-on-a-chip

Direct laser acceleration is analogous to microwave-driven particle accelerators, with some key differences:

• Lasers produce radiation in very short pulses, allowing much larger electric fields without causing breakdown $\geq 1 \text{ GV/m}$ instead of $100 \text{ MV/m}$

• Since the wavelength is very short ($\sim 1 \text{ micron}$), the particle bunches produced are extremely short ($\sim 30 \text{ nm} \leq 100 \text{ attosecond}$) leading to applications in ultrafast science

• Much of the core technology required (lasers, optics, fibers, and semiconductor “chip” manufacture) is developed aggressively by industry

![Photonic Crystal Fiber](image1)

![Photonic Crystal "Woodpile"](image2)
High Gradient Microwave Acceleration

- Extensive R&D on breakdown limitations in microwave structures
  - US High Gradient Collaboration
  - CERN and Japan

- In the last few years:
  - X-band gradients have gone from ~50 MV/m loaded to demonstrations of ~150 MV/m with ~100 MV/m expected routinely
  - Greatly improved understanding of breakdown and limits