High Gradient Microwave Accelerators—Limits and Prospects

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Conference on the Application of Accelerators in Research and Industry
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Introduction

• Technology history
• Development status
  – Present status
  – Ongoing X-band technology & industrialization program
• Application studies
  – Compact linac example (MEGa-ray 250 MeV linac)
  – Compact XFEL optimization
  – Rf gun program
X-band rf Development

• SLAC began the X-band rf technology program in 1987
  – Path towards high gradient future linear collider
  – KEK joined development program in early 1990’s

• First generation technology built into NLC Test Accelerator in early 1990’s
  – 50 MW klystrons, SLED-II pulse compression, 1.8 meter structures
  – Limited by rf breakdown to ~40 MV/m

• Second generation rf system completed in 2004
  – Dual-mode SLED-II pulse compression, 60-90 cm structures, solid state modulators
  – Operated more than 2000 hr at >65 MV/m with 300 MeV acceleration
NLC Test Accelerator (X-band)

- Constructed in 1996 using 1\textsuperscript{st} generation NLC rf components
- Operated at \(~40\ \text{MV/m}\) with 41.8-m structures in 1997 (350 MeV)
- Primarily used for rf testing and high gradient studies since 2000
- Routine 24 hr operation >3500 hrs / yr
NLC/JLC Rf System (2004)

- 500 MW rf power, 400 ns rf pulses $\rightarrow$ 65 MV/m gradient
(475 MW, 400 ns Pulses Required)

Output Power
(Gain = 3.1, Goal = 3.25)

Combined Klystron Power
High Gradient Performance (2004)

5 Structures after ~500 hr of Operation and
8 Structure Average after >1500 hr of Operation

Graph showing breakdown rate at 60 Hz with 400 ns pulses vs. unloaded gradient (MV/m).

- Single Structures
- Eight Structure Average

NLC/GLC Rate Limit
High Gradient Microwave Acceleration (2010)

- 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
Measuring Breakdown Limits (2010)

- The combination of analytic modeling, simulation and experiments have made great progress in understanding

Doebert & Adolphsen

Tantawi & Dolgashev
Layout of Linac RF Unit
(All Existing Hardware)

Nine T53 Structures ($a/\lambda = 13\%$) or Six H60 Structures ($a/\lambda = 18\%$)
X-band RF System Status at Present

- 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

- 3rd generation technology is available now
  - 200+ M$ linear collider R&D effort from 1980’s
  - Extensive array of rf components have been developed
  - All components available with industry except klystrons

- NLC program ended without development of commercial suppliers or ongoing large-scale demonstration
  - Working to develop industrial suppliers
Accelerator Structures (Two Examples)

- H75 with full wake damping and slotted cells (75 cm long)
- >100 MV/m @ 150ns
- Operate with 50 ns bunch train – up to 1 Amp average current

- T53 with smaller a/λ is more efficient for lower charge at 100 MV/m
- No wake damping but 100 mA would be OK
Existing RF Distribution Hardware

**High Power RF Components**

- **RF Vacuum Flanges and gasket**
- **Pump-out**
- **RF LOAD**
- **Circular Guide Phase Shifter**
- **H-hybrid Phase/Attenuator**
- **Magic H Hybrid at 600 MW, 1.435\" height**

Movable Short at circular ends
X-Band and Future Opportunities

- 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 XFELs in Switzerland, Italy, 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
  - Can operate with single bunch or bunch train
- To expand X-band use, need to have components industrialized
- Building 250 MeV linac in collaboration with LLNL for ICS
- Looking for other opportunities to develop technology
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
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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X-band Cost Optimization

- Working to improve cost estimates for X-band linacs
- Expectation is X-band is ~50% cost of S-band and ~30% cost of L-band
  - Gathering 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%
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
  - Engaging industry in klystron program to increase production rate

- Other components:
  - Pulse compression systems only require conventional machining
  - Fermilab industrialized early X-band structures rapidly in 2002
  - Bay area companies produce all structure cells
  - Modulators are already produced commercially
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 $\epsilon$
  - Lower emittance at low charge (@thermal emittance dominated)

- Rf gun construction in collaboration with LLNL
Workshop on X-band RF Technology

Workshop on X-Band RF Technology for FELs

March 5, 2010
SLAC National Accelerator Laboratory
Menlo Park, California

First Announcement: WORKSHOP ON X-BAND RF TECHNOLOGY FOR FELs, to be held at SLAC on the afternoon of March 5, 2010 1:30PM - 5:30PM.

Following the Future Light Source workshop at SLAC (see FLS 2010), there will be a workshop on the afternoon of March 5 that will:

1) Motivate the choice of X-band (11.4 GHz or 12 GHz) rf technology for a compact XFEL

2) Review the progress at SLAC and other labs in developing and manufacturing X-band components: modulators, klystrons and accelerator structures

3) Provide a forum for vendors to present their X-band production capabilities.

The goal is to generate a broader interest by labs to develop compact X-band based FELs as an evolution beyond the current S-Band and C-band systems. We particularly encourage vendors to attend to help motivate this process.

Workshop with ~45 people attending from labs and industry: CPI, L3, Thales, Radiabeam, ScandiNova, DTI, INFN, KEK, CERN, CEA, LANL, LLNL, Tsinghua, UWis
Summary

- The 15 year, ~200 M$ development of X-band technology produced a suite of robust, high power components
  - Most hardware EXISTS
- X-band technology affords a low cost, compact means of generating 100 MeV – multi-GeV, low emittance bunches.
  - Operate with single or multi-bunch train at >120 Hz
- Working on X-band rf gun technology to support high brightness (single rf frequency) compact linacs
- To facilitate X-band use, components must be industrialized and a small demonstration accelerator built
- Working with LLNL to build 250 MeV linac for MEGAray
  - Looking for other opportunities to demonstrate technology
Extra
High Performance Computing

DOE Computing Resources:

NERSC at LBNL - Franklin Cray XT4, 38,642 compute cores, 77 TBytes memory, 355 Tflops

NCCS at ORNL - Jaguar Cray XT5, 224,256 compute cores, 300 TBytes memory, 2331 Tflops, 600 TBytes disk space

Track3P: dark current simulations

Dark current @ 3 pulse risetimes

- 10 nsec
- 15 nsec
- 20 nsec

Track3P: dark current simulations

Red: primary; Green: secondary

Data

Fig. 7. Pulse shapes of section input, of the RF pulse for 30-cavity TW section tests.
Breakdown Modeling

- Rf breakdown common problem:
  - Accelerator designs
  - Fusion physics
  - Satellite systems
  - Industry

- Analytic and simulation modeling compared with experiments

![Graph showing simulated and measured data with a scale of 50 nm and 10 µm.]
Measuring Breakdown Limits

- The combination of analytic modeling, simulation and experiments have made great progress in understanding

![Graphs showing breakdown limits](image)
Understanding Accelerator RF Materials

RF Cavity for $\Delta T$ Studies

Investigating Cu and Cu-alloys, Mo, Ti, ...

Intergranular fractures 500X
## Compact X-ray FEL (CXFEL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>( L_{\text{CLS}} )</th>
<th>( \text{CXFEL} )</th>
<th>Unit</th>
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<tr>
<td>Bunch Charge</td>
<td>( Q )</td>
<td>250</td>
<td>250</td>
<td>pC</td>
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<tr>
<td>Electron Energy</td>
<td>( E )</td>
<td>14</td>
<td>6</td>
<td>GeV</td>
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<td>Emittance</td>
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<td>0.4-0.5</td>
<td>( \mu )m</td>
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<td>Undulator Period</td>
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<td>Mean Und. Beta</td>
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<td>Sat. Length</td>
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<td>30</td>
<td>m</td>
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<td>Sat. Power</td>
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<td>GW</td>
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<tr>
<td>Photons/Pulse</td>
<td>( N_\gamma )</td>
<td>2</td>
<td>0.7</td>
<td>( 10^{12} )</td>
</tr>
</tbody>
</table>
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