RF and Electronics Research in Accelerator Research Department-A

Presented by Sami G. Tantawi for the High Power RF Group, the Accelerator Structure Group and the Electronics Research Group
High Power RF Group

- Sami Tantawi
- Christopher Nantista
- Valery Dolgashev
- Perry Wilson
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Our group goals is to advance the state of the art of high-power rf components and sources. These include:

1- Ultra-High-Power RF components at X-band frequencies and higher
2- Passive Pulse compression systems
3- Active RF components
4- Active Pulse compression systems
5- RF components and analysis codes for microwave tubes
6- RF components and analysis codes for Accelerator structures
7- Experimental and theoretical studies of RF breakdown phenomenon in high vacuum structure.
Dualmode Resonant Delay lines ~30m

RF Input to the 4 50 MW klystrons

Single mode waveguide input to the pulse compression system; 100 MW/Line for 1.6 µs

Compressed output > 600 MW 400 ns.

Output Load Tree

NLC experimental rf pulse compression system

Dual mode waveguide carrying 200 MW

RF Input to the 4 50 MW klystrons
The Head of the pulse compression system

- **TE\(_{01}/TE_{11}\) to loads**
- **TE\(_{01}\) to delay Lines**
- **Super Hybrid**
- **Pumpout**
- **Dualmode directional coupler**
- **Dualmode Combiner**
- **Two fundamental mode inputs**
Dualmode Rectangular-to-Circular Taper
Sled Head Design: Basically three planer hybrids on one single substrate
Sled Head Simulations

TE\textsubscript{20} straight through MSLED-II with copper losses:

@ 516 MW,

|E\textsubscript{max}| = ~45.8 MV/m

|H\textsubscript{max}| = ~156 kA/m

TE\textsubscript{10} straight through

with copper losses:

\begin{tabular}{cccc}
(P 1 M 1) & (P 1 M 2) & (P 2 M 1) & (P 2 M 2) \\
0.0020 & 0.0110 & 0.9999 & 0.0008 \\
0.0110 & 0.0077 & 0.0009 & 0.9999 \\
0.9999 & 0.0008 & 0.0020 & 0.0110 \\
0.0008 & 0.9999 & 0.0110 & 0.0077 \\
\end{tabular}
Dualmoded SLED-II Performance
December 4, 2003 11 am
$\text{TE}_{01}$-Input $\text{TE}_{01}$-Output
Low-Level RF Architecture

 PLL to 11.424 GHz
 Bi-phase Modulator
 IQ-Modulator
 Timing Switch
 Voltage-controlled Switch

 119 MHz

 AFG 1

 Computer
 Data Acquisition

 From High Power rf measurements

 Klystron 1
 Klystron 2
 Klystron 3
 Klystron 4
Multimoded SLED-II output with feedback

- **Input**
- **Output**

**Graph Description:**
- The graph plots Power (MW) against Time (µs).
- The black line represents the **Input**.
- The blue line represents the **Output**.
- The graph shows a sharp increase in output at approximately 1.5 µs, followed by a sharp decrease.

**Note:**
- Sami Tantawi (1/27/2004)
Conclusion:

• We have introduced a fully dual mode rf system.

• We have shown design and experimental data for over moded components that propagate two modes at the same time. These components perform all possible functions found in single moded rf systems.

• At the operating frequency of 11.424 GHz, the peak electric field is \( \sim 49 \text{ MV/m} \) (400 ns) and the peak magnetic field is \( \sim 0.17 \text{ MA/m} \) (400 ns). This should be low enough for a reliable high power operation of the system (remain to be seen).

• We have invented several new measurement techniques and instrumental components needed for characterizing dual moded rf systems.
• Dual-mode rf pulse compression system achieved peak power of about 580 MW; 130% of NLC spec.

• Dula-moding reduce delay-line length by 50%.

• Modular multimode components allow multiple pulse compression configurations.

• Overmoded components keep electric field < 49 MV/m and Magnetic Field < 0.17 MA/m at power levels of 600 MW.

• The system had 14 trips due to the overmoded system after 39 million pulses at 400 ns and above 500 MW.

8-Pack Phase 2 Power Distribution

- 6 dB directional coupler
- 4.8 dB directional coupler
- 3 dB directional coupler
- hybrids
- structures
New Development of RF Components, 

**More Precession and Looser Tolerances**

Height taper and rectangular (0.8 inch height) to circular mode converter, length 112.41 mm

Electric field, max. 24.2 MV/m for 100MW input power

Magnetic field, max. surface field ~50 kA/m

Tolerance analysis: length of “elliptical” part and rectangular part are ±0.1 mm for mode conversion < 50dB
Waveguide high gradient study

Goals:

• RF breakdown vs. geometry (low magnetic field waveguide vs. high magnetic field waveguide); same electric field for same peak power and surface area
• Different materials: copper, gold, stainless steel, molybdenum
• 3D Particle-In-Cell simulations of the breakdown dynamics

Low magnetic field waveguide, height 10 mm

High magnetic field waveguide, height 1.3 mm

Light spectrum measured during breakdowns in copper waveguide

Measurements, 24 April 2001, 18:13:40, shot 45

3D PIC simulations, 4x4 mm emitting spot, electron current 7kA, copper ion current 30A

Maximum breakdown electric fields for different materials

S. Tantawi and V. Dolgashev
Single cell traveling (TW) and standing wave (SW) structure 11.4 GHz high gradient study

Goals:
• RF breakdown vs. circuit parameters (SW vs. TW)
• RF breakdown vs. different surface processing technique (etching, baking)
• RF breakdown vs. different materials: copper, molybdenum, molybdenum-copper

Electric field lines in single cell traveling wave structure

Electric field lines in single cell standing wave structure

Bead-pull measurements of single cell TW structure

S. Tantawi, V. Dolgashev, C. Nantista (SLAC), Y. Higashi, T. Higo (KEK)
Beam image on a spectrometer-beam-profile-monitor

Before breakdown

Profile of the beam during breakdown pulse, horizontal shift dominated by the spectrometer dispersion

28_May_04_4:43, Chris Adolphsen, Steffen Doebert
3D PIC simulation of a breakdown in single-cell TW structure, emission from downstream side of the first iris (cell breakdown)

Video capture of a breakdown event in SW20PI,
Marc Ross, Douglas McCormick
August 2001
Breakdown currents and beam, 3D PIC simulations
Compact Delay Line development

\[
\begin{align*}
D_g &= 6.725” \\
T &= 0.1” \\
D_i &= 3” \\
P &= 8.500”
\end{align*}
\]
Wrap-Around Mode Converter for Tap-off, and extraction, tested to 470 MW
Experimental Setup for the high power testing of nonreciprocal overmoded device
Semiconductor High-Power High Frequency rf switches

• Overmoded structure, spatially combined devices

• Tested to 13 MW/device at X-band

• Solved the contact problem

• The speed of the switch is still an open question
Beam Diagnostics Structures

Beam quadrupole moment monitor for emittance measurement developed with Far-Tech, Inc. in SBIR collaboration:

Quad cavity magnetic field pattern.

Geometry of Quad cavity and waveguide circuit.

Signal mapped around axis with NLCTA beam.

Follow-up collaboration with Far-Tech, Inc. proposed to develop and test prototype of their multi-cell structure design for measuring quadrupole and dipole (BPM) moments.

C. Nantista
Last year
Our development of ultra-high-power RF components and pulse compression systems lead to the a successful demonstration of an RF system suitable for NLC

This year
1- Continue our development of RF components for NLC by adding a distribution system to the current RF pulse compression system

2- Converting two of the NLCTA station into dual-moded pulse compression system

3- We are performing a series of experiments on active RF components which we expect to push the state of the art of semiconductor rf switches and nonreciprocal Ferrite switches by a few orders of magnitude

4-We are performing a series of experiments on single cell Traveling wave accelerator structures to understand the breakdown phenomenon and the role of materials in determining the limits on high gradients.
RF Structures Group

• Juwen Wang
• Gordon Bowden
• Roger Miller

• Roger Jones
• Jim Lewandowski
Mission for RF Structures Group

Mission

We design, engineer and test accelerator structures for future linear colliders operating under extremely high gradient conditions with superior properties in higher modes suppression.

The activities

• Accelerator Theoretical Studies.
• Simulation and Computer Aided Accelerator Design.
• Mechanical Design.
• Fabrication Technologies Studies.
• Microwave Characterization.
• High Power Experiments.
- Design, fabrication and tuning of nine testing accelerator structures for high gradient test at NLCTA.
- NLC prototype structures R&D.
  - Design optimization for efficiency and high gradient performance.
  - HOM studies: Design simulation and microwave measurement.
  - Trapped mode studies: Simulation and microwave measurement confirmation.
- Redesign of accelerator cavity for finalized NLC structures.
- Theoretical studies in beam dynamics issues related to frequency and alignment tolerances due to high order dipole wakefields.
- Wire measurement of wakefields for multi-cell accelerator structures.
- Ten structure related publications.
Comparison of maximum iris surface field for different structure designs at an unloaded gradient of 65 MV/m. The red curve is for H60VG3N ($a/\lambda=0.18$), which has rounded shaped irises – the others have elliptical shaped irises, which lowers the peak field. This structure also has a reduced field in the first several cells. The green curve is for H60VG3S18 ($a/\lambda=0.18$), which shows the effect of the elliptical shaped irises. The light blue curve is for H60VG3S17.
### Basic RF Parameters of NLC Prototype Structures

<table>
<thead>
<tr>
<th>Structure name</th>
<th>HDDS (H60VG4SL17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure length</td>
<td>62 cm (including couplers)</td>
</tr>
<tr>
<td>Number of acceleration cells</td>
<td>53 cells + 2 matching cells</td>
</tr>
<tr>
<td>Average cell iris radius</td>
<td>$&lt; \frac{a}{\lambda} &gt; = 0.17$</td>
</tr>
<tr>
<td>Phase advance / cell</td>
<td>$5\pi/6$</td>
</tr>
<tr>
<td>Group velocity</td>
<td>4.0 ~ 0.9 % speed of light</td>
</tr>
<tr>
<td>Attenuation parameter $\tau$</td>
<td>0.64</td>
</tr>
<tr>
<td>Filling time</td>
<td>118 ns</td>
</tr>
<tr>
<td>Q value</td>
<td>7000 ~ 6500</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>51 ~ 68 M$\Omega$/m</td>
</tr>
<tr>
<td>Coupler</td>
<td>Wave Guide type</td>
</tr>
<tr>
<td>1st Band dipole mode distribution</td>
<td>Sech$^{1.5}$ distribution with $\Delta f \sim 11% (4\sigma)$</td>
</tr>
<tr>
<td>$\frac{E_s}{E_a}$</td>
<td>2.22 – 2.05</td>
</tr>
<tr>
<td>Required input power</td>
<td>59 MW</td>
</tr>
<tr>
<td>Gradient without beam $&lt;E_0&gt;$</td>
<td>65 MV/m</td>
</tr>
<tr>
<td>Beam loaded gradient $&lt;E_L&gt;$</td>
<td>52 MV/m</td>
</tr>
</tbody>
</table>
Envelope of Wake for Four-Fold Interleaving of GLC/NLC X-Band Accelerating Structures

Each dot represents the location of a particular bunch in the train of 192 bunches.
High Gradient Structure Development

- Designed, fabricated and tested 34 structures with over 20,000 hrs of high power operation.
- Improved structure preparation procedures - includes various heat treatments and avoidance of high rf surface currents.
- Found lower input power structures to be more robust against rf breakdown induced damage.
- Developed ‘NLC/GLC Ready’ design with required wakefield suppression features – it is 33% as long (60 cm) and requires 40% of the power of the 1.8 m design.
Structure Fabrication at SLAC

Ready for Final Braze

After Braze
HOM Coupler Design and Microwave Measurement
Optimized accelerator cavities for future NLC structures

To improve the shunt impedance of the structures by 10 to 15%, a structure incorporating rounded cells is being studied and several test cups will be machined and tested in the coming year. Pictures show two types of proposed symmetric accelerator cups: full rounded cavity (left) and leek-head cavity (right).
Wire Measurement of Wakefields

- Using a 300-micron thick brass wire, measurements of the structure S-parameters are made to compute the impedances for the monopole band and higher dipole mode bands.

- The test results for a standing-wave structure, a short traveling-wave structure, and the RDDS1 structure show a reasonable agreement with computer simulations.
Advanced Electronics Group, ARDA

L. Beckman, J. Fox, T. Mastorides, D. Teytelman, D. Van Winkle, Y. Zhou
GBoard 1.5 GS/sec. processing channel

- Next-generation instability control technology
- SLAC, KEK, LNF-INFN collaboration - useful at PEP-II, KEKB, DAFNE and several light sources.
- Transverse instability control
- Longitudinal instability control
- High-speed beam diagnostics (1.5 GS/sec. sampling/throughput rate)
- Builds on existing program in instability control and beam diagnostics.
- Significant advance in the processing speed and density previously achieved.
- US-Japan Cooperative Project
PEP-II fast impedance control loops - Limitations of cavity impedance control due to klystron saturation

A major effort by the group involves understanding the high-current instability limits in PEP-II. Our machine physics measurements have led to a better understanding of the limitations of impedance control in the PEP-II RF systems. Due to klystron saturation a linear impedance control model is not applicable.

For the HER at 1 A the growth rates rise from linear prediction of 0.12 ms\(^{-1}\) to actual 1-1.8 ms\(^{-1}\).

These high growth rates were limiting HER currents above 1380 mA.

We are attacking this limitation through a new RF woofer channel in the longitudinal feedback paths, and a novel klystron linearizer within the low level RF processing.
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Grow/damp measurements for the low modes

During these measurements we turn off both wideband (LFB) and narrowband (LGDW) channels.

Measures open-loop growth and closed-loop damping for the fundamental driven modes.

Due to optimized gain partitioning the system can recapture beam motion at larger amplitudes. For the grow/damp measurements this allows longer growth intervals and better SNR.

Larger dynamic range of the new woofer will allow it to handle significantly larger beam transients due to injection, RF, etc.
HOM growth and damping rates

Taken at 2x the normal operating gain

Growth rate of 0.2 ms\(^{-1}\) and damping rate of 0.17 ms\(^{-1}\).

Very little margin, especially at the nominal gain.

A separate LGDW allows the wideband channel to run at this higher gain providing better HOM control.
LGDW Commissioning summary

This prototype has been tested twice for development MD efforts - it was commissioned in May 2004 and is now run as part of the HER machine configuration.

Commissioning in the HER involved:

• Woofer channel setup and control filter tuning
• Gain partitioning optimization
• Growth and damping rates for the low modes
• Growth and damping rates for the HOMs
• Fine tuning of the broadband filter parameters for best partitioning between LGDW and broadband feedback, especially as they interact for the low modes.

The low group-delay woofer was tested up to 1550 mA.

Prior to this LGDW commissioning we were limited to 1380 mA with very tight operational margins - running with 1 -3 longitudinal aborts per day.
Klystron linearizer: block diagram

We have started a study to develop a technique to improve the impedance control. Compare the input of the klystron and the output, use amplitude modulator to make the two match. Linearizes the klystron so that large- and small-signal gains are identical. Feedback does increase the effective klystron delay.

Has been simulated, currently testing a bench prototype. We plan to test this idea on one of the PEP-II LER stations before the shutdown.
Dc power levels - klystron model and linearized output

SPECTRUM
A: RL
10.00 dBm

Klystron Model
Open Loop

DIV
2.000

RBW = 200 Hz
START = -13.0 dBm

START STOP

RANGE : R = 0. T = 10 dBm

13.0 dBm
7.0 dBm

Att1 = 5.75 dB
Att1 = 4 dB
Att1 = 7 dB

Significant accomplishments related to PEP-II high-current commissioning -

- Development and installation of the prototype low group delay woofer. Tests show the channel increases the stable stored current in the HER from 1380 to 1550 (plus) mA.
- Machine development related to measurement and control of coupled-bunch bunch instabilities - studies of transverse and longitudinal stability margins, identification of more optimal configurations for transverse feedback stability.
- Continued analysis of the low-level RF systems and feedback stability, understanding of RF saturation effects on impedance control. Development of klystron linearizer idea, possible applicability of single sideband comb architecture in PEP-II LLRF systems.
- Transfer of system level knowledge of PEP-II RF to accelerator physicists and operations group via formal 2 day RF tutorial (over 48 participants). Development of fault file analysis tools, techniques to better configure RF systems. Selection and recruitment of new SLAC staff with RF engineering expertise to strengthen expertise in this area.

GBoard Processing Channel

- Continued design and development of the 1.5 gigasample (GBoard) processing channel (joint development project with KEK and LNF-INFN). Simplification of ECL high speed mux-demux functions into FPGA based reconfigurable logic, initial lab tests of high speed links between ADC and FPGA components in this scheme.

Goals for 2004/2005

- Commissioning of Gboard 1.5GS/sec. baseband channel, initial tests at PEP-II and other facilities
- Lab and Accelerator tests of the prototype klystron linearizer
- Commissioning of the production low group delay woofer channels for HER and LER
- High-Current PEP-II stability analysis and technology R&D for increased currents and luminosity