A CW L-Band Micro-Pulse Klystron

Frederick Mako, Ph.D., PI
Edward Cruz, Ph.D.,
Frederick Mako III, and
Linton Floyd, Ph.D.

August 8-9, 2017

DOE, Office of Nuclear Physics, SBIR/STTR Exchange Meeting

FM Technologies, Inc., Chantilly, VA, USA
FMT Capabilities

- Founded in 1987, FM Technologies, Inc. (FMT) is a technology company with expertise in: charged particle beams, particle accelerators, plasma physics, electron/ion/microwave beam interaction with materials, microwave source development, pulsed power, and integration of these areas.

- FMT has several projects approaching the commercial development stage:
  - Ceramic/Ceramic & Ceramic/Metal joining for use in high temperature chemical conversion processes
  - Self-Bunching Electron Guns with/without Current Amplification for RF Accelerators and RF sources
FMT Facilities/Equipment

- Headquartered in Chantilly, VA, FMT has 10,000 ft² of laboratory and office space available.

- Offices equipped with multi-core workstations with a variety of simulation and design software.

- Laboratory has a full machine shop & plasma processing equipment:
  - Conventional & CNC lathes with high speed tool post grinder
  - Conventional & 4-axis CNC milling machines
  - Grinding and sanding equipment
  - Acetylene, arc and spot welders
  - Plasma cutting torch, RAM EDM
  - Vertical & horizontal band saws
  - Diamond saws
  - Small (digital) & large drill presses
  - Microwave assisted chemical vapor deposition system
  - RF and DC 3-gun sputtering system
  - 2473K brazing/joining furnace
FMT Facilities/Equipment

- **Experimental hardware owned by FMT includes:**
  - Pulsed Power Electron Beam and RF sources
    - Electron Beam System (1MV x 40kA x 0.1μs)
    - L-band (0.5 and 5 MW pulsed)
    - S-band (0.8, 1, 2.6 and 13 MW pulsed; 1, 2 & 6 kW CW)
    - X-band (0.25, 0.75 & 1.5 MW pulsed)
    - Broadband Amplifiers (50-2500 MHz, 50-900W CW)
  - MEIJI optical microscope w/ video out (400x, 2.5μm resolution)
    - Oscilloscopes
      - Ten 100-400MHz digital scopes
      - One 50GHz sampling scope
    - Pulsed & DC magnetic coils to 2T
    - Cryo pump
    - Nine vac-ion pumps, 2-400 L/s
    - Seven turbo pumps, 60-400 L/s
    - Fourteen roughing pumps
    - 1.5 MJ Capacitor bank
  - High-power RF components
    - Circulators L-Ka
    - Isolators L-X
    - Phase/amplitude adjusters
    - 0.1-1 MV pulse modulators
  - Chemicals and glassware
  - 0.1-100kW Power supplies and other test equipment and electronics
Project Rationale and Approach

- Conventional CW Klystrons are expensive and inefficient
- FMT has been developing a self-bunching electron gun, known as the micro-pulse gun or MPG, for use as a driver for both RF sources and linacs
- RF fed into the MPG produces narrow electron bunches that are 3-5% of the RF period; electron current is proportional to the input RF power
- A post accelerated MPG beam sent into a cavity tuned to its RF input frequency produces very high RF powers, this klystron like configuration is called a micro-pulse klystron or MPK
- Narrow bunches from the MPG allow the MPK to achieve a wall-plug efficiency near 80%
- The MPK can reduce wasted energy by a factor of eight compared to a conventional CW klystron (JLAB), suggesting the MPK is a green technology
- Thomas Jefferson Laboratory could be one beneficiary of the MPK, reducing their annual electric bill from $5.77M to $2.38M.
  - Assumptions: 340 8kW tubes at 33% efficiency, electricity $0.1/kW-hr operating 7000hrs/year
Gain Condition: $\delta_1 \delta_2 (1-T) > 1$, which leads to exponential growth in electrons limited by space charge.
MPG Self-Bunching

$\text{t = 0.35 \, ns}$

$\text{t = 1.70 \, ns}$

$\text{t = 193.50 \, ns}$
L-MPG Bunching Characteristics

Anode Collision Current vs. Time

\[ T = \frac{1}{f} = 668 \text{ ps} \]
\[ f = 1.497 \text{ GHz} \]
CW L-MPG Performance

L-MPG Average Electron Current & Energy vs RF Power In
f=1.497GHz

Avg Gun Current(A)

Avg Internal Gun Cathode Emission Current

Electron Energy

RF Input to Beam Conversion Efficiency(%)
Technology Readiness
Experimental Verification of MPG Bunching

Current trace of L-band MPG micro-bunches showing one bunch per RF period
- pulse width ~40 ps
- peak current density ~22 A/cm²

Applied RF power in cavity (top)
20 A/cm² transmitted macro-pulse at S-band (bottom)
Peak micro-bunch current is about 20x higher than average
Examples of L-X MPG’s and a Gatling MPG
Two Primary Applications for the MPG: Microwave Tubes and Accelerators
Objectives for L-band CW MPK

- Achieve a high (~80%) wall plug efficiency with reasonable gain (~38dB includes solid state driver)
- Achieve an 8-12kW RF CW Output
- Achieve a low (<15kV) accelerating potential
- Final goal is to achieve a buildable and practical design
The L-MPK, A CW L-Band Klystron

- Output Power: 11.5 kW CW
- Beam Voltage: -12 kV (assume 95% efficient)
- Beam Current: 1.04 A
- Drive Power: 500 W (assume solid state amplifier with 24dB gain & 45% efficient)
- Frequency: 1497 MHz
- Wall Plug Efficiency & Gain: 80.7% & 37.6dB
- Existing Technology Efficiency: ~33%
- L-MPK waste energy is 12.3% of the existing technology, suggesting the L-MPK is a Green Technology
Wall Plug Efficiency & RF Power Out vs RF Power In

L-MPK Efficiency & Output Power vs Input RF Power

f=1.497 GHz, Output Cavity Efficiency=91%,
L-MPG SS Amp Driver Efficiency & Gain=45% & 24dB

Wall Plug Efficiency at 15kV
Wall Plug Efficiency at 12kV
Wall Plug Efficiency at 9kV
RF Power Out at 15kV
RF Power Out at 12kV
RF Power Out at 9kV
Front End of L-MPG with DC Break/Feedthrough
Coaxial to Waveguide Transmission

Coaxial Converter to Waveguide Transmission Efficiency

Frequency (GHz)

Transmission (%)
Transmission Past Pumping Ports

![Graph showing Power Transmission From Pumping Port]

- **Frequency (GHz)**: 1.45 to 1.55
- **Power Transmission Through Port (%)**: 99 to 100

**Legend:**
- Simulation (line)
- Experiment (triangle markers)
DC Break/RF Feedthrough Transmission

Transmission for DC Break/RF Feed

Transmission (%)

Frequency (GHz)
L-MPG with DC Break & Feedthrough

Output beam collector for measuring total current
RF Reflected Power Without & With Beam


Reflected Power from Anode Grid

- Simulation
- Experiment
- No Slits Simulation
- No Slits Experiment

Reflection from Beam Loaded Taper & L-MPG

- Simulation
- Experiment
L-MPG Performance

L-MPG Electron Average Current & Energy vs RF Power

f=1.497GHz

- Avg Transmitted Current, T=0.3
- Tranverse Emittance
- Electron Energy

Input RF Power (W)

Avg Transmitted Gun Current (A) & Transverse Emittance (mm-mrad)
Comparison of Actual L-MPG Current Density Distribution to Simulated

![Graph showing comparison of actual and simulated current density distribution.](image-url)
L-MPG Beam Heating of Anode Grid
Displacement of Anode Towards Cathode Due to Beam Heating
High temperature furnace capable of 2400°C. Inset shows sample being joined at 1663°C.

Upgrading Furnace for Joining
Summary and Status

- L-MPG built, operational and expected performance in agreement with design, except for “bump” in current density distribution.

- Localized current density distribution will need to be flattened by redesigning and rebuilding existing L-MPG anode.

- Choices for redesigning the L-MPG anode include:
  - In planar geometry, the anode thermal conductivity will need to be increased.
  - A cylindrical Anode-Cathode geometry has the effect of producing uniform expansion under beam heating, which enables compensation for grid spacing.

- Simultaneously, the joining furnace chamber has been successfully expanded in volume by 10x to accommodate the joining required for the high-power RF load and cavity and other joining.