FMT

Rostoker Memorial Symposium

Novel Particle and Radiation Sources and Advanced Materials

Frederick (Rick) M. Mako
President of FM Technologies, Inc. and Electron Technologies, Inc.

August 24-25, 2015

FM Technologies, Inc., 4431-H, Brookfield Corporate Dr., Chantilly, VA USA 20151
Web: www.fm-technologies.com Tel: (703) 818-9400 Fax: (703) 818-7090 fmako@fm-technologies.com

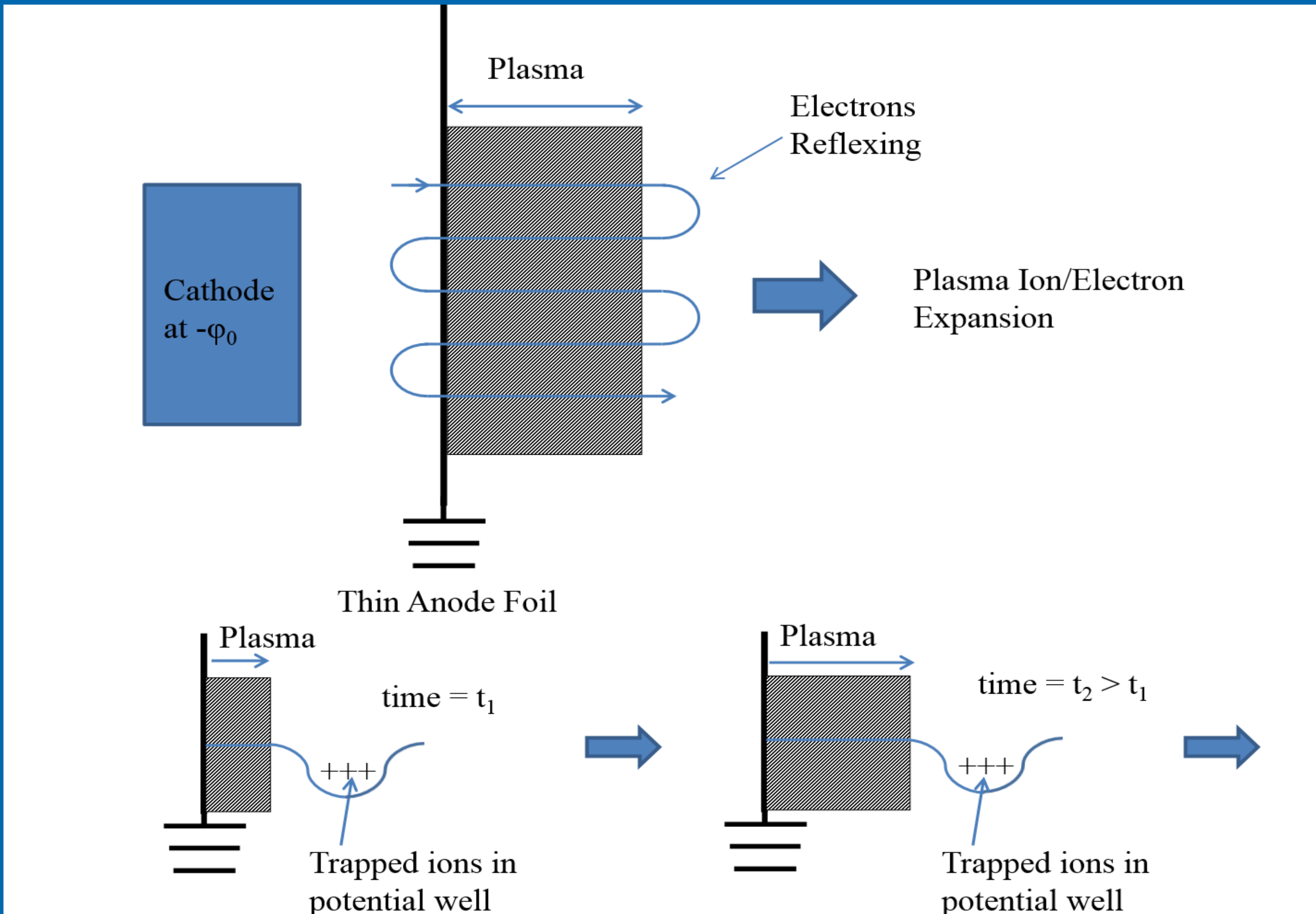
My Rostoker Relationship

- Thesis advisor from 1974 to 1979
  - Experimental and Theory thesis work focused on Collective Ion Acceleration using an Intense Electron Beam.
  - I also have to give credit to Amnon Fisher for being the driving force behind the laboratory, who along with Chuck Roberson provided invaluable expertise.
- Rostoker instructed graduate classes in Plasma Physics, Math-Physics and Pulsed Power
- Relationship has been maintained over many decades since graduation

Outline

- Collective Ion Acceleration - A Brief History
- The Rostoker Influence and My Evolution to Form FM Technologies, Inc. & Electron Technologies, Inc.
- Multipacting and the Creation of the Micro-Pulse Electron Gun (MPG)
- Applications of the MPG to Accelerators and Microwave Tubes
- Materials Processing and Application to Ethylene Production
- Summary

Collective Ion Acceleration by Reflexing Electron Beam - Model



Collective Ion Acceleration by Reflexing Electron Beam - A Brief History

[1] "One-Dimensional Model of Relativistic Electron Beam Propagation", PIC Simulation (relativistic),
This provided the basis for a large potential energy well greater than or equal to electron kinetic energy and showed some promise for gas ionization to provide captive ions and acceleration to high energy.

[2] "The Expansion of a Plasma into a Vacuum", Finite Difference Computation (non-relativistic),
Demonstrated that ions could continue to accelerate to near the electron velocity, thus achieving "the holy grail", i.e., $E_i \sim E_e * M_i / m_e$. Electrons had a constant temperature and Boltzmann distribution.

[3] "Formation of Fast-Electron Cloud during Injection of Intense Relativistic Electron Beam into Vacuum",
Theory, first calculation to provide an analytic expression of the electron beam produced potential energy well.

[4-5] "Collective Ion Acceleration Controlled by a Gas Gradient", Experiment & Theory (non-relativistic),
First validation of theory by experiment. By experimentally deducing the electron density distribution the constrained theory is then used to predict the ion energy distribution which is then compared to experiment.

[6] "Collective Ion Acceleration by a Reflexing Electron Beam: Model and Scaling", Experiment, PIC Simulation & Theory. PIC simulation added to [4] it provide clarification to the phase unstable mechanism.

[7] "Laser Acceleration of Ions for Radiation Therapy", Theory (relativistic).
Demonstrated that ions could continue to accelerate to much higher energy. Electrons had a continuous source of laser energy. Perhaps the solution for high energy ion acceleration.

Collective Ion Acceleration by Reflexing Electron Beam – Ion Equations of Motion

(1) Ion Continuity Equation

$$\frac{\partial n_i}{\partial t} + \frac{\partial (v_i n_i)}{\partial z} = 0$$

(2) Ion Equation of Motion

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial z} = -\frac{q}{M}\frac{\partial \phi}{\partial z}$$

(3) Electron Density, n_e, as a Function of Electrostatic Potential, ϕ

$$n_e(\phi) = \frac{\sqrt{2m}}{e}\int_{-e\phi}^{E_{\max}} \frac{1}{v_e}\frac{dJ_e}{dE_e}\, dE_e$$

(4) Experimentally Derived Electron Current Density, J_e, as a Function of Electron Energy, E_e, α is Determined by Experiment

$$J_e(E_e) = -J_{e_0}\left(1 - E_e / E_{\max}\right)^{\alpha}$$

(5) Non-Relativistic (velocity=v_e) Electron Density, n_e, as a Function of Potential, ϕ

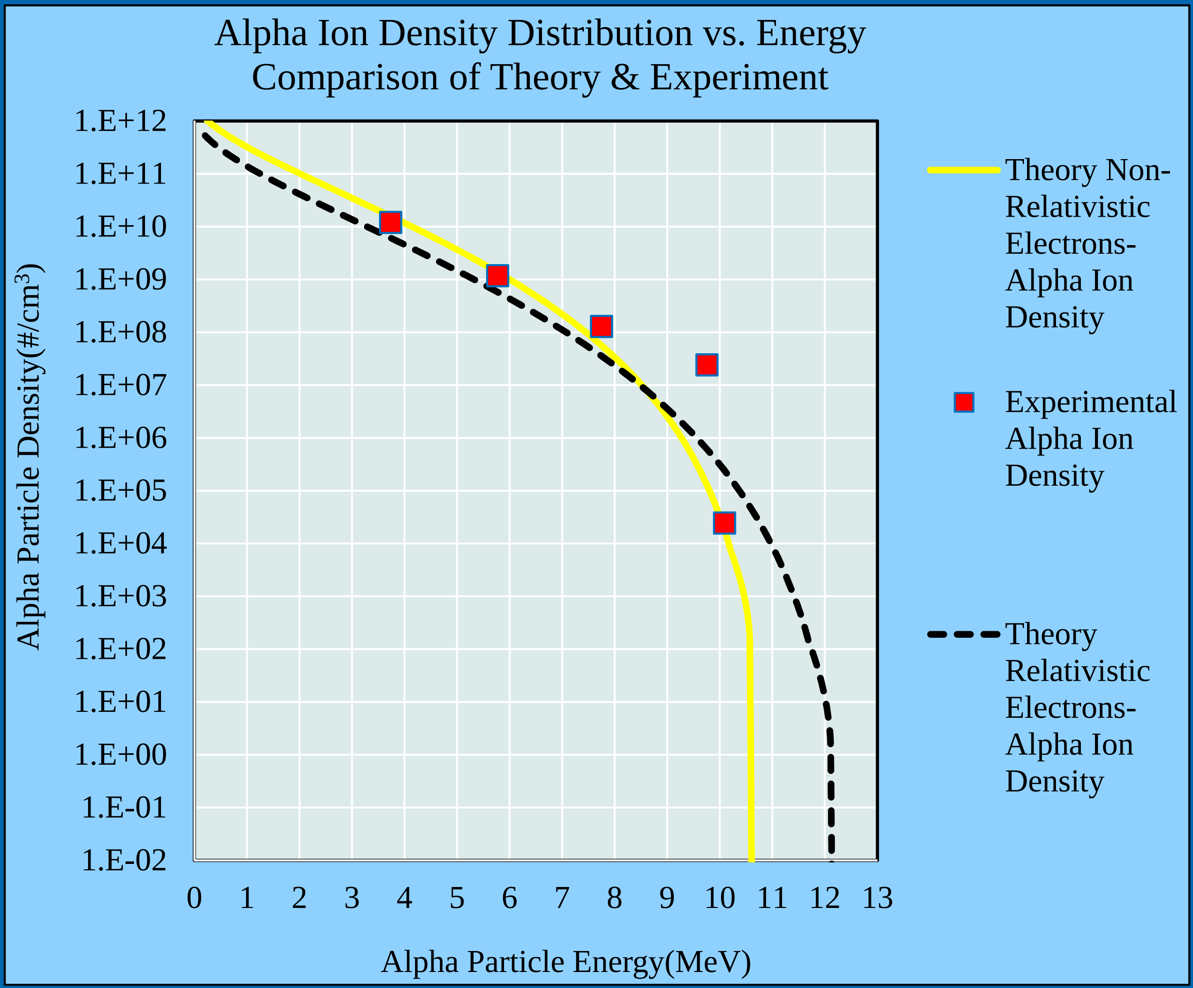
$$n_e(\phi) = \sqrt{\frac{2m}{E_{\max}}}\,\frac{J_{e_0}\alpha}{e}\,\frac{\Gamma(1/2)\Gamma(\alpha)}{\Gamma(1/2+\alpha)}\left(1 + \frac{e\phi}{E_{\max}}\right)^{\alpha - 1/2}$$

(6) Ultra-Relativistic (v_e=c) Electron Density, n_e, As a Function of Potential, ϕ

$$n_e(\phi) = \frac{2J_{e_0}}{e\,c}\left(1 + \frac{e\phi}{E_{\max}}\right)^{\alpha}$$

Equations (1) & (2) are closed by (3) assuming quasi-neutrality. Solution Proceeds by Self-Similar Calculation.

Ref: Eq. (1) – (5) [4-6] and Eq.(6) [7]



For Non-Relativistic Electrons the Maximum Ion Energy is:

$E_i = Z_i\, e\, \phi_o (2\alpha)$

For Ultra-Relativistic Electrons the Maximum Ion Energy is:

$E_i = Z_i\, e\, \phi_o\, (2\alpha + 1)$

For the Experiment:

$\alpha = 3.42$, $e\phi_o = 0.8\text{MeV}$

$J_{e_0} = 2.04\ \text{kA/cm}^2$

- Non-relativistic treatment gives slightly better agreement to data
- Maximum energy well below expectation [$(M/m)\, e\, \phi_o$]
- Number of energy ions drops off rapidly for practical applications
- The low ion energy and number resulted in termination funding in the early 80’s
- High Power Lasers appear to be the solution for High Energy Ions

The Rostoker Effect

- Direct influence from studying under Rostoker is great knowledge in Pulsed Power, Electron and Ion Beam Formation and Transport.

- Indirect, serendipitous influence in Pulsed Power, Particle and Radiation Beam Interaction with Materials.
  - For example: Ti anode foil bonded to graphite cathode resulted in TiC, which can be used to make electrical contacts with diamond for detectors and hard ceramics for cutting tools, along with WC.

- So what have I been doing since I completed a thesis under Rostoker?

My Path After Rostoker

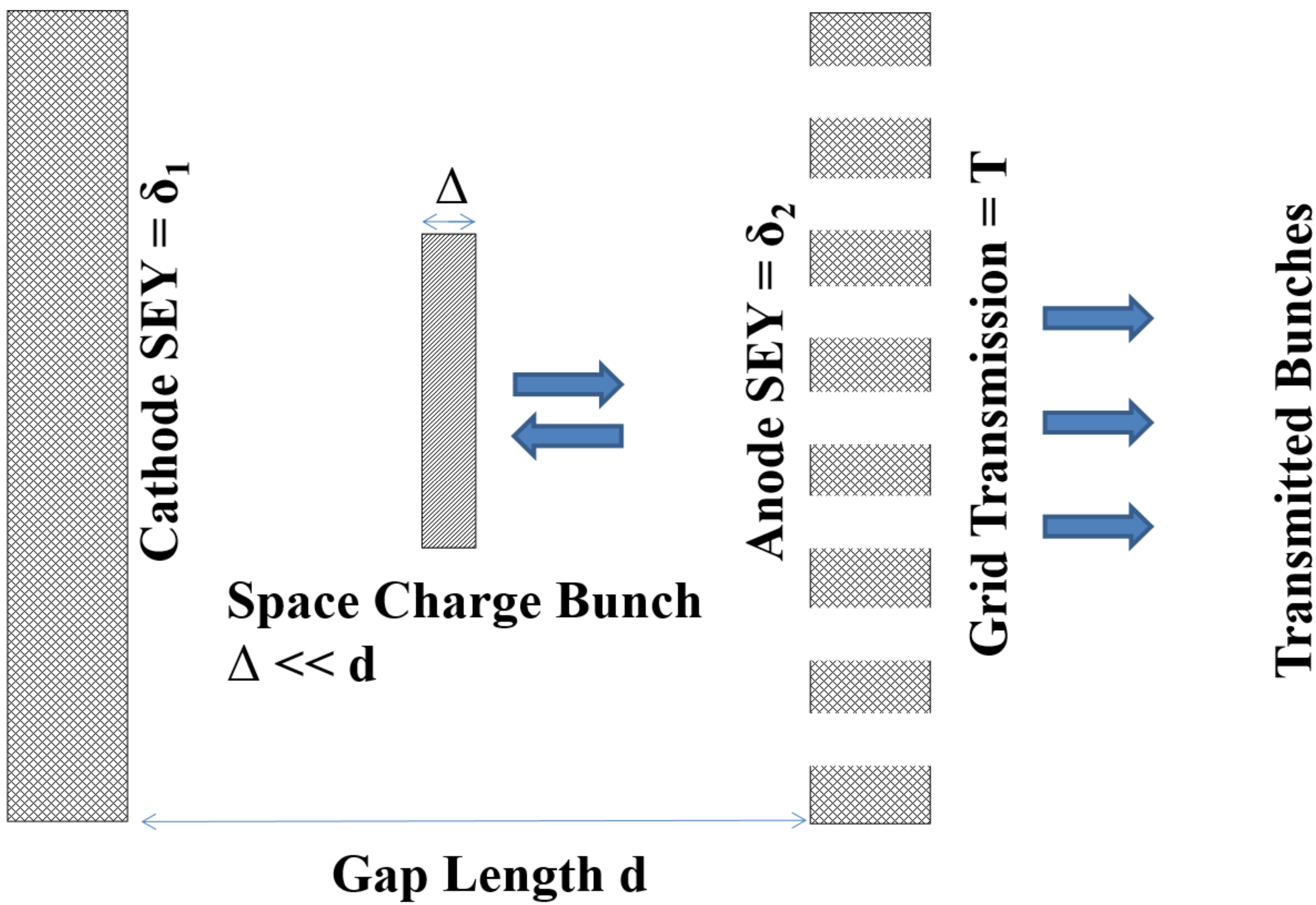
- Worked for the Naval Research Laboratory for 8 years and contributed to 6 projects in Ion, Electron Acceleration and Microwaves.
- Opened FM Technologies, Inc. (FMT) in 1987 and Electron Technologies, Inc. in 2014, completed to date 144 Contracts in Particle & Radiation Beam, Pulsed Power & Advanced Materials.
- FMT contracts from many foreign and domestic government agencies and commercial entities.

The Micro-Pulse Electron Gun

- Multipacting: hated by many, loved by few
- In particular, accelerator and microwave tube designers are always trying to get rid of it
- But we have found a positive attribute of multipacting that is useful for both of the above applications
- The creation of the Micro-Pulse Gun (MPG) exploits secondary electron emission and more, specifically multipacting to form a narrow self-bunching RF fed electron gun [8-16]

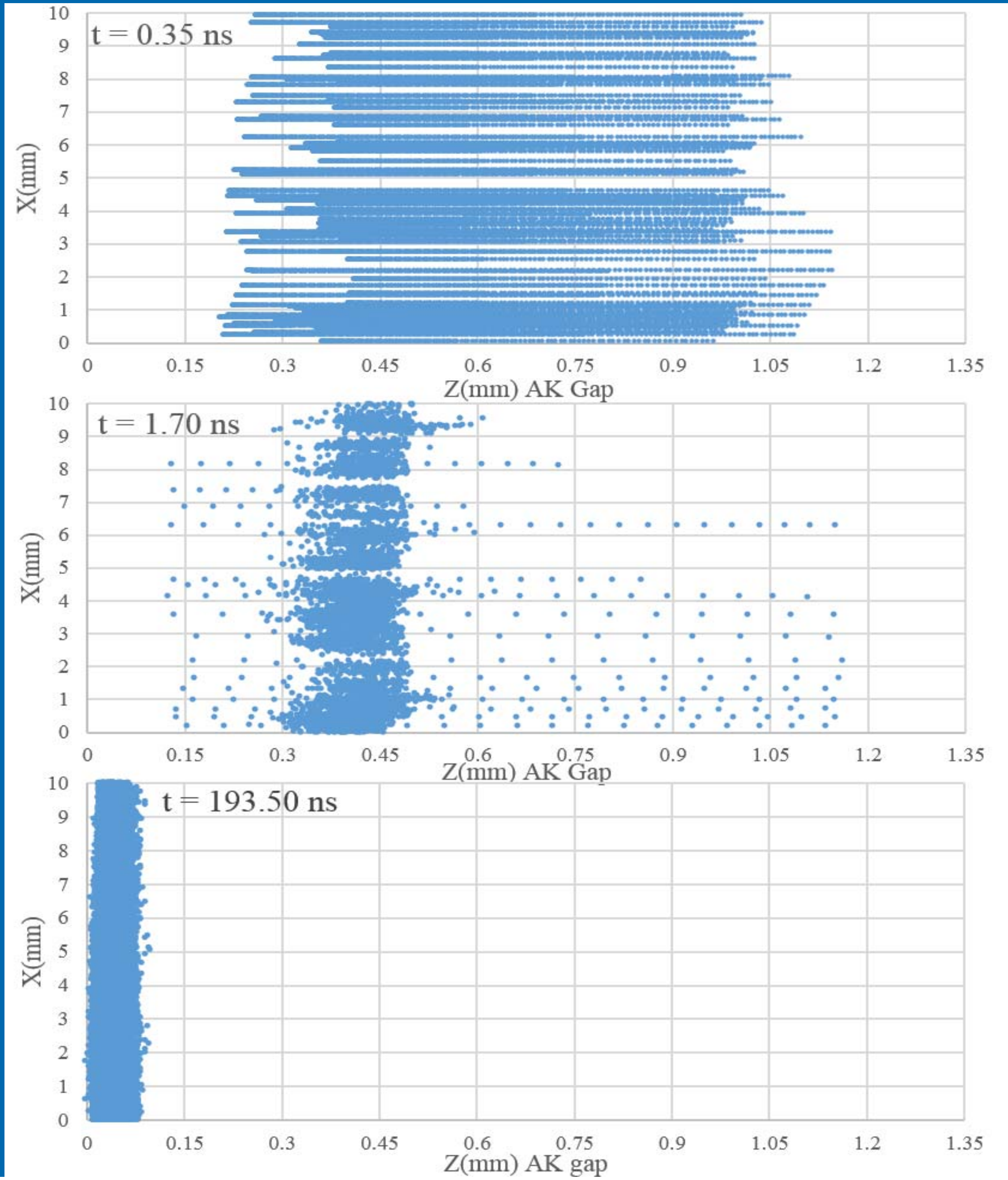
FMT

Model for Self-Bunching Electron Gun

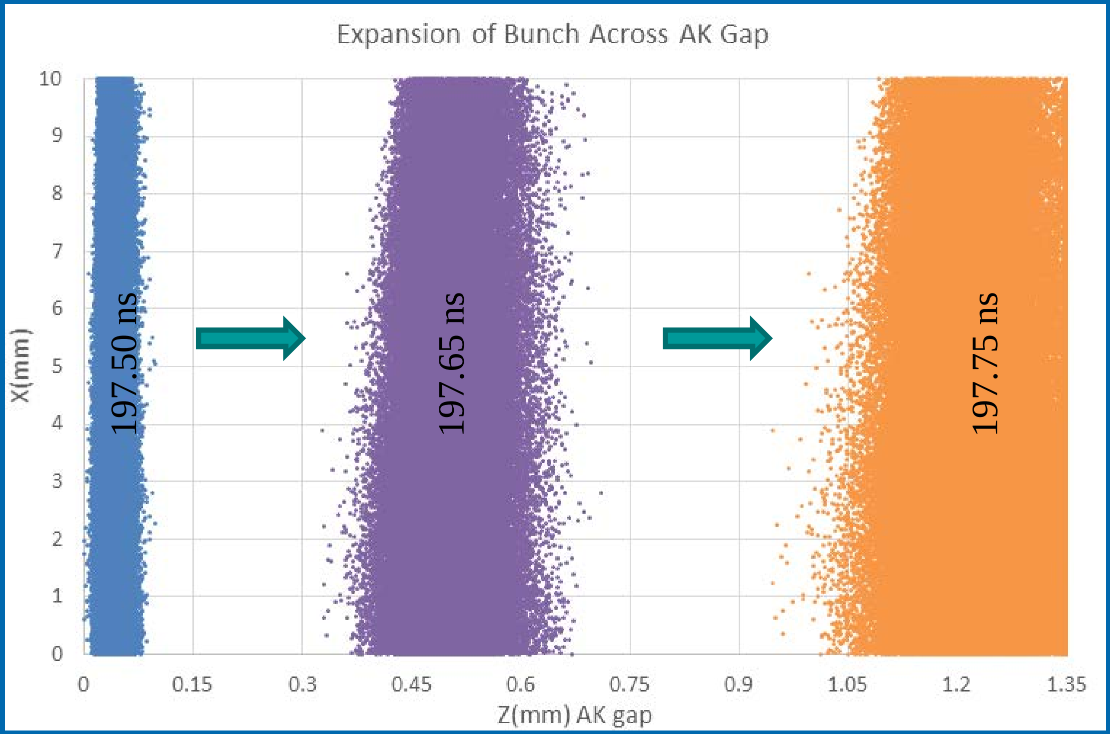


Gain Condition: $\delta_1\delta_2(1\text{-}T) > 1$, which leads to exponential growth in electrons limited by space charge.

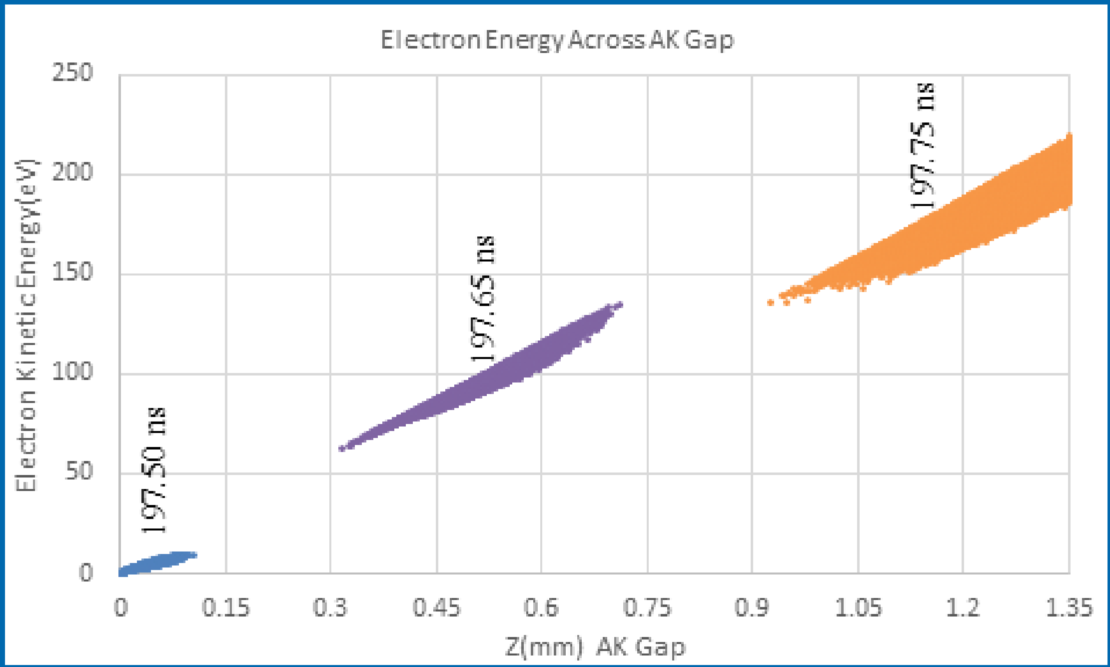
MPG Self-Bunching

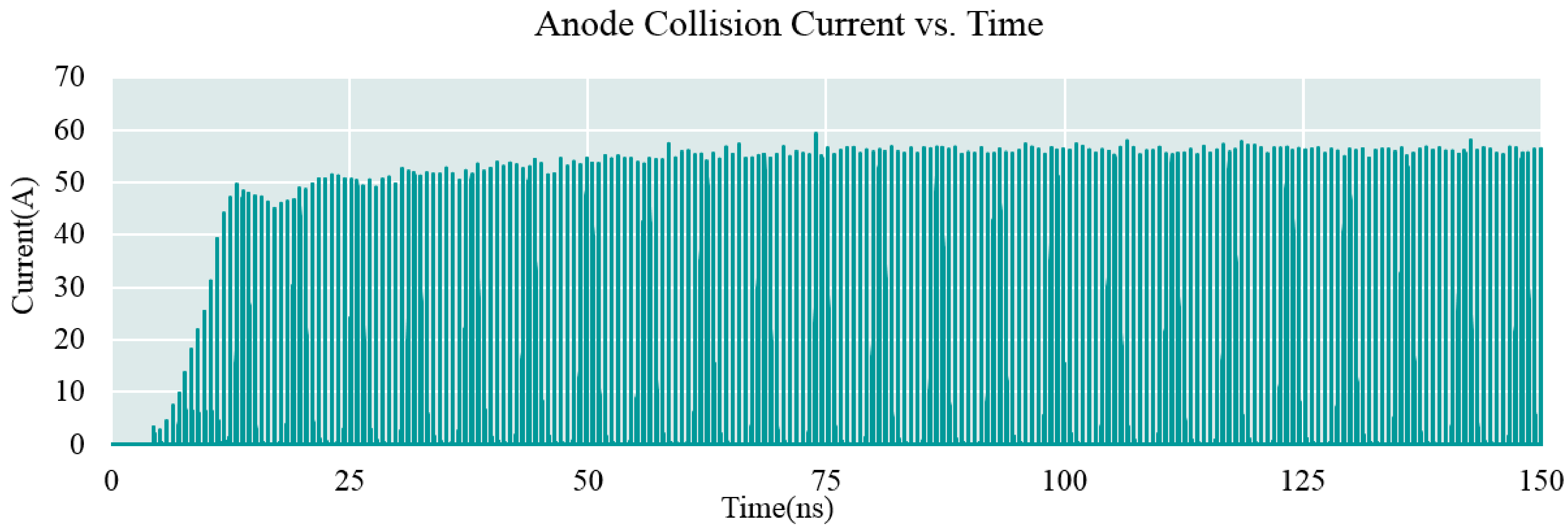


f=1.497 GHz

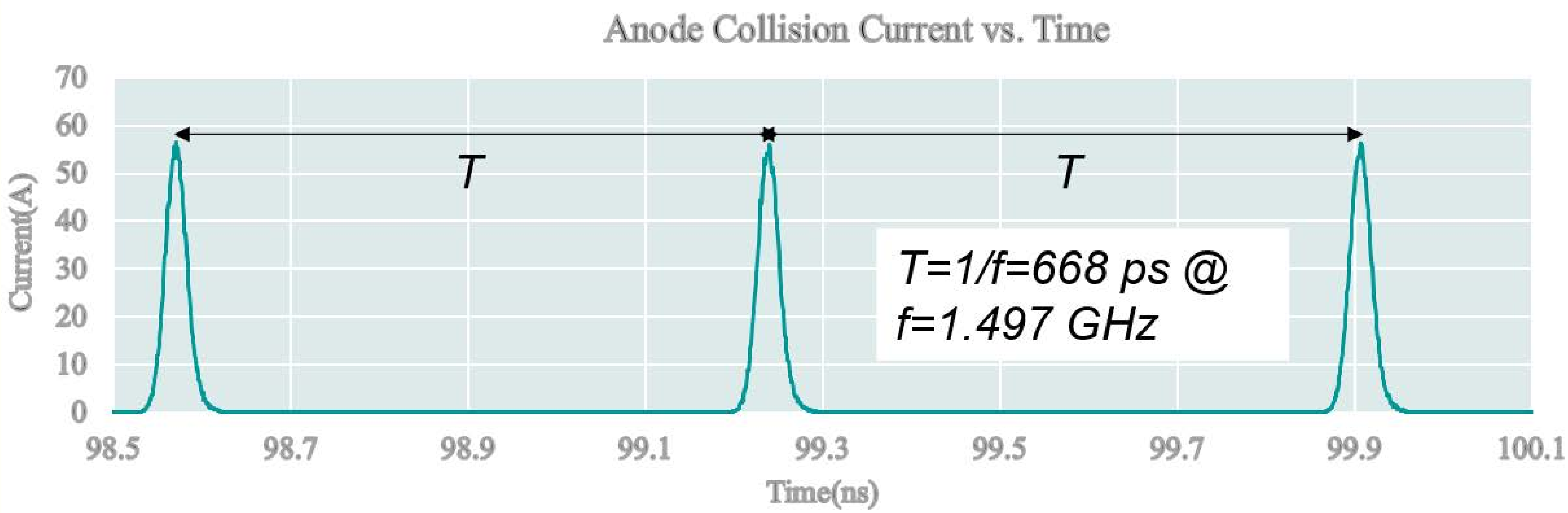

Expansion of Bunch Across AK Gap
X(mm)
Z(mm) AK gap
197.50 ns
197.65 ns
197.75 ns
0
1
2
3
4
5
6
7
8
9
10
0
0.15
0.3
0.45
0.6
0.75
0.9
1.05
1.2
1.35

f=1.497 GHz


Electron Energy Across AK Gap
Electron Kinetic Energy(eV)
Z(mm) AK Gap
197.50 ns
197.65 ns
197.75 ns
0
50
100
150
200
250
0
0.15
0.3
0.45
0.6
0.75
0.9
1.05
1.2
1.35



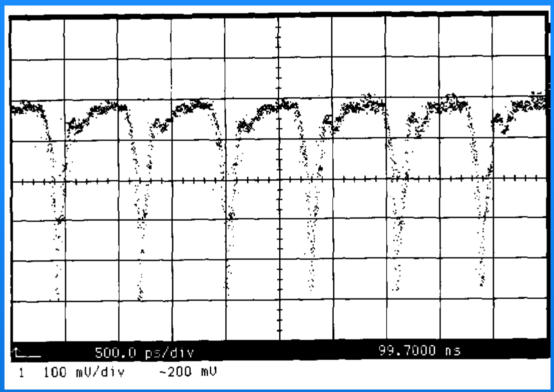
Anode Collision Current vs. Time
Current(A)
Time(ns)



Anode Collision Current vs. Time
Current(A)
Time(ns)
T
T
T=1/f=668 ps @
f=1.497 GHz

Technology Readiness

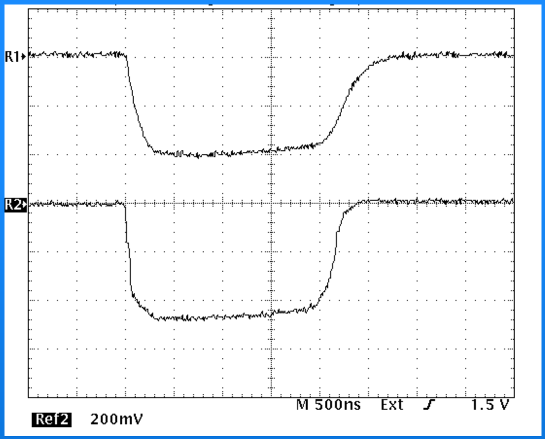
Experimental Verification of MPG Bunching



Current trace of L-band MPG micro-bunches showing one bunch per RF period

- pulse width ~40 ps
- peak current density ~22 A/cm^2

L-band experiment showing tapered waveguide and L-band MPG

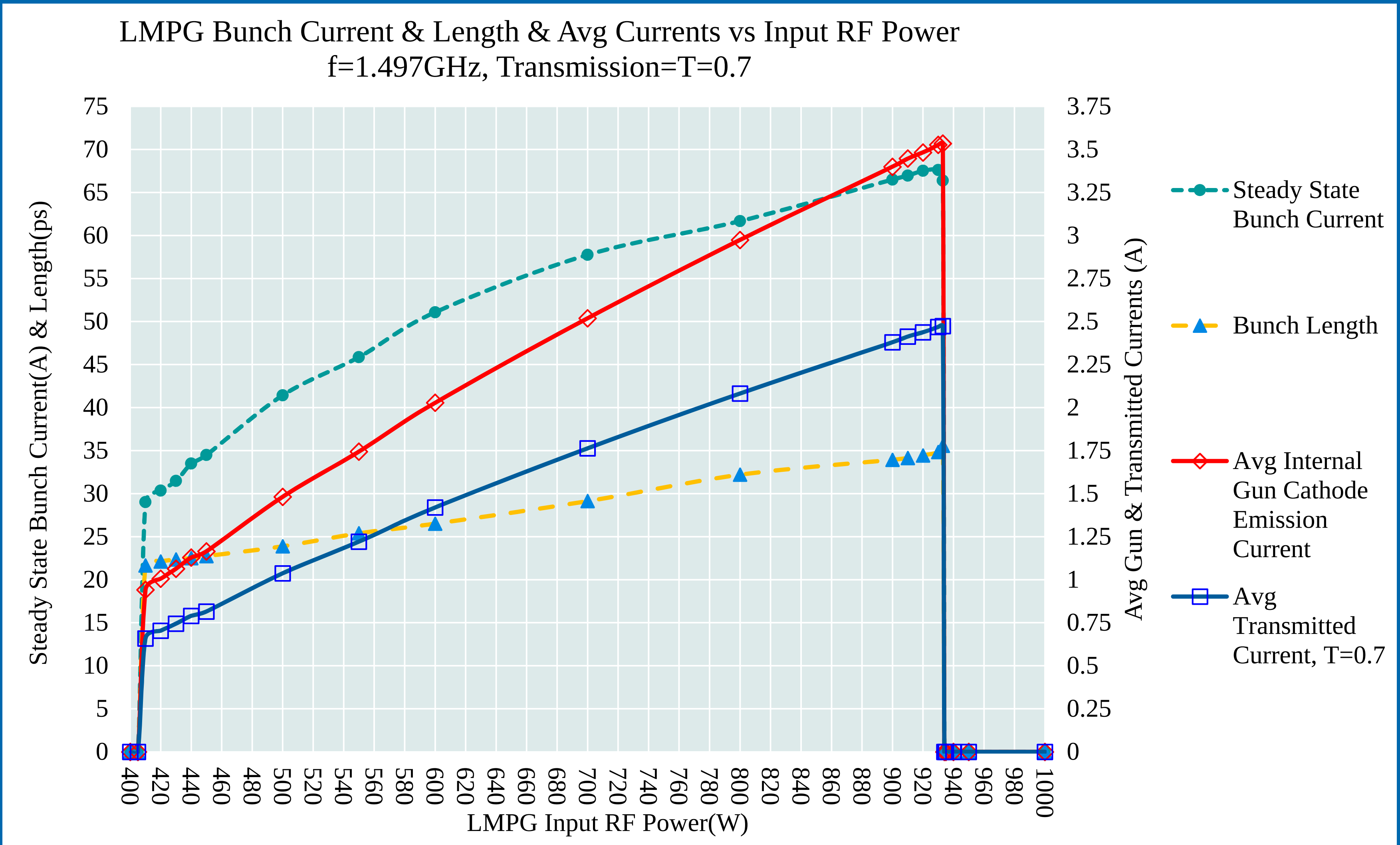


Applied RF power in cavity (top)

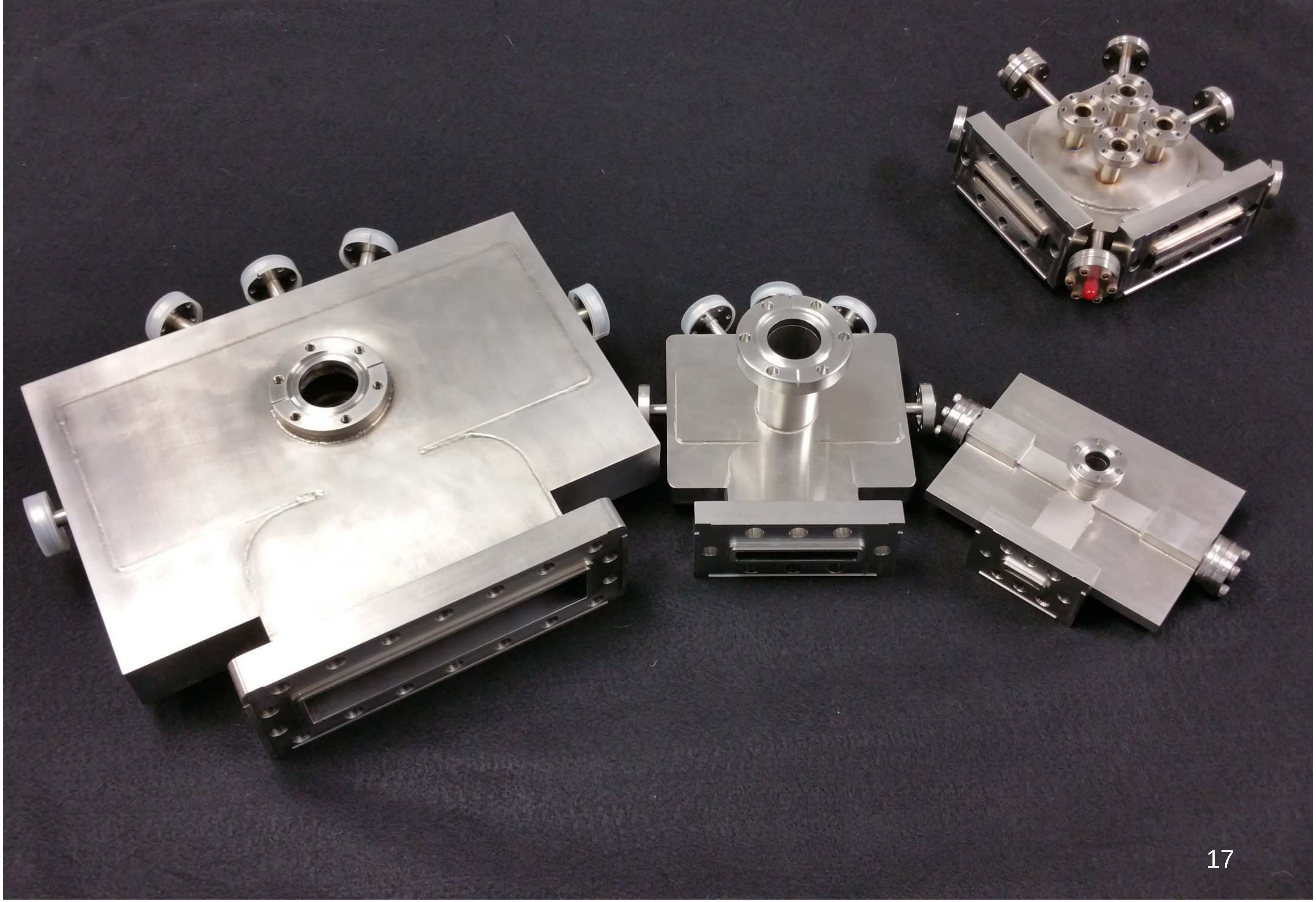
20 A/cm^2 transmitted macro-pulse at S-band (bottom)

Peak micro-bunch current is about 20x higher than average

CW LMPG Performance



FMT



Two Primary Applications for the MPG: Microwave Tubes and Accelerators

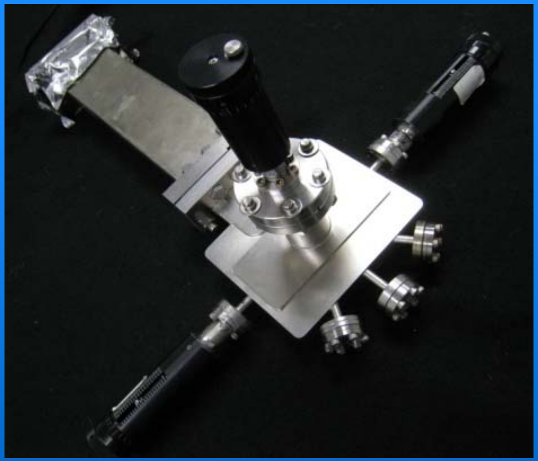
Technology Readiness

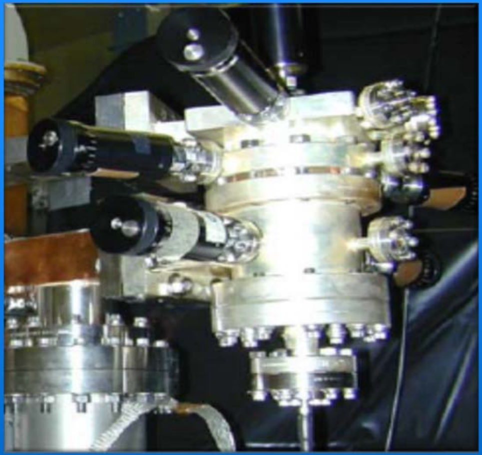
S-band MPG Beam Acceleration Demonstration

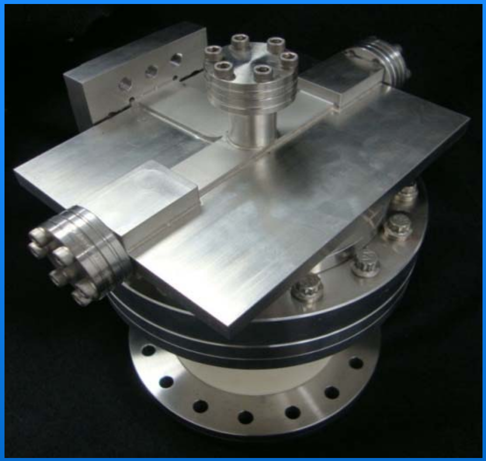
– MPG brazed to short commercial RF linac and installed in a magnetron driven RF system

– Beam reached the design energy of 1.25 MeV at 160 mA avg. with a normalized transverse emittance of 3.8 mm-mrad, thus validating the MPG application RF linac application

Technology Readiness
Examples of MPGs

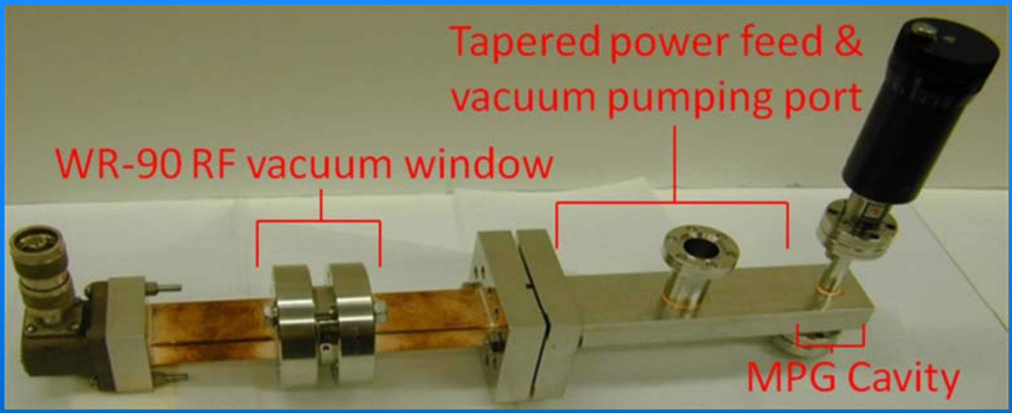

S-band MPG, 2.85 GHz, 20 A avg.


S-band MPG, 2.99 GHz, 175 mA avg.


X-band MPG, <12 GHz, 2 A avg.

Have:
– 15 times higher current than presently available by existing medical devices

Need:
– 8 times higher energy
– Readily achievable w/ RF acceleration



X-band MPG, <10 GHz, 0.5A avg.

Desired Advances in Medical Linacs*

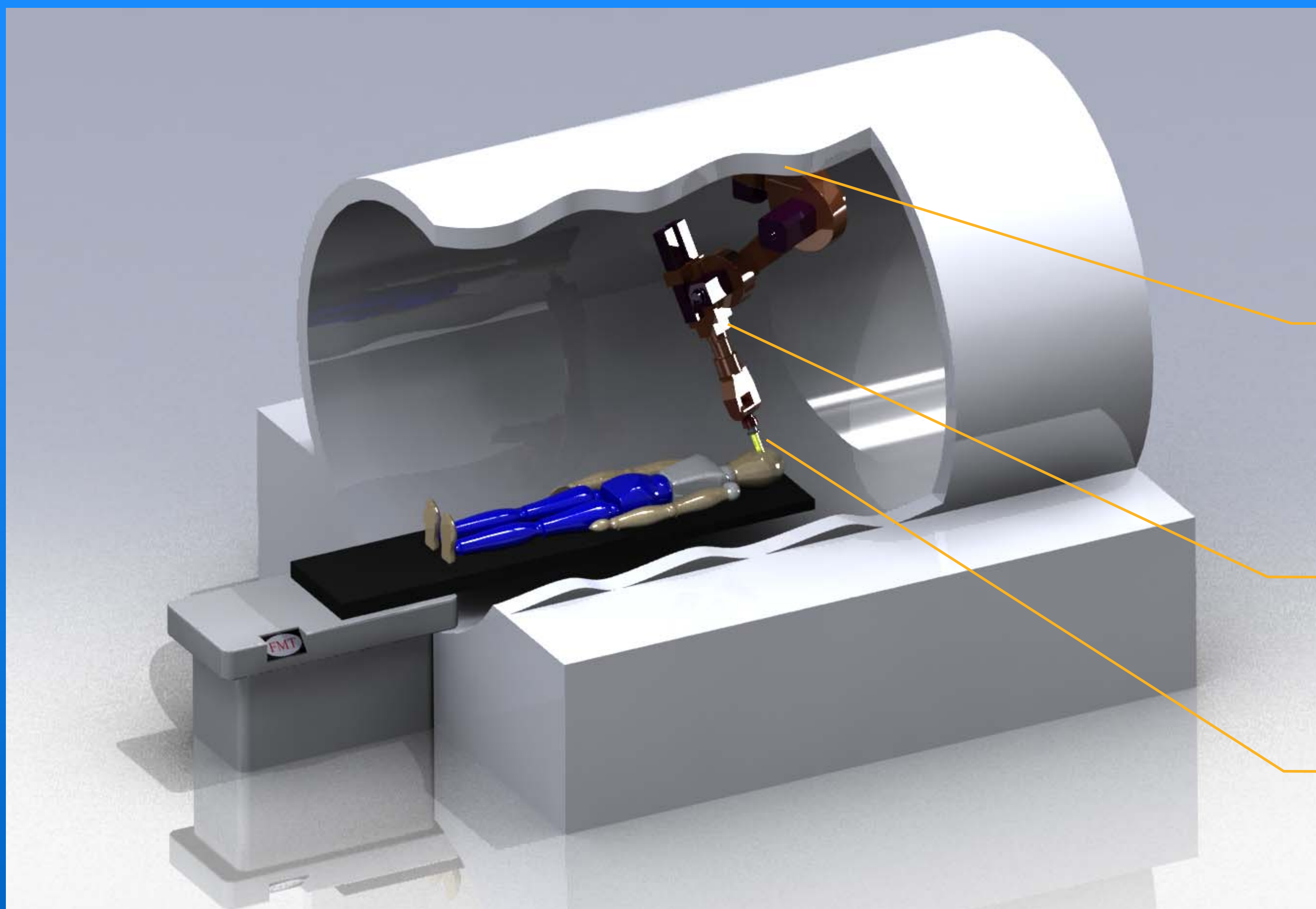
1. Higher energy, compact, robotically mounted machine for accurate and precise treatment of both deep and shallow tumors
   - Two primary vendors can treat deep tumors but cannot be mounted on a robotic arm
   - Third primary vendor uses robotic arm but requires high monitor unit, longer times to treat deeper tumors such as abdomen and bladder cancers
2. Rapid energy selection and power adjustment during exposure for accurate true 3D conformal tumor treatment
3. Increased dose rate to shorten exposure time
   - Improves dose accuracy
   - Mitigates impact of patient motion, e.g. breathing
4. Significant reduction of facility size and shielding requirements

Need for higher dose rate, higher current and energy, higher frequency, tunable and versatile compact medical linear accelerators (linac)

* Prime source –highly regarded medical physicist from New York

3DRad™

Integrated Concept w/ Imaging and Shielding



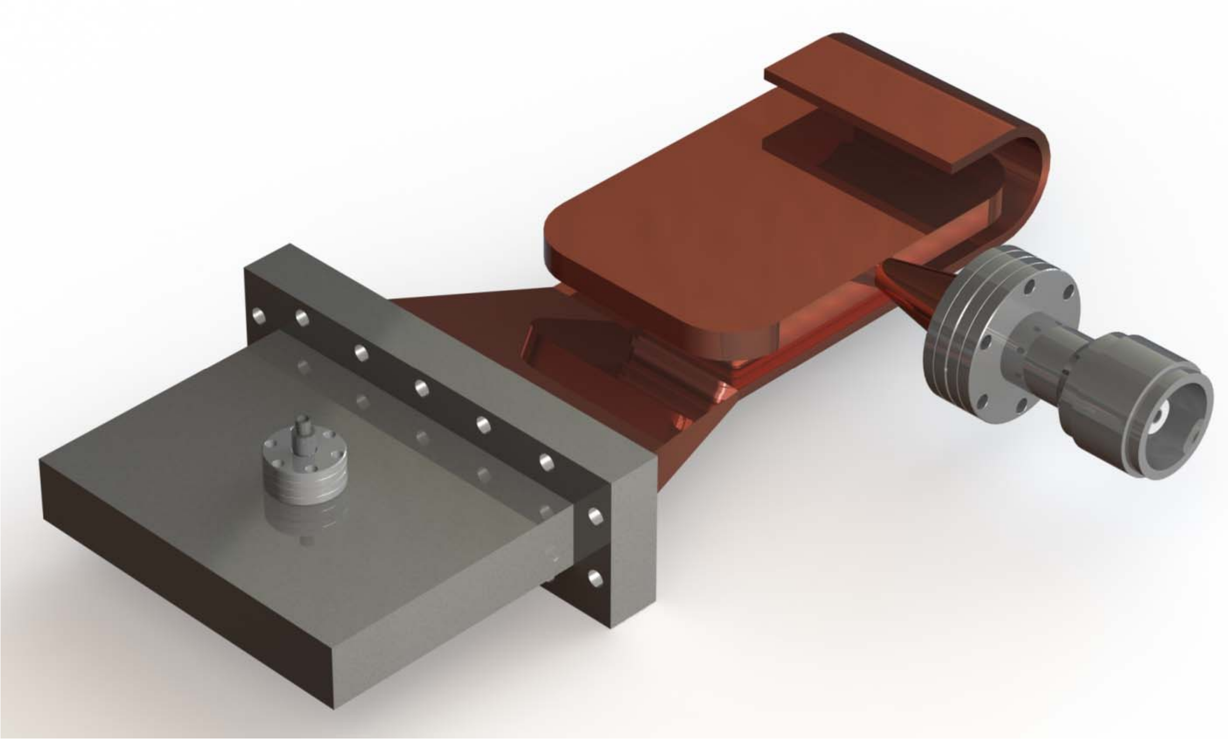
Cut-away of X-ray shielding

Multi-axis 3DRad™ w/ integrated imaging

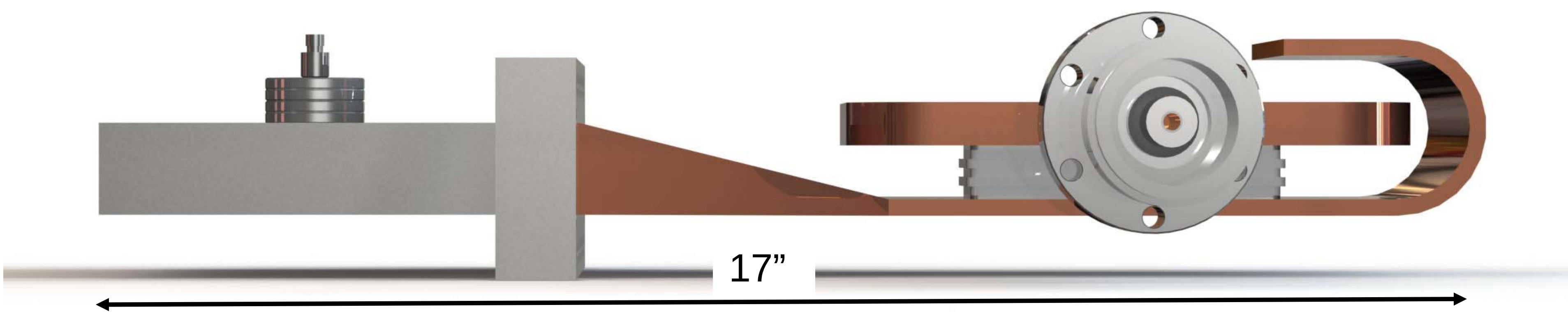
Treatment by X-ray or electron beam

MPG Klystron Tube Development

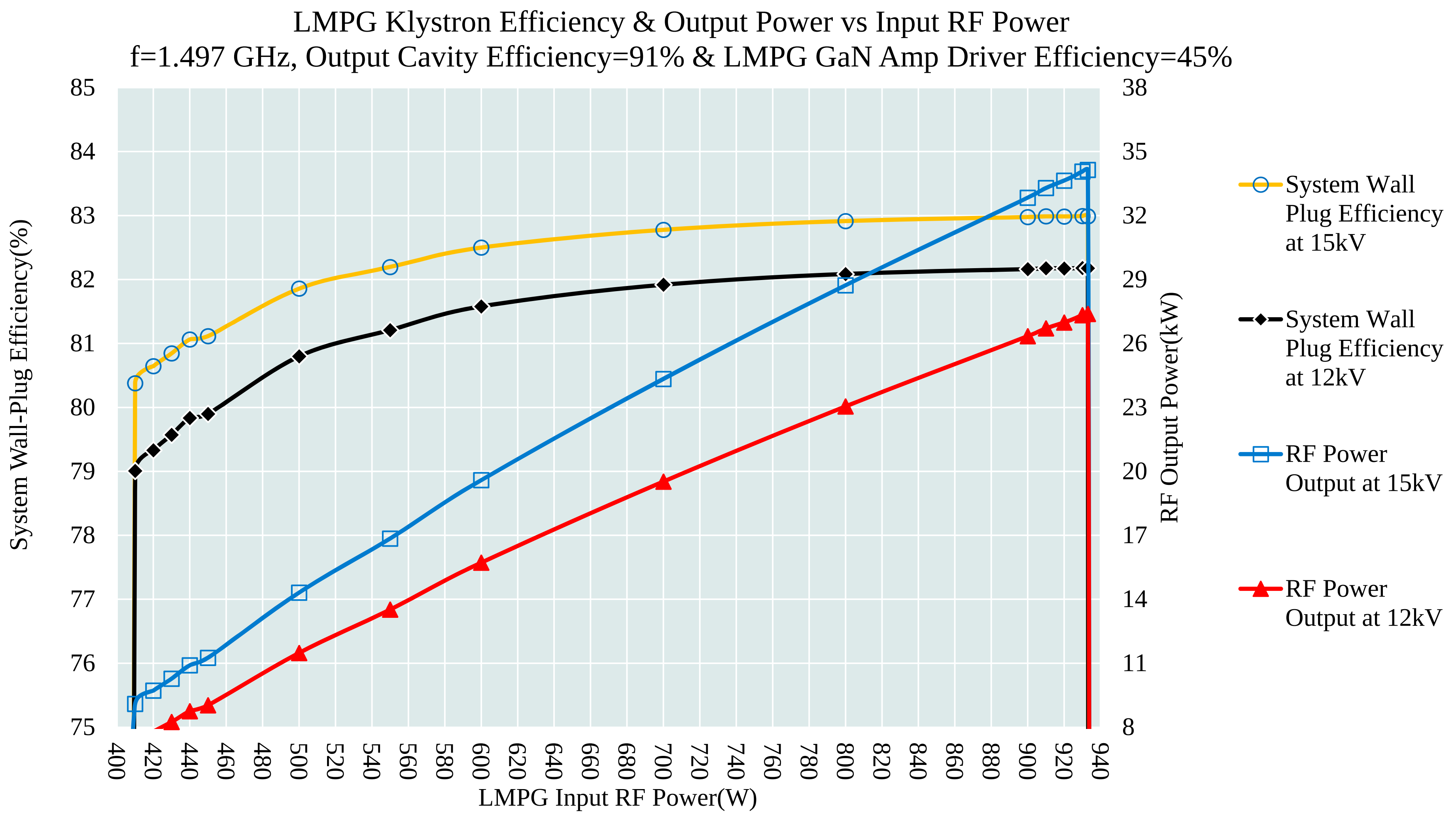
FMT The LMPK, A CW L-Band Klystron



- Output Power: 14.3 kW CW
- Beam Voltage: 15 kV
- Beam Current: 1.04 A
- Drive Power: 500 W
- Frequency: 1497 MHz
- Efficiency: 81.9%
- Existing Technology Efficiency: <30%
- L-MPK Wasted Energy<10% of Existing Technology, thus L-MPK is a Green Technology



CW LMPK Performance



Ethylene Production

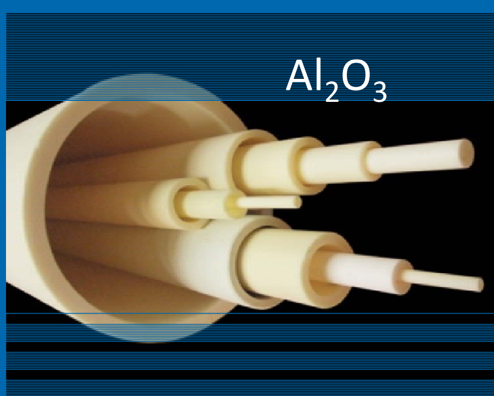
- Hydrocarbon feedstock cracked in a pyrolysis furnace
  - Superalloy temperature limited (~1150 °C)
  - Increased production capacity desired
    - Requires higher operating temperature
  - Production limited by capabilities of furnace coil material
- Furnace coils traditionally are superalloy
  - Coils experience: extreme thermal cycling, coking, carburization, oxidation and creep during service
  - Fe-Ni-Cr superalloy family reaching ultimate operating limits
- SiC furnace coils are better in almost every way
- With SiC at 1250^{o}C → 10% more throughput → $10B increase in revenue

Why Use Ceramics?

- Chemical and atmospheric inertness
- High temperature mechanical strength
- High creep resistance
- Possible candidates for ethylene production:
  - Silicon nitride (Si_3N_4)
  - Fused quartz (SiO_2)
  - Alumina (Al_2O_3)
  - Silicon carbide (SiC)

SiC vs. Ceramics/Metals

- SiC has superior properties
  - Thermal conductivity >3X better than Al_2O_3
  - Thermal shock resistance 2X that of Si_3N_4
  - Does not lose strength at high temperature (out to 1900°C)
  - Hardness, i.e. scratch resistance, 65% greater than Si_3N_4 or Al_2O_3
  - Tensile Strength >5x at >1150°C than superalloys
  - Thermal Conductivity Equal to superalloys > 1150°C
  - Reduced Coking, Oxidation Resistant & Almost No Creep Rate

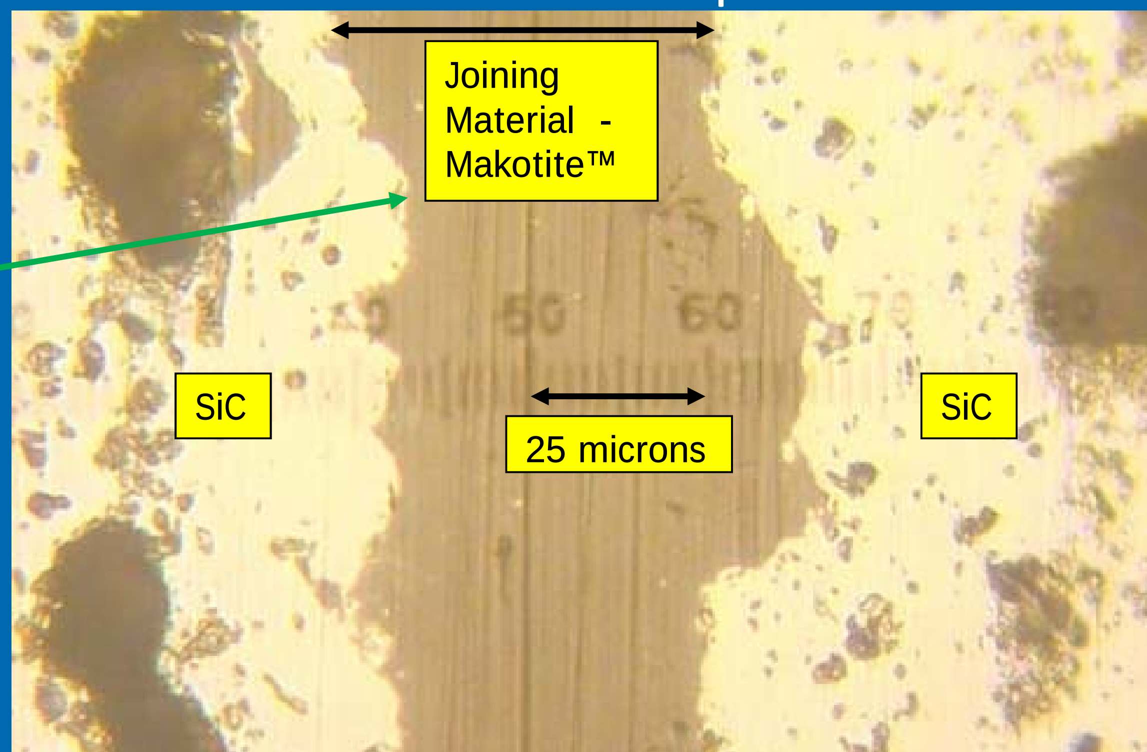


Silicon Carbide Joining

- 20+ years of ceramic joining R&D by FMT [17-28]
- Early joining work provided oxidation resistance and strength, the joining methods were:
  - SiC to metal joining using pulsed electron beam technology
  - SiC to SiC joining using a polymer and microwave joining technologies
- FMT development has SiC-SiC/SiC-metal joints that are:
  - Helium leak tight
  - Oxidation and coke resistant
  - Very strong, equal to SiC received material
  - 1150-1400°C service temperature for SiC to SiC
  - 700-900°C service temperature for SiC to metal
- Applications include: Petrochemical Furnace Coils, Nuclear Fuel Rods and Solar Receivers

FMT SiC Joining Technology

- Various SiC to SiC tube joints
- SiC plug joint with 400X photomicrograph
  - Note features completely filled to below 0.25µm
- All joints helium leak tight
- 1150-1400°C service temperature



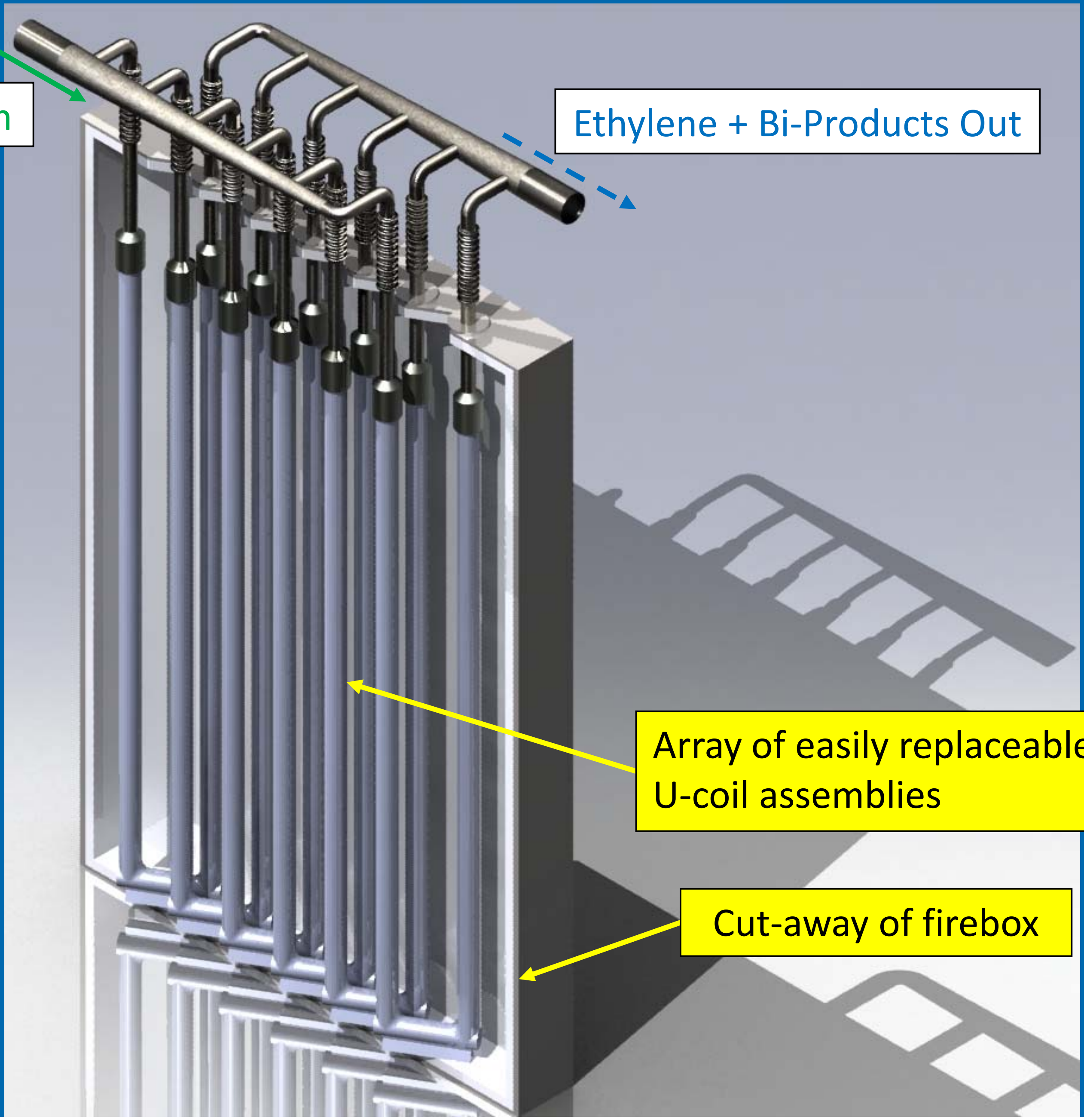
FMT SiC Joining Technology Using Makotite™

- Various SiC to metal joints
- All joints He leak tight
- 700-900°C service

FMT SiC Joining Technology Using Makotite™

- Complete miniature SiC coil assembly
- Helium leak tight and structurally strong
- Oxidation resistant and coke resistant
- 1150-1400°C service for SiC portion
- 700-900°C service for metal portion
- Can be welded to superalloy pipe
- Bellows provide stress relief

SiC Coil Field Installation



Summary

- The Future of Ion Acceleration Appears to be with Lasers
- MPG Applications: Accelerators and Microwave Tubes
- MPG Driven Medical Linac (3DRad™) Has Clinical Advantages
- MPG Gives a Green Path for Future Klystrons
- Makotite™ Joining Technology Yields Superior Performance SiC Furnace Coils for Ethylene Production
- Makotite™ Joining Also Has Applications to Nuclear Fuel Rods and Solar Receivers

My time visiting Norman always came with excitement!

FMT

Norman we will surely miss you!!

Bibliography

1. J. W. Poukey and N. Rostoker, "One-Dimensional Model of Relativistic Electron Beam Propagation," *Plasma Physics,* v13, 897, (1971).
2. J. E. Crow, P. L. Auer and J. E. Allen, "The Expansion of a Plasma into a Vacuum," *Journal of Plasma Physics,* v14, P1, 65, (1975).
3. D. D. Ryutov and G. V. Stupakov, "Formation of Fast-Electron Cloud during Injection of Intense Relativistic E-Beam into Vac.," *Sov. J. Plas. Phy, v*2, N4, 309, (1976).
4. F. Mako, A. Fisher, N. Rostoker, D. Tzach, and C.W. Roberson, "Collective Ion Acceleration Controlled by a Gas Gradient", IEEE Trans. Nucl. Sci., **26**, 4199 (1979).
5. F. Mako, A. Fisher, C.W. Roberson, N. Rostoker and D. Tzach, Collective Ion Acceleration Controlled by a Gas Gradient, "Collective Methods of Accelerations", ed. by N. Rostoker and M. Reiser, Harwood Academic, New York, 317 (1979).
6. F. Mako and T. Tajima, "Collective Ion Acceleration by a Reflexing Electron Beam: Model Scaling", Phys. Fluids, **27**(7), 1815 (1984).
7. T. Tajima, D. Habs and X. Yan., "Laser Acceleration of Ions for Radiation Therapy," *Reviews of Accelerator Science & Technology,* v1, 1, (2008).
8. F. Mako and W. Peter, "High-Current Micro-Pulse Electron Gun", Proc. Particle Accelerator Conf., IEEE Cat. 93CH3279-1, 2702, (1993).
9. F. Mako and L. K. Len, "Self-Bunching Electron Guns", Proc. Particle Accelerator Conf., IEEE Cat. 99CH36366-1 70 (1999).
10. F. Mako, L. K. Len and W. Peter, "Self-Bunching Electron Guns", Advanced Accelerator Conf., CP472, 875, AIP Press, NY (1999).
11. J. A. Nation, L. Schachter, F. Mako, L. K. Len, W. Peter, C. M. Tang and T. Srinivasan-Rao, "Advances in Cold-Cathode Physics and Tech.", Proc. IEEE, **87**(5), 865 (1999).
12. F. Mako and L. K. Len, "Self-Bunching Electron Guns", in High Energy Density Microwaves, ed. R. M. Phillips, AIP, CP474, 41 (1999).
13. S. K. Guharay, L.K. Len and F. Mako, "High-Current Micro-Pulse Electron Guns and Accelerator Applications", Proc. Particle Accelerator Conference, 2084 (2001).
14. F. Mako and W. Peter, Electron Gun for Producing Incident and Secondary Electrons, Pat. No. 7,285,915 B2 10/23/ (2007).
15. F. Mako, Electron Gun Having Multiple Transmitting and Emitting Sections, Pat. No. 6,633,129 B2 10/14/ (2003).
16. F. Mako and A. Fisher, Robust Pierce Gun Having Multiple Transmitting and Emitting Section, Pat. No. 6,642,657 B2 11/04/ (2003).
17. F. Mako, Pulsed Electron Beam Joining, "Proceedings of a Workshop on Applications of Accelerators", edited by W.B. Herrmannsfeldt, A.M. Sessler and J.R. Alonso, (SLAC-430, LBL-35023, CONF-931248, UC-400, 49, (1993).
18. F. Mako, R. Silberglitt and L. K. Len, Pulsed Electron Beam Joining of Materials, (Israel) Pat. No. 118126/2 10/03/ (1994).
19. F. Mako, R. Silberglitt and L. K. Len, Pulsed Electron Beam Joining of Materials, Pat. No. 5,599,468 02/04/ (1997).
20. R. L. Bruce, S. K. Guharay, F. Mako, W. Sherwood, E. Lara-Curzio, "Polymer-Derived SiC/SiC Composite Fabrication and Microwave Joining for Fusion Energy Applications", Proc. 19^{th} IEEE/NPSS Symp.on Fusion Engr., Atlantic City, NJ, Jan. 22-25, 426, (2002).
21. F. Mako and R. L. Bruce, Ceramic Joining, US Pat. No. 6,692,597 B2 02/17/ (2004).
22. S. K. Guharay, F. Mako, Y. Tian, "Joining of SiC components and evaluation of joint characteristics", Plasma Facing Components 2004 Workshop at Univ. Illinois at Urbana-Champaign, IL., "http://fusion.anl.gov/ALPS_Info_Center/2004-05-04/agenda.html" May 3-5 (2004).
23. F. Mako and R. L. Bruce, Ceramic Joining, PRC (China) Pat. No. ZL02824111.8 06/11/ (2008).
24. F. Mako and R. L. Bruce, Ceramic Joining, US Pat. No. 8,337,648 B2 12/25/ (2012).
25. F. Mako, E. Cruz, Y.Tian, J. Schilling, "New Silicon-Carbide Joining Technology", AIChE, #352574, Ethylene Producers Conf., 2014 Spring National Meeting, New Orleans, LA, March 30 – April 3 (2014).
26. F. Mako, E. Cruz and F. M. Mako III, "System and Method for Producing Chemicals at High Temperature", filed 12 March (2015).
27. F. Mako, E. Cruz and F. M. Mako III, "Mixed Oxide Materials for Helium Leak Tight, Oxidation Resistant and High Strength Joints Between High Temperature Engineering Materials", filed 27 March (2015).
28. F. Mako, E. Cruz and F. M. Mako III, "Method for Joining Ceramics to Ceramics or Ceramics to Metals, and Apparatus", filed 27 March (2015).