Development of 100 kW Continuous Wave Radiofrequency Amplifier for Linear Accelerator

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Omega-P R&D, Inc. Yale University

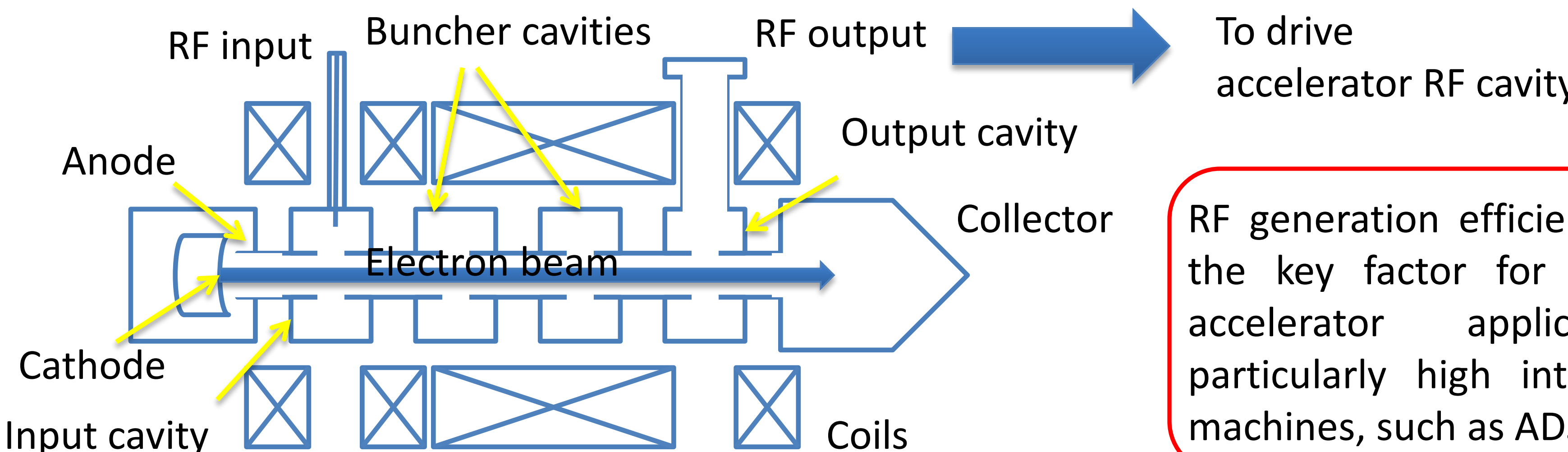
Outline

- 1.3 GHz 2.5MW Omega-P ILC MBK Demonstration
- 952MHz CW 100kW MBK Conceptual Design
- 650MHz CW 100kW MBK Development
- Efficiency Enhancement with
  Partially Grounded Depressed Collector

KLYSTRON 101

Klystron, a class of radiofrequency amplifiers, amplifies RF signals by converting the kinetic energy in a DC electron beam into radio frequency power.

- Electron beam produced by a thermionic cathode and accelerated by high-voltage electrodes
- RF fed into the input cavity causing the electrons to form bunches at the input frequency.
- Additional buncher cavities to reinforce the bunching.
- RF oscillations excited in the output cavity coupled out through a coaxial cable or waveguide.
- Spent electron beam with reduced energy captured by a collector electrode.



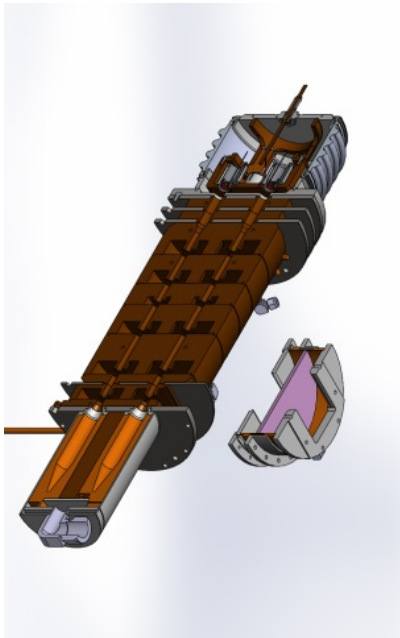
RF generation efficiency is the key factor for many accelerator application, particularly high intensity machines, such as ADS

Multiple-Beam Klystrons (MBKs)

- Use multiple electron beamlets with separate beam tunnel but common cavity gaps.
- Lower space-charge effects which can debunch the beam
- reduced operating voltages and shorter circuit lengths

Multi-Beam Klystron For ILC

1.3 GHz multi-beam klystron (MBK) for International Linear Collider (ILC)



Design
Omega-P, Inc.

Assembly
CCR

Initial Test
CPI
Communications & Power Industries

Current
Yale University

Next
SLAC NATIONAL ACCELERATOR LABORATORY

Design Values

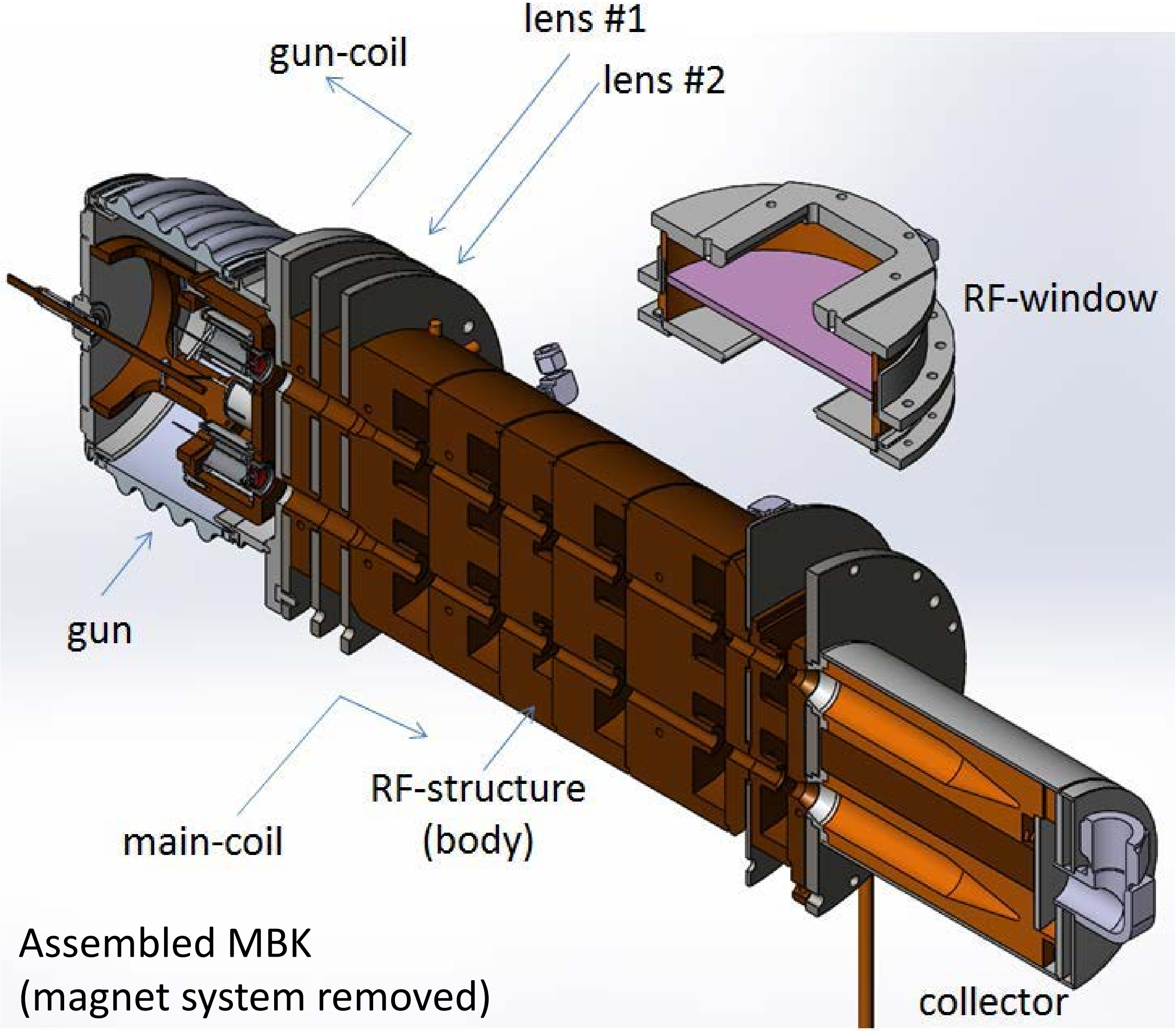
COMPACT	six-beamlet quadrant, 54" high
LOW-VOLTAGE	operating voltage of 60 kV
HIGH-POWER	2.5 MW, 50 dB gain
LONG PULSE	1.5 ms RF pulses
HIGH EFFICIENCY	65%

This tube construction was supported by several SBIR grants DE-SC0000926, DE-SC0000927, DE-SC0007532 and DE-SC0007533 to Omega-P, Inc. from Department of Energy, Office of High Energy Physics

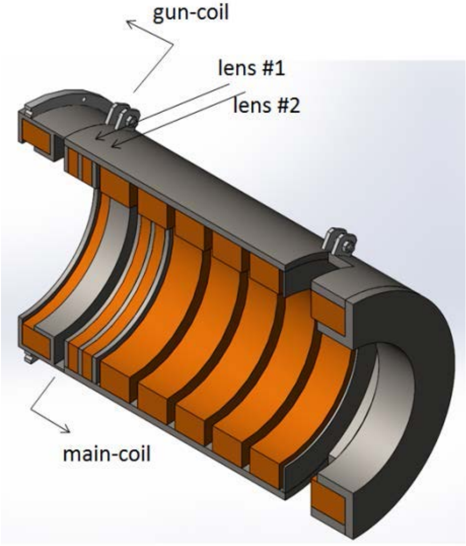
Collaboration: *Omega-P, Inc., Yale University, Calabazas Creek Research, and Communications & Power Industries.*

2.5MW Omega-P ILC MBK Structure

Components: six beamlet electron gun, six beam tunnels, RF structure with the input, buncher (gain, second-harmonic, penultimate-#1 and #2) and output cavities, magnetic system, and six channel electron beam collector.



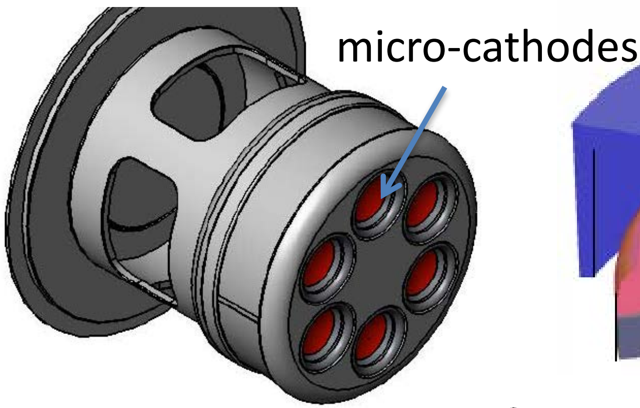
Assembled MBK
(magnet system removed)

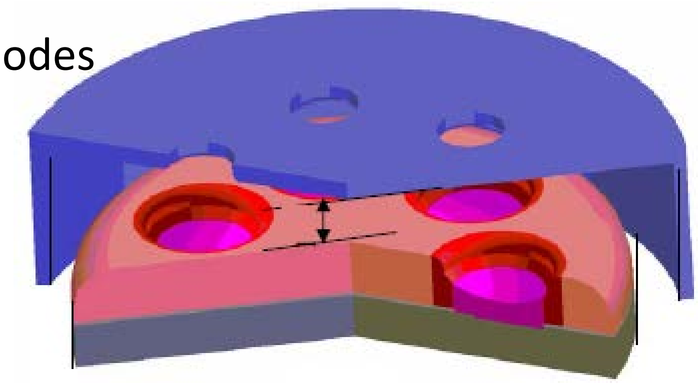


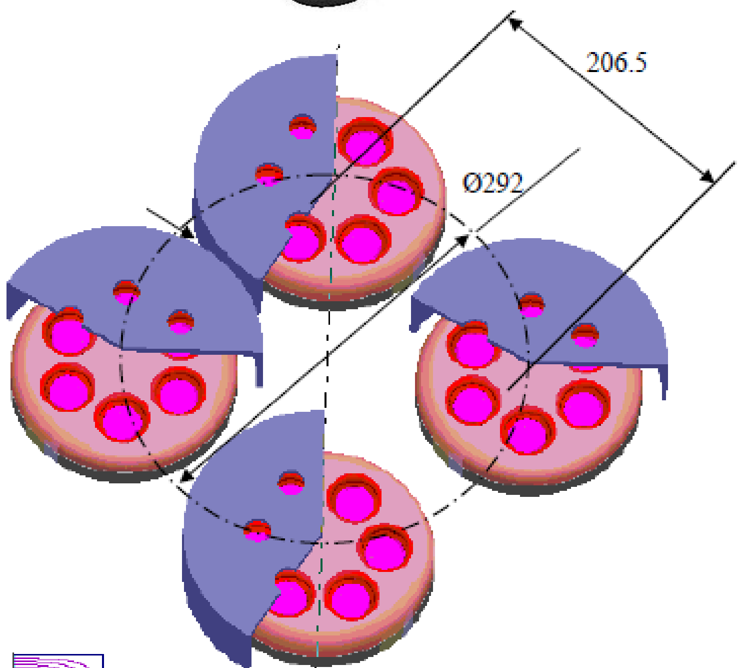
magnet system

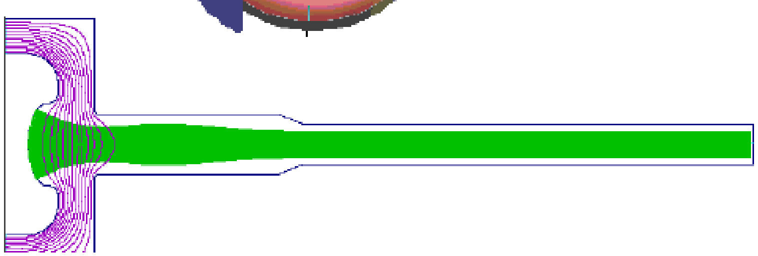
Collector

Electron Gun for Omega-P ILC MBK









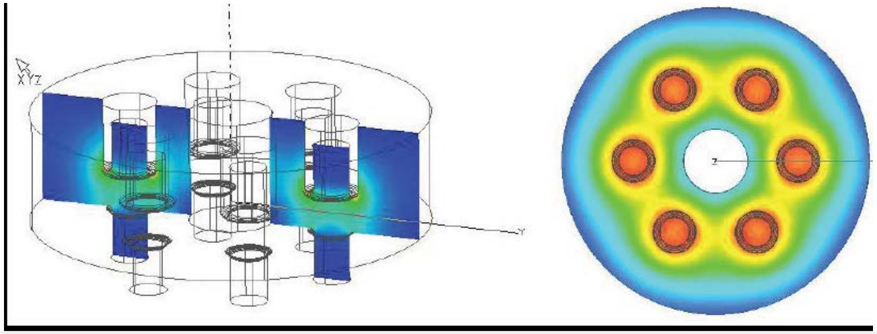
Gun for a 10-MW and 2.5-MW , 1.3-GHz, Low-Voltage Multi-Beam Klystron

Number of cathodes in one gun unit	6	
Beam voltage	60	kV
Beam-let current	12	A
Beam-let micro perveance	0.816	
Peak cathode loading	2.1	A/cm^2
Cathode loading in center	1.6	A/cm^2
Peak electric field on focus electrode	65	kV/cm
Cathode diameter	28	mm
Diameter of focus electrode	164	mm
Diameter of anode	192	mm

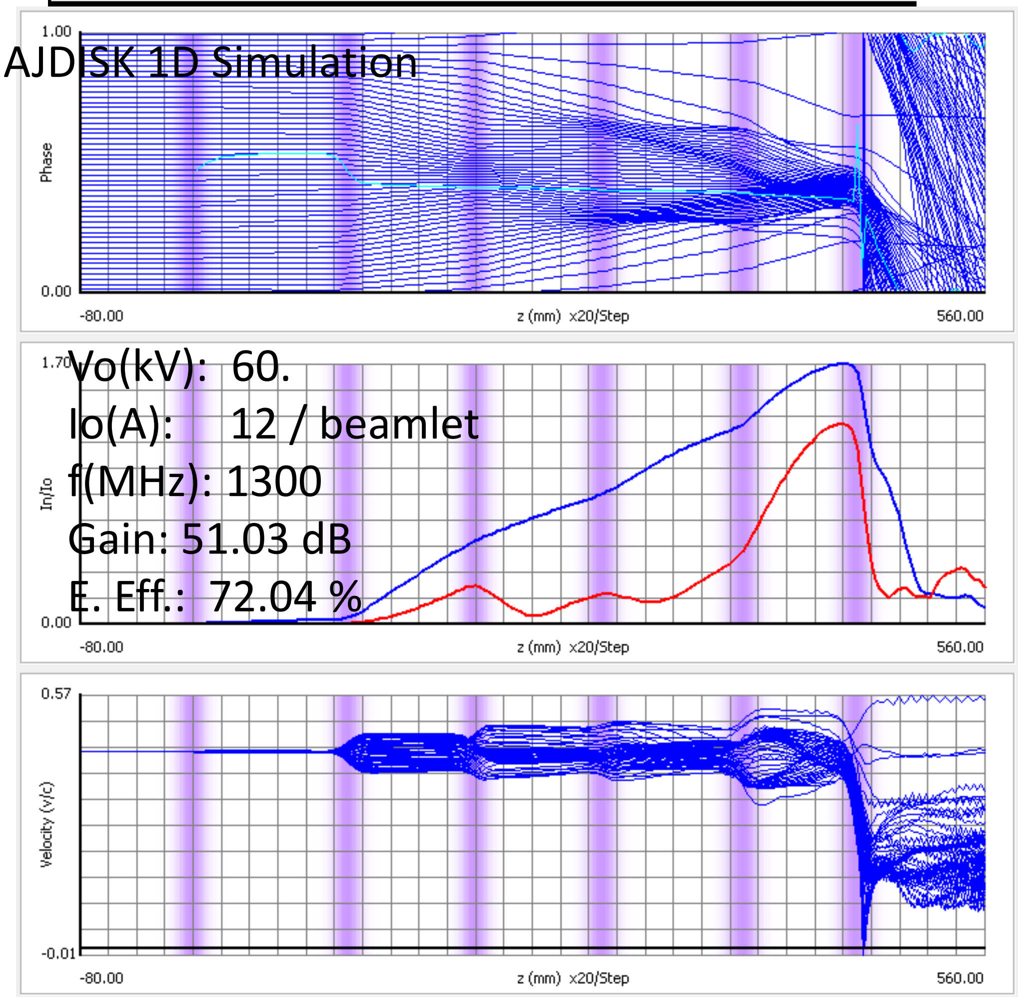
Beam-let and magnetic system parameters

Beam-let tube diameter	16	mm
Operating Beam-let Diameter	10	mm
Operating Magnetic Field in Solenoid	1000	G
Operating Magnetic Field on Cathode	124	G
Brillouin Magnetic Field (D_{beam}=10mm)	370	G
Brillouin Relationship ($B_{solenoid}/B_{Br}$)	2.7	
Operating Current in Cathode Solenoid	96.25	A-turn per cm
Operating Current in Main Solenoid	801.4	A-turn per cm

Beam Dynamics of Omega-P ILC MBK



AJDISK 1D Simulation



Vo(kV): 60.

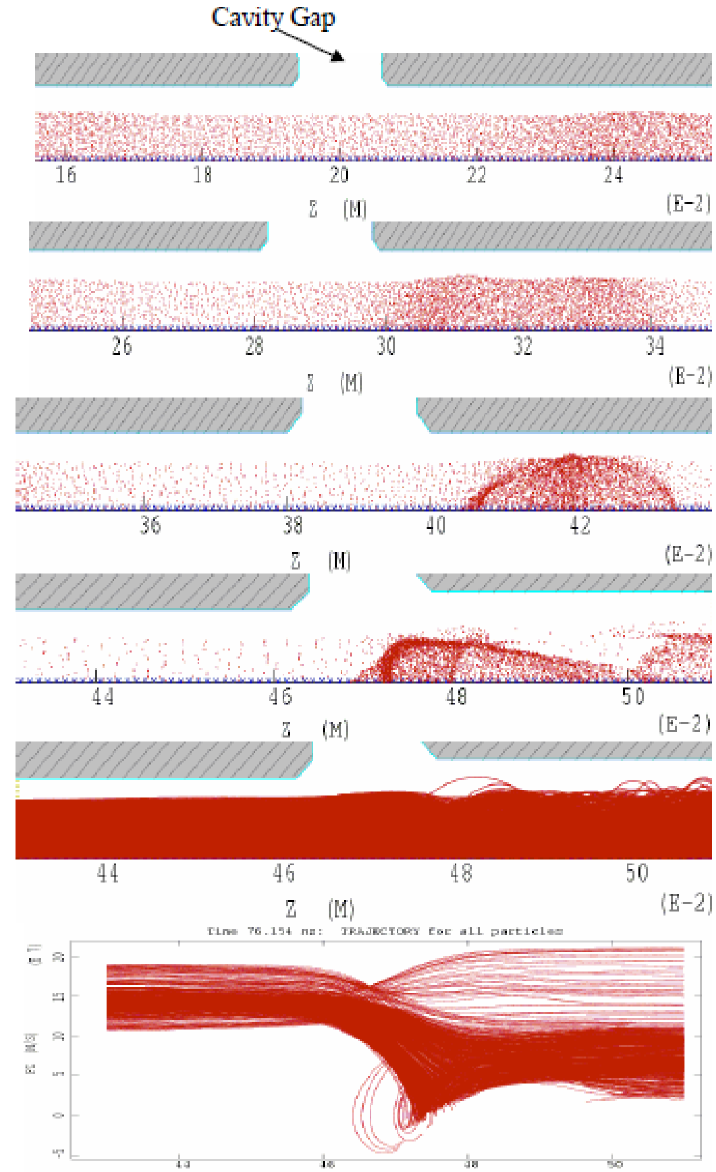
Io(A): 12 / beamlet

f(MHz): 1300

Gain: 51.03 dB

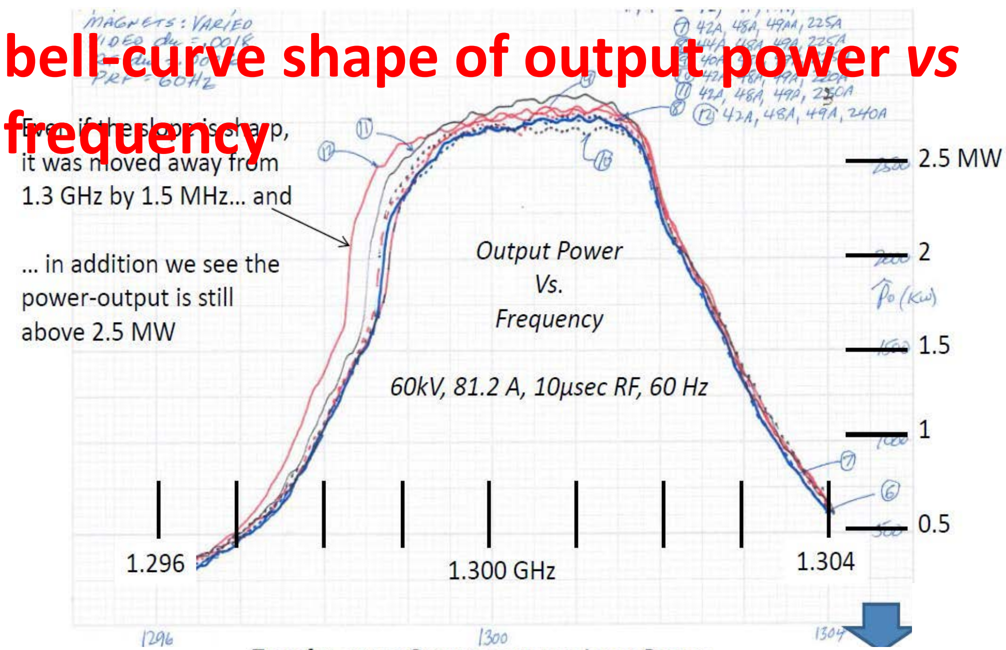
E. Eff.: 72.04 %

2D Simulations. MAGIC Results. Beam Dynamics



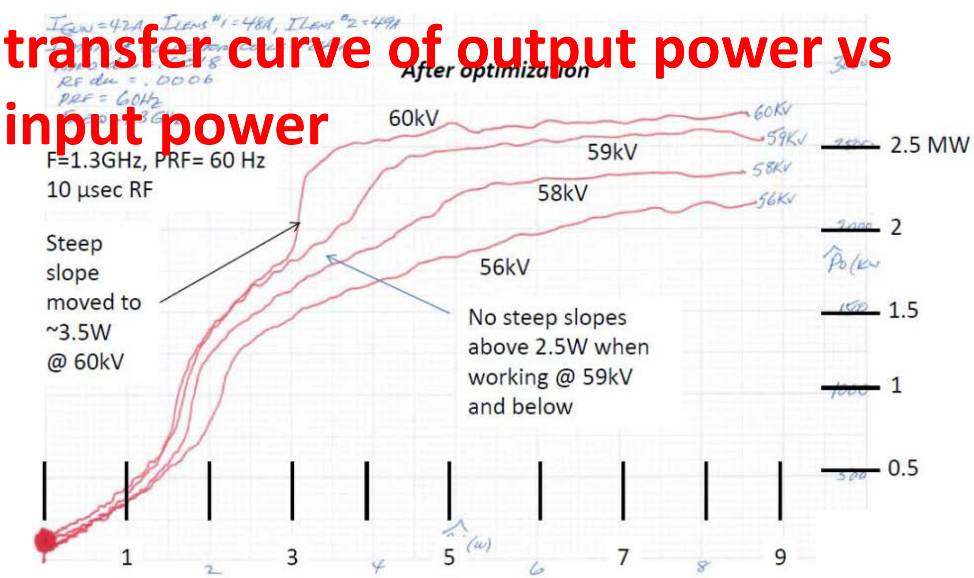
Test Results of Omega-P ILC MBK

bell-curve shape of output power *vs* frequency



Transfer curve: Output-power vs Input Power

transfer curve of output power vs input power

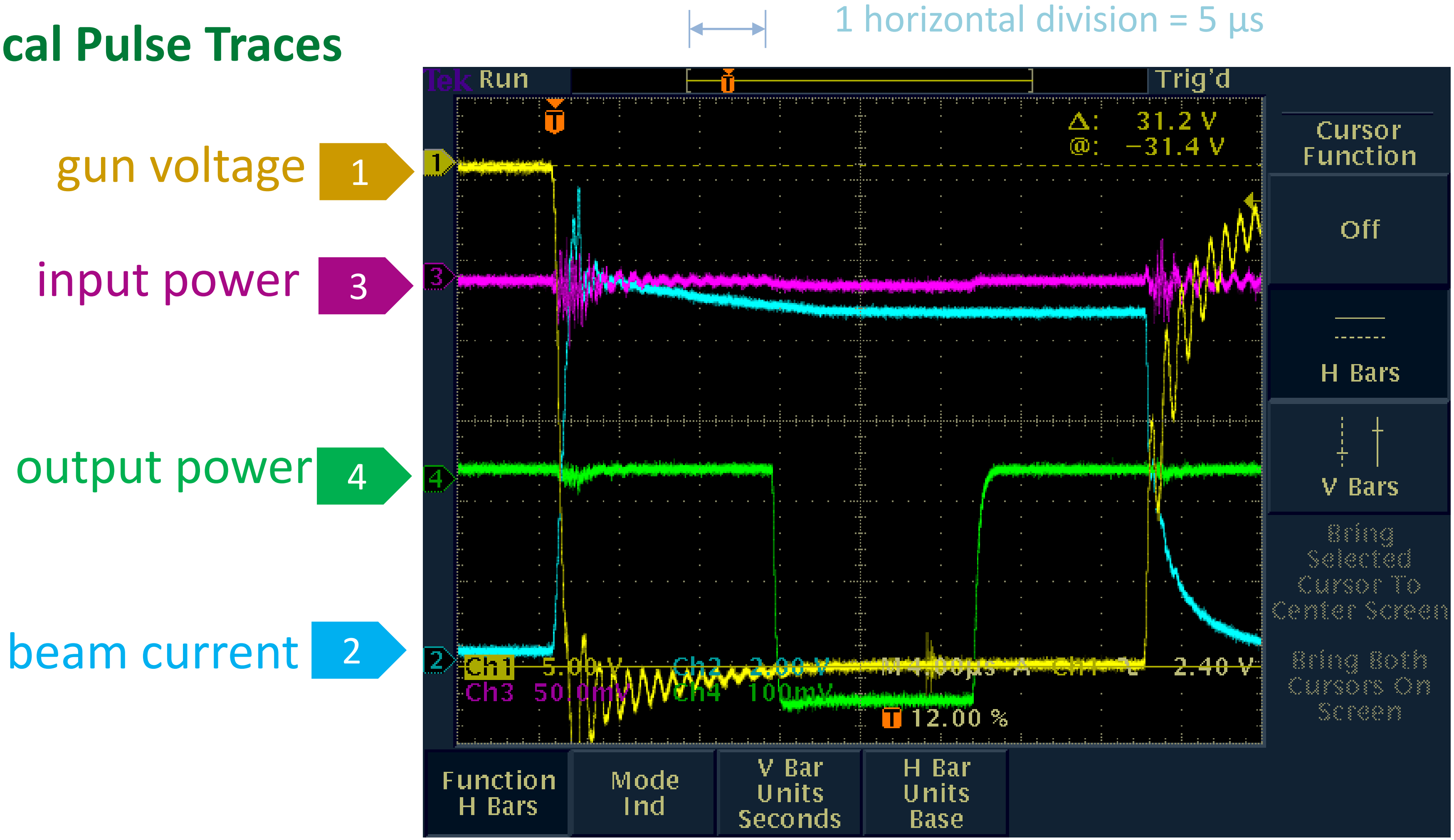


Initial Test @ CPI Site
RF trials less than 3 days

- Conditioning without RF drive (140 µs pulses at a 60 Hz repetition rate up to 66kV) was stopped at 53% of full rated duty.
- RF tests done at 10-15 µs RF pulses, output up to 2.86 MW at operating voltage 60 kV with 56 dB gain and high efficiency (59%) with acceptable beam interception.
- No showstopper for achieving full duty operation (i.e. 1.6 ms pulses at a 10 Hz repetition rate).

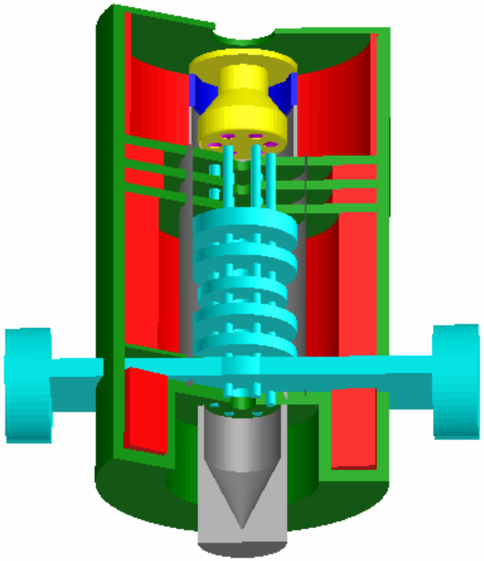
Pulse Traces of Omega-P ILC MBK

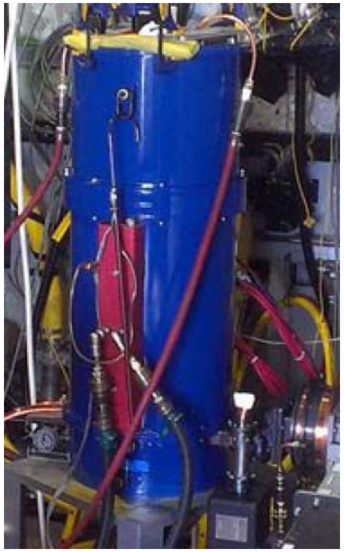
Typical Pulse Traces

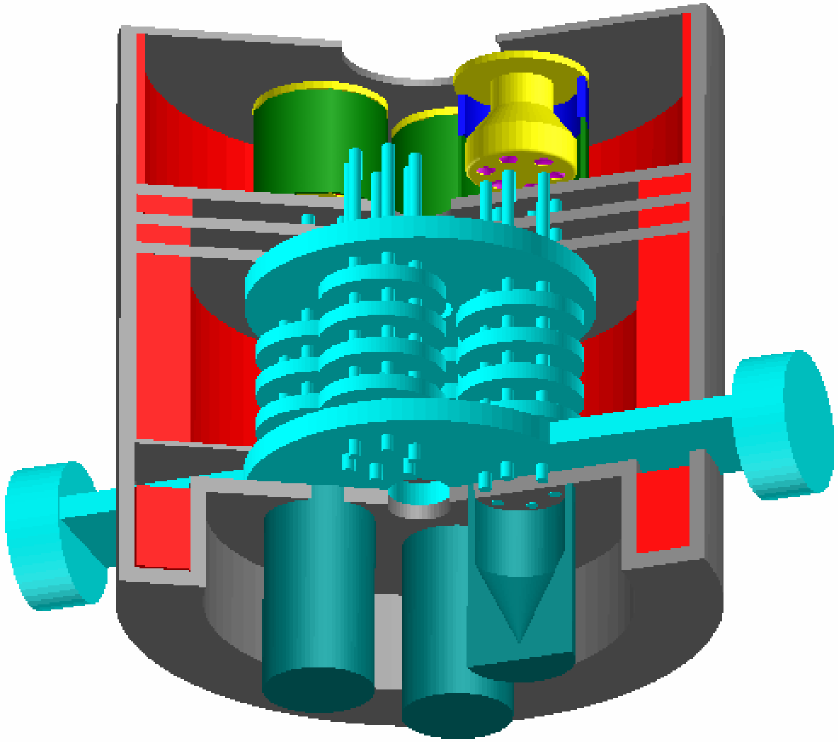


This ILC MBK configuration is close to parameters for CW operation. As it has demonstrated close-to-design performance, it will be the basis for a CW MBK design.

2.5MW MBK as Prototype of 10MW Version







2.5 MW QUADRANT KLYSTRON PARAMETERS

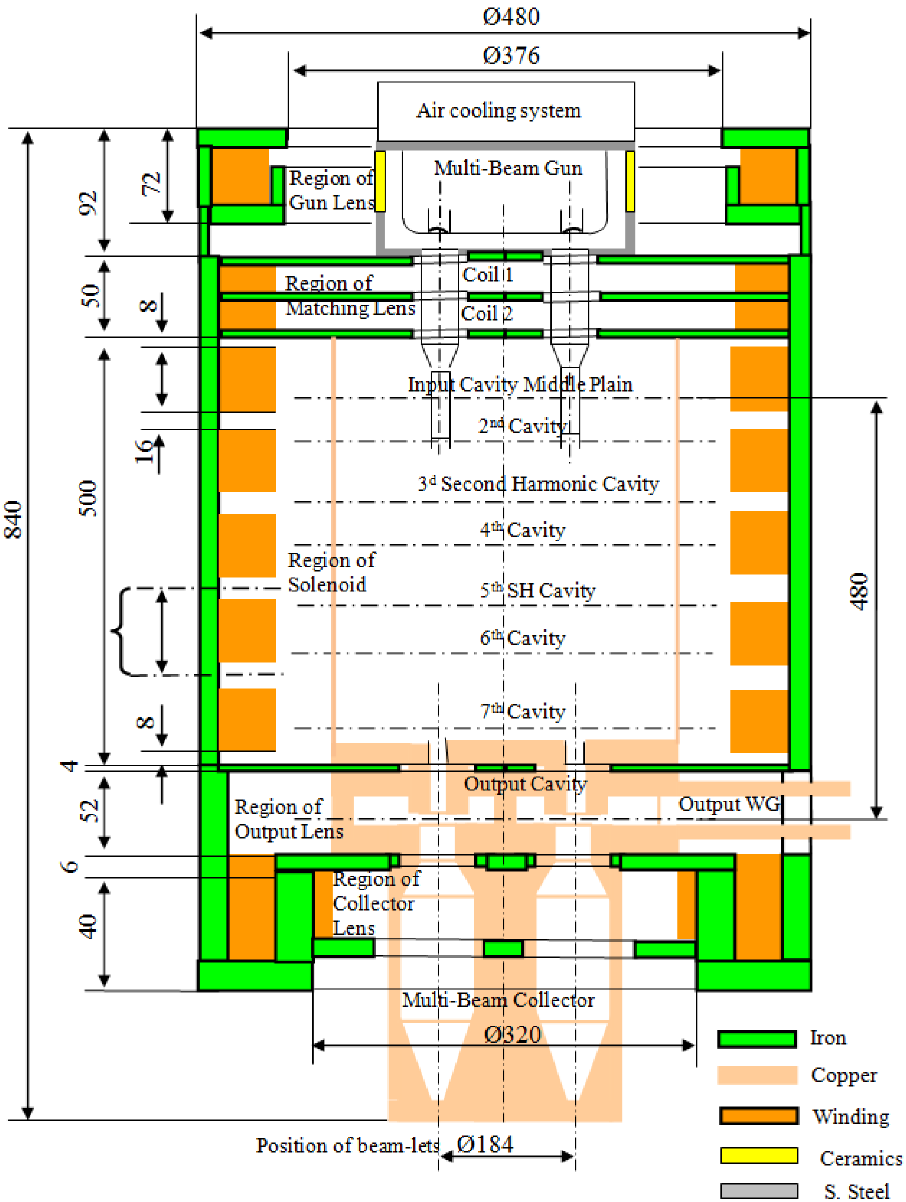
Operating Frequency	1300	MHz
Beam Voltage	60	kV
Number of Beam-lets	6	
Beam-let Current	12	A
Beam-let Micro Perveance	0.816	
Total Beam Current	72	A
Total Micro Perveance	4.9	
Simulation Efficiency	66.6	%
Practical Efficiency	62 – 63	%
Output RF Power	2.5	MW
Average Output RF Power	40	kW
Pulse Duration	1.5	ms
Saturated Gain	50	dB
Saturated Input RF Power	25	W
Solenoid Magnetic Field	1000	G
Drift Tube Diameter	16	mm
Beam Diameter	10	mm
Peak Cathode Loading	2.1	A/cm^2
Peak of Electric Field on Focus Electrode	65	kV/cm
Peak Surface Electric Field in Output Cavity	95	kV/cm

TABLE OF 10 MW KLYSTRON PARAMETERS

Operating Frequency	1300	MHz
Beam Voltage	60	kV
Number of Beam-lets	24	
Beam-let Current	12	A
Beam-let Micro Perveance	0.816	
Total Beam Current	288	A
Total Micro Perveance	19.6	
Simulation Efficiency	65.3	%
Practical Efficiency	60 – 63	%
Output RF Power	10.7	MW
Average Output RF Power	150	kW
Pulse Duration	1.5	ms
Saturated Gain	50	dB
Saturated Input RF Power	100	W
Solenoid Magnetic Field	1000	Gs
Drift Tube Diameter	16	mm
Beam Diameter	10	mm

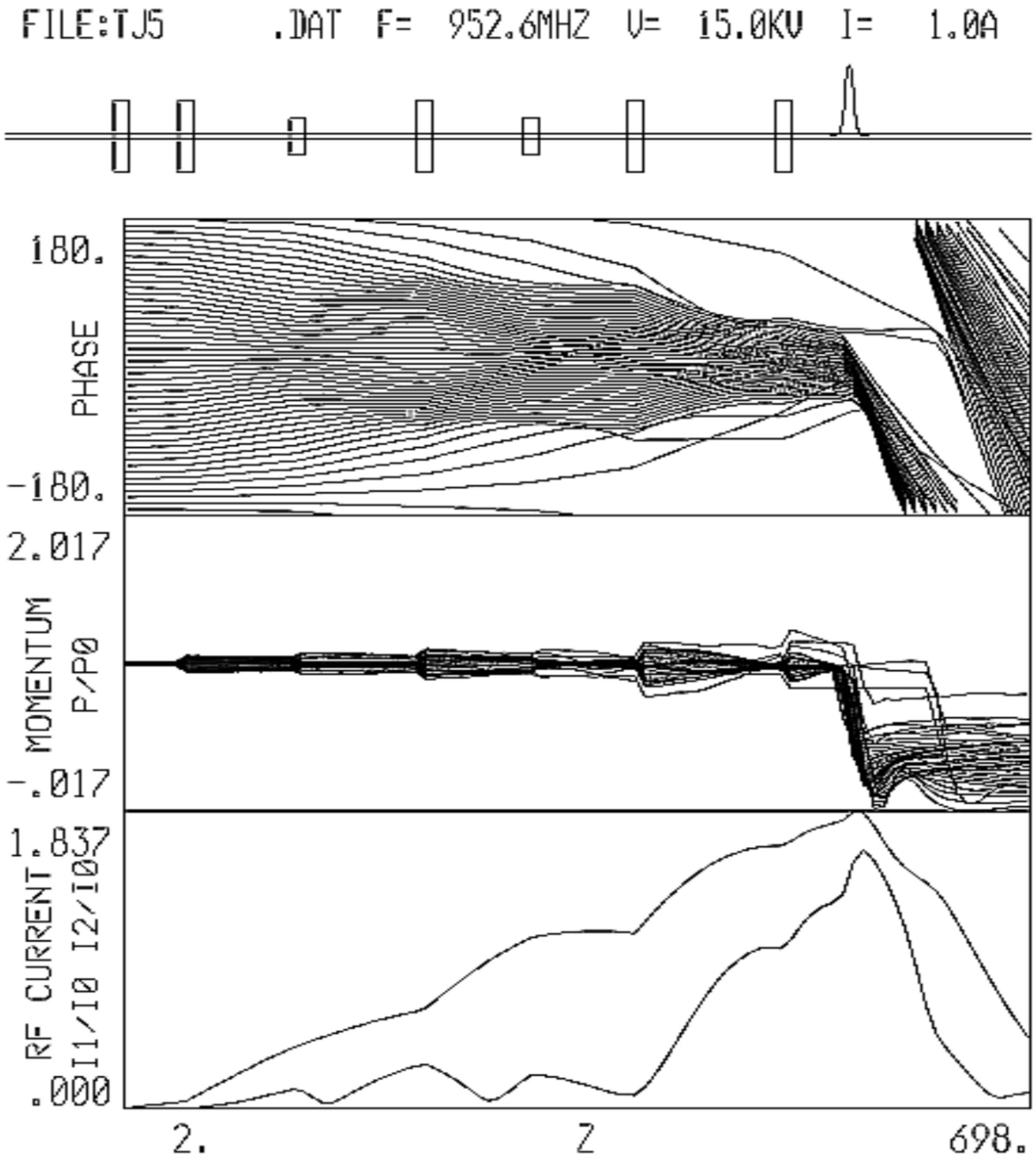
Conceptual Design of 952 MHz 100 kW MBK

952.6 MHz 100kW CW MBK for Electron Ion Collider (EIC) Application



Number of cavities	8	
Number of beam-lets	12	
Operating frequency	952.6	MHz
Beam voltage	15	kV
Single beam-let current	1	A
Total beam current	12	A
Beam-let micro-perveance	0.544	$\mu AV^{-3/2}$
Beam power	180	kW
Output RF power	126	kW
Input RF power	24	W
Saturated efficiency	70	%
Saturated gain	37	dB
Cathode loading	1.4	A/cm^2
Length of cavity circuit	~550	mm
Total length of CW MBK	~850	mm
Maximum magnetic field	400	Gauss
Power of magnetic system	<1	kW
Maximum collector power	120	kW

Beam Dynamics of 952MHz CW MBK

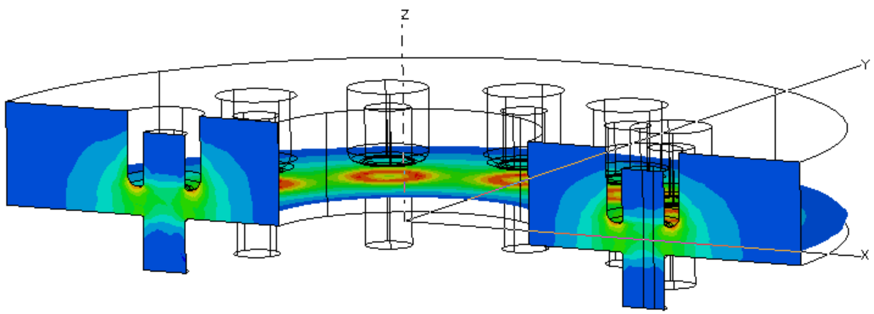


Development of 650 MHz 100 kW CW MBK

- The initial test of 1.3 GHz 2.5MW Omega-P ILC MBK has validated circuit design and construction techniques.
- Conceptual design of 952MHz CW 100kW MBK has been studied, so that 650 MHz version with similar performance and dimensions can be readily scaled.
- Development of 650MHz CW 100kW MBK for Proton accelerator application has been initiated.
- Similar to 10 MW ILC MBK based on 2.5MW version, clustering multiple quadrants to provide higher power (>= 500 kW CW) can be designed, as the beam dynamics and collector in each quadrant can be designed identically.

Preliminary Design of 650 MHz 100 kW CW MBK

Use configuration similar to 952MHz MBK
8 cavities, 12 beamlets

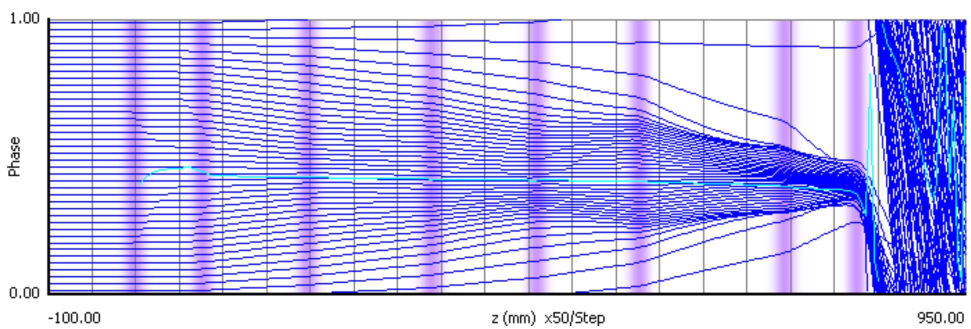


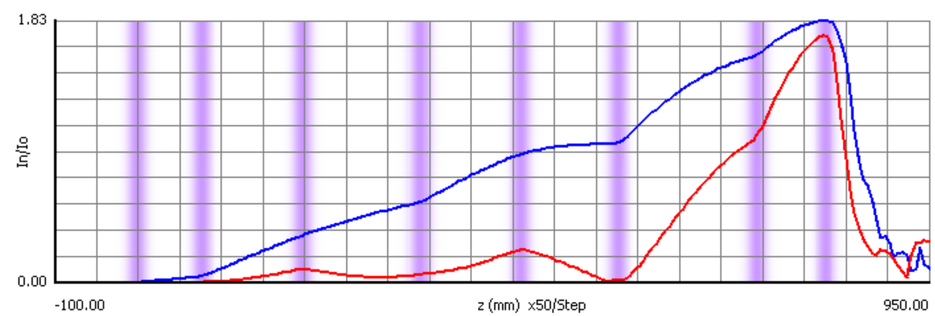
Each Beamlet

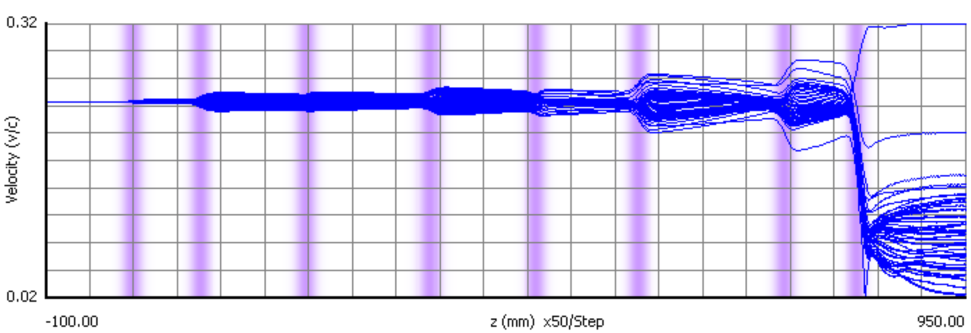
Beam Voltage (kV)	15.000
Beam Current (A)	1.000
Frequency (MHz)	650.000
Pin (W)	2.000

Gain: 37.73 dB
Pout: 11.870 kW

C. Eff.: 98.66 %
E. Eff.: 81.17 %
Total: 80.08 %

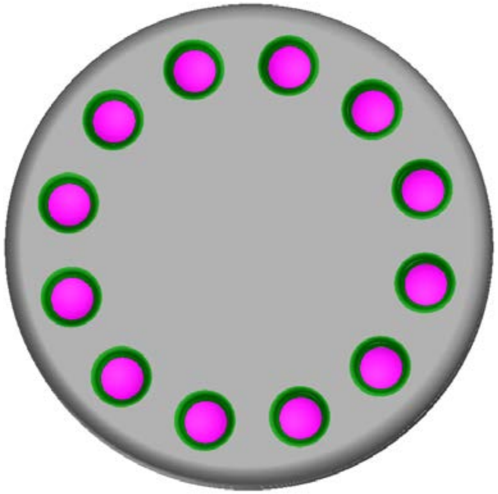


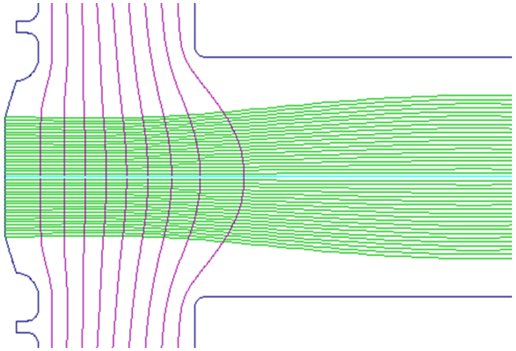


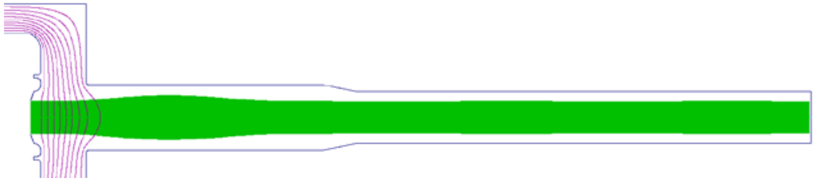


Preliminary 1D optimizations of the proposed 100kW CW klystron show rather high efficiency 80%. This will translate to at least 70% in the efficiency when 2D and/or 3D optimizations are performed.

Electron Gun of 100 kW CW MBK



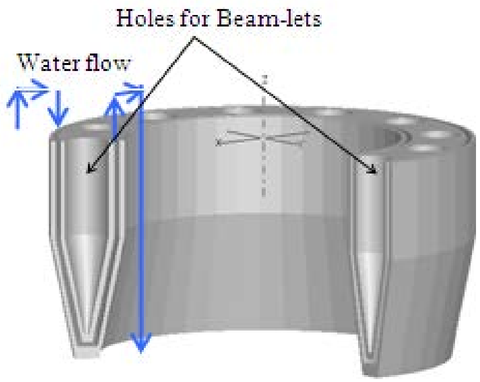


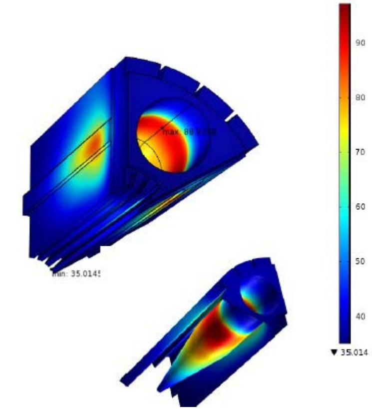


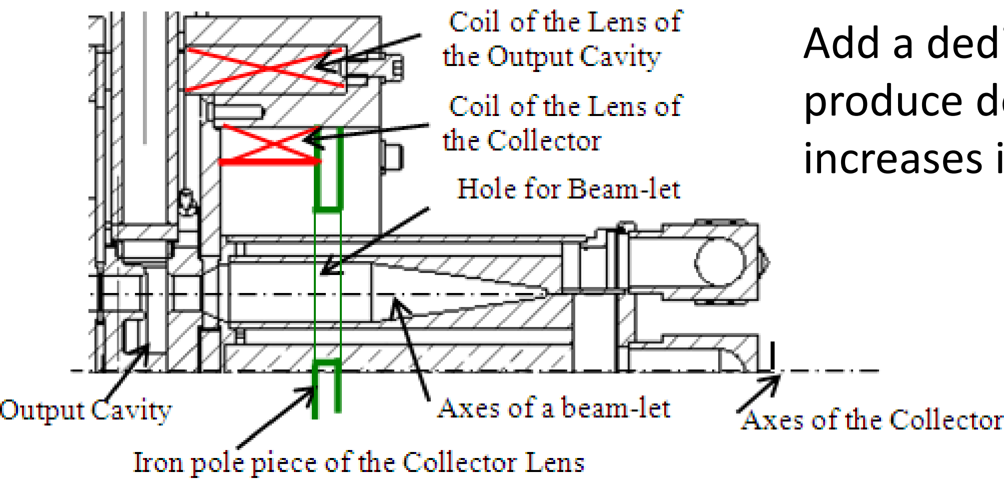
General features

- ❑ 12 micro-cathodes placed on a circle. Each micro-cathode forms a separate beam-let.
- ❑ low cathode loading (1.4A/cm^2) to increase the life time of the cathode.
- ❑ homogeneous magnetic field near to the cathode by gun coil.
- ❑ Beam focusing provided by gun coil, two lenses, and main solenoid, which allows adjust diameter of a beam-let in the solenoid to minimize beam-let ripples.

Collector Design of 100 kW CW MBK

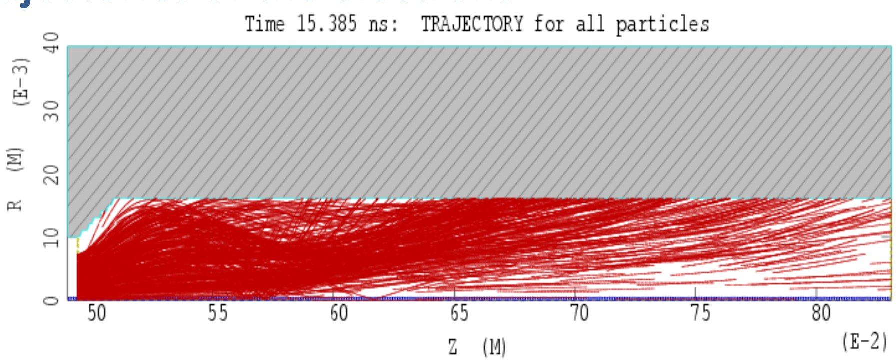


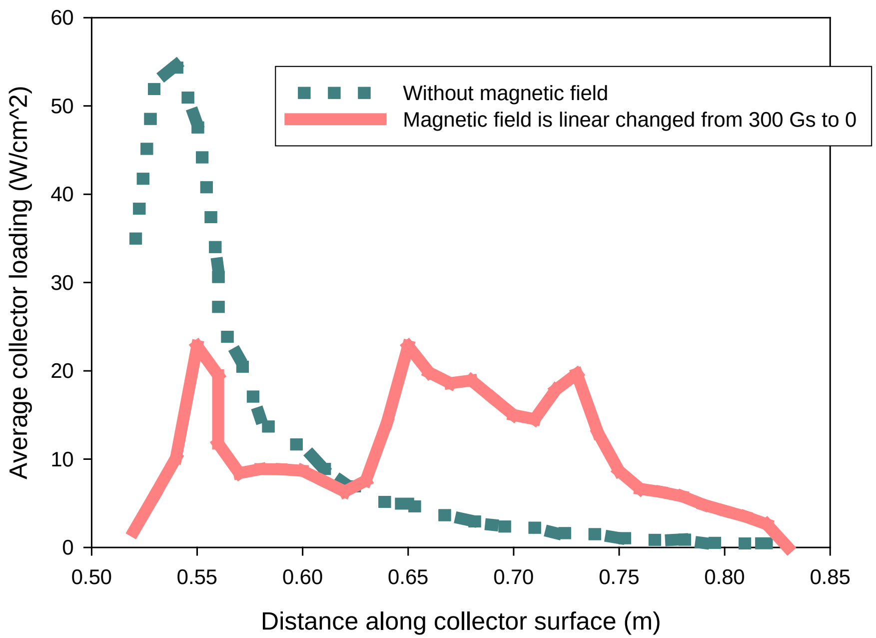




Add a dedicated magnetic lens in the collector to produce defocusing field, reduce peak loading and increases its power capability.

Trajectories of the electrons

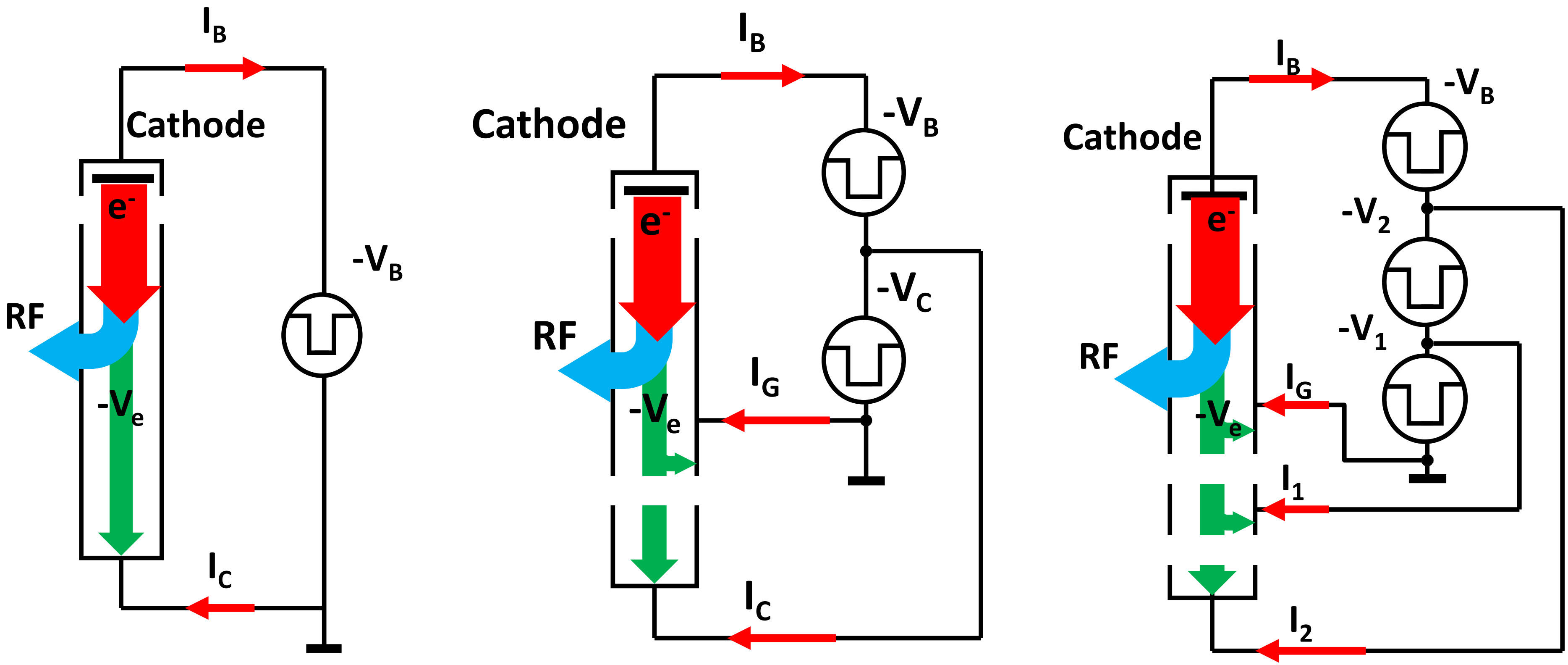




Review: Depressed Collector

Schematics of Microwave Tubes

without DC | with Single-Stage DC | with Multi-Stage DC



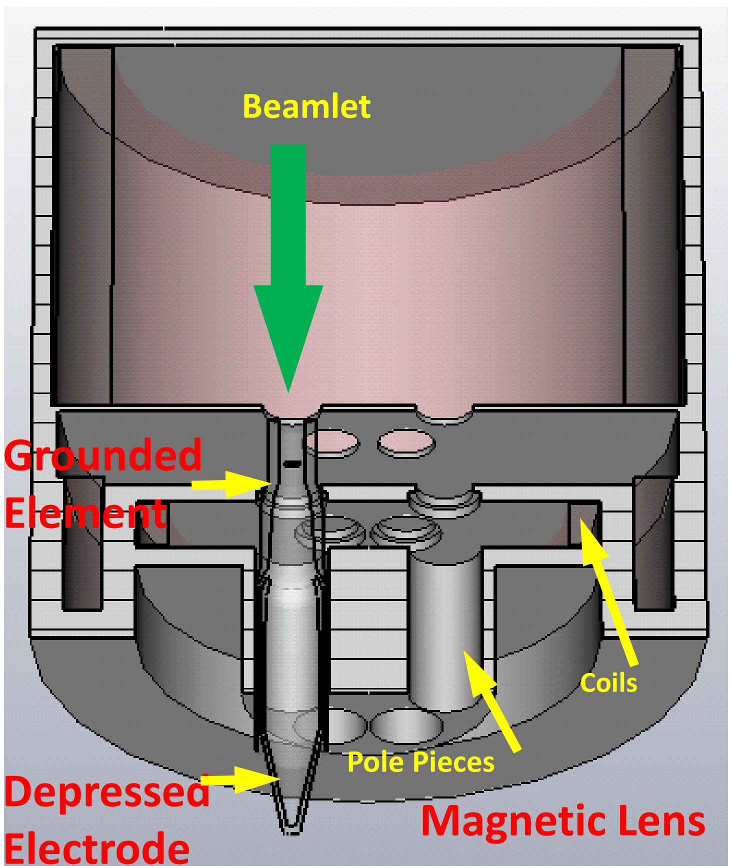
For efficiency enhancement, optimize the recovered power $\boldsymbol{I_c(V_c)}$x$\boldsymbol{V_c}$ for the spent beam entering the depressed collector, where $\boldsymbol{V_c}$ depressed potential, $I_C = \int_{V_C}^{\infty} J(V)dV$ collected current, and $\boldsymbol{J}$(V) current distribution vs. voltage

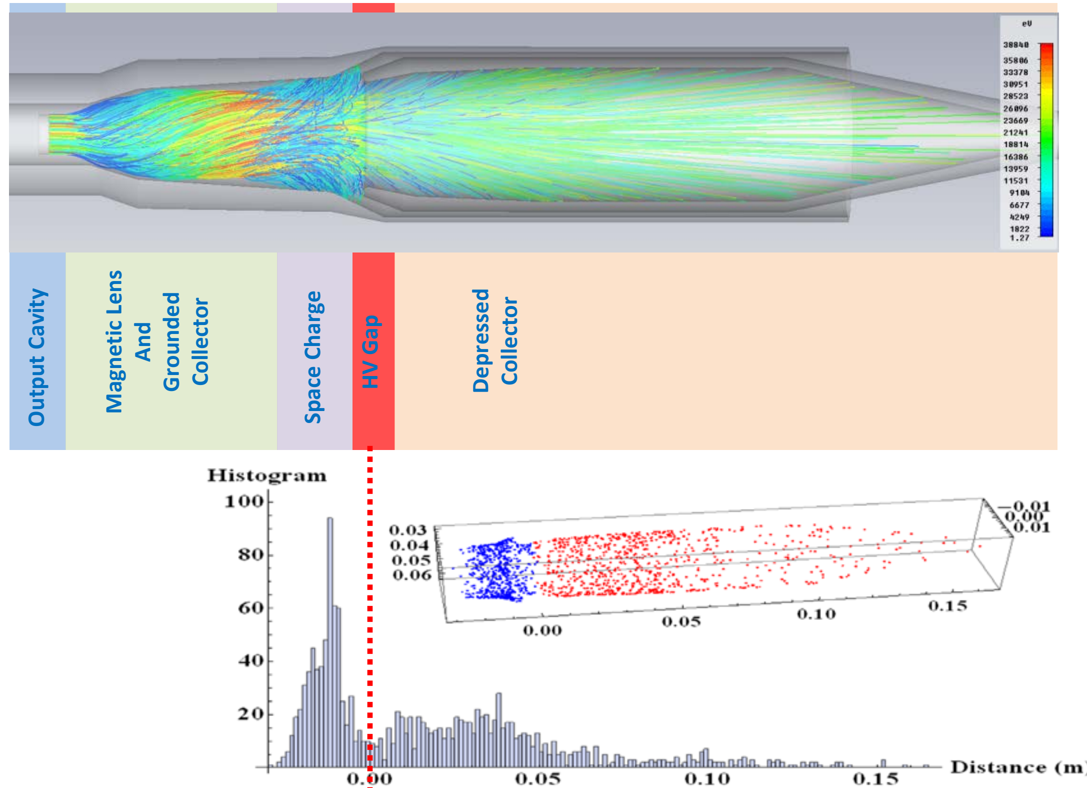
Novel Depressed Collector Design for MBK

Partially-Grounded Depressed Collector (PGDC)

Composition:

- Grounded Element
- Magnetic Lens
- Depressed Electrode

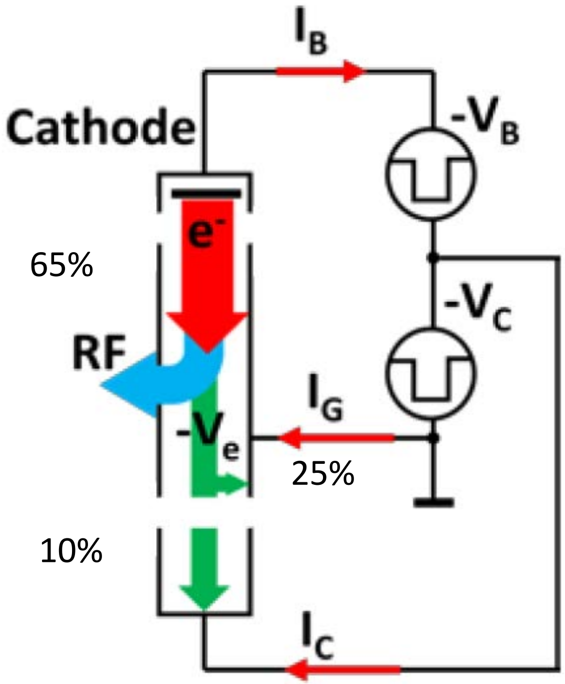


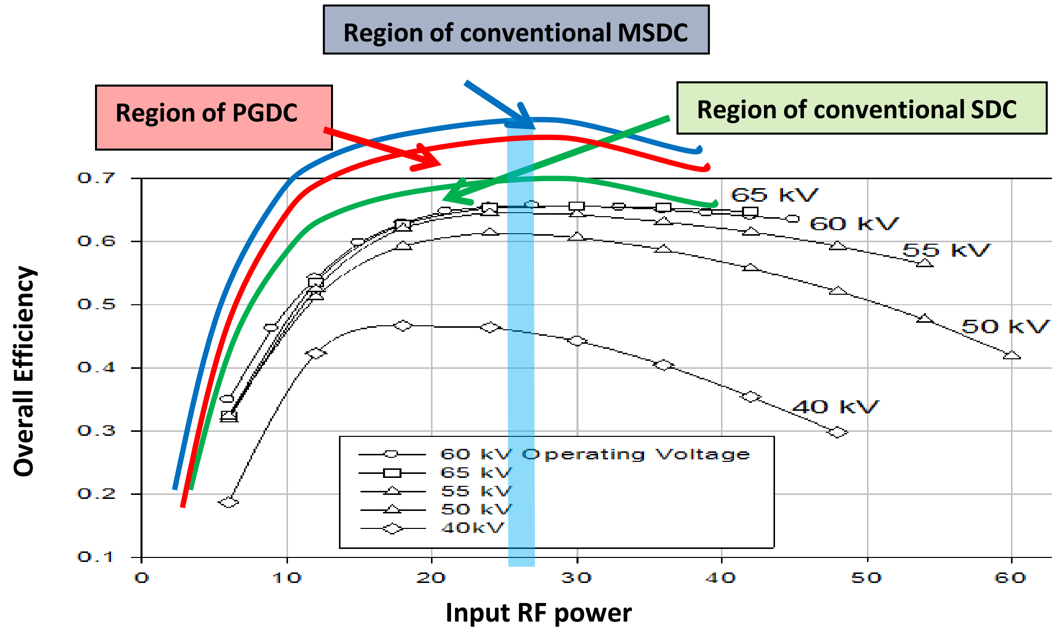


❑Steep B-field gradient and space charge forces
→transverse deflection and trapping electrons

❑Grounded section absorbing otherwise reflected low-energy electrons

Total Efficiency for ILC MBK with PGDC





Optimal tube efficiencies above **75%** for a single-stage PGDC

Partially grounded depressed collector

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Publication type	Grant
Application number	US 14/846,151
Publication date	Jun 6, 2017
Filing date	Sep 4, 2015
Priority date	Sep 4, 2014
Also published as	US20160071681, WO2016037075A1
Inventors	Yong Jiang, Vladimir TERYAEV, Jay Hirshfield
Original Assignee	Omega-P, Inc., Yale University

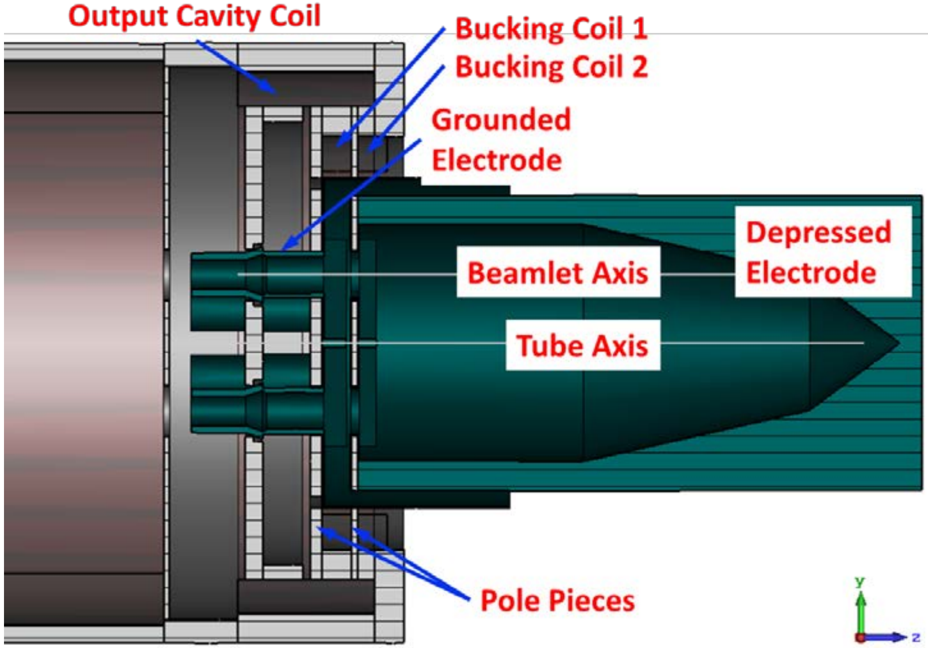
DoE SBIR FY17 Phase II Funded

Reference:

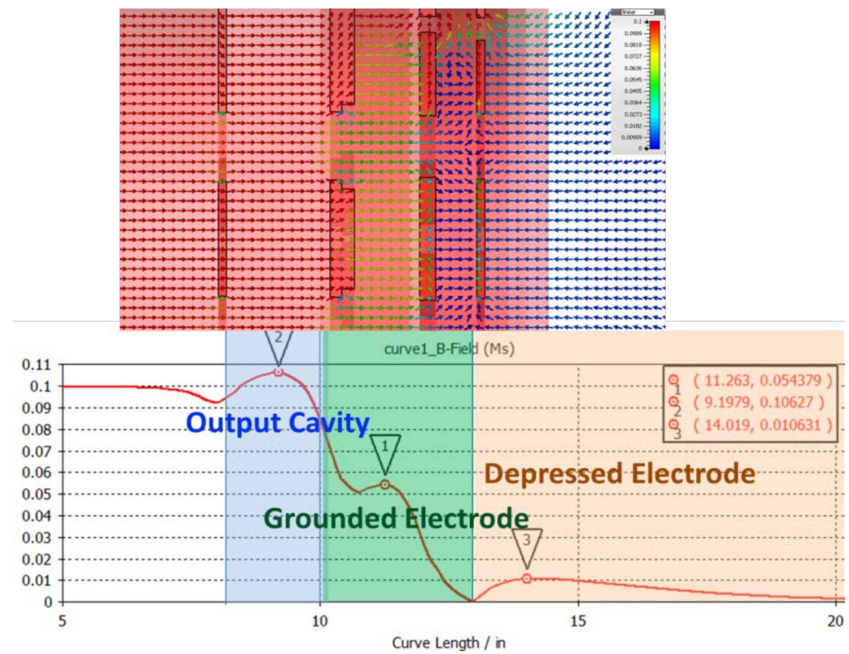
Y.Jiang, V.E.Teryaev, J.L.Hirshfield, "Partially Grounded Depressed Beam Collector," in Electron Devices, IEEE Transaction, vol.62, no.12, pp.4265-4270(2015)

3D Model in CST Particle Studio

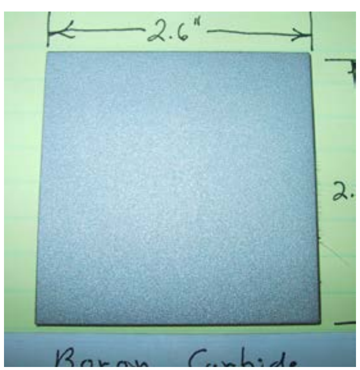
3D Modeling of PGDC

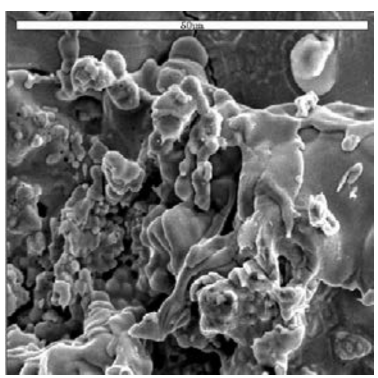


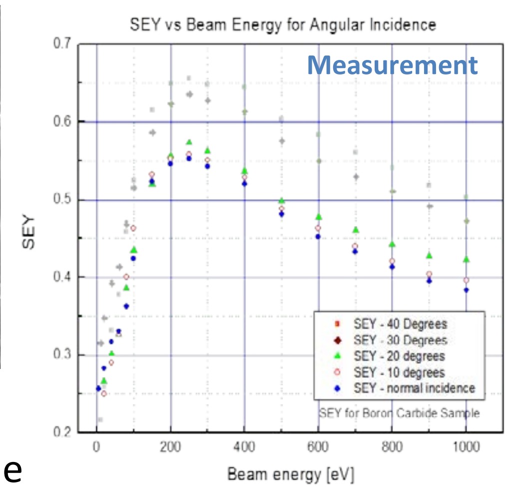
Magnetic field distribution

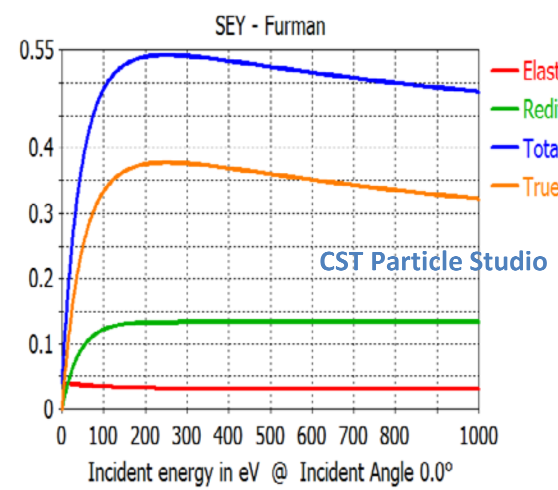


Secondary Emission





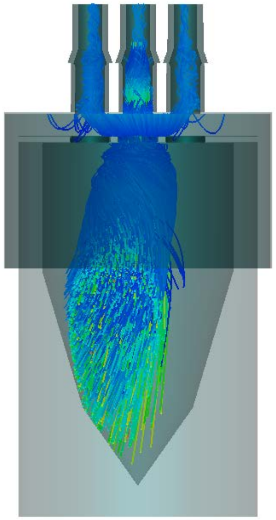


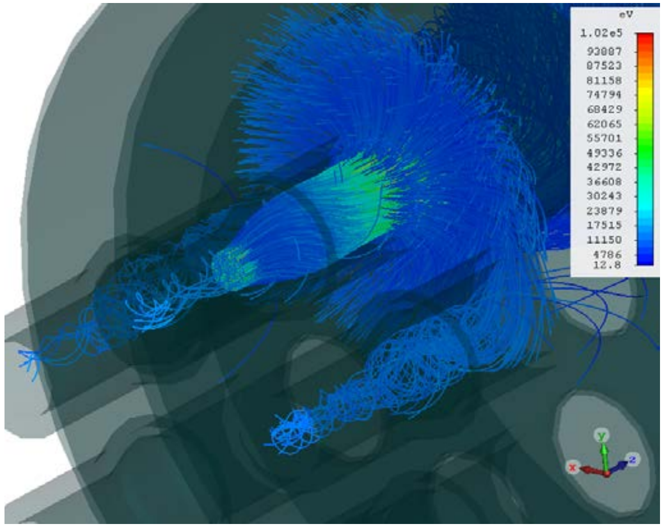


OFHC Copper Coated with Plasma Sprayed Secondary Emission Suppressor Boron Carbide

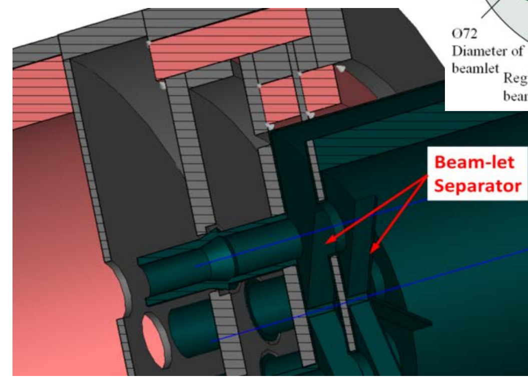
3D Model Optimization

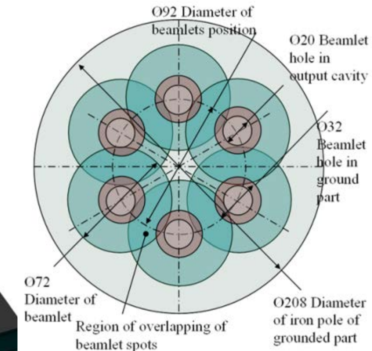
3D Simulation without Secondary Emission and Separator



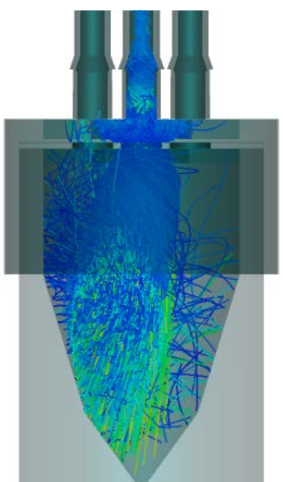


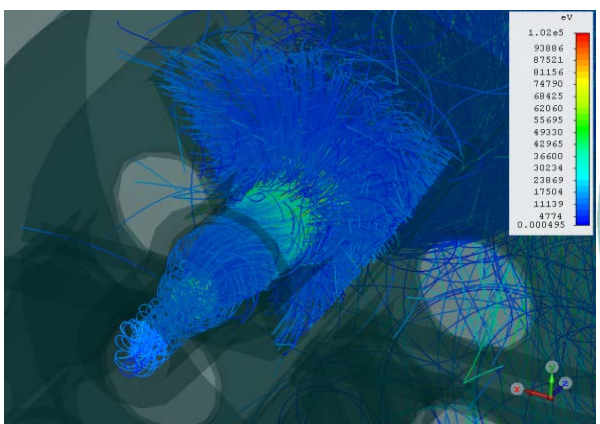
Detailed View

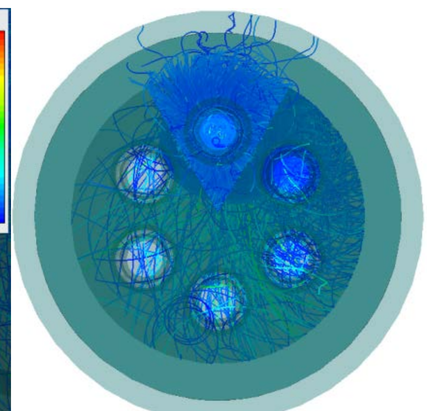




3D Simulation with Secondary Emission and Separator





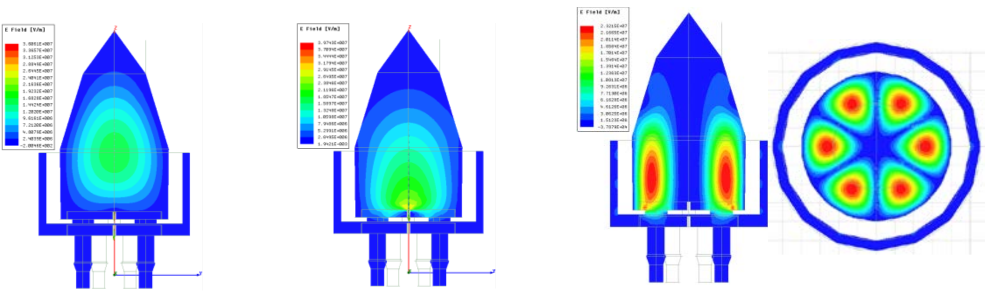


- collector efficiency 32.1%
- total tube efficiency 73.2%
- about 8% improvement
- approach theoretical expectation

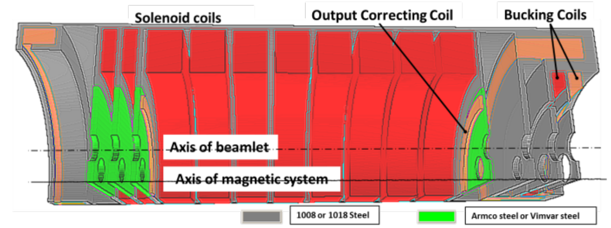
Other Considerations in Design

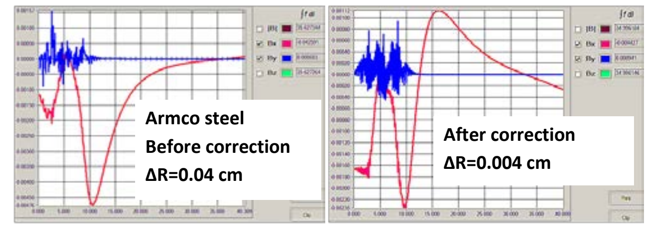
Possible Excited Modes in Depressed Collector

TE_{111}, TM_{010}, and TM_{310}

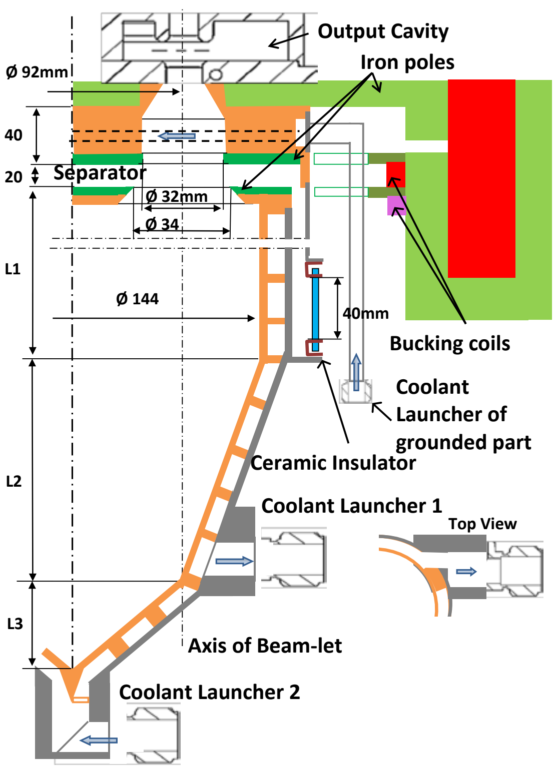


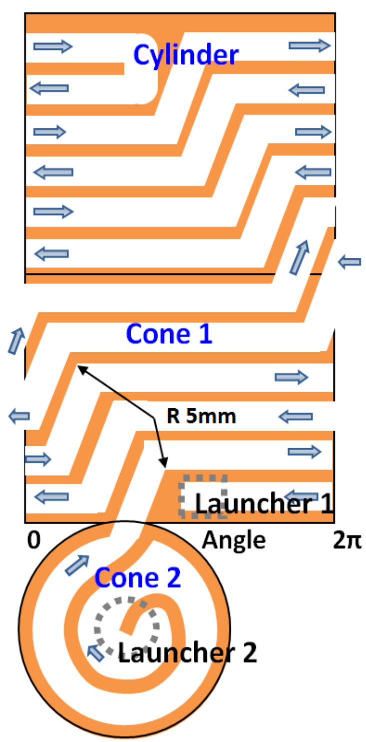
Transverse Magnetic Field

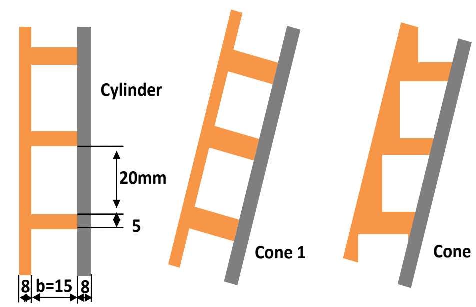


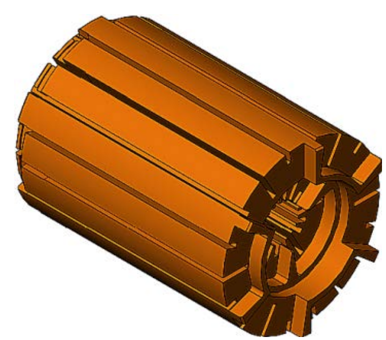


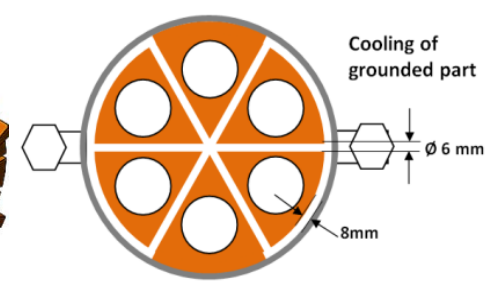
Cooling Channel and Insulator Design





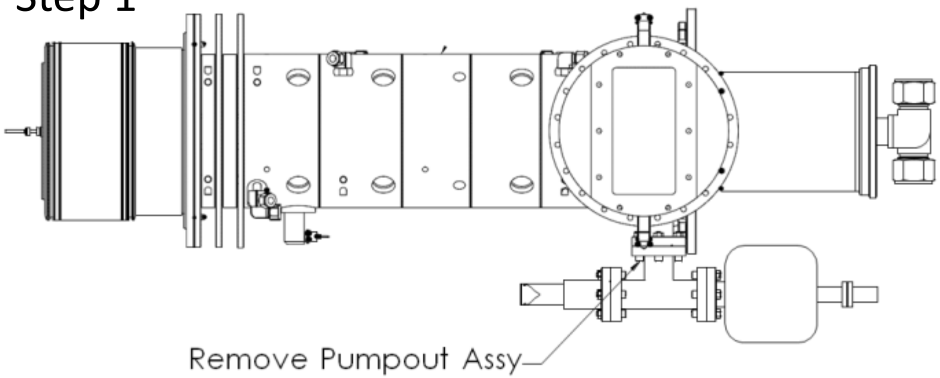




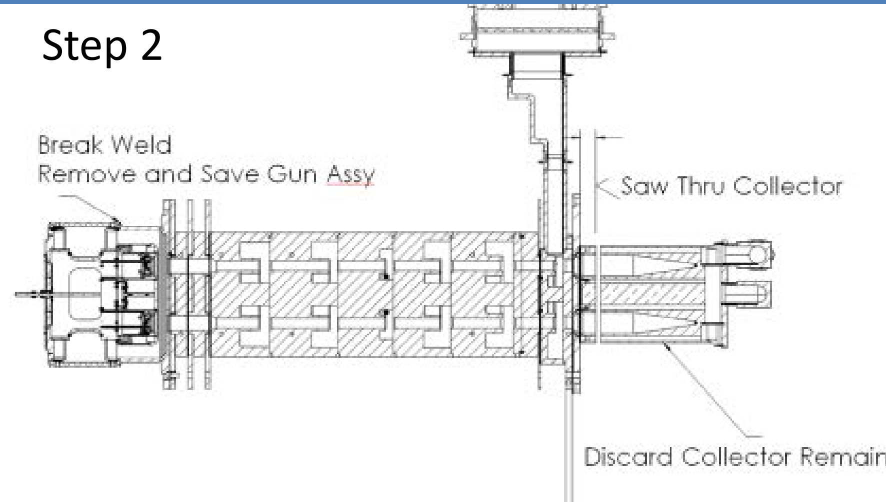


Omega-P ILC MBK Rework Plan

Step 1

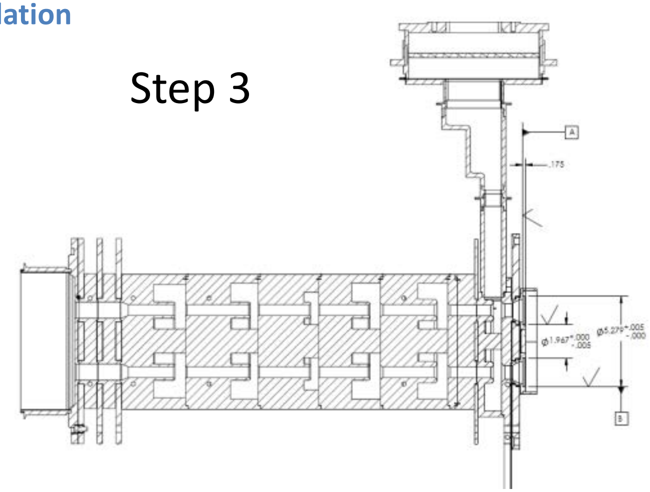


Step 2



O-MBK before magnet installation

Step 3



- ❑Remove magnet and pump-out assembly
- ❑Remove weld joint of the electron gun to the tube body, save away gun assembly
- ❑Saw off old collector at a location near to the output cavity pole piece
- ❑ Machine away the collector remnant
- ❑Outer shell of the old collector provide a welding location to install the new PGDC
- ❑Modify magnet and add collector bucking coils, output cavity correcting coil and pole pieces.

DoE SBIR Phase II Campaign

1. Test to full capacity at SLAC
2. Rework at CCR to add PGDC
3. Test again to compare tube efficiency

Summary

- 1.3 GHz 2.5MW Omega-P ILC MBK has been constructed. Good performance has been demonstrated in the initial test. It will be further tested to its full capacity during Phase II.
- Conceptual design of 952MHz CW 100kW MBK has been studied.
- Development of 650MHz CW 100kW MBK has been initiated. Main techniques have been proven, but further support required.
- Novel collector design will be applied to improve MBK efficiency.

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Omega-P R&D, Inc.

Yale University

http://bpl.yale.edu