L-Band High-Efficiency IOT

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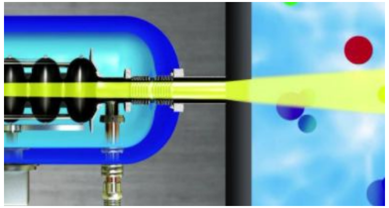
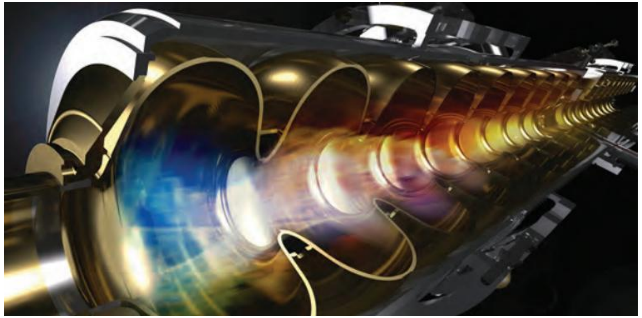
DOE ARDAP Accelerator Stewardship

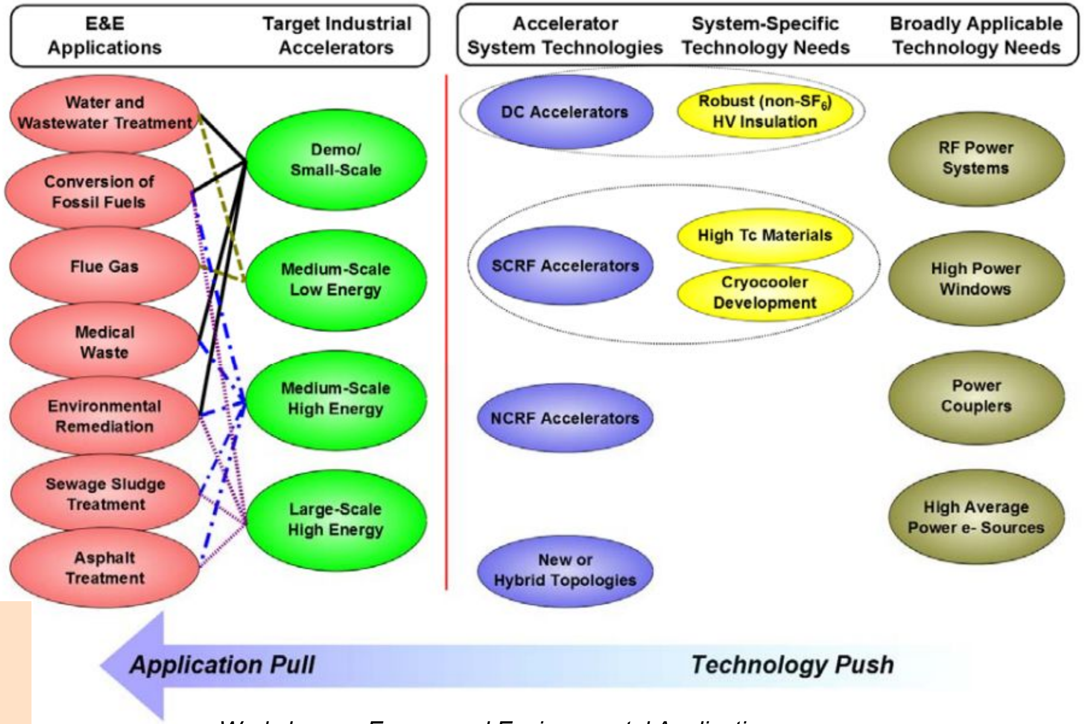
Motivation

- High average power accelerator systems for environmental and energy applications





Need high efficiency RF sources for next generation high average power accelerators



Workshop on Energy and Environmental Applications of Accelerators, DOE report 2015

Peak Power Cost and Scaling with Pulse Length of RF Source (from AC in to RF at Accelerating Structure)

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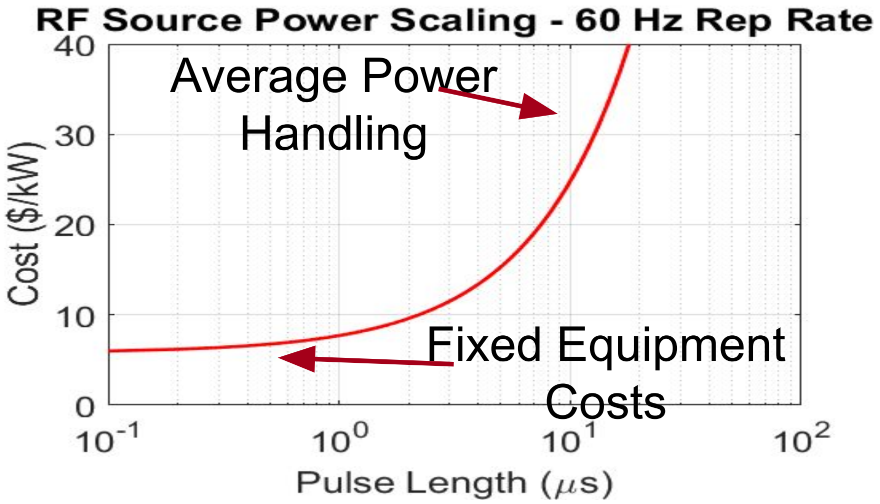
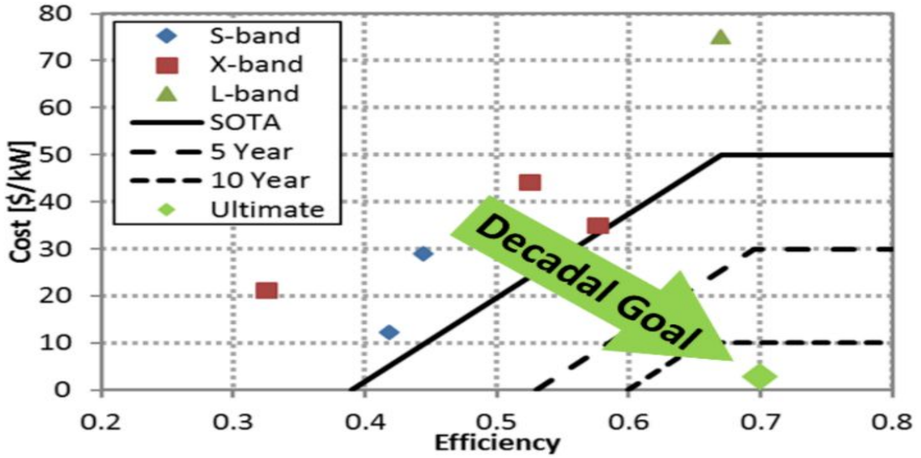
- Meeting the decadal goal of 70% efficiency at $2/kW is an *extremely* difficult challenge, regardless of frequency
- Peak power cost of RF source also scales with duty



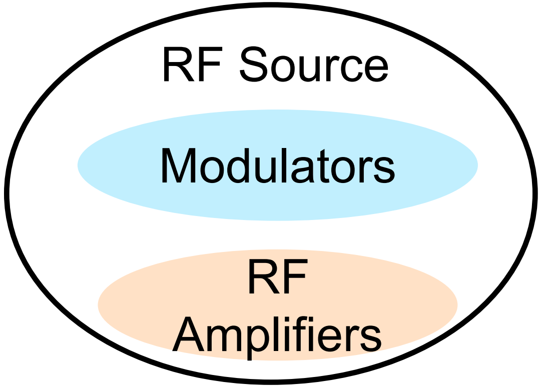


*Radiofrequency Accelerator R&D Strategy Report

Cost-scaling with duty has big impact – Model needs refinement as we progress towards decadal goal of $2/kW peak

The Present State of the Art Is Not Close to Fulfilling the Need: Basic and Applied R&D is Necessary

	Efficiency	*$/kW$_{peak}$*
Scandinova Modulator	90%	$10/kW
SLAC ILC Marx	88%	$40/kW
SLAC XL-4	40%	$20/kW
Common Household Cooker Magnetron	65%	$13/kW
CPI VKS-8262	45%	$8/kW
Total System Goal*	**70%**	**$2/kW**



Must increase total efficiency from 40% up to 70%, while decreasing cost by 10x

Research Thrusts

RF and Beam Physics

Novel Topologies

Fabrication Methodologies

Research Objectives

Low-Cost Systems

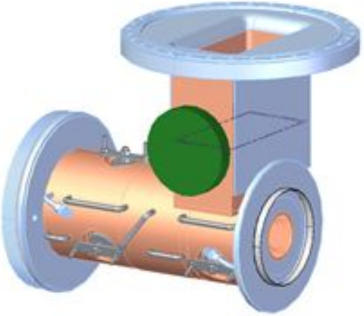
High Efficiency Systems

*System goals come from the 2017 DOE RF Accelerator R&D Strategy Report

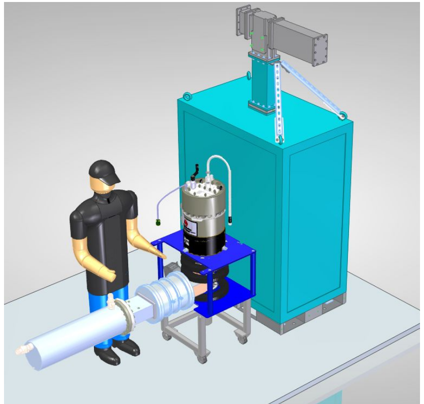
High Efficiency Inductive Output Tubes (HEIOTs)

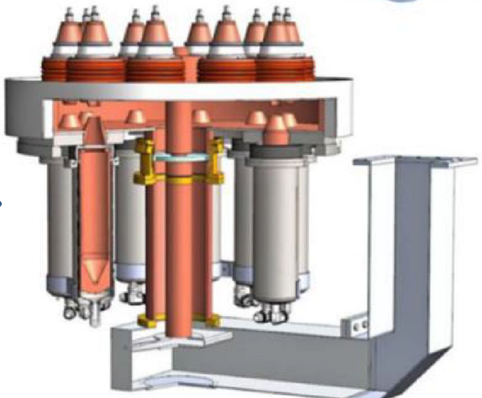
- Toward >80% DC-to-RF efficiency at 1 MW

- Efficiency is critical, must be maintained at variable output power levels
- Target: MW of CW at 1.3 GHz
  - 100 kW single RF source
  - Power combing
- Industrial partnership: Stellant system
- Applications: high average power accelerators



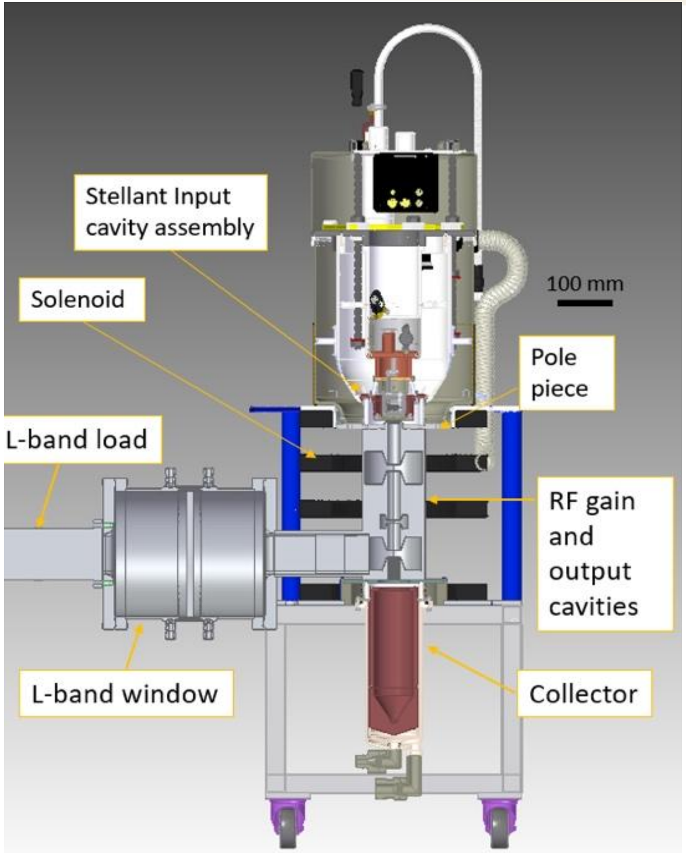
Single-beam Prototype: 1.3 GHz / 100 kW CW / 80% efficiency

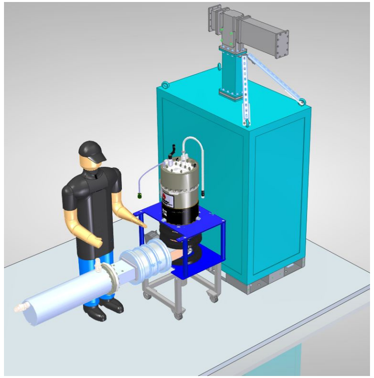




Conceptual design: RF circuit for 10-beam / 1 MW device

High Efficiency Inductive Output Tubes (HEIOTs)





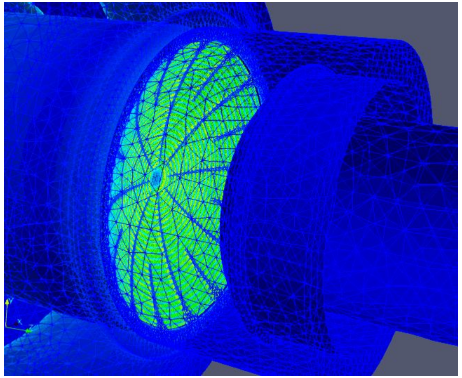
Parameter	Value
Cathode Voltage	40 kV
Frequency	1.3 GHz
Input RF power	550 W
Grid Bias	−220 V
Average Beam Current	3.2 A
Peak Focusing B-Field	470 G
Output power	100 kW
Peak efficiency	80%
Cavity 1 frequency	1.315 GHz
Cavity 2 frequency	2.615 GHz
Output cavity frequency	1.305 GHz
Output external Q	100

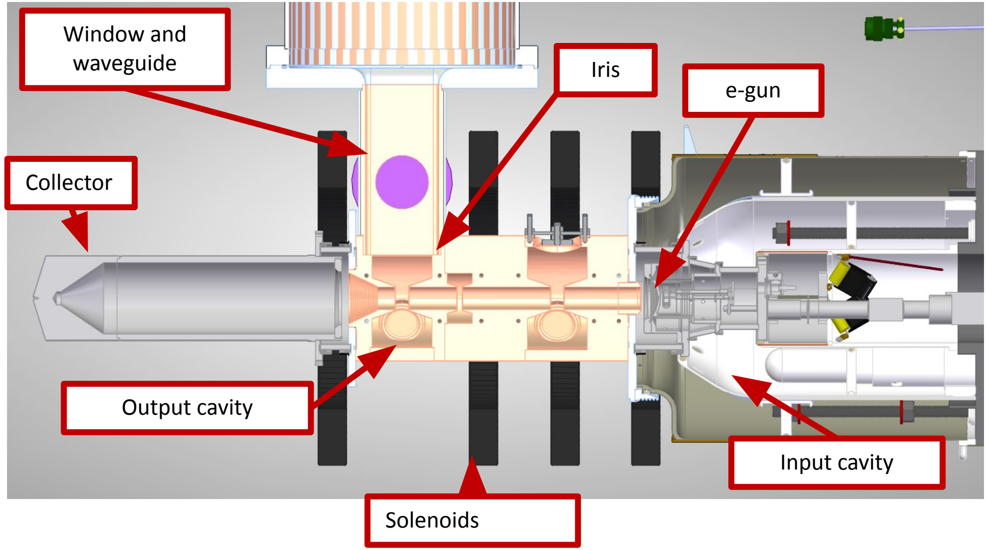
SLAC Stellant IOT 4447 is in production

Leveraging Advanced Modeling for IOT DEsign

IOT limitation in frequency can be pushed through understanding RF and beam dynamics in 3D

THis effort needed a rigorous understanding of the design complexity and how to leverage commercial part to optimize cost and efficiency





Parallel Electromagnetic Code Suite ACE3P

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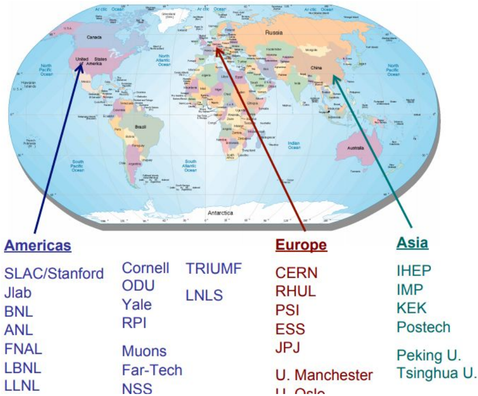
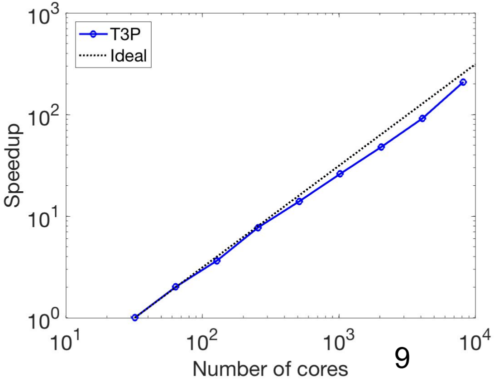
- Conformal, higher-order, massively-parallel finite-element based electromagnetic codes running on NERSC

ACE3P: Parallel Finite Element EM Code Suite
(Advanced Computational Electromagnetics, 3D, Parallel)

ACE3P Module	Accelerator Physics Application
Frequency Domain:	Omega3P – Eigensolver (w/ damping)
	S3P – S-Parameter
Time Domain:	T3P – Transients & Wakefields
	Pic3P – Particle-In-Cell (self-consistent)
Particle Tracking:	Track3P – Dark Current and Multipacting
Multi-Physics:	TEM3P – EM-Thermal-Mechanical

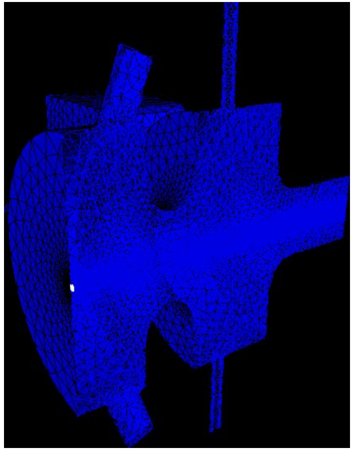
Fidelity | **Speed** | **Scale**





Particle in Cell Module for RF Gun Design: PIC3P

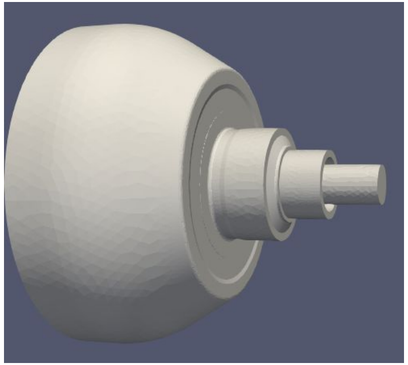
- **Low-energy space-charge calculations**
  - Self-consistent modeling of RF guns up to ~ 10 MeV (e-)
  - Space-charge, image charge effects, time retardation and wakefield effects are included from first principles, no “knobs“ to turn
  - Load RF map(s) (Omega3P or HFSS) and solenoid map(s)
  - Causal moving window technique for efficiency



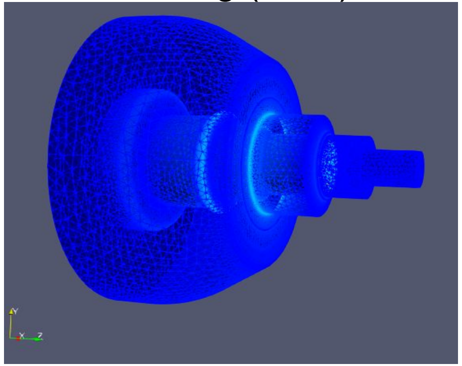
- **Particle distributions**
  - Simple distribution generator
  - Read-in of arbitrary distributions
  - Field emission, thermionic emission models
- **Diagnostics**
  - Full 6D phase space dump at given times
  - Automatic calculation of moments (1^{st} & 2^{nd} order) and emittances
  - Visualization through commercial and in-house codes

IOT Simulation Workflow

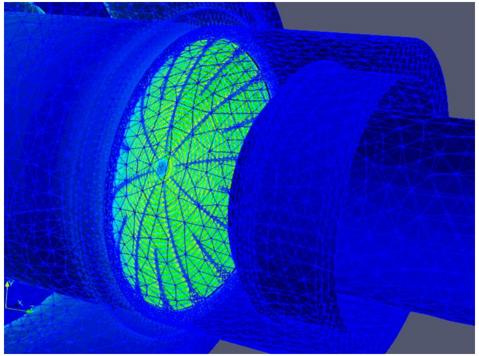
RF vacuum space



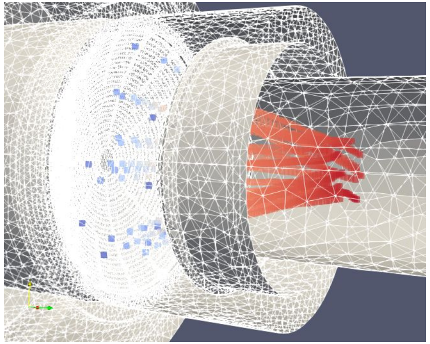
meshing (cubit)



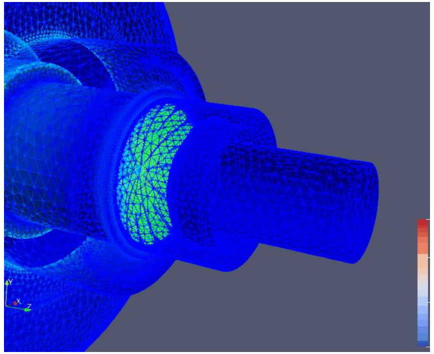
RF mode calculation



PIC simulation (PIC3P)



Post processing



A user-friendly environment for ACE3P simulation workflow on high performance computing (HPC)

Elements of RF IOT Gun Simulations in ACE3P

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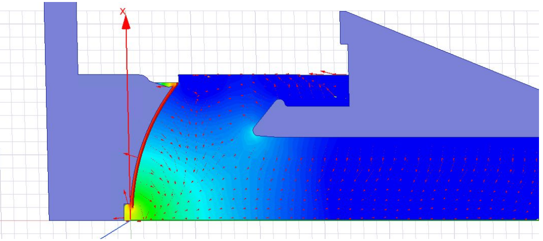
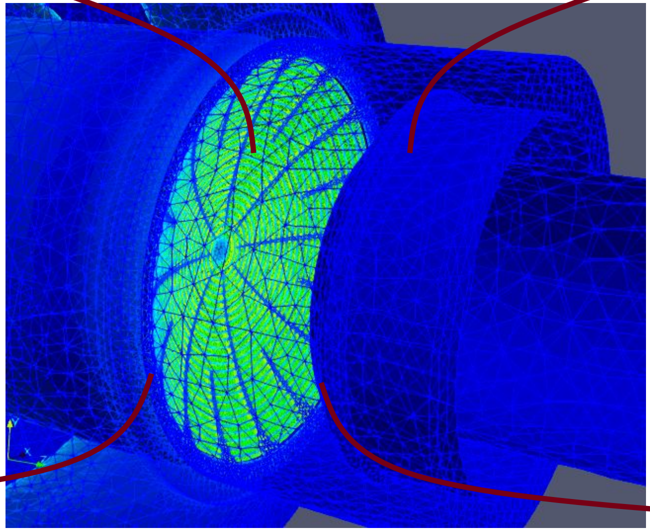
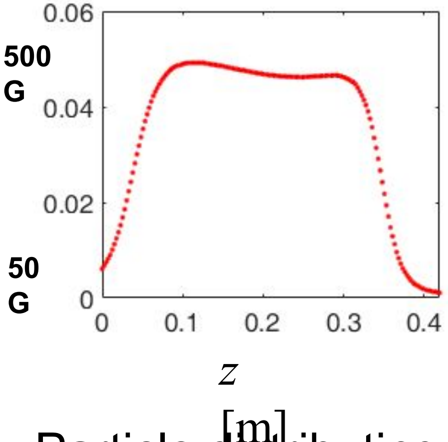
Electrostatic accelerating field distribution (Maxwell or GUN3P)





Focusing optics (Maxwell)



RF mode distribution (HFSS or Omega3P)

Particle distributing (Thermionic-field emission model)

$$J = AT\exp\left(-W/kT\right)\exp\left(-\sqrt{e^2E/(4\pi\epsilon_0)}/(KT)\right)$$

IOT RF Gun Design and Simulation Setup

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Design parameters

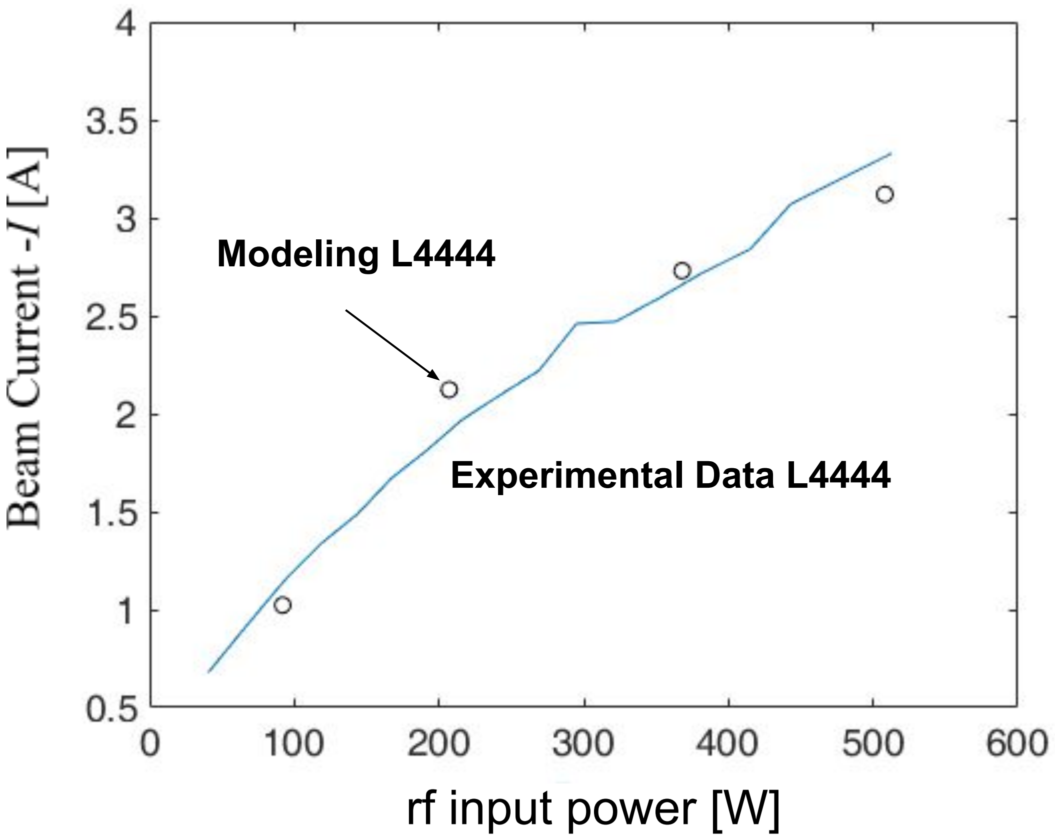
Parameter	Value
Beam Voltage (kV)	40
Anode Diameter (mm)	25.4
Grid bias (V)	−200
Cathode to Anode distance (mm)	20
Frequency (GHz)	1.3
Cathode-grid separation (mm)	0.3
Beam average current (A)	3.2
Peak to average current ratio	26%
Peak axial magnetic field (G)	600

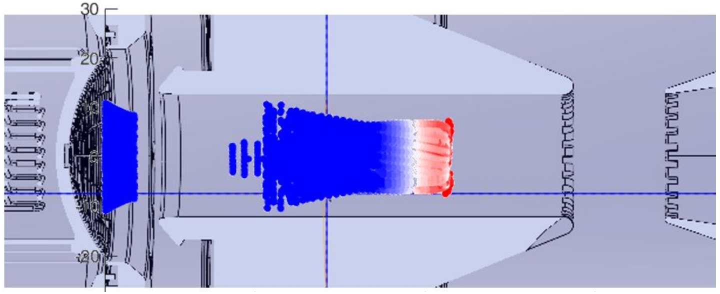
Simulation parameters

Parameter	Value
Mesh type	Tetrahedra
Mesh density	Gradient
Number of particles	~5x10^5
Number of nodes	16
Number of codes/node	32
Time step size	~ 1 ps
Simulation time	~ min/node/time step

*Also used UHF model to benchmarking

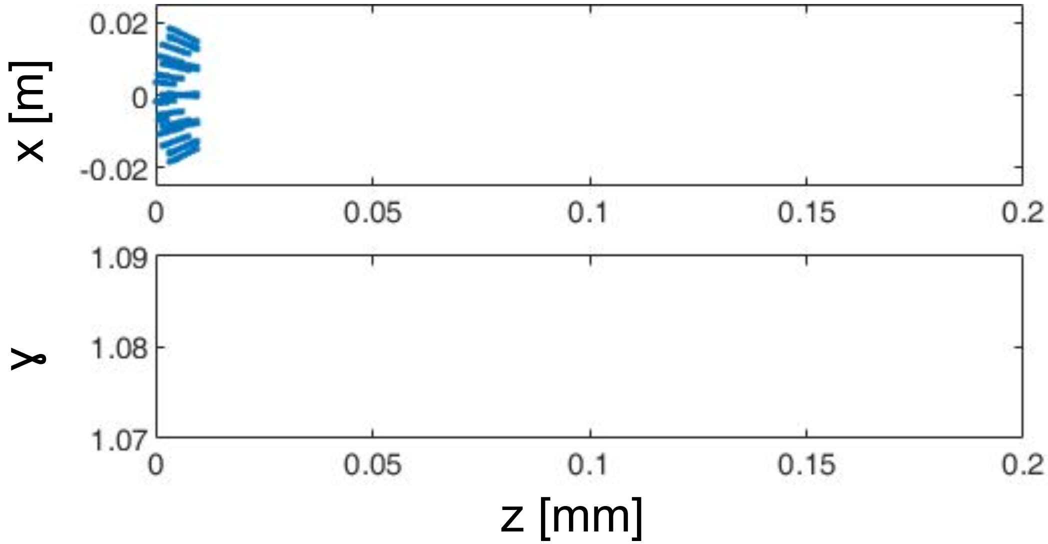
Benchmark Against Experimental Data of L4444 UHF Gun

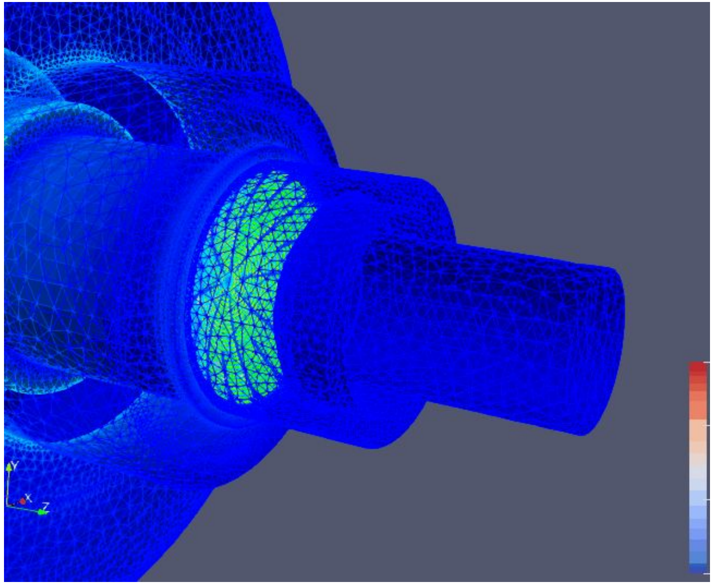




L4444 UHF IOT

Model of L-Band IOT RF Gun Beam Dynamics with PIC3P



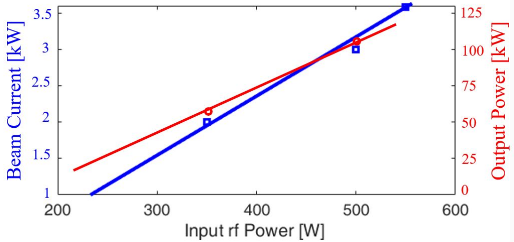


- Understanding beam transient 6D phase-space is essential to optimize the RF circuit downstream

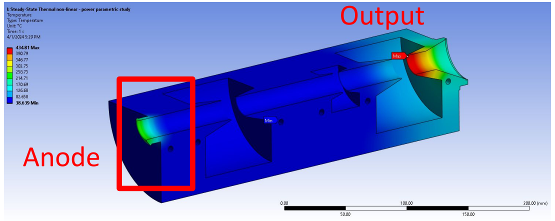
HE IOT

- Fundamental and second harmonic cavities have been designed to achieve high efficiency
  - Cavity design with high R/Q cavities
- 3D simulations predicted >80% efficiency with 100 kW power at 1.3 GHz
  - Design includes tolerances study and detuning effects
  - Cavities were designed for high R/Q and low thermal load
- Thermal and mechanical design:
  - Heat loads from RF power loss and from e- beam deposited power to design water cooling channels
  - Output slots/transitions to reduce multipactor
  - Braze assembly is designed for compact and efficient assembly

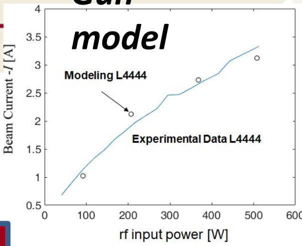
Simulated transfer curve

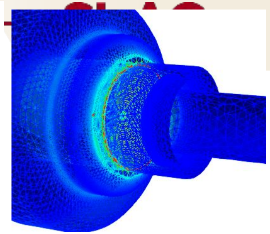


Simulated thermal load

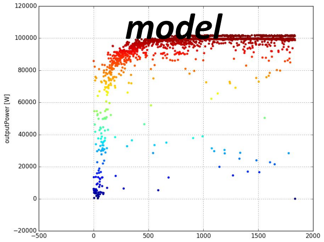


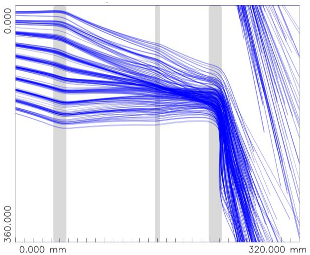
Gun model



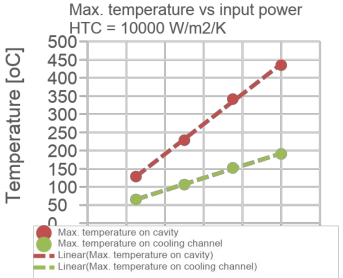


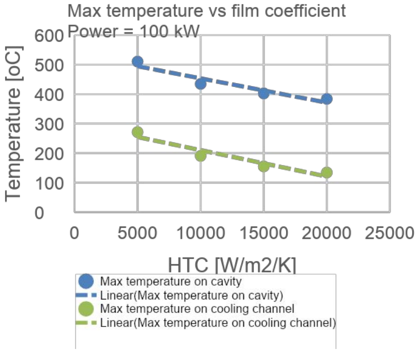
RF model





Thermal model

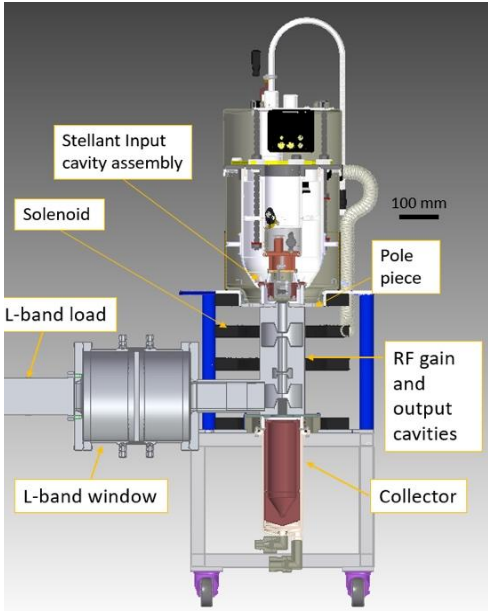


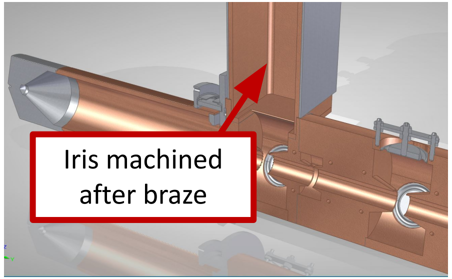


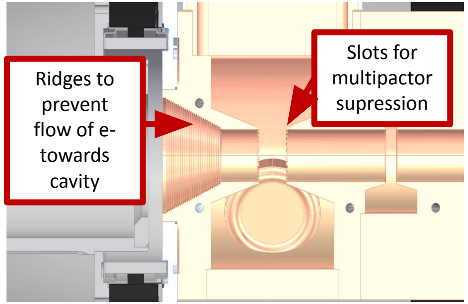
Production of L-Band SLAC/Stellant HEIOT

- The following major components have been designed and manufactured:
  - Input cavity ✓
  - Gun assembly ✓
  - Collector assembly ✓
  - RF window ✓
  - Collector ceramics ✓
  - Solenoids (TY 4) ✓
  - High power RF load ✓
- Mechanical design features some advanced features:
  - Easier machining of iris coupling to window waveguide
  - Multipactor suppression and prevention of electrons from collector
  - Selection of new UHV seal for L-band window and modification of matching waveguide flange
  - Modifications on cooling loops based on thermo-mechanical analysis
    - Required water flow to cool cavity body at 100 kW average power
    - Correct for throttle losses and water pressure

4447 HEIOT assembly



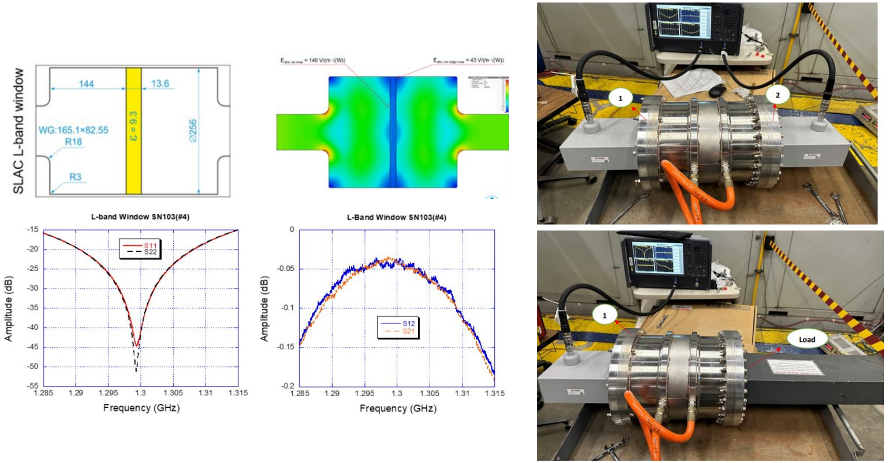




Production of L-Band SLAC/Stellant HEIOT

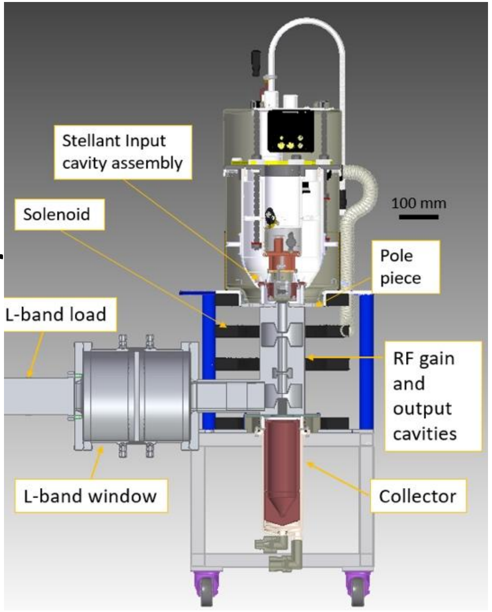
- 3 sets of body parts are being manufactured, contingencies for modifications
- Testing is planned starting Fall 2024
  - Long lead items were manufacturing of body, RF load (1.5 year), seals, etc
  - Plan for assembly and test at Stellant L-Band test stand
- CPC amplifier shipped and received by Stellant
- RF water load manufactured and shipped to Stellant
- RF high power window manufactured, cold tested, QC and shipped to Stellant

RF window manufactured and cold test



CPC L-Band driver amplifier

4447 HEIOT assembly



Conclusion

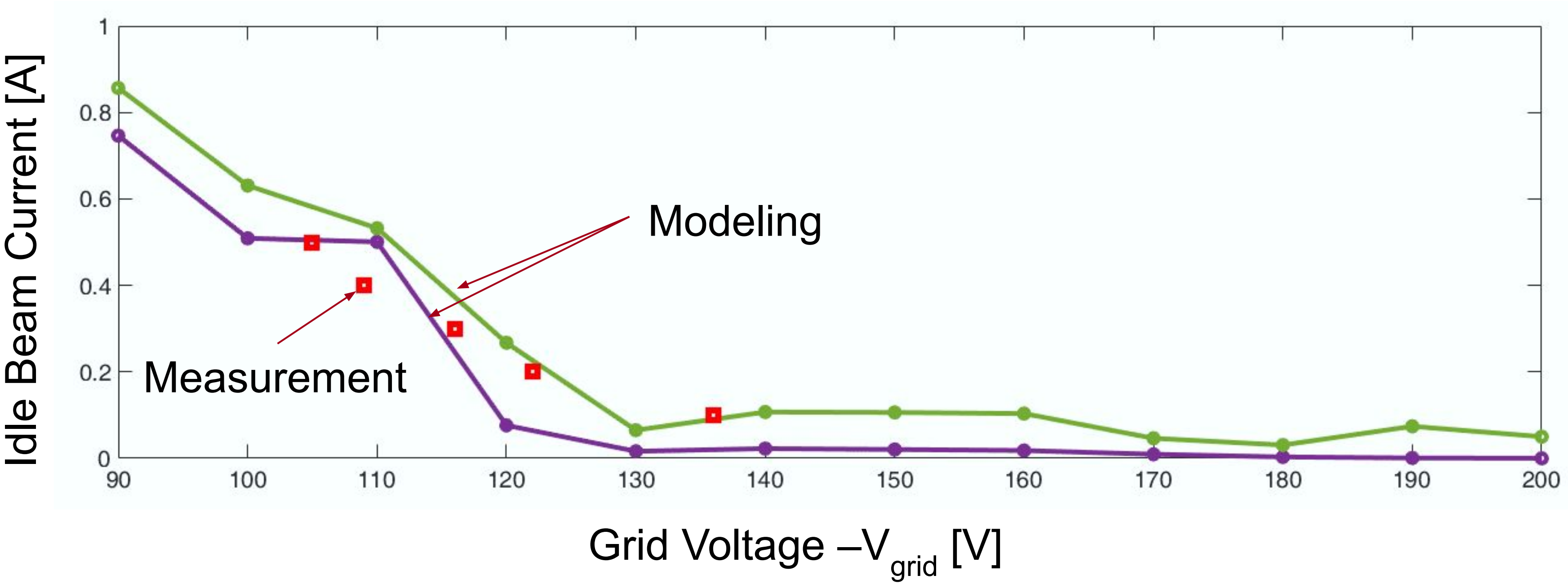
- HE IOT design paves the way for novel accelerator application

- Production of IOT is a major challenge
  - Working with industrial partner leverage expertise in procurement and testing
  - Supply chain issues for ceramics, weldments, etc

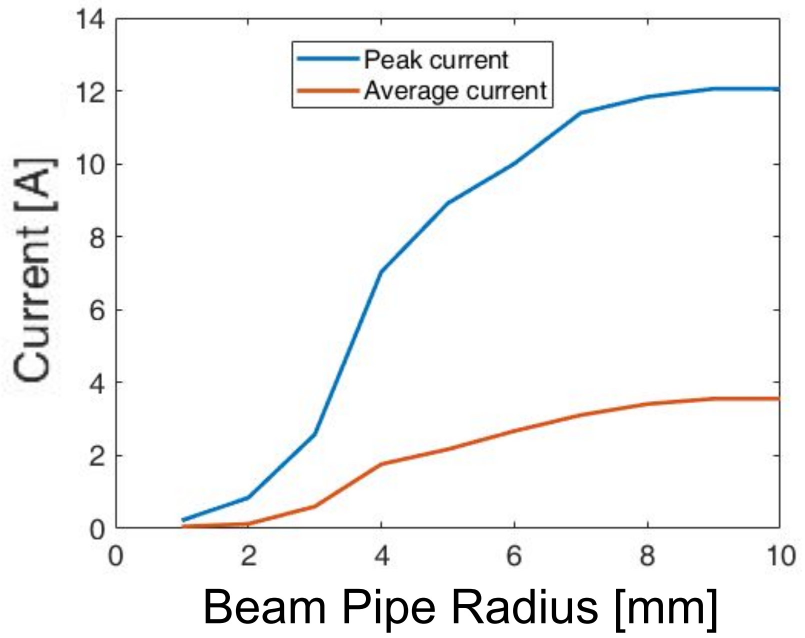
- Plans for testing in end of 2024

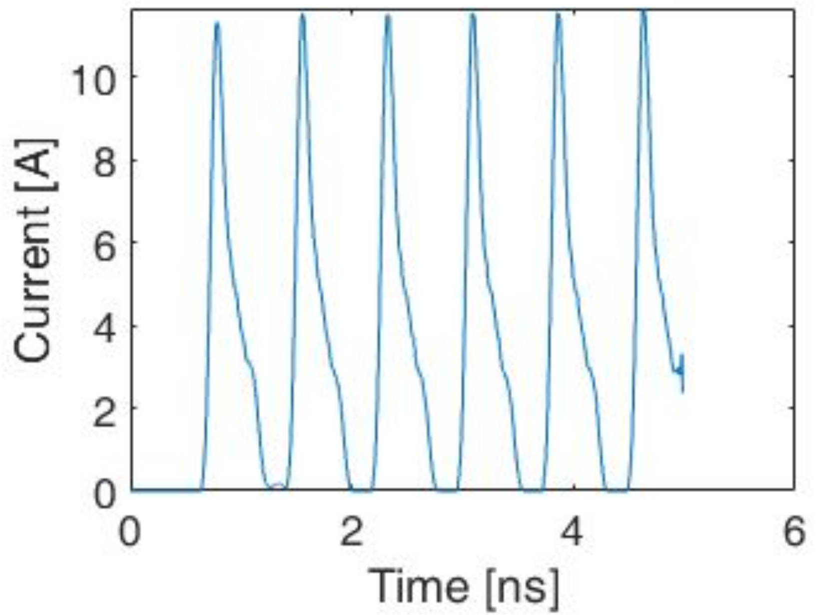
- Extension to multi-beam IOT with output combiner is in progress

Benchmark Against Experimental Data of L4444 UHF Gun



Model of L-Band IOT RF Gun Beam Dynamics with PIC3P





- Particle distribution shows a signature of the harmonic contents of the bunch