Modeling and Design of the SLAC 75XP4 Klystron

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Stanford University | U.S. DEPARTMENT OF ENERGY

Motivation: Cool Copper Collider (C^3) Demo

C^3 is a SLAC-led initiative for a next-generation collider

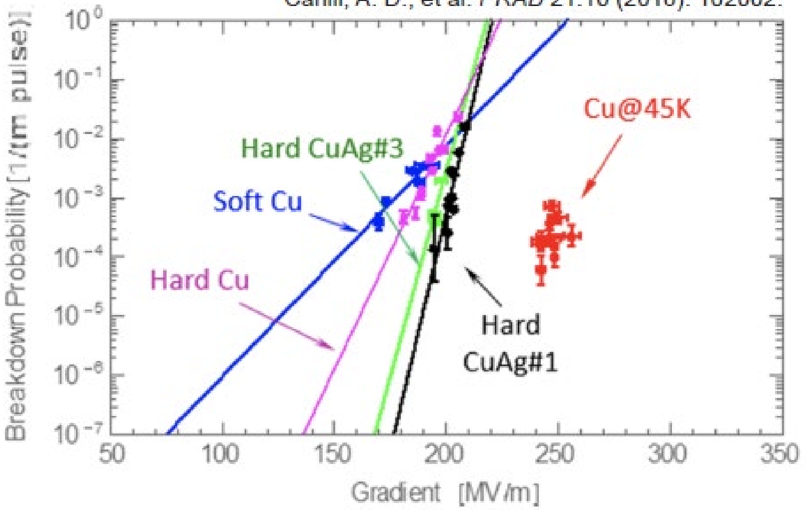
Concept: Copper linac, cooled with liquid N_2. Why?

- Higher efficiency, higher accelerating gradient, and lower breakdown rate than room-temperature copper structures
- Normal conducting RF with no pulse compressors required
- Lower cost than superconducting: No need for a helium cryoplant or superconducting cavities

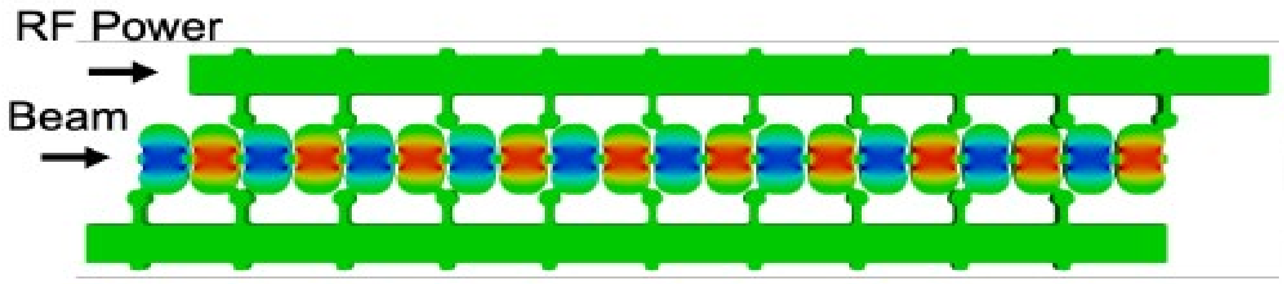
Demo facility will require ~30 MW/m @ X- or C-band

Efficient, low-cost RF source R&D is essential for a C^3 demo

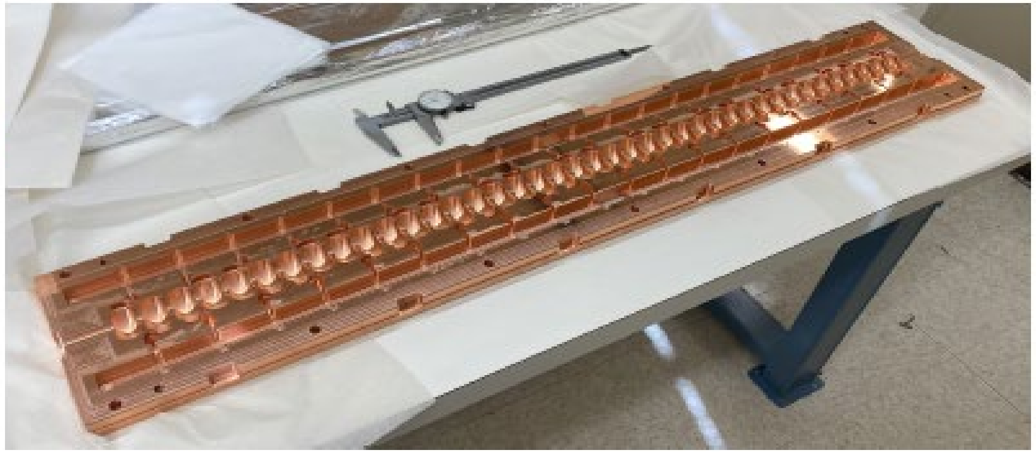
Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.



First C^3 structure at SLAC



Electric field magnitude for equal power from RF manifold



75XP Series Klystrons as RF sources for C^3

The SLAC 75XP is a PPM-focused, X-band klystron designed for 75 MW peak power

Motivated/funded by the Next Linear Collider (NLC) program

Years of engineering effort → attractive candidate for a potential C^3 demonstrator

Specification	Target
Beam Voltage	490 kV
Beam Current	257 A
RF Output Power	75 MW
Frequency	11.424 GHz
RF Pulses	1.5 µs @ 60 Hz
Saturated Gain	55 dB
Bandwidth	75 MHz
Efficiency	60%

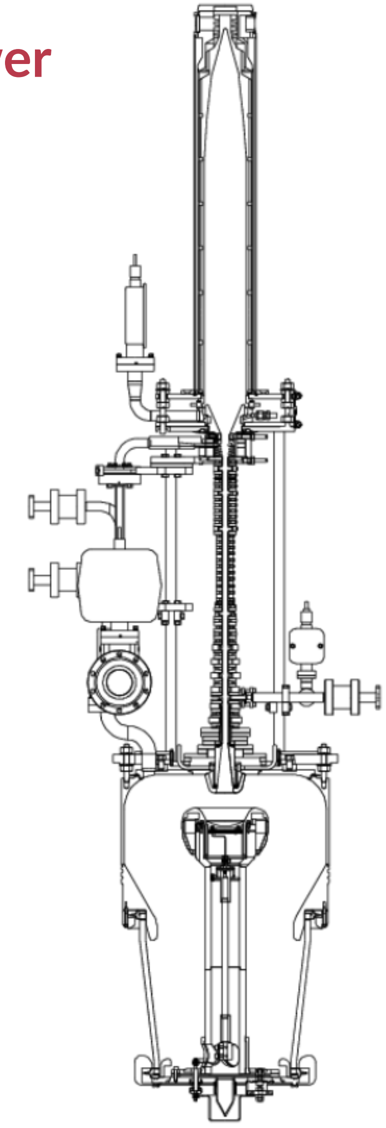
Design Features:

Large "DESY" HV gun insulator

7-cavity gain circuit

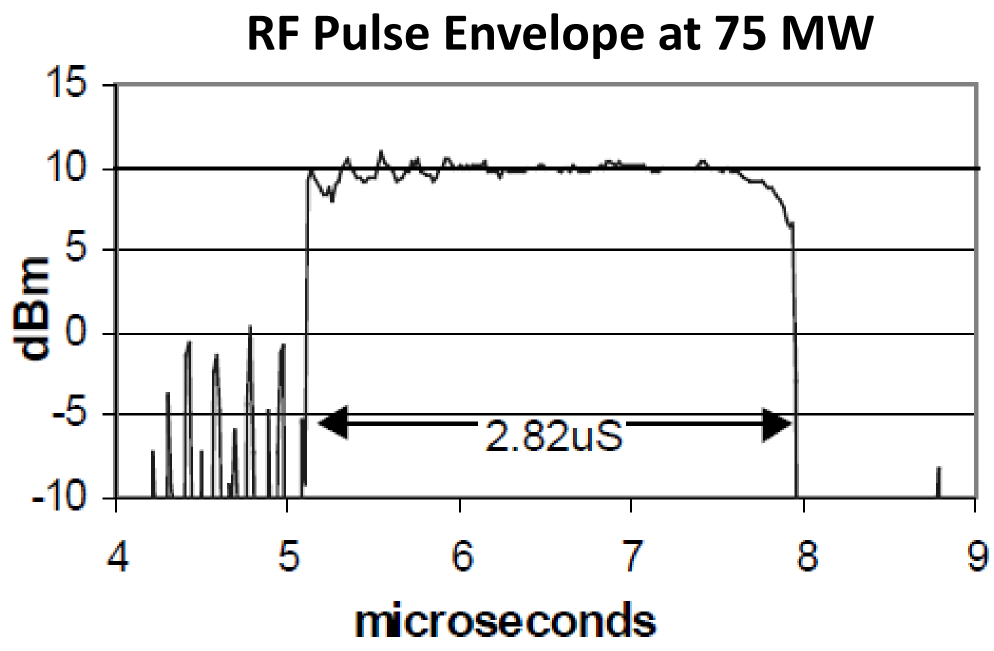
5-cell extended-interaction output

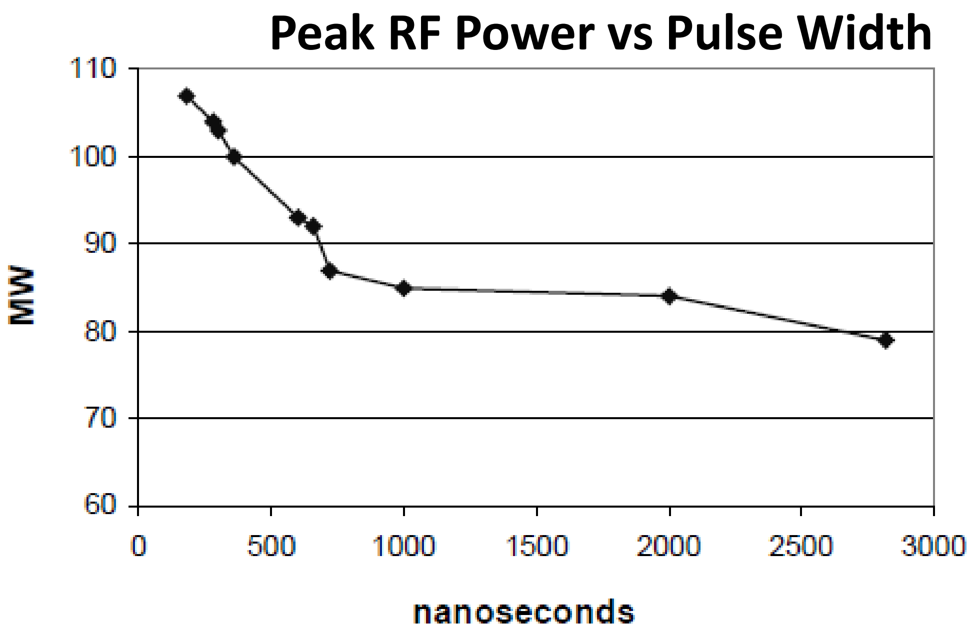
Isolated collector



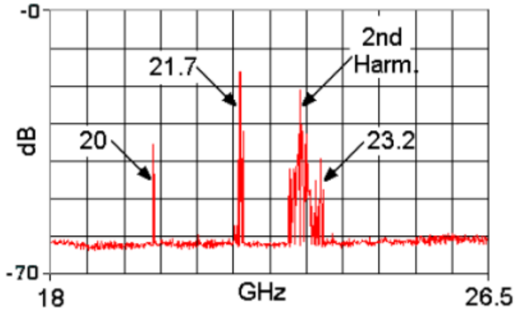
75XP1 Test Results

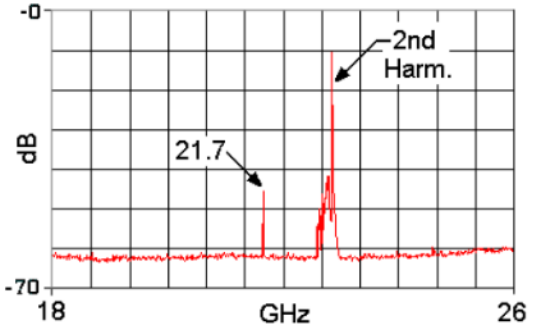
- **The original 75XP-1 was built, and eventually reached 79 MW at 2.8 μs in test**
- Power levels exceeding 100 MW were measured at shorter pulse widths





Gun and output oscillations were observed, but corrected after rework





Design Modifications for the 75XP3

The 75XP3 series was a full-tube design iteration of the 75XP1

Goal was to make a “design for manufacturing” in support of NLC:

- Introduced clamp-on “clam-shell” magnet assemblies to allow pre-test
- Removed the adjustable gun design / tightening of gun tolerances
- Modified cavity spacings
- Modified beam tunnel sizes / tailpipe and cooling
- Gun coil assembly added for adjusting beam match into PPM stack during test
- Implementation of dual-window output

75XP3 Specifications

All specs identical to the 75XP1 **except:**

Pulse width target increased to 3.2 microseconds (for a while…)

Compact Gun Redesign for 75XP3

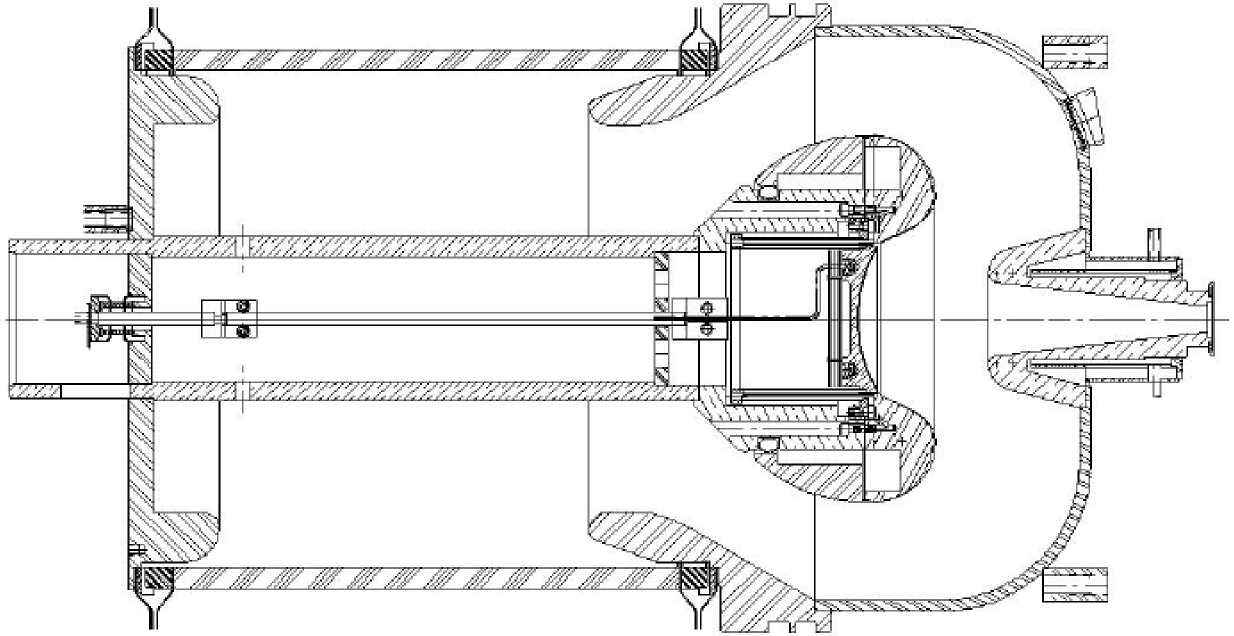


Figure 1. Electron gun outline as implemented in the XP3 klystron devices.

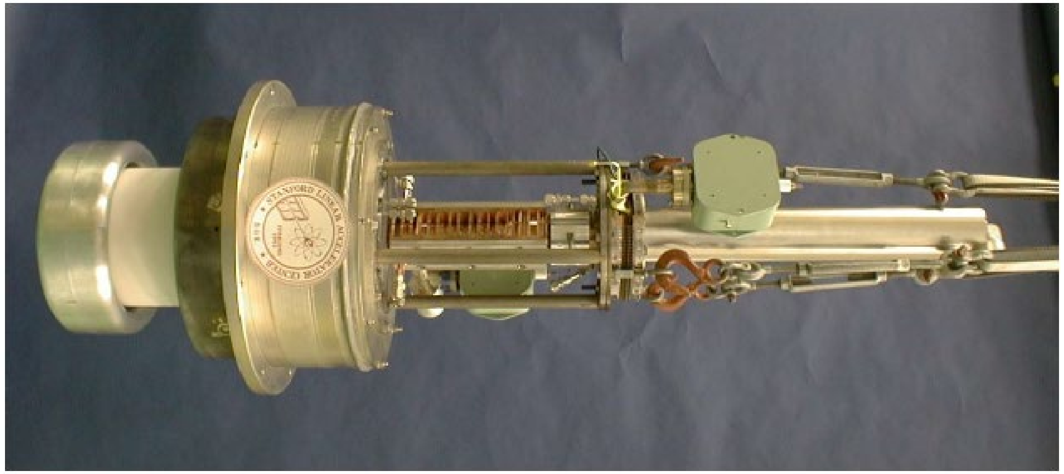
75XP3 Diode

Gun/PPM/Collector Diode was built to validate new components for the 75XP3:

- New beam tunnel size and focusing magnets
- New compact gun and collector designs
- Addition of gun coil assembly

Gun oscillation at 3.17 GHz corrected w/ loss collar

After loss collar added, 99.9% transmission, ran to full beam spec at 490kV / 3 μs / 120 Hz



Summary of 75XP3 Serial Numbers

75XP3-1 (first serial number):

- First tube with clamped-on magnets
- **Result: OP Oscillation @ 11.7 GHz**
  - Arose due to a fabrication error. It is suppressed when output chain is assembled correctly

75XP3-2:

- Also used clamped-on magnets
- **Result: Died from gun arc at 3.2 microsecond pulse width**
  - Smaller gun size had reduced safety factor; also, 3.2 µs was 2x original design target
  - Also observed a gun oscillation

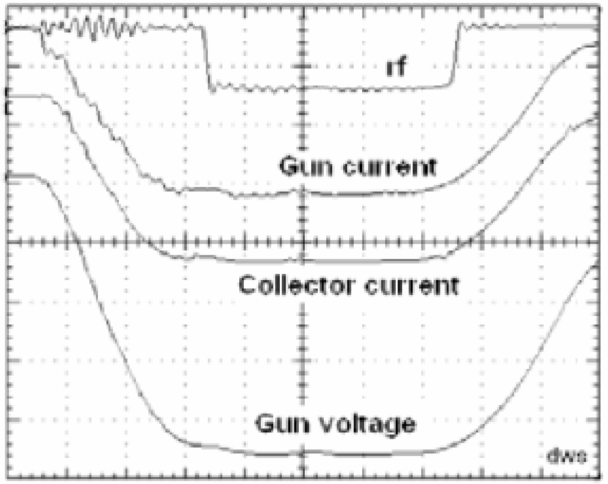
75XP3-3: Added gun loss ceramic

- **Result: Met specification**
  - 75 MW @ 120 Hz / 1.6 µs
  - NLC spec at this point was reduced back to 1.6 µs
  - Some beam intercept
  - No temperature monitoring due to clamp-on magnet stack

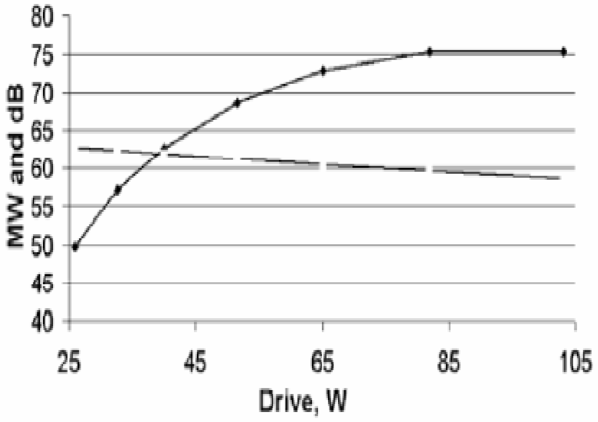
75XP3-4: Integral Pole Pieces

- **Result: Met specification again**
  - 75 MW @ 120 Hz / 1.6 µs
  - Beam loss was 1.3%
  - Needed slight voltage increase to meet power

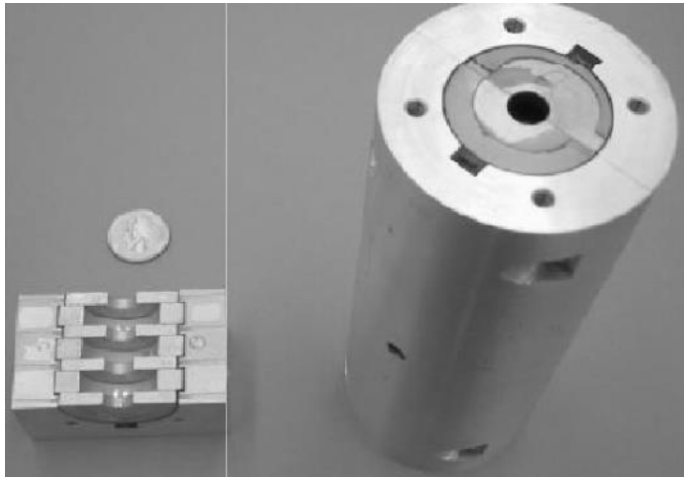
RF, current, and voltage waveforms for 75XP3-4



Power & gain vs. drive



Lessons learned from the 75XP3

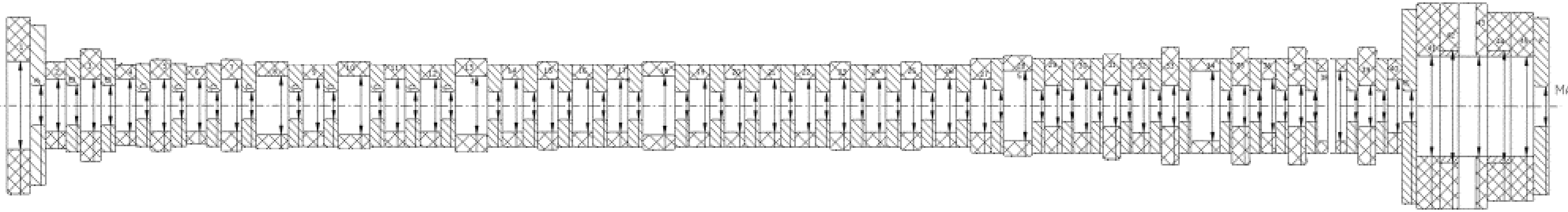


75XP series met specifications, and in some cases exceeded them (over 100 MW at < 500 ns)

Gun & output oscillations were a recurring but solvable challenge.

Key issues identified:

- 75XP1, XP Diode, and 75XP3-2 were susceptible to gun oscillations
- Magnetic circuit is quite complicated (i.e., expensive & hard to build)
- At high duty, runaway condition with NdFeB magnets overheating
- Body current vs. gun coil current settings were a “bit touchy”



The 75XP4 Redesign

The next design iteration, 75XP4, was partially complete when NLC was cancelled

The goal was to make the 75XP4 more robust against 75XP3 failure modes:

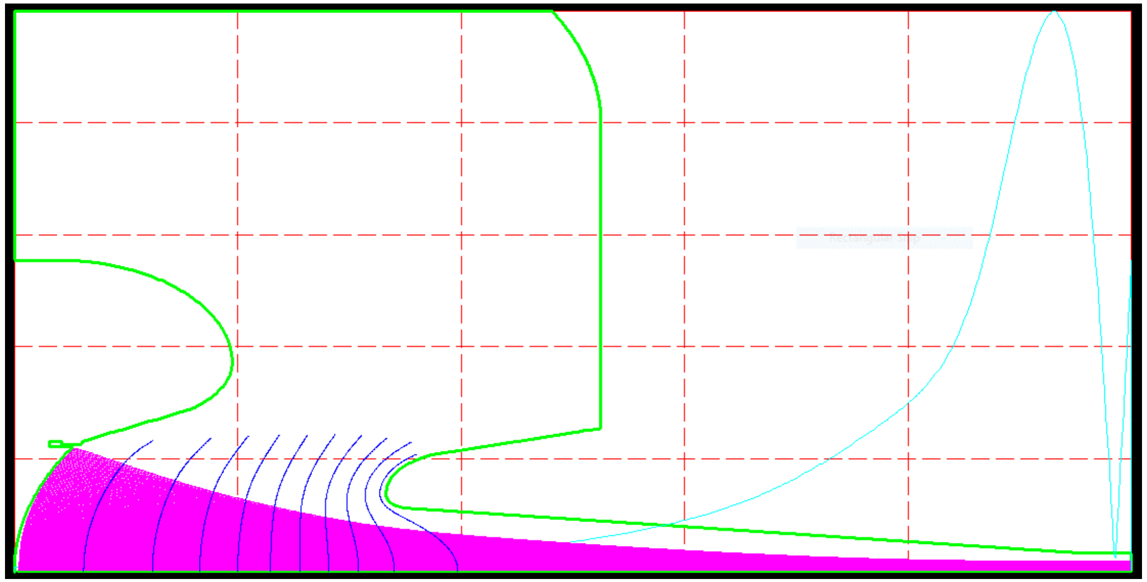
- Potential for gun and output oscillations
- Complexity of PPM stack
- Runaway conditions of overheating magnets near output
- Design sensitivity of gun coils
- High gradient RF breakdown in output

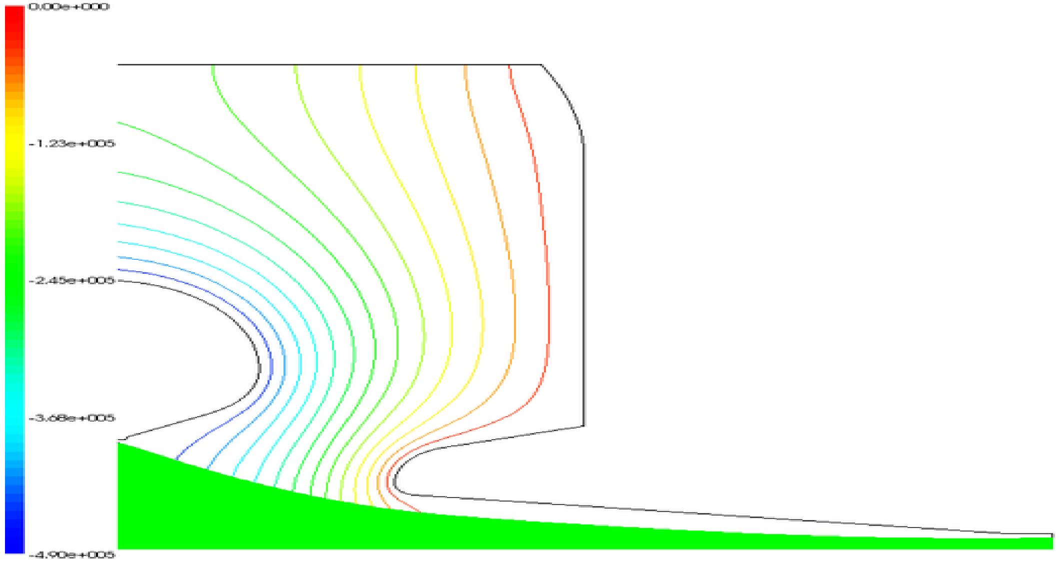
For the C^3 demonstrator source, we simulated the design that was already completed, and made further changes to address past issues.

75XP4 Electron Gun

Gun re-modeled with & without magnets for beam trajectory and gradients

- Simulations in both EGUN and MICHELLE, for use in TESLA & MAGIC sims
- Correct perveance & beam size, gradients < 20 MV/m
- Gun can was reshaped to suppress past oscillation modes



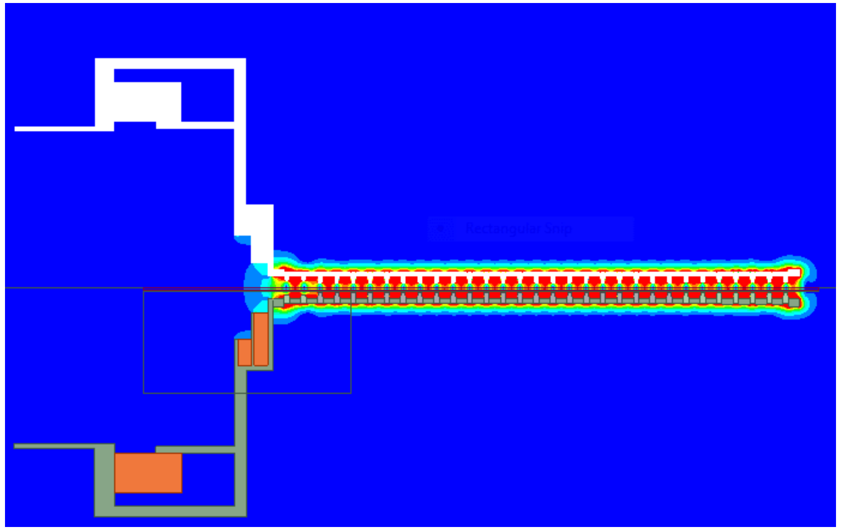


EGUN and MICHELLE models of gun in good agreement. ~260A @ 490 kV / 60% fill factor

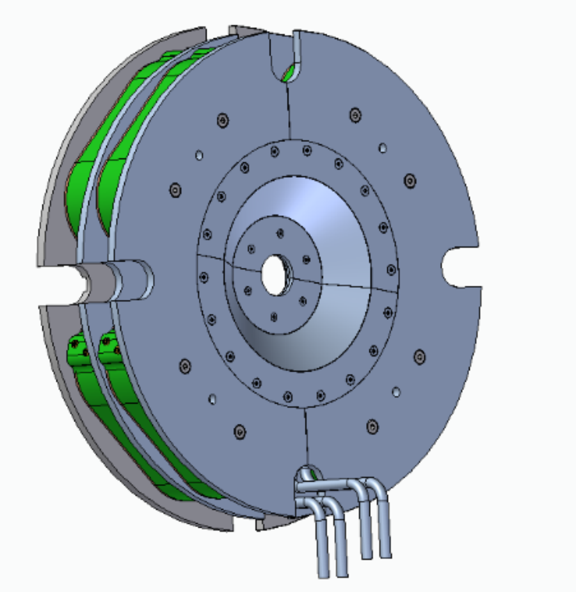
75XP4 New Magnet Modifications

75XP4 magnet stack is much simpler than the previous 75XP tubes

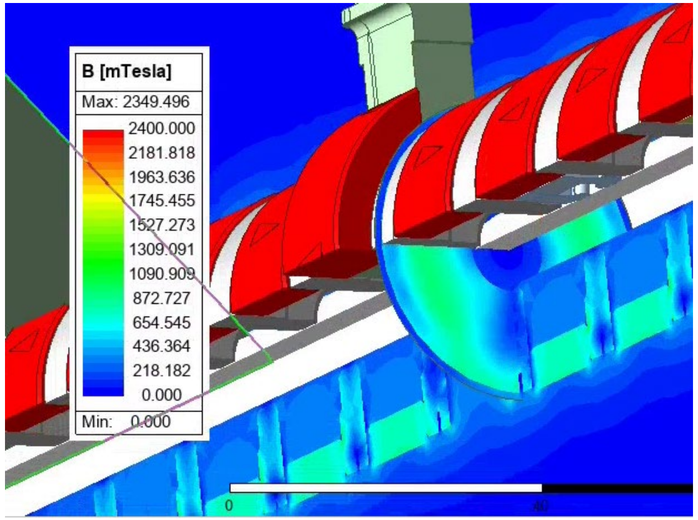
- All NdFeB magnets replaced with SmCo – higher grades available today
- Only 3 magnet variants – reduced from ~40 unique magnets
- Wound-on gun solenoid replaced with off-axis pot coils - simulated in 3D



Simplified magnet stack model in Ansys Maxwell



Off-axis coils for easier assembly



3D magnet simulations

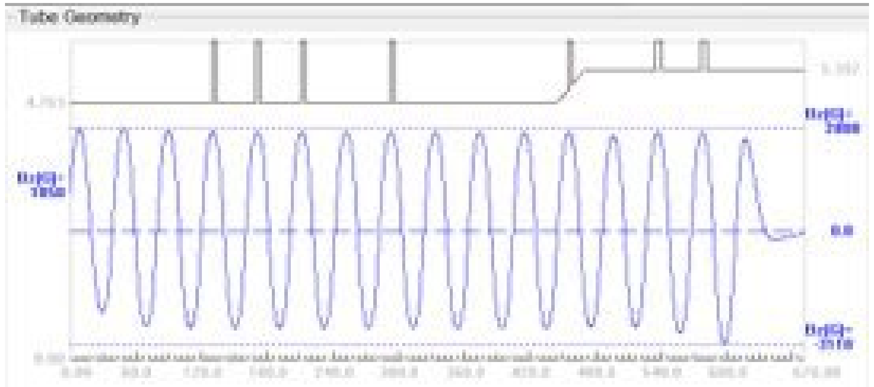
75XP4 DC Beam Transmission

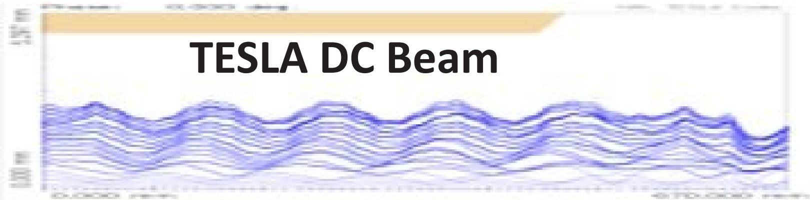
DC beam simulated in both TESLA and MAGIC 2D to check for beam transmission

- Coil adjusted for cathode field that minimizes DC beam scalloping
- No beam intercept observed in either simulation

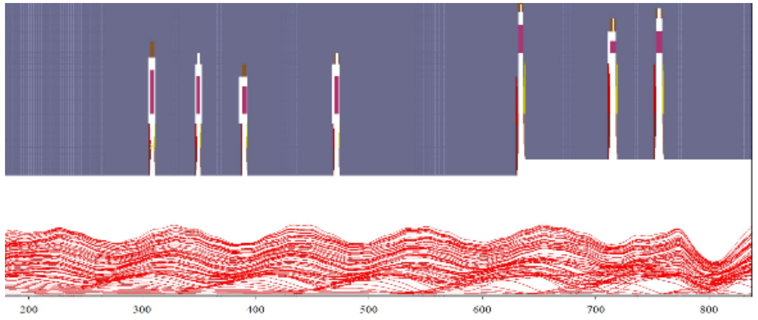
Spent beam was exported for collector thermal modeling; no modifications needed

B-field Profile in TESLA

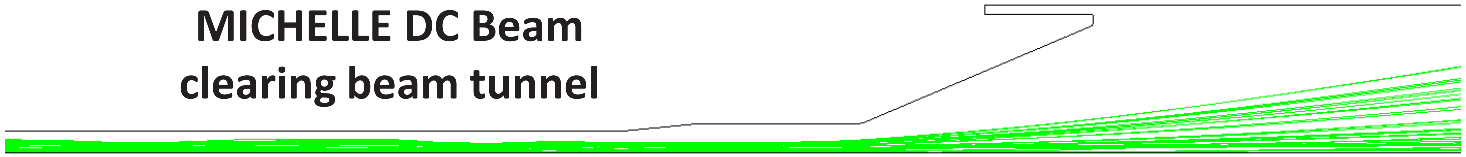




TESLA DC Beam



MAGIC DC Beam



MICHELLE DC Beam clearing beam tunnel

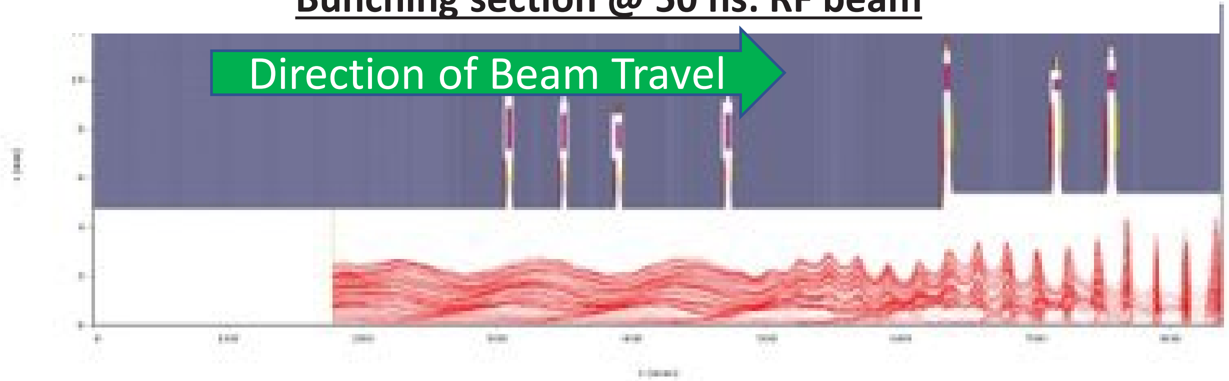
MAGIC2D PIC Simulations

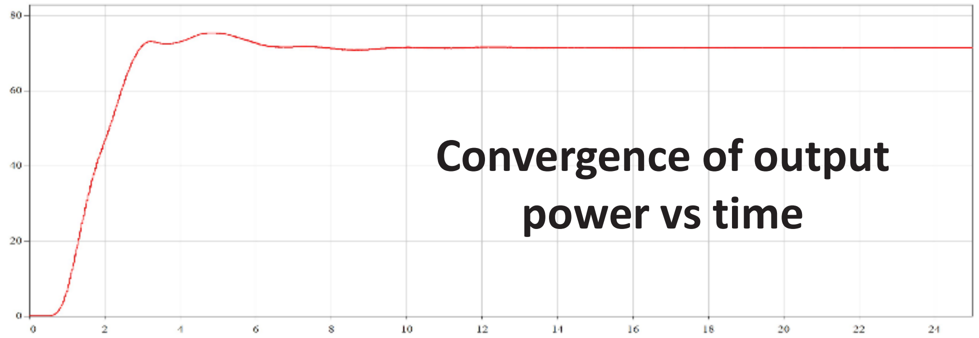
RF performance simulated in MAGIC 2D

- 72 MW achieved with 40 W drive; Gun coil & beam voltage may be adjusted in test

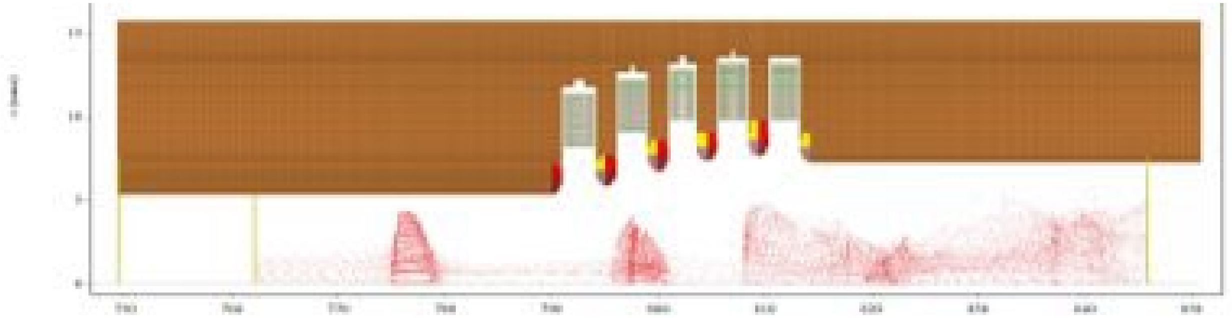
Will confirm models in CST Microwave Studio, TESLA-Z, and MAGIC 3D while build proceeds

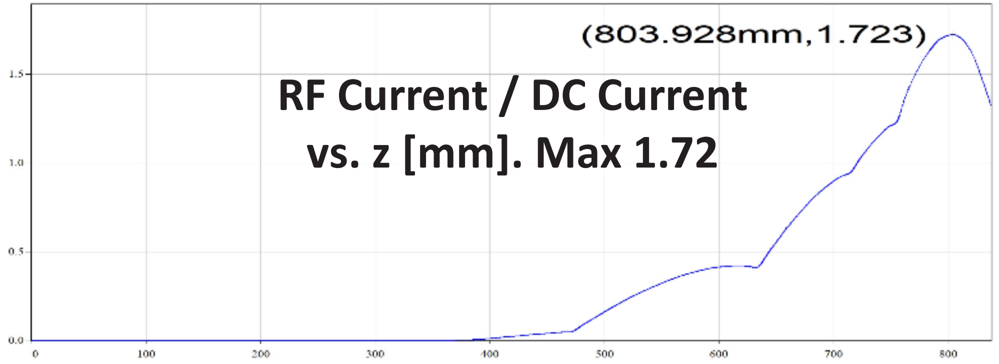
Bunching section @ 50 ns: RF beam





Output structure: 72 MW power extraction, no intercept

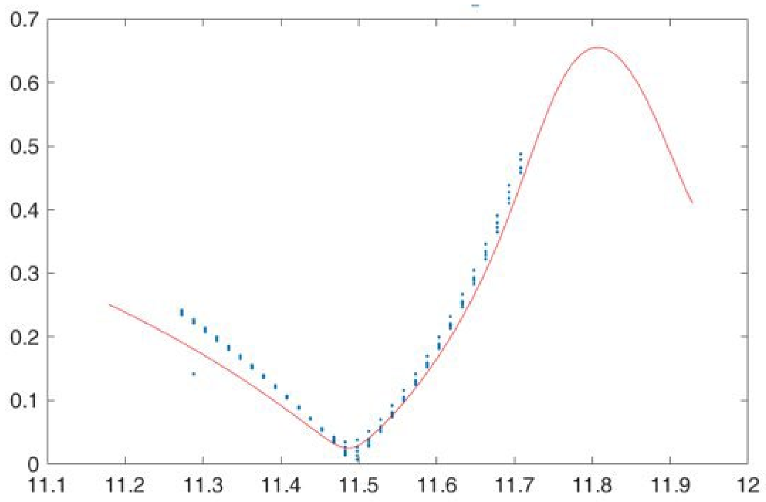




75XP4 Cavities & OP redesign

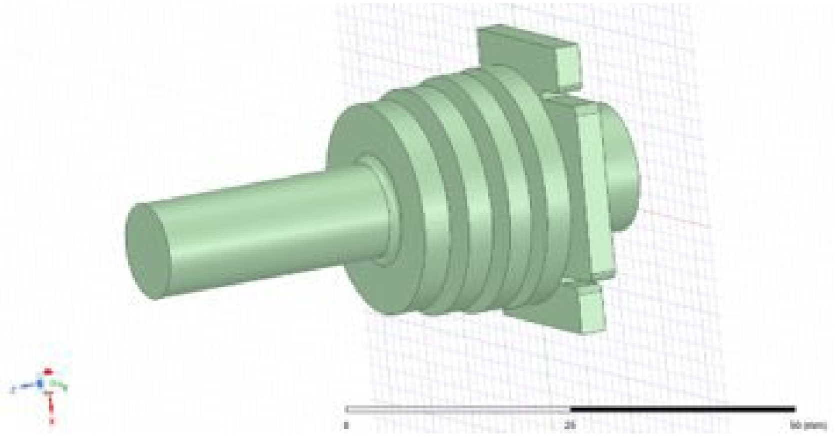
Original output cavity design (coupler cell) at risk of RF breakdown

- Output coupler cell was reoptimized to meet more modern RF breakdown criteria
- Original design: Sharp edges and small radius nose led to high surface currents
- New design: “Racetrack” coupler layout to minimize gradients and surface currents
- RF pulse heating reduced by ~3x; cell impedance unchanged from original design

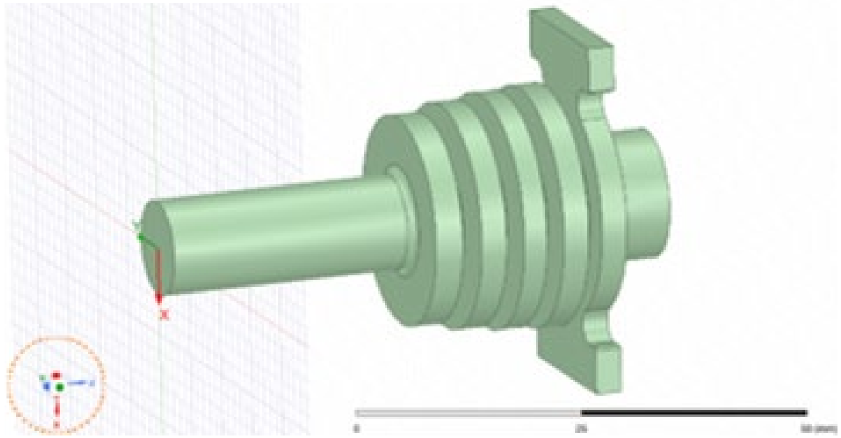


Old vs. New S_{11} vs Freq.

Output Pulse Heating Reduced from 152 K → 50 K



Original (square) output cell



New (racetrack) output cell

First prototype 75XP4 is under construction now

Next steps

Stability analysis of gun, drift tunnel modes, and output cavity

- Analytical approach – mode search & beam loading calculations w/ ACE3P
- Computational approach – Long-duration 2D & 3D PIC models w/ noisy beam

Hot test of existing 75XP3 klystron (still on pumps after 20 years!)

Fabrication/test of XP4 diode assembly (gun + collector) to retire risks:

- Gun oscillations
- HV standoff issues
- Gun perveance adjustments
- Collector power handling

Thank you!

This work would not be possible without building on decades of past efforts from the former SLAC Klystron Department.

Some material in this presentation was borrowed heavily from published SLAC-PUB articles and presentations by Daryl Sprehn, Arnie Vlieks, and Erik Jongewaard. Erik continues to be a fountain of knowledge for our department today.