MICROWAVE POWER PRODUCTS

High Efficiency 50MW X-band Klystron Development

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Workshop on Efficient RF Sources

Chateau de Bossey, Geneva, Switzerland, 4-6 July, 2022

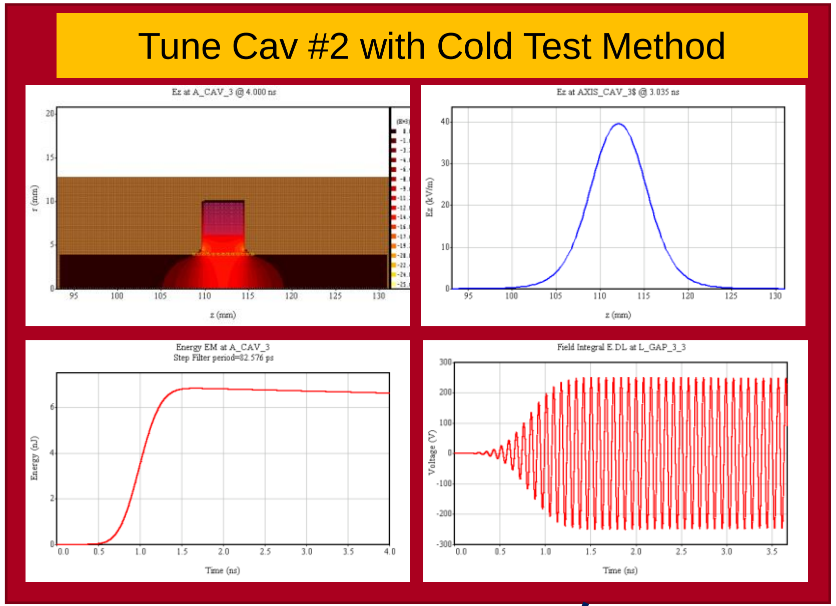
Outline

- Collaboration with CERN to develop a 50 MW, 12 GHz high efficiency klystron (HEX) since 2019
- Design effort at CPI
  - MAGIC simulation of CERN design with a 2^{nd} harmonic **triplet** (June 2020)
  - Alternate CPI design **without** a 2^{nd} harmonic cavity (Jan 2021)
  - MAGIC simulation of updated CERN design with a 2^{nd} harmonic **doublet** (June 2022)
  - Beam optics & magnetics designs for the high efficiency tube
- Prototype fabrication based on VKX-8311A Klystron at CPI
- Summary

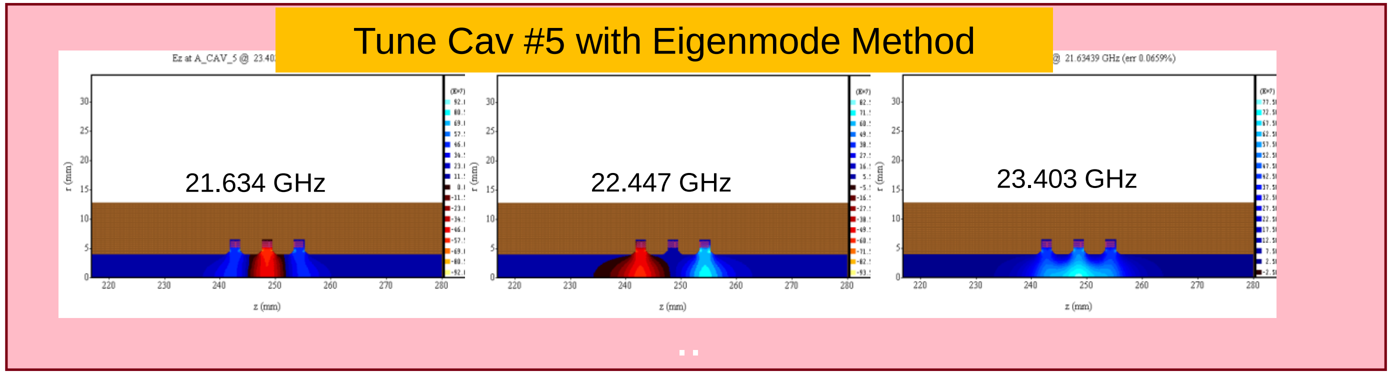
MAGIC Simulation of CERN HEX design

- MAGIC-2D simulation setup based on KlyC input from CERN
- Initial results & problems; Solutions by CERN
- Optimization of output gap tuning by CPI using MAGIC
- MAGIC results of optimized design with ideal beam & uniform B field
- Preliminary beam optics and magnetics design
- Preliminary MAGIC-2D simulation with simulated beam

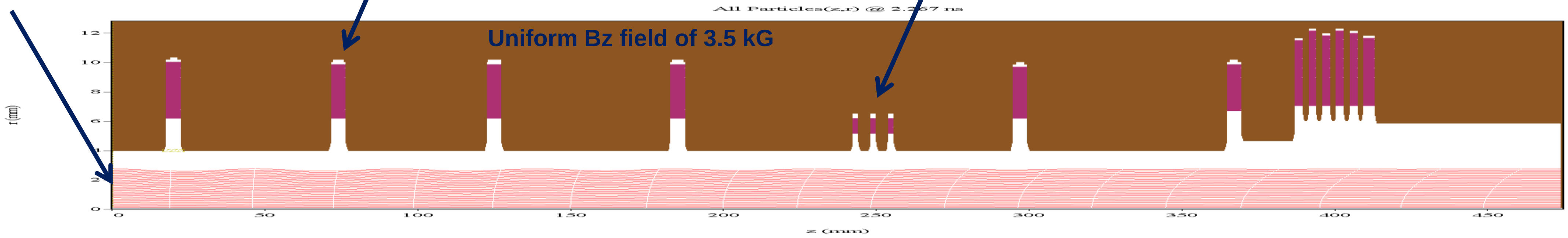
MAGIC-2D Model



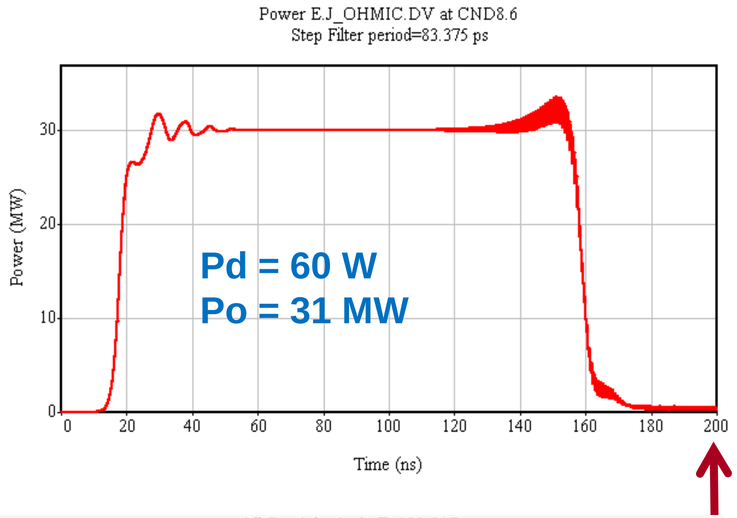
- Set up MAGIC-2D model based on settings from KlyC
- Tune all cavities using cold test or eigenmode methods
- In MAGIC-2D, use ideal beam injection & uniform B field of Bz = 0.35 T

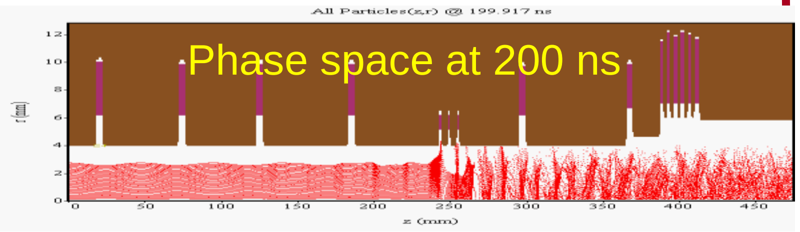


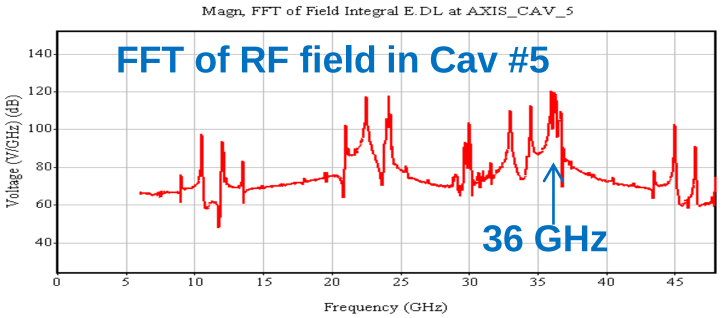
Ideal laminar beam injection
400 kV, 190 A



Hot Simulation Result for CERN Design v1





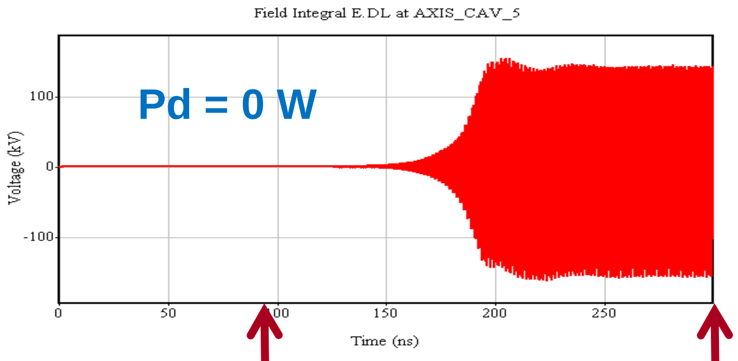


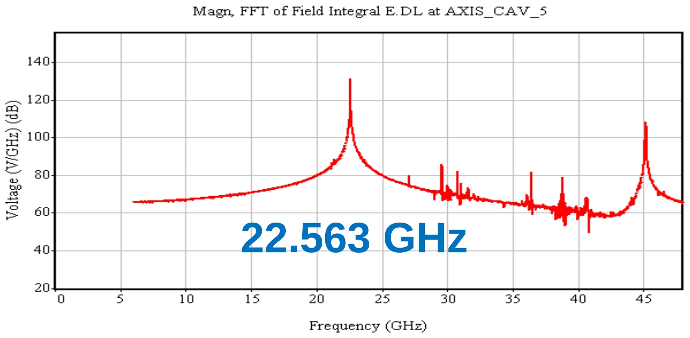
Problems from initial hot simulation results

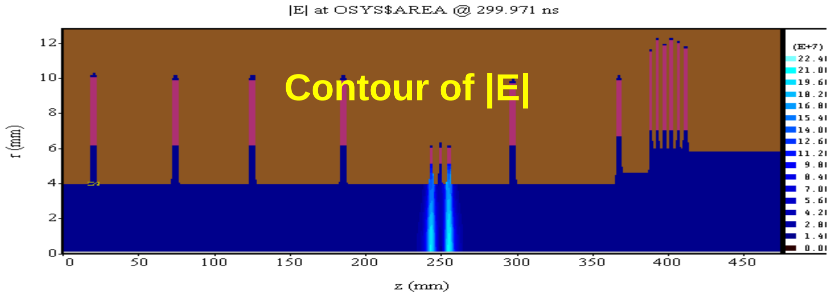
- Saturated output power was low, only 30 MW for 41% efficiency
- Output power collapses after 130 ns due to instability in the triplet 2nd harmonic cavity. FFT of gap field shows peaks around 36 GHz near 3rd harmonic
- Modifying the triplet geometry to move the cavity resonant frequency away from 36 GHz did not affect the instability

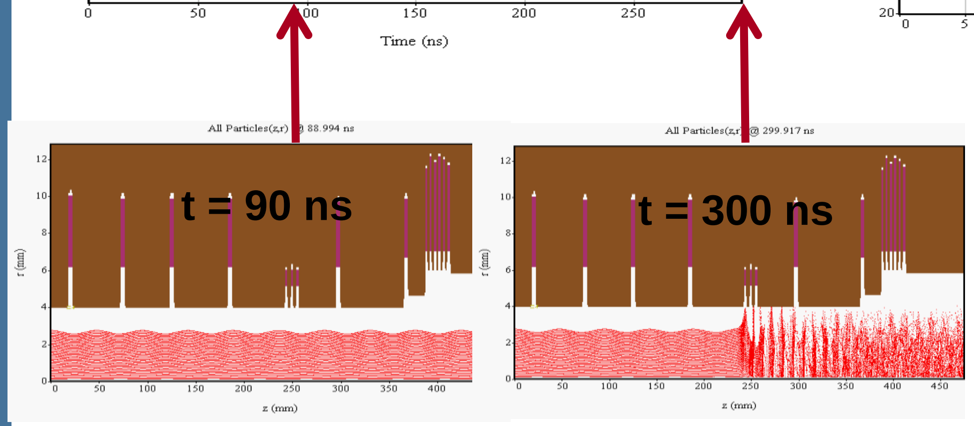
Simulation with Zero Drive Power

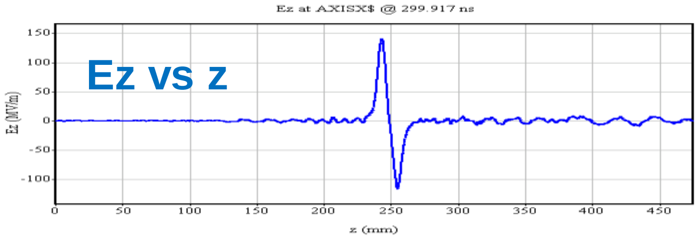
- MAGIC simulation with zero drive revealed the source of instability to be a monotron oscillation due to the $\pi/2$ mode near 22.5 GHz.





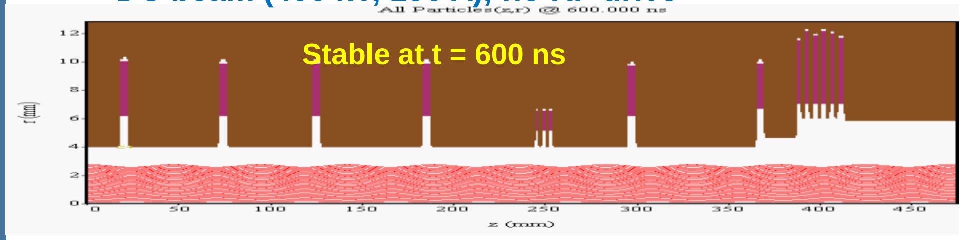


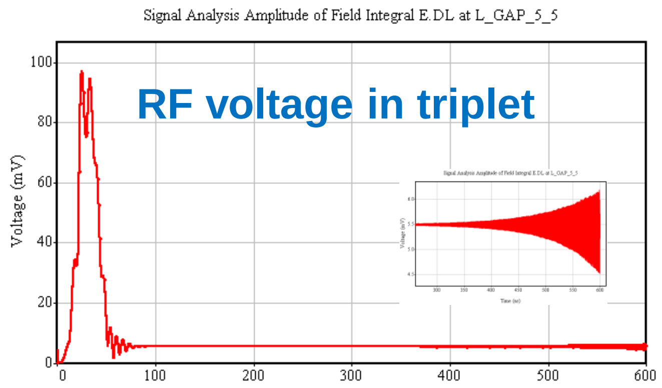


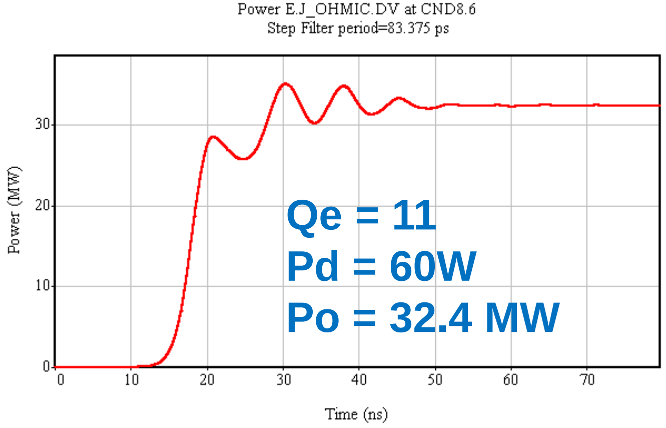


New Design of 2^{nd} Harmonic Triplet, v3

DC beam (400 kV, 190 A), no RF drive

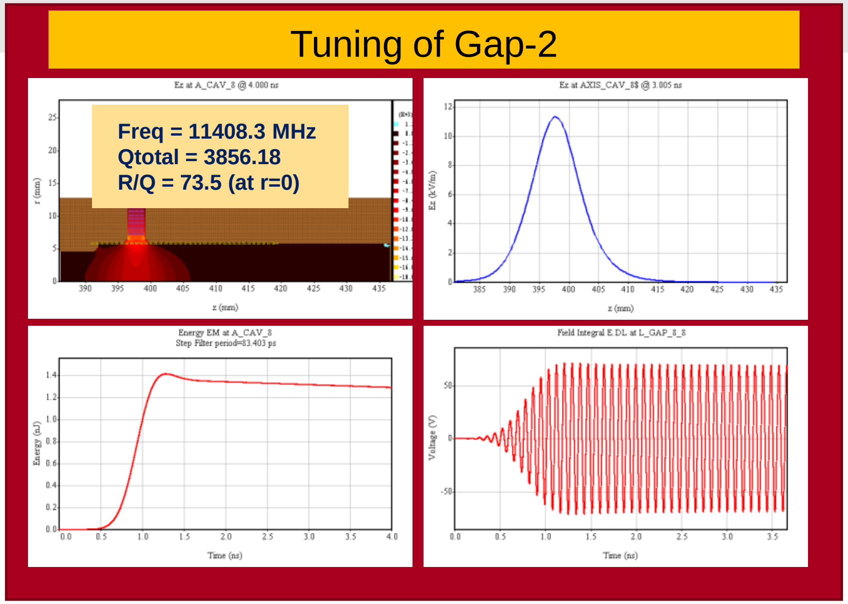


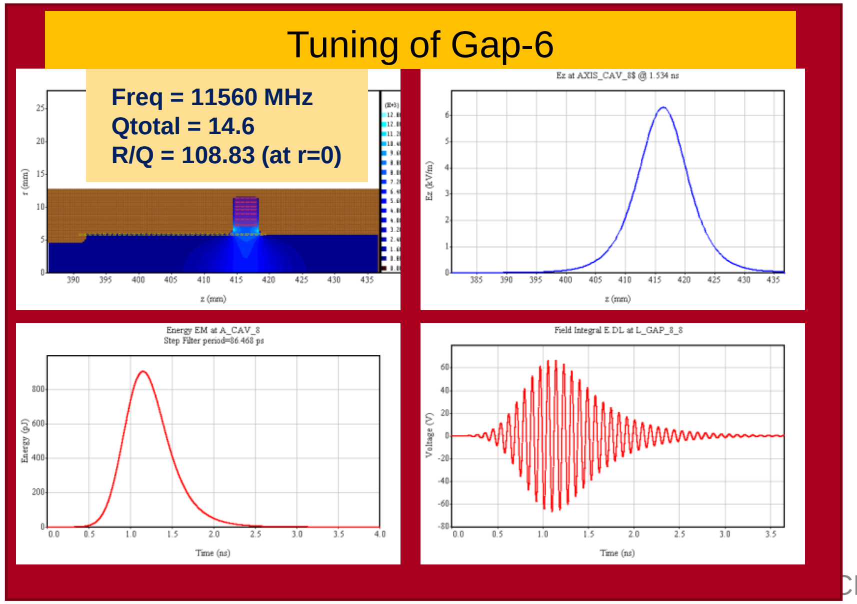




- After monotron oscillation was found to be the source of instability, CERN redesigned the triplet with a shorter gap length
- Zero drive test in MAGIC up to 600 ns showed no instability
- Reducing the Qe of the last output gap improved efficiency from 41% to 43%

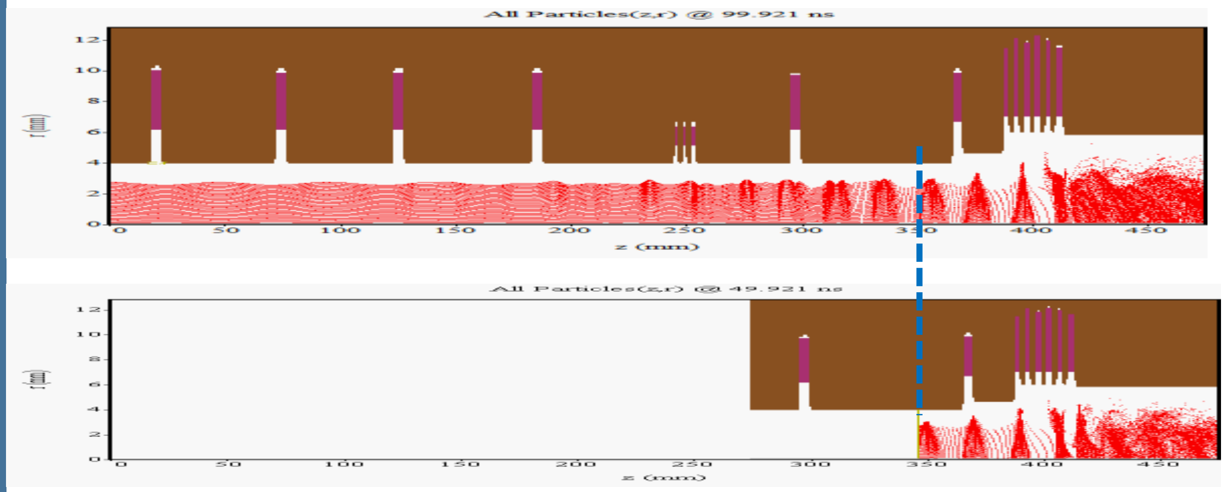
CERN Method of Output Gap Tuning





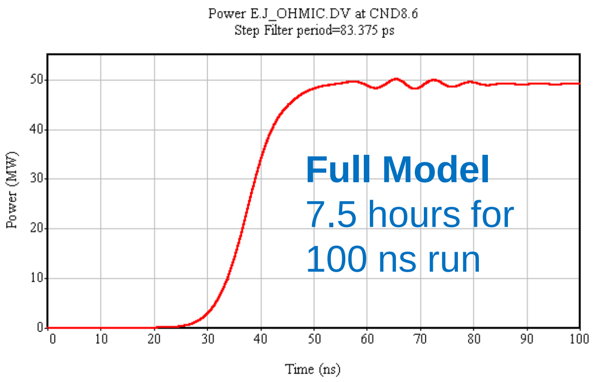
- Modified MAGIC setup to allow individual tuning of each output gap
- Match CERN method of output gap tuning – tuning one gap at a time
- Frequencies were found to be ~1% too low for most single gap cavities in the previous MAGIC model
- After fine tuning each gap, efficiency improved to 59%

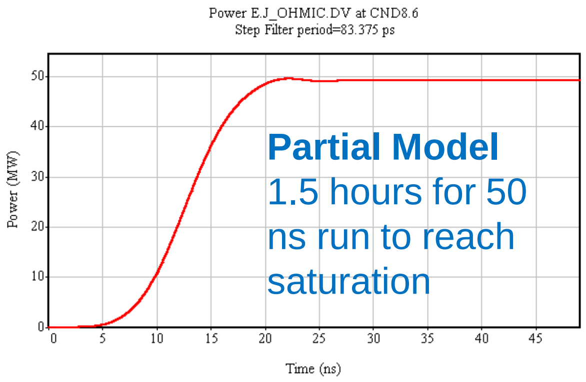
Optimize Output Tuning with Partial MAGIC Model



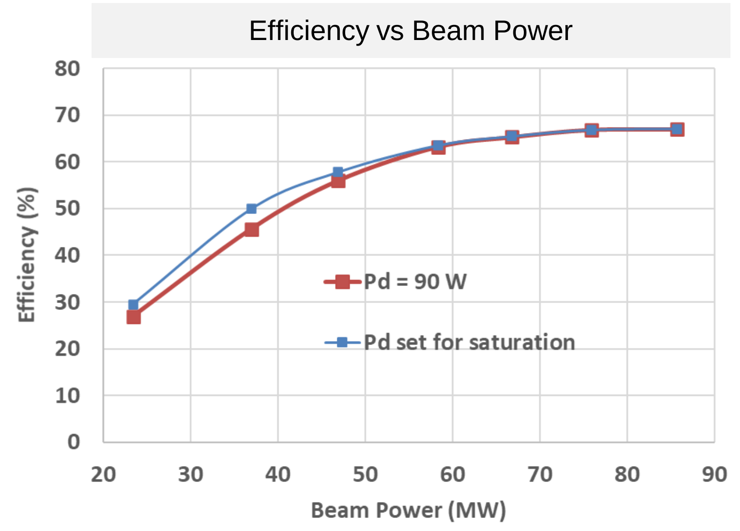
- Export beam after the 6th cavity and inject the bunched beam into a smaller MAGIC model
- Faster optimization of output tuning
- Optimized output design achieved 52 MW, 68% efficiency

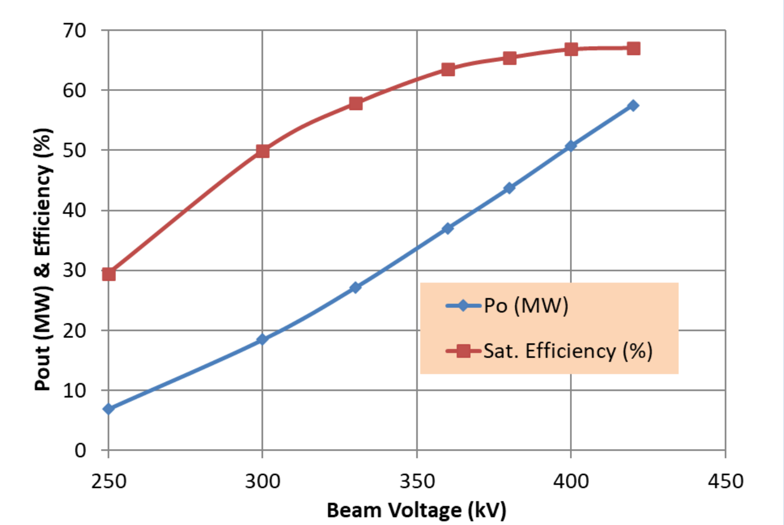
Partial model is 10x faster reaching steady state

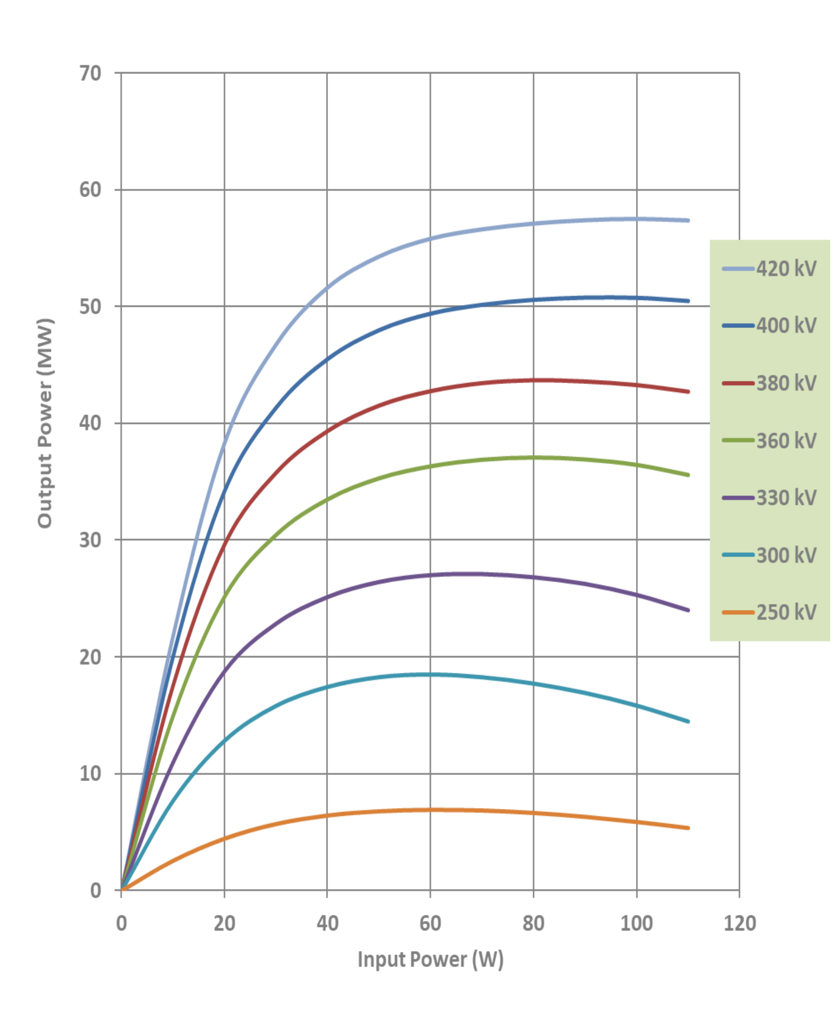


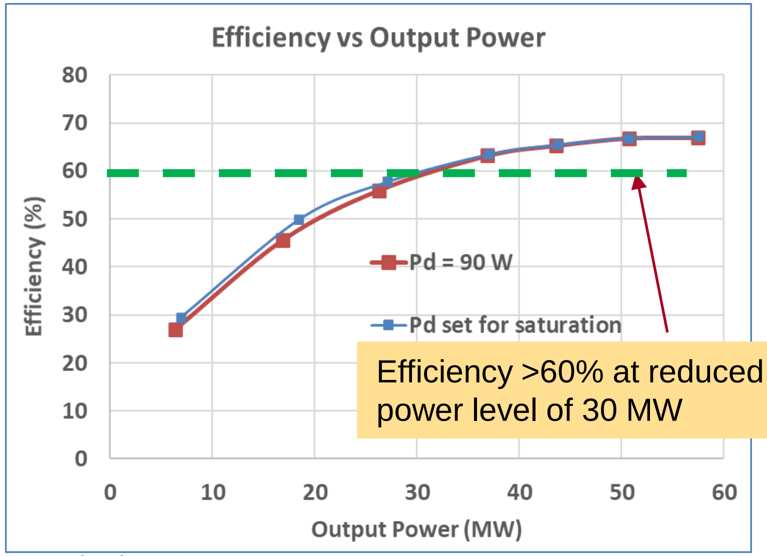


MAGIC Result of Optimized Design with Ideal Beam





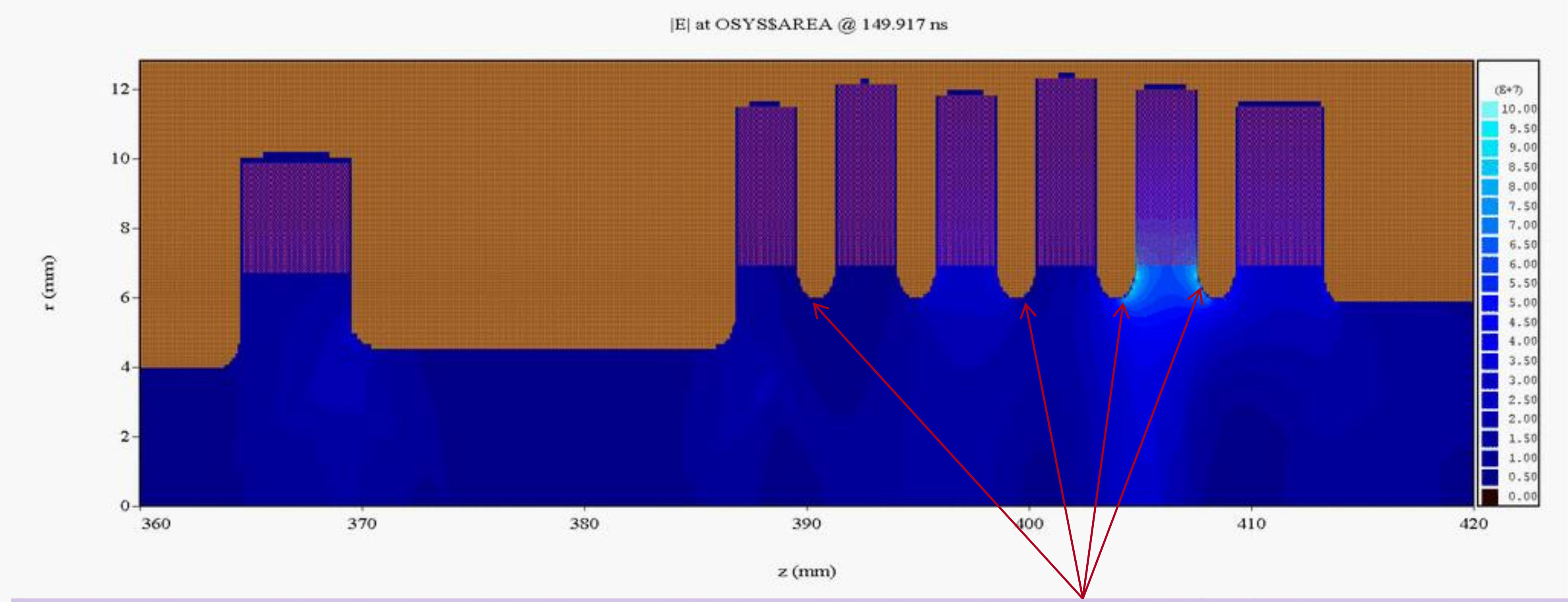




Efficiency >60% at reduced power level of 30 MW

Using the optimized OP tuning, construct drive curves at different beam voltages

Surface E-field in Output Cavity



Plot of |E| contour shows maximum E-field gradient at iris #1, 3, 4 at different RF phases
Emax ~ 96 MV/m @ Po = 51.3 MW with Pd = 100 W

Beam Optics Design for CERN HEX Klystron

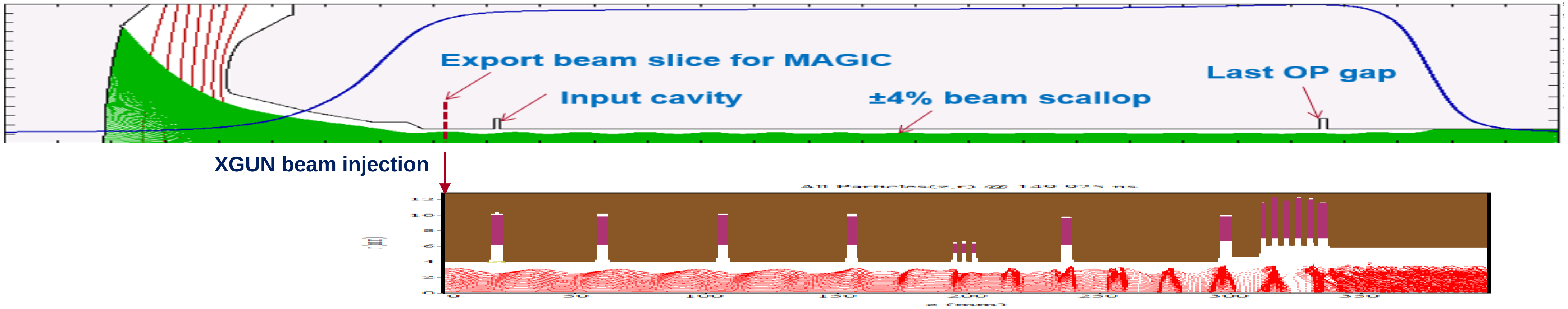
XGUN Design of Electrostatic Beam Optics

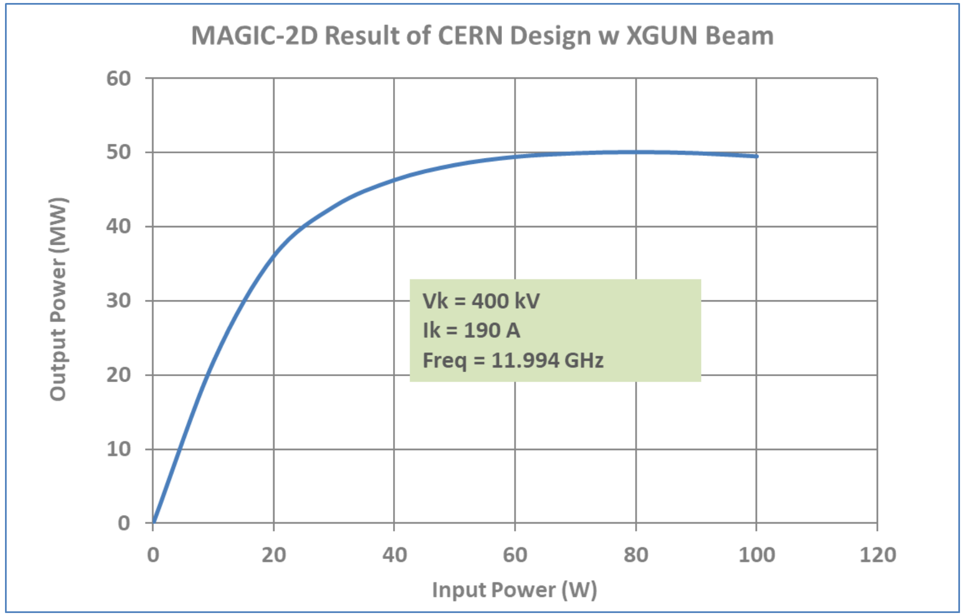
- Perveance = 0.75×10^{-6} $A/V^{1.5}$
- Tunnel diameter = 8 mm
- Beam diameter = 5.8 mm at electrostatic minimum
- Vk = 400 kV, Ik = 191 A
- Cathode loading = 6.5 A/cm^2 maximum

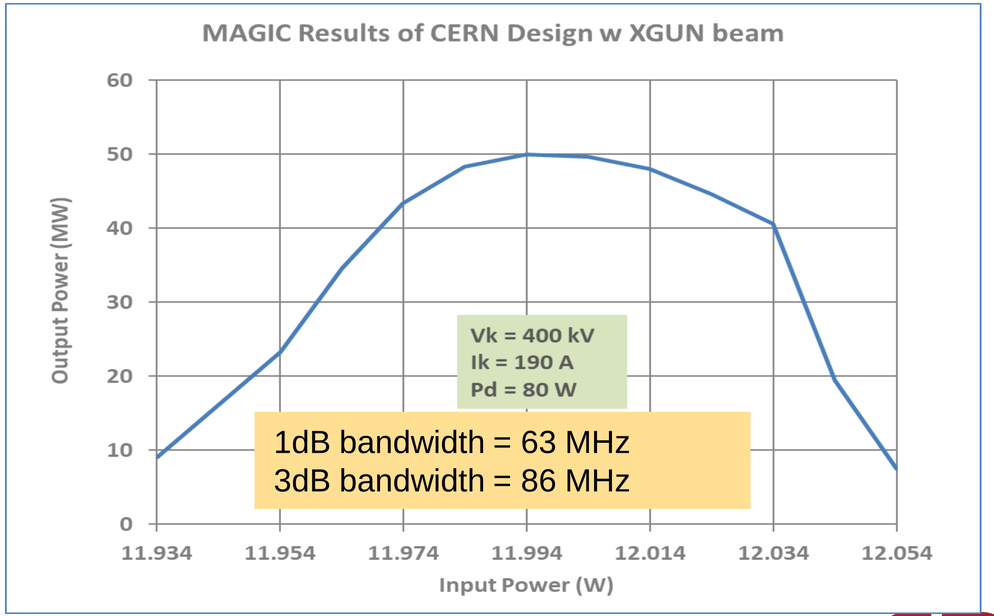
Magnetics Design

- Based on VKX-8311 solenoid design
- Peak field at output cavity is 5.47 kG, 3.65 times the Brillouin field of 1.5 kG
- Optimized magnetic field profile to minimize beam scallop to +/-4%

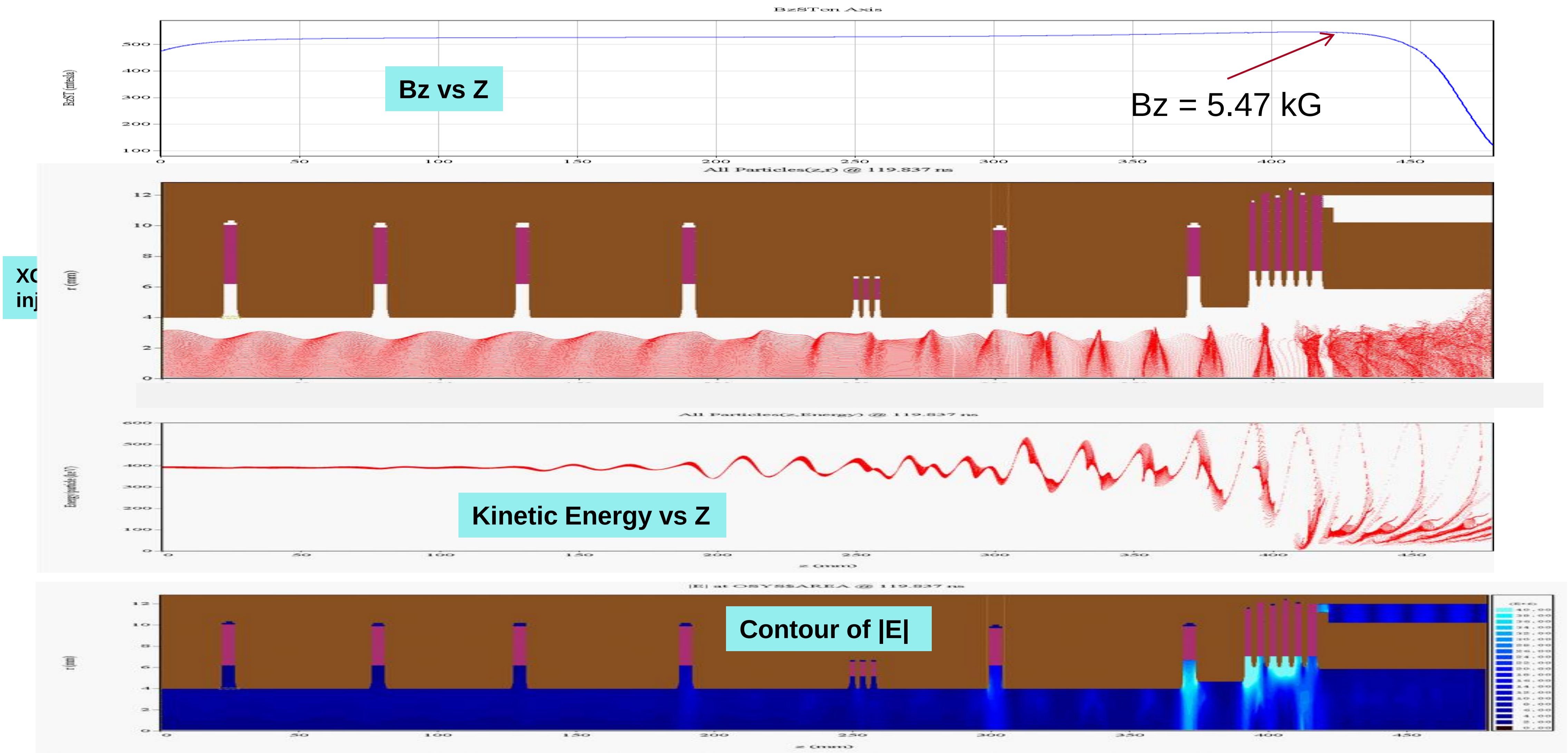
MAGIC Simulation with XGUN Beam





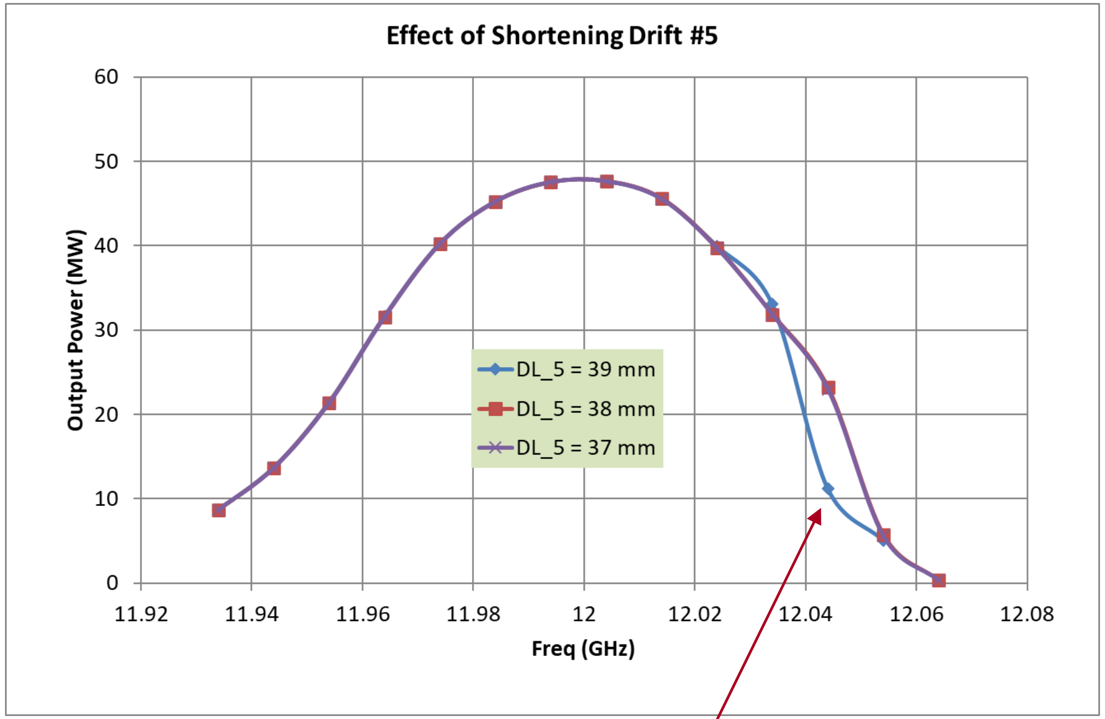


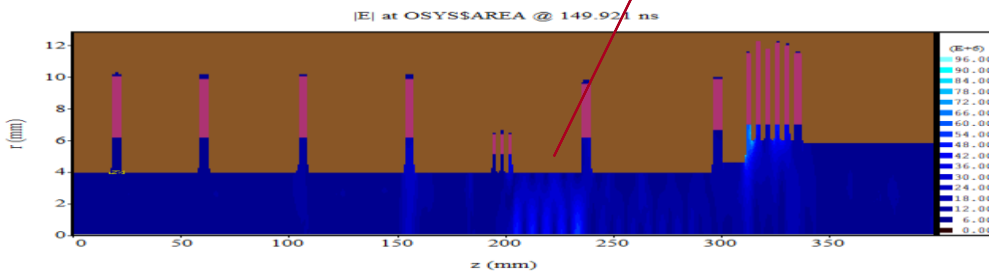
MAGIC Simulation with Imported XGUN Beam



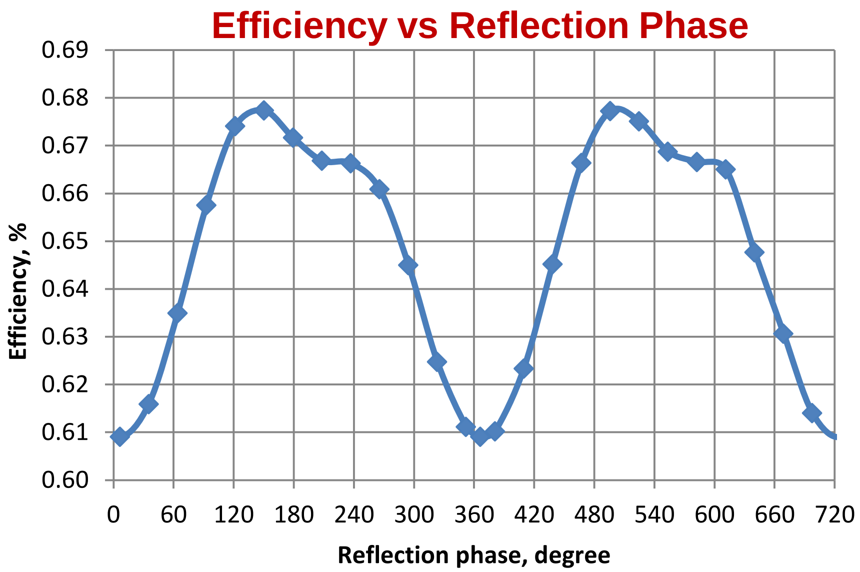
Tunnel mode at 36 GHz

- Bandpass curve at saturation shows power dip at 12.044 GHz; Indication of tunnel mode in the drift section between cav #5 & 6 near 36 GHz
- Reducing the drift length by 1 mm to increase tunnel mode frequency from 36 GHz to 36.27 GHz
- MAGIC results with shorter drift lengths (38 mm, 37 mm) eliminates dip at 12.044 GHz
- No change in output power at other frequencies



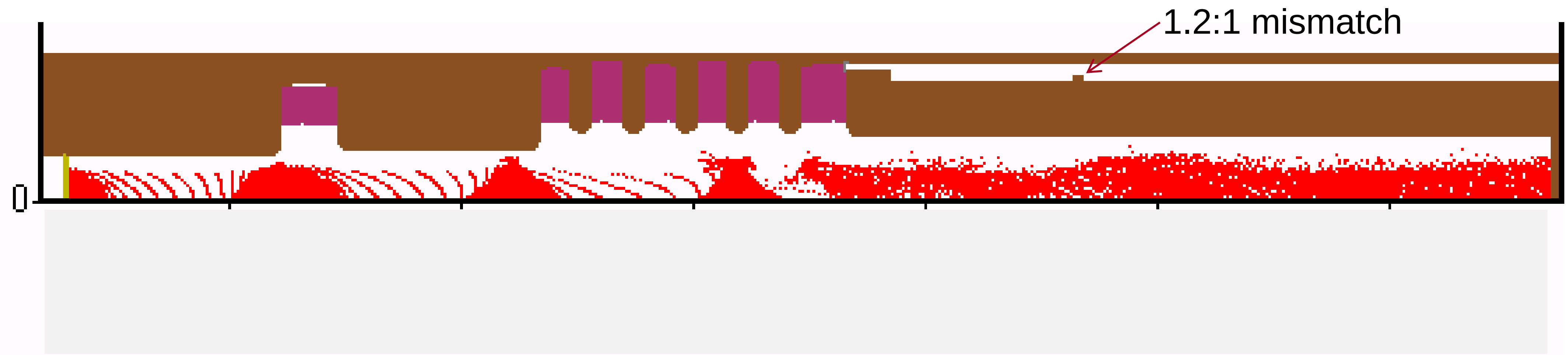


Effect of 1.2:1 External Mismatch

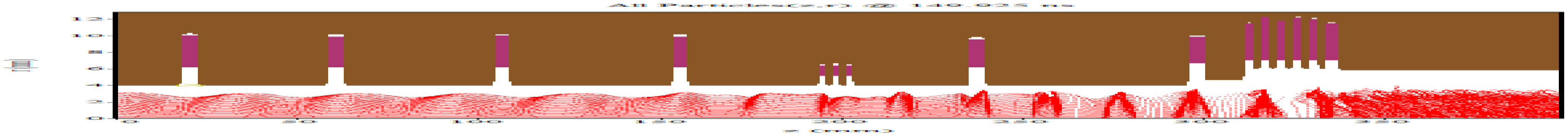


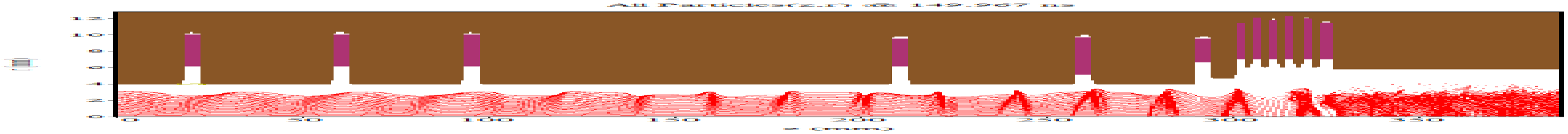
<u>Study the effect of external 1.2:1 mismatch at different phase</u>

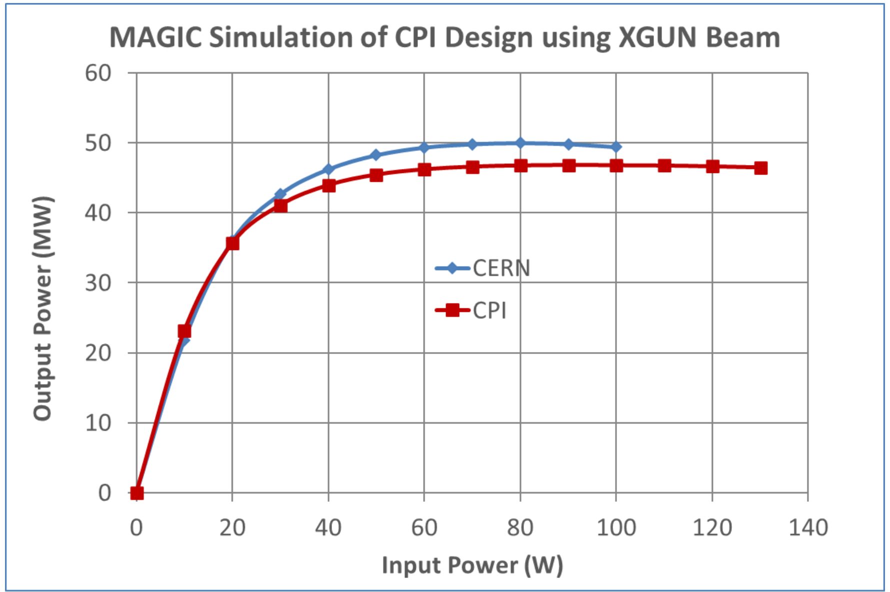
- Add a 10 Ohm coaxial waveguide section to last gap
- Tune the coupling between coax and last gap to achieve Qe of 11
- Add a step on the inner conductor of the coax and tune the size to achieve 1.2 : 1 mismatch
- Change the phase of mismatch by moving the step location (half wavelength = 12.5 mm $\rightarrow$ 360 deg in Reflection Phase)
- Run MAGIC simulation with mismatch at different z locations and plot **Efficiency vs Reflection Phase**
- **No reflected electrons for all reflection phases**

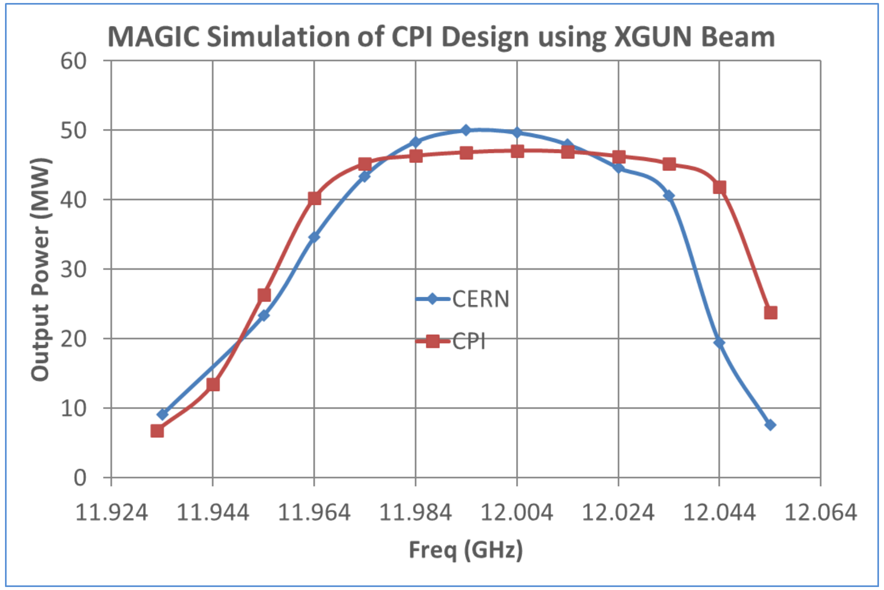


Comparison of CERN & CPI Designs w XGUN Beam

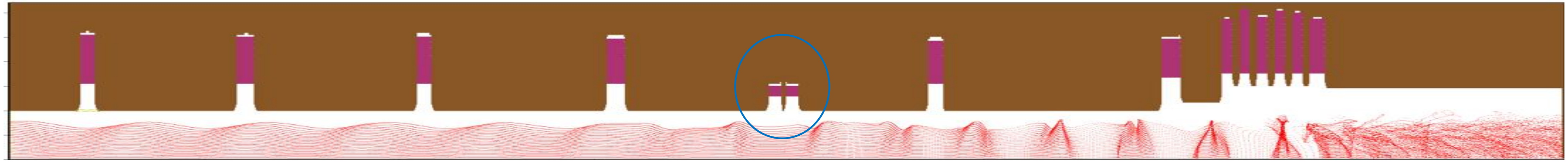


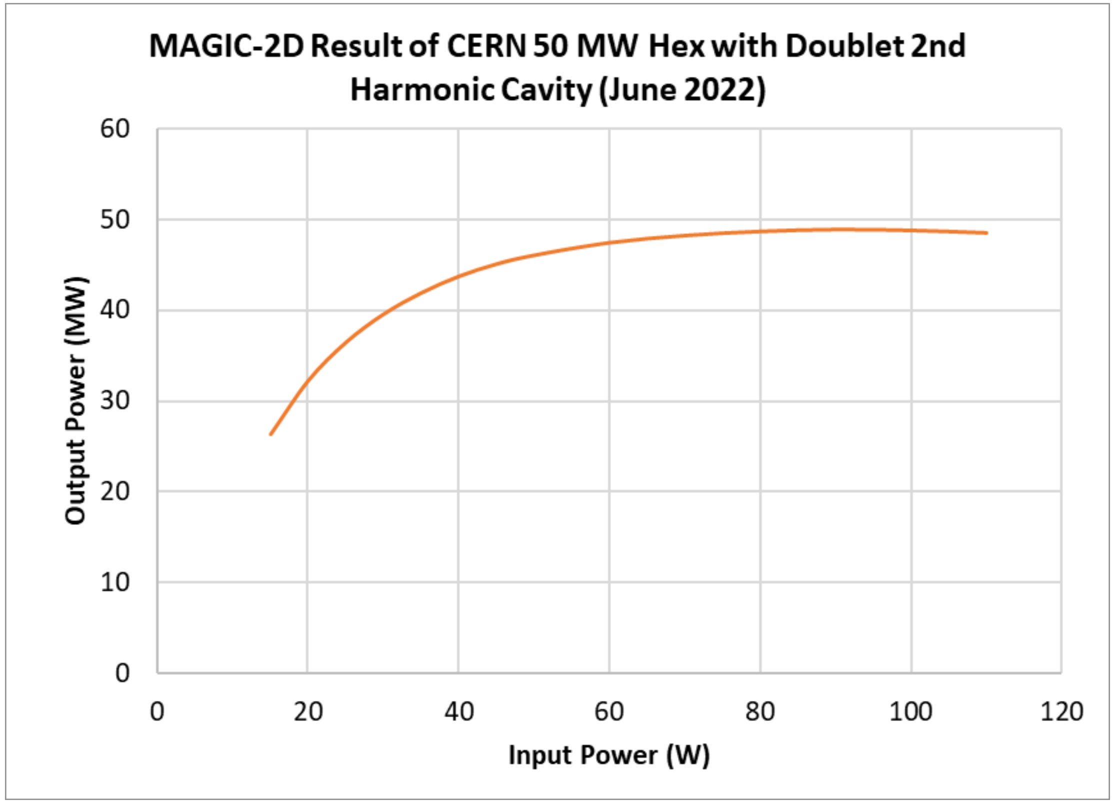


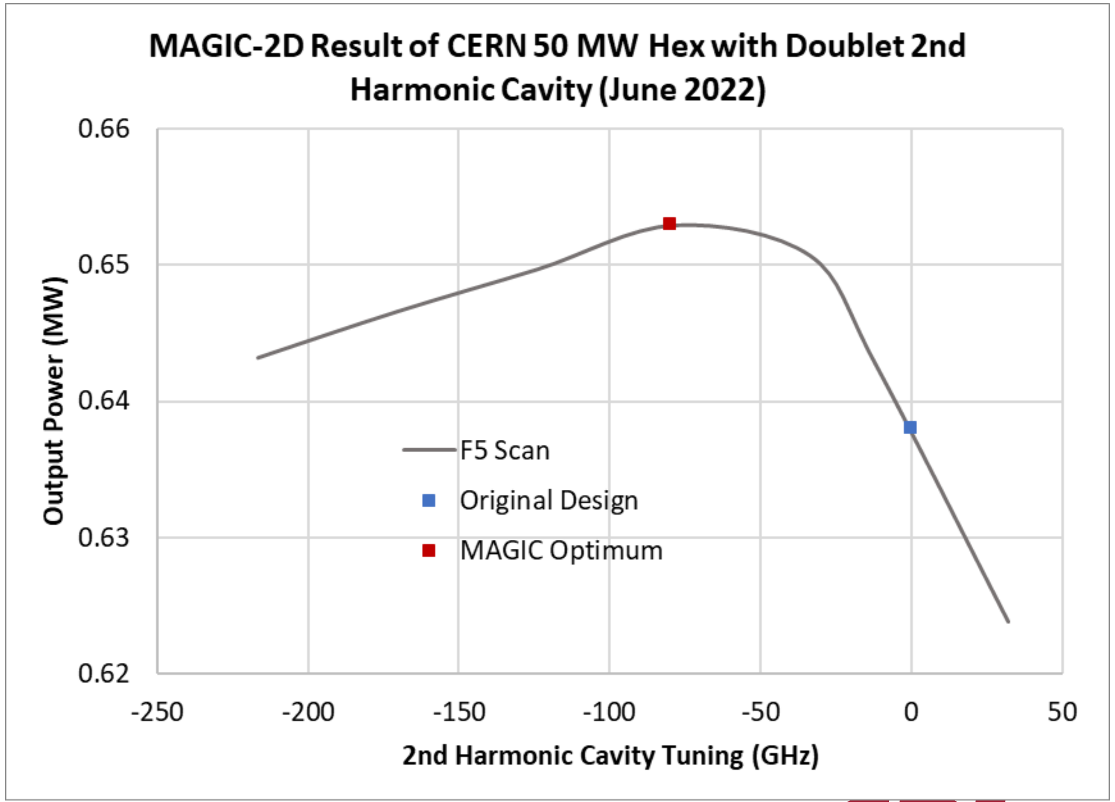




MAGIC Result of Updated Design w 2^{nd} Harmonic Doublet

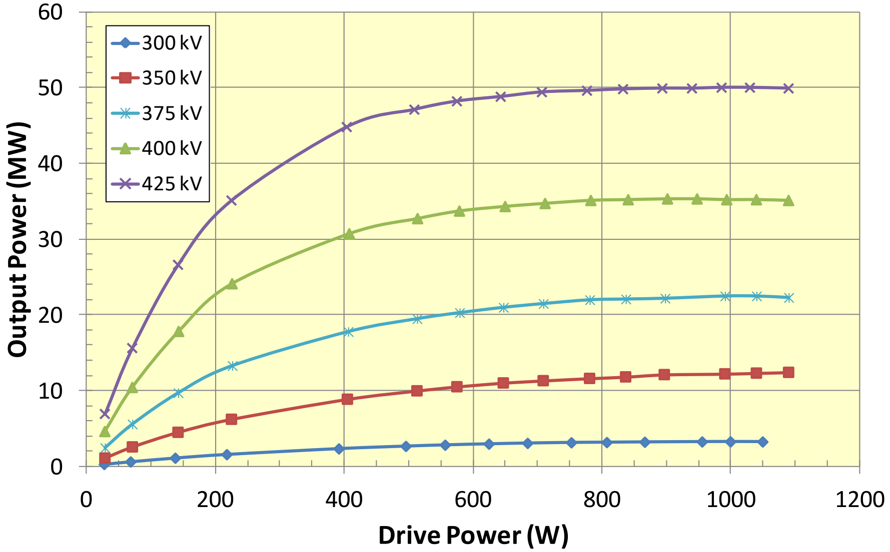


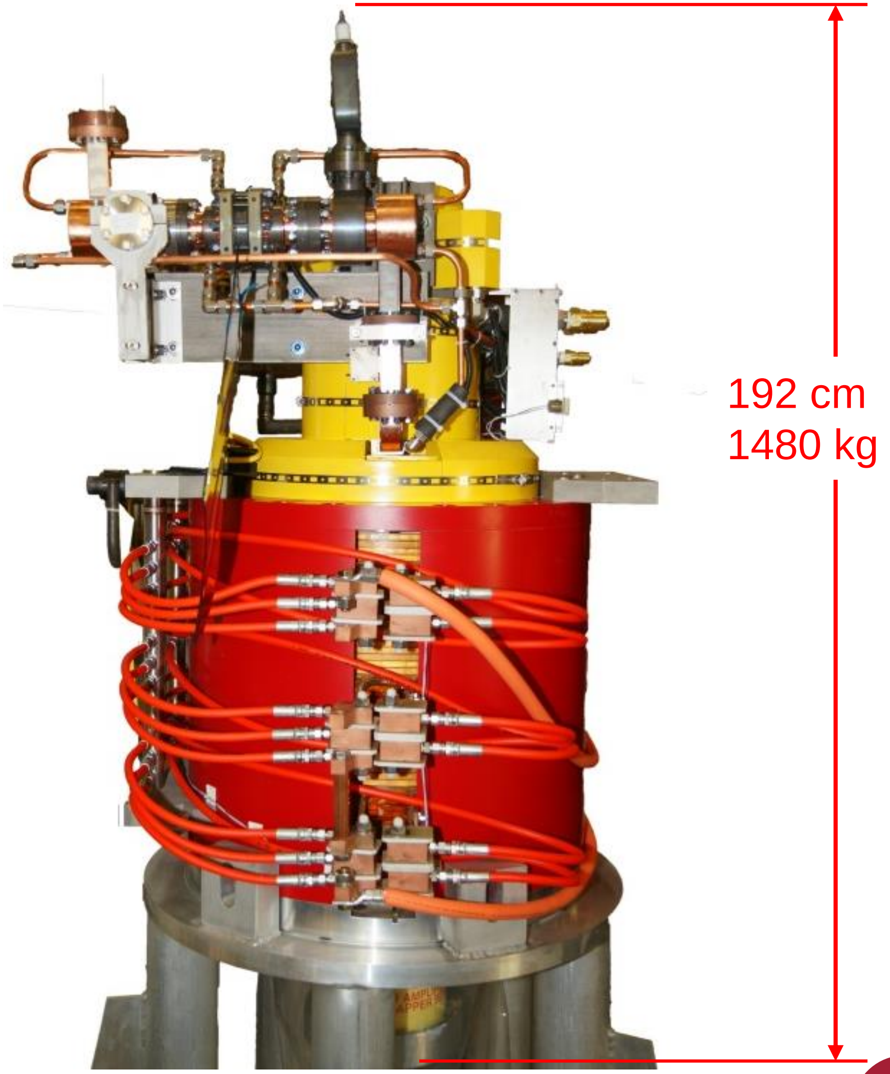




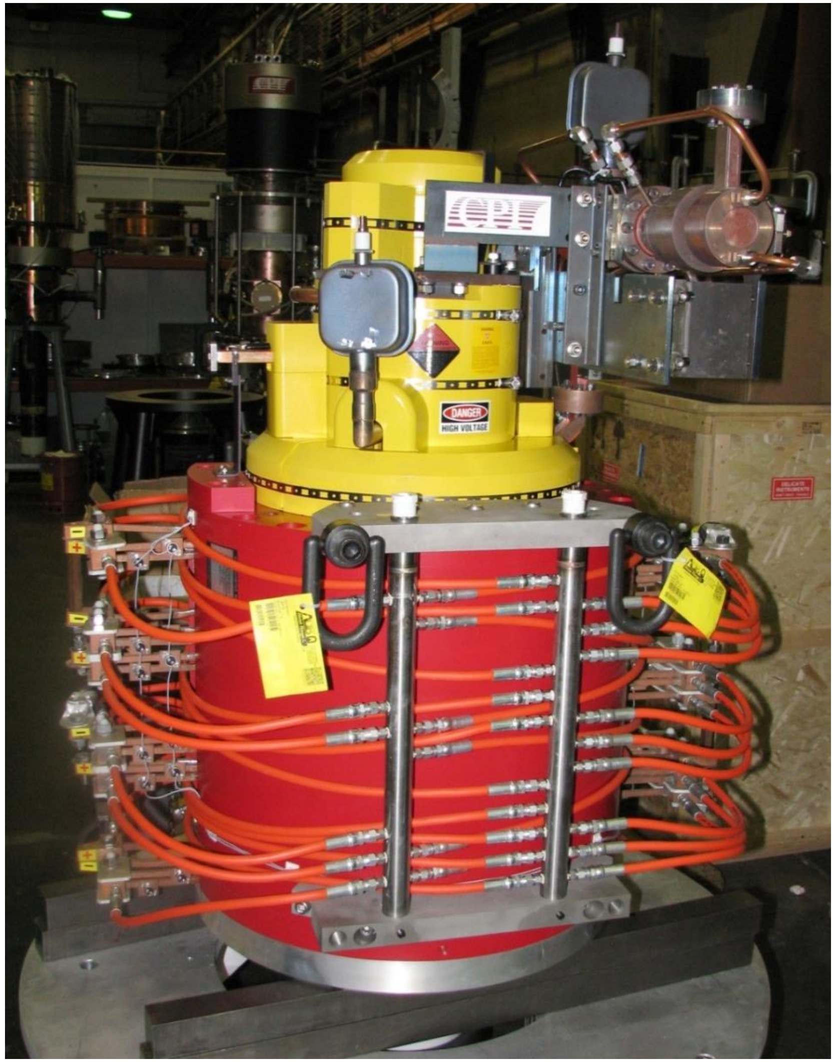
VKX-8311A Klystron

Typical Operating Parameters		
Item	Value	Units
Beam Voltage	**425**	kV
Beam Current	**325**	A
Frequency	**11.994**	GHz
Peak Power	**50**	MW
Ave, Power	**5**	kW
Sat. Gain	**49**	dB
Efficiency	**38**	%
Duty	**0.009**	%



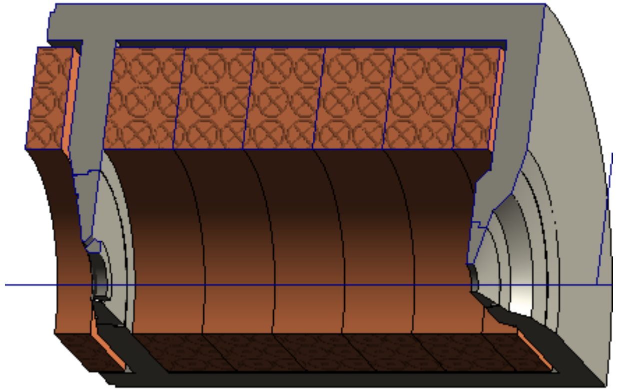


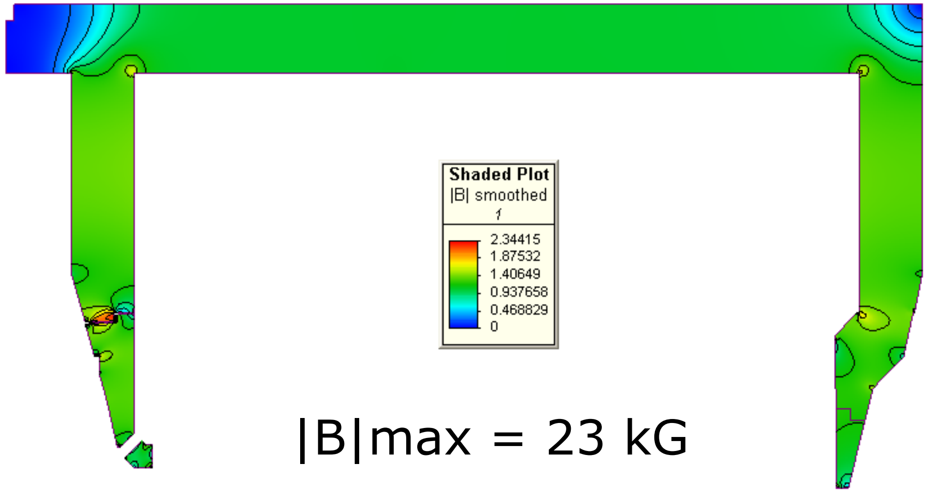
SLAC XL-4 & XL-5 to CPI VKX-8311



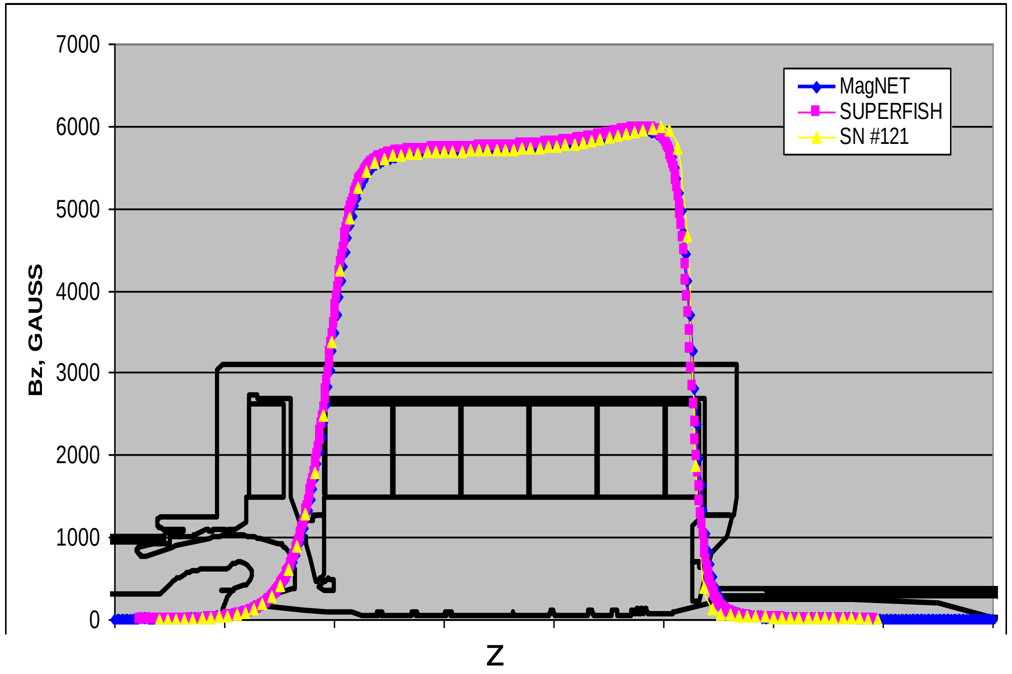
- SLAC developed the XL-4 and XL-5 50 MW X-band klystrons
  - development over ~20 years
  - >40 klystrons made
- Design transitioned to CPI
  - electrical design preserved
  - mechanical changes made for ease of assembly and use
  - testing of S/N 001 done at SLAC
- Thanks to Andy Haase, Daryl Sprehn, Lisa Bonetti, Joe Olszewski, John Eichner and Mike Fazio
- CPI has manufactured ten VKX-8311 klystrons for several customers since 2014

VKX-8311 Solenoid





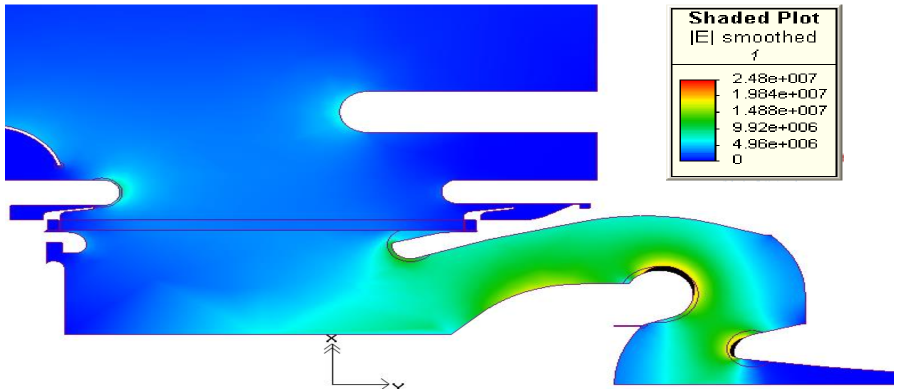
|B|max = 23 kG



- Six main coils divided into two groups, one bucking gun coil
  - heavy gage tubing with water cooling (300 A)
- Good agreement between measured profile and Superfish / MagNet simulations
- The same solenoid will be used for the high efficiency design

VKX-8311 Electron Gun

- Diode gun
  - Scandate cathode (11 A/cm^2)
  - Perveance = 1.2 x 10^{-6} A/V$^{1.5}$
- Excellent optics required
  - 110:1 area convergence (magnetic compression)
  - 330 MW/cm^2 beam power density



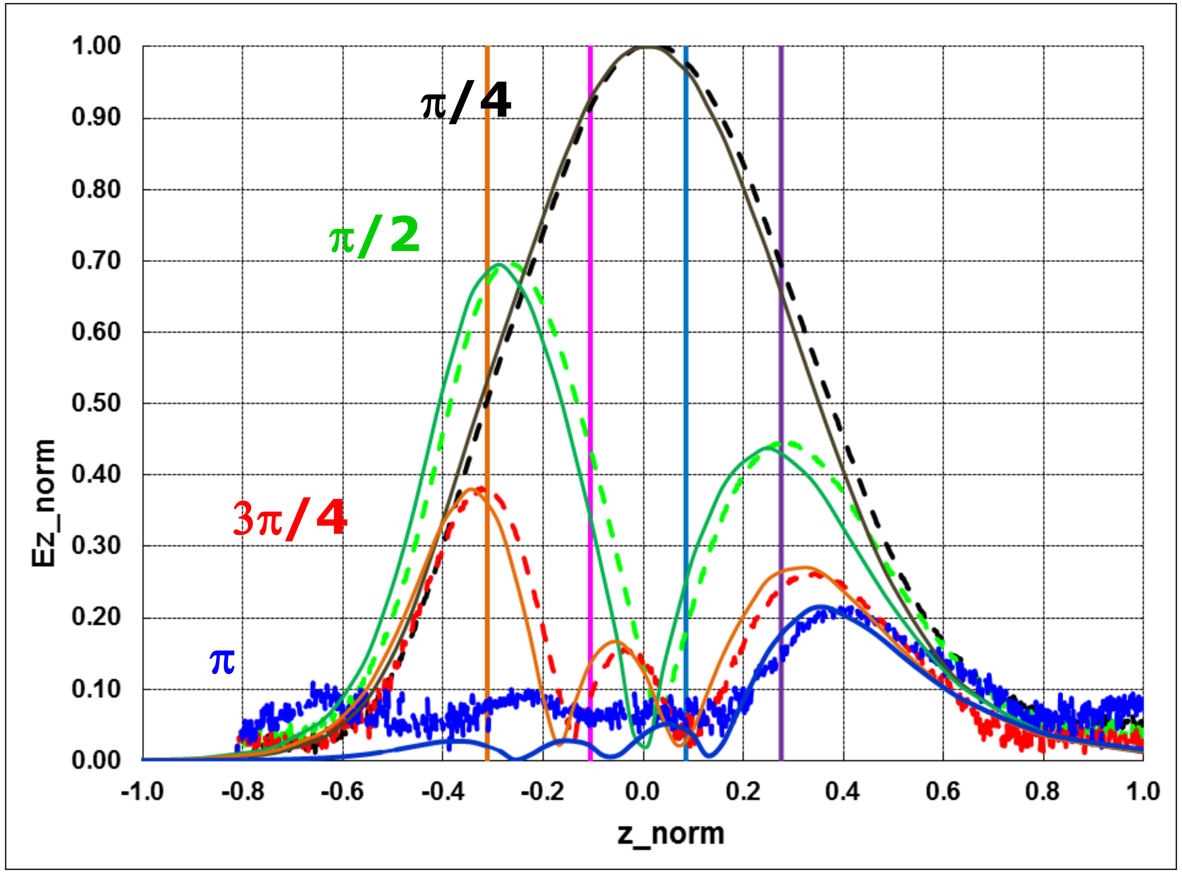
- 245 kV/cm peak gradient
  - cleanliness, surface finish, proper processing all critical

VKX-8311A RF Body

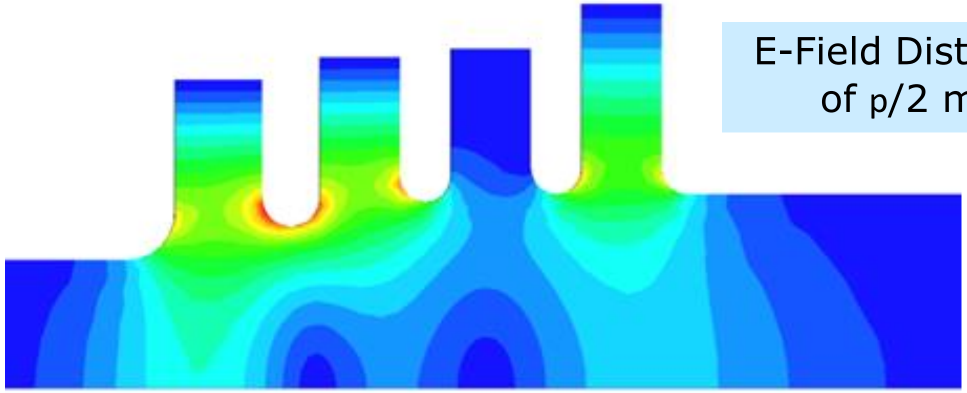
- Seven cavity circuit
  - three in-band buncher cavities
  - three inductively tuned cavities for efficiency enhancement
  - disc loaded, double iris output cavity
  - WR90 input and output
  - integral cavity trim tuners
  - integral water cooling
- Large tunnel diameter used to ease beam optics design
- RF gradients limited to ~55 MV/m
  - reduces rf discharges
  - drives choice of output circuit

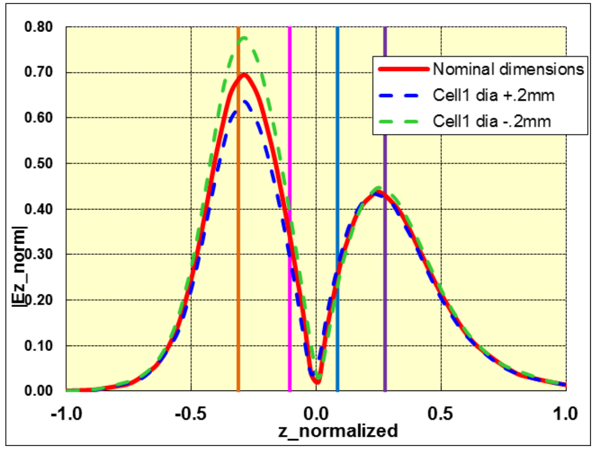
Electric Field in VKX-8311 4-Gap Output

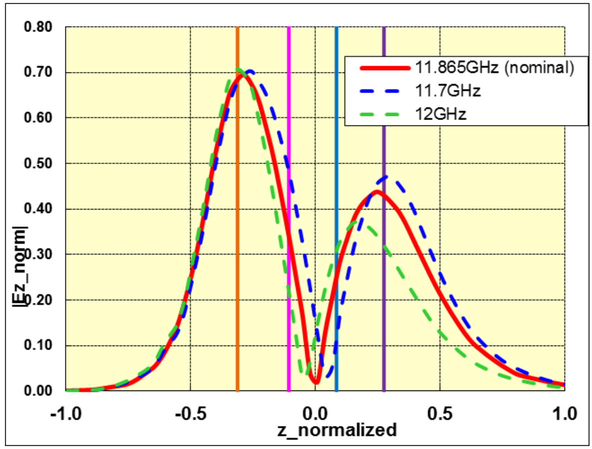
Normalized Magnitude of Axial Field for First Four Modes



E-Field Distribution of p/2 mode







Solid curves: driven mode simulated fields
Dashed curves: cold test measured fields
Vertical lines: mid-gap locations

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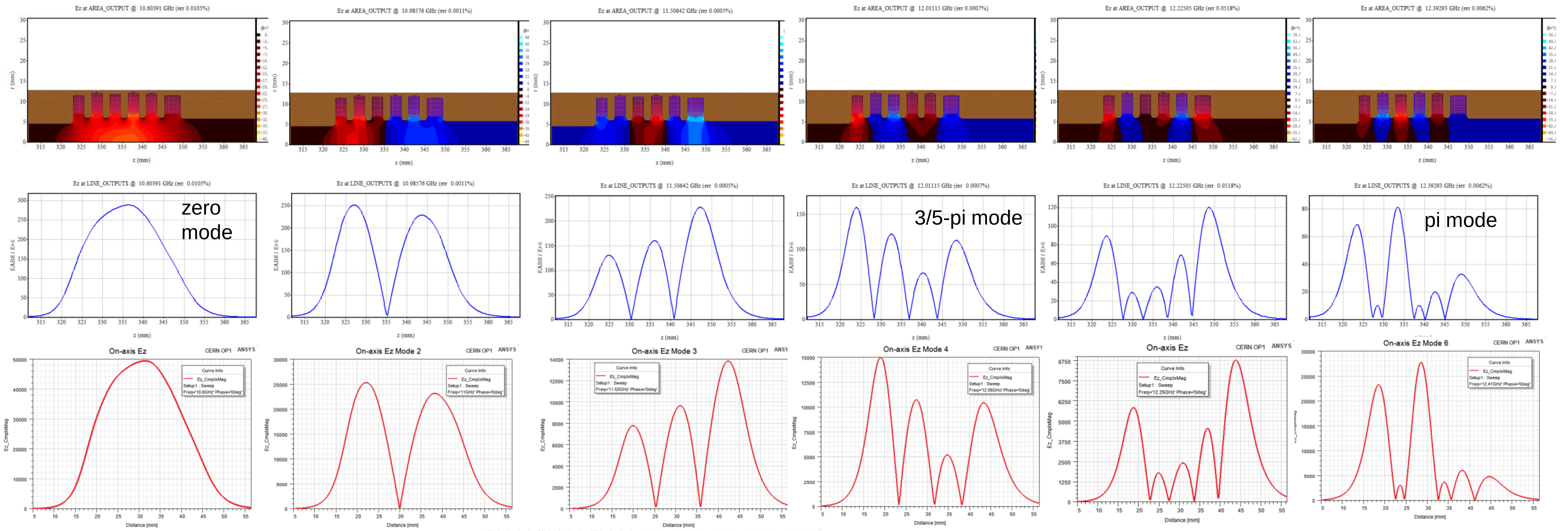
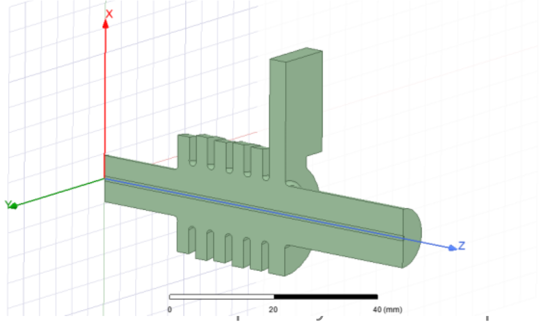
HEX 6-Gap Design: MAGIC-2D Eigenmode vs HFSS Driven Modal

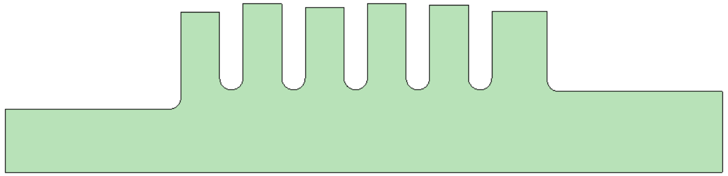


- CERN design of 6-gap OP with single waveguide output
- Each gap was adjusted to match the optimized MAGIC frequency

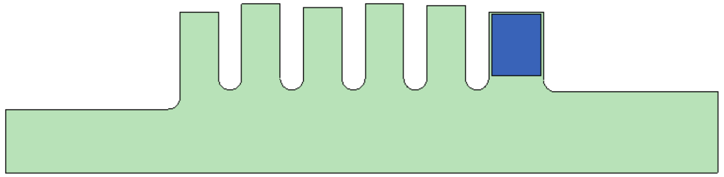


ANALYST 2D Eigenmode Solver

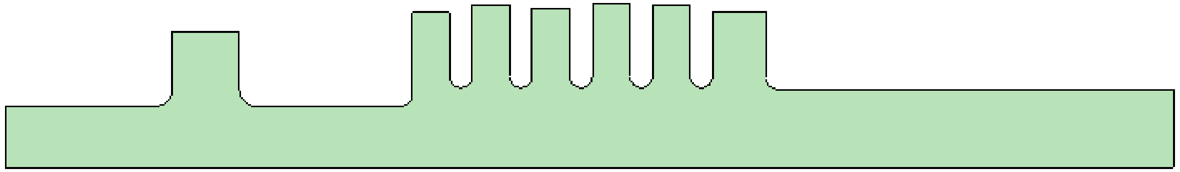
- Model 6-gap output in ANALYST 2D eigenmode solver
- Compare with MAGIC eigenmode results for lossless case
- Study the effect of adding resistive loss in Gap #6
- Perform sensitivity study to assess the effect of gap geometry on mode frequencies and gap E-field



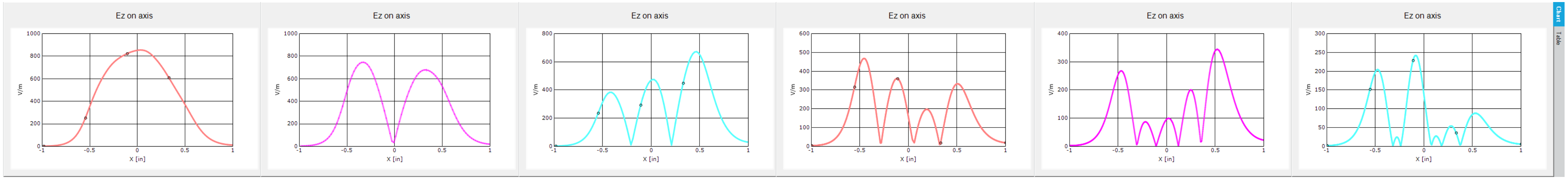
Compare lossless case with MAGIC



Study effect of loss in Gap #6



Study effect of penultimate cavity



Summary

- CERN & CPI collaboration to develop a 50 MW, 12 GHz HEX
- Two stable designs achieving over 60% efficiency
- New beam optics and magnetics designs for HEX
- Finalizing design for 6-gap output
- Negotiation underway with INFN/CERN for prototype fabrication
- Prototype will be based on existing VKX-8311A
  - New electron gun
  - New RF circuit (similar mechanical design approach but improved alignment scheme)
- Prototype fabrication expected to start in 2022

Thank you!