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Normal-Conducting Photoinjector for High Power CW FEL

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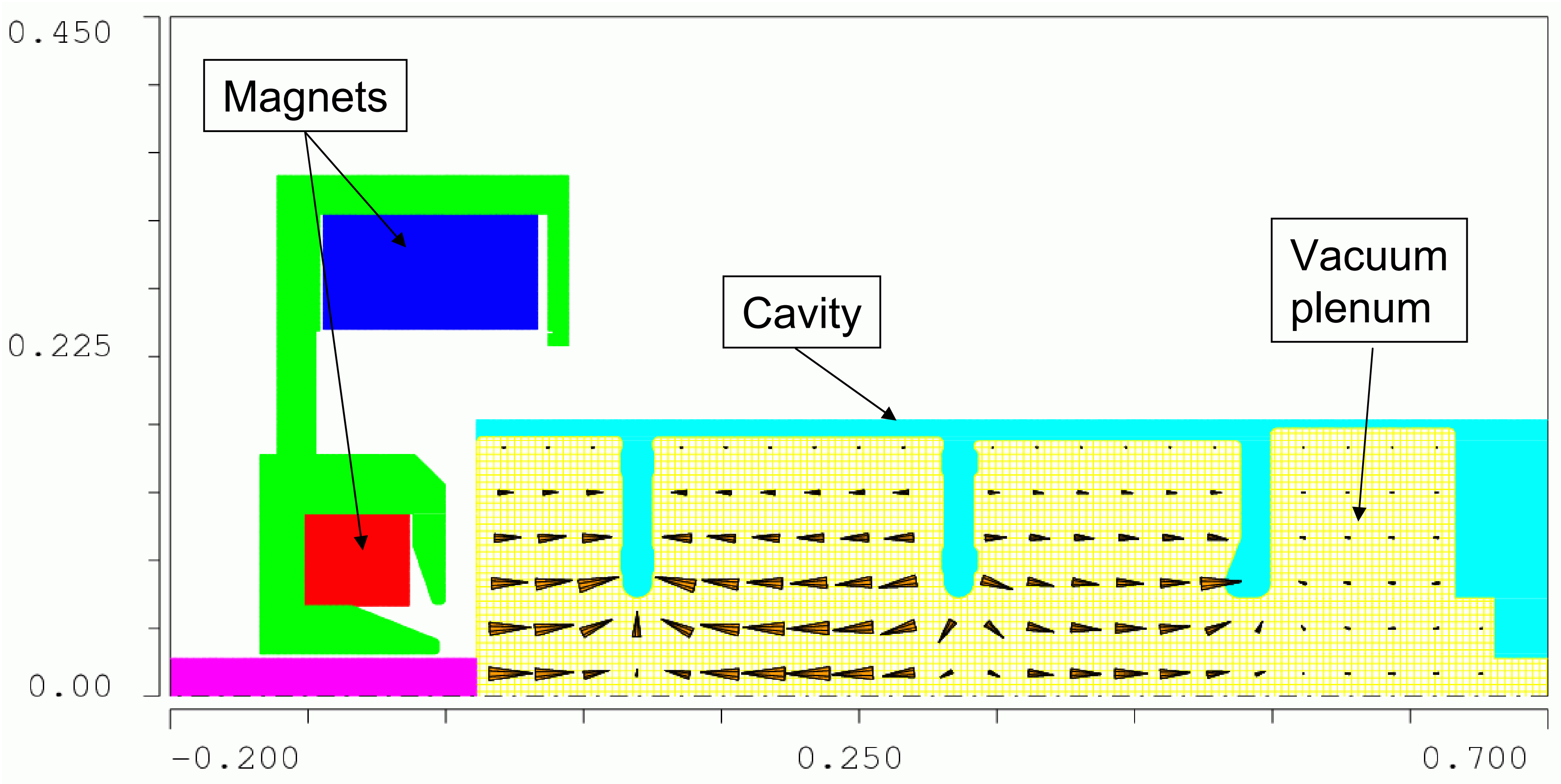
An RF photoinjector capable of producing high continuous average current with low emittance and energy spread is a key enabling technology for high power CW FEL. The design of a 2.5-cell, π-mode, 700-MHz normal-conducting RF photoinjector cavity with magnetic emittance compensation is completed. With average gradients of 7, 7, and 5 MV/m in its three accelerating cells, the photoinjector will produce a 2.5-MeV electron beam with 3-nC charge per bunch and transverse rms emittance below 7 mm-mrad.

Electromagnetic modeling has been used extensively to optimize ridge-loaded tapered waveguides and RF couplers, and led to a new, improved coupler iris design. The results, combined with a thermal and stress analysis, show that the challenging problem of cavity cooling can be successfully solved. Fabrication of a demo 100-mA (at 35 MHz bunch repetition rate) photoinjector is underway. The design is scalable to higher average currents by increasing the electron bunch repetition rate, and provides a path to a MW-class amplifier FEL.

Normal-Conducting RF Photoinjector

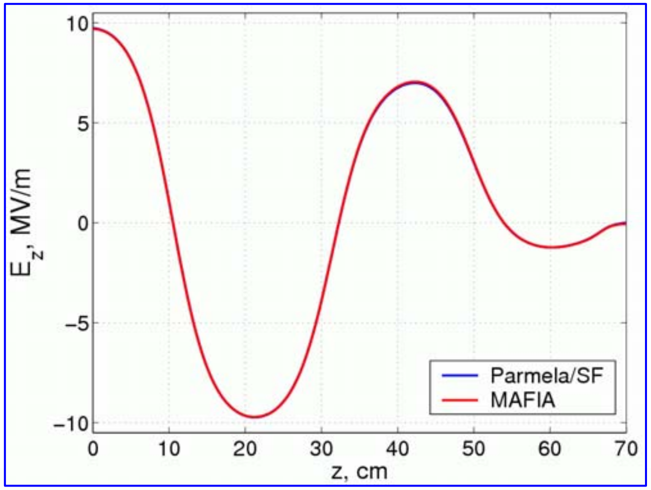
- Requirements and parameters:
  - CW, 700-MHz RF; emittance < 10 mm·mrad at the wiggler
  - 3 nC per bunch, 100 mA at 35-MHz bunch rep rate (→ 1 A)
- Design:
  - split cavities: 2.5-cell PI (old 777 design: 7,7,7 MV/m, 2.70 MeV
    → new 775 design: 7,7,5 MV/m, 2.54 MeV)
    + booster (4 cells, 4.5 MV/m, 5.5 MeV)
  - PI: 2.5 cells, emittance-compensated, on-axis electric coupling
  - 100 mA: P_w (668 kW) + P_b (254 kW) → 1 A: 668 kW + 2540 kW
- EM modeling: cavity, RF couplers, and ridge-loaded tapered waveguides
- Beam dynamics – TS2 versus Parmela
- Thermal & stress analysis, manufacturing → AES, *Medford, NY*

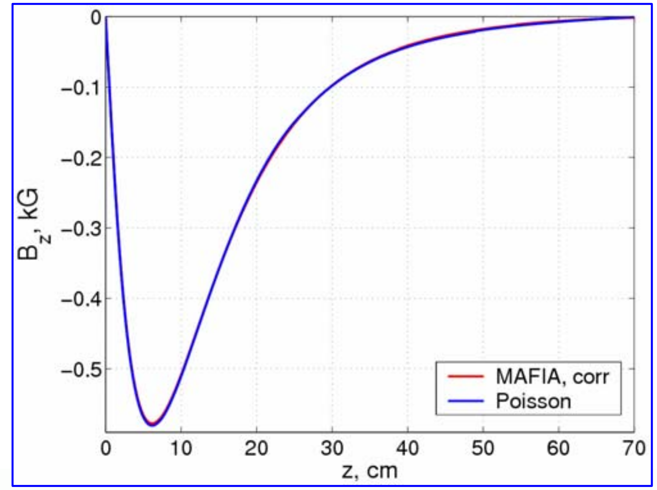
2.5-cell RF Photoinjector Cavity

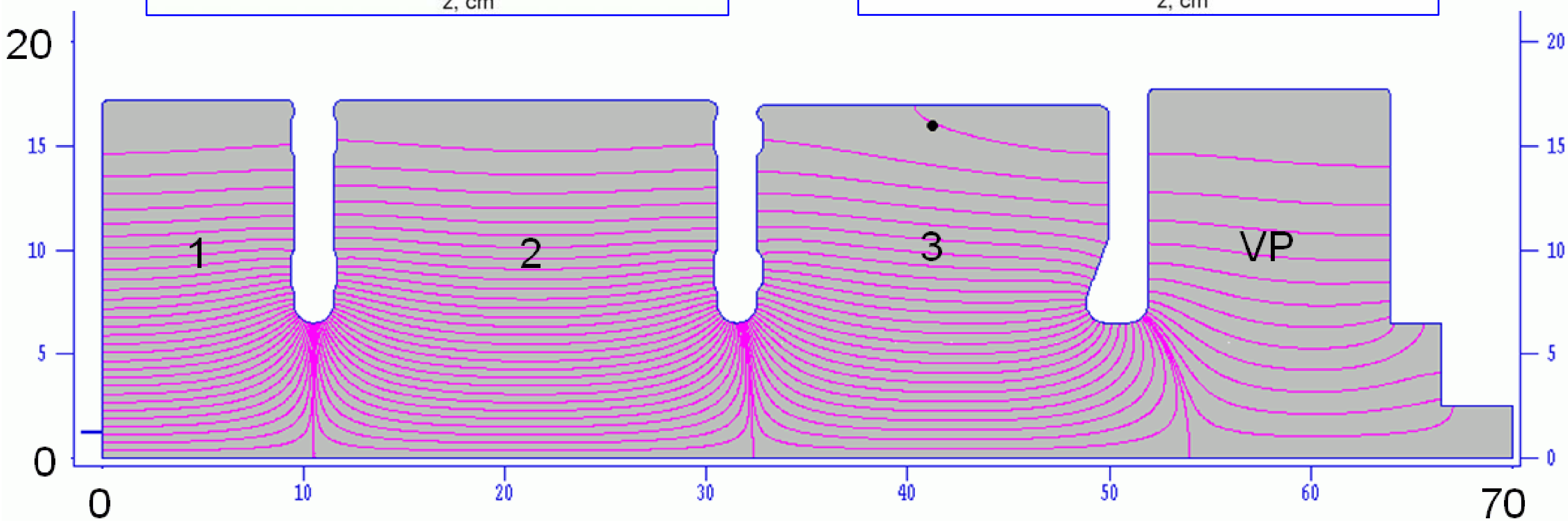


MAFIA model of 2.5-cell cavity with magnets and vacuum plenum

2.5-cell RF Photoinjector Cavity

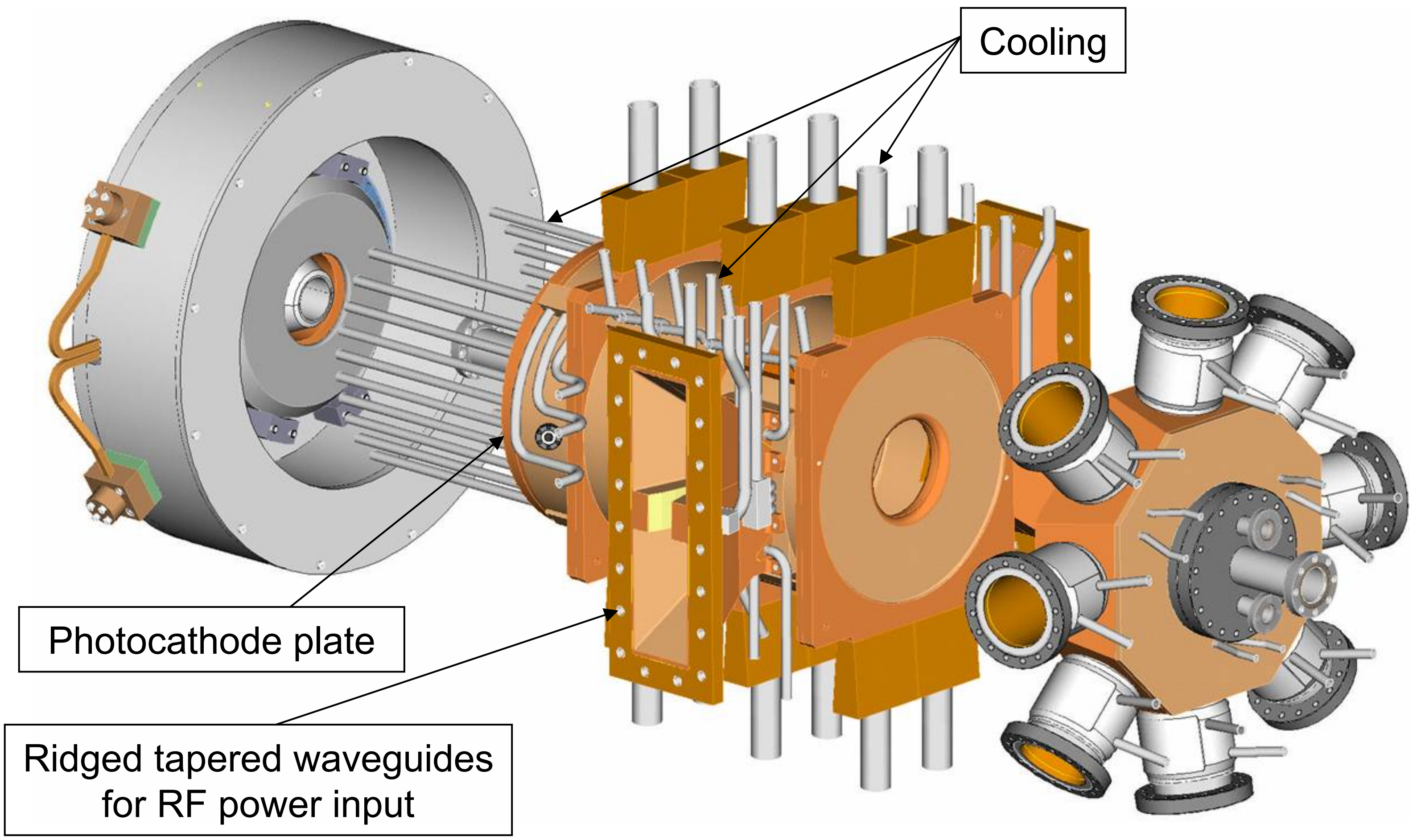






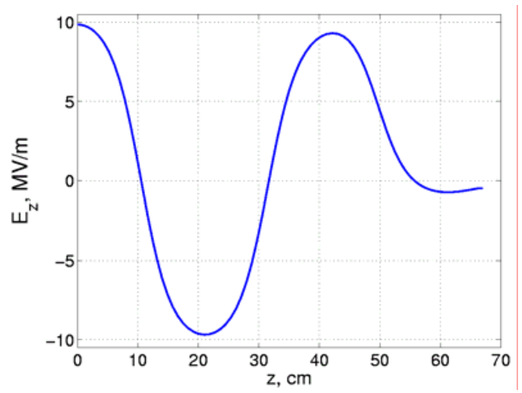
2.5-cell PI with vacuum plenum – SF & MAFIA results

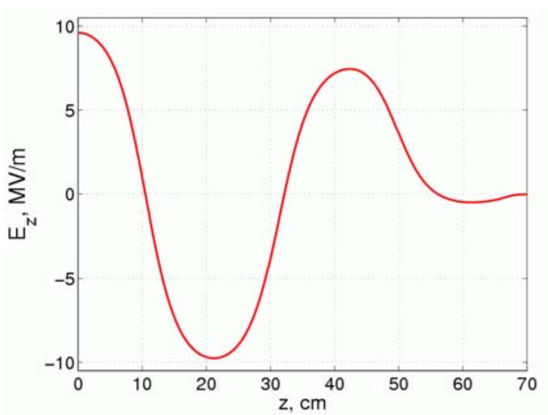
Normal-Conducting RF Photoinjector



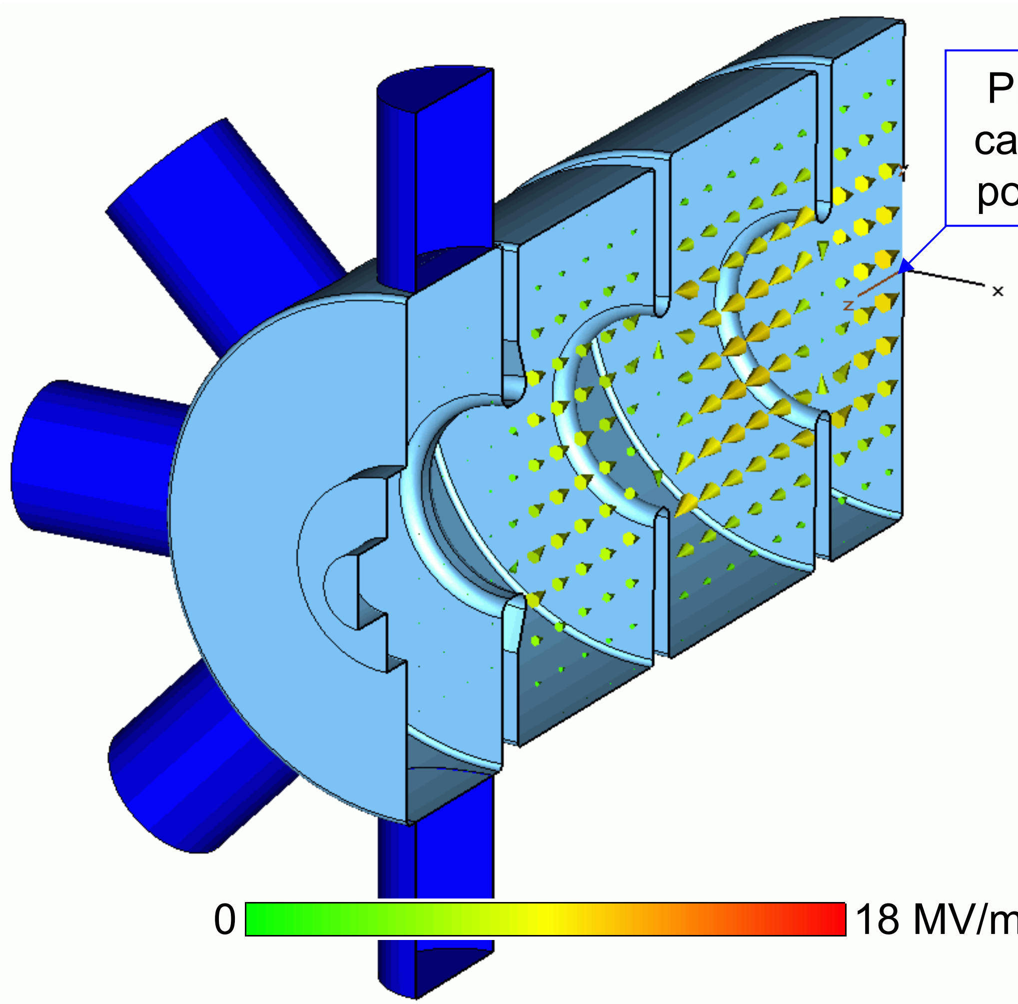
2.5-cell PI with emittance-compensating magnets (left) and vacuum plenum (right)

NC RF Photoinjector: Microwave Studio Modeling



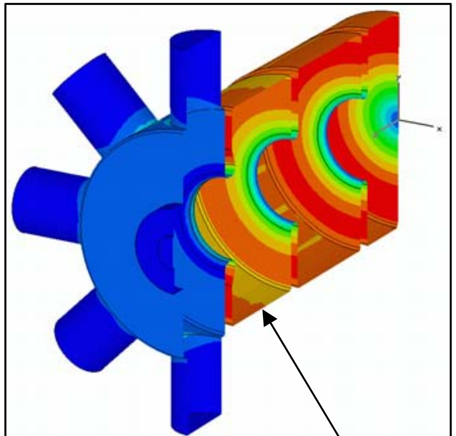


On-axis electric field for 777(old) and 775 designs

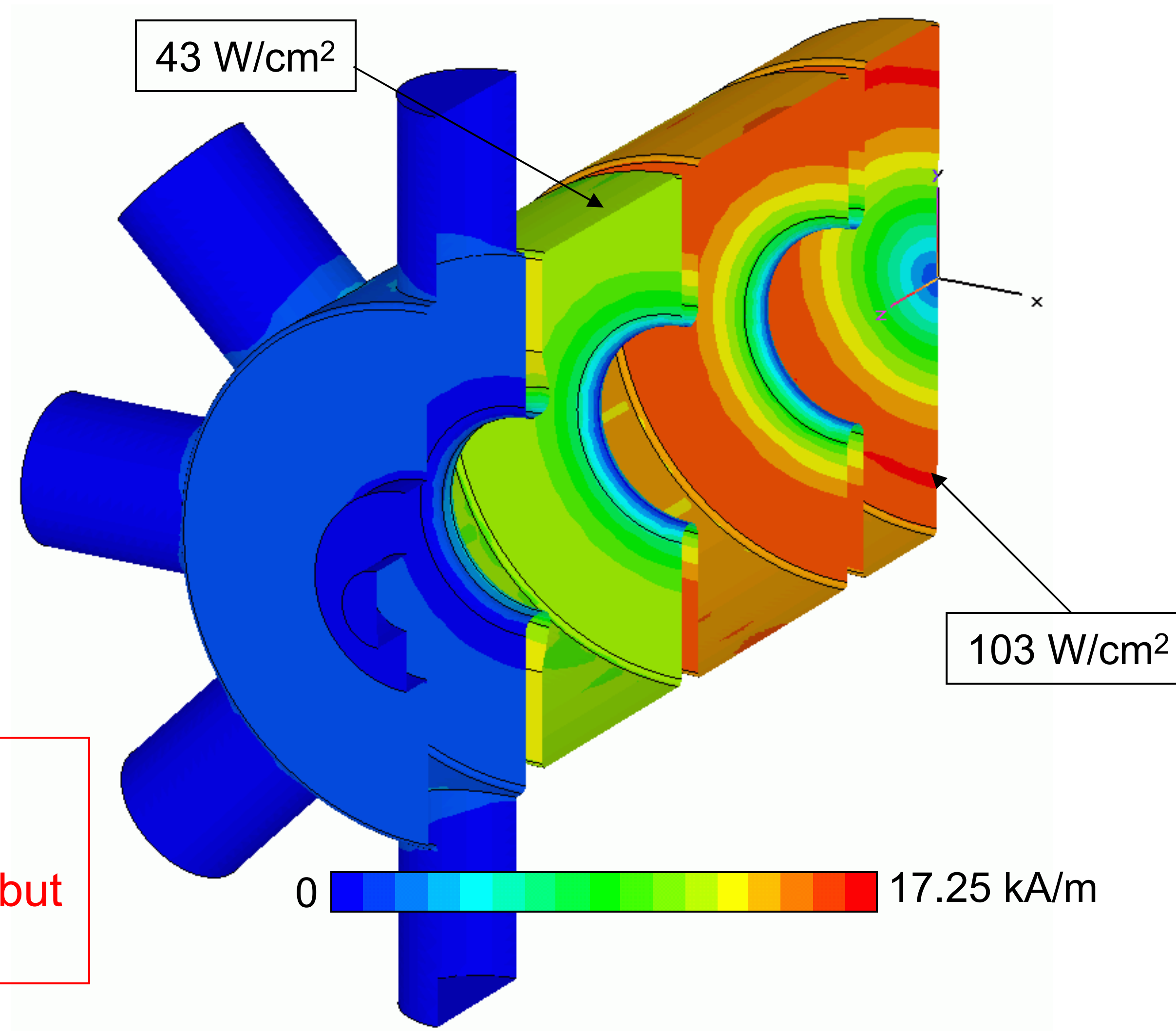


Electric field of π-mode in 2.5-cell cavity: E_0=7 MV/m in cells 1&2, 5 MV/m in cell 3.

NC RF Photoinjector: Microwave Studio Modeling



For comparison: in the old (777) design 75 W/cm^2 in 3rd cell



Power in the 775 design:

P_w = 668 kW versus

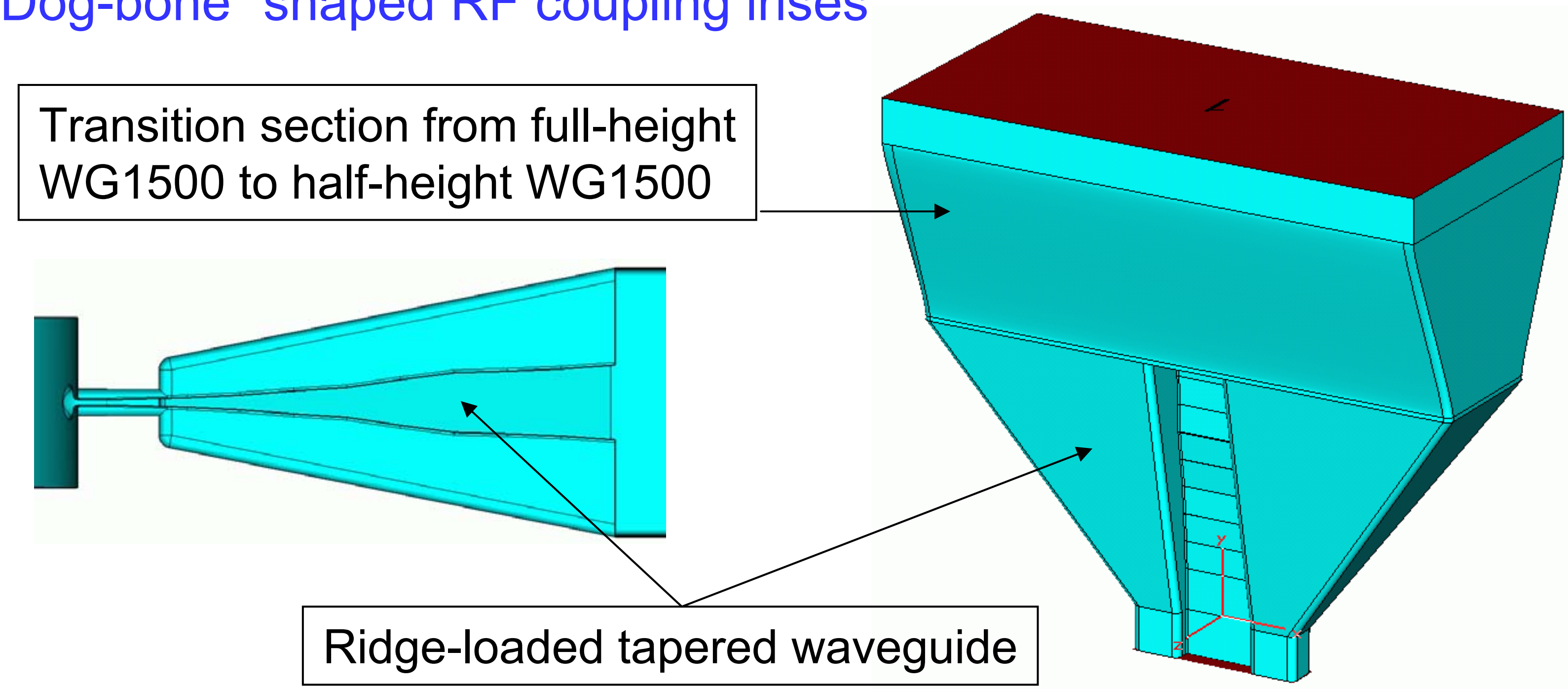
P_b = 254 kW for 100 mA, but

P_b = 2540 kW for 1 A

Surface current distribution for the π-mode in 2.5-cell photoinjector cavity (775)

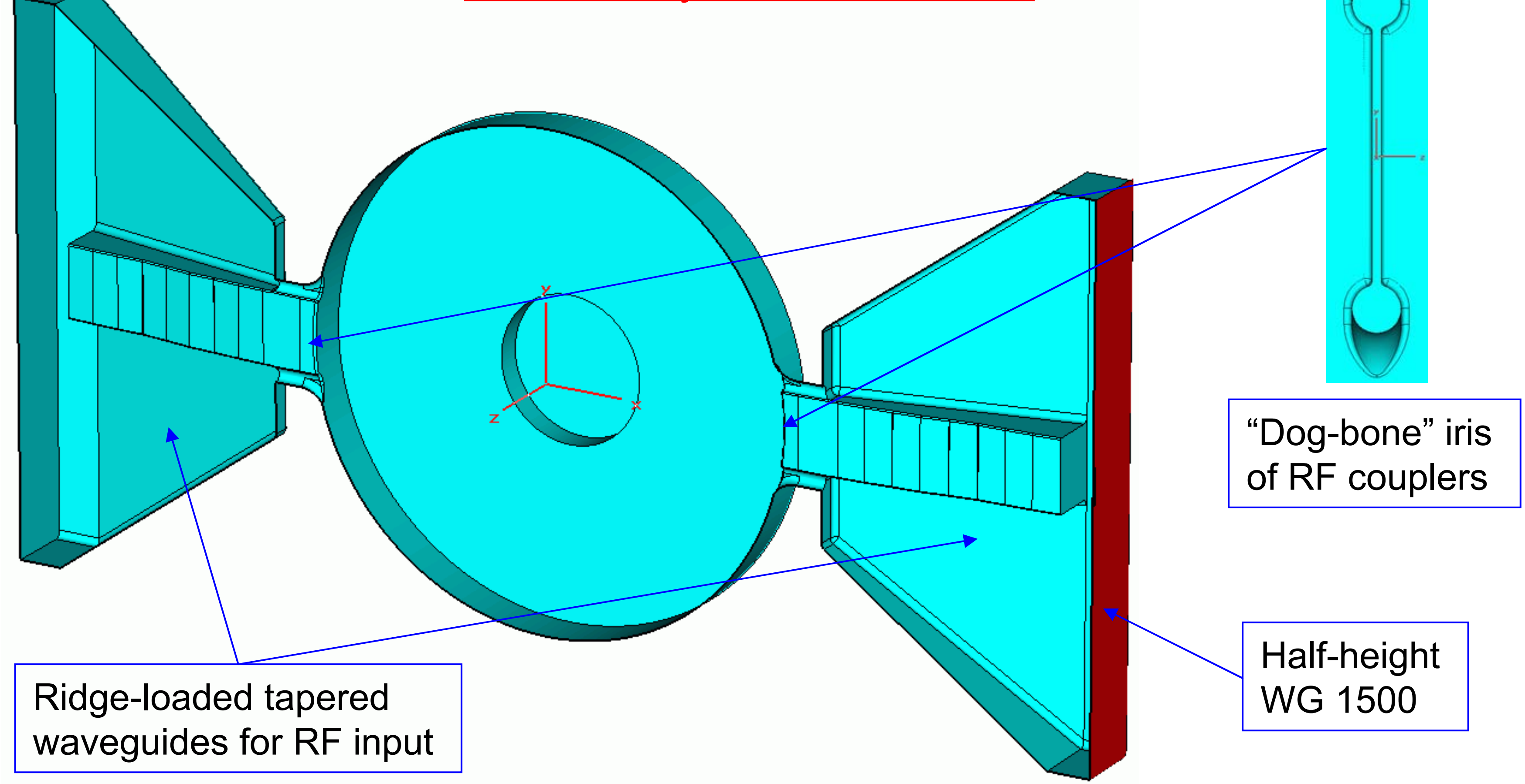
RF Power for NC Photoinjector

- 922 kW of RF input power for 100 mA beam current:
  - CW, 700-MHz RF power is fed through two waveguides
- Ridge-loaded tapered waveguides (RLWG)
  - Design is based on LEDA RFQ and SNS power couplers
  - Ridge profile is found by SF calculations for cross sections (LY), and checked using MicroWave Studio (MWS) 3-D calculations
- "Dog-bone" shaped RF coupling irises



EM Modeling of RF Coupler

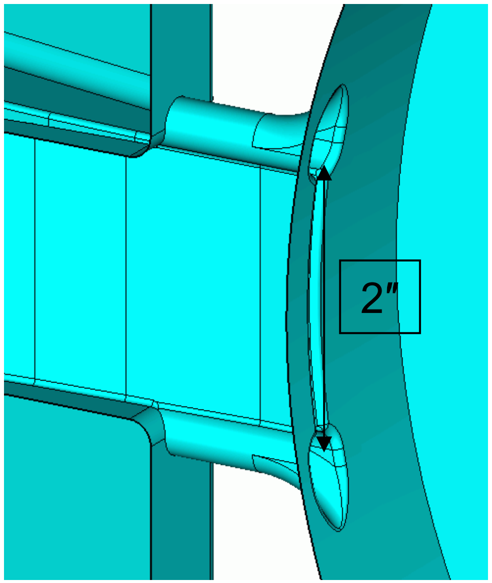
General layout of the model



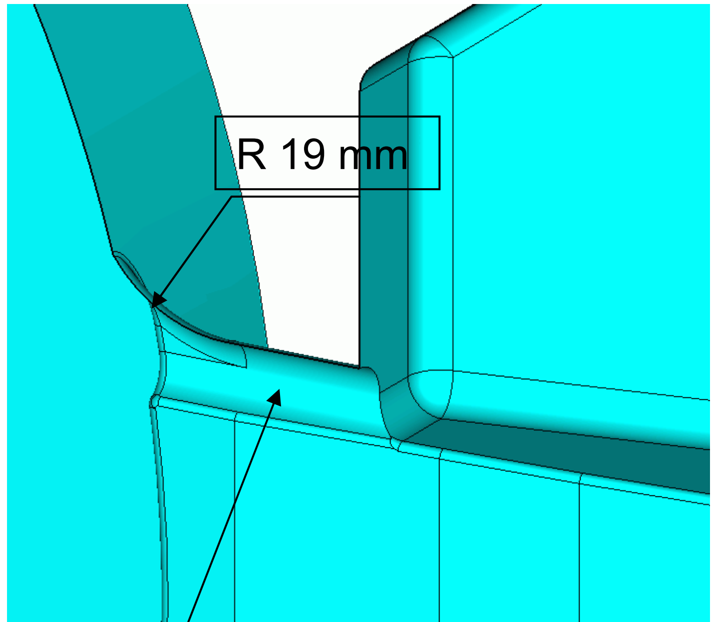
RF coupler model. Tapered ridge-loaded waveguides are coupled to the 3rd cell of photoinjector cavity (modeled here by a pillbox) via irises cut through thick walls.

EM Modeling of RF Coupler

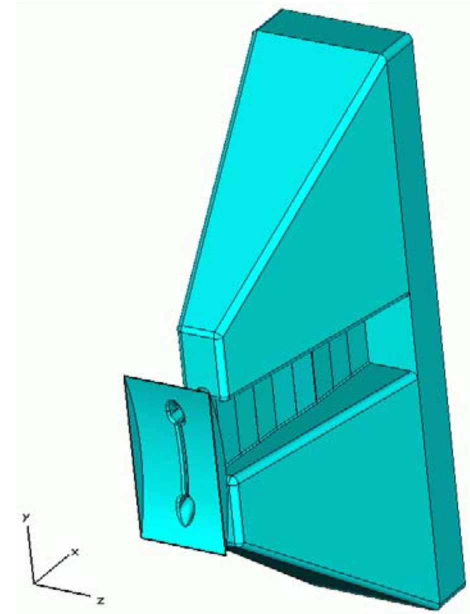
Details of coupler irises



“Dog-bone” iris of RF couplers



Hole Ø 9.5 mm



Ridge-loaded tapered waveguide & iris

RF coupler model. Details of coupler irises and ridge-loaded tapered waveguides. The wall thickness near the iris is 1.2″, the iris gap width is 1.8 mm.

EM Modeling of RF Coupler

Procedure

For 100 mA, the required WG-cavity coupling is $\beta_c = \frac{P_w + P_b}{P_w} = 1.38.$

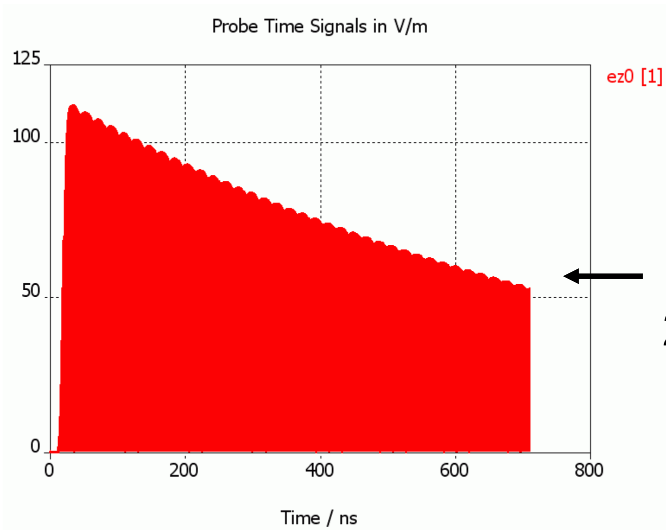
For the pillbox model, the required coupling is $\beta_{pb} = \beta_c \frac{W_c}{W_{pb}} \left(\frac{H_{pb}}{H_c} \right)^2 \frac{Q_{pb}}{Q_c}.$

Then the required Q_e for the model is $Q_e = \frac{Q_c}{\beta_c} \frac{W_{pb}}{W_c} \left(\frac{H_c}{H_{pb}} \right)^2 = 1933.$

We calculate Q_e in the model directly using time-domain simulations with MicroWave Studio (MWS), and adjust the coupling. After that, again in MWS, an RF signal with a constant amplitude is fed into waveguides to find the match point (P_{out} = 0), and calculate the field and surface power distributions at the match.

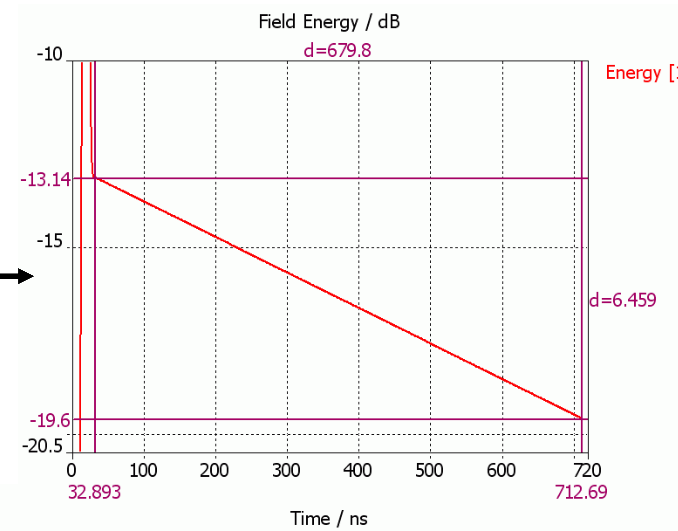
S.S. Kurennoy, L.M. Young. "RF Coupler for High-Power CW FEL Photoinjector", PAC2003, p. 3515.

EM Modeling of RF Coupler: Time Domain (TD)



MWS time-domain calculations:

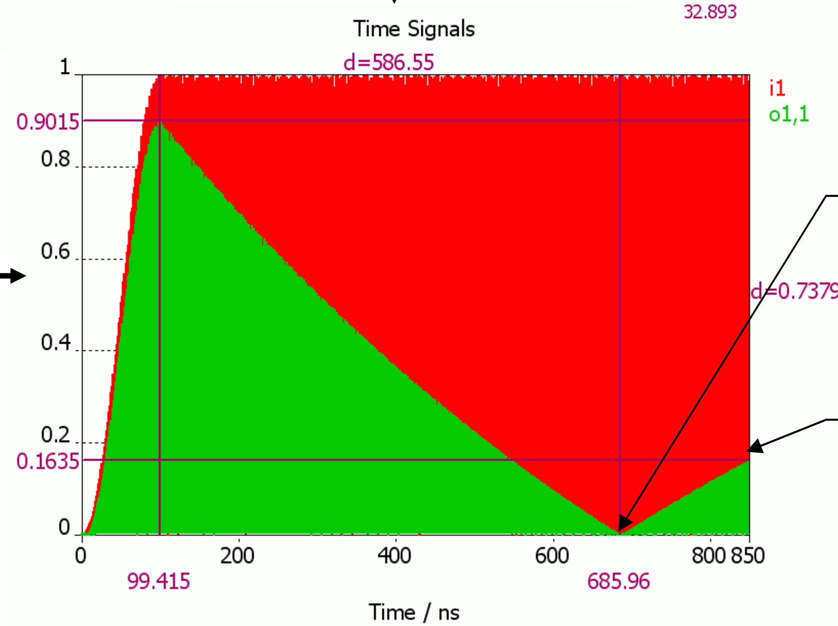
1. Determine Q_e
2. Find match point



Amplitudes of:

RF input signal

Output signal



Match point for
I_{beam} = 100 mA:
$P_{out} = 0$

Thermal test point:
$I_{beam} = 0$
$P_{out} = 0.025 P_{in}$

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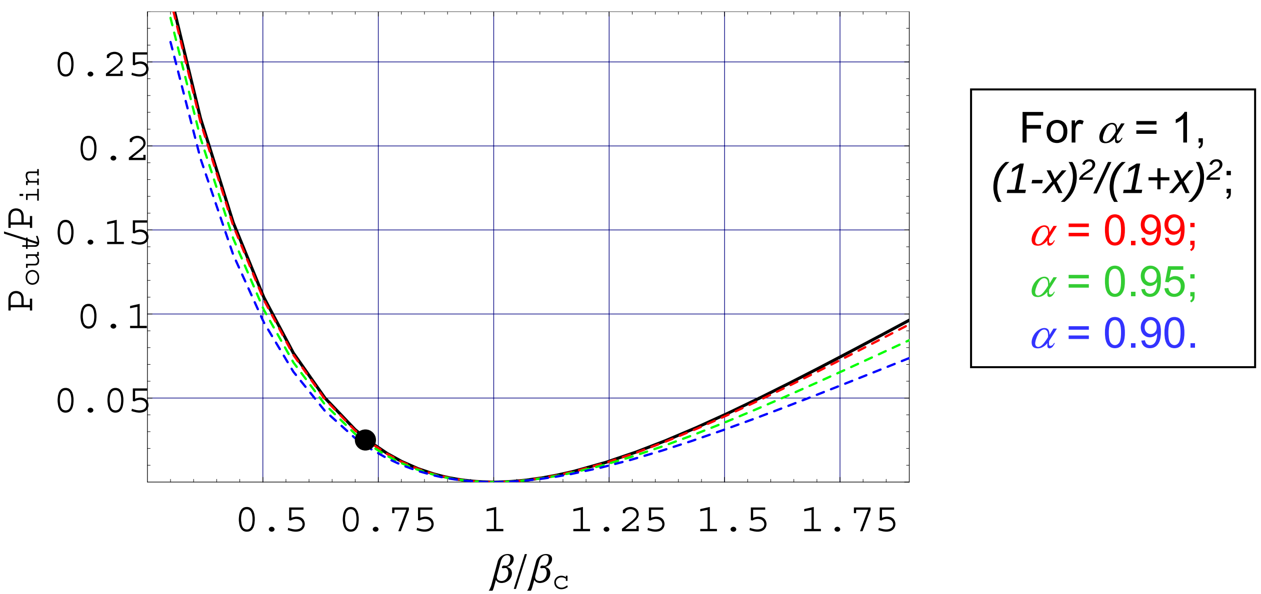
EM Modeling of RF Coupler

From energy balance $P_{in} - P_{out} = P_w + P_b \equiv \beta P_w$ one can find power ratio

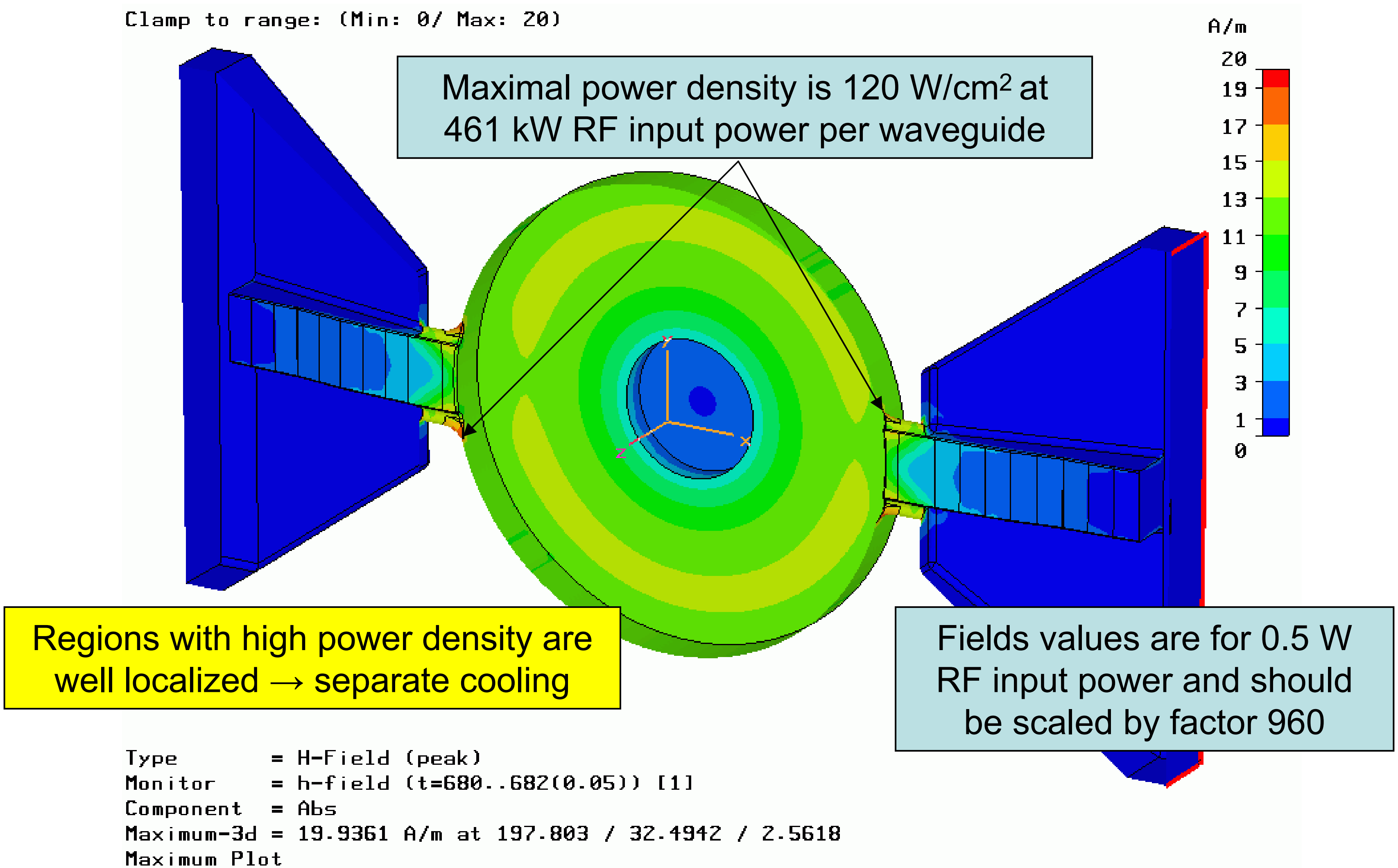
$$\frac{P_{out}}{P_{in}} = 1 - \frac{\beta}{\beta_c} f\left(\alpha, \frac{\beta}{\beta_c}\right), \quad \text{where} \quad f\left(\frac{1}{y}, x\right) = \left(\frac{1 + y\sqrt{1 + \left(y^2 - 1\right)x}}{1 + y^2 x}\right)^2 .$$

Coefficient $0<\alpha<1$ is the amplitude ratio of the input and reflected waves, $1-\alpha \ll 1$.

For $\beta = 1$, $\beta_c = 1.38$, ratio $P_{out}/P_{in} \approx 0.025$, practically independent of value of α.

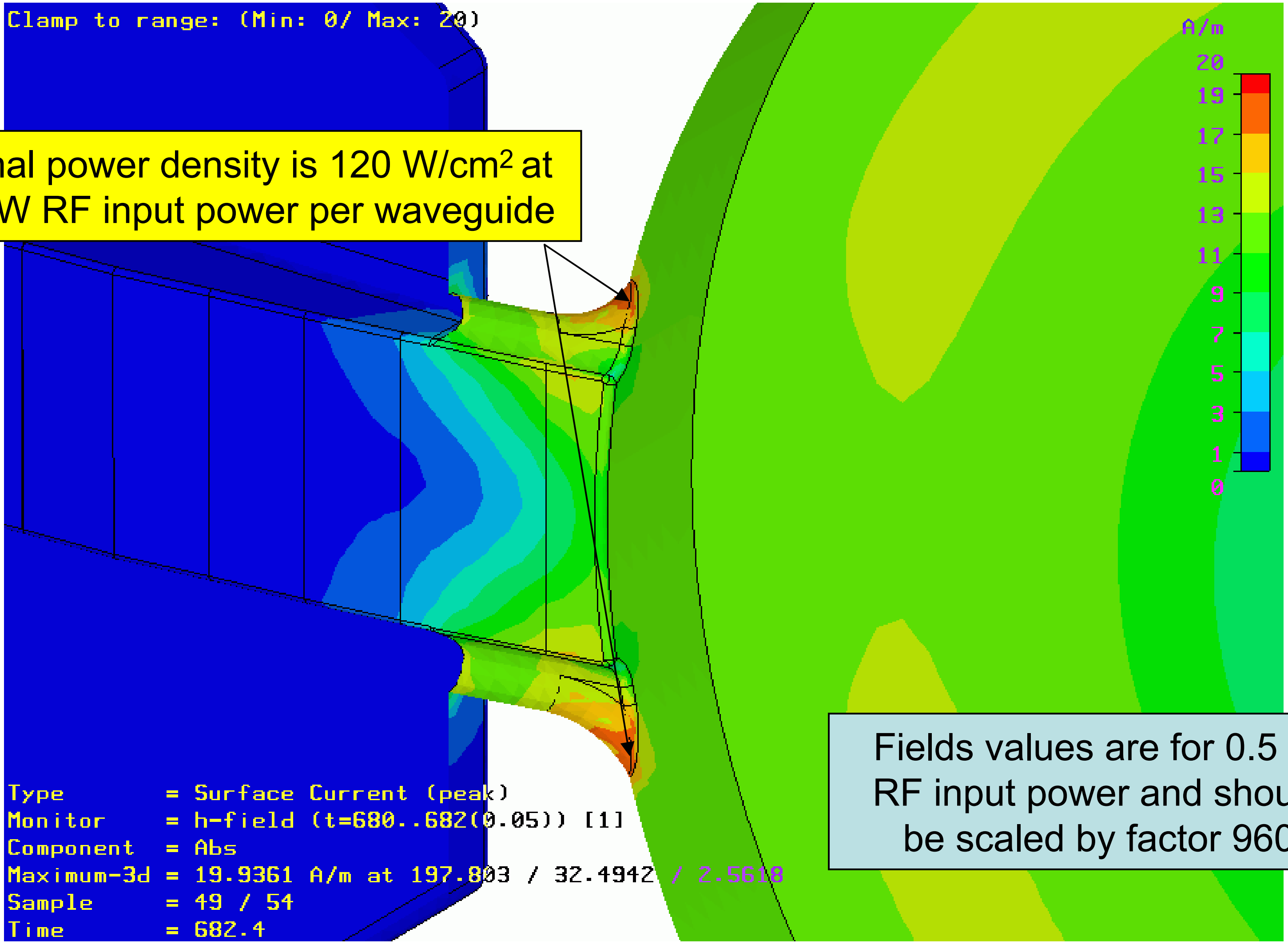


EM Modeling of RF Coupler: TD Results



Surface magnetic fields at the match point from MWS time-domain simulations

EM Modeling of RF Coupler: TD Results

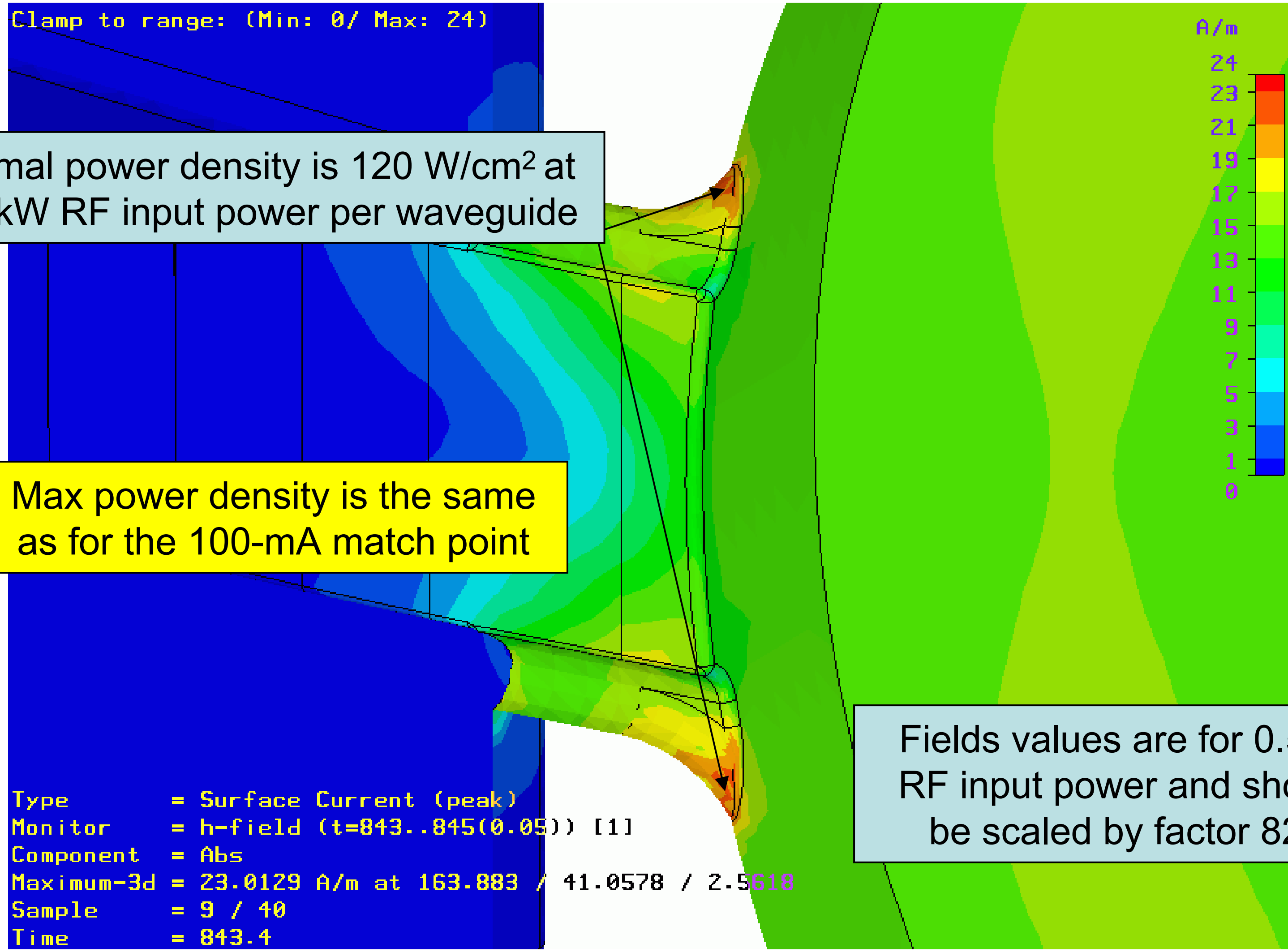


Maximal power density is 120 W/cm² at 461 kW RF input power per waveguide

Fields values are for 0.5 W RF input power and should be scaled by factor 960

Surface currents near the irises at the match from MWS time-domain simulations

EM Modeling of RF Coupler: TD Results



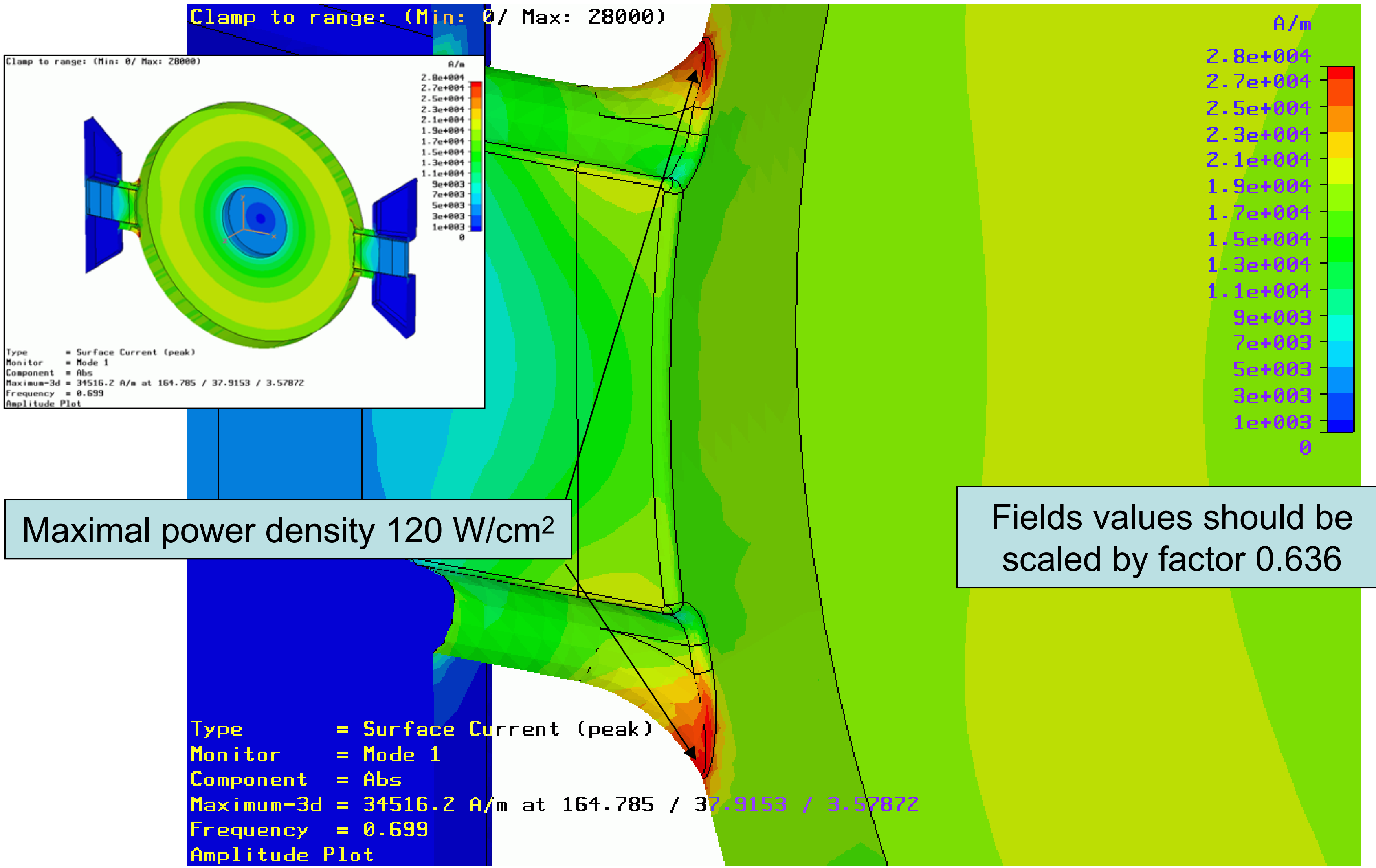
Maximal power density is 120 W/cm^2 at 342 kW RF input power per waveguide

Max power density is the same as for the 100-mA match point

Fields values are for 0.5 W RF input power and should be scaled by factor 827

Surface currents near the irises at thermal-test point (no beam, 2.5% reflection)

EM Modeling of RF Coupler: Eigensolver X-check



Surface currents from MWS eigensolver calculations (mesh 3.006M for 1/8)

EM Modeling of RF Coupler: Results for 775

MWS time domain

Mesh, K points	Max *dP/ds*, W/cm^2
111	107
111*	104*
312	120
312*	119*
760	114
760*	114*

MWS eigensolver

Mesh, K points	Max *dP/ds*, W/cm^2
86	95
201	109
734	120
1539	122
3006	118

Compare to 43 W/cm^2 at smooth wall in the 3rd cell far from irises: power ratio is < 2.8 → field enhancement due to irises is < 1.65

For 777 design max *dP/ds* was 220 W/cm^2

* W/o beam, 342 kW per WG (incl. 2.5% reflection)

For reference: in the LEDA RFQ couplers max *dP/ds* ≈ 150 W/cm^2, while the power ratio (max / smooth wall) was about 10

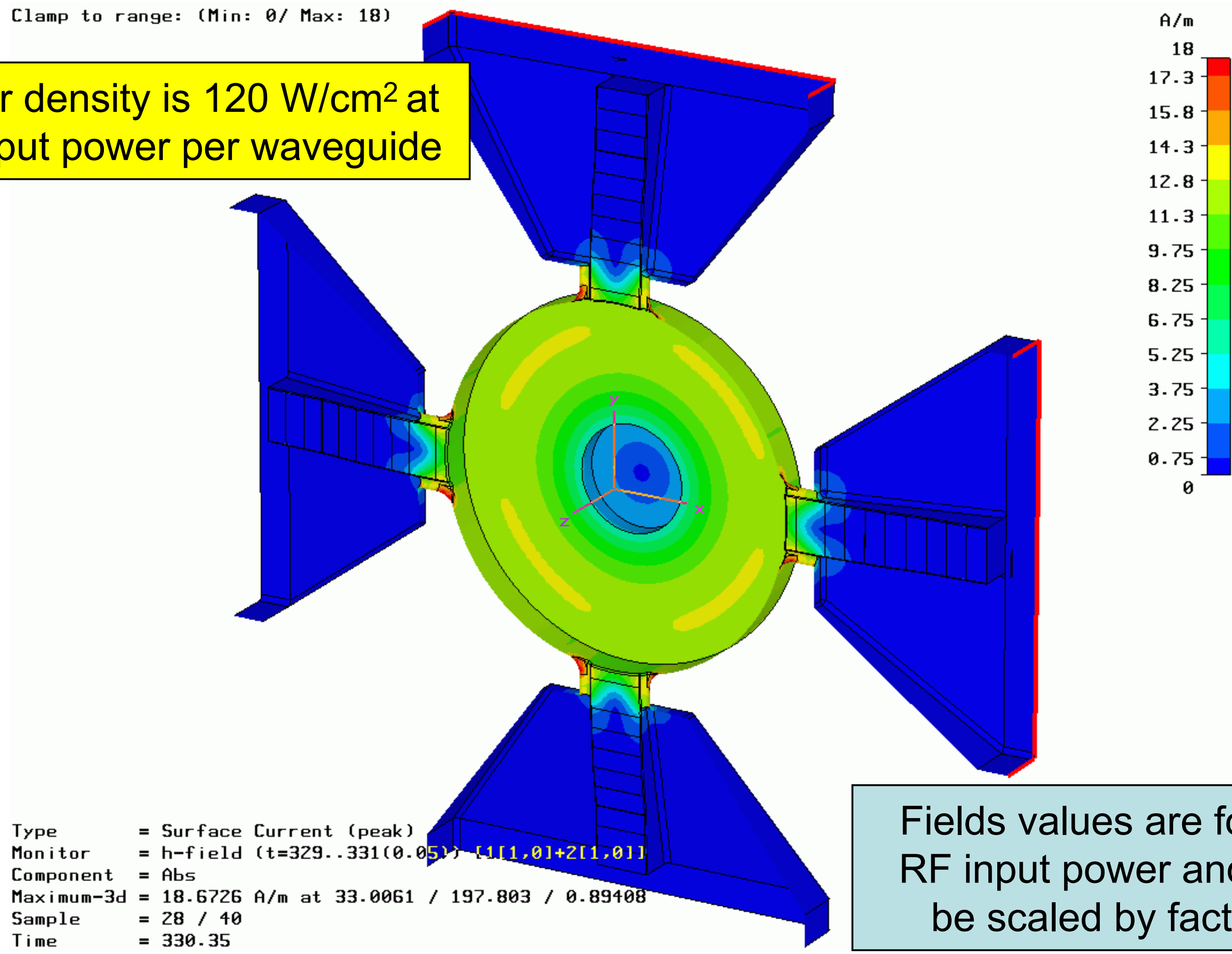
Maximal values of surface power density from MWS calculations

NC Photoinjector, RF Couplers : Summary

- 100-mA operation of normal conducting photoinjector requires almost 1 MW of CW 700-MHz RF power that will be fed through two ridge-loaded tapered waveguides.
- RF coupler design is based on LEDA RFQ and SNS couplers. The coupler-cavity system is modeled using a novel approach with direct MWS time-domain simulations. Results for the maximal power density are checked using eigensolvers.
- The coupler design is optimized using 3-D EM modeling to reduce the maximal surface power density on the coupler irises:
  - Increased hole radius and wall thickness; blended iris edges;
  - Field enhancement is only 65% compared to smooth cavity walls.
- In the 775 PI cavity, the max power density near the irises is only 15% higher than max in the smooth cavity. This design reduces stresses and facilitates cavity cooling. Thermal management is still challenging but feasible.
- The PI cavity is being manufactured by AES. Its thermal tests with full RF load are scheduled at LANL (LEDA) in early 2006.

RF Cavity Model with 4 RLWG: Matched at 0.46 A

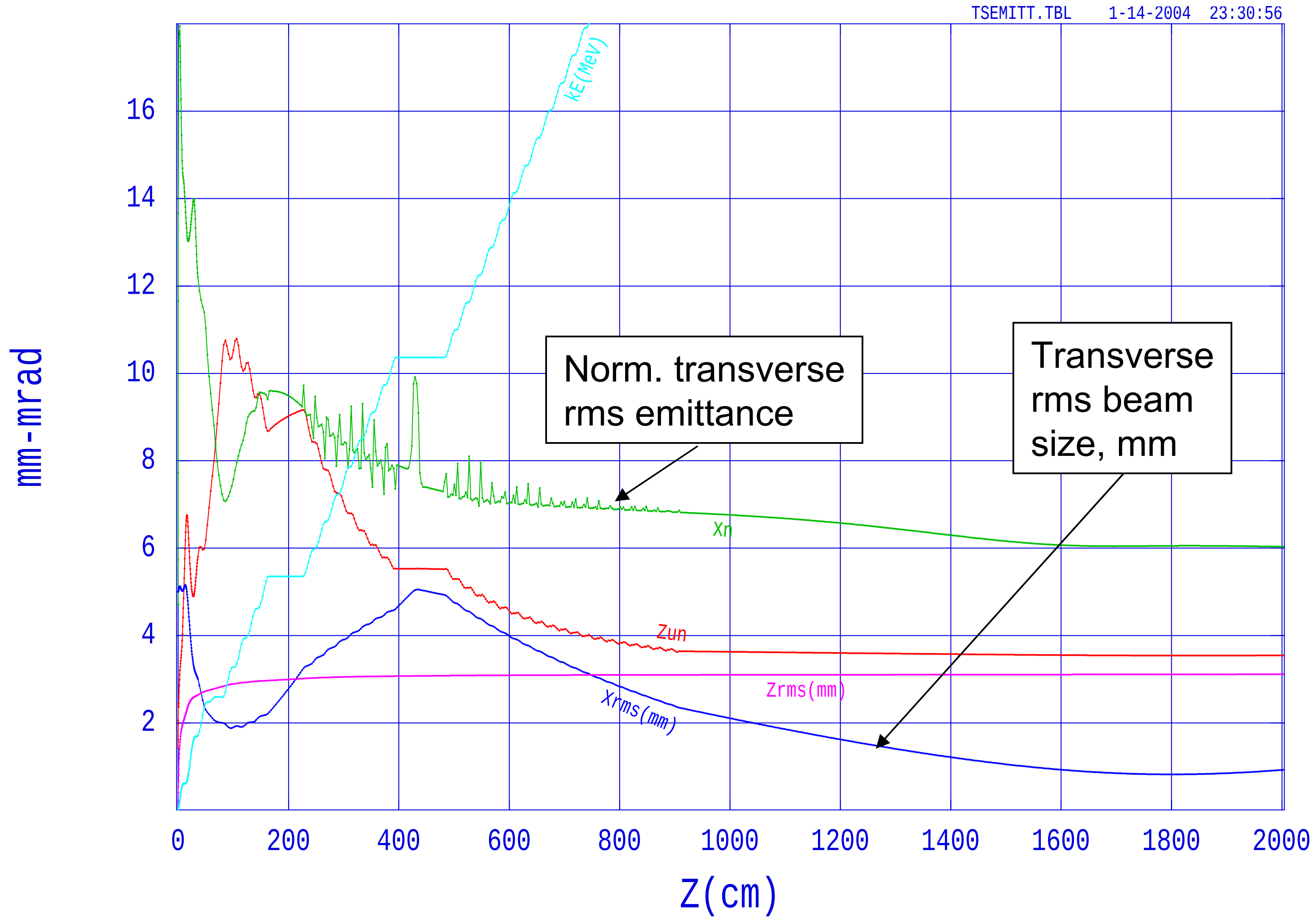
Maximal power density is 120 W/cm² at 461 kW RF input power per waveguide



Fields values are for 0.5 W RF input power and should be scaled by factor 960

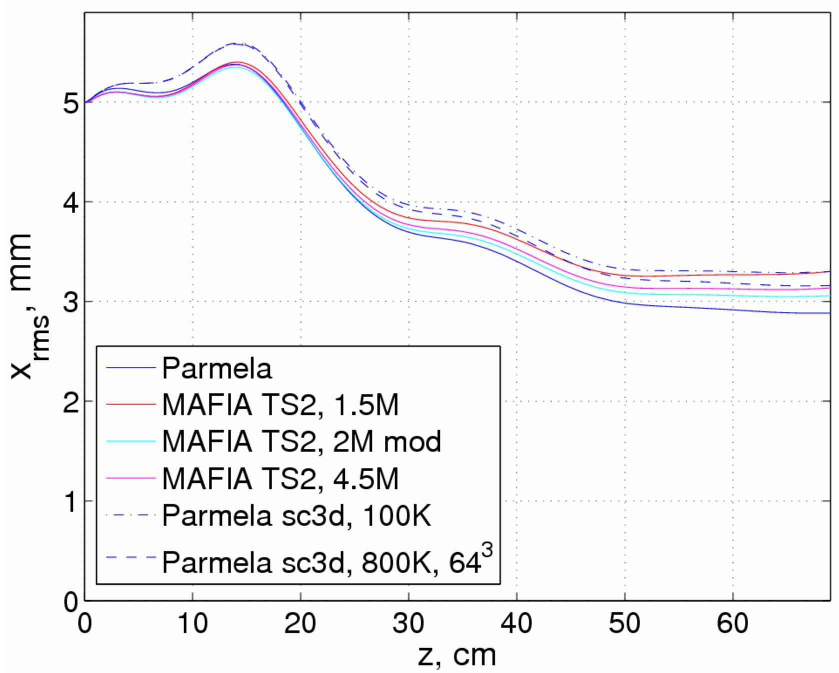
Surface currents at the match point from MWS time-domain simulations

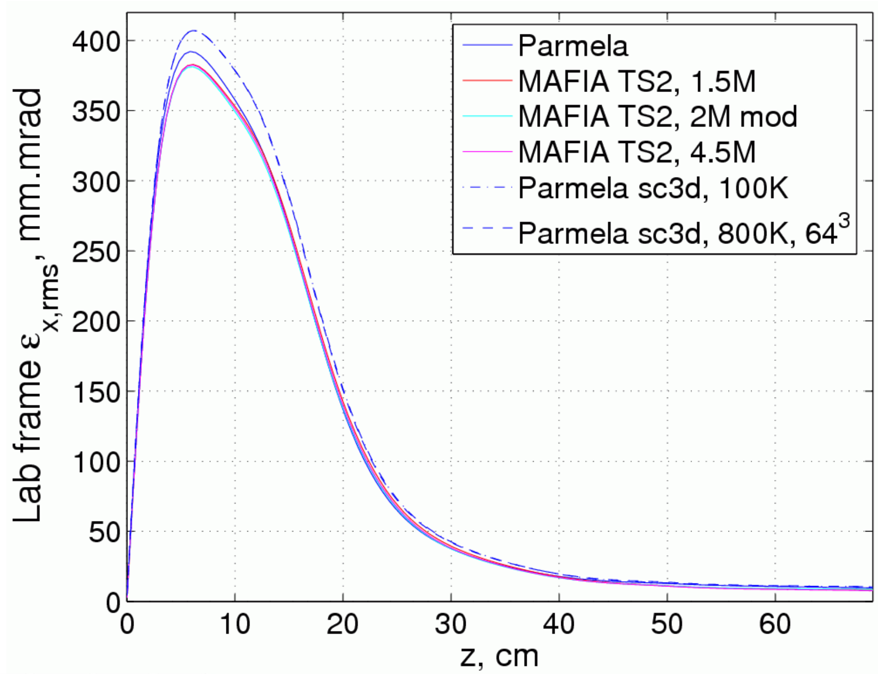
2.5-cell Photoinjector: Beam Dynamics

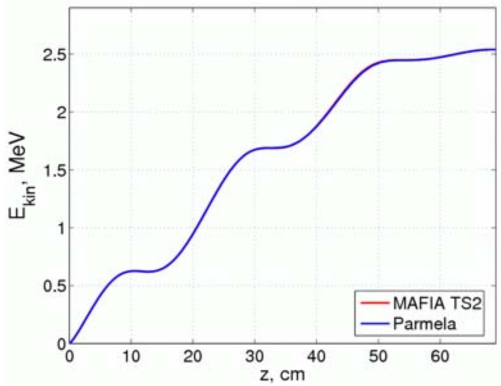


Parmela simulations of 2.5-cell PI + booster + linac (L. Young)

2.5-cell Photoinjector: Beam Dynamics



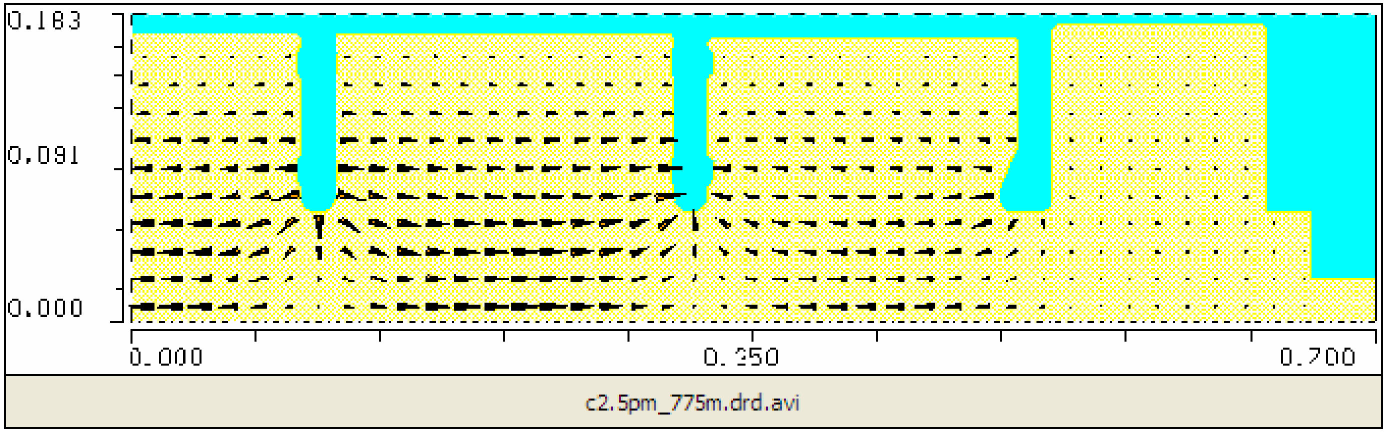




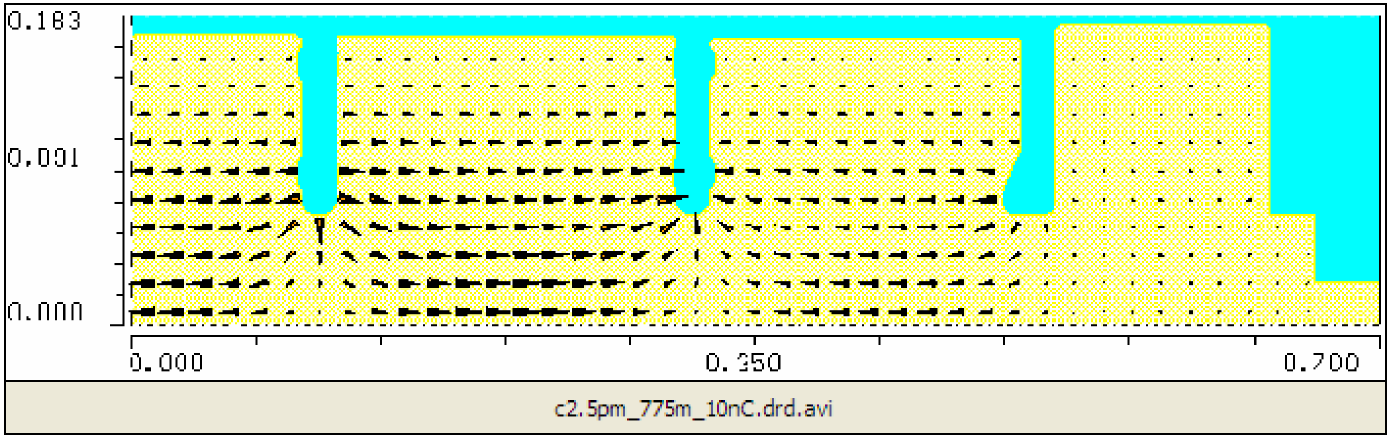
Comparison of MAFIA TS2 and Parmela results for 3-nC bunch charge

2.5-cell Photoinjector: Beam Dynamics

3 nC



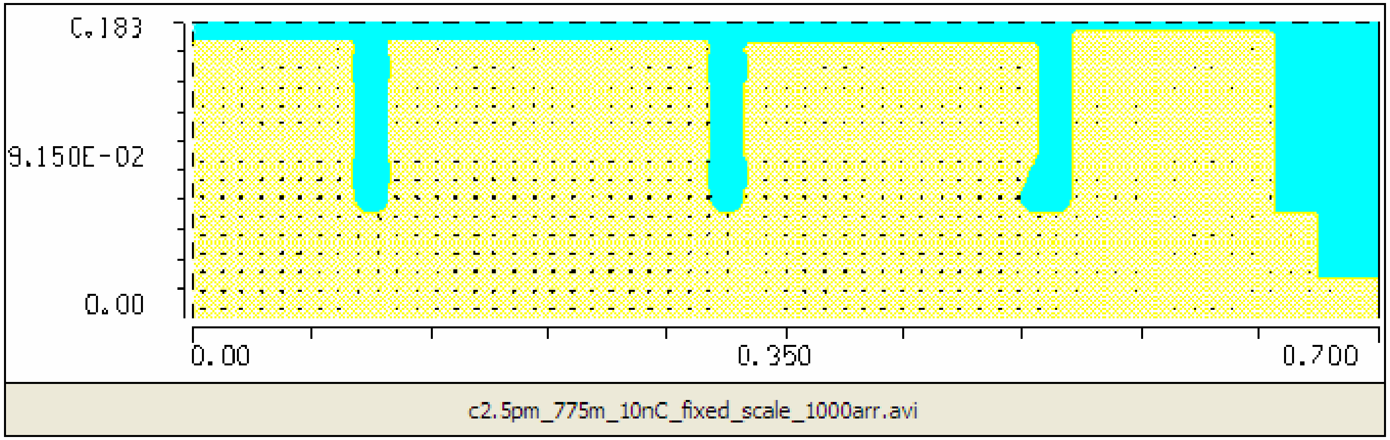
10 nC

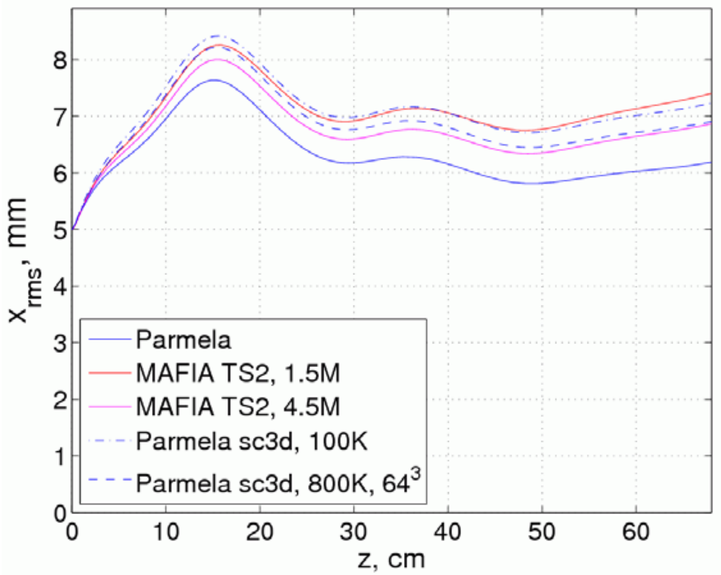


MAFIA TS2 simulations of 2.5-cell PI (wake fields included)

2.5-cell Photoinjector: Beam Dynamics

10 nC,
E-scale
is fixed





MAFIA TS2 simulations of 2.5-cell PI: 10-nC bunch charge

Beam dynamics in photoinjector: Summary

- 100-mA operation of the normal-conducting 700-MHz CW photoinjector requires 3-nC bunches at 35-MHz bunch repetition rate. Higher currents are achievable with higher bunch repetition rates.
- Beam dynamics in the PI RF cavity is modeled using Parmela and MAFIA TS2 particle-in-cell (PIC) simulations. Results for 3 nC are in agreement.
- Wake fields effects are weak, even for 10 nC per bunch. TS2 simulations with multiple bunches at 350-MHz repetition rate show identical parameters of bunches at the cavity exit.
- The PI cavity is being fabricated by AES. Its thermal tests with full RF load are scheduled at LANL (LEDA facility) in early 2006.