Dark Current Simulation And Structure R&D

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SLAC

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KEK

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Outline

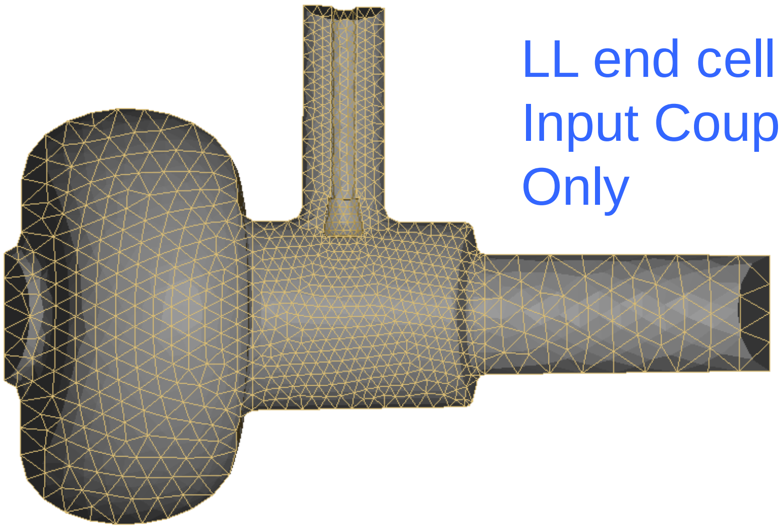
- ACE3P – Parallel Finite Element Codes
- Progress in T18vg2.6 Dark Current Simulation
- Low RF Heating Input Coupler for HG Structure
- Cavity Optimization

ACE3P Suite

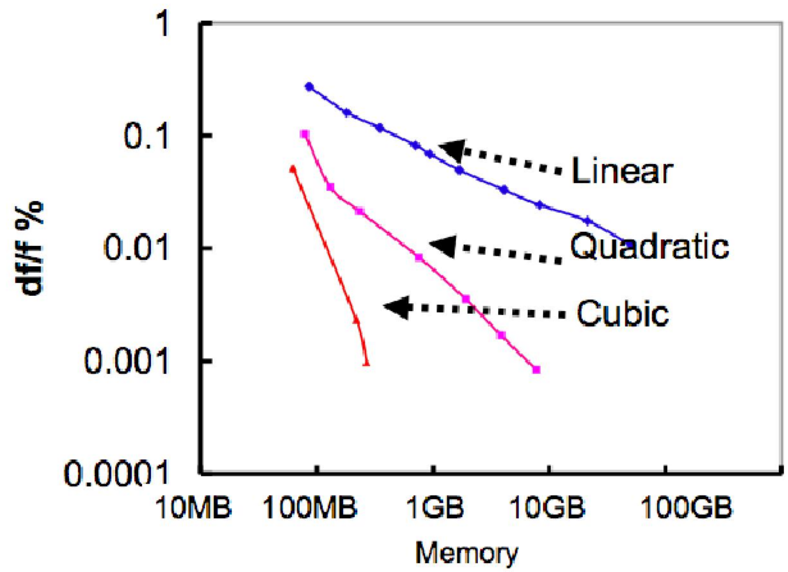
ACE3P – Advanced Computational Electromagnetics
Parallel Finite Element Implementation

Omega3P	*Complex Eigensolver*
S3P	*S-Parameter*
T3P	*Transients & Wakefields*
Track3P	*Dark Current and Multipacting*
Pic3P	*Self-Consistent Particle-In-Cell*
Gun3P	*Space-Charge Beam Optics*
TEM3P	*Multi-Physics EM-Thermal-Mechanical*
V3D	*Visualization of Mesh, Field and Particles*

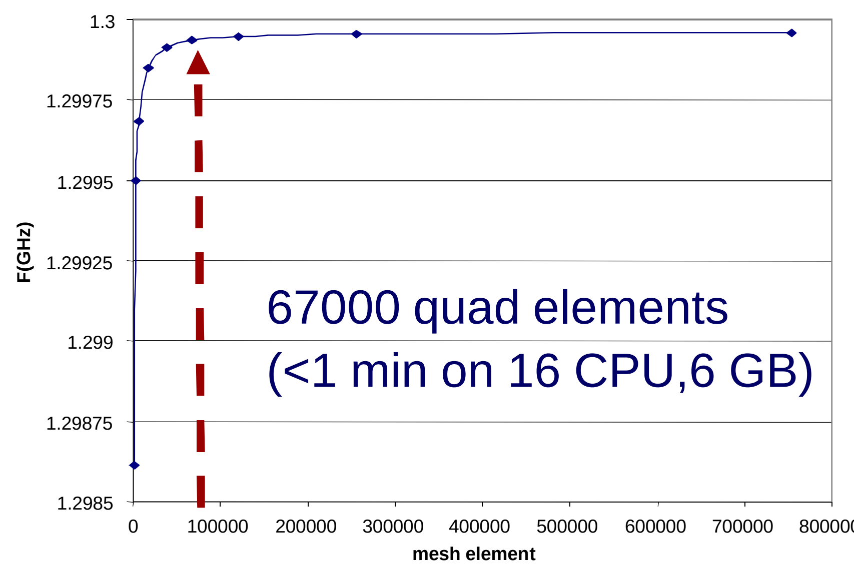
Key Strength of ACE3P



LL end cell with Input Coupler Only



- **Tetrahedral Conformal Mesh**
  w/ quadratic surface
- **Higher-order Finite Elements**
  p = 1-6
- **Parallel Computing**
  large memory & speedup



MP/DC Simulation Using *Track3P Module*

- 3D parallel high-order finite-element particle tracking
- Using RF fields obtained by Omega3P (resonant mode), S3P (traveling wave) and T3P (transient fields)
- Curved surfaces for accurate surface fields
- Emission models include thermal, field and secondary

- Benchmarked with measurements
  – Rise time effects on dark current for an X-band 30-cell structure
  – Prediction of MP barriers in the KEK ICHIRO cavity

MP and DC Simulation Using *Track3P*

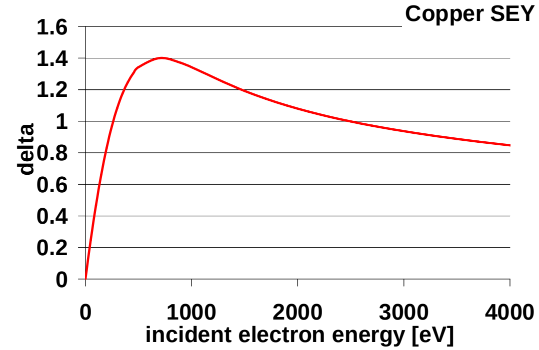
Multipacting Simulation

- Analyze resonant conditions – location, order and type
- Calculate multipacting map using impact energy and SEY data

Dark Current Simulation

- Track Field Emitted (FN) & Secondary Electrons

$$J(r,t) = 1.54\times 10^{\left(-6+\frac{4.52}{\sqrt{\varphi}}\right)} \frac{(\beta E)^2}{\varphi} e^{\left(\frac{-6.53\times 10^9 \varphi^{1.5}}{\beta E}\right)}$$



- Analyze accumulated effects of DC current & power
  - DC current monitor
  - DC surface power monitor

CLIC T18vg2.6
Dark Current simulation

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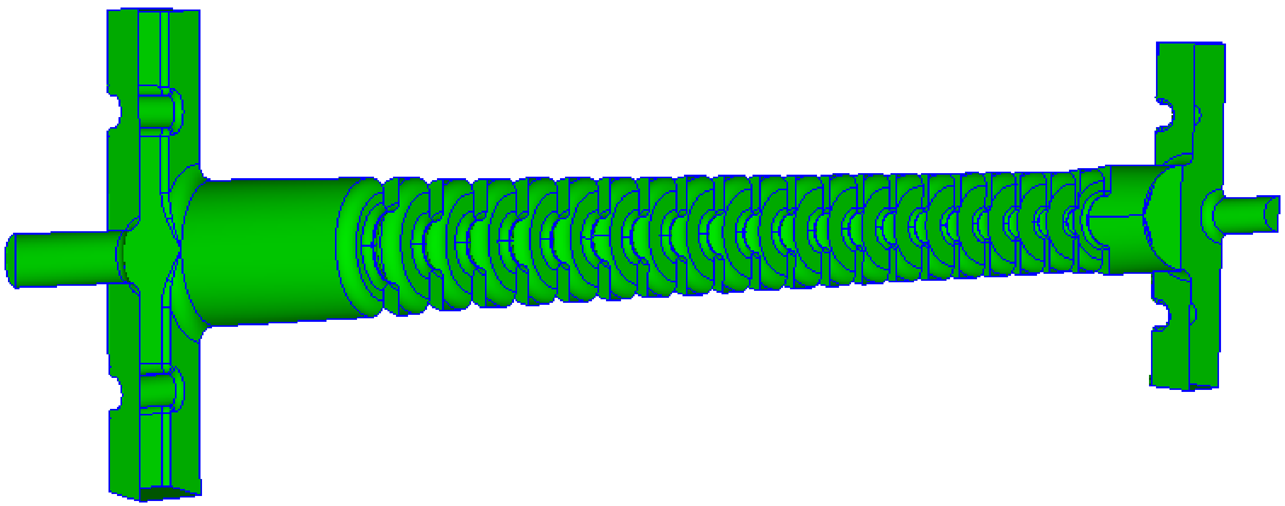
July 8, 2009

T18vg2.6 Structure

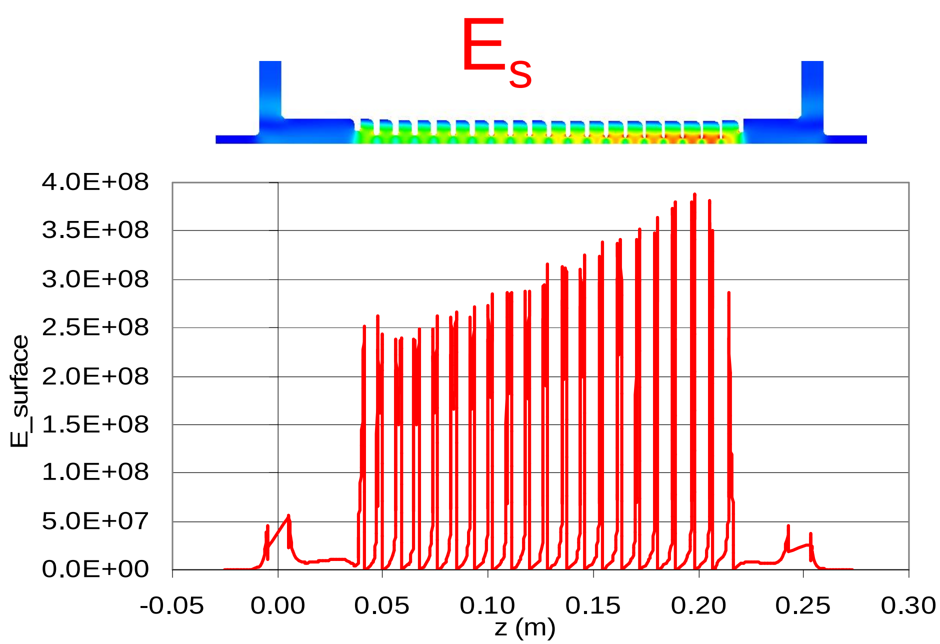


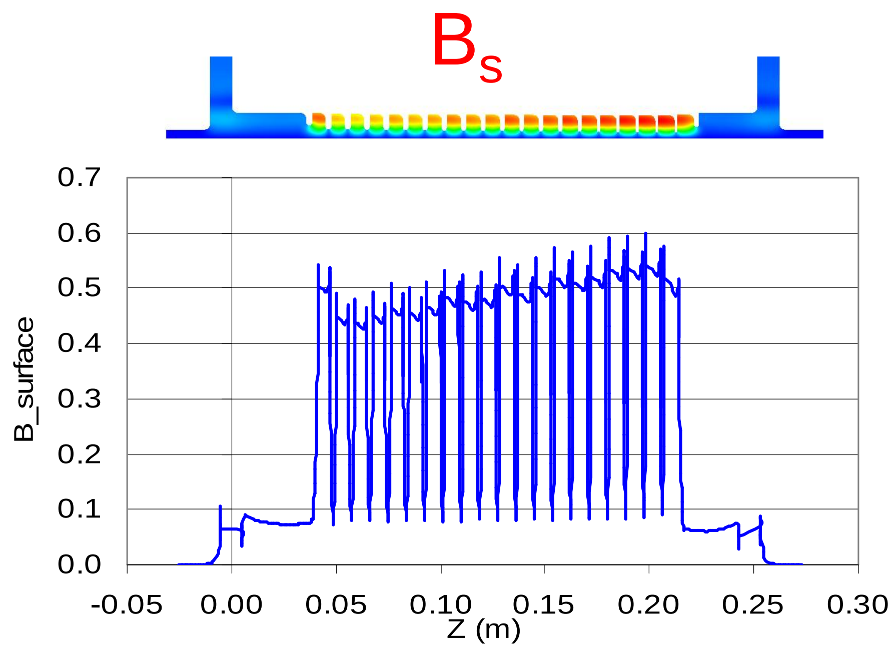
- This structure is being tested at KEK and SLAC
- Comparison between measurement and simulation in progress

T18 Structure Fields

RF fields obtained using S3P with surface loss

S11=0.014; S22=0.032; S12=0.82

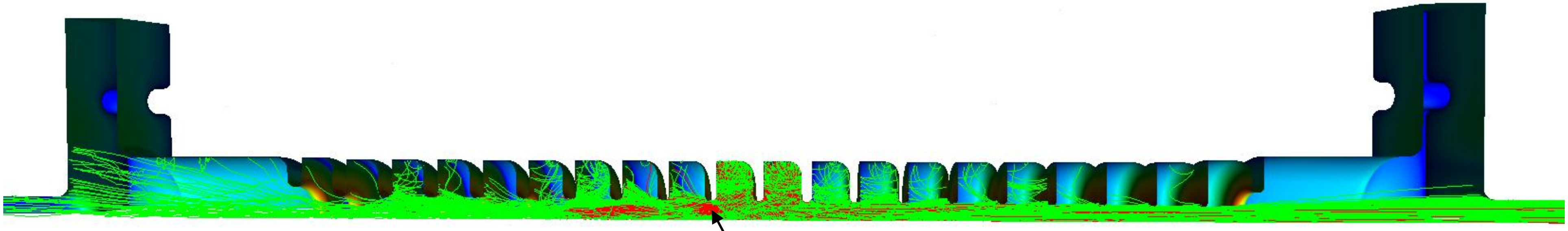




Structure tapered: higher E fields at output end

Higher B field at the output end, not as significant as E field

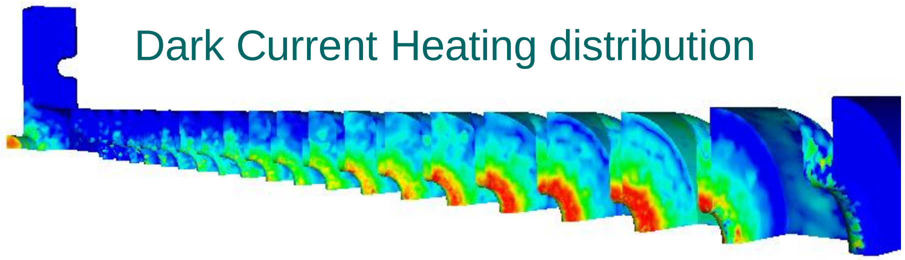
Dark Current Simulation



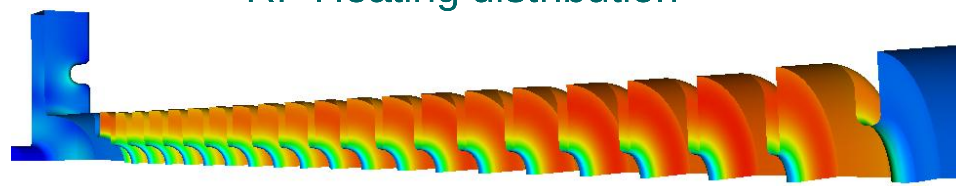
- Intercepted electrons deposit energy into the wall and result in heating.
- Captured electrons are accelerated downstream and may induce IP background.

Dark Current Heating

Dark Current Heating distribution

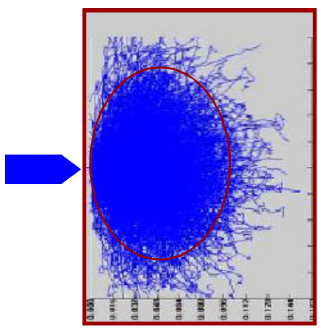


RF Heating distribution



Assumed emitters uniformly distributed. In reality, most likely clusters of emitters, result in local hot spots.

High energy electron penetration into material



Sharon Lee
ICSE2006

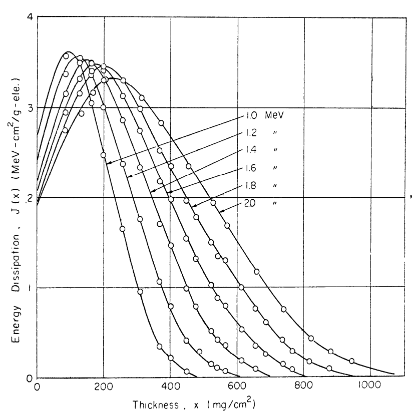


Fig. 9. Energy dissipation curves of electrons in copper.

Yohta Nakai JJAP-2-743

Dark Current Heating

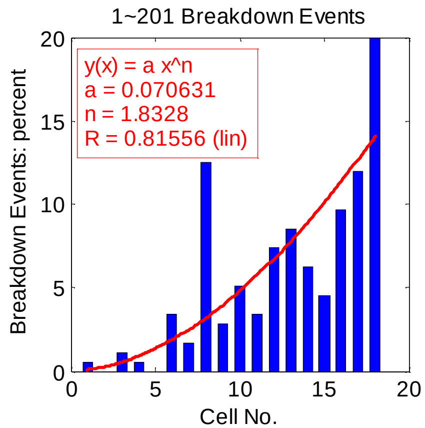
- Interception concentrated in high E region around iris
- Impact energy could be as high as a few MeV
- Depth of energy deposit ~ 1-2 hundred microns
- Significantly higher heating at the output end
- Heating distribution correlate well with breakdown rate

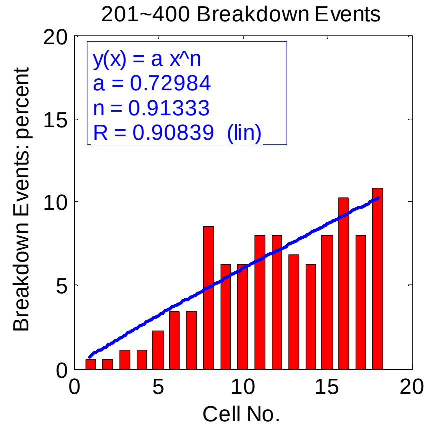
RF Pulse Heating

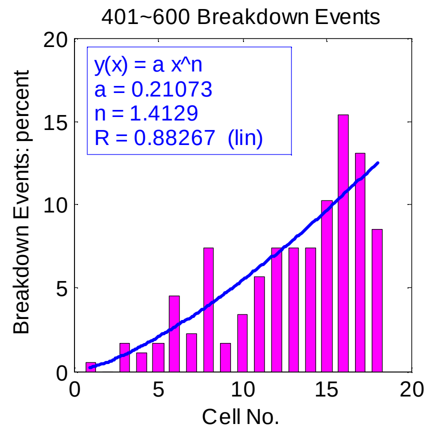
- High on the outer wall where electric field is “low”.
- Depth ~ skin depth
- Temperature rise is around 25^0C at 100MV/m, 200ns pulse length
- At Eacc=80 MV/m; (Hs/Ea~0.004), Power_max=1.4 GW/m^2

High Power Test Data - Breakdown Distribution

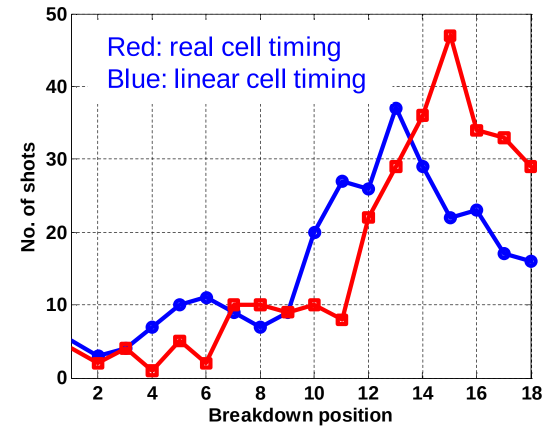
F. Wang

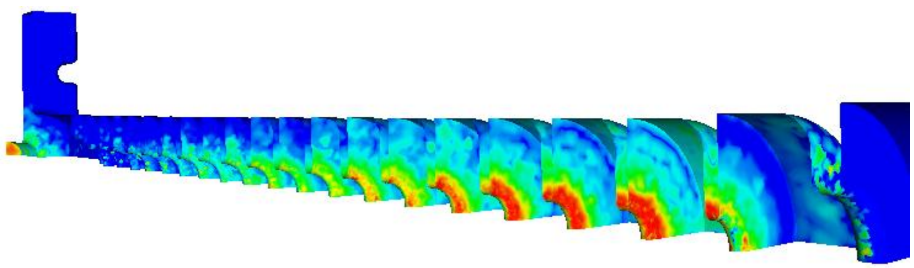






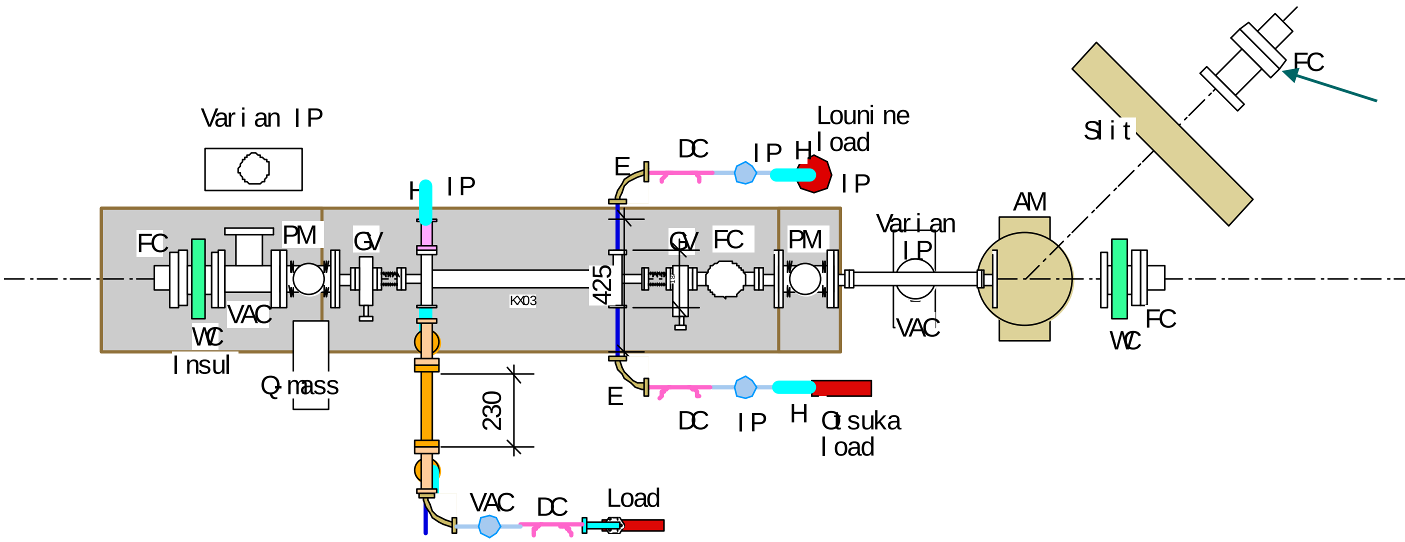
KEK, Higo





- Breakdown rate significantly higher at the output end
- Good correlation with field enhancement and dark current heating at the output end

Dar Current Measurement & Comparison with Simulation

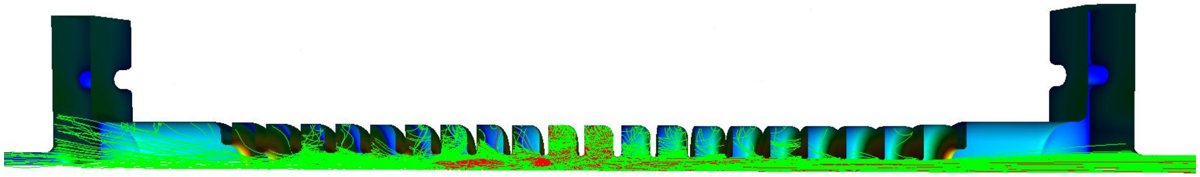


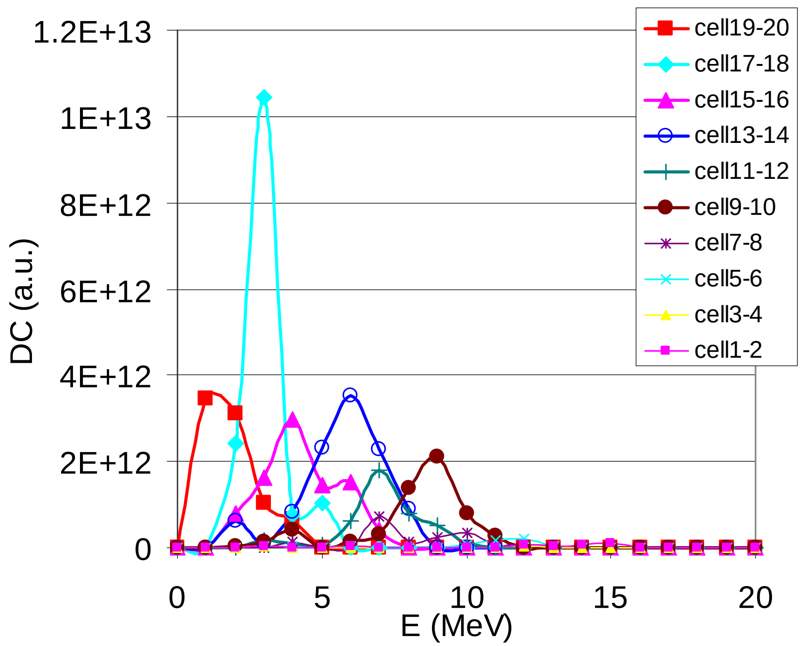
Faraday Cup to measure dark current

Schematic of KEK high power test and dark current measurement

SLAC is also setup for similar measurement

Energy of Captured Dark Current vs Location





Simulation

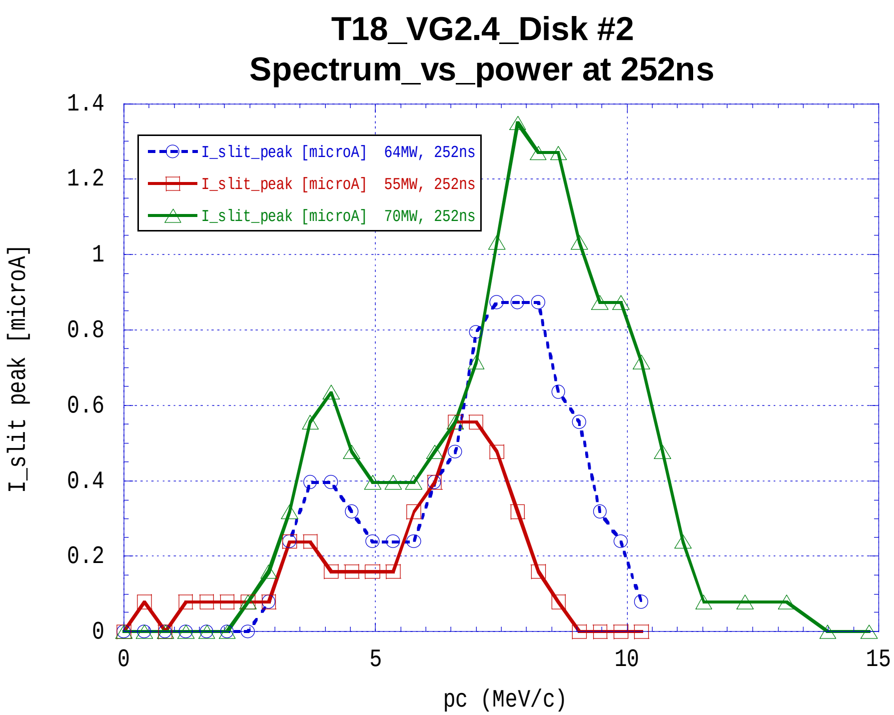
Electron energy as function of emission location.

- Eacc=97MV/m.
- Higher cell number indicates downstream location

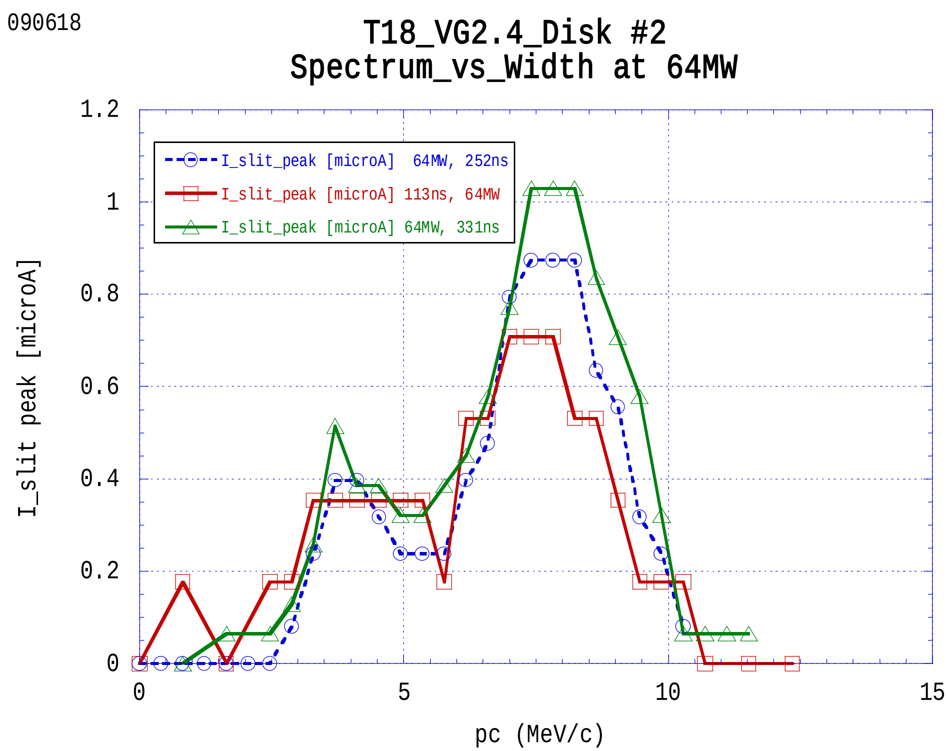
Electrons emitted upstream are accelerated to higher energy (monitored at output end).

T18_VG2.4_Disk_#2
Dark current spectra measured 18 June 2009

Dependence on power



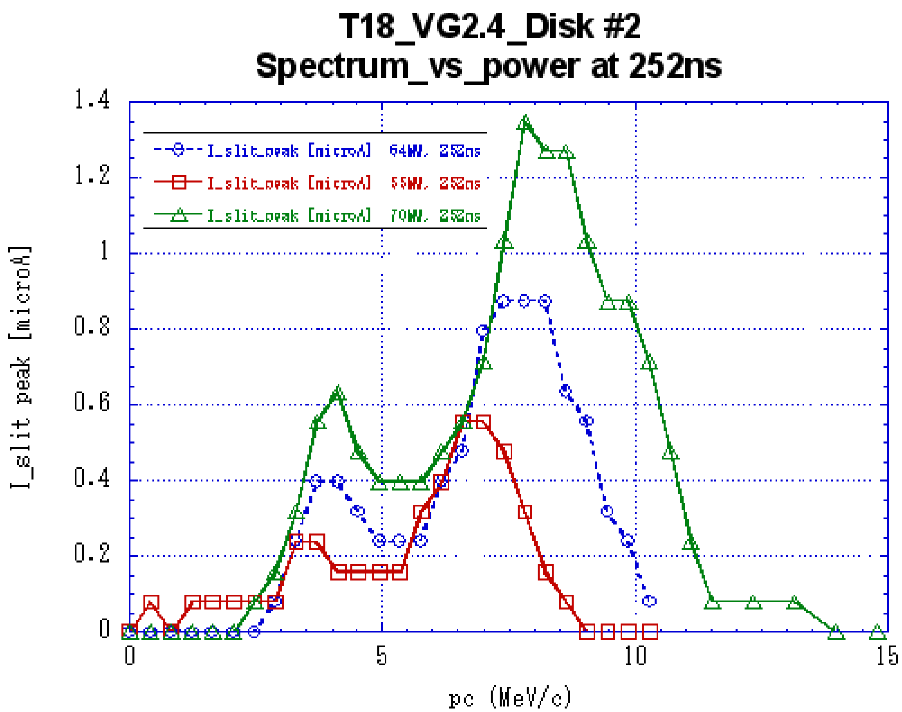
Dependence on width

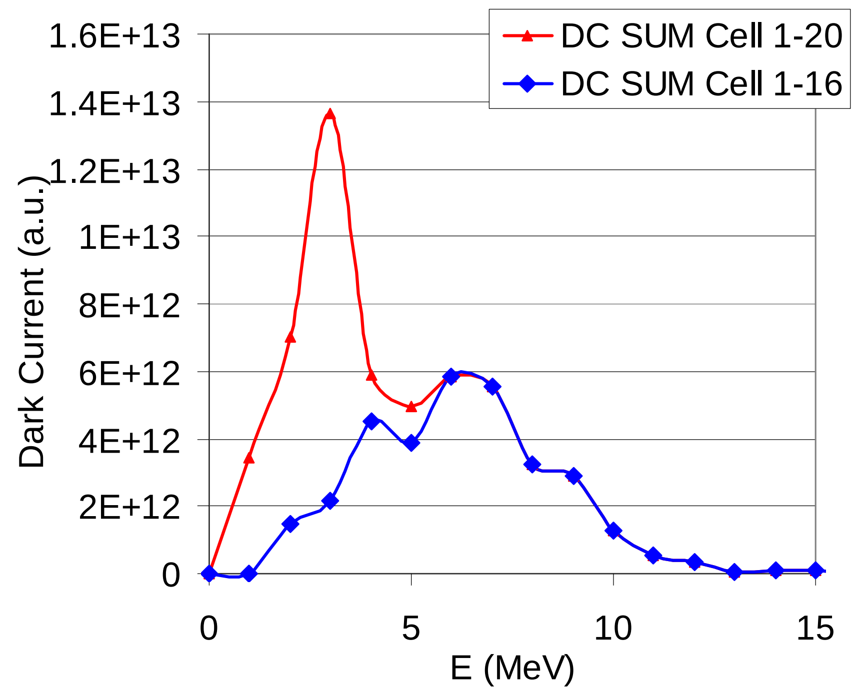


Measurement Data at KEK (Higo)

Higo 090703

Dark Current Spectrum Comparison





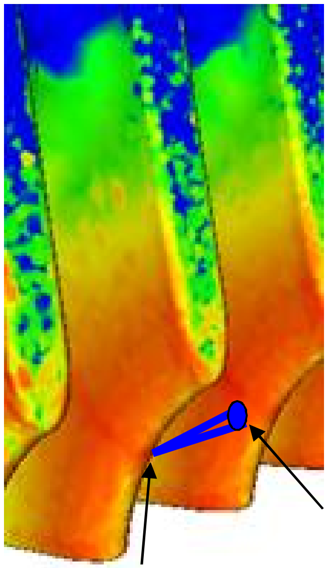
Measured dark current energy spectrum at downstream (need to scale by 1/(pc)

Spectrum from Track3P simulation, 97MV/m gradient.

"Certain" collimation of beampipe on dark current is considered in simulation data. More detailed analysis Needed.

Individual Field Emitter

- Field emission current density based on FN can be significant
  - with beta=50, Eacc=100 MV/m,
  - J_{peak} ~10^{13} A/m^2
- Uniform emission (with typical beta) result too high in current
- Need to study effects of individual emitters

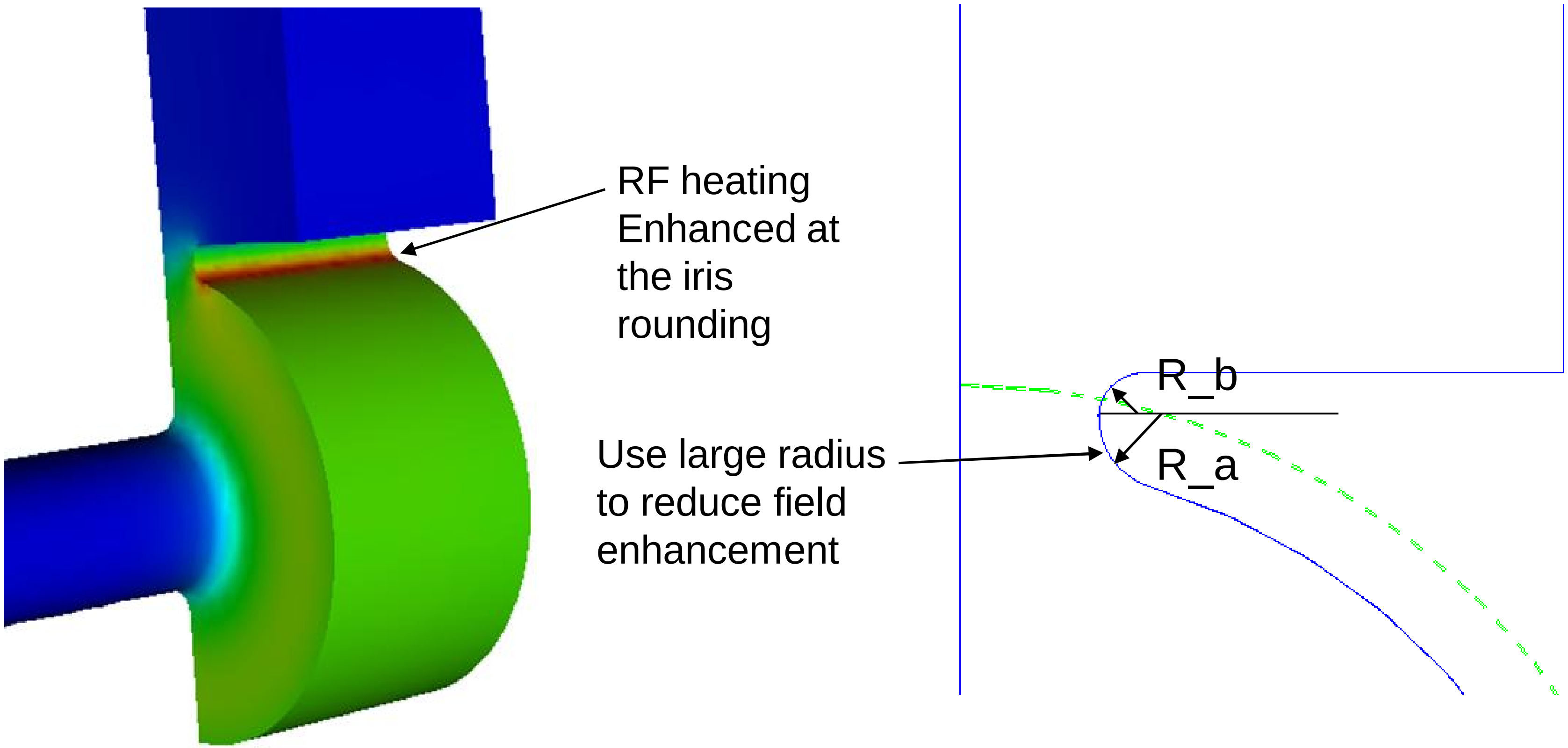


- In progress
  - Realistic assumption of emitter parameters – size & density …
  - More detailed analysis and comparison with measurement of captured dark current

Structure Design

Low H-field Enhancement Coupler
For High Gradient 3-cell Test Stack

Fat-lip Coupler

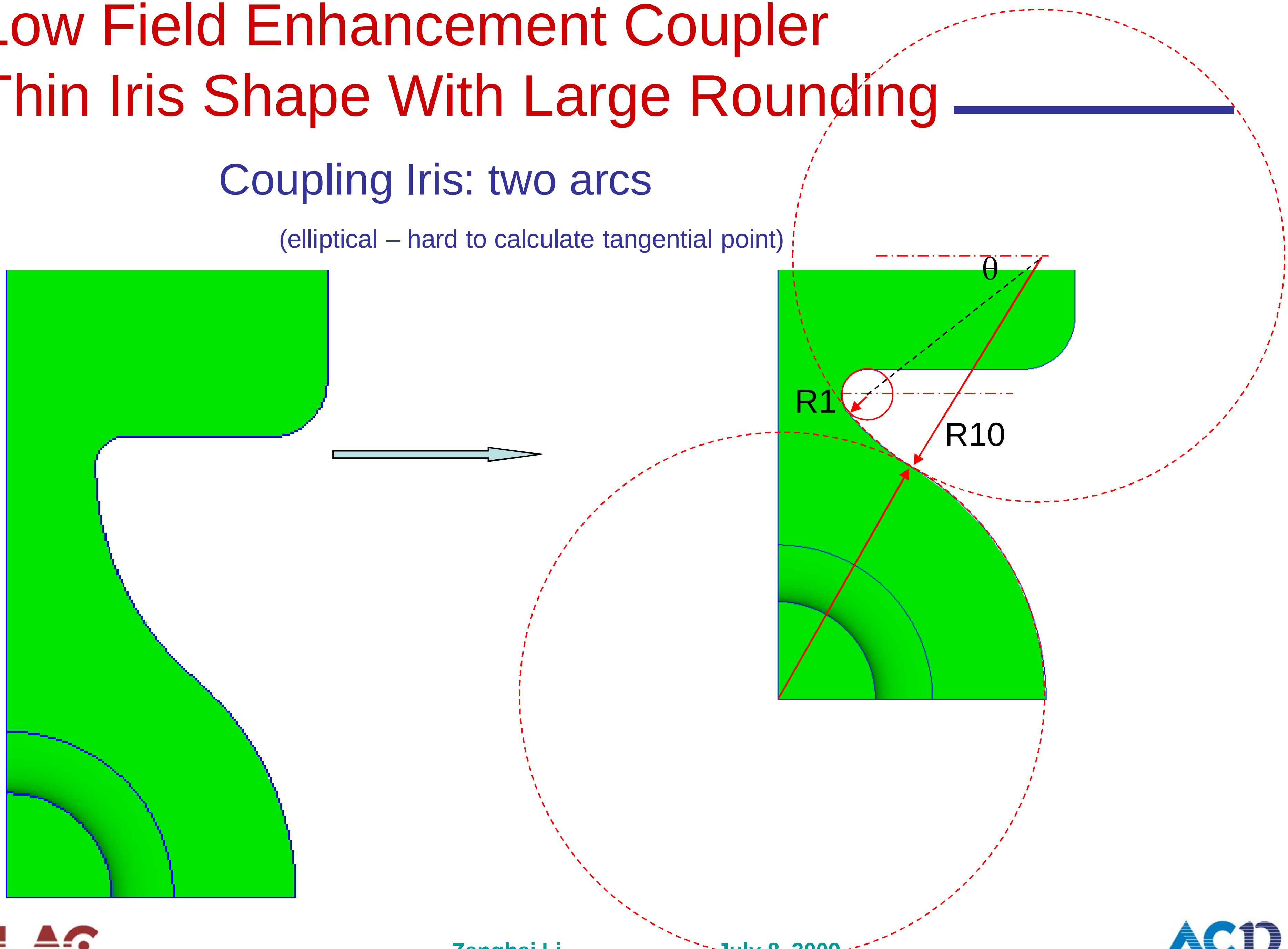


Large rounding lead to “thick” iris -> large opening –> field enhancement

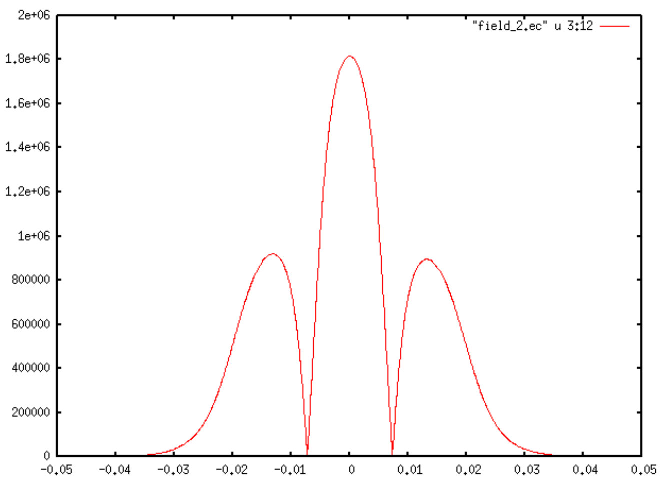
Low Field Enhancement Coupler
Thin Iris Shape With Large Rounding

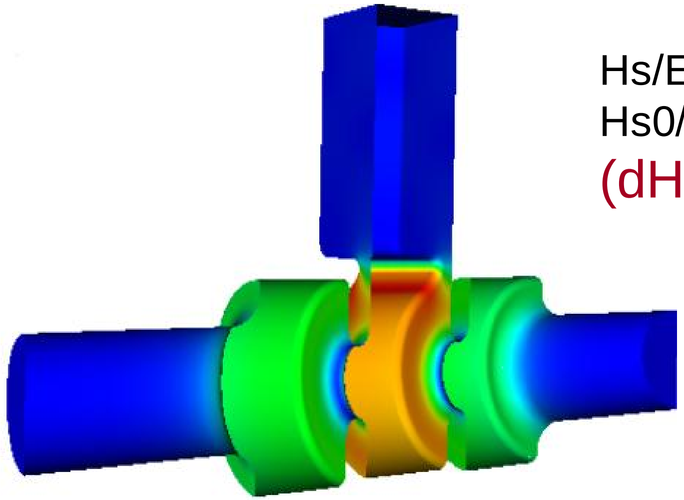
Coupling Iris: two arcs

(elliptical – hard to calculate tangential point)

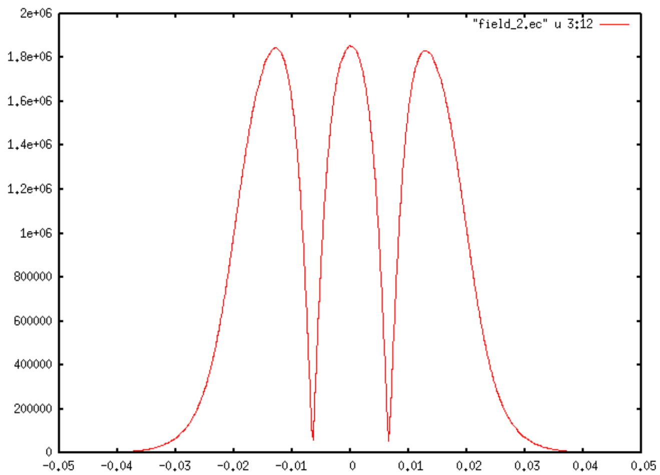


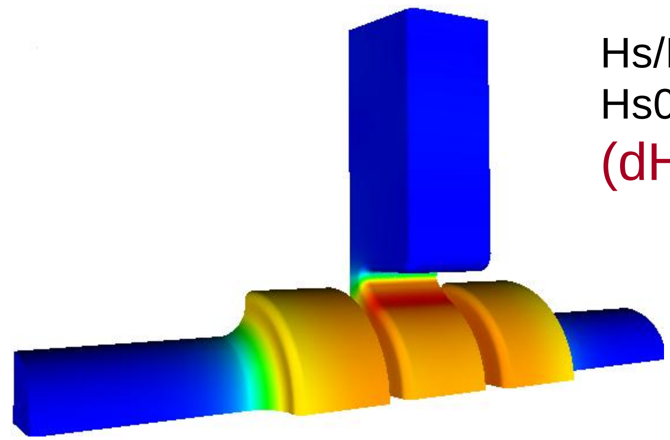
Low Field Enhancement Coupler For 3-Cell Test Stack





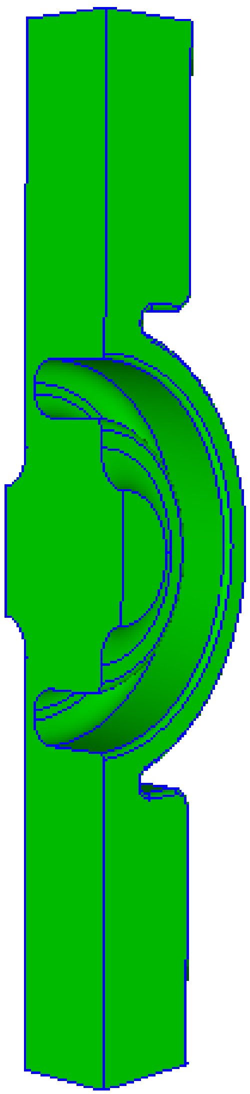
Hs/Ea=3.90 (A/m)/(MV/m)
Hs0/Ea=3.23 (A/m)/(MV/m)
(dHs/Hs0 = 1.21)

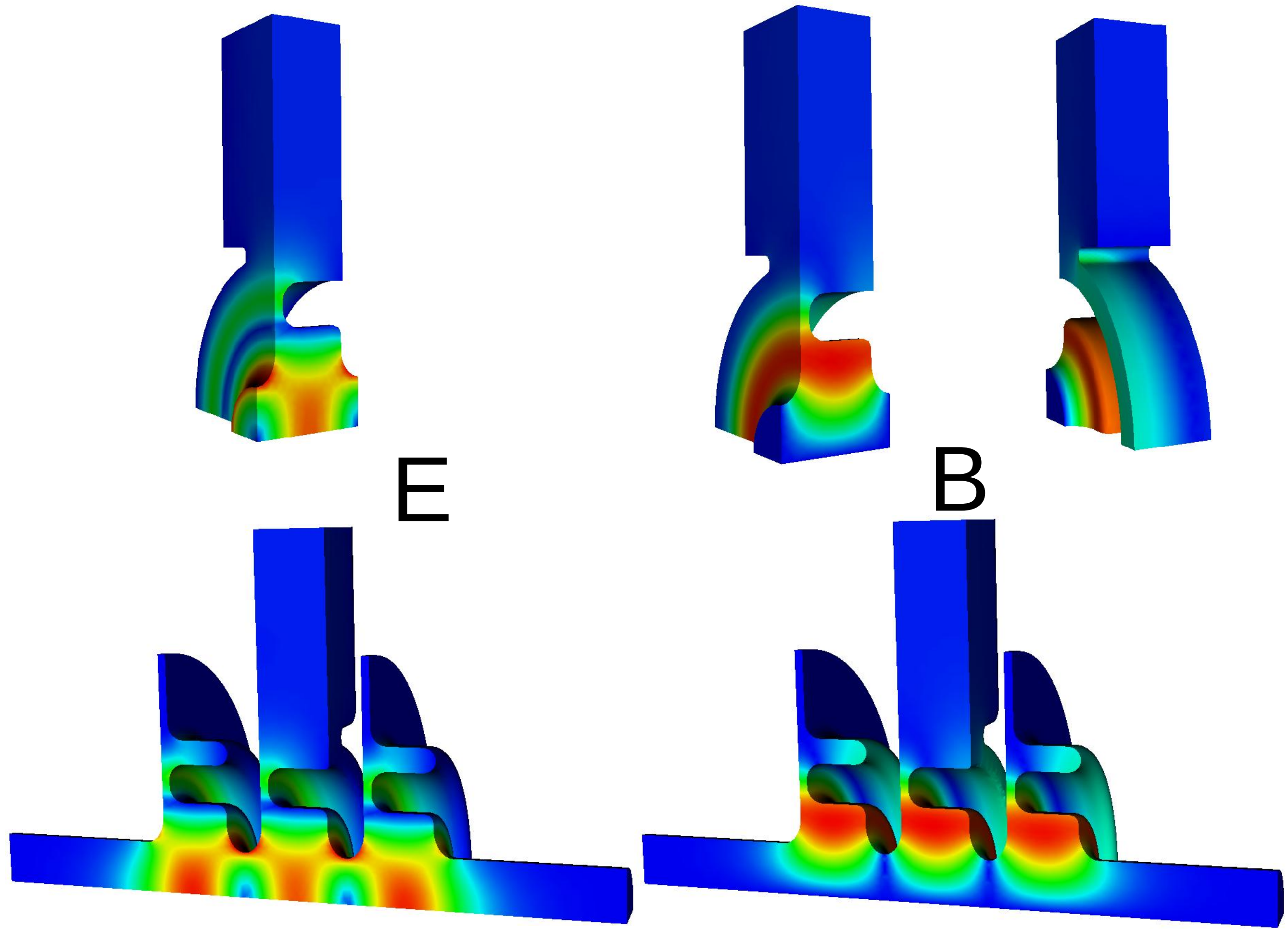




Hs/Ea=3.99 (A/m)/(MV/m)
Hs0/Ea=3.35 (A/m)/(MV/m)
(dHs/Hs0=1.19)

Choke Cell Coupler With “no” Field Enhancement





- No Field enhancement
- Choke parameters need to be optimized to avoid multipacting and other side effects

Finite Element Optimization Tool for Structure Design and Optimization

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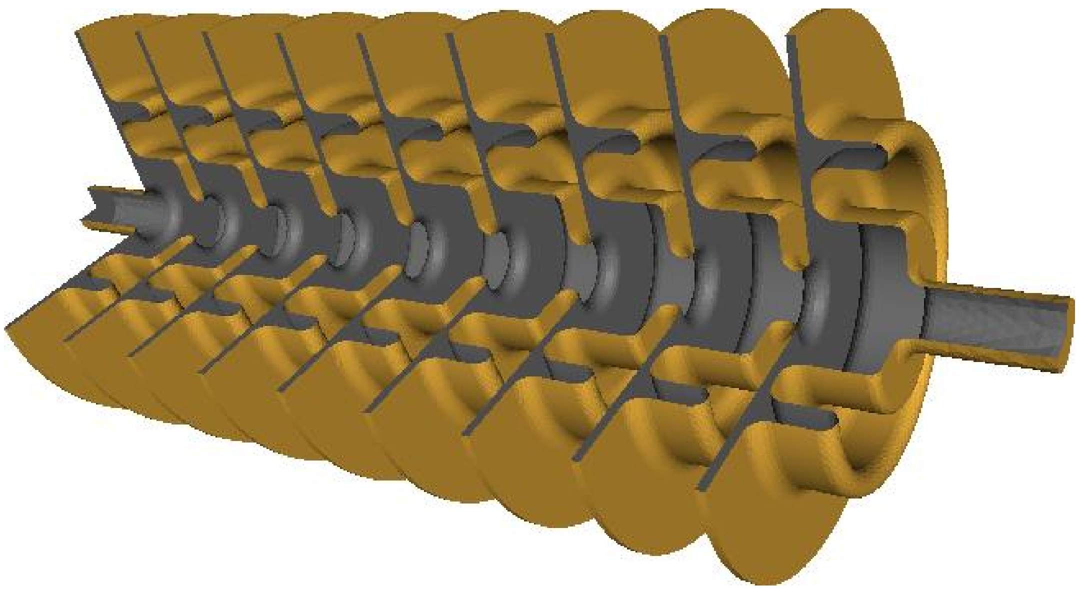
Cavity Design through Optimization

- Choke cavity as example
- PDE-constraint optimization
  - Objective function is specific to design goal
  - Design variables are the shape parameters
  - Quasi-Newton method (BFGS) may be used



(Initial design by Valery
Cavity model by S. Pei)

Shape Optimization

Objective Function -- the weighted least-squares fit

$$\mathcal{J} = -\beta Q_a + \alpha \sum Q_{HOM} + \gamma \sum_{j=1}^{9} \left(\left| e(x_j) \right| - \left| \bar{e} \right| \right)^2 - \delta V_a$$

Lagrangian:

$$\begin{aligned} \mathcal{L}(\mathbf{d}, \mathbf{e}, k, \mathbf{t}, \xi, \eta) = \mathcal{J} &+ \mathbf{t}^T (\mathbf{Ke} + jk\mathbf{We} - k^2 \mathbf{Me}) \\ &+ \xi(\mathbf{e}^H \mathbf{Me} - 1) \\ &+ \eta(\Re(\mathbf{e})\mathbf{M}\Im(\mathbf{e})) \end{aligned}$$

d: shape parameters,
e: eigenvector, k: eigenvalue,
t, ξ, and η are adjoint variables (Lagrange multipliers)

Complex Nonlinear Eigenvalue Problem

- With finite-element discretization $\vec{\mathbf{E}} = \sum e_i \mathbf{N}_i$
- The eigenvalue problem:

$$\mathbf{K}\mathbf{e} + j \sum_m \sqrt{k^2 - k_{c_m}^2}\, \mathbf{W}_m \mathbf{e} = k^2 \mathbf{M}\mathbf{e}$$

$$\mathbf{K}_{ij} = \int_\Omega (\nabla \times \mathbf{N}_i) \cdot \tfrac{1}{\mu} (\nabla \times \mathbf{N}_j)\, d\Omega$$

$$\mathbf{M}_{ij} = \int_\Omega \mathbf{N}_i \cdot \epsilon \mathbf{N}_j \, d\Omega$$

$$(\mathbf{W}_m)_{ij} = \int_\Gamma (n \times \mathbf{N}_i) \cdot (n \times \mathbf{N}_j) d\Gamma$$

- Frequency: $f_i = \dfrac{\Re(k)_i c}{2\pi}$
- External Q: $Q_i = \dfrac{\Re(k)_i}{2\Im(k)_i}$
- Fields: $\vec{\mathbf{H}} = \dfrac{1}{\mu c k} \sum e_i \nabla \times \mathbf{N}_i$

Optimality Conditions

$$\delta\mathcal{L}(\mathbf{d},\mathbf{e},k,\mathbf{t},\xi,\eta)=0$$

d: shape parameters,
e: eigenvector, k: eigenvalue,
t, ξ, and η are adjoint variables

State equations

$$\mathbf{K}\mathbf{e}_i + jk_i\mathbf{W}\mathbf{e}_i - k_i^2\mathbf{M}\mathbf{e}_i = \mathbf{0}$$
$$\mathbf{e}_i^H\mathbf{M}\mathbf{e}_i = 1$$
$$\Re(\mathbf{e}_i)^T\mathbf{M}\Im(\mathbf{e}_i) = 0$$

Adjoint equations

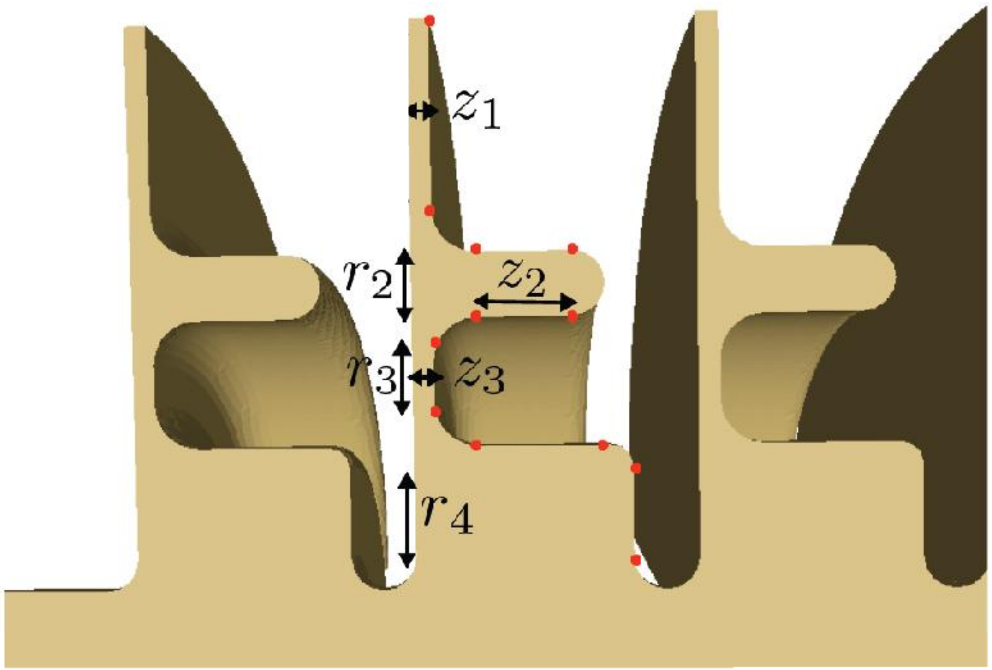
$$\mathbf{K}\mathbf{t} + (jk)^*\mathbf{W}\mathbf{t} - \left(k^2\right)^*\mathbf{M}\mathbf{t} + \xi_i\mathbf{M}\mathbf{e} + j\eta\mathbf{M}\mathbf{e}^* = \frac{\partial\mathcal{J}}{\partial\mathbf{e}}$$
$$j\mathbf{t}^T\mathbf{W}\mathbf{e}^* + 2k^*\mathbf{t}^T\mathbf{M}\mathbf{e}^* = \frac{\partial\mathcal{J}}{\partial k}$$

Inversion equations

$$\frac{\partial\mathcal{L}}{\partial d_p} = \frac{\partial\mathcal{J}}{\partial d_p} + \sum_{i=1}^{n_a}\left[\frac{1}{2}\mathbf{t}_i^H\left(\frac{\partial\mathbf{M}}{\partial d_p}\mathbf{e}_i + jk_i\frac{\partial\mathbf{W}}{\partial d_p}\mathbf{e}_i - k_i^2\frac{\partial\mathbf{K}}{\partial d_p}\mathbf{e}_i\right) + \frac{1}{2}\text{c.c.}\right.$$
$$\left. + \frac{1}{2}\xi\mathbf{e}_i^H\frac{\partial\mathbf{M}}{\partial d_p}\mathbf{e}_i + \eta_i\Re(\mathbf{e}_i)^T\frac{\partial\mathbf{M}}{\partial d_p}\Im(\mathbf{e}_i)\right]$$

Design Parameters

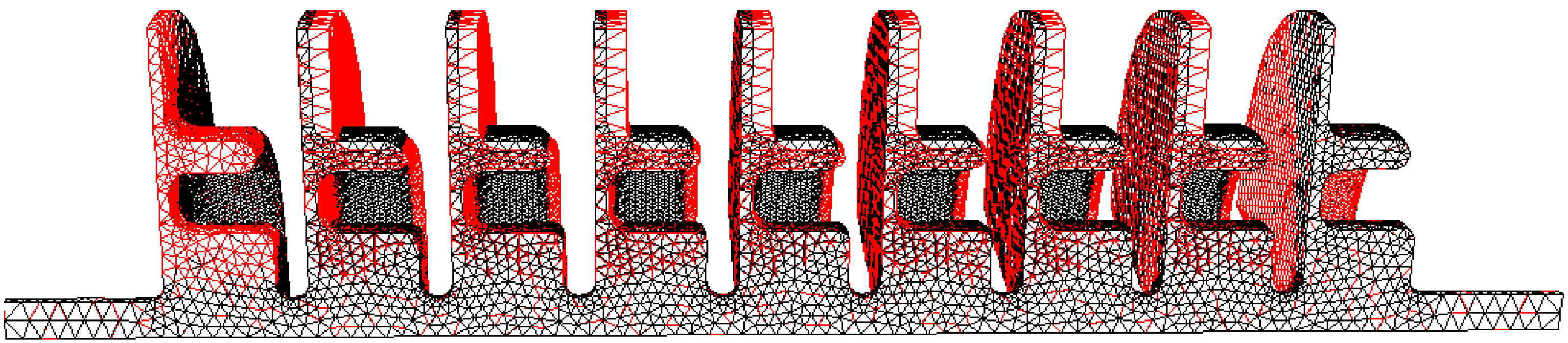
- **Optimization goals**:
  - Set accelerating mode frequency to 11.424 GHz.
  - Satisfy field flatness for the accelerating mode.
  - Maximize external Q for the accelerating mode.
  - Minimize external Q value for the higher order modes (HOM).
- **Shape parameters:**
  - Design variables are CAD parameters.
  - 7 middle cells are identical.
  - Parameters have simple bounds.



Optimized Shape of Choke Cavity

Optimized shape parameter changes in microns							
Cell1	Cell 2-8						Cell 9
r4	r2	r3	r4	z1	z2	z3	r4
0.5	-1219	382	-7.5	1771	583	224	-0.2

Initial design Optimized design



Choke Cavity – Initial vs Optimized

- Accelerating Mode

  Acc. Frequency = 11.423875 GHz (initial)

  Acc. Frequency = 11.424012 GHz (optimized)

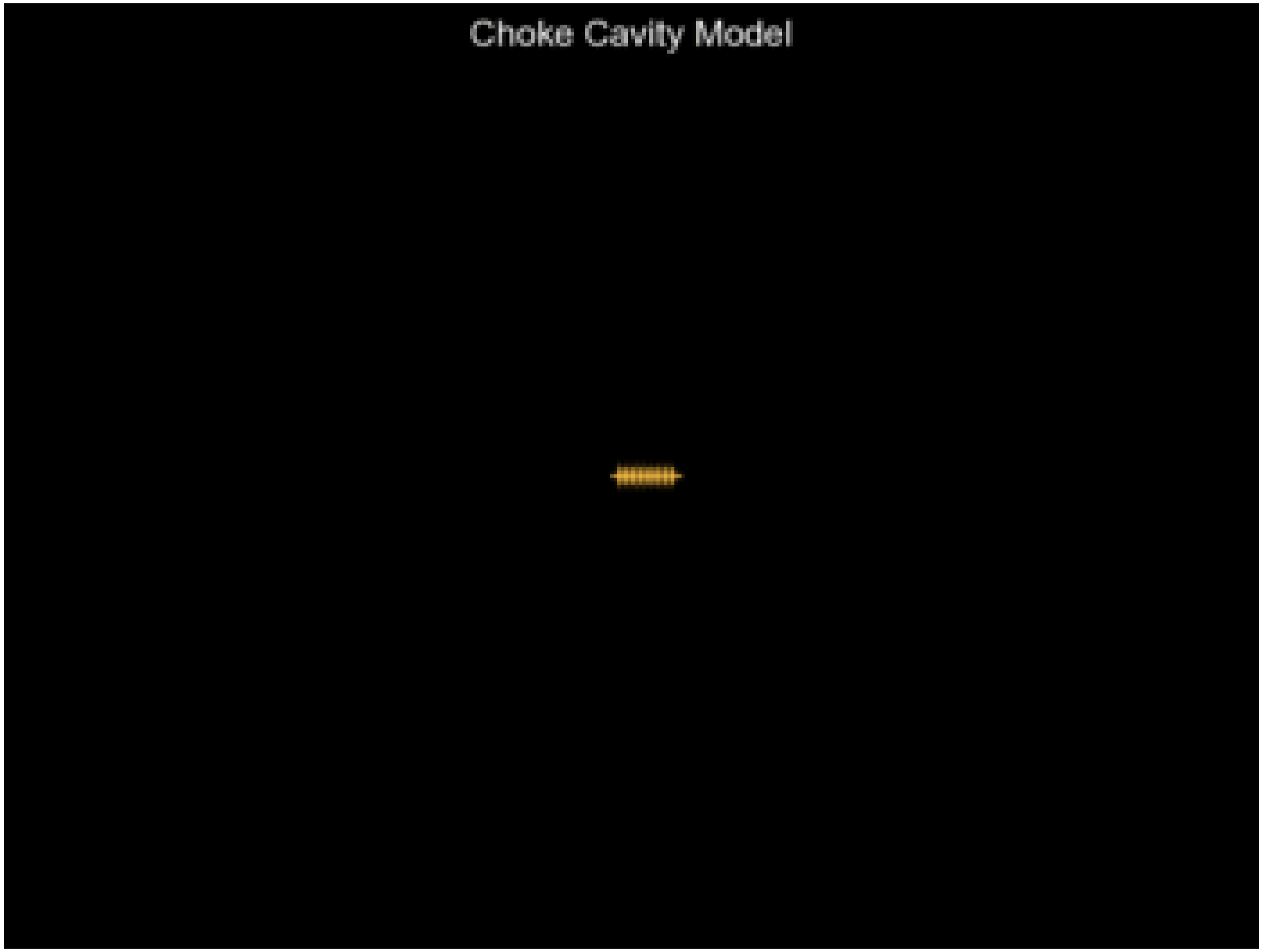
  Qacc = 7.508 e9 (initial)

  Qacc = 1.400 e10 (optimized)

- Higher order modes: **Q values decreased by factor of 5**

Q values for High Order Modes						
Initial	305.55	190.64	95.86	26.38	28.53	31.30
Optimized	41.67	63.15	45.84	16.29	16.46	9.80

Choke Cavity - Optimized Cavity Performance



High gradient choke mode structure optimized to reduce wakefield effects of higher-order dipole modes

Summary

- Track3P is a parallel multipacting and dark current simulations code based on finite element mesh. It provides an effective tool for observing quantities inside structure such as (effect of) dark current intercepted by interior wall of a high gradient structure
- Progress is being made in simulating CLIC T18 structures using Track3P. Preliminary comparisons with measurement performed
- Low surface field coupler developed for high gradient test structures
- Advanced optimization tool being developed for structure R&D