Summary of 2023 work advances

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AITANA MEETING
1-2 FEBRUARY 2024, VALENCIA, SPAIN

Outline

- Limitation of conventional RF cavities
- Dielectric Assist Accelerating (DAA) cavity
- Dielectric Disk Accelerating (DDA) cavity
- Conclusion and next steps

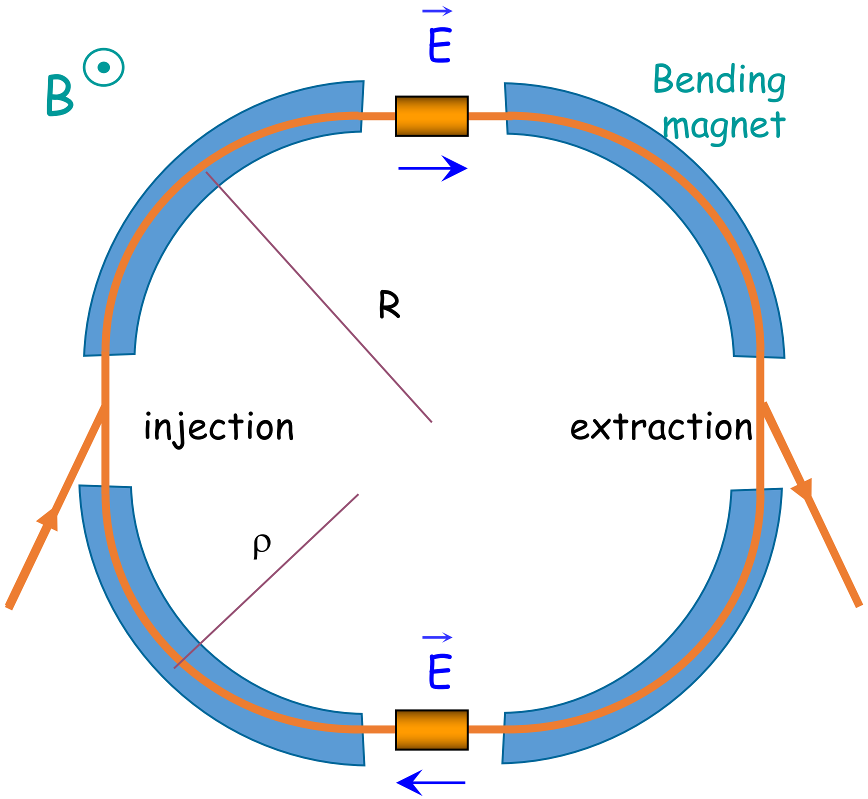
Limits of conventional accelerators

- **Synchrotrons:**
  - Few RF cavities -> No need for very high electric fields
  - Many bending magnets -> Energy loss by **synchrotron radiation**

$$\Delta E[\text{GeV}] = \frac{6.034\times10^{-18}}{\rho[\text{m}]}\left(\frac{E[\text{GeV}]}{m_0[\text{GeV}/c^2]}\right)^4$$

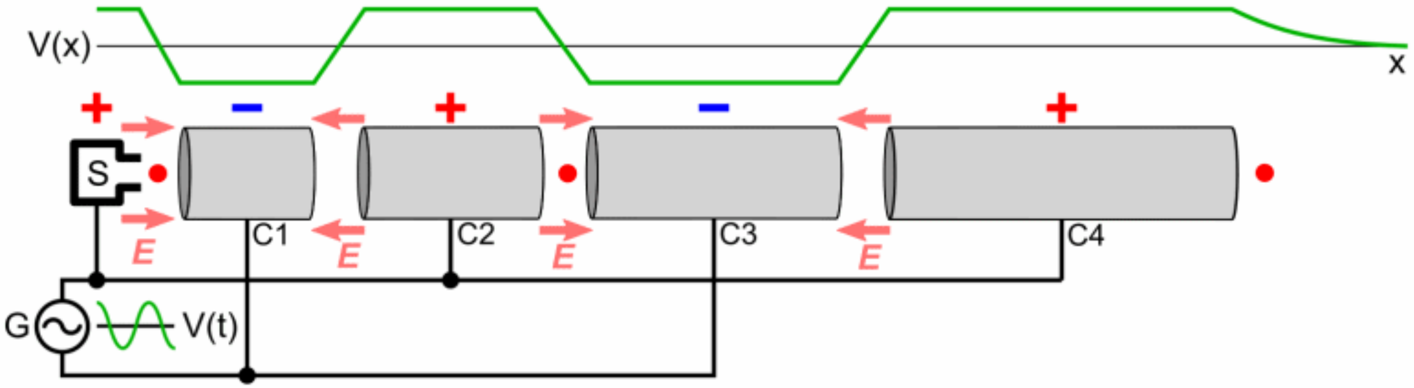
m_0: rest mass
E: energy
ρ: radius of curvature

Key constraint for **light particles**



- **Linear accelerators**
  - Few bending magnets -> No energy loss by synchrotron radiation
  - Many RF cavities -> High accelerating gradient or large machines.

Gradients limited around **100 MV/m** due to **surface breakdown**



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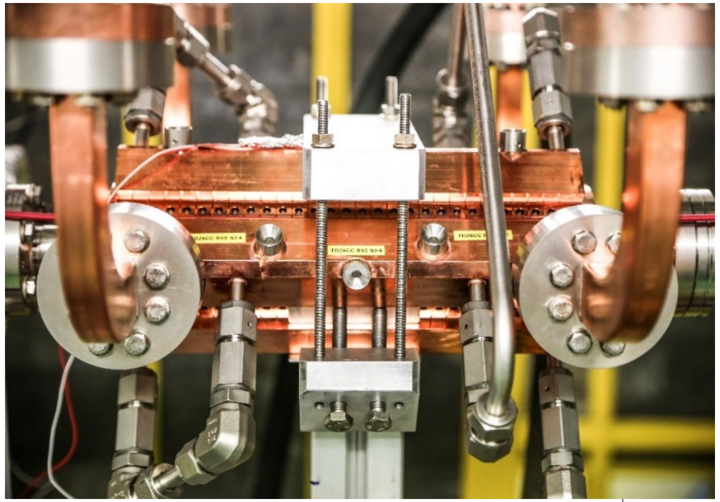
Surface breakdown phenomenology

RF signals

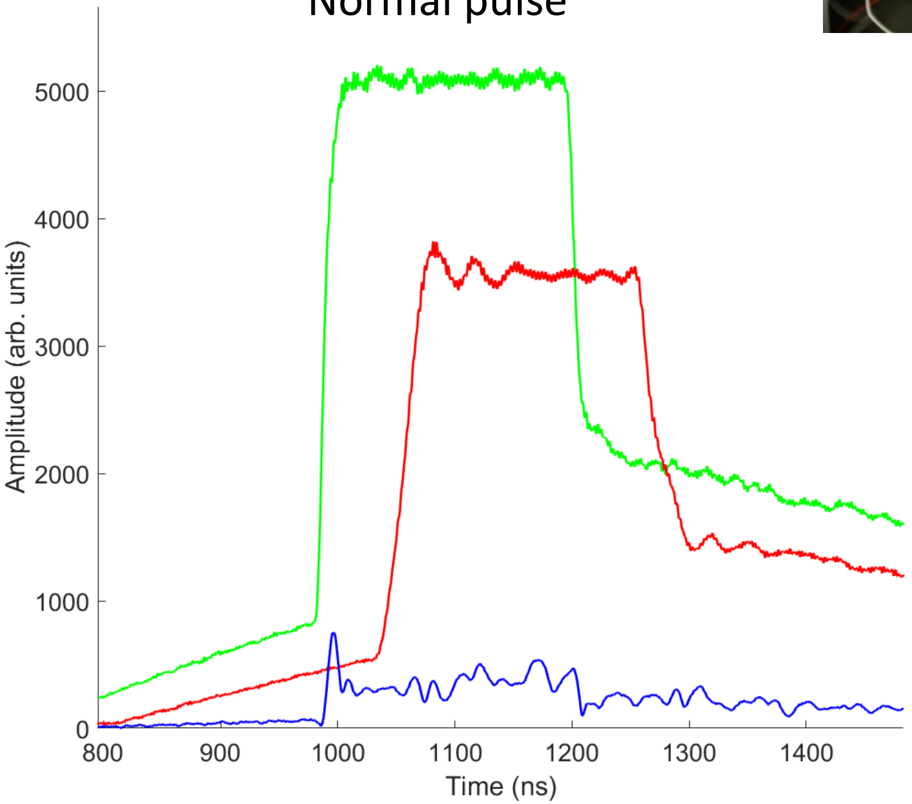
incident power

reflected power

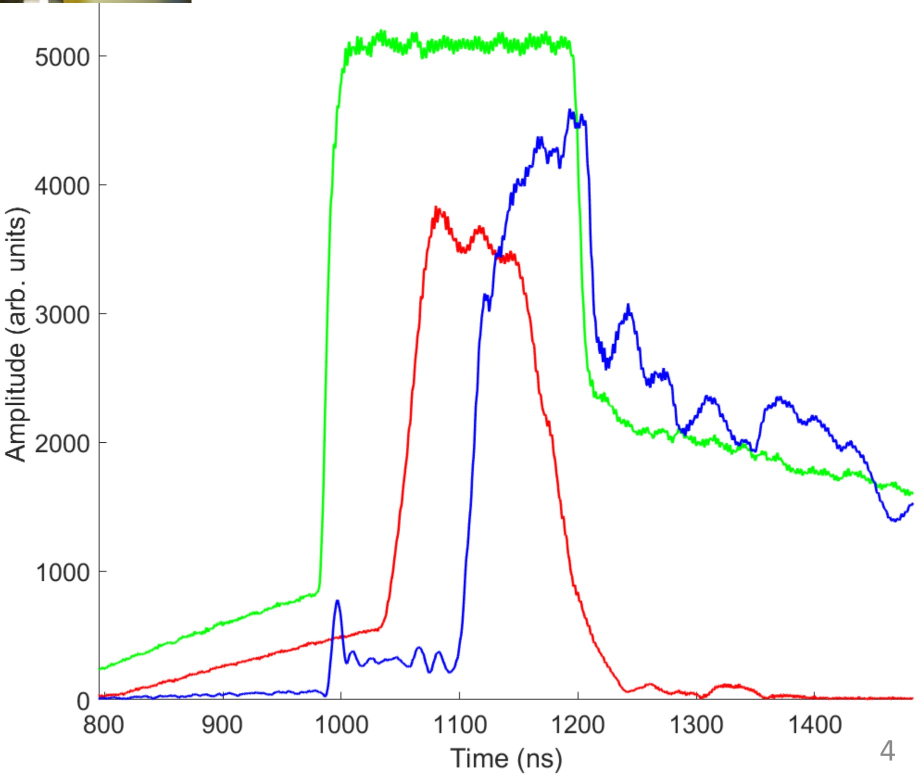


transmitted power

Normal pulse



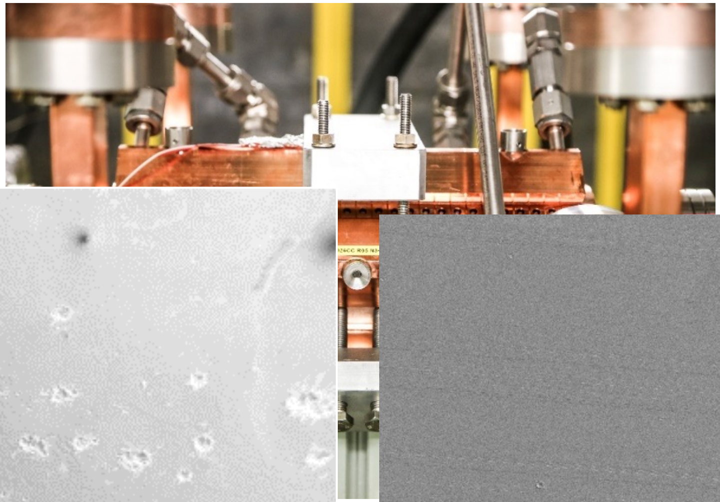
Breakdown pulse



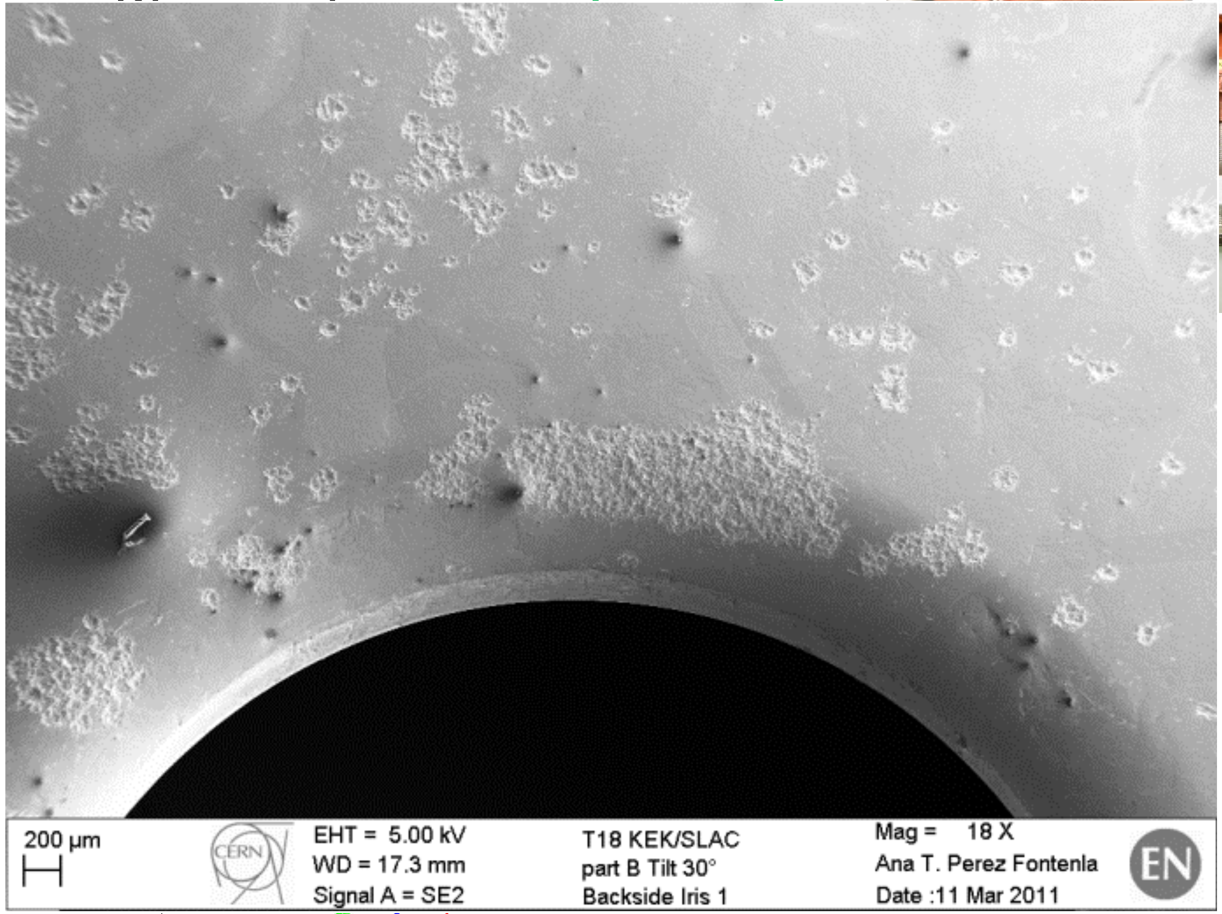
Walter Wuensch – CAS RF School: https://indico.cern.ch/event/1212689/contributions/5377907/

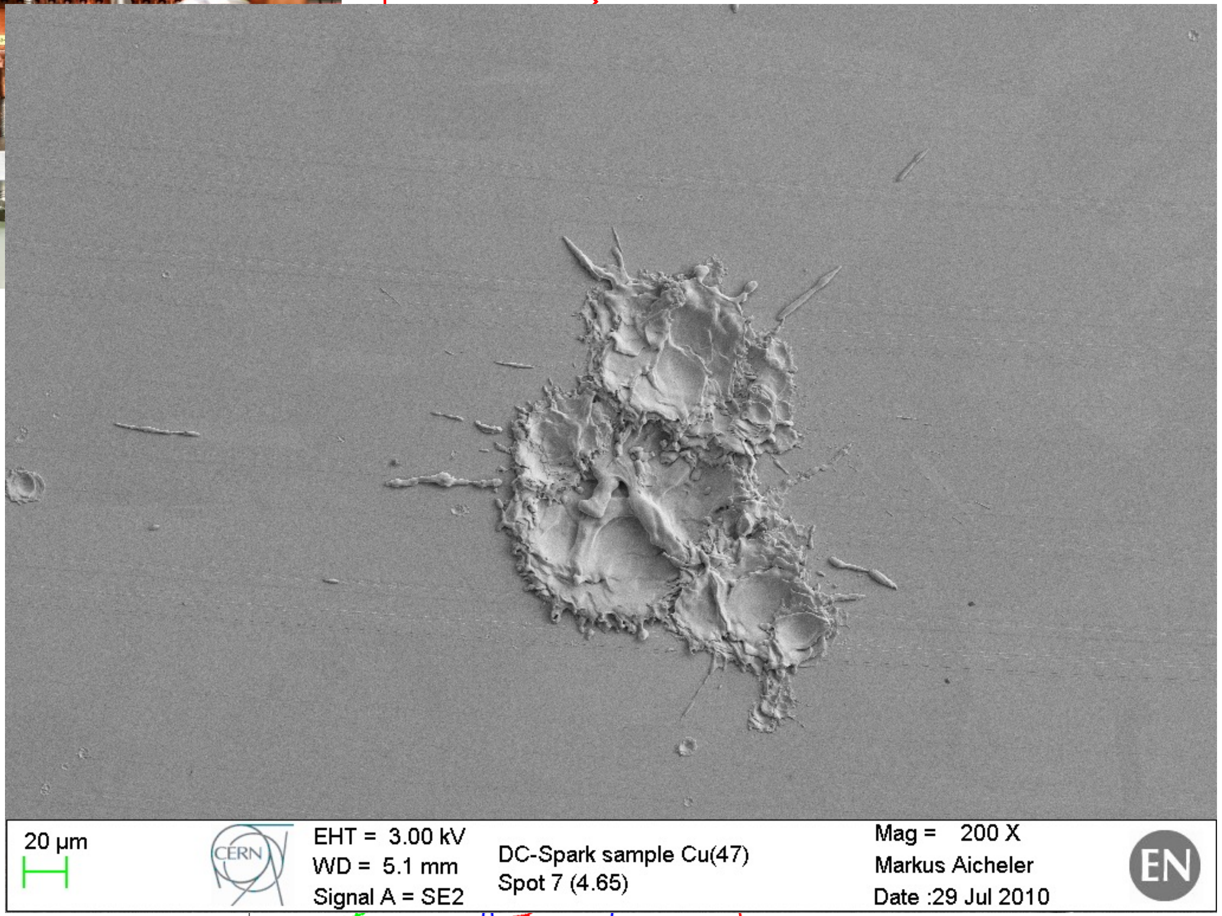
Surface breakdown phenomenology

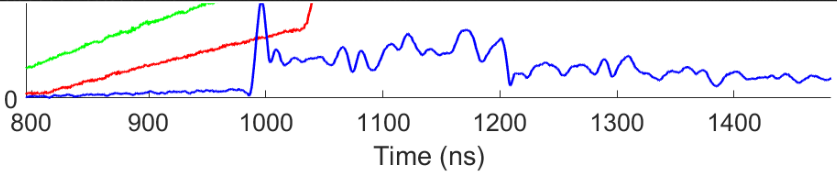
incident power

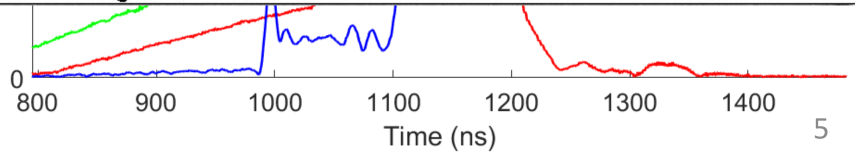


transmitted power









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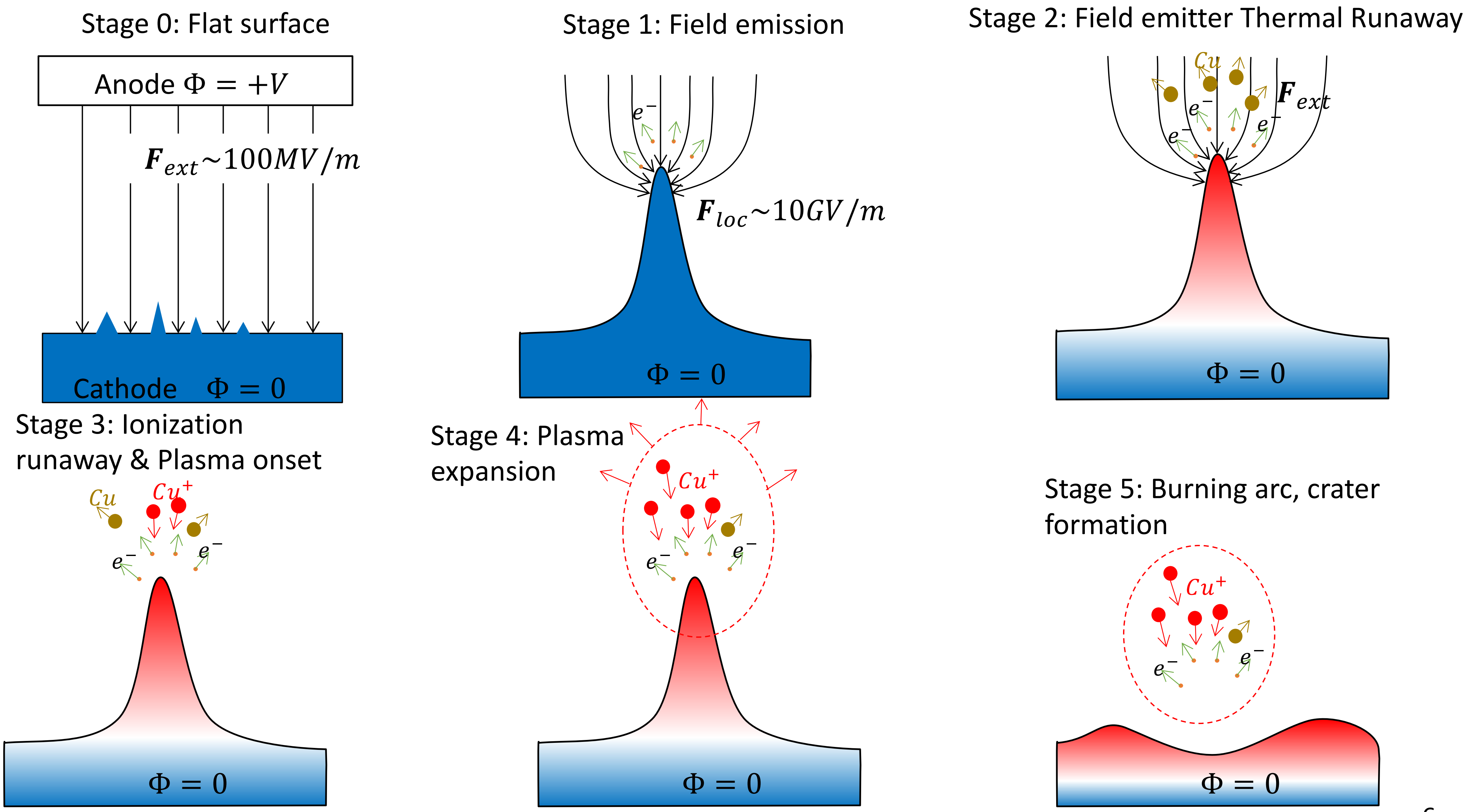
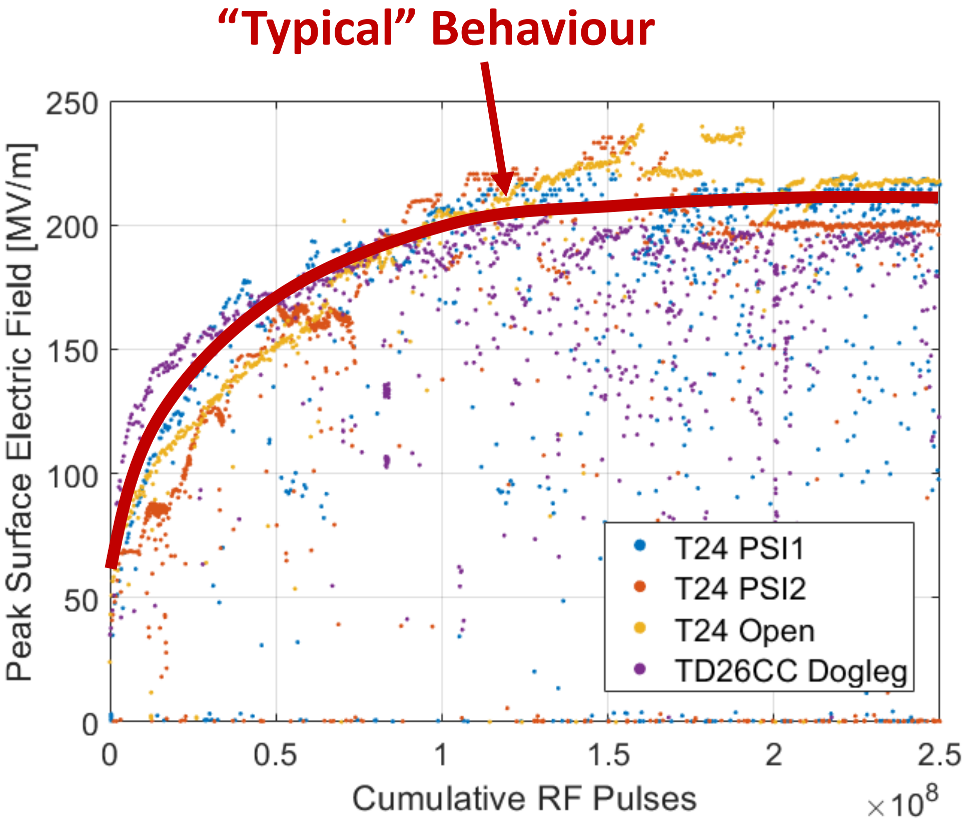
Surface breakdown initiation

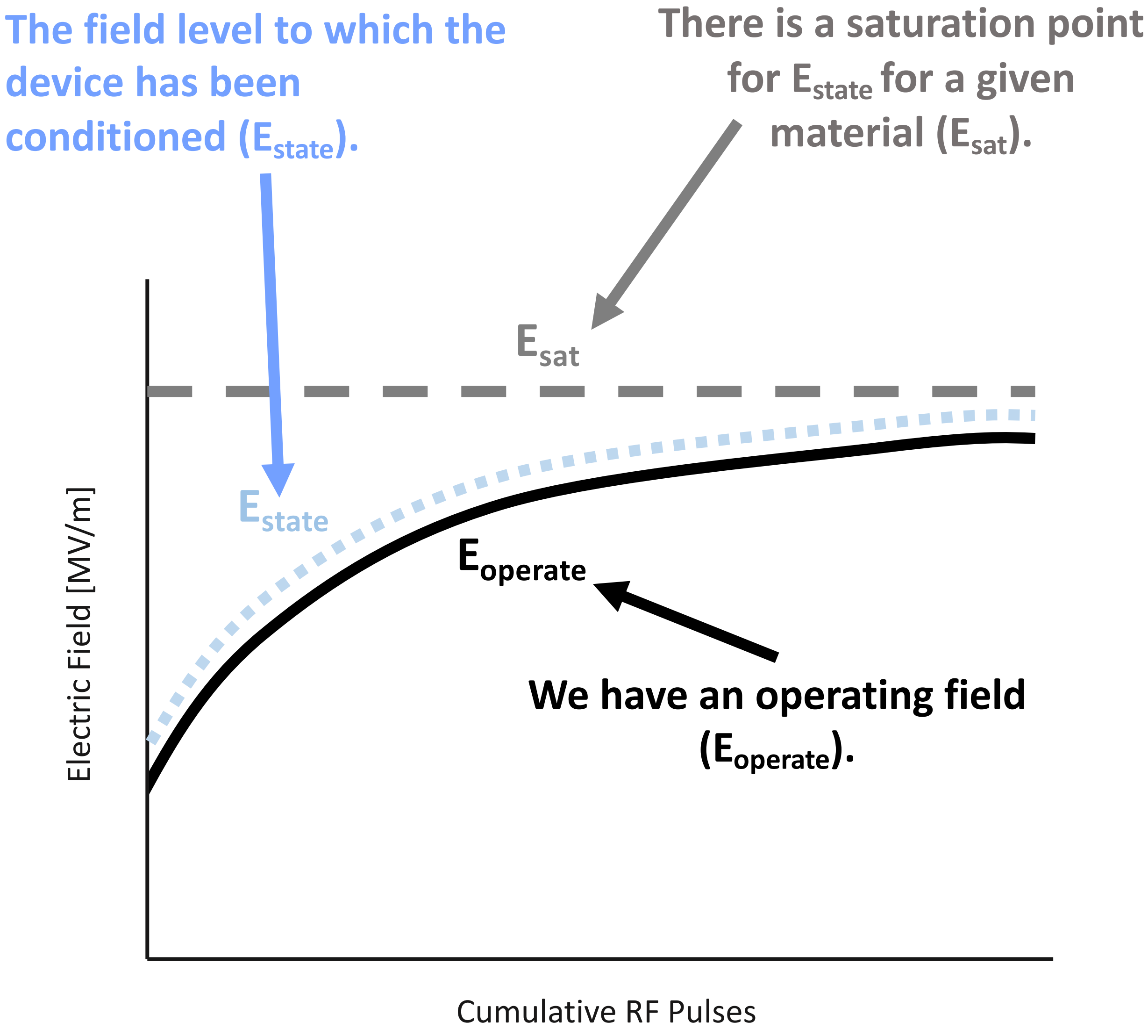


Andreas Kyritsakis et al. University of Tartu, MeVArc 2022: https://indico.cern.ch/event/1099613/contributions/4969668/

RF Conditioning

- Start at low electromagnetic field level.
- Gradually increase field keeping a safe breakdown rate.
- Reach field saturation.



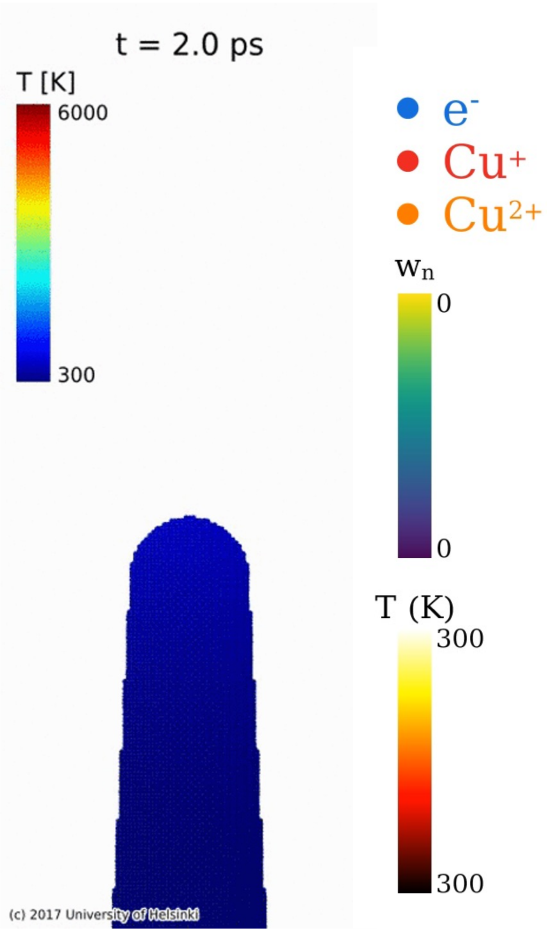


Lee Millar, CERN. MeVArc 2022: https://indico.cern.ch/event/1099613/contributions/4969646/

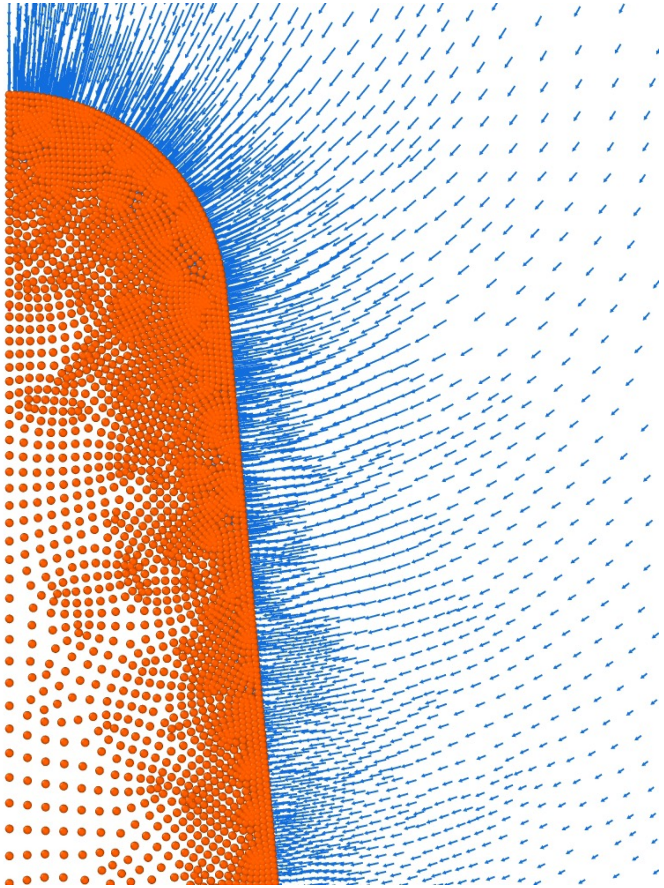
Complexity of surface breakdown

- Simulation: ns, nm, simple systems
- Experiment: sec, mm, complex systems

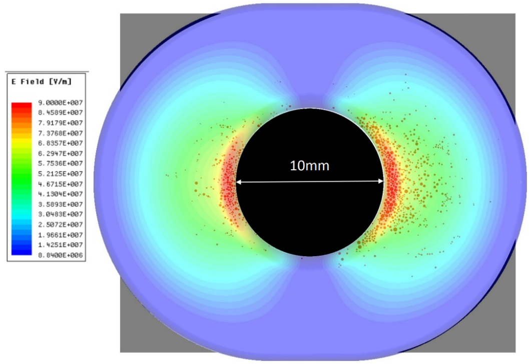
Molecular Dynamics

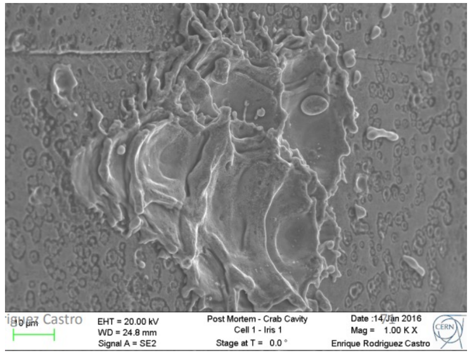


FEMOCS

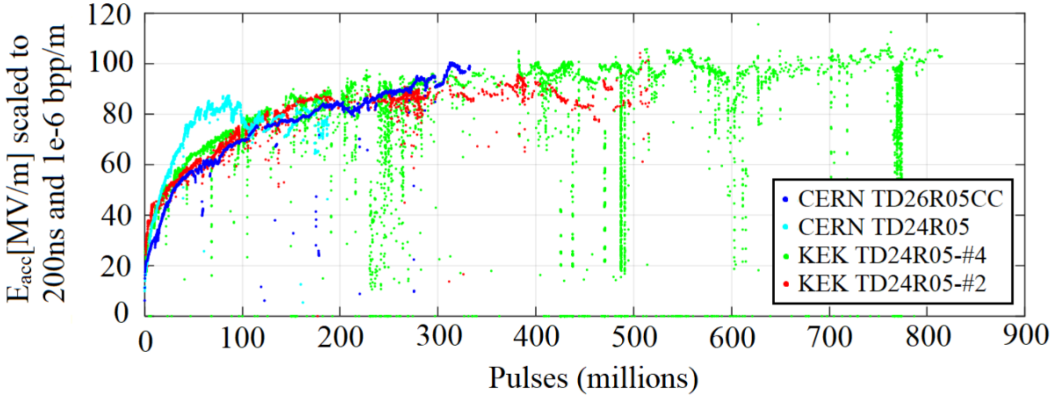


Post-mortem analysis



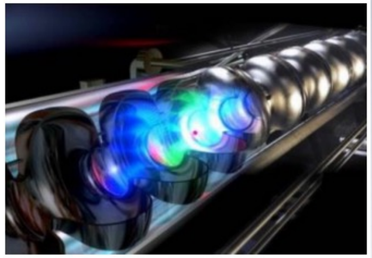


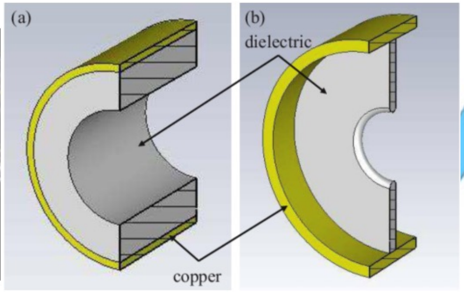
Conditioning curves & history

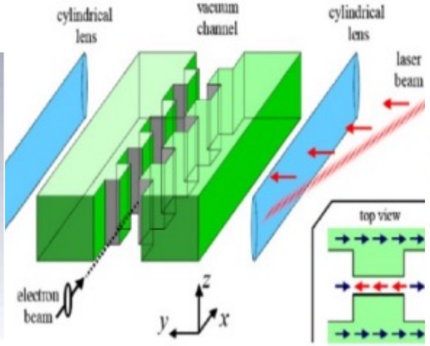


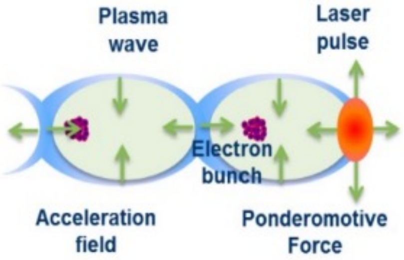
Andreas Kyritsakis et al. University of Tartu, MeVArc 2022: https://indico.cern.ch/event/1099613/contributions/4969668/

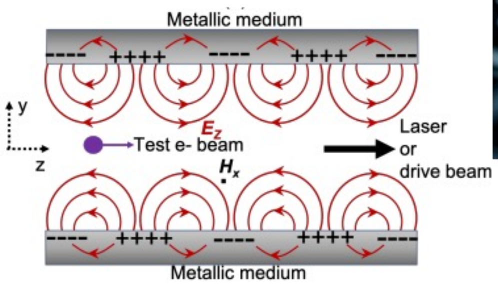
Novel accelerators

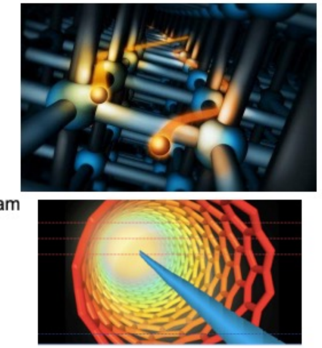










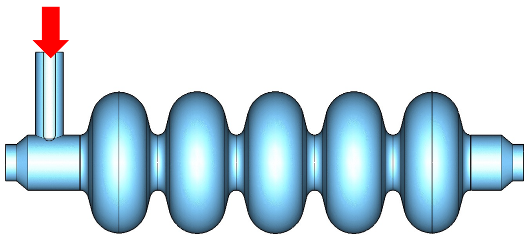


	Conventional RF cavities	Dielectric Loaded RF cavities	Dielectric laser – driven acceleration (DLA)	Plasma / Laser wakefield acceleration (PWFA / LWFA)	Plasmonic acceleration	Solid-state plasma Wakefield acceleration
Based on	Normal / superconducting cavities	Metallic and dielectric	Quartz / silicon structure	Gaseous plasma	Excitation of plasmons	Crystals, nano-channels, Carbon Nanotubes
Max. longitudinal electric field	~ 100 MV/m	~ 100 MV/m (?)	~ 10 GV/m	~ 100 GV/m	~ 100 GV/m	$\sim 1-100$ TV/m (prediction)
Limitation	Surface breakdown	Multipactor and breakdown (?)	Damage threshold	Wave breaking	Beam matching with excited plasmonic oscillations	Wave breaking

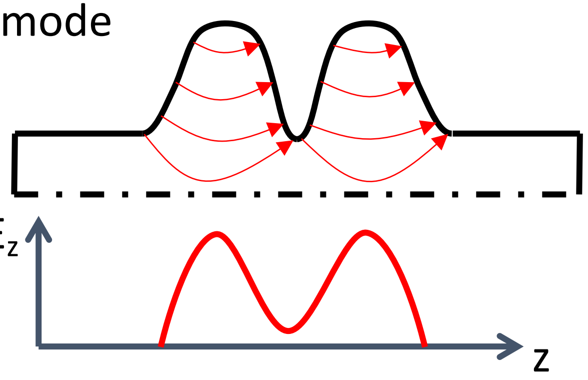
Hard to get high quality beams

Standing Wave Acceleration Cavities

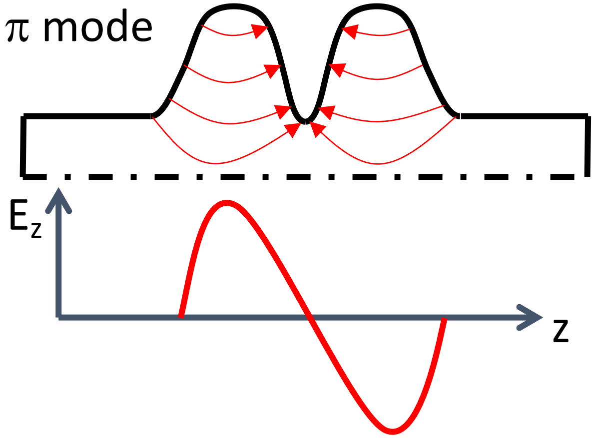
P RF in



0 mode



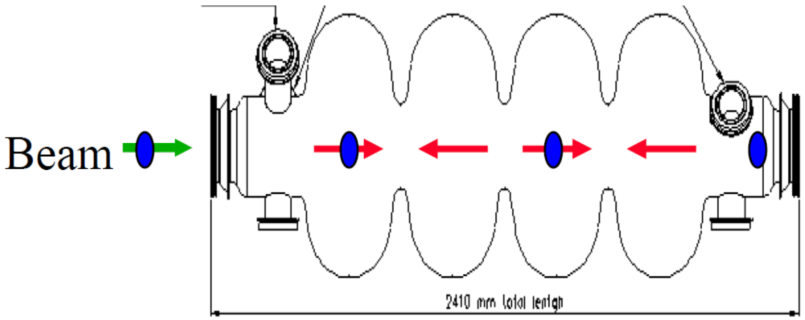
π mode



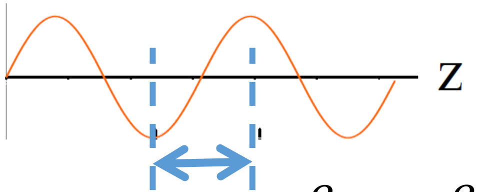
Cylindrical single (or multiple cavities) working on the **TM_{010}-like** mode are used

Synchronization condition

π mode



Electric field (at time t_0)



$$d = \frac{\beta c}{2 f_{RF}} = \frac{\beta \lambda_{RF}}{2}$$

β: particle velocity
d: distance between cells
f_{RF}: RF frequency
c: speed of light in vacuum

Figures of merit:

- ❑ Shunt impedance: efficiency of the acceleration mode.

$$R = \frac{\hat{V}_{acc}^2 T^2}{P_{diss}} \quad [\Omega]$$

NC cavity R~1MΩ SC cavity R~1TΩ

- ❑ Quality factor: efficiency to store RF energy .

$$Q = \omega_{RF} \frac{W}{P_{diss}}$$

NC cavity Q~10^4 SC cavity Q~10^{10}

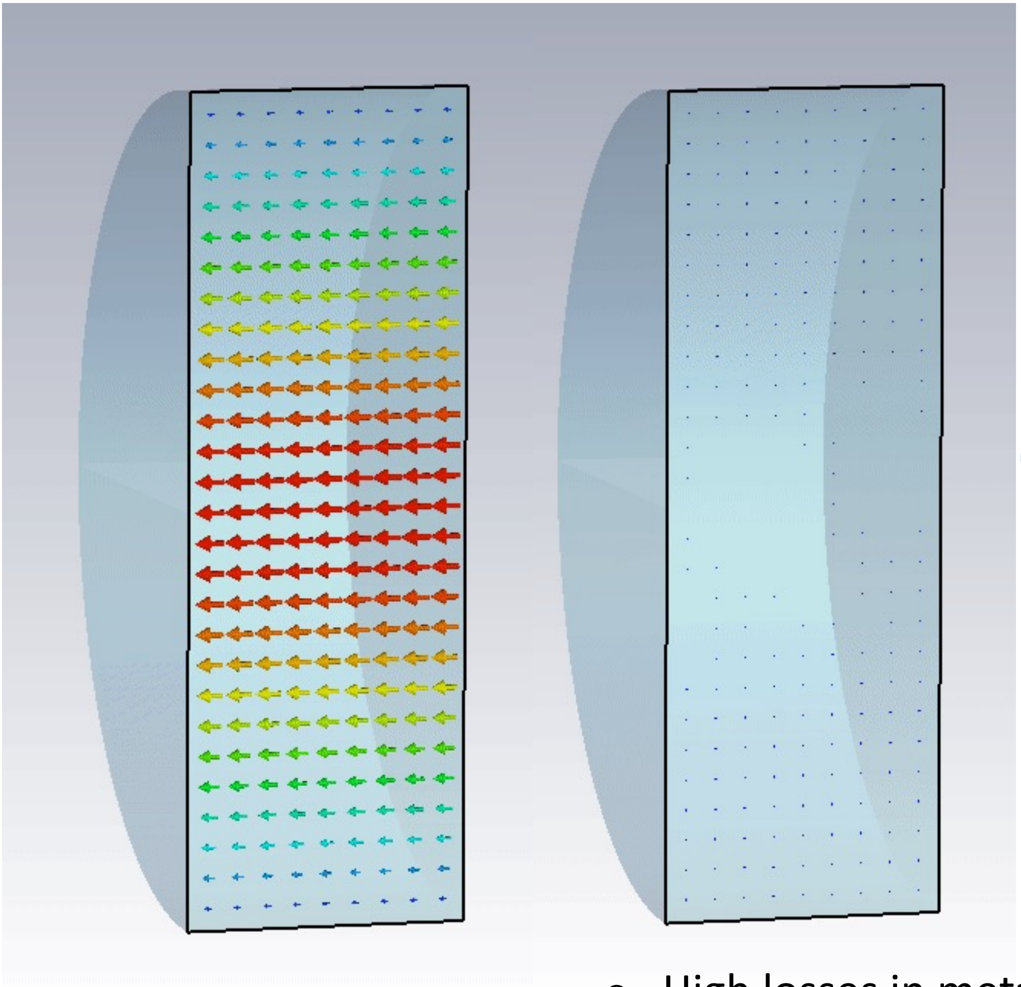
- ❑ R/Q: pure geometric qualification factor.

$$\frac{R}{Q} = \frac{\hat{V}_{acc}^2 T^2}{\omega_{RF} W} \sim 100\ \Omega$$

Copper structure single cell

Pillbox cavity TM_{010}

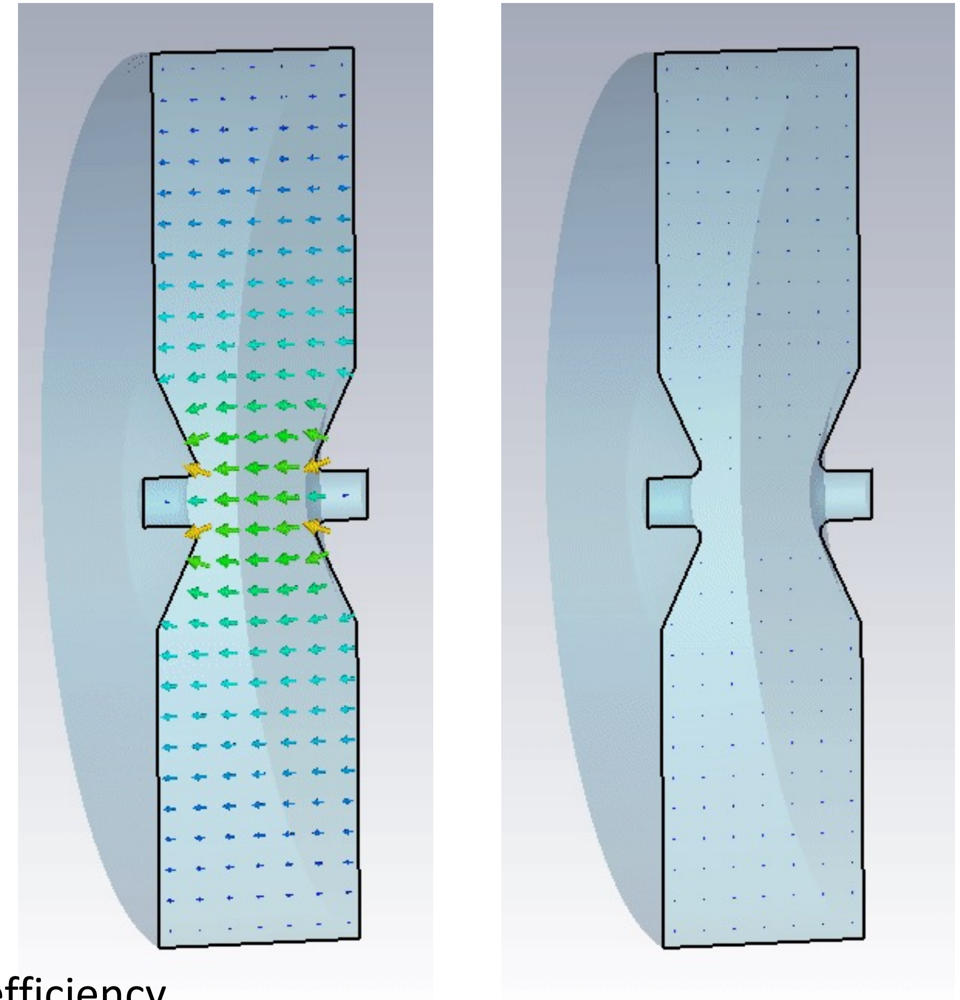
Electric field   Magnetic field



Optimization →

Accelerating cavity mode TM_{010}

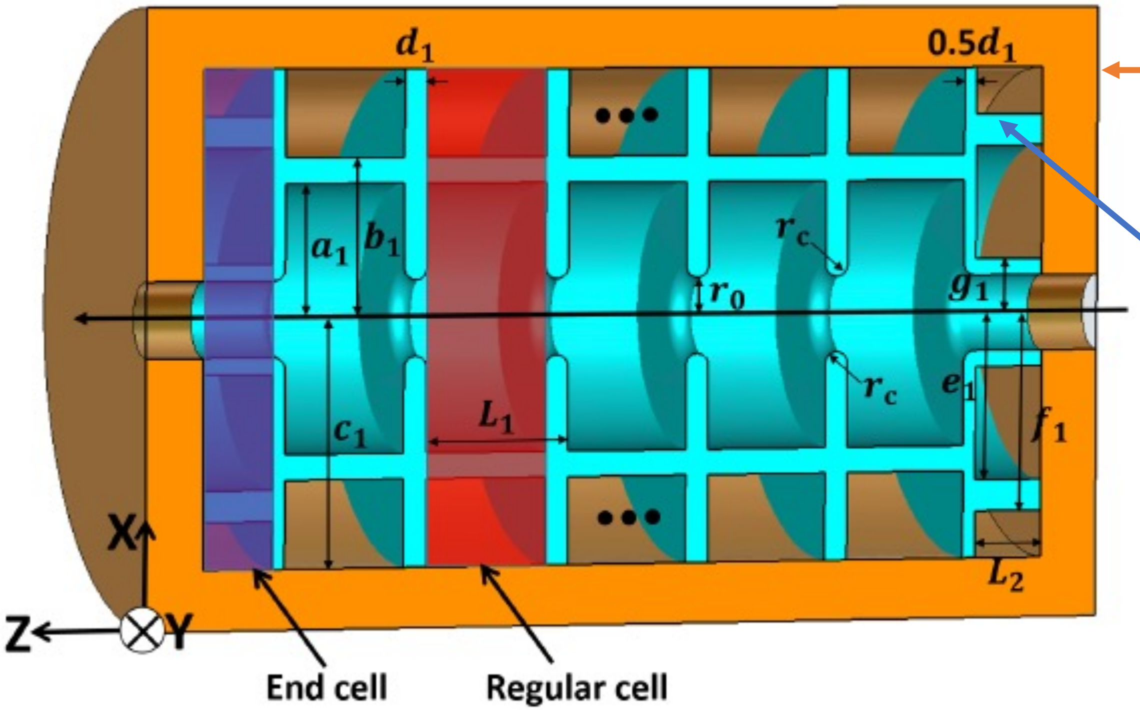
Electric field   Magnetic field

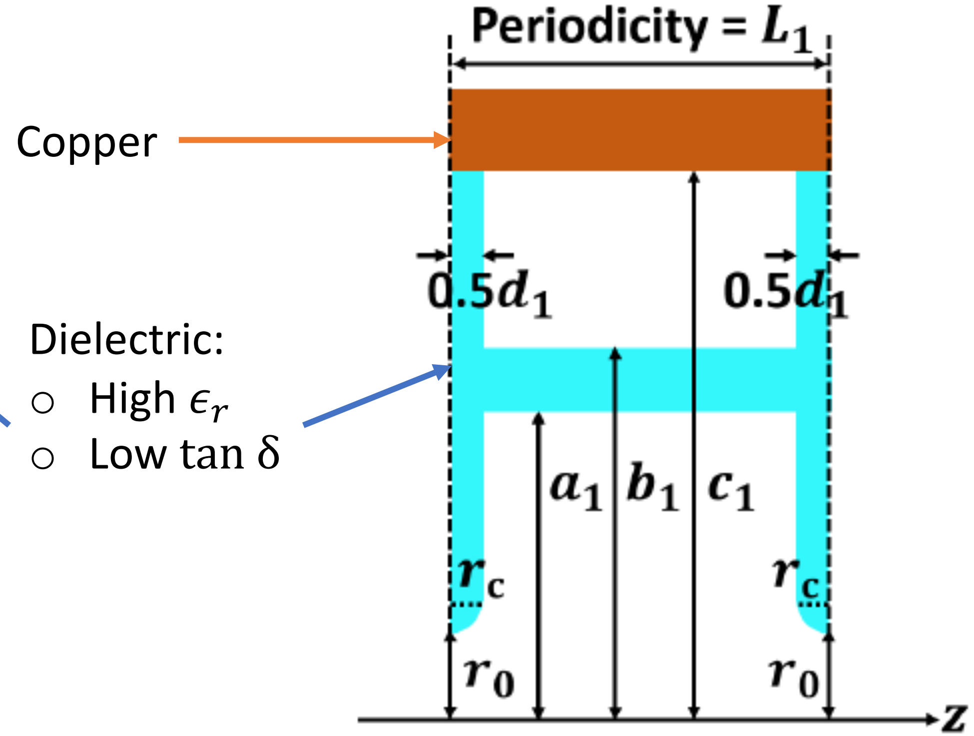


- ○ High losses in metallic walls: low RF efficiency.
- ○ High peak electric field in metal: field emission and RF breakdown.

Dielectric Assist Accelerating (DAA) cavity

Standing wave **Low β particles** **S-band**





D. Satoh, M. Yoshida, and N. Hayashizak, "Dielectric assist accelerating structure." *Physical Review Accelerators and Beams*, vol. 19, 1, pp. 1011302, 2016

Investigations Into *X*-Band Dielectric Assist Accelerating Structures for Future Linear Accelerators. Yelong Wei, Alexej Grudiev.

TABLE I

LIST OF DIELECTRICS STUDIED IN THE OPTIMIZATION

Material	Acronym	ε_r	tan δ
CVD Diamond	Diamond	5.7	10^{-4}
MgO	D9	9.64	6×10^{-6}
$MgTiO_3$	D16	16.66	3.43×10^{-5}
$BaTiO_x$	D50	50.14	8×10^{-5}

Working under $TM_{02} - \pi$ mode:

- High Q_0.
- Dielectric helps to decrease cavity size.
- Low electric field in metal.
- Axial symmetry

Resonant frequency for the mode depends on the combination of a_1, b_1, c_1

Energy range for hadrontherapy

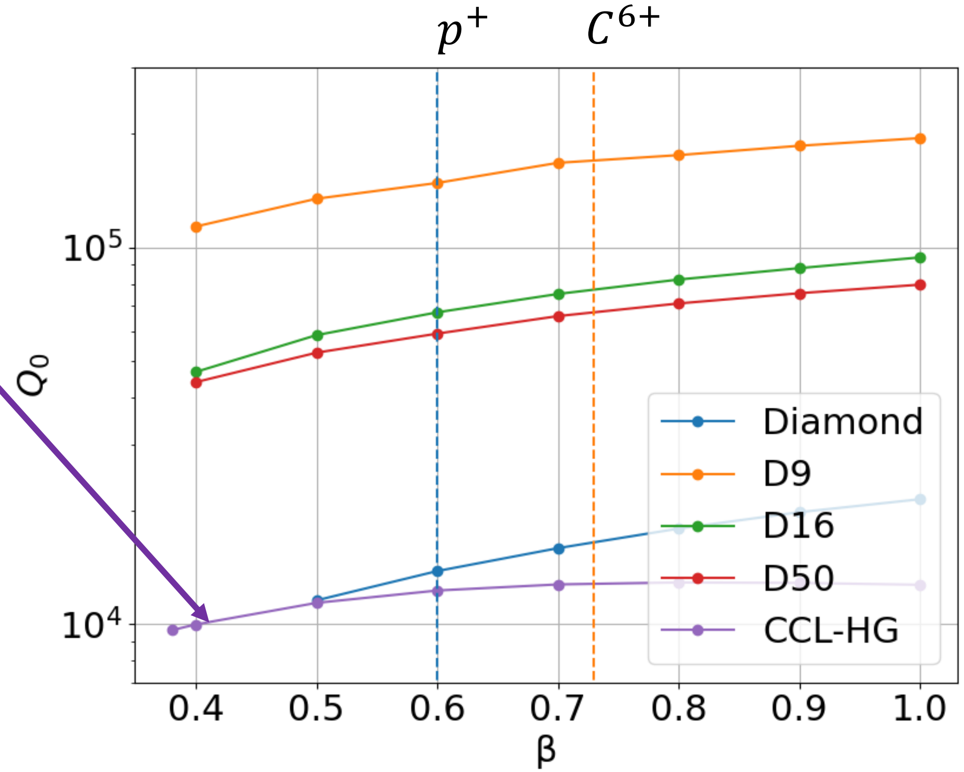
$$Q = \omega_{RF} \frac{W}{P_{diss}}$$

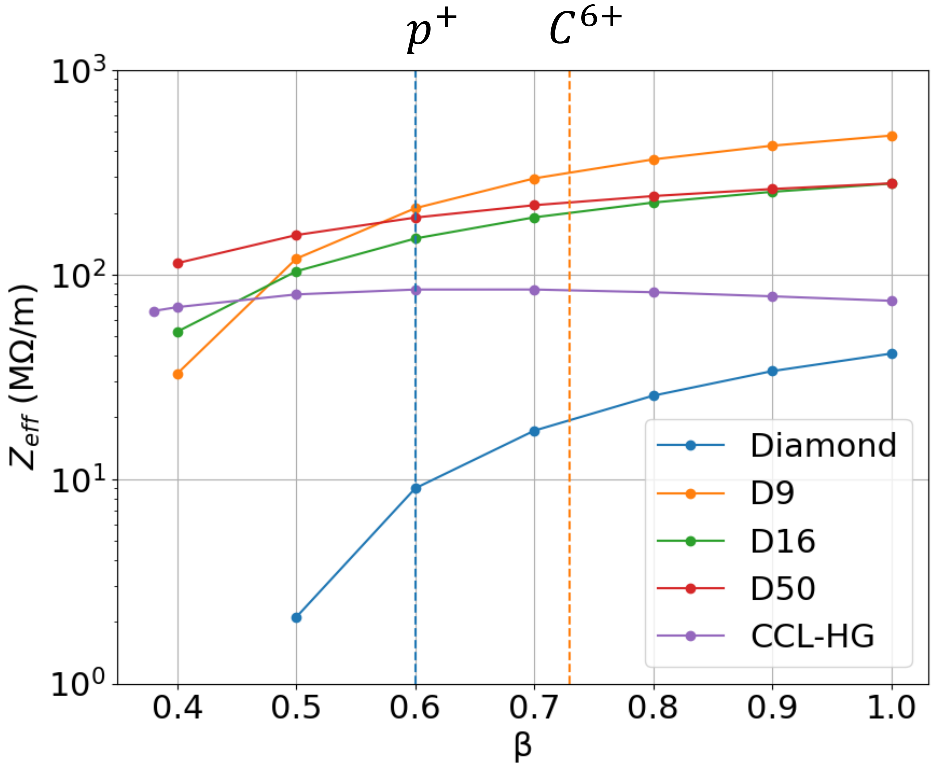
$$R = \frac{\hat{V}_{acc}^2 T^2}{P_{diss}} \quad [\Omega]$$

- Protons: $70 - 230$ MeV $\rightarrow \beta : 0.37 - 0.6$
- $^{12}C^{6+}$: $100 - 430$ MeV/u $\rightarrow \beta : 0.43 - 0.73$

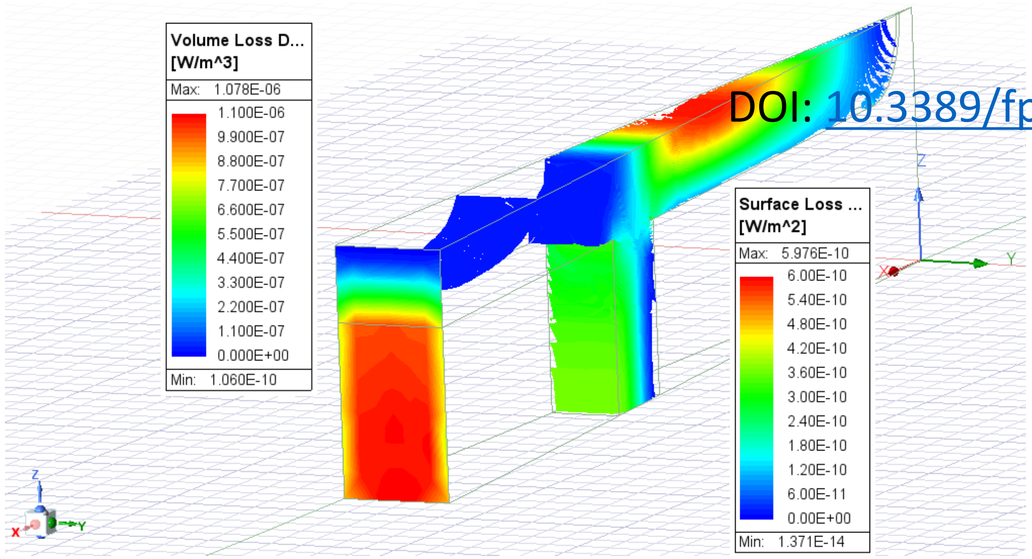
Bencini, V. (2020). *Design of a novel linear accelerator for carbon ion therapy* (Doctoral dissertation, Rome U.).

- ❑ Design compared with a **normal cooper cavity** for proton therapy (purple).
- ❑ Factor 1.5 to 100 improvement depending on the material and characteristics.

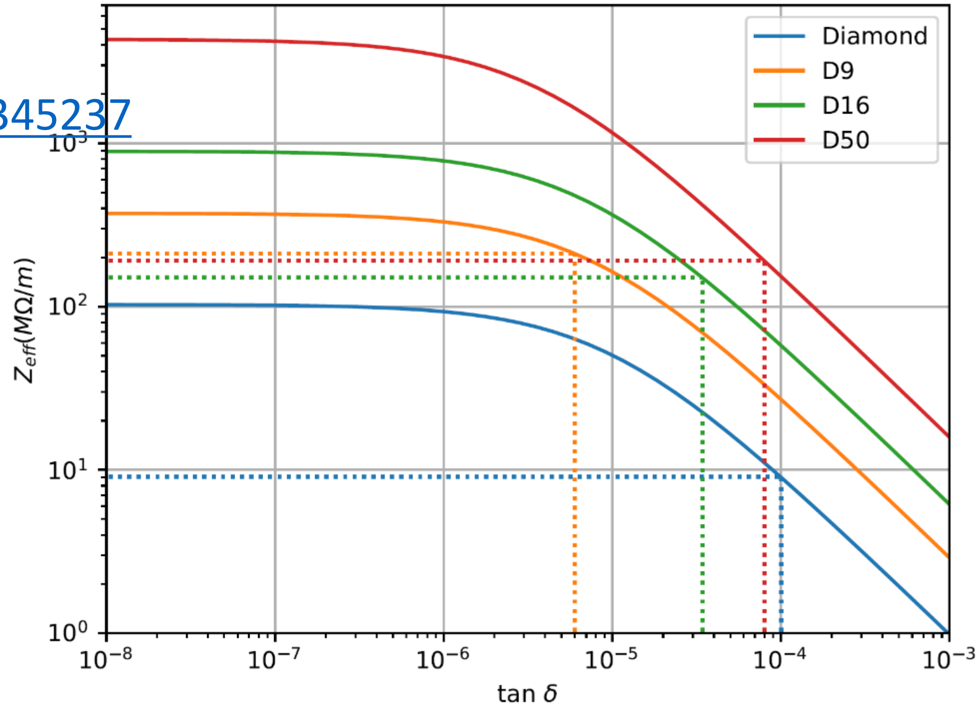


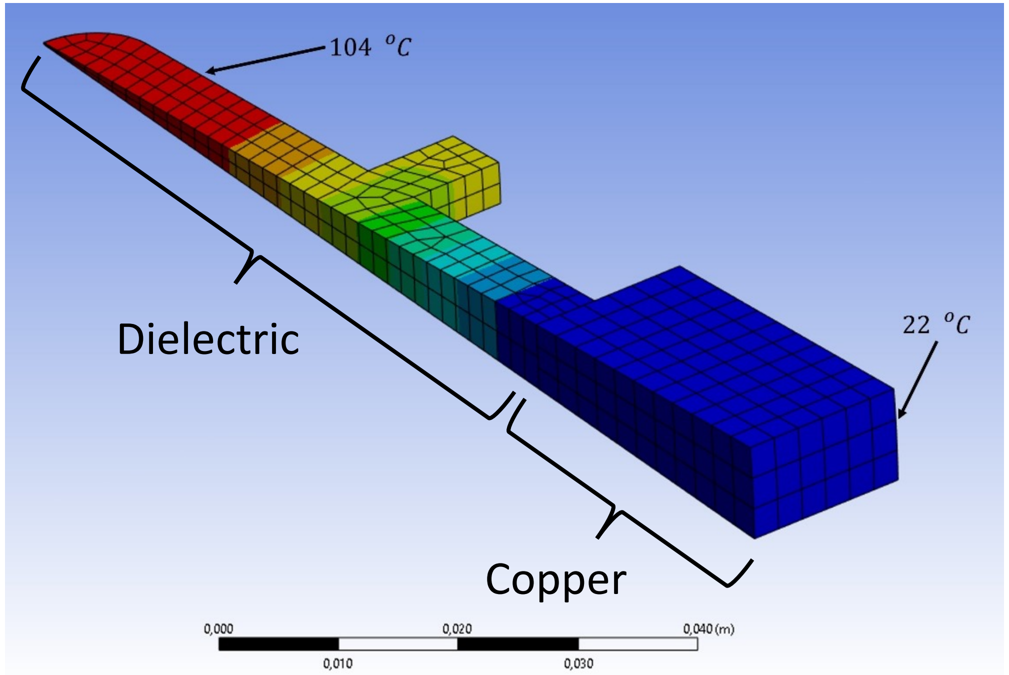


Challenges



DOI: 10.3389/fphy.2024.1345237

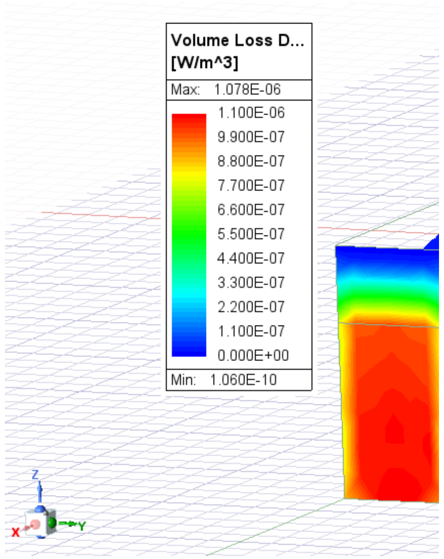


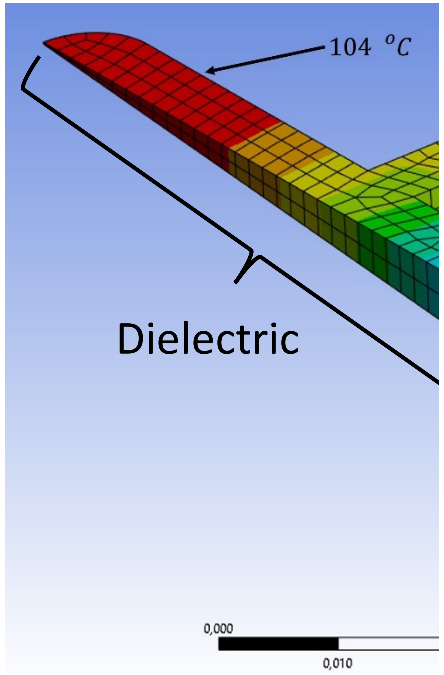


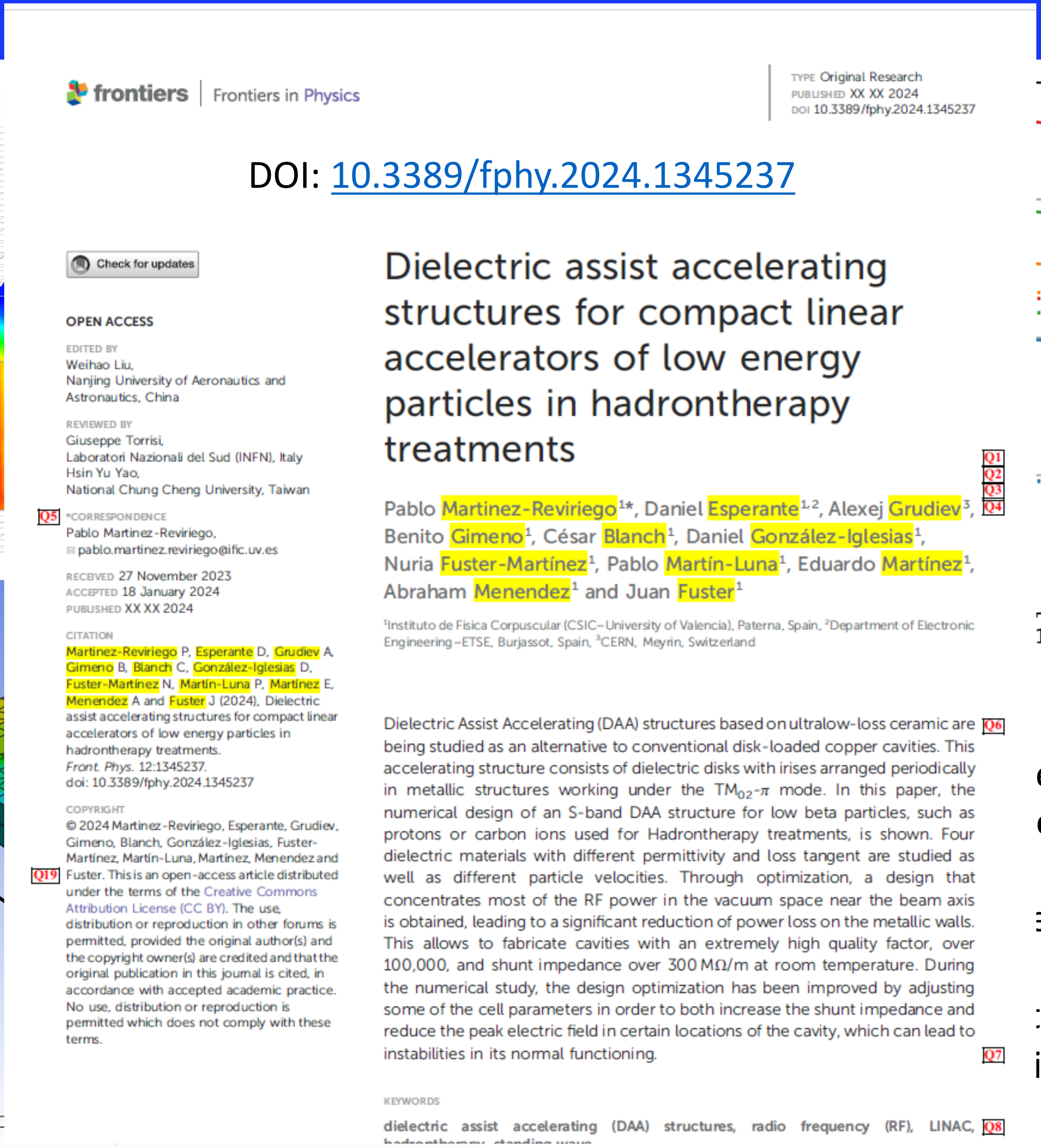
Challenges

- ❑ Finding the right material (high ϵ_r and small $\tan\delta$).
- ❑ Mechanize the geometry within the tolerances required.
- ❑ Mitigation of non-linear EM phenomena such as multipactor.
- ❑ Field singularities at triple point junctions.
- ❑ Cooling of the ceramic

Challenges







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Dielectric assist accelerating structures for compact linear accelerators of low energy particles in hadrontherapy treatments

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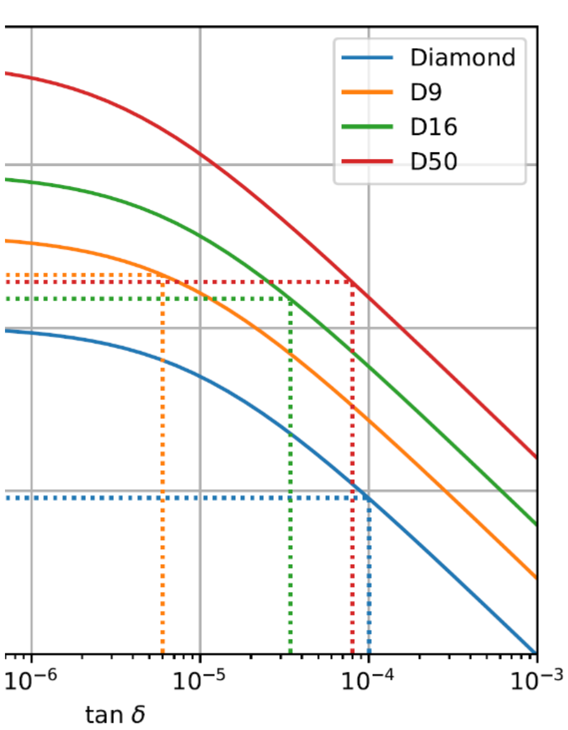
Dielectric Assist Accelerating (DAA) structures based on ultralow-loss ceramic are being studied as an alternative to conventional disk-loaded copper cavities. This accelerating structure consists of dielectric disks with irises arranged periodically in metallic structures working under the TM_{02}-π mode. In this paper, the numerical design of an S-band DAA structure for low beta particles, such as protons or carbon ions used for Hadrontherapy treatments, is shown. Four dielectric materials with different permittivity and loss tangent are studied as well as different particle velocities. Through optimization, a design that concentrates most of the RF power in the vacuum space near the beam axis is obtained, leading to a significant reduction of power loss on the metallic walls. This allows to fabricate cavities with an extremely high quality factor, over 100,000, and shunt impedance over 300 MΩ/m at room temperature. During the numerical study, the design optimization has been improved by adjusting some of the cell parameters in order to both increase the shunt impedance and reduce the peak electric field in certain locations of the cavity, which can lead to instabilities in its normal functioning.

KEYWORDS
dielectric assist accelerating (DAA) structures, radio frequency (RF), LINAC,



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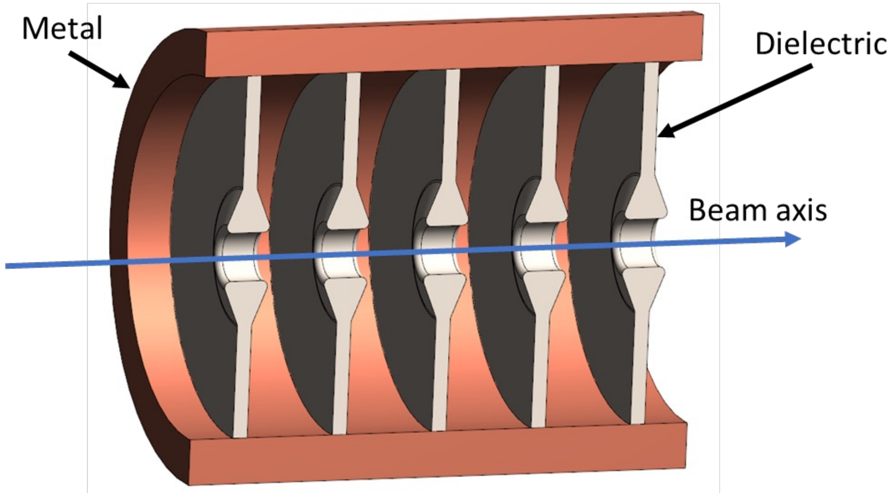
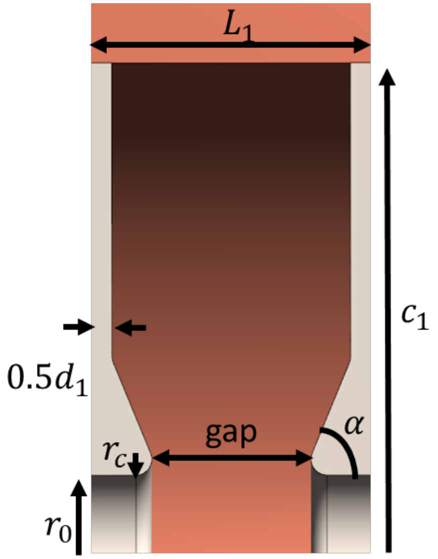
Dielectric Disk Accelerating (DDA) cavity

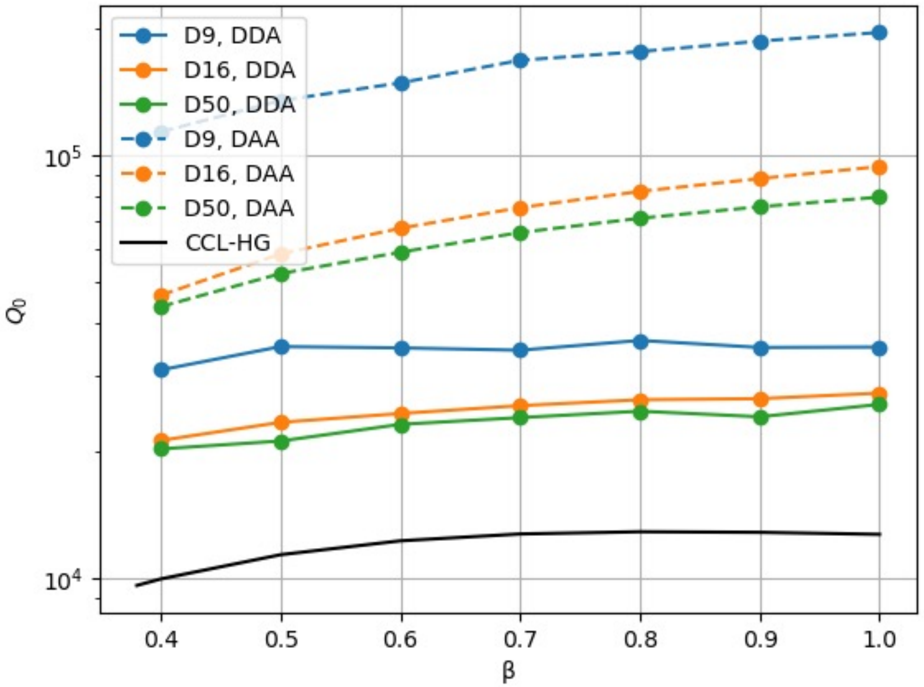
- **Goal:** design a prototype to test dielectric cavities.

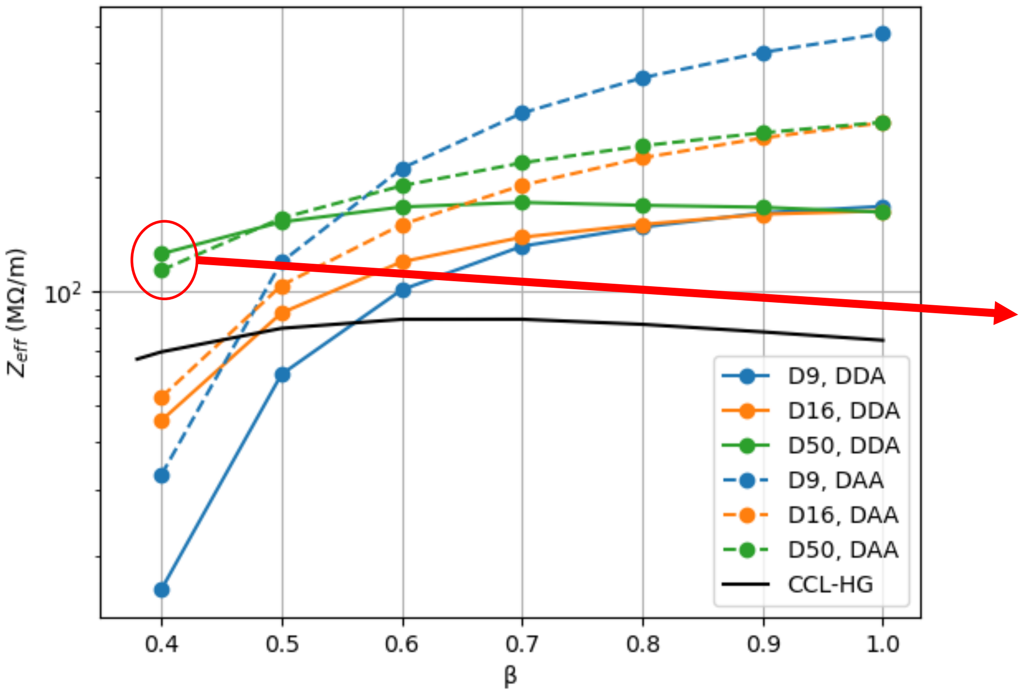




Advantages:
- Simpler geometry
- Less sensitive to material

Challenges:
- Multipactor
- Fabrication





DDA structure with **D50** material for $\boldsymbol{\beta = 0.4}$ is a promising solution.

Dielectric Disk Loaded Accelerating (DDA) Cavity

Pros:

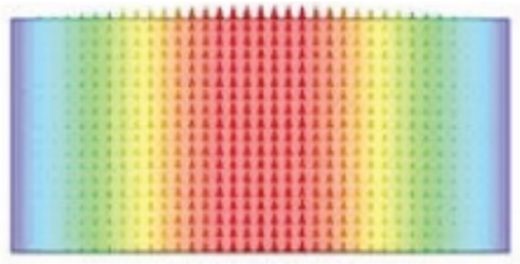
- Coupling can be adjusted easily
- Low coupling to other modes
- Low magnetic field in coupling cavity
- Low electric field on coupling metallic iris.
- More symmetry.

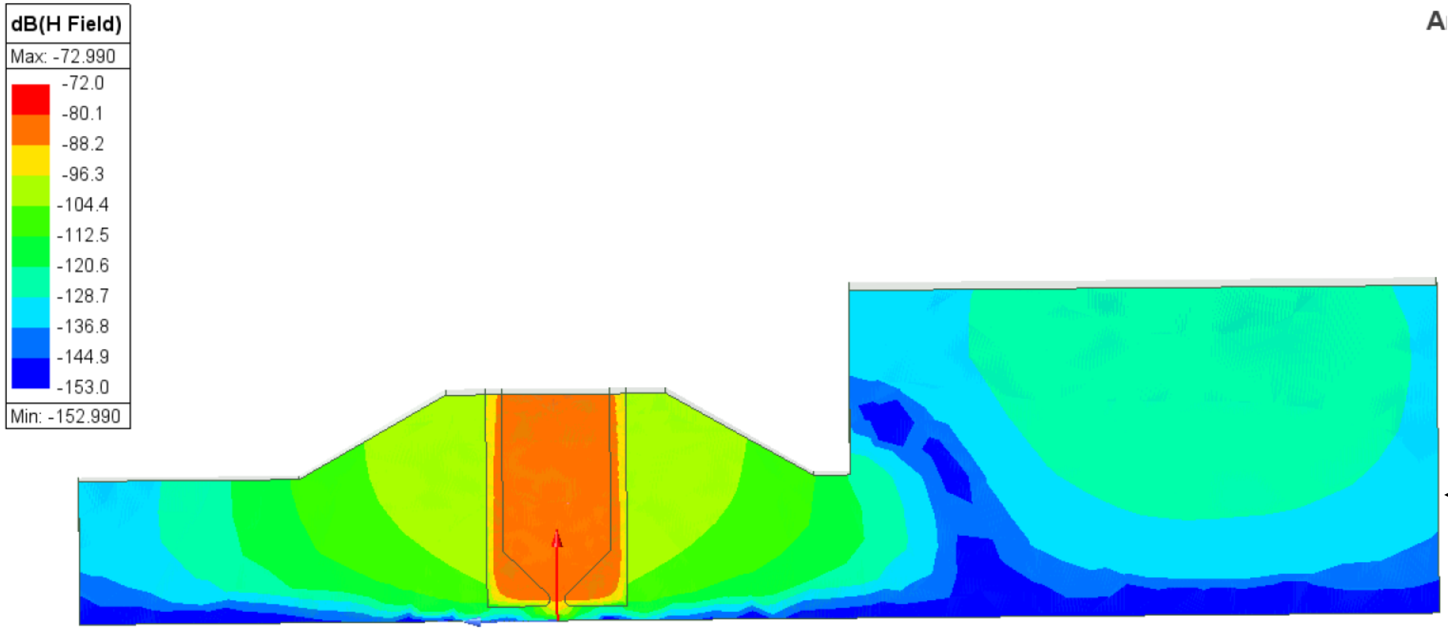
Cons:

- Mode launcher needed.

Laboratory output:
Rectangular waveguide

TE_{10}

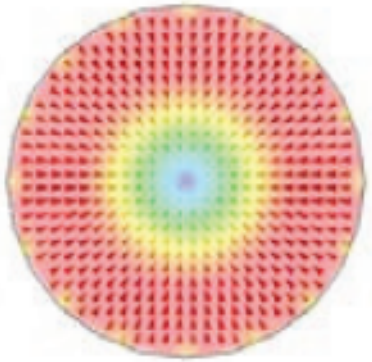




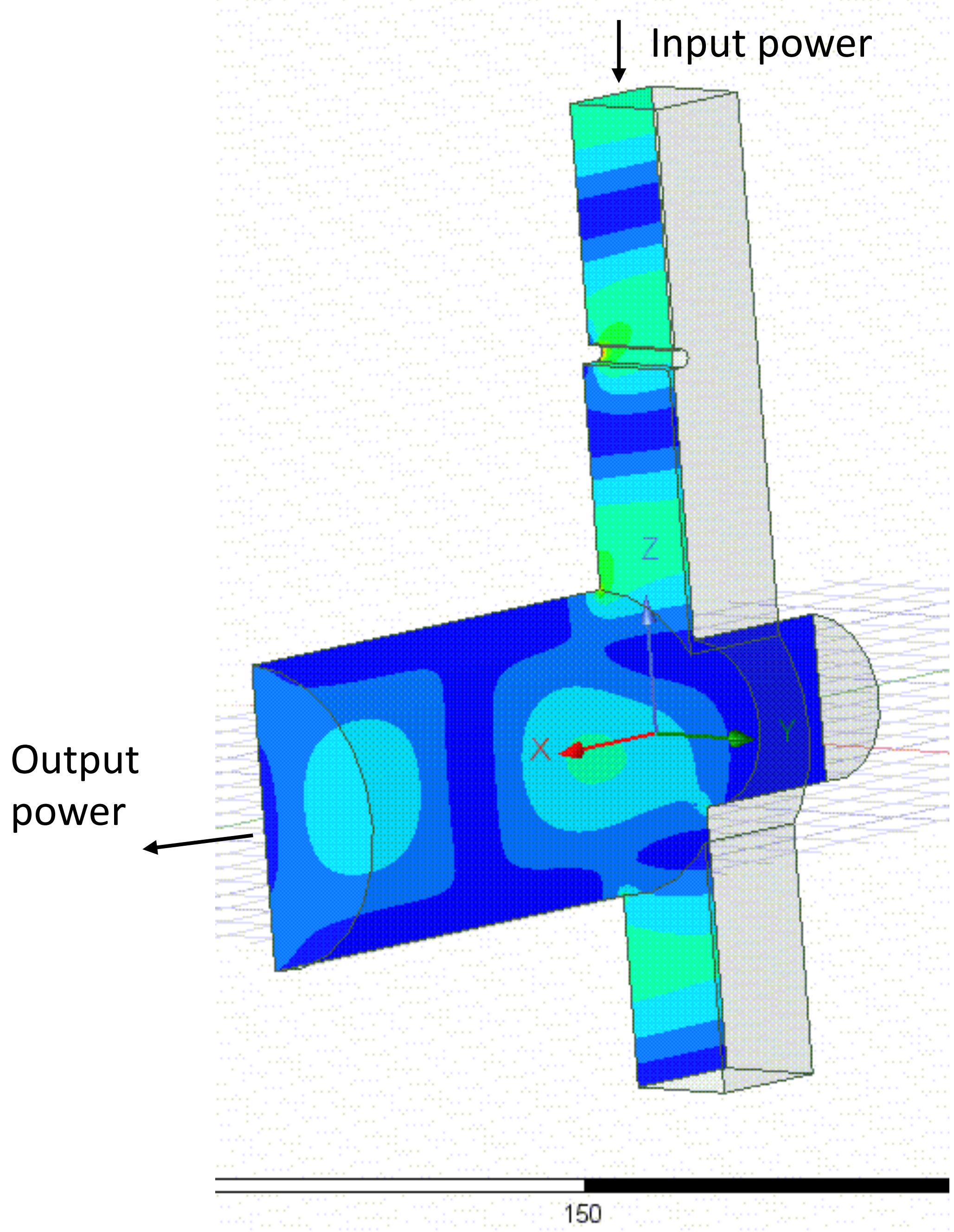
Input power

Cavity input:
Circular waveguide

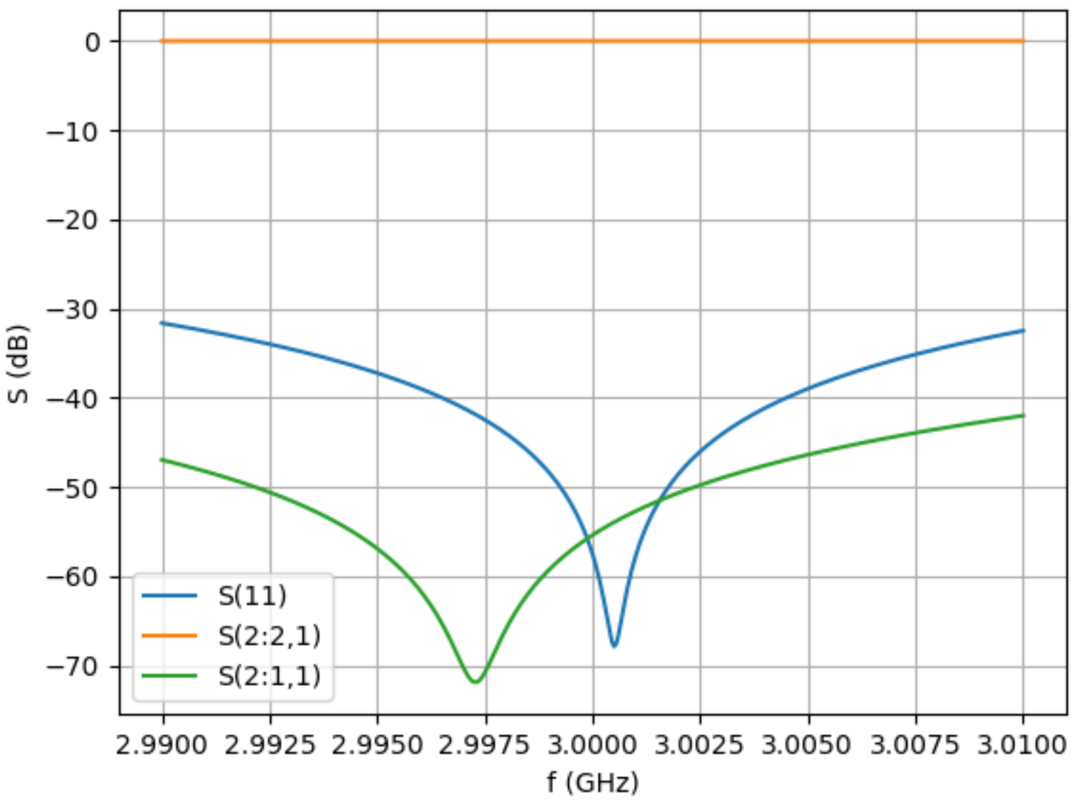
TM_{01}



Mode Launcher



- Minimize reflection: $S(1,1)$
- Minimize transmission to TE_{11}: $S(2:1,1)$
- Maximize transmission to TM_{01}: $S(2:2,1)$



Conclusions and next steps

- DAA results are promising but difficult to realize.
  - Paper published!!
- DDA prototype designed: good performance and easier fabrication

  Next steps:
  - Multipactor mitigation
  - Material testing and structure fabrication
  - Mode launcher fabrication

Conclusions and next

- DAA results are promising but difficult to
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New year resolution: Write PhD thesis

Contents

Back up

Non Linear effects

Field Emission

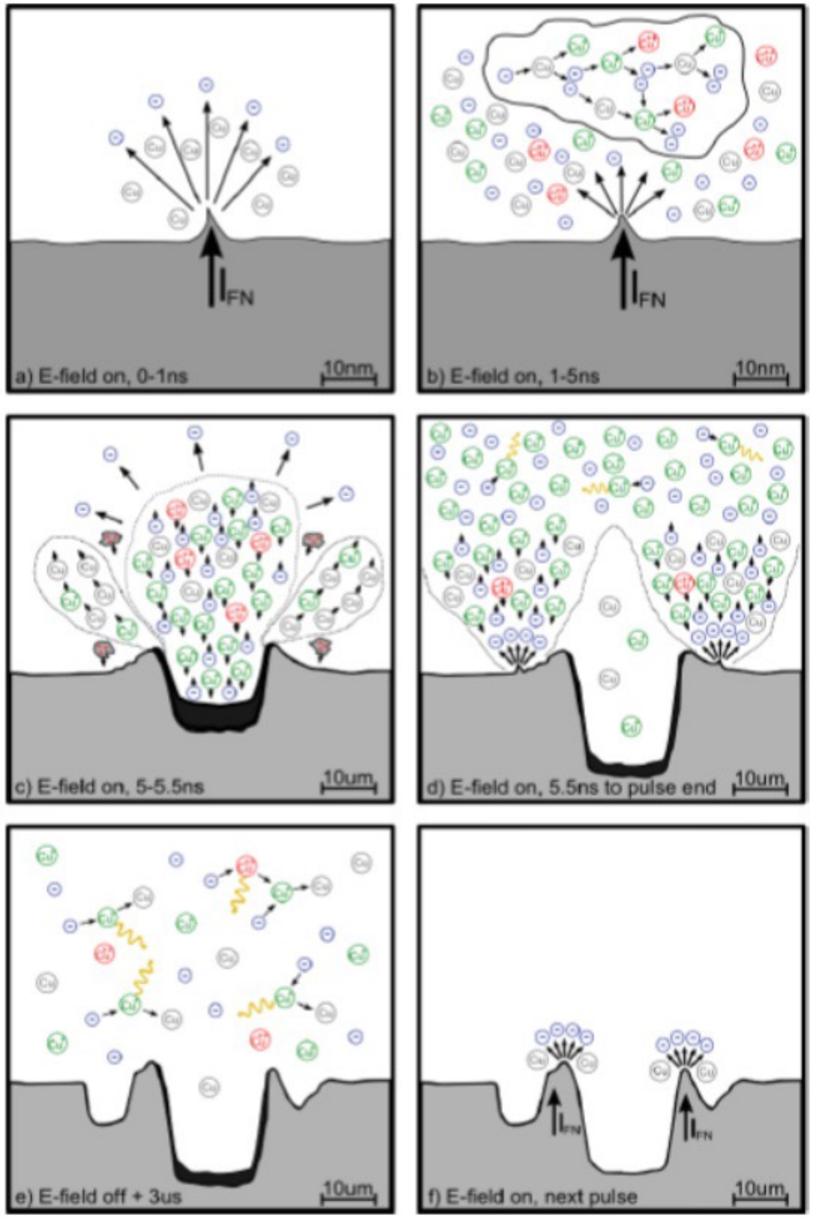
- Electrons are emitted by **tunneling** due to **High surface electric fields** following **Fowler-Nordheim equation**.

RF Breakdown

- Electron currents burn protrusions **evaporating ion atoms**.
- Ions and electron cloud interact with electromagnetic fields proudcing **reflection effects**.

Radiation

- Electrons interaction with walls translates into high radiation dose due to **bremsstrahlung photon emission**.

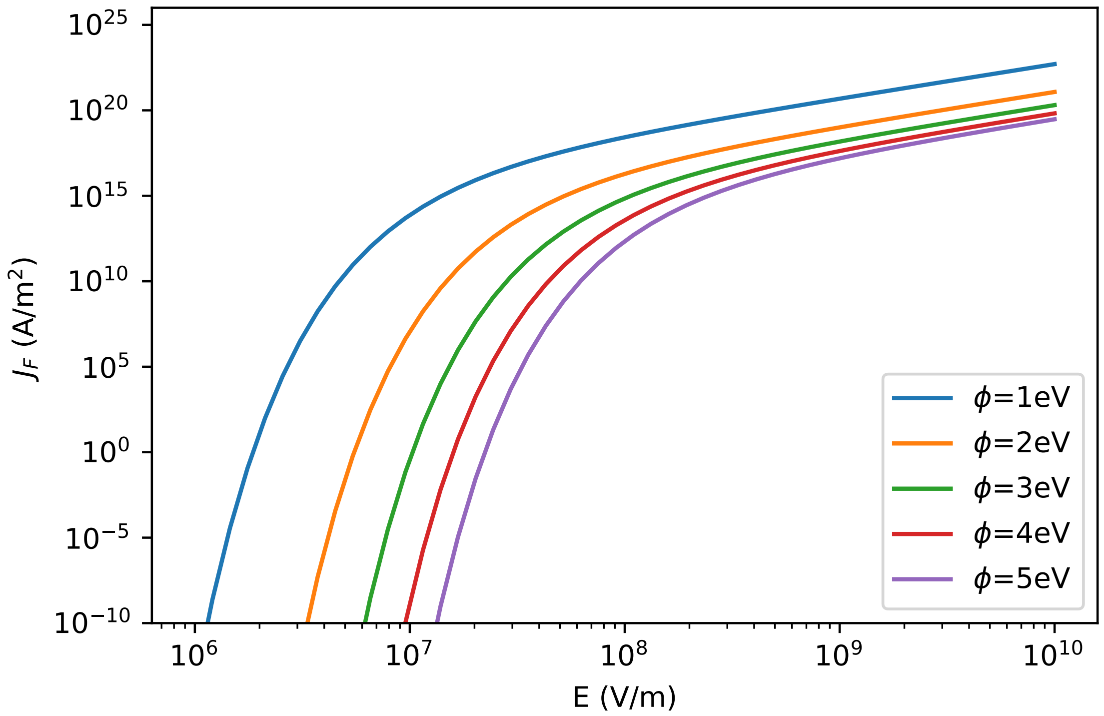


Field emission

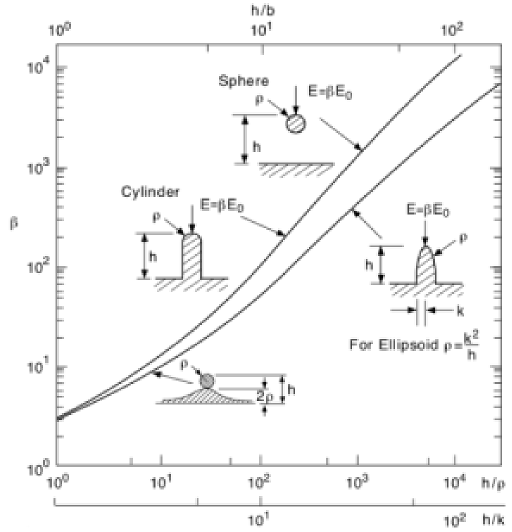
Fowler-Nordheim equation: Electrons are emitted through tunneling due to **high surface electric field**.

$$j_F = \frac{1.54 \times 10^{-6} \times 10^{4.52\phi^{-0.5}} E^2}{\phi} \exp\left[-\frac{6.53 \times 10^9 \phi^{1.5}}{E}\right] \mathrm{A/m^2}$$

- Work function ϕ: depends on material and geometry.



Surface roughness:
Local enhacement factor β for different geometries of idealized metallic microprotusions: $\mathbf{E_{id} = \beta \cdot E}$

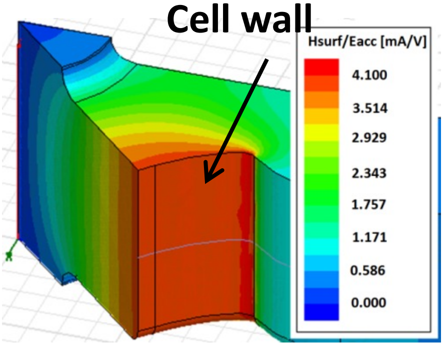


High-Gradient limitation

❑ Surface magnetic field

Pulsed surface heating produced material fatigue -> cracks.

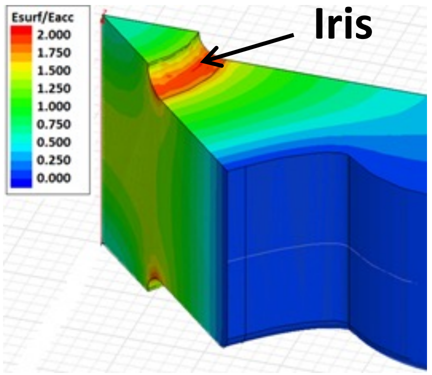
$$\Delta T \propto H_s^2 \sqrt{t_p},$$
$$\boldsymbol{\Delta T}_{\mathbf{max}} = \mathbf{50^oC}$$



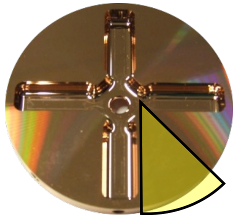
❑ Field emission due to surface electric field

- RF breakdowns; Electron emission initiates vacuum arcs. The exact mechanism is still unclear.
- Breakdown rate (BD/pulse.m) -> Operation efficiency;
- Local plasma triggered by field emission -> Erosion of surface;
- Dark current capture -> Efficiency reduction, detector backgrounds.

$$E_s = 200\frac{MV}{m}$$



[W. Wuensch et al. Phys. Rev. ST Accel. Beams **12**, 102001 (2009)]



❑ RF power flow

RF power flow and/or iris aperture has a strong impact on achievable E_{acc} and on surface erosion.

Modified Poynting vector:

$$S_c = |Re(\vec{S})| + \frac{1}{6}|Im(\vec{S})|$$
$$5\ MW/mm^2$$

RF breakdown criteria

- Kilpatrick's Criterion.

$$f = 1.64[MHz](E_s[MV/m])^2 \exp\left(\frac{-8.5}{E_s[MV/m]}\right)$$

  - Underestimation

- P/C

$$P = \frac{v_g a}{\omega}\frac{Q}{R}E_{acc}^2$$

C: Circumference of iris

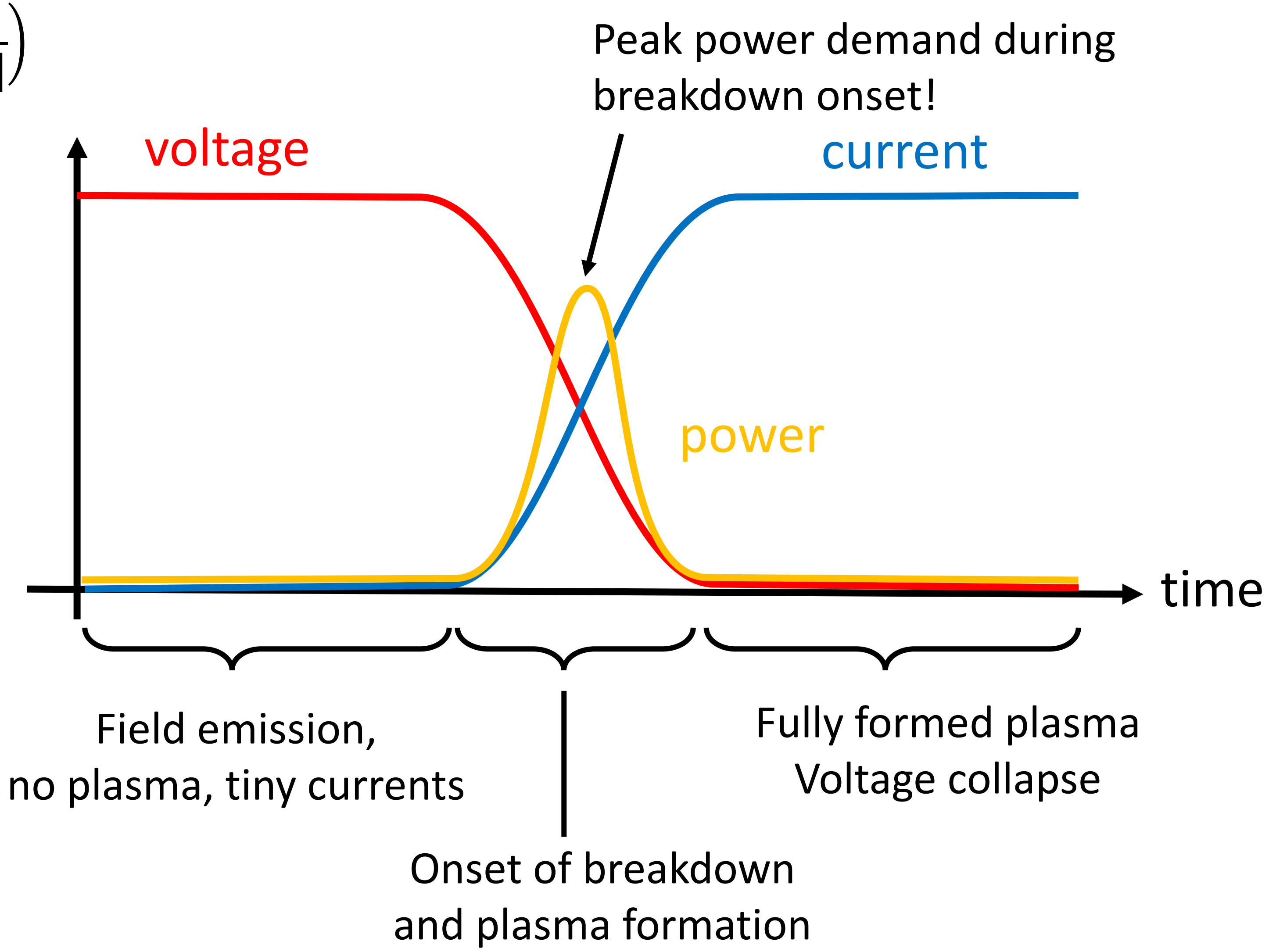
  - Only valid for travelling wave

- Modified Poynting Vector: $S_c < 5$ MW/mm²

$$S_c = Re(\boldsymbol{S}) + \frac{1}{6}Im(\boldsymbol{S})$$

  - Exceptions found (Crab cavity)

- Local Power Coupling

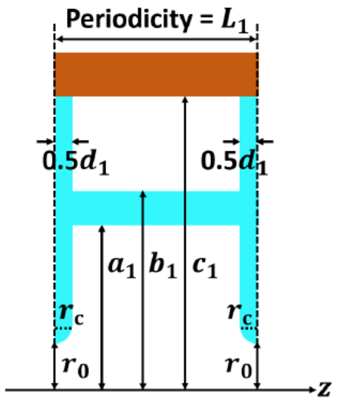


Jan Paszkiewicz, CERN. HG2021: https://indico.fnal.gov/event/22025/contributions/209953/

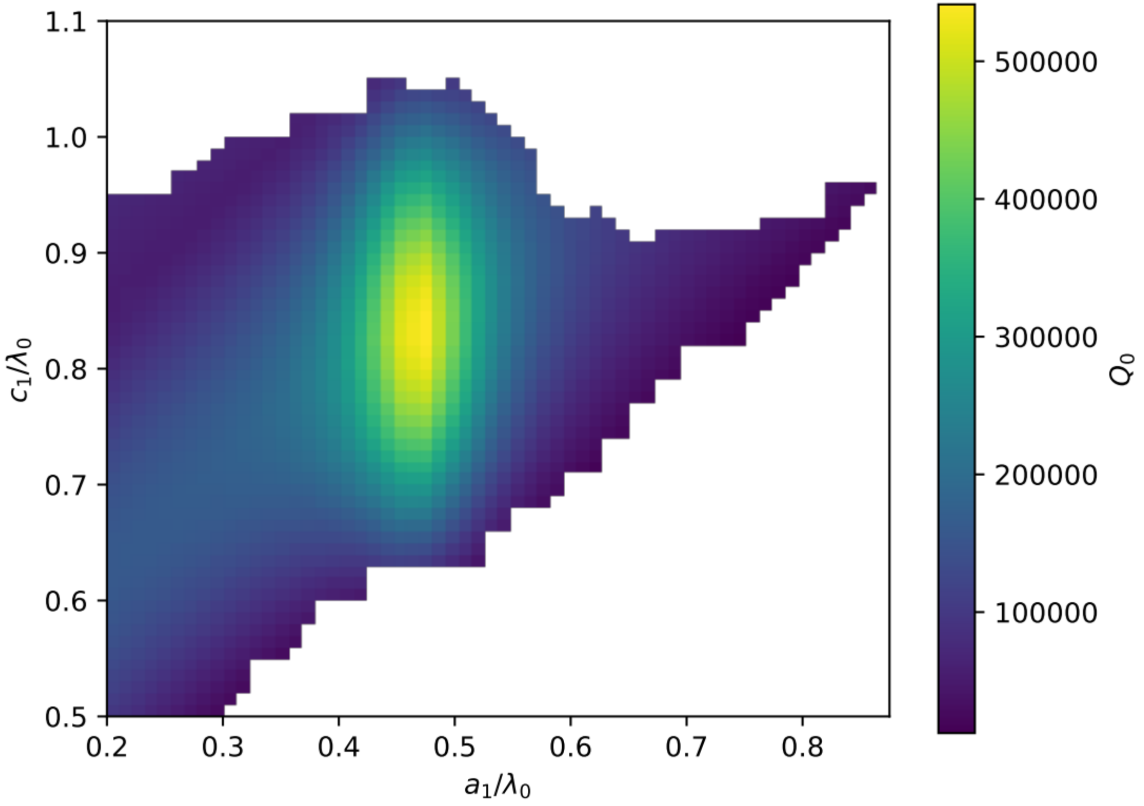
DAA cavity single cell design

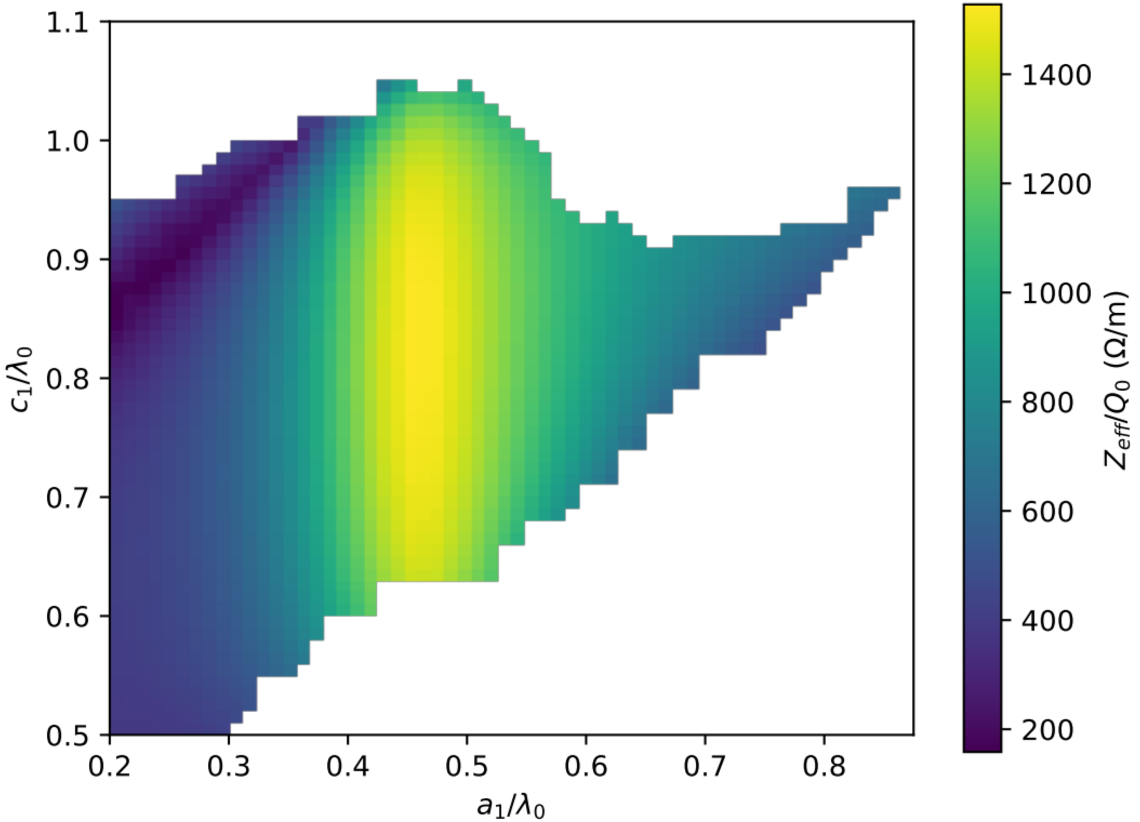
Resonant frequency for the mode depends on the combination of a_1, b_1, c_1:

- ❑ Scan for a_1, c_1 and we look for the value of b_1 that makes $f = (3000 \pm 2)$ MHz.
- ❑ Look for the values of a_1, b_1, c_1 that maximizes Z_{eff}, Q_0

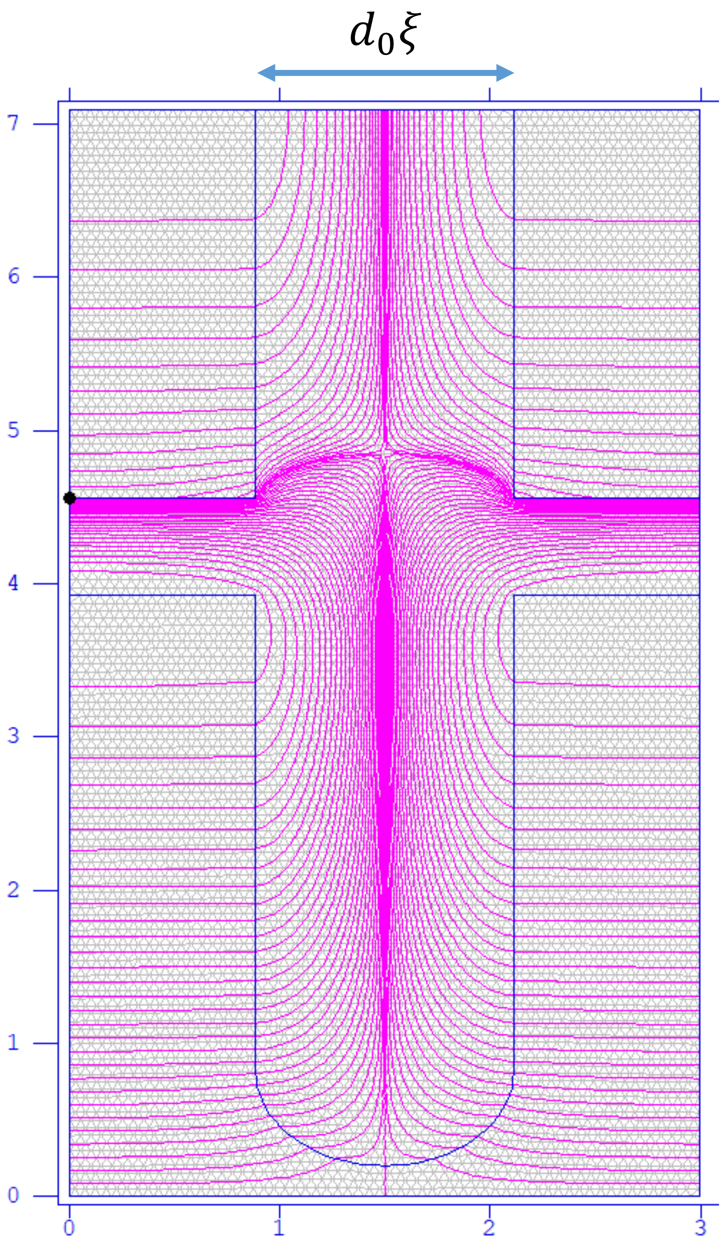


Example for ideal material: $\epsilon_r = 16.66$, $\tan\delta = 0$ and $\beta = 0.6$





DAA cavity single cell iris optimization



$\epsilon_r = 16.66, \beta = 0.6$

Scan in iris thickness: $d_0 = \lambda_0/(4\sqrt{\epsilon_r})$

Iris thickness = $d_0\xi$

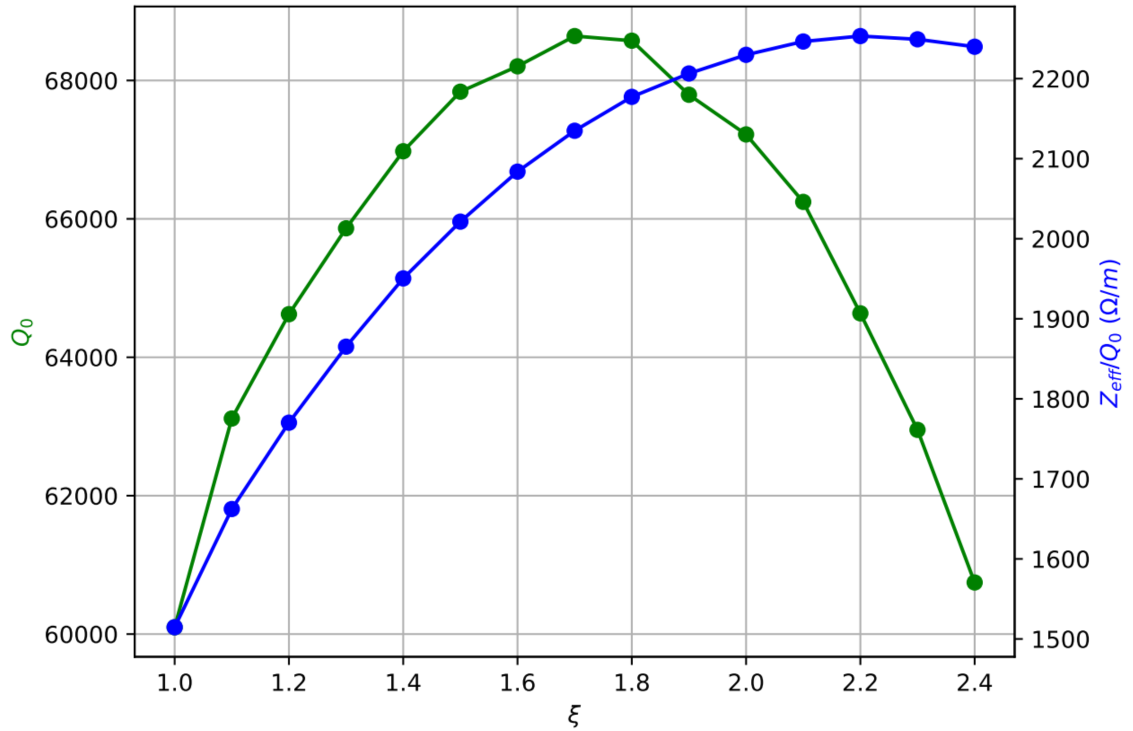


TABLE I
LIST OF DIELECTRICS STUDIED IN THE OPTIMIZATION

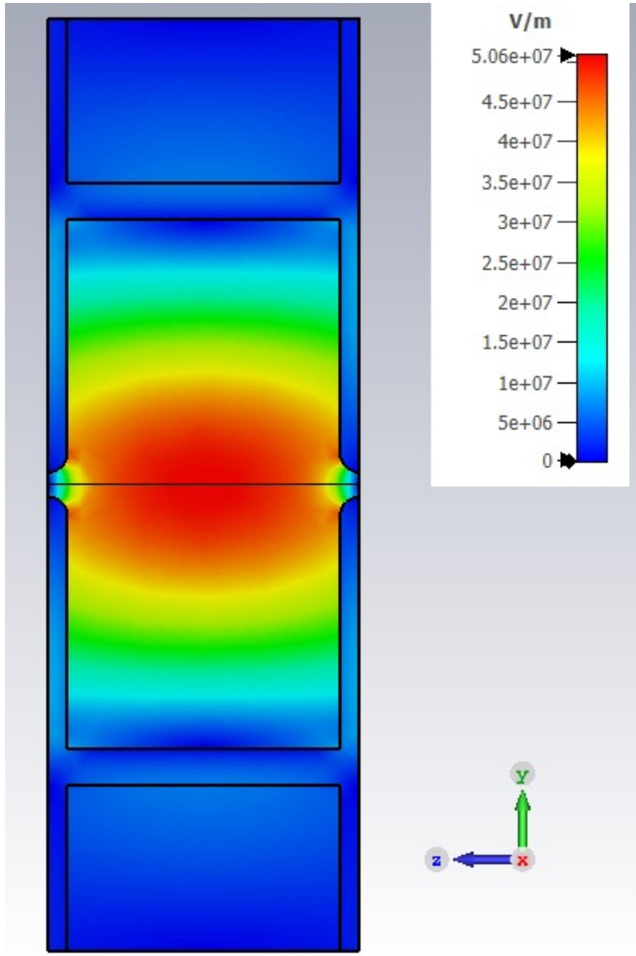
Material	Acronym	ε_r	$\tan\delta$
CVD Diamond	Diamond	5.7	10^{-4}
MgO	D9	9.64	6×10^{-6}
$MgTiO_3$	D16	16.66	3.43×10^{-5}
$BaTiO_x$	D50	50.14	8×10^{-5}

High Power Test Results of X-Band Dielectric Disk Accelerating Structures. Ben Freemire

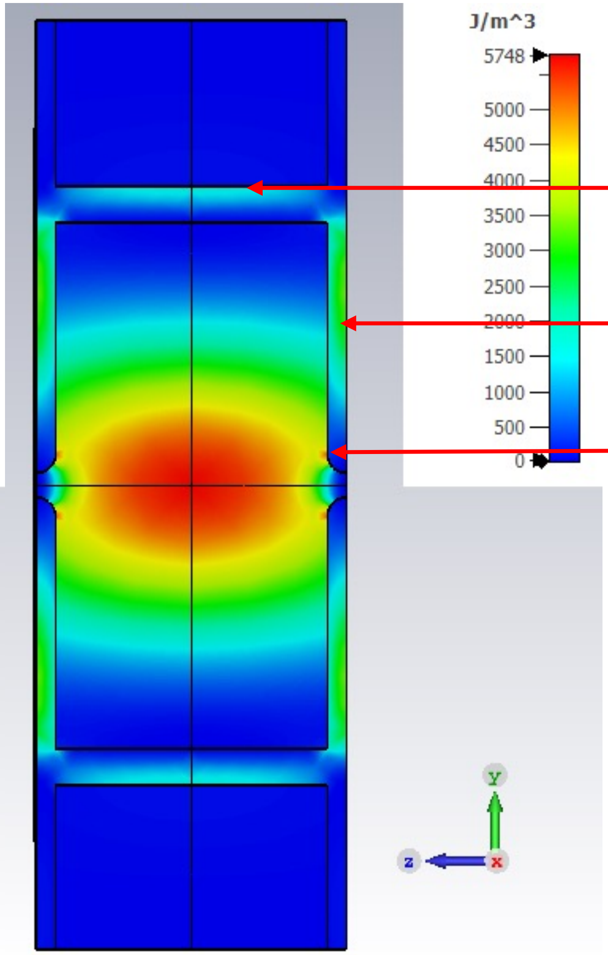
$\beta = \{0.4, 0.5, \ldots, 1\}$

DAA cavity single cell solution

Electric field



Electric Energy



$D = \epsilon E$

$E_{\parallel,1} = E_{\parallel,2}$

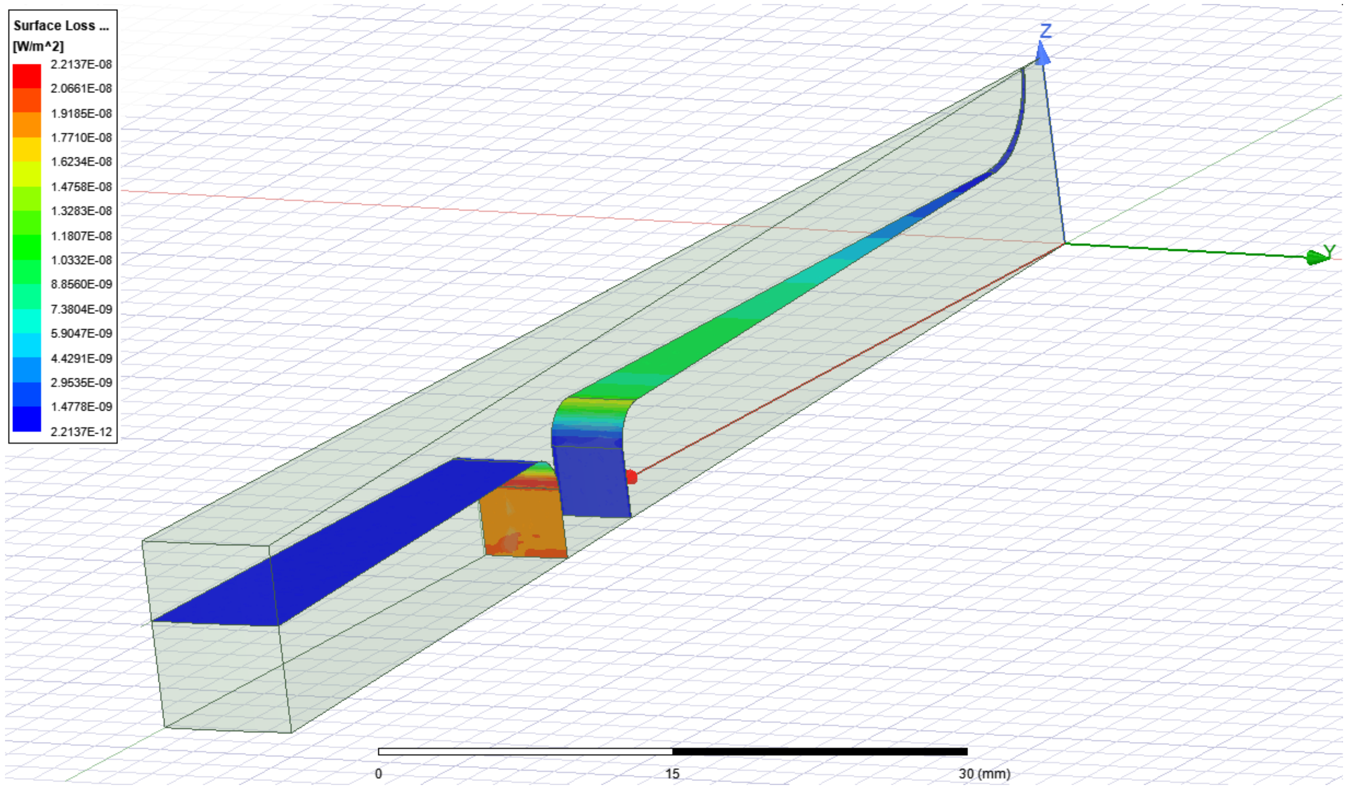
$D_{\perp,1} = D_{\perp,2}$

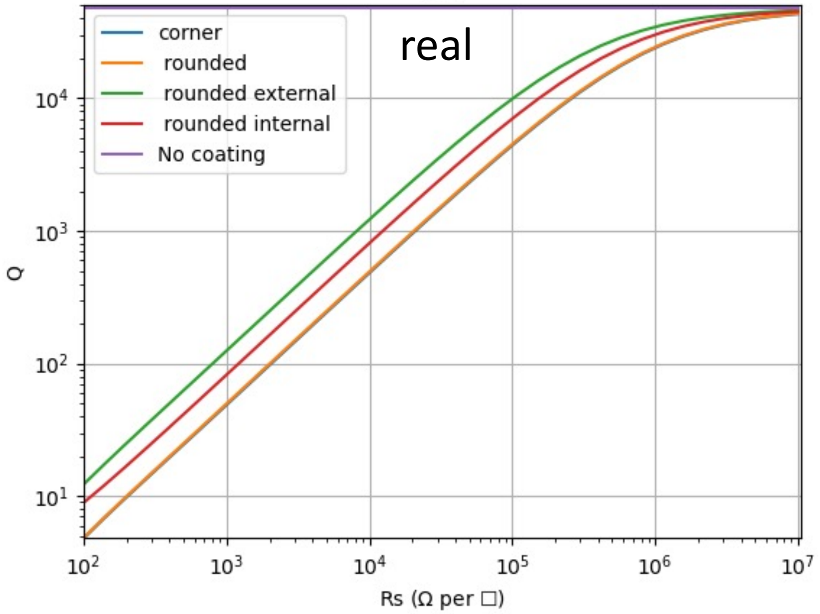
1st: Parallel boundary
- E is constant
- High D inside dielectric

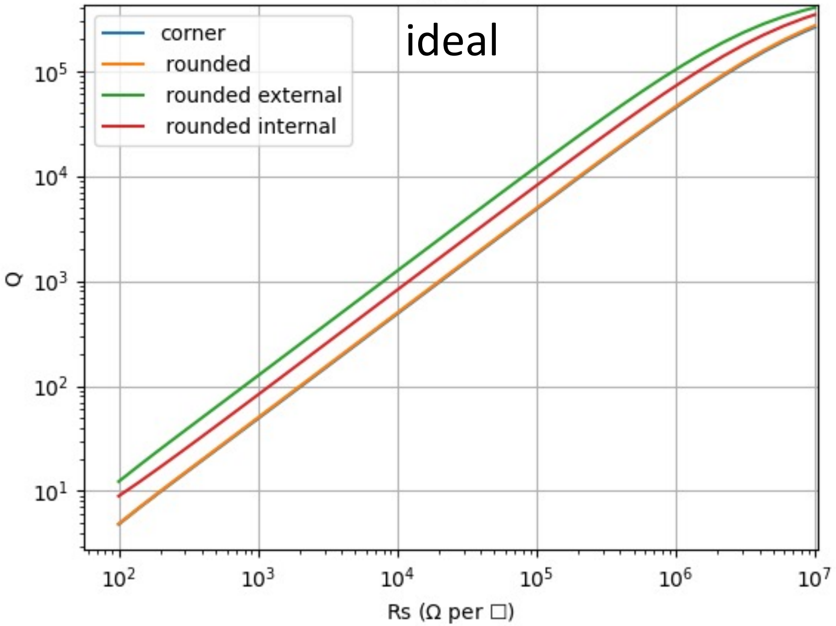
2nd : D is conserved along the dielectric

3rd : Perpendicular boundary
- D is constant
- High E in vacuum

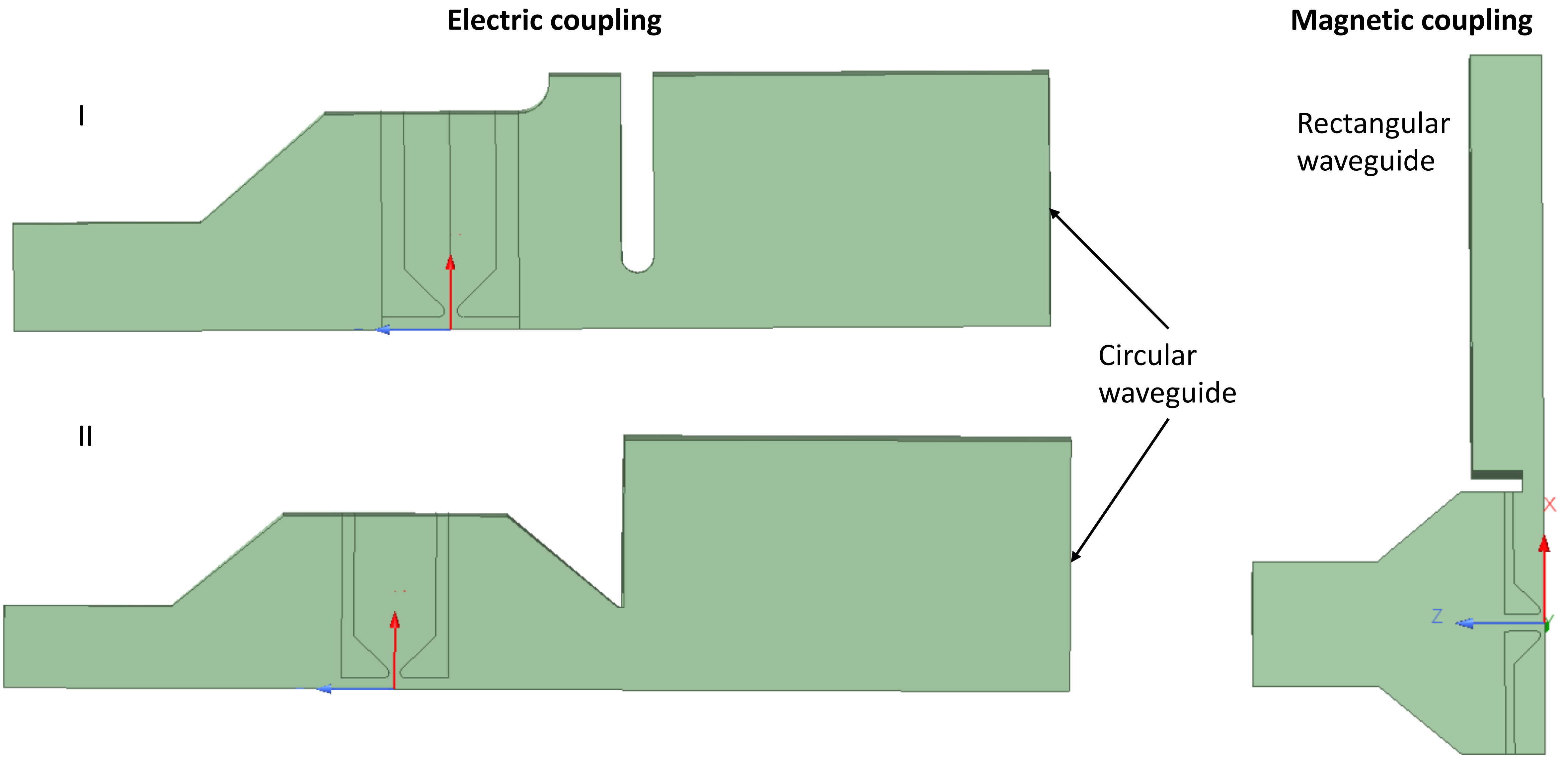
Coating losses







DDA prototype



Dielectric Disk Loaded Accelerating (DDA) Cavity

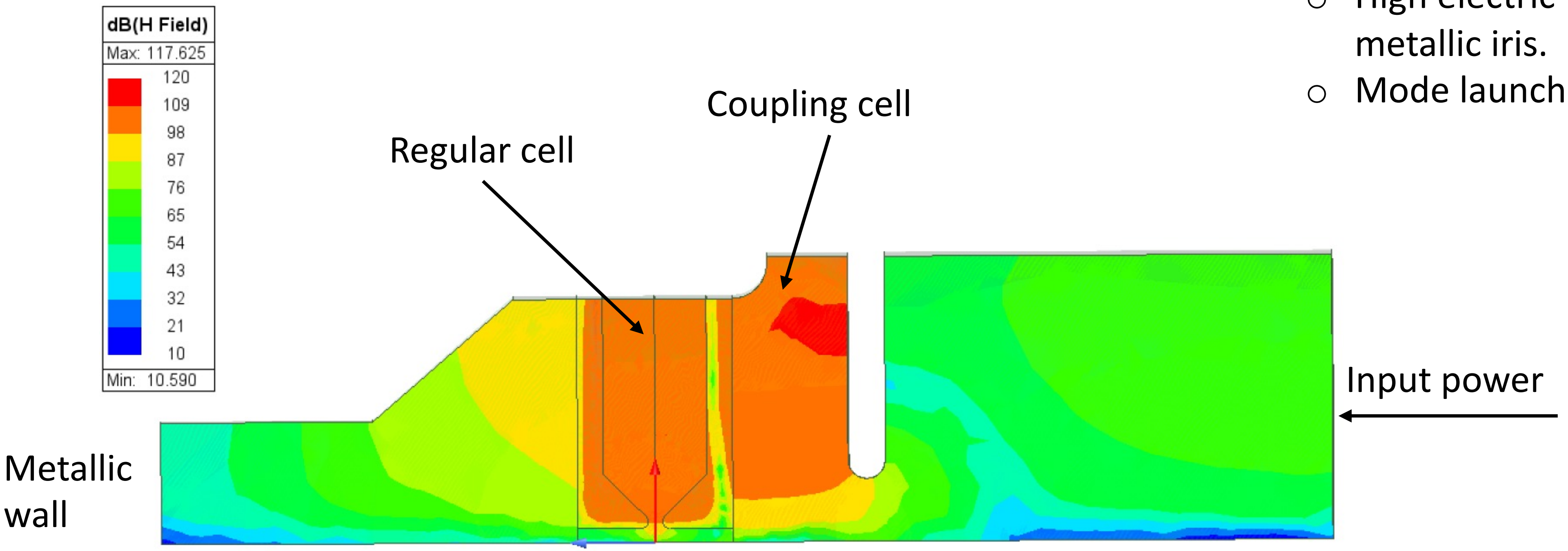
Pros:

- Coupling can be adjusted easily
- Low coupling to other modes

Cons:

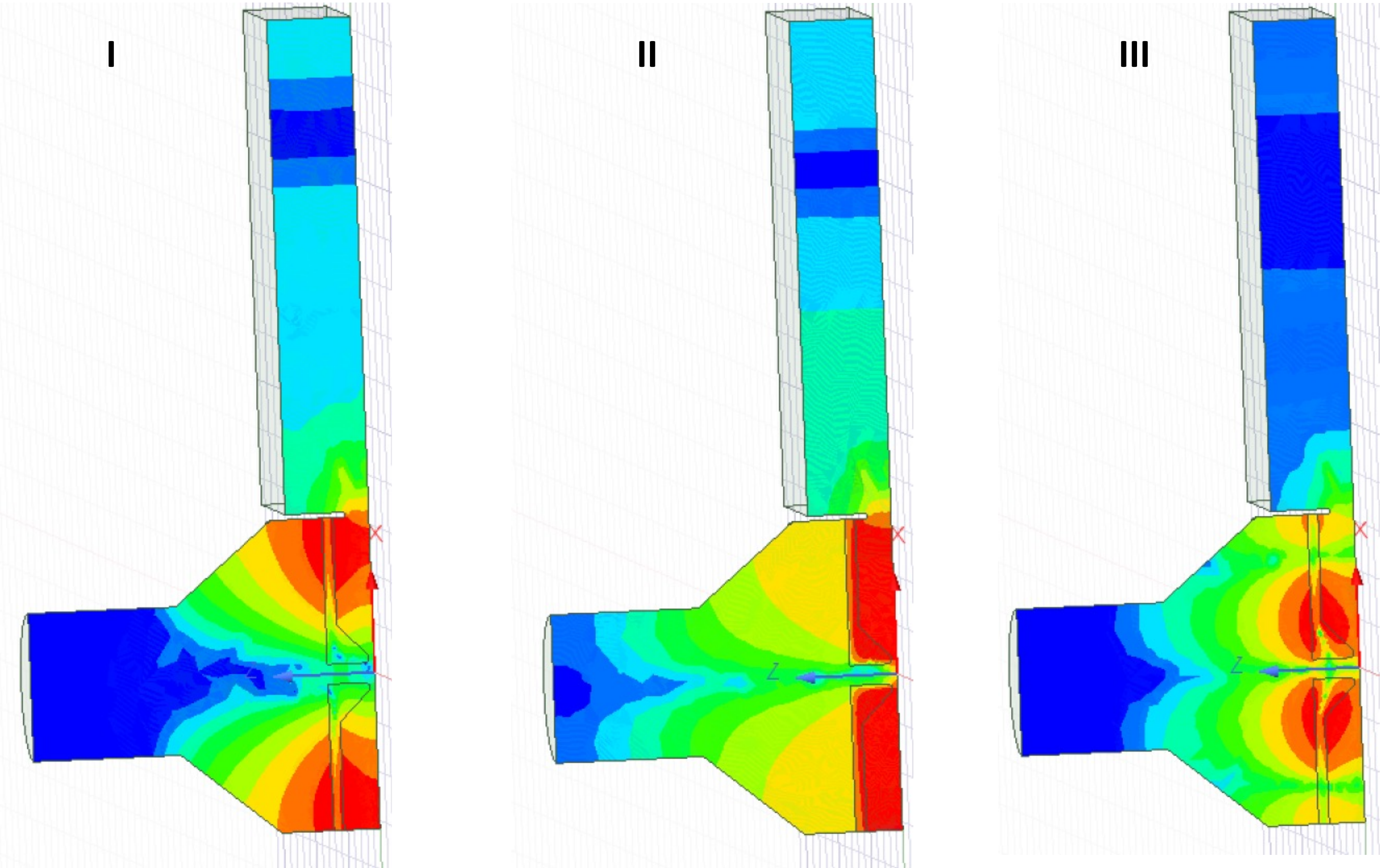
- High magnetic field in coupling cavity: lower Q
- High electric field on coupling metallic iris.
- Mode launcher needed.

Electric coupling I



Dielectric Disk Loaded Accelerating (DDA) Cavity

Magnetic coupling



Pros:

- Low magnetic field in coupling cavity:
- Low electric field on coupling metallic iris.
- No need for mode launcher.

Cons:

- Low coupling to mode
- Similar coupling to other modes

Dielectric Disk Loaded Accelerating (DDA) Cavity

$\mathrm{D50}, \beta = 0.4, \epsilon_\mathrm{r} = 50.14, \tan\delta = 8\times10^{-5}\ \xi = 1.5, gap = 0.2\ cm, \alpha = 45^o, r = 0.1\ cm$

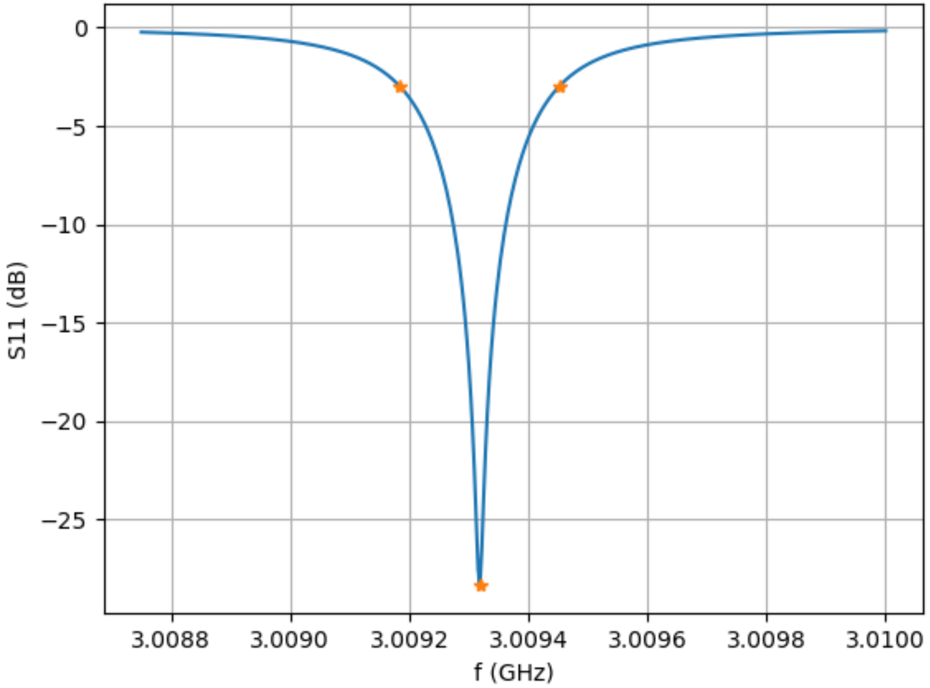
Electric coupling II

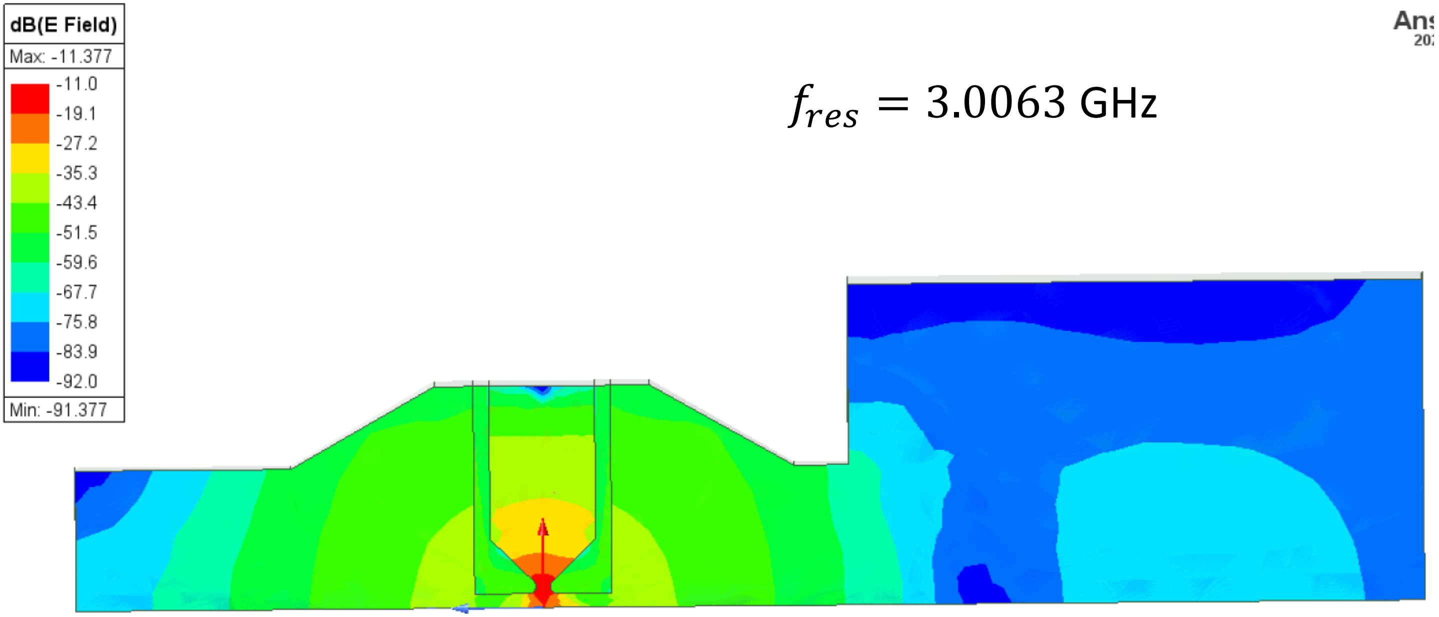
Eigenmode solver

Parameter	value
Q_0 (regular cell)	21503
Q_{ext}	22070
Q_l	11380
Q_0 (total)	23494

$f_{res} = 3.0063$ GHz

$$Q_l = \frac{f_{res}}{BW} = 11197$$





Input power