Beam - RF Interactions in Twisted Cavities

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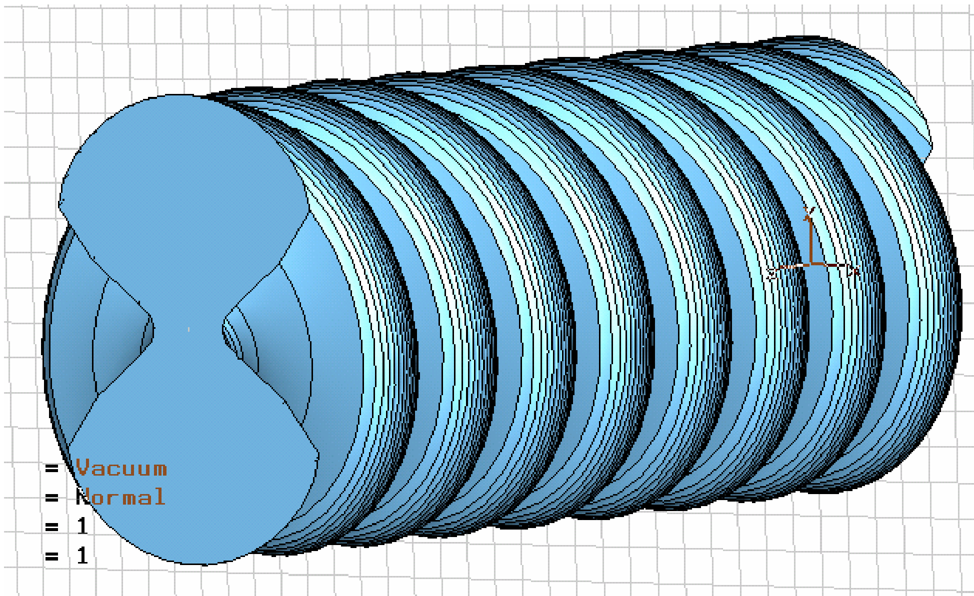
Motivation

1) **Twisted structures are promising candidates for accelerating cavities at velocities $\beta \leq 1$.**
2) **Maxwell's equations were initially solved in twisted geometries using perturbation methods at small twist rates.**
3) **They are now accurately solved for arbitrary twist rates by 2D and 3D finite difference methods.**
4) **Bench models have been constructed and modes compared with numerical solutions (M. Awida, Y. Kang, et al. This conference). Prototype structures are being fabricated.**
5) **We have initiated time-dependent 3D particle tracking studies to support the development of twisted accelerating cavities.**

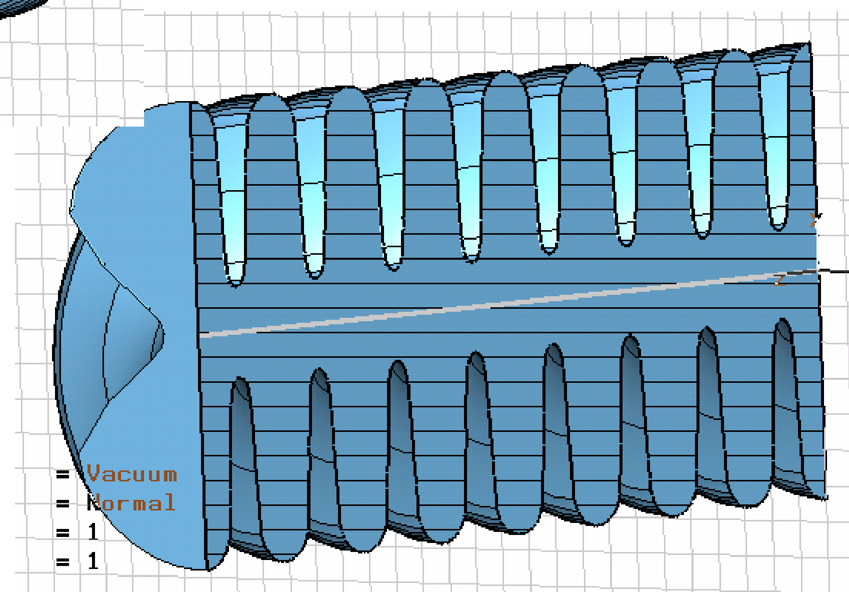
Twisted Waveguide with Dumbbell Cross Section



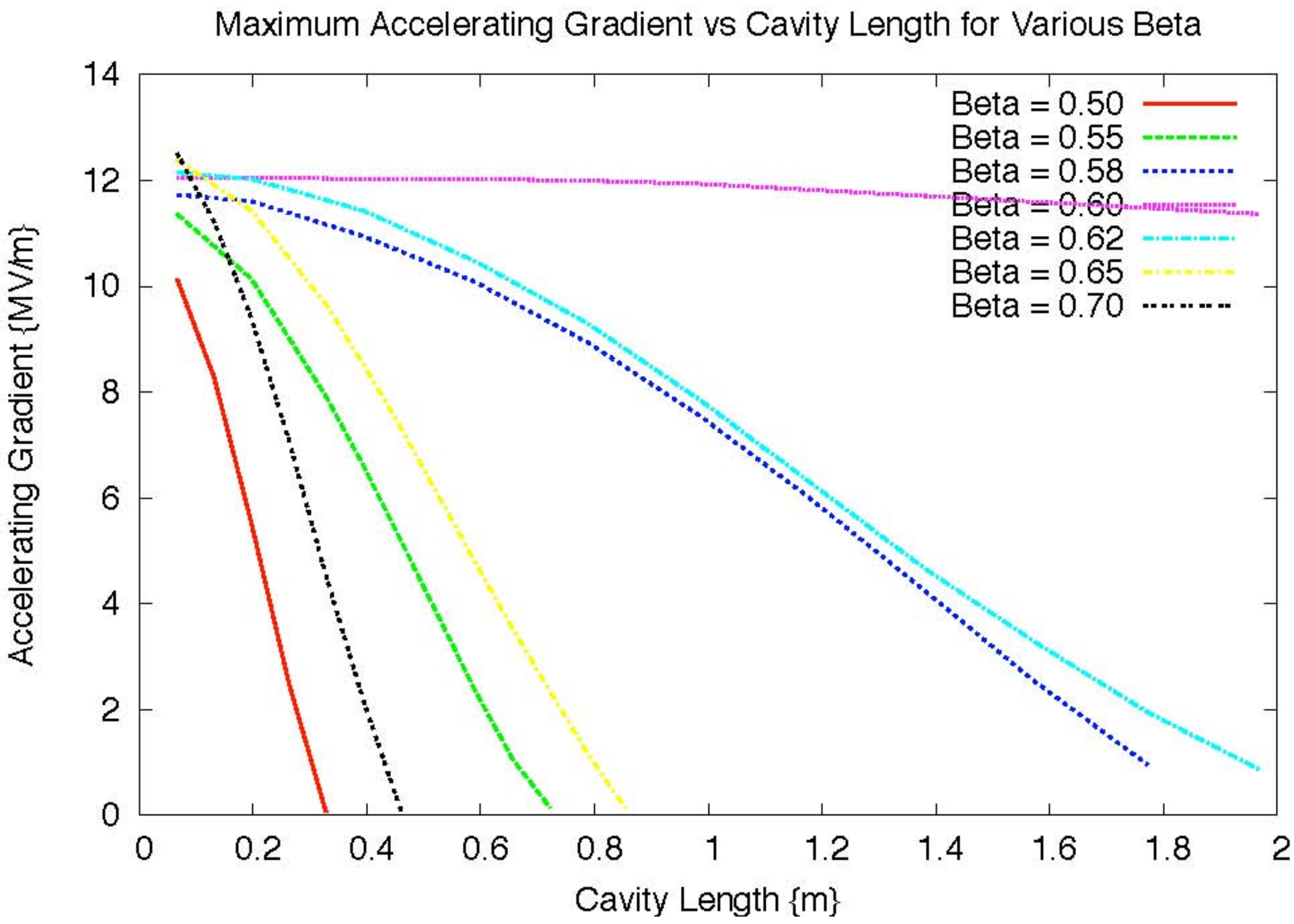
Tracking assumptions:

* ORBIT code time-dependent Lorentz tracker
* Ignore collective effects
* Use time-dependent 3D fields from numerical cavity solution
* Ignore end effects
* Track protons

ν=2.74 GHz
L_{tw}=6.6 cm
β=0.6
Set E_{max}=24 MV/m



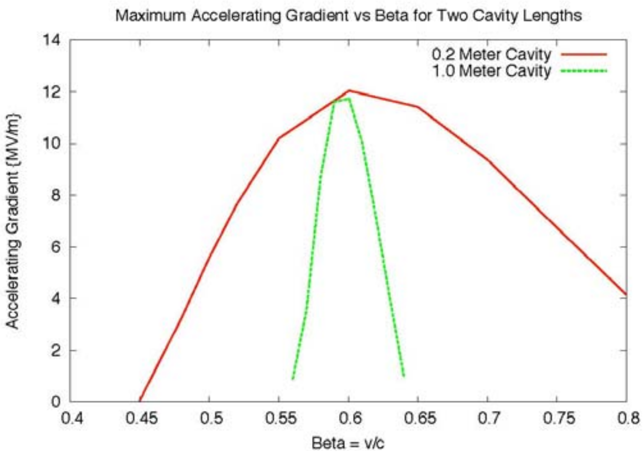
On-axis tracking: Accelerating Gradient Decreases with Increasing Number of Field Periods

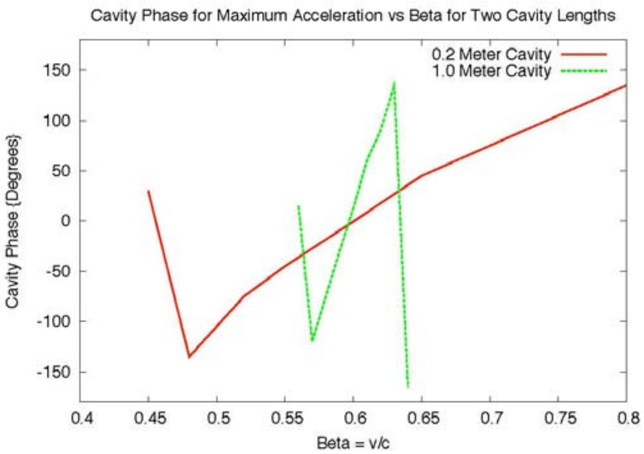


- * 1 m ≈ 30 FP
- * Loss due to phase slip
- * Cavity lengths varied by replicating periodic solutions

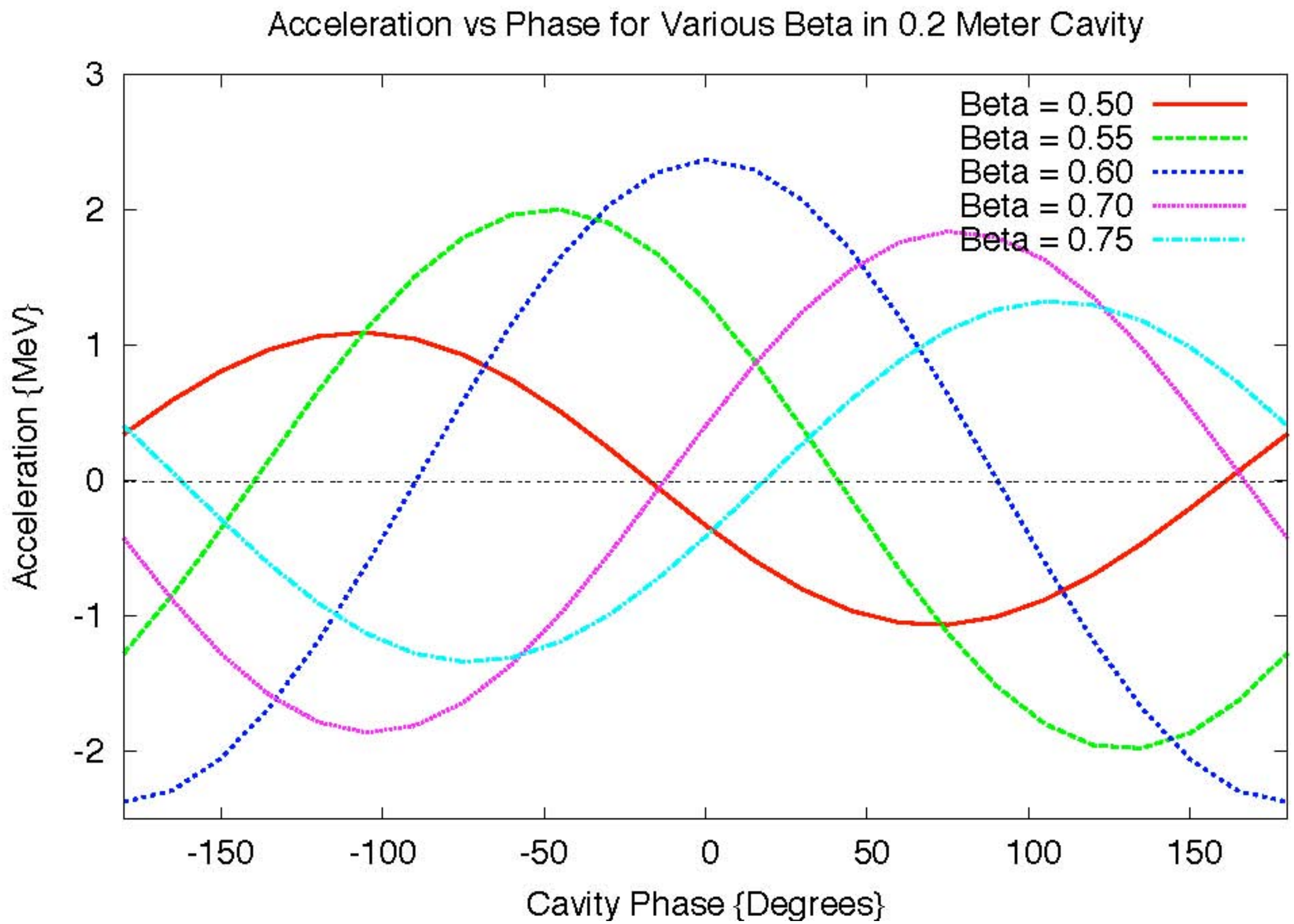
Accelerating Gradient vs Velocity β

- **For a 1 meter cavity (30 field periods), 1/3 the acceleration is lost with β deviations of ±0.02.**
- **For an 0.2 meter cavity (6 field periods), protons having 0.52<β<0.72 get at least 2/3 the accelerating gradient.**
- **The relative phase between the protons and the cavity for maximum acceleration is a strong function of the particle velocity.**



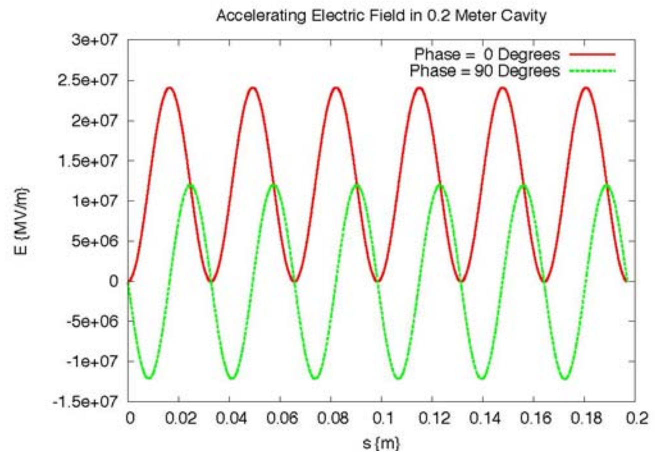


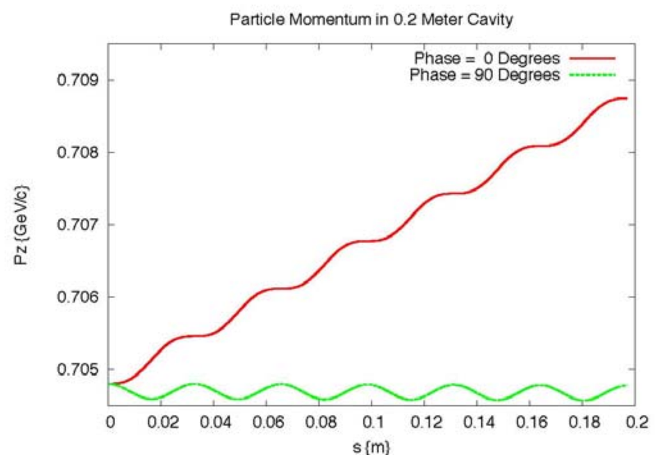
Acceleration vs Phase for Different Velocities



Accelerating Fields and Particle Momenta for Different Phases

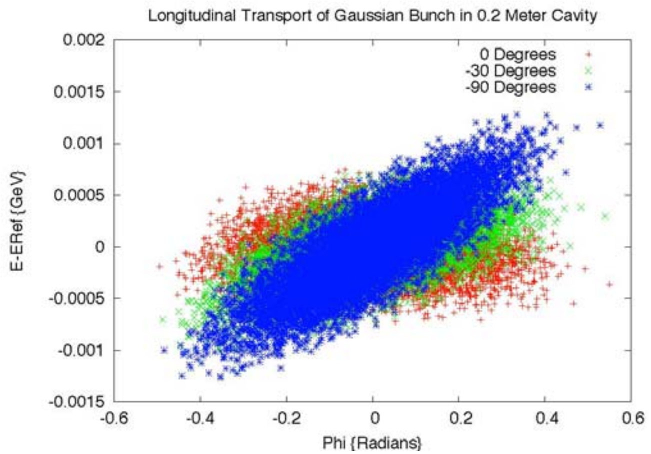
- **Maximum acceleration decreases for velocities away from cavity β.**
- **Phase for maximum acceleration is a strong function of velocity.**
- **Depending on relative phase, cavity can accelerate or decelerate.**

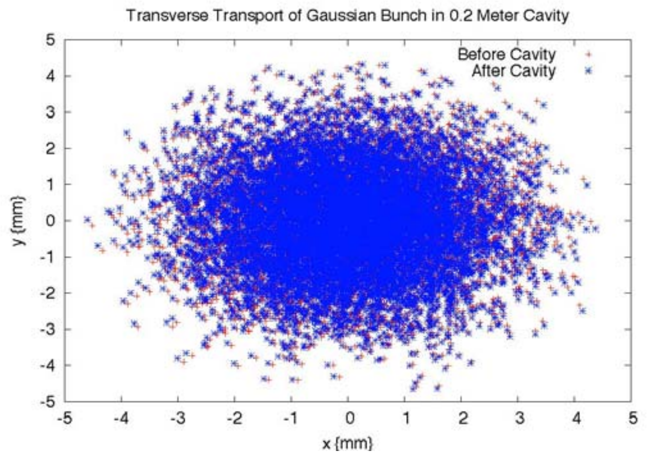




Acceleration of Bunches

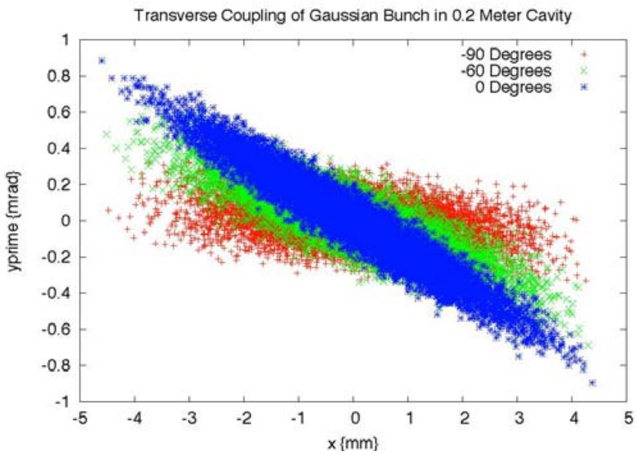
- **Accelerate 6D Gaussian bunch with:**
  - **$\sigma_x=\sigma_y=1.4$ mm**
  - **$\sigma_{x'}=\sigma_{y'}=0.14$ mradians**
  - **$\sigma_\varphi=9$ degrees**
  - **$\sigma_E=0.23$ MeV**
- **Study bunch behavior with respect to reference particle.**
- **Longitudinal focusing depends on relative phase.**
  - **At -30 degrees, particles get ~86% of maximum acceleration.**
- **For transverse motion:**
  - **Coordinates change little over length of cavity, but appear to rotate clockwise and expand slightly in x.**
  - **More can be learned by examining transverse momenta.**

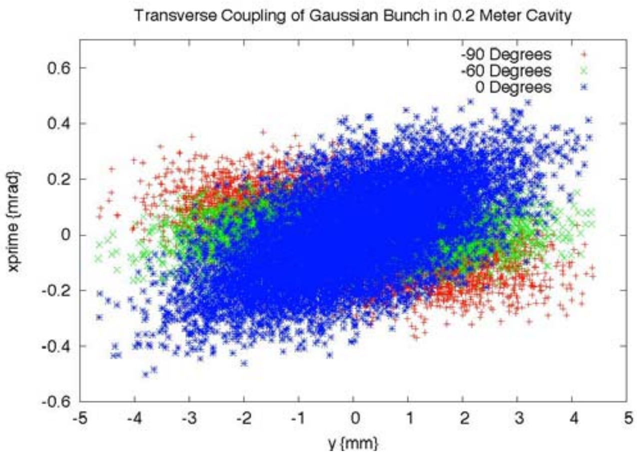




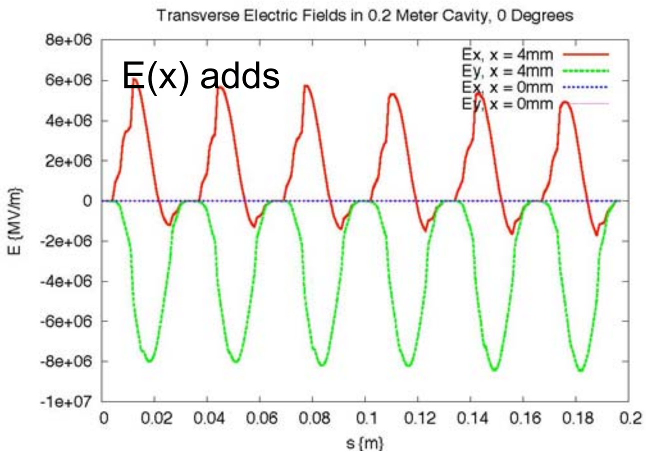
Effect of Transverse Fields

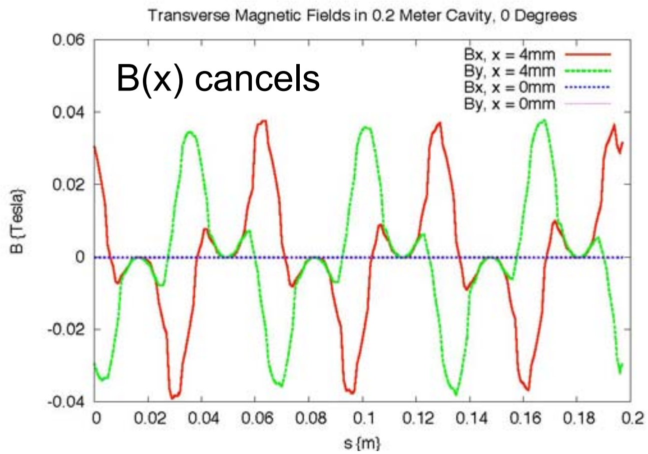
- **The transverse fields couple the motion in the horizontal and vertical planes.**
- **The coupling strength is quite linear in the coordinate sizes.**
- **The effect is more than twice as pronounced in the horizontal plane than in the vertical plane.**
- **Although the effect weakens with increasing separation of particle phase and maximum accelerating phase, it is present at likely phases for acceleration.**
- **The observed coupling is independent of velocity over the range of accelerated particles.**

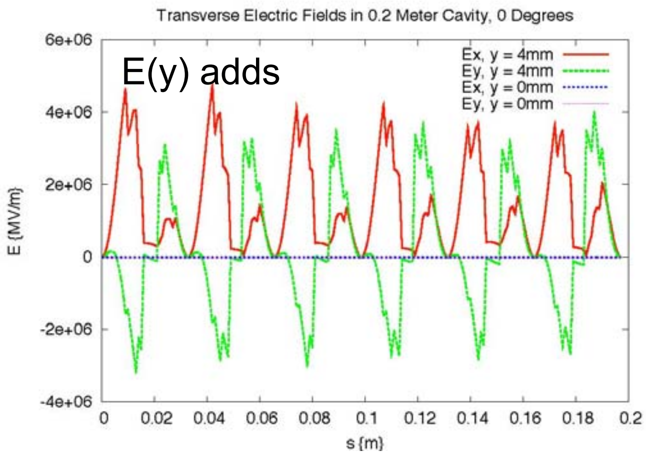


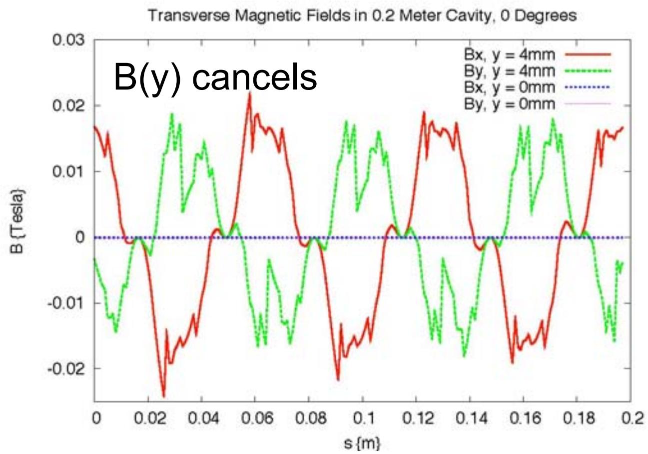


Source of the Coupling: Transverse E



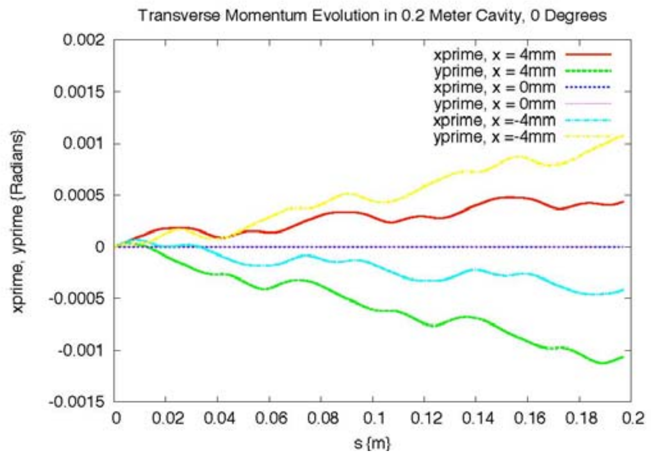


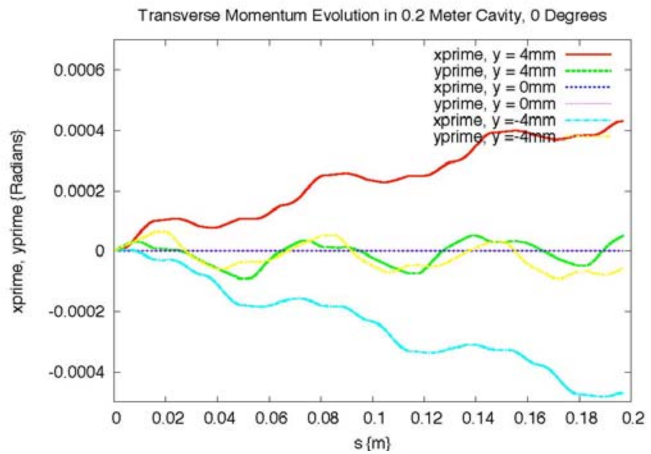




Transverse Momentum Change

- **Horizontally displaced protons get vertical kicks.**
- **Vertically displaced protons get horizontal kicks.**
- **The kicks lead to clockwise rotation.**
- **The beam is defocused horizontally, but not vertically.**
- **Beam focusing issues can be addressed by including quadrupole magnets.**
- **For controlling coupling, skew quadrupoles are required.**





Next Steps

- These results are just an initial exercise in tracking in twisted RF cavities. We learned that:
  - Twisted cavities can effectively accelerate protons over an acceptable range of velocities provided that the cavities have a limited number (~6) field periods.
  - Longitudinal dynamics (acceleration and focusing) of bunches appears to behave conventionally.
  - Transverse dynamics shows coupling between the x and y planes off axis due to transverse electric fields.
- We need to factor these results in to the iteration of the cavity design.
- We need to study other cavities: different β, different cross sections, $\beta=1$ for electrons.
- We need to generalize the model:
  - Consider end field effects.
  - Consider space charge and beam loading.
  - Incorporate into lattice design with tracking.