Wake Fest 07

Where all of your wake questions will be answered

Well…at least they will be acknowledged

Anyway… the talks will be posted

Chris Adolphsen Dec 11, 2007

Coupler Short-Range Wakefield Kicks

Karl Bane and Igor Zagorodnov

Wake Fest 07, 11 December 2007

Thanks to M. Dohlus; and to Z. Li, and other participants at
C. Adolphsen's Thursday morning RF meeting at SLAC

In the ILC linac rf cavities, the fundamental mode (fm) and higher mode (hm) couplers break the structure symmetry => transverse wakefields are excited even on the cavity axis

Outline:

- Numerical calculation of the transverse wakes of the three couplers (of a cavity) in a beam pipe

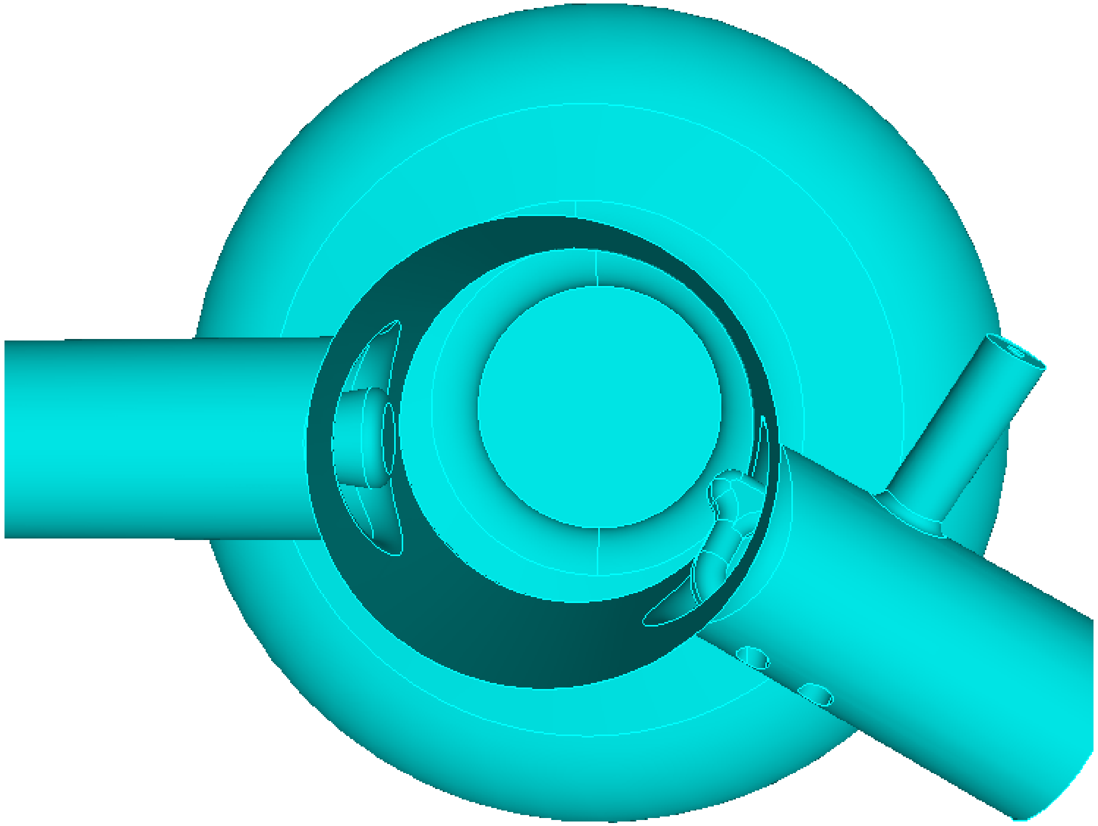
- Analytical estimates (for confirmation)

- Asymptotic result after several cavities (with couplers)

- Estimate of effect on ILC beam

- Conclusions

Detailed View of FM and HM Couplers



- Note complicated post-in-cavity geometry

(Zenghai Li)

2. Analytical Approximation

• High frequency impedance of an abrupt transition in a beam pipe, e.g. an iris or the ILC couplers can be obtained using the *Optical Approximation*

• Result depends only on cross-sectional shape of object (and the beam pipe shape)

• This is a lower order effect than the *Diffraction Model* (high frequency impedance of a cavity with beam pipes) => for the ILC couplers, the cavities around the posts can be ignored

Refs:

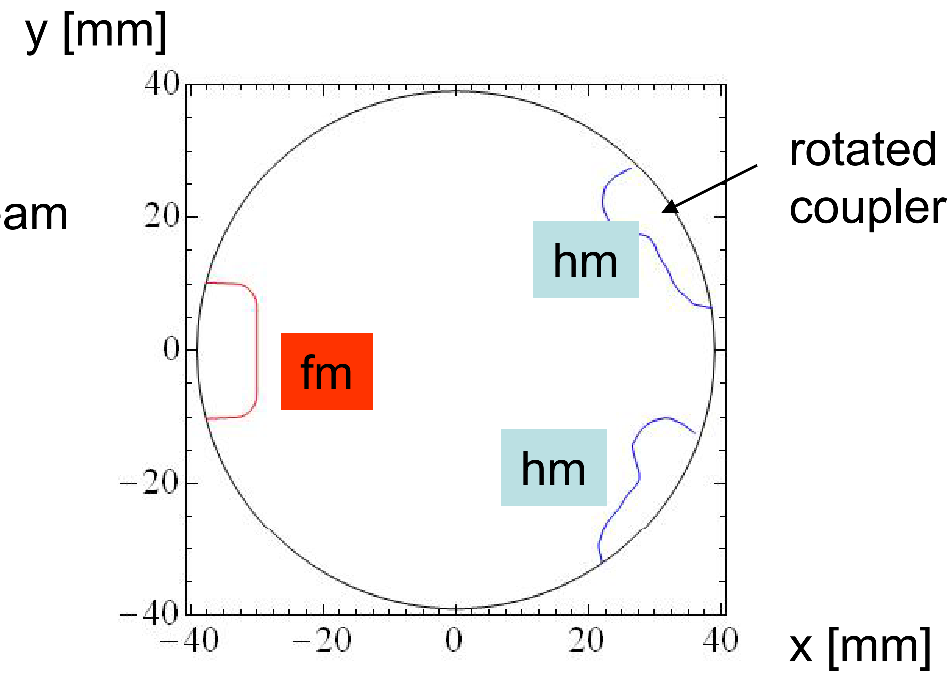
1. Stupakov G., Bane K.L.F., Zagorodnov I., *Optical approximation in the theory of geometric impedance*, Physical Review--STAB, **10**: 054401, 2007.

2. Bane K.L.F, Stupakov G., Zagorodnov I., *Impedance Calculations of Non-Axisymmetric Transitions Using the Optical Approximation*, Physical Review--STAB, **10**: 074401, 2007.

Comparison with Numerical Results

	k_x^{rms}	k_y^{rms}
Numerical	-16.5	-16.5
Analytical	-24.0	-20.0

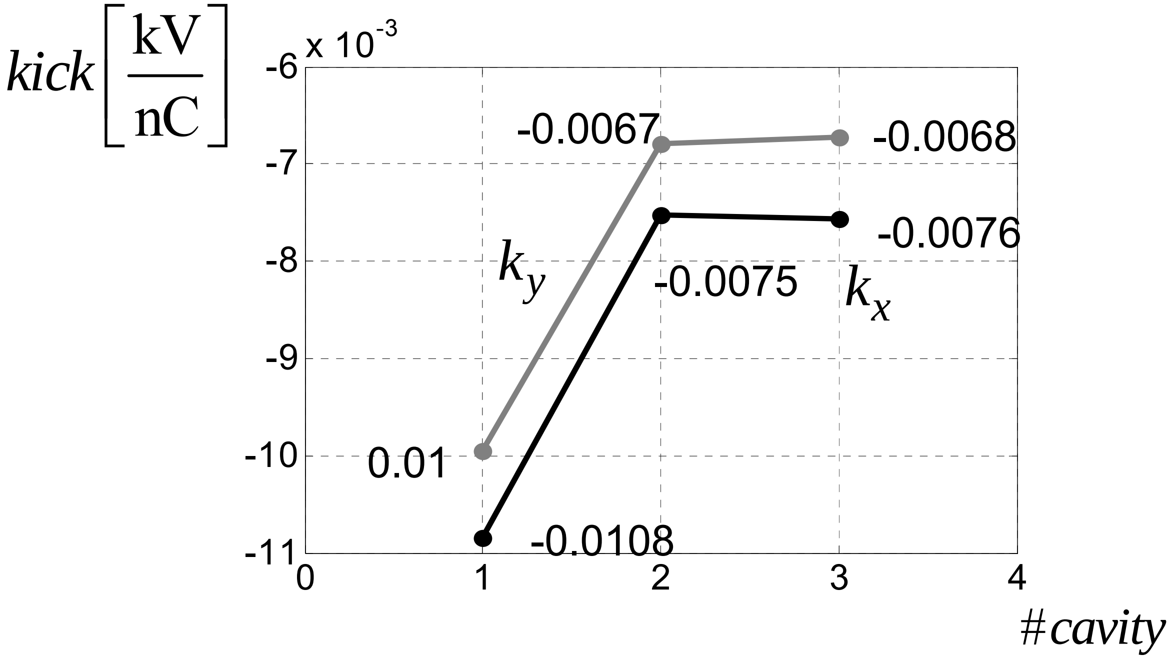
$k_\perp^{rms}$ [V/nC] *for the three couplers in a beam pipe*



• Z. Li proposes rotating upstream coupler by 180° =>

analytical result: k_x^{rms}= 7 V/nC, k_y^{rms}= -0.3 V/nC

Summary



Case I. Couplers in infinite pipe of r=39mm

$$\mathbf{k}_{\perp} = \begin{pmatrix} -0.0211 \\ -0.0188 \end{pmatrix} \left[\frac{\mathbf{kV}}{\mathbf{nC}} \right]$$

Case II. Cavity with couplers in infinite pipe

$$\mathbf{k}_{\perp} = \begin{pmatrix} -0.0108 \\ -0.0100 \end{pmatrix} \left[\frac{\mathbf{kV}}{\mathbf{nC}} \right]$$

Case IV. "Periodic" solution

$$\mathbf{k}_{\perp} = \begin{pmatrix} -0.0076 \\ -0.0068 \end{pmatrix} \left[\frac{\mathbf{kV}}{\mathbf{nC}} \right]$$

From a simple analytical calculation, obtain k_x= -0.009 kV/nC, k_y= -0.006 kV/nC

About a factor 3 reduction compared to Case 1

5. Conclusions

Coupler wake of ILC structure will spread out the beam size by ~60%

Slope of wake is negligible compared to cavity wake

Z. Li's modified geometry will make the effects become negligible; smaller iris cavity that shadows couplers will also have ~0 coupler wake effect

Need to do:

Numerically verify that slope of wake of couplers asymptotically reduces by a factor ~2—3

Numerically calculate 3 cavity wake for σ_z= 300 μm

Simulate coupler wake effect for discrete focusing lattice

Wake Fest 07 - ILC wakefield workshop at SLAC

Wakefield simulations for ILC cavity

V. Yakovlev, I. Gonin, A. Lunin, and N. Solyak,

Fermi National Laboratory

11 December, 2007

The couplers break the RF field symmetry and cause transverse RF kick.

The couplers break the symmetry of the cavity and cause transverse wake field.

Both RF kick and wake fields may be a reason of a beam emittance dilution.

DESY* made the first calculations of the RF kick and wake fields. The calculations show that both RF kick and wake fields may be a serious problem that could require the cavity improvement.

More detailed investigations are necessary!

***I. Zagorodnov, and M. Dohlus, ILC Workshop, DESY,31 May, 2007**

Simple estimations:

For a=39 mm, l=20 mm, h=9 mm
$W_\perp \approx 10^{-2}$ V/pC.
For Q=3.2nC $\Delta p_\perp c$ ~**30 V**
It is equivalent to the cavity transverse displacement by 4 mm.
For RF kick $\Delta p_\perp c \sim 2\pi\sigma \cdot \mathrm{Im}(U_y)/\lambda_{RF}$= **3V**

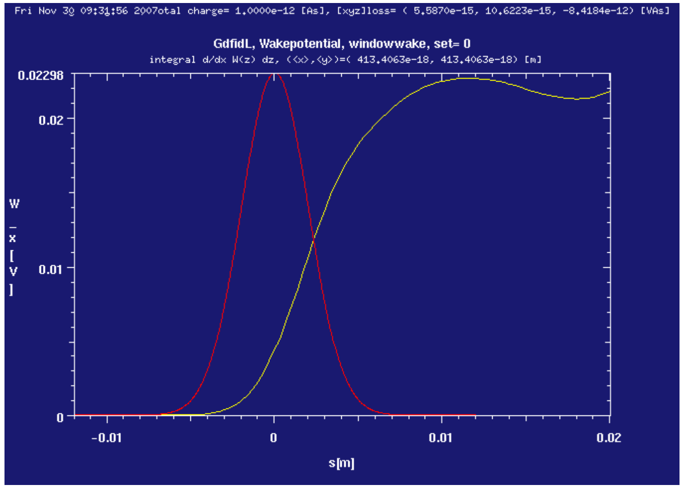
Wake kick is ~ 10 times higher than RF kick!

$$\gamma\varepsilon \approx \gamma(z_{\max})y_{\max}y'_{\max} \approx \frac{Q^2 W_y^2(0,0)\beta^3\gamma_0}{4U_0^2 L^2}\left[1+\left(\frac{\gamma_0}{\gamma(z)}\right)^{\frac{1}{2}}\right]$$

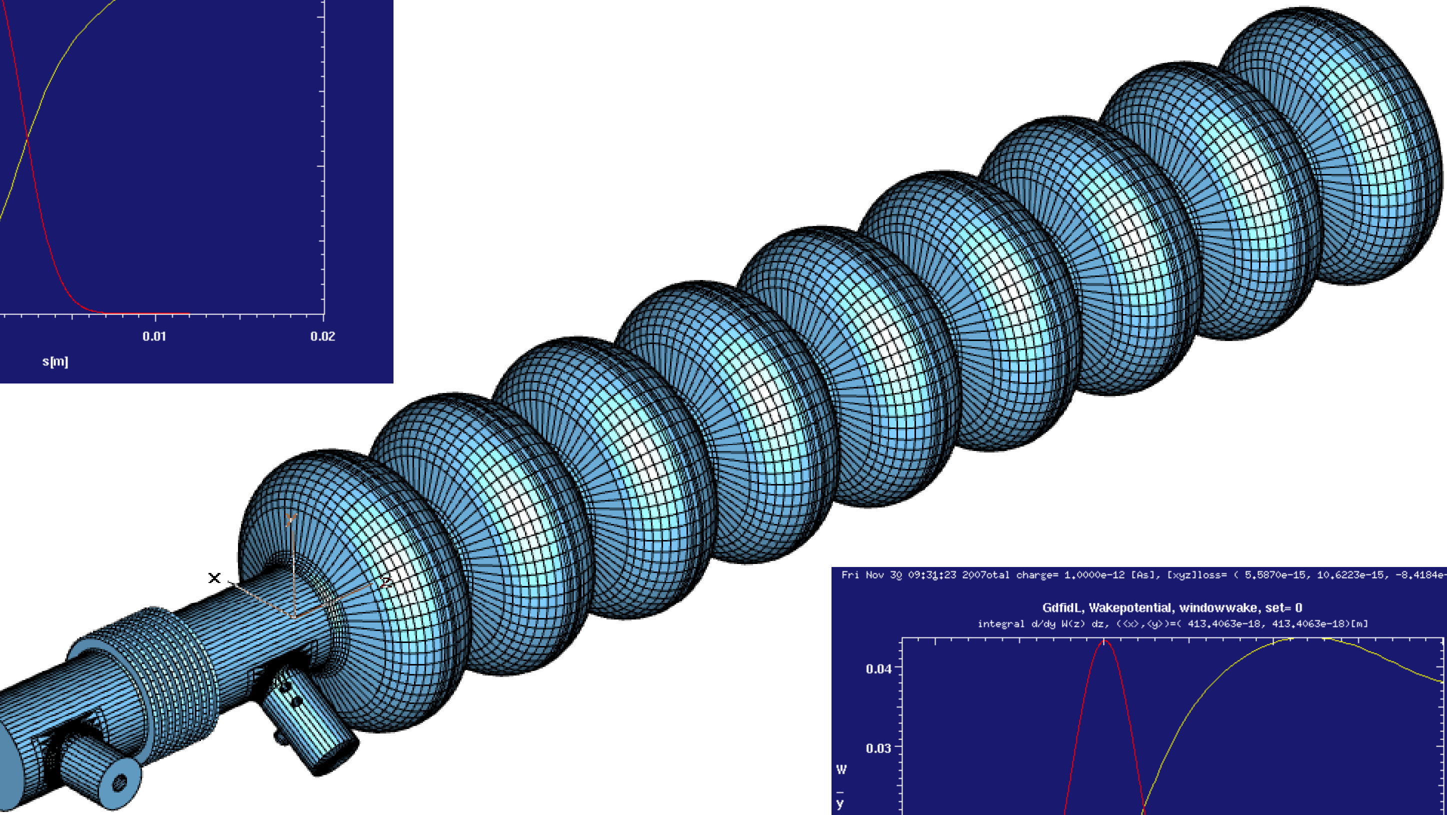
(L- the cavity + coupler unit length, Q is a bunch charge)

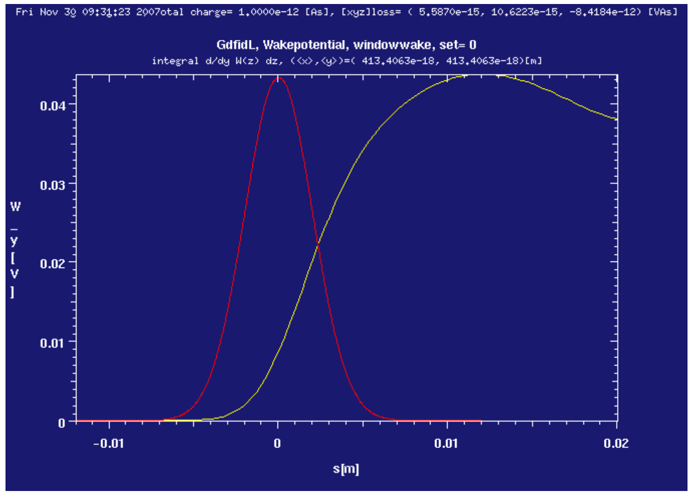
Emittance dilution ~100 times higher, or >20 nm, that is unacceptable.

The GdfidL Electromagnetic Field simulator*



-wakes: longitudinal and transverse



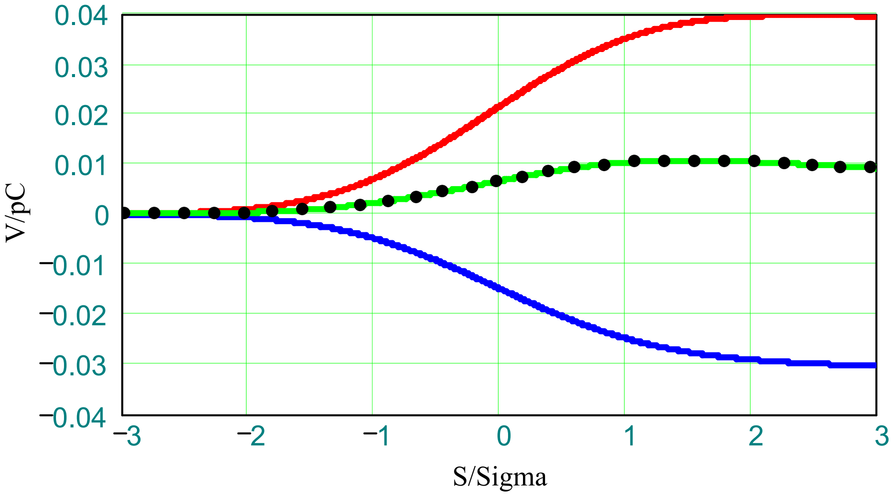


* http://www.gdfidl.de

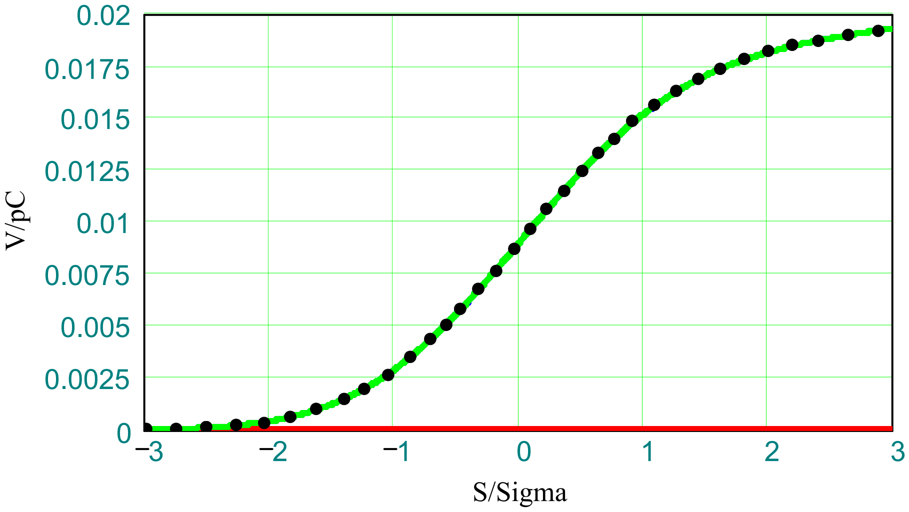
Wake superposition.

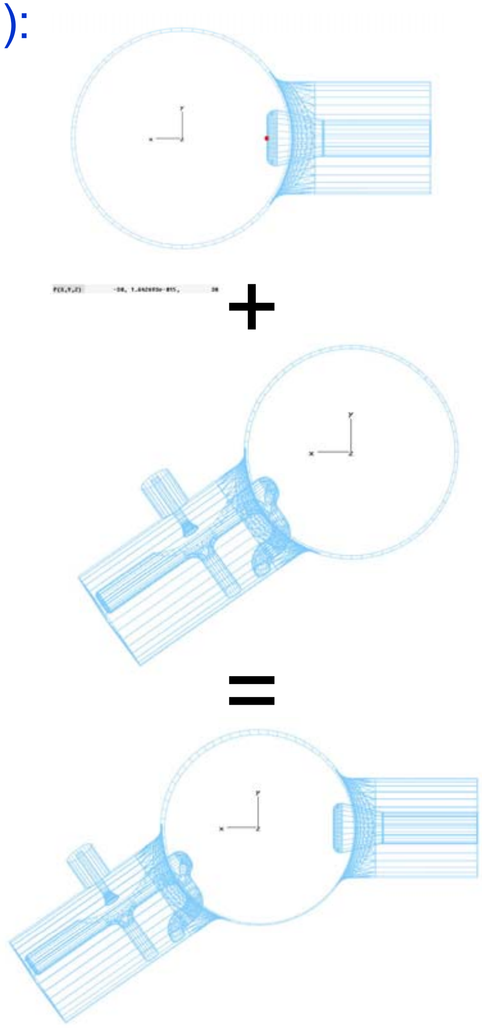
I. Main coupler and downstream HOM coupler (σ=1mm):

$W_x(s)$



$W_y(s)$

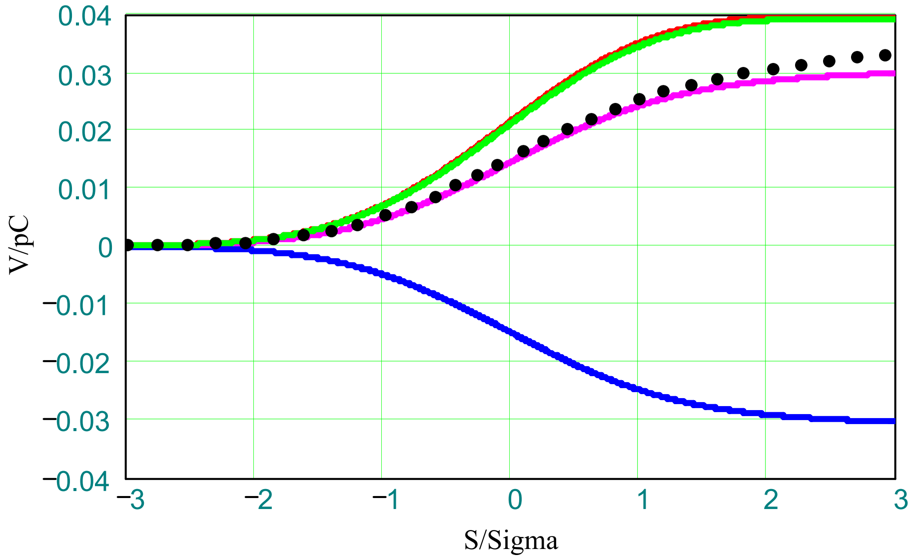




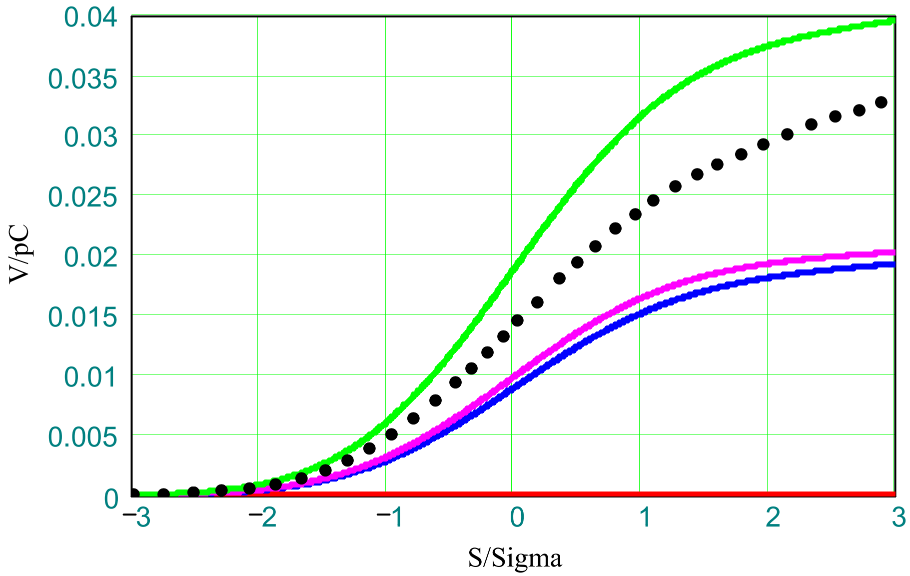
Red - main coupler, blue - downstream HOM, green - sum of them, dots – direct calculations of the entire geometry. Superposition works pretty well.

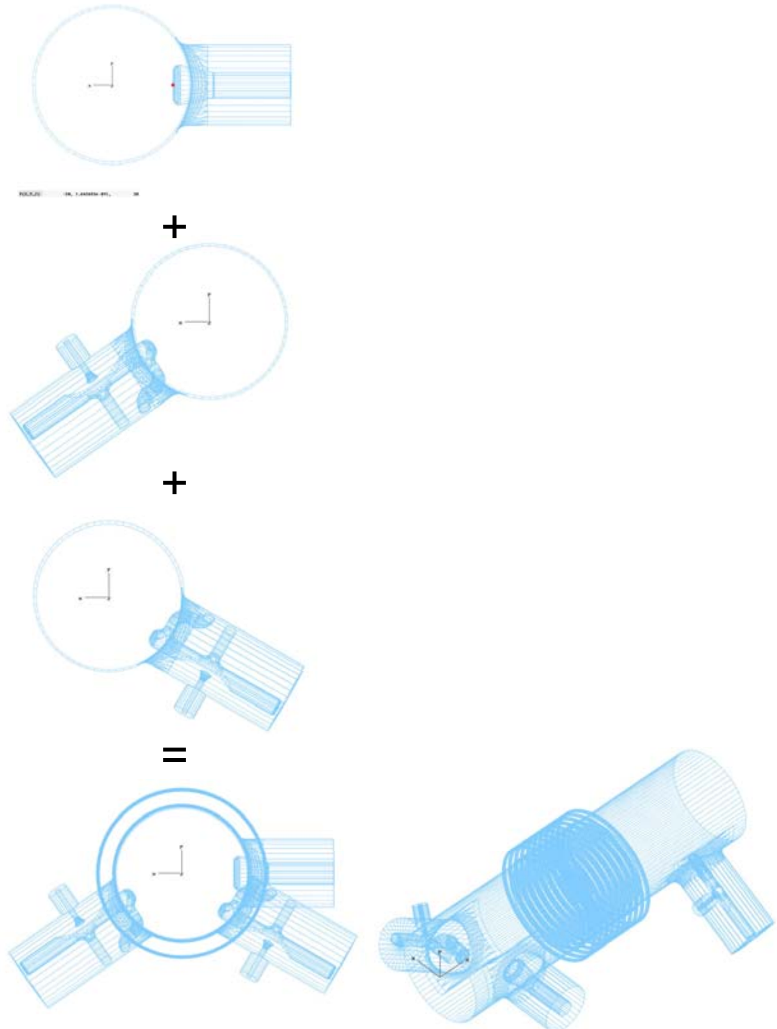
II. Main coupler + downstream HOM coupler + upstream HOM coupler (σ=1mm):

$W_x(s)$



$W_y(s)$

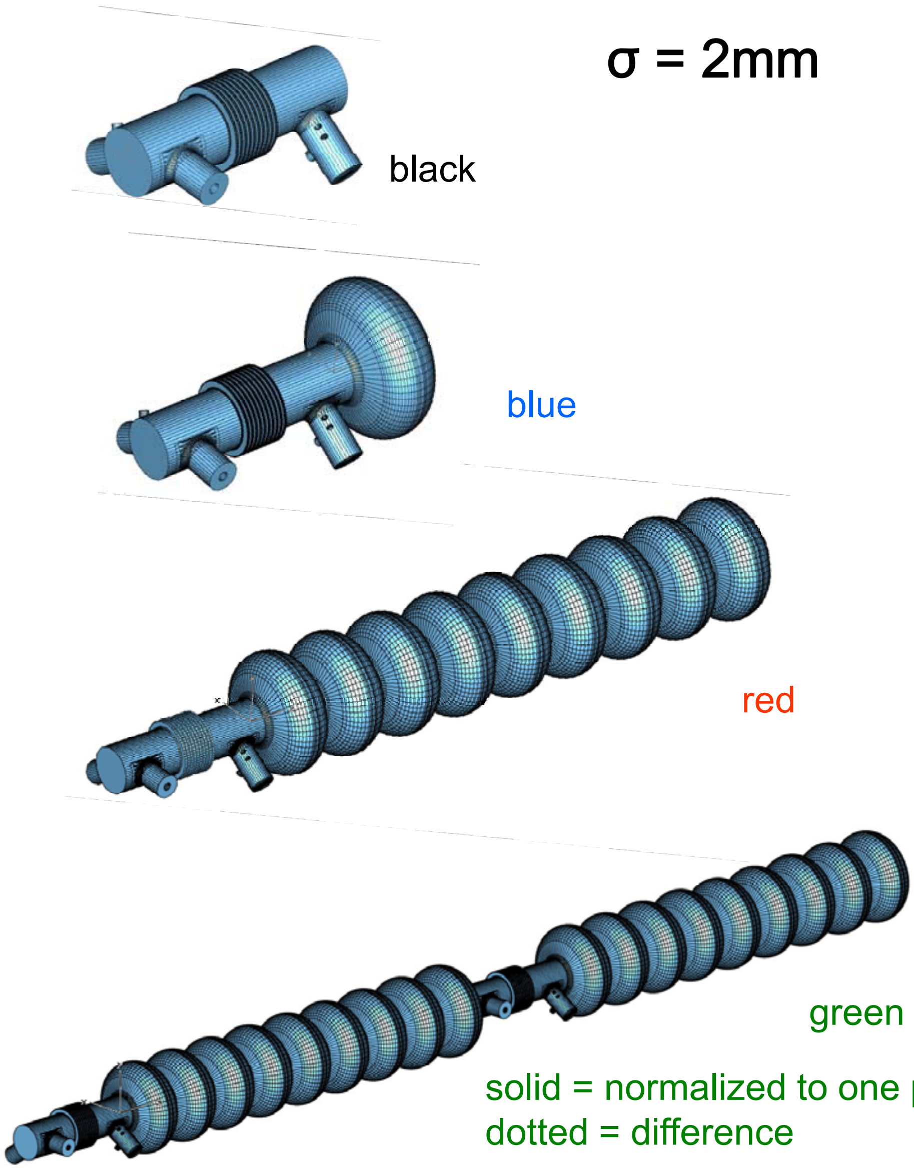


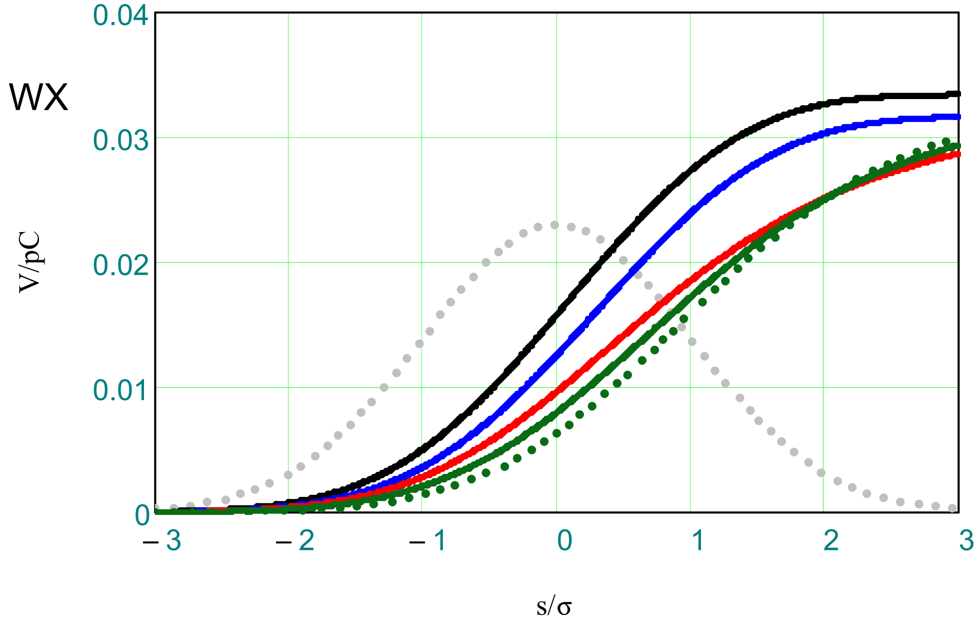


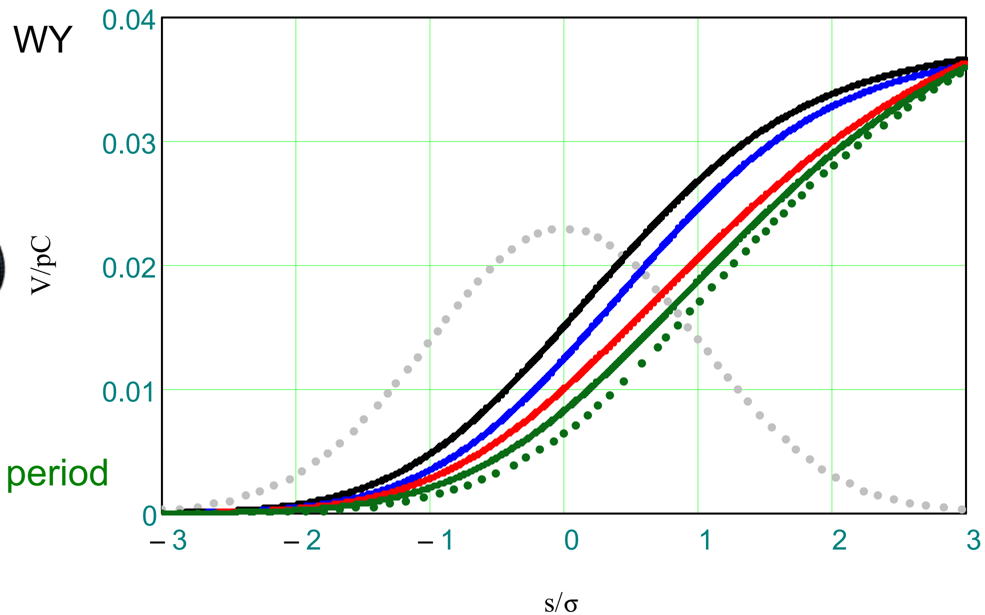
Read - main coupler, blue - downstream HOM, pink - upstream HOM, green-sum of them, dots- direct calculations of the entire geometry.

Wake shielding by RF structure

σ = 2mm

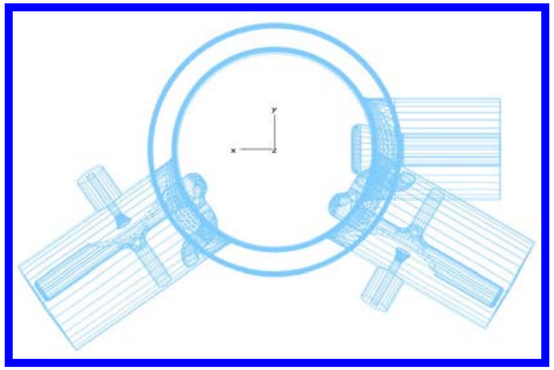




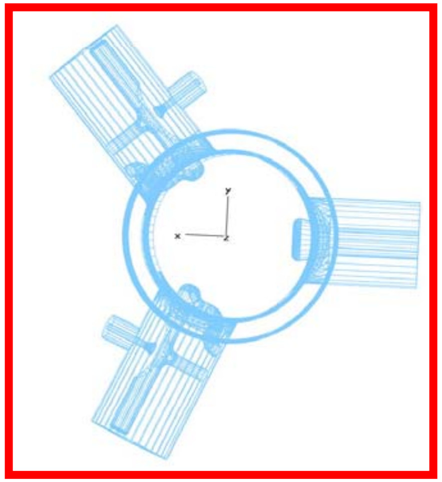


solid = normalized to one period
dotted = difference

HOM couplers rotation (suggested by M. Dohlus, and I. Zagorodnov).
Symmetrical case, rotation angle is 82.5°



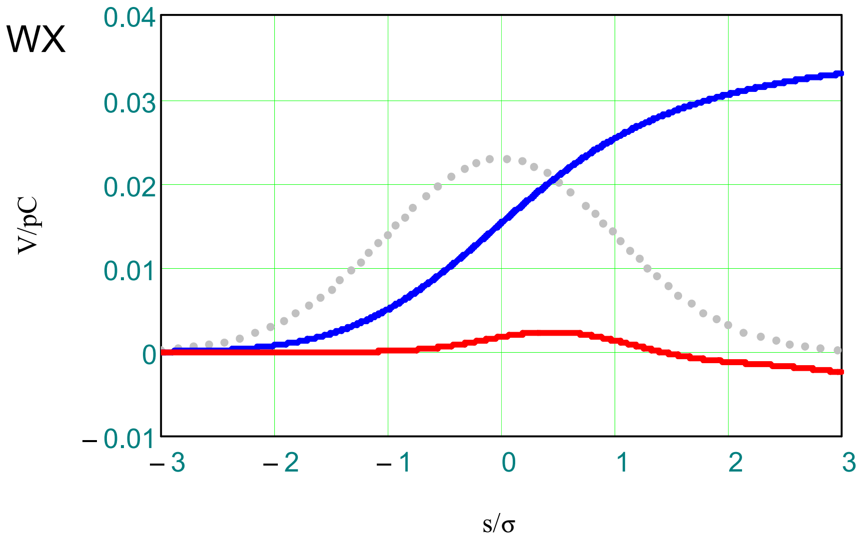
σ = 1mm



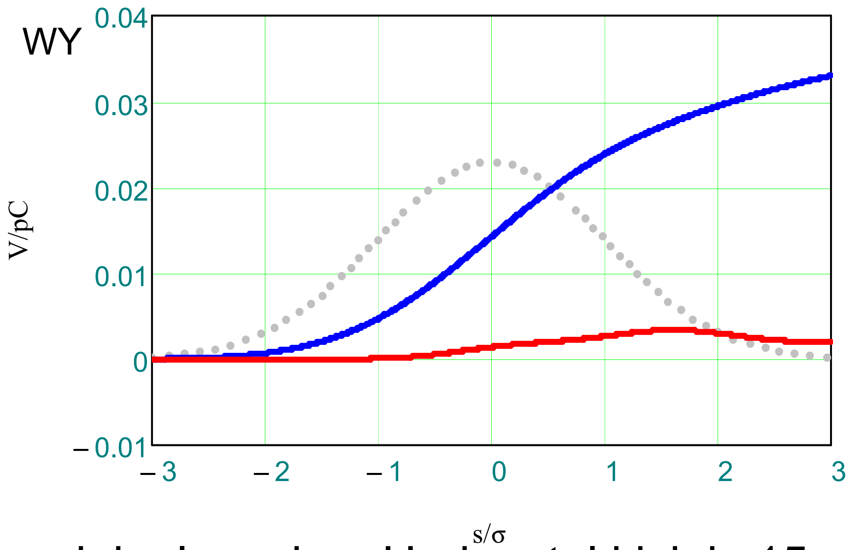
kx = 0.015 V/pC
ky = 0.014 V/pC

kx_rot = 0.0010 V/pC
ky_rot = 0.0014 V/pC

WX



WY



Vertical kick is 10 times smaller than in the original version. Horizontal kick is 15 times smaller.

Coupler RF kick simulations.

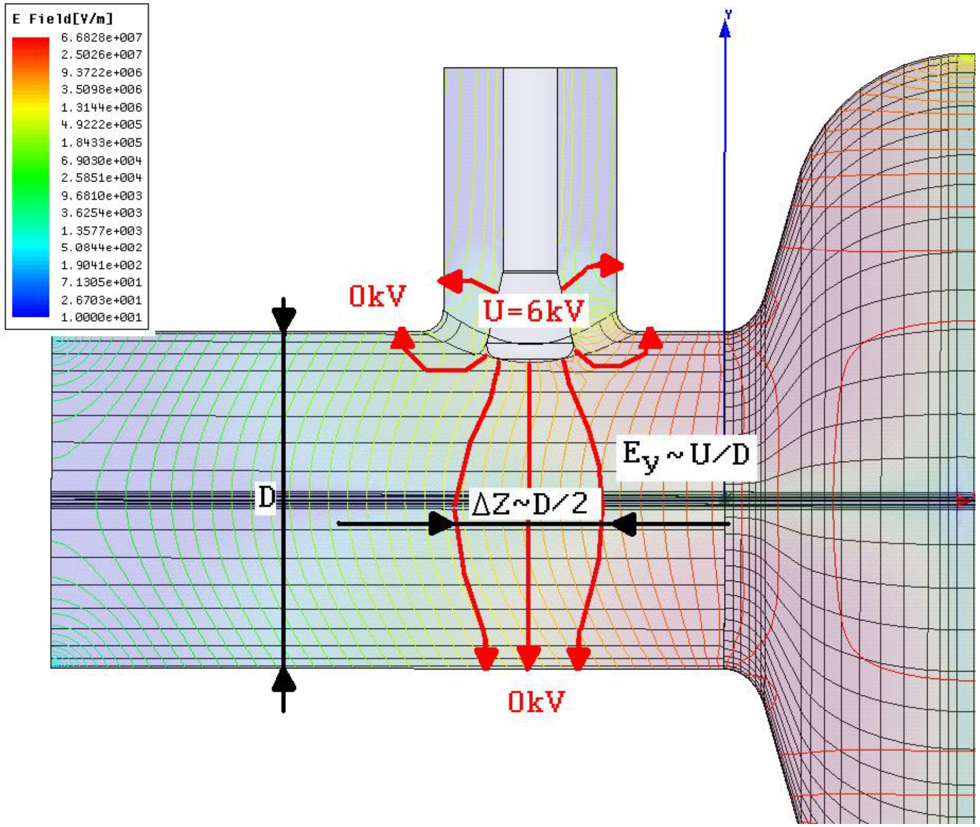
V. Yakovlev, I. Gonin, A. Lunin, and N. Solyak,

Fermi National Laboratory

11 December, 2007

RF kick

Simple estimations of the transverse fields caused by the main coupler:



RF voltage*:*

$U=(2PZ)^{1/2}$, Z–coax impedance;

for P=300 kW and Z≈70 Ohms

$U \approx 6$ kV

Transverse kick:

$\Delta p_y \cdot c \approx eE_y \Delta Z \approx eU/D \cdot D/2 = eU/2$.

$$\frac{\Delta p_y c}{\Delta U_{acc}} \approx \frac{U}{2U_{acc}} = \frac{6kV}{2 \times 30MV} = 100 \times 10^{-6}$$

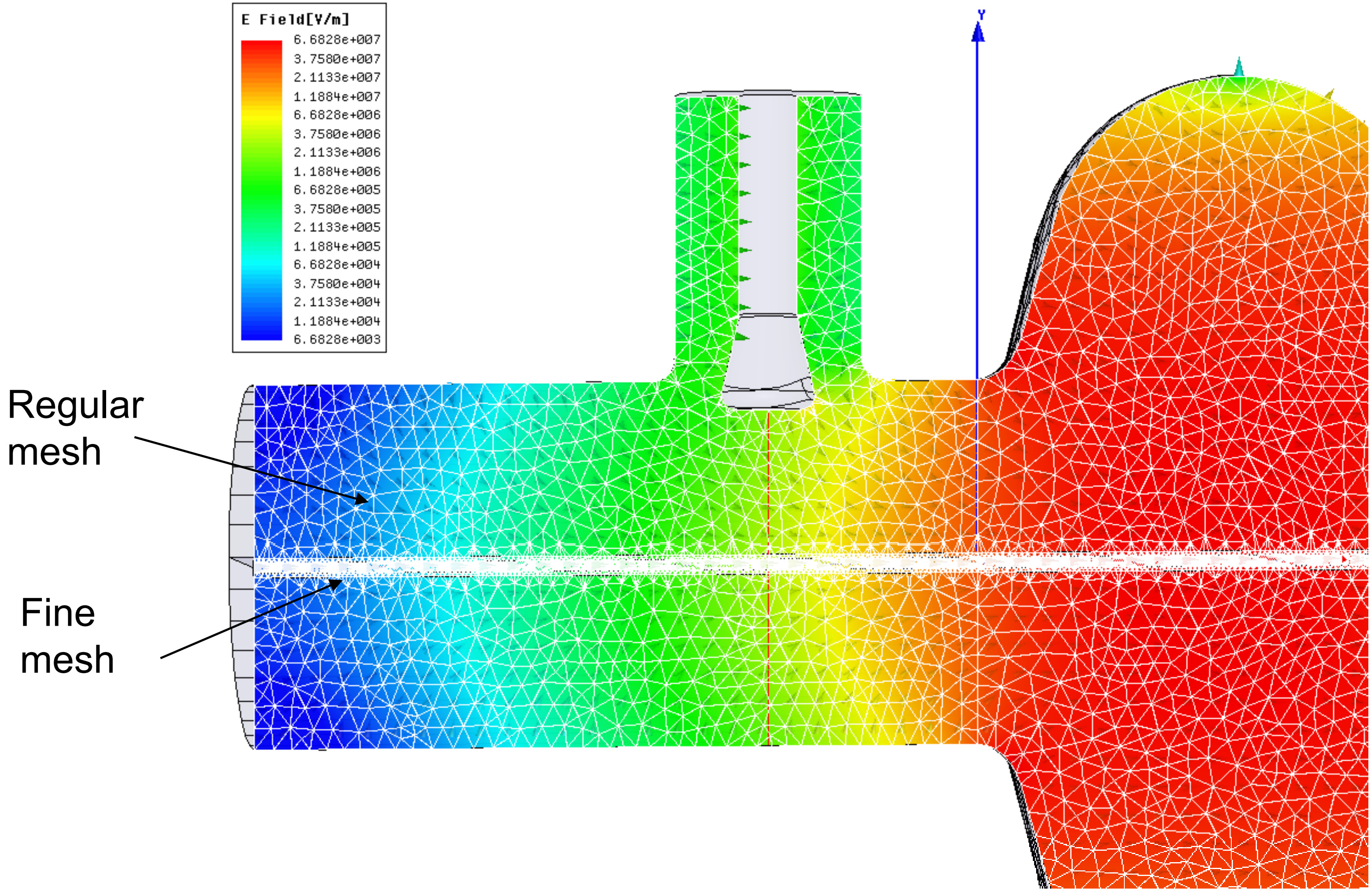
The RF field calculation precision should be better than 10^{-5}!

Transverse kick caused by the couplers acts on a bunch the same direction for all the RF cavities of the linac.

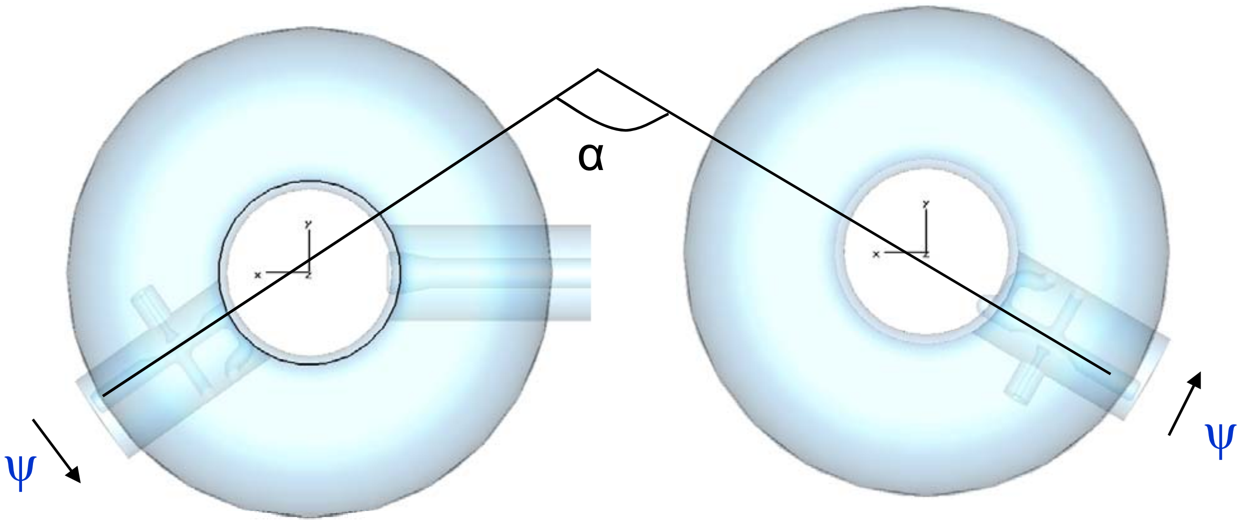
Real part may be compensated by the linac feedback system;

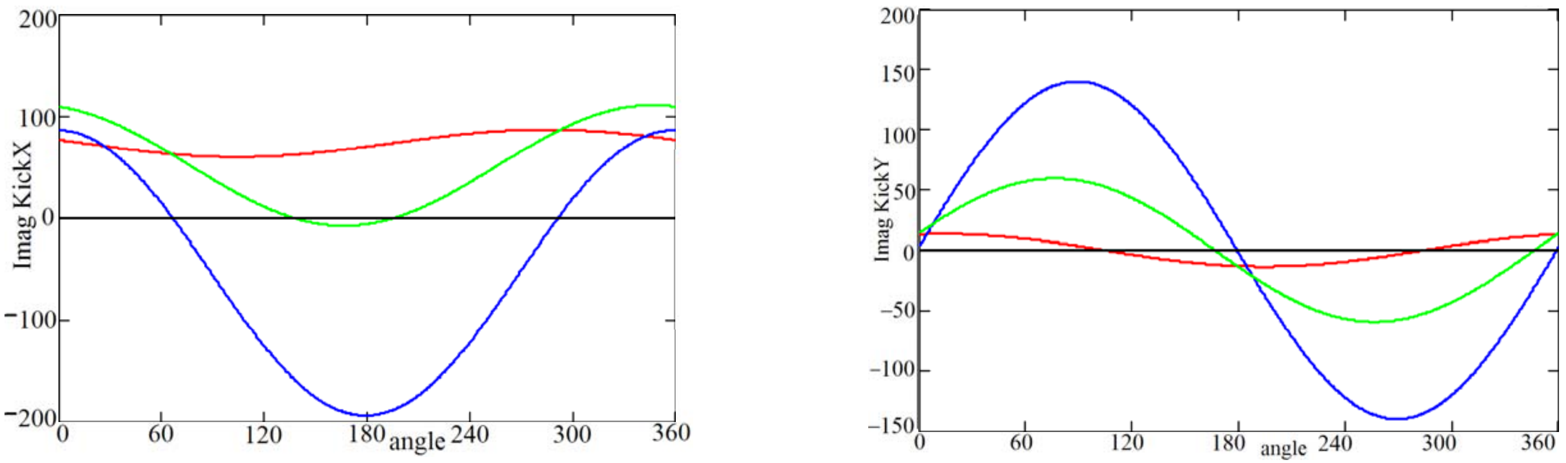
Imaginary part dives the beam emittance dilution.

Mesh generation for HFSS for high-precision field calculations near the axis:



Total number of the mesh nodes is up to 500,000





Imaginary parts of V_x (left) and V_y (right) vs. angle of rotation of both HOM couplers simultaneously when the angle between the coupler is fixed and equal to 115º *.

Red curve for Linac (φ=-5.1°), blue for BC1 (φ=-105°), and green for BC2 (φ=-27.6°)

*Angle α=115º provides optimal damping of both polarization of dipole modes and was determined experimentally.

RTML, Bunch Compressor-1.

One unit, 3 cryo-modules, each CM contains 8 RF cavities and quad.

Present coupler orientation: $\nu_1=G_y/G=4\cdot 10^{-6}$ –vertical RF kick.

U_0=5 GeV, σ=9mm, $<\beta_y>\approx$30m, $\gamma\varepsilon_y$=20 nm.

$\delta(\gamma\varepsilon_y) \approx 1/4 \cdot \gamma \sigma_y \sigma_{y'}$, where

$\sigma_y = \sqrt{(\gamma\varepsilon_y)\beta_y/\gamma} = 13\mu m$ and $\sigma_{y'} = \dfrac{\Delta p_y c}{U_0} = \dfrac{2\pi \nu_1 G l \sigma}{U_0 \lambda_{RF}} = 1.5\times 10^{-7} rad;$

l≈25 m – length of RF system. Thus, $\delta(\gamma\varepsilon_y) \approx 5nm$

Required value of the vertical emittance is 20 nm. The HOM coupler rotation by ~180° may reduce the vertical emittance dilution in BC1.

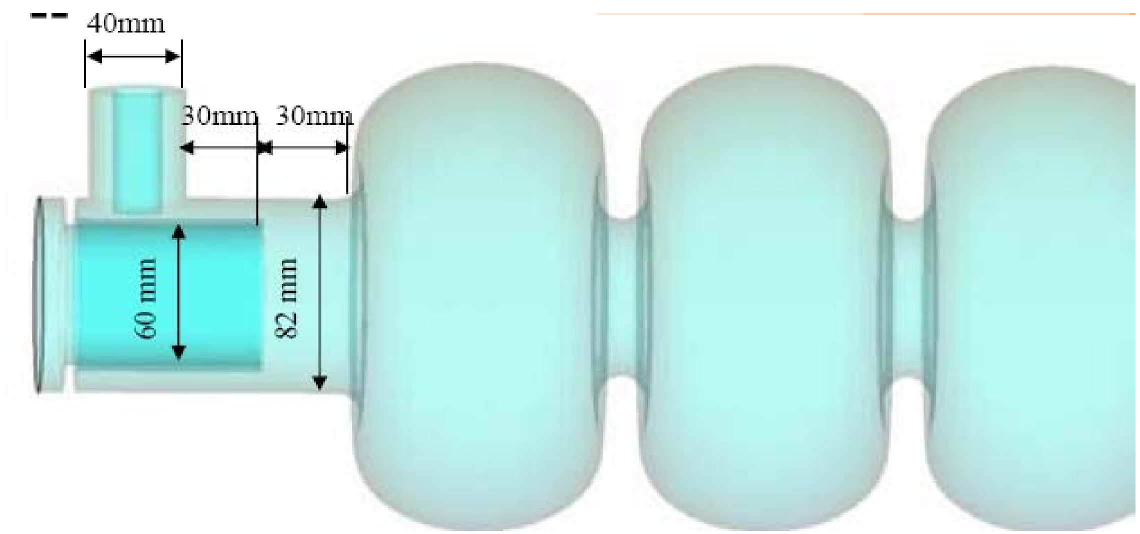
RTML, Bunch Compressor-2.

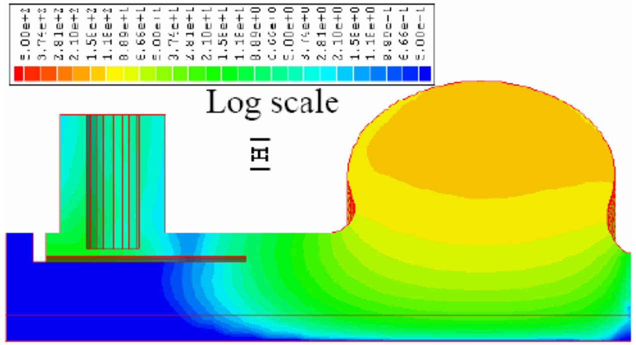
Present coupler orientation: $\nu_1=G_y/G=15\cdot 10^{-6}$ –vertical RF kick.

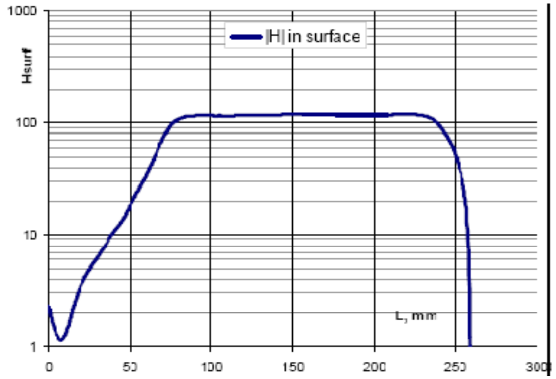
U_0=5 GeV, U_{max}=15 GeV, σ=1mm, $<\beta_y>\approx$80m.

$$\gamma\varepsilon \approx \gamma(z_{\max}) y_{\max} y'_{\max} = \frac{\pi^2 \nu^2 G^2 \sigma^2 \beta^3 \gamma_0}{\lambda_{RF}^2 U_0^2} \left[1 + \left(\frac{\gamma_0}{\gamma(z)} \right)^{\frac{1}{2}} \right] = 13.5nm$$

A new idea of a compact detachable coupler unit* that provides axial symmetry of the RF field and the cavity geometry in the beam channel:





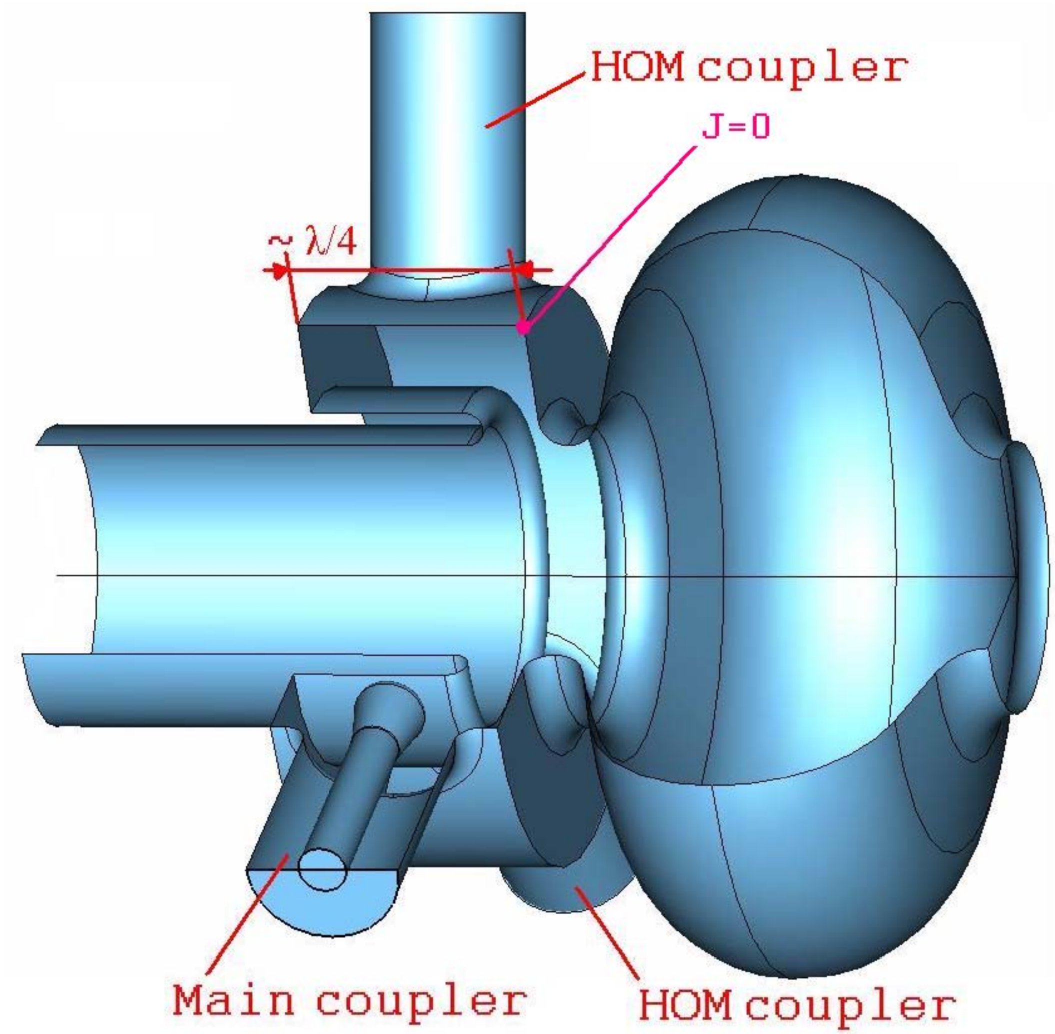


➢The unit provides both required coupling of the operating mode and suppression of the HOMs;

➢Simulations show that it is free of multipacting.

*N. Solyak, T. Khabiboulline, 2d ILC Workshop, Snowmass, Aug 14-18, 2005

An idea of a compact detachable quarter wave coupler unit that provides axial symmetry of the RF field and the cavity geometry in the beam channel:



Coupler RF Kick Simulation Using Omega3P and S3P

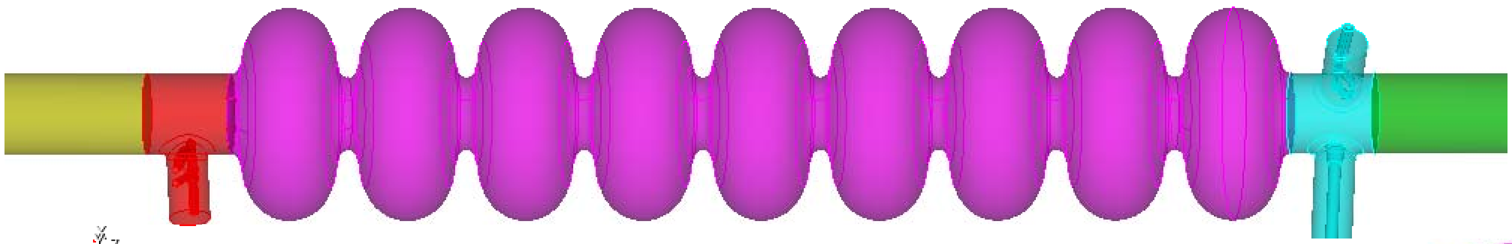
Zenghai Li

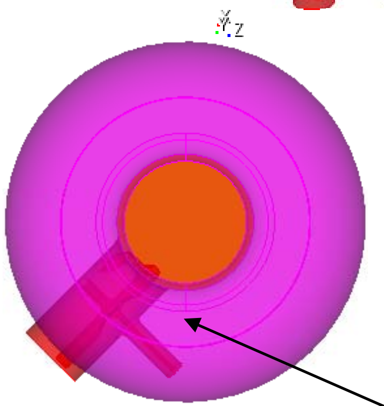
Advanced Computations Department
Stanford Linear Accelerator Center

WakeFest07 – Dec 11, 2007

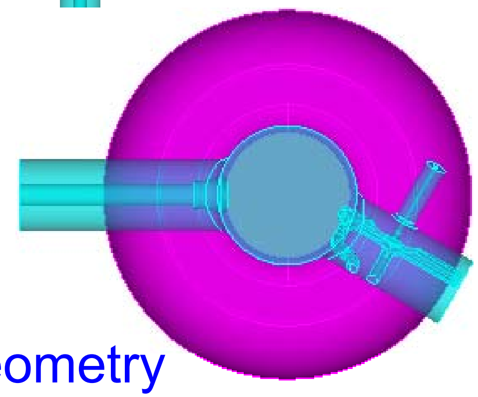
High Fidelity Geometry & Field Modeling In Omega3P & S3P

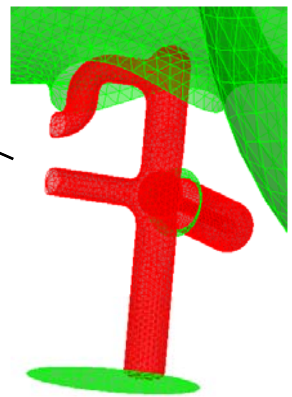
Fields in coupler regions are orders smaller than fields in the regular cells. High accuracy field modeling needed.





Complicated geometries in end groups



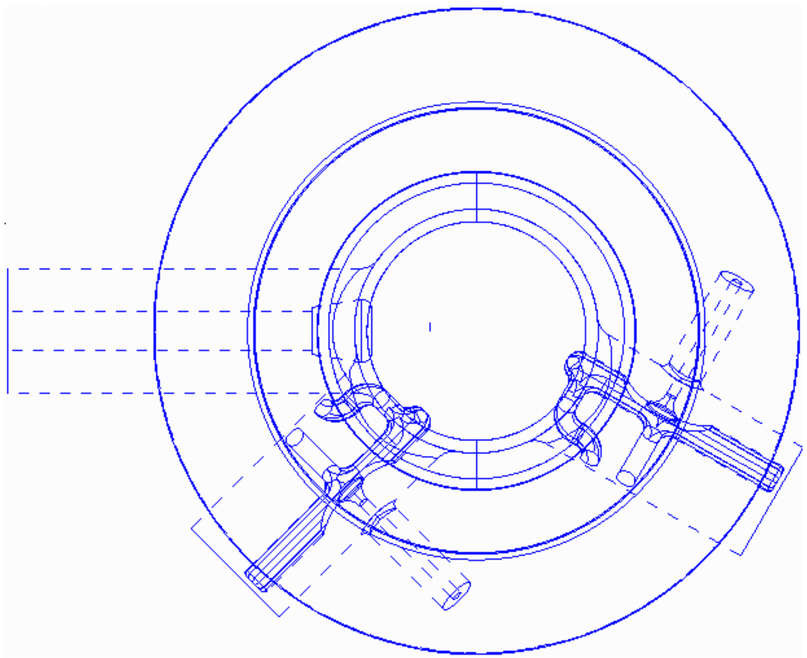


- High fidelity modeling of geometry using unstructured tet mesh
- High field accuracy using higher order interpolation base function

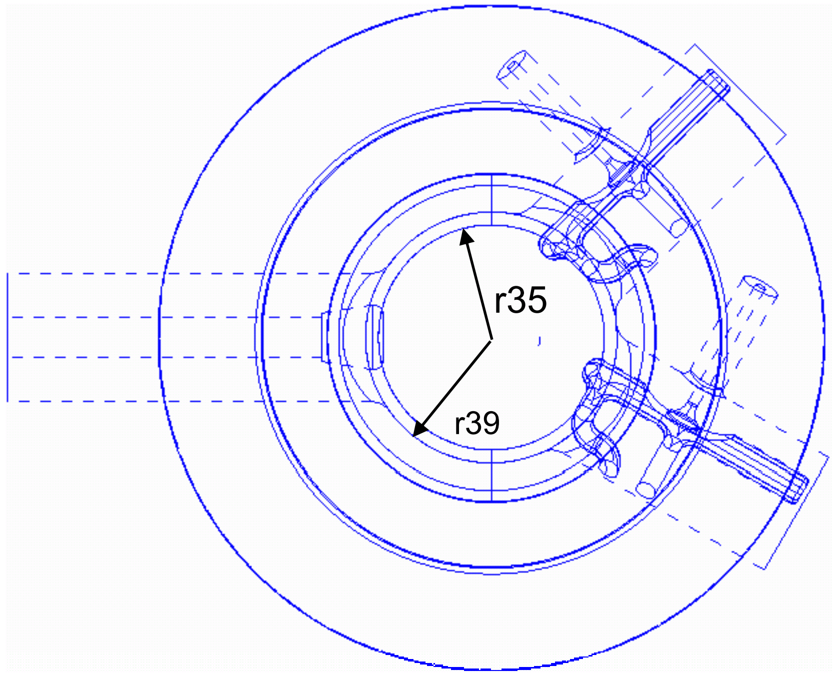
End-group Modification

- Rotate up-hom by 180 degree about z
- To minimize SW kick (Karl's talk)
- Effect on RF kick ?

TDR



TDRM
(TDR modified)



Summary

- SW and TW wave fields in coupler region are modeled using Omega3P and S3P
- “Significant” beam centroid and head-tail kicks are found due to coupler asymmetry
- Redesign of end group to minimize RF kicks discussed
- Beam simulation needed to understand impact of RF kicks.

MANCHESTER 1824
The University of Manchester

Wake-fields and Beam Electrodynamics

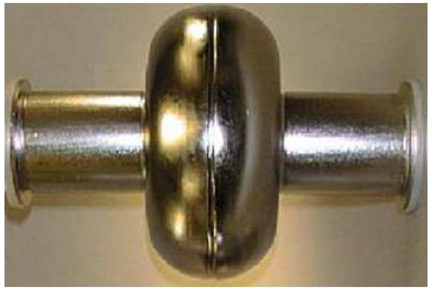
Roger M. Jones, Univ. Manchester/Cockcroft Inst.

Wake-fields and HOM beam dynamics for the ILC:

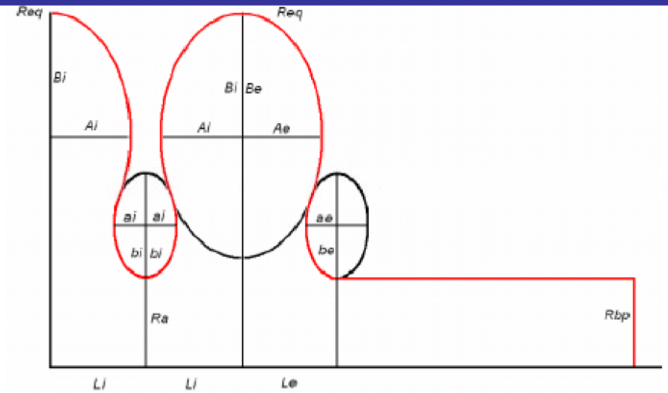
- 1. Main linac e.m. field and beam electrodynamics simulations for ACD high gradient cavities
- 2. Globalised matrix technique of cascading
- 3. Review of x-y transverse coupling
- 4. Crab cavity wire simulations and measurements
- 5. HOM measurements at FLASH (FP7)



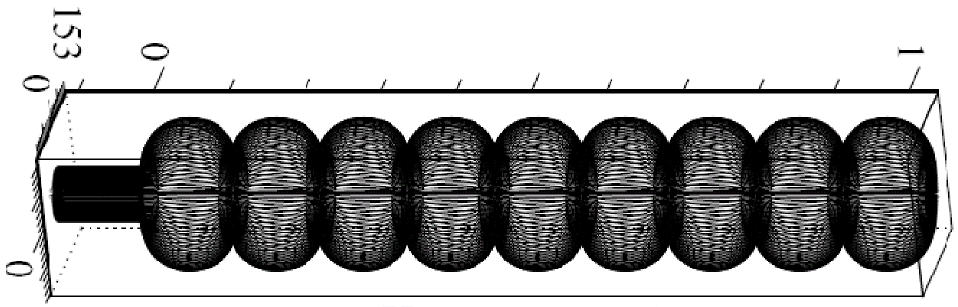

1. HOMs in Re-Entrant Cavity



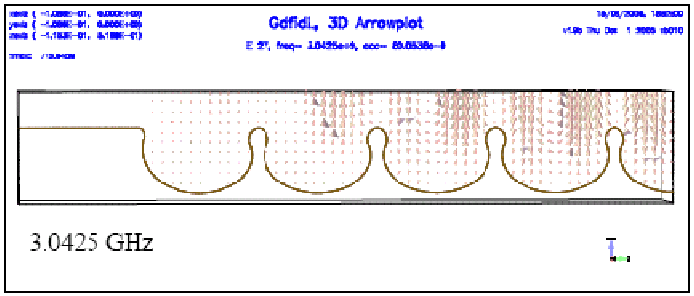
Cornell Single-Cell
RE Cavity

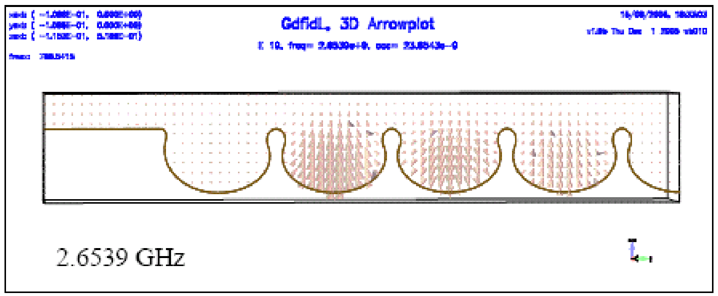


Parameters for GdfidL Simulations

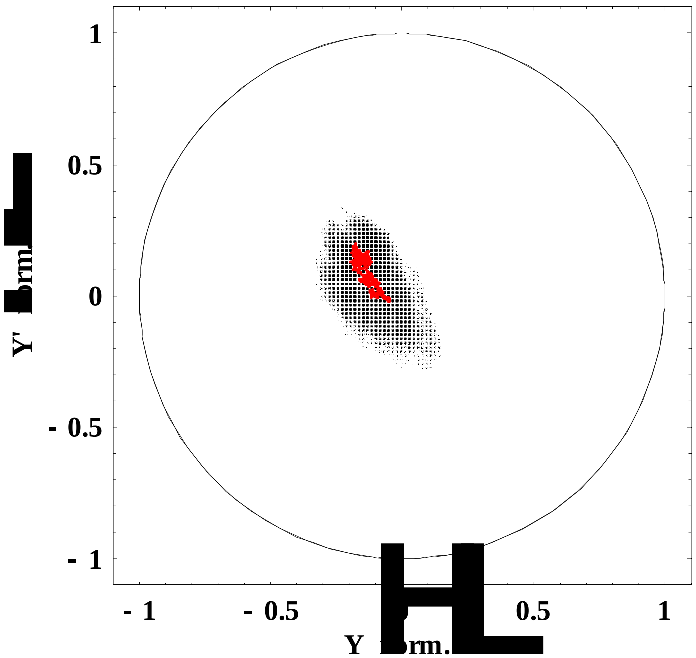


9-Cell RE Cavity

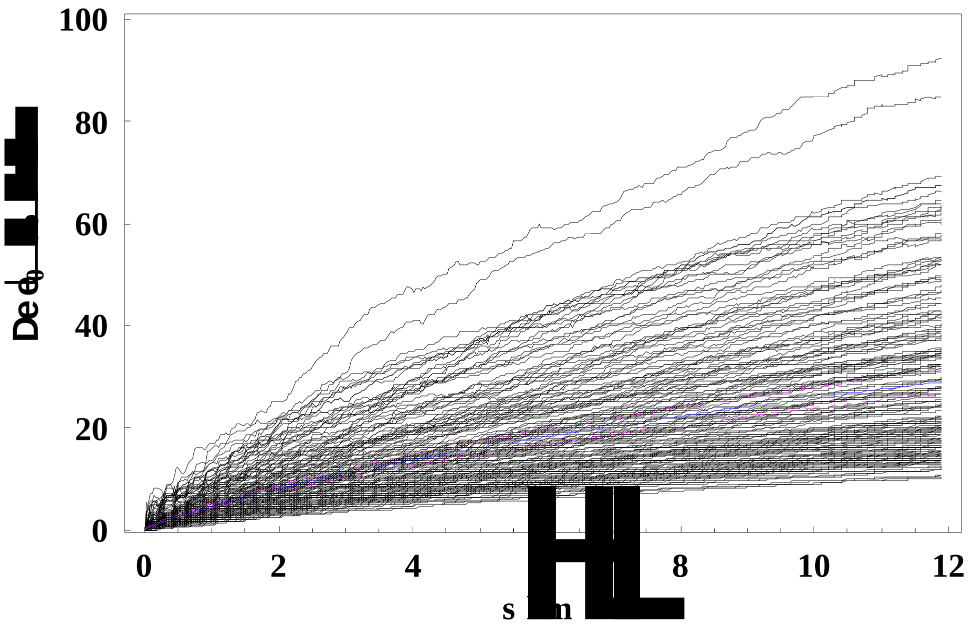




Simulations of Trapped Modes in RE Cavities



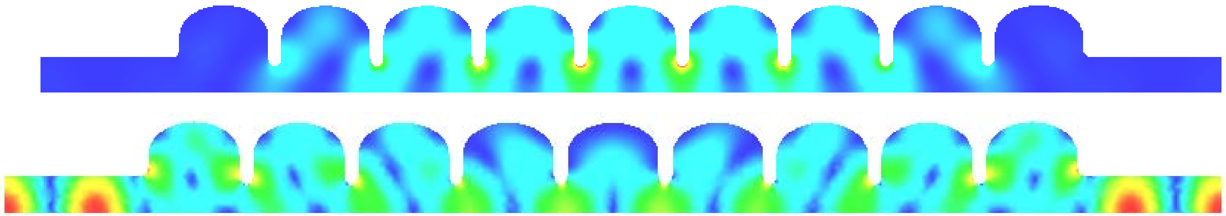
Y-Y' phase space at end of linac



Emittance dilution due to long-range wake-fields damped with a Q of 10^6 in Re-entrant cavity. The beam is offset with $1\sigma_y$ (~12.4 μm).
The mean dilution is 17.25 % (with a standard error of .25 %). 200 machines are indicated together with the mean and the 95% confidence level.

1. HOMs in Ichiro Cavity

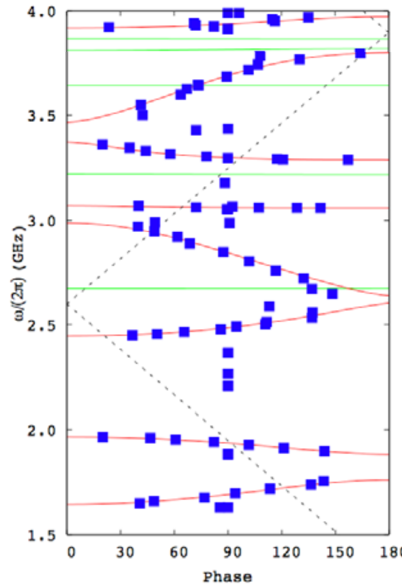
Ichiro Cavity fabricated at KEK



Trapped mode ~2.4498GHz

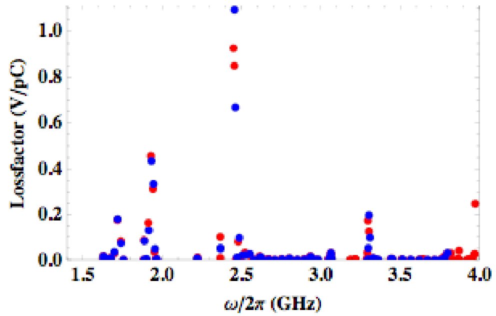
Multi-cavity mode ~2.6420GHz

Simulations of E-field of the 3rd band modes in Ichiro cavities



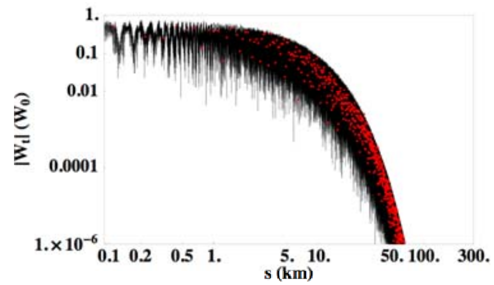
Dispersion curves of first 8 dipole and 5 sextupole bands

See Glasman, Jones et al. SRF2007 pubs.

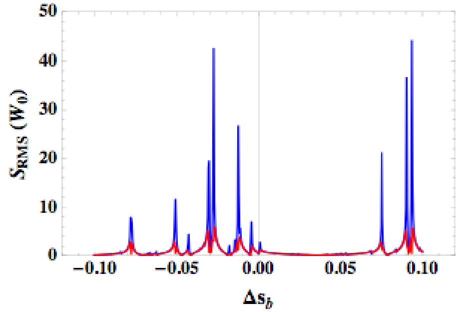


Comparison of Loss factors calculated with GdfidL (red) and MAFIA 2D (blue)

Detailed studies conducted on HOMS in Ichiro cavity. Sensitivity to systematic changes in frequency investigated. Detailed comparison of codes –MAFIA,HFSS, GdfidL, Analyst.

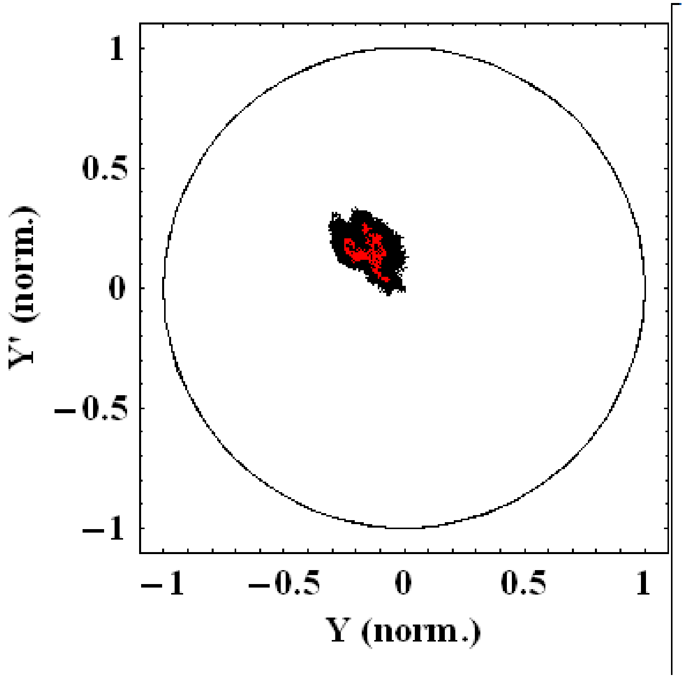


Envelope of long-range wake-field

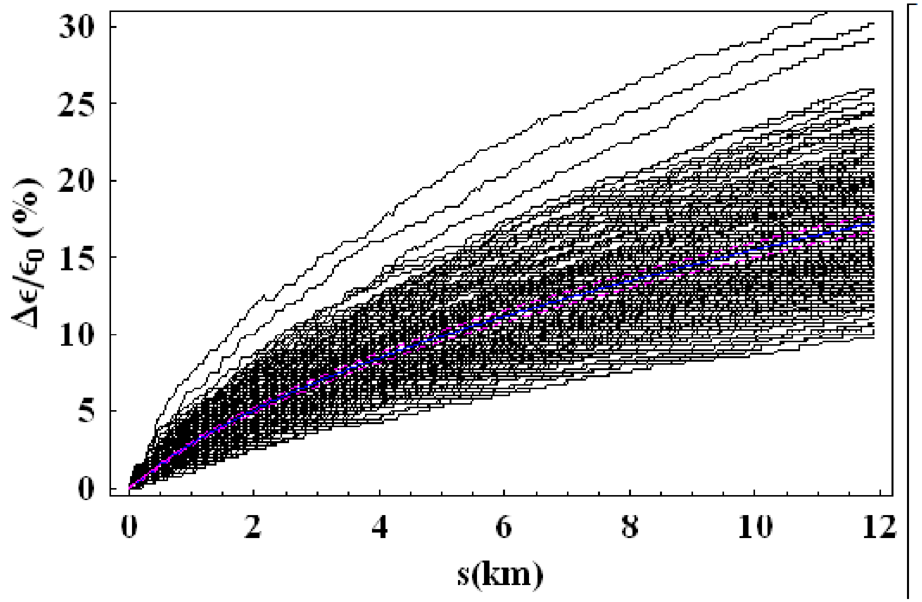


Sensitivity of RMS wake to small changes in bunch spacing

1. Beam Dynamics in Ichiro Cavity



Y-Y' phase space at end of linac



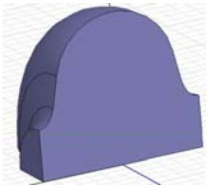
Emittance dilution due to long-range wake-fields damped with a Q of 10^6 in Ichiro cavity. The beam is offset with $1\sigma_y$ (~12.4 μm).
The mean dilution is 17.25 % (with a standard error of .25 %). 200 machines are indicated together with the mean and the 95% confidence level.

2. EM Field in High Gradient Cavities

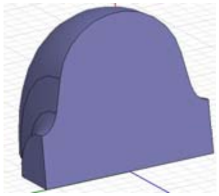
- **Simulation of Higher Order Modes (HOMs) in high gradient cavities**
- **Utilise 3D codes: GdfidL, HFSS, Analyst**
- **Use 2D codes, ABCI, Echo2D for bulk of cavity structures.**
- **Develop interface that *cascades* given sections to make more efficient calculations of overall fields.**
- **Focus on:**

1. **Re-entrant -Cornell Univ. design**
2. **Low-loss (Ichiro variant) –KEK design.**

2. Cascaded Computation of HOMs

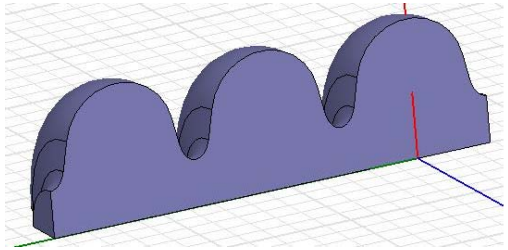


$$\underline{\underline{S}} = \begin{bmatrix} \underline{\underline{S}}_{11} & \underline{\underline{S}}_{12} \\ \underline{\underline{S}}_{21} & \underline{\underline{S}}_{22} \end{bmatrix}$$



$$\underline{\underline{S}} = \begin{bmatrix} \underline{\underline{S}}_{22} & \underline{\underline{S}}_{21} \\ \underline{\underline{S}}_{12} & \underline{\underline{S}}_{11} \end{bmatrix}$$

=>

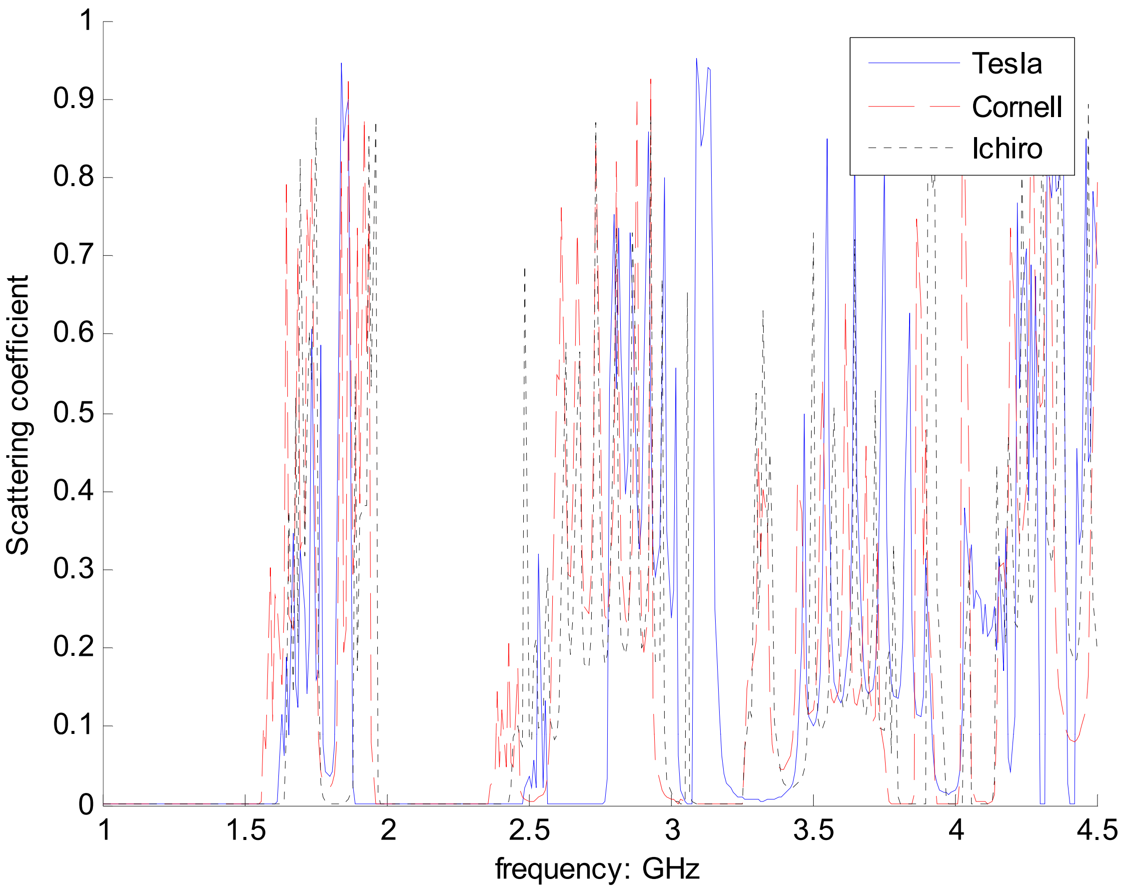


$$\underline{\underline{S}}_{11} = \underline{\underline{S}}^a_{12}\left[\underline{\underline{I}} - \underline{\underline{S}}^b_{11} \ \underline{\underline{S}}^a_{22}\right]^{-1} \underline{\underline{S}}^b_{11}\underline{\underline{S}}^a_{21} + \underline{\underline{S}}^a_{11}$$

$$\underline{\underline{S}}_{12} = \underline{\underline{S}}^a_{12}\left[\underline{\underline{I}} - \underline{\underline{S}}^b_{11} \ \underline{\underline{S}}^a_{22}\right]^{-1} \underline{\underline{S}}^b_{12}$$

$$\underline{\underline{S}}_{21} = \underline{\underline{S}}^b_{21}\left[\underline{\underline{I}} - \underline{\underline{S}}^a_{22} \ \underline{\underline{S}}^b_{11}\right]^{-1} \underline{\underline{S}}^a_{21}$$

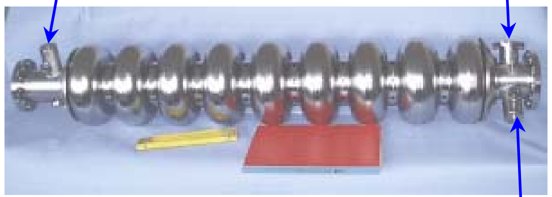
$$\underline{\underline{S}}_{22} = \underline{\underline{S}}^b_{21}\left[\underline{\underline{I}} - \underline{\underline{S}}^a_{22} \ \underline{\underline{S}}^b_{11}\right]^{-1} \underline{\underline{S}}^a_{22}\underline{\underline{S}}^b_{12} + \underline{\underline{S}}^b_{22}$$

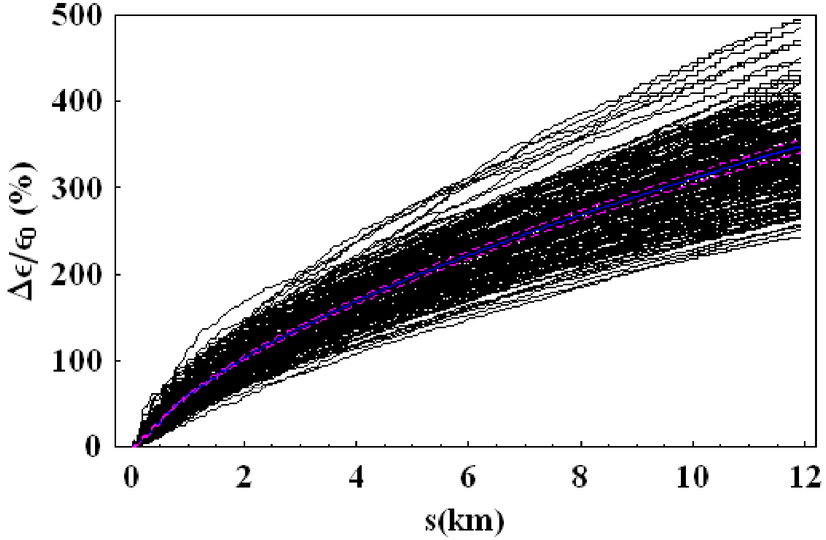


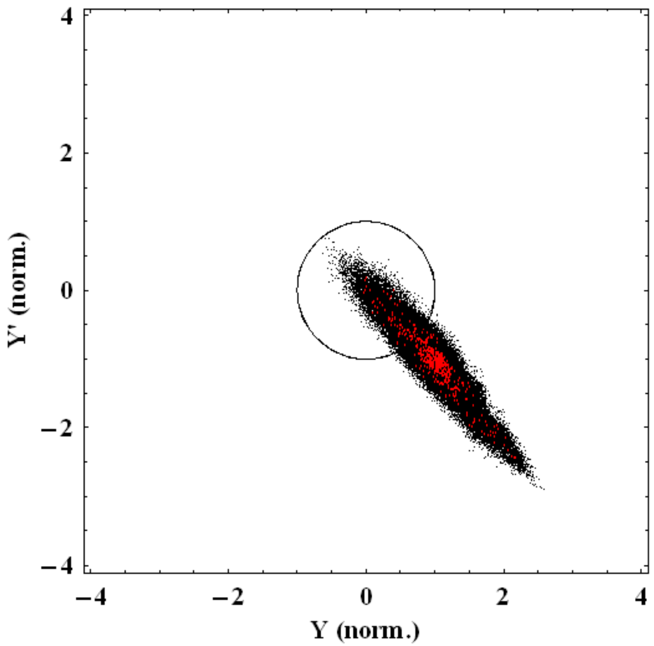
- **Enables the distribution of HOMs to be computer for a whole series of cavities**
- **Multi-module simulations are in progress and have been reported on a PAC07 and SRF07**

3. Degenerate Dipole Mode Rotation and E.M. Field Coupling

- ➢ Vertical emittance dilution from zero vertical injection offset
- ➢ 1 sigma horizontal injection offset







- •500 particles in all simulations and 200 machines shown
- •Initial vertical and horizontal offset 0 μm and 270μm (~ σ_x), respectively.
- •(c.f. initial beam $\sigma_{y,x}$ ~ 10.1 μm, 270 μm)
- •*Fixed azimuthal orientation of couplers.*
- •Long range wakes included in simulations

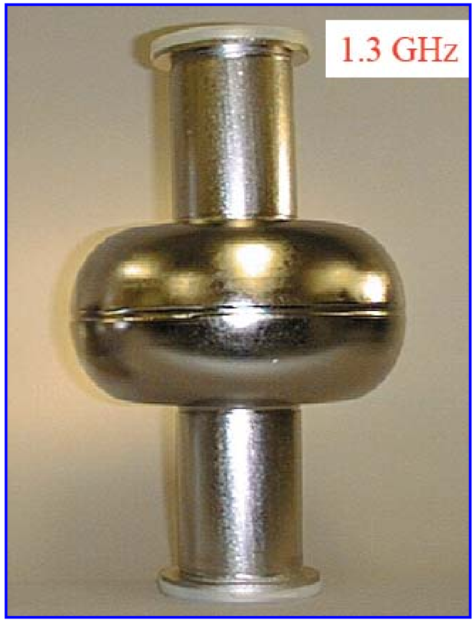
Fixed Azimuthal Phase Distribution (Yoff=0).

3. Degenerate Dipole Mode Rotation and E.M. Field Coupling

- Increase the damping of the HOM modes? At present the damping is ~10^4 - 10^5. It may be difficult to reduce the damping even further?

- The dipole frequency degeneracy's are already split –by ~ 400 kHz to 800 kHz. Increasing the splitting (which can be achieved by making markedly asymmetrical cavities) to say 10 MHz may allow the influence of mode coupling to be minimal over the length of the linac.

- Splitting the tune of the linac. Present design is 60/60 – horizontal/vertical. This may be the most straightforward to implement.



Re-entrant cavity shape is shown. Taken from Rong-Li Geng SRF 2005

Amelioration of Large Emittance Dilution?

4. ILC 3.9 GHz Crab Cavity

CKM Cavity design parameters
3.9 GHz
13 cells length = 0.5 m
B_{max} = 80 mT
E_{max} = 18.6 MV/m
L_{eff} = 0.5 m
$P_{\perp}$ = 5 M V/m

Courtesy: FNAL

The ILC crab cavity is based on the FNAL deflecting mode cavity.

To minimise wakefields for the short time structure of the ILC bunches, the number of cells must be optimised against overall length and new couplers designed.

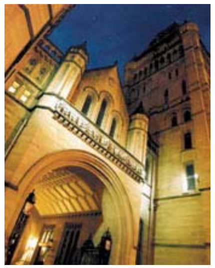
A 3.9 GHz cavity was favoured it is compact longitudinally and transversely.

5. High Precision SC Cavity Alignment/Diagnostics/BPM with HOM Measurements

Nicoleta Baboi, Olivier Napoly, Ursula van Rienen

<u>Roger M. Jones</u>

DESY, CEA Saclay, Univ. of Rostock, Univ. of Manchester/ Cockcroft Inst.



<u>Invited talk at EGARD-OMIA,CERN. Spokesperson on behalf of Accelerator and Beam Studies and HOM FP7 collaboration</u>

Generalized Long-Range Transverse Wakefields

A. Kabel

Advanced Computations Department
Stanford Linear Accelerator Center

December 11, 2007

Coupling:

- Kick factor has to be generalized to a hermitian *kick matrix*
- Real-valued off-diagonal elements can be removed by rotating by δ
- Imaginary ones remain:

$$H - \frac{\sin\omega_t}{2}(p_{\bar{x}}^2 + \beta^2 p_{\bar{y}}^2) - \frac{\alpha}{2}(\bar{x}^2 + \bar{y}^2 (p_x\bar{y} - p_y\bar{x}) \sin\Delta)$$

- (β: amplitude ratio, Δ: phase angle (a, ib^*), $\alpha = \frac{|a|^2 q_l q_t}{2\omega_n \gamma m}$)
- Mode can be characterized by strength α, excentricity $1-\beta^2$, coupling angles δ and Δ.

Conclusion

- Wakefields of realistic cavities may have fewer symmetries: coupling, rotating modes
- Generalized normal-mode expansion formalism: Kick factors need to be replaced by hermitian kick matrices
- We have a toolchain to extract these matrices from high-fidelity frequency-domain calculations and plug them into tracking studies
- Proof-of principle tracking studies with *Lucretia*
- Future studies: 3rd bands, imperfections, misalignments, feedback, ...

HOM measurements at FLASH & SVD data analysis

12th December, 2007

Stephen Molloy,
SLAC

International Linear Collider at Stanford Linear Accelerator Center

Higher Order Modes

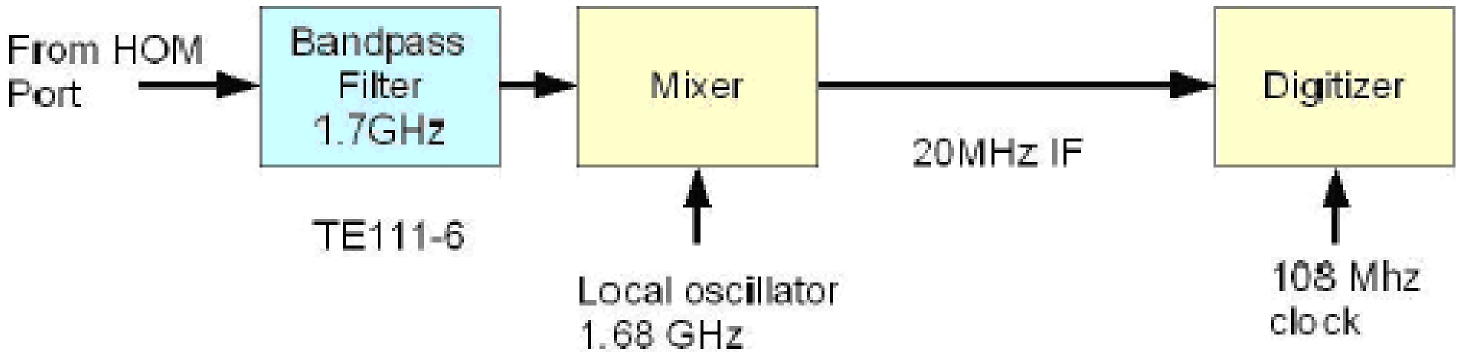
- The 9 cells of the cavities act like coupled resonators.
  - Each standard mode can have 9 different longitudinal distributions.
    - i.e. Different passbands with 9 modes each.
  - Modes distinguished by differing phase advance per cell.
- Modes synchronous with the beam (i.e. phase velocity = *c*) have strongest coupling to the beam,
  - Indicated by a large R/Q.
- Monopole modes,
  - First monopole passband is TM-like, and contains the 1.3 GHz accelerating mode.
  - First higher order monopole band lies between 2.38 – 2.46 GHz.
- Dipole modes,
  - TE-like between 1.6 – 1.8 GHz.
  - TM-like between 1.8 – 1.9 GHz.
- Quadrupole modes,
  - First quadrupole band is at ~2.3 GHz.

Benefits of using HOMs as Diagnostics

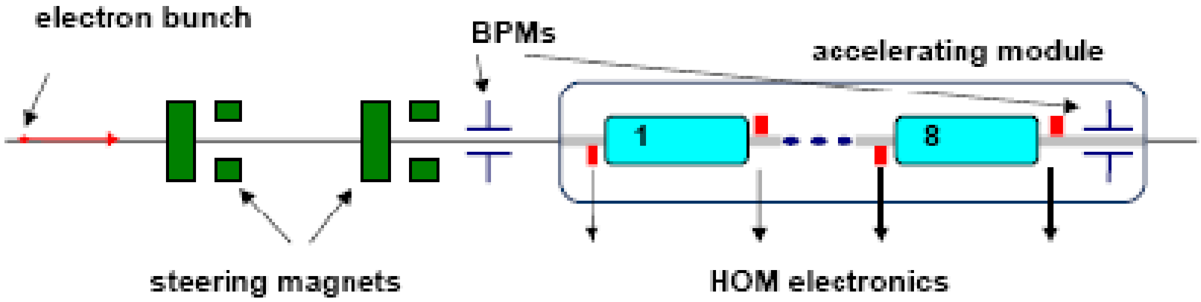
- No need to install new beamline hardware
  - HOM power must be coupled out of the cavities to prevent BBU, etc.
  - Therefore beamline and cryogenic hardware already exists.
- Large proportion of linac length occupied by structures.

Dipole Mode Measurement

- Simulations show that the 6th mode in the 1st passband has a strong coupling to the beam,
  - R/Q = ~5.5 Ohms/cm^2
  - Frequency = ~1.7 GHz
- Design narrow band electronics to observe this mode only.
  - Filter around 1.7 GHz (20 MHz bandwidth)
  - Mix with 1.679 GHz LO
  - Digitise at 108 MHz
- 1.697 GHz tone added before mixer to provide a constant amplitude, 18 MHz, calibration signal.

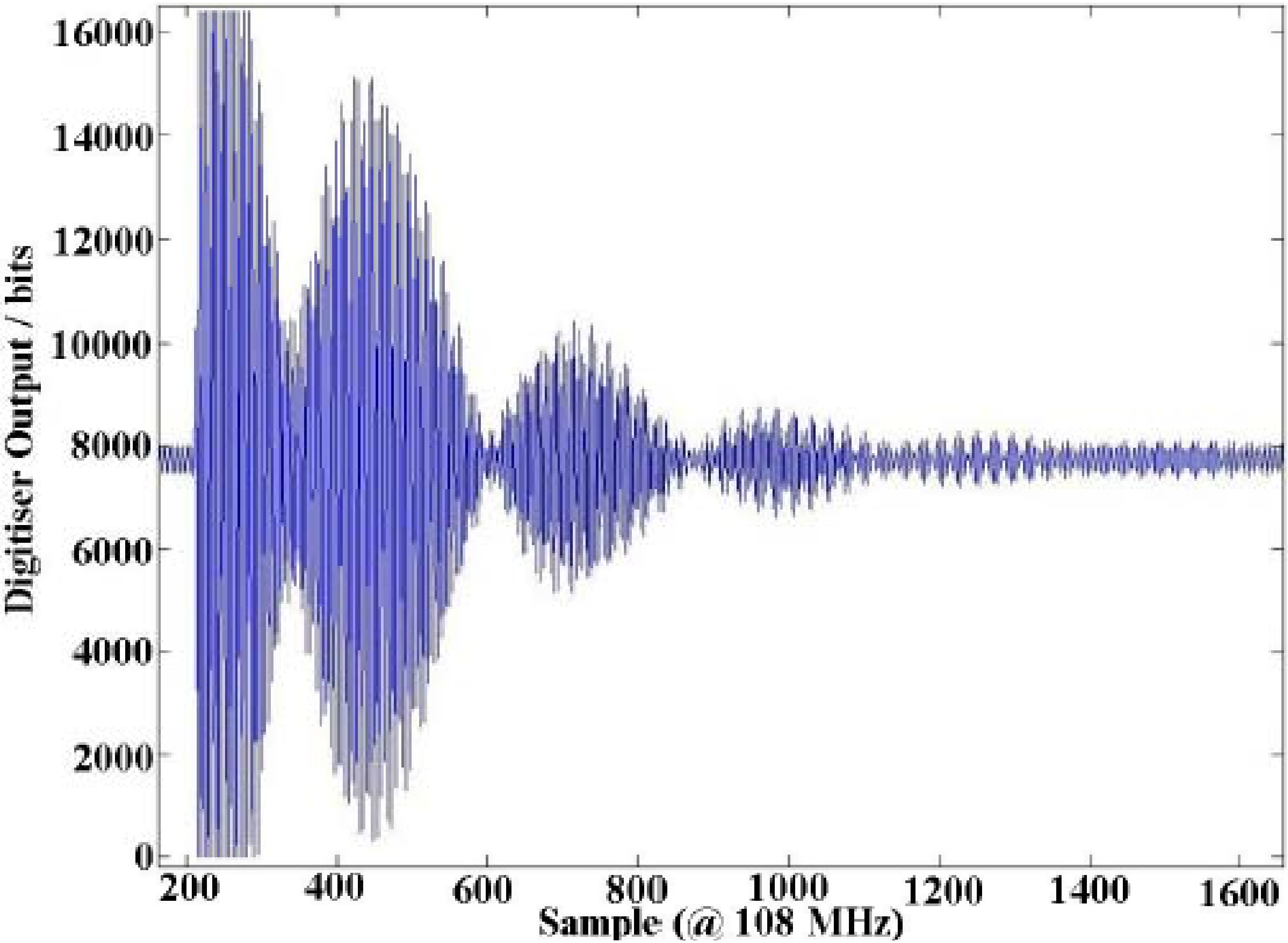


HOM calibration method



- Develop model for the machine
- Steer beam using two correctors upstream of the accelerating module.
  - Try to choose a large range of values in (x,x') and (y,y') phase space.
- Record the response of the mixed-down dipole mode at each steerer setting.

Example Waveform



Analysis – Singular Value Decomposition

- SVD decomposes a matrix, *X*, into the product of three matrices, *U*, *S*, and *V*.
  - *U* and *V* are unitary.
  - *S* is diagonal.
- It finds the "normal eigenvectors" of the dataset.
  - i.e. "modes" whose amplitude changes independently of each other.
  - These may be linear combinations of the expected modes.
- Use a large number of pulses for each cavity.
  - Make sure the beam was moved a significant amount in x, x', y, and y'.
- Does not need *a priori* knowledge of resonance frequency, Q, etc.
  - Similar to a Model Independent Analysis.

Summary

- HOMs have been used to monitor the position of the FLASH beam
- Due to their potentially destructive nature, these modes must be coupled out anyway
  - Thus, beamline hardware already exists
- "Standard" cavity analysis is troublesome (please see next talk)
  - SVD provides a way to extract the information
- Analysis works for multibunch beam
  - Despite high Q / short interbunch time
- Successfully implemented at FLASH as part of their control system

TTF HOM measurement analysis with curve fitting method

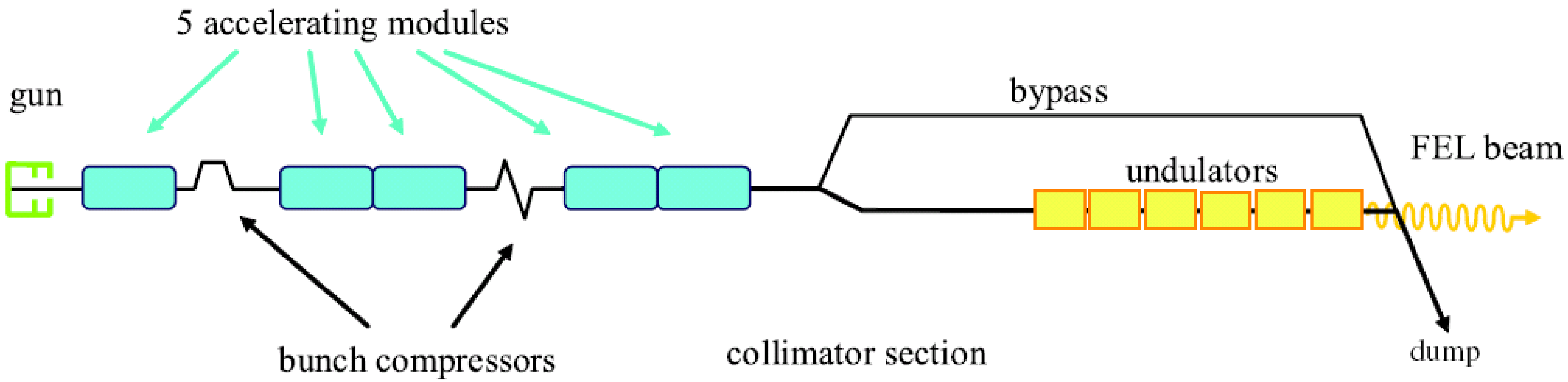
Shilun Pei

with

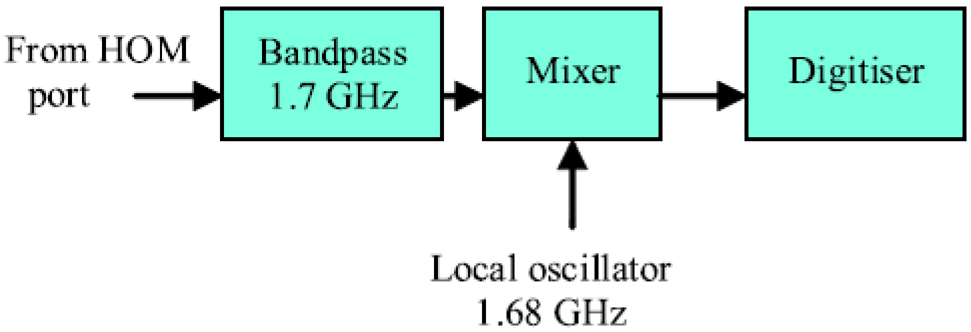
Chris Adolphsen, Zenghai Li, Karl L. Bane, et al.

SLAC, Dec. 12, 2007

Flash facility



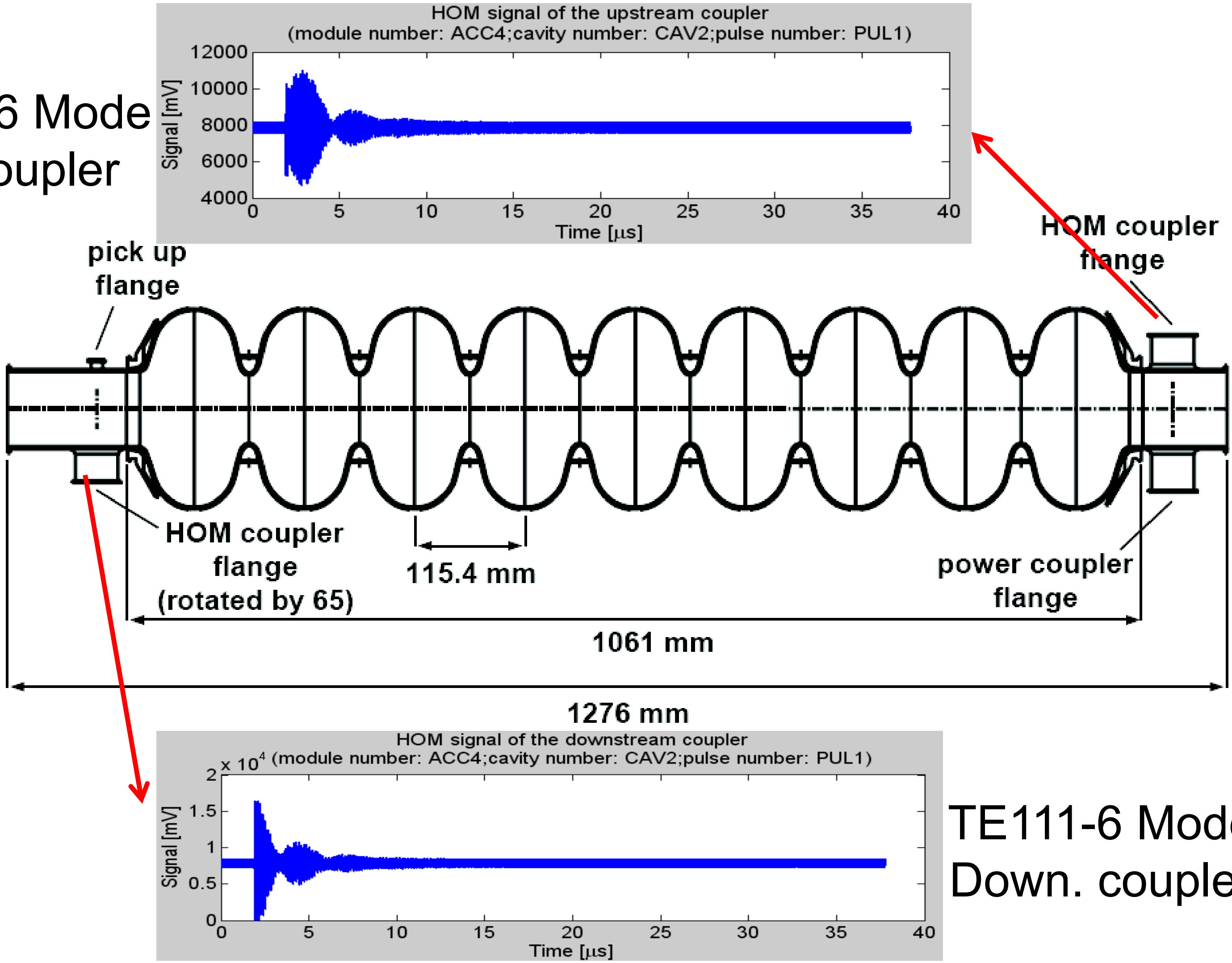
Schematic of Flash facility



Schematic of the mix-down electronics for measurement of the TE111-6 Mode (S. Molloy et al)

Time domain HOM signal

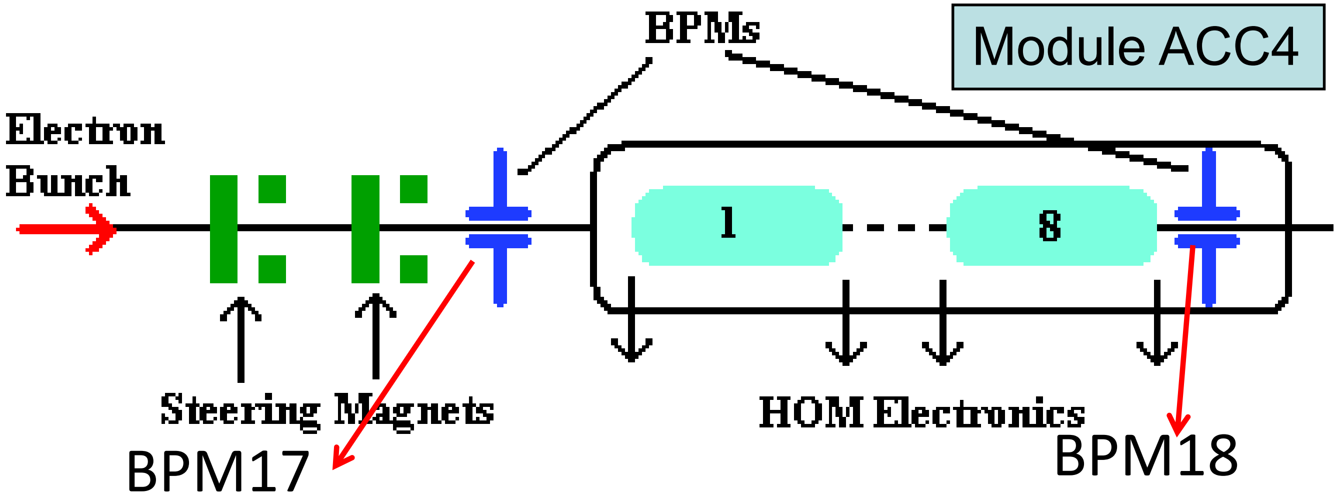
TE111-6 Mode
Up. coupler

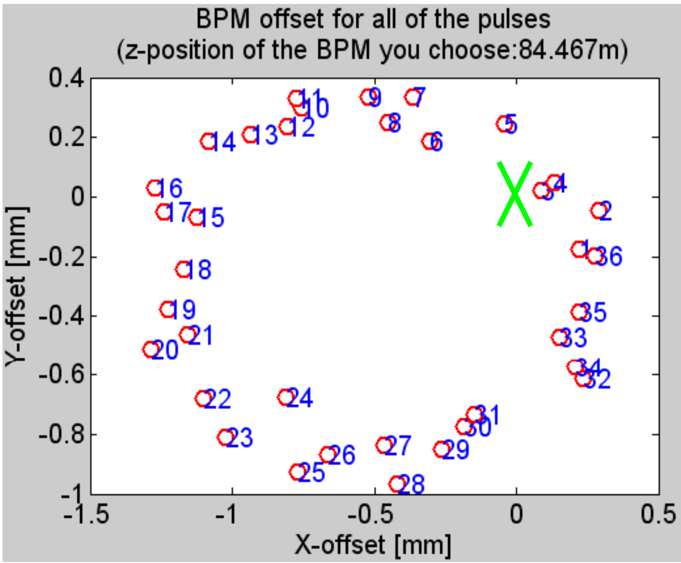


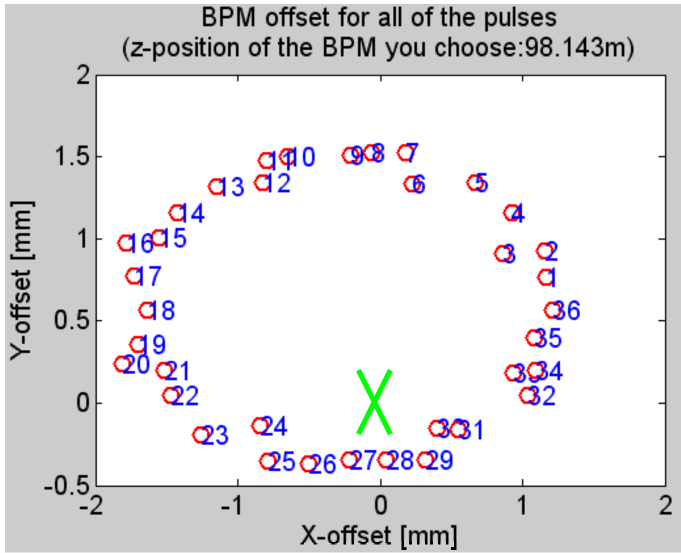
TE111-6 Mode
Down. coupler

2007-01-22T091106.mat (S. Molloy et al)

Steering setup for the experiment





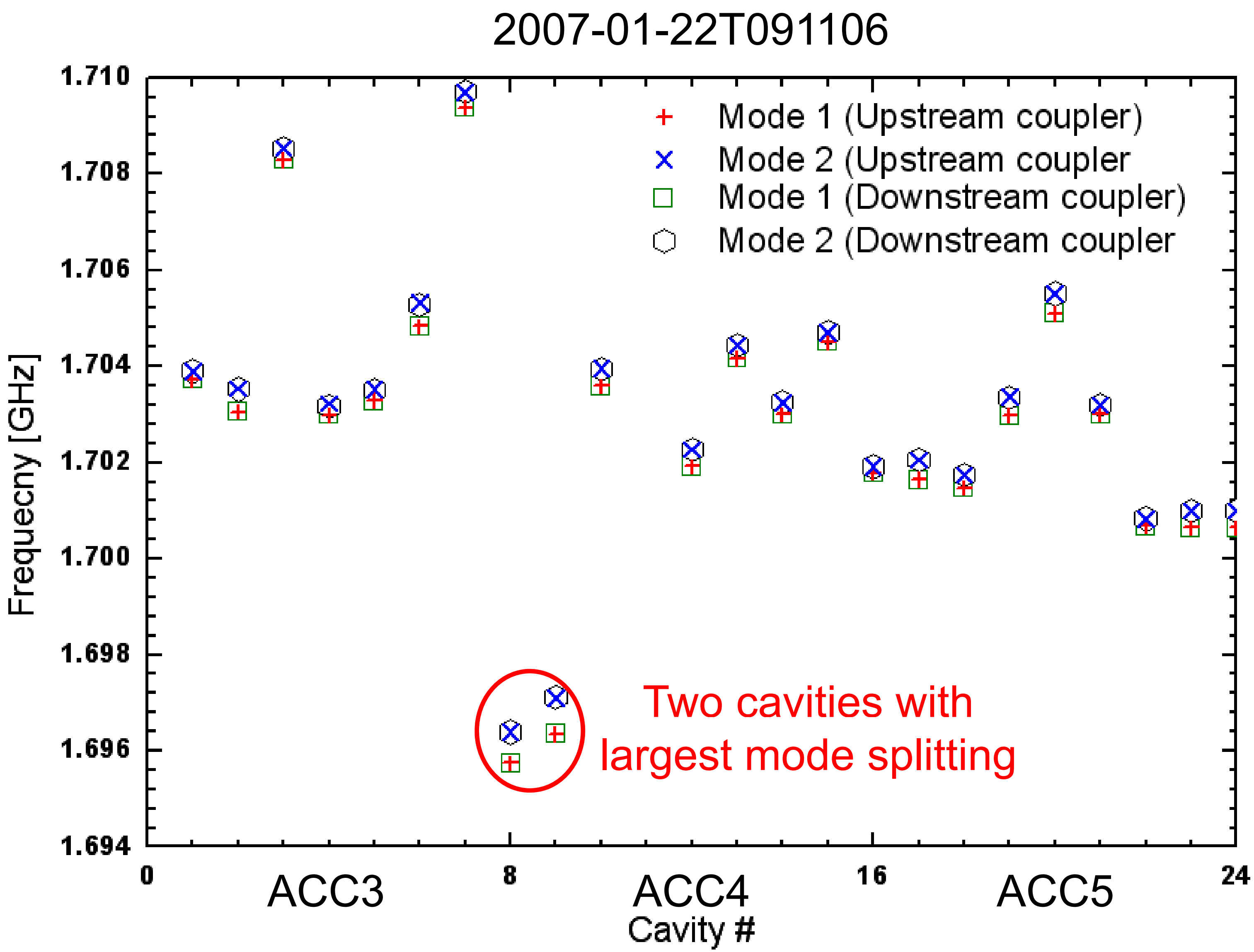


2007-01-22T091106.mat (Stephen Molloy et al)

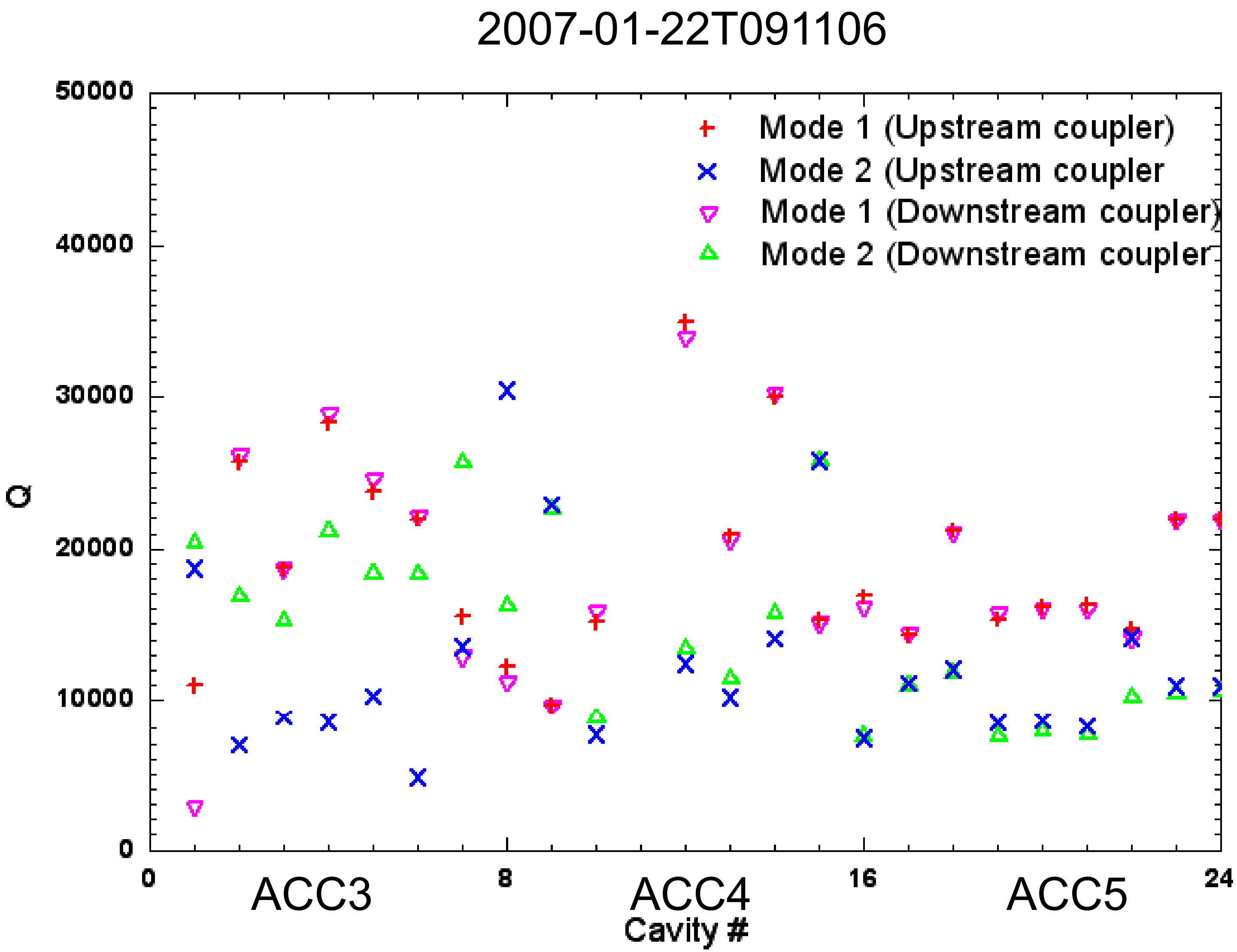
Summary(1)

- We have investigated one new method to analyze the HOM signal data, and some results have been obtained.
- The new method can be used to extract the HOM mode frequency, Q and relative phase from the HOM signal data. On the other hand, this method can also be used to find the HOM mode center, polarization axis, mode axis along the cavity, while careful handling of beam timing information need to be considered both in measurement and analysis.
- Comparing with SVD, this method is more physical, and can also be used in the beam diagnostic data analysis to obtain the beam position and beam trajectory obliquity.

Cavities in ACC3/ACC4/ACC5 (1)



Cavities in ACC3/ACC4/ACC5 (2)



Summary(2)

- More measurements need to be done to get better understanding of HOM mode characteristics.
  - Sampling time or sampling frequency need to be increased to increase frequency resolution.
  - Do the measurements when the beam travel through the cavity along a circle with pure beam offset or the beam travel through the cavity along different beam trajectory with different obliquity angle while the initial beam position is fixed.
  - Try to get the absolute initial angle of the HOM signal in the measurements to separate the HOM signal caused by different sources.
  - ……