RTML Overview (FY08)

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FNAL

- RTML progress in FY08
- Discussion of coupler kick & wake simulation results
- Emittance growth due to coupler in BC
- Magnetic Stray fields measurements
- Summary and future plans

RTML Progress in FY2008

- Simulations of coupler RF kick and wakes and studies of emittance growth in RTML BC
  - **Different bunch length and different end-group geometries**
  - **Documentation:** WakeFest07, EPAC08 (DESY/FNAL/SLAC)
- Design of the Single-stage BC (two designs):
  - BC1S wiggler based – (including re-design of diagnostic and matching section and post-acceleration linac (5→15GeV) - *A.Latina*
  - Alternative chicane BC -*Eun-San Kim*
- Studies of Emittance growth and control in Bunch Compressor
  - **Single stage BC** *(A.Latina/FNAL, E-S.Kim/Korea)*
  - **Two stage BC** *(K.Kubo/KEK, A.Latina/FNAL)*
- ILC-CLIC RTML collaboration:
  - **Dark current**
  - **BPM design**

RTML Progress in FY2008 (2)

- Design and preliminary studies of all three Pulsed Extraction Lines for emergency beam abort (MPS) and tune-up *(S. Seletskiy)*
  - **Different beam parameters and requirements**
  - **Specifications for all elements (magnets, kickers, septum magnets, collimators, etc.)**
  - **Documentation: Report, SLAC preprint, EPAC08**
- Magnetic Stray field studies (requirements for return line <2nT) – *(D. Sergatskov)*
  - **ILC: H < 2 nT (f>1Hz); CLIC: H< 0.2 nT (f>10Hz)**
  - **Measurements in A0/FNAL area, demonstrated ~3nT**
- Code development
  - **Support and develop codes, incorporation of a new physics (coupler kick and wake) and BBA algorithms in codes:**
    - Merlin, Placet, Sad, Lucretia (FNAL&Dehli Univ)and CHEF
    - GdFidL on computer farm to support wake field and dark current simulations.
  - **cross-checking results** *(Kruecker/Latina/Kubo/Ostiguy):*
    - Lucretia/SAD/Merlin/ Placet (RF kick/wake- Dehli Univ/FNAL)
    - CHEF vs. Lucretia – DFS algorithm in ML

RTML Progress in FY2008 (3)

Technical Systems:

- Re-evaluation of the Vacuum system for RTML return line *(Xiao Qiong, IHEP/China)*
  - **Conceptual design of vacuum system and specs for SS passivated and non-passivated tubes.**
  - **Component counts and Cost estimation.**
- Magnetic Stray field studies (requirements for return line <2nT) – *(D.Sergatskov)*
  - **ILC: H < 2 nT (f>1Hz); CLIC: H< 0.2 nT (f>10Hz)**
  - **Measurements in A0/FNAL area, demonstrated ~3nT**
- Design and prototyping of the SC quadrupole for RTML cryomodule and Low energy part of the ML *(V.Kashikhin)*
  - **First prototype was built and tested. Studies of stability of the center underway.**
- Ground Motion studies at Fermilab site *(J.Volk)*
  - **Effect of natural sources of motion (tides, rain fall, earth quakes) and cultural sources (sump pumps, cryoplant, etc.)**
  - **Lot's of multi-year measurements in Aurora mine, MiINOS hall available for analysis and models for emittance studies**

Emittance Growth in RTML

Summary of Studies (LET meeting, Dec.2007 SLAC)

Region	BBA method	Dispersive or chromatic mean emittance growth	Coupling mean emittance growth
Return Line	KM and FF to remove beam jitter	0.15 nm	2 nm (with correction)
Turn around Spin rotator	KM and Skew coupling correction	1.52 nm (mostly chromatic)	0.4 nm (after correction)
Bunch Compressor	KM or DFS and Dispersion bumps	>5 nm (KM+bumps) 2.7 nm (DFS+bumps)	0.6 nm (w/o correction)
Total		~5 nm almost all from BC	3nm (w/o complete correction)

- Effect of coupler RF kick & wakes and Dynamic effects are not included
- Emittance growth is large (pre-RDR budget 4nm, might be ≤10nm)
- Need further studies to reach goals for emittance growth
- Cross-checking with different codes (important)

Effect of coupler on emittance growth

- Couplers introduce transverse RF kick and wakes (DESY 2007)
- Effect of coupler is significant for long bunch in RTML BC.
- Can be compensated by adjusting CM tilt or using crab cavities

Summary Tables of the vertical emittance growth, induced by the Coupler RF-Kick and Wakes in perfectly aligned BC.

Single-stage BC +post-acceleration 5-15 GeV

Correction algorithm	$\Delta\varepsilon_y$ - RF kick	$\Delta\varepsilon_y$ -Wakes	$\Delta\varepsilon_y$ Total
1-to-1 correction + bumps	1.9 nm	1.4 nm	3.4 nm
+ crab cavity correction*			0.47 nm*
+ Girder pitch optimization**			0.4 nm**

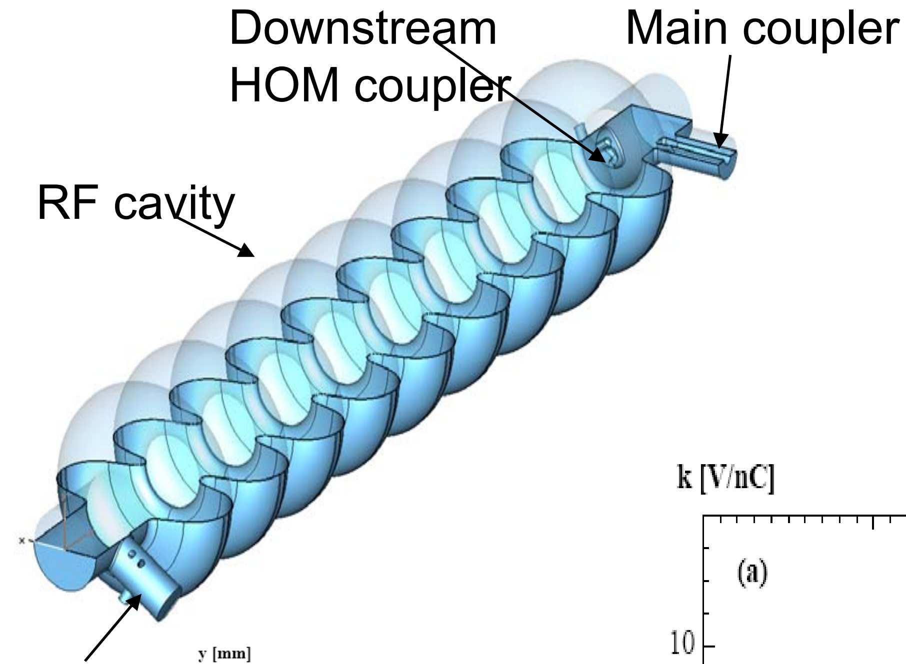
* Each CM have CC at the end, replacing one of the ILC cavity
** Range of CM tilt ~30urad (~300 um displacement with step resolution ~10um)

Baseline design: BC1+BC2

Correction algorithm	$\Delta\varepsilon_y$ -RF kick	$\Delta\varepsilon_y$-Wakes	$\Delta\varepsilon_y$-Total
1-to-1 corr. + bumps	1.59 nm	2.8 nm	5.5 nm
1-to-1corr.+Skew corr			2.5 nm
Girder pitch optimization			0.58 nm

Girder (CM) pitch optimization is very effective for emittance control

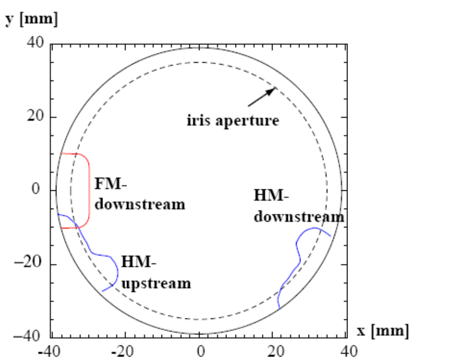
Simulations of Coupler Kick and Wakes



The couplers break the RF field symmetry and cause transverse RF kick and Wakes DESY,2007. Simulations: DESY/FNAL/SLAC

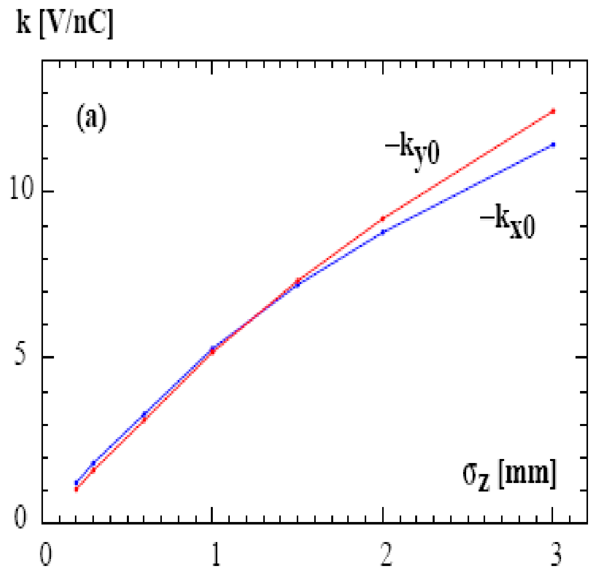
Total RF KICK (FNAL):

$$\frac{\vec{V}_{\perp}}{V_a} \times 10^6 = \begin{pmatrix} -105.3 + 69.8i \\ -7.3 + 11.1i \end{pmatrix}$$

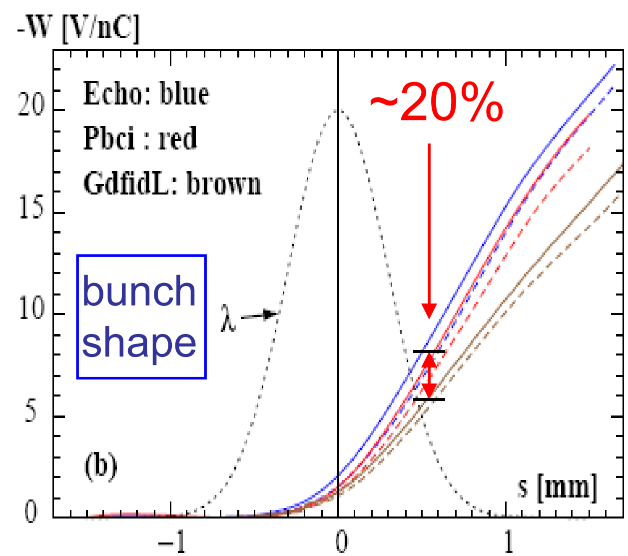


The profiles of the 3 couplers, as seen from the downstream end.

Coupler Transverse Wakefield



On-axis kick factor vs. σ_z



$W_x(s)$-solid,, $W_y(s)$-dashed for σ_z = 300 μm.

Status of RF–kick calculation

Three groups made rf kick simulations:

- *FNAL: N. Solyak, et al, EPAC2008, MOPP042*
- *DESY: I. Zagorodnov, and M. Dohlus, LCWS/ILC 2007*
- *SLAC: K.L.F. Bane, et al, EPAC2008, TUPP019*

ALL the three groups have different results !

	FNAL $Q=3.5\times10^6$ HFSS	DESY $Q=2.5\times10^6$ MAFIA	SLAC $Q=3.5\times10^6$ OMEGA3P
$10^6 \cdot (V_x/V_z)$	-105.3+69.8i	-82.1+58.1i	-88.3-60.2i*
$10^6 \cdot (V_y/V_z)$	-7.3+11.1i	-9.2+1.8i	-4.6+5.6i

*Probably, typo

- The most critical is vertical rf kick. Acceptable vertical emittance dilution in the ILC linac is to be ≤5 nm. (maybe a little more???)
- Emittance dilution is proportional to the rf kick squared. Calculated vertical kick differs ~6 times ➔ emittance dilution caused by rf kick ONLY may differ ~36 times!

Why difference ?

Main reasons:

- ✓ Effect is extremely small, about 5-6 orders of magnitude smaller than the longitudinal fields in cavity;
- ✓ In additions, cancelation takes place between upstream and downstream coupler.

It demands very high precision of the field simulations, better than 10^{-6}, that is a severe challenge for all numerical methods and codes.

Possible other reasons:

- ✓ Different calculated geometries or numerical models;
- ✓ Different assumptions (loaded Q, etc);
- ✓ Different numerical approximation of the fields (in some codes E and H fields are calculated with different precision that should be taken into account);
- ✓ Different methodical convergence for the methods used.

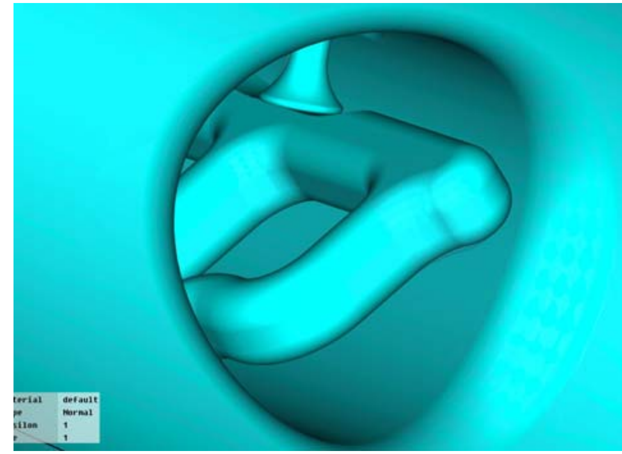
Geometry ?

- FNAL and SLAC compared geometries. As a result, vertical rf kick ($V_y/V_z \times 10^{-6}$) calculated by SLAC, changed from

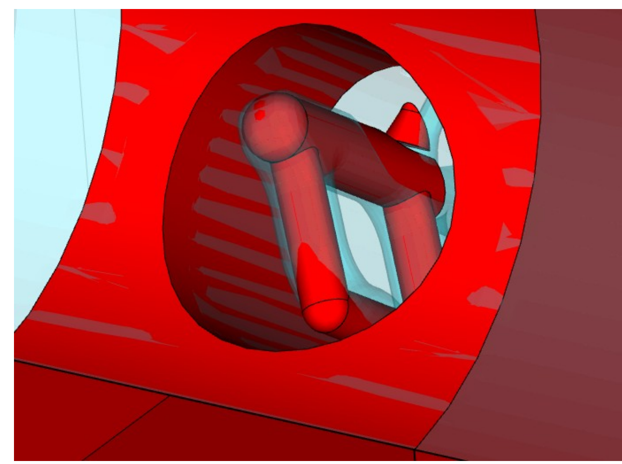
  -22.4+6.1i* to **-4.6 +5.6i****

- DESY (I. Zagorodnov) provided to FNAL the geometry used for simulations. Difference is found in the geometry description (no rounding, simplified coupler geometry, etc). Geometry was used for wake calculation. We have no information whether it was used for rf kick.

**Z. Li, Wake Fest 2007; ** K.L.F. Bane, et al, EPAC2008*



FNAL and SLAC (the same now, but the results still differ)



DESY (red) and FNAL (blue)

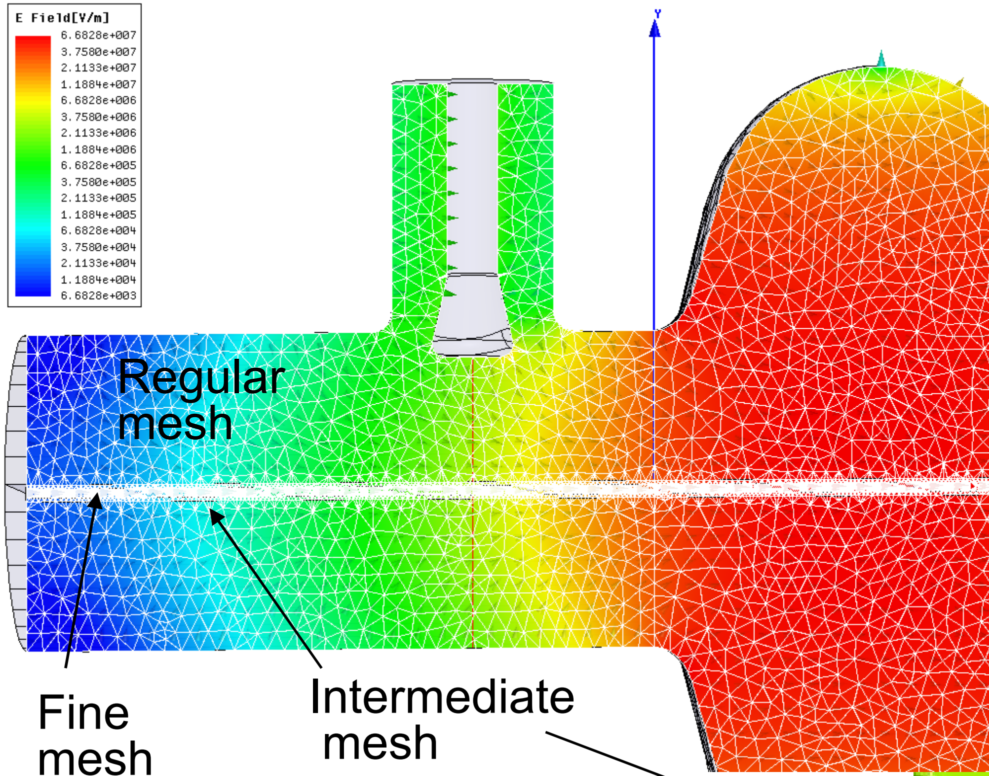
FNAL approach:

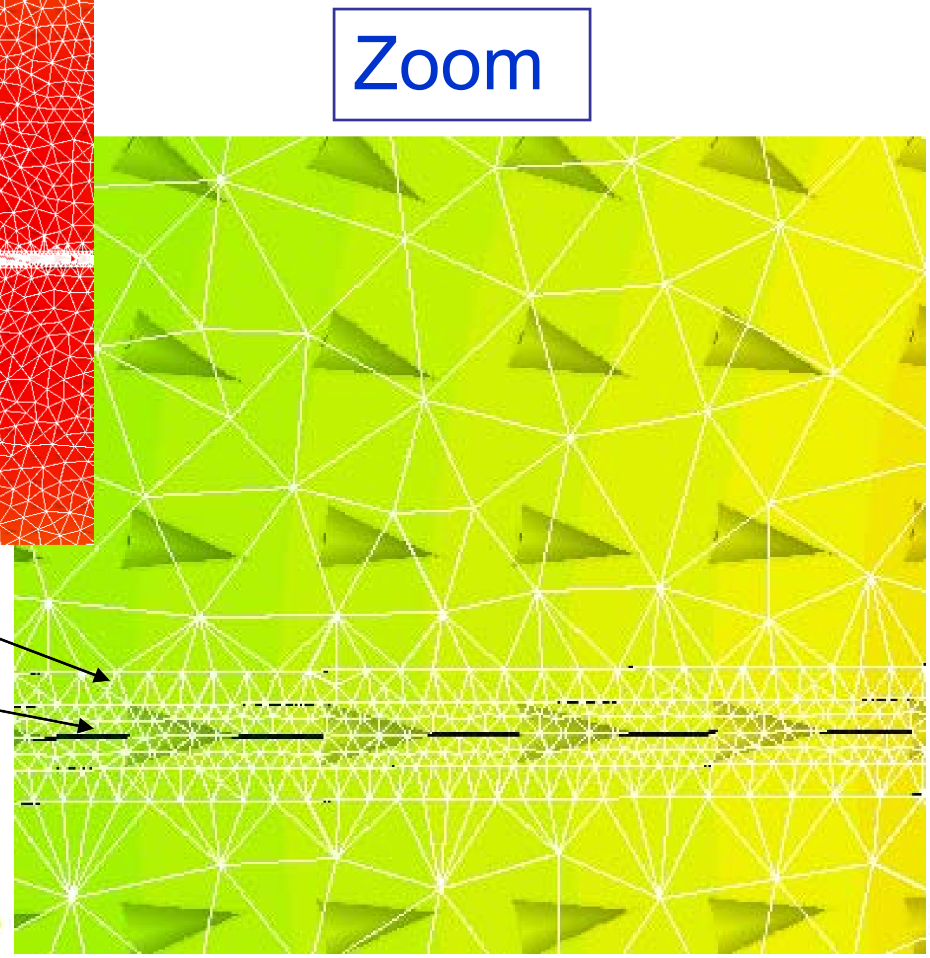
- HFSS code that allows the non-uniform mesh;
- A special three-zone mesh that allows accurate filed description near the axis.
- Intermediate mesh necessary to match the fine mesh near the axis and regular mesh in the rest of the cavity;
- A special symmetrized mesh pattern was used in order to reduce the mesh noise. Different ways of the mesh symmetrization near the axis were used;
- The number of mesh nodes was up to 0.5×10^6;
- Cross-check of the direct rf kick calculations by Panofsky – Wenzel theorem application;
- Investigation of the numerical noise influence.

An attempt was done to apply Micro Wave Studio, but it demonstrate poor convergence and strong noise. However, it's results do not contradict to the HFSS results.

Remember, that FNAL results for kick is larger, than other groups and emittance growth results are the most pessimistic!

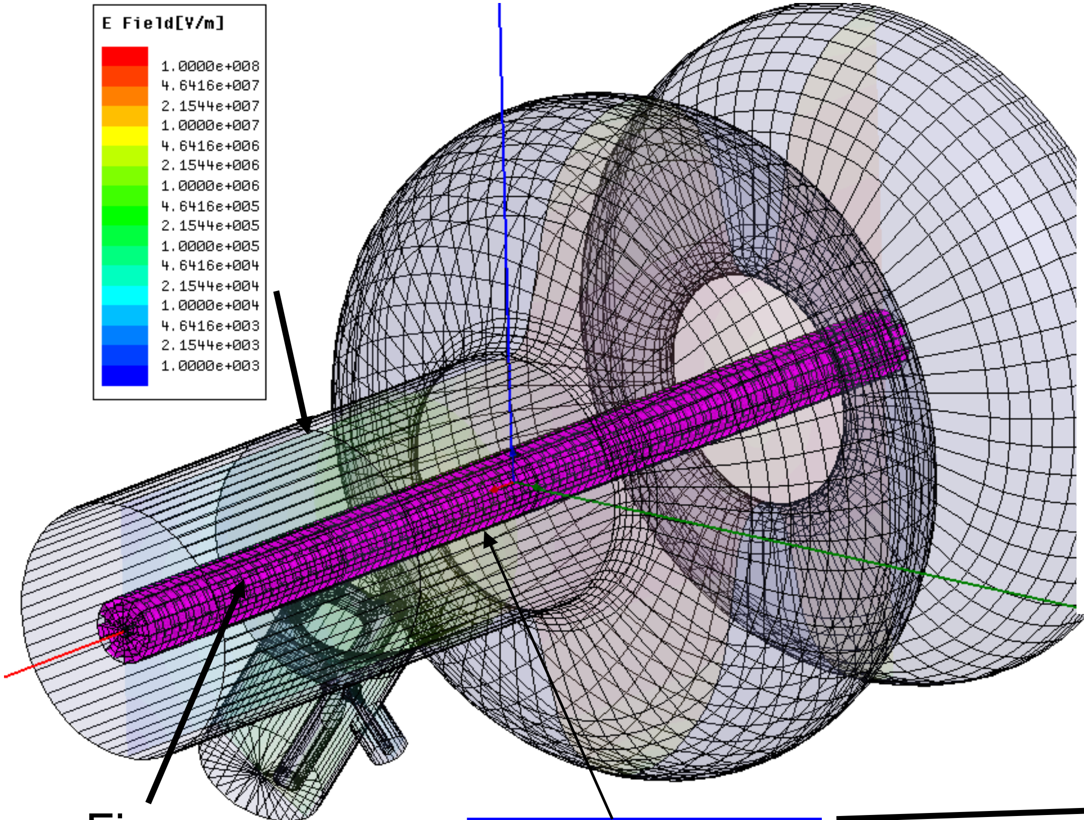
Mesh generation for HFSS for high-precision field calculations near the axis:



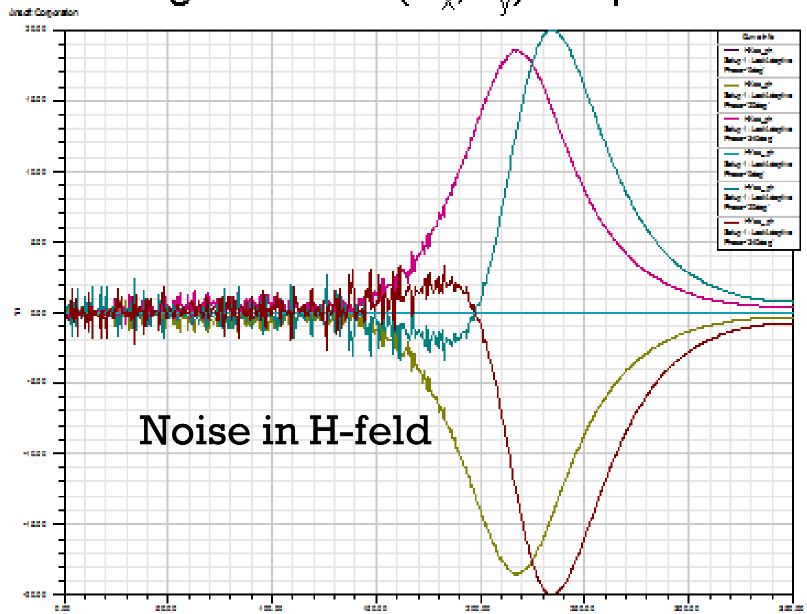


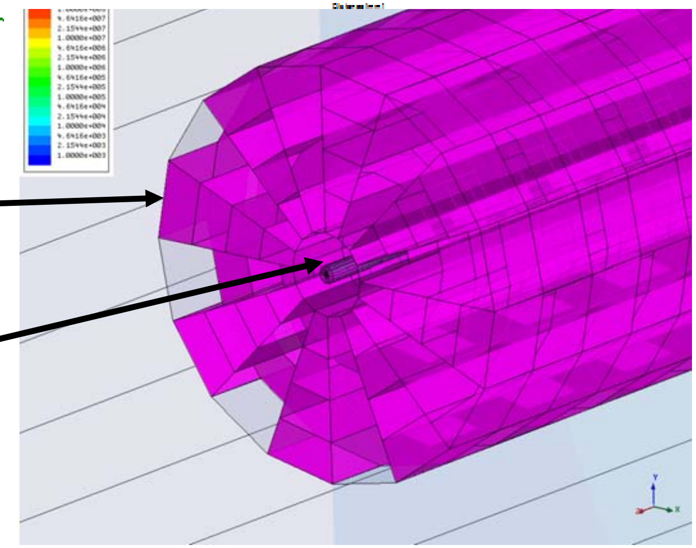
Total number of the mesh nodes is up to 500,000

Symmetrized mesh pattern with reduced noise



Magnetic field (H_x,H_y) snapshots





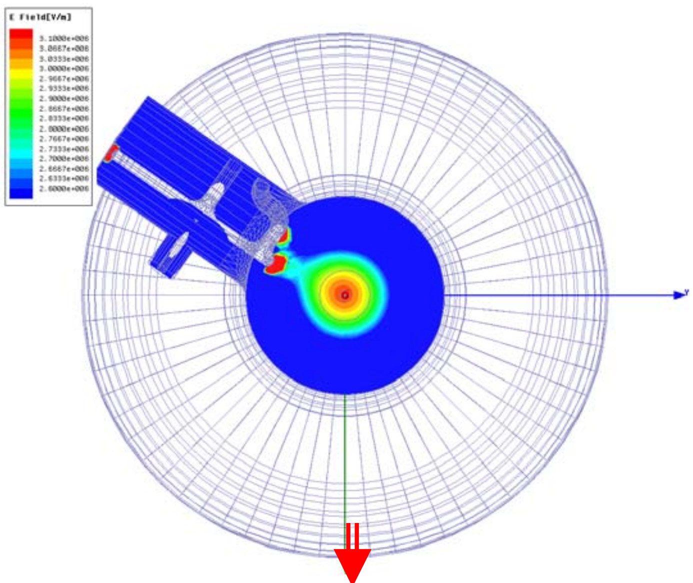
Fine mesh

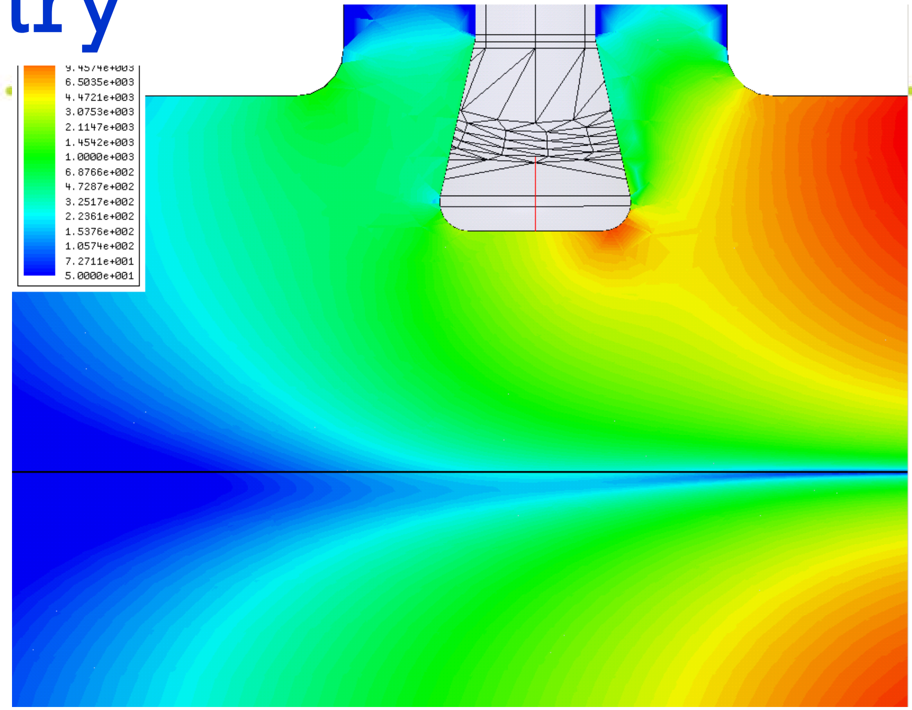
Intermediate mesh

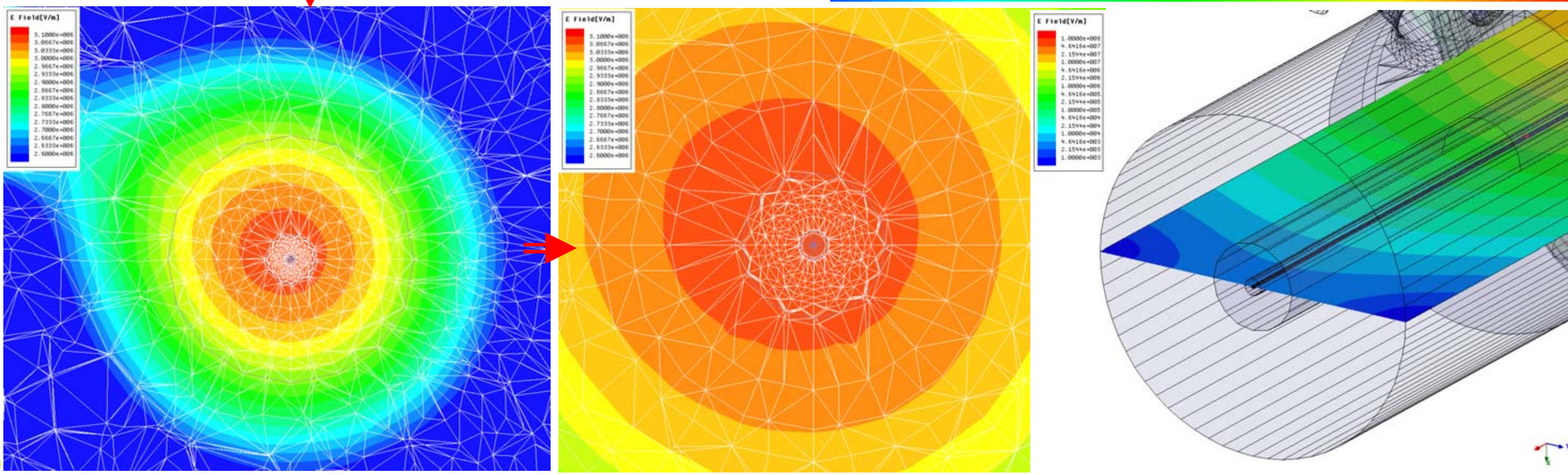
Fine mesh

Fine mesh repeats the pattern of the intermediate one.

Field asymmetry



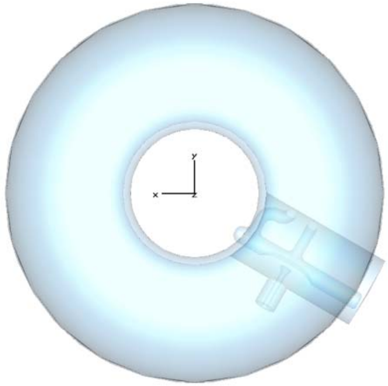




Results of kick calculations

RF KICK: UPSTREAM END

	direct	PW
$10^6 \cdot V_{x}/V_z$	-68.8+3.7i	-65.6+7.6i
$10^6 \cdot V_{y}/V_z$	-48.3-3.4i	-53.1-2.1i



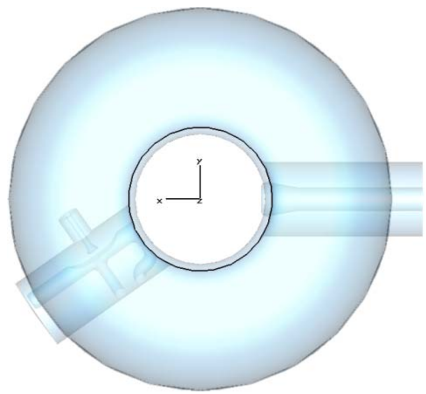
$$Vx := \int_0^{Zend} \left[(EX(z) - HY(z)) \cdot \exp\left[i \cdot (\kappa \cdot z - \phi) \right] \right] dz$$

$$Vy := \int_0^{Zend} \left[(EY(z) + HX(z)) \cdot \exp\left[i \cdot (\kappa \cdot z - \phi) \right] \right] dz$$

Direct integration of fields component (Lorentz force equation)

RF KICK. DOWNSTREAM END

	direct	PW
$10^6 \cdot V_{x}/V_z$	-36.5+66.1i	-27.3+67.2i
$10^6 \cdot V_{y}/V_z$	41.0+14.5i	40.9+12.8i



$$\Delta \vec{V}_{\perp} = i \frac{v}{\omega} \vec{\nabla}_{\perp} (\Delta V_{II})$$

Panofsky-Wenzel (PW) theorem

(in order to cross-check direct calculations only)

TOTAL RF KICK:

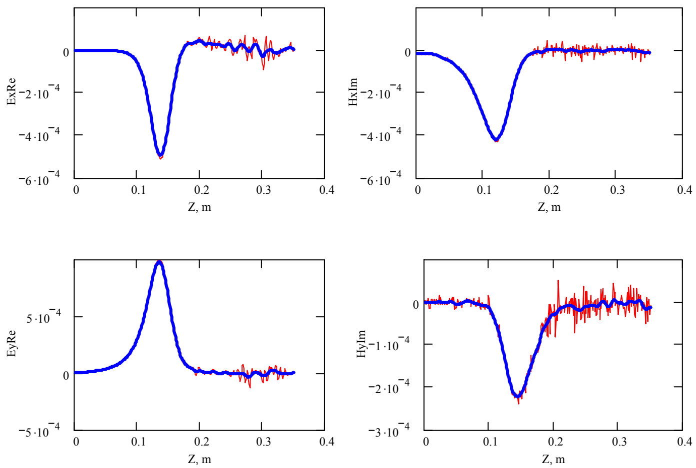
	direct	PW
$10^6 \cdot V_{x}/V_z$	-105.3+69.8i	-92.9+74.8i
$10^6 \cdot V_{y}/V_z$	-7.3*+11.1i	-12.2+10.7i

#MWS simulations were done as well, and the results are consistent to the result of HFSS simulations.

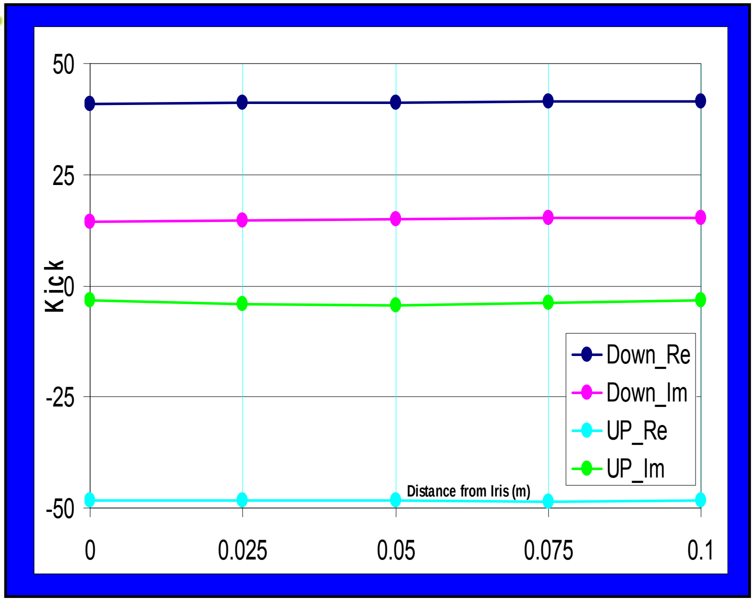
**Cancellation between upstream and downstream couplers!*

Kick dependence on the integration path

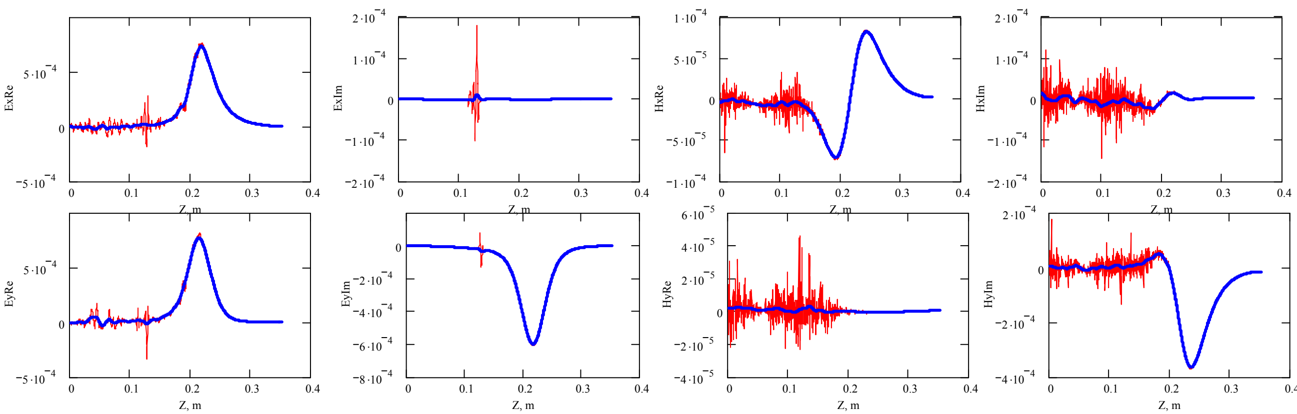
UPSTREAM HOME



Z_{end}	Re	Im
0.35	-48.3	-3.40
0.325	-48.44	-3.85
0.3	-48.2	-4.33
0.275	-48.3	-4.12
0.25	-48.34	-3.35



DOWNSTREAM HOME+PC



Z_{end}	Re	Im
0	40.87	14.32
0.025	41.13	14.55
0.05	41.24	15.0
0.075	41.44	15.24
0.1	41.47	15.32

No dependence, that means that the cavity fields do not contribute to the kick.

Conclusion:

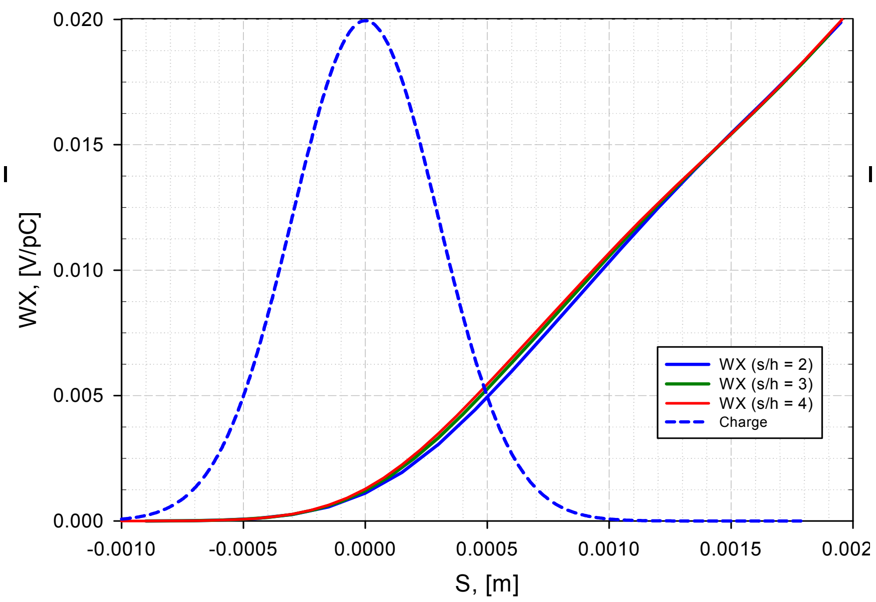
- In emittance simulations we are using the biggest value of the rf kick, which may be over-estimated;
- It is not critical for the main linac, where effect of the rf kick is negligible, but may be critical for BC.

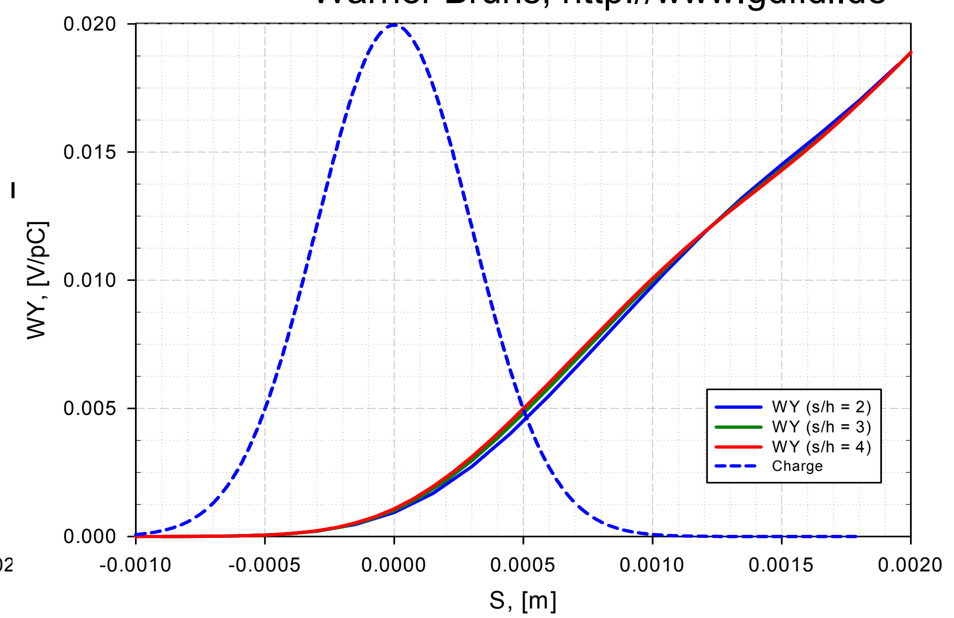
The results of the three groups are to be cross-checked!

The GdfidL Wakefield Simulations*

- Coupler wakefields, calculated by GdfidL are lower , than DESY and Weiland results (less than 20%).
- FNAL demonstrated convergence of results in term of mesh size (see results below) and length of the system (number of cavities) for bunch length from 0.2 mm to 9mm. It were very time consuming simulations. Other groups do not confirm convergence of presented results.

* Warner Bruns, http://www.gdfidl.de





The wake field wake dependence on the longitudinal coordinate *s* for different mesh size (σ =0.3 mm).

What is important for the emittance dilution

Simple model, β = const along the linac.

$$\frac{dP_y}{dt} = F_{focus} + F_{kick},$$

$$F_{kick} = G \cdot \left(\mathrm{Re}\left(\upsilon_y e^{iks+i\varphi}\right)\right) + Q \cdot W_y(0,0,s) \approx$$

$$G \cdot \left(\mathrm{Re}\left(\upsilon_y e^{i\varphi}\right)\cos(ks) - \mathrm{Im}\left(\upsilon_y e^{i\varphi}\right) \cdot ks\right) + Q \cdot W_y(0,0,0) + Q \cdot W_y' \cdot s \approx$$

$$\left[G \cdot \mathrm{Re}\left(\upsilon_y e^{i\varphi}\right) + Q \cdot W_y(0,0,0)\right] + \left[Q \cdot \frac{\partial W_y}{\partial s} - G \cdot k \cdot \mathrm{Im}\left(\upsilon_y e^{i\varphi}\right)\right] \cdot s \equiv F_0 + s \cdot F'$$

where: *G - acceleration gradient, Q - drive bunch charge,*
$k=2\pi/\lambda_{RF}$; λ_{RF} - RF wavelength, φ - RF phase,
$\upsilon_y=(V_y/V_z)$ - RF kick; W_y-vertical wake potential per unit length,
s - distance from the bunch center, $s<<\lambda_{RF}$.

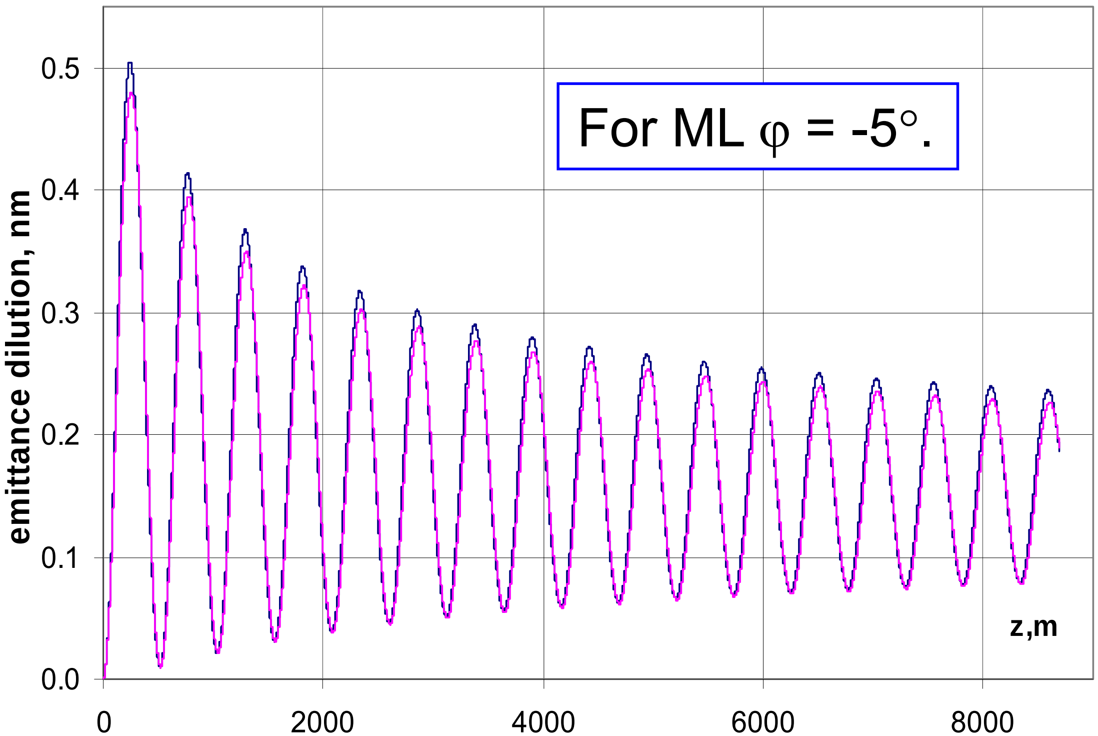
- The first term is responsible for force that acts on the bunch particles the same way, and, thus, may be compensated using the beam alignment technique (if this term is small enough).
- The second term is responsible for the kick different for the different parts of the bunch and, thus, cannot be compensated.

$$\frac{\partial^2 y}{\partial z^2} + \frac{1}{\gamma(z)} \cdot \frac{\partial \gamma(z)}{\partial z} \cdot \frac{\partial y}{\partial z} + \frac{y}{\beta^2} = \frac{F' s \gamma(0)}{U_0 \gamma(z)},$$

Equation of motion

$$\varepsilon \approx \varepsilon_0 + \frac{(F')^2 \sigma^2 \beta^3 \gamma_0}{2U_0^2} \left(1 - 2\sqrt{\frac{\gamma_0}{\gamma(z)}} \cos(z/\beta) + \frac{\gamma_0}{\gamma(z)} \right)$$

Emittance dilution



Emittance change vs. *z* calculated numerically using PLACET (red) and analytically (blue).

$$\Delta\varepsilon \sim \left[Q \frac{\partial W_y}{\partial s} - G \cdot k \cdot \mathrm{Im}\left(\upsilon_y e^{i\varphi}\right) \right]^2 \sigma^2$$

- $\partial W_y / \partial s < 0,$
- $-k\,\mathrm{Im}\left(\frac{V_y}{V_z} e^{i\varphi} \right) < 0.$

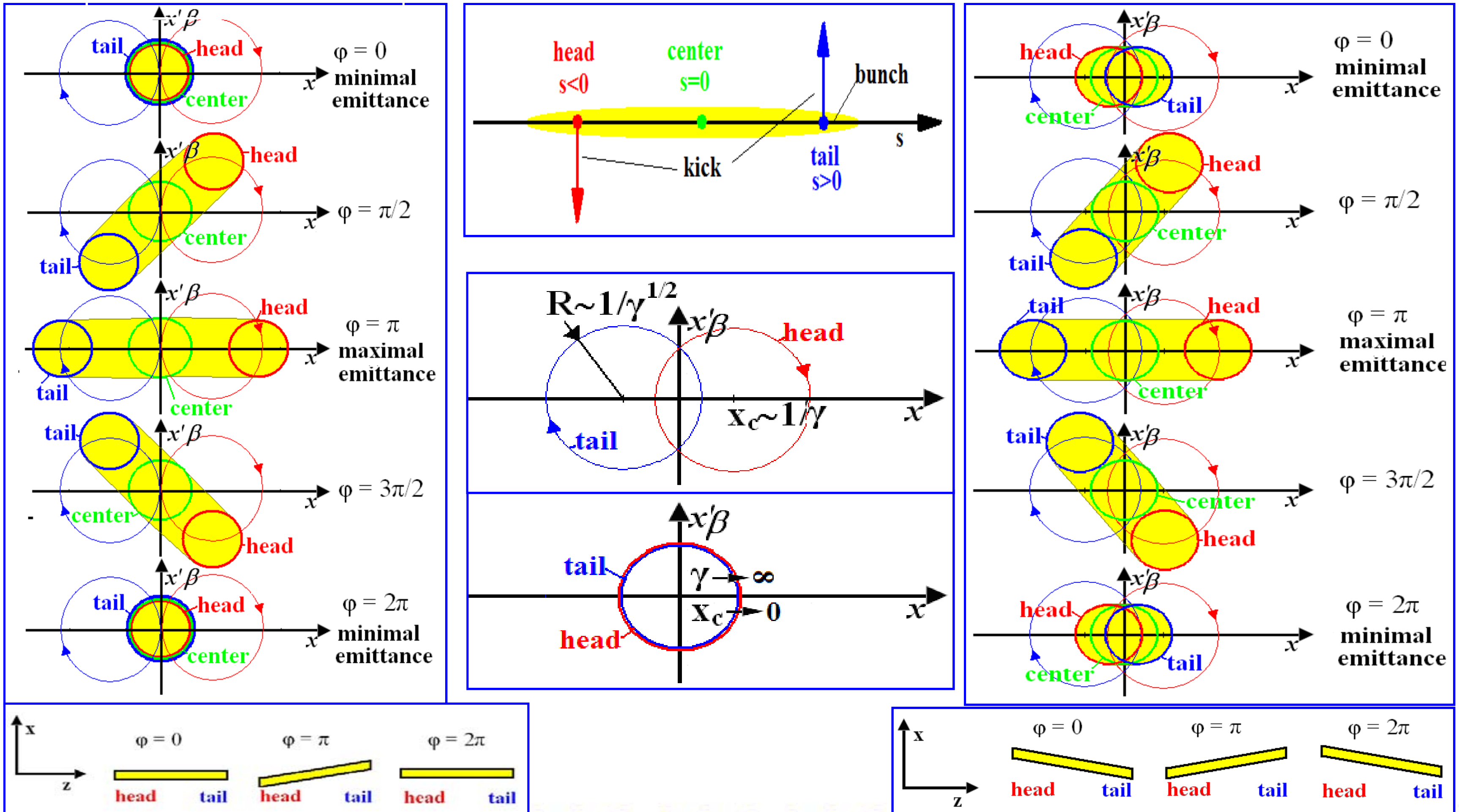
- No compensation
- Emittance dilution is higher for longer bunch. Biggest effect for BC

How it works ?

RF kick and wake caused by the couplers depend strongly on the particle position inside the beam, but not on the transverse coordinate.

No acceleration

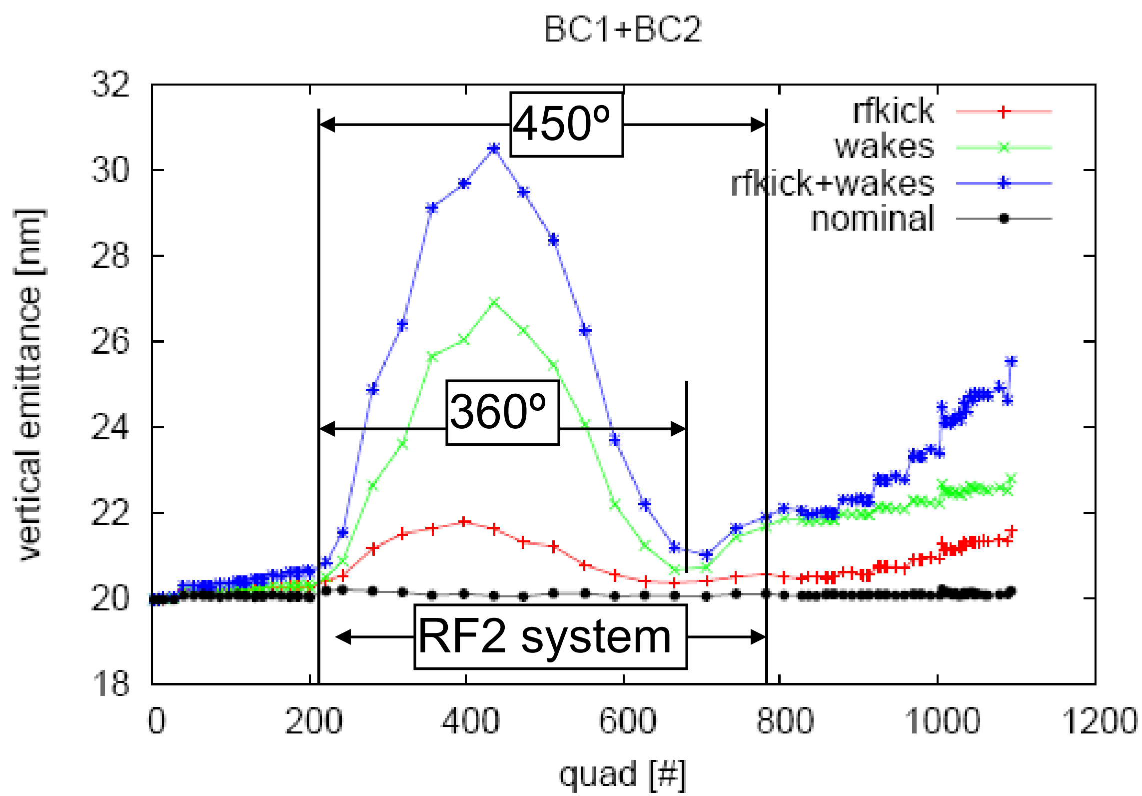
Acceleration



RF-Kick and Wakefields in the Couplers in BC1+BC2

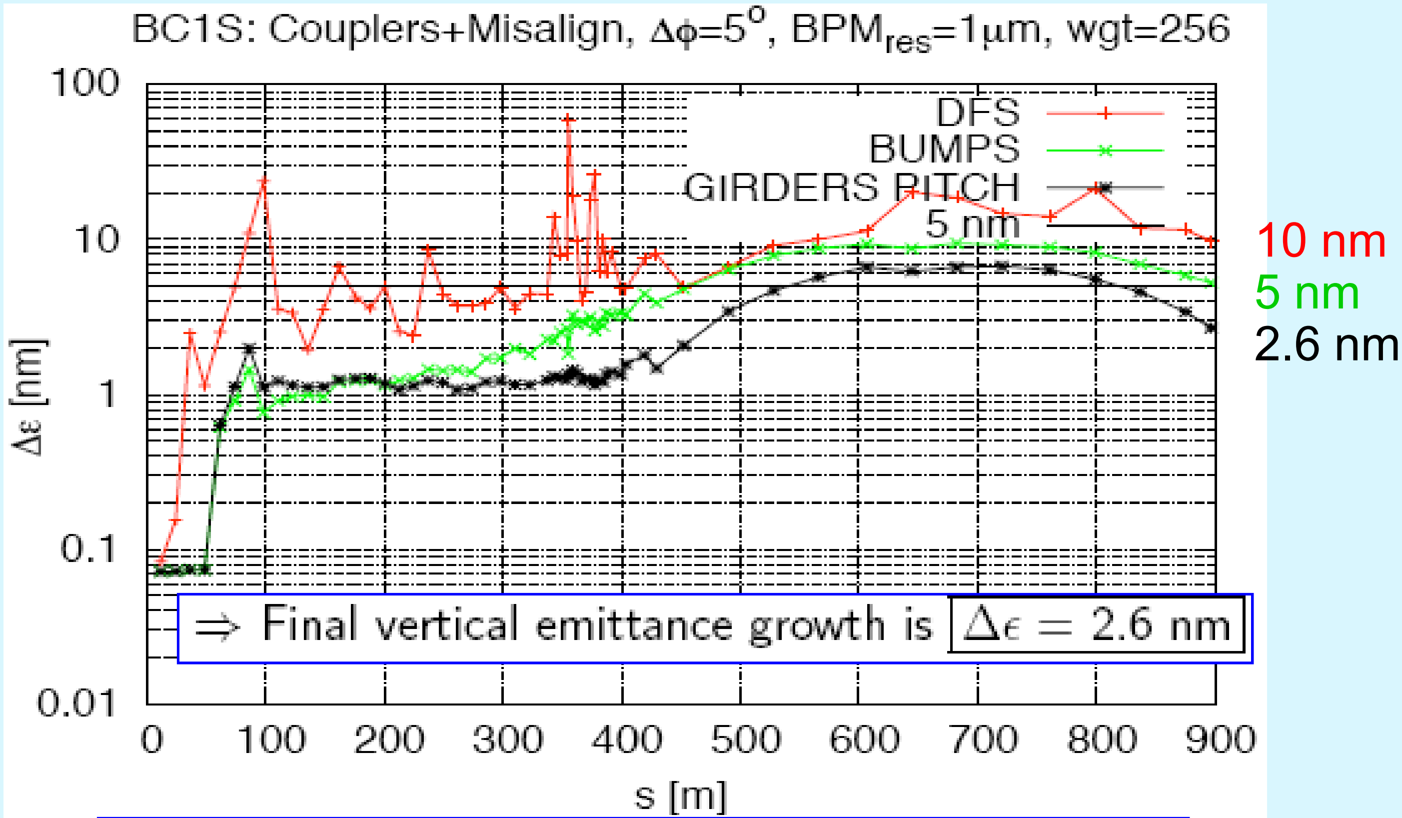
- Let's compare with the impact of these kicks on the baseline design ILC2007b
  ⇒ effect in the whole BC: unpublished result!
- Couplers' kicks and their correction using 1-to-1 steering and dispersion bumps

Dilution of the Vertical Emittance can be reduced if phase advance in RF2 reduce to 360°



⇒ Final vertical emittance growth is $\Delta\epsilon_y \simeq 5.5$ nm

Coupler and Misalignments in BC1S



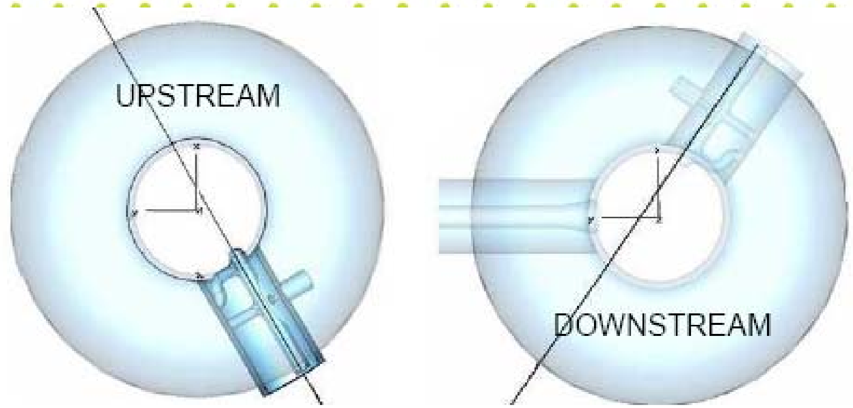
• Emittance Growth along the beamline, 1 machine

- BC1S (incl. diagnistics+matching+acceletration linac 5→15 GeV).
- Standard misalignments (300 um/300urad); ISR +coupler RF kick/wake
- 1-to-1, DFS and bumps, girder optimization

Reduction effect of the coupler kick & Wake

1. Symmetrical coupler geometry (upstream coupler rotated 104°)

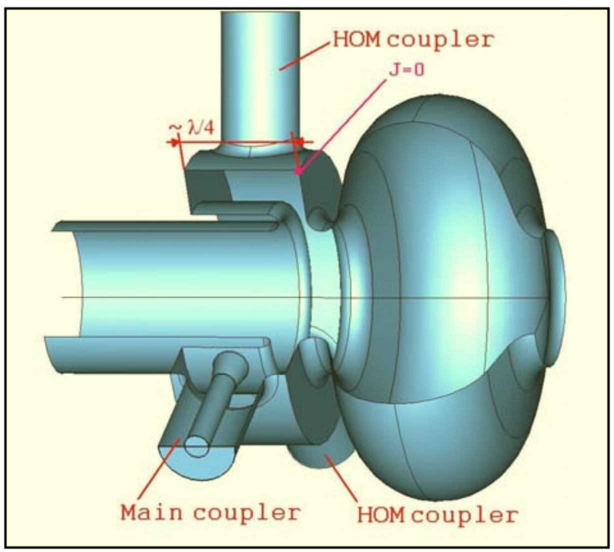
DESY, SLAC

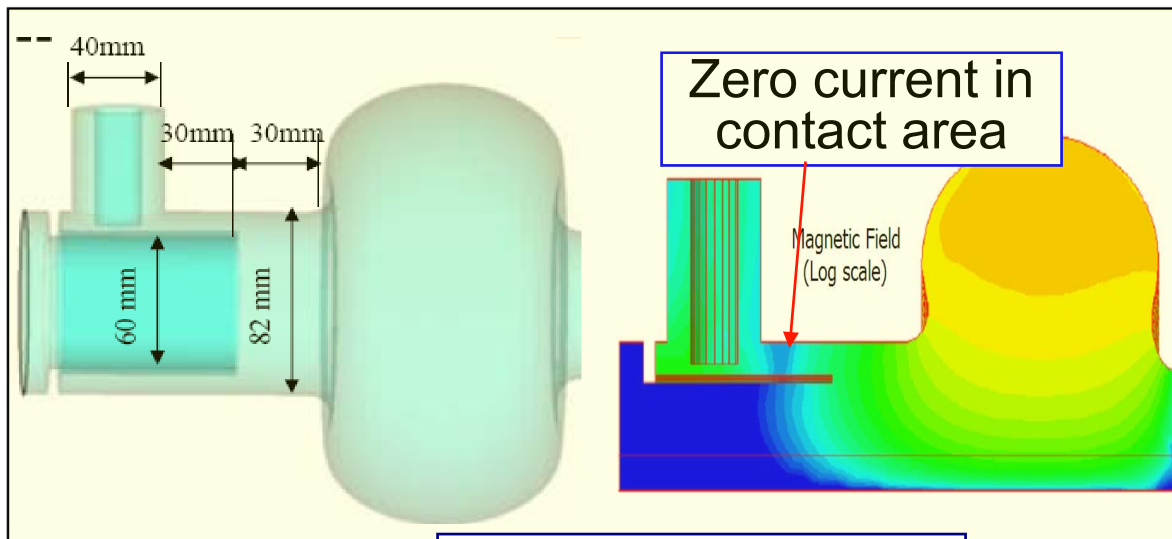


Does not work

- Wakes – OK
- But RF kick increases

2. Compact detachable coupler unit that provides axial symmetry of the RF field and the cavity geometry in the beam channel:





Other possible compensation schemes:
- by Cryomodule tilt
- by using Crab Cavity

Magnetic Stray Fields Studies

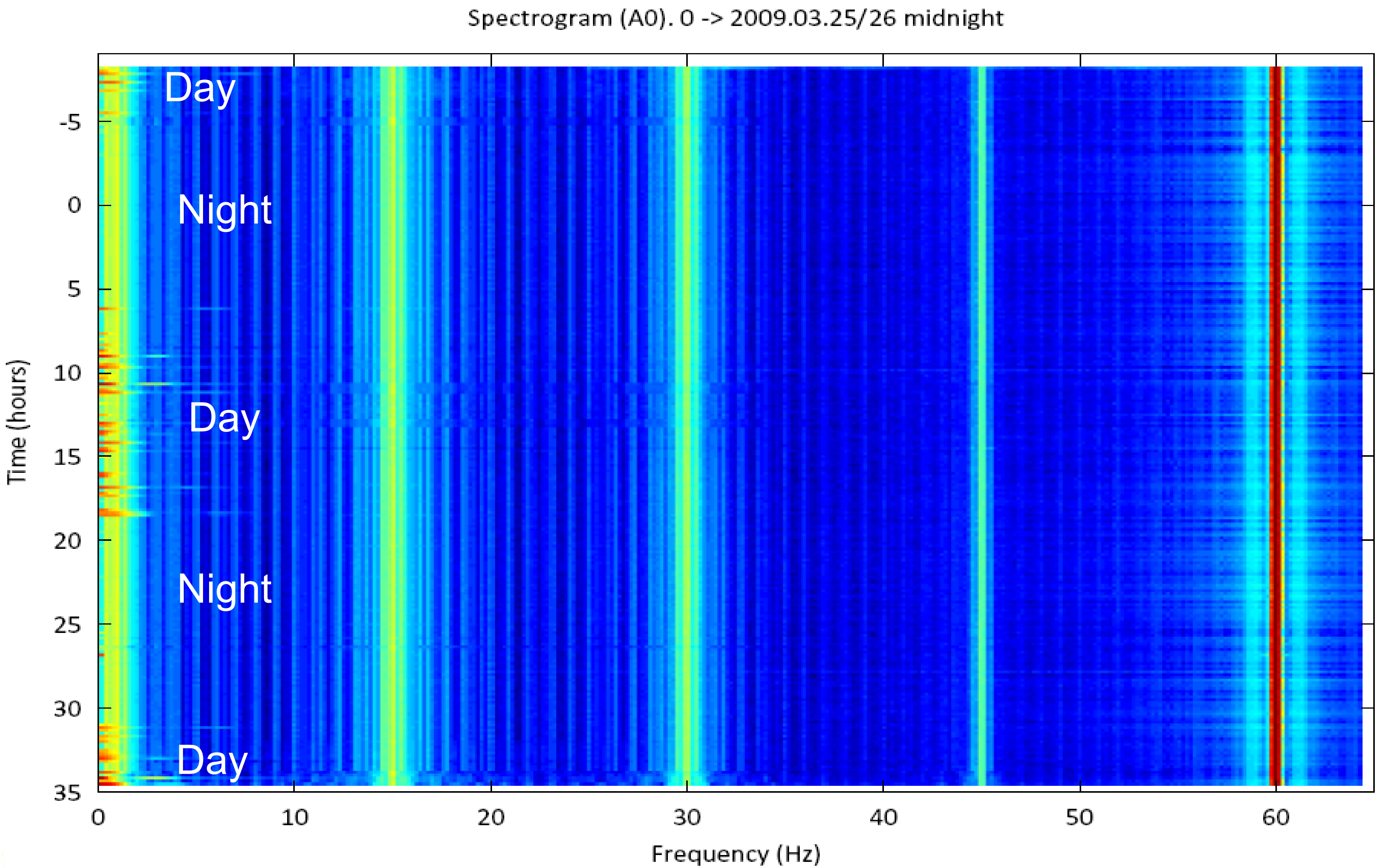
- RTML requirement for stray fields in Return Line < 2nT (freq>1Hz)
- SLAC measurements (at Station A) are promising (~2nT)
- Need more studies for different sites. Stability of 60Hz is an issue

Hardware:
- 3-axis fluxgate magnetometer
- 0.1mT full scale
- DC to 3 kHz
- 20 pT/sqrt(Hz)

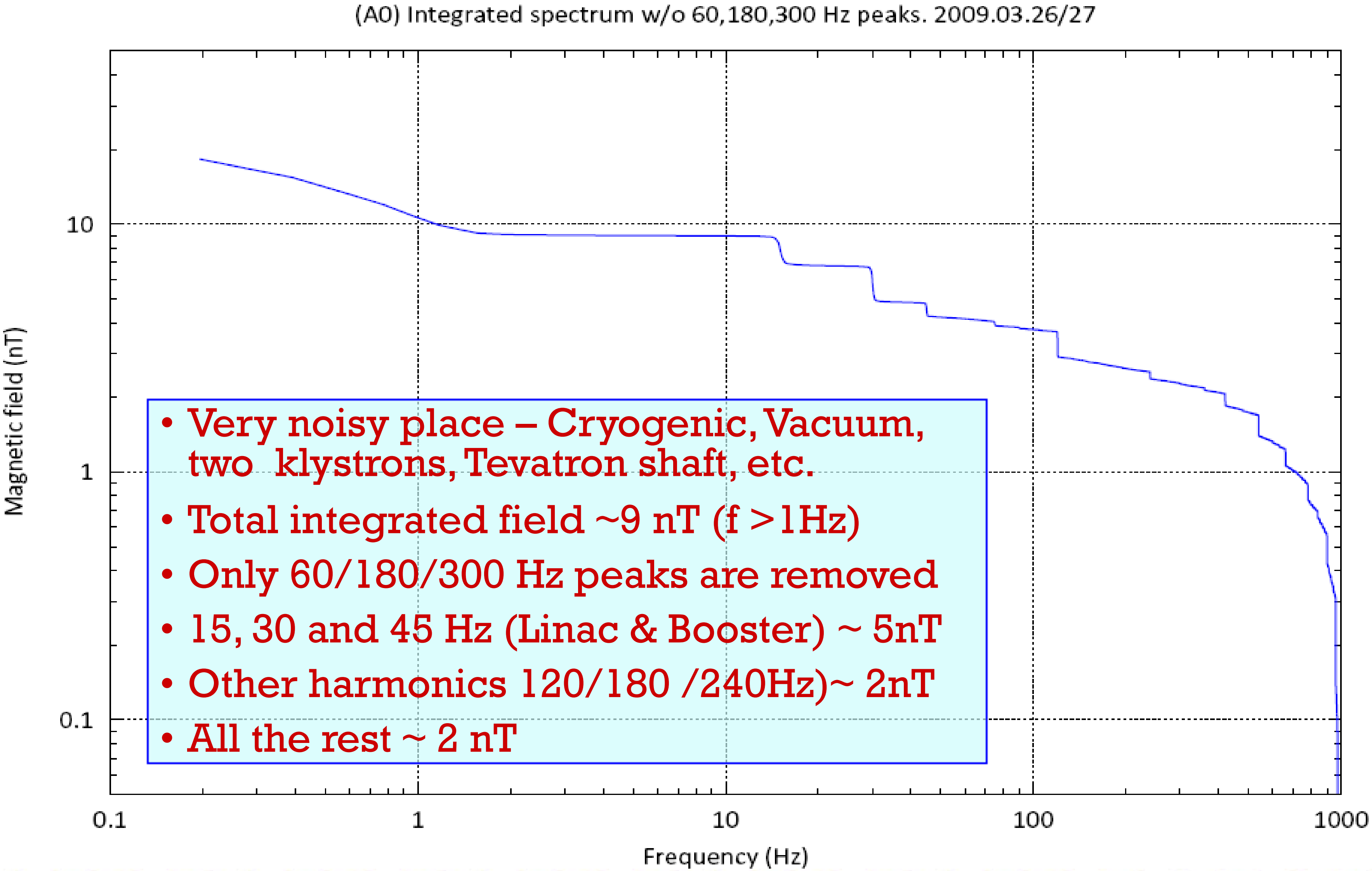
Measurement:
- Near klystron
- In shielded cave (20m from kly)
- Klystron On/Off

Fermilab A0 experimental area with cryogenic and 5 MW klystron/modulator

Stray magnetic fields: Spectrogram



Integrated spectrum



- Very noisy place – Cryogenic, Vacuum, two klystrons, Tevatron shaft, etc.
- Total integrated field ~9 nT (f >1Hz)
- Only 60/180/300 Hz peaks are removed
- 15, 30 and 45 Hz (Linac & Booster) ~ 5nT
- Other harmonics 120/180 /240Hz)~ 2nT
- All the rest ~ 2 nT

Conclusion

Progress in RTML design was achieved in a few areas (2008)

- **Emittance preservation in Bunch compressor**
  - Effect of coupler kick and wake on emittance growth
  - CM tilt optimization to compensate cavity and coupler tilt → very effective for emittance control but requires a special movers with step < 10um)
- **Design of Single-stage BC, incl. diagnostics and matching**
- **Design of all extraction lines for baseline lattice and preliminary design of EL for single-stage BC.**
- **Magnetic stray field measurement (requirements <2nT)**
- **Re-evaluation of vacuum system for return line to provide required vacuum P<10 nTorr.**

• We supported important studies started in previous years

- **Ground motion and vibration studies in deep tunnel (FNAL)**
- **Design, prototyping SC magnet for RTML and low energy**

Progress was limited by available resources in FY08

Conclusion (2)

- Effect of coupler kick and wake is understood and we proposed methods which reduce emittance growth in BC→ CM tilt or Crab Cavity.
- Value of coupler kick, calculated by three groups (DESY/FNAL/SLAC) is differ and need to be cross-checked.

Future work on critical R&D

- Continue Accelerator Physics Studies (with K.Kubo AP group):
  - **Complete Static emittance preservation studies**
    - Implement new alignment models and stray-field models
  - **Start multi-bunch and Dynamic simulation in RTML !!!**
    - Design/review of FB/FF system
  - **Continue Code development**
- Continue Study of magnetic stray-field
- Amplitude-phase stability Studies at FLASH (9-mA studies - Sept.09 ?)
- Support MM studies:
  - **Complete design, optimization and single-stage BC. Emittance preservation studies in both lattices (BC1S and short design):**
  - **RE-design DRX, transport Lines in Central Area (new configuration of sources)**
- Technical systems:
  - **Complete evaluation of RTML vacuum system**
  - **Prototyping SC quad for low energy ML and RTML**
  - **Re-evaluate alignment requirements for RTML Cryomodules**

Resources !!!