Wakes and Energy Spread During Energy Recovery

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Outline

- Energy Loss vs. Energy Spread
- Wake Fields from ERL Vacuum Components
- Possible Method for Reducing Energy Spread
- Conclusions

First Consideration for Beam

Beam's electromagnetic fields interact with its vacuum chamber in two ways - The first is

- Non-resonant Power Loss with 1.3 GHz bunch freq. & charge of 77 pC

$$P_{loss} = 7.7 \text{ W} \left\{ \frac{k(\sigma_z)}{1 \text{ V/pC}} \right\}$$

Loss parameter

(28 KW for CESR)

  - Not a serious problem, BUT very sensitive to resonantly excited trapped modes (could be enhanced 100-500x)

- Assume 200 W dissipation limit for most vacuum structures with water cooling:

$$\boxed{\max\{k(\sigma_z)\} = 26 \text{ V/pC}}$$

Second Consideration for Beam

- Second interaction is thru the Induced Wake Voltage
  - Voltage for particle following charge, q depends on its longitudinal position, s, within the bunch due to the effect of all vacuum chamber components in ERL

$$V_{\parallel}(s)\Big|_{\text{entire ERL}} = q\ W_{\parallel}(s)\Big|_{\text{entire ERL}}$$

  - Increases the energy spread, Δ_E, of the bunch
- Limitation:
  - At high energy, the energy spread is usually not serious, BUT as the beam decelerates the effect is magnified x 500
  - Maximum acceptable beam energy spread at the dump places a limit on the maximum wake field, i.e.

$$\max\left\{eV_{\parallel}(s)\Big|_{\text{entire ERL}}\right\} \le \kappa\ \max\left\{\Delta_E\Big|_{\text{dump}}\right\}$$

where $0 \le \kappa \le 1$ (e.g. $\kappa \sim 0.5$)

Peak Wake Function Limit

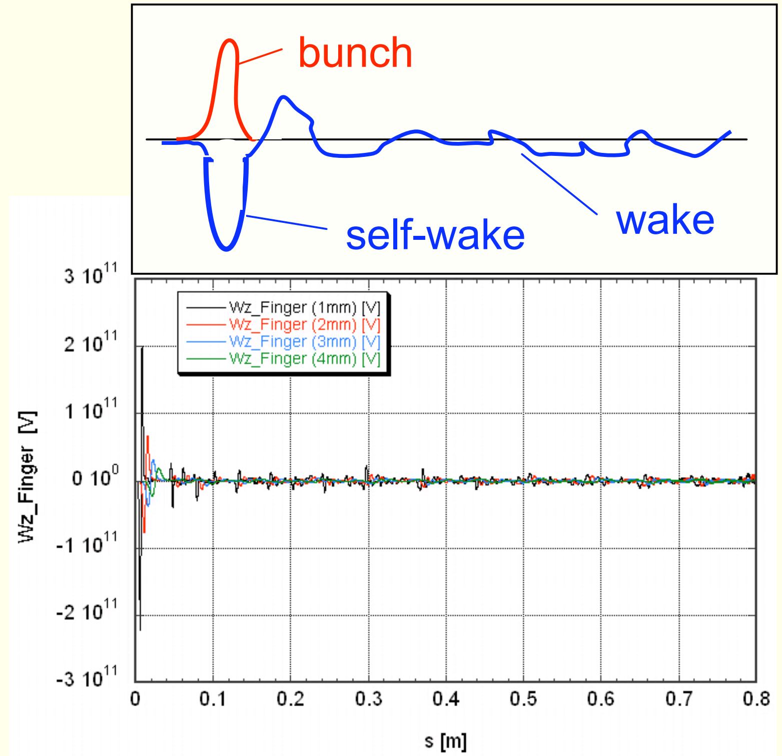
- Estimating maximum energy spread at the dump
  - Decelerated beam at the Dump:
    - Average Beam Energy at the Dump: E = 10 MeV
    - Acceptable Maximum Energy Spread at the Dump: ΔE = 5 MeV
- Cast limit in terms of wake field $W_{||}$
- Limit depends on operating charge:
  - Mode A operation (77 pC & σ_z= 0.6 mm):

$$\max\left\{ W_{||}(s)\Big|_{\mathrm{entire\ \ ERL}} \right\} = \frac{1}{q} \max\left\{ eV_{||}(s)\Big|_{\mathrm{entire\ \ ERL}} \right\}$$

$$\leq 0.5 \ \frac{1}{q} \max\left\{ \Delta E\Big|_{\mathrm{dump}} \right\} \approx (0.5) \frac{5 \ \ \mathrm{MeV}}{77\mathrm{pC}}$$

$$\approx \boxed{32 \ \ \mathrm{kV/pC}}$$

Effects of Wake Function



- Self-Wake
  - Direct interaction of the bunch with vacuum chamber
    - Strongest within the bunch since all of the different modes of the structure are excited “in phase”
- Wake from preceding bunches
  - Non-resonant
    - Generally much smaller than self-wake since different modes destructively interfere with each other
  - Resonant
    - Occurs when a mode in structure is a harmonic of the bunch repetition frequency, $1/T_{bb}$
    - Amplitude grows over duration of one filling time for this mode
      - Could enhance $W_{||}$ by as much as 100-500x
  - I will ignore the wake from preceding bunches

Wake Fields from ERL Vacuum Components

- Estimate effects for the following structures
  - Choose the larger impact discontinuities

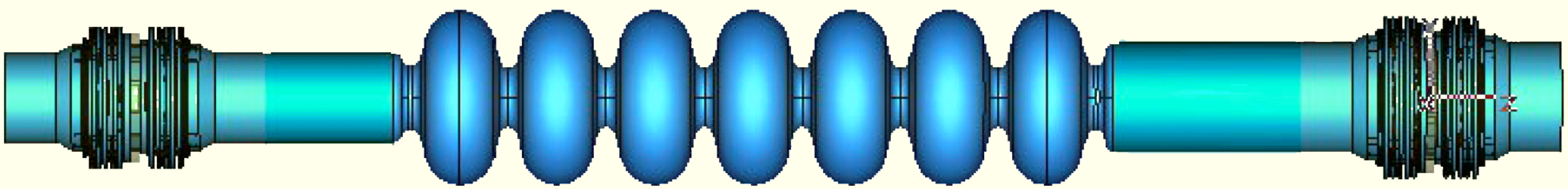
Accelerator Cavities & HOM Loads	Tapered Transitions
Expansion Joints	Gate Valves
BPM's	Resistive Wall Wake
Flanges	Roughness Wake
Clearing electrodes	Undulator Chambers

  - Gaussian Shaped Bunch: σ_z = 0.6 mm
  - Estimates made using ABCI for cylindrically symmetric 2-D geometries
    - Two exceptions (one of the Expansion Joints & the Clearing Electrode were calculated in 3-D with MAFIA)
    - Third exception (RF HOM Loads were calculated with NOVO: 2-D)

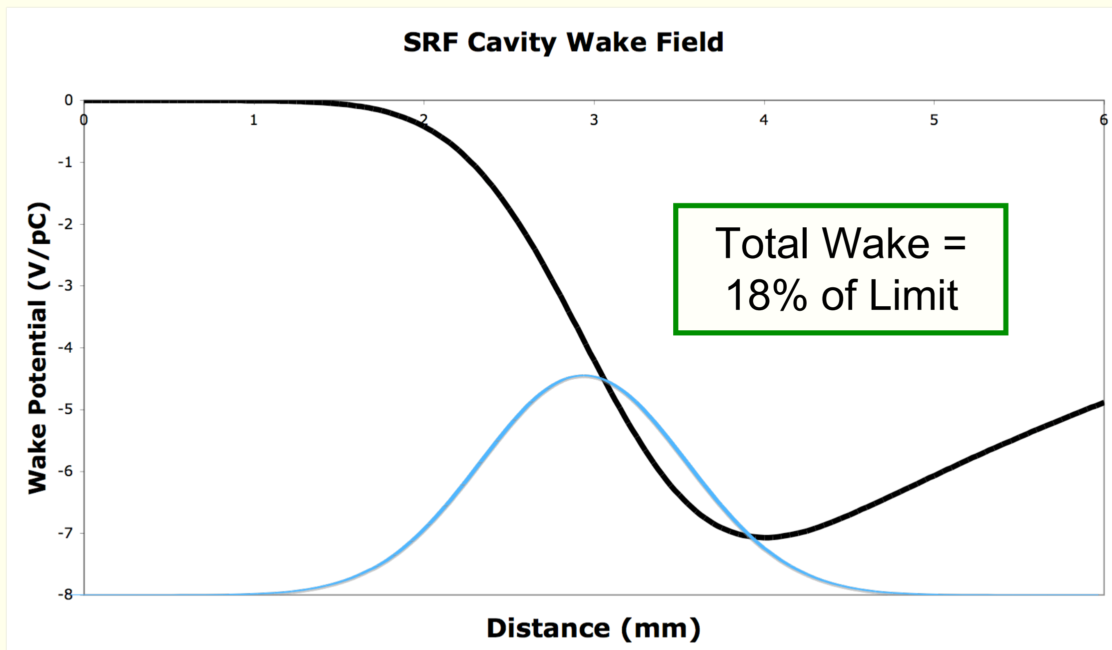
Estimating Self-Wake Functions

- Linac accelerator RF cavities
  - 7 cells (scaled from the 9 cell Tesla cavities)
  - Min, Max $\{W_{||}\}$ = -14.2, 0.0 V/pC k_{HOM} = 7.3 V/pC
  - Quantity = 400 (x 2 for the two passes thru the RF)

HOM Power per unit = 2 x 50 W

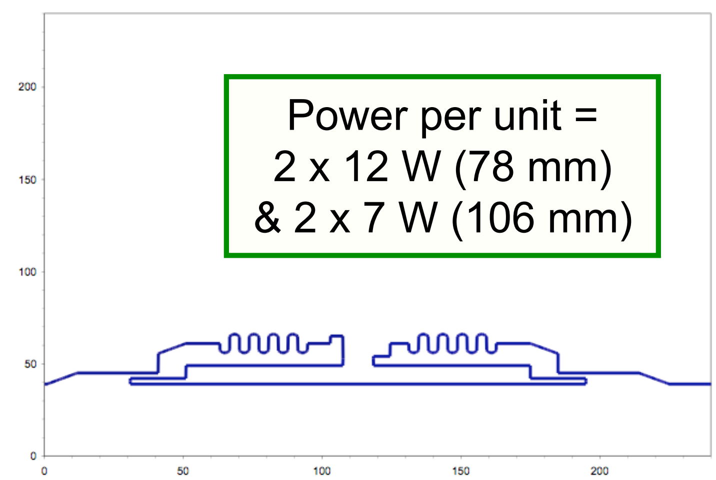


HOM Load   HOM Load

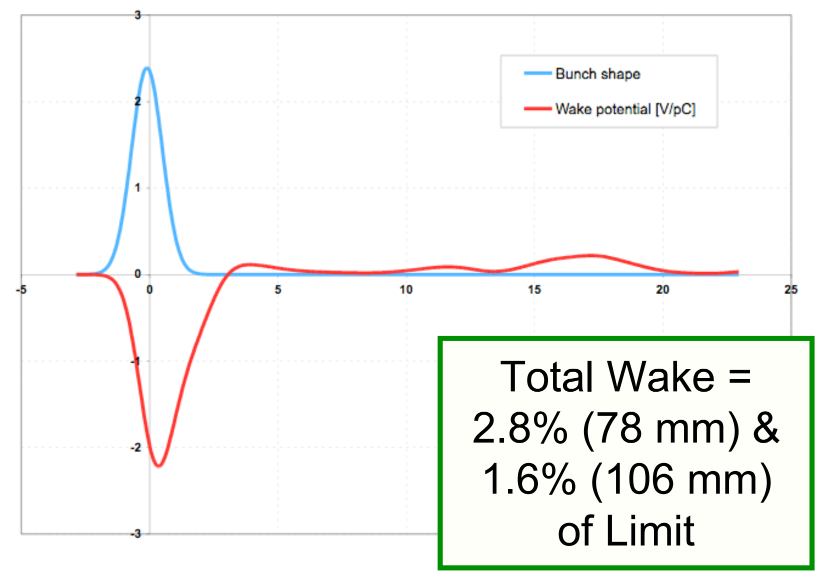


Estimating Self-Wake Functions

- RF Cavity Higher Mode Loads
  - Geometric (ignoring ferrite properties) (2 pipe radii)
  - (78 mm) Min, Max $\{W_{||}\}$ = -2.22, 0.0 V/pC k = 1.60 V/pC
  - (106 mm) Min, Max $\{W_{||}\}$ = -1.24, 0.0 V/pC k = 0.89 V/pC
  - Quantity - 78 mm & 106 mm I.D. Pipes (each type:200 x 2)

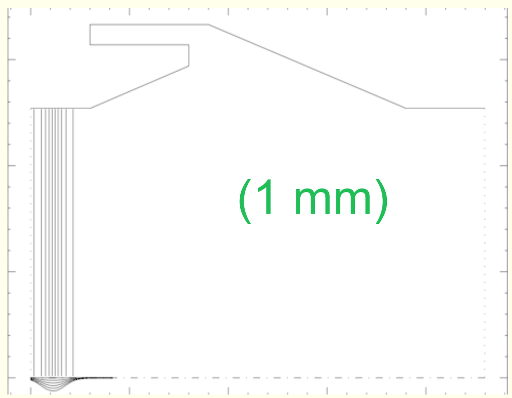


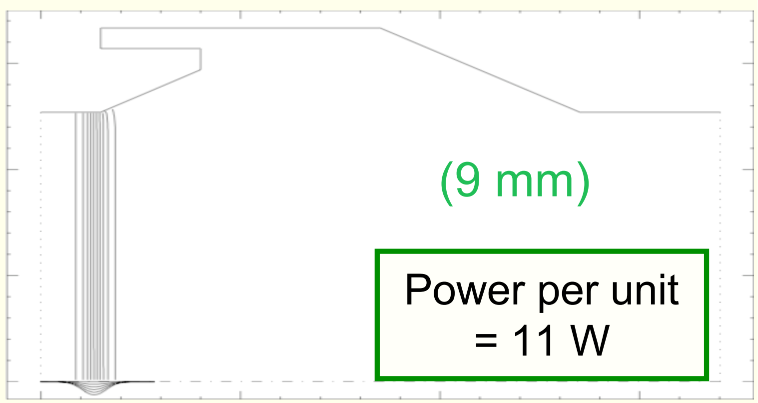
NOVO Calculation
By S. Belomestnykh

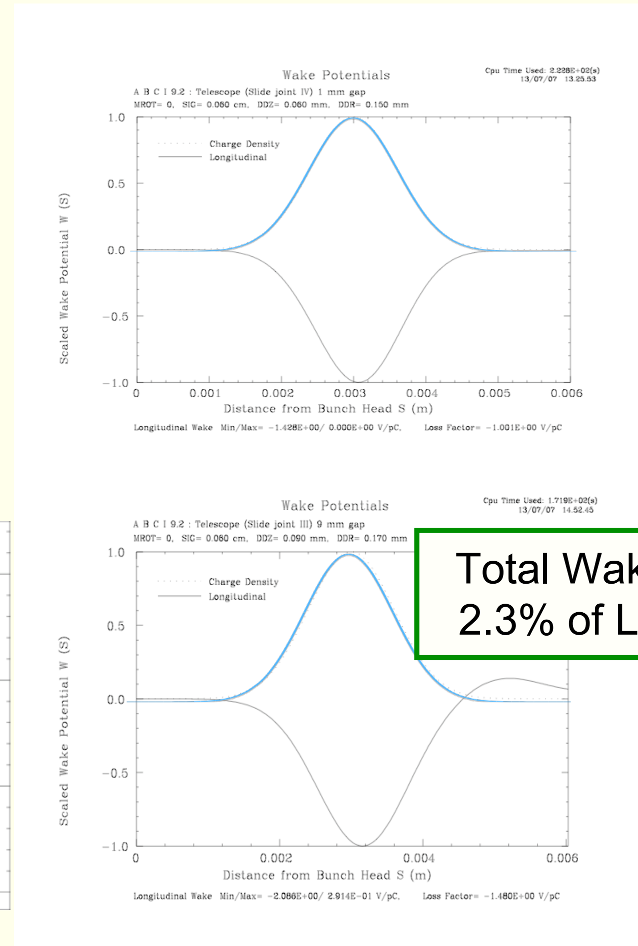


Estimating Self-Wake Functions

- Expansion Joints (Telescoping) (2 gaps)
  - (1 mm) Min, Max $\{W_{||}\}$ = -1.43, 0.0 V/pC   k = 1.00 V/pC
  - (9 mm) Min, Max $\{W_{||}\}$ = -2.09, 0.29 V/pC   k = 1.48 V/pC
  - Quantity = 356
  - Use the Wake from 9 mm gap

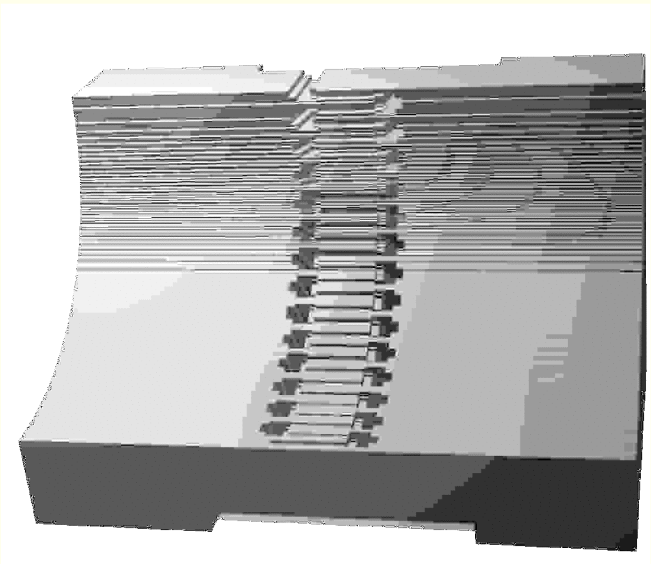


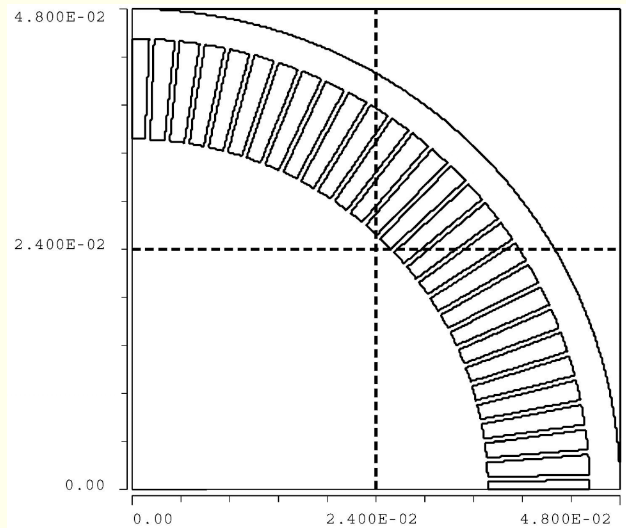




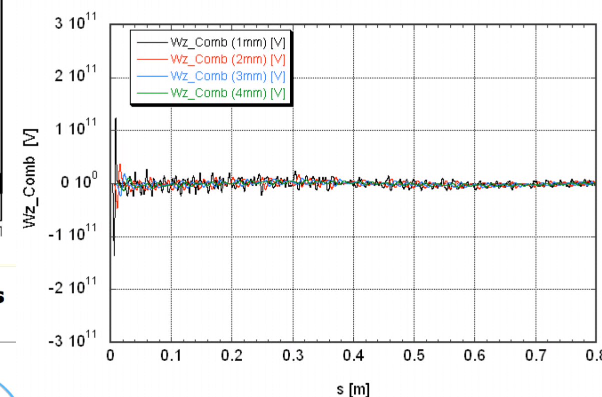
Estimating Self-Wake Functions

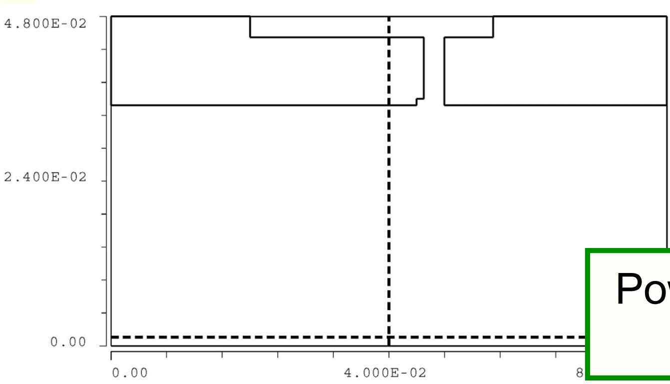
- <u>Alternate</u> Expansion Joint (Interdigitated Fingers)
  - Min, Max $\{W_{||}\}$ = -0.135, 0.12 V/pC   k = 0.131 V/pC
  - Quantity = 0



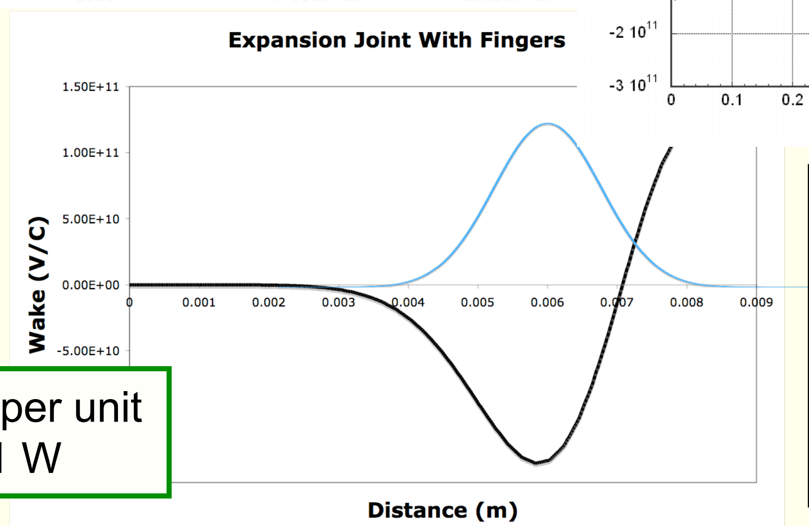


If Telescoping Expansion Joints were replaced by these, Total Wake = 0.15% of Limit





Power per unit = 1 W

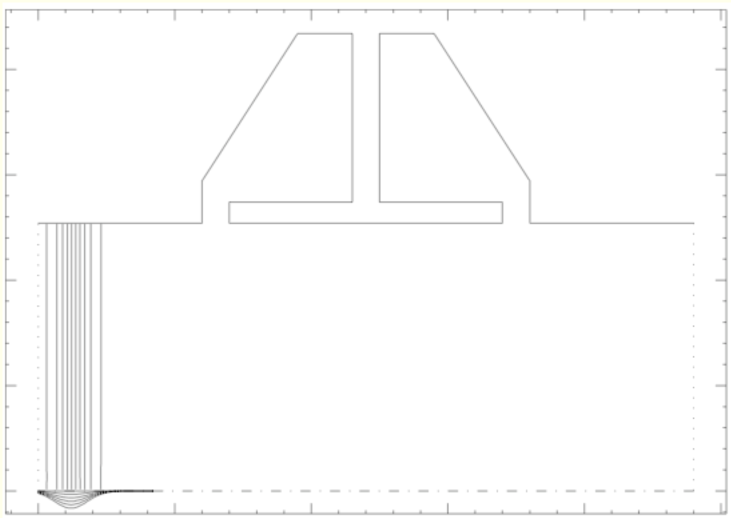


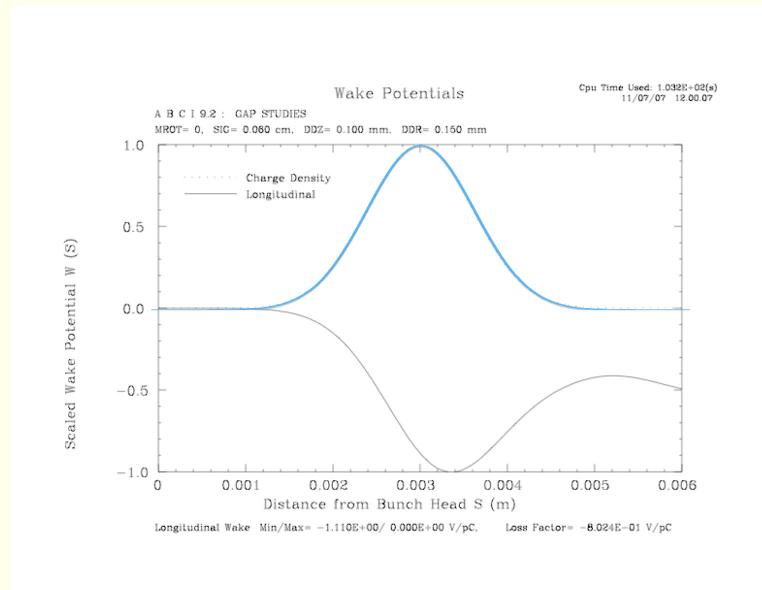
MAFIA Calculation by Y. Suetsugu KEK

Estimating Self-Wake Functions

- Beam Position Monitor (Button)
  - Min, Max $\{W_{||}\}$ = -0.52, 0.0 V/pC   k = 0.36 V/pC
  - Gap around button = 1 mm
  - Quantity = 664

Power per unit = 2.8 W



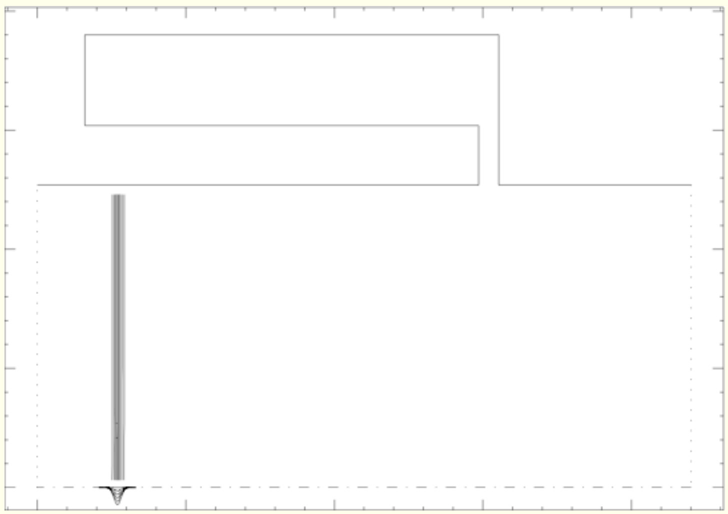


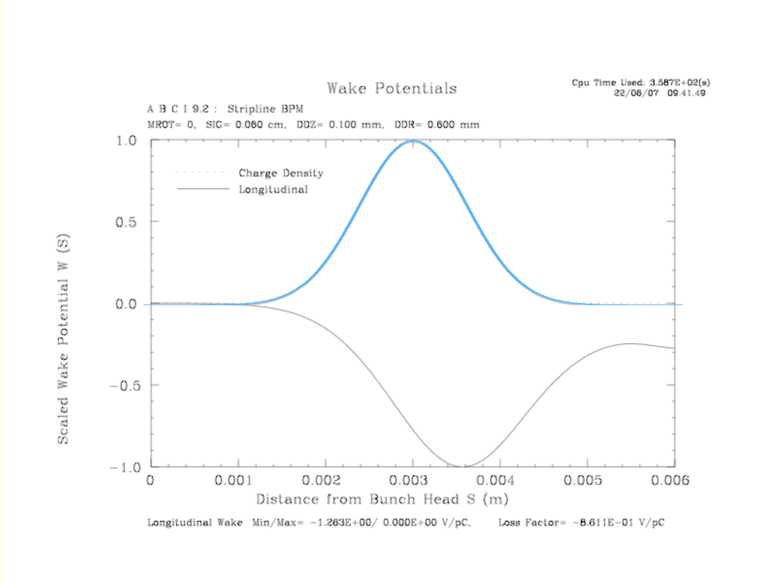
Total Wake = 1% of Limit

Estimating Self-Wake Functions

- Beam Position Monitor (Stripline)
  - Min, Max $\{W_{||}\}$ = -0.56, 0.0 V/pC   k = 0.38 V/pC
  - Gap = 2 mm
  - Quantity = 20

Power per unit = 2.9 W





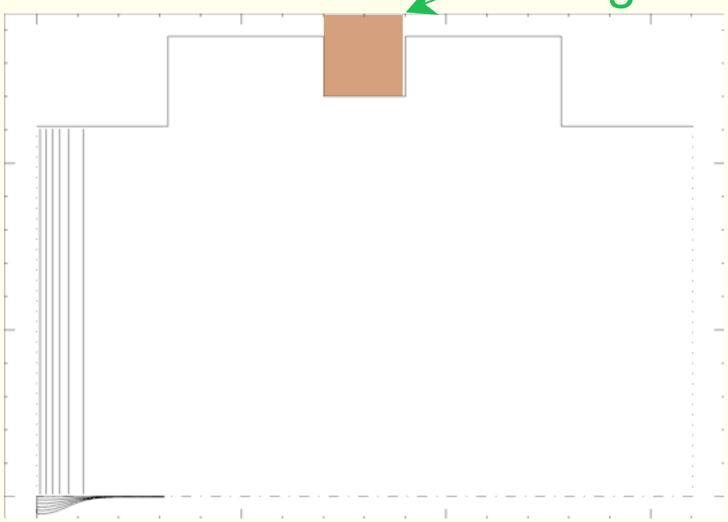
Total Wake = 0.04% of Limit

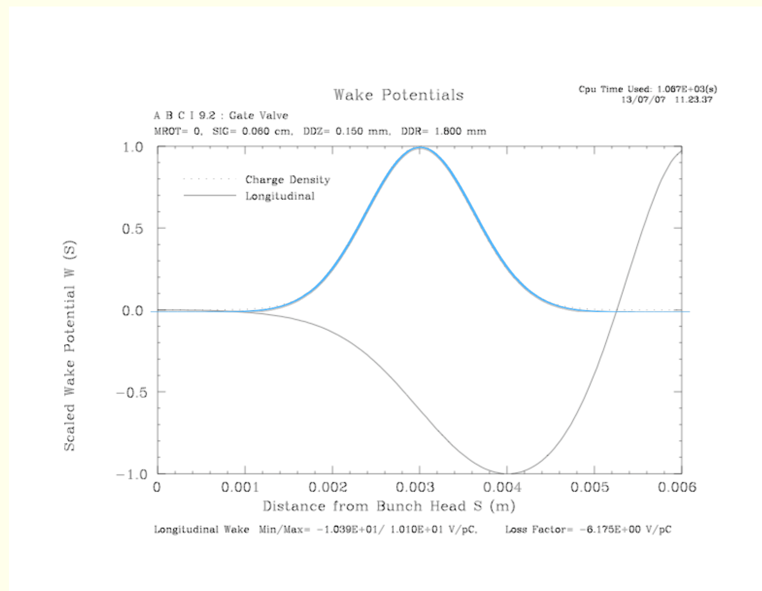
Estimating Self-Wake Functions

- Flange Joint (pair)
  - Min, Max $\{W_{||}\}$ = -2.54, 0.0 V/pC   k = 1.79 V/pC
  - Quantity = 356

Power per unit = 14 W

Varian Flange with Cu gasket



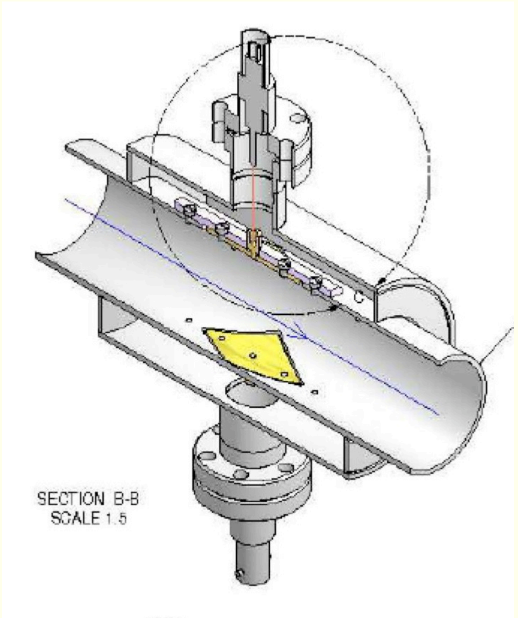


Total Wake = 2.4% of Limit

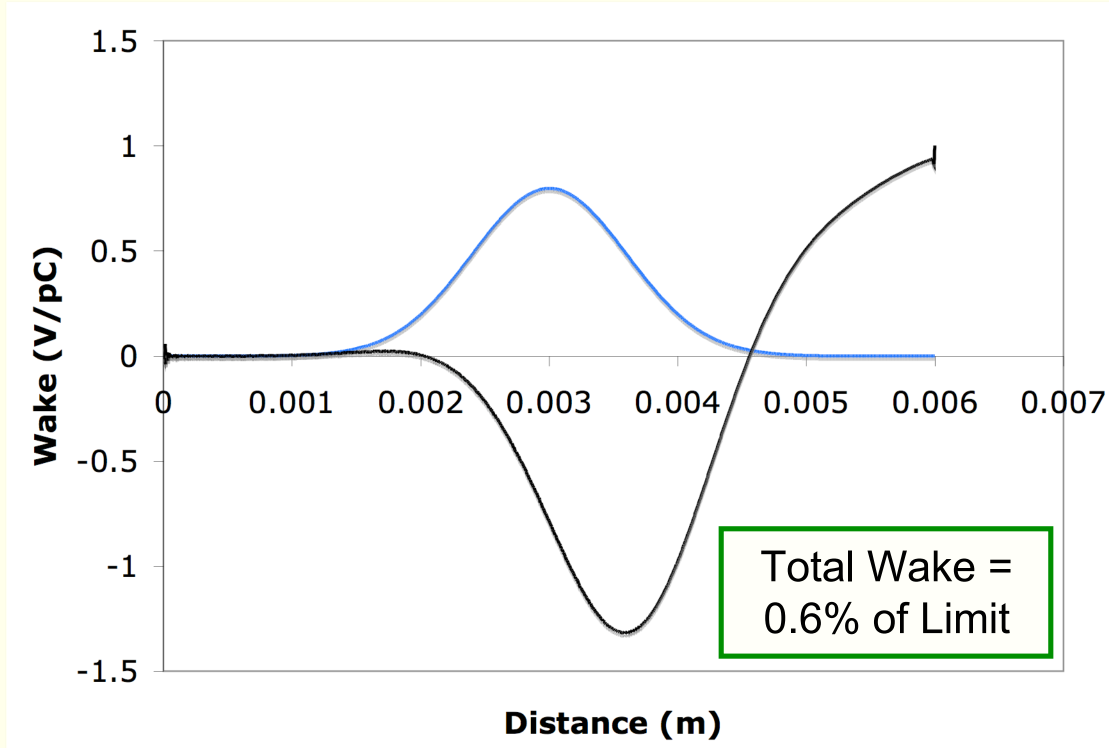
Estimating Self-Wake Functions

- Clearing Electrode
  - Min, Max $\{W_{||}\}$ = -1.2, 0.9 V/pC   k = 0.25 V/pC
  - Quantity = 150

Power per unit = 1.9 W



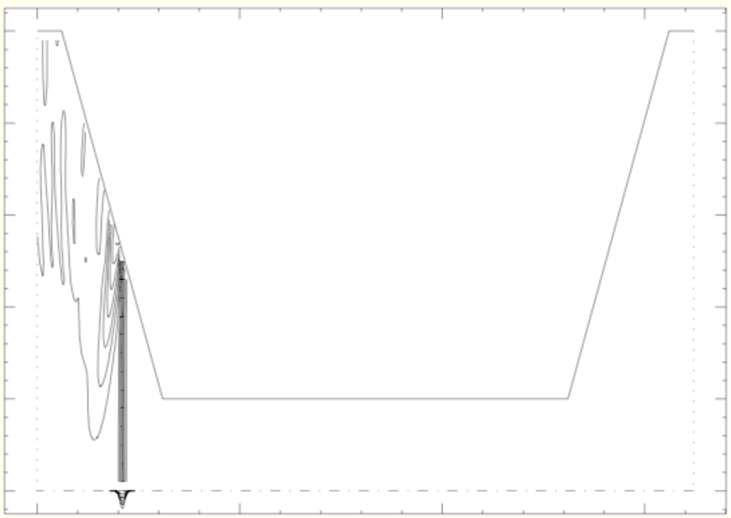
MAFIA Calculation by Yi Xie

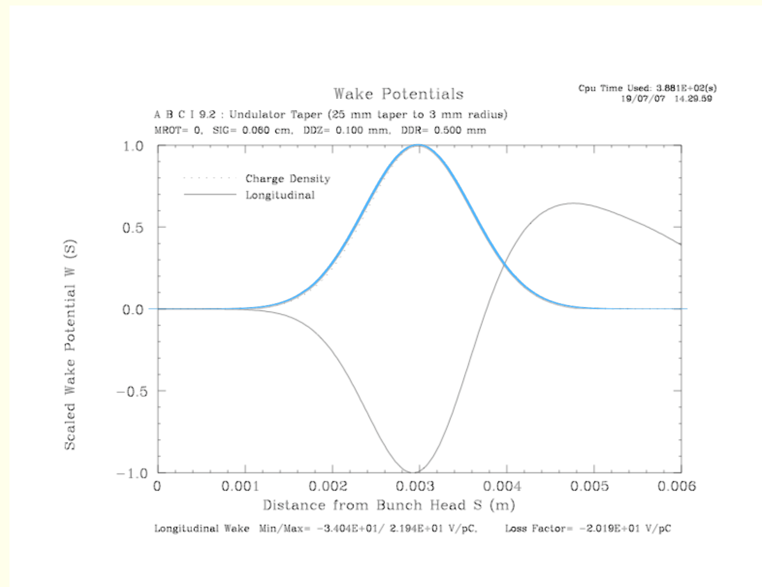


Estimating Self-Wake Functions

- Undulator Chamber Tapers
  - Actual chamber is rectangular 5 x 40 mm
  - Model with 25 mm Long Taper to 3 mm Radius Pipe
  - Min, Max $\{W_{||}\}$ = -56.6, 0.0 V/pC   k = 32.3 V/pC
  - Quantity = 18

Power per unit = 160 W



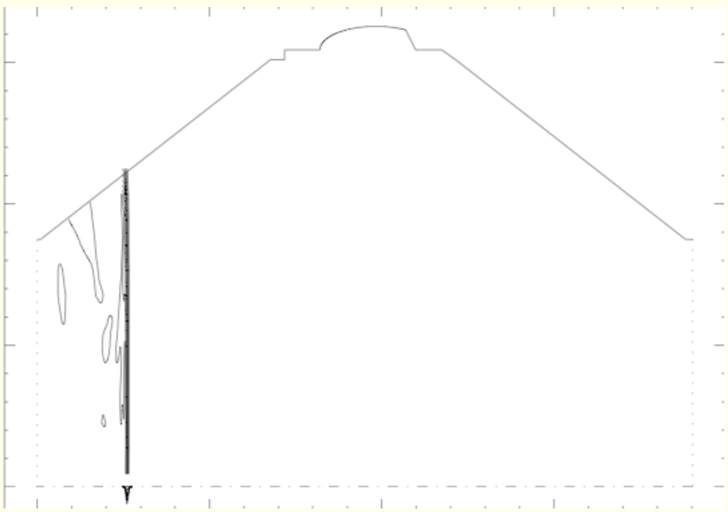


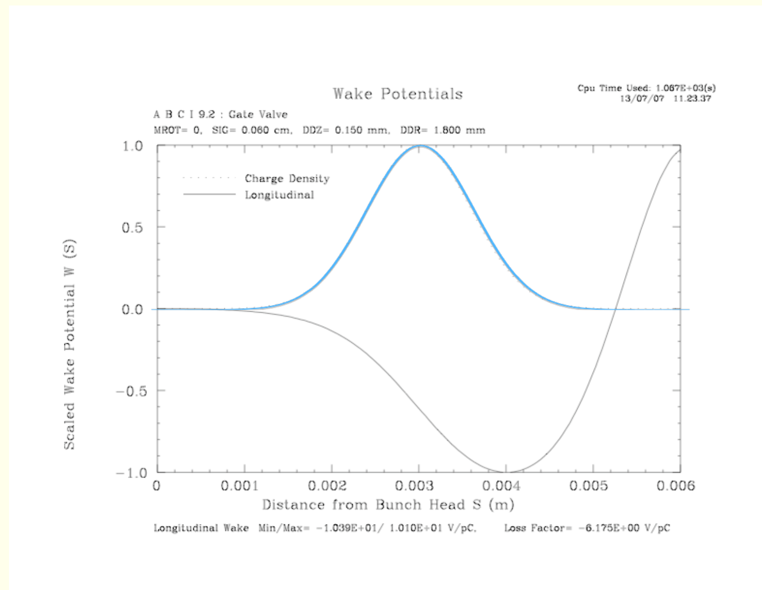
Total Wake = 1.9% of Limit

Estimating Self-Wake Functions

Power per unit = 48 W

- Gate Valves
  - Min, Max $\{W_{||}\}$ = -10.4, 10.1 V/pC   k = 6.18 V/pC
  - Tapered out to a much larger radius than needed
  - Quantity = 68





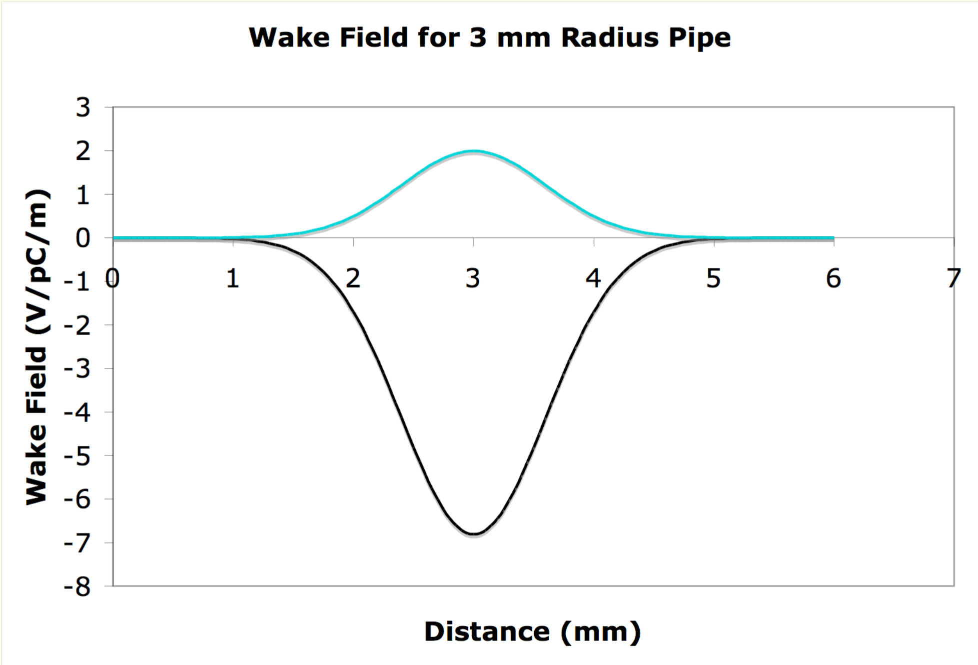
Total Wake = 2.2% of Limit

Estimating Self-Wake Functions

- Resistive Wall of Vacuum Chamber per meter
  - Stainless steel — Length
    - Radius: 12.7 mm (normal beam pipe) — 2.5 km
    - Radius: 3 mm (undulator chambers) — 144 m
  - (12.7 mm) Min, Max $\{W_{||}\}$ = -1.6, 0.0 V/pC k = 1.1 V/pC
  - (3.0 mm) Min, Max $\{W_{||}\}$ = -6.8, 0.0 V/pC k = 4.8 V/pC

Power per m =
8.5 W (12.7 mm)
37 W (3 mm)

If the chambers are Aluminum, these effects are x 0.30



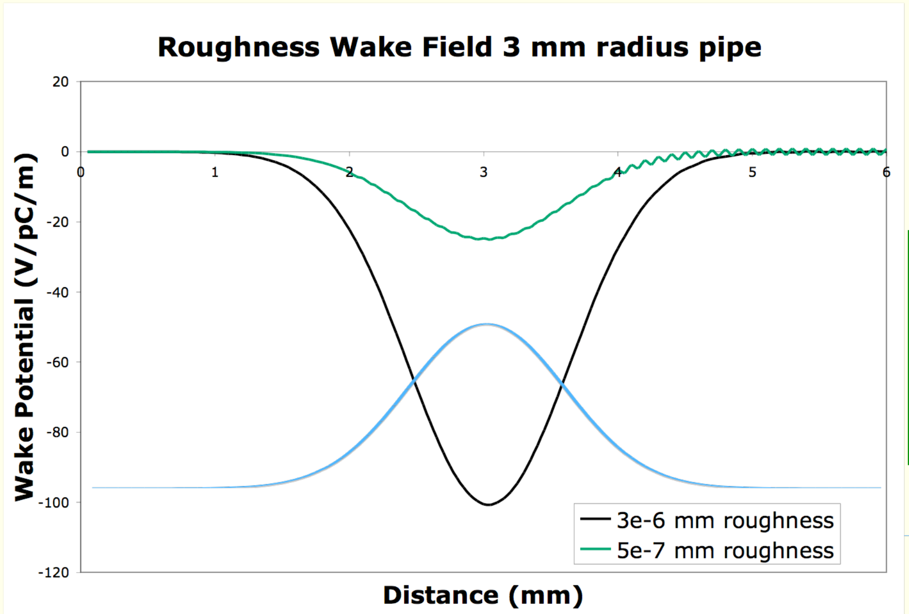
Total Wake =
12.5% (12.7 mm)
3% (3 mm)
of Limit

Estimating Self-Wake Functions

- Roughness of Vacuum Chamber Wall (<u>per meter</u>)
  - Stainless steel — Roughness — Length
    - Radius: 12.7 mm (normal beam pipe) — 3 μm — 2.5 km
    - Radius: 3 mm (undulator chambers) — 0.5 μm — 144 m
  - Correlation Length = Roughness
  - (12.7 mm) Min, Max $\{W_{||}\}$ = -5.6, 0.2 V/pC   k = 3.5 V/pC
  - (3.0 mm) Min, Max $\{W_{||}\}$ = -25, 0.8 V/pC k = 17.5 V/pC

Power per m =
27 W (12.7 mm)
135 W (3 mm)

Wakes scale
~ Roughness



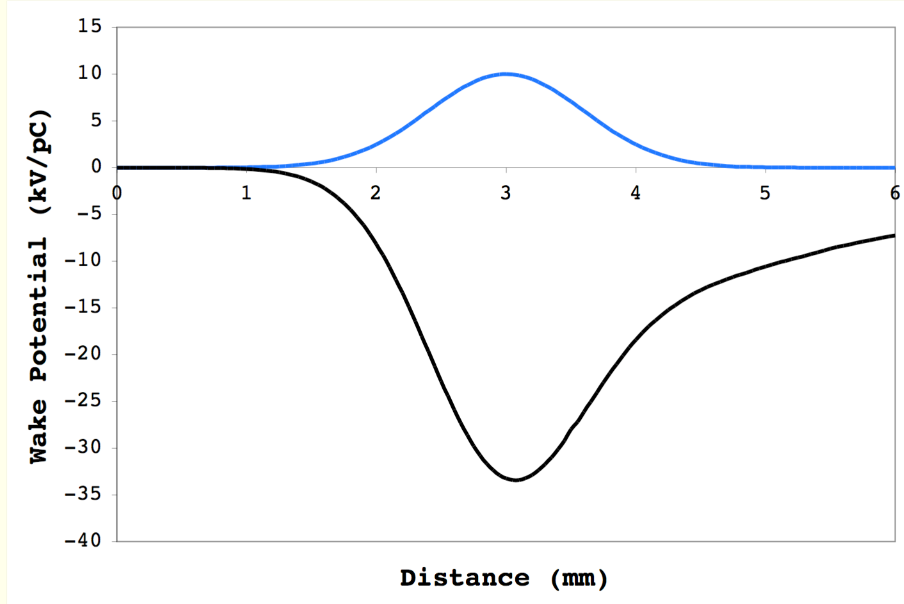
Total Wake =
44% (12.7 mm)
11% (3mm)
of Limit

Estimated Total Self-Wake

- Peak Wake

$$\max\left\{ W_{\|}(t)\Big|_{ERL} \right\} = 33 \ \text{kV/pC}$$

Same as 32 kV/pC Limit



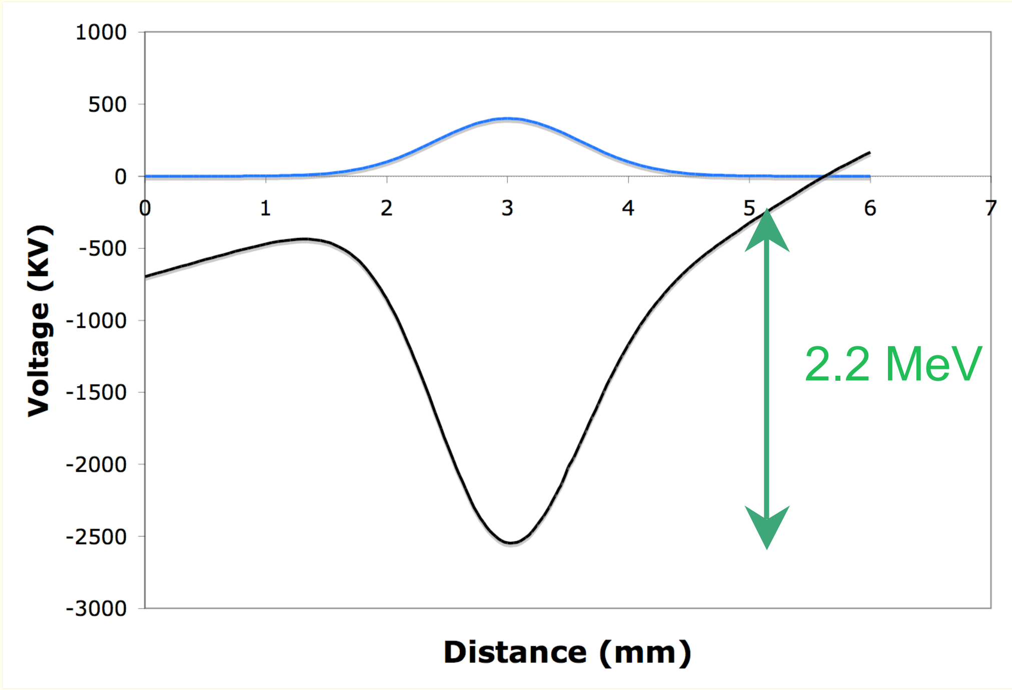
Component	Number	Total -Wake (KV/pC)	Total +Wake (KV/pC)	Total k (KV/pC)
7 Cell RF Cavity	800	$\boxed{-11.32}$	0	5.81
HOM Load (78 mm)	400	-0.89	0	0.64
HOM Load (106 mm)	400	-0.50	0	0.36
Expansion Joint	356	-0.74	0.10	0.53
BPM (Button)	664	-0.35	0	0.24
BPM (Stripline)	20	-0.01	0	0.01
Flange Joint	356	-0.90	0	0.64
Clearing Electrode	150	-0.18	0.14	0.04
Gate Valve	68	-0.71	0.69	0.42
Resistive Wall (12.7 mm)	2500	-4.00	0	2.75
Roughness (12.7 mm)	2500	$\boxed{-14.00}$	0.50	8.75
Undulator Taper (3 mm)	18	-0.61	0.37	0.36
Resistive Wall (3 mm)	144	-0.98	0	0.69
Roughness (3 mm)	144	-3.60	0.12	2.52

Total k
= 23.8KV/pC

Total HOM Power
= 183 KW

Possible Methods for Reducing Energy Spread from Wakes

- Correct Slope of Wake Field
  - Run RF Off Crest for slope compensation
- Result for ΔE (Between +/- 3.3 σ_z)
  - Present Example
    - Reduces 2.6 MeV to 2.2 MeV
    - Not much help
- Other Possibilities
  - Reduce Charge/Bunch
  - Increase Dump Energy
  - Lengthen Bunch
  - Larger Beam Pipe



Conclusions

- Higher Order Mode Loss not a serious problem
  - Unless there are resonant trapped modes
- Wake Fields from Large Fraction of Components
  - Max{$W_{||}$} ~ 100% of proposed limit

    (Limit is ΔE= 2.5 MeV for 10 MeV Beam at the Dump)

    (RF Cavity & Roughness Wakes dominate)
  - Should consider compensation methods
  - Have only included self-wakes, ignoring
    - Wakes from preceding bunches
    - Wakes from any resonant trapped modes
  - Future considerations
    - Remaining discontinuities, e.g. Vacuum pump ports, X-ray crotches
    - Effect on longitudinal dynamics, esp.
      bunch compression & higher bunch charge options