NLC - The Next Linear Collider Project

Damping rings aperture and impedance studies

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Damping rings lattice studies

- ZDR (1996)
  - 4-quad TME cells
  - 19 cells per arc
  - 30 m wiggler
- Changes (1998)
  - k = 0
  - Increased circumference
  - 50 m wiggler
  - Increased momentum compaction
  - Increased physical apertures
- Changes (1999)
  - 3-quad TME cells
  - 15 cells per arc
- Changes (2000)
  - Increased quad spacing in wiggler straight
  - Re-introduce gradient

SLAC

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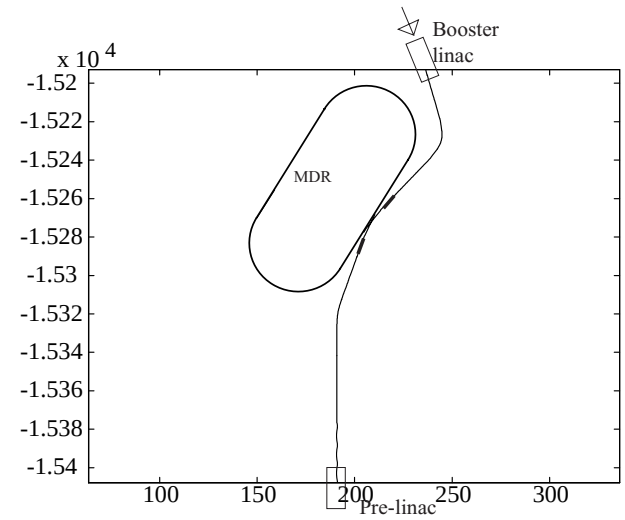
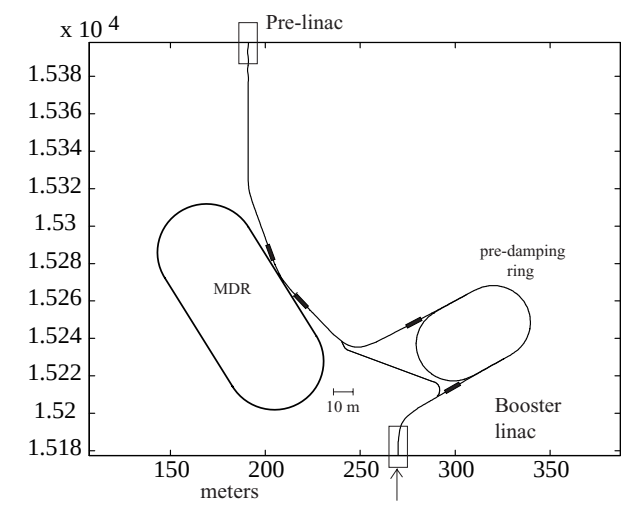
Dave Robin

NLC Damping Rings Complex

- Reduce emittance of low-energy $e^+ e^-$
- Stable platform for injection into linacs
  - Similar to 3rd generation light sources

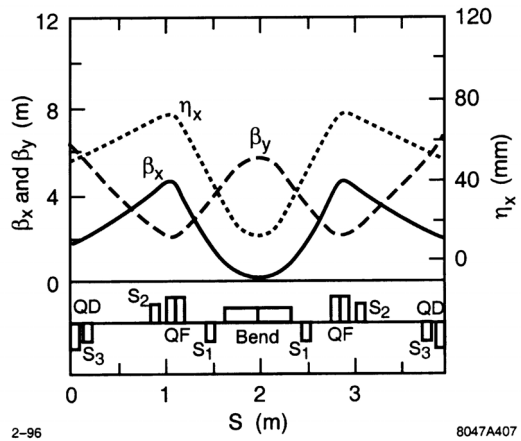
	Pre-damping ring	Main damping rings
Energy (GeV)	1.9 – 2.1	1.9 – 2.1
Circumference (m)	214	297
Bunch spacing (ns)	2.8	2.8
Fill pattern	2 trains 95 bunches	3 trains 95 bunches
	2 gaps 100 ns	3 gaps 68 ns
Damping time (ms)	< 5.21	< 5.21
N_{max}/bunch	1.9×10^{10}	1.6×10^{10}
Current (mA)	800	750
Injected norm. emittance $\gamma\varepsilon$ X/Y (m-rad)	$< 9 \times 10^{-2}$ (edge)	$< 150 \times 10^{-6}$ (rms)
Extracted norm. emittance $\gamma\varepsilon$ X/Y (m-rad)	$< 1 \times 10^{-4}$	$< 3 \times 10^{-6}$ / 0.03×10^{-6}
RF voltage (MV)	2	1.5
Momentum compaction	0.0051	0.00066
Energy spread (%)	0.09	0.09
Bunch length (mm)	8.4	3.8
Wiggler field (T)	2	2
Vacuum pressure (Torr)	1×10^{-9}	1×10^{-9}
Maximum rep. Rate (Hz)	120	120

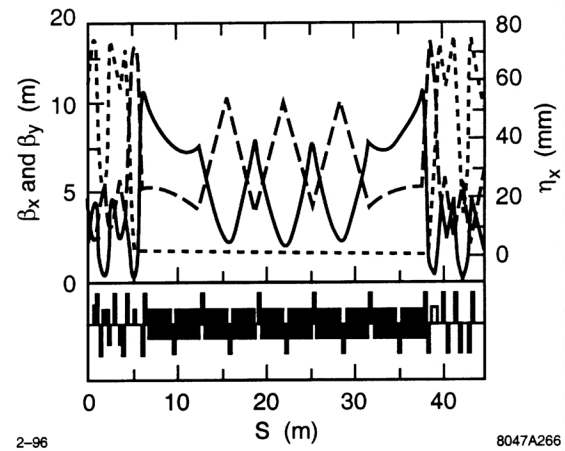


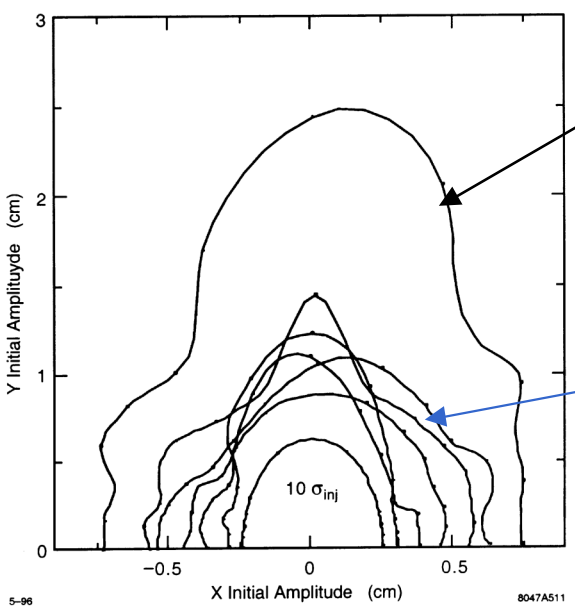


ZDR lattice

- ◊ 4-quad TME cells
- ◊ 19 cells per arc
- ◊ 30 m wiggler
- ◊ k = 1.9
  - → Good dyn. aper.







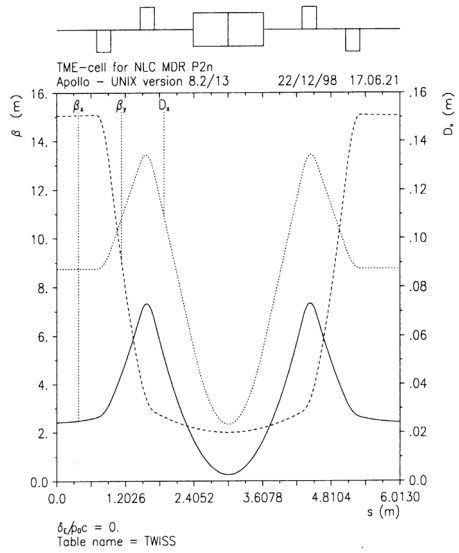
Bare lattice

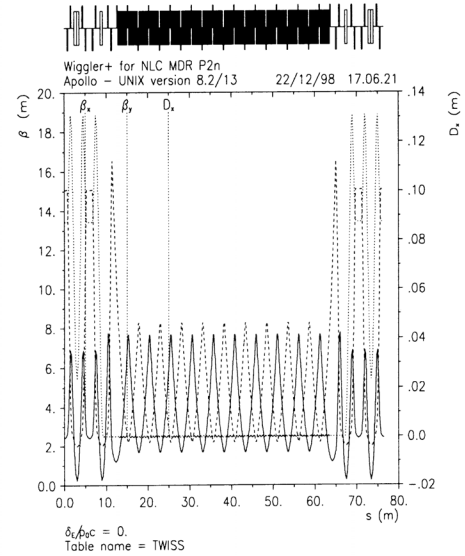
errors

all elements	
except bends:	x,y = 100 µm
bends:	x,y = 200 µm
all elements;	z = 1 mm, θ = 1 mr
all magnets:	$\Delta B/B = 10^{-3}$
energy:	$\delta p/p < 1\%$

Changes after ZDR

- ◊ Circumference increased
- ◊ 3-quad TME cells
- ◊ Longer (50 m) wiggler
- ◊ Increased momentum compaction
- ◊ Increased physical apertures
- ◊ k = 0
- ◊ Increased quad spacing in wiggler straight
- ◊ Decreased cells/arc





		Point A	Point B	Point C	
tune	**H**	**25.160**	**24.160**	**25.160**	
	V	**10.150**	**12.150**	**12.150**	
α		**5.102e-4**	**5.185e-4**	**4.486e-4**	
ε		**6.559e-10**	**8.649e-10**	**8.100e-10**	
dyn.)	**H**	**0.4**	**0.65**	**1.2**	**[mm]**
aper.)	**V**	**1.4**	**2.8**	**4.0**	**[mm]**

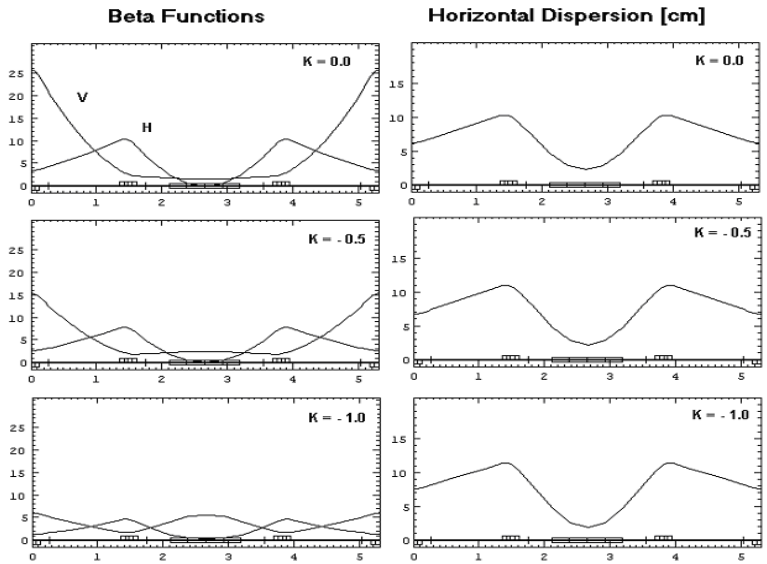
Dynamic aperture is too small ≈ 1σ $_{x,y}$
Natural chromaticity is too large

	H	V
Tune	~ 25	~ 10
Natural Chrom.	~ 40	~ 60

TME Cell Modification

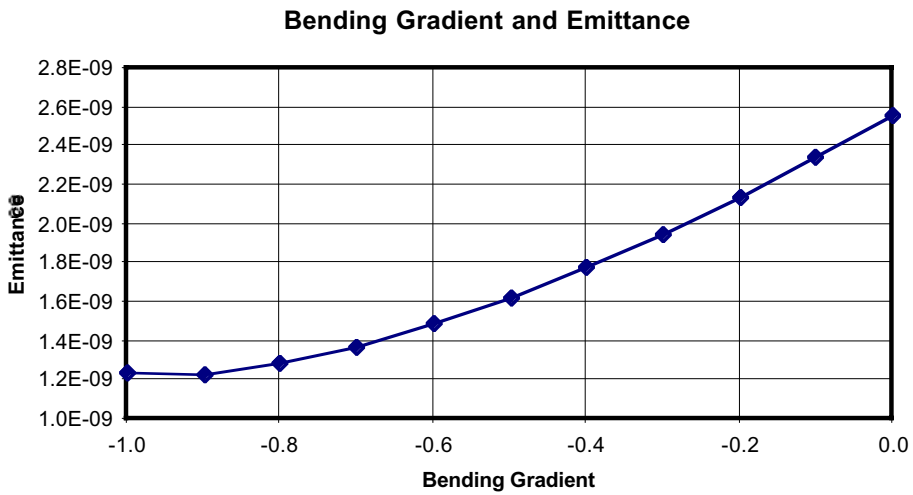
Re-instate gradient in bends

TME ring - no long straights



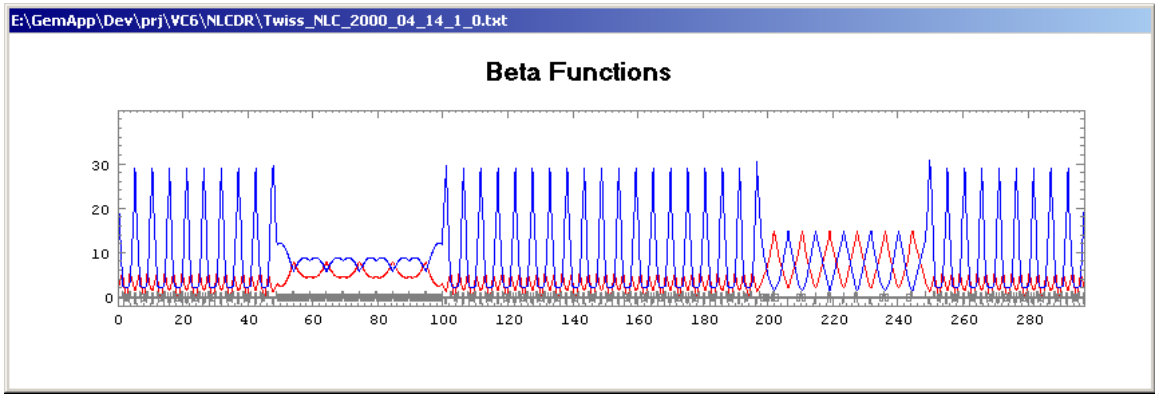
KB	MomComp.	E Spread	BetaH	BetaV	ChromH	ChromV	SD	SF	Emittance	Tx	Ty	Tz	RadLoss
0.0	1.10E-0	7.02E-0	3.59	25.94	-28.43	-25.14	-47.9	126.8	2.56E-0	1.02E-0	1.02E-0	5.12E-0	1.16E+05
-0.1	1.10E-0	7.09E-0	3.43	23.77	-27.13	-22.74	-47.9	125.9	2.34E-0	9.84E-0	1.02E-0	5.22E-0	1.16E+05
-0.2	1.11E-0	7.16E-0	3.26	21.65	-25.79	-20.43	-48.0	125.1	2.14E-0	9.50E-0	1.02E-0	5.32E-0	1.16E+05
-0.3	1.11E-0	7.23E-0	3.08	19.57	-24.40	-18.21	-48.5	124.5	1.95E-0	9.18E-0	1.02E-0	5.43E-0	1.16E+05
-0.4	1.11E-0	7.30E-0	2.90	17.54	-22.97	-16.08	-49.3	124.1	1.78E-0	8.89E-0	1.02E-0	5.53E-0	1.16E+05
-0.5	1.10E-0	7.37E-0	2.72	15.56	-21.49	-14.08	-50.8	124.1	1.63E-0	8.61E-0	1.02E-0	5.65E-0	1.16E+05
-0.6	1.10E-0	7.45E-0	2.52	13.62	-19.94	-12.21	-53.4	124.6	1.49E-0	8.35E-0	1.02E-0	5.76E-0	1.16E+05
-0.7	1.09E-0	7.52E-0	2.31	11.72	-18.31	-10.50	-57.7	126.2	1.38E-0	8.12E-0	1.02E-0	5.88E-0	1.16E+05
-0.8	1.08E-0	7.60E-0	2.09	9.87	-16.58	-9.03	-65.4	129.4	1.28E-0	7.91E-0	1.02E-0	6.00E-0	1.16E+05
-0.9	1.07E-0	7.67E-0	1.83	8.05	-14.70	-7.90	-79.8	136.1	1.22E-0	7.72E-0	1.02E-0	6.11E-0	1.16E+05
-1.0	1.03E-0	7.72E-0	1.53	6.26	-12.66	-7.34	-111.1	150.4	1.24E-0	7.59E-0	1.02E-0	6.19E-0	1.16E+05

ε vs k

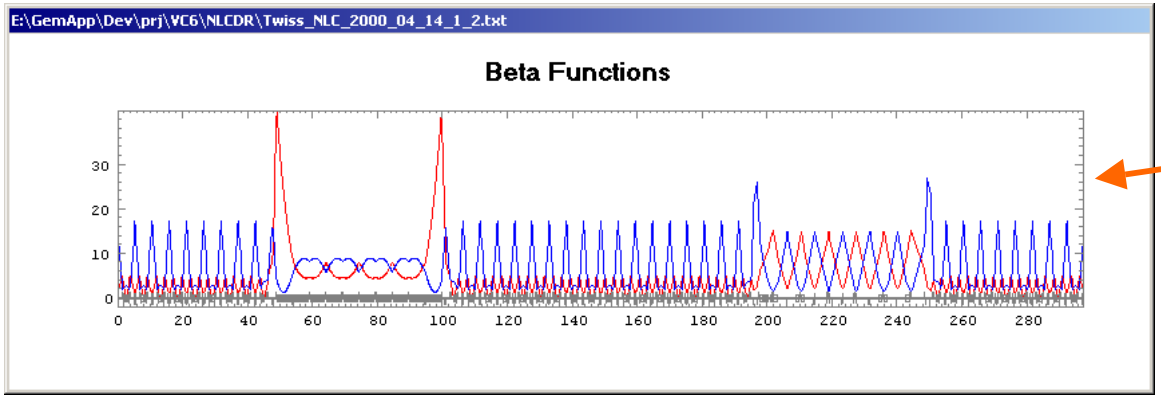

Bending Gradient and Emittance
2.8E-09
2.6E-09
2.4E-09
2.2E-09
2.0E-09
1.8E-09
1.6E-09
1.4E-09
1.2E-09
1.0E-09
Emittance
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Bending Gradient

1st fit to straights with k = -0.5

◊ "original" lattice

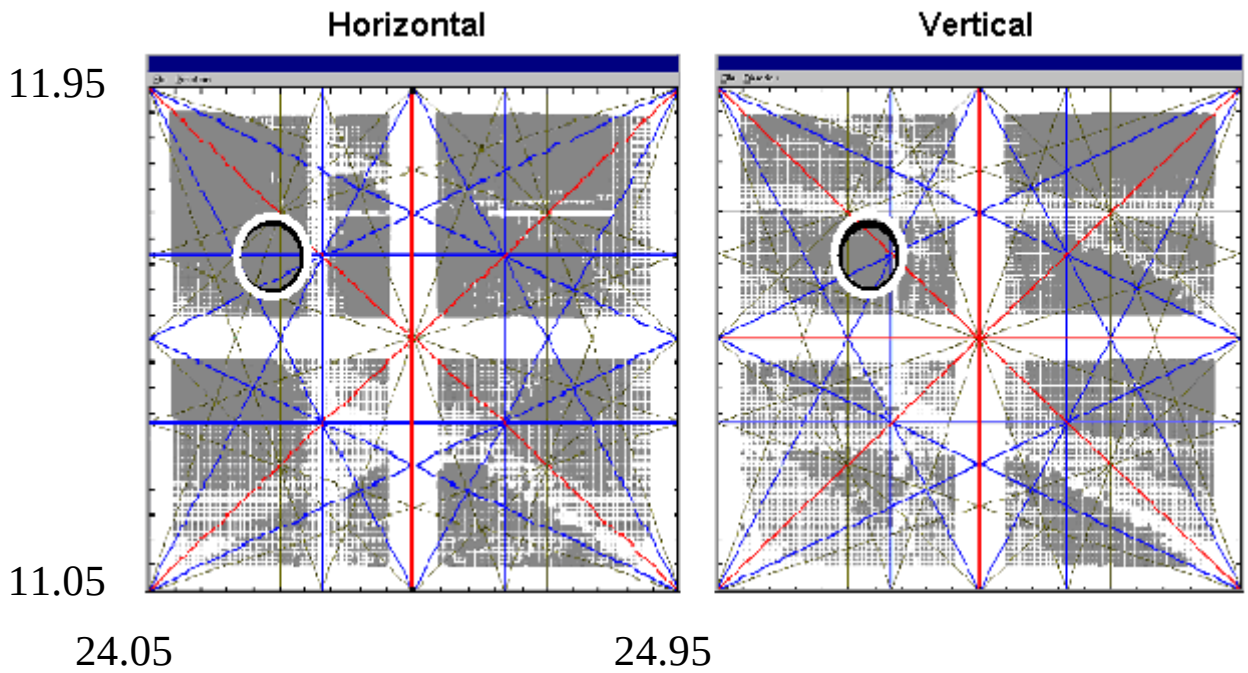


◊ After first attempts at fitting



Track this lattice

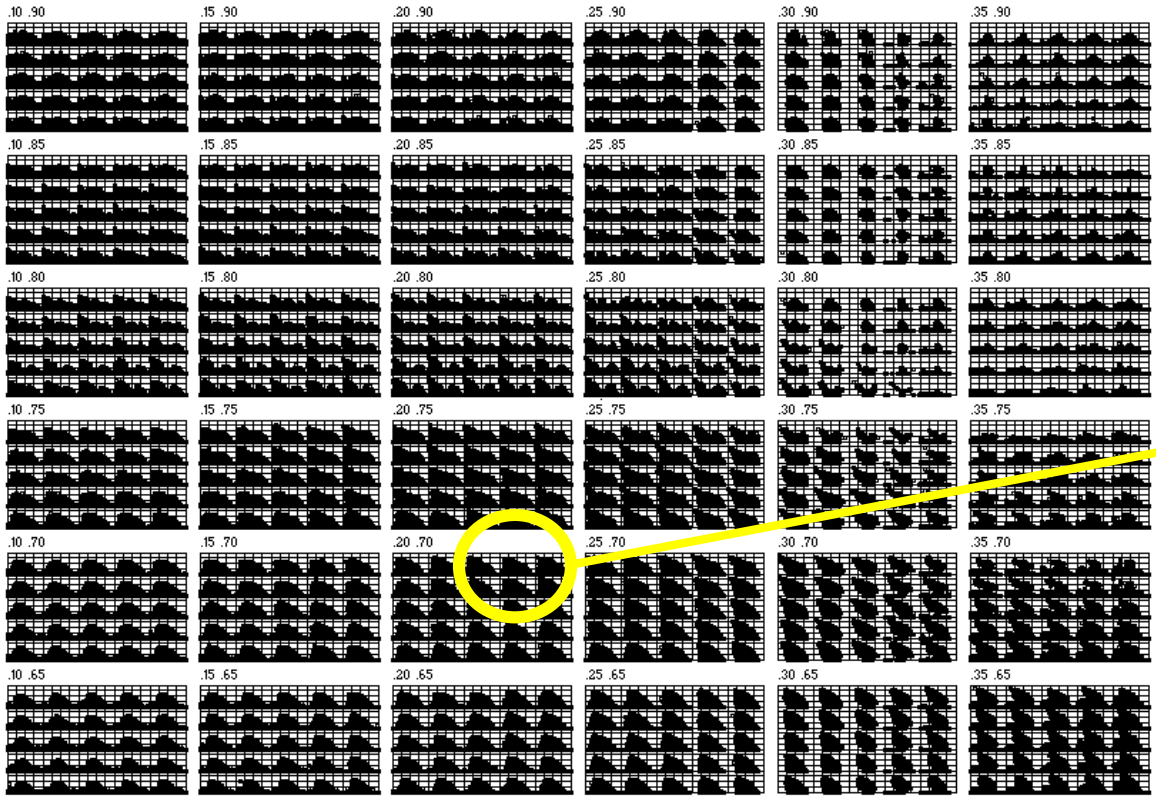
Aperture scans

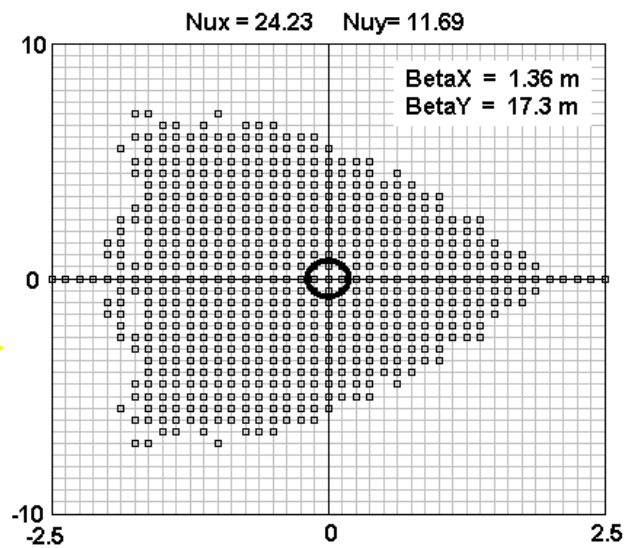


Darker is better

Aperture scans

◊ $\nu_x \approx 24.25, \nu_y \approx 11.75$



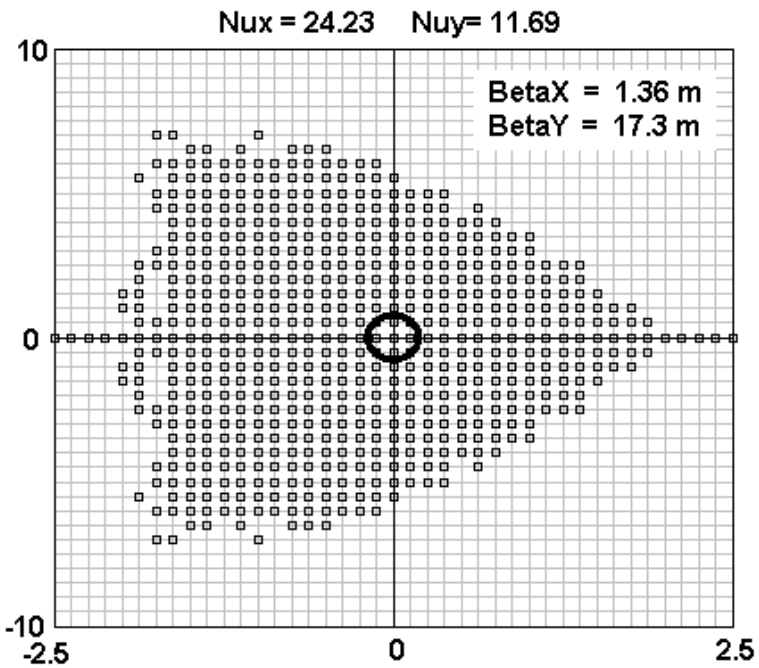


400 turns

At center quad

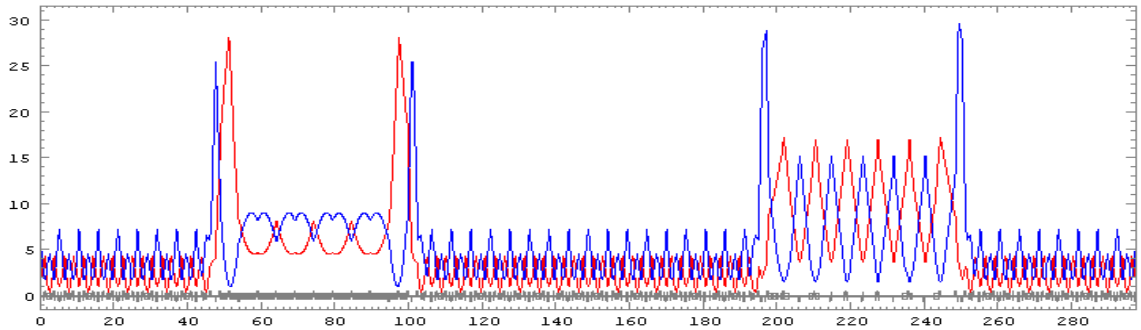
Dynamic aperture - 1st fit

- **Dynamic aperture:**
  - horizontal = 1.875 mm
  - vertical = 5.5 mm
- **Injected beam emittance ~ 4.0e-8**
- **Beam Size**
  - X = 2.0e-4 √1.36 = 2.3e-4 m = 0.23 mm
  - Y = 2.0e-4 √17.3 = 8.3e-4 m = 0.83 mm
- **Dynamic Aperture / Beam Size**
  - **H: 1.875 / 0.23 = 8.2**
  - **V: 5.5 / 0.83 = 6.6**

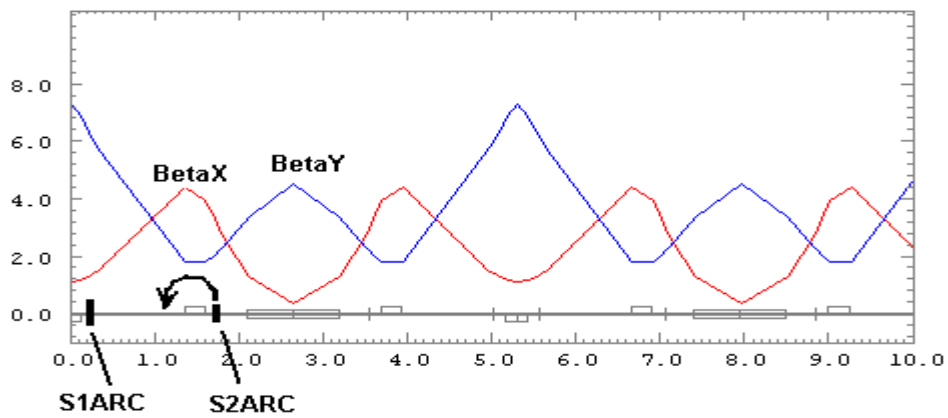


2nd fit to straights with k = -0.5

- Improve matching to straights



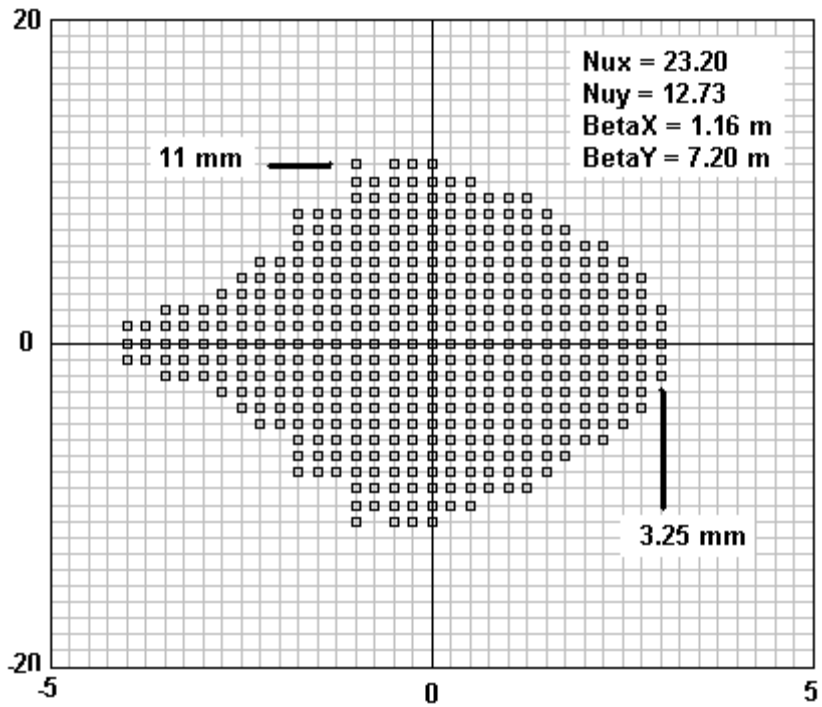
- Move sextupole to larger β_x/β_y



Track this lattice

Dynamic aperture - 2nd fit

Betatron tune	H	23.24130
	V	12.82657
Momentum compaction		4.71933e-004
Chromaticity	H	-30.97266
	V	-23.50721
Damping partition	H	1.09212
	V	1.00000
	E	1.90788
Radiation loss		683.03 keV
Natural energy spread		8.88780e-004
Natural emittance		7.84718e-010
Radiation damping	H	5.264438 msec
	V	5.749380 msec
	E	3.013486 msec



- **Dynamic Aperture / Beam Size**
  - **H: 3.25 / 0.22 = 15**
  - **V: 11 / 0.537 = 20**

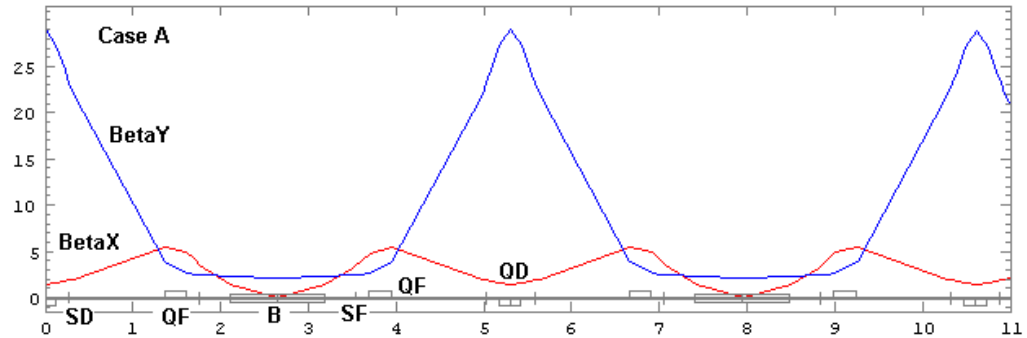
Dynamic aperture studies

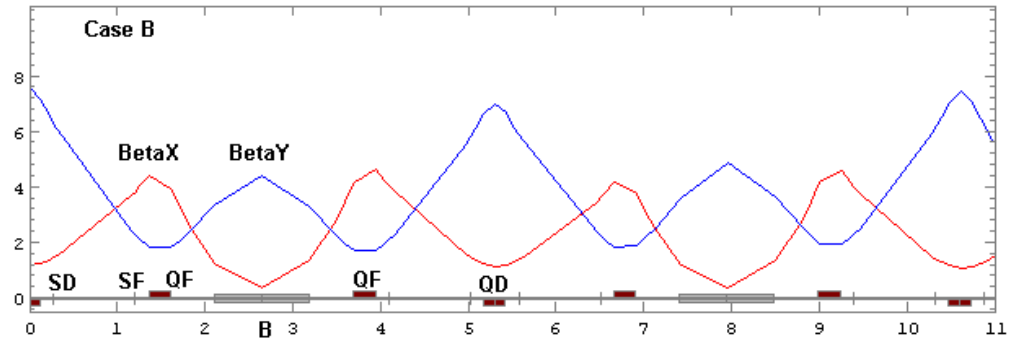
◊ Dynamic aperture improved from ≈ 1 σ to > 15 σ

→Introduced gradient magnet

→Early attempts at matching

→Moved SXT's





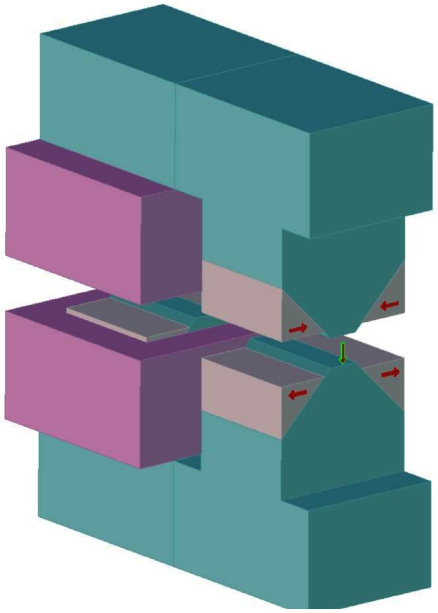
⇒Need to improve matching into straights

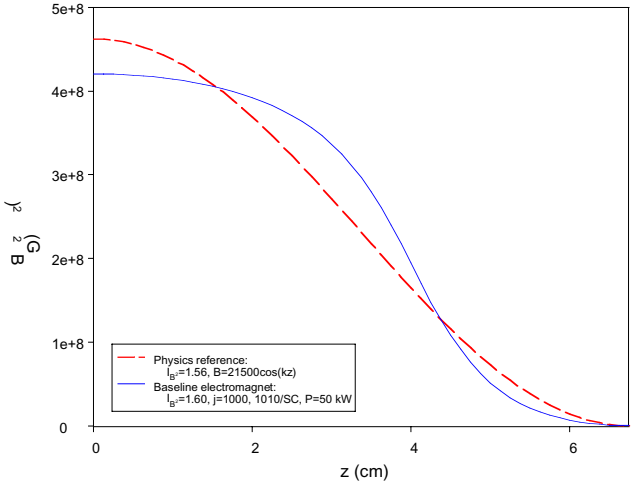
⇒Need to include errors

⇒Need to include real wiggler field

Electromagnet Wiggler

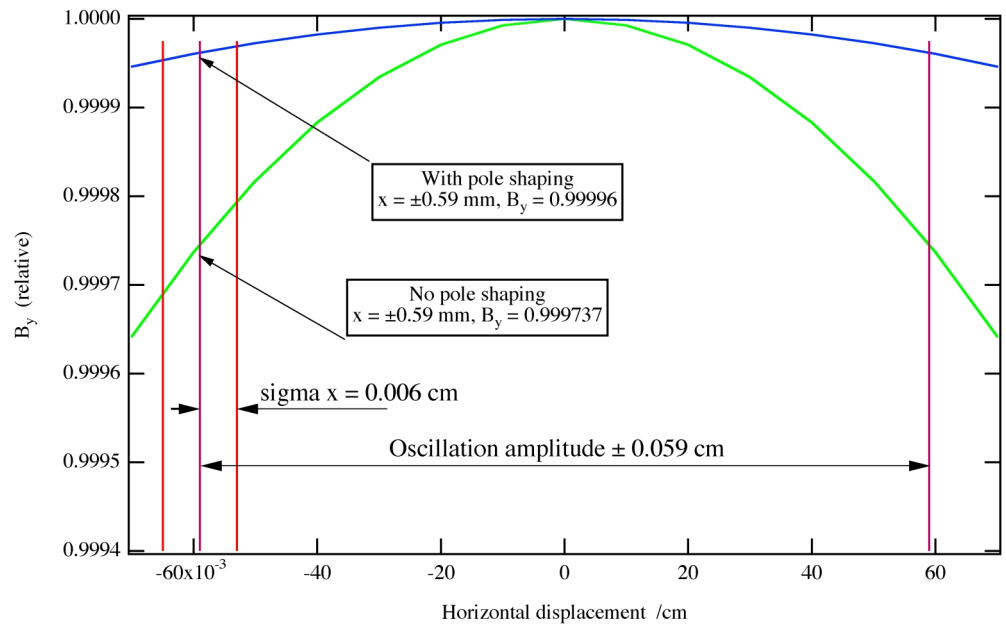
PARAMETER	VALUE	UNITS
Peak field on axis	2.05	T
Integrated B^2	106	T^2m
Wiggler period	270	mm
Magnet gap	20	mm
Number of wiggler sections	10	
Length of wiggler section	4.51	m
Quadrupole spacing	5.09	m
Total length of wiggler straight	50.9	m
Vacuum chamber height	16	mm
Transverse field flatness		
End field adjustability	0.006	T-m
Coil current density	1000	A/cm^2
Input power per wiggler section	100	kW
Radiated power per wiggler section	<55	kW
Average power absorbed/photon stop	23	kW
Total power exiting wiggler straight	60	kW



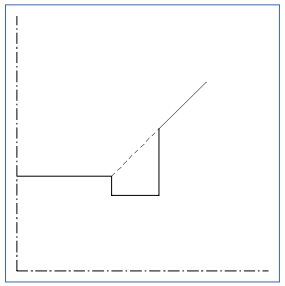


Lattice studies

- Wiggler effects may seriously degrade nonlinear dynamics
  - Experience at SSRL BL11
    - →Lifetime reduction (30%)
    - →Lifetime dependence on transverse position
    - →Reduced dynamic aperture
    - →Increased tune shift with amplitude



- Developing 3-D wiggler field in tracking codes
  - Analyze non-linear effects
    - →Set limits on field flatness



Pole-tip shaping

Instabilities in rings

- Single-bunch effects
  - ◊ Increase in beamsize (transverse and longitudinal)
    - → Instabilities
      - > Impedance driven, two-beam driven
    - → IBS
  - ◊ Beam loss
  - ◊ "Bursting" phenomena particularly difficult
    - → SLC - "sawtooth", NSLS - coherent radiation bursts
      - > Severe consequences downstream of damping rings

◊ Requires very careful vacuum chamber design

> Reduce short-range wakefields

⇒ *Understand wakefield / impedance model*

⇒ *Understand instability models*

Instabilities in rings

- Coupled-bunch motion
  - Bunch-to-bunch energy spread
    - → Energy spread in extracted bunch trains
  - Beam loss

> Damp resonances
>
> ⇒ Cavities, BPM's, septa, kicker magnets, …
>
> Feedback systems
>
> ⇒ Control residual motion

Impedance related effects

- Broadband
  - Microwave instability

$$p = \frac{2\pi\,|\eta|\left(\frac{E}{e}\right)(\beta\sigma_p)^2}{\left|\frac{Z_{||}}{n}\right|_{eff}}$$

  - Transverse mode coupling

$$b = \frac{4\left(\frac{E}{e}\right)\nu_s}{\langle \mathrm{Im}(Z_\perp)\,\beta_\perp\rangle R}\,\frac{4\sqrt{\pi}}{3}\,\sigma_l$$

→Related to "effective" impedance experienced by a single bunch

> Short-range wakefield

⇒ All vacuum chamber components

- Narrowband
  - Coupled-bunch instabilities

$$\Delta\omega_{transverse} = -\,j\,\frac{I\,f_0}{2\frac{E}{}}\,\beta_{x,y}\,Z_{eff}^{trans.}$$

$$\Delta\omega_{longitudinal} = j\,\frac{I f_{rf}}{2\frac{E}{e}}\,\alpha_p\,\frac{f_0}{f_s}\,Z_{eff}^{long.}$$

→Related to narrow-band resonant impedance

> Long-range wakefield

⇒ RF cavities

⇒ Resistive wall

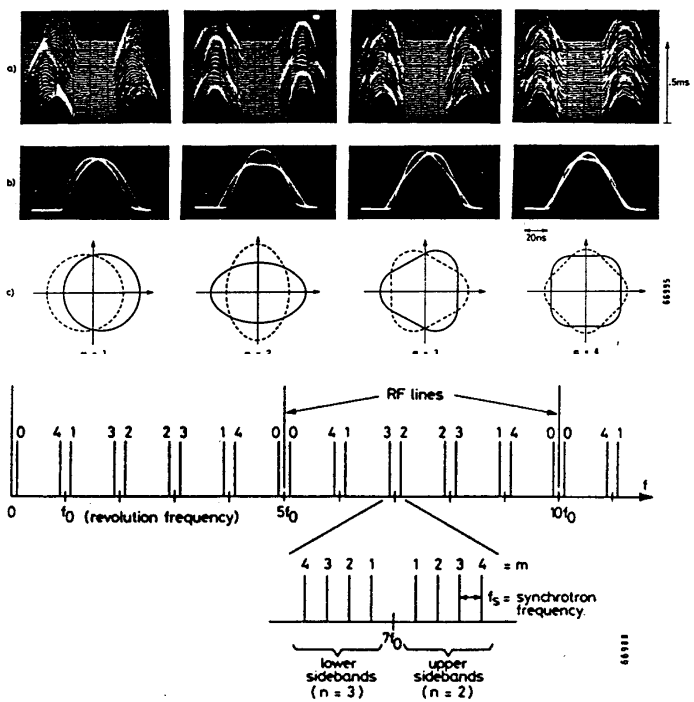
- Heating
  - Power deposited in a resistive impedance may cause heating and damage

Bunch modes

♦ Longitudinal

$$\underset{\text{eff}}{\text{long.}} = \sum_{p=-\infty}^{p=+\infty} \frac{\omega_p}{\omega_{rf}} e^{-(\omega_p \sigma \tau)^2} Z^{\text{long.}}$$

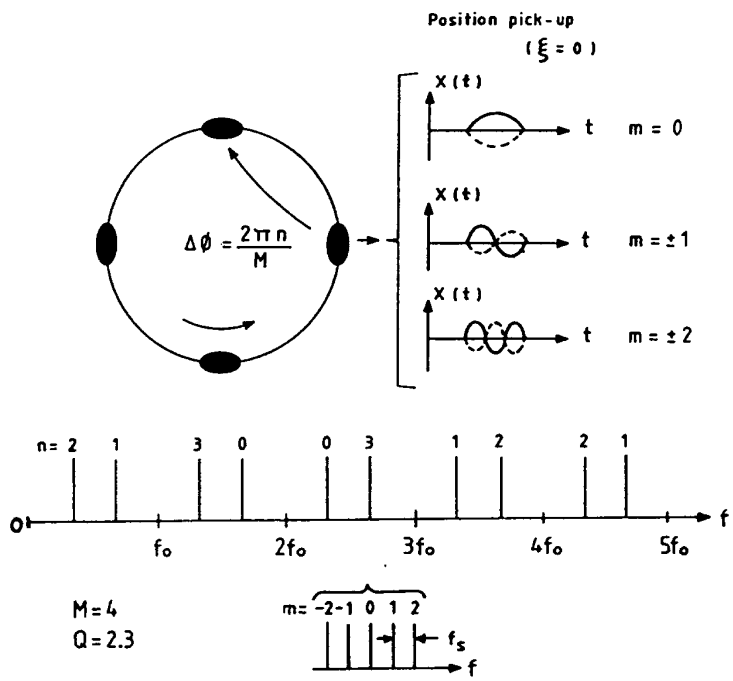
$$\omega_p = (pM + n + mQ_s)\,\omega_0$$



♦ Transverse

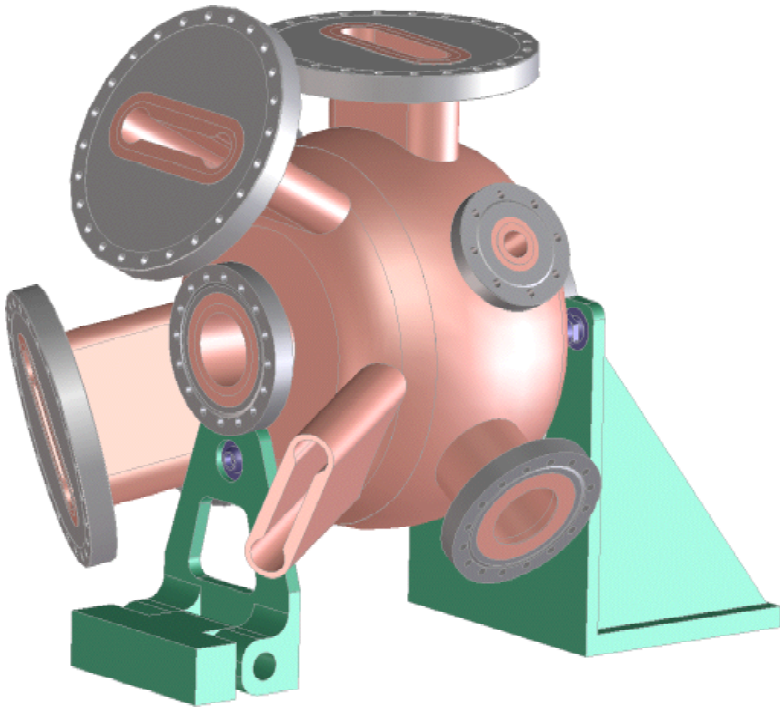
$$\underset{\text{eff}}{\text{trans.}} = \sum_{p=-\infty}^{p=+\infty} e^{-(\omega_p \sigma \tau)^2} Z^{\text{trans.}}$$

$$\omega_p = (pM + n + Q_{x,y} + mQ_s)\,\omega_0$$



HOM Damped Cavity

- Baseline design developed and improved on PEP-II design
  - Three damping waveguides
  - Modified cavity cross-section
  - Improved waveguide coupling apertures
  - Improved fabrication techniques



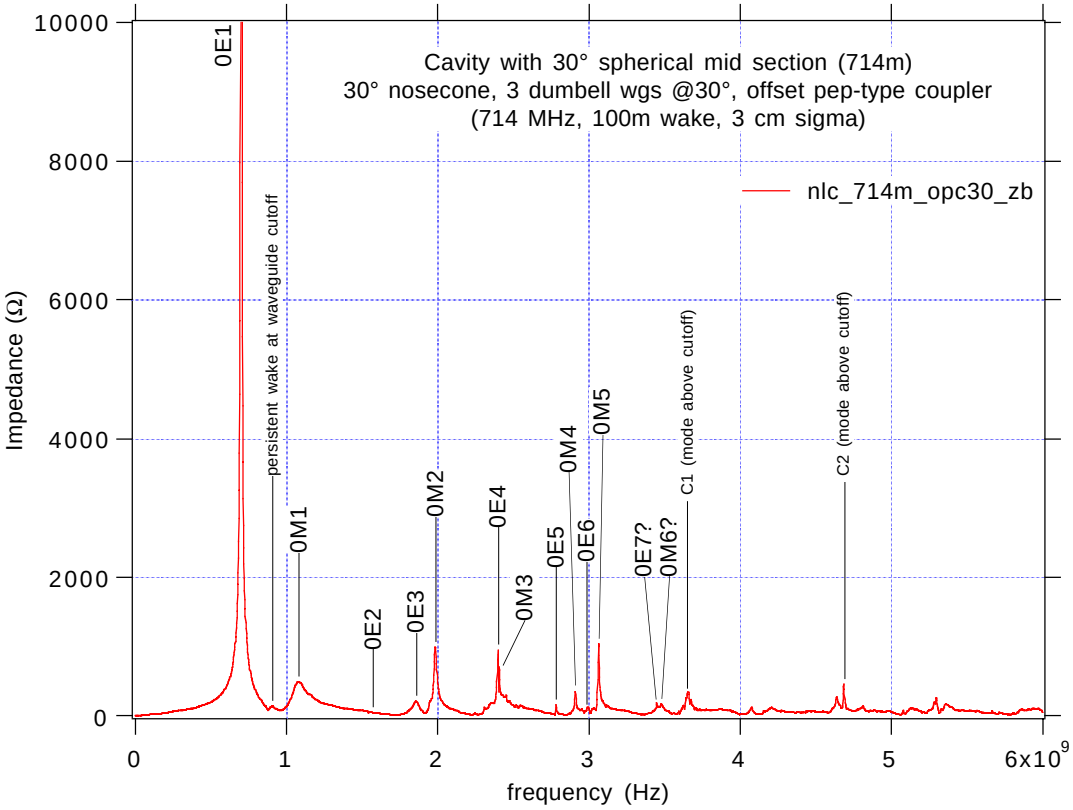
Berkeley

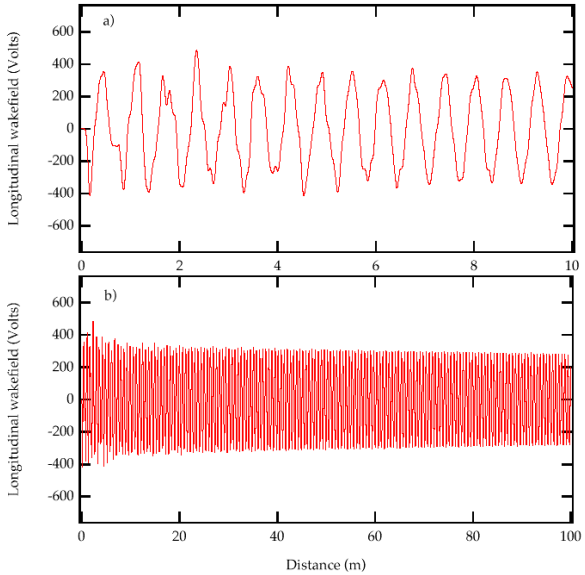
Bob Rimmer

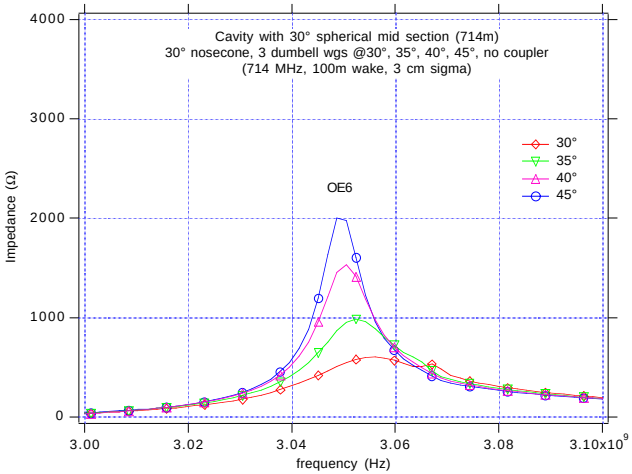
MAFIA calculations of long-range wakefields

HOM damping

- Longitudinal

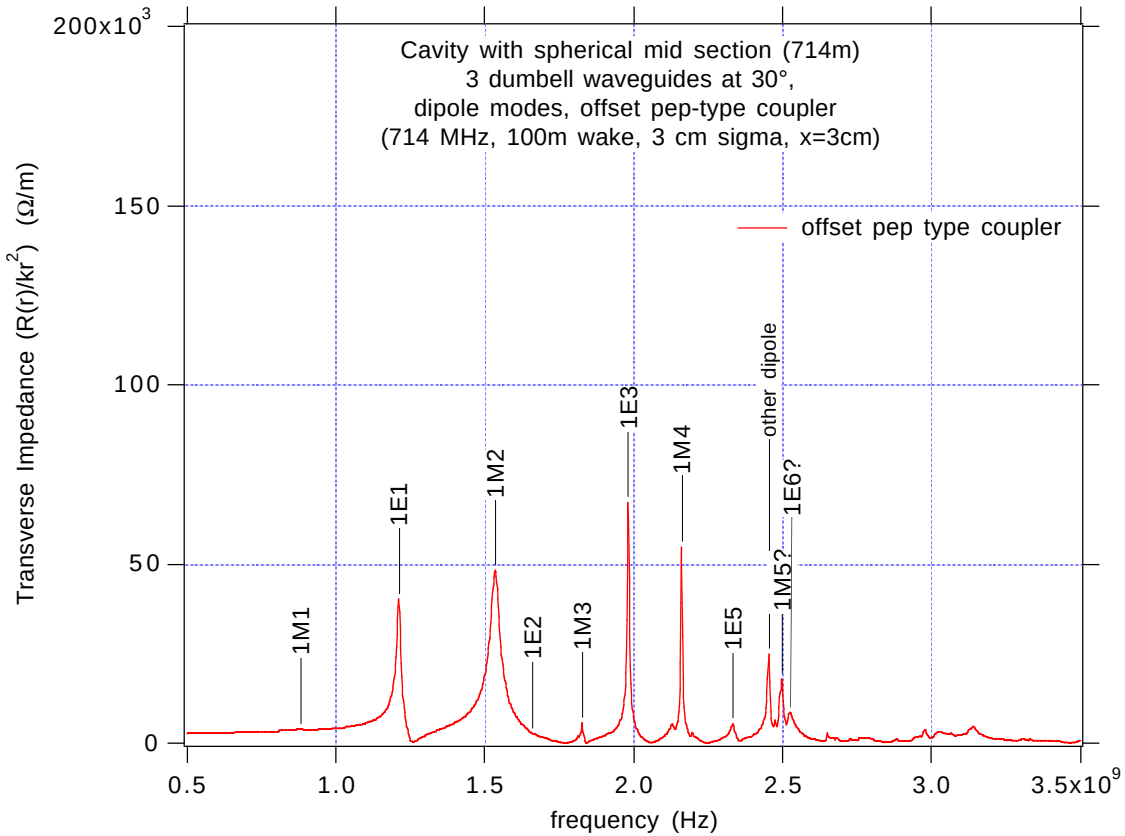


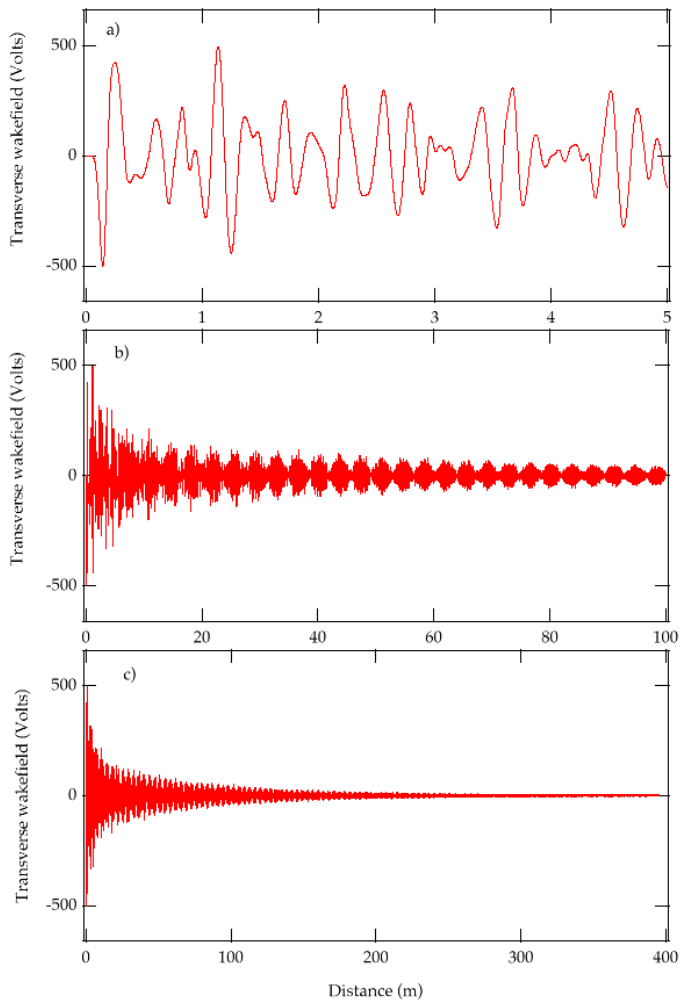




HOM damping

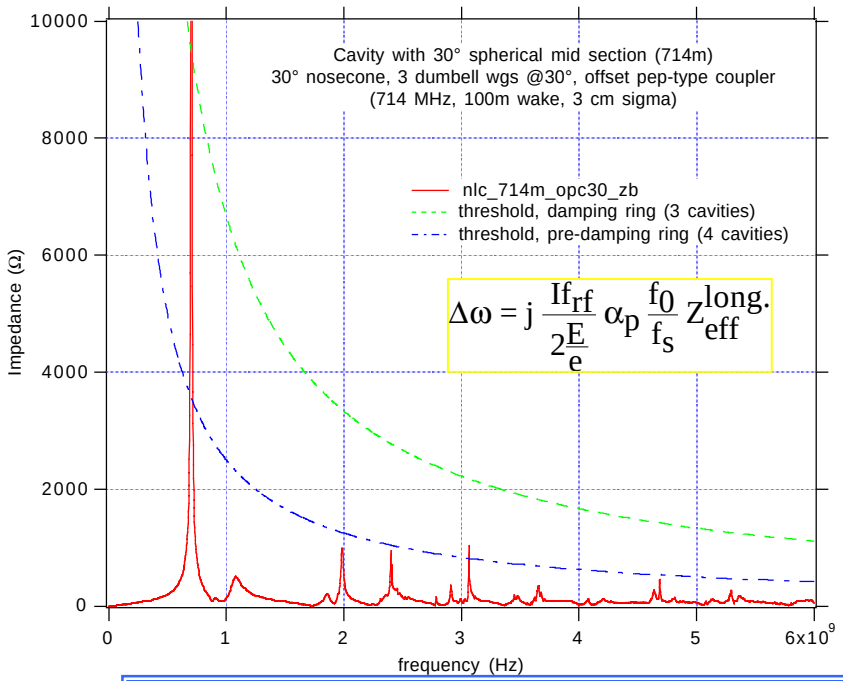
- Transverse



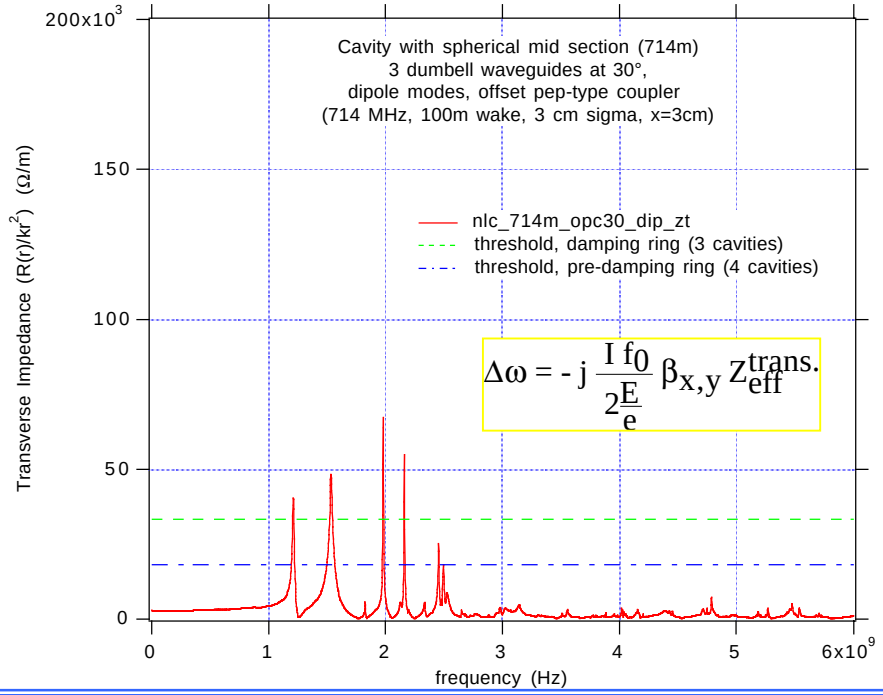


HOM Damping

- Longitudinal modes



- Transverse modes



→ Higher-order modes strongly damped

> *Transverse feedback system required*

⇒ *HOM's, resistive wall , and electron/ion instabilities*

Broadband Impedance Model

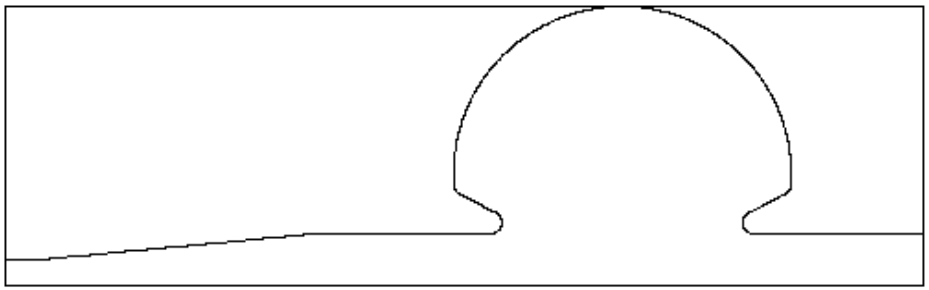
SLAC

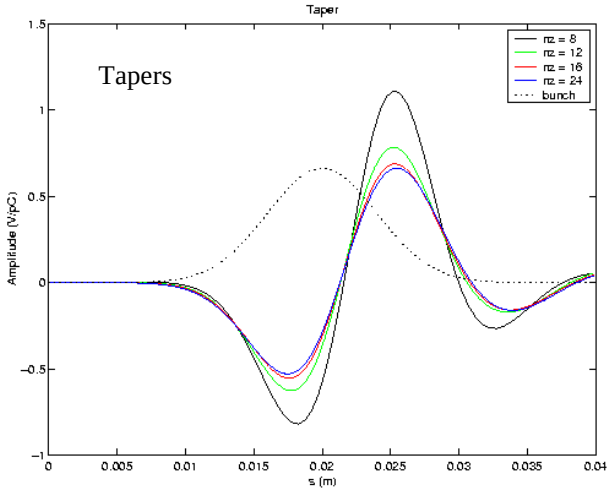
Cho Ng

- Major vacuum chamber components
  - → RF cavities (3)
  - → Resistive wall (300 m Al)
    - > Small vacuum chamber
  - → BPM's (159)
    - > High-frequency resonances
  - → Ante-chamber slots (102)
  - → Bellows shields (102)
  - → Injection and extraction magnets (2)
  - → Feedback kickers (2)

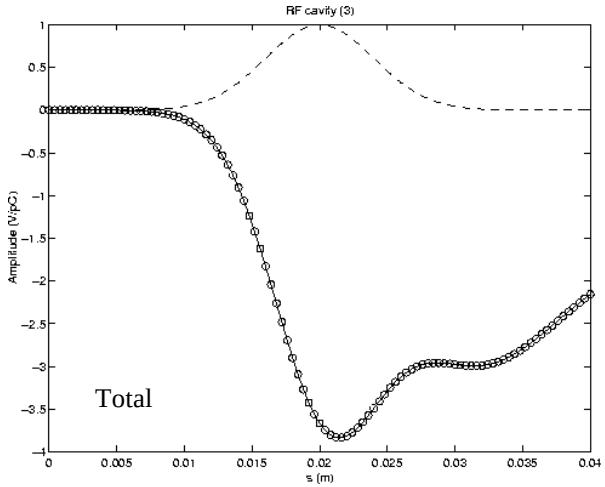
MAFIA calculations of short-range wakefields

RF cavity





- scaled to 714 MHz from PEP-II
- tapered to beampipes at ends of RF section
  - 3 cavities, 2 tapers
- ignore crosstalk between cavity and taper
- taper wakefield sensitive to mesh size $\frac{a\phi}{\Delta z}\frac{\sigma_s}{\Delta z} > 100$
- loss factor:
  - Cavity 0.970 V/pC
  - Tapers 0.067 V/pC
- inductance from tapers = 0.41 nH



Longitudinal resistive wall

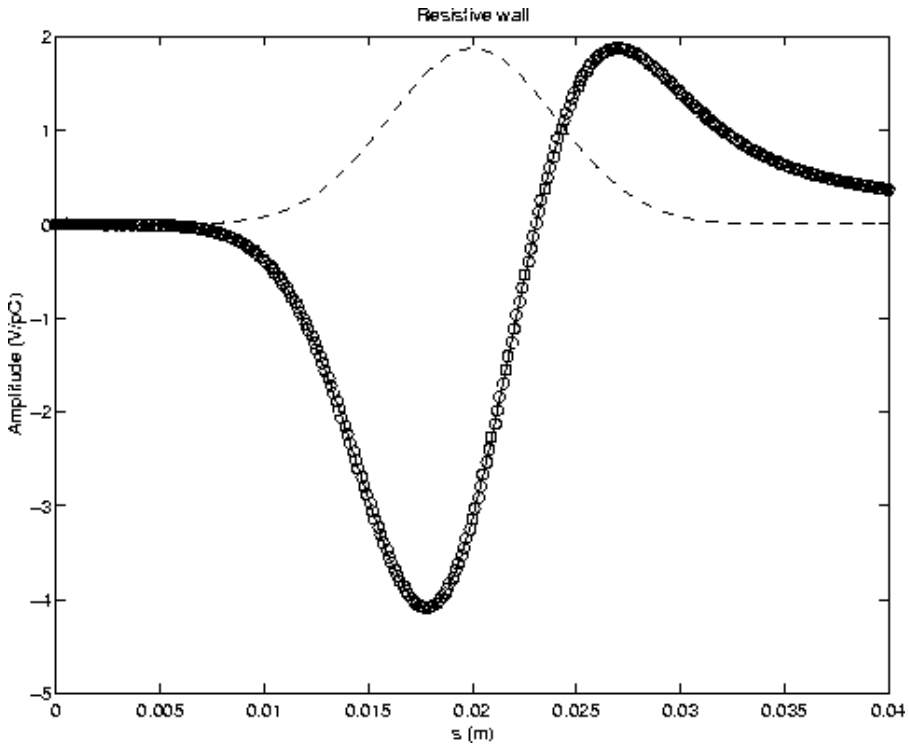
- Longitudinal
  - Short-range wake is strong for very small vacuum chambers and short bunches

$$W_z(s) = \frac{C}{4b\sigma_z^{3/2}} \sqrt{\frac{c}{2\pi\sigma_{d.c.}}}\, f(s/\sigma_z)$$

$$f(u) = |u|^{3/2}\, e^{-u^2/4} \left(I_{1/4} - I_{-3/4} -+ I_{-1/4} +- I_{3/4}\right)\Big|_{u^2/4}$$

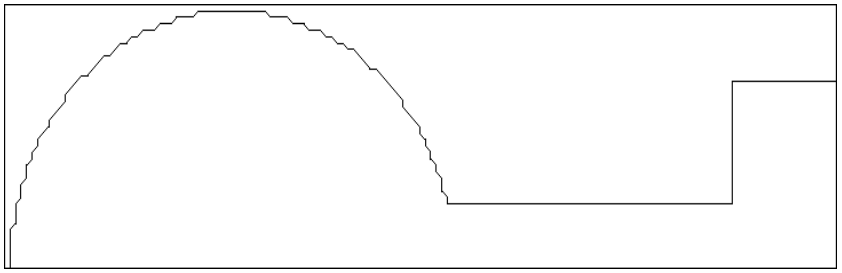
- Resistive heating

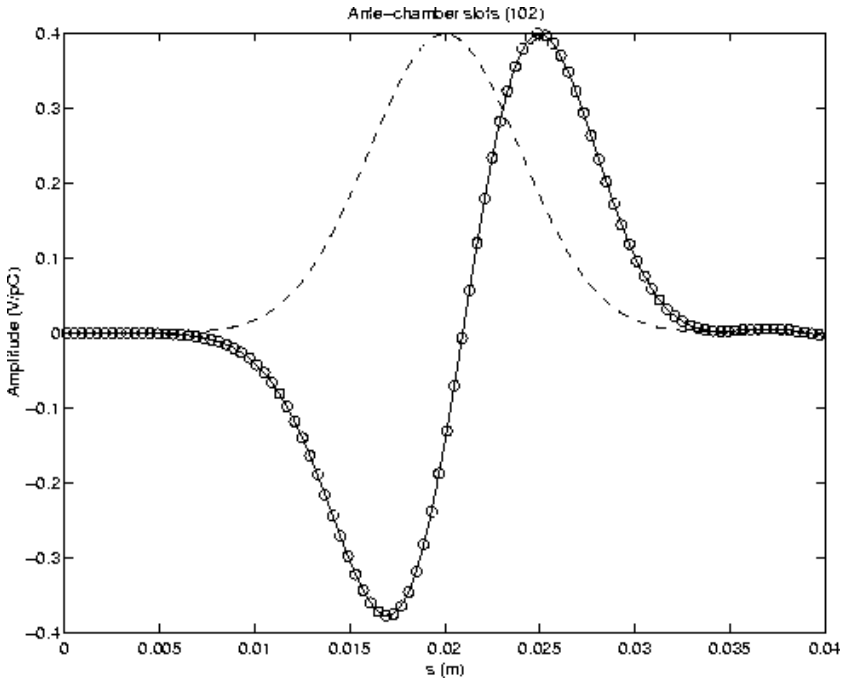
$$= \frac{L}{8\pi^2 r} I_0^2\, \Gamma\left(\frac{3}{4}\right) \sqrt{\frac{\mu_o}{2\sigma_{dc}}}\, \frac{T_b}{\sigma_t^{\left(\frac{3}{2}\right)}}$$



- 250 m vacuum chamber 1.6 cm radius
- 50 m wiggler chamber 0.8 cm radius
- loss factor = 1.867 V/pC

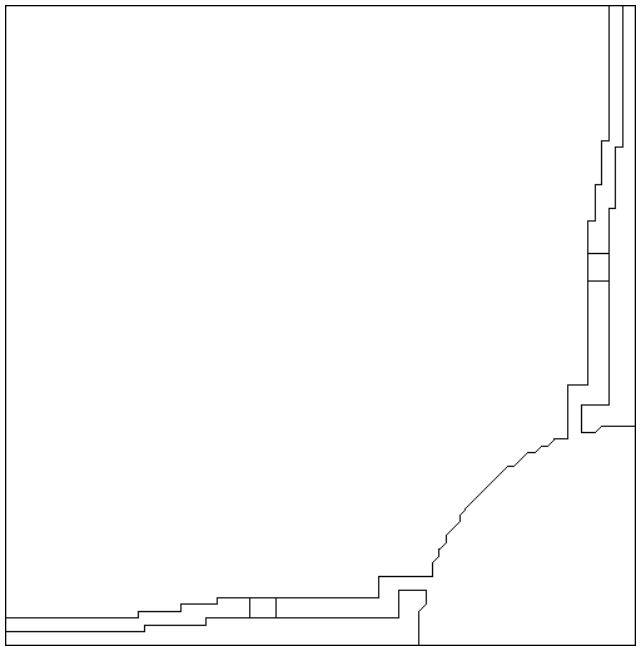
Ante-chamber slot

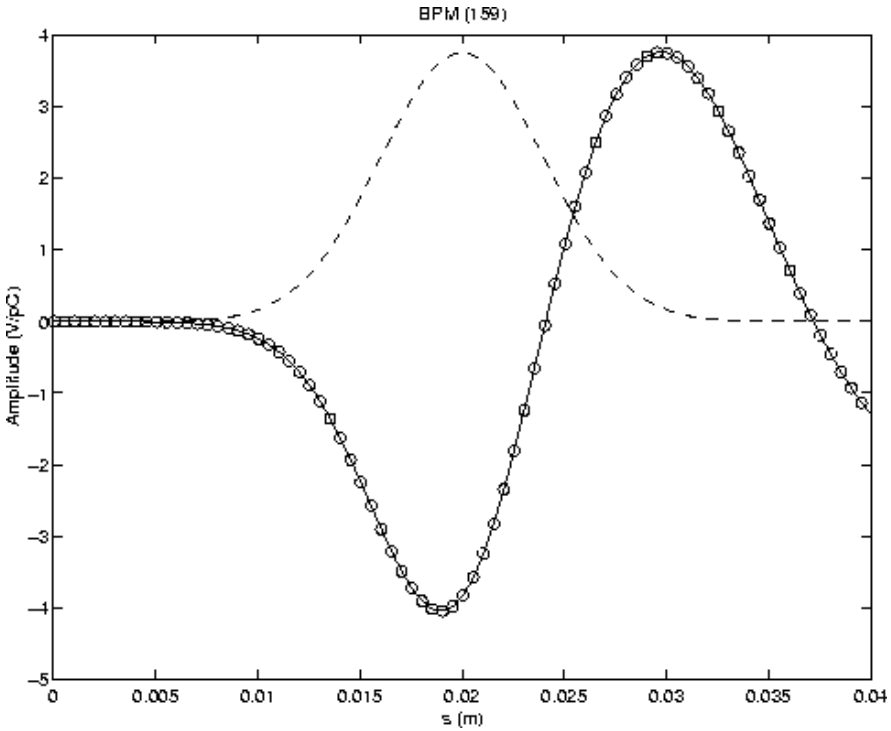




- 8 cm wide
- tapers inside slots at both ends
- loss factor = 6.65×10^{-4} V/pC
- inductance = 2.72×10^{-3} nH
- 102 slots

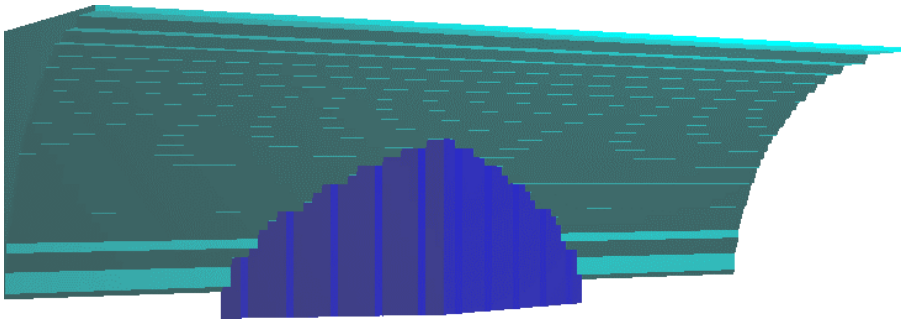
BPM

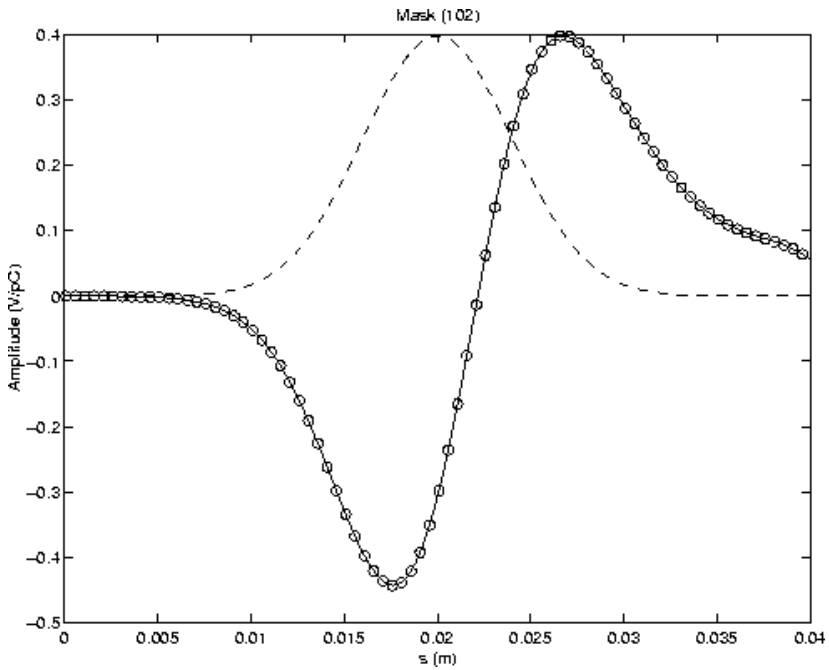




- four 8 mm buttons
- loss factor = 0.014 V/pC
- inductance = 0.019 nH
- 159 BPMs

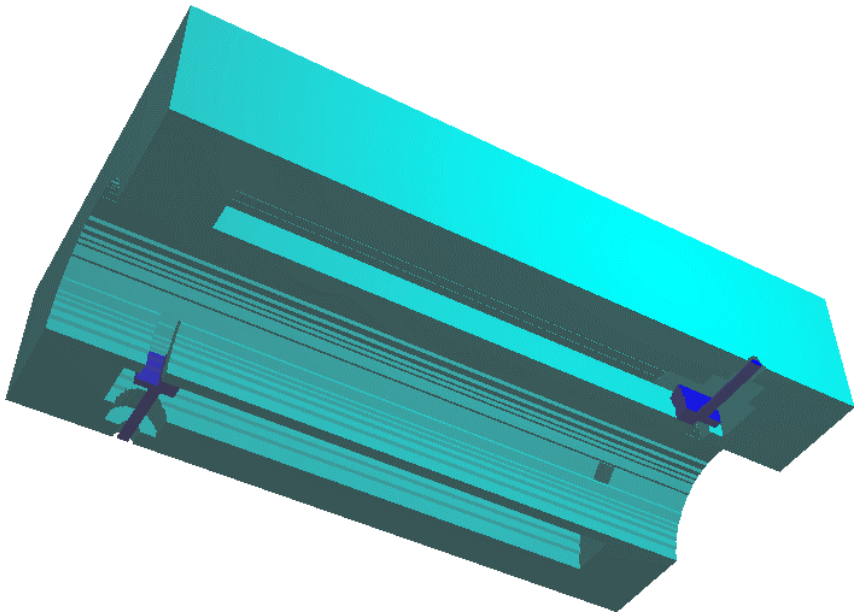
Synchrotron radiation mask

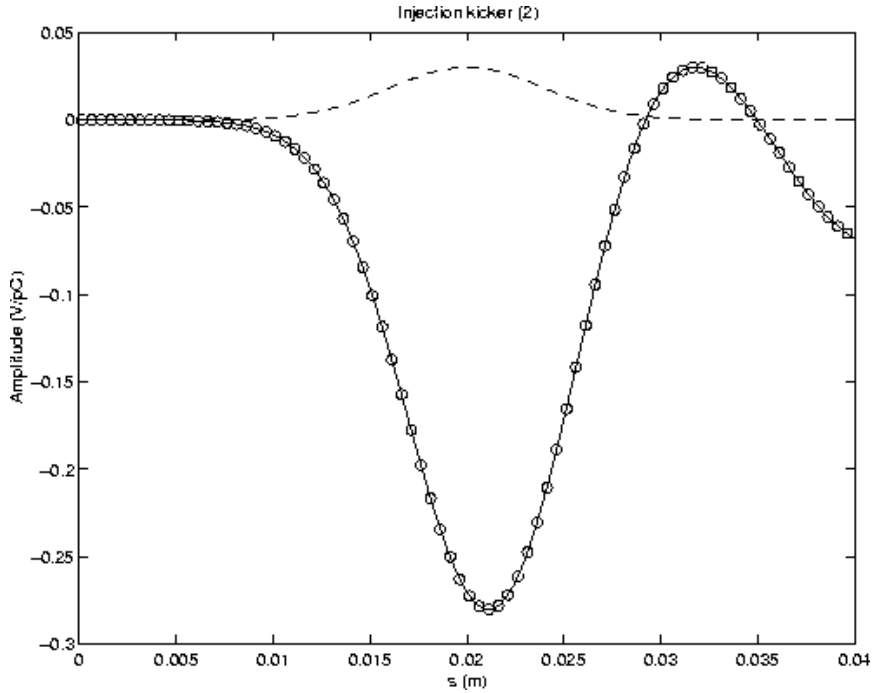




- 2 mm depth, 2.5 cm long
- loss factor = 0.0016 V/pC
- inductance = 0.0039 nH
- 102 bellows masks

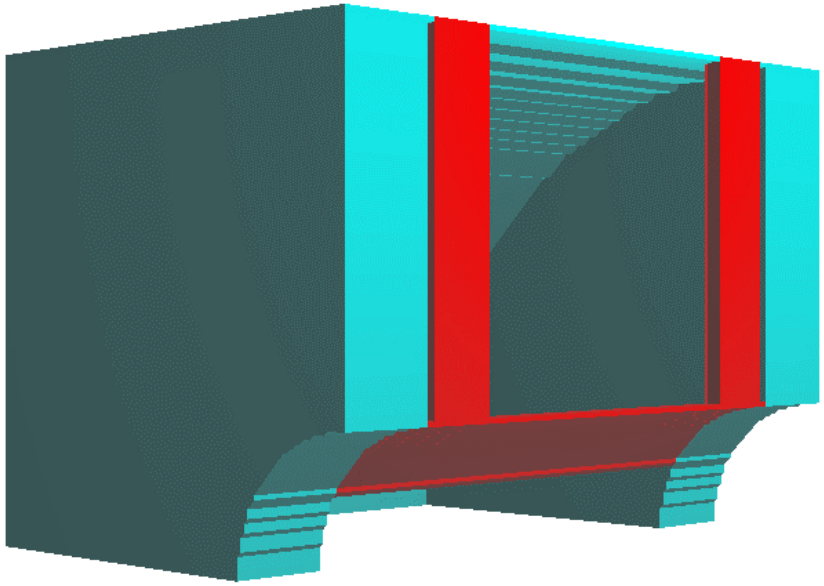
Injection / extraction kicker

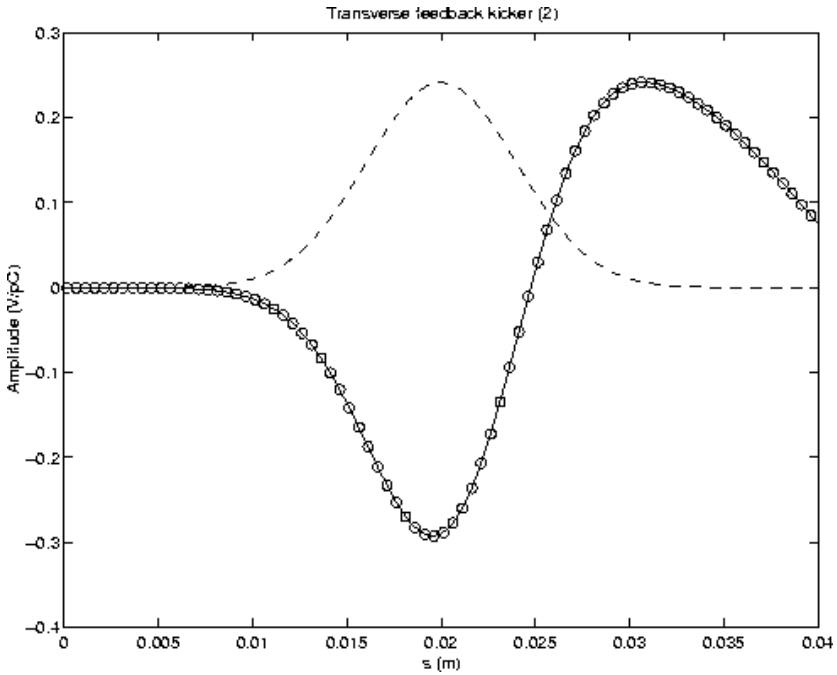




- DELTA-type kicker
- 4 mm wide slots
- loss factor = 0.096 V/pC
- inductance = 0.103 nH
- 2 kickers

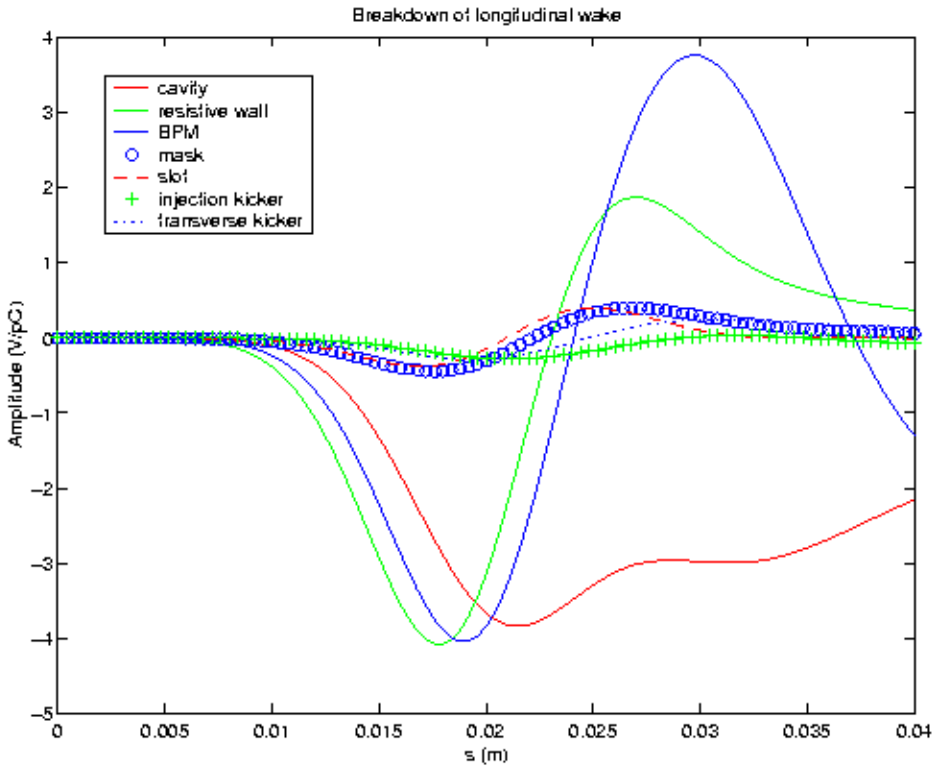
Transverse feedback kicker

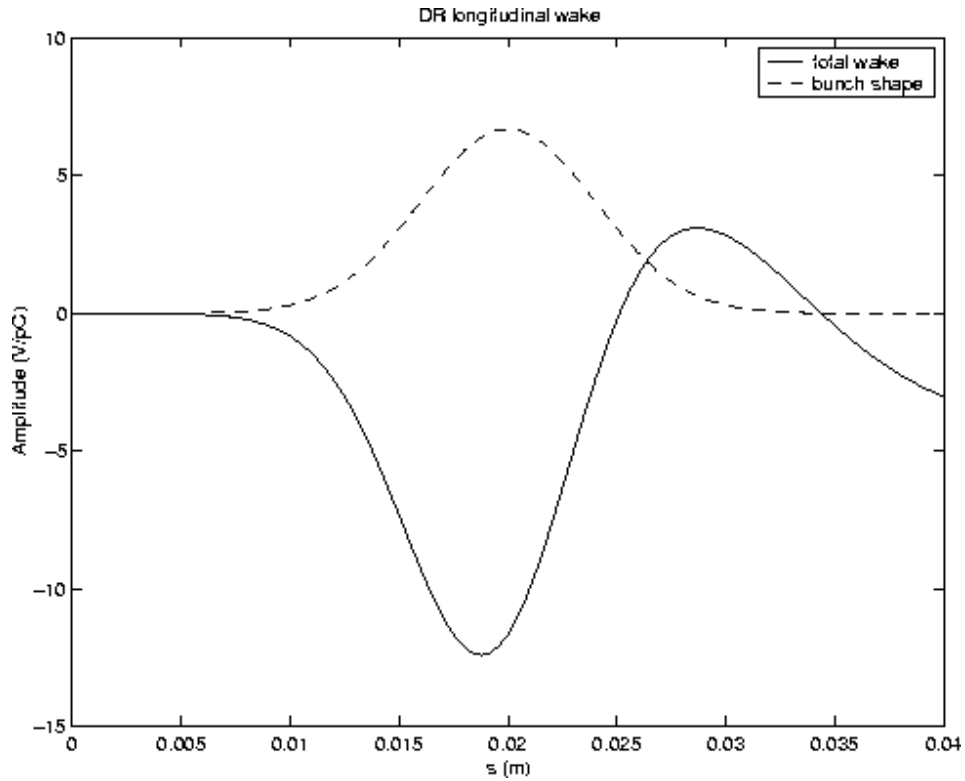




- two 1.6 cm wide slots
- loss factor = 0.086 V/pC
- inductance = 0.107 nH
- 2 transverse feedback kickers

Breakdown of longitudinal wake





Longitudinal wake summary

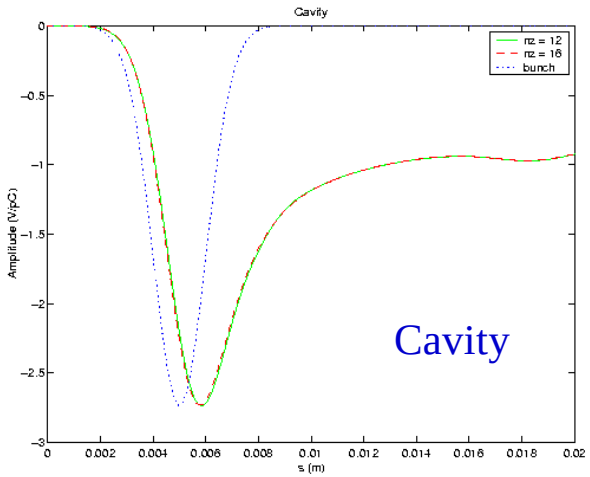
Components	Loss factor (V/pC)	Inductance (nH)
◊ RF cavities	2.976	0.410
◊ BPMs	2.226	2.970
◊ ante-chamber slots	0.068	0.277
◊ bellows masks	0.168	0.326
◊ injection / extraction kickers	0.192	0.210
◊ transverse feedback kickers	0.171	0.214
◊ 300 m resistive wall	1.867	
♦ TOTAL	7.67	4.4

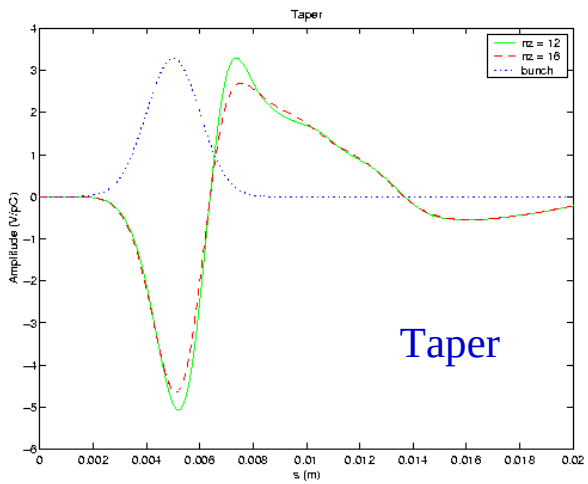
$\Rightarrow Z/n \approx 0.028\ \Omega$

Broadband impedance calculation

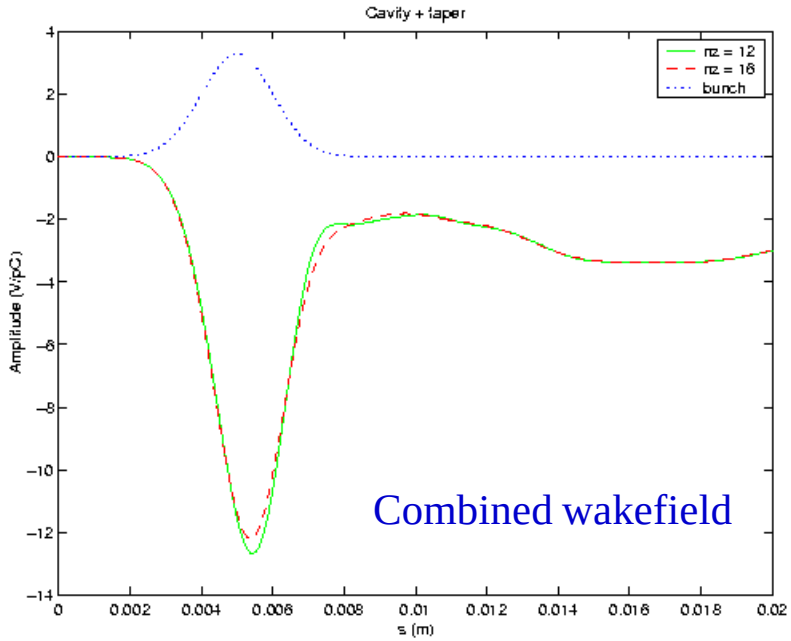
- Require "delta-function" or "Green's function" wake for inclusion in self-consistent singlebunch phenomena modeling
  - → Particle tracking
  - → Numerical solution of Fokker-Planck equation
  - → Modal analysis from Vlasov equation
    - > Improvement over broadband impedance models
    - > Require wake from very short bunch to generate an effective Green function
      - ⇒ Dense mesh
      - ⇒ Long run time

RF cavity Green's function wakefield



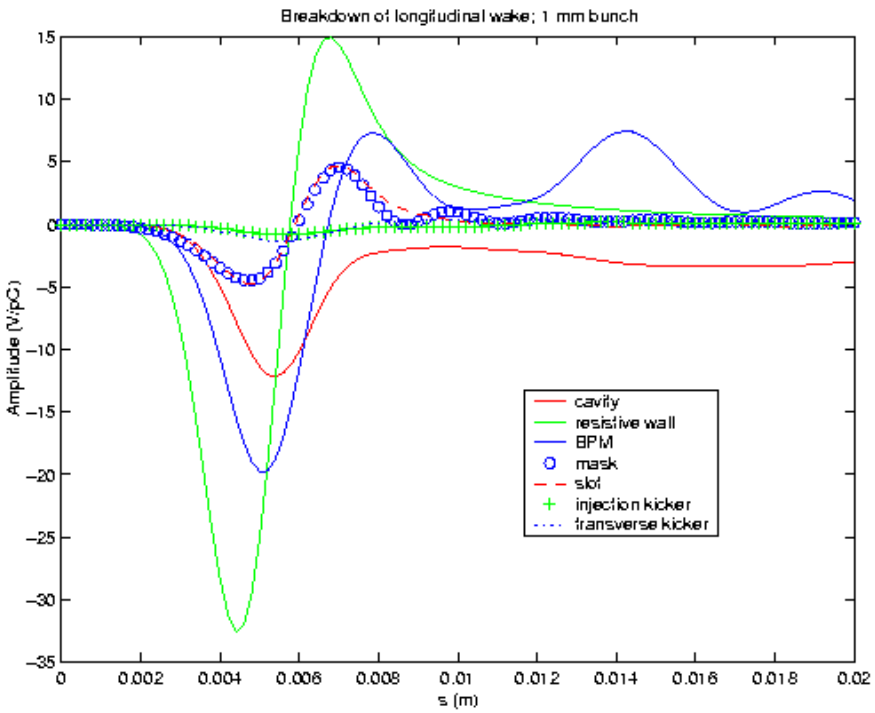


- breakdown into cavity and taper
- cavity as diffraction model
- taper highly resistive
- overall wakefield sensitive to mesh size due to taper

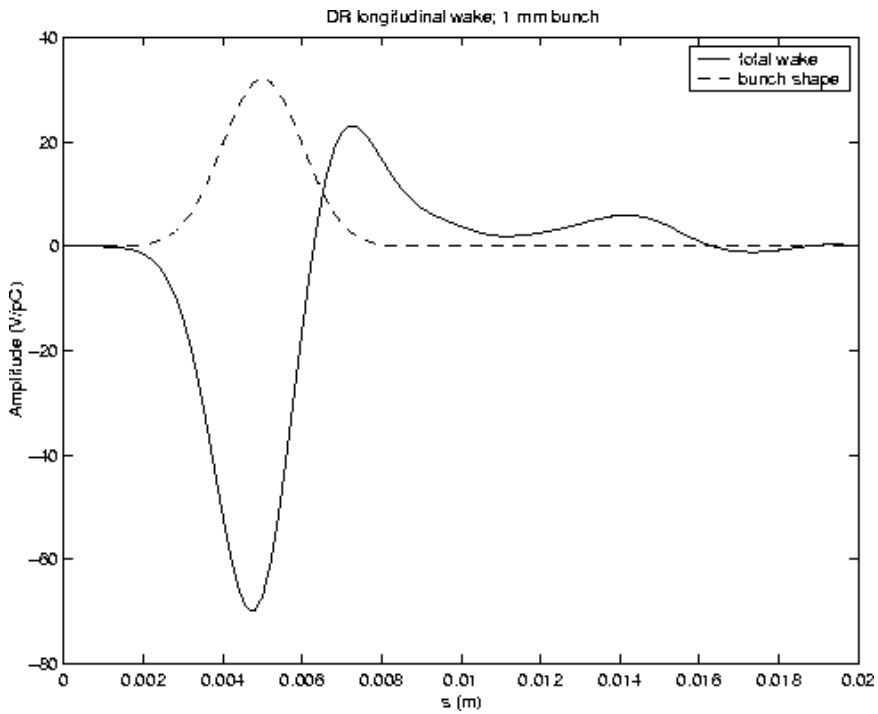


Longitudinal Green's function wakefield

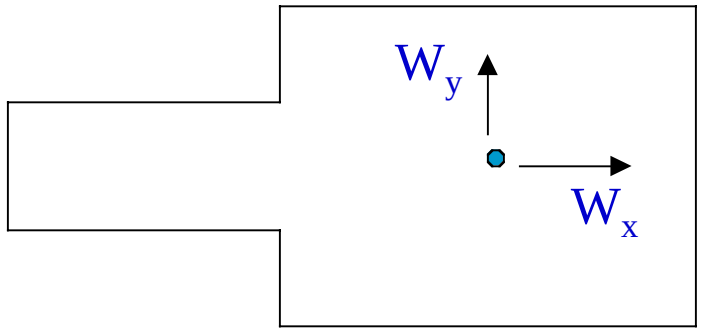
Breakdown



Total



Transverse broadband impedance



- Cylindrically symmetric structures: $W_x = W_y$
- Non-cylindrically structures:
  - different horizontal and vertical components
  - non-vanishing kick on beam axis
  - transverse wakefield determined by subtracting the dc component
  - wakefield component normally larger in the direction of asymmetry

Transverse resistive wall

- Increasing radius helps but usually not an option
- Use high-conductivity materials where possible
  - ρ = 17.7 nΩ-m Cu, 33 nΩ-m Al, 900 nΩ-m st. st.
  - Transverse coupled-bunch motion dominated by resistive wall at low frequency

$$W_1(s) = \frac{C}{b^3\sigma^{1/2}} \frac{c}{2\pi} \sqrt{\frac{Z_o}{2\sigma_{d.c.}}}\, f(s/\sigma_z)$$

$$f(u) = |u|^{1/2}\, e^{-u^2/4} \left(I_{-1/4} \pm I_{1/4}\right)\Big|_{u^2/4}$$

$$Z_{transverse}^{resistive\ wall} = A\,(1+j)\,\frac{c\,L}{\pi\, b^3} \sqrt{\frac{\mu_0\,\rho}{2}}\,\frac{1}{\sqrt{\omega}}$$

$$= \pi^2/12$$

$$A_{horizontal} = \pi^2/24$$

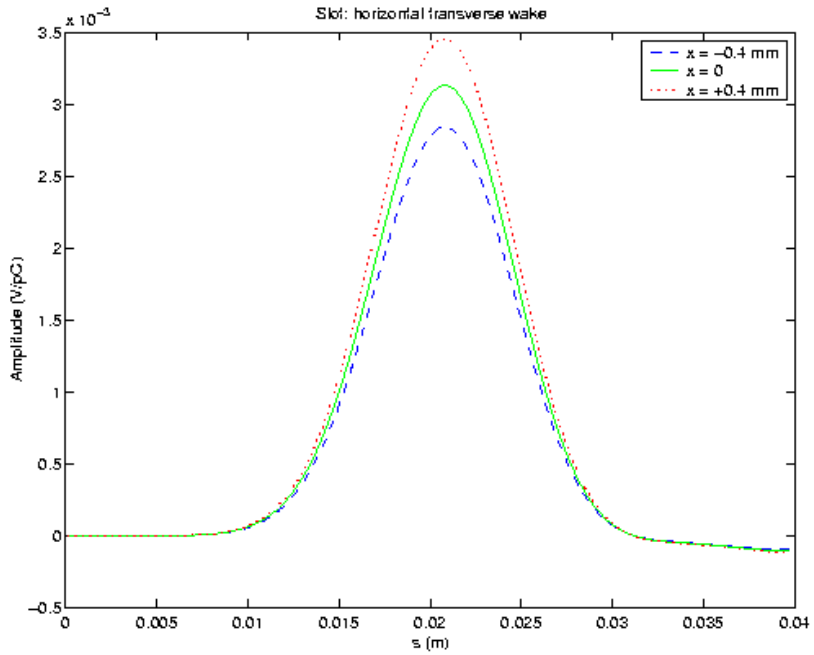
$$= 1$$

→Lowest mode determined by tune

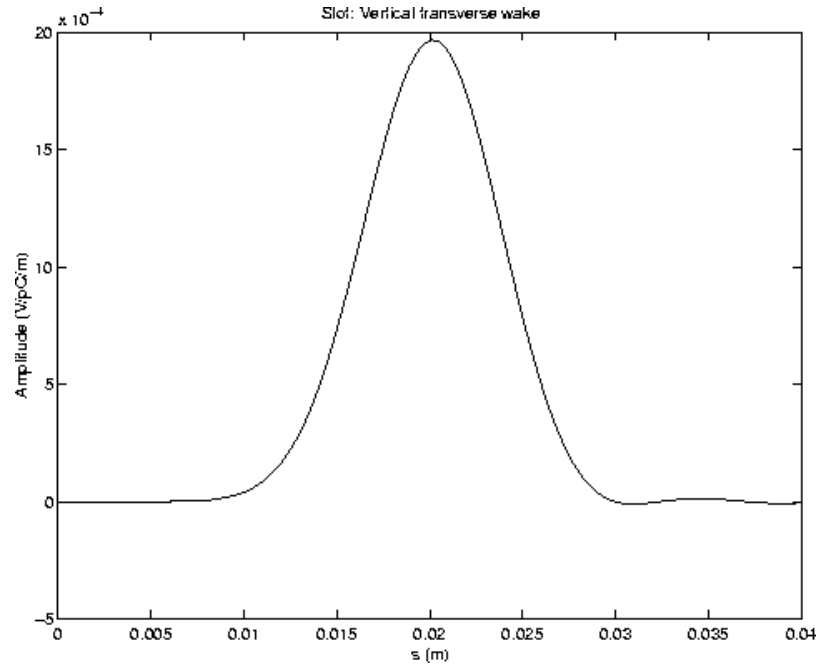
$$\omega = 2\pi f_{orbit}(1 - \Delta Q)$$

Slot transverse wakefield

Horizontal



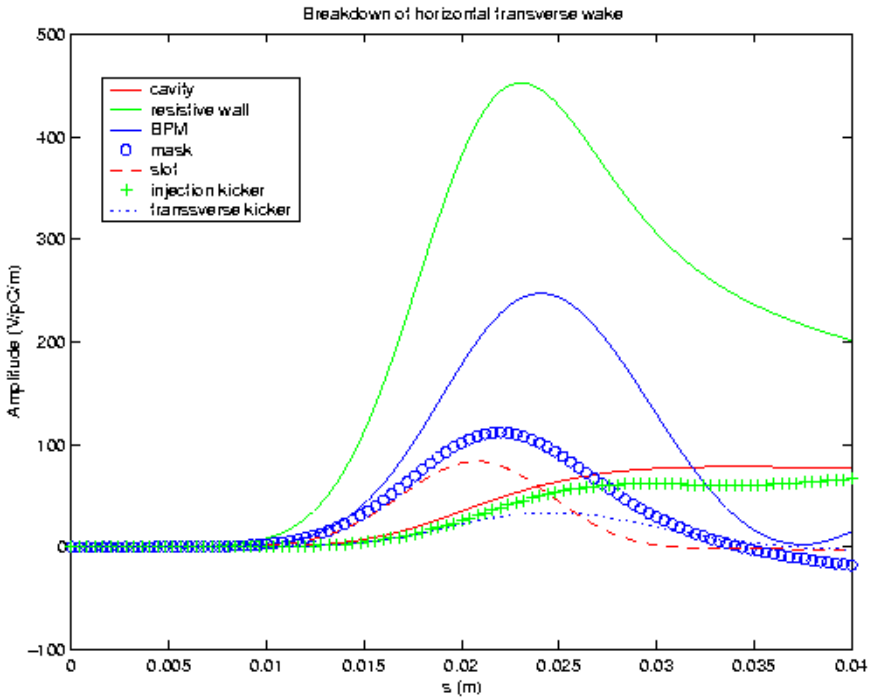
Vertical



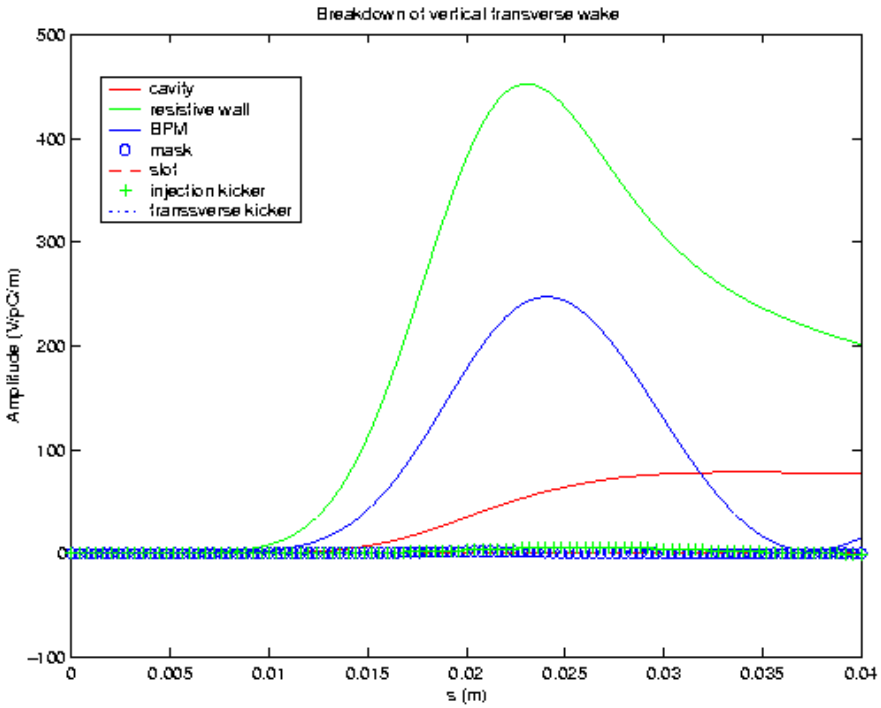
- Kick factor = 0.55 V/pC/m
- Kick factor = 1.32×10^{-3} V/pC/m

Breakdown of transverse wakefield

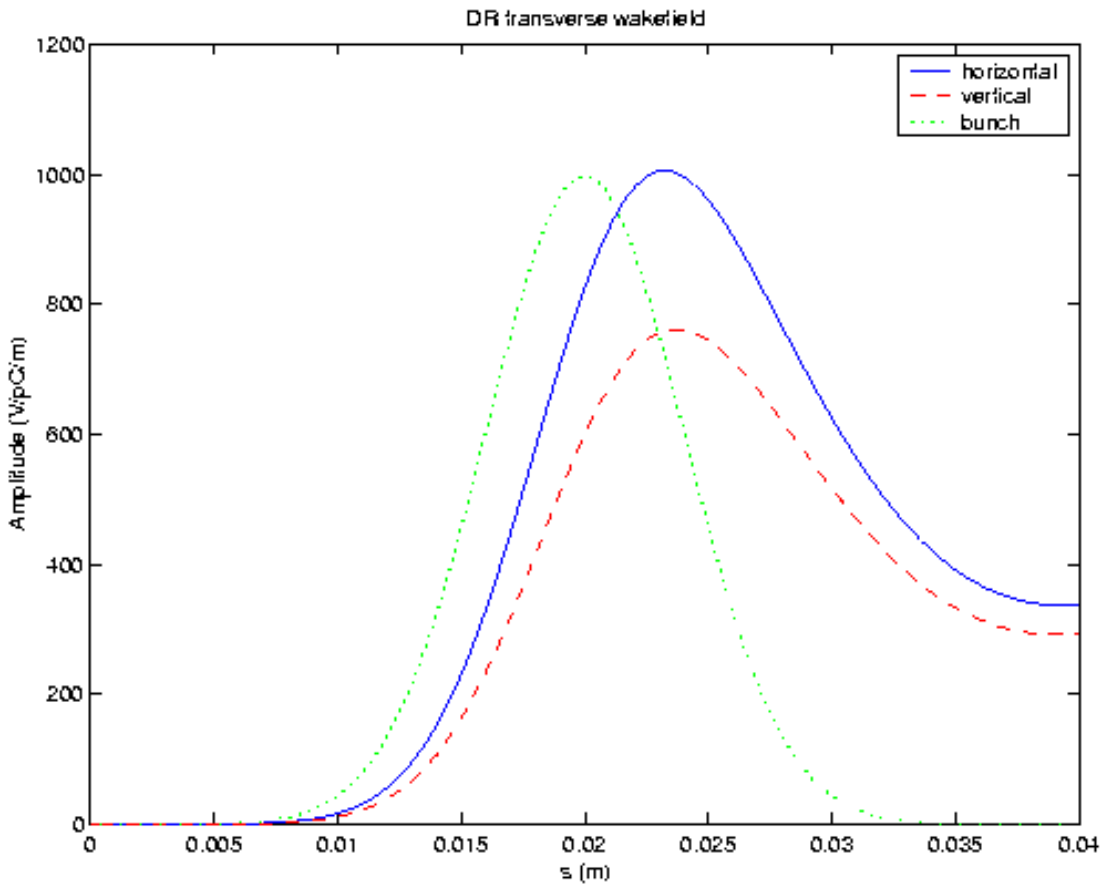
Horizontal



Vertical



Total transverse wakefield

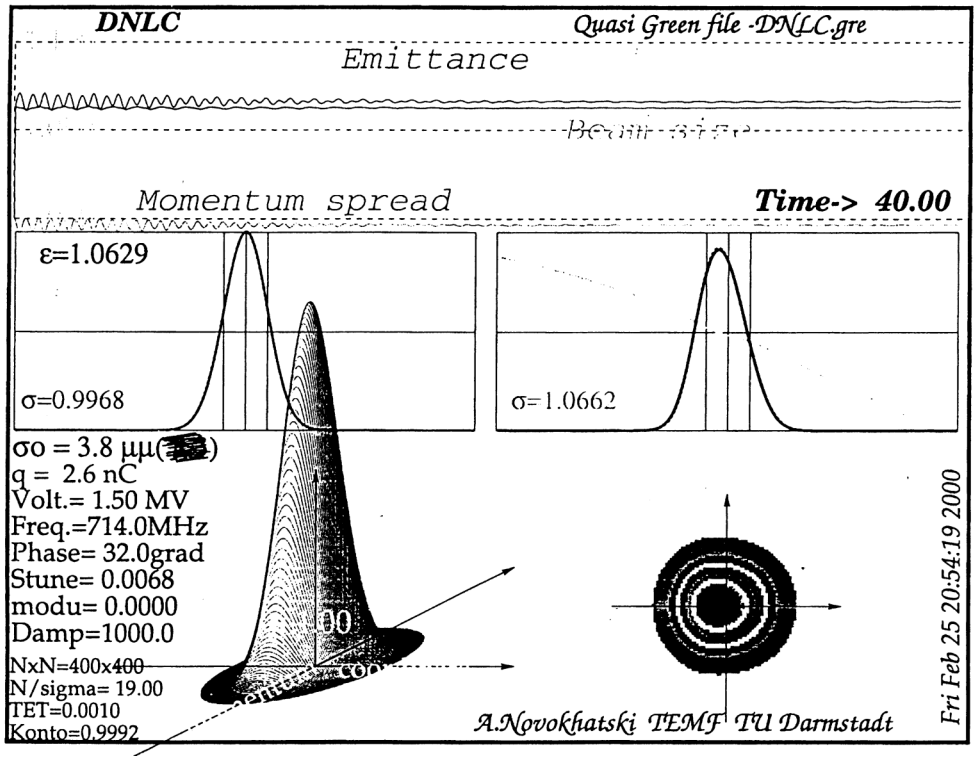


Transverse wake summary

Components	H kick factor (V/pC/m)	V kick factor (V/pC/m)
◊ RF cavities	36	36
◊ BPMs	147	147
◊ ante-chamber slots	56	0.13
◊ bellows masks	77	1.2
◊ injection / extraction kickers	25	2.9
◊ transverse feedback kickers	19	0.4
◊ 300 m resistive wall	321	321
♦ TOTAL	681	508

Instability calculations

- NOVO wakefield calculations
  - Generated "quasi" Green function from 1 mm wake
- Beam stable longitudinally
  - Nominal charge 2.6 nC
    - → potential well distortion
      - > Bunch lengthening 6.3 %
  - Signs of RF instability seen at 2-3 times nominal charge per bunch
    - → may be damped by radiation?
- Transverse stability t.b.d.

T. U. D.

Alexandre Novokhatski