Energy Spread and Bunch Length Measurements in the ATF

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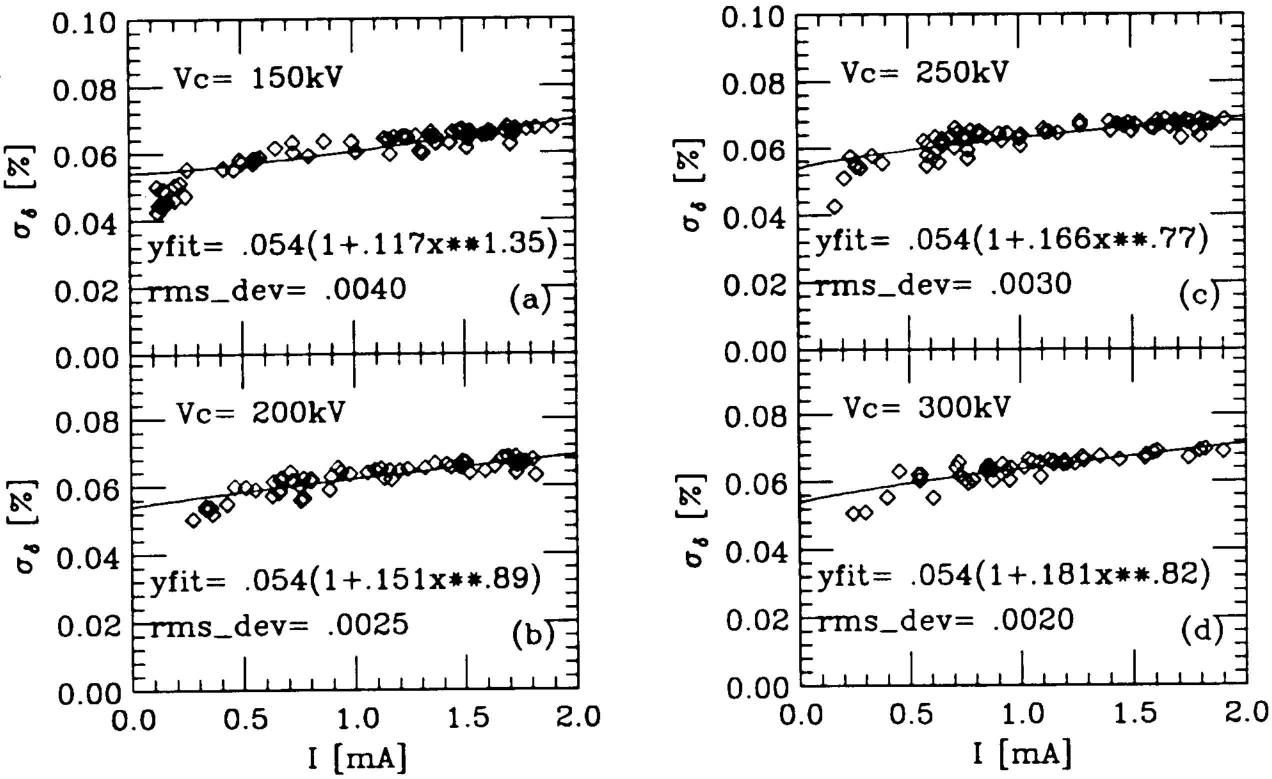
Earlier streak camera bunch length measurements in the ATF, have found lots of unexpected current dependent bunch lengthening. The impedance was estimated to be 4 times larger than calculations. If we can't do better than that, how can we have confidence in the performance of an NLC.

H. Hayano, et al, "Impedance Measurements at ATF DR," EPAC98.

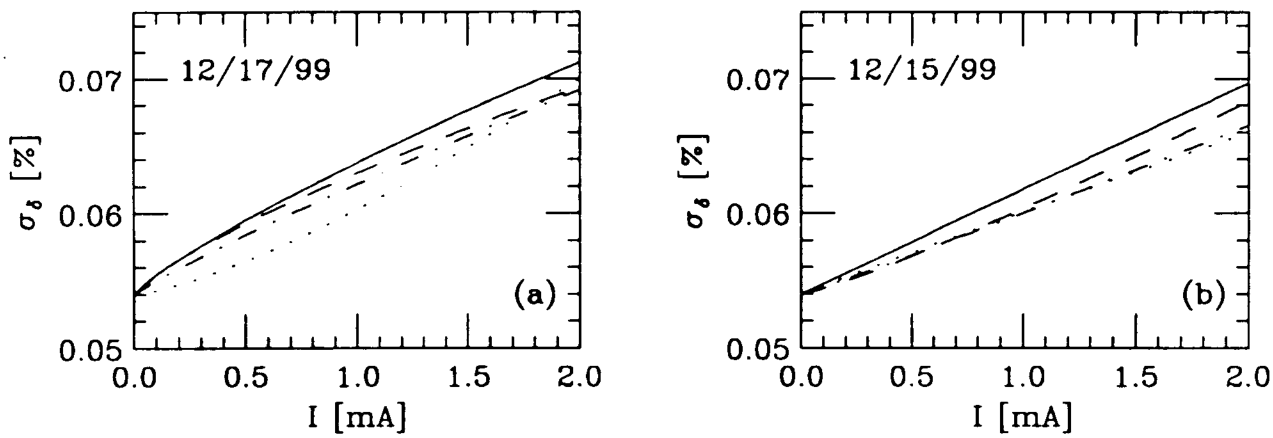
K. Bane, et al, "Bunch Lengthening and Current-Dependent Energy Spread at ATF," ATF Report 98-38, Dec. 98.

– We repeated the measurements, taking care about space charge in the streak camera. We took lots of data, used fitting, and the statistical method of maximum likelihood to estimate the errors.

Energy Spread Measurements



~30% growth at I=2mA



Vc= 300 kV: solid
Vc= 250 kV: dashes
Vc= 200 kV: dotdash
Vc= 150 kV: dots

V_c/kV	$\sigma_\delta(2mA)$/% 12/17	12/15
150	.070 ± .002	
200	.069 ± .001	.066 ± .001
250	.069 ± .001	
300	.071 ± .001	

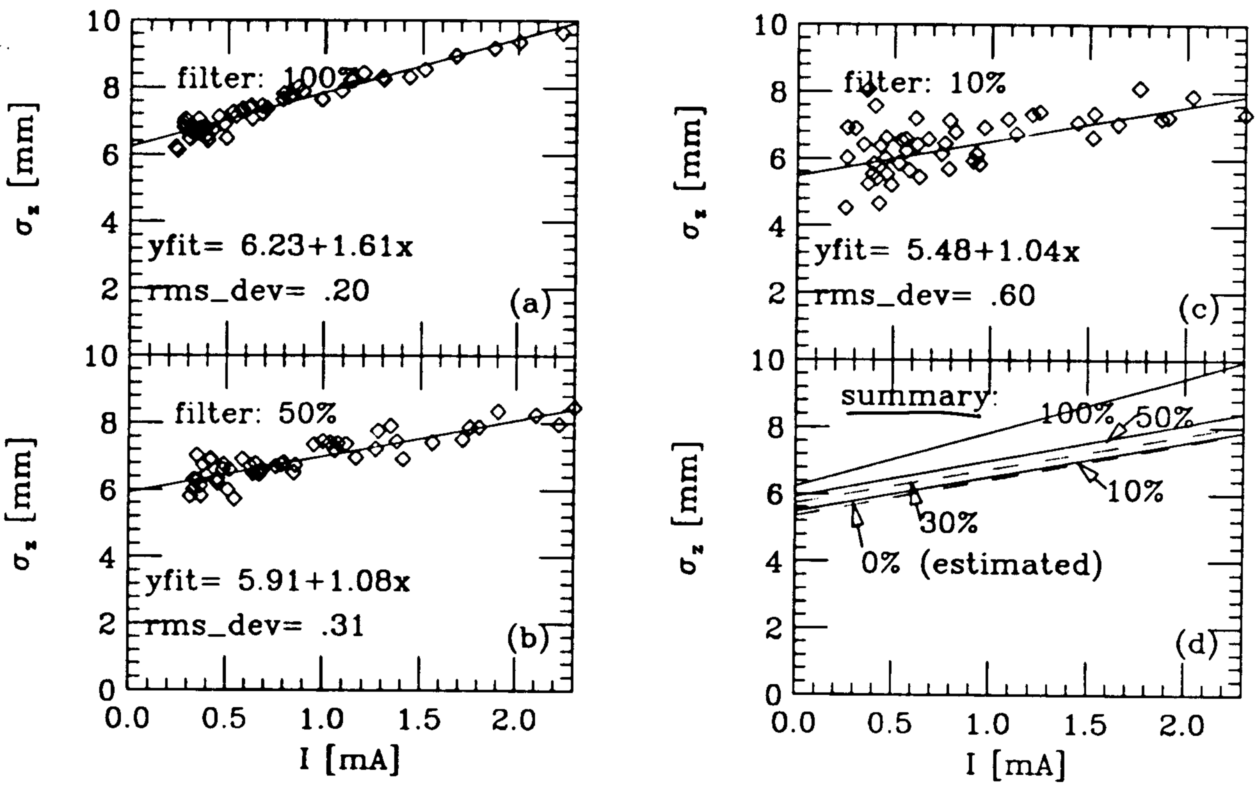
2σ difference significant?

- not inconsistent with σ_δ increasing with V_c increasing
- microwave instability probably not significant

Bunch Length Measurements using a Streak Camera

A. Check on space charge effect in Streak camera

Use different filters

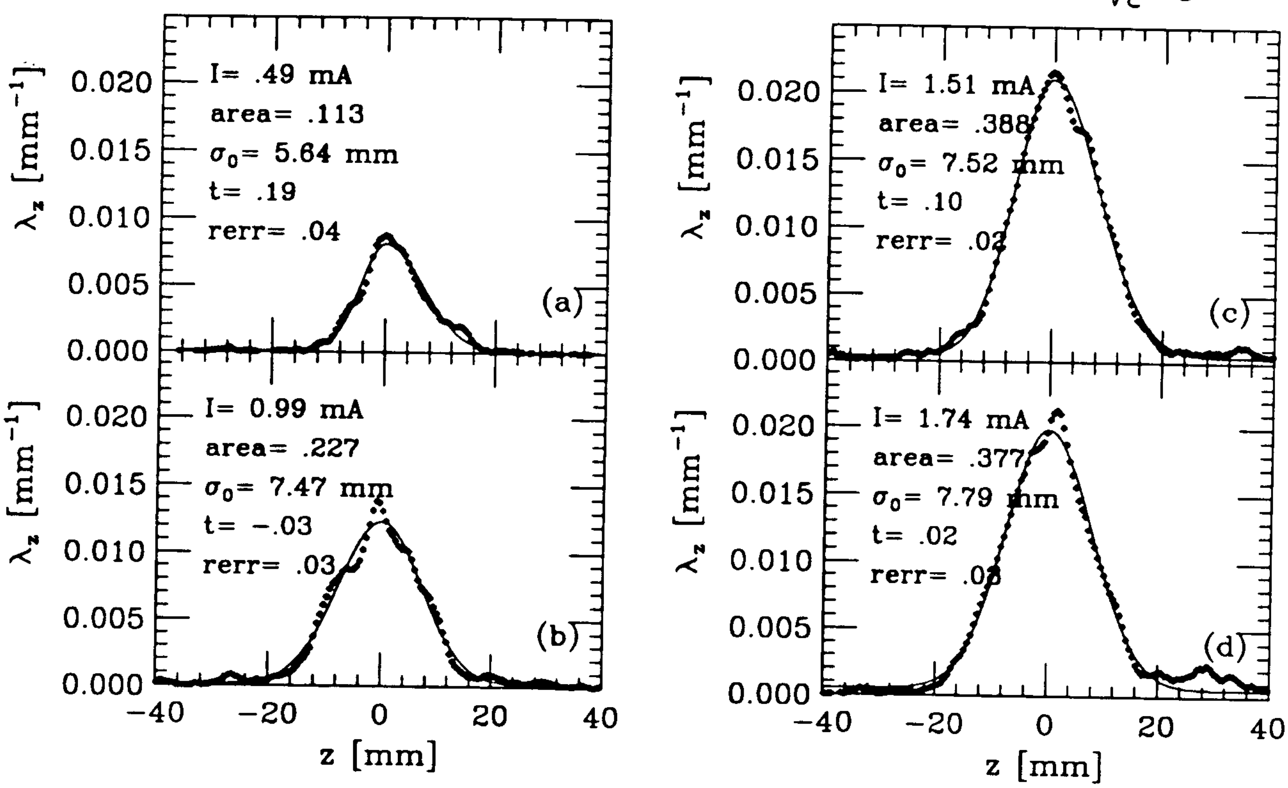


- too much light => space charge; too little light => noise level increases
- note 50% and 10% curves have same slope

→ choose 30% for bunch length measurements

Typical scans

$V_c = 200\,kV$



Fit to asymmetric gaussian: $\lambda_z = \frac{A}{\sqrt{2\pi}\,\sigma_o} \exp\left[-\frac{1}{2}\frac{(z-\bar{z})^2}{\sigma_o^2(1\pm t^2)}\right] \quad z \gtrless \bar{z}$

extract σ_o, asymmetry parameter t

Note for t small: $z_{rms} \approx \sigma_o$

skew moment, $s \approx \frac{4t}{\sqrt{2\pi}}$

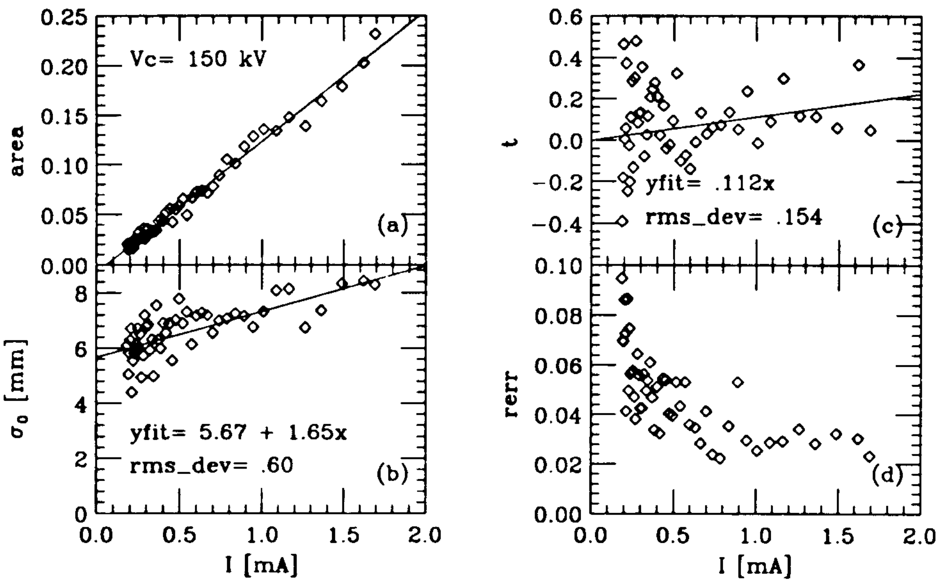


Figure 5: Bunch length as function of current for V_c = 150 kV. Given are the parameters of the asymmetric Gaussian fit to the measured profiles. The curves are straight line fits to these results.

expect $t \simeq a I$ with $a > 0$

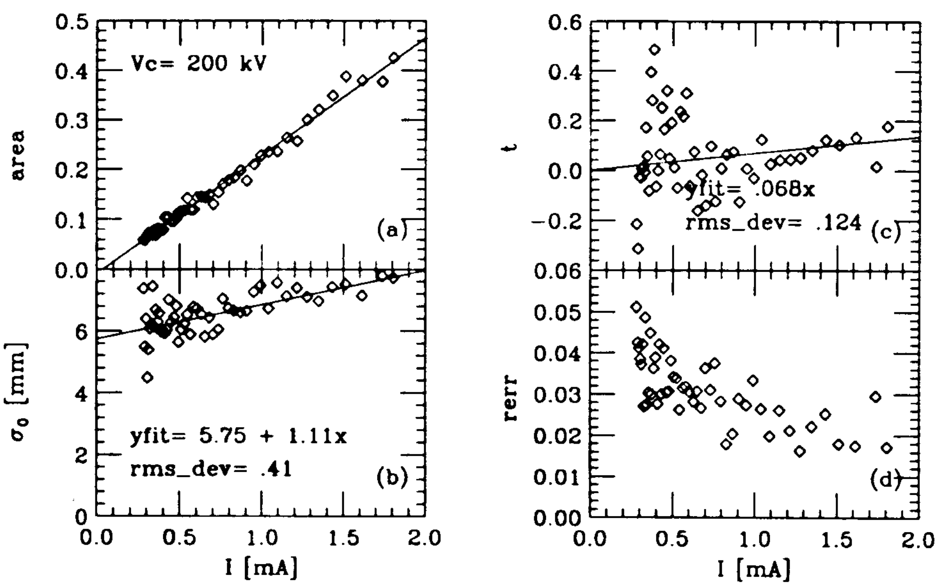


Figure 6: Bunch length as function of current for V_c = 200 kV. Given are the parameters of the asymmetric Gaussian fit to the measured profiles. The curves are straight line fits to these results.

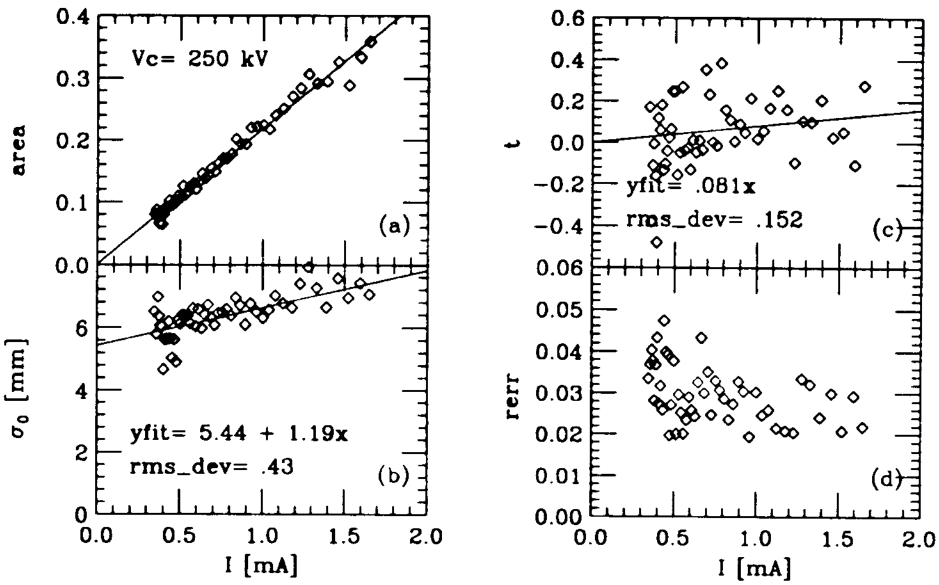


Figure 7: Bunch length as function of current for V_c = 250 kV. Given are the parameters of the asymmetric Gaussian fit to the measured profiles. The curves are straight line fits to these results.

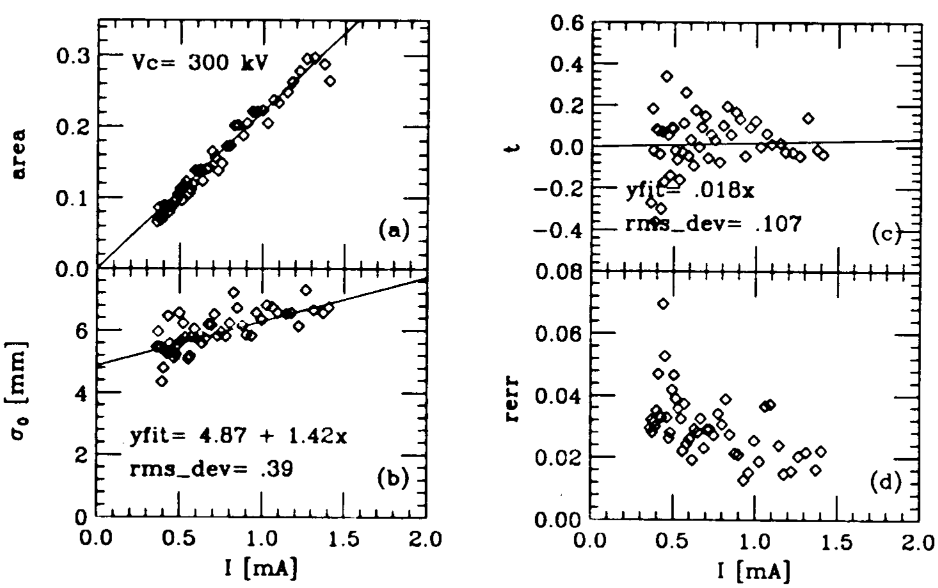


Figure 8: Bunch length as function of current for V_c = 300 kV. Given are the parameters of the asymmetric Gaussian fit to the measured profiles. The curves are straight line fits to these results.

Summary of Linear Fits to Data

Table 2: Summary of linear fits to the rms length σ_0 and asymmetry factor t. The resulting values of σ_0 and t at $I = 2$ mA are also given. Note that we believe that all the measured lengths are systematically low, by a factor of about 30%.

V_c [kV]	$\sigma_0 = aI + b$: a [mm/mA]	b [mm]	σ_0(2mA) [mm]	$t = cI$: c [1/mA]	t(2mA)
150	1.65±.03	5.67±.02	8.95±.10	.112±.004	.220±.010
200	1.11±.02	5.75±.02	7.95±.05	.068±.002	.135±.005
250	1.19±.02	5.44±.02	7.80±.05	.081±.003	.160±.005
300	1.42±.02	4.87±.02	7.75±.05	.018±.003	.035±.005

— V_c = 150 kV results much larger than others

— σ_0 decreases with increasing V_c

— t: scatter much larger than estimated errors

— problem with sweep unit calibration ⇒ σ_0 should be multiplied by 1.4

— at V_c = 200 kV, σ_0(0 mA) should equal 6.2 mm

⇒ corrected σ_0(0 mA) is 30% high

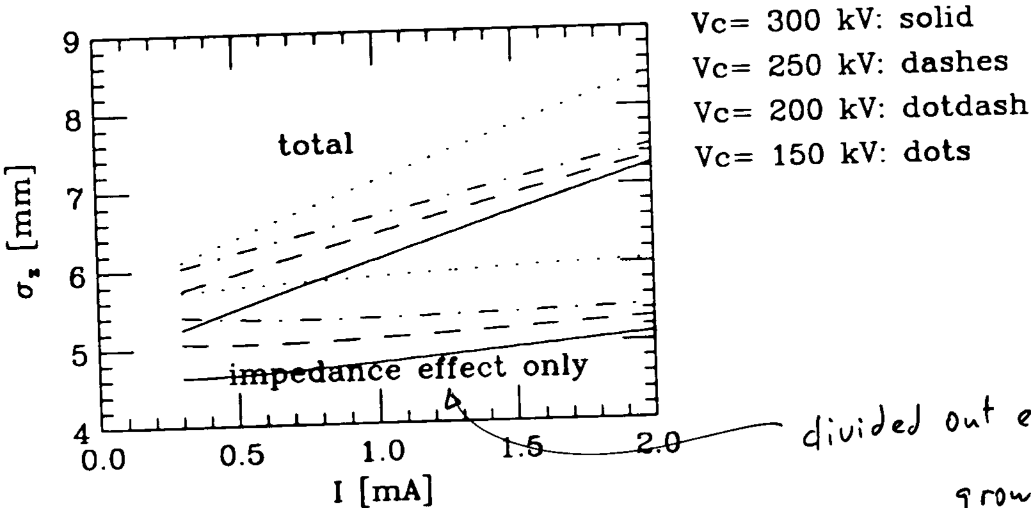
Table 3: Comparison with earlier bunch length measurements. $I = 1.5$ mA.

V_c [kV]	On Resonance?	σ_z(1.5mA) [mm] [σ_z(1.5mA)/σ_z(.5mA)]: Ref.[1]	Ref.[2]	Here
200	no	9.2 [1.13]		7.40 ± .05 [1.18±.01]
300	no	7.8 [1.14]	10.3 [1.26]	7.00 ± .05 [1.25±.02]
300	yes		9.1 [1.22]	

(Ref.[1], Ref.[2]: earlier measurements; Here values: should add 1.4 scale factor)

— agreement absolutely, relatively with Ref[2] results [K. Bane, et al]

— disagreement with Ref[1] results [Hayano, et al]



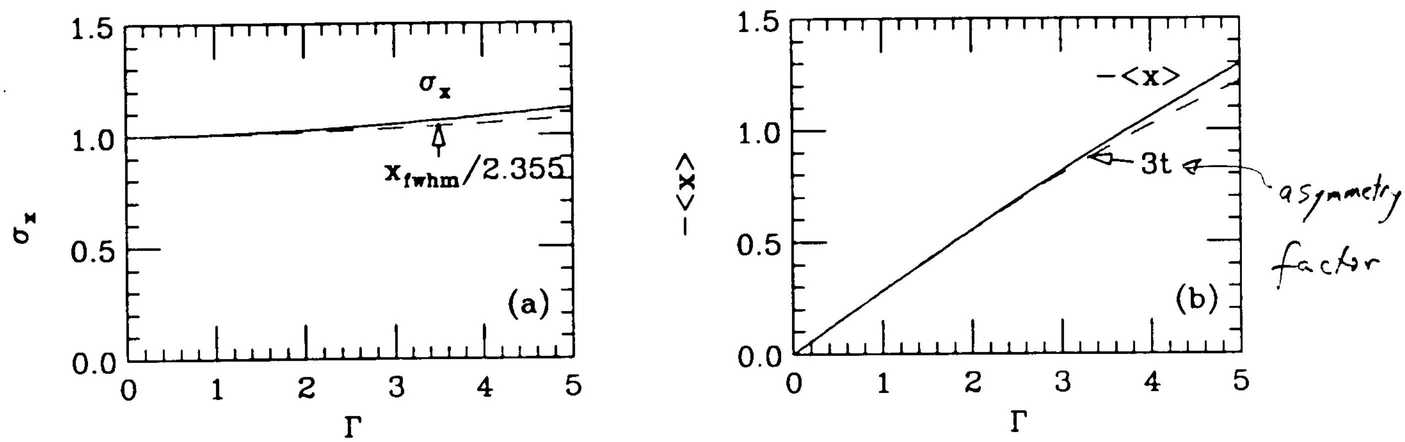
divided out energy spread growth (measured)

=> potential well bunch lengthening is small

$V_c = 200kV, I = 2mA$, growth ~ 8%

Potential Well Distortion

A. Resistive Impedance: $V_{ind} = -RI$, R resistance, a constant



- Solution of Haïssinski Equation

for resistive impedance, solution is analytic (A. Ruggiero)

normalized parameters: $x = z/\sigma_{z0}$, $y = \dfrac{eNc\lambda_z R}{V_c' \sigma_{z0}}$, $\Gamma = \dfrac{eNcR}{V_c' \sigma_{z0}^2}$

$$y = \sqrt{\frac{2}{\pi}} \, \frac{e^{-x^2/2}}{\coth(\Gamma/2) + \operatorname{erf}(x/\sqrt{2})}$$

- For ATF: $\sigma_{z0} = 6.2\,mm$, $V_c = 200\,kV$, $I = 2\,mA$, $R = 400\,\Omega$ ← rf cavities, same as SLC damping rings

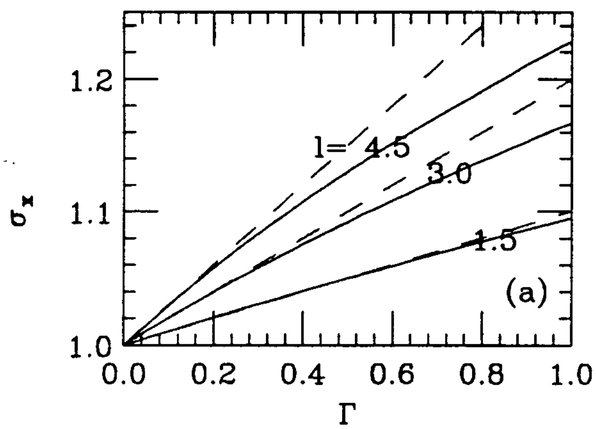
$\Rightarrow \Gamma = .59$, $\sigma_x = 1.00$, $\langle x \rangle = -.17$, $t = .06$

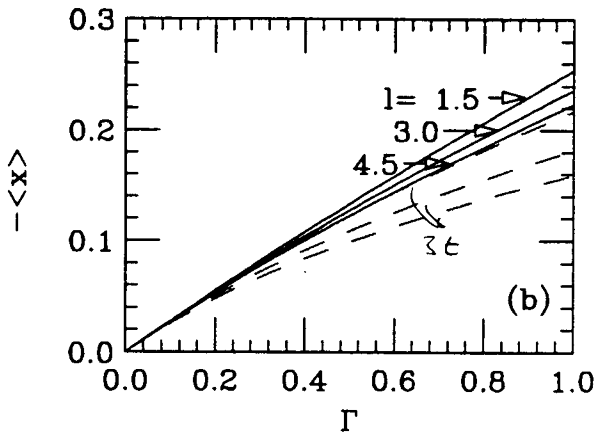
→ $\Rightarrow -1.1°$ at 714 MHz

B. Series Resistance Plus Inductance

- good model if impedance is dominated by cavities plus high frequency resonators like slots, holes, etc.

- Haïssinski Eqn: $y' = -\frac{y(x+y)}{1+\ell y}$, with normalized inductance $\ell = \frac{cL}{R\sigma_{z0}}$





-- linear approx: $\sigma_x = 1 + .067\,\ell\Gamma$

- For ATF: $R = 400\,\Omega$, $L = 14\,nH$ ($\ell = 1.3$)

  $V_c = 200\,kV$, $I = 2\,mA$

  $\Gamma = .59$, $\sigma_x = 1.05$, $\langle x \rangle = -.16$, $t = .05$ — similar to pure resistive impedance

- we take measured bunch lengths, divided by the energy spread growth, and fit to this model. We keep $R = 400\,\Omega$ and fit for L.

- to allow for a calibration error in the streak camera, we fit

  $\sigma_z(2\,mA)/\sigma_z(0.5\,mA)$

Results of fit to ~~fixed~~ series resistive + inductive impedance

R fixed (= 400 Ω), L varying

Table 4: The ratio $\sigma_0(2\text{mA})/\sigma_0(.5\text{mA})$ before and after correction, and the fitted inductance L (normalized to $L_0 = 14$ nH) obtained from the series resistance and inductance model (discussed below).

V_c [kV]	before correction $\sigma_0(2\text{mA})/\sigma_0(.5\text{mA})$	after correction $\sigma_0(2\text{mA})/\sigma_0(.5\text{mA})$	after correction L/L_0
150	1.38±.02	1.10±.08	4.0±4.5
200	1.26±.02	1.07±.04	2.0±1.5
250	1.29±.02	1.10±.04	3.0±1.5
300	1.39±.02	1.15±.04	5.5±2.5

Calculated total inductance $L_0 = 14$ nH

Total Result:

$$L = (3.0 \pm 1.0)\, L_0 = (45 \pm 15)\,\text{nH}$$

...nclusions

- Bunch length measurements agree with earlier measurements, (Dec 98)

  but appear to be too large (30-40%)

- Fitting bunch length measurements to R+L series impedance, with R=400Ω (representing the rf cavities), the effective inductance L = (45±15) nH - about 3 times larger than calculated results

Suggestions for Future Measurements

- repeat measurements with beam on coupling resonance
  - more accuracy in measuring impedance
  - more sensitivity to see microwave threshold
- energy spread measurements:

  change tune (coupling) see if results are consistent with intra-beam scattering
- during measurements, keep track of ν_s, damping partition, etc.

  maybe learn why $V_c = 150$ kV absolute results so much larger
- measure φ_s vs N using SLAC built apparatus - complimentary
- ν_s vs N - complimentary
- use synchroscan streak camera now at end of ATF linac
- independent method of measuring σ_z. eg. spectrum method (see eg. Ieiri)