Beam Loss Mechanisms and Mitigation at SLC

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- **SLAC Linear Collider (SLC) operated from 1987 to 1998**
  – See N. Phinney et al for performance summary
- **This talk:**
  – Source intensity instability
  – Damping Ring bunch lengthening and instability
  – Linac / collimator instability ‘amplification’
  – What to look for at CLIC

SLC Parameters

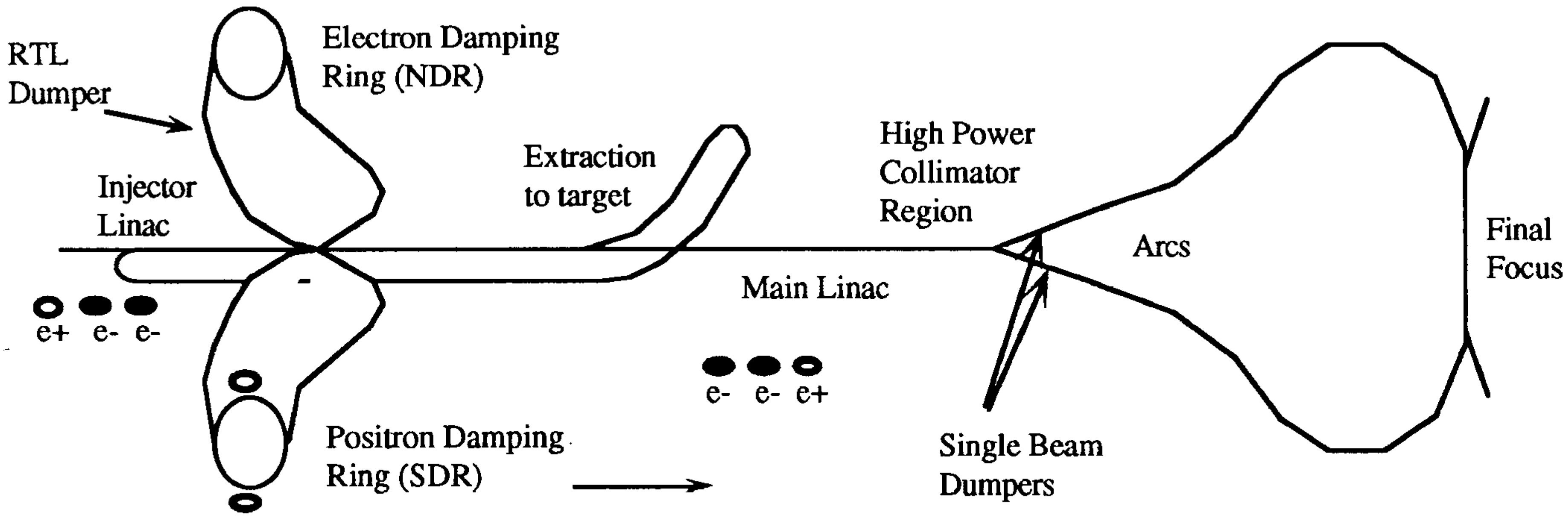
E_cm	**92 GeV**	**Z_0 resonance**
n_b +/-	3-4e10	At collision point; source intensities much higher
f_rep	120 Hz	MPS rate limit to either 10 or 1 Hz
P_beam	35 kW	single bunch, full energy
sig_x/y	100/10	microns at the end of the linac
sig_z	1 mm	
Lumi	3e30	

Parameter 'performance' Summary

Table 1: Design and achieved SLC beam parameters

	Design	Achieved	Units
Beam charge	7.2e10	4.2e10	$e^{\pm}$/bunch
Rep. rate	180	120	Hz
DR ε_x	3.0e-5	3.0e-5	m rad
DR ε_y	3.0e-5	3.0e-6	m rad
FF ε_x	4.2e-5	5.5e-5	m rad
FF ε_y	4.2e-5	1.0e-5	m rad
IP σ_x	1.65	1.4	μm
IP σ_y	1.65	0.7	μm
Pinch factor	220%	220%	Hd
Luminosity	6e30	3e30	$cm^{-2}sec^{-1}$

e+ / e- bunches in SLC

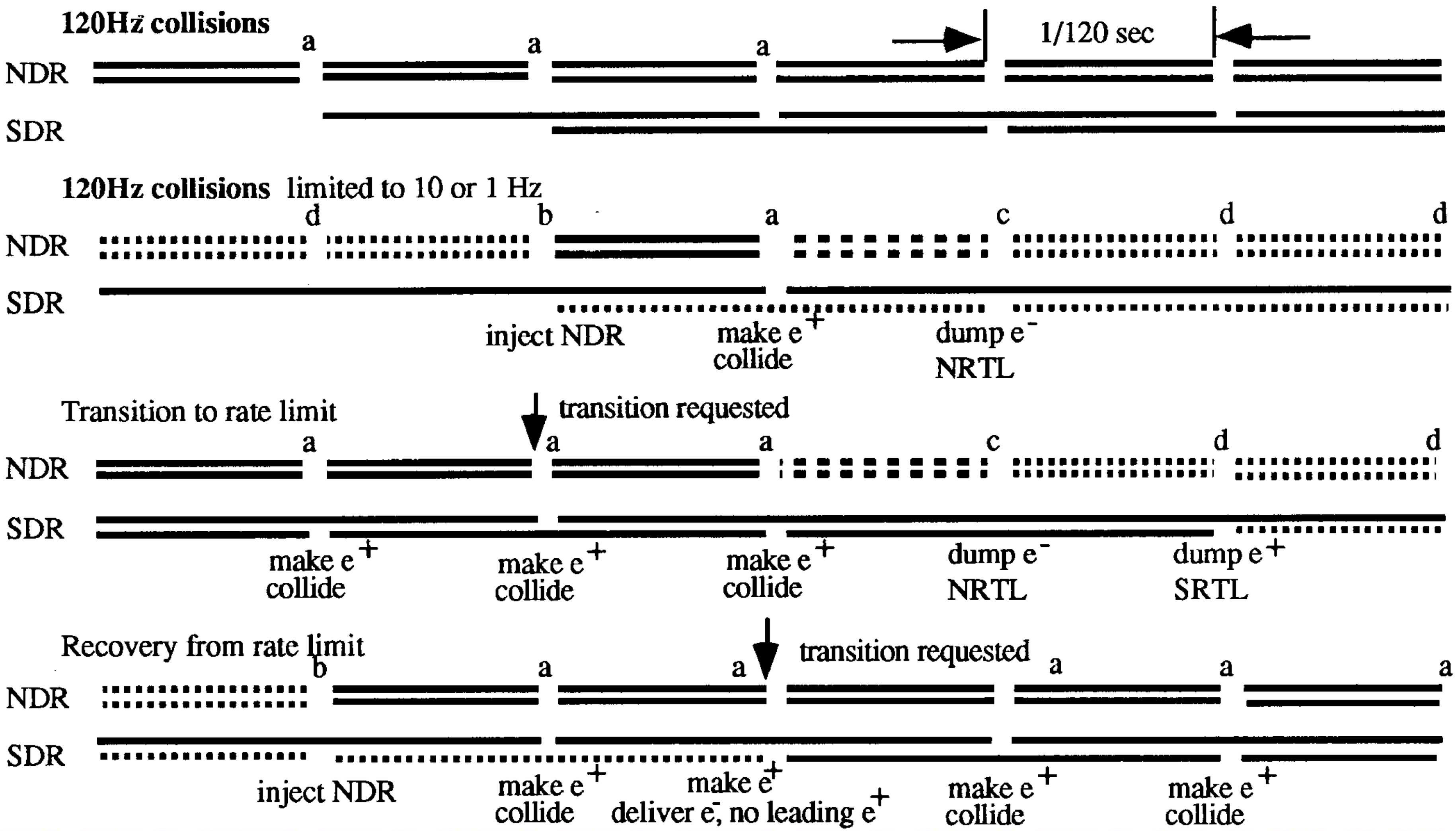


- e+ are both delivered and generated on a given pulse
- e+ from pulse *n* will collide on pulse *n*+2
- extraction line, high power collimators (linac end), arc and beam delivery entrance are critical locations

Limiting beam power

- **Assumption: Damage is less likely when all systems are functioning properly**
  - (marginal for beam-defining devices – collimators)
- **sometimes 'errant beam detector' (EBD) will indicate problem even when all systems seem to function properly**
  - (→beam dynamics← topic of this talk)
- **low power copy of the nominal beam may be required to allow study / testing mitigations**
- **transition between low / nominal power must be 'perfect'**
- **At SLC – low power copy was made by lowering the repetition rate**
  - (average power the main concern - rather than single pulse damage)
- **vicious circle or 'Catch-22' can easily happen**

Damping Ring in transition

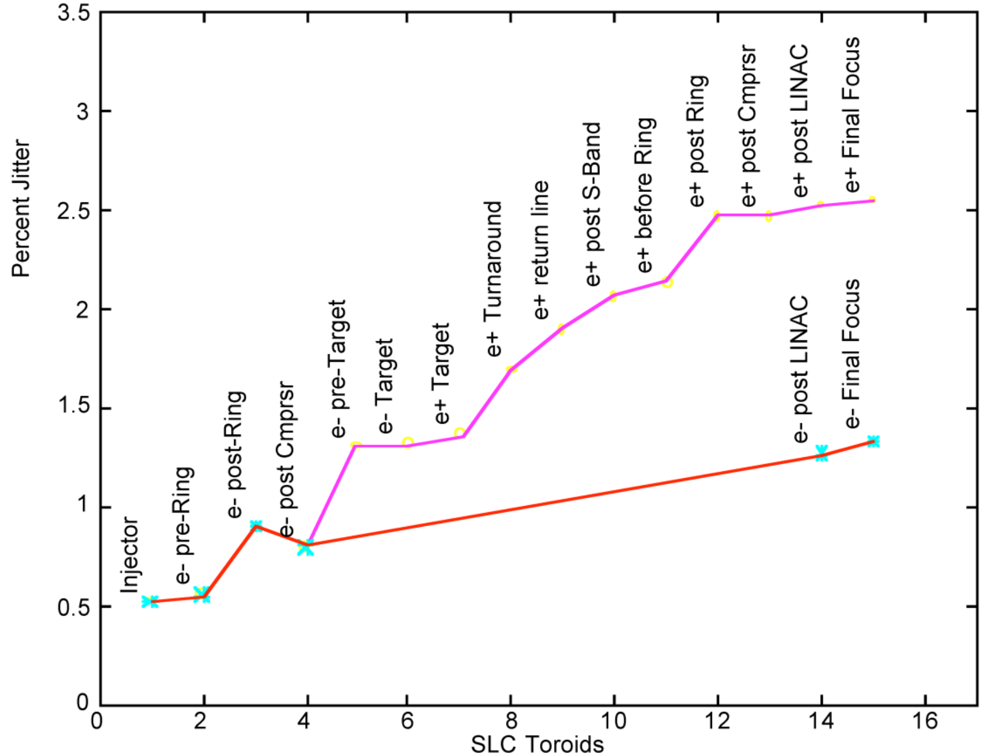


Intensity jitter

- **jitter ≡ pulse-to-pulse stability of the machine**
  - intensity, energy and trajectory jitter
  - collimation, collimator-wakes, ring beam dynamics, linac long-range wakes couple all three tightly

- **e+ and e- intensity jitter**

sig_I/I for ~ 100 pulses (full rate – 1 sec) vs position in entire complex



e+ jitter grows 3x (losses!)

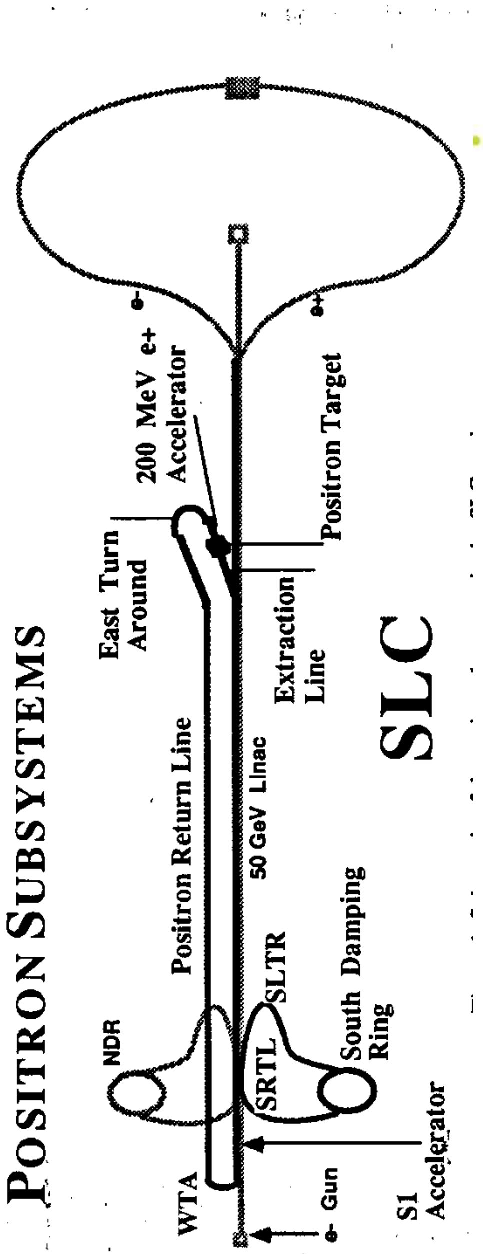
e- jitter grows 1.5x

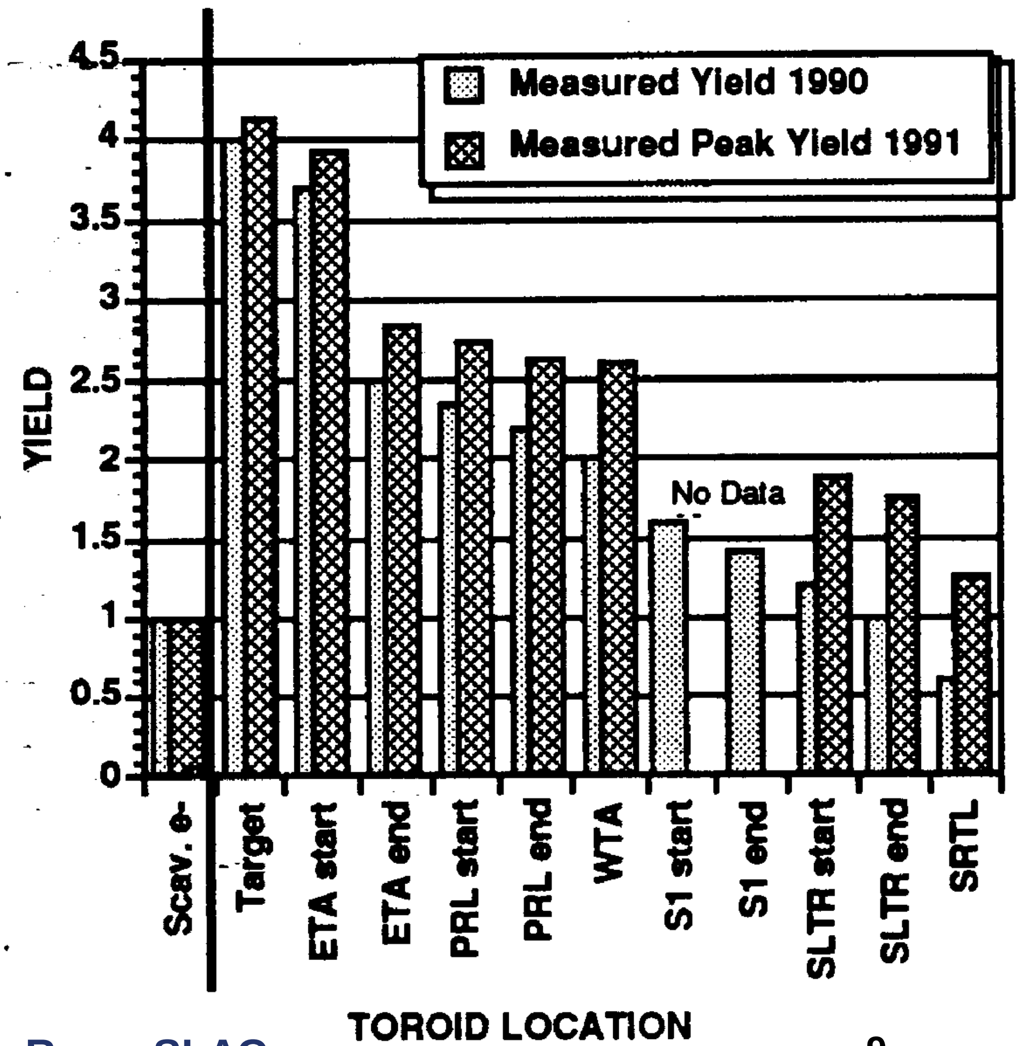
e- (target) 1.5x

SLC Positron Source

E_targ	30 GeV	2/3 point 47 GeV linac
n_b +	8e10	at 250 MeV
loss locations		1. incoming target energy definition – target bunch last of 3 2. outgoing target energy 3. 1.2 GeV S-band linac – positron bunch last of 3 4. damping ring injection
emit_n	0.01	m-radians normalized
sig_z	4 mm	

SLC Positron system beam loss pattern





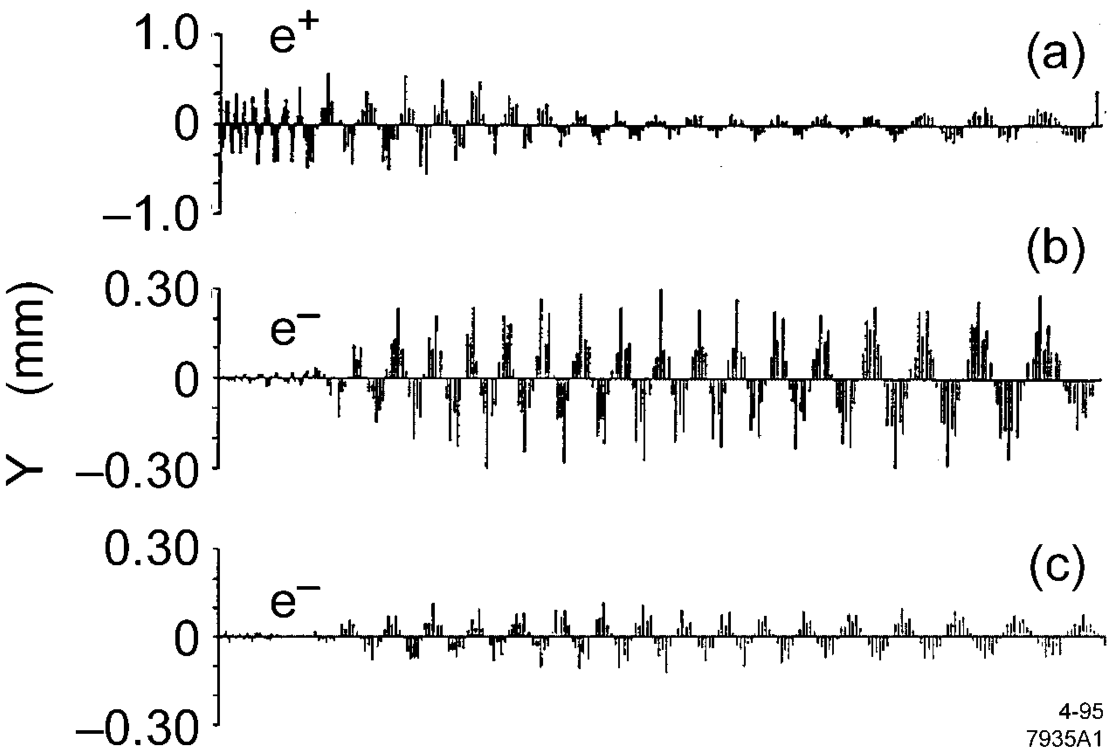
Linac long range wake

- **Couples intensity jitter of lead bunches to**
  - energy (0^{th} order) and
  - trajectory (1^{st} order) of trailing bunches
- **Also couples trajectory jitter**

Linac 'y' trajectory

e+ (leading) coupled to e- (following)

after 'split tune' (c)



SLC Damping Rings

- **impedance-driven bunch lengthening and transverse mode-coupling instability (TMCI)**
  - primary deficiency
  - also acceptance
- **Complete vacuum chamber replacement mid-life (1992)**
- **Longer bunch →outside compressor acceptance → non-linear compression 'tails'**
  - compression-related beam-loss
  - distorted linac phase space
  - strong collimator kicks
  - mitigated using internal 'pre-compression' →
- **TMCI**
  - intensity, energy and trajectory jitter
  - instability → 'errant beam' collimator losses / coll. damage

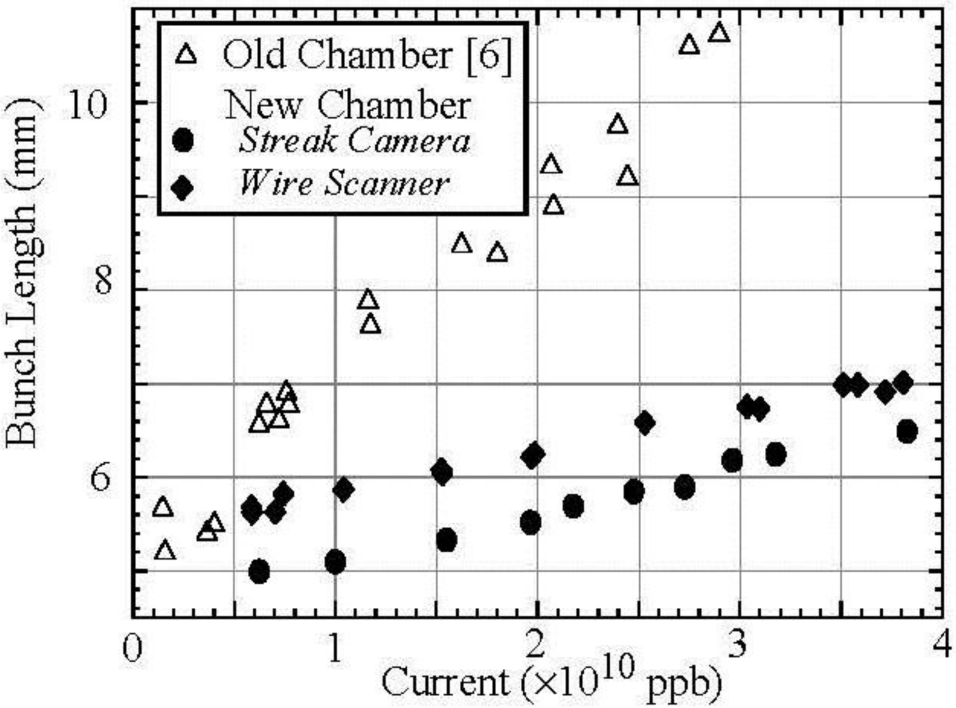
Damping Ring Vacuum Chamber:

Table I. Vacuum Chamber Inductance (nH)

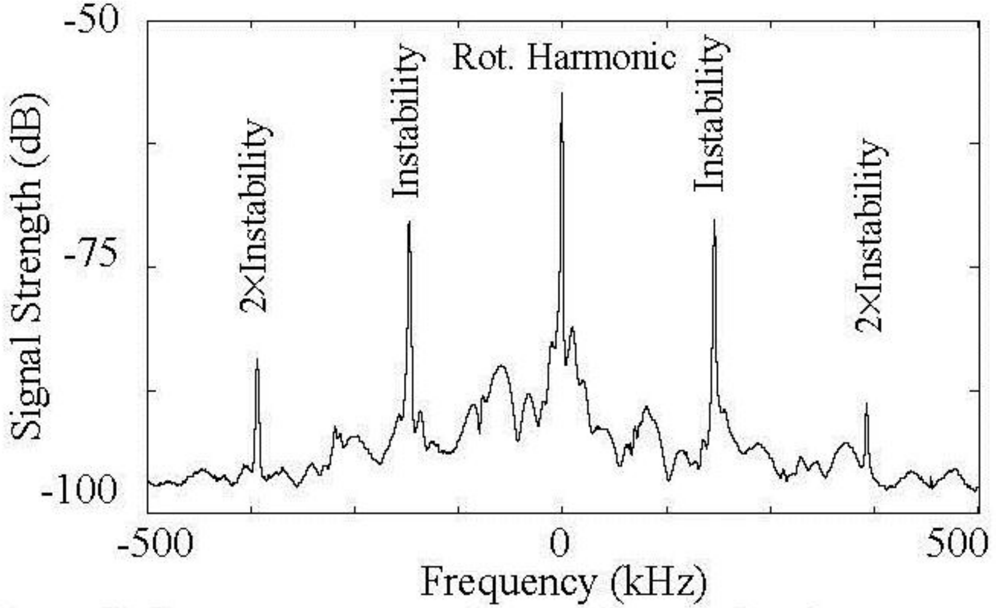
Element	Old Chamber[†]	New Chamber*
Synch. Radiation Masks	9.5	----
Bellows	----	1.1
Quadrupole to Dipole Chamber Transitions	9.3	2.4
Ion Pump Slots	0.2	0.05
Kicker Magnet Bellows	4.1	----
Flex Joints	3.6	----
Beam Position Monitors	3.5	0.2
Other	2.4	2.4
TOTAL	33	6

- Inductance reduced 5x
- before: 2x bunch lengthening
- after: 1.3x

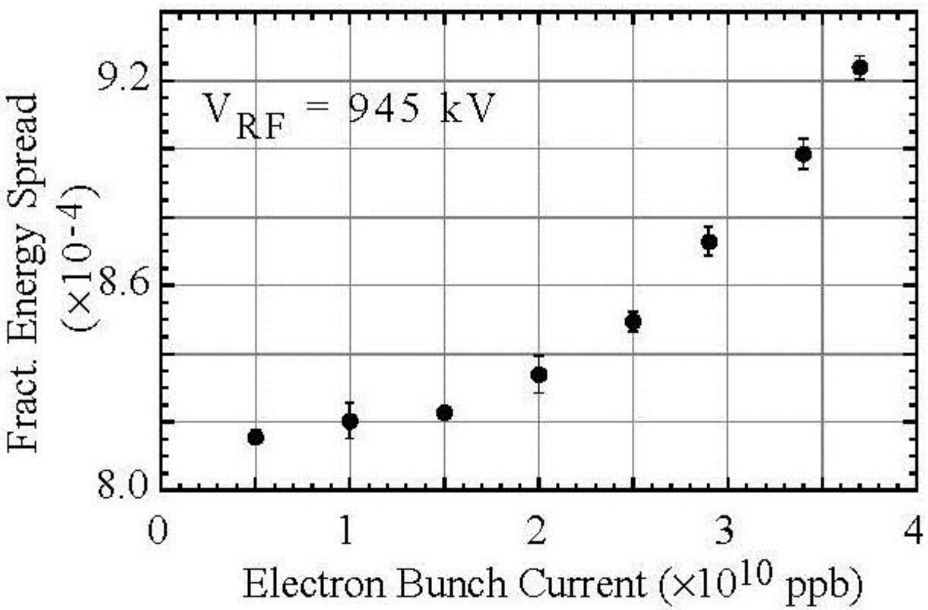
- New chamber showed instability threshold ~ 3e10



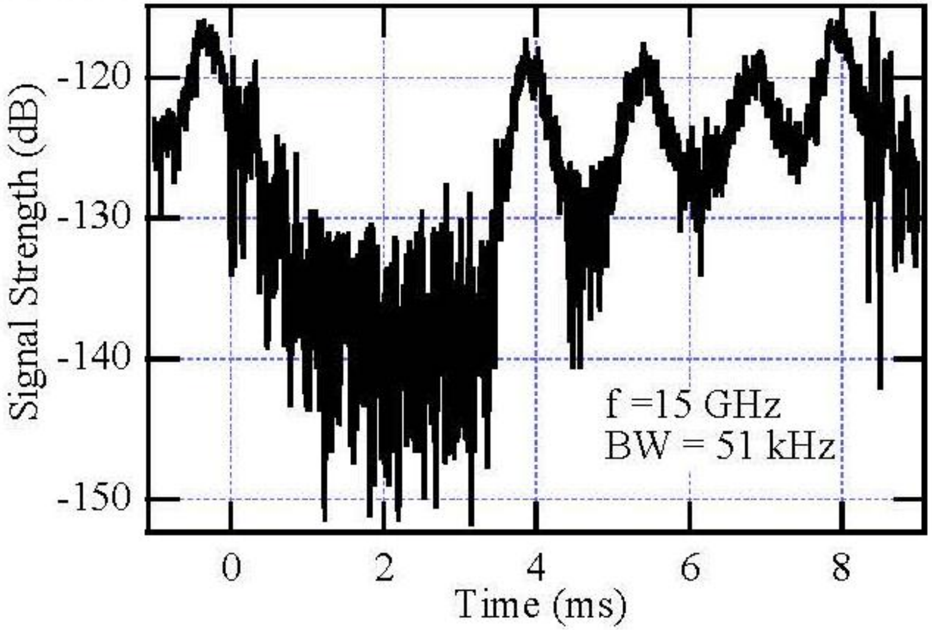
Longitudinal instability



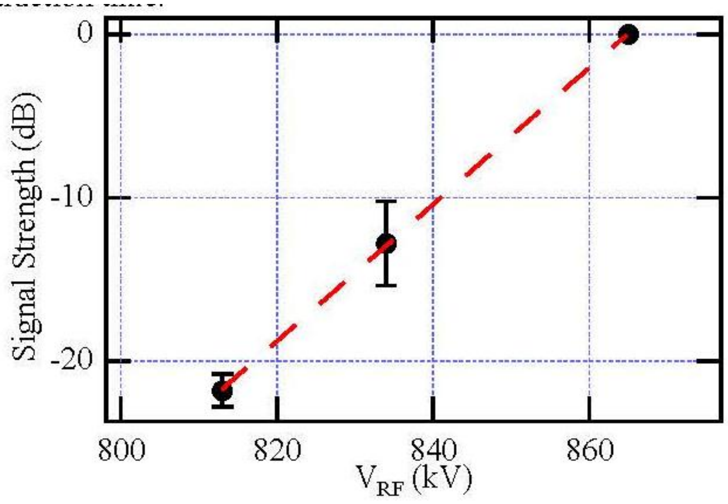
- detected using rotation side-bands at 1/sig_z (25 GHz)

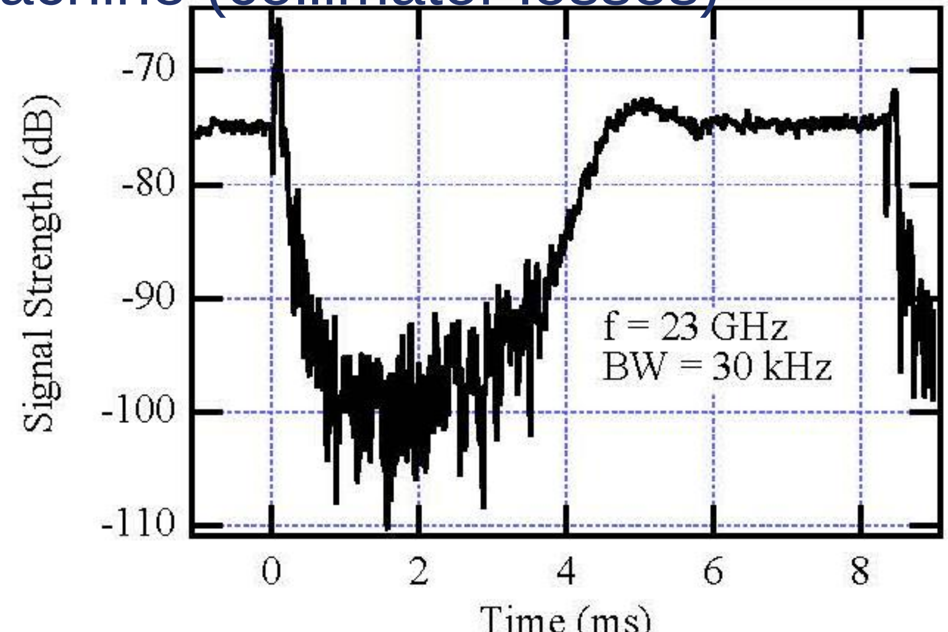


Instability during damping cycle

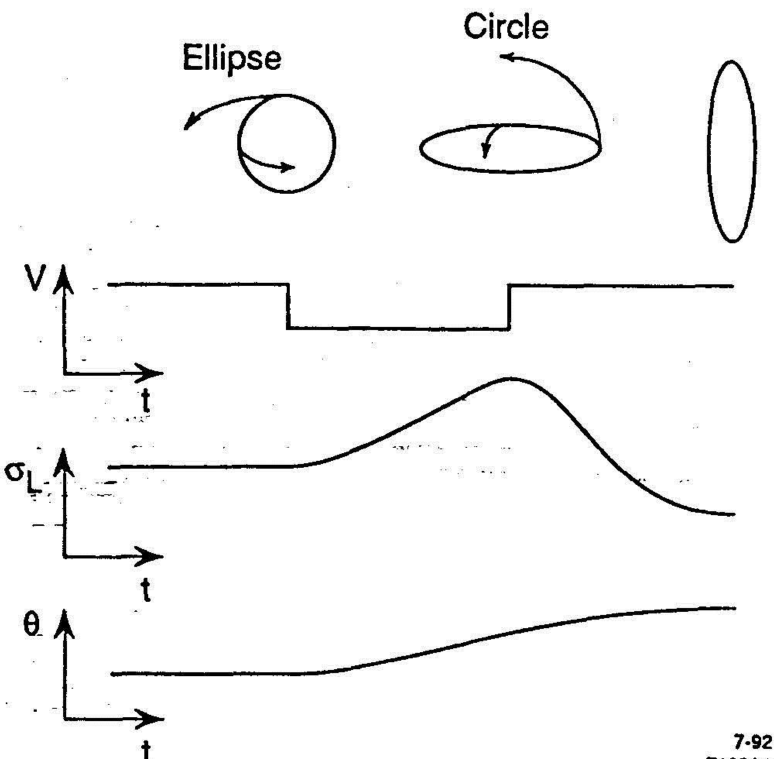


- arbitrary instability ‘phase’ at extraction was single largest source of full-power machine (collimator losses) protection trips





Pre-compression:



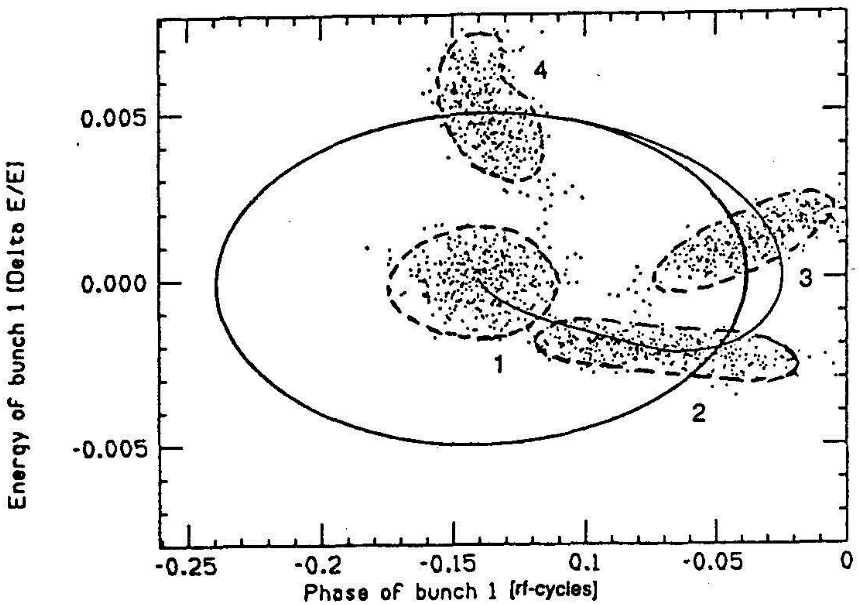


Figure 2: Pre-compression simulation.

A sample of 200 particles is tracked in the presence of the changing rf-voltage. The rf is switched off first and the

Pre-compression in action:

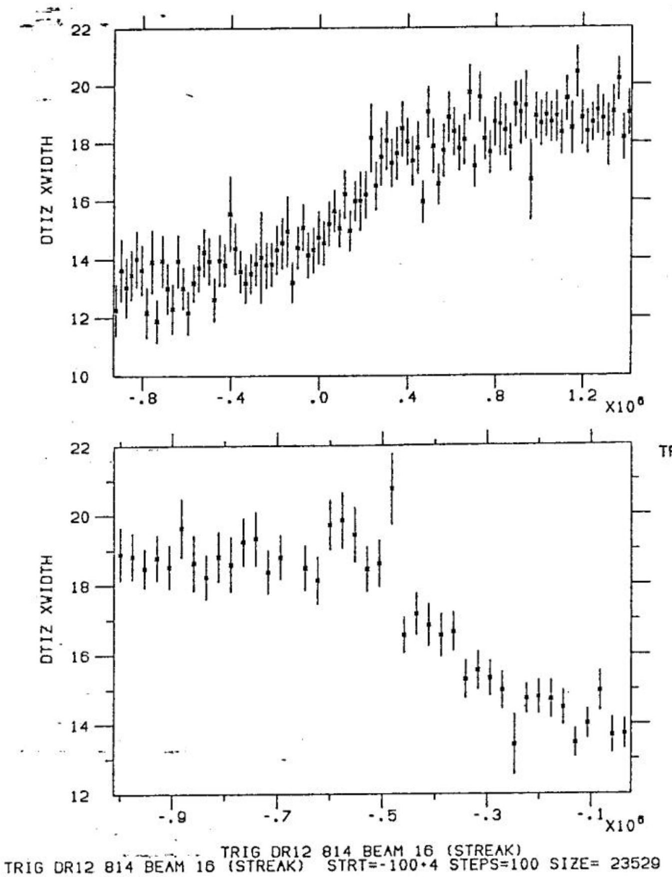


Figure 4: Bunch length during the DR RF ramp.

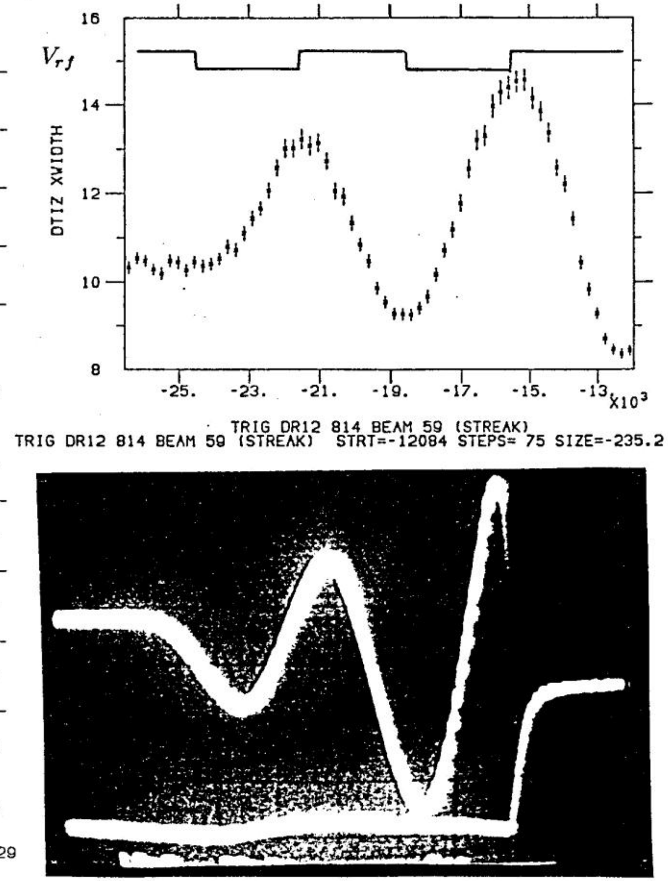


Figure 5: Pre-compression of the bunch length.

helped reduce bunch length to closer to compressor acceptance and ‘synchronize’ instability phase

Linac Collimation:

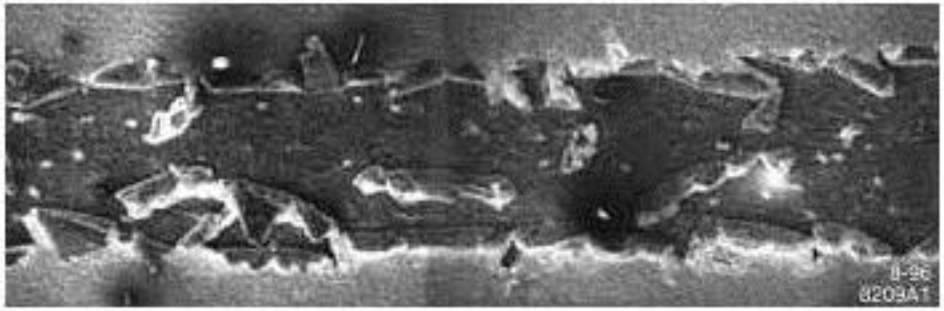
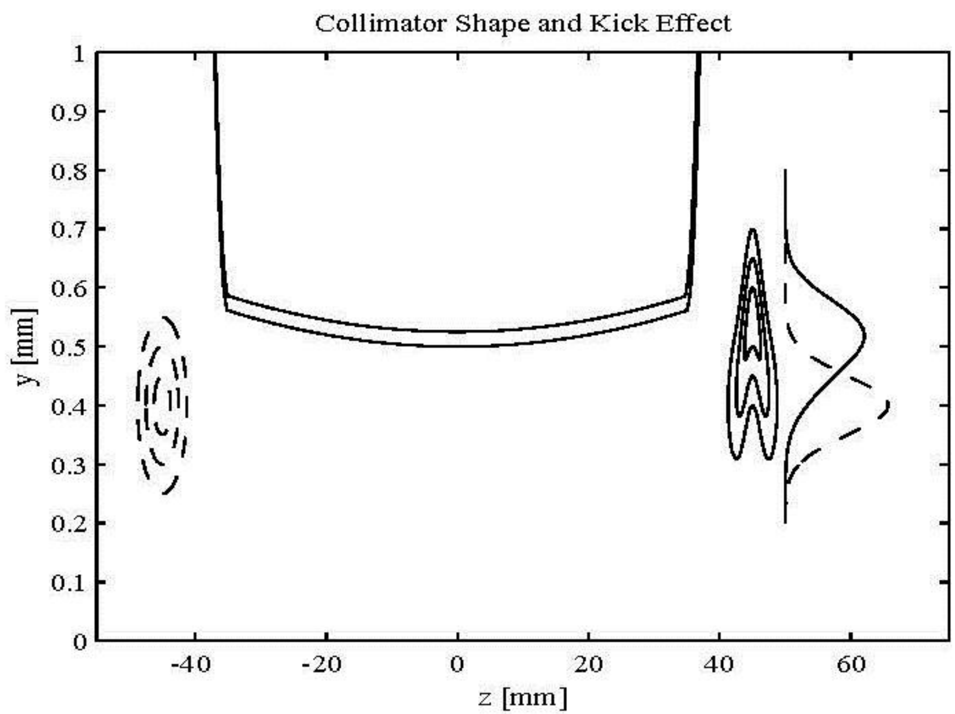


Fig. 1: Damaged collimator surface (stripe width ≈1 mm). The beam enters at the left, creating gold flakes and spherules.

- 47 GeV (max) collimation system
- typical gap <1mm

- Collimator surface damage
- de-lamination
- (Au coated to reduce resistive wake)



SLC

- The SLAC Linear Collider (SLC) was intended in part to demonstrate that linear colliders could work.
- Even though it did not meet luminosity goals, physics goals were met and remain comparable to LEP results.
- **Stabilizing the SLC was the most difficult challenge and transitions in beam power, caused by frequent machine protect system faults were the most serious source of instability.**
- **MPS faults, in turn, were caused through amplification of relatively small damping ring impedance-related longitudinal instabilities in a kind of chain reaction that involved the ring, bunch compressor, normal-conducting linac and collimation systems.**