Simulations of Beam Dynamics from Cathode to Undulator at VISA

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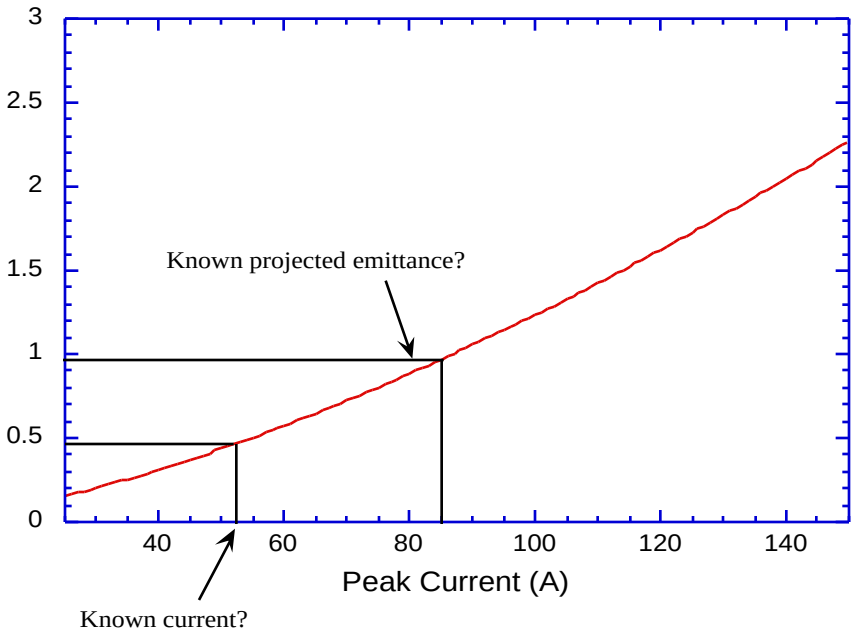
Outline

- Need to understand anomalies in VISA in saturation regime
- Boundary conditions from experiment
- PARMELA/ELEGANT simulations of compression in ATF beamline 3
- Benchmark model for bunch-length measurements
- Pass particles on to GENESIS analysis

Compression in ATF BL3 during VISA experiment?

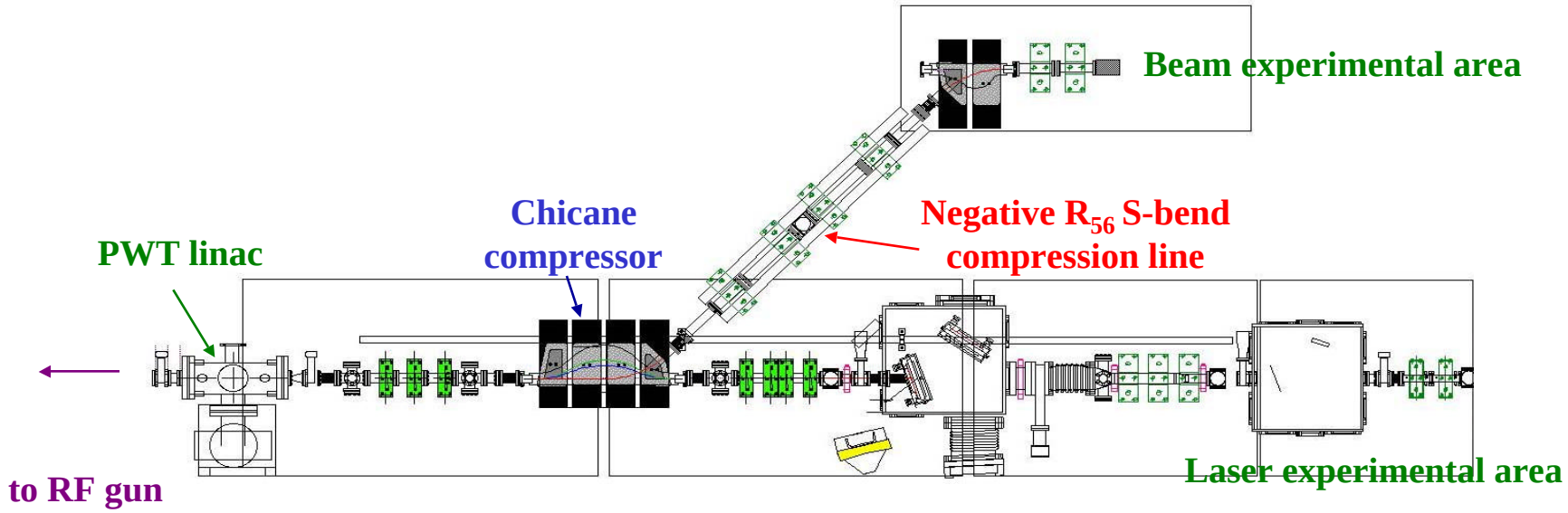
- Experimental anomalies (as of 4/30/2001)
  - maximum gain observed when rf phase shifted off-crest" a few degrees
  - Measurements of beam size indicate dispersion error
  - Asymmetric beam inside undulator
  - Single spike in FEL output spectrum
  - Beam parameters not consistent with observed gain length, 18.7 cm.
- Look at compression
  - Measure
  - Simulate



From M. Xie formula, for 18.7 cm gain length at 165 pC charge

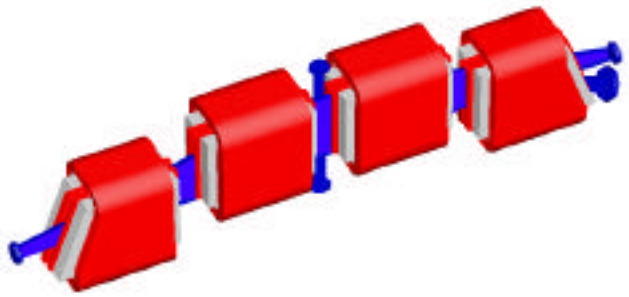
Context for compressor studies: Neptune at UCLA

- Inline chicane compressor
- S-bend compression beamline (like BNL ATF)
- Allows two types of compression
- Tools developed for analysis, measurement (also BNL compr.)



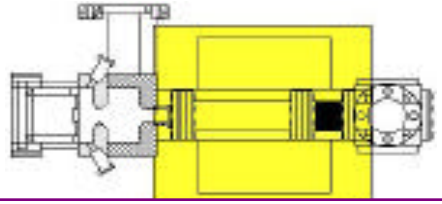
Compression I: Chicane

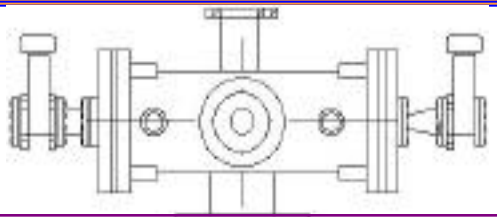
- Negative chirp applied to beam (forward of crest in linac). Positive R_{56} then compresses beam
- Mapping (to first order) all initial phases to the same final phase, $\frac{\partial \phi_1}{\partial \phi_0} = 0$ (like parallel-to-point optics)
- Final current profile limited by rf curvature, or dynamical nonlinearities
- Final current has sharp rise, long tail
- Space charge and wakes degrade compression

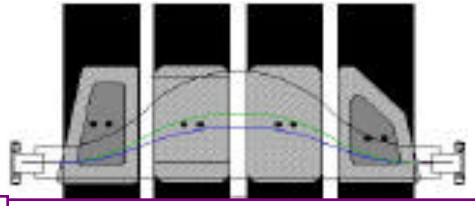


UCLA Compressor chicane for BNL ATF expts.

Phase and configuration space pictures of chicane compression



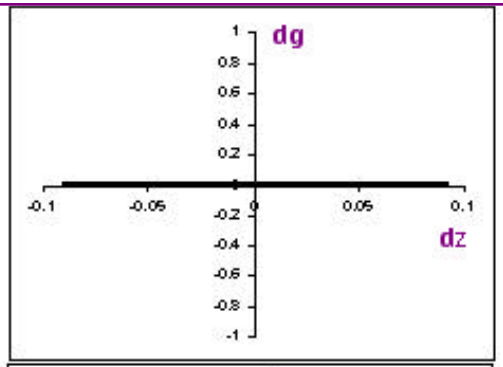


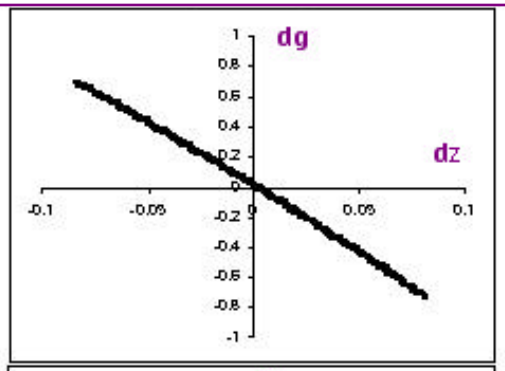


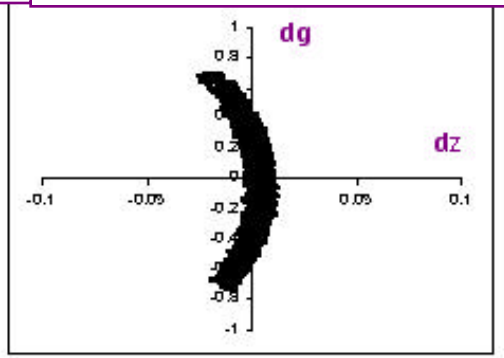
Pulse longitudinal phase space at cathode; current projection

Phase space after linac (negative chirp)

Phase space after chicane, linear correlation removed

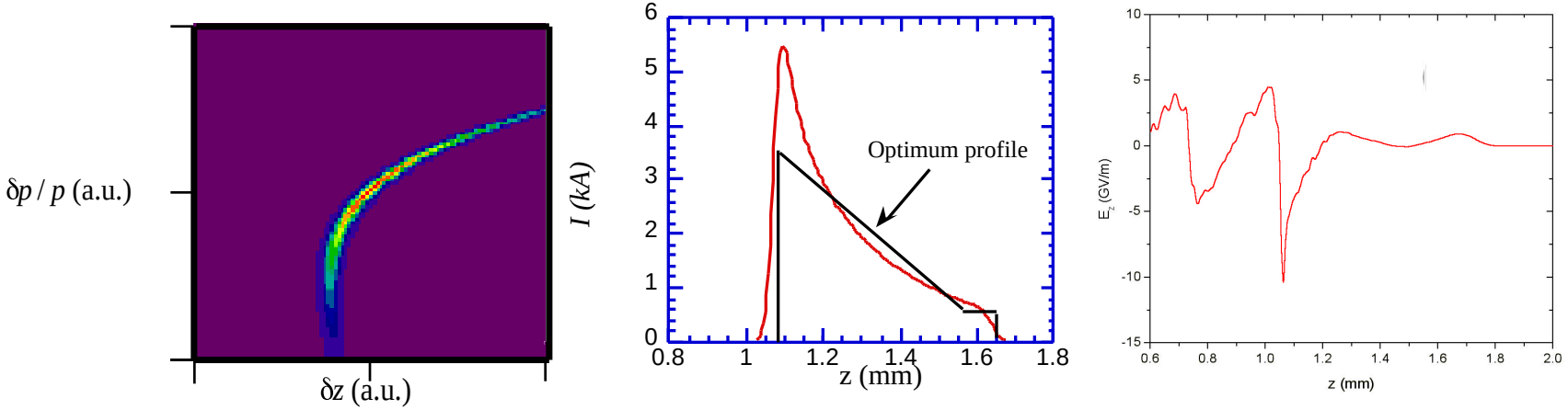






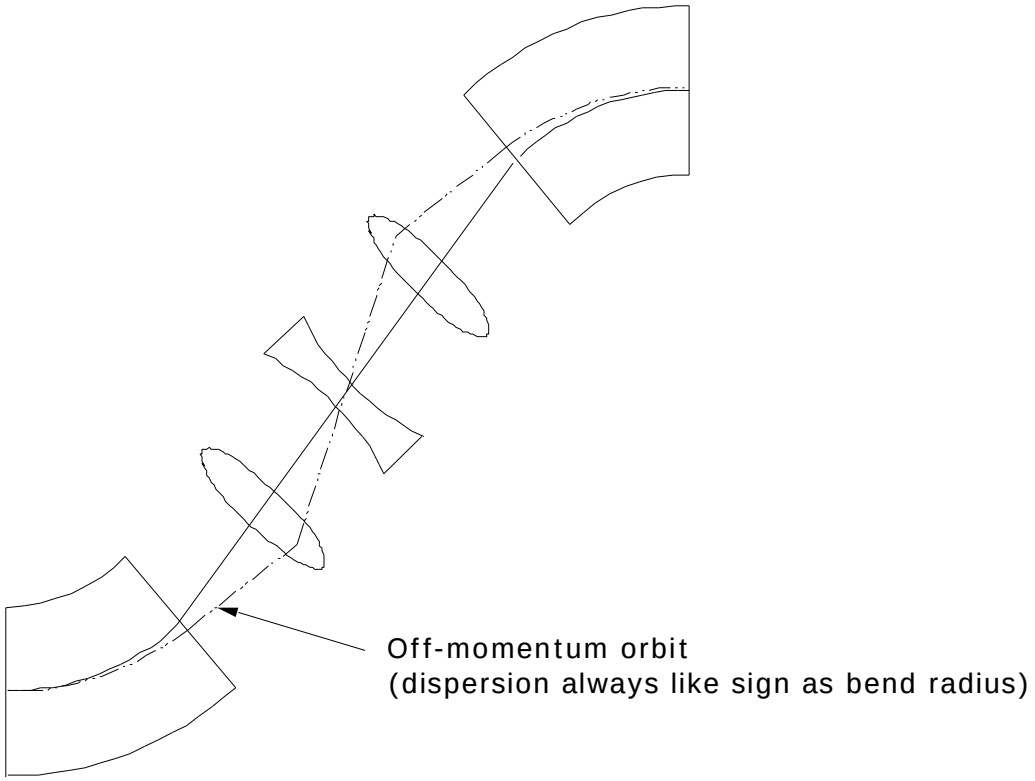
Ramped beam current, sharp leading edge

Creation of compressed, ramped beams for high XFMR ratio PWFA



- ORION study shown
- Negative R56 gives correct ramp
- Currrent profile still based on curvature of phase space…

A simple dispersion-killing bend line: ATF Beamline 3



Chicanes v. "Double-bends"

- The linear analysis uses longitudinal "drift" parameter

$$R_{56} \equiv \partial z / \partial \left(\delta p / p \right) = \int_L \frac{\eta_x}{R} ds - \frac{L}{\gamma^2}$$

- Changes significantly only in bends
- Standard chicane

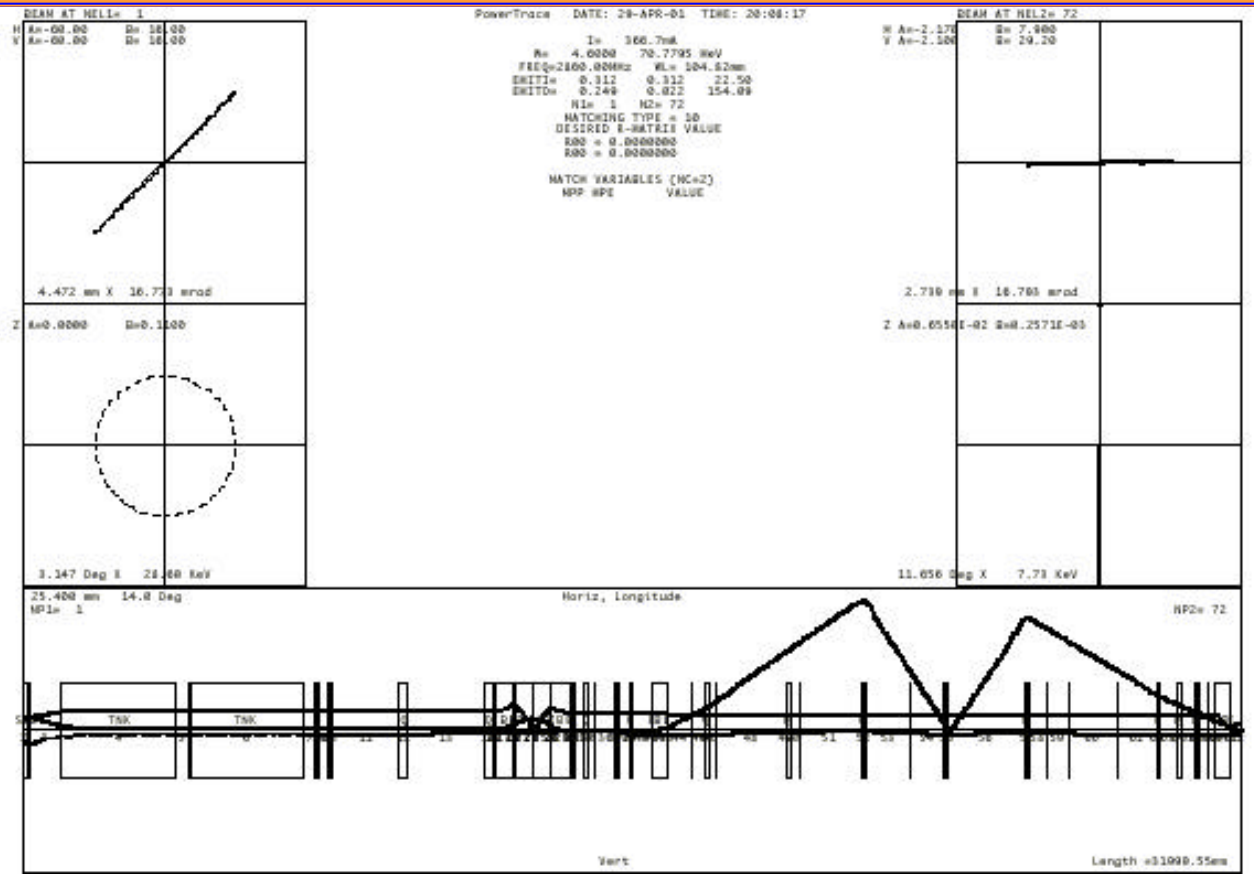
$$R_{56,Ch} = 4R\left[\tan\theta - \theta\right] - \frac{L}{\gamma^2} \quad \frac{2}{3} R\theta^3$$

- S-bend parameter

$$R_{56,S} = 2R\left[\theta - \sin\theta\right] - \frac{L}{\gamma^2} \quad -\frac{1}{3} R\theta^3$$

- Only 4-bend chicane is simple, others depend on optics between bends
- Linear analysis is NOT good enough for photoinjectors and this type of beamline

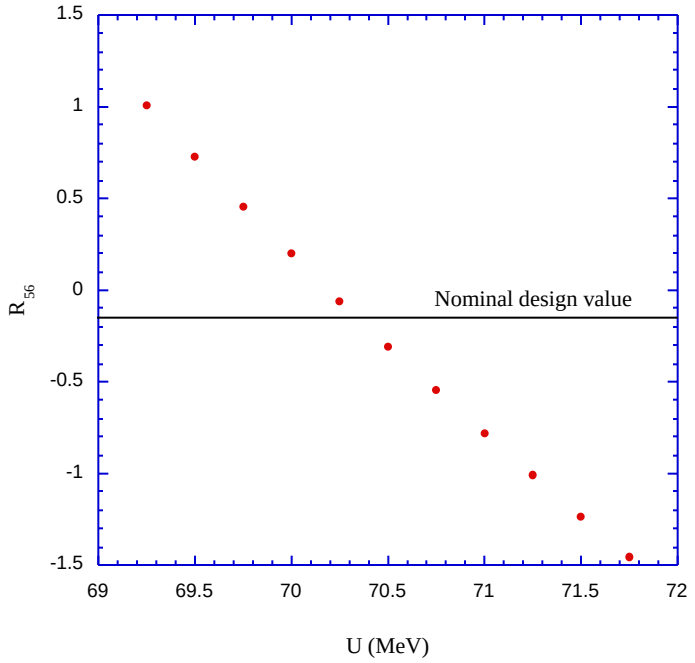
Beamline 3: Linear analysis



Trace 3D shows excessive dispersion/beam size, extreme sensitivity to errors…

Off-energy operation

- "Design R_{56}" is small — need to run >40 degrees off-crest to compress
- But beamline 3 is very unstable with respect to central energy (rf phase)
- R_{56} can vary radically
- Another way of saying this… T_{566} is large and ~constant
- Larger compression vs. emittance growth

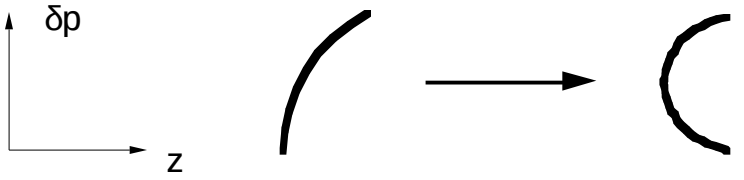


R56 from TRACE 3D, note T_{566} is derivative of line

Second order compression

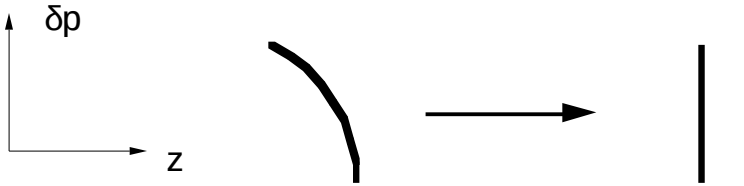
- Transformation

$$z_f = z_i + R_{56}\frac{\delta p_i}{p} + \frac{1}{2}T_{566}\left(\frac{\delta p_i}{p}\right)^2$$



Case 1: Negative R56 (energy too high), curvature of phase space enhanced, low peak current

- Parameters evaluated at design point

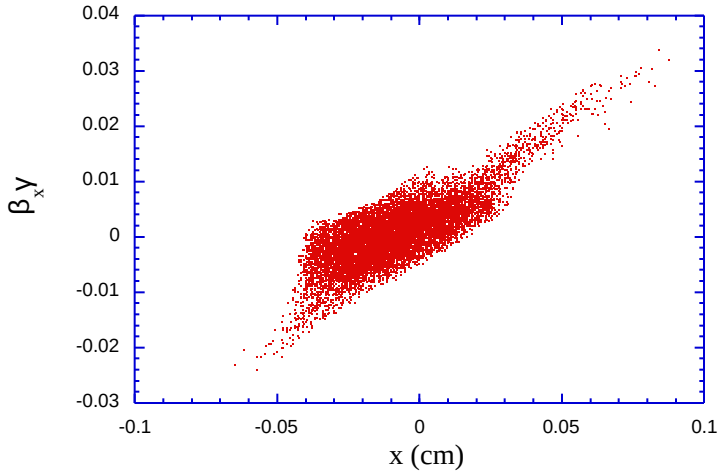


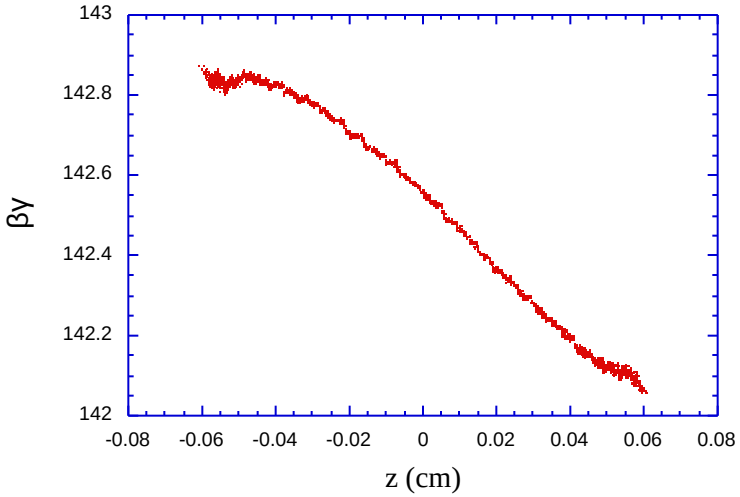
Case 2: Positive R56 (energy too low, what you get from rephasing...), curvature of phase space reduced, very high peak current

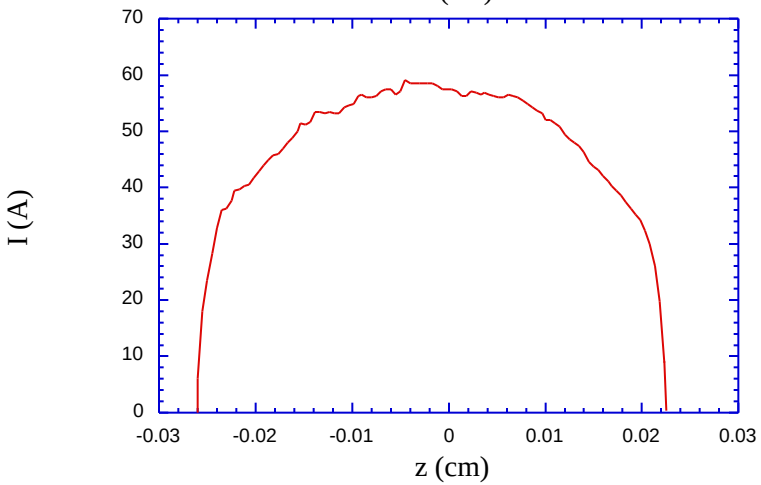
Analysis, with boundary conditions

- PARMELA
  - Produce measured Q (200 pC) ε (<1 mm-mrad), current (55 A) and energy spread (0.17% after rephasing).
- ELEGANT
  - Include coherent synchrotron radiation
  - Include scraper
  - Optimize peak current by changing “design” energy
  - Compare results to Golay cell measurement of CTR
- GENESIS
  - FEL - hope for the best…

Beamline 3 initial conditions from PARMELA

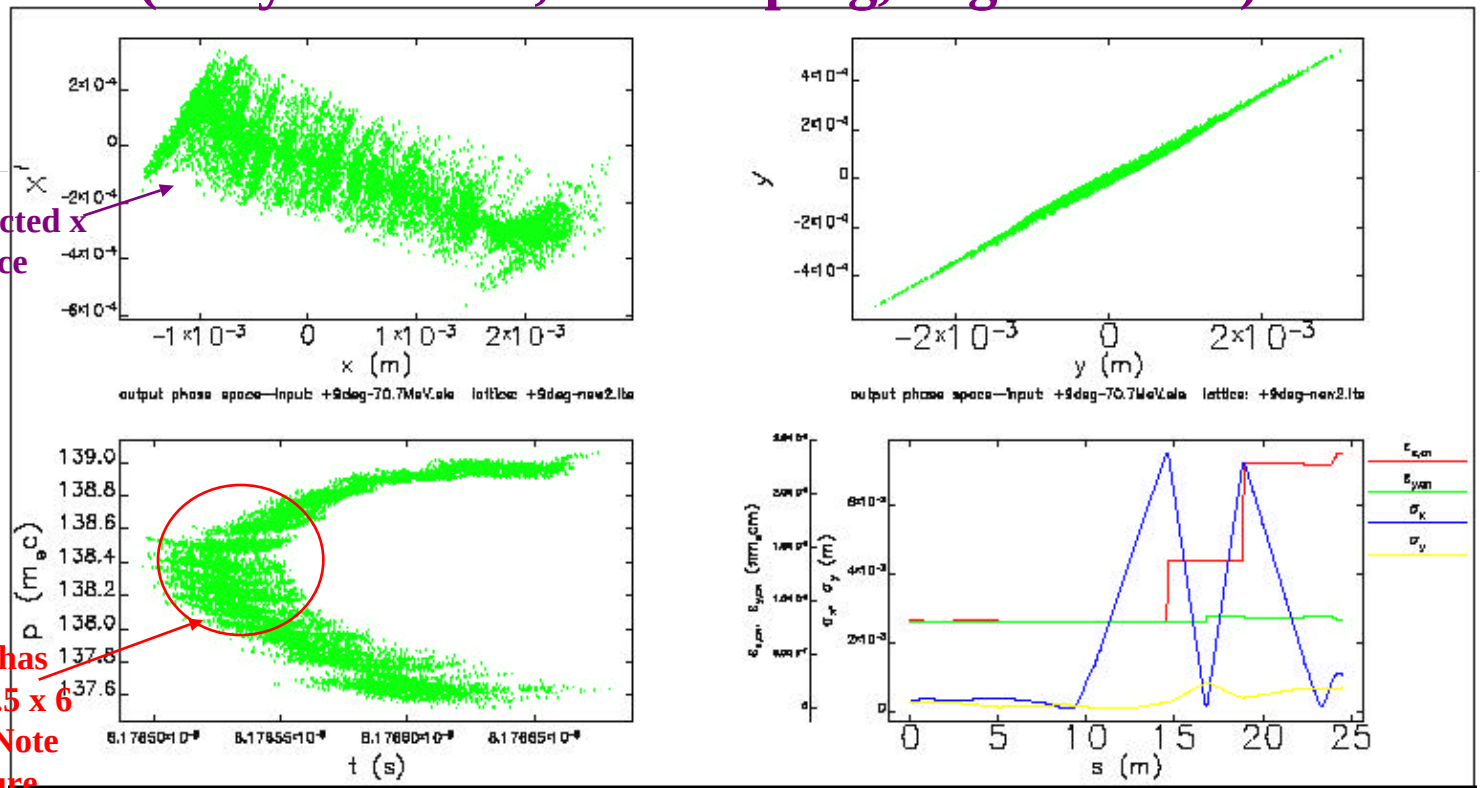






Some iteration needed to understand the mechanism of nonlinear compression — wakes and space-charge are important!

ELEGANT simulation of beamline 3
(early trial case, no scraping, negative R56)



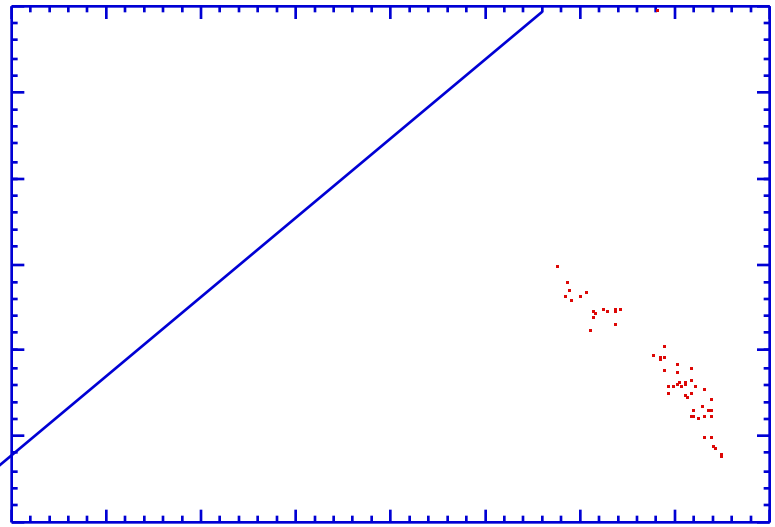
Large projected x emittance

Beam core has emittances 0.5 x 6 mm-mrad. Note large curvature…

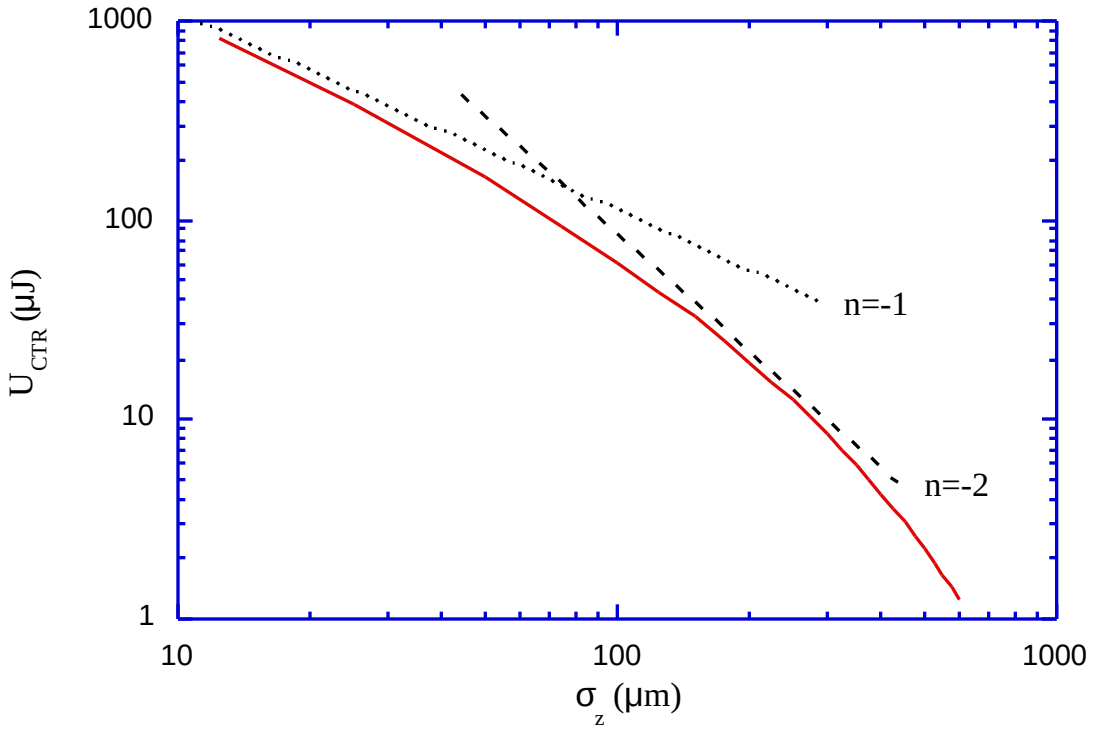
Strong compression, with positive R_{56}! 100 fsec beam core…

Dispersion not correctly cancelled, R56 large, w/ wrong sign!

ELEGANT-predicted final state: transverse phase space



Single Golay-cell CTR bunch length measurement



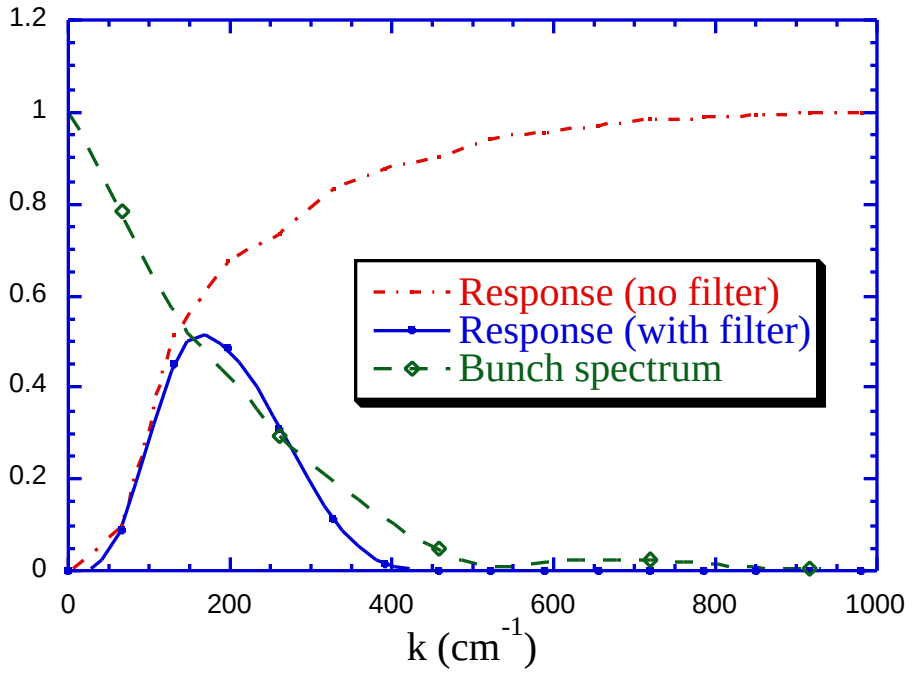
- Poor man's bunch length monitor developed after 4/30
- One Golay cell
- CTR power spectrum is a strong function of bunch length
  - Inherent power law inverse with bunch length
  - Finite radiator effects
- Simple low pass filter allows calibration of where one is on the curve…
- Detailed comparison with simulation particles possible

Comparison with simulation

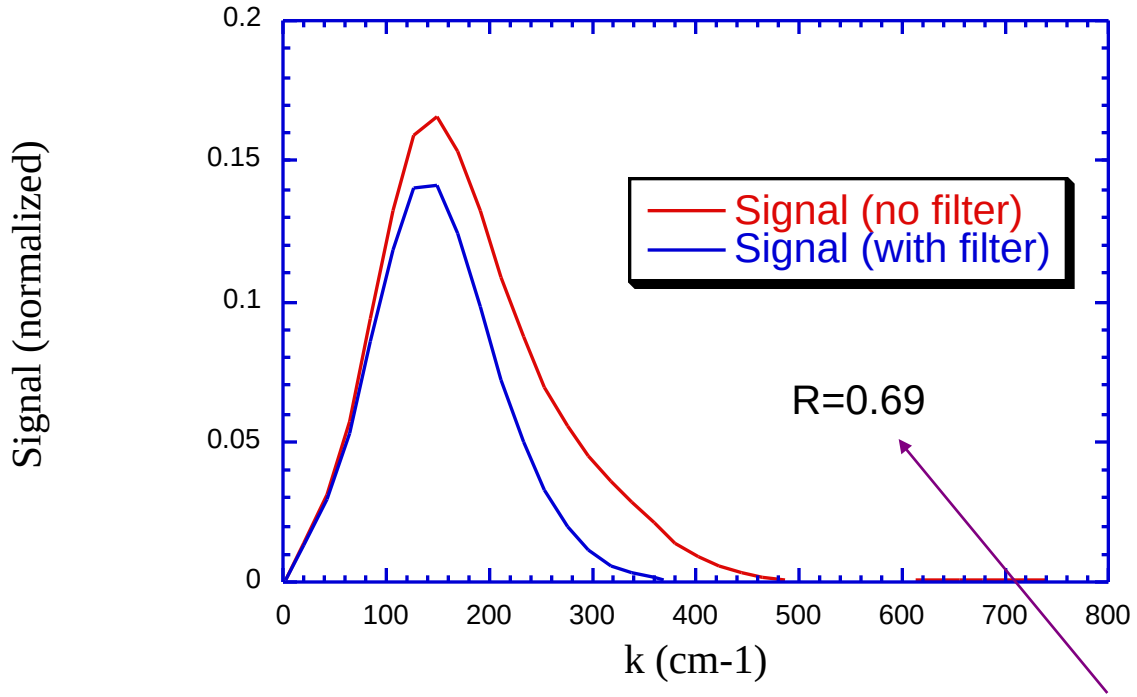
- Peak ratio of signal w/,w/o filter is

$$R = 0.68$$

- Calculate system spectral response, including finite radiator size (w/Reiche) and diffraction effects
- Obtain beam spectrum from PARMELA/ELEGANT simulation
- Sensitive test

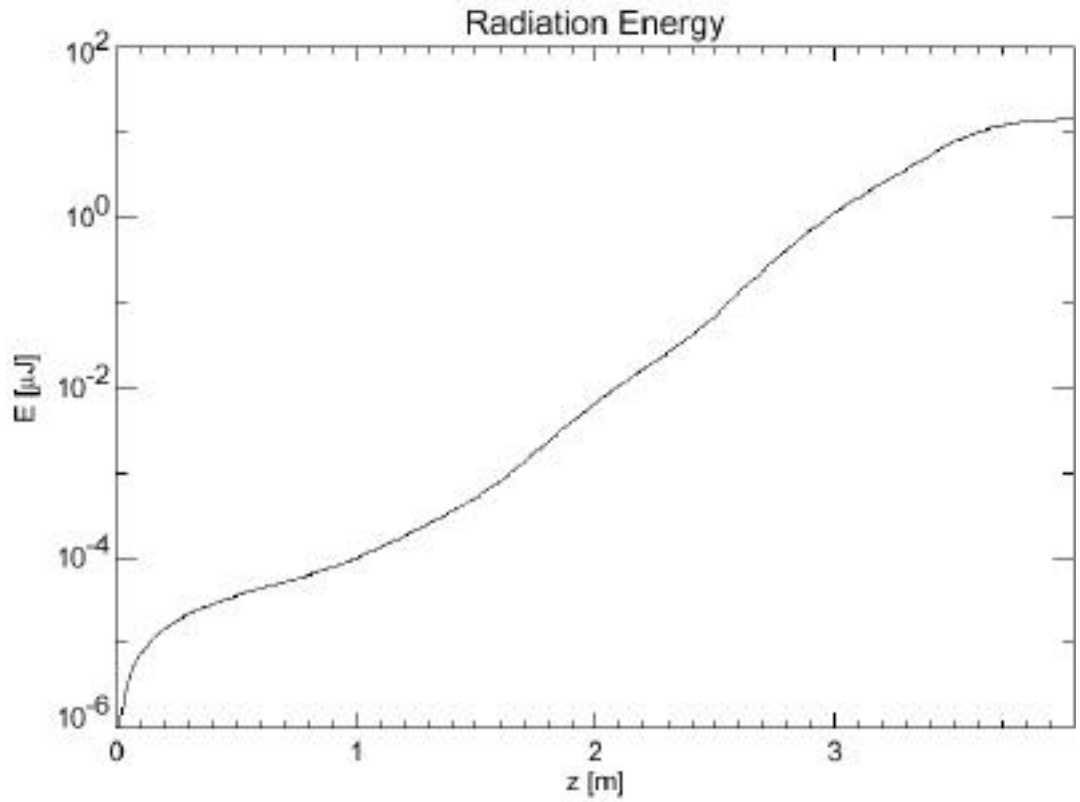


Simulated CTR signal ratio in agreement with measurement



'nuff said.

Sven's Answer (more to come!)



Very promising

Conclusions

- Good insight into beam behavior in the VISA experiment
- Nonlinear compression mechanism dominates longitudinal dynamics
- Simulation of ATF injector and beamline 3 with PARMELA/ELEGANT obeys experimental boundary conditions
  - CTR measurement well-modelled
- Particles handed off to GENESIS