VISA

A SASE-FEL Experiment

or

A Beam Diagnostic and Simulation Bench-mark Experiment

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for the

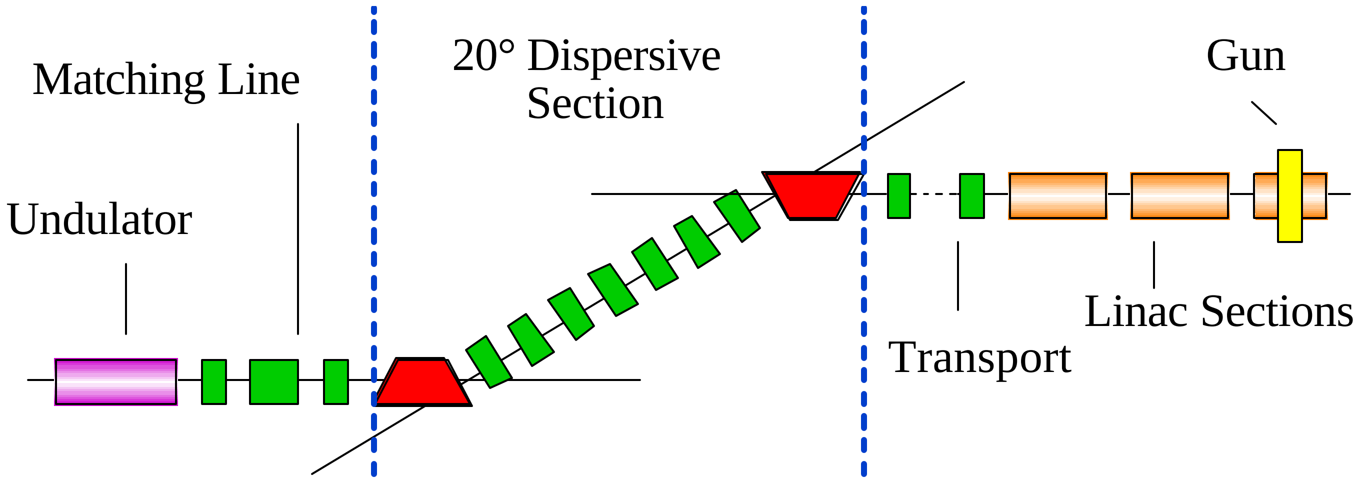
BNL-LLNL-SLAC-UCLA

VISA collaboration

Outline

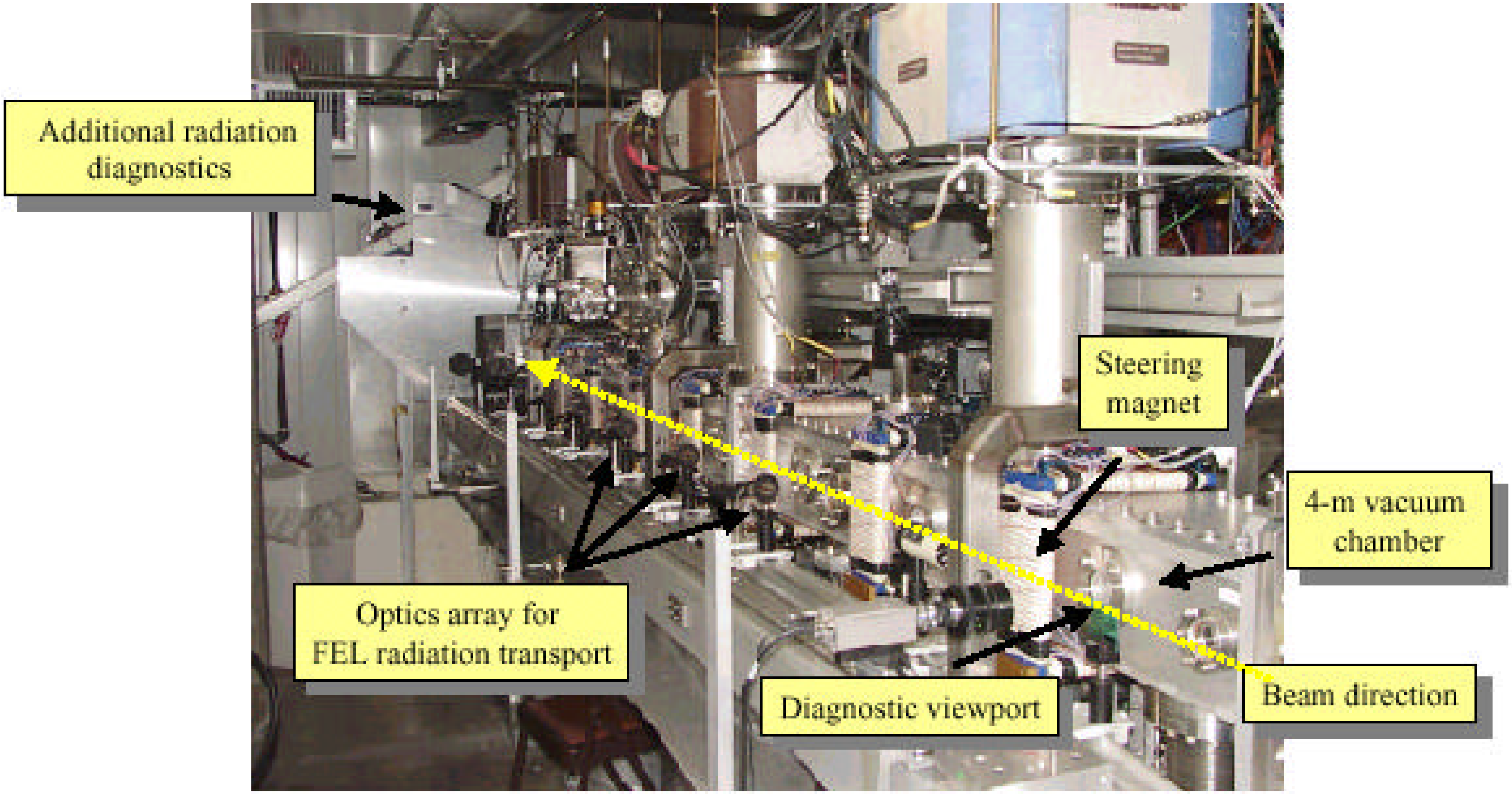
1. Experimental system
2. Beam compression and beam measurements
3. Simulations and data analysis
4. Harmonics
5. Conclusions

VISA Beamline



- Gun and Linac Section (1.6 cell photo-emission gun and 2 SLAC type linac structures operating at S-Band, generate 71 MeV beam)
- 20° double-bend dispersive transport section
- Beam line III, with VISA matching optics and 4-m long strong focusing undulator (K=1.26)
- Wavelength about 830nm.

Undulator and experimental system



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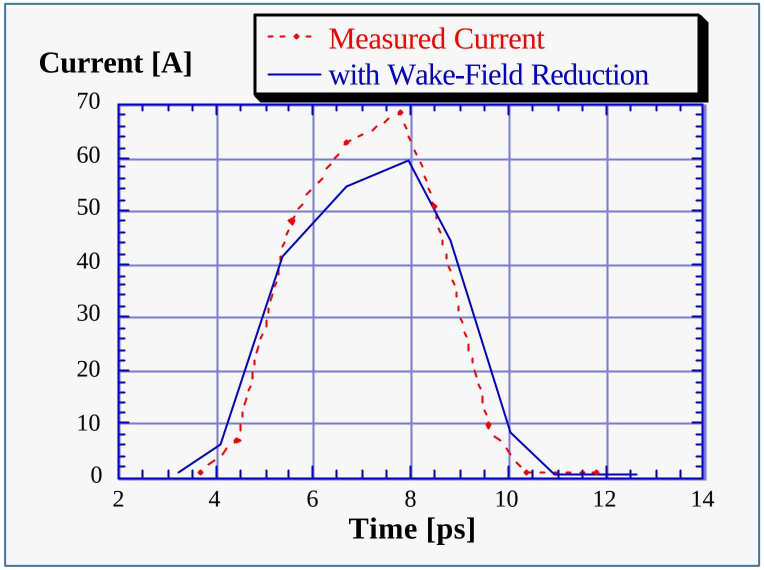
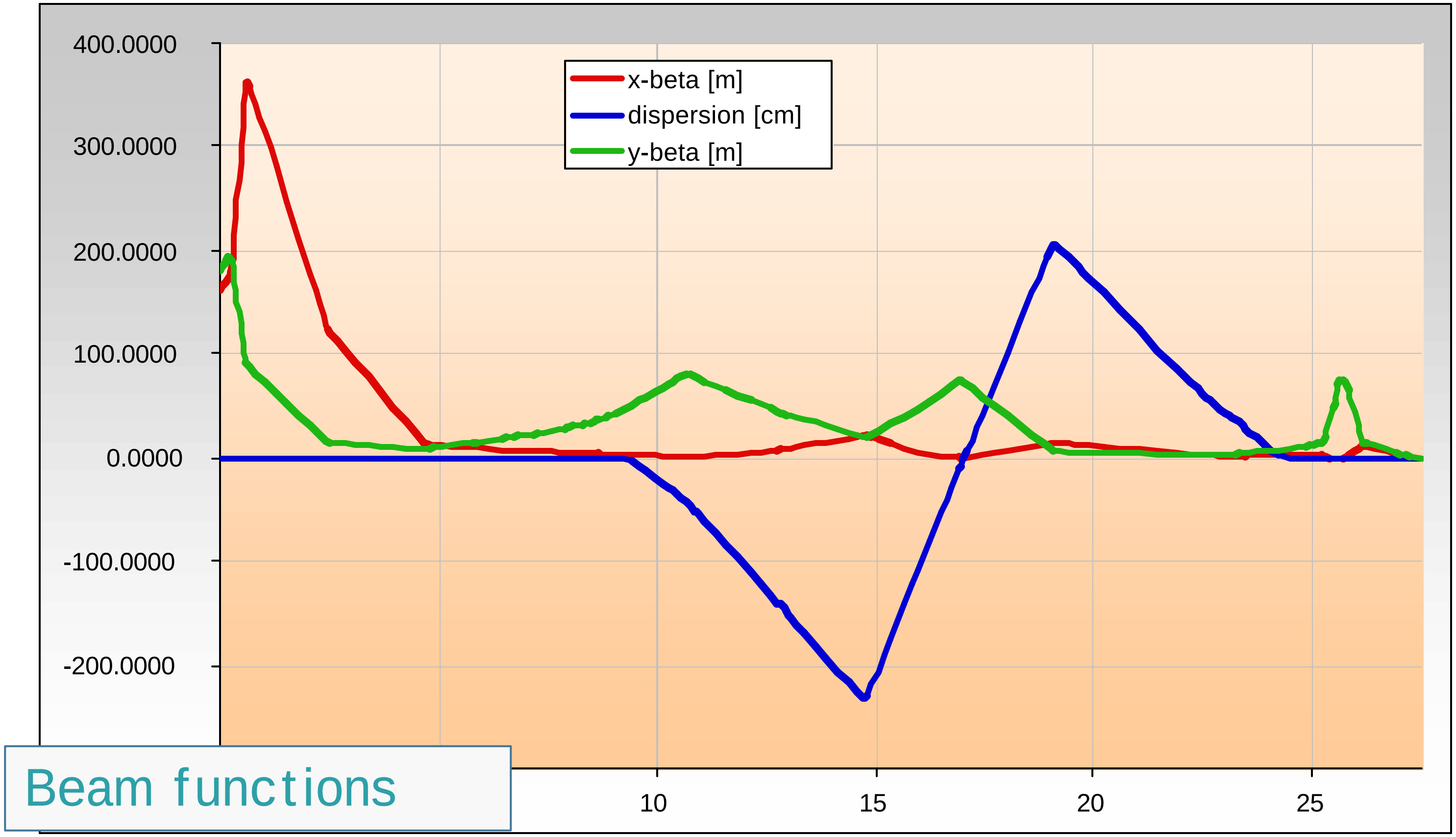
Beam at linac exit

- The projected normalized beam emittance , measured with a quadrupole scanning technique, at the linac exit is about 1.5 mm-mrad for a charge around 200pC .
- Bunch length measurements were done changing the linac phase to introduce an energy chirp in the electron bunch and measuring a dispersion-dominated horizontal beam profile after the initial 20° bend. They indicate a nearly flat longitudinal beam distribution and a peak current of about 55A.

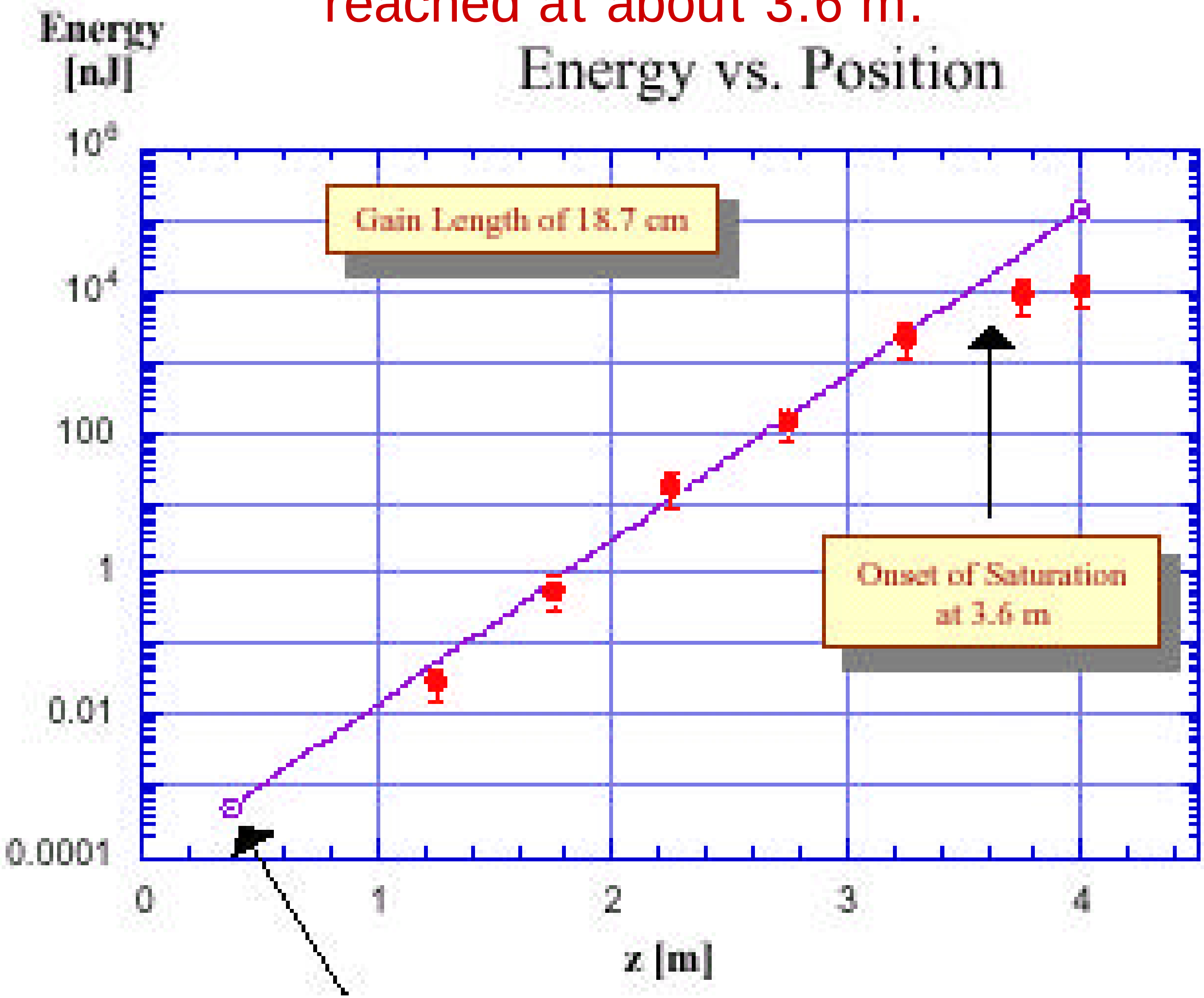
With this beam characteristics the saturation length is larger than 4m.



The “dog-leg” beam line can produce compression, increasing the peak current.

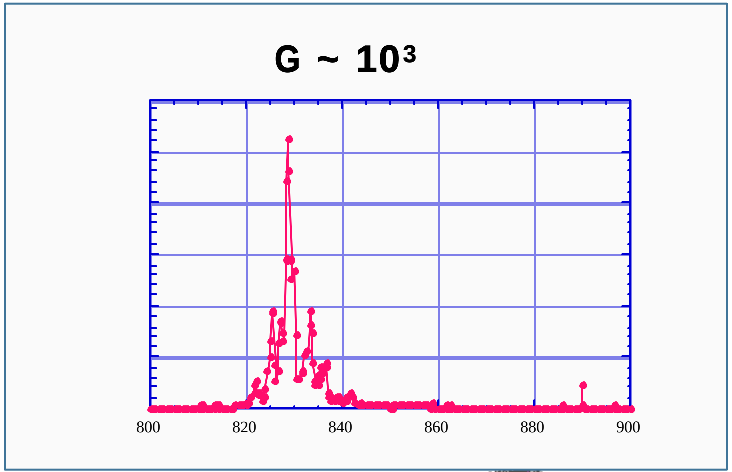


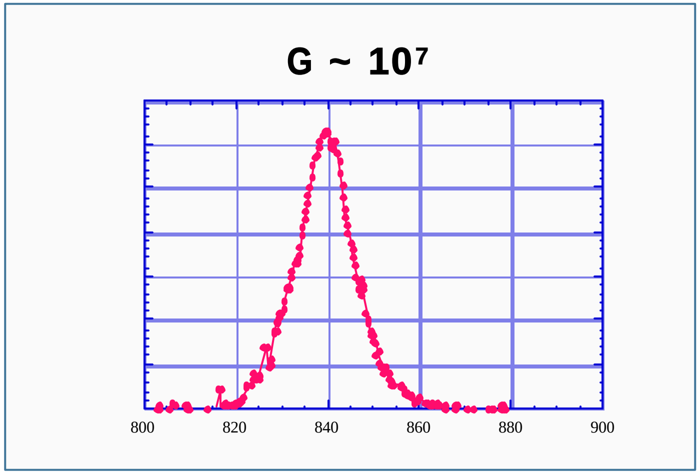
Using beam compression, saturation is reached at about 3.6 m.

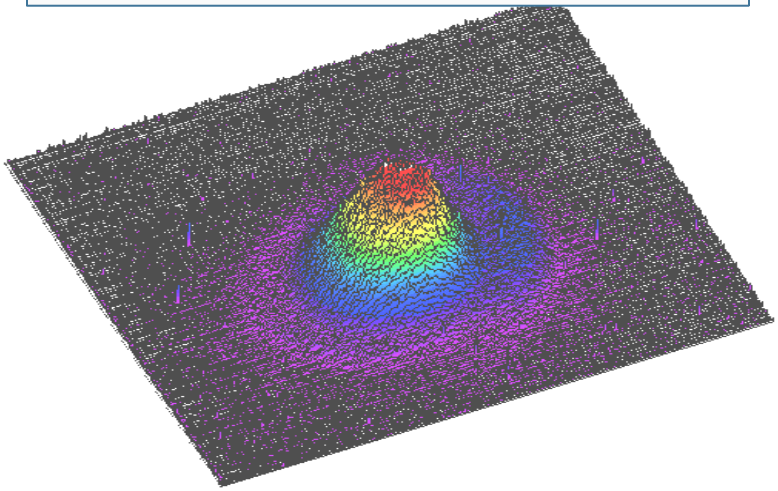


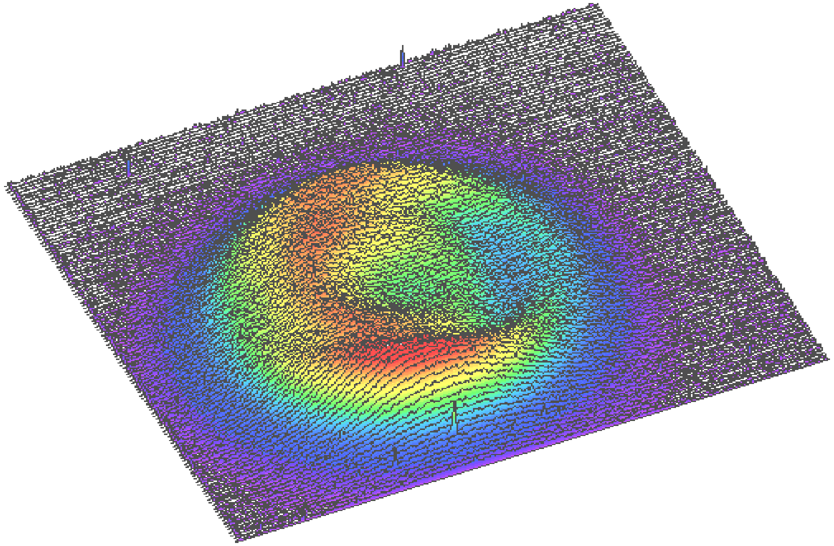
Two regimes with different characteristics.

Spectra and angular distributions of FEL radiation at low and high gain.









Beam compression and high gain

- The high gain is obtained by chirping and compressing the beam.
- Chirping is produced by changing the linac RF phase respect to the photo-injector.
- Compression is then obtained in the double bend.

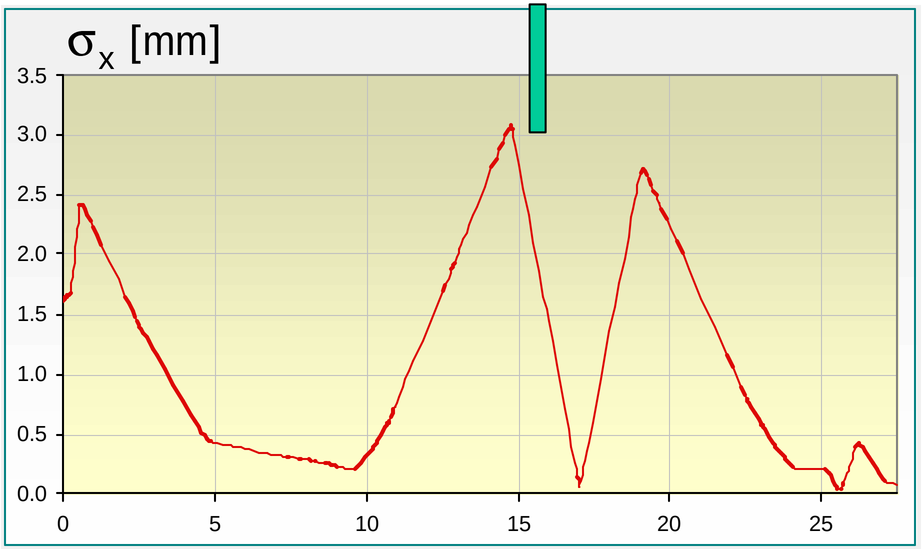
$$\boxed{z_f = z_i + R_{56}\frac{dp}{p} + \frac{1}{2}T_{566}\left(\frac{dp}{p}\right)^2}$$

$$\boxed{T_{566} = \frac{\partial R_{56}}{\partial (dp/p)} \approx -7\ \mathrm{m/rad}^2}$$

The compression is nonlinear. The T566 term is important.

Beam scraping and RF phase control

- The bending dipole to ATF Beamline 1, acts as a scraper with a 1.5 cm aperture.
- Charge loss at the scraper depends on the beam energy and is very sensitive to changes in the RF phase.



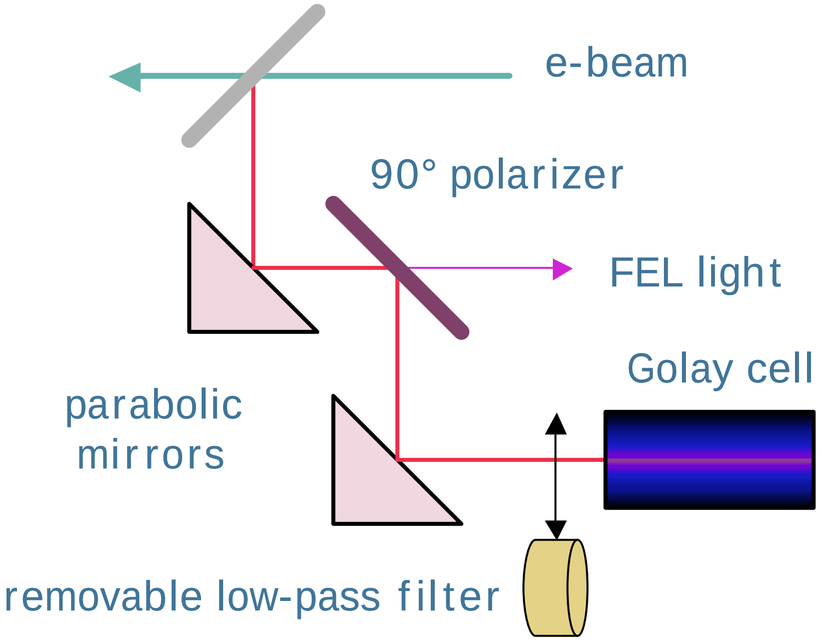
<u>Measuring the charge loss at the collimator allows to</u>

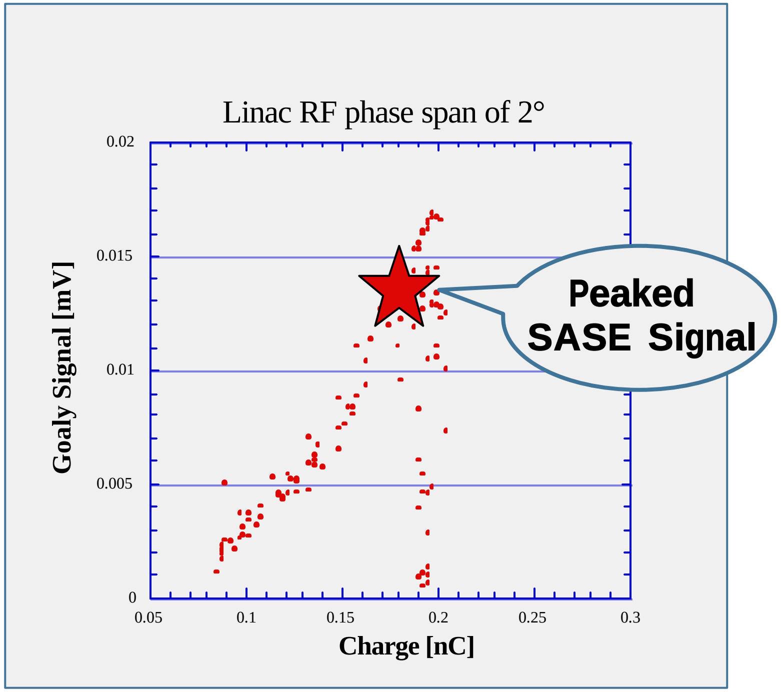
1. Monitor phase drifts.
2. Use the same system operating point for FEL measurements.

Measure of beam compression with Golay cell and CTR

- The electron bunch length and the compression are measured with a single Golay cell observing the intensity of the CTR from a mirror inserted at the undulator exit. The spectral fluence of the CTR is proportional to the square of the Fourier transform of the beam longitudinal distribution, giving a signal inversely proportional to the electron beam bunch length, with a sharp cut-off at an RMS bunch length due to the diffraction and Golay cell response.

Measure of beam compression with Golay cell and CTR





<u>System allows following measurements:</u>

1. Scanning linac RF phase and observe CTR and FEL signal. Very sensitive to phase.
2. Inserting a remote controlled low-pass filter for a quantitative estimate of a bunch length (starting with the assumption about bunch shape).

Measure of beam compression with Golay cell and CTR

CTR data show strong compression. The CTR signal peaks sharply within a narrow (<2°) window of the linac RF phase. Inserting a low-pass filter with a known frequency roll-off allows a quantitative assessment of the high frequency CTR component. Measurements with and without filter give a signal ratio of 0.68 at the SASE operating point, providing a quantitative benchmark for the numerical modeling of the system.

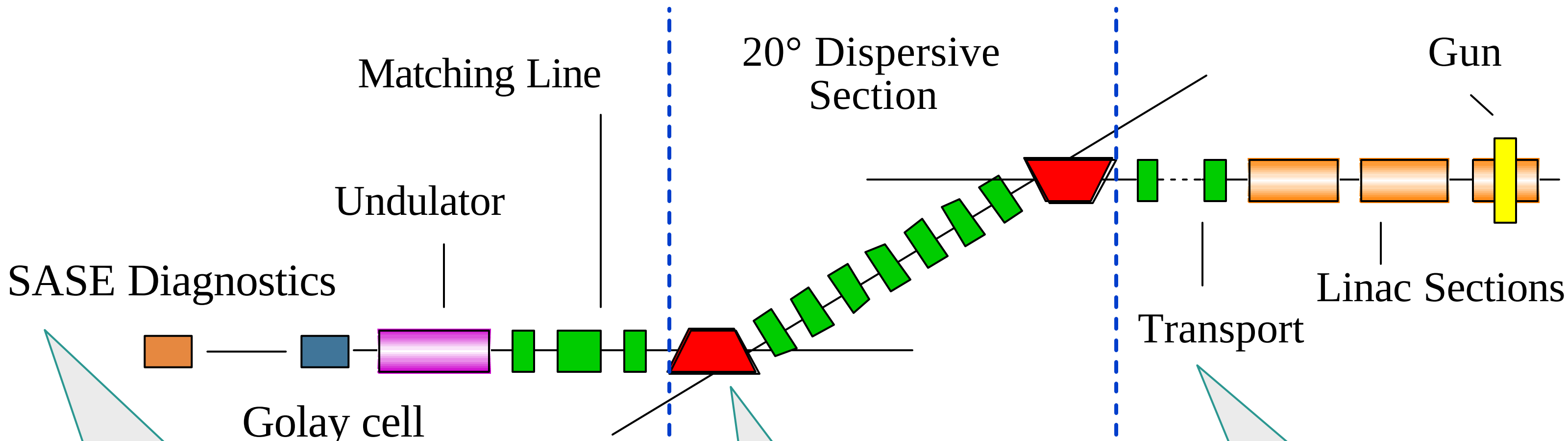
The compression observed is mostly due to the large (negative) second order compression coefficient T_{566} in the dispersive section, which under the linac operating conditions removes the parabolic component of the longitudinal phase space distribution. The effect is to compress the electron bunch by a factor near to 5, giving a peak current of about 250 A, consistent with the CTR and SASE spectral data.

Beam and FEL simulations

Non-linear effects during the beam transport are important. To understand the electron beam properties in the undulator, a full cathode-to-undulator simulation of the experiment has been done:

- UCLA-PARMELA models photo-emission, acceleration and emittance compensation from the gun to the linac exit; the results match the beam properties measured after the linac.
- ELEGANT models the beam dynamics and longitudinal compression in the dog-leg as a function of linac phase, including coherent synchrotron radiation (CSR); results match the Golay cell measurements of CTR;
- Numerical simulations show that the slice emittance growth due to CSR is not significant, while the second order dispersion term, combined with the large sliced energy spread after the linac, is important, and gives a slice emittance in the undulator of about 4 μm.

GENESIS ELEGANT PARMELA

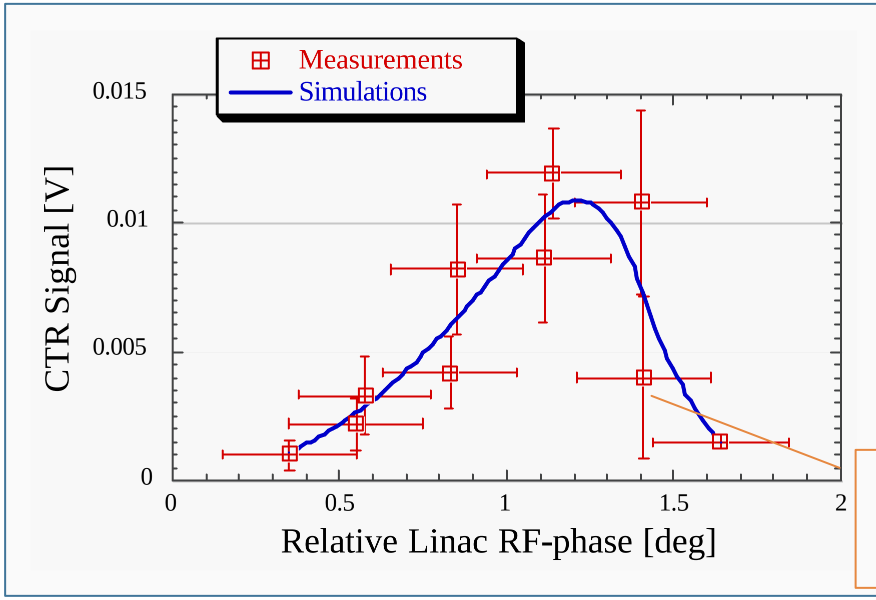


at peak lasing:
L_G ~ 18.5 cm
L_{SAT} ~ 3.6-3.8 m
E_{SAT} ~ 20 μJ
$\Delta\omega/\omega$ ~ 1.2 % (single spike)

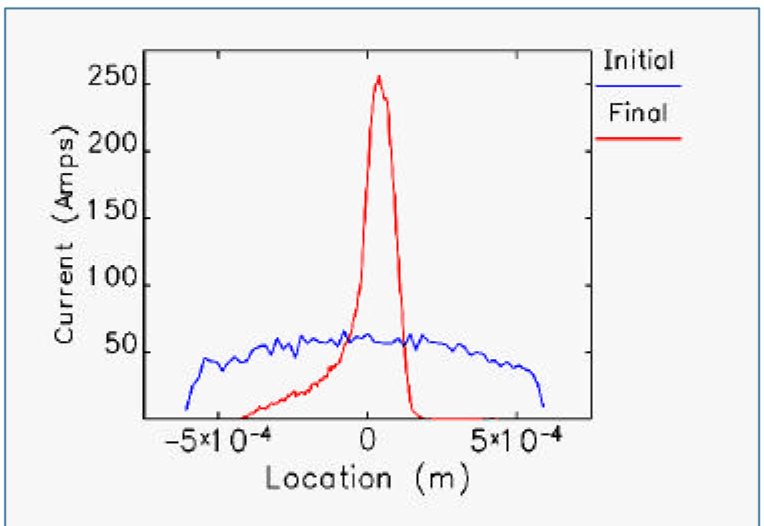
(at FEL operating point)
$\Delta p/p$ ~ 0.14 - 0.20 %
transmission ~ 70 %
compression ~ x 5 (CTR)

Q ~ 200 pC
I_P ~ 55 Amp
$\Delta p/p$ ~ 0.05 % (uncorrelated)
$\varepsilon_{?}$(projected) ~ 1 - 2 mm-mrad

Simulations and data



Simulating CTR. The ELEGANT output fits the measurement.

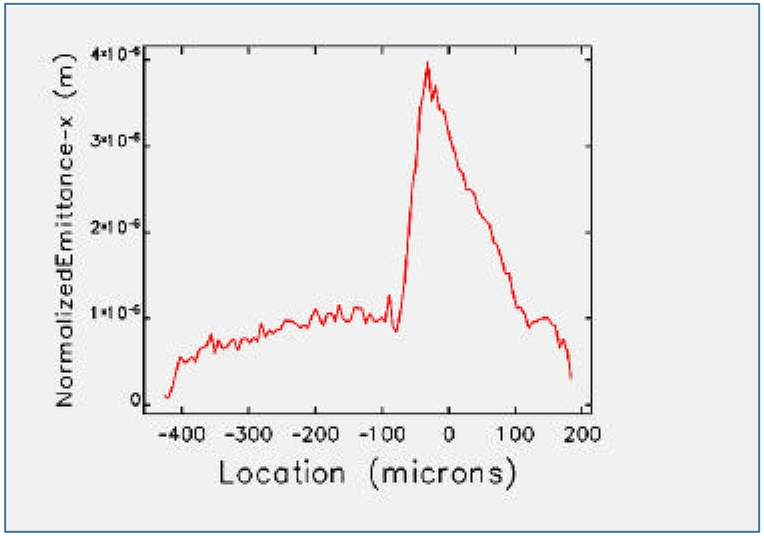


Current distribution at undulator entrance. From Elegant simulations

Simulations and data

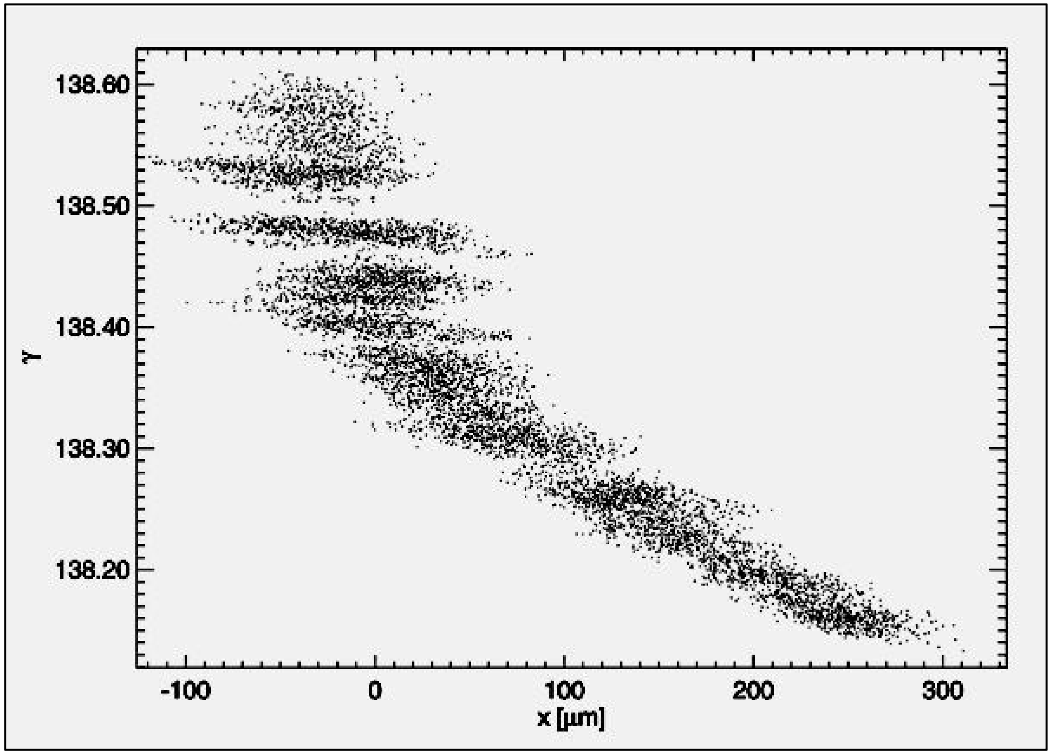
Slice emittance at undulator entrance.
The lasing part of the beam has

$\varepsilon^{<slice>} < 4$ μm-rad.



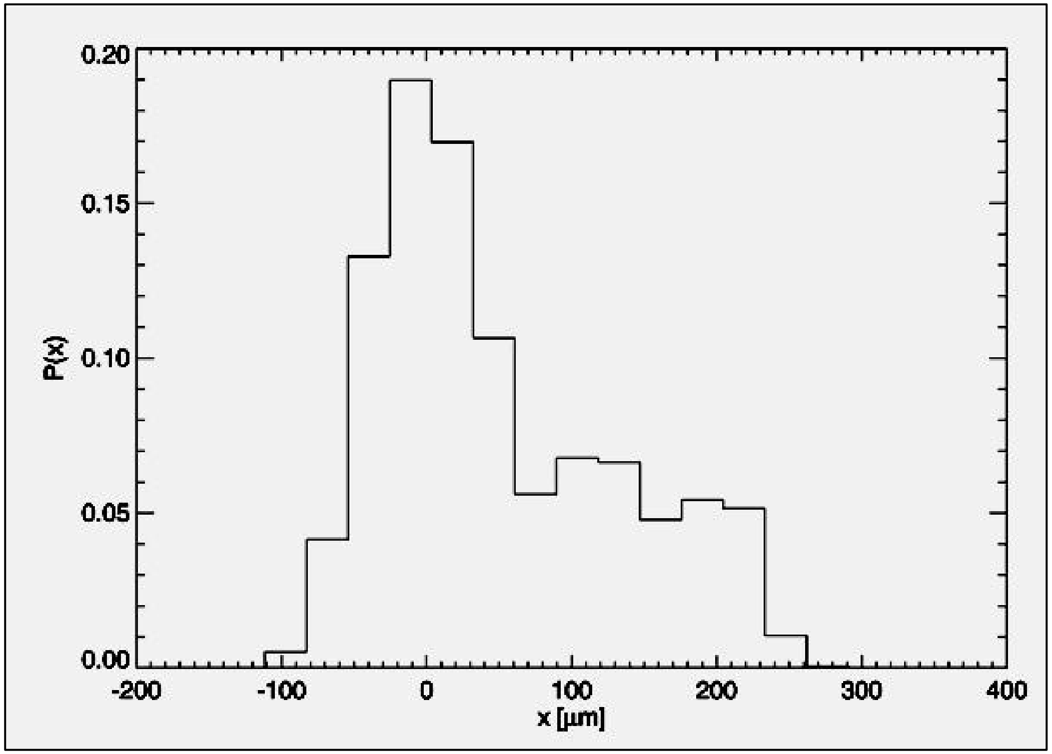
Beam transverse phase space after dog-leg

$\gamma\,(x)$



Beam transverse phase space after dog-leg

x-distribution



FEL intensity data

- Due to the strong sensitivity of the compression to small changes in the phase of the linac respect to the photo-injector, the SASE signal fluctuations are generally dominated by the system RF phase jitter.
- To enable data reduction for the FEL measurements, the collimator is used to trace the linac RF phase changes by monitoring the charge loss in the dispersive section.

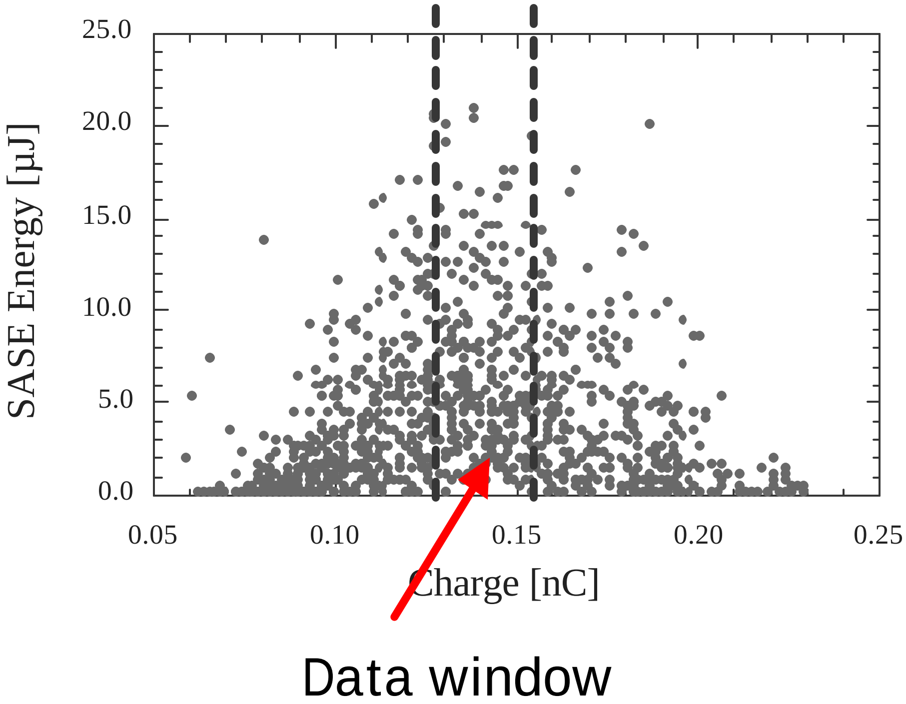
FEL intensity data

- On the right hand side of the plot, the linac operates near nominal phase, and all the charge is transmitted through the dispersive section; however there is no compression and the gain is small.

- When the linac phase advances, bunch compression increases the FEL gain, while the charge loss in the collimator become significant.

- At the optimal operating point the charge loss is around 30%; the gain does not decrease because most of the scraping removes a non-lasing tail of the beam.

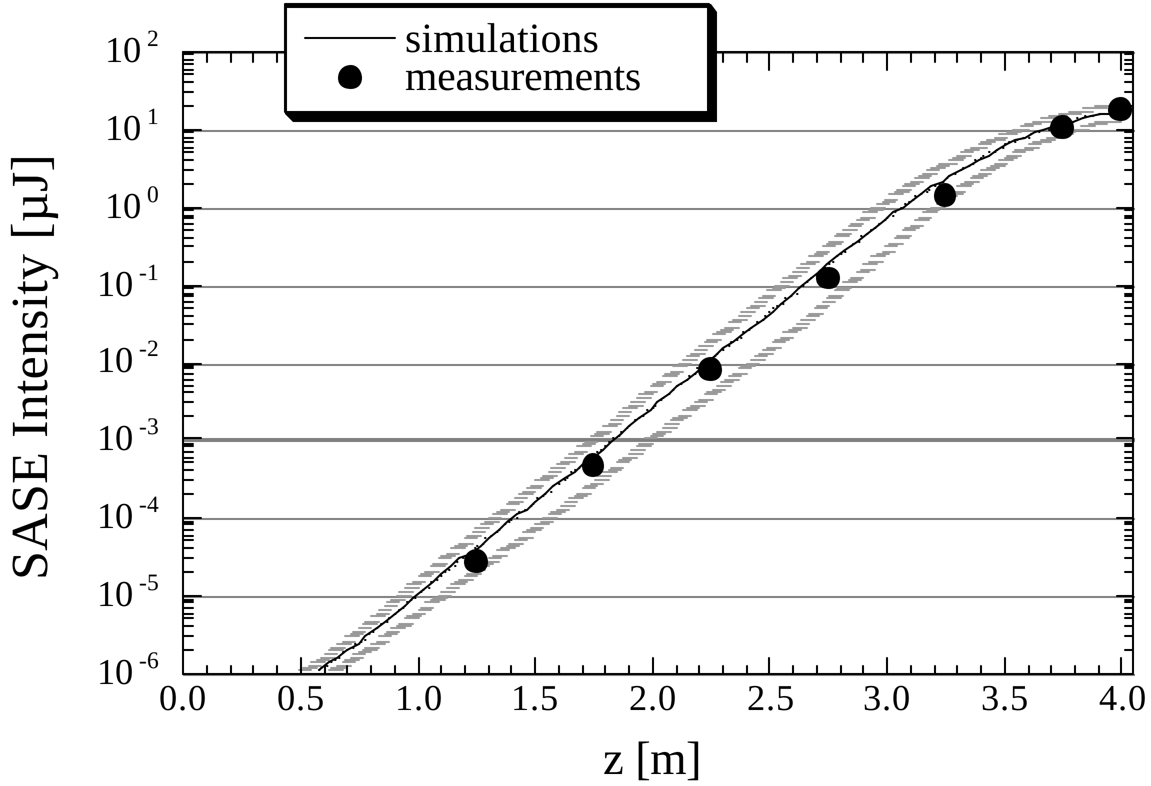
- To the left of the peak the linac phase increase reduces the gain due to overcompression and charge loss at the collimator.



Charge and RF phase are connected by the collimator

FEL intensity data and simulations

- SASE intensity measurements along the undulator length.
- The data points are the RMS value of the shots selected within the charge window .
- The lines are the Genesis results using the Parmela-Elegant output

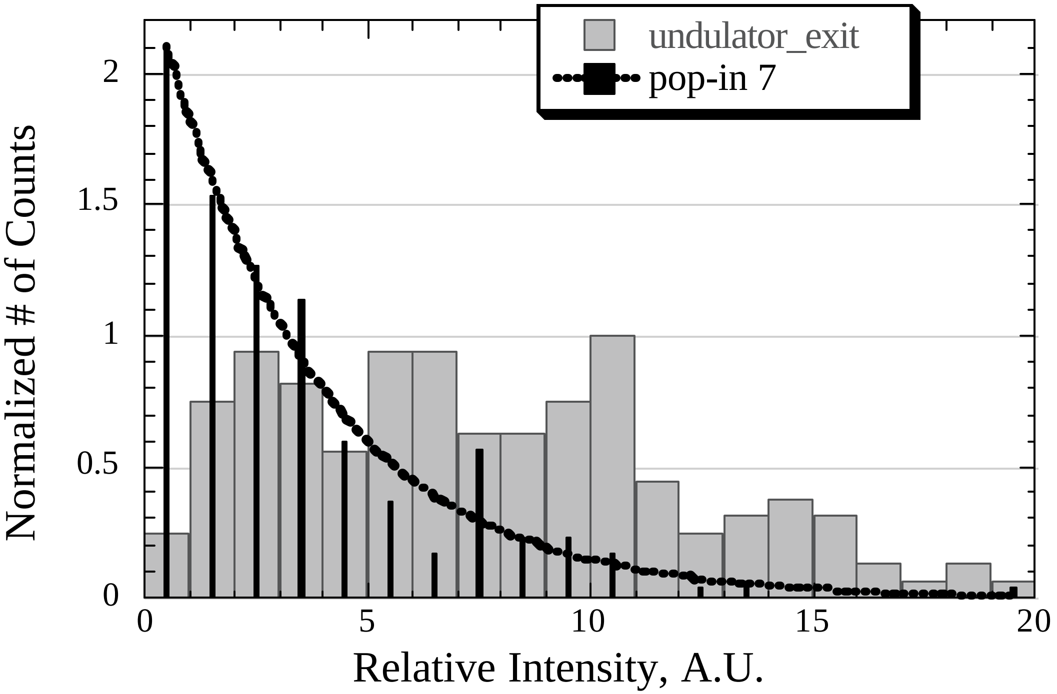


FEL intensity data:

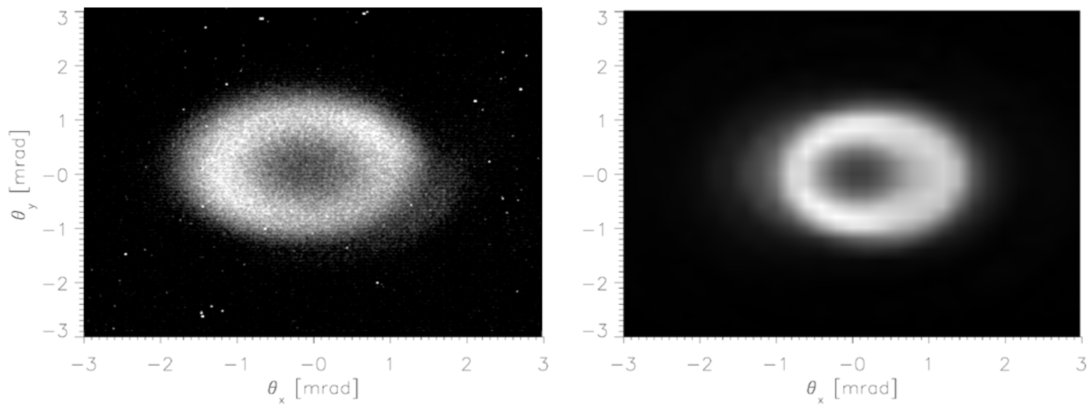
Statistical properties of the SASE signal

- Shot-to-shot measurements of the SASE-FEL intensity inside the undulator can be fitted with a negative exponential distribution associated with the single spike lasing, in agreement with the spectral measurements.

- At the end of the undulator the statistical distribution is different, with the mean value of the measured intensity much closer to the maximum of the distribution.

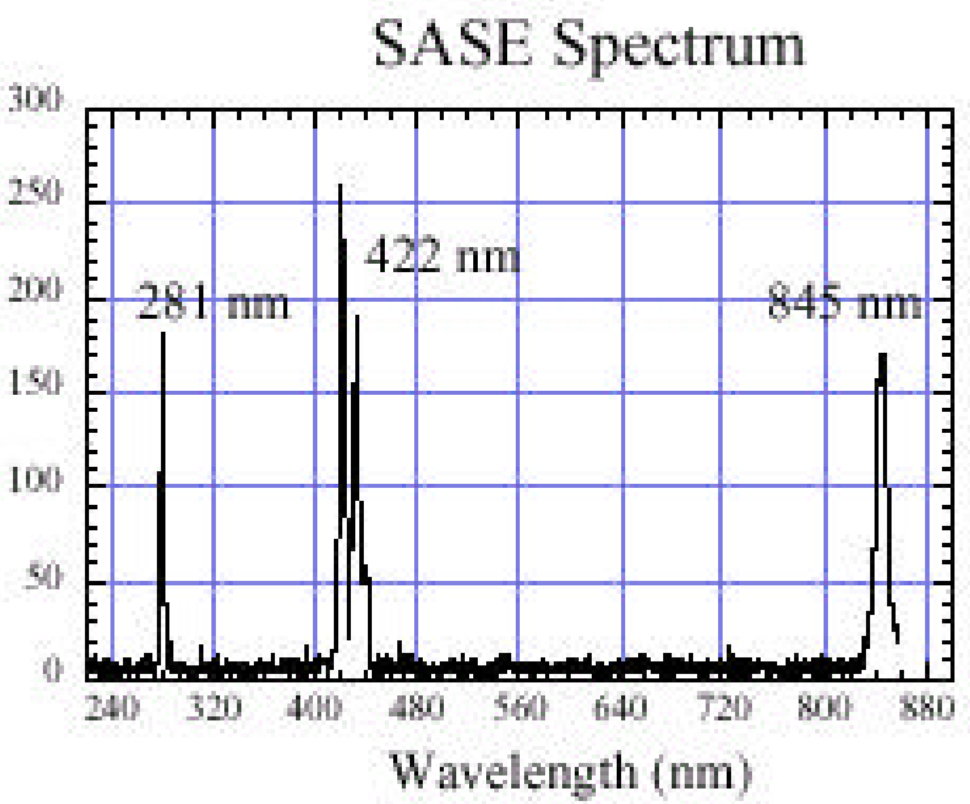


Measured and simulated angular distribution at saturation



Simulation done with Genesis use the Parmela-Elegant output.

Harmonic generation



Conclusions

1. VISA has reached saturation in less than 4 m using a compact, strong focusing undulator.
2. Strong harmonics have been measured, in agreement with expectations.
3. For the first time a start-to-end simulations with Parmela-Elegant-Genesis reproduces the bunch length, FEL intensity and spectral-angular measurements.
4. The separation of system and SASE intensity fluctuations has allowed for the first time to measure the statistical properties of a SASE-FEL at saturation.