Beam Physics and Light Source R&D at the APS

S. Milton

Mission Statement

- To provide accelerator physics expertise in order to insure that the APS continues to achieve and maintain excellence as a world-class synchrotron light source.
- To perform innovative research and development in the area of the physics of beams.

List of Recent Topics Investigated

Work by machine physicists within both ASD and AOD

- Machine Model Development
- Low-Emittance Lattice
- Top-up Issues
- Canted Insertion Devices
- X-ray BPM (Machine Distortions)
- Converging Beta Lattice
- Machine Impedance Modeling and Measurements
- Multibunch Instability Studies
- Single-Bunch Instability Studies
- High-Current Operation
- Electron Cloud Studies
- Orbit Stability Enhancement
- Sophisticated Operational Control Code Development
- Electron Gun Upgrades
- Self-Amplified Spontaneous Emission
- Smith-Purcell Radiation
- Small-Angle Thomson Scattering
- Longitudinal Dynamics for RIA
- CSR Effects on the Electron Beam
- Coupling Issues in Machines
- Transport Theory for Muon Colliders
- High-Brightness Electron Beam Generation
- Spallation Neutron Source

Focus on Two Examples

- APS Lattice Model Improvements
- The APS Free-Electron Laser

APS Lattice Model Improvements

Work primarily done by V. Sajaev

Motivation

- From the beginning of the APS storage ring operation there was a significant difference between the model and the real storage ring.
- This is merely a fact that the APS storage ring is a complicated machine containing 400 quadrupoles and 280 sextupoles and 80 dipoles, and each individually powered focusing element can be a source of errors.
- All together, small perturbations significantly change the linear optics and can seriously affect the performance of the storage ring.
- The difference presents difficulties when tuning the machine to new lattices such as the low-emittance or converging β-function lattices.
- The development of an accurate model presents a significnat challenge for such a complicated machine.
- It was decided, nevertheless, to meet the challenge and develop a method for fast linear lattice calibration using orbit response matrix measurements.

Response Matrix Measurement and Fitting*

- The response matrix is defined by the linear lattice of the machine and, therefore, can be used to calibrate the linear optics in a storage ring.
- Modern storage rings have a big number of steering magnets and precise BPMs, so measurements of the response matrix provides a very large array of precisely measured data.
- The main idea of the analysis is to adjust the quadrupole gradients of a computer model of the storage ring until the model response matrix best fits the measured response matrix.
- This has been applied successfully on smaller machines…however...

* The method was first suggested by Corbett, Lee and Ziemann at SLAC and refined by Safranek at BNL. A very careful analysis of response matrix was done at NSLS X-ray ring and at ALS. Similar method was used at ESRF for characterization and correction of the linear coupling and to calibrate quadrupoles by families.

Challenges

Shear Size of the Model.

NSLS X-ray ring:	626 parameters used to fit 8,640 elements
ALS:	500 parameters used to fit 15,744 elements
APS (the entire ring):	2,240 parameters and about 560,000 elements
APS (used):	1,200 parameters used to fit 28,800 elements

Note:

- X-ray ring and ALS are able to store the beam without sextupoles. This is not possible in the APS.

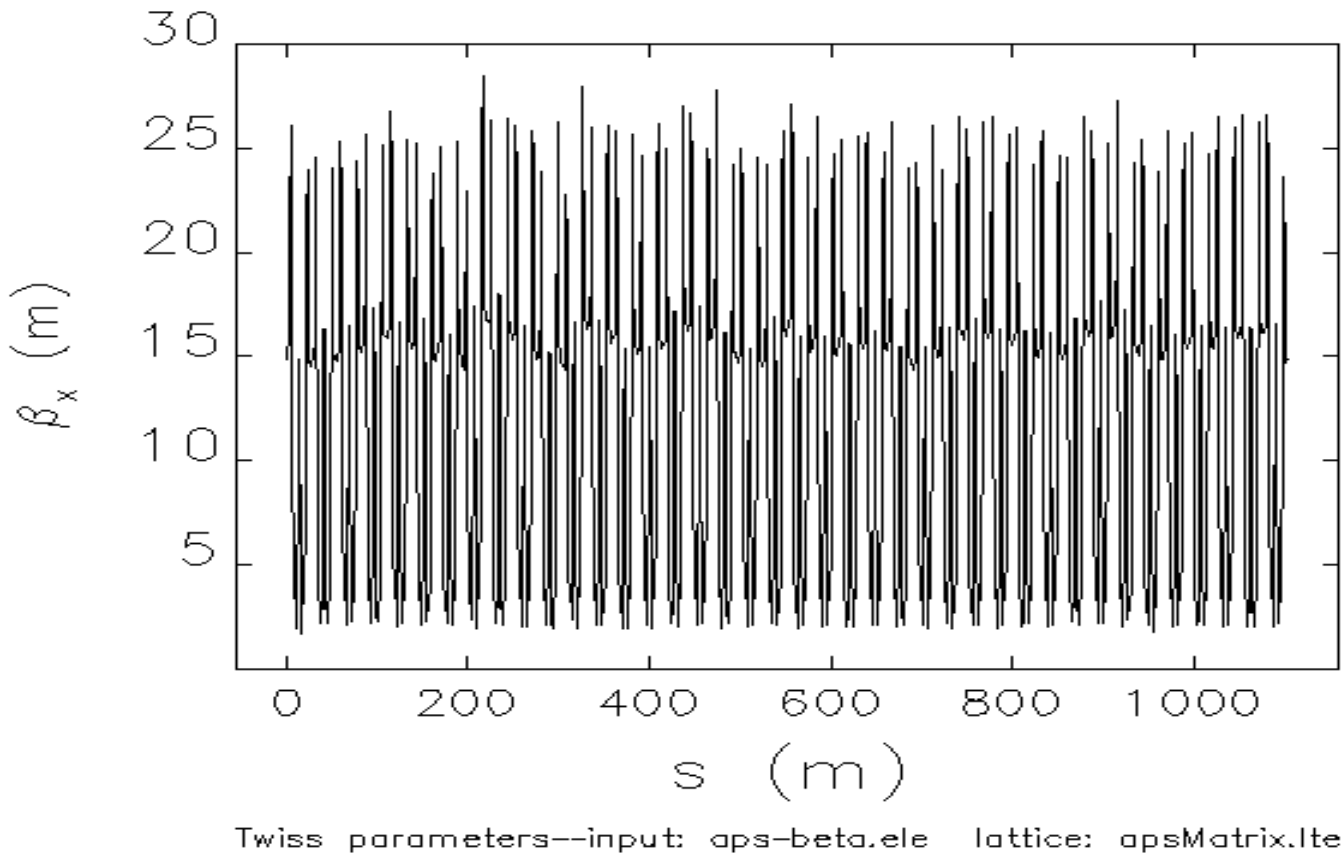
Also Note the Degeneracy of the Model

- average betatron phase advance per one quadrupole:

APS -	0.088
X-ray ring -	0.17
ALS -	0.28

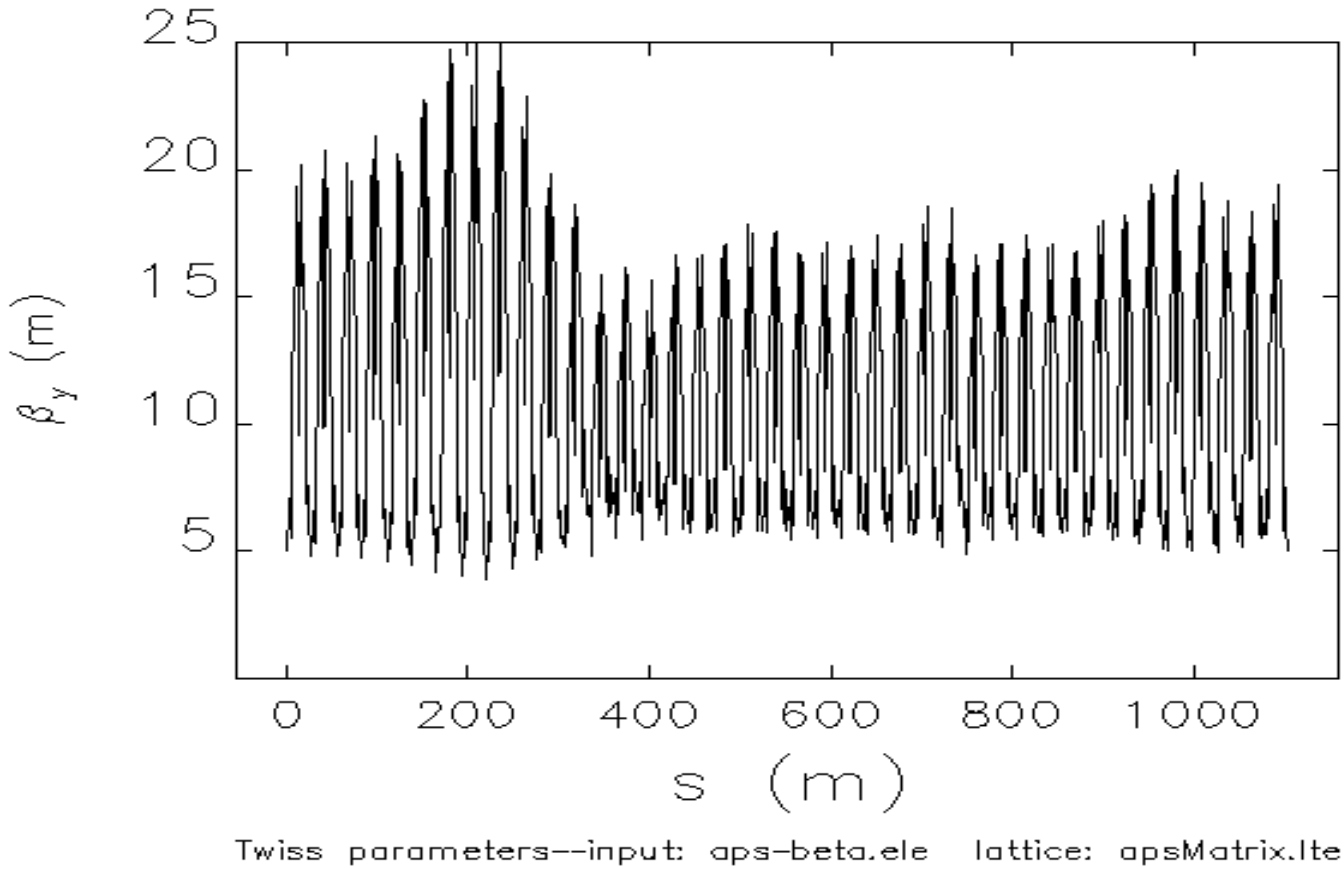
Standard user lattice β-functions

Calculated horizontal β-function using calibrated model.



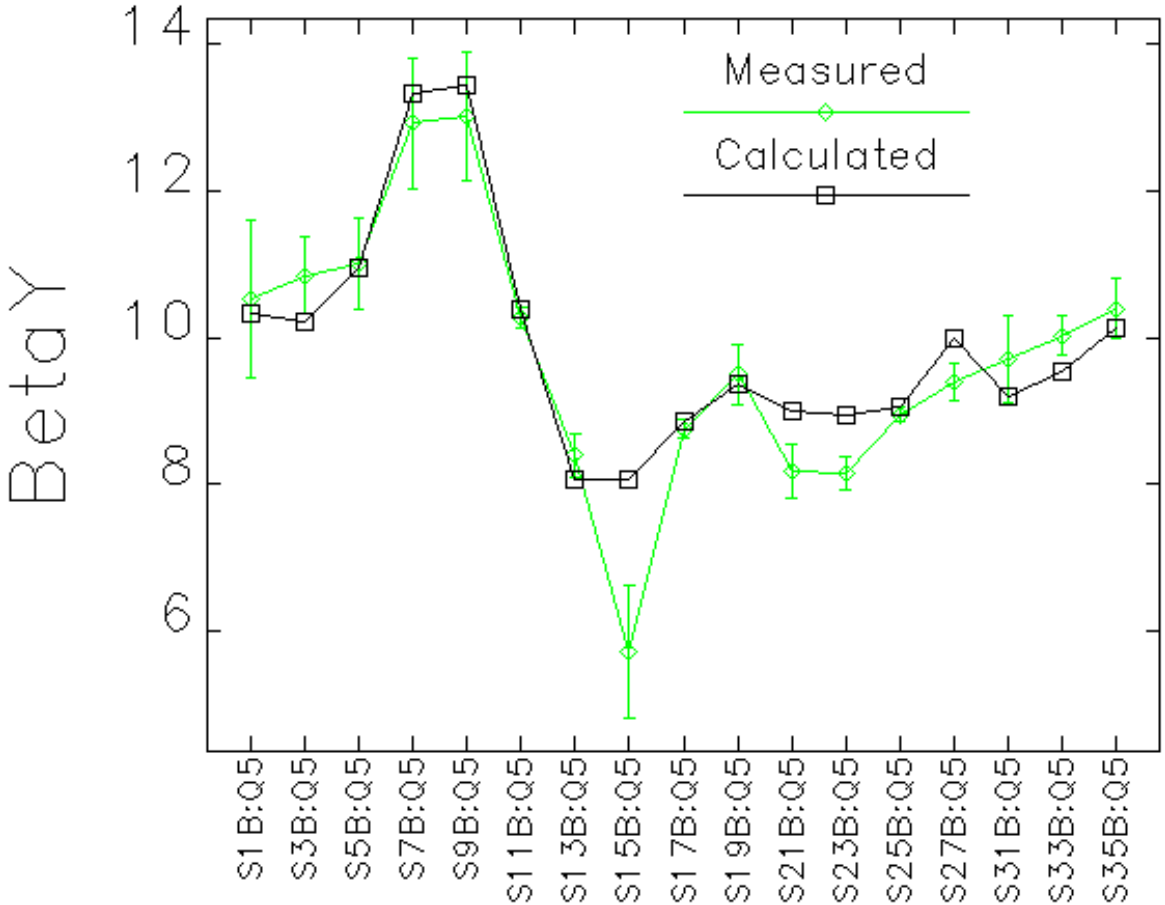
Standard user lattice β-functions

Calculated vertical β-function using the calibrated model.



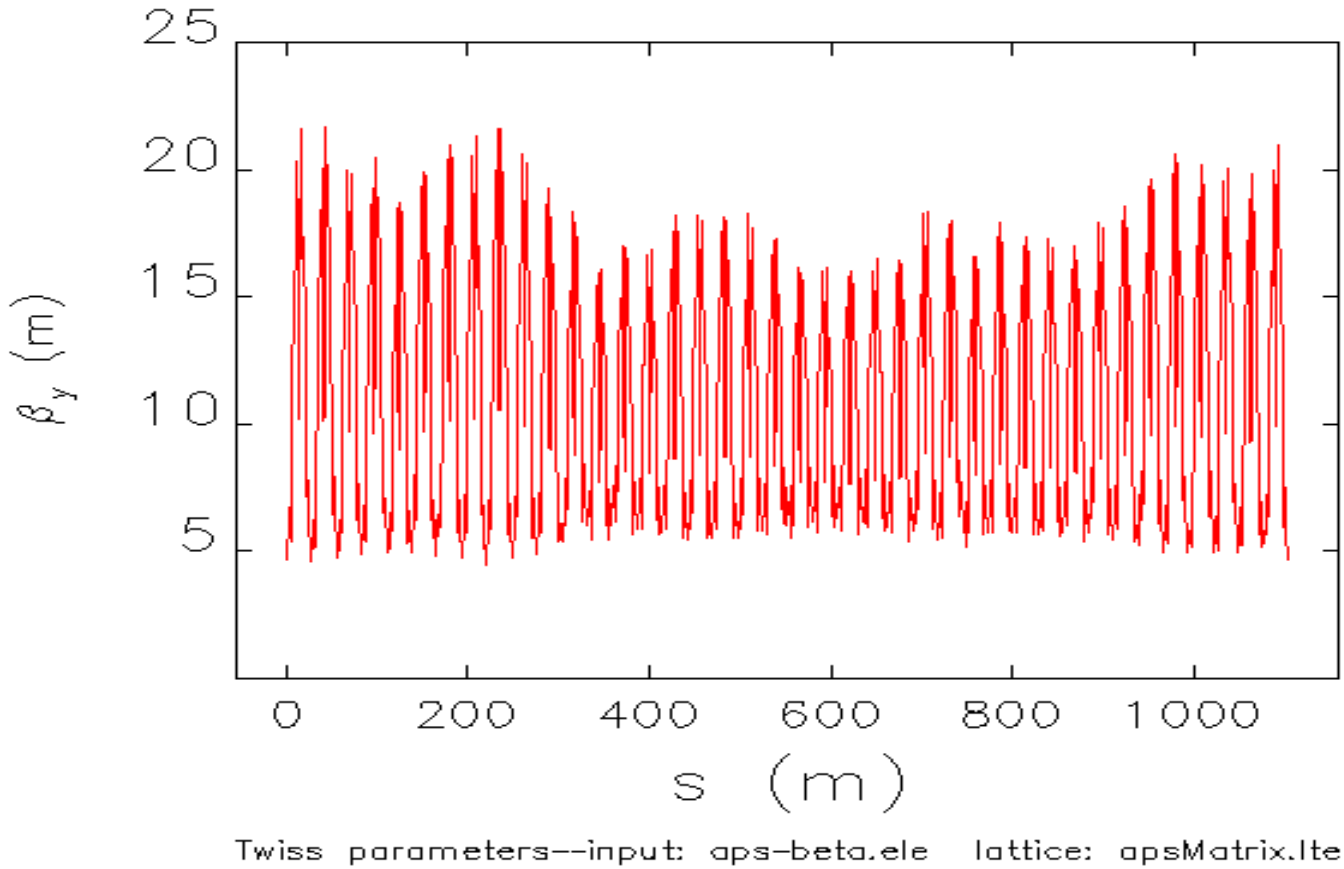
Standard User Lattice β-functions

Calculated and measured vertical β-functions at some Q5 locations:



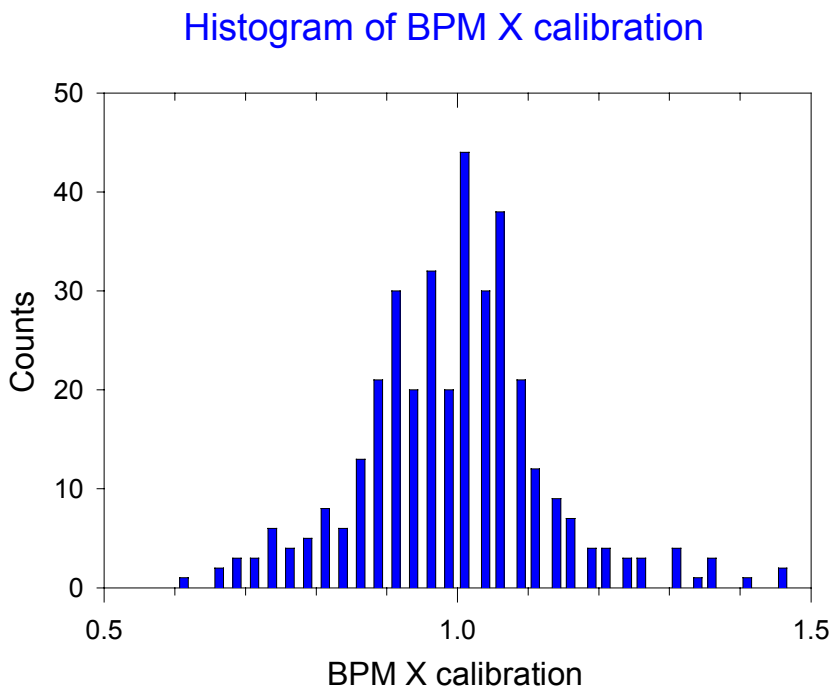
Preliminary correction

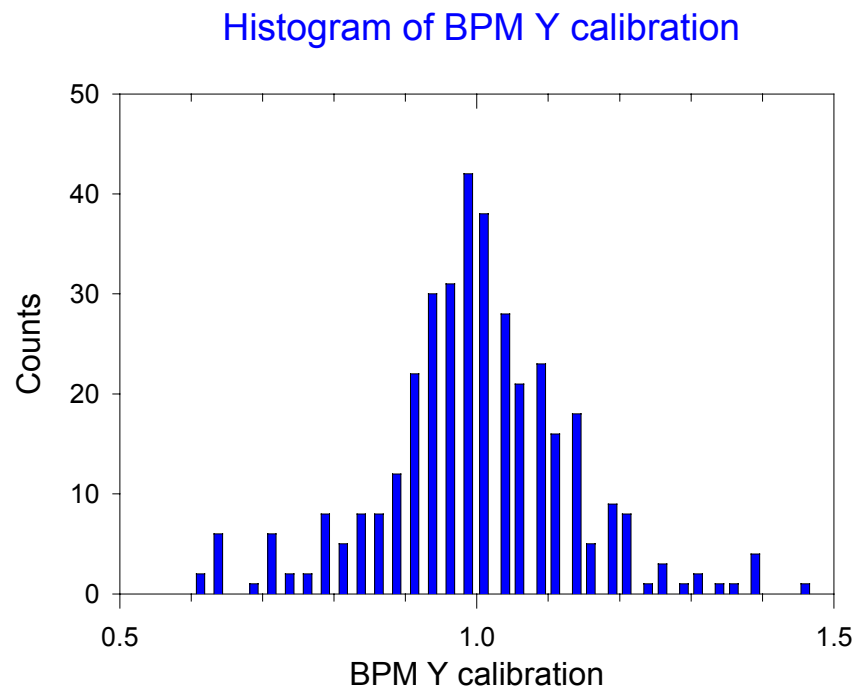
Preliminary correction using only a few singular values has been attempted. Its effect on the machine was in perfect agreement with prediction.



BPM calibration

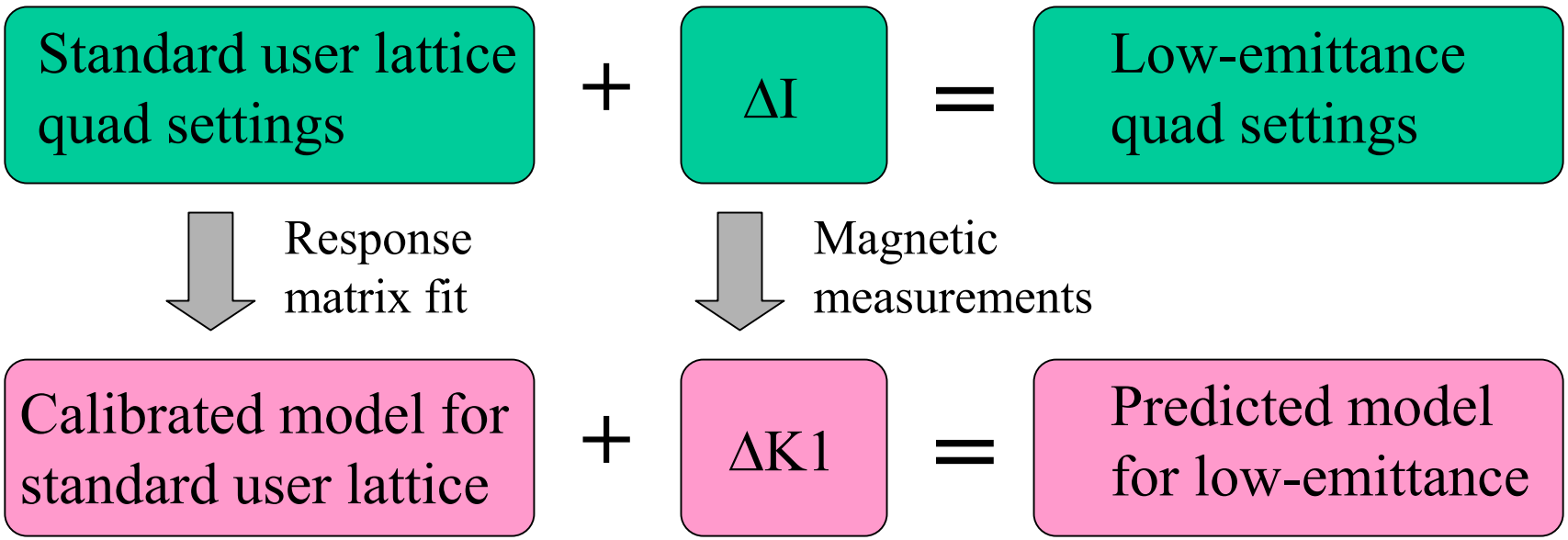
As an added benefit the method provides a simultaneous calibration of all the storage ring BPMs





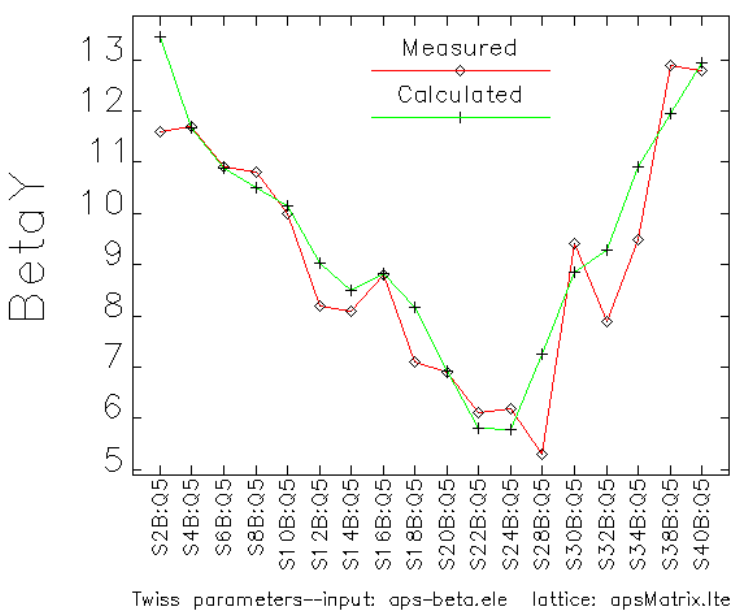
Low-emittance lattice β-functions

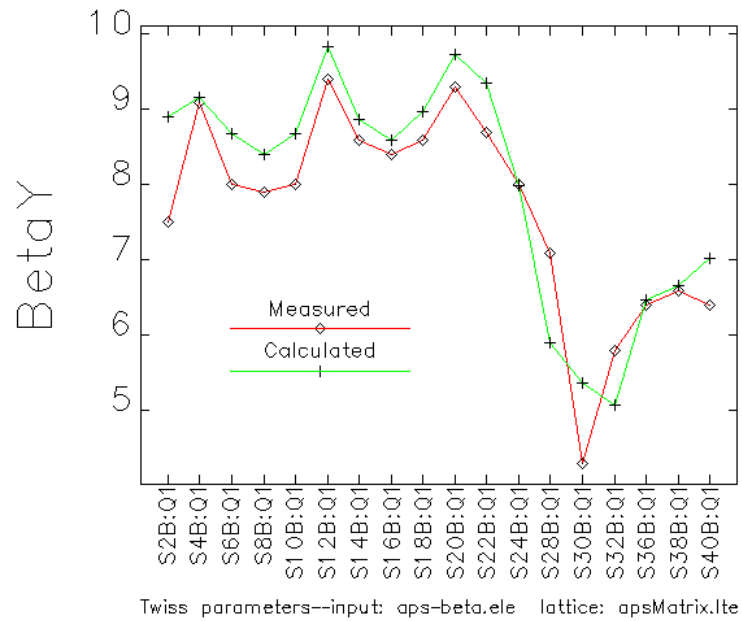
The response matrix of the low-emittance lattice has not yet been measured. However, one can use the calibrated standard user lattice model for prediction of the β-function perturbation in the low-emittance lattice.



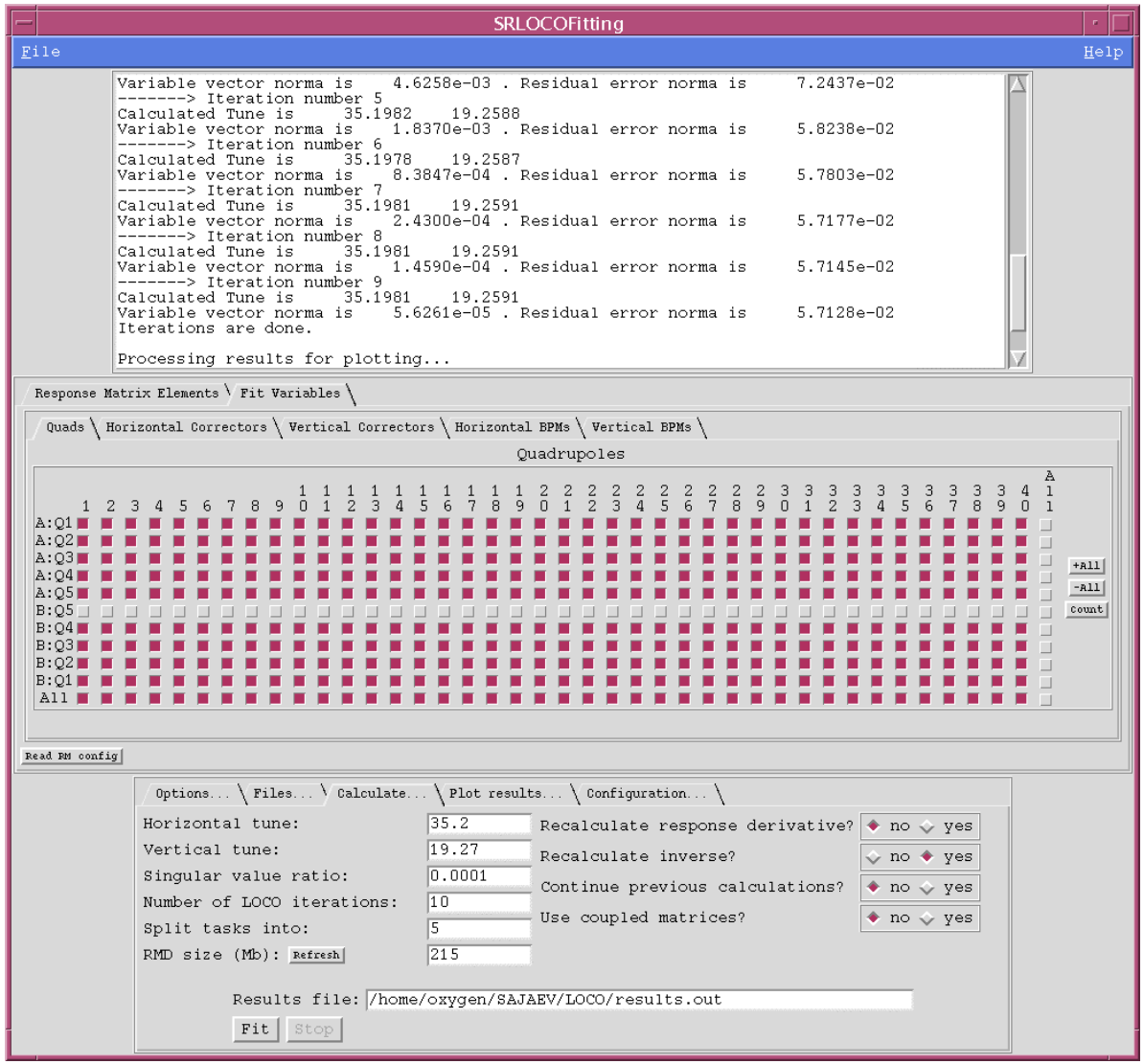
Low-emittance lattice β-functions

Vertical β-functions measured by conventional quad-scan method and predicted ones at some Q5s (left) and Q1s (right)





Mature TCL/TK Interface



- A sophisticated interface has been developed for the project.
- This is common among many of the complex beam physics studies and also among day-to-day operational tasks.

Conclusion to this Section

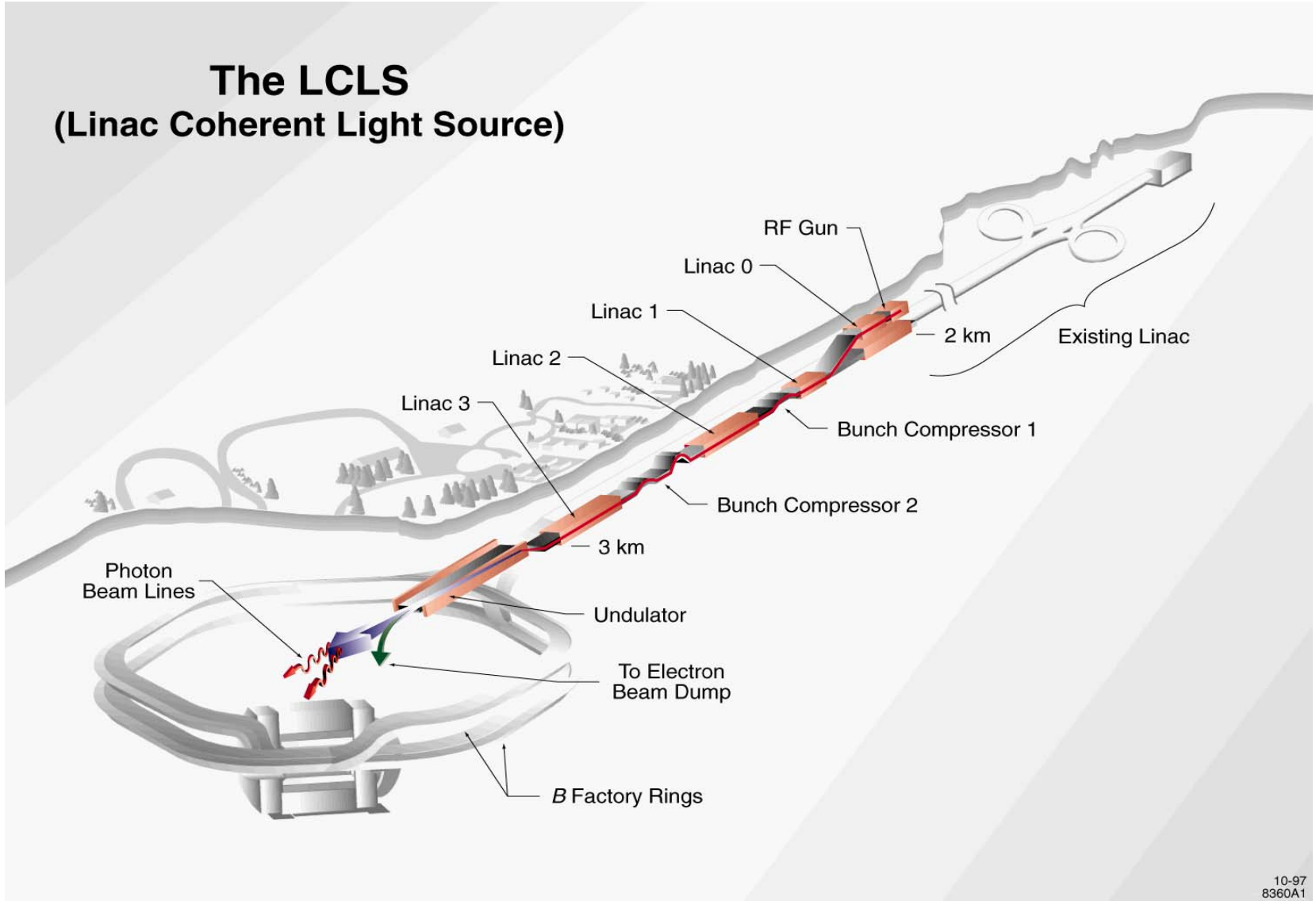
A precise model of the standard user lattice has been created.

Future Plans Using the Improved Model

- Further verification of the created model
- Global and local linear coupling characterization and correction/control
- Use the precise linear model to better understand nonlinear features of the ring

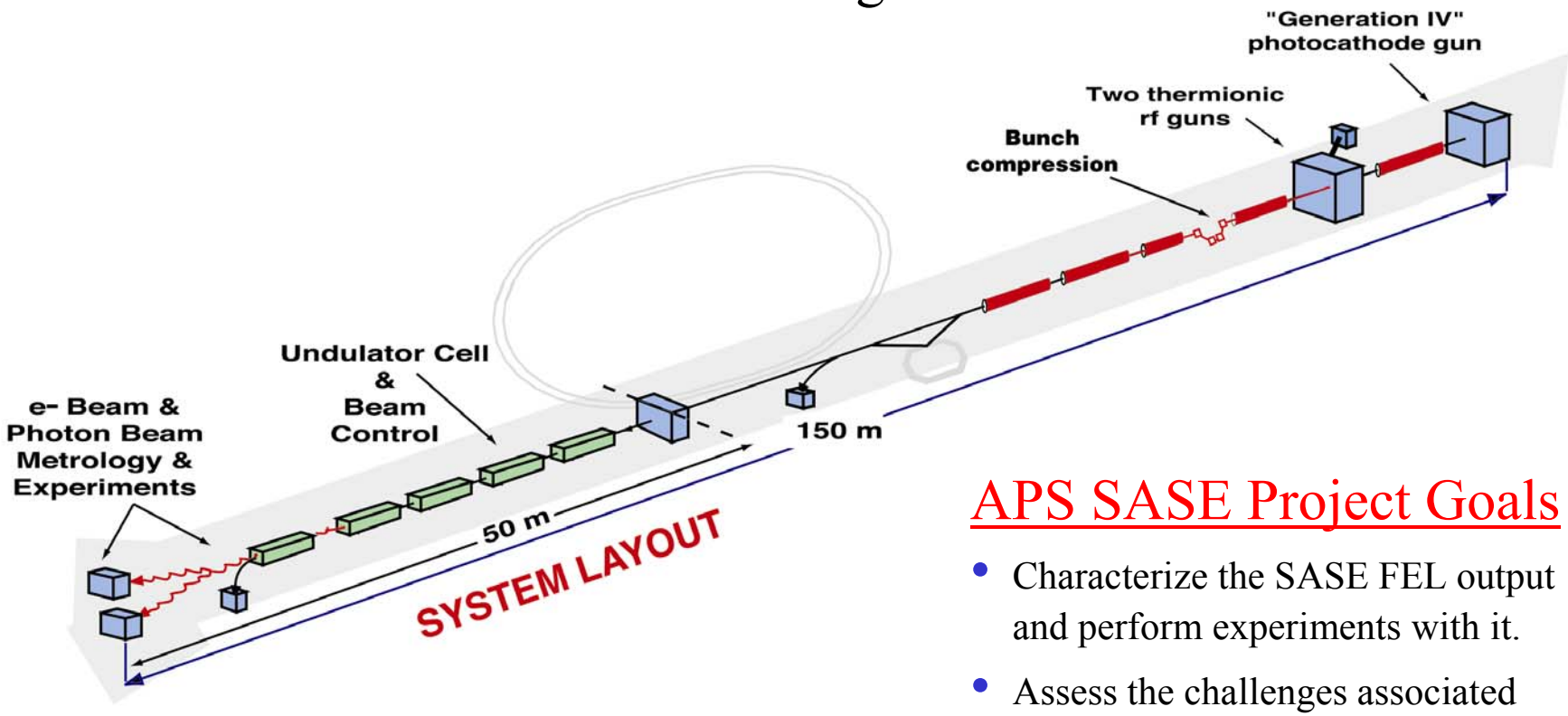
The APS FEL

Prototype for the Next Generation



The APS SASE FEL Schematic

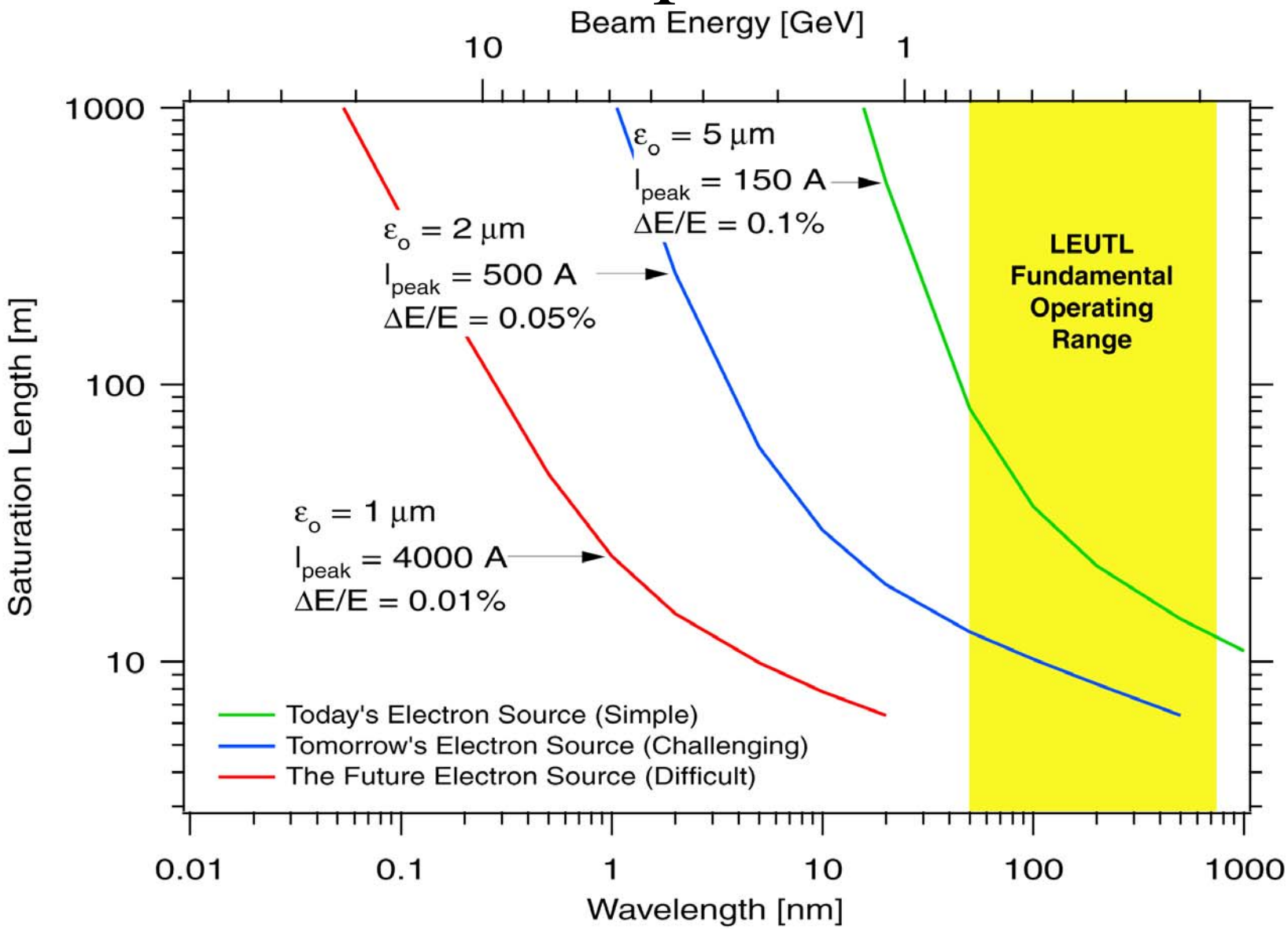
The Low-Energy Undulator Test Line System
Present Configuration



APS SASE Project Goals

- Characterize the SASE FEL output and perform experiments with it.
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine.

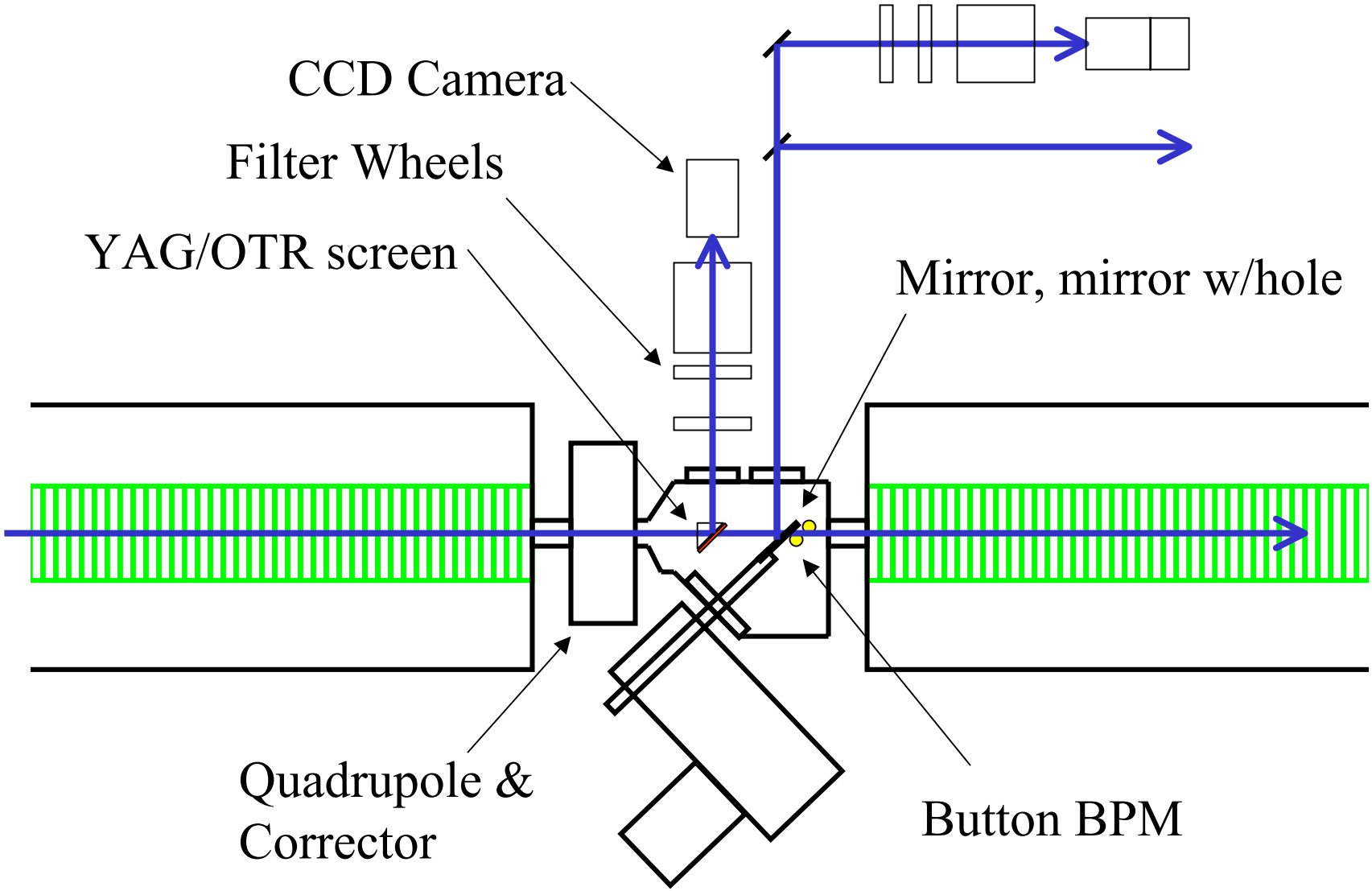
Beam Requirements



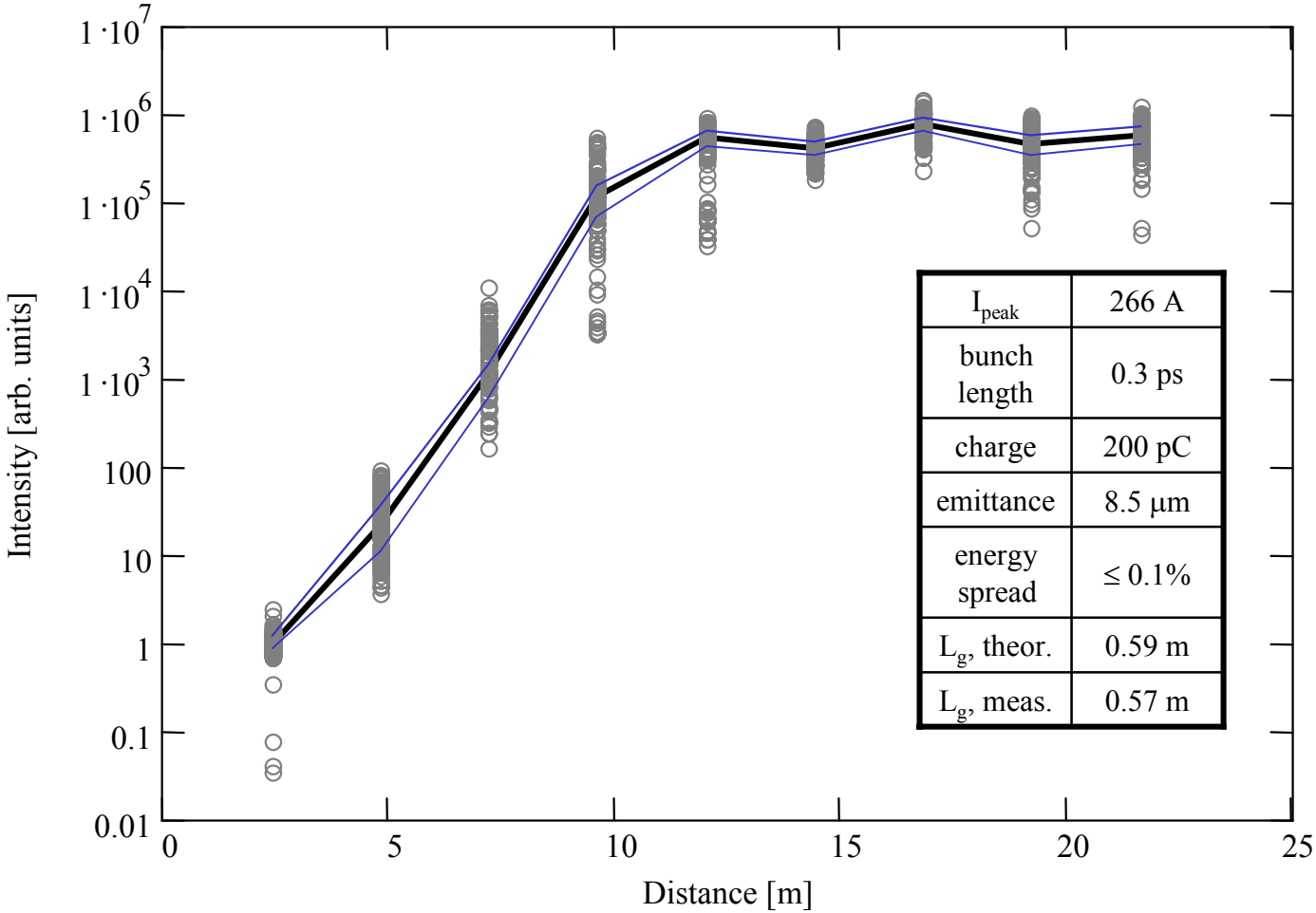
Basic Parameters for the APS FEL

PARAMETERS			
Wavelength [nm]	Regime 1 530	Regime 2 120	Regime 3 51
Electron Energy [MeV]	217	457	700
Normalized rms Emittance (π mm-mrad)	5	3	3
Energy Spread [%]	0.1	0.1	0.1
Peak Current [A]	100	300	500
Undulator Period [mm]	33		
Magnetic Field [T]	1.0		
Undulator Gap [mm]	9.3		
Cell Length [m]	2.73		
Gain Length [m]	0.81	0.72	1.2
Undulator Length [m]	5 x 2.4 then 9 x 2.4	9 x 2.4	10 x 2.4

Undulator Line Diagnostics

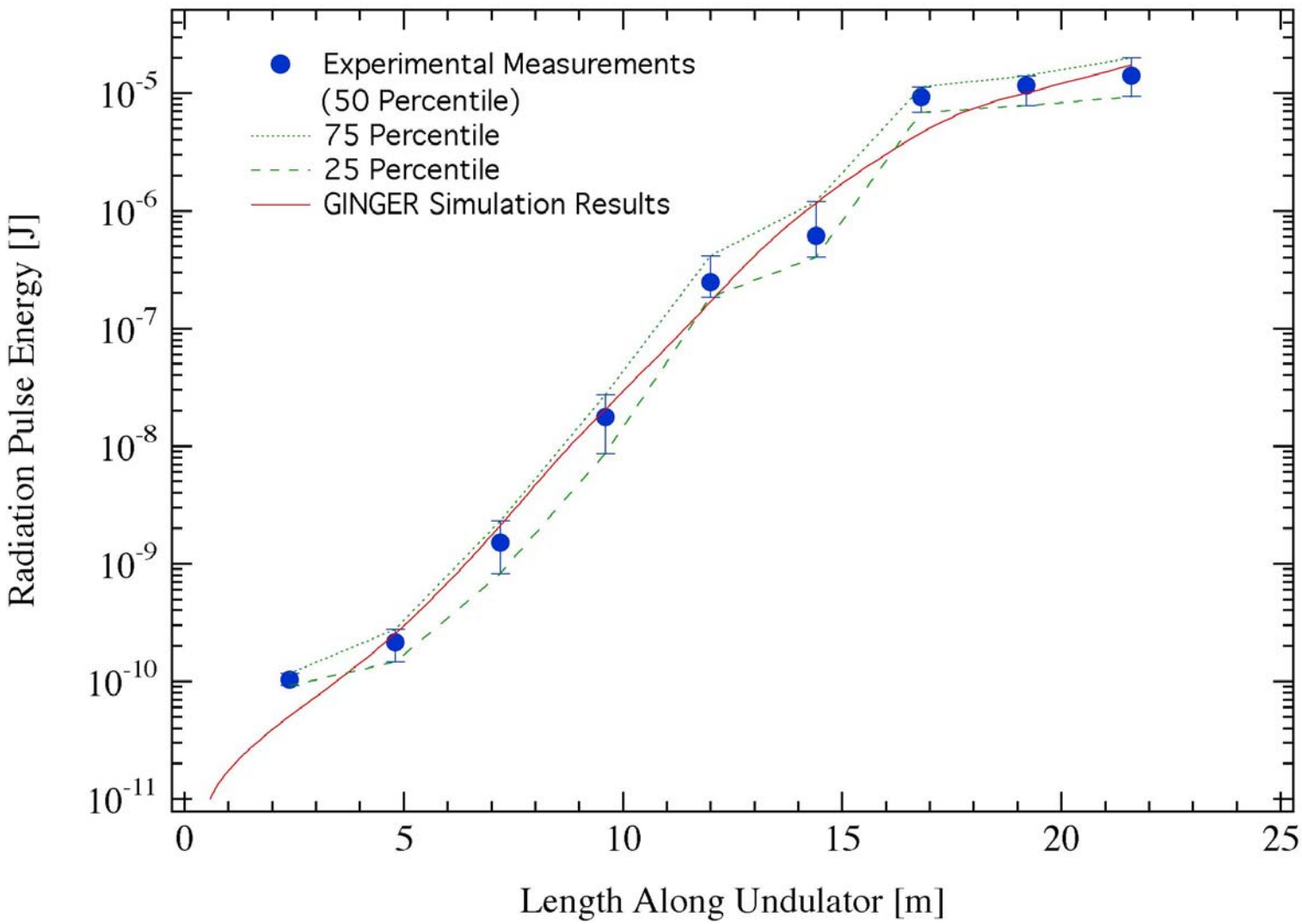


Optical Intensity vs. Distance: Gain

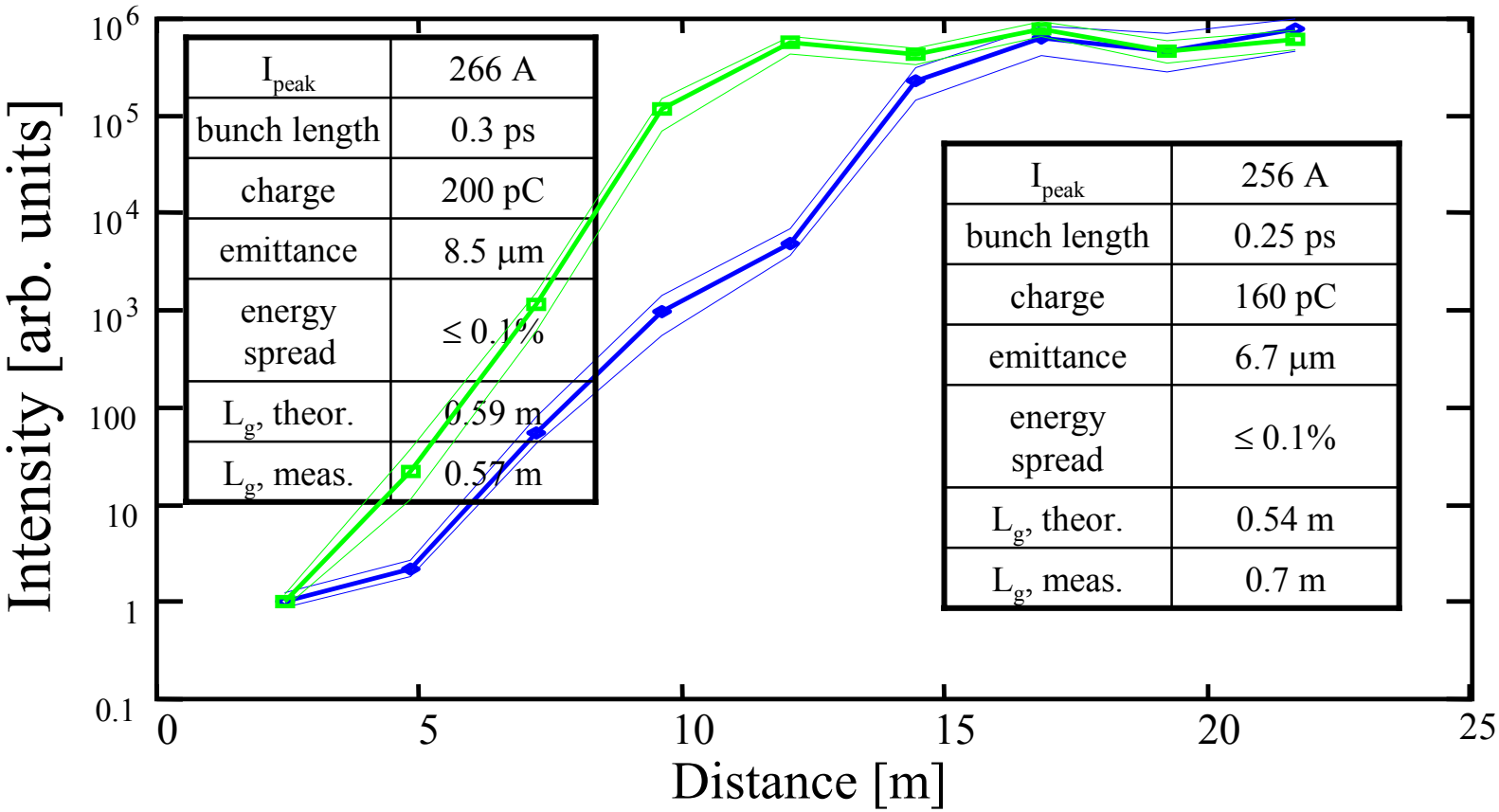


I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 μm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

Absolute Energy vs. Distance



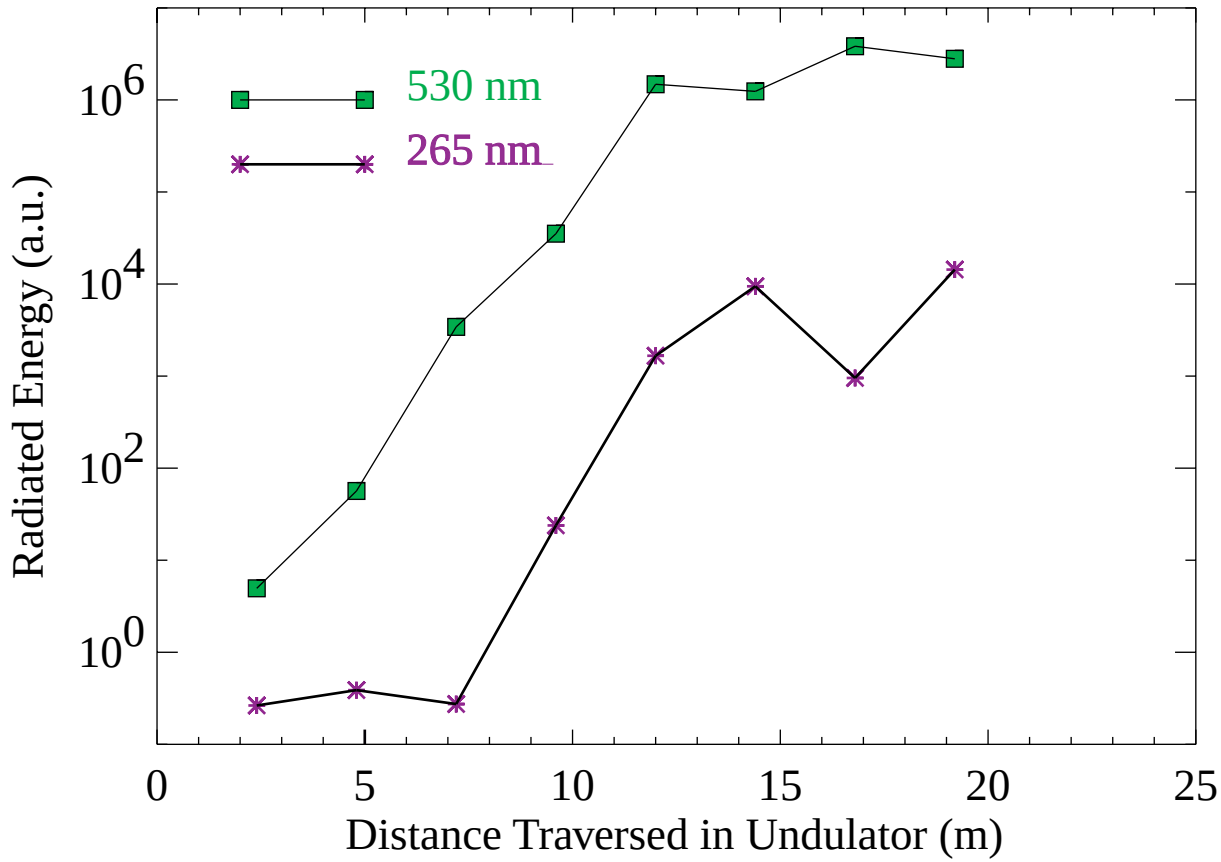
Trajectory & Matching Effects



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 µm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

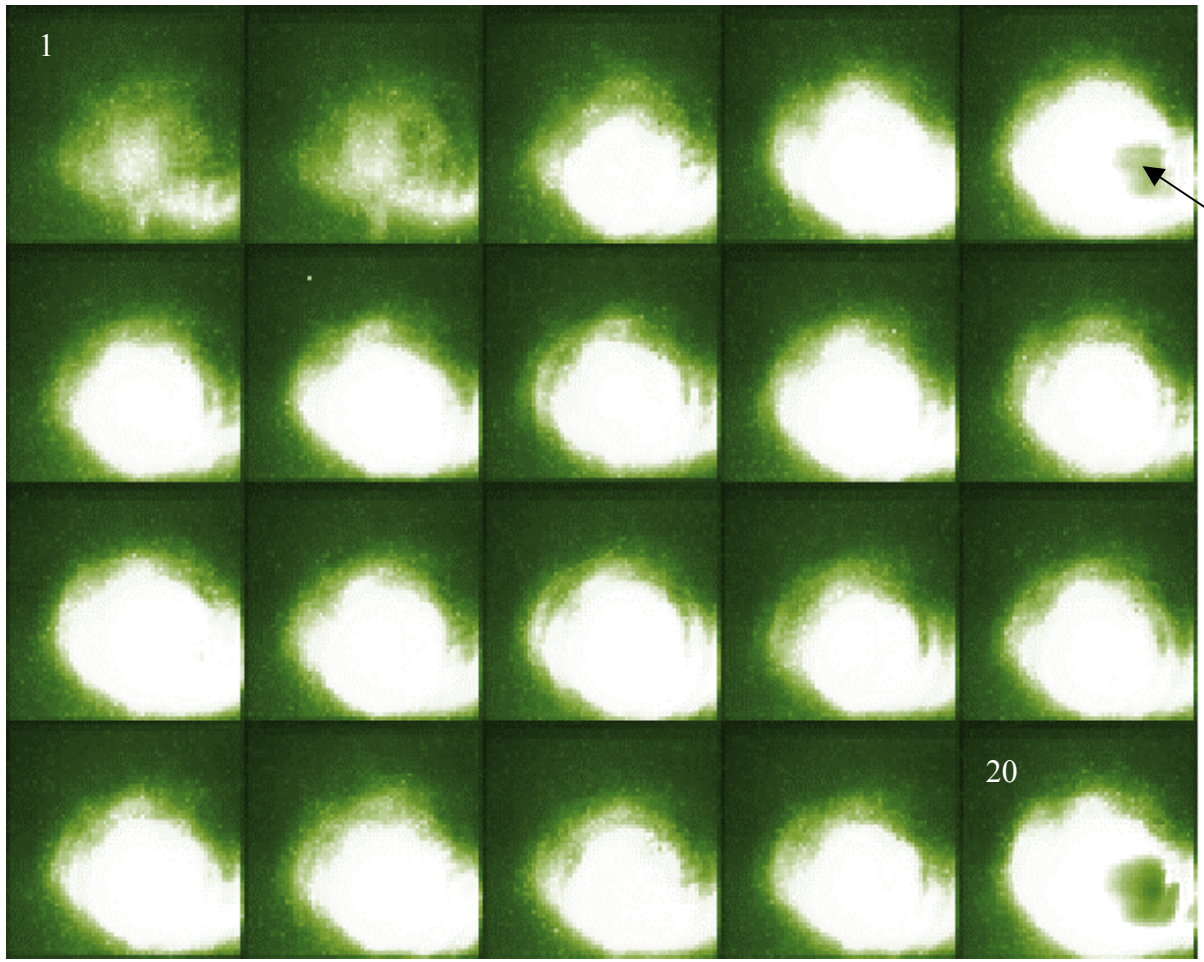
I_{peak}	256 A
bunch length	0.25 ps
charge	160 pC
emittance	6.7 µm
energy spread	≤ 0.1%
L_g, theor.	0.54 m
L_g, meas.	0.7 m

Harmonics vs. Distance



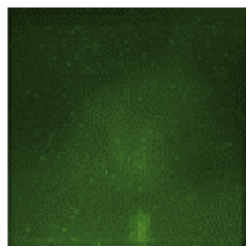
First SASE Gain at 120 nm

Sequential Images of 120 nm SASE Signal

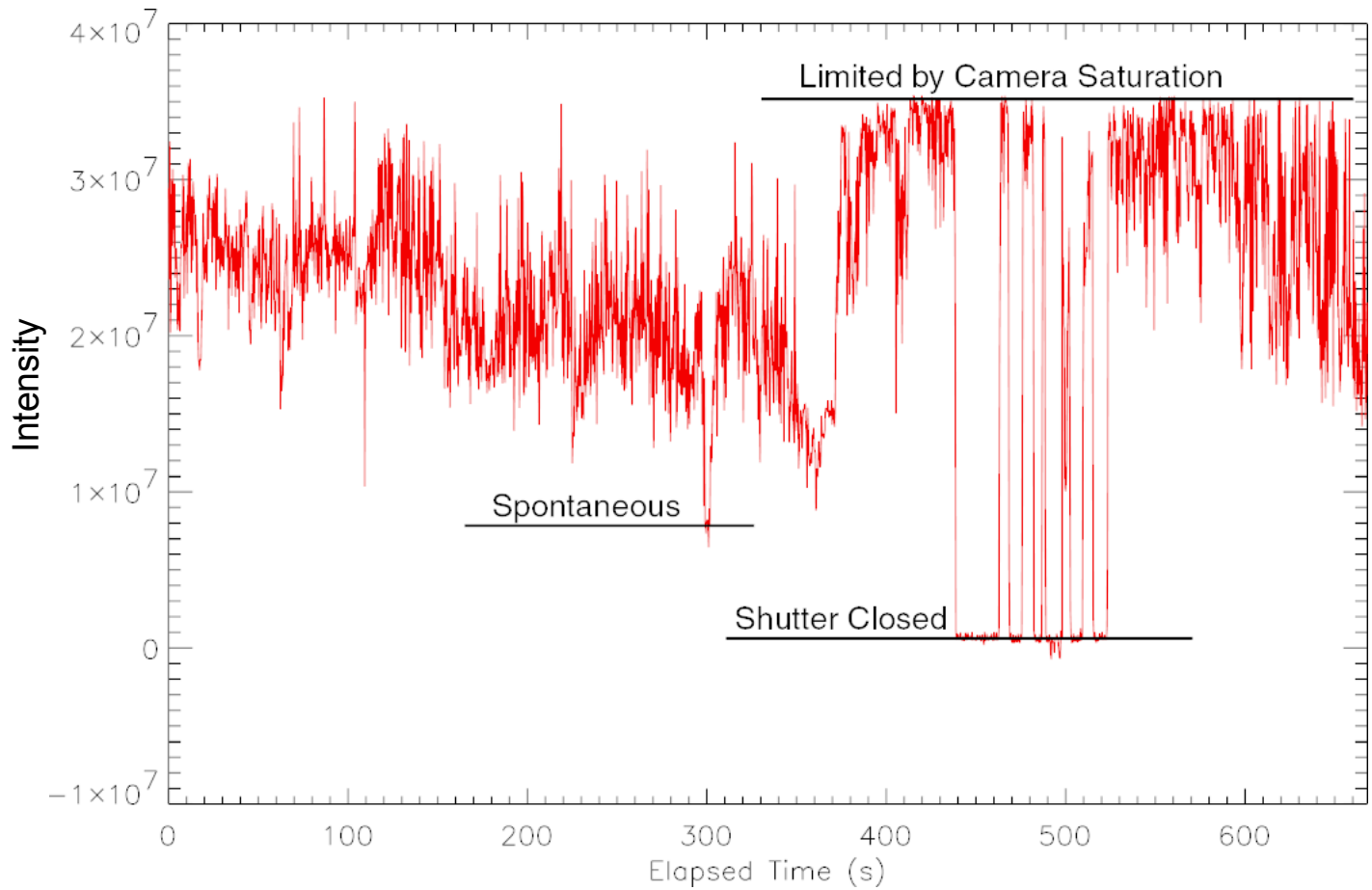


- Charge and other beam parameters constant. Only steering varied.
- "Burn" hole due to extreme saturation of the CCD detector.
- Inherent fluctuations not clearly visible due to saturated CCD.

Spontaneous Signal



120 nm Intensity vs. Time

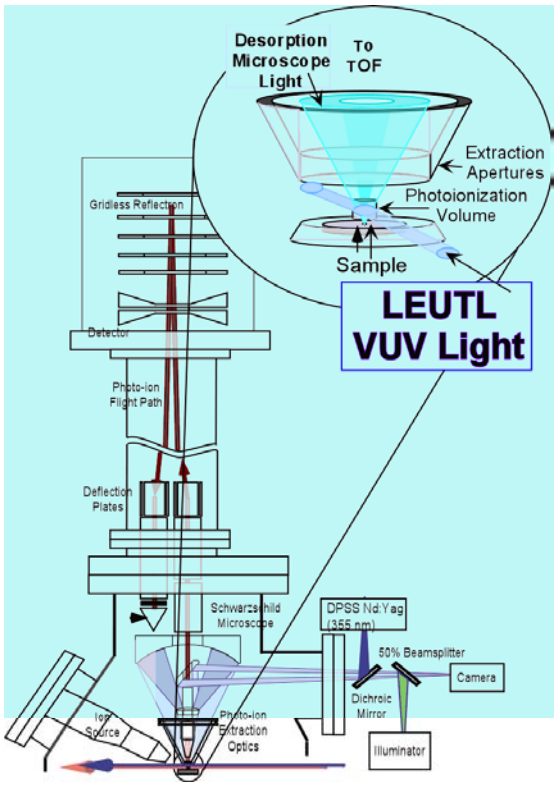


- Dynamic range severely limited by dark current and binning of pixels.
- Will cool camera in future runs and limit repetition rates.
- Background subtraction performed.

The First APS FEL Experiment

Single Photon Ionization / Resonant Ionization to Threshold (SPIRIT)

M. Pellin MSD/ANL



Coming 2002

SPIRIT will use the high VUV pulse energy from LEUTL to uniquely study –

- **Trace quantities of light elements**:
  H, C, N, O in semiconductors with
  100 times lower detection limit
- **Organic molecules <u>with minimal</u> <u>fragmentation</u>**
  cell mapping by mass becomes feasible
  polymer surfaces
  modified (carcinogenic) DNA
  photoionization thresholds
- **Excited states of molecules**
  cold wall desorption in accelerators
  sputtering of clusters

Future Upgrade

- Interleaving Operations For Top-up
- Shorter Wavelengths
- Complete VUV Optics Upgrade
- First Pioneering Experiment
- Beam Energy Upgrade (4 additional accelerating structures)
- 2nd-Generation SASE Devices
  - RAFEL
  - Self-Seeding
  - “After burner”
  - ……?

Summary

- The APS Beam Physicists continue to pursue subjects that will result in a clear and quantifiable improvement in the APS storage ring performance.
  - The example given was the continuing development of a detailed and accurate machine model.
- They are also studying topics important to the development of the next generation light sources and are considered a leader in the world in this technology.
  - The APS SASE-Based FEL is one of only two systems in the world capable of sustained studies in this important area.

(Cont.) Summary

- There exists an active and healthy R&D program in the area of the Physics of Beams and Light Sources Technologies.
- APS continues to be viewed as an attractive place to do significant R&D in both accelerator and the Physics of Beams.