NANOMETER BEAM GENERATION AND MEASUREMENTS IN KEK-ATF2

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(On behalf of ATF2 collaboration)
NAPAC, Oct 1 2013

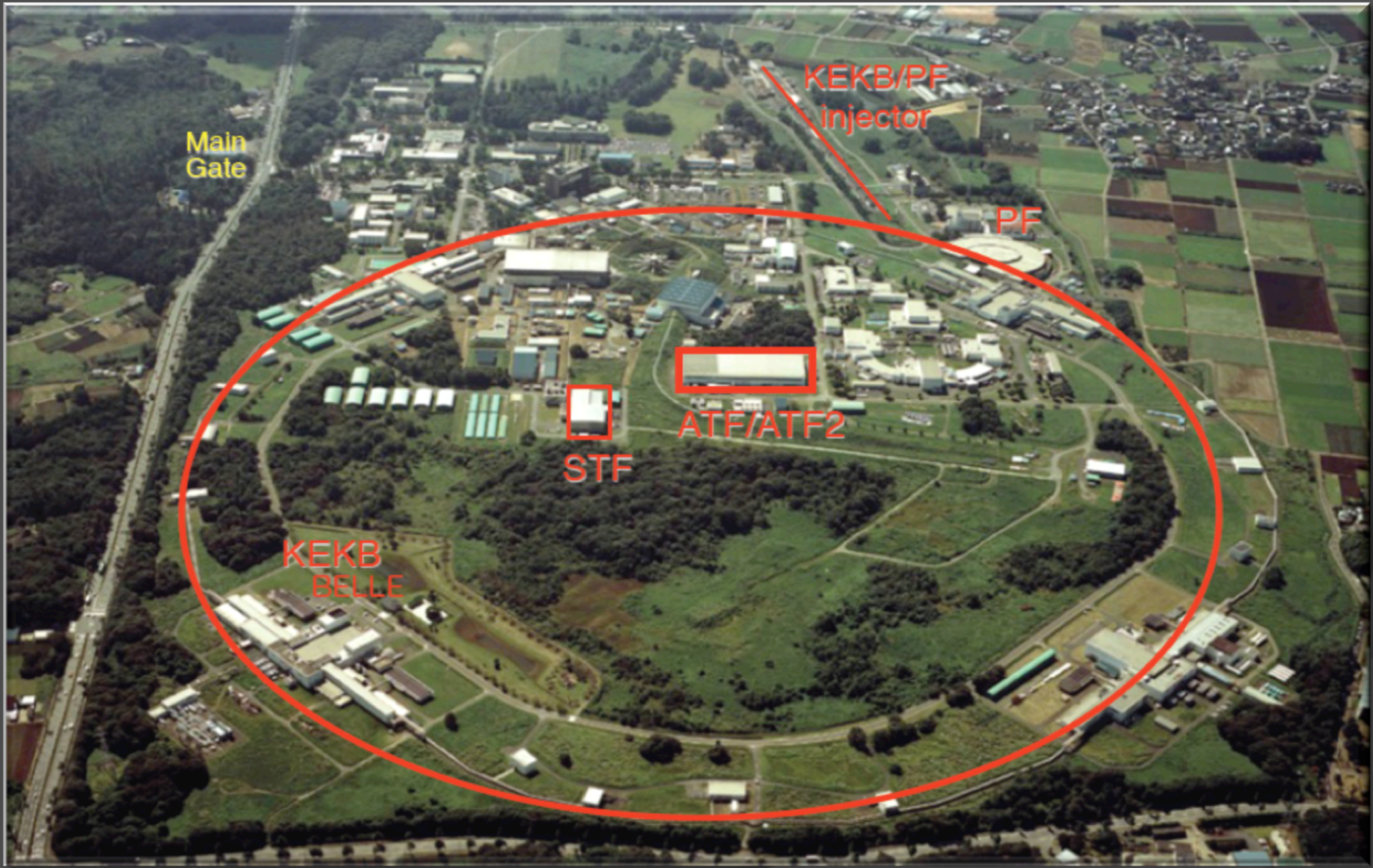
Overview

- The ATF2 test facility
  - Overview of facility and its goals
- Current status of main experimental program
  - Outline of current status, looking towards FFS program at ILC
- The future of the ATF2 program.

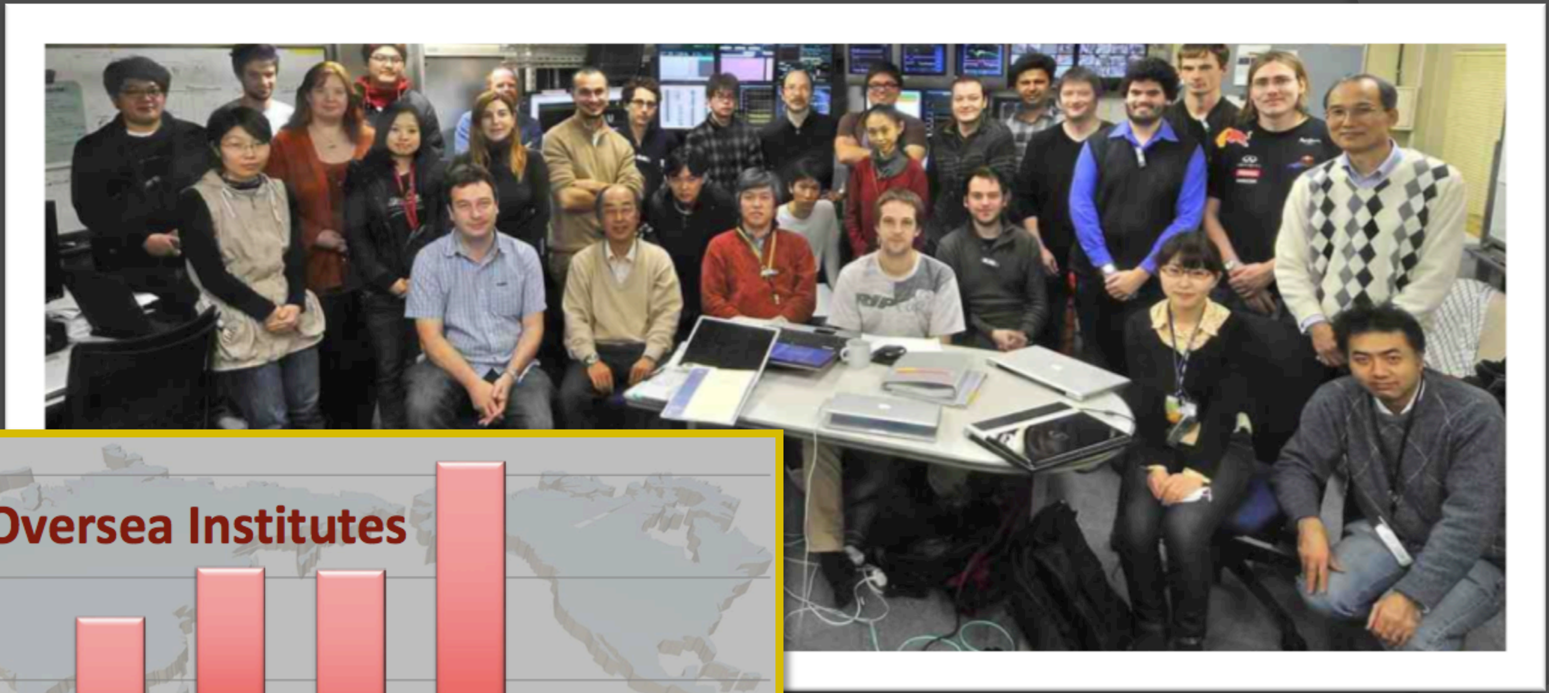
ATF2 Project Goals

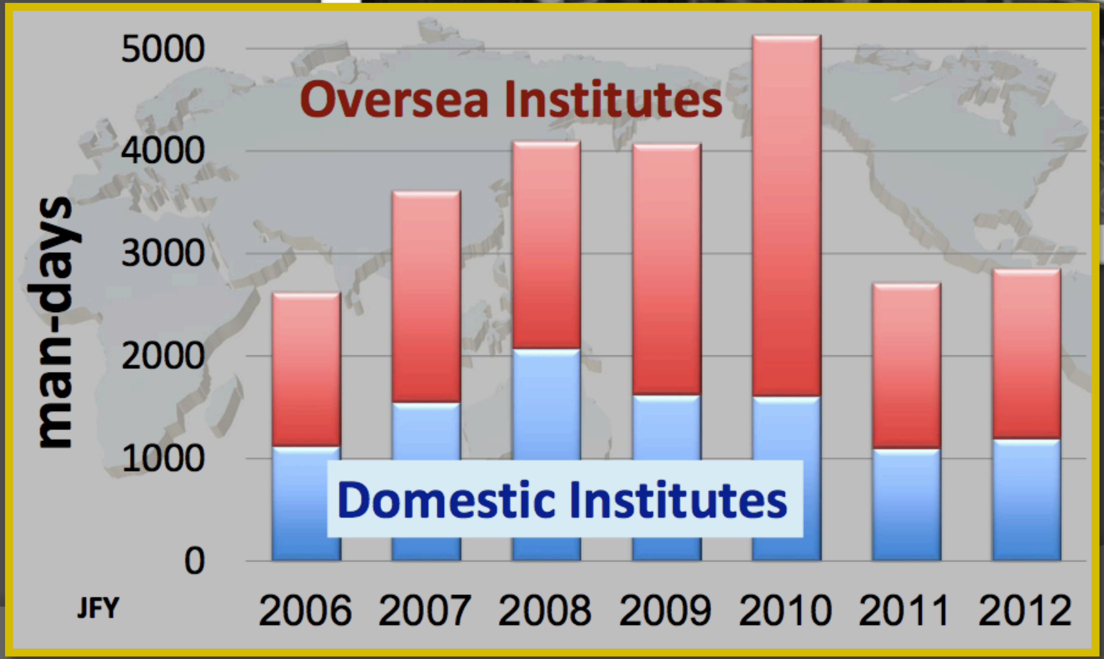
- Experimental verification of the ILC FFS scheme
  - Development of beam tuning procedures and demonstration of operability of "local" chromaticity correction optics
  - Maintain IP vertical position with few-nm precision (multi-bunch) Demonstrate long-term beam size stability Understand tune-ability as a function of chromaticity
  - Understand limits of focusing capabilities of this optics design
- Development of ILC instrumentation
  - BPMs, movers, MHz feedback, 1-um Laserwire, straightness-monitor, OTRs, wirescanners, HA-PS, fast pulser, beam tilt-meter …
- Education of young generation for future linear colliders
  - Active participation of graduate students and post-docs
- Operation of complex accelerator in an international setting with in-kind hardware contributions and joint efforts on commissioning & operation

ATF2 @ KEK



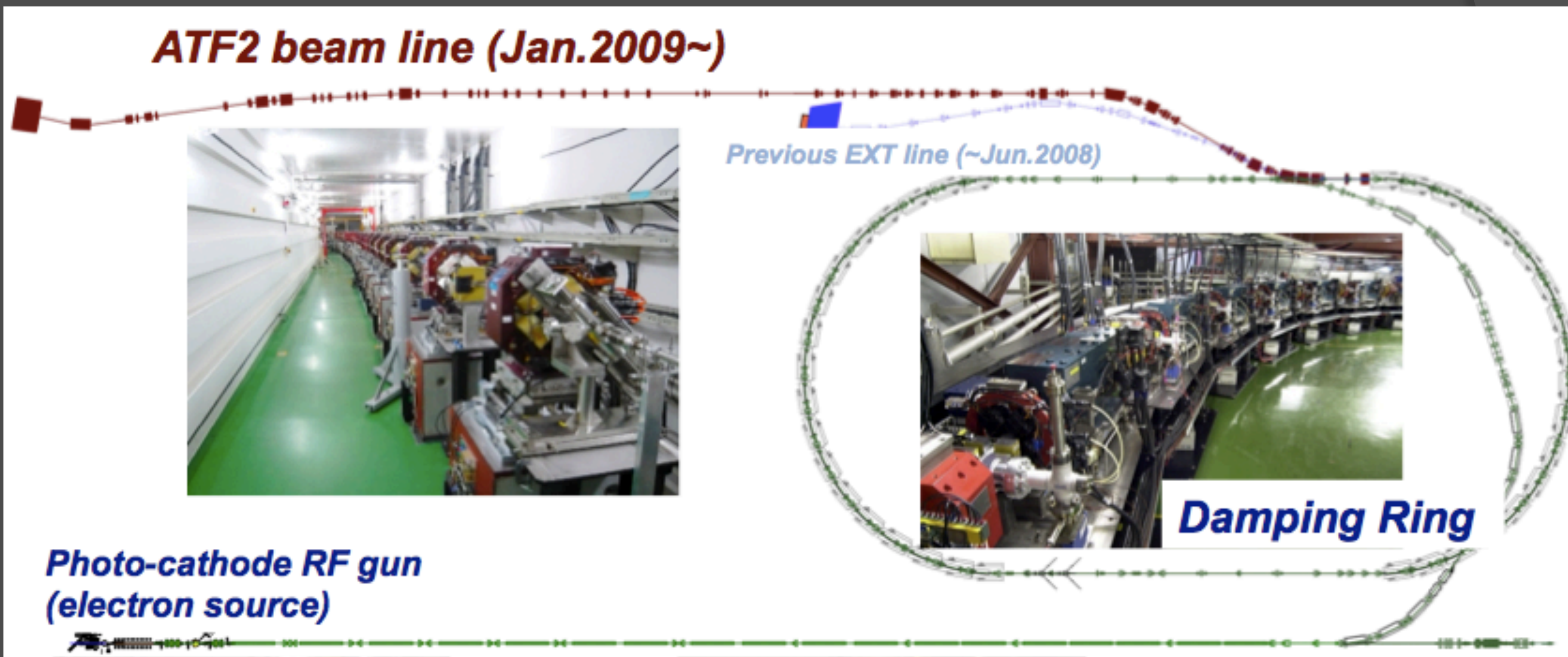
International Collaboration



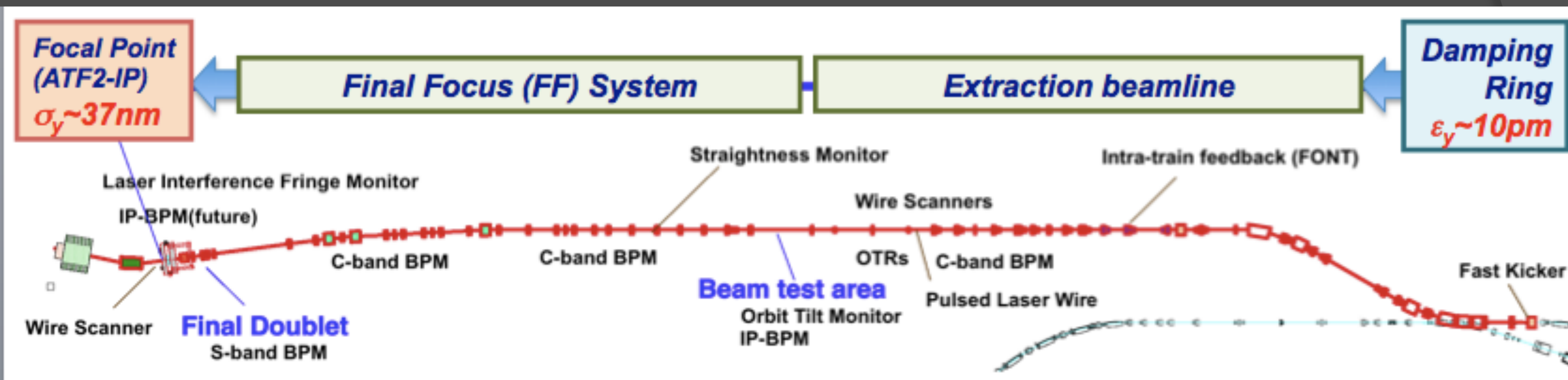


- 21 Institutes
- 11 countries
- 67 People

ATF2 Facility Layout



ATF2 Facility Layout



Final Focus System (FFS)

- Scale test of ILC FFS optics

Extraction Line (EXT)

- Extract beam from DR
- Correct for coupling and dispersion errors
- Correctly match beam into final focus system.

Achieving High Luminosity in Linear Colliders

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D \quad \left\{ \begin{aligned} n_b N f_{rep} E_{cm} &= P_{beams} \\ &= \eta_{RF \rightarrow beam} P_{RF} \end{aligned} \right\}$$

$$L = \frac{1}{4\pi E_{cm}} \left(\eta_{RF} P_{RF}\right) \left(\frac{N}{\sigma_x \sigma_y} H_D \right)$$

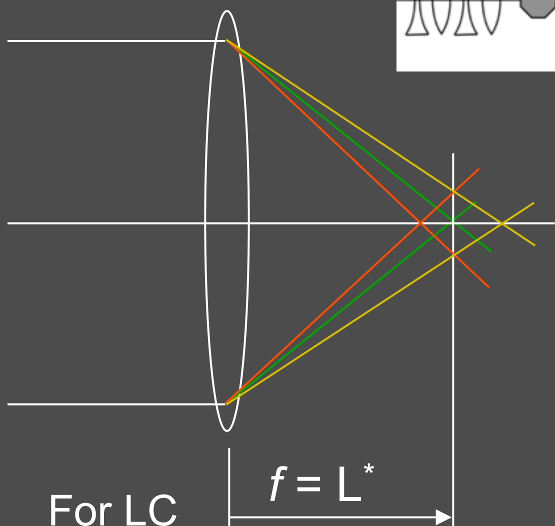
Linac technology
- Efficiency
- Available power

Beam-beam effects
- Beamstrahlung
- Disruption

Strong focusing
- Optical aberrations
- Stability, tolerance

Keep ($\sigma_x + \sigma_y$) large to reduce beamstrahlung:
- leads to neccesity of large aspect-ratio beams
- coupling important!

Final Focus Chromaticity and "Local" Correction

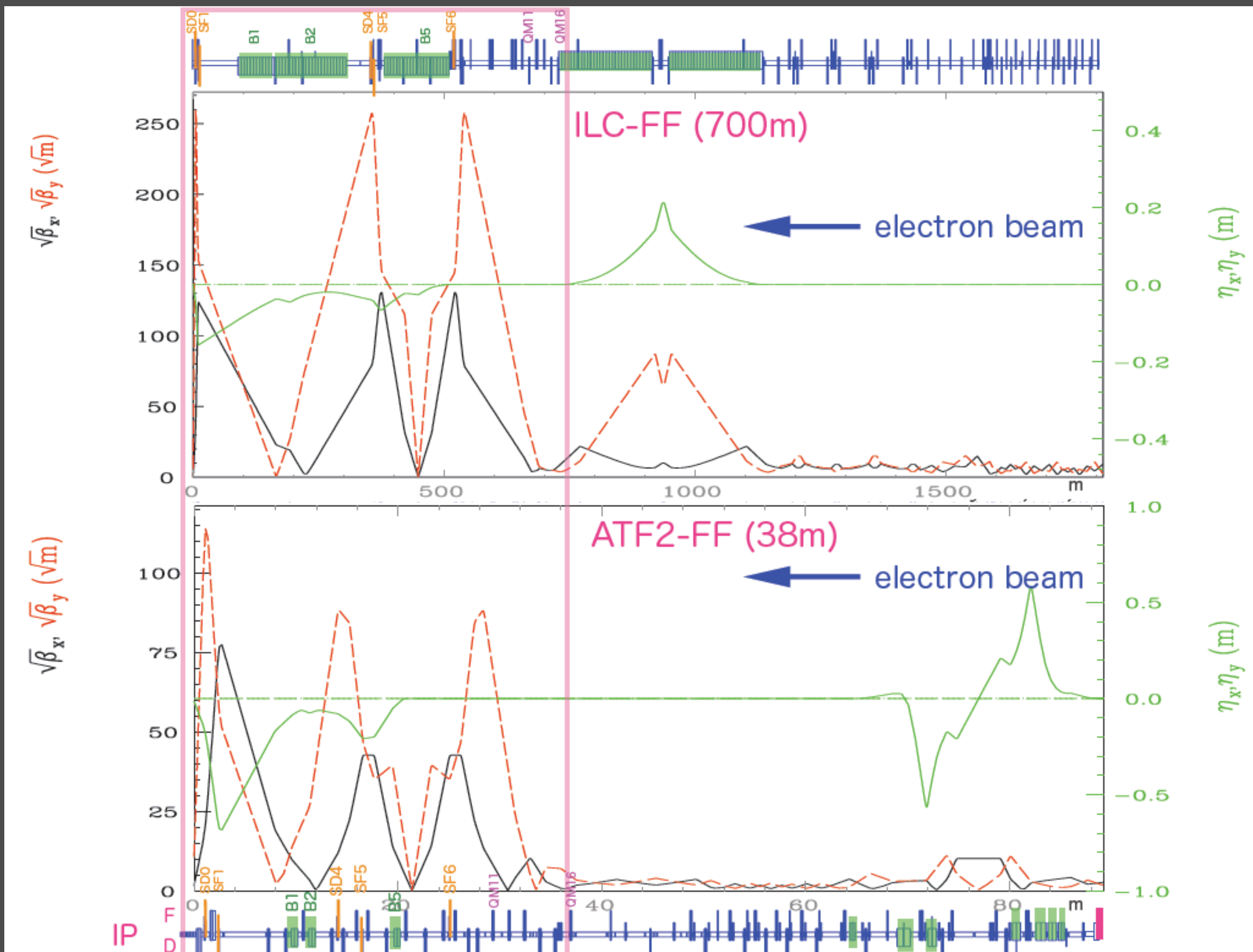


$$\xi_y^* \equiv L^*_y / \beta^*_y \qquad \left\langle \Delta y_{IP}^2 \right\rangle = \xi_y \delta_{\text{rms}}^2$$

$$\Delta\sigma/\sigma \sim \sigma_E . L^*/\beta^* \qquad \xi_y = \int K_1(s)\beta(s)ds$$

- For LC
  - $L^* \sim 3$ - 5 m
  - $\beta^* \sim 0.05 - 0.4$ mm
  - $\sigma_E \sim 0.1 - 0.2$ %
- => $\Delta\sigma/\sigma \sim 10 - 200$: Too Big!
- Chromaticity of final doublet must be compensated
- In fact, most of aberrations that arise from FFS come from the fact that final doublet chromaticity must be compensated

Scale Test of ILC FFS Optics



- Scaled design of ILC local-chromaticity correction style optics.
- Same chromaticity as ILC optics.
- At lower beam energy, this corresponds to goal ~37nm IP vertical beam waist.

<u>Typical DR Parameters</u>

ε_x = 1.4-1.9nm

ε_y = 10-15 pm

E = 1.3 GeV

<u>ATF2 IP parameters</u>

β_x / β_y = 4cm / 0.1mm

σ_x / σ_y = 9um / 37nm

Rep. Rate = 3.12 Hz

ATF2 Parameters

	ILC (TDR 500 GeV)	ATF2	FFTB	ATF2 (pushed)	CLIC (CDR 3 TeV)
L^* (m)	3.5 / 4.5 [a]	1	0.4	1	3.5
ε_y (pm.rad)	0.07	12	22	12	0.003
$\xi_y \sim (L^*/\beta_y^*)$	7,300 / 9,400 [a]	10,000	4,000	40,000	50,000
$\sigma_E(\%)$	0.07/0.12 [b]	0.08	0.1	0.08	0.3
$\Delta\sigma_y/\sigma_y \sim (\sigma_E.L^*/\beta_y^*)$	5/9, 7/11 [b,a]	8	4	32	150
$\sigma_y(nm)$ *design*	5.9	37	52	23	1
$\sigma_y(nm)$ *measured*	–	65 ± 5 [c]	70 ± 6	–	–
$\beta_x^*(mm)$	11	4 (40^c)	10	4	4
$\beta_y^*(mm)$	0.48	0.1	0.1	0.025	0.07

[a] SiD/ILD ILC detector configurations
[b] Positron/electron side of ILC
[c] March 2013 results and configuration of ATF2 with bunch charge 80-130 pC

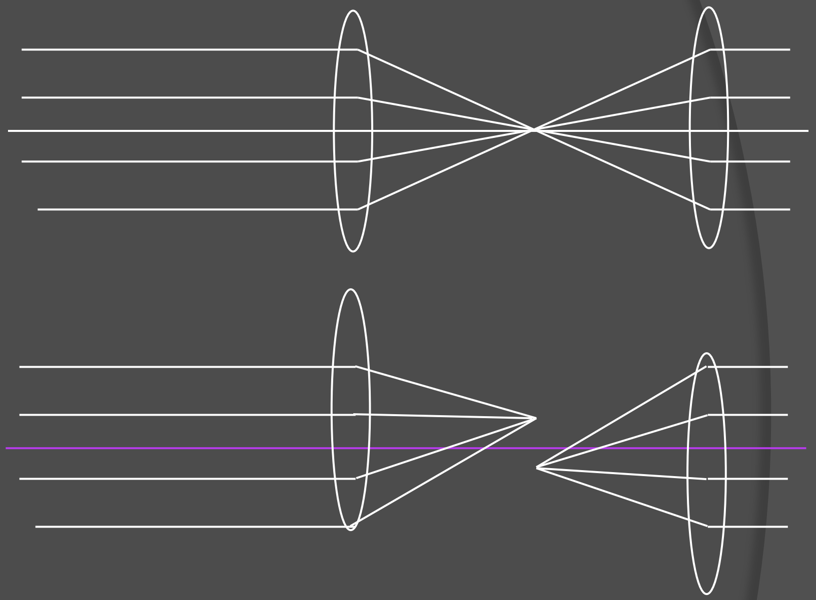
- Want to understand how the level of chromaticity in the final focus optics affects the tunability
- Can adjust ATF2 optics to range from something that is applicable to ILC to that of close to CLIC levels of chromaticity.

'Static' Error Sources

- Installed positions
  - Horizontal / vertical / roll
  - Survey tolerances for ATF2 typically ~100um / 300urad
- Alignment
  - BPM -> magnet field centres
  - Installation tolerances for ATF2 few-100 um
- Magnetic fields
  - Systematic and random integrated field strength deviations from model
  - Quality of fields – relative strengths of magnetic multipoles

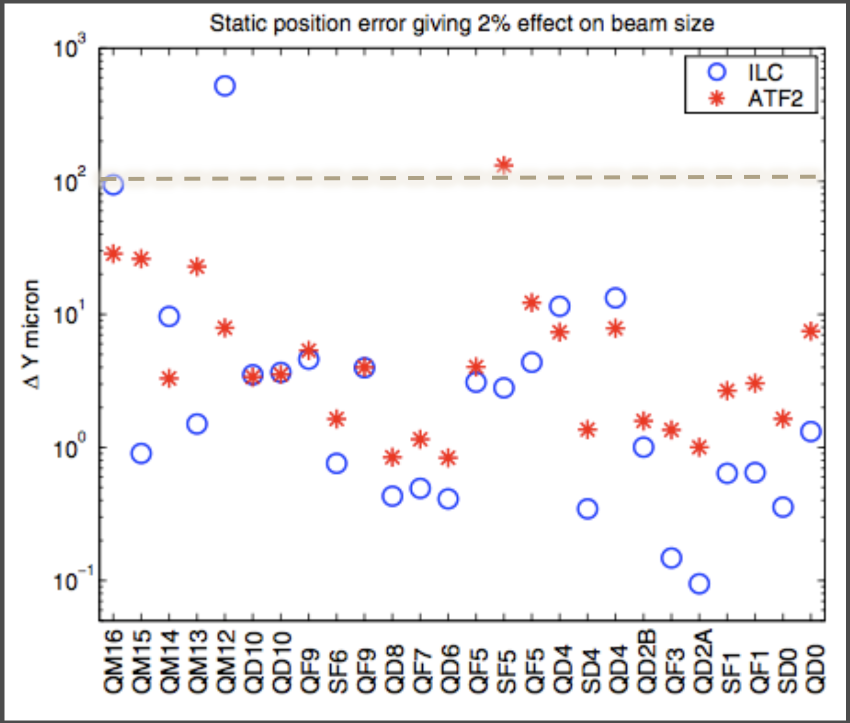
Dynamic Error Considerations

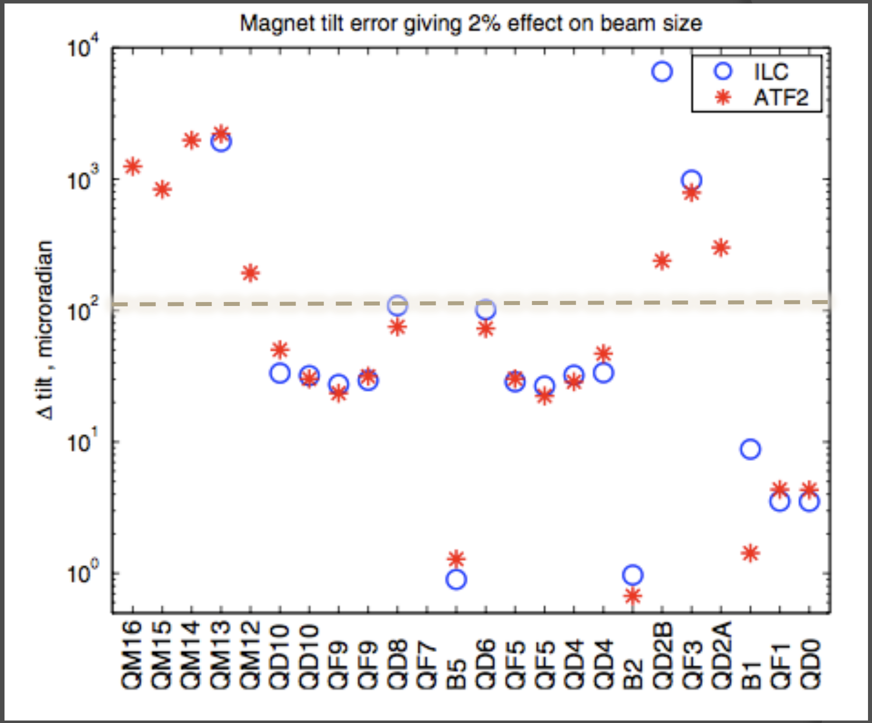
- Need to worry about many jitter sources at nanoscale
- Ground motion
  - Natural and cultural
  - Especially final doublet
- Mechanical jitters
- Temperature drifts
  - e.g. 1 degree ~ 10um motion in most metals -> large on nanoscale!
- Magnetic field drifts
  - Including Earth's



- Parallel-point focusing
- Tolerance of FD ~nm!

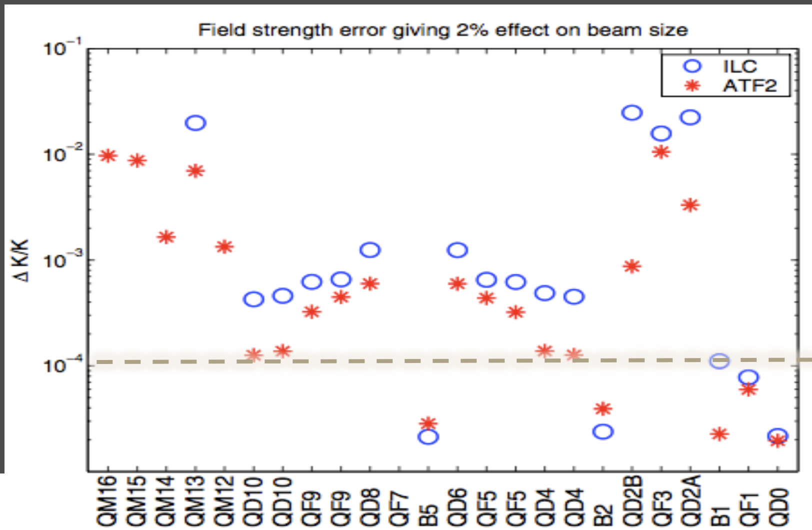
Tolerances on Placement Errors



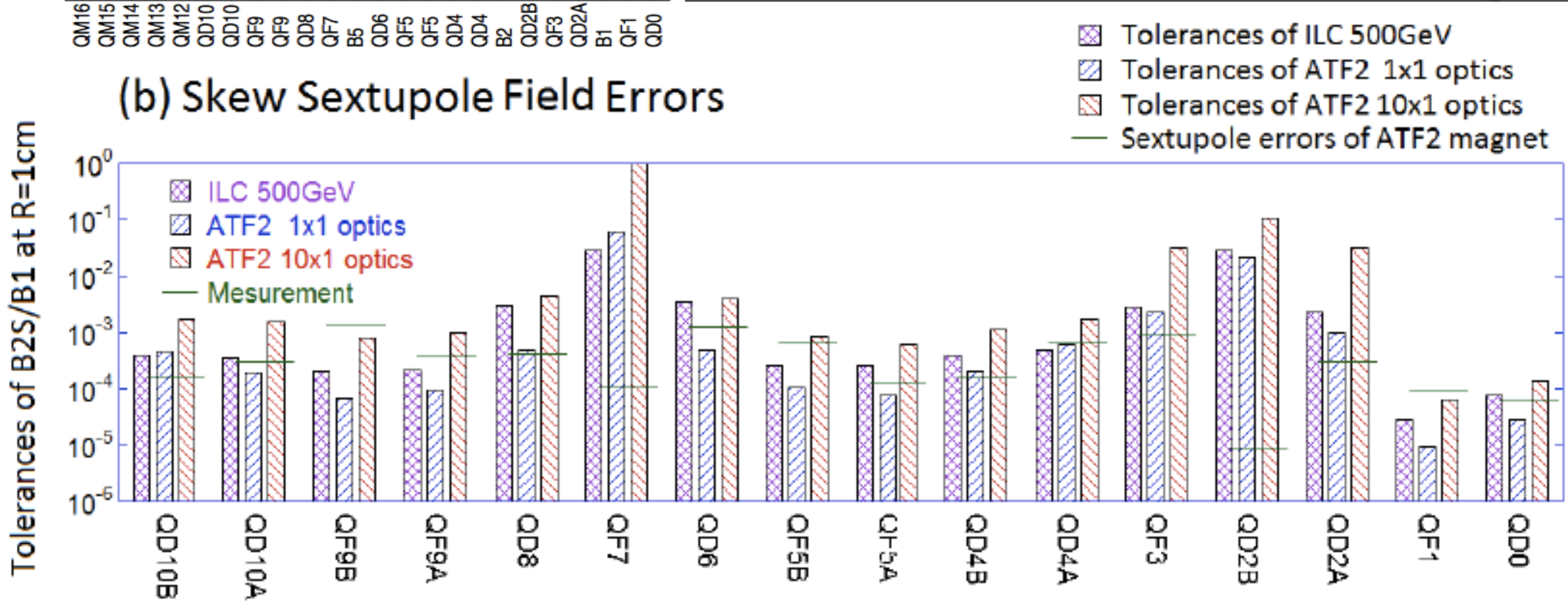


- Like ILC (and CLIC), tolerances for many magnets much tighter than can be realised
- Need to rely on active tuning

Tolerances on Magnetic Field Errors



- Setting accuracy and field quality tolerances also imply reliance on active tuning methods



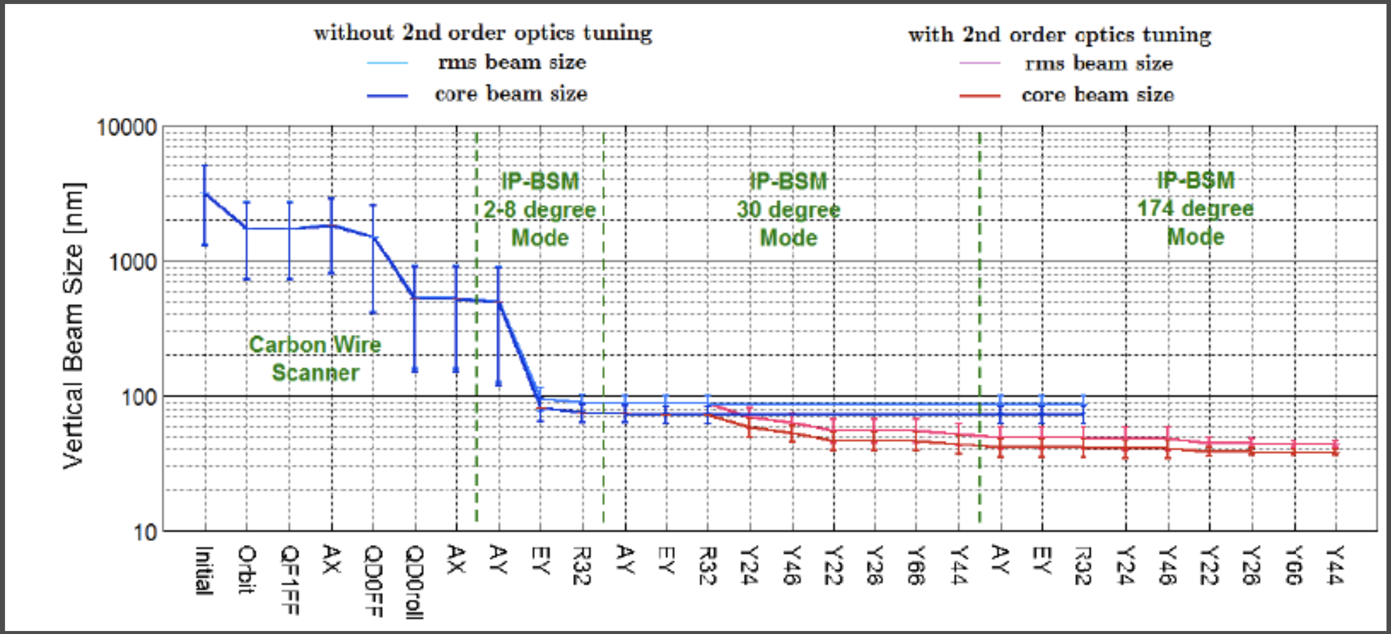
Optics Setup (Pre-FFS Tuning)

- BPM Calibration
- Steering
- BBA
- Global Dispersion correction
- Extracted emittance measurement
- Extracted coupling correction
- Beta matching
- Model and optics verification

IP Aberration Tuning

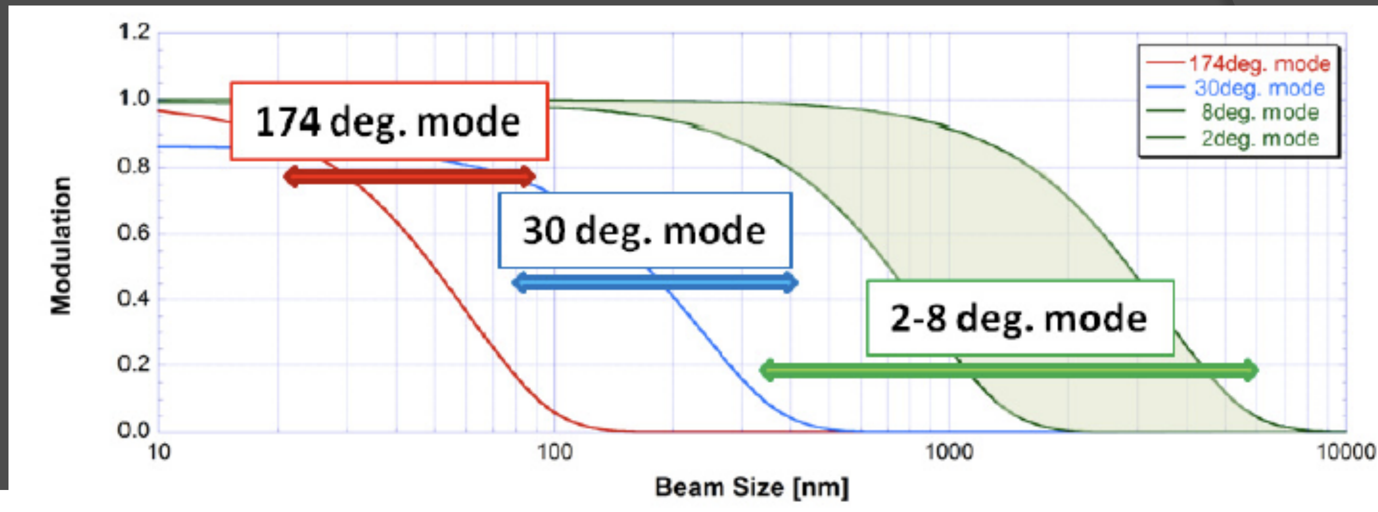
- Linear tuning knobs using pre-computed orthogonalised horizontal/vertical moves of 5 FFS Sextupole magnets.
  - alpha_x, eta_x, alpha_y, eta_y, <x’y>
- Non-linear tuning knobs using strength changes of 5 FFS Sextupoles & 4 skew-Sextupoles
  - Y22, Y26, Y44, Y46

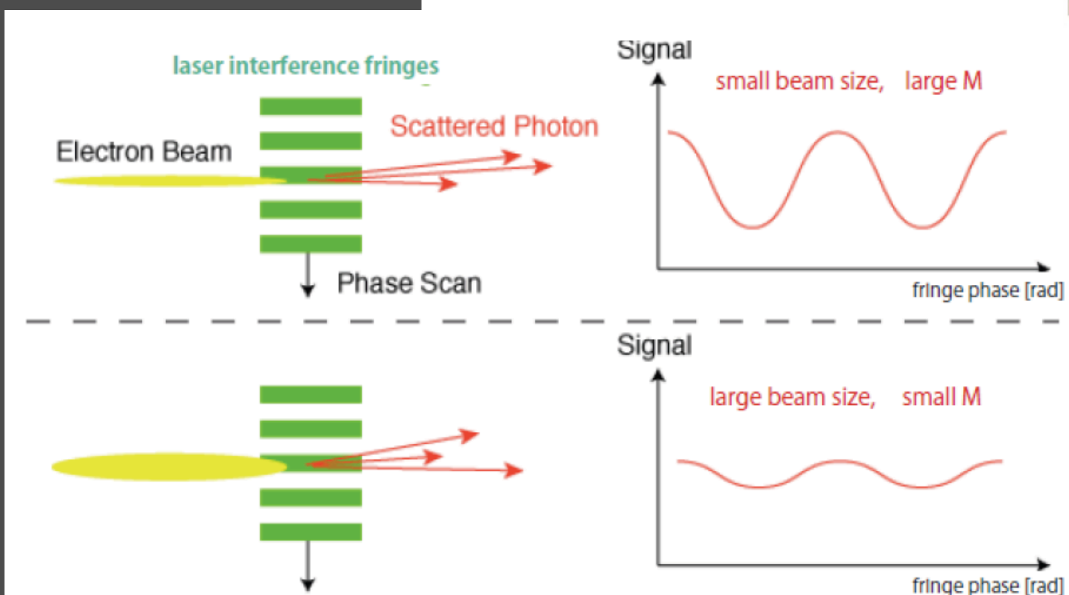
Simulations



- Simulations performed of complete tuning procedure in presence of errors using multiple simulation code.
- Important to verify to understand validity of similar LC simulations.

IP Beam Size Measurement



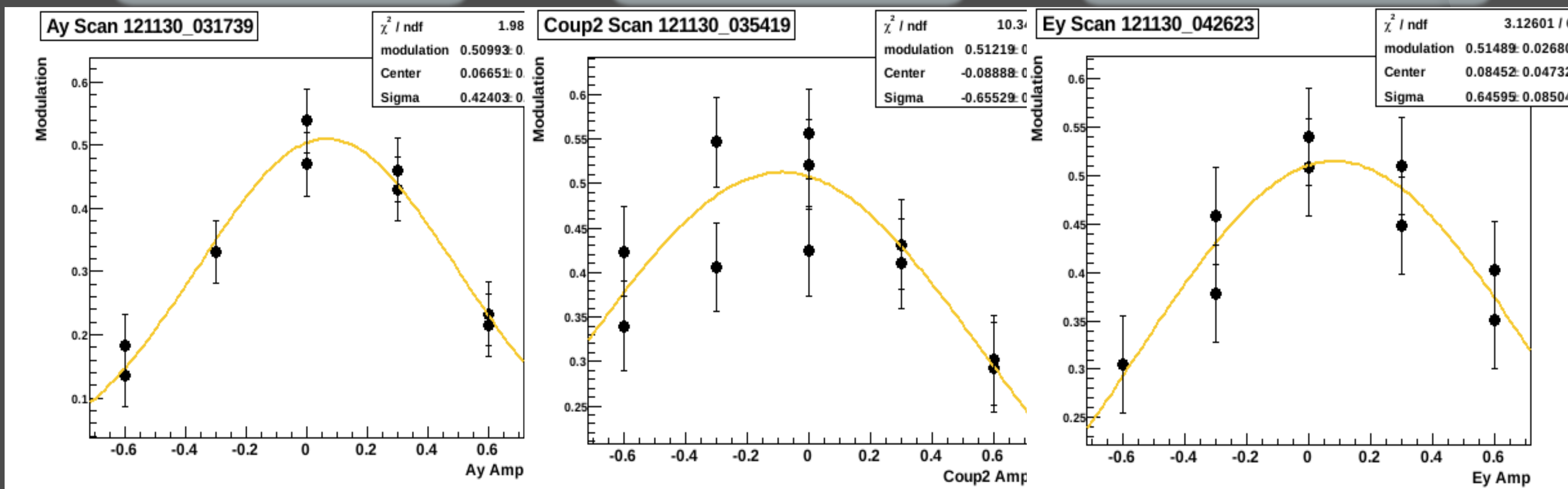


$$M = C\left|\cos\theta\right|\exp\left[-2\left(k_y\sigma_y\right)^2\right] \quad , \quad k_y = \pi/d$$

$$\sigma_y = \frac{1}{k_y}\sqrt{\frac{1}{2}\ln\left(\frac{C\left|\cos\theta\right|}{M}\right)}$$

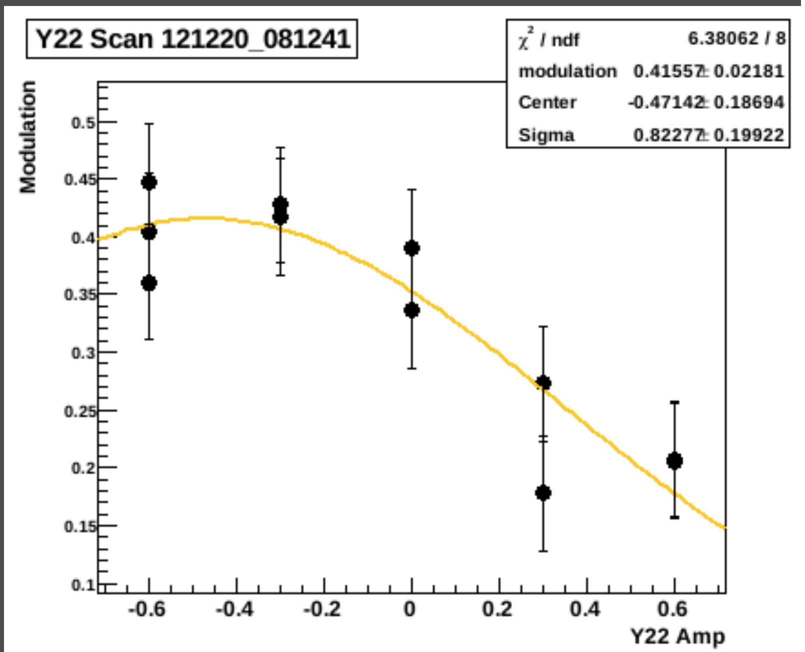
IP Multi-Knob Scans (linear)

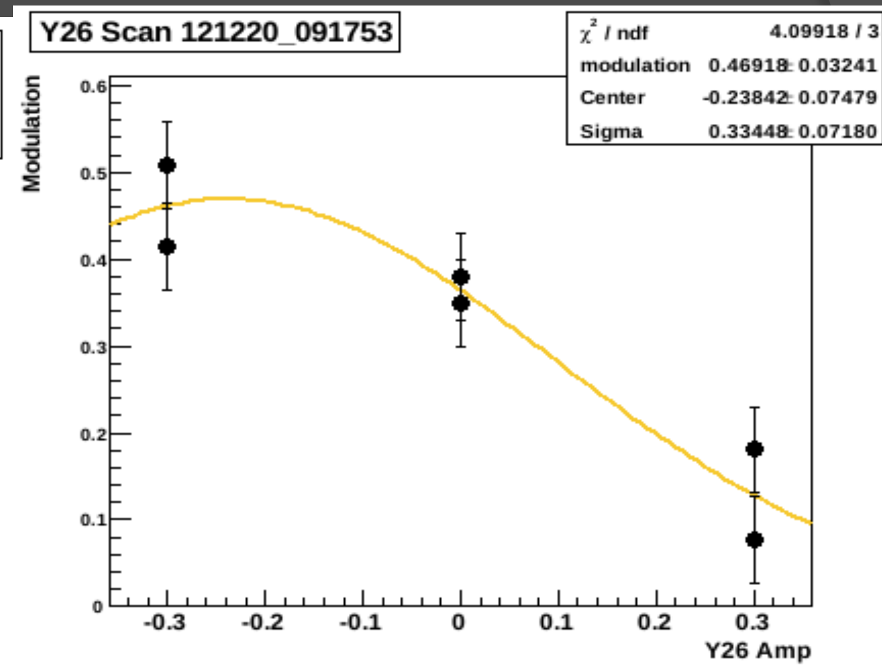
Vertical Waist | Coupling | Vertical Dispersion



- Design multiknobs using model to orthogonally tune waist, coupling and dispersion at IP
  - Use coordinated horizontal and vertical moves of 5 FFS sextupoles
- Orthogonality looks good, once a given knob set, subsequent scans are centered near zero.

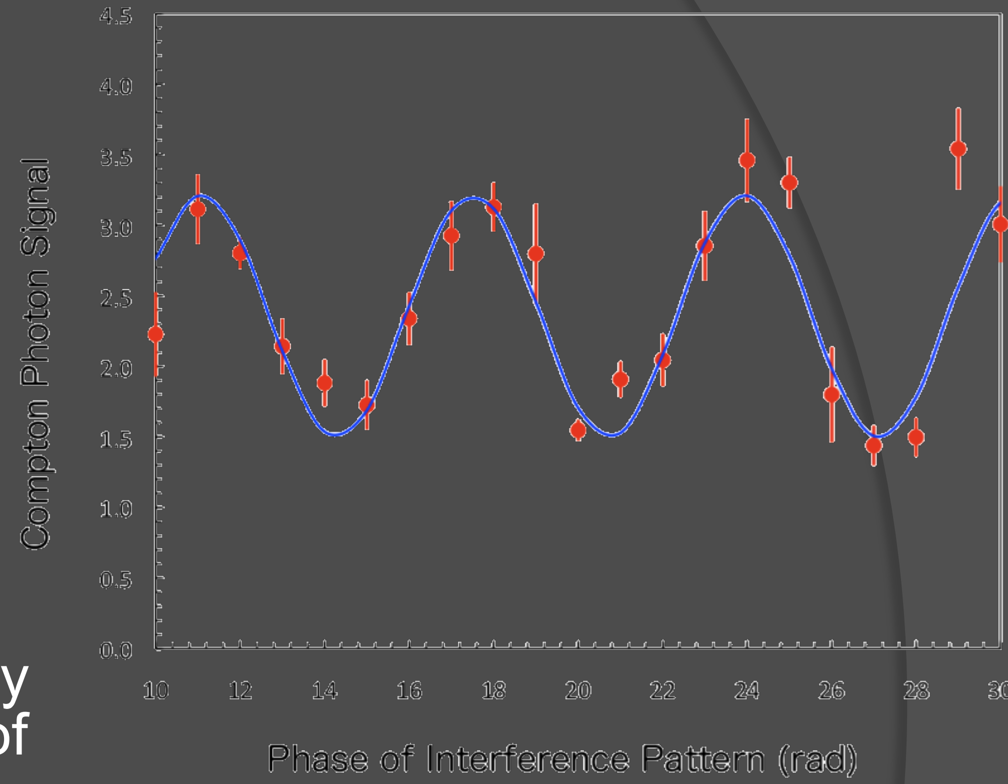
IP Multi-Knob Scans (non-linear)





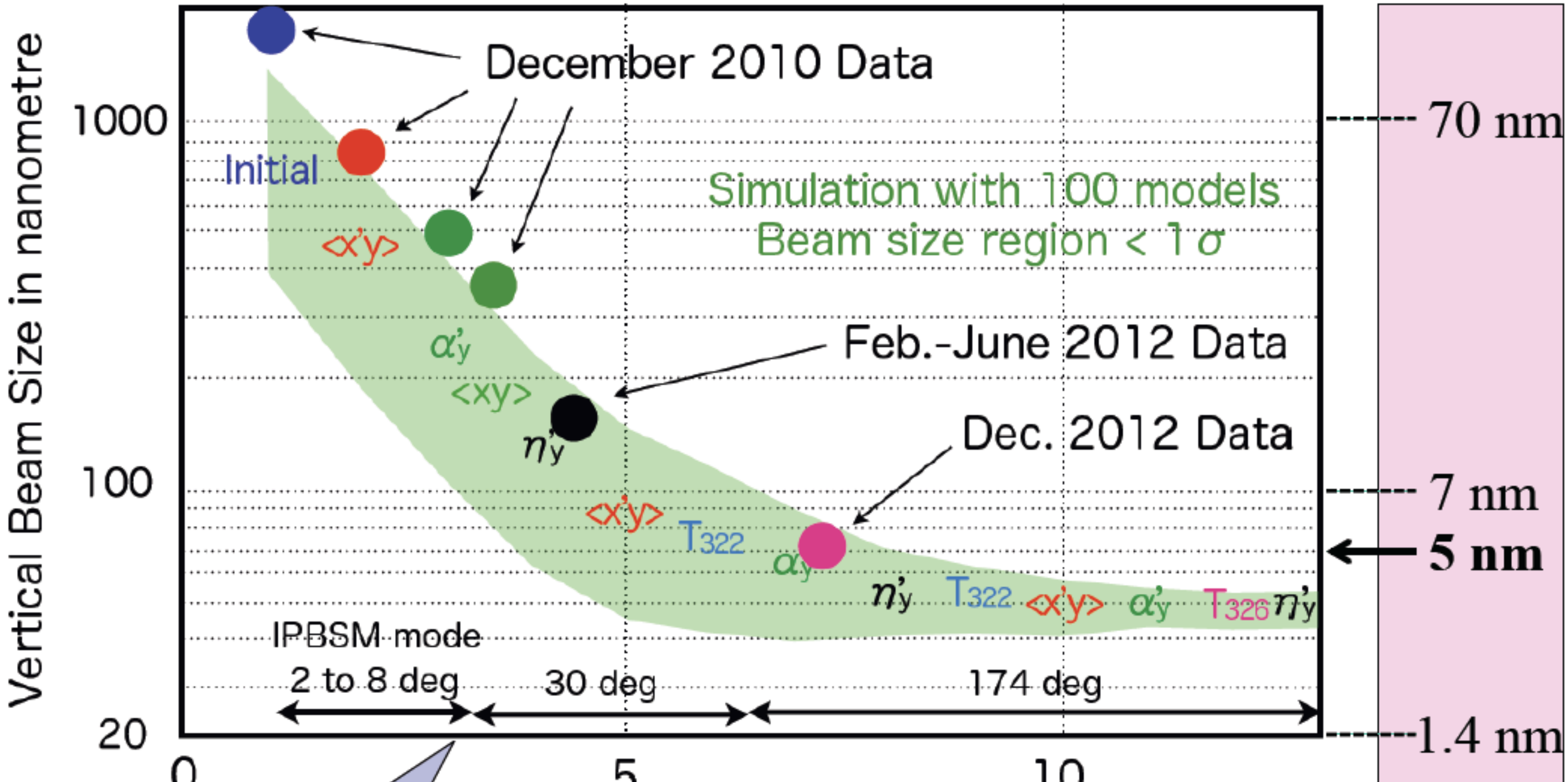
- Non-linear knobs using 4 skew-sextupole strengths
- Two effective non-linear knobs used
  - Y22 (second-order coupling of Y from X')
  - Y26 (second-order chromo-geometric term)

Current Status



- Tuned vertical beam size on 4 separate occasions (Dec 2012, March & May 2013) to <70nm and maintained for ~hour durations.
  - Compare with chromatically uncorrected performance of FFS ~450nm
- Demonstrated chromaticity correction of local chromaticity correction optics
- Demonstrated feasibility for application of this optics for achieving ILC required beam sizes
  - (ILC energy-scaled beam size of ~5nm)

Vertical Beam Size Achieved



ATF2 results at 1.26 GeV/ beam

Rescaled to 250 GeV/beam

ATF2 Review by ILC GDE, Apr 2013

ATF2 review: General statements

"...The extensive upgrades and improvements to the machine itself, including critical sub-systems such as the **IPBSM**, together with the **organized approach to shifts and personnel training**, have resulted in significant gains in terms of understanding and characterizing the accelerator, resulting in a best-recorded beam size of **64 nm.**"

Continuing Studies with ATF2

- Understand limitations to reach beta-limited vertical beam size of 37nm. Expect mainly due to ATF2-specific problems:
  - IP beam size monitor systematics
    - Beam position jitter with respect to fringes
    - Laser fringe pattern distortions
    - Affects final tuned beam size measurements and tuning process
  - Wakefields (long ~8mm bunch length at ATF2)
    - Currently need to operate at low charge (80-200 pC)
    - Measured wake effect at ~100-140 nm / nC (quadrature addition to beam size)
- Comparison with simulations
- Tuning performance (beam size and tuning time) vs. chromaticity by further reducing beta_y
- nm-level beam stabilization at the IP (multi-bunch operations)
  - Ground motion studies using accelerometers to reconstruct GM spectra in real-time which can be of use to optimize orbit feedback.

Summary

- The primary aim of the ATF2 experimental program was to confirm the validity of the “local chromaticity correction” scheme employed by future LC designs
  - We believe we have now confirmed this design by focusing the beam <70nm in height on several occasions
- Beam operations are continuing to understand limitations to further reductions in beam size (concentrating on wakefields and IPBSM systematics).
- Work is starting on the nm-level stabilization of the IP
  - New IP chamber with high-resolution cavity BPM triplet installed over summer shutdown.