Accelerator Test Facility at KEK

Linear Collider Damping Ring Prototype

ATF is the only test facility with ~LC emittance

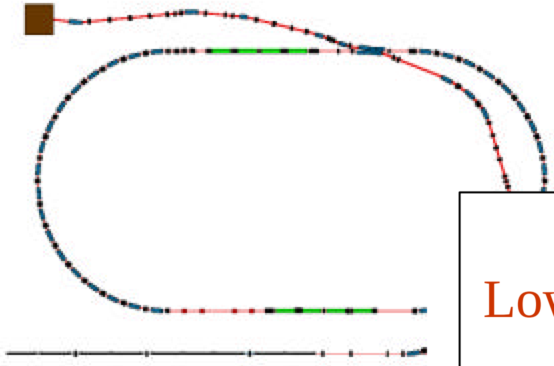
Marc Ross

From the SLC to the NLC

(from D. Burke)

- Two Issues…
  - Energy x 10 beyond SLC
  - Luminosity x 10,000 beyond SLC

- Experience basis of NLC/JLC
  - ATF creation of low emittance beams
  - NLCTA X-band technology
  - FFTB manipulate, focus and measure
  - ASSET multi-bunch emittance preservation
  - SLC ….

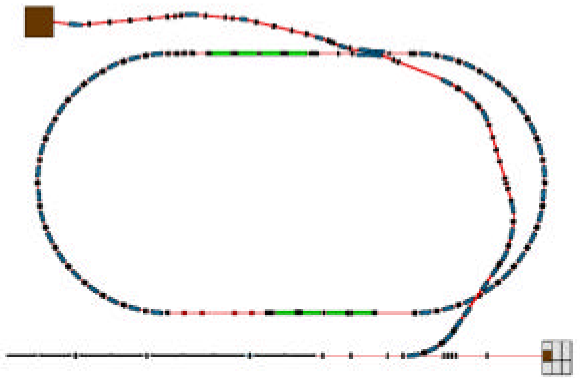


Linear Collider Damping Rings

High current	0.75 A
Low emittance and coupling	ε_y ~ 10 pm; 0.5% coupling
	(SLC ε_y ~ 1.3 nm)
Rapid injection/extraction	120 Hz cycle
Fast damping	5 ms

- Collective effects:
  - –Intra-beam scattering (this talk)
  - –Space charge tune shift (TESLA 17 km ‘ring’)
  - –Two-stream (fast ion/electron cloud – B factory)
  - –Impedance driven (SLC ‘sawtooth’)

ATF is intended to test the above



Damping ring comparison – design parameters

	NLC MDR 120Hz	ALS	ATF	SLC
E (GeV)	1.98	1.9	1.28	1.19
C	299.792 m	196.7 m	138.6 m	35.3 m
Lattice	36 cell TME	12 cell TBA	36 cell FOBODO	22 FODO
ε_x_{eq}	0.560 nm rad	5.60 nm rad	1.4 nm rad	18.2 nm rad
t_x, t_y, t_z	4.85, 5.09, 2.61 ms	15, 21, 13.5 ms	12, 17, 11 ms	3.06
U/turn (bend/ID)	247 keV, 530 keV	250 keV, 20 keV	41.4 keV, 29 keV	93.1 keV
σ_z / δ	3.60 mm / 0.1%	6.00 mm / 0.08%	6 mm / 0.06%	8 mm / 0.07%
α	2.95×10^{-4}	1.62×10^{-3}	2.14×10^{-3}	0.018
G_v / acceptance	1.07 MV, 1.5%	1.1 MV, 3%	0.3 MV, 1%	0.8 MV, 1%
Coupling	0.5%	3% (0.5%)	0.6%	~ 10%
Bunch Charge	0.75×10^{10} / 1.5×10^{10}	0.60×10^{10}	1.0×10^{10}	4×10^{10}
Lifetime	minutes?	4.6 hours	~5 minutes	10's of minutes

ATF studies:

- Single bunch emittance
  - Evidence for intra-beam scattering
  - Correction schemes
- Emittance measurements
- Planned single bunch

- Instrumentation RD at ATF
- Multi bunch

Emittance:

	γe_x	ge_y	
– NLC spec:	3e-6	2e-8 m-rad	
– ATF achieved:	5e-6	6e-8	
– ATF expected	5e-6	<1e-8	(0.1% cpl)

– Single bunch; 1.28 GeV; 1e10 ppb (NLC: 1.98 GeV; 8e9)

Minimum theoretically possible emittance → SR opening angle ge_y ~ 5e-10 (0.2 pm for ATF)

What are important emittance issues?

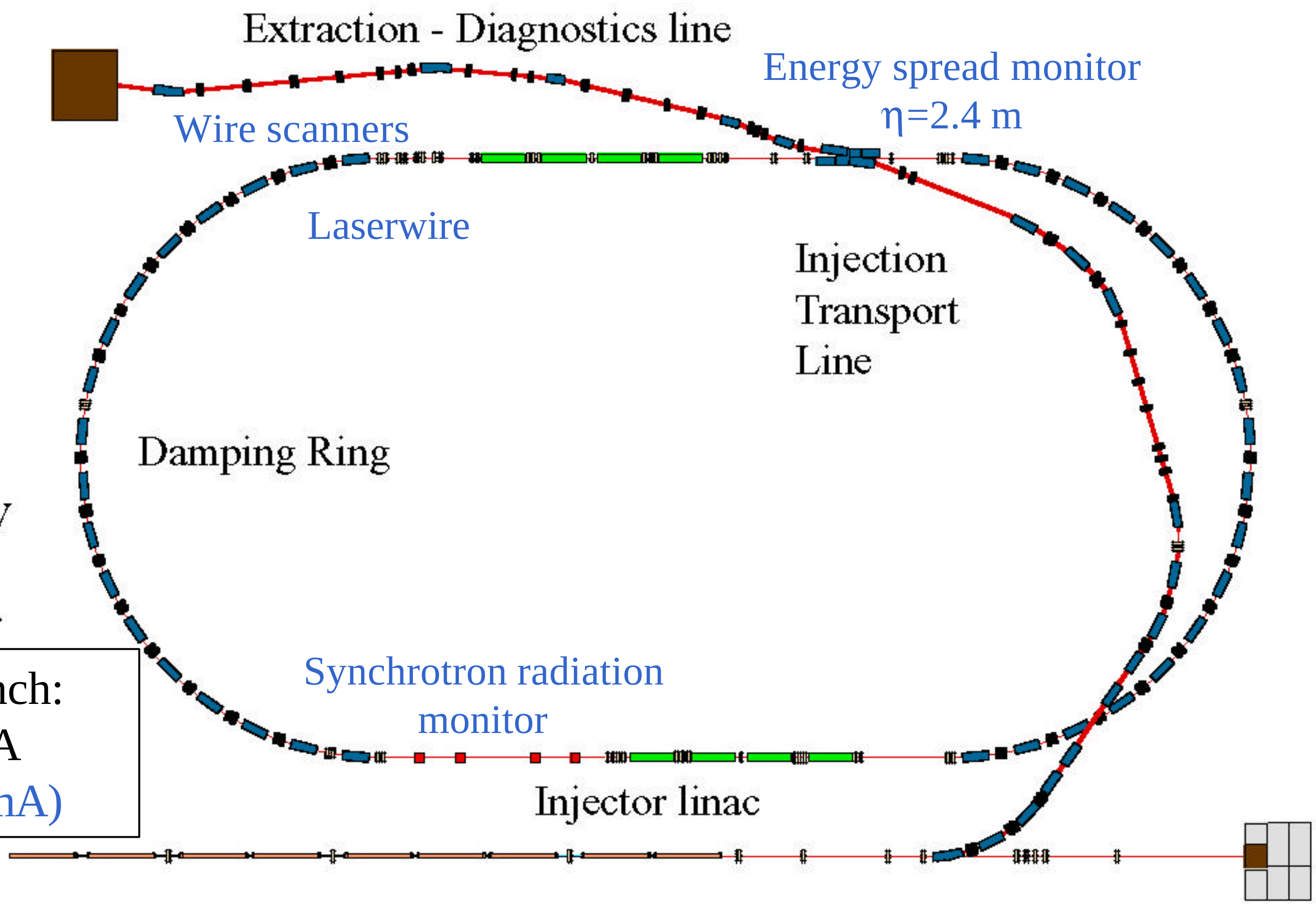
–ring dispersion / coupling correction

–intra-beam scattering

–extraction line optical aberration correction

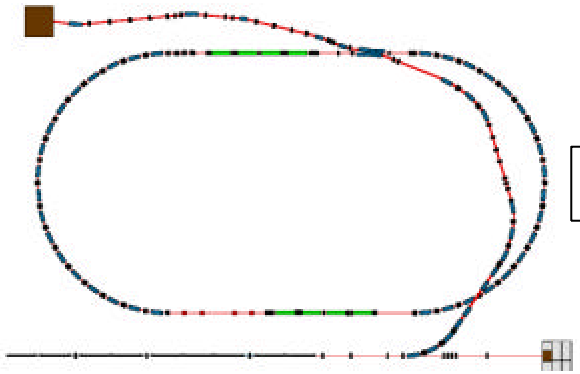
–instrumentation

Accelerator Test Facility - KEK



Single bunch:
I < 3 mA
(SLC 60 mA)

KEKの敷地内に運転中のJLCのための試験加速器



Collective effects – single bunch

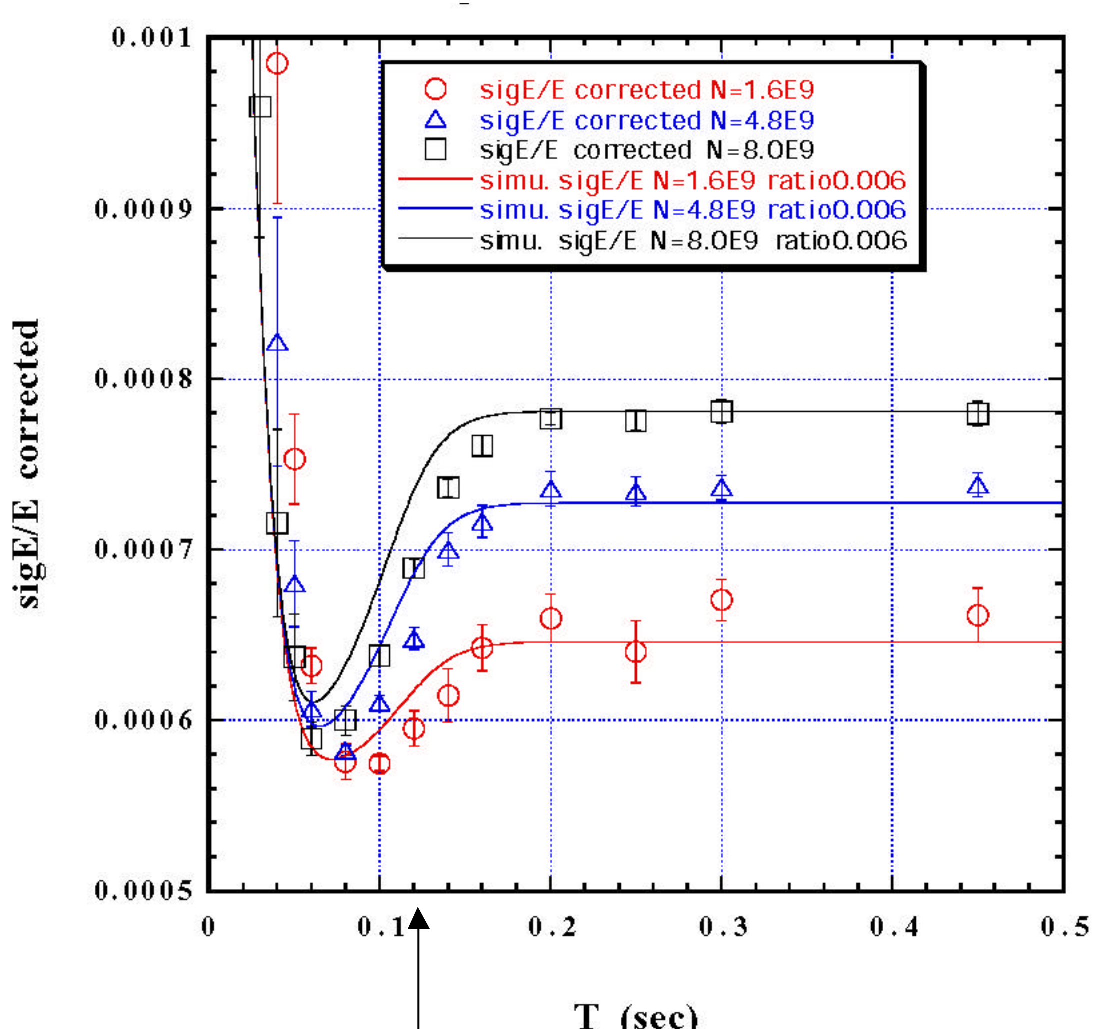
Cause either coherent instability or incoherent emittance growth

- Intra-beam scattering
  - Key topic of ATF work
    - Low energy (1.3GeV)
    - poor damping (w/o EM wigglers)
    - excellent extracted beam energy spread diagnostic
  - more studied at proton machines (primary *L* limit in RHIC)
  - important single bunch emittance driver for NLC
  - no threshold: dependence on bunch volume
- Potential well distortion
- “Microwave” instability
  - serious problem at SLC
    - worse with ‘strong’ but still a problem with ‘weak’
    - definite threshold observed
    - Not expected at ATF

Evidence for IBS – vertical coupling into s_E

Evolution of energy spread following injection for I :

1.6e9	4.8e9	8.0e9
0.6	1.7	2.8 mA



Sequence:

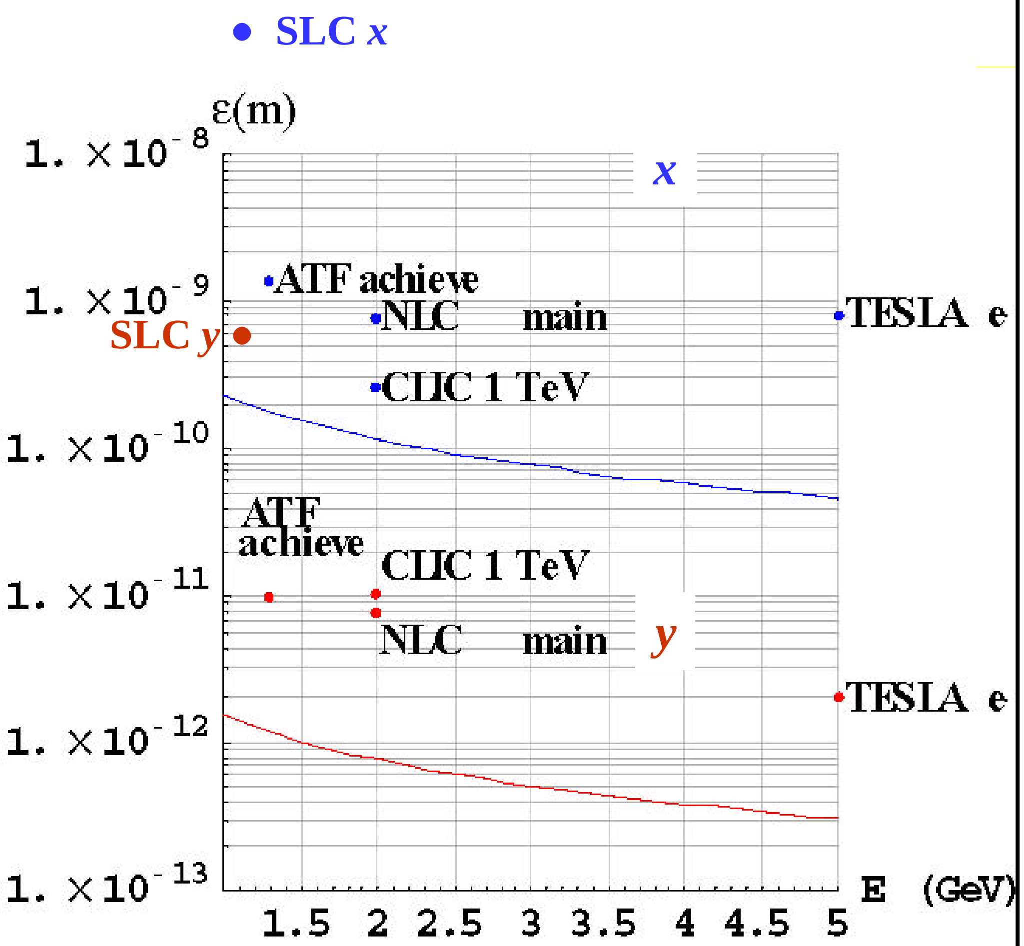
- Vertical still large – no effect on *x* and *E*
- Vertical damped – increase in *x* and *E*
- minimum at 70ms (2.5 τ_rad)

Nominal extraction time for NLC DR – IBS growth < equilibrium

Simulation consistent when coupling →

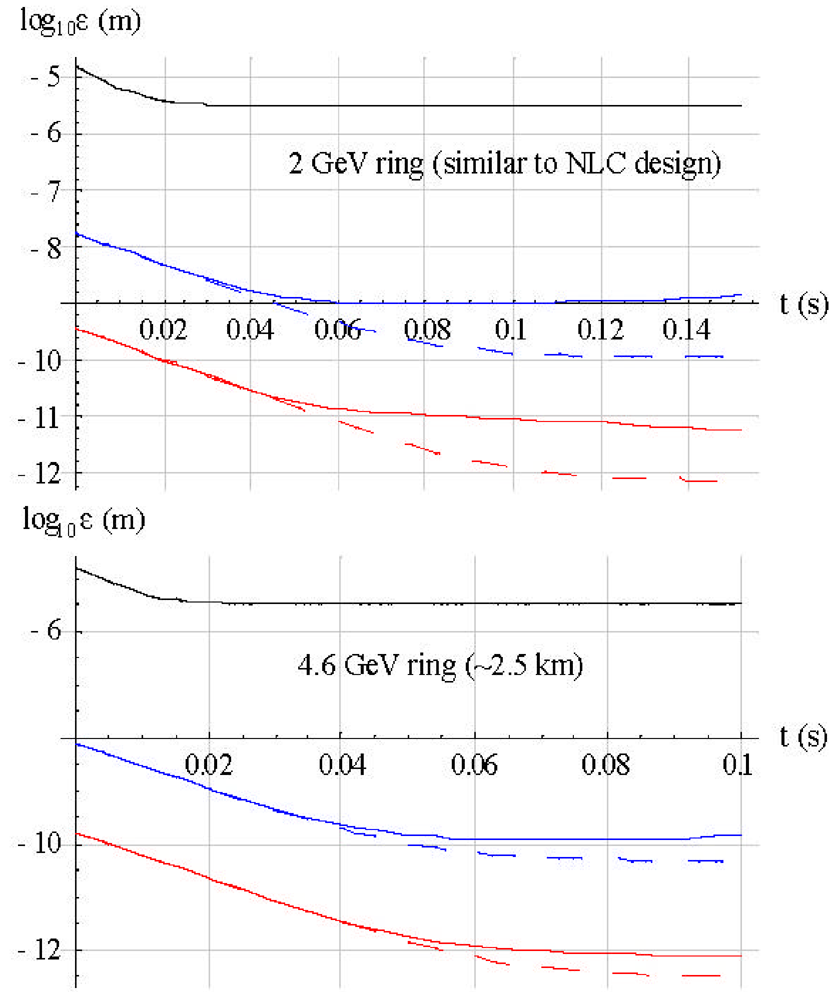
$$\varepsilon_y / \varepsilon_x = 0.006$$

Damping ring comparison

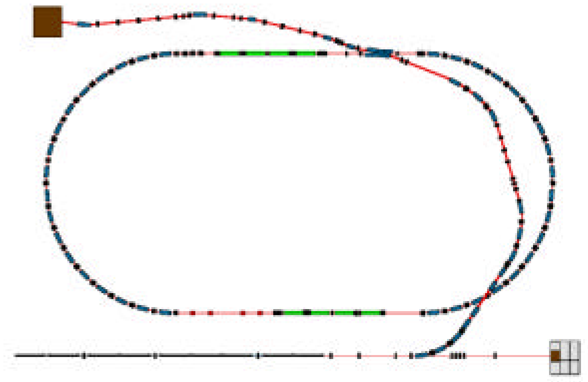


Geometric emittances vs E for LC DR's
(J. Jowett – PAC01)

CLIC Damping ring studies – showing importance of IBS for DR designs



z, *x*, *y* emittance *vs* time – 2 CLIC DR designs (dashed – low I – no IBS)

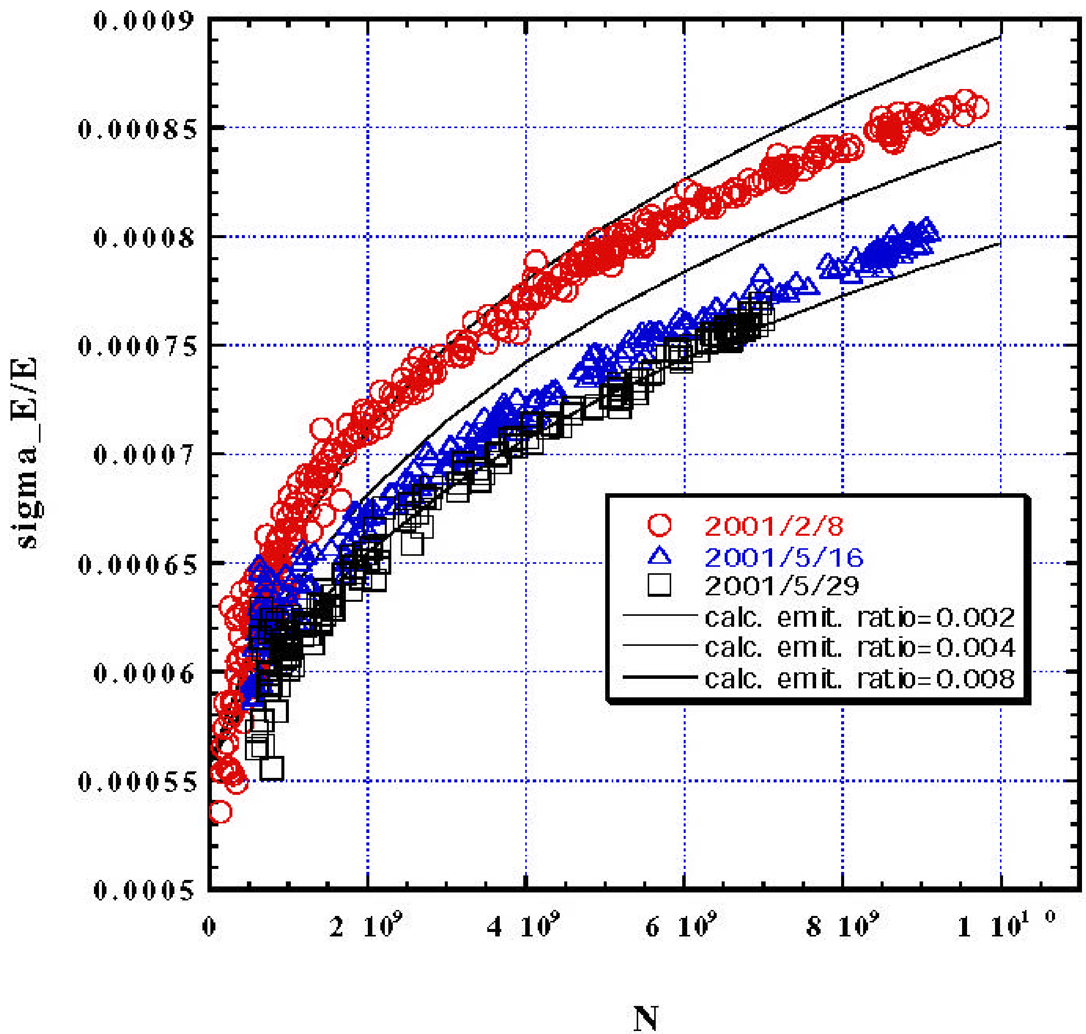


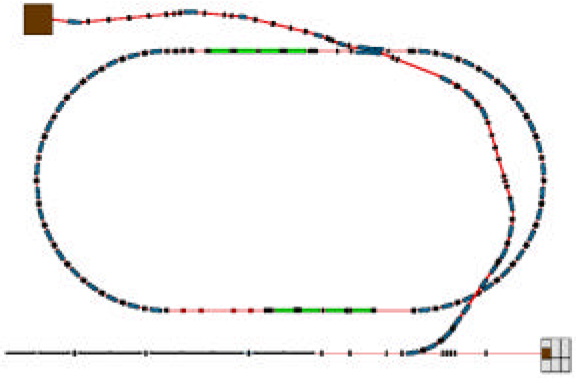
Energy spread *vs* I

$\sigma_{E/E}$ measured using extraction line screen

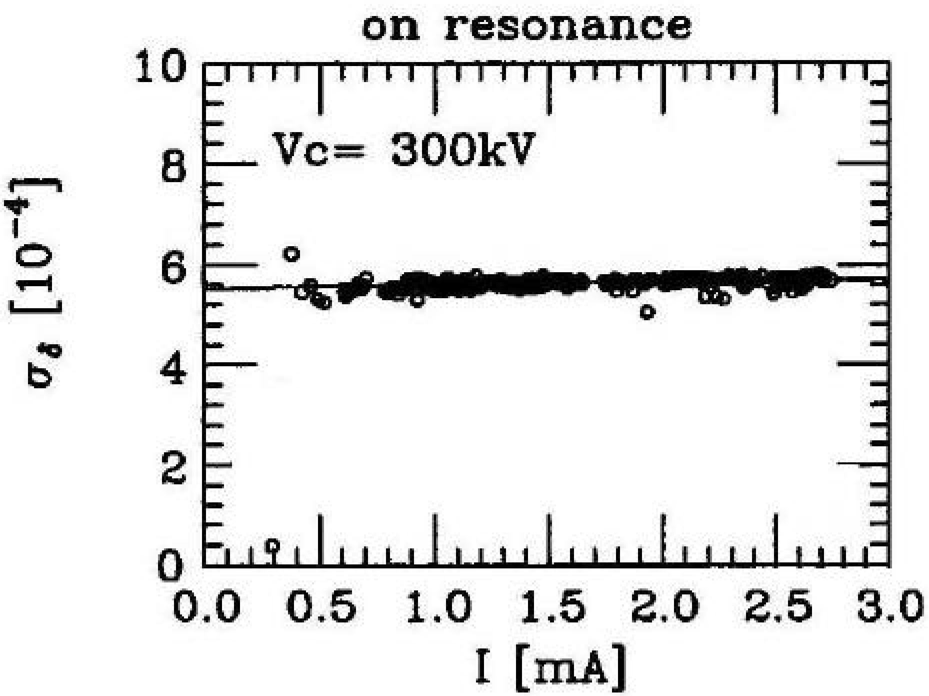
Data from 3 days:
Variation due to tuning & screen monitor performance

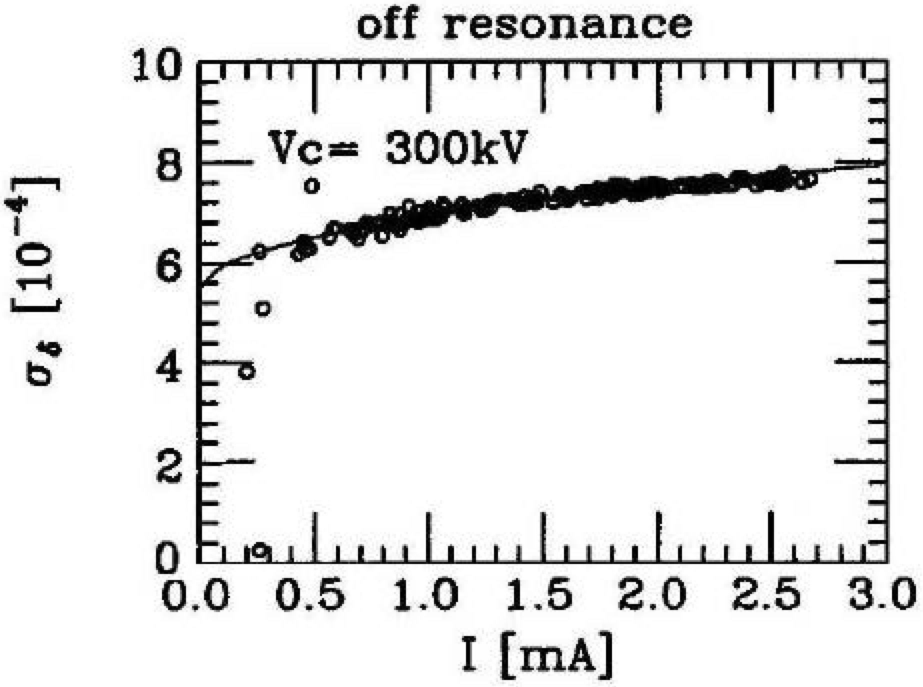
- Zero current energy spread ~ 5.5e-4 is close to expected.





Energy spread on/off n_x=n_y coupling resonance – showing IBS effect

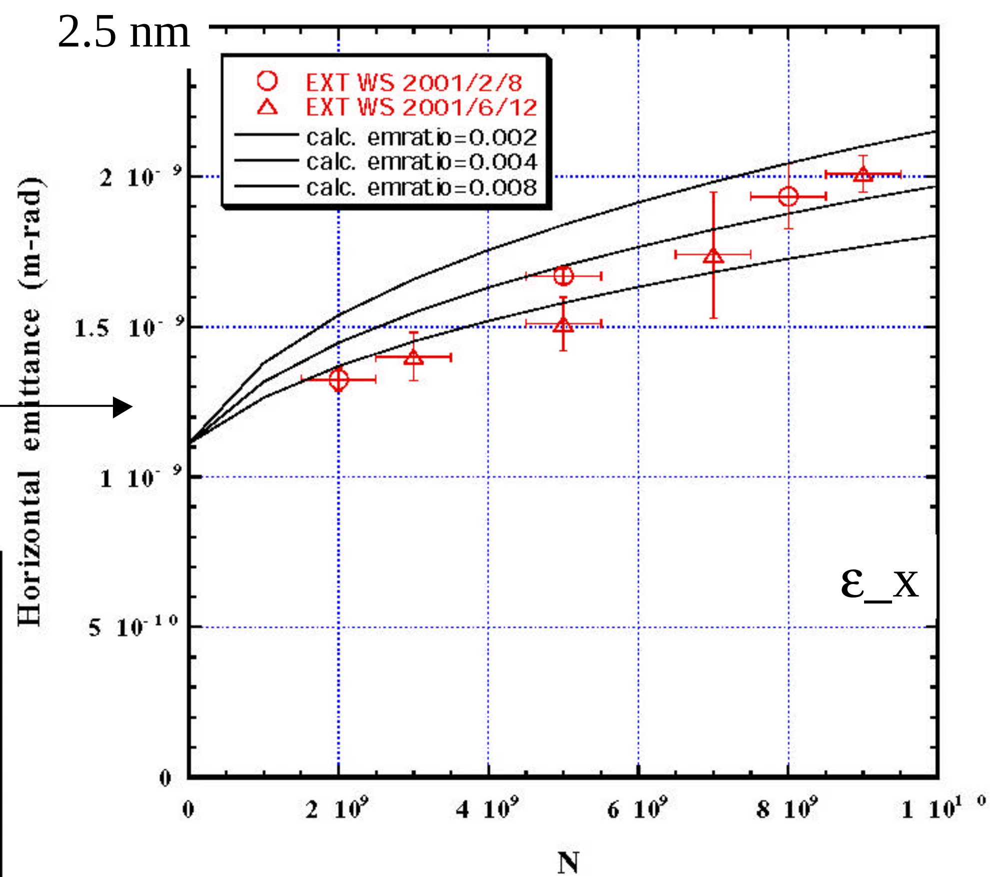


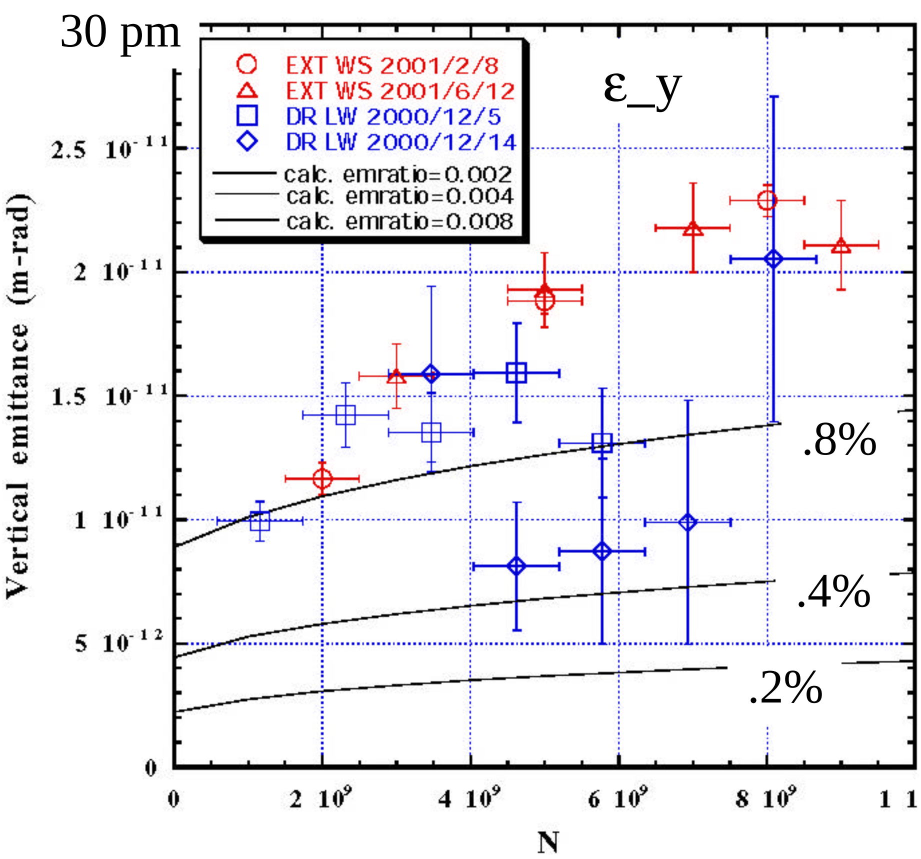


Emittance *vs* intensity

Wire scanner and ring laserwire results

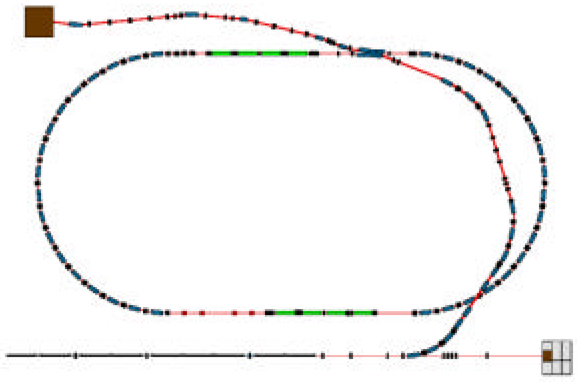
NLC target





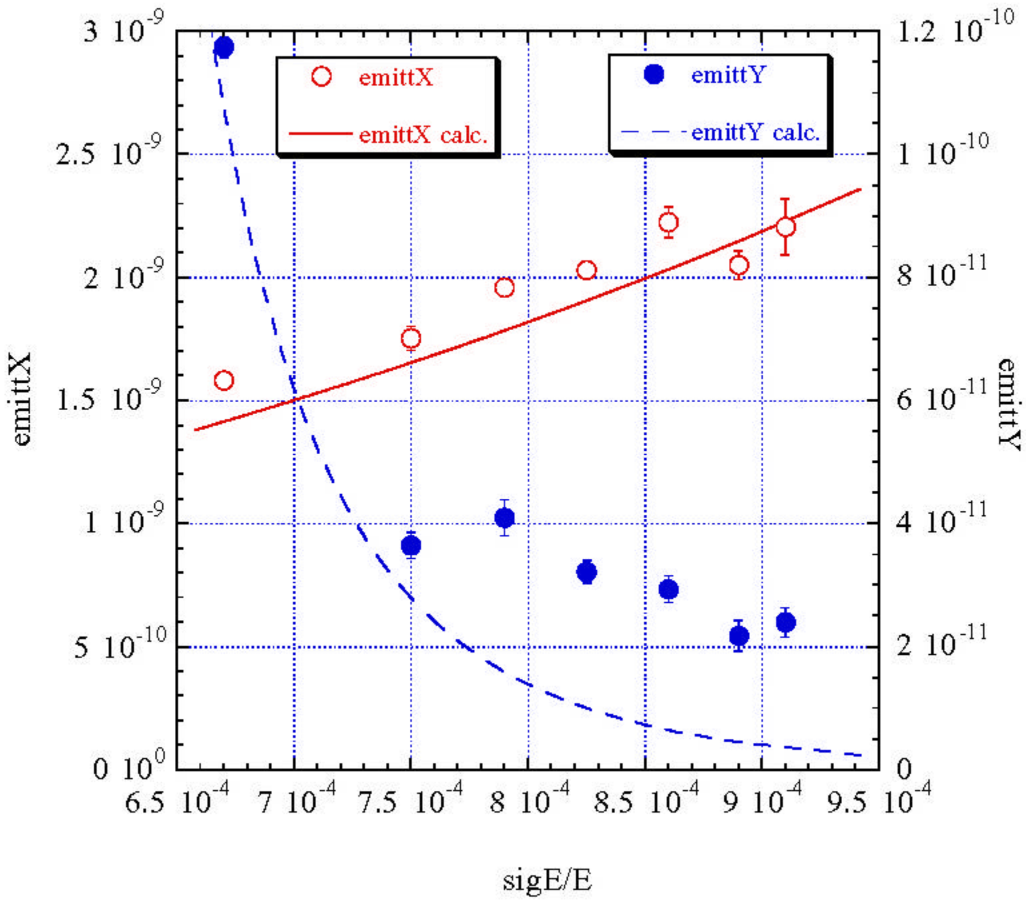
NLC target

- Extraction line wire scanner emittance (red)
- Ring – internal – laserwire (*y* only) (blue)
- Simulation uses zero current ε_x



Emittance vs energy spread

- e_y inconsistent with expectations
- ?
  - IBS theory/simulations
  - coupling/emittance dilution in extraction line
  - measurement related errors



negative correlation between ε_y and δ shows that η is not dominant in ε_y measurement

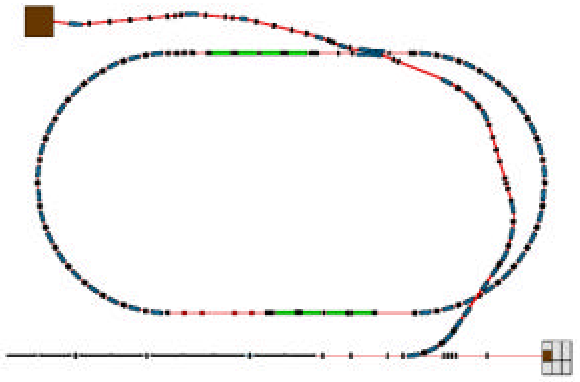
Intra-beam scattering - e growth mechanism

Beam phase space temperatures in rest frame: 7000:35:1 (*x*, *y*, *z*)

- energy flows into *z* from *x* – diffusion
- kicks back into *x* where η ≠ 0
  - η ≠ 0: off-energy particles are not on equilibrium trajectory following energy exchange
  - → effective transverse kick
  - → emittance growth
- if η = 0; no harm done
- effect on ε_y ?

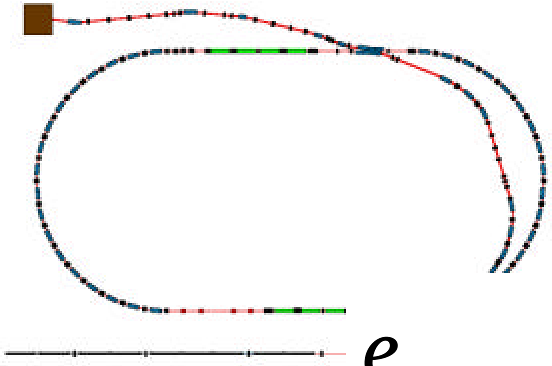
$$\frac{1}{t_{x(IBS)}} \propto \frac{1}{e_x^2 e_y s_z}$$

- Similar to synchrotron radiation
  - growth rate = damping rate at equilibrium
  - collisions involve energy exchange between particles
  - but: SR from bends only; IBS everywhere
  - also: IBS interaction with other collective effects



Intra-beam scattering – theory

- small transfer approximation of Touschek lifetime
  - limitation in SR sources
- Bjorken & Mtingwa + Piwinski + LeDuff
  - *x–y* coupling and microwave related σ_z distortion not included in most simulations
  - interaction with other instabilities
- Factor 2 discrepancy for proton machines
  - depending on model
  - (RHIC, p_bar, V/LHC with ions)
- Tail generation – (should be important for downstream users)
  - cut-off parameter introduced
    - reduces computed ‘rms’ emittance by 30%



IBS – relative growth rate

$$H = \left[\eta^2 + (\beta\eta' + \alpha\eta)^2\right]/\beta$$ *dispersion invariant*

$$\frac{e_{y0}}{e_{x0}} = \frac{\langle H_y \rangle_B \, J_x}{\langle H_x \rangle_B \, J_y}$$

Zero current emittance – determined by SR in bends

$$\frac{de_y}{de_x} = \frac{\langle H_y \rangle \, J_x}{\langle H_x \rangle \, J_y}$$

Emittance growth from IBS – determined by dispersion throughout

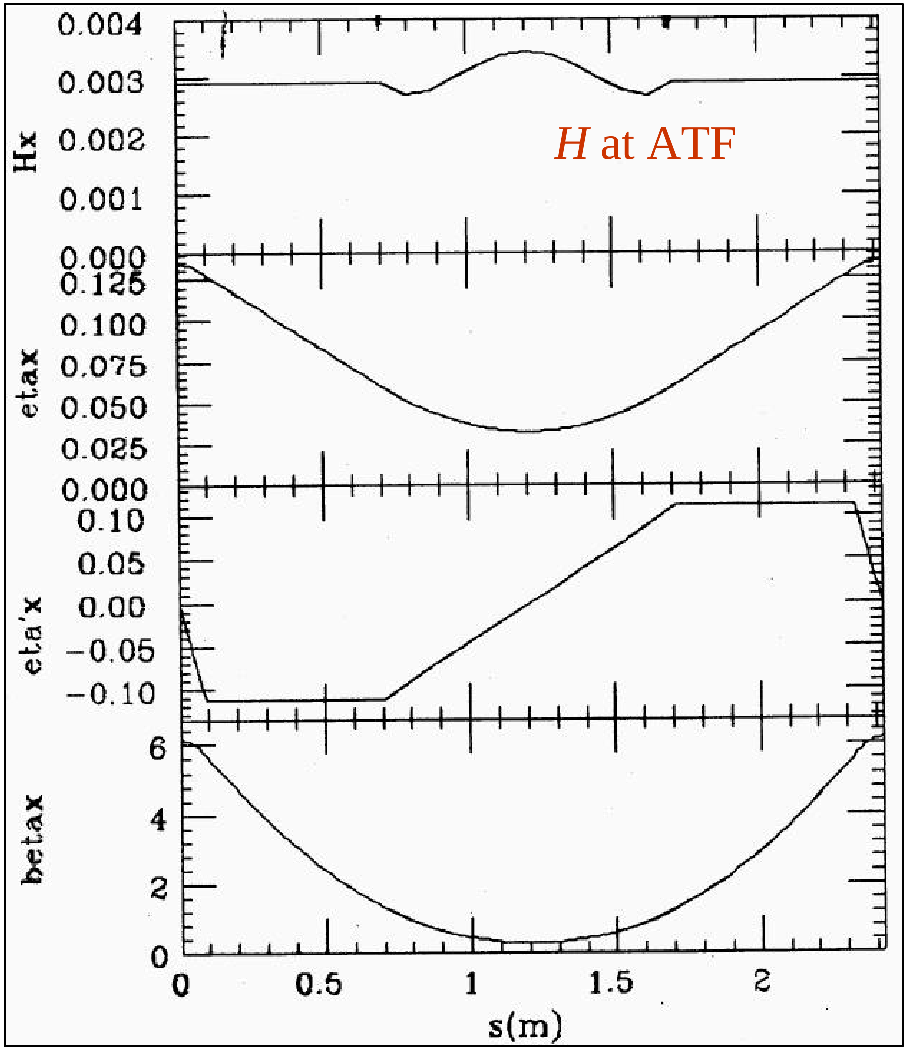
for emittance generated through residual *h* as opposed to residual coupling

Divide and assume that there is nothing special about h_y in the bends $\langle H_y \rangle_B \approx \langle H_y \rangle$

$$\frac{\langle H_x \rangle_{bends}}{\langle H_x \rangle} = \frac{(\varepsilon_y - \varepsilon_{y0})/\varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0})/\varepsilon_{x0}}$$

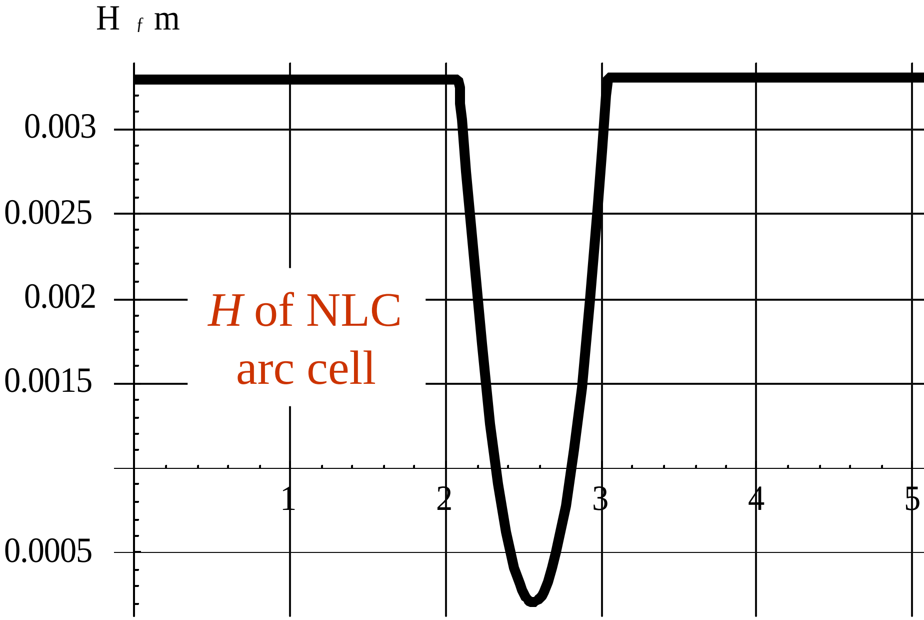
(Tor & Kubo)

Dispersion invariant – *H* – for ATF and NLC design



$$\frac{\langle H \rangle_{bends}}{\langle H \rangle} = 1.6 @ ATF$$

$$\frac{\langle H \rangle_{bends}}{\langle H \rangle} = 0.64 @ NLC$$



NLC DR – A. Wolski (LBL)

Emittance results

- ε_y0 extrapolation is poor
- Observed energy spread & horizontal emittance growth indicates a 2 - 3 x smaller vertical emittance than observed
- Growth ratio shows a similar factor
- measurements made 4/00 to 6/01

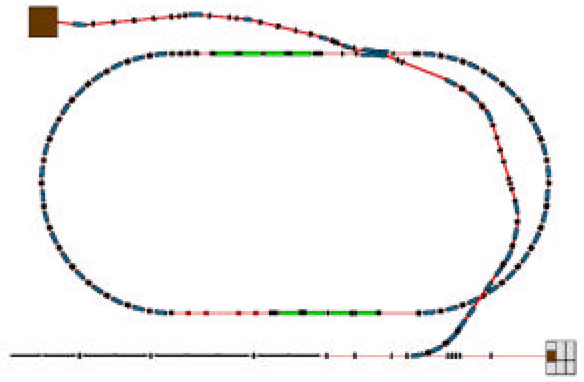
Table of emittance measurements: (e-9/e-11 *x/y*, not normalized)

		e_x0	e_x	e_y0	e_y	r
extracted	wires 4/00	1	1.85	1	3	2.35
extracted	Dec-00	1.1	2.2	1.7	4	1.35
extracted	Feb-01	1.1	2.2	0.7	2.8	3.00
extracted	Apr-01	1	2.4	1.2	2.5	0.77
extracted	Jun-01	1.2	2.1	0.9	2.3	2
ring	L wire	1.1	2.2	0.7	1.9	1.71

- IBS: 1 < *r* < 1.6 (ATF)

  x/y cpl *h*_y

$$r = \frac{(\varepsilon_y - \varepsilon_{y0})/\varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0})/\varepsilon_{x0}}$$



Constraints on measurement/optical errors from estimate of *r*

- for example – a coupled mixture, as would be generated by a skew quad

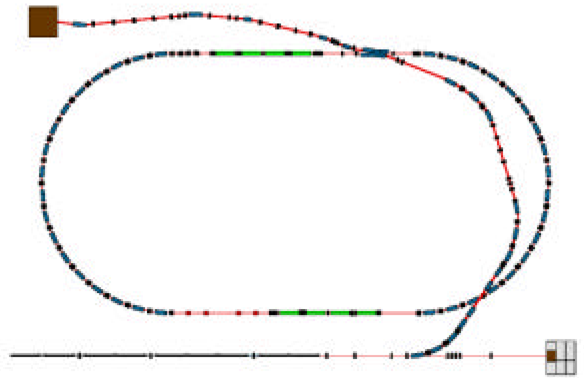
$$\varepsilon_{y\text{meas}} = \varepsilon_{y\text{real}} + k\varepsilon_x$$

(*k* independent of I)

- only makes sense if:

$$\frac{\varepsilon_y}{\varepsilon_{y0}} < \frac{\varepsilon_x}{\varepsilon_{x0}}$$

- inconsistent with 00/01 data



- Random seed ‘SAD’ simulation results

Orbit correction/emittance optimization

K. Kubo

Simulated vertical emittance after each correction

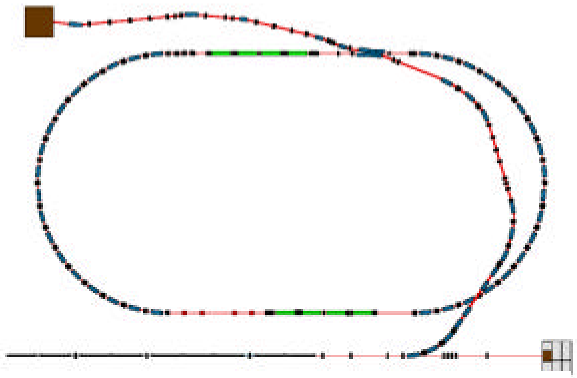
	Average	<1.1E-11 rad-m
COD	2.28 (E-11 rad-m)	20 %
V COD-dispersion	1.67	51 %
Coupling	0.58	91 %

Misalignment : as measured

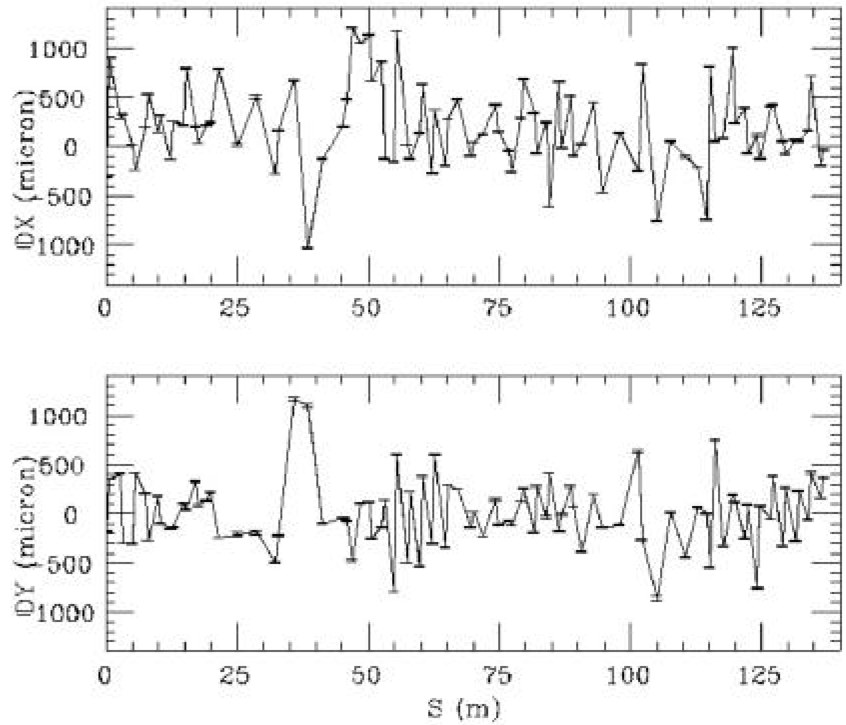
+ random 30 micron offset

+ random 0.3 mrad. rotation

BPM error : offset 300 micron, rotation 0.02 rad.



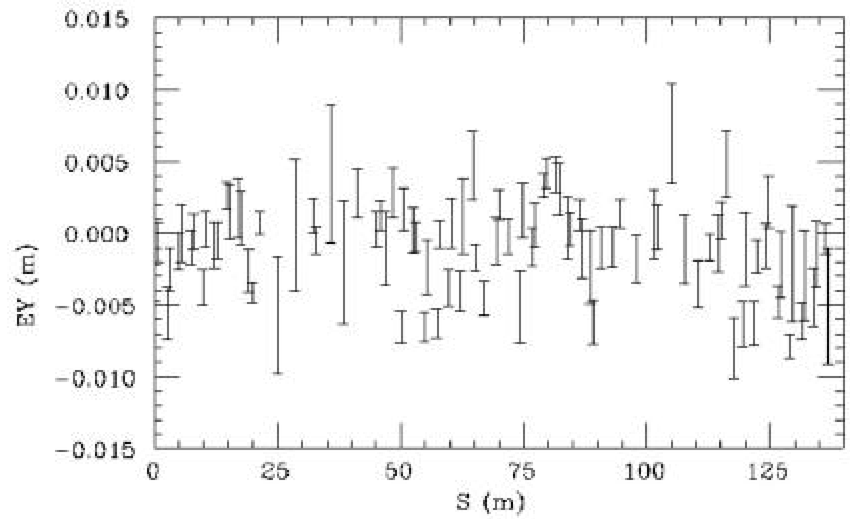
Ring orbits



- Raw BPM readings
- Energy spread measurement an excellent practical indicator of convergence

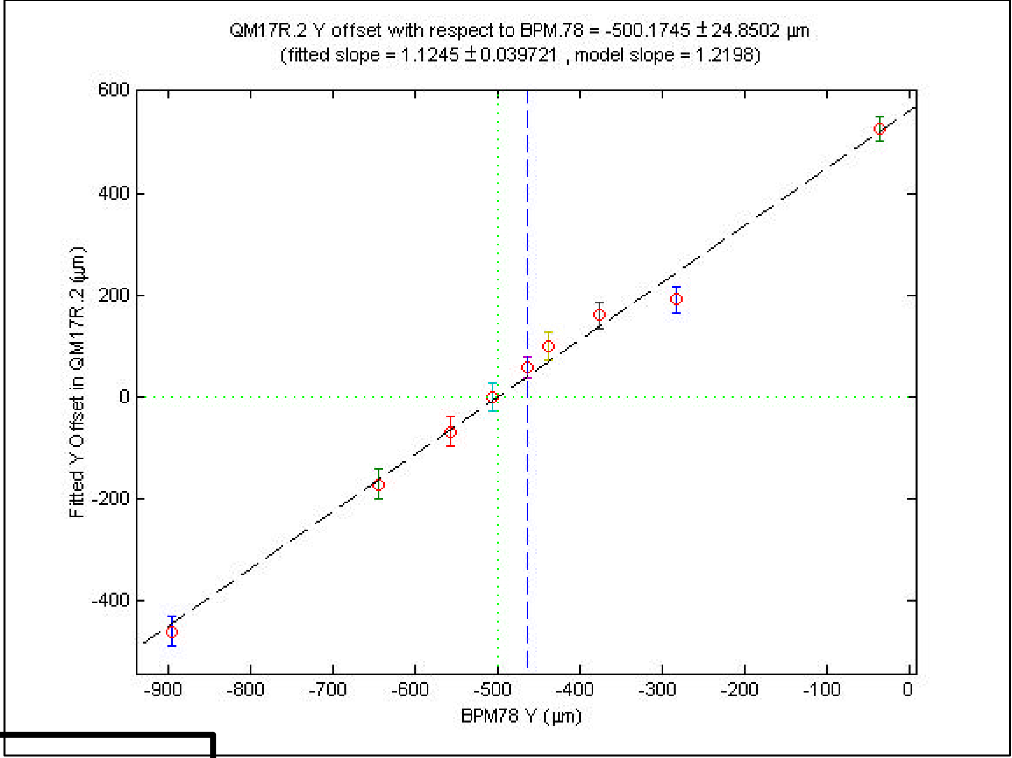
$$\eta_{rms} \approx 3mm$$

Measured Vertical Dispersion in DR



Beam-based alignment

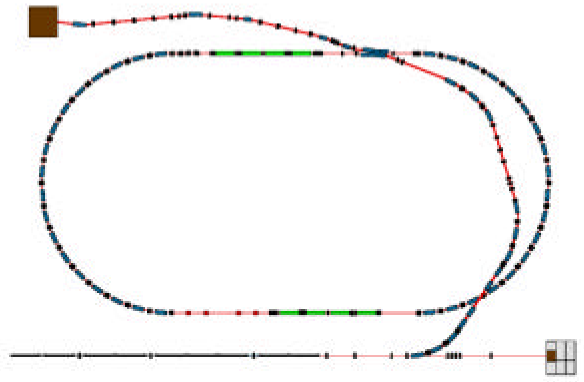
Each quad has an independent trim
Refit model for each qtrim setting
→for each of several local bump amplitudes, measure/fit qtrim kick:



Name	Data Taken On	Y Offset w.r.t. nearest BPM (µm)
QM17R.2	01APR18	-500.2 ± 24.9
QF2R.10	01APR26	+52.5 ± 11.9
QF2R.11	01MAY15	-161.6 ± 7.0
QF2R.12	01MAY15	-612.3 ± 25.9
QF2R.13	01MAY15	+160.9 ± 10.2
QM16R.2	01MAY15	-0.4 ± 4.2

Typical BBA resolution: 10µm
Quad/BPM Offset rms: 300µm

Repeatbility – not tested
BPMs ~100



Summary – single bunch low emittance

- relative growth *not* explained by aberrations in extraction line
- ring simulation indicates unreasonably small vertical emittance
- ring tuning relies on poorly optimized BPM system

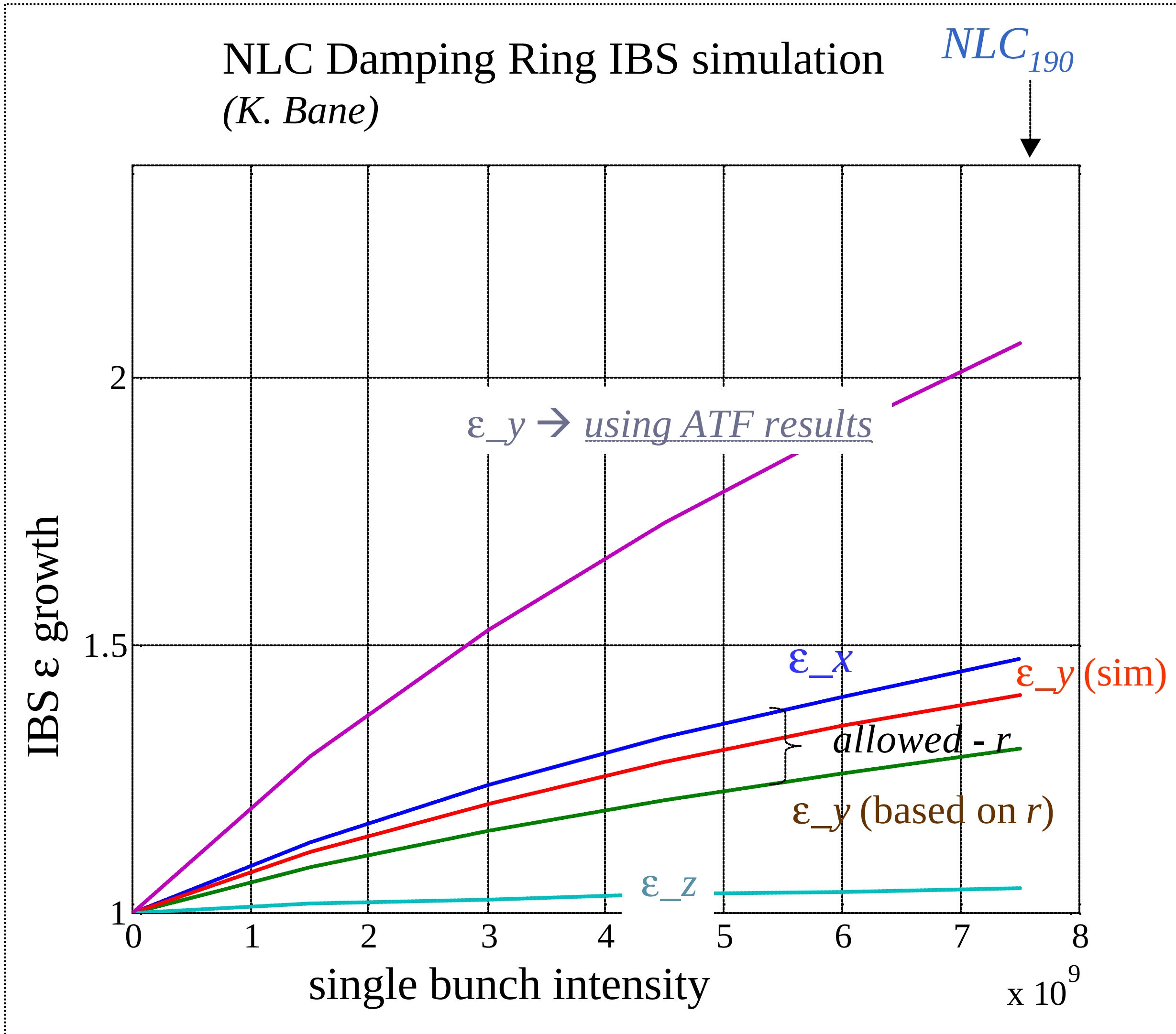
- Plans: → reduce coupling and speed up optimization
  - complete ring beam-based alignment
    - How realistic is the simulation input?
      - In particular the rotation estimates of ~ 1 degree for BPMs
  - BPM system improvements
    - extraction line (RF dipole mode cavity BPMs)
    - ring

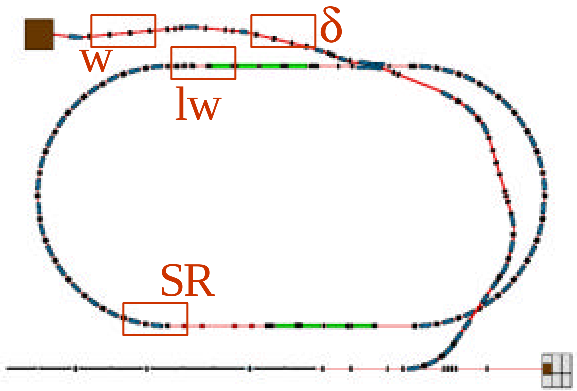
Single bunch study plans

- ZDR prediction for ε_x @ 2 GeV: ~ 20% growth at 1e10
  - What is the impact of the ATF result on the NLC damping ring design?
- ε_{yo} is too high
  - coupling and dispersion correction
  - BPM resolution and beam-based alignment
  - understanding of low intensity, low emittance instrument resolution
- Simulation done with equilibrium beam – not extracted beam (1.4 x)

$$r = \frac{(\varepsilon_y - \varepsilon_{y0})/\varepsilon_{y0}}{(\varepsilon_x - \varepsilon_{x0})/\varepsilon_{x0}}$$

NLC$_{95}$ →

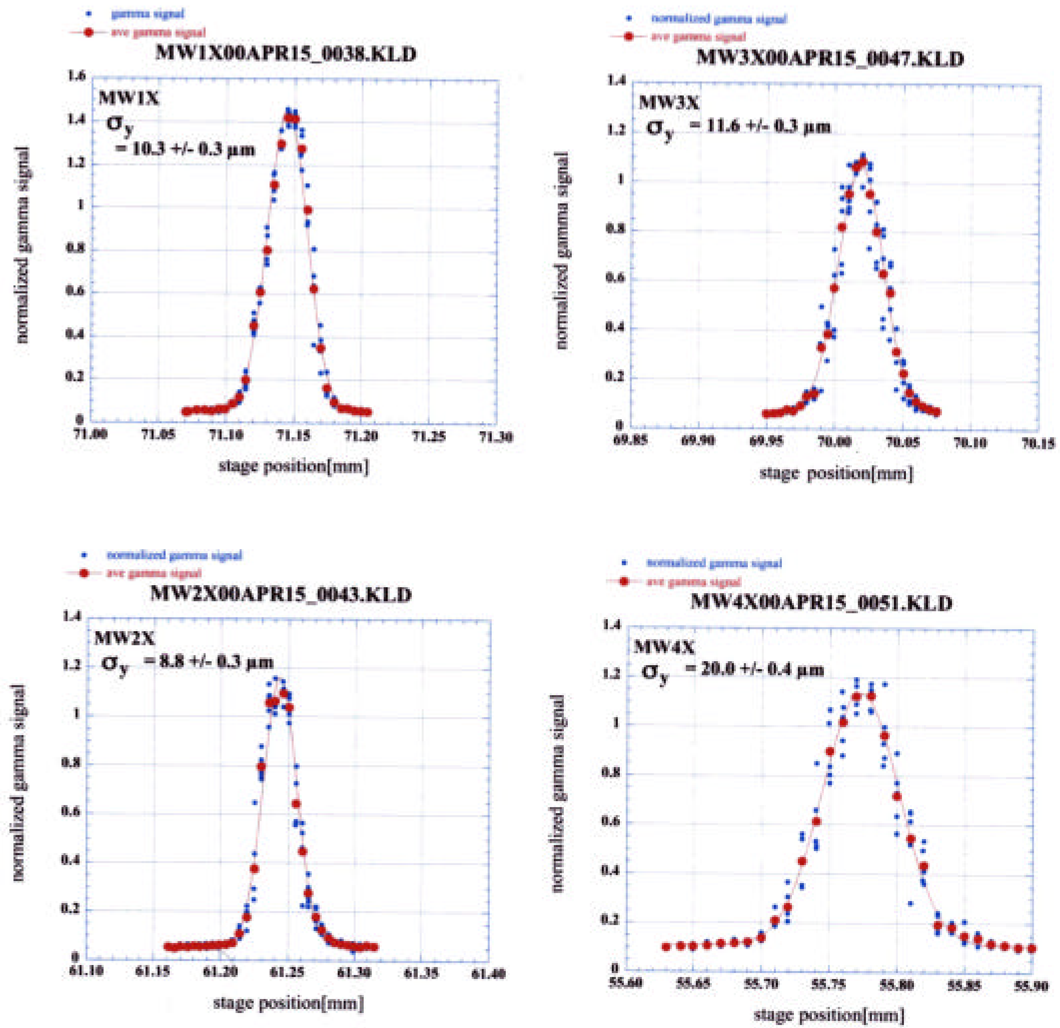


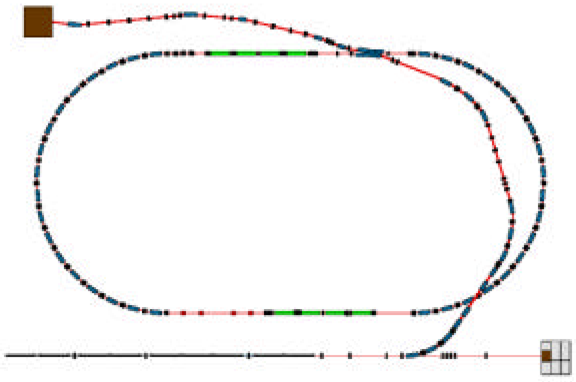


Emittance measurement devices

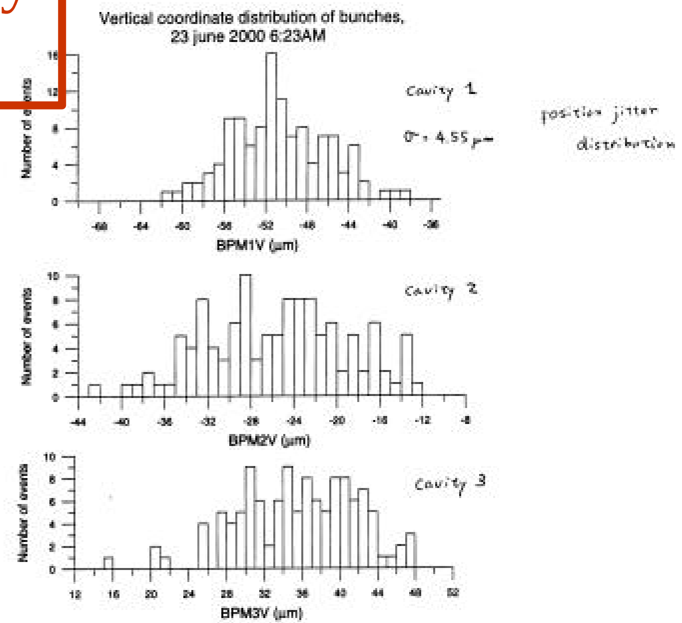
- wire scanners - in the extraction line…
  - few micron beam size resolution
  - 2-3 micron beam jitter
  - control of *h* to few mm
- laserwire – in the ring…
- energy spread – extraction line optics
- SR monitor (results not included)

Stability of beam size measurement by wire scanners



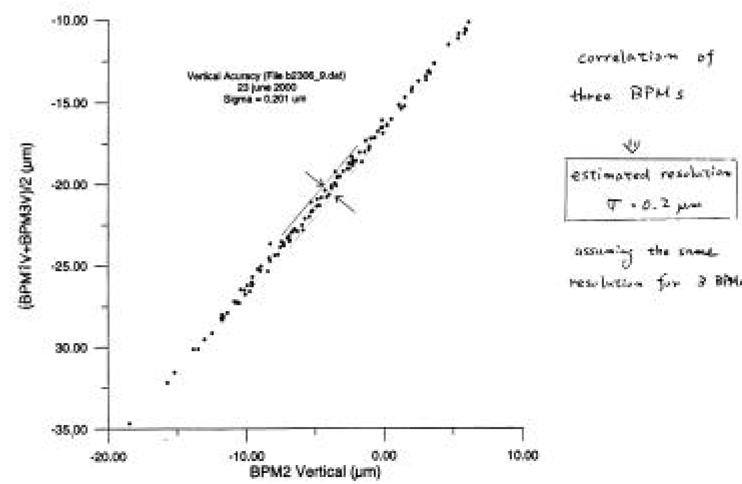


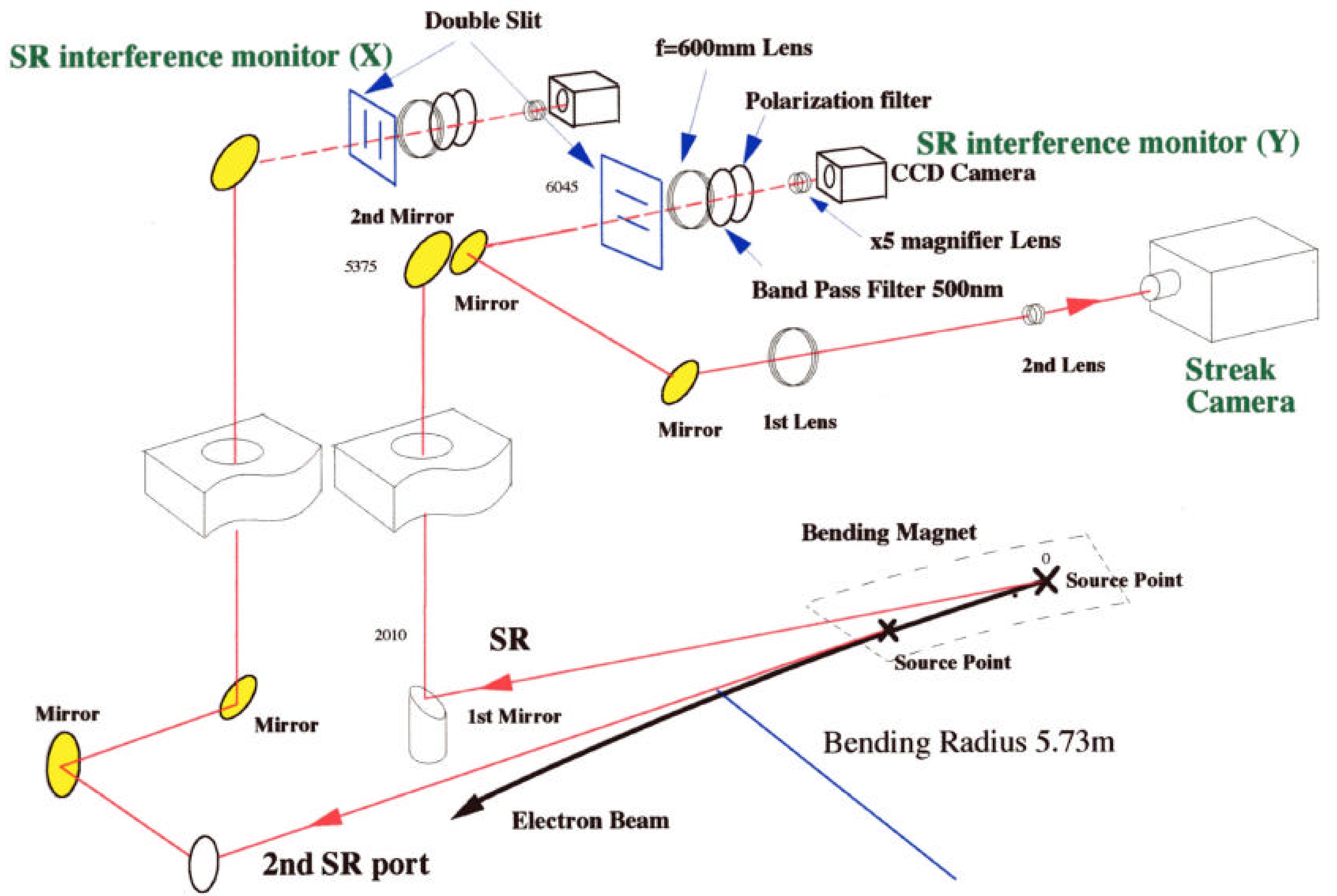
Extraction line cavity BPMs



- C-band
- Developed and built at Protvino
  - 6 ea installed 2001
- 200 nm resolution

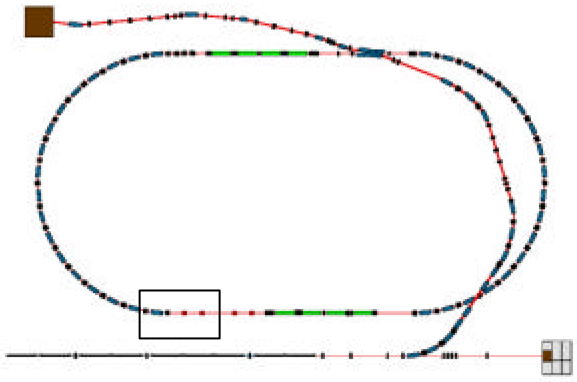
- show 4 µm rms beam centroid motion
  - (σ/3)





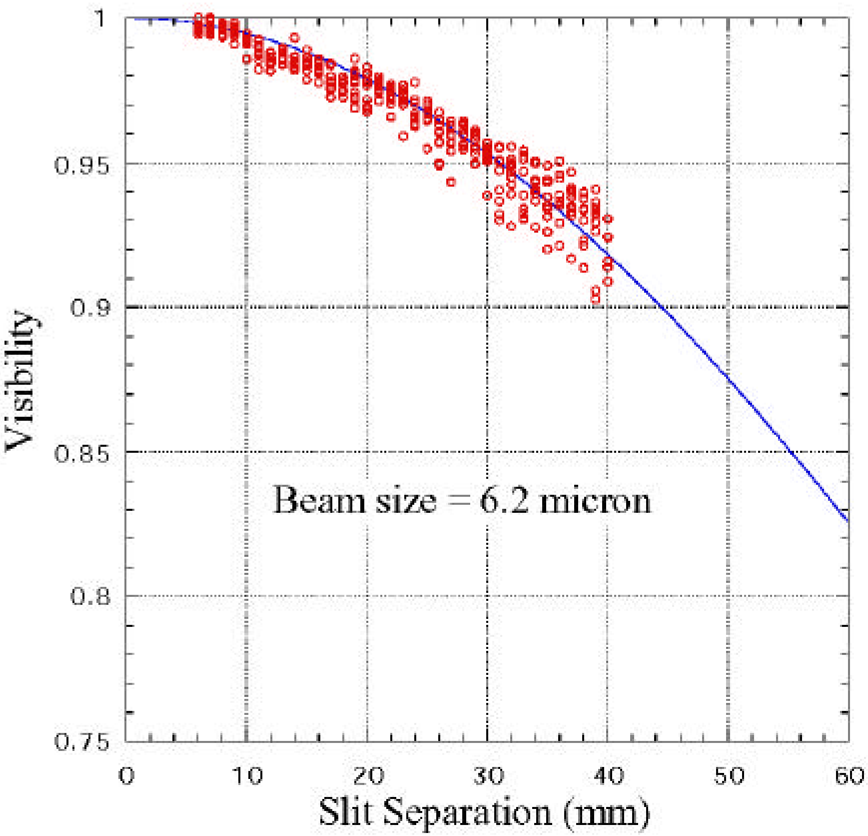
SR monitor optics set-up

2nd SR port in Oct. 2000



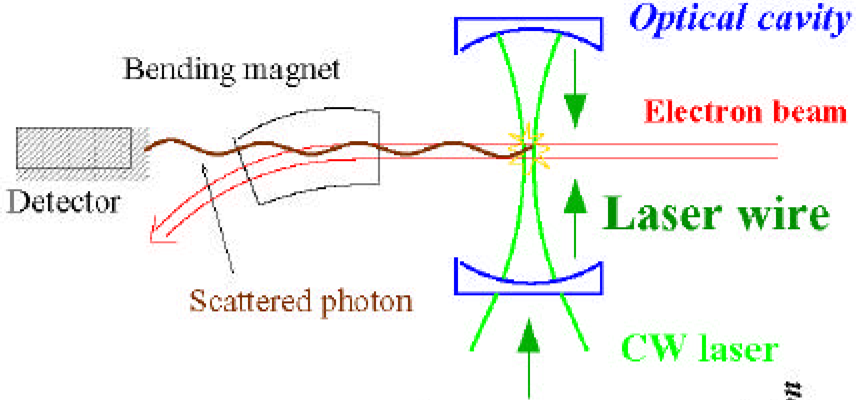
Synchrotron radiation interferometer

- measure depth of 2 slit modulation vs slit spacing
- 6.2 um
- ε_y ~ 1.6 e-11
- beats diffraction limit by ~ 6x
- Problems:
  - centering
  - stability (esp. vibration
  - mirror damage
  - no light at large angles (also apertures)

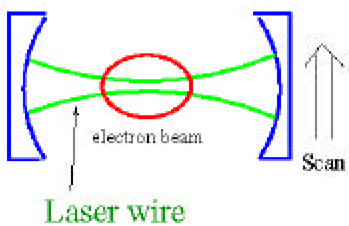


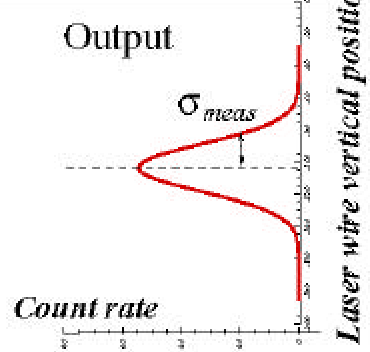
Ring laserwire

Principle of the laser wire



Front view

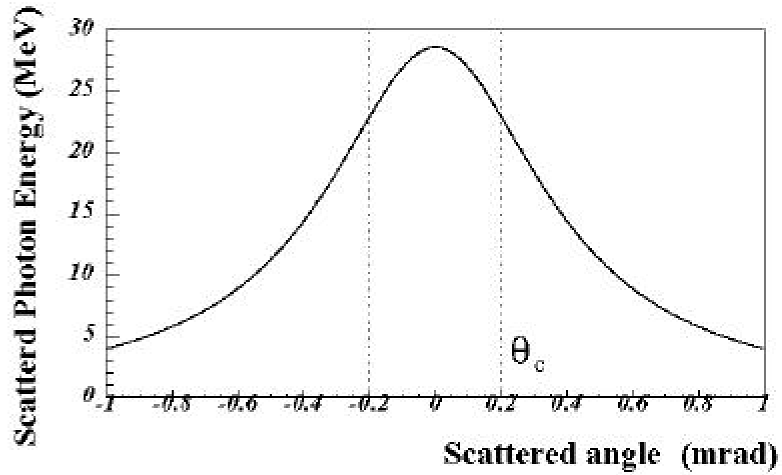




$$\sigma_{meas} = \sqrt{\sigma_y^2 + \sigma_{lw}^2}$$

Optical cavity realizes (***thin*** / ***intense***) ***Laser wire***

The energy of scattered photon vs the scattered angle



Count rate on Single bunch : N

$$N = \frac{W}{\sqrt{2\pi}\, h\nu\, c} \frac{N_e}{\sigma_{meas}} \int^{\theta_c} \frac{d\sigma_{compton}}{d\Omega} d\Omega$$

- N_e : *Number of electron* (10^{10})
- σ_{meas} : *Measured size* ($10\,\mu m$)
- W : *Laser intensity (10W)*
- $h\nu$: *Laser wave length (532nm)*

N = 1kHz

Written by H.Sakai

One scattered particle per 2000 turns

Ring laserwire raw data

Data taking procedure

1 Set the table position

2. Strage electron beam in damping Ring.

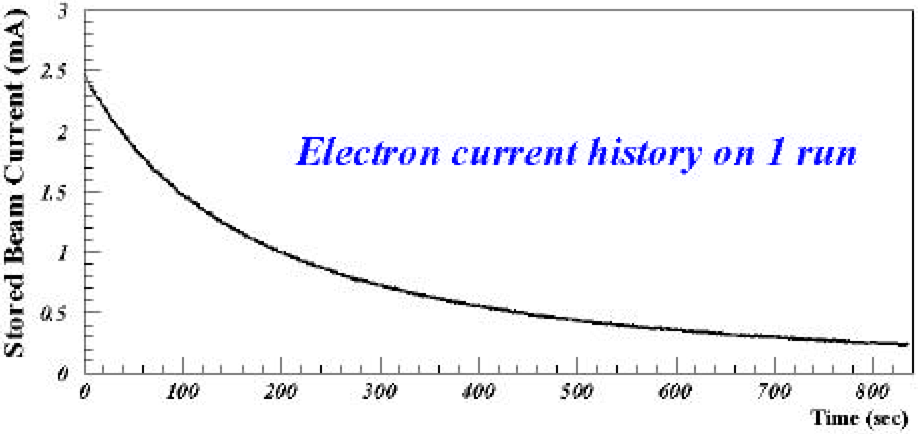
3. Data taking every 1 second

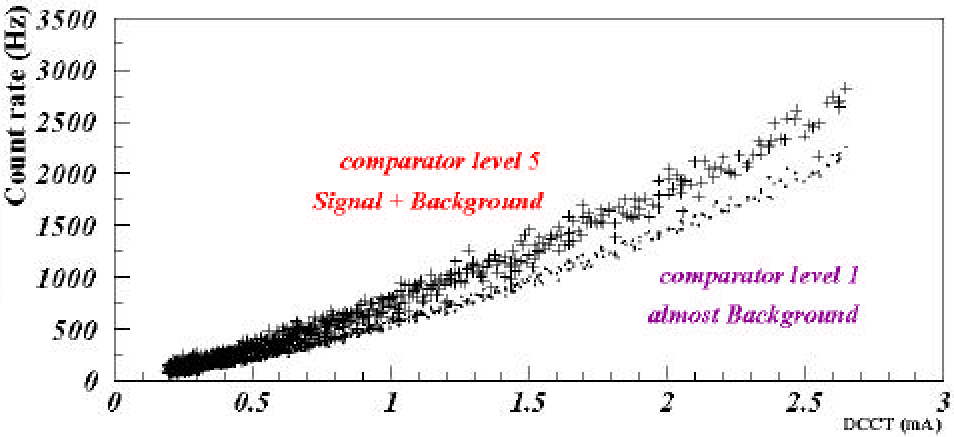
4. Finish the data taking after 10-15 minute.

5 Change the table position

6. Continue from 2. to 5. until getting the beam profile

1 run corresponds to the procedure 2.-5.





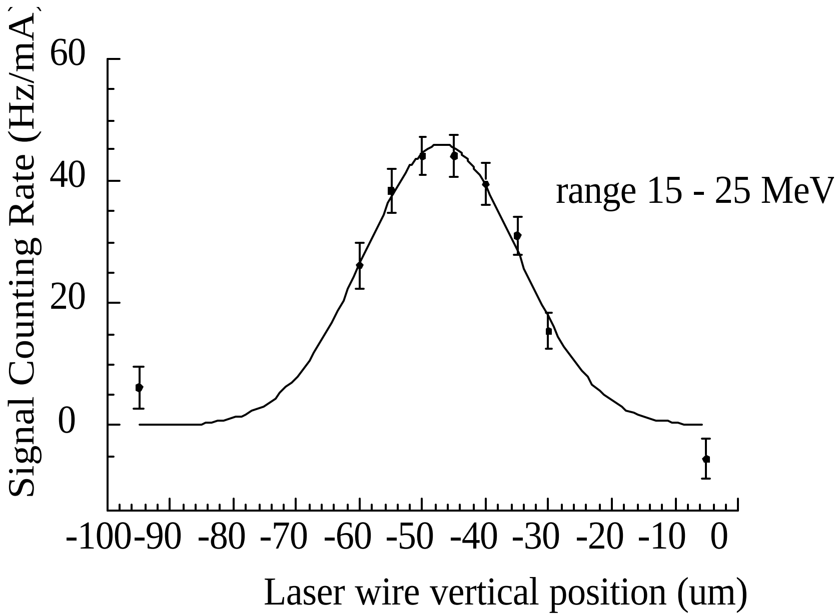
Count rate on each comparator level on 1 run

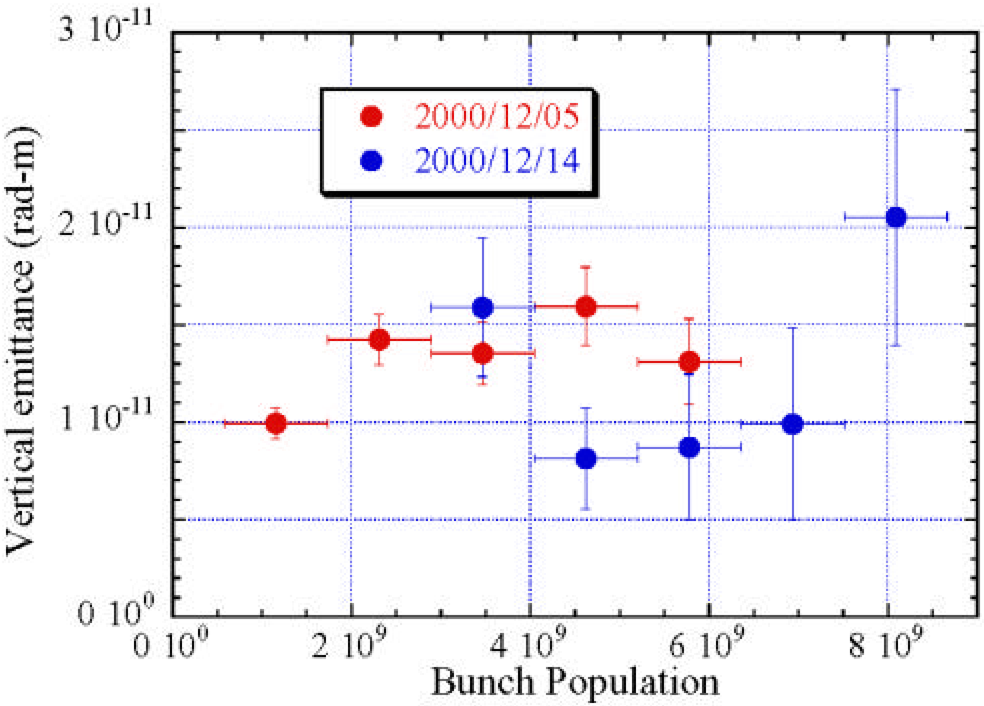
Comparator ~ compton energy discriminator

Written by H.Sakai

Ring Laserwire monitor

- Resonant cavity close to focus cut-off
  - uses CW laser
  - cavity gain 300
  - measurement ~ 1 hour

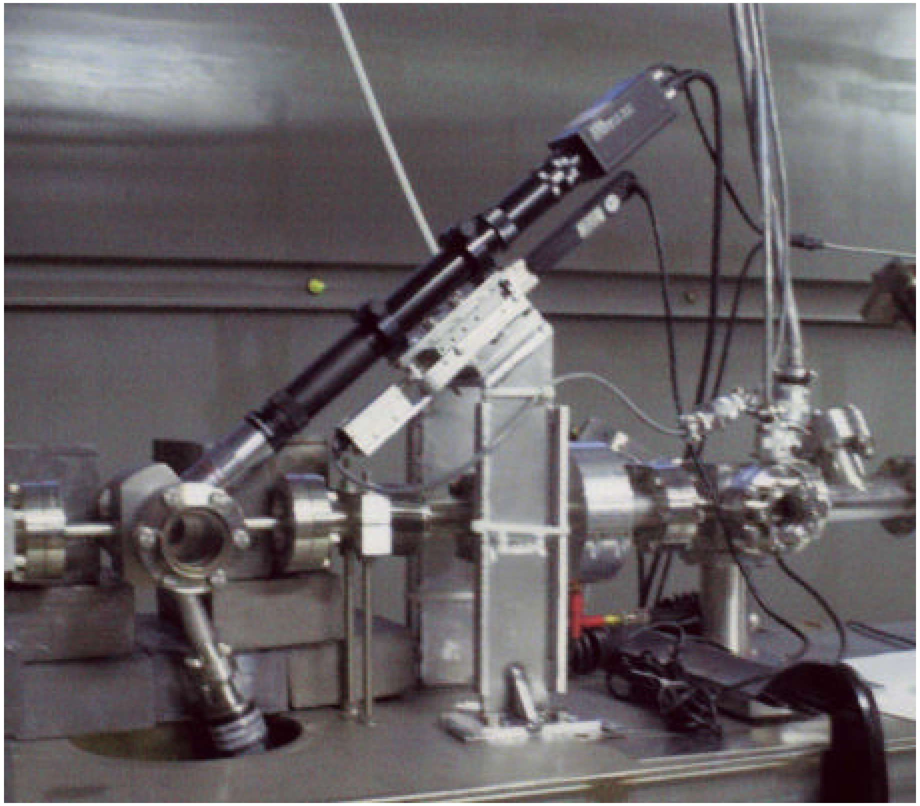




Development of a transition radiation profile monitor -OTR

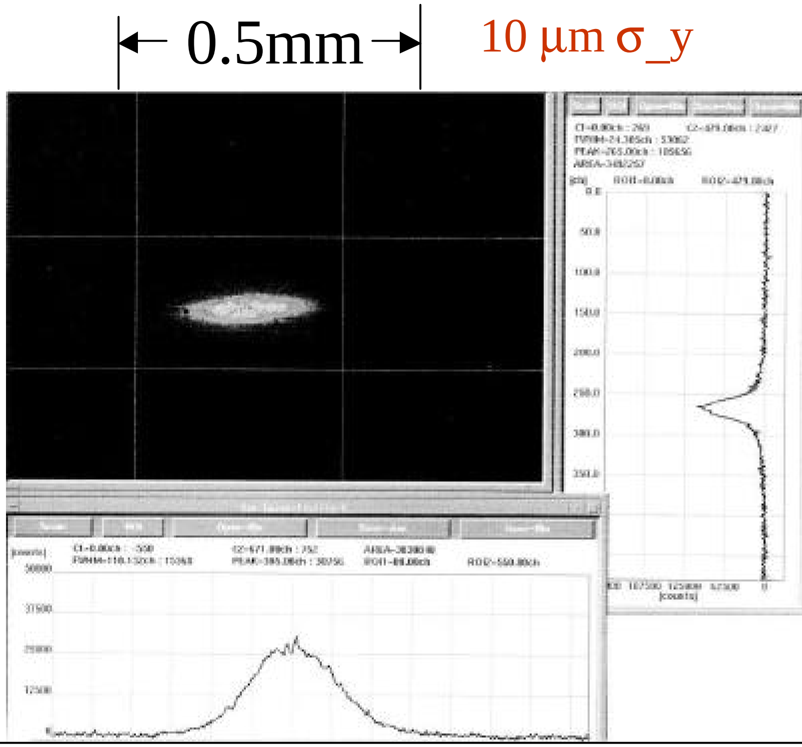
- some controversy over minimum resolvable beam image
  - achieved 7μm (12/00) well beyond purported limit – *OTR provides light at very large angles → high resolution*
  - much better than synchrotron radiation
  - smallest OTR spot imaged to date
- theoretical limit: ~ λ

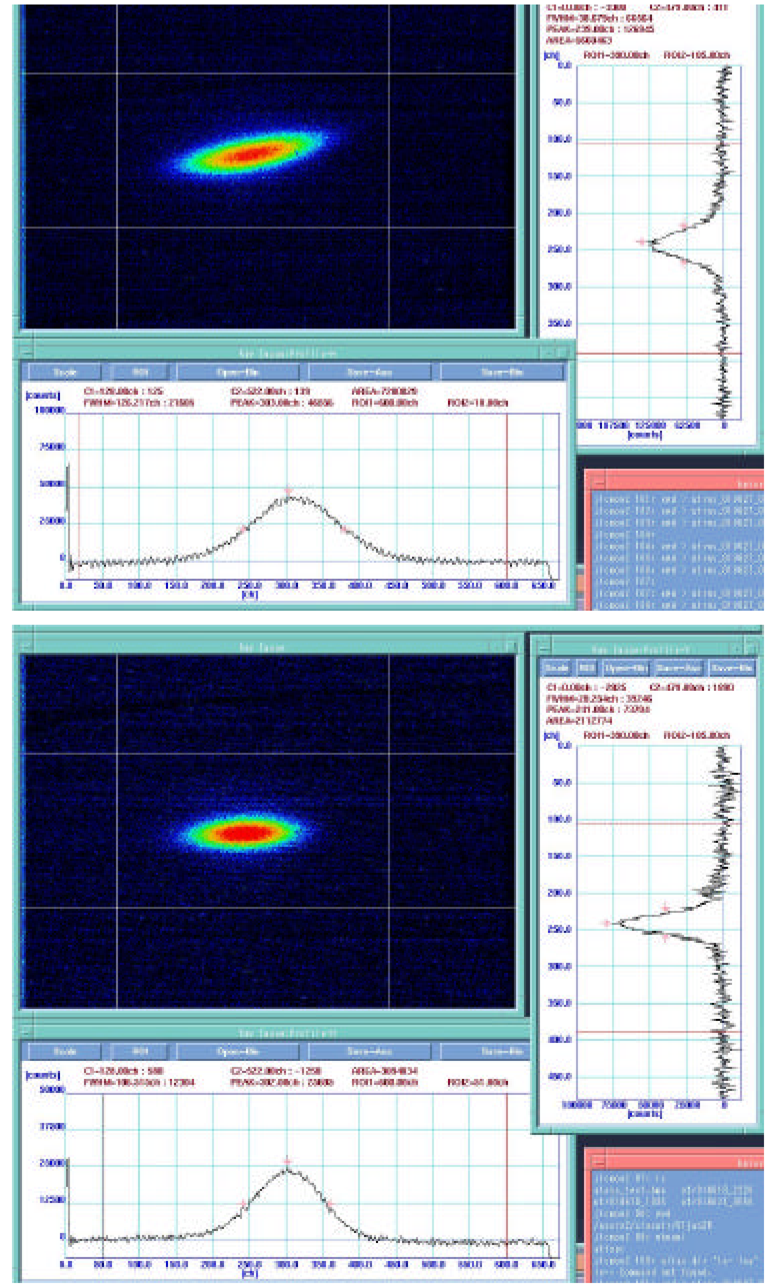
- Parameters for ATF OTR (built at SLAC)
  - resolution – 2μm
  - field of view – 300 x 200 μm (or ~2x)
  - depth of field – 8 μm vertical displacement
  - OK light for normal camera – 5e9 ppb
  - Industrial microscope objective
  - 35 mm working distance
  - various target materials



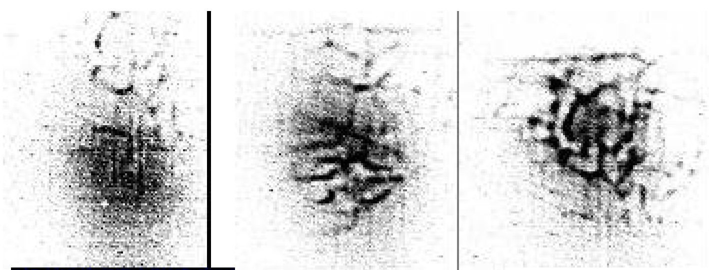
SLAC–built very high resolution OTR

OTR images & target damage

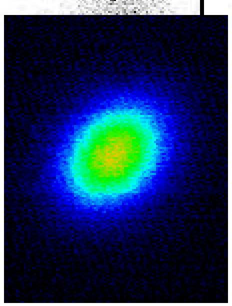




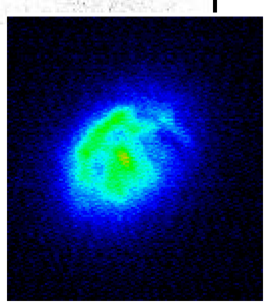
successive images illustrating damage:

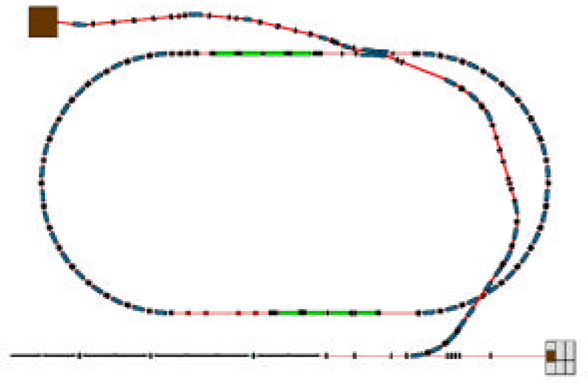


Cu
7e9
20x12µm

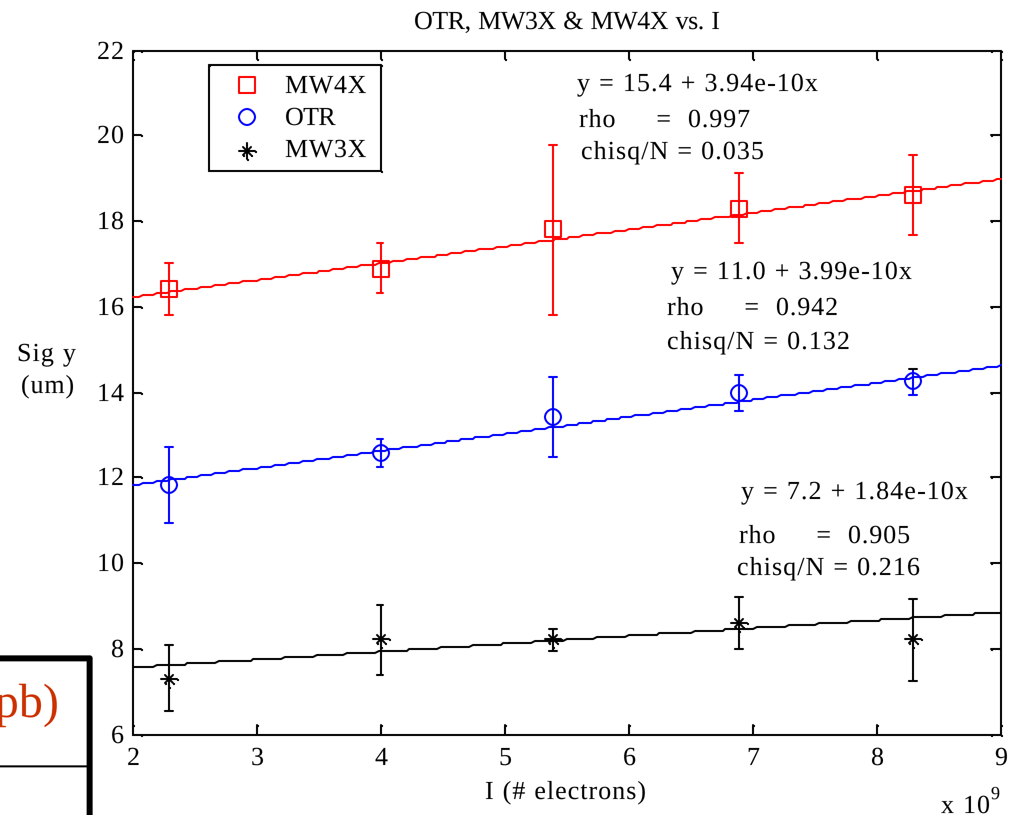


Be 5e10
10x13µm





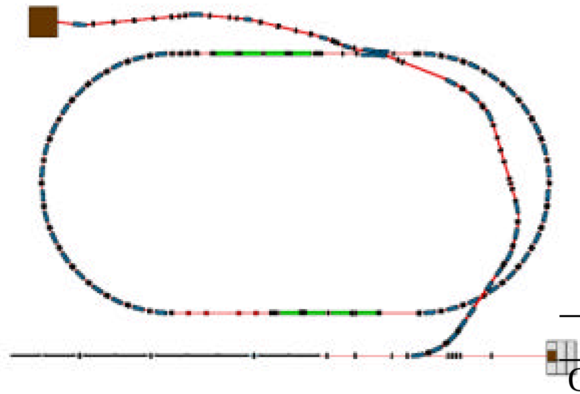
Be OTR and wire scanner *vs* I



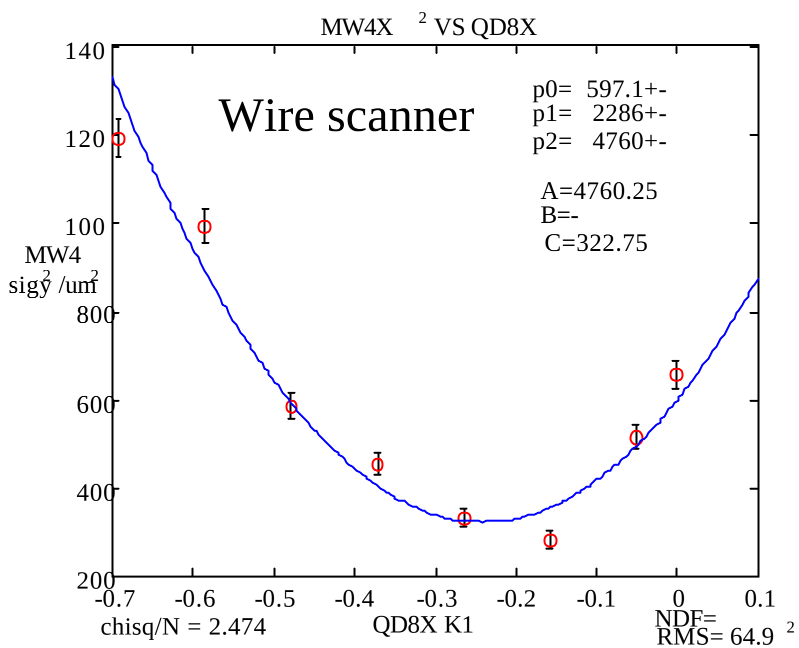
IBS is incoherent, beam size growth slope should be the same at all scanners

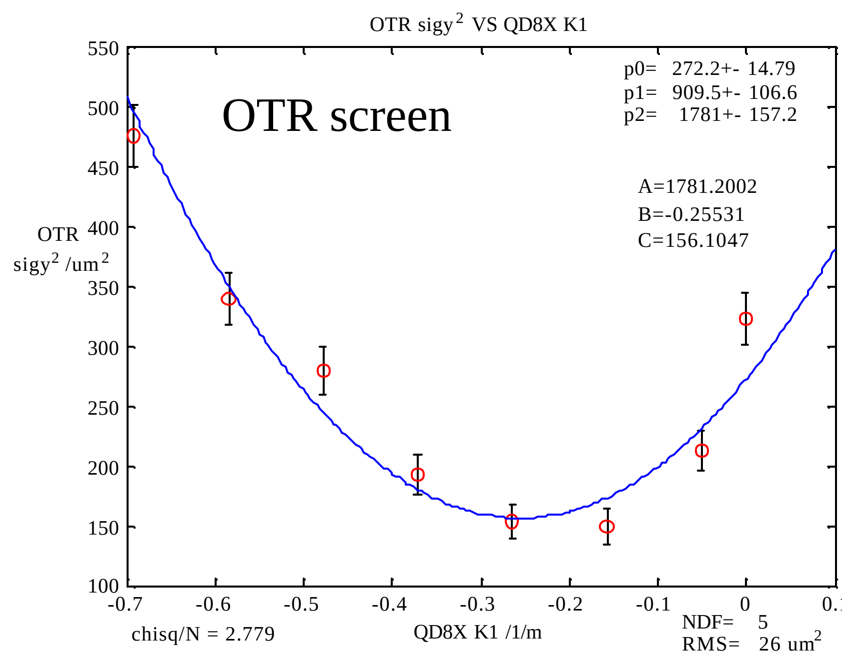
Monitor	Slope – σ_y / I (ppb)
WS – MW4X	3.94 μm/ 1e10
WS - MW3X	1.84
OTR Imager	3.99

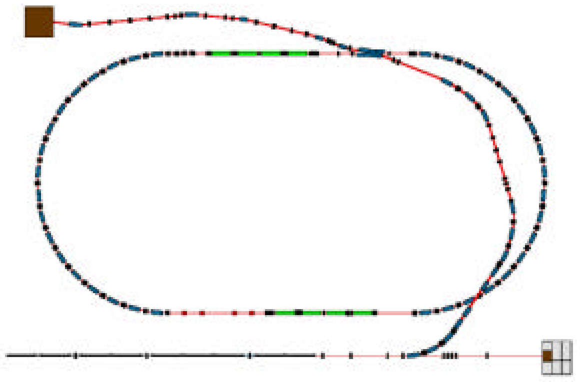
Quad-emittance scan – OTR and nearby wire scanner



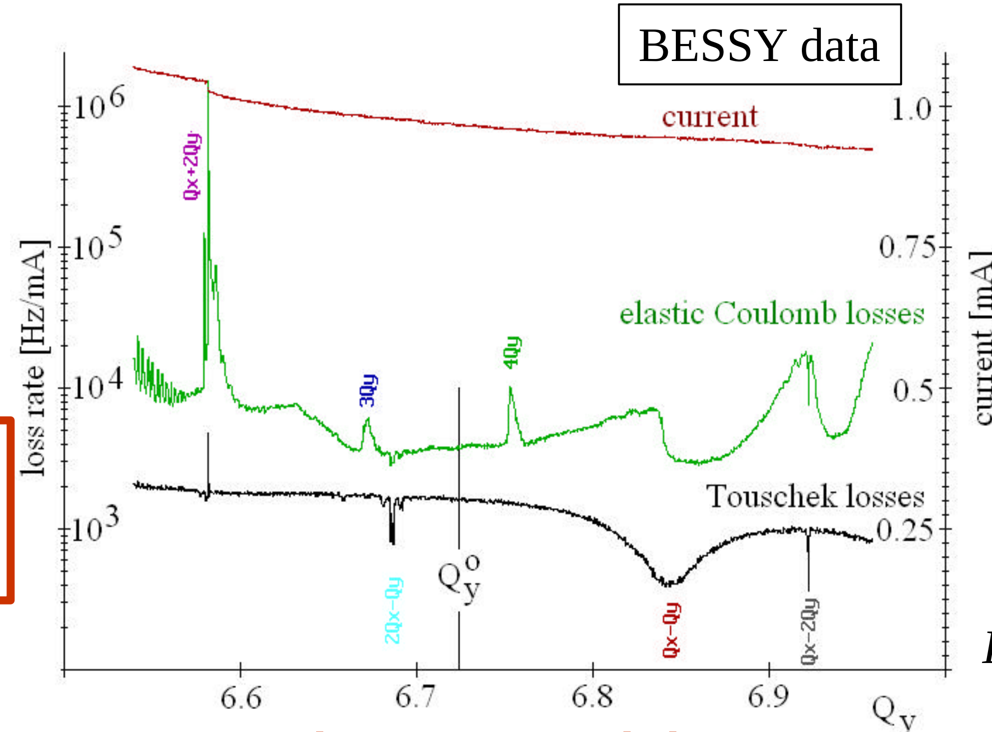
Device	ε_y	Comments
OTR	27 ± 1 pm	quad scan
OTR no tilt	18 ± 1 pm	Tilt removed from Y scans
MW3X	22 ± 1 pm	quad scan
MW4X	28 ± 1 pm	quad scan
5 wire	26 ± 1 pm	multi-wire scan





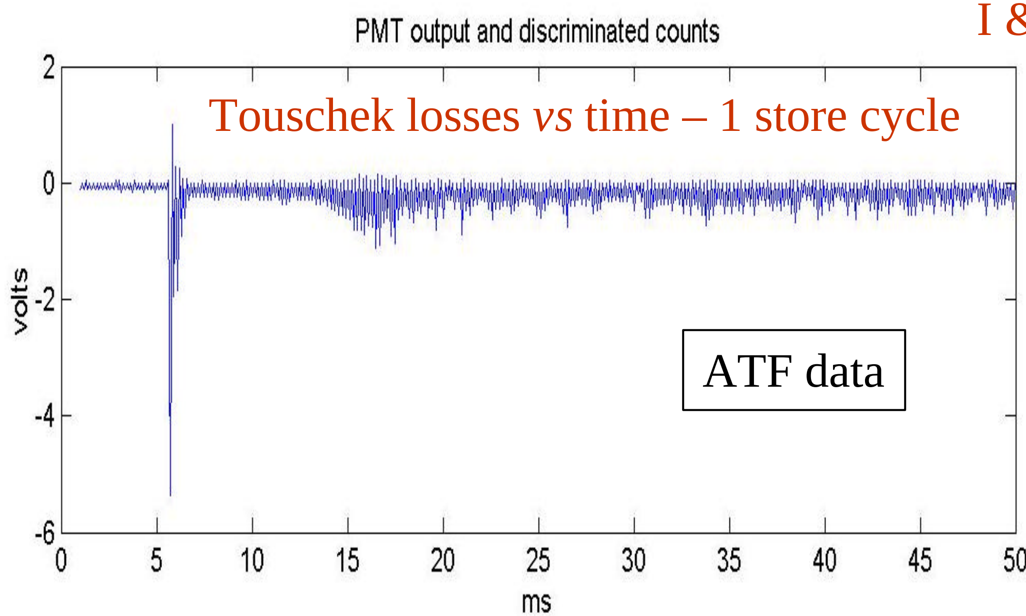


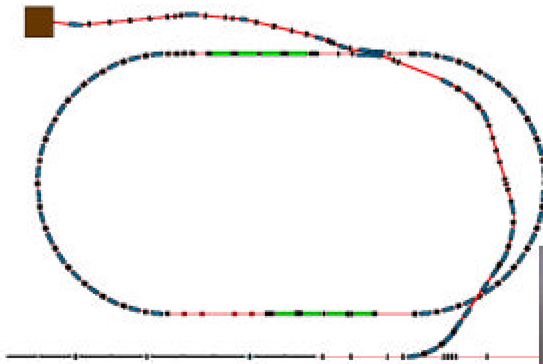
Beam Dynamics from Loss monitors - BESSY



P. Kuske

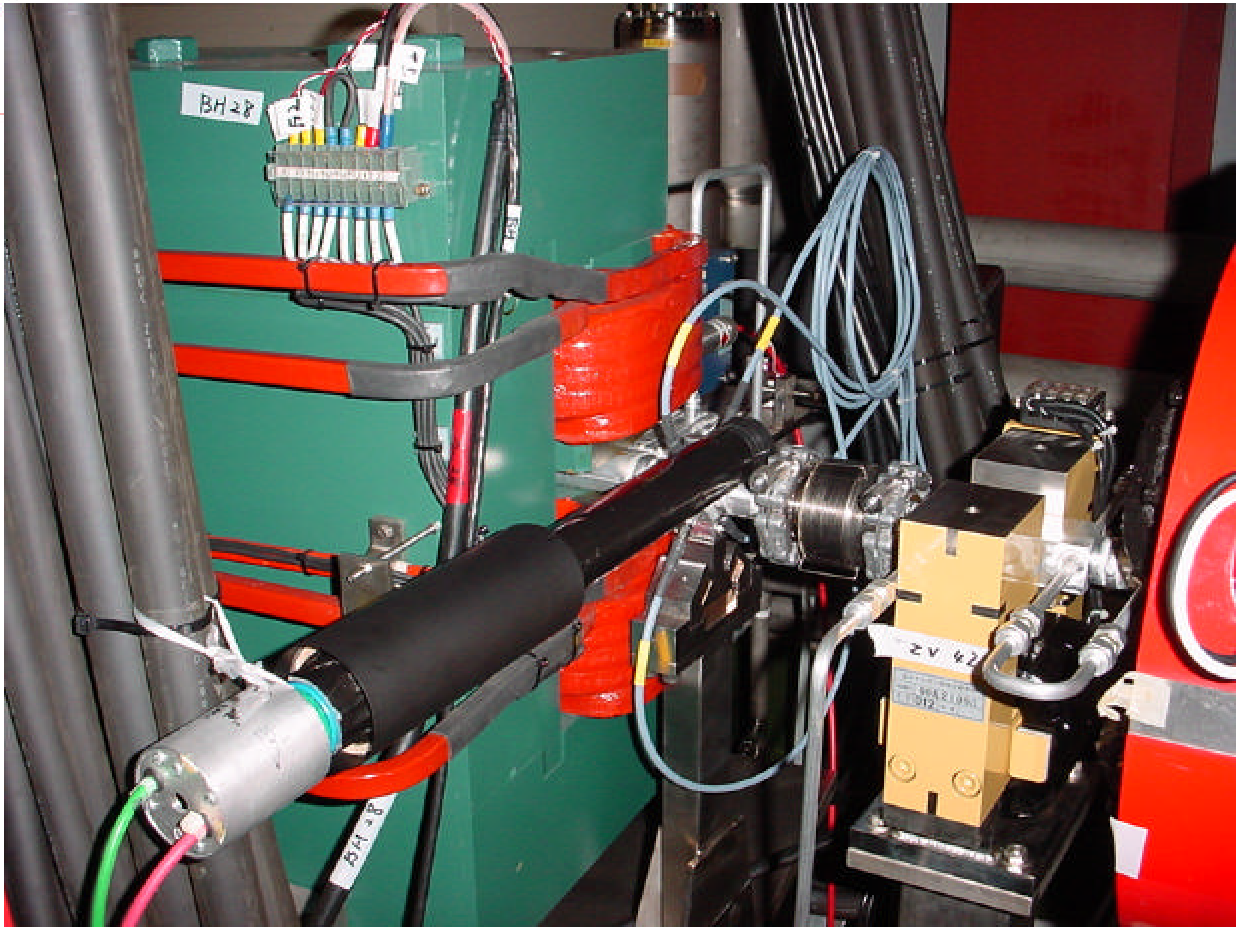
I & bm-gas &Touschek Losses vs tune





ATF loss monitor counter installation

BESSY loss monitors mounted in pairs to count Touschek coincidences



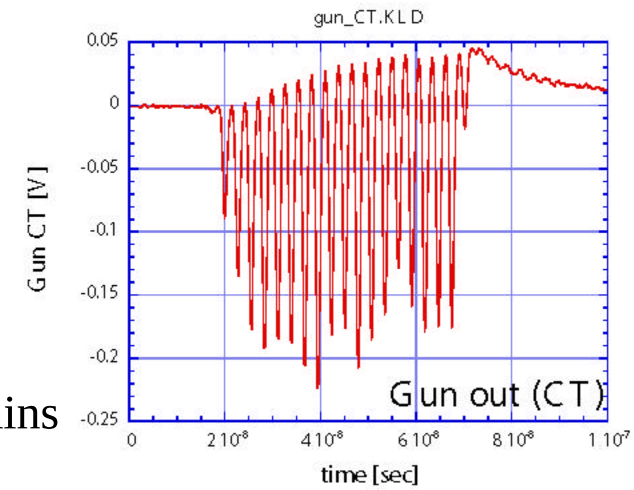
Multi-bunch operation

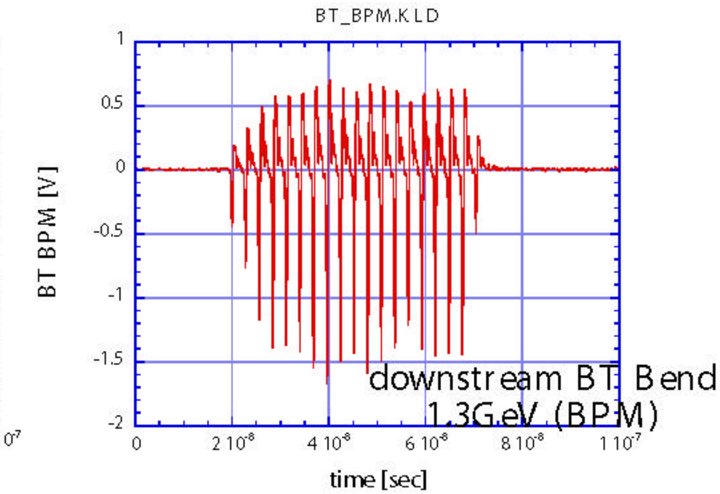
Multi-bunch
intensity *vs* time

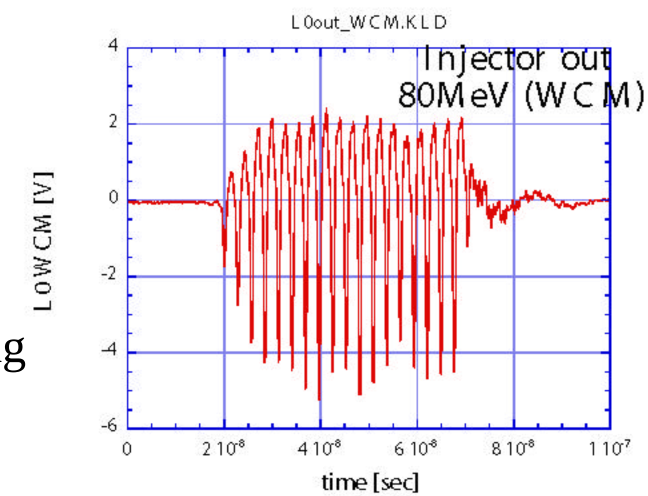
ATF multi-bunch parameters:

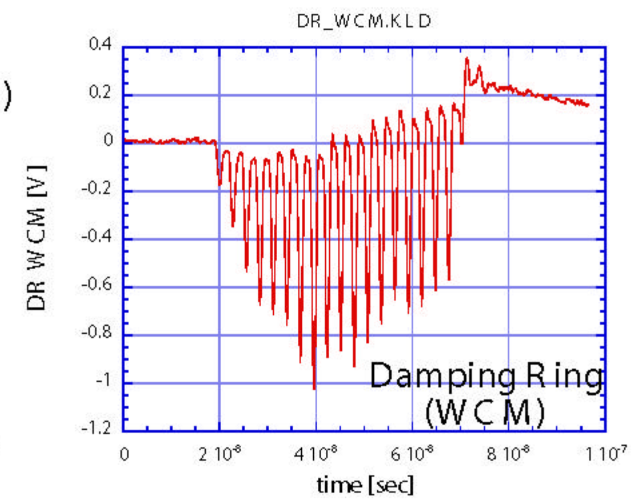
- up to 4 each 20-bunch trains
- bunch spacing 2.8 ns
- typical I/bunch ~ ¼ of single bunch ops

- Focus so far:
    - Instrumentation
    - Throughput
    - Source / linac loading compensation
        - Gun pulser distortion
        - SHB loading



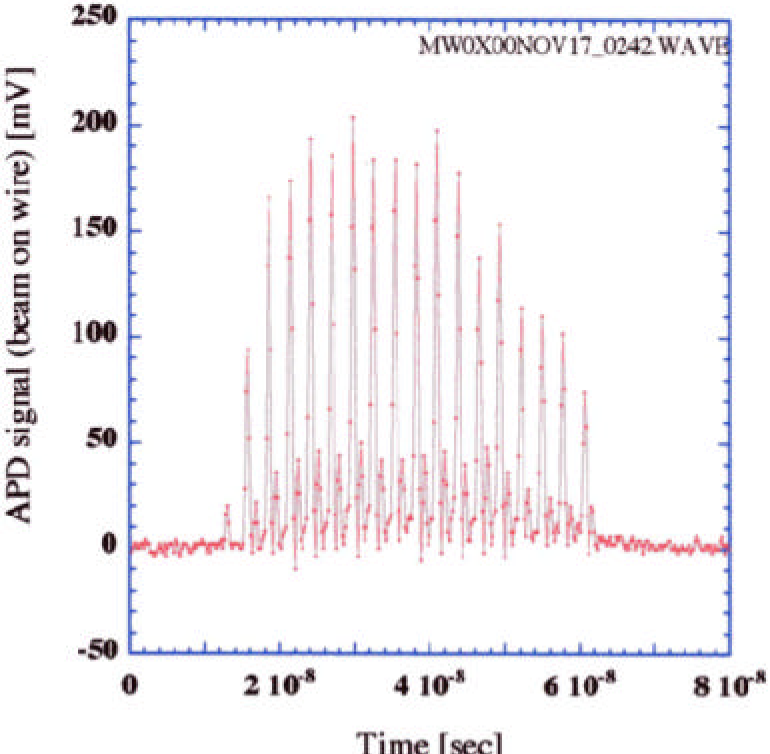


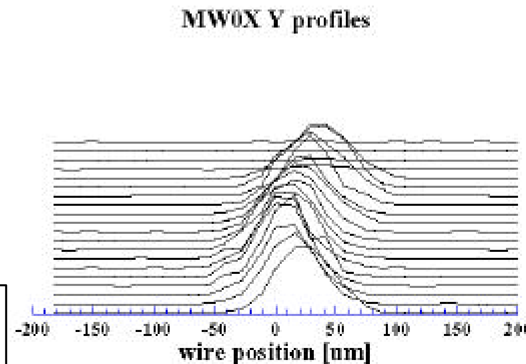


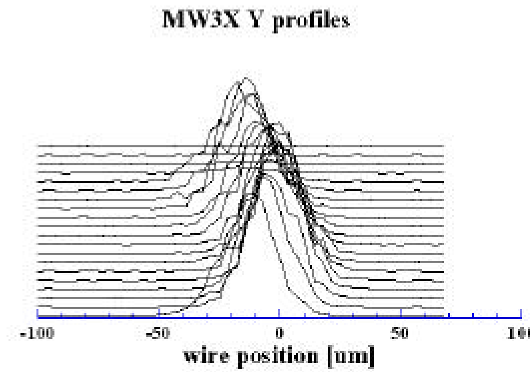


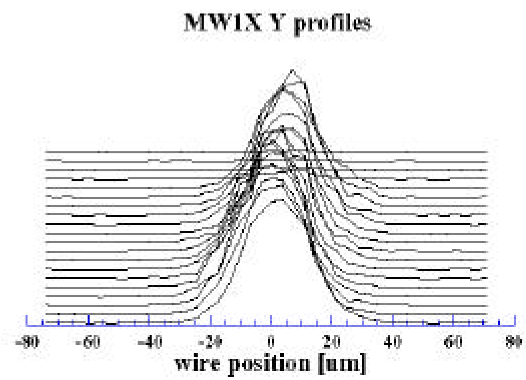
Multi-bunch operation- extraction line wire scans

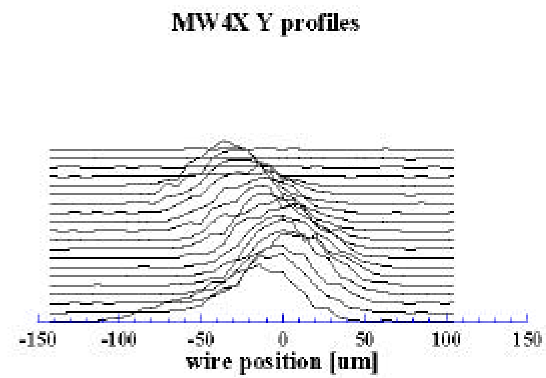
Cerenkov light from avalanche photodiode – all bunches scanned at once



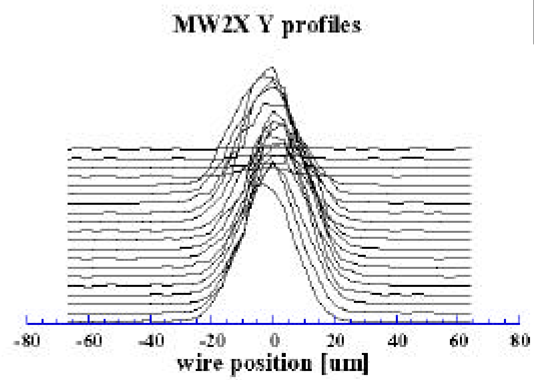








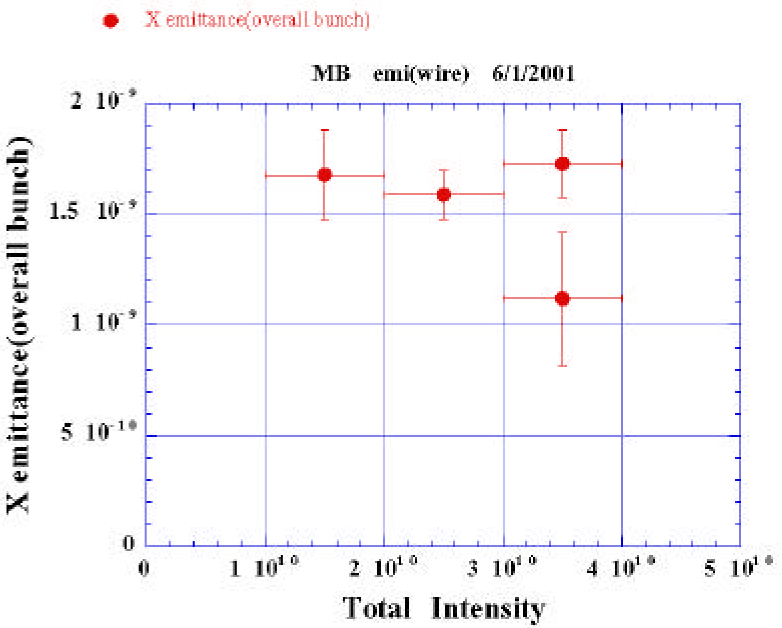
Distortion caused by ?

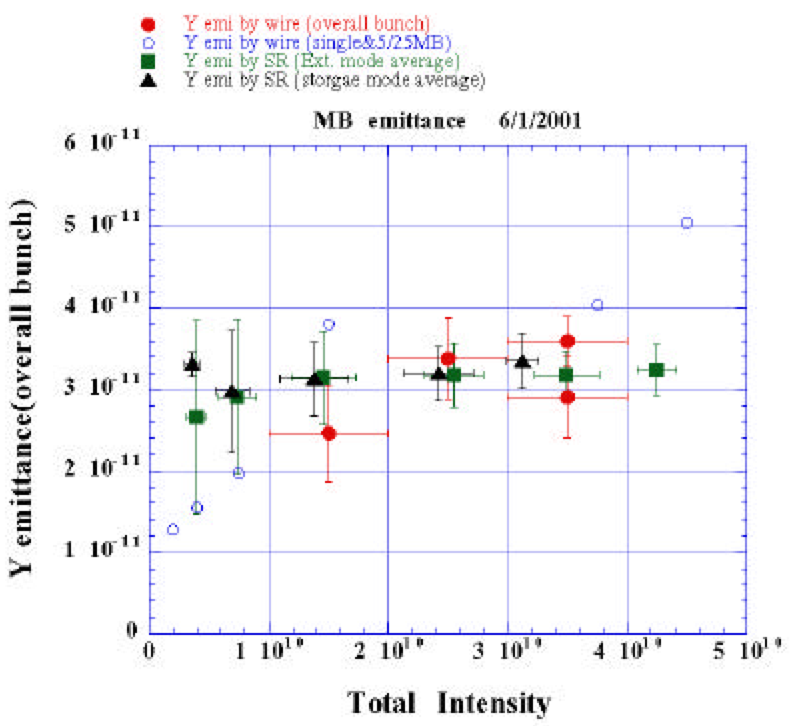


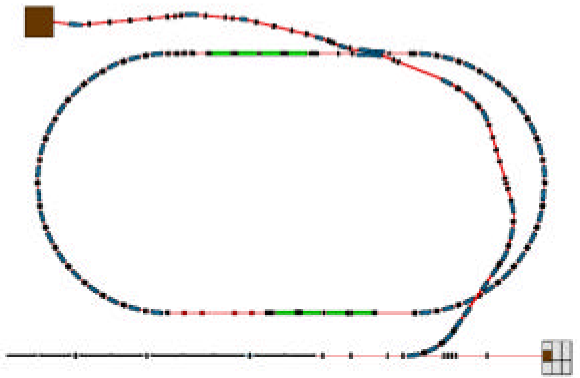
6/21/2001 multibunch wire scan

Multi-bunch operation-extraction line wire scans

- 20 bunches; typical single bunch Imax ~ 2.5e9 (4x lower than single bunch
- ε_y increases 1.5x
- vacuum system improved 2001



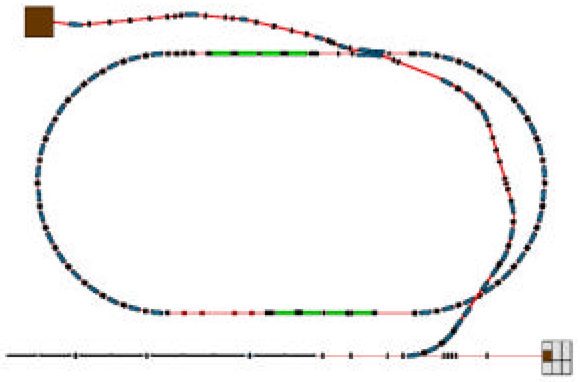




ATF Operation

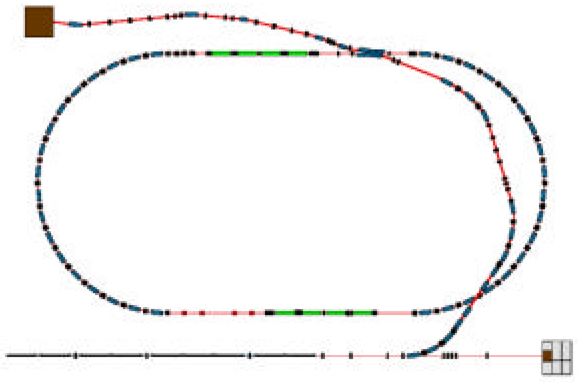
- ATF operates 20 weeks/year for a 4 1/3 day block /week
  - ~ 2 wks on/ 2 wks off (startup effects are significant)
- Users (~ students) get about 1/4 time
  - Effective uptime ~ 55 days/year
- Stability is critical for ~10 pm emittance
  - Typical beam sizes are 50 x 8 µm
- Single shot BPM resolution is ~15µm
- Beam pulse rate is 1.5 Hz

- Precise measurements require long periods of checking/setup



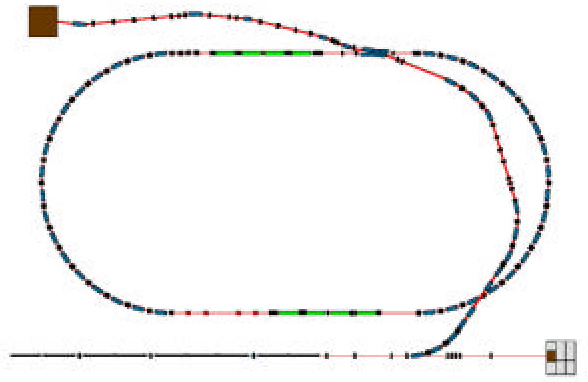
ATF Support

- Operation is limited by funds (KEK) and manpower (KEK)
  - ~10 physicists (6 FTE) + 8 graduate students
  - SLAC participation began 1997
    - 1 FTE average by ~ 8 SLAC staff travelling to ATF
    - ~ 100K$ / year for hardware development
  - Contributions from Japanese universities and BINP/Protvino
  - Minimal involvement from other labs (CERN, DESY…)



ATF Plans

- ATF is the only LC test facility with capability for transverse beam dynamics studies
  - collective effects, tolerances, optimization, control, stability, technology…
  - dynamics of small beams is critical for all proposed LCs
- ATF will be used for pioneering physics research and engineering development studies
  - We must examine ways to extend ATF for the study of LC emittance propagation



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照沼　信浩
内藤　孝
栗木　雅夫
奥木　敏行
峠　暢一

荒木　栄
大森　恒彦
阪井　寛志
酒井　いずみ
今井　貴之
福田　将史
本田　洋介
武藤　俊哉
P. Karataev

(___ → helped with presentation)