John Adams Institute for Accelerator Science

Imperial College London

Royal Holloway University of London

UNIVERSITY OF OXFORD

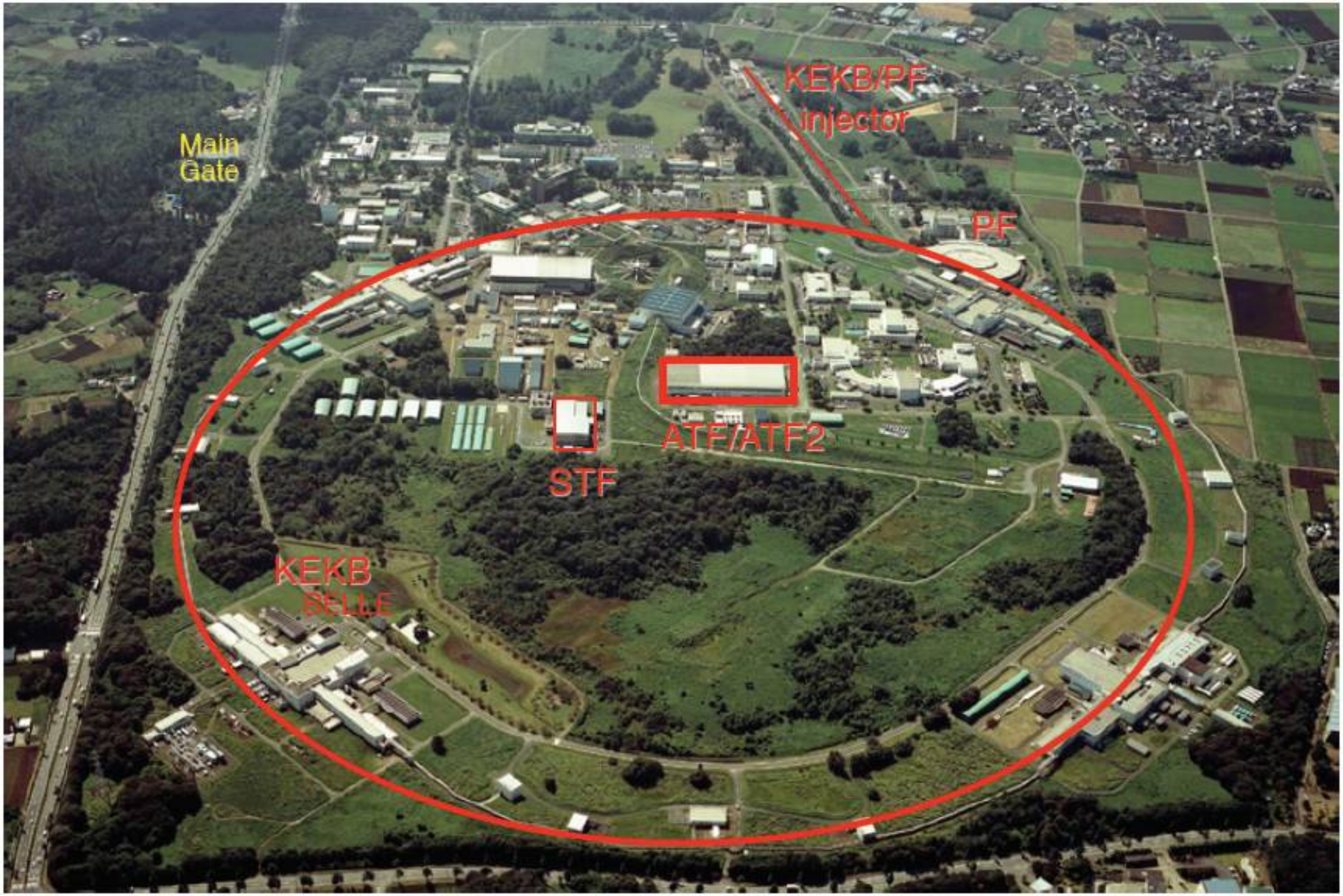
Experimental and Theoretical Progress LC Final Focus Design and ATF2 Facility

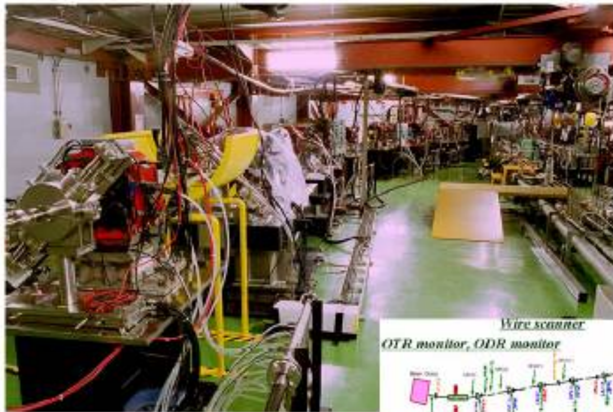
Andrei Seryi

John Adams Institute for Accelerator Science

for the ATF/ATF2 international collaboration

EAAC2013

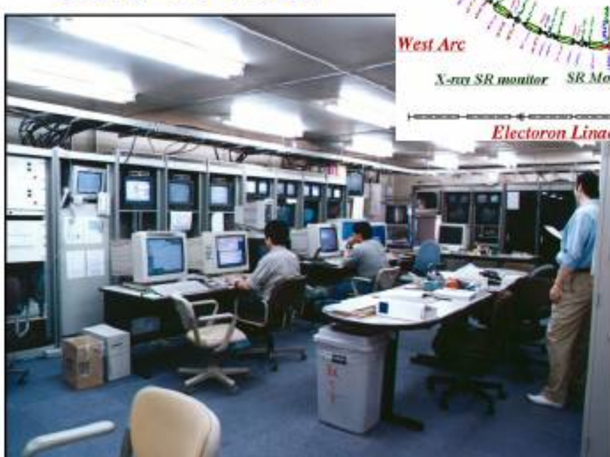

KEKB/PF
injector
Main
Gate
PF
ATF/ATF2
STF
KEKB
BELLE

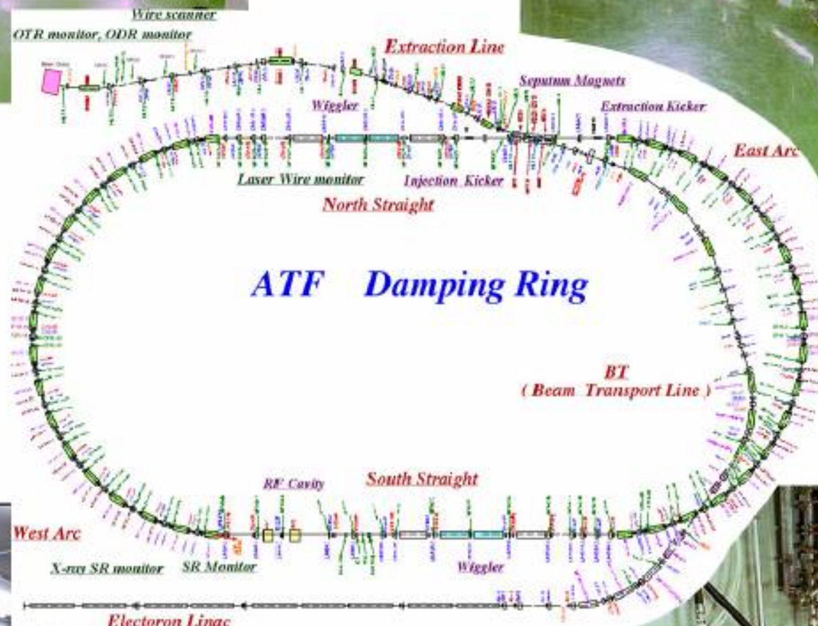


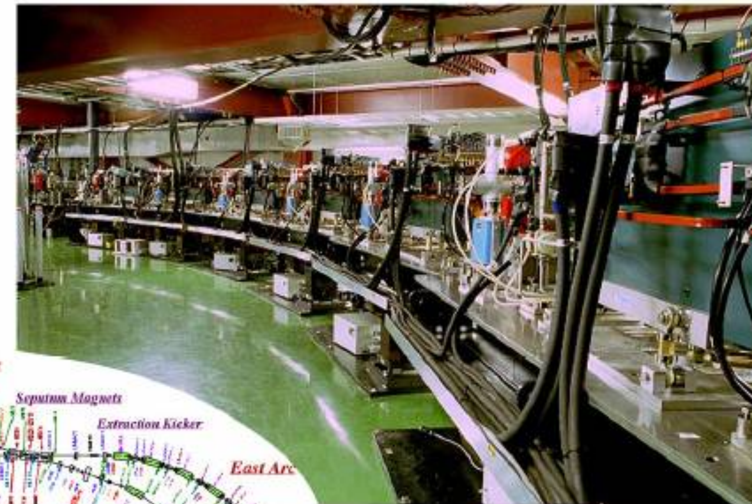
Extraction Line

ATF and ATF2

Control Room



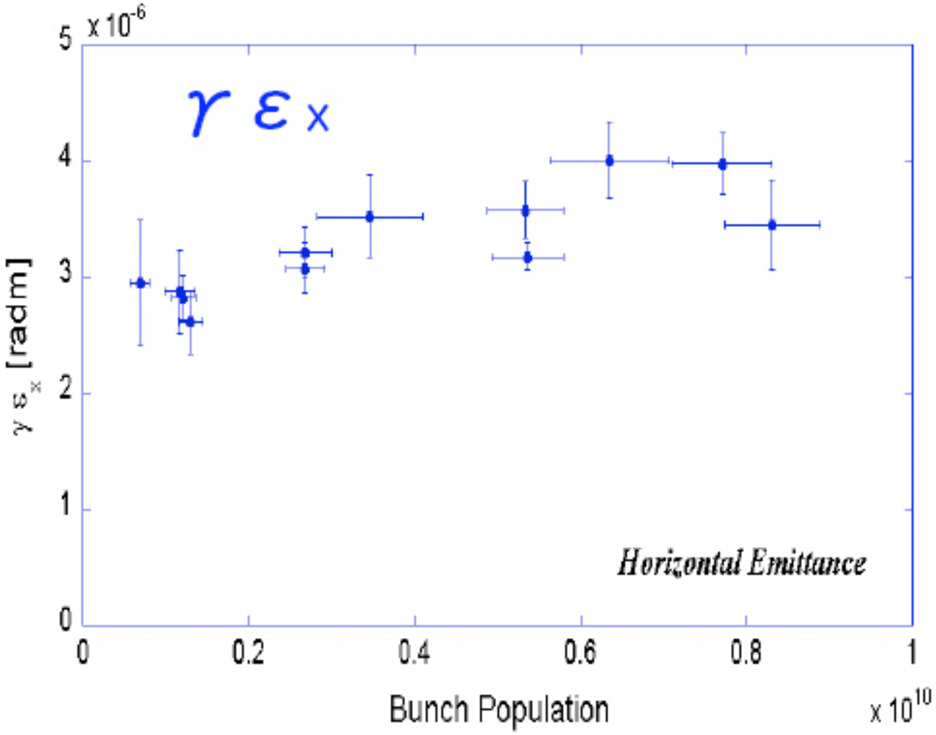


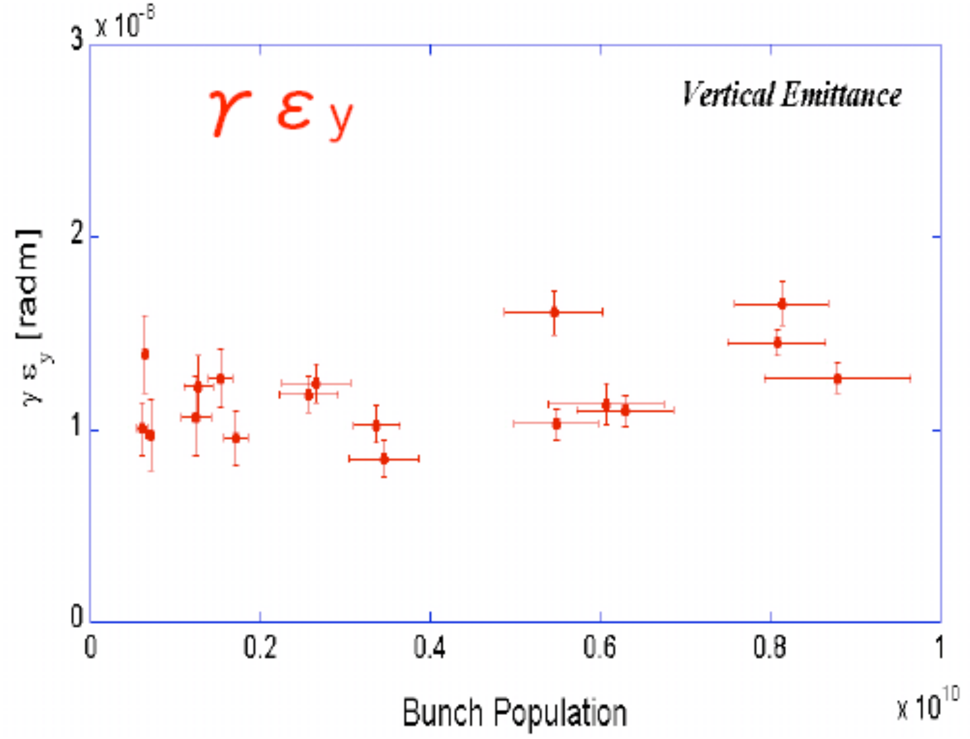


Damping Ring

Linac

Low emittance in ATF

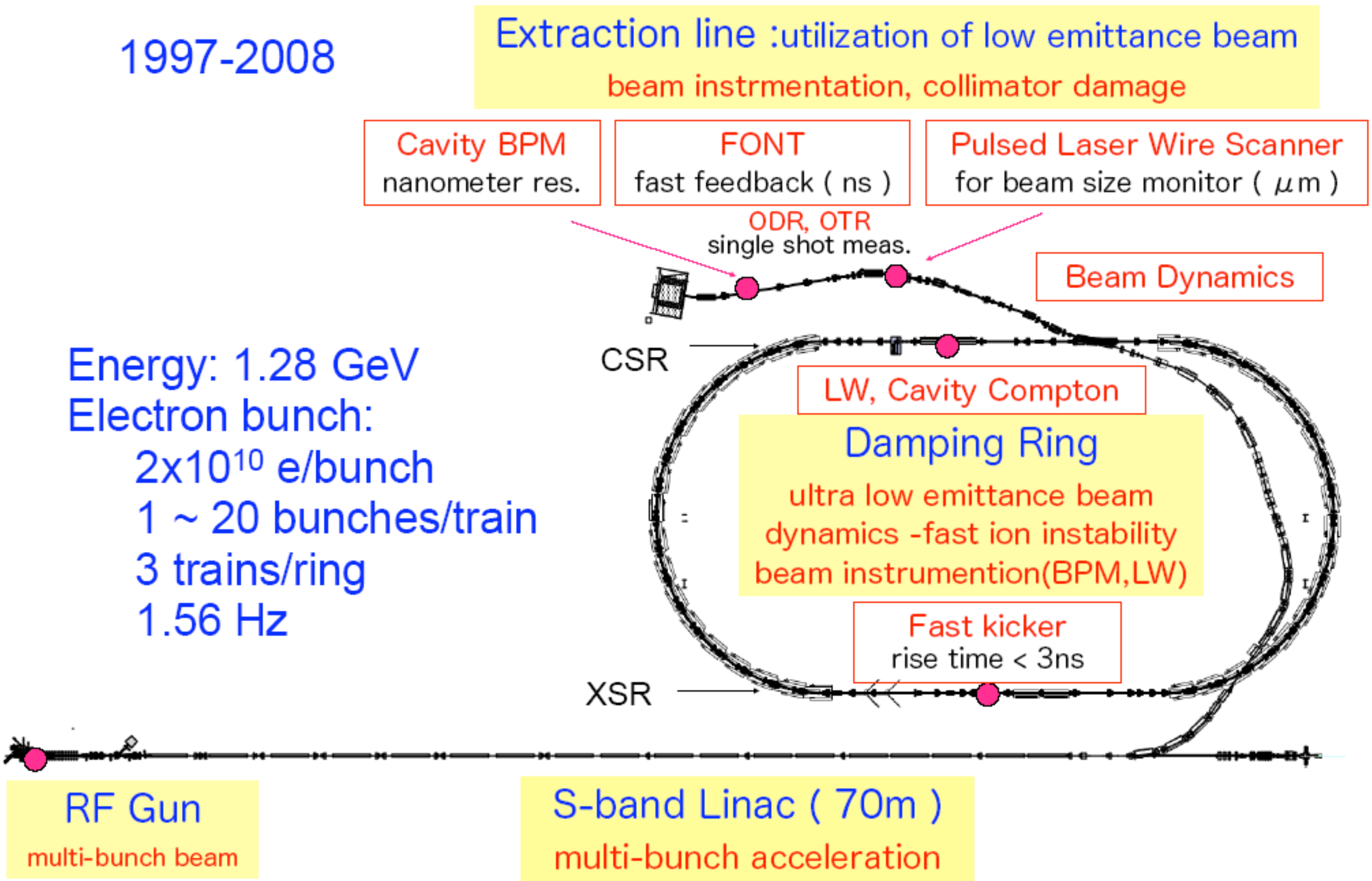




Accelerator Test Facility, KEK

1997-2008

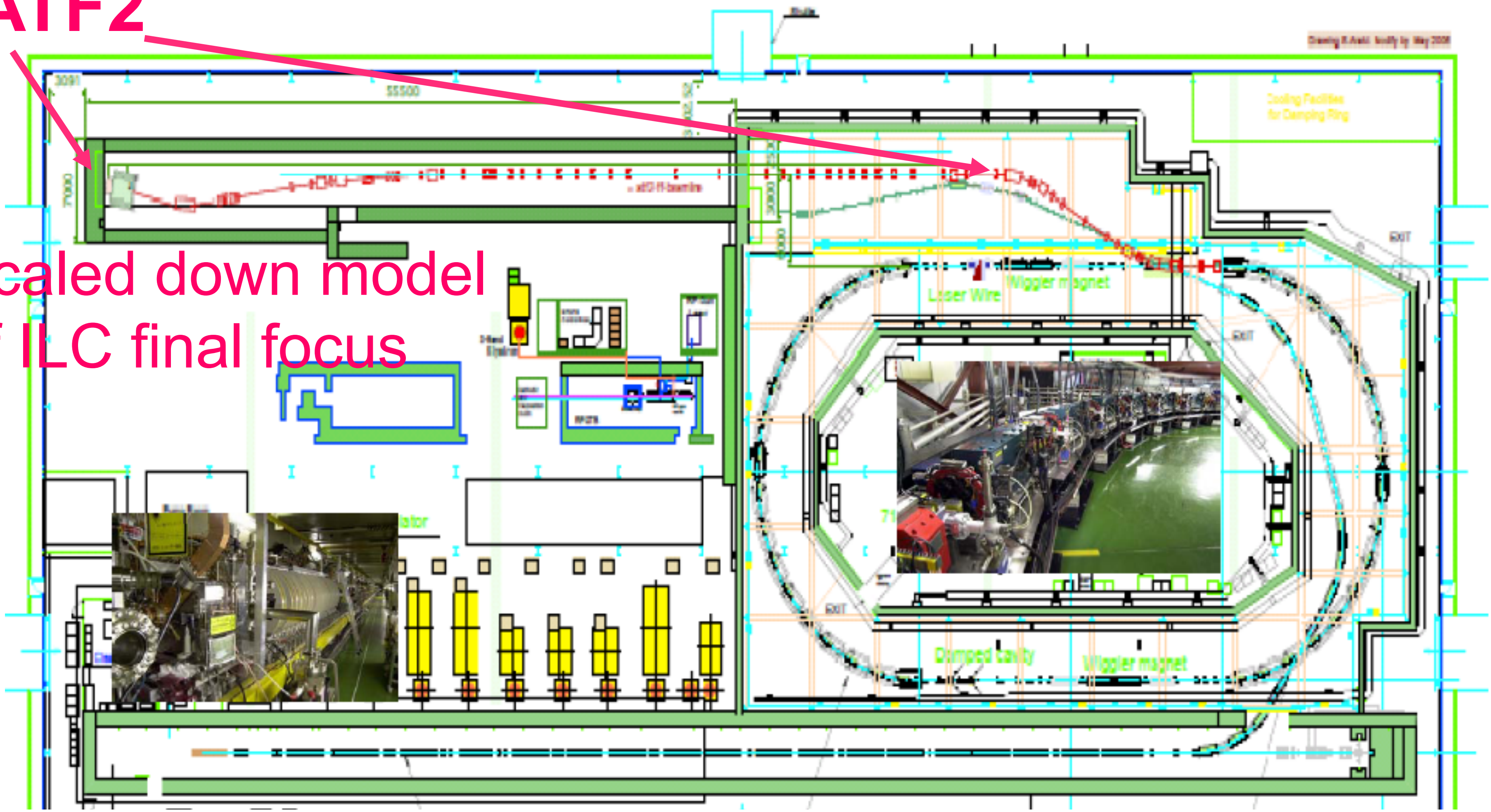
Energy: 1.28 GeV
Electron bunch:
- 2×10^{10} e/bunch
- 1 ~ 20 bunches/train
- 3 trains/ring
- 1.56 Hz



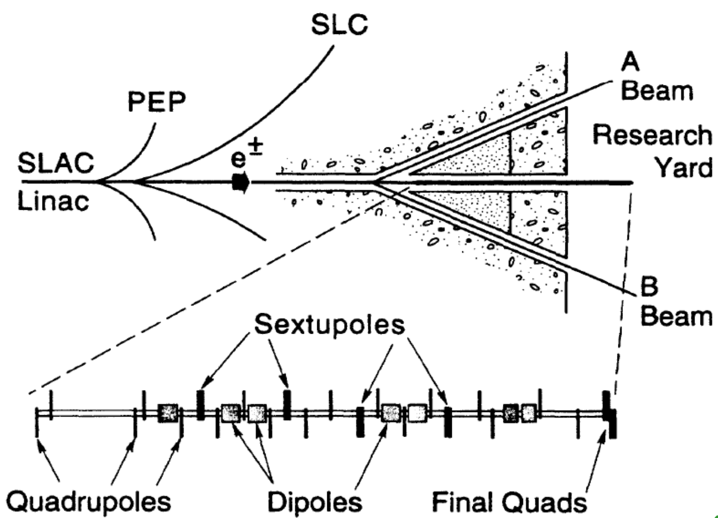
ATF
Accelerator Test Facility
at KEK

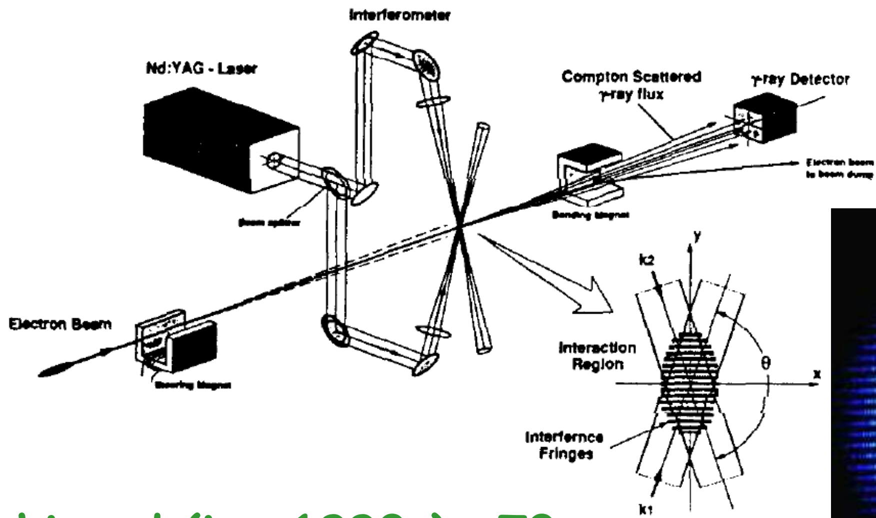
ATF2

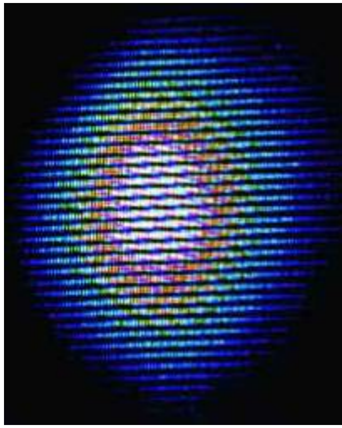
Scaled down model of ILC final focus



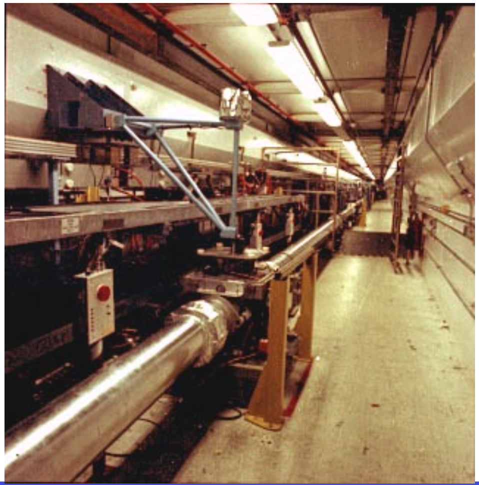
Final Focus Test Beam –
optics with traditional non-local chromaticity compensation

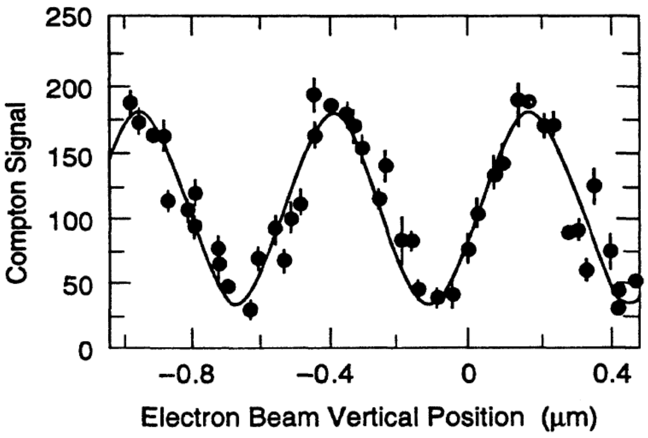






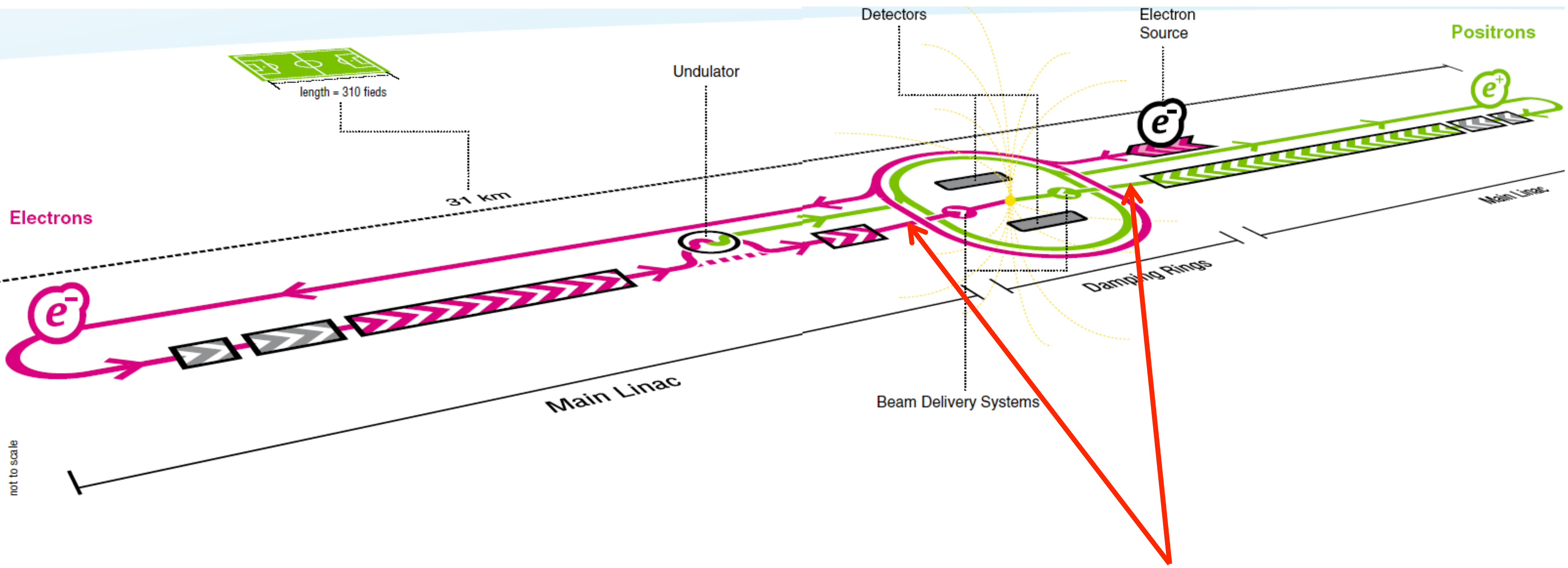
Achieved (in ~1990s) ~70nm vertical beam size





ILC BDS: from end of linac to IP

International Linear Collider

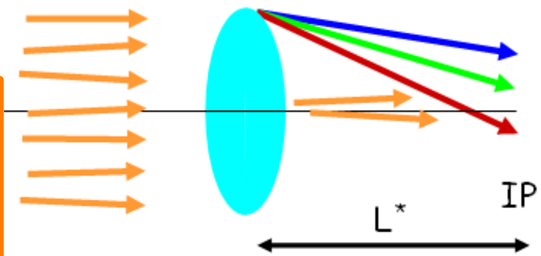


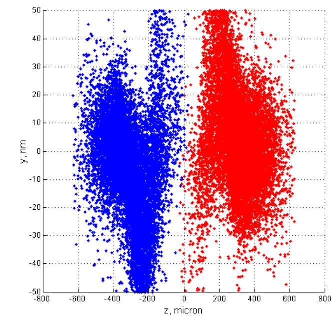
Beam Delivery System (BDS)

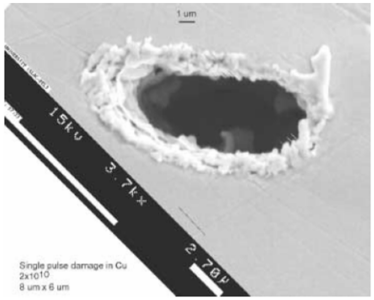
BDS includes:
Final Focus (FF), Collimation System, Diagnostic Section, Extraction line, etc.

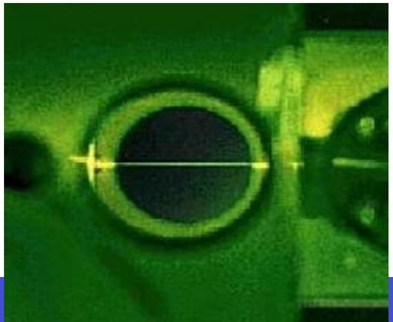
Factors driving design of BDS

- **Final Doublet chromaticity**
  - local compensation of chromaticity
- **Beam-beam effects**
  - background, IR and extraction design
- **SR emittance growth in BDS bends**
  - weak and long
- **Halo collimation**
  - survivability of spoilers
- **Beam diagnostics**
  - measurable size at laser wires
- …



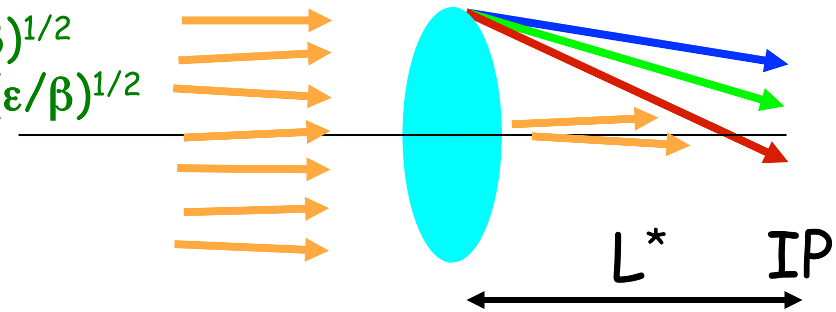






How big is chromaticity in FF?

Size: $(\varepsilon\ \beta)^{1/2}$
Angles: $(\varepsilon/\beta)^{1/2}$



Size at IP:
$L^*\ (\varepsilon/\beta)^{1/2}$
$+\ \ (\varepsilon\ \beta)^{1/2}\ \sigma_E$

Beta at IP:
$L^*\ (\varepsilon/\beta)^{1/2} = (\varepsilon\ \beta^*)^{1/2}$
$\Rightarrow\ \ \beta^* = L^{*2}/\beta$

Chromatic dilution:
$(\varepsilon\ \beta)^{1/2}\ \sigma_E\ /\ (\varepsilon\ \beta^*)^{1/2}$
$= \sigma_E\ L^*/\beta^*$

- The final lens need to be the strongest
  - (two lenses for both x and y => “Final Doublet” or FD)
- FD determines chromaticity of FF
- Chromatic dilution of the beam size is $\Delta\sigma/\sigma \sim \sigma_E\ L^*/\beta^*$

Typical:

σ_E -- energy spread in the beam ~ 0.002-0.01
L^* -- distance from FD to IP ~ 3 - 5 m
β^* -- beta function in IP ~ 0.4 - 0.1 mm

- For typical parameters, $\Delta\sigma/\sigma$ ~ 15-500 too big !
- => Chromaticity of FF need to be compensated

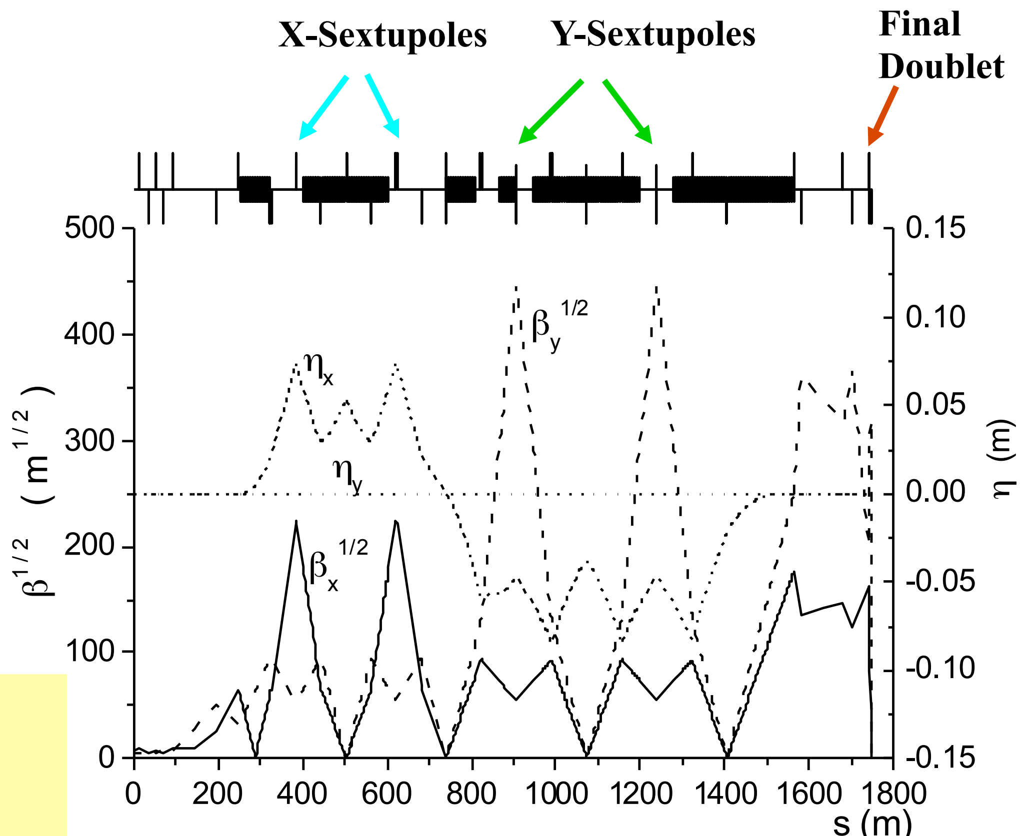
TeV FF with non-local chromaticity compensation

- Chromaticity is compensated by sextupoles in dedicated sections
- Geometrical aberrations are canceled by using sextupoles in pairs with M= -I

Chromaticity arise at FD but pre-compensated 1000m upstream

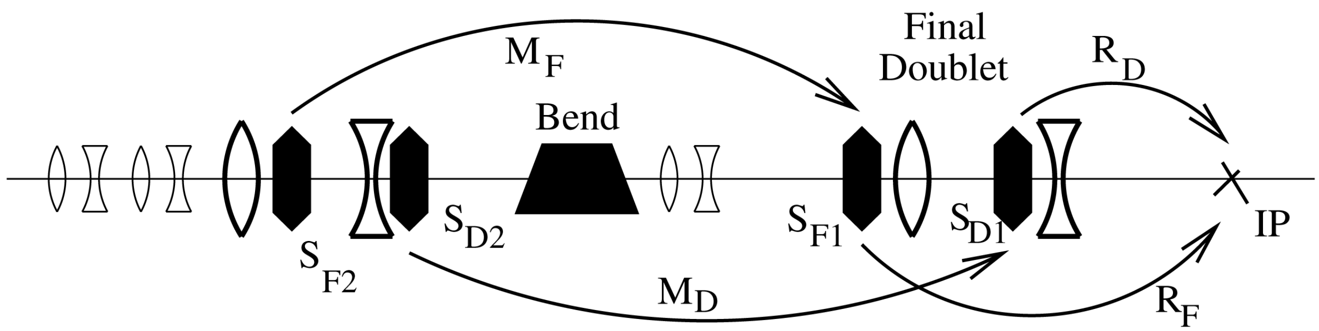
Problems:

- Chromaticity not locally compensated
  - Compensation of aberrations is not ideal since M ≠ -I for off energy particles
  - Large aberrations for beam tails



Traditional FF
(NLC FF, circa 1999)
L*=2m, TeV energy reach

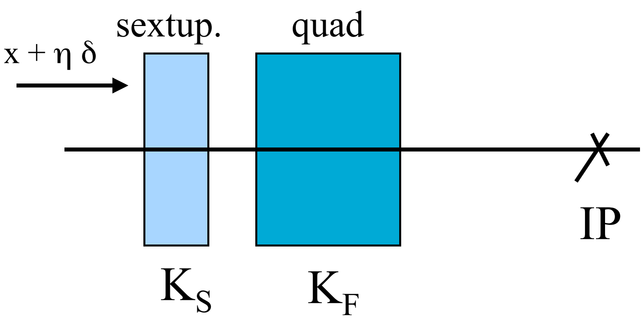
FF with local chromatic correction



- Chromaticity is cancelled **locally** by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD
- 2nd order dispersion produced in FD is cancelled locally provided that half of horizontal chromaticity arrive from upstream
- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend
- Higher order aberrations are cancelled by optimizing transport matrices between sextupoles

P.Raimondi, A.Seryi, PRL, 86, 3779 (2001)

Chromatic correction in FD



- Straightforward in Y plane
- a bit tricky in X plane:

Quad:

$$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) \Rightarrow K_F(-\delta x - \eta\delta^2)$$

chromaticity

Second order dispersion

Sextupole:

$$\Delta x' = \frac{K_S}{2}(x+\eta\delta)^2 \Rightarrow K_S\eta(\delta x + \frac{\eta\delta^2}{2})$$

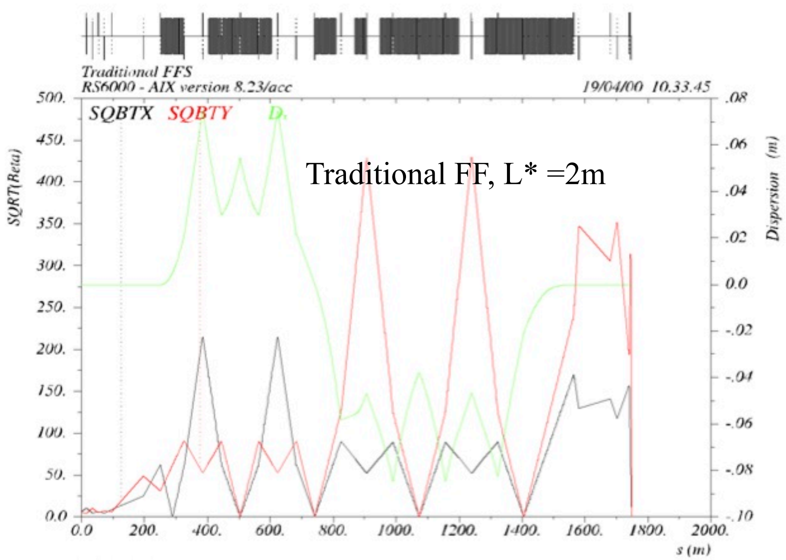
If we require $K_S\eta = K_F$ to cancel FD chromaticity, then half of the **second order dispersion** remains.

$$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F(-\delta x - \frac{\eta\delta^2}{2})$$

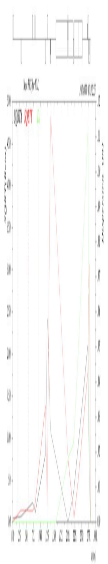
$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{\eta}$$

Solution:
The β-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the **second order dispersion** as well.

Compare FF designs

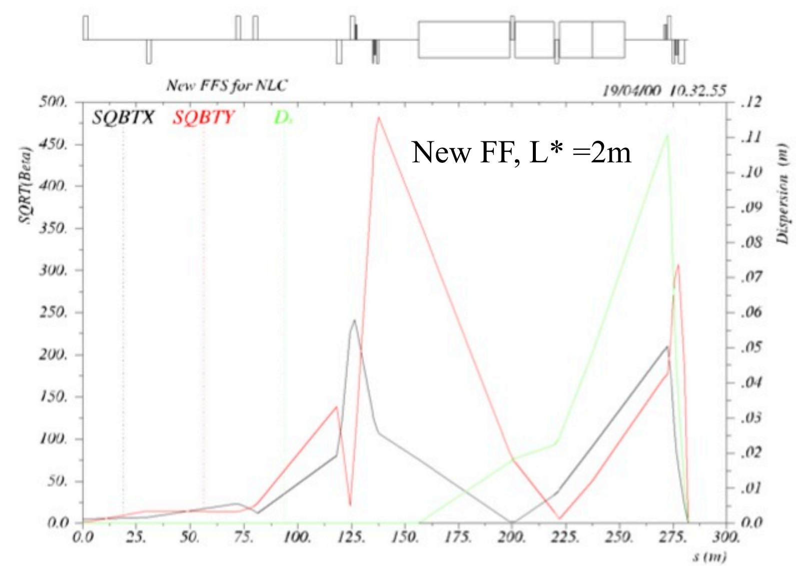


FF with local chromaticity compensation with the same performance can be ~300m long, i.e. 6 times shorter

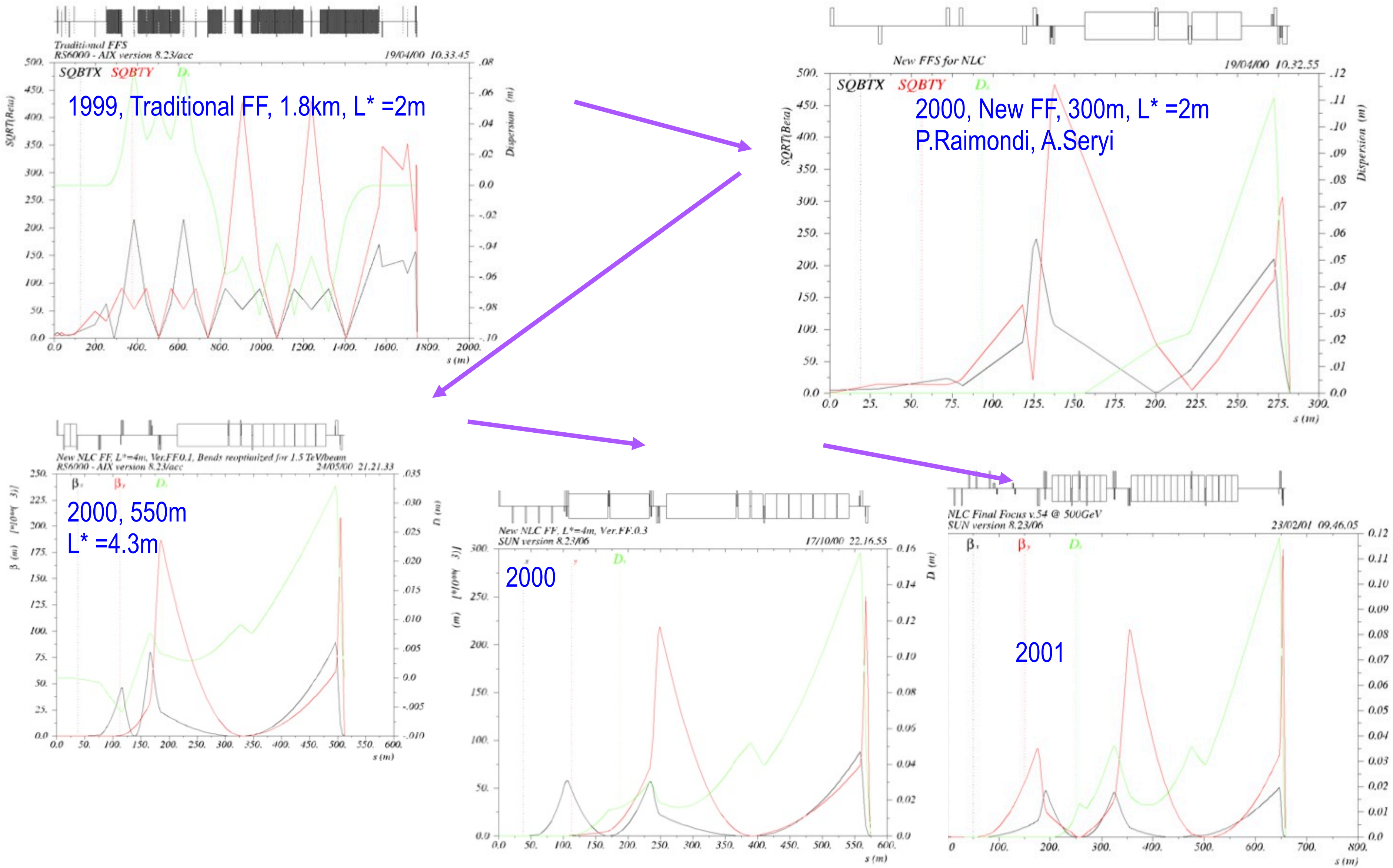


new FF

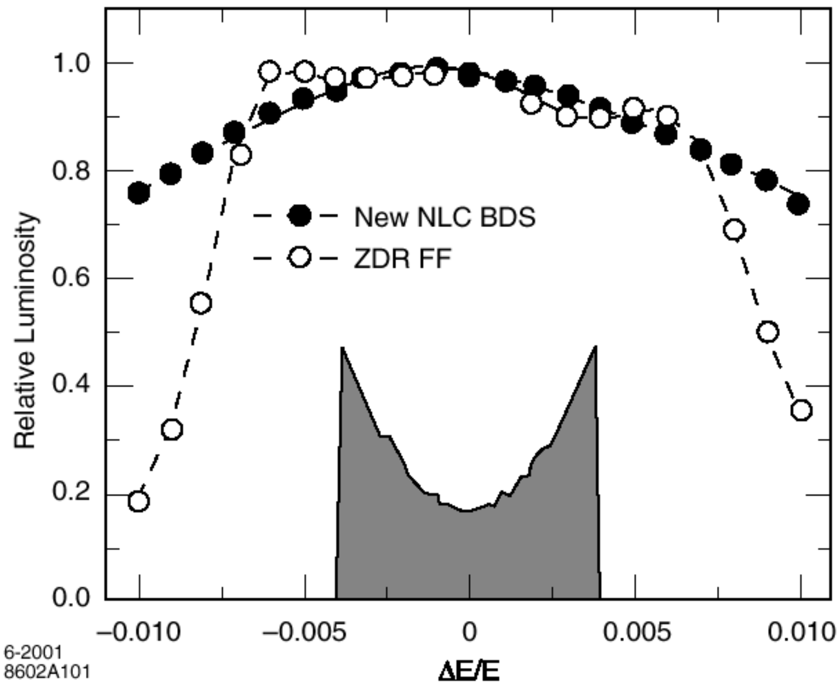
Moreover, its necessary length scales only as $E^{2/5}$ with energy! One can design multi-TeV FF in under a km!

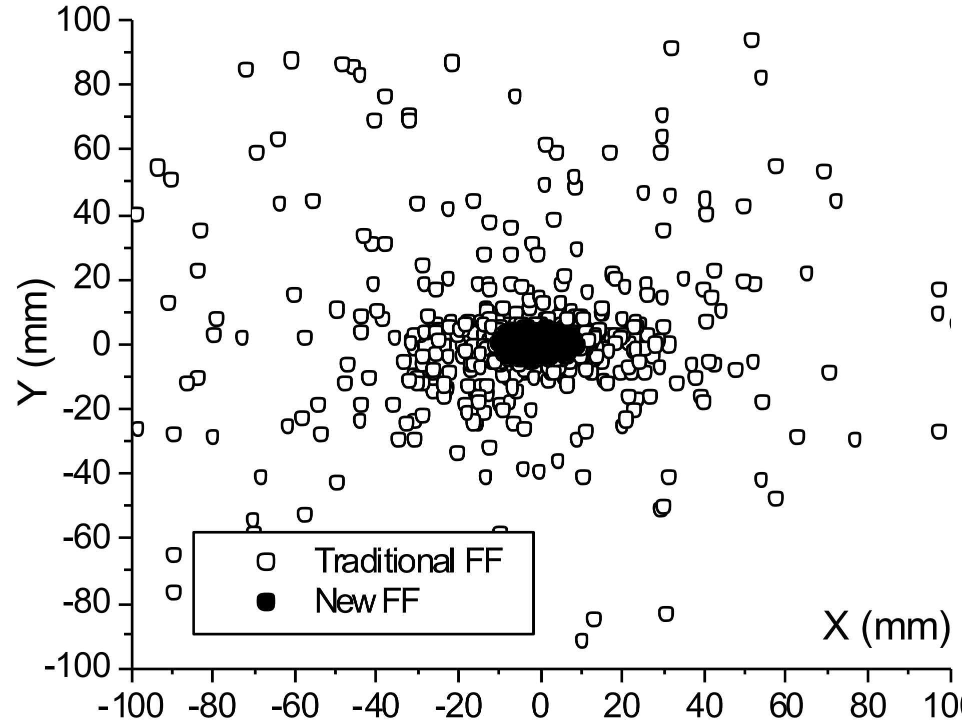


FF optics with local correction



IP bandwidth & halo generation

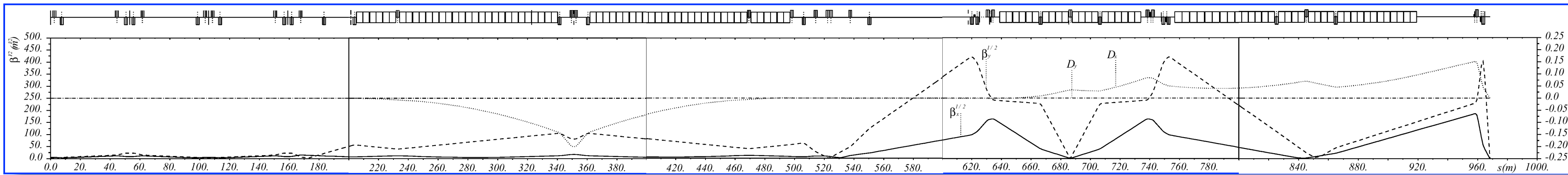


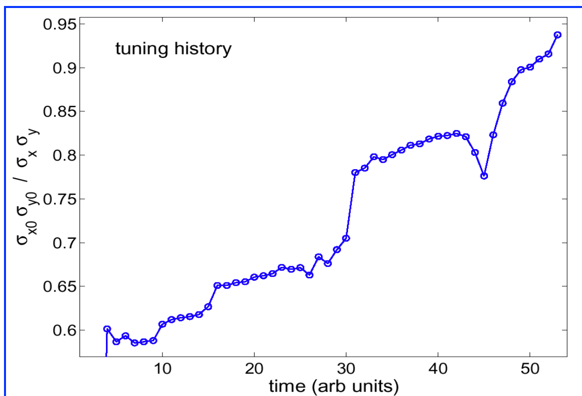


Bandwidth of FF with local chromaticity correction can be better than for system with non-local correction

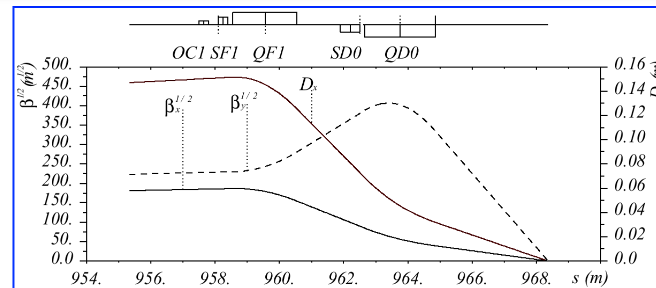
- **FF with non-local chr. corr. generate beam tails due to aberrations and it does not preserve betatron phase of halo particles**
- **FF with local chr. corr. has much less aberrations and it does not mix phases particles**

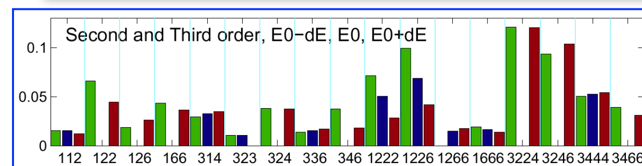
BDS design methods & examples

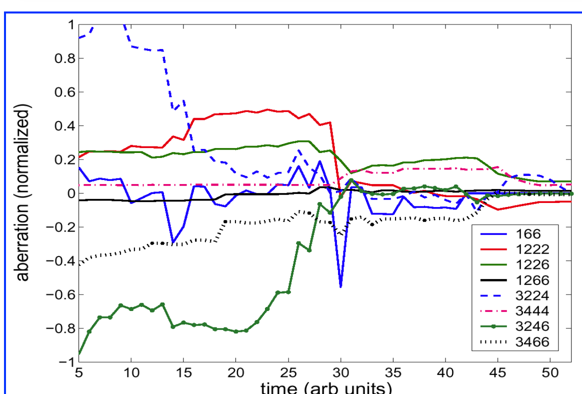


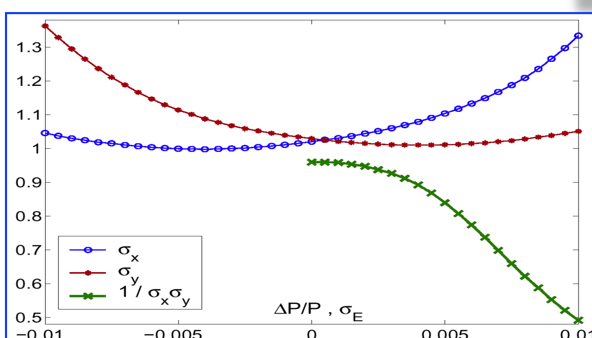


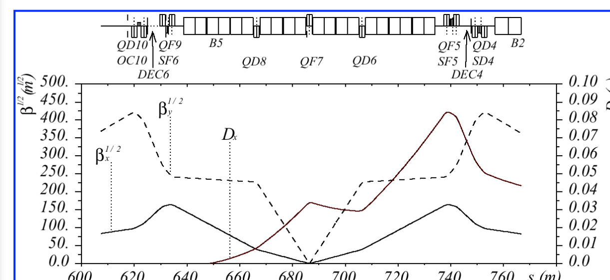
Example BDS optics; design history; location of design knobs



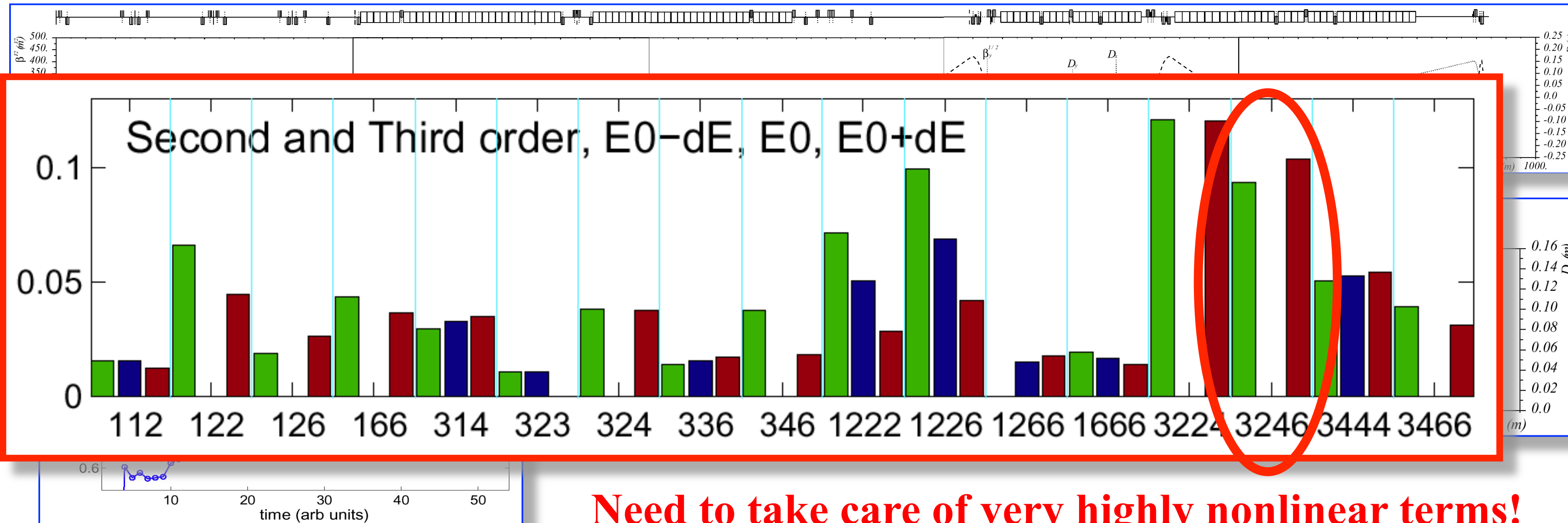






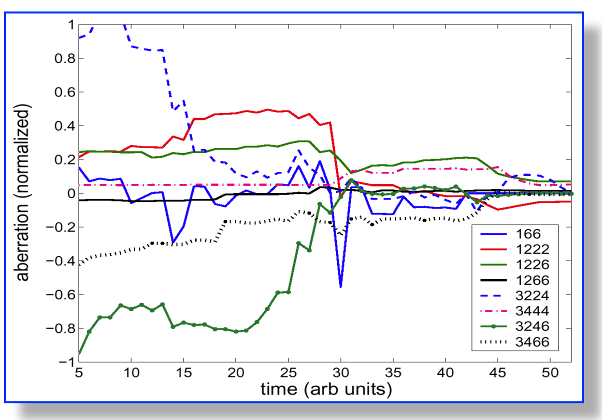


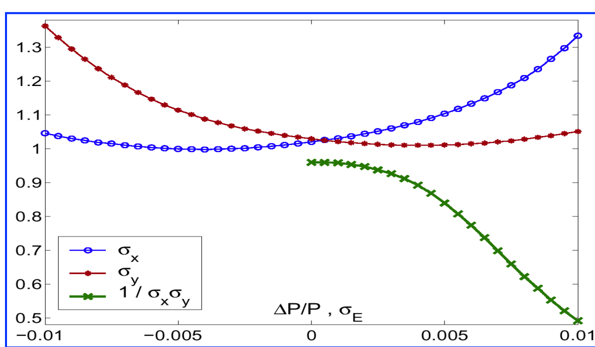
BDS design methods & examples

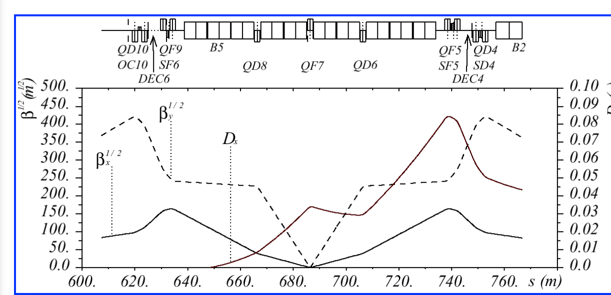


Need to take care of very highly nonlinear terms!

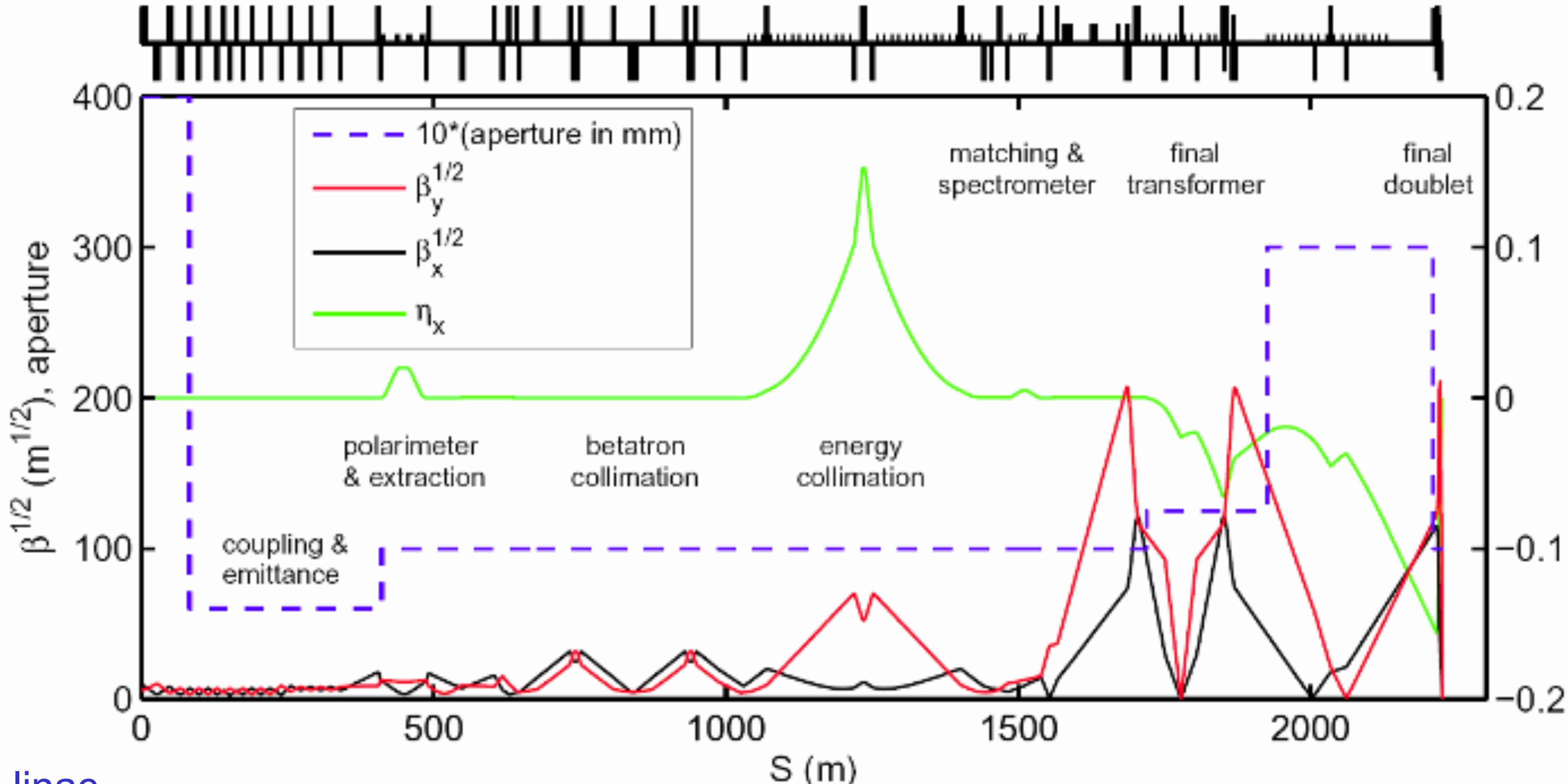
Example: y ~ U (x', y', E²) - FOURTH ORDER







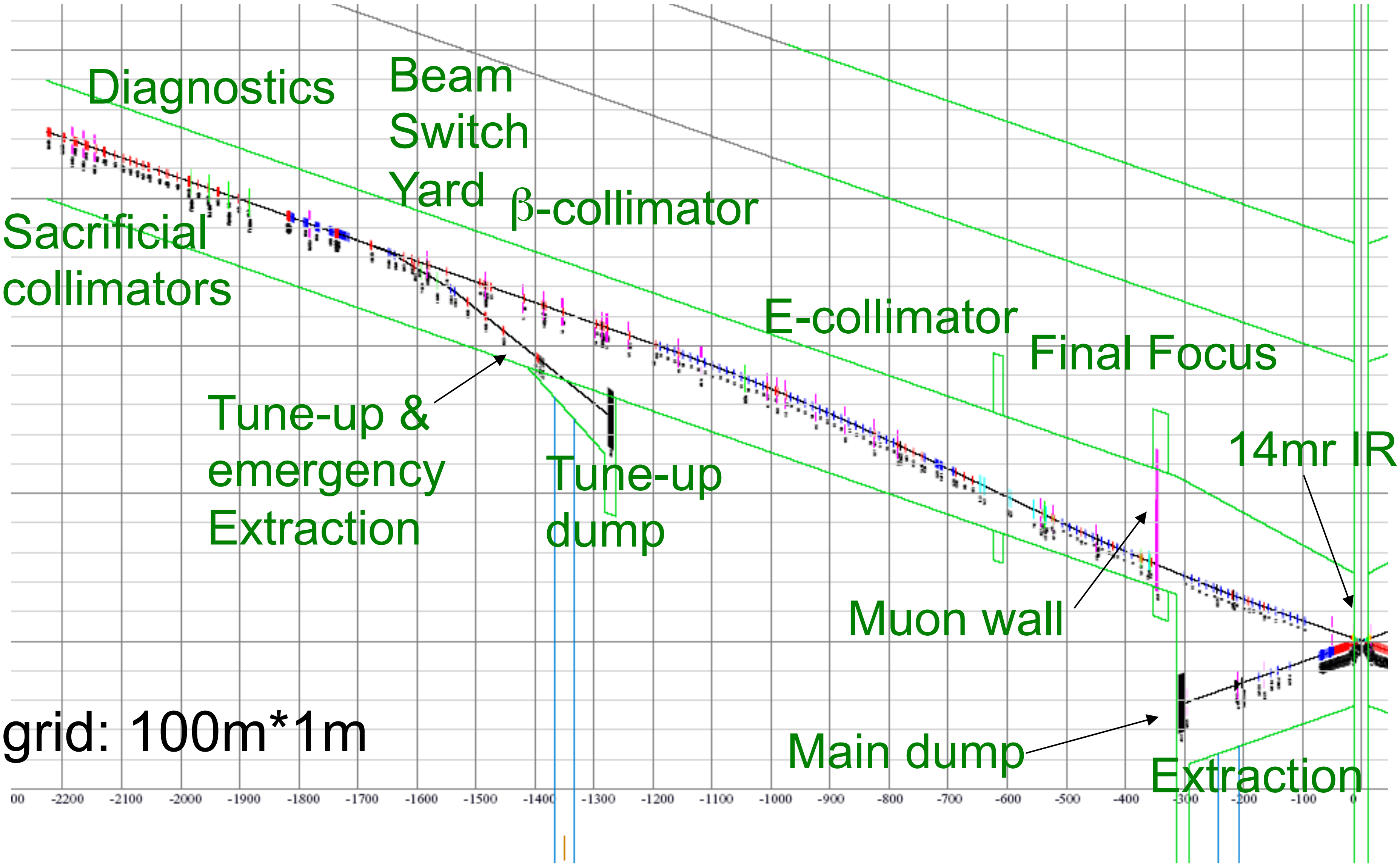
BDS functions and optics



linac

IP

ILC Beam Delivery subsystems

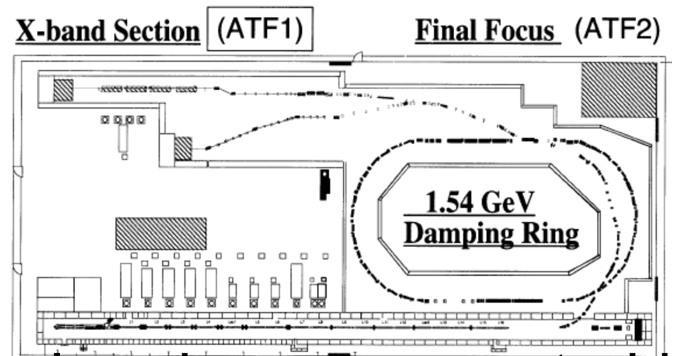


Parameters of ILC BDS

Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	655/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	31/14
Nominal beta-function at IP, β^*, x/y	mm	21/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.162/18.5
Nominal bunch population, N		2×10^{10}
Max beam power at main and tune-up dumps	MW	18
Preferred entrance train to train jitter	σ	< 0.5
Preferred entrance bunch to bunch jitter	σ	< 0.1
Typical nominal collimation depth, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50

ATF2

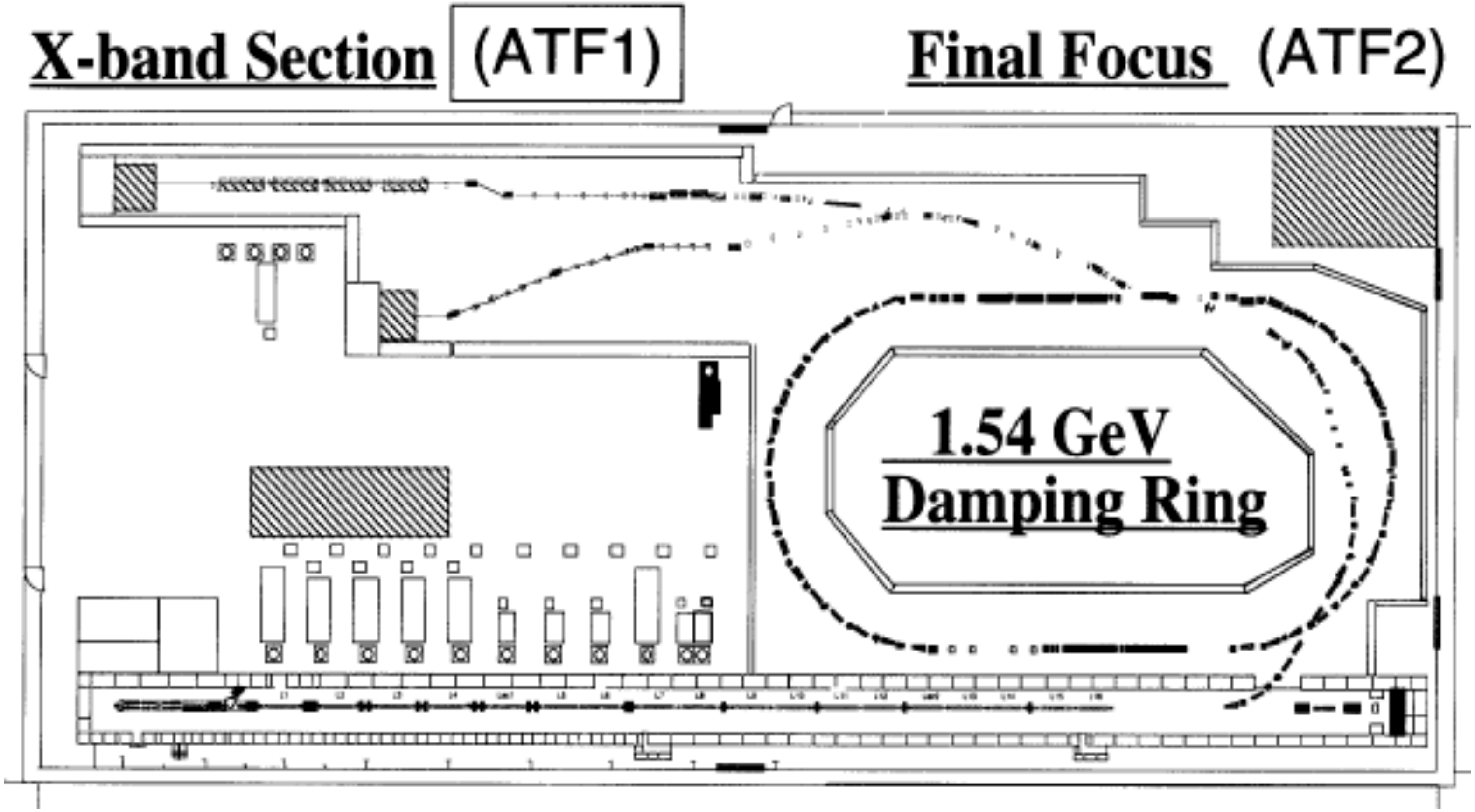
- **The idea of a new test facility at ATF, to prototype the advanced final focus, for linear collider, was conceived in 2002 at Nanobeam workshop in Lausanne**
- **Idea evolved, and has now been realized in iron and concrete**



Early scheme presented by Junji Urakawa

- **ATF2 goals**
  - **prototype ILC Final Focus system**
  - **develop FF tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs)**
  - **learn achieving ~37nm size & ~nm stability reliably**

- **ATF2 final goal – help to ensure collisions of nanometer beams, i.e. luminosity of ILC**



Early scheme as presented by
Junji Urakawa at Nanobeam 2002

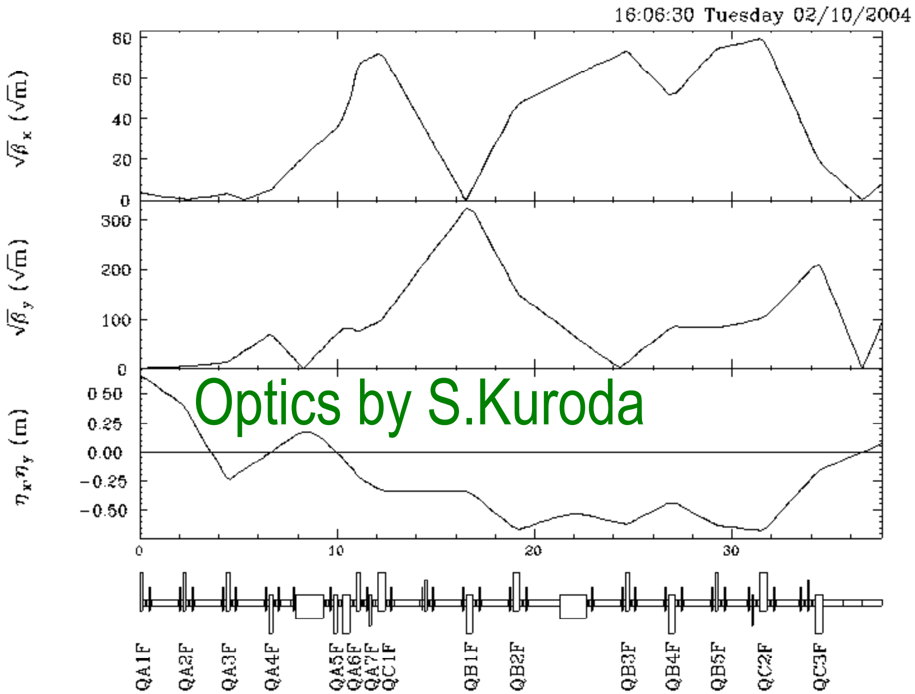
ATF2 major milestones

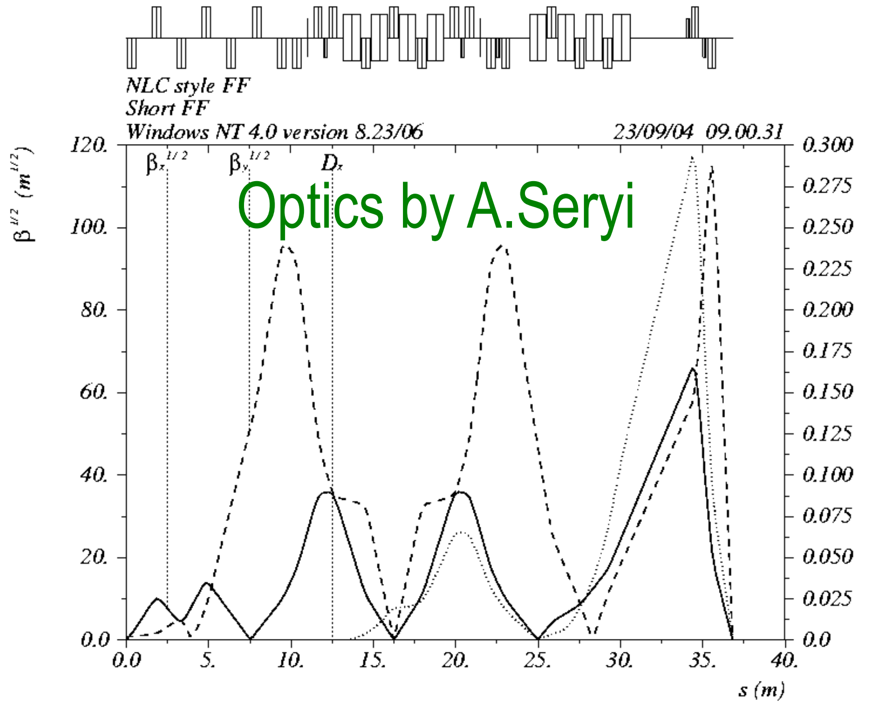
- **September 2002, Nanobeam workshop, Lausanne**
  - idea of new Final Focus test facility at ATF
- **January 2005, SLAC, first ATF2 workshop**
  - compared two optics versions, selected ILC-like design
  - stated the need to document the Proposal
- **May 2005, ATF2 mtg at KEK**
  - collaboration organization & MOU, task sharing, 1st version of schedule (commissioning start range: 02.2007-02.2008)
- **August 2005**
  - ATF2 Proposal, Vol.1 (technical description) released

ATF2 Proposal: 110 authors, 25 institutions

- **February 2006, SLAC, 1st ATF2 Project Meeting**
  - ATF2 Proposal, Vol.2 (organization, cost & contributions) released
- **May 2006, KEK, 2nd ATF2 Project Meeting …**
  - detailed design & role sharing
- **… May 2008, BINP Novosibirsk, 6th ATF2 Project Meeting**
  - Review of construction status and commissioning readiness
- **… *To date: 14 ATF2 Project Meetings***

Optics considered for ATF2 in 2005

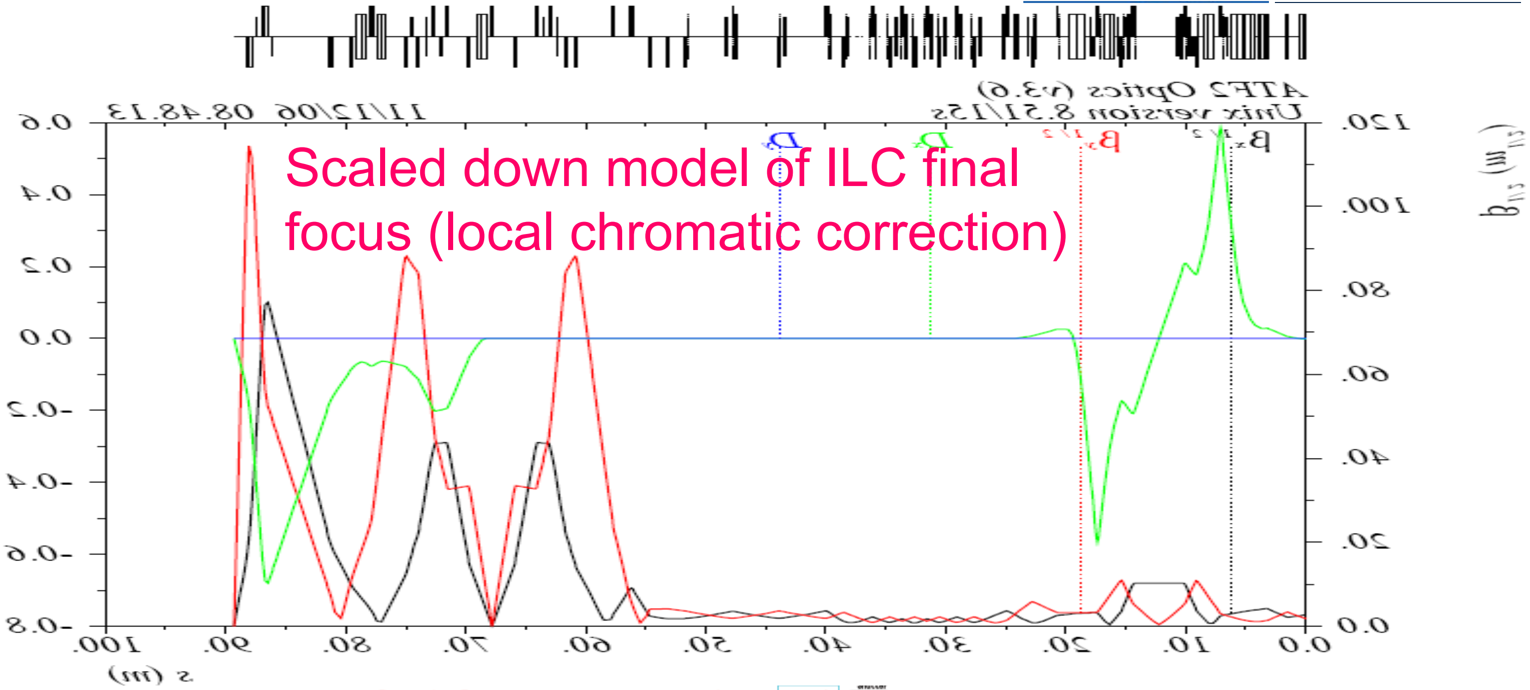


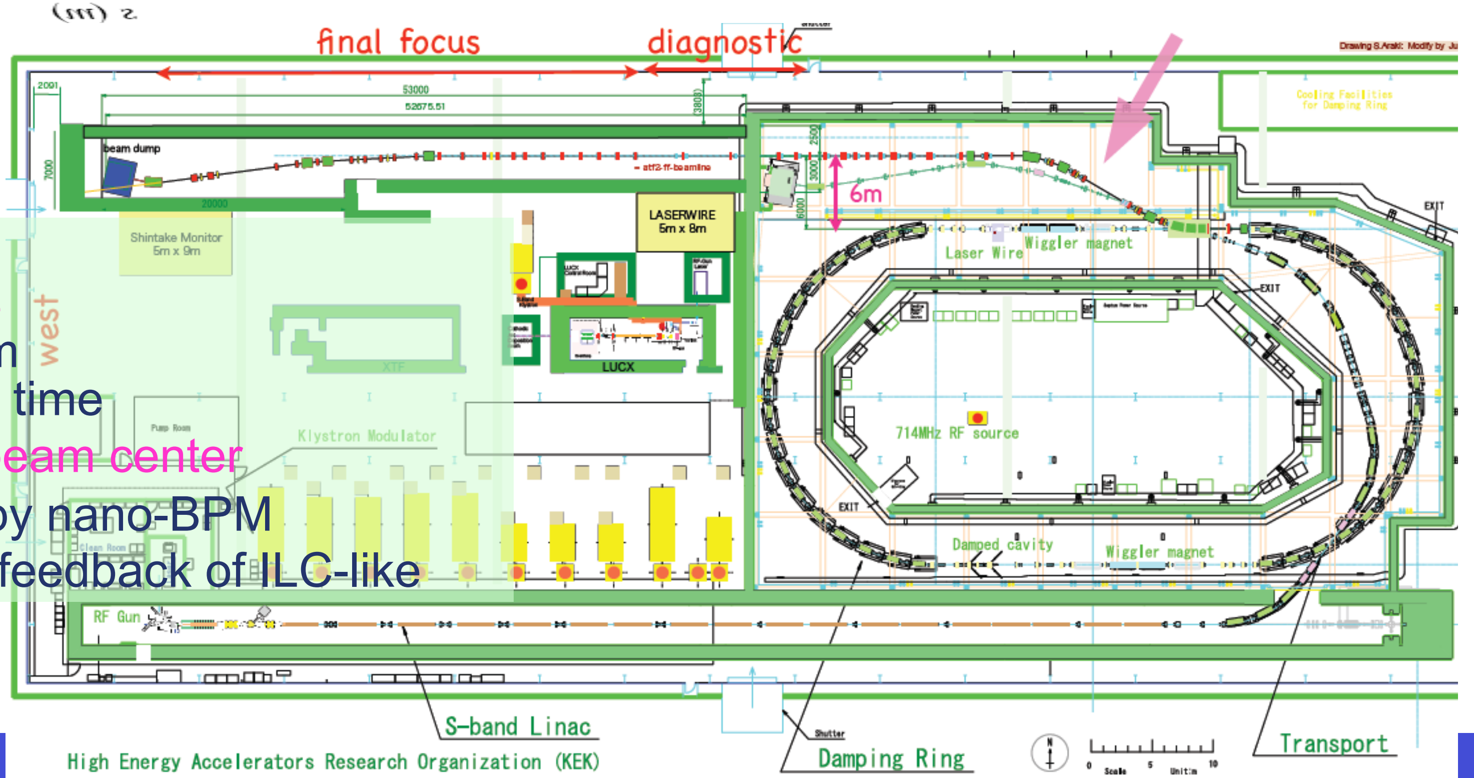


Optics with L*=1m, and IP β_x=4mm, β_y=0.1mm
(same Y chromaticity as present ILC parameters)

Parameters used
$\gamma\varepsilon_x$=3e-6 m , $\gamma\varepsilon_y$=3e-8 m, E=1.54 GeV

ATF2 – model of ILC BDS

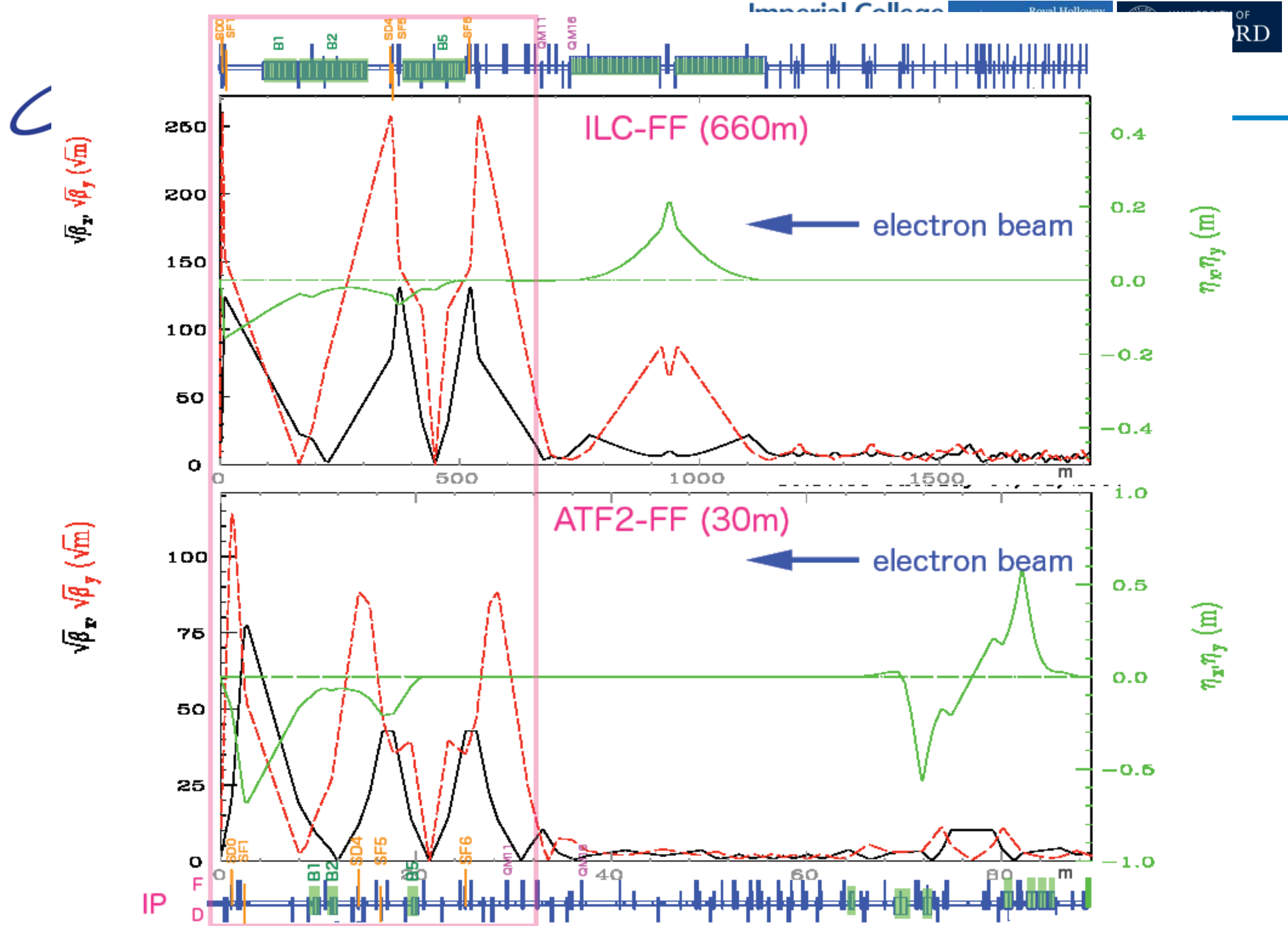




ATF2 goals

(A) Small beam size
- Obtain σ_y ~ 35nm
- Maintain for long time

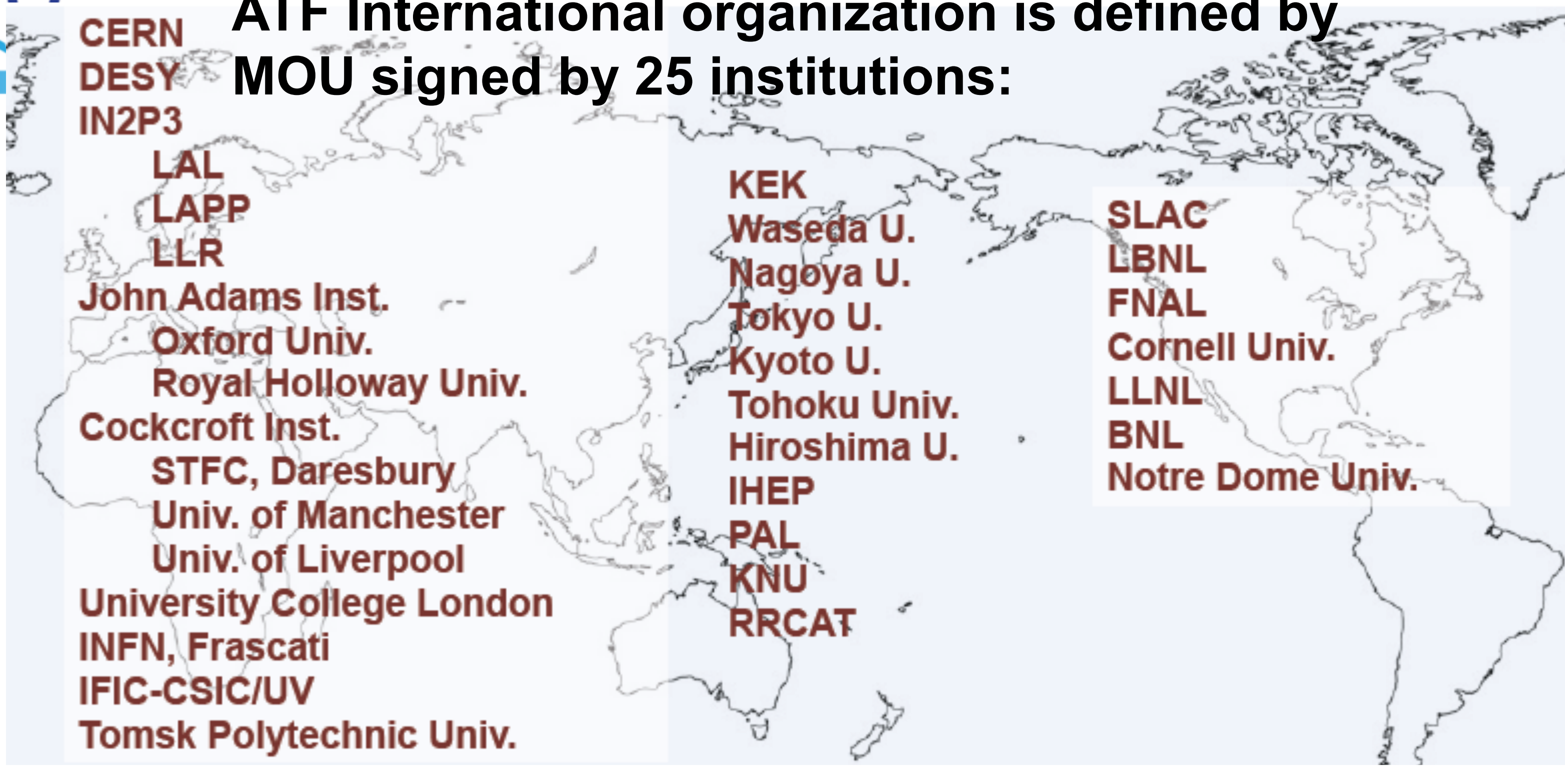
(B) Stabilization of beam center
- Down to < 2nm by nano-BPM
- Bunch-to-bunch feedback of ILC-like train


ILC-FF (660m)
electron beam
ATF2-FF (30m)
electron beam
SD0
SF1
B1
B2
SD4
SF5
B5
SF6
QM11
QM16
IP
F
D
m

ATF2 & ILC parameters

Parameters	ATF2	ILC
Beam Energy, GeV	1.3	250
L*, m	1	3.5-4.2
$\gamma\varepsilon_{x/y}$, m*rad	3E-6 / 3E-8	1E-5 / 4E-8
IP $\beta_{x/y}$, mm	4 / 0.1	21 / 0.4
IP η’, rad	0.14	0.094
σ_E, %	~0.1	~0.1
Chromaticity	~1E4	~1E4
$n_{bunches}$	1-3 (goal A)	~3000
$n_{bunches}$	3-30 (goal B)	~3000
N_{bunch}	1-2E10	2E10
IP σ_y, nm	37	5

ATF International organization is defined by MOU signed by 25 institutions:



MOU: Mission of ATF/ATF2 is three-fold:

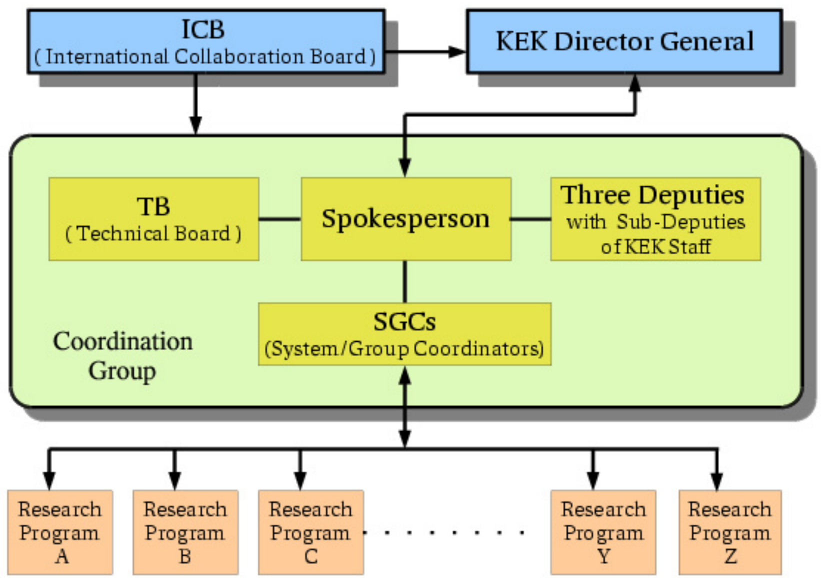
- ATF, to establish the technologies associated with producing the electron beams with the quality required for ILC and provide such beams to ATF2 in a stable and reliable manner.
- ATF2, to use the beams extracted from ATF at a test final focus beamline which is similar to what is envisaged at ILC. The goal is to demonstrate the beam focusing technologies that are consistent with ILC requirements. For this purpose, ATF2 aims to focus the beam down to a few tens of nm (rms) with a beam centroid stability within a few nm for a prolonged period of time.
- Both the ATF and ATF2, to serve the mission of providing the young scientists and engineers with training opportunities of participating in R&D programs for advanced accelerator technologies.

http://atf.kek.jp/

ICB: decision making body for executive matters related to the ATF collaboration (chair: Ewan Paterson, SLAC)

TB: assist the Spokesperson in formulating the ATF Annual Activity Plan, including the budget and beamtime allocation and assist the ICB in assessing scientific progress. (co-chairs: A.Wolski, CI, E.Elsen, DESY)

ATF International Collaboration



Spokesperson:
direct and coordinate the work required at ATF/ATF2 in accordance with the ATF Annual Activity Plan, report the progress to ICB and the progress and the matters related to KEK budget to director of KEK
(Junji Urakawa, KEK):

Deputies of Spokesperson: carry out tasks in the areas of

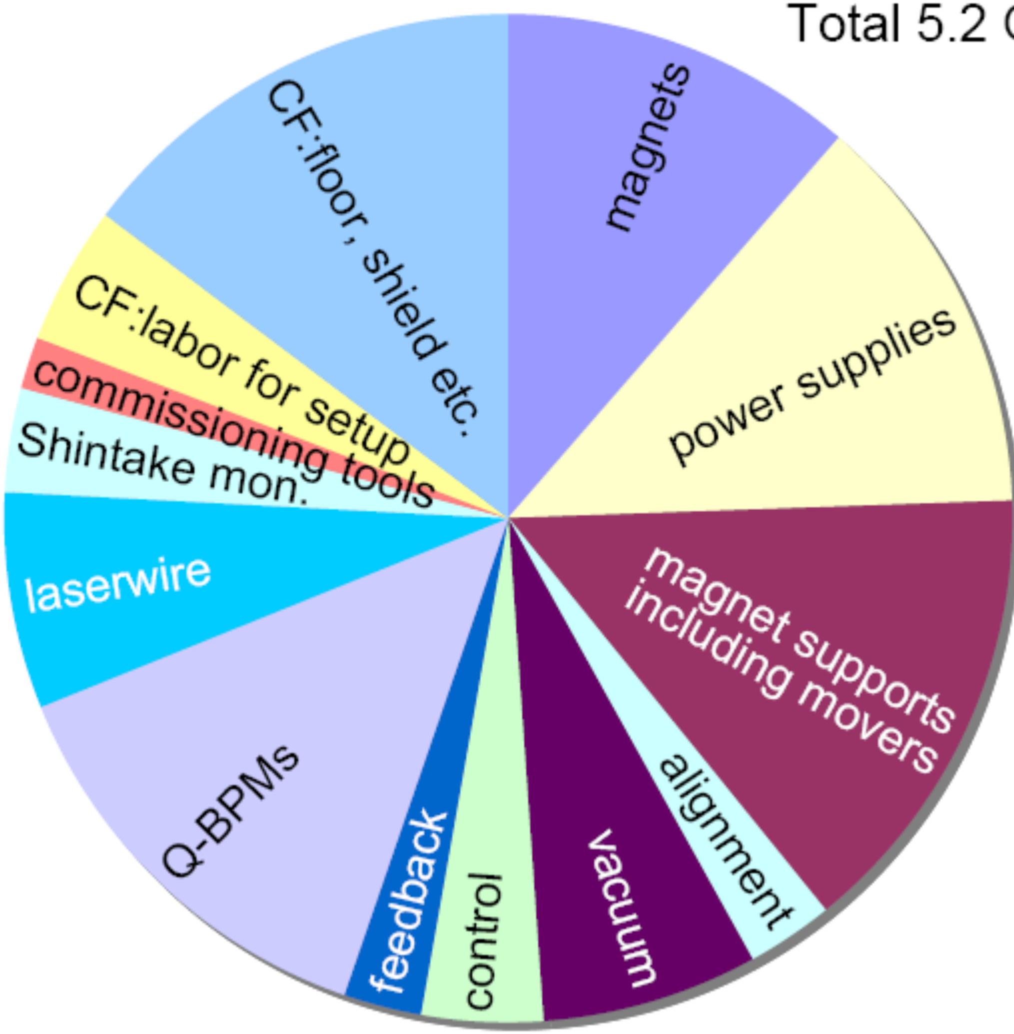
- Beam operation (Shigeru Kuroda, KEK)

- Hardware maintenance (Nobuhiro Terunuma, KEK)

- Design, construction and commissioning of ATF2 (Andrei Seryi, SLAC)

Org. snapshot ~2010

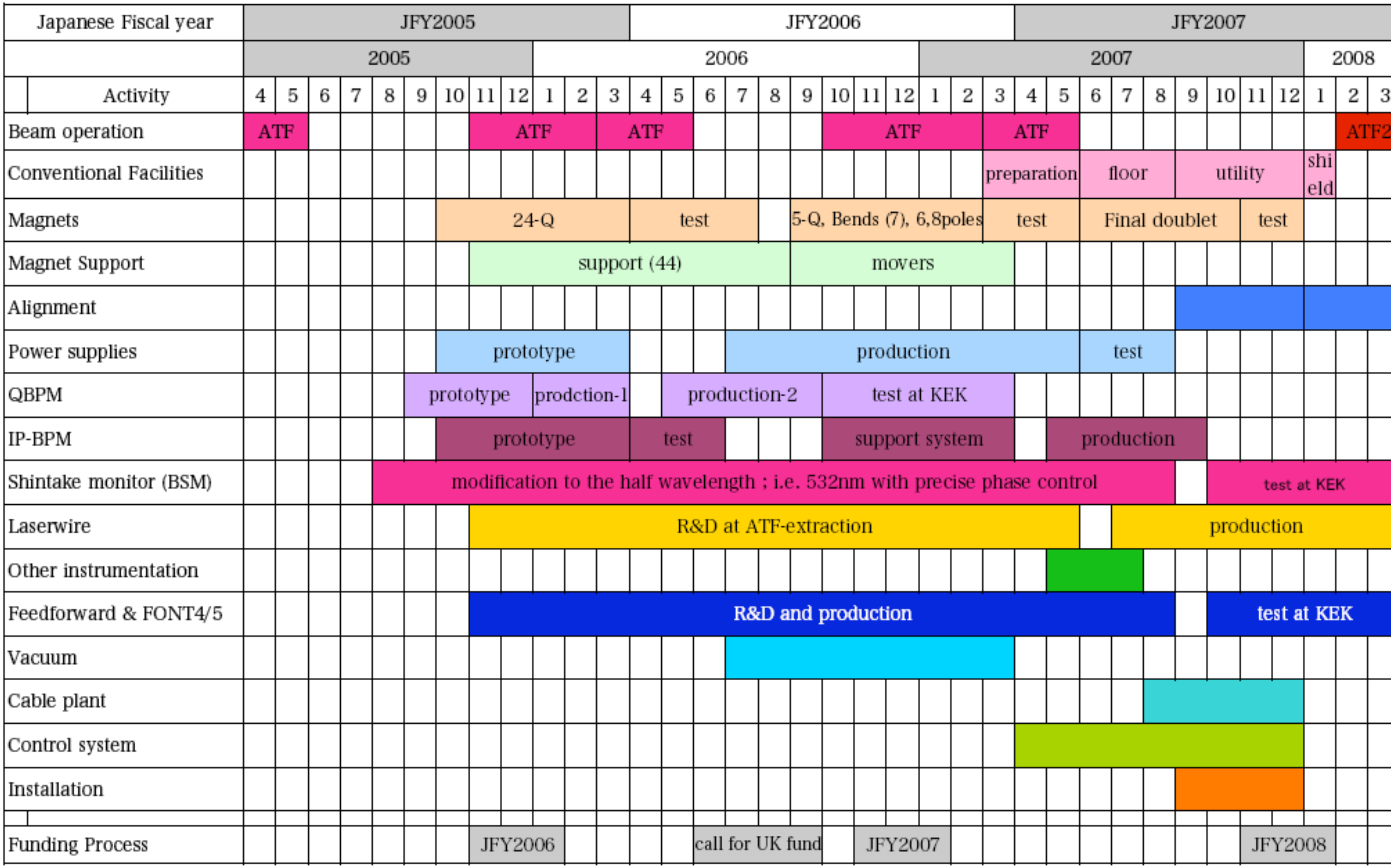
ATF2 cost



Cost distribution of the components normalized by the total cost, where the in-kind ones are also included

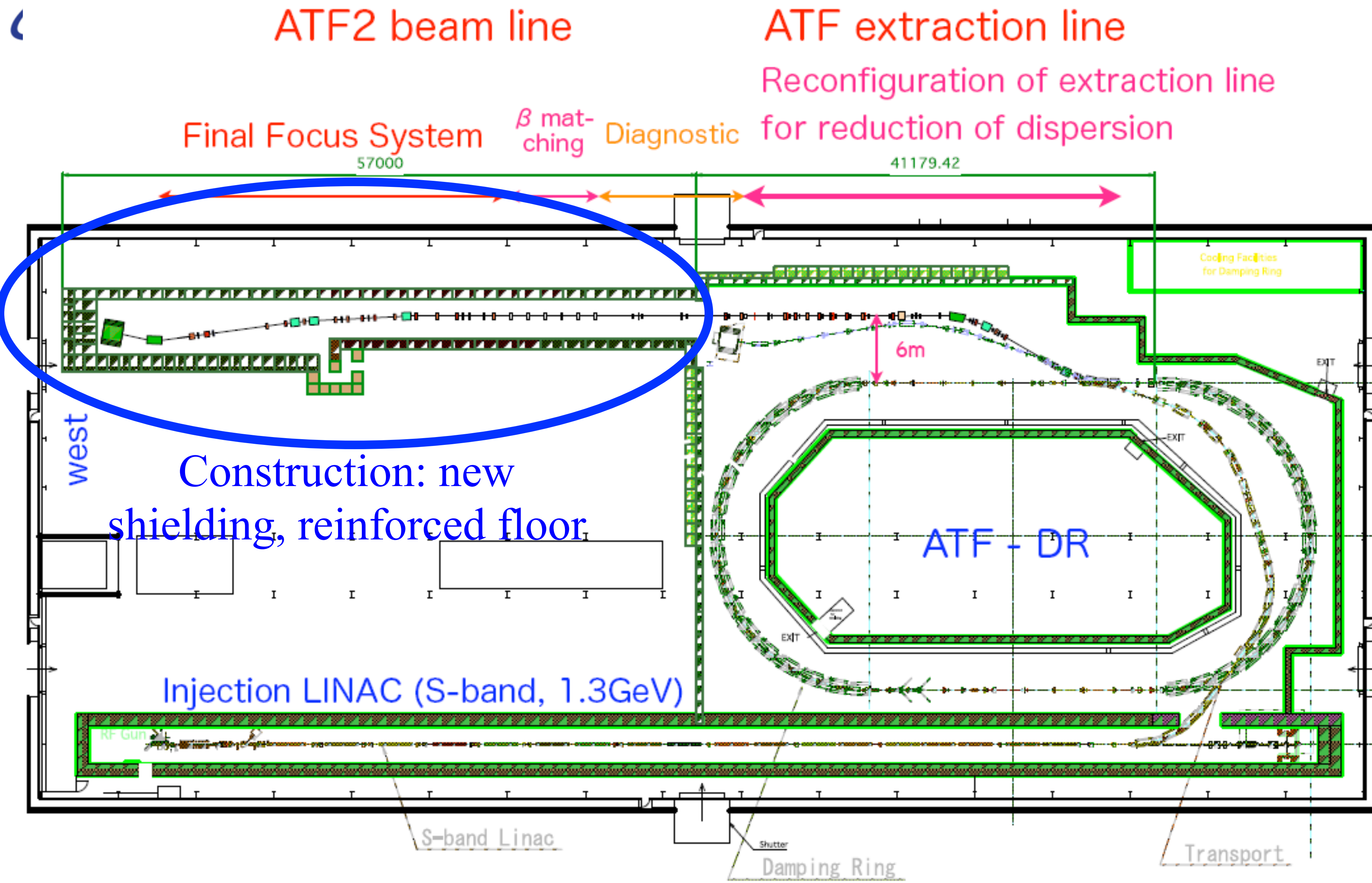
as seen in mid 2005 (from ATF2 Proposal, Volume 2)

(Oku-yen is 100*1E6 yen)



Outline of the ATF2 time schedule, as seen in mid 2005 (from ATF2 Proposal, Volume 2)

Layout & civil construction



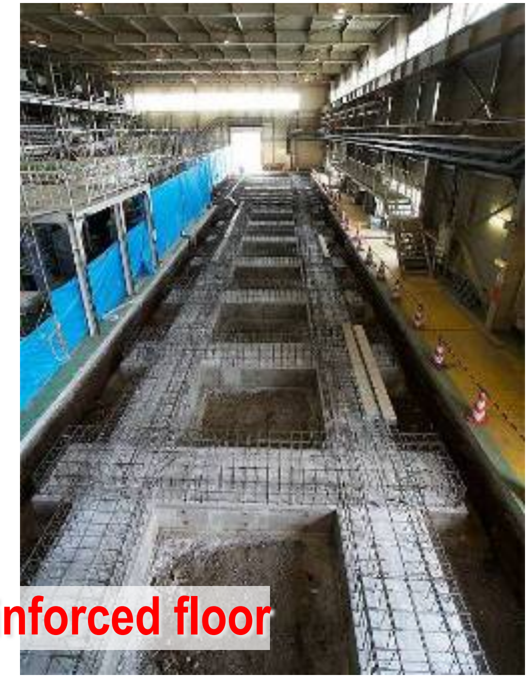
ATF2 construction in 2007

Aug – Dec

Assembly hall before construction

Assembly hall emptied for construction

Photos:
Nobu Toge



Construction of reinforced floor

Construction of shielding

ATF2 floor piles
~ 13m x 38 sets

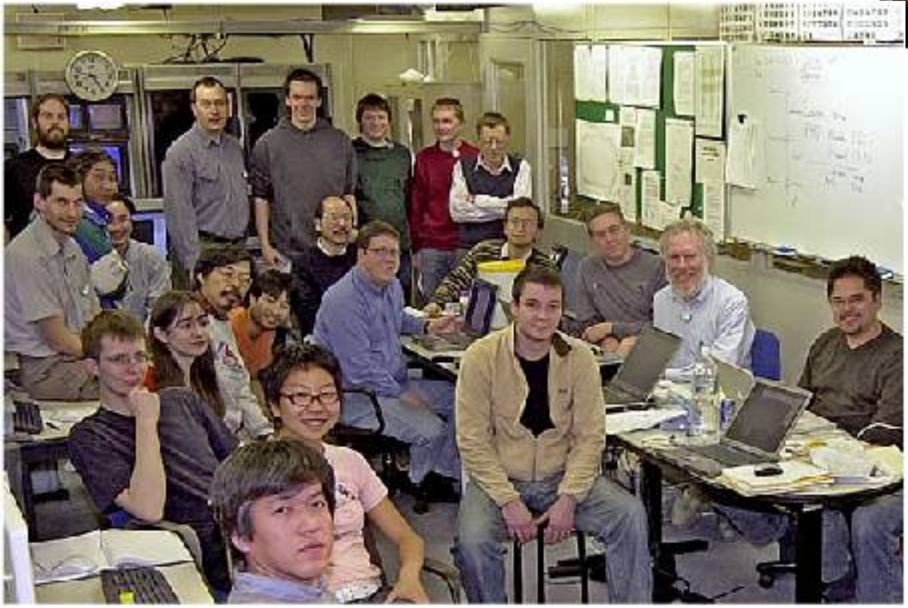
2007/8/24

ATF2 floor base structure

Finalizing the ATF2 floor

ATF collaboration & ATF2 facility

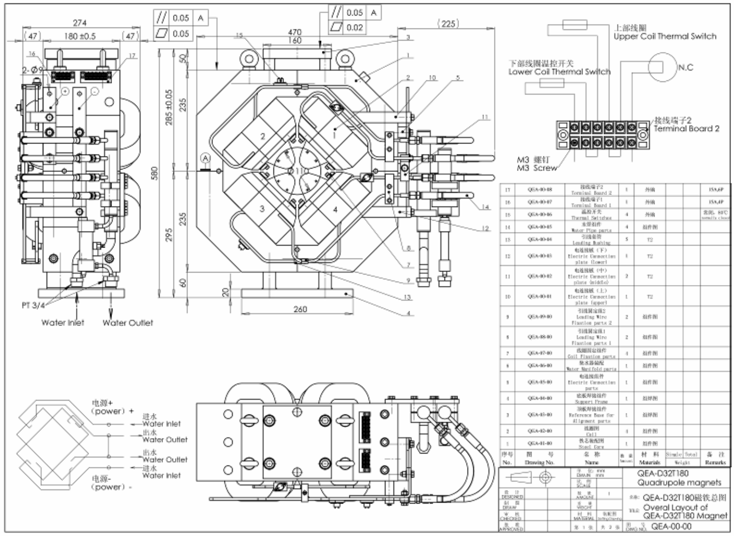
- **ATF2 will prototype FF,**
- **help development tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs),**
- **help to learn achieving small size & stability reliably,**



- ATF2 is one of central elements of BDS EDR work, as it will address a large fraction of BDS technical cost risk.
- **Constructed as ILC model, with in-kind contribution from partners and host country providing civil construction**

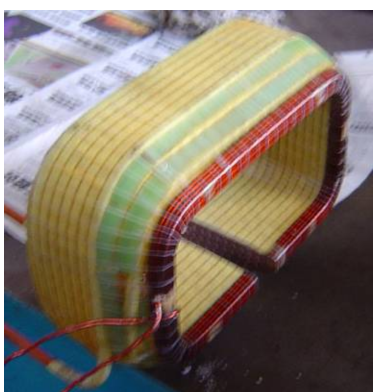
Power Supplies and Magnet system

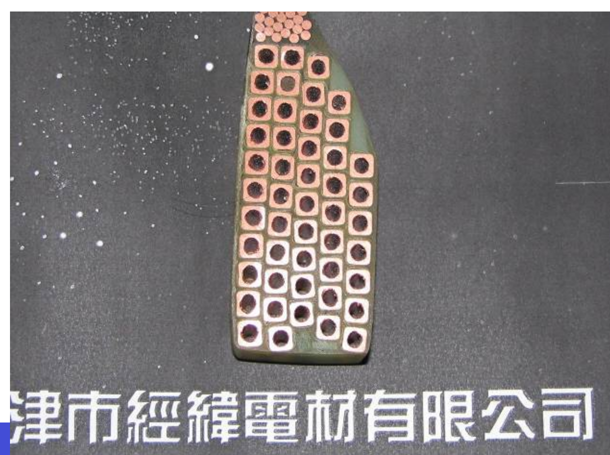
SLAC-built High Availability Power Supplies installed, connected and tested at ATF2



C.Spencer (SLAC) at IHEP, Beijing, Dec 2005

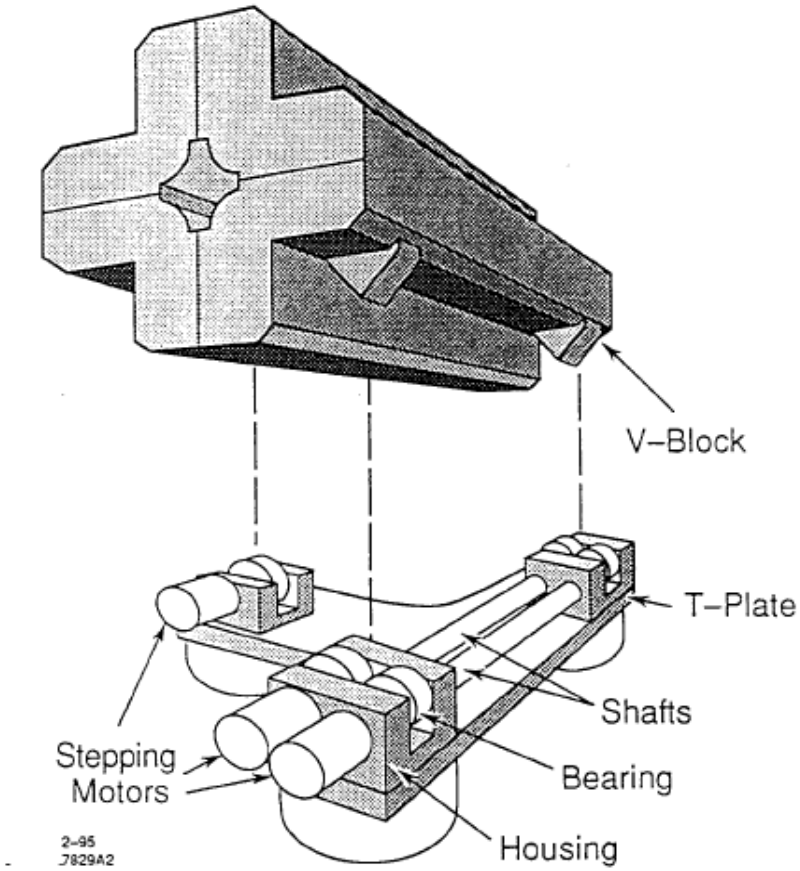
Beamline quads: SLAC / IHEP design, QC / production, measurements

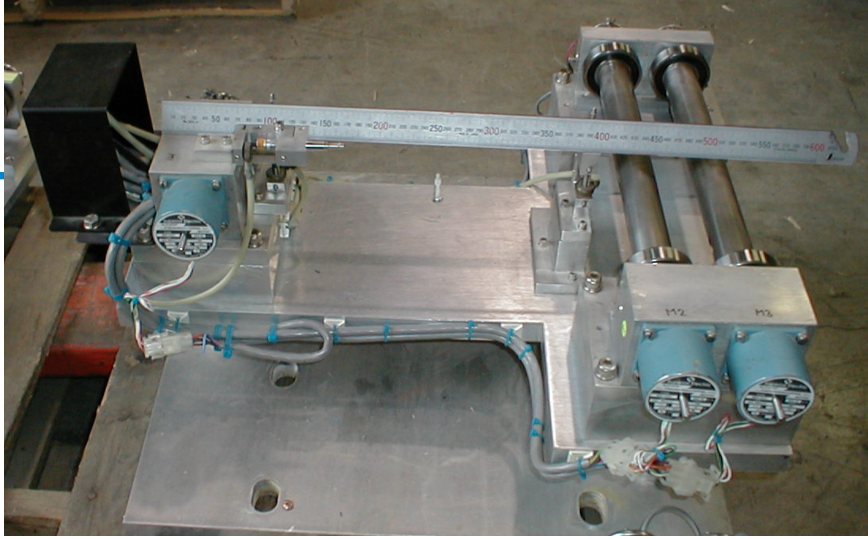




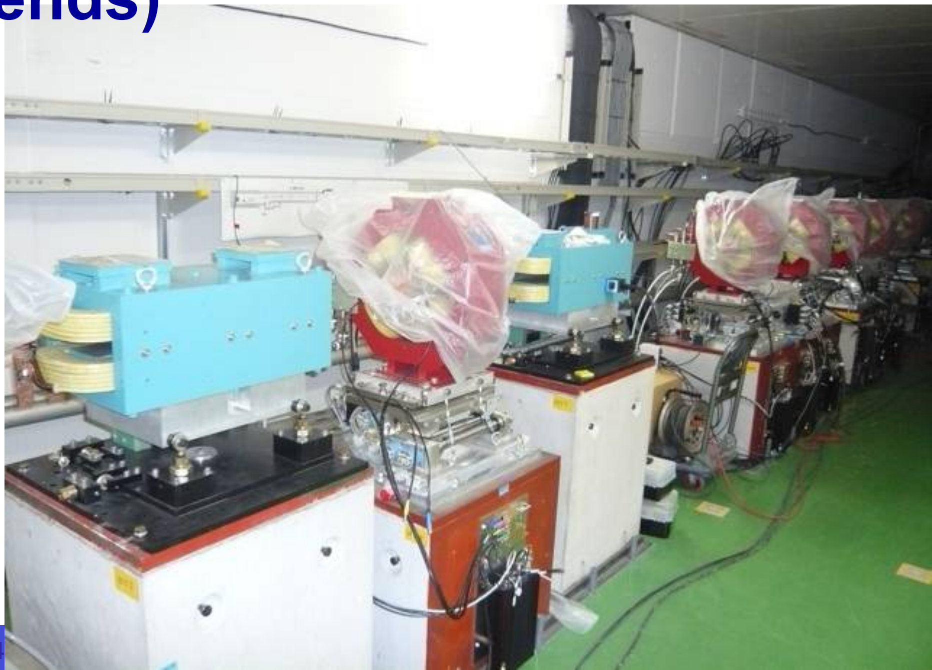
First ATF2 quad, Jan 2006

Beamline movers





- **FFTB cam movers were refurbished and used for all and magnets of ATF2 (except bends)**



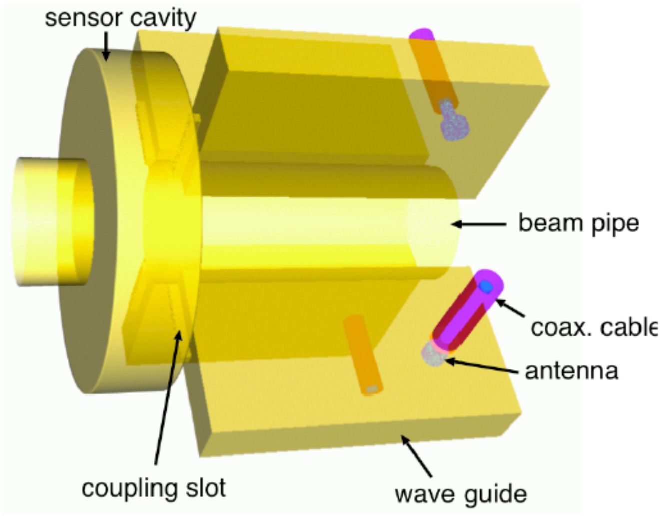
ATF2 construction – January 2008

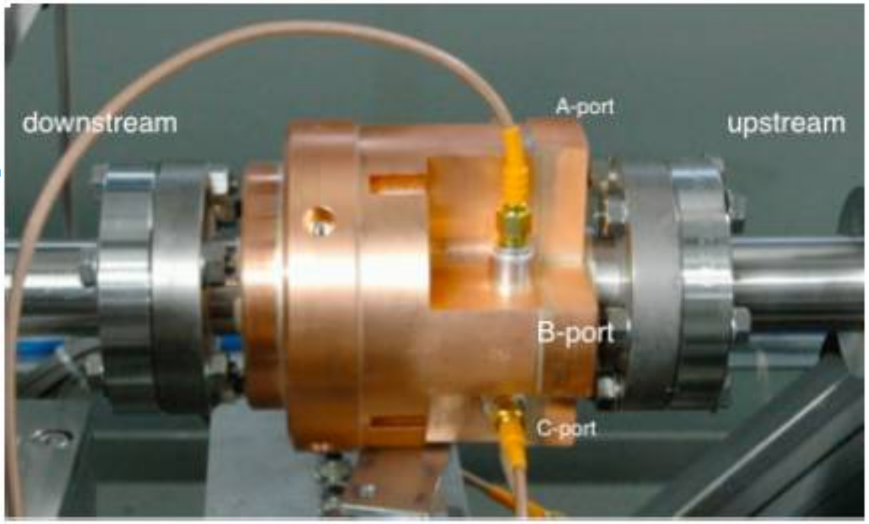
The last regular quadrupole is going to the destination

~20 sets of supports, movers & quads were installed in January. R.Sugahara et al

Cavity BPMs

ATF2 beamline magnets equipped with cavity BPMs



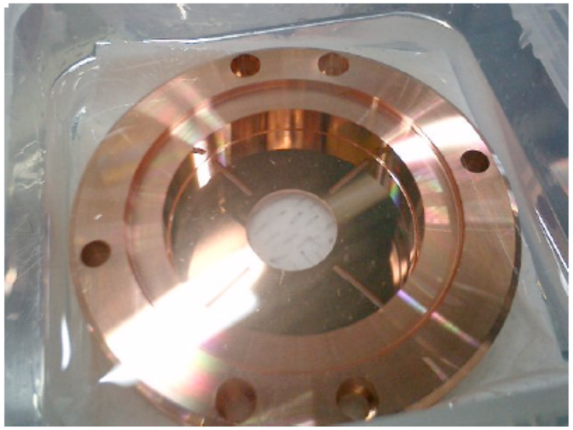


Prototype at PAL

C-band

Sub 100 nanometer resolution

Large dynamic range >500um

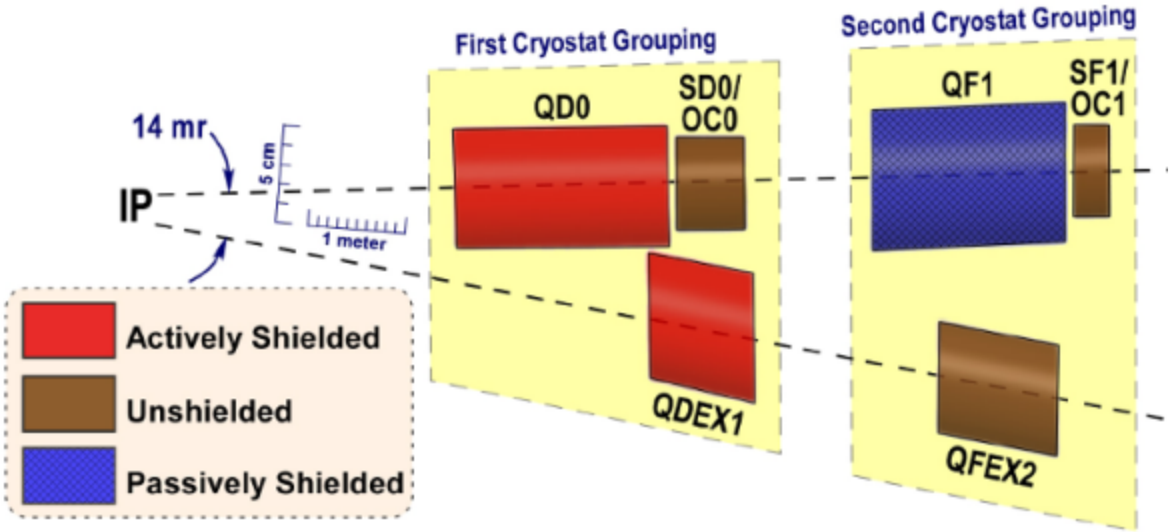


Cavity BPMs

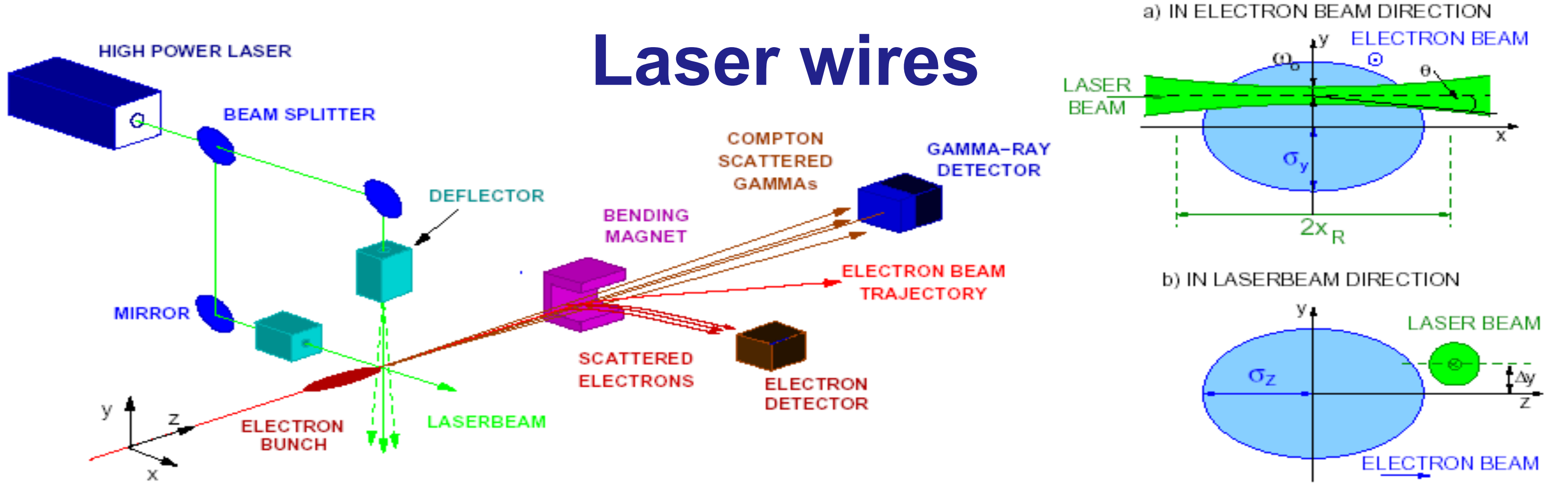
Cavity BPMs and SLAC front-end electronics modules provide sub-micron resolution of beam position

ATF2 final doublet

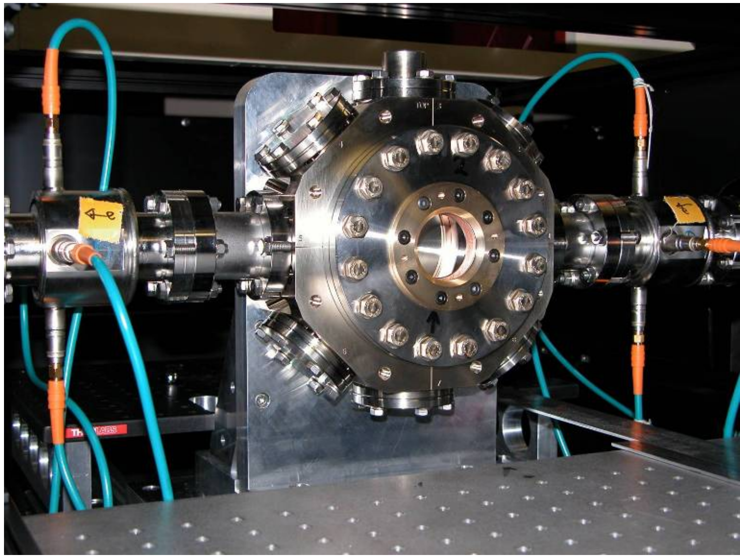
ILC Final Doublet layout



Laser wires



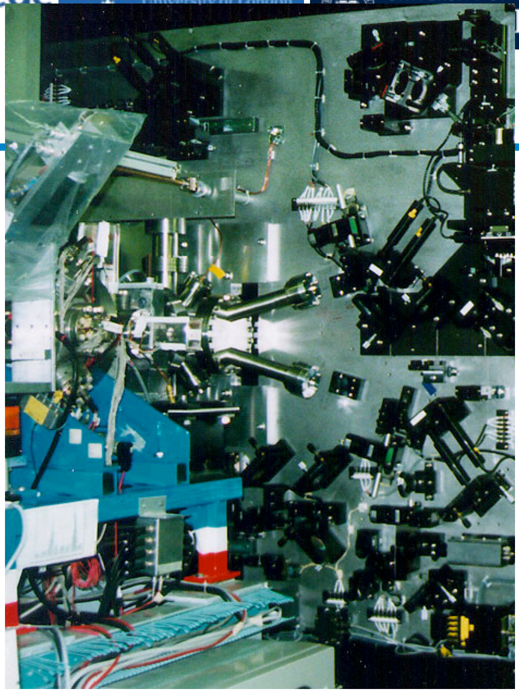
- Goal: non-destructive diagnostics for ILC
- (ATF2 is tuned with carbon wires and OTRs)
- Studies in ATF extraction line
- Aim to measure 1 μm spot beam
- Aim at 150ns intra-train scan
- Located at ATF2 in a place with μm spot
- Presently achieved resolution ~1μm



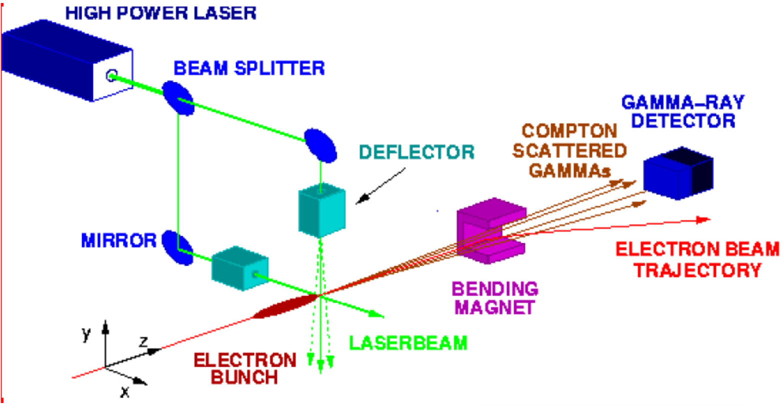
Laser wire chamber at ATF, JAI

Advanced beam instrumentation at ATF2

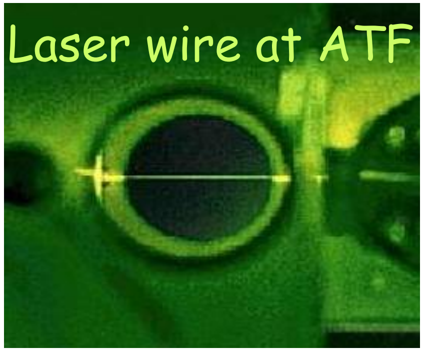
- BSM to confirm 35nm beam size
- nano-BPM at IP to see the nm stability
- Laser-wire to tune the beam
- Cavity BPMs to measure the orbit
- Movers, active stabilization, alignment system
- Intratrain feedback, Kickers to produce ILC-like train

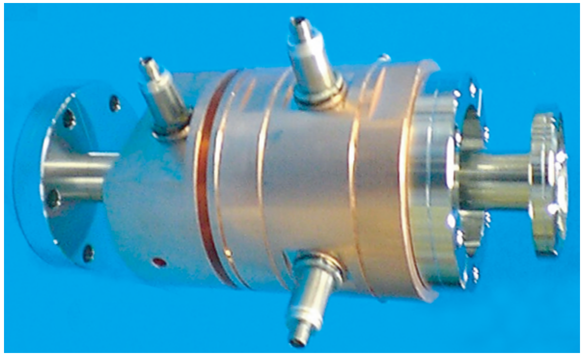


IP Beam-size monitor (BSM) (Tokyo U./KEK, SLAC, UK)



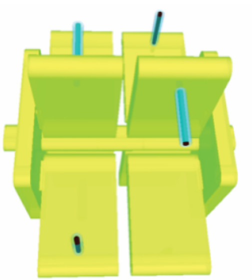
Laser-wire beam-size Monitor (UK group)





Cavity BPMs, for use with Q magnets with 100nm resolution (PAL, SLAC, KEK)

Cavity BPMs with 2nm resolution, for use at the IP (KEK)



Magnets and Instrumentation at ATF2

22 Quadrupoles(Q), 5 Sextupoles(S), 3 Bends(B) in downstream of QM16

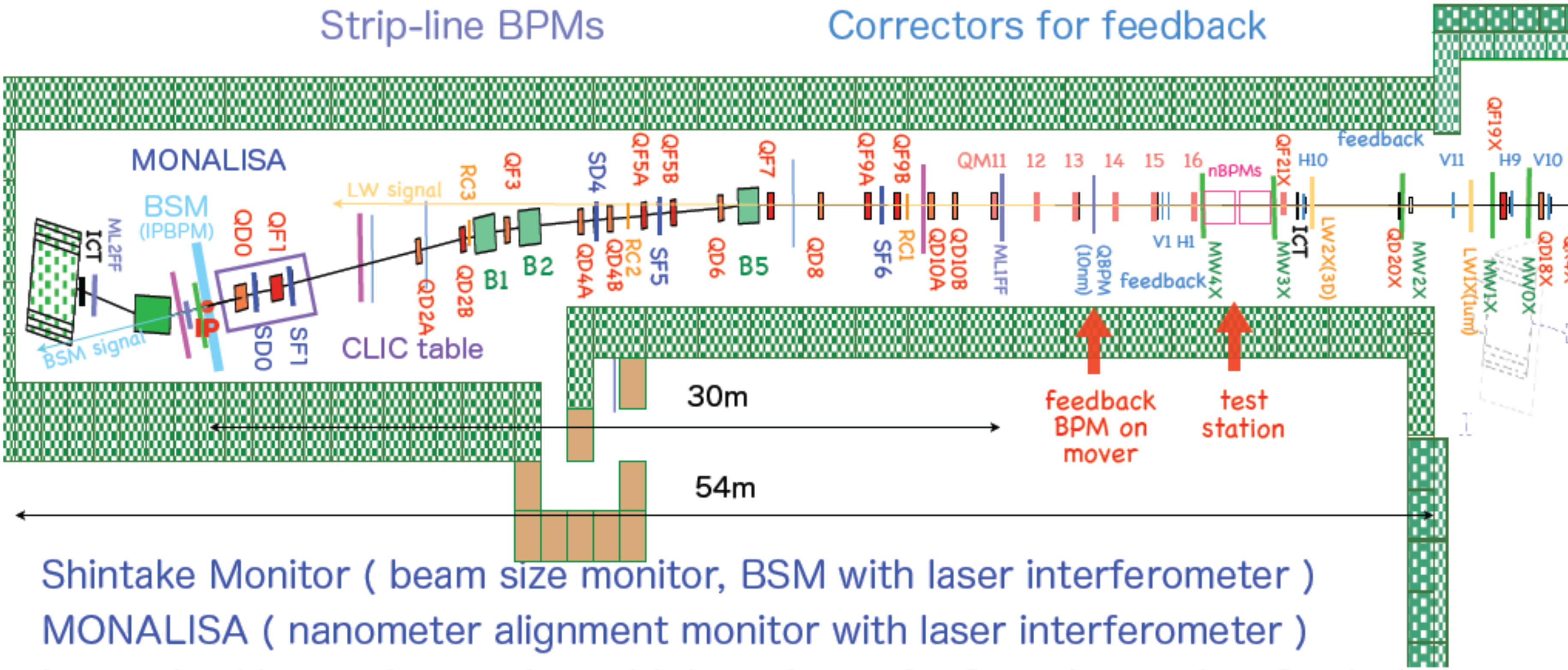
All Q- and S-magnets have cavity-type beam position monitors(QBPM, 100nm).

3 Screen Monitors

5 Wire Scanners, Laserwires

Strip-line BPMs

Correctors for feedback



Shintake Monitor (beam size monitor, BSM with laser interferometer)

MONALISA (nanometer alignment monitor with laser interferometer)

Laserwire (beam size monitor with laser beam for 1 μm beam size, 3 axies)

IP intra-train feedback system with latency of less than 150ns (FONT)

Magnet movers for Beam Based Alignment (BBA)

High Available Power Supply (HA-PS) system for magnets

Beam Size Monitor

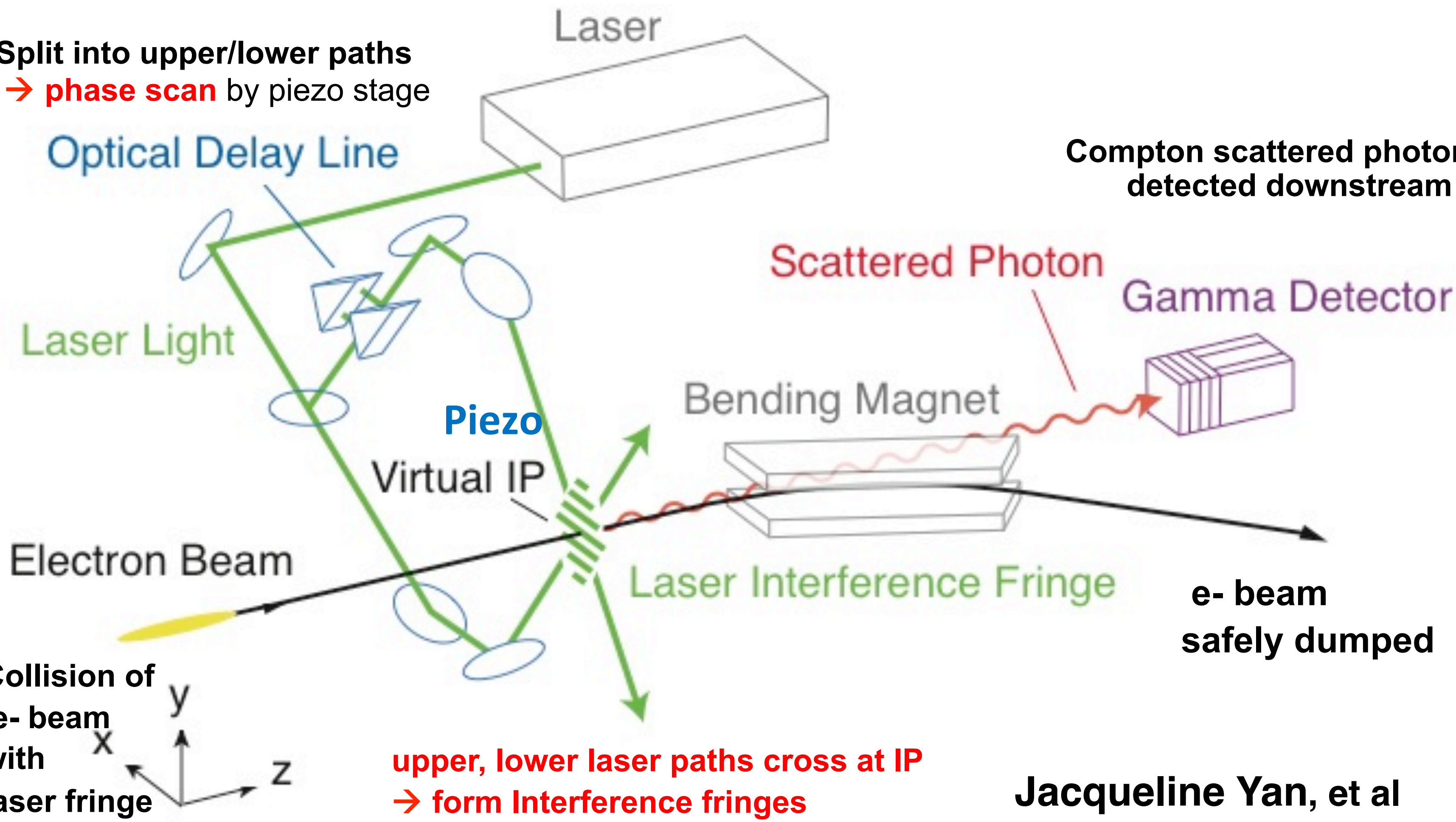
- Use **laser interference fringes** as target for e- beam

The only device able to measure σ_y < 100 nm !!

- Crucial for ATF2 beam tuning and realization of ILC

Split into upper/lower paths
→ phase scan by piezo stage

Compton scattered photons detected downstream



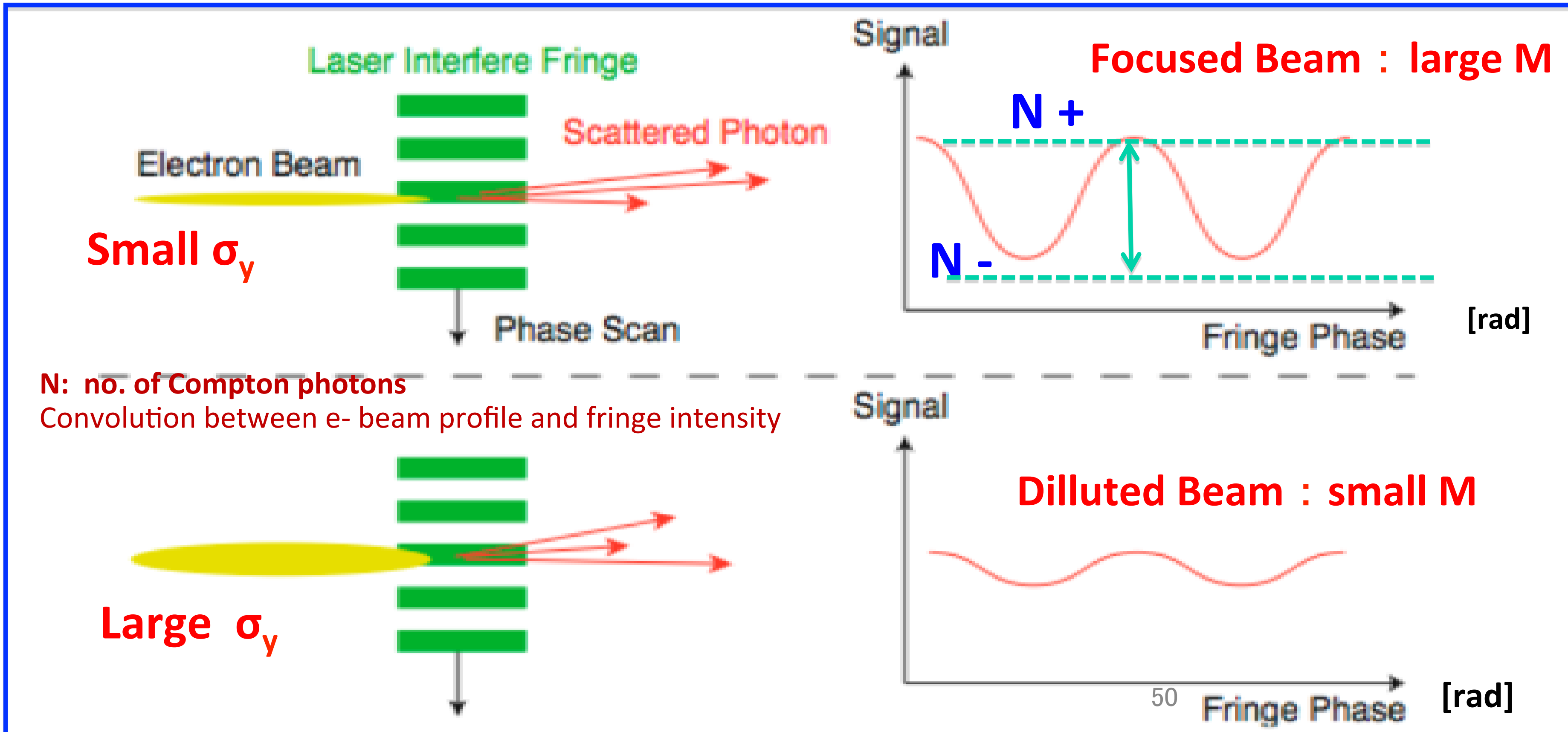
e- beam safely dumped

Collision of e- beam with laser fringe

upper, lower laser paths cross at IP
→ form Interference fringes

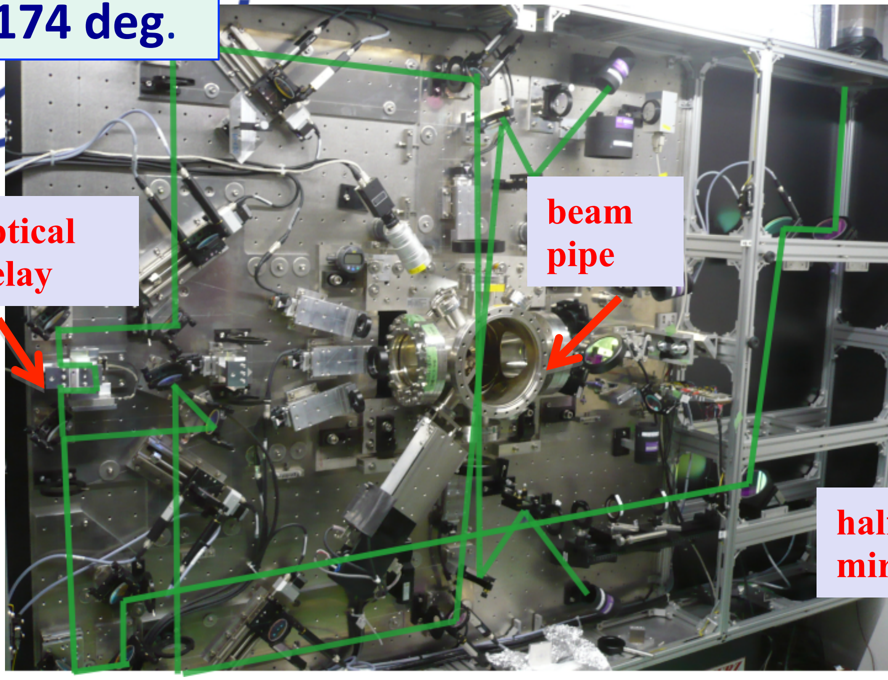
Jacqueline Yan, et al
University of Tokyo

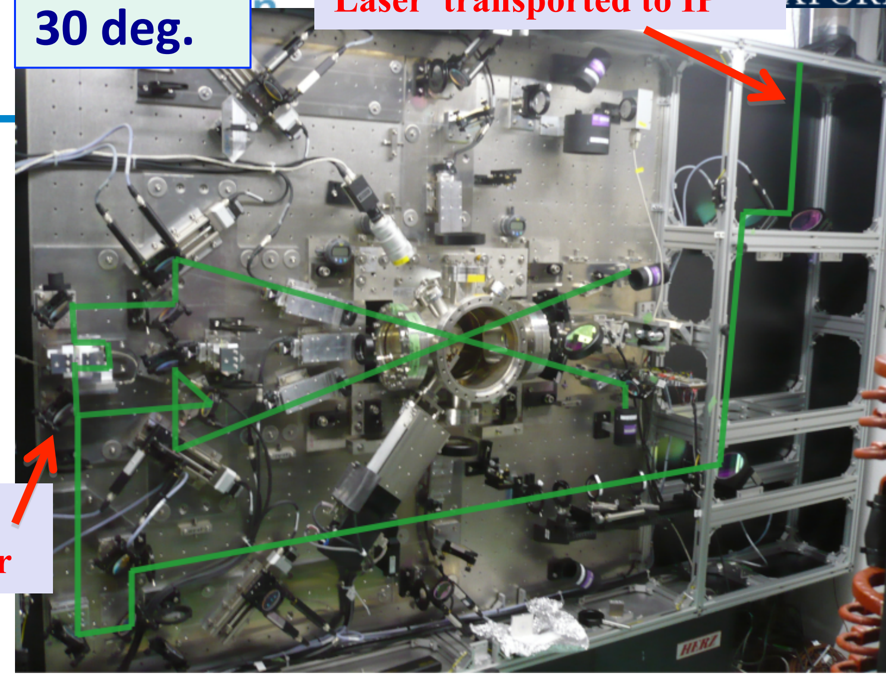
Detector measures signal **Modulation Depth "M"**

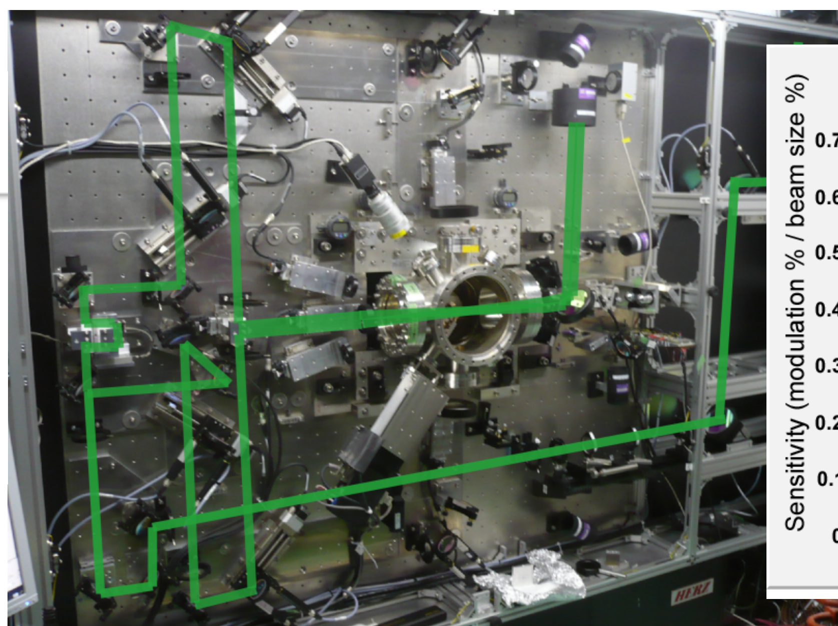


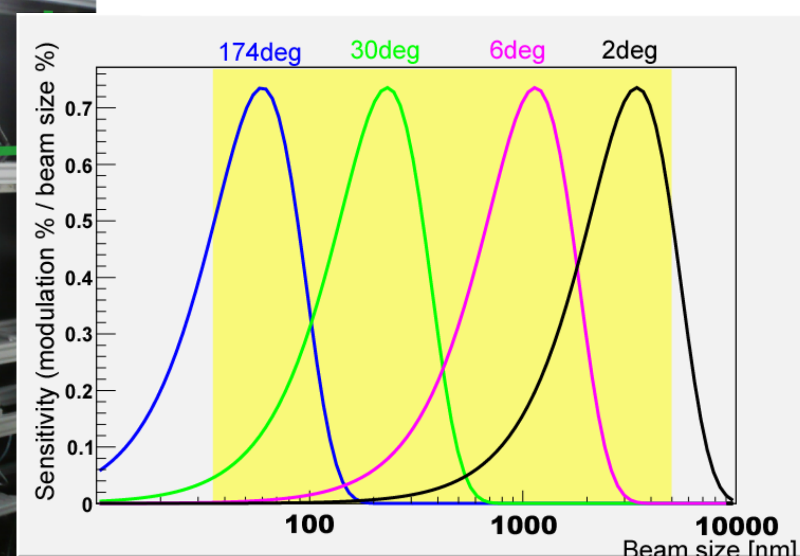
N: no. of Compton photons
Convolution between e- beam profile and fringe intensity

Jacqueline Yan, et al
University of Tokyo

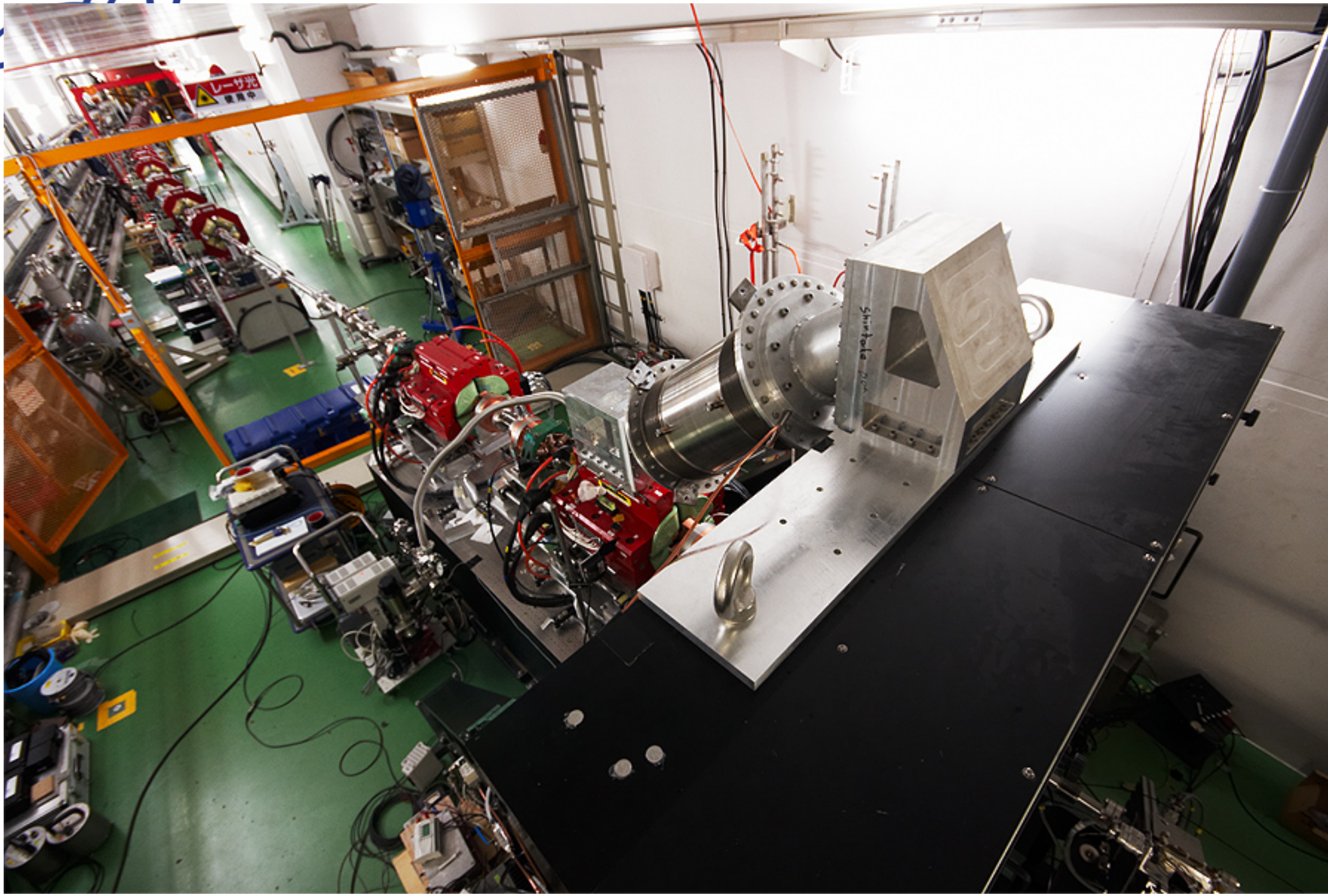








Crossing angle continuously adjustable by prism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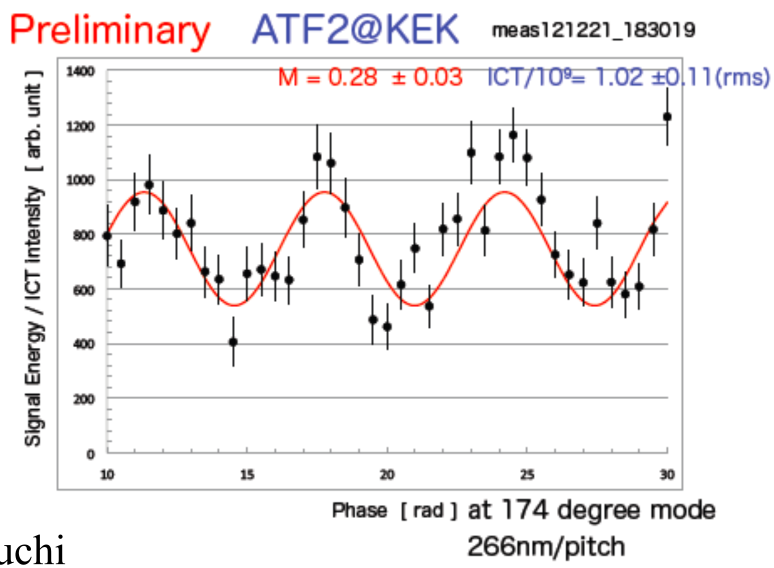
使用中

ATF2 results – December 2012



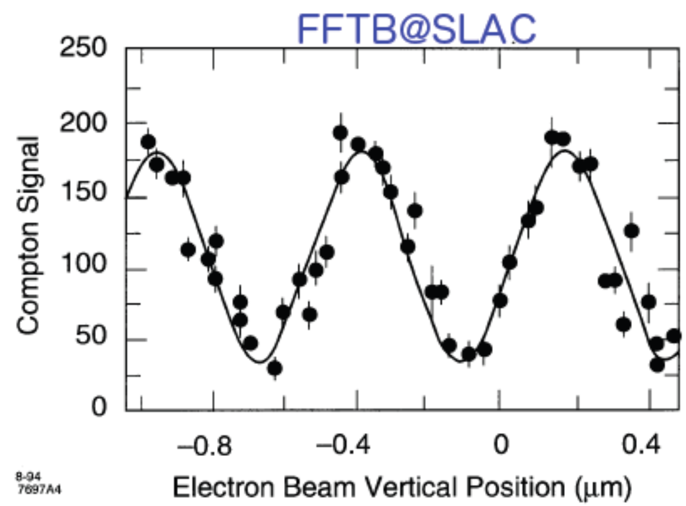
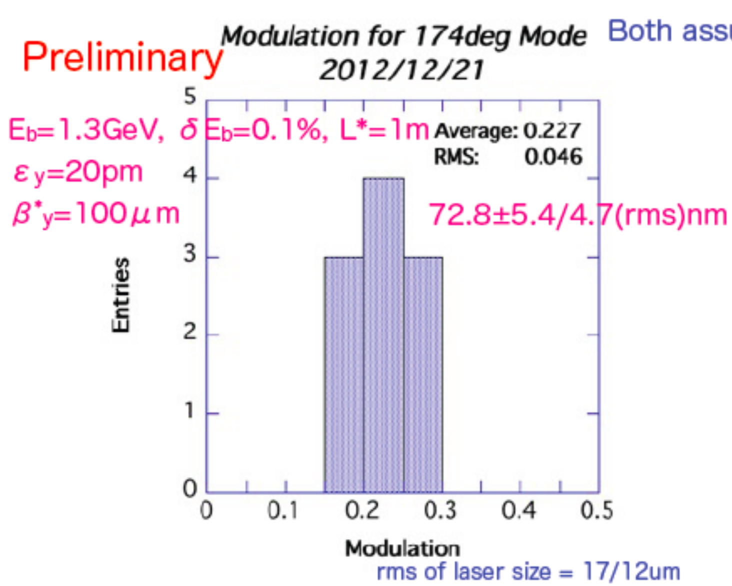


Figure 5.6: Laser-Compton beam size measurement performed in May of 1994. The measured size is 77±7 nanometers.

Slide: T.Tauchi



Both assumes no modulation reduction

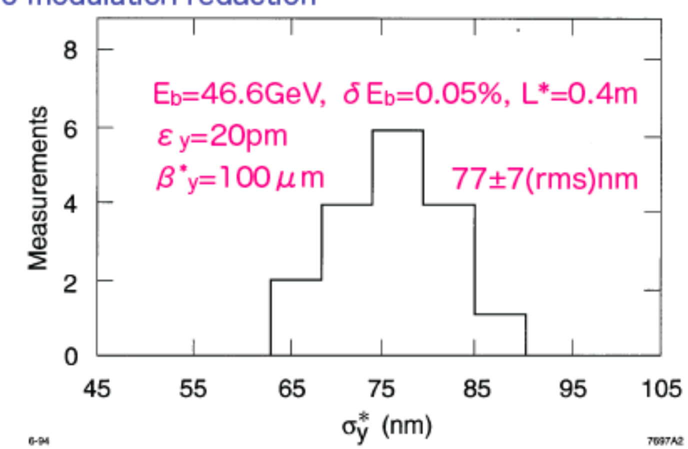
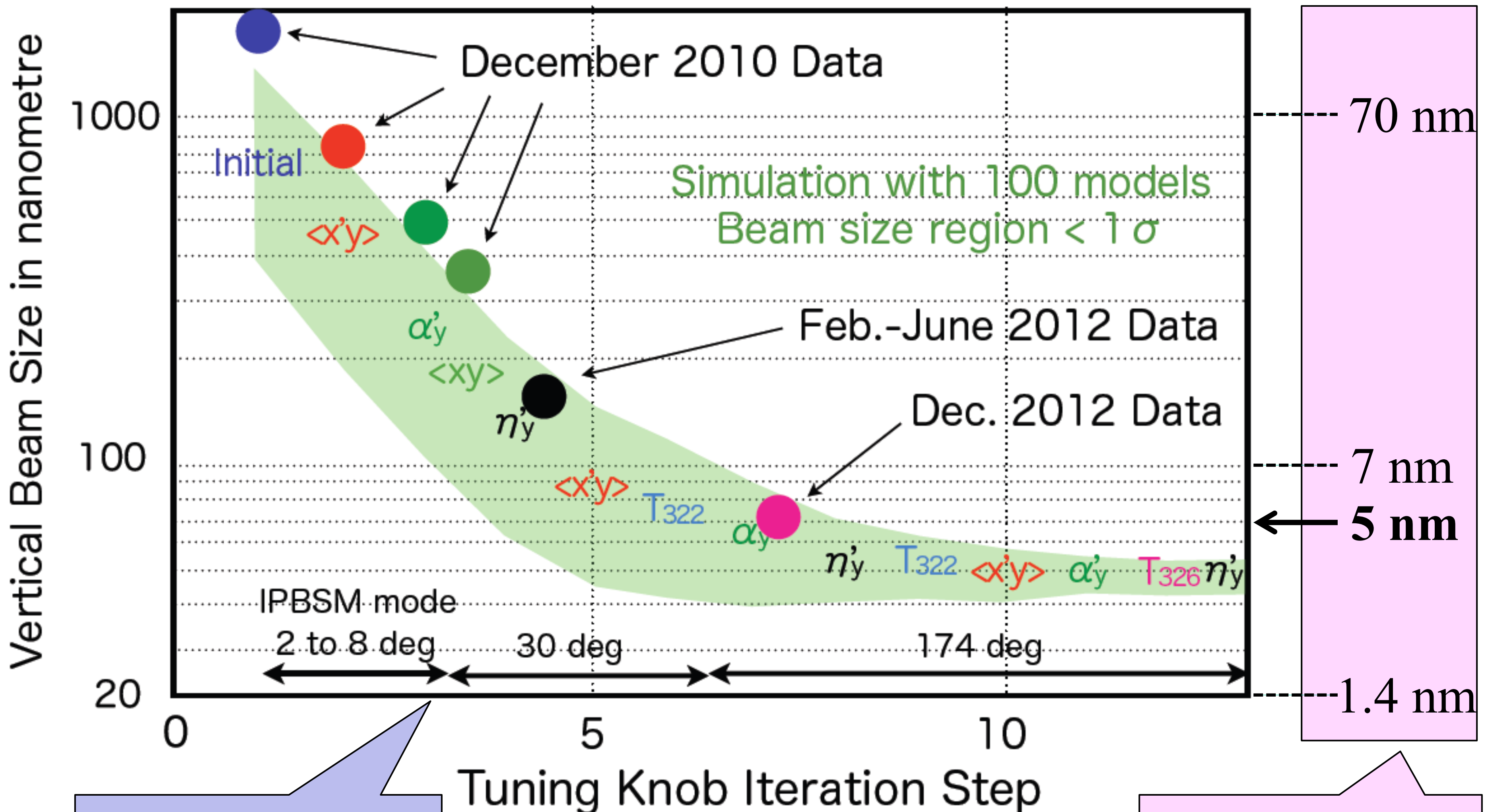


Figure 5.7: Histogram of measurements made during the last 3 hours of the May, 1994 FFTB run. Average size measured was 77 nm, with an RMS of 7 nm.

rms of laser size = 50um -> M reduction of 10%

2013年 1月 7日 月曜日

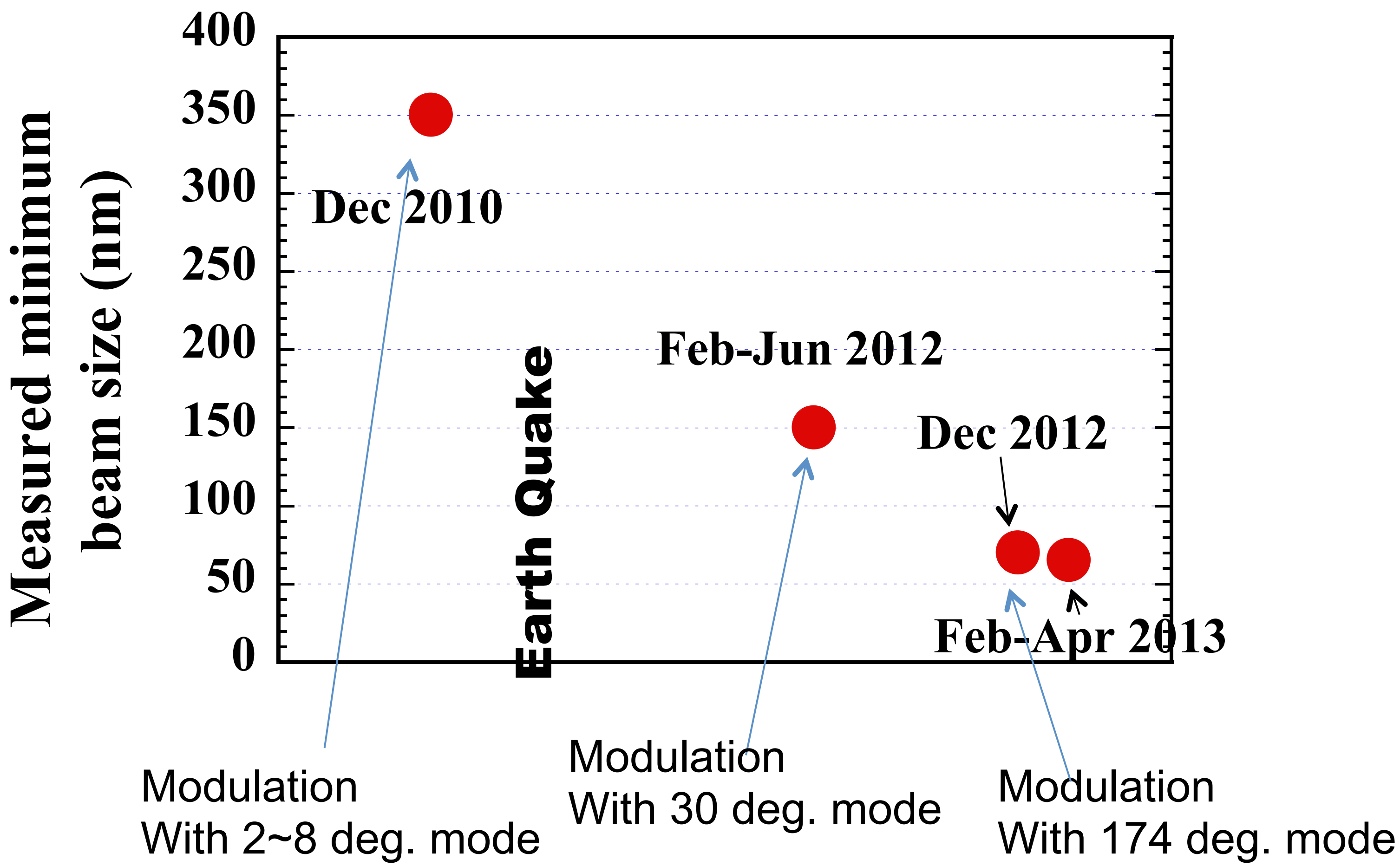
ATF2 results & scaling to 250GeV/beam



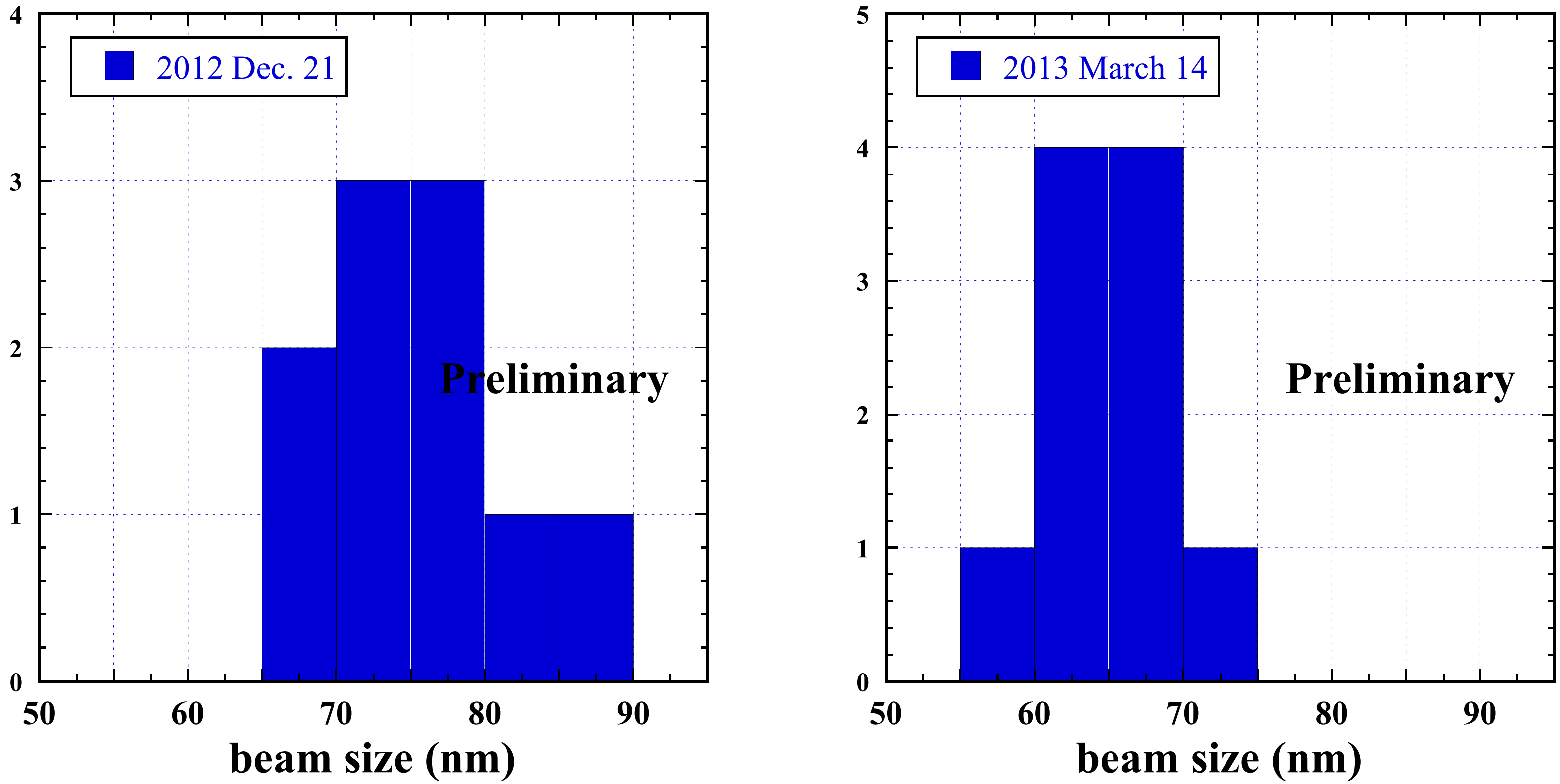
ATF2 results at 1.26 GeV/ beam

Rescaled to 250 GeV/beam

History of measured beam size



<70 nm beam size confirmed first in Dec. 2012, and continuously observed



Beam size evaluated assuming no systematic error of the beam size monitor.

ATF2 review by ILC GDE, Apr 2013:

ATF2 review: General statements

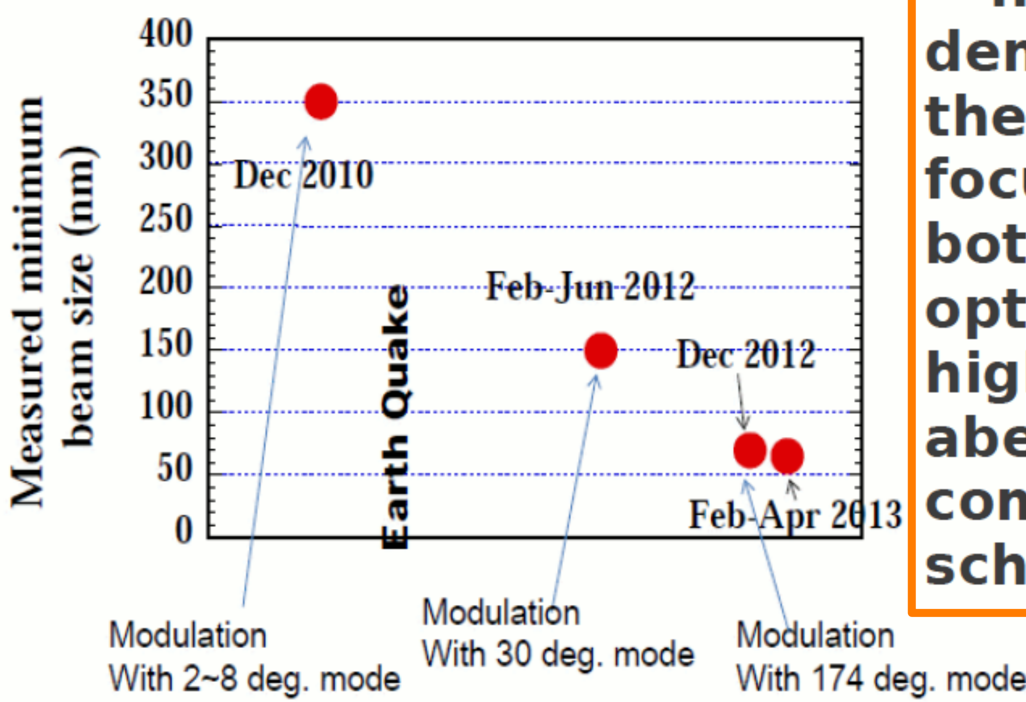
"...The extensive upgrades and improvements to the machine itself, including critical sub-systems such as the **IPBSM**, together with the **organized approach to shifts and personnel training**, have resulted in significant gains in terms of understanding and characterizing the accelerator, resulting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

ATF2 review by ILC GDE, Apr 2013:

Goal 1: 37 nm

- Reached 64 nm
- Tuning from ~3000 nm
- Suppression of aberrations confirmed to about ~90%
- Bunch charge ~10^9 e-!!
- **"...successful demonstration of the compact final focus optics and both the linear optics tuning and high-order aberration compensation schemes involved"**

Kubo



Summary

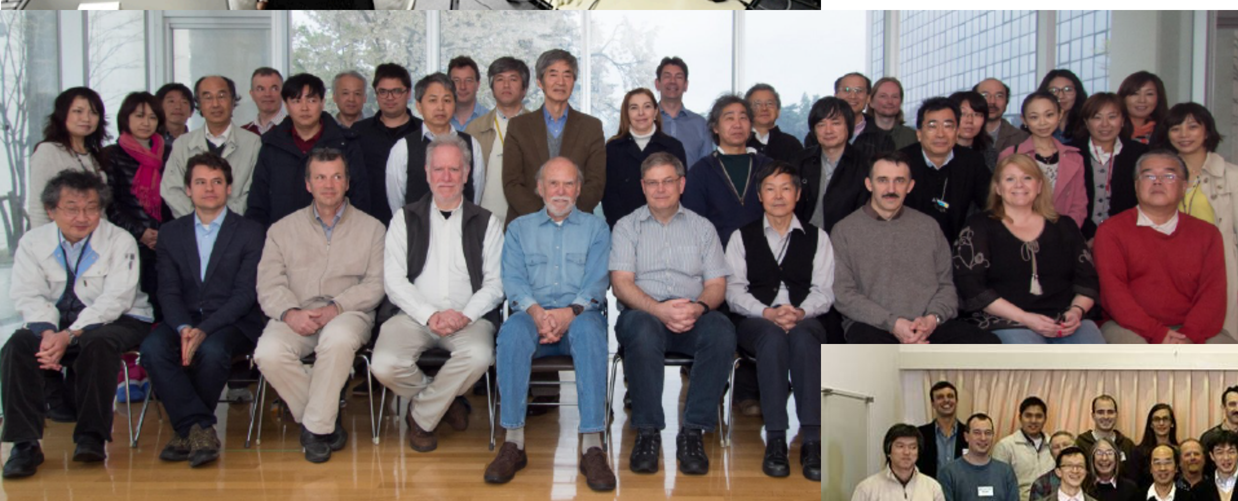
- Final Focus with local chromatic correction works in theory and in practice
- The ATF/ATF2 international collaboration successfully demonstrated operation of ILC-like final focus system
- The ATF2 project was realized as ILC-like international project, with in-kind contributions
- The ATF2 is a great training and advanced accelerator research facility

Imperial College London

Royal Holloway University of London

UNIVERSITY OF OXFORD

Thanks to all colleagues in the ATF Collaboration!



EXTRA SLIDES

USPAS – Summer of 2014

Unifying physics of Accelerators, Lasers and Plasma – synergy and bridge

Instructors:

Andrei A. Seryi, John Adams Institute for Accelerator Science, UK

Purpose and Audience
This one-week course will aim at creation of bridges and connections between three areas of physics, ***essential for developments of next generation accelerators – physics of accelerators, lasers and plasma.*** The course will be suitable for students of various levels between senior undergraduate and graduate students in physics, those who are interested in enhancing their ability to work successfully on development of next generation facilities, devices, scientific instruments, arising from synergy of these three areas.

Looking for support of the community for this initiative

USPAS – Summer of 2014

Objectives

This course will focus on the key phenomena and concepts of accelerator, laser and plasma physics, building-up cross-understanding in these three areas. Upon completing this course, students become fluent in physics concepts, terminology and methods used in these three areas, and should become more effective in their research and innovations that span across these fields.

Instructional Method

This course will offer a series of lectures during morning sessions, followed by afternoon tutorial sessions. The tutorial sessions will be focused on considering and solving various problems and mini-projects by small teams of several students, followed by oral reports. Homework problems will be assigned daily. There will be a final exam on the last day of the class.

Course Content

During the course we will focus on several key phenomena, for example compressing particle bunches and laser pulses, instabilities in particle beams and in plasma, etc., and will focus on ***in-depth understanding of similarities and differences of physics***, as well on studying ***differences of terminology and mathematical apparatus used for description of similar phenomena*** in these areas of physics. During our work on problems and mini-projects we will use the methodology of the ***theory of inventive problem solving*** to come to innovative solutions based on scientific effects across and outside the considered areas.