19th ATF2 Project Meeting

Beam tuning for low β* optics - highlights

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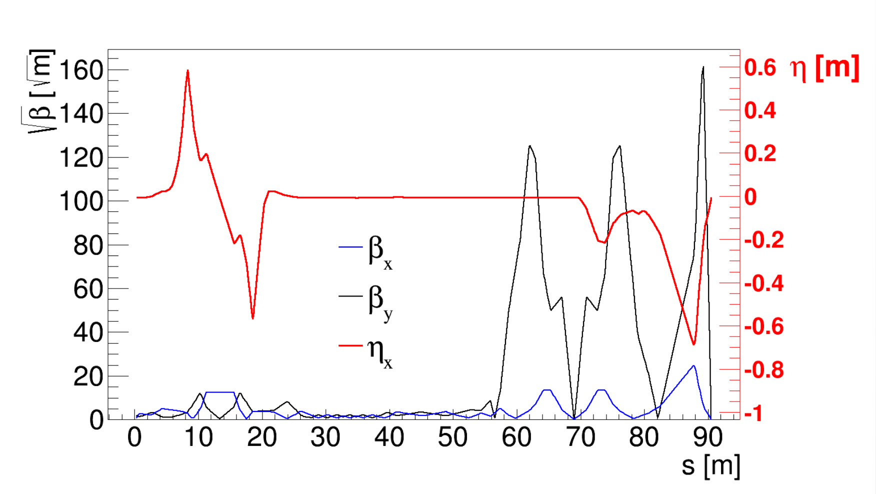
Motivation for half β_y^* (10x0.5 optics)

Collecting the experience and having a training before the ultra-low β^* optics:

- Preparing tools for optics modification, measurement and control;
- Checking the beam size tuning performance in more demanding conditions;
- Finding the issues and addressing them.

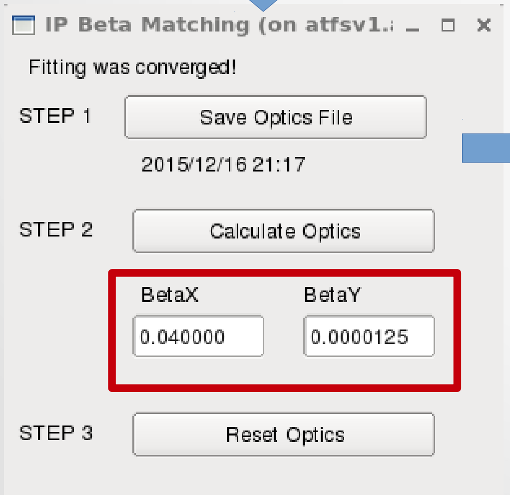


10x0.5 optics (on the plot) has been tested in ATF2 since December 2014.

The expected IP vertical beam size is 26 nm, assuming vertical emittance ε_y = 12pm.

Experimental results, December 2015 – optics rematch

ATF2 control system tool for optics rematch. Calculates the strength of QD20X, QF21X, QM10-16FF required to set the desired β^* values.



Fitting was converged!

STEP 1

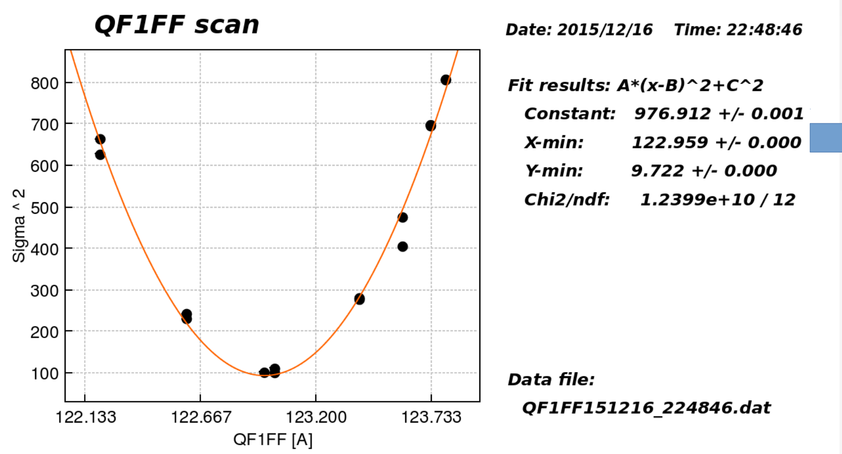
2015/12/16 21:17

STEP 2

BetaX: 0.040000

BetaY: 0.0000125

STEP 3



```
Date: 2015/12/16   Time: 22:48:46

Fit results: A*(x-B)^2+C^2
  Constant:   976.912 +/- 0.001
  X-min:      122.959 +/- 0.000
  Y-min:      9.722 +/- 0.000
  Chi2/ndf:    1.2399e+10 / 12

Data file:
  QF1FF151216_224846.dat
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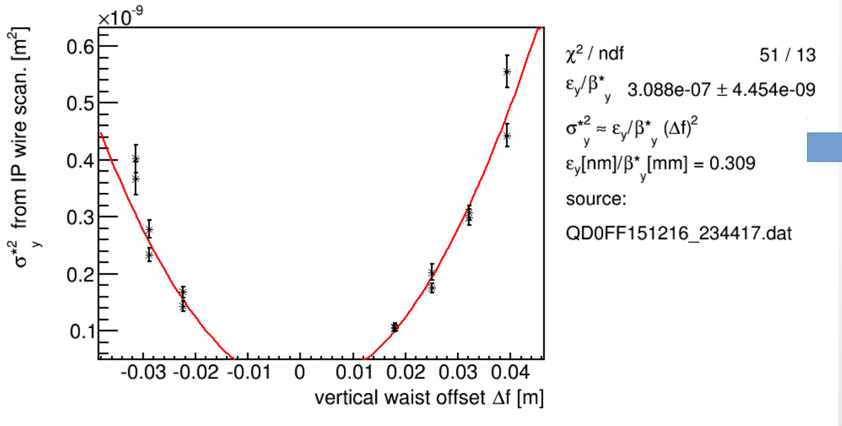
ε_x = 1.27 nm

β_x^* = 74.6 mm

β_x^* doesn't meet the design

but no time to correct it.

Model mismatch!



χ^2 / ndf 51 / 13

ε_y/β^*_y 3.088e-07 ± 4.454e-09

$\sigma^{*2}_y \approx \varepsilon_y/\beta^*_y\ (\Delta f)^2$

ε_y[nm]/β^*_y[mm] = 0.309

source:

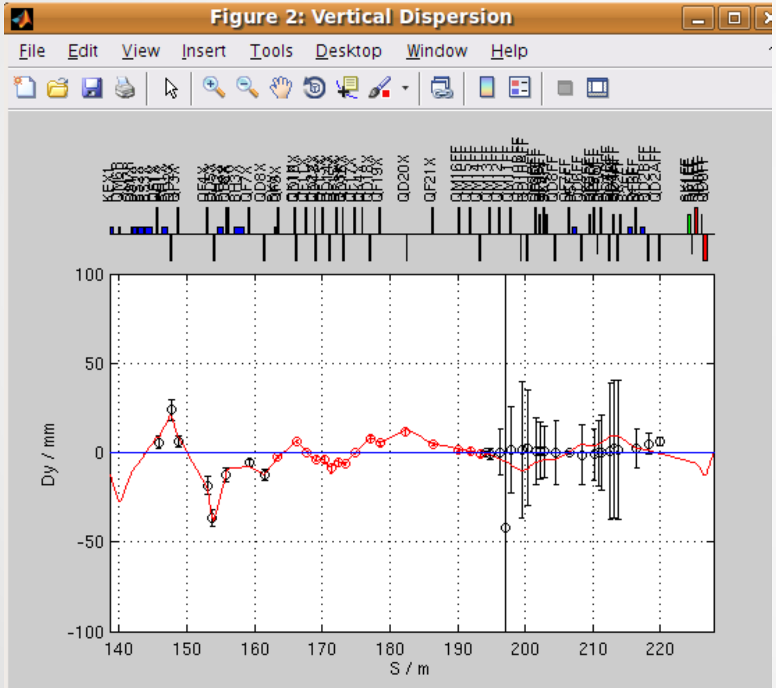
QD0FF151216_234417.dat

$\varepsilon_y/\beta_y^* = (0.309 \pm 0.004)\cdot 10^{-12}$

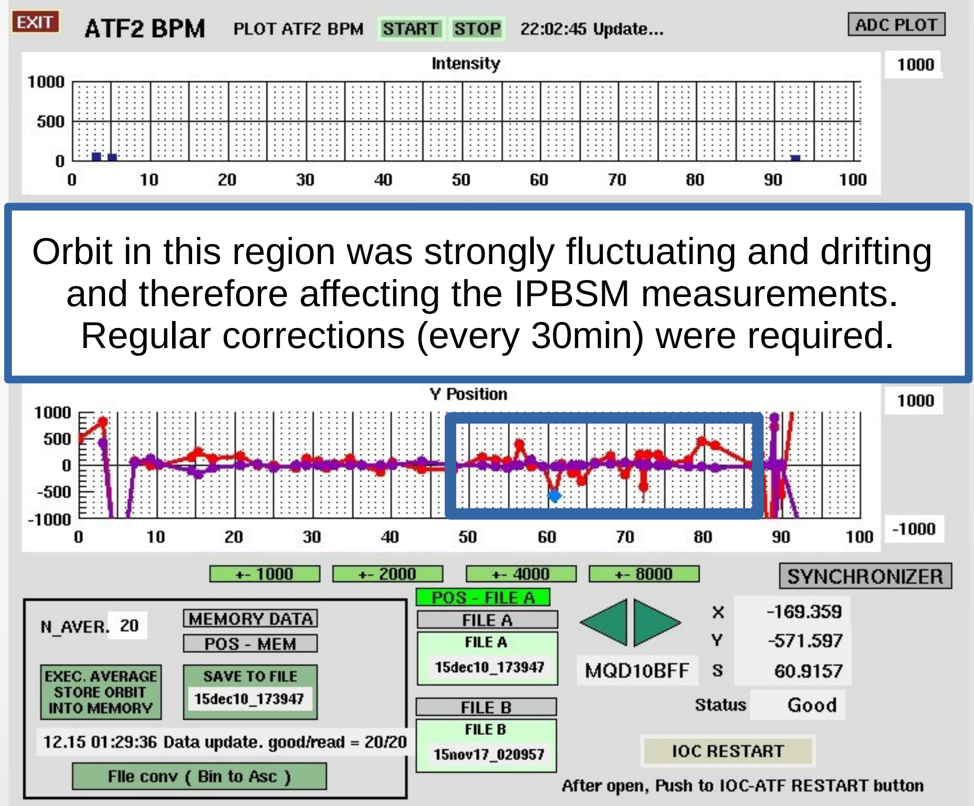
ε_y = 16.0 ± 1.4 pm (mOTR)

β_y^* = 52.8 ± 4.6 μm

Experimental results, December 2015 – orbit correction



Orbit after correction using ZH1FF & ZV1FF:



22:02:45 Update...

N_AVER. 20

SAVE TO FILE 15dec10_173947

FILE A 15dec10_173947

FILE B 15nov17_020957

X -169.359
Y -571.597
S 60.9157
Status Good

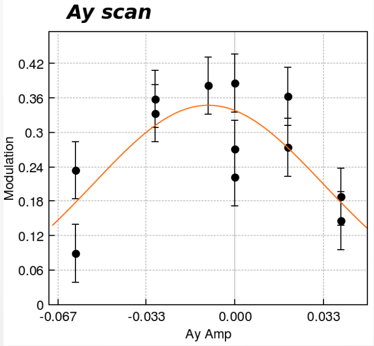
12.15 01:29:36 Data update. good/read = 20/20

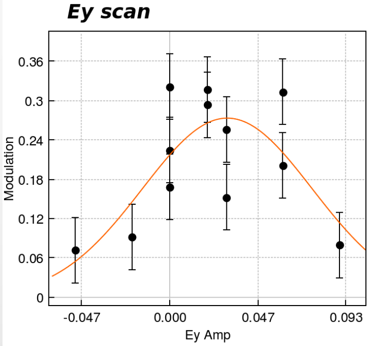
After open, Push to IOC-ATF RESTART button

Orbit in this region was strongly fluctuating and drifting and therefore affecting the IPBSM measurements. Regular corrections (every 30min) were required.

Experimental results, December 2015 – beam size tuning

- QF1FF and QD0FF scans using wire scanner
- Waist (α_y), dispersion (E_y), x'y-coupling (Coup2) knobs in IPBSM 7deg mode → switched to 30deg mode
- Waist (α_y), dispersion (E_y), x'y-coupling (Coup2) knobs in IPBSM 30deg mode → 0.7 of modulation
- Trying to switch to IPBSM 174deg mode but couldn't find the modulation
- Back to IPBSM 30deg mode. Applied scans: Horizontal (ZH1FF) and vertical (ZVFB1FF) orbit, reference cavity vertical position, QF3FF vertical position, waist (α_y), dispersion (E_y) → 0.64 modulation
- Switching to IPBSM 174 deg mode
- Waist (α_y), dispersion (E_y) scans → very fluctuating →
- Y22, Y26, Coup2, ZVFB1FF, RefCavVpos scans:
  - The modulations decreasing with time down to ~0.2
- End of the study after 24 hours
- Lowest measured vertical IP beam size was about 60 nm.

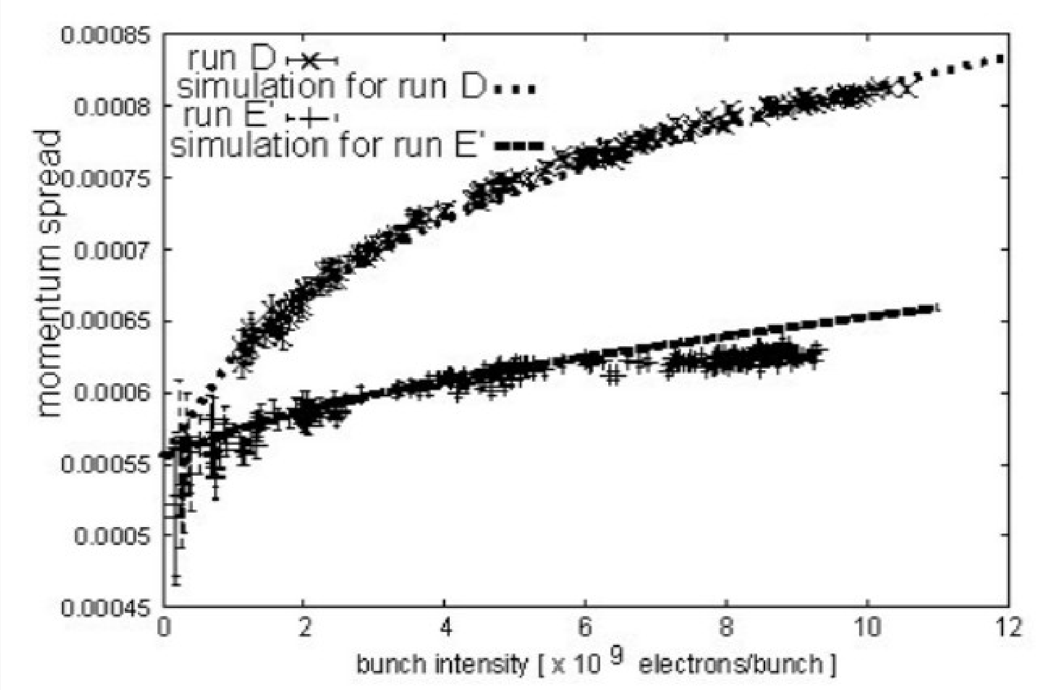




Identified issues and remarks about the beam size tuning

- Model mismatch – experiment shows a linearly scaling mismatch between the model and the machine. Optics adjustment is possible after 2-3 iterations.
- Wakefields – operating at very low beam intensity (10^9) is only possible. It causes the IPBSM measurement to be very noisy and time consuming. The orbit feedback efficiency is also low for low beam intensity. (More details in other presentations at this meeting.)
- **Orbit steering – we don't have a tool for automatized, repeatable and efficient orbit steering. The IP beam size seems to be very sensitive to the orbit change.**
- **Time – beam size tuning is very time consuming. In 174deg mode one scan takes ~1h and we have ~13 knobs (3 linear, 6 nonlinear, ~4orbit) to be applied several times.**
- **Energy spread for low beam intensity is smaller (<u>less than factor 2</u>) than nominal. It should make the beam size tuning easier and allow to decrease the strength of sextupoles.**

Momentum spread vs beam intensity in DR



Y. Honda et al.Phys. Rev. Lett. 92, 054802

What next?

- We would like to continue this study during spring 2016.
- Ideas:
  - Recording the beam orbit during the tuning and trying to estimate its impact on the beam size
  - Trying to scan the sextupoles strength independently
  - Comparing different optics cases (20x1, 10x1, 20x0.5, 10x0.5)
  - Assigning longer periods (at least 48h) for continuous tuning with given optics
  - Investigate the effect of lower energy spread
- Octupole magnets are expected to be assembled at CERN in March. Its impact on beam tuning will be studied in May/June 2016.

Extra slides

Time

- 24 hours were given for low betay*
- EXT line: 2h
- Optics matching: 4h
- Getting to 174deg mode: 5h (it took us 10h, but probably because of lack of experience. 5h should be enough.)
- In 174 deg mode one scan takes ~1h. There are ~13 knobs (3 linear, 6 nonlinear, ~4 orbit). 3 iterations over all scans: 39h
- Minimum time for beam size tuning: 50h

Motivation for ultra-low β* in ATF2

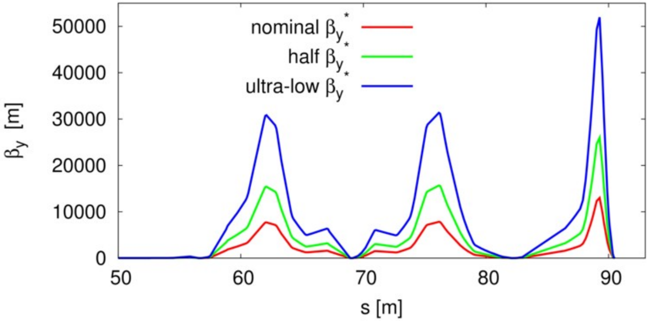
- **ATF2 ultra-low β* optics is a project to test the tunability of the Final Focus System at the chromaticity level comparable with CLIC.**
  - Larger chromaticity ξ makes the Final Focus System more difficult to operate.
  - Level of chromaticity ξ_y in ATF2 is comparable to ILC.
- **Ultra-low β* optics also gives the opportunity to lower the IP vertical beam size down to about 20 nm and collect the experience with strong beam focusing and very small beam at the IP.**
  - Utilization of octupole magnets for stronger beam focusing will be tested.

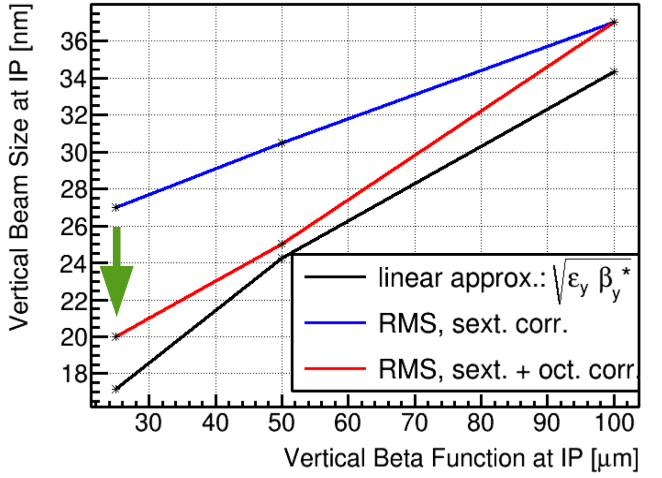
	β_y* [µm]	$\sigma^*_{y,\ design}$[nm]	L* [m]	$\xi_y \sim (L^*/\beta_y^*)$
ILC	480	5.9	3.5/4.5	7300/9400
CLIC	70	1	3.5	50000
ATF2 nominal	100	37 (44[a])	1	10000
ATF2 half β_y*	50	25[b]	1	20000
ATF2 ultra-low β_y*	25	20[b]	1	40000

[a] measured, June 2014

[b] using octupoles

IP vertical beam size for ultra-low β*





Decreased β_y* causes the increase of β_y in the Final Focus region. In consequence the beam size is larger in the FF and more sensitive to beam line imperfections. It was checked that:

- **magnetic multipole fields** and
- **fringe fields**

are limiting factors for the IP beam size.

Proposed mitigation method:

- Installation of two octupole magnets
  - Corrects both multipole fields and fringe fields.
  - Makes sextupoles strength adjustment easier and therefore allows for more effective chromaticity correction.
  - **Brings the IP beam size from 27 nm to 20 nm for ultra-low β* optics.**

Beam size tuning simulations

Simulation conditions:

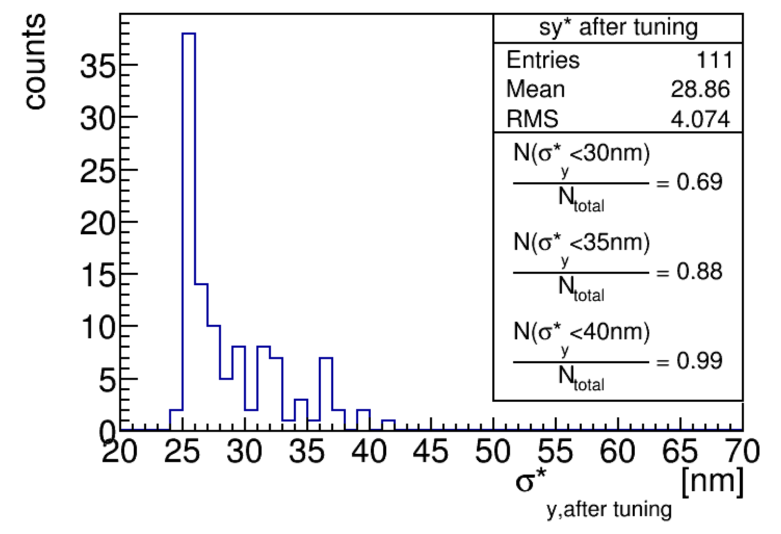
- The following random errors are applied to the lattice:
  - Quads, Sexts position and tilt errors:

    $\Delta x = \Delta y = 100\ \mu m$ (Gaussian)

    $\Delta\theta = 200\ \mu rad$ (Gaussian)
  - Quads, Sexts strength error:

    $\Delta K = 0.1\%$ (Gaussian)
- Measured multipole fields errors are also applied.
- $dp/p = 0.0008$
- 111 seeds

Result:



- Beam size clearly smaller than for 10x1 optics
- Increased tuning difficulty is observed

Experimental results, June 2015

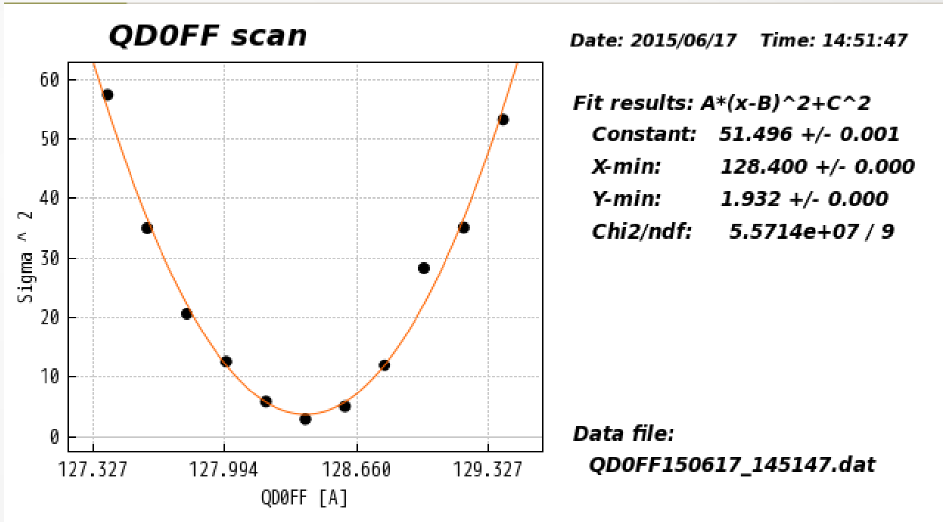
- The optics was set up in the experiment by iterations of matching quads adjustments and β_y* measurements.
- The β_y* value was estimated from the beam divergence at the IP extracted from the IP beam size scan by changing the QD0FF current:

$$\boxed{\beta^* \approx \frac{\varepsilon}{\sigma^2}(\Delta f)^2}$$

Δf – distance from nominal IP

- For **measured (OTR) vertical emittance of 14.4 +/- 1.1 pm**, the β_y* estimated from scans

β_y= 47.3 +/- 4.3 µm
(50 µm is a design)

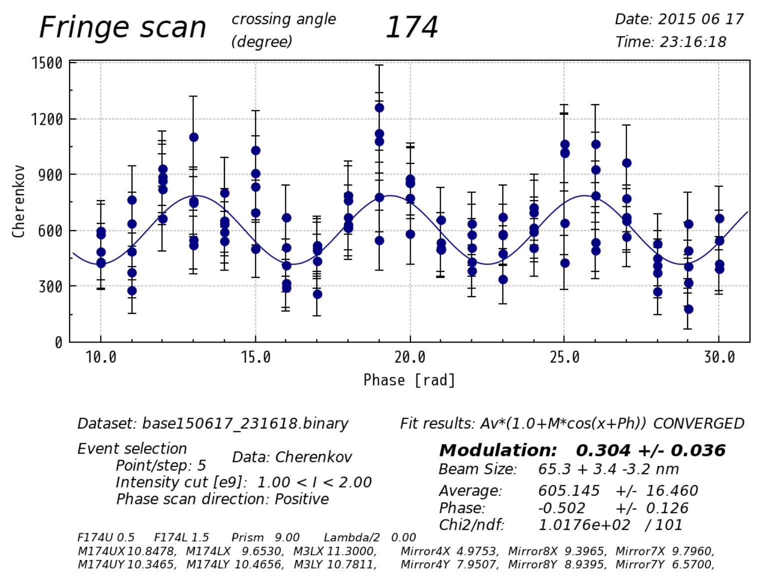


Date: 2015/06/17 Time: 14:51:47

```
Fit results: A*(x-B)^2+C^2
   Constant:   51.496 +/- 0.001
   X-min:      128.400 +/- 0.000
   Y-min:      1.932 +/- 0.000
   Chi2/ndf:    5.5714e+07 / 9
```

Data file:
QD0FF150617_145147.dat

Experimental results, June 2015



```
Fringe scan   crossing angle   174                       Date: 2015 06 17
              (degree)                                   Time: 23:16:18

Dataset: base150617_231618.binary         Fit results: Av*(1.0+M*cos(x+Ph)) CONVERGED

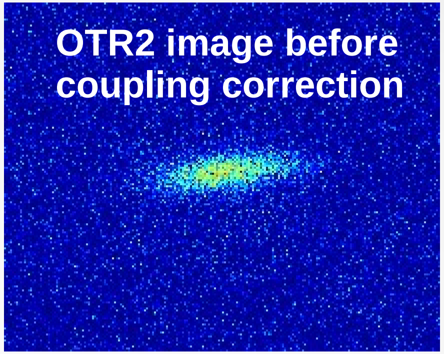
Event selection                              Modulation:   0.304 +/- 0.036
      Point/step: 5      Data: Cherenkov     Beam Size:    65.3 + 3.4 -3.2 nm
      Intensity cut [e9]:  1.00 < I < 2.00
      Phase scan direction: Positive         Average:      605.145   +/-  16.460
                                             Phase:        -0.502    +/-  0.126
                                             Chi2/ndf:     1.0176e+02  / 101
F174U 0.5    F174L 1.5    Prism   9.00    Lambda/2   0.00
M174UX 10.8478,  M174LX   9.6530,  M3LX 11.3000,    Mirror4X  4.9753,  Mirror8X  9.3965,  Mirror7X  9.7960,
M174UY 10.3465,  M174LY  10.4656,  M3LY 10.7811,    Mirror4Y  7.9507,  Mirror8Y  8.9395,  Mirror7Y  6.5700,
```

- The first experience with half β_y* optics was collected during the December 2014 and April-May-June 2015 runs in ATF2.

- Beam size tuning (June'15) with the use of the linear knobs:
  - IP vertical beam size was about **65 nm**
  - Far from **expected 28.5 nm** (assuming measured emittance)
  - The same beam size was measured one day before in $10\beta_x 1\beta_y$ optics (should be easier to operate).

Experimental results, December 2015 - emittance

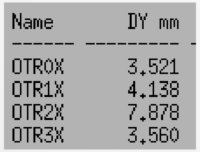
- Emittance was measured twice:
- Before the coupling correction in EXT line:
  1.72 ± 0.02 nm (horiz.) and 19.1 ± 0.3 pm (vert.)
- After the coupling correction in EXT line:
  1.73 ± 0.03 nm (horiz.) and 16.0 ± 1.4 pm (vert.)



OTR2 image before coupling correction

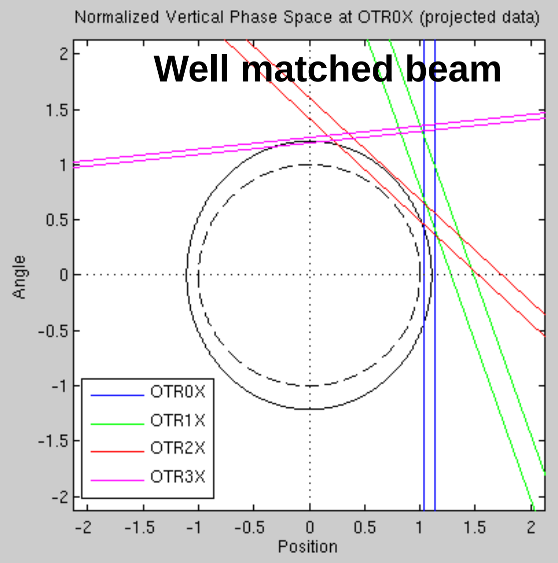
➔ Coupling correction was done by scanning the skew quads in EXT line

➔ Vertical dispersion was corrected in the OTRs region for the time of measurement



Name	DY mm
OTR0X	3.521
OTR1X	4.138
OTR2X	7.878
OTR3X	3.560

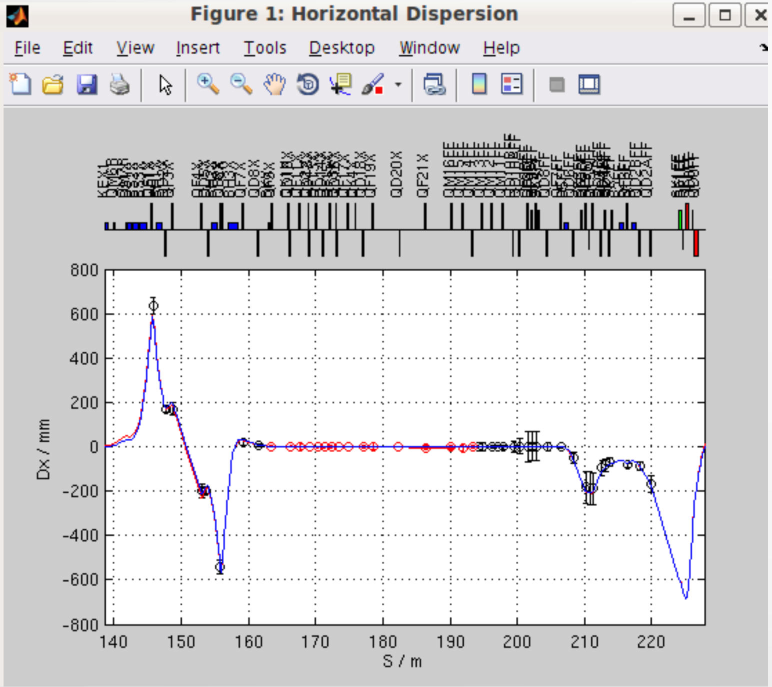
➔ Coupling correction is important for reliable emittance measurement

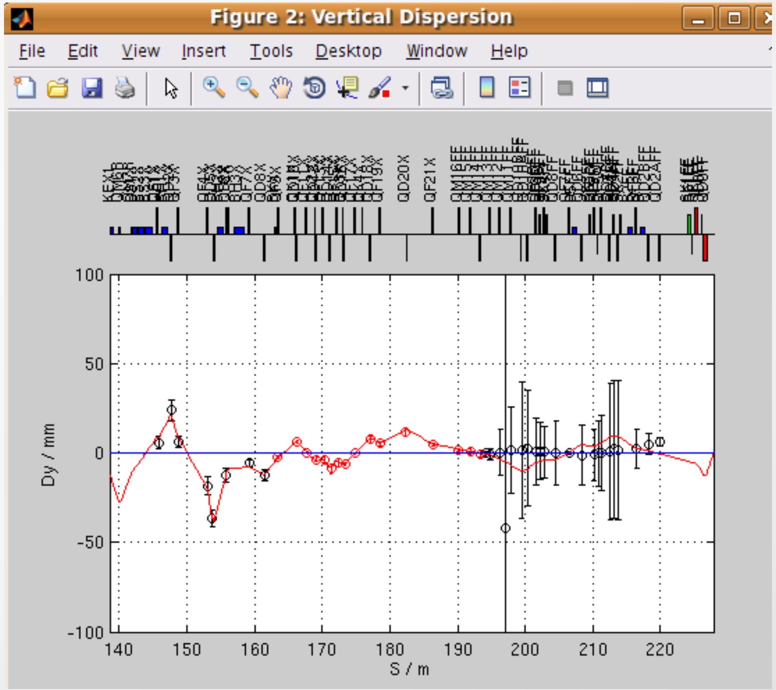


Well matched beam

Experimental results, December 2015 - dispersion

Dispersion was well corrected before the beam size tuning.





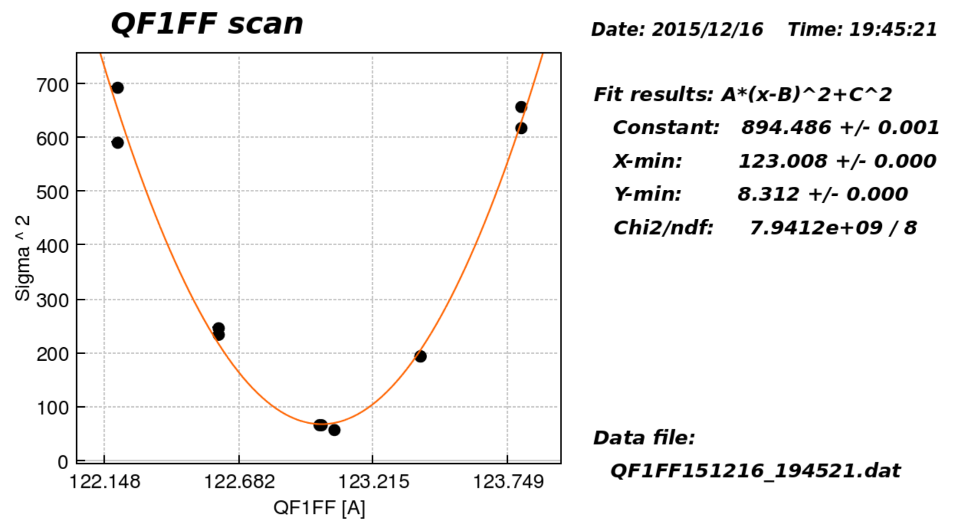
Experimental results, December 2015 – β_x* estimation

- β_x^* was estimated by measuring the horizontal IP beam size for several QF1FF settings.
- Horizontal IP beam size can be precisely measured using the wire scanner, so both β_x^* and ε_x can be estimated from the parabolic fit:

$$\sigma^2_{meas} = \varepsilon\beta + \frac{\varepsilon}{\beta}(\Delta f)^2$$

- Output from the ATF2 control system application:
  - **ε_x = 1.04 nm, β_x^* = 66.6 mm**

    (sorry for not including the uncertainties,
    I don't know them yet)



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Date: 2015/12/16    Time: 19:45:21

Fit results: A*(x-B)^2+C^2
  Constant:   894.486 +/- 0.001
  X-min:      123.008 +/- 0.000
  Y-min:      8.312 +/- 0.000
  Chi2/ndf:    7.9412e+09 / 8

Data file:
  QF1FF151216_194521.dat
```

Experimental results, December 2015 – β_y* estimation

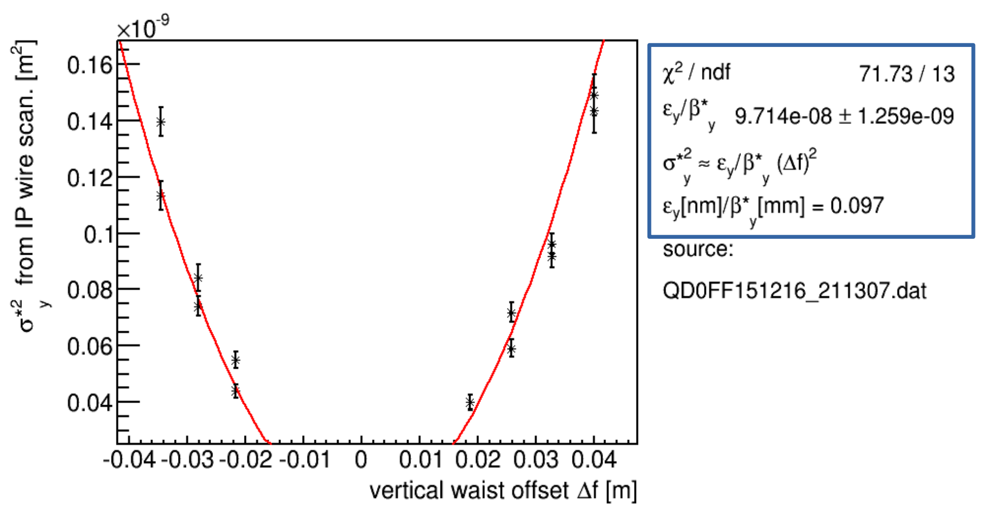
- β_y^* was estimated by measuring the horizontal IP beam size for several QD0FF settings.
- Vertical IP beam size cannot be precisely measured using the wire scanner, so only ratio ε_y/β_y^* can be estimated by fitting the simplified formula:

$$\sigma^2_{meas} \approx \frac{\varepsilon}{\beta}(\Delta f)^2$$

- Only points where $\sigma_y^* > 5$ µm are included (wire scanner limitation)
- **Estimated $\beta_y^* = 165 \pm 15$ µm**, for $\varepsilon_y = 16.0 \pm 1.4$ pm from mOTR measurement, and ε_y[nm]/β_y^*[mm] = 0.097 ± 0.001.
- It agrees with ATF2 control system application output.

emittance[nm] / beta*[mm] = 0.103154

- **Measured β^* values did not meet the design (40mm, 50 µm). Optics rematch was needed.**



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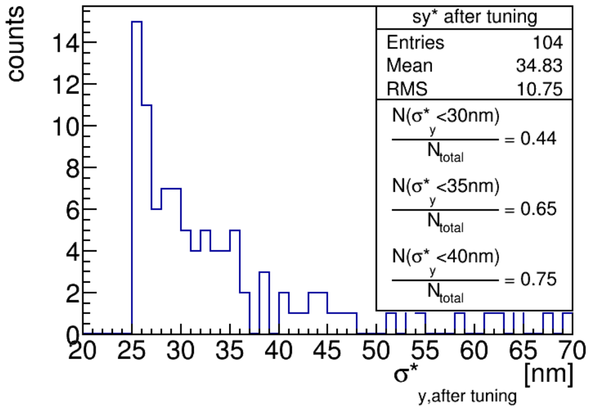
QD0FF151216_211307.dat

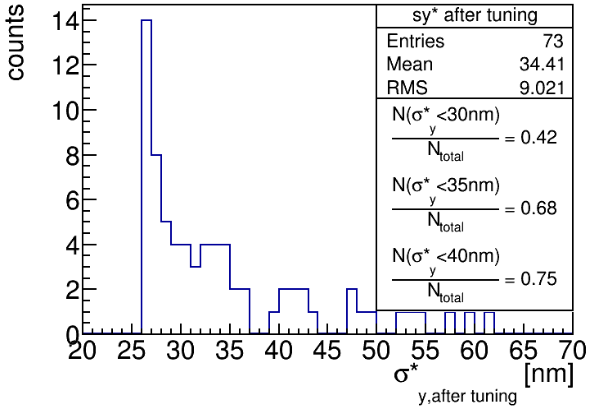
Thank you!

Tuning simulations. Different beam size definitions

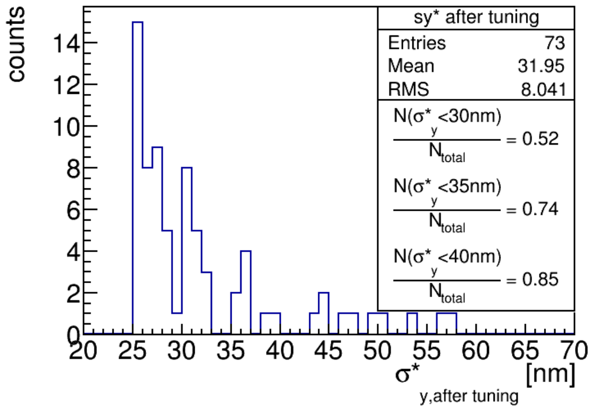
rms



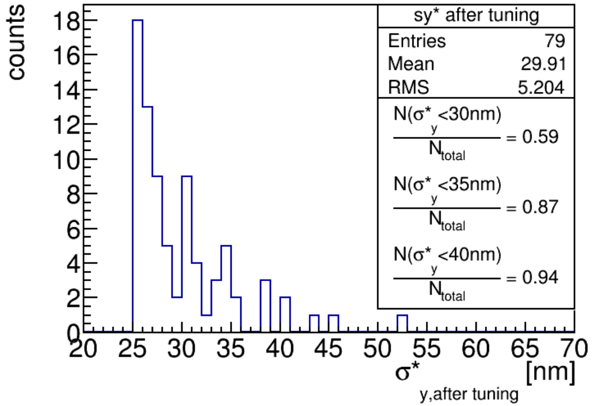
shintake



core



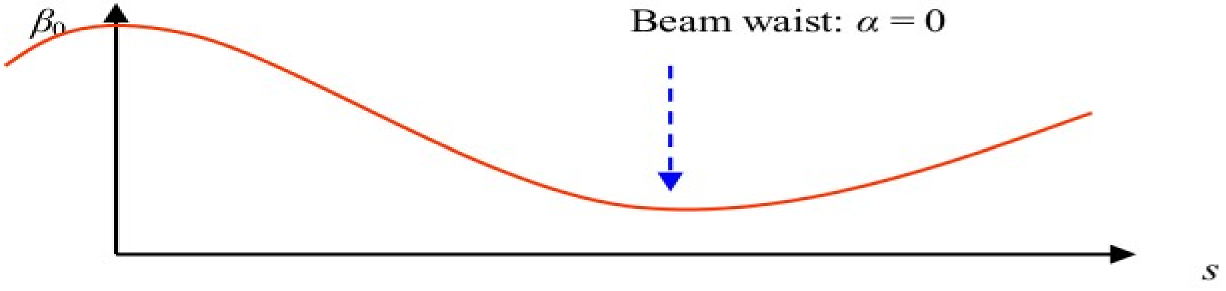
core w/o R31



Concept

In the vicinity of beam waist the beam size increases with the distance from the beam waist position to the measurement point (Δf) [1]:

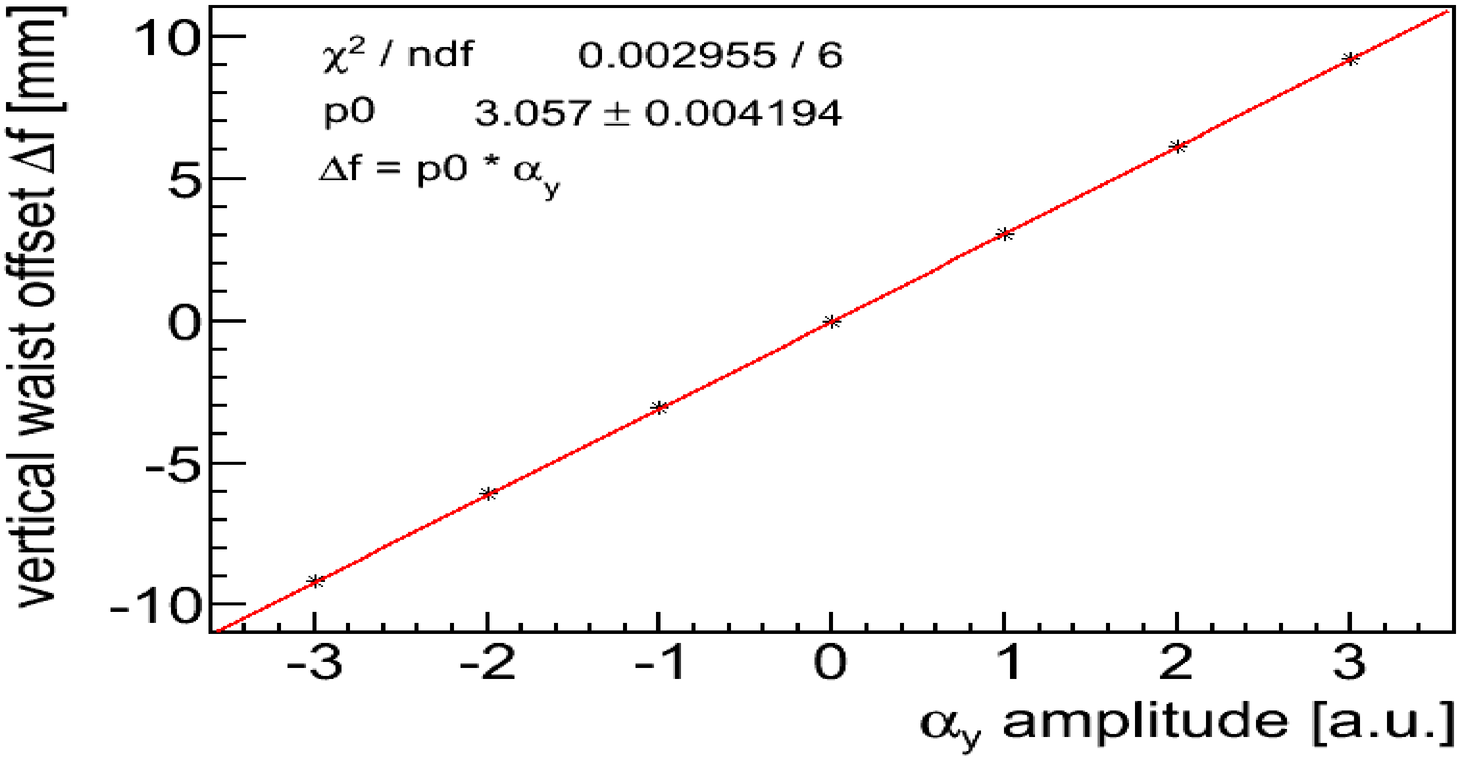
$$\sigma^2_{meas} = \varepsilon\beta + \frac{\varepsilon}{\beta}(\Delta f)^2 + \sigma^2_{aberr}$$

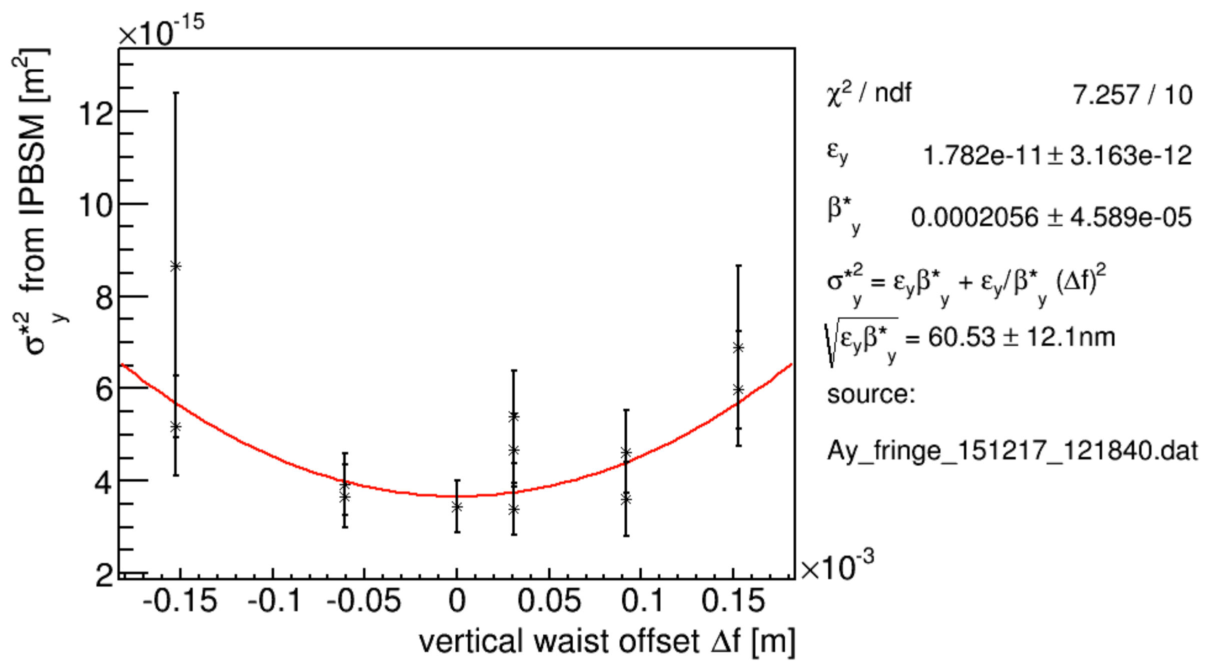


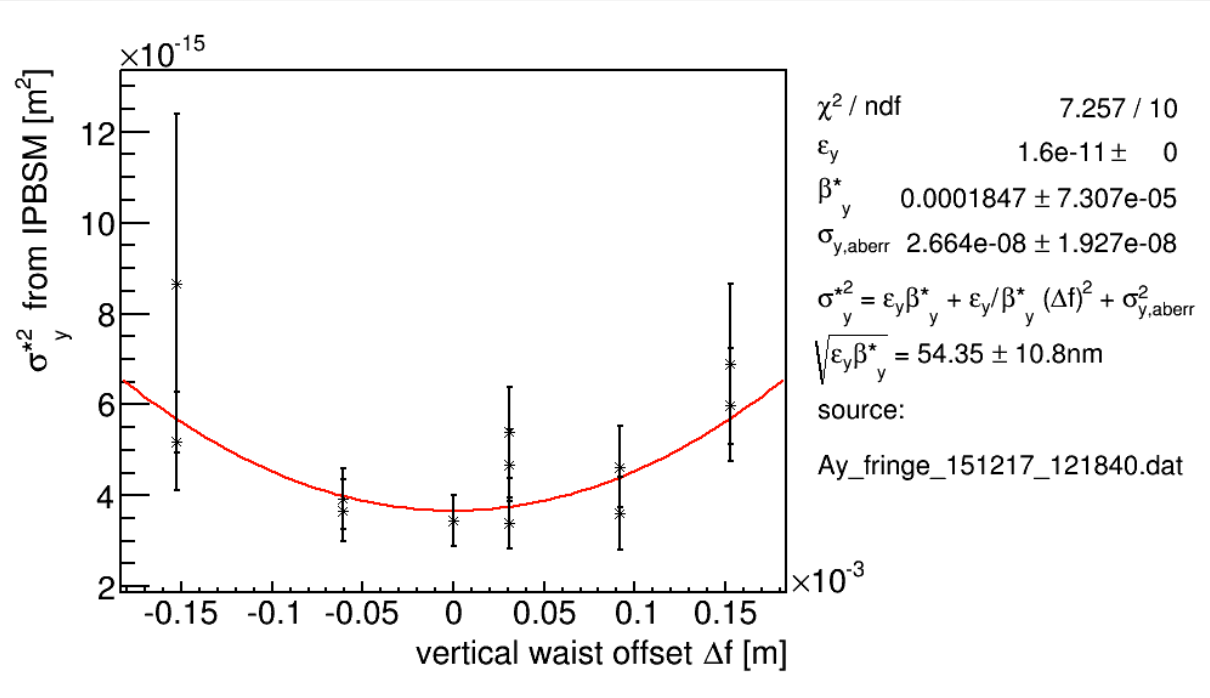
[2]

[1] S. Bai et al. PRSTAB 13, 092804 (2010)
[2] figure from arxiv:1303.6514

Beam waist offset (Δf) calibration




$\times 10^{-15}$
σ^{*2}_y from IPBSM [m^2]
2
4
6
8
10
12
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
$\times 10^{-3}$
vertical waist offset Δf [m]
χ^2 / ndf 7.257 / 10
ε_y 1.782e-11 ± 3.163e-12
β^*_y 0.0002056 ± 4.589e-05
$\sigma^{*2}_y = \varepsilon_y\beta^*_y + \varepsilon_y/\beta^*_y\,(\Delta f)^2$
$\sqrt{\varepsilon_y\beta^*_y}$ = 60.53 ± 12.1nm
source:
Ay_fringe_151217_121840.dat



$\times 10^{-15}$
σ^{*2}_y from IPBSM [m^2]
2
4
6
8
10
12
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
$\times 10^{-3}$
vertical waist offset Δf [m]
χ^2 / ndf 7.257 / 10
ε_y 1.6e-11 ± 0
β^*_y 0.0001847 ± 7.307e-05
$\sigma_{y,\mathrm{aberr}}$ 2.664e-08 ± 1.927e-08
$\sigma^{*2}_y = \varepsilon_y \beta^*_y + \varepsilon_y / \beta^*_y (\Delta f)^2 + \sigma^2_{y,\mathrm{aberr}}$
$\sqrt{\varepsilon_y \beta^*_y}$ = 54.35 ± 10.8nm
source:
Ay_fringe_151217_121840.dat