Transfer line from injector to LESR

Peter Kuske, Felix Kramer, Falk Hoffmann, HZB

Beam Tests and Commissioning of Low Emittance Storage Rings,
Workshop, 18-20 February, Karlsruhe, Germany

Typical Transfer Line

WE5RFP002 P.J. Chou, et al. Proceedings of PAC09, Vancouver, BC, Canada

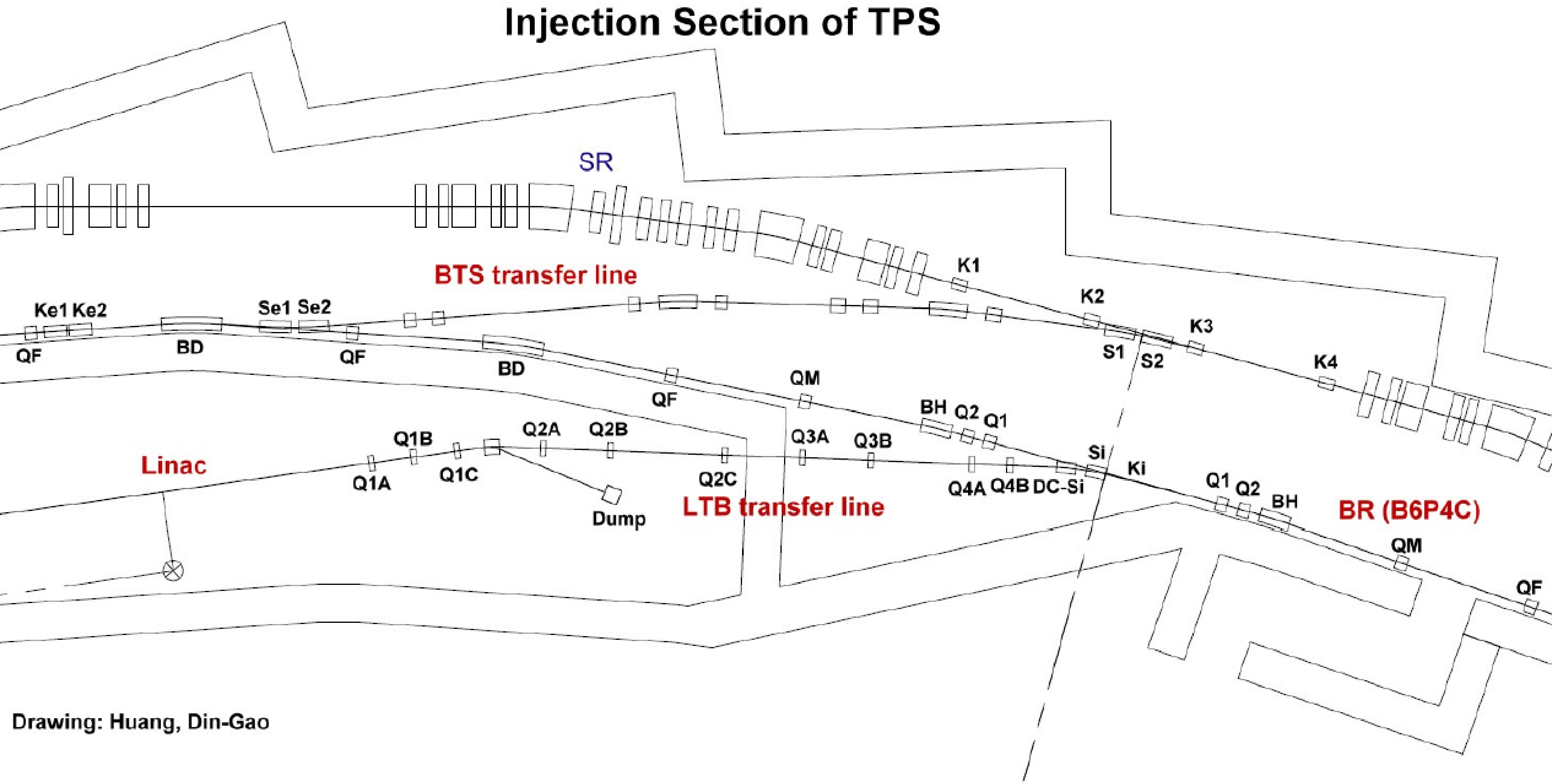
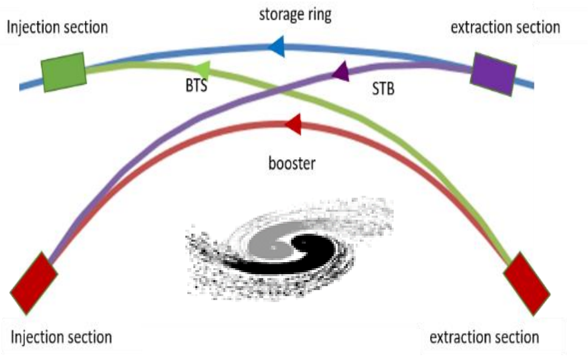


Figure 1: A schematic layout of transfer lines from linac to booster and booster to storage ring.

Typical Transfer Line

The high energy transport lines for the HEPS in China, Jingyi Li, 2018-12-14, 1st meeting IAC



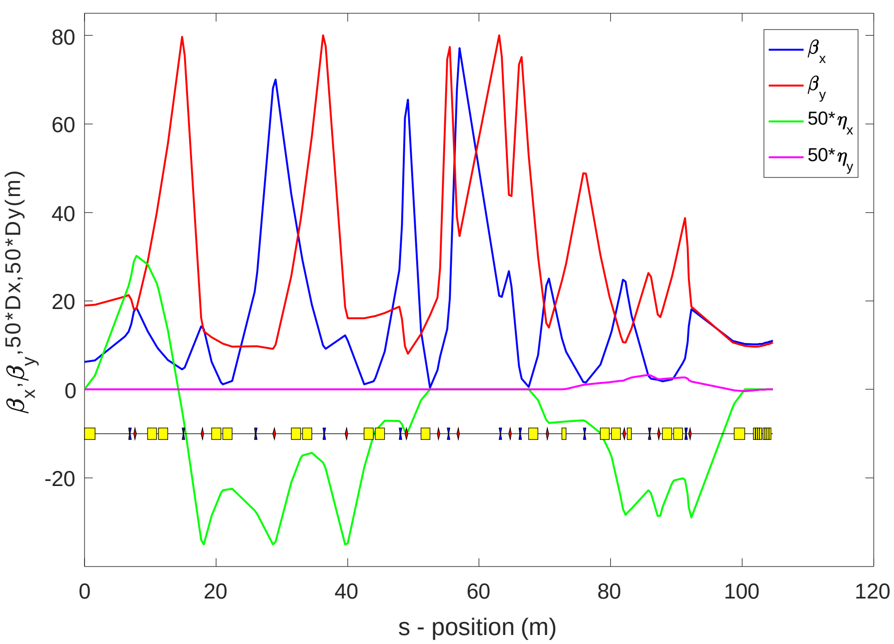
BTS and STB：almost symmetric in layout

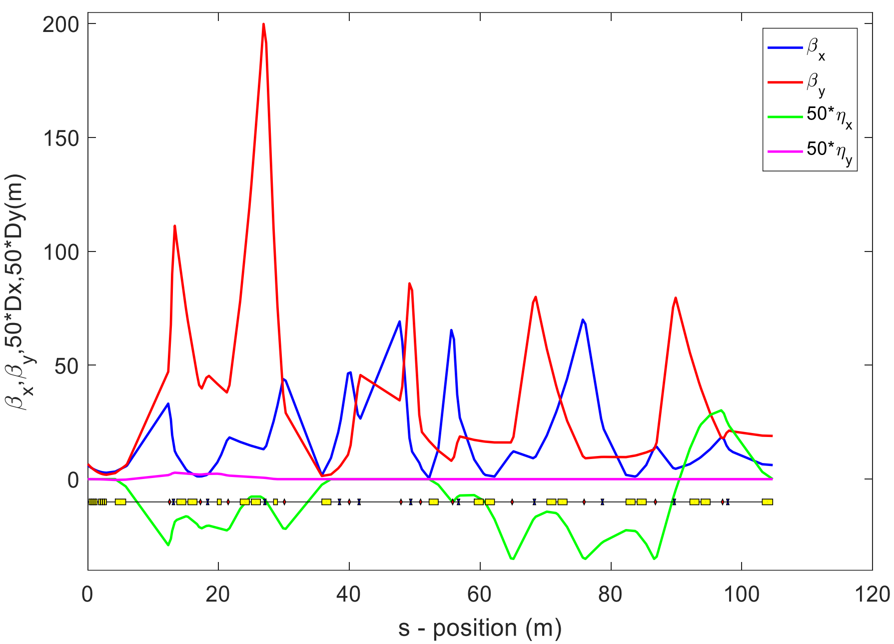
BTS:104.66m, 104.72 m

14 horizontal bending dipoles and a Lambertson in the booster

2 vertical bending dipoles and a Lambertson in the storage ring

The achromatic section: 15m, 6 quadrupoles





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I. Design Philosophy

Target is transparent top-up injection with 100% injection efficiency

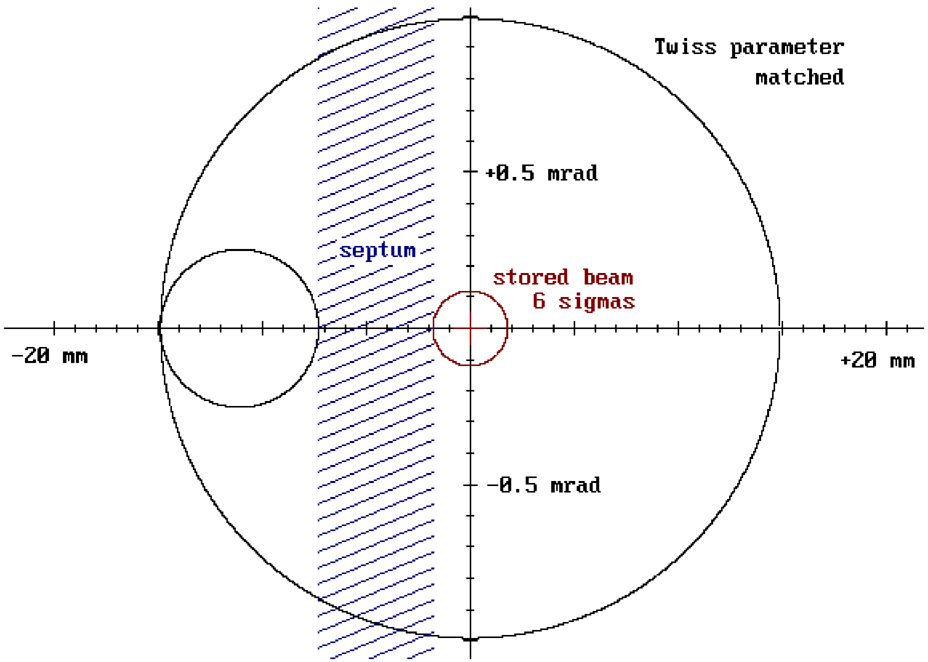
Transfer line design:

- **Efficient and stable beam transport**
- **Beam matching – position and particle distribution**
  in all dimensions
  with certain flexibility
- **Measurement of relevant parameters**
  single pass BPMs, ideally with bunch-by-bunch resolution
  couple of beam size monitors (OTR), separation of energy
  spread and horizontal emittance
  charge monitors, beam loss monitors (BLMs)
  real time injection efficiency monitor, DCCTs in
  synchrotron and storage ring, injection synchronized
  monitoring pulsed magnets, peak, width, pulse shape
- **Archiving all parameters**
- **Energy control – top-up safety interlock, collimators or PS settings**

Perfect injection into low emittance rings is very challenging – best matching is required
a) In position – find and keep the optimum location, where injection works best

b) In beam size – off-axis injection schemes:

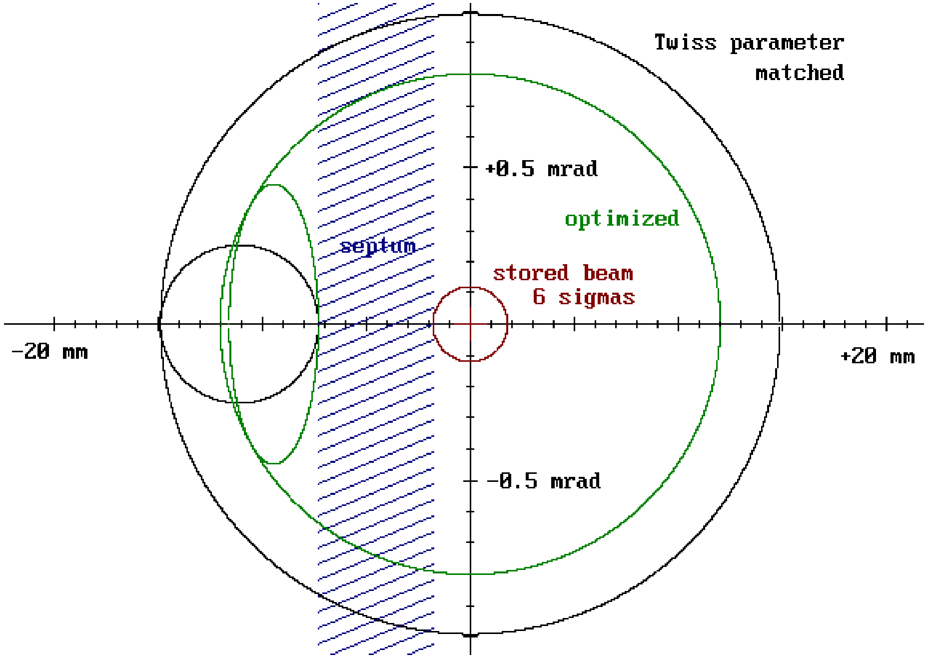
Matched – $\beta_{inj} = \beta_{sto}$, $\alpha_{inj}=\alpha_{sto}=0$



b) In beam size – off-axis injection schemes:

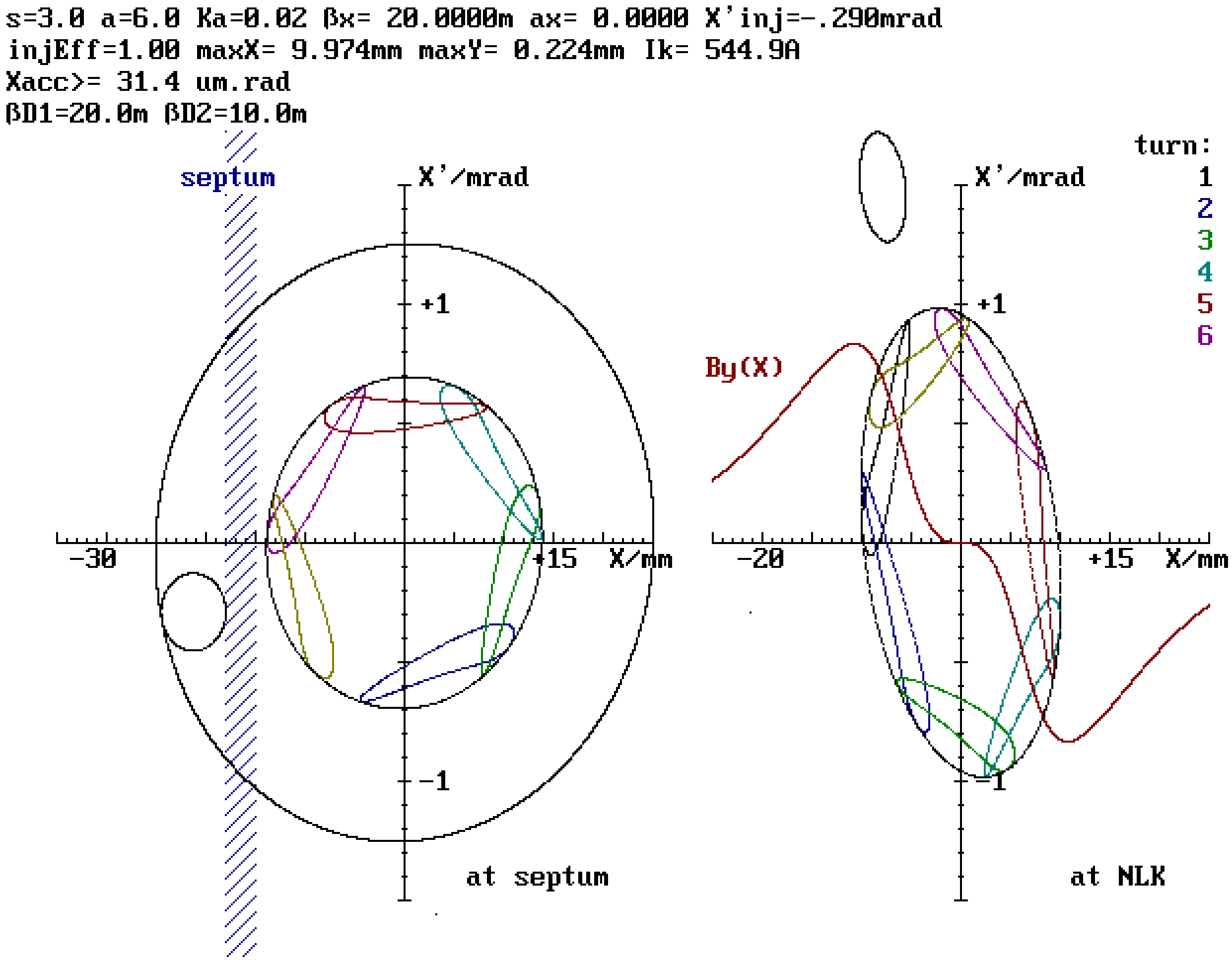
Andreas Streun, “SLS booster-to-ring transferline optics for optimum injection efficiency”, SLS-TME-TA-2002-0193, May, 2005

optimized – $\beta_{inj} < \beta_{sto}$, $\alpha_{inj}=\alpha_{sto}=0$



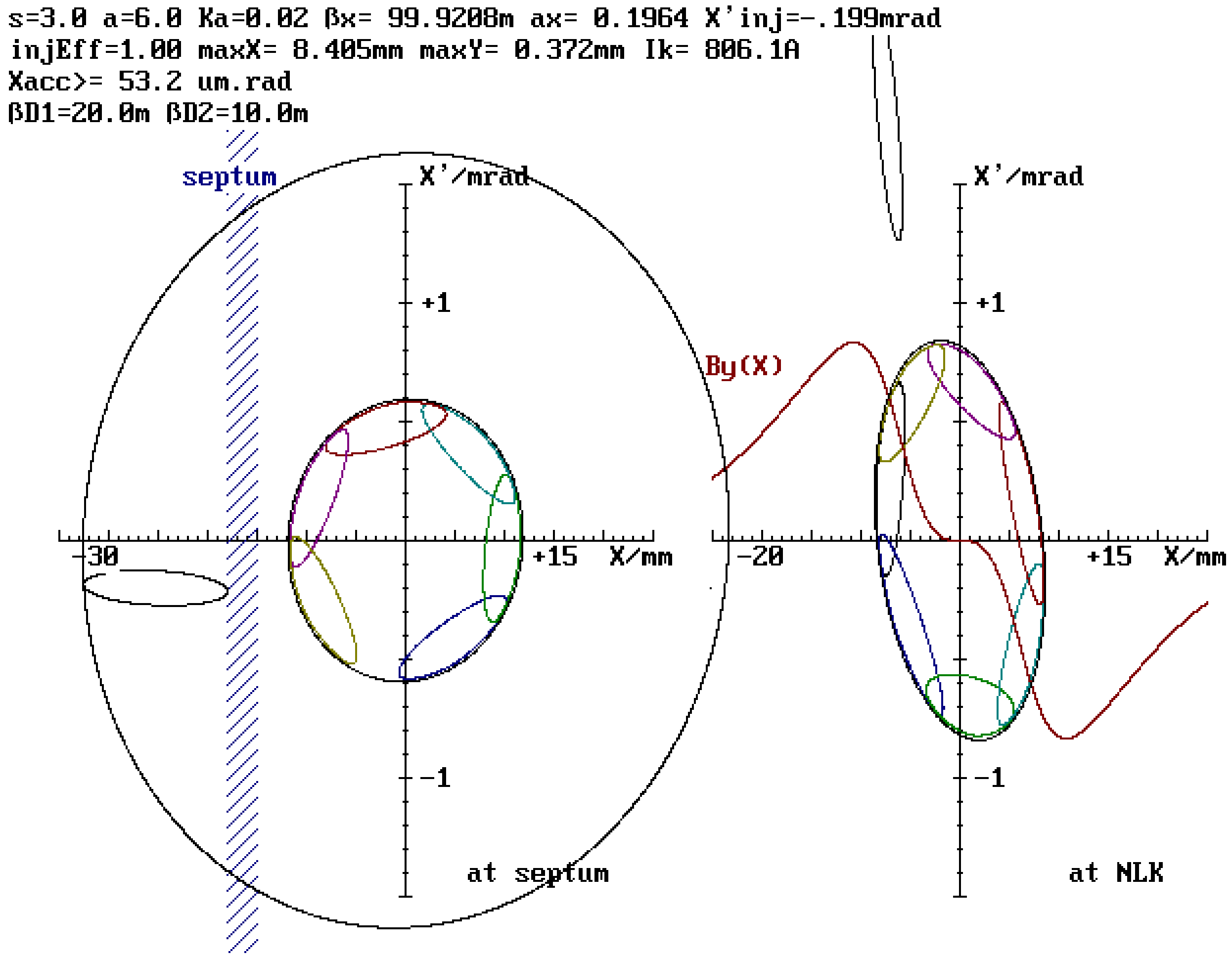
- **optimization works for most of the transverse off-axis injection schemes except the non-linear kicker**
- **with smaller and smaller emittance of stored and injected beam most of the valuable dynamic aperture eaten up by septum**

b) In beam size – off-axis injection schemes with Non Linear Kicker (NLK):



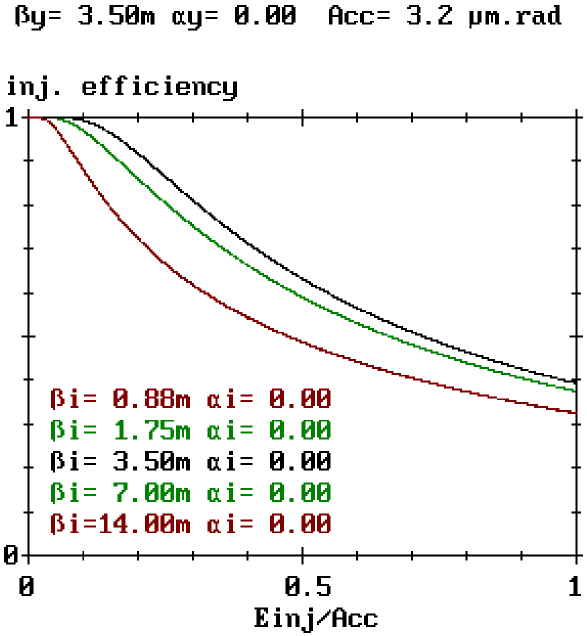
Matched injection parameters: injection angle=-0.29mrad, $ß_x$=20m, α_x~0.0
Aperture requirement: 14mm @ septum

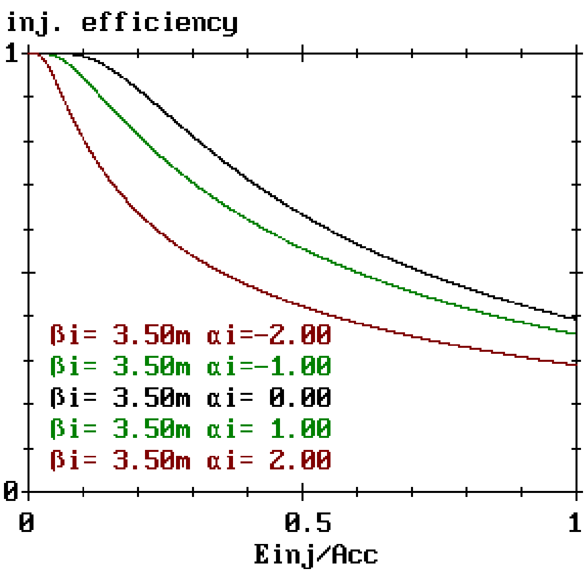
b) In beam size – off-axis injection schemes with Non Linear Kicker (NLK):



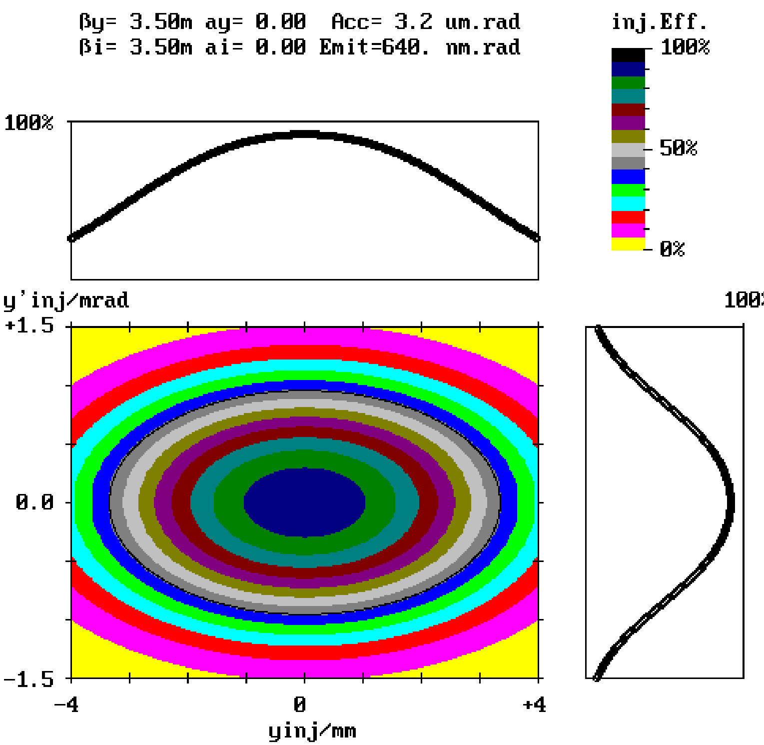
Optimized injection parameters: injection angle, $ß_x$~100m, α_x~0.2
Aperture requirement reduced by 1.5 mm
analysis of chosen injection scheme and search optimal parameter set

II.3 Impact of Transverse Mismatch on Injection Efficiency





Vertical mismatch: "hard edge" acceptance, Acc, given by collimators or small gap vacuum chambers. Good injection efficiency if σ of the Gaussian injected beam <0.1·Acc.
For perfectly matched Twiss-parameters and mis-steered beam the situation is shown below:

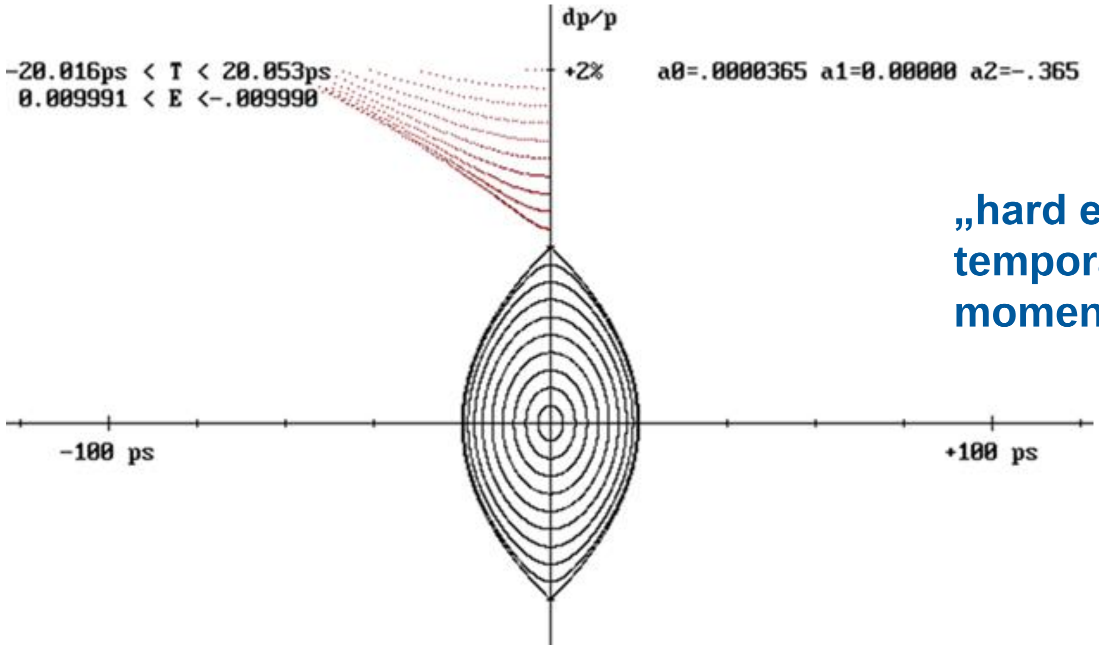


Critical for low-α mode and BESSY VSR

Momentum compaction factor: $$\alpha = \alpha_0 + \alpha_1 \frac{\Delta p}{p} + \alpha_2 \frac{\Delta p^2}{p} + \alpha_3 \frac{\Delta p^3}{p} \dots$$

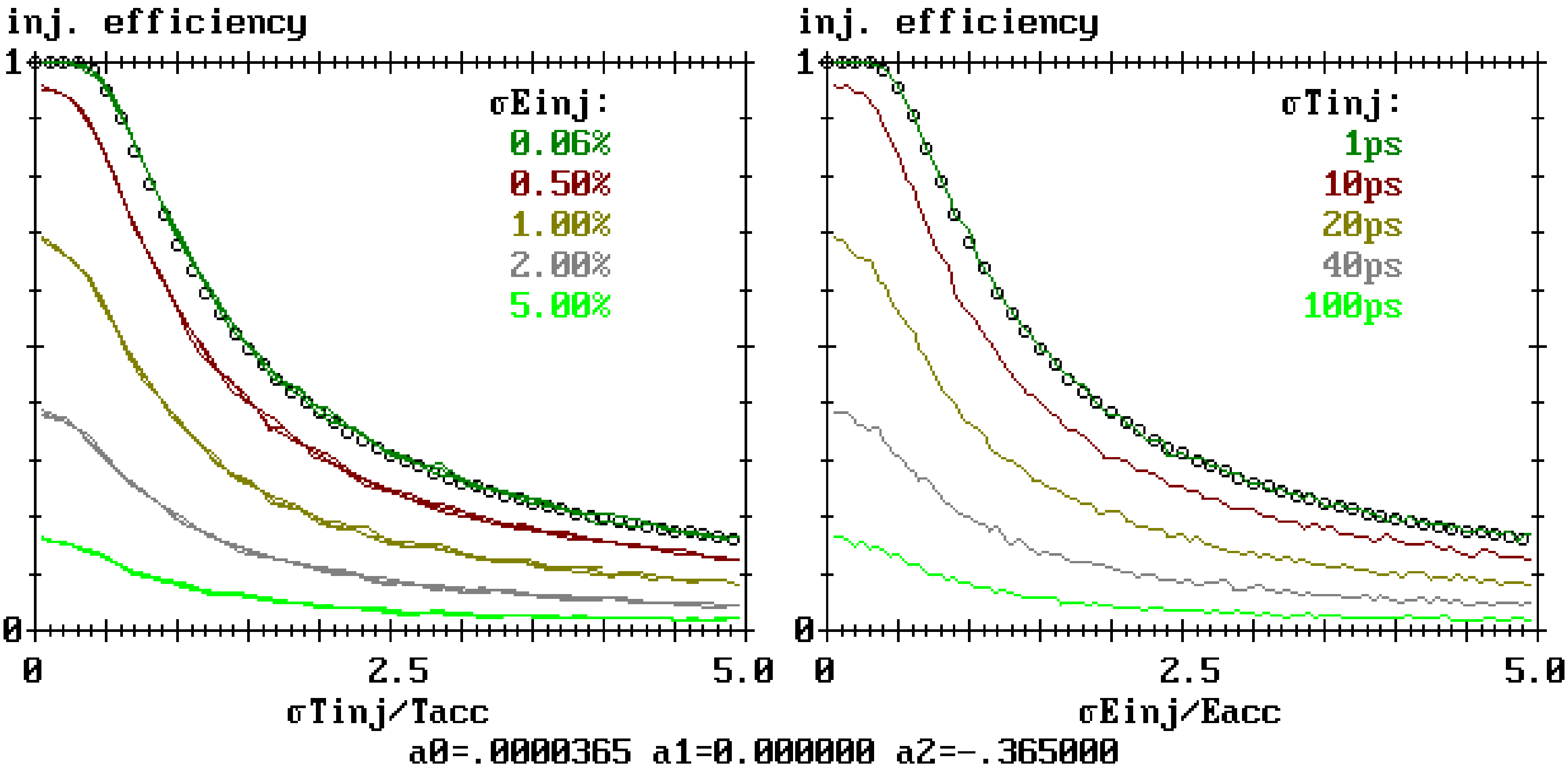
Operating conditions at BESSY: α_1=0 with carefully chosen sextupole settings.

Momentum acceptance: $$E_{acc} = \pm \sqrt{-\frac{\propto_0}{\propto_2}}$$



„hard edge“
temporal aperture, T_{acc}=20ps
momentum aperture, E_{acc}=±1%

Energy spread of injected beam, $\sigma_{Einj}=6\cdot10^{-4}$, better than needed
bunch length of injected beam, σ_{Tinj}=60ps: less than 30% injection efficiency.



You can't do much for better matching in the transfer line. Solutions: increased RF-power in synchrotron (BESSY, Soleil), or longitudinal bunch rotation

Without beam:

- **Hardware commissioning after FAT and SAT**
- **After installation and alignment:**
  integration tests – controls, interlocks, diagnostics, polarity, …
- **Development of high level application software for fast error recognition**
  correlate BPM channel signals with steering actions
  reversed magnet polarities or BPM cabling errors can occur
- **Develop software for basic commissioning tasks:**
  Image analysis of screens, quadrupole scan for emittance determination
  (strategy to separate emittance from energy spread)
  orbit response measurement and optics analysis
  beam-based alignment with respect to quadrupole magnets
  automated optimization based on observations
- **Extended integration tests (NSLS-II) –** (G.M. Wang, et al., IPAC2015, TUPHA007)
  test of hard- and software with simulated signals and responses
  software for basic features like save/restore, conditioning magnets, ...

With beam – injector operational:

- **Optimize extraction – timing, pulse shapes**
  easier to adjust with a shielded dump line
- **Check hardware and diagnostics, perform dedicated tests**
- **Beam transmission without any quadrupole magnets** (low emittance injector)
- **Orbit, steering, and beam-based alignment**
- **Quadrupole scans for emittance determination**
- **Optics determination and adjustment to target values**

- **Optimization of final injection conditions**
  injection septa, kicker (hor.), position, timing (ver. and long.)
  with first turn measurements in the storage ring or injection efficiency

- **Don't underestimate the power of automated optimization procedures**
  Transmission, injection efficiency, injection bump closure, …
  Once the archives are filled, machine learning techniques can most likely improve performance even further

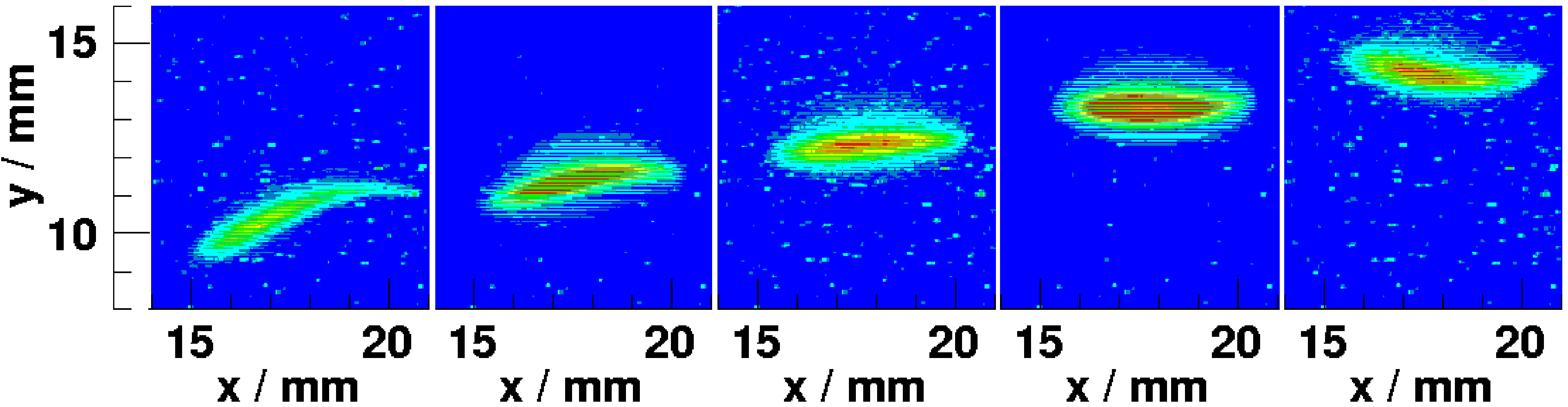
BESSY experience:

Empirically found optimum performance of transfer line not in agreement with simulations

We used old fashion diagnostics with limited performance (screens instead of BPMs,...)

VI.1 Images of Extracted Beam

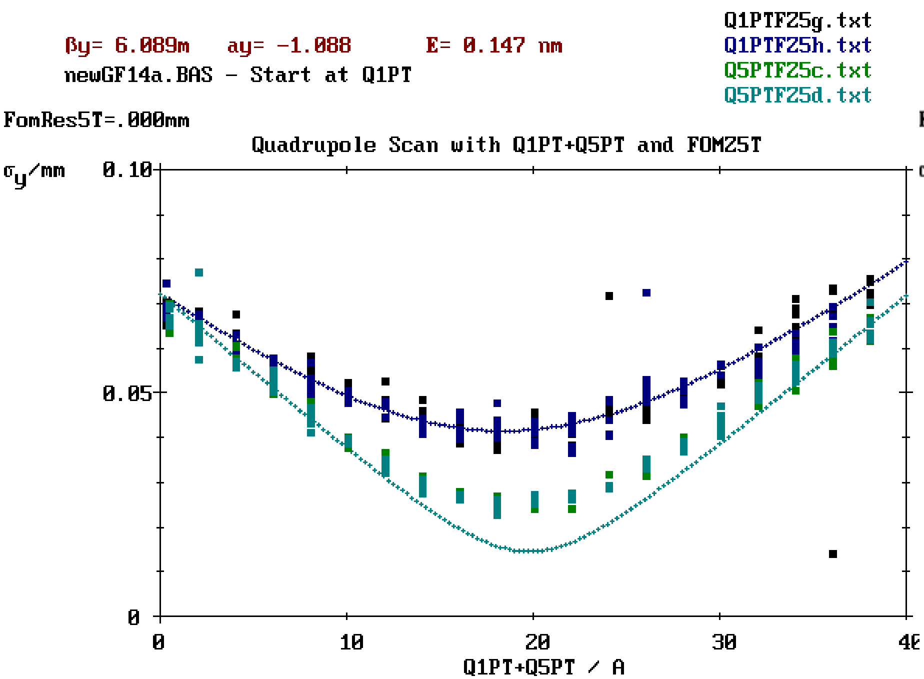
Images as a function of the vertical beam position in the synchrotron

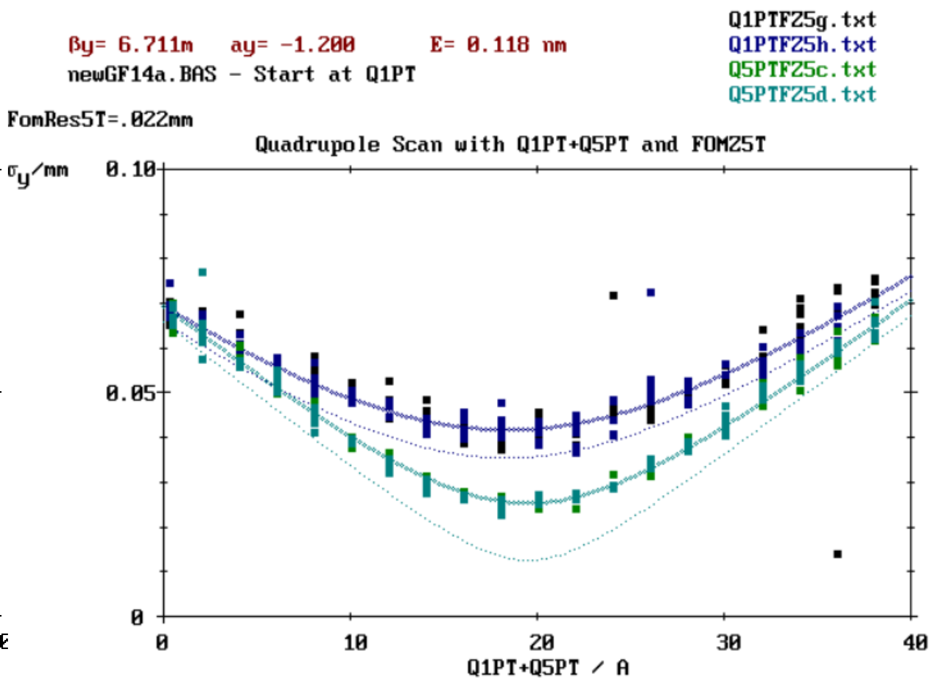


Strong non-linear effects – broken mid-plane symmetry, most likely from septum magnet

Similar effects (vertical emittance degradation) have been observed at ATF @ KEK

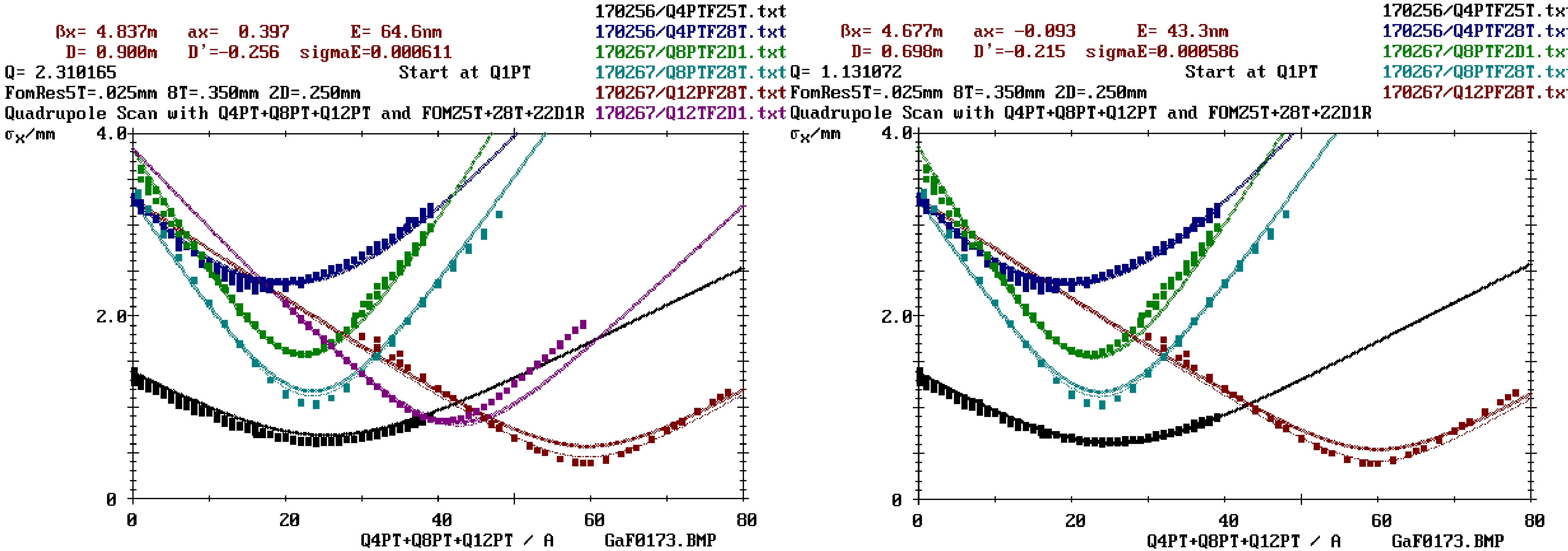
- **Results for the vertical emittance did depend on the screen used**
- **Determined resolution using 2 quadrupoles with short and long distance to screen**
- **Assuming a finite resolution of the beam size monitors results in a single set of results:**





dots are experimental results, thick line predicted dependance, thin line – true beam size

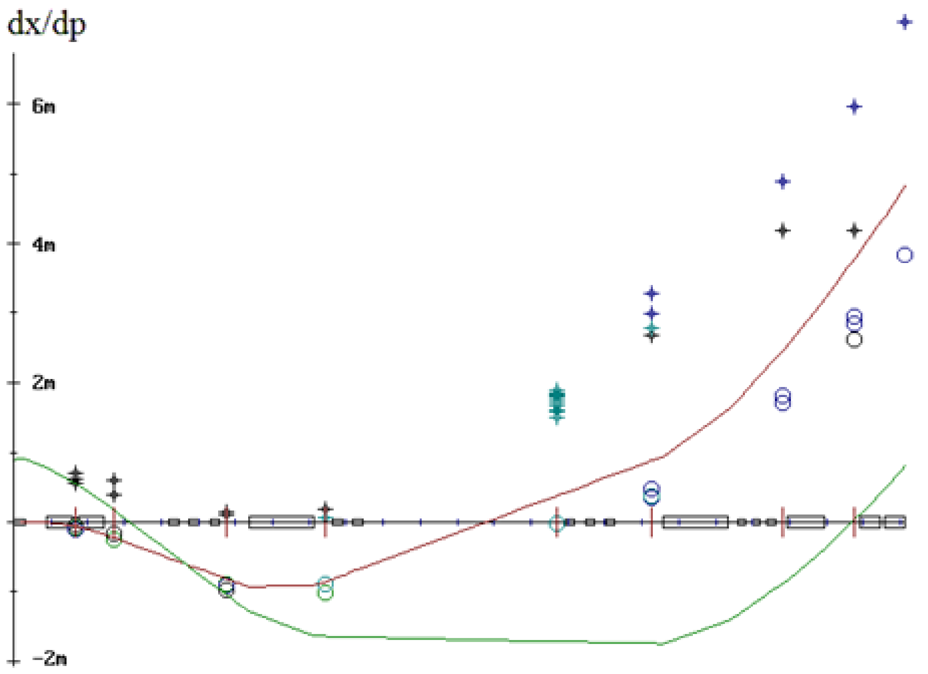
determination of $ß_x$, α_x, ε_x, D_x, D_x' und σ_ε requires more than one quadrupole scan and dipole in between to change dispersion



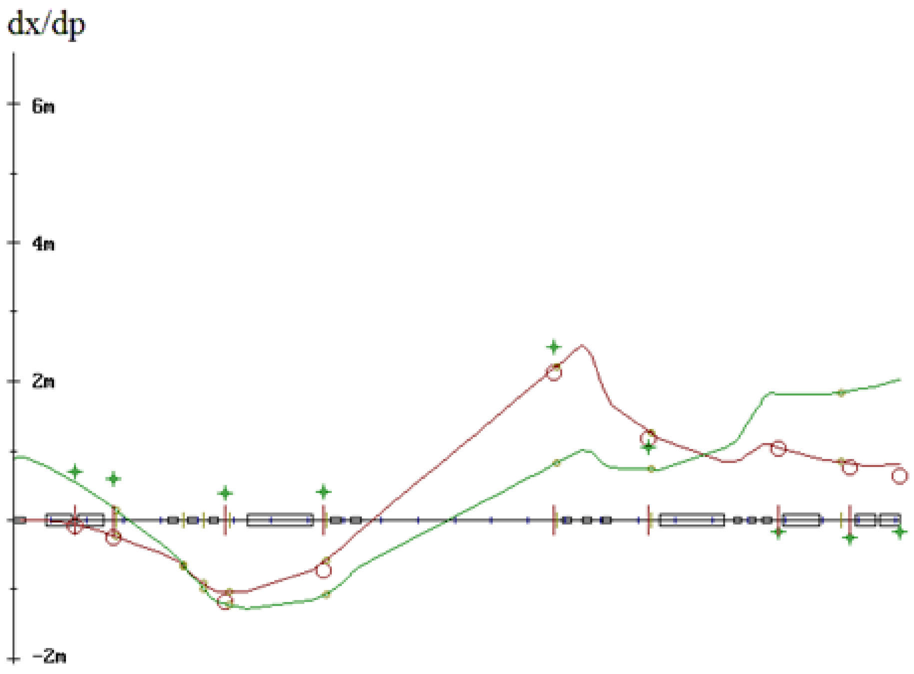
energy spread: σ_ε~6·10^{-4}, independent on extraction time
emittance - ε_x~70±20 nm·rad or ε_x~50±10 nm·rad, for late and early extraction

Position	$ß_x$/m	α_x	Dx/m	Dx‘
at Q3PT	7.6	-0.6	0.2	-.06
at Q4PT	8.2	-0.85	0.2	0.18

all quadrupoles set to zero:



nominal quadrupole settings:

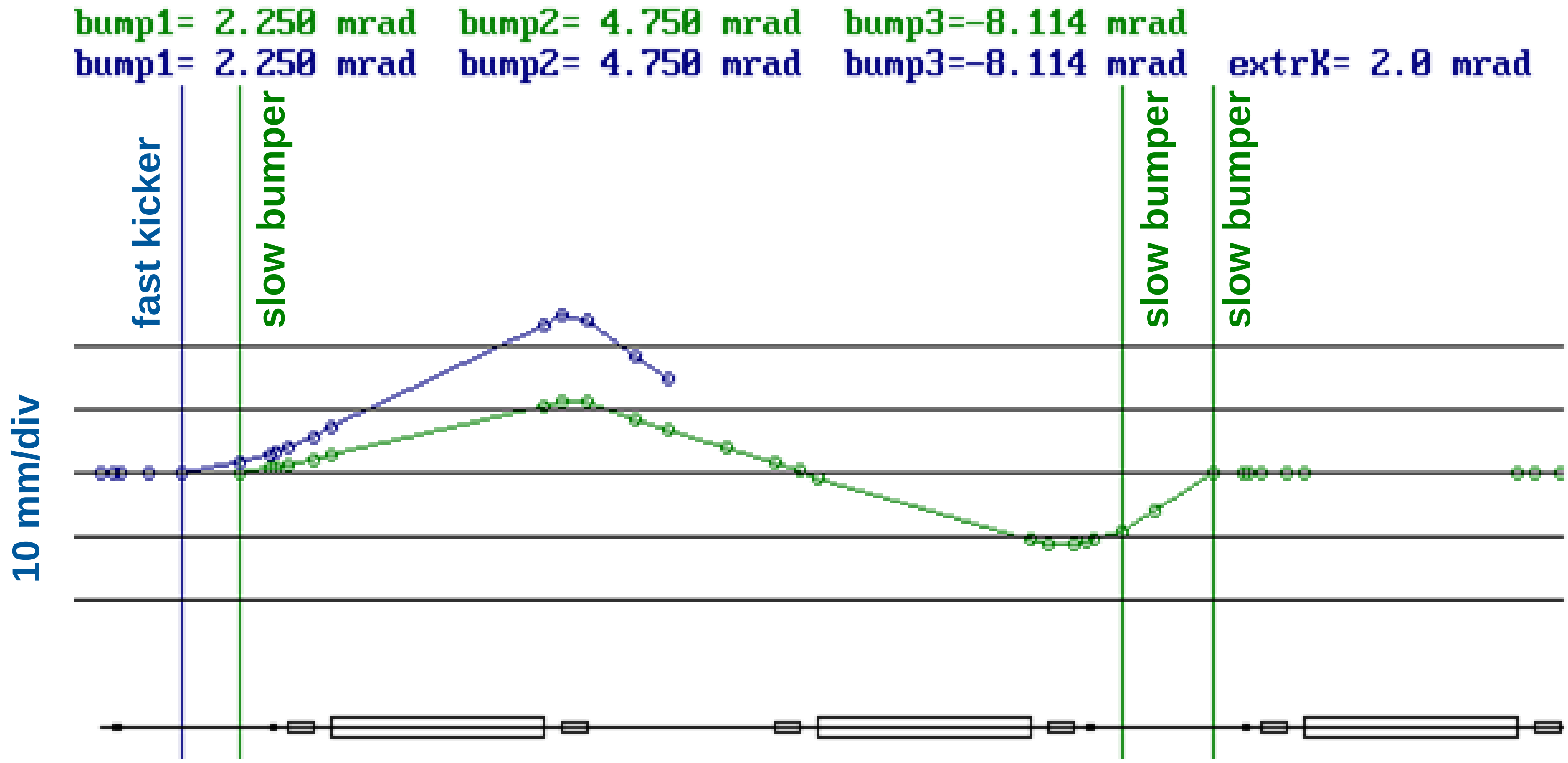


theoretical expectations = lines, measurements = dots and crosses

green curve and crosses – RF-variation in the booster
red curve and circles – variation of the extraction time

display starts with the last quadrupole in the synchrotron seen by the extracted beam
obviously focusing error at the beginning of the transfer line

in green: orbit due to slow bump
In blue: kicked beam on its way to the septum magnet



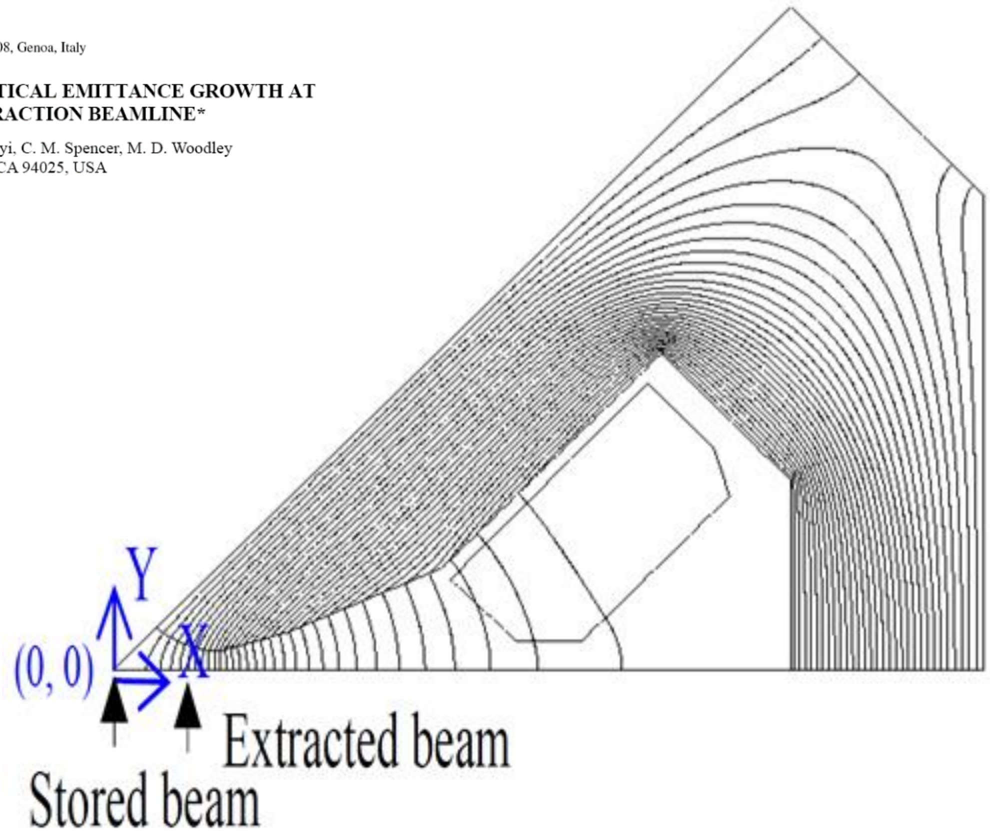
large orbit offset in focusing quadrupole QF where gradient levels off – reduced gradient equivalent to defocusing quadrupole,
Slightly smaller defocusing effect in sextupole magnet due to slow bump

IV.3 Gradient Reduction in Last Quadrupole Magnet

MOPP047 Proceedings of EPAC08, Genoa, Italy

SIMULATION STUDIES ON THE VERTICAL EMITTANCE GROWTH AT THE EXISTING ATF EXTRACTION BEAMLINE*

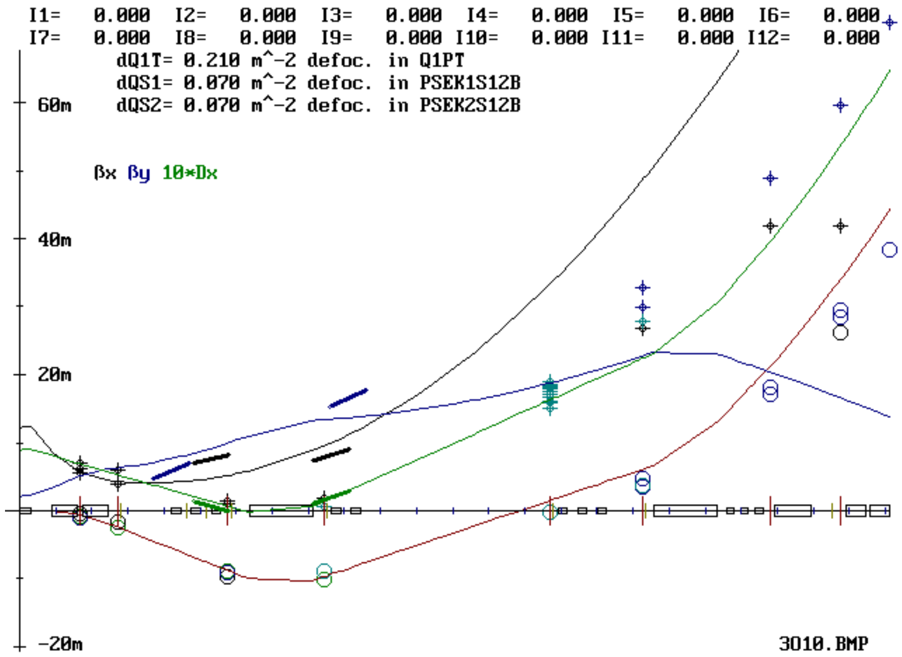
F. Zhou[+], J. Amann, S. Seletskiy, A. Seryi, C. M. Spencer, M. D. Woodley
SLAC, Menlo Park, CA 94025, USA



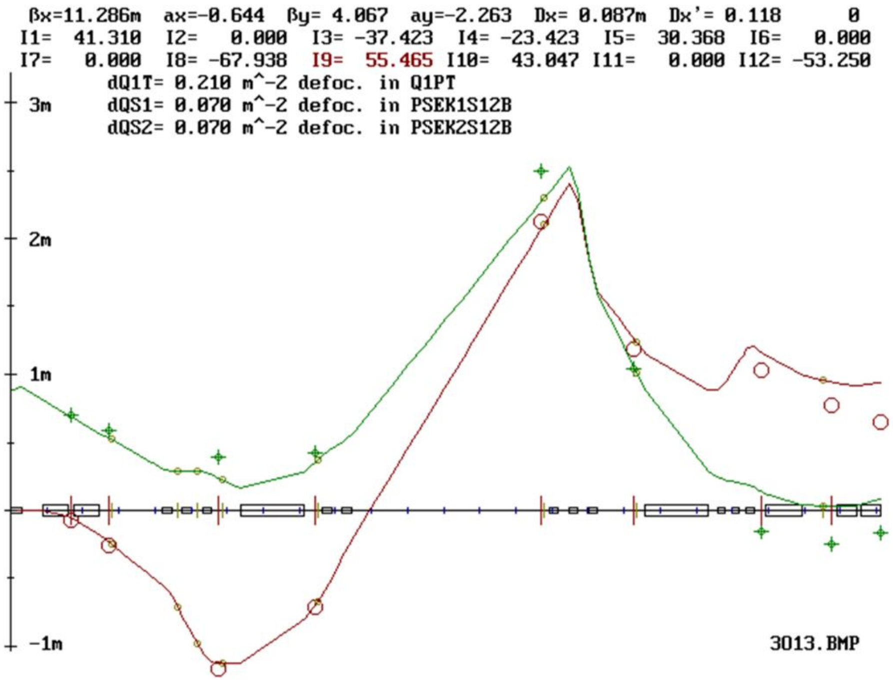
- The extracted beam experiences a considerably reduced focusing gradient in the last quadrupole magnet before entering the septum magnet
- Together with some additional gradients in the extraction septa the measured optics parameters can be reproduced.

VI.4 Comparison of Measured and Simulated Parameters – with Distributed Defocusing in the final QF and Septa

all Q's zero

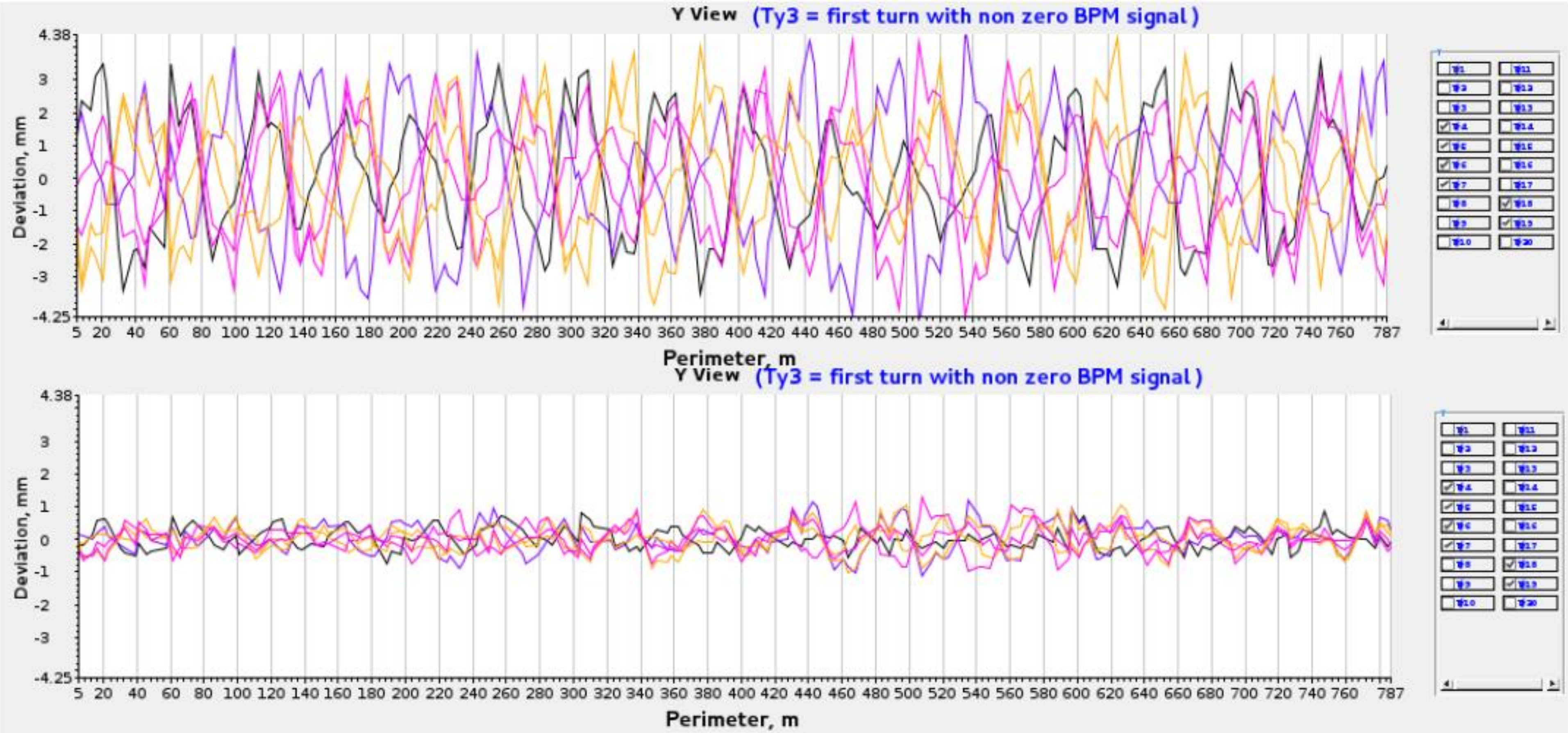


all Qs nominal settings



This model is used to design more optimized matching conditions for injecting with our Non-Linear Kicker.

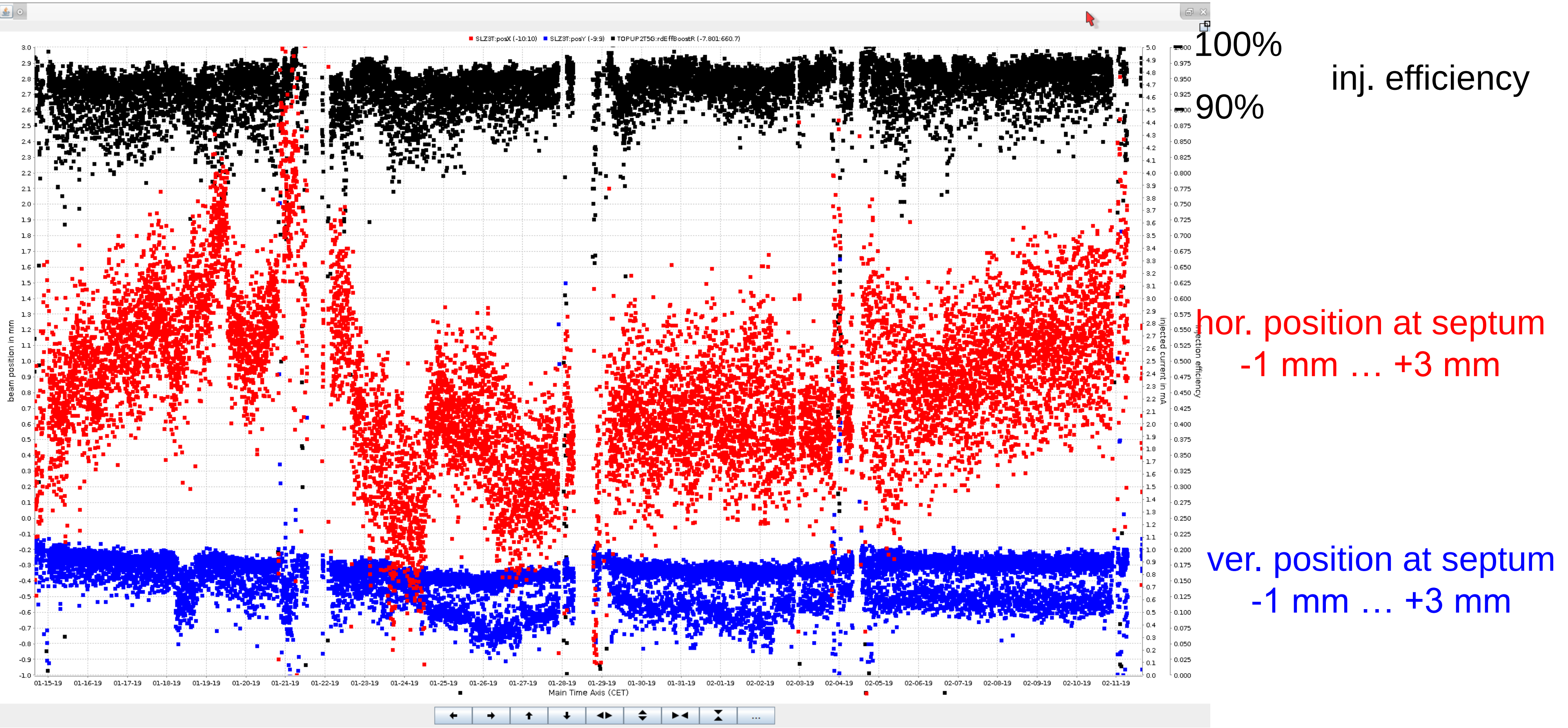
Injection optimization based on the observation of the vertical orbit on the first turns in the storage ring



Turn-by-turn data for optimizing longitudinal and horizontal injection parameters

G.M Wang, et al., “NSLS-II Storage Ring Injection Optimization“, IPAC2015,TUPHA004

Injection efficiency and beam position at the septum entrance over 4 weeks hybrid multi-bunch operation



The BPM seems to function well, vertical position quite stable, two branches correspond to single and multi bunch injections. Large horizontal drifts are under study, many pulsed elements involved.

- TL commissioning is part of LESR commissioning
- Be well prepared
- Little time for TL commissioning
- Expect surprises
- Transfer line optimization is essential for the overall performance

Goal: efficient and transparent top-up injection any questions?