The 14th JKPS title:

Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique

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POSTECH

Why is this paper selected?

1. Wanted to understand research being conducted in linear accelerators
2. Interested in learning how error studies were performed
3. Believed the methods could be applicable to eLABS

Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique

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(Received 10 July 2013; published 19 May 2014)

Accurate measurements of the transverse beam properties are essential to understand and optimize particle beams. We present an optimized method that uses three quadrupole magnets and one profile monitor to measure the full 4D transverse matrix of the beam. The method has been applied to the SwissFEL Injector Test Facility (SITF) at the Paul Scherrer Institute (Villigen). The SITF is the principal test bed and demonstration plant for the SwissFEL project, which aims at realizing a hard-x-ray free-electron laser in 2017. Simulations, measurements, and results of cross-plane coupling correction are presented.

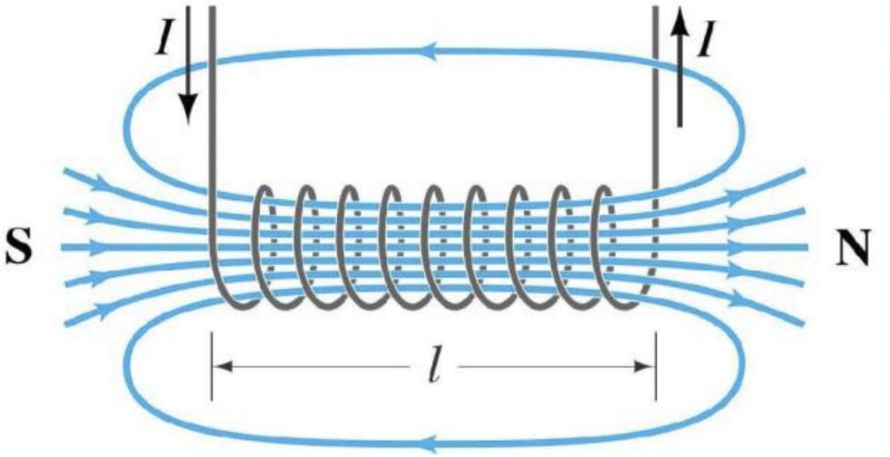
DOI: 10.1103/PhysRevSTAB.17.052801 PACS numbers: 29.20.Ej, 41.60.Cr, 41.85.-p, 29.27.Fh

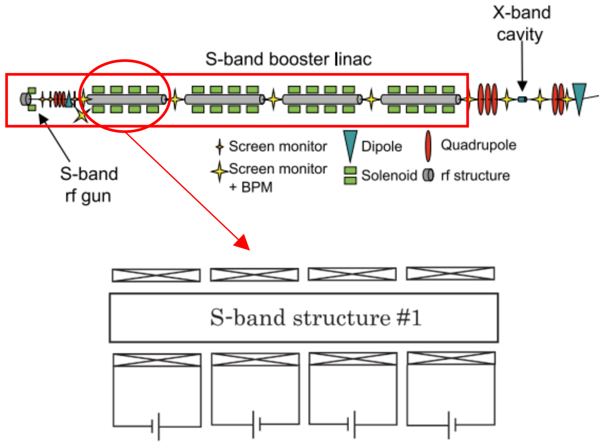
Background

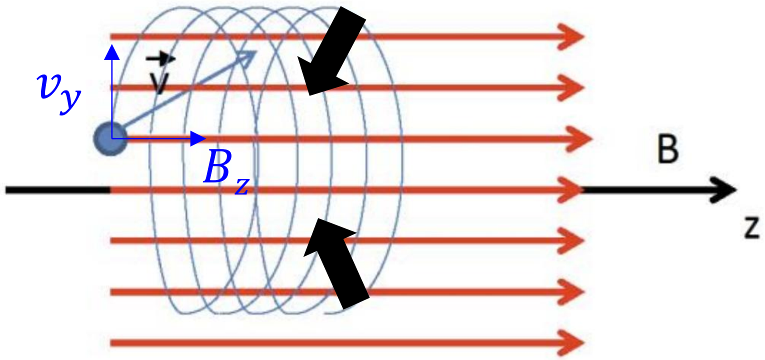
1. Solenoid

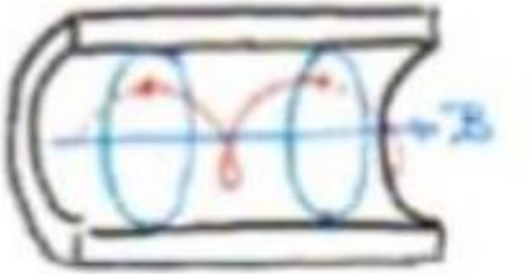
- $\vec{F} = q(\vec{v} \times \vec{B})$
- Radially confines the electron beam.
  - $v_x \rightarrow F_y$
  - $v_y \rightarrow F_x$

  → **<u>XY coupling motion</u>**





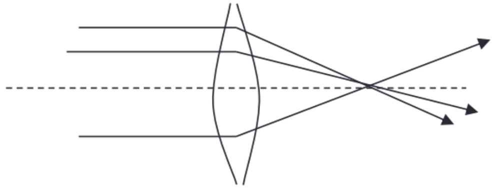


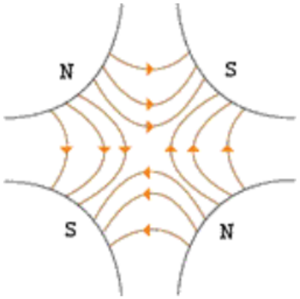


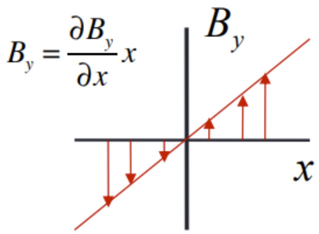
Background

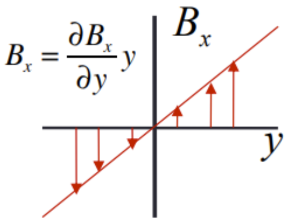
2. FODO cell

Quadrupole:

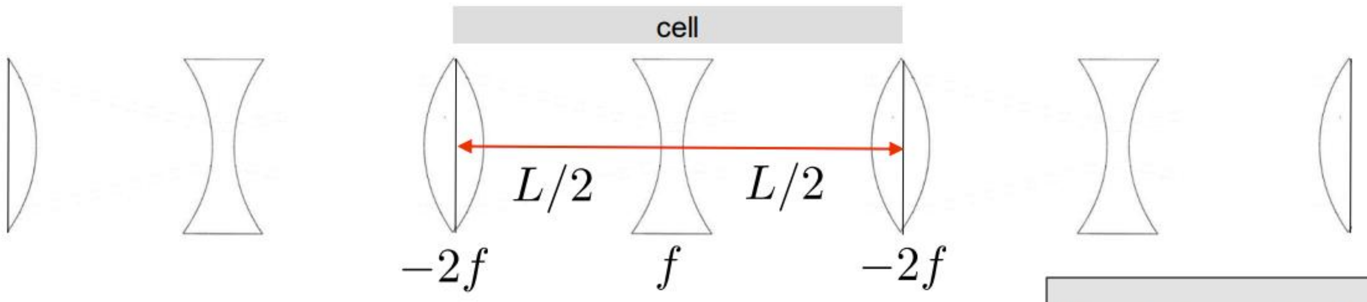








Note: $\vec{\nabla} \times \vec{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y}$

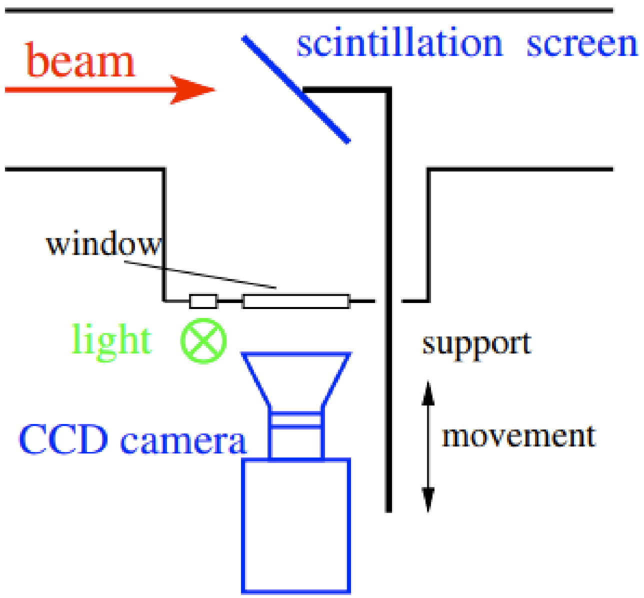


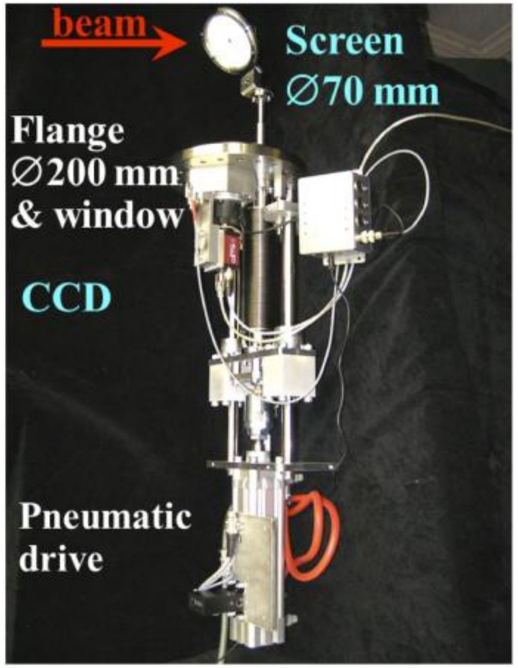
$$\boxed{\textbf{Focal length } (f) = \frac{1}{kl_q}}$$

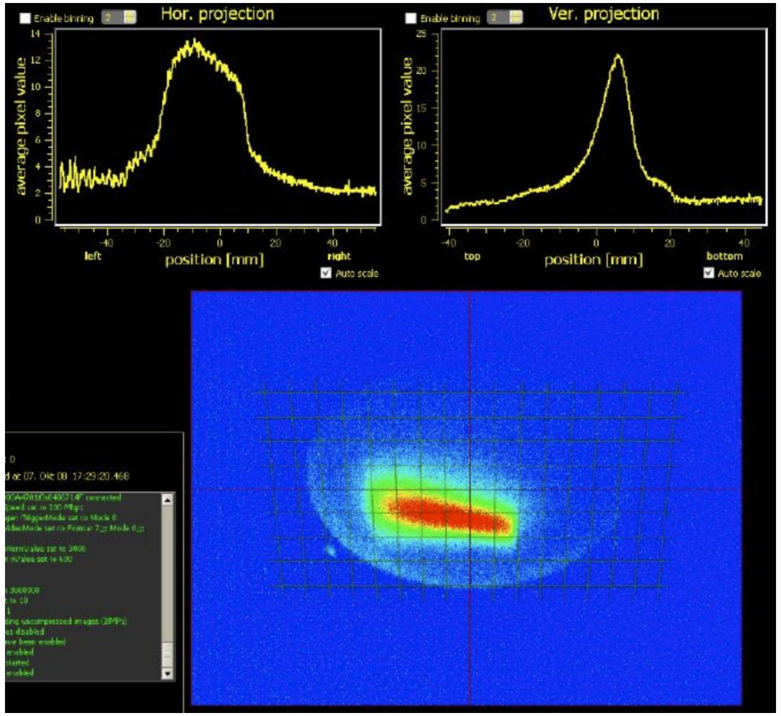
Background

3. **Beam profile monitor** (via scintillation screen)

- Diagnostic devices for **measuring the transverse spatial distribution**
- Beam particles hit the screen and make it glow with visible light.

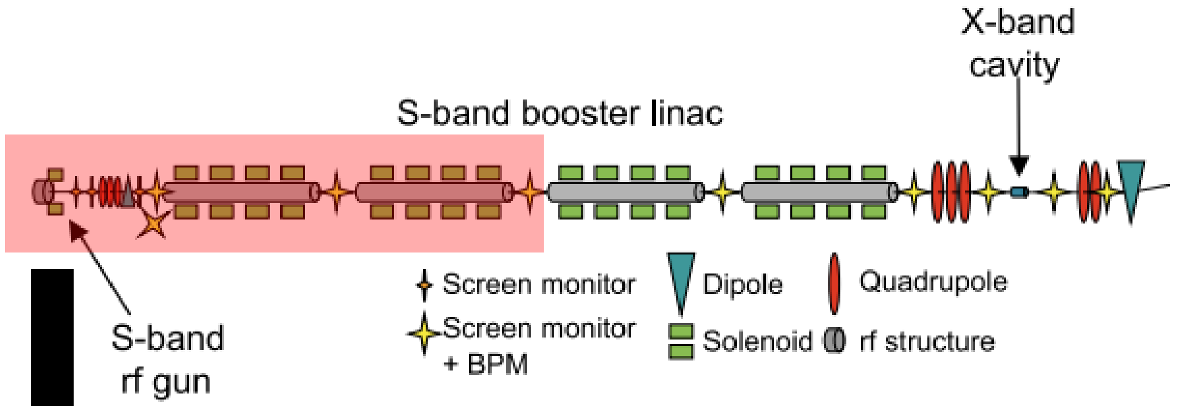






Introduction

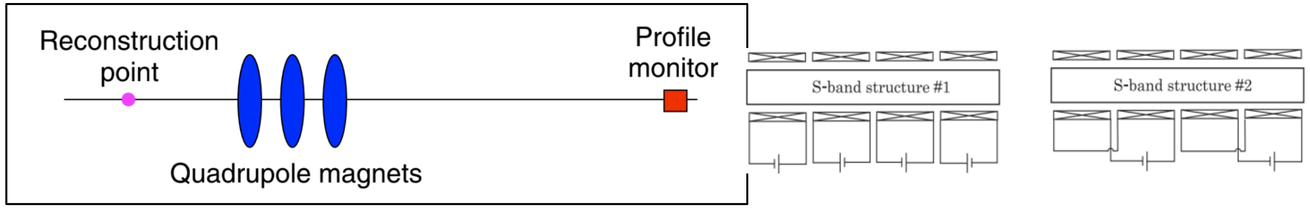
Motivation



<Scheme of SwissFEL Inject Test Facility (SITF)>

1. Effects of XY coupling remain under-researched (~2014)

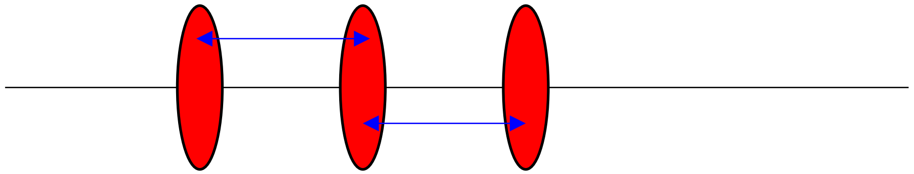
2. Strong xy coupling effect to unpredicted motion
   - Increasing apparent(=projected) 2D emittance



3. Deteriorate FEL laser performance
   - Making accurate measurements of transverse coupling effects essential
   - **Requirement coupling factor: $C < 0.01$**

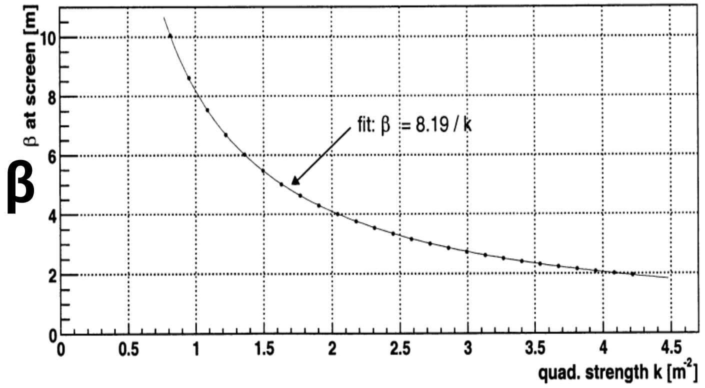
➢ Optimization required via multiple-quadrupole scan

Reconstruction method

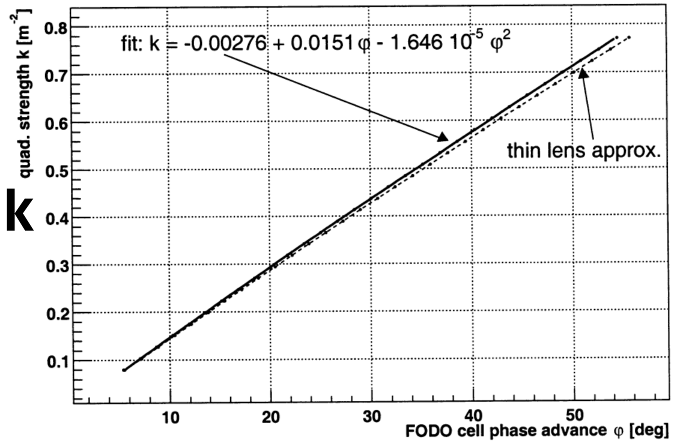


1. Single-optics/multiple-locations
   - Fixed optics(=quadrupole strengths), multiple locations
   - Requirement
     - ➢ Order of 100 m beamline or high field strength QM. → **Not suitable for SITF**.

2. <u>Multiple-optics/single-location (Selected)</u>
   - Variable optics, fixed location
   - Continuously operational (Parasitic measurements)
   - Require shorter beamline (~ order of 10 m)

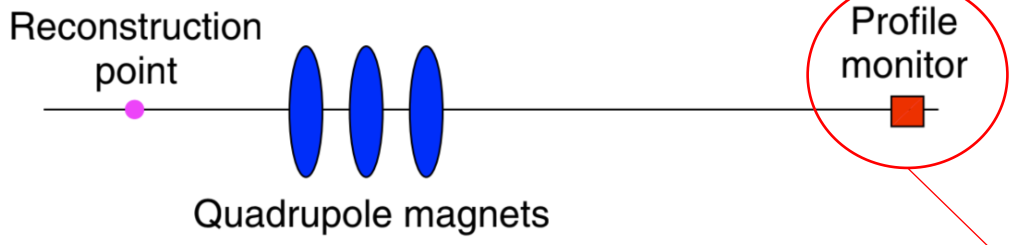


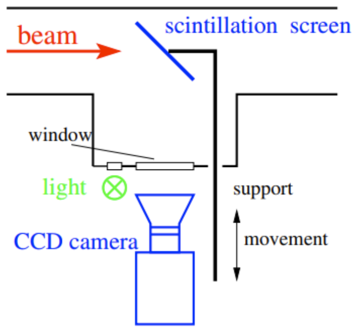
Quad. strength k [m^{-2}]



Phase advance [deg]

Theory

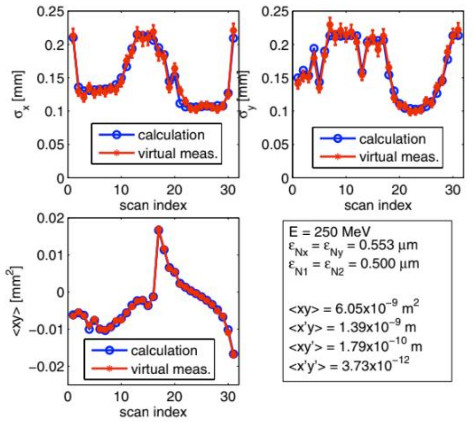




- 4D beam matrix: $\sigma^{4D} = \begin{bmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{bmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy}^T & \sigma_{yy} \end{pmatrix}$

: coupling elements

$$\langle xy\rangle = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\Sigma I(x,y)}$$



- Coupling make emittance growth $C = \sqrt{\frac{\varepsilon_x \varepsilon_y}{\varepsilon_1 \varepsilon_2}} - 1 \geq 0$

- $\sigma_s^{4D} = R\sigma_{s_0}^{4D} R^T$ where R is transport matrix

$$\langle x^2\rangle_s = R_{11}^2 \langle x^2\rangle_{s_0} + R_{12}^2 \langle x'^2\rangle_{s_0} + 2R_{11}R_{12}\langle xx'\rangle_{s_0}, \quad (10)$$

$$\langle y^2\rangle_s = R_{33}^2 \langle y^2\rangle_{s_0} + R_{34}^2 \langle y'^2\rangle_{s_0} + 2R_{33}R_{34}\langle yy'\rangle_{s_0}, \quad (11)$$

$$\langle xy\rangle_s = R_{11}R_{33}\langle xy\rangle_{s_0} + R_{12}R_{33}\langle x'y\rangle_{s_0} + R_{11}R_{34}\langle xy'\rangle_{s_0} + R_{12}R_{34}\langle x'y'\rangle_{s_0}. \quad (12)$$

Measured

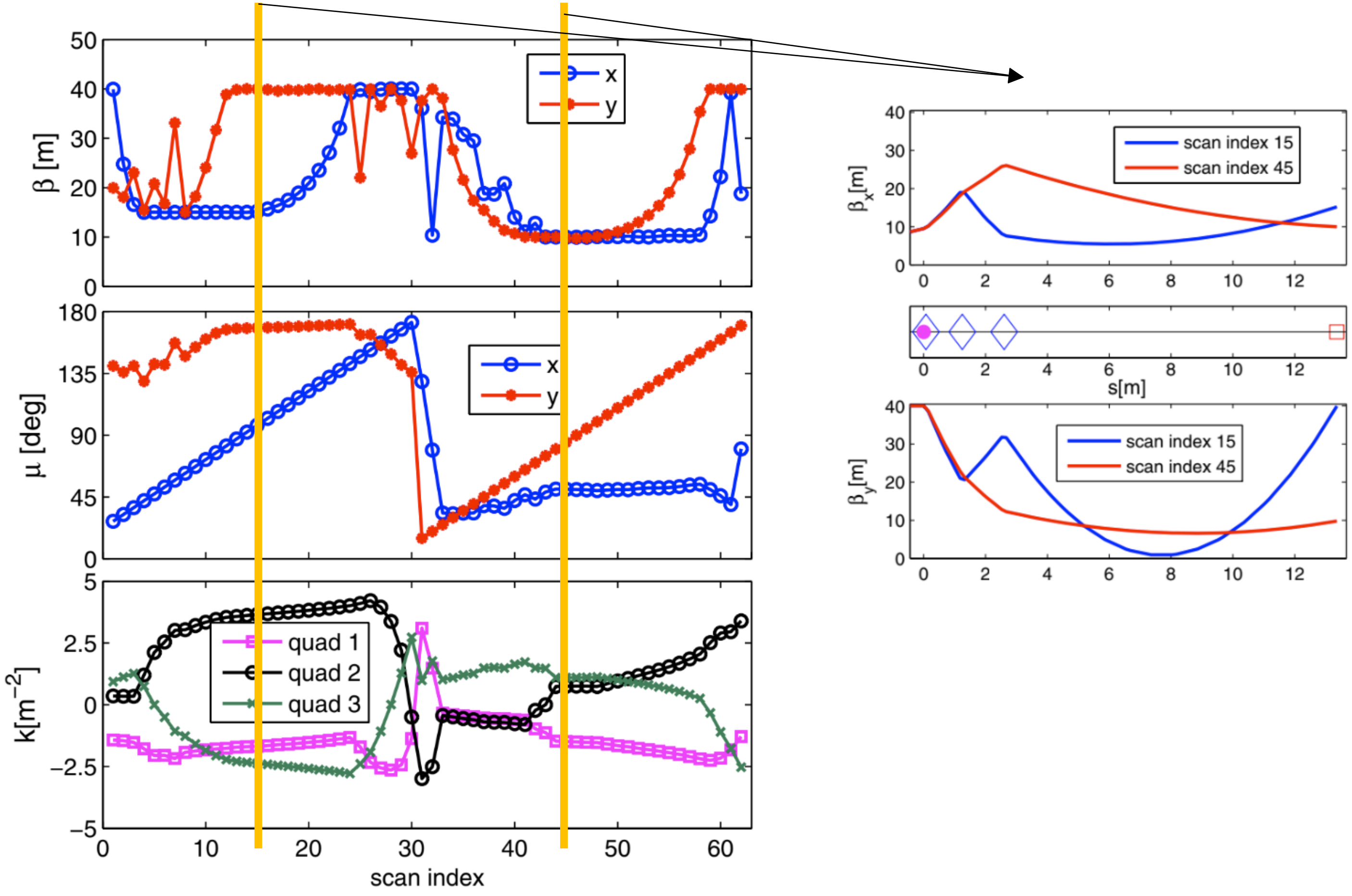
Reconstruction

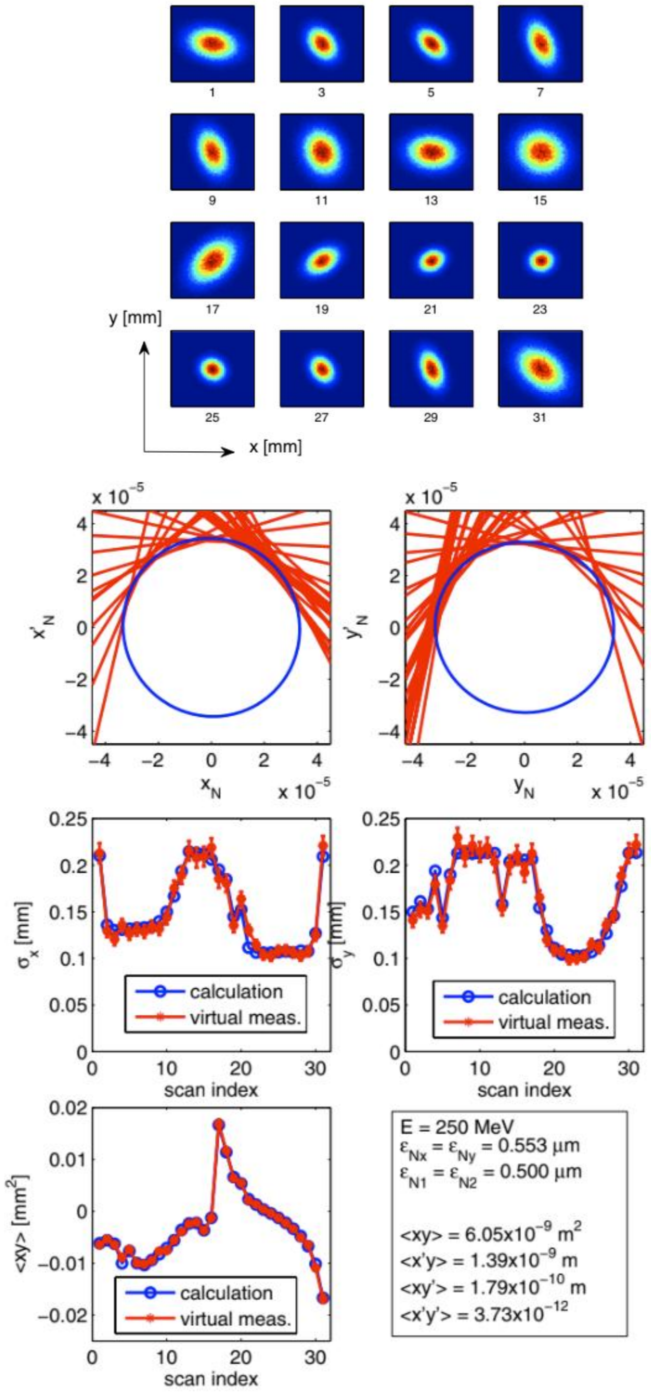
At least 4 measurements

Simulation setup

Multiple-optics/single-location

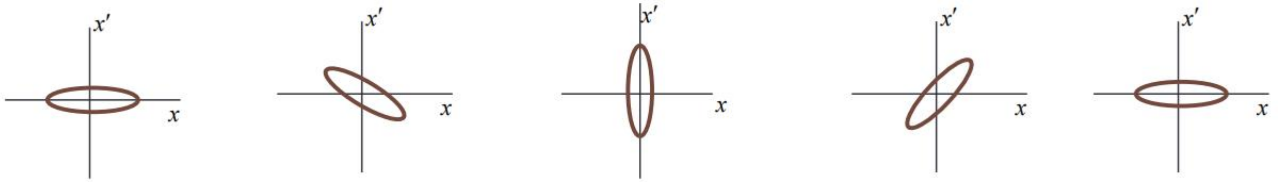
- Quadrupole strength k sweep
- β: 10 ~ 40 m





Error study with particle tracking simulation (ELEGANT)

Matching parameter



β = max
α = 0
➔maximum

β = decreasing
α >0
➔focusing

β = min
α = 0
➔minimum

β = increasing
α < 0
➔defocusing

Motion at each point bounded by

$$|x(s)| \leq A\sqrt{\beta(s)}$$

$$M = \frac{1}{2}(\beta\gamma_d - 2\alpha\alpha_d + \gamma\beta_d) \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

Measured

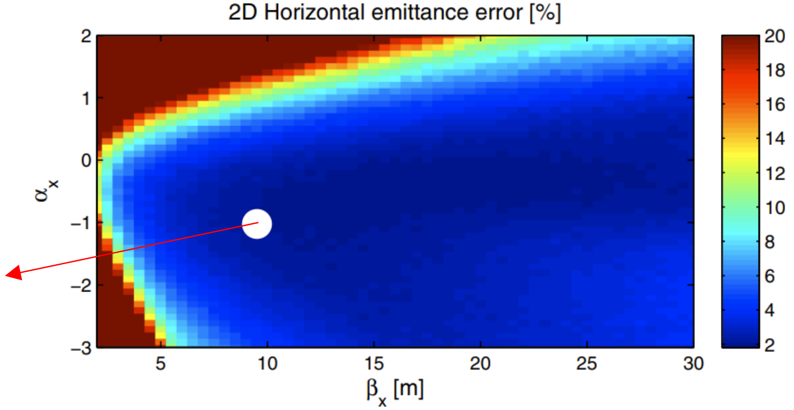
Designed

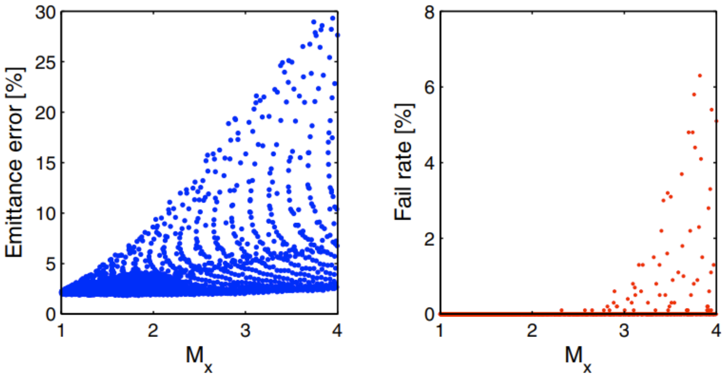
Well-matched: M=1

Mismatched: M>1

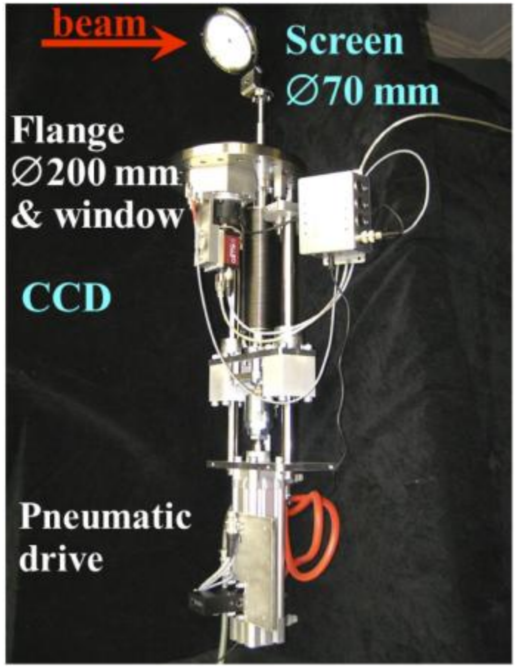
In practical, $M_x = 1.06$, $M_y = 1.00$

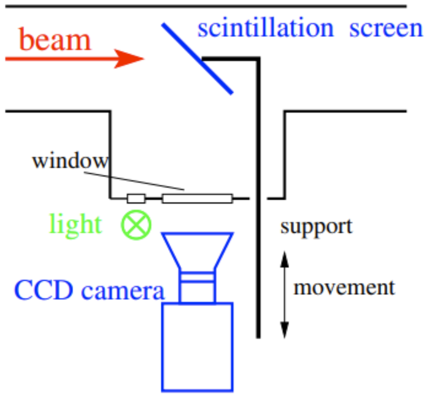
Matched solution region





Error study for simulation



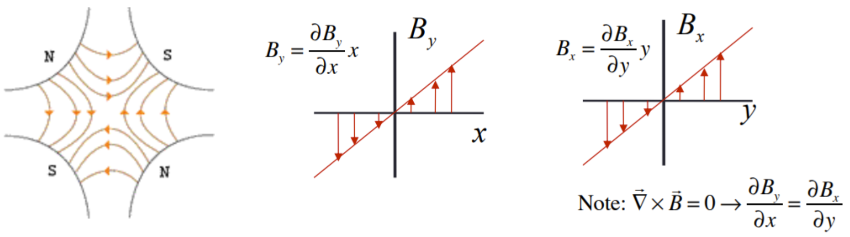


Profile monitor resolution	Error in beam parameter measurements (sizes and $\langle xy\rangle$)	15 μm in beam size resolution 4 nm in emittance resolution 1.1% in 2D emittance error 1.7% in intrinsic emittance error
Profile monitor calibration	Error in beam parameter measurements	1.0% in beam size error 2.0% in 2D emittance error 2.9% in intrinsic emittance error
Cross-plane rotation of the profile monitor	Error in beam parameter measurements	0.5° in rotation error

Error study for simulation

1. **Single quadrupole focusing error**

Quadrupole field error	Error in transfer matrices	0.2% of field error 0.3% in 2D emittance error 1.0% in intrinsic emittance error
Quadrupole tilt	Additional coupling	1 mrad of tilt

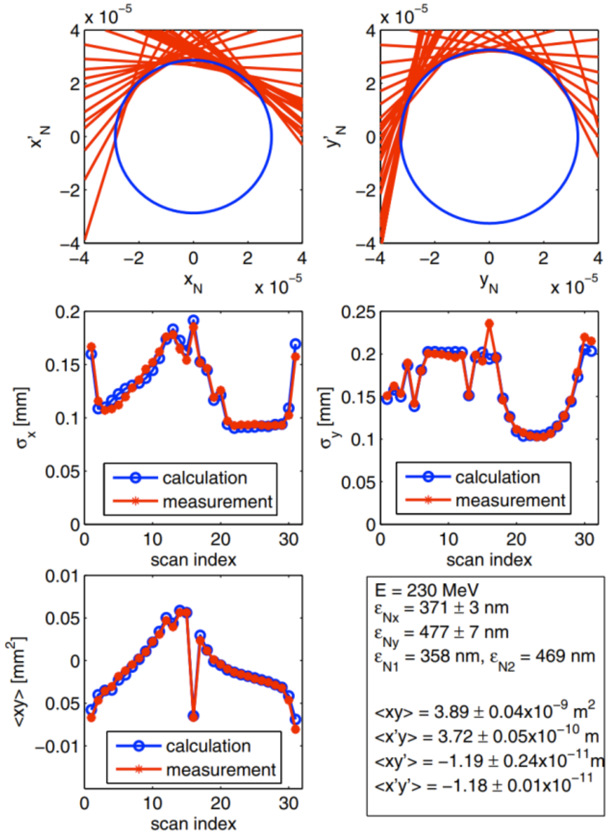


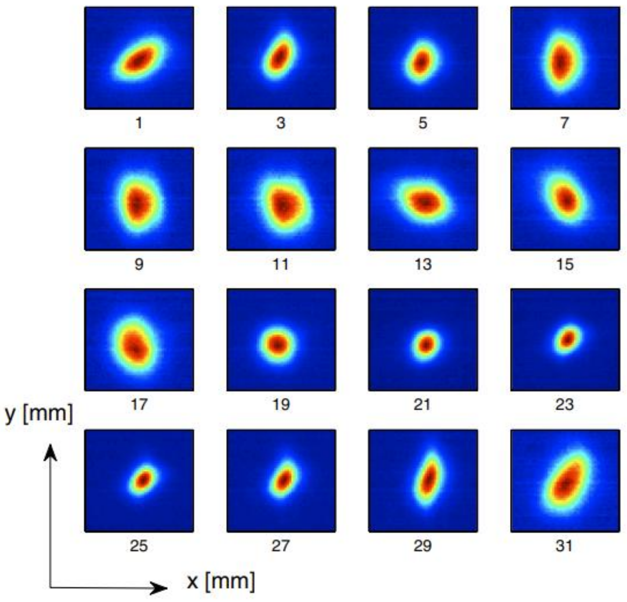
$$\Delta kl = \frac{\Delta Kl}{(B\rho)}$$

Energy uncertainty	Error in transfer matrices and emittance normalization	0.1% in energy error 0.3% in 2D emittance error 0.3% in intrinsic emittance error
Optics mismatch	Nonoptimal phase-space coverage	Increase of statistical errors for mismatched beams
Chromaticity	Error in beam parameter measurements	Negligible
Energy spread and dispersion	Error in beam parameter measurements	Negligible

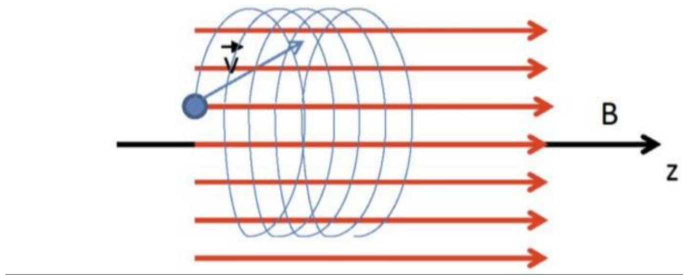
Experiment

1. Investigation beam size

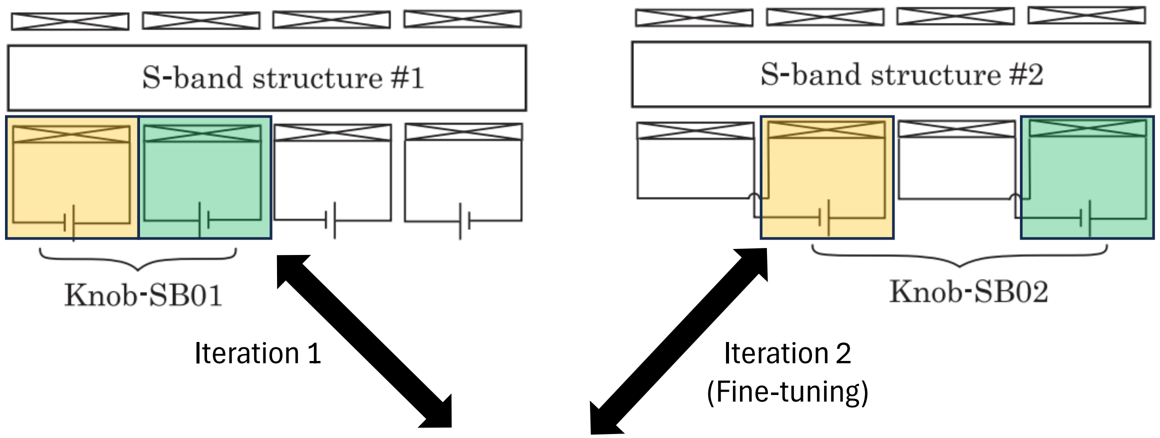




2. Solenoid settings for coupling



<XY coupling motion>



Apply asymmetric correction current

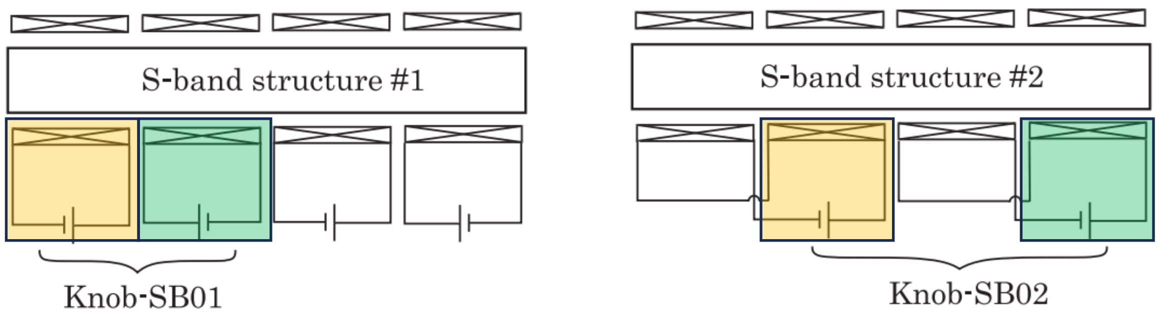
→ Generating xy coupling

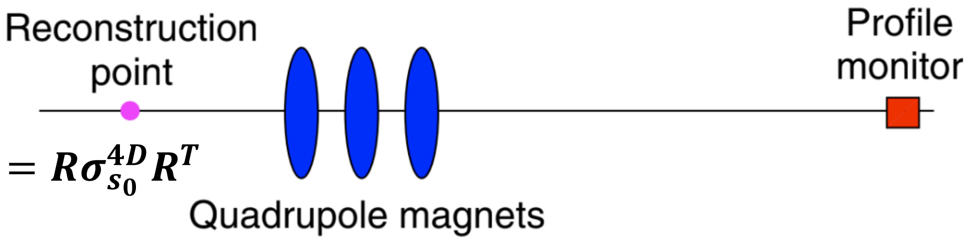
$$S_{ij} = \frac{\partial \sigma_i}{\partial k_j}$$

Results

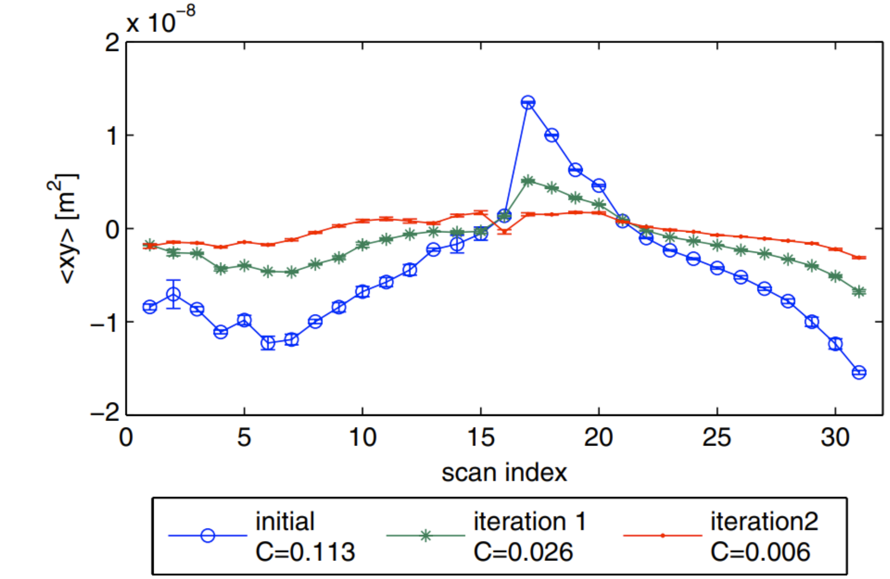
- $S_{ij} = \frac{\partial \sigma_i}{\partial k_j}$, $S = U\Sigma V^T$
- $\vec{C} = \Delta k = S^{-1}\sigma$

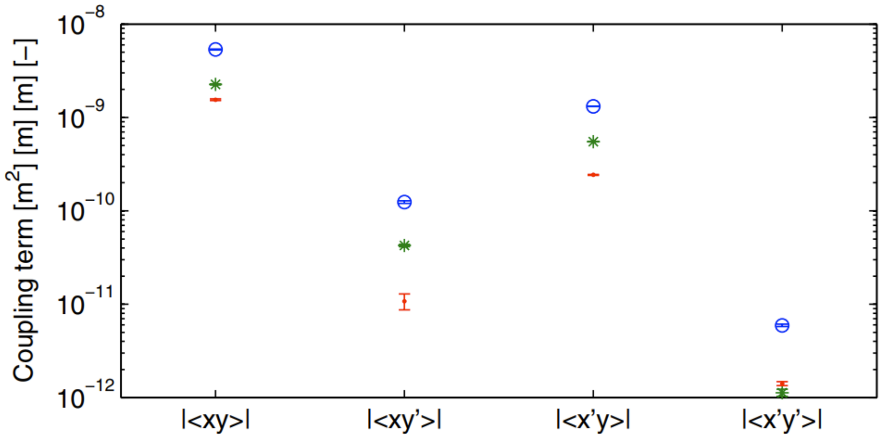
- $\vec{C} = S^{-1}\begin{pmatrix} \langle xy \rangle \\ \langle xy' \rangle \\ \langle x'y \rangle \\ \langle x'y' \rangle \end{pmatrix}$





$$\sigma_s^{4D} = R\sigma_{s_0}^{4D} R^T$$





Conclusion

1. **Optimized 4D beam matrix measurement**
   - Using triplets and one profile monitor to reconstruct all beam moments from size and correlation measurements.

2. **High accuracy reconstruction**
   - < 3 % error in 2D emittances and < 5 % in intrinsic emittances, demonstrated at SITF.

3. **Effective coupling correction**
   - calibrated knobs reduced coupling factor from 0.113 to 0.006 in two iterations.