Nondestructive beam energy-spread monitor using multi-stripline electrodes

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Motivation

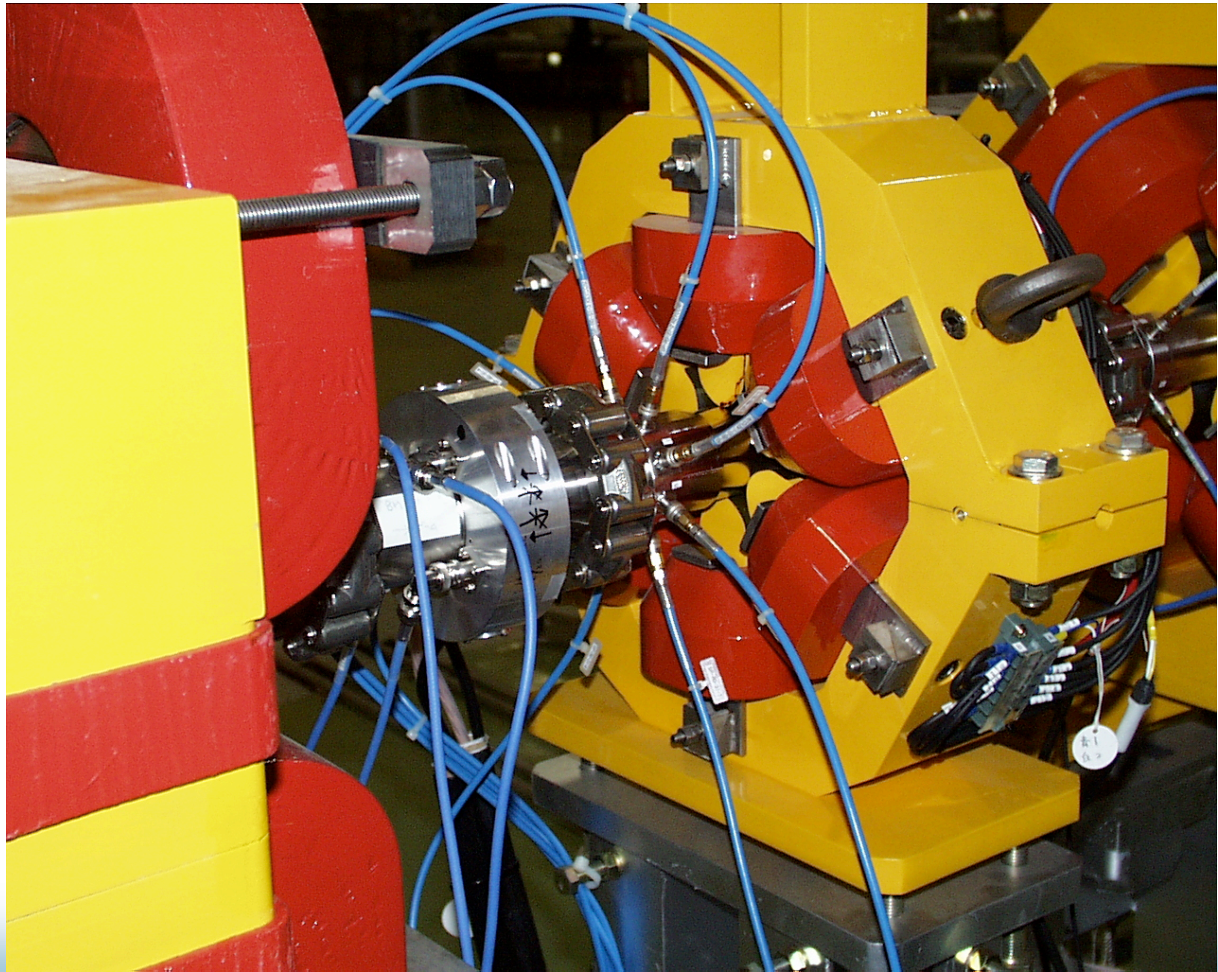
- Beam feedback controls in daily operation of the linac
  - Beam position feedback
  - Beam energy feedback
  - Beam energy-spread feedback (*under construction*)

  → A nondestructive energy-spread monitor contributes toward further stable operation/injection of the linac.

  → We developed the new beam energy-spread monitor with multi-stripline electrodes.
- This work was strongly motivated by a pioneering work by R. H. Miller, et al.[*HEAC'83*, pp.602-605].

  → They showed that a stripline-type BPM with four pickups could be utilized as a nonintercepting emittance monitor.
- Also our previous work using similar stripline-type BPMs [*Jpn.J.App. Phys*. 40 (2001), pp.890-897] demonstrated that the higher-order (second- and third-order) moments of an electron beam were directly measured depending upon the transverse beam sizes.

Beam Energy-Spread Monitor with Eight Stripline-Type Electrodes



Multi-Stripline Energy Spread Monitor: Mechanical design parameters

(a)

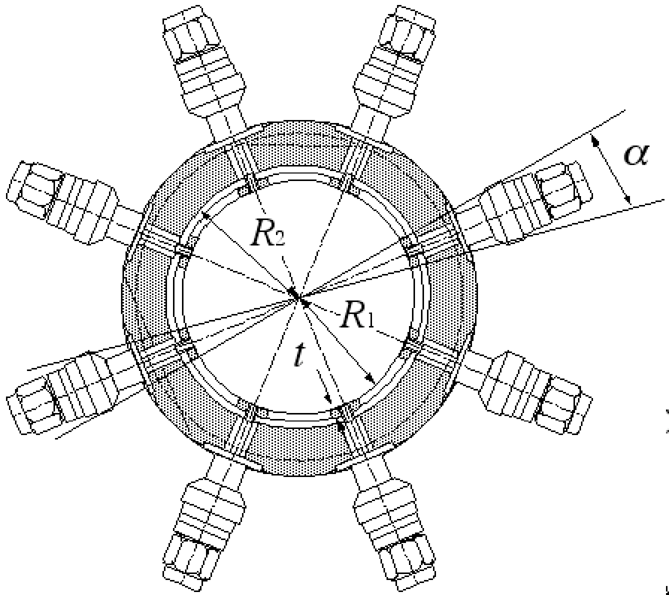
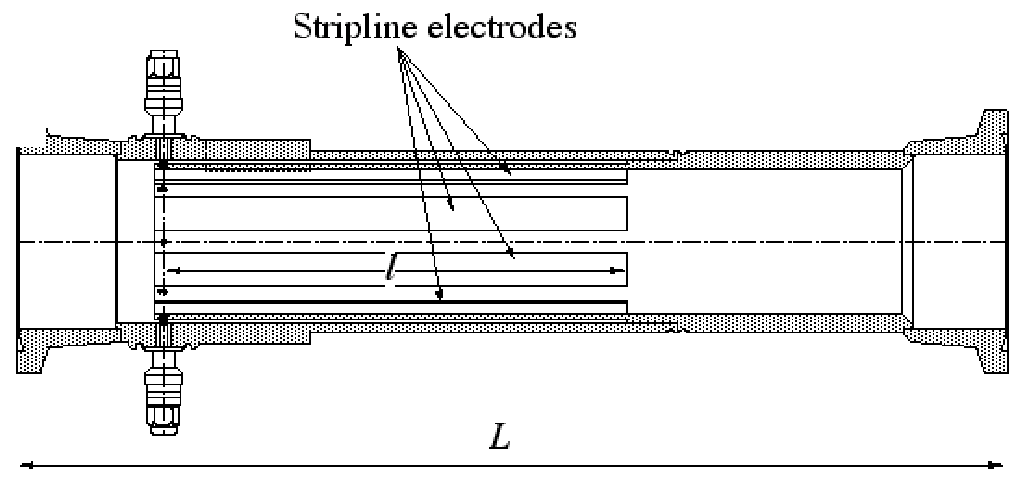


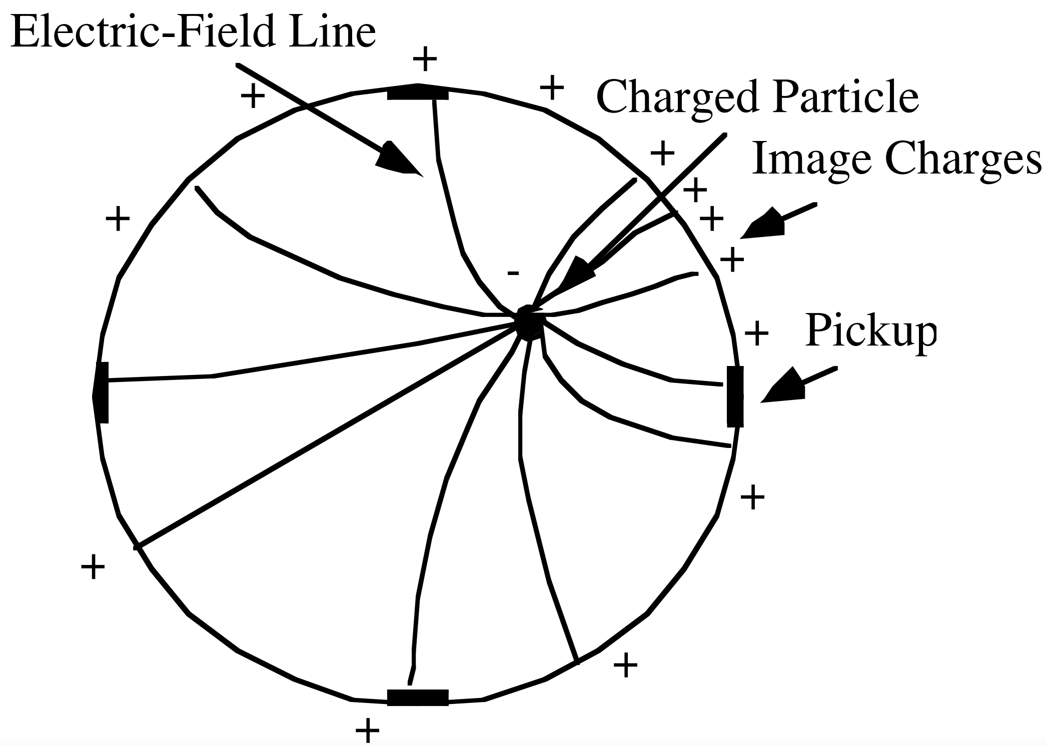
TABLE I: Mechanical design parameters of the BESM.

Mechanical parameter	
Innner radius R_1 (mm)	20.6
Outer raidus R_2 (mm)	23.4
Electrode angular width α (deg)	15
Electrode thickness t (mm)	1.5
Electrode length l (mm)	132.5
Total length L (mm)	283

)



Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam: Beam-Induced Electric-Field Lines



Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam:

Wall current formula and its multipole expansion

- For a conducting round duct, the image charge density by a line charge is formulated by,

$$j(r,\phi,R,\theta) = \frac{I(r,\phi)}{2\pi R}\frac{R^2 - r^2}{R^2 + r^2 - 2rR\cos(\theta - \phi)},$$

- Expanding the image charge density in a power series of r/R,

$$j(r,\phi,R,\theta) = \frac{I(r,\phi)}{2\pi R}\left[1 + 2\sum_{n=1}^{\infty}\left(\frac{r}{R}\right)^n \cos n(\theta - \phi)\right].$$

Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam:

Wall current formula and its multipole expansion(cont'd)

- Assuming the transverse *r*-distribution $\rho(r)$ of a traveling charged beam, the total image charge *J* is formulated by,

$$J(R,\theta) = \int_0^R \int_0^{2\pi} j(r,\phi,R,\theta)\,\rho(r)\, r\,dr\,d\phi.$$

- It is easily expanded by the power series,

$$J(R,\theta) \cong \frac{I_b}{2\pi R}\left\{1 + \frac{2}{R}\left[\langle x\rangle\cos\theta + \langle y\rangle\sin\theta\right]\right.$$

$$+\frac{2}{R^2}\left[\left(\langle x^2\rangle - \langle y^2\rangle + \langle x\rangle^2 - \langle y\rangle^2\right)\cos 2\theta + 2\left(\langle xy\rangle + \langle x\rangle\langle y\rangle\right)\sin 2\theta\right]$$

$$\left. + \text{higher orders}\right\}.$$

Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam:

Wall current formula and its multipole expansion(cont'd)

- The multipole moments are defined

  for the 1st-order moment,

$$\langle x \rangle = \int x j(x,y) \square (x,y)\, dxdy, \quad \langle y \rangle = \int y j(x,y) \square (x,y)\, dxdy,$$

, for the 2nd-order moment,

$$\langle x^2 \rangle = \int x^2 j(x,y) \square (x,y)\, dxdy, \quad \langle y^2 \rangle = \int y^2 j(x,y) \square (x,y)\, dxdy,$$

and for the xy coupling term,

$$\langle xy \rangle = \int xy j(x,y) \square (x,y)\, dxdy.$$

Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam:

Wall current formula and its multipole expansion(cont'd)

- Assuming a gaussian function for the transverse charge distribution, the total image charge density is formulated by,

$$J(R,\theta) = \frac{I_b}{2\pi\sigma_x\sigma_y}\iint \frac{j(r,\phi,R,\theta)}{I(r,\phi)} \exp\left[-\frac{(x-x_0)^2}{2\sigma_x^2}\right]\exp\left[-\frac{(y-y_0)^2}{2\sigma_y^2}\right]dxdy,$$

$$\begin{aligned}
J(R,\theta) \approx \frac{I_b}{2\pi R}\Bigg\{ & 1 + 2\left(\frac{x_0}{R}\cos\theta + \frac{y_0}{R}\sin\theta\right) \\
& + 2\left[\left(\frac{\sigma_x^2-\sigma_y^2}{R^2} + \frac{x_0^2-y_0^2}{R^2}\right)\cos 2\theta + 2\frac{x_0 y_0}{R^2}\sin 2\theta\right] \\
& + 2\left[\frac{x_0}{R}\left(\frac{3(\sigma_x^2-\sigma_y^2)}{R^2} + \frac{x_0^2-3y_0^2}{R^2}\right)\cos 3\theta + \frac{y_0}{R}\left(\frac{3(\sigma_x^2-\sigma_y^2)}{R^2} + \frac{3x_0^2-y_0^2}{R^2}\right)\sin 3\theta\right] \\
& + \text{higher orders}\Bigg\},
\end{aligned}$$

Multipole Analysis of 8-Electrode BESM

- The multipole moments are defined
  - for the 1st-order (dipole) moments,

$$J_{dx} \equiv \frac{\langle x \rangle}{R} = \int_0^{2\pi} J(R,\phi)\cos\phi\, d\phi \Big/ \int_0^{2\pi} J(R,\phi)\, d\phi \approx \frac{\sum_{i=1}^{8} V_i \cos\phi_i}{\sum_{i=1}^{8} V_i},$$

$$J_{dy} \equiv \frac{\langle y \rangle}{R} = \int_0^{2\pi} J(R,\phi)\sin\phi\, d\phi \Big/ \int_0^{2\pi} J(R,\phi)\, d\phi \approx \frac{\sum_{i=1}^{8} V_i \sin\phi_i}{\sum_{i=1}^{8} V_i},$$

  - and for the 2nd-order (quadrupole and skew) moments,

$$J_q \equiv \frac{1}{R}(\langle x^2 \rangle - \langle y^2 \rangle + \langle x \rangle^2 - \langle y \rangle^2) = \int_0^{2\pi} J(R,\phi)\cos 2\phi\, d\phi \Big/ \int_0^{2\pi} J(R,\phi)\, d\phi \approx \frac{\sum_{i=1}^{8} V_i \cos 2\phi_i}{\sum_{i=1}^{8} V_i},$$

$$J_s \equiv \frac{1}{R^2}(\langle xy \rangle + \langle x \rangle \langle y \rangle) = \int_0^{2\pi} J(R,\phi)\sin 2\phi\, d\phi \Big/ \int_0^{2\pi} J(R,\phi)\, d\phi \approx \frac{\sum_{i=1}^{8} V_i \sin 2\phi_i}{\sum_{i=1}^{8} V_i},$$

Multipole Analysis of 8-Electrode BESM (cont'd)

- Using the 2nd-order (quadrupole and skew) moments, the skew angle (*x*-*y* coupling) of the beam is formulated by

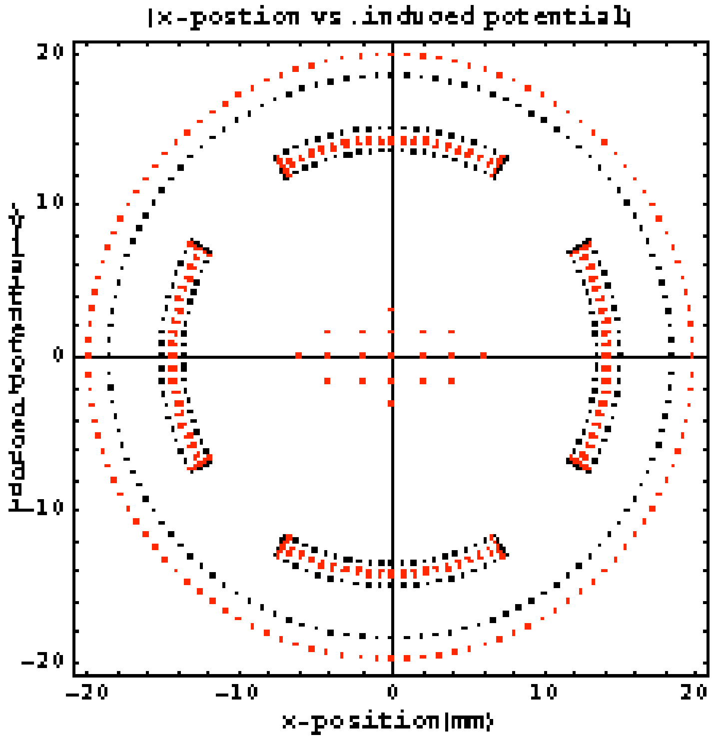
$$\theta_{skew} = J_s / 2J_q ,$$

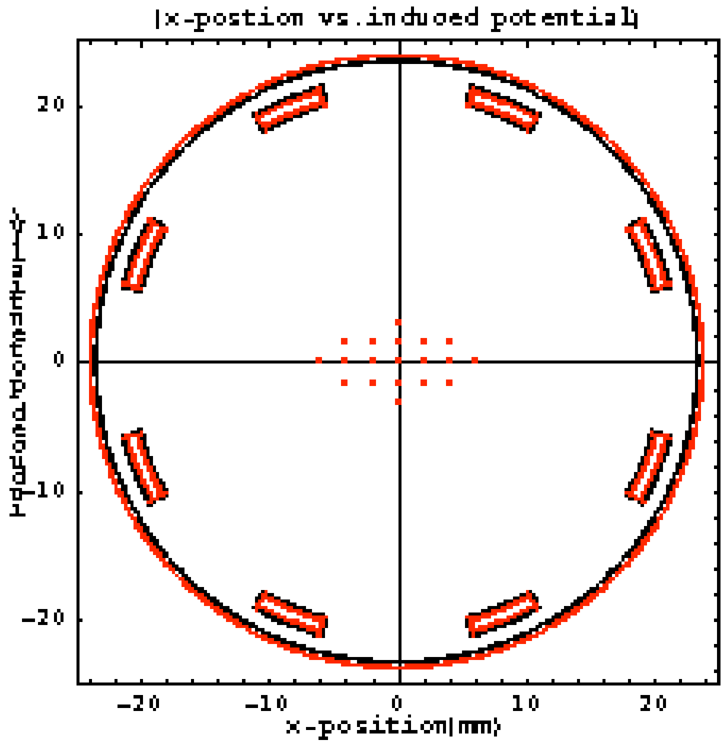
- and the beam energy spread is also formulated using the optics parameters and transverse emittances by

$$\langle x^2 \rangle - \langle y^2 \rangle = \beta_x \varepsilon_x + \left(\eta_x \frac{\Delta E}{E} \right)^2 - \beta_y \varepsilon_y + g.$$

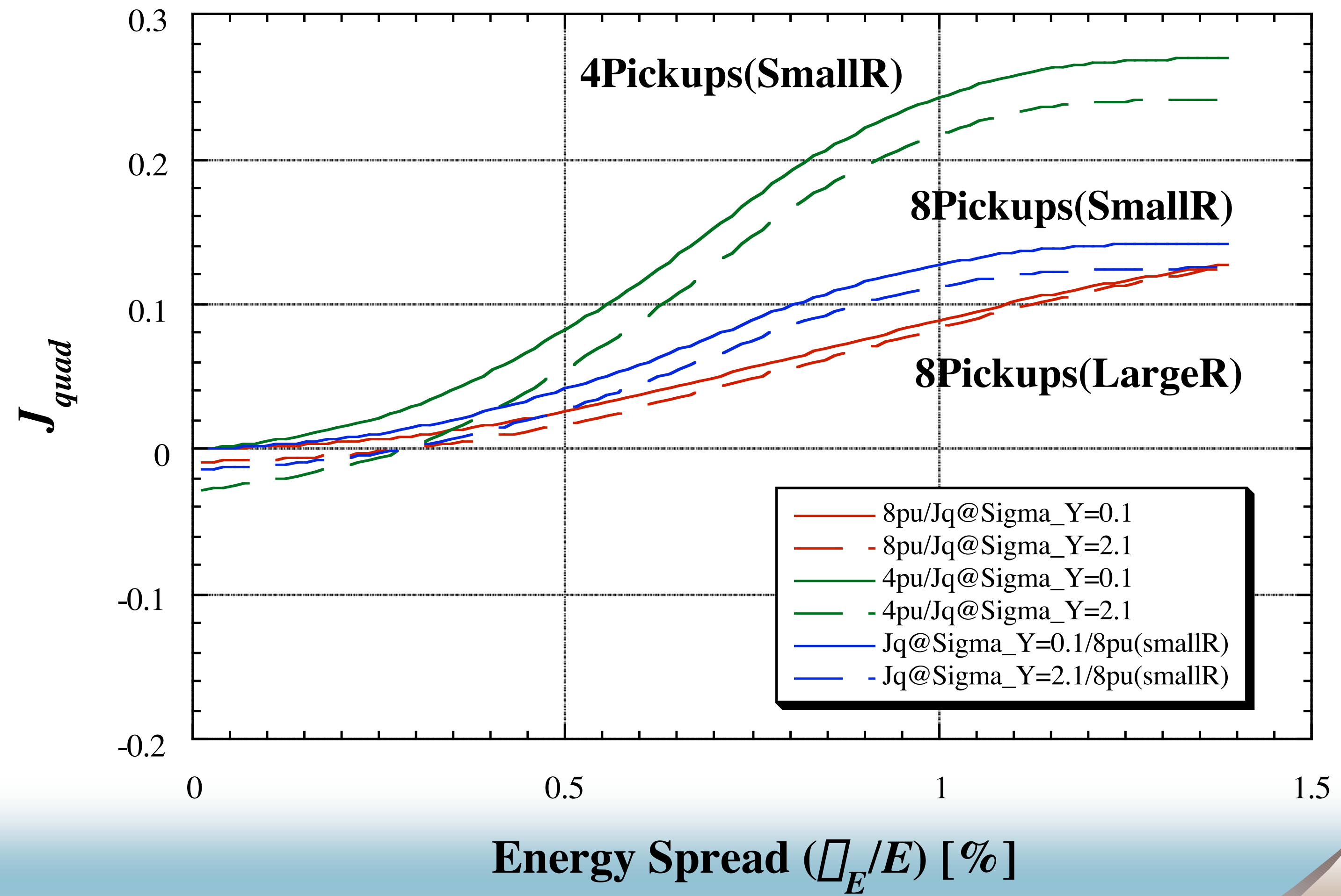
where *g* is the offset due to the gain imbalance and the geometrical errors of the pickups.

Multi-Stripline Energy Spread Monitor: Charge Simulation Method

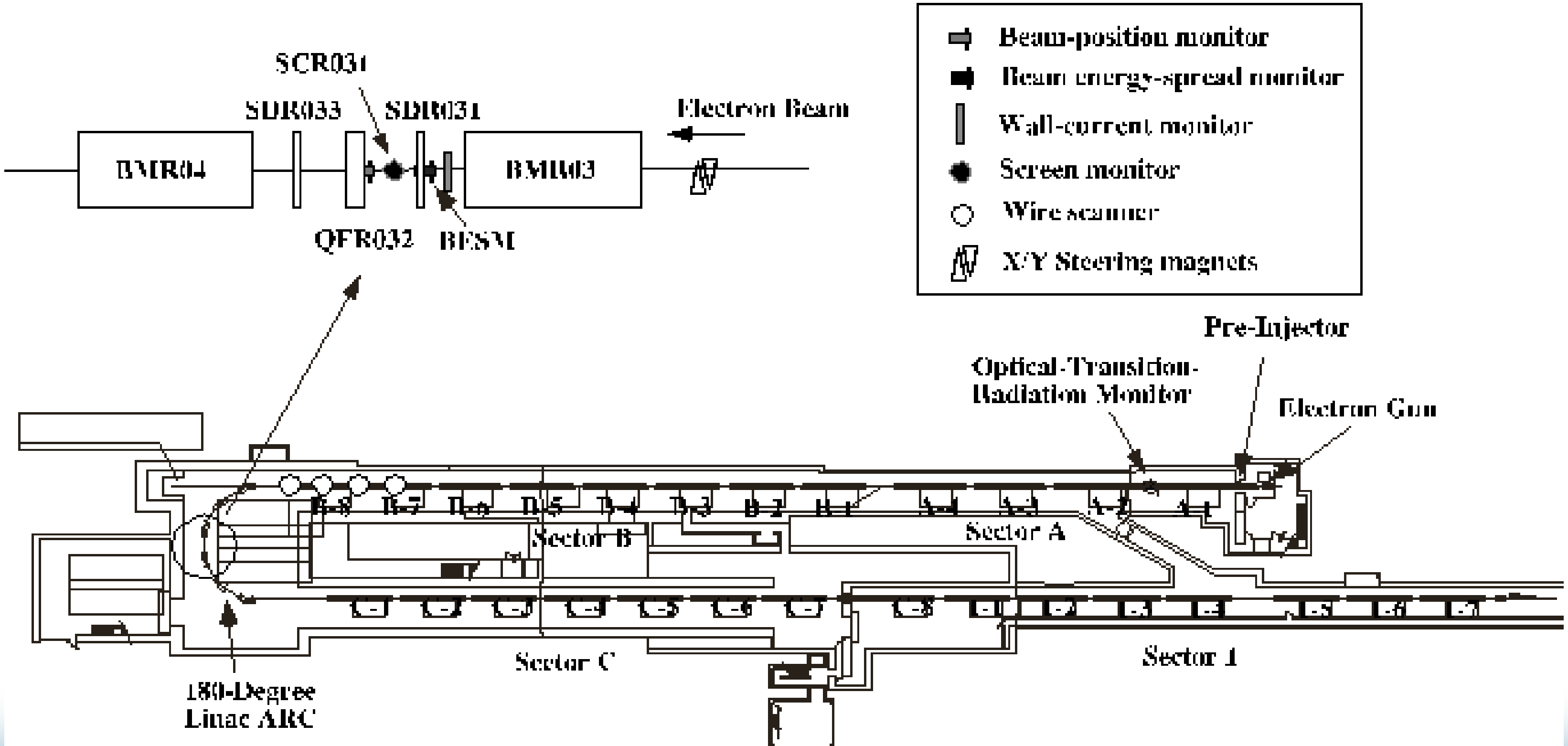




Multi-Stripline Energy Spread Monitor: J_{quad}-Sensitivity Calculation



Beam Test at the 180-degree J-arc section of the injector linac



Beam Test:Experiment and beam condition

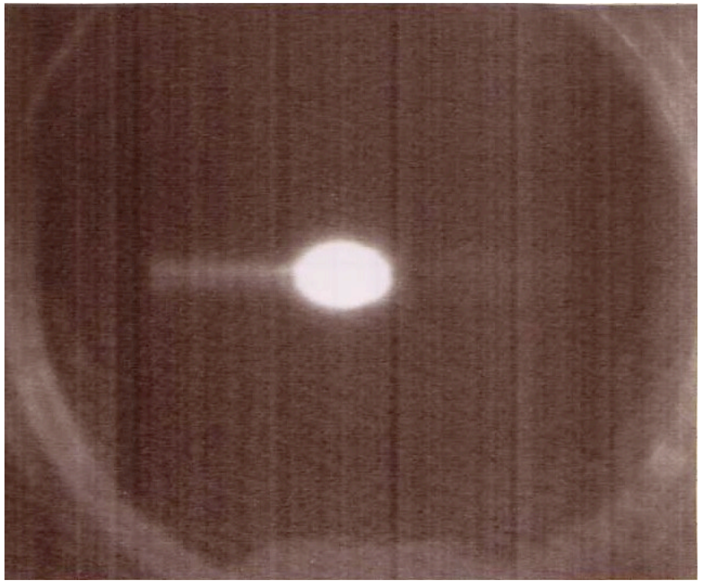
1. Beam Conditions:

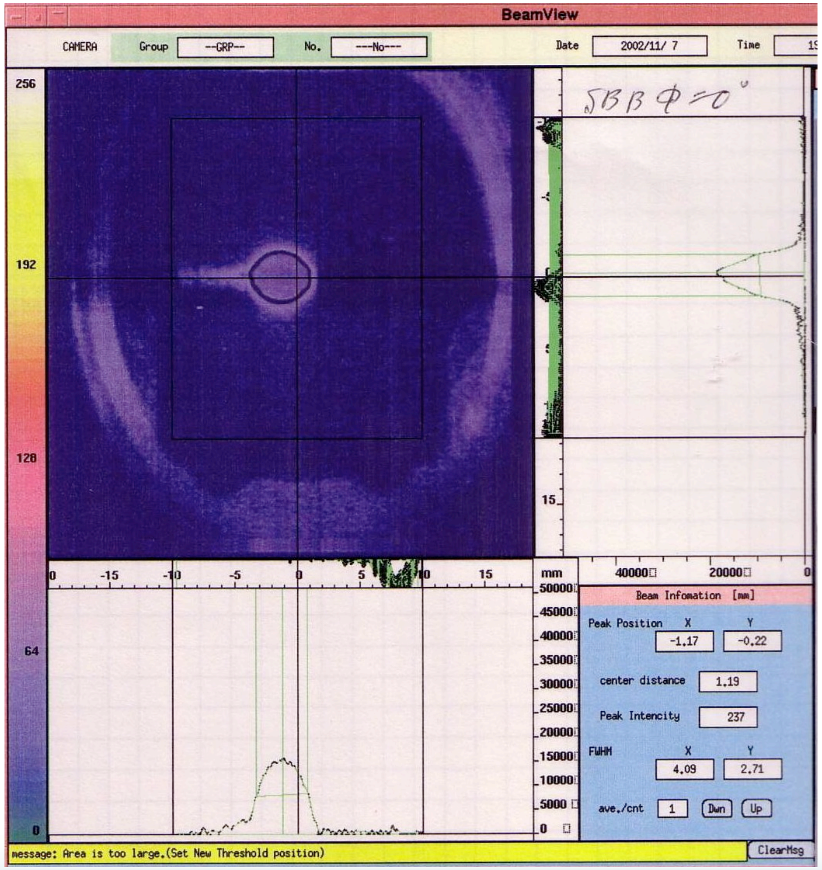
   •single bunch (KEKB) electron and high-current e-/e+ production beam (bunch width=12ps, bunch charge=0.9 and 8nC, repetition rate=25Hz)

   •beam energies (E_b=1.7GeV) at the linac J-arc.

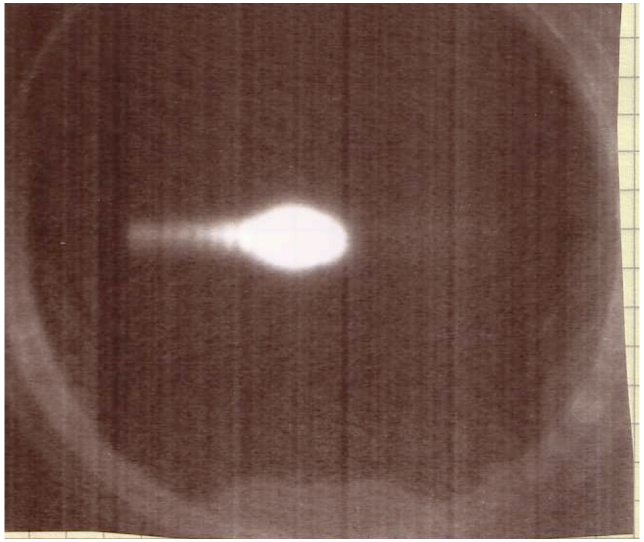
2. Second-order moments (quadrupole and skew moments) were measured by the BESM depending upon the rf phase of the booster klystron and the transverse beam positions.
3. Beam-size calibration was performed by a fluorescent screen monitor with a high-resolution image processing system.
4. Data-acquisition system of the BESM comprises a signal-digitizing system of a fast oscilloscope(LeCroy WavePro 950) with a sampling rate of 8-GS/s (BW=1GHz) and a PC/Linux-based computer with a Pentium IV microprocessor at 2.2GHz.

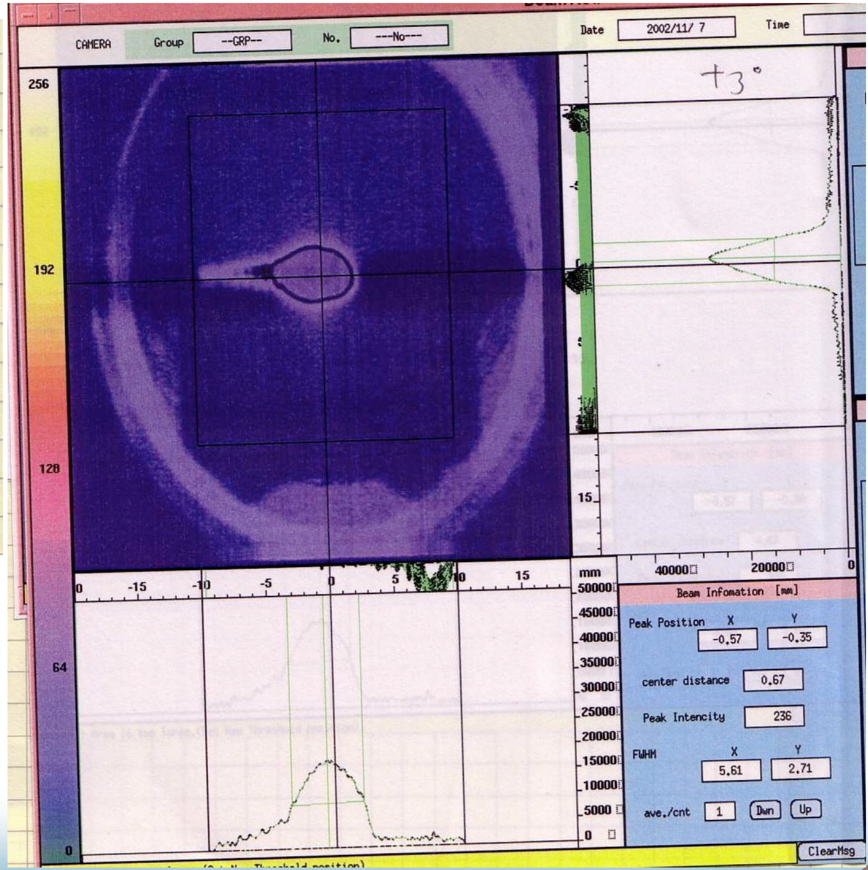
Experimental Results: phase=0deg (0.9-nC e- beam)





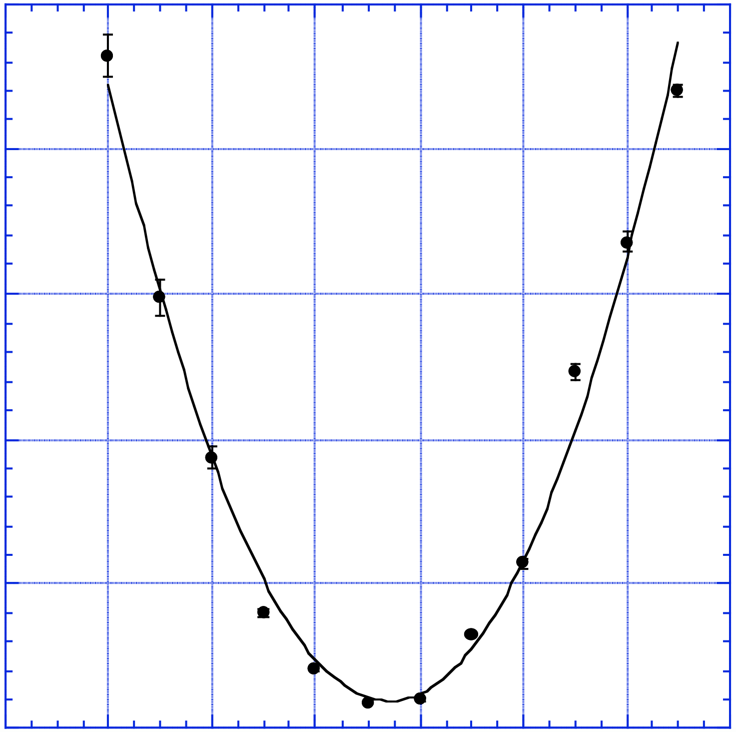
Experimental Results: phase=+3deg (0.9-nC e- beam)





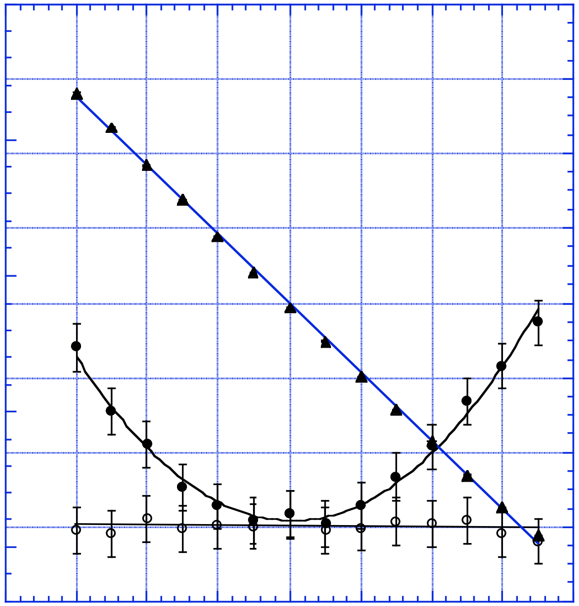
Experimental Results:

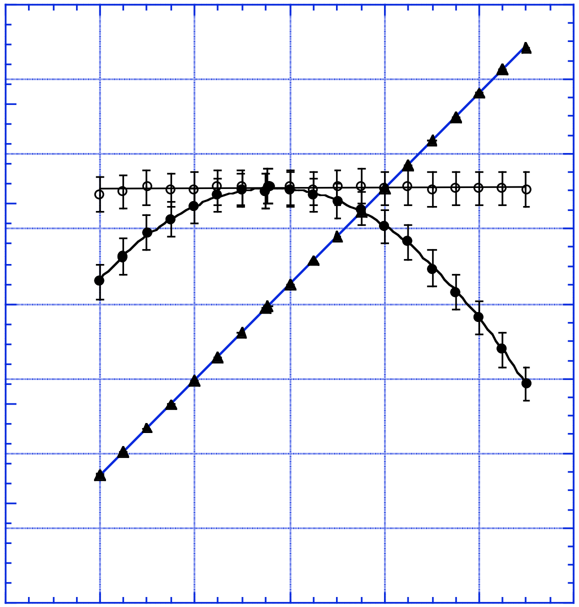
Beam-size measurement by the screen monitor system depending on the rf phase (0.9-nC e- beam)



Experimental Results:

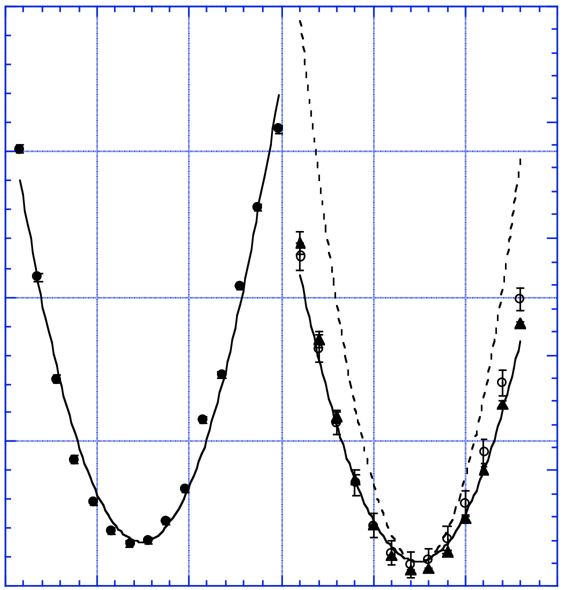
Variations of the horizontal and vertical beam-position dependence of J_{quad}

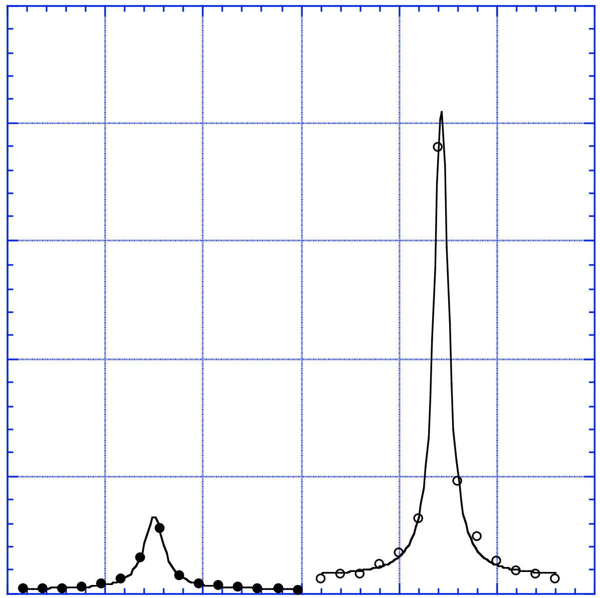




Experimental Results:

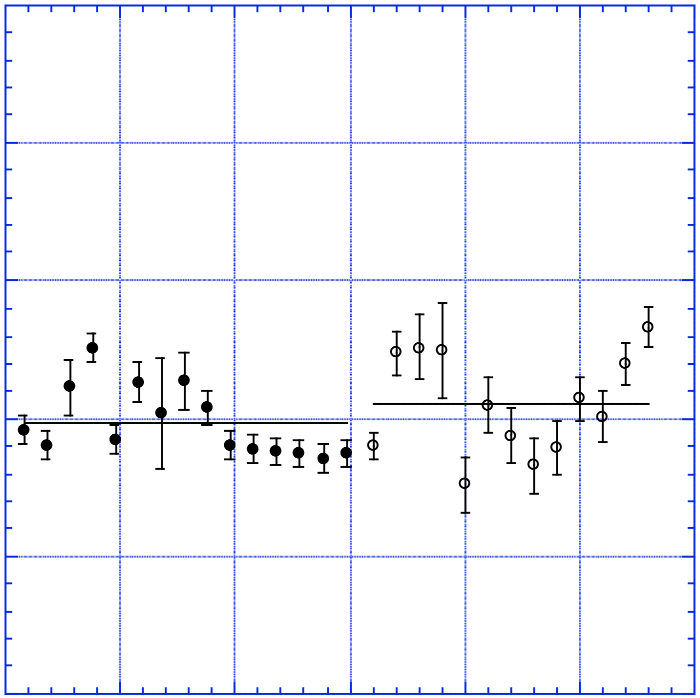
Variations of J_{quad} and the rf phase resolution depending on the rf phase(0.9 and 8-nC e- beams)





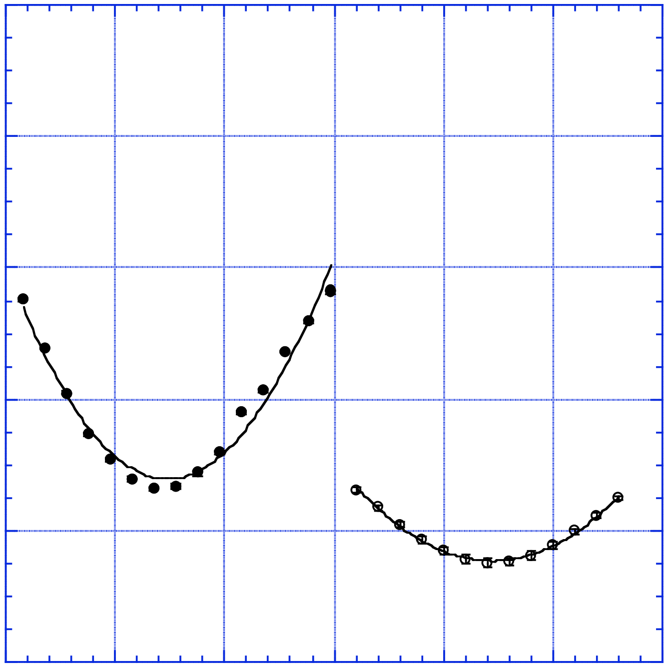
Experimental Results:

Variations of the skew angles depending upon the rf phase(0.9 and 8-nC e- beams)



- The obtained skew angles in average are
  - 21 and 20 mrad for the 0.9- and 8-nC e- beam over the measured region of the rf phase.

Experimental Results:
Variations of the beam energy spread depending upon the rf phase

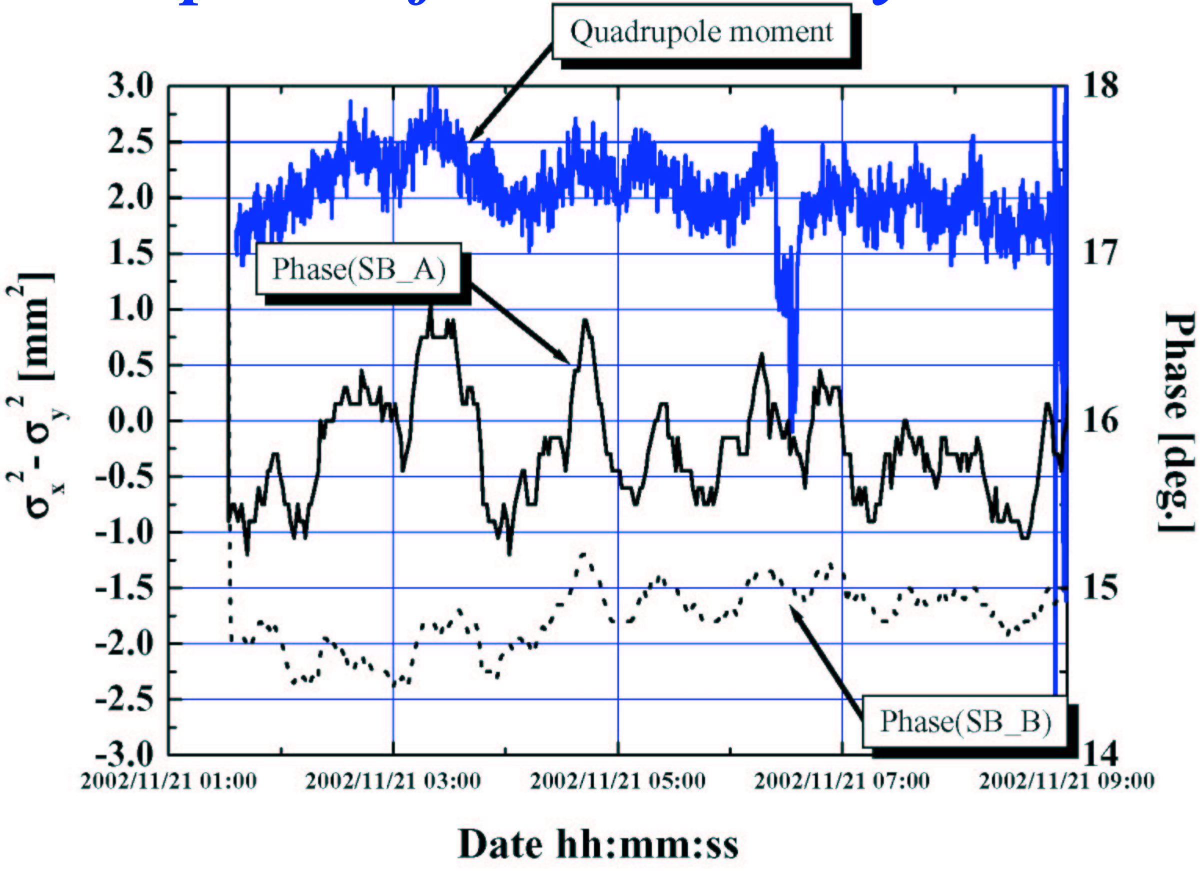


- The obtained beam energy spreads were
  - 0.150±0.007% for the 0.9-nC e-,
  - and 0.264±0.004% for the 8-nC e-/e+ production at the rf phase of the energy-spread minimum

The resolution of the measurement is on the order of 10^{-3} depending upon the beam charge and the rf phase.

Experimental Results:

Time trend of the beam energy spread and the rf phase of the booster klystron



Conclusions

- •Result of the beam-size measurement by the BESM is consistent well with that obtained by the fluorescent screen monitor system, where the 2nd-order moments need to be corrected with the transverse beam positions.
- •RF phase resolutions were
  - less than 1 deg. for the high-current primarly electron(8-nC) beam,

    and less than 1 deg. over the region of ±1 deg. apart from the rf phase at the energy-spread minimum.
- •Beam energy spreads were
  - 0.150±0.007% for the 0.9-nC electron beam,
  - and 0.264±0.004% for the 8-nC e- beam, and the resolution is on the order of 10^{-3} depending upon the beam charge and the rf phase.
- •Skew angles of the electron beam were
  - 21 and 20 mrad in average over the measured region of the rf phase for the 0.9- and 8-nC electron beam, respectively.