Emittance Measurements of Ion Beams Extracted from the High-Intensity Permanent Magnet ECR Ion Source

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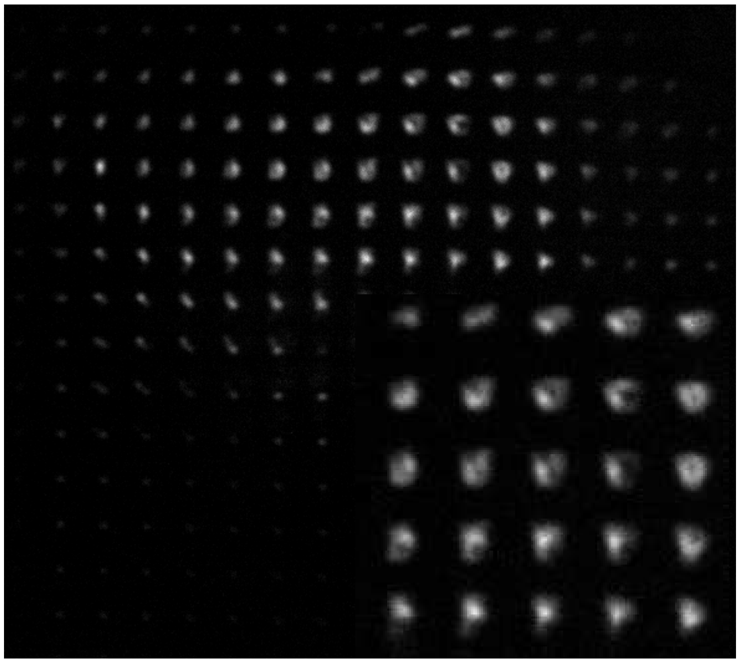
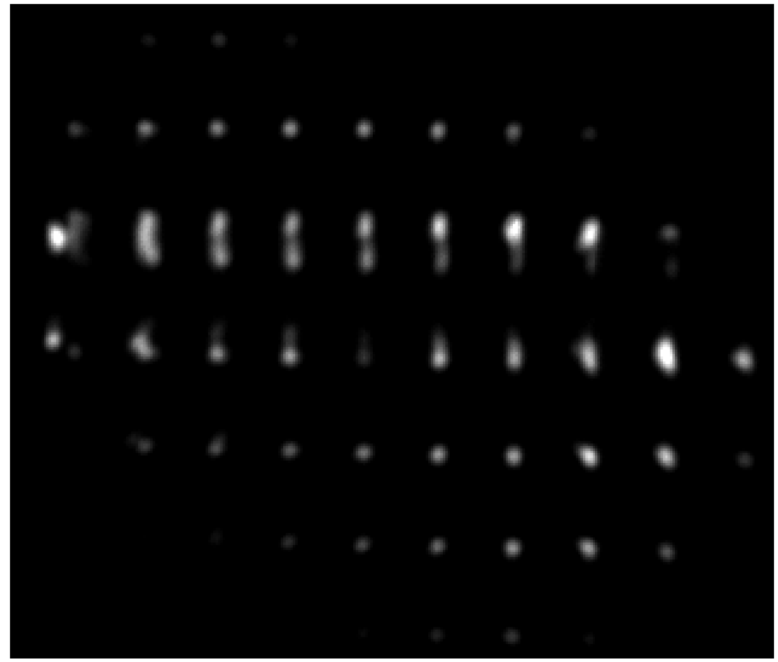
Why Pepper Pot – Scintillator Screen Emittance Meter?

- Emittance of ECR beams has complicated structure



$^{16}O^{7+}$



$^{209}Bi^{20+}$

- Slit and Alison type scanners can not provide full information about such phase space distributions

Choice of visualization screen

Requirements:

- High sensitivity
- Reasonably long life-time
- Wide dynamic range

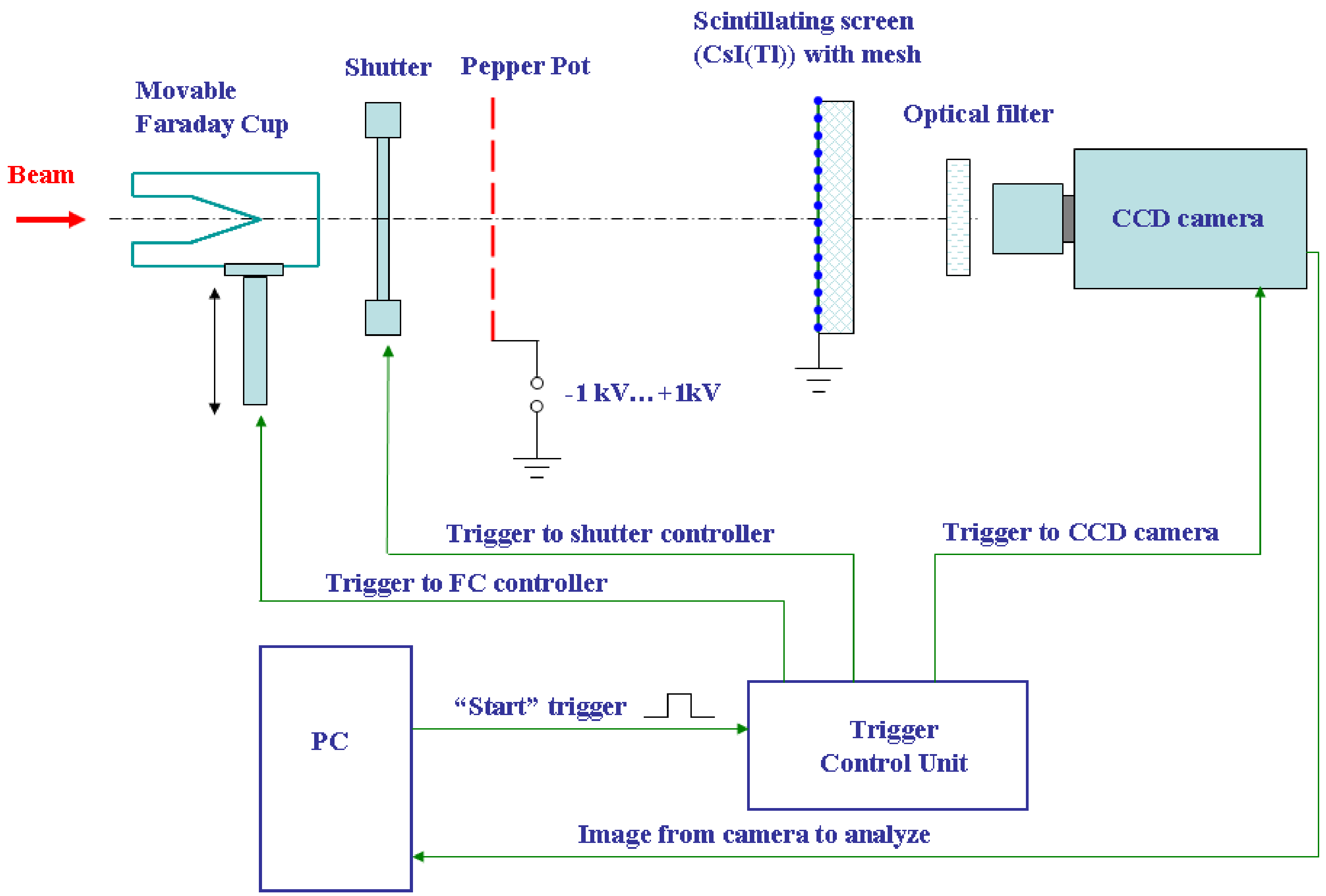
Almost no data available for typical ECRIS currents and energies

Possible choices:

- Phosphor screen: P11 (ZnS:Ag) was tested; sensitivity significantly dropped after about 1 min (total) irradiation by $^{209}Bi^{20+}$ ion beam with energy of 75 keV/charge and current density (at pepper pot plate) of about 2 µA/cm^2
- MCP-phosphor screen: restricted dynamic range of MCP, high cost, such option seems to be the only possible choice for very low intensities (≤ 1nA/cm^2)
- Scintillators: CsI(Tl) and YAG:Ce were tested; both have shown good sensitivity and life-time;

CsI(Tl) was chosen due to lower cost.

Emittance meter structure



Emittance meter structure (cont.)

- "Slow" shutter – FC with diameter 46 mm:

  - protection of "fast" shutter from damage by ion beam with power up to 10 W

  - measurements of ion beam current at the entrance of emittance meter

- "Fast" shutter - iris-type UNIBLITZ-CS65S with aperture 65 mm and minimum dwell time of 18 ms

  - protection of scintillator from degradation by long-time ion beam irradiation

- Pepper pot mask – Ta plate Ø 70 mm x 380 µm, 415 holes with diameters 100 – 104 µm and spacing 3 mm

- Scintillator – CsI(Tl), Ø 80 mm x 3 mm, grounded fine Nickel mesh with transparency 88.6% and cell size 200 µm is attached to scintillator front surface to prevent charge build-up caused by ion beam

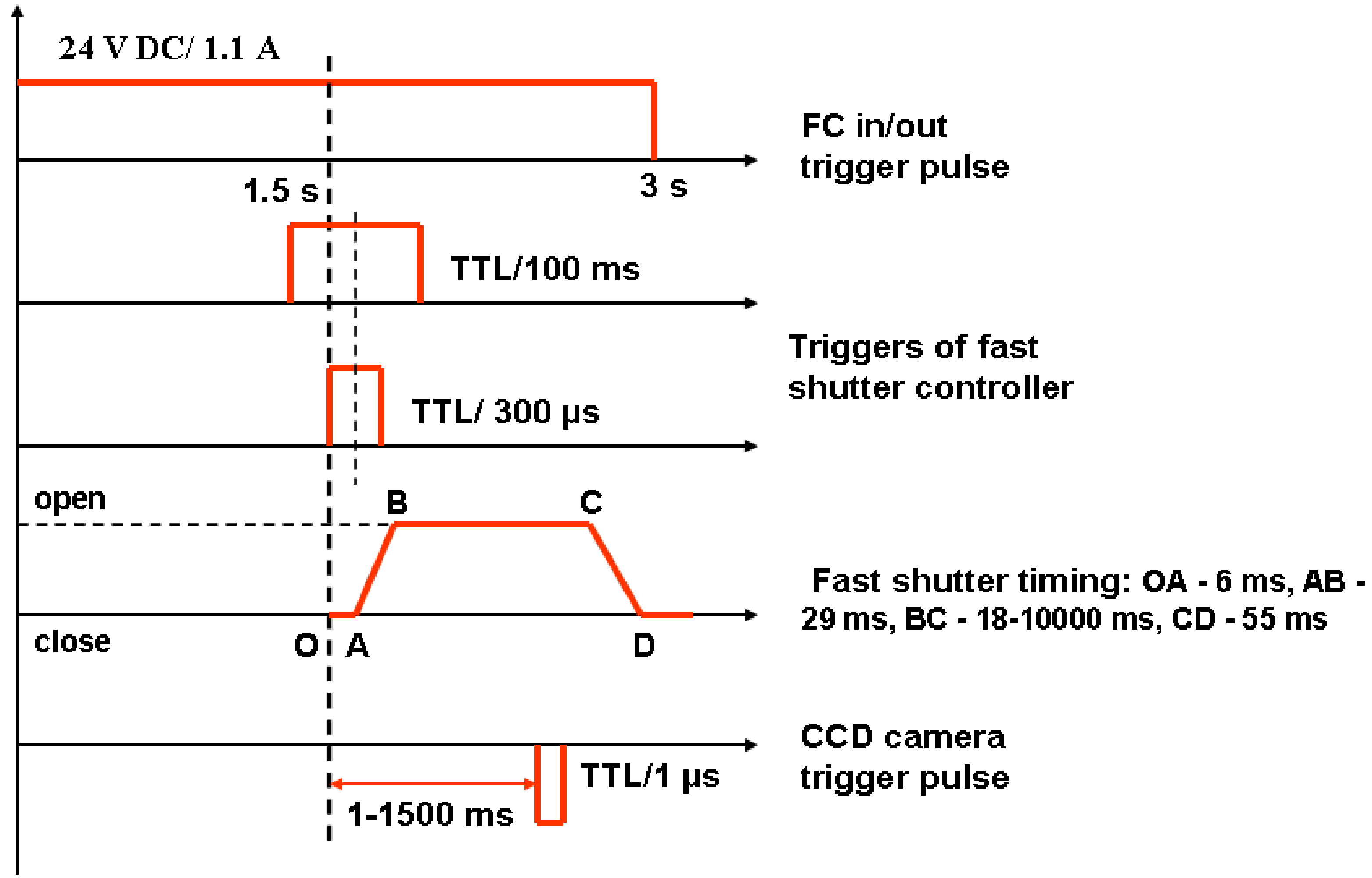
- CCD camera – 2 Mpix digital IMI TECH IMB-147FT 12-bit Firewire Monochrome:

  - pixel size – 4.6x4.6 μm^2

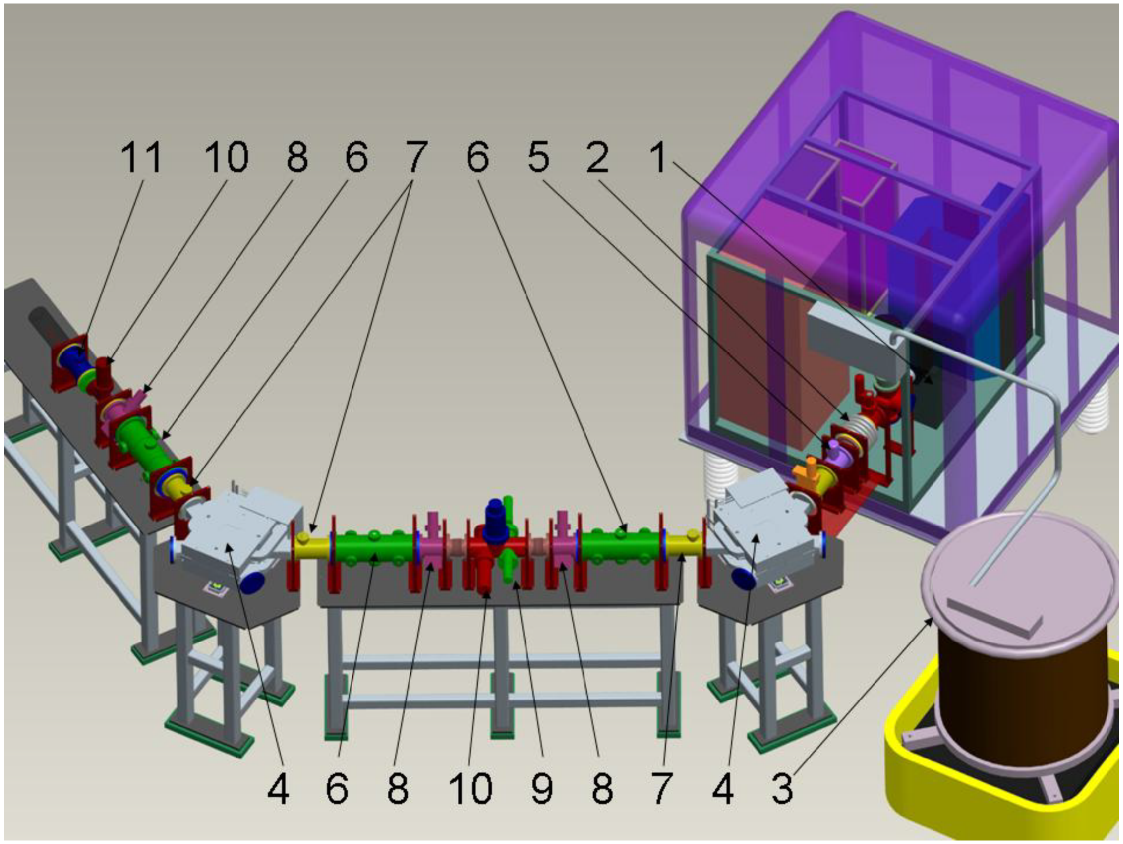
  - shutter speed – adjustable from 1 µs to 65 s

  - adjustable gain

Emittance meter timing



General view of ECR ion source and LEBT line



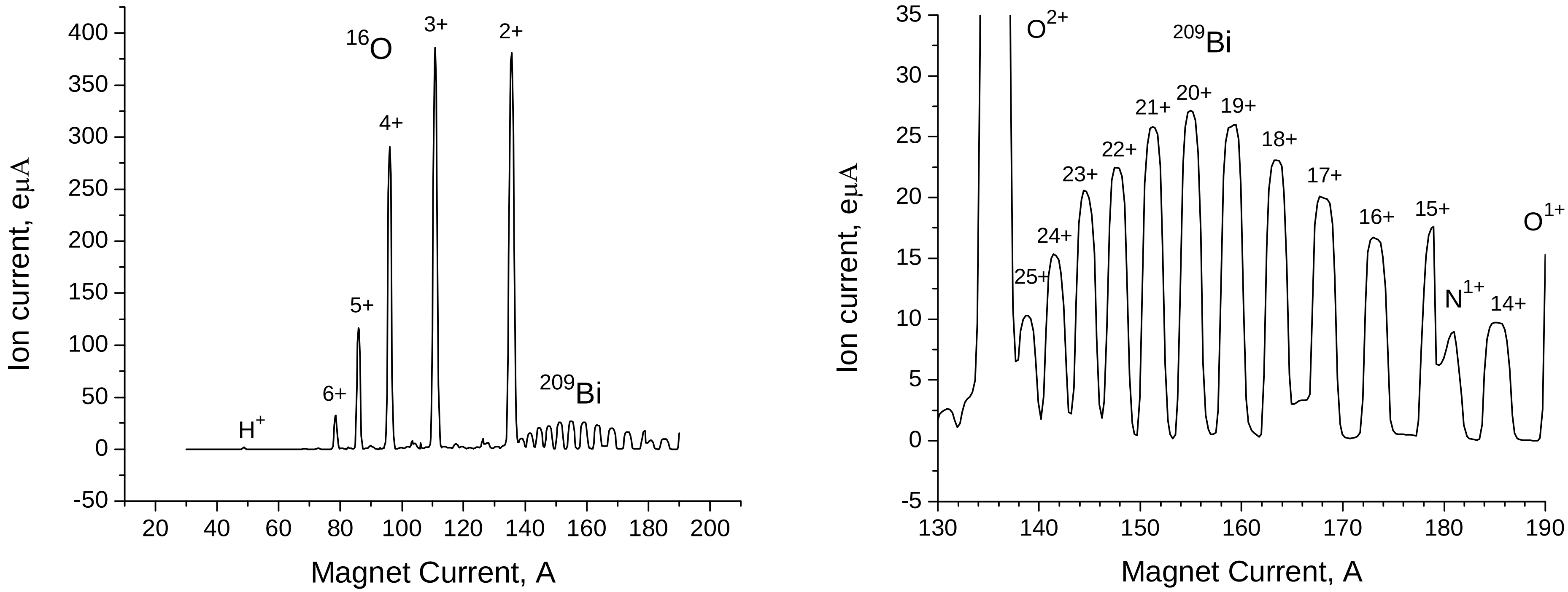
1 - All permanent magnet ECRIS installed on HV platform, 2 - 75-kV accelerating tube, 3 - isolation transformer, 4 - 60° bending magnet, 5 - Einzel lens, 6 - electrostatic quadruple triplet, 7 - electrostatic steers, 8 - rotating wire scanner, 9 – moveable horizontal slits, 10 – moveable Faraday cups, 11- emittance meter

Parameters of BIE-100 All Permanent Magnet ECR Ion Source*

- Axial peak field (injection region) – 13 kG
- Axial field at extraction – 6.6 kG
- Axial central magnetic field – 4.2 kG
- Maximum radial field (at chamber wall) – 11 kG
- Aluminum plasma chamber: length – 17.5 cm, diameter – 6.4 cm
- Extraction aperture – 8 mm
- Heating: 2 kW/14 GHz klystron + 700 W/12.75-14.5 GHz TWT RF amplifier
- Extraction potential – up to 25 kV
- HV platform potential – up to 75 kV

*D. Z. Xie. Rev. Sci. Inst. v. 73 (2), 2002, pp. 531 – 533.

Currents of ions with different masses and charge states



- ^{209}Bi ions were produced using oven method
- Oxygen used as support gas to enhance intensity of Bi highly charged ions
- Current of Bi^{17+} - Bi^{23+} ions – 1 – 1.5 pμA

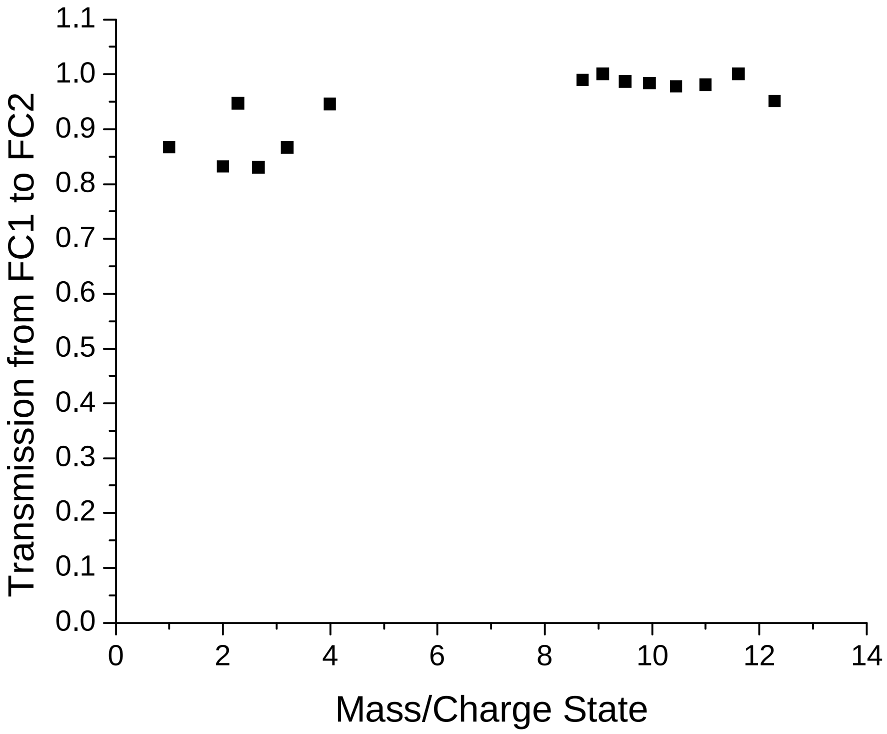
Transmission from source exit to emittance meter

El.	Hydrogen		Oxygen						Bismuth											
Ion	1+	2+	7+	6+	5+	4+	3+	2+	25+	24+	23+	22+	21+	20+	19+	18+	17+	16+	15+	14+
I, μA	2	0.6	1.0	32	118	292	387	378	10	15	21	23	26	27	26	23	20	17	12	10

- Total current of Oxygen ions (FC1) – 1.56 mA
- Total current of Bismuth ions (FC1) – 0.23 mA
- Total current of all ion species (FC1) – 1.8 mA
- Total current extracted – 3.8 mA

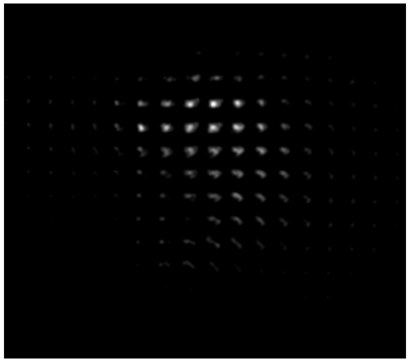
Transmission from source exit to FC1 – 47%

Transmission from source exit to emittance meter – 40 – 47 %



Processing of pepper pot image: software input

O^{5+}, 113.5 µA/375 keV



- Pepper-Pot system parameters:

 - Number of X and Y holes and their spacing

 - Distance between the Pepper-Pot plate and the scintillator screen

- Camera calibration: This was done using a pepper pot irradiation by external light source. The ratio of the distance between two holes to the number of pixels separating their images on the camera is the calibration factor in mm/pixel.
- The analysis procedure is automatic and does not involve a manual selection of hole images (peaks). Additional information to help guide the analysis procedure is needed:
- - Peak noise level: peaks below this level are ignored
- - Max/Min distance between two consecutive peaks
- - Max/Min difference in amplitude between two consecutive peaks

Steps of the pepper-pot image analysis procedure

- Read in image data: both 8-bit BMP and 16-bit PNG files are supported
- Produce the X and Y profile by integrating over the other dimension.
- Find peaks in a profile: An input peak noise level is used as well as the Max/Min distance between peaks and the Max/Min difference in peaks amplitudes.
- The noise level in a profile is determined by averaging the content of both edges of the real signal.
- The hole-peak assignment is performed assuming that both the pepper-pot plate and the camera are centered on the beam axis. An optional shift of the assignment is possible using additional input.
- Based on the hole-peak assignment, the position u and angle u' is determined for every pixel of the real signal in a profile.

Calculation of the beam emittance and twiss parameters

- Pixel data is used for the statistical calculation instead of the peak data for better accuracy

- For every pixel “i” of the profile we know the position u(i), the angle u’(i) and the content (intensity) w(i)

- We first compute the average values: <u>, <u’>, <uu>, <uu’>, <u’u’> then the sigma values: σ(u,u), σ(u’,u’) and σ(u,u’):

$$\langle u\rangle = \frac{\sum_i u_i * w_i}{\sum_i w_i}; \quad \sigma(u,u) = \langle u^2\rangle - \langle u\rangle^2; \quad \sigma(u',u') = \langle u'^2\rangle - \langle u'\rangle^2; \quad \sigma(u,u') = \langle uu'\rangle - \langle u\rangle\langle u'\rangle$$

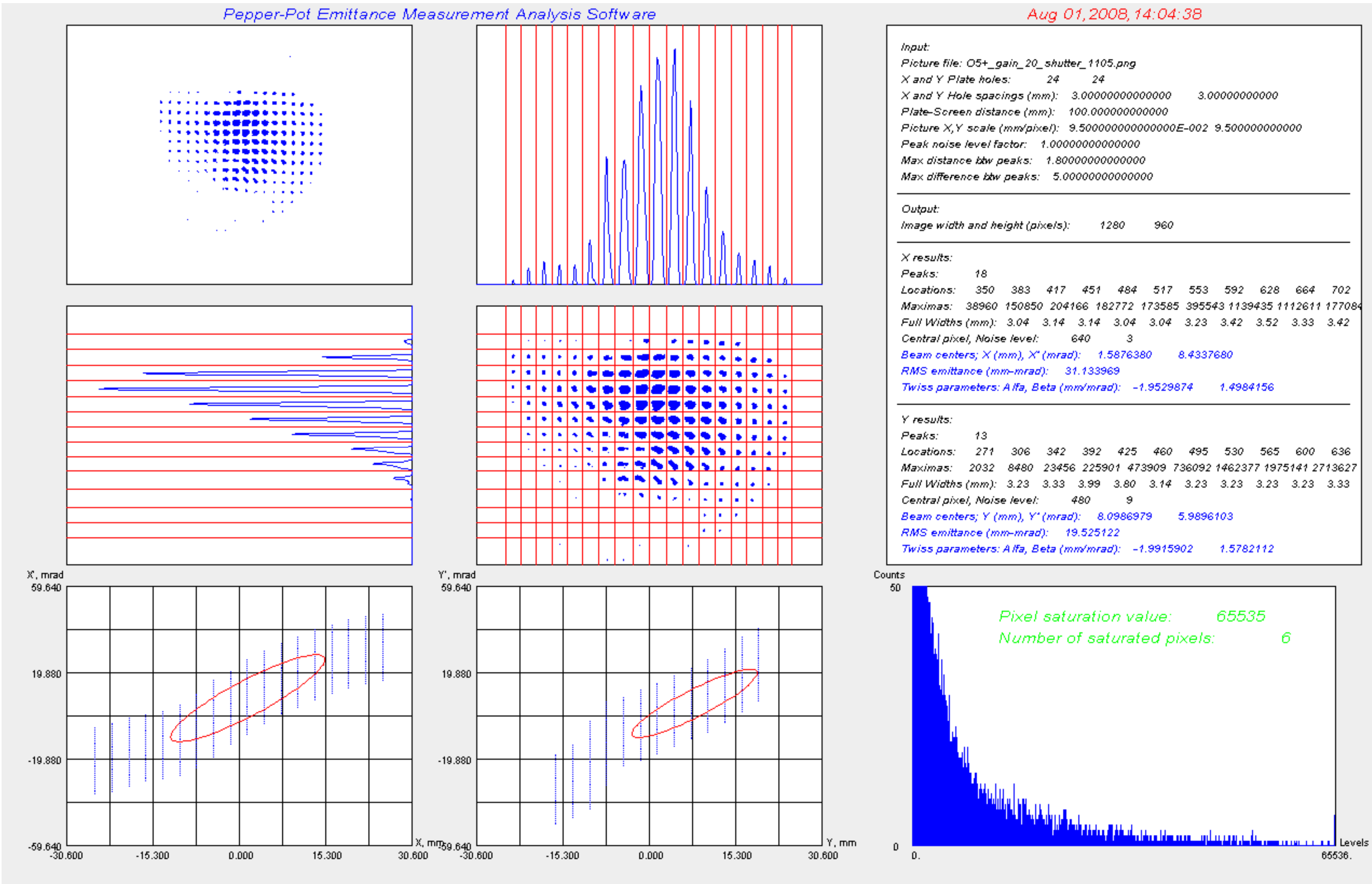
- The RMS beam emittance is then determined using the expression:

$$\varepsilon(u,u') = \sqrt{\sigma(u,u) * \sigma(u',u') - \sigma(u,u')^2}$$

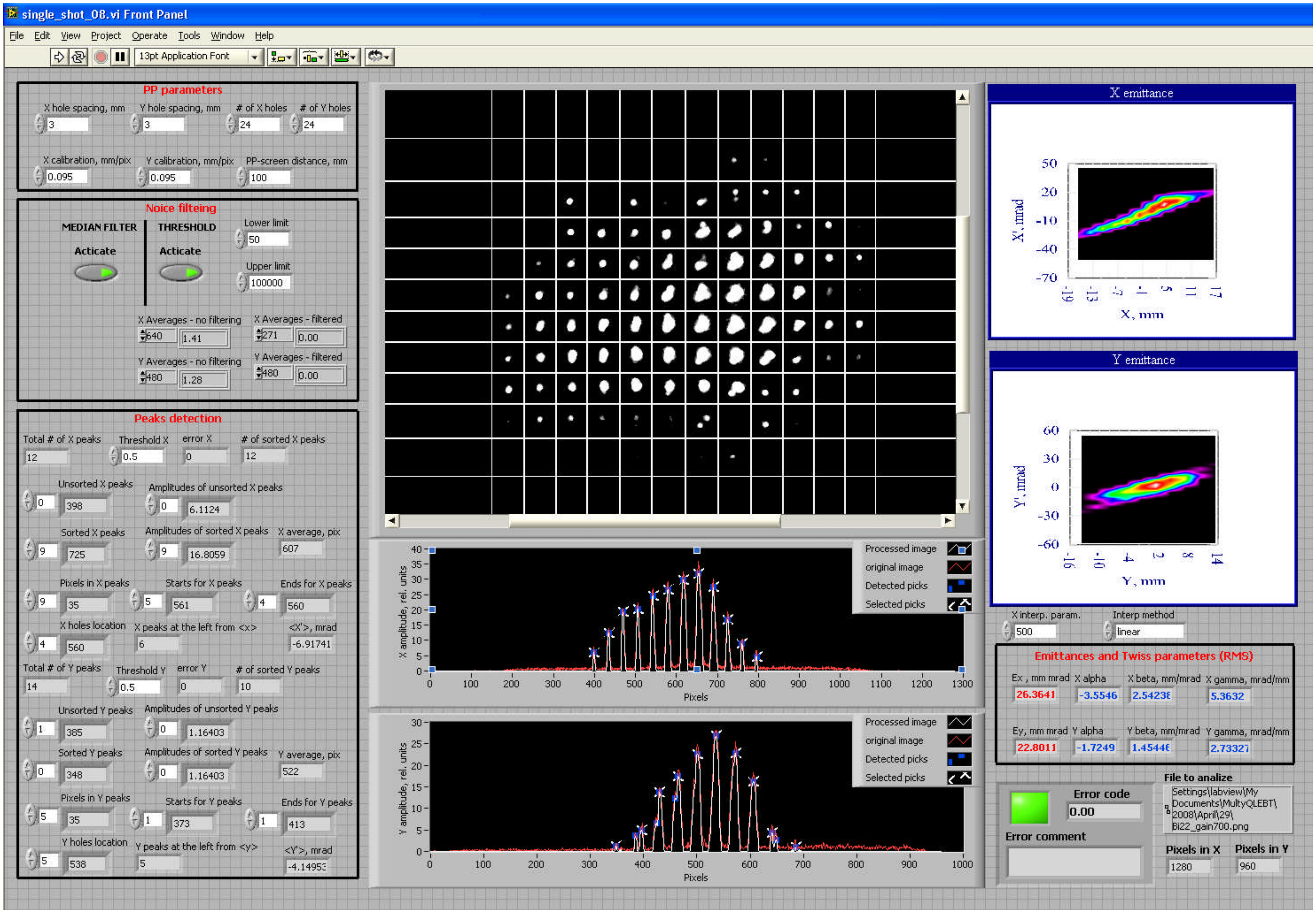
- The Twiss parameters are then determined using:

$$\alpha(u,u') = -\frac{\sigma(u,u')}{\varepsilon(u,u')}; \qquad \beta(u,u') = \frac{\sigma(u,u)}{\varepsilon(u,u')}; \qquad \gamma(u,u') = \frac{\sigma(u',u')}{\varepsilon(u,u')}$$

Pepper pot image analysis software



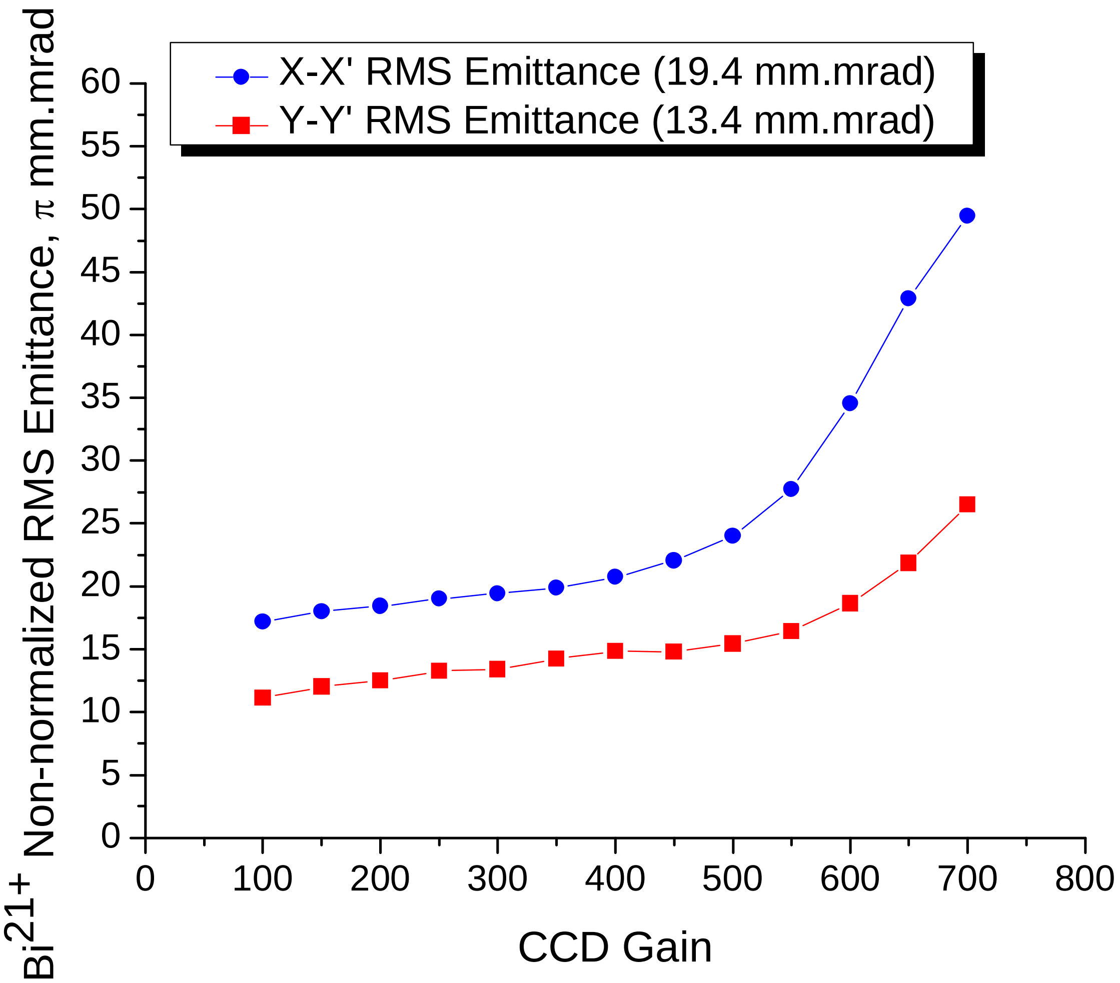
LabVIEW based software for on-line measurements



Emittance analysis software

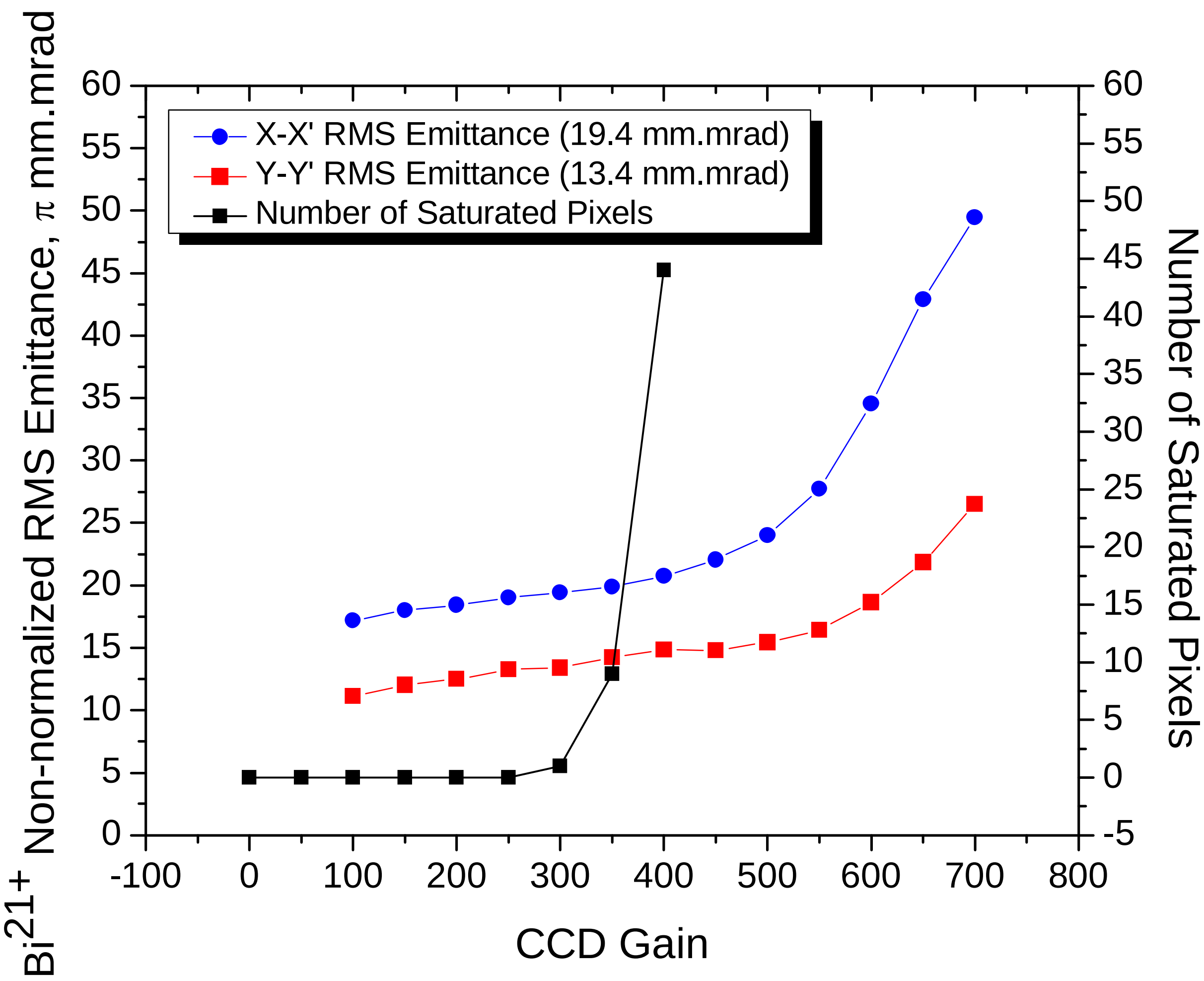
- Both versions of emittance analysis software developed and used are 2D analysis software (x-x’ and y-y’ projections of full x-x’-y-y’ 4D phase space are supposed to be independent of each other and be able completely describe phase space distribution)
- It is not true for ECRIS ion beams - 2D (x-x’ and y-y’) emittance can not completely describe complicated phase space distributions (for example, in many cases x’ depends on y and y’ depends on x)
- 4D (x-x’-y-y’) emittance analysis software and the best way of results presentation should be developed to take full advantage of 4D pepper pot emittance meter

Choice of CCD camera parameters



Which value is “true” emittance value?

Choice of CCD camera parameters (cont.)

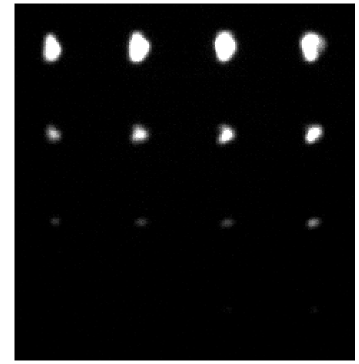


Criteria applied to all emittance measurements – number of saturated pixels between 1 and 10!

Does CsI (Tl) scintillator have linear response?

Calibration pepper pot mask was used to check CsI (Tl) linearity:

- 4x4 array of holes with diameters 10 μm, 20 μm to 300 μm (20 μm step)
- 5 mm spacing between holes



If $D_{hole} << D_{image}$, D_{image} will be defined by emittance of ion beam and should be approximately the same for all holes.

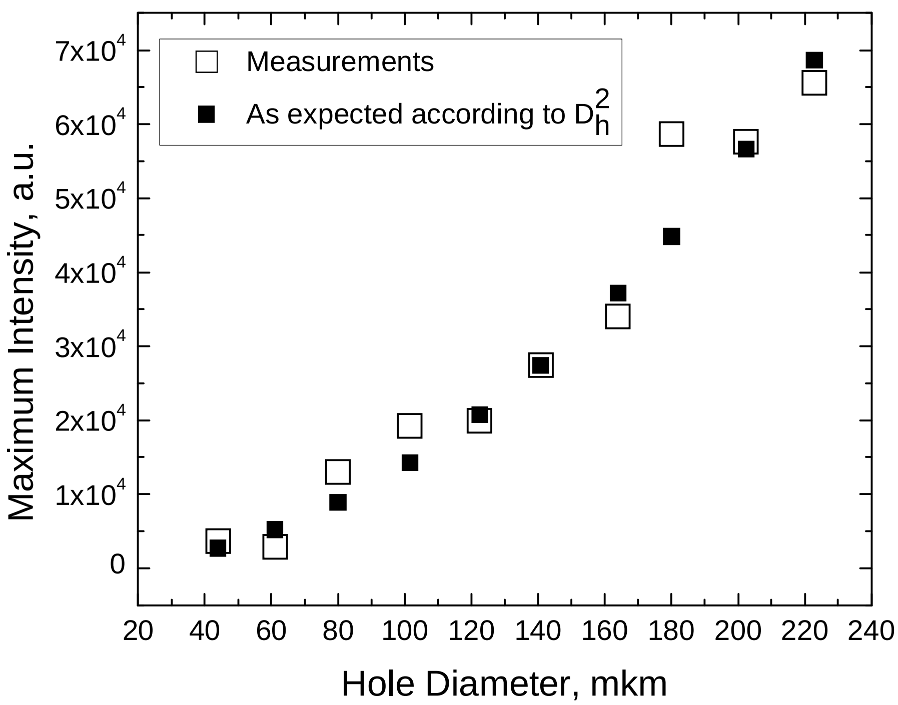
Then, if beam has homogeneous current distribution across 15x15 mm2 area, ion current at scintillator is proportional to $(D_{hole})^2$.

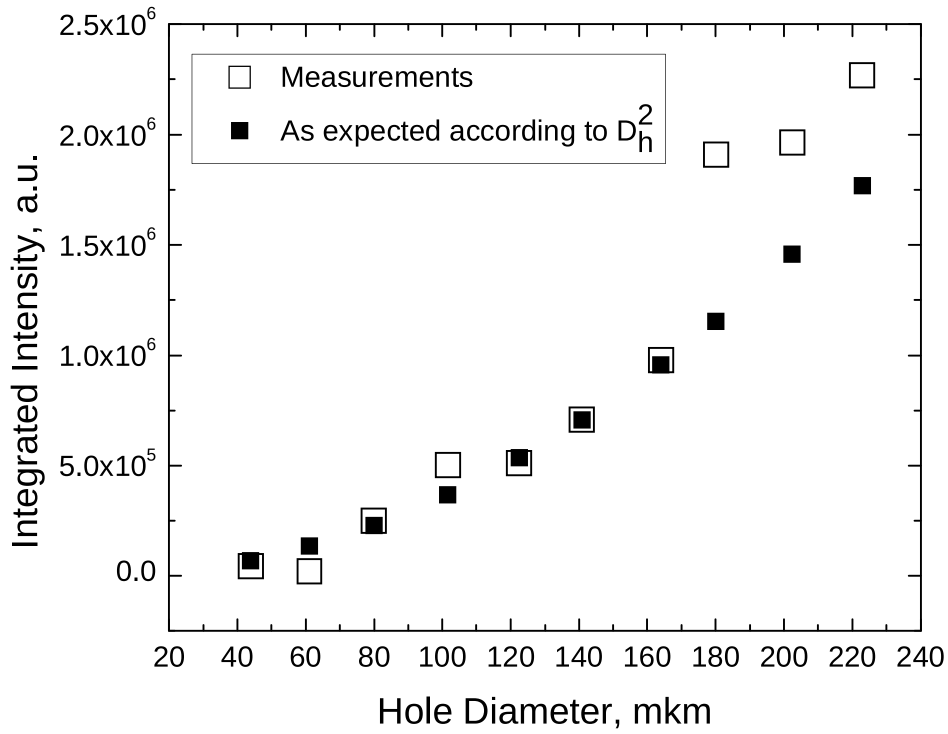
If scintillator has linear response, light output should follow this relation too.

The main challenge of this approach is very big spatial fluctuations of ion beam intensity – 3 – 10 times over 15x15 mm^2 for focused ion beams of different ion species.

It was improved to about 40 - 50% by switching off all electrostatic quads along LEBT (total ion current dropped by about factor 5).

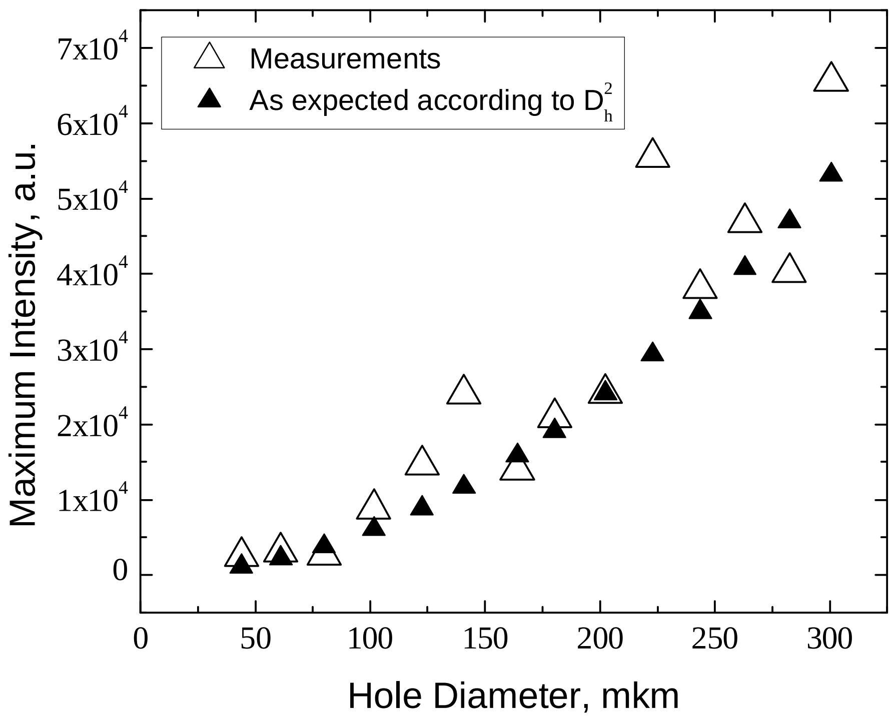
Does CsI (Tl) scintillator have linear response? (cont.)

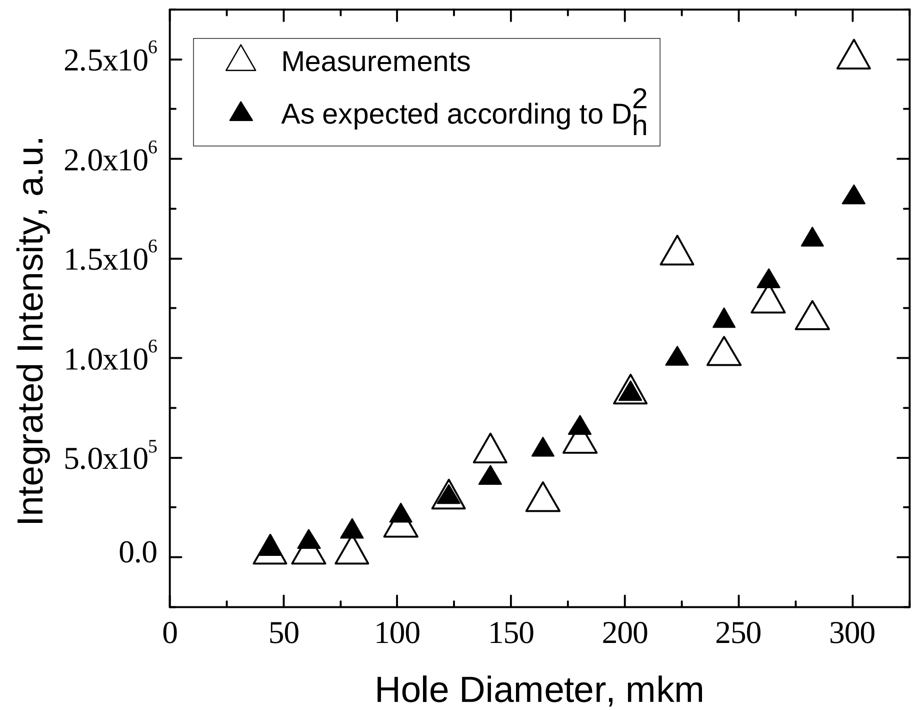




O^{6+} ion beam, energy – 450 keV, current density (at pepper pot plate) – 0.24 μA/cm^2

Does CsI (Tl) scintillator have linear response? (cont.)

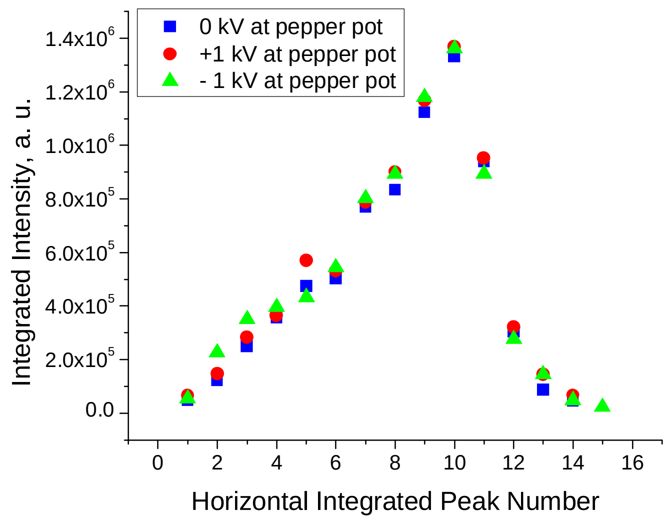


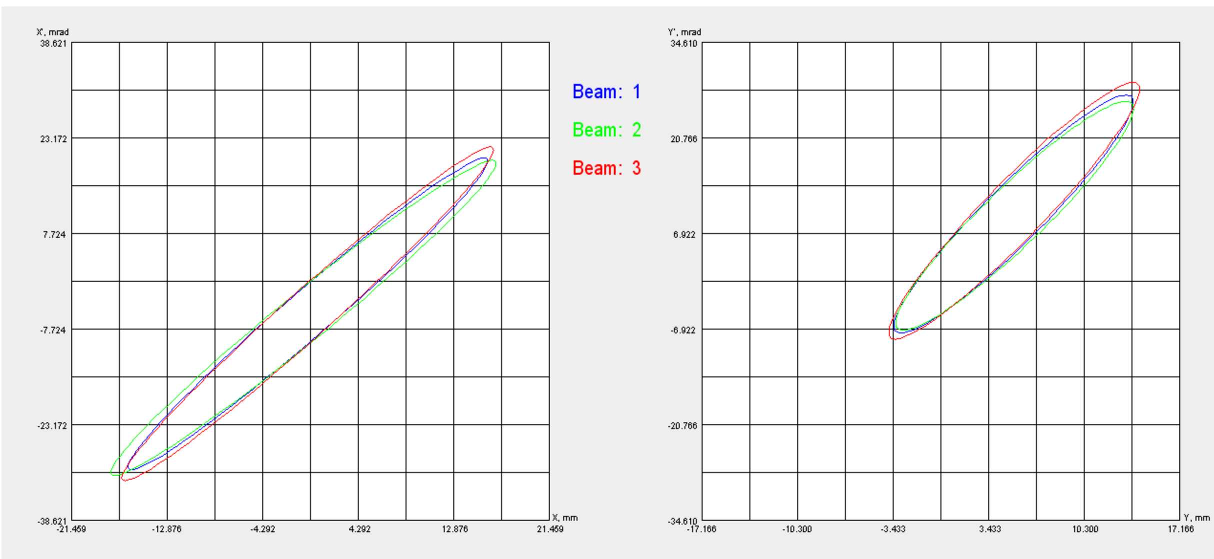


Bi^{20+} ion beam, energy – 1.5 MeV, current density (at pepper pot plate) – 0.4 µA/cm^2

CsI (Tl) scintillator dynamic range – better than 50

Influence of pepper pot plate potential on measured emittance





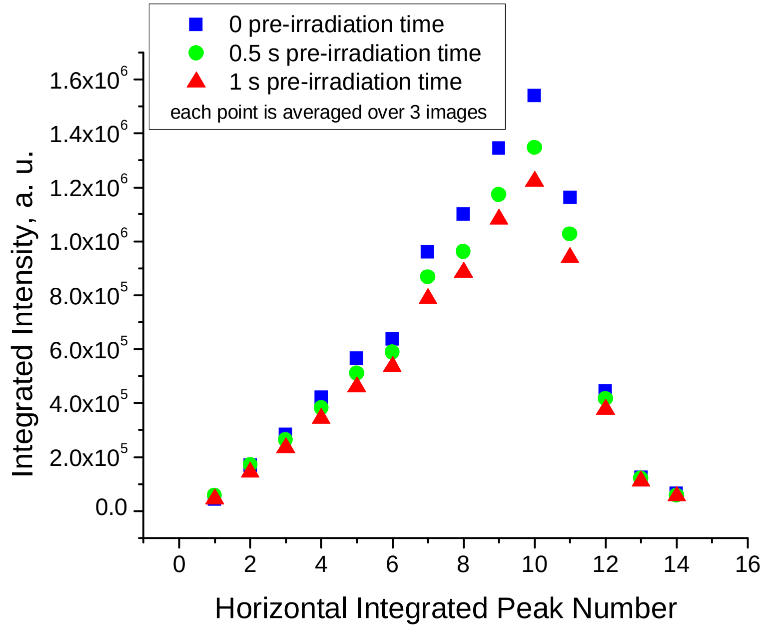
5 RMS emittance ellipses ($^{209}Bi^{20+}$ with energy 75 keV/charge state):

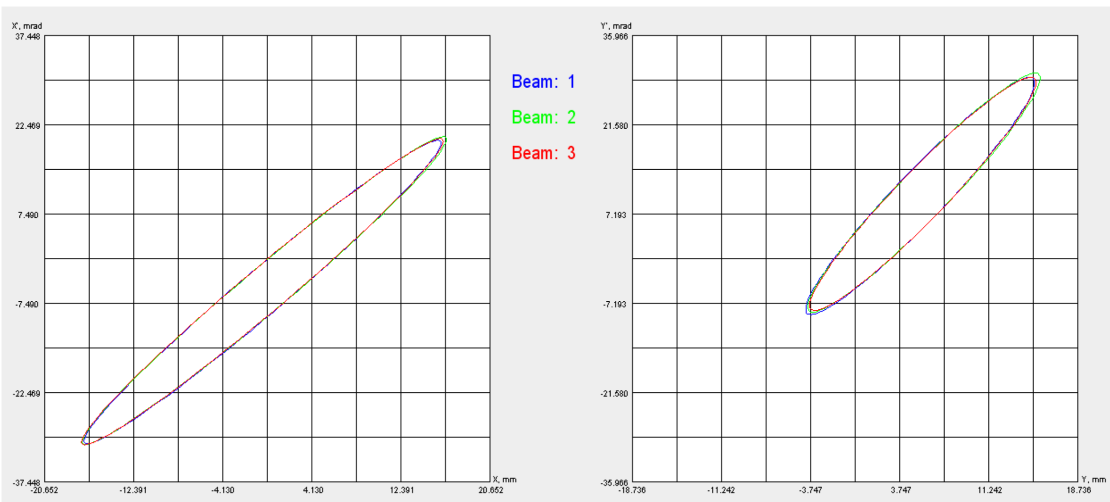
blue line – 0 kV at pepper pot plate,

green line - -1 kV,

red line - +1 kV

Influence of scintillator pre-irradiation time on measured emittance





5 RMS emittance ellipses ($^{209}Bi^{20+}$ with energy 75 keV/charge state):

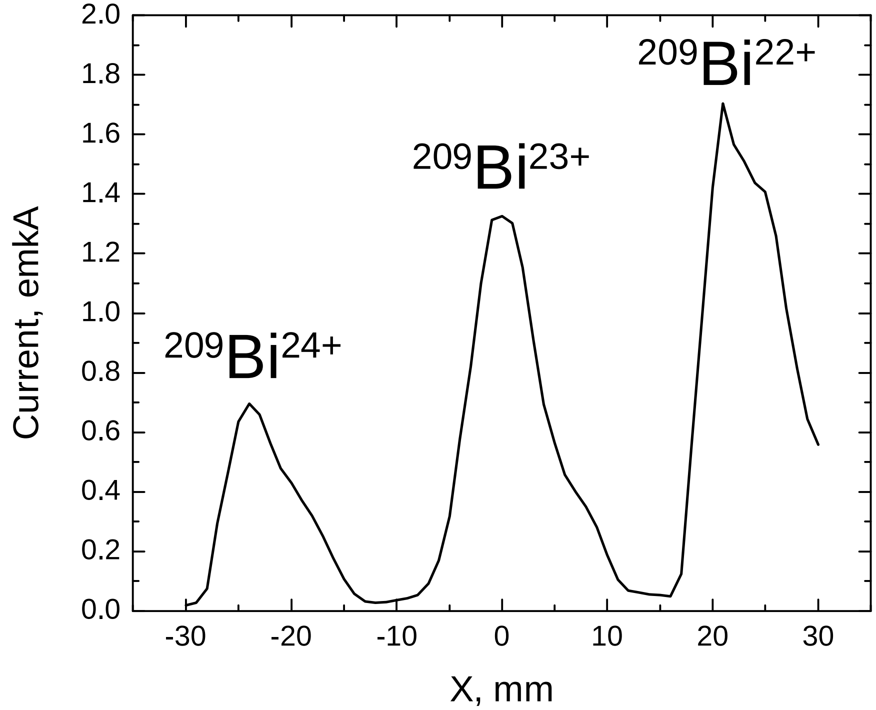
blue line – 0 s pre-irradiation time

green line – 0.5 s

red line - 1 s

Emittance measurements for different ion species

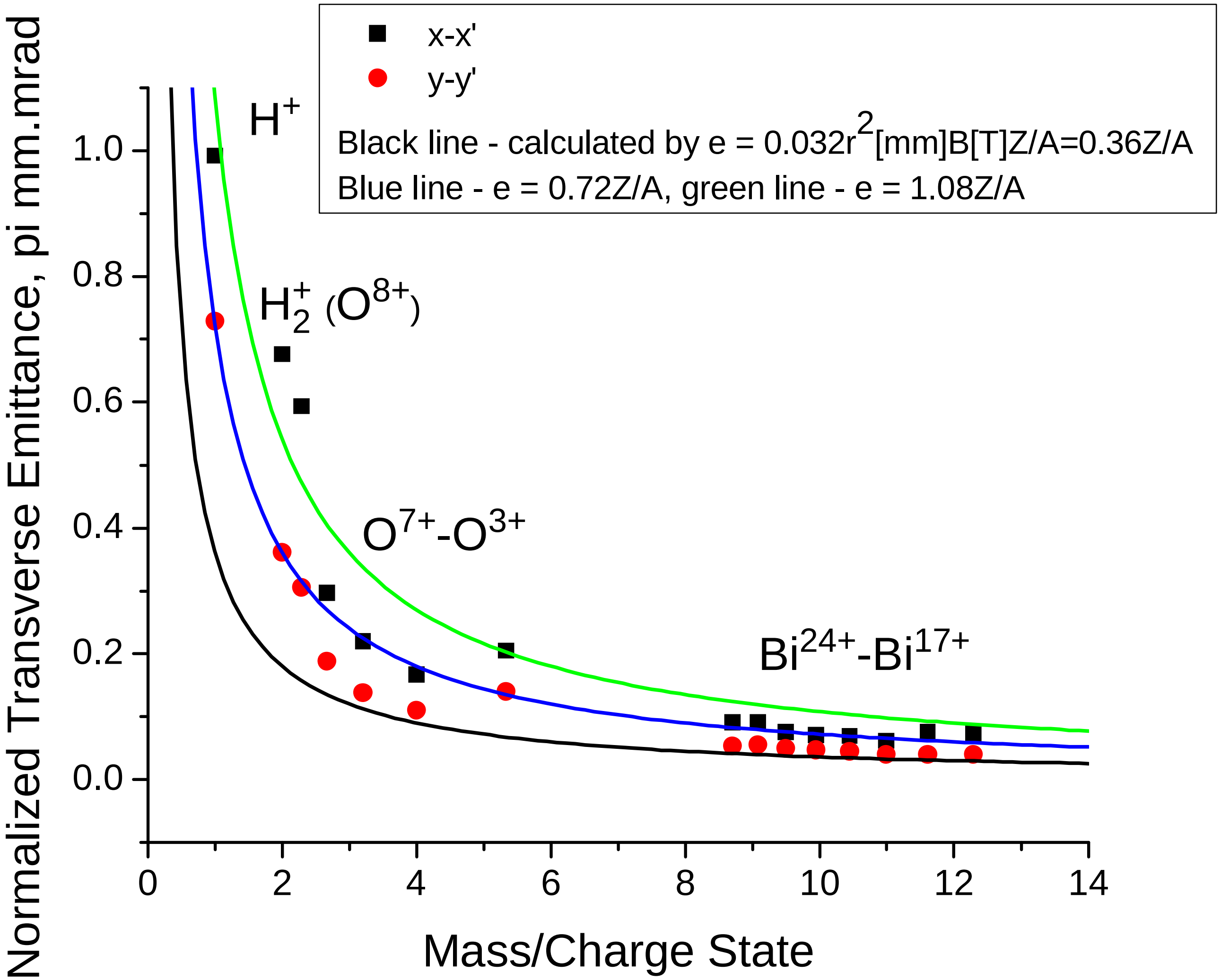
- For each ion specie beam was centered by adjusting both bending magnets
- Slits were scanned for each ion specie



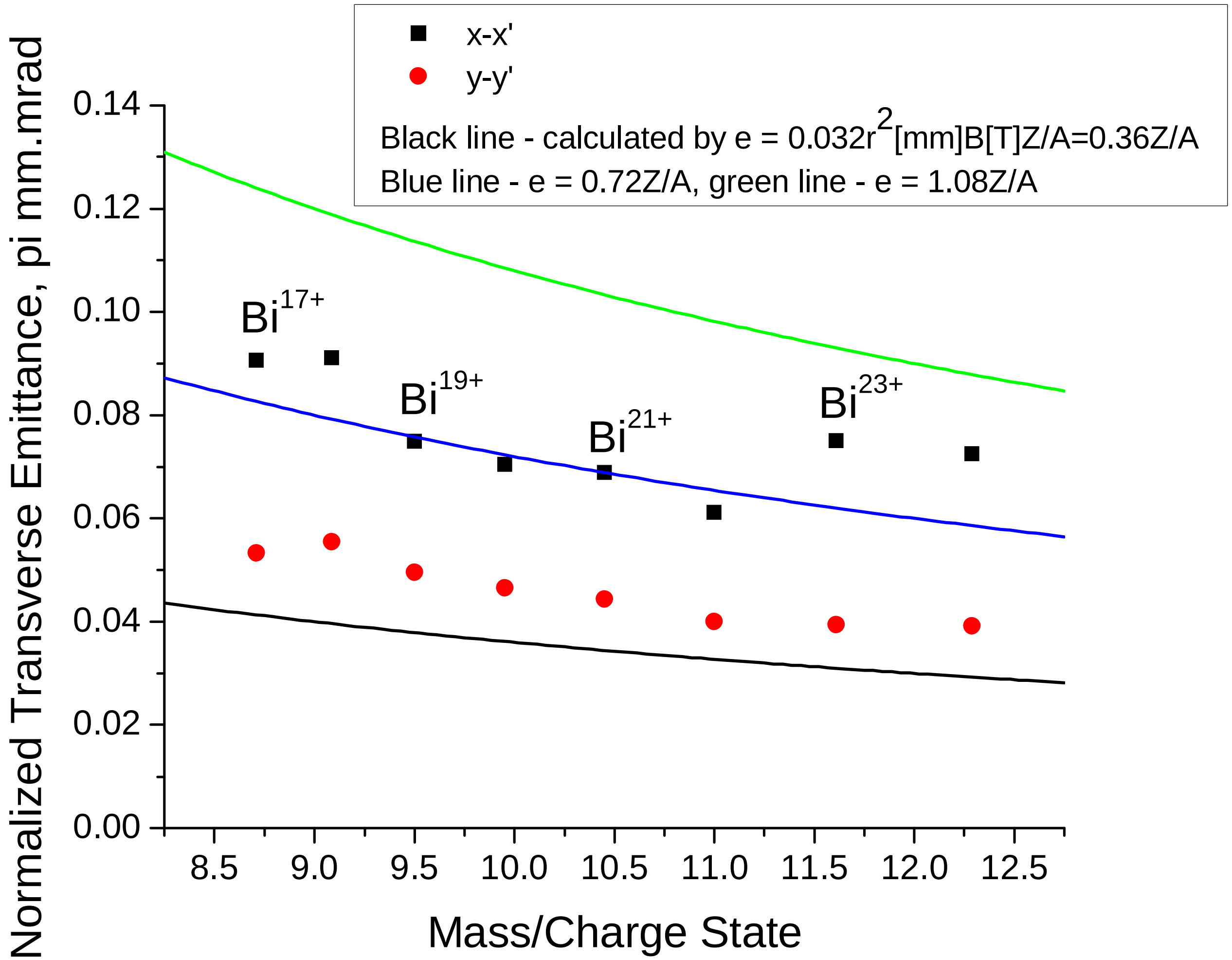
Resolution was better for all other ion species

- Horizontal slits between bending magnets were adjusted to cut single ion specie
- Transmission from source exit to emittance meter – 40 – 47% for all ion species

Emittance measurements for different ion species (cont.)



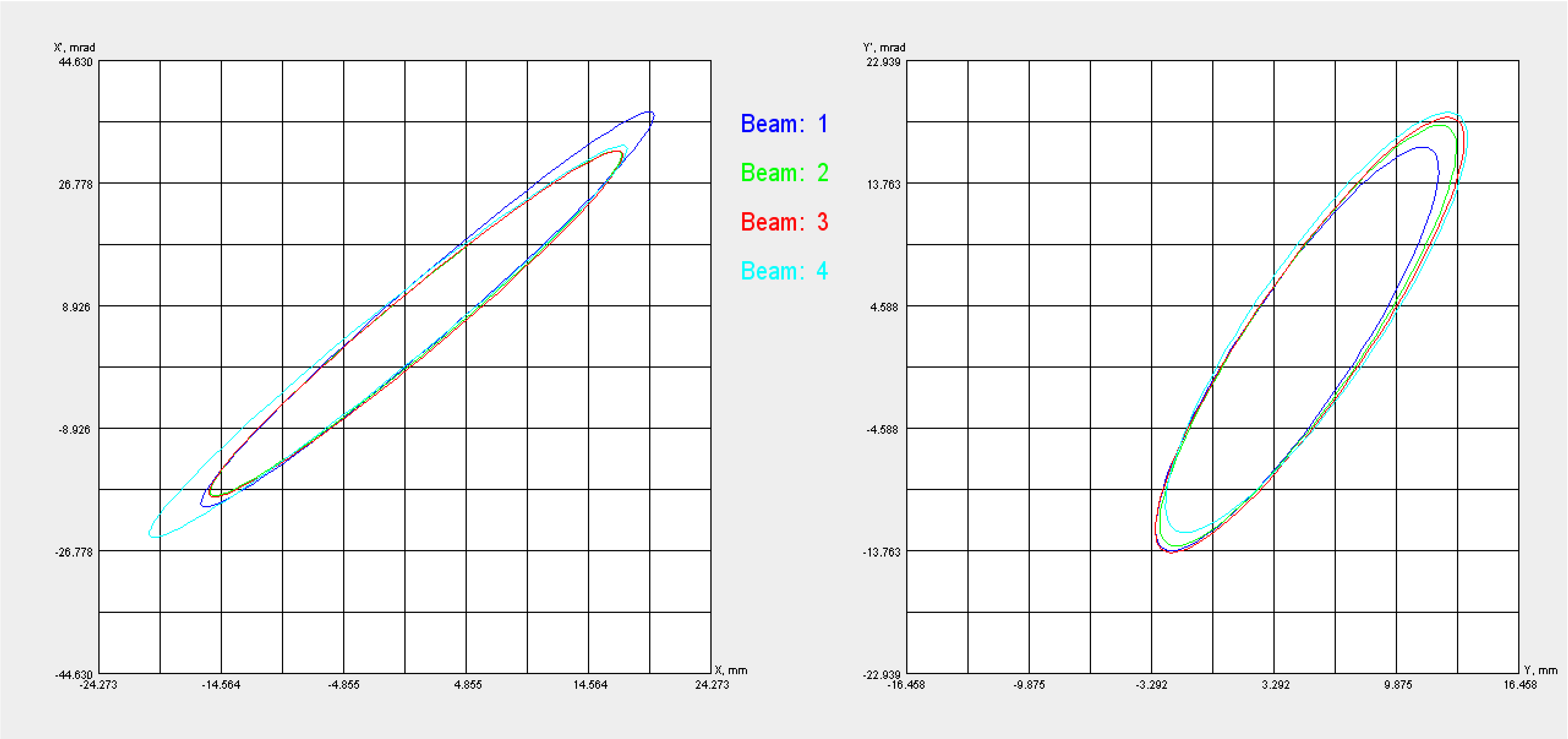
Emittance measurements for different ion species (cont.)



Emittance measurements for different ion species (cont.)

- x-x' emittance is higher than y-y' emittance for all ion species, probably, due to:
  - higher x-x' acceptance of the first bending magnet
  - asymmetric ion beam distribution at ECR exit
- Dependence of emittance on M/Z ratio qualitatively well follows the dependence of emittance due to beam rotation induced by decreasing ECR axial magnetic field
- Emittance values are 1.2 - 3.2 times higher than emittance due to beam rotation induced by decreasing ECR axial magnetic field; it means that ion temperature in plasma, non-homogeneous extraction electric field, non-linear space charge contributions to emittance are comparable or even higher than contribution of beam rotation induced by decreasing ECR axial magnetic field
- Emittance increases with increasing of charge state for both oxygen and bismuth ions

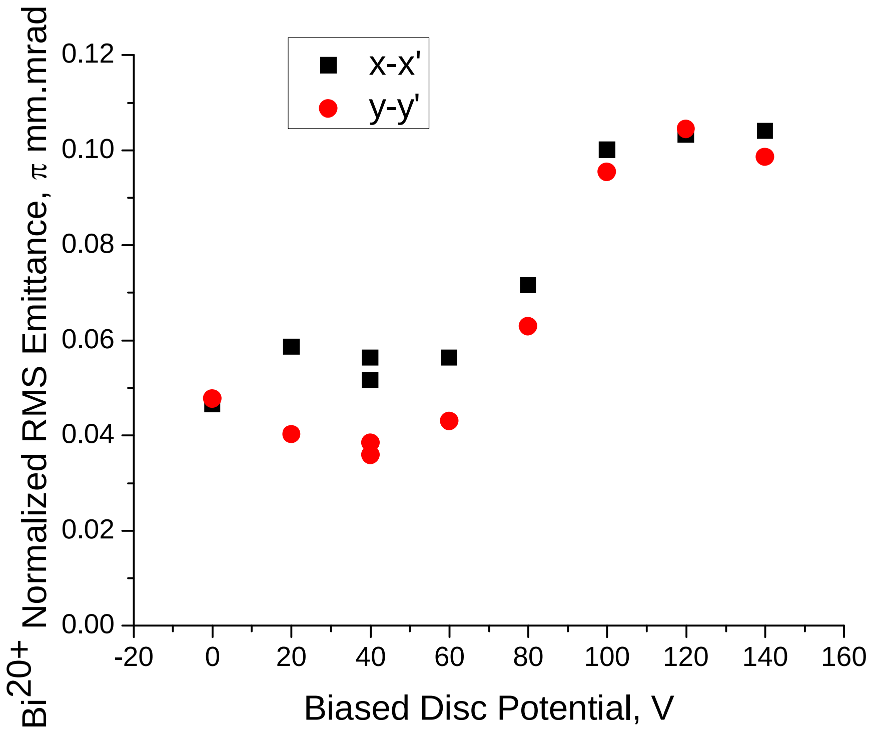
Emittance measurements for different ion species (cont.)

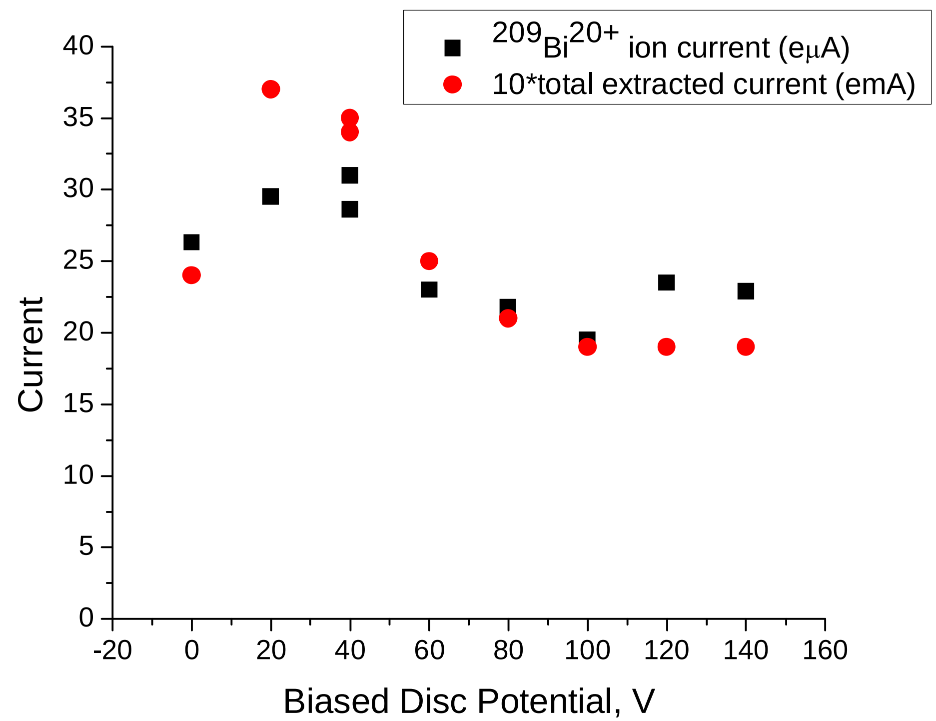


5 RMS emittance elipses: $^{209}Bi^{18+}$, $^{209}Bi^{20+}$, $^{209}Bi^{22+}$, $^{209}Bi^{24+}$

Energy - 75 kV/charge state

Dependence of emittance on biased disc potential





- Brightness of $^{209}Bi^{20+}$ is maximal for -40 V biased disc potential
- $E_{x\text{-}x'}/E_{y\text{-}y'}$ depends on biased disc potential

Summary

- 4D pepper pot – scintillator (CsI (Tl)) on-line emittance meter was developed and used to study emittance of DC ion beams extracted from ECR ion source

- A special attention was paid to linearity of registration system:

  - no saturation of CsI(Tl) light output was found for ion current densities typical for ECR ion sources

  - emittance measurement errors can be minimized by choosing CCD camera gain and shutter speed just at the boundary of CCD saturation

- Emittance of all ion species extracted from ECRIS was measured:

  - Dependence of emittance on M/Z qualitatively very well follows the dependence of emittance due to beam rotation induced by decreasing ECR axial magnetic field

  - Measured emittance values can not be explained by ion beam rotation only for all ion species and contribution to emittance of ion temperature in plasma, non-linear electric fields and non-linear space charge is comparable or even higher than contribution of ion beam rotation

  - Emittance increases with increasing of charge state for both oxygen and bismuth ions

  - Emittance and brightness can be optimized by biased disc potential