Tomography for beams with intense space charge

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Motivation

The requirement:

Many applications need well regulated beams with high intensity and low emittance

The challenge:

Beams are born at low-energies where space charge forces are an issue

- Can cause emittance growth
- Halo formation possible
- Propagating waves

Approach

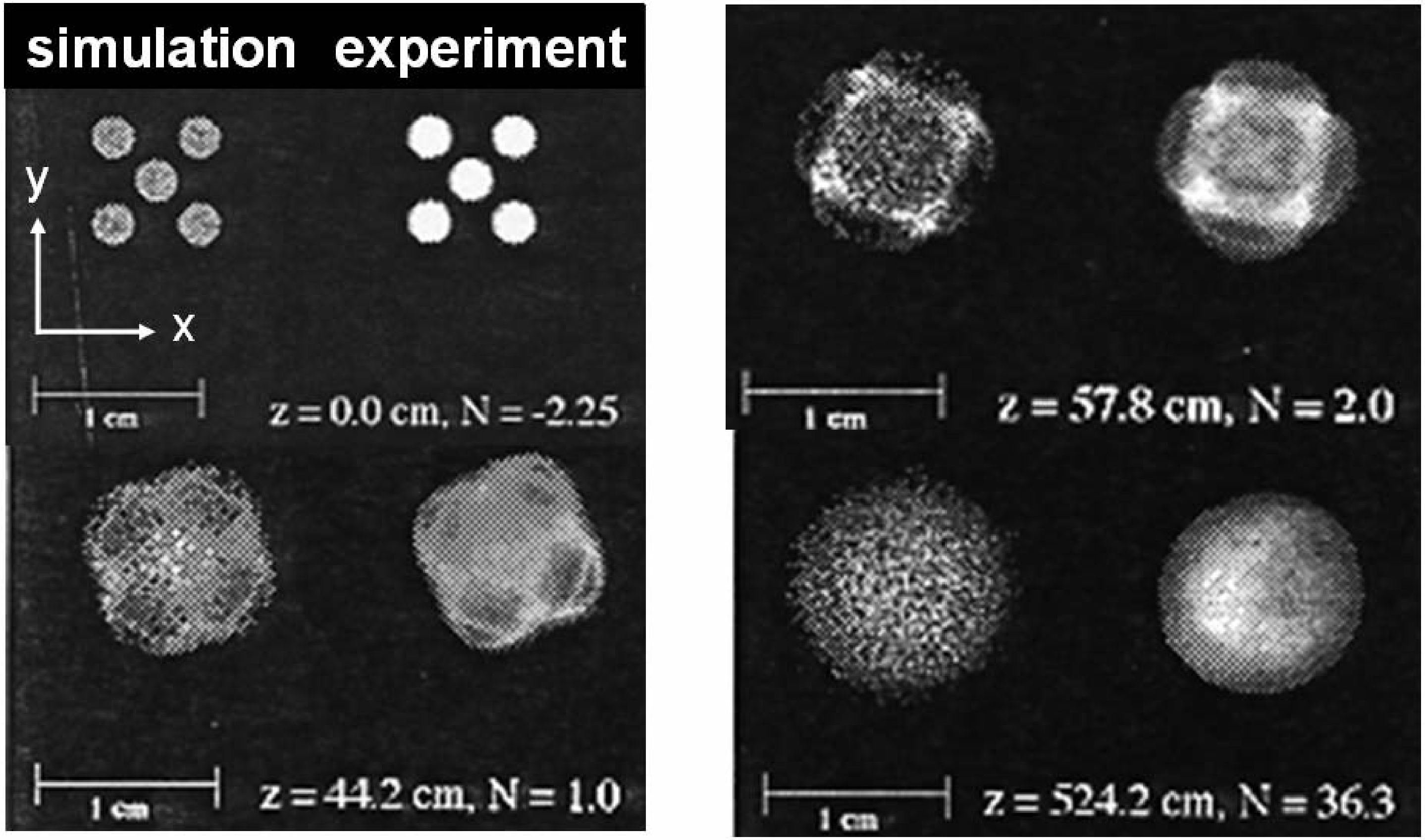
- To understand space charge we need an accurate phase space diagnostic
- Tomography is a good candidate, but to date, has been used only for beams with little space charge
- <u>This study</u> further develops and uses tomography for beams with intense space charge

Outline

1. Example
2. History/Overview
3. Extension to Beams with Space Charge
4. Simulation/ Validation of Tomography
5. Experimental Results

Motivation Example

- Multi-Beamlet Merger

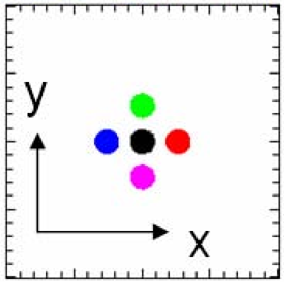


Haber, Kehne, Reiser and Rudd, Physical Review A (1991)

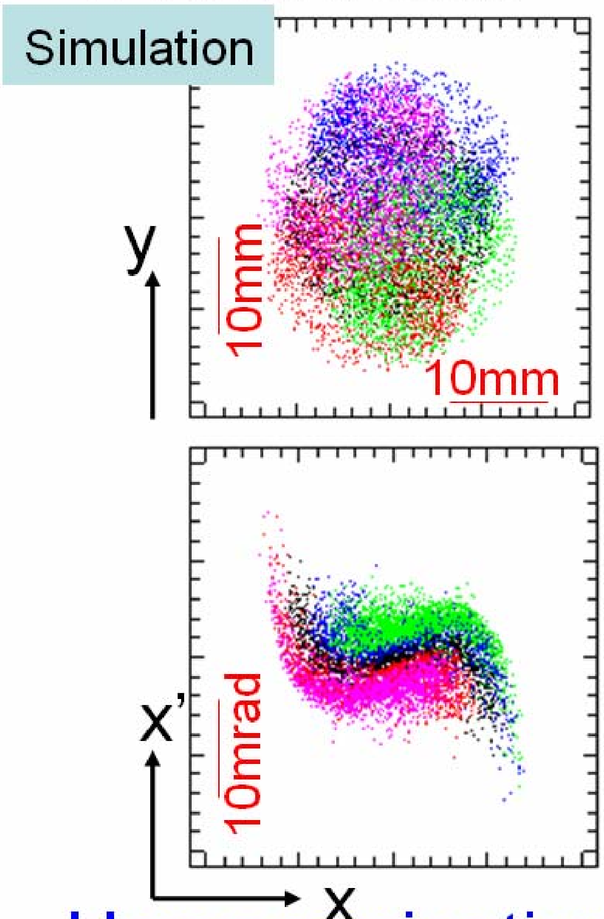
- What happens in phase space?

Importance of Phase Space

- Initial distribution



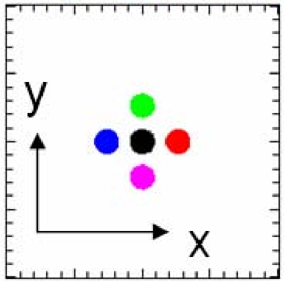
- Downstream



- Homogenization of a beam is different in configuration and phase space

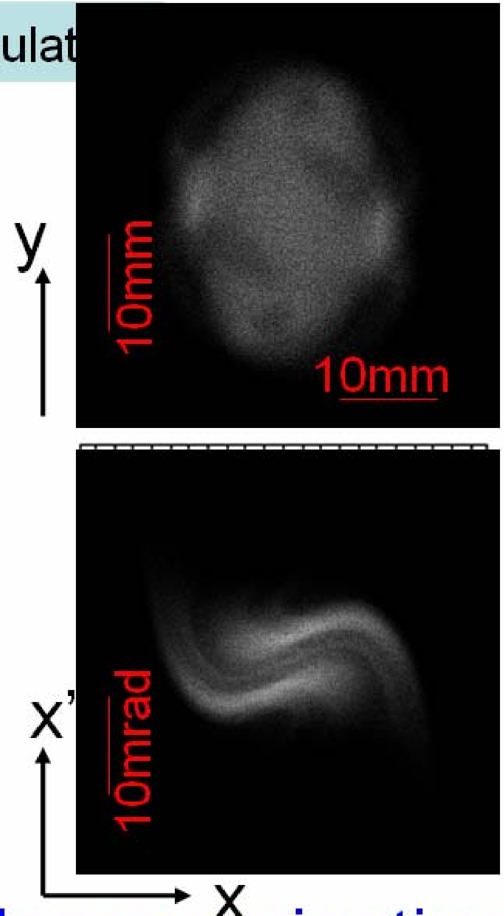
Importance of Phase Space

- Initial distribution



- Downstream

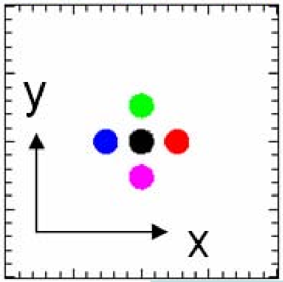
Simulat



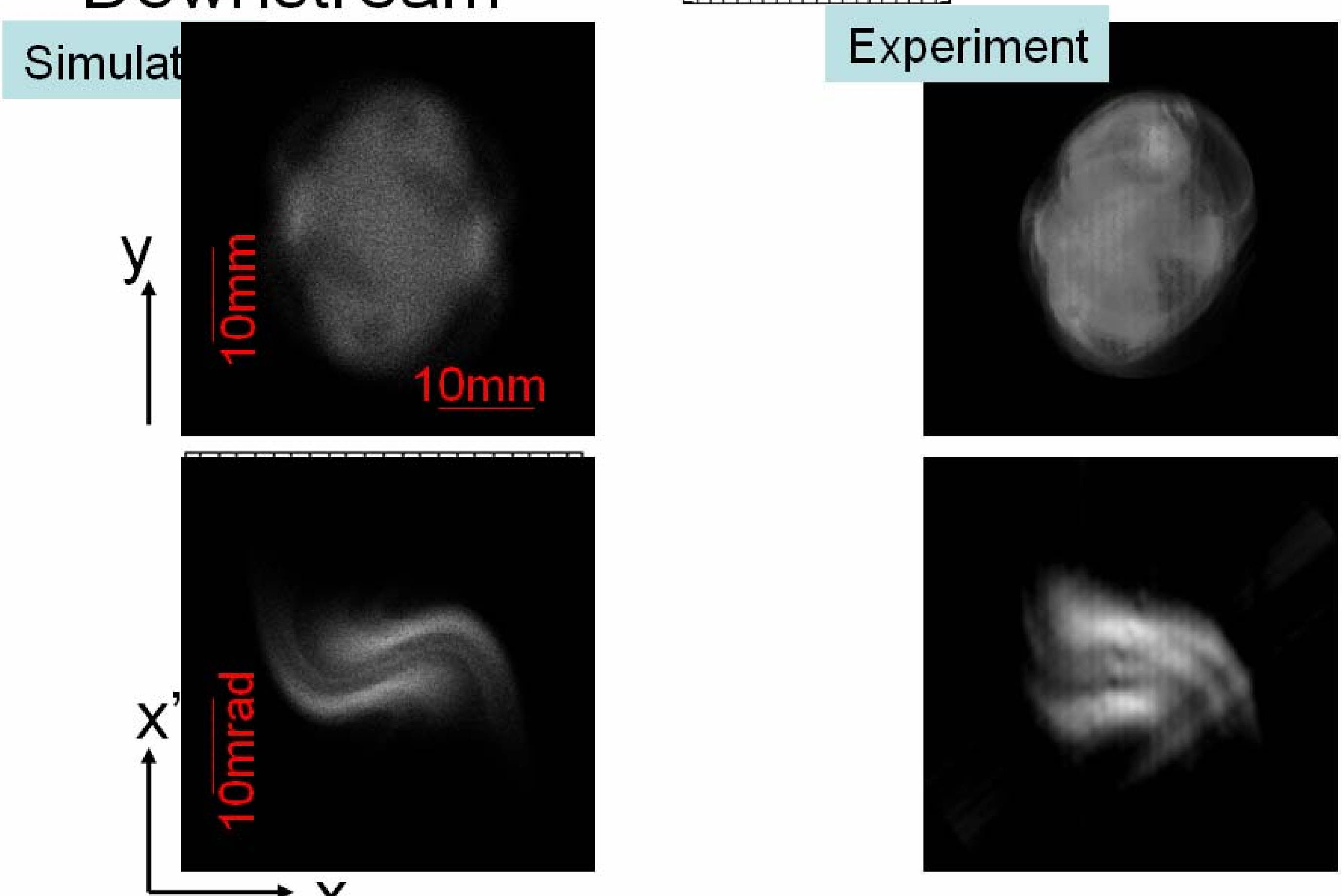
- Homogenization of a beam is different in configuration and phase space

Importance of Phase Space

- Initial distribution



- Downstream



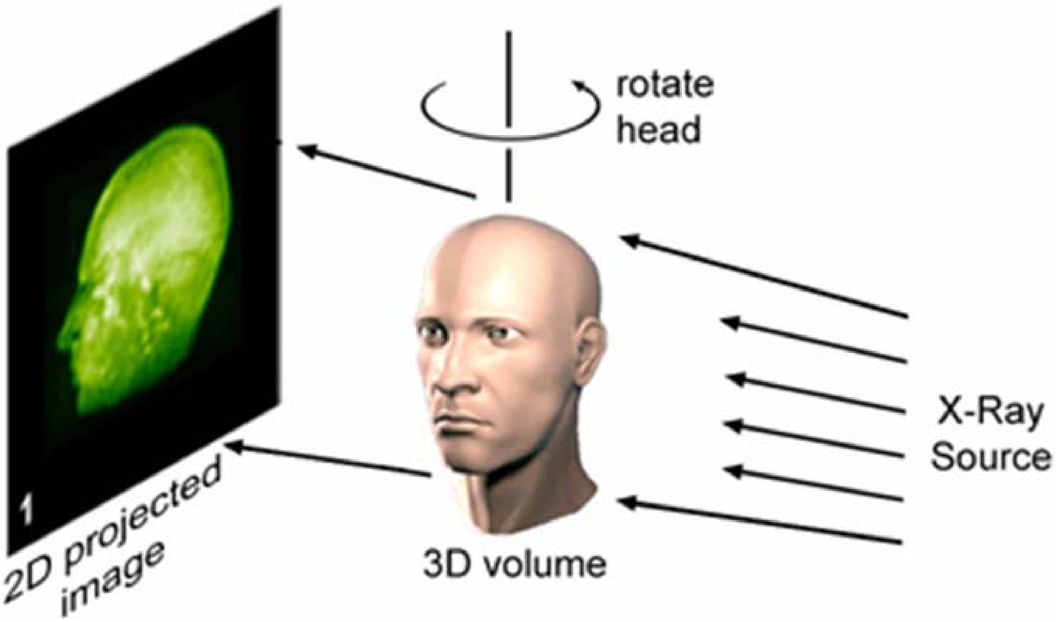
- Homogenization of a beam is different in configuration and phase space

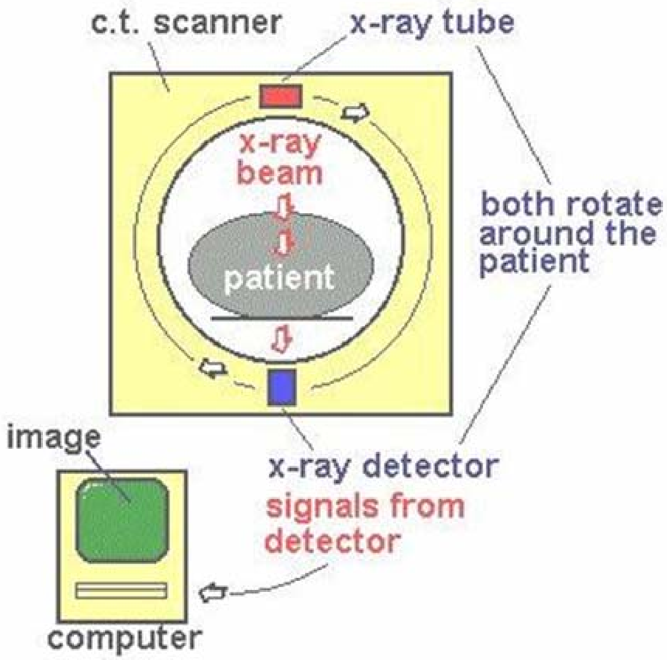
Tomography (CAT Scan)

- Tomography is the technique of reconstructing an image from its projections

Abel (1826)

Radon (1917)





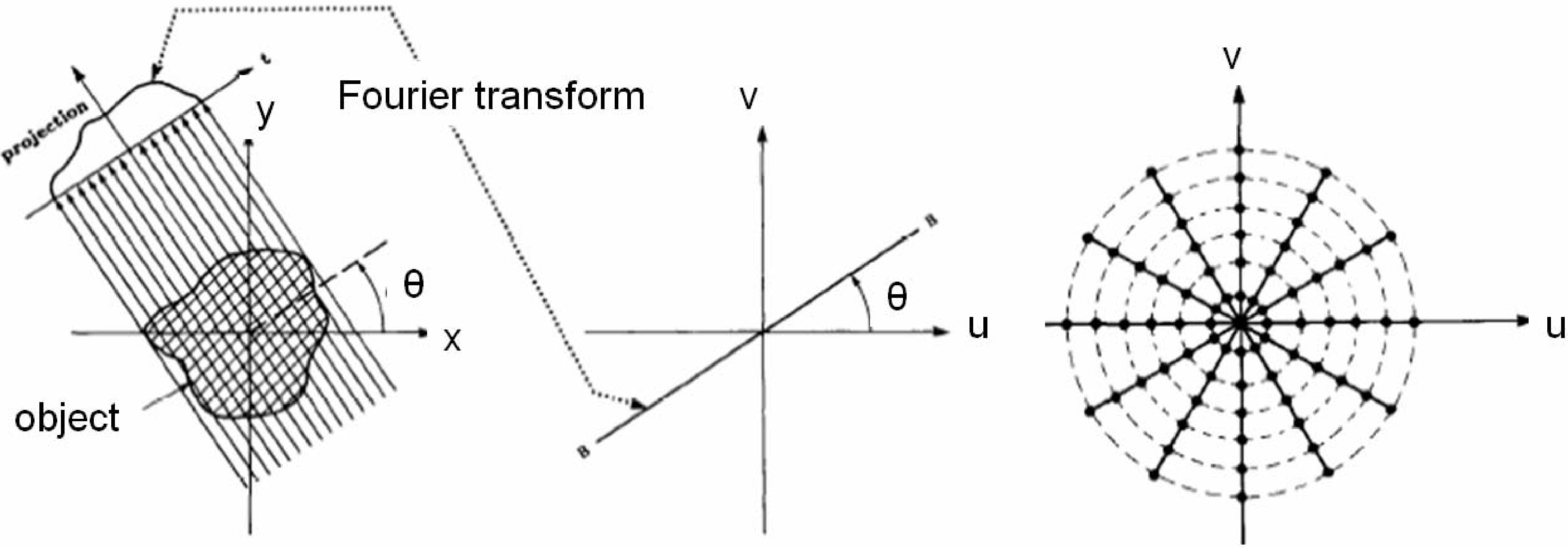
http://www.sv.vt.edu/

http://universe-review.ca

Tomography Algorithm

Fourier Slice Theorem

Fourier transform of a parallel projection is equal to a slice of the two-dimensional Fourier transform of the original object.



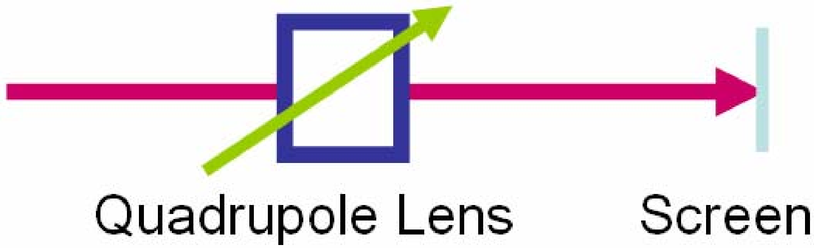
space domain | frequency domain | frequency domain

Kak and Slaney, Principles of Computerized Tomographic Imaging (1988)

Tomographic Examples

- Multi-screen method
  - Sander et al. 1979
  - Minerbo et al. 1981
  - Honkavaara et. al. 2005
  - Holder et. al. 2006
- Multi-turn
  - Hancock et al. 1999
  - Connolly et al. 2000
- Multi-slit
  - Raparia et. al. 1997
  - Adachi et. al. 1998
  - Anderson et. al. 2002
  - Friedman et. al. 2004
- Cherenkov Radiation
  - Chen et al. 2003
- Quad-scan Method
  - Fraser et al. 1979
  - McKee et al. 1995
  - Sawamura et al. 1998
  - Geitz et al. 1999
  - Brunken et al. 2000
  - Yakimenko et. al. 2003
  - Montag et. al. 2004
  - Ohgaki et. al. 2004
  - Li, PhD Dis. et al. 2004
  - Zhou et al. 2006

Quad-Scan Tomography



- Quadrupoles rotate the phase space distribution

- Single particle: $x'' = -\kappa x + F_{SC}$ $\qquad \kappa = \dfrac{qB}{\gamma m a v}$

- No SC: $x'' = -\kappa x$

Is this equation familiar?

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\sqrt{\kappa_x} z & \frac{1}{\sqrt{\kappa_x}} \sin\sqrt{\kappa_x} z \\ -\sqrt{\kappa_x}\sin\sqrt{\kappa_x} z & \cos\sqrt{\kappa_x} z \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

- With SC: Very complicated! Need approximations

Beam Tomography with space charge

- Single particle equation: $$x'' = -\kappa x + F_{SC}$$
- Assume linear forces: $$x'' = -(\kappa_{x,0} - \frac{2K}{X(X+Y)})x$$
- Find X, Y by solving envelope equations:

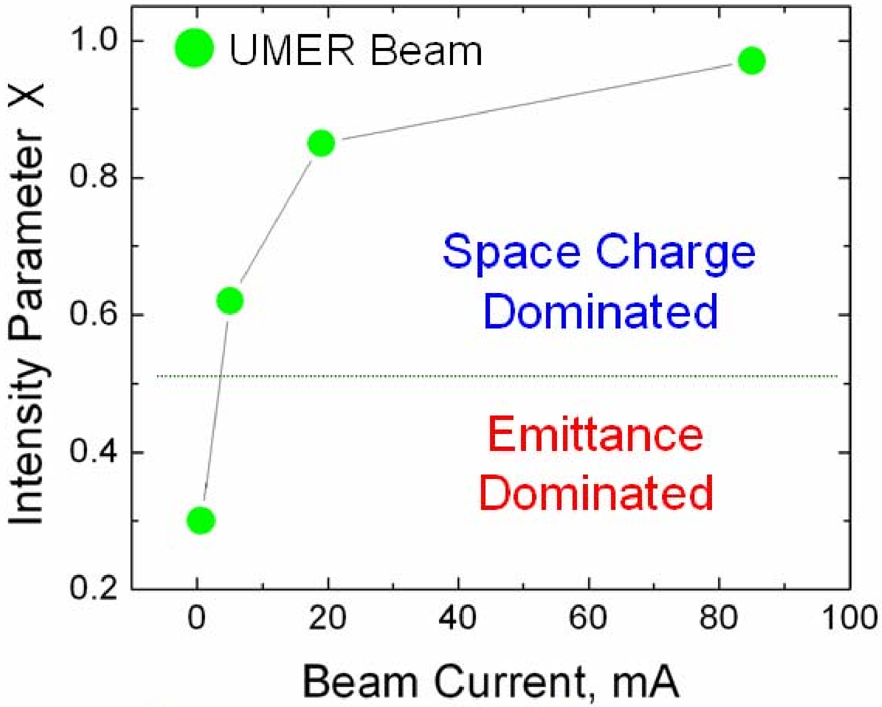
$$X'' + \kappa_x X - \frac{2K}{X+Y} - \frac{\varepsilon_x{}^2}{X^3} = 0 \qquad Y'' + \kappa_y Y - \frac{2K}{X+Y} - \frac{\varepsilon_y{}^2}{Y^3} = 0$$

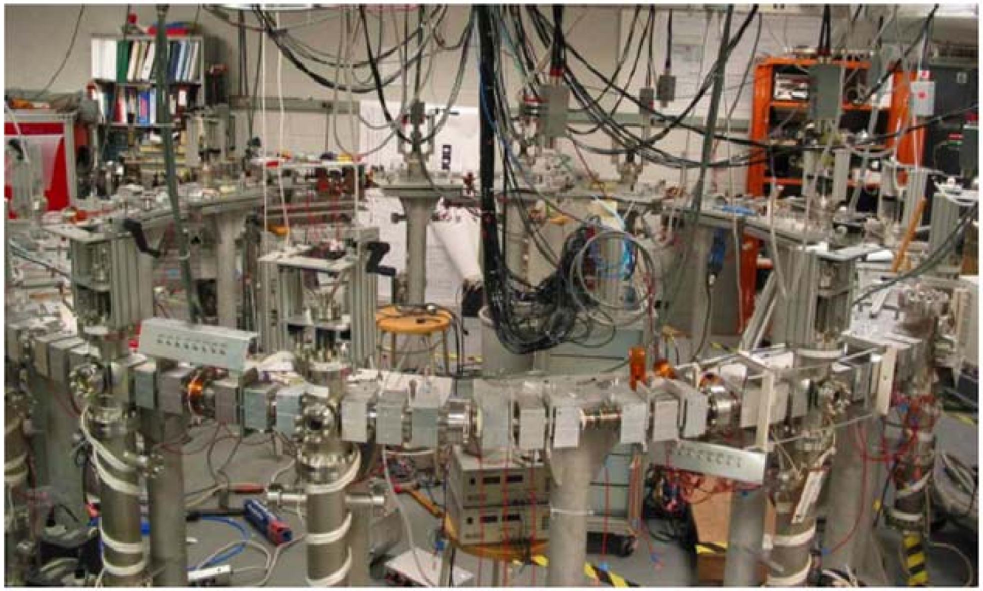
- Get transport matrix

Stratakis et al. Physical Review ST - AB 9, 112801 (2006)
Geitz et al. PAC 1999

The University of Maryland Electron Ring

- UMER is serving as a low-cost model of high intensity accelerators





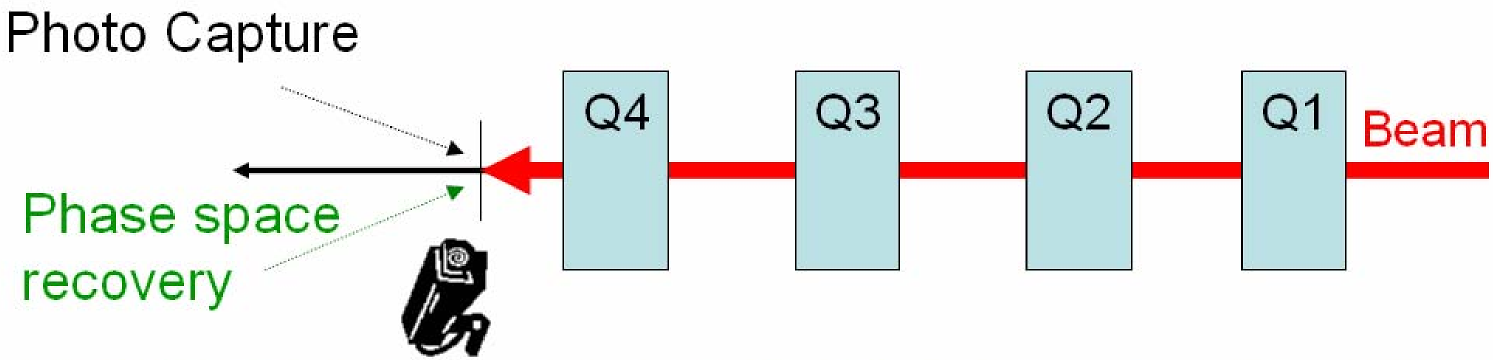
$$K = \frac{qI}{2\pi\varepsilon_0 m (c\beta\gamma)^3}$$

$$\chi \equiv \frac{1}{1 + \frac{\beta\gamma I_0}{2I}\left(\frac{\varepsilon_n}{a^2}\right)}$$

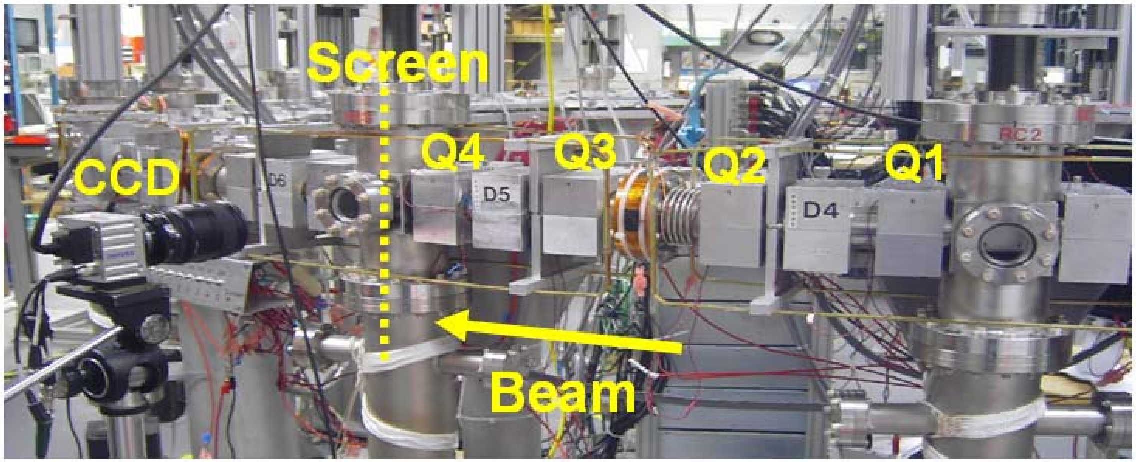
Energy	10 keV
Current range	0.6-100 mA
rms Emittance, norm	0.2-3 μm
Zero-Current Tune	7.6
Depressed Tune	1.5 – 6.5

Kishek (TUZBAB03) – talk
Walter(TUPAS047), Bernal(THPAS030) - posters

Tomography Diagnostic Configuration



Simplified configuration



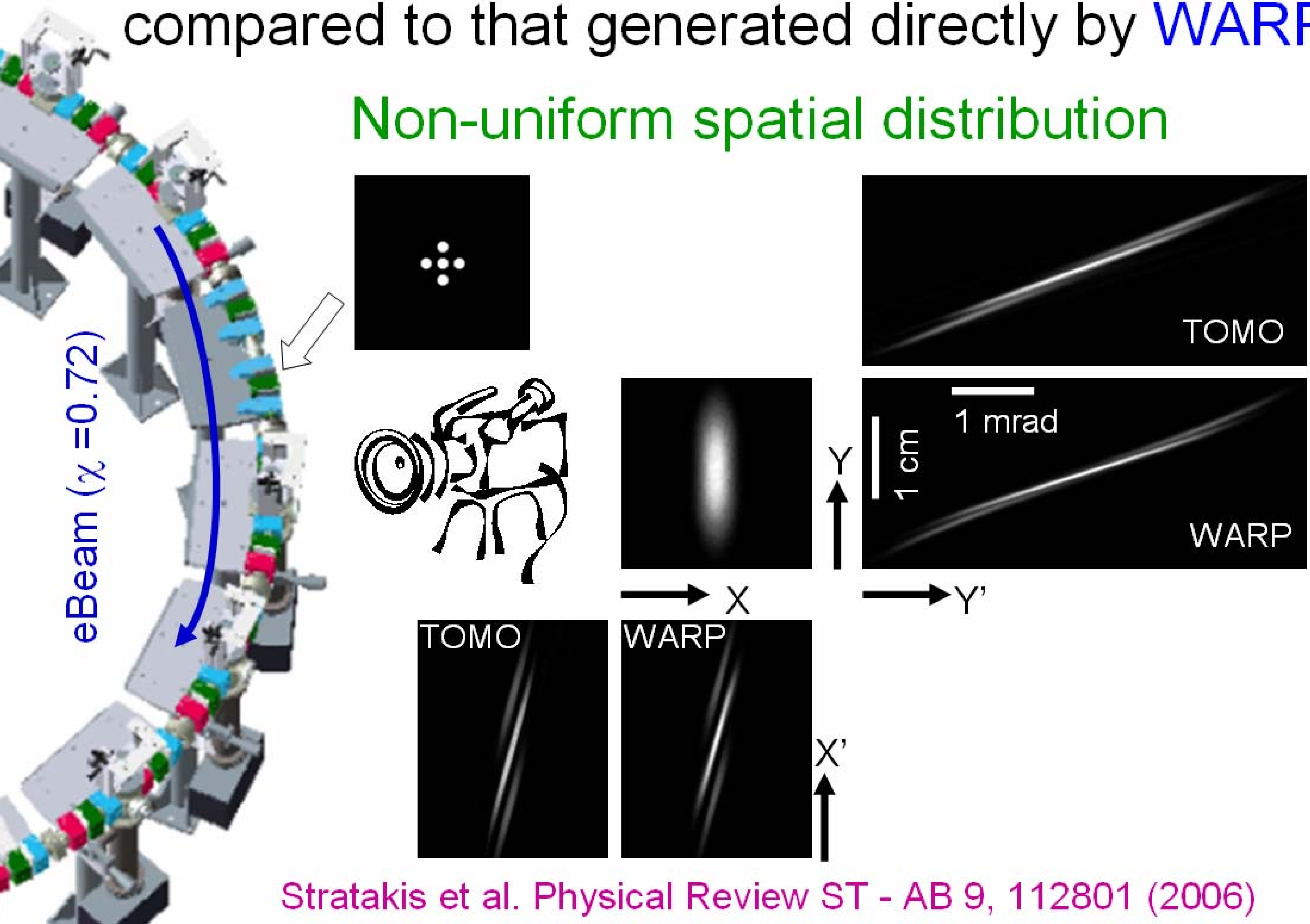
Experimental configuration

- Four magnets where employed for the tomographic recovery of the phase space

Tomography Simulation/ Validation

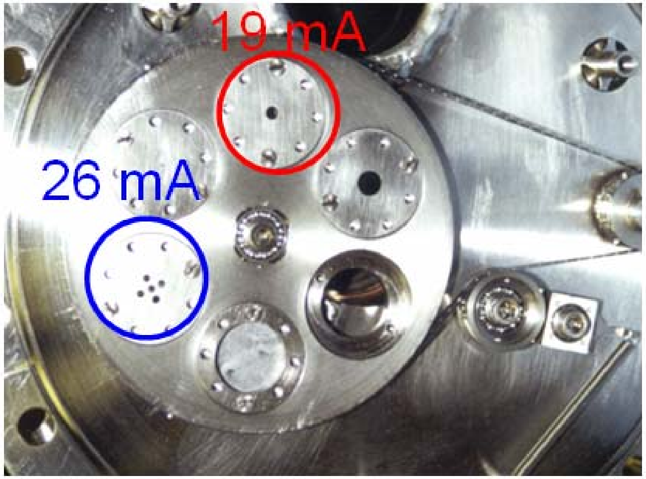
- Reconstructed phase space by Tomography is compared to that generated directly by WARP.

Non-uniform spatial distribution



Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

Experiments with Intense Beams

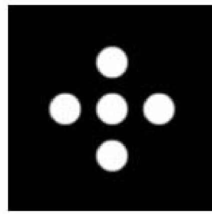


- Experiment 1:

  Uniform beam evolution (19mA, χ=0.85).

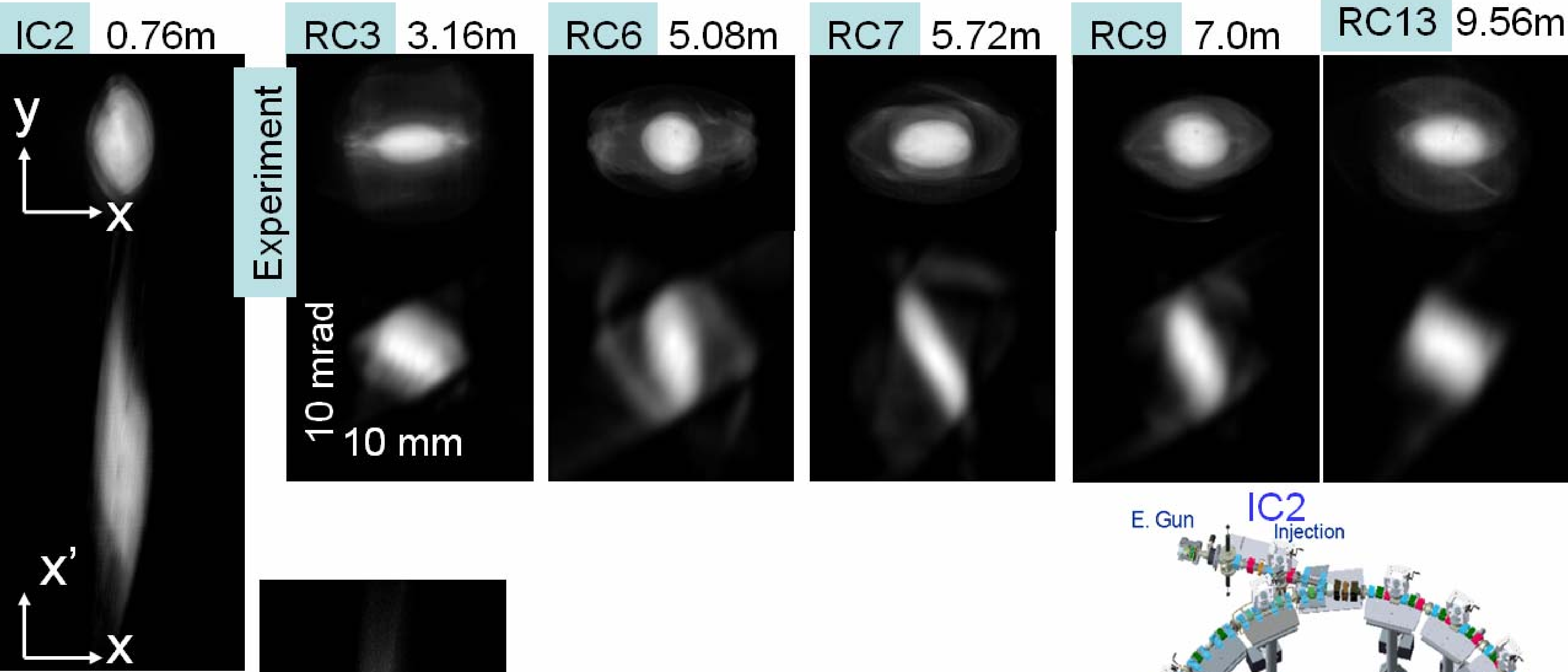
- Experiment 2:

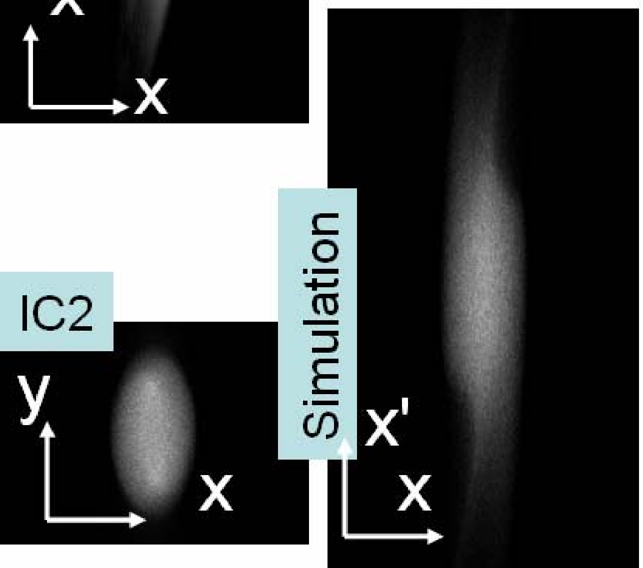
  Nonuniform beam evolution (26mA, χ=0.91).



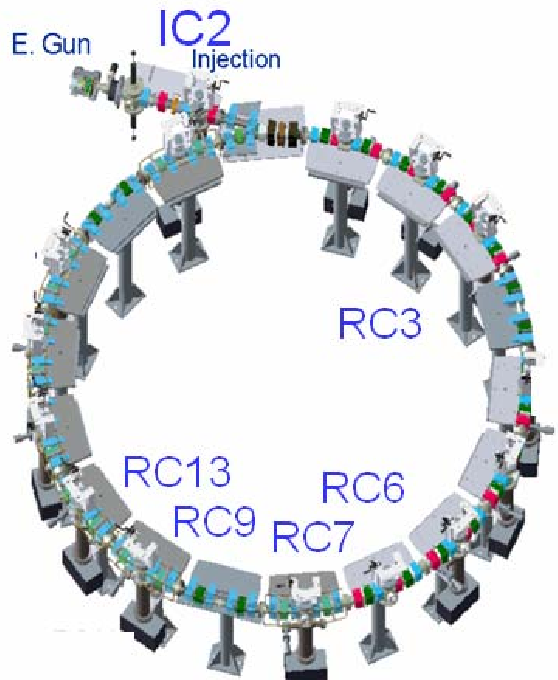
Experiment 1: Single Beamlet Transport

XX’ Reconstruction





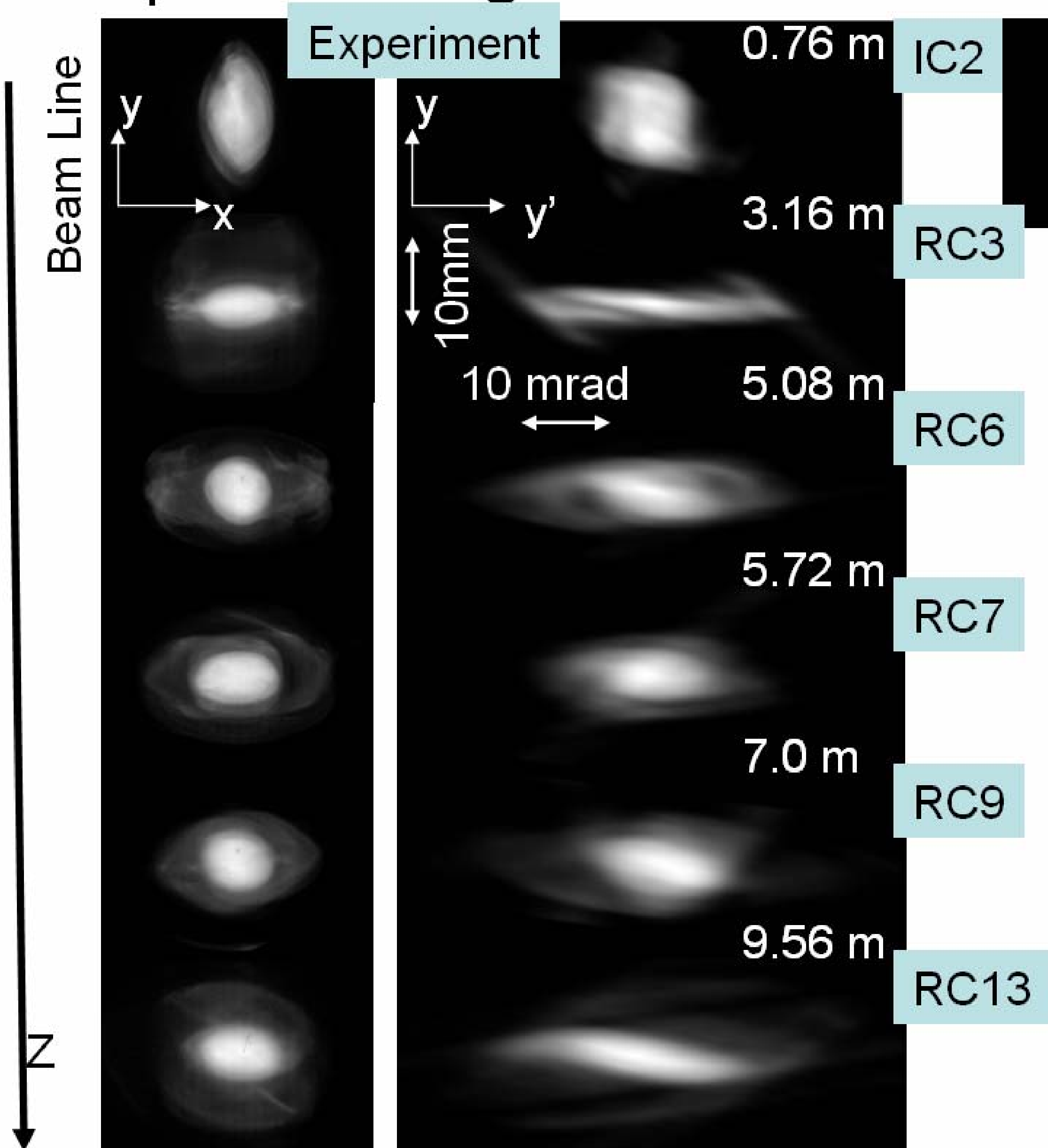
Haber (THPAS031) - poster

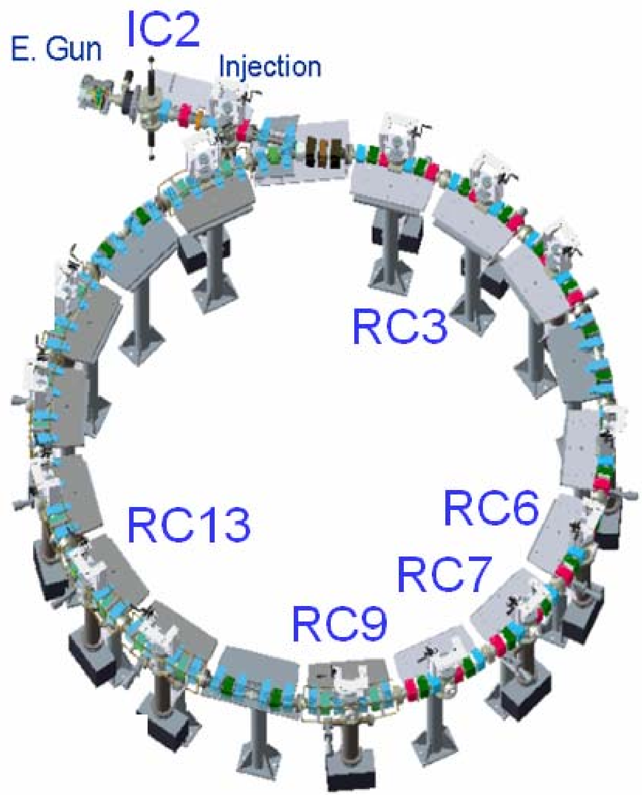


Experiment 1: Single Beamlet Transport

YY' Reconstruction

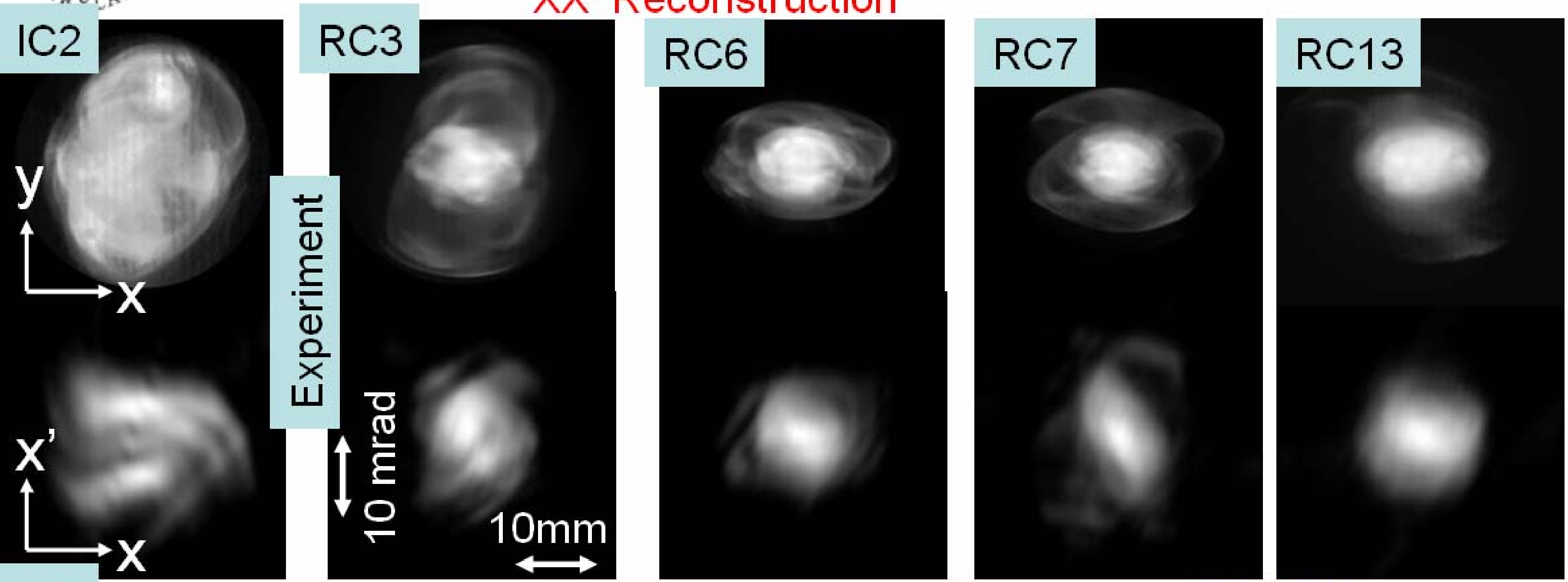
- Space Charge Dominated Beam (19mA, χ=0.85)

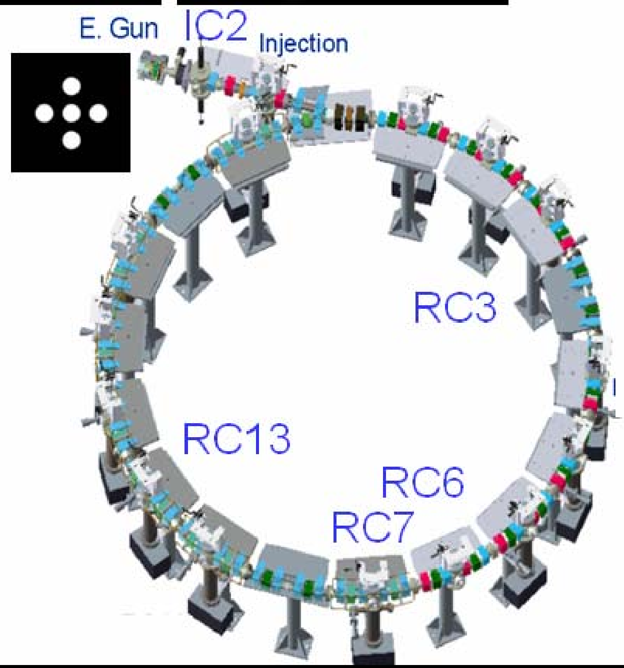




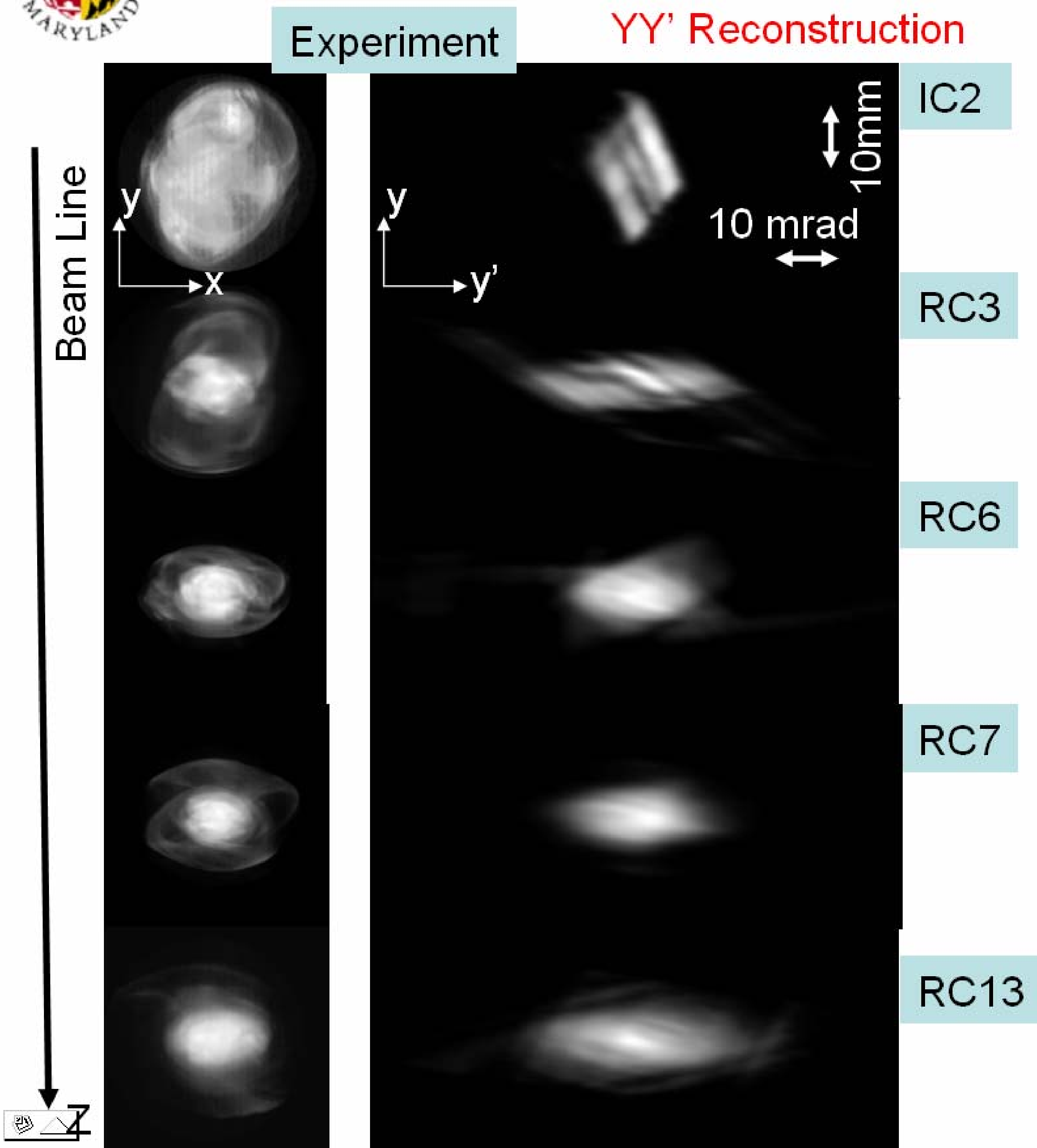
Experiment 2: Multibeamlet Transport

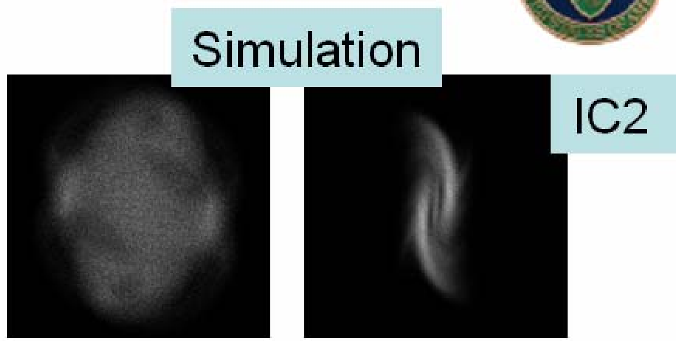
XX' Reconstruction

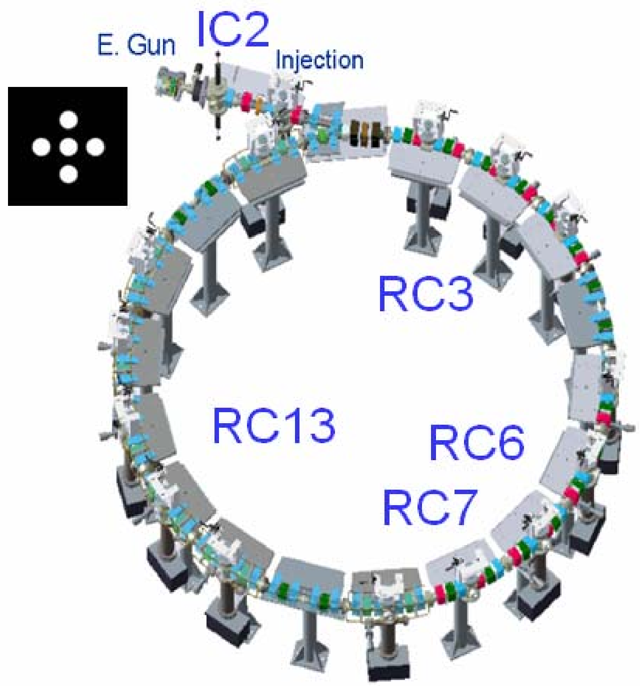




Experiment 2: Multibeamlet Transport







Conclusions

- Extended Tomography to beams with space charge
- Simulation validated accuracy of technique
- Experimental measurements reveal evolution of beam halo and multi-beamlet merger

Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

Acknowledgments

Not shown (but thanks, too):

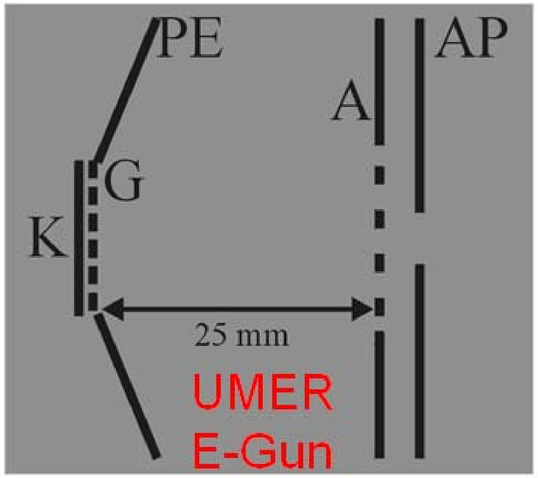
outside group

- Dr. D. Grote
- Dr. A. Friedman
- Dr. V. Yakimenko
- Dr. H. Li

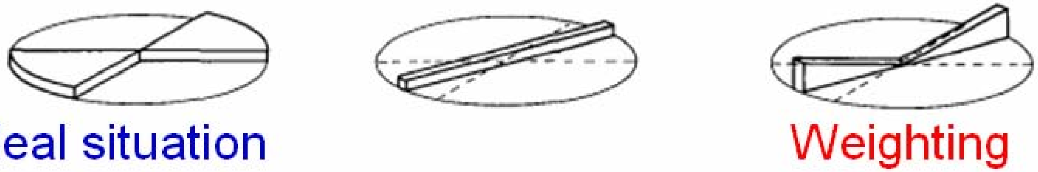
UMER group

- Dr. D. Sutter
- K. Tian
- B. Beaudoin
- M. Holloway
- C. Wu

Backup



Filtered Backprojection Algorithm (FBA)

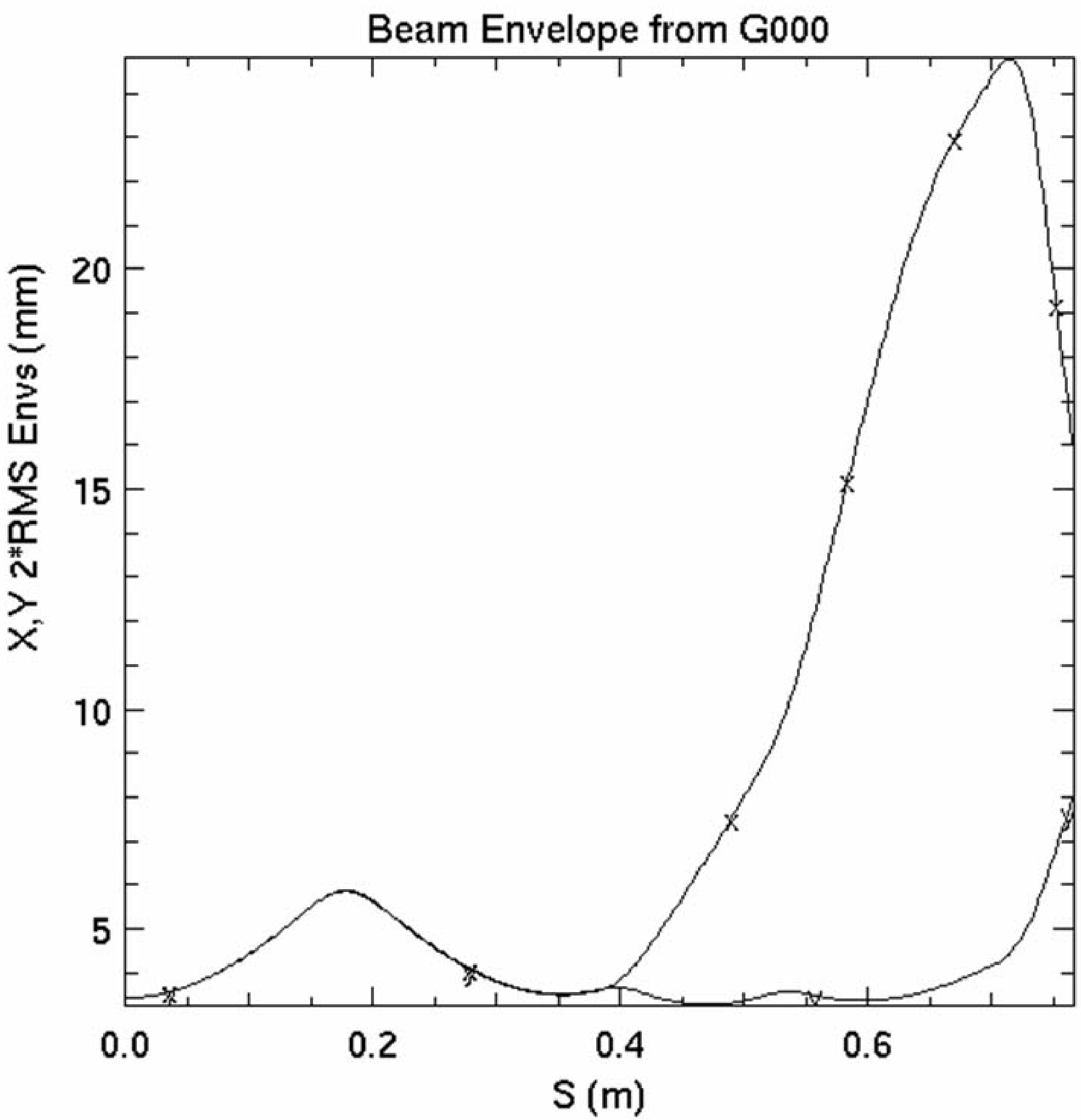


- A simple weighting in the frequency domain is used to take is projection and estimate a pie-shaped wedge of the object's Fourier transform.
- We multiply the value of the Fourier transform of the projection and multiply it by the width of the wedge at that frequency
- Apply inverse Fourier Transform of the filtered projections

Quad Scan Tomography

Article	Beam/Facility	Energy / Current	G. Perveance
Brunken et al. 2000	S-DALINAC	8MeV/ 10^{-6} A	2.5 10^{-14}
McKee et al. 1995	Duke	44MeV / 0.2A	3.5 10^{-11}
Ohgaki et al. 2004	KU-FEL	10 MeV/ 0.1A	1.3 10^{-9}
Yakimenko et al. 2003	Brookhaven	50 MeV/ 100A	1.2 10^{-8}
Zhou et al.2006	Brookhaven	60 MeV/ 266A	1.9 10^{-8}
Montag et al. 2004	RHIC	54 MeV/ 330A	3.2 10^{-8}
Sawamura et al. 1998	JAERI	16 MeV/ 100A	3.4 10^{-8}
Geitz et al. 1999	TeslaTF	16 MeV/ 200A	7.0 10^{-7}
Fraser et al. 1979	LAMPF	0.75-100MeV/ 18mA	10^{-5} -10^{-8}
Li H. PhD Dis. 2004	UMER	10 keV/ 0.007A	1.0 10^{-4}

For UMER: G. Perveance 10^{-6} to 10^{-3}



Q1= -1.67A
Q2= -1.49A
Q3= 3.5A