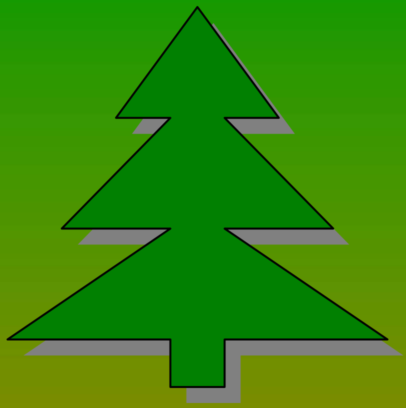


Happy St. Nick's Day

Beam Diagnostics at the AWA Facility

…the other ½ of the story

Lunch Seminar

John Power

December 6, 2005

AWA Playing Cards
Collect them all!

Zeke Yusof

Haitaow Wang

John Power

Wanming Liu

Chunguang Jing

Richard Konecny

Feng Gao

Wei Gai

Felipe Franchini

Manoel Conde

Sergey Antipov

Accel. R&D group activities …

AWA Facility
Beam Driven Structure Testing
Beam Diagnostic Measurements
Control System
DAQ system
RF System
Laser System
Vacuum/Beamline
Photocathode Development
Community Service

Advanced Structure Development
Design, Simulation, Fabrication

Administrative
ES&H, Conferences, Reviews, Publications

Mission Statement
Explore novel charged particle acceleration methods for future HEP machine

NRL
RF Driven Structure Testing

Beam Physics
Beamline Design
Beam Simulation
support for experiments

Miscellaneous
ILC Activities
NLC breakdown

Beam Diagnostics
Design, Simulation, Fabrication

Theory
Multipactor, Schottky Emission

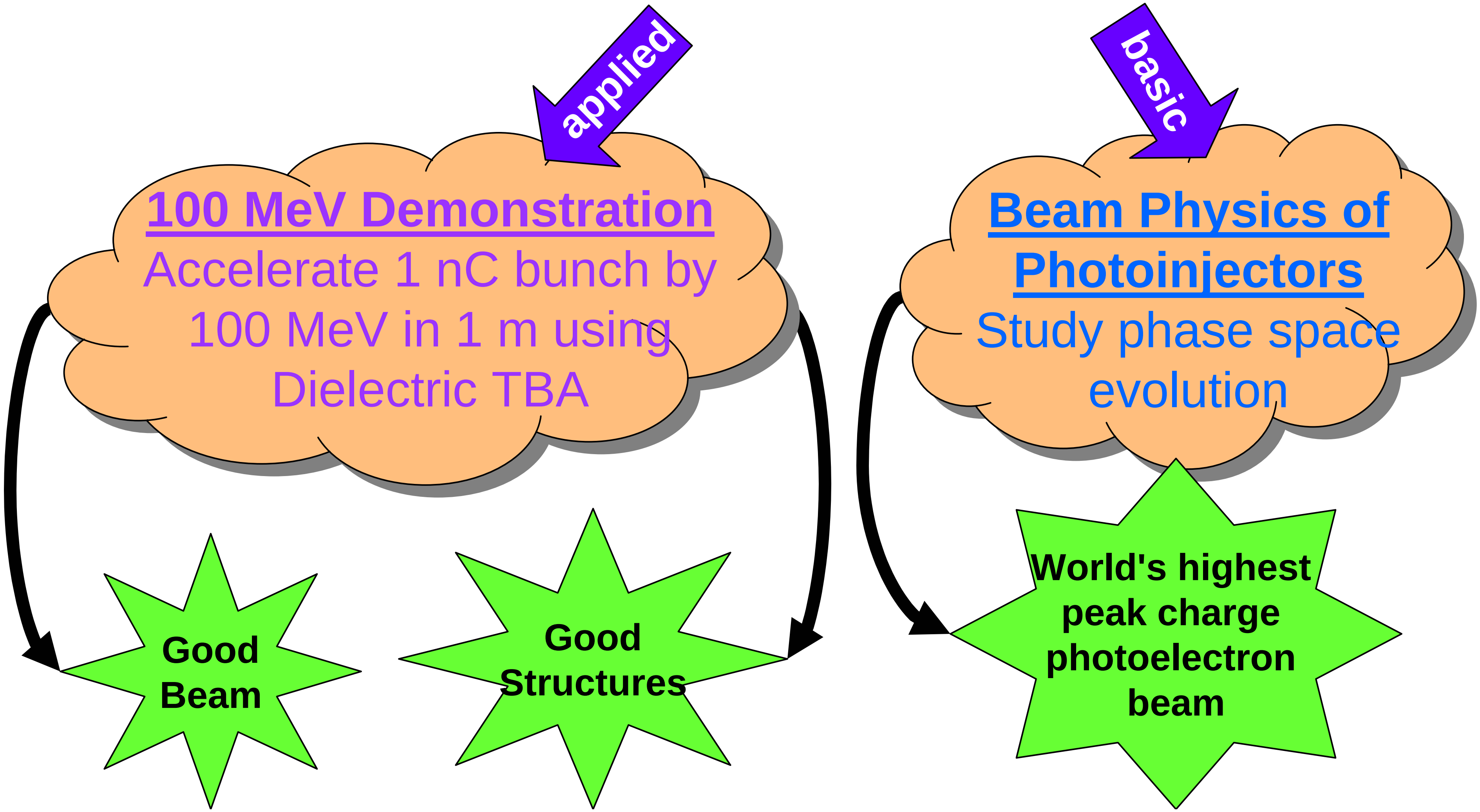
Exotic Structures
Design, Simulation, Fabrication

Primary Challenge → Operating an accelerator with a small group

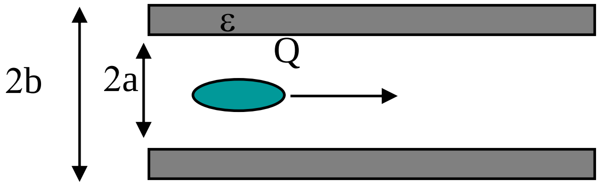
(I)
Why do beam diagnostics at the AWA facility?

The future of accelerator-based HEP

- HEP needs a path to **High Energy** and **High Luminosity**
- AAC seeks **High Gradient** & **High Brightness** technology
- Group develops **Wakefield Acceleration** & **RF photoinjectors**



How does wakefield acceleration depend on beam quality?



W_z longitudinal wake
σ_r transverse beam size
δ empirical number
ε_N Normalized emittance
γ Lorentz factor
Q Total Charge
σ_z Bunch length
β Beta function of the beam
λ Excited WF Wavelength

High Charge (photocathode)

Short Bunch (killer!)

$$W_z \propto \frac{Q}{a^{1.5}} e^{-2\left(\frac{\pi\sigma_z}{\lambda}\right)^2}$$

small tube
means
small bunch

Beam quality

$$\sigma_r = [\frac{\varepsilon_N}{\gamma}\beta]^{1/2}$$

Beam energy (= $$)

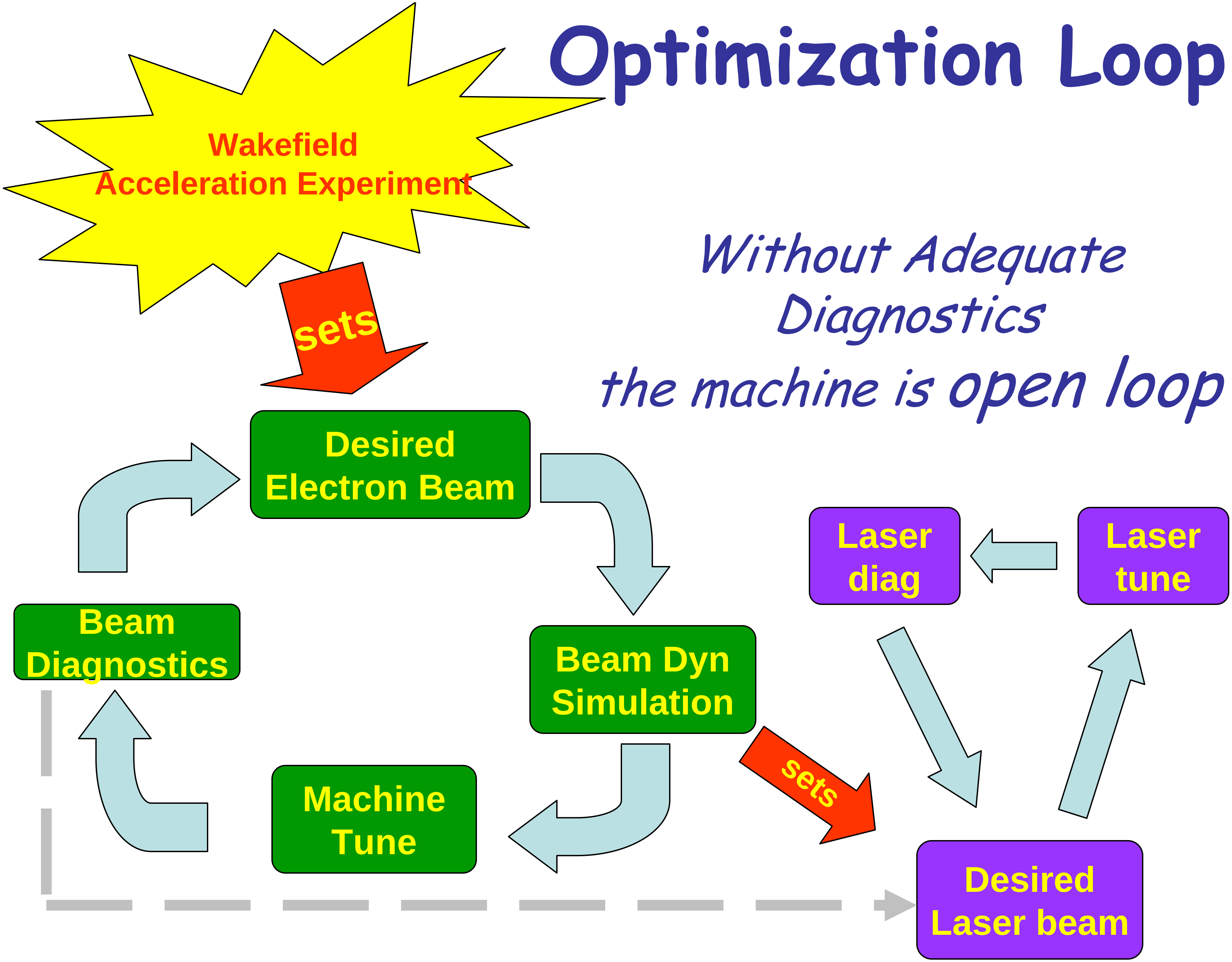
Good diagnostics
can affect these.

Rich guys
can affect these.

Optimization Loop

Without Adequate Diagnostics

*the machine is **open loop***



(II)

What do we want to know about the BEAM?

Everything but … beam diagnostics are difficult at low energy and high brightness!!!

Ideally → we'd like to know

– **$\{x_i$, $p_i\}$ i=1..N**

– of all ($N \sim 10^{10}$) particles ($N \sim 10^{10}$)

– at all times **{t}**

Practically→ continuous distribution function → statistical description

easy

0^{th} moment of the distribution (N)

Charge

$$Q = e\int \rho(\vec{x}, \vec{p}, t)\, d^3x$$

1^{st} moments of the distribution (centroid vector 1x6)

Transverse position (**<x>**, **<y>**)

Longitudinal position (**<z>**→ relative beam-RF phase)

Transverse momentum (**< p_y>**, **< p_y>**)

Longitudinal momentum (**<p_z>** → energy)

$$\langle x \rangle = \frac{\int x\rho(\vec{x}, \vec{p}, t)\, d^3x}{\int \rho(\vec{x}, \vec{p}, t)\, d^3x}$$

2^{nd} moments of the distribution (spread matrix 6x6)

Transverse: profile, divergence, emit

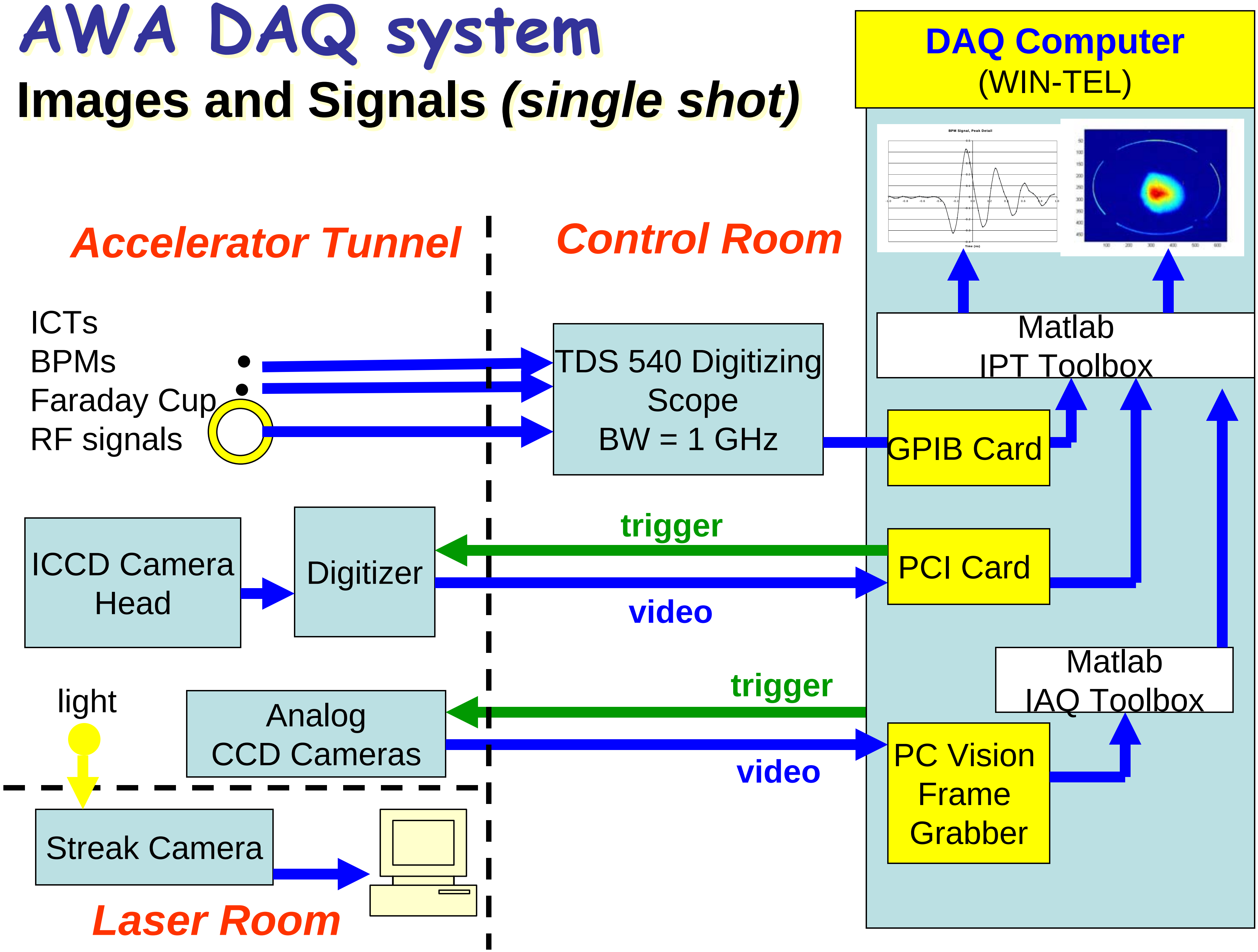
Longitudinal: energy spread; bunch length; emit

$$\langle x^2 \rangle$$

hard

AWA DAQ system

Images and Signals *(single shot)*

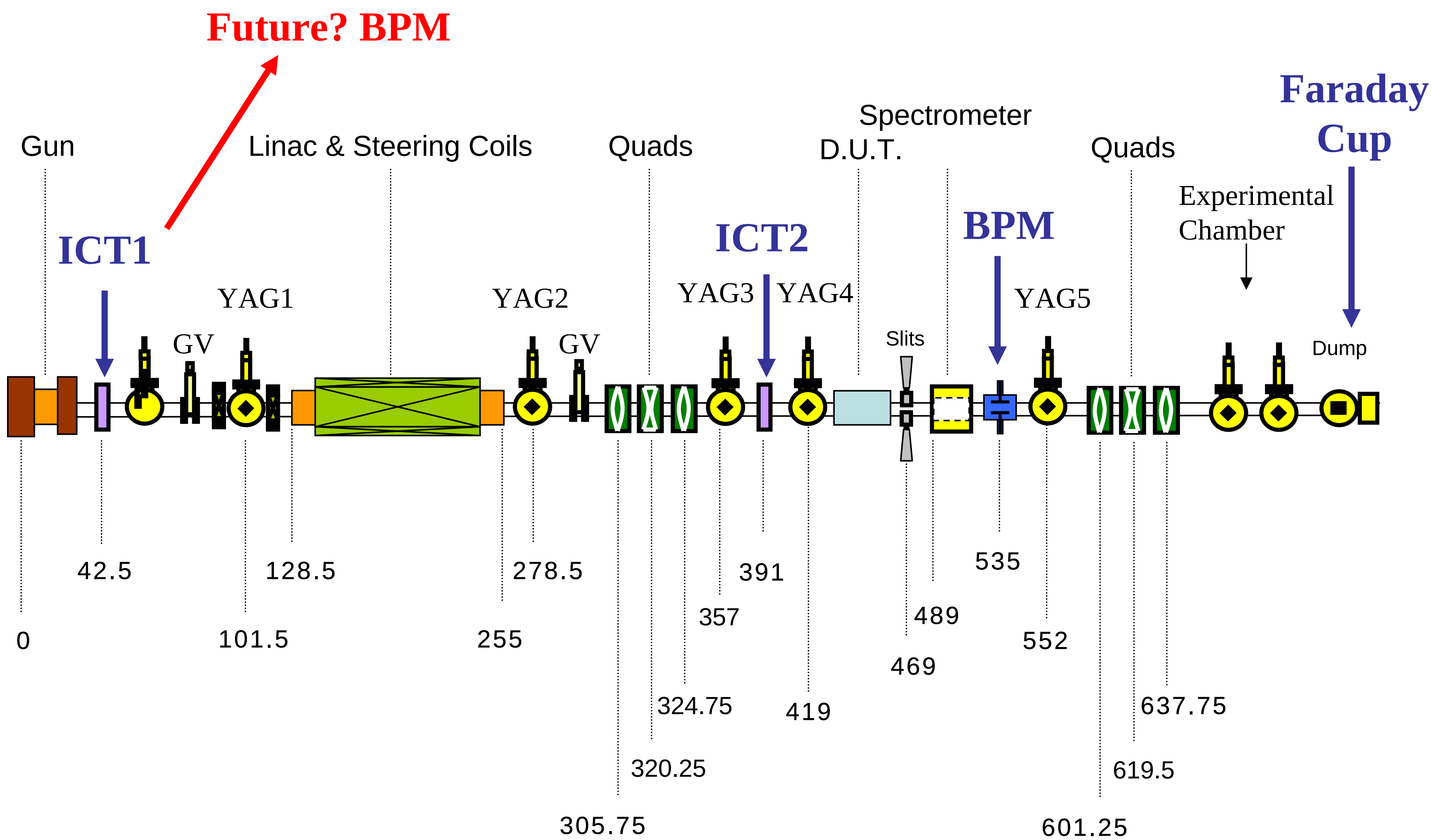


(III)
Measuring the 0^{th} Moment

Q CHARGE

The 0th moment (the easy one): CHARGE

0.1nC < Q < 100 nC



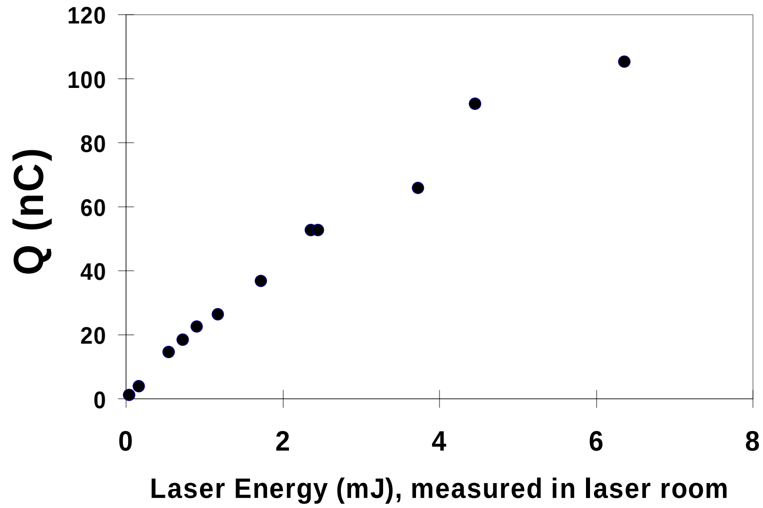
The 0th moment: Charge

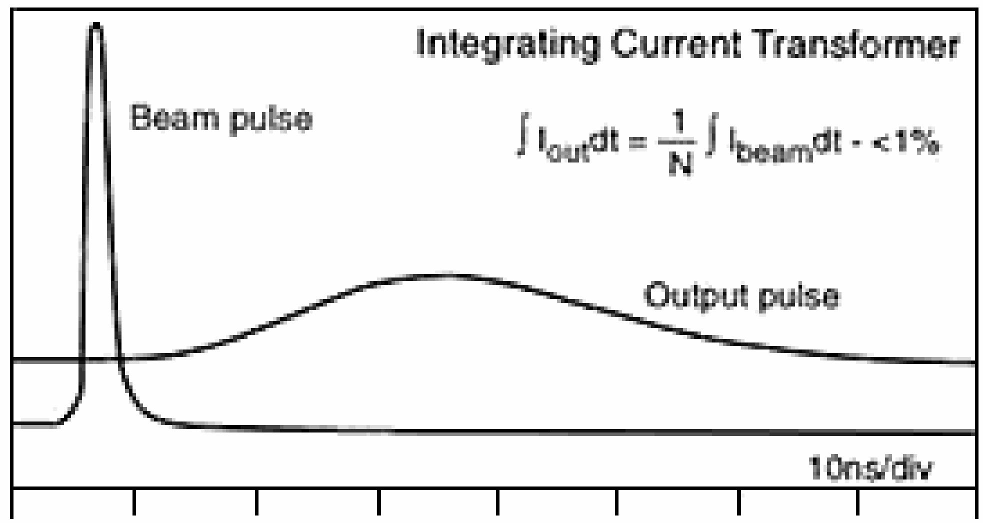
experiment
in use

Relative merits …

1. ICT → easy to use (our staple)

- **Nondestructive; Single shot**
- **Commercial:** Bergoz, but accurate calibration difficult





Good for: 1 psec < σ_z < 1 μsec

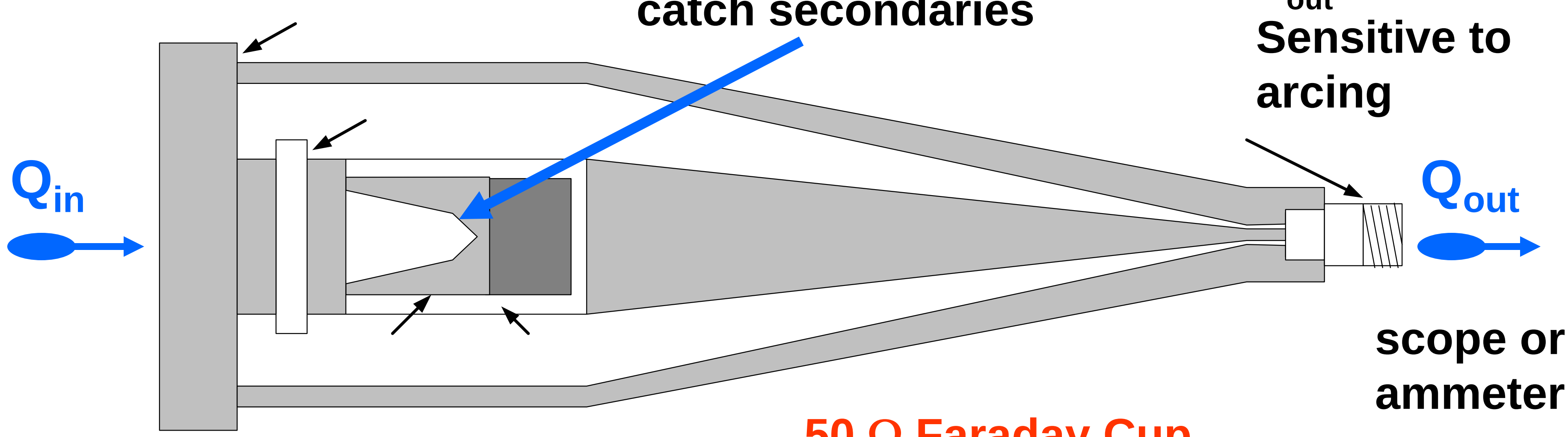
The 0th moment: Charge

experiment
in development

Relative merits …

2. Faraday Cup → more difficult (doubles as beam dump)

- Destructive; average current (typically); can be single-shot
- **Homemade:** must be carefully designed to capture secondaries, and matched into 50 Ω.



50 Ω Faraday Cup
Rise time ~ 300 psec

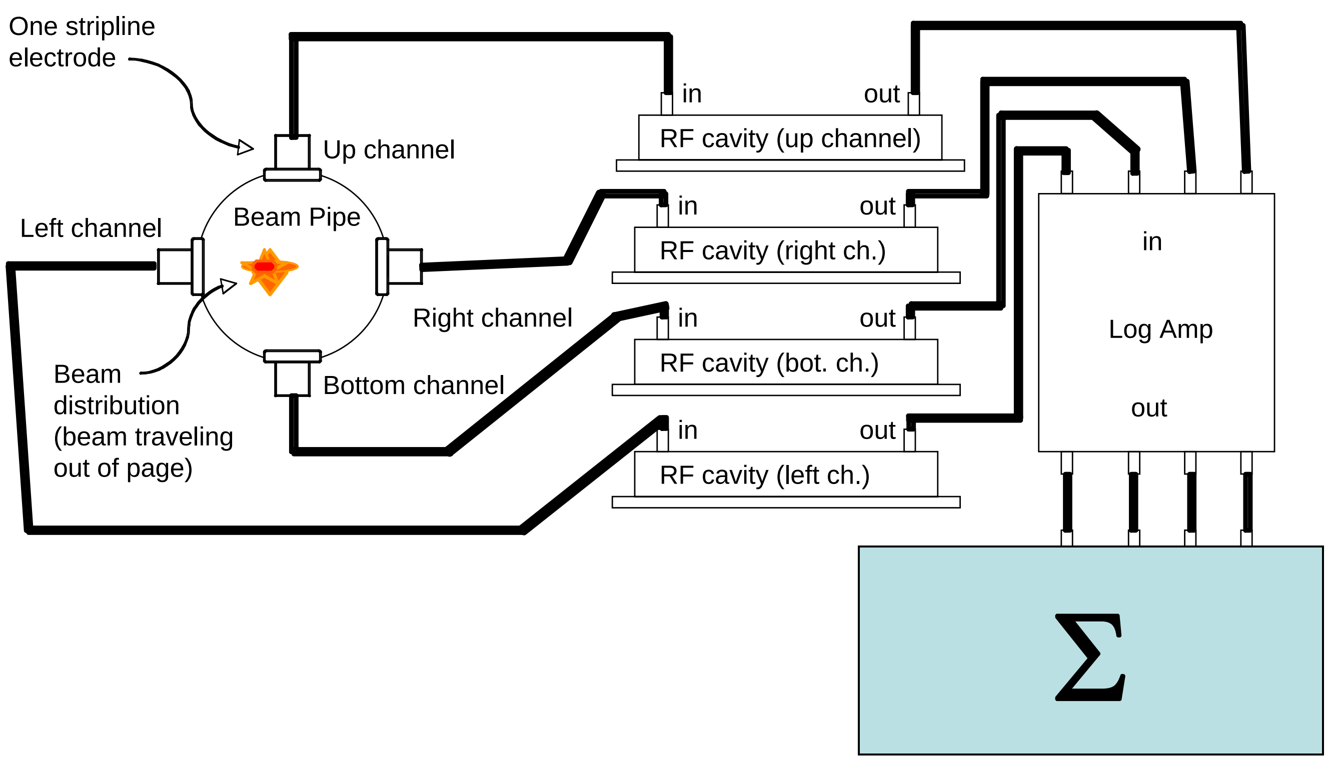
The 0th moment: Charge

experiment
in development

Relative merits …

3. BPM → difficult, but has other uses

- Nondestructive; single-shot; wide dynamic range
- **Homemade:** 3D EM simulation, complicated mechanical fabrication, non-negligible impedance, sophisticated calibration



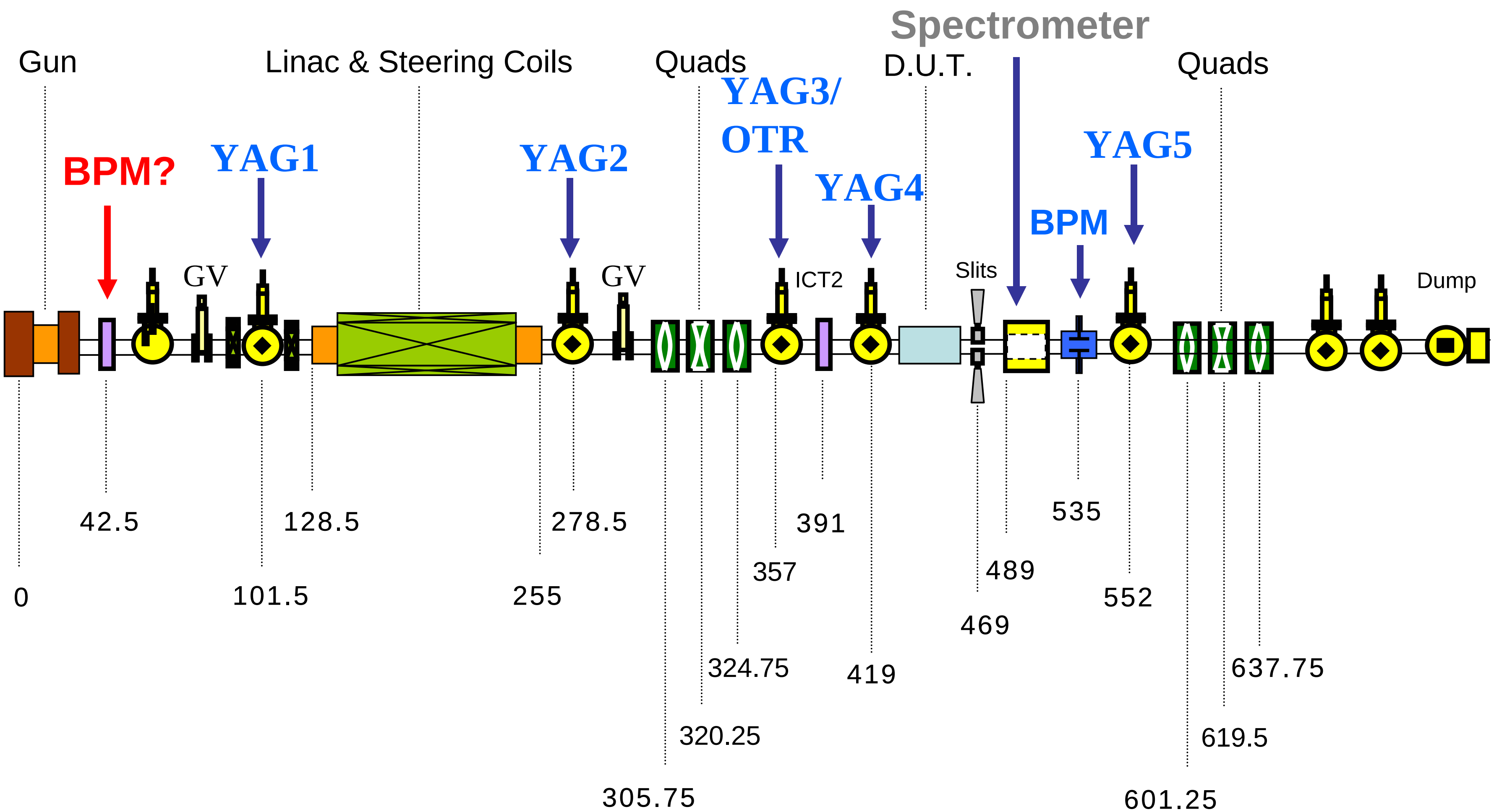
(IV)
Measuring the 1st Moments

$$\begin{pmatrix} \langle x \rangle \\ \langle y \rangle \\ \langle z \rangle \\ \langle p_x \rangle \\ \langle p_y \rangle \\ \langle p_z \rangle \end{pmatrix}$$

the mean vector

The 1st moments: CENTROIDS

transverse & longitudinal, position & angle



timing energy transverse position

1^{st} moments: centroid

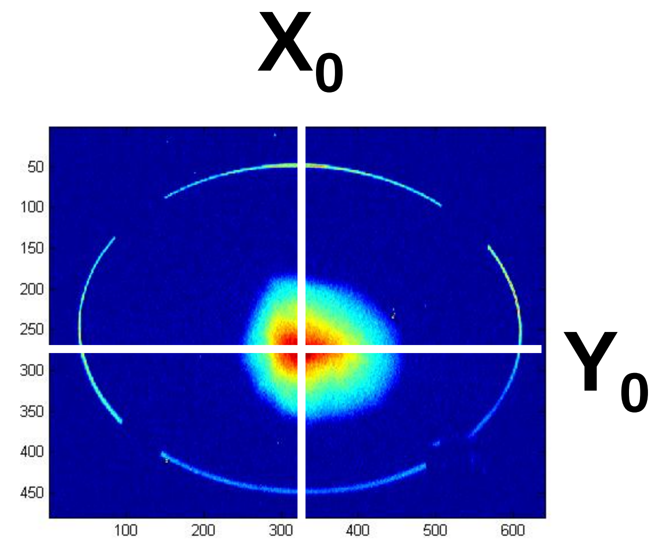
experiment in use

Transverse position (Horiz & Vert Offset) #1

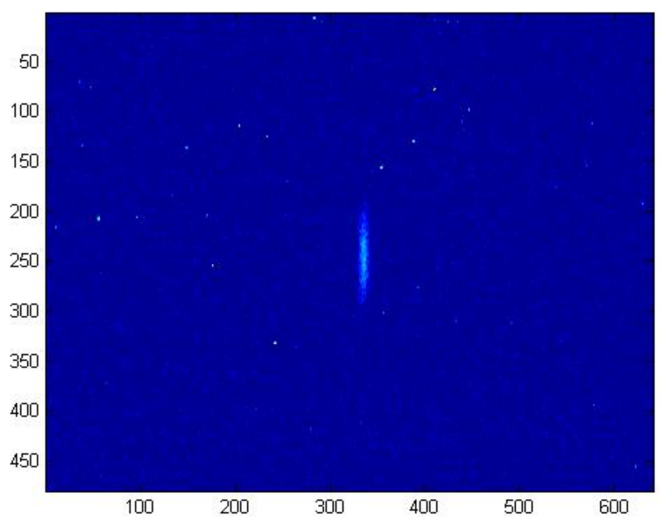
Radiation Emitting Screens

YAG:Ce:

- destructive,
- analyze image offline



Same Q



OTR:

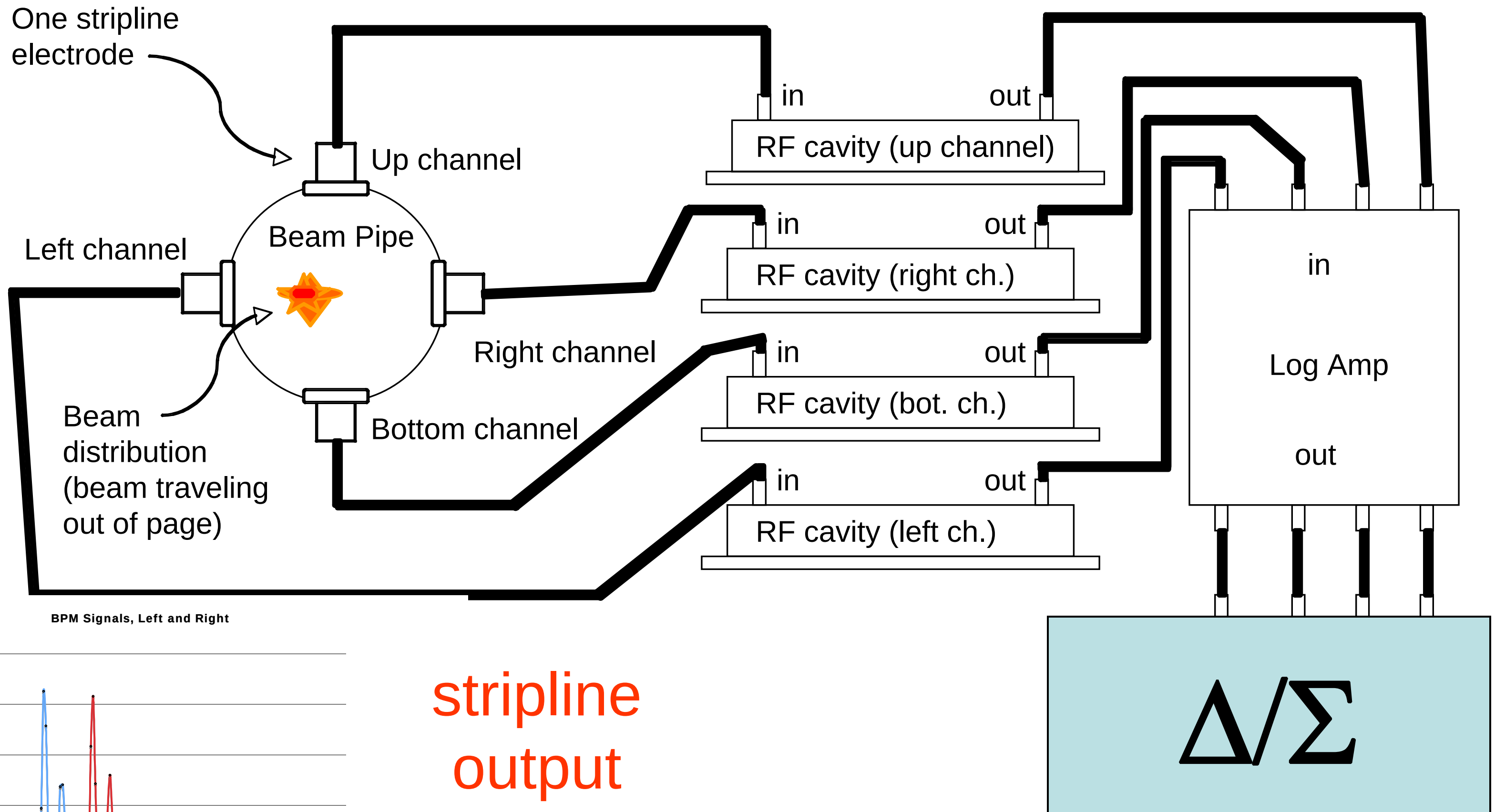
- ditto as YAG:Ce
- very little light
- prompt radiation

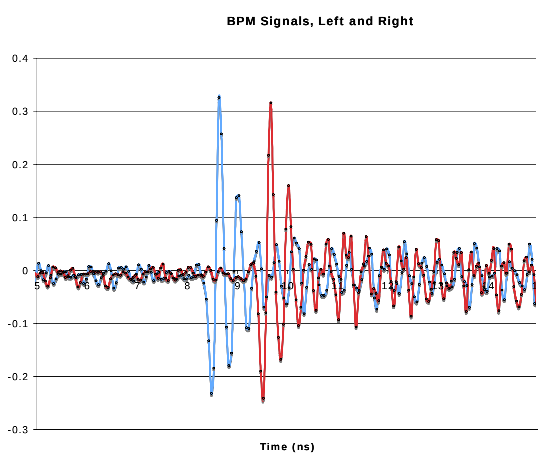
1st moments: centroid

experiment
in development

Transverse position (Horiz & Vert Offset) #2

stripline BPM: non destructive; signal shot





stripline output
measured at AWA
f = 2856 MHz

1st moments: centroid

experiment in use

Longitudinal position (timing/phase) #1

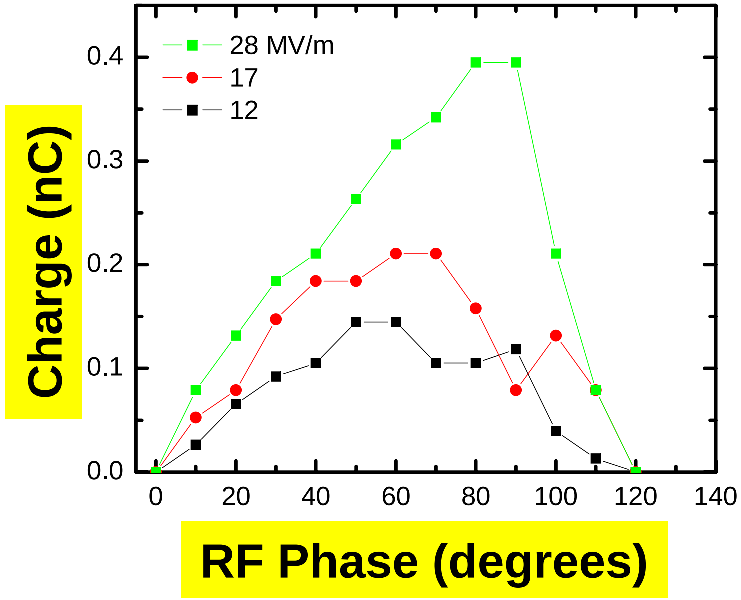
Position/ϕ → beam RF phase to RF reference phase

beam property vs.. ϕ:

Energy, Energy Spread, emittance, bunch length, etc.

Q vs.. ϕ

– destructive and slow
– absolute Gun Phase, but low precision, (+/- 10^0)
– Sensitive to gun gradient, charge jitter, machine drift (not real-time)

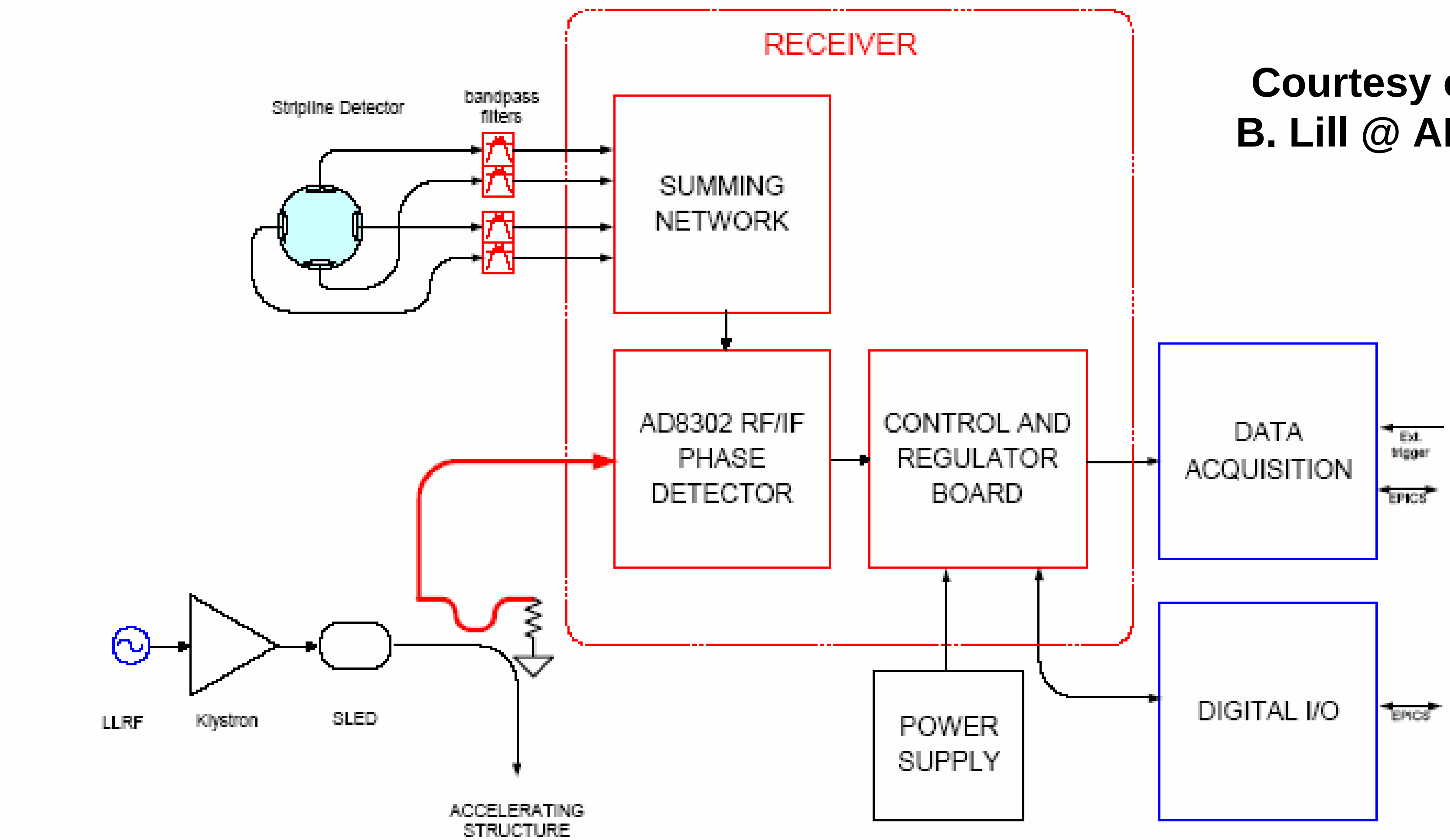


1st moments: centroid

experiment
in development

Longitudinal position (timing/phase) #2

BPM-based technique
→*Nondestructive; real time monitor*
→*relative Gun Phase, High precision (+/- 1^0)*



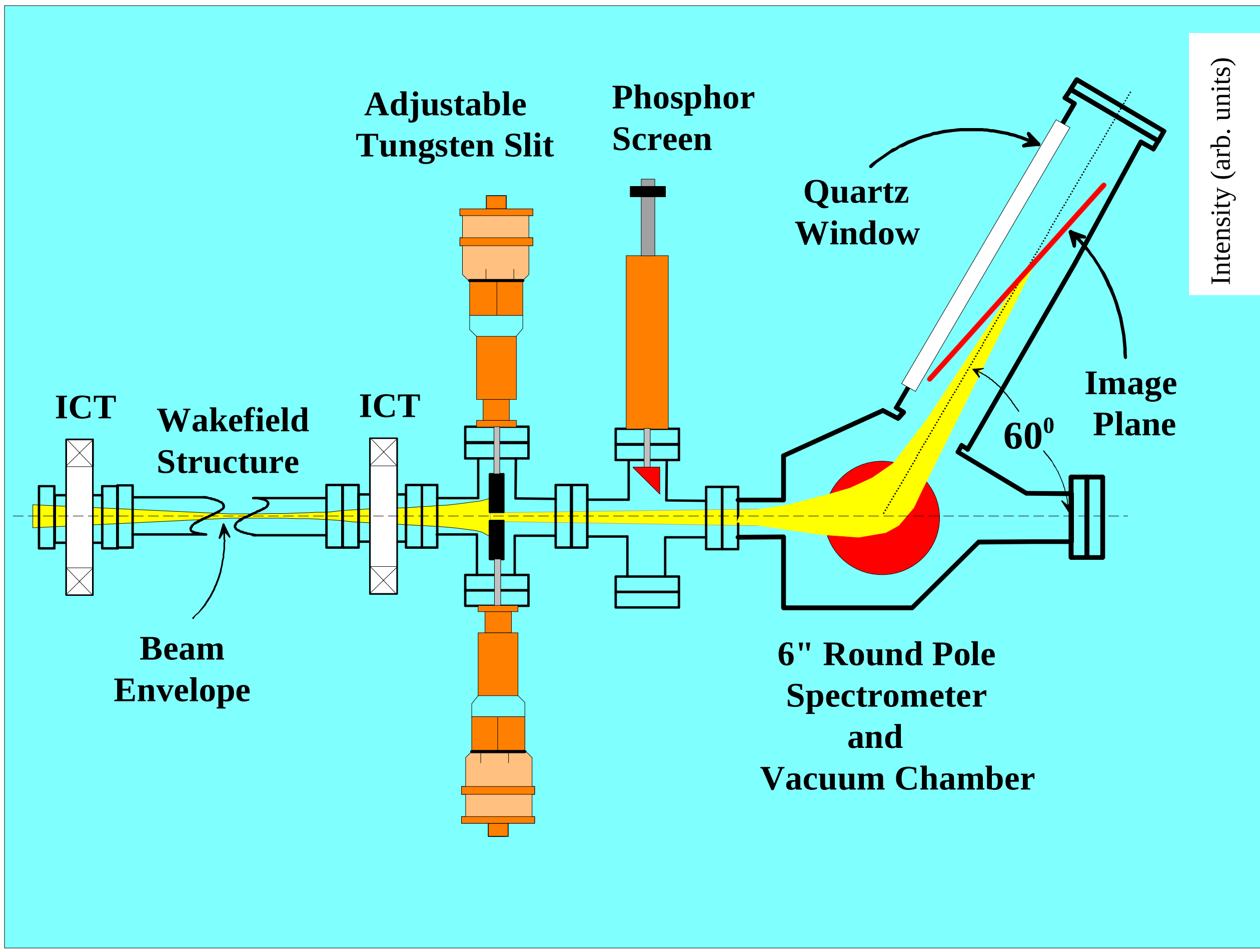
Courtesy of
B. Lill @ APS

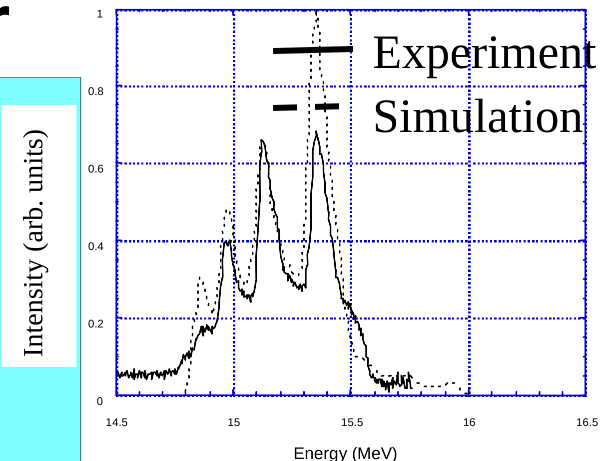
1st moments: centroid

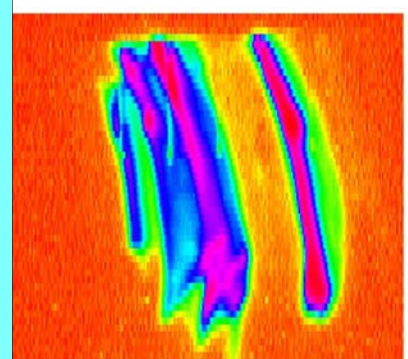
experiment
in use

Longitudinal angle (energy) #1

The AWA Imaging Spectrometer







(V)
Measuring the 2nd Moments

$$
\begin{matrix}
\langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle & \langle xz \rangle & \langle xz' \rangle \\
\langle x'x \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle & \langle x'z \rangle & \langle xz' \rangle \\
\langle yx \rangle & \langle yx' \rangle & \langle y^2 \rangle & \langle yy' \rangle & \langle yz \rangle & \langle yz' \rangle \\
\langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'^2 \rangle & \langle y'z \rangle & \langle y'z' \rangle \\
\langle zx \rangle & \langle zx' \rangle & \langle zy \rangle & \langle zy' \rangle & \langle z^2 \rangle & \langle zz' \rangle \\
\langle z'x \rangle & \langle z'x' \rangle & \langle z'y \rangle & \langle z'y' \rangle & \langle z'z \rangle & \langle z'^2 \rangle
\end{matrix}
$$

the sigma matrix

2^{nd} moments (the hard one)

theory

some formalism → 36, 2^{nd} moments

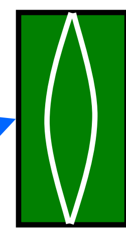
1. The beam matrix: **σ**
 (the covariance matrix)
 →9, 2x2 matrices

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yx} & \sigma_{yx} \\ \sigma_{zx} & \sigma_{zx} & \sigma_{zx} \end{bmatrix}$$

2. The transfer matrix
 → e.g. quadrupole

$$A_F = \begin{bmatrix} \cos(\sqrt{\kappa}l) & \sin(\sqrt{\kappa}l)/\sqrt{\kappa} \\ -\sqrt{\kappa}\,\sin(\sqrt{\kappa}l) & \cos(\sqrt{\kappa}l) \end{bmatrix}$$

$$\sigma(s_2) = R\sigma(s_1)R^T$$



$\sigma(s_1)$ $\sigma(s_2)$

3. 9 second moments (usually ignore non-diagonal elements)

$$\sigma_{xx} = \begin{bmatrix} \beta_x\varepsilon_x & -\alpha_x\varepsilon_x \\ -\alpha_x\varepsilon_x & \gamma_x\varepsilon_x \end{bmatrix}$$

$\sigma_{11} = \sqrt{\beta_x\varepsilon_x}$ spread in position

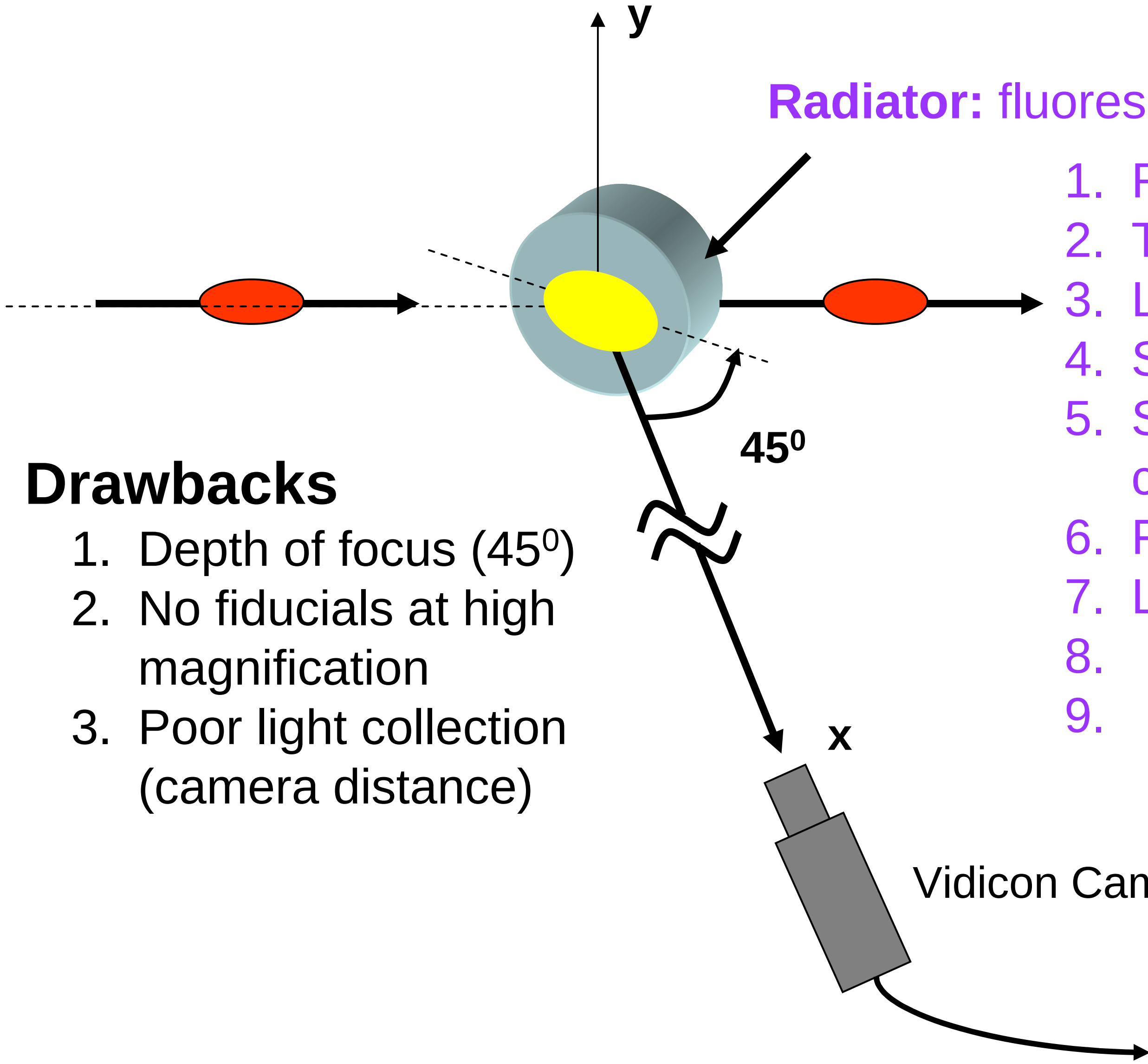
$\sigma_{22} = \sqrt{\gamma_x\varepsilon_x}$ spread in angle

$$\det(\sigma_{xx}) = \left(\beta_x\gamma_x - \alpha_x^2\right)\varepsilon_x^2 = \varepsilon_x^2$$

The Profile: generating and capturing

experiment
in use

The Old Imaging System



Radiator: fluorescent, OTR, Cherenkov

1. Response time
2. Thickness
3. Light yield
4. Spatial Resolution
5. Spectrum match to camera
6. Fiducial marks
7. Linearity
8.
9.

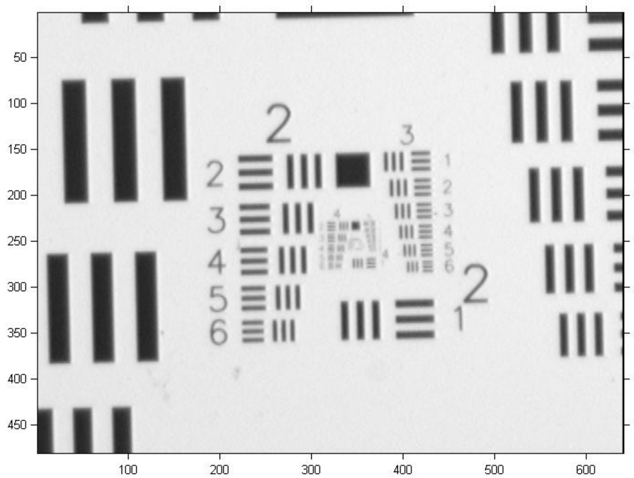
Drawbacks

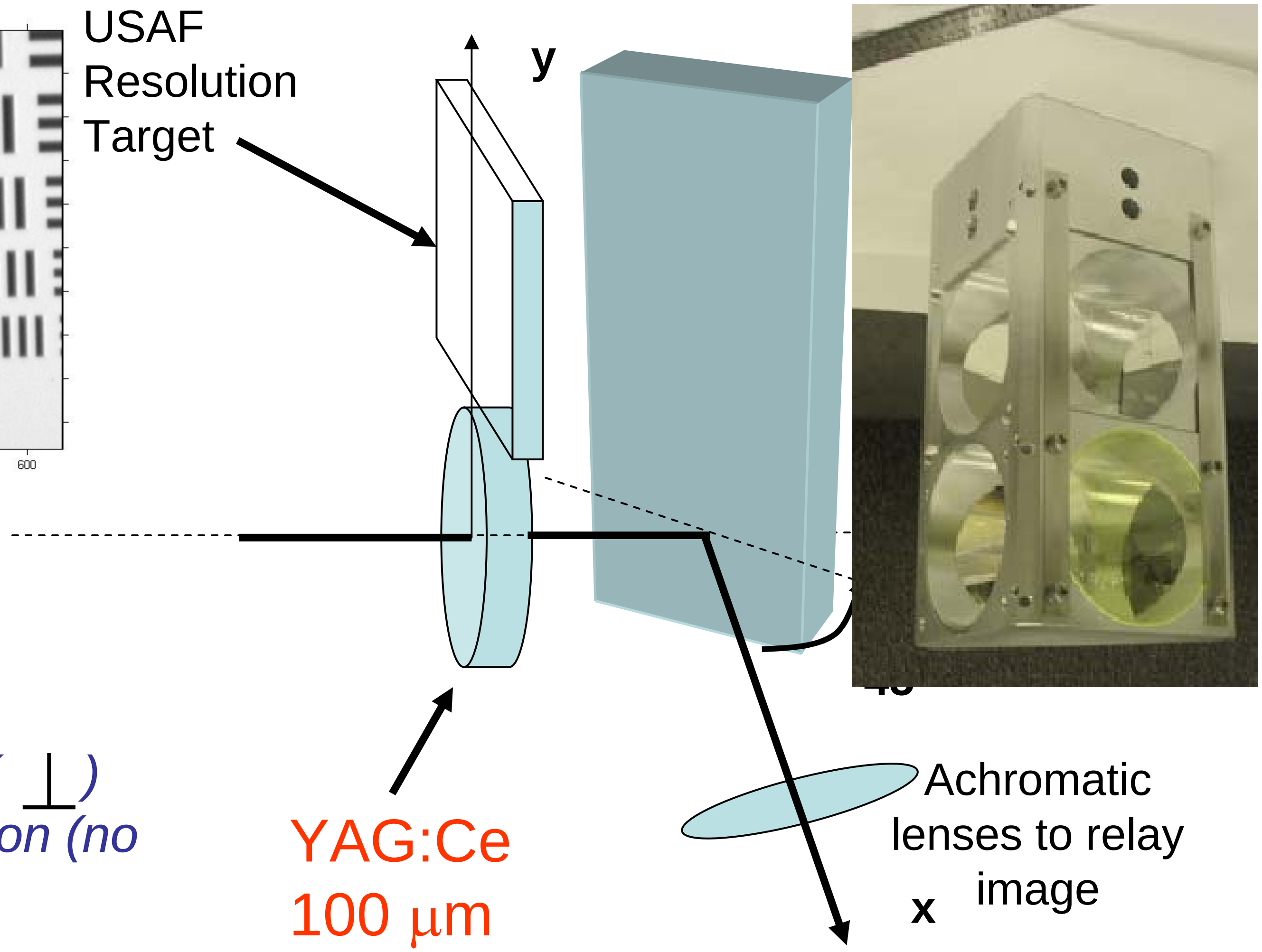
1. Depth of focus (45^0)
2. No fiducials at high magnification
3. Poor light collection (camera distance)

The Profile: generating and capturing

experiment
in development

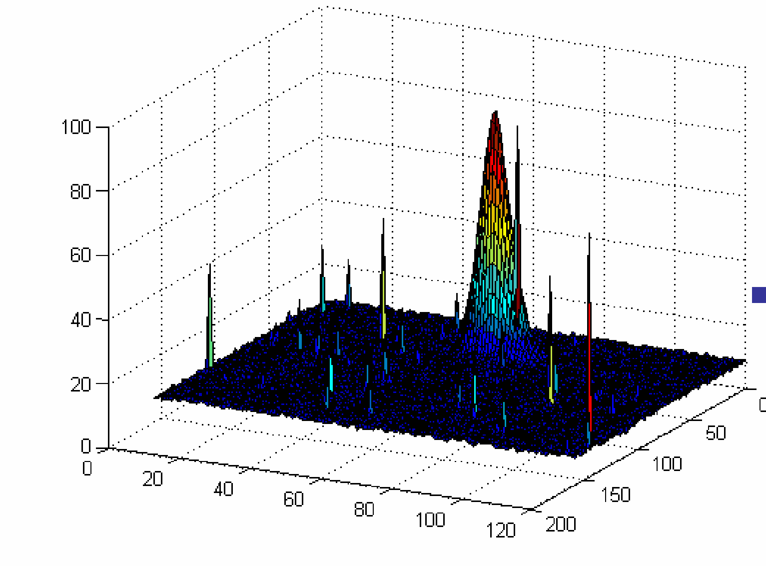
The New Imaging System





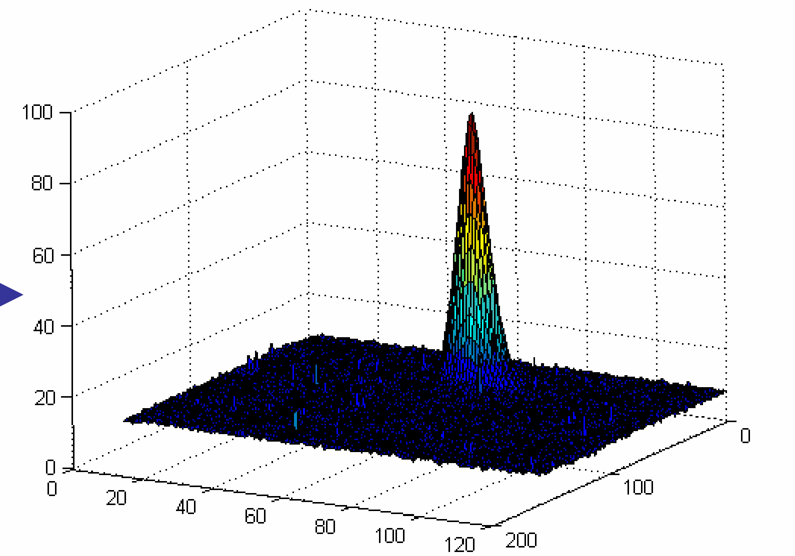
1. *Depth of focus (⊥)*
2. *Low-magnification (no fiducials at high magnification)*
3. *Improved light collection*

The Profile: Extracting it from the image experiment

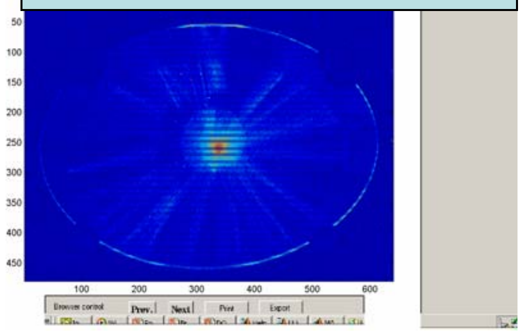


Remove

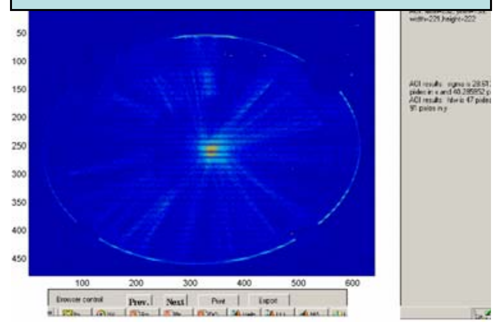
X-ray Noise



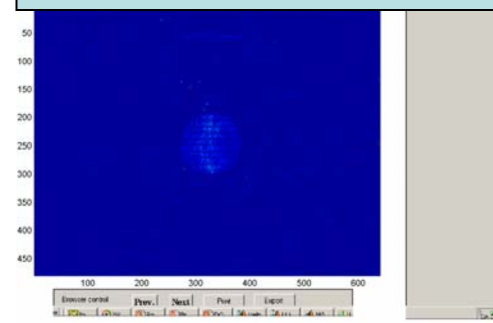
1. Raw Image



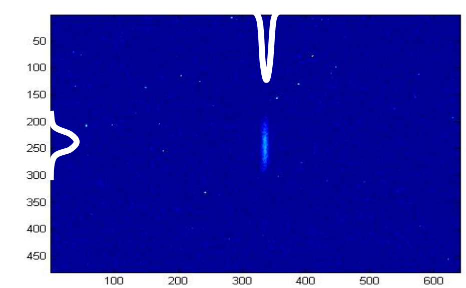
2. Background Image



3. Subtracted Image



Finally → calculate standard deviation of projectio[n]
→ fit to a function (e.g. Gaussian)



Emittance Measurements at the AWA

Transverse emittance

1. Modified 3 Screen
2. Modified Quad-Scan
3. Pepper Pot
4. OTR-based

Longitudinal Emittance

1. Never attempted at AWA (instead → separate energy spread & bunch length)
2. New Idea: Time resolved spectrometer

1. Modified 3 screen technique

theory

transverse emittance → measure beam envelope

1. **Standard 3-screen doesn't work (ignores space-charge).**

$$\sigma = \begin{bmatrix} \beta\varepsilon & -\alpha\varepsilon \\ -\alpha\varepsilon & \gamma\varepsilon \end{bmatrix} \qquad \sigma_2 = R\sigma_1 R^T \qquad \beta\gamma - \alpha^2 = 1$$

→

[1] 3 unknowns: α, β, ε
[2] Ignore space charge
[3] Measure beam at 3 screens

2. A Modified 3-screen Technique that includes space-charge in the model of the beam drift.

$$\sigma''(s) + \kappa_0(s)\sigma(s) - \frac{\varepsilon^2}{\sigma(s)^3} - \frac{K}{4\sigma(s)} = 0$$

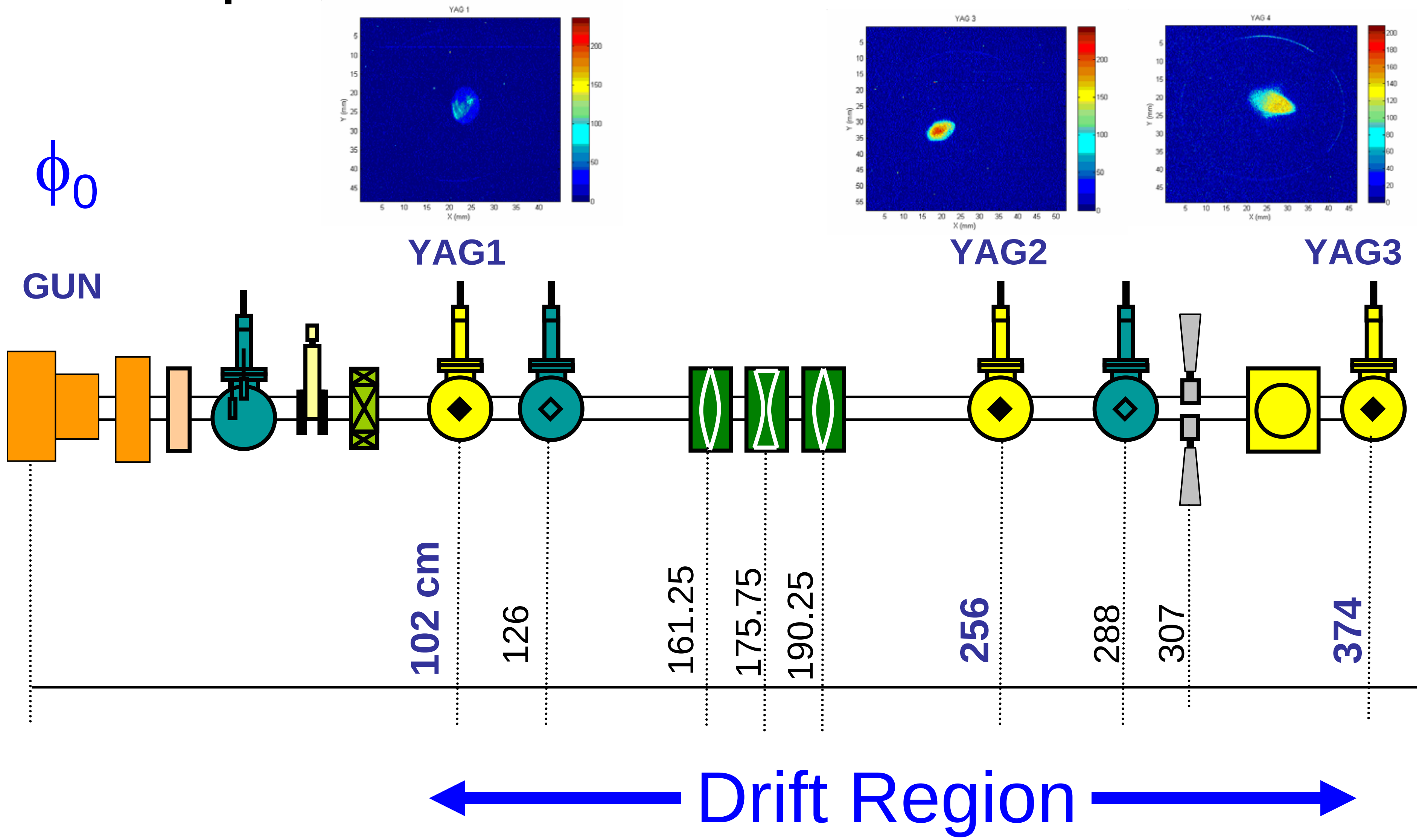
[1] 4 unknowns: σ, σ', ε, K
[2] K from Q & σ_z
(or 4 screens)

$$R = \frac{K\sigma^2}{4\varepsilon^2}$$

1. Modified 3-screen technique

experiment

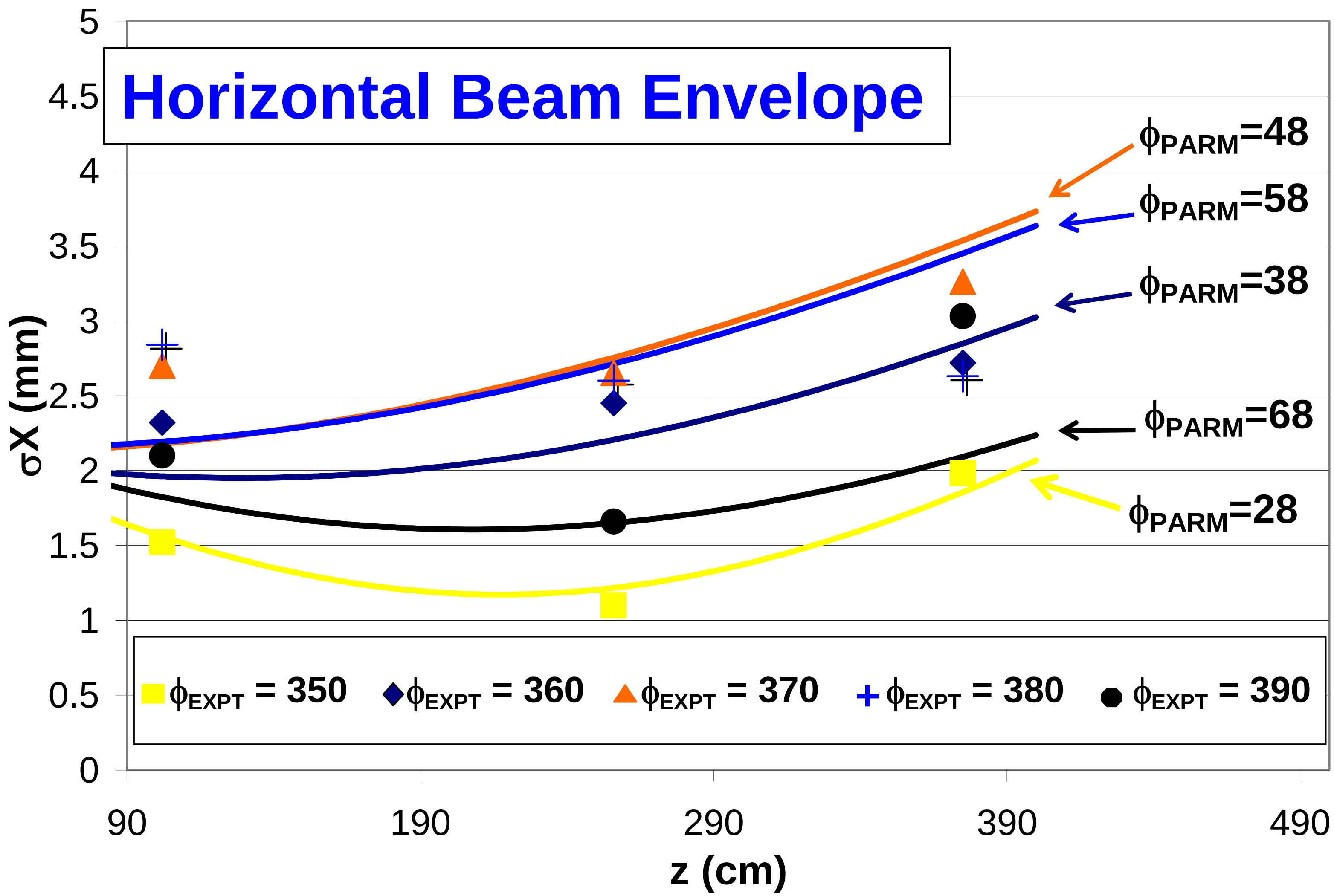
Measure spot size at 3 locations



1. Modified 3-screen technique

experiment

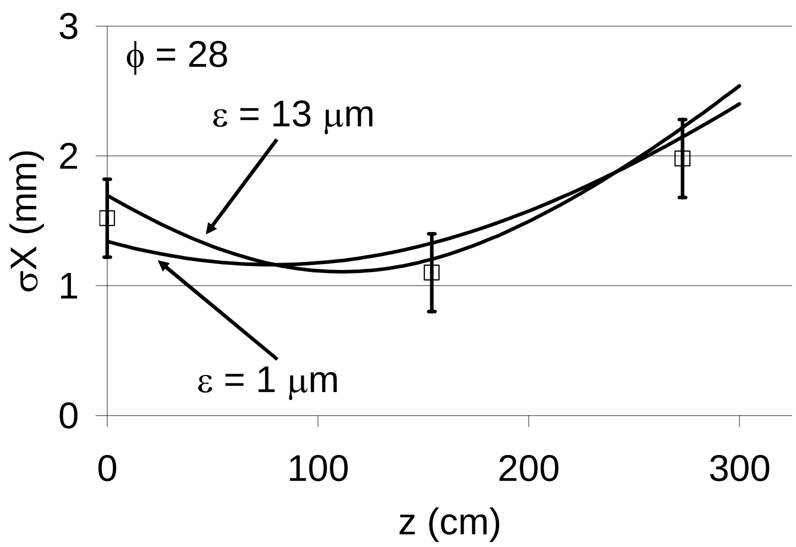
Comparison Between PARMELA and Measured Spot Sizes

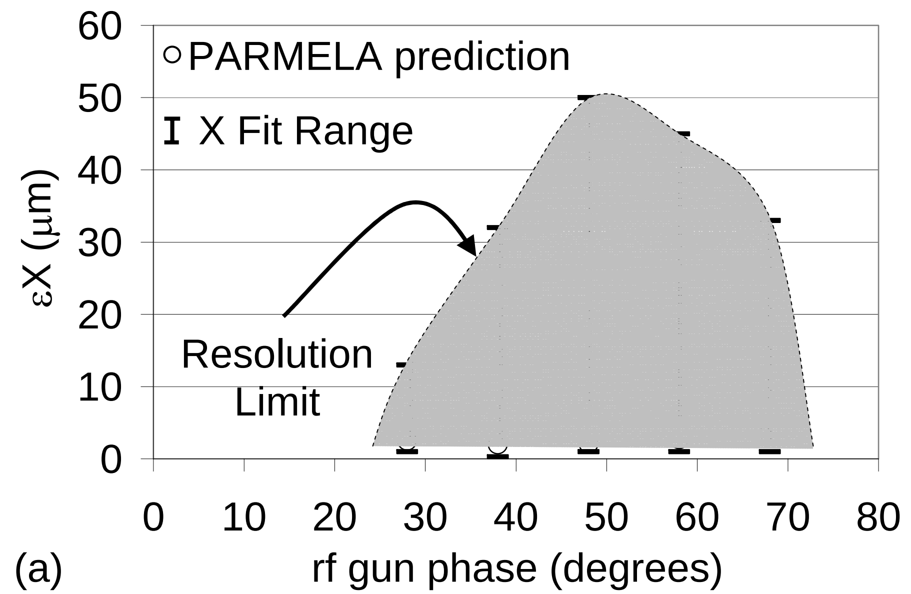


1. Modified 3-screen technique

transverse emittance: Fit data to envelope equation to extract emittance

(e.g. RF Phase = 28^0)





(a)

Technique has low emittance resolution for heavily space charge dominated beam

1. Space charge is large
2. Beam spots are measured with limited resolution (+/- 300 μm)

$$R = \frac{K\sigma^2}{4\varepsilon^2} \longrightarrow 100 < R < 1000$$

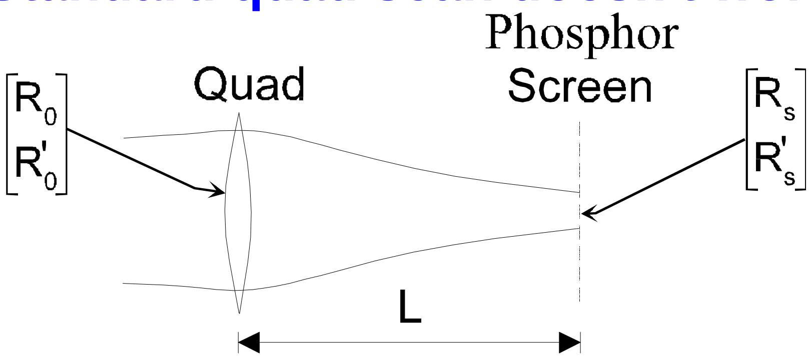
Drive beam is heavily space-charge dominated

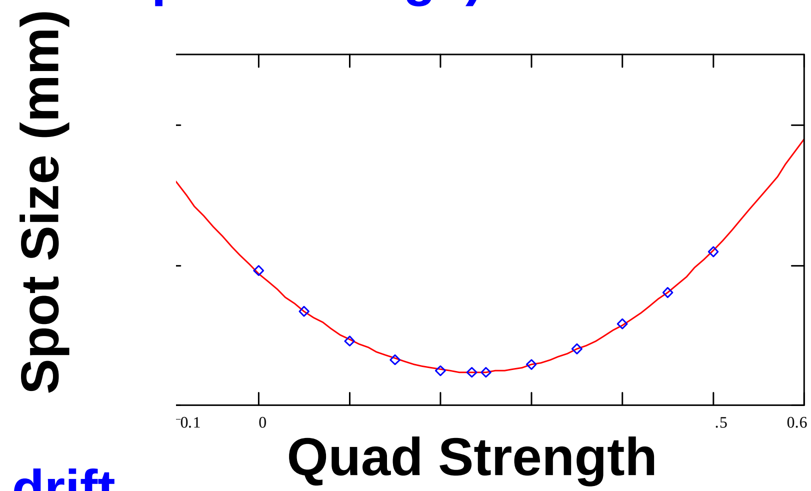
2. Modified Quad Scan technique

theory

transverse emittance

1. **Standard quad scan doesn't work (ignores space-charge).**





2. **Include space-charge in model of beam drift**

$$a_x'' + \kappa_{x0}(s)\,a_x - \frac{\varepsilon^2_{x,rms}}{a_x^3} - \frac{3K_3(1-f)}{5\sqrt{5}\,(a_x + a_y)\,a_z} = 0$$

$$a_y'' + \kappa_{y0}(s)\,a_y - \frac{\varepsilon^2_{y,rms}}{a_y^3} - \frac{3K_3(1-f)}{5\sqrt{5}\,(a_x + a_y)\,a_z} = 0$$

$$a_z'' + \kappa_{z0}(s)\,a_z - \frac{\varepsilon^2_{z,rms}}{a_z^3} - \frac{3K_3 f}{5\sqrt{5}\,a_x a_y} = 0$$

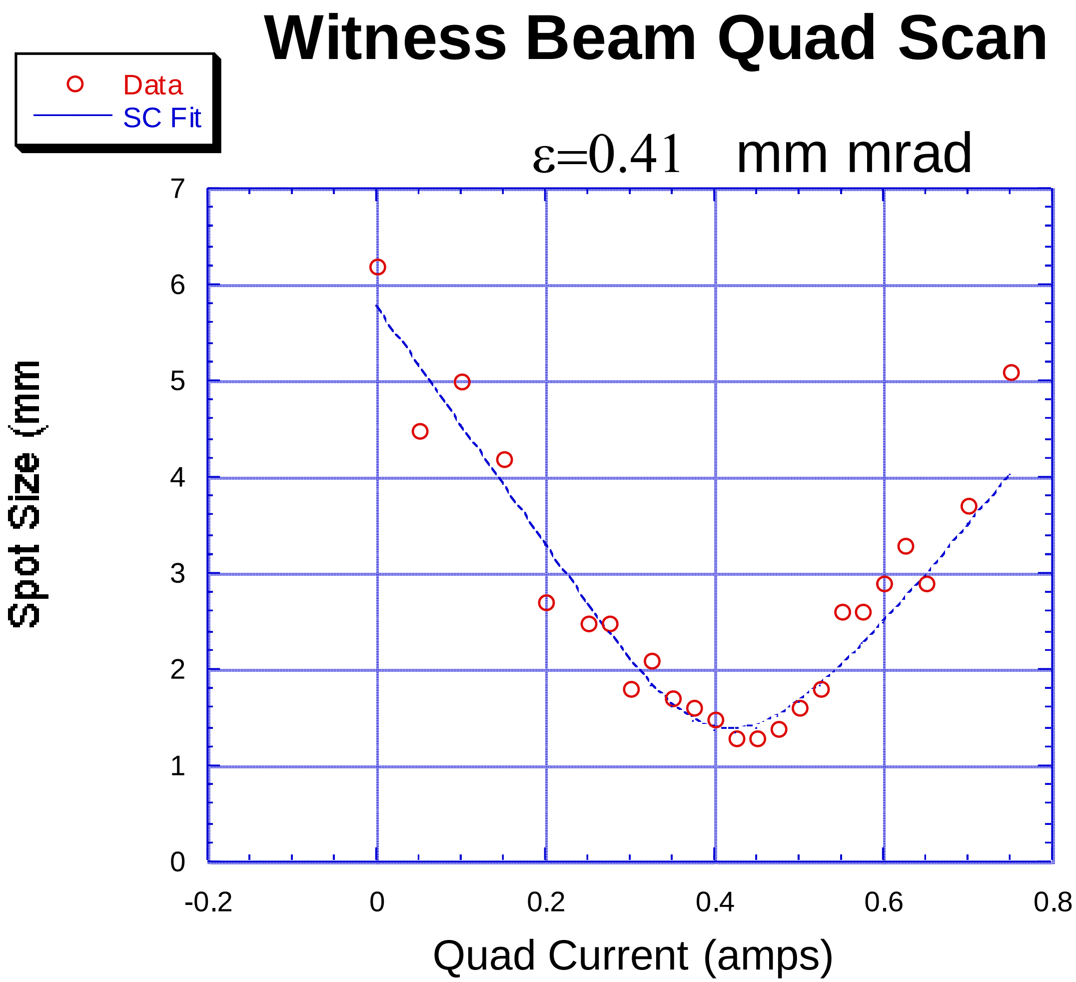
1. Space charge couples motion
2. 3 unknowns ε, a, a' (1D)
   6 unknowns: (2D)
   9 unknowns: (3D)
3. Assume K from Q & σ_z

2. Modified Quad Scan technique

transverse emittance

Least squares fitting

$$\chi^2 = \sum_i \left(R_{measured,i} - R_{fit,i}\left[R_0, R_0', \varepsilon\right] \right)^2$$



For witness beam

$$R = \frac{K\sigma^2}{4\varepsilon^2} = 10$$

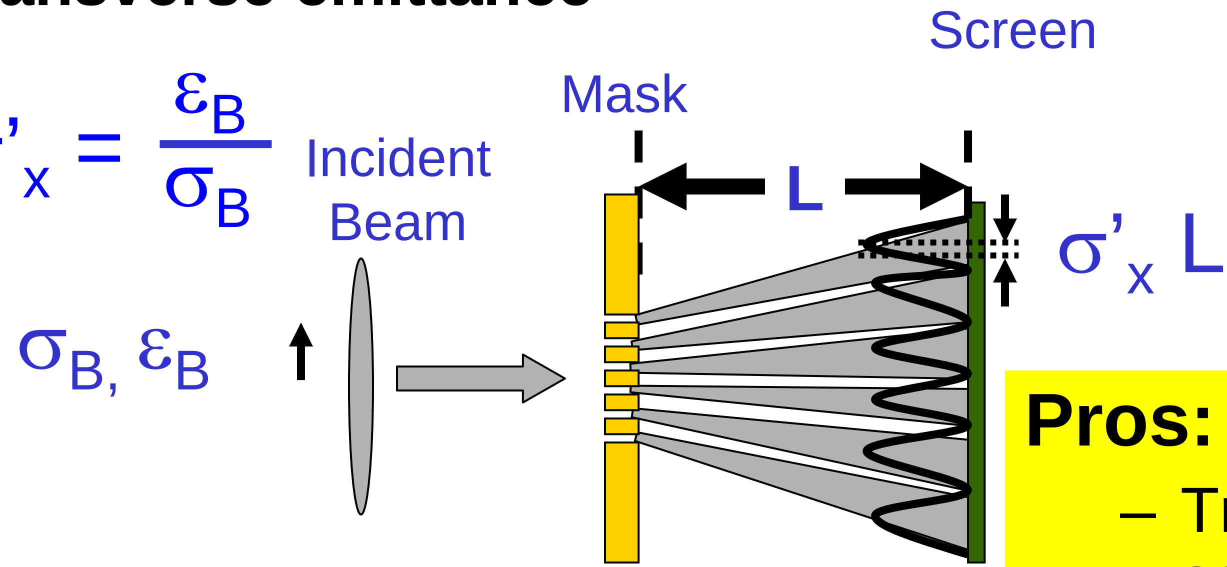
Same problem as 3-screen

→ low emittance resolution for heavily space charge dominated beams

3. Pepper Pot technique

transverse emittance

$$\sigma'_x = \frac{\varepsilon_B}{\sigma_B}$$



Pros:

- True phase space sampling (model free)
- single shot

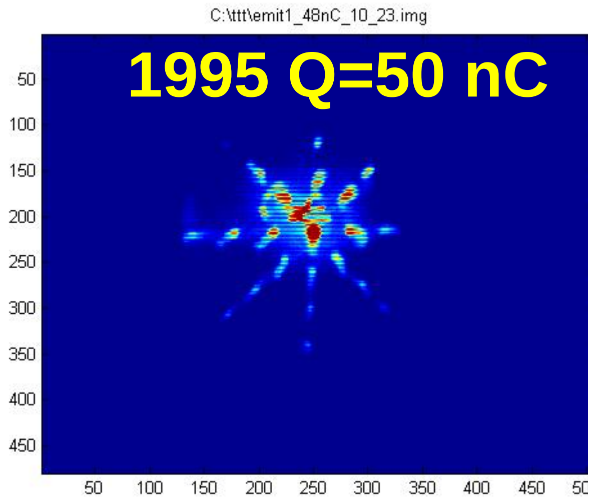
Cons/Difficulties:

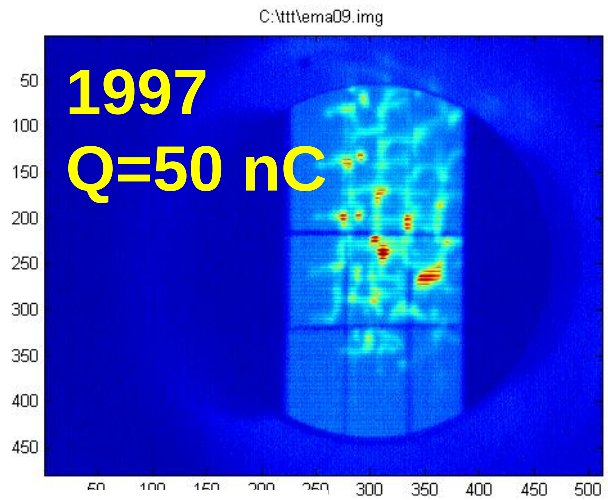
- Simulations
  - Is contribution of scattered particles negligible?
  - Are space charge forces in drift negligible?
  - What is the effect of energy spread?
- Imaging System design
  - Resolution
  - Light Collection

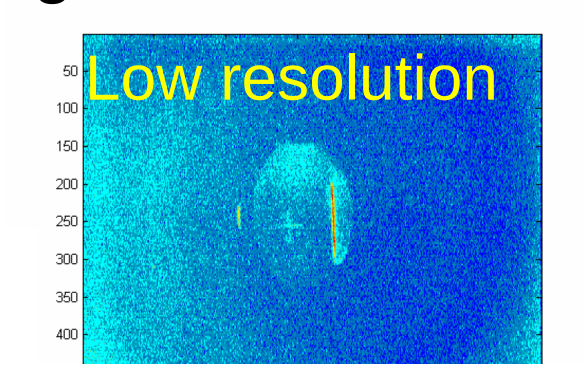
3. Pepper Pot technique

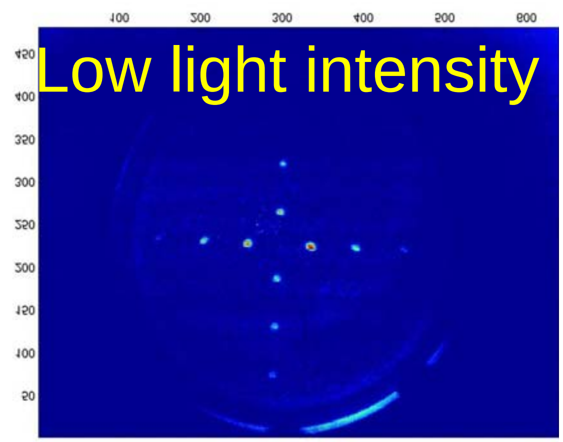
transverse emittance → residual space charge effect

Pepper pot images over the years …









Spots poorly separated
ILL behaved beamlets

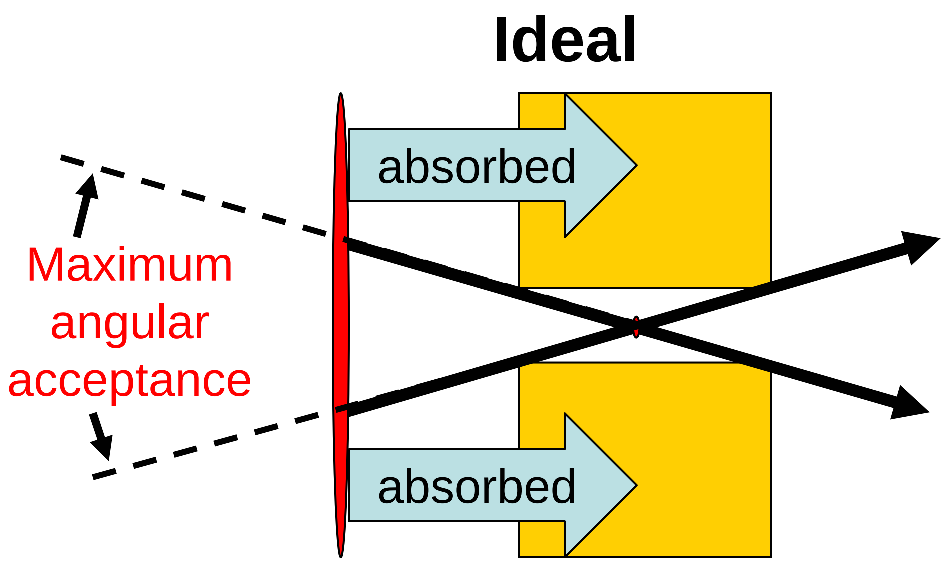
Only low resolution estimates of the emittance so far

Developing a better understanding of entire pepper pot system

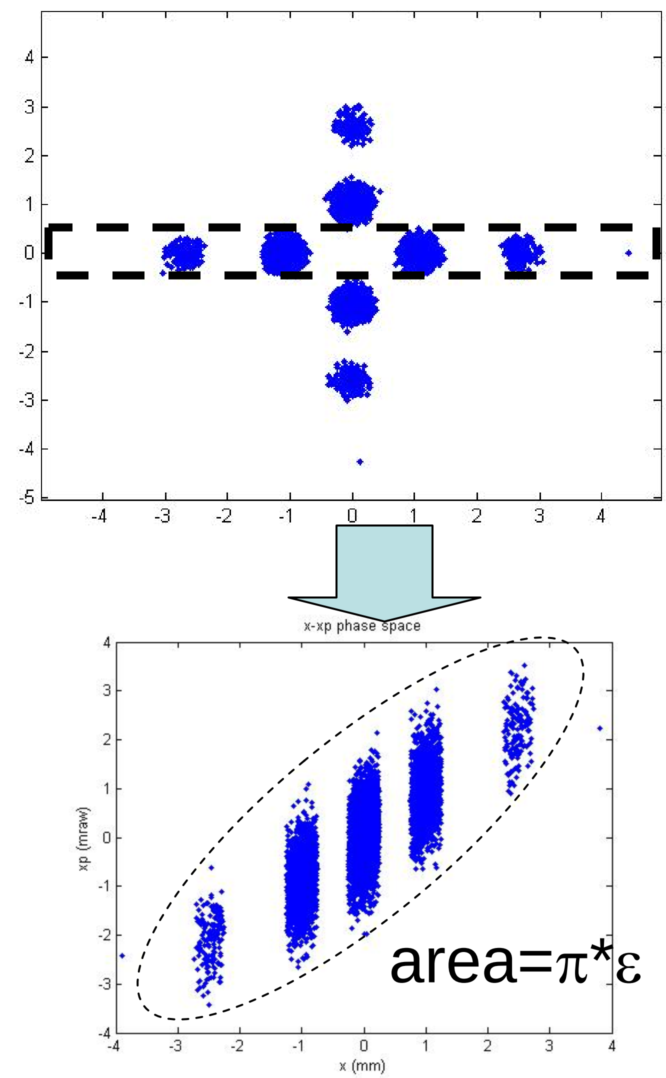
3. Pepper Pot technique

simulation

transverse emittance → slit scatter



PARMELA Simulation



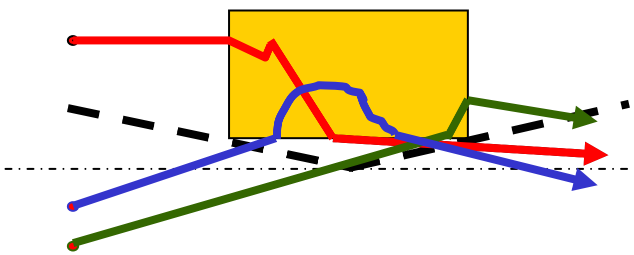
simulation

3. Pepper Pot technique

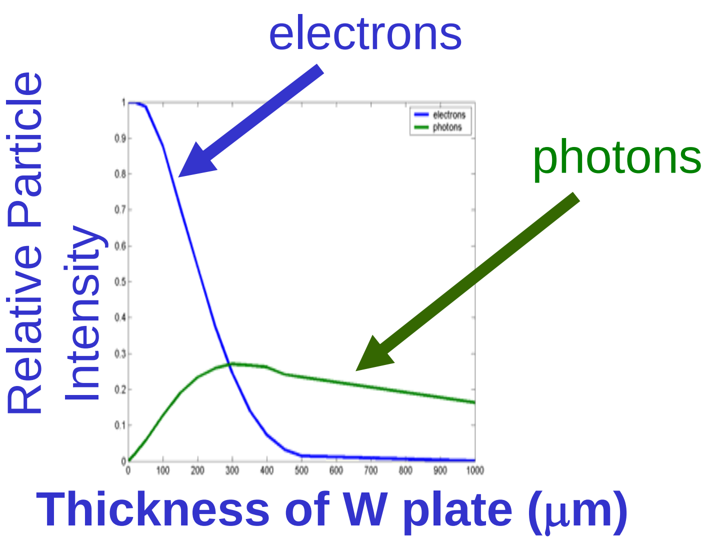
transverse emittance → slit scatter

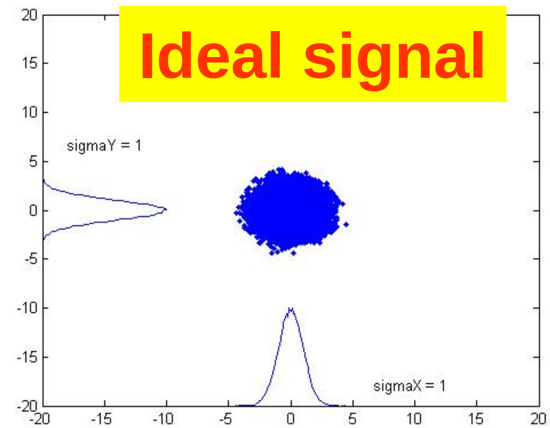
Realistic beam-target simulations w/ EGS4

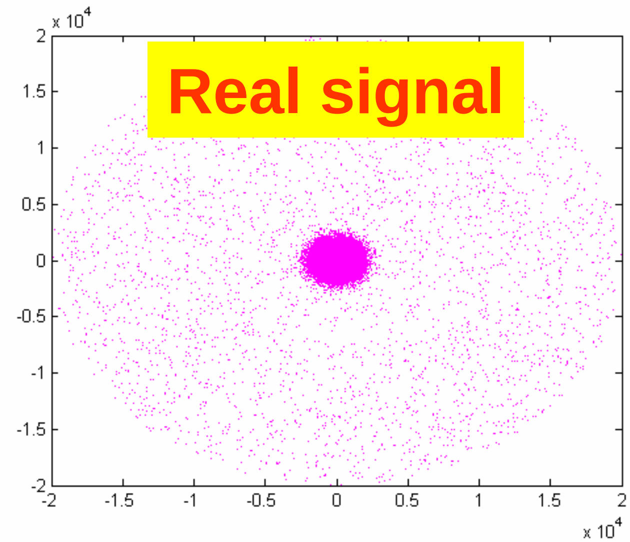
Slit scatter



Multiple scattering & attenuation



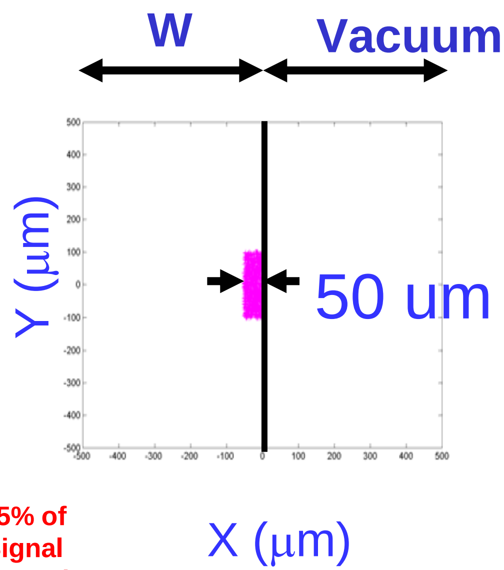


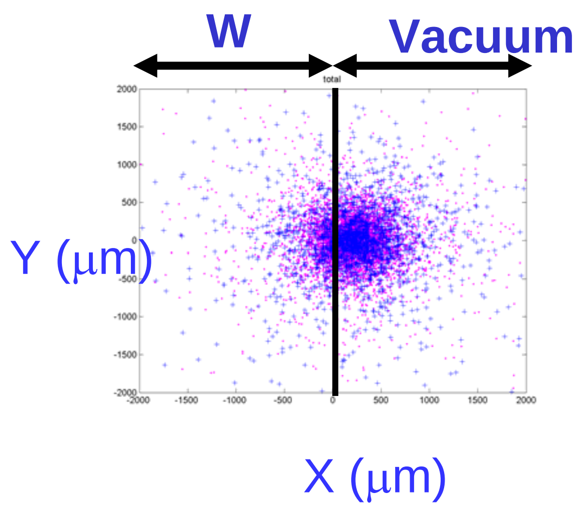


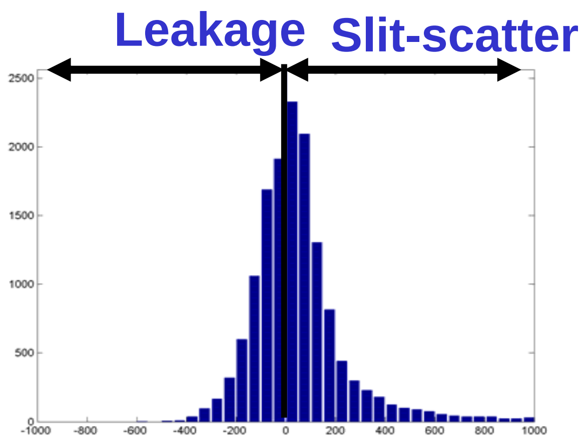
simulation

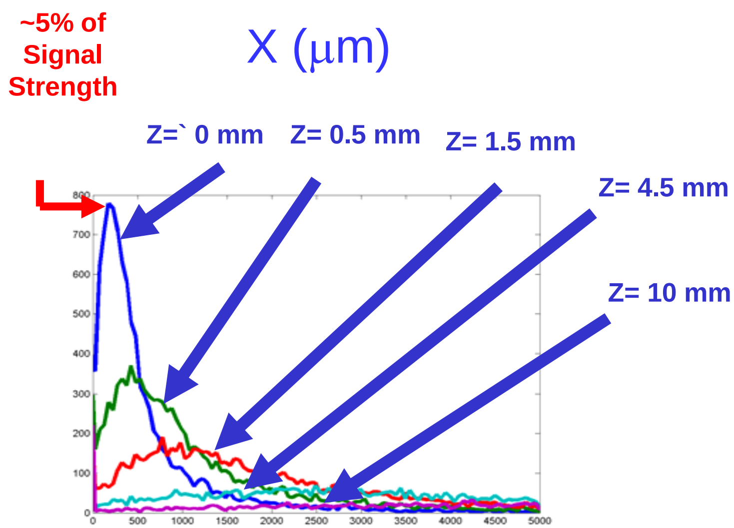
3. Pepper Pot technique

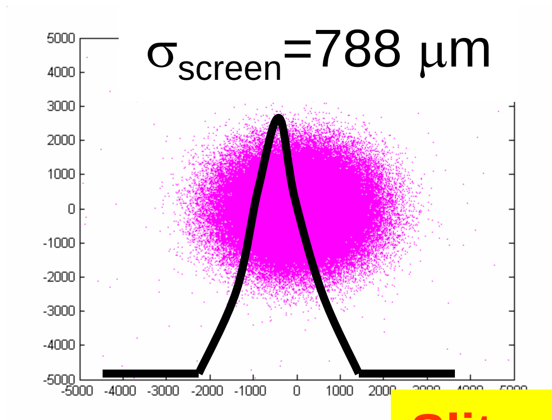
transverse emittance → slit scatter











Result of Fit

σ_{true}=1.50 mrad

σ_{fit}=1.49 mrad

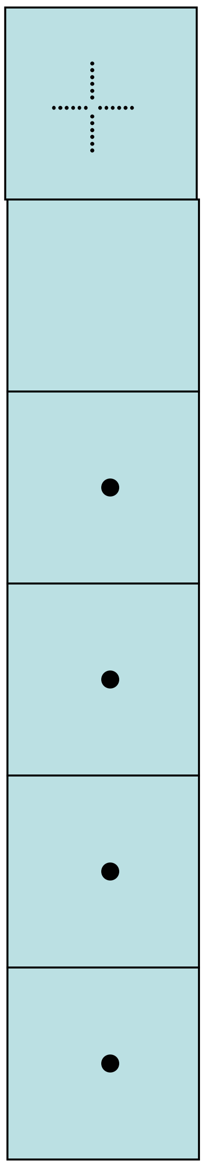
Slit-scattering is not a major problem for 8 MeV case.

3. Pepper Pot technique

experiment

transverse emittance → residual space charge effect

$$\sigma''(s)+\kappa_0(s)\sigma(s)-\frac{\varepsilon^2}{\sigma(s)^3}-\cancel{\frac{K}{4\sigma(s)}}=0$$



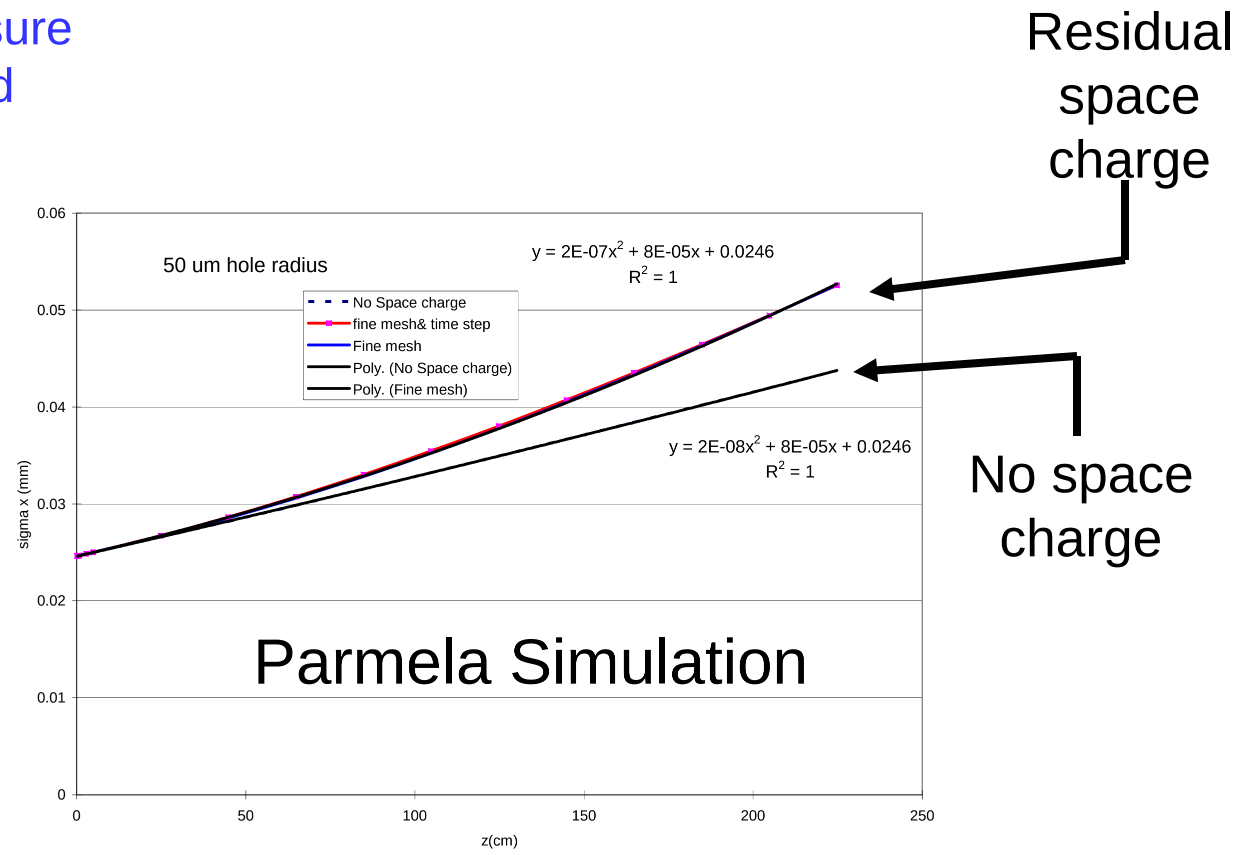
blank to measure background

12.5 μm

25 μm

50 μm

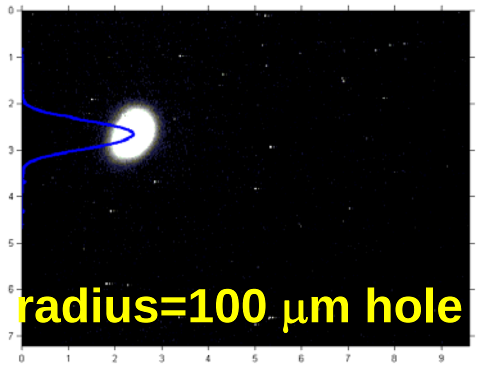
100 μm

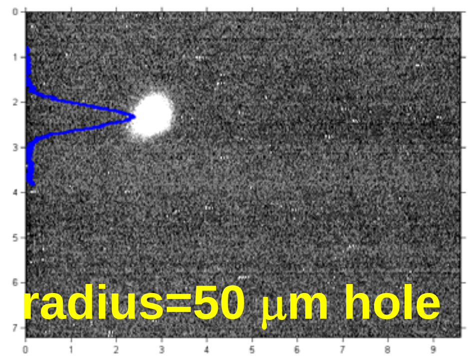


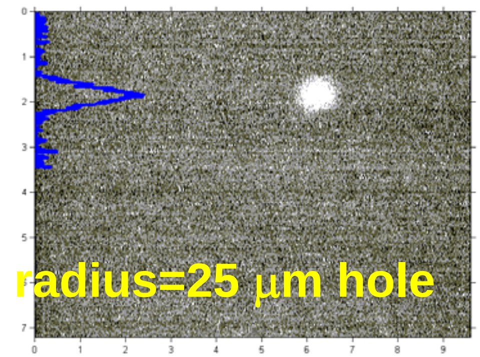
3. Pepper Pot technique

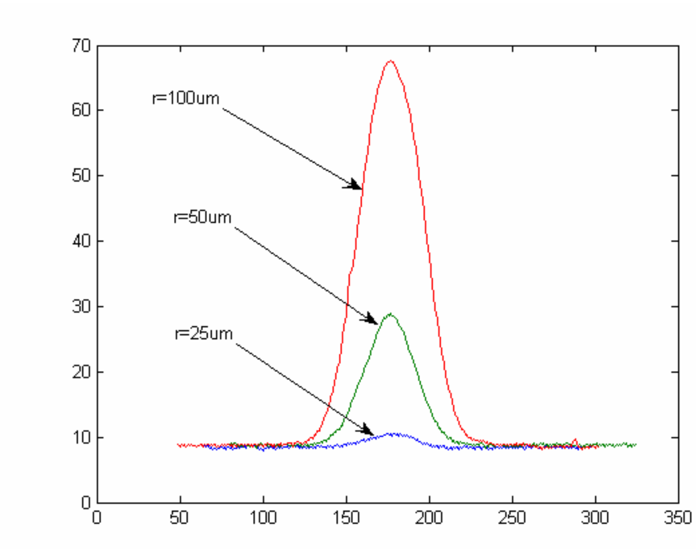
experiment

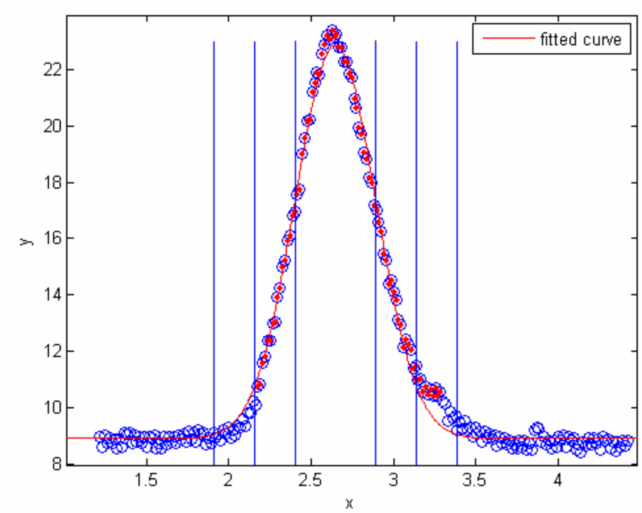
transverse emittance → residual space charge effect











Hole Radius (μm)	sigmaH (μm)	sigmaV (μm)	stdH (μm)	stdV (μm)
25	219	208	193	184
50	217	235	193	207
100	219	237	198	207

3. Pepper Pot technique

transverse emittance → residual space charge effect

Measured spot sizes agree (σ_H = 219 μm, 217 μm, 219 μm)

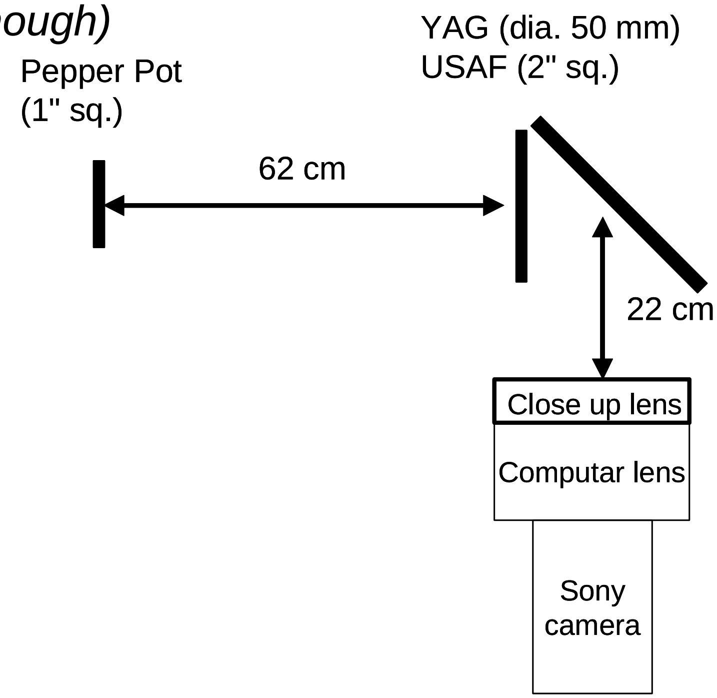
- absence of residual space charge forces?
- resolution of the imaging system?

What resolution is needed?

- $\sigma_{meas}^2 = \sigma_{true}^2 + \sigma_{res}^2$
- if $\sigma_{res} = (1/3) * \sigma_{true}$ then 5% error *(good enough)*
- σ_{true} = 200 um → σ_{res} < 70 um

The Imaging System

- Computar lens 135 mm F/1.8
- Object distance = 260 mm
- Sony Camera 8-bit CCD



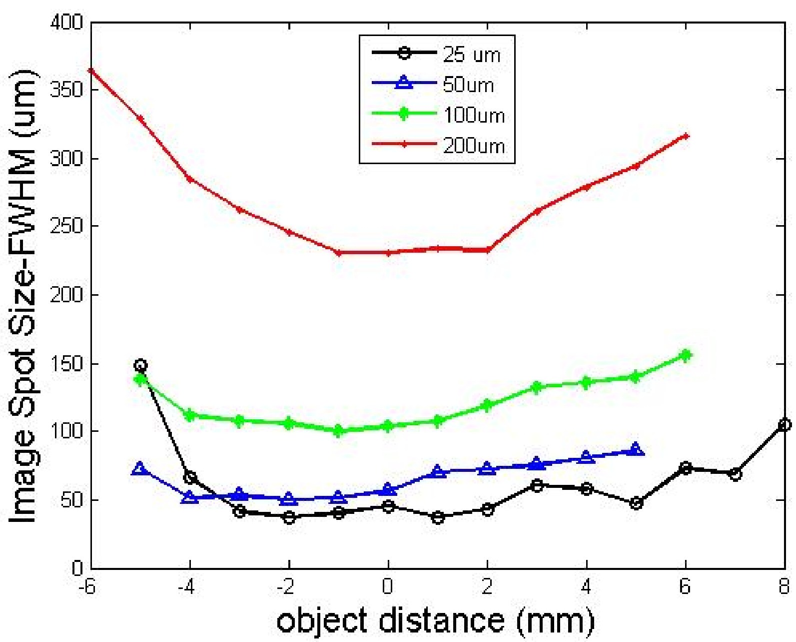
3. Pepper Pot technique

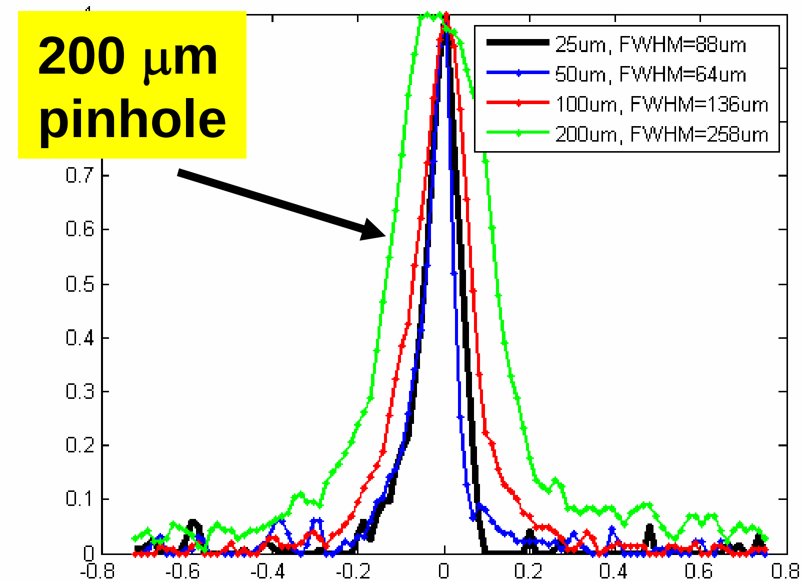
experiment

transverse emittance → residual space charge effect

Point Spread Function of Imaging System

What is the smallest spot of light our *Imaging System* can measure?





Sensitive to the depth of focus

Conclusion:

1. Can't tell what caused agreement
2. Need to repeat experiment with

4. Optical Transition Radiation

theory

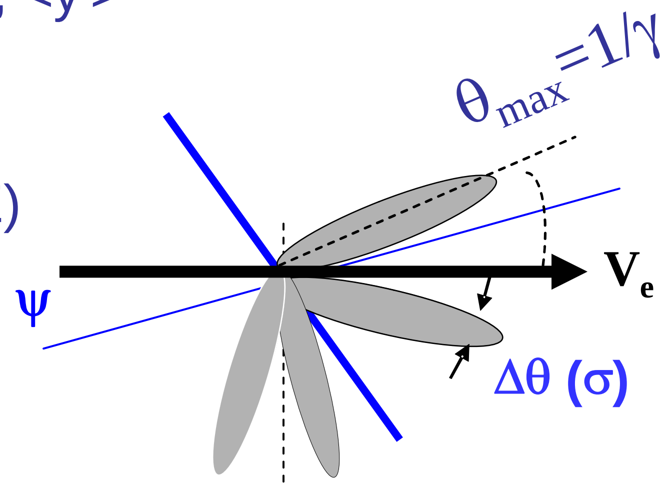
transverse emittance (collaboration with R. Fiorito @ UMD)

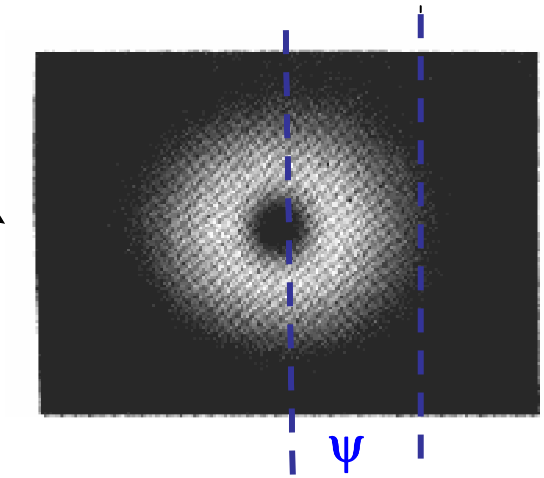
Far Field Imaging
(angular distribution)

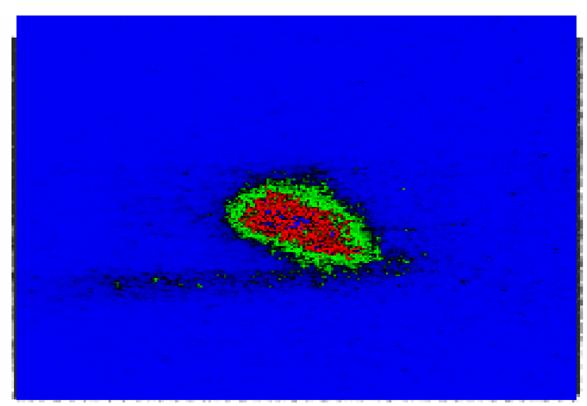
- trajectory angle <x'>, <y'>
- divergence σ'_x, σ'_y
- energy (E)
- energy spread (dE/E)

Near Field Imaging
(spatial distribution)

- mean <x>, <y>
- size σ_x, σ_y







theory

4. OTR Interferometer

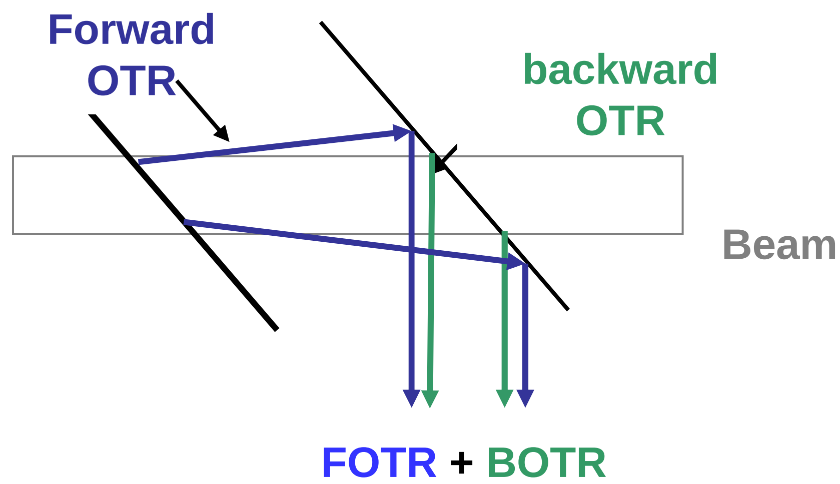
transverse emittance → greater sensitivity to beam parameters

High Energy

50 MeV, 650 nm

L=formation length

$\sim \gamma^2\lambda \sim$ 40 mm

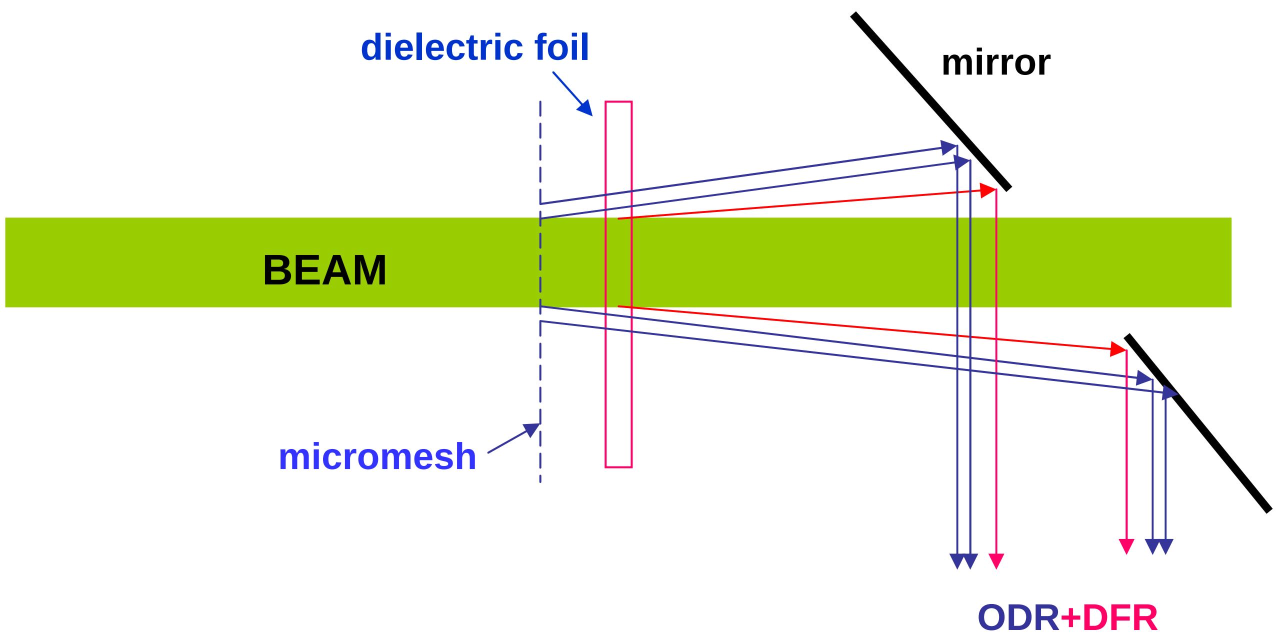


Low Energy

8 MeV, 650 nm

L=formation length

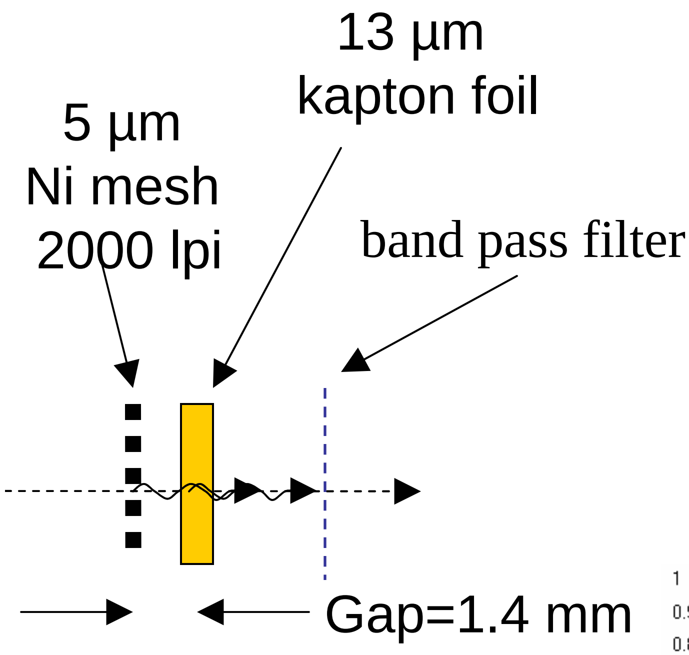
$\sim \gamma^2\lambda \sim$ 1 mm



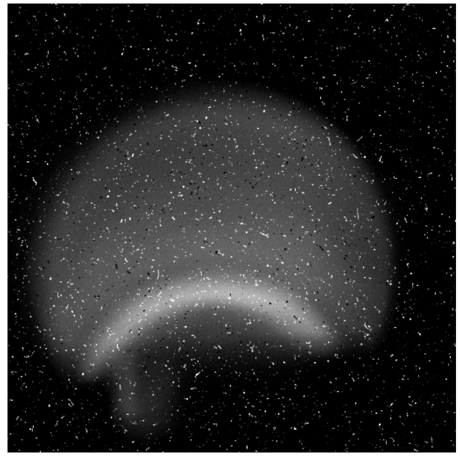
4. Optical Transition Radiation

experiment

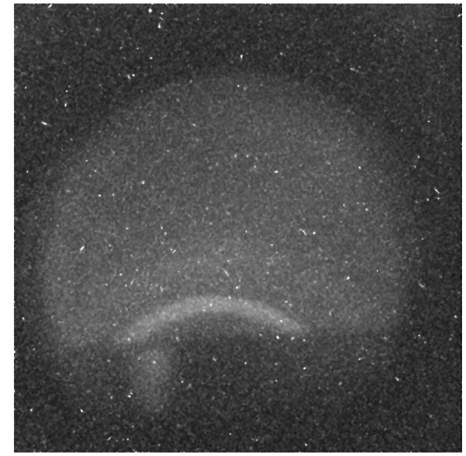
transverse emittance → first experiment (2004)



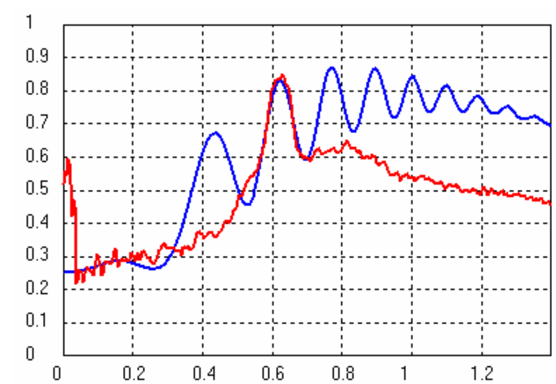
666 x 80 nm
band pass filter



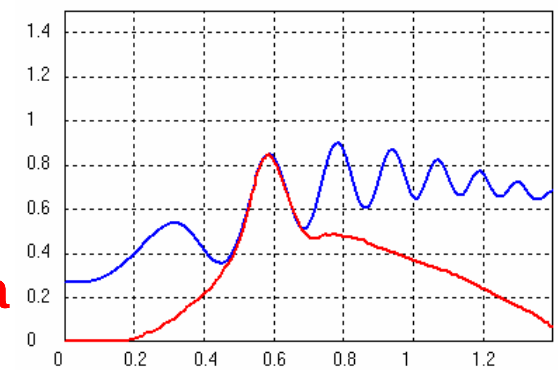
505 x 10 nm
band pass filter



simulation



data



Observation angle (1/γ units) Observation angle (1/γ units)

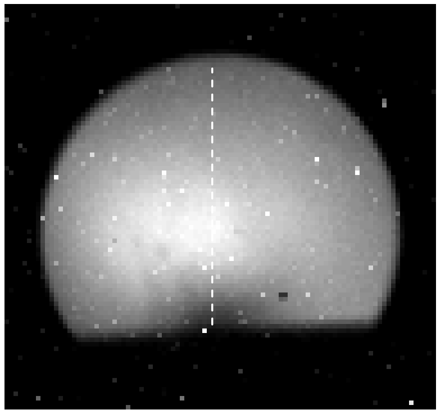
Conclusion '04 exp't:
missing fringes due to misalignment of beam to mirror to center of the interferometer

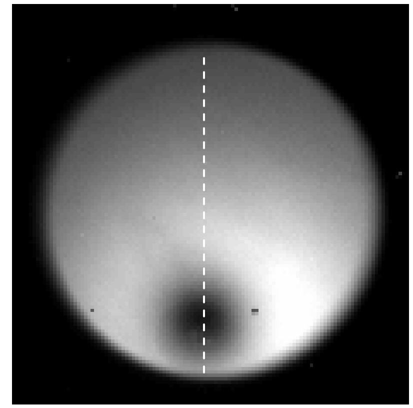
Applying the OTR-based diagnostic to low energies

4. Optical Transition Radiation

transverse emittance → second experiment (2005)

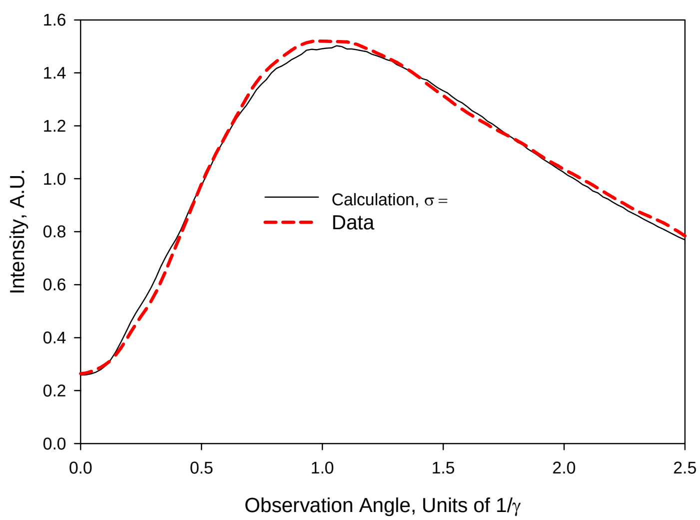
washed out
ODR-DFR
Interference
pattern



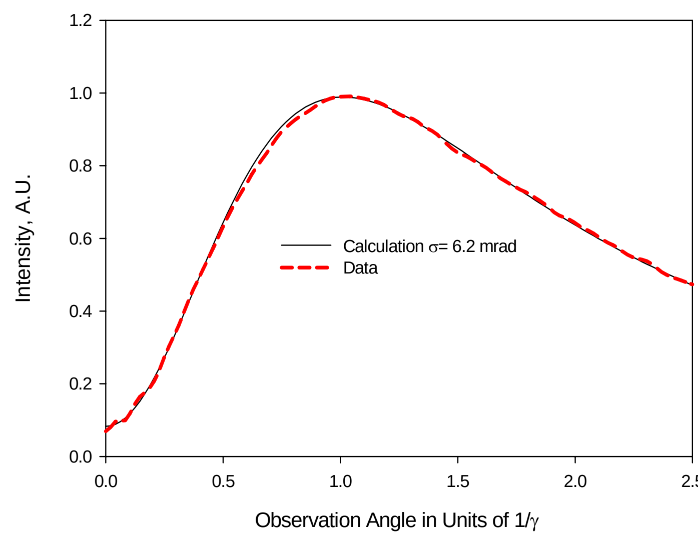


large divergence
(σ= 6.2mr)
verified by
single foil OTR
measurement

ODR- Dielectric Foil (λ = 505nm X 10 nm filter)



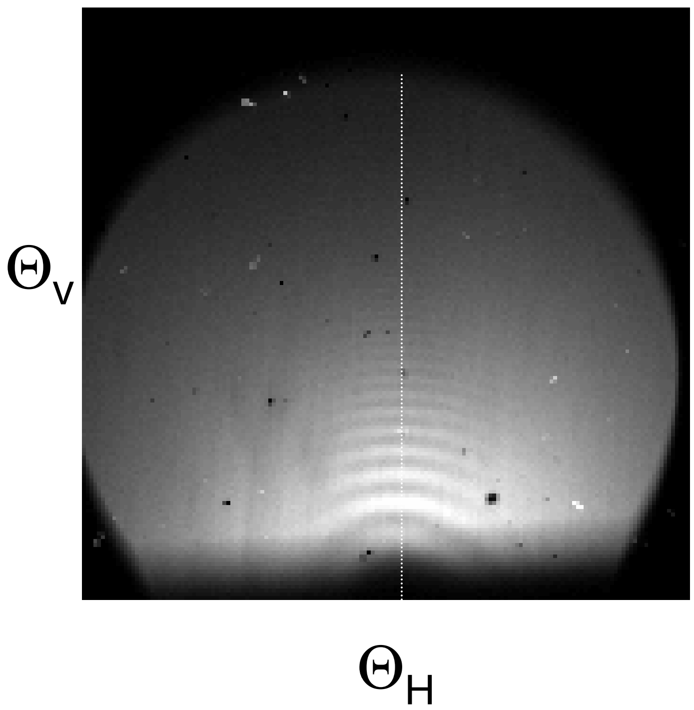
OTR from Mirror no filter

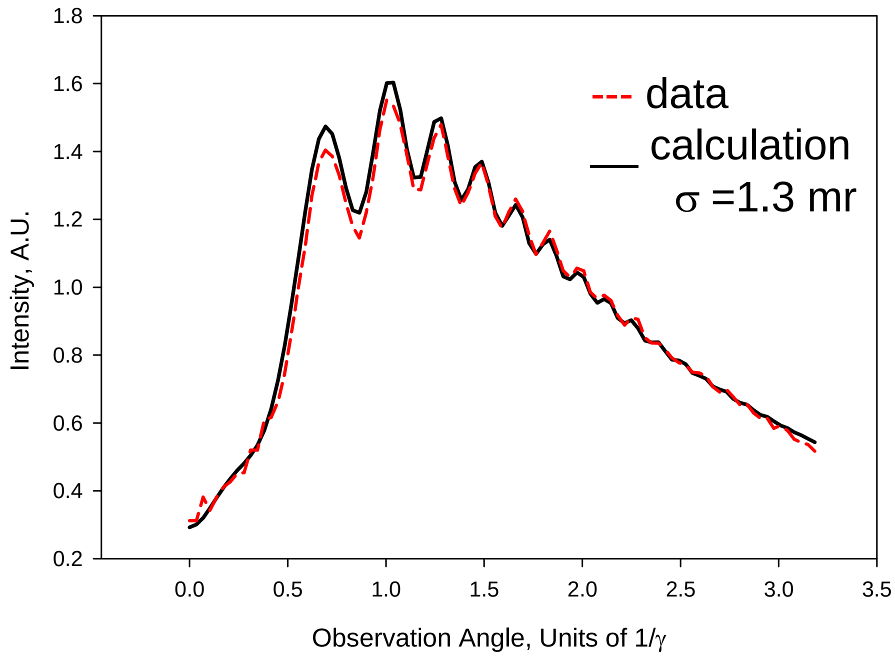


4. Optical Transition Radiation

experiment

transverse emittance → second experiment (2005)

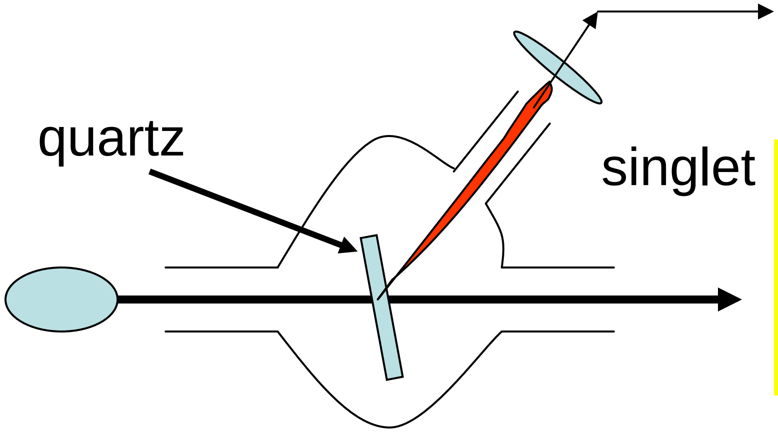




Observed ODR-DFR Interferences at E= 14.2 MeV (Oct. 7, 2005) when beam divergence lowered by vertically expanding beam experiment

Cherenkov/OTR + Streak Camera

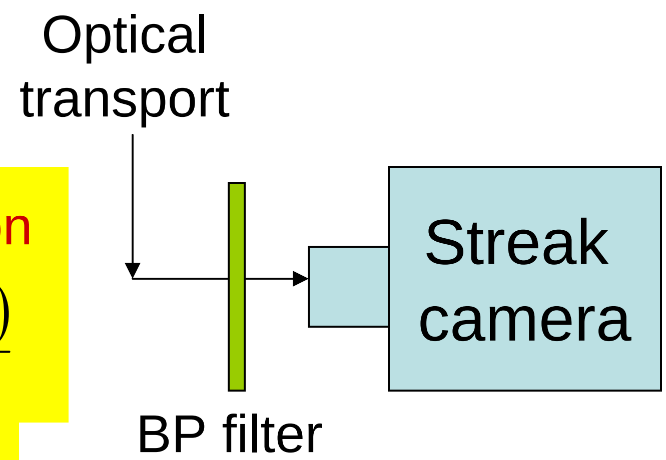
longitudinal → bunch length



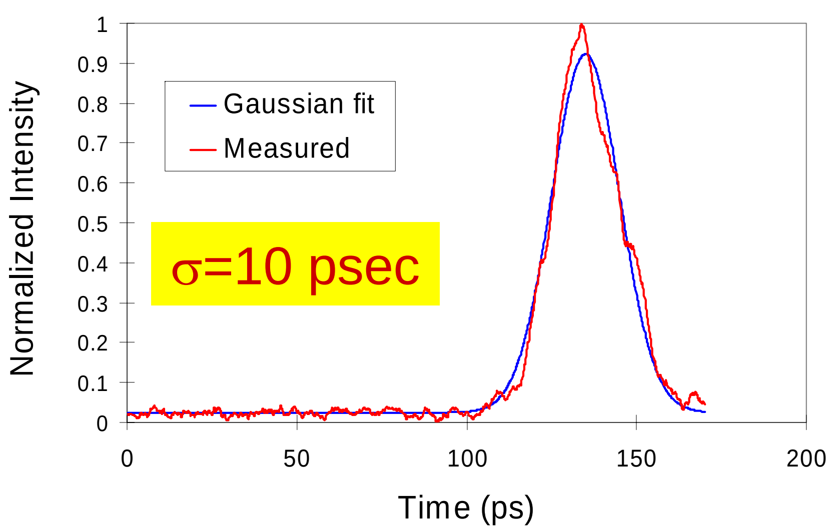
Time dispersion

$$\Delta t = \frac{R \cdot n \cdot \sin(\theta_c)}{c}$$

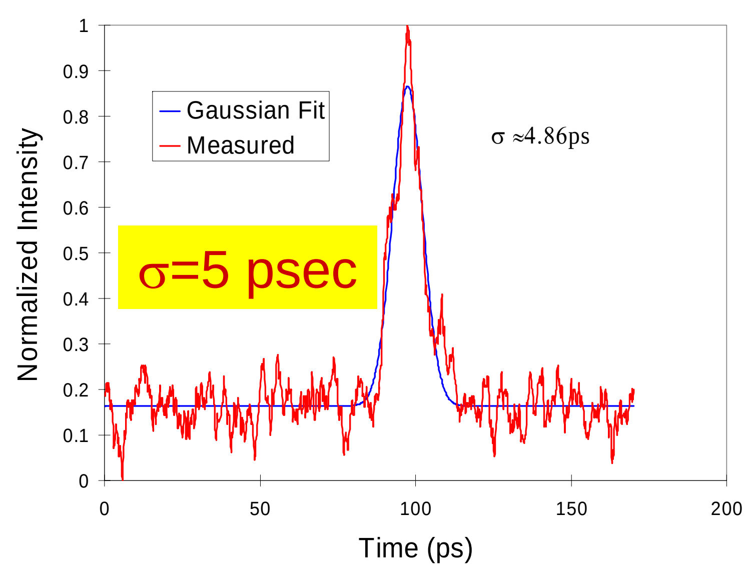
Δt=3.7 psec



Measured 35 nC Electron Pulse with no filter

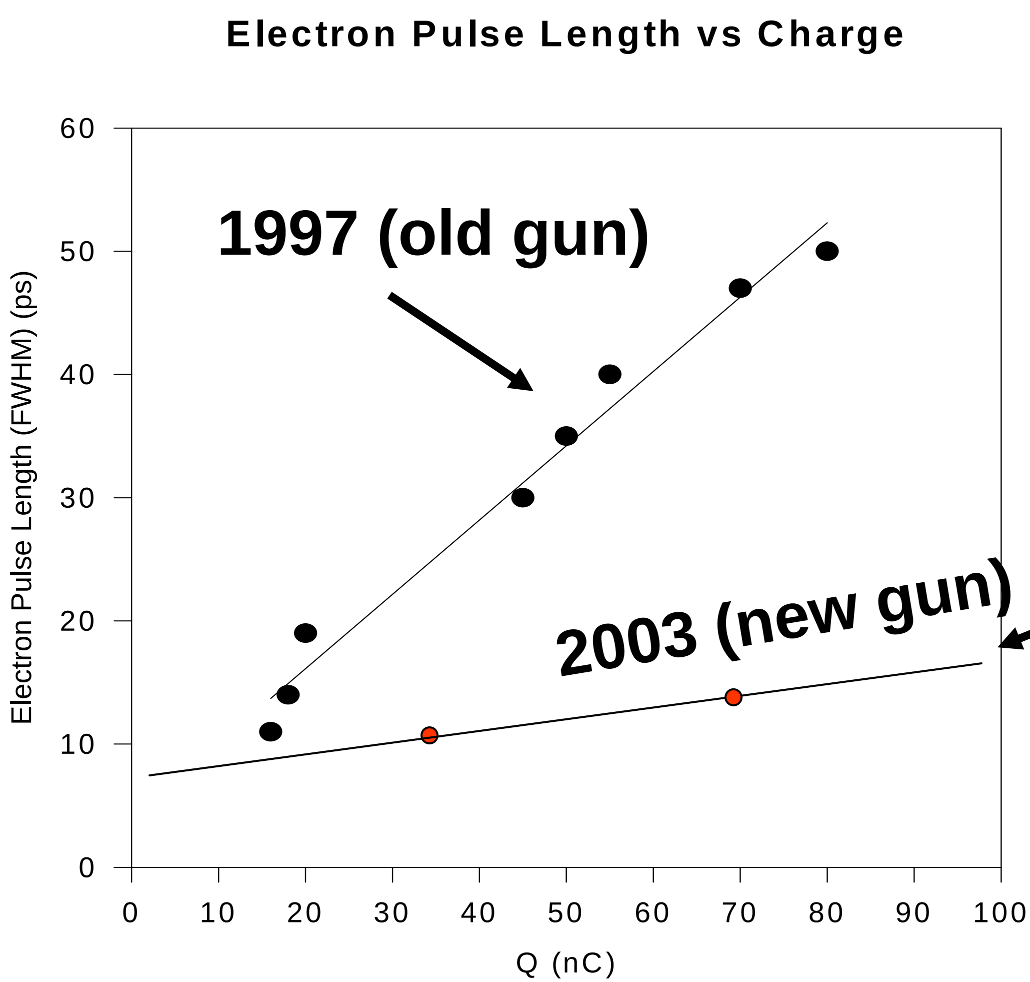


Measured 35 nC Pulse with green filter



Cherenkov/OTR + Streak Camera

longitudinal → bunch length



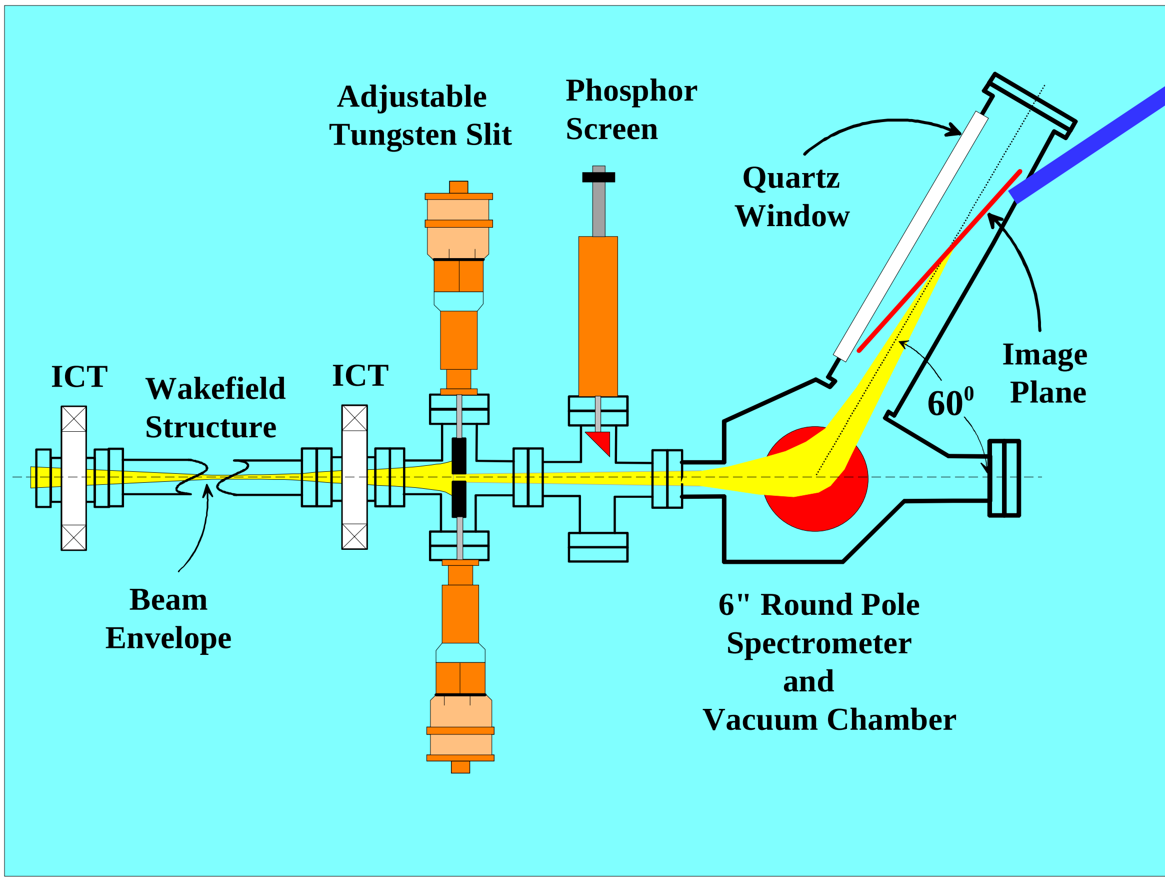
Parmela Sims

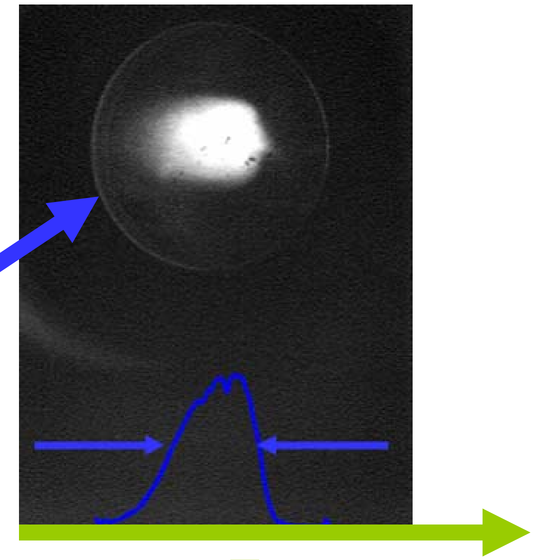
Q (nC)	FWHM_Z (psec)
1	6
20	9
25	10
50	12
100	13

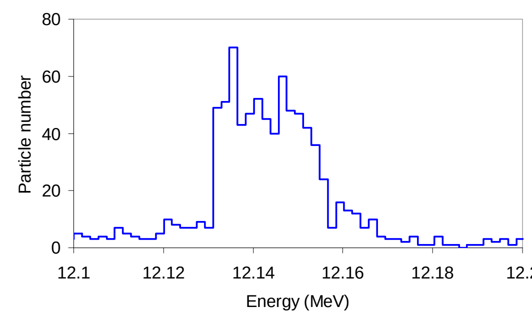
AWA Imaging Spectrometer

experiment

longitudinal → energy spread





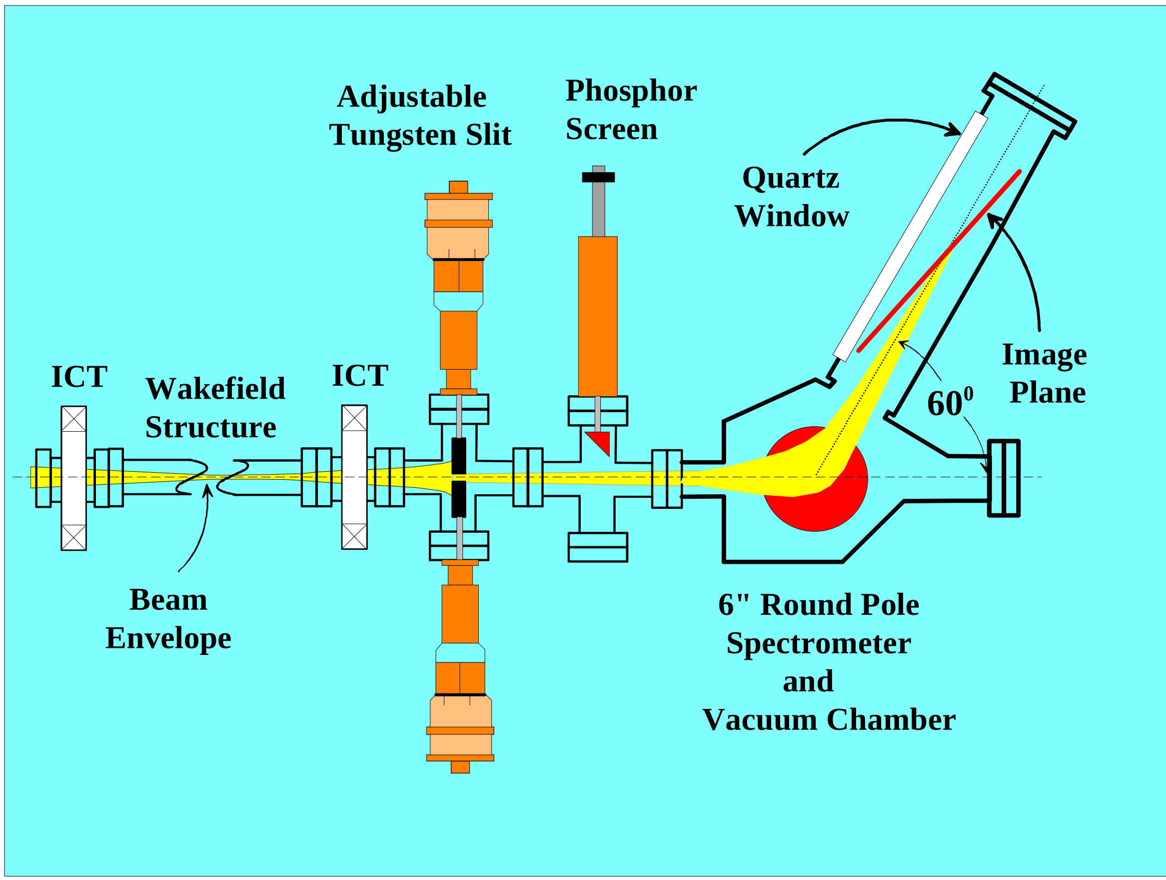


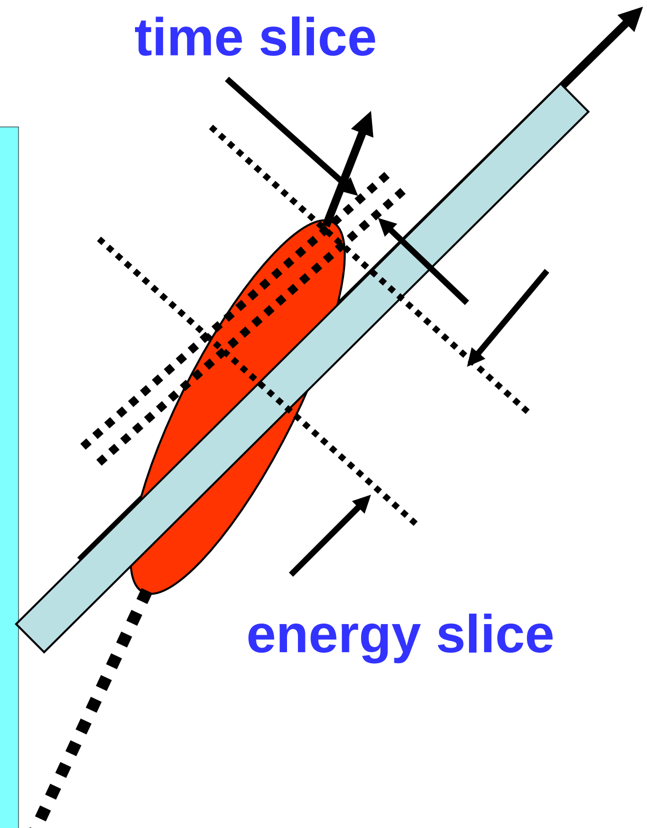
Parmela Simulation

Energy spread: 12% (FWHM) @ 20 nC

Spectrometer w/ Cherenkov Imaging Plane

longitudinal emittance → idea





Future Improvements

- **BPM:** Design, fabricate, install a 1.3 GHz BPM
  - Nondestructive; Charge & Centroid monitoring; RF gun phase measurement to +/- 1^0
- **New Imaging System:**
  - Eliminates DOF problem; known resolution
- **In pursuit of an Online Transverse Emittance Monitor**
  - **Pepper Pot:** complete simulations, perform experiment Feb 06
  - **ODR-DFRI:** next exp't March 06; pursue optical pepper pot
- **Longitudinal Emittance:** develop cherenkov image plane for spectrometer

Summary

High gradient wakefield acceleration

needs

ultra-high quality beam

delivered through the structure

needs

successful optimization and
improvement of the beam quality

needs

state of the art beam diagnostics