The LANSCE Area-C Experiment

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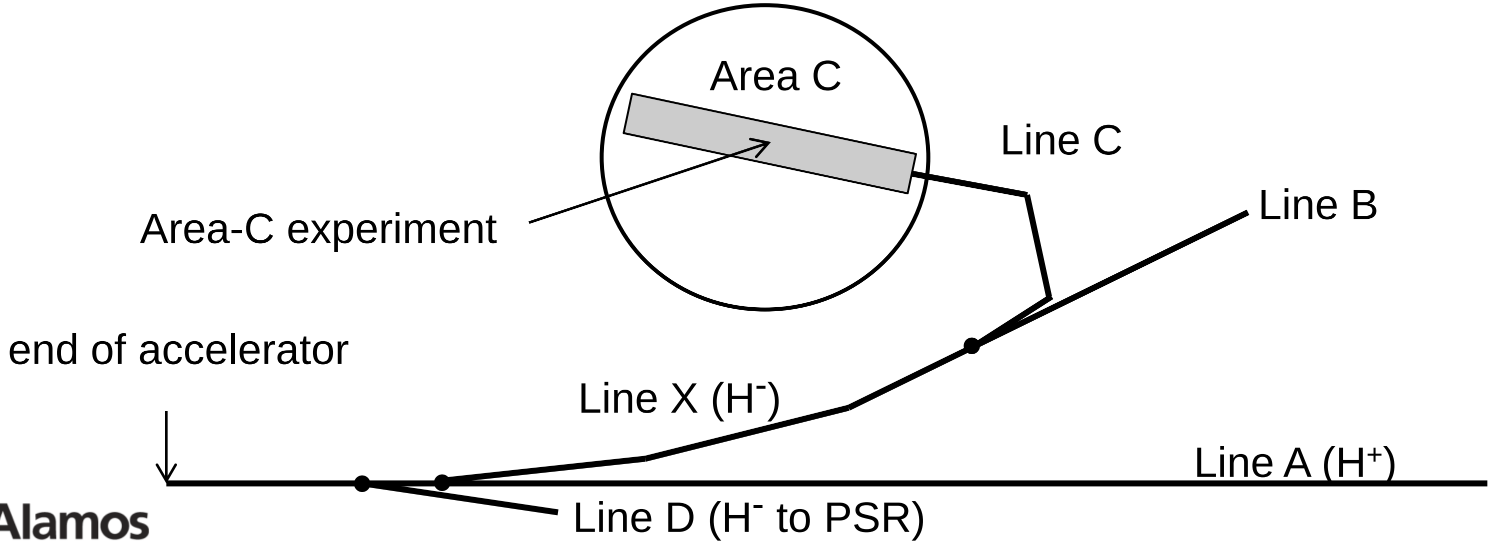
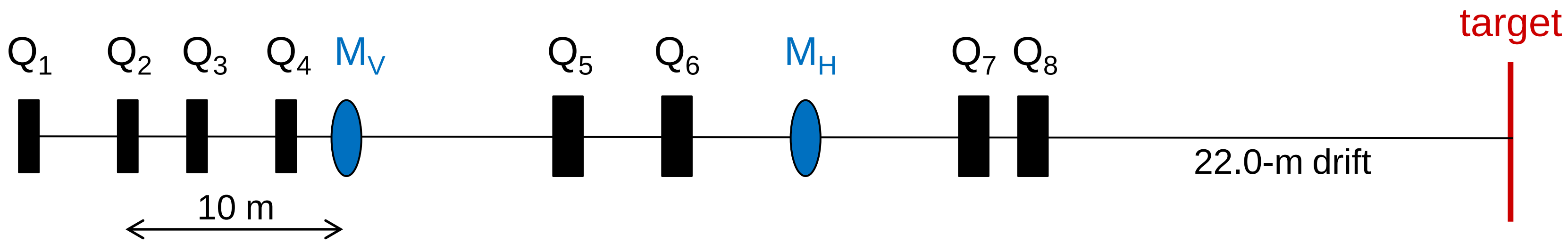
Overview

- **Objective was to experimentally study a nonlinear expander, with same multipoles and same quadrupole functions as expander for Accelerator for Production of Tritium (APT)**
  - APT was going to have a 1.767-GeV, 100-mA cw proton beam
- **Experiment was performed in LANSCE Area C**
  - 800-MeV H^- beam was stripped to H^+ at start of Line C
  - 1-nA average current, with typically a few μA peak current during macropulse

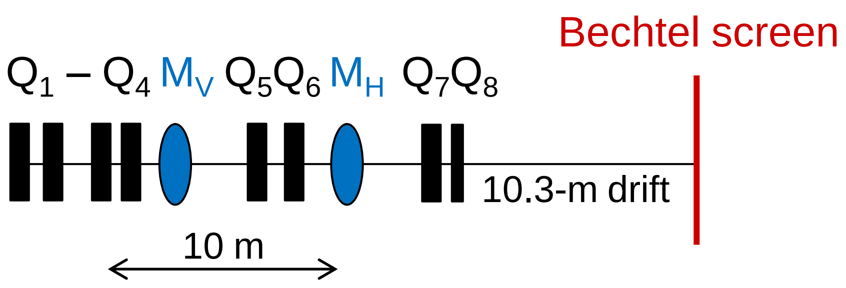


Area-C Expander is Shortened Version of APT Expander

APT expander: overall length of about 68.5 m



Area-C expander: overall length of about 29.9 m



Q_1 through Q_8: quadrupoles

M_V, M_H: multipoles

Experiment History

- Planning started in 1995
- Nonlinear-magnet design and construction started in 1995
- Beamline was assembled with previously used quadrupoles
- Experiment was performed between February 1997 and August 1997
- Beam-loss studies for APT were performed in late 1996 / early 1997 and showed some losses in limiting apertures (i.e., nonlinear expander)
- Collimation upstream of nonlinear elements was shown effective in protecting limiting apertures, but losses could not be ruled out
- Decision to use raster magnets was made before start of experiment

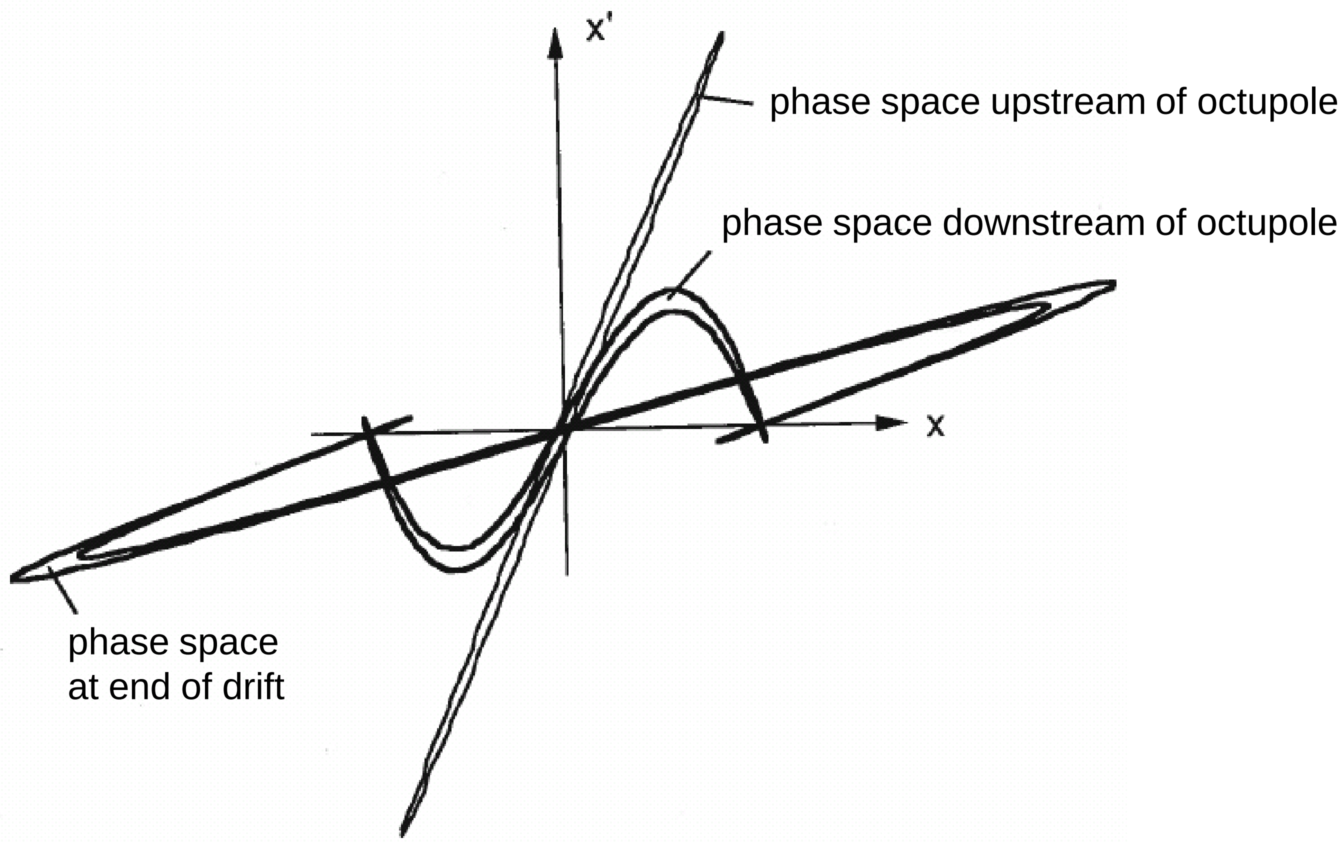
Experiment was not given great importance and was defunded immediately upon completion

LANSCE Approach to Expander Design

- A uniform beam distribution inside a specified rectangular area, with no beam outside area, is desired
- Actually, transform a distribution with hot beam center and elliptical footprint into a more uniform distribution with rectangular footprint
- Use octupoles to redistribute beam
- Use duodecapoles to avoid over-focusing of far beam fringes

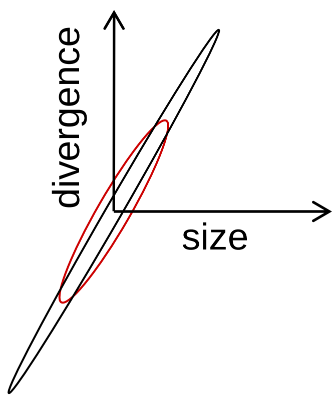
Achieving Beam Redistribution Using Octupoles

phase space to 4σ is shown



Remarks About Redistribution Using Octupoles

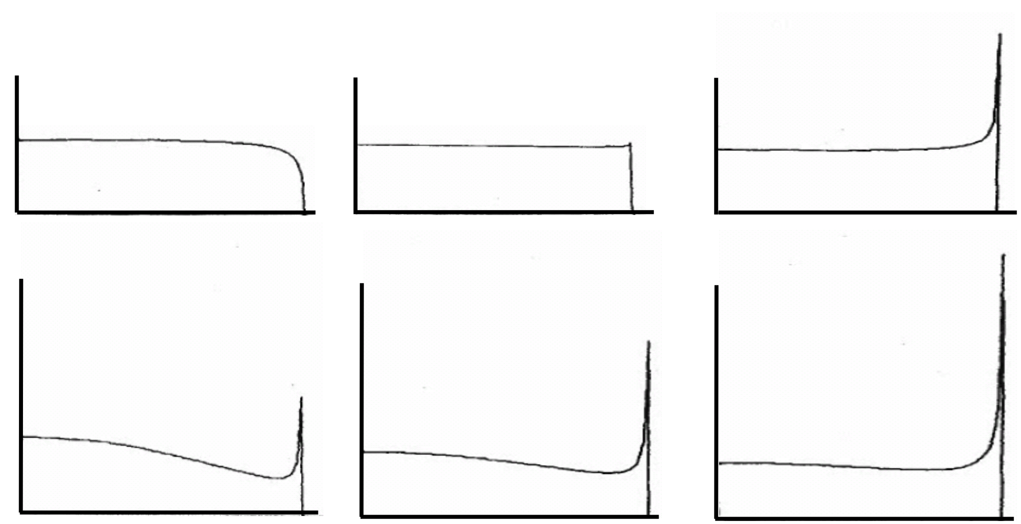
- **Beam spot at octupole must have large aspect ratio, to avoid x-y coupling**
- **Octupole redistributes beam in one transverse plane**
- **Two octupoles are needed for redistribution in both transverse planes**
- **Uniformity of output-beam distribution depends on input-beam distribution and input-beam rms parameters**



possible octupole
Input beams

parabolic profile →

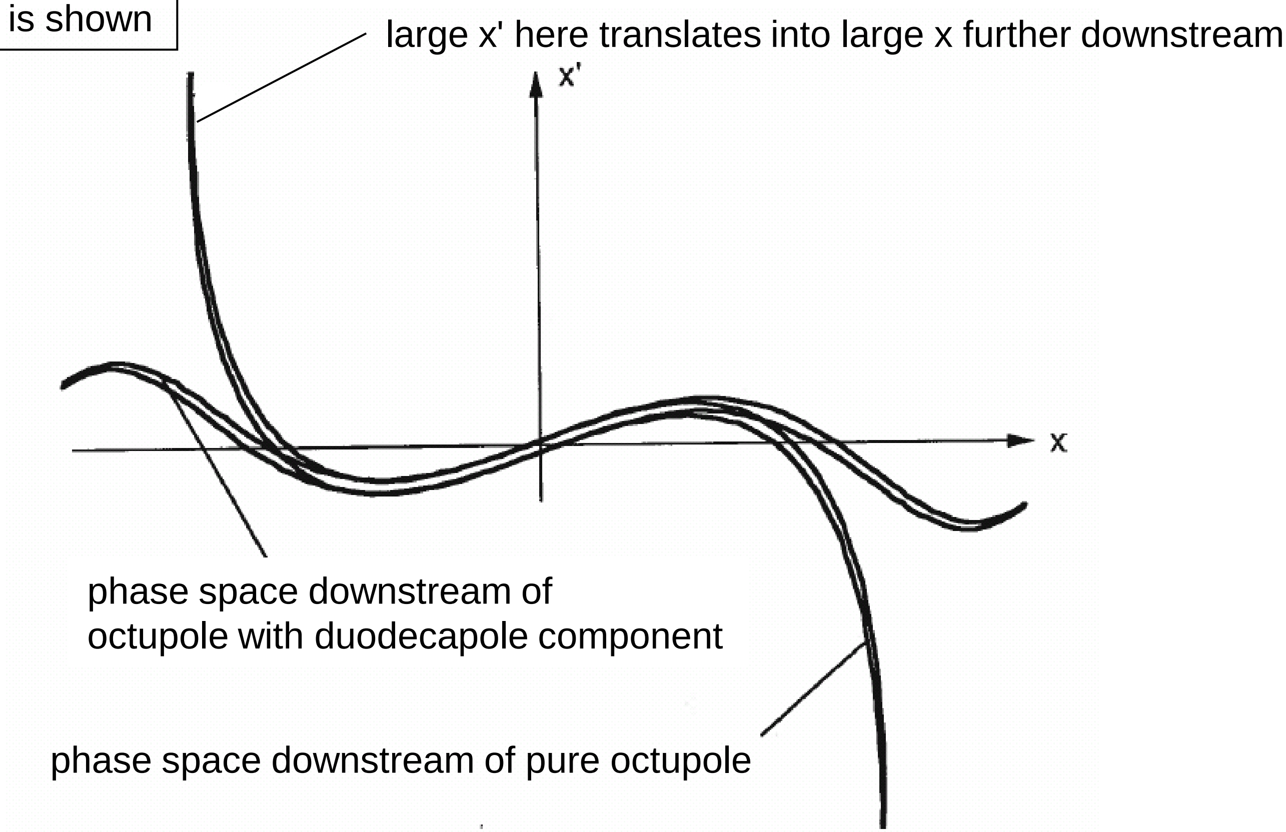
Gaussian profile →



Duodecapole Component in Octupole Prevents Over-Focusing of Beam Halo

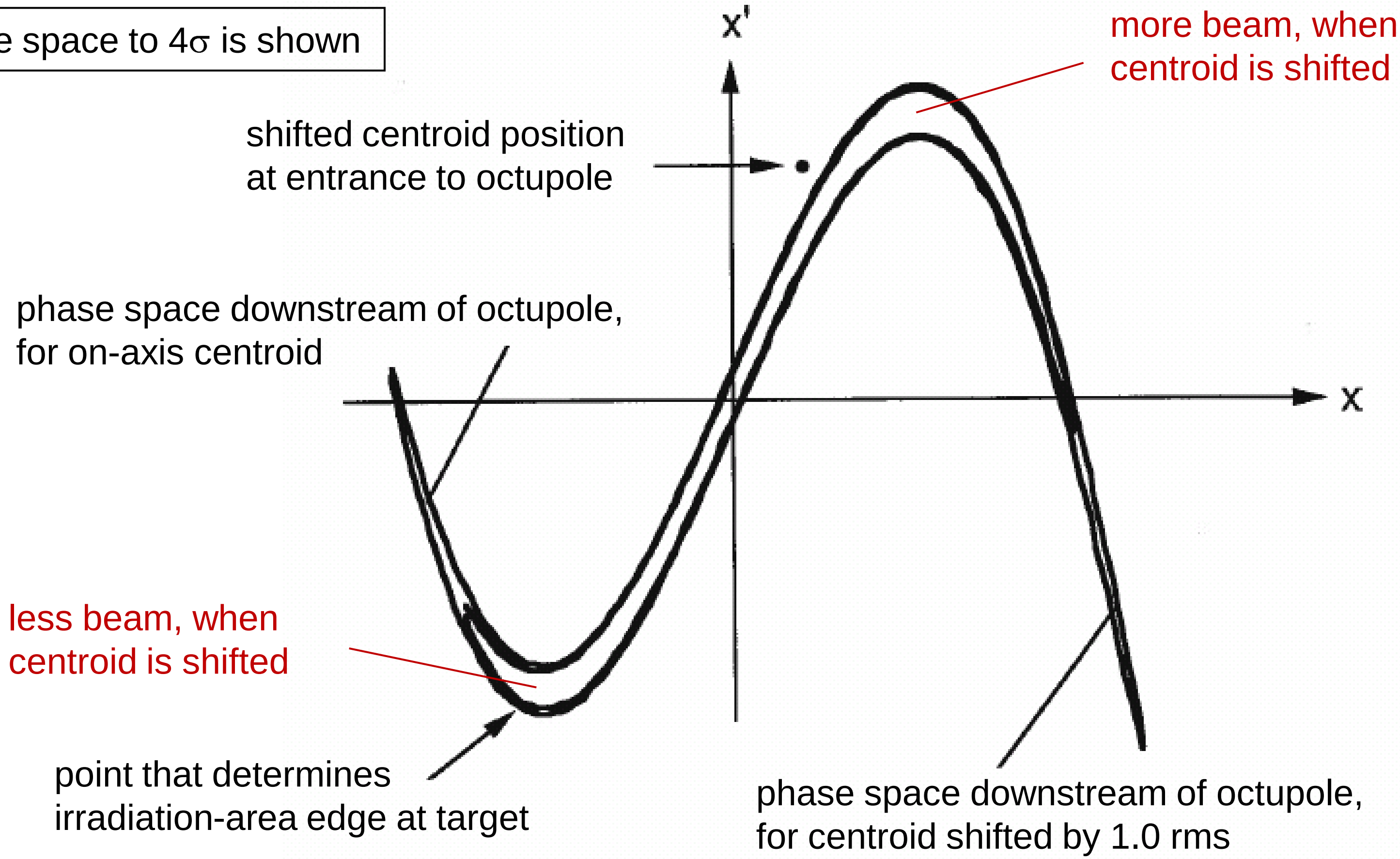
- **Phase-space manipulation solely by octupole over-focuses beam halo and causes downstream beam loss**

phase space to 7σ is shown

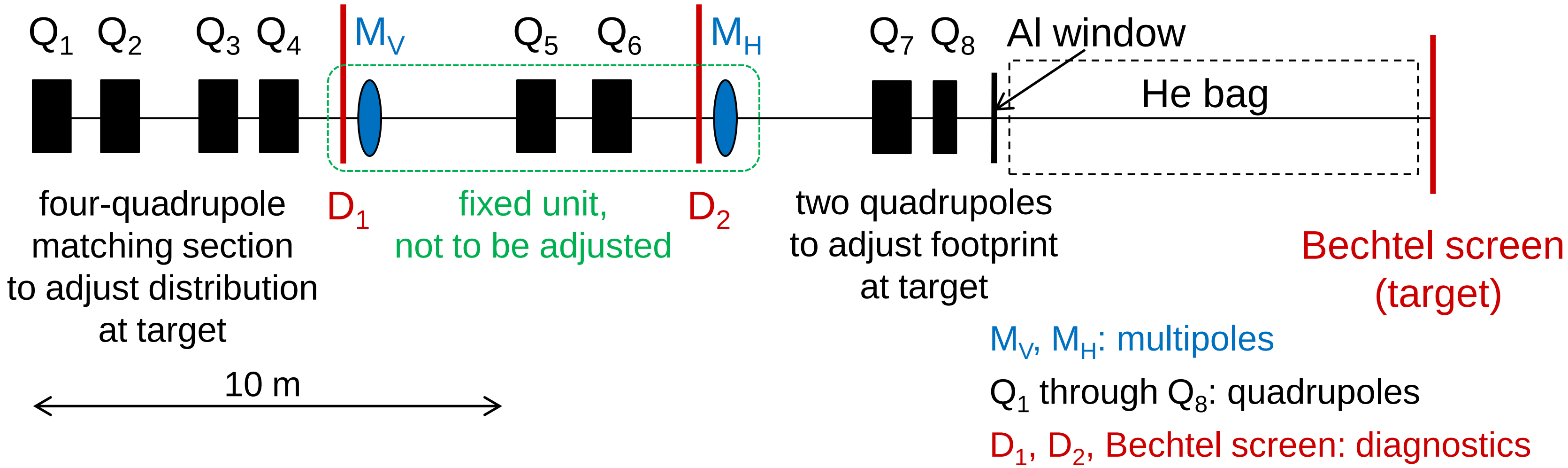


Beam Jitter Does Not Move Footprint Edges, but Does Produce Skewed Distributions

phase space to 4σ is shown



Details of Area-C Expander



- **Design M_V Q_5 Q_6 M_H as a fixed unit, requiring a particular y'/y ratio at M_V and a particular x'/x ratio at M_H (plus, x«y at M_V, y«x at M_H)**
- **Adjust Q_1 through Q_4 in response to observed distribution at target**
  - if center too peaked, increase rms beam parameters at M_V and/or M_H
  - if spikes along edges too large, decrease rms beam parameters at M_V and/or M_H
- **Adjust Q_7 and Q_8 in response to observed footprint at target**

Experiment Timelime

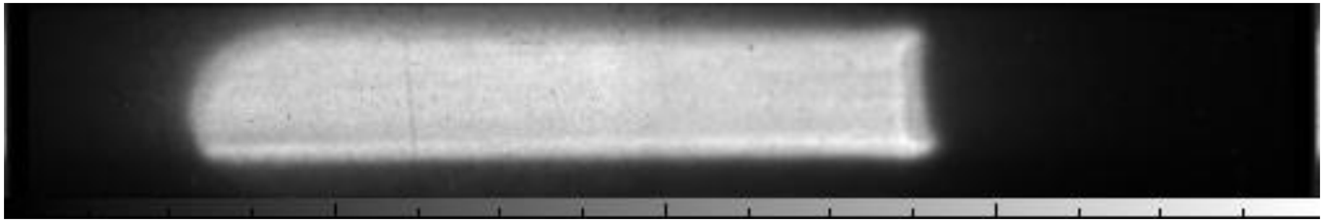
- Experiment consisted of six 24-hour runs, about one month apart
- February and March runs: multipoles not yet in place
- April run: second multipole (M_H) in place
- May, June, and August runs: both multipoles in place

Determining Matching-Section Input Beam

- **Spent an inordinate amount of time trying to accurately characterize matching-section input beam from quadrupole-scan data**
  - Most effective quadrupole/diagnostic combinations were predicted to be Q_4/D_1 or Q_1/D_2 for horizontal phase space, Q_2/D_1 or Q_1/D_2 for vertical phase space
- **Initially experienced countless problems with diagnostics (ghost images, fiducials interfering with data, out-of-focus camera systems, camera and digitizer saturation problems)**
- **After resolving these problems, first took raw data (April), then discovered usefulness of subtracting background data (off line in May, on line in June), and finally could determine FWHM sizes and matching-section input-beam parameters on line (June)**
- **However, process was never fully automated, so that each time we set matching-section quadrupoles according to best-guess beam of previous run**

Source of Beam Clipping Found and Removed

- **Severe beam clipping was observed at Bechtel screen during May and June runs**
- **Clipped beams have rounded edges**

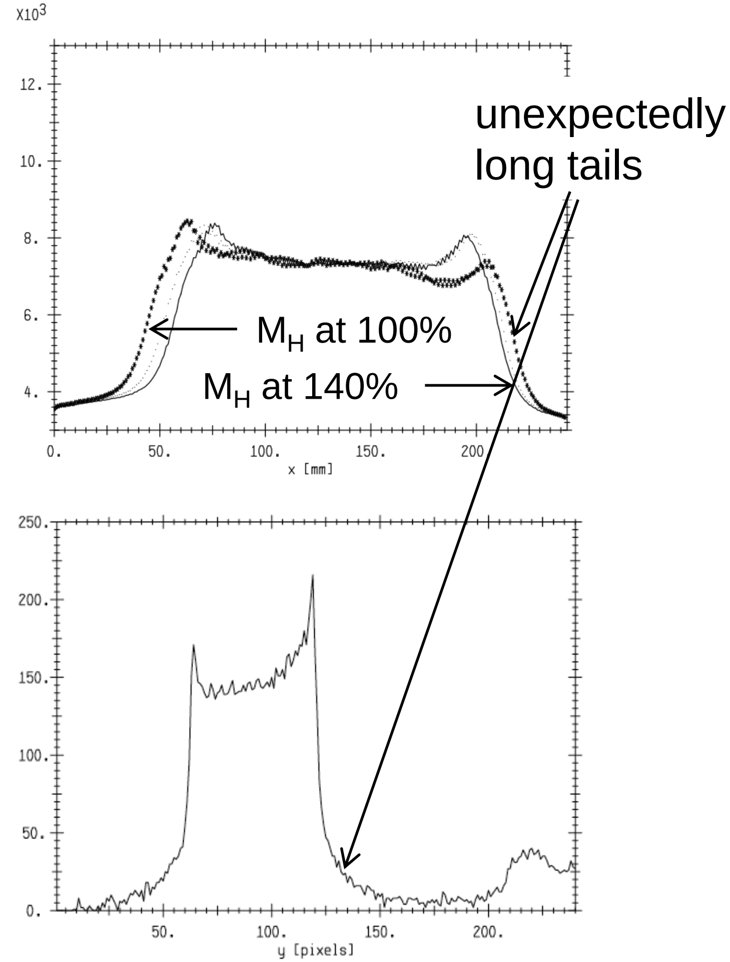


typical beam spot with beam clipping

- **Simulation showed that to produce a rounded edge, restricting aperture must be at or downstream of M_H**
- **Inspection revealed that 4-inch pipe through steering magnet downstream of M_H was low by about 1.5 cm at downstream end**
- **Offending pipe was replaced with 8-inch pipe and clipping was not observed during August run**

Puzzle of Long Tails in Profiles of Redistributed Beams

- **April run: took data at Bechtel screen and observed long tails in horizontal profiles of redistributed beam**
  - Tried to explain with scattering in Al window, and possibly deflated He bag
  - Tried to explain with magnet roll errors
  - Tried to explain with large momentum spread in beam
- **May run: took data at D_2 and observed same long tails in vertical profiles of redistributed beam**
  - Scattering could be ruled out



Explanation for Long Tails in Profiles of Redistributed Beams

- **Following August run: took data of edge of D_2 phosphor with light shining on phosphor, and of other illuminated sharp-edged objects, against black background and saw same long tails as exhibited by column plots of observed beams**
- **Appears to be artifact of camera system**

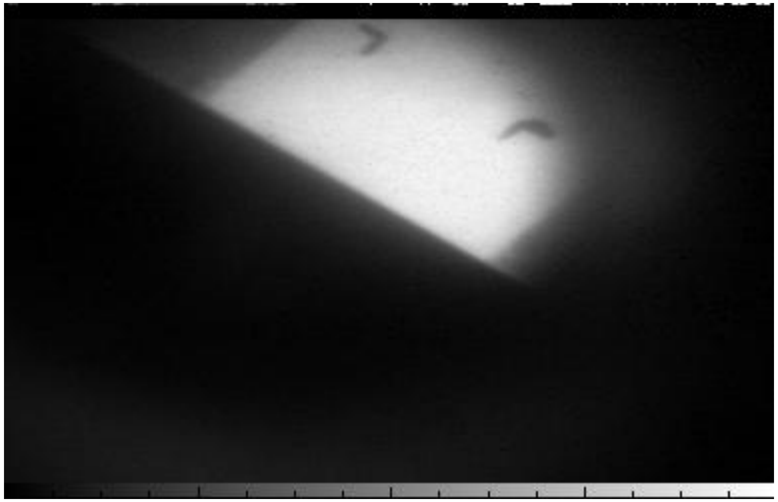
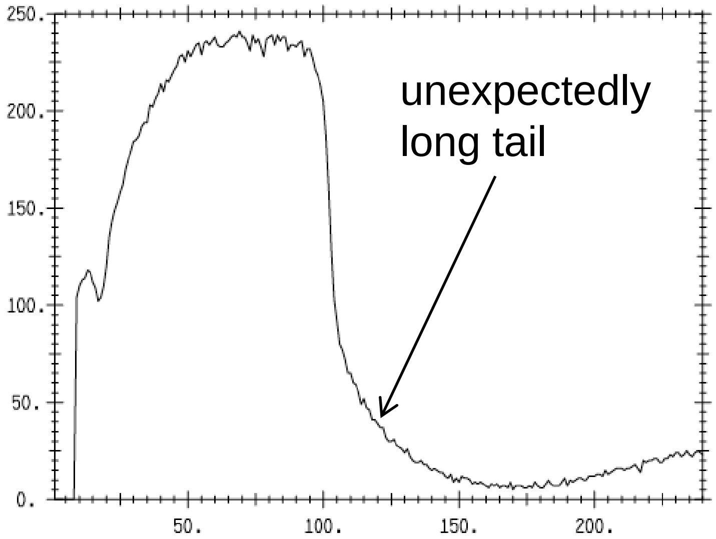
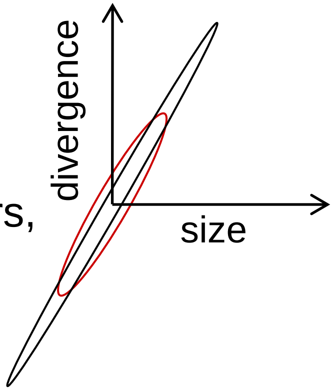


image of phosphor screen



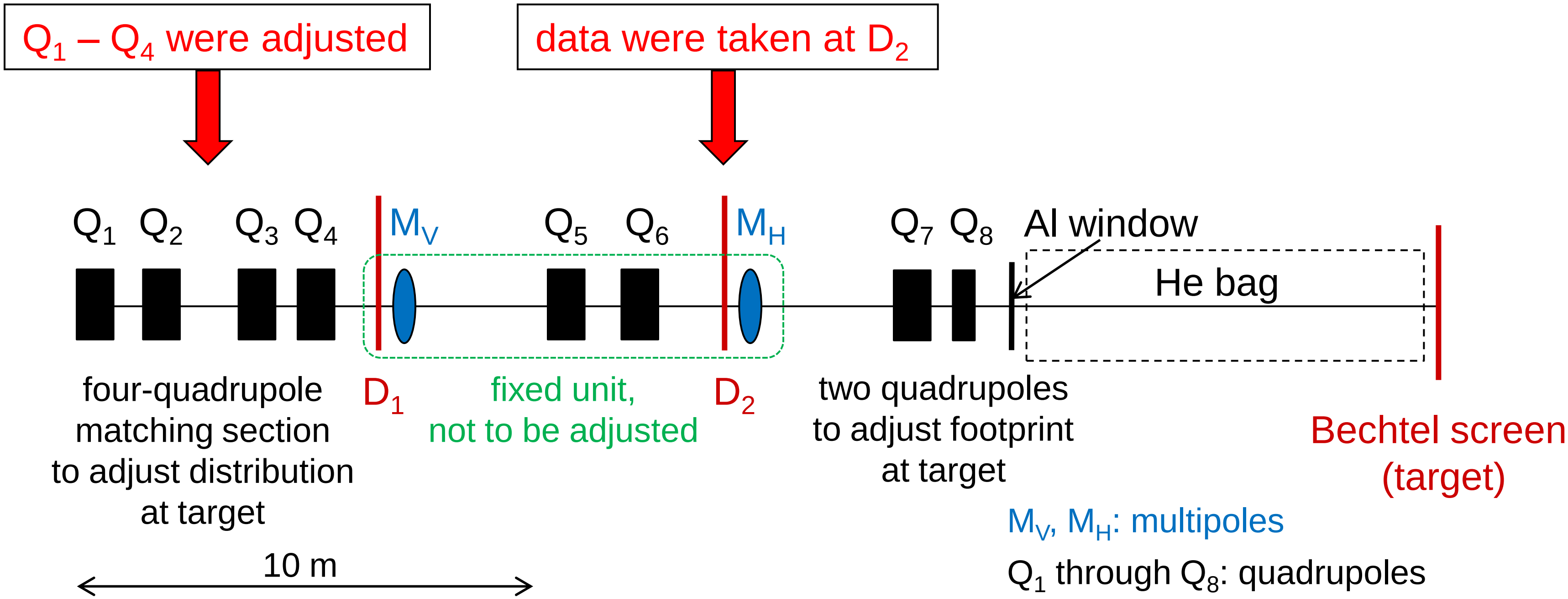
column plot of data

Adjustment of Beam Distribution with $Q_1 - Q_4$ (General Remarks)



- **For expander to work properly**
  - first multipole (M_V) has sets of allowed input-beam parameters, with fixed ratio of vertical rms divergence to rms size
  - second multipole (M_H) has sets of allowed input-beam parameters, with fixed ratio of horizontal rms divergence to rms size
- **Proper settings of $Q_1 - Q_4$ require knowledge of**
  - matching-section input-beam parameters
  - matching-section geometry and properties of matching-section quadrupoles
- **Predictions are that**
  - beams with small rms parameters at multipoles evolve into distributions that are peaked in center
  - beams with large rms parameters at multipoles evolve into distributions with depleted centers and large spikes around edges
  - beam jitter causes skewed distributions
  - distribution edges are not affected by beam jitter

Adjustment of Beam Distribution with $Q_1 - Q_4$



M_V, M_H: multipoles

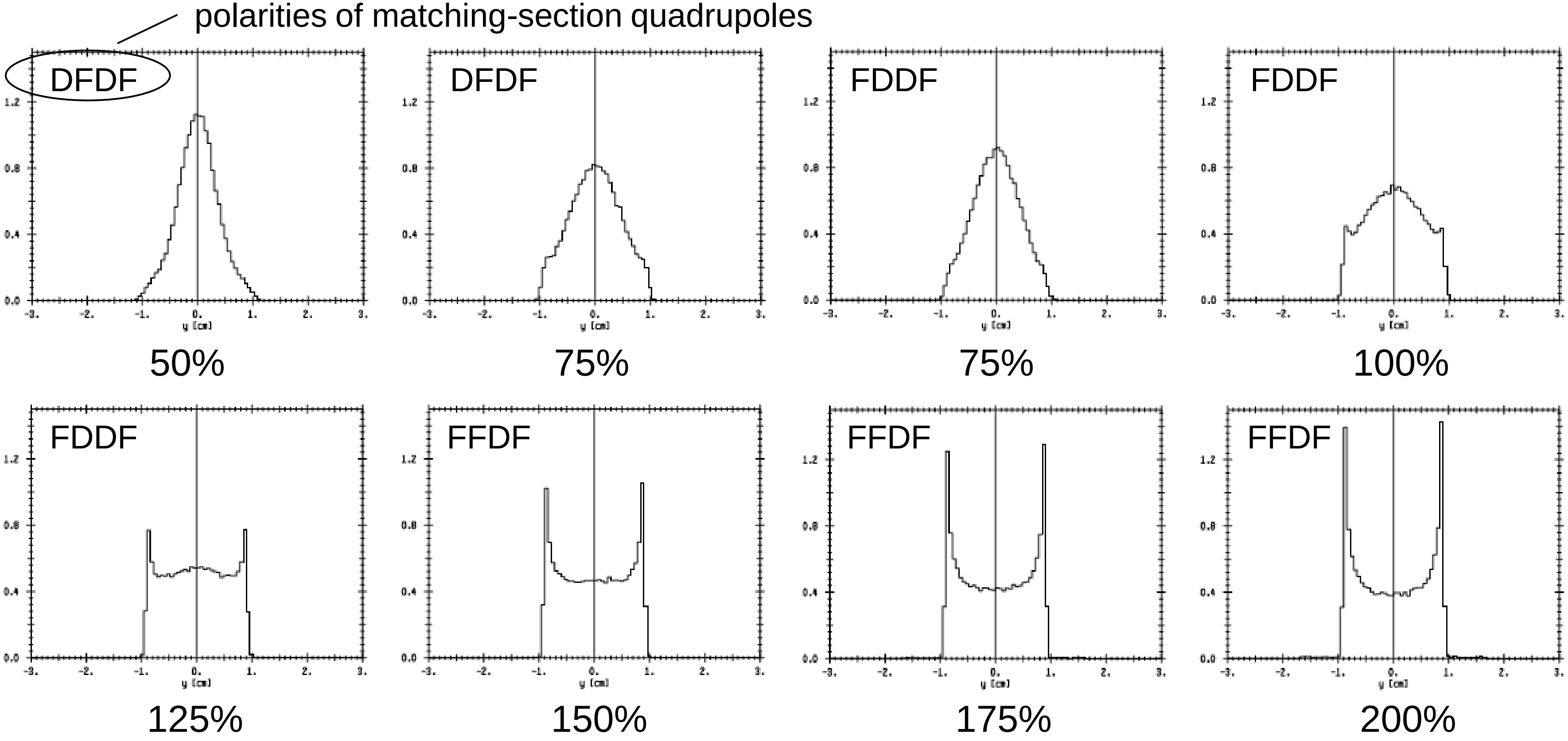
Q_1 through Q_8: quadrupoles

D_1, D_2, Bechtel screen: diagnostics

Adjustment of Beam Distribution with $Q_1 - Q_4$

- Determined rms beam parameters at multipoles for which beam is predicted to evolve into a “most desirable” distribution (a 100% focus)
- Computed eight sets of settings of $Q_1 - Q_4$, to achieve rms beam parameters of between 0.5 and 2.0 times above-mentioned parameters (the 50% to 200% foci)
- For each set of settings, took data at D_2
- Compared predicted (from simulations) vertical profiles at D_2 to column plots through centers of beam spots
- Found good qualitative agreement between predictions and data
- Long tails on column plots are believed to be artifact of camera system
- Distribution edges remained stationary for all beam-focus percentages
- Distribution edges remained stationary despite obvious beam jitter

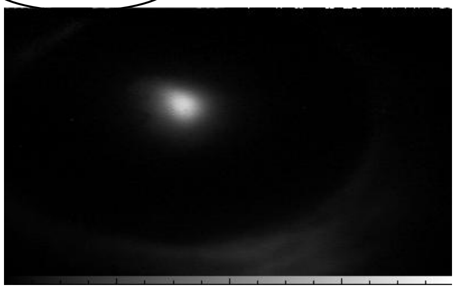
Predicted Vertical Beam Profiles at D_2 for Various Beam-Focus Percentages



Observed Beam Spots at D_2 for Various Beam-Focus Percentages

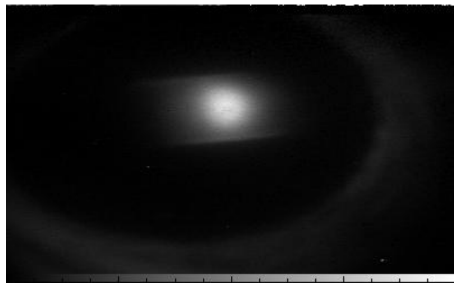
polarities of matching-section quadrupoles

DFDF



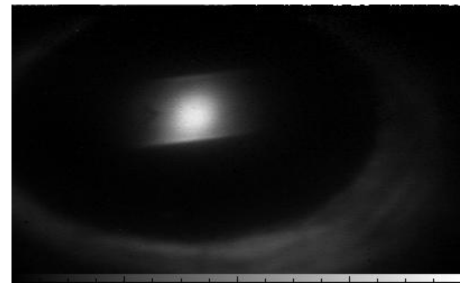
50%

DFDF



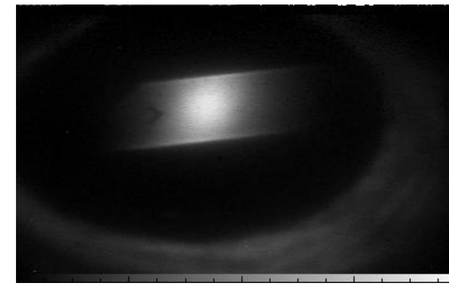
75%

FDDF



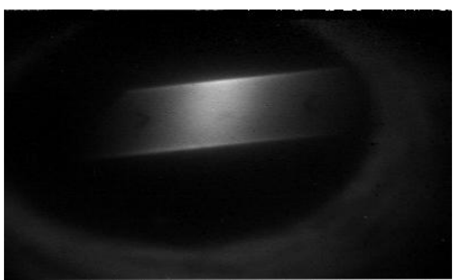
75%

FDDF



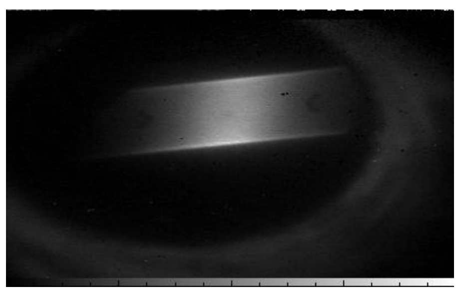
100%

FDDF



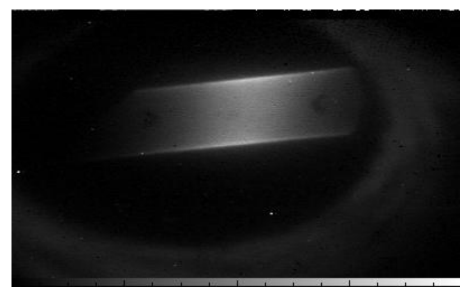
125%

FFDF



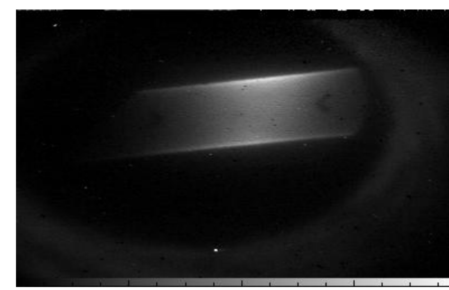
150%

FFDF



175%

FFDF

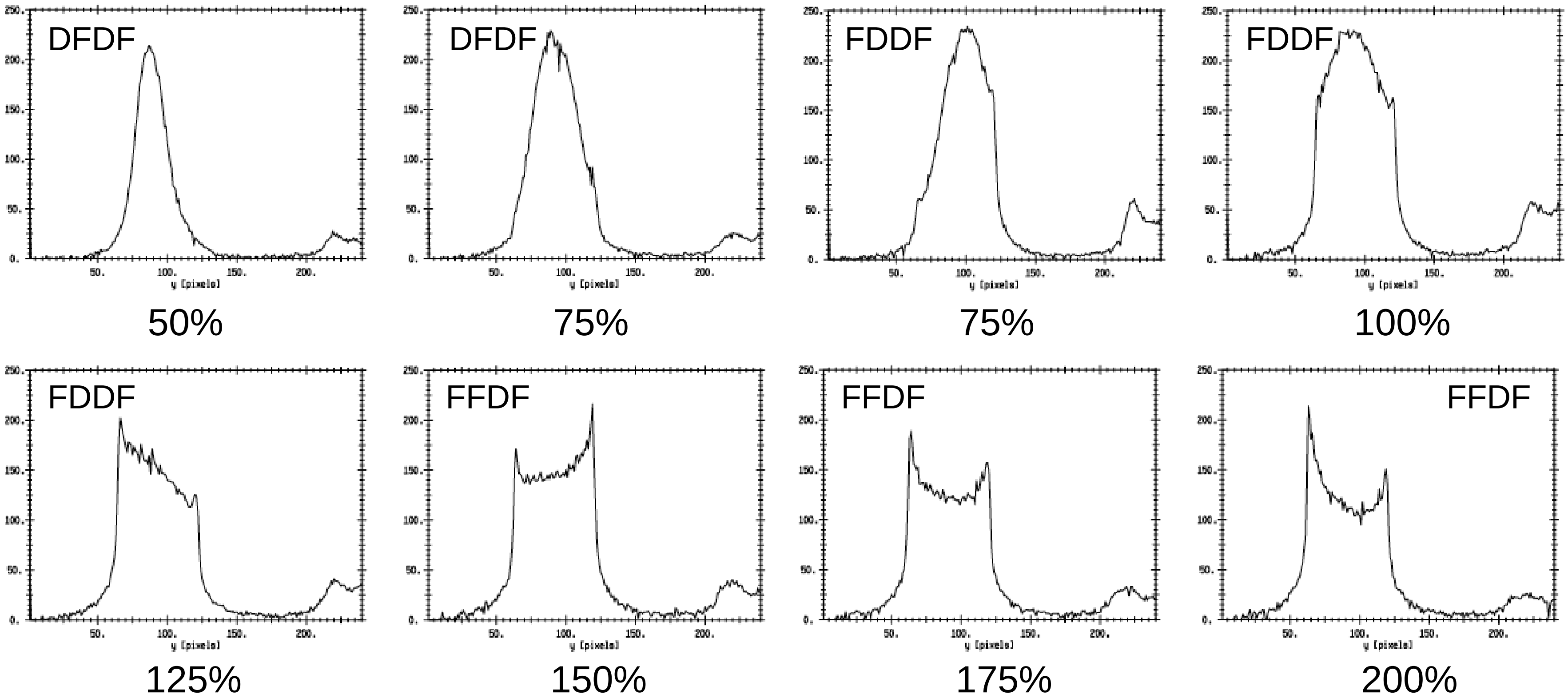


200%

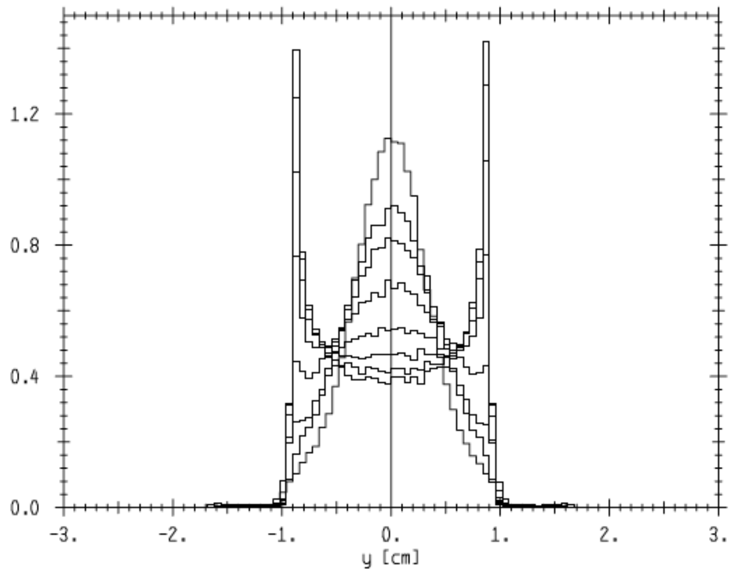
beam-focus percentages

note: tilt of beam edges is due to camera perspective

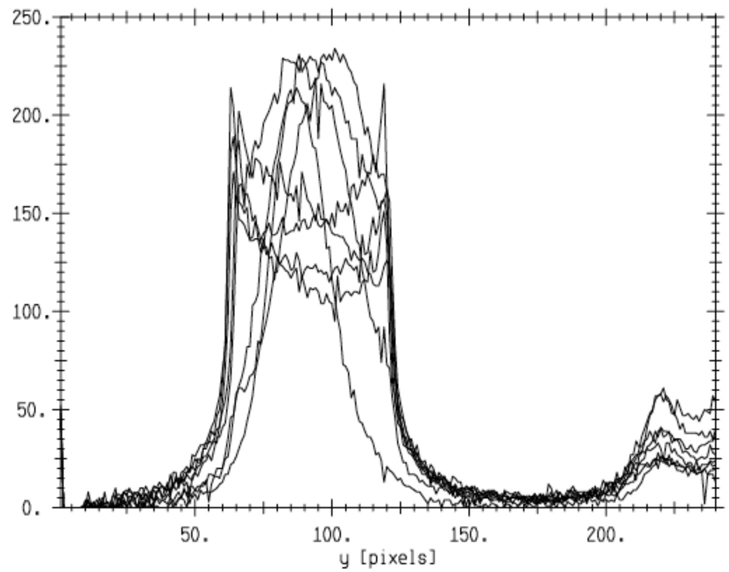
Column Plots of Data from D_2 for Various Beam-Focus Percentages



Predicted and Observed Vertical Beam Profiles at D_2 for Various Beam-Focus Percentages

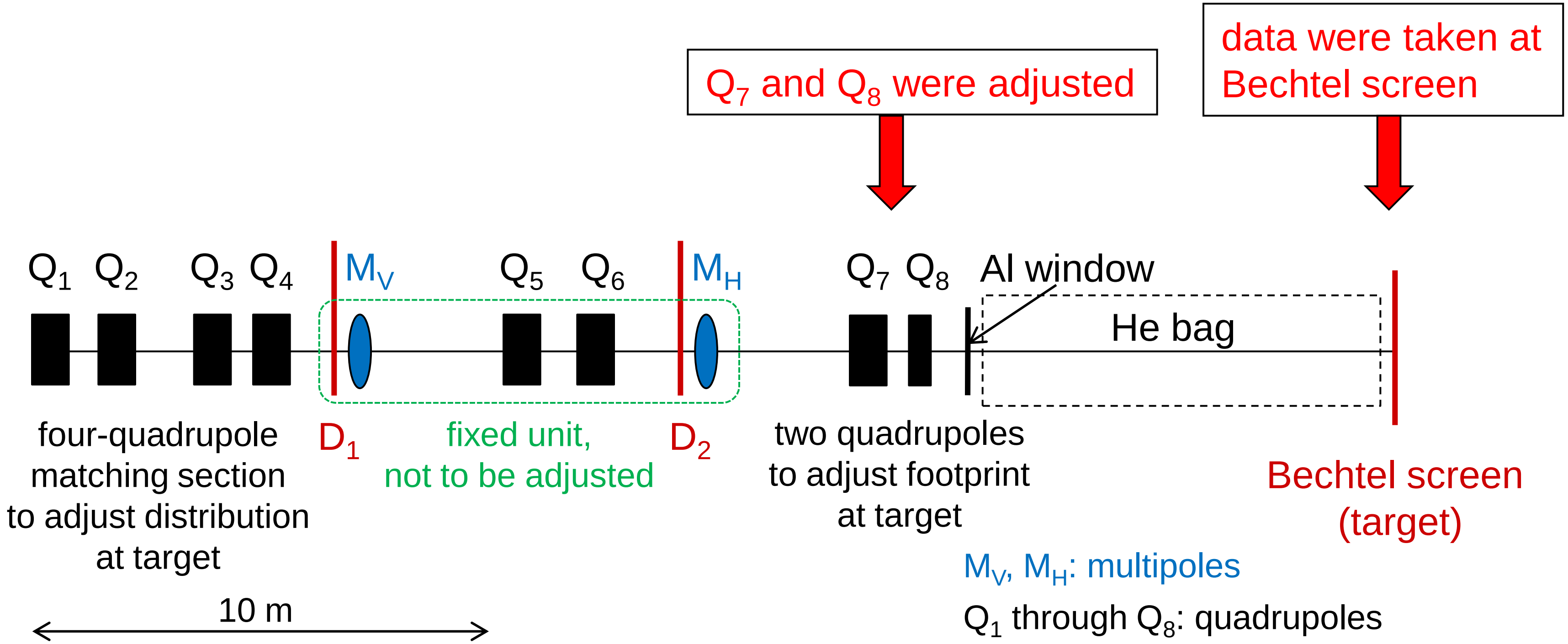


predicted vertical beam profiles at D_2



column plots of observed beam spots at D_2

Adjustment of Beam Footprint at Bechtel Screen with Q_7 and Q_8



M_V, M_H: multipoles

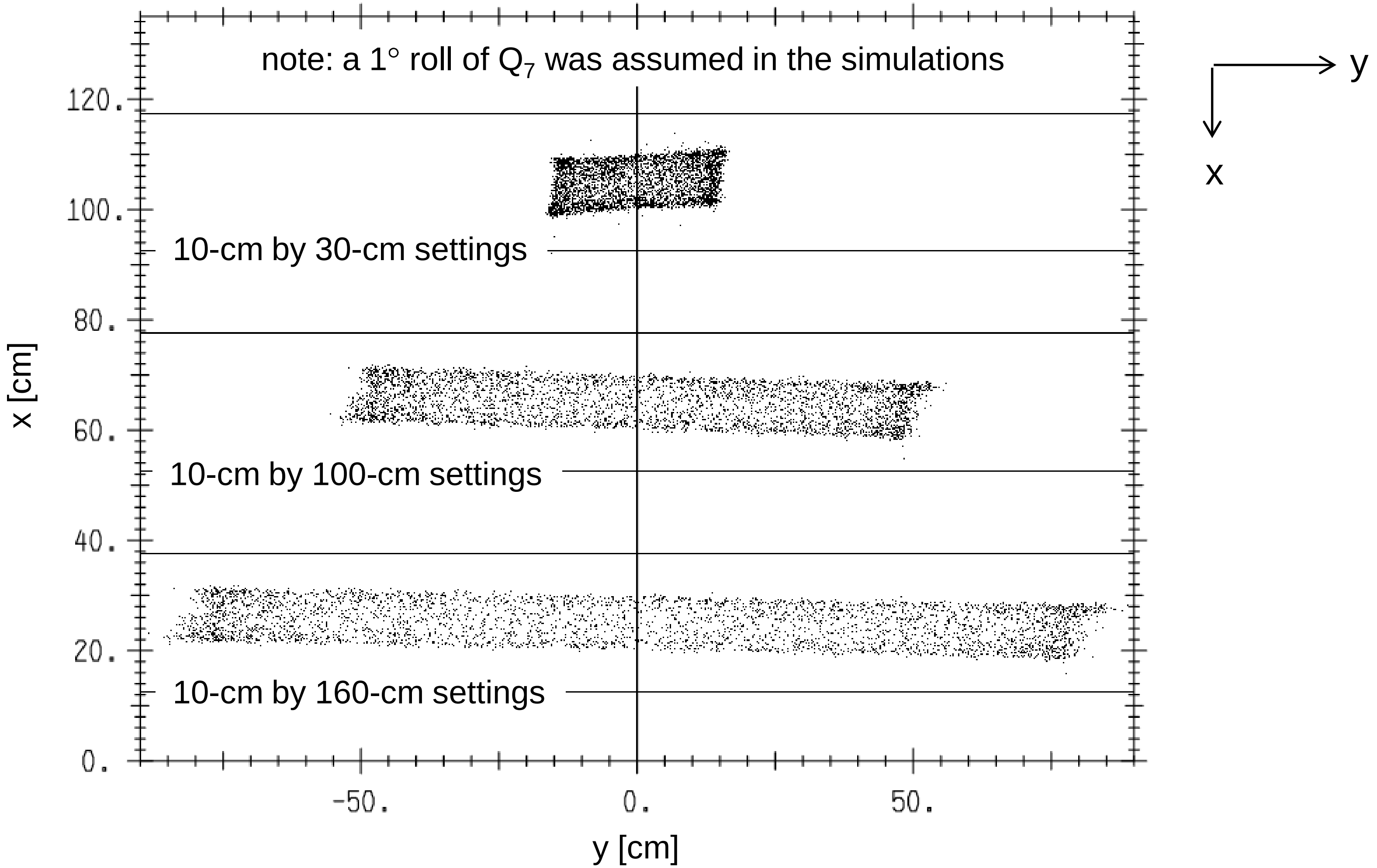
Q_1 through Q_8: quadrupoles

D_1, D_2, Bechtel screen: diagnostics

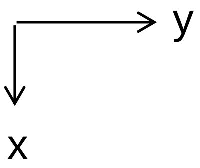
Adjustment of Beam Footprint at Bechtel Screen with Q_7 and Q_8

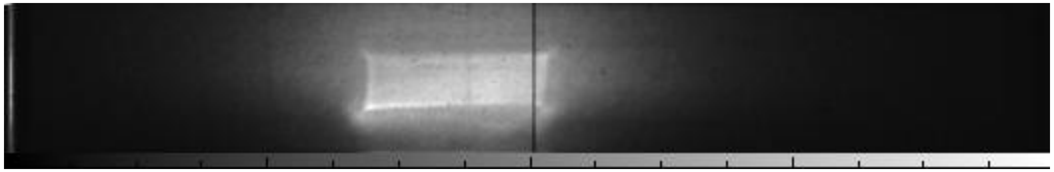
- Computed three sets of settings of Q_7 and Q_8, predicted to yield 10-cm by 30-cm, 10-cm by 100-cm, and 10-cm by 160-cm footprint
- Took data at Bechtel screen
- Compared predicted beam spots to observed ones
- Good qualitative agreement between predictions and data
- Wide range of beam footprints can be achieved by adjusting Q_7 and Q_8
- Adjustment of footprint size did not visibly affect distribution
- Roll errors in Q_7 or Q_8 will cause tilted footprints at target
- Tilted footprints observed at Bechtel screen are possibly due to 0.5° roll of Q_7

Predicted Beam Footprints at Bechtel Screen for Three Sets of Settings of Q_7 and Q_8

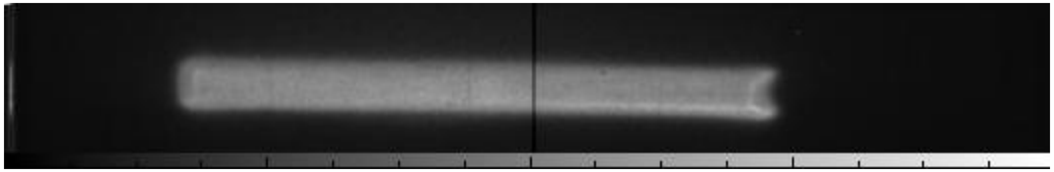


Observed Beam Footprints at Bechtel Screen for Three Sets of Settings of Q_7 and Q_8

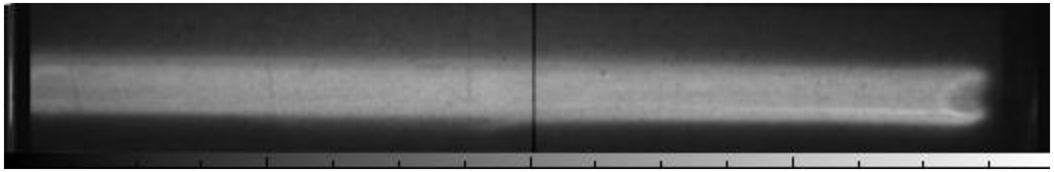




10-cm by 30-cm settings



10-cm by 100-cm settings



10-cm by 160-cm settings

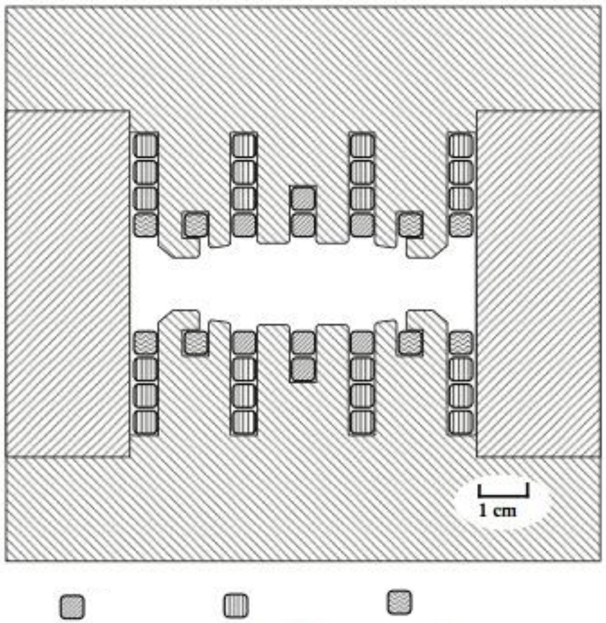
notes: tilts in footprints are possibly due to a 0.5° roll of Q_7

LANSCE Area-C Multipoles (General Remarks)

- **For nominal fields in 0.5-m-long M_V (6.5×10^4 T/m^3, 1.2×10^8 T/m^5), have 0.8 T at radius of about 2.3 cm**
- **For nominal fields in 0.5-m-long M_H (1.85×10^4 T/m^3, 0.13×10^8 T/m^5), have 0.8 T at radius of about 3.5 cm**
- **Magnets difficult to build, at best**
  - If shaping octupole pole pieces to generate duodecapole component, independent adjustment is not possible
  - If building short sections of octupole and duodecapole magnets, it lengthens multipole and acts somewhat differently from a combined-function magnet

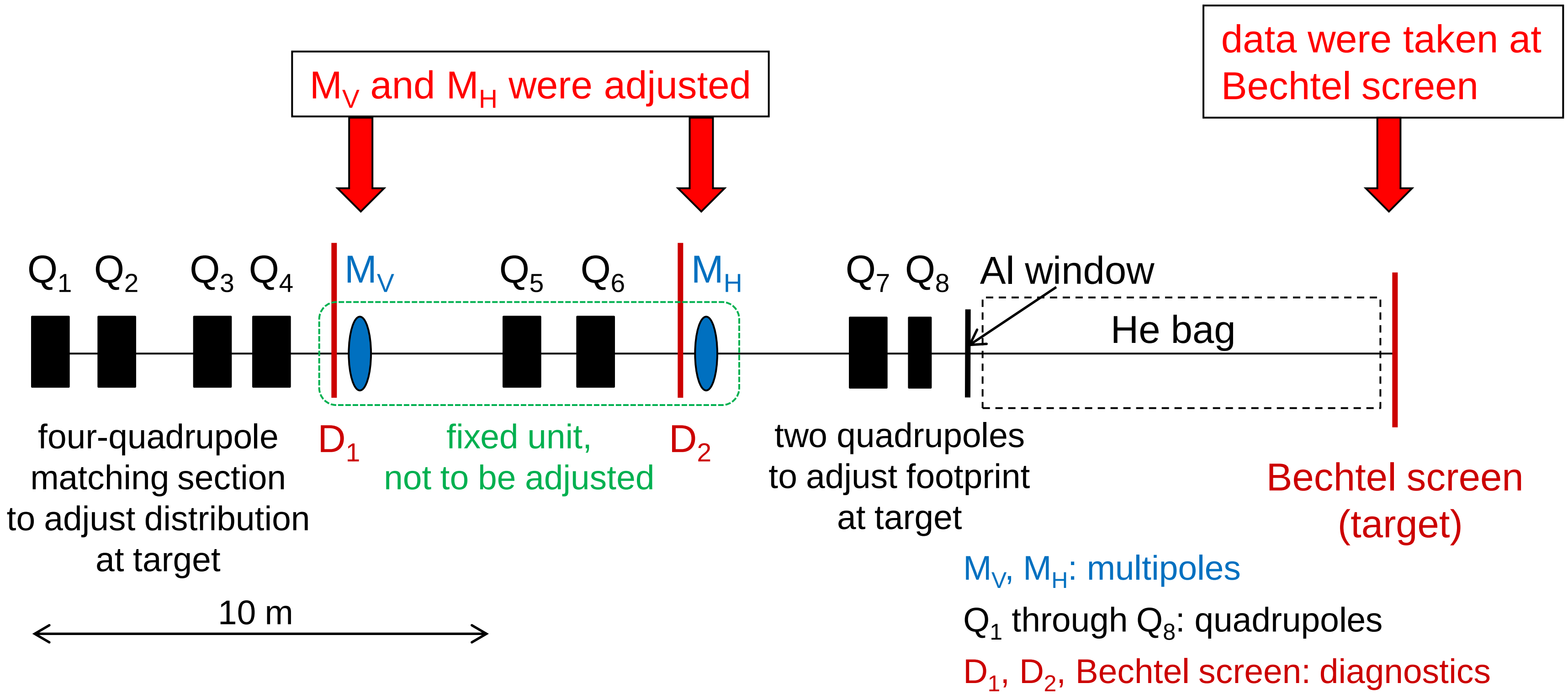
LANSCE Area-C Multipoles
(Actual Magnet Design)

- Special magnets were designed, with 12 poles and elongated apertures
- Magnets have independently adjustable quadrupole, octupole, and duodecapole windings
- Major-axis fields were measured with individual windings energized
- Sets of coefficients were computed from measurements, allowing computation of fields inside magnet apertures
- Magnets can achieve on-axis fields that are comparable to originally requested fields
- Nominally, duodecapole windings are off
- Elliptical pipe in M_V has a=0.62 cm, b=2.57 cm, elliptical pipe in M_H has a=4.43 cm, b=1.10 cm



multipole cross section

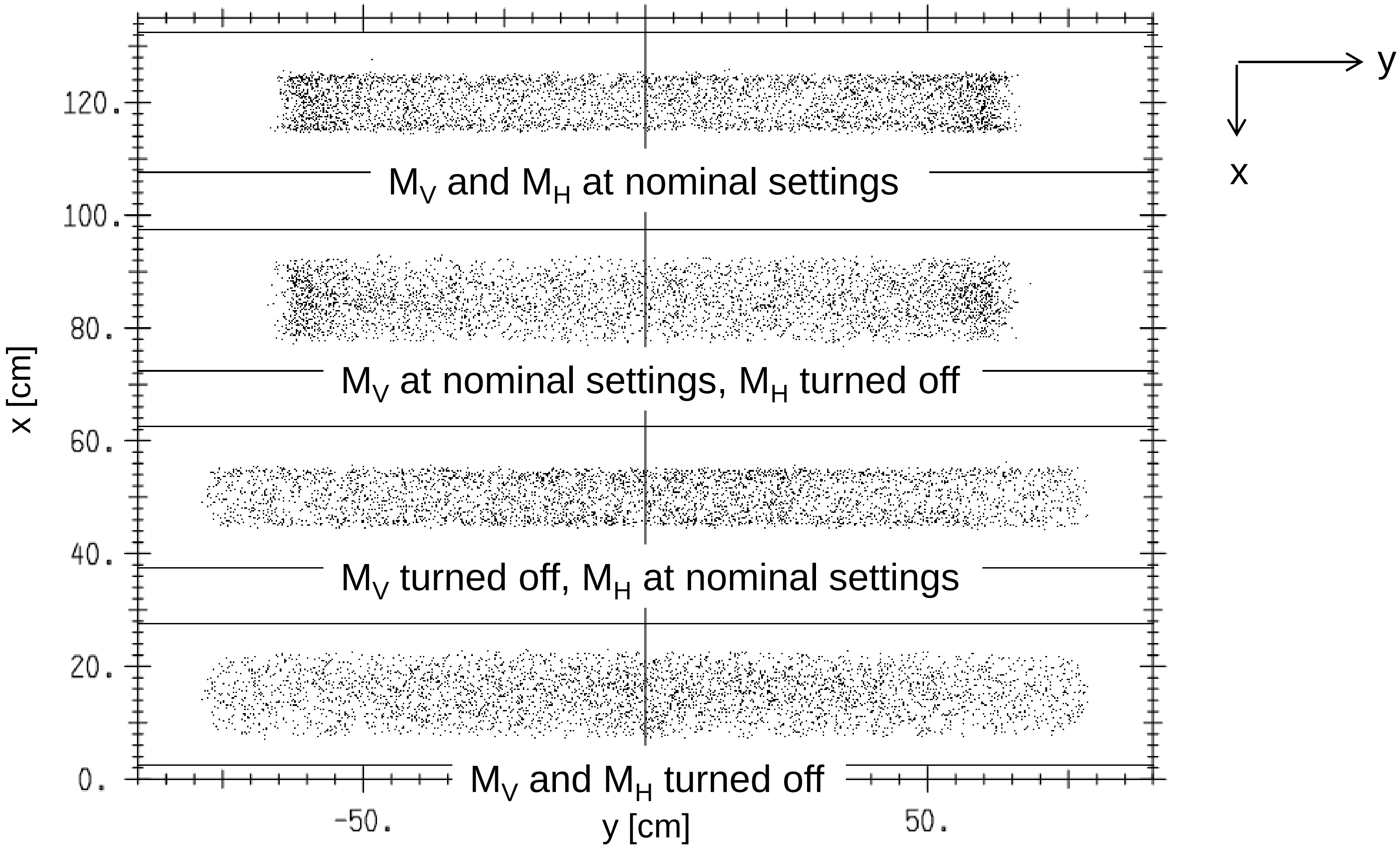
Adjustments of M_V and M_H



Beam Footprints and Distributions with Nominal and Non-Nominal Settings of Multipoles

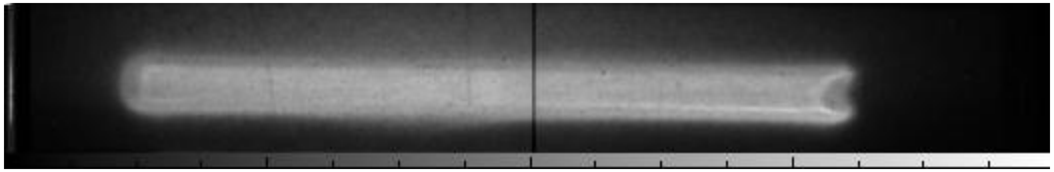
- Recorded beam spot at Bechtel screen with both multipoles at nominal settings and with one or both multipoles turned off
- Compared predicted beam spots to observed ones
- Good qualitative agreement between predictions and data in appearance of beam spots
- For nominal settings of multipoles, essentially no beam loss is predicted
- Substantial beam loss is predicted with one or both multipoles turned off, namely about 12% and 22%, respectively
- Adequate diagnostics for assessing beam loss were not available
- Clipped appearance of beam with multipoles turned off is apparent
- Aperture of Q_8 was known to be under-dimensioned (4-inch radius, where 5-inch radius would have been desirable)

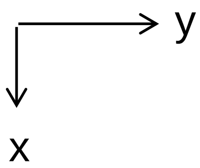
Predicted Footprints at Bechtel Screen with Nominal and Non-Nominal Settings of M_V and M_H



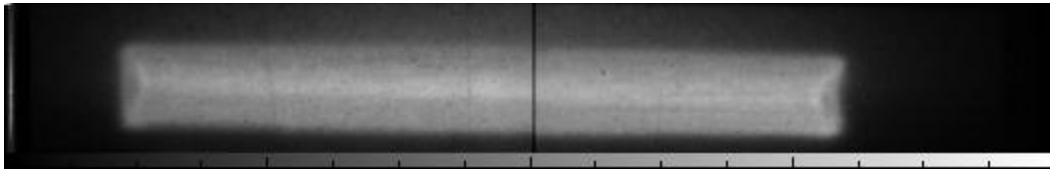
note: no quadrupole roll errors were assumed in simulations

Observed Footprints at Bechtel Screen with Nominal and Non-Nominal Settings of M_V and M_H

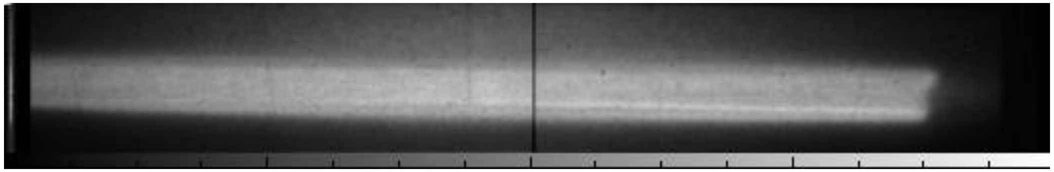




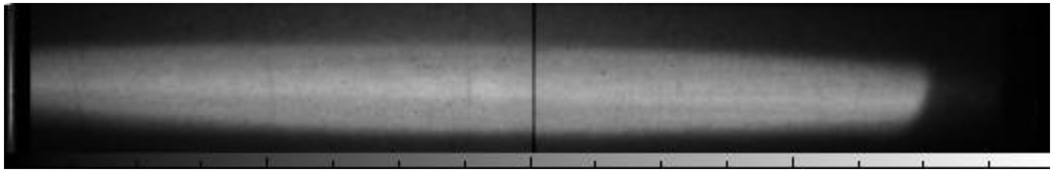
M_V and M_H at nominal settings



M_V at nominal settings, M_H turned off



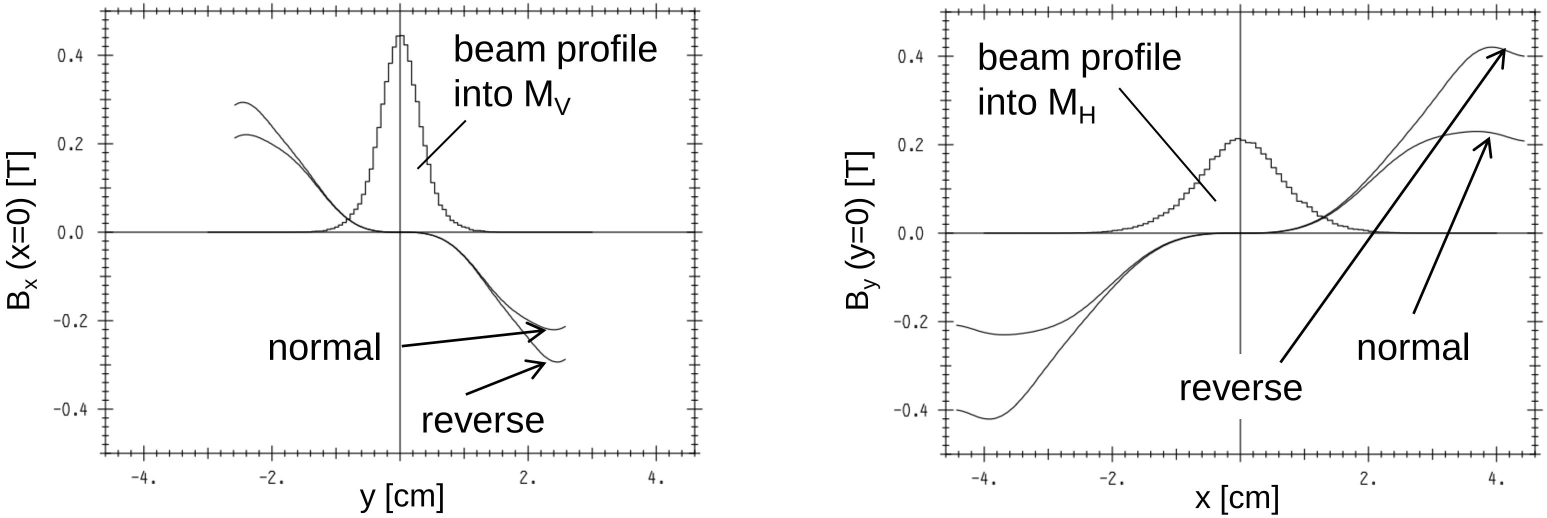
M_V turned off, M_H at nominal settings



M_V and M_H turned off

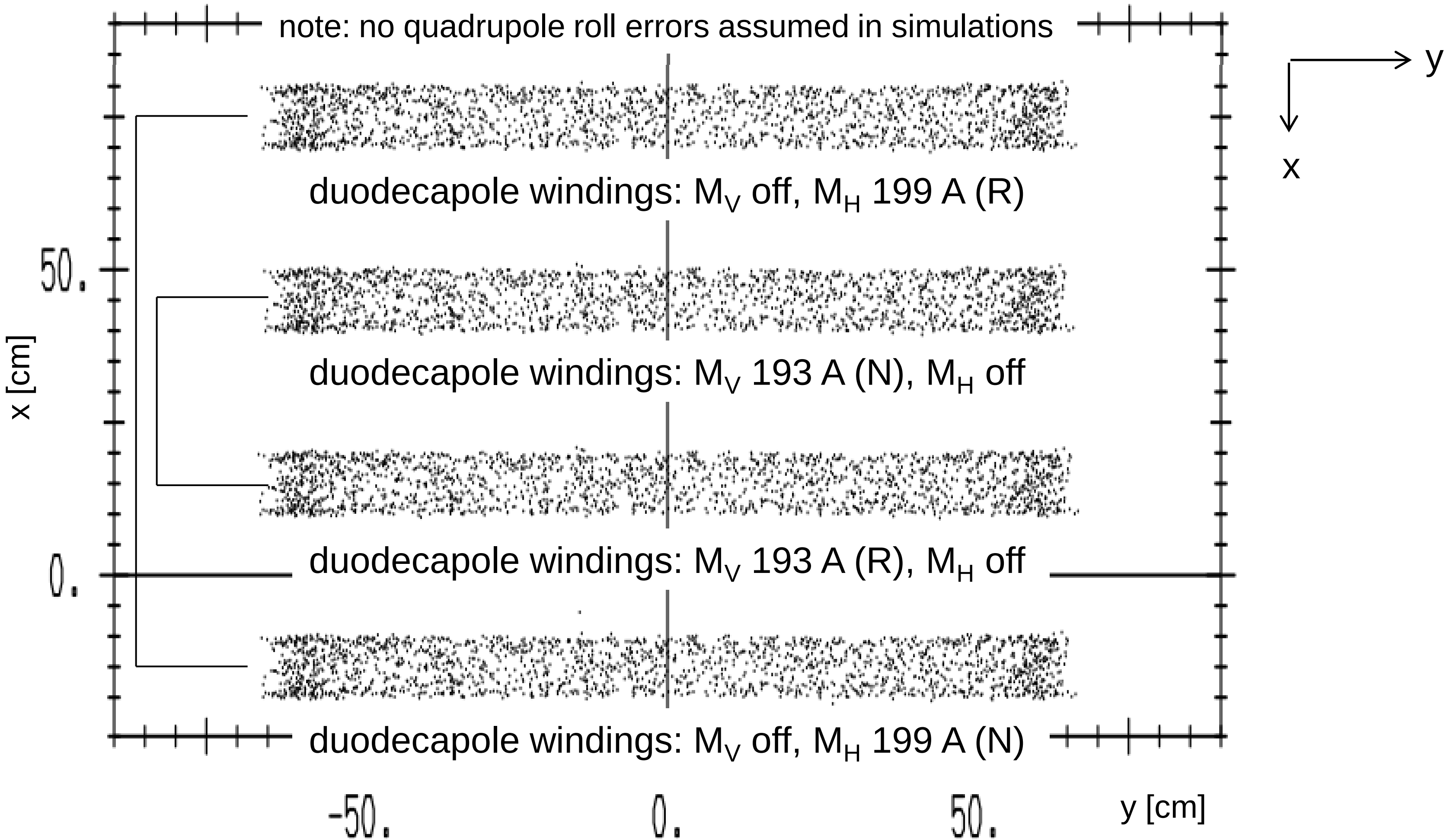
Duodecapole Windings of Multipoles Energized

- **Recorded beam spot at target with duodecapole windings in multipoles energized**
- **Predicted that all spots should be essentially identical, because major-axis fields in region of significant beam are essentially identical**

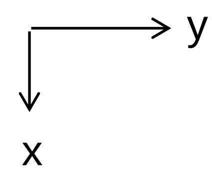


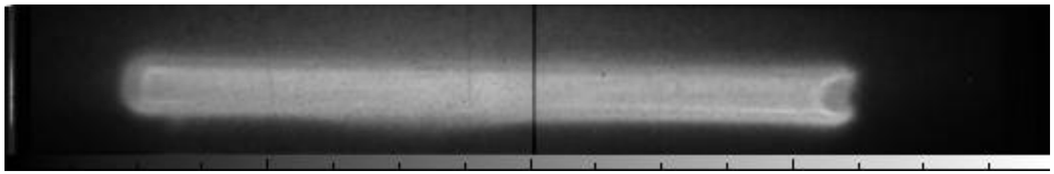
- **All predicted spots are essentially identical and all observed spots are essentially identical**

Predicted Footprints at Bechtel Screen with Duodecapole Windings of Multipoles Energized

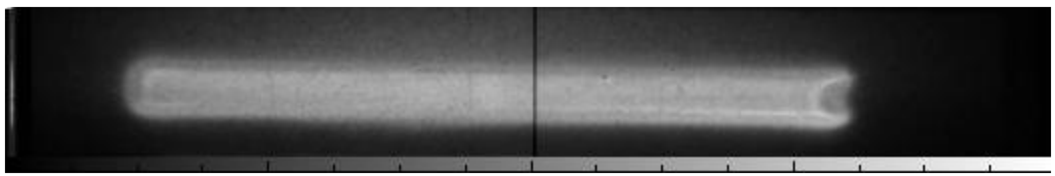


Observed Footprints at Bechtel Screen with Duodecapole Windings of Multipoles Energized

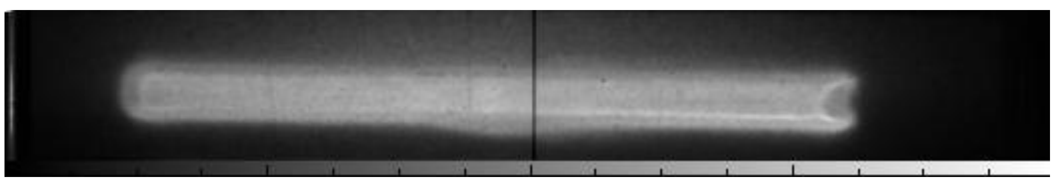




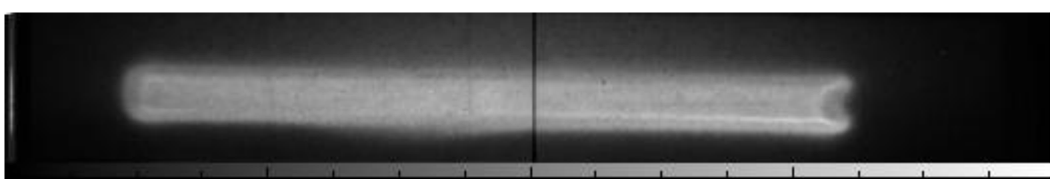
duodecapole windings: M_V off, M_H 199 A (R)



duodecapole windings: M_V 193 A (N), M_H off



duodecapole windings: M_V 193 A (R), M_H off



duodecapole windings: M_V off, M_H 199 A (N)

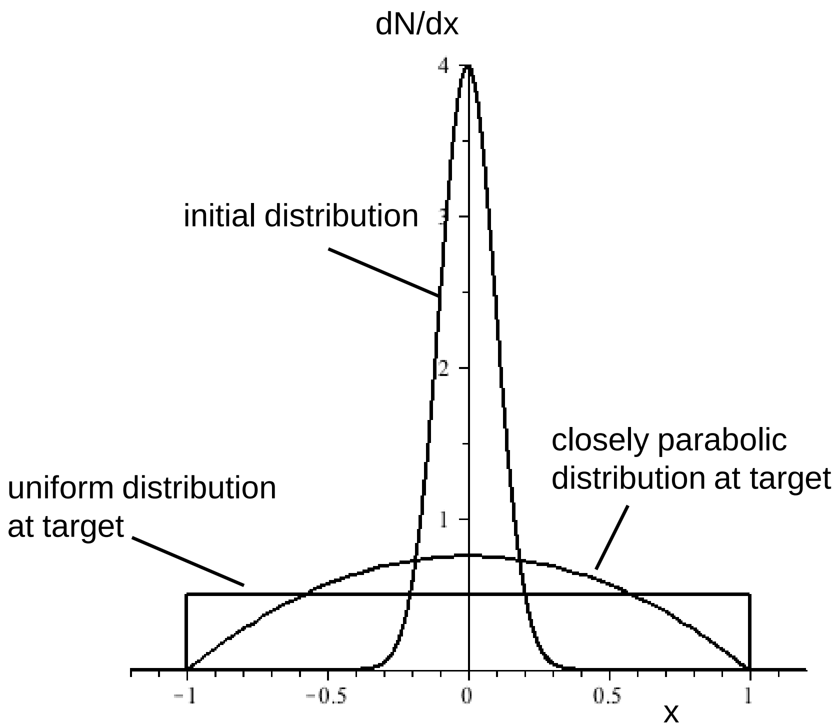
Conclusions about Area-C Experiment

- We demonstrated that we understand how to adjust matching-section quadrupoles to get different distributions at target, all with same footprint
- We demonstrated that we understand how to adjust last two quadrupoles to get different footprint sizes
- Jitter was observed and did not move distribution edges, but did skew distributions

Prerequisites for a Successful Beam-Redistribution System

- **A state-of-the-art accelerator**
  - Preferably dedicated to a single species
  - No mismatches in the accelerator that might cause two-Gaussian distributions
  - No cavity configurations that will cause large fluctuations in emittance or energy
  - Minimal jitter; jitter control upstream of beam expander if necessary
- **Good characterization of all magnets**
- **Good diagnostics**
- **On-line processing of data to determine matching-section input beam, and subsequent on-line determination of settings of matching-section quadrupoles based on input beam and beam distribution at target**
- **Beam redistribution in one plane should be much more straightforward than redistribution in both planes**

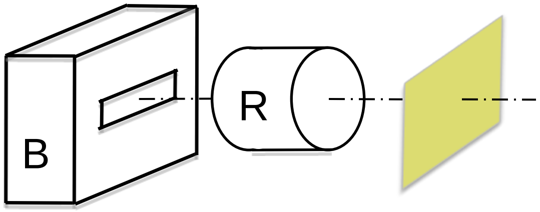
Formalism Exists for Magnet Design to Transform Given Input Beam into Desired Output Beam



See Jason, Blind,& Halbach, PAC 1997 for initial considerations. Further in-depth results to be published

- **With an initially Gaussian beam a magnet that produces a field proportional to the error function of x yields a precisely uniform beam**
- **Varying the initial beam size produces other distributions**
- **No beam is found outside the specified limits**
- **Slight adjustment of magnet trim coils accommodates distributions off nominal**
- **Simpler magnets can be designed to produce nearly equivalent distributions**

Formalism for Magnet Design to Transform Given Input Beam into Desired Output Beam Explained



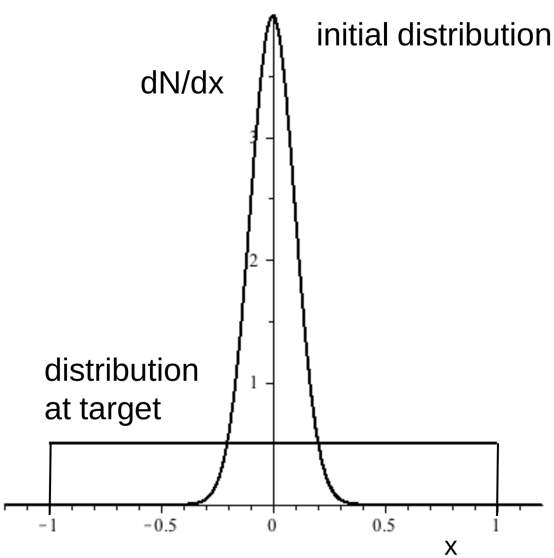
- **Consider nonlinear magnet B, followed by linear transport R to target**
- **Make** $R_{11}+a\ R_{12}=0$ **where** a **is slope of input beam in** xx'
  - not required, but simplifies magnet
  - for R, consider a drift of length L, so that $a=-1/L$ (note that no quadrupoles are needed to produce ribbon beams)
- **Can write a first-order differential equation in terms of input beam distribution and desired output-beam distribution – analytically soluble in some cases (uniform distribution is simplest)**
- **Solution provides field needed on axis**
- **Pole shape can be determined in complex plane**

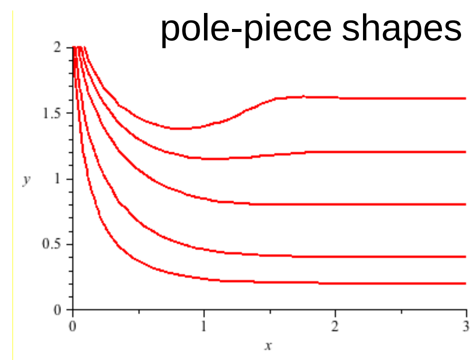
Solution for Uniform Distribution From Gaussian Distribution is Error-Function Field

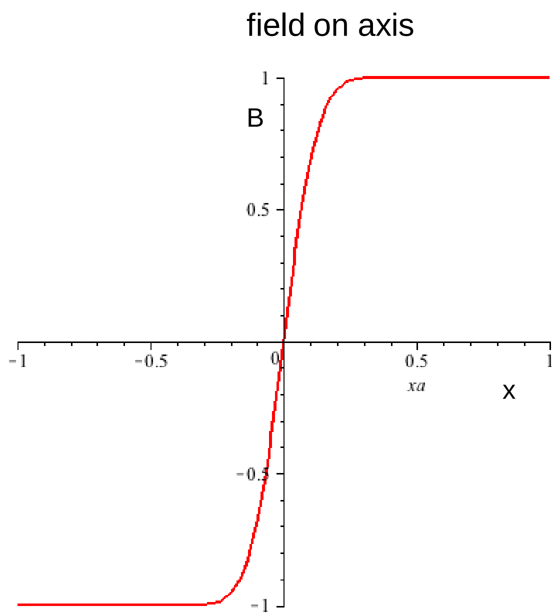
$$B = \frac{2w}{L} Erf\left(\frac{x}{\sqrt{2\sigma_0}} \right)$$

where w is desired beam width at target, σ_0 is rms of Gaussian input beam, and B is angular deflection in the magnet ($Bl/B\rho$).

Set $L=w=1$, $a=-1$, and $\sigma_0=0.1$ for our examples.

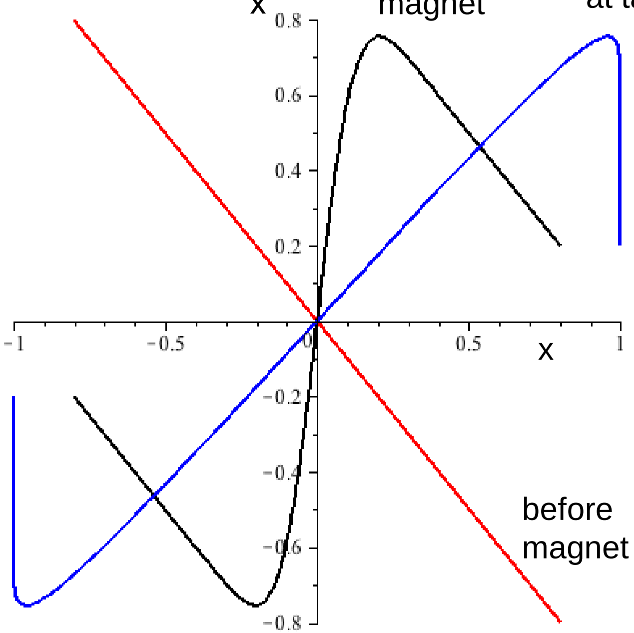






Target Beam Has Hard Limits for Any Input Distribution; Varying Input-Beam Size Changes Distribution

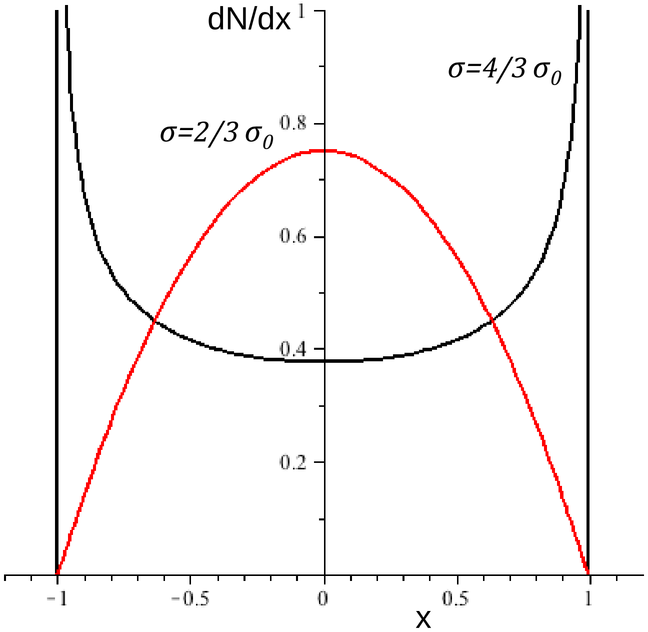
Phase space for a small-emittance beam



Erf magnet case

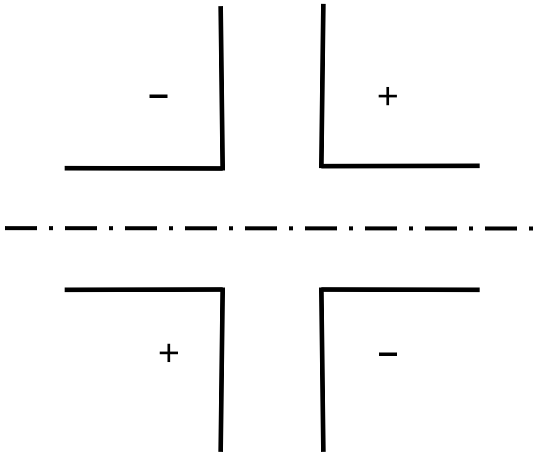
Vary input-beam size

a nearly exact parabolic distribution can be made with the smaller input beam

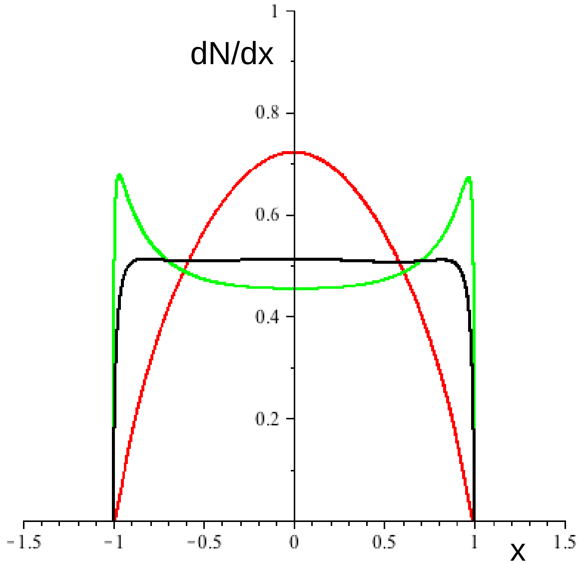


A magnet for an exact parabolic distribution has been determined

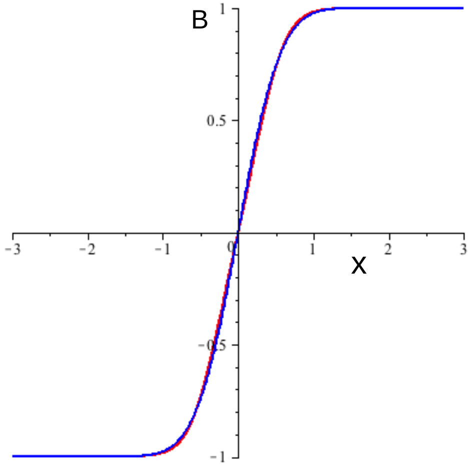
A Simpler Magnet Gives Similar Results



two dipoles,
beam into page



distributions at target for Gaussian input beams with three rms sizes (smallest: red; largest: green)

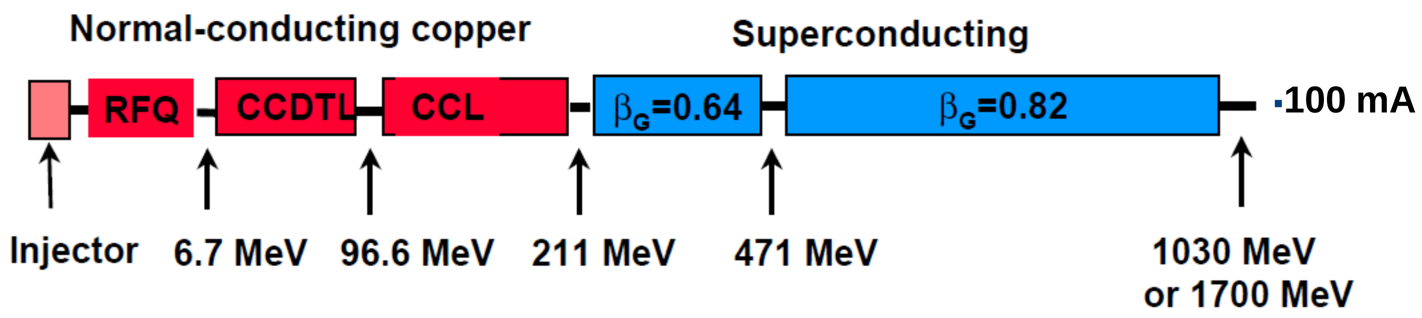


comparison of dipole (red) and Erf (blue) magnets' fields

Summary of Alternative Beam Distributors

- **If the input beam is known, an exact distribution can be made at the target**
- **For a given initial and target distribution, a field distribution and hence magnet pole shapes can be determined**
- **For input distributions off nominal, the output distribution can be varied by changing beam size at magnet**
- **…Or the magnet can be adjusted by coils or coils in slots on the poles**
- **The output distributions are strictly limited to the specified size; unlike with octupole redistribution there are no tails**
- **Magnifications are adjustable by simply changing the magnet field**
- **Ribbon beams and two-dimensional distributions can be made with focusing configurations similar to that of the octupole method**

▪APT project in the 1990s established a new technology base for high-average power proton linac technology.

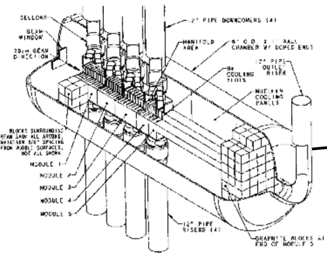


- \- Superconducting cavities were used above 200 MeV.
- \- Normal-conducting quadrupoles used for transverse focusing.

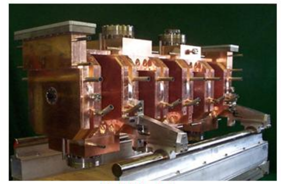
\- High availability (90%) was an important APT design goal.
\- Required new approach to the low-energy part of the linac – LEDA facility demonstrated 100-mA, CW, DC injector/RFQ technology.

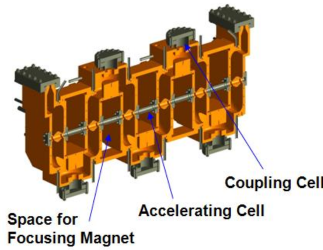
\- Became the basis for most new high-average power designs that followed.

Significant technical progress was made before the APT Project was cancelled.



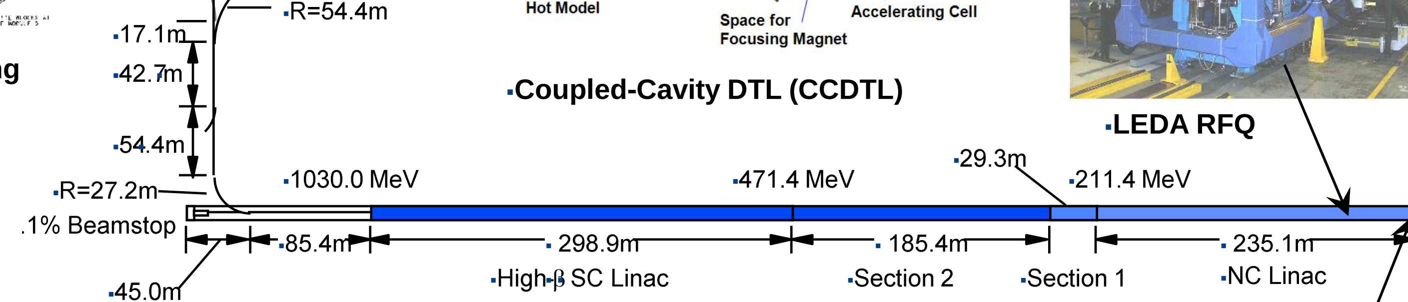
Schematic of Tuning Beam Dump

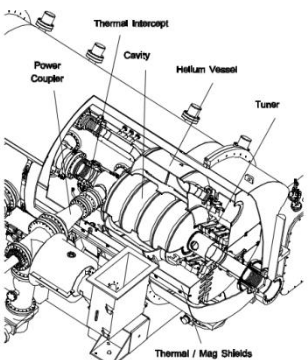




Coupled-Cavity DTL (CCDTL)

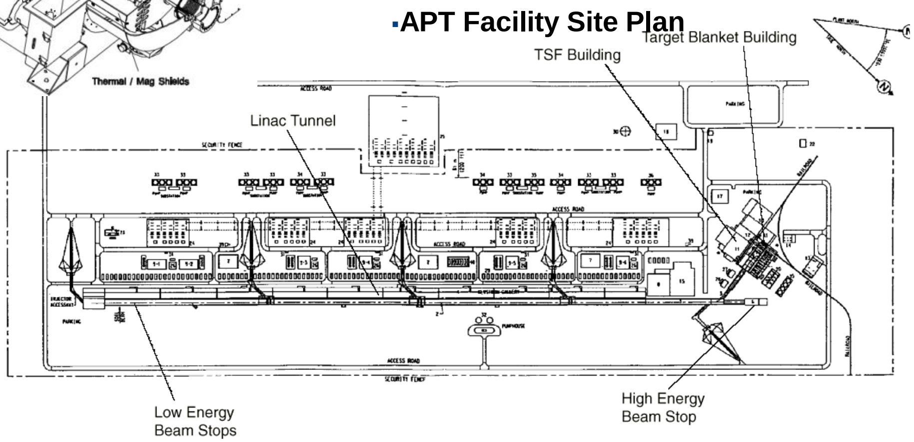
LEDA RFQ





Detailed Cryomodule Design

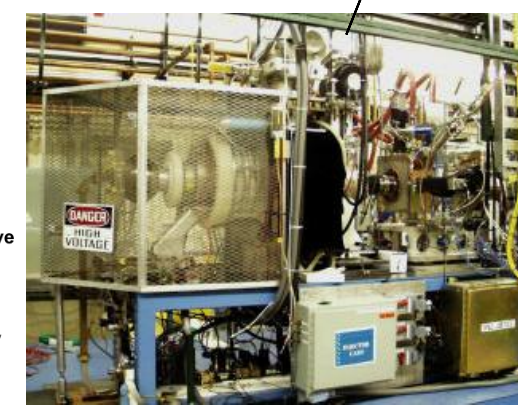
APT Facility Site Plan



Major injector components
- 2.45-GHz microwave ion source
- single-gap extractor
- dual magnetic solenoid, gas-neutralized LEBT

Pertinent ion source parameters
- 800-1200 W of 2.45-GHz microwave power
- 85% ≤ proton fraction ≤ 95%

Key injector beam parameters
- proton current >110 mA at 75-keV
- emittance <0.2 ≤ mm-mrad (normalized)



LEDA H^+ injector including LEBT (Low Energy Beam Transport)