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Measurement of the Internal Magnetic Fields of Plasmas using an Alpha Particle Source

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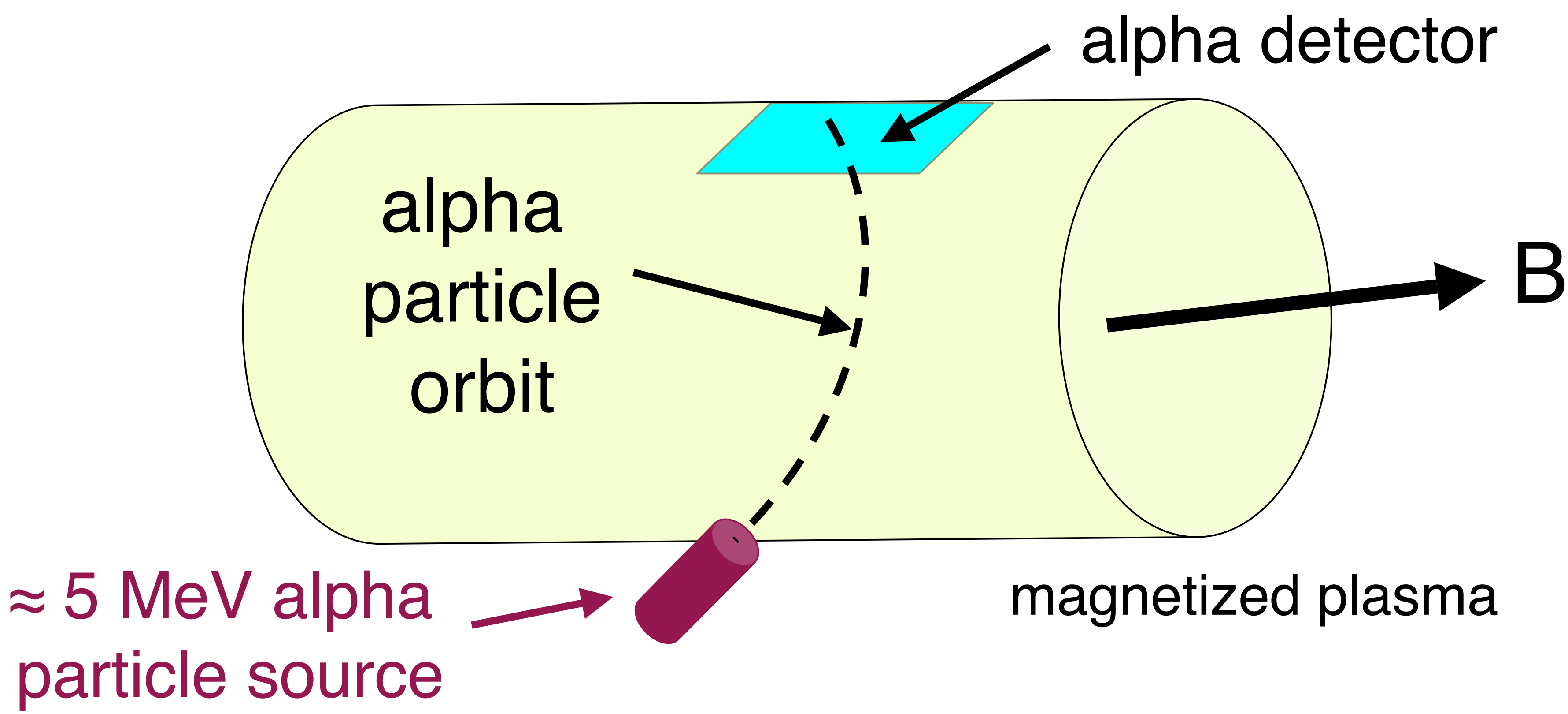
ABSTRACT

The internal magnetic fields of plasmas could be measured under certain conditions from the integrated v x B deflection of MeV alpha particles emitted by a small radioactive source. The alpha source and large-area alpha particle detector would be located inside the vacuum vessel at the wall. Alphas with a typical energy of 5.5 MeV (^{241}Am) can reach the center of almost all laboratory plasmas and magnetic fusion devices, so this method can potentially determine the q(r) profile of tokamaks or STs. Orbit calculations, background evaluations, and conceptual designs for such a vxB (or “AVB”) detector are described.

Basic Idea

- Use alpha orbit trajectories through plasma to measure B(r)
- Alpha orbits reach plasma center whenever B(kG)•a(m) < 3



Advantages

- High energy alpha source (e.g. 5.5 MeV alpha from ^{241}Am) is relatively cheap compared to any high energy beam
- Detection using large-area scintillator screen should be relatively simple and cheap
- Unfolding of B field from measurements is relatively simple, assuming multiple simultaneous alpha trajectories

Limitations

- Strong alpha source ($S_\alpha \approx$ 1 mCi $\approx 4 \times 10^7$ α/sec) must be handled carefully, e.g. protected from heat

- Large area alpha detector on inside wall may be intrusive (should be located in far scrape off-layer)

- Alpha measurement becomes difficult due to the x-ray and 3 MeV proton background in D-D plasmas when $T_e > 1$ keV and $S_{DD} >> S_\alpha$

=> Mainly useful for low fusion rate plasmas (not ITER !)

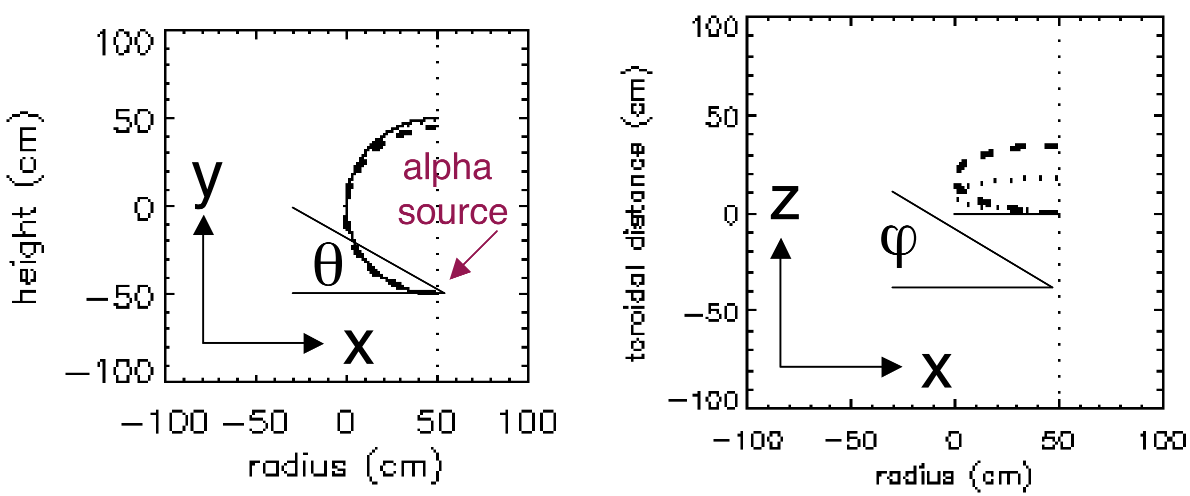
Alpha Trajectory Calculations

- Uniform B of varying direction (~ tokamaks)
- Cylindrical model for q(r) profile in NSTX
- Realistic numerical model for NSTX

Uniform B of Varying Direction

Use approximate NSTX plasma field and geometry
(x=radial direction, y=poloidal direction, z=toroidal direction)

Three alpha orbits with varying B angles χ (χ=0 => toroidal B)



initial conditions:
E = 5 MeV
B = 6.5 kG
$\theta = \varphi = 0°$
χ = 0° (solid)
= 10° (dot)
= 20° (dash)

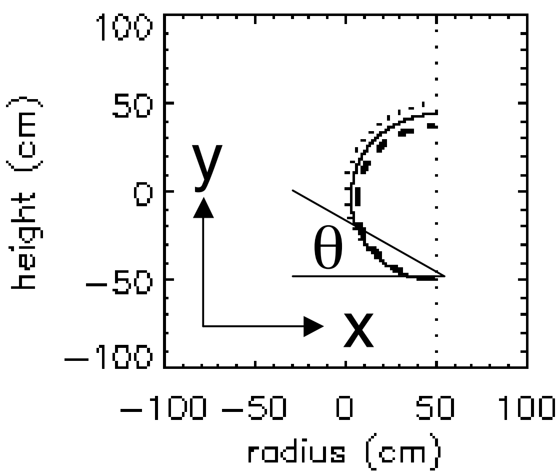
Alpha orbit plane rotates with field line direction angle χ

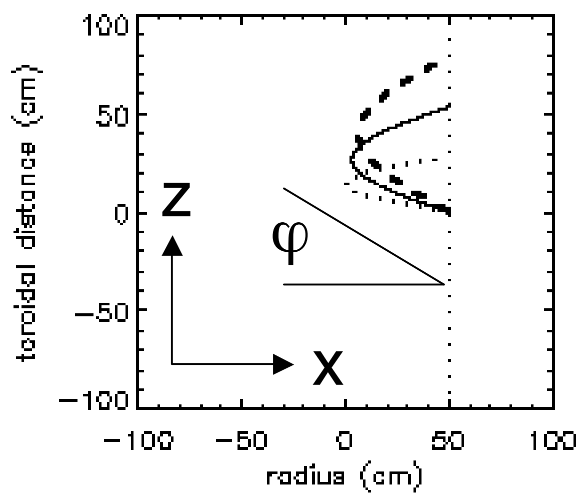
Toroidal impact location: $\Delta z(\chi) \approx 2\rho \sin \chi$

Effect of Finite Aperture Size

Spread in toroidal launch angle also changes z-impact location

Three alpha orbits with varying toroidal launch angles φ





initial conditions:
- $E = 5$ MeV
- $B = 6.5$ kG
- $\theta = 0°$, $\chi = 0°$
- $\varphi = 20°$ (solid)
- $= 10°$ (dot)
- $= 30°$ (dash)

Alpha orbit becomes helix with z-impact dependent on φ

Toroidal impact location: $\Delta z(\varphi) \approx \pi\rho \sin \varphi$

Main Principle of Measurement

- Alpha orbit plane rotates with (average) field line angle χ
- Measurement of toroidal impact location determines χ
- Spread in alpha source $\Delta\varphi$ also affects toroidal impact
- Accuracy of χ *measurement limited by* $\Delta\varphi$:

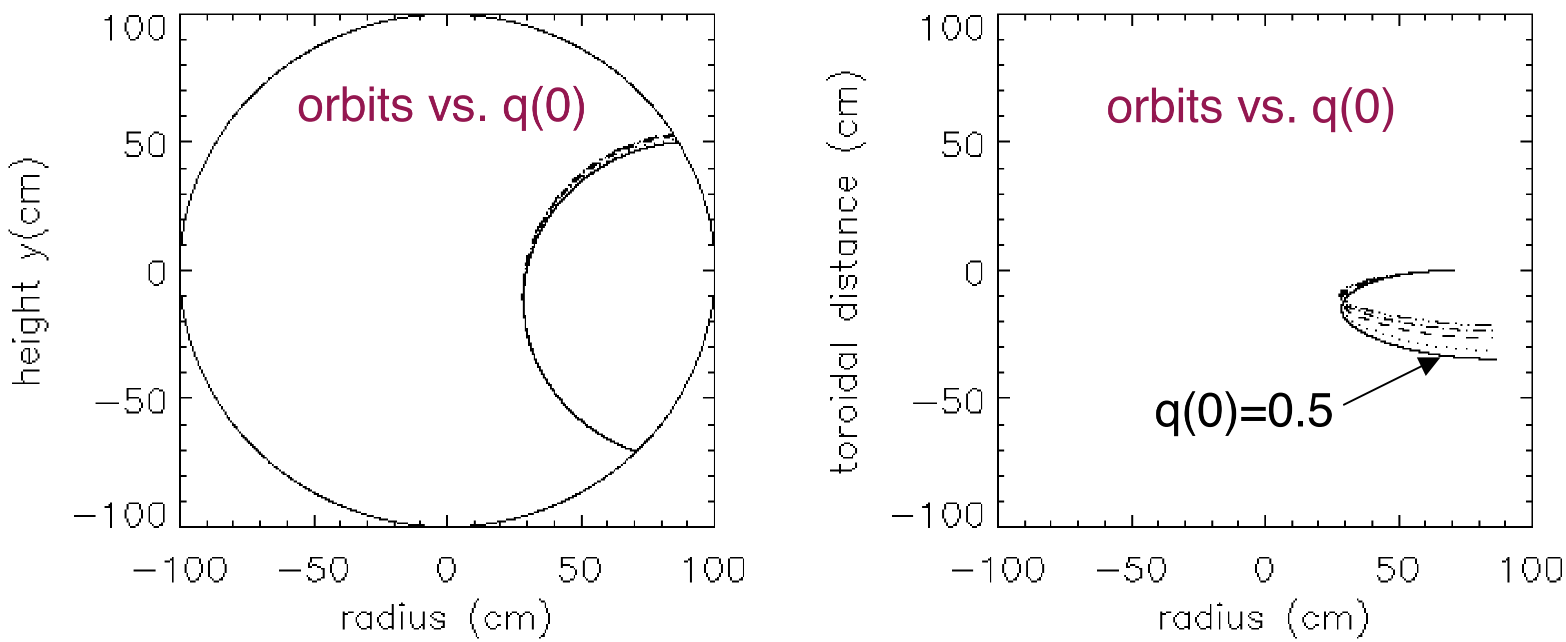
$$\Delta\chi \approx (\pi/2)\,\Delta\varphi$$

e.g. to measure χ *to within 1°, need to have alpha source aperture spread of* $\Delta\varphi \approx 0.7°$

Cylindrical Model for NSTX

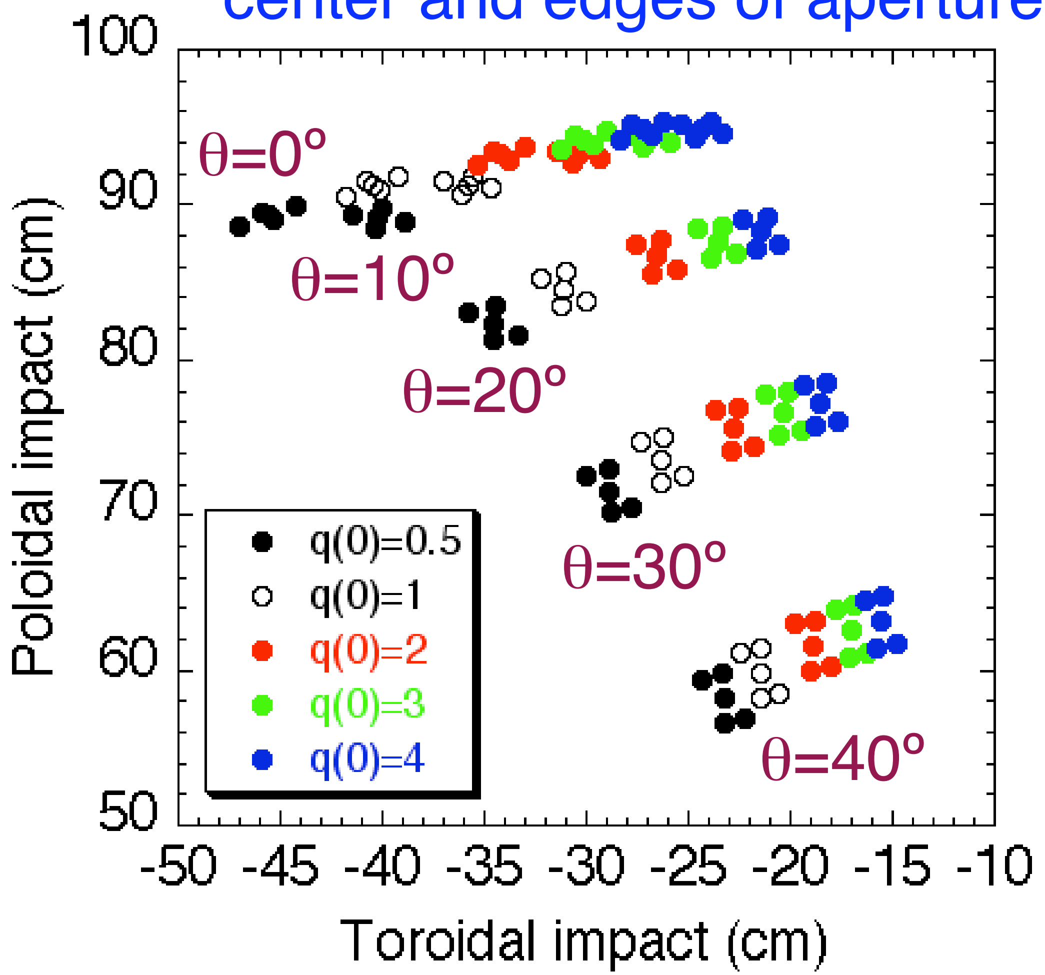
- Model NSTX with B=5 kG, R=200 cm, a=100 cm, q(a)=1
- Assume q(r) = q(0) + [q(a)-q(0)](r/a) with q(0)= 0.5, 1, 2, 3, 4

Typical results for E=5 MeV, B=5 kG, φ=0°, θ=20°



Alpha Impact Location vs. q(0)

four points for each θ and q(0):
center and edges of aperture

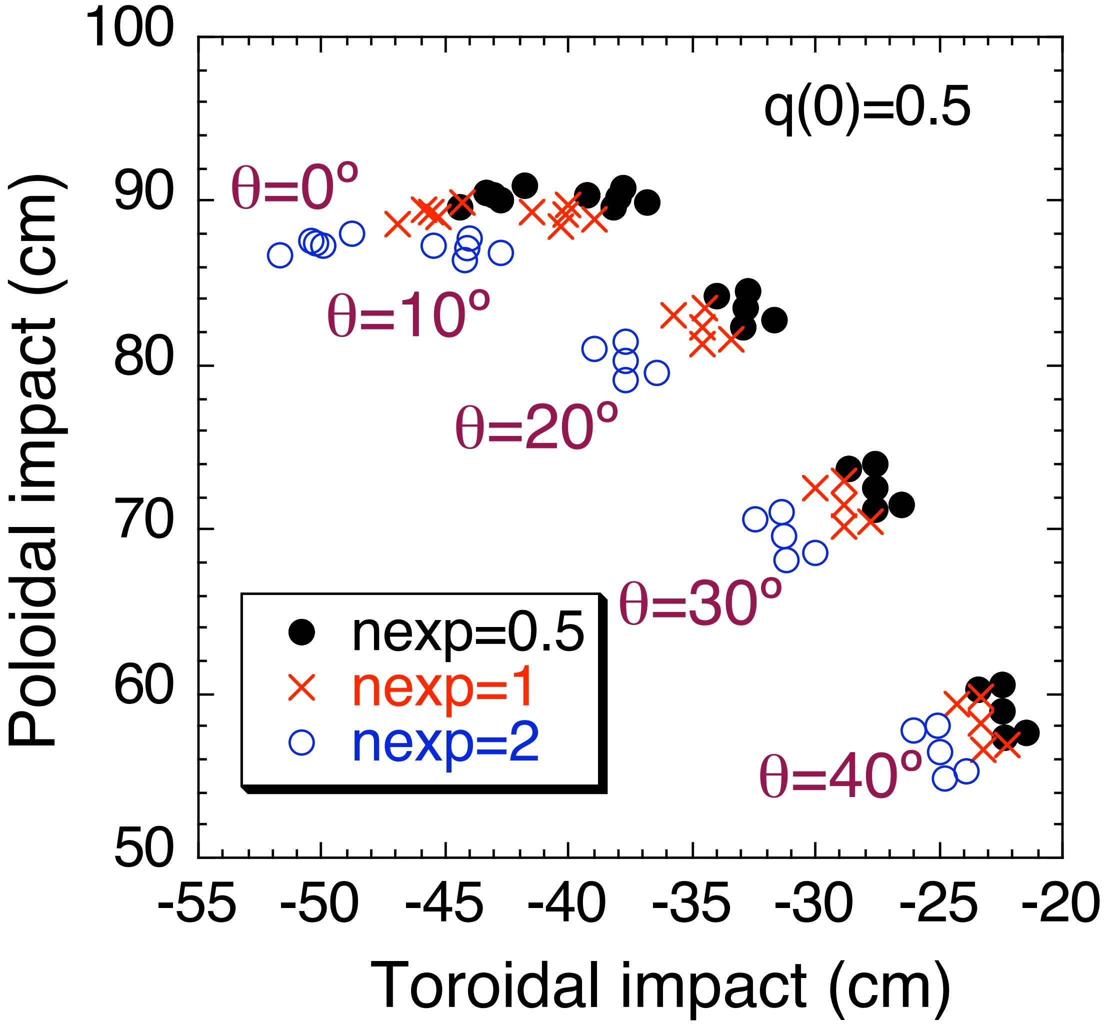


NSTX Plasma:
B_{tor} = 5 kG
R = 200 cm
a = 100 cm
q(a) = 1

Alpha source:
E_α = 5 MeV
θ= various
Δθ = 2°
φ = 0°
Δφ = 0.4°

Alpha Impact Location vs. q(r) Shape

$q(r)= q(0) + [q(a)-q(0)](r/a)^{nexp}$ with nexp = 0.5, 1, 2



NSTX Plasma:

B_{tor} = 5 kG

R = 200 cm

a = 100 cm

q(a) = 1

q(0)=0.5

Alpha source:

E_α = 5 MeV

θ= various

$\Delta\theta$ = 2°

φ = 0°

$\Delta\varphi$ = 0.4°

Implications of Cylindrical Modeling

- The q(0) variations can be separated by their toroidal impact locations for an alpha source aperture with toroidal spread $\Delta\varphi = 0.4°$, roughly consistent analytical estimate since $\Delta\chi \approx 3°$ for these cases

- The q(r) variations for a given q(0) and q(a) are similar to the q(0) variations, i.e. may be *difficult to unfold* q(r) shape without independent knowledge of q(0)

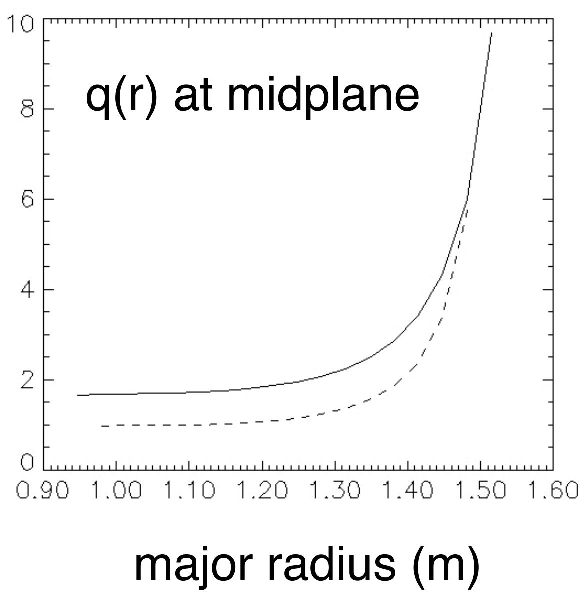
- The variation in poloidal angle maps out a smooth curve in the detector plane for each q(r) => poloidal aperture could be a slit for increased count rate

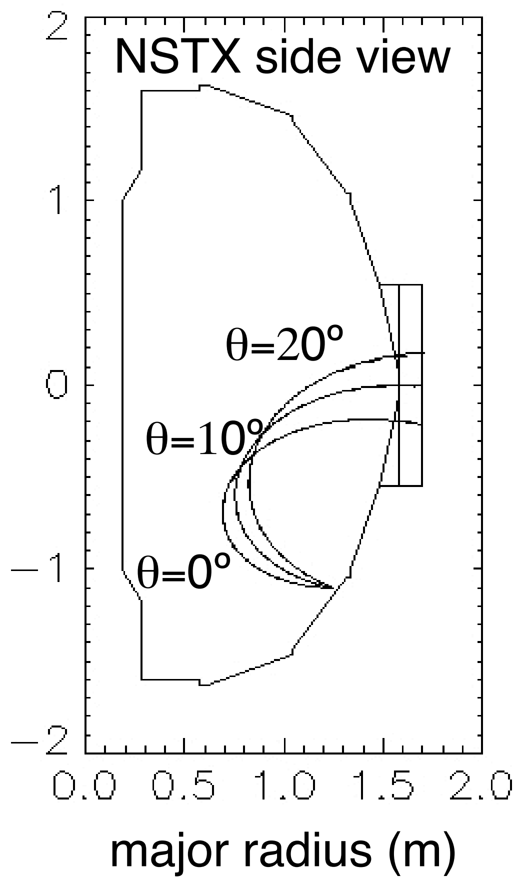
Realistic NSTX Alpha Orbits

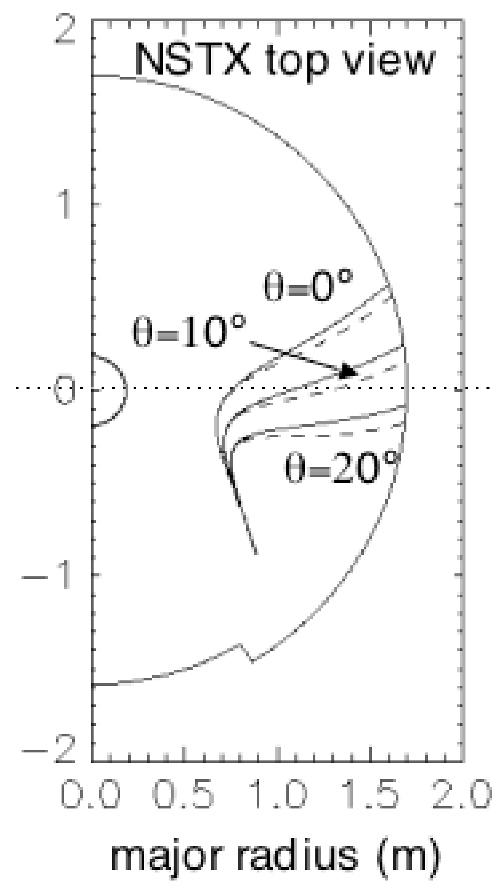
- Cylindrical model ≈ consistent with realistic NSTX q(r)

E_α = 5.5 MeV

EFITs for shot #104033
B=4.5 kG, I=770±10 kA
solid line @ t=169 msec
dashed line @ t=295 msec

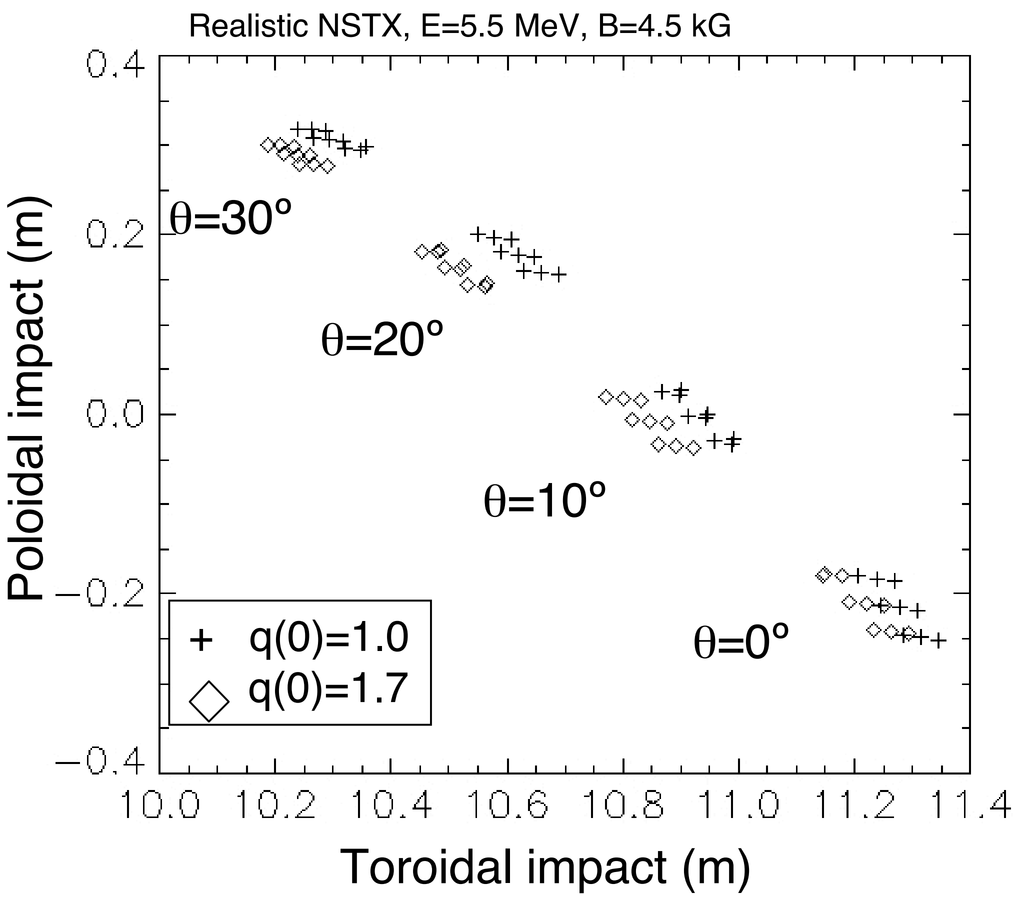






Alpha Impact Location vs. q(r)

- Realistic model results are roughly consistent with cylindrical model



NSTX Plasma:

B_{tor} = 4.5 kG

R = 85 cm

a = 65 cm

q(a) = 8

Alpha source:

E_α = 5.5 MeV

θ= various

$\Delta\theta$ = 5°

φ = 0°

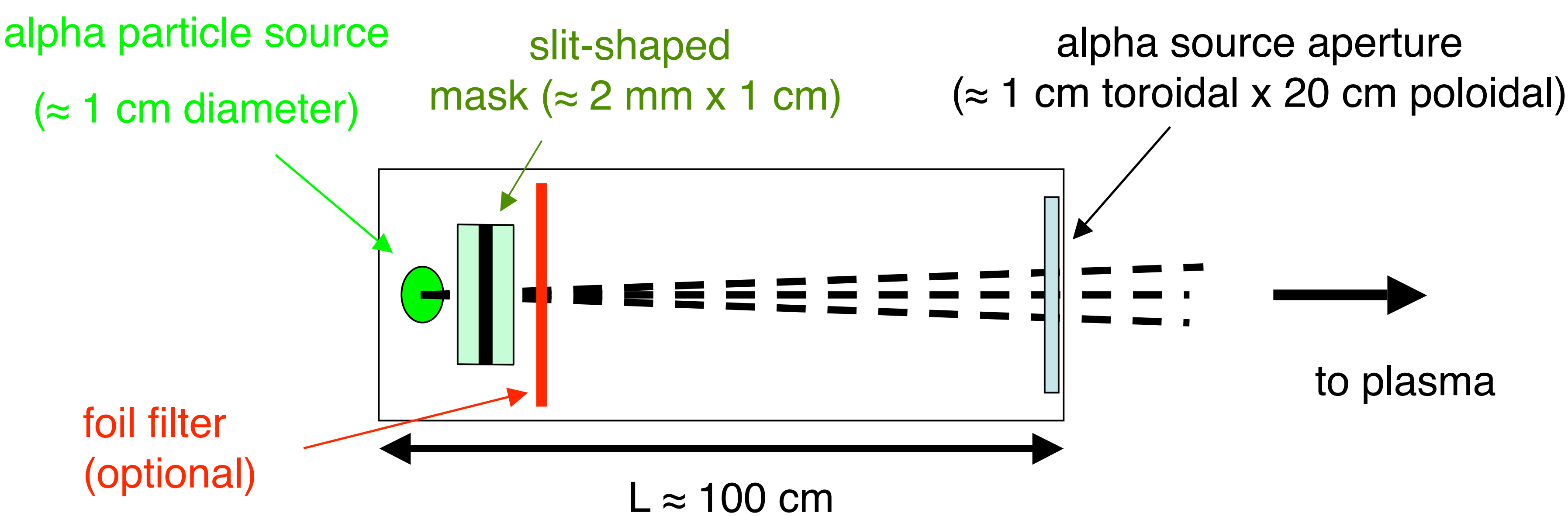
$\Delta\varphi$ = 0.6°

Unfolding the q(r) Profile

- Each aperture slit will produce a single curved line on the alpha detector plane dependent on the q(r) profile
- Multiple slits should produce information about q(r) profile, e.g. by sampling different radial regions using varying toroidal angles or alpha energies
- Ideally, to unfold N points on the B(r) profile will require ~ N apertures to determine B direction
- Initially, a single aperture measurement might be used to constrain the q(r) profile, e.g. to estimate q(0)

Alpha Source Characteristics

- Strongest available alpha source ≈ 1 mCi of ^{241}Am / 1 cm^2
- For aperture with $\Delta\varphi$ = 0.6° and $\Delta\theta$ = 10° => $S_\alpha \approx 5\text{x}10^3$ α/sec
- Foil filter can reduce alpha energy from ≈ 5.5 MeV to ≈ 1 MeV



Alpha Detector Design for NSTX

- Detector size ≈ 40 cm x 40 cm (see alpha impact maps)
- Spatial resolution (pixel size) ≤ 1 cm (see same maps)
- Maximum count rate ≈ 10^4 alphas / sec / aperture
- Probably need pulse height discrimination to avoid backgrounds (energy resolution roughly 50%)

=> Could be made from 40 x 40 array of discrete silicon detectors (e.g. Ortec Ultra series), but this would be prohibitively expensive (≈ $1M) and difficult to monitor

Soft X-ray Background

- Plasma x-ray energy flux >> alpha energy flux onto detector

- But most x-rays can be blocked by a ≈ 5 μm gold foil
  (which will slow alpha down from ≈ 5.5 MeV to ≈ 3 MeV)

x-rays transmission in Au foil vs. plasma temperature (NIST)

$f \approx 10^{-6}$ for $T_e = 0.5$ keV
$f \approx 10^{-4}$ for $T_e = 1$ keV
$f \approx 10^{-2}$ for $T_e = 2$ keV

=> Foil should stop most background for $T_e \leq 1$ keV or so

=> Remaining background will be very small pulse heights

Fusion Product Loss Background

- Fusion product ion from D-D reactions have similar energy and gyroradius as alphas from ^{241}Am source
- These will be lost from plasma center to detector whenever alphas from center can reach detetctor => *background*
- 1 MeV Triton and 0.8 MeV ^{3}He stopped by 5 μm gold foil, but 3 MeV proton will not be stopped by this foil
- If detector is just thick enough to stop 3 MeV alphas ($\approx$ 10 μm of silicon), then 3 MeV proton will deposit only $\approx$ 0.3 MeV

=> protons could be distinguished by pulse height analysis

Backgrounds for Various Devices

- Backgrounds depend mainly on plasma T_e and S_{DD}
- Backgrounds should be negligible for ET-like plasma, and relatively minor for MST and NSTX OH plasmas
- But backgrounds *severe* for NBI heated NSTX plasmas

Parameter	ET (UCLA)	MST(Wisc.)	NSTX (PPPL)
T_e (keV)	≈0.3-0.5	≈0.5	≈0.5 (OH) - 2 (NBI)
n_e (10^{13} cm^{-3})	≈0.2	≈1	≈1 (OH) - 3 (NBI)
neutrons/sec	≈10^6	≈10^8	≈10^9 - 10^{14}
(protons/α)*	<0.01	~0.1-1	~1 (OH) - 10^5 (NBI)
(x-ray/α)**	~0.1	~1	~1 (OH) - 10^5 (NBI)

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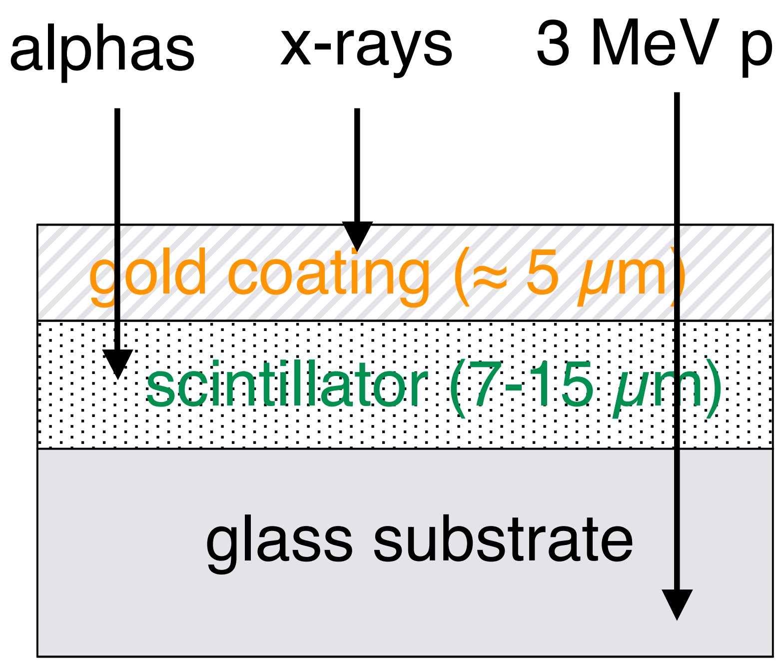
* (number of 3 MeV protons / number of AVB alphas) onto detector

** (x-ray energy flux / AVB alpha energy flux) onto detector after 5 μm gold foil

Scintillator Detector Option

- phosphor screen (e.g. ZnS) can detect single alphas (e.g. with intensified CCD camera
- good spatial resolution (≈ 1 mm)
- fast response time (> 1-30 μs)
- has poor energy resolution, but probably its good enough to distinguish 3 MeV alphas from 3 MeV proton & x-ray backgrounds



Amorphous Silicon Detector Option

- Sold by Perkin-Elmer for medical and industrial radiation imaging

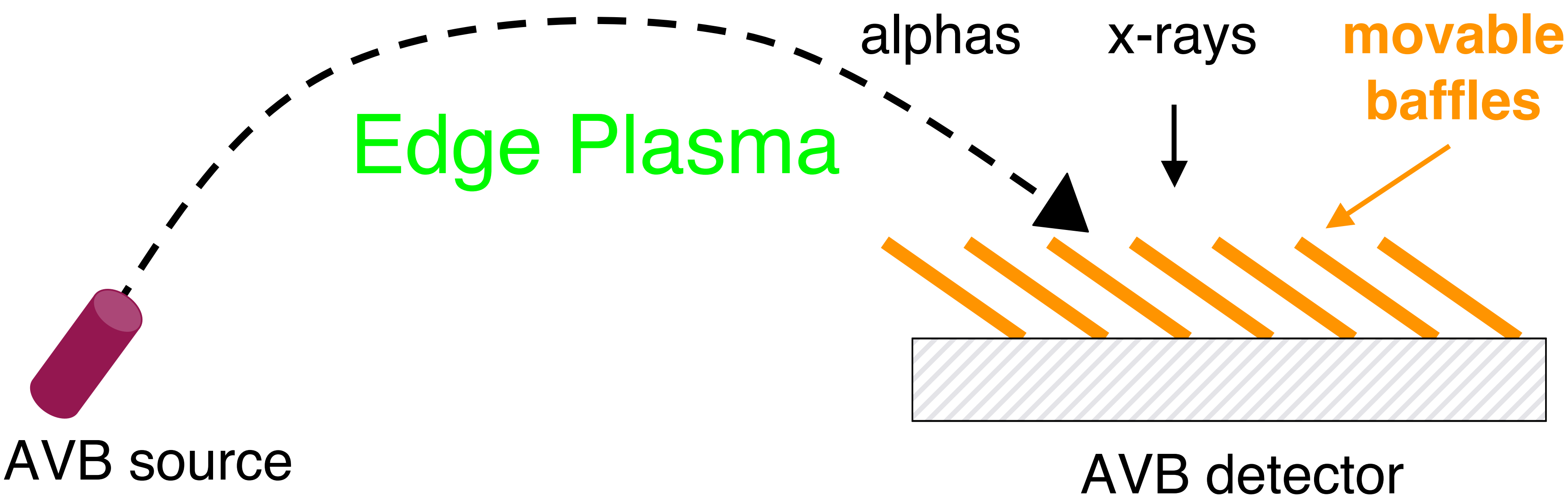
- Can be 40 cm x 40 cm with 1024 x 1024 pixels, but frame rate only 7 Hz

- Should have improved alpha pulse-height discrimination compared with scintillator detector

- Probably can be custom fabricated and instrumented to for AVB detector (e.g. by Princeton Scientific Instruments)

Edge q(r) in NSTX NBI Plasmas

- Backgrounds in NBI plasmas might be avoided by aiming AVB alphas only through edge plasma and adding baffles to block x-rays and 3 MeV protons from center
- Backgrounds should only be due to cold edge plasma



Summary

- Alpha v x B detector can be used to measure the internal magnetic fields of plasma when:

  $T_e \leq 1$ KeV and $S_{DD} \leq 10^{10}$ / sec (roughly)

- Two concepts for AVB detector are:

  - scintillator screen + optical coupled output to CCD
  - amorphous silicon array w/electrical output tp PHA

- Hope to try this on ET and NSTX

Want More Information ?

Name	e-mail address