A Visit to Helically Symmetric Experiment (HSX)
- Field-line Tracing by Electron Beam and Fluorescent Mesh -

Hiro Takahashi

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Princeton Plasma Physics Laboratory

Visit over two brief periods:
- Sep. 9 (Thu) - 13 (Mon)
- Sep. 20 (Mon) - 23 (Thu)

OUTLINE

- **HSX Project - Introduction.**
  - Device.
  - People.
  - Diagnostics Development.
  - Physics Program.
- **Method of Field-line Tracing by Electron Beam and Fluorescent Mesh.**
  - Principle.
  - Electron Beam.
  - Fluorescent Mesh.
- **First Look at Data — Some Cool Stuff.**
  - Closed Flux Surfaces.
  - Islands.
  - Rotational Transform Analysis.
- **Second Look at Data — Some Intriguing Stuff.**
  - Bright Stars in Very Dark Space.
  - Smeared Spots.
  - Turns - Which, Which Way, and How Many?
  - 'Two-dot Event.'

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  - On Electron Beam Based Field-line Tracing.
  - On HSX Project.
- **Recommendations to NCSX Group.**
  - On Field-line Tracing Diagnostic Development.
    * Collaborate Closely with HSX Group.
    * Develop Stable Electron Gun.
    * Assess Also Methods Other than Fluoresenct Mesh.
    * Match Dynamic Ranges Carefully.
    * Provide a Beam Interrupter.
    * Measure Beam Width.
    * Make Reference LED's Much Smaller and Less Bright.
    * Obtain 'User-friendly' Very Fast Field-line Tracing Code.
  - On Machine Construction.
    * Assess Impact of Minute Difference in Individual Coil Currents.
    * Measure Accurately *Relative* Current in Individual Coils.
    * Float Vessel Electrically.
    * Assure Complete Darkness.
    * Schedule Enough Time for Measurement.

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HSX PROJECT

The Helically Symmetric Experiment (HSX) is in the HSX Plasma Laboratory of the University of Wisconsin-Madison. It is also called the Torsatron/Stellator Laboratory.

- Proposed: 1992.
- Approved: 1993.
- First plasma: August, 1999.

The 'incubation' period included the time lost by a vendor that failed to meet the coil manufacturing specs. The coils were later fabricated in house by the University staff.

An impressive hardware achievement for a small university group.

HSX PROJECT - Cont.

Potential for becoming a GREAT physics study platform, because of:

- Very cleverly conceived device for addressing a range of physics issues by turning only a few 'controllable knobs,' and
- Willingness of people involved to 'hunker down' and tackle basic but important issues.

Areas of some concern — diagnostics and plasma production.

HSX DEVICE

The following viewgraphs are from Simon Anderson's paper at the 12th International Stellarator Workshop, Madison, WI.

- Photo of HSX (Fig. 1).
- Parameter list.
- Phot of a main coil (Fig. 2).
- Schematic of auxiliary coils (Fig. 3).
- Theoretical rotational transform profile (Fig. 4).
- Monte-Calro diffusion coefficient (Fig. 5).

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HSX Assembled

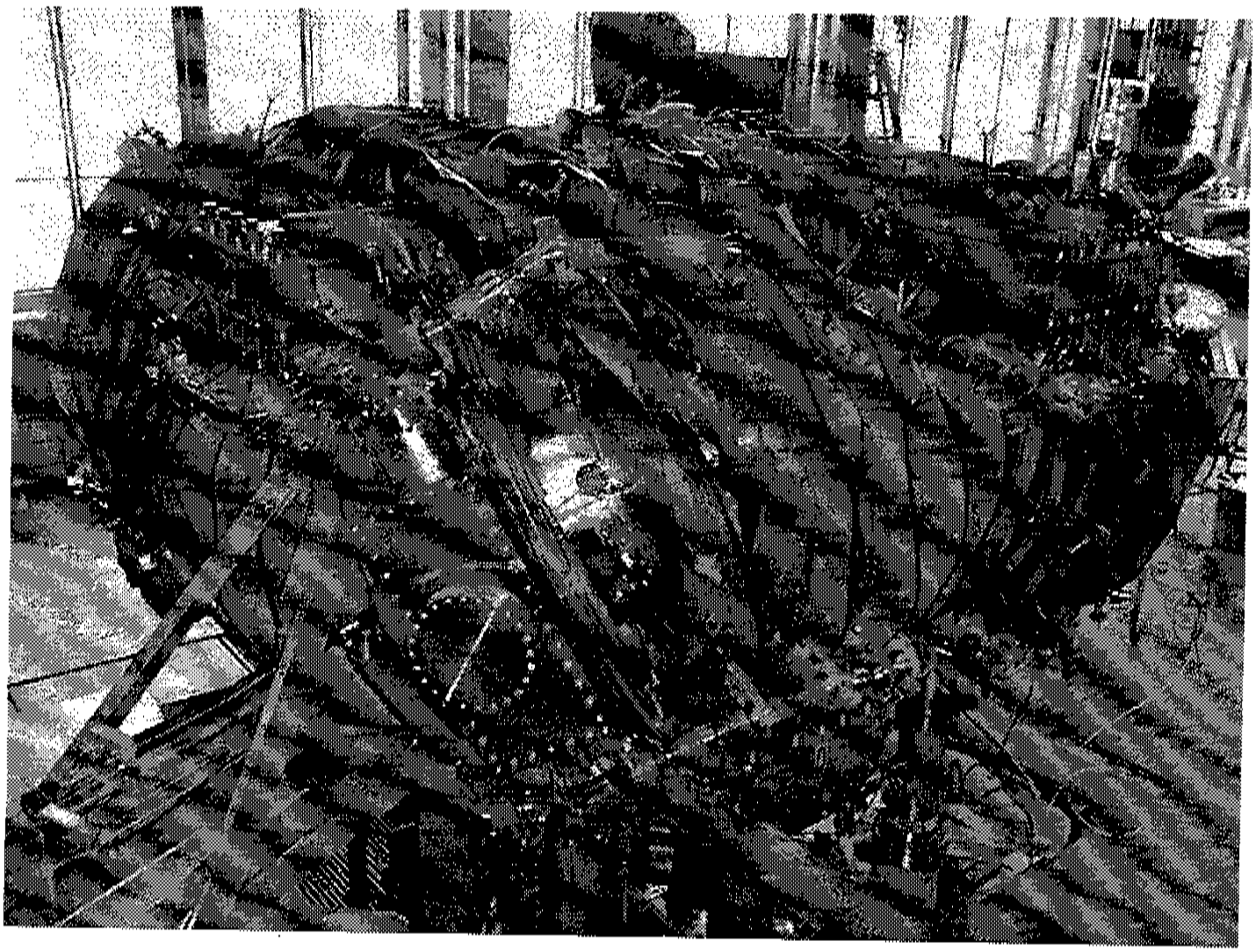

Fig. 1

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The HSX Stellarator

Major Radius	1.2 m
Average Plasma Minor Radius	0.15 m
Plasma Volume	~.44 m^3
Number of Field Periods	4
Helical Axis Radius	20 cm
Rotational Transform	
Axis	1.05
Edge	1.12
Number of Coils/period	12
Average Coil Radius	~ 30 cm
Number turns/coil	14
Coil Current	13.4 kA
Magnetic Field Strength (max)	1.37 T
Magnet Pulse Length (full field)	≤ 0.2 s
Auxiliary Coils (total)	48

Estimated Parameters with 28 GHz ECRH

Heating Power (source)	200 kW
Power Density	.45 W/cm^3
Density (cut-off)	1×10^{13} cm^{-3}
T_{eo} (LHD scaling, 100 kW)	700 eV
τ_E (LHD scaling)	2 ms
υ_e^*	≤ 0.1

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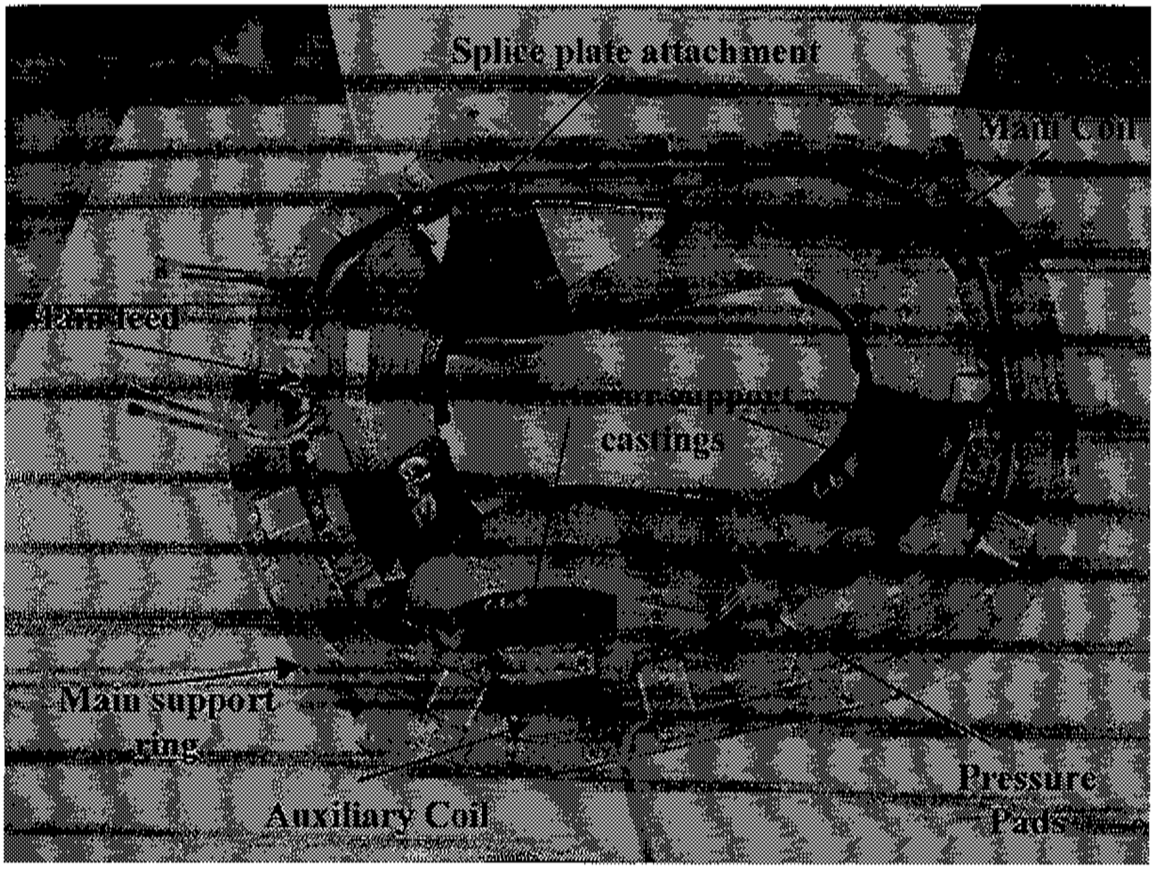
Coil Module Assembly



- Each coil is initially aligned in a stainless steel support ring and pressure pads, which are epoxied to the coil, mount the coil into the ring
- An auxiliary coil is positioned and clamped on the support ring
- The castings are then fitted to the coil-ring assembly, and final match drilling of the ring to accept the splice plate bolts is performed

Fig. 2

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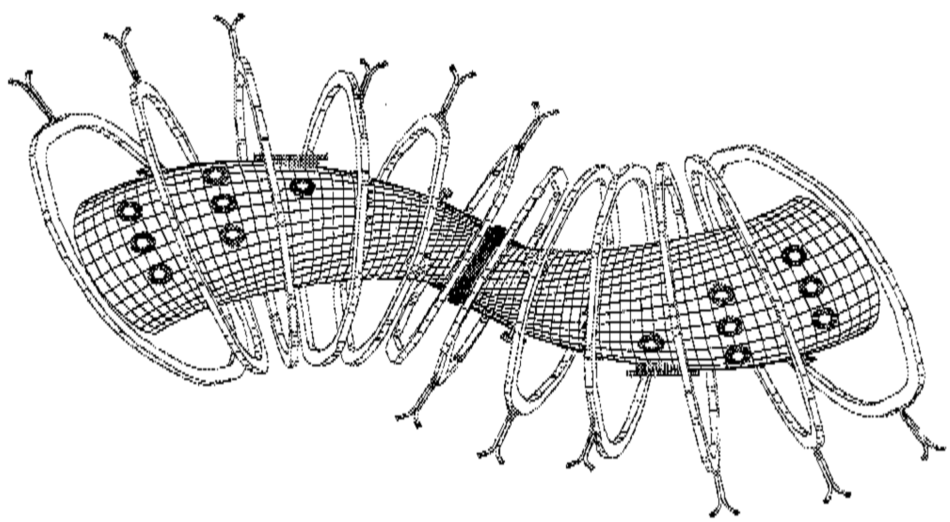
Flexibility is obtained through the Auxiliary Coils

Auxiliary Currents:

\+ + + - - - - - - + + +

MIRROR

\- - - - - - - - - - - - WELL



Noncircular, planar auxiliary coils with 10% A-T of main coil set allow for independent control of transport and stability

Configuration	Auxiliary Current	Dominant Feature
QHS	None	Best transport
MIRROR	3 coils on either end opposite to coils in center	Transport similar to conventional stellarator
WELL	All aux currents oppose main coil current	Well depth and stability increases

Fig. 3

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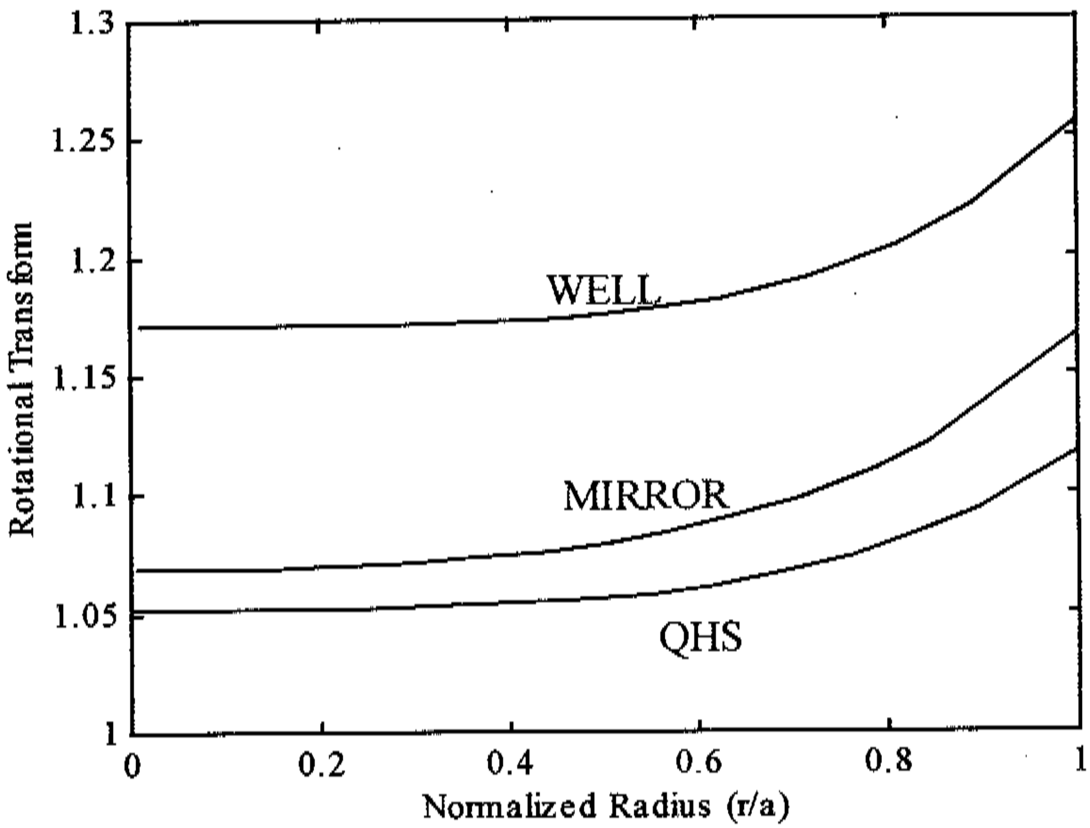
Mirror configuration compared to QHS



MIRROR mode has similar transform to **QHS** with large increase in neoclassical transport

Configuration	Center Transform	Edge Transform
QHS	1.05	1.12
MIRROR	1.07	1.16
WELL	1.17	1.26

Fig. 4

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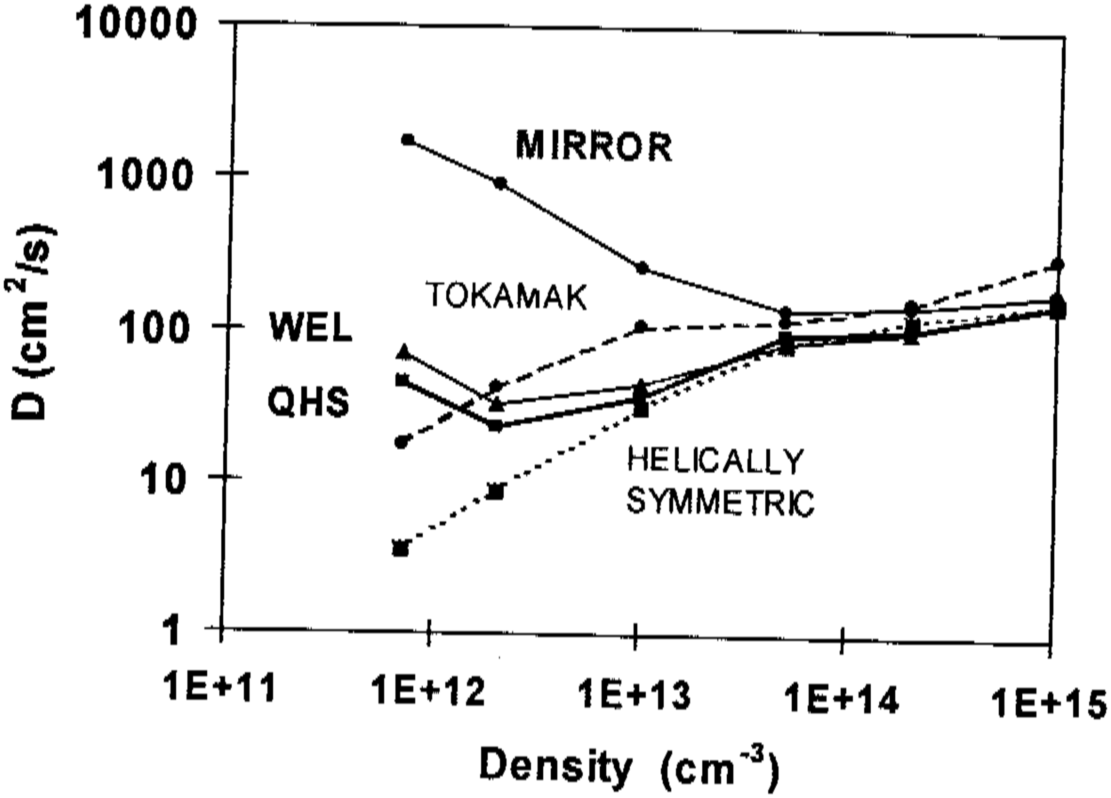
Monte-Carlo Diffusion Coefficient



- Electron monoenergetic diffusion coefficient, assuming **NO** radial electric field
- Diffusion in **QHS** is 1-2 orders of magnitude less than conventional stellarator in low collisionality regime
- MIRROR mode increases transport back to level of conventional stellarator
- WELL configuration shows small degradation of neoclassical transport from QHS case

Fig. 5

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PEOPLE

Co-PI's:

- David T. Anderson
- **F. Simon B. Anderson**
- Joseph N. Talmadge

Graduate student: **Victor Sakaguchi** - Master's Thesis.

A few other technical staff members, visitors, and technicians.
About half a dozen other graduate students.

Graduate students play a significant role in research, and sometimes set the pace of experiment.

DIAGNOSTICS DEVELOPMENT

Many diagnostics are being developed by collaborators.

1. A nine-chord interferometer by UCLA for the density profile and turbulence characteristics.
2. An eight-channel Thomson scattering diagnostic transferred from the predecessor machine, Interchangeable Module Experiment (IMX).
3. An ECE Imaging system by UC Davis for collecting second harmonic X-mode emission (2D electron temperature profile and fluctuations where it is optically thick).
4. SXR diagnostic.
5. Visible spectroscopy.

All of these diagnostics are hoped to become operational in a little over a year from now.

Collaborating diagnosticians want to develop the state of the art, 2nd and 3rd generation, diagnostics using HSX as a platform.

The HSX group wants to have something quicker to look at the plasma; even 1st generation diagnostics will do.

HSX HAS EVERYTHING.... ALMOST

- HSX has helical symmetry.
- HSX has low neoclassical transport.
- HSX has large effective rotational transform.
- HSX has no toroidal curvature.
- HSX has small parallel viscous damping.
- HSX has auxiliary coils.
- HSX has small parallel currents.
- HSX has varying stability limits.
- HSX has mirror configuration.
- Confined high energy particles, small banana width, high equilibrium β, small particl drift, minimal direct loss orbits,....
- ....

Feel the mental entropy rising.

CAUSAL HIERARCHY OF 'THINGS'

Each level of causal hierarchy has only a couple of central 'things:'

- Control 'Knobs.'
  - Auxiliary Coil Hook-up Sequence.
  - Momentum Input Source (Not in Present Program).
- Magnetic Configurations Produced by Control Knobs.
  - QHS.
  - Mirror.
  - Well (Hill).
- Attributes of Magnetic Configurations.
  - Helical Symmetry (Degree of Constancy of Field Strength along a Field Line).
  - Depth (Height) of Magnetic Well (Hill)
- Plasma Physics Consequences of Attributes.
  - Neoclassical Transport.
  - Parallel Currents (Pfirsch-Schleuter and Bootstrap).
  - Parallel Viscous Damping.
  - Ideal Local MHD Stability.

BASIC STRATEGY OF PHYSICS PROGRAM

- With respect to studying expected low neoclassical transport, use symmetry breaking to produce controlled degradation of a good initial state (QHS).
- With respect to studying unknown state of anomalous transport, induce flow shear to see its relevance, and to reduce it to reveal underlying much lower neoclassical transport.
- With respect to studying the stability of MHD modes, vary the well depth to cross the stability boundary back and forth to see their relevance to transport.

PHYSICS PROGRAM

The physics program is described in detail in the proposal/progress report. The following list is compiled from the report (shortened or re-phrased).

1. Verify Existence of Good Vacuum Flux Surfaces.
2. Verify Reduction in Neoclassical Transport.
   - (a) Drift Surfaces of a Passing Electron.
   - (b) Diffusion Coefficient of an Electron or Ion Population.
   - (c) Parallel Currents.
3. Verify Reduction in Direct Orbit Loss due to Helical Symmetry.
4. Measure Radial Electric Field and Study Physics of Improved Confinement Regimes.
5. Study Variation of Neoclassical Electron Thermal Conductivity.
6. Study Fluctuation-induced Transport in the Near Absence of Toroidal Curvature.

FIELD-LINE TRACING

The following viewgraphs are from Victor Sakaguchi's paper at the 12th International Stellarator Workshop, Madison, WI.

- Principle (Fig. 6).
- Electron gun (Fig. 7).
- Fluorescent mesh (Fig. 8).

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Cutaway view of experimental setup

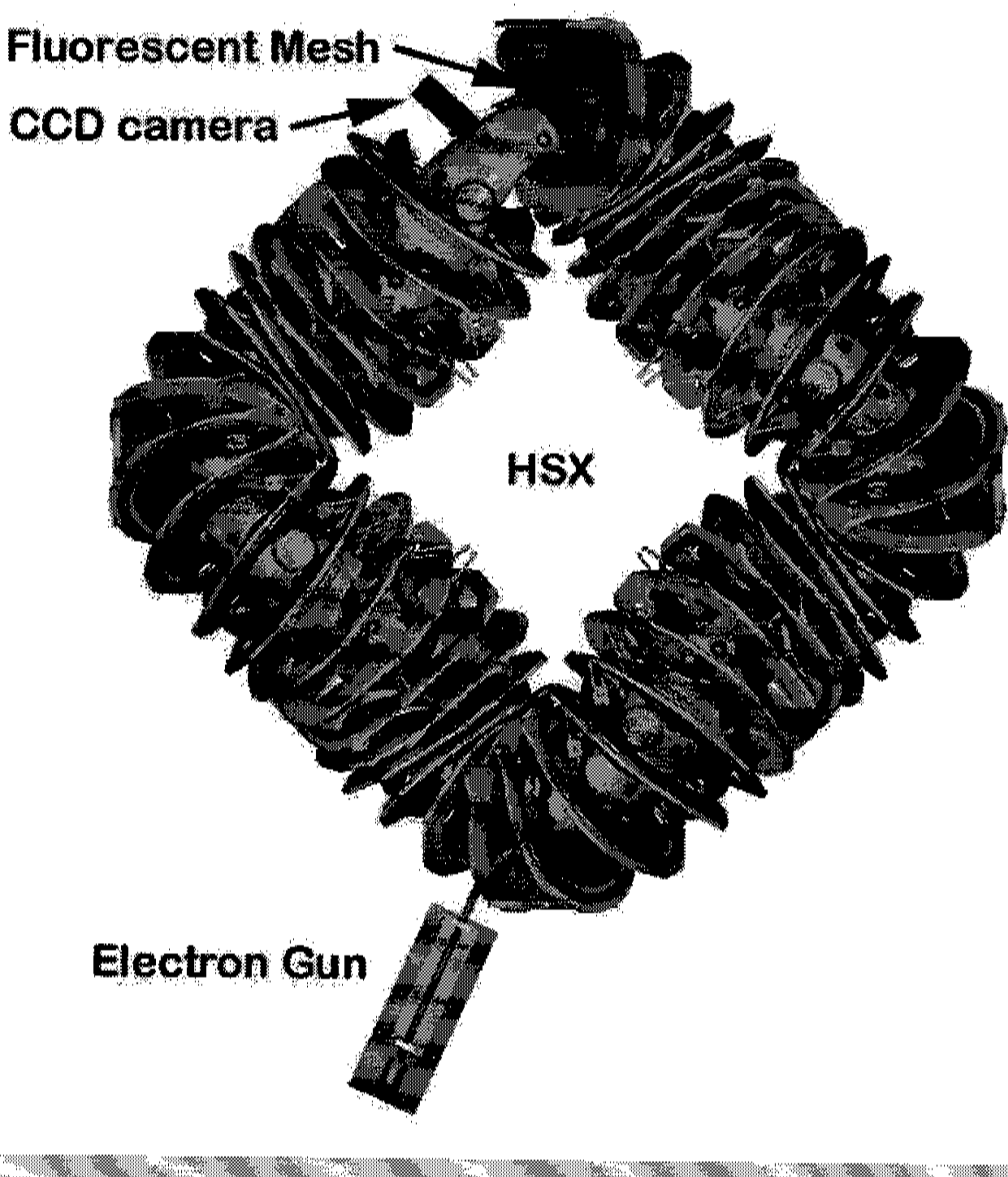
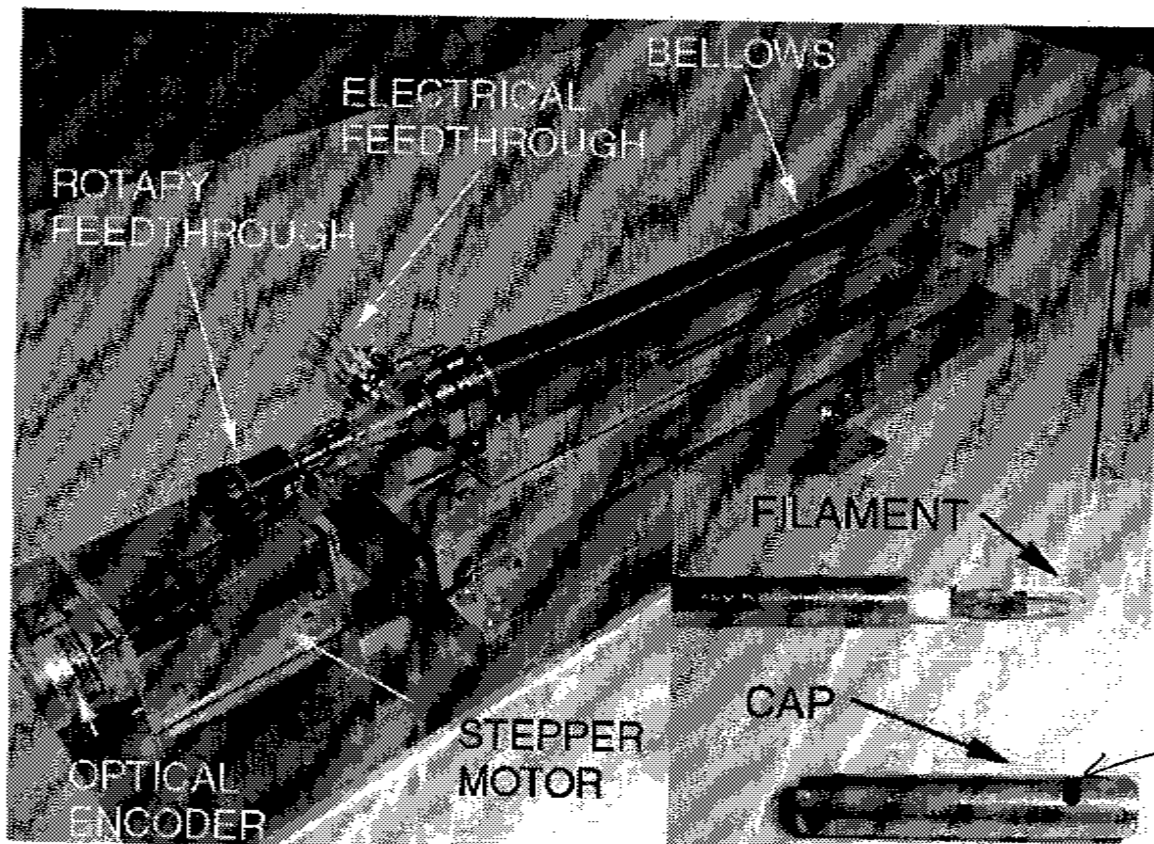


Fig. 6

V. Sakaguchi

Electron gun assembly



Thoria-coated iridium ribbon 1 mm wide

100 ev acceleration

2mm hole

6mm tube

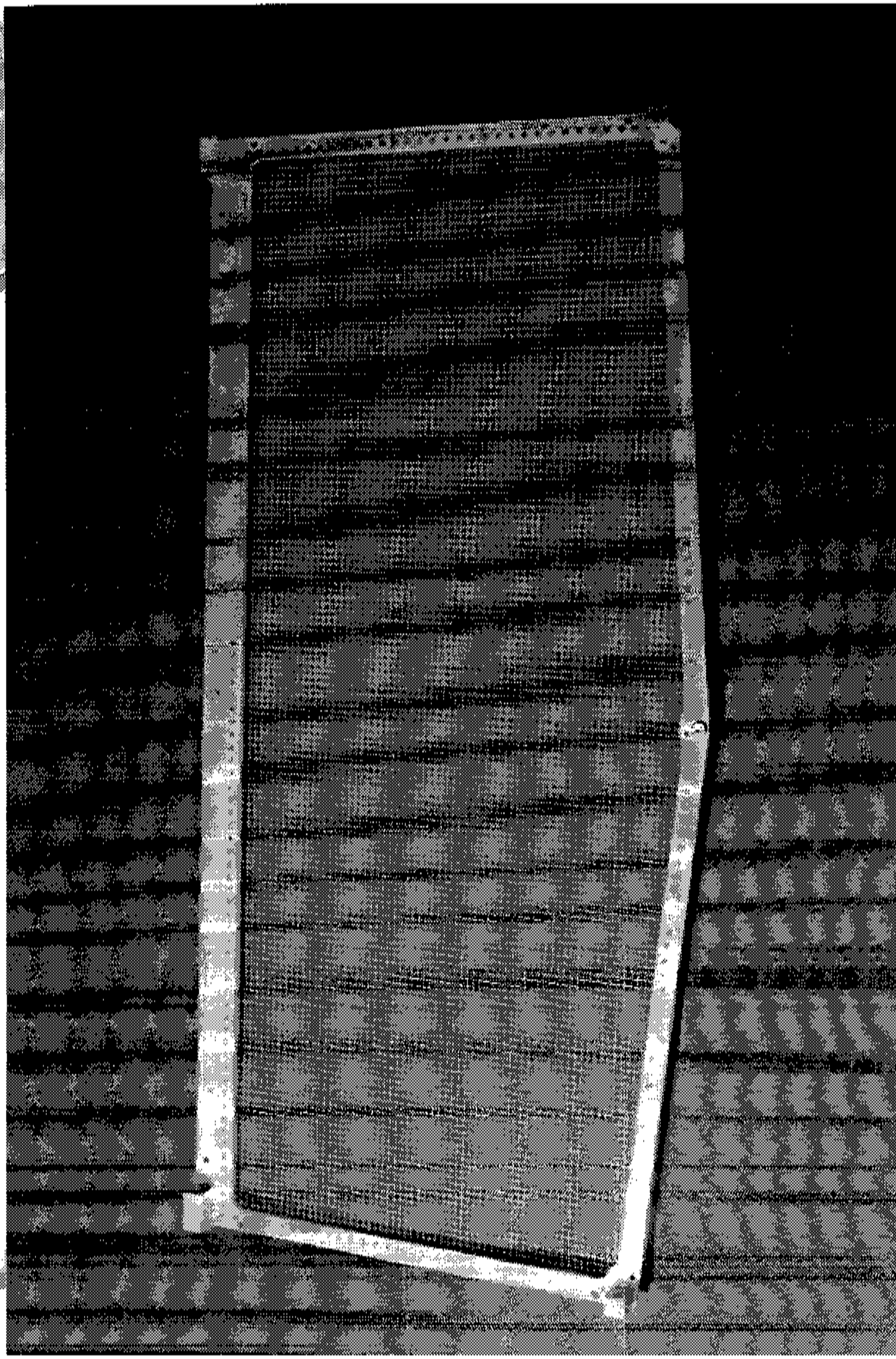
Fig. 7

V. Sakaguchi

← ~31 cm →

Outboard side

~64 cm



Inboard side

Fig. 8

Wire spacing 3mm
Wire Diam 0.076mm

V. Sakaguchi

IMAGE OF A CLOSED FLUX SURFACE ON FLUORESCENT MESH

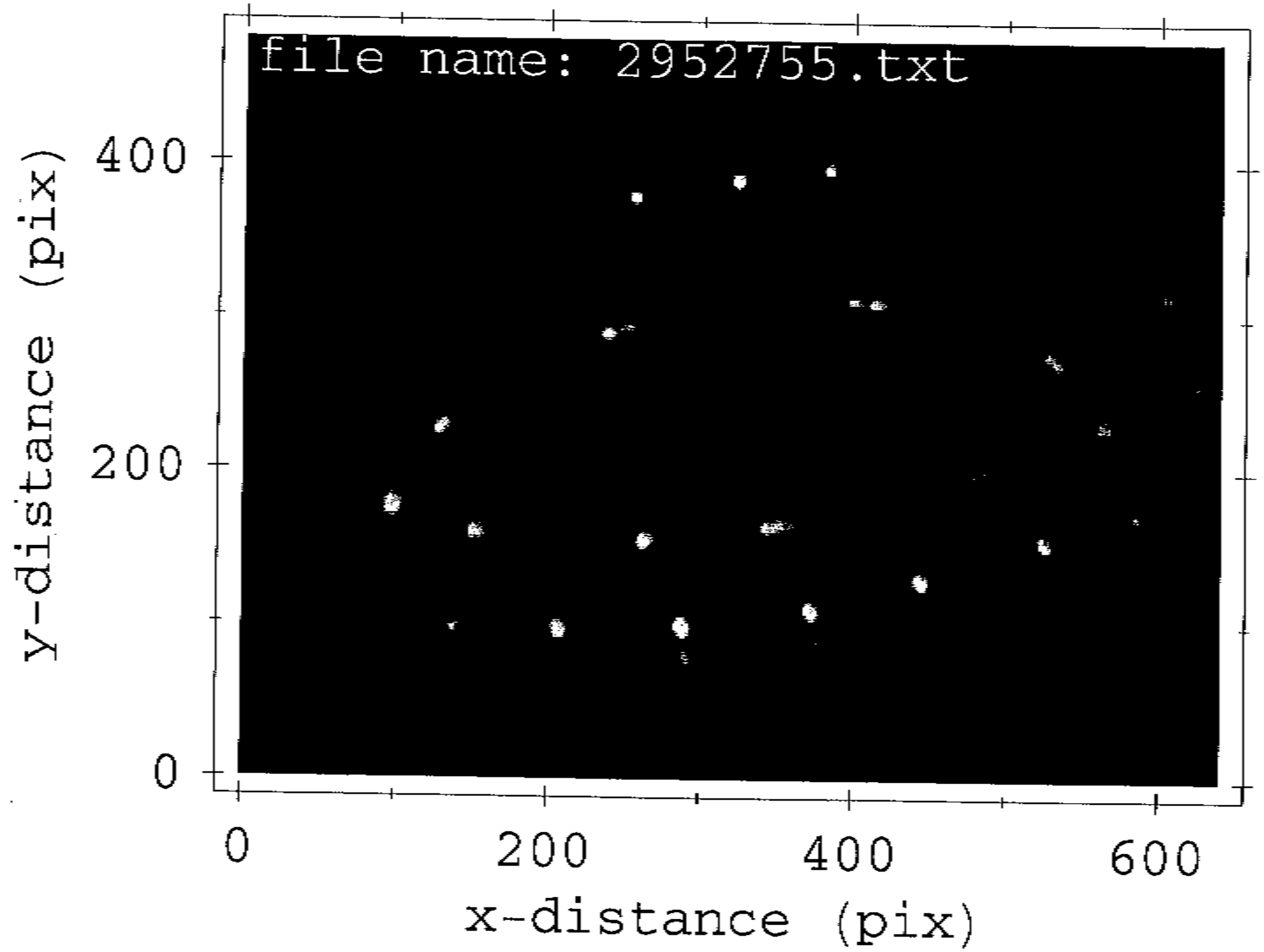


Fig. 9 Light spots on an 'inner circle' are produced by the beam striking the mesh. Spots on an 'outer circle' are reference LED's. The lower (upper) edge is the inboard (outboard) side of the torus. The image is not corrected for optical distortion.

GALLERY OF CLOSED FLUX SURFACE IMAGES

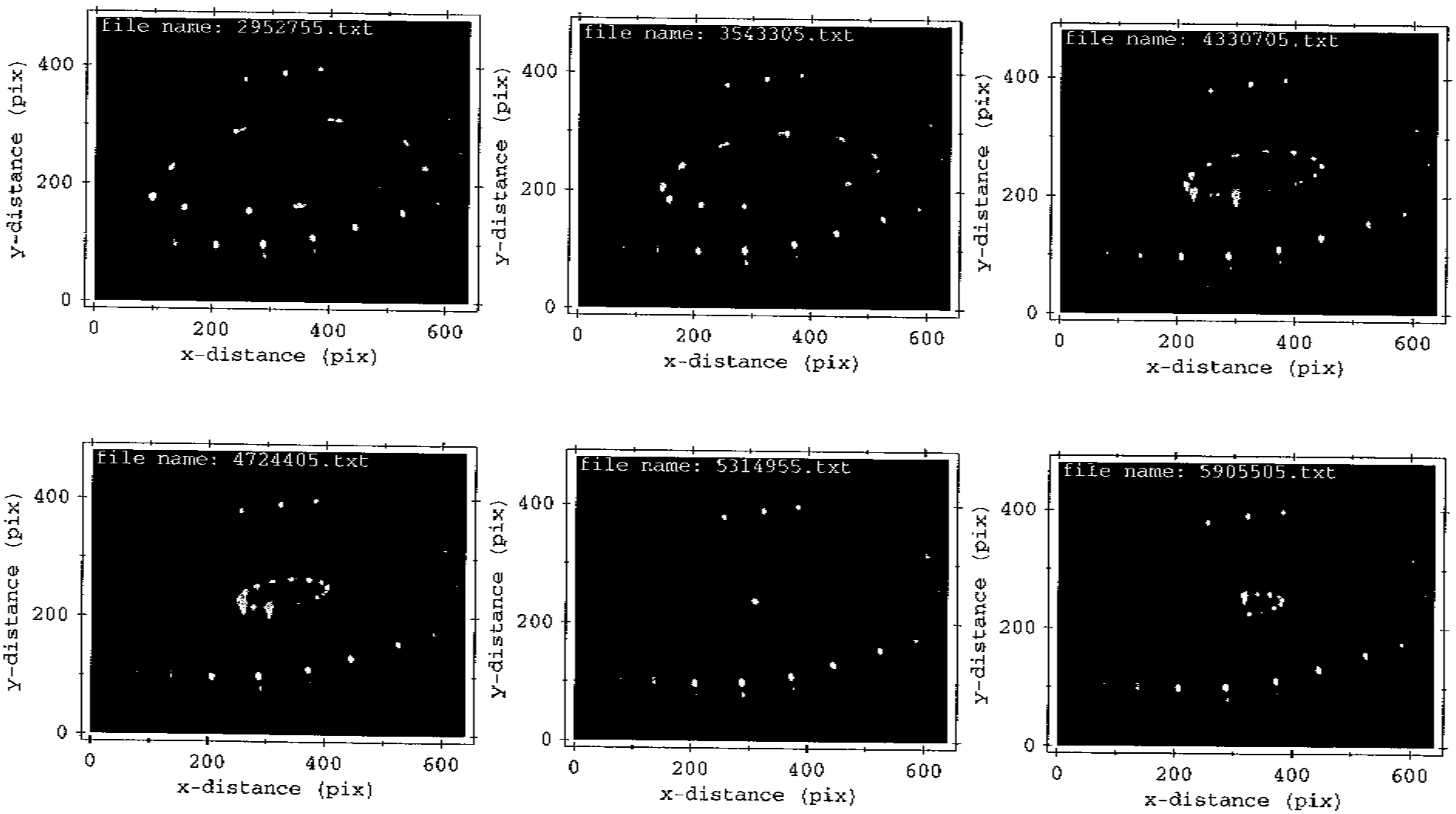


Fig. 10 A series of images taken as the gun moved radially from outboard side to inboard side, passing through magnetic axis on the way. The progression is from the top left and rowise.

ROTATIONAL TRANSFORM ANALYSIS

The following viewgraphs are from Victor Sakaguchi, Simon Anderson, and Joseph Talmadge.

- 'Dot count' and 'dot sequence' methods (Fig. 11).
- 'Dot sequence' method — analysis (Fig. 12).
- 'Dot sequence' result — experiment (Fig. 13).
- 'Dot sequence' result — theory (Fig. 14).
- Experimental and theoretical rotational transform profiles (Fig. 15).

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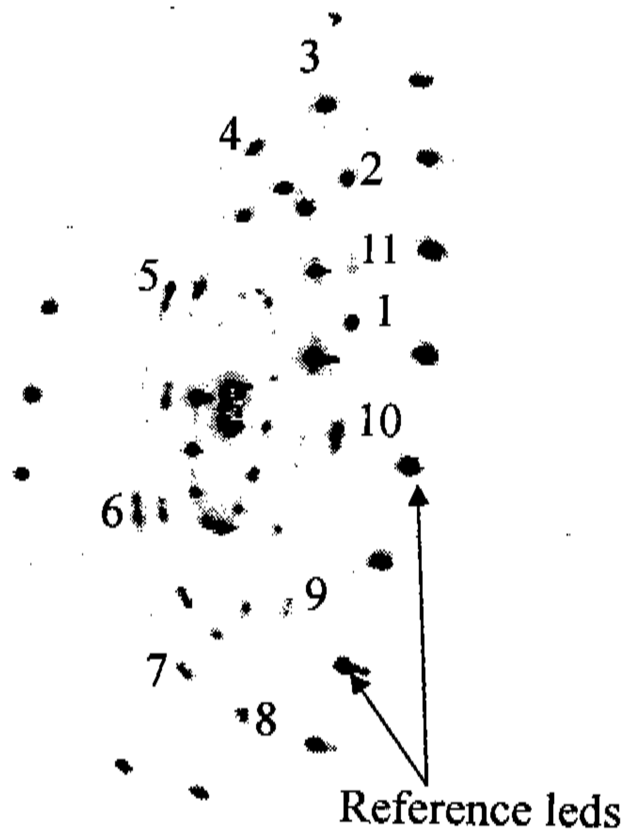
1 kG QHS e-beam



- First 'dot' is from a half toroidal transit from the known gun radial launch position
- subsequent 'dots' make a complete toroidal transit, and 1+ poloidal transits
- number of 'dots' per 2π poloidally provide a measure of ι

Fig. 11

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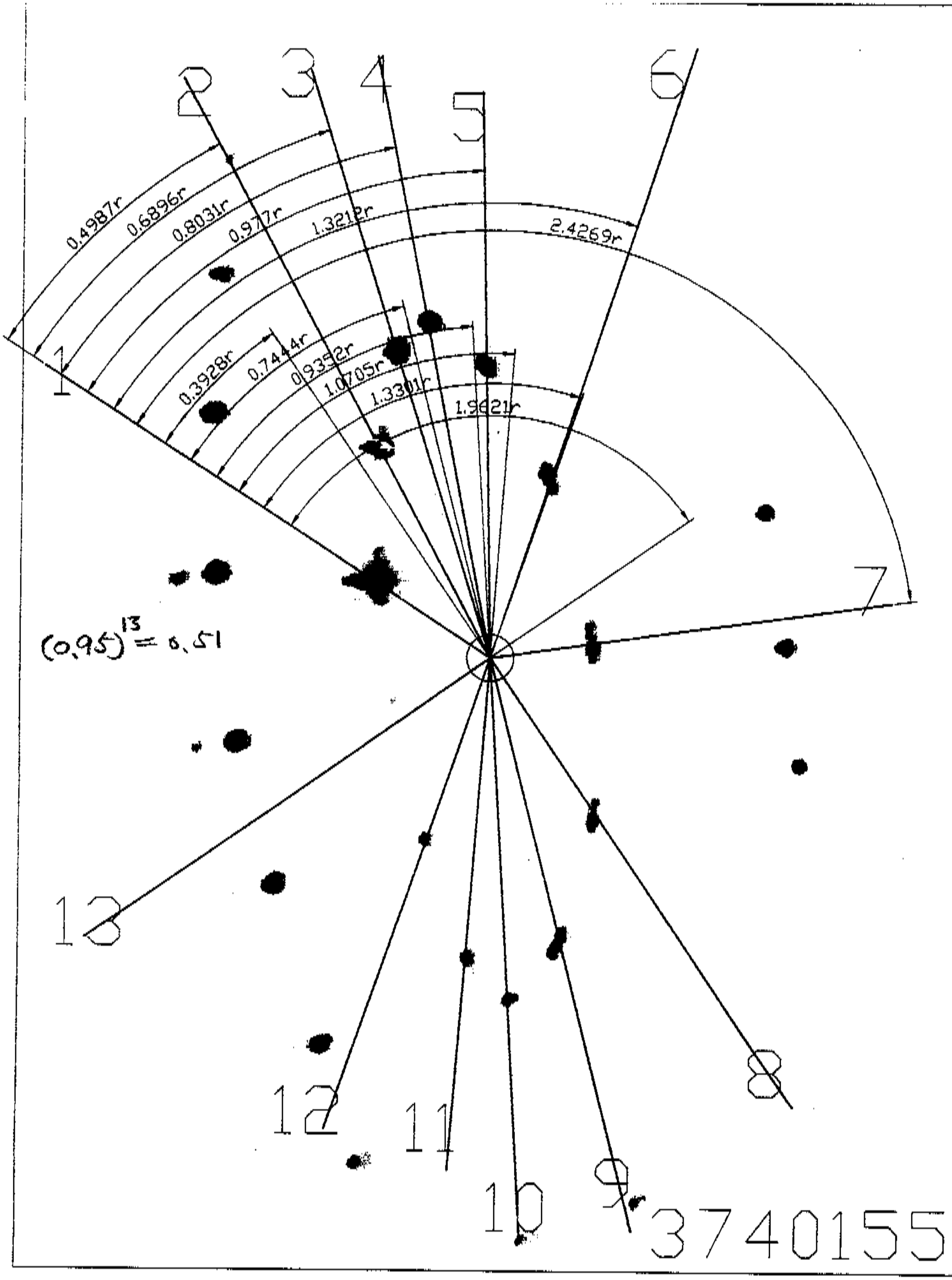

Fig. 12

V. Sakaguchi

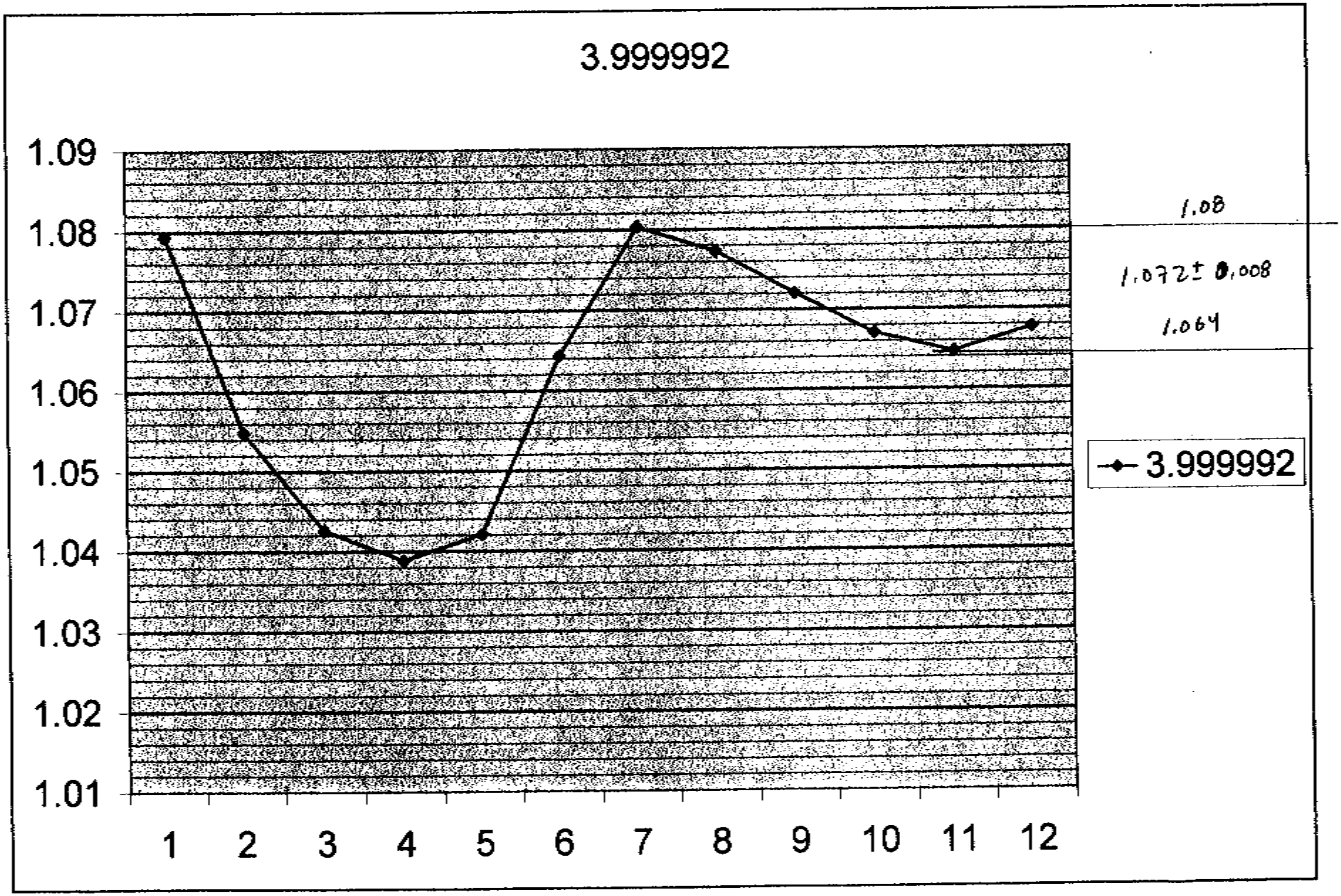

Fig. 13

V. Sakaguchi

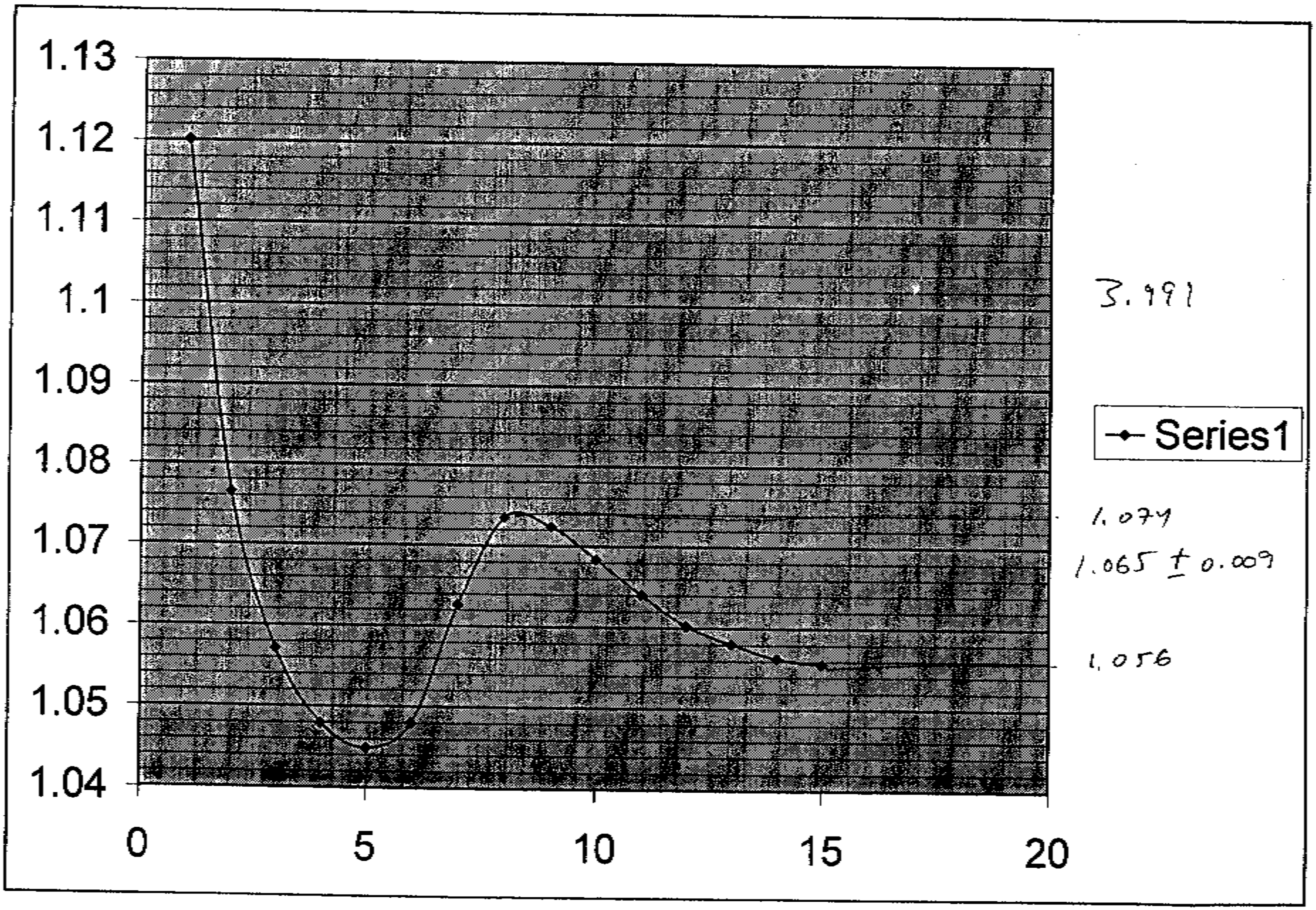

Fig. 14

J. Talmadge

SA-cc

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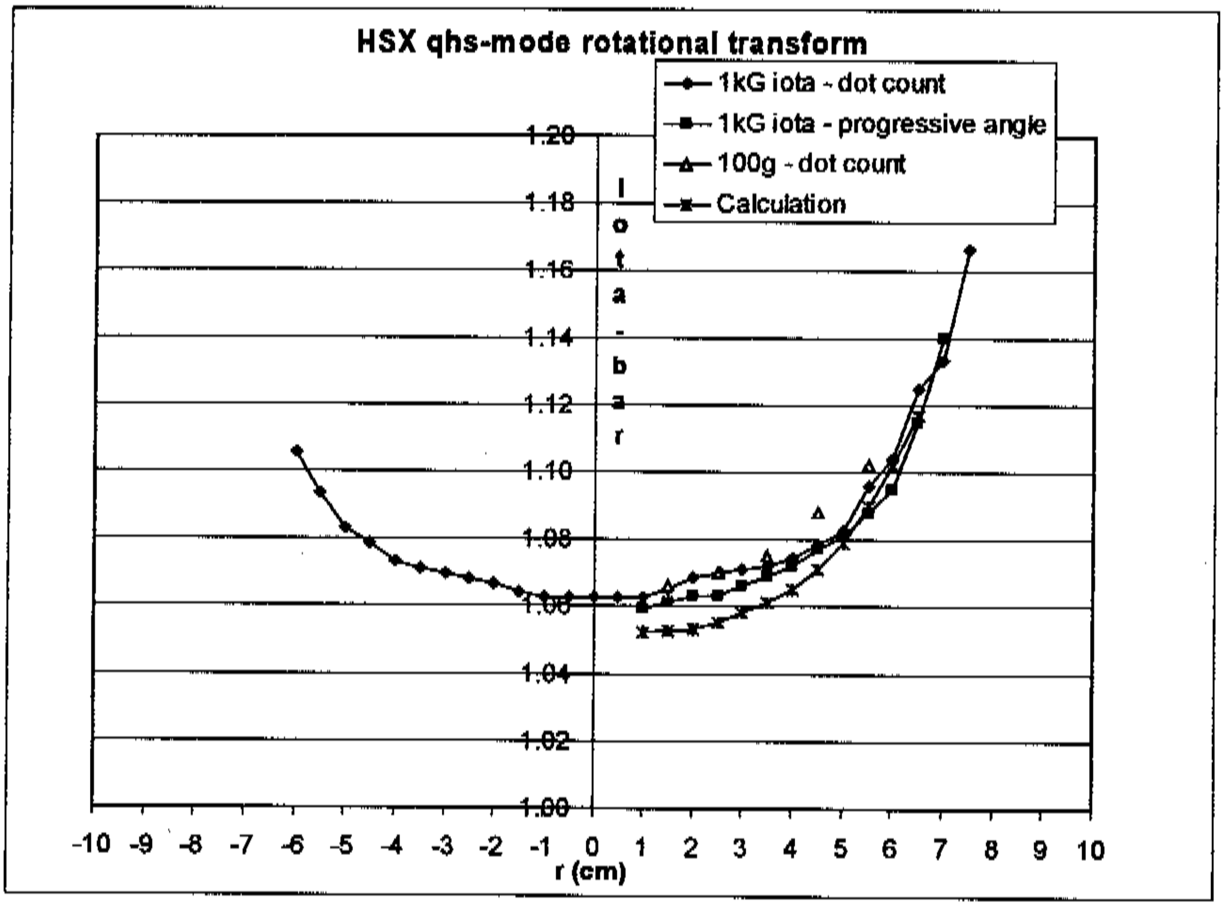
Rotational transform profile



- Iota-bar from 2 different methods of analysis
- Includes a scan at 1 kG and 100 gauss
- Comparison to electron transit information from Biot-Savart calculation
  - 14 filaments, 64 segments/filament, 48 coils

Fig. 15

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ROTATIONAL TRANSFORM ANALYSIS — ASSESSMENT

The observed small discrepancy may be insignificant in terms of making any difference in device performance. Identifying the cause of discrepancy is, however, important.

The following are possible causes in the descending order of likelihood.

1. Interpretation of field-line tracing data.
2. Device construction accuracy.
3. Theoretical calculations.

IMAGE OF ISLANDS ON FLUORESCENT MESH ($B_t = 1$ kG)

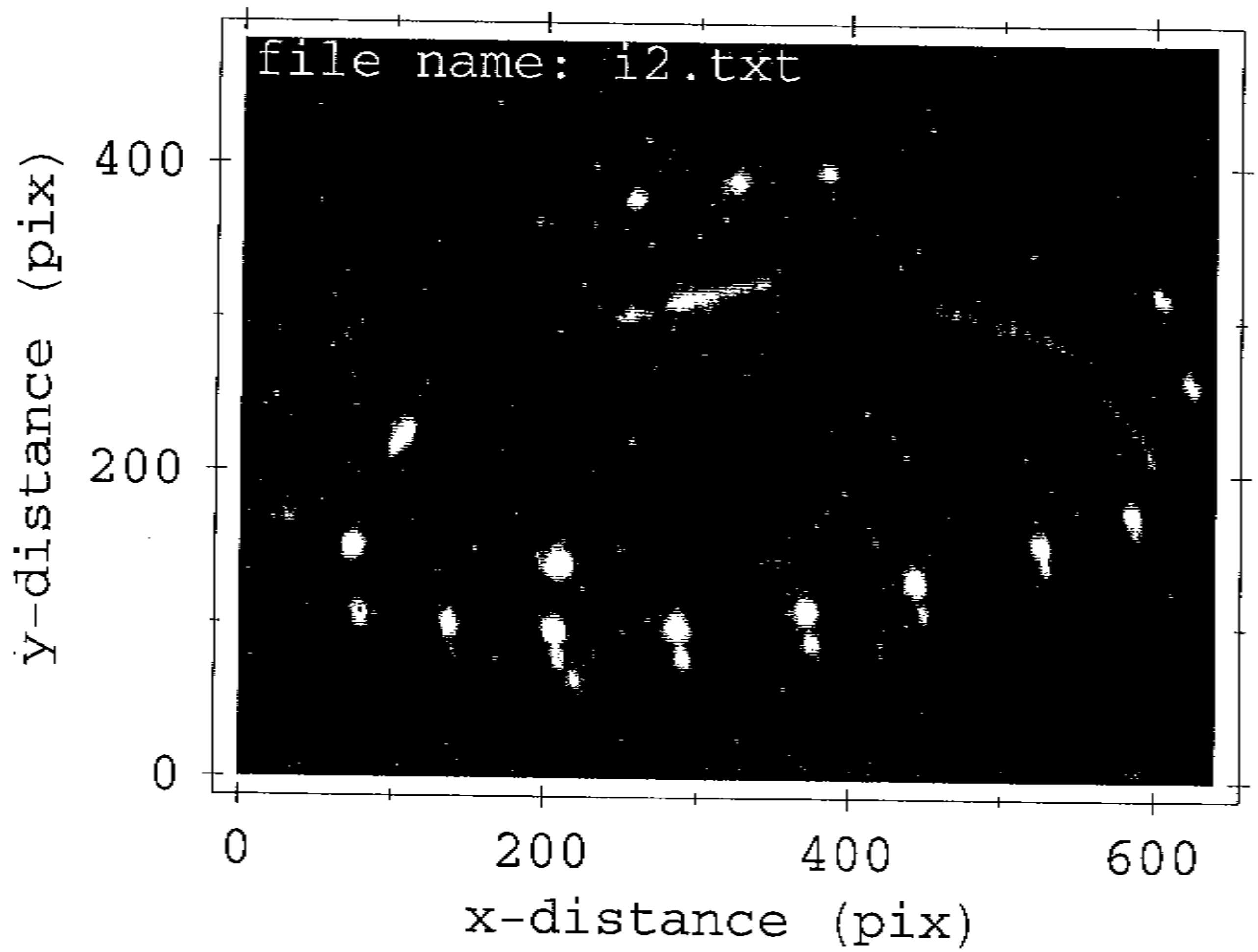


Fig. 16 The field-line tracing diagnostic can detect islands (theoretical calculations predict 8/7 islands at plasma periphery). This picture was generated by 'frame-grabbing' an image indirectly from a video tape, rather than directly from the CCD camera, and has high background noise. The image was 'enhanced' by trimming high-intensity peaks and expanding low-intensity ranges.

IMAGE OF ISLANDS ON MESH - White on Black ($B_t = 0.1$ kG)

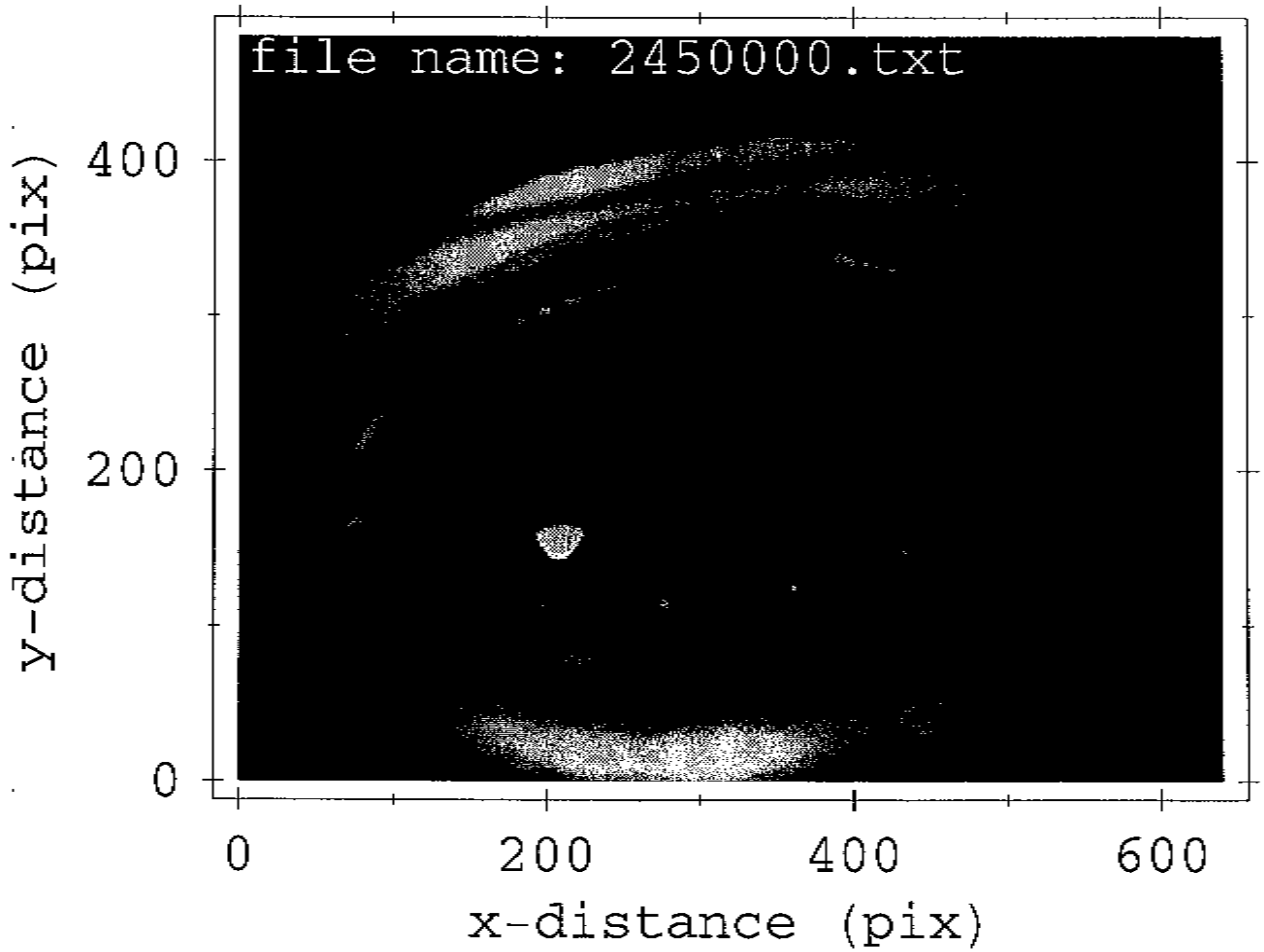


Fig. 17 The field-line tracing diagnostic can detect islands (theoretical calculations predict 8/7 islands at plasma periphery). Stray light leaking from an inperfectly sealed port makes bright reflection from vessel walls. The image was 'enhanced' by trimming high-intensity peaks and expanding low-intensity ranges.

IMAGE OF ISLANDS ON MESH - Black On White ($B_t = 0.1$ kG)

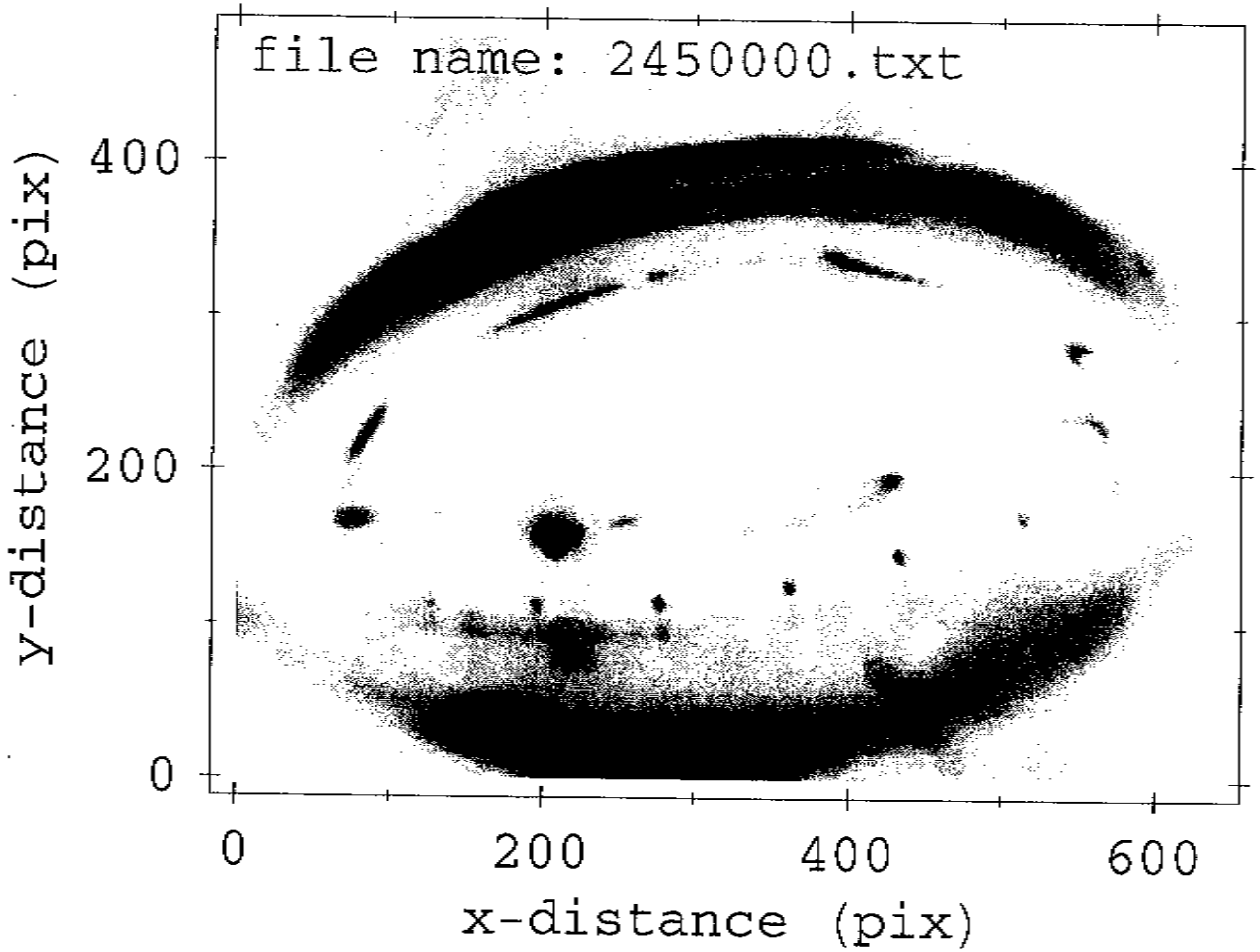


Fig. 18 The field-line tracing diagnostic can detect islands (theoretical calculations predict 8/7 islands at plasma periphery). Stray light leaking from an inperfectly sealed port makes bright reflection from vessel walls. The image was 'enhanced' by trimming high-intensity peaks and expanding low-intensity ranges.

YES, IT'S A STELLARATOR!

A major milestone is achieved by the HSX group in demonstrating that this device is a good magnetic trap.

SECOND LOOK AT DATA — SOME INTRIGUING STUFF

- Bright stars in very 'dark' space - unstable beam and dynamic range mismatches.
- Smeared spots - lots of turns or tiny islands?.
- Turns - which, which way, and how many?
- 'Two-dot event' - scary.

'Bright Stars in Very Dark Space' - Dynamic Range Mismatches

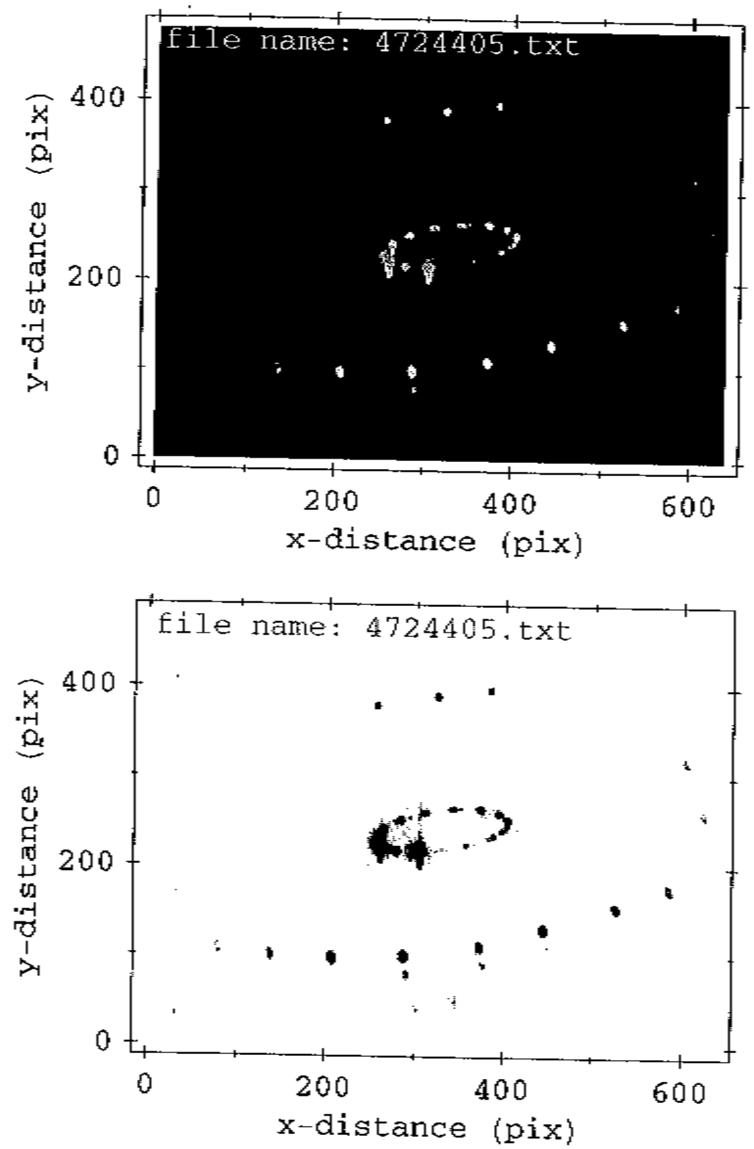


Fig. 19 'Flares' in otherwise very dark space.

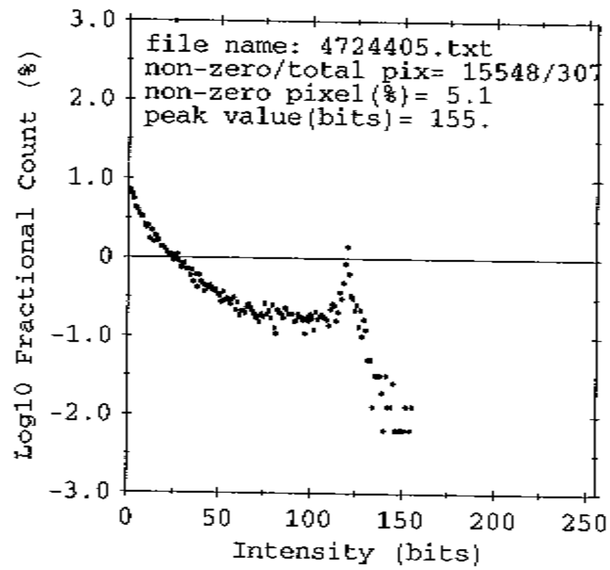


Fig. 20 Number of pixels occupying each intensity level: only 5.1 % of pixels non-zero.

Three issues are raised: (a) CCD pixels saturate, (b) unused digitizer head-room, and (c) useful data below digitzer least significant digit (lsd) - the last being most important.

Better matched dynamic ranges allow many more turns to be followed.

SMEARED SPOTS — MANY TURNS OR TINY ISLANDS?

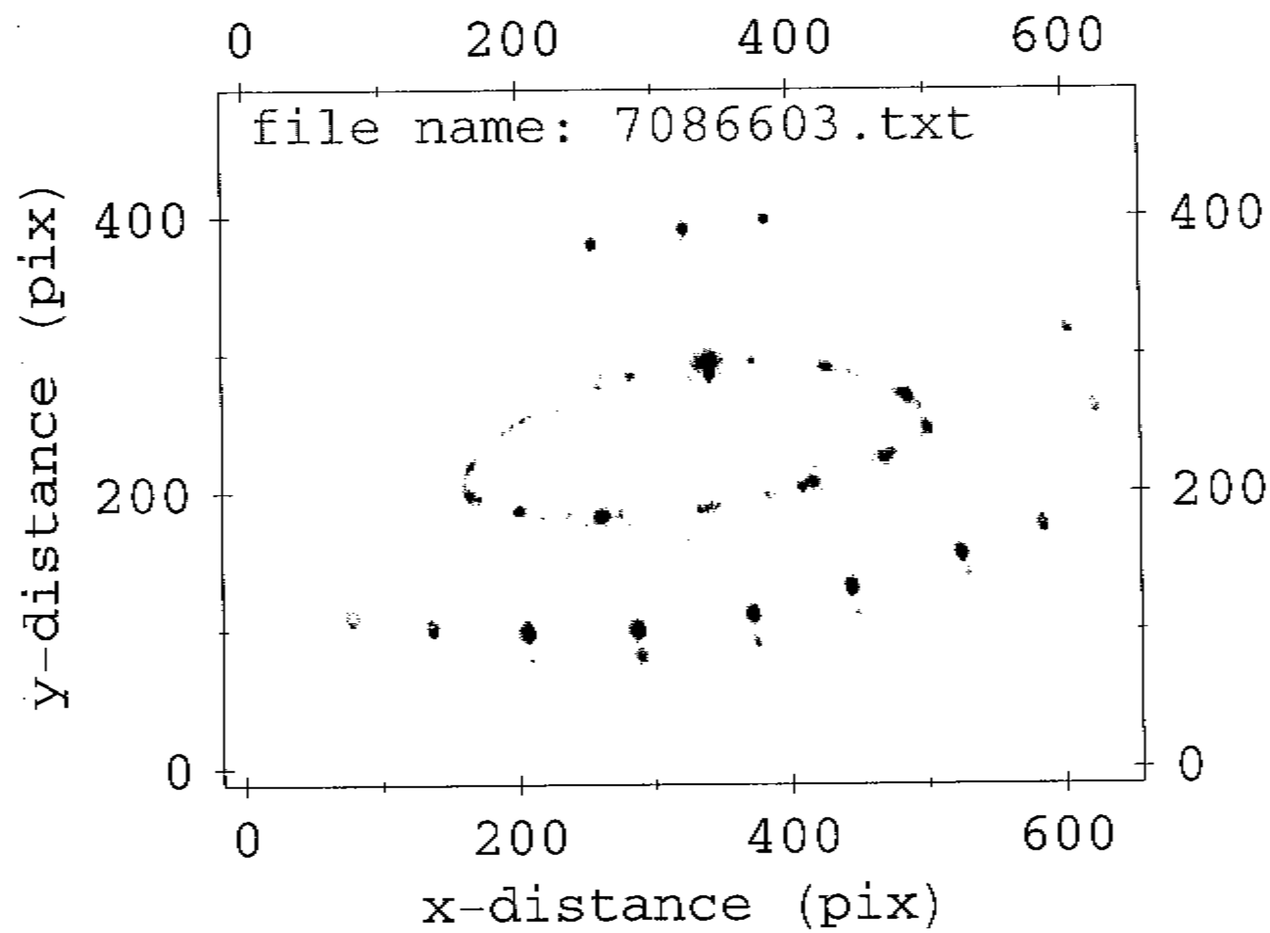


Fig. 21 Some spots are spread out, or smeared, along the flux surface. Are they result of many turns? If so, we did not count the turns right in the analysis before. Are they tiny islands (theory says they must exist)? If so, we need better resolution.

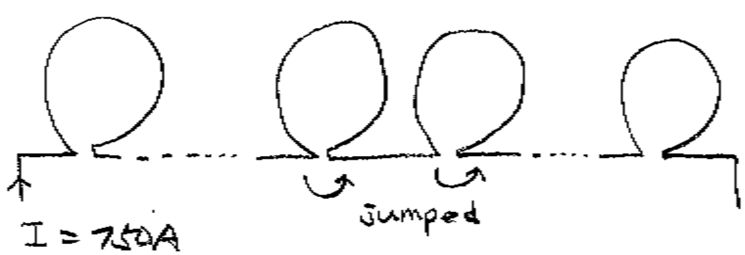
'TWO-SPOT EVENT' - HAPPENINGS

In the very first attempt to trace field lines with 750 A in the main coils,

1. Only two spots appeared on the fluorescent mesh.
2. Two of forty eight coils *connected in series* were found to carry little or no current.
3. No signs of arcing damage were evident at the busswork/coil joints.

The 'current jump' occurred at a transition section — an inhouse-made structure — between parallel-plate busswork and coaxial busswork.

As engineering 'happenings' the event had a happy ending. The joints were found to have less than required number of insulation sheets. Beefing up the insulation restored the current to the coils.



'TWO-SPOT EVENT': IMPLICATIONS

But implications of the event can be significant, because:

1. The beam went around a couple of times as if seeing nothing wrong, then suddenly found something very wrong, and jumped out of bounds.
2. Series connection did not guarantee the same current in all coils.
3. The entire or most of the current evidently jumped the insulation, but left no discernible evidence.

Here are some of scary thoughts.

1. If only small part of current jumped, would the beam go around many times, and then suddenly decide to jump out of bounds?
2. How do we know that no current jumped?
3. How small is 'small part?'

SUMMARY

Electron beam based field-line tracing:

- Is a powerful tool for demonstrating the existence of flux surfaces.
- Needs further development in engineering and analysis techniques for studying finer features of flux surfaces.
- Has potential for uncovering many interesting phenomena for magentic traps.

HSX Project:

- Has potential for becoming a great physics study platform.
- Has passed an important milestone in demonstrating the existence of a large volume of nested closed flux surfaces.
- Future challenges include plasma production and diagnostic development.

RECOMMENDATIONS TO NCSX GROUP

- On Field-line Tracing Diagnostic Development.
  - Collaborate Closely with HSX Group.
  - Develop Stable Electron Gun.
  - Assess Also Methods Other than Fluoresenct Mesh.
  - Match Dynamic Ranges Carefully.
  - Provide a Beam Interrupter.
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  - Obtain 'User-friendly' Very Fast Field-line Tracing Code.
- On Machine Construction.
  - Assess Impact of Minute Difference in Individual Coil Currents.
  - Measure Accurately *Relative* Current in Individual Coils.
  - Float Vessel Electrically.
  - Assure Complete Darkness.
  - Schedule Enough Time for Measurement (This is the killer).