Science & Technology Facilities Council
Rutherford Appleton Laboratory

Star Trek plasma shields:

Measurements and modelling of a diamagnetic cavity

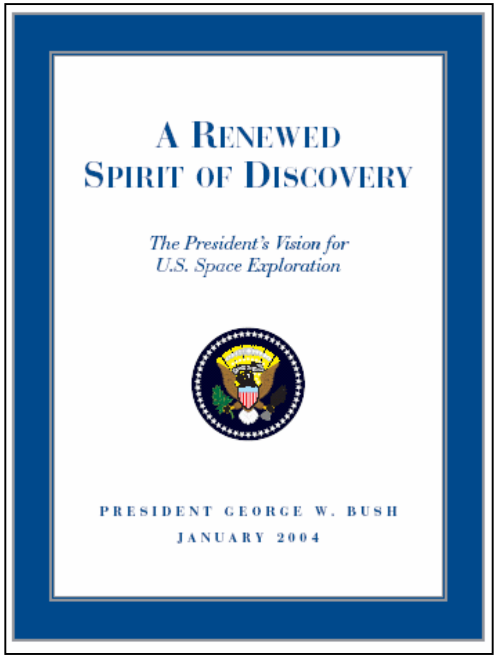
Ruth Bamford[1],

K. J. Gibson[2], A. J. Thornton[2], J. Bradford[1],
R. Bingham[1,6], L. Gargate[1,3], L.O. Silva[3], R.A. Fonseca[3],
M. Hapgood[1], C. Norberg[4], T. Todd[5], R. Stamper[1]

[1]Space Plasmas, Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK
[2] Department of Physics, University of York, Heslington, York,YO10 5DD, UK
[3]Centro de Física dos Plasmas, Inst Superior Técnico, 1049-001 Lisboa, PORTUGAL
[4] Umea University, Box 812, 981 28 Kiruna, SWEDEN.
[5] UKAEA, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK
[6]Physics Department, University of Strathclyde, Glasgow G4 0NG, UK

THE UNIVERSITY of York · University of Strathclyde Glasgow · INSTITUTO SUPERIOR TÉCNICO Universidade Técnica de Lisboa · UMEÅ UNIVERSITET · UKAEA

Motivation: Can humans survive the radiation of space?



NASA Authorization Act of 2005

NASA's GOALS:

1. Complete the Space Station.
2. Develop and fly the "Crew Exploration Vehicle" now called, ORION, no later than **2014**.
3. Return to the Moon no later than **2020**.
4. Extend human presence across the solar system and beyond.

5. Initial budget ~$16.2B,
6. Total budget > $100B

Most of the technical problems have envisaged solutions.

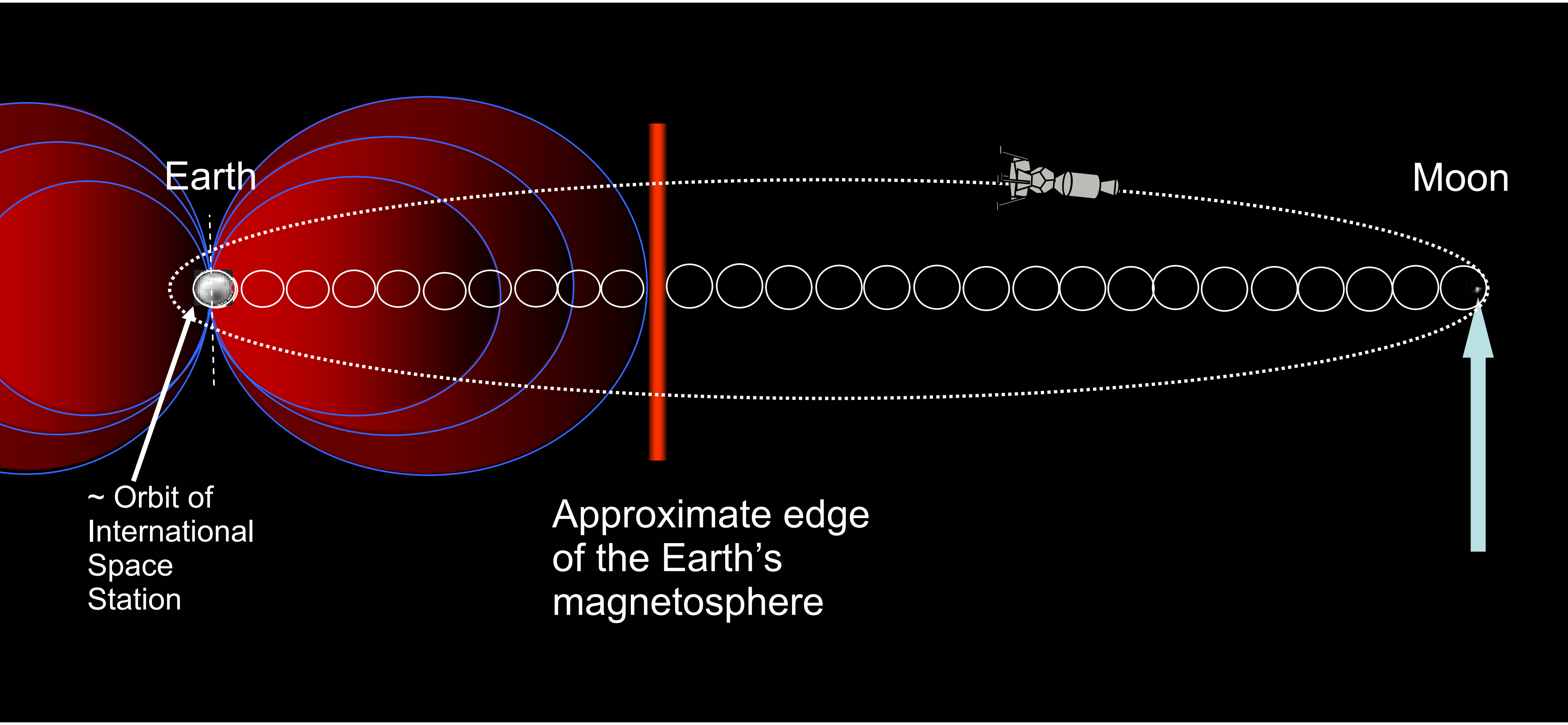
Except for the susceptibility of living tissue to the increased radiation bombardment of interplanetary space.

This talk concerns a possible means to solve this problem.

Introduction

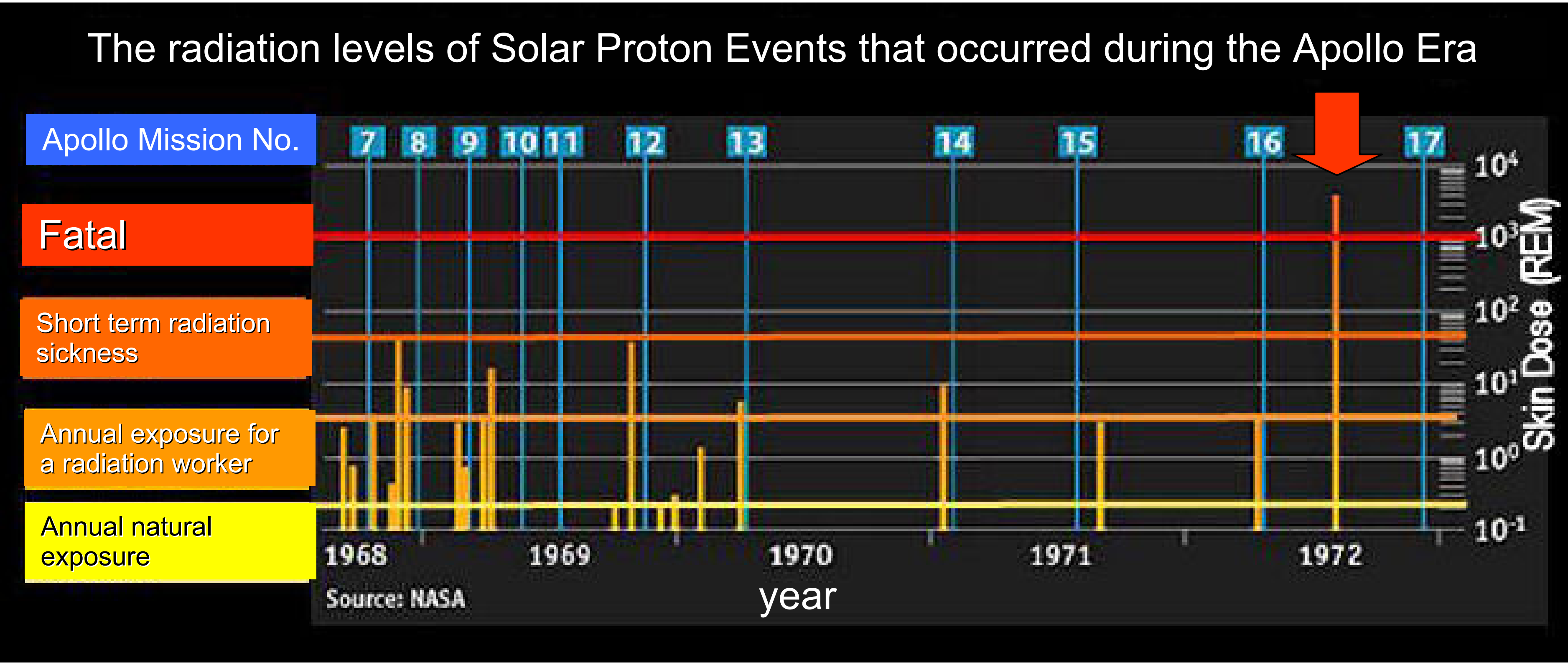
- Background to spacecraft protection
- Results from the LinX Linear plasma eXperiment
  - Interaction of plasma beam with static dipole field
- Comparison with results from computer simulations
- Summary and conclusions

The radiation hazard to astronauts is much greater outside the Earth's magnetosphere



A photograph from the Odyssey space craft looking back at the Earth-Moon system when the spacecraft was on route to Mars

The Apollo astronauts were lucky not to be killed by radiation



- Need to bring the dose levels down to *acceptable risk* level
- Trip to Mars 18 months
- Radiation hazard of energetic protons in particular is Mission critical – described by NASA as the only possible "show-stopper"[1]

1 Frank Cucinotta, Chief Scientist for NASA's Radiation Research Program at the Johnson Space Center

Limited number of options available for spacecraft protection

1. Build a wall – material shield.
2. Help biology cope better – Biochemical.
3. Active shield (magnetic, plasma, etc)

   cf Star Trek deflector shield….

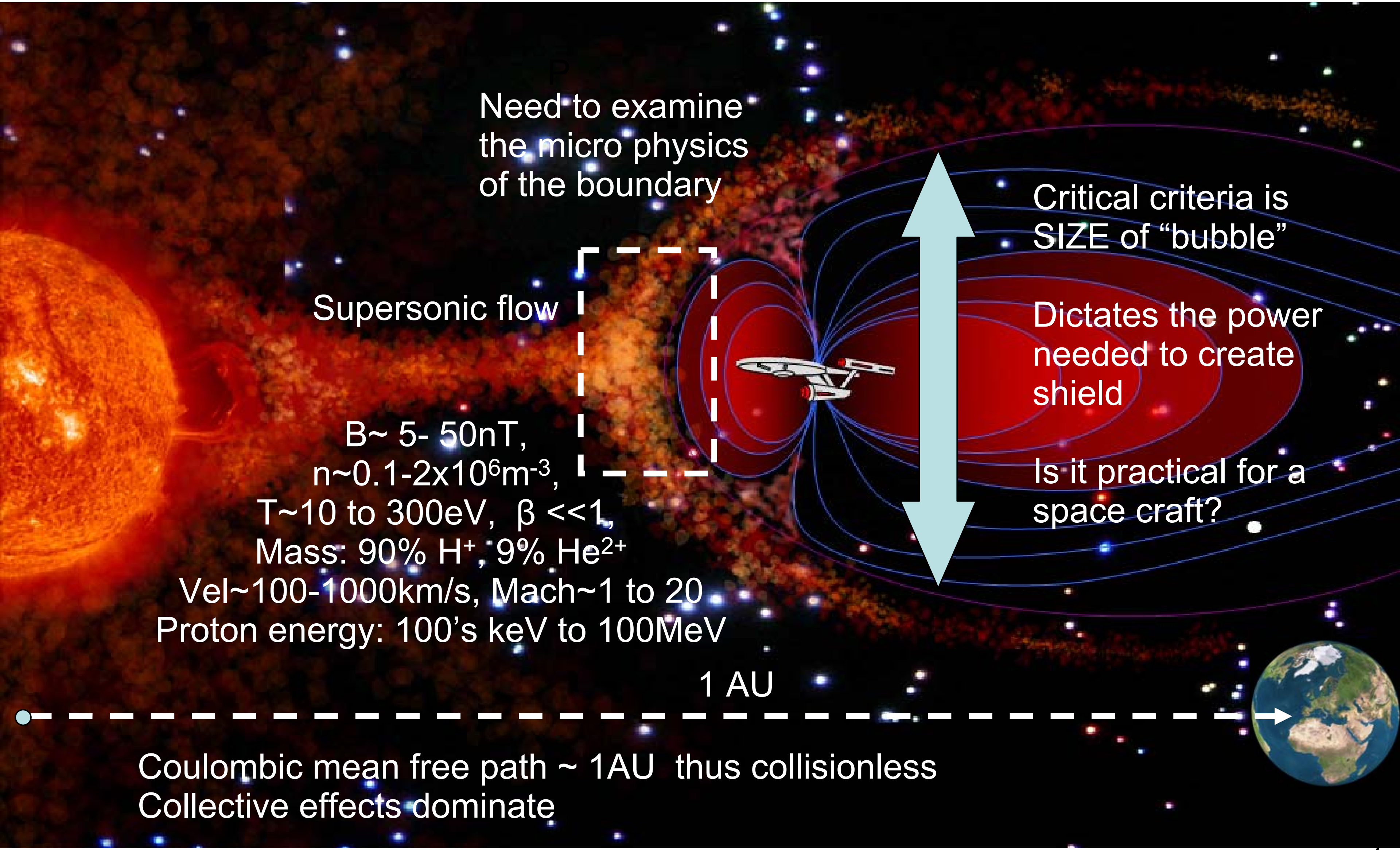
All approaches are likely to be needed since no individual method is likely to reduce the risk to an acceptable level.

Active shielding is the subject of this talk.

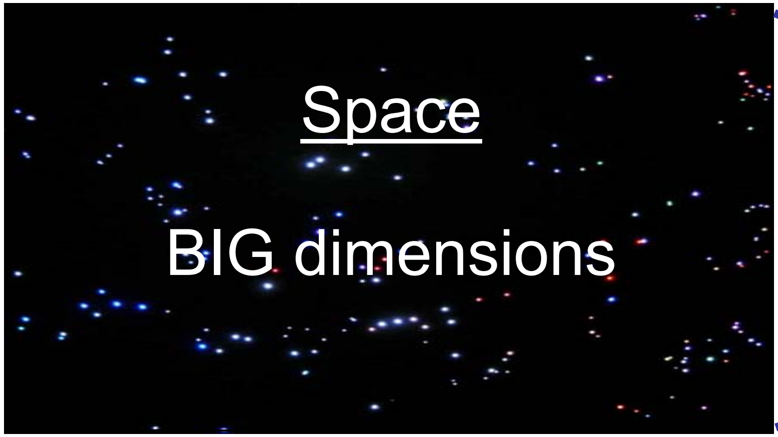
Could an active shield possibly work from a physics point of view?
If they can, would it be practical from an engineering point of view?

In this work, we will begin to answer the first question in order to start to address the second question…..

Active shields offer the potential to mimic the shielding effect of the Earth's magnetosphere



The large dimensions of space have to be compressed self consistently into the laboratory scale



Compress absolute scale

Maintain dimensionless plasma parameters

Laboratory

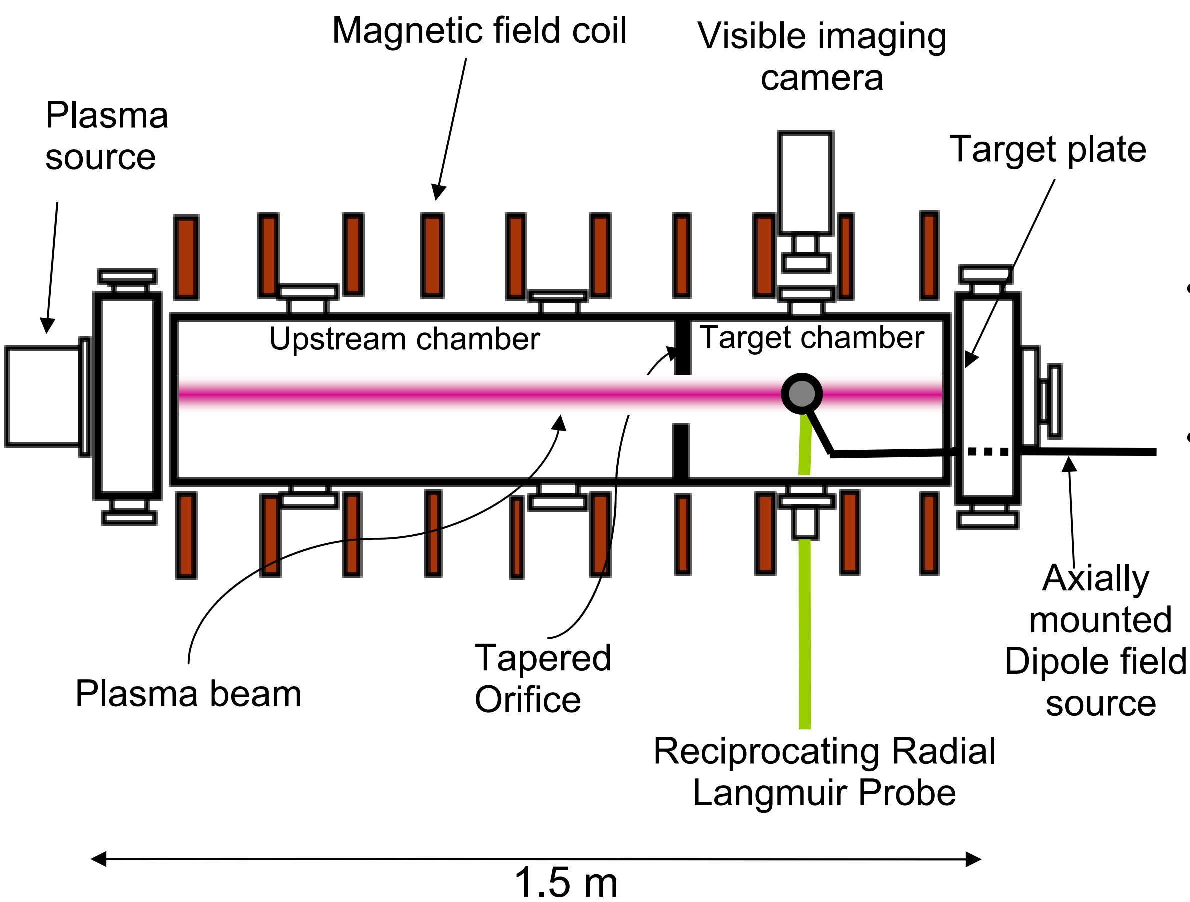
Direct simulation of lab conditions
Validate code

Simulation

Computer simulation of Space

3D, PIC, hybrid code
dHybrid
Heritage: ICE code on JET, AMPTE

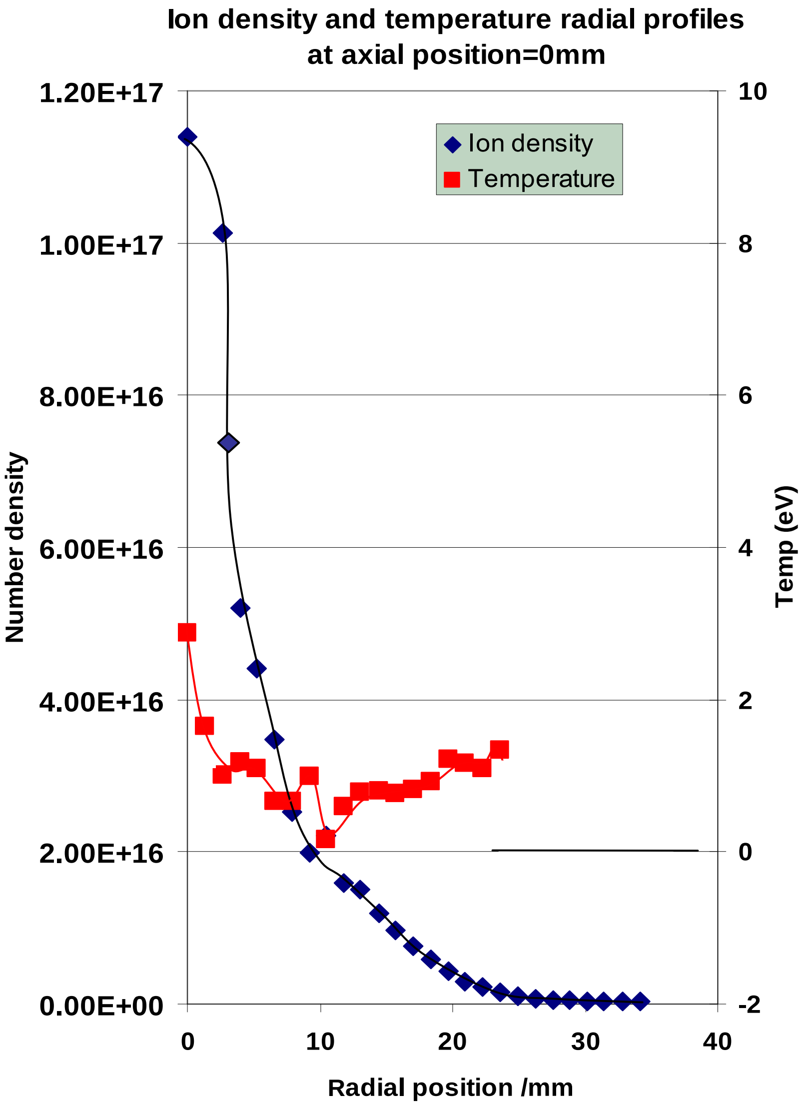
LinX provides a excellent platform for laboratory astrophysics



- Linear plasma eXperiment (LinX)
- Magnetically confined plasma beam propagates along device to a target chamber:

Beam: 10-20 cm diameter, B ~ 0.07T axial , T~ 5-15 eV, n~ 10^{16} to 10^{19} m^{-3}, hydrogen, MACH> 3

Impinging plasma beam has Mach number ~3



Upstream plasma density profile reveals beam width of the order of 10-20mm

Electron temperature profile rather flat with peak temperature of ~2.5eV

In the absence of direct measurements of the parallel ion energy, we infer flow velocity from the sheath coefficient, alpha, defined by

$$\varphi_p = \varphi_f + \alpha T_e$$

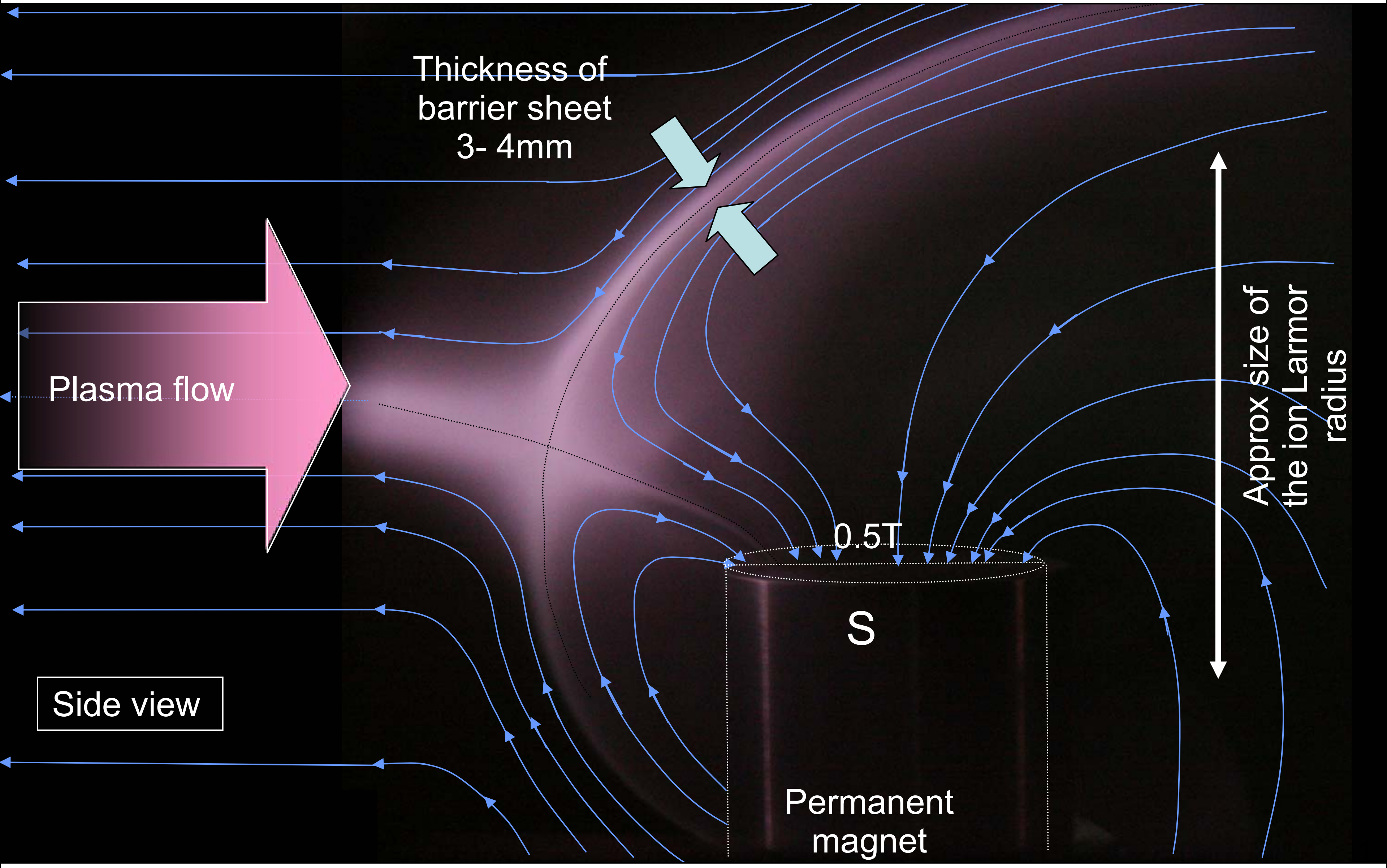
For isotropic, subsonic hydrogen plasma we expect α = 3.3, but the upstream plasma in LinX has α = 1.7

A full treatment including effects of probe collection areas for ions and electrons and secondary emission predicts a form for α

$$\alpha = -\frac{1}{2}\ln\left(2\pi\mu\Psi^2 M^2(1+\gamma_s{}^2)\right)$$

From which we infer that the plasma in LinX has Mach number M~3

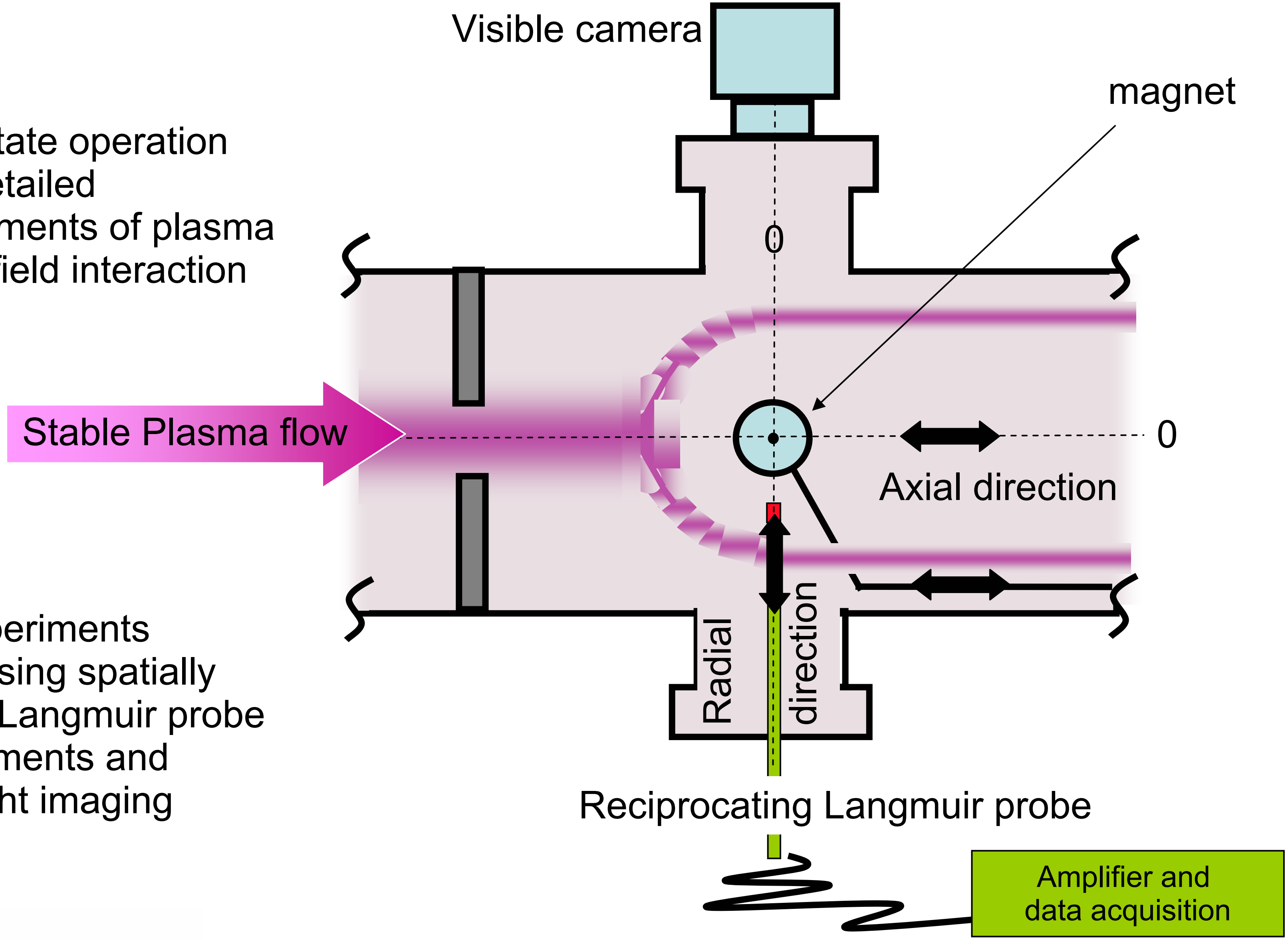
Plasma stream is deflected in an apparently stable narrow layer around the magnet



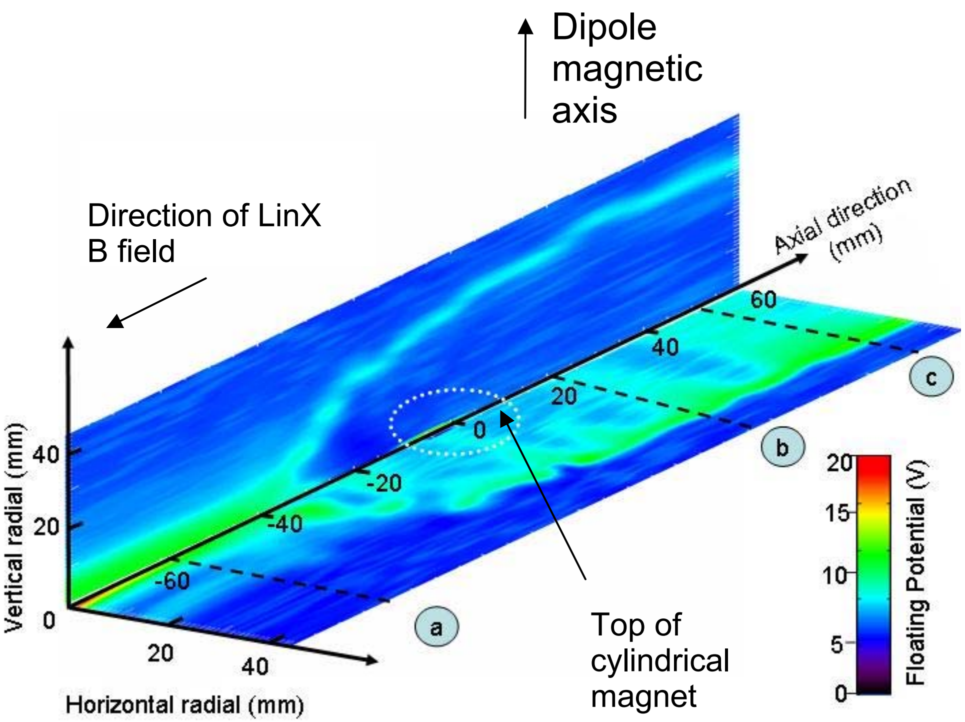
Spatial profiles can be created by systematically scanning a reciprocating probe and the dipole source

Steady state operation allows detailed measurements of plasma – dipole field interaction

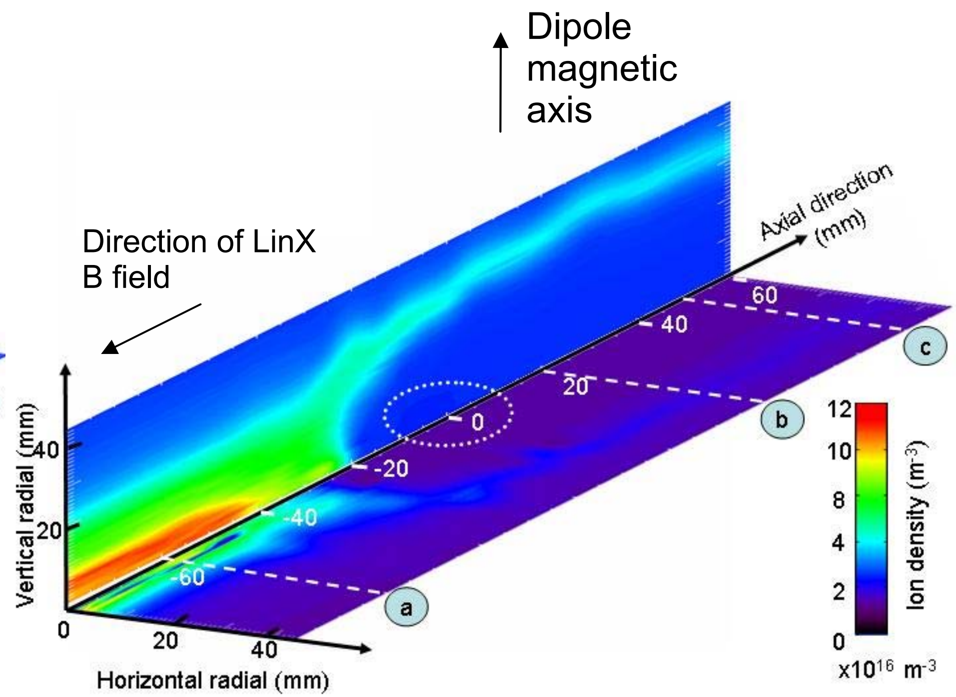
Initial experiments studied using spatially resolved Langmuir probe measurements and visible light imaging



2-D maps of floating potential and ion density indicate that the width of the plasma layer is much less than ion Larmor radius



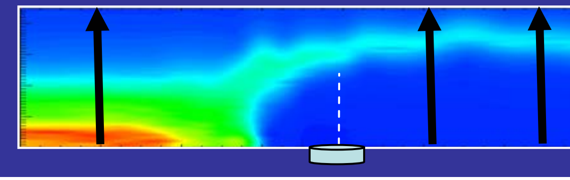
Floating potential



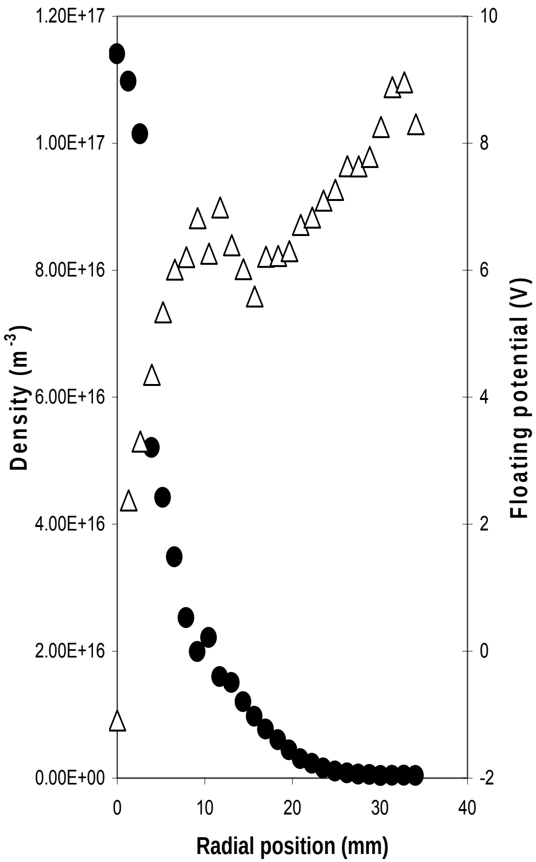
Ion density

- 2-D maps obtained by radial scanning Langmuir probe and axially scanning dipole field source
- Structure of potential and density confirm visible imaging: plasma is deflected into a narrow layer of scale length << ion Larmor radius

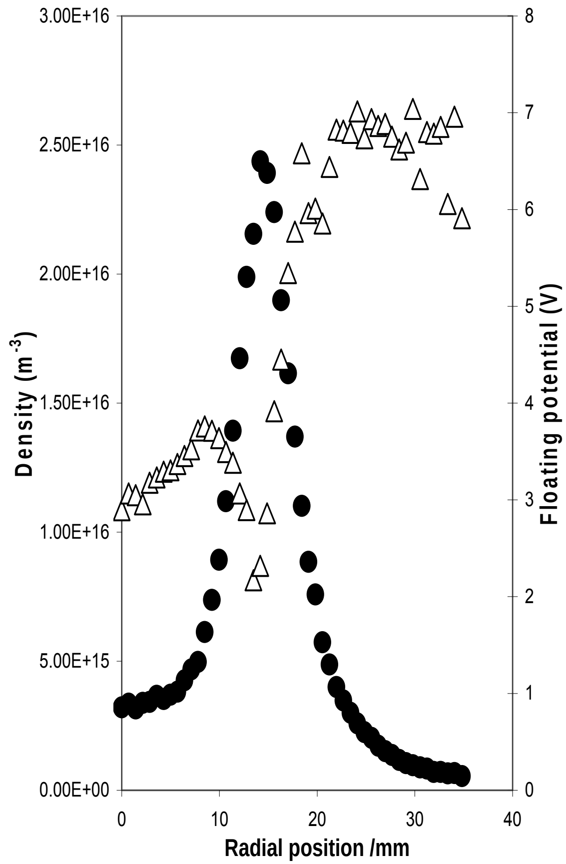
Ions are confined in local potential well



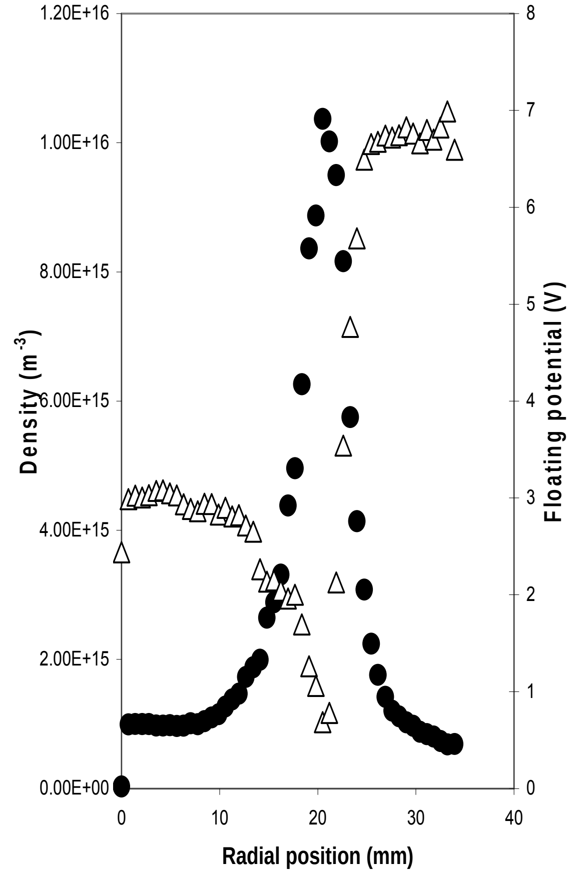
60mm upstream



20mm downstream

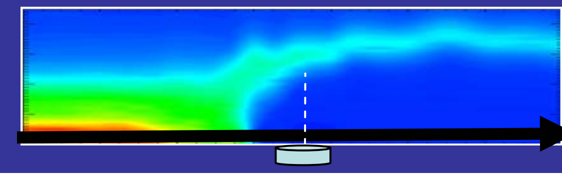


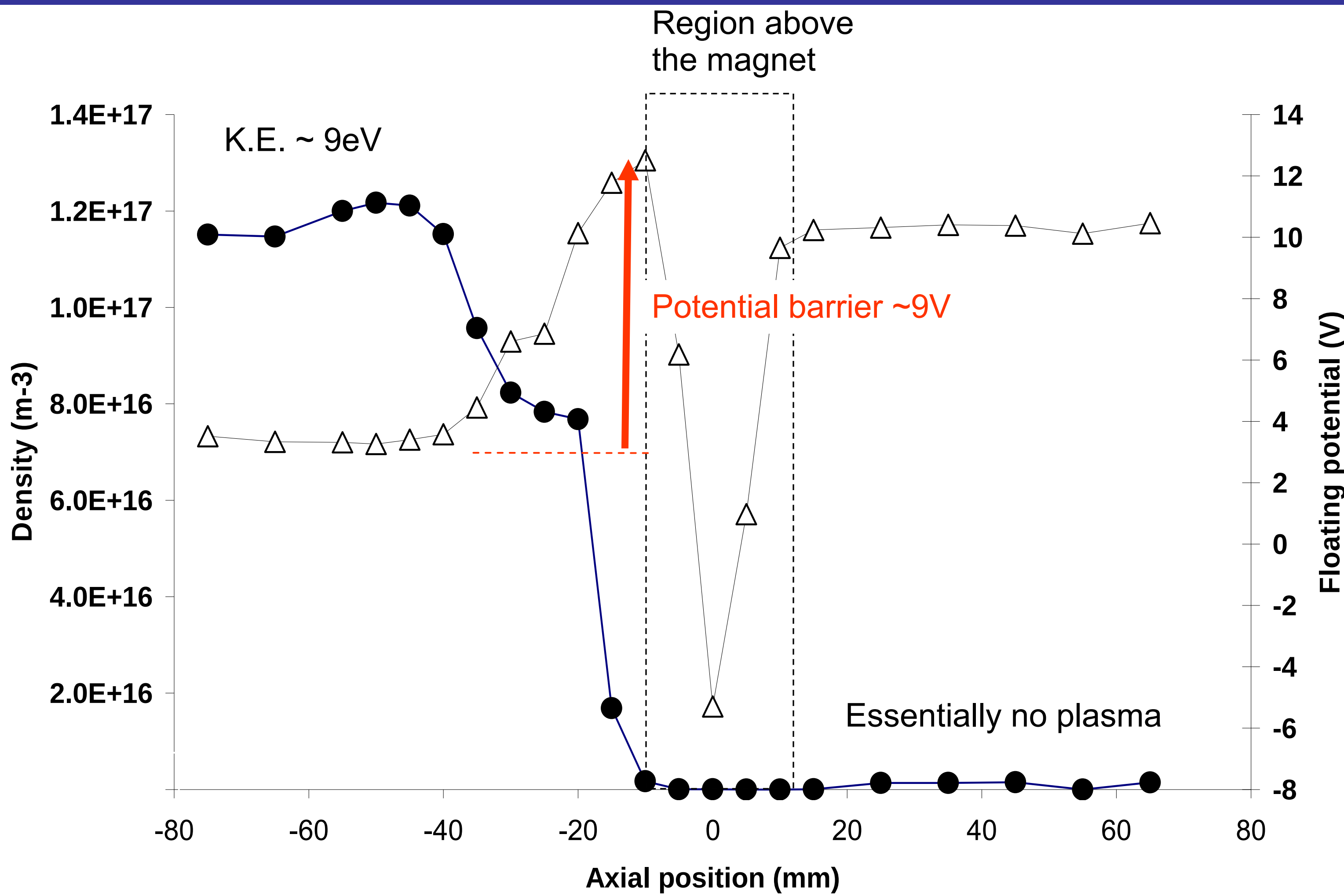
60mm downstream

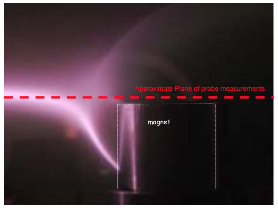


Detailed radial profiles reveal local potential well, “depth” is well matched to expected perpendicular ion energy

Axial profiles reveal potential barrier in dipole field region and cavity devoid of plasma

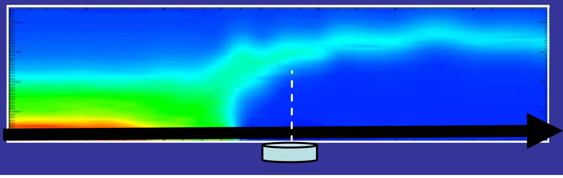


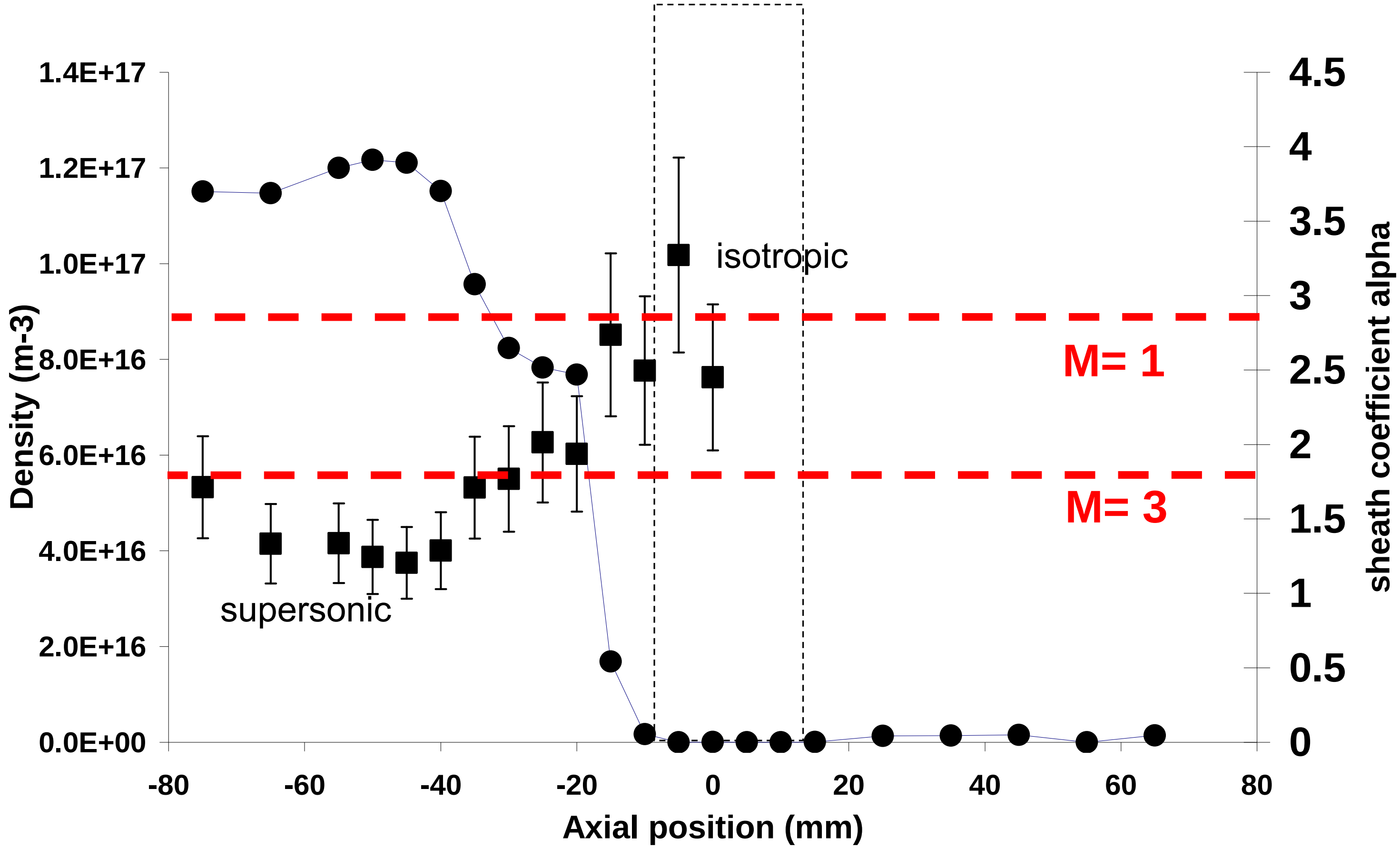




Form of potential above magnetic pole may be associated with local plasma structure as indicated in visible imaging

Plasma is slowed to subsonic velocity





- reduction in plasma flow in dipole field region is consistent with potential barrier
- Mach number indicates substantial reduction in flow velocity

Hybrid code modelling most appropriate for modelling laboratory mini-magnetospheres

- Plasma physics of the intermediate scale
  - Size of the spacecraft is << ion Larmor radii
- Using particle-in-cell hybrid simulations using the code dHybrid[1]. Fluid electrons, kinetic ions.
- Full kinetic not feasible as yet, due to the time and scale lengths
- Visualization performed with the osiris[2] framework
- Used to understand and to optimize present day lab experiments but also to link the simulation and experimental work to the space plasma environment

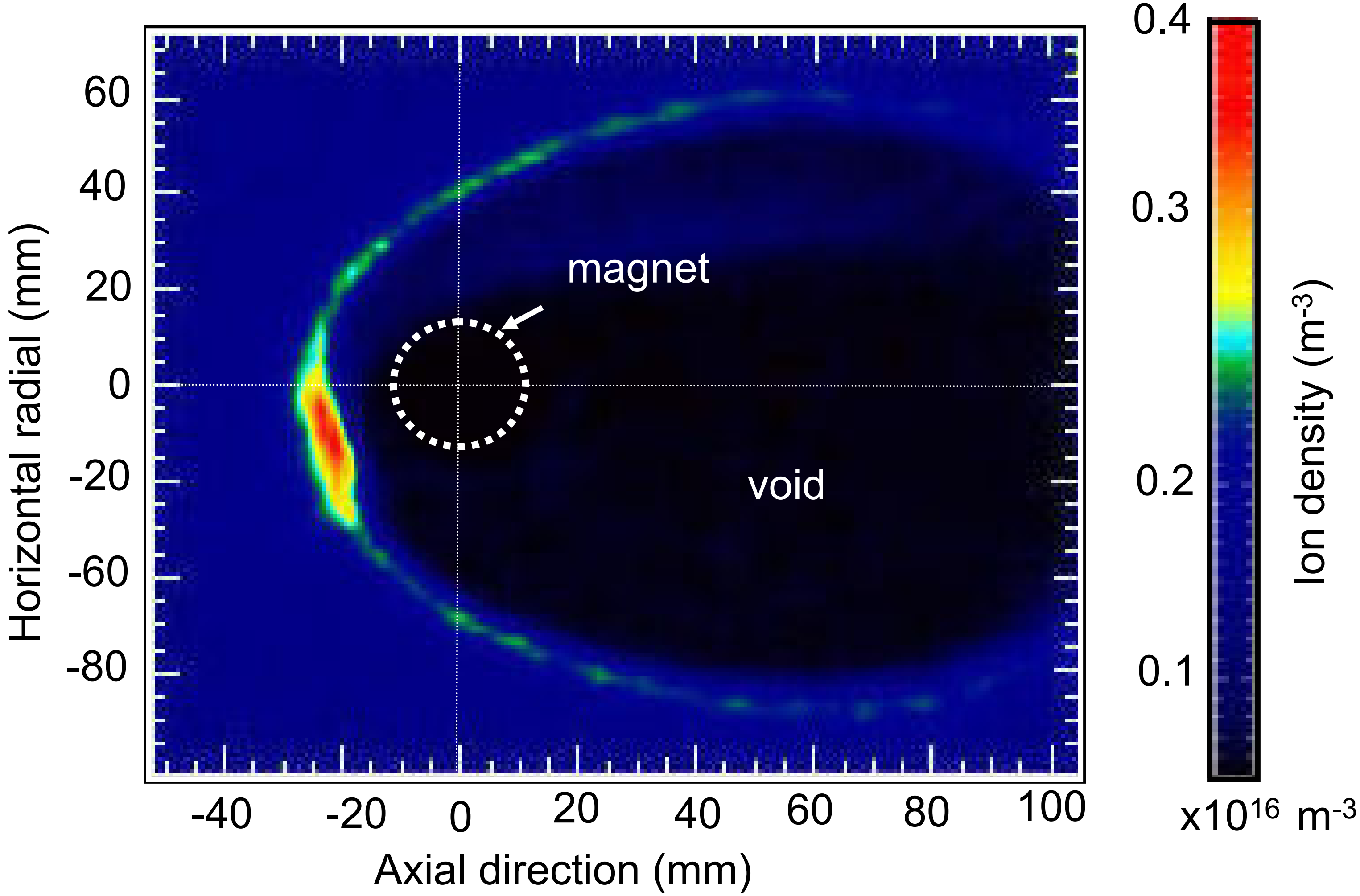
- It was found that the magnetopause distance to the dipole origin increases with increasing magnetic field intensity of the dipole and with decreasing kinetic pressure of the flowing plasma, as expected from theory.

1 L. Gargate, et al Comp. Phys. Commun. 176, 419 (2007)

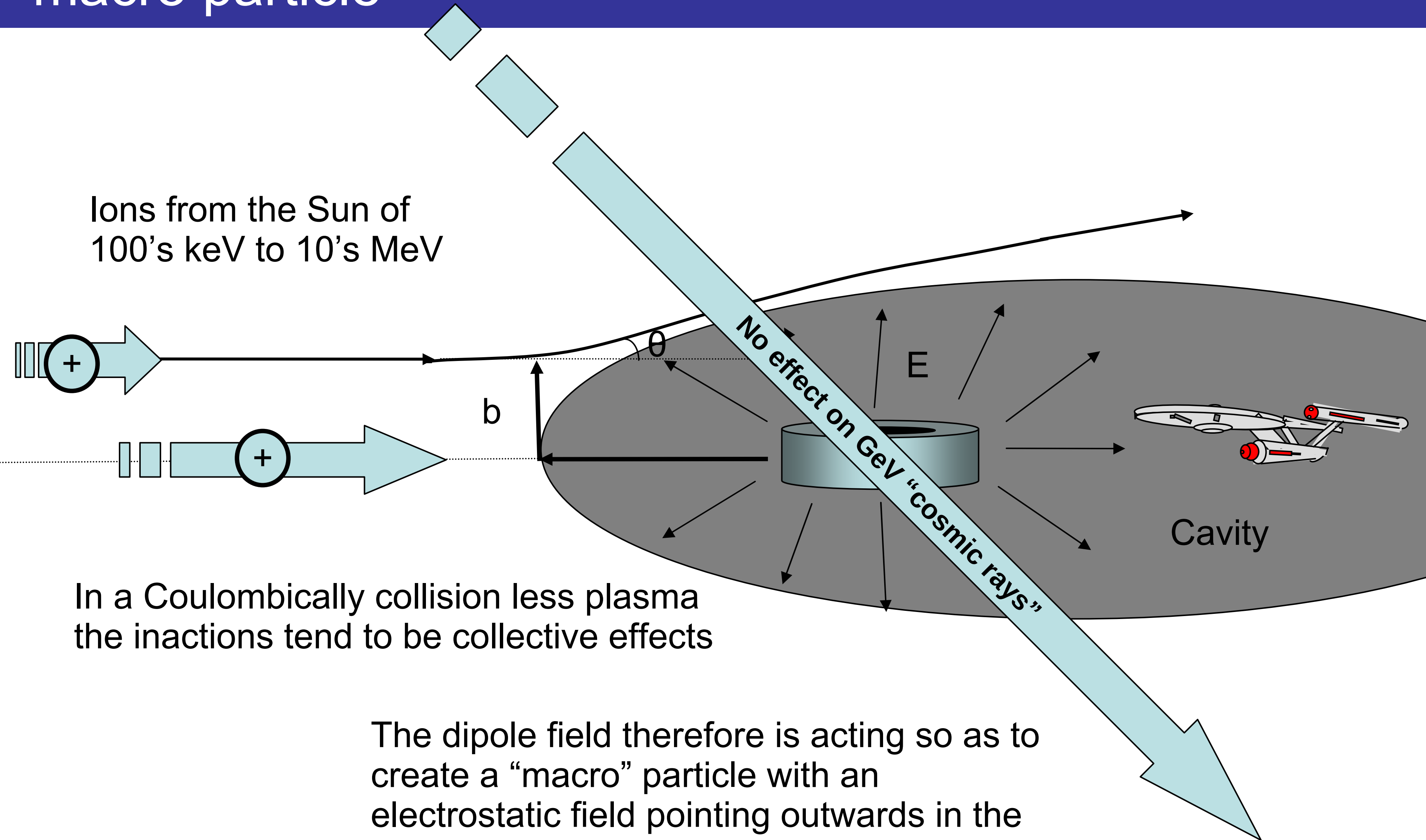
2 R. A. Fonseca, et al, Lecture Notes on Computer Science 2331, 342, Springer-Verlag, Heidelberg (2002)

dHybrid simulation results show narrow boundary and plasma cavity devoid of incident plasma

Modelled ion density of the laboratory experiment



The intuitive analogy is with Rutherford Scattering on a "macro particle"



In a Coulombically collision less plasma the inactions tend to be collective effects

The dipole field therefore is acting so as to create a "macro" particle with an electrostatic field pointing outwards in the frame of reference of the incoming particle

Summary & Conclusions part 1 of 2

- It has been demonstrated in simulation and laboratory experiment that can create an **effective transport barrier to supersonic plasma flow**.
- Interior of "hole" in plasma stream is essentially devoid of plasma.
- Boundary scale length is **much less than the ion Larmor radii scale ~ 1/10th.**
- Thus the magnetic "bubble" needed to act as a **shield can be much smaller** ~100m compared to the > 20km considered previously.
- Fundamentally this demonstrates the critical need to consider **plasma particle kinetics** at boundaries.
- The LinX experiment offers an ideal platform to study a range of fundamental plasma physics phenomenon that are of relevance to astrophysical contexts.

Summary & Conclusions part 1 of 2. Future work

- So far have established proof-of-principle only.
- Need to do systematic measurements in many regions and compare these with simulations.
- We have initial data on impulse response showing some very interesting physicss also showed that particularly with the addition of the time dimension and reactive response, great care in the interpretation is needed.

Thank you, and live long and prosper…

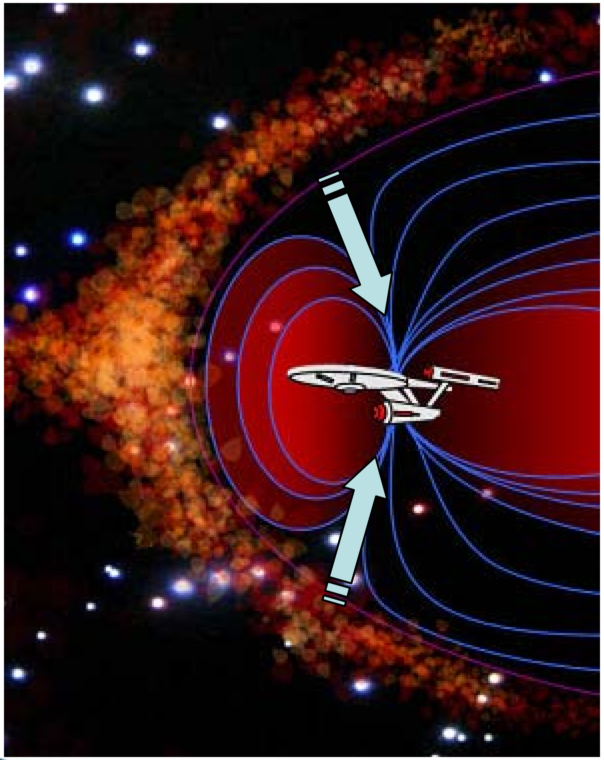
spares

Ruth Bamford

Digitally signed by Ruth Bamford
DN: cn=Ruth Bamford, o=RAL, ou=SSTD, email=R.Bamford@rl.ac.uk, c=GB
Date: 2008.06.25 09:58:04 +01'00'

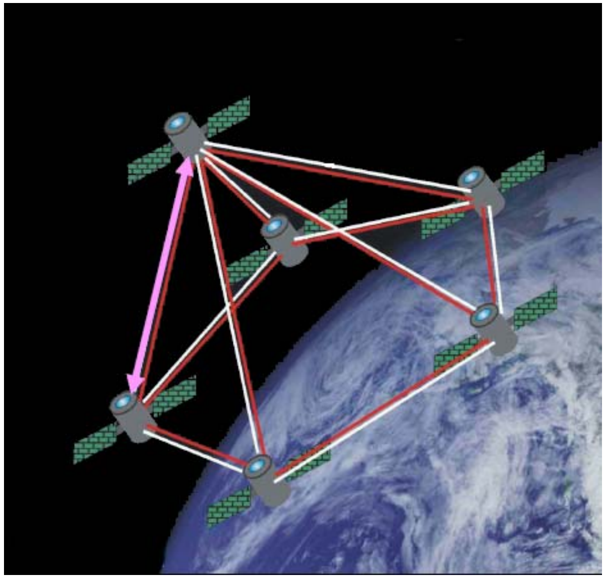
There are conceptual solution to dealing with the radiation from the poles

The action of the dipole field does not just deflect particles but also funnels some particles preferentially into the magnetic poles, just like that which creates the Earth's Aurora.

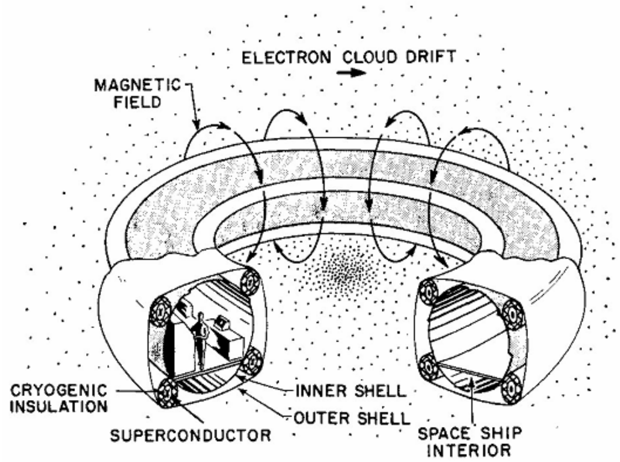


<u>Possible solutions include:</u>

Formation flying

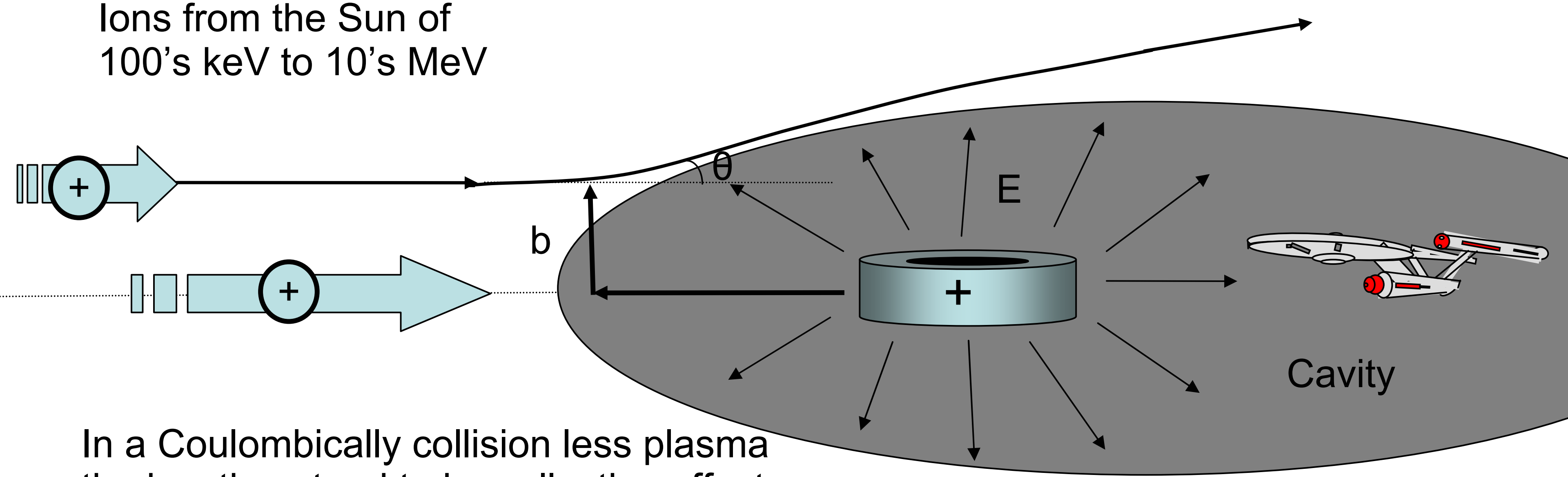


Torus space craft



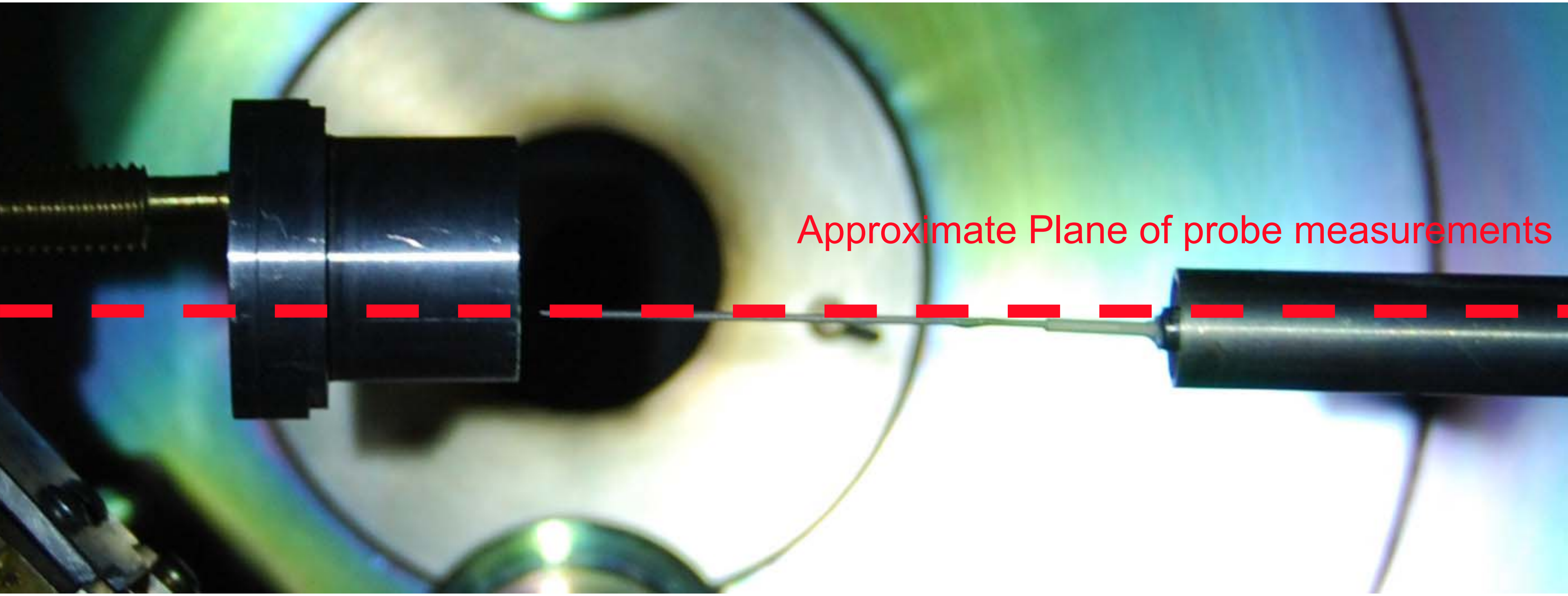
The intuitive analogy is with Rutherford Scattering on a “macro particle”

Ions from the Sun of
100’s keV to 10’s MeV



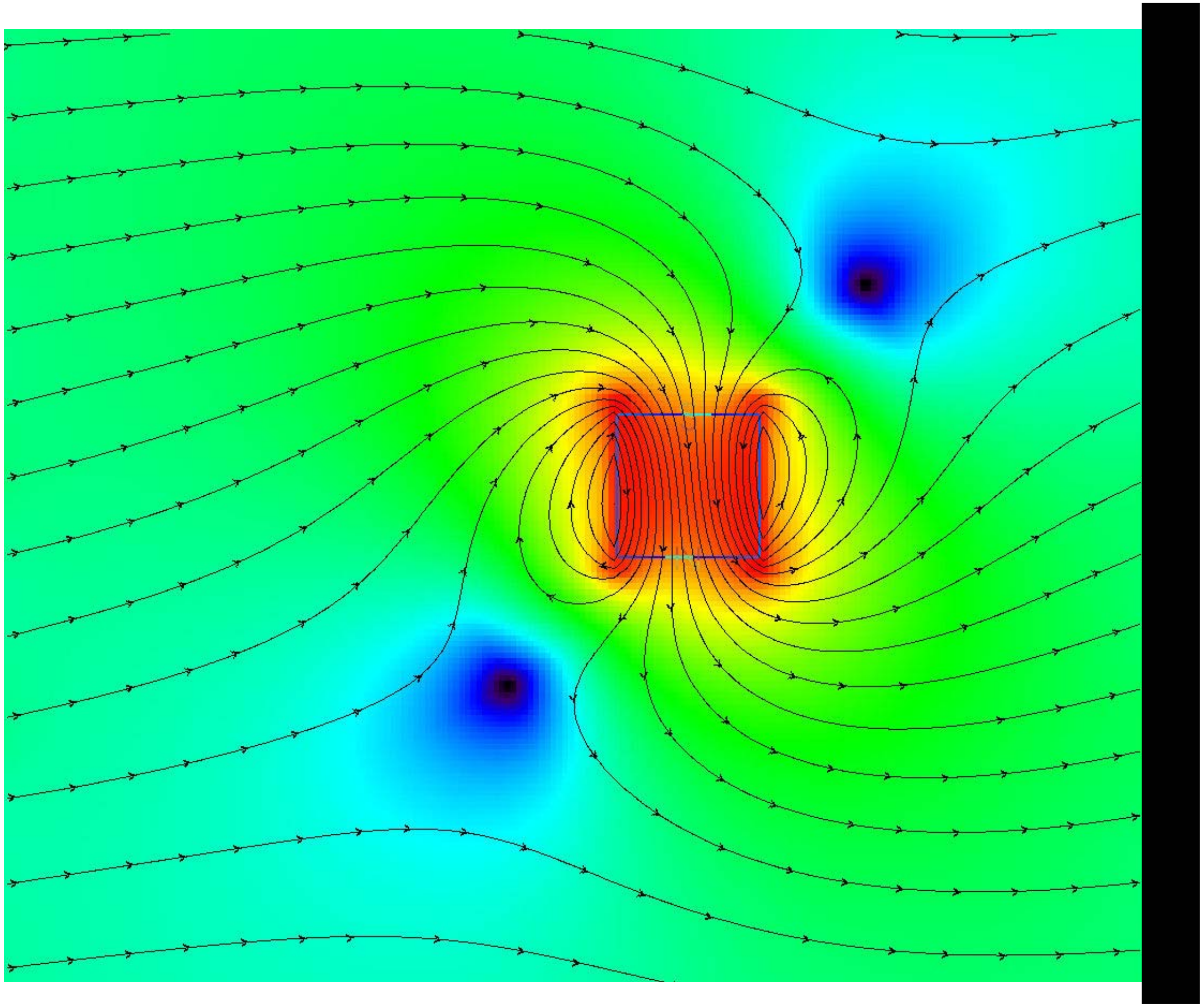
In a Coulombically collision less plasma
the inactions tend to be collective effects

The dipole field therefore is acting so as to create a “macro” particle with an electrostatic field pointing outwards in the frame of reference of the incoming particle

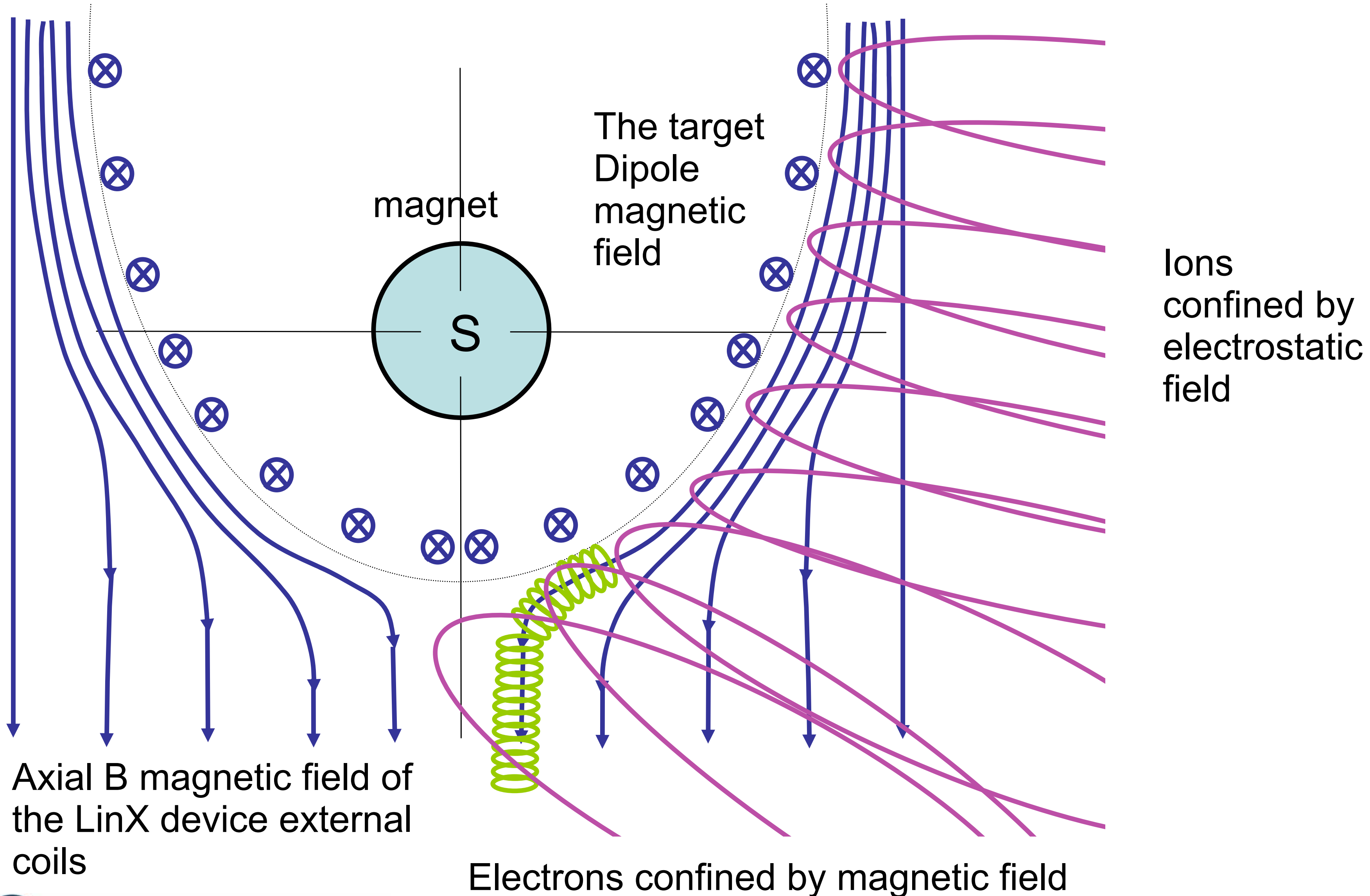


\Week 15\Setup 17_09_07\DSC_0184.JPG

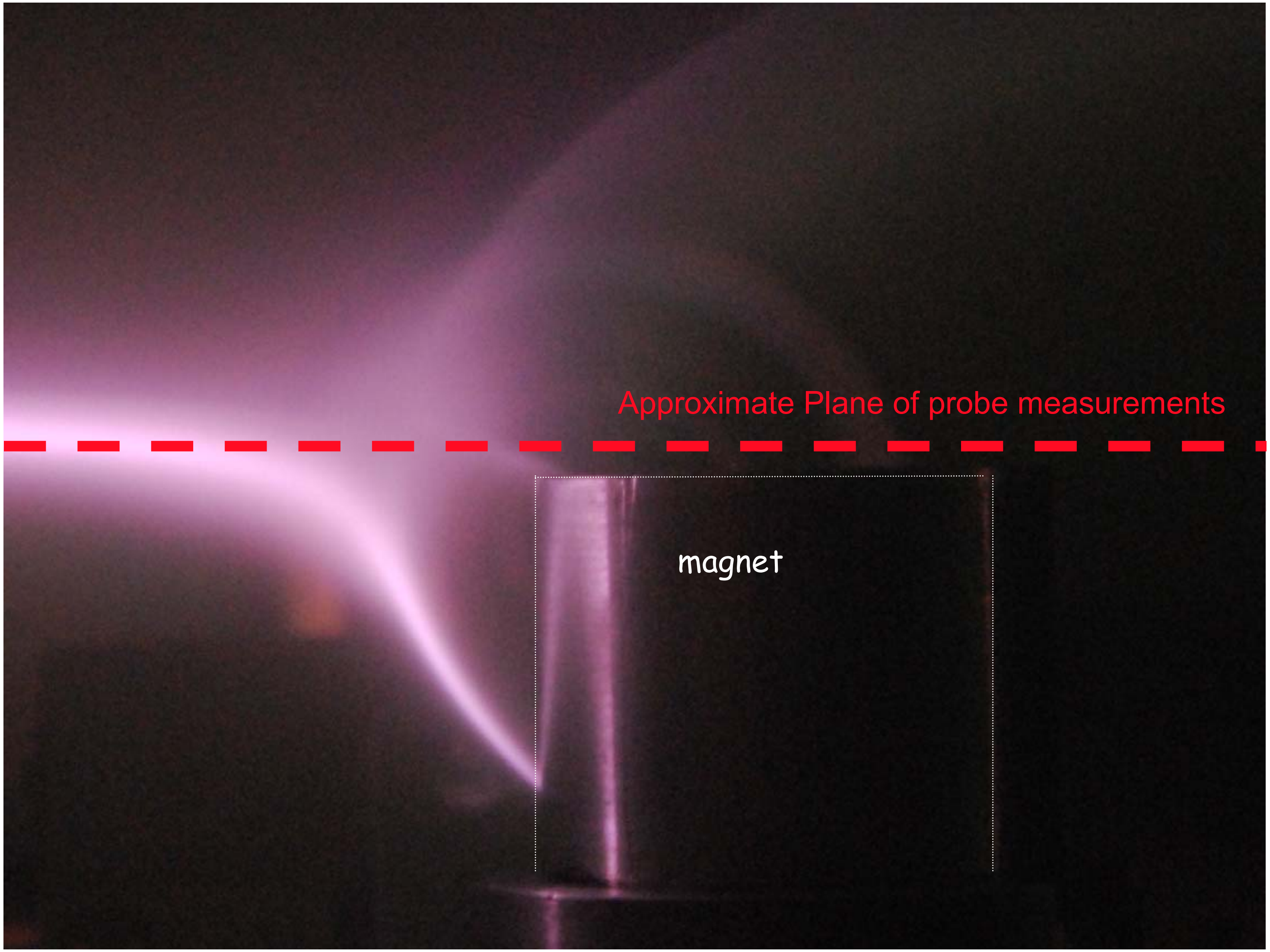
Vacuum field simulation



Ions confined electrostatically



Plasma stream is deflected in an apparently stable narrow layer around the magnet



The experimental apparatus