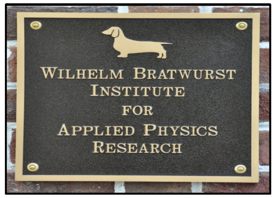
MUSC
MEDICAL UNIVERSITY of SOUTH CAROLINA



Inertial Electrostatic Confinement; Small Scale Nuclear Fusion for Non-Energy Applications

Daniel R. Knapp

Medical University of South Carolina

and

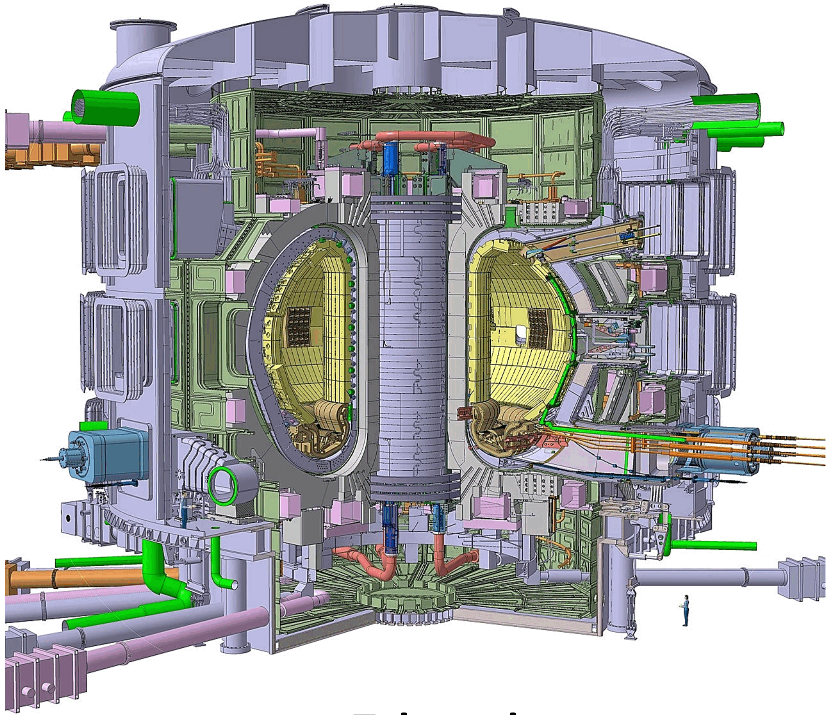
Wilhelm Bratwurst Institute

Charleston, South Carolina, 29425 USA

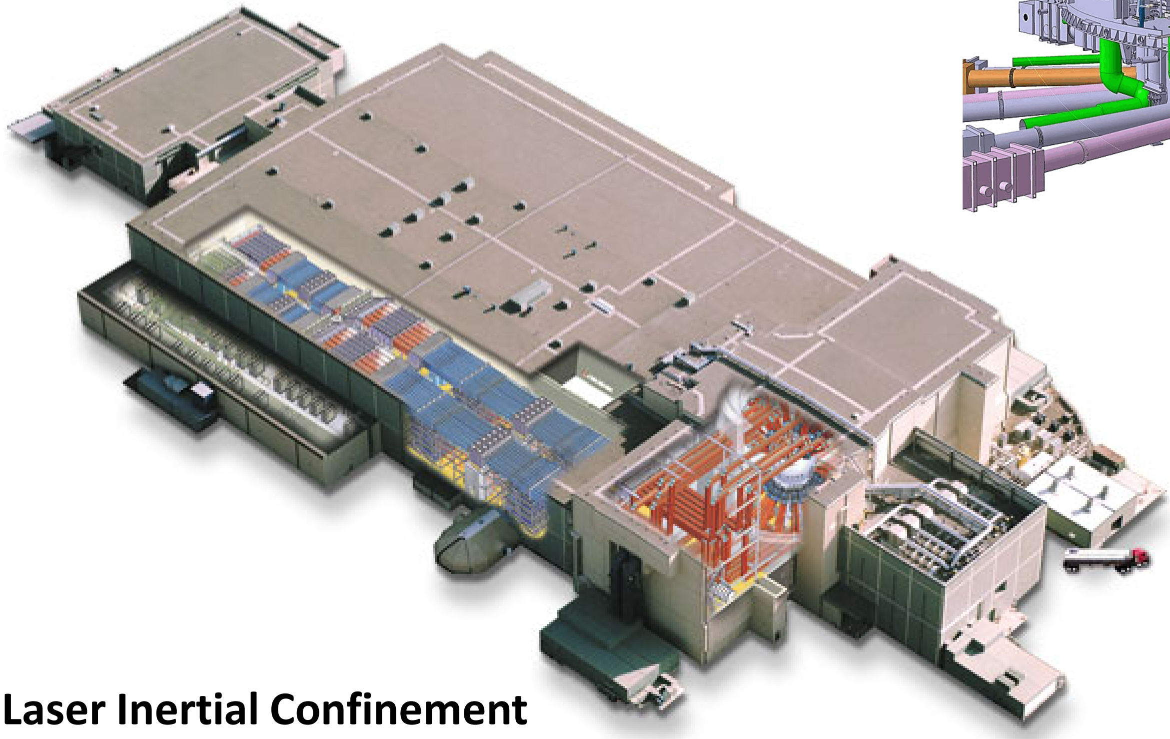
ICTP-IAEA College on Advanced Plasma Physics

August, 2014

Major Current Projects in Nuclear Fusion

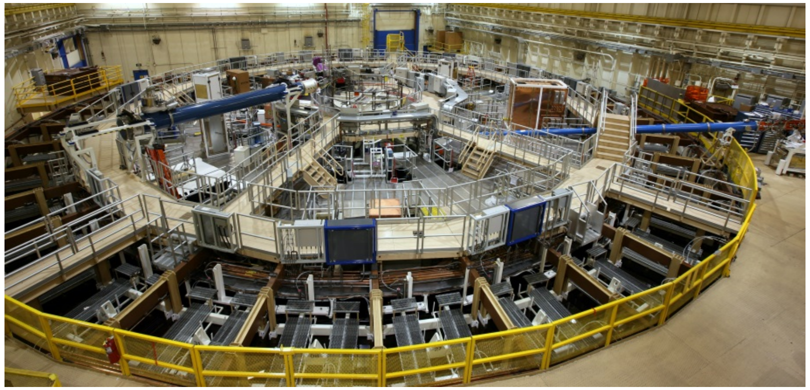


Tokamak
ITER, Cadarache, FR

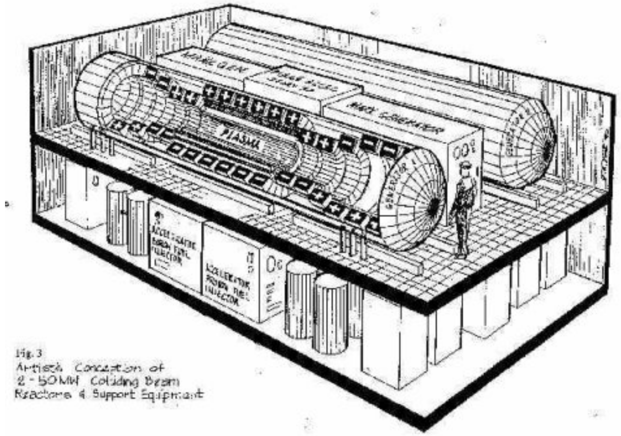


Laser Inertial Confinement
National Ignition Facility, LLNL, US

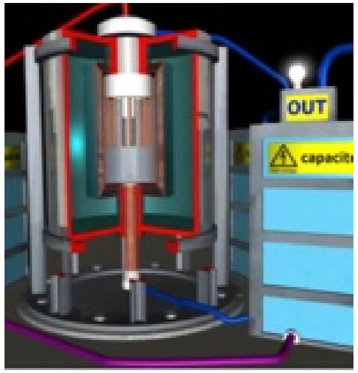
Some Other (Smaller) Approaches to Nuclear Fusion



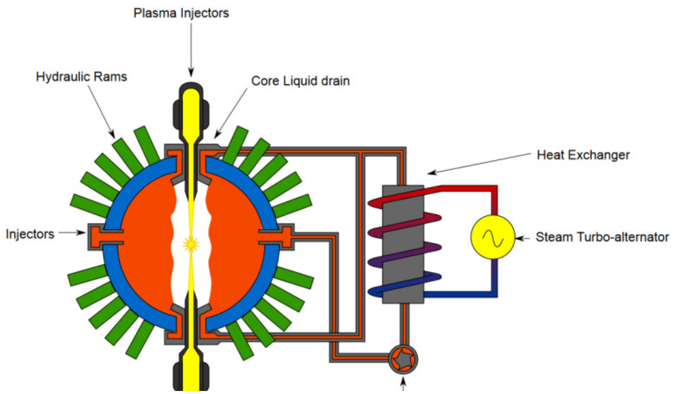
Z-Pinch (Sandia Laboratories Z-Machine)



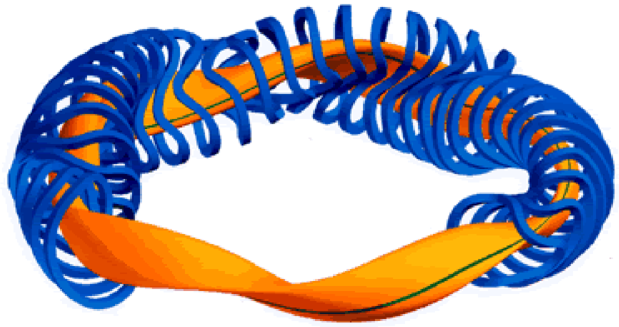
"Field Reversed Configuration" (Tri Alpha Energy)



Dense Plasma Focus
(Lawrenceville Plasma Physics)



Magnetized Target Fusion
(General Fusion Inc.)



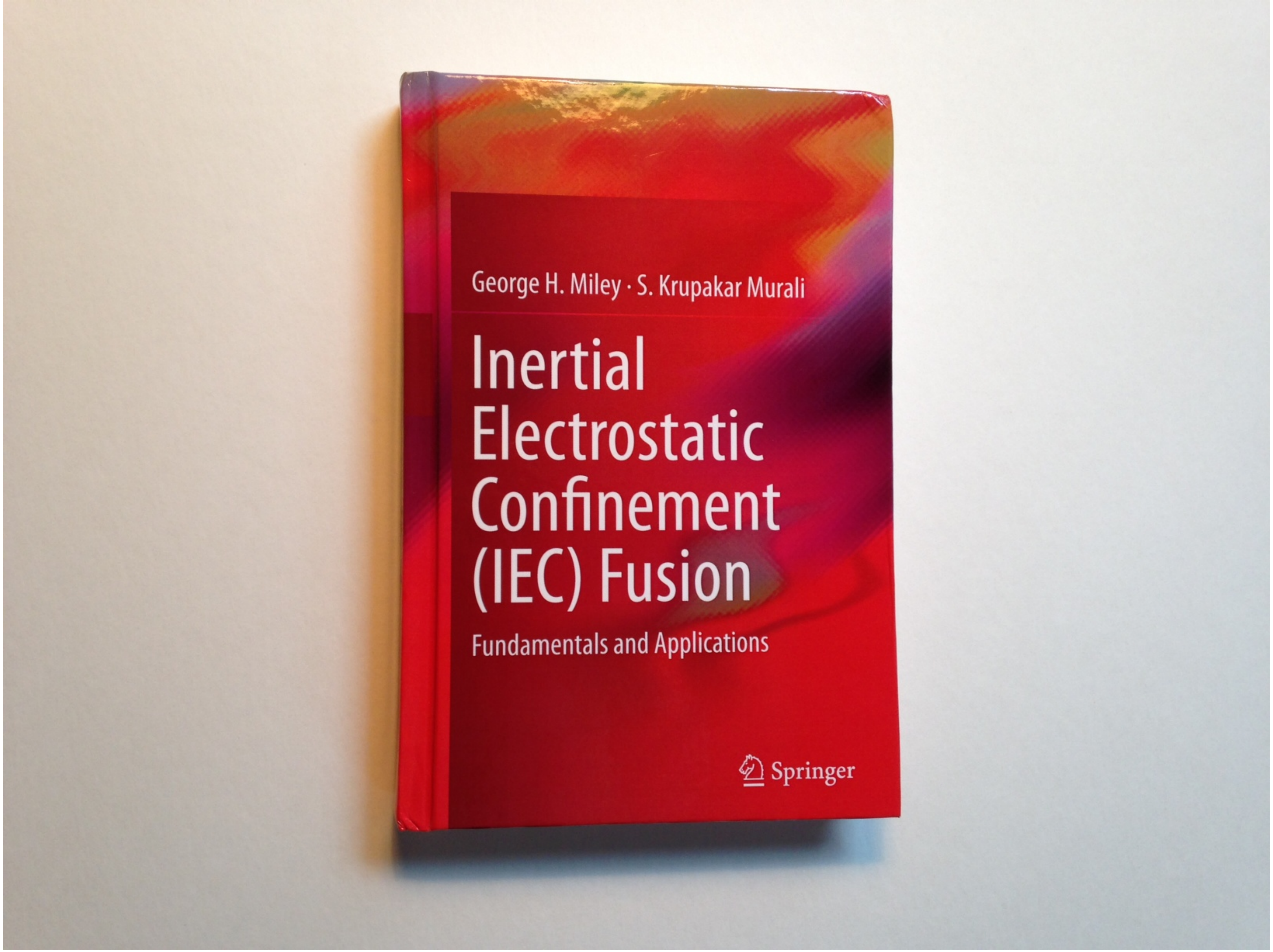
Stellarators
(e.g. Wendelstein 7-X in Germany)

The topic of this presentation (still smaller devices):

<u>Inertial Electrostatic Confinement (IEC) Fusion:</u>

- **Farnsworth-Hirsch Fusor**
- **Polywell® (EMC2)**
- **Other gridless IEC designs**
- **Lockheed's new device (IEC?)**

(IEC is <u>NOT</u> "Cold Fusion" !!!)


George H. Miley · S. Krupakar Murali
Inertial Electrostatic Confinement (IEC) Fusion
Fundamentals and Applications
Springer

Nuclear Fusion Reactions

$^{2}H + {}^{3}H \rightarrow {}^{4}He$ (3.5 MeV) + n^{0} (14.1 MeV)

$^{2}H + {}^{2}H \rightarrow {}^{3}H$ (1.01 MeV) + p^{+} (3.02 MeV) [50%]
$^{2}H + {}^{2}H \rightarrow {}^{3}He$ (0.82 MeV) + n^{0} (2.45 MeV) [50%]

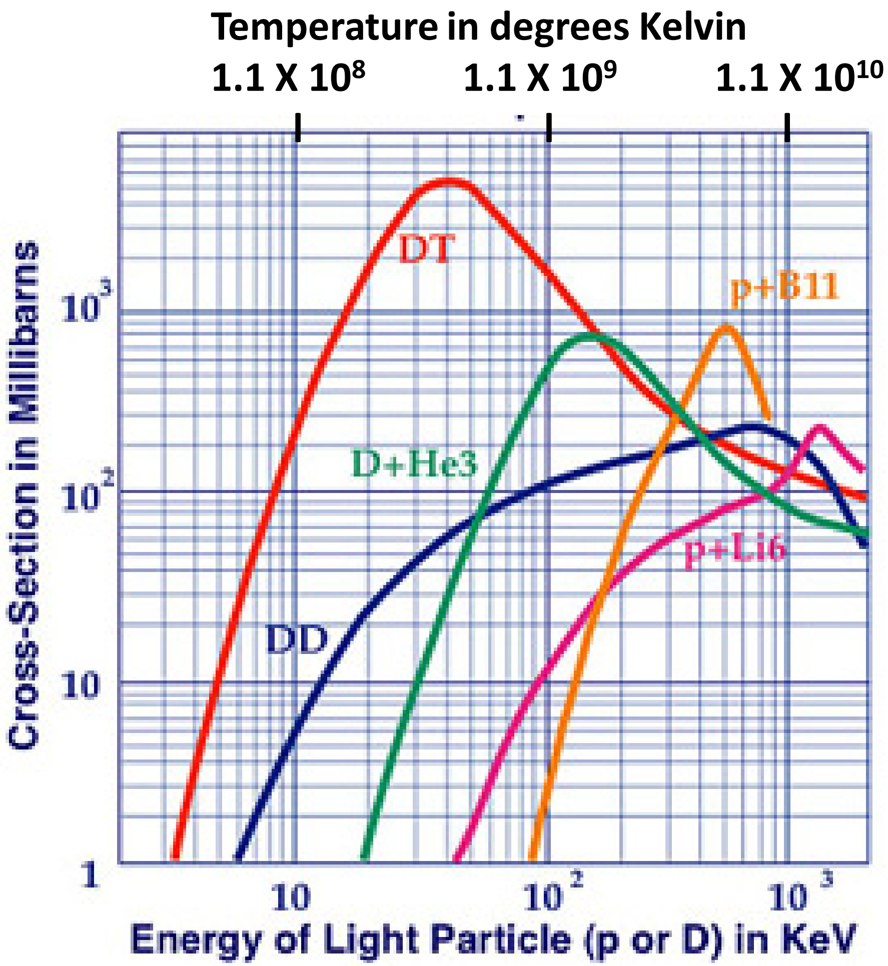
$^{2}H + {}^{3}He \rightarrow {}^{4}He$ (3.6 MeV) + p^{+} (14.7 MeV)

$p^{+} + {}^{6}Li \rightarrow {}^{4}He$ (1.7 MeV) + ^{3}He (2.3 MeV) *

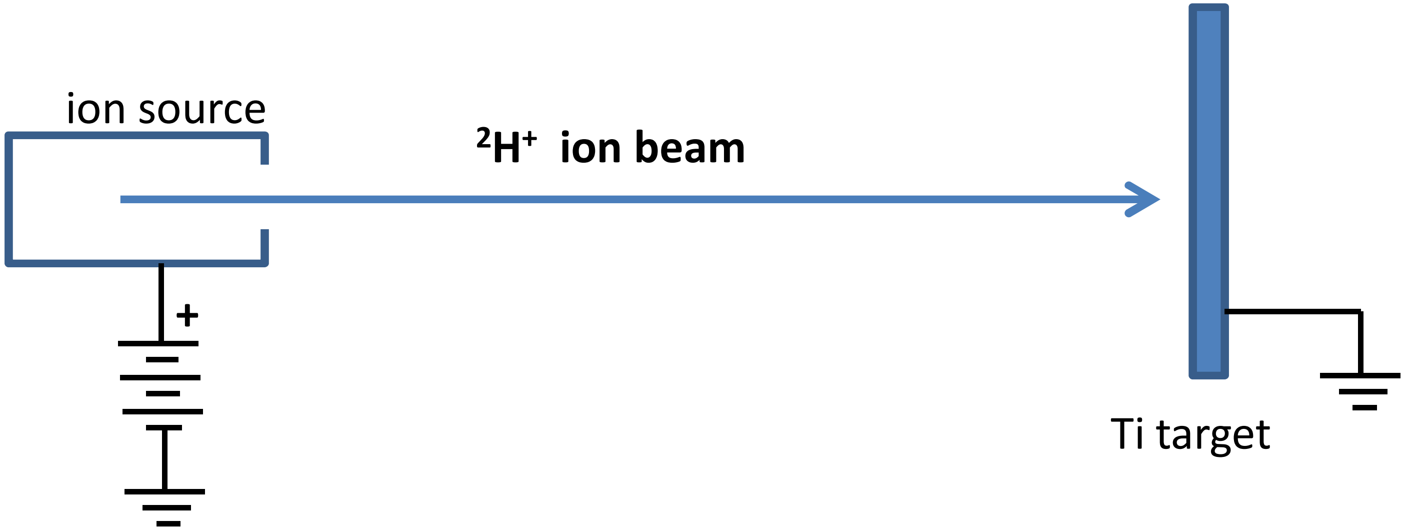
$p^{+} + {}^{11}B \rightarrow 3\ {}^{4}He$ (8.7 MeV) "aneutronic"

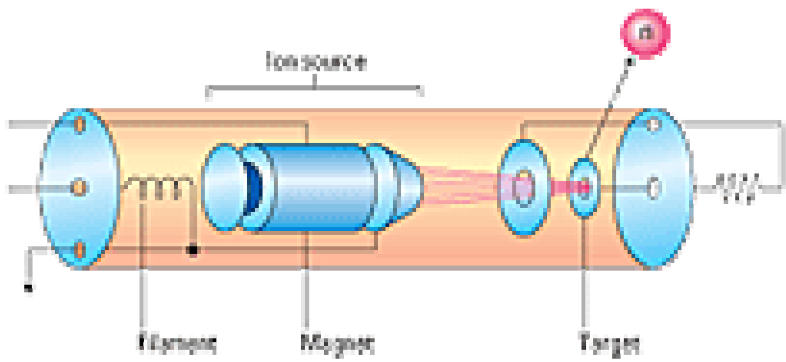
* where it all started – Cockcroft & Walton, 1932

Nuclear Fusion Cross Sections



Beam-Target Nuclear Fusion



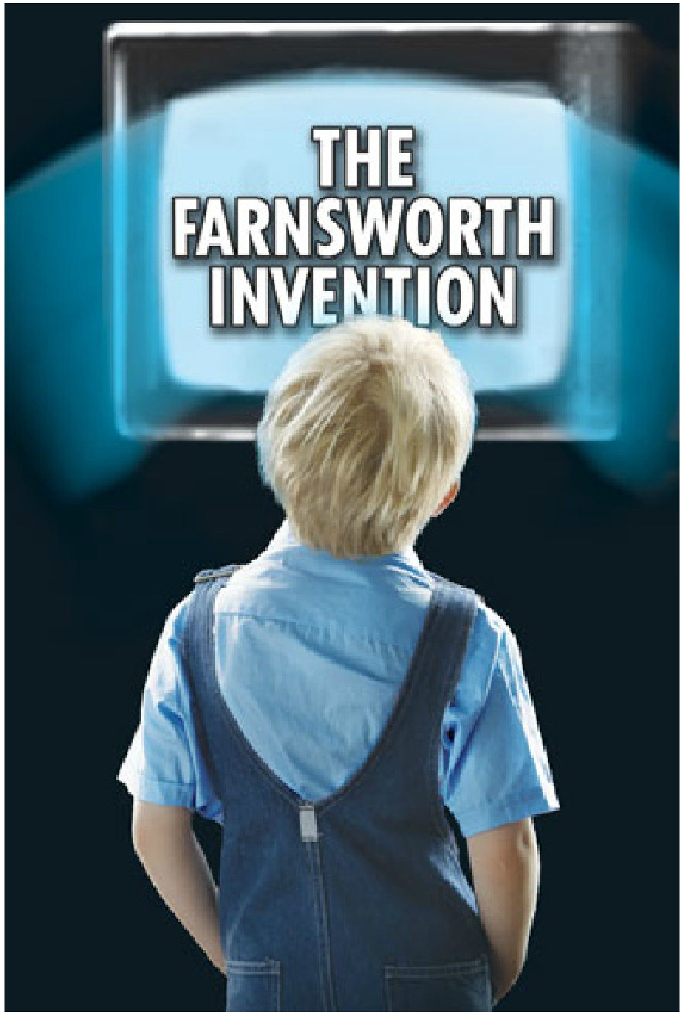


Schlumberger Ltd.

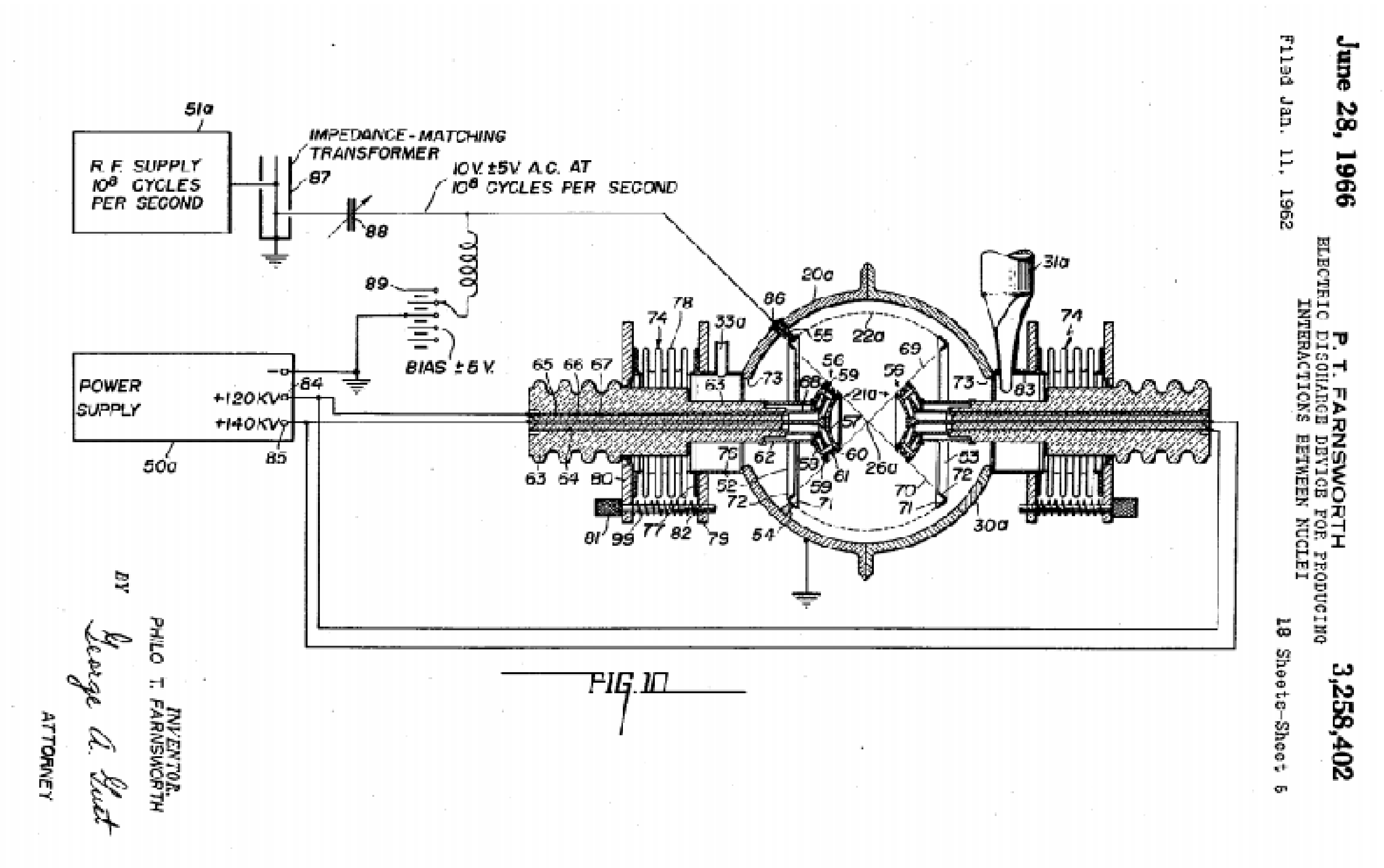
Beam-Target Nuclear Fusion – Gas Phase Target

Philo Farnsworth
inventor of electronic television
8/19/1906-3/11/1971

The Farnsworth Invention
a play by Aaron Sorkin
Music Box Theatre
Broadway, New York
December 3, 2007 –
March 2, 2008



Farnsworth's Other Invention - IEC Fusion Device



P. T. Farnsworth, U.S. Patent 3,258,402 June 28, 1966

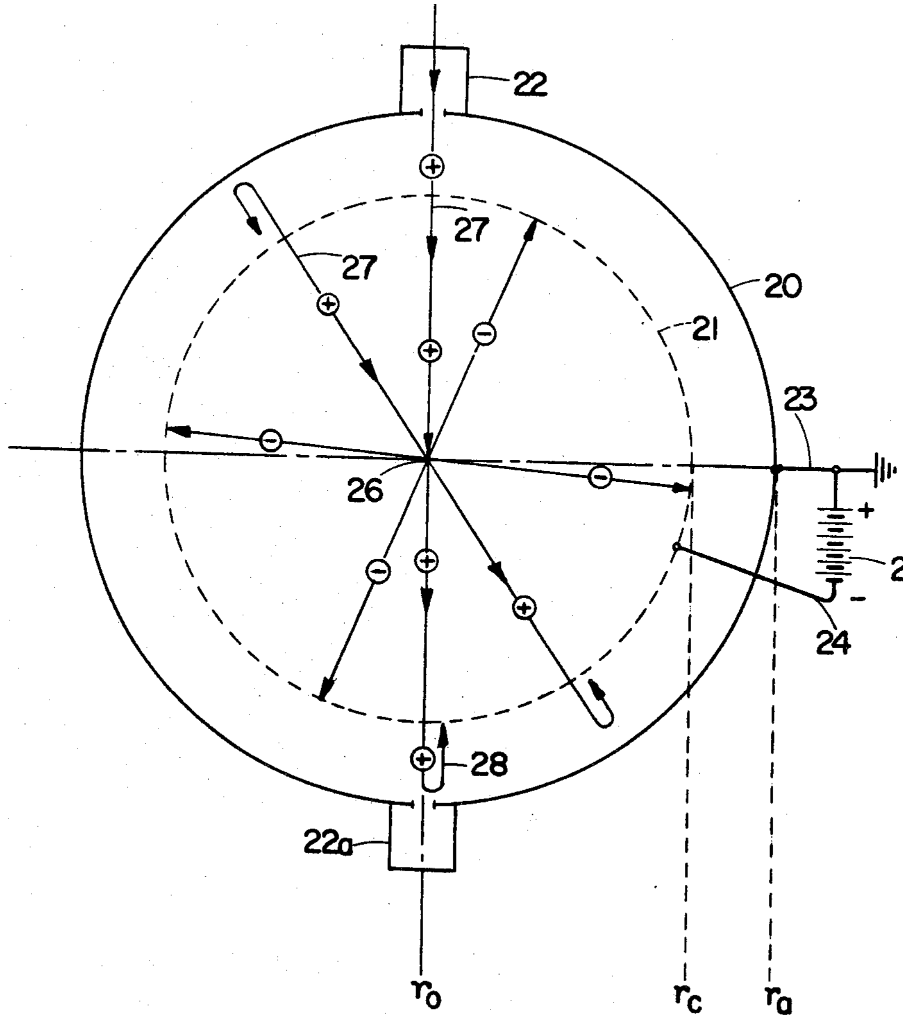
Farnsworth wasn’t actually the first :

As Professor Linder mentioned last week, Oleg Lavrentyev actually put forth the idea first (1950), but Andre Sakarov didn’t think it would work.

After the secrecy surrounding fusion work was lifted, Lavrentyev ultimately published his idea:

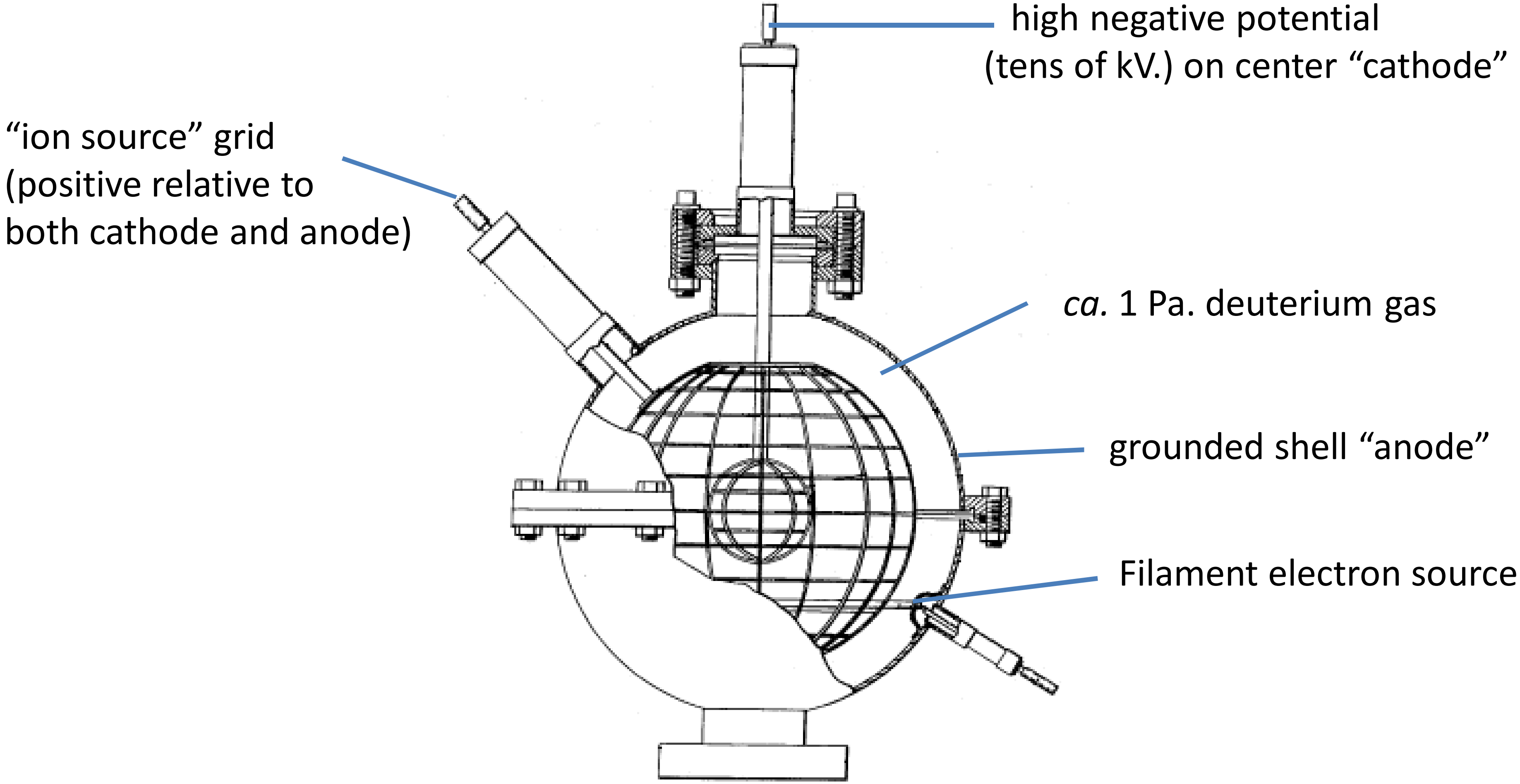
Lavrentyev, O.A. *et al.* (1963) Jenergiya i plotnost’ionov v jelektromagnitnoj lovushke. Ukrain. Fiz. 8:440–445.

Farnsworth Fusor



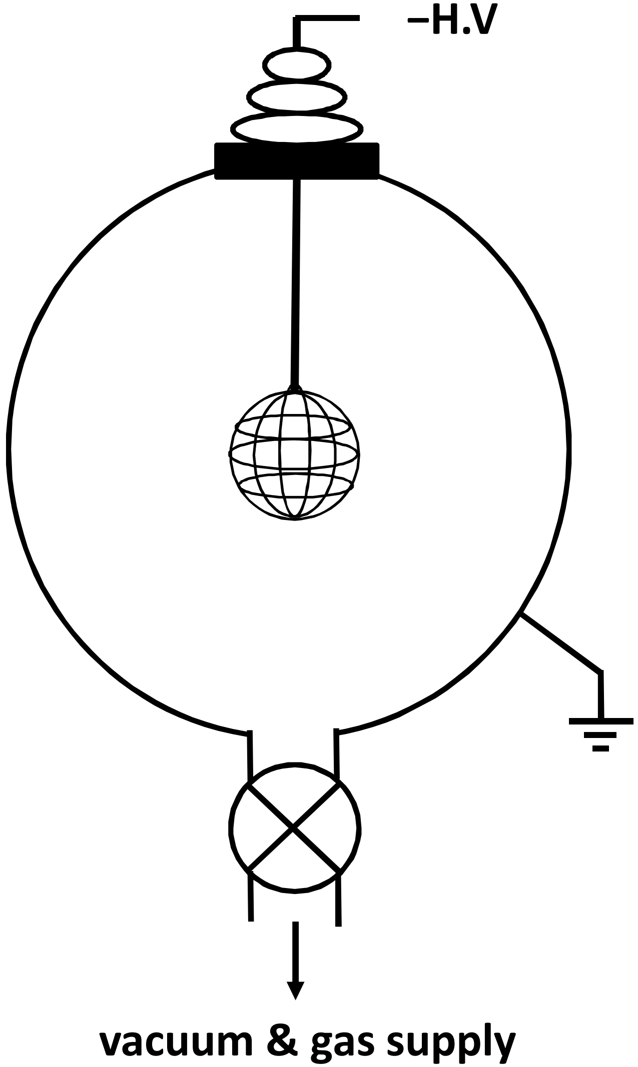
P. T. Farnsworth, U.S. Patent 3,386,883 A June 4, 1968

Farnsworth–Hirsch Fusor



G.A. Meeks, R.L. Hirsch, U.S. Patent 3,530,497 September 22, 1970

Basic “Farnsworth Fusor”



Arguments that IEC Fusion Cannot Yield Net Energy

Bremsstrahlung losses exceed the fusion power produced.

T. H. Rider, A general critique of inertial-electrostatic confinement fusion systems, M.S. thesis, Massachusetts Institute of Technology, 1994.
T.H. Rider, "A general critique of inertial-electrostatic confinement fusion systems, *Physics of Plasmas* 2 (6), p. 1853-1872 (Jun. 1995).

Coulomb collisions →Maxwellian distribution on the ion–ion collisional time scale; power required to prevent this is greater than the fusion power produced.

W.M. Nevins, Can inertial electrostatic confinement work beyond the ion-ion collision time scale? *Physics of Plasmas* 2: 3804-3819, 1995.

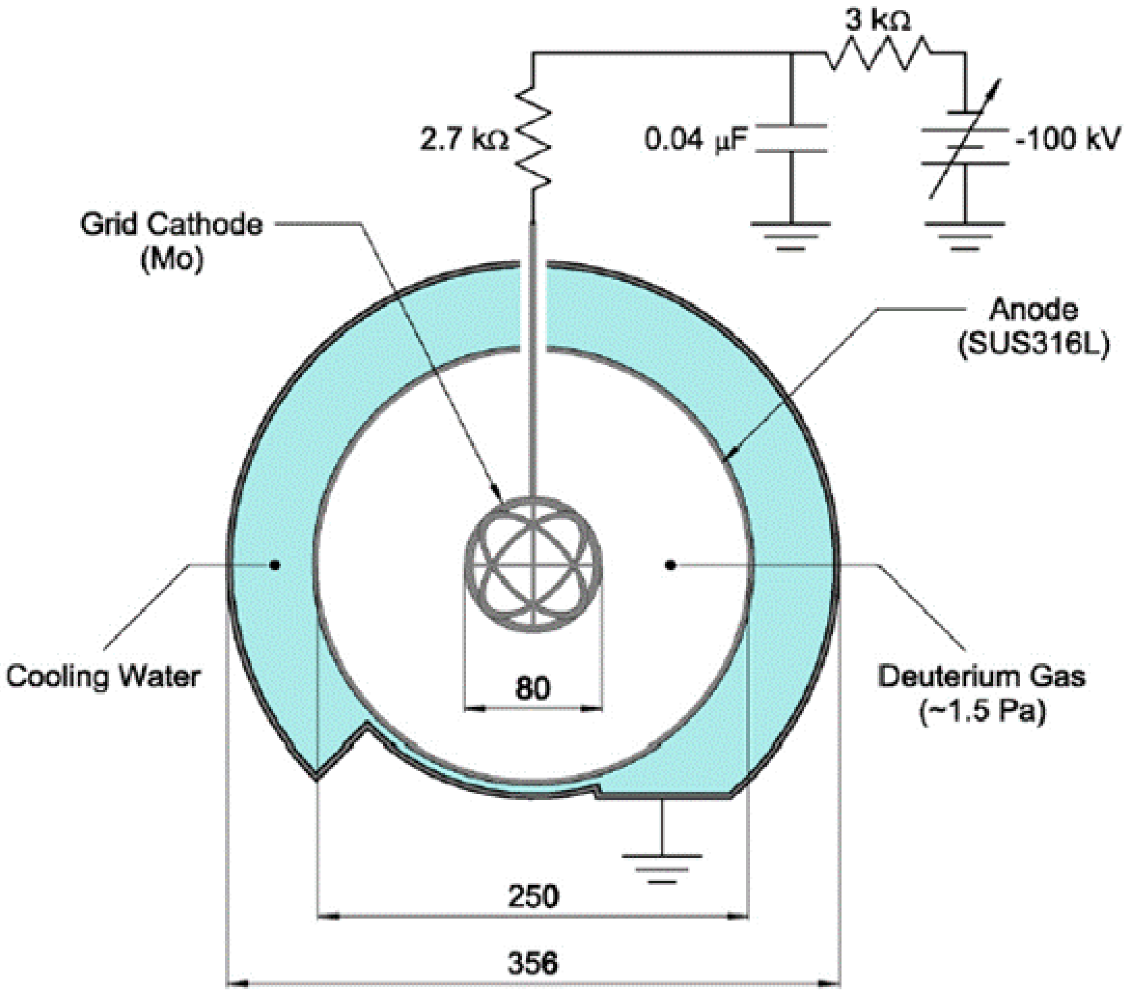
Applications of Nuclear Fusion

1. Energy production

2. Neutron and other energetic particle sources
    a. landmine detection
    b. nuclear materials detection
    c. neutron radiography
    d. neutron transmutation doping
    e. medical isotope production
    f. research applications

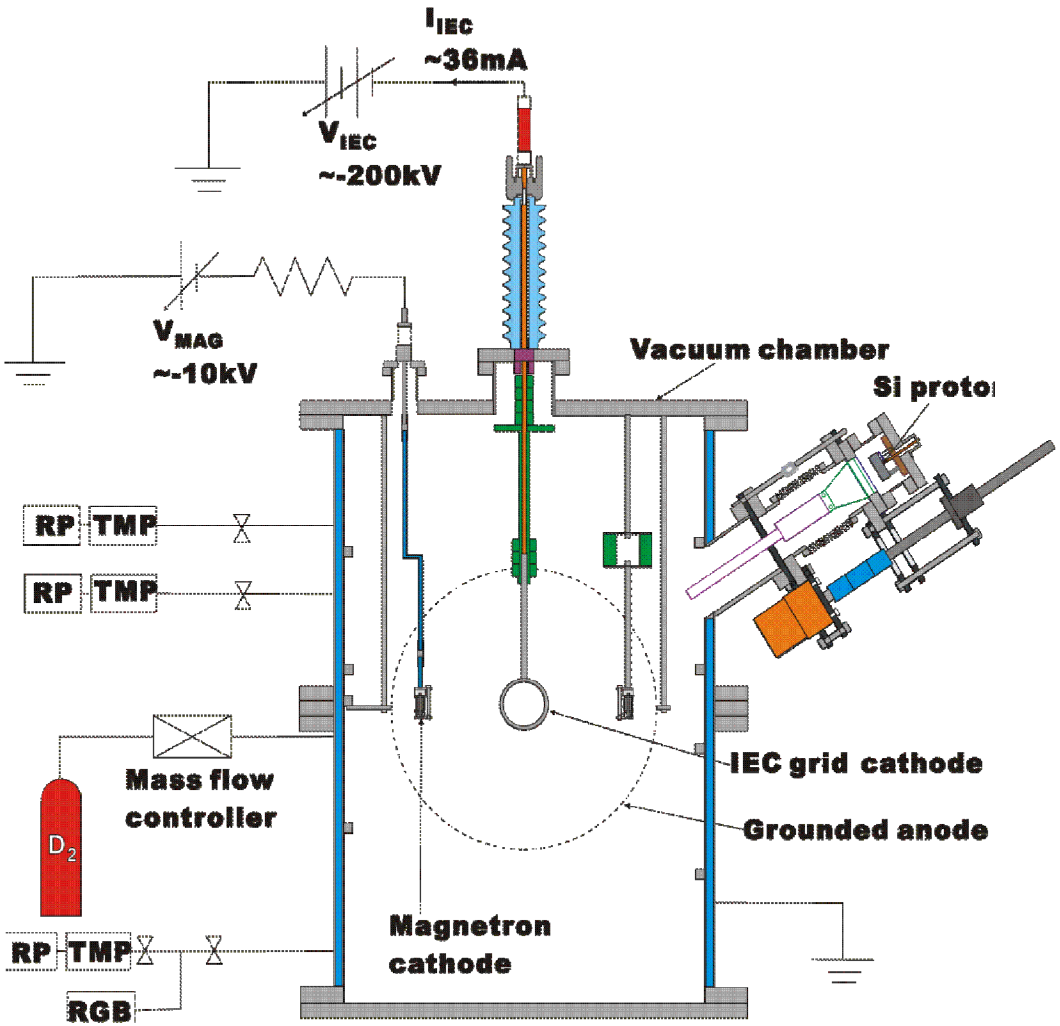
3. Spacecraft propulsion

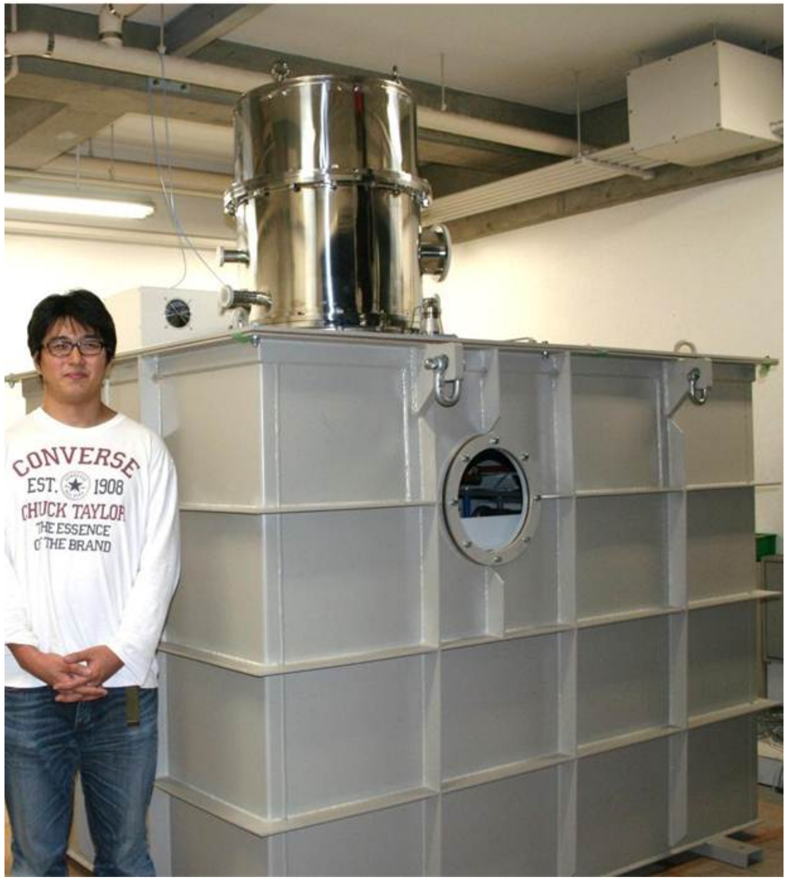
IEC Neutron Source (10^7/sec) for Landmine Detection



Institute of Advanced Energy, Kyoto University

Pulsed 200 kV IEC Device for Nuclear Materials Detection





Institute of Advanced Energy, Kyoto University

Commercial IEC Fusion Neutron Generator

NSD-GRADEL-FUSION, Luxembourg

Medical Isotope Production Using IEC Neutron Generator

Molybdenum-99 precursor of Technetium-99m

The most widely used isotope for medical imaging

$^{2}H + {}^{2}H \rightarrow {}^{3}He$ (0.82 MeV) + n^{0} (2.45 MeV)

^{235}U (low enrichment; water solution) + $n^{0} \rightarrow {}^{99}Mo$ (fission product)

Molybdenum-99 (^{99}Mo) $\rightarrow$ Technetium-99m (^{99m}Tc)

SHINE™ Medical Technologies

Phoenix Nuclear Labs, LLC

Madison, Wisconsin, USA

University Research Groups Pursuing IEC Fusion Research

1. University of Wisconsin (US)
2. University of Illinois (US)
3. University of Maryland (US)
4. Tokyo Institute of Technology (Japan)
5. Kyoto University (Japan)
6. Tokai University (Japan)
7. Kansai University (Japan)
8. University of Sydney (Australia)
9. Shahid Beheshti University (Iran)
10. Gazi University (Turkey)

Primary scientific meeting: U.S.-Japan Workshop on Inertial Electrostatic Confinement Fusion

11th – 2009 University of Wisconsin
12th – 2010 Kansai University, Osaka
13th – 2011 University of Sydney
14th – 2012 University of Maryland
15th – 2013 Kyoto University
16th – 2014 University of Wisconsin

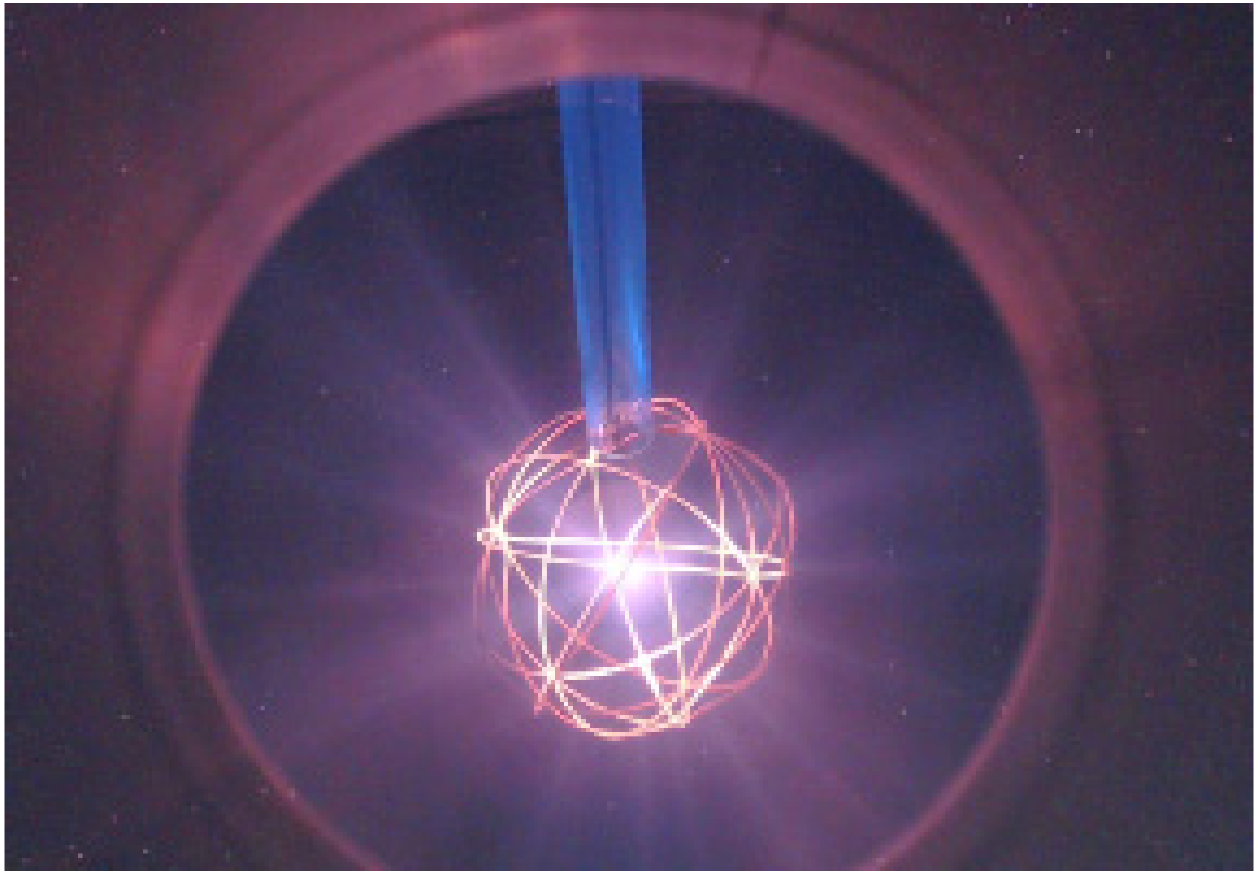
Problems Presented by the Grid in a Gridded Fusor

1. Ion bombardment heats the grid leading to thermionic electron emission.

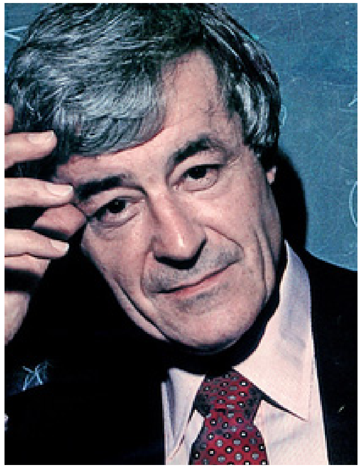
2. Electron emission causes power loss and neutralization of the fuel ions.

3. Grid heating eventually melts the grid.

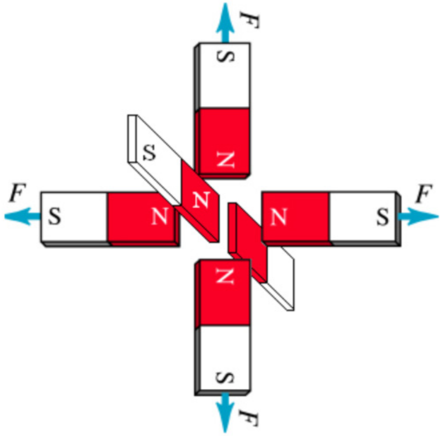
Grid Heating in Fusor



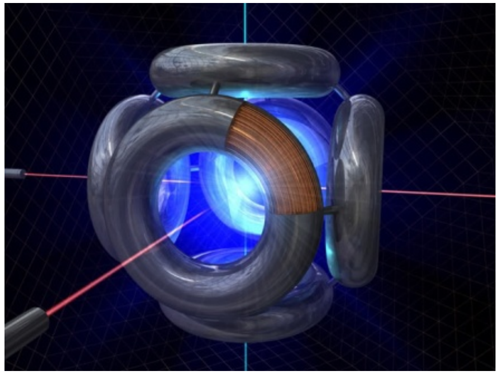
The Polywell®



Robert W. Bussard
8/11/1928-10/6/2007

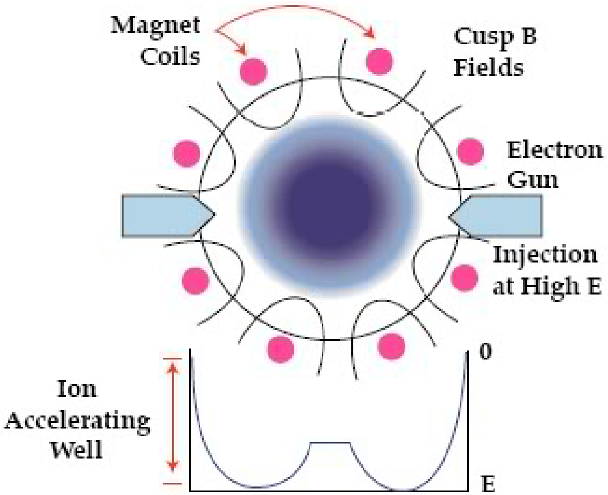


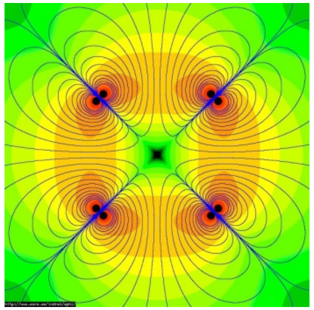
3D Magnetic Trap



Four Coil Polywell
http://www.polywellnuclearfusion.com

Wiffle Ball





Computer plot of magnetic field lines from four coils
www.mare.ee

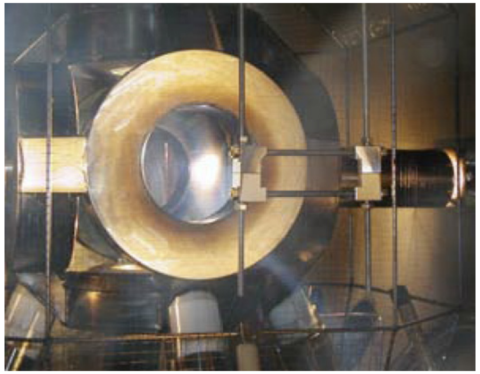
R. W. Bussard, 57th International Astronautical Congress (IAC) Valencia, Spain, October, 2006.
http://www.askmar.com/ConferenceNotes/2006-9%20IAC%20Paper.pdf

Polywell Devices – EMC2 Inc.

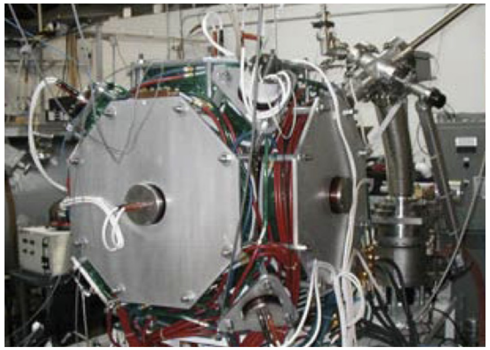
WB-1 permanent magnets

WB-2

WB-3



WB-4



WB-5

WB-6

10^9 DD fusions/sec at a potential well of 10 kV.

Polywell Research Support from the U.S. Navy

"R&D- ENERGY: NUCLEAR (APPLIED RESEARCH/EXPLORATORY DEVELOPMENT)"

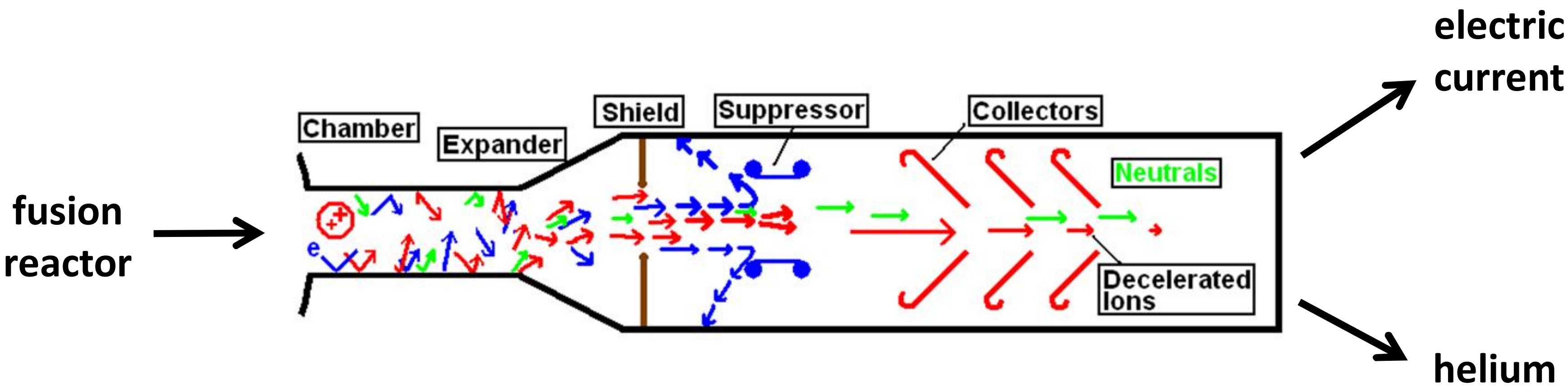
www.fpds.gov/ezsearch/

May 21, 2013	$780,000	"Plasma Wiffleball 8.0"
April 29, 2013	$300,000	"Plasma Wiffleball 8.0"
Feb. 25, 2013	$600,000	"Incremental funding for Plasma Wiffleball 8.0"
Aug. 23, 2012	$1,120,000	"Plasma Wiffleball 8.0"
May 03, 2012	$1,200,000	"Plasma Wiffleball 8.0"
June 22, 2011	$2,022,678	"Plasma Wiffleball concept exploration"
June 08, 2011	$100,000	"R&D concept exploration on Plasma Wiffleball 8.0"
Jan. 20, 2011	$1,000,000	"Research & development of the AGEE Plasma Wiffleball"
Sept. 10, 2010	$1,350,000	"The contractor shall construct and test a small scale MG insulated, Wiffleball Polyhedral device, WB8"
Sept.11, 2009	$3,216,825	"..concept exploration and technology demonstration of the Advanced Gaseous Electrostatic Energy (AGEE) concept..WB8"
May 20, 2009	$331,174	"Wiffleball 7.1"
March 03, 2009	$299,843	"Wiffleball 7.1"
Dec. 17, 2008	$99,355	"Research study for the AGEE Development"
Dec. 08, 2008	$99,355	"Polywell Fusion Device Ion Injection Gun"
Nov. 5, 2008	$93,123	"Advanced Gaseous Electrostatic Energy "
August 21, 2007	$1,750,000	"applied/exploratory engineering (fusion research)"

Total Polywell funding to date - $17,558,191 (including 1997-2005)

Direct Energy Conversion

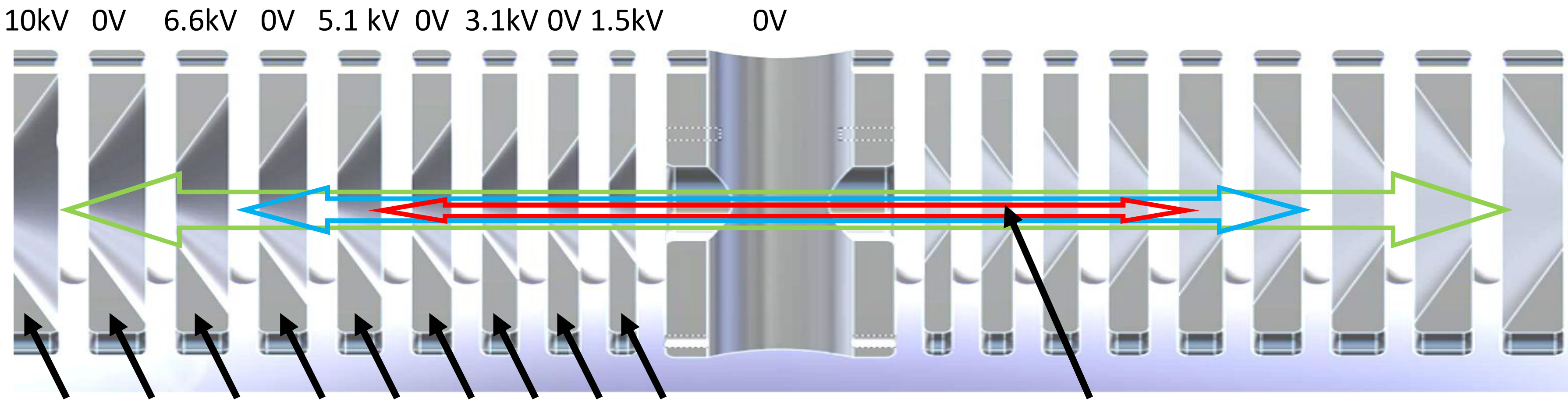
$$p^{+} + {}^{11}B \rightarrow 3\ {}^{4}He \quad (8.7\ \mathrm{MeV})$$

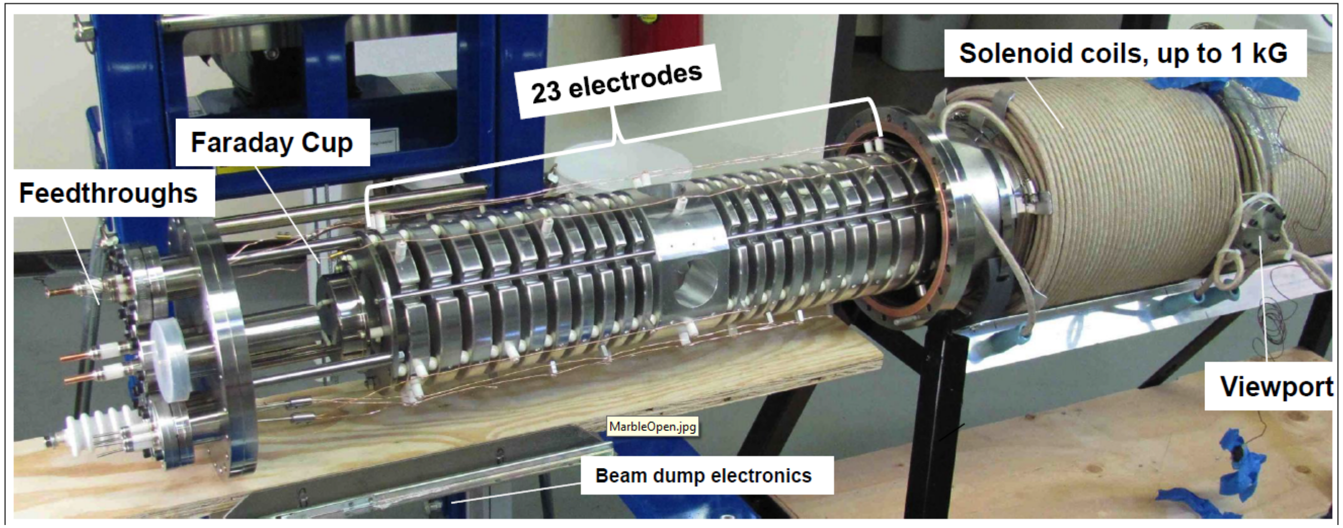


The first regular publication by the EMC2 group:

J. Park, N.A. Krall, P.E. Sieck, D.T. Offermann, M. Skillicorn, A. Sanchez, K. Davis, E. Aldrson, G. Lapenta, High Energy Electron Confinement in a Magnetic Cusp Configuration, arXiv:1406.0133 (2014)

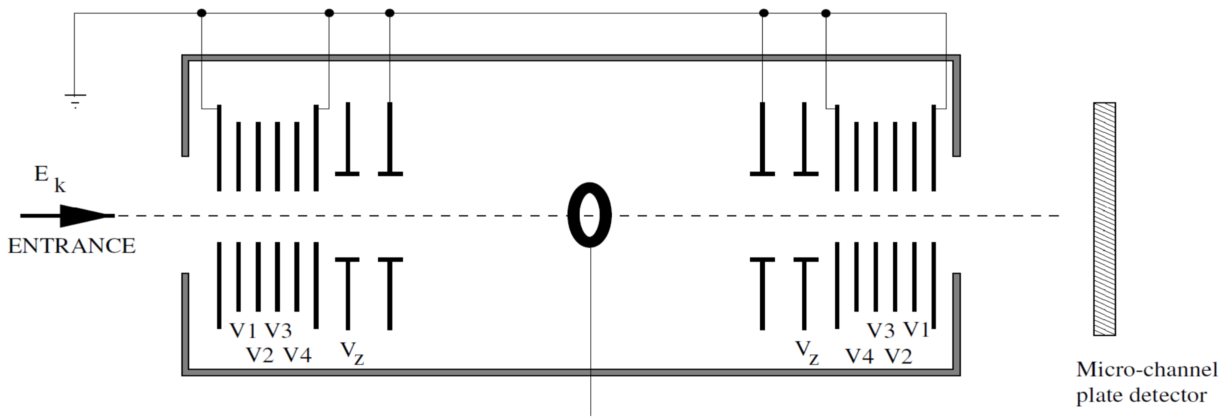
Multiple Ambipolar Beam Line Experiment ("MARBLE")



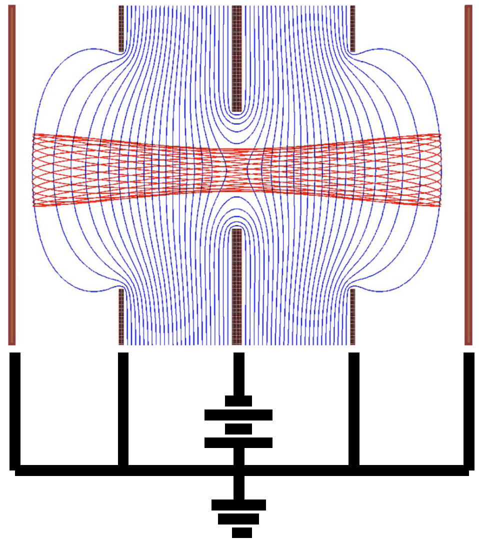


A. Klein, The Multiple Ambipolar Beam Line Experiment (MARBLE), presented at the 13th U.S. - Japan Workshop on Inertial Electrostatic Confinement Fusion, Sydney, 2011.

Linear Electrostatic Ion Trap

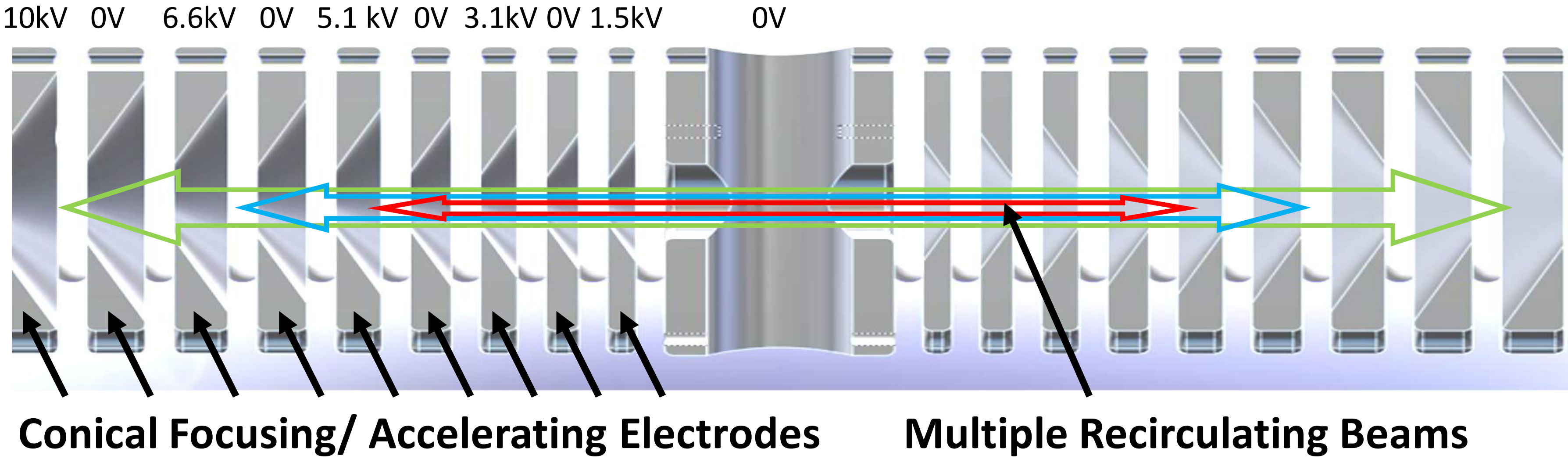


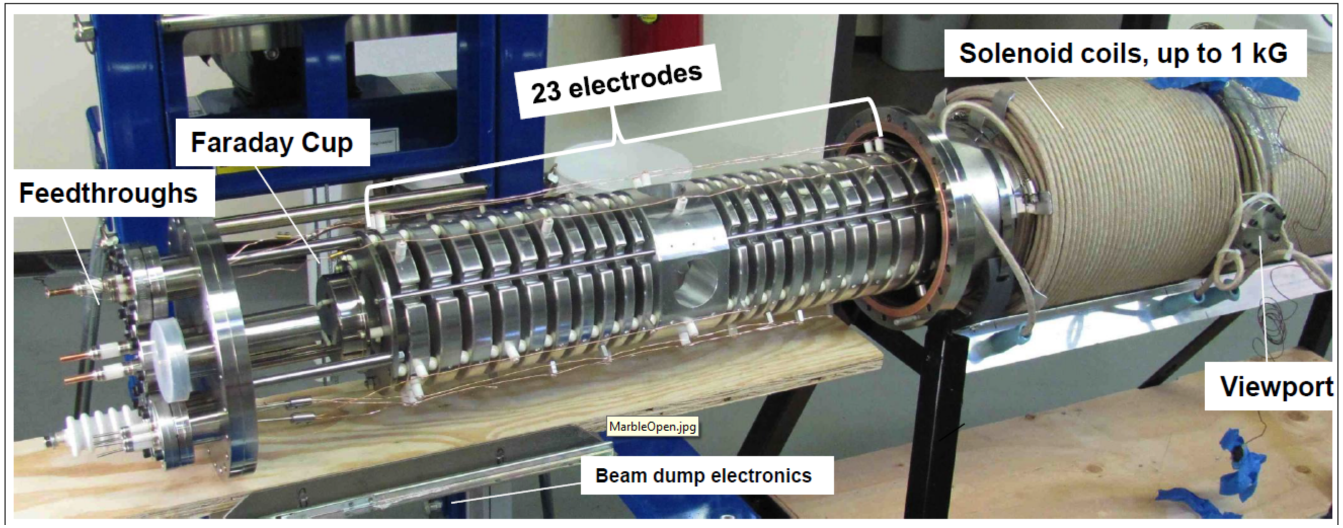
L. H. Andersen, O. Heber, D. Zajfman, Physics with electrostatic rings and traps, *Journal of Physics B* 37, R57–R88, 2004.



A. V. Ermakov and B. J. Hinch, An electrostatic autoresonant ion trap mass spectrometer**,** *Review of Scientific Instruments* **81**, 013107, 2010.

Multiple Ambipolar Beam Line Experiment ("MARBLE")





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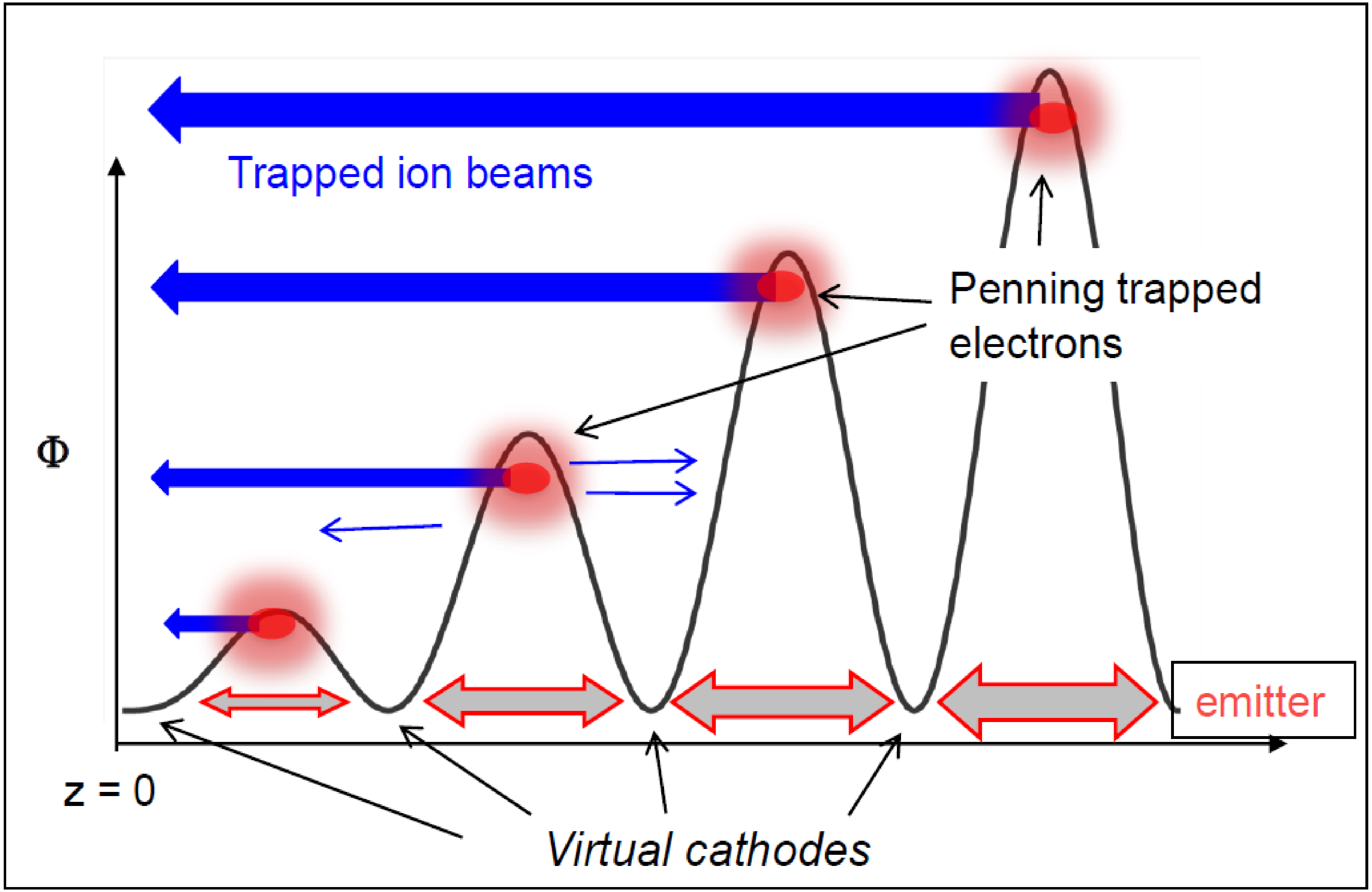
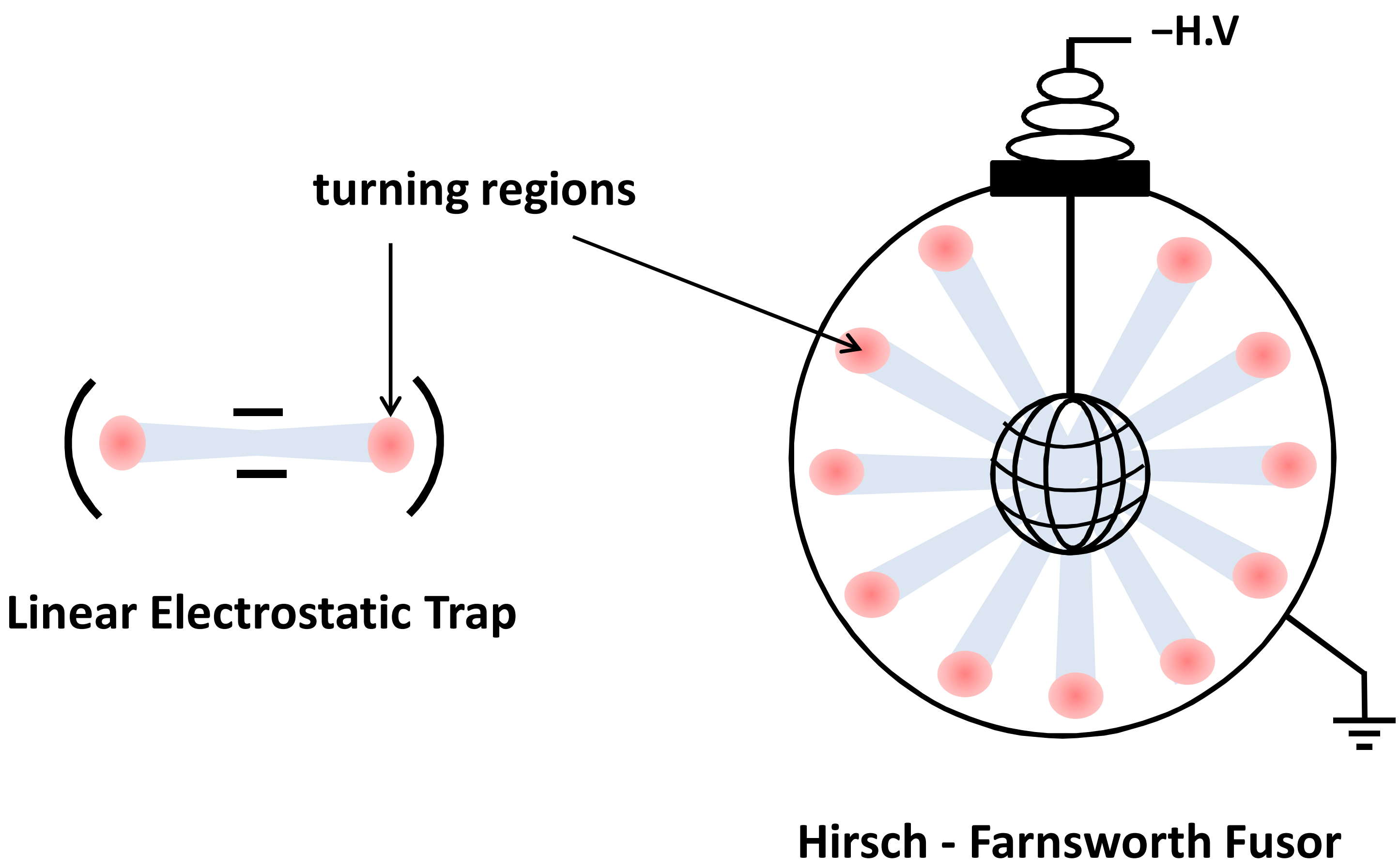


A. Klein, The Multiple Ambipolar Beam Line Experiment (MARBLE), presented at the 13th U.S. - Japan Workshop on Inertial Electrostatic Confinement Fusion, Sydney, 2011.

Turning Regions in Electrostatic Traps



Fusor in "Star Mode"

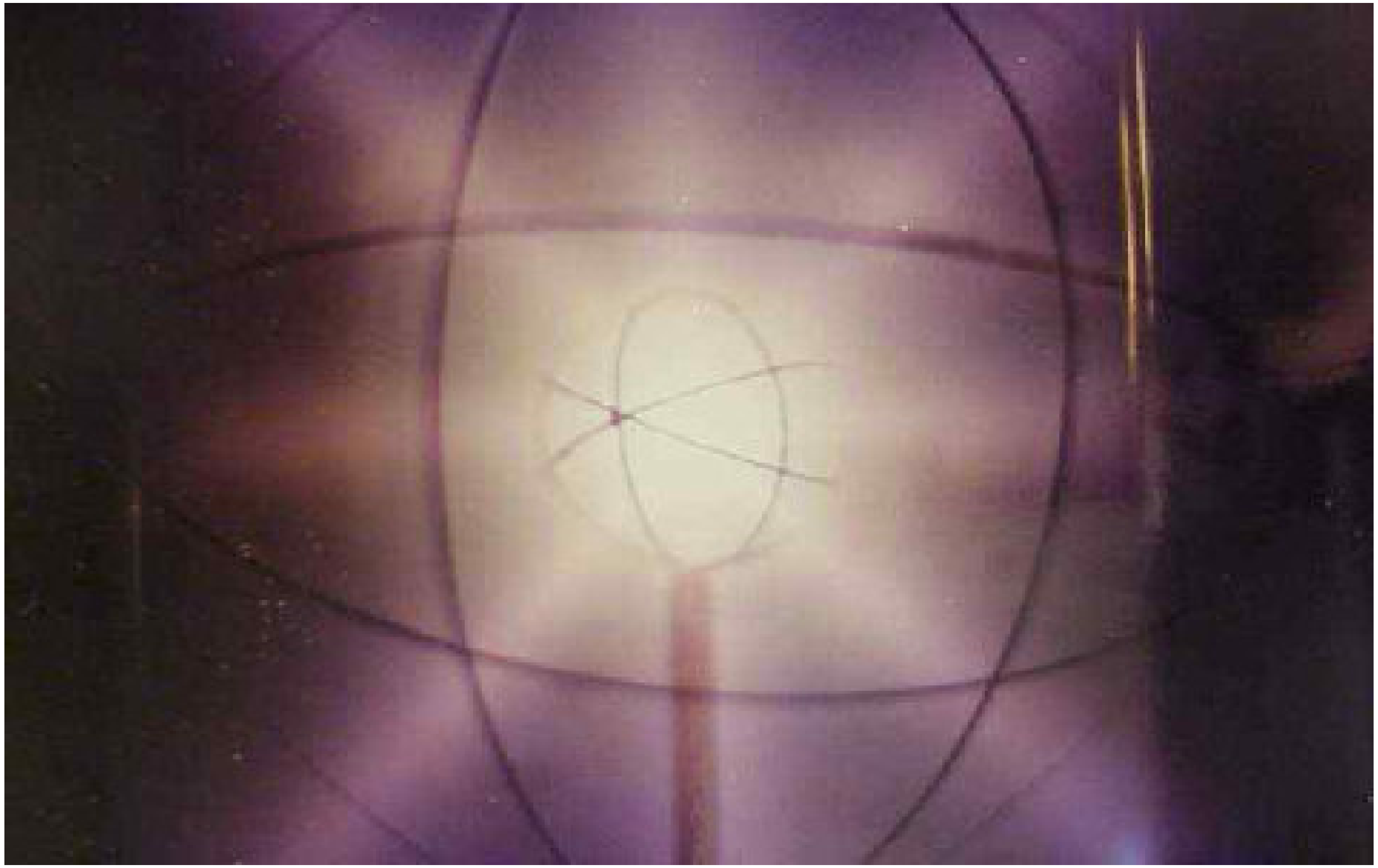
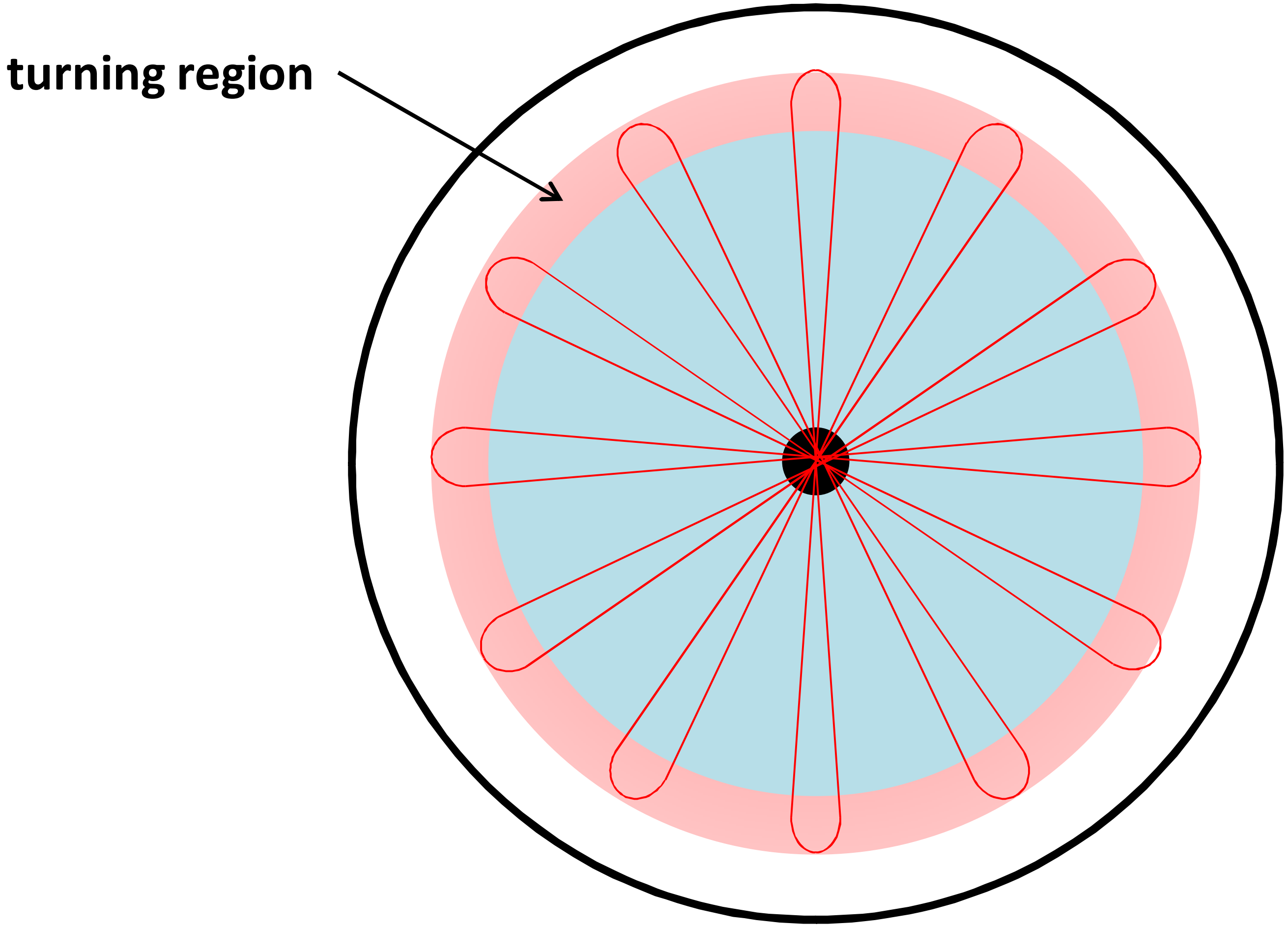
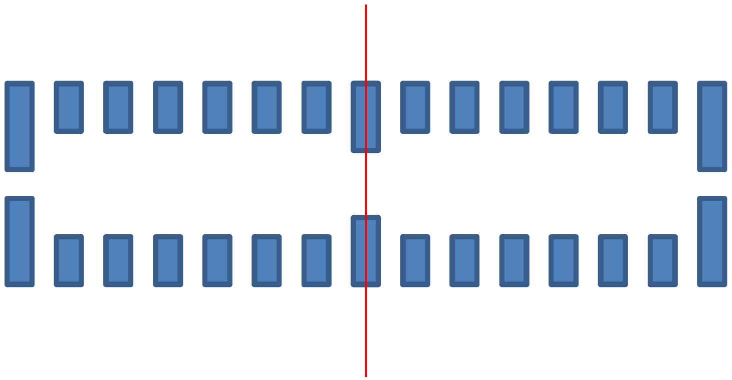


Photo from Wikipedia Commons

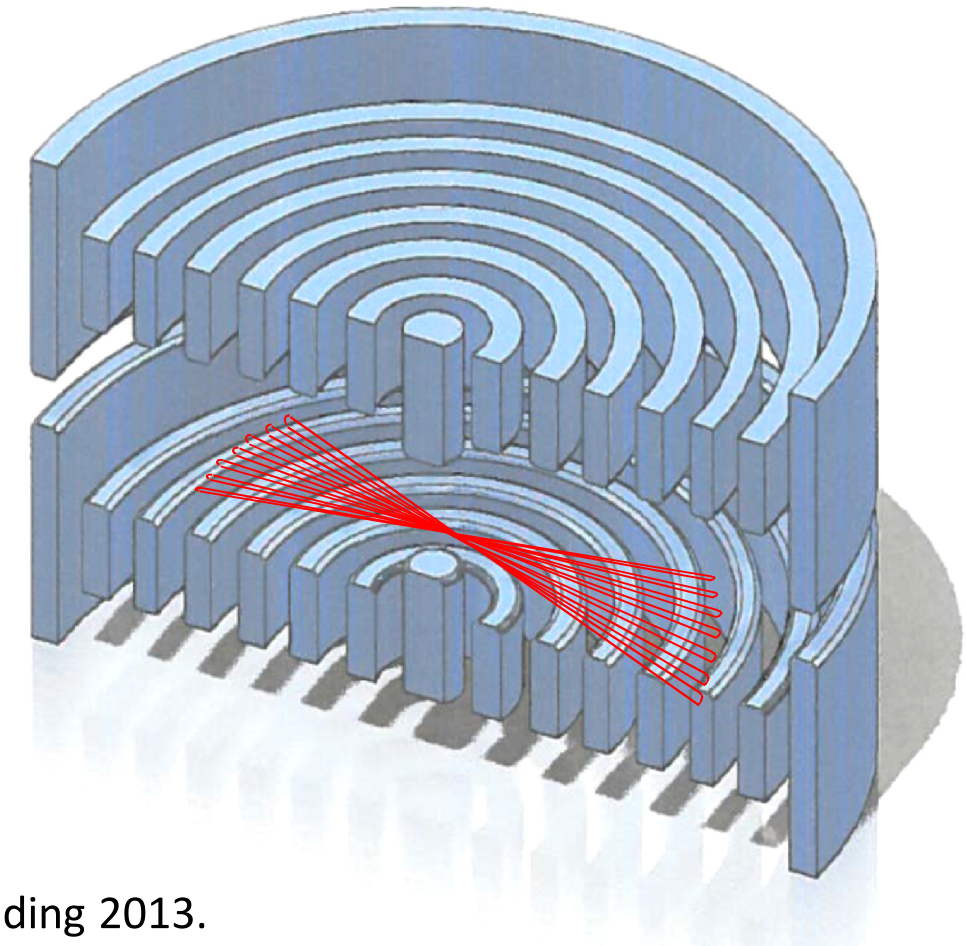
Gridless Planar (Disc) Electrostatic Ion Trap



Planar Electrostatic Ion Trap

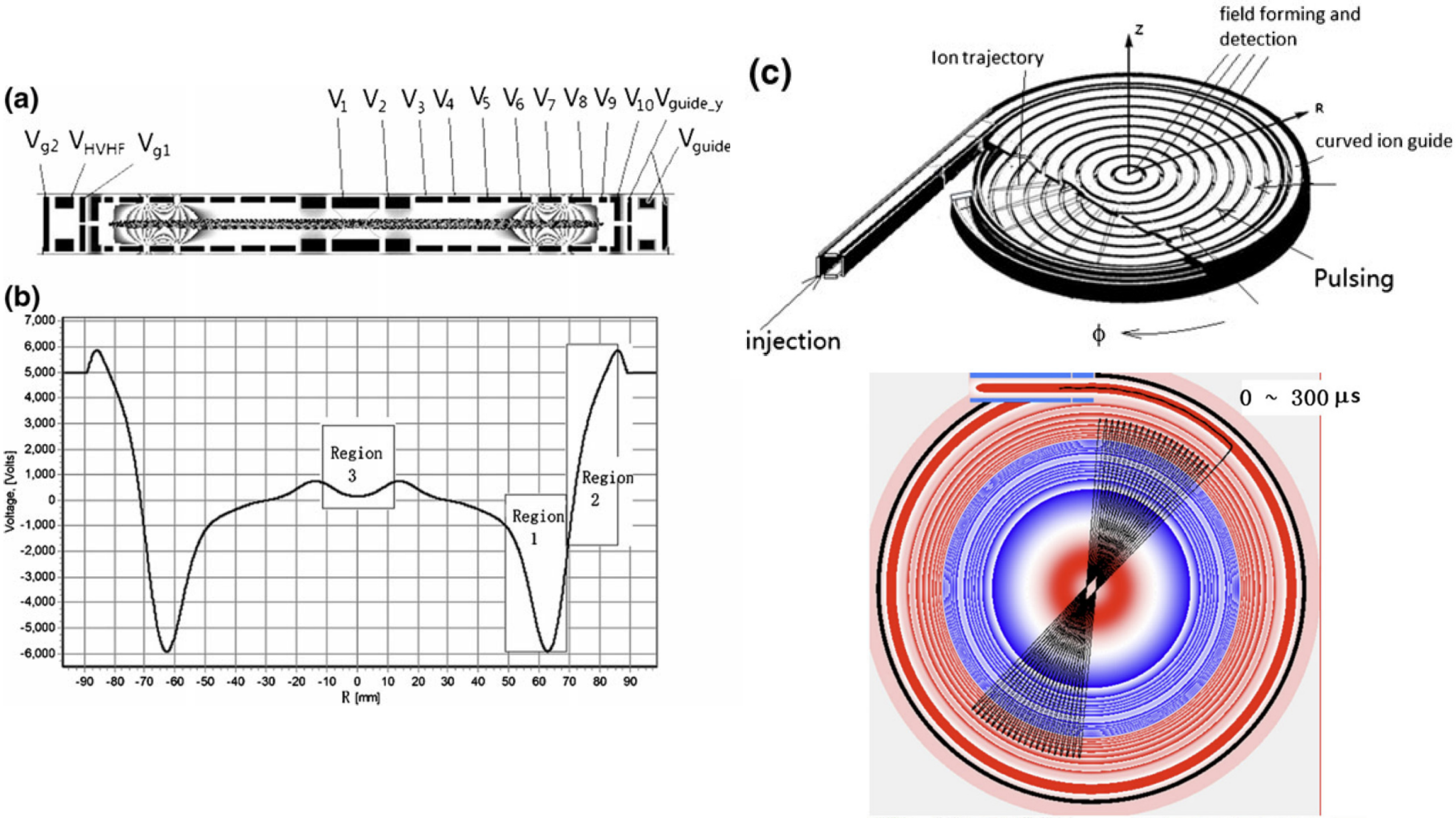


Rotate around vertical axis



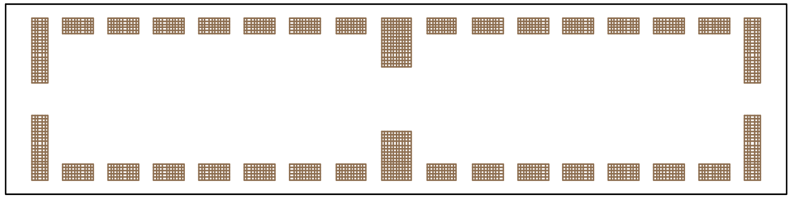
D.R. Knapp, U.S. Patent Application Pending 2013.

Proposed Planar Electrostatic Ion Trap Mass Spectrometer



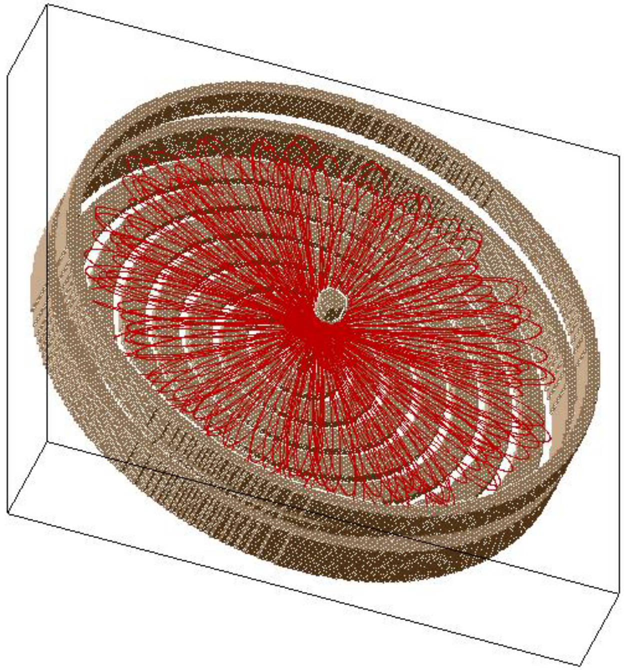
L. Ding, R. Badheka, Z. Ding, H. Nakanishi, A Simulation Study of the Planar Electrostatic Ion Trap Mass Analyzer, J. Am. Soc. Mass. Spectrom. 24: 356-364, 2013.

Planar Electrostatic Ion Trap



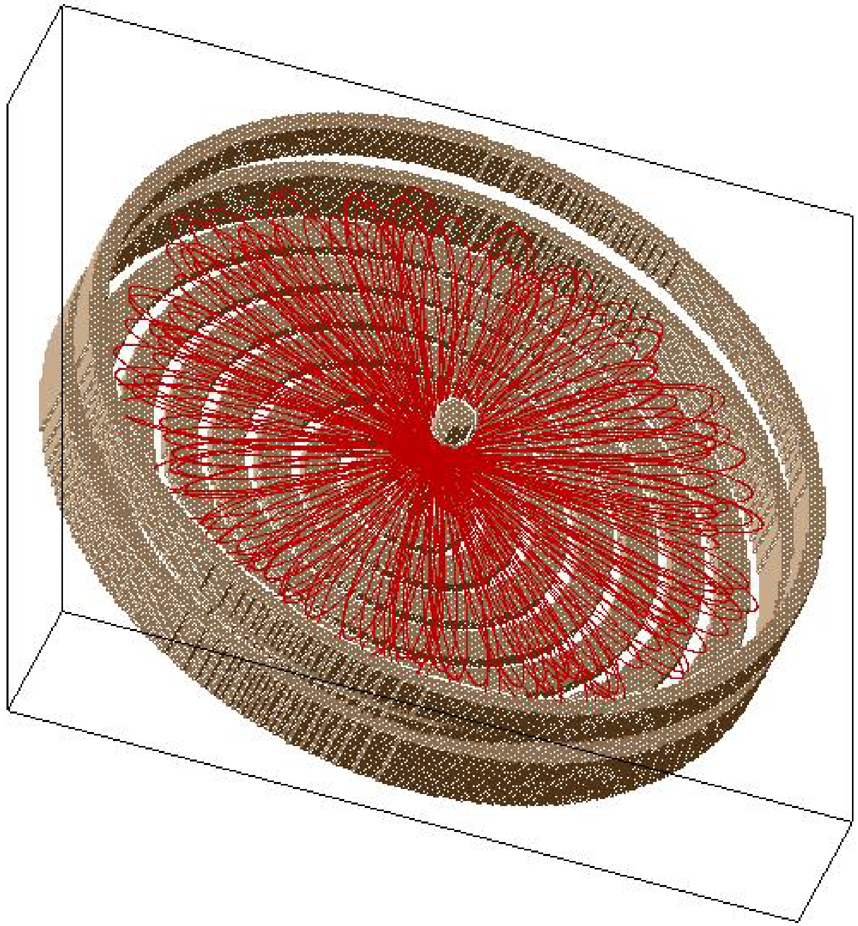
Rotate around vertical axis

Simulation of ion trajectories for ions originating at single point with 0.1 eV tangential K.E

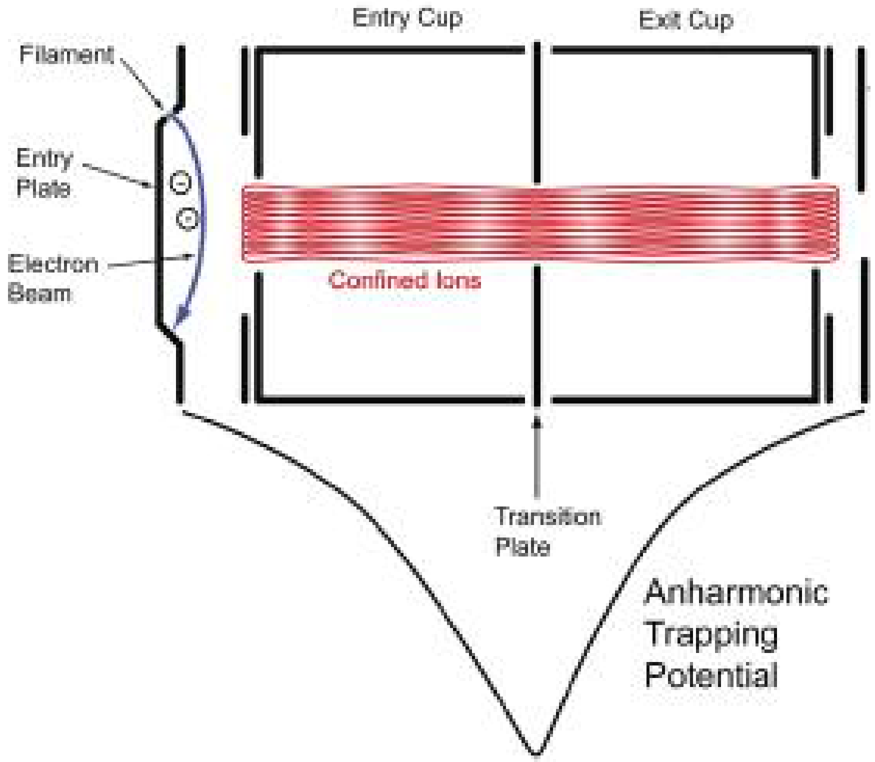


Cutaway view with top electrode rings removed

How to Generate Ions with Tangential K.E. Inside the Trap?



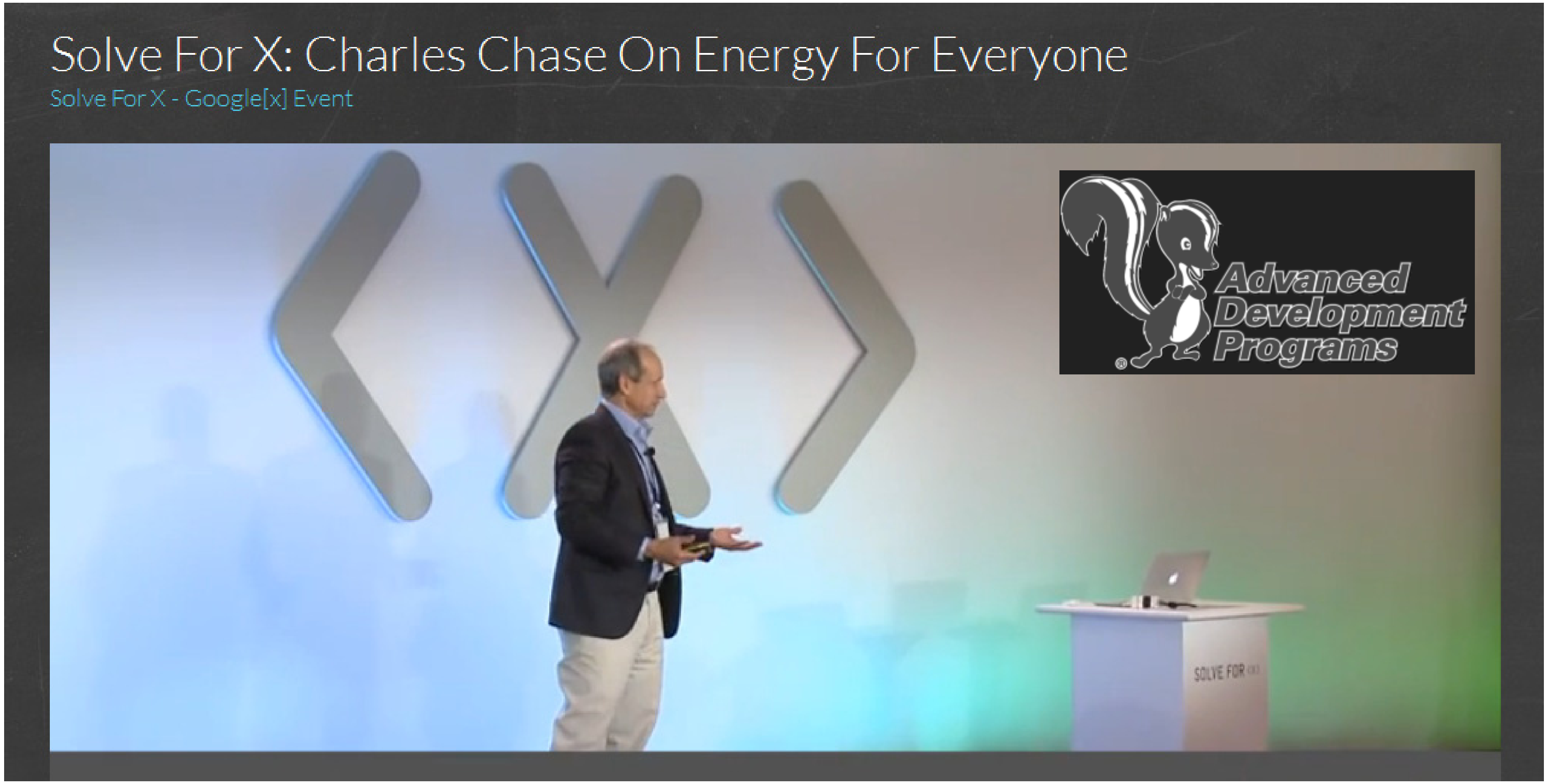
Brooks Automation VQM 830 Residual Gas Analyzer



Prototype Single Potential Trap under Construction

What’s new in fusion development?

Recent Report of Work at the Lockheed Martin Skunkworks

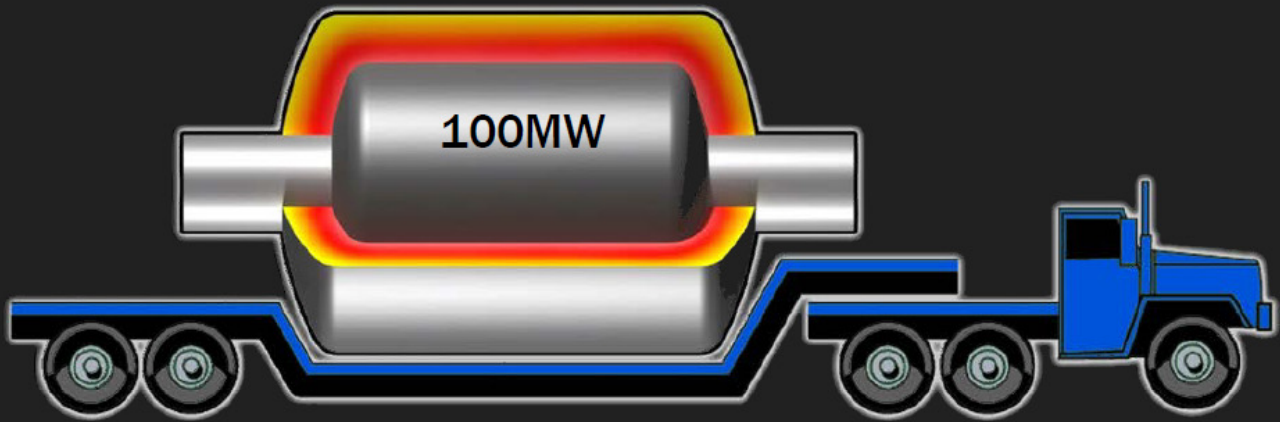


"**Solve For X** is a place to hear about and discuss radical technology ideas for solving global problems."

Posted January 11, 2013   www.solveforx.com

www.solveforx.com/moonshots/solve-for-x-charles-chase-on-energy-for-everyone

Compact Fusion



Lower development costs

Faster design cycle: 2025 vs 2050

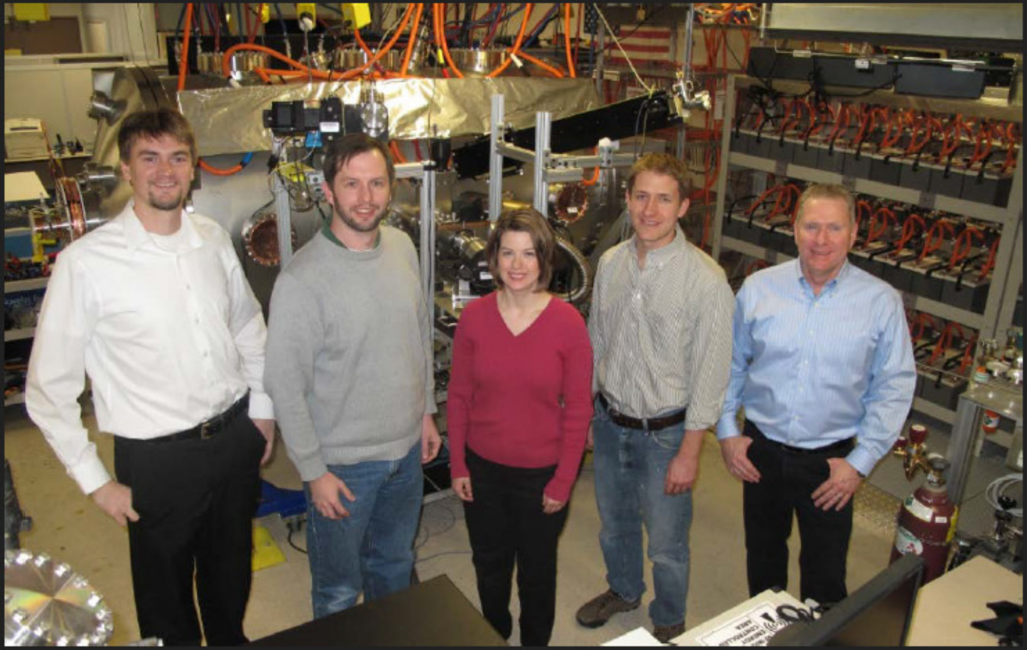
Lower magnetic fields: Lower weight

Distributed power generation

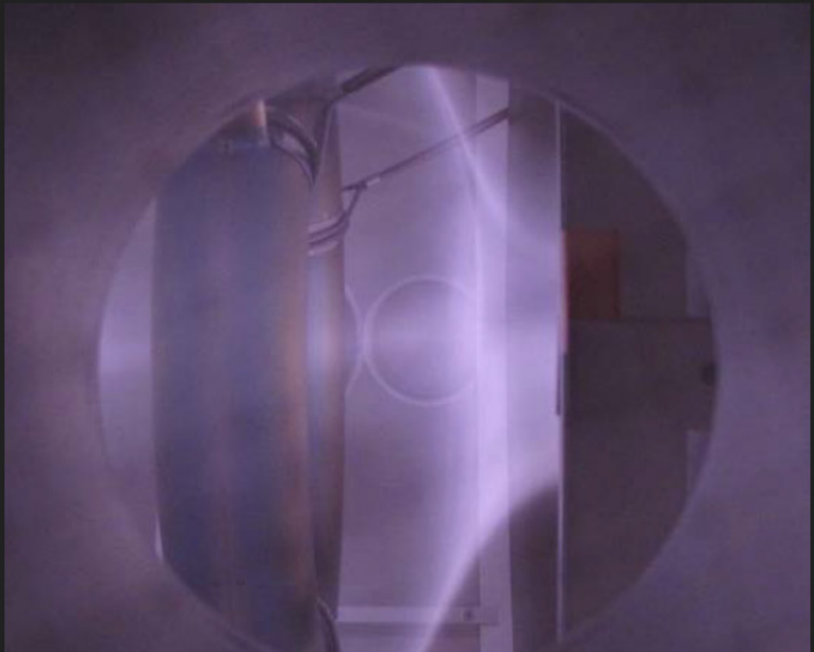
Advanced Development Programs

www.solveforx.com/moonshots/solve-for-x-charles-chase-on-energy-for-everyone

The Adjacent Possible



T4 experiment



New magnetic configuration

High β: 10-fold improvement

β = Plasma Pressure / Magnetic Pressure

Advanced Development Programs

Summary

Several alternative approaches to nuclear fusion are under study.

Some offer the possibility of small power reactors.

Some are particularly useful for non-energy applications.

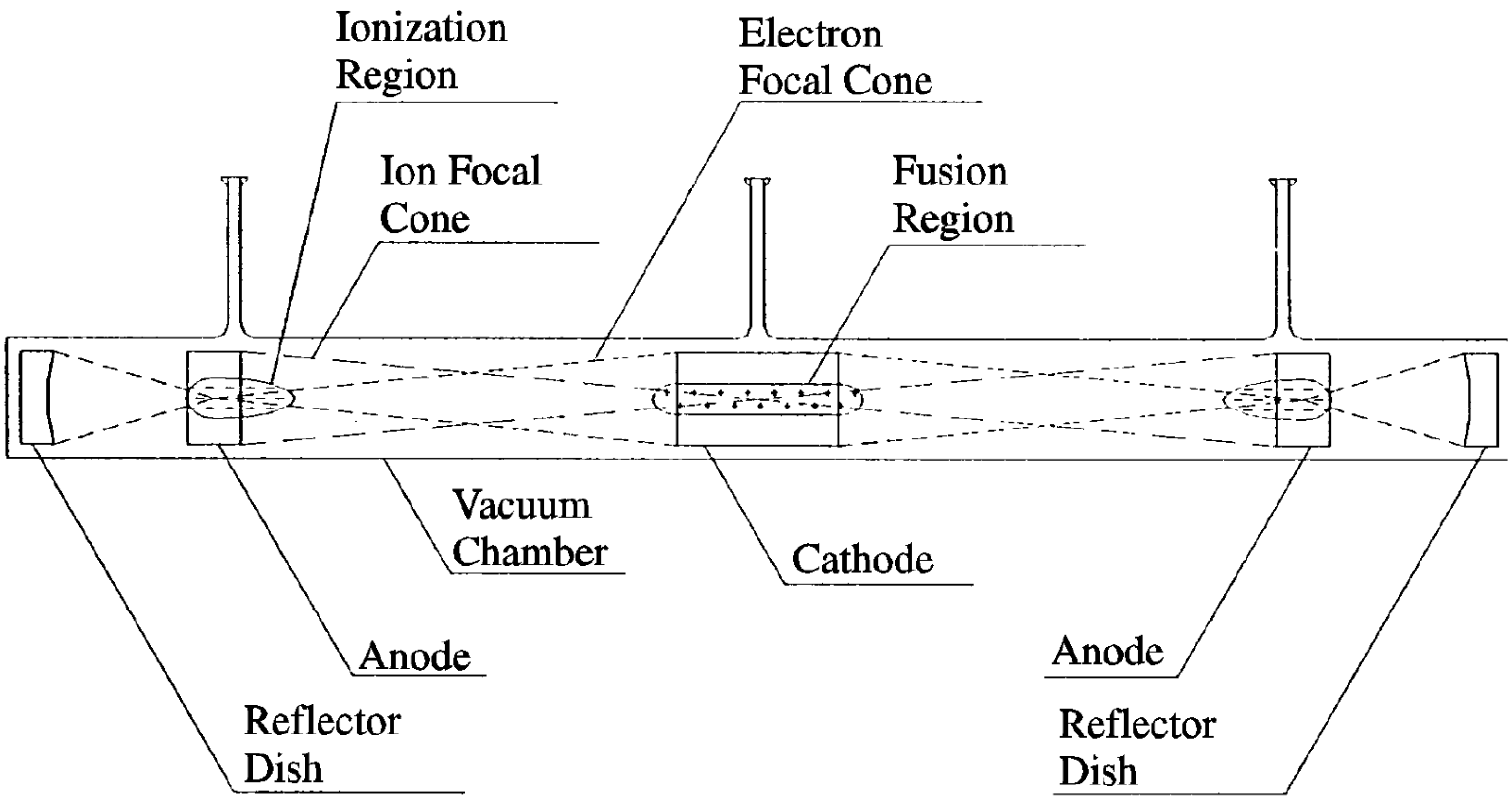
IEC devices are particularly simple for such applications.

Gridless IEC devices could yield much improved performance.

End

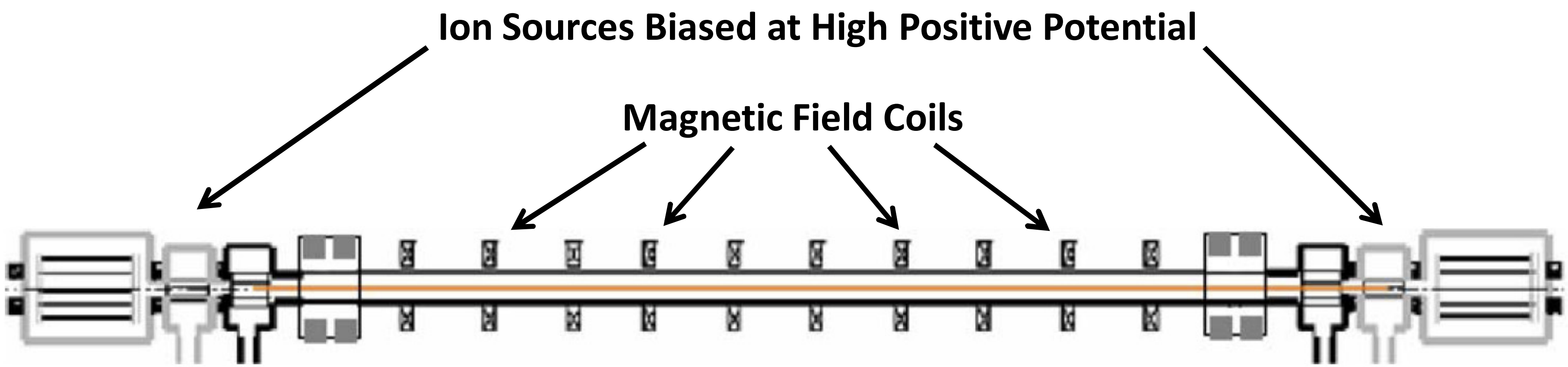
Extra Slides

Cylindrical Geometry/Linear Electrostatic Trap IEC Device



G. H. Miley, A portable neutron/tunable X-ray source based on inertial electrostatic confinement, Nucl. Instrum. Meth. Physics Res. A 422, 16-20, 1999.

Proposed Beam – Beam Collision Device

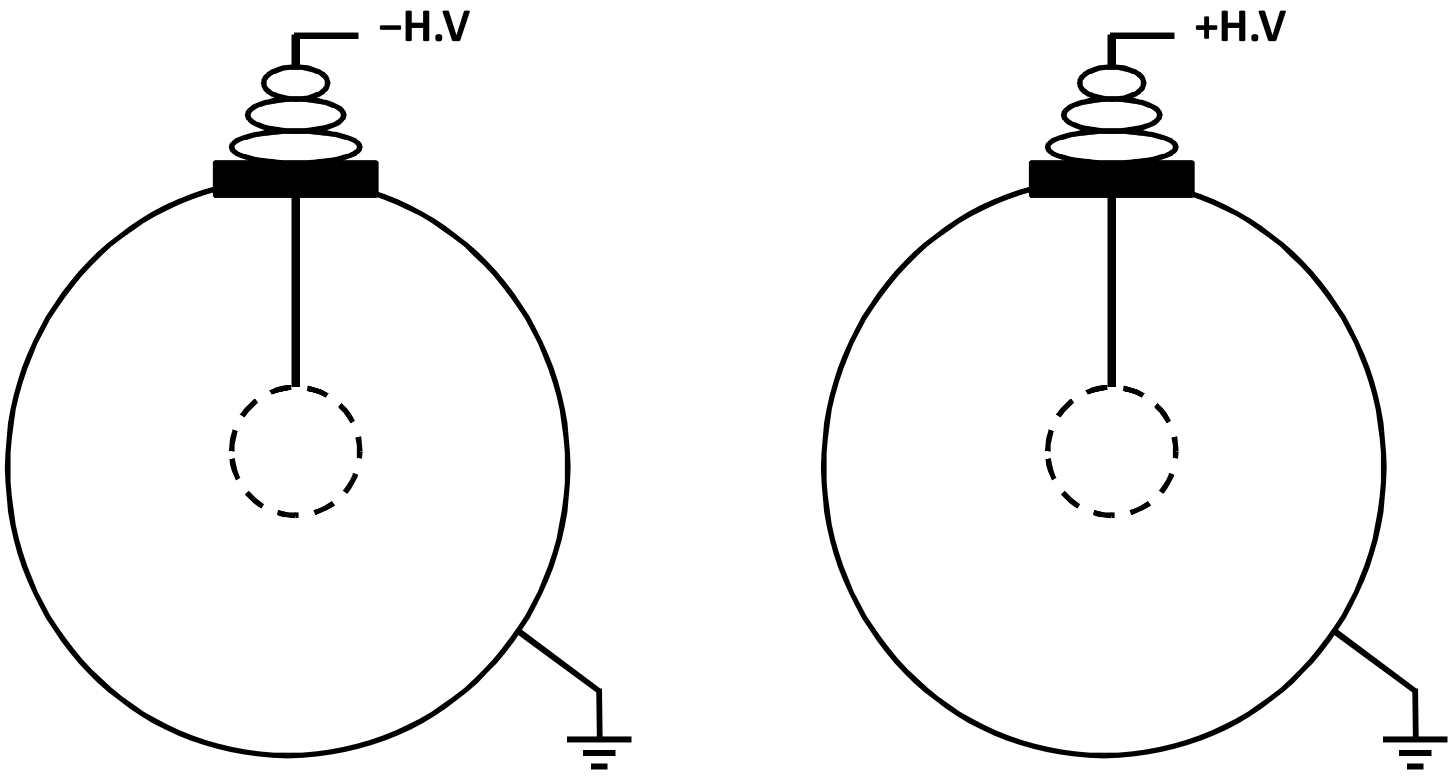


A Conceptual Drawing of the Neutron Generator

H. Momota and G. H. Miley, Neutron Source Based on a Counter-Deuterium Beam Linear IEC, J. of Fusion Energy 28, 191-194, 2009.

The Wilhelm Bratwurst Institute for Applied Physics Research

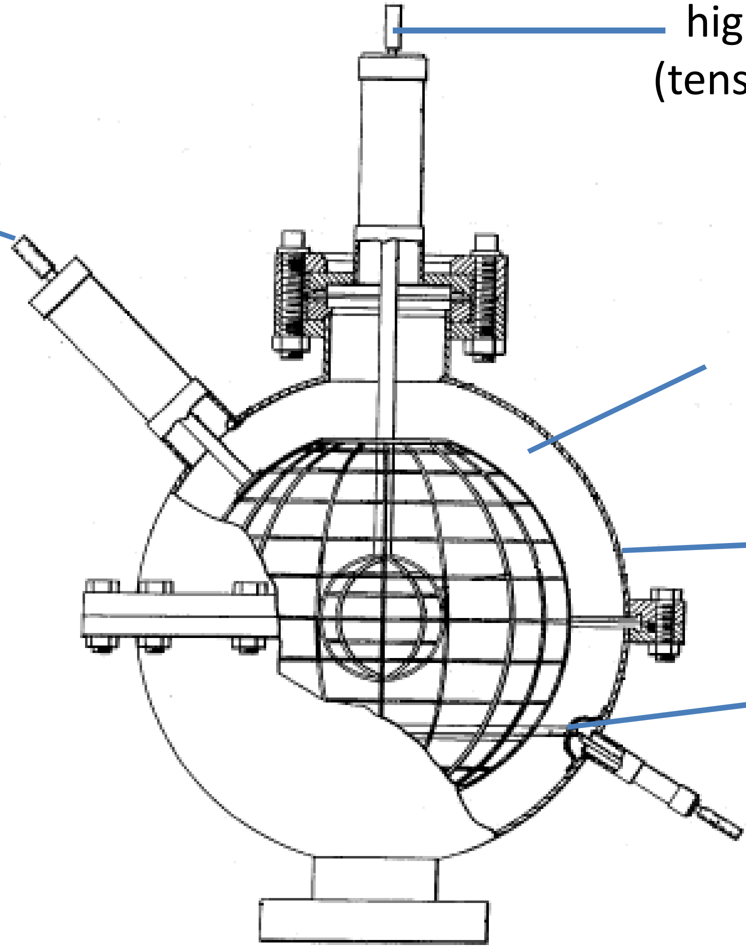
Elmore-Tuck-Watson Device



Hirsch - Farnsworth Fusor **Elmore - Tuck - Watson**

W. C. Elmore, J. L. Tuck, K. M. Watson, On the Inertial-Electrostatic Confinement of a Plasma, *Physics of Fluids* 2(3)1959.

Farnsworth–Hirsch Fusor



G.A. Meeks, R.L. Hirsch, U.S. Patent 3,530,497 September 22, 1970 — “Hirsch–Meeks Fusor”

IEC Fusor Science Fair Project

Taylor Wilson explaining his fusor science fair project to Barak Obama. 2/7/2012