מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Measuring $a_{\beta\nu}$ in ^{6}He using an Electrostatic Ion Trap

Guy Ron
Hebrew University of Jerusalem
for the WIRED/WISETrap/NeA Collaboration

הקרן הלאומית למדע

PAZY
EXCELLING IN SCIENCE

BSF
United States – Israel
Binational Science Foundation

Ernshaw's Theorem

S. Earnshaw, Trans. Cambridge Philos. Soc. 7, 97 (1842)

A collection of point charges cannot be maintained in a stable stationary equilibrium configuration solely by the electrostatic interaction of the charges.

Restatement of Gauss' Law (for free space)

$$\nabla \cdot E \propto \nabla \cdot F = -\nabla^2 \phi = 0$$

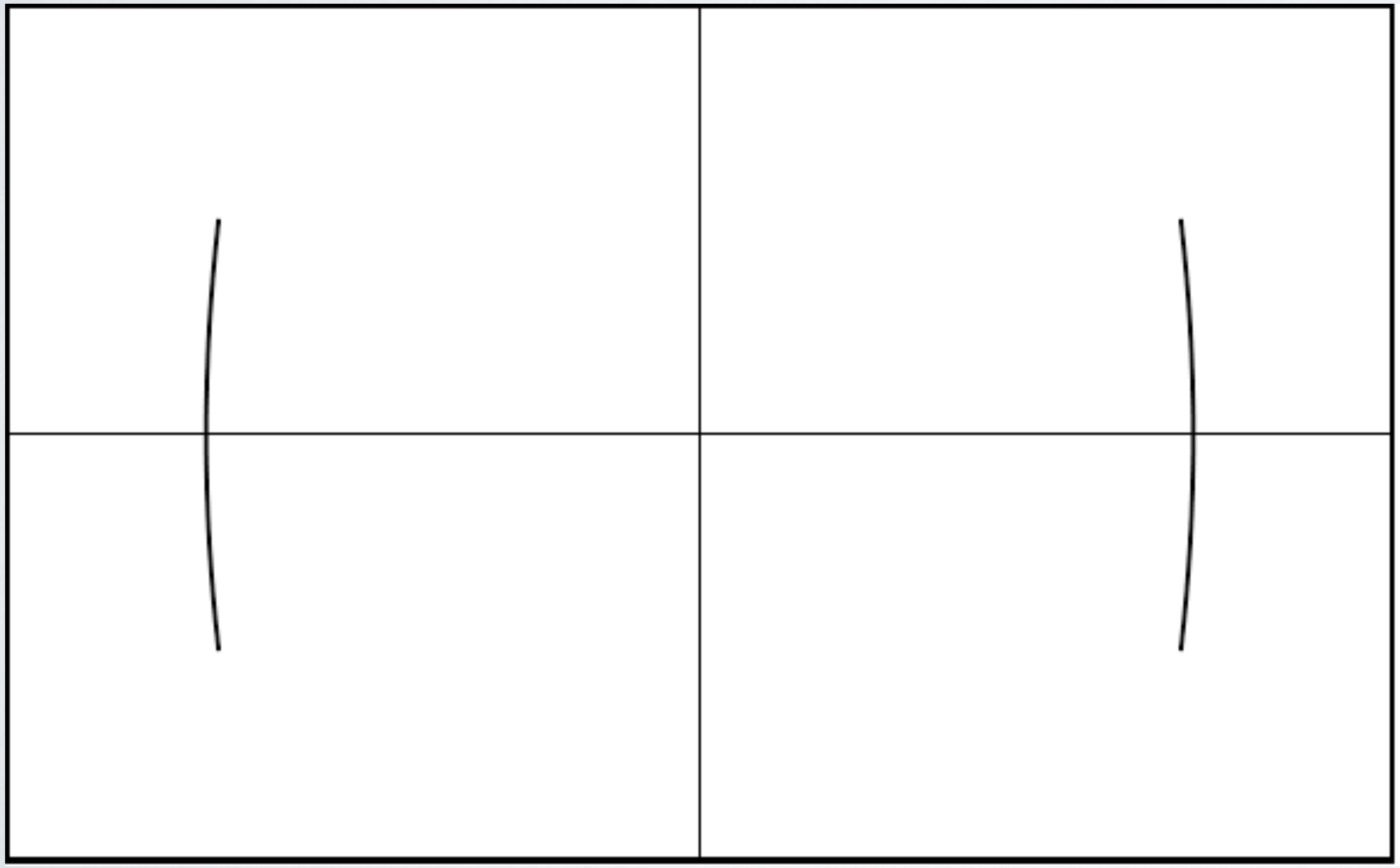
No local minima or maxima in free space (only saddle points).

Naively speaking → No electrostatic ion traps

Non Electrostatic:
Time varying ("Paul trap", MOT) & Magnetic fields ("Penning trap").
Electronic correction.

But what about moving ions...

Ernshaw's theorem talks about stationary charges.
Moving charges in an electrostatic field actually "see" changing fields.
Trap design very similar to a resonant cavity for laser light.



Optical Stability Condition

$$\frac{L}{4} \leq f \leq \infty$$

Confining Potential Maximum

$$q\,e\,V_s > E_k$$

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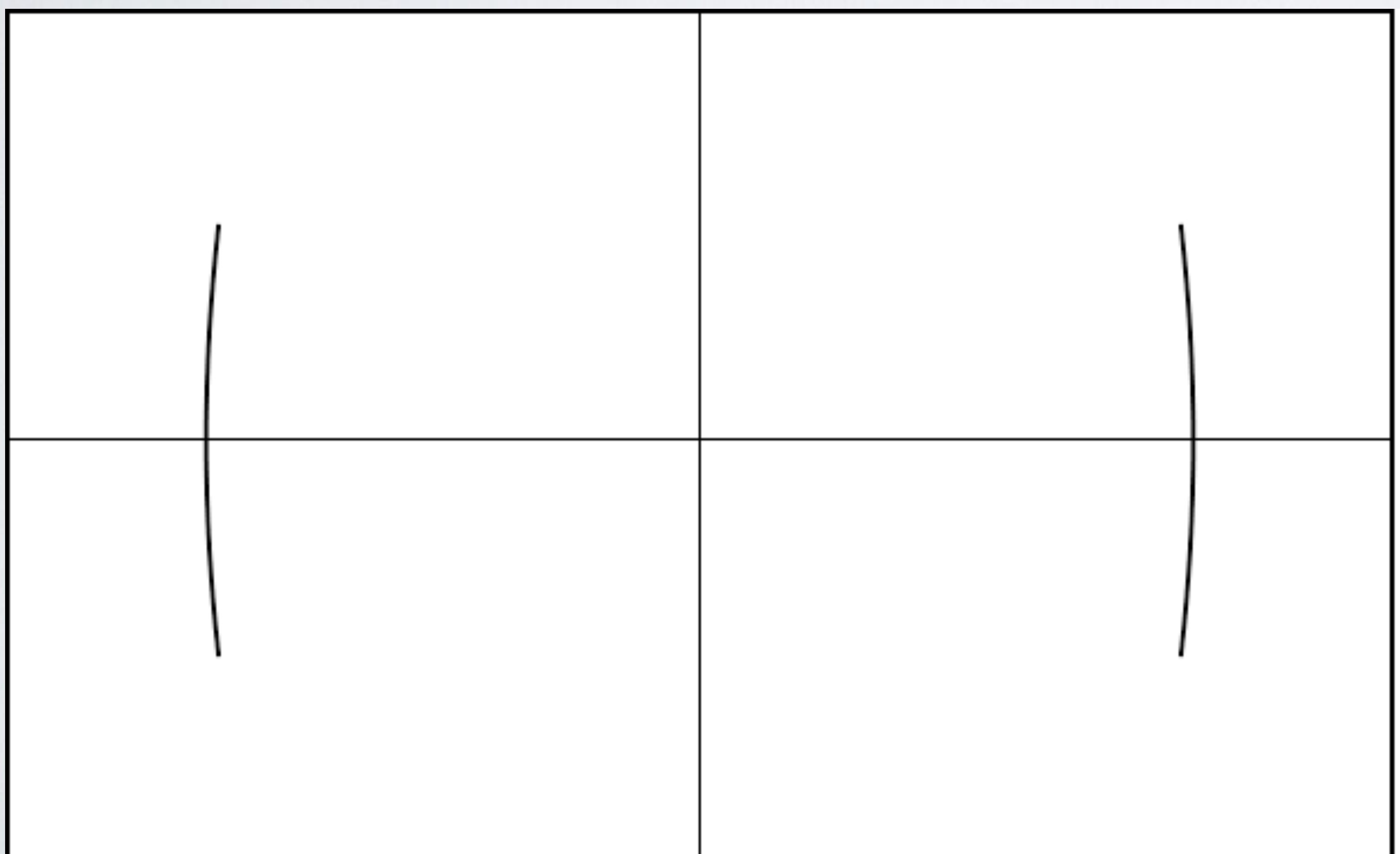

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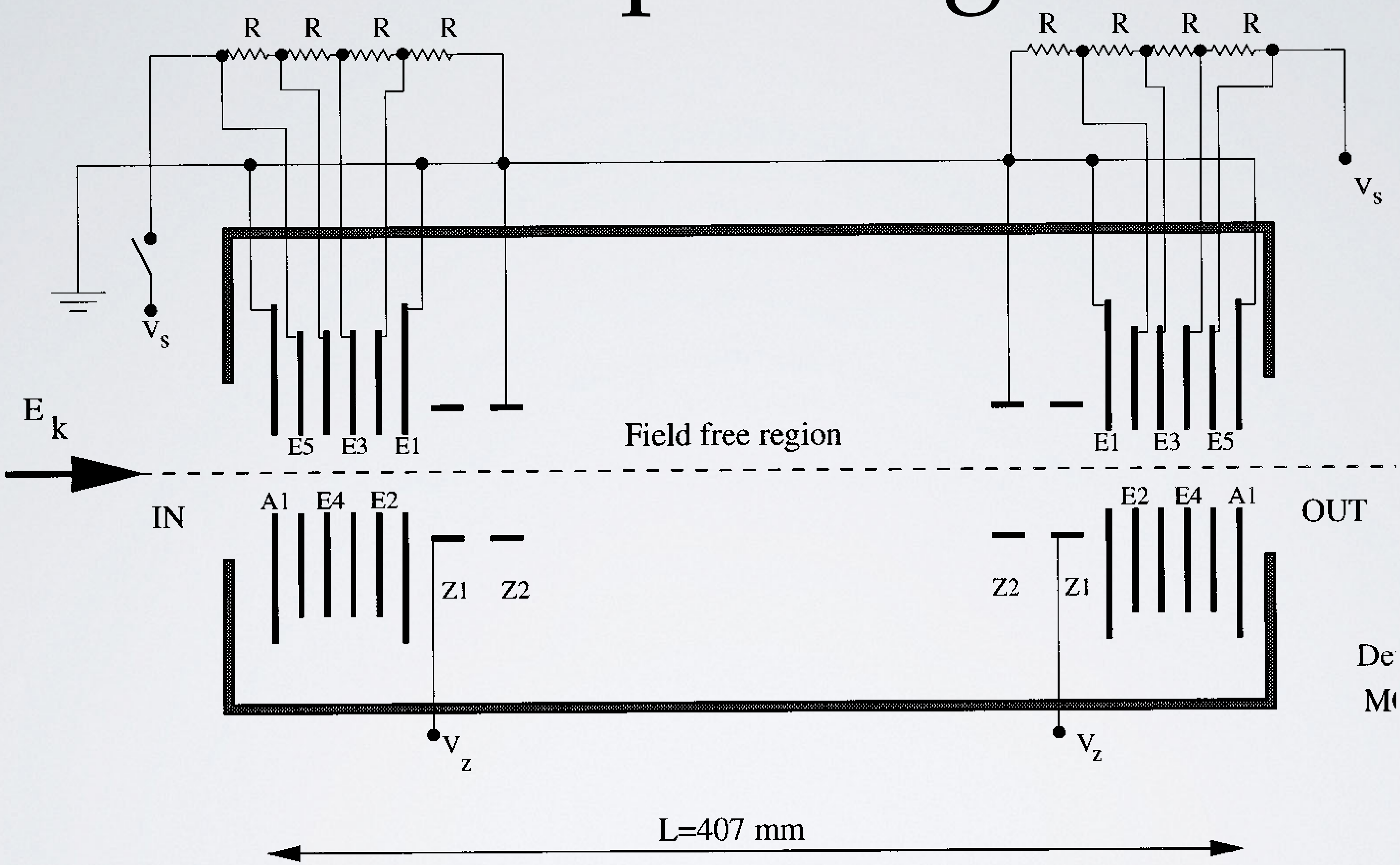
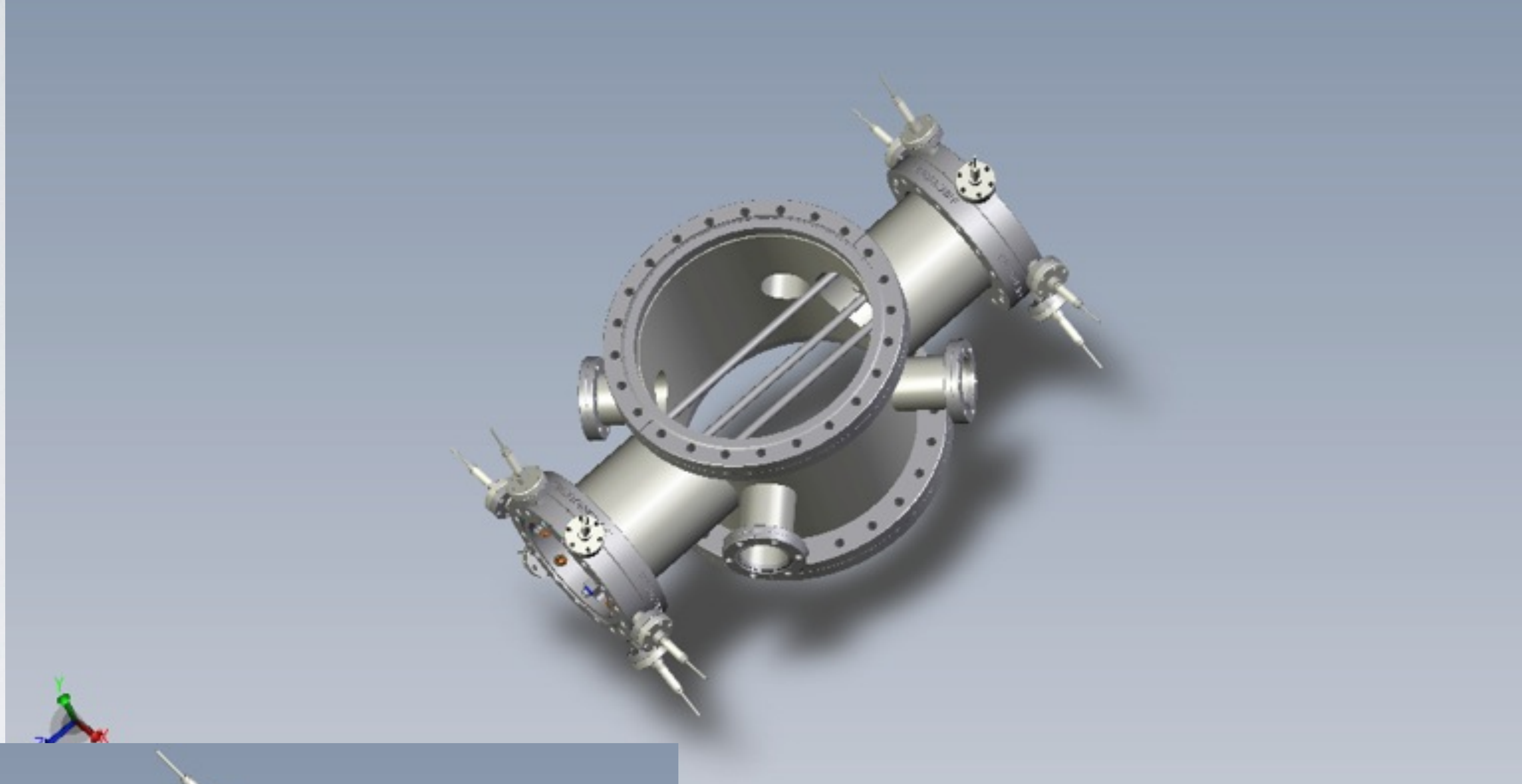
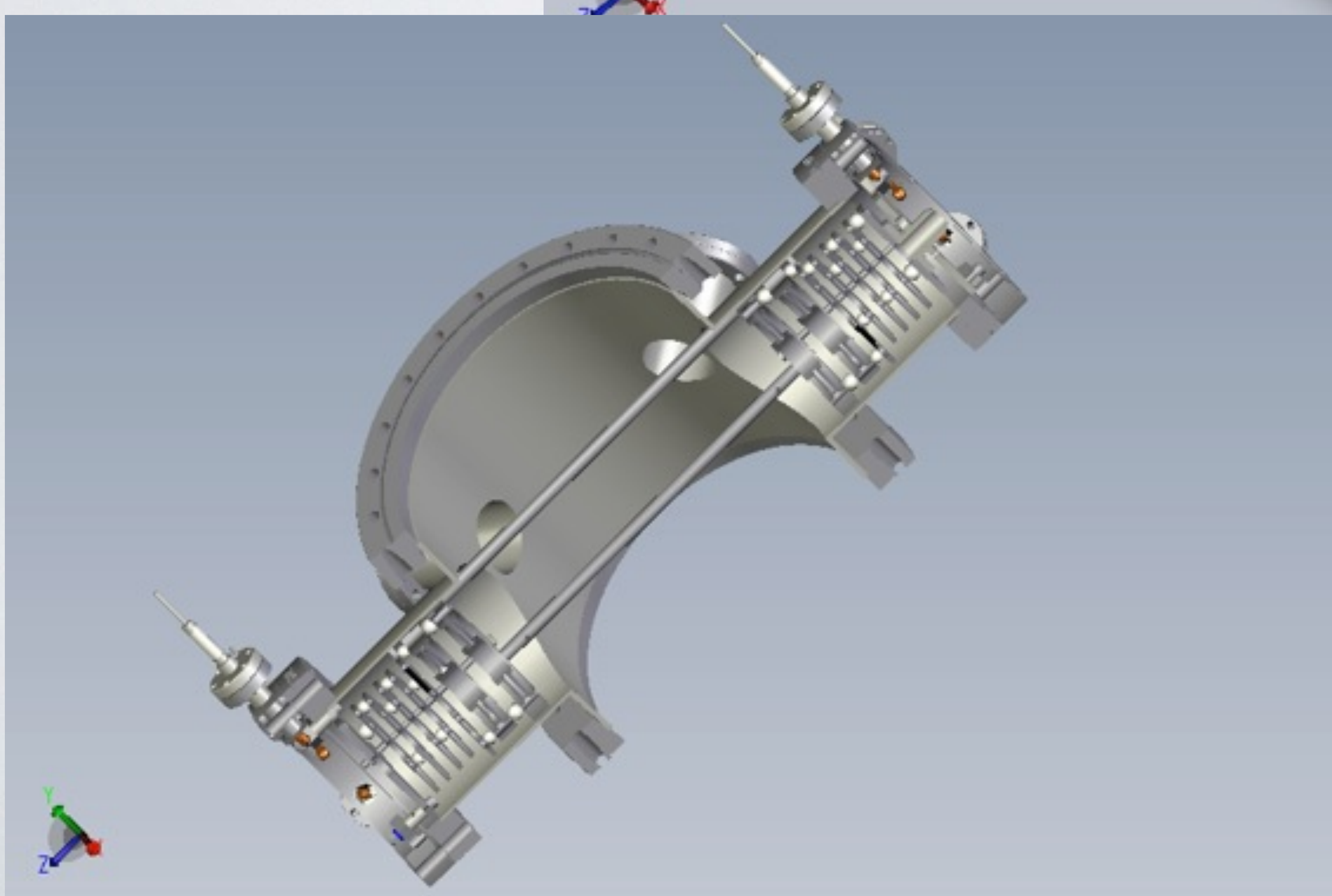
Trap Design

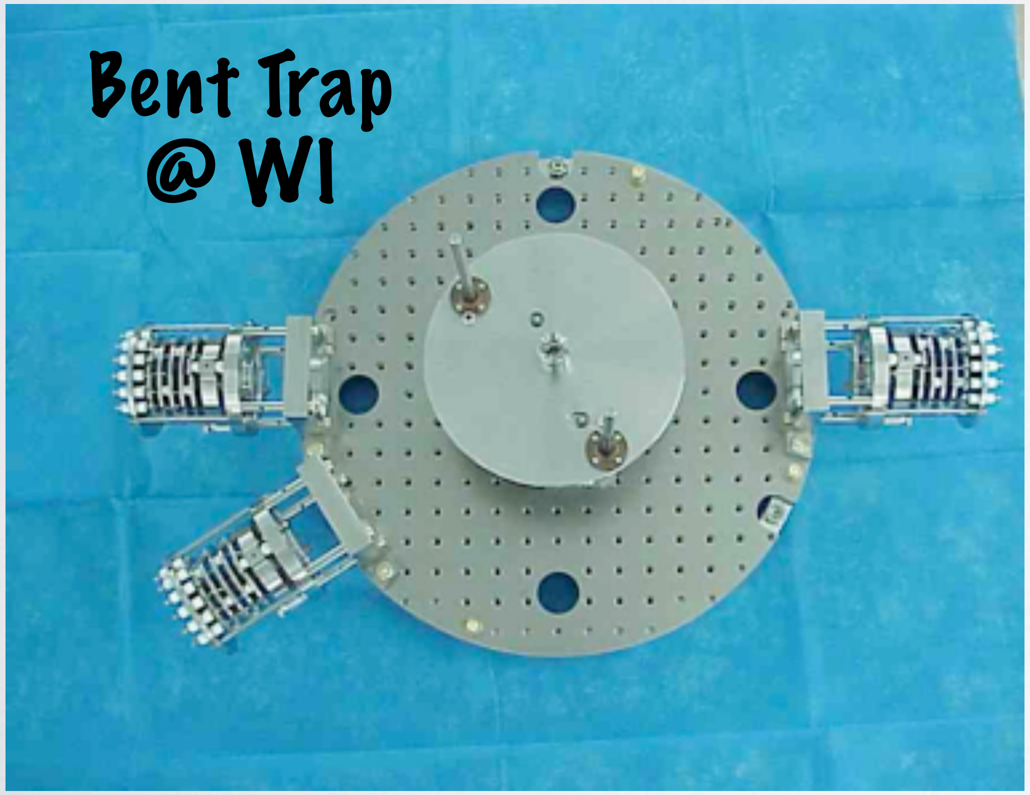


Realized at the Weizmann Institute (Israel). Also used in a cryogenic setup in Heidelberg. Our setups exist at WI and LBL.

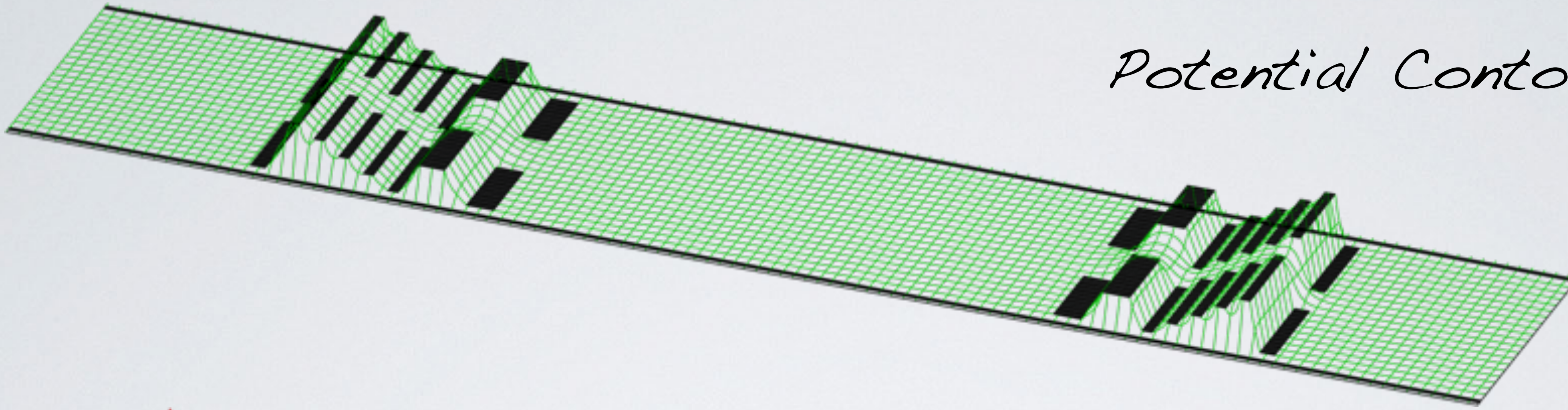




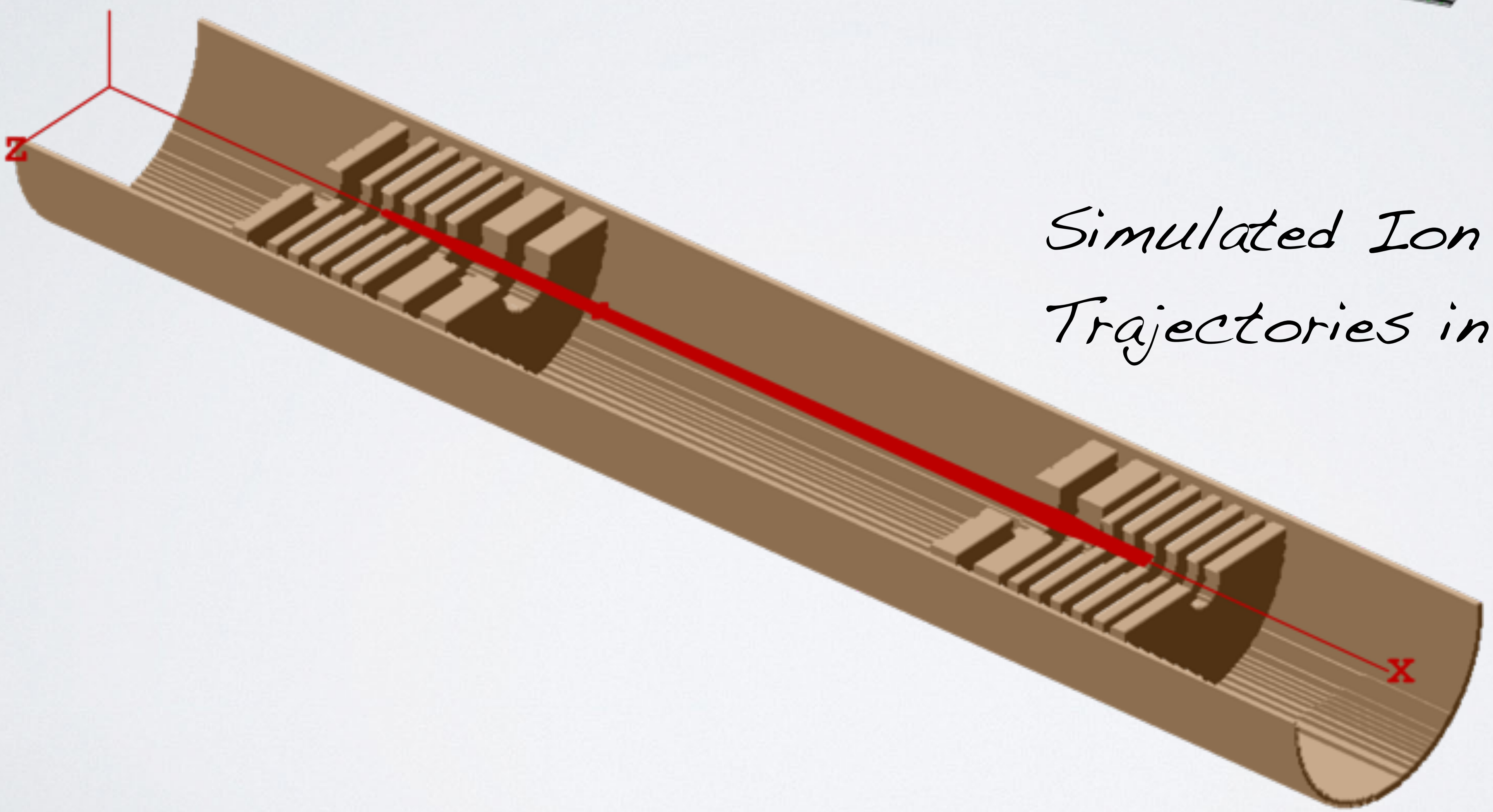

Construction
@ LBL


Bent Trap
@ WI


Andrew Wong (undergrad)
@ Berkeley



Potential Contours

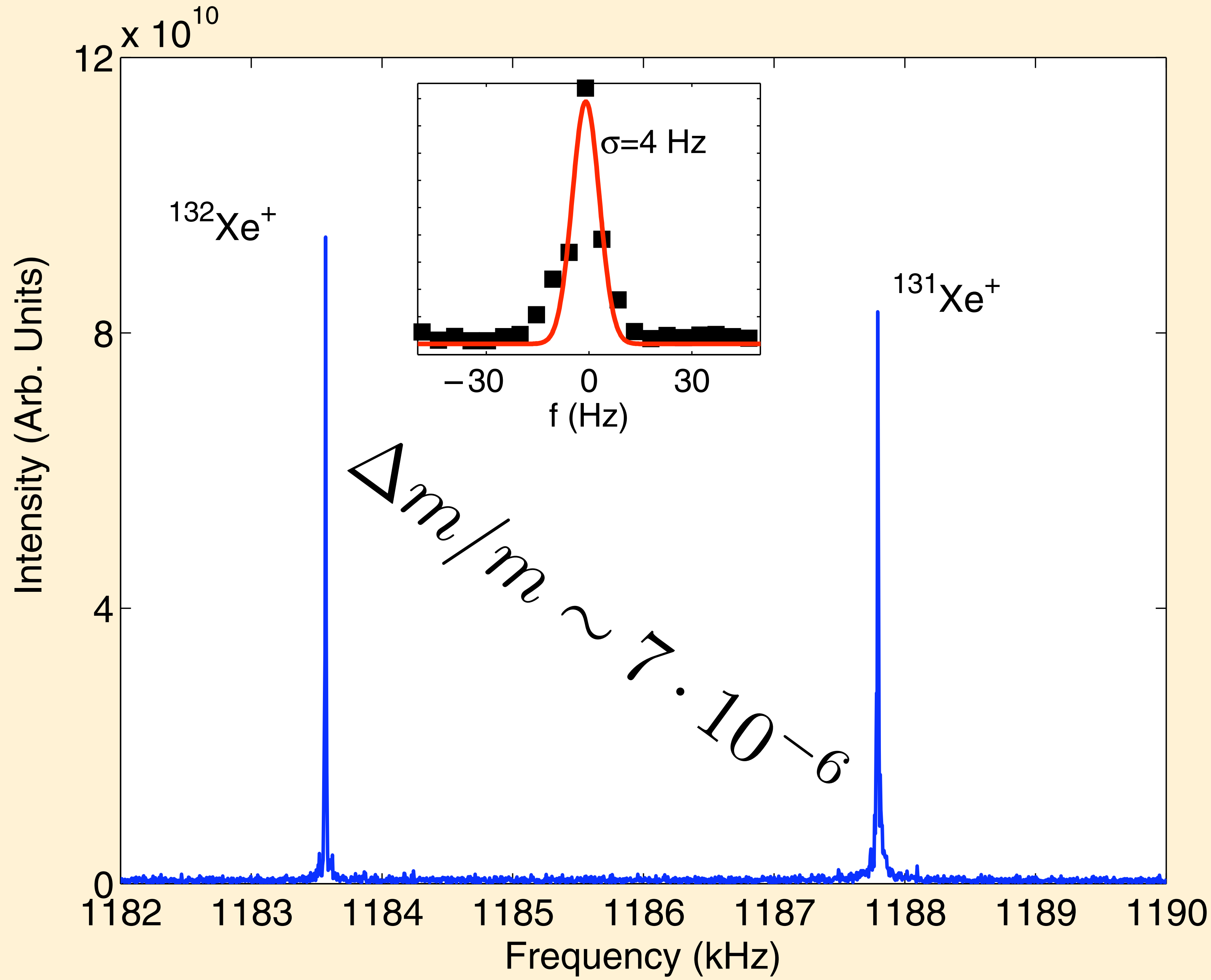


Simulated Ion Trajectories in Trap

FT Spectroscopy

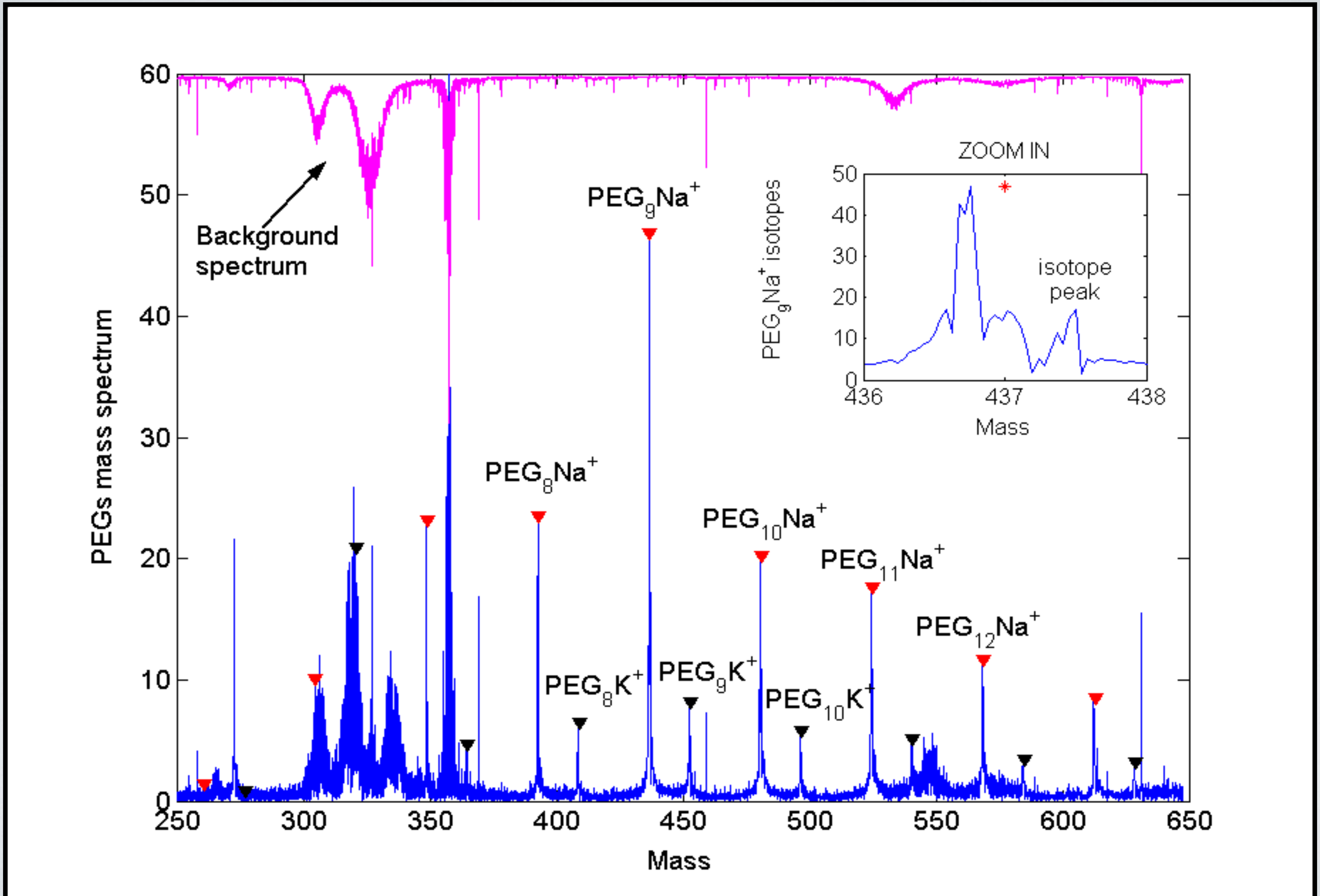
Trap selective in q/E.
Different isotopes have a different oscillation frequency in the trap.

FT Spectroscopy

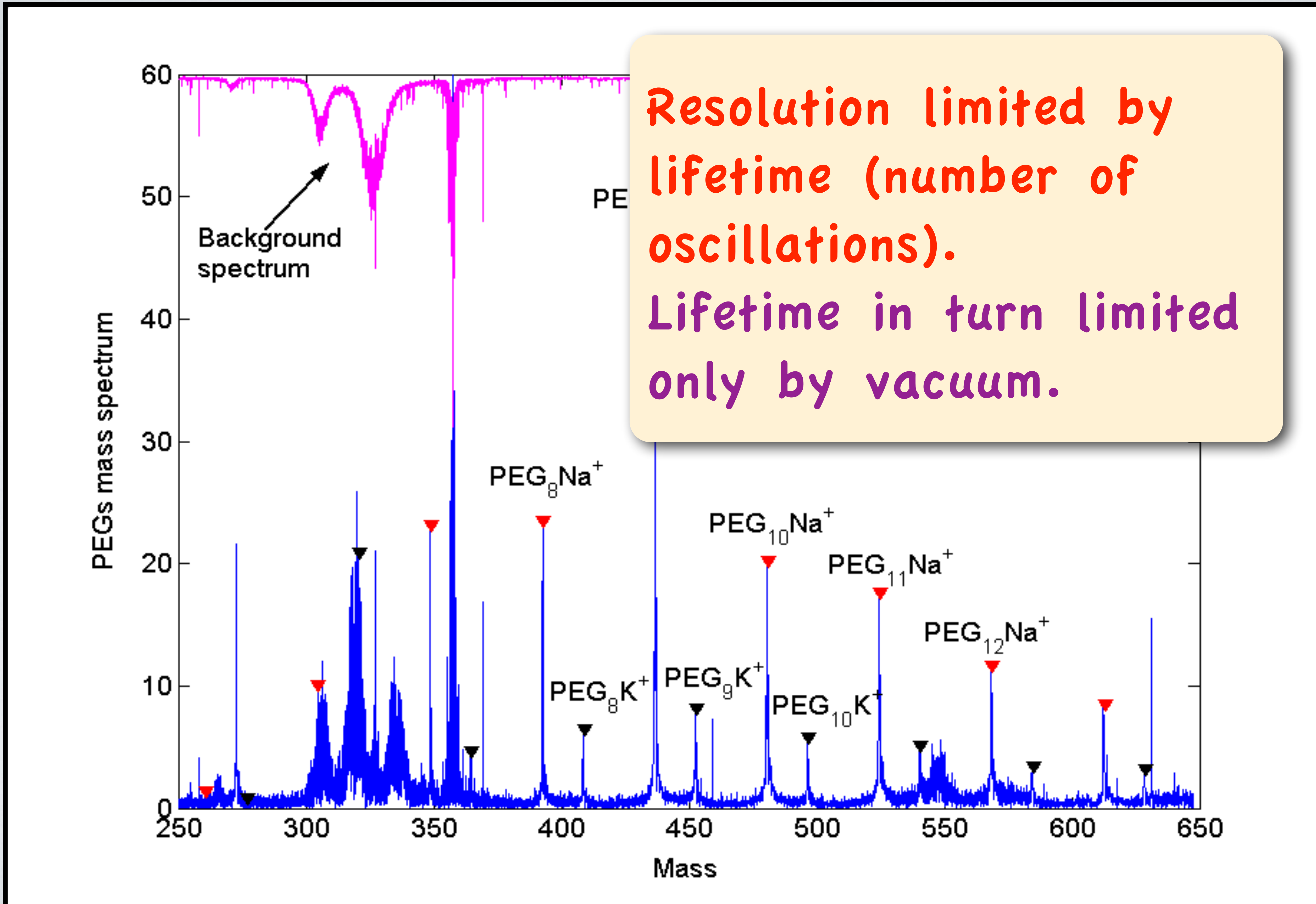


D. Strasser J. Phys. B: At. Mol. Opt. Phys. 36, 953 (2003)

FT Spectroscopy



FT Spectroscopy



Resolution limited by lifetime (number of oscillations).

Lifetime in turn limited only by vacuum.

The β-Decay EIBT Scheme

Trap moving ions in Electrostatic Ion Beam Trap.

Simple, cheap setup.

No need for acceleration of products - simple detection scheme.

Kinematic focusing.

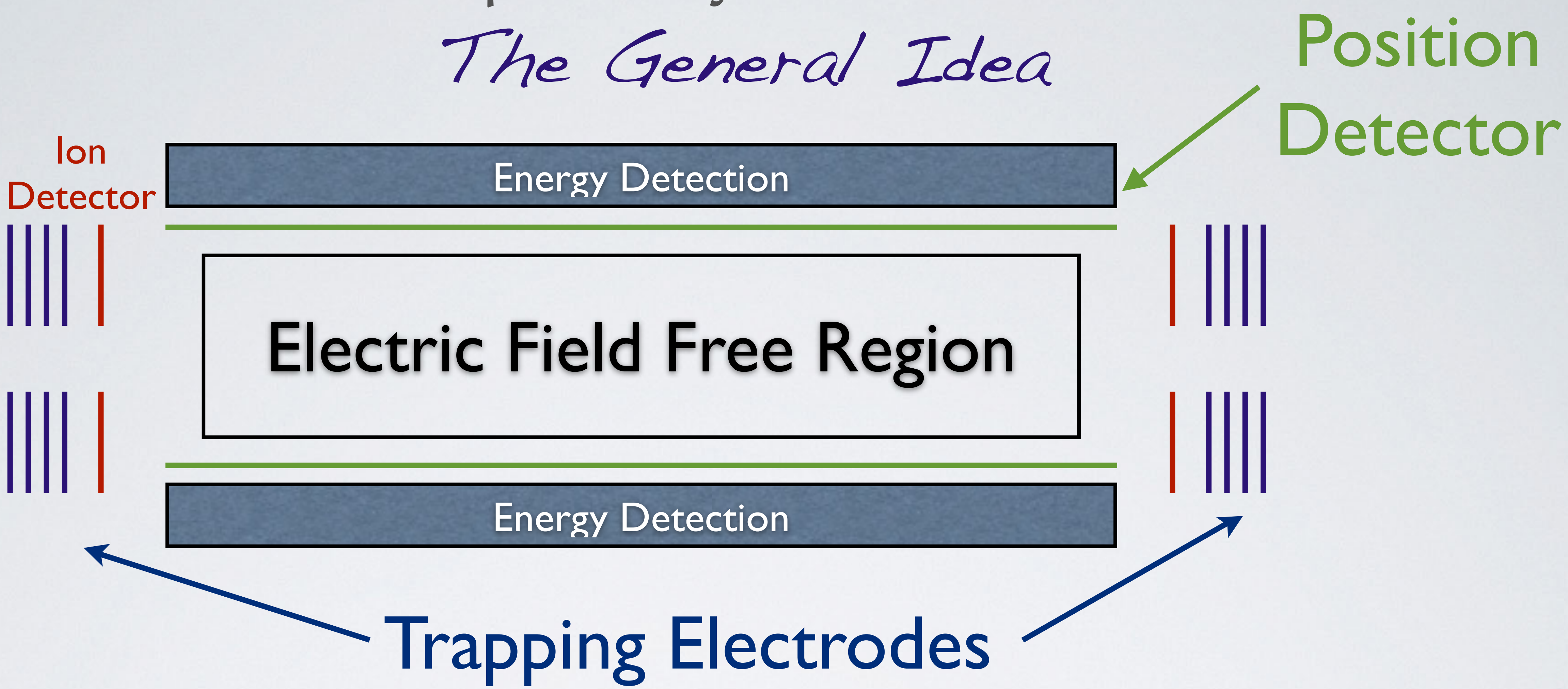
Decay in field free region.

Moving system - position of decay harder to infer.

Large initial spatial extent (bunch).

β-Decay Studies

The General Idea



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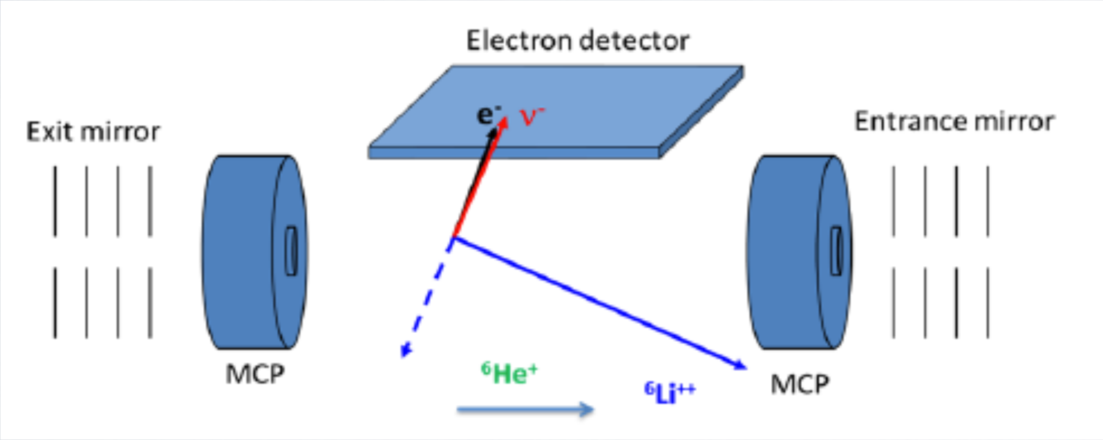

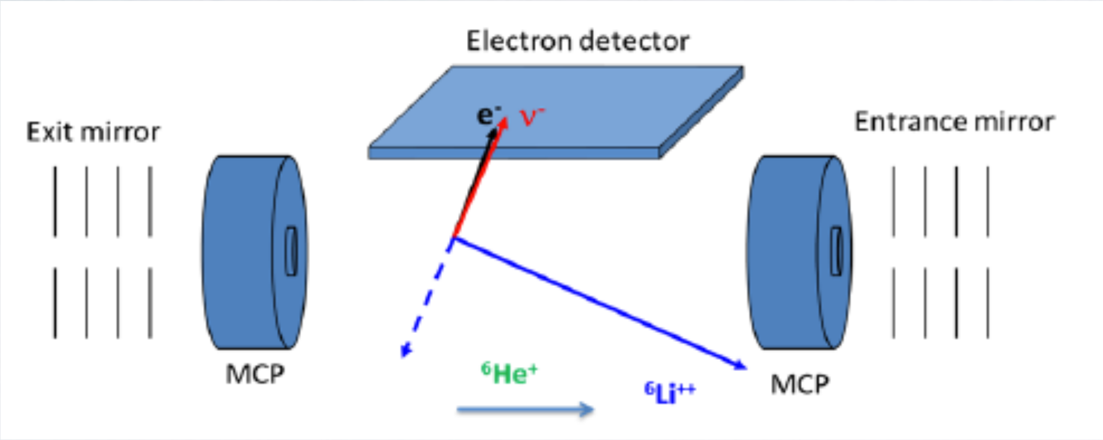

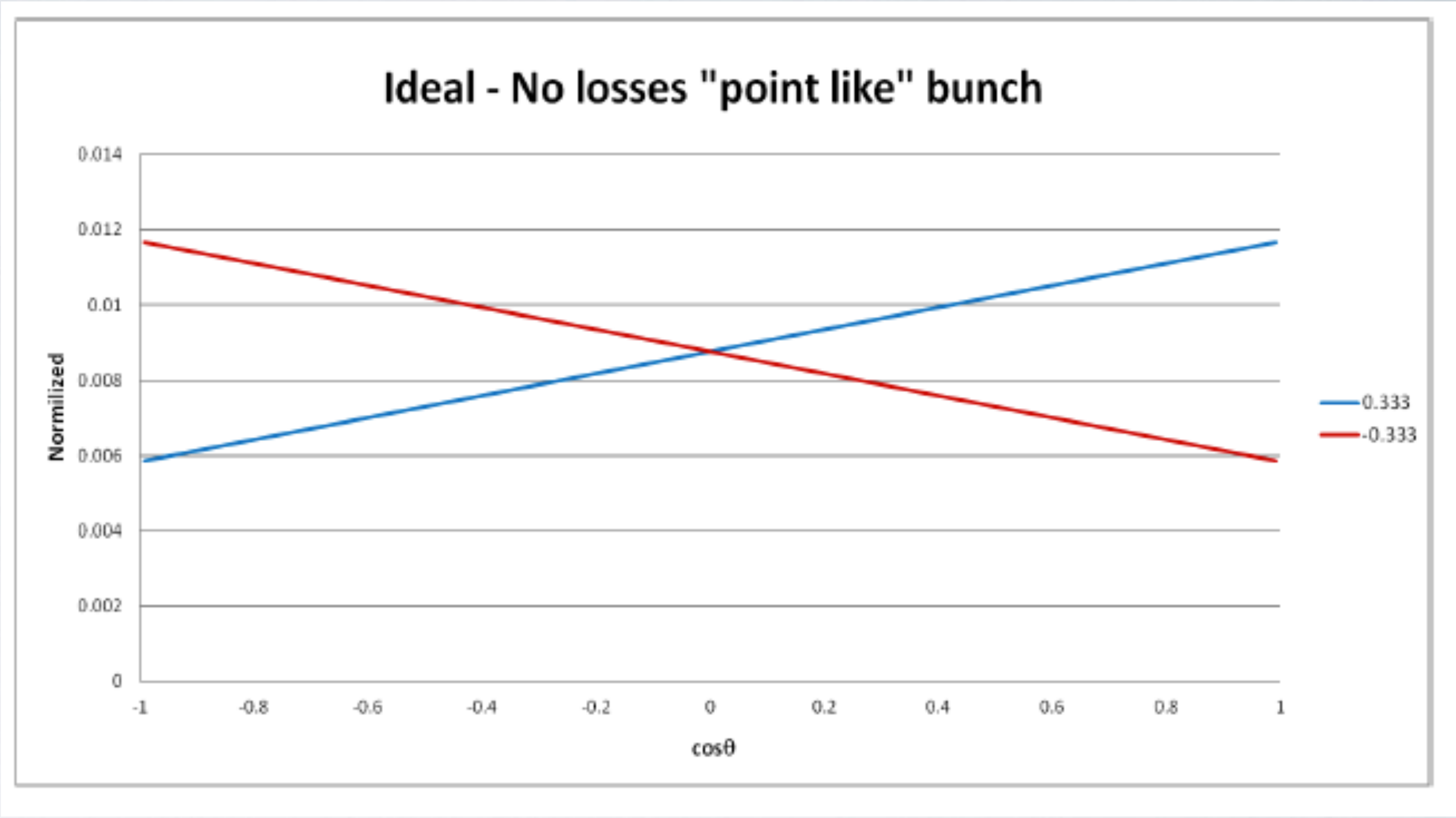

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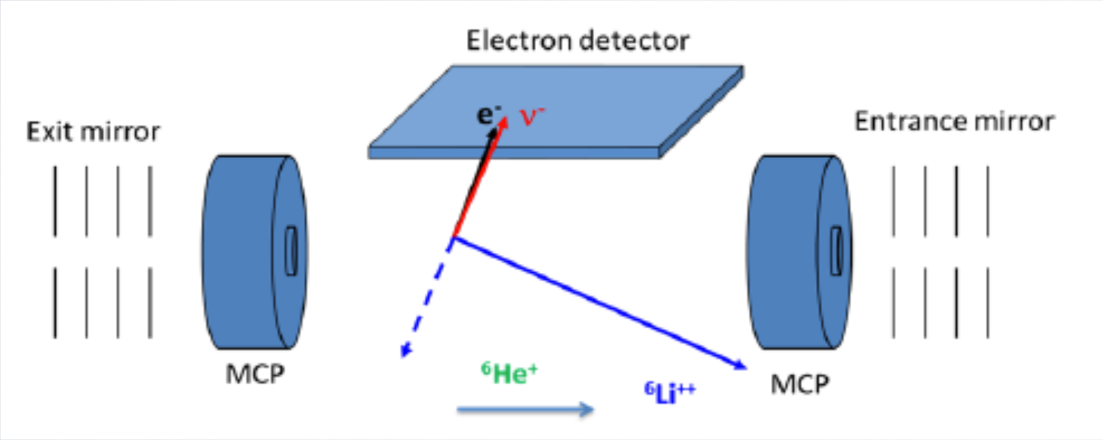

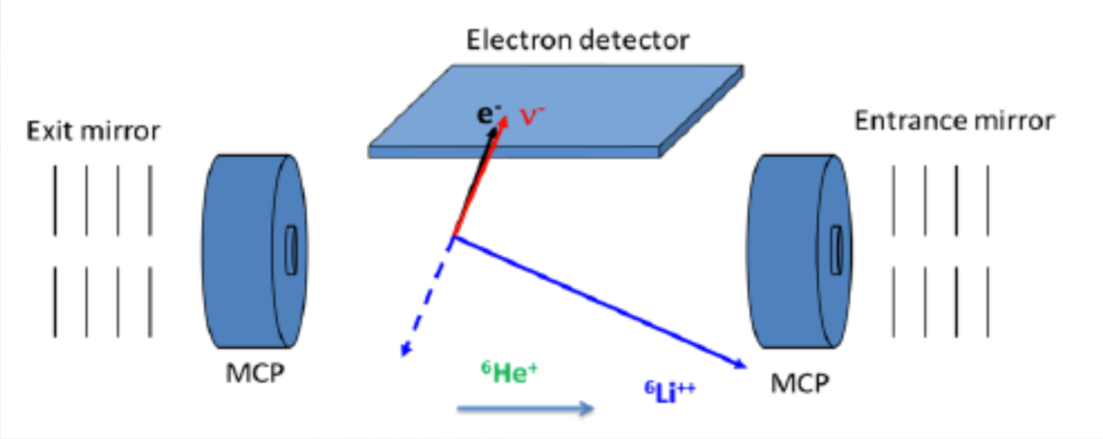

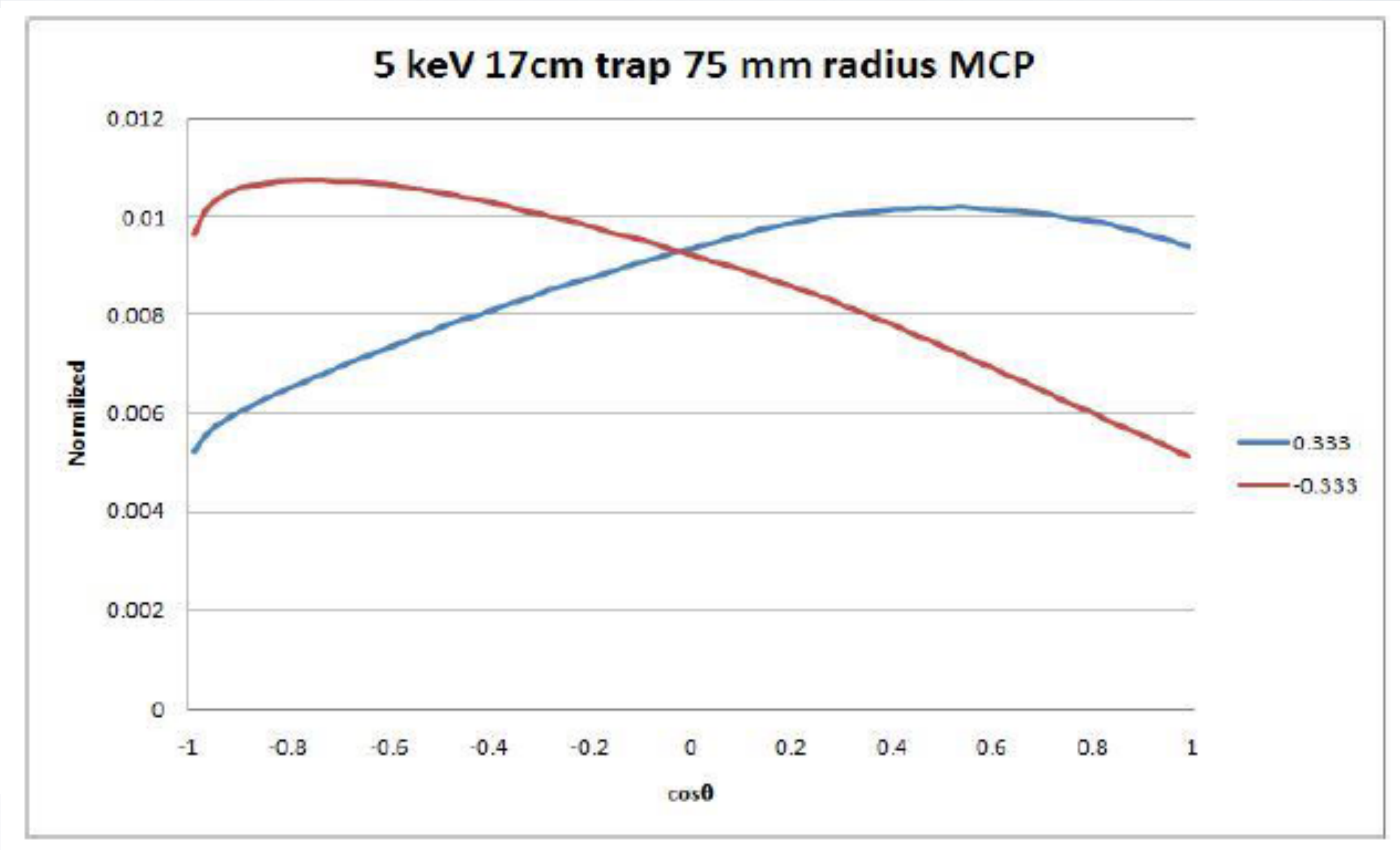

1e6 events gives 0.6% stat. uncertainty

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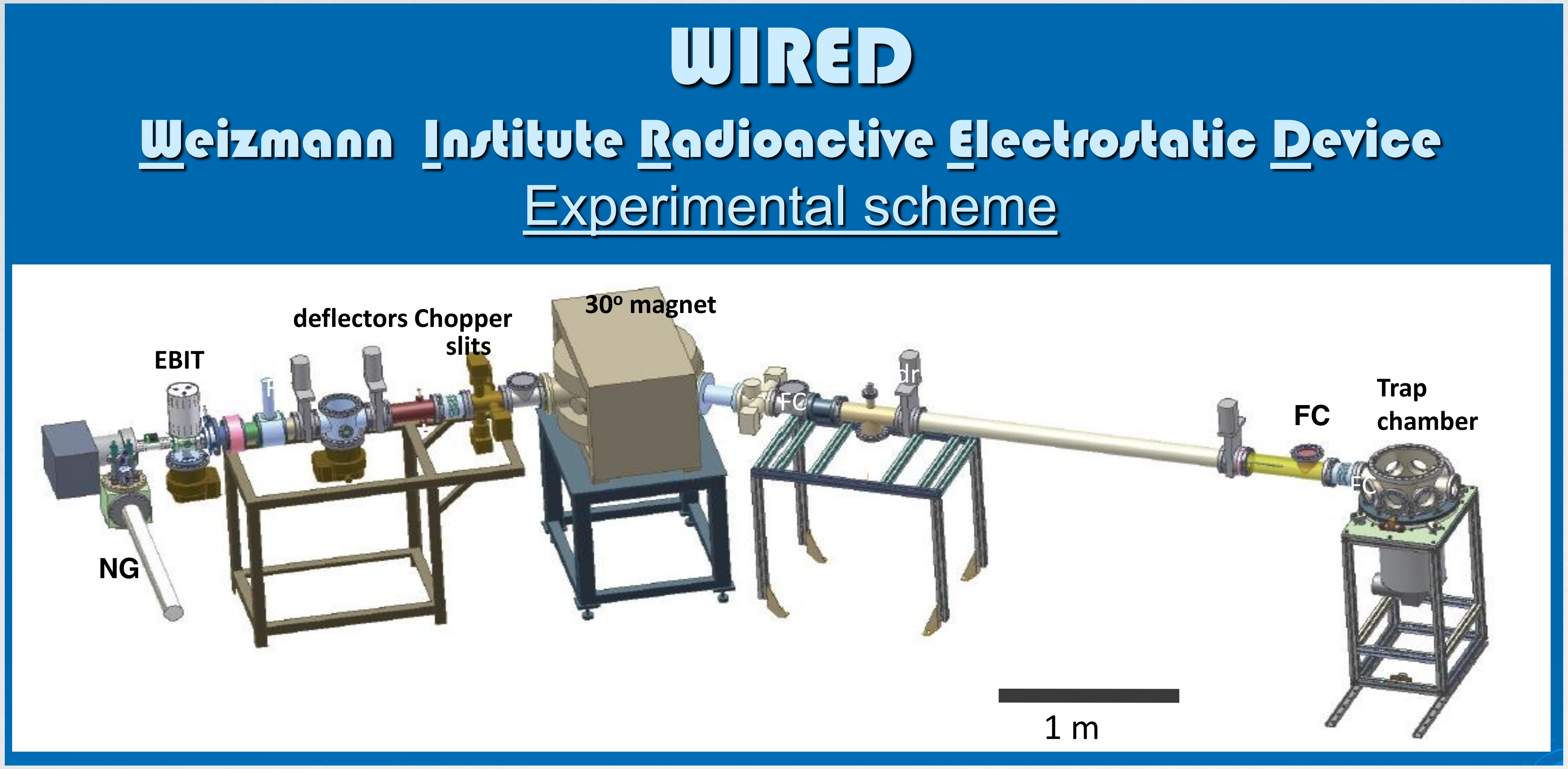
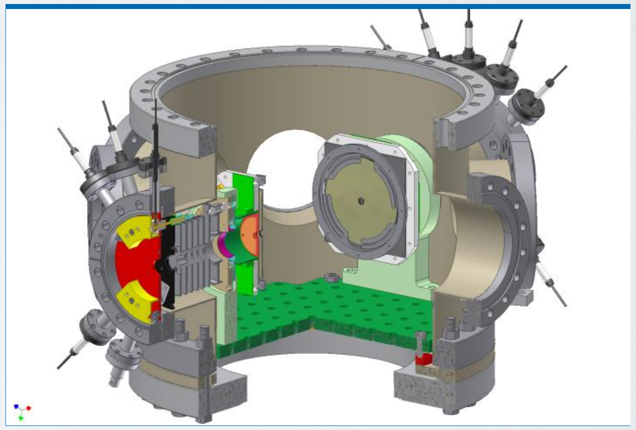
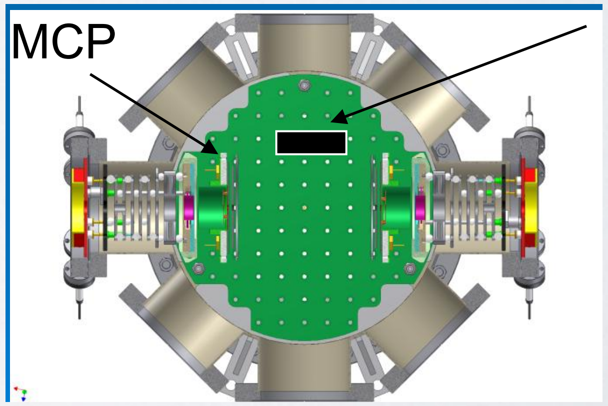
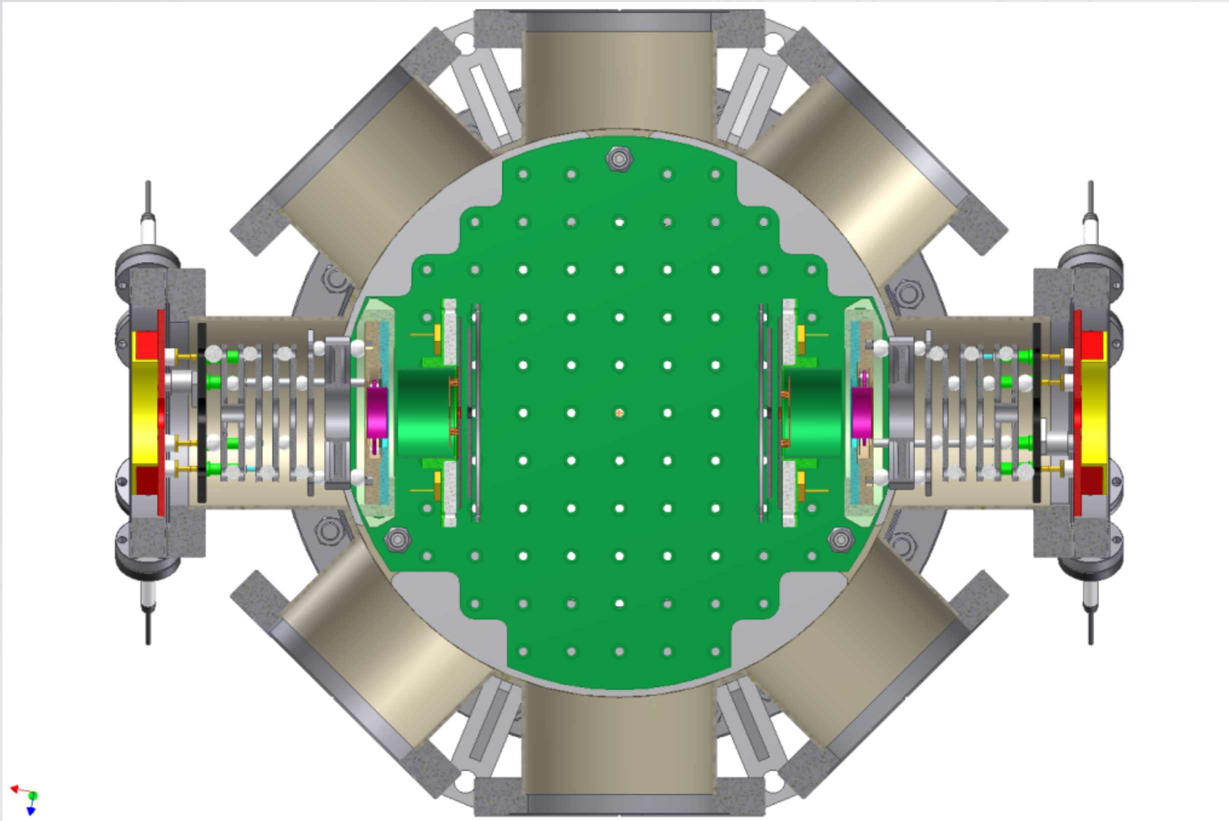
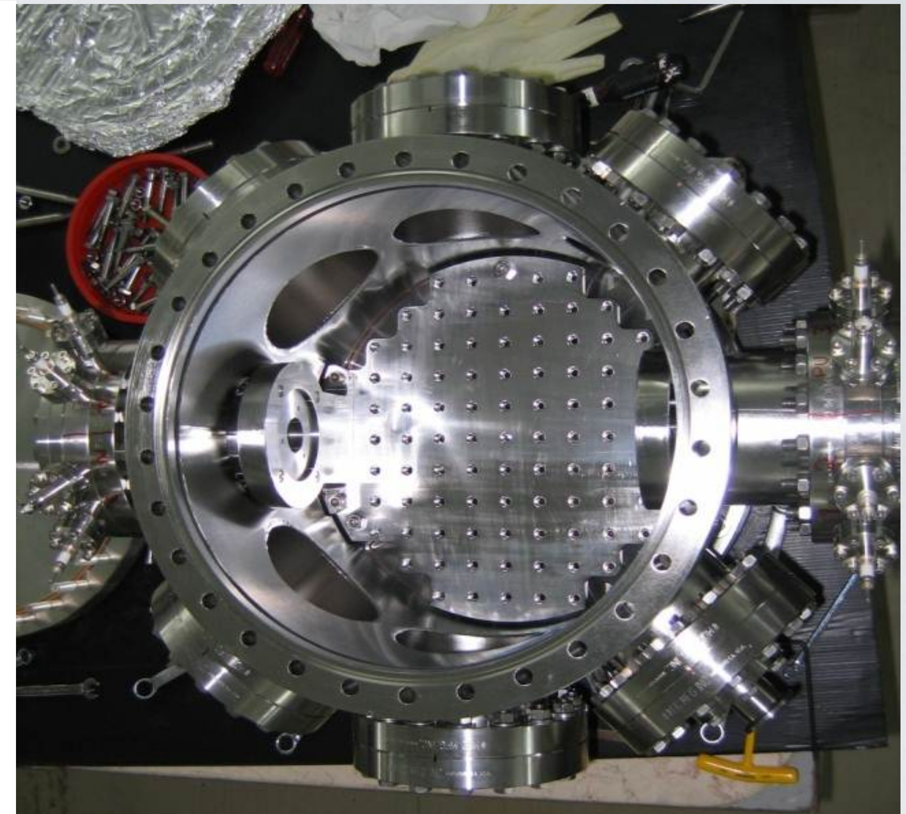
Where are we now @ WI?

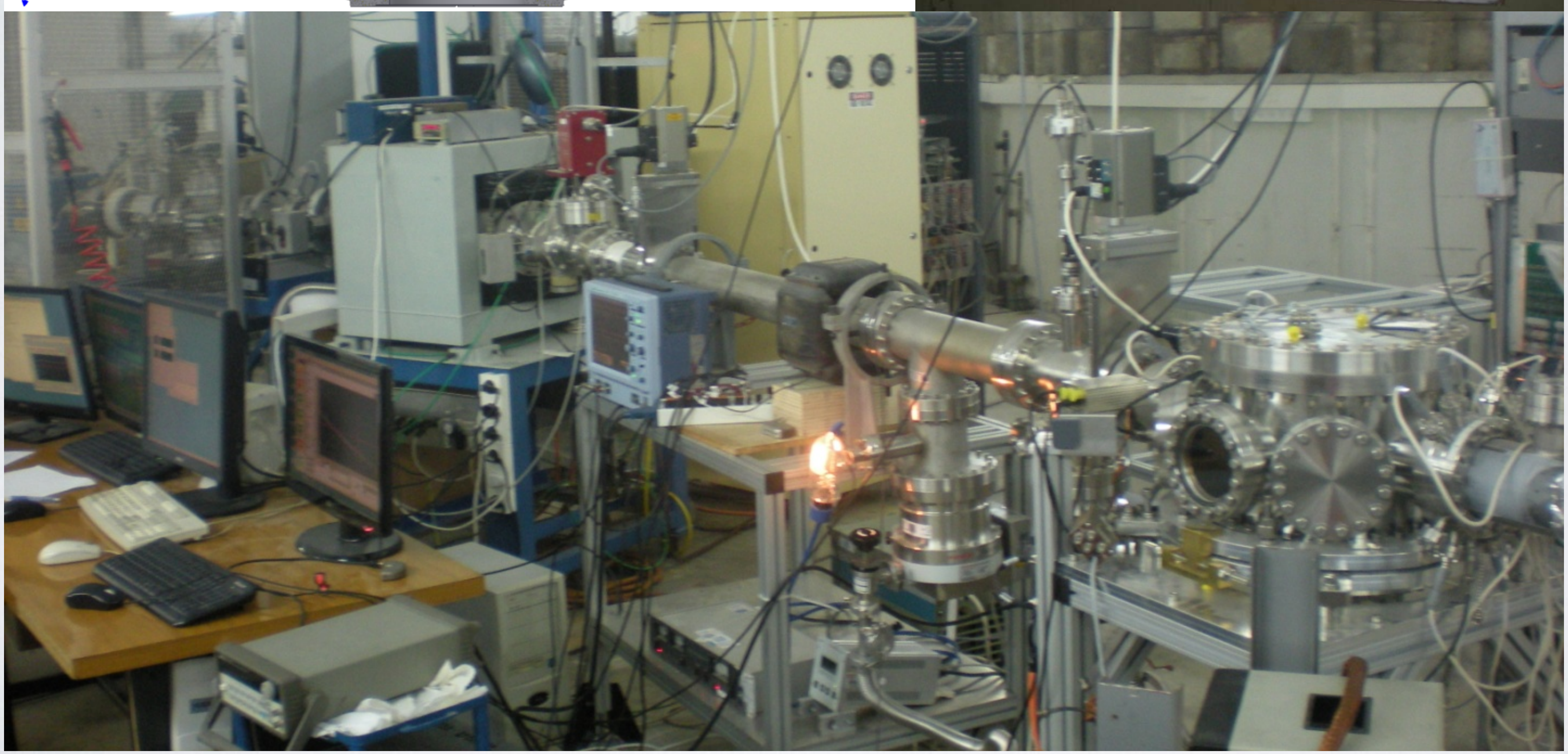


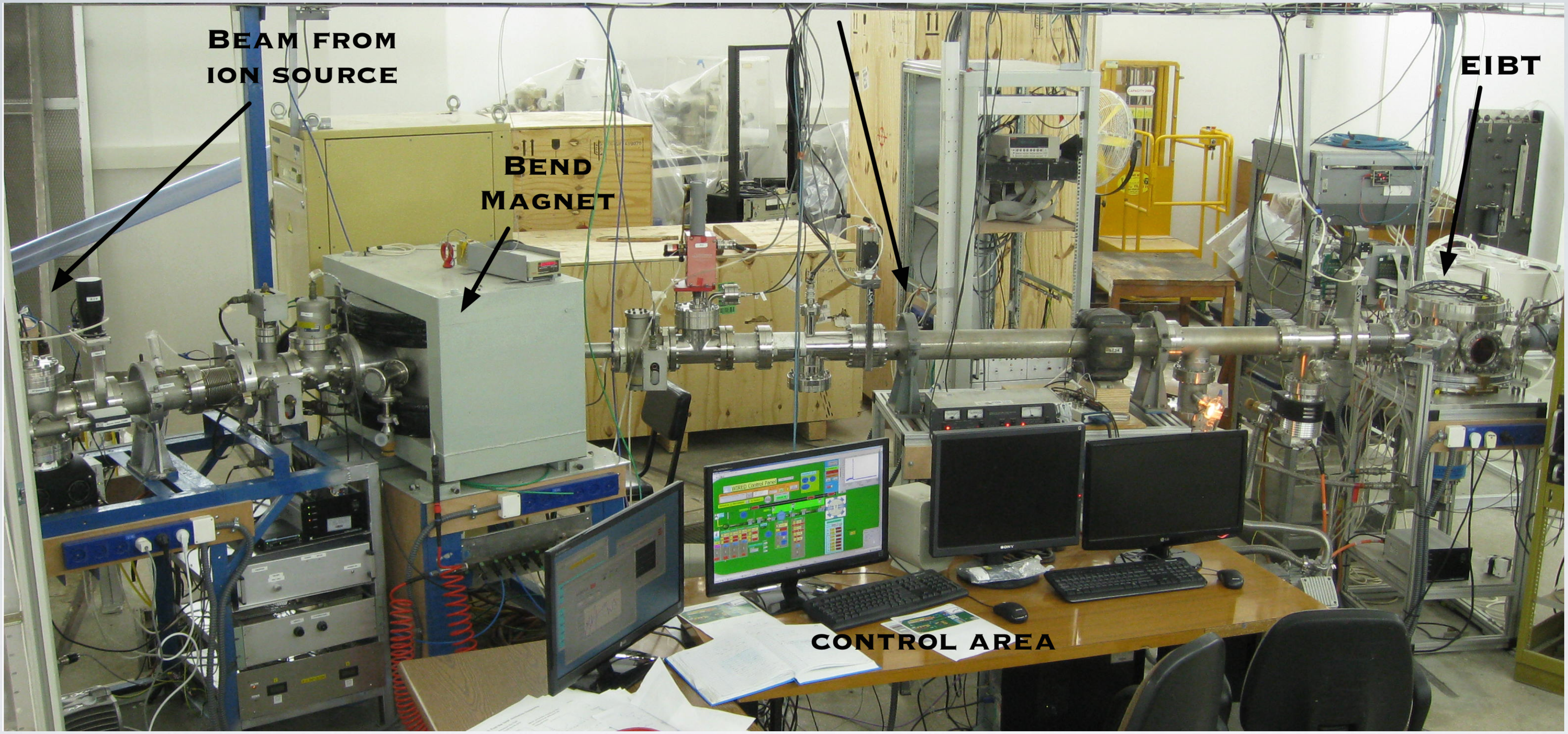


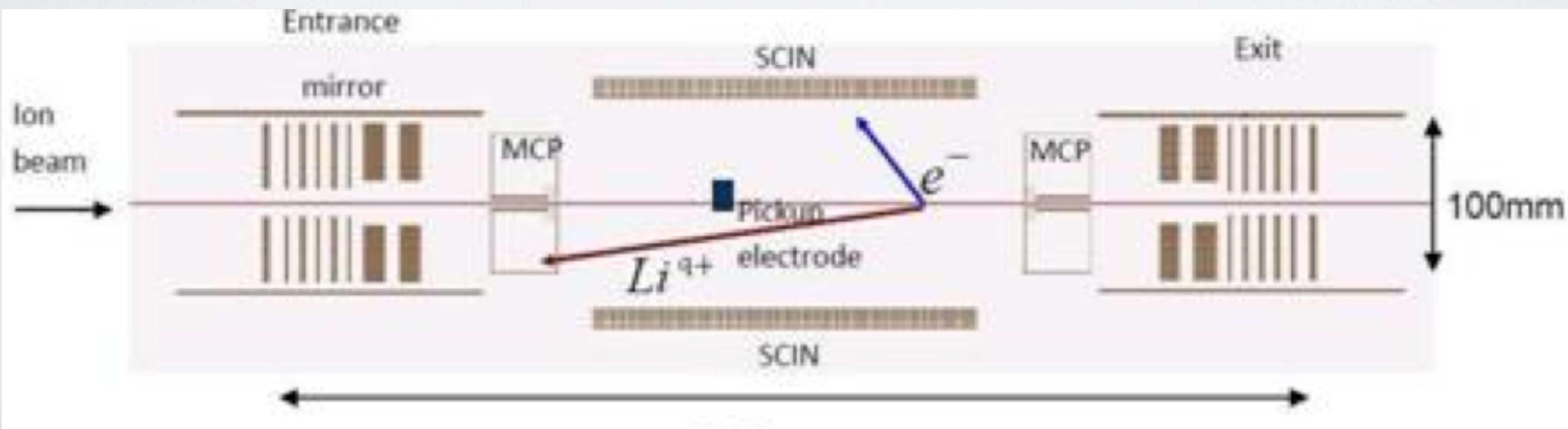




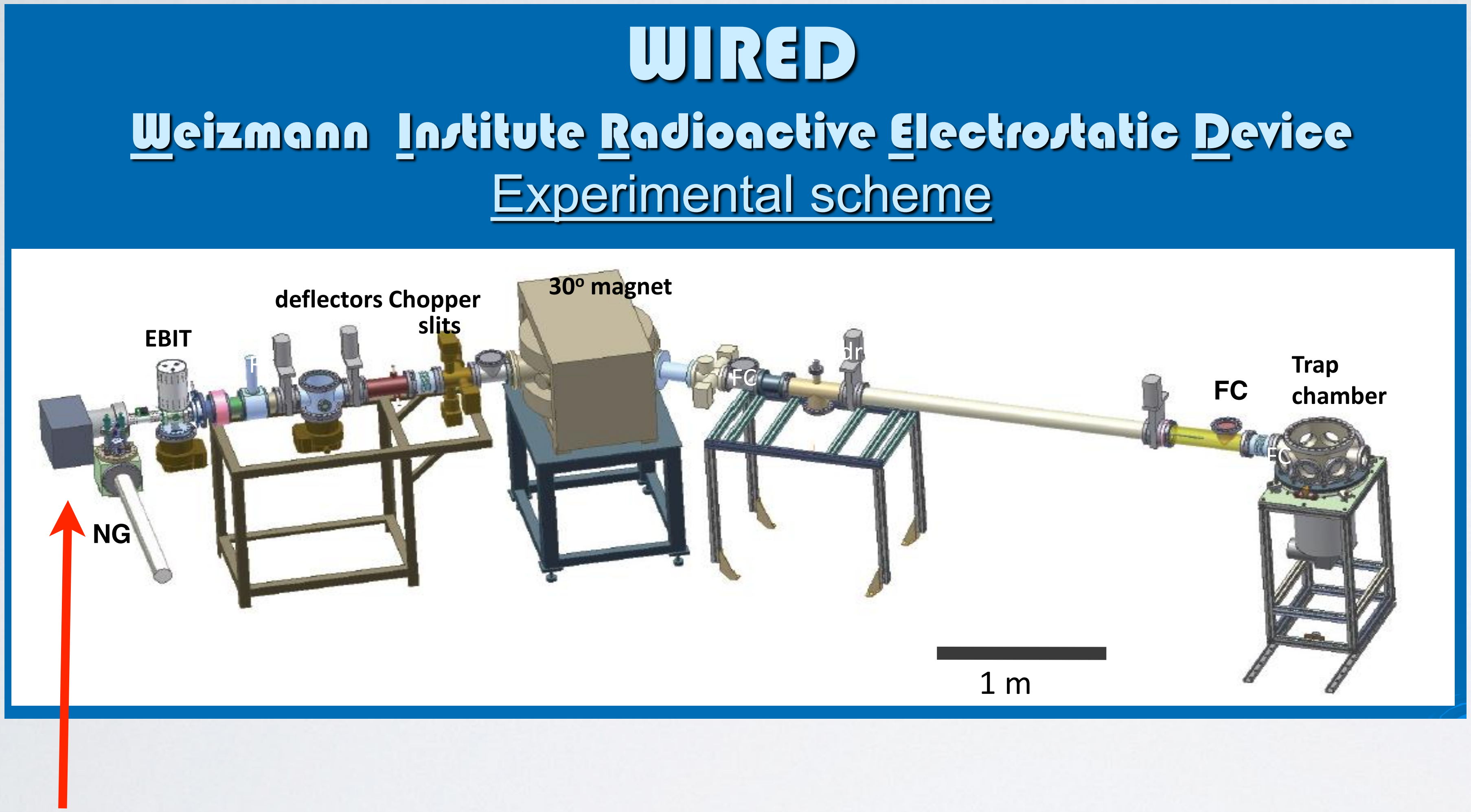





Beam from ion source
Bend Magnet
EIBT
Control area


Entrance mirror
SCIN
Exit
Ion beam
MCP
MCP
e⁻
Pickup electrode
Li q+
100mm
SCIN

Neutron Generator

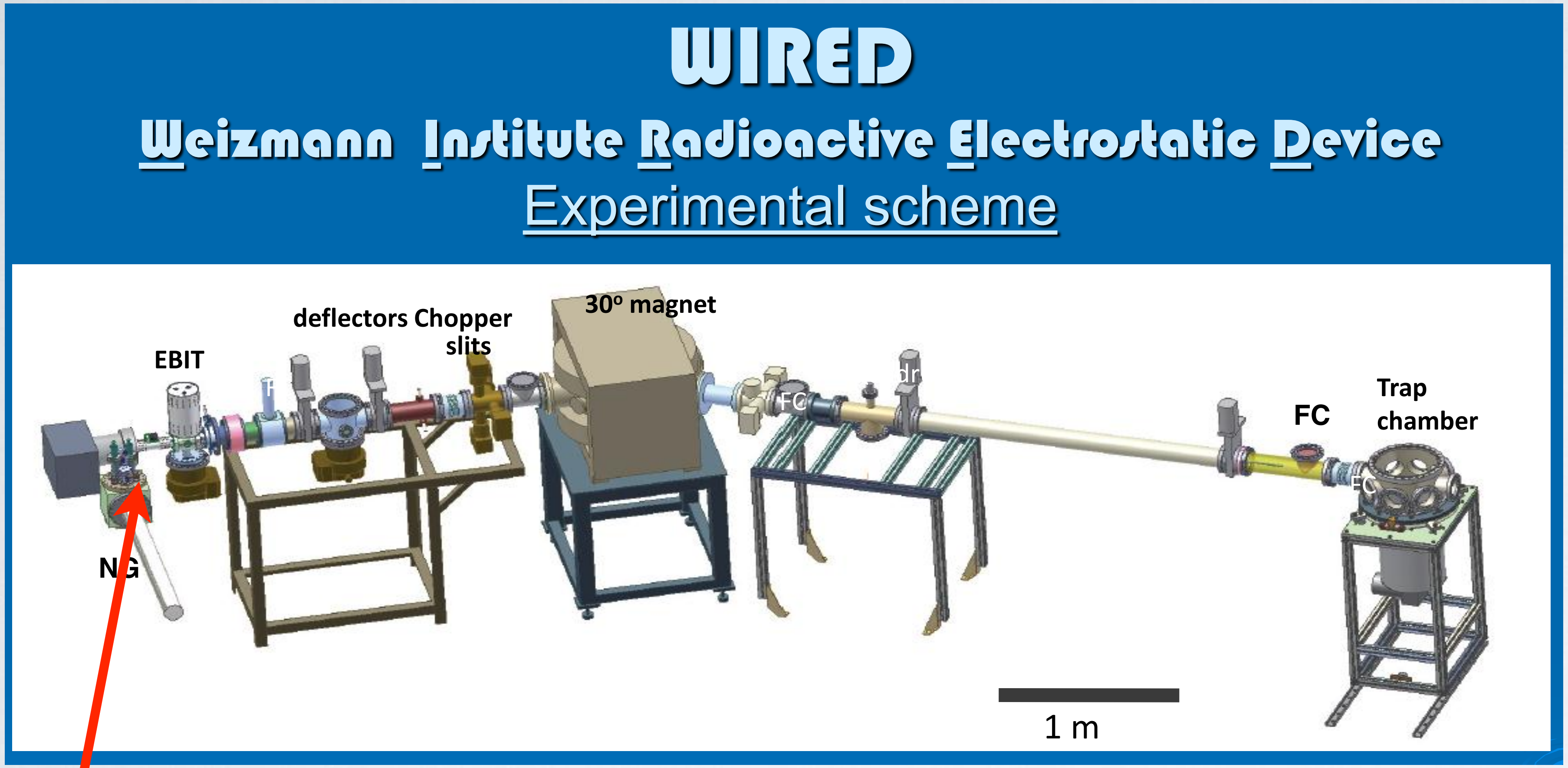


$D + T \rightarrow n + {}^{4}He \quad E_n = 14.2$ MeV,

Production rate ~10^{10} n/s

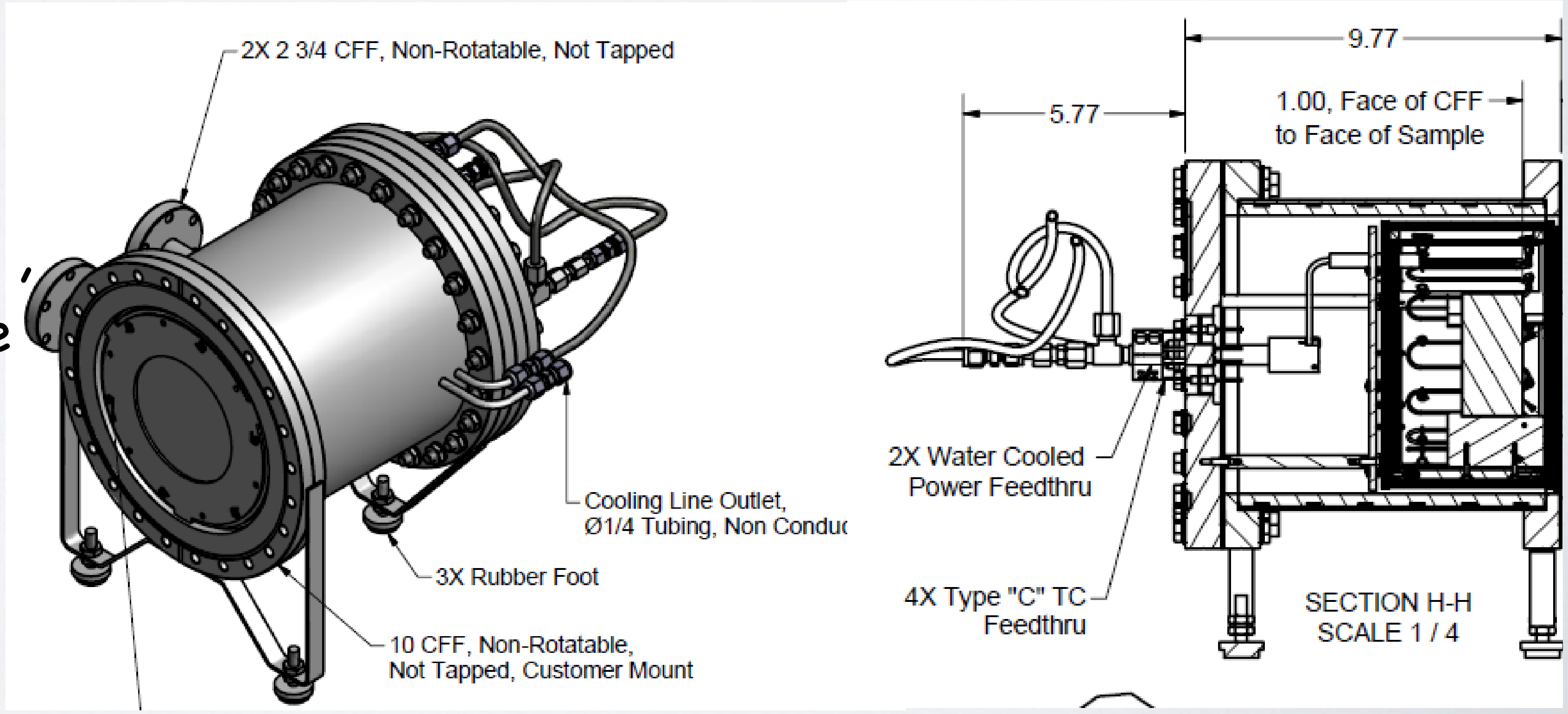
Supplied and commissioned at WI

Furnace + BeO Target

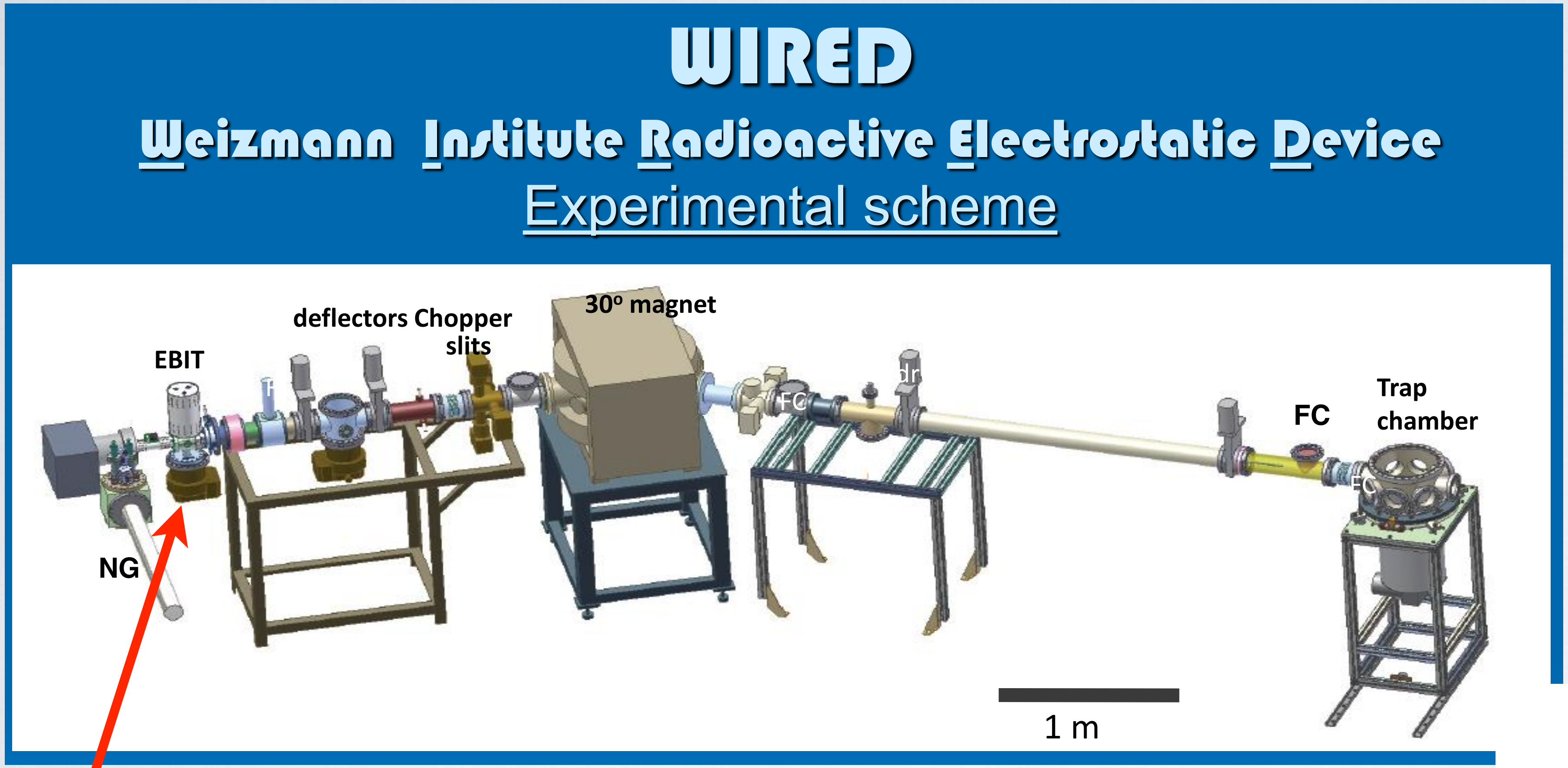


The 14 MeV neutrons hit a hot (1500K) BeO target, as a result , ^{6}He nuclei are produced via the (n, α) reaction.

Porous BeO 80 mm x 2 mm discs delivered and stored



Buncher / Accumulator



EBIT - **DREBIT** (Dresden, Germany)

Neutral ^{6}He enter the EBIT, ionized, accumulated and bunched.

Custom made for efficient ^{6}He injectio..

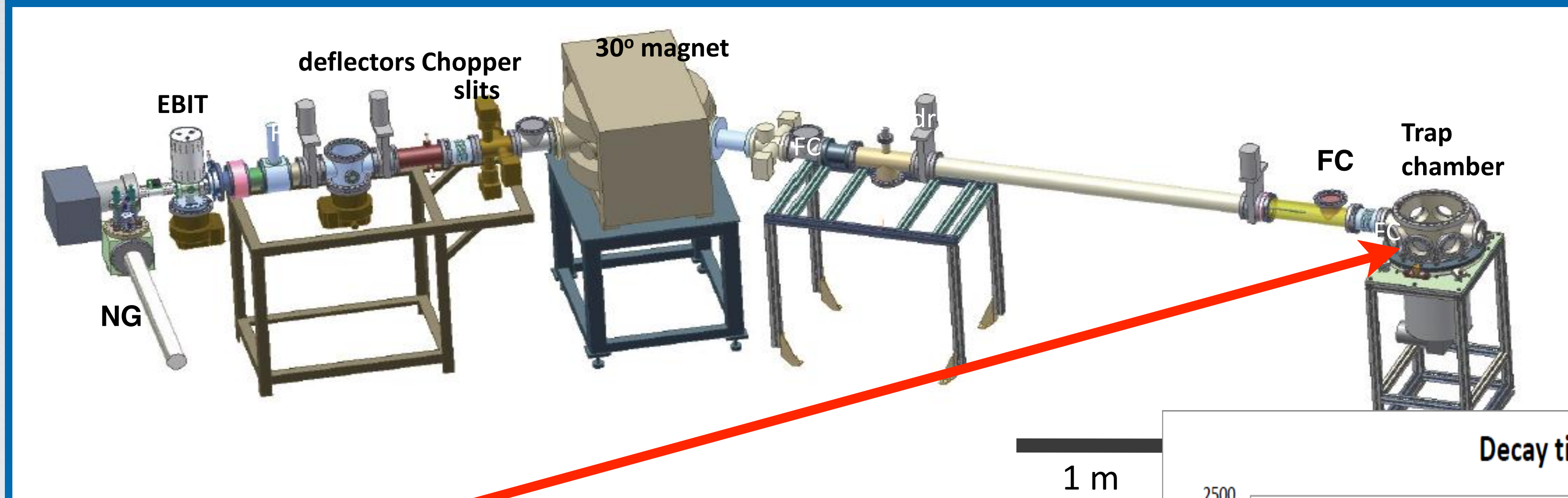
Waiting at WI for commissioning

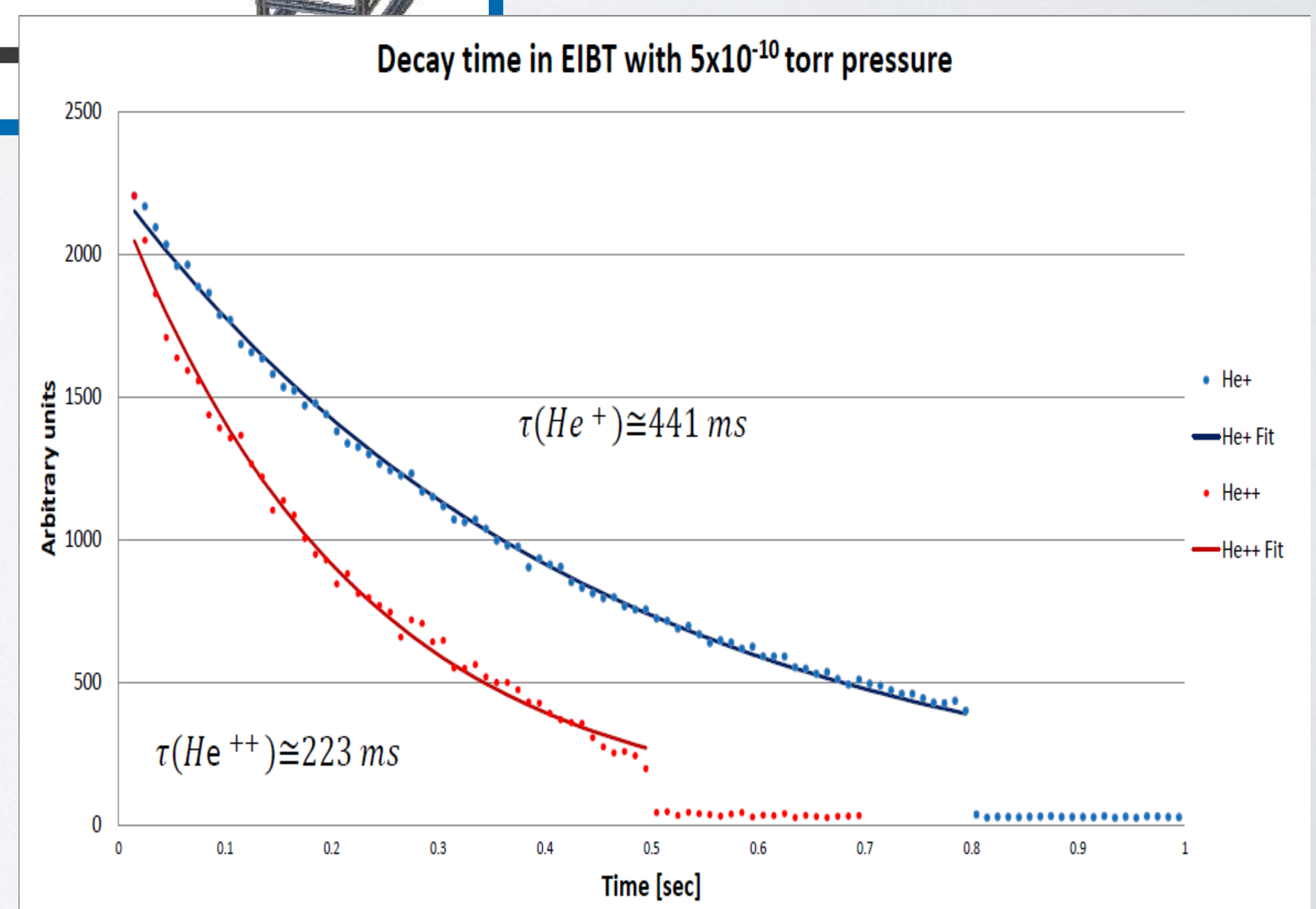
Trap

WIRED

Weizmann Institute Radioactive Electrostatic Device

Experimental scheme





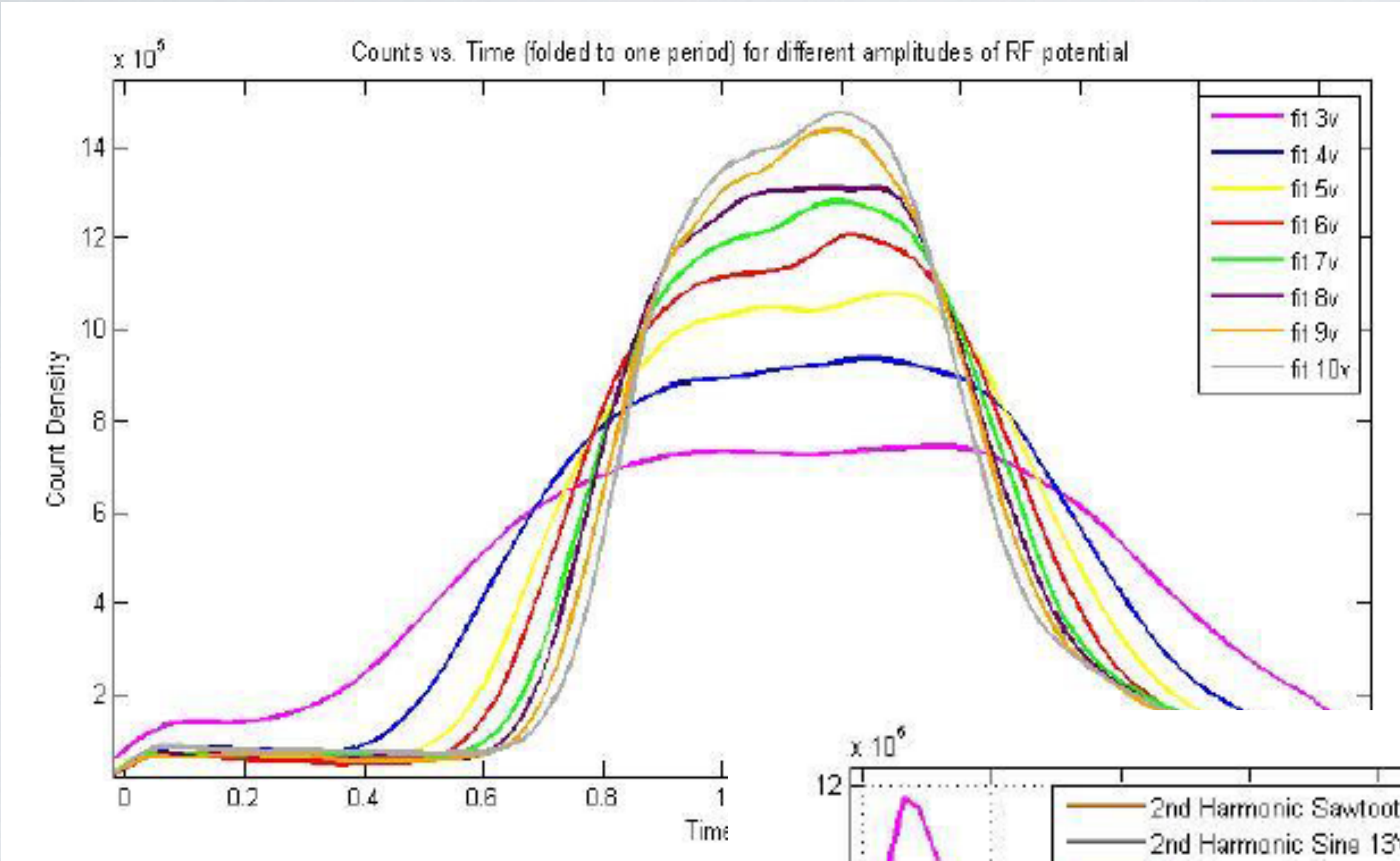
Stable isotopes trapped

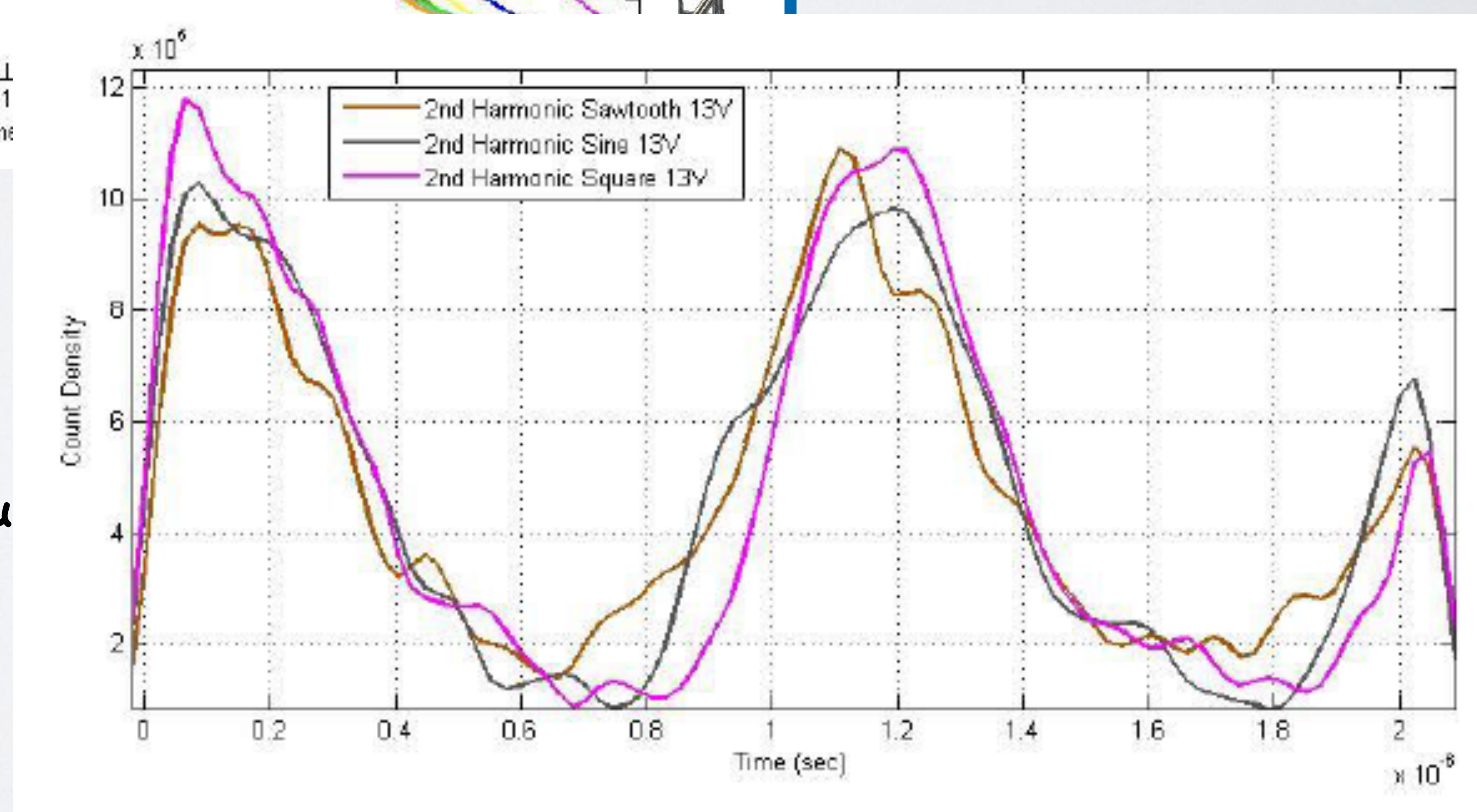
Detectors:

- MCP's
- Plastic Scintillator with multiple photomultipliers

Electronics - ADC, TDC,...

Trap





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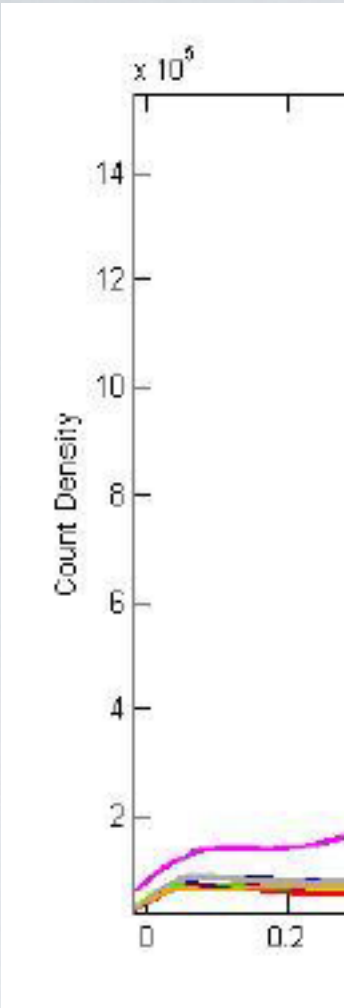

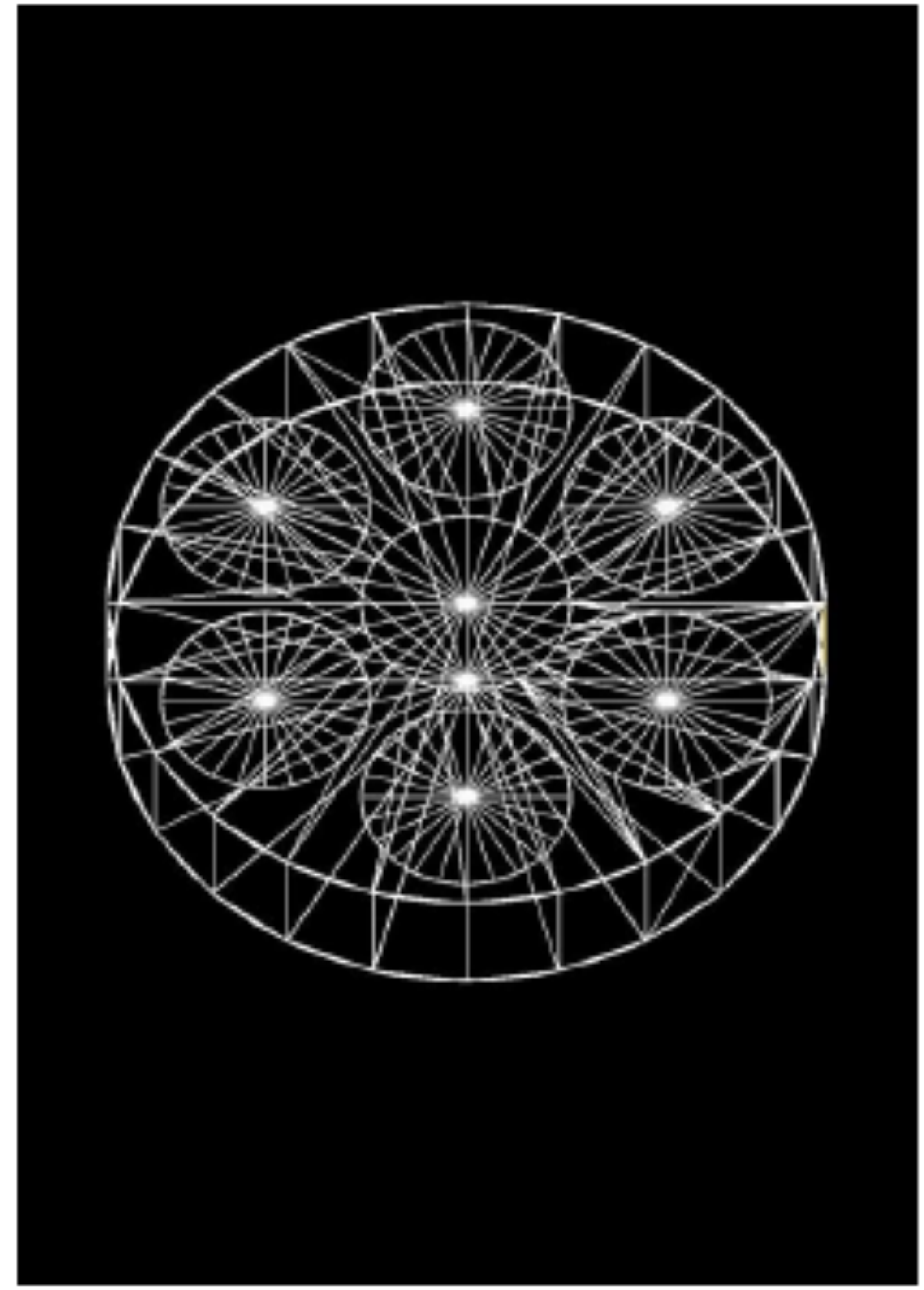

Stable isoto
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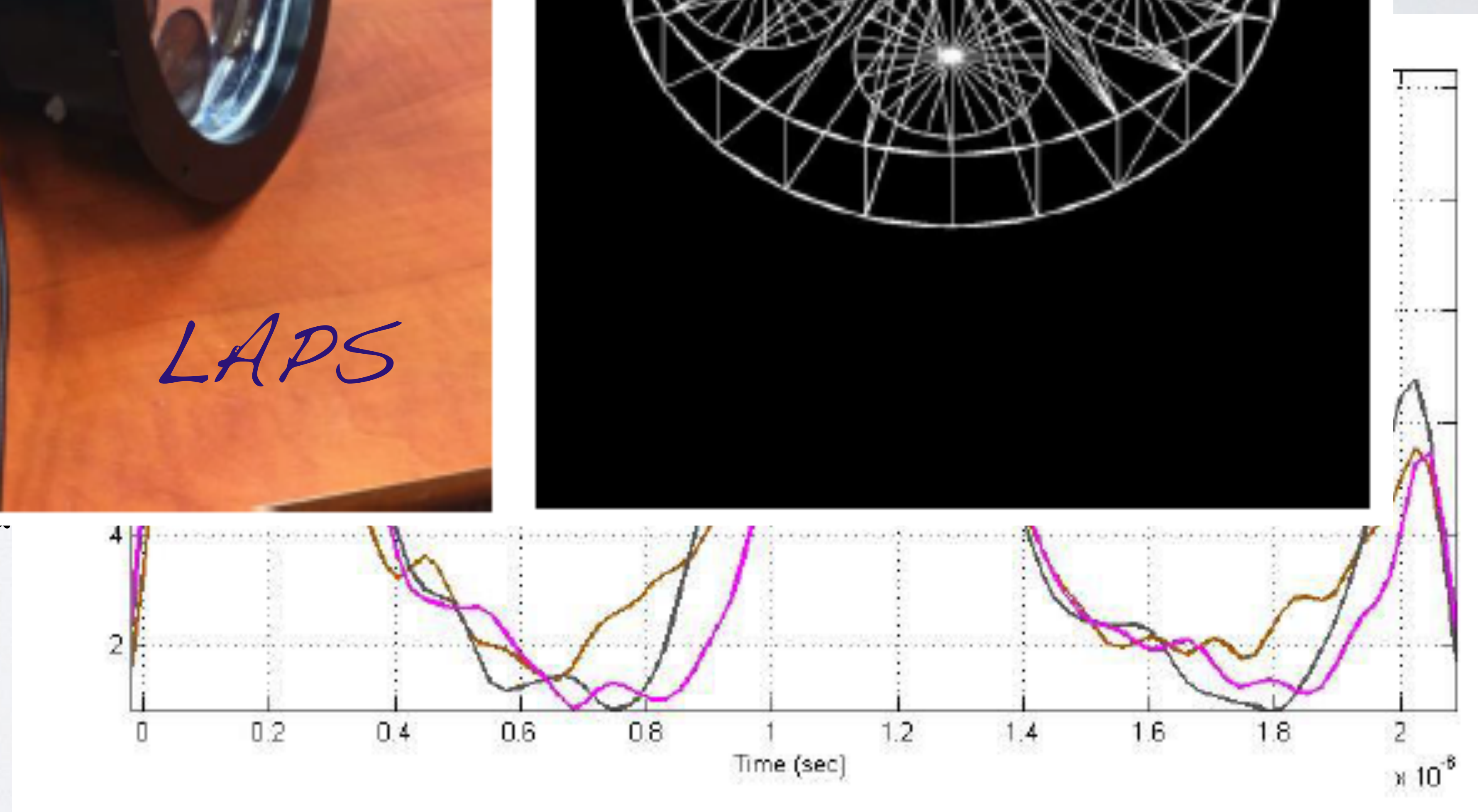
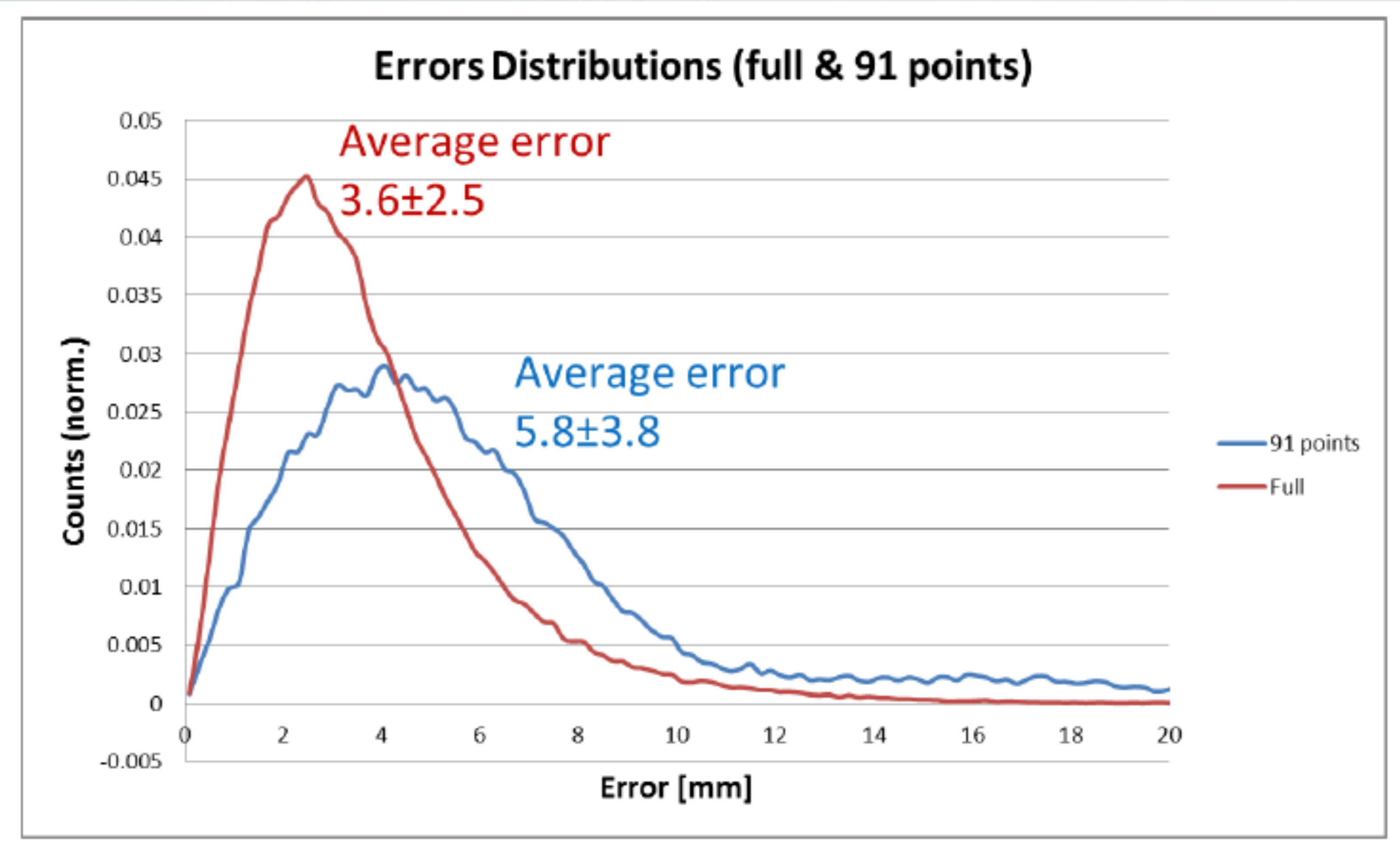
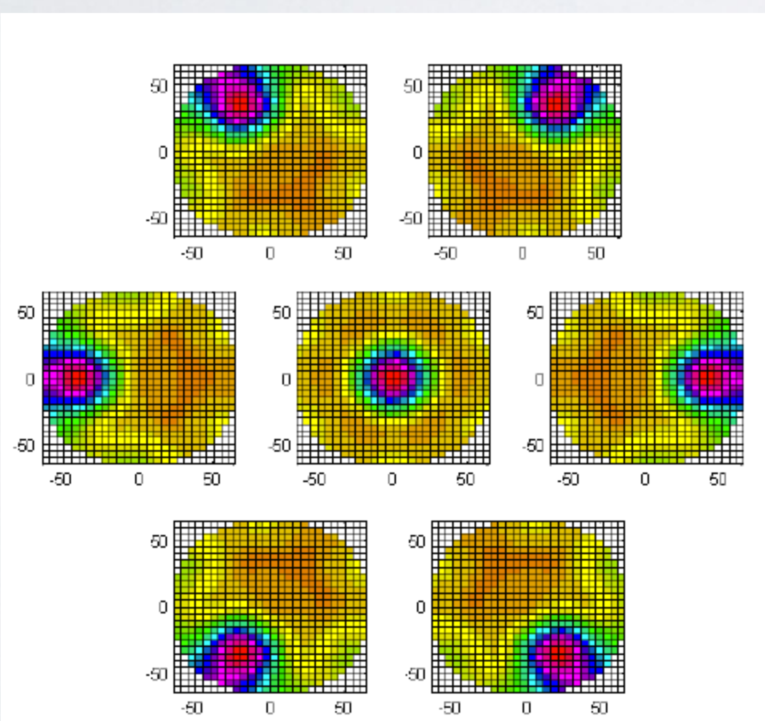
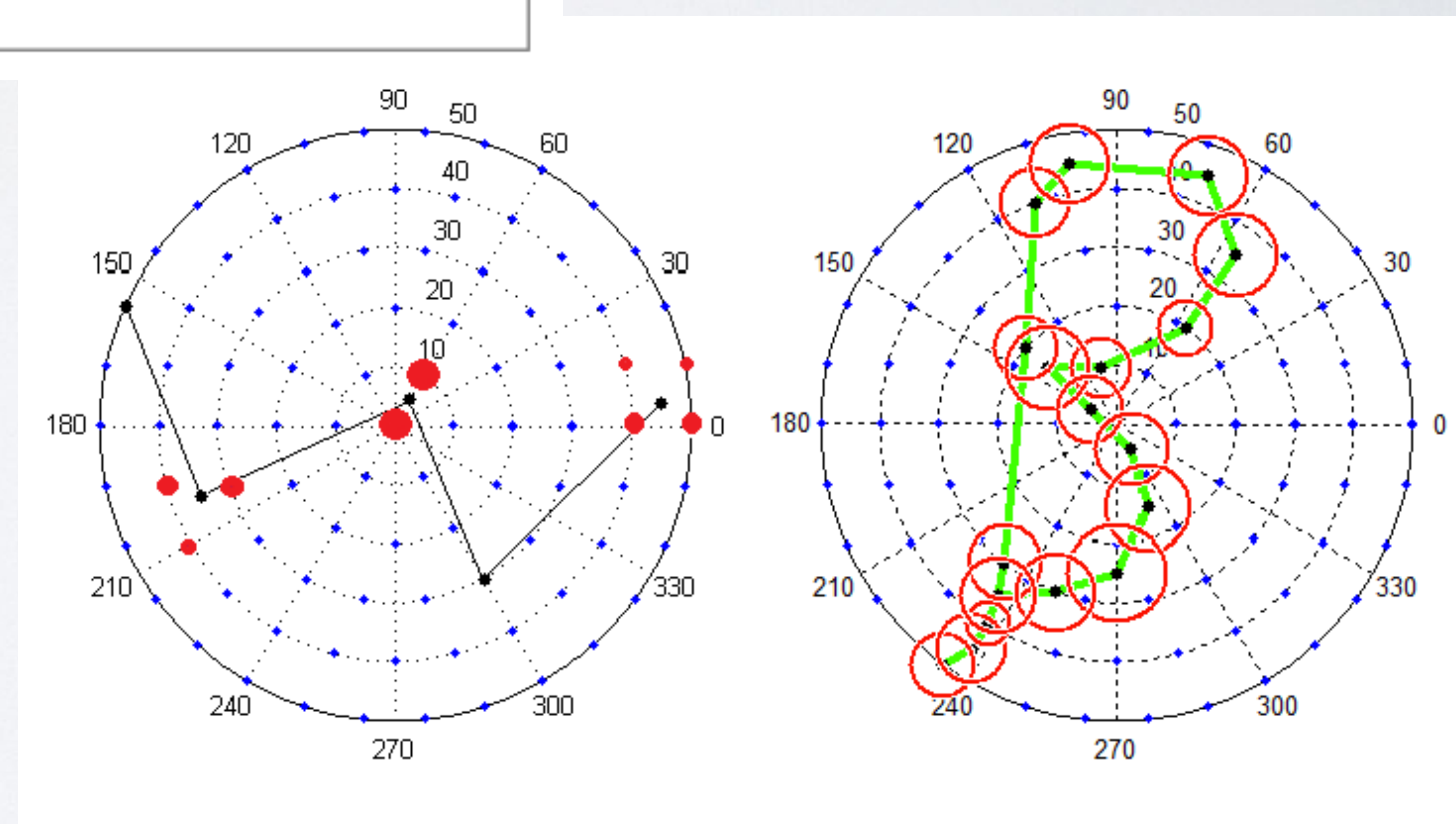
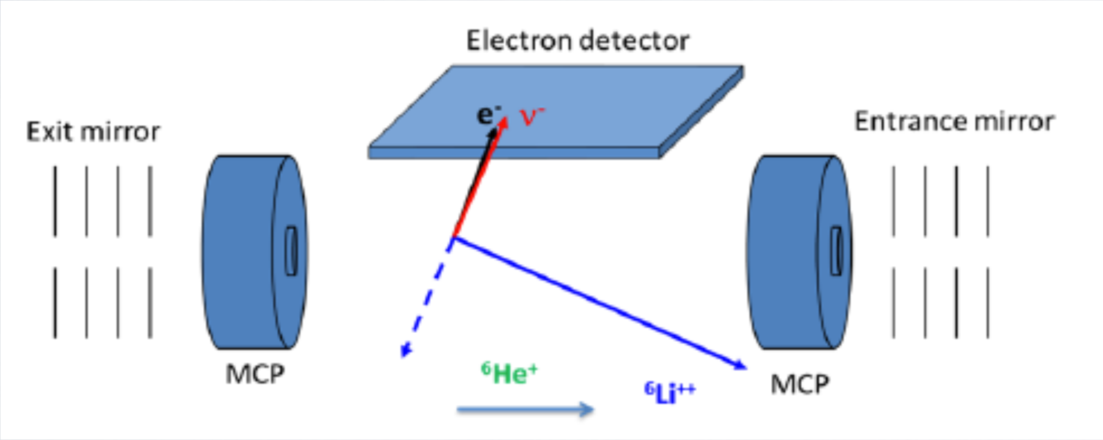


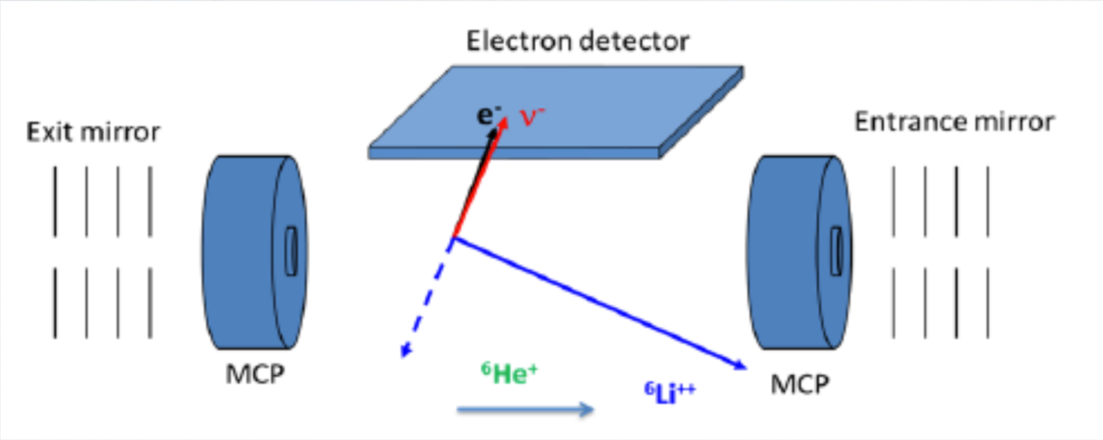
LAPS Calibration Maps



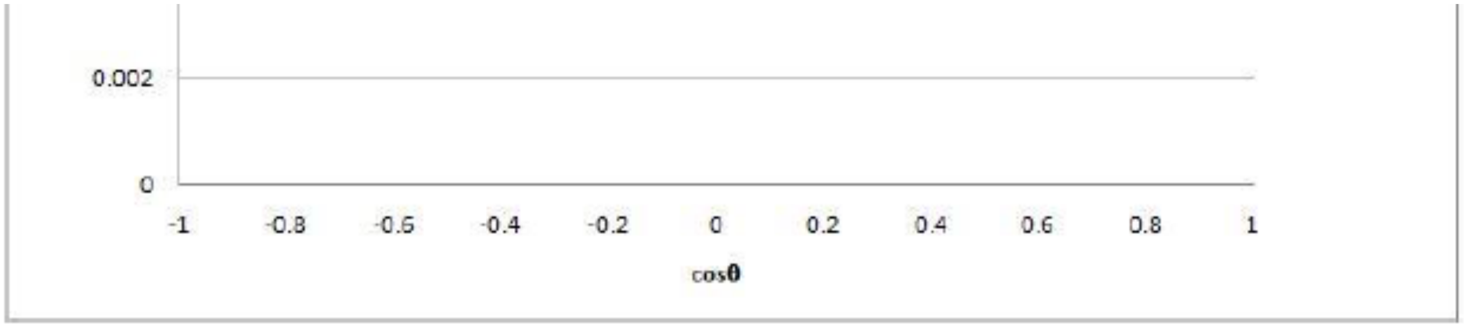








Source	Uncertainty	$\Delta a_{\beta\nu}$ ($\times 10^{-3}$)
LAPS Energy	5 %	0.86
LAPS Position	5 mm	0.71
MCP Position	1 mm	0.22
^{6}Li TOF	5 ns	0.23
Bunch size	1 cm	1.38
Total		1.80



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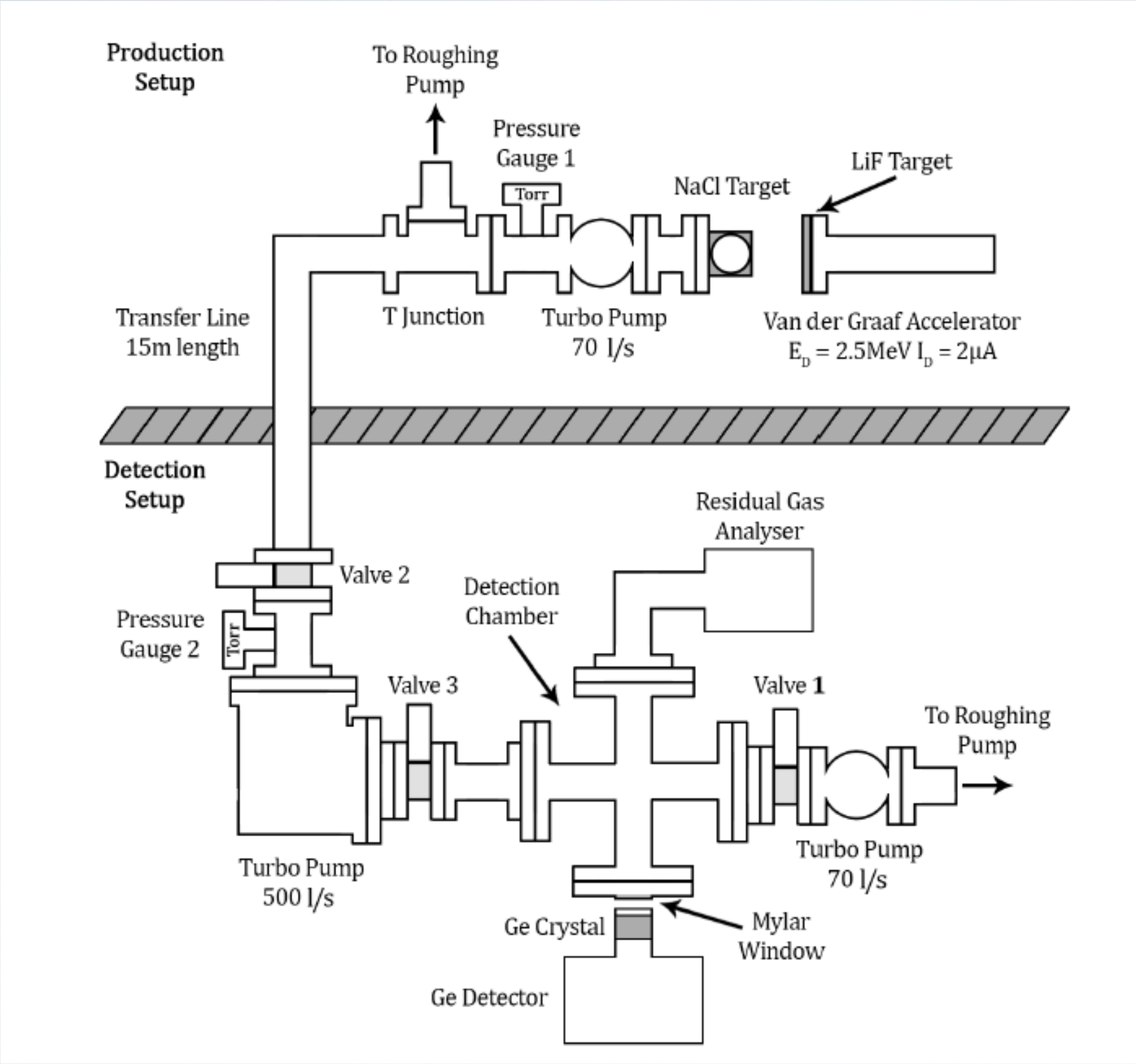
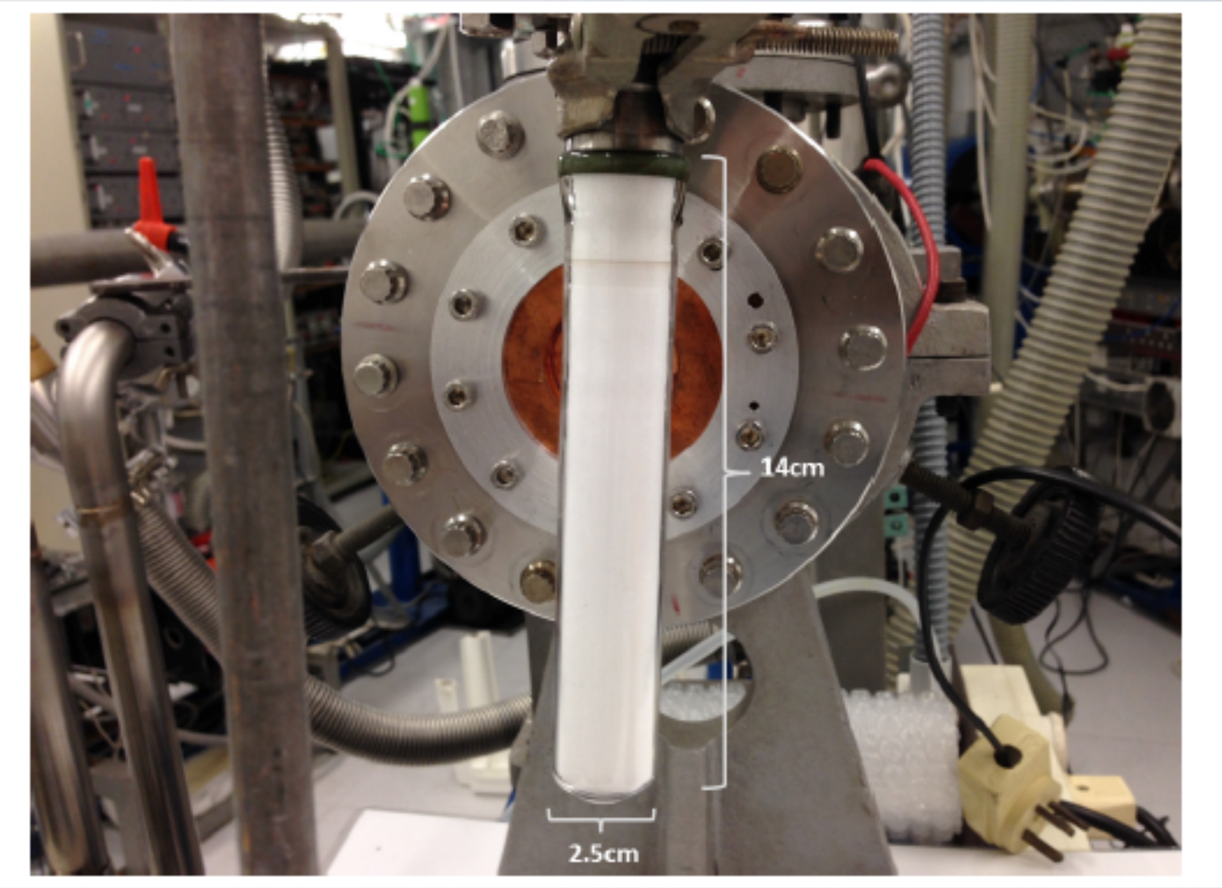
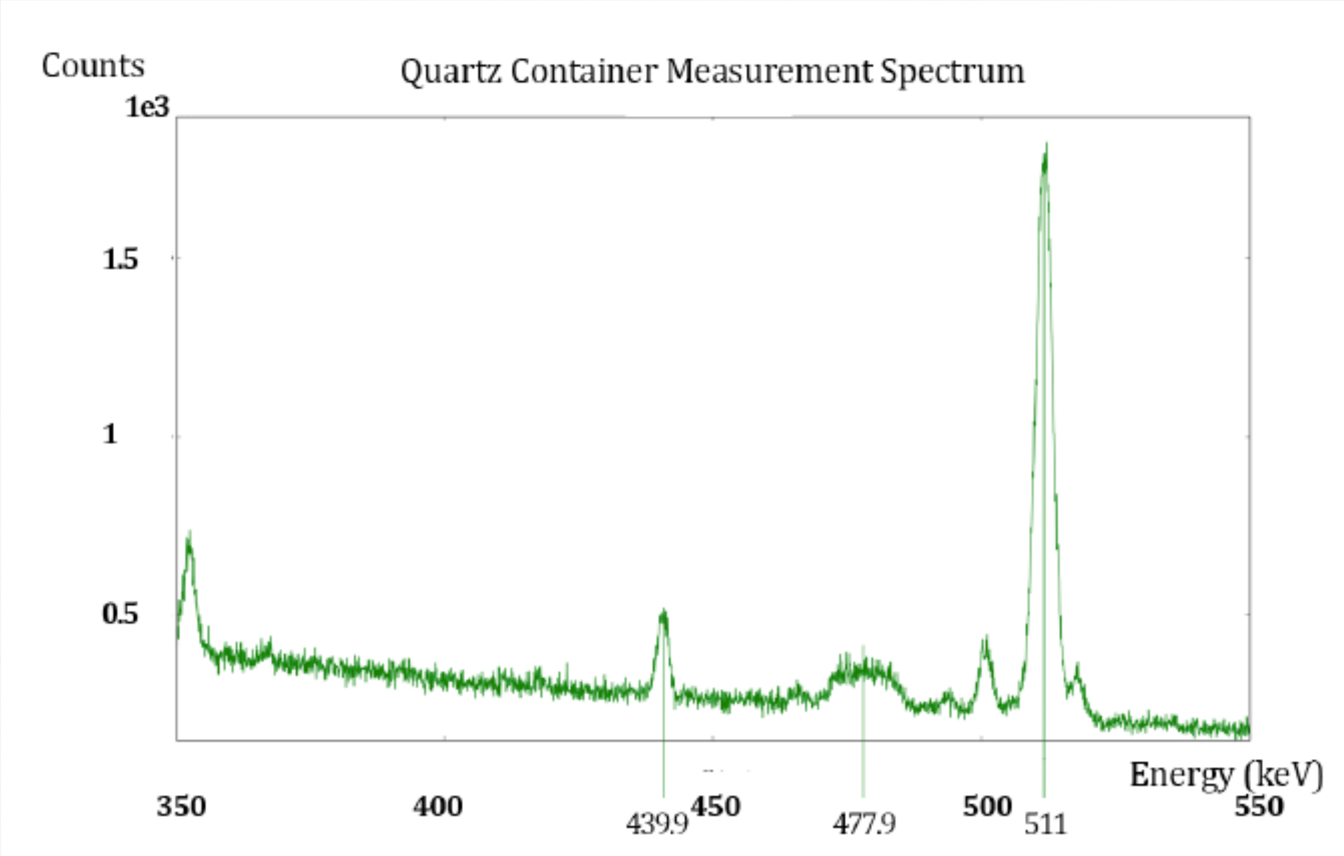
Production Tests – ^{23}Ne





^{23}Ne production and transport demonstrated.

Currently replacing heating element to increase yield.



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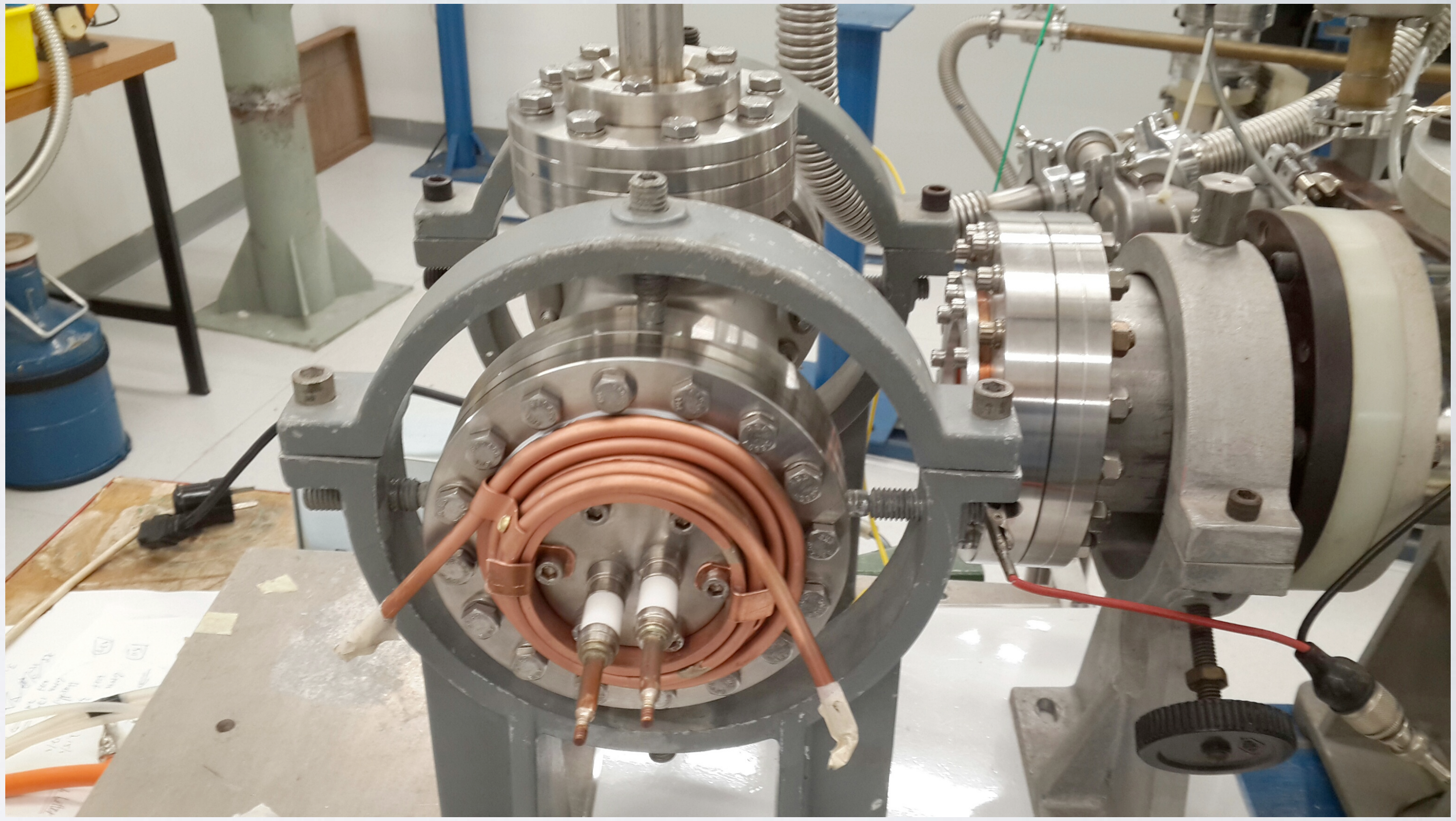
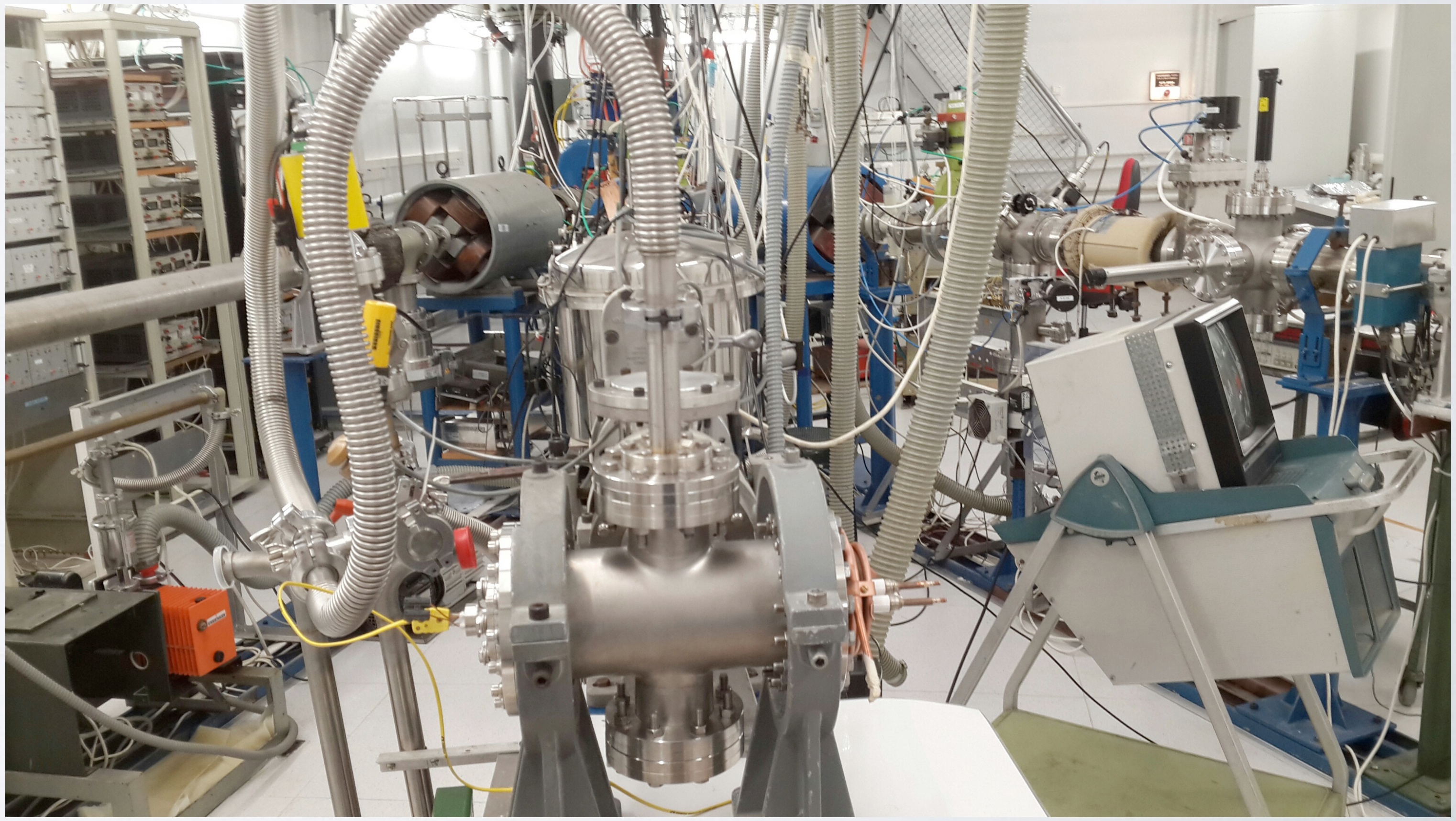




New production chamber containing evaporation source heater + crucible installed over the last week.
Should allow us to melt the NaCl.
First run planned for next week.

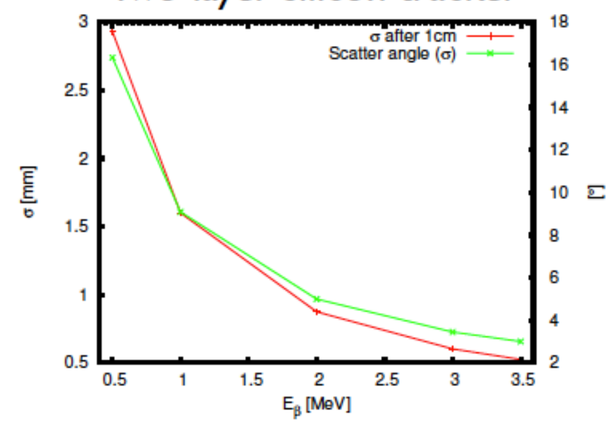
Direct cos(θ) reconstruction

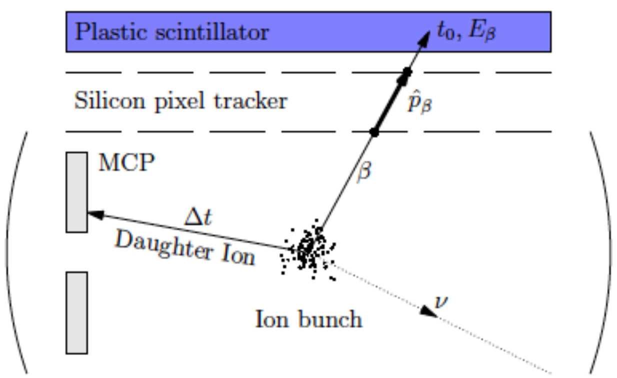
One layer silicon + ion bunch located by pick-up electrode

STAR HFT silicon tracker
thickness: 50μm
position resolution: 20μm

Ion bunch longitudinal extent: ~5mm

Two-layer silicon tracker





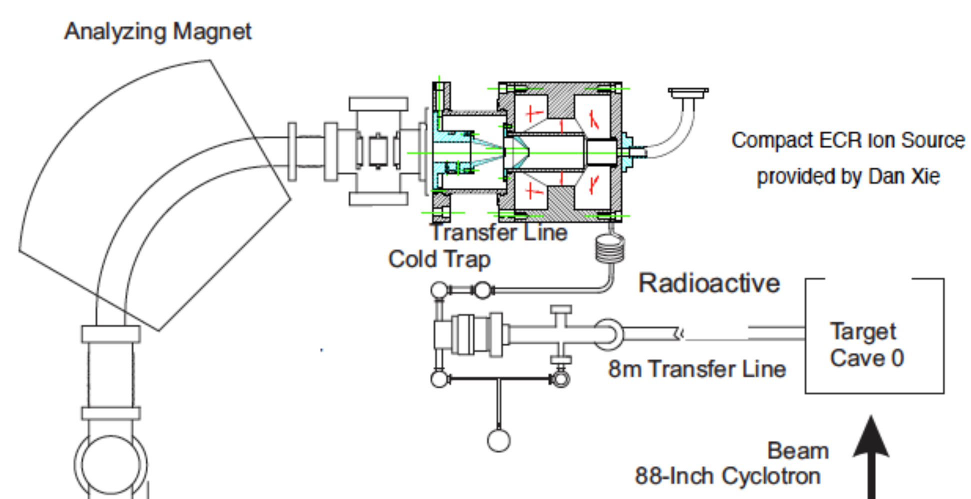
$p_\nu^2 = p_e^2 + p_+^2 + 2p_e p_+ \cos\theta_{e+}$

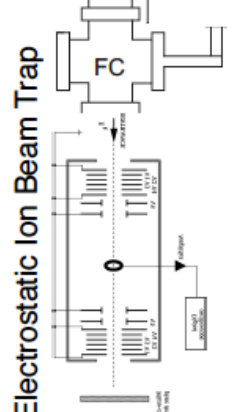
$p_+^2 = p_e^2 + p_\nu^2 + \ldots$

$\sqrt{p_e^2 + m_e^2} + \sqrt{p_\nu^2 + m_\nu^2} = Q + (m_e + \ldots$

Sufficient to measure:
beta direction (no ene...

LBL setup almost identical.
Using silicon tracker for beta detection/tracking.
Based on STAR HFT Tracker.
Program led by Yuan Mei.

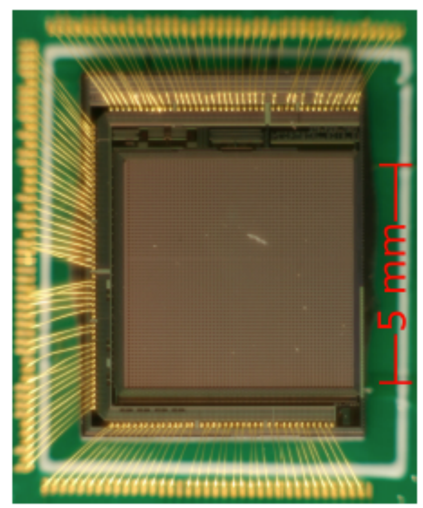


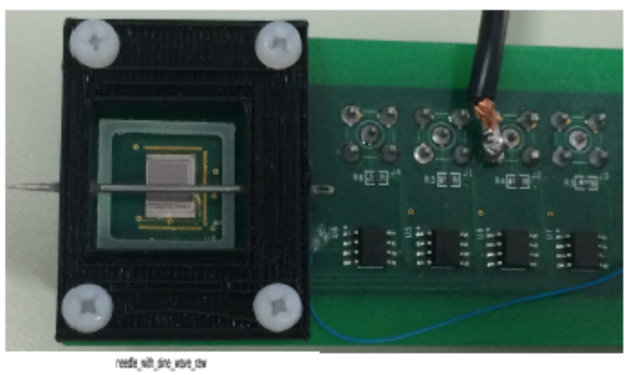


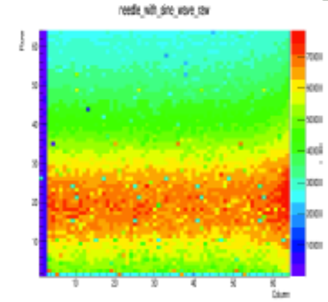
Part of O-14 apparatus

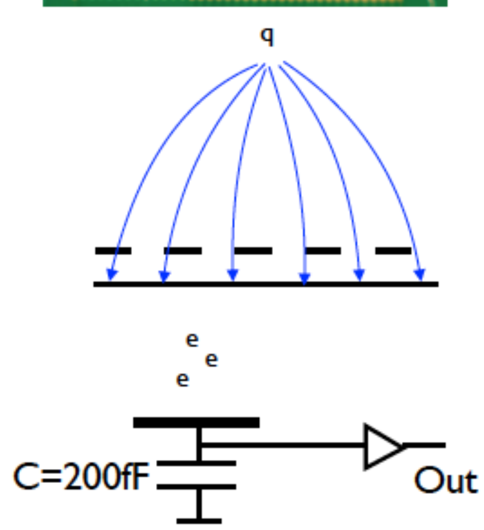
Located on Cyclotron roof

Transverse beam profile measurement





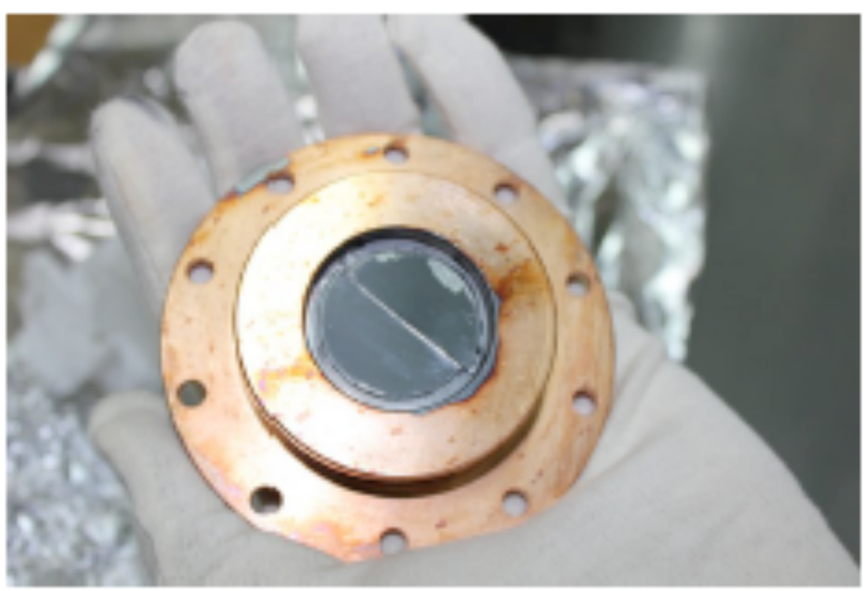


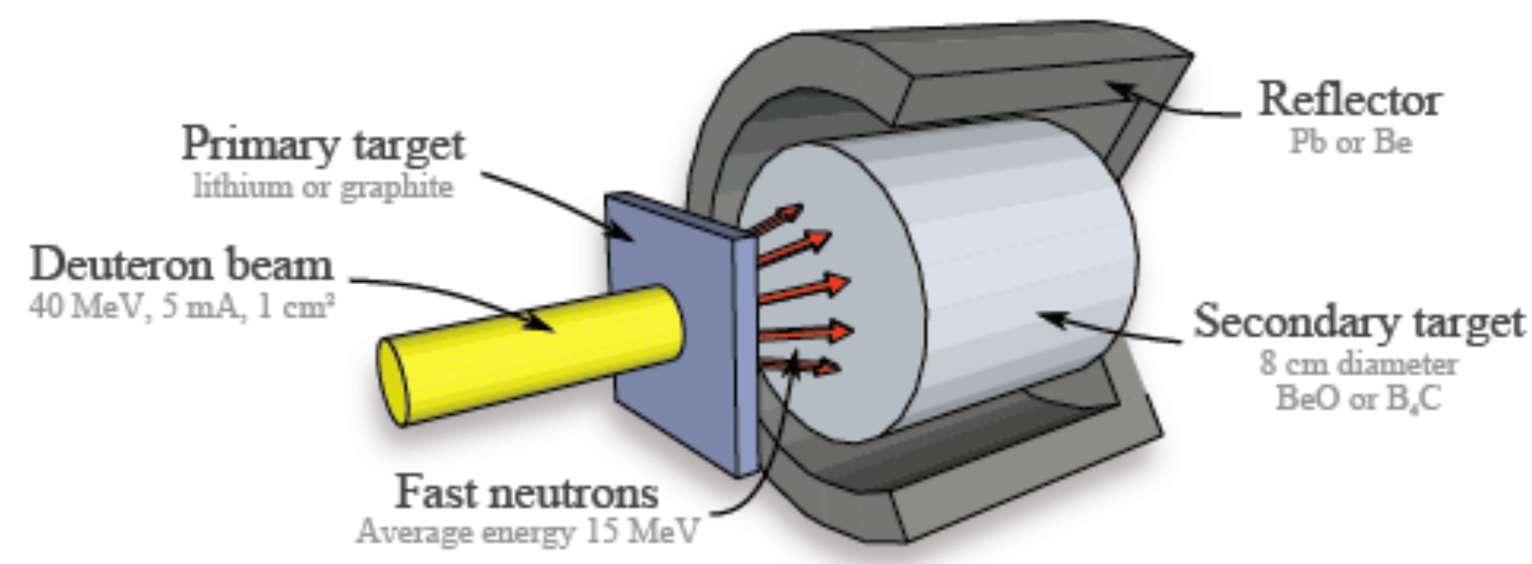


- 80X80μm pixel size, 64x64 pixel array
- Standard 0.35μm CMOS process, no post-processing
- First version already working, with high noise
- Second version, <30 e- noise on each pixel, available late-2014
- In-chip signal processing, good for large scale array

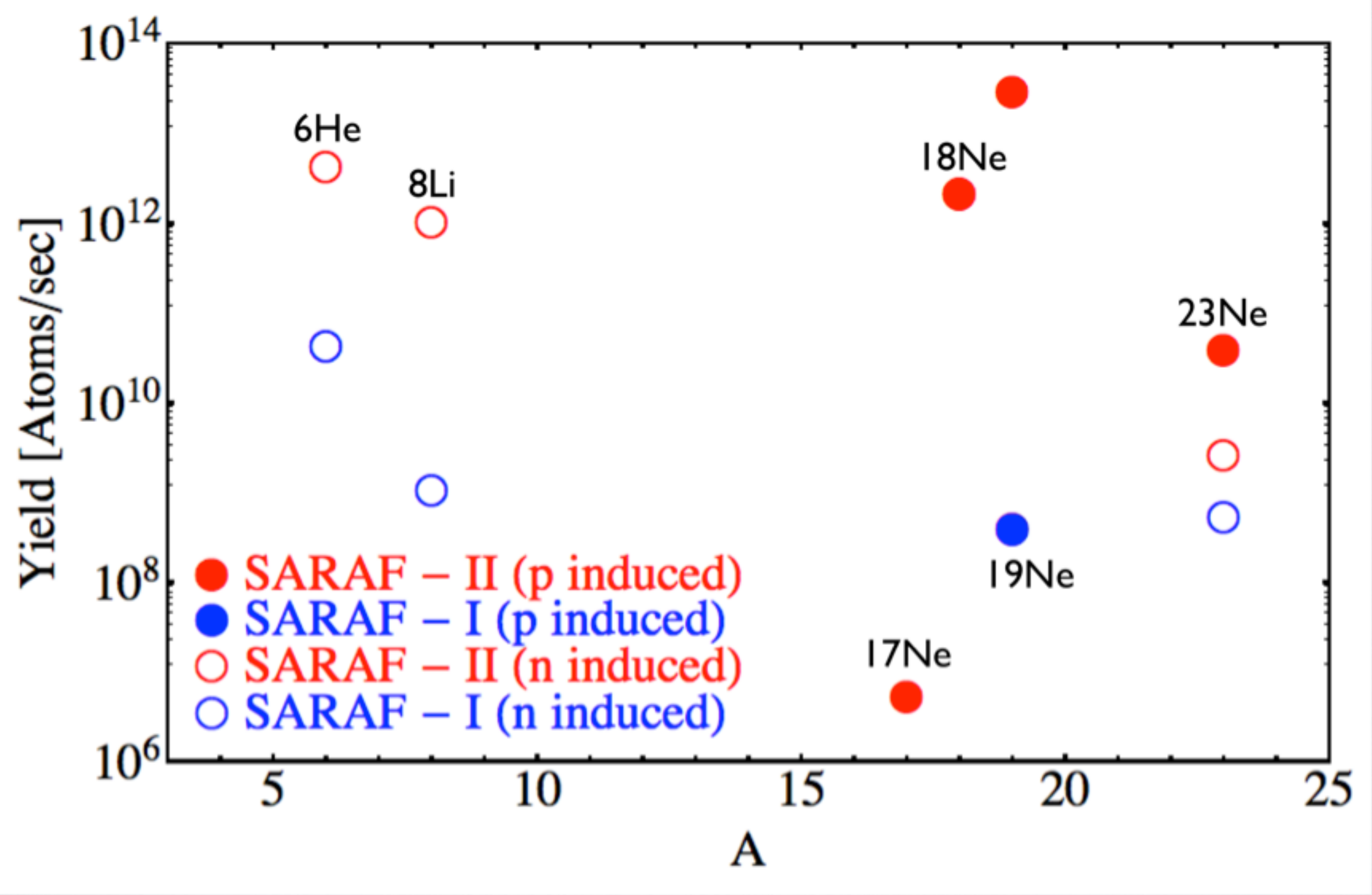
SARAF

- New, (very) high current p/d accelerator (5mA/up to 40MeV) under construction at SOREQ.
- Neutron production also possible with Liquid-Li (for eg., but under construction).
- Currently running d beams on LiF target (SARAF/WI) for neutron beam production (very similar energy to NG).

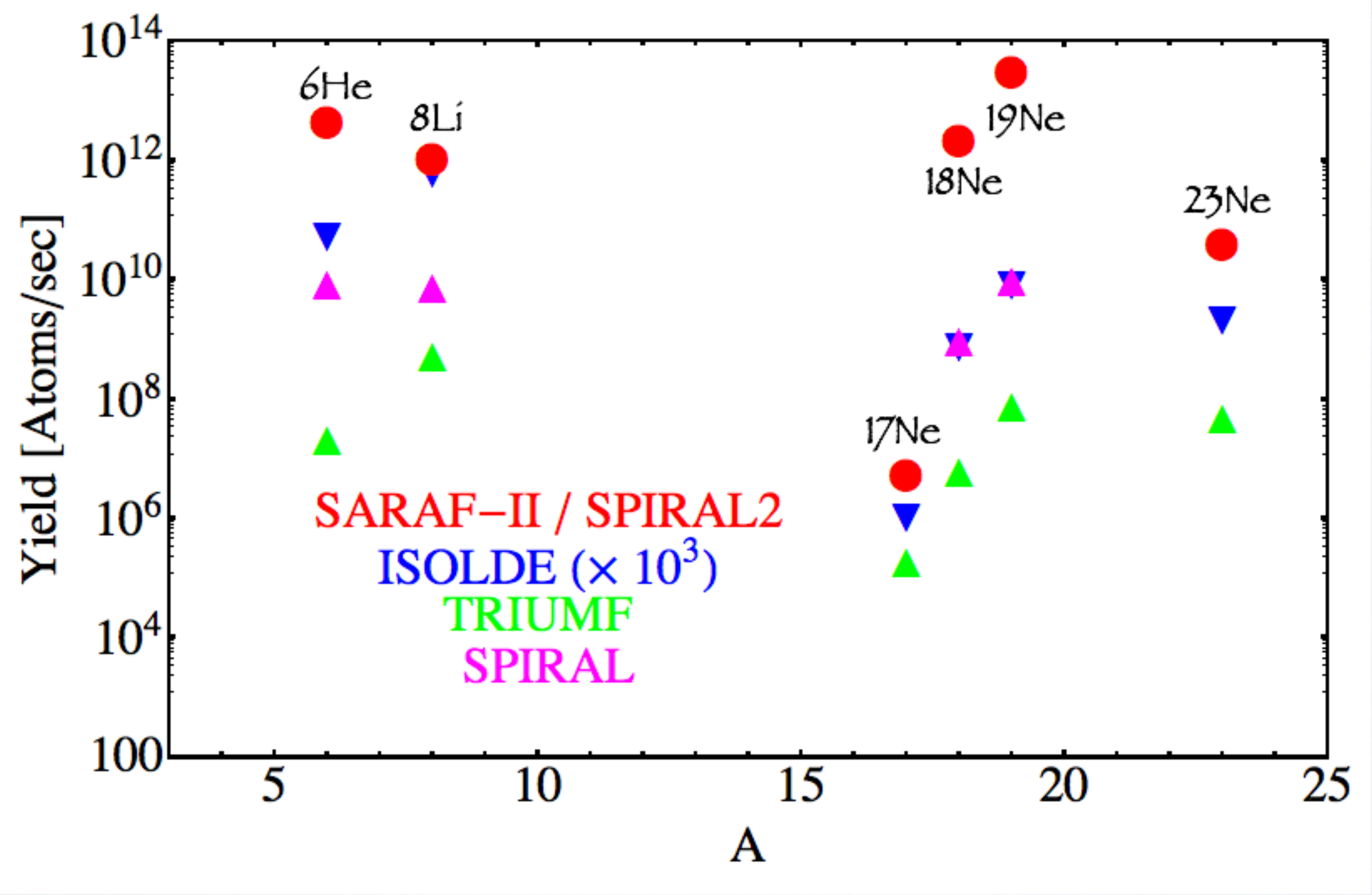


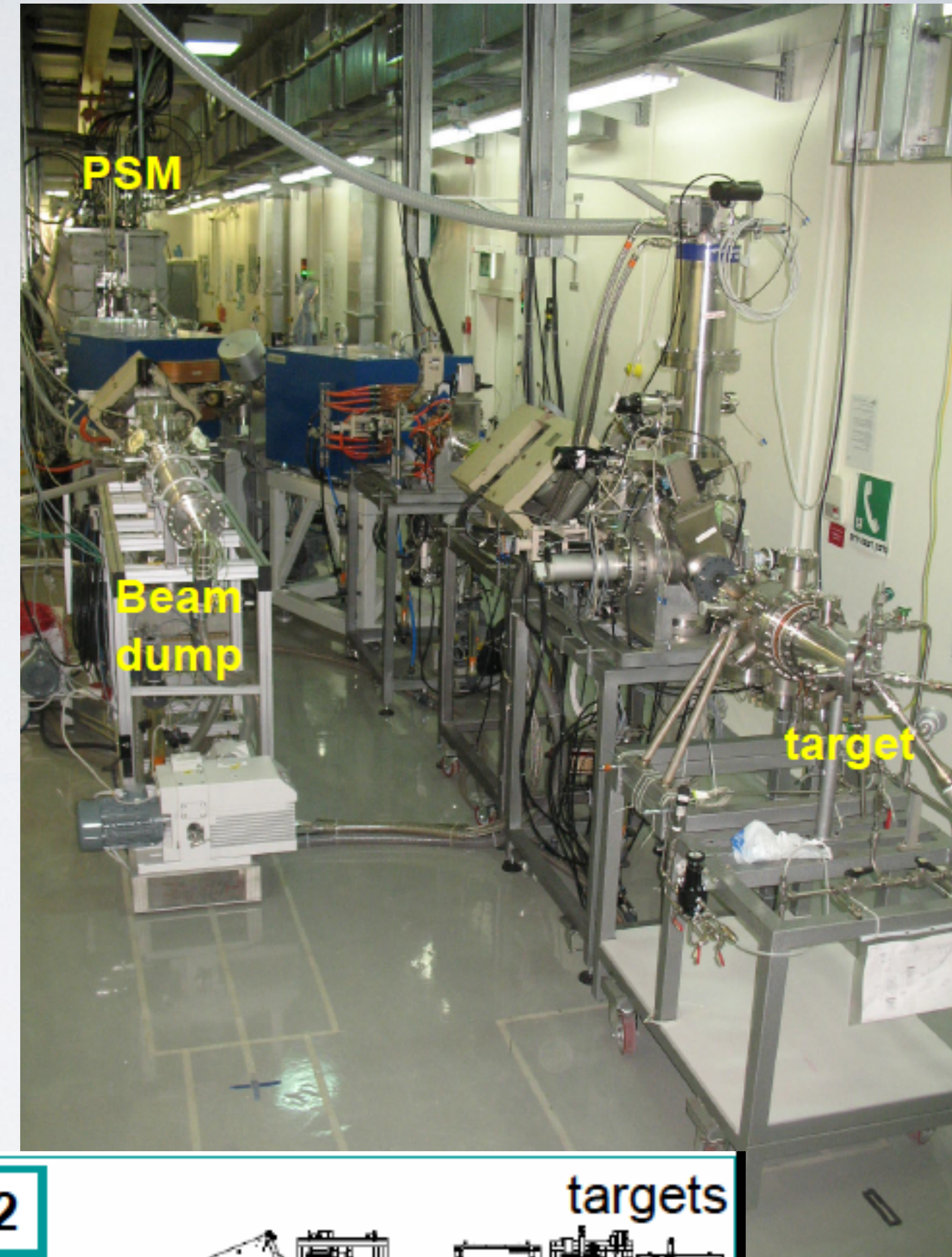


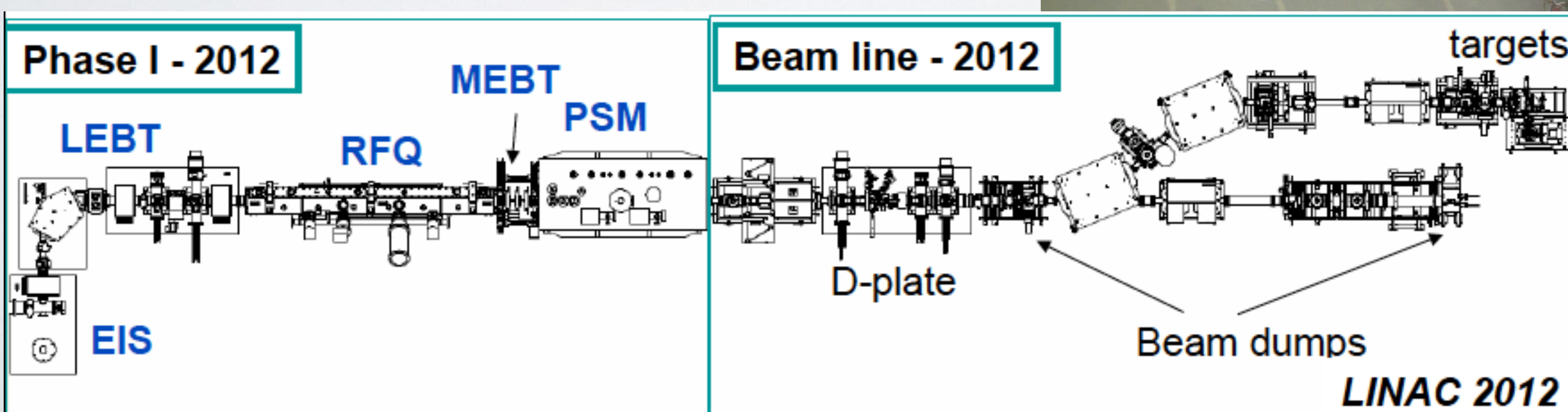
SARAF Projected Yields



SARAF Projected Yields

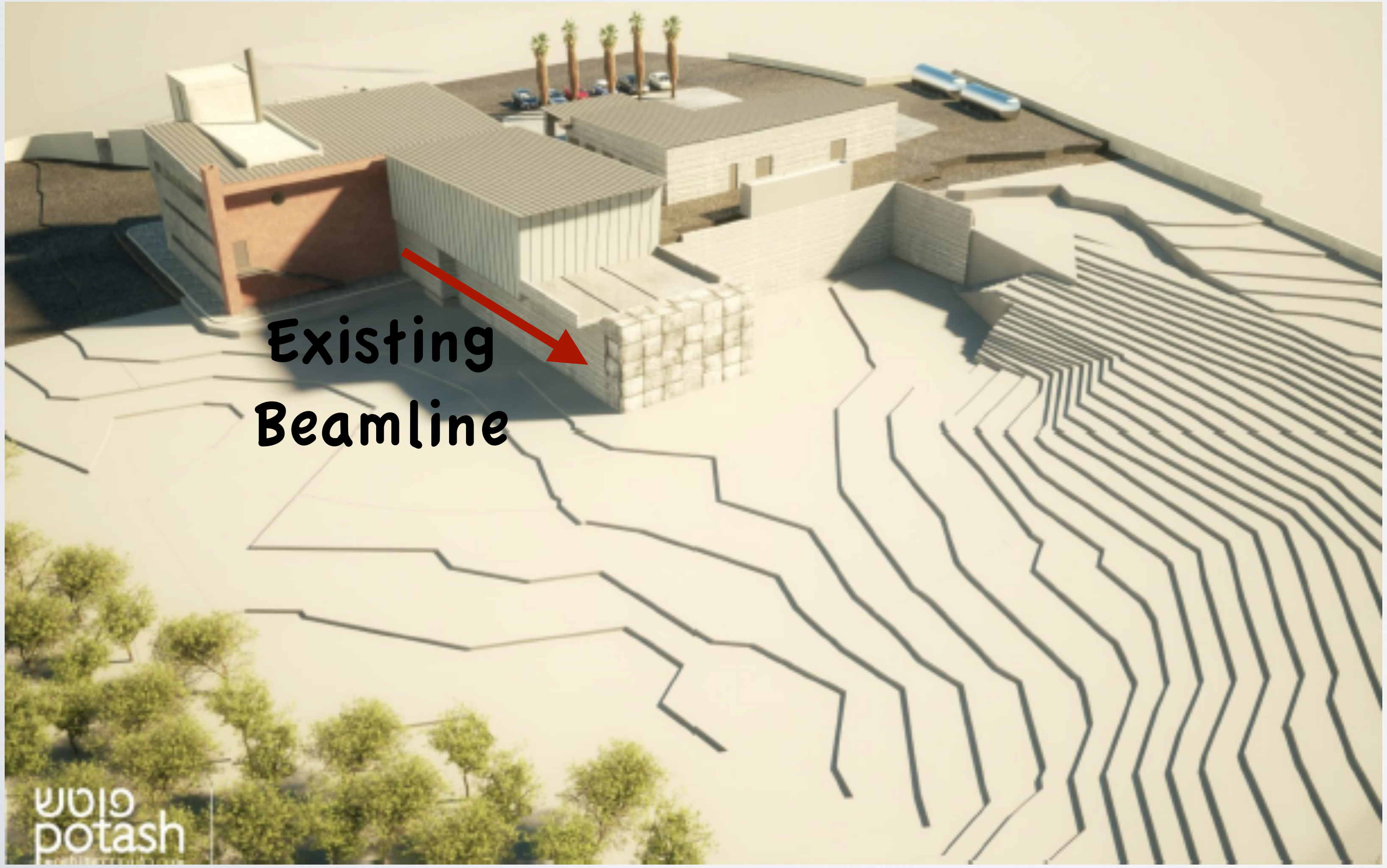



PSM
Beam dump
target


Phase I - 2012
Beam line - 2012
LEBT
RFQ
MEBT
PSM
EIS
D-plate
Beam dumps
targets
LINAC 2012

SARAF Phase-I Target Area

* ~2MEuro project approved by IAEA + Support from Pazy Foundation.
* Construction of dedicated beam line, 2 production targets, and 4 experimental areas.
* Experimental areas for: Laser lab, EIBT, Neutron activation, Positron production.
* Target date - labs open end of 2015.



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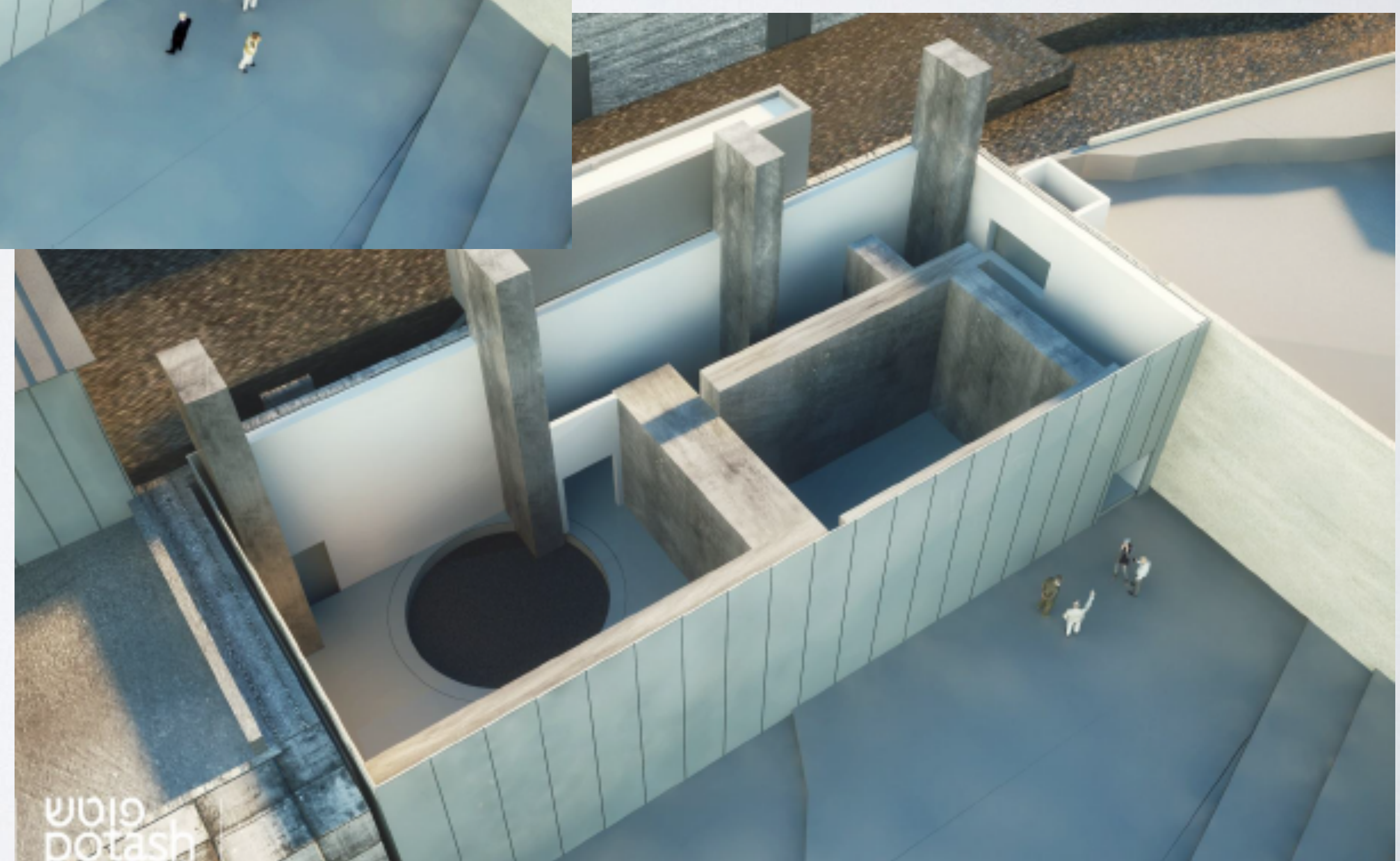
SARAF Phase-I Target Area

Lab Areas:
Electrostatic trap
MOT Trap
Activation measurements
Slow positron beam

Production area:
2 production targets
(LiLiT + Replaceable)



Polarization Dependent Observables

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu}\right] \left[\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}\right] + \frac{< \vec{J} >}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] \right\}$$

- Requires polarization of initial sample.
- Measurement typically of position asymmetry.
- Usually flip field for systematic control.

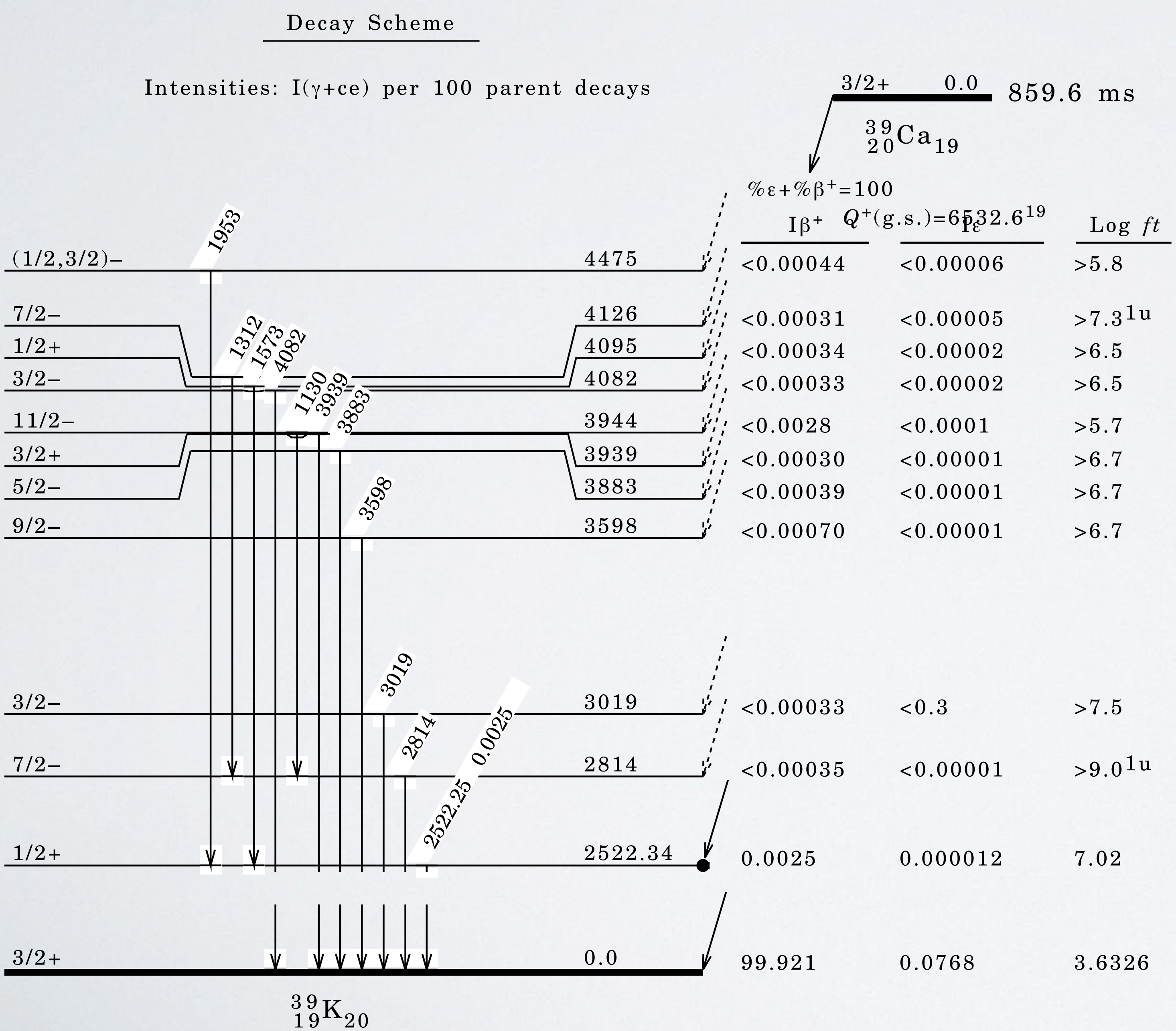
Neat trick

- Add on-axis magnetic field for Zeeman splitting.
- On-axis field does not effect the trajectories (V X B = 0).
- Polarize ions with circularly polarized lasers.
- Due to large doppler shift (high energy ions) → two independent ion populations (parallel/anti-parallel).
- MCP hit is determined by direction of ion → each MCP sees only one population.
- Need polarizable ions (usually singly ionized alkaline earth metals - which look like alkali metals when singly ionized).

EXAMPLE ^{39}K

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu}\right] \left[\frac{J(J+1) - 3 < (\vec{J}\cdot\vec{j})^2 >}{J(2J-1)}\right] + \frac{<\vec{J}>}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] \right\}$$

Translates to TOF on MCPs



$$^{39}Ca \rightarrow {}^{39}K + \beta^+ + \nu_e$$

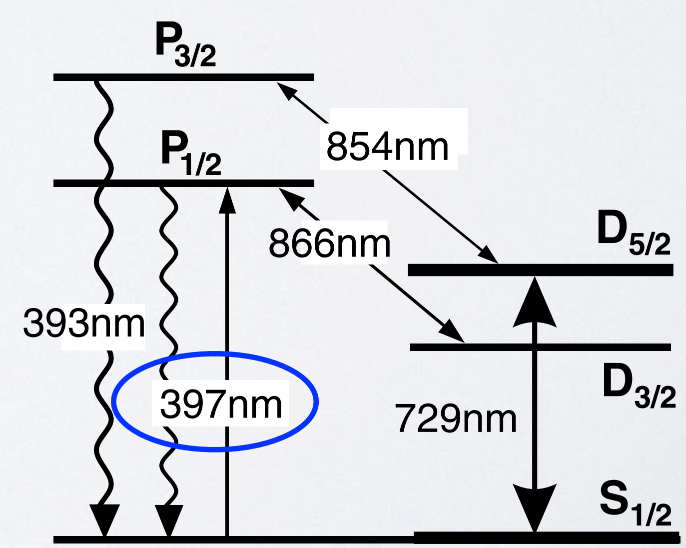
Mirror decay $3/2^+ \rightarrow 3/2^+$

Combination GF and F but calculable

Q = 6.532 MeV

$\tau_{1/2}$=860 ms

For 4.2keV ~360GHz doppler shift → 720GHz separation.



"High Energy" Chemistry

An experiment looking for a theorist

- Production of radioactive molecules/dimer/clusters is fairly trivial (usually a side effect of the production of radioactive atoms/ions).
- Ionization of such molecules - also trivial.
- ES trap can easily trap molecules of hundreds of amu (also used for bio-molecules).

- Radioactive decay dumps a lot of energy and momentum into the decay products.
- Time scale for decay/emission of shakeoff products is effectively instantaneous.

- Detect molecular decays in ES trap.
- Energy/Momentum sharing between decay products (electronic interaction timescales?).
- Angular correlation in decays (potential?).
- High detection efficiency.
- Mass resolution good enough for selection of different numbers of radioactive atoms in clusters

$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}{}^{23}\mathrm{Na}_3}{{}^{4}\mathrm{Na}_{23}} \sim \frac{2}{92}$$

$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}_2{}^{23}\mathrm{Na}_2}{{}^{4}\mathrm{Na}_{23}} \sim \frac{4}{92}$$

Trivial

Future Studies

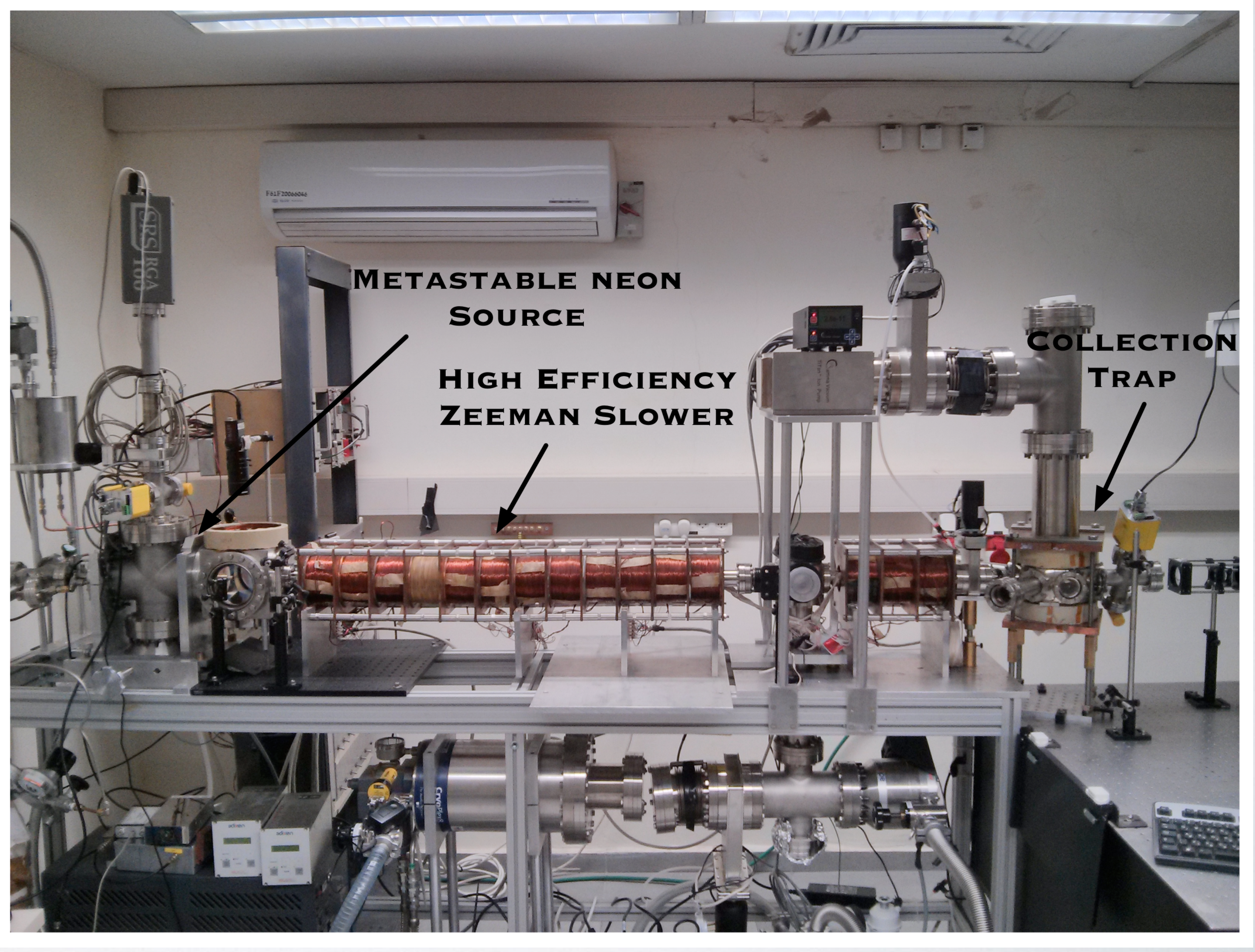
(Undergraduate/Graduate Projects/Theses)

- Production methods.
- Transverse/Longitudinal cooling of ion bunch.
- Detection Schemes.
- Ion beam polarization.
- Detector designs.

4 Slides about atom traps....

Ne Atop Trap Setup @ HUJI
NeAT Facility

* Stable isotope trap complete (once laser fixed...).
* Science chamber being designed.
* New source installed and tested.
* Rare neon production tested.
* Isotope shift experiment being set up.
* Moving to new lab @SARAF end of 2015.



Ne Atop Trap Setup @ HUJI
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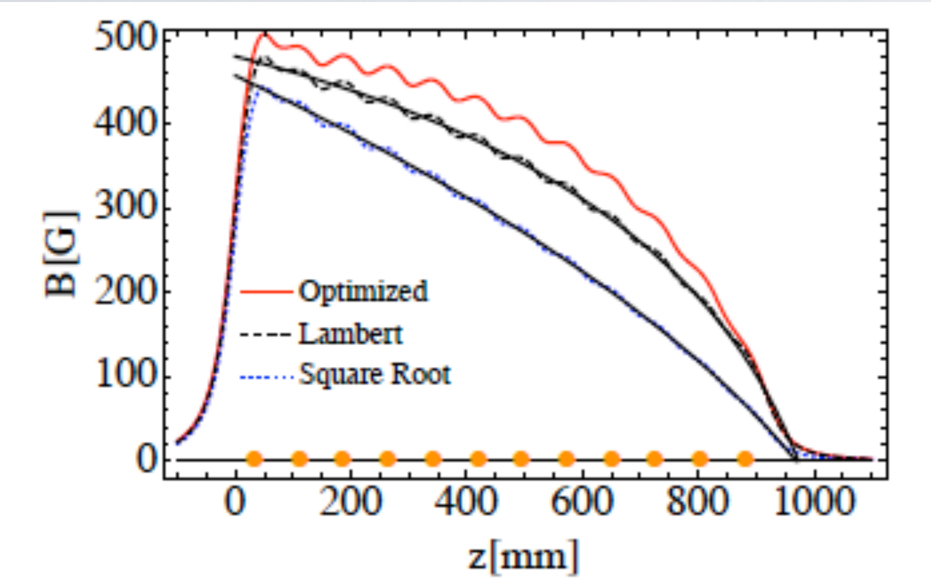

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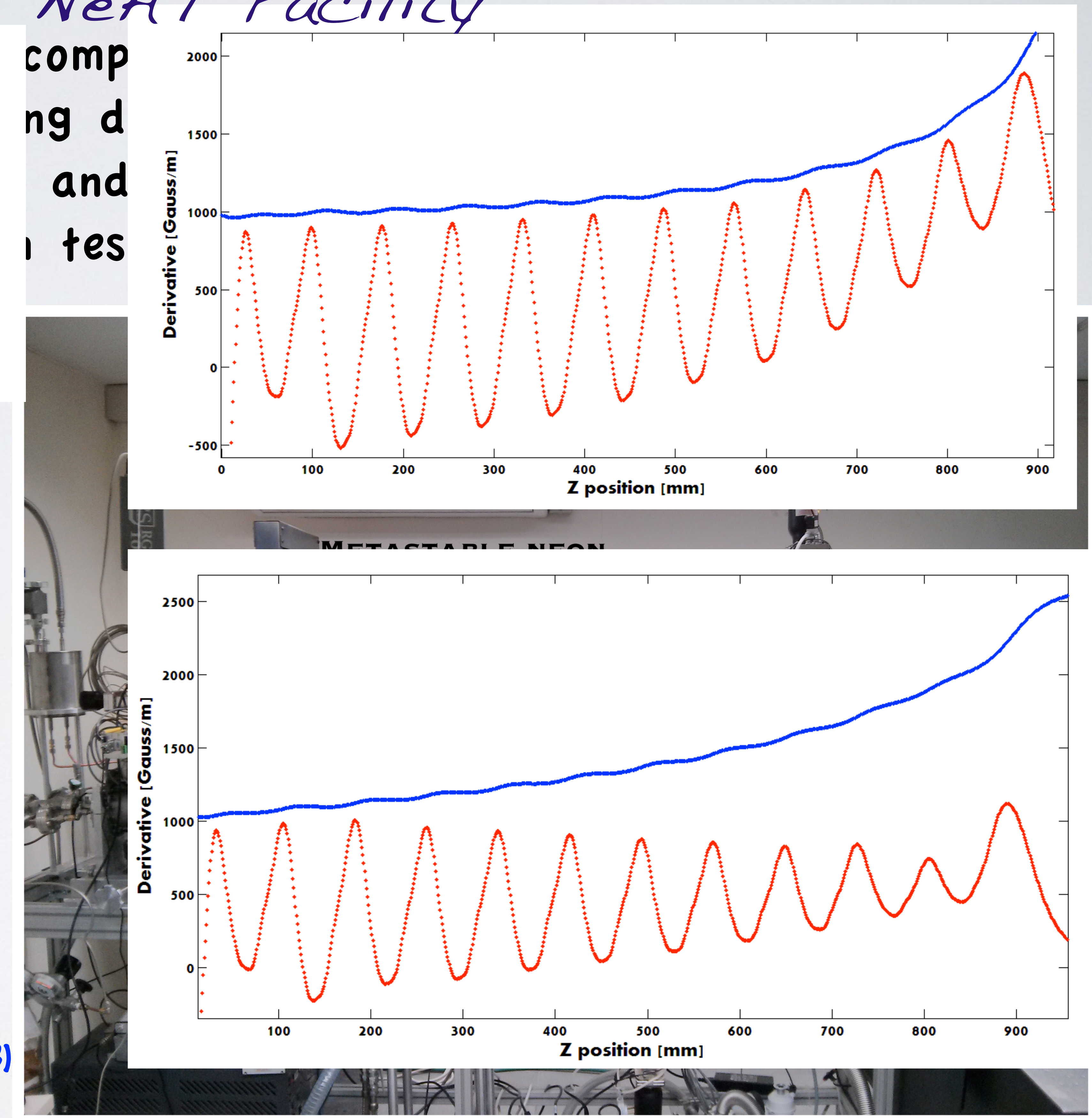
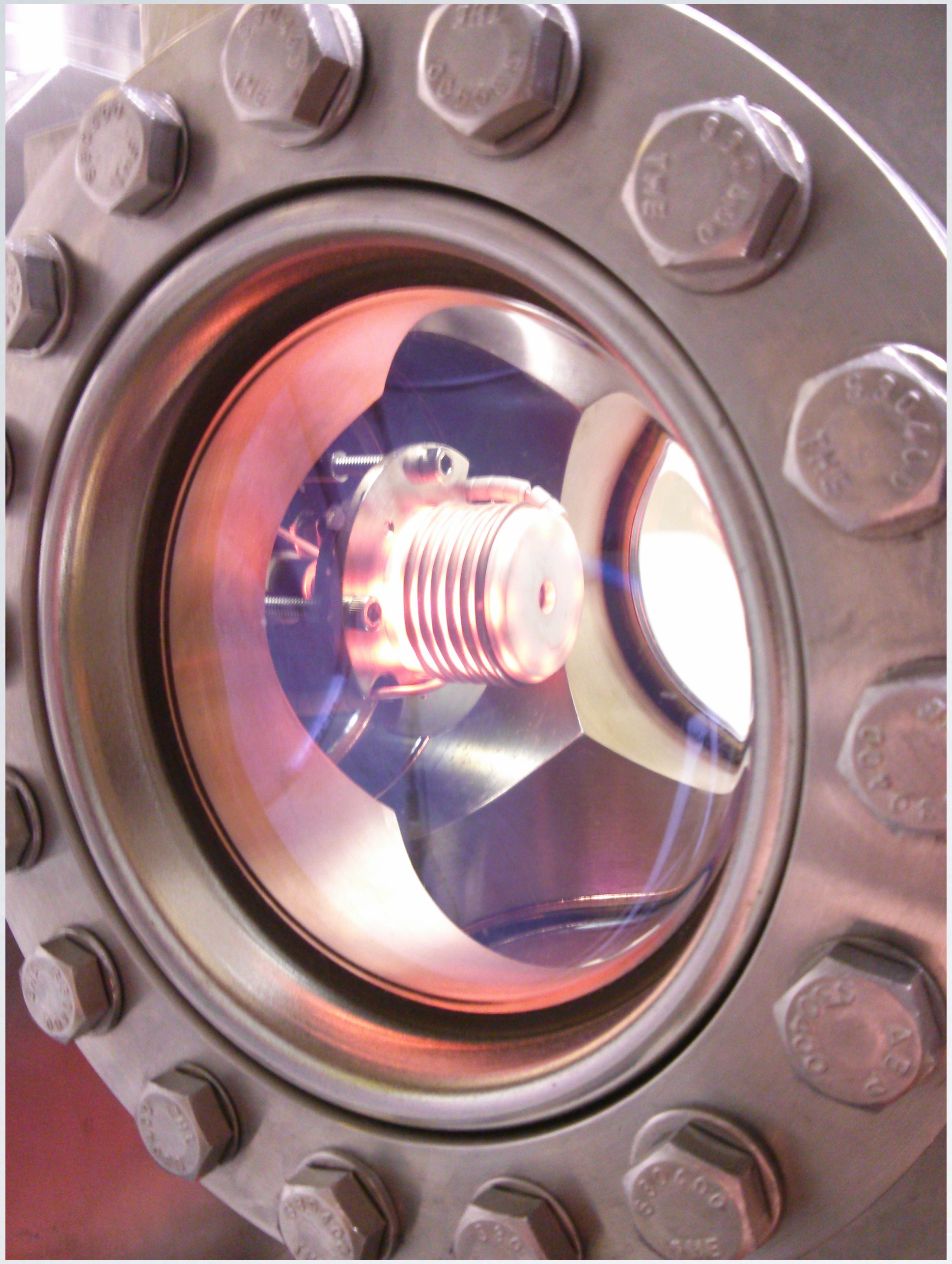
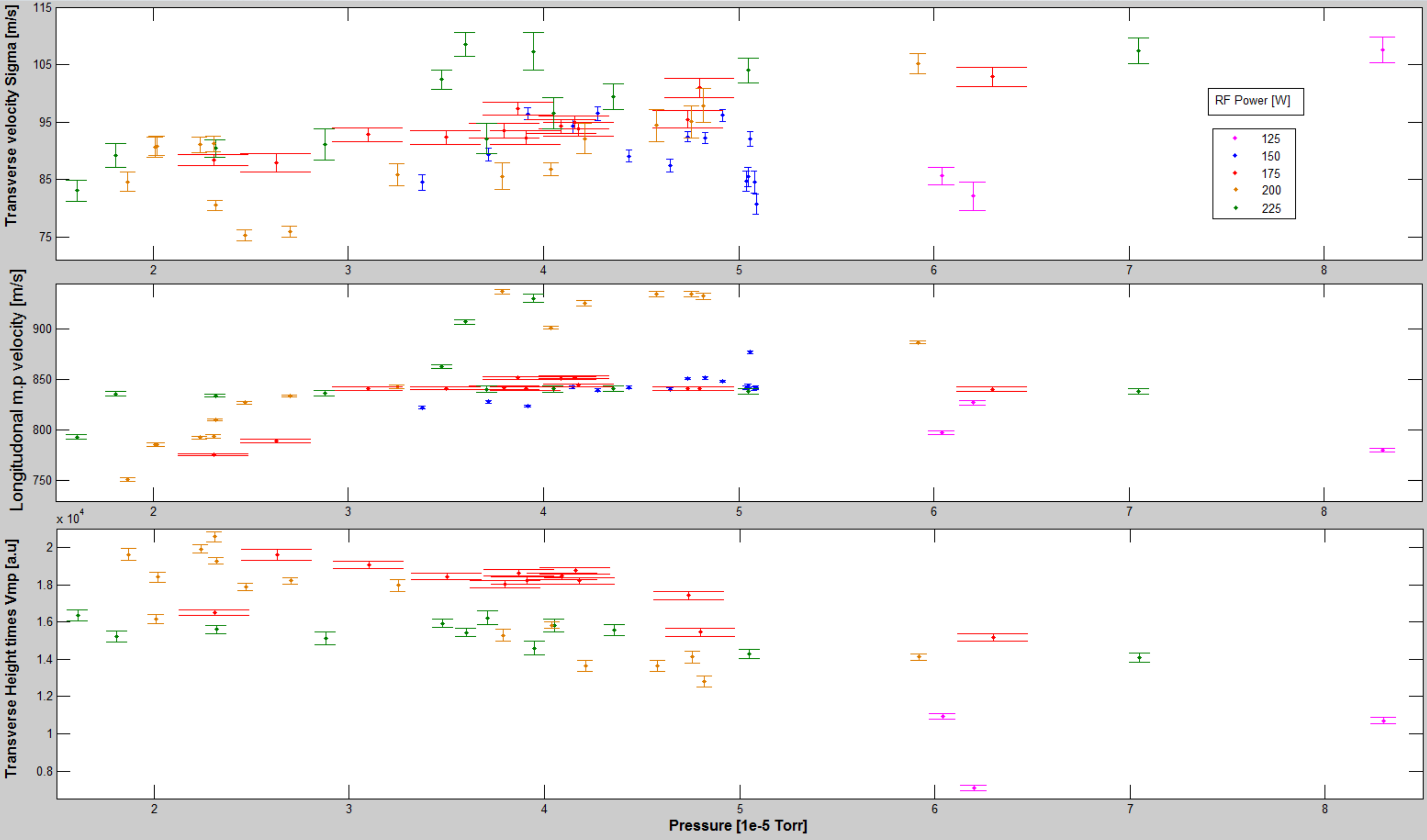
up.

- Moving to new lab @SARAF end of 2015.



Ben Ohayon and GR, JINST 8, P02016 (2013)
B. Ohayon, Y. Shalibo, and GR, In preparation





Transverse velocity Sigma [m/s]
Longitudonal m.p velocity [m/s]
Transverse Height times Vmp [a.u]
x 10^4
Pressure [1e-5 Torr]
RF Power [W]
125
150
175
200
225

Summary

- It is possible to circumvent Ernshaw's theorem by electrostatic trapping of a moving bunch of ions.
- Trap design is extremely simple and cheap (much more so than conventional ion or optical traps).
- Trap design is almost a "black box" which can be easily transported to different experimental facilities.
- Ongoing development at LBL/WI.
- On track for ^{6}He measurements (and possibly ^{23}Ne/^{19}Ne).
- New facility/labs planned for end of 2015 w/very high yields.

Graduate/postdoc positions available!!!

In collaboration with:

WI:
Micha Hass
Daneil Zajfman
Oded Heber
Sergey Vaintrub
Tsviki Hirsch (NRCN)
David Melnik
Yigal Sachar

MPIK Heidelberg:
Klaus Blaum
Andreas Wolf
Dirk Schwalm

LBL:
Stuart Freedman (deceased)
Yuan Mei
Yury Kolomensky
Brian Fujikawa

HUJI:
Guy Ron
Tom Segal