Fishing in a sea of Xe

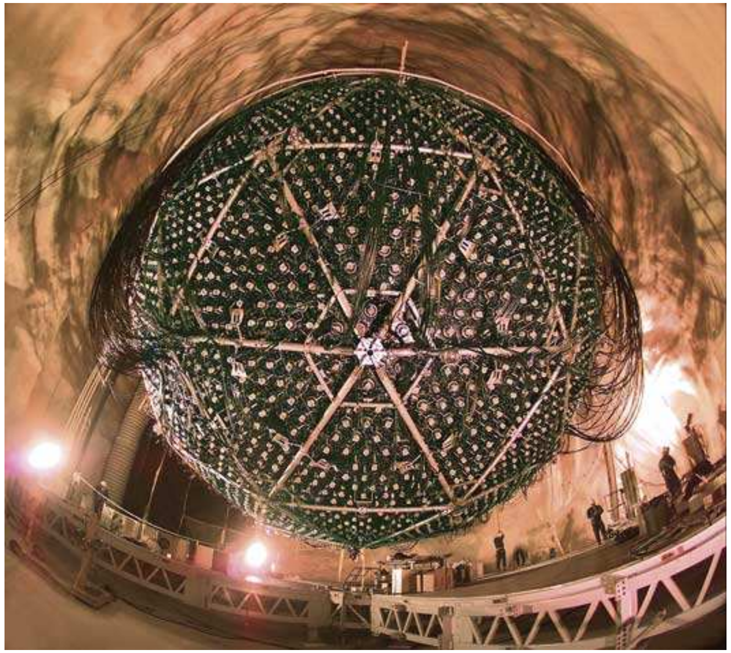
Barium-ion tagging for ^{136}Xe double-β decay studies with EXO

- The EXO-200 experiment
- Advantages of Ba^{++} tagging
- Ba^{++} tagging in GXe at Stanford

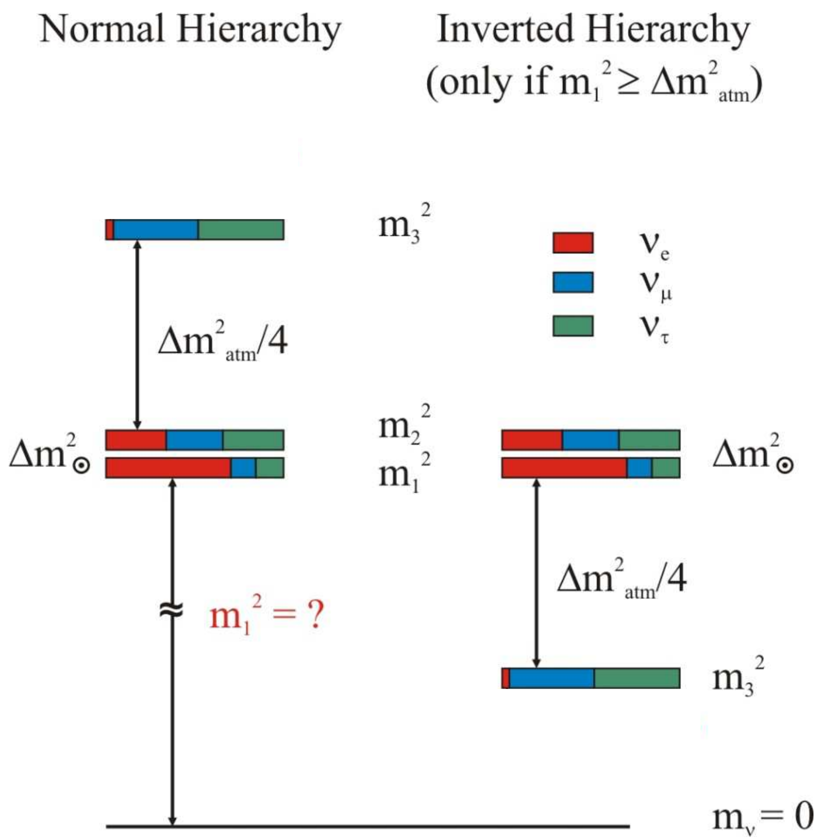
Thomas Brunner

TRIUMF – November 15, 2013

Neutrino oscillations



SNO, picture taken from http://www.oit.on.ca



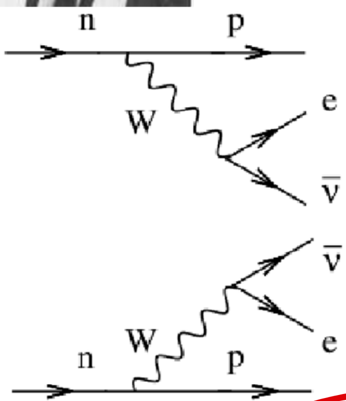
Relative mass scale

- Indicate a neutrino mass [1]
- Determination of mixing angle θ_{ij}
- Indicate mass hierarchy
- Determination of δm^2

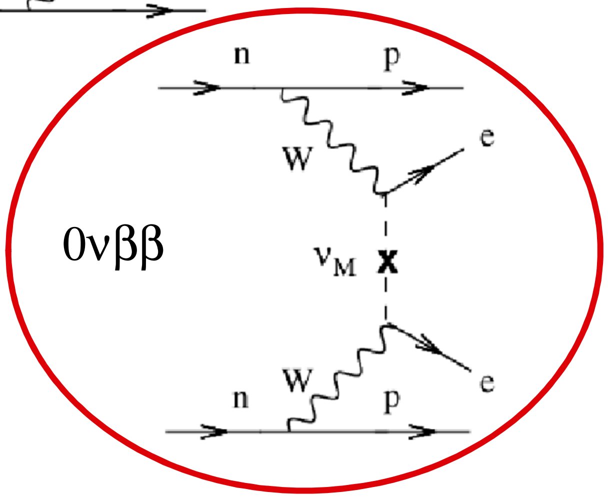
[1] T. Kajita and Y. Totsuka, Rev. Mod. Phys. 73(2001)85

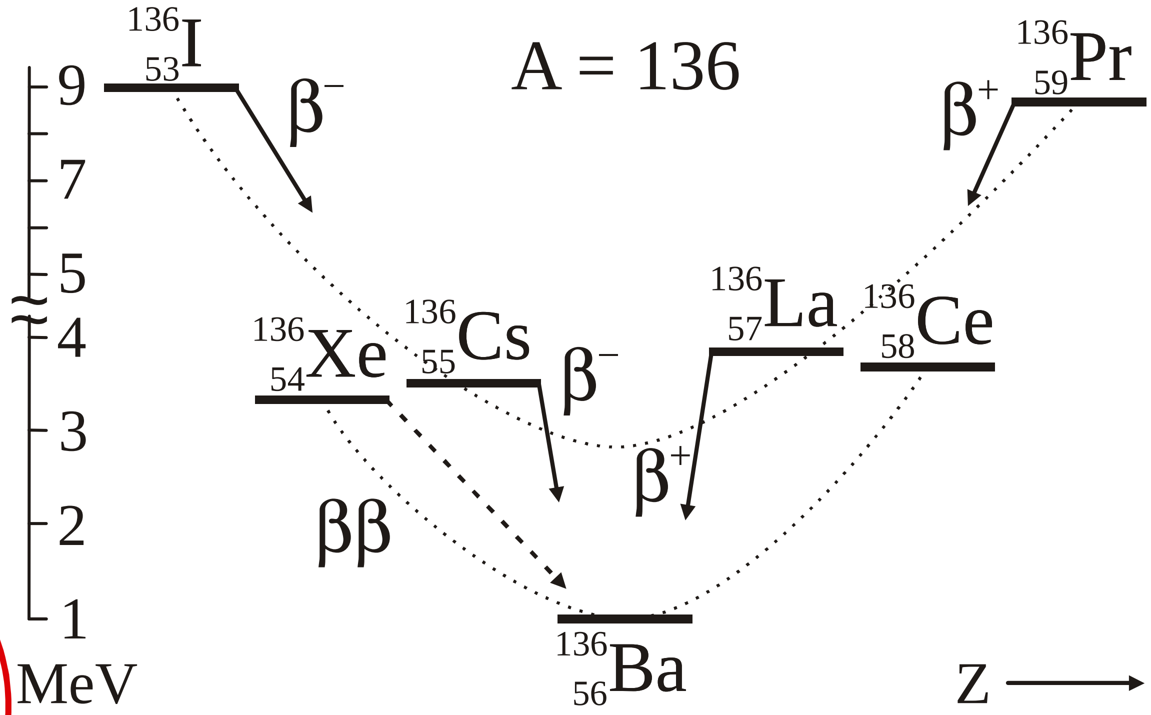
Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512



$2\nu\beta\beta$

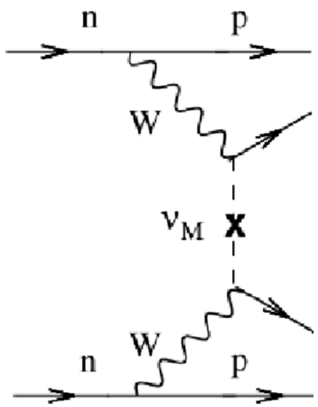


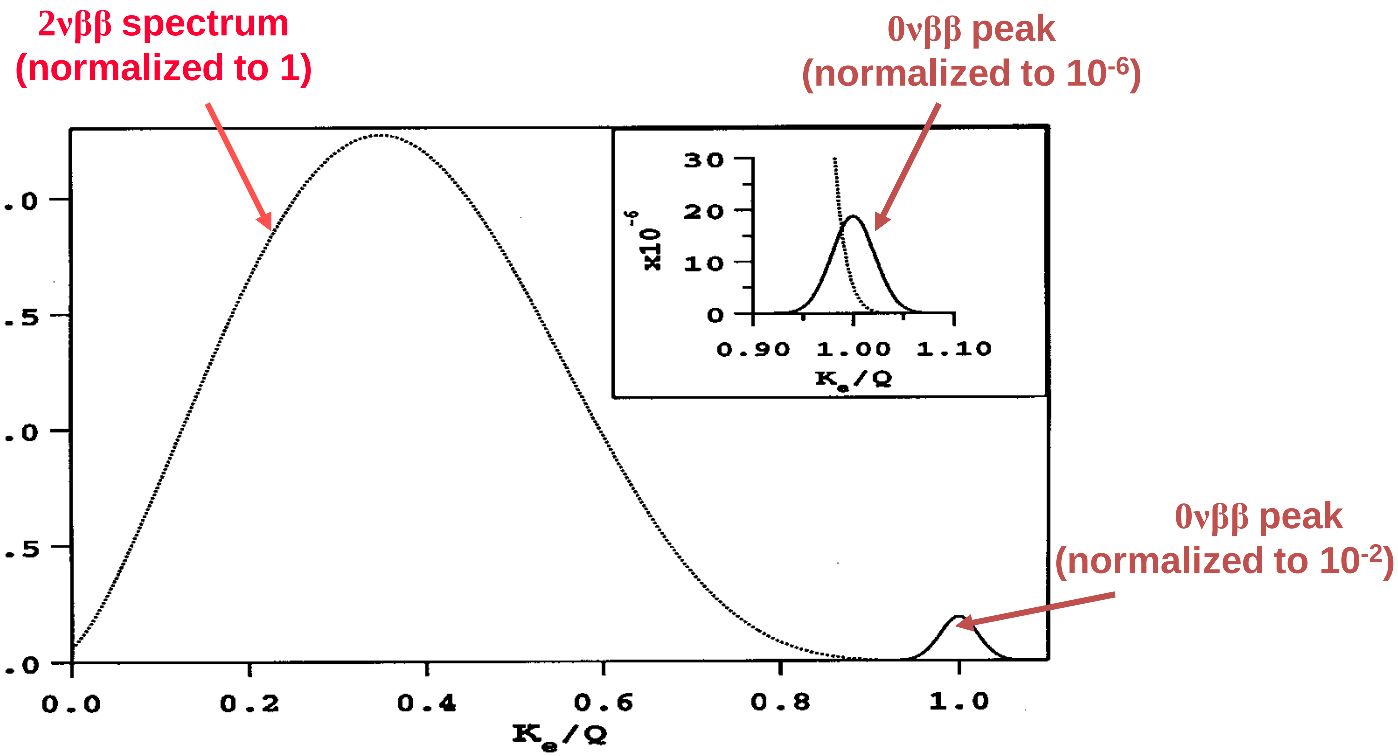


This process can only occur for a Majorana neutrino!

Some candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Neutrinoless double beta decay





$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \left\langle m_\nu \right\rangle^2$$

$G^{0\nu}$ is a phase space factor
$M^{0\nu}$ is the nuclear matrix element

Effective Majorana mass: $$\left\langle m_\nu \right\rangle = \left|\sum_i U_{ei}^2 m_i \, \varepsilon_i\right|$$ (light neutrino exchange mechanism only)

Challenges of double-β decay experiments

$$T_{1/2} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

- ε detection efficiency
- A isotopic abundance
- M active mass
- T exposure
- b background rate
- ΔE energy resolution

$T_{1/2}^{0\nu} > 10^{24}$ years !!

→Need:

- high target mass
- high exposure
- low background rate
- good energy resolution

<u>Natural radiation decay rates</u>

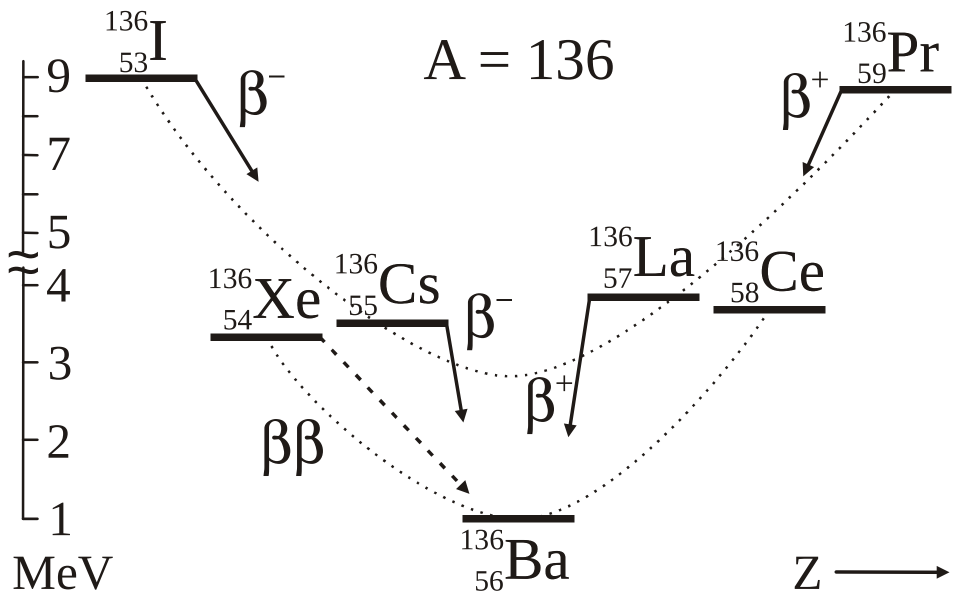
A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

0νββ decay	>1000 x rarer than 2νββ
Age of universe	1.4 x 10^{10} years

Advantages of ^{136}Xe

- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

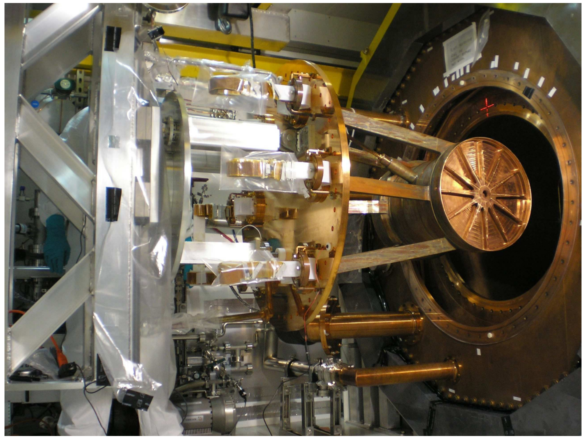


Advantages of ^{136}Xe

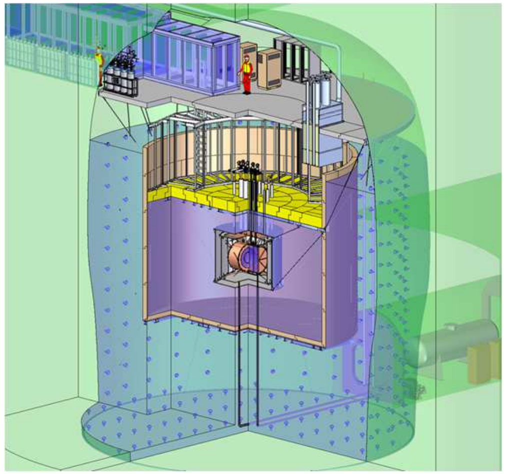
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC



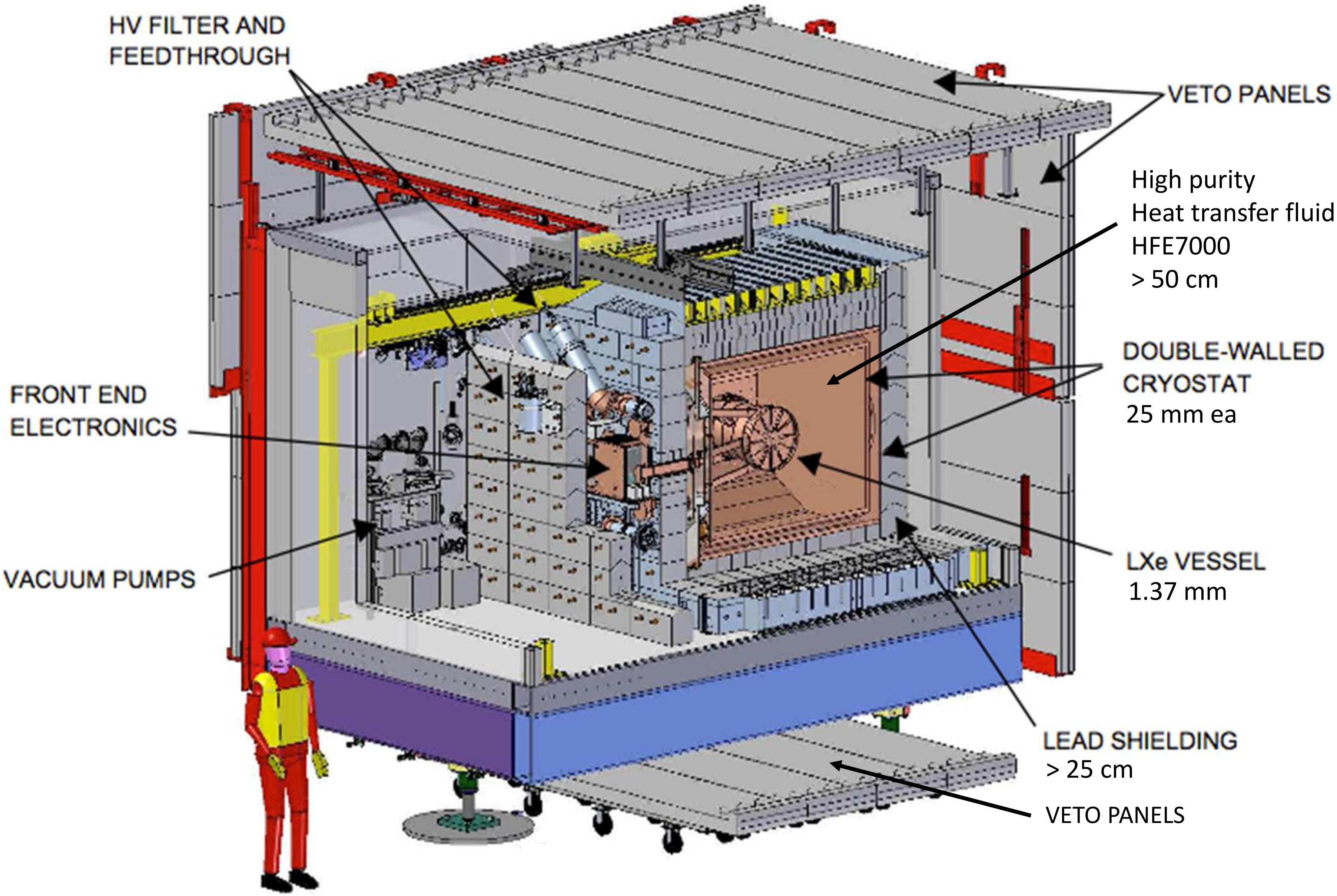
2. nEXO: 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)

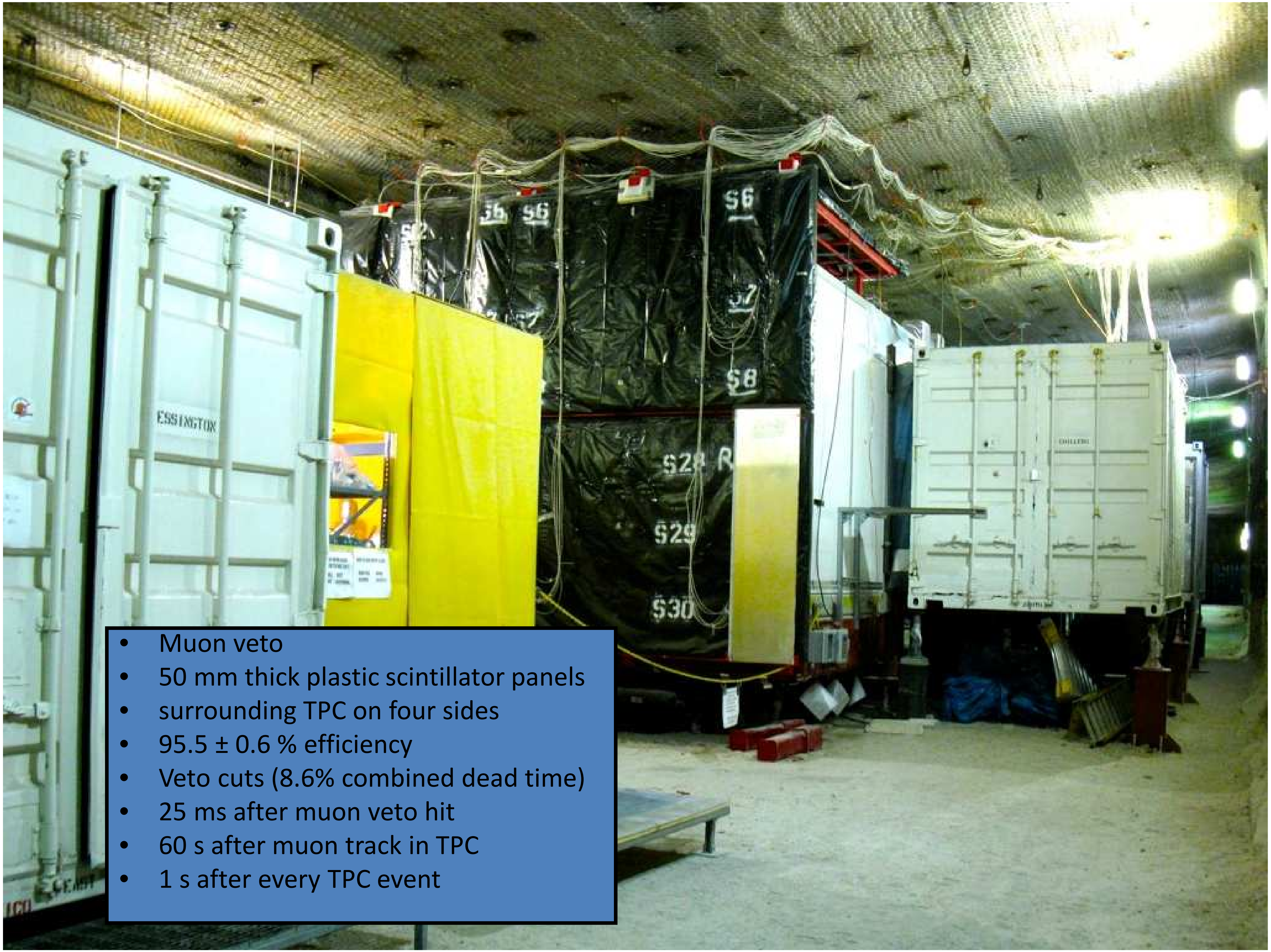


EXO-200

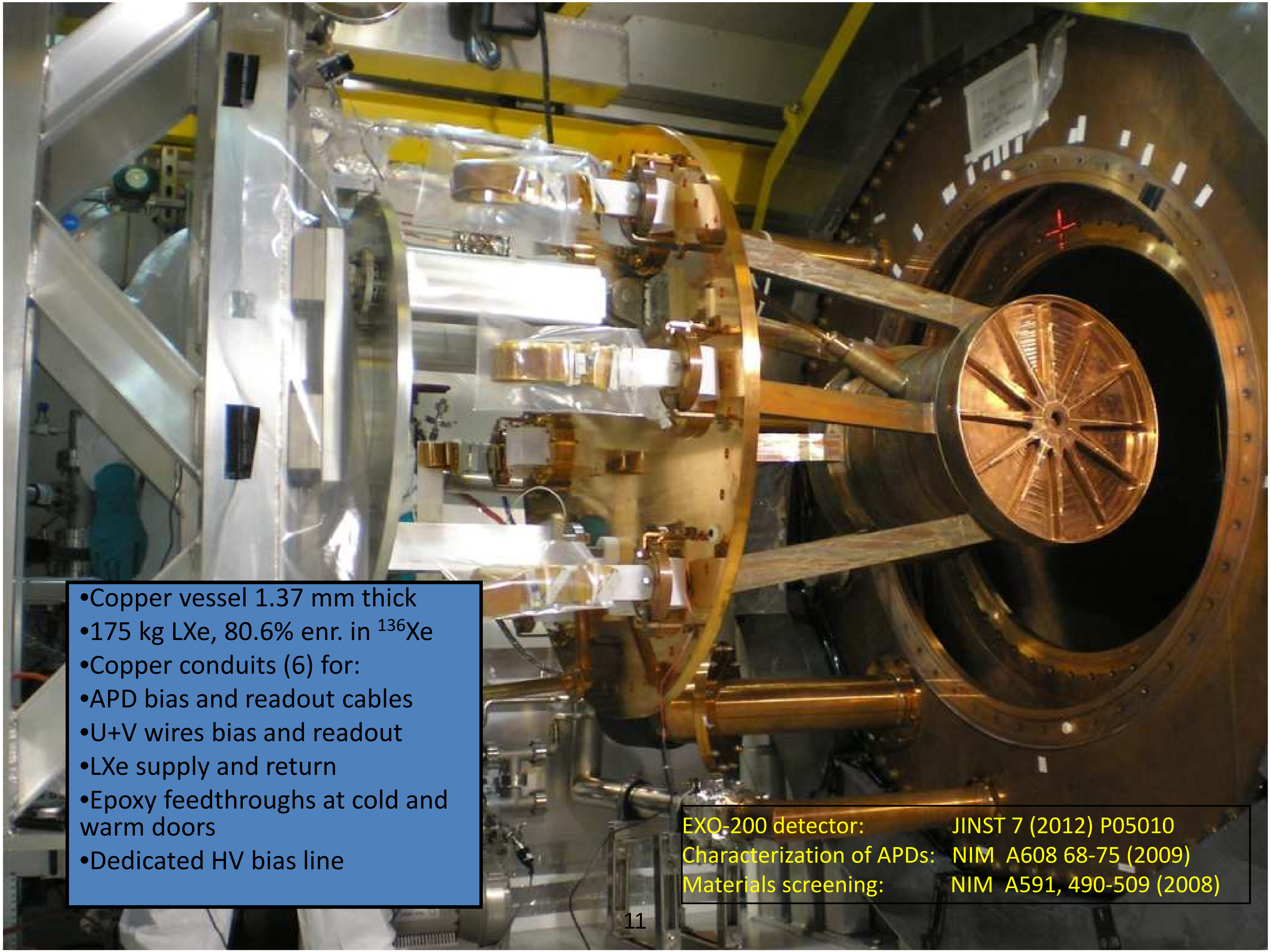
- Located at the Waste Isolation Pilot Plant at 32°22'30"N 103°47'34"W (Carlsbad, NM).
- 2150 feet depth, ≈1585 mwe flat overburden
- U.S. DOE permanent repository for nuclear waste
- Low radioactivity levels:
  - U, Th <100ppb
  - Radon background < 10 Bq/m^3

The EXO-200 Detector





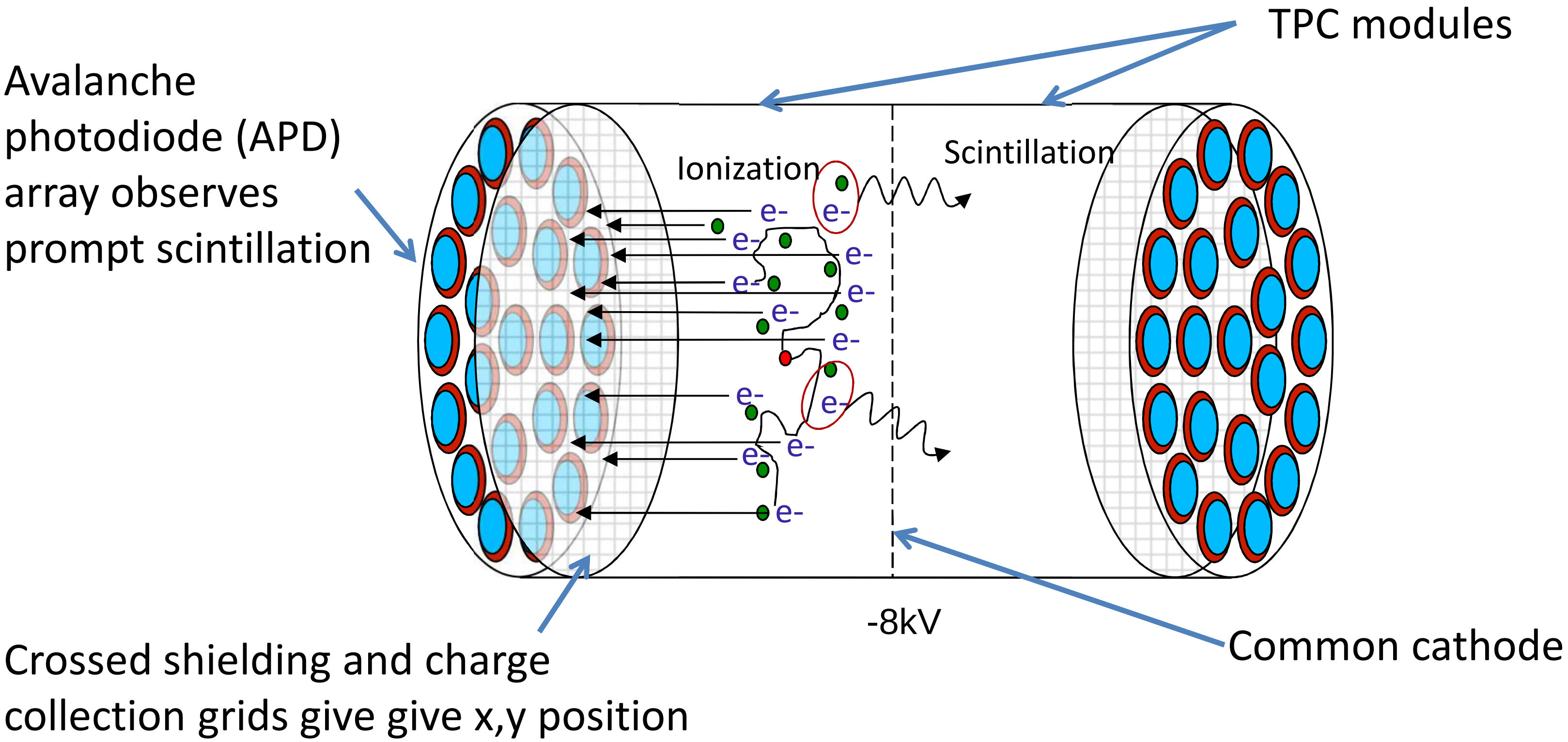
- Muon veto
- 50 mm thick plastic scintillator panels
- surrounding TPC on four sides
- 95.5 ± 0.6 % efficiency
- Veto cuts (8.6% combined dead time)
- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event



- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line

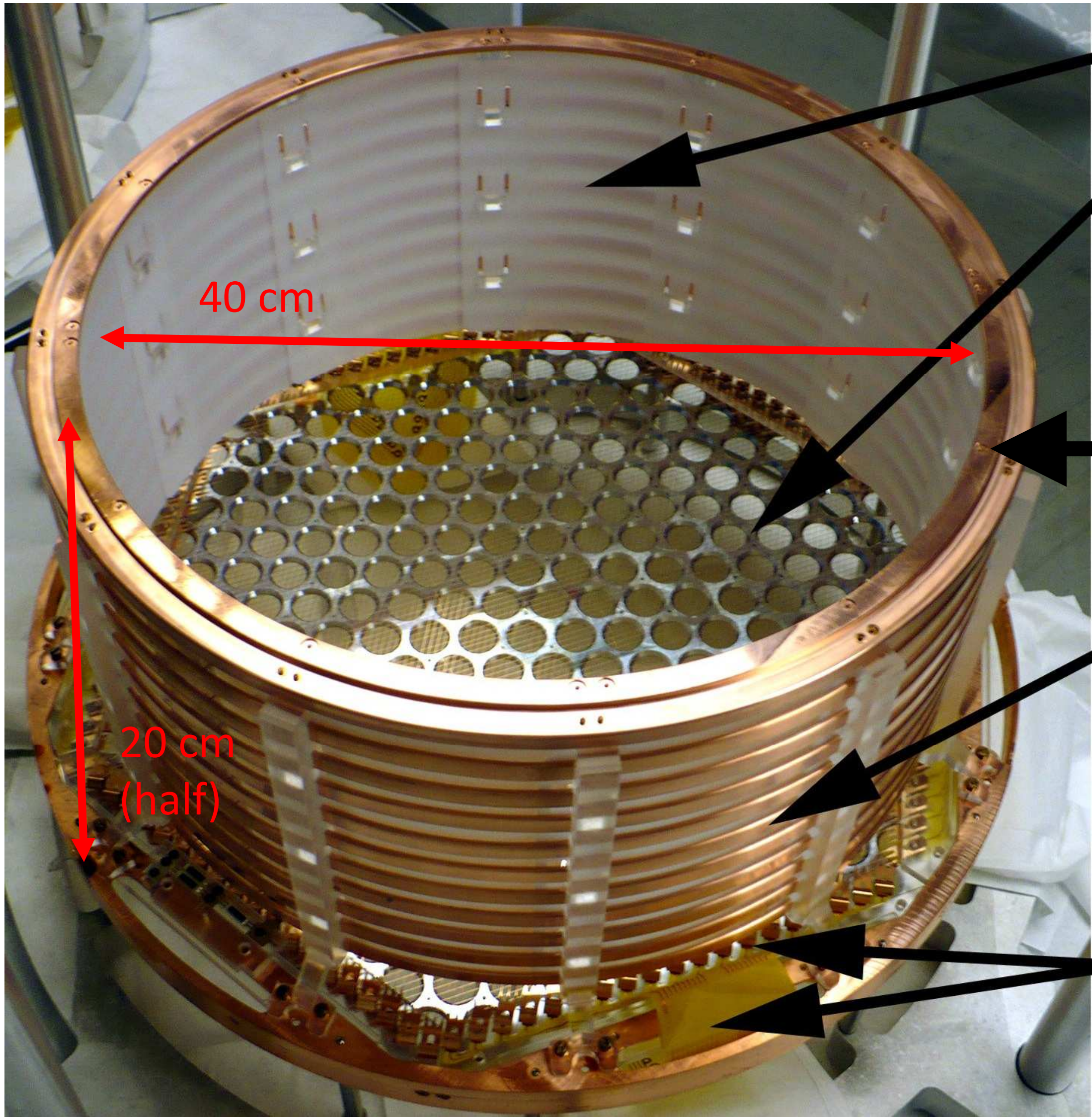
EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

EXO-200 Time Projection Chamber (TPC) Basics



- Z-position from the time difference between scintillation and ionization
- Event energy from the combination of ionization and scintillation
- TPC allows rejection of some gamma backgrounds because Compton scattering results in multiple energy deposits

EXO-200 TPC



Teflon Reflectors
(increase light collection)

APD plane and wire planes
(wires are photo-etched)

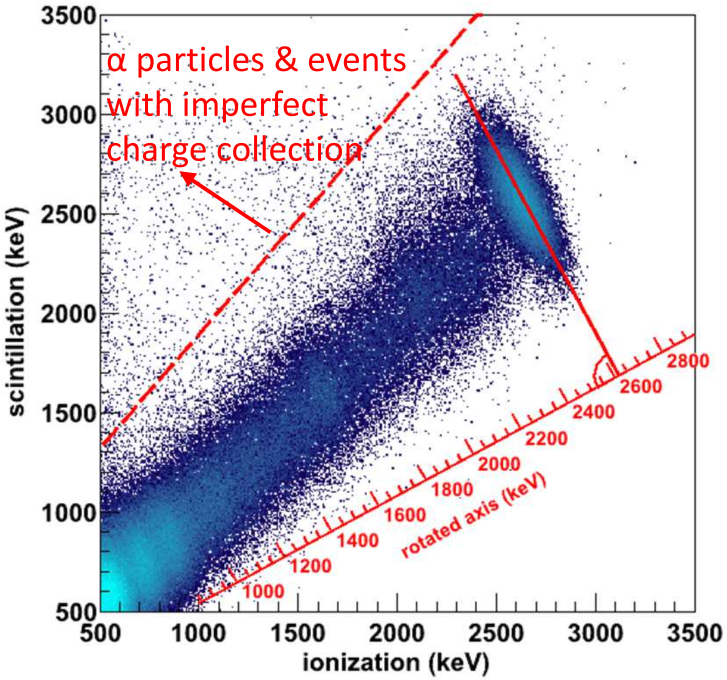
Central HV plane
(photo-etched phosphor bronze)

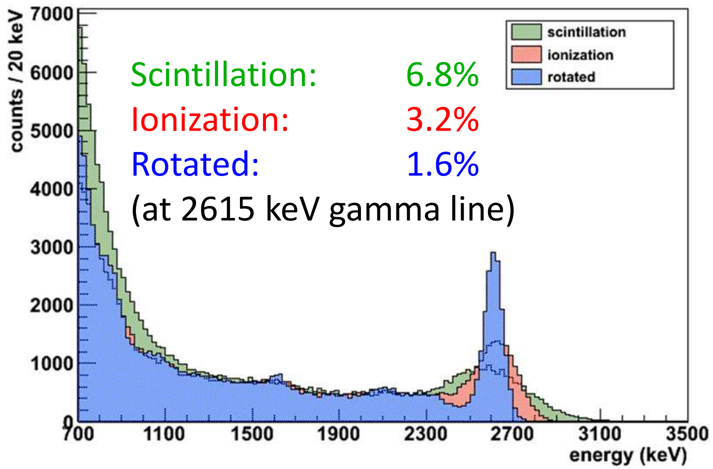
Acrylic supports
and field shaping
rings

Kapton flex cables
(spring connections
eliminate solder joints
and glue)

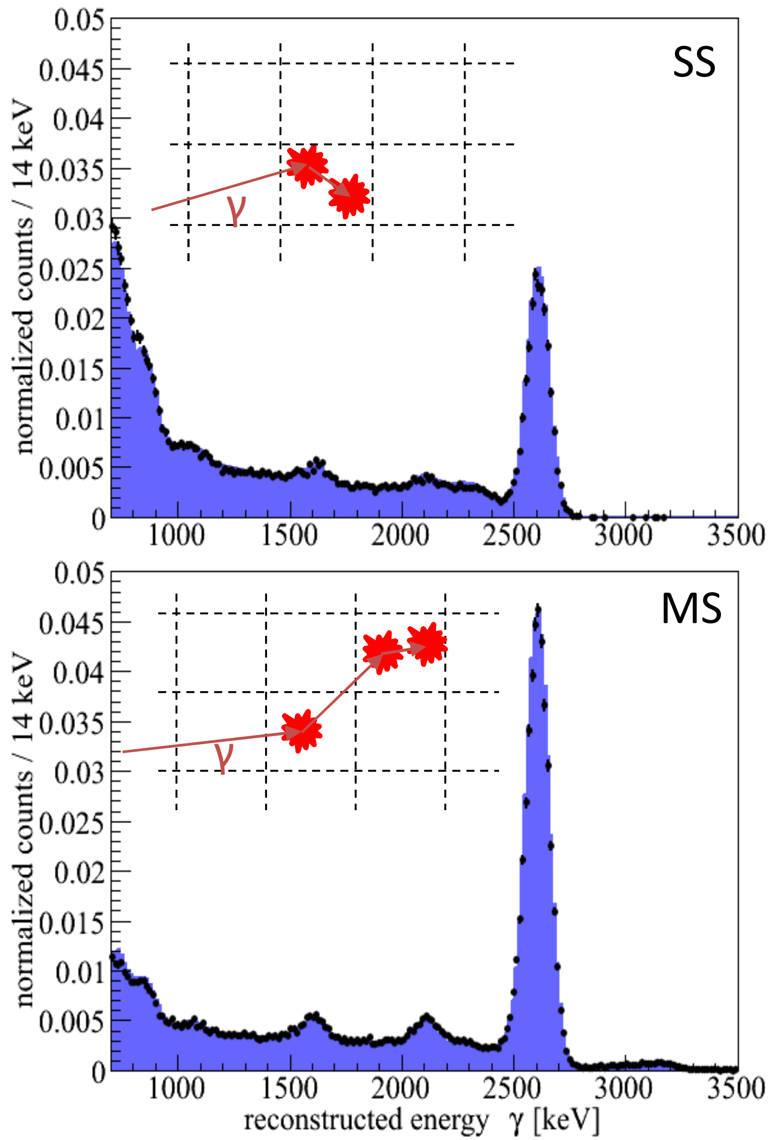
Top EXO-200 features

Scintillation and charge





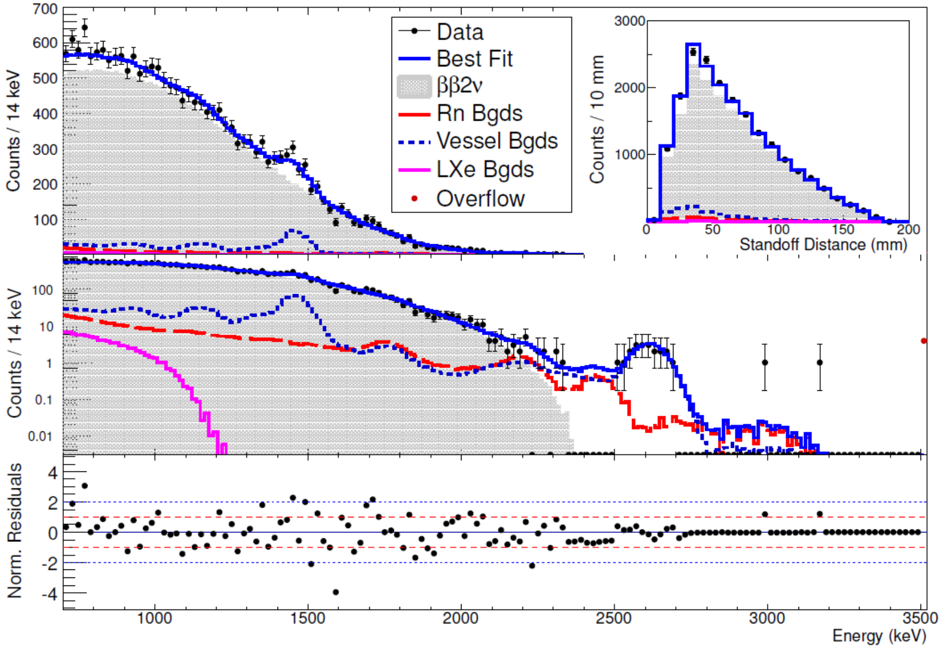
Single site vs multi site



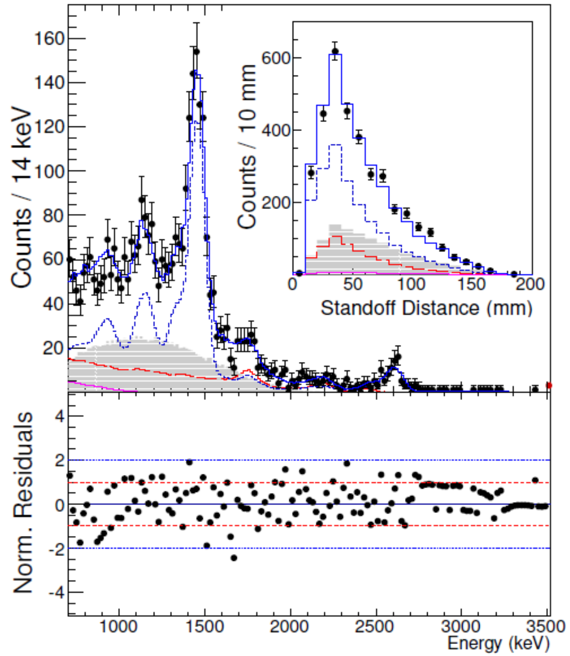
arXiv:1306.6106v3

Latest Result for 2νββ

Single-Site Spectrum



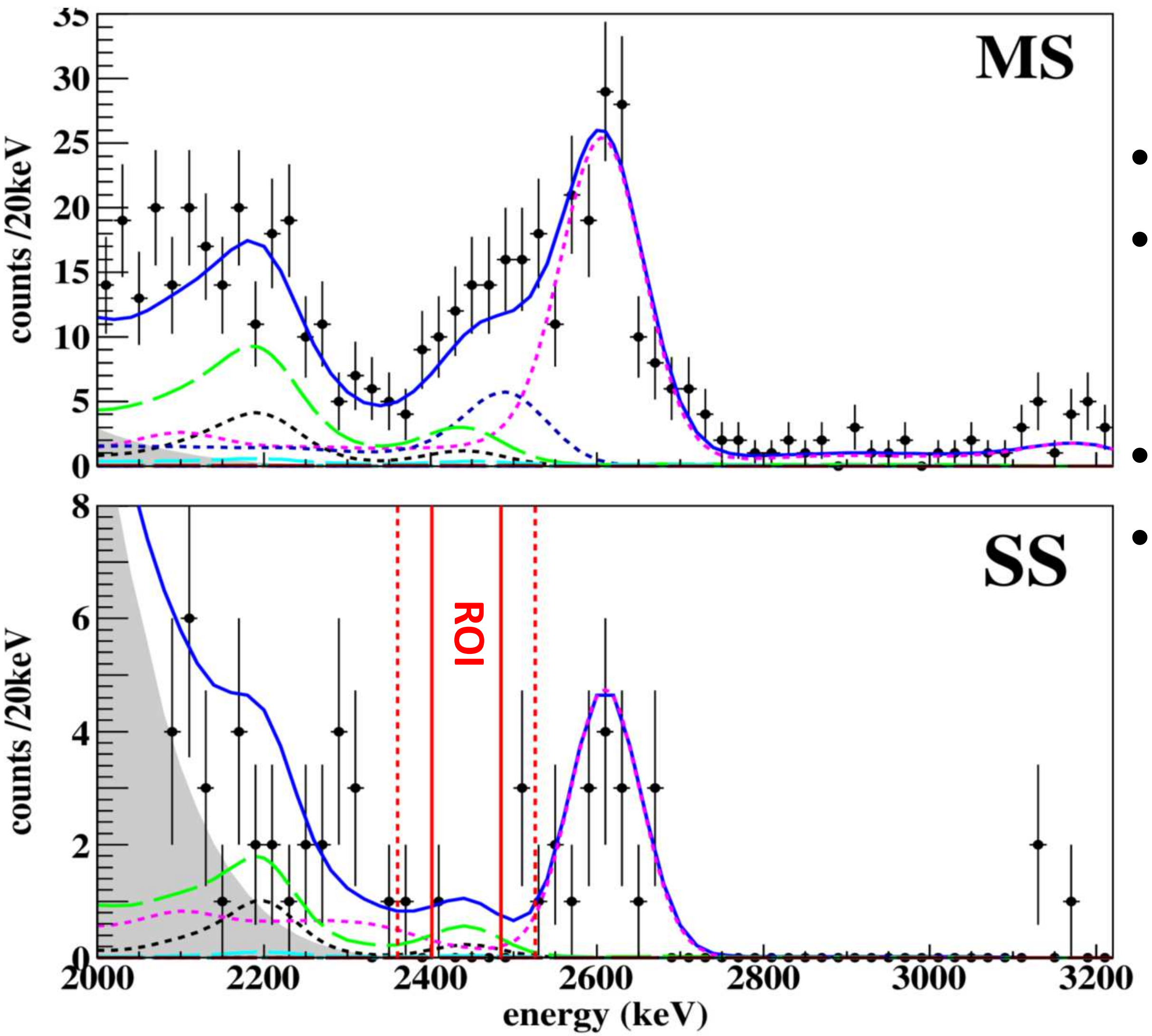
Multi-Site Spectrum



- Single and multi-site spectra analyzed above 700keV.
- Binned log-likelihood fit, in both energy and standoff distance, including 2νββ and gamma backgrounds
- Significant improvement made in understanding fiducial volume, resulting in much improved systematic uncertainty (3%)
- Resulting 2νββ half-life consistent with previous measurements

$T_{1/2}$ (10^{21}yr)	2.165 +/- 0.016 (stat) +/- 0.059 (sys)
Exposure (kg*yr)	23.14
2νββ Detection efficiency	57.88%
2νββ events from fit	19042
Nuclear Matrix Element (MeV^{-1})	0.0218 +/- 0.0003

Non detection of 0νββ decay mode

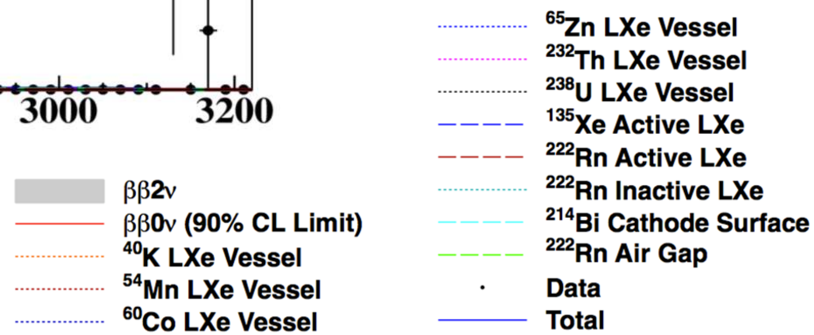


Zoomed around 0νββ region of interest (ROI)

- ROI (1σ interval)
- Background estimation is: 4.1±0.3 events ➔ (1.5 ±0.1) 10^{-3} $kg^{-1}yr^{-1}keV^{-1}$
- 1 event found (no signal)
- **Profile likelihood used to determine (90% CL)**

$$T_{1/2}^{0\nu\beta\beta}\left({}^{136}Xe\right) > 1.6 \cdot 10^{25}\ \mathrm{yr}$$

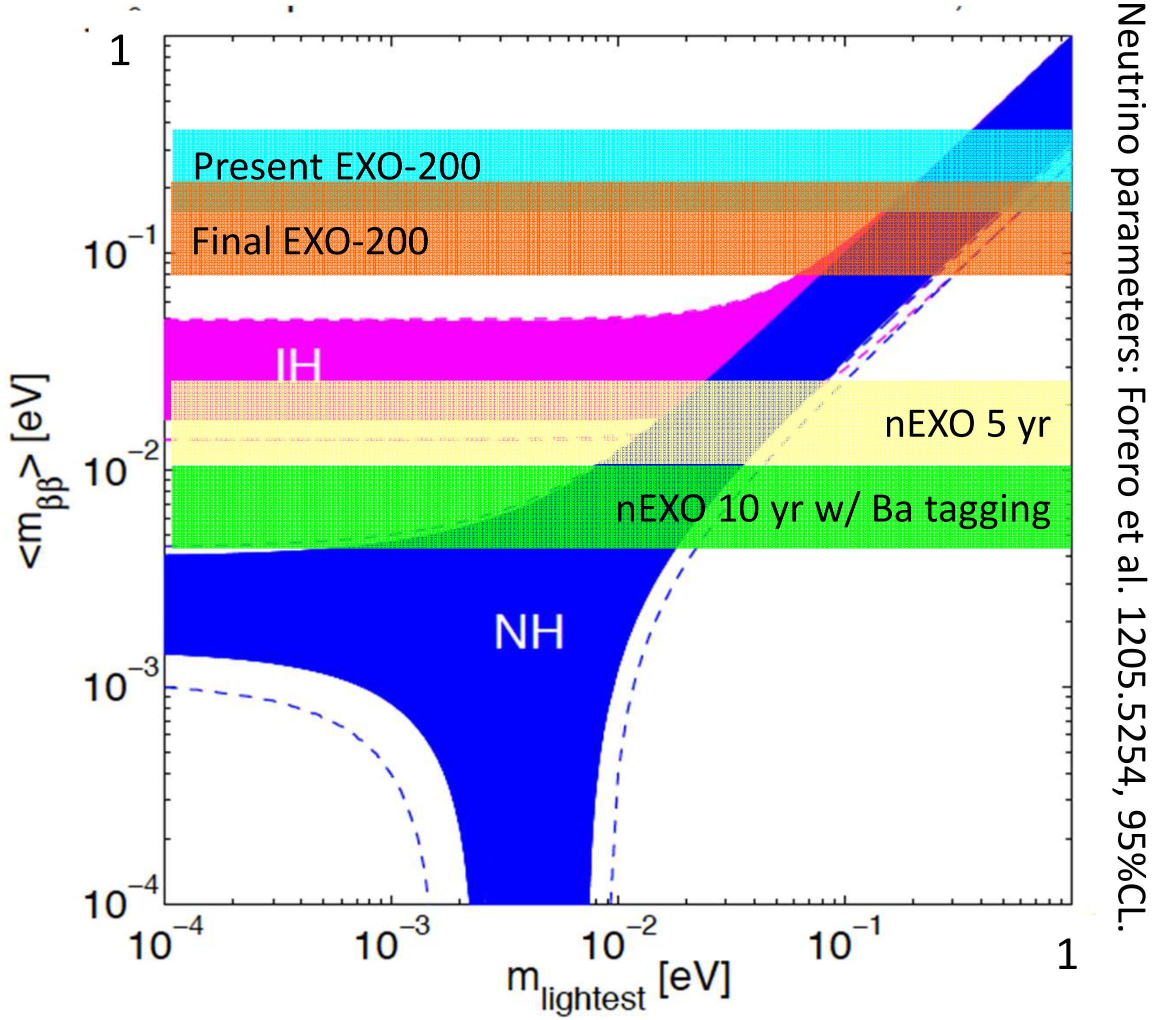
$$\left\langle m_{\beta\beta} \right\rangle < 140 - 380\ \mathrm{meV}$$



[PRL: 109 (2012) 032505]

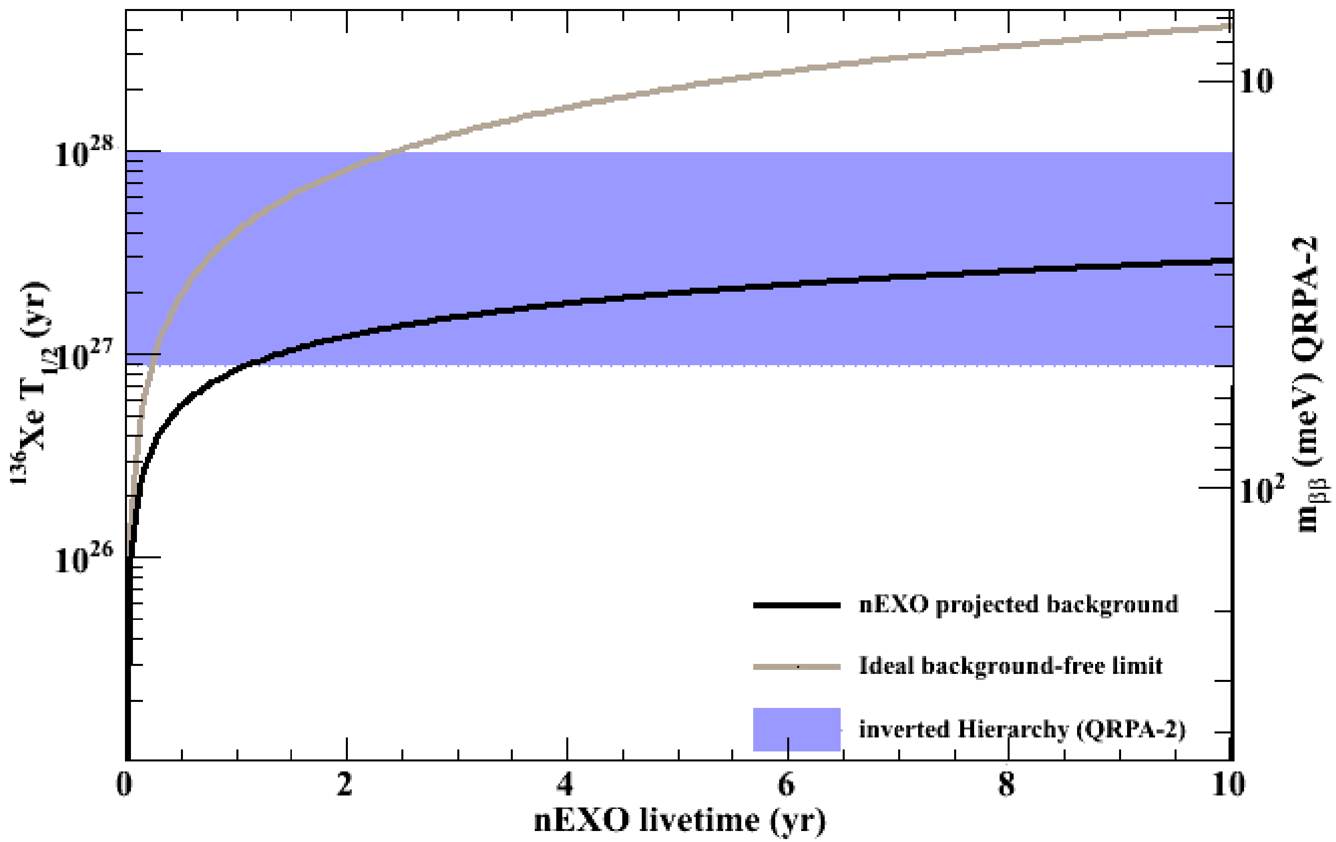
Enriched Xenon Observatory

- Multi-phase program
- EXO-200, in operation:
  - 200 kg LXe
  - Sensitivity: 100-200 meV
- Multi-ton EXO, R&D underway:
  - 1-10 ton liquid/gas Xe
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba^{++} tagging



→ **Development of nEXO started**

nEXO projections



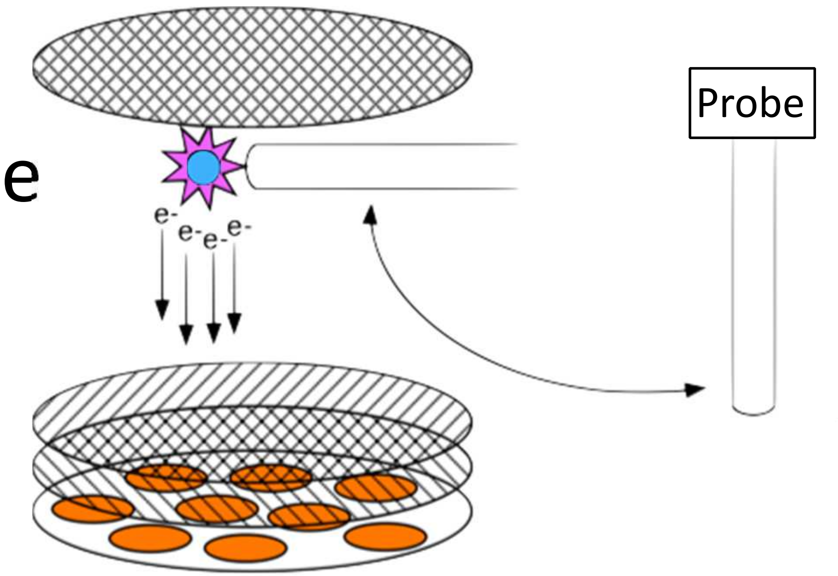
Idea: Perform a background-free measurement by identifying the decay product → Ba-ion tagging

Sensitivity with background $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$$

Sensitivity without background $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/2}$$

Tagging from Liquid

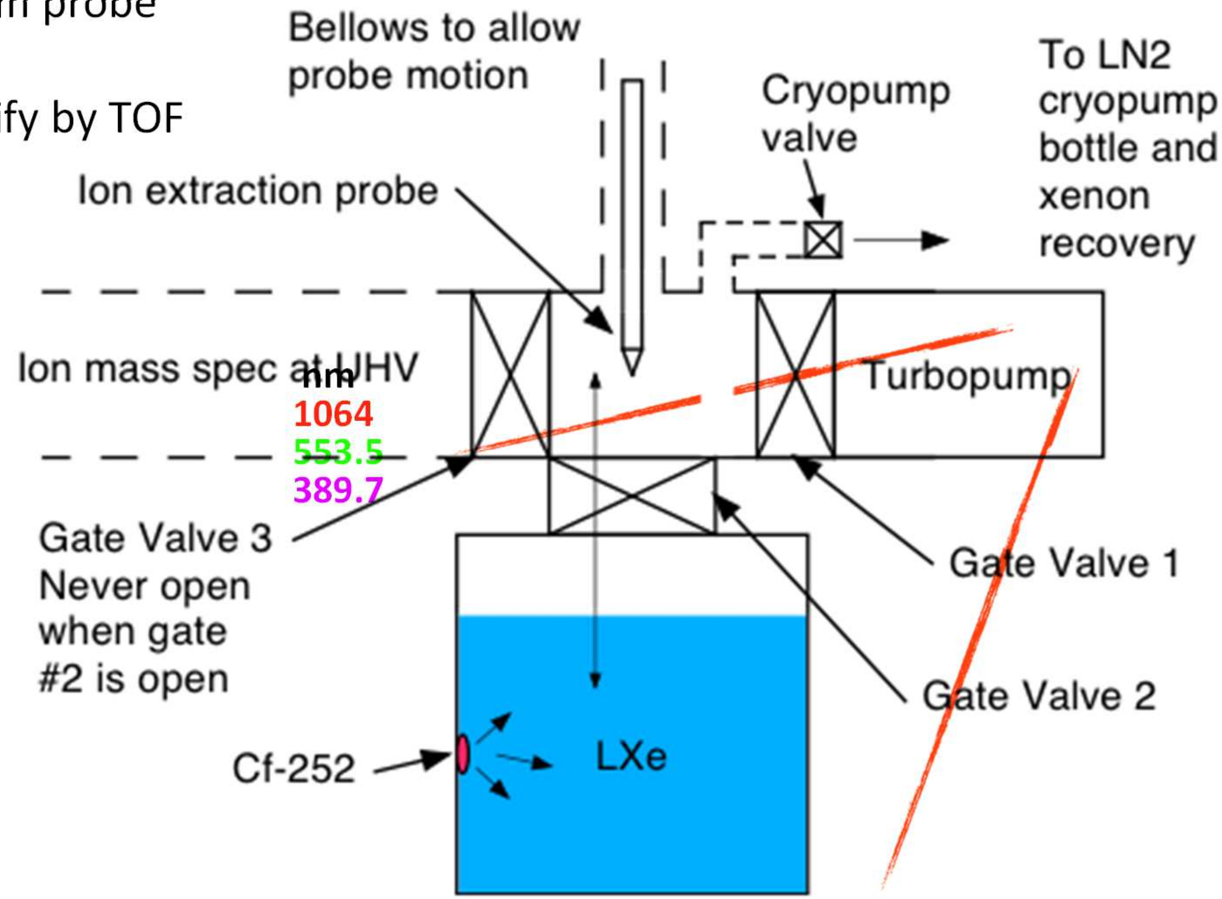
- Detect and localize decay
- Send probe in to region of decay
- Confine the Ba^{++} on probe
- Remove the probe
- Identify the barium



Ba$^+$ tagging at Stanford

<u>… in liquid Xe</u>

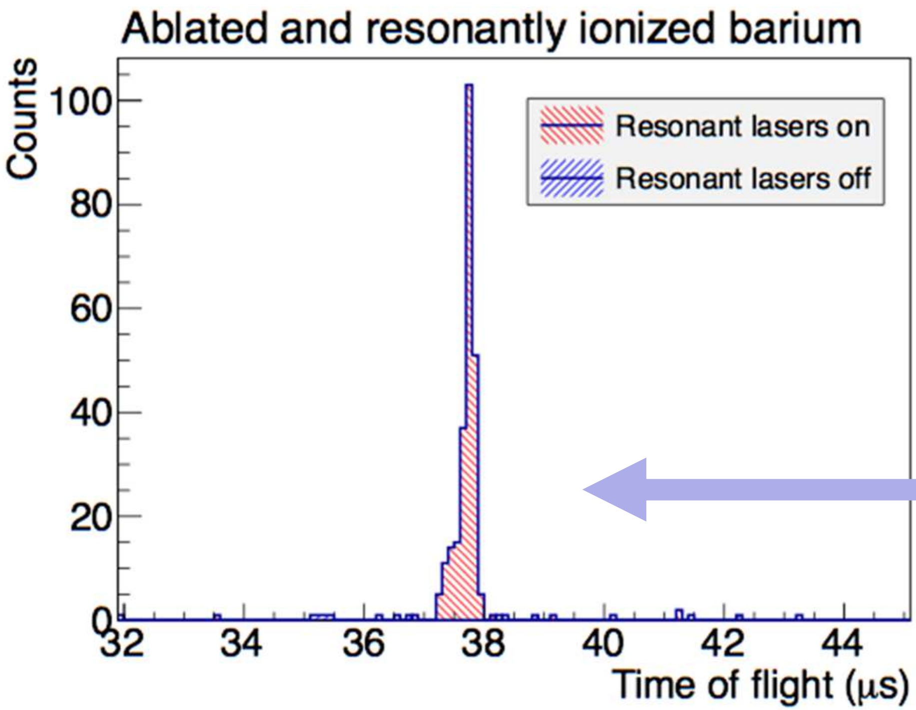
- Move probe close to Ba$^+$ ion in LXe
- Attach Ba$^+$ ion to probe
- Move probe out of LXe
- Laser-ablate Ba atom from probe
- Laser-ionize Ba$^+$
- Accelerate Ba$^+$ and identify by TOF

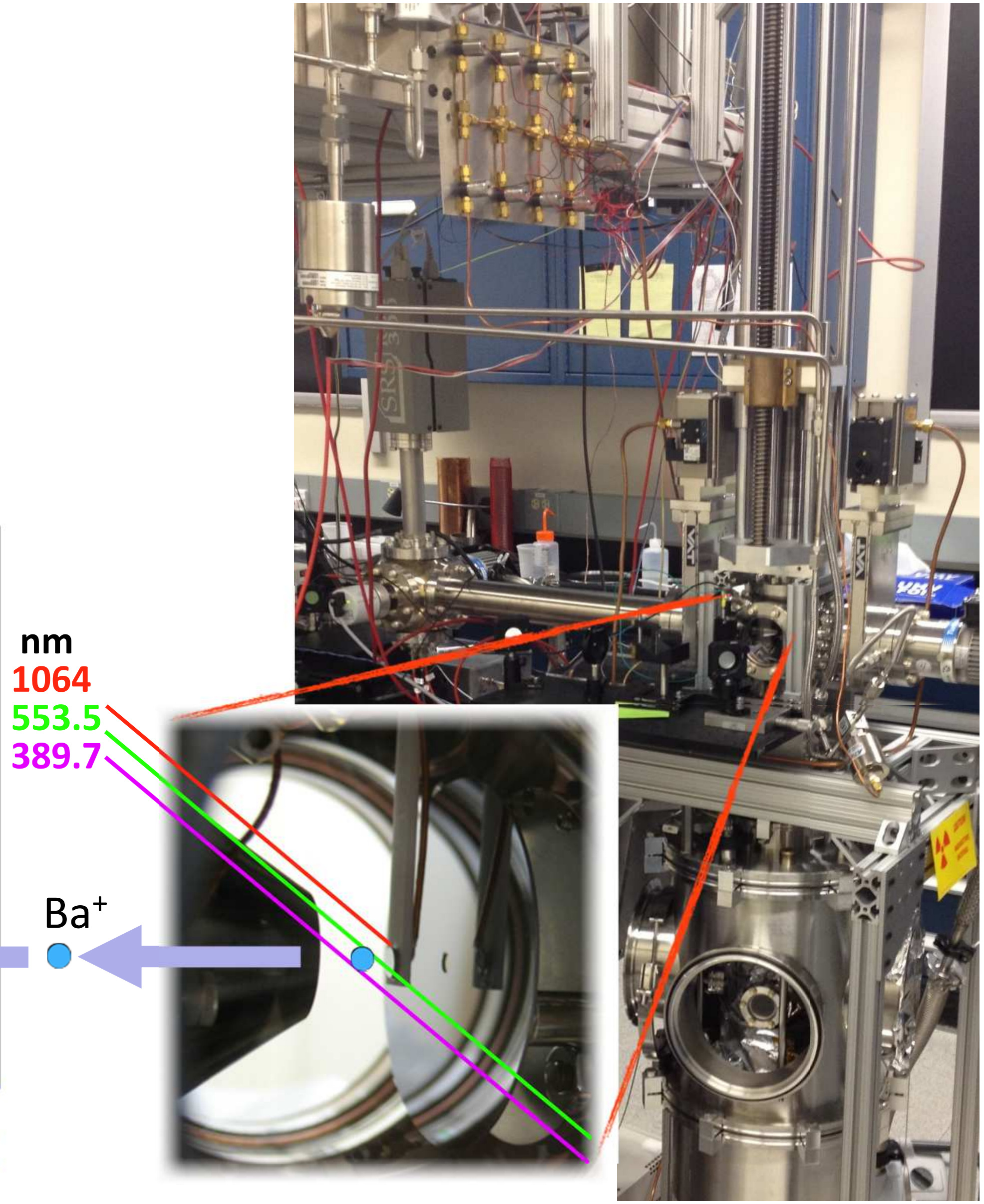


Ba⁺ tagging at Stanford

<u>… in liquid Xe</u>

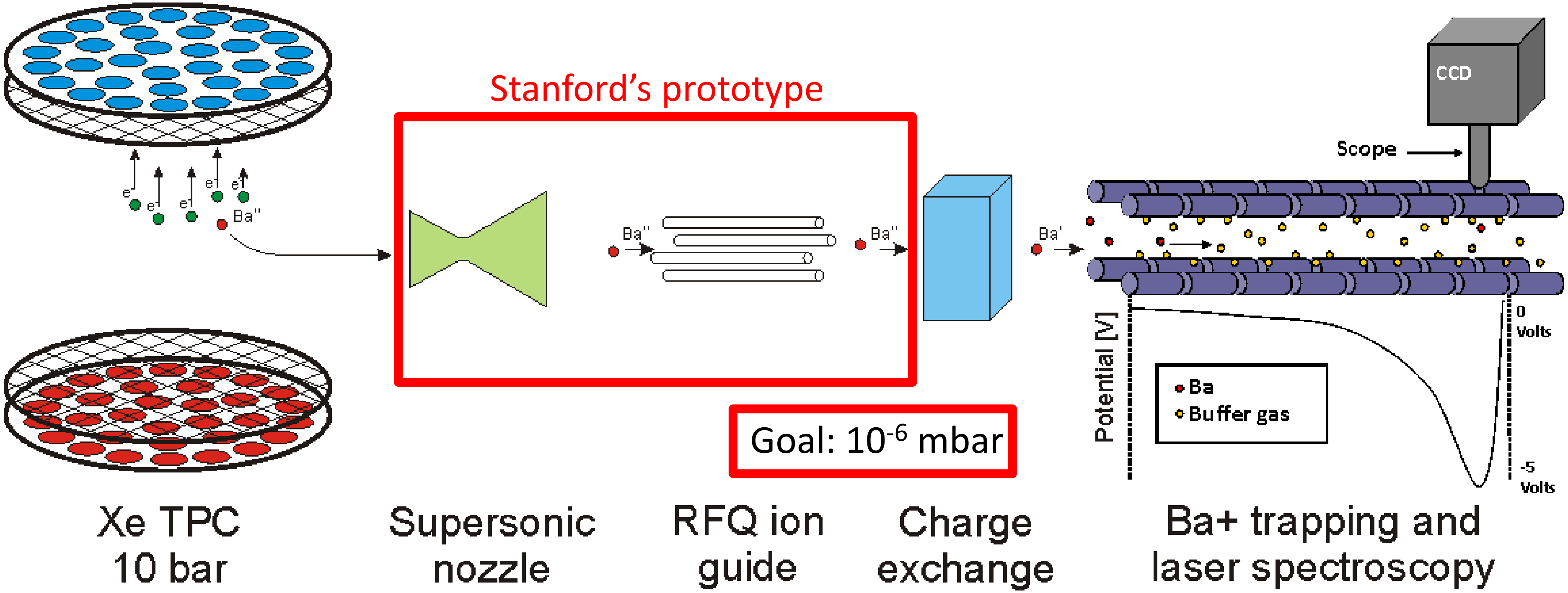
- Move probe close to Ba^+ ion in LXe
- Attach Ba^+ ion to probe
- Move probe out of LXe
- Laser-ablate Ba atom from probe
- Laser-ionize Ba^+
- Accelerate Ba^+ and identify by TOF



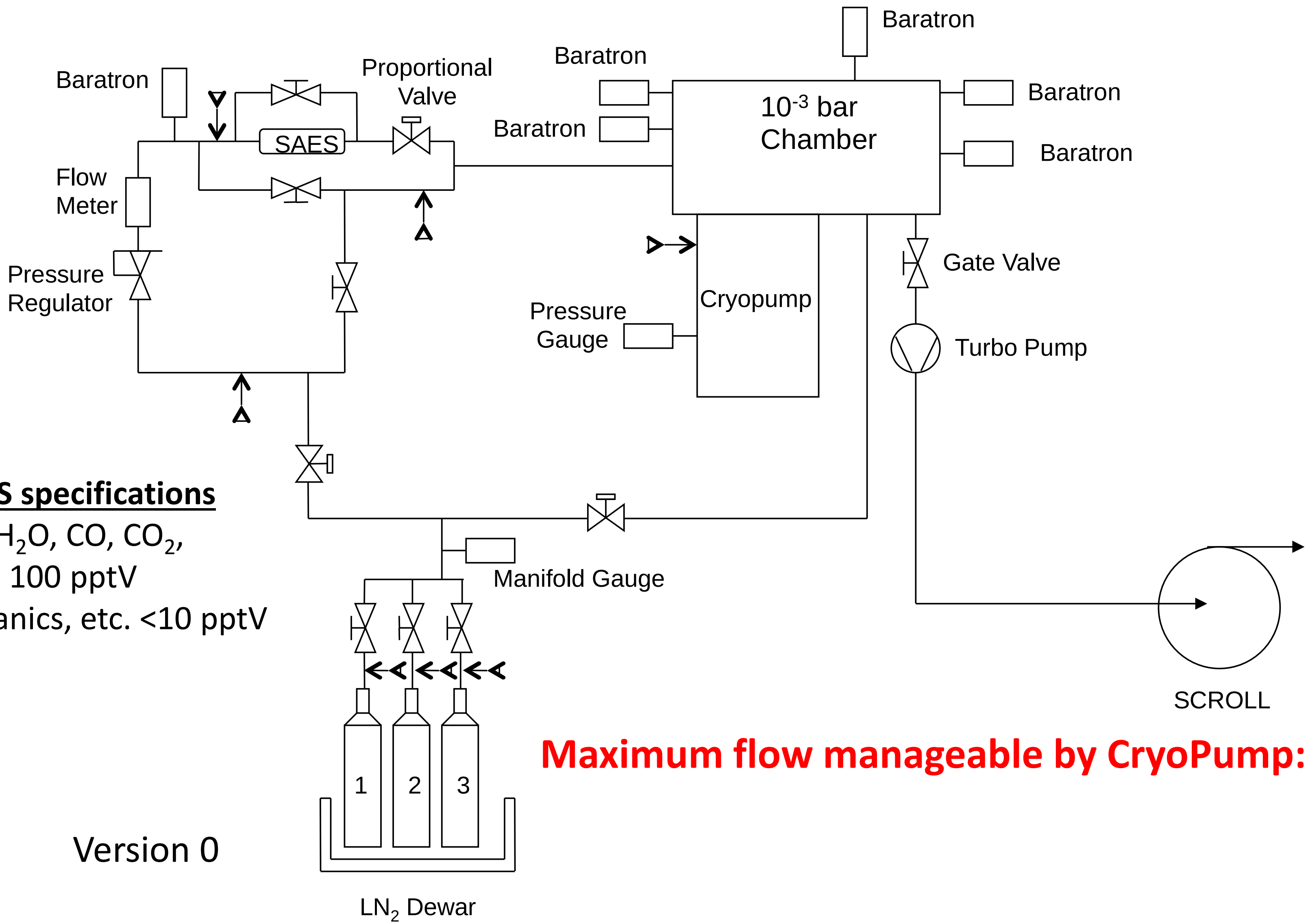


General Concept of Ba^{++} Tagging

- Guide Ba^{++} in high pressure Xe inside the TPC (10 bar) to a nozzle
- Extract Ba^{++} with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide Ba^{++} to identification



Recirculation System at Stanford



Xe ice

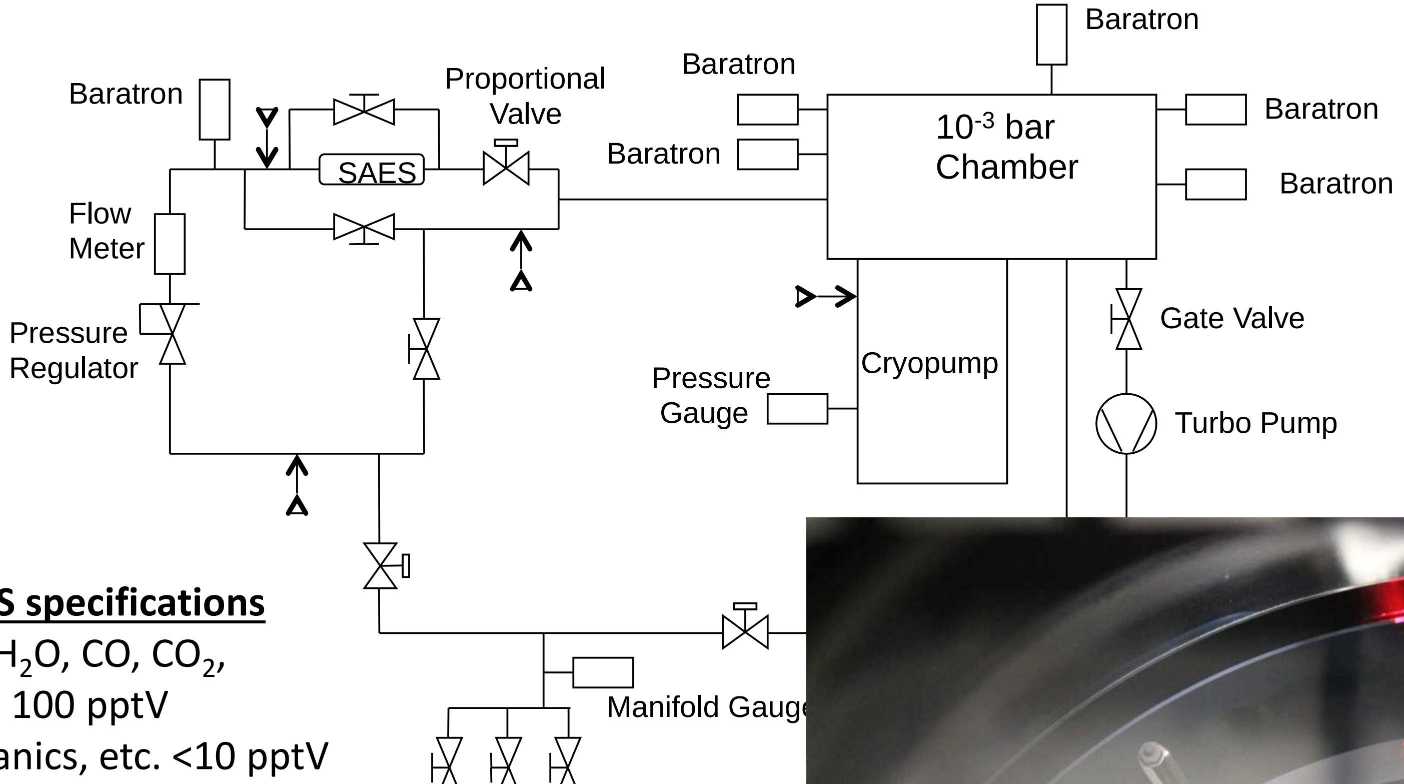
SAES specifications

O_2, H_2O, CO, CO_2,
H_2 < 100 pptV
Organics, etc. <10 pptV

Maximum flow manageable by CryoPump: 0.5 g/s

Version 0

Recirculation System at Stanford



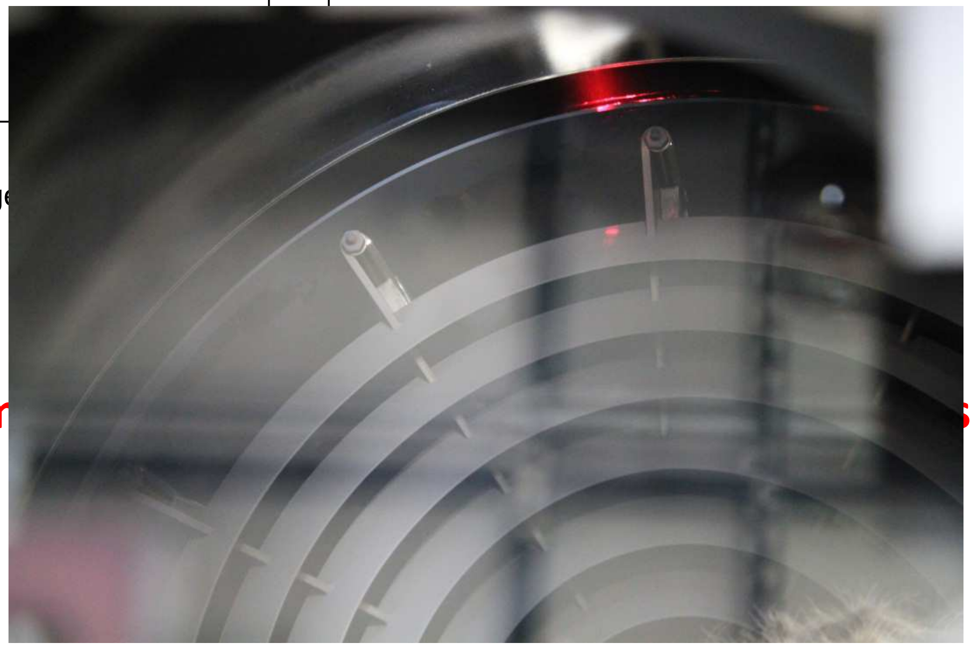
SAES specifications

O_2, H_2O, CO, CO_2,
H_2 < 100 pptV
Organics, etc. <10 pptV

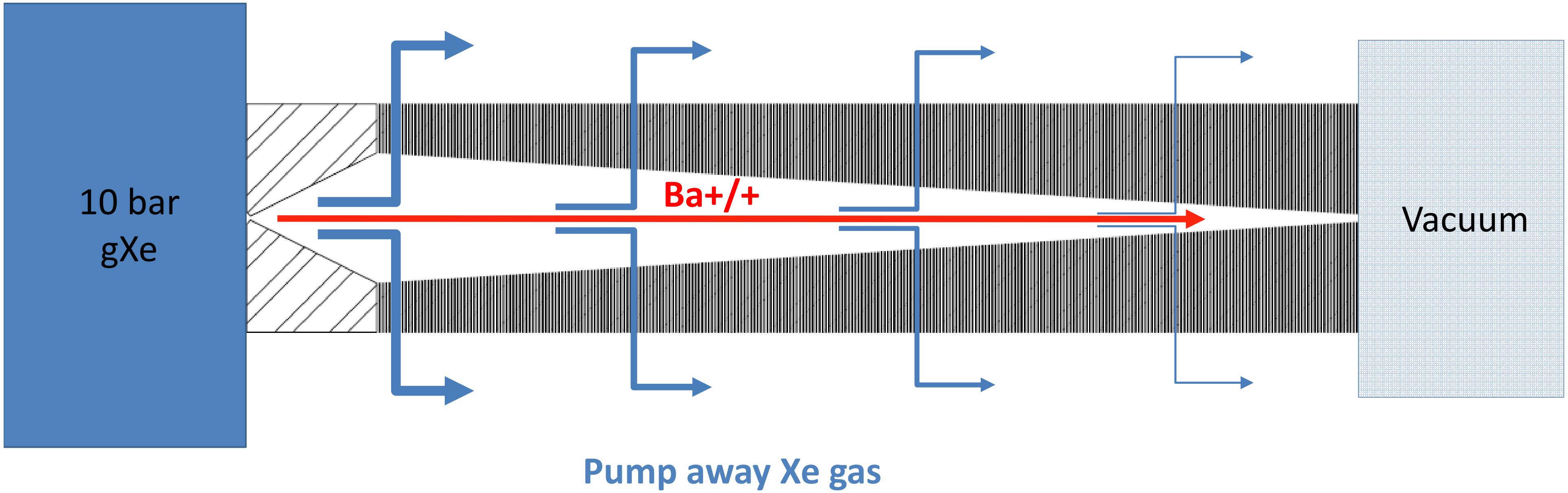
Version 0

Maxim

Xe ice



RF-funnel concept: V. Varentsov



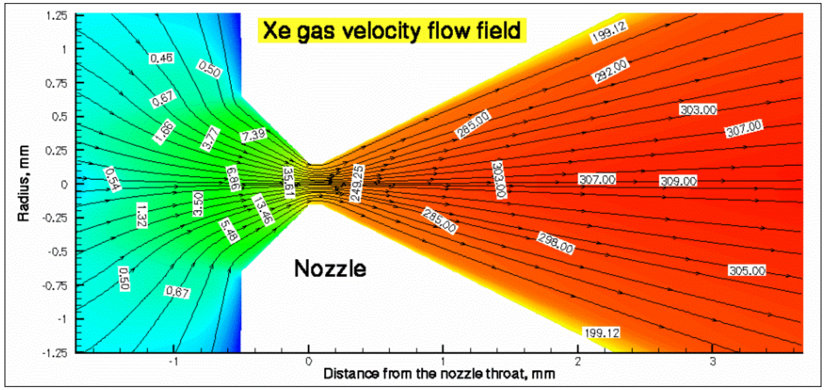
RF-funnel concept:

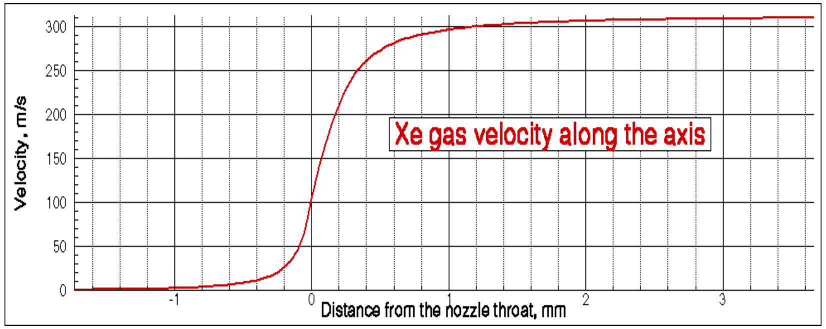
- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_0 = 10 bar, P_a = 1 mbar

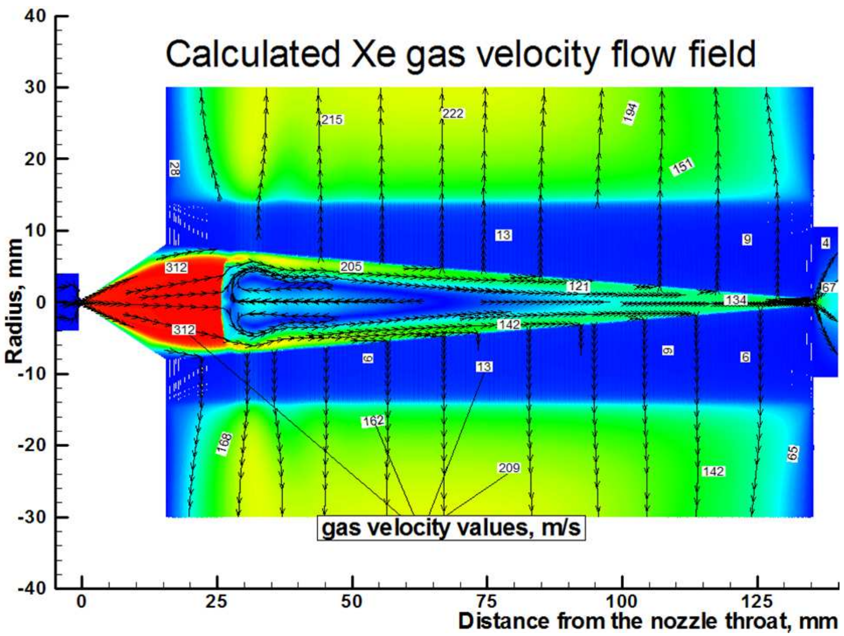
V_{RF} = 120 V
f = 10 MHz
Simulated Ba^+ transmission
~95%

V_{RF} = 25V
f = 2.6 MHz
Simulated Ba^+ transmission
~72%

Victor's simulations







<u>Converging-diverging nozzle</u>

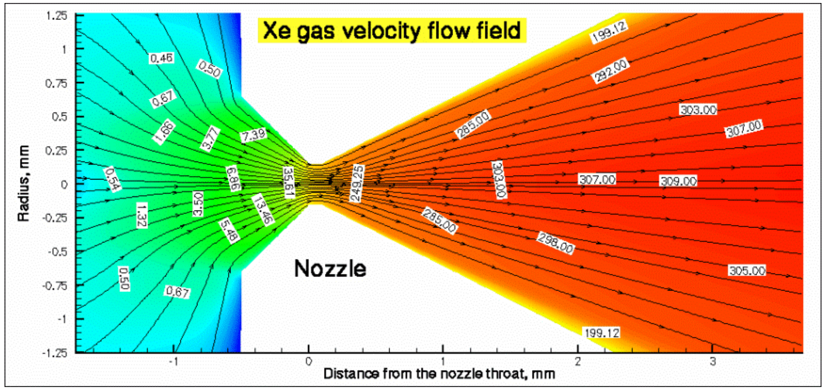
Half-angle of subsonic cone	45°
Half-angle of supersonic cone	26.6°
Throat diameter	0.28 mm
	0.33 g/s
Exit diameter	16.0 mm
Subsonic part length	0.5 mm
Supersonic part length	15.5 mm

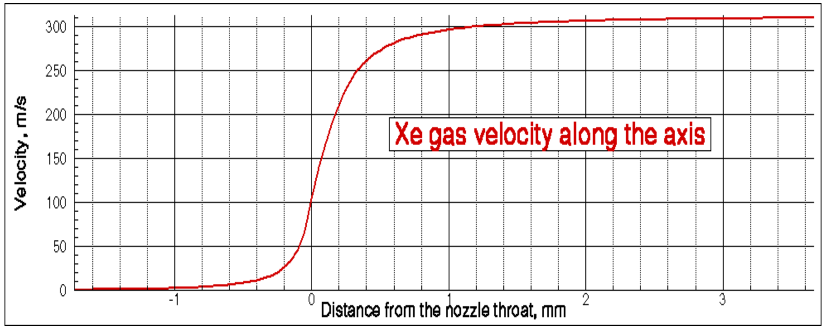
<u>RF-funnel electrodes</u>

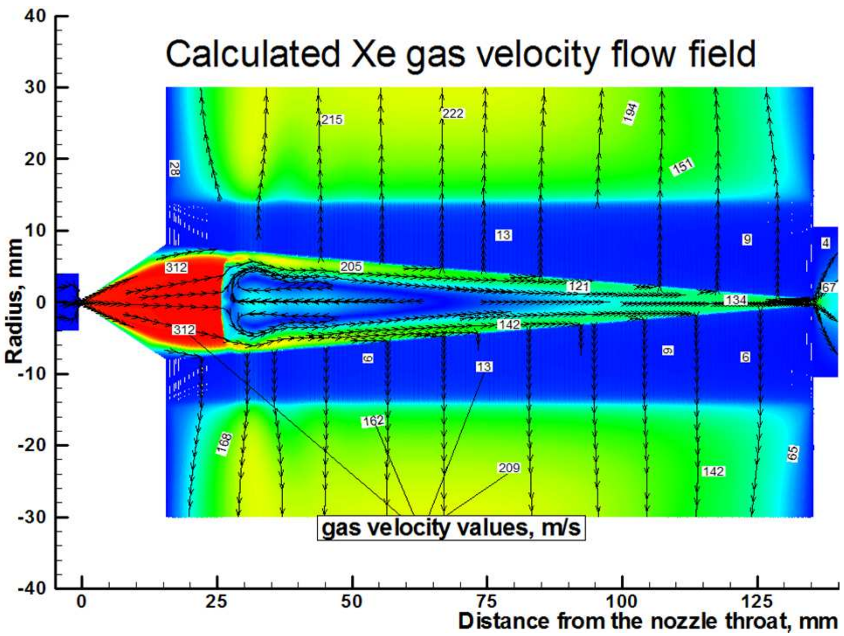
Entrance aperture diameter	16.0 mm
Exit aperture diameter	1.0 mm
Ring electrode diameter	28 mm
Change in aperture diam./el.	0.05mm
Ring electrode thickness	0.1 mm
(design tolerance)	+/- 2.54 μm
Gap between electrodes	0.25 mm
Total number of electrodes	301

arXiv:1302.6940v1

Victor’s simulations







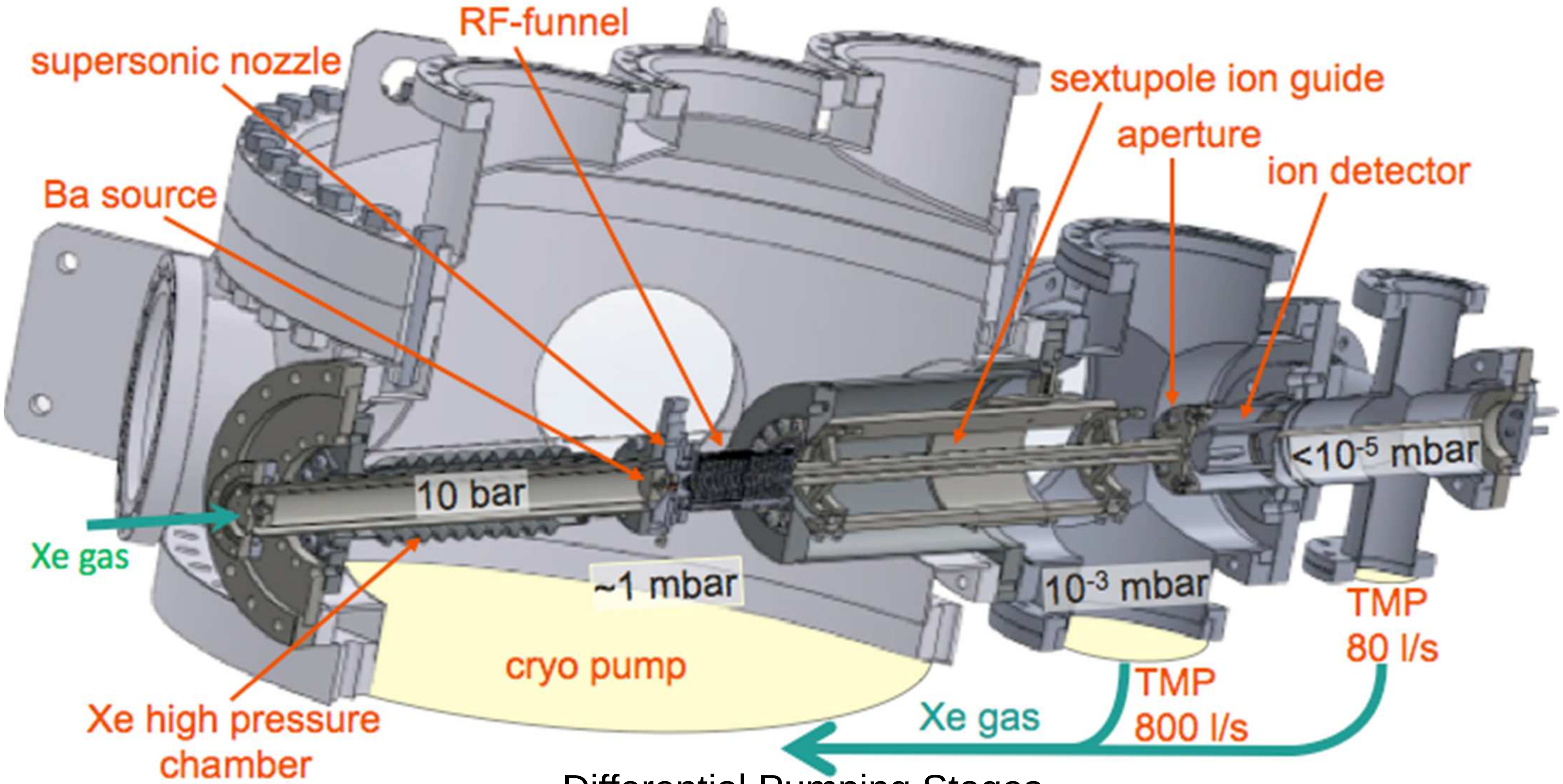
<u>Converging-diverging nozzle</u>

Half-angle of subsonic cone	45^{o}
Half-angle of supersonic cone	26.6^{o}
Throat diameter	0.28 mm
	0.33 g/s
Exit diameter	16.0 mm
Subsonic part length	0.5 mm
Supersonic part length	15.5 mm

<u>RF-funnel electrodes</u>	Cowboy Units
Entrance aperture diameter	0.6299”
Exit aperture diameter	0.0394”
Ring electrode diameter	1.1024”
Change in aperture diam./el.	0.0020”
Ring electrode thickness	0.0040”
(design tolerance)	0.0001”
Gap between electrodes	0.0100”
Total number of electrodes	301

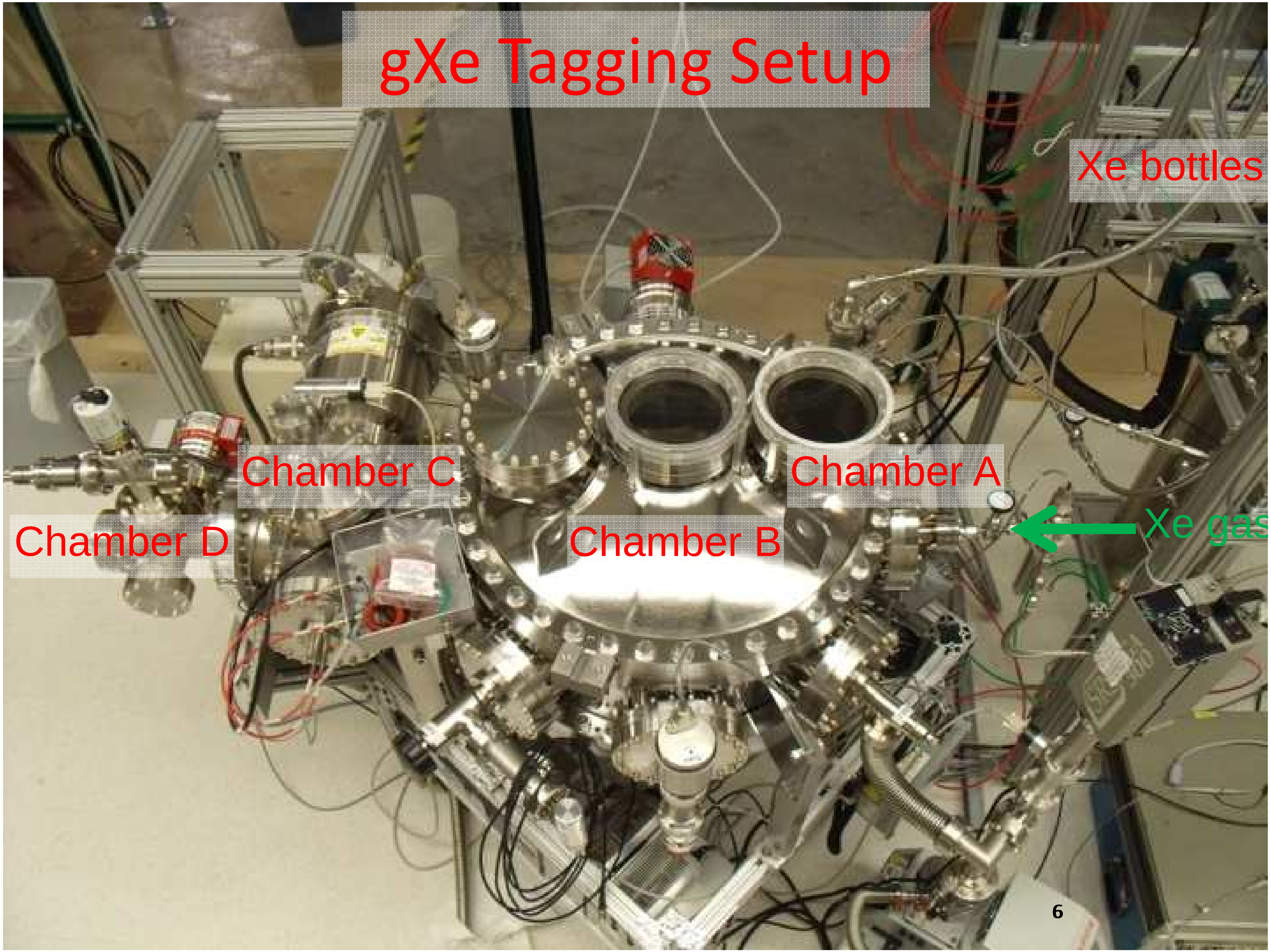
arXiv:1302.6940v1

Stanford's Prototype

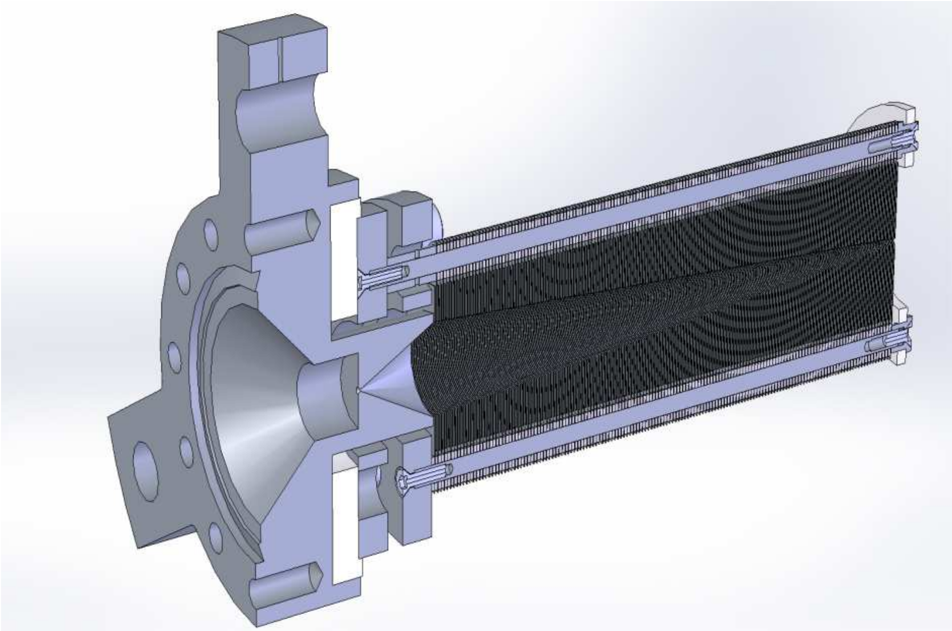


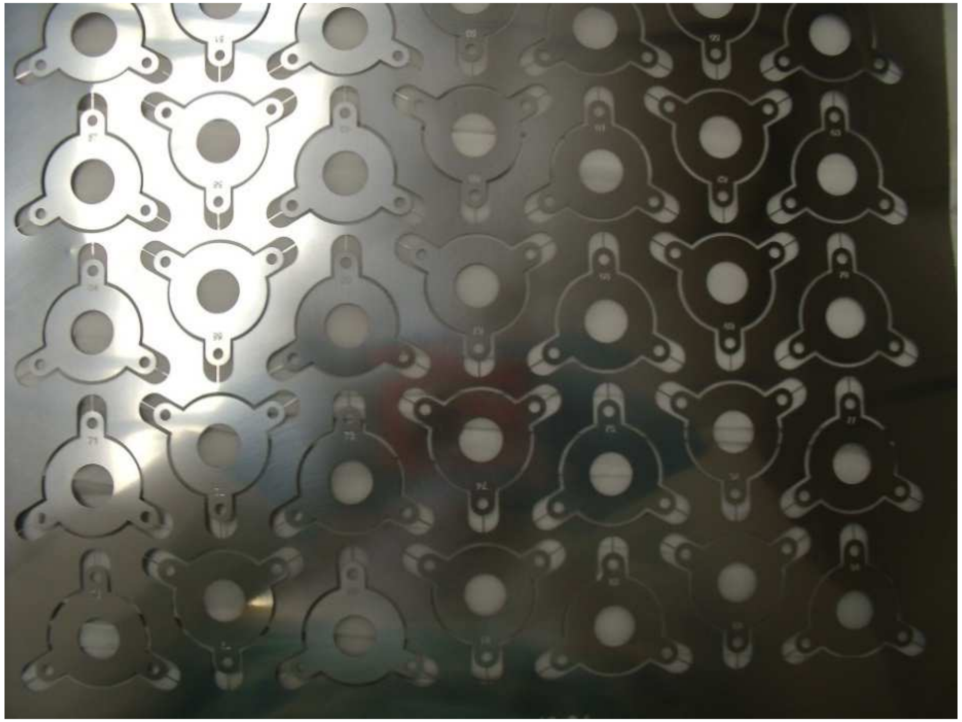
Differential Pumping Stages

Chamber A	Chamber B	Chamber C	Chamber D
High pressure Xe gas	Funnel chamber	SPIG chamber	Detection chamber
10 bar	~1 mbar	10^{-3} to 10^{-4} mbar	$< 10^{-5}$ mbar

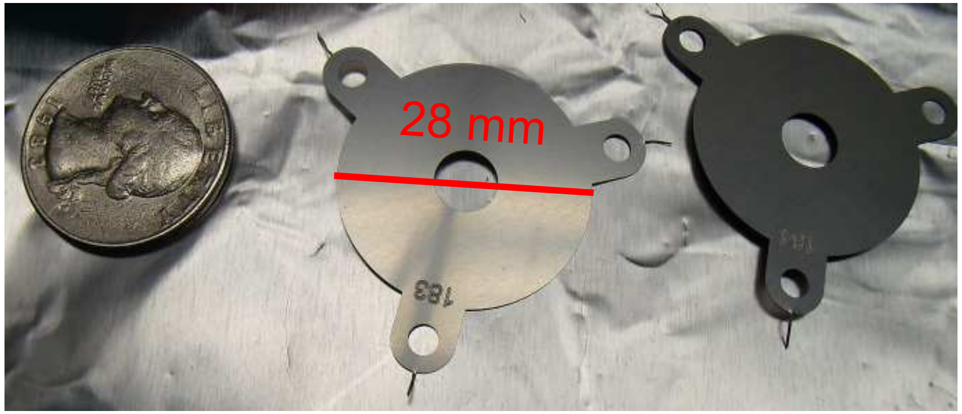

gXe Tagging Setup
Xe bottles
Chamber C
Chamber A
Chamber D
Chamber B
Xe gas

RF-Funnel

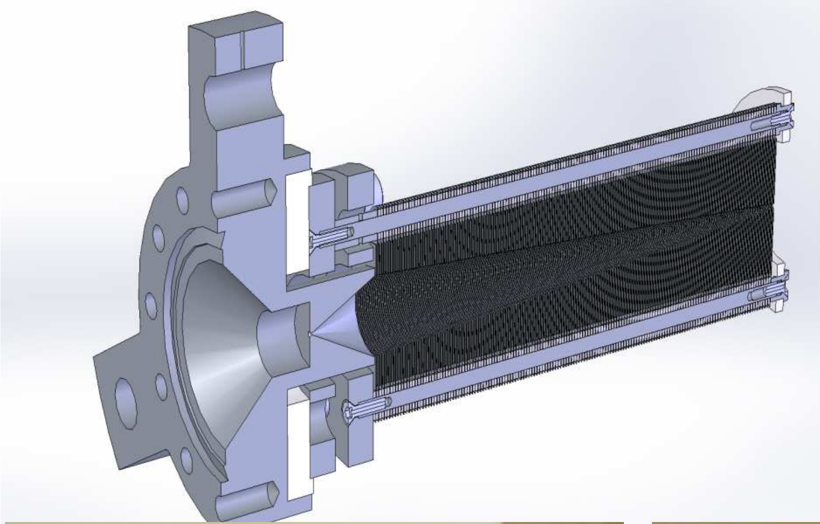




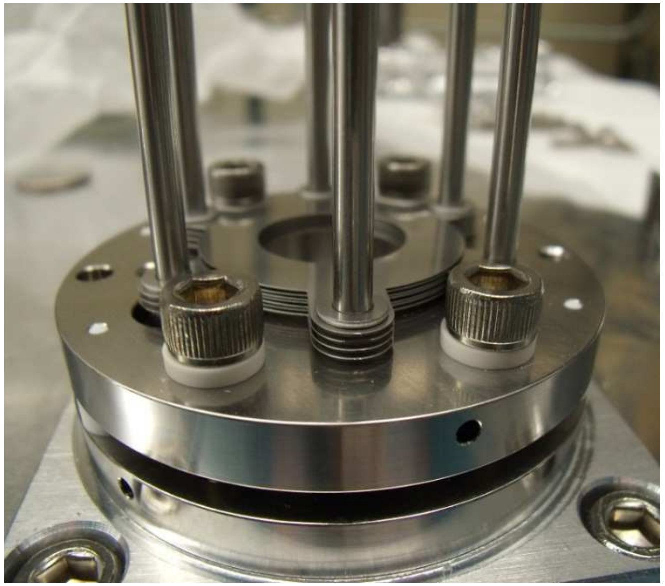
- 336 (301 + spares) photo-etched electrodes by Newcut
- 6x7 electrodes/sheet @ 8 sheets
- Metal sheet: 0.1016 mm (+/- 0.00254 mm)



RF-funnel

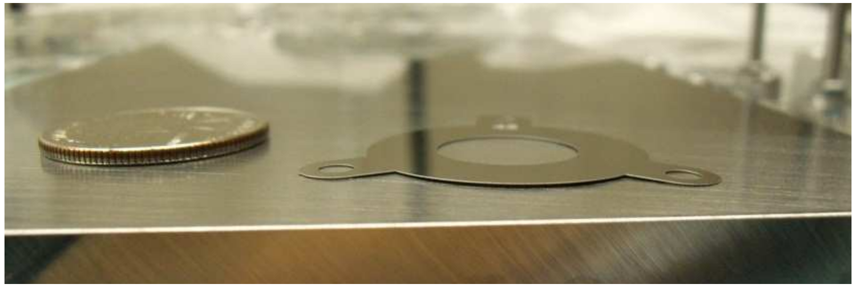


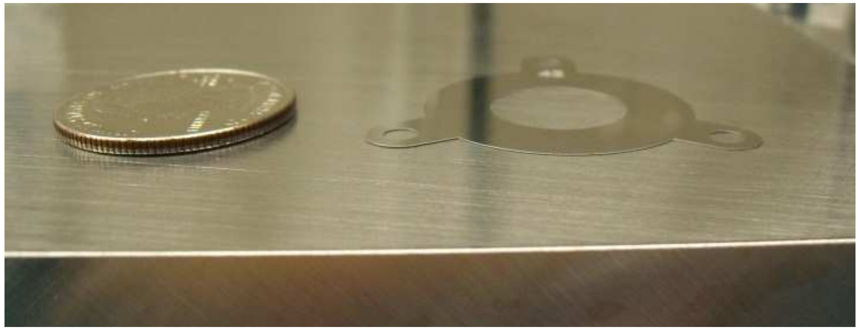

301 photo-etched electrodes
42 electrodes/sheet
Metal sheet: 0.1016 mm (+/-0.00254 mm)



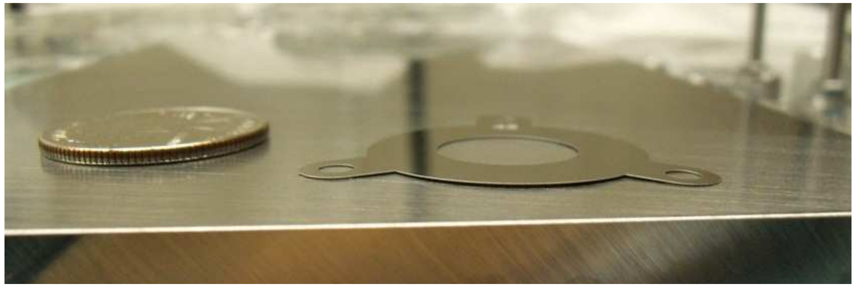
RF-funnel assembly

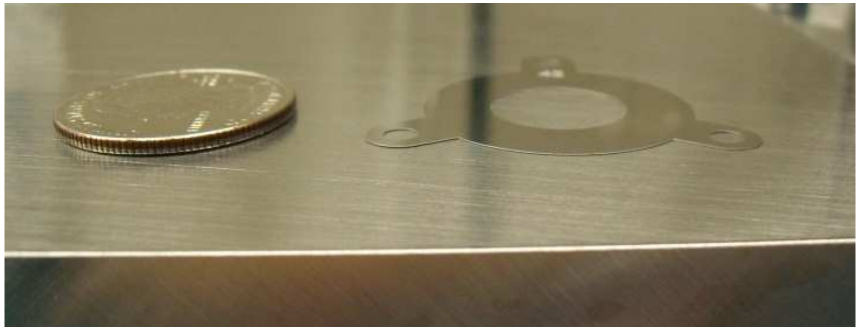
- The tolerances on the thickness of the electrodes is very tight.
- The flatness of the electrodes is pretty bad.

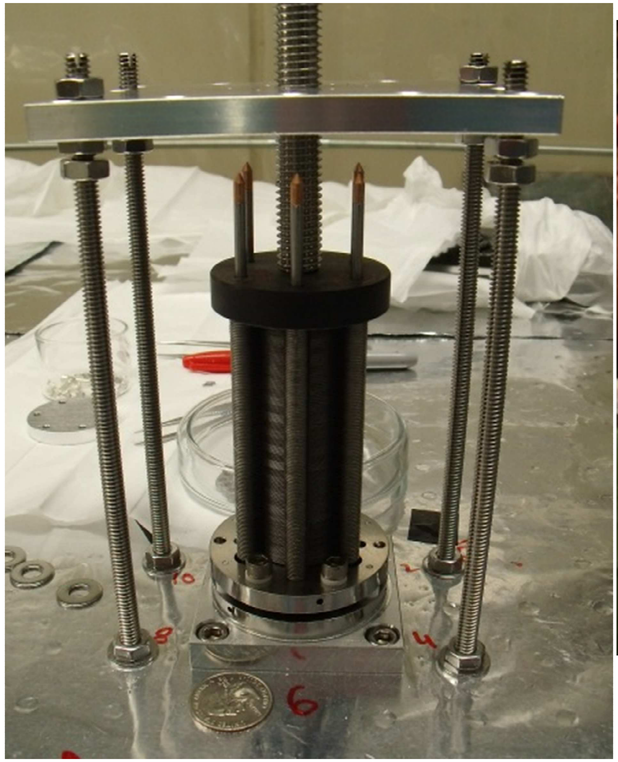




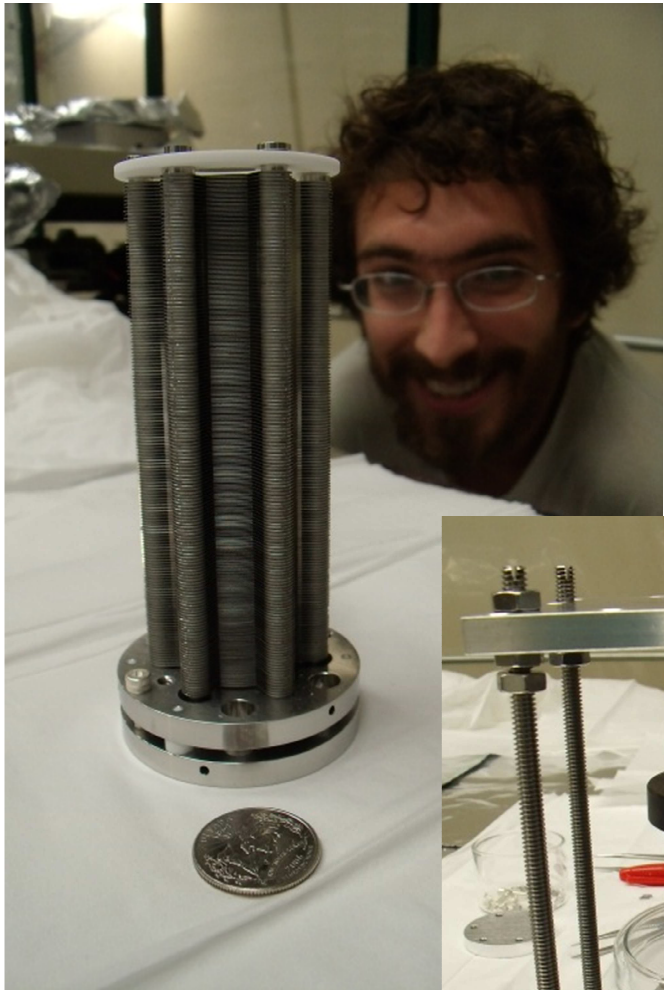
RF-funnel assembly



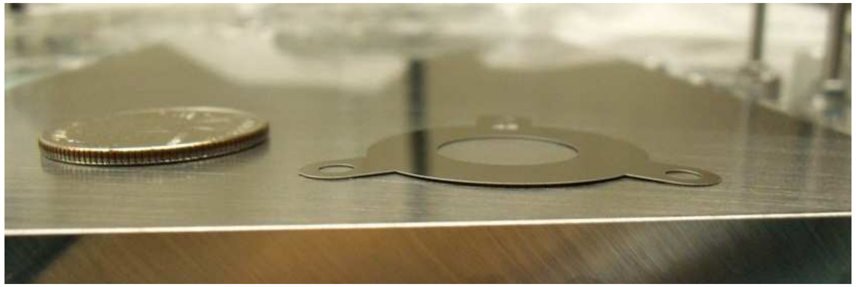


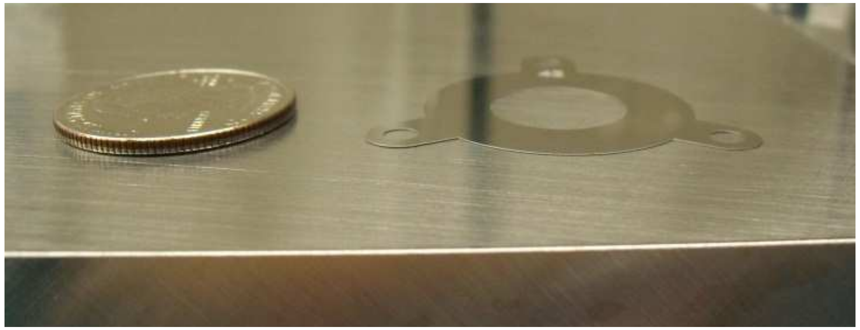


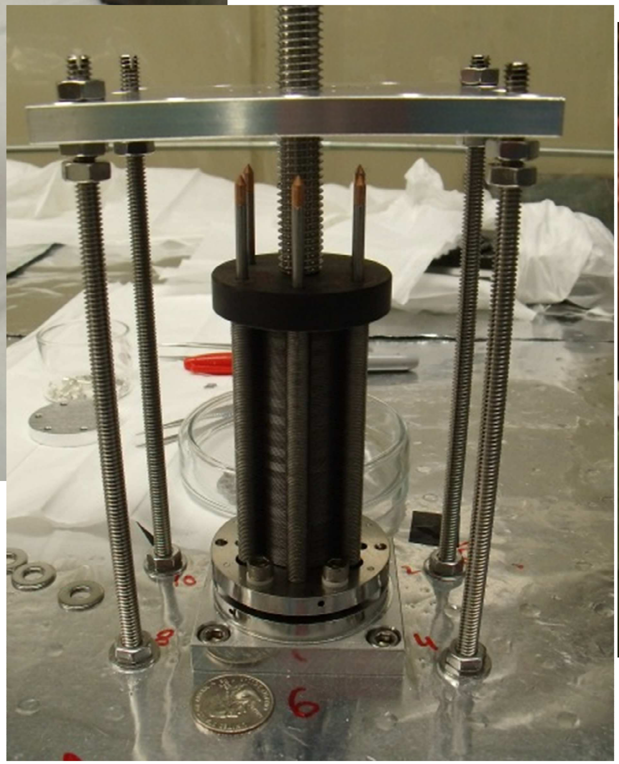
RF-funnel reloaded



Visual short indicator:
Dan ☹ → short
Dan ☺ → no short

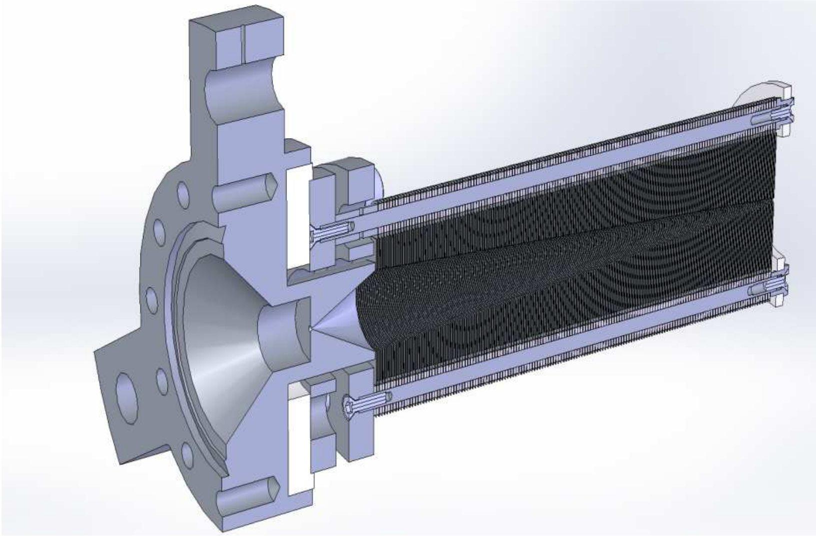


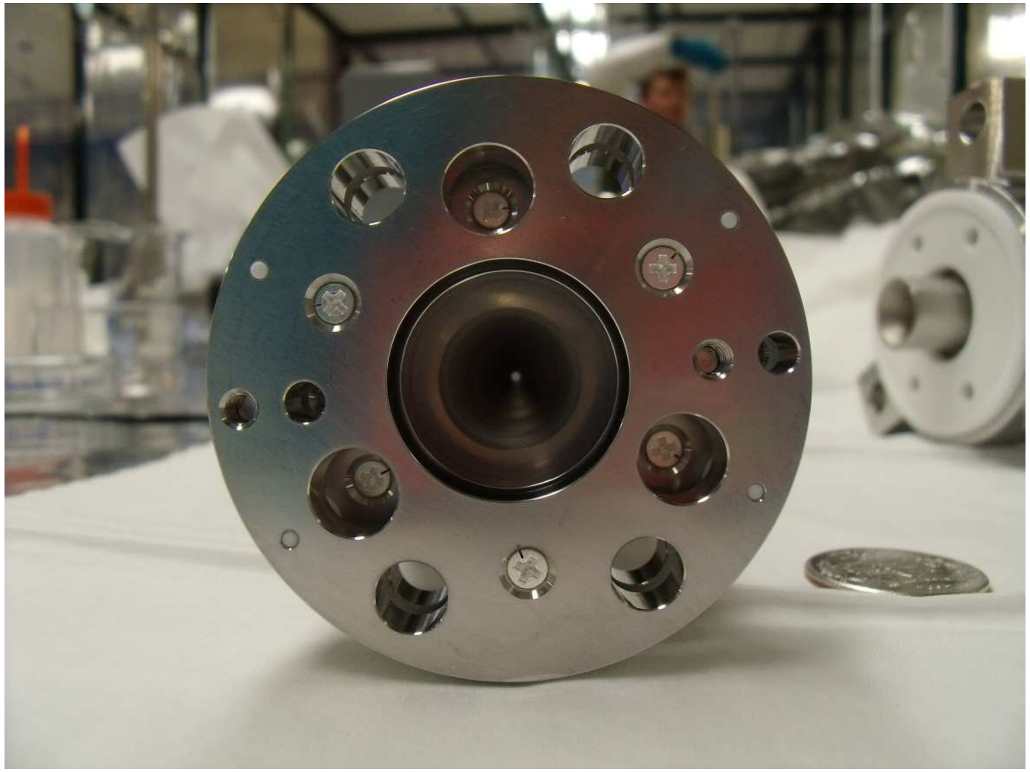




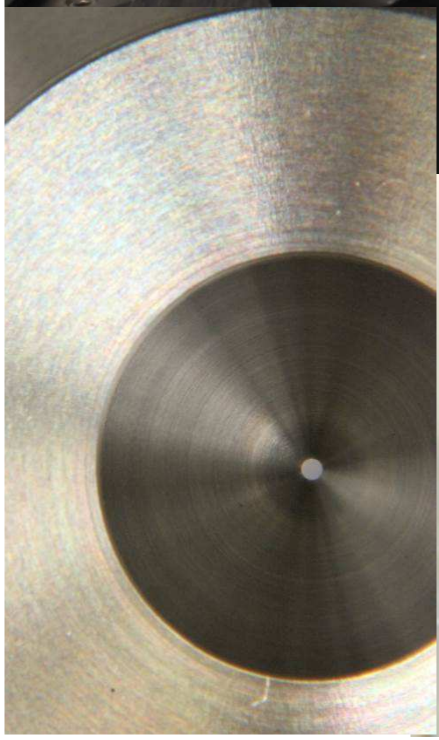
RF-funnel completed

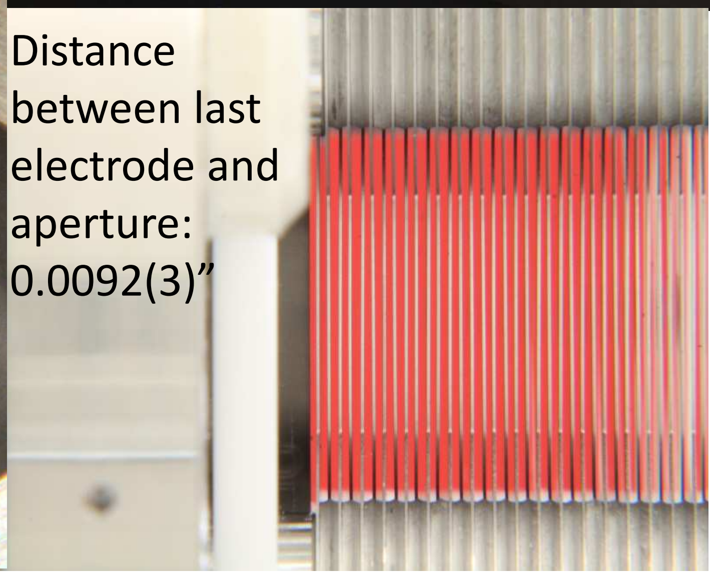
(C=6.086nF@1kHz, f_{res} ~2.6MHz)





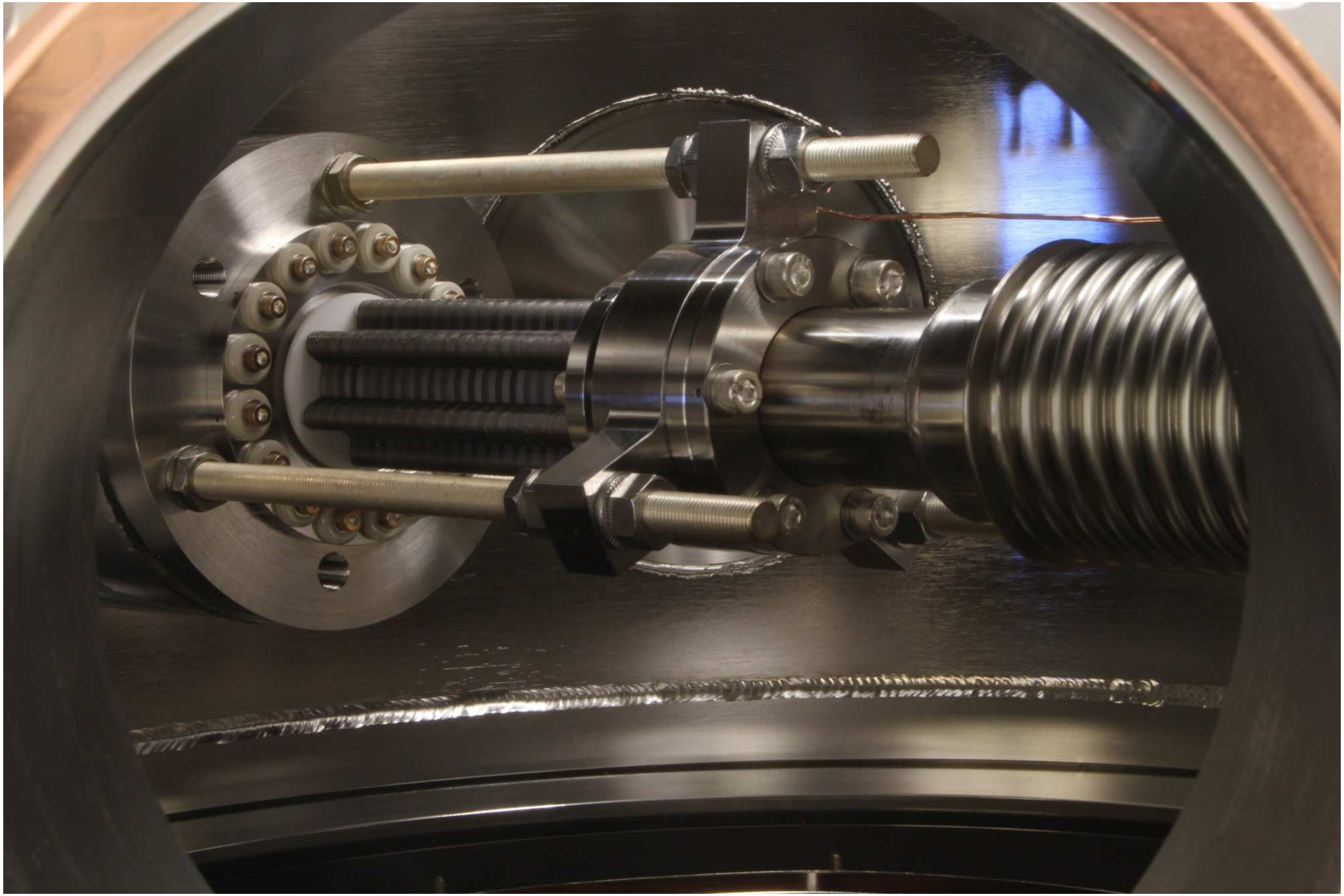
Installed Funnel



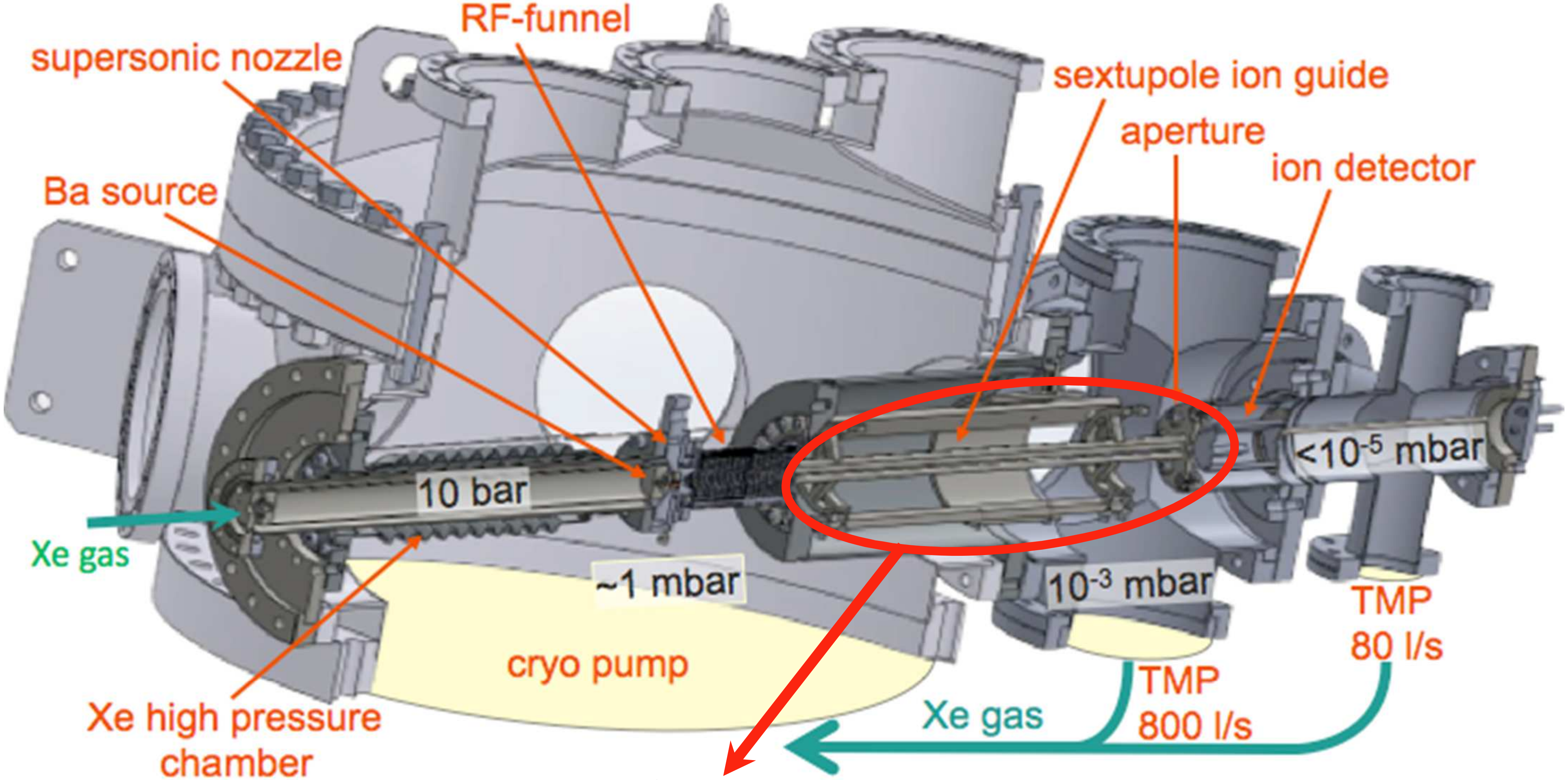


Distance between last electrode and aperture: 0.0092(3)”

The RF Funnel Installed In Chamber B



Downstream Ion Optics



<u>SPIG ion guide:</u>

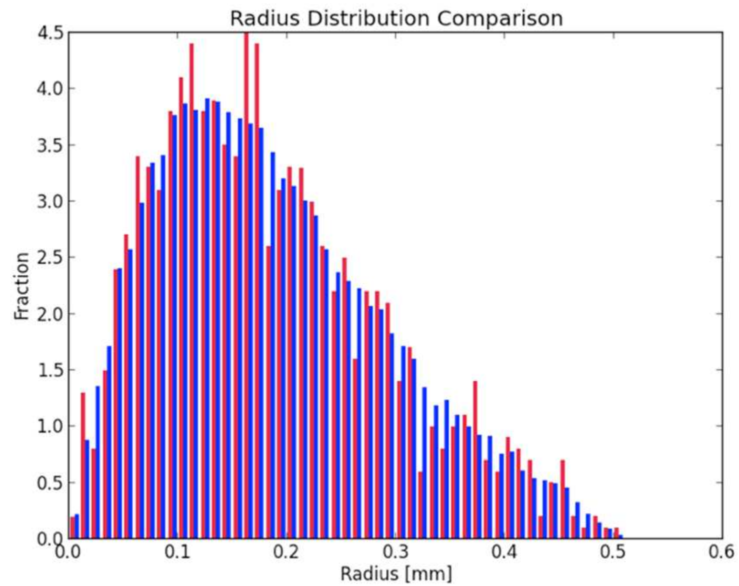
- 3/16” diameter rods
- 2 RF+DC fields
- 1 DC extraction field

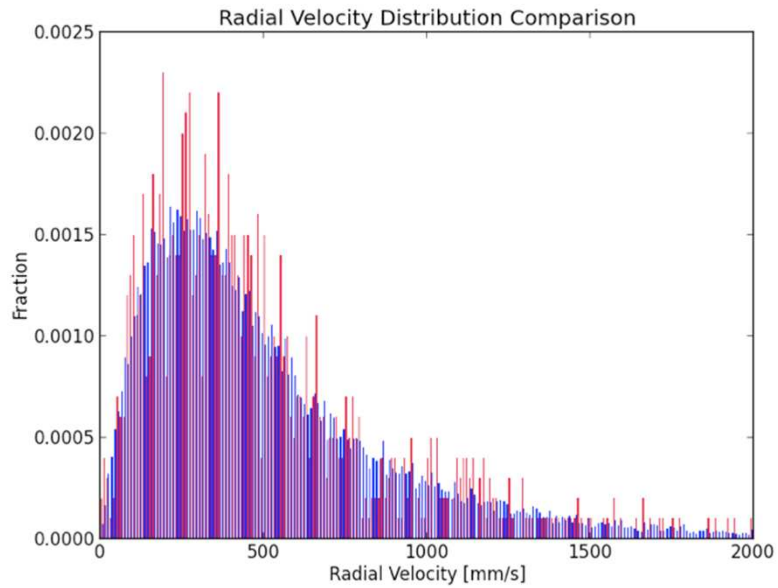
Downstream Ion Guide Simulations

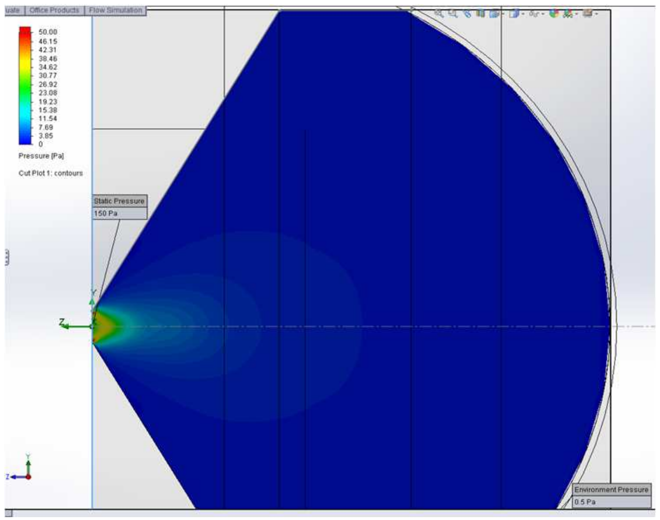
D. Fudenberg

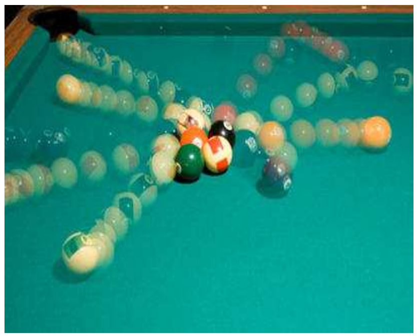
Challenges:

- Transport ions from 1 to 10^{-4} mbar
- Ions reconstructed from Victor's RF-Funnel simulations
- Convey across a distance of 0.48 m
- Focus ions through a small aperture
- Xe - Ba Collisions





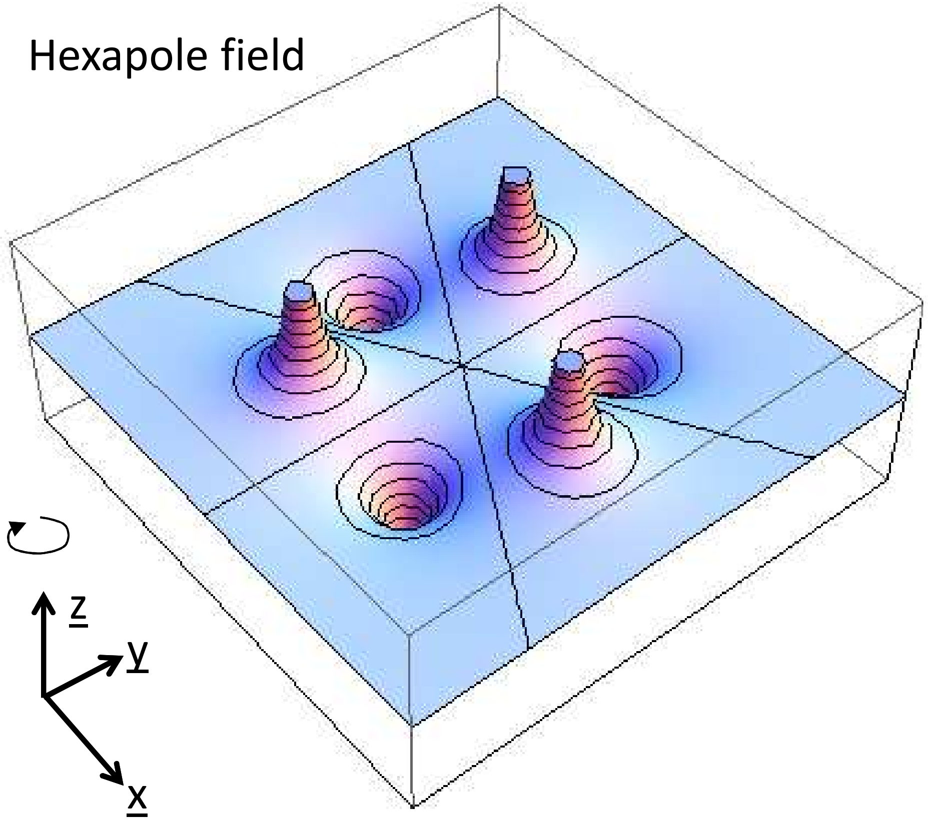


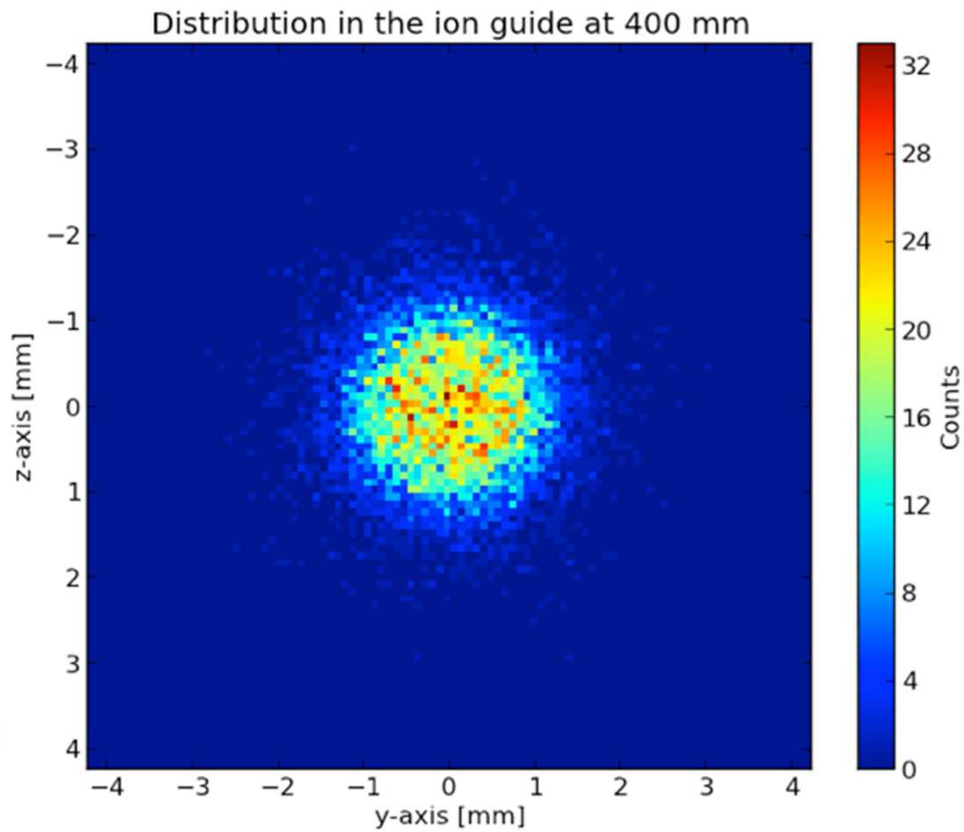


Details of Full Simulation

- Simulated in two stages
  - To 400 mm : 91.2%
  - Thru Aperture to CEM: 83.8 %

Hexapole field

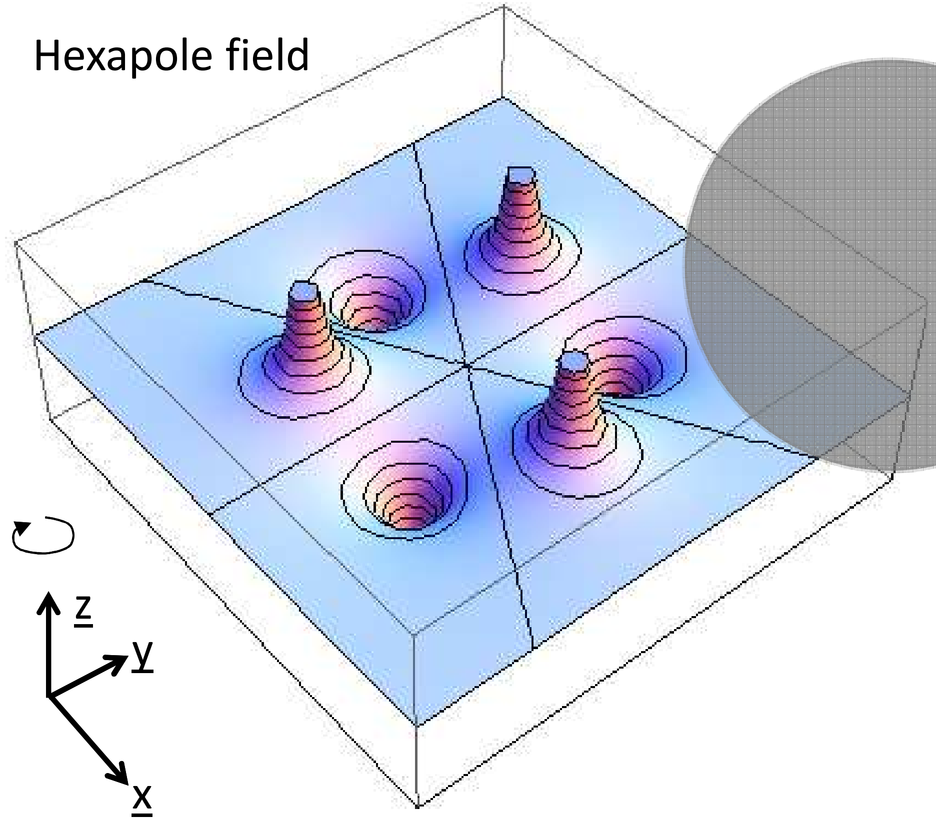


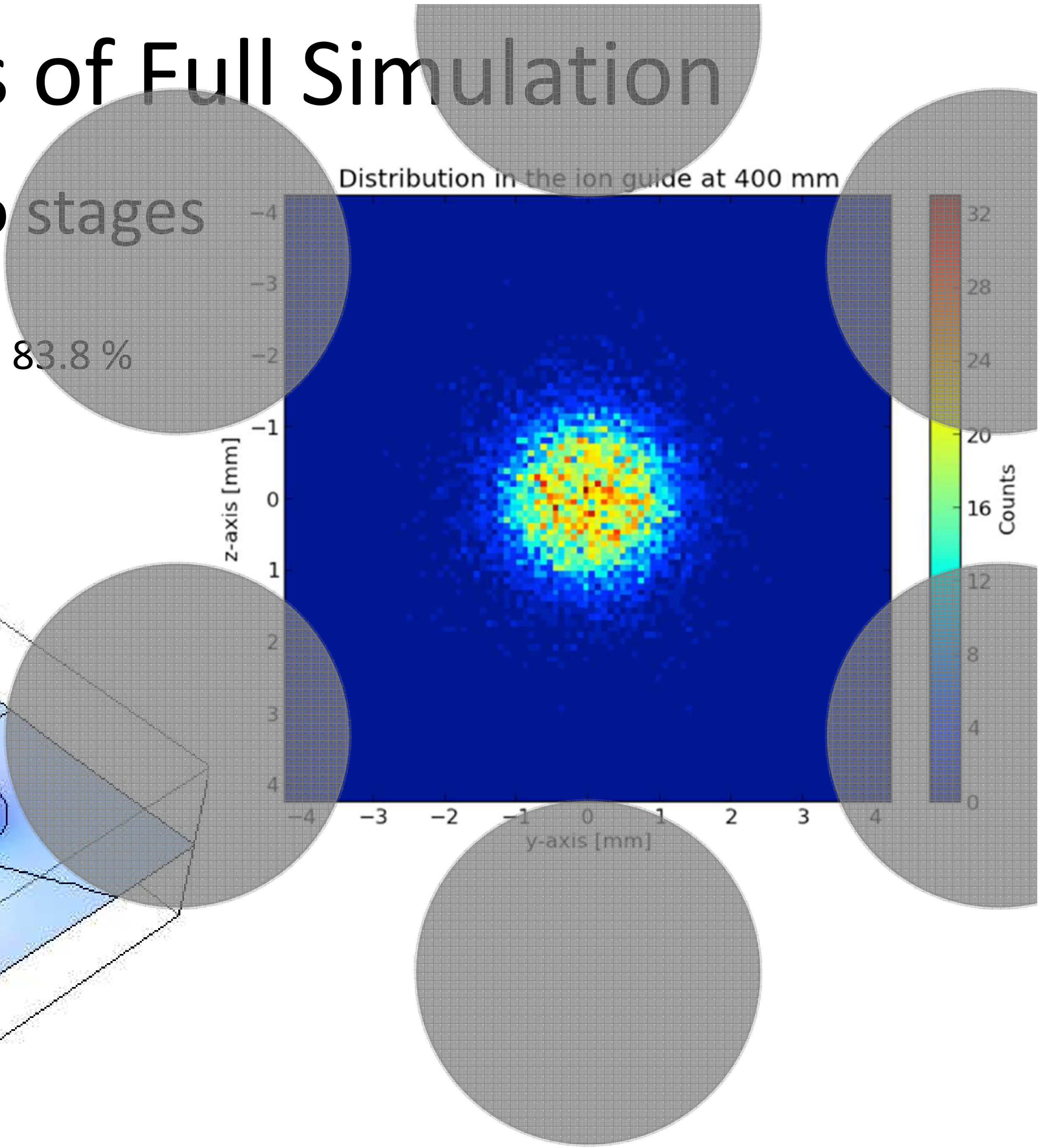


Details of Full Simulation

- Simulated in two stages
  - To 400 mm : 91.2%
  - Thru Aperture to CEM: 83.8 %

Hexapole field

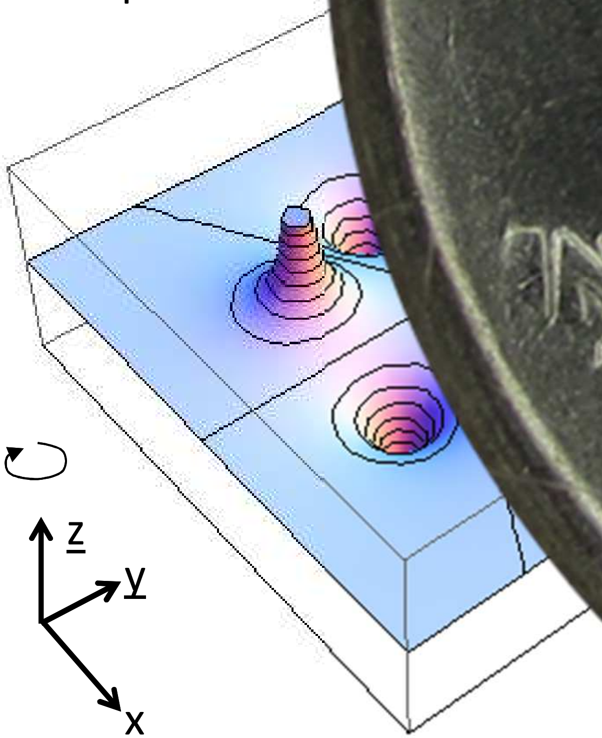


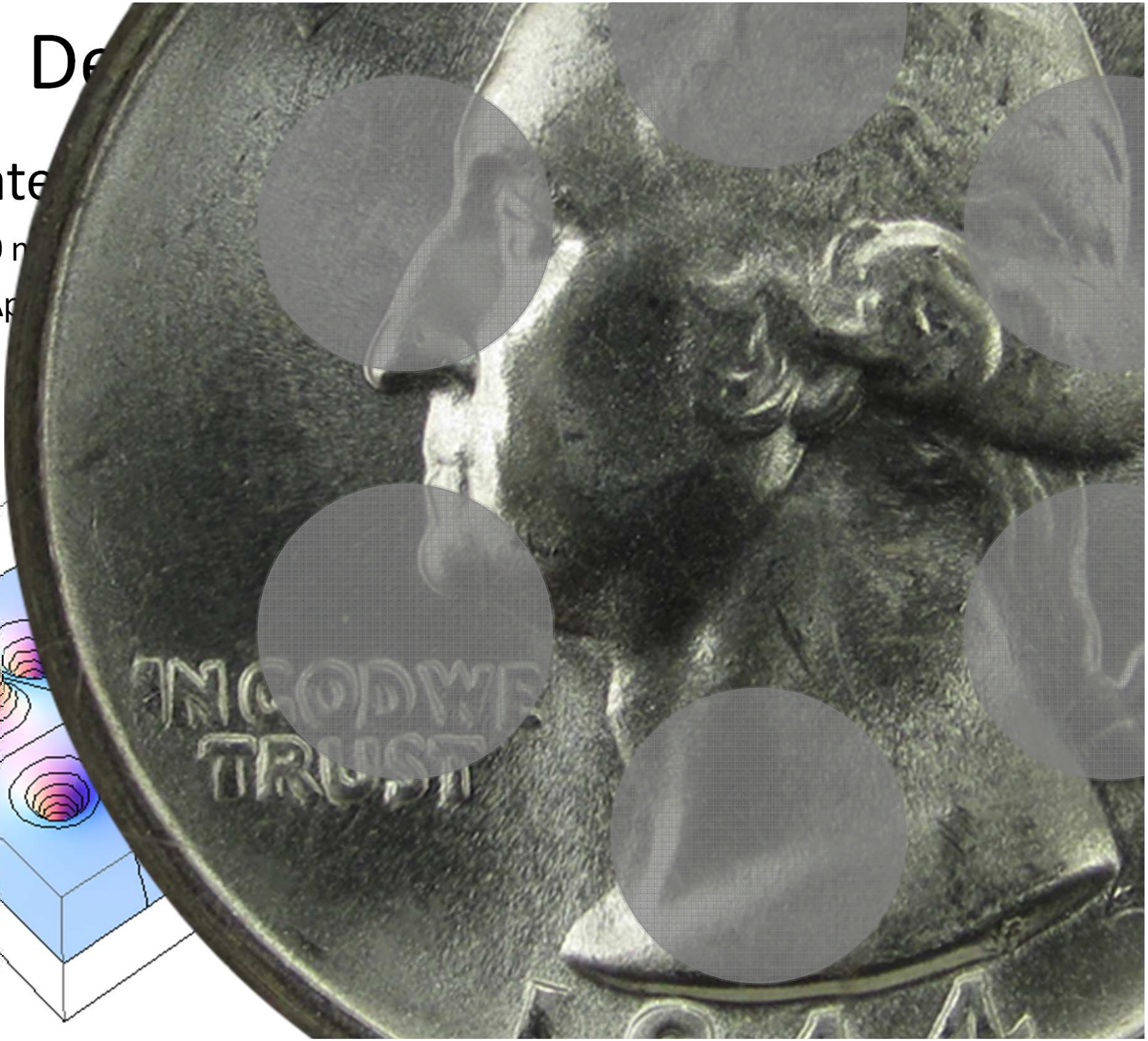


De

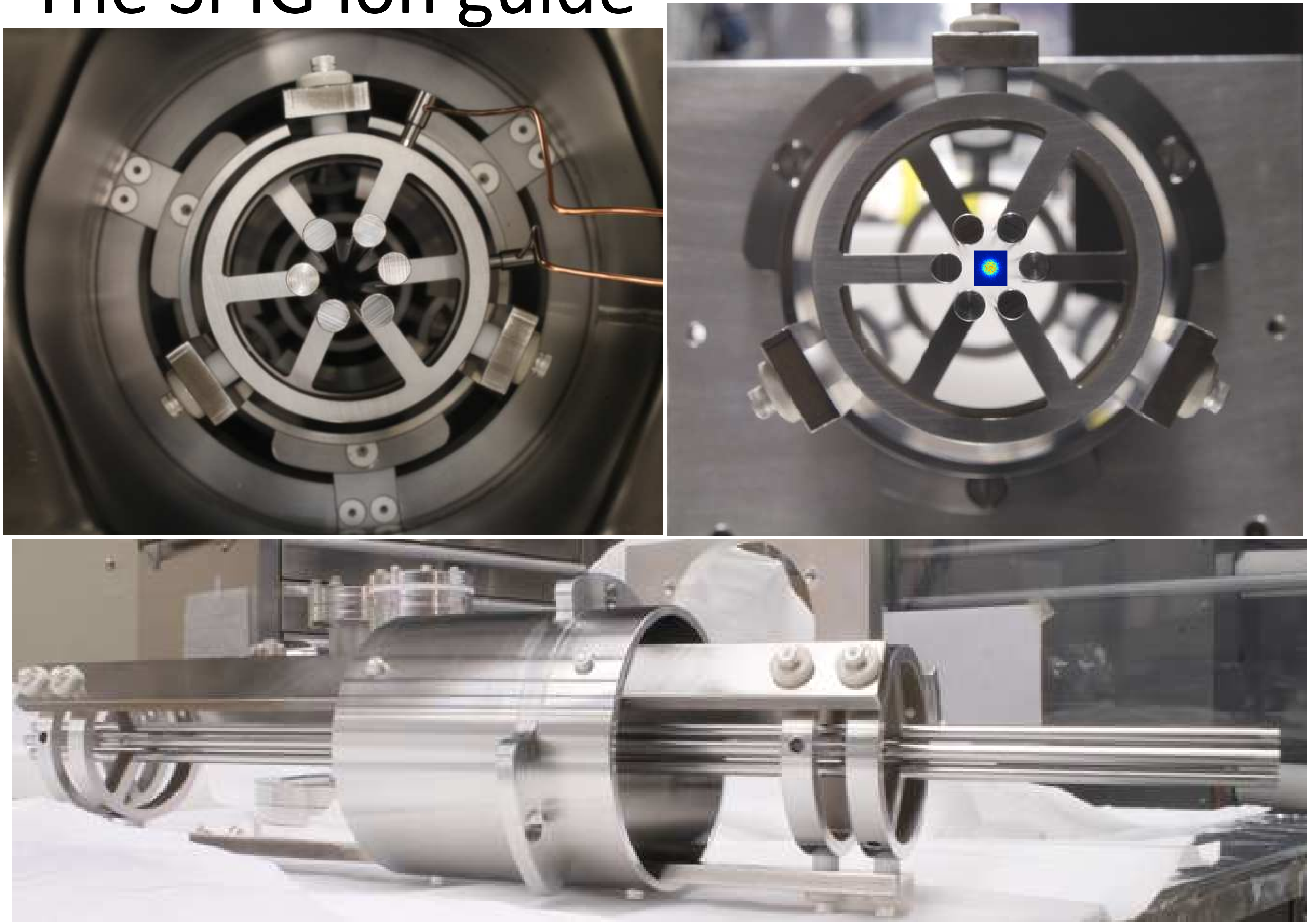
- Simulate
  - To 400 n
  - Thru Ap

Hexapole field

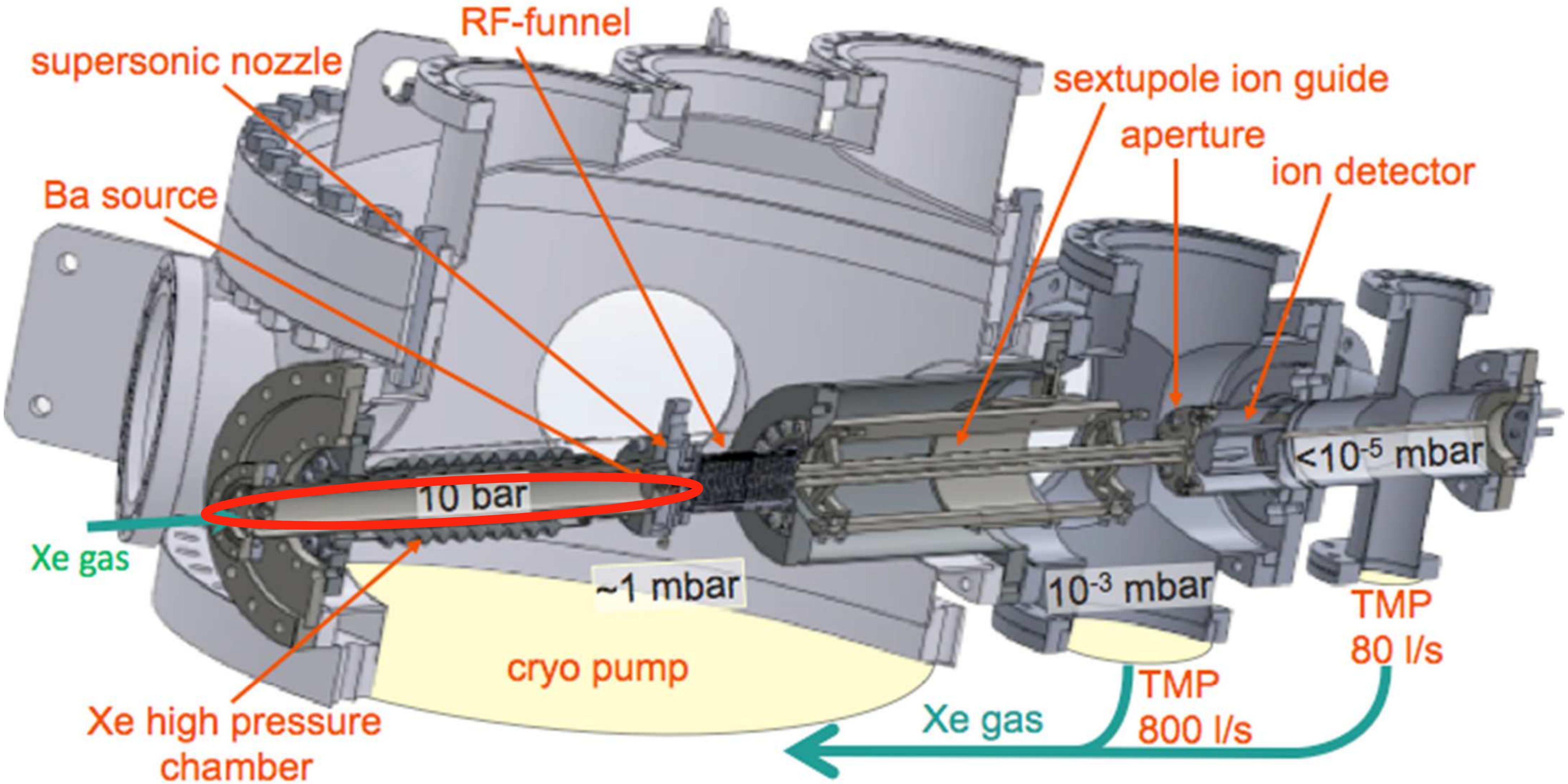




The SPIG ion guide



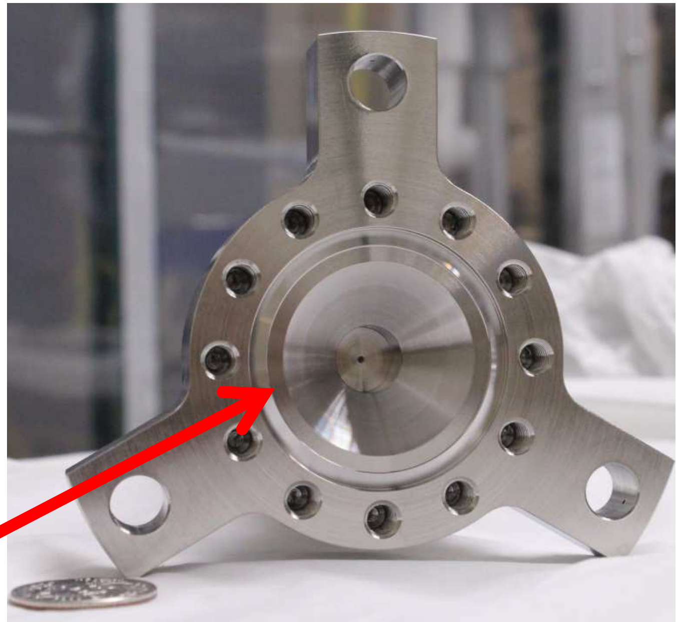
Ba Source and Holder

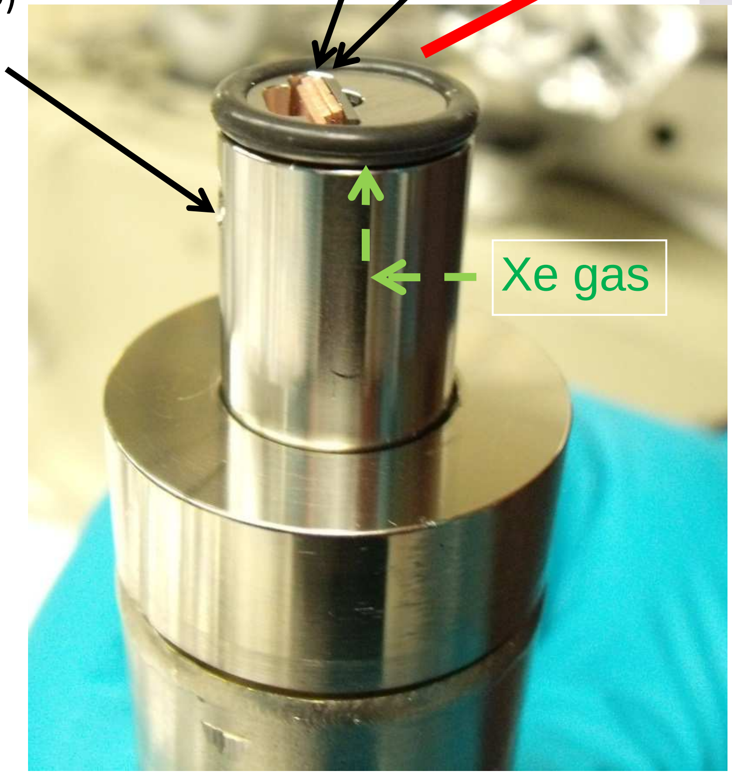


Source holder with dummy source or real source

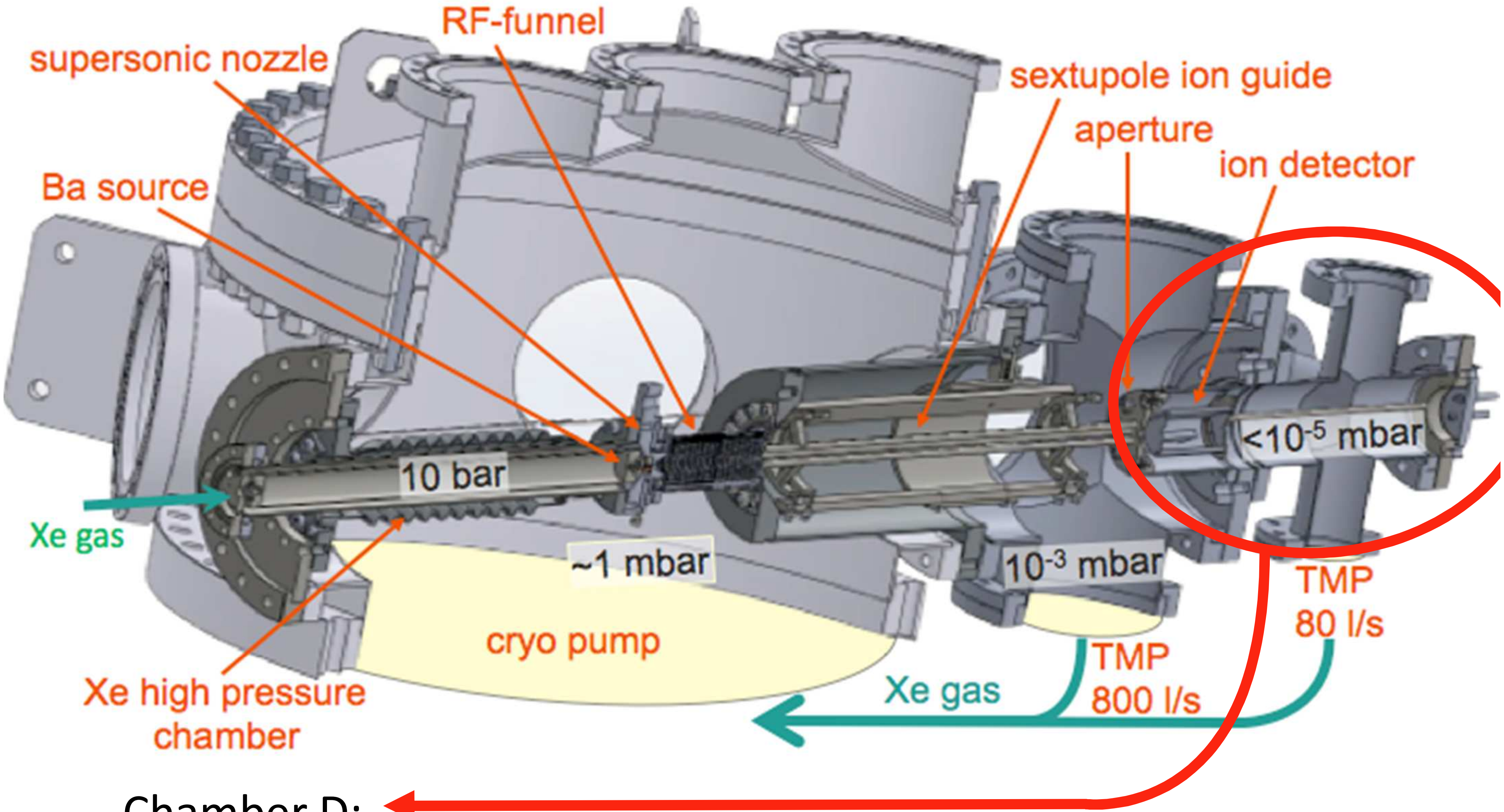
- Electroplating of ^{148}Gd onto 0.250” x 0.375” Si/SS plate
- Evaporate BaF (~10 nm) onto ^{148}Gd source
- ^{148}Gd activity before BaF coating ~250 Bq
- Dummy source without activity

Rev. Sci. Inst. **81** 113301 (2010)





Ion Detection



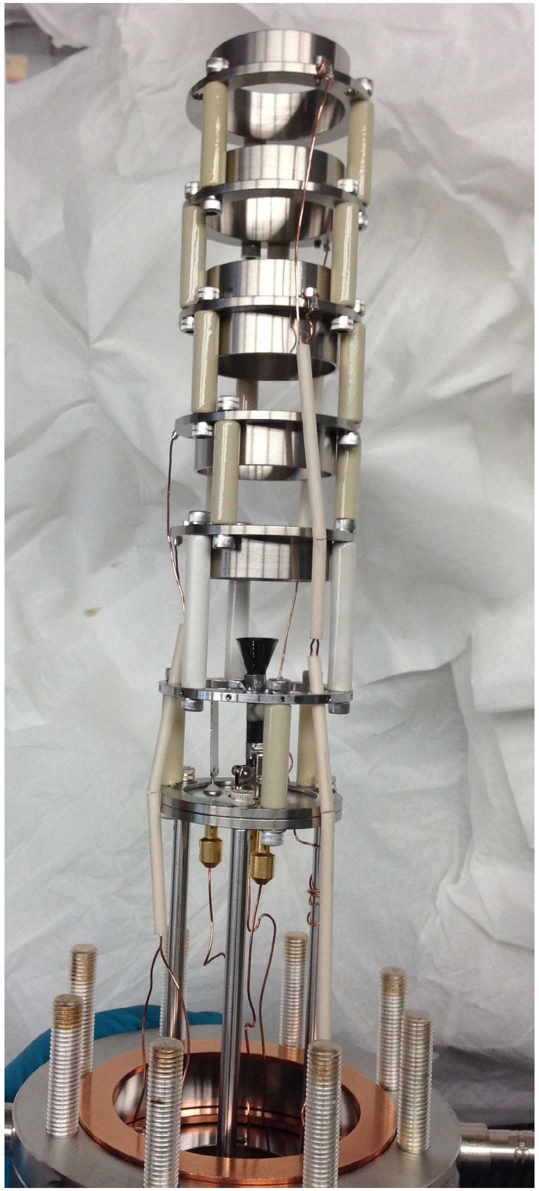
<u>Chamber D:</u>

- Reaches ~4x10^{-9} torr
- During Xe/Ar gas operation pressure is ~5 x 10^{-6} mbar

Ion detector for chamber D

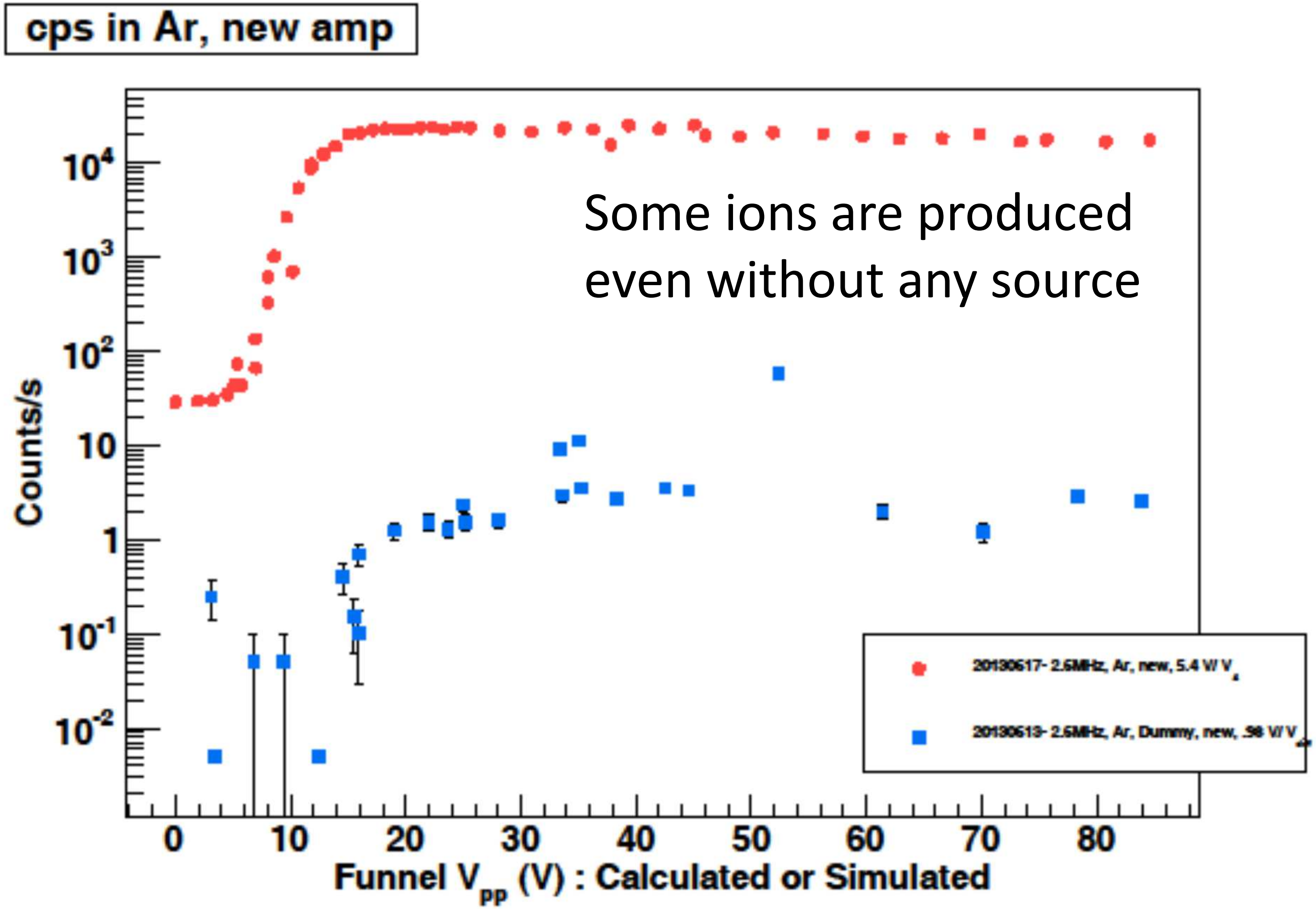
Channeltron

Channeltron with lenses



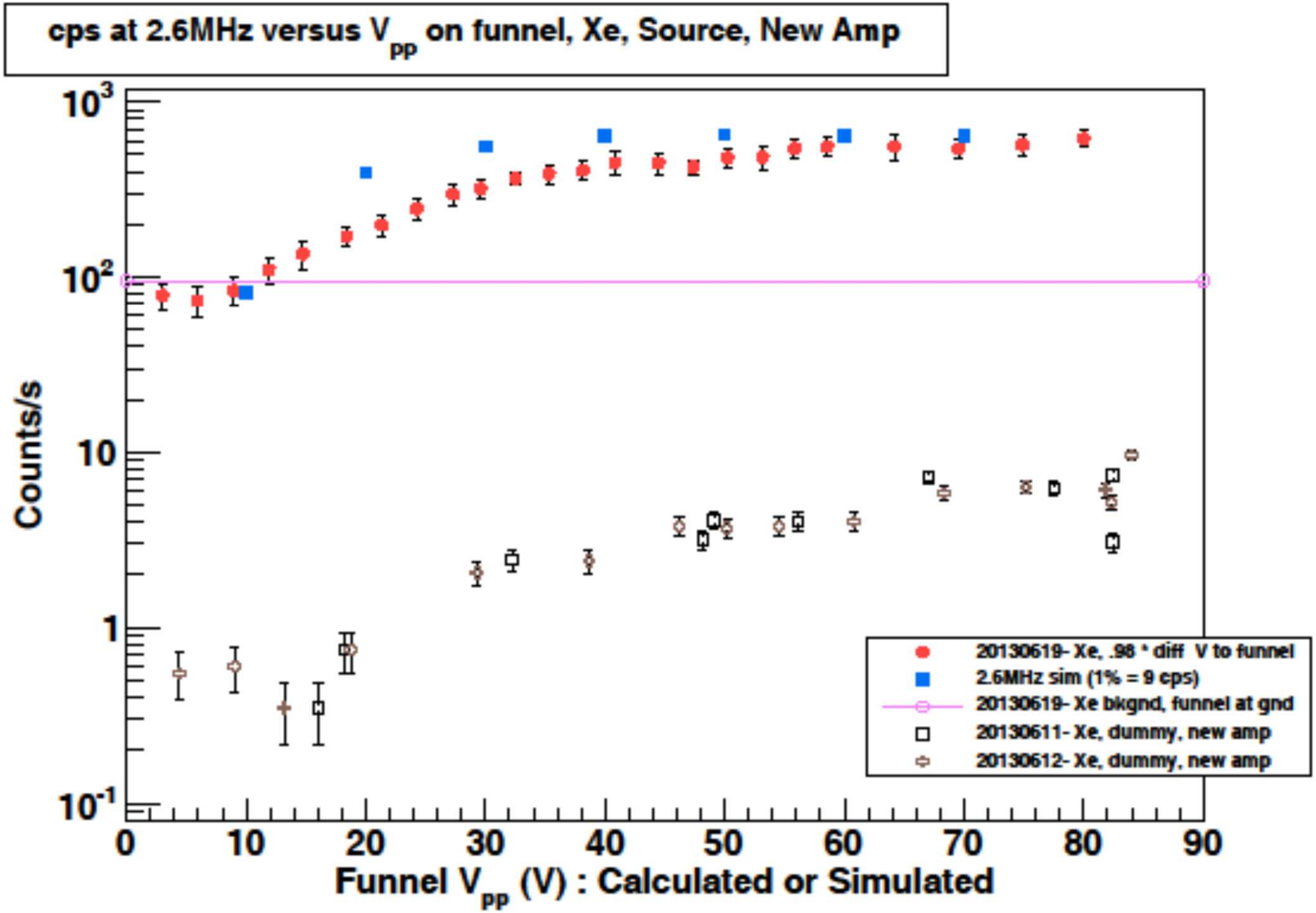
MKS MicroVision 2 RGA with lenses

Source dummy vs. Ba^+ source in Ar

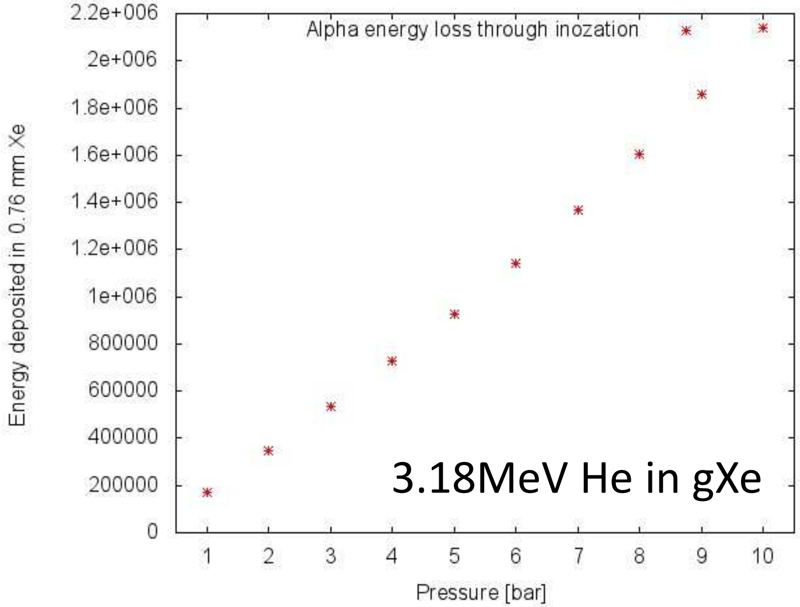


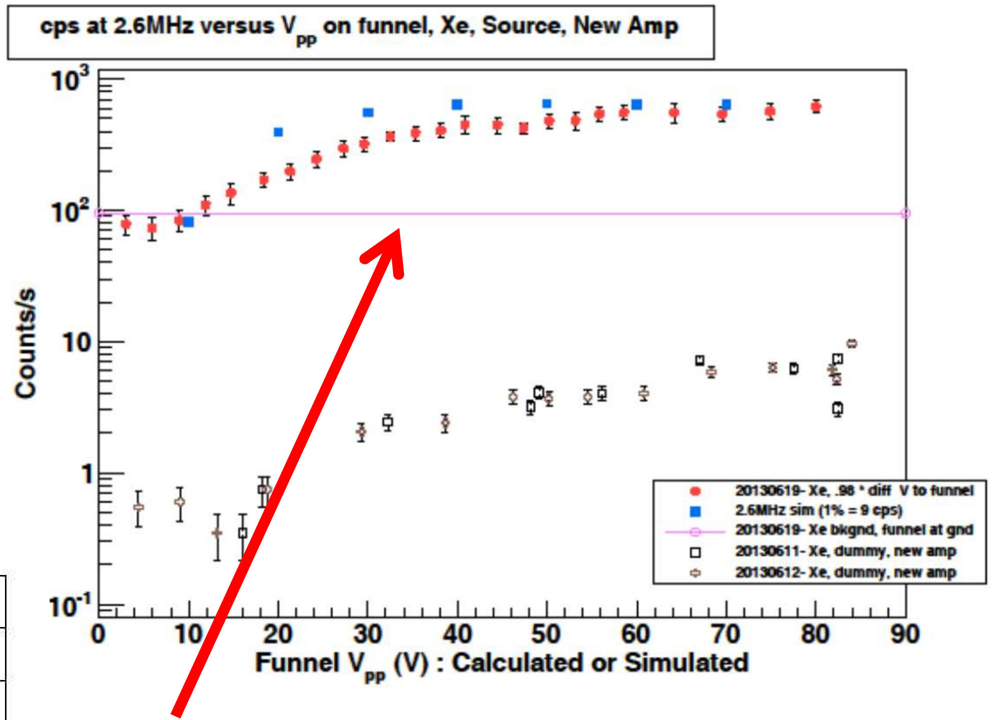
Some ions are produced even without any source

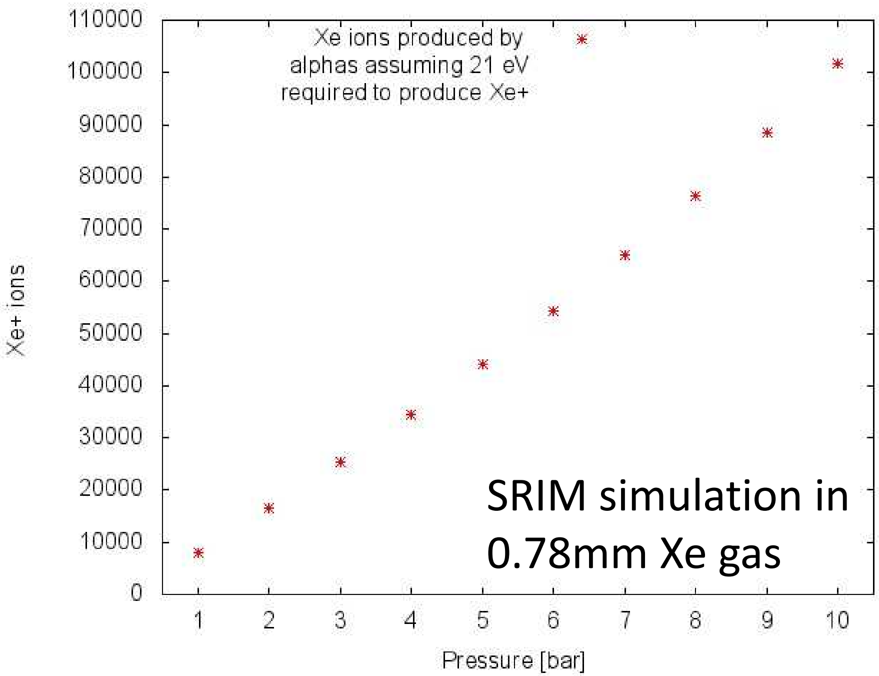
Xe gas operation



What are we seeing?





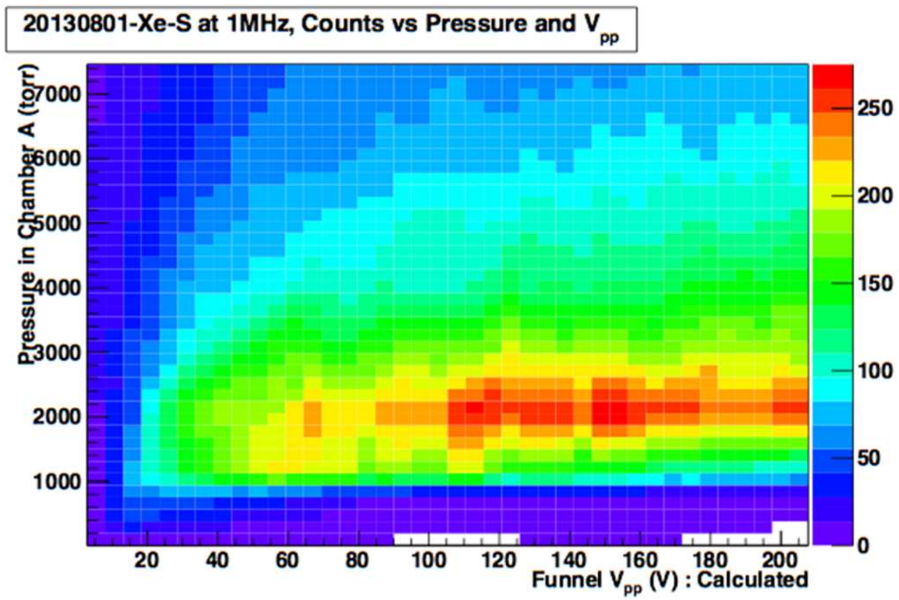


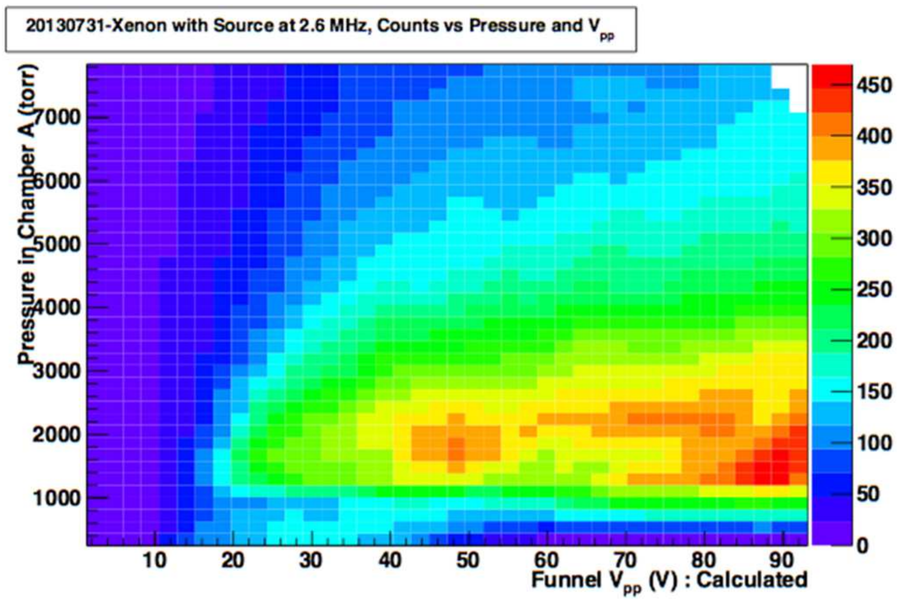
Gedankenexperiment:
Assume flow reduction of factor ~250, measured ~90cps on CEM required about 22500 ions in the jet (neglecting SPIG and detection efficiency)
Assuming 60% efficiency → 37k-ions/s in funnel with Ba^{+} source

Another gedankenexperiment

- Xe flow is about 0.35 g/s → 1.6 * 10^{21} ions/s
- Extraction of 700 ions/s is a reduction of 18oom
- Assuming 2 Ba^{+} ions out of these 700

  → Only reduction of 350 left ;-)





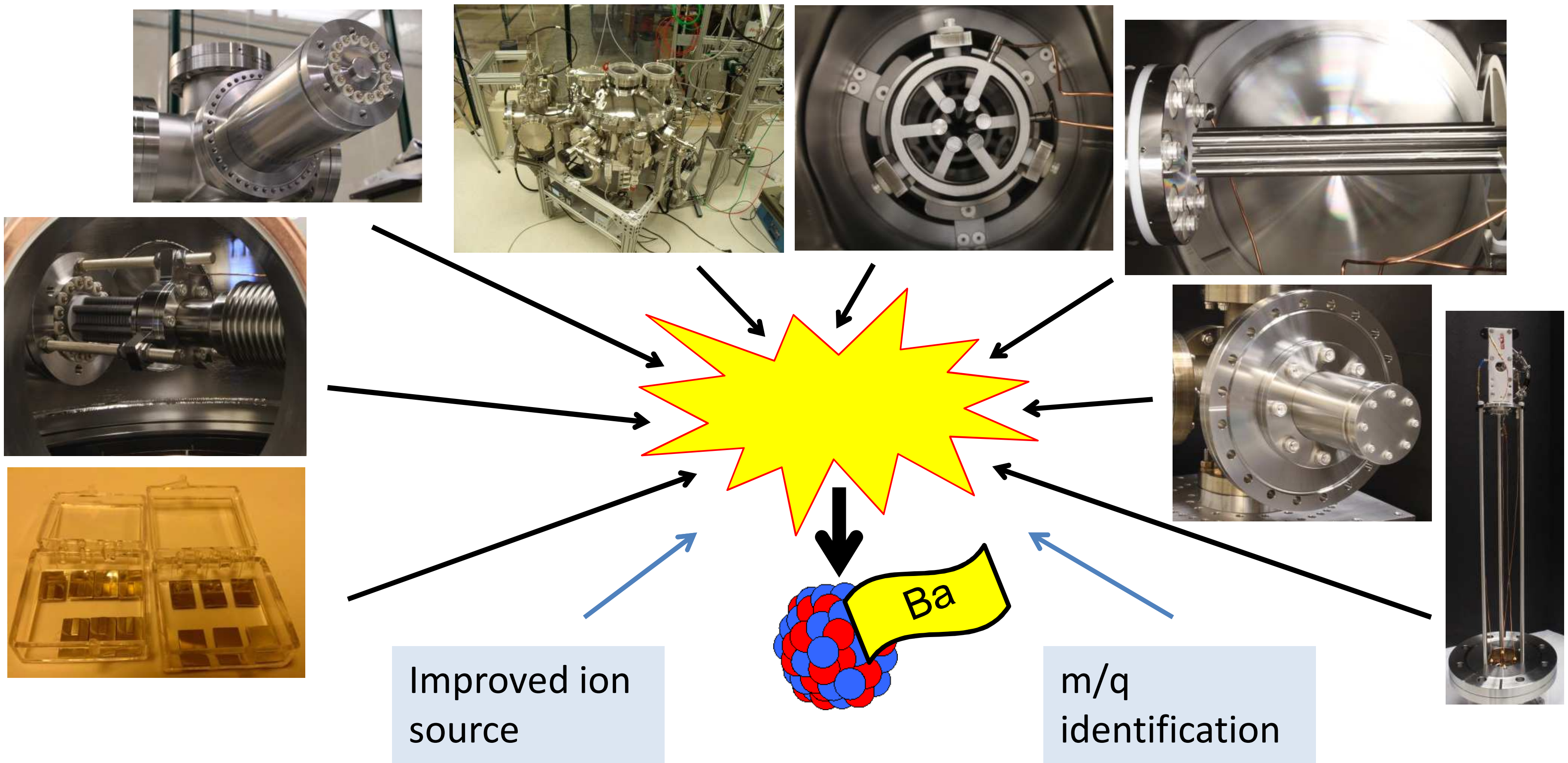
Next Steps – stay tuned

Fabricate ion source with new ion source design (0.010” gap)

Determine means to identify ions by q/m → design a multi-reflection TOF mass spectrometer

Determine the possibilities to measure Ba^{++} source activity

Determine efficiency of funnel



The EXO Collaboration

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke

University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, F. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith

Duke University, Durham NC, USA – P.S. Barbeau

University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, J. Walton, M. Tarka, L. Yang

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, Y. Zhao

Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman

University of California, Irvine, Irvine CA, USA - M. Moe

ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, M. Lodato, C. Mackeen, K. Malone, A. Pocar, D. Shy, J.D. Wright

University of Seoul, South Korea - D.S. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, A. Dragone, K. Fouts, R. Herbst, S. Herrin, A. Johnson, R. MacLellan, K. Nishimura, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, M. Weber, L. Wen

Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – P.A. Amandruz, D. Bishop, J. Dilling, P. Gumplinger, R. Kruecken, C. Lim, F. Retiere, V. Strickland