Nuclear Science and Security Consortium
Virtual Scholar Showcase 2020

Towards a More Sensitive Measurement of the Atomic Electric Dipole Moment of ^{225}Ra

6/2/2020

Roy Ready
Michigan State University

NSSC
NUCLEAR SCIENCE and SECURITY CONSORTIUM

June 2 - 3, 2020

Introduction

Planned Graduation Date: September 2020

Lab Mentor
Nick Scielzo, LLNL

precision gamma-ray intensity measurements of long-lived fission products

FRIB

Academic advisor
Jaideep Singh, MSU

Electric field and atom source upgrades for an improved measurement of the permanent electric dipole moment (EDM) of Radium-225

- **Research Focus Area: Nuclear and Particle Physics**
- **Crosscutting area: Nuclear Data**

2019 Nuclear Security Bootcamp (Washington DC)

Left to right: Allison Macfarlane, Roy Ready, Chris Cahill

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Focus of this presentation

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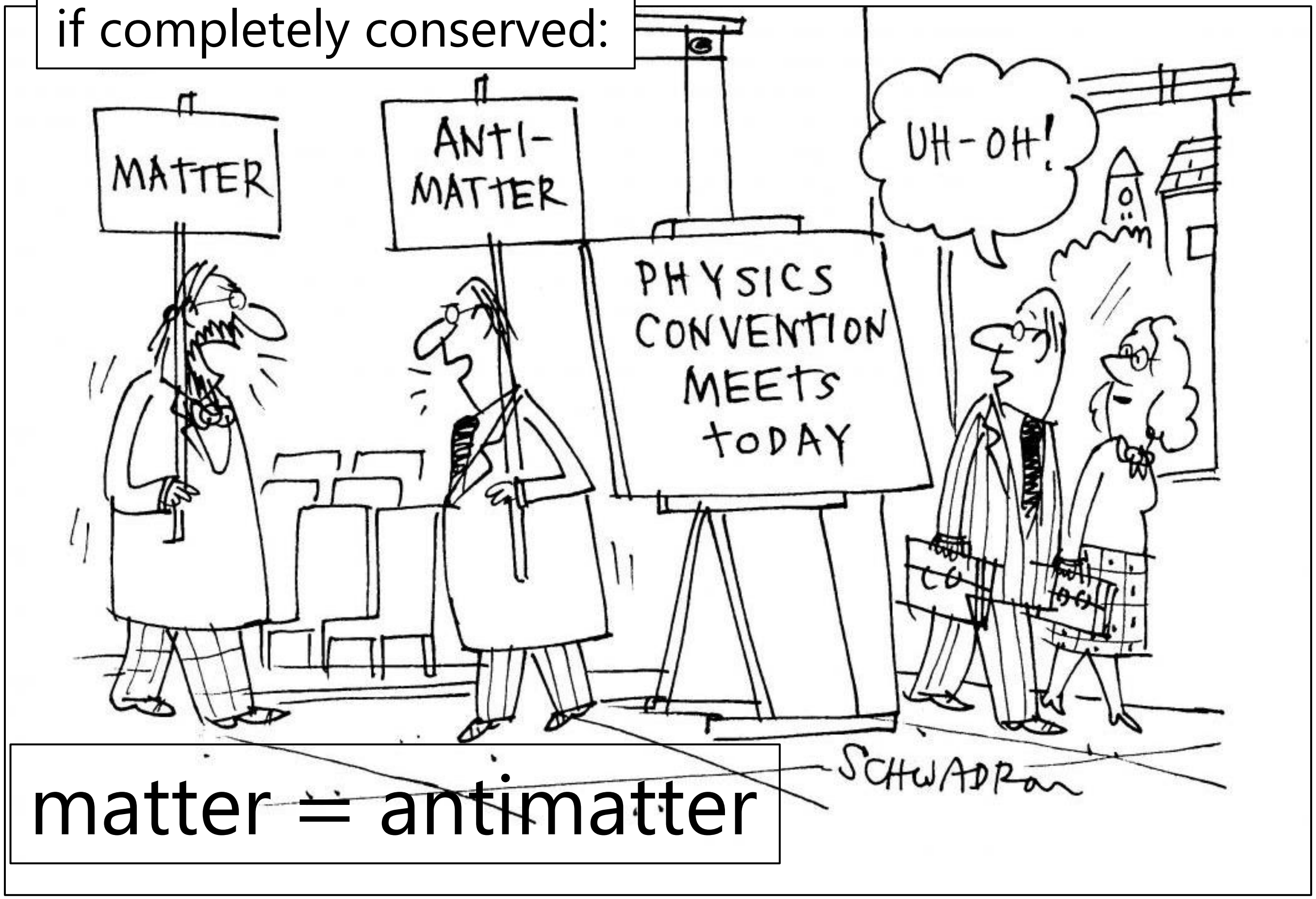
Charge (C) Parity (P) conservation

if completely conserved:



matter = antimatter

Image by Harley Schwardron

CP violation → matter ≫ antimatter

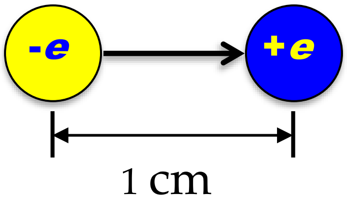
Image by Harley Schwardron

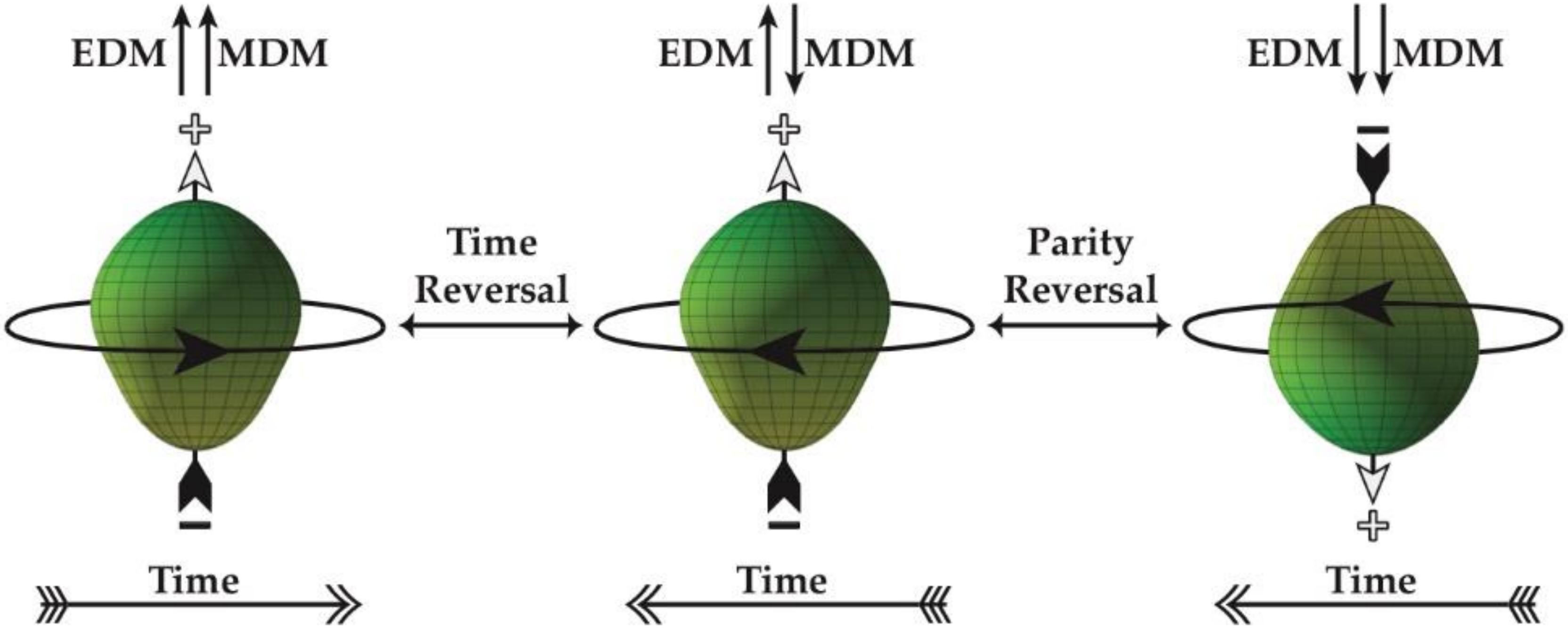
EDMs are CP-violating properties of atoms

permanent Electric Dipole Moment (EDM)

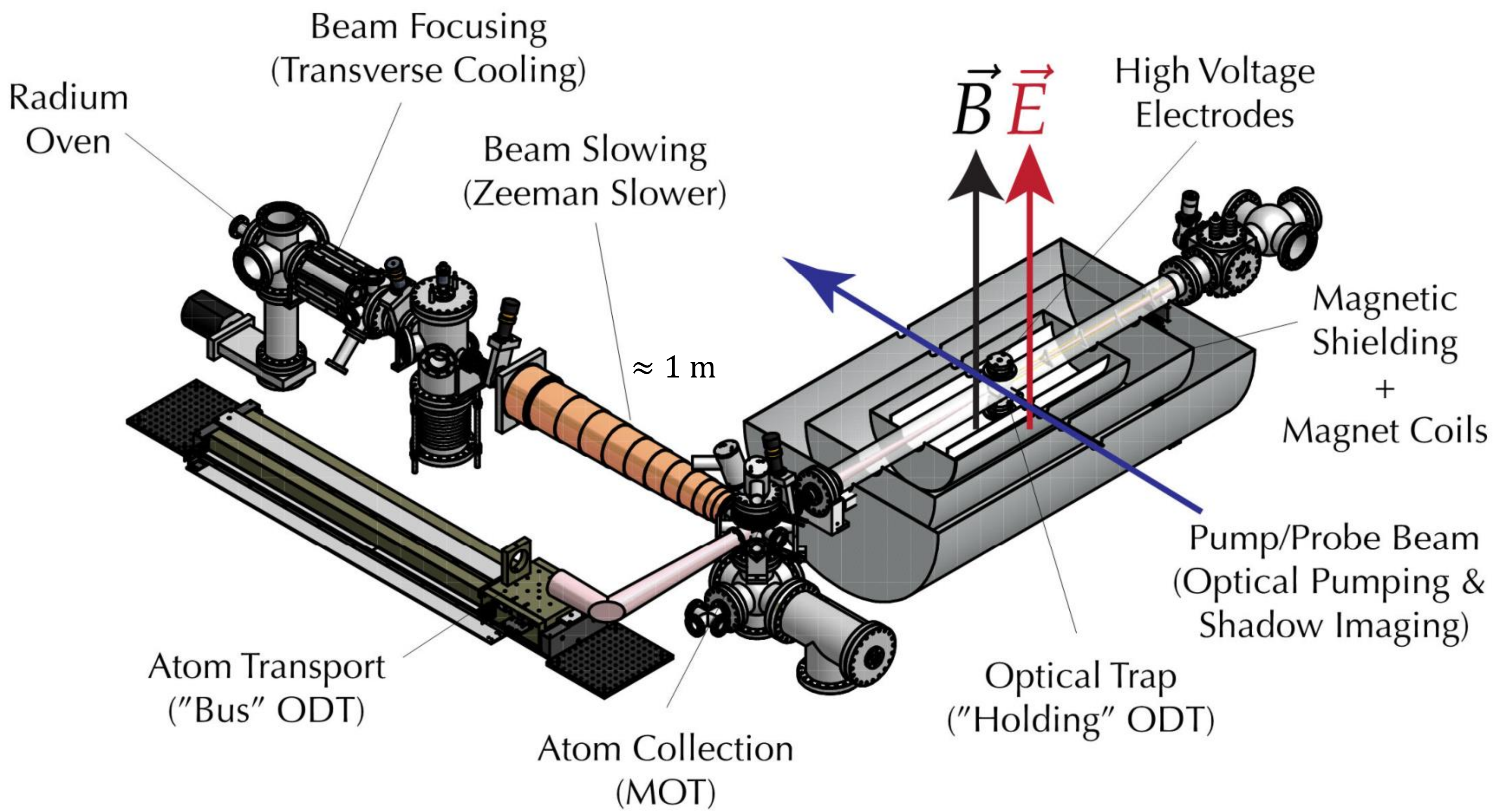
EDM unit: *e* cm

$$\mathcal{H} = -\mu\left(\frac{\vec{S}\cdot\vec{B}}{S}\right) - d\left(\frac{\vec{S}\cdot\vec{E}}{S}\right)$$



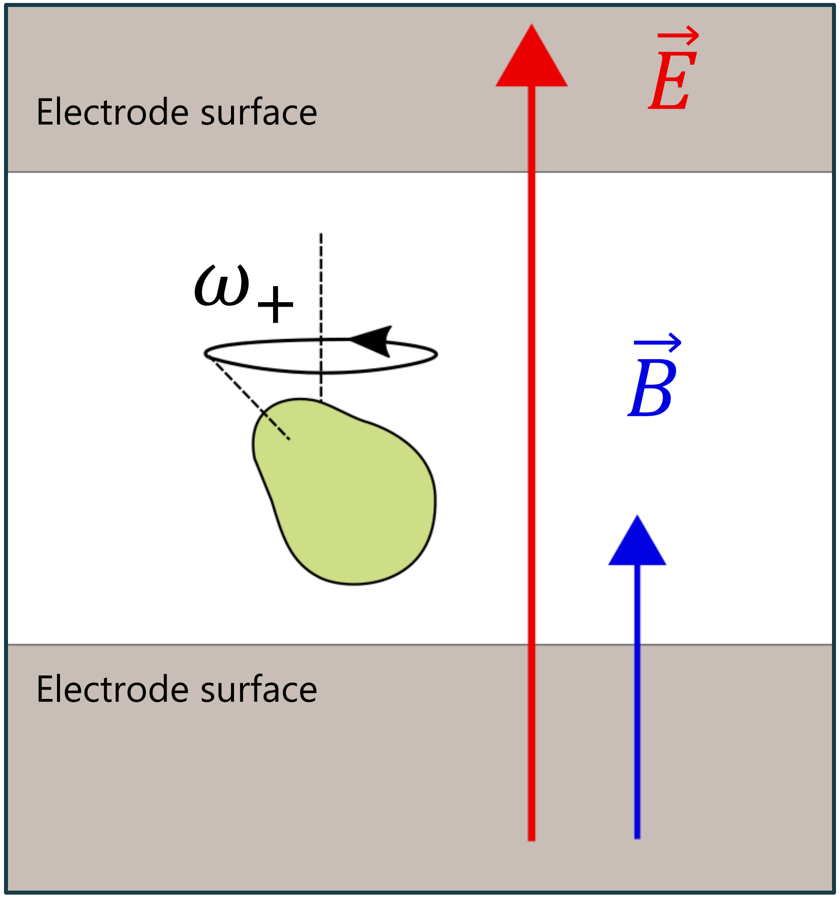


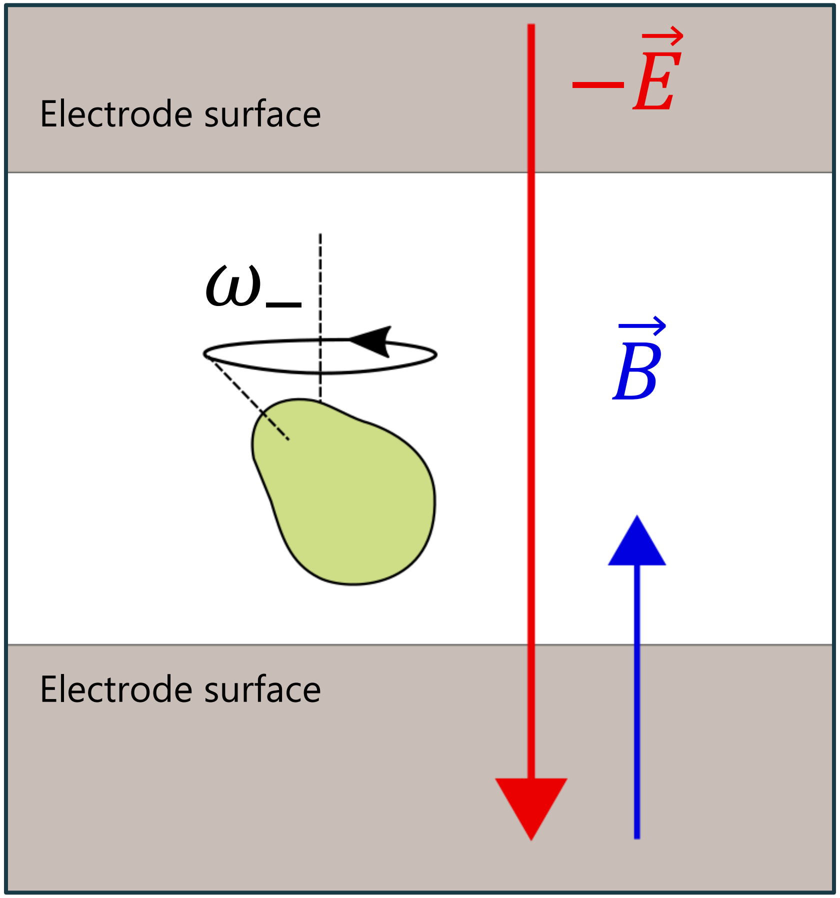
Ra EDM apparatus



Measuring a permanent EDM

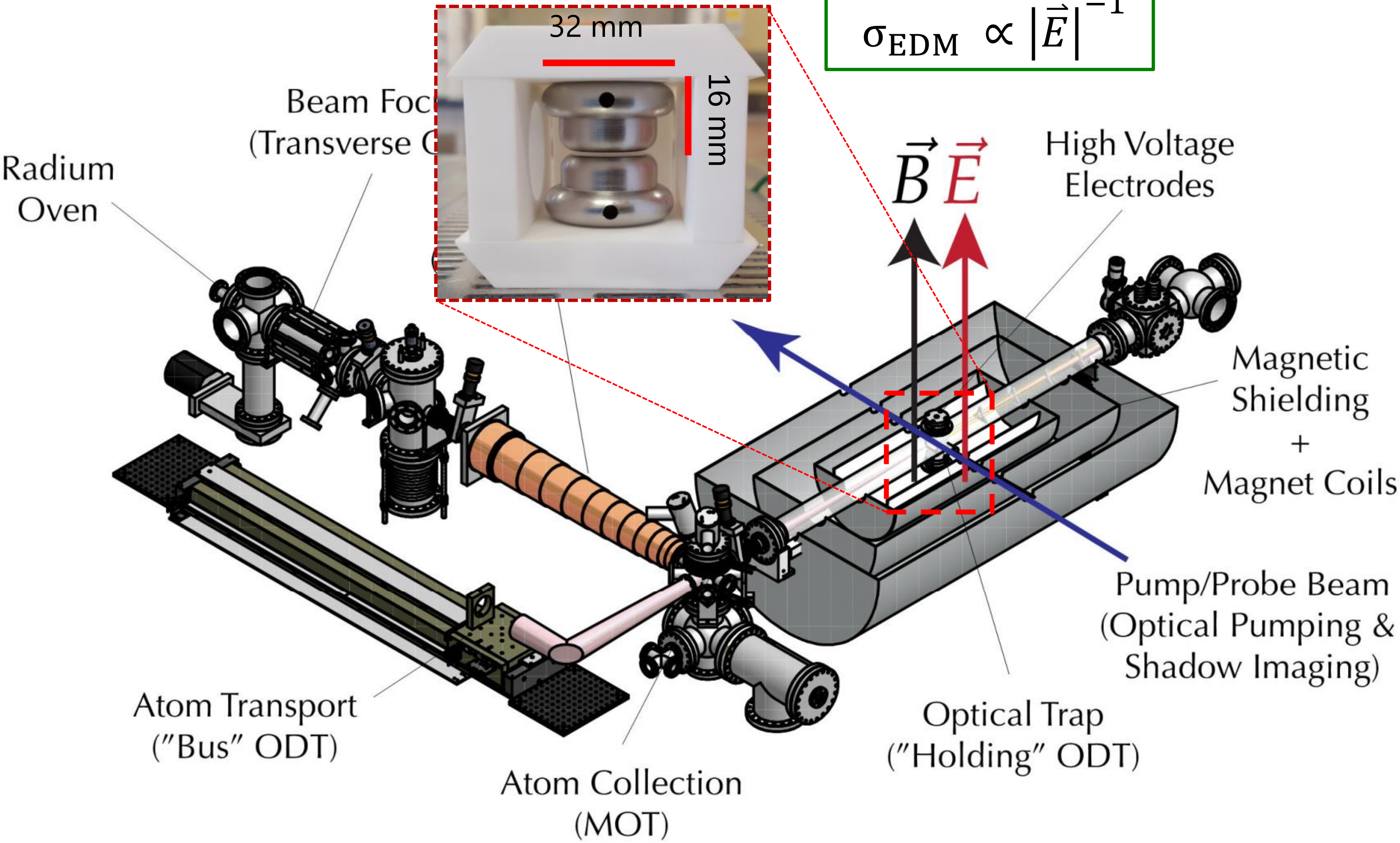
$$\hbar\omega_{\pm} = 2\mu B \pm 2dE \qquad \Delta\omega = \frac{2\mu\Delta B}{\hbar} + \frac{4dE}{\hbar}$$





Electric field upgrade

$$\sigma_{\mathrm{EDM}} \propto \left|\vec{E}\right|^{-1}$$



Surface decontamination to reduce discharges

Spinlab walkway

FRIB

HP-rinsed & dried (link)

NSCL

electrode removal & installation, packaging

Argonne

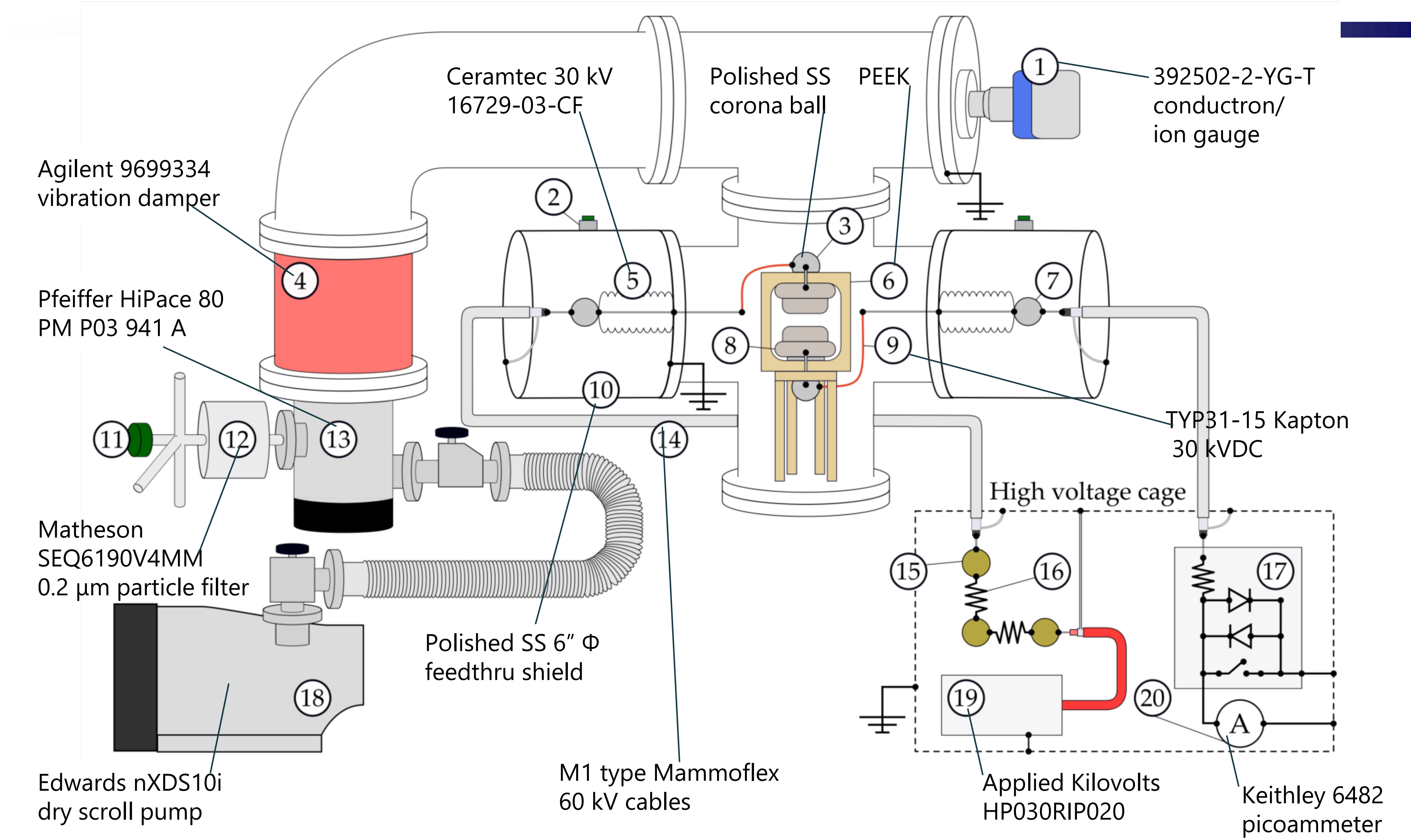
proof of principle with homemade clean room

clean room built @ ANL and new electrodes installed in science chamber

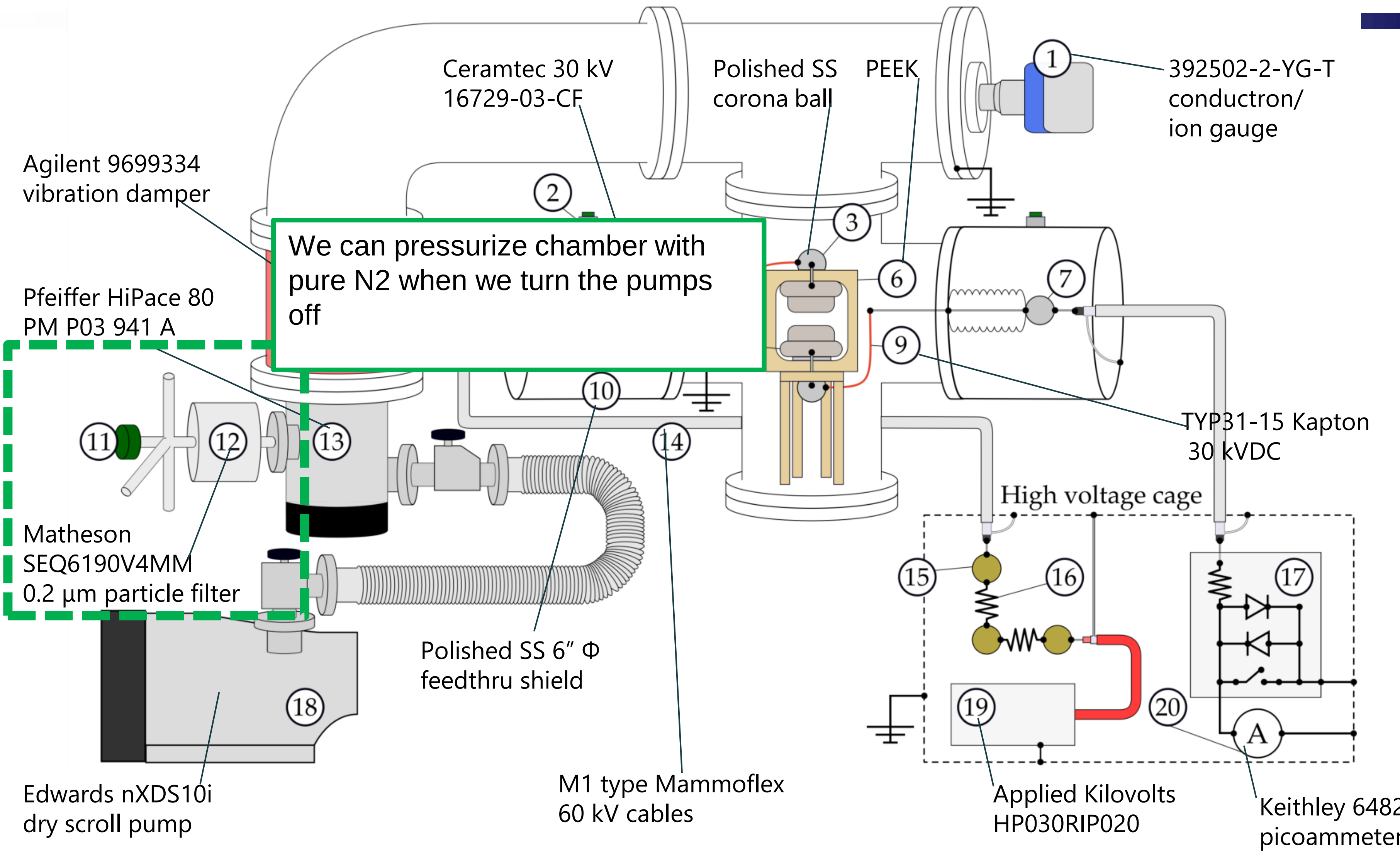
April **May** **October** **May**

2017 **2018**

MSU high voltage test station schematic

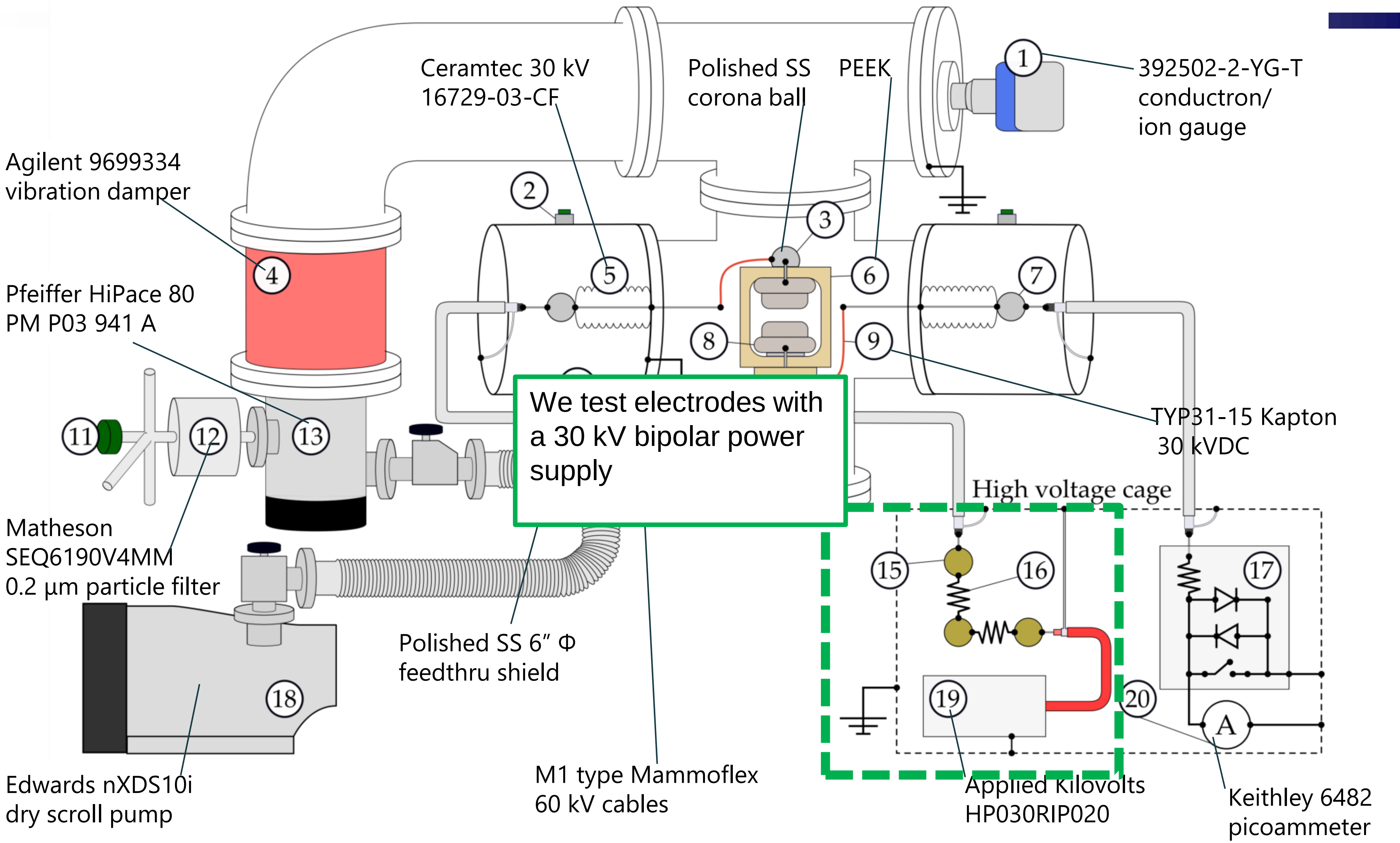


MSU high voltage test station schematic

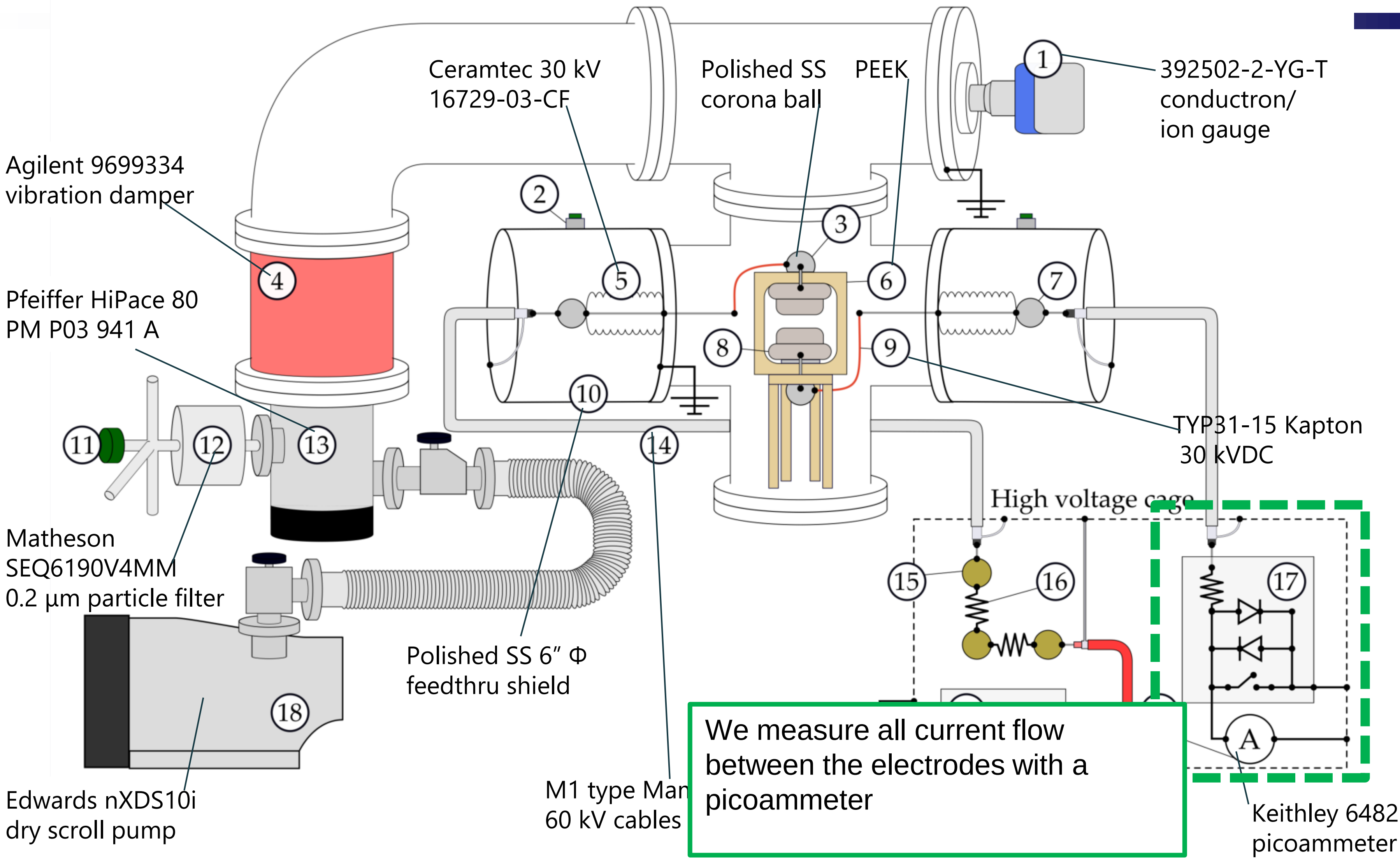


We can pressurize chamber with pure N2 when we turn the pumps off

MSU high voltage test station schematic

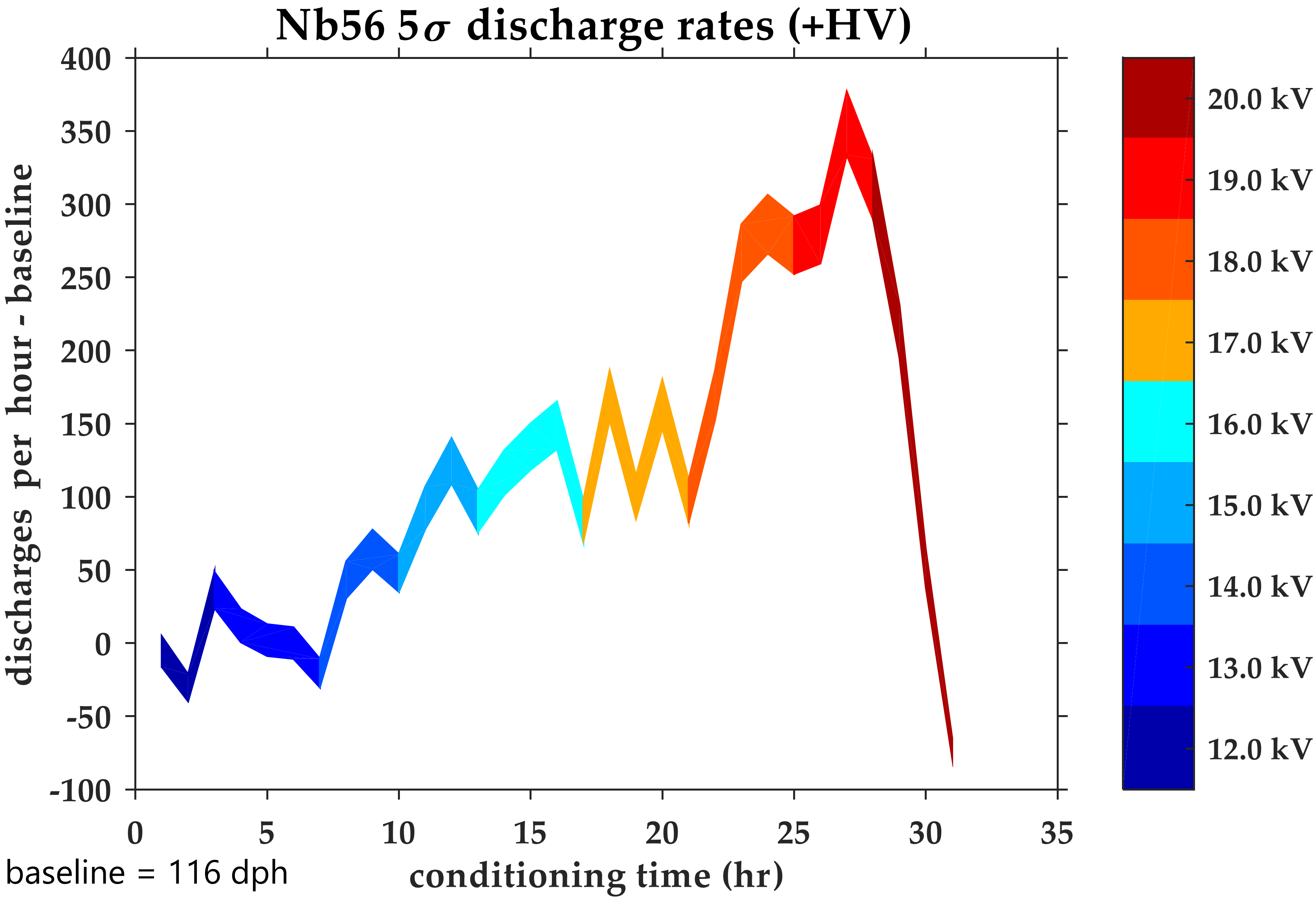


MSU high voltage test station schematic



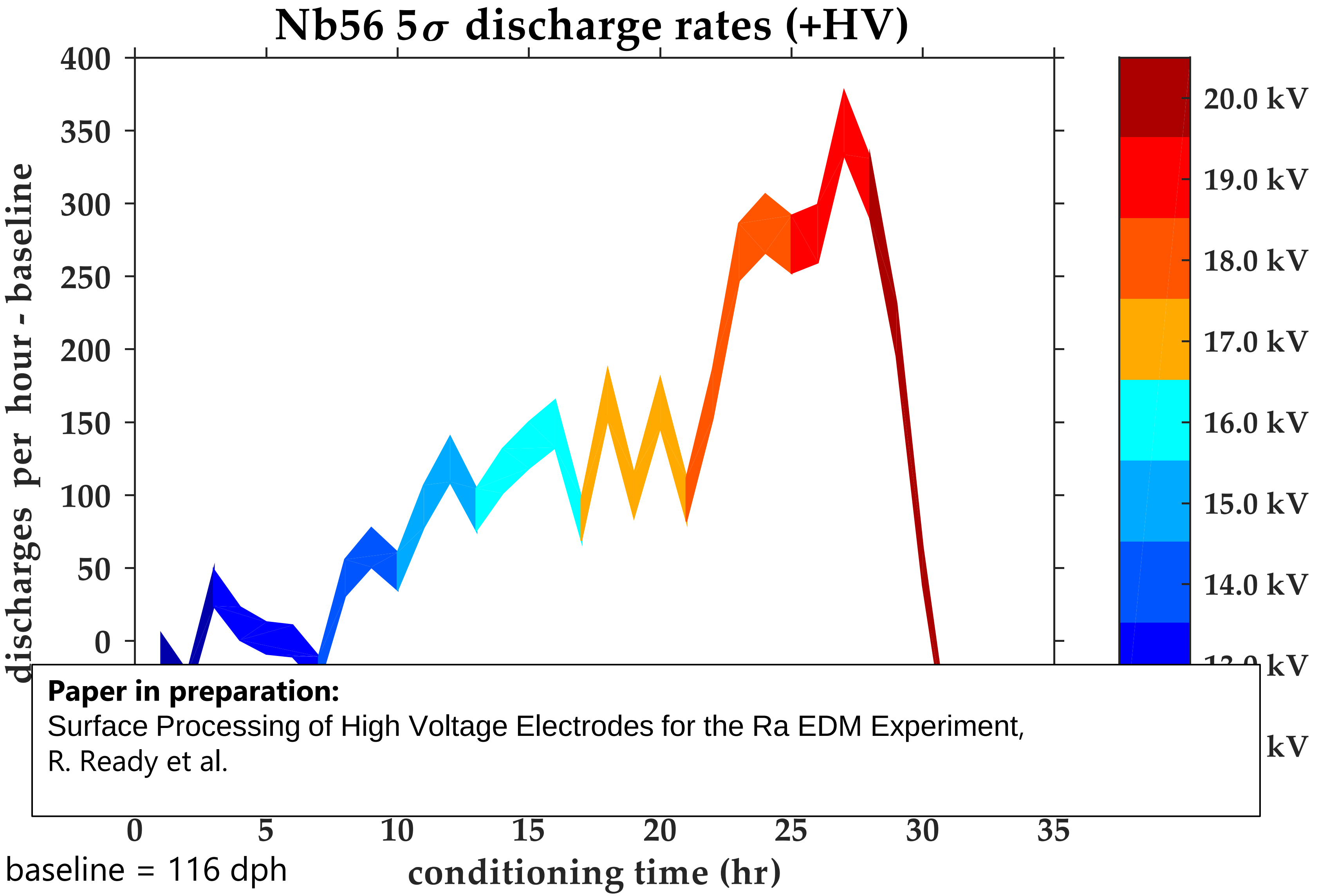
We measure all current flow between the electrodes with a picoammeter

Conditioning to reduce discharges



baseline = 116 dph

Conditioning to reduce discharges

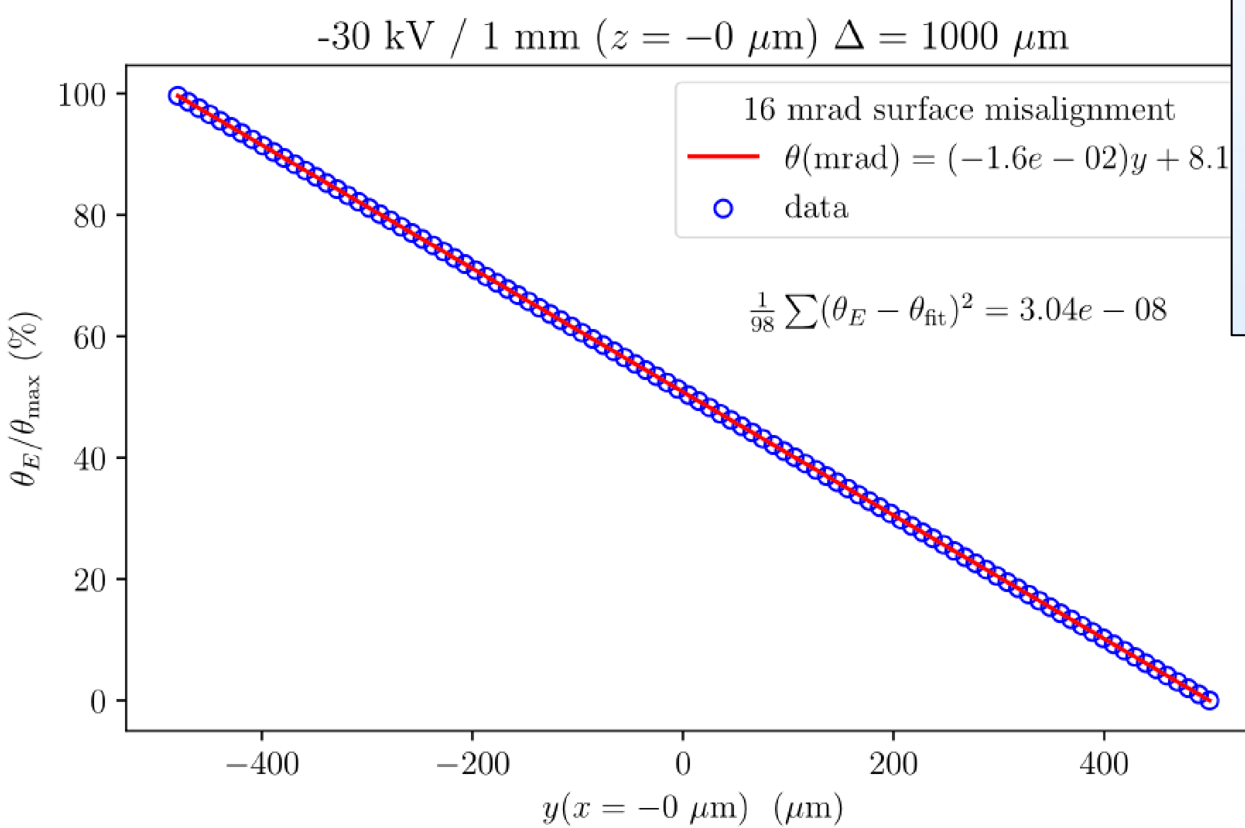


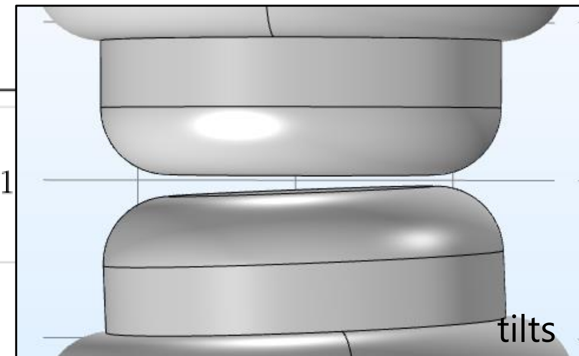
Paper in preparation:
Surface Processing of High Voltage Electrodes for the Ra EDM Experiment,
R. Ready et al.

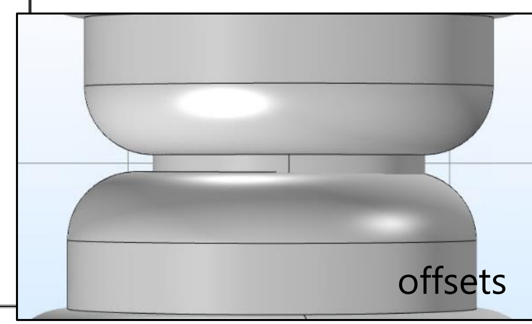
baseline = 116 dph

electric field tilts cause EDM systematic

- Machining tolerances of the electrodes / electrode holder and installation introduces small misalignments
- Under what conditions do misalignments affect the EDM measurements?

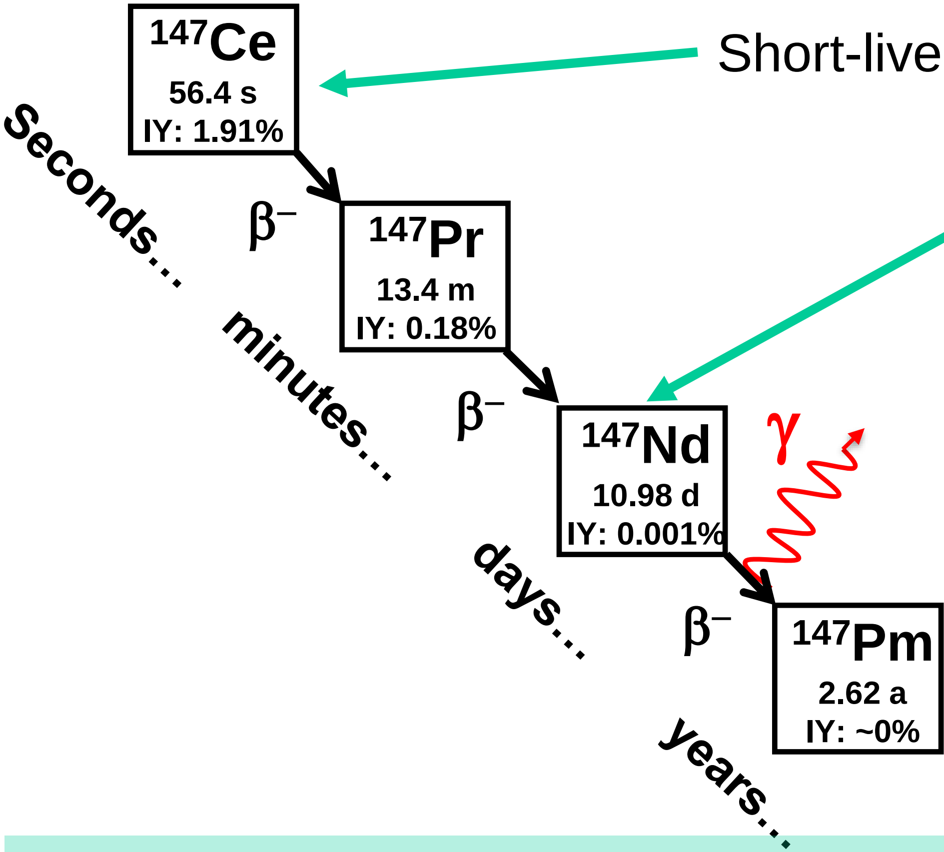






Long-lived fission products as diagnostics for national security applications

Beta decay chain of radioactive fission products (A = 147)



Short-lived isotope produced in fission

Long-lived isotope used to determine fission product yields (stockpile stewardship)

γ-ray spectroscopy a reliable tool to determine fission-product yields (FPY):

$$FPY \propto \frac{N_\gamma}{I_\gamma}$$

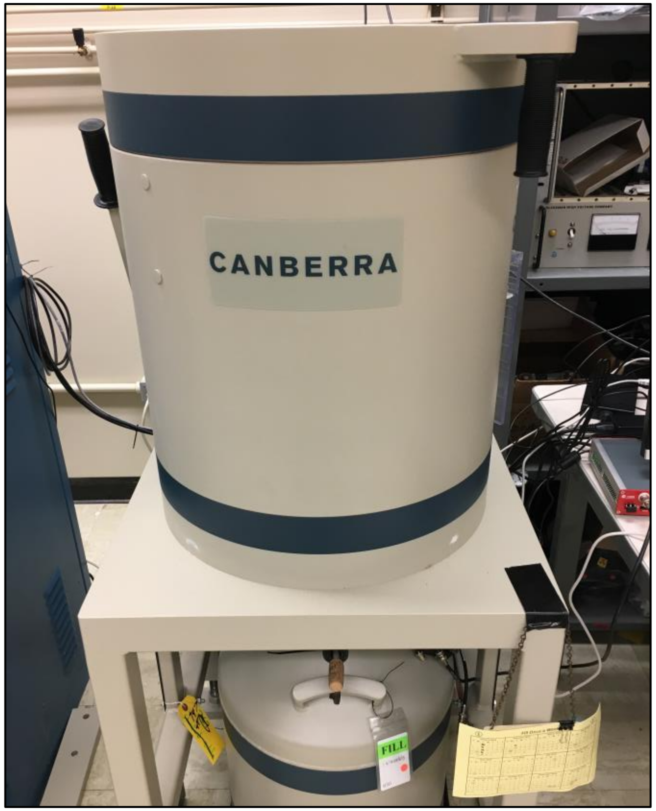
Many long-lived isotopes have BRs with uncertainties of 5—30%

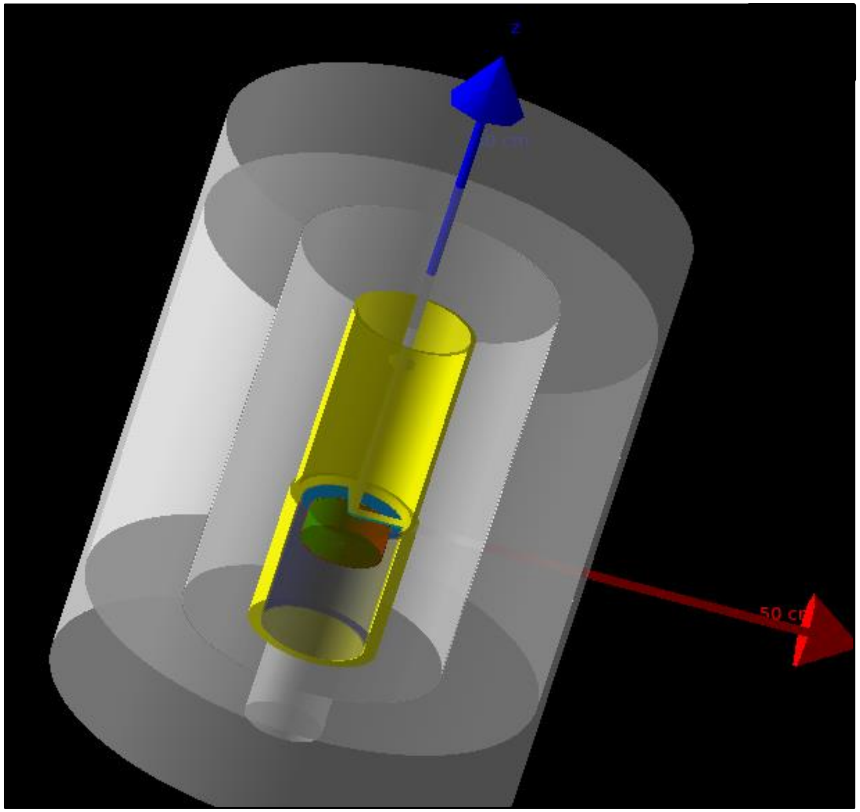
Need to be measured to better precision to improve FPY uncertainty

LLNL-PRES-774819

Building a simulation model of the LLNL setup

- Detector efficiency calibration: want a simulation that can reproduce results of calibrated source measurements
- NSSC practicum: new LLNL detector system modeled in Geant4

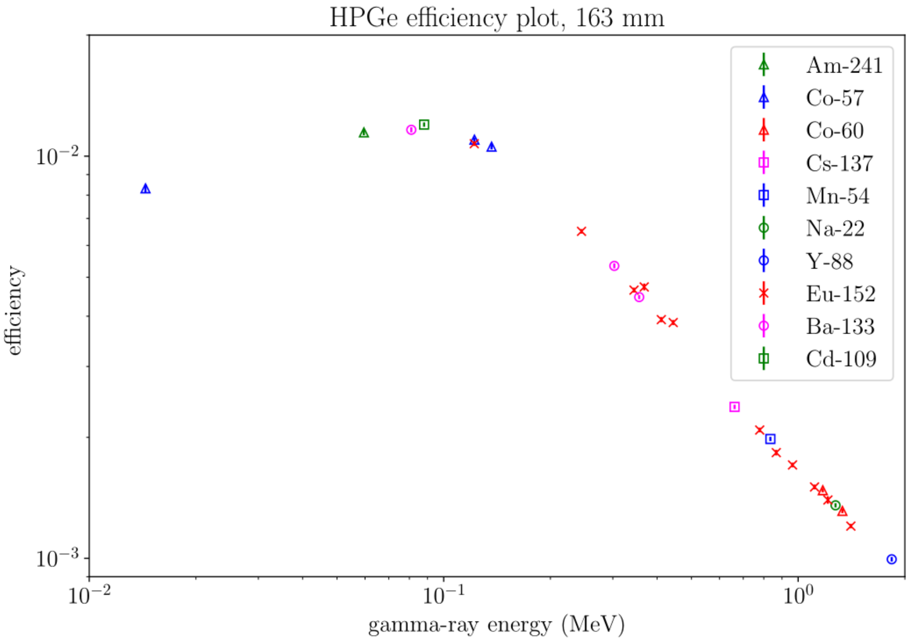




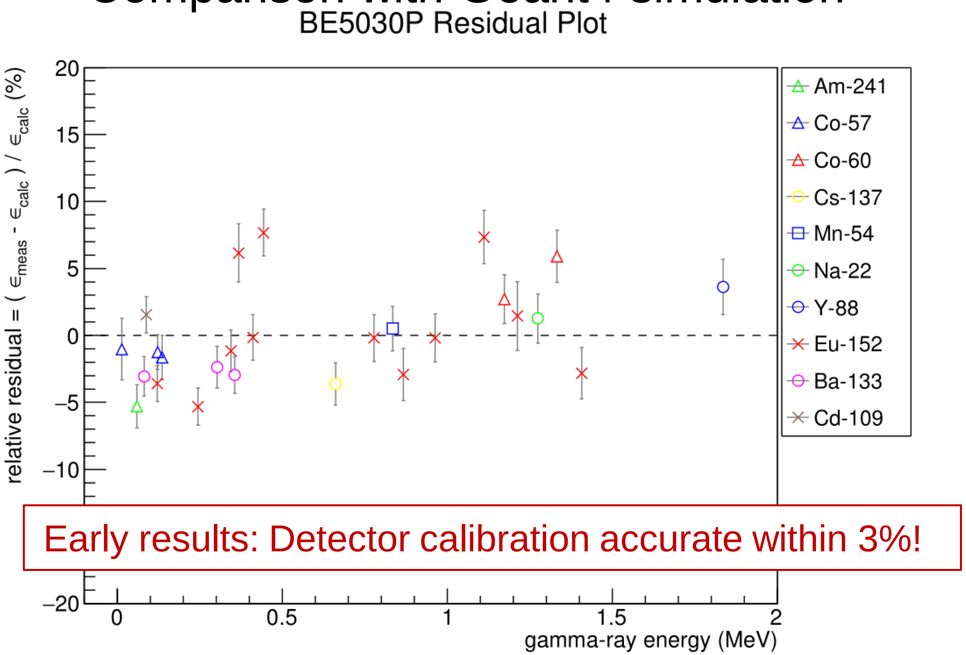
Left: detector shielding and cryostat.
Right: Geant4 model of detector, sample holder, and shield

Comparing measured data to Geant4 simulation

Measured intensities of sources



Comparison with Geant4 simulation



Early results: Detector calibration accurate within 3%!

EDM Work:
- Build custom instrumentation
- Simulate electrostatic behavior in COMSOL
- Measure small (~pA) electrode leakage
- Data analysis in ROOT

Gamma-ray work:
- Build custom instrumentation
- Simulate detector efficiency in Geant4
- Measure low-background gamma-ray emission
- Data analysis in ROOT

LLNL-PRES-774819

NSSC experience: γ-ray spectroscopy at LLNL

Workshops, seminars, programs attended:
- 2019 NSSC Workshop, LLNL
- 2019 UPR, Raleigh
- 2019 Nuclear Security Policy Bootcamp, DC
- 2018 NSSC Workshop, SNL
- 2017 Michigan State University visit to Los Alamos

NSSC practicum: 1/7/2019—3/29/2019

How has being a part of the NSSC benefitted you?
- Exposure to gamma-ray spectroscopy
- Opportunities to present practicum research
- Network with excellent scientists at a great laboratory



Left to right: Nick Scielzo (lab mentor), Kay Kolos, Keenan Thomas

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NSSC practicum: 1/7/2019—3/29/2019



Next steps:
Searching for γ-ray post doc positions at LBNL, ORNL

Left to right: Nick Scielzo (lab mentor), Kay Kolos, Keenan Thomas

Ra EDM Acknowledgements

Thanks to: Jaideep Singh (advisor) and MSU graduate committee, lots of Spinlab students, Ra EDM collaboration, NSCL Mechanical design team, Machine shop, Electronics and Controls, FRIB chemical engineer team, Clean room support, Electronics and Controls, NSSC and Sean Liddick

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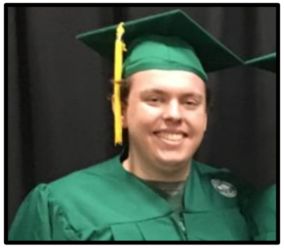

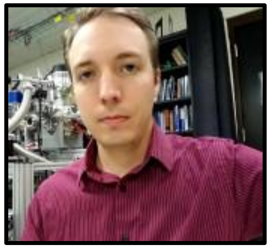

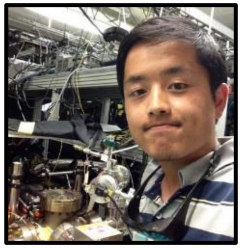

NSSC Acknowledgements

Thanks to: (LLNL) Kay Kolos, Dave Ruddle, Mark Stoyer, Keenan Thomas, Anton Tonchev, Nick Scielzo (NSSC) Charlotte Carr, (MSU) Sean Liddick, Jaideep Singh, and a bunch more!

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Extra slides

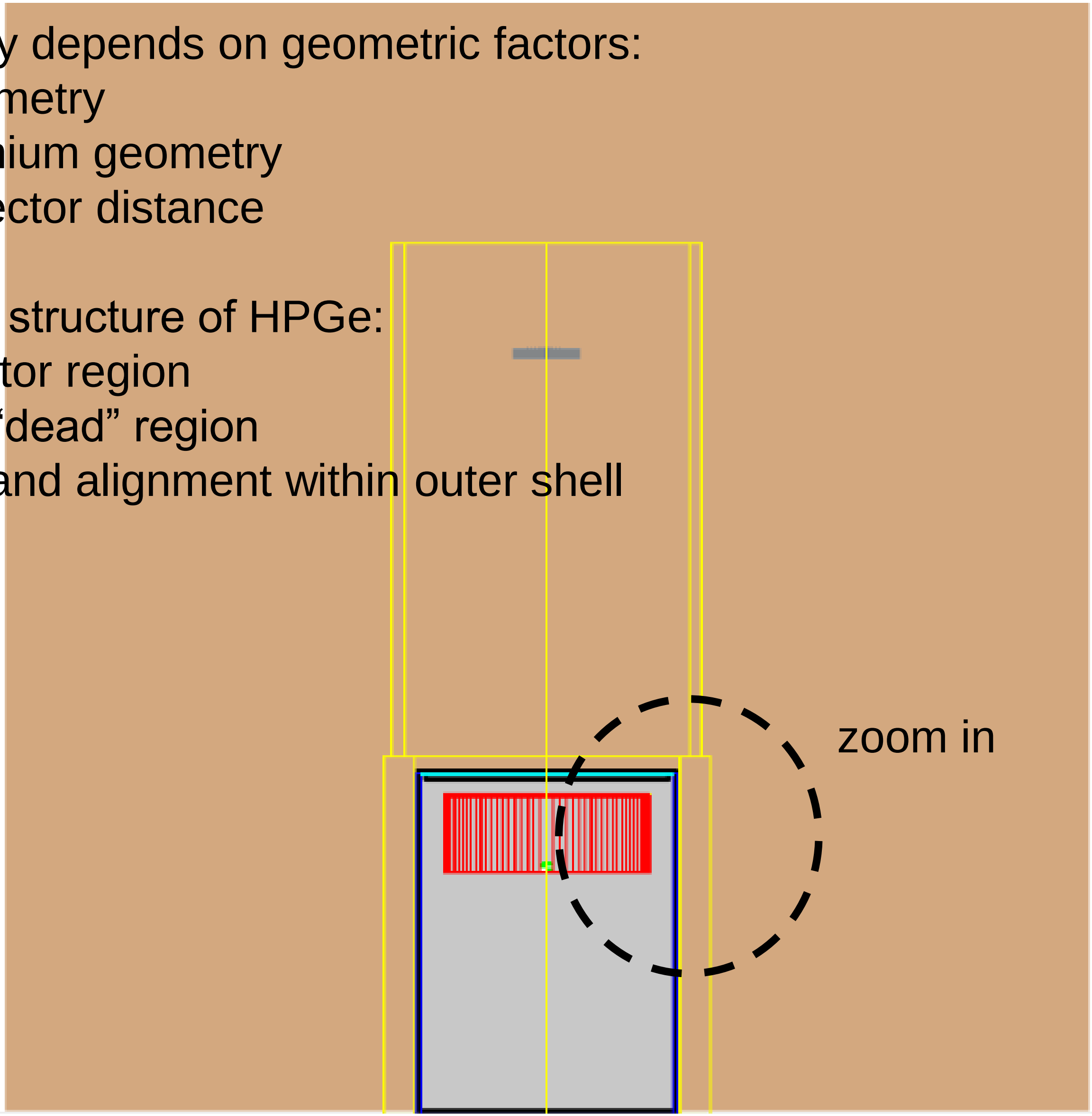
LLNL detector setup (2D cross section)

Model accuracy depends on geometric factors:

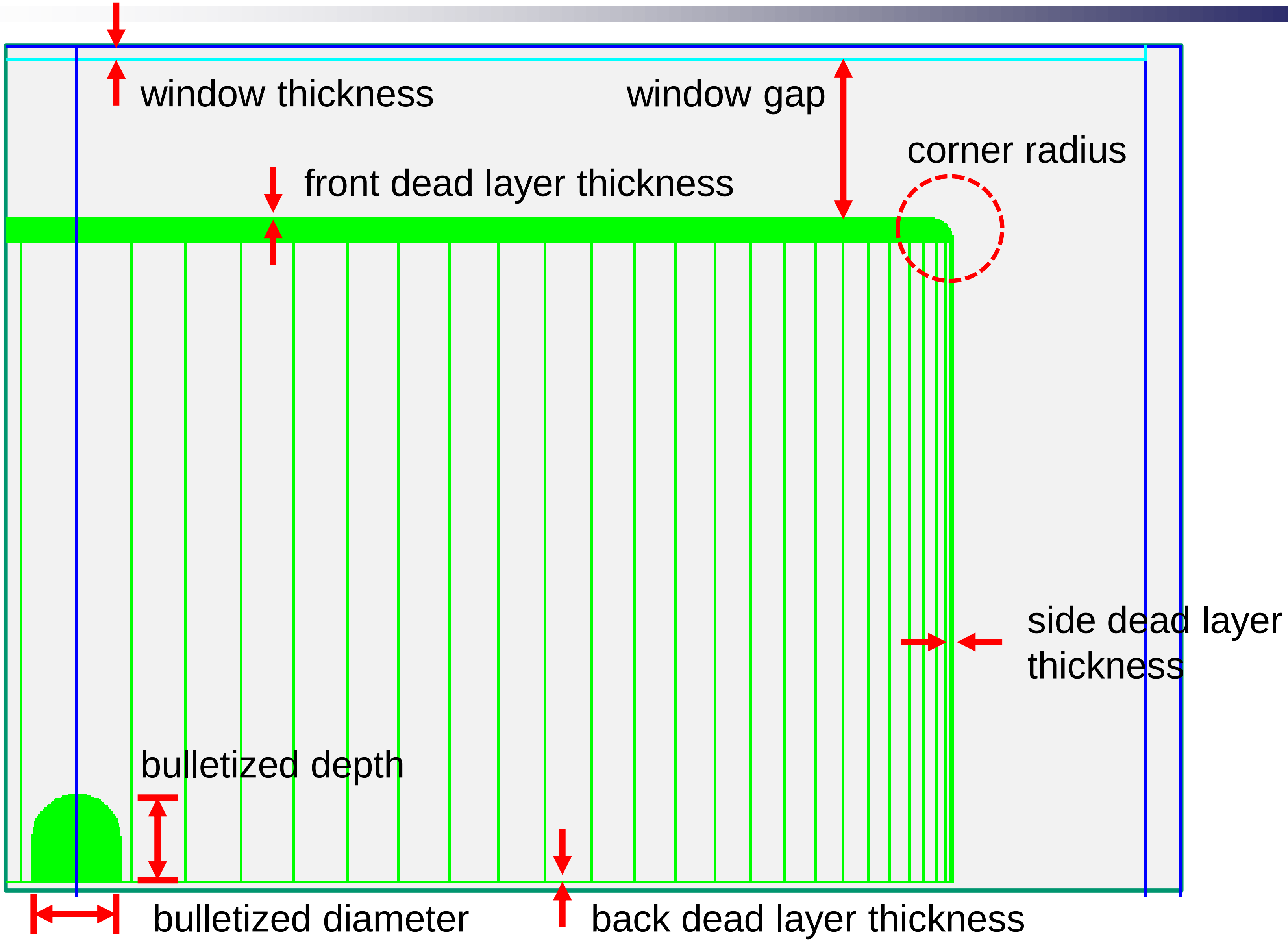
- sample geometry
- bulk germanium geometry
- sample-detector distance

… and internal structure of HPGe:

- active detector region
- inactive, or "dead" region
- positioning and alignment within outer shell



Detector parameterization (a subset)



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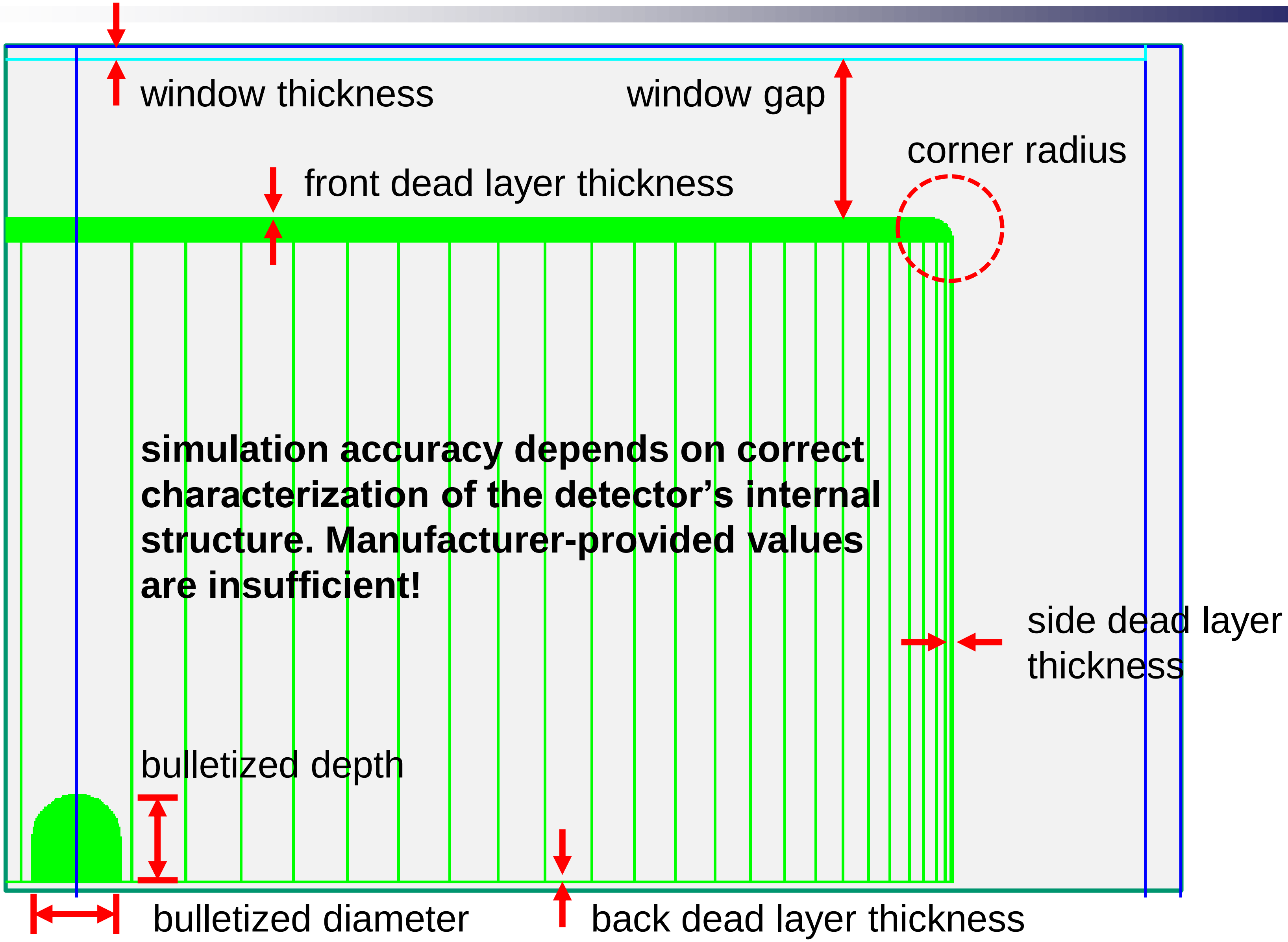
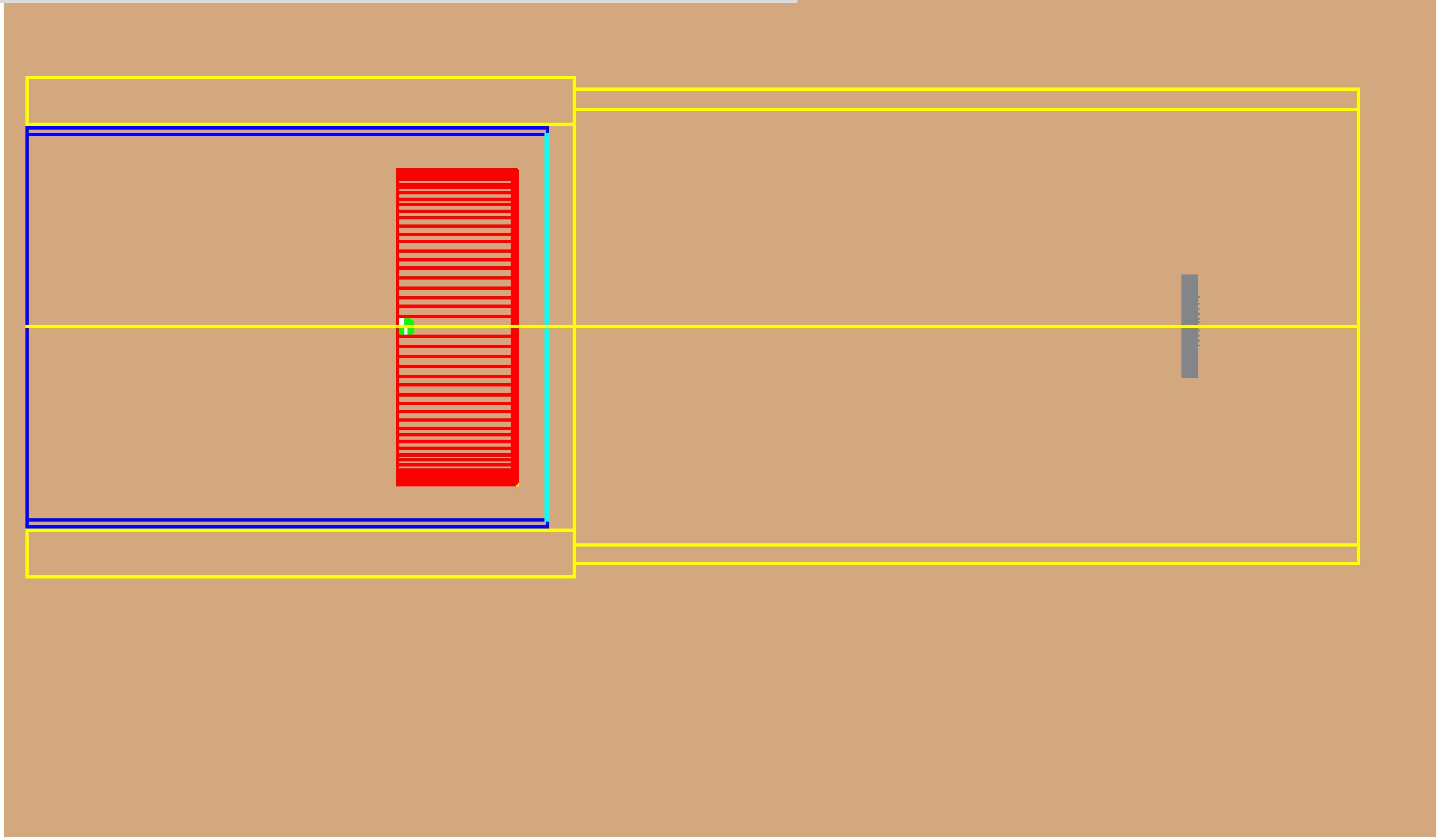


simulation accuracy depends on correct characterization of the detector's internal structure. Manufacturer-provided values are insufficient!

Simulating detector efficiency

- Monte Carlo simulation
- For a given gamma-ray energy, generate many instances of particles with random initial vectors



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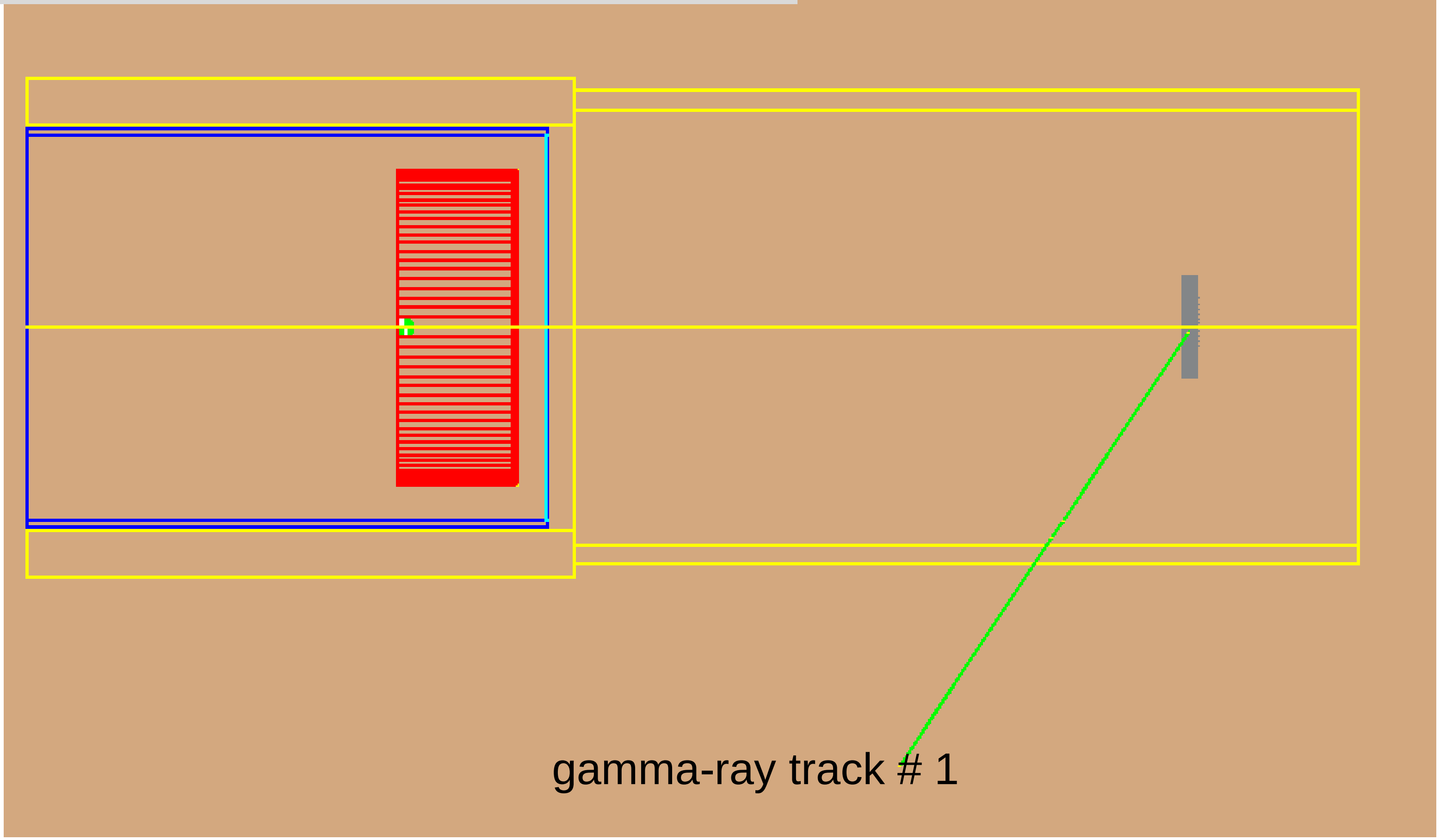

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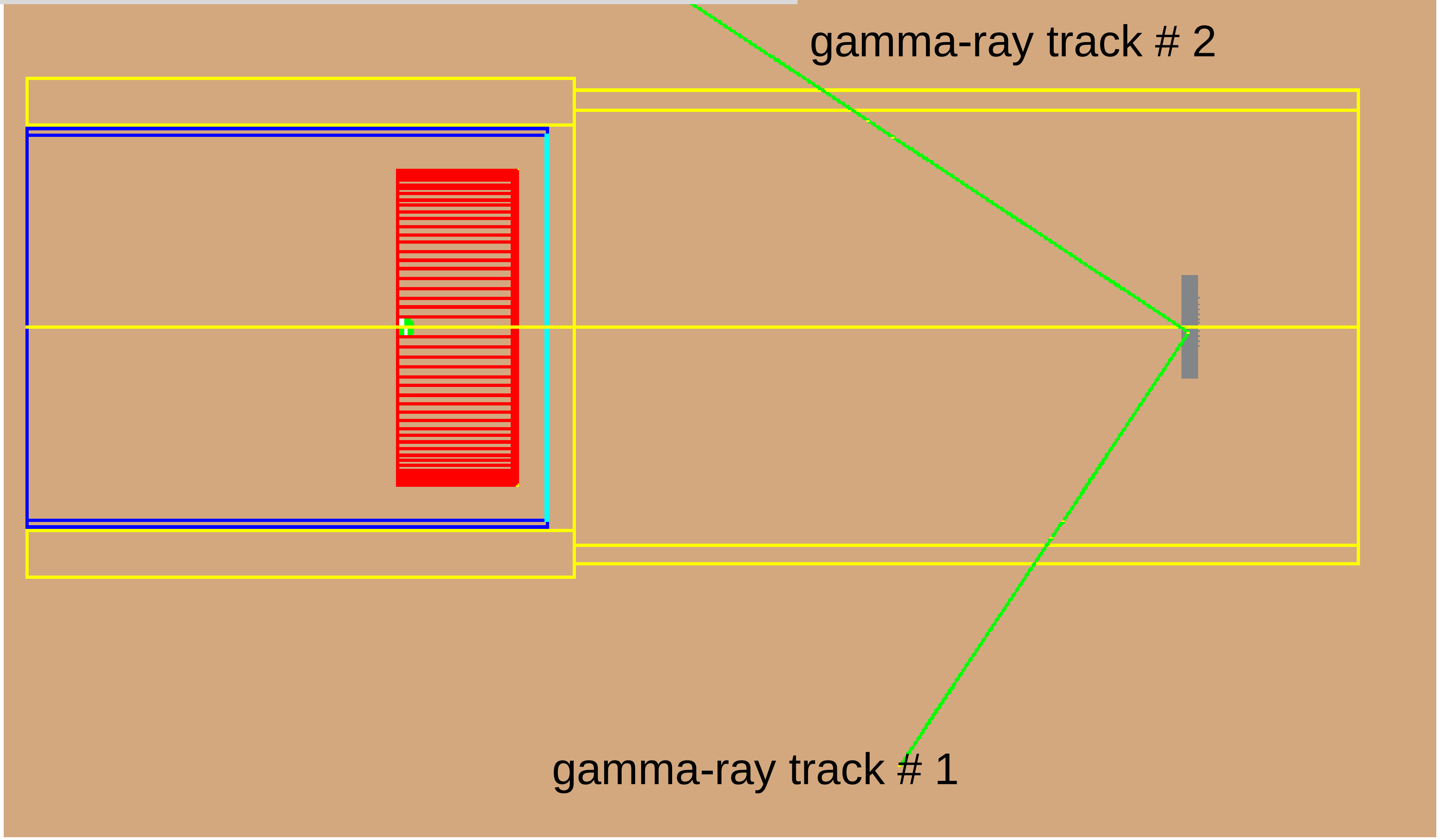

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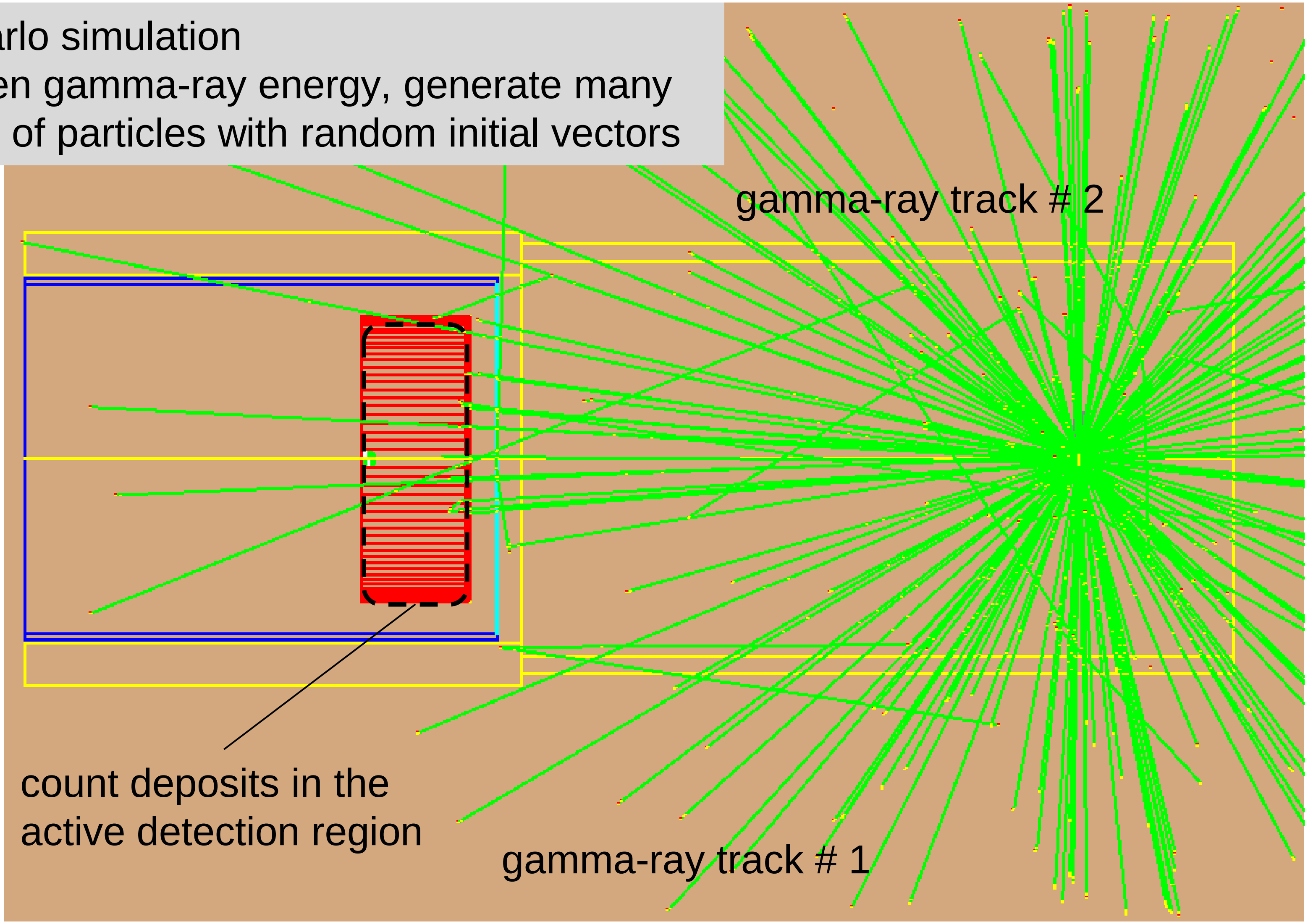
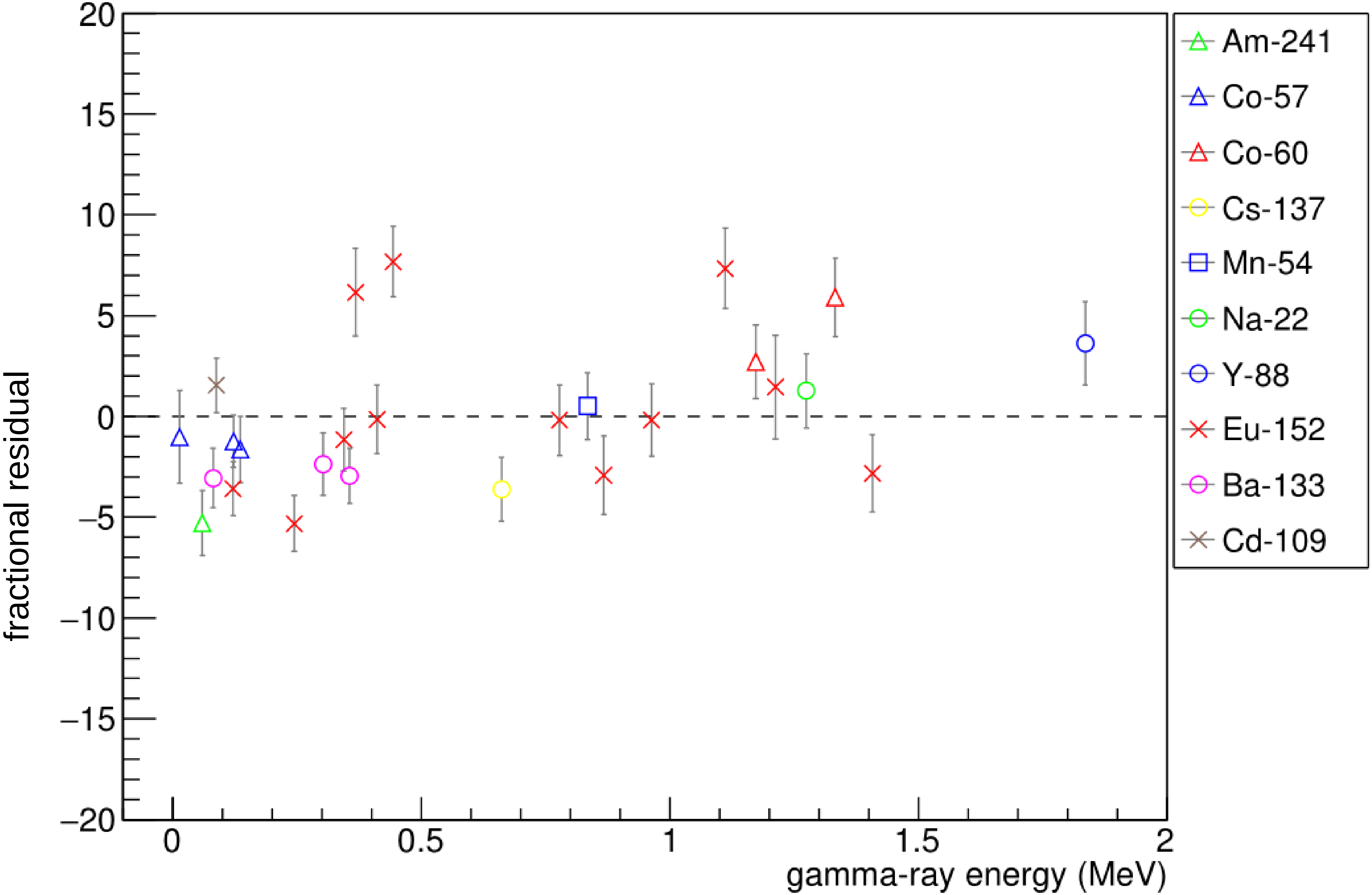


Results: measurement-simulation comparison



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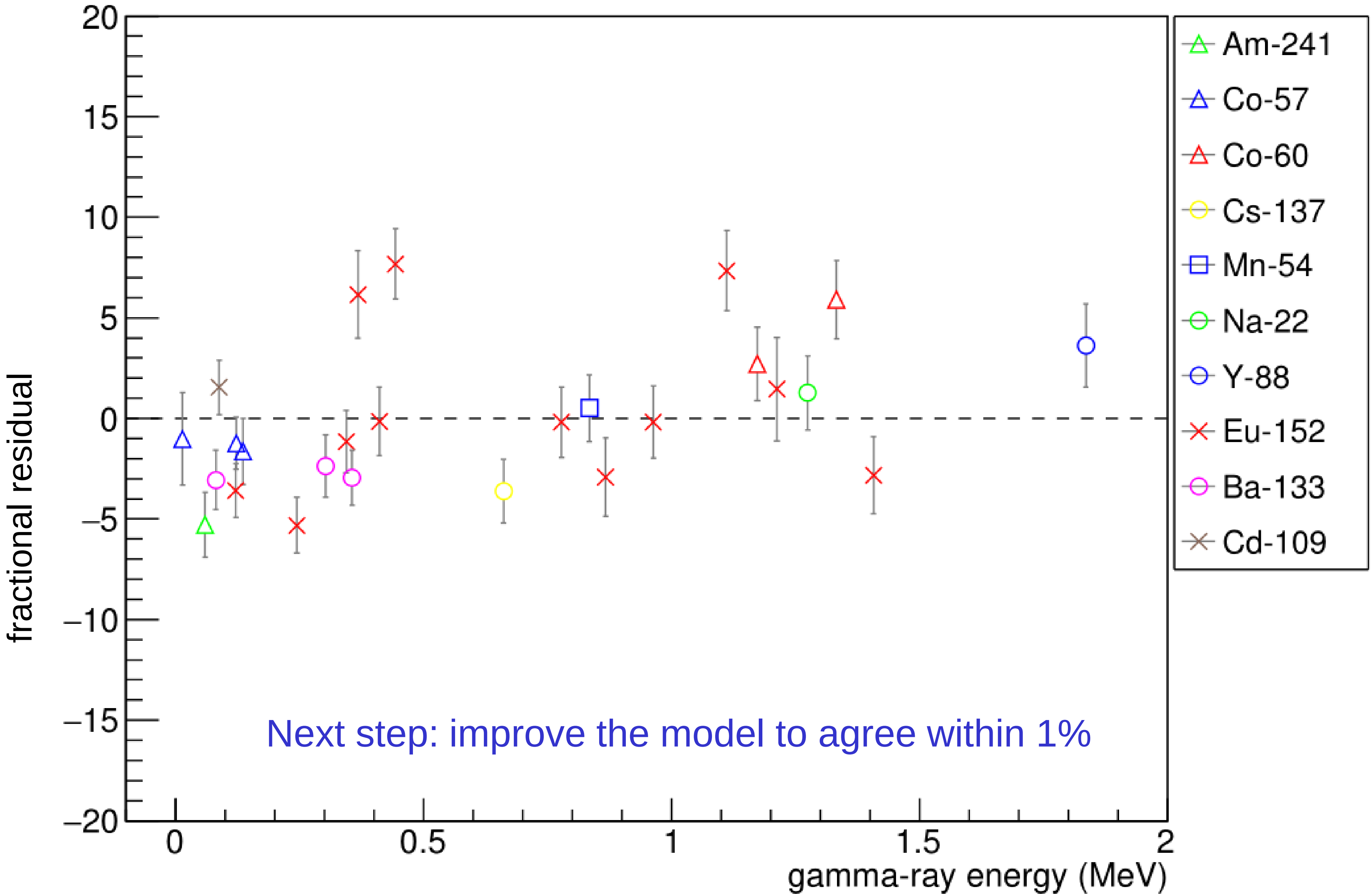
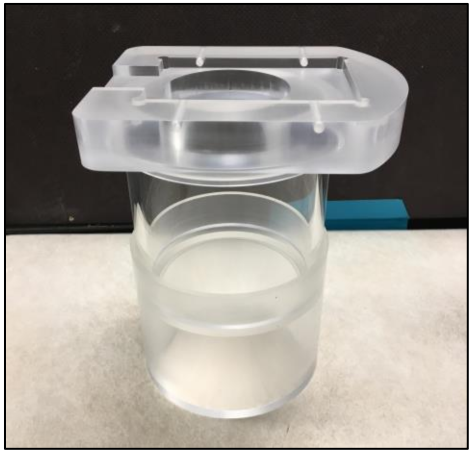


Conclusions and outlook

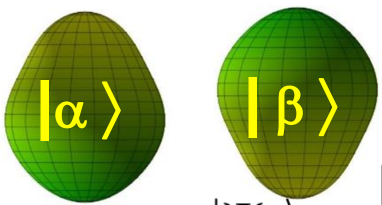
Summary:
- Simulation model of new LLNL γ-ray detector system developed and tested
- Initial simulation-to-data comparison consistent within 3% (weighted average)
- Custom position-repeatable sample holding apparatus designed and fabricated

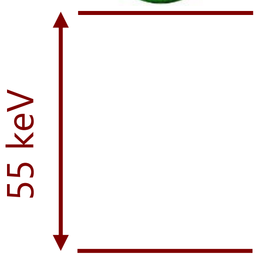
Near-term plans:
- Rerun calibration measurements with new sample holder
- Perform refined spectra analysis (e.g. account for summing effects)
- Goal: 1% or better detector calibration
- Setup coincidence measurement with detector and LLNL 4π gas counter
- Measure γ-ray intensities for fission products

pictured: newly-fabricated sample-holding apparatus



Enhanced sensitivity in Radium-225





$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

Nearly degenerate parity doublet [1]

$$S \equiv \langle\Psi_0|\, S_z \,|\Psi_0\rangle$$

Large S due to octupole deformation [2]

$$= \sum_{k\neq 0} \frac{\langle\Psi_0|\, S_z \,|\Psi_k\rangle \langle\Psi_k|\, V_{PT} \,|\Psi_0\rangle}{E_0 - E_k} + \text{c.c.},$$

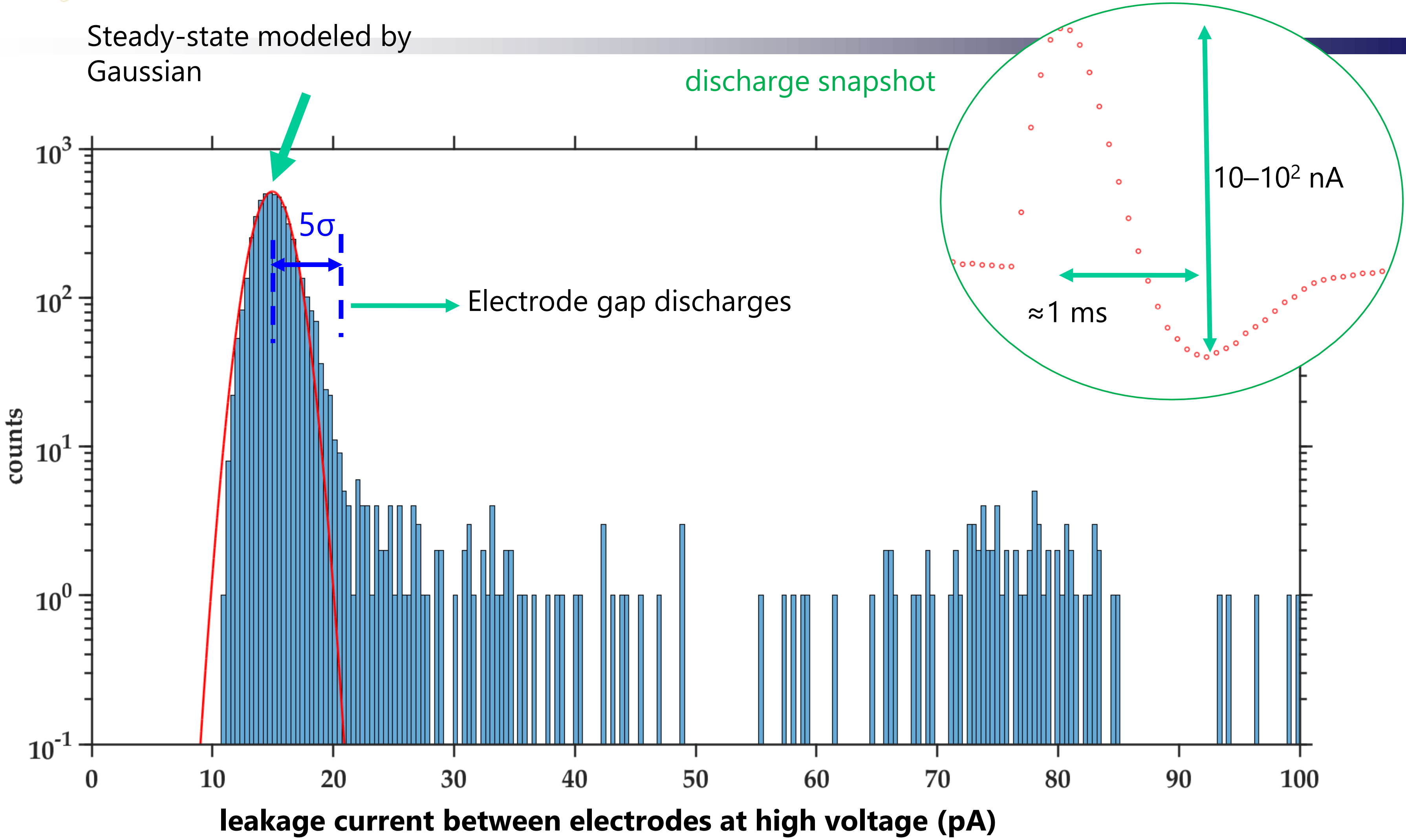
where $$S_z = \frac{\langle er^2 z\rangle}{10} - \frac{\langle r^2\rangle \langle ez\rangle}{6}$$

Total Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Ref.
SIII	300	4000	[3,4,5]
SkM*	300	2000	[3,4,5]
SLy4	700	9000	[3,4,5]

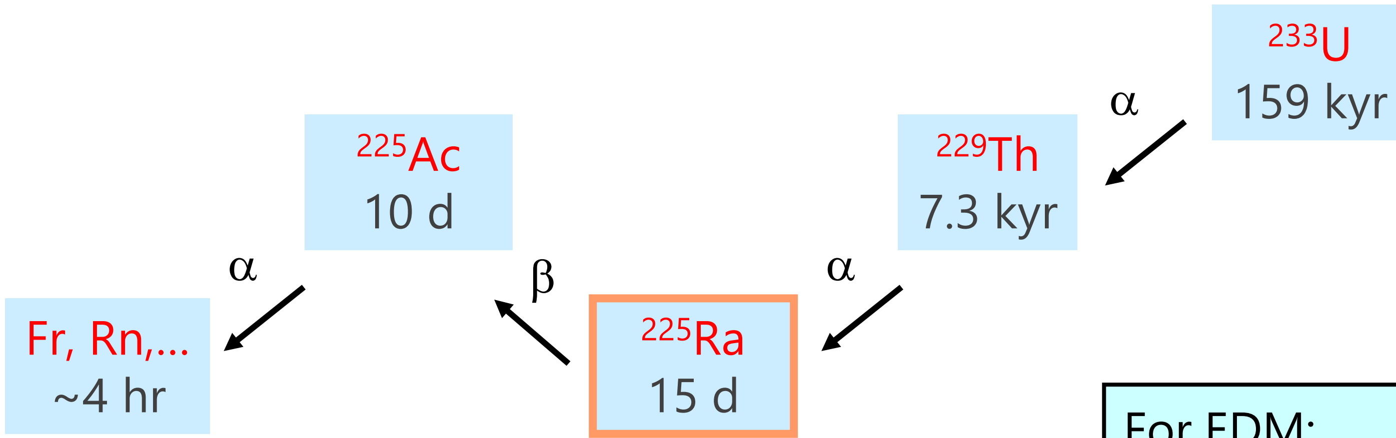
[1] Haxton & Henley PRL 51, 1937 (1983). [2] Auerbach, Flambaum, & Spevak PRL 76, 4316 (1996).
[3] Dobaczewski & Engel PRL 94 232502 (2005) . [4] Ban et al. PRC 82 015501 (2010).
[5] Dzuba et al. PRA 66 012111 (2002).

Characterizing current discharges



Code available at
https://github.com/royferd/leakage-analysis

Source of Radium atoms



- 510 ng = 20 mCi = 730 MBq ^{225}Ra sources from:

  National Isotope Development Center (Oak Ridge, TN)

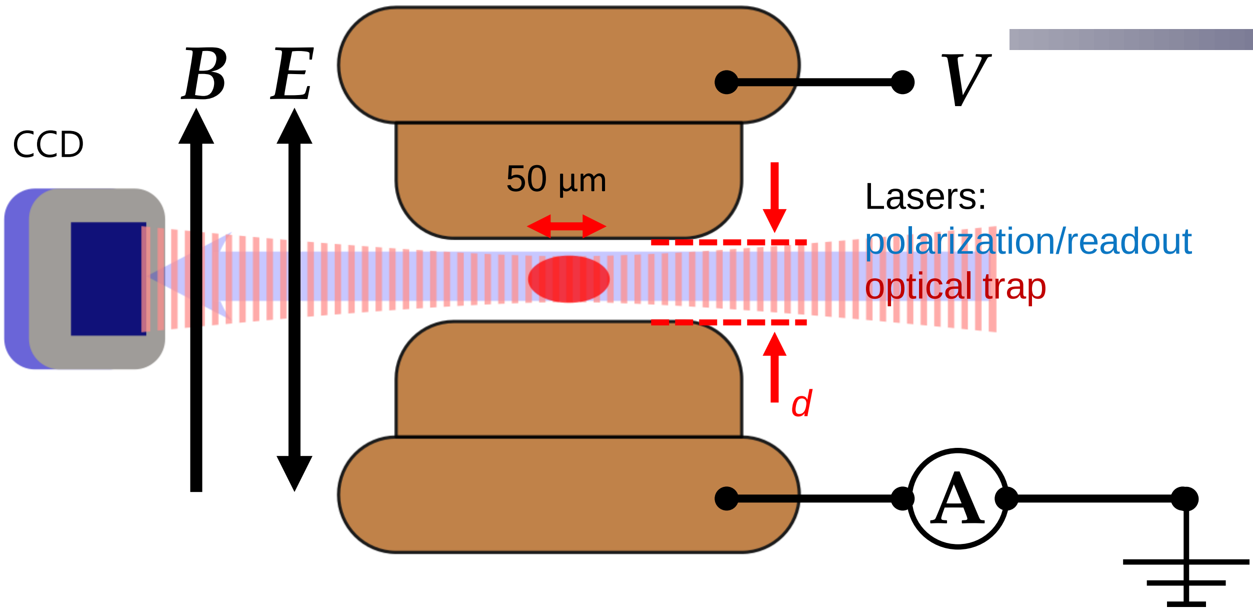
- 4000 ng = 4 μCi = 0.15 MBq ^{226}Ra test source
- Integrated Atomic Beam Flux ~ 10^8/s

Facility for **R**are **I**sotope **B**eams
Yield for ^{225}Ra ~ (10^9 to 10^{10})/s

For EDM:
^{225}Ra
Nuclear Spin = ½
$t_{1/2}$ = 15 days

For Testing:
^{226}Ra
Nuclear Spin = 0
$t_{1/2}$ = 1600 yrs

EDM search using atoms held in Optical Lattice



^{225}Ra
Nuclear Spin = ½
Electronic Spin = 0
$t_{1/2}$ = 15 days
Low vapor pressure

- Trap allows the efficient use of ^{225}Ra [3]
- Long coherence time (100 s) [1]
- negligible "$\mathbf{v} \times \mathbf{E}$" systematics [3]
- High electric field (up to 30 kV/mm) in vacuum
- Light-induced systematic effects can be controlled [2]!

Electrode generation	First	Second
Gap size *d* (mm)	2.3	1.0
Electric field *E* (kV/mm)	6.5	≤ 30

[1] Romalis & Fortson PRA 59, 4547 (1999). [2] Chin et al. PRA 63, 033401 (2001).
[3] Bishof et al. PRC 94, 025501 (2016)

Path to increased statistical sensitivity

EDM Upper Limit 95% CL ($\times 10^{-23}$ *e* cm)	Improvements	Electric field (kV/mm)	Date	Ref.
50	Proof of principle	6.7	10—12/2014	[1]
1.4	τ 2 → 20 s	6.5	6/2015	[2]

$$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2\, E \sqrt{\epsilon\, N\, T \tau}}$$

$\hbar$ Planck constant / 2π
E Electric field
ϵ Detection efficiency
N Number of atoms
T Total integration time
τ Spin precession time

[1] PRL 114 233002 (2015). [2] PRC 94 025501 (2016)

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≤ 0.14	E, ϵ	≥ 15.0		

$$\sigma_{\mathrm{EDM}} = \frac{\hbar}{2\,E\sqrt{\epsilon\, N\, T\tau}}$$

Upcoming run:
Electrode E-field phase I
(6.5 kV/mm → ≥ 15.0 kV/mm)
Detection efficiency (ongoing work at ANL)

In development:
longitudinal slower phase II
trapped atom # × 100

[1] PRL 114 233002 (2015). [2] PRC 94 025501 (2016)

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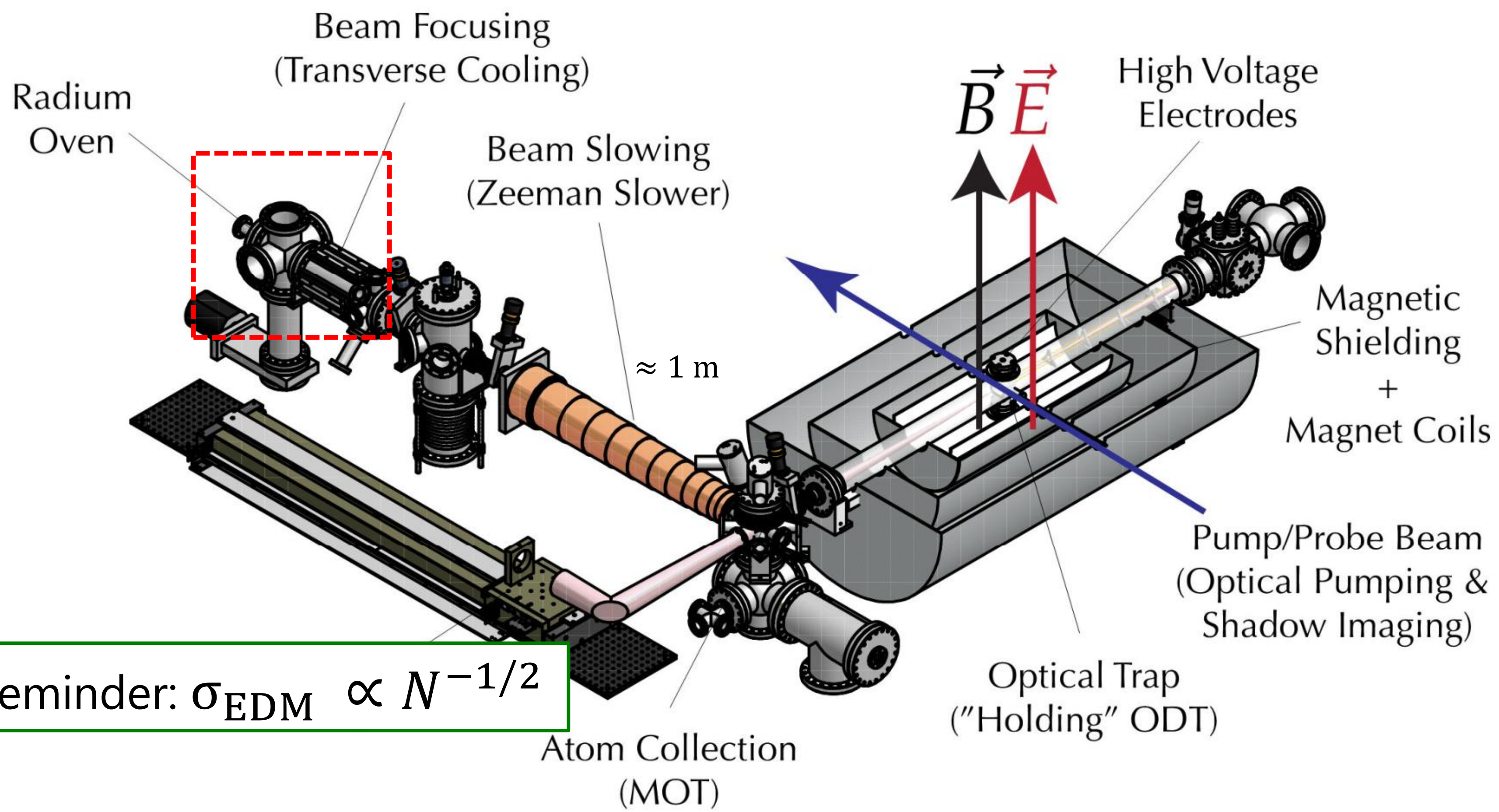
Ra EDM apparatus: atom source



reminder: $\sigma_{\text{EDM}} \propto N^{-1/2}$

FRIB isotope harvesting test stand

How efficiently can we harvest → prepare → use radium atoms?

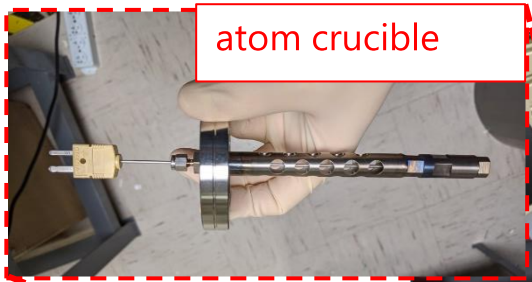
Goal: develop a method to measure the absolute in-beam atom rate to ≤ 20%

collect $\boldsymbol{N}$ atoms

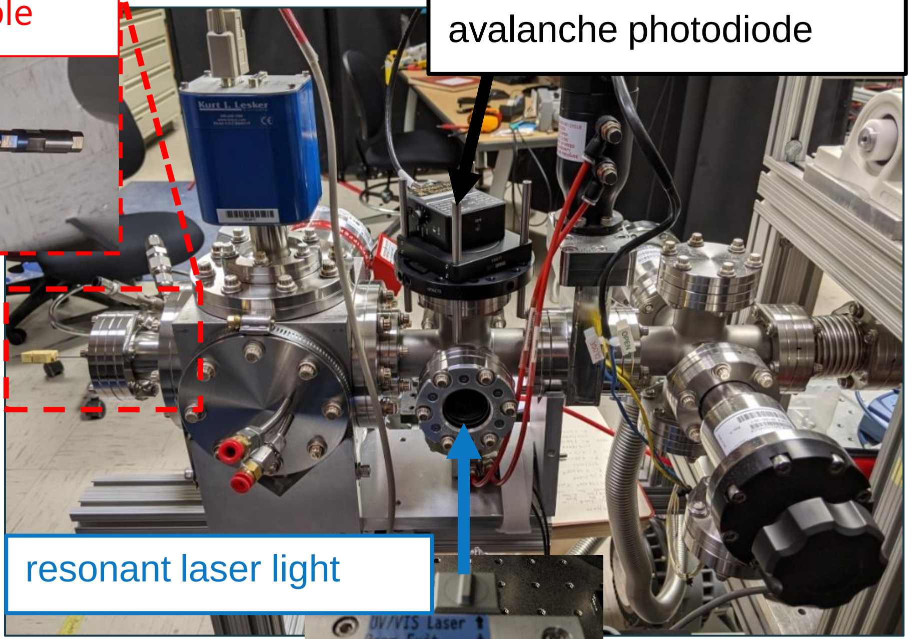
prepare the atoms

Chemistry

load $\boldsymbol{N'}$ atoms

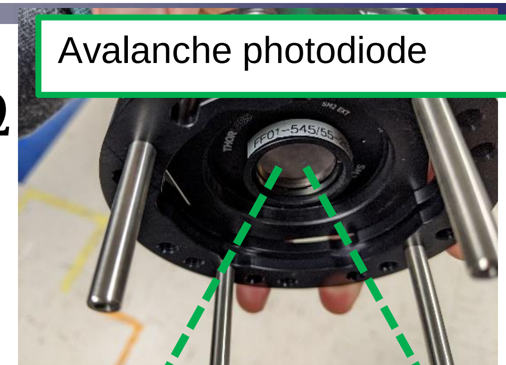


Measure atom $\boldsymbol{dN'/dt}$, calculate $\boldsymbol{N'}$



Modeling the atom source

Atom rate: $\mathrm{d}N'/\mathrm{d}t \propto \int j(\theta) \times F(\vec{r}) \times d\Omega$



- $j(\theta)$: **angular distribution**
- $F(\vec{r})$: **excitation rate**
- $d\Omega$: **solid angle**