FRIB

A dual electron/positron linac and laser spectroscopy system for nuclear charge radii measurements

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November 28, 2024

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

Probing nuclei with electromagnetic probes

- Electron/Positron scattering
- Jefferson Lab electron (CEBAF)/positron (LERF) beams

Rare Isotopes

- Facility for Rare Isotope Beams
- RI masses and nuclear radii

Toward an advanced (un)polarized e±-Rare Isotope US facility

- US national labs map
- Dual e±/laser spectroscopy facility
- Diversifying the nucellar science workforce

Nuclei: Spherical vs. Deformed

Where are protons & neutrons?

- Shell model

What about nuclear shapes

- Quadrupole moment: how deformed are nuclei?

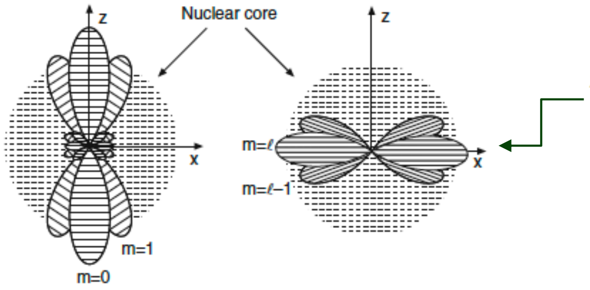
$$Q_{class} = \int (3z^2 - \mathbf{x}^2)\rho(\mathbf{x})d^3x$$

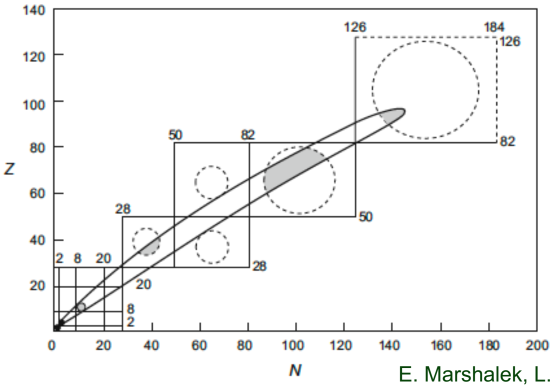
$$\langle R \rangle = (ab^2)^{1/3}; \Delta R = a - b$$

$$Q_{ellipsoid} = \frac{2}{5}Ze(a^2 - b^2) = \frac{6}{5}Ze\langle R \rangle^2 \varepsilon$$

$$\varepsilon = \frac{2}{3}\frac{\Delta R}{\langle R \rangle}$$

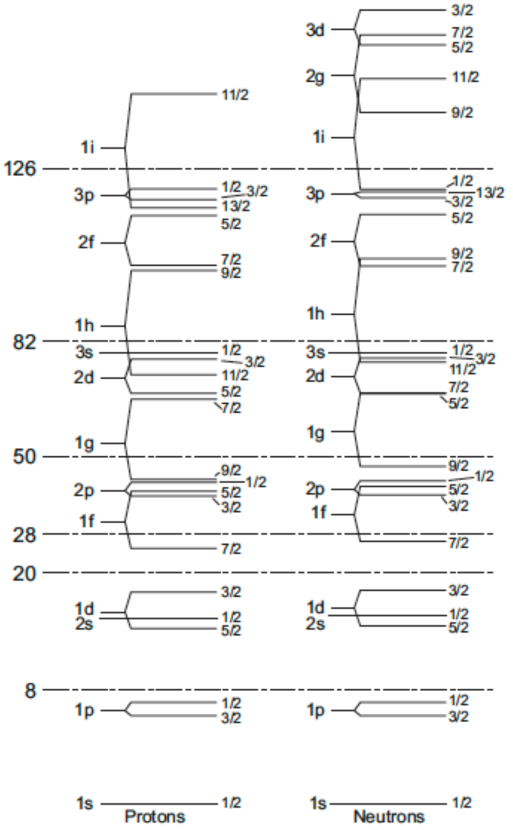
$$Q_{red} = \frac{Q_{ellipsoid}}{Ze\langle R \rangle^2}$$





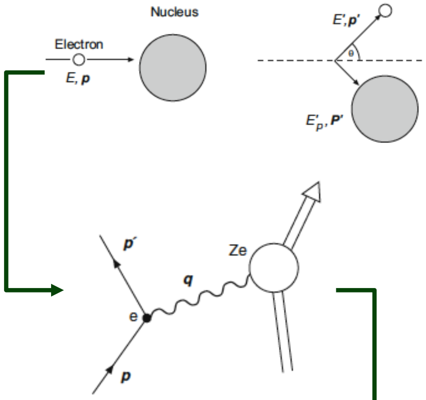
E. Marshalek, L. Person, R. Sheline
Rev. Mod. Phys. 35, 108 (1963)

P.F.A. Klingenberg, Rev. Mod. Phys. 24, 63 (1952)

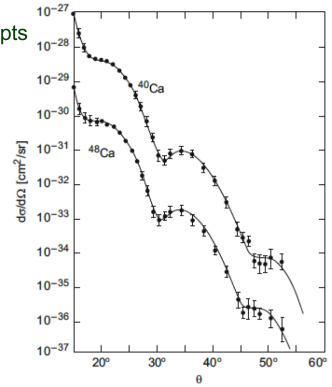


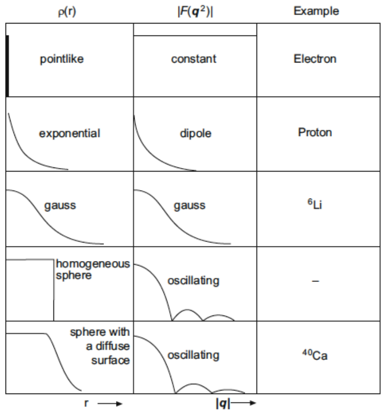
Nuclear Size: From the Small Guys! [1]

B. Povh, K. Rith, C. Scholz, F. Zetsche, W. Rodejohann
Particles and Nuclei, An Introduction to the Physical Concepts

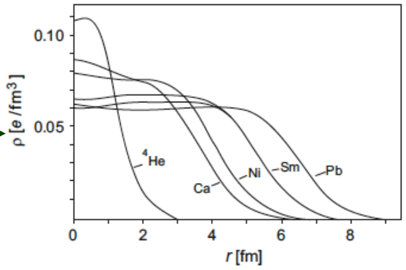


$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{\text{Mott}} \cdot \left|F(q^2)\right|^2$$





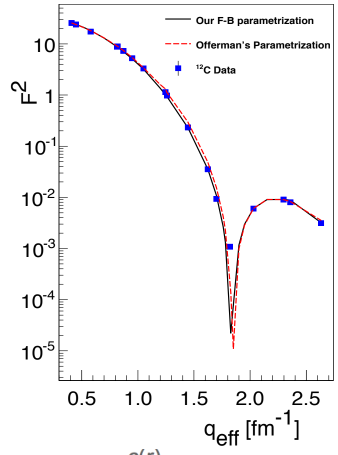
ρ(r)	|F(q²)|	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	⁶Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	⁴⁰Ca

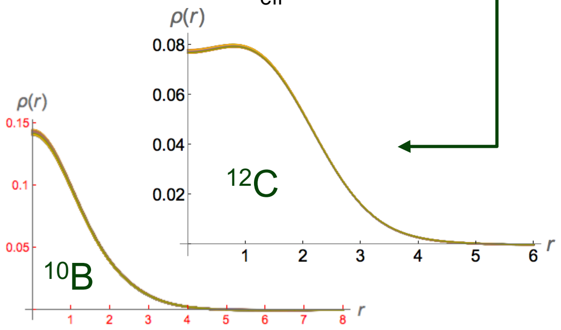


$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \mid F(Q^2) \mid^2$$

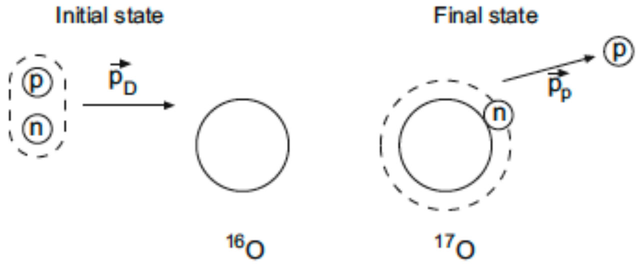
$$F_p(q^2) = \frac{1}{4\pi}\int d^3r\, j_0(qr)\rho_p(r)$$

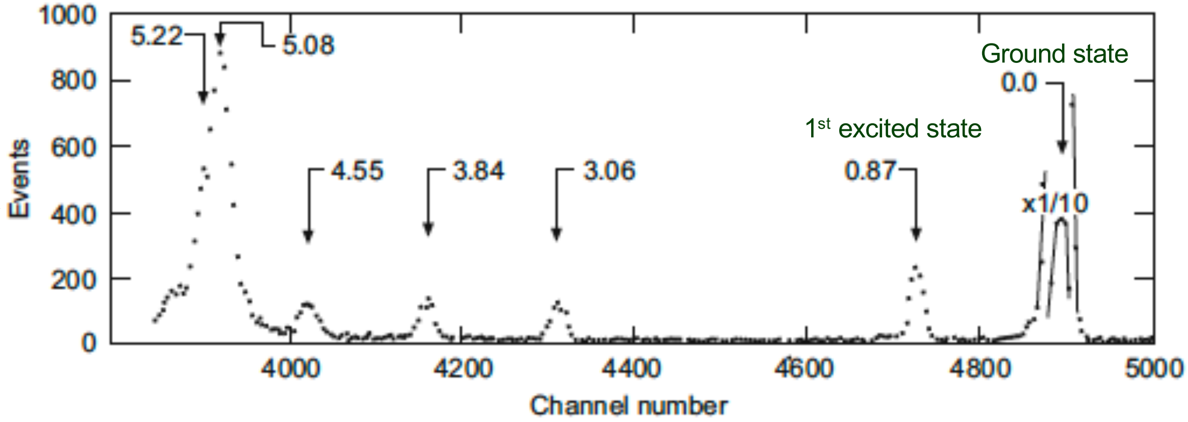
$$\begin{aligned} ZF_p &= 4\pi\int_0^\infty \rho_p r^2 dr \\ &= \sum_{\nu=1}^{\infty}(-1)^{\nu+1}\frac{4\pi R_p}{q_\nu^2}a_\nu \end{aligned}$$

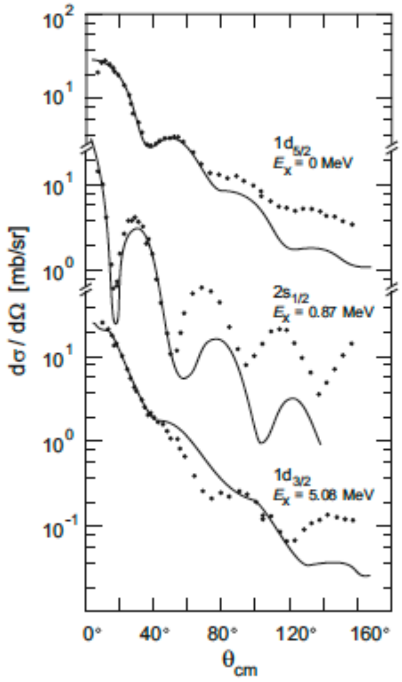




Nuclear Size: From the Big Guys! [2]



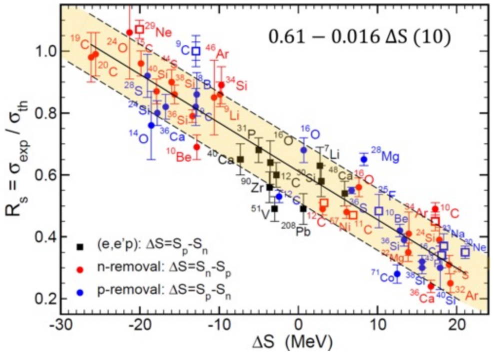


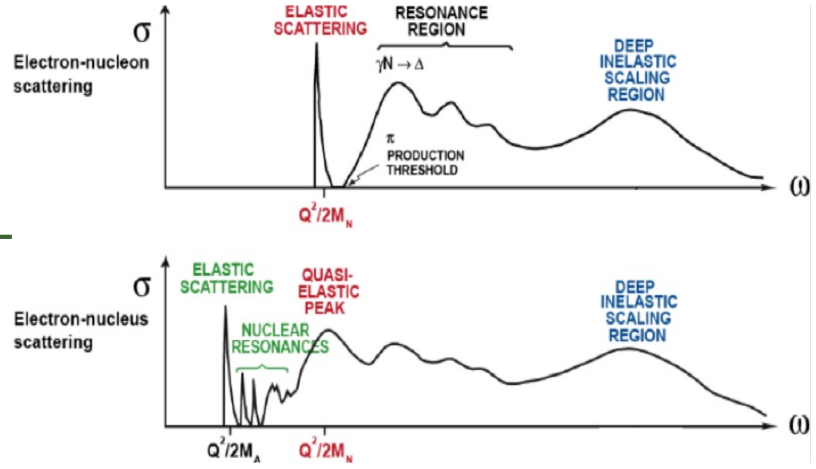


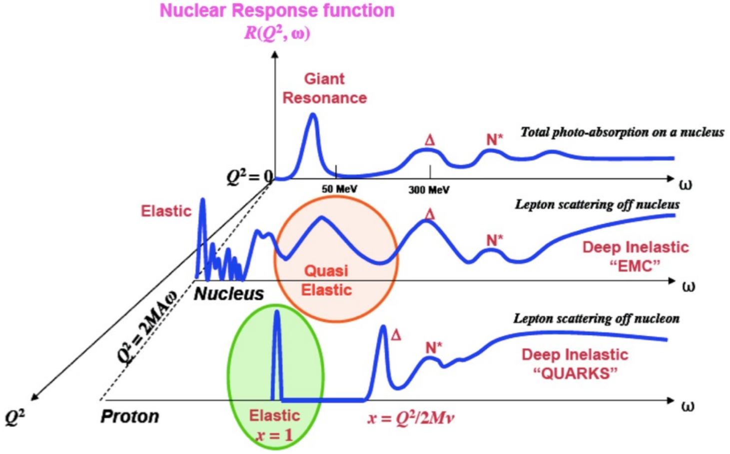
B. Povh, K. Rith, C. Scholz, F. Zetsche, W. Rodejohann
Particles and Nuclei, An Introduction to the Physical Concepts

Electromagnetic Probes

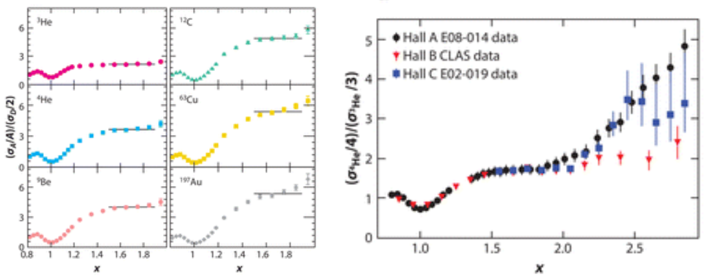
J. A. Tostevin and A. Gade
Phys. Rev. C **103**, 054610 (2021)







J. Arrington, N. Fomin and A. Schmidt
Ann. Rev. Nucl. Part. Sci., **72**,307-337 (2022)



Nuclear Tomography:
Importance of Spin Observables

$$\frac{d\sigma_v}{d\Omega_\eta} = \frac{|\mathbf{k}|}{k_\gamma^{cm}} P_\alpha P_\beta \{ R_T^{\beta\alpha} + \varepsilon_L R_L^{\beta\alpha}$$
$$+ [2\varepsilon_L (1+\varepsilon)]^{1/2} ({}^cR_{TL}^{\beta\alpha} \cos\phi_\eta + {}^sR_{TL}^{\beta\alpha} \sin\phi_\eta)$$
$$+ \varepsilon ({}^cR_{TT}^{\beta\alpha} \cos 2\phi_\eta + {}^sR_{TT}^{\beta\alpha} \sin 2\phi_\eta)$$
$$+ h [2\varepsilon_L (1-\varepsilon)]^{1/2} ({}^cR_{TL'}^{\beta\alpha} \cos\phi_\eta + {}^sR_{TL'}^{\beta\alpha} \sin\phi_\eta)$$
$$+ h (1-\varepsilon^2)^{1/2} R_{TT'}^{\beta\alpha} \},$$

Meson electro-production

G. Knöchlein, D. Drechsel, L. Tiator
Z. Phys. **A352**, 327-343 (1995)

3D nucleon tomography!!
(DVCs, parton distributions …)

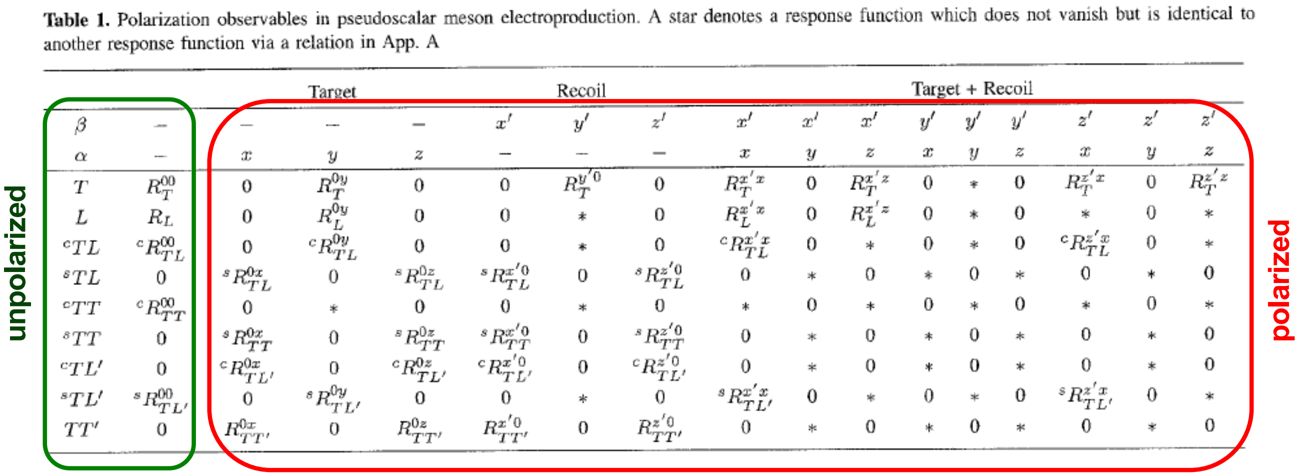
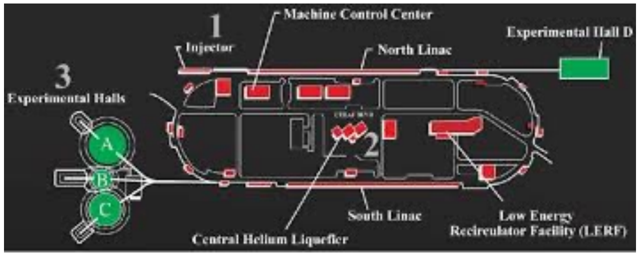


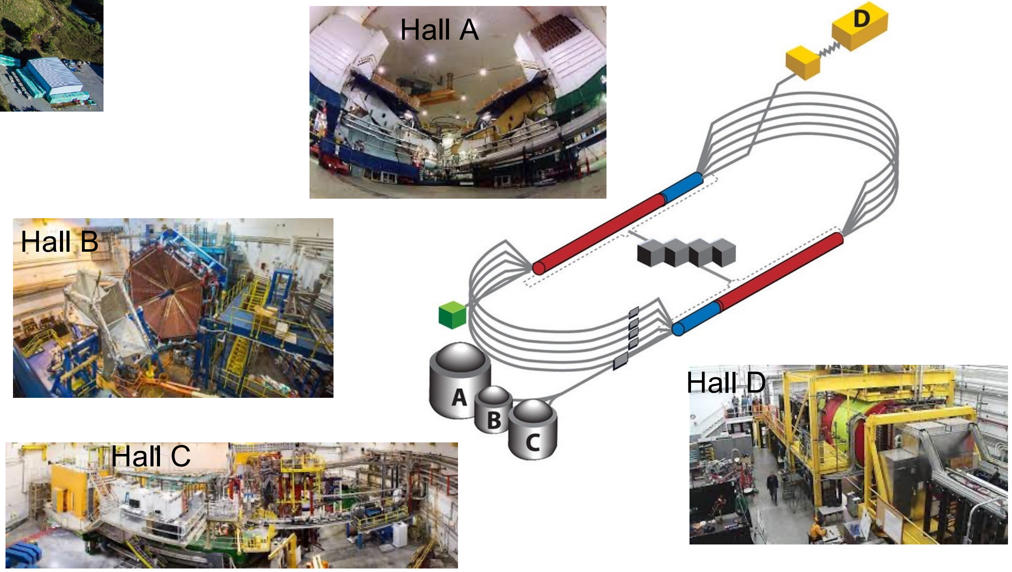
Table 1. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A

		Target			Recoil			Target + Recoil								
β	–	–	–	–	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	–	x	y	z	–	–	–	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	$*$	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	$*$	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	$*$	0	$*$	0	$*$
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	$*$	0	${}^cR_{TL}^{x'x}$	0	$*$	0	$*$	0	${}^cR_{TL}^{z'x}$	0	$*$
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTT$	${}^cR_{TT}^{00}$	0	$*$	0	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	$*$	0	${}^sR_{TL'}^{x'x}$	0	$*$	0	$*$	0	${}^sR_{TL'}^{z'x}$	0	$*$
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0

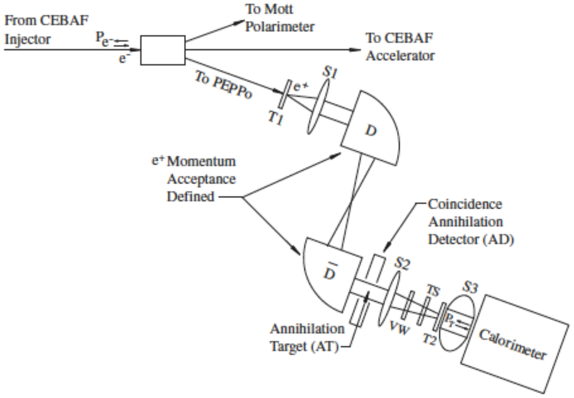
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

12 GeV, 14 kW
Polarized e$^-$
CW (1.5 GHz)



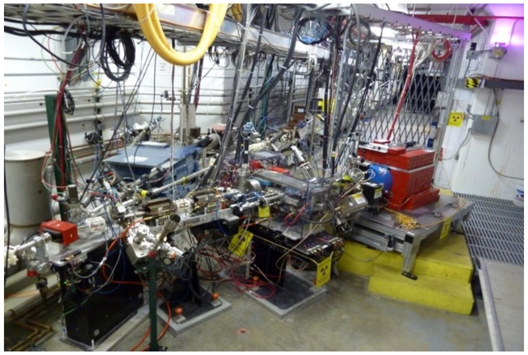


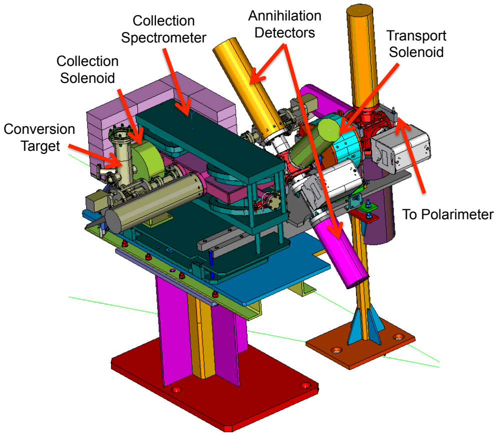
Polarized Positron Beams – 20 years later!
(... possible scheme for the EIC)

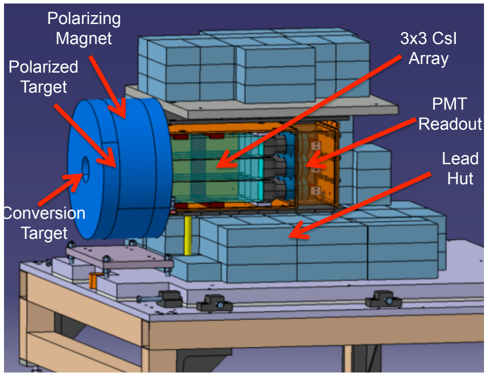


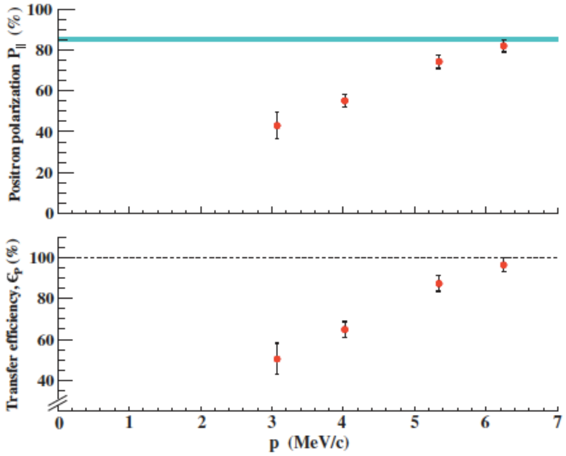
<u>P</u>olarized <u>E</u>lectrons for <u>P</u>olarized <u>Po</u>sitrons
D. Abbott *et al.*, PRL **116**, 214801 (2016)

- Experiment in the CEBAF injector
- Highly polarized positrons
- 80% @ 6.5 MeV
- R&D for EIC
- **Last PhD @ HU (A. Adeyemi, 2016)**

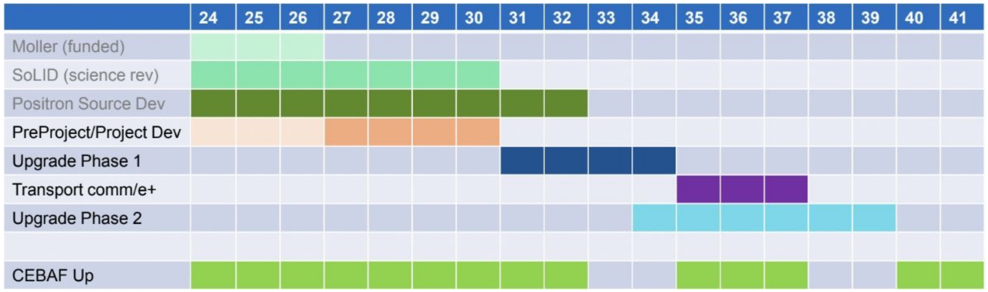








Future of JLab with Positrons

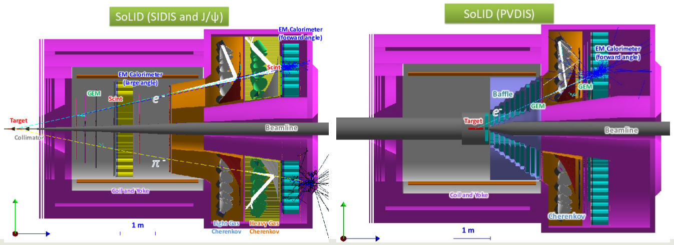


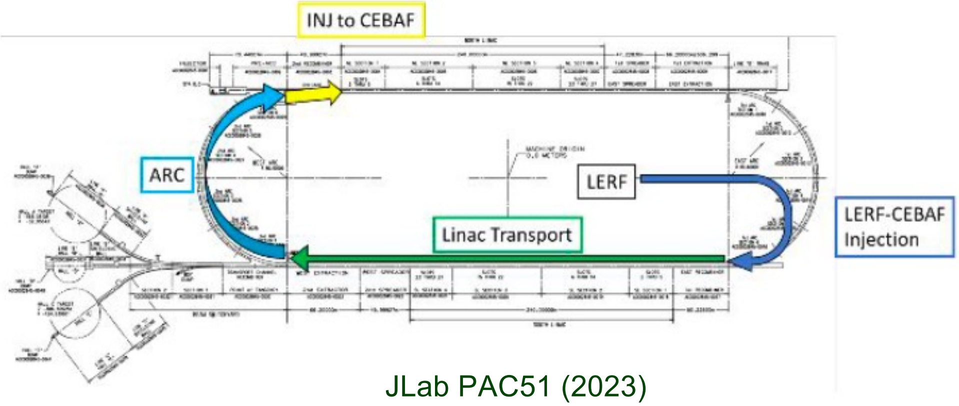
	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Moller (funded)	🟩	🟩	🟩															
SoLID (science rev)	🟩	🟩	🟩	🟩	🟩	🟩	🟩											
Positron Source Dev	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
PreProject/Project Dev	🟧	🟧	🟧	🟧	🟧	🟧	🟧											
Upgrade Phase 1								🟦	🟦	🟦	🟦							
Transport comm/e+												🟪	🟪	🟪				
Upgrade Phase 2											🟦	🟦	🟦	🟦	🟦	🟦		
CEBAF Up	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩	🟩			🟩	🟩

← 22 GeV

Solenoidal Large Intensity Device (SoLID)

- Precision 3D momentum imaging in the valence quark region
- Exploring the origin of the proton mass and gluonic force in the non-perturbative regime
- Beyond Standard Model searches complementary to Möller





JLab PAC51 (2023)
21/37 (57%) proposals/LOIs for e⁺!!

Neutron skin puzzle: the role of virtual excitations [1]

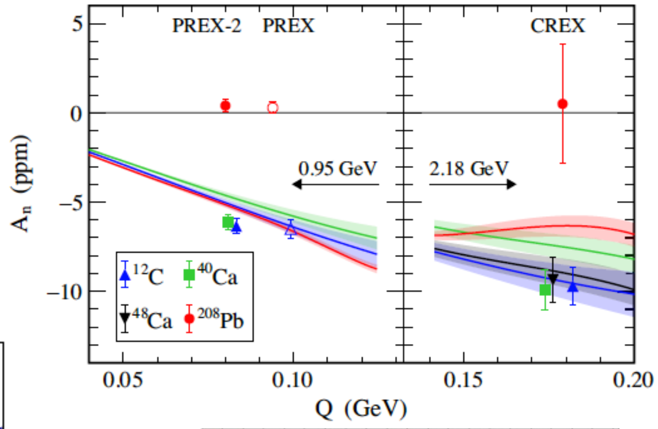
PREX: D. Adhikari et al., PRL, **126**, 172502 (2021)

- ^{208}Pb: $R_n - R_p = 0.283 \pm 0.071$ fm

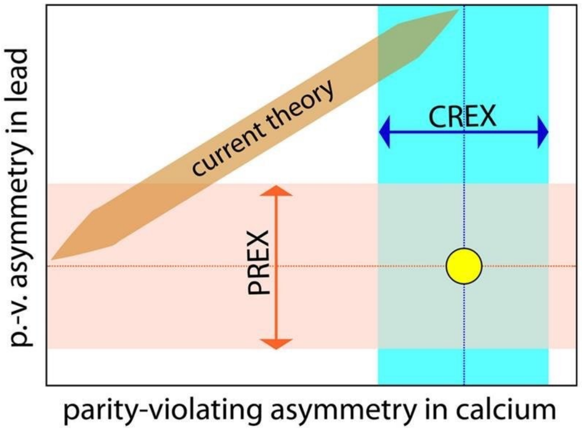
CREX: D. Adhikari et al., PRL, **129**, 042501 (2022)

- ^{48}Ca: $R_n - R_p = 0.121 \pm 0.026$ (exp) ± 0.024 (model) fm

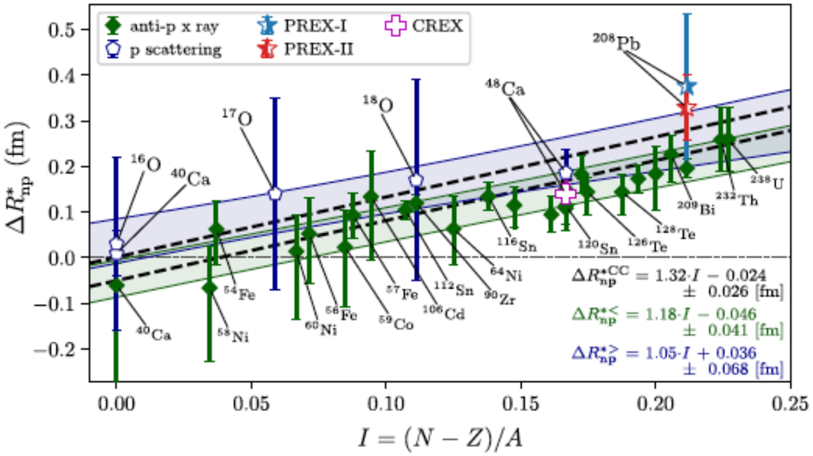
Adhikari et al, PRL 128, 142501 (2022)

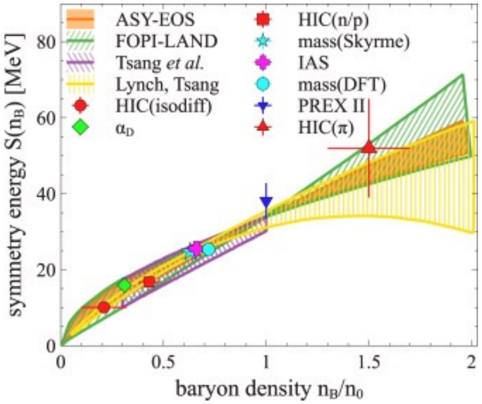


P.-G. Reinhard, X. Roca-Maza, and W. Nazarewicz
PRL**129**, 232501 (2022)



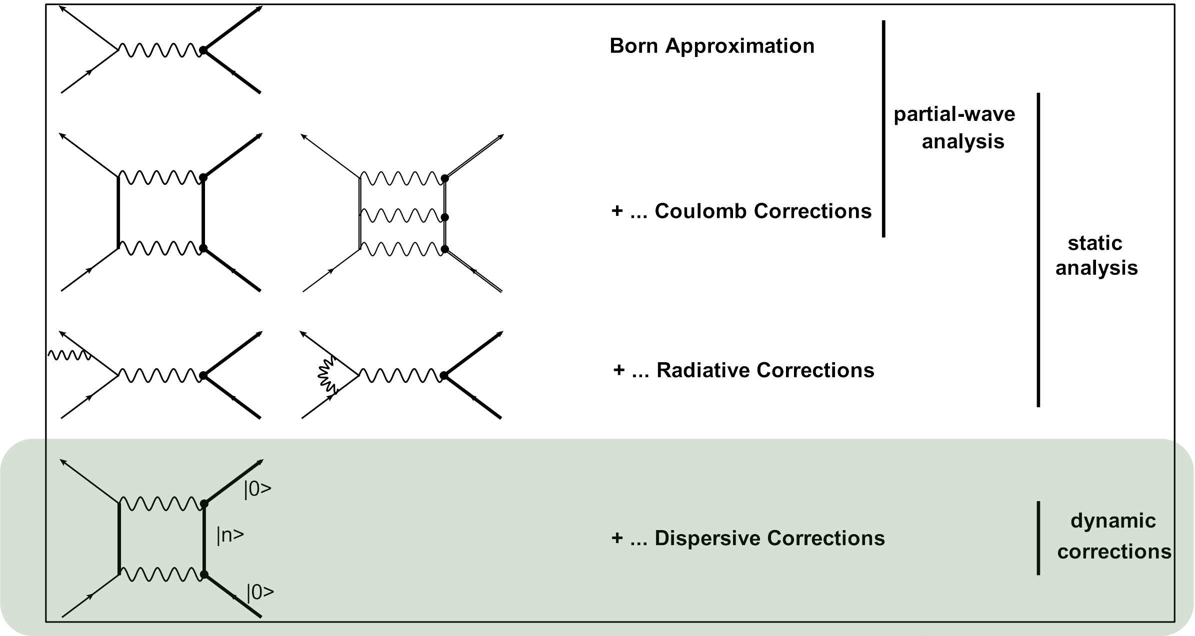
S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen
PRL**130**, 032501 (2023)





A. Sorensen et al, Prog. Part. Nucl. Phys., 134, 142501 (2024)

Neutron skin puzzle: the role of virtual excitations [2]



Born Approximation

partial-wave analysis

+ ... Coulomb Corrections

static analysis

+ ... Radiative Corrections

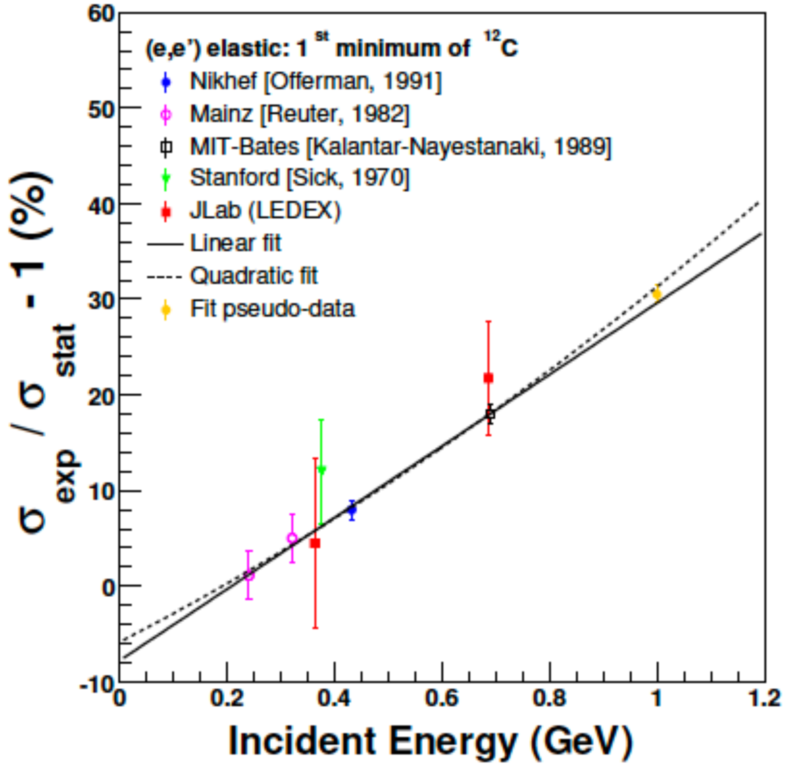
+ ... Dispersive Corrections

dynamic corrections

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left|F(q^2)\right|^2 \longrightarrow$$

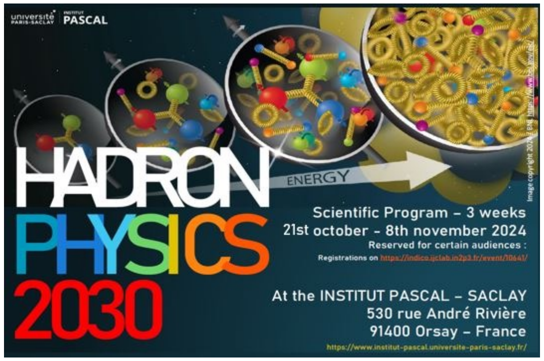
$$\begin{aligned} |\mathcal{M}_{elast+disp}|^2 &= (\alpha q_e Z)^2 \left[F(q^2)\right]^2 \\ &+ 2(\alpha q_e Z)^3 \left[F(q^2)\mathcal{R}e\{G(q^2)\}\right] \\ &+ (\alpha q_e Z)^4 \left[|\mathcal{R}e\{G(q^2)\}|^2 + |\mathcal{I}m\{G(q^2)\}|^2\right] \end{aligned}$$

P. Gueye et al., Eur. Phys. Jour. **A56**:126 (2020)



D H Jakubassa-Amundsen, J. Phys. G: Nucl. Part. Phys. 51 (2024) 035105: ~5 MeV
D H Jakubassa-Amundsen, PHYSICAL REVIEW C **105**, 054303 (2022) : <400 MeV

Neutron skin “PREX puzzle”: the role of virtual excitations [3]



Scientific Program – 3 weeks
21st october – 8th november 2024
Reserved for certain audiences :
Registrations on https://indico.ijclab.in2p3.fr/event/10641/

At the INSTITUT PASCAL – SACLAY
530 rue André Rivière
91400 Orsay – France
https://www.institut-pascal.universite-paris-saclay.fr/

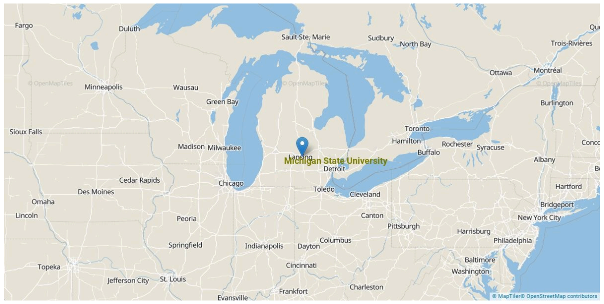
Transverse beam asymmetries on nuclei

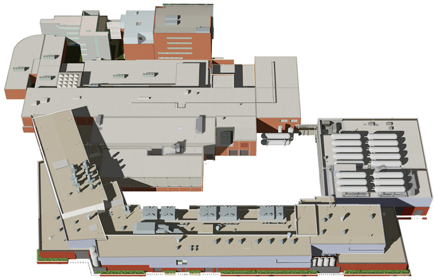
- Good agreement with theory for nucleon and light nuclei

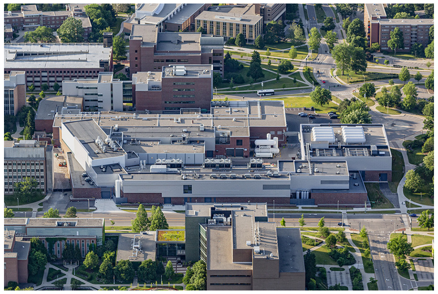
Puzzling disagreement for ^{208}Pb measurement

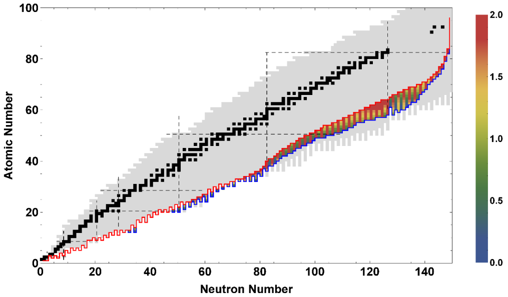
- Theory
  - Need to include additional electron interactions
    - With highly excited intermediate nuclear states, magnetic terms, etc. (e.g., effects of higher orders in α)
  - Possible impact on equation of state (e.g., PREX)
  - Interesting nuclear effects!
- Experiment
  - Need additional measurements for intermediate-mass targets (e.g., Al, Ca, Fe …)
    - Koshchii et al. PRC, **103**, 064316 (2012)
  - PAC53 proposal to JLab (PI: P. Gueye)
    - Qualitative assessment.   : electron beam and unpolarized; comparison with “best” theoretical calculation
    - Quantitative measurement: comparison between electrons and positrons (e.g., JLab positron program; ~2030)

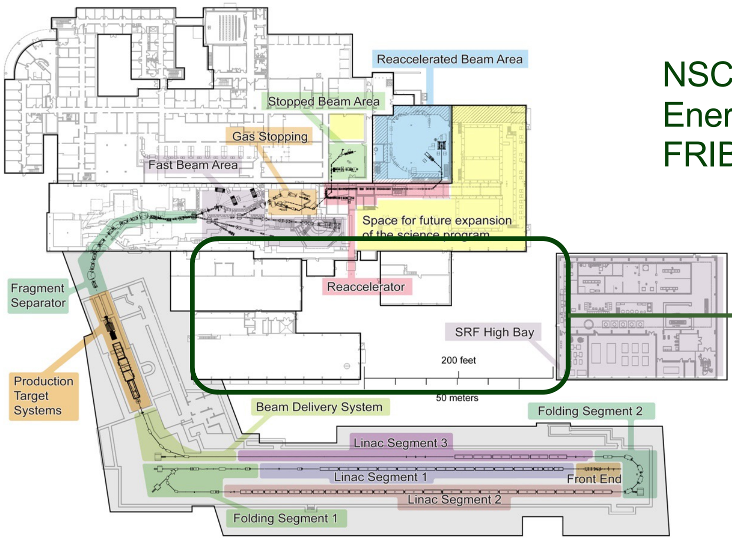
Facility for Rare Isotope Beams (www.frib.msu.edu; start: May 10, 2022)



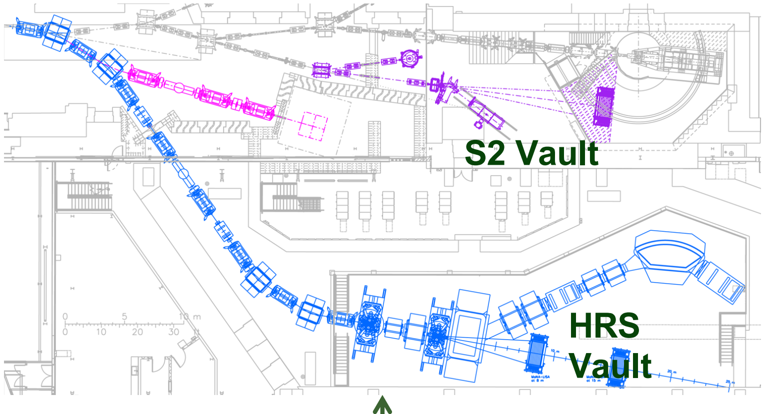








NSCL : ~100 MeV/u
Energy : ~200 MeV/u
FRIB400 : ~400 MeV/u



CD2 review in October

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

Facility for Rare Isotope Beams Offers Discovery Potential

FRIB is a US Department of Energy Office of Science User facility

- Open to researchers from around the world based on scientific merit

FRIB's key feature is 400 kW beam power

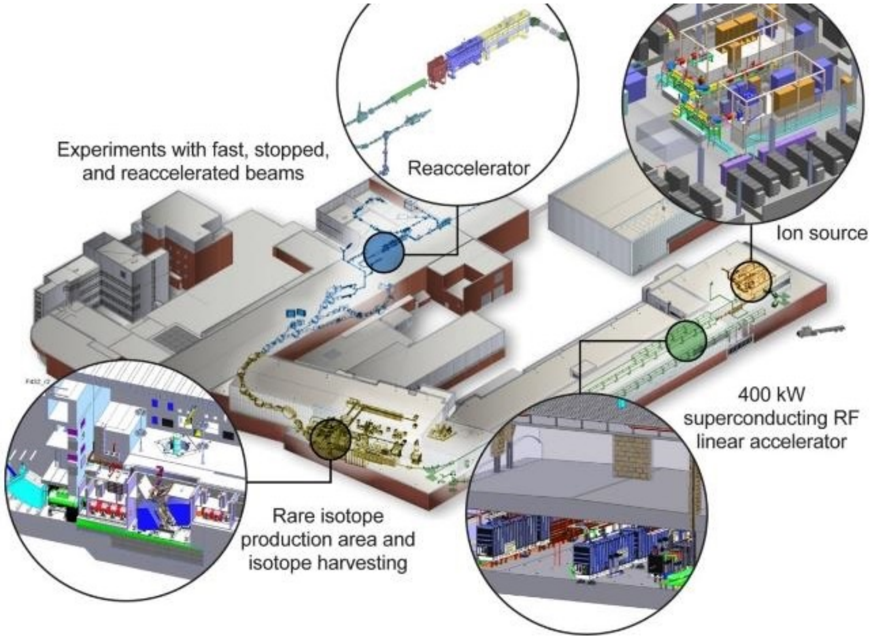
- 8 pμA or 5 x 10^{13} ^{238}U/s

Experiments with fast (200 MeV/u), stopped (trapped), and reaccelerated beams (0.6 to 10 MeV/u)

Separation of isotopes in-flight provides

- Fast development time for any isotope
- Beams of all elements and short half-lives

Isotope harvesting capability from beam dump water)



Thomas Glasmacher,
FRIB Laboratory Director

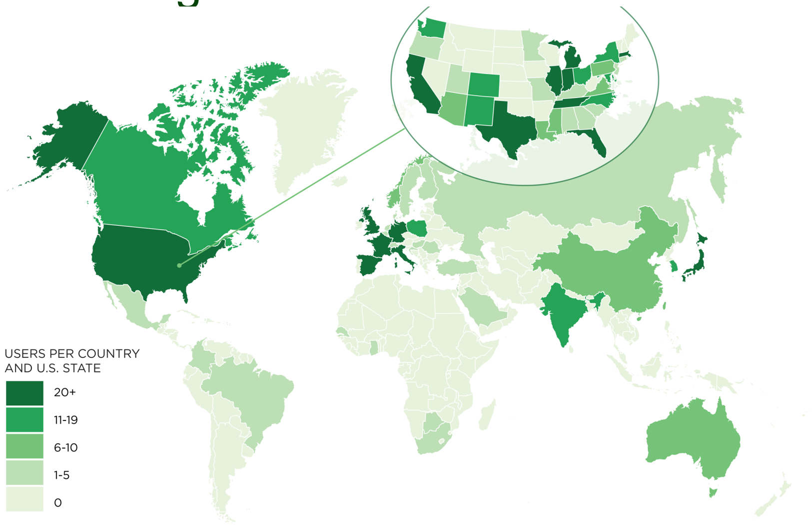
FRIB’s Integrated Scheduling and Operations Strategy Allowed for Early High-Impact Publications

From A. Gade slides

>1800 users worldwide

FRIB ramped from 1 kW beam power to 10 kW within 1 year

Working on 20 kW



Crossing $N = 28$ Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

H. L. Crawford *et al.*
Phys. Rev. Lett. **129**, 212501 – Published 14 November 2022

Physics See Viewpoint: Probing the Limits of Nuclear Existence

Microsecond Isomer at the $N = 20$ Island of Shape Inversion Observed at FRIB

T. J. Gray *et al.*
Phys. Rev. Lett. **130**, 242501 – Published 13 June 2023

Physics See synopsis: Excited Sodium-32 with a Spherical Wave Function

Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB

O. B. Tarasov, A. Gade, K. Fukushima, M. Hausmann, E. Kwan, M. Portillo, M. Smith, D. S. Ahn, D. Bazin, R. Chyzh, S. Giraud, K. Haak, T. Kubo, D. J. Morrissey, P. N. Ostroumov, I. Richardson, B. M. Sherrill, A. Stolz, S. Watters, D. Weisshaar, and T. Zhang
Phys. Rev. Lett. **132**, 072501 – Published 15 February 2024

Physics See Research News: Five New Isotopes Is Just the Beginning

Precision Mass Measurement of the Proton Dripline Halo Candidate ^{22}Al

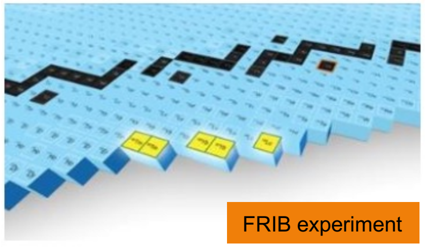
S. E. Campbell, G. Bollen, B. A. Brown, A. Dockery, C. M. Ireland, K. Minamisono, D. Puentes, B. J. Rickey, R. Ringle, I. T. Yandow, K. Fossez, A. Ortiz-Cortes, S. Schwarz, C. S. Sumithrarachchi, and A. C. C. Villari
Phys. Rev. Lett. **132**, 152501 – Published 9 April 2024

Proton Shell Gaps in $N = 28$ Nuclei from the First Complete Spectroscopy Study with FRIB Decay Station Initiator

I. Cox *et al.*
Phys. Rev. Lett. **132**, 152503 – Published 12 April 2024

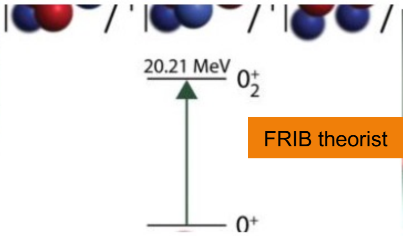
Results From Experimental and Theoretical Research at FRIB are Published as 16 DOE Science Highlights for NP

From A. Gade slides


FRIB experiment

The Facility for Rare Isotope Beams Observes Five Never-Before-Seen Isotopes

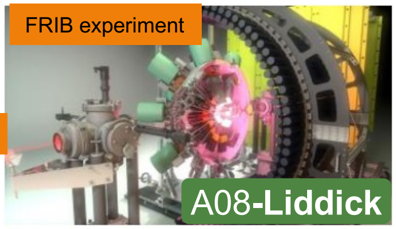
The discovery of new isotopes demonstrates the user facility's discovery potential.



FRIB theorist

New Calculations Solve an Alpha Particle Physics Puzzle

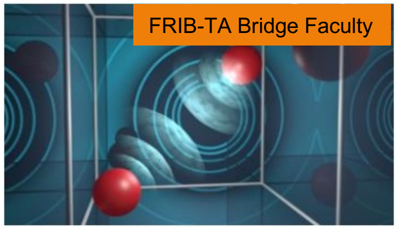
A new experimental measure of Helium-4's transition from its ground energy state to an excited state closes an apparent gap with theoretical predictions.


FRIB experiment

A08-Liddick

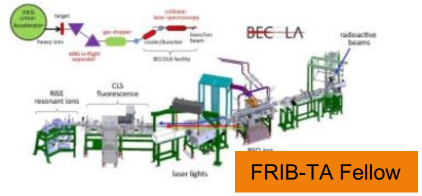
Long-Lived State in Radioactive Sodium Discovered at the Facility for Rare Isotope Beams

A newly discovered excited state in radioactive sodium-32 has an unusually long lifetime, and its shape dynamics could be the cause.


FRIB-TA Bridge Faculty

Understanding Charged-Particle Bound States in Periodic Boxes

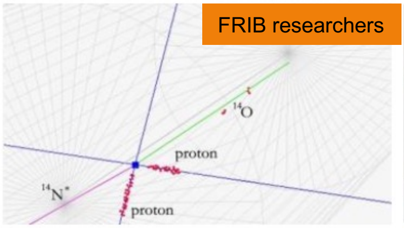
Finite geometry reveals fundamental properties of charged quantum systems.



FRIB-TA Fellow

Nuclear Charge Distribution Measurements May Solve Outstanding Puzzle In Particle Physics

By reanalyzing the distribution of active protons in nuclei, researchers found a possible solution to a particle physics puzzle involving quarks.



FRIB researchers

Researchers Develop a Novel Method to Study Nuclear Reactions on Short-Lived Isotopes Involved in Explosions of Stars

Scientists take pictures of a nuclear reaction in the laboratory to understand processes inside the cores of stars.


FRIB experiment

A08-Liddick

First Science Results from FRIB Published

Researchers have published the results from the first experiment at the Facility for Rare Isotope Beams, measurement of 5 new half-lives, in Physical Review Letters.


FRIB researchers

A Novel Way to Get to the Excited States of Exotic Nuclei

Scientists find a new approach to access unusual excited nuclear levels.

FRIB development

A18-Kanemura

Innovative FRIB Liquid-Lithium Charge Stripper Boosts Accelerator Performance

The Facility for Rare Isotope Beams has demonstrated an innovative liquid-lithium charge stripper to accelerate unprecedentedly high-power heavy-ion beams.


FRIB researchers

Record-Breaking Radiation Detection Pins Down Element Formation in Stellar Novae

A weak proton emission following beta decay constrains the formation of elements in stellar nova explosions and determines their peak temperature.

Rare Isotope Nuclear Radii

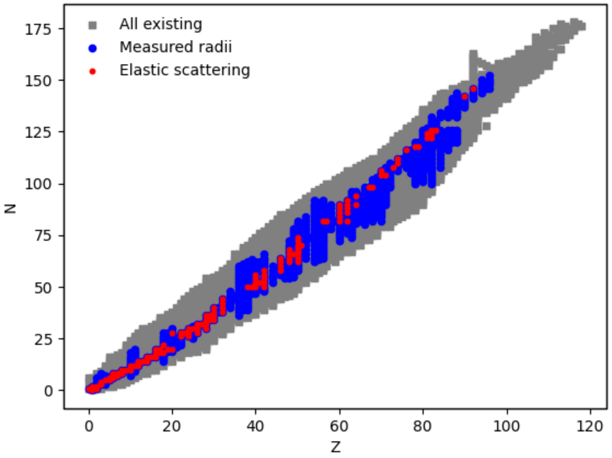
Ambar Rodriguez Alicea, MS (2024)

$$\rho(r) = \frac{1}{2\pi^2}\int F(q)\,\frac{\sin(qr')}{qr}\,q^2 dq$$

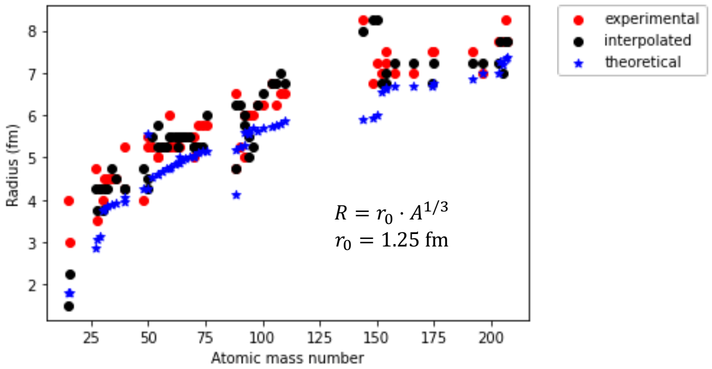
$$= \sum a_\nu j_0(qr)$$

$$F(q) = 4\pi\int \frac{\sin(qr'/\hbar)}{qr'/\hbar}\,r'^2\rho(r')dr'$$

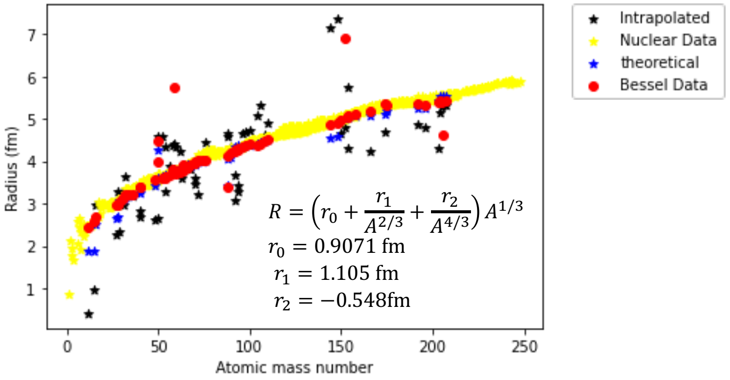
$$j_0(qr) = \sum_{n=0}^{\infty}\frac{(-1)^n(qr)^{2n}}{2^{2n}(n!)^2} = \frac{\sin(qr)}{qr}$$

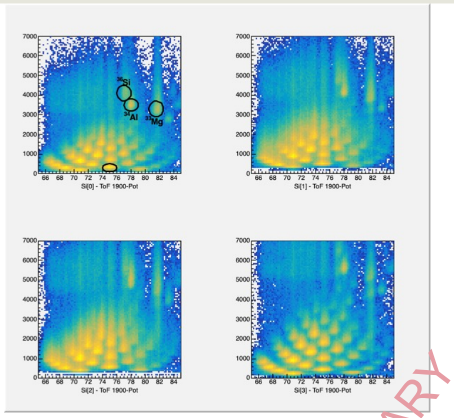


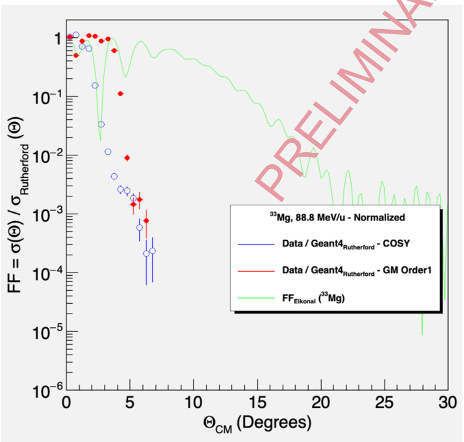
H. DeVries etal., At. Data Nuc. Data Tables, **36**, 495-536 (1987)



I. Angeli and K. P. Marinova, At. Data Nuc. Data Tables, **99**, 69-95 (2013)



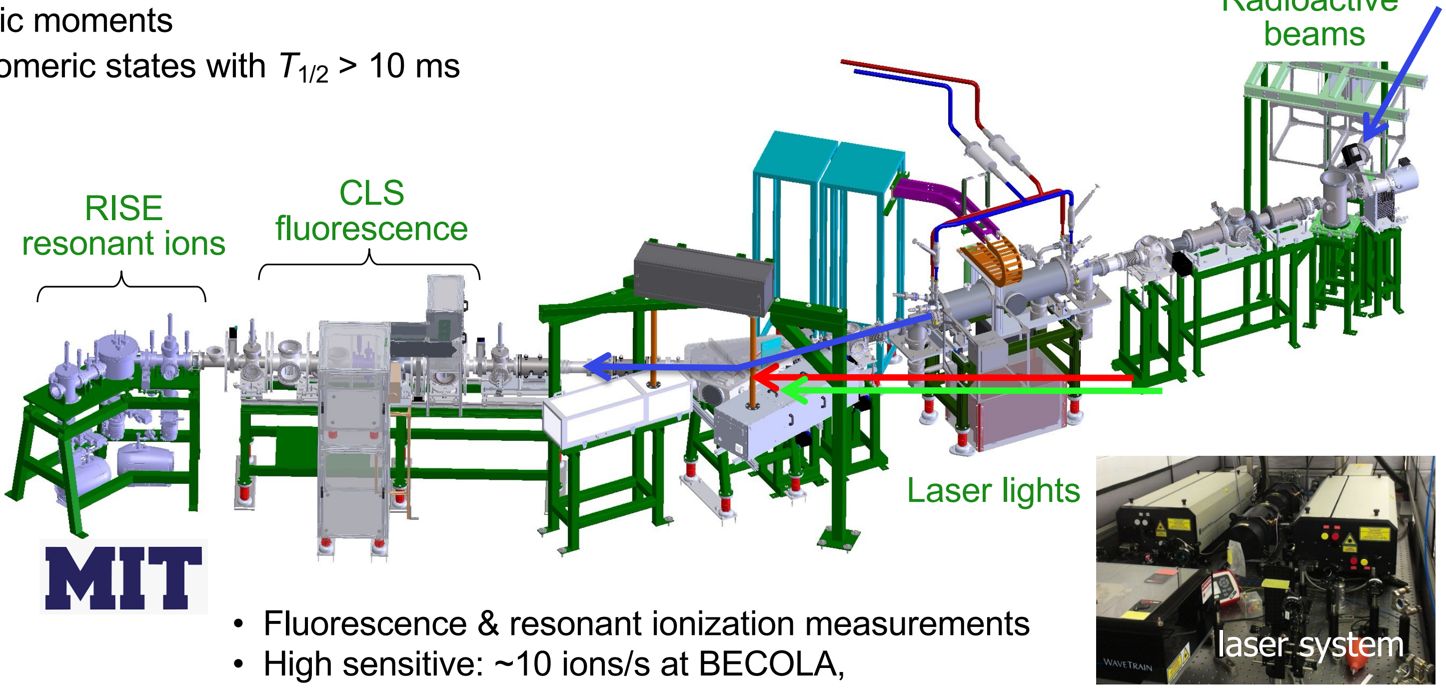




Laser Spectroscopy @ FRIB: BECOLA Facility

Courtesy K. Minamisono

- Beam Cooling and Laser spectroscopy (BECOLA)
- Determine diff. rms charge radius from Isotope Shift
- Electromagnetic moments
- Ground and isomeric states with $T_{1/2} > 10$ ms

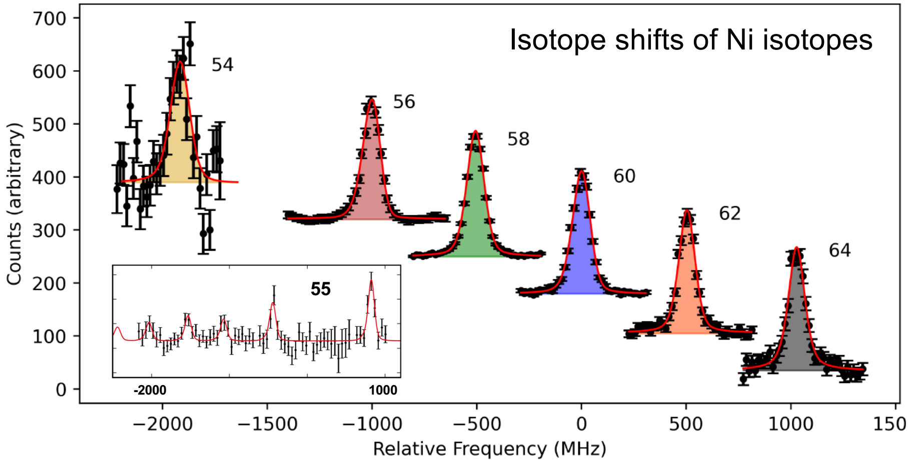


- Fluorescence & resonant ionization measurements
- High sensitive: ~10 ions/s at BECOLA,

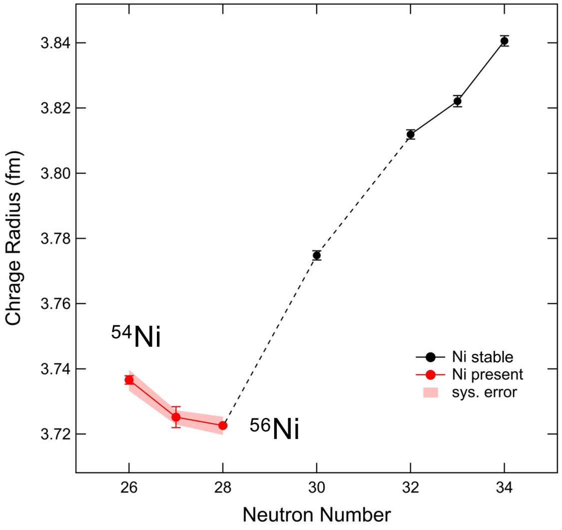
Charge Radii of ^{54,55,56}Ni Reveal a Surprising Similarity to ^{48}Ca at *N* = 28

Courtesy K. Minamisono

- Discontinuity, so called the kink structure, in a chain of charge radii is commonly observed at all Magic numbers.
- However, what the strength (steepness) of the kink implies is an open question.
- Kink at ^{56}Ni was investigated, which is know to be “soft” as doubly-Magic nucleus.



- Isotope shifts of hyperfine spectra **relative to stable ^{60}Ni** were measured for the neutron-deficient ^{54,55,56}Ni by laser spectroscopy
- Differential mean square charge radii $\delta\langle r^2\rangle$ were extracted.



Charge radii were deduced from the $\delta\langle r^2\rangle$ and radius of stable ^{60}Ni.

Kink at the neutron-number *N* = 28 is clearly observed.

F. Sommer et al., PRL 129, 132501 (2022)

Need absolute charge radii

Courtesy K. Minamisono

- **Model independent, *R* can be determined with ~ 0.005 fm**
- **Sensitive to $\boldsymbol{\delta\langle r^2\rangle}$ and requires reference to deduce absolute radius**: $R^2 = \boldsymbol{R^2_{\mathrm{ref}}} + \delta\langle r^2\rangle$
    - R_{ref} can be evaluated from e-scattering and μ-capture experiments.
    - but R_{ref} is not always available with high enough needed precision.
- **Using King plot, *k* and *F* can be experimentally evaluated,**
    - IF there are ≥ 3 (stable) isotopes of the element, whose *R* are know.
    - Otherwise need to rely on atomic theories
        - Typically with a few ~ 10% uncertainty
        - Ab-initio is feasible for 5 electron systems so far.
- **Once *k* and *F* are known, they can be applied to deduce unknown $\boldsymbol{\delta\langle r^2\rangle}$**
- In general, $\delta\langle \mathrm{r}^2\rangle$ is replaced by $\delta\langle \mathrm{r}^2\rangle + \widetilde{c_2}\delta\langle \mathrm{r}^4\rangle + \widetilde{c_3}\delta\langle \mathrm{r}^6\rangle + \cdots$
    - Contribution is very small and difficult to determine
- **Need absolute *R* of stable as well as radioactive but near stable nucleus to go further away from stable isotopes, where there is enhanced chance of discovery.**

Electron/Rare Isotopes Systems

RI-RIKEN

- SCRIT: Self-Confining Radioactive isotope Ion Target

Facility for Anti-proton and Ion Research (FAIR, Germany)

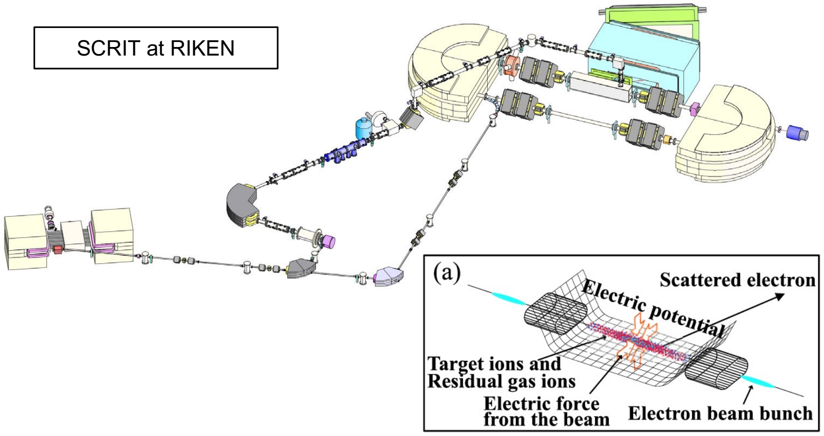
- ELISE: Electron-Ion Scattering in a Storage Ring

DUBNA (Russia)

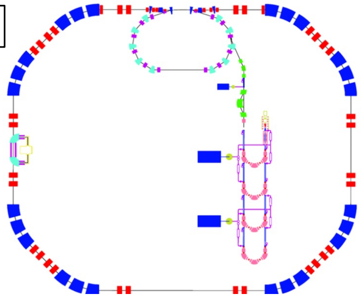
- DERICA: Dubna Electron-Radioactive Ion Collider fAcility

K. Tsukada et al., Phys. Rev. Lett. **131**, 092502
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.092502

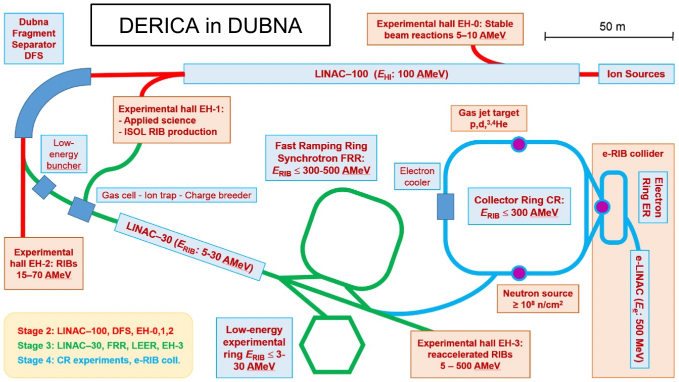
SCRIT at RIKEN



ELISE at FAIR



DERICA in DUBNA



Dubna Fragment Separator DFS

Experimental hall EH-0: Stable beam reactions 5–10 AMeV

50 m

LINAC–100 (E_{HI}: 100 AMeV)

Ion Sources

Experimental hall EH-1:
- Applied science
- ISOL RIB production

Low-energy buncher

Gas cell - Ion trap - Charge breeder

Fast Ramping Ring Synchrotron FRR: $E_{RIB} \leq$ 300-500 AMeV

Gas jet target p,d,^{3,4}He

Electron cooler

Collector Ring CR: $E_{RIB} \leq$ 300 AMeV

e-RIB collider

Electron Ring ER

e-LINAC (E_e: 500 MeV)

LINAC–30 (E_{RIB}: 5-30 AMeV)

Experimental hall EH-2: RIBs 15–70 AMeV

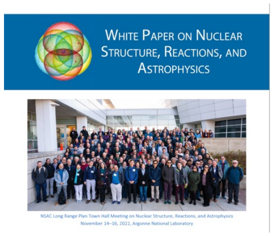
Neutron source $\geq 10^8$ n/cm^2

Stage 2: LINAC–100, DFS, EH-0,1,2
Stage 3: LINAC–30, FRR, LEER, EH-3
Stage 4: CR experiments, e-RIB coll.

Low-energy experimental ring $E_{RIB} \leq$ 3-30 AMeV

Experimental hall EH-3: reaccelerated RIBs 5 – 500 AMeV

Toward a Possible $e^{\pm}$-RIB Concept @ FRIB


White Paper on Nuclear Structure, Reactions, and Astrophysics

Jefferson Lab

University of Virginia

RIKEN

université PARIS-SACLAY

Université Paris Cité

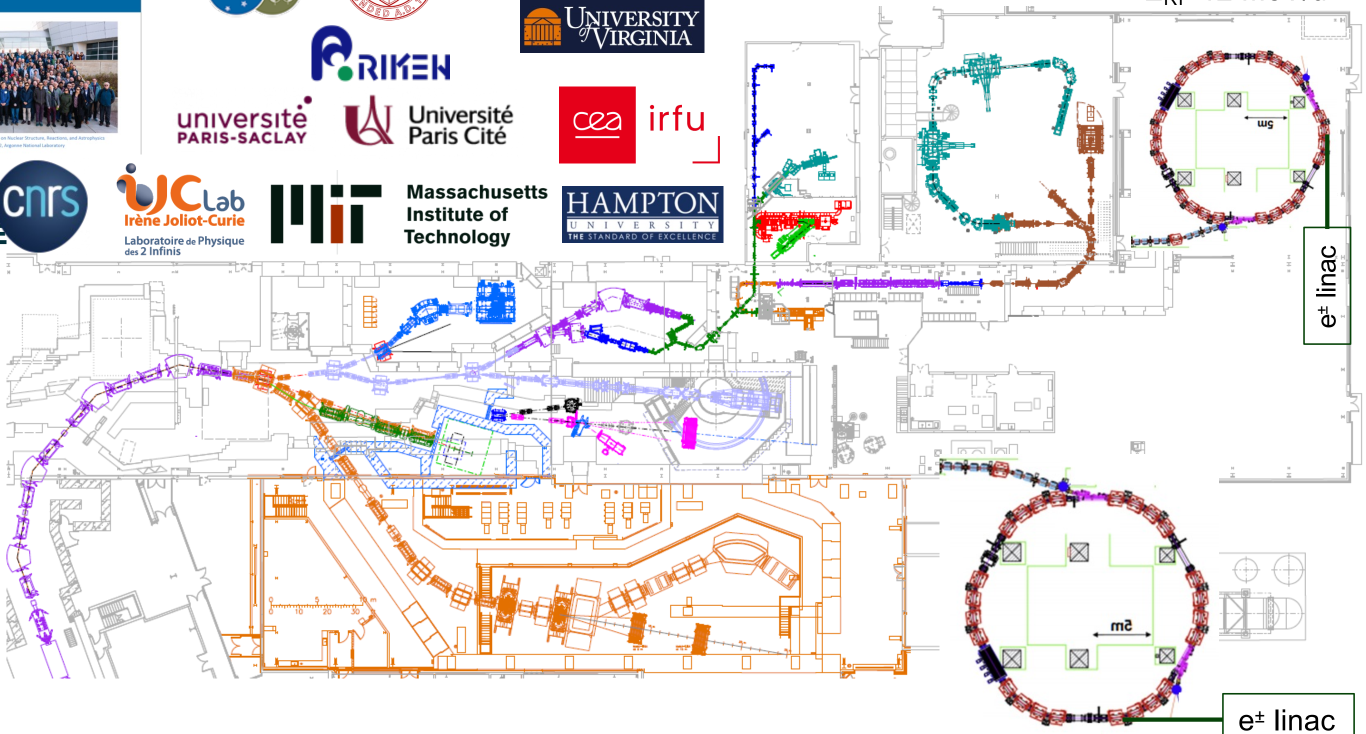
cea irfu

cnrs

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

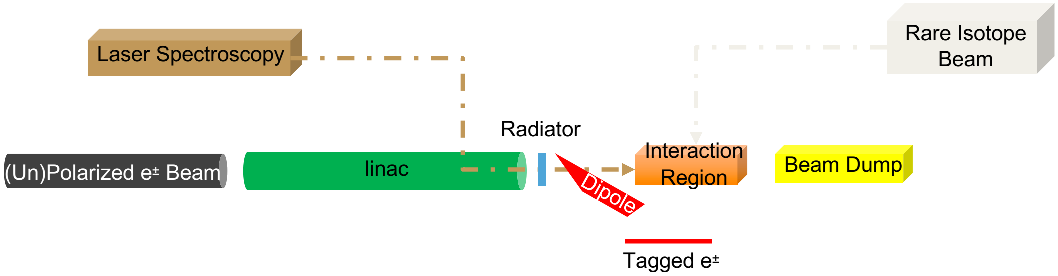
Massachusetts Institute of Technology

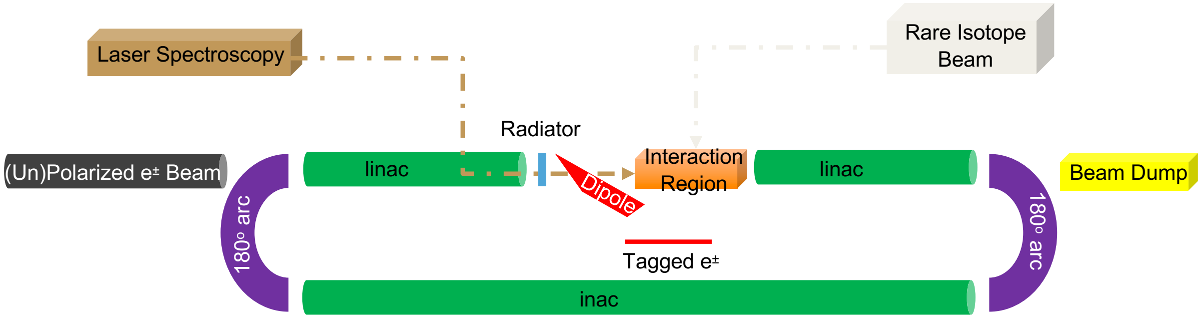
HAMPTON UNIVERSITY THE STANDARD OF EXCELLENCE



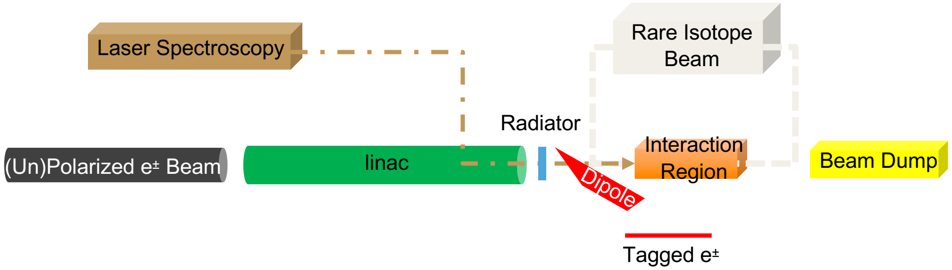
Disclaimer: project not endorsed by the FRIB laboratory

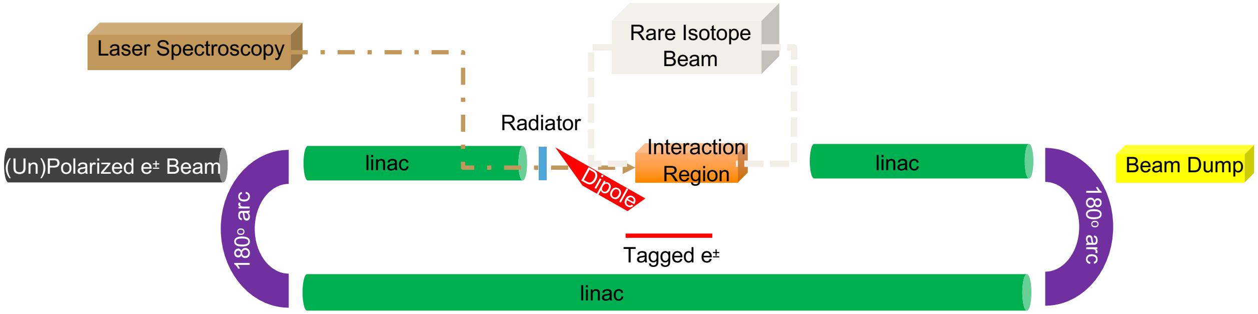
Trap Based Concept





Recirculated Based Concept



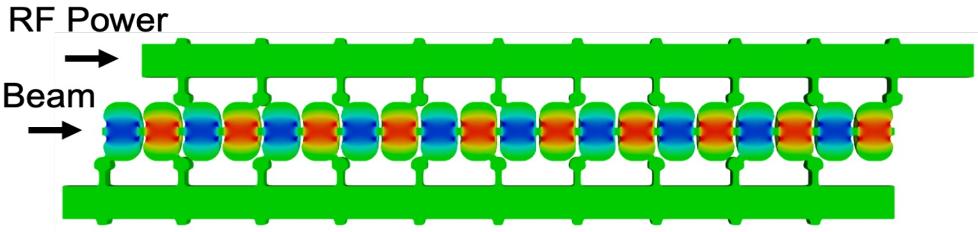


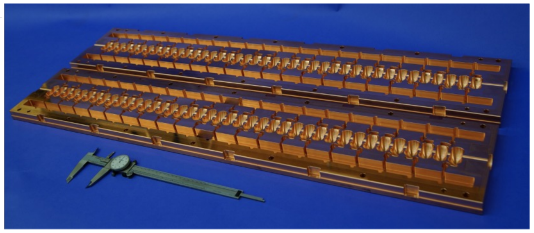
Accelerator Technology

Courtesy J. Maxson

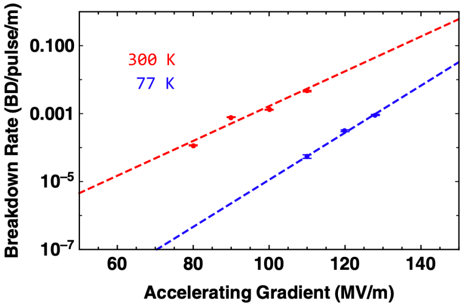
Breakthrough in the Performance of RF Accelerators

- Distributed power to each cavity from a common RF manifold (no on-axis coupling)
- 1-m structure to achieve 150 MeV from 150 keV injection
- Full system design requires modern virtual prototyping



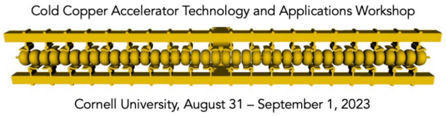


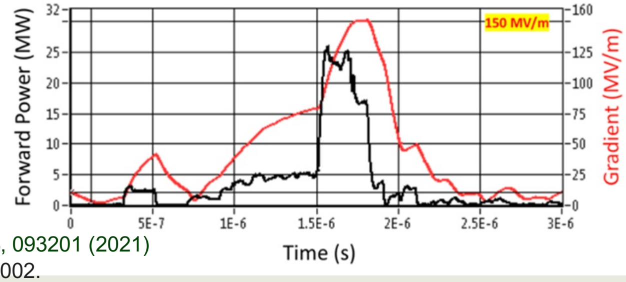
Tantawi, Sami, et al. *PRAB* 23.9 (2020): 092001



Cool/Cold Copper Cavity (C^3)

- Operation at cryogenic temperatures (LN_2 ~80-K)
- Robust operations at high gradient (up to 120 MeV/m)
- Frequency: C-band 5.712 GHz
- Results driven by SLAC, UCLA, LANL, Radiabeam

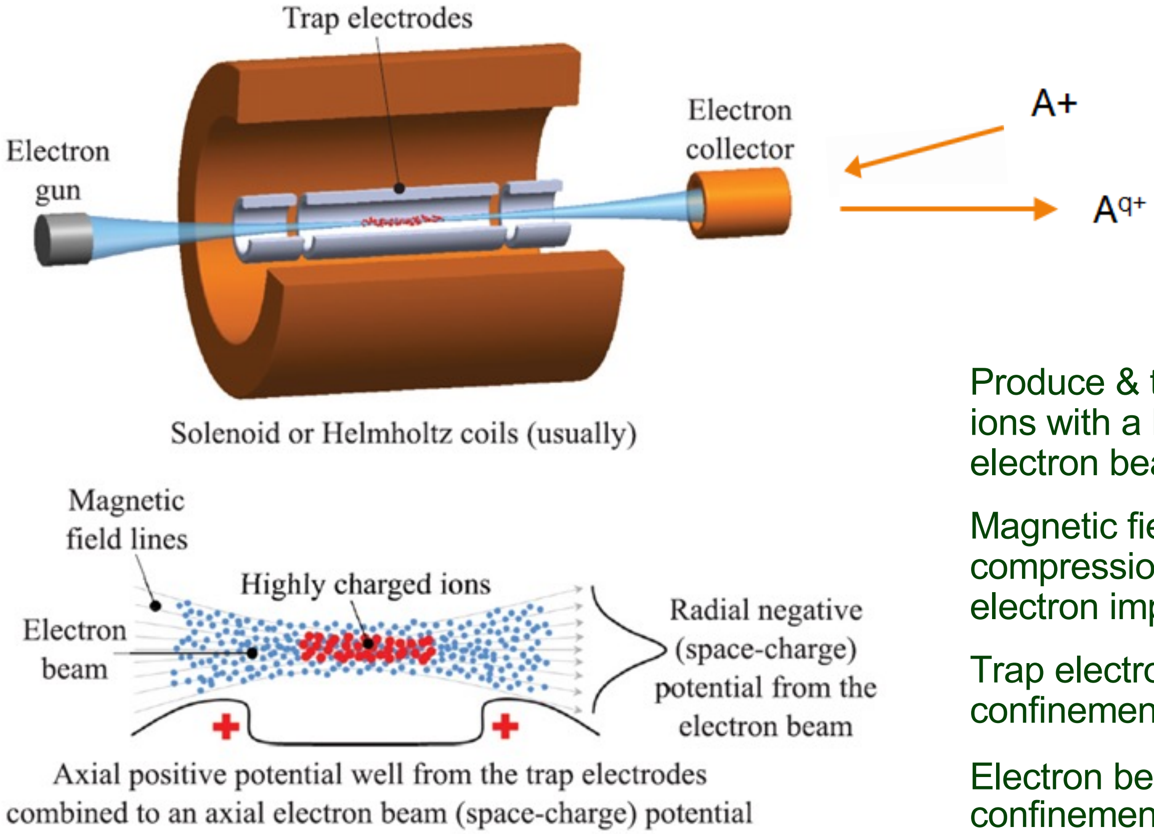




M. Nasr et al., Phys. Rev. Acc. Beams, **24**, 093201 (2021)
A. D. Cahill et al. *PRAB* 21.10 (2018): 102002.

Working Principle of an EBIS/T

Courtesy A. Lapierre



Produce & trap highly charged ions with a high-current density electron beam

Magnetic field: Electron-beam compression & Ionization by electron impact

Trap electrodes: Axial confinement

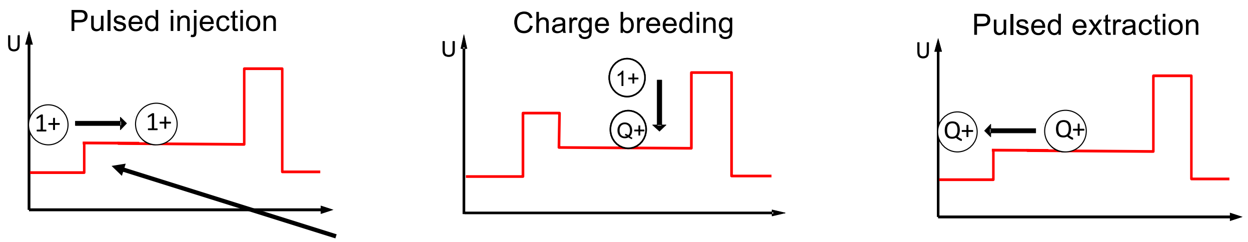
Electron beam: Radial confinement

How do we inject & extract ions?

Two ion injection schemes

Courtesy A. Lapierre

- Pulsed (dynamic ion capture)


Pulsed injection

Charge breeding

Pulsed extraction

Ions axially trapped with potential well created by 2 barriers

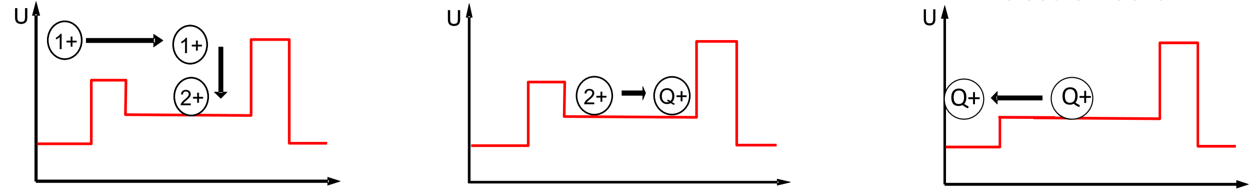
Lower barrier potential

Quasi-continuous

Over-the-potential barrier injection
"Quasi-continuous"

Charge breeding

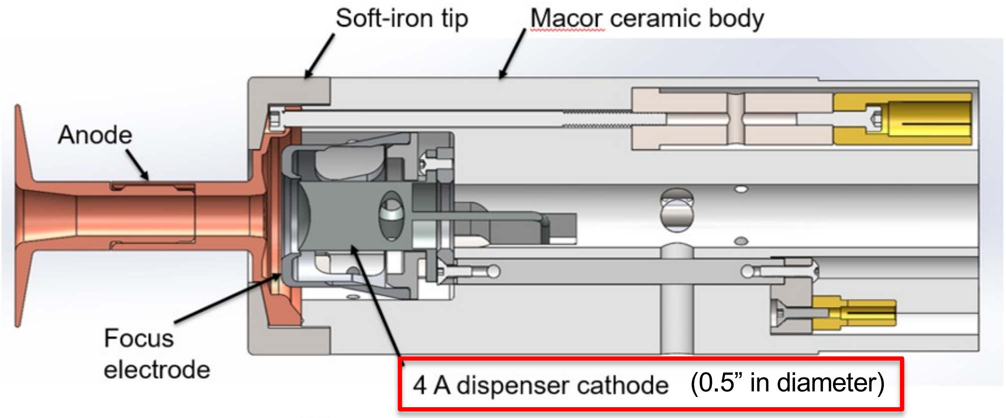
Lower-the-barrier extraction
"Pulsed extraction"



Future Electron-Gun Upgrade for Higher Electron Current

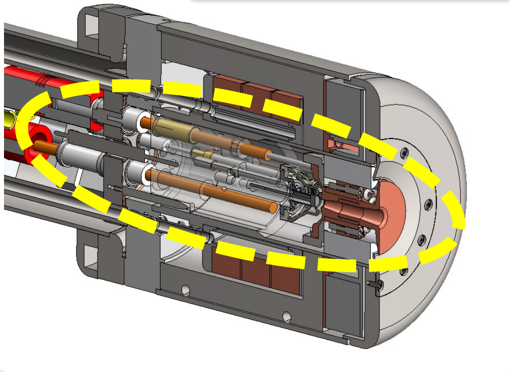
Courtesy A. Lapierre

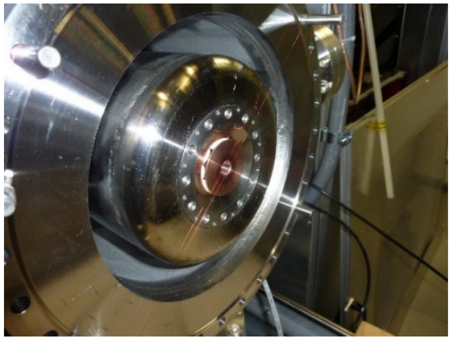
New dispenser cathode modular insert to be placed in the existing EBIT electron gun



4 A dispenser cathode (0.5” in diameter)

- Status
  - Construction completed
  - In commissioning





Expected Intensities from the EBIT Upgrade

Courtesy A. Lapierre

Parameters/Properties	Present e-gun	Upgrade, Phase 1	Upgrade, Phase 2
Cathode diameter (type)	6.35 mm (Ba/W)	12.7 mm (Ba/W)	12.7 mm (Ba/W)
E-beam current	300 – 600 mA	2 A	4 A
E-beam radius	~200 μm	~400 μm	~400 μm
Current density	170 - 340 A/cm^2	432 A/cm^2	864 A/cm^2
Acceptance	12 mm mrad	40 mm mrad	50 mm mrad
Acceptance pulse width	~40 μs	~40 μs	~40 μs
Charge capacity	2E10 e	1E11 e	2E11 e
Max pulsed Ne^{8+} rate	6E9 pps	6E9 pps	6E9 pps
Max pulsed Ar^{16+} rate	1E9 pps	2E9 pps	4E9 pps
Max DC Ne^{8+} rate	2E10 pps	1.5E11 pps	3E11 pps
Max DC Ar^{16+} rate	8E8 pps	7E9 pps	3E10 pps

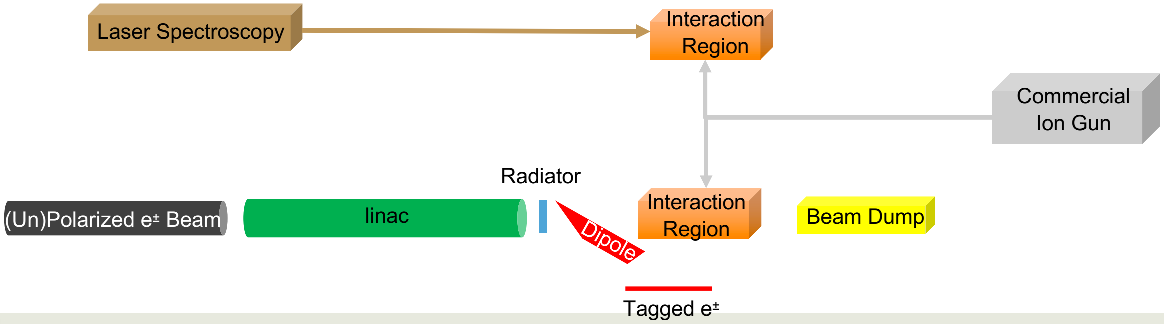
Advanced Rare-isotope for Electron Scattering (ARES) Concept [1]

Highly compact/Low cost

- Space is always an issue!
- There are enough large billion dollar scale projects

Requires training facility

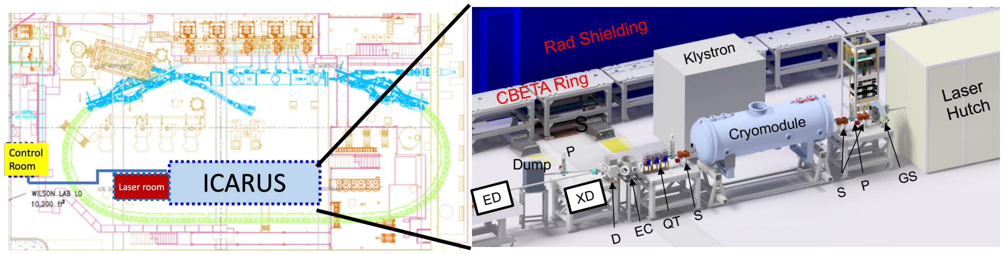
- Blend between electron/rare isotope communities
- Include untaped workforce (US: Minority Serving Institutions)
  - » No DoE lab housed/operated by any MSI
  - » SLAC: Univ. California, Fermilab/ANL: University of Chicago, FRIBL Michigan State …

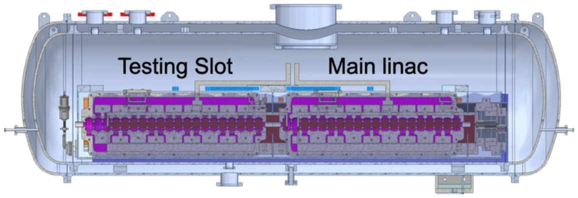


Test/Standalone Facility

NSF/MRI: project

- ICARUS: Instrument for Cryogenic Accelerator Research and Ultrafast Scattering (Fall 2023)
- Response: not funded (October 2024) – preliminary design completed
- Partners: Cornell, SLAC, UCLA, LANL, MSU





Standalone facility at Virginia State University

- Workshop on **January 31-February 1, 2025**
- Petersburg, Virginia

Targets

- Radioactive: San Jose State University
- Polarized targets

google map search

Thank You!

Paul Guèye

T: 517-908-7481

E: gueye@frib.msu.edu