# Overview of Worldwide High Intensity Heavy Ion Linacs

Peter N. Ostroumov

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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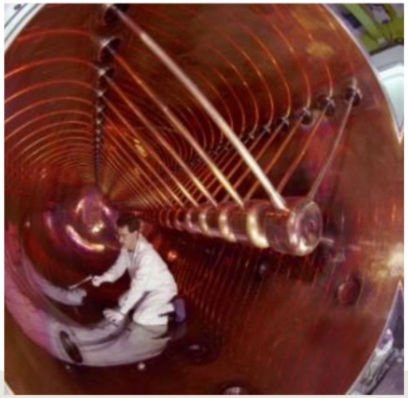
# Outline

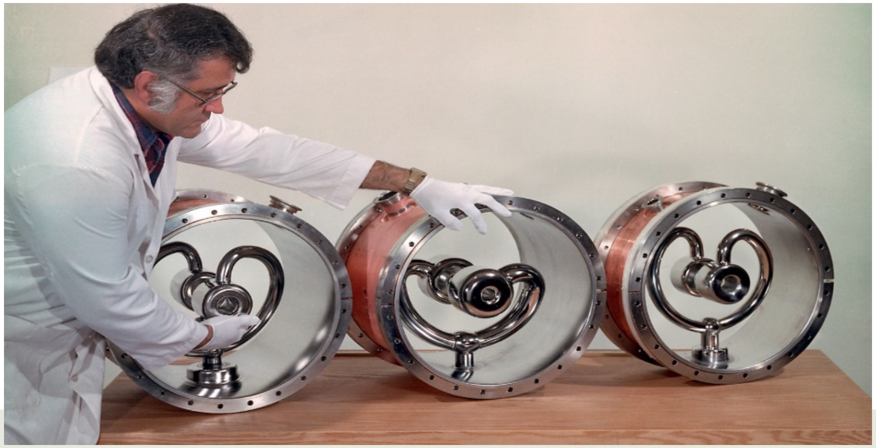
- First heavy ion accelerators
  - Pulsed room temperature – GSI
  - CW superconducting - ANL
- ECR sources
- CW RFQs
- Linac upgrades in GSI
- Compact heavy ion injector to NICA in Dubna
- RIKEN plans
- Progress in RAON
- FRIB
  - Beam acceleration with the first 3 cryomodules
  - Study of accelerated beam properties
  - Energy upgrade plans in FRIB
- Acknowledgments

# First Heavy Ion Accelerators

- UNILAC, GSI, experiments started in 1976
- Pulsed, high intensity, room temperature structure
  - Wideroe, Alvarez
- ~1.5 pmA uranium
- Upgrades: Wideroe structure was replaced with RFQ and IH
- Higher intensities are required for FAIR, ~4 pmA LEBT, ~2 pmA Linac
- CW SC linac is being developed

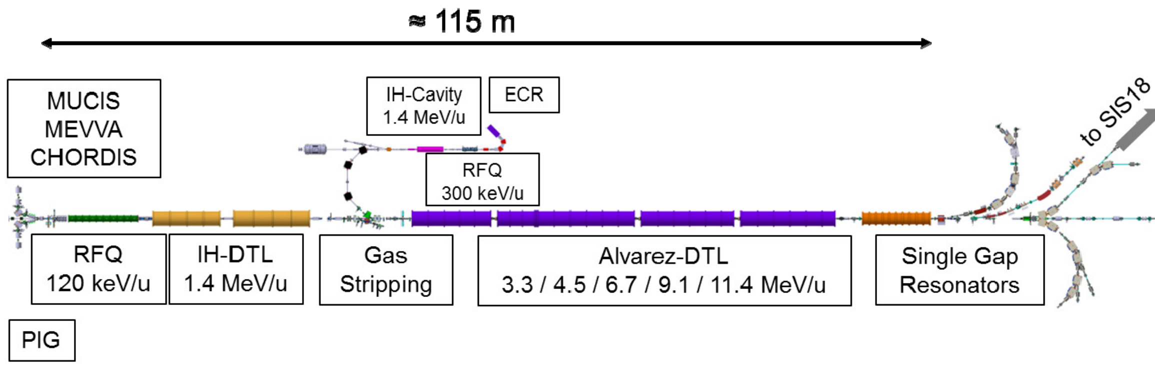


- ATLAS, ANL, experiments started in early 1980s
- CW, 3-4 gap SC resonators
  - Split-ring, 4-gap QWRs
- ~3 pμA medium mass ions
- Upgrades: CW RFQ, 2-gap QWRs, new cryomodules with high performance cavities in separated vacuum



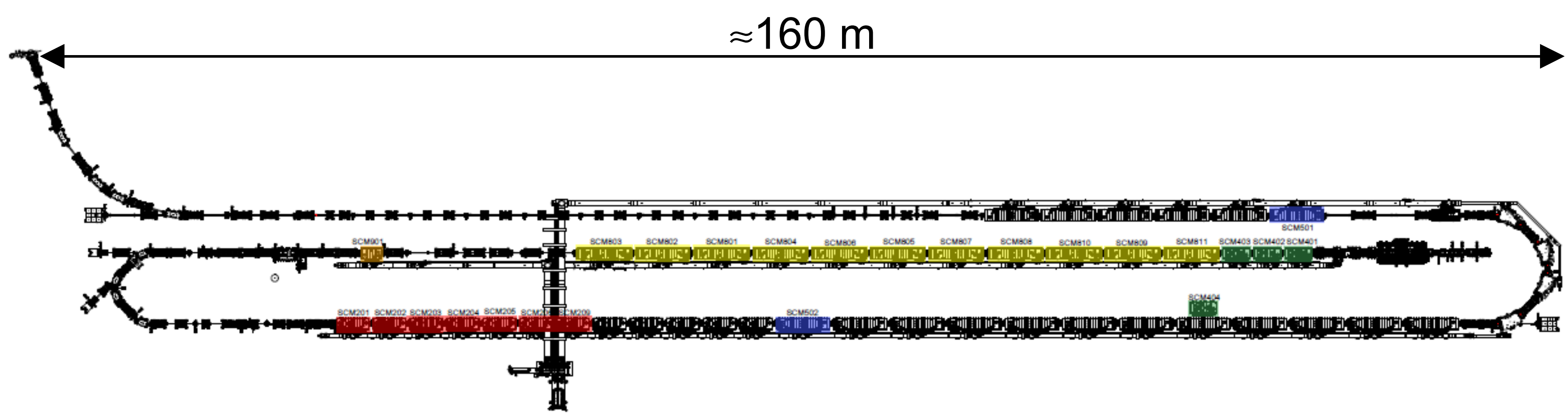
# Modern High Intensity HI Linacs

- UNILAC, Germany: Pulsed ion source, RFQ, IH, Gas stripper, Alvarez, Single Gap



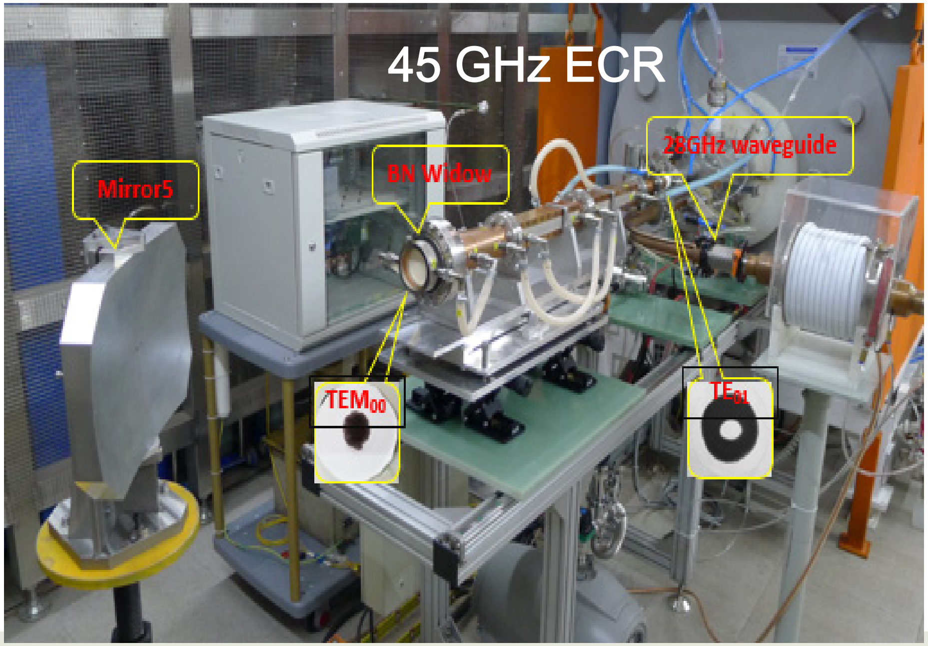

Sascha Mickat, TU2A03 Layout of the New Fair Post-stripper DTL for Intense Heavy Ion Beams

- FRIB, USA: ECR, RFQ, QW SC cavities, Lithium stripper, HWRs



# Most Advanced SC ECRs in IMP, Lanzhou

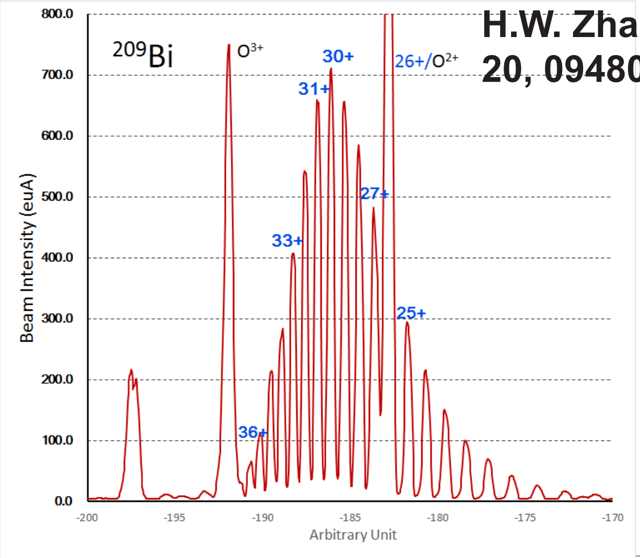
- SECRAL-I and SECRAL-II produced record beam intensities for highly charged heavy ions
  - Innovative SC magnet structure: solenoids are inside the sextupole magnet
- High charge state ion beam production with new microwave coupling
- The first experiments are started with 45 GHz ECRIS
  - Plasma heating with 28 GHz +45 GHz +18 GHz, 45 GHz is applied via optical transmission line

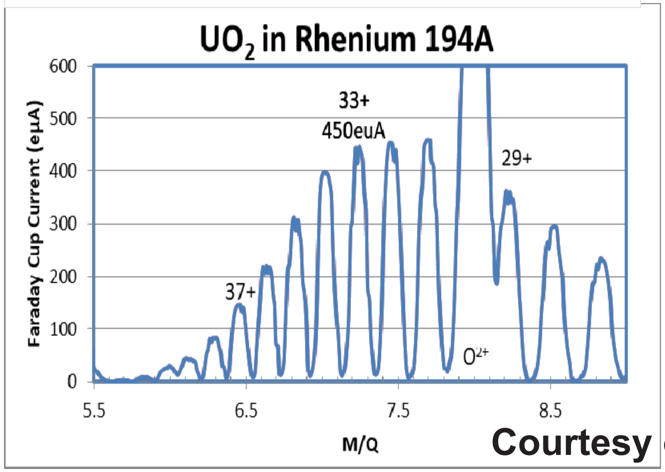
# Recent Performance of ECRs in IMP (SECRAL) and LBNL (VENUS)

| Ion Beam | IMP, eμA | VENUS (eμA) |
|---|---|---|
| $^{16}O^{6+}$ | 6100 | 4750 |
| $^{40}Ar^{12+}$ | 1420 | 1060 |
| $^{40}Ar^{16+}$ | 620 | 523 |
| $^{40}Ar^{18+}$ | 15 | 4 |
| $^{40}Ca^{11+}$ | 710 | 854 |
| $^{40}Ca^{14+}$ | 270 | 285 |
| $^{86}Kr^{18+}$ | 1020 | 770 |
| $^{86}Kr^{28+}$ | 146 | 100 |
| $Xe^{26+}$ | 1100 | |
| $Xe^{30+}$ | 320 | 330 |
| $Xe^{42+}$ | 15 | 6 |
| $^{209}Bi^{31+}$ | 680 | 300 |
| $^{209}Bi^{50+}$ | 10 | 27 |
| $^{238}U^{33+}$ | 202 | 440 |

Record intensities are shown in red




H.W. Zhao,et.al. PRAB, 20, 094801 (2017)




Courtesy of D. Xie (LBNL)

http://icfa-bd.kek.jp/Newsletter73.pdf, Ion Sources, Issue Editors: G. Machicoane and P. N. Ostroumov

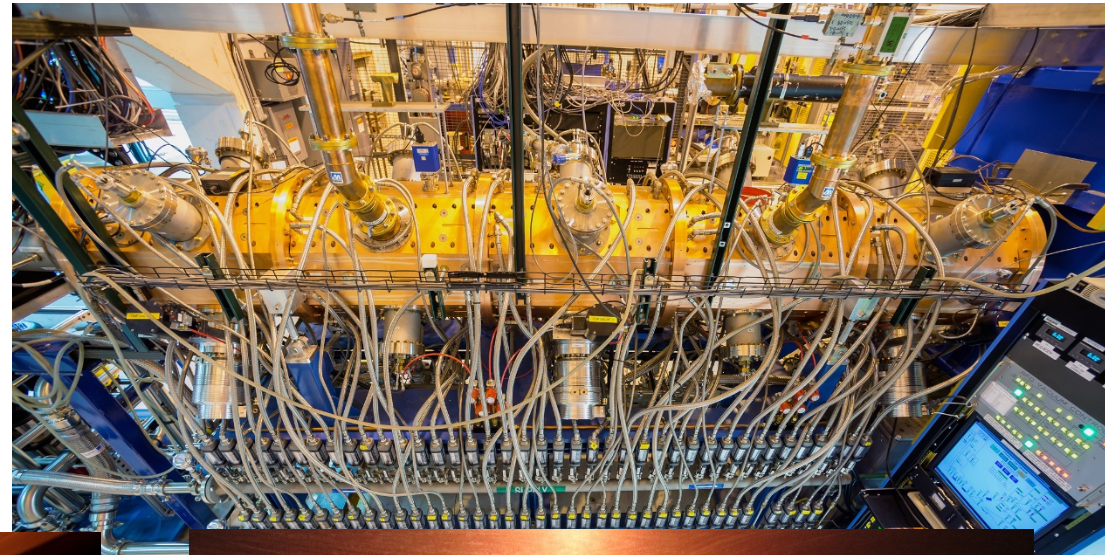
# CW RFQs,

| | ANL | FRIB | GANIL | RAON | IMP |
|---|---|---|---|---|---|
| f, MHz | 60.625 | 80.5 | 88.0 | 81.25 | 81.25 |
| Type | 4-vane with windows, brazed | 4-vane, brazed | 4-vane, bolted | 4-vane, brazed | 4-vane, brazed |
| A/q | 7 | 7 | 3 | 7 | 6.8 |
| V, kV | 70 | 60-115 | 100-113.5 | 50 – 138.5 | 70 |
| $K_p$ | 1.42 (1.6) | 1.63 | 1.65 | 1.7 | 1.55 |
| P, kW | 60 | 90 | 177 | 94 | 57 |
| L, m | 4 | 5 | 5 | 5 | 6 |
| W, keV/u | 300 | 500 | 750 | 500 | 500 |
| Status | 6 years in operation, >5000 h/year | Not yet in routine operation at full design power | | | |

- Significant issue with CW RFQs: if RFQ trips and does not recover quickly in several seconds, it takes long time to resume operation, ~20-40 min
- For highest operational reliability $K_p$ should be as low as possible

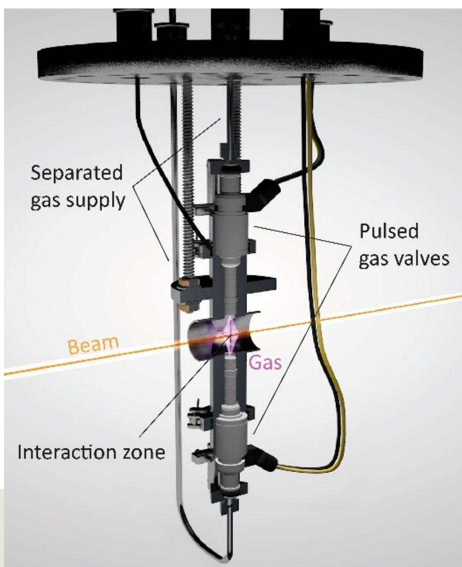
# Long Term Operation of ANL CW RFQ

- This RFQ is with trapezoidal modulation
- Discharge traces are everywhere including low field areas, K<1.4
- Very reliable in operation
- Recommendation: keep $K_p$ below 1.5

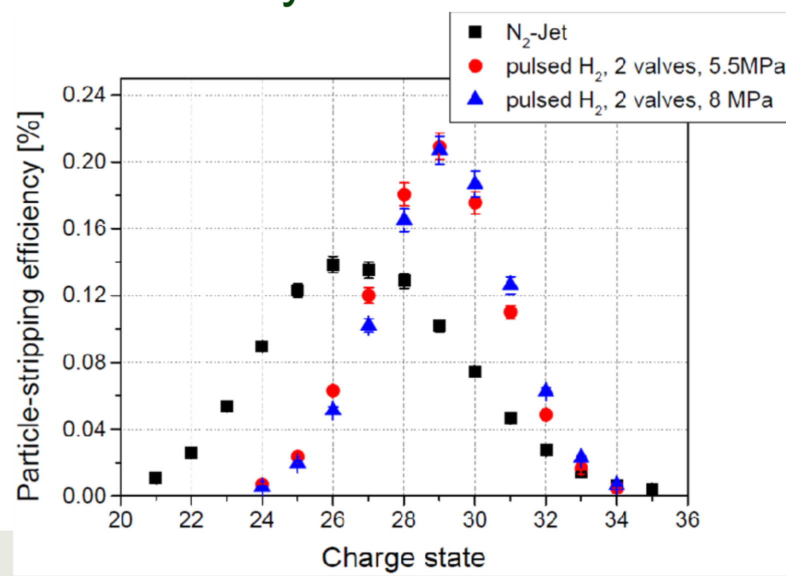


# Recent Advances in GSI

- Increase of stripping efficiency: He gas is much more efficient than $N_2$
- Development and test of 4D transverse diagnostics: determine 4x4 beam matrix using rotatable about Z-axis slit-multiwire system
- Transverse emittance re-partitioning for better injection into synchrotron
- Proof of $4^{th}$ order space charge resonance in a linac
- Experimental varification of Hofmann's charts
- Improved performance of the high current Injector
- SC cavity development
- First beam tests with a CW-Linac crossbar H-Mode cavity



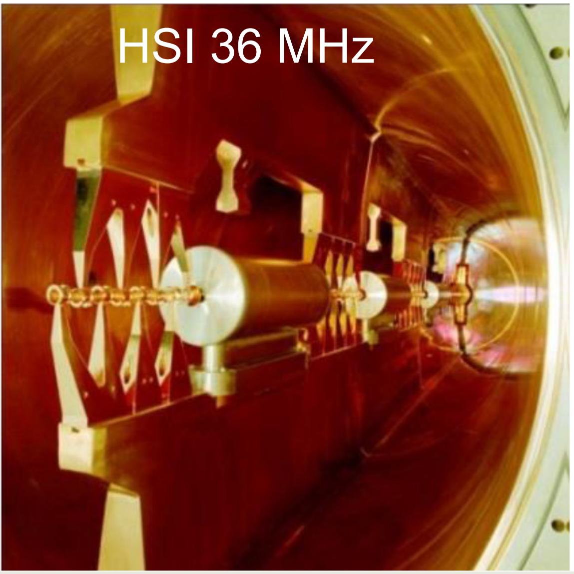

Peter Gerhard, FR1A05 Development of Pulsed Gas Strippers for Intense Beams of Heavy and Intermediate Mass Ions

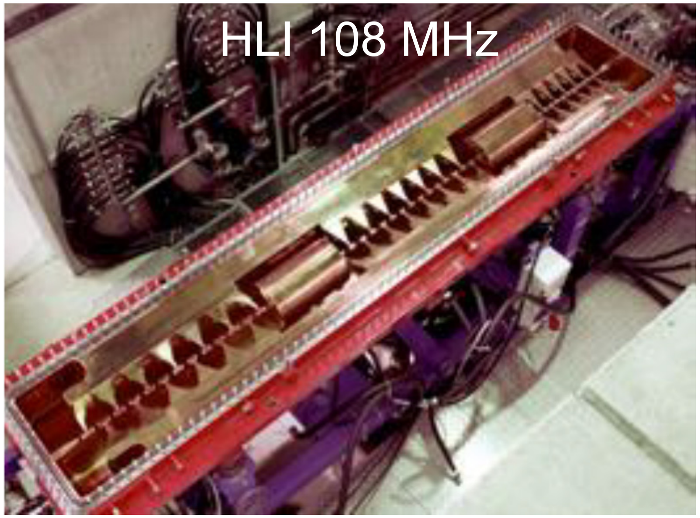


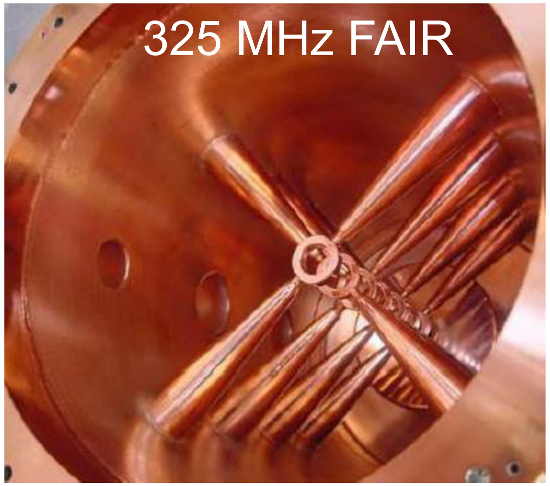
# Development of Accelerating Structures at GSI & University of Frankfurt

- Development of IH (interdigital H-type) and CH (cross-bar H-type) structures
  - Very high shunt impedance for $\beta \leq 0.3$
- Superconducting CH structures
  - Beam acceleration is demonstrated
- UNILAC high intensity performance:
  - LEBT: ~4pmA uranium
  - HIS (high current injector): ~2 pmA
  - Post-stripper: ~0.5 pmA
  - Replace Alvarez DTL


Winfried A. Barth, TU2A01 First Acceleration of Heavy Ion Beams with a Superconducting Continuous Wave HIM/GSI CW-linac

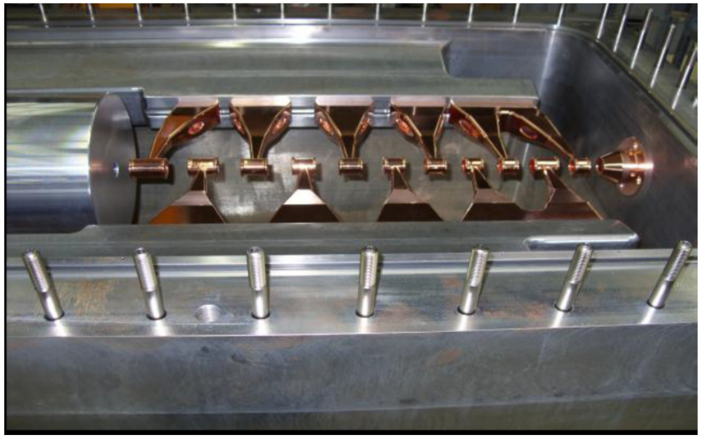


# NICA Injector Linac, Dubna

- Nuclotron-based ion collider
- Combination of RFQ and IH cavities with triplet focusing inside the resonator
  - RFQ, 100 MHz, IH – 200 MHz
  - In operation since 2016
  - Pulsed, low duty cycle linac
- Designed and built by a vendor related to University of Frankfurt
- Similar heavy ion accelerators have been installed at CERN and BNL

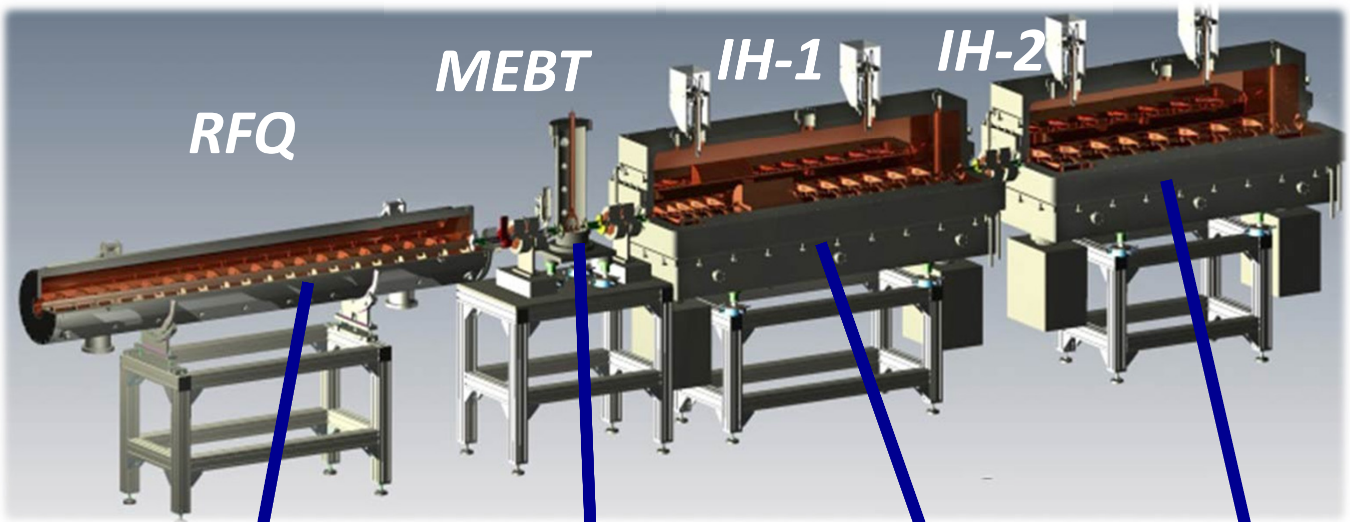


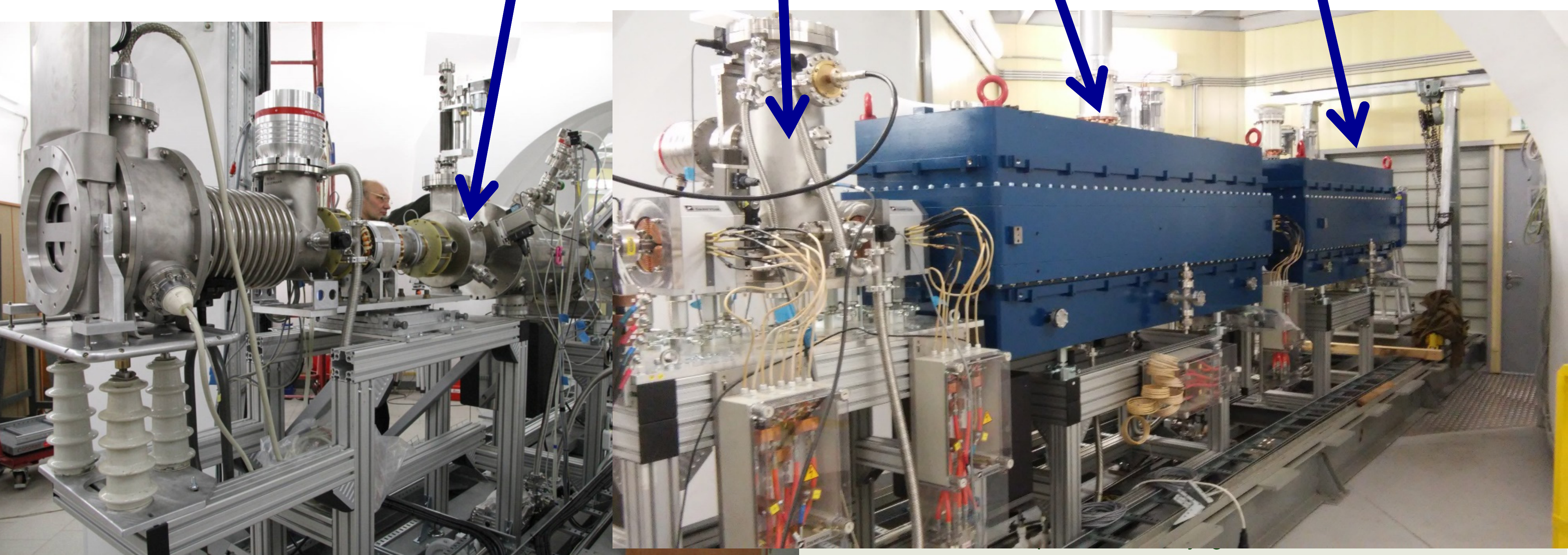
| | |
|---|---|
| q/A ratio | 0.16 ÷ 1 |
| Injection energy, MeV/u | 0.017 |
| Extraction energy, MeV/u | 3.2 |
| Frequency, MHz | 100.625 |
| Linac beam repetition rate | up to 4 |
| Peak current, mA | 10 |
| Pulse duration, μs | up to 30 |
| Normalized (90%) emittance_inj, π mm mrad | 0.15 |
| Normalized (90%) emittance_extr, π mm mrad | 0.8 |
| Energy spread, keV/u | 25 |
| Transmission, % | 91 |
| Length including LEBT & MEBT, m | ~ 11 |

# NICA Injector

- In operation since 2016

Andrey Butenko, TH1P02 Injection Complex Development for the NICA-project at JINR



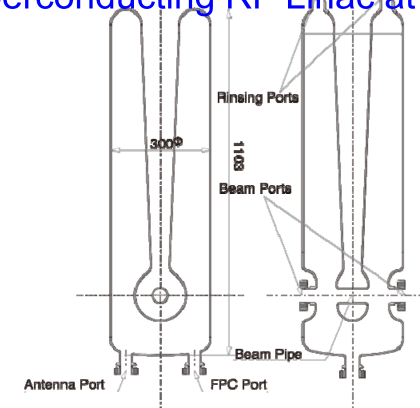
# RIKEN

Naruhiko Sakamoto, WE2A03 Construction Status of the Superconducting RF Linac at RIKEN RIBF

- Production of super-heavy elements
- Nihonium

$$^{70}Zn + ^{209}Bi \rightarrow ^{278}Nh + n$$

- 0.47 pμA on target
- Energy upgrade with SC cavities



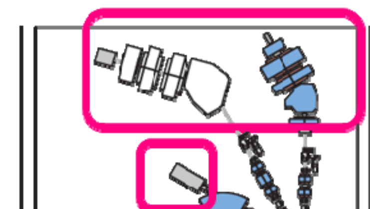

2019

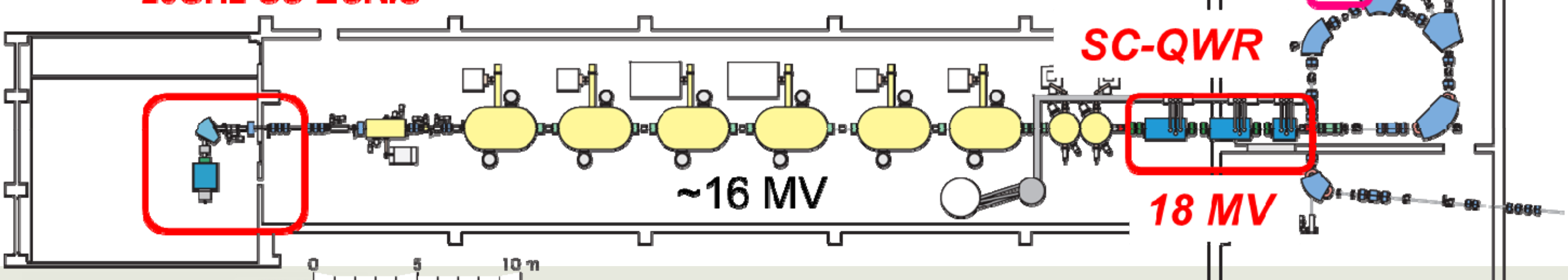
E: 6.5 MeV/u for M/q=5 → *Super Heavy Elements: Z ≧ 119*

7.5 MeV/u for M/q=4

12 MeV/u for M/q=2 → *RI production for medical research*

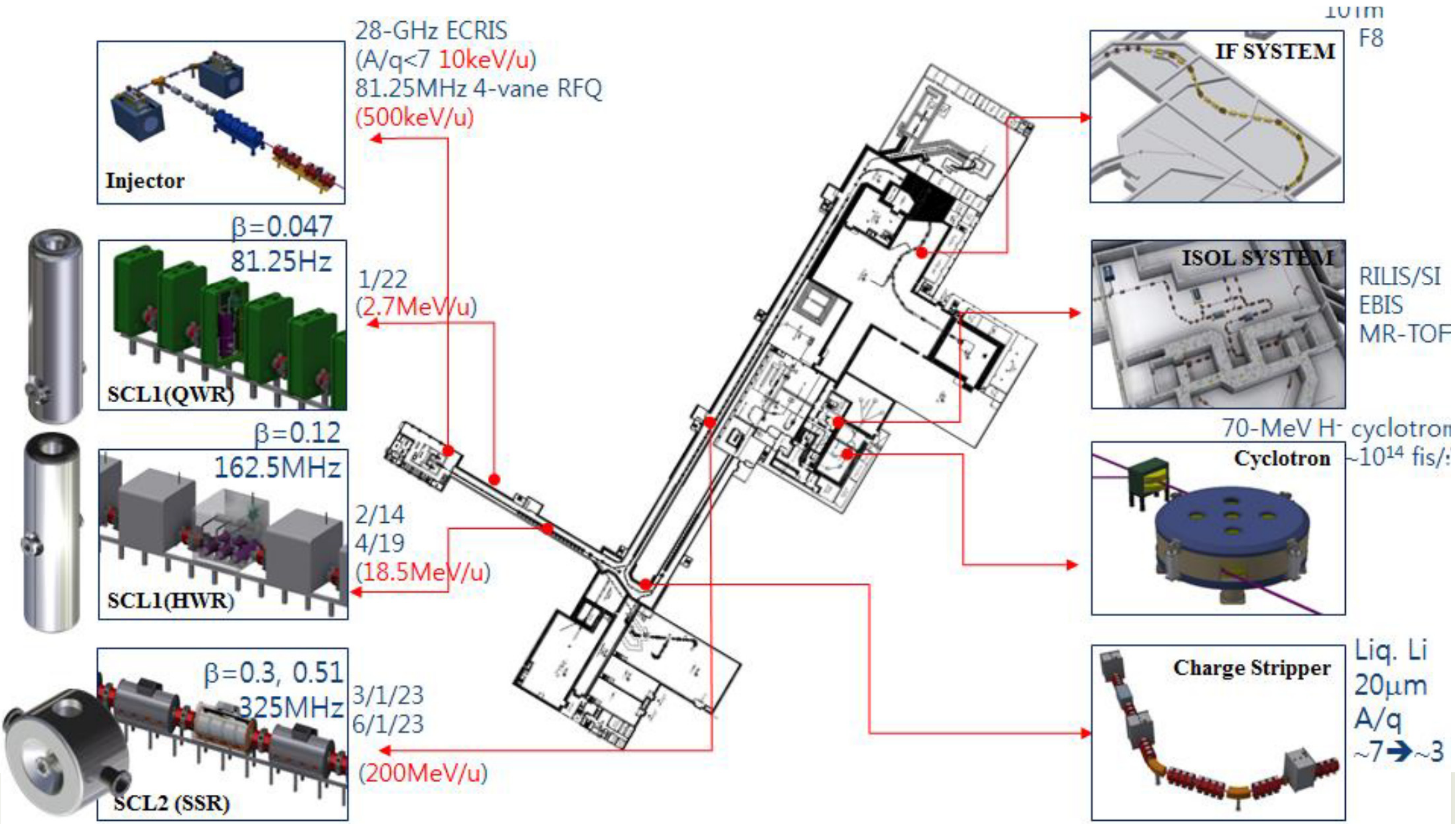
*28GHz SC-ECRIS*





# RAON at Daejeon

- 200 MeV/u uranium, 400 kW.



# RAON at Daejeon

- Construction progress

- 2018.11: Starting mass production of QWR, HWR cavities
- 2019.04: Starting SCL3 Installation
- 2020.06: Starting Beam Commissioning of SCL3
- 2020.12: Civil Construction Finished
- 2021.10: Starting Beam Commissioning of SCL2
- 2021.12: RISP Construction Phase Finished

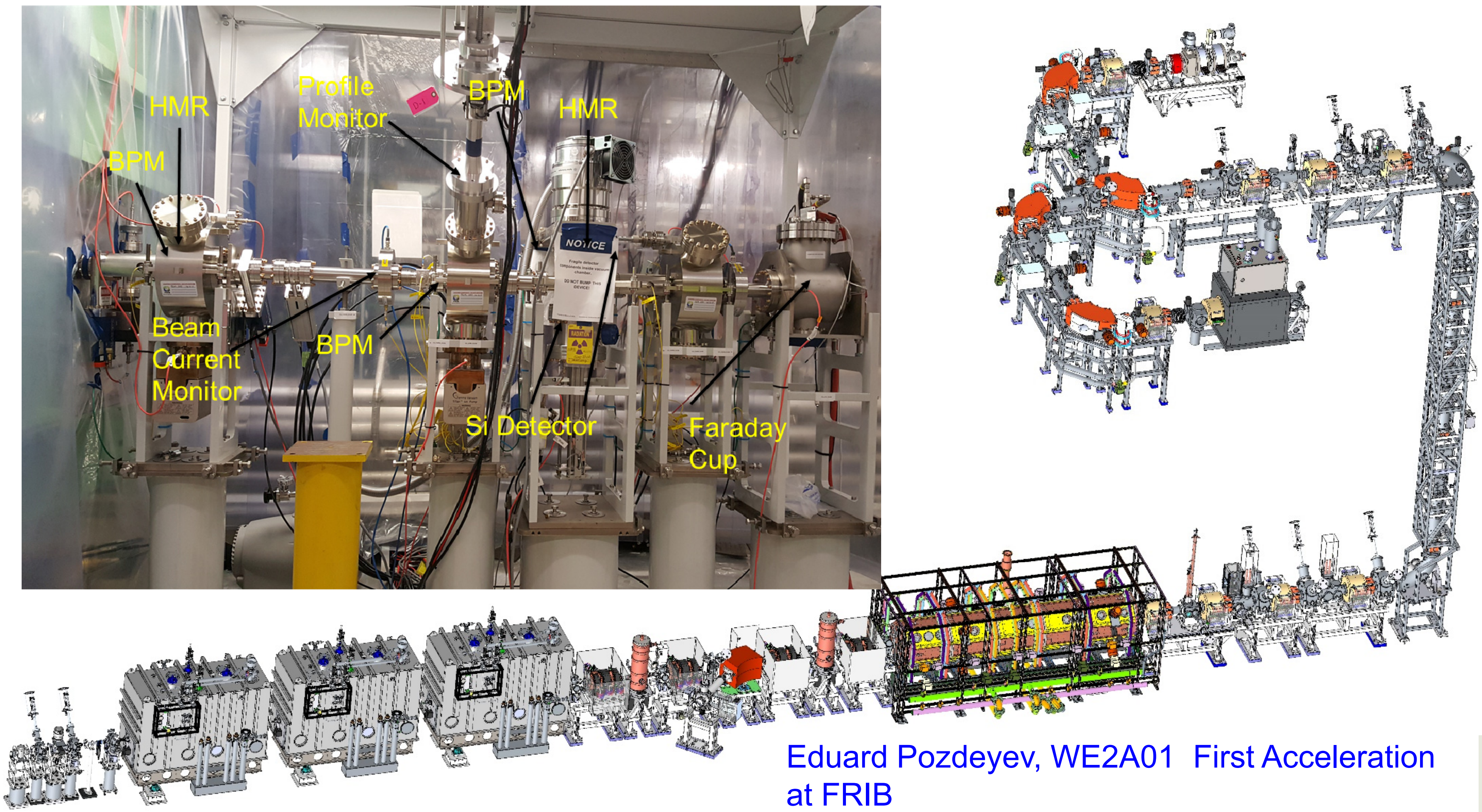
# FRIB Cryomodules in Tunnel

- LS1 cryomodule production is finished
- Module production rate is steady at one per month in the past 12 month
- LS2, LS3 installation is ongoing in the tunnel
- On track to complete all cryomodule assembly work by the end of 2019


Chris Compton, TU1A04 FRIB Cavities and Cryomodule Production

# Beam Commissioning in Three Cryomodules

- Front End including 500 keV/u RFQ and MEBT
- Three cryomodules of $\beta_{OPT}$=0.041 SC cavities: 12 cavities and 6 solenoids
- Diagnostics station



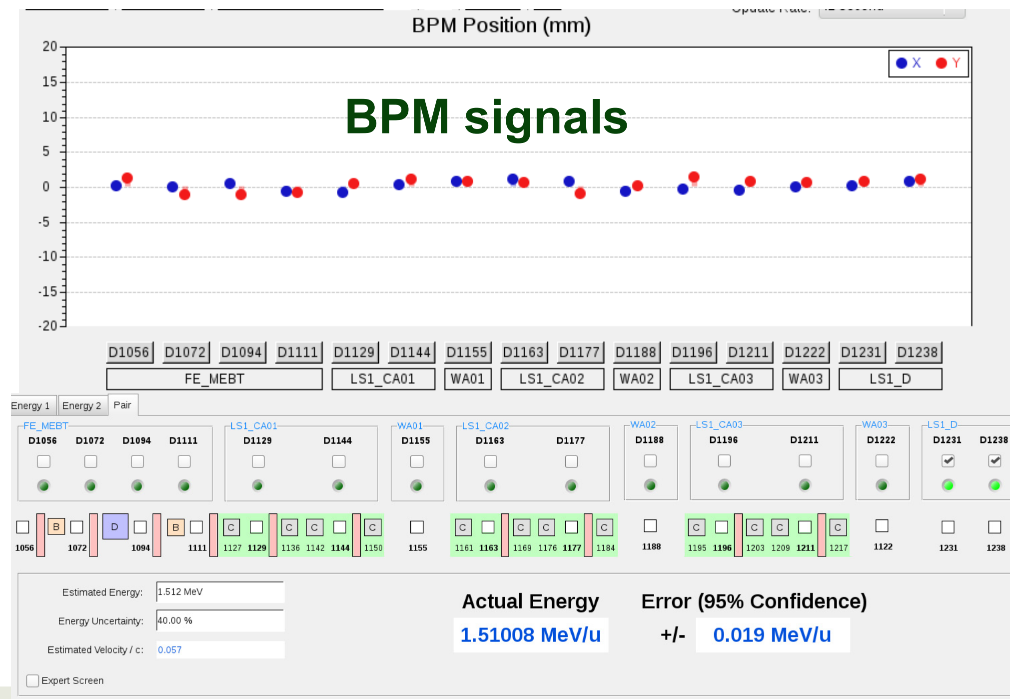

Eduard Pozdeyev, WE2A01 First Acceleration at FRIB

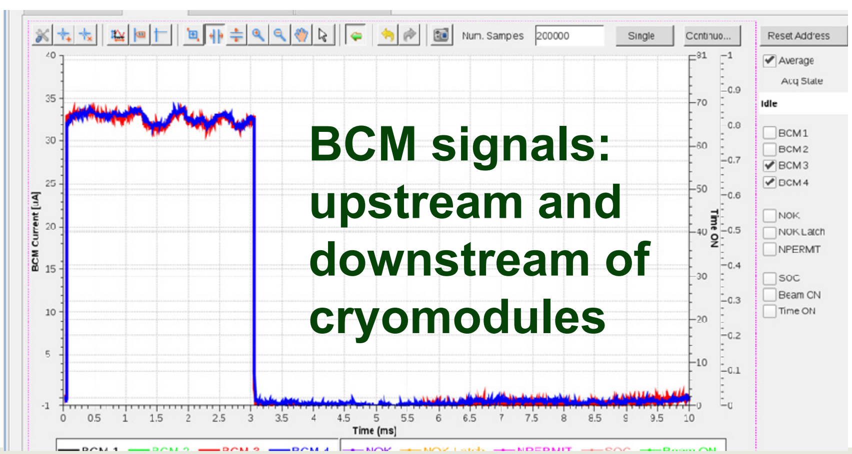
# Main Results of Beam Commissioning

- KPPs for both Ar and Kr beams were met in 3 days of operation
- Ar beam energy in the baseline design is 1.48 MeV/u
  - The beam was accelerated up to 2.3 MeV/u
- Transverse  and longitudinal emittances were measured
- Accelerating gradients of all cavities (SRF and bunchers) were calibrated with beam
- 2 settings of the MHB were tested: maximum transmission and minimum emittance
- Many on-line Python scripts have been developed and applied during 2-week beam studies
- Cavity failure study:  cavity #4 was turned off and setting of cavities #2,3,5,6 were adjusted to provide the design beam energy after the cavity #6
- Machine protection system is tested and activated to run high power beam
  - We worked with pulsed beam created by LEBT chopper
- Beam current monitors were crucial to optimize 100% beam transmission and cross-check Faraday Cups
- All BPMs were calibrated for absolute energy measurement using any pair of BPMs

# Acceleration of 33 µA Argon Beam

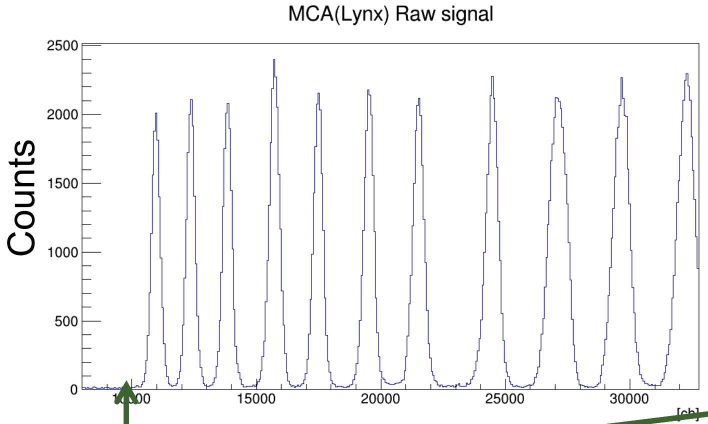
- 33 uA $Ar^{9+}$ accelerated to 1.5 MeV/u with 30% duty factor
- Can produce 38 kW on target if accelerated to the design energy in CW mode
- 3 msec pulse at 100 Hz repetition rate. MPS was activated using differential signals from BCMs
- Further increase of duty cycle was limited by outgassing from FC
- "Halo monitor rings" (HMR) were used as Faraday Cups for "quick" beam tuning during the phase scan:
  no beam losses after tuning
- Absolute beam energy measured with SiD and pair of BPMs



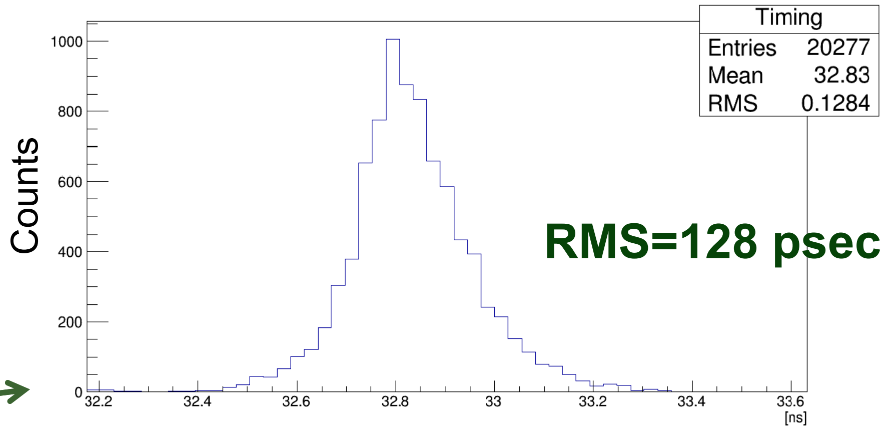



# Beam Measurement Results

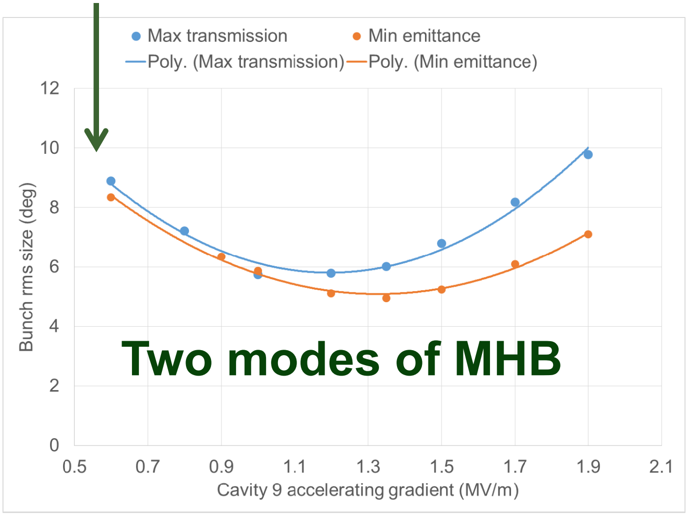
## Argon beam energy after each cavity



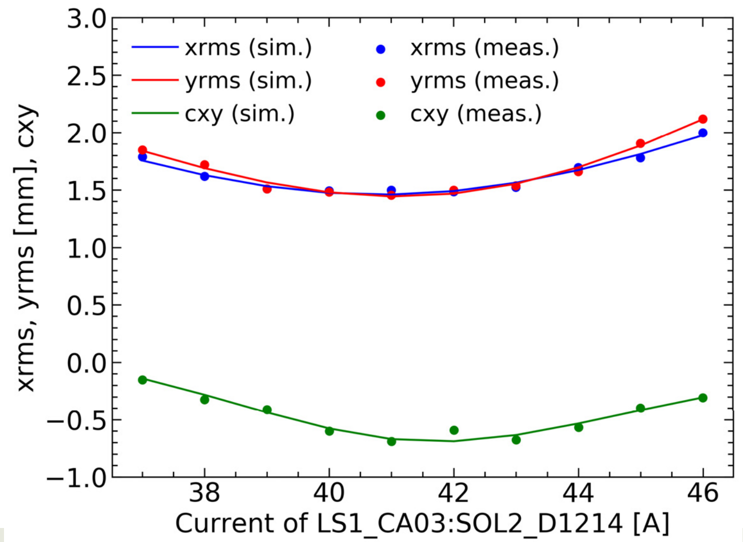

## Bunch shape




## Silicon detector

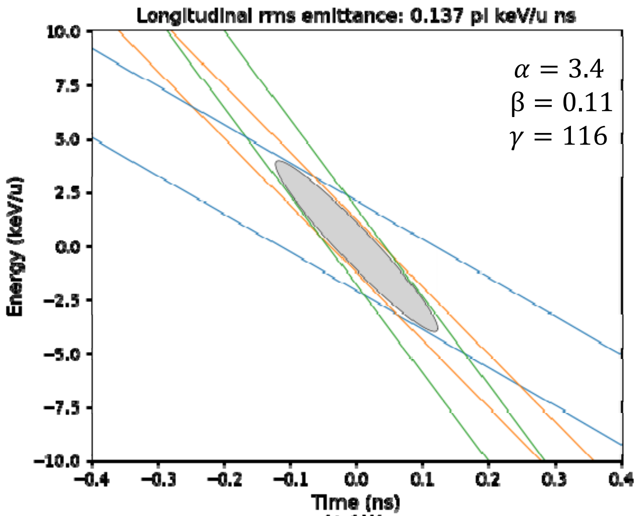


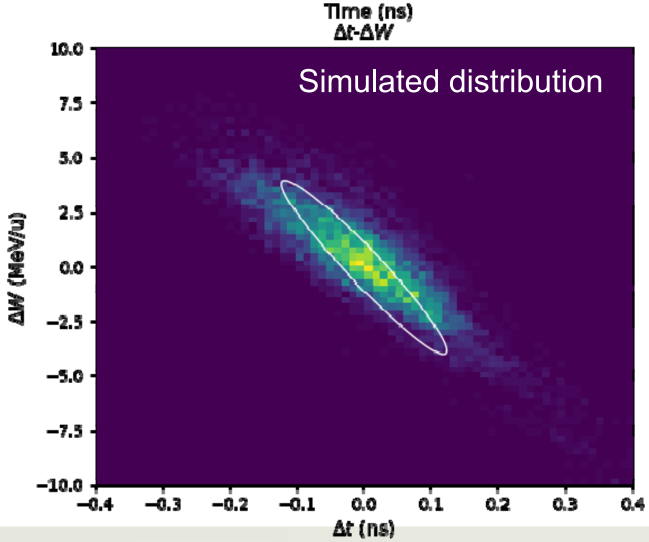

## Solenoid scan, profile monitor



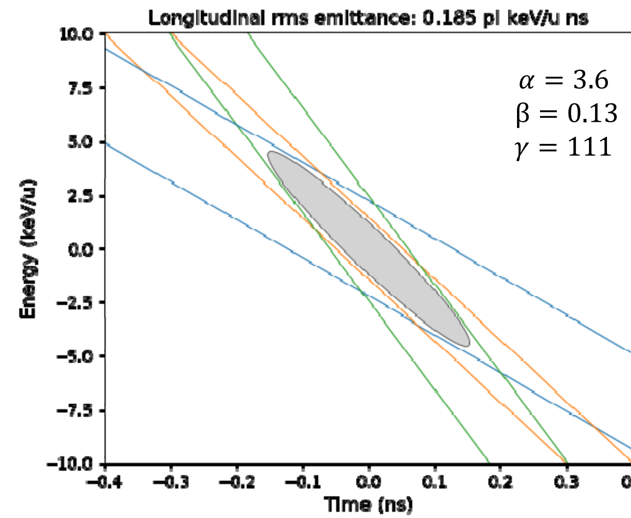
# Longitudinal RMS Emittance from Bunch Shape Measurements

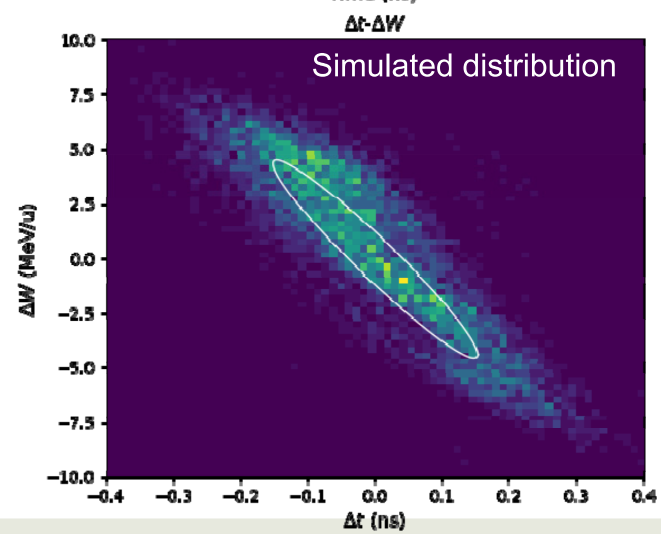
## Minimum long. emittance tune



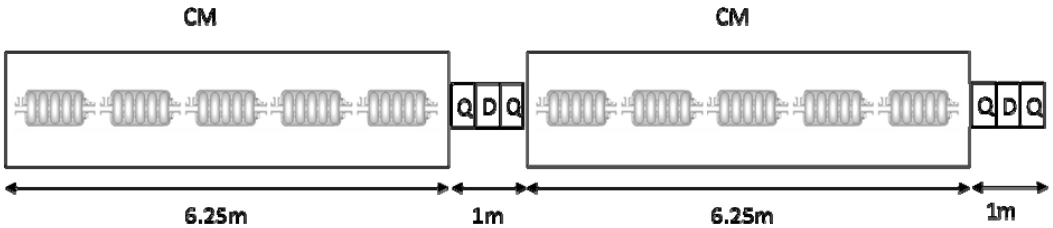

## Maximum beam transmission tune



# Planning for 400 MeV/u Uranium in FRIB

- We launched FRIB energy upgrade R&D
- Elliptical SC cavities




## Cavity & cryomodule parameters

| | |
|---|---|
| Frequency (MHz) | **644** |
| $\beta_{opt}$ | **0.65** |
| Number of cells | **5** |
| $L_{eff}$, (cm) | **71** |
| $V_0$ (MV) | **12.4** |
| Expected surface resistance (nΩ) | **5** |
| Dynamic heat load per cavity at 2K (W) | **17.1** |
| Number of cryomodules | **11** |
| Number of cavities per cryomodule | **5** |
| Number of cavities required for FRIB upgrade | **55** |
| Length of the focusing period (cryomodule plus warm section) (m) | **7.25** |
| Total dynamic heat load at 2K in upgraded segment of FRIB linac (W) | **~940** |

# Acknowledgments


- Many thanks to my colleagues for their contribution to this presentation

  - Winfried Barth, GSI-HIM, Darmstadt, Germany
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  - Dr. Anatoly Sidorin, JINR, Dubna, Russia
  - Daniel Xie, LBNL, USA
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