CW heavy ion accelerator with adjustable energy for material science

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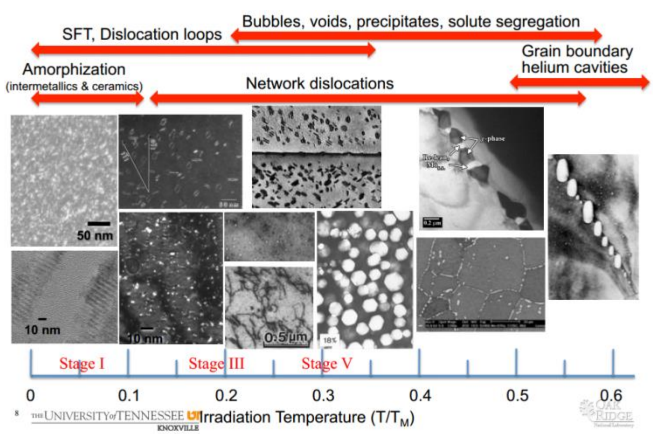
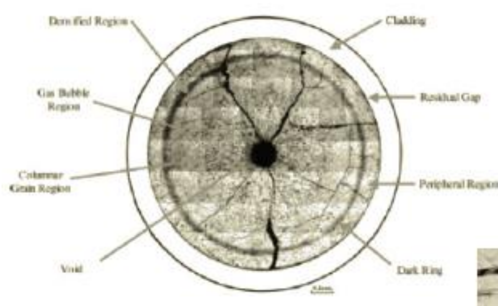
Motivation

- More advanced nuclear materials are needed to increase tolerance to accidents, extend fuel burn-up and reduce facility costs.
- A facility that can imitate the fission products damage to the materials in nuclear reactors, but at much higher rates, is required.
  - Irradiation introduces a large population of defects in a material
  - Fuel is subjected to ~1 displacement per atom (dpa) per day in reactors
  - Required doses (400-2000 dpa) can be accumulated in convenient reactors in 3-10 years





Fuel cracking

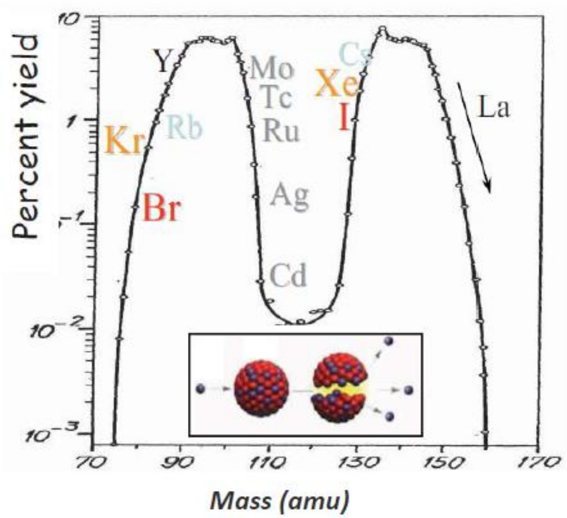
Stress corrosion cracking

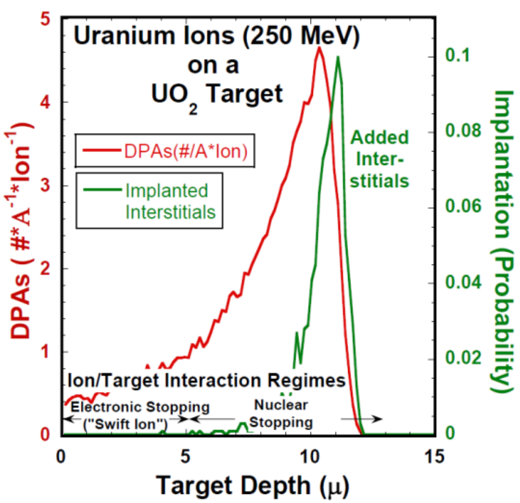
Ref: S. Zinke "Comments on demo designs and issues", FPA 13 talk, Washington DC

Requirements

Such a facility should:

- Accelerate heavy ions to energies ~1 MeV/u *(fission products)*
- Deliver mixed beams with same q/A
  - e.g. $^{86}Sr^{15+}$ and $^{132}Xe^{23+}$
- Provide beam penetration into samples to avoid surface effects
- Separate damage and interstitial effects
- Provide enough beam current density for rapid damage accumulation

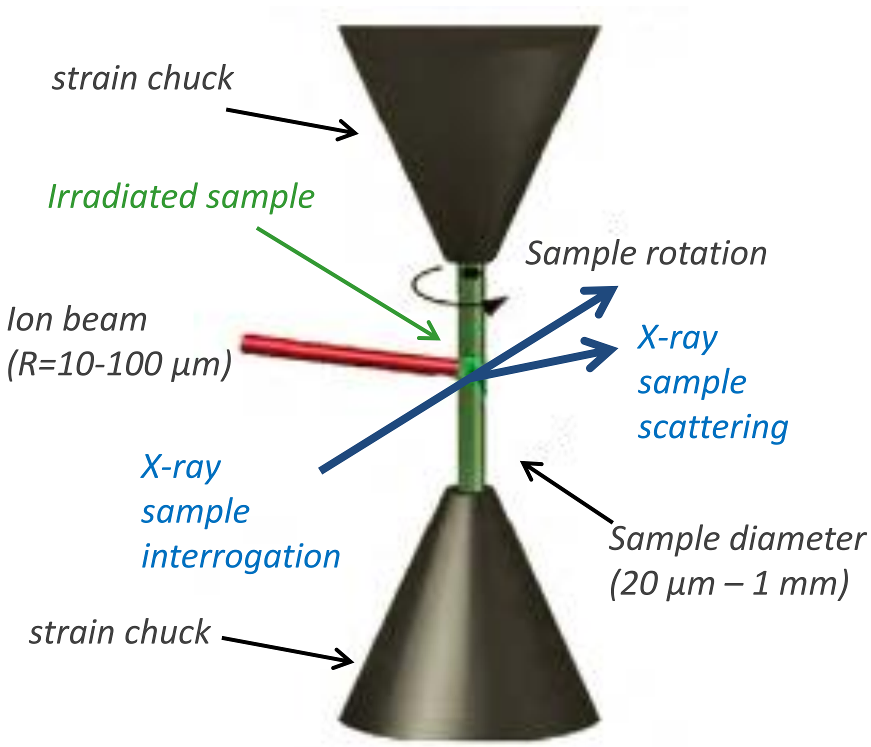




Ref: www.ne.anl.gov/XMAT

XMAT Facility

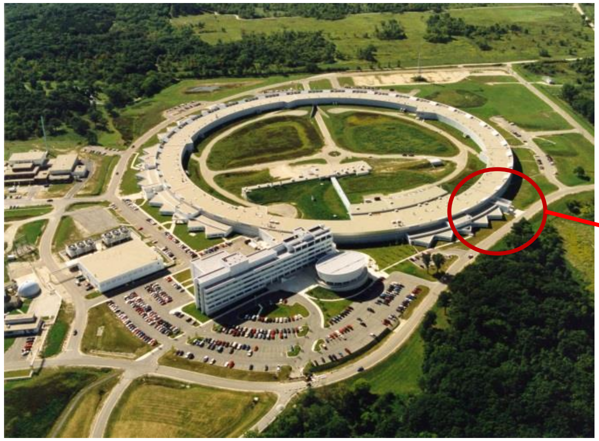
- The XMAT facility will combine the relatively high energy ion acceleration capability with the high-energy X-ray analysis capability of the Advanced Photon Source (APS) to enable rapid in-situ analysis of ion radiation damage in material

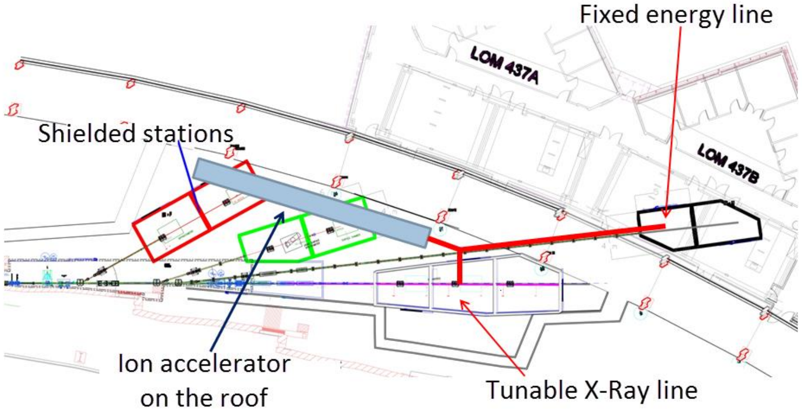


- High-energy heavy ion irradiation (e.g. 1.2 MeV/u)
- Material studies beyond surface effects.
  - According to SRIM all ions with energy ~1 MeV/u penetrate ~10 microns inside UO_2 sample
- High damage doses and rates allow rapid screening
  - 25 – 200 dpa/hour
- Possibility to follow all aspects of radiation damage to materials in nuclear reactors
  - Several fission fragments
  - Irradiation, strain and temperature loads
  - Focused or uniform damage
- In situ X-ray analysis!

Advanced Photon Source

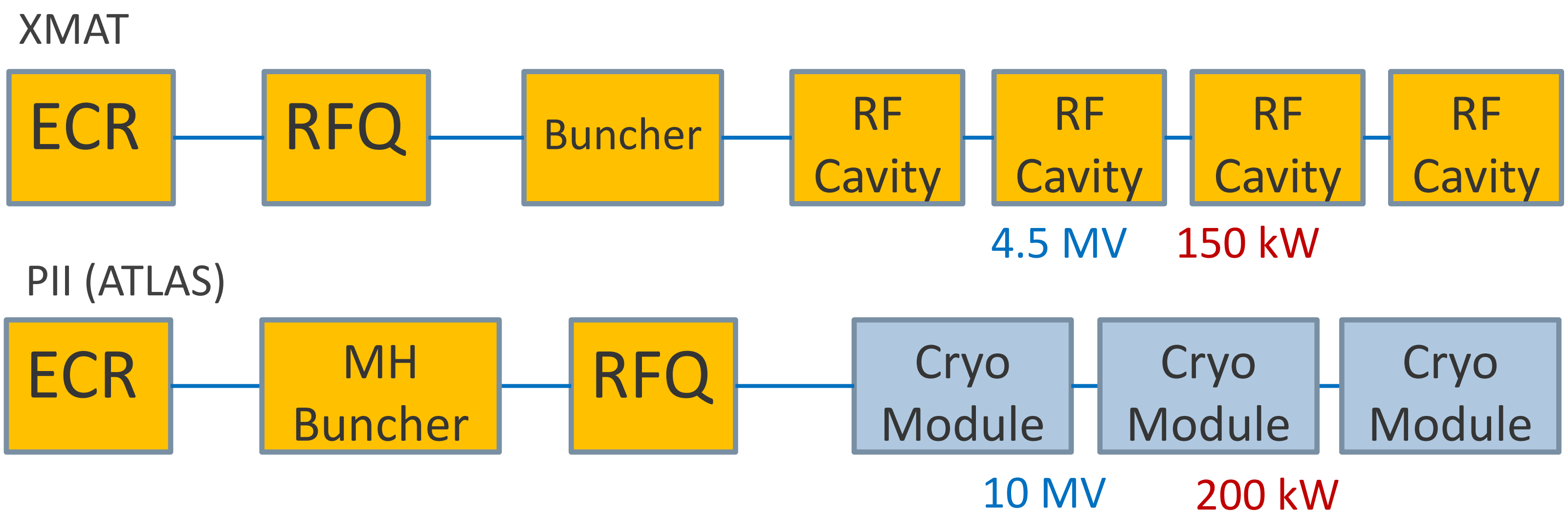
- Ex-situ analysis only allows to study the damage effects, not understand the damage process
- Argonne National Laboratory has a unique tool for in situ microscopic analysis of radiation damage process – Advanced Photon Source





- Argonne Team: **Michael Pellin** (PSE), **Jon Almer** (APS), **Tom Ewing** (NE), **Hawoong Hong**, (APS), **Meimei Li** (NE), **Marius Stan** (NE), **Latif Yacout** (NE), **Di Yun** (NE) + others

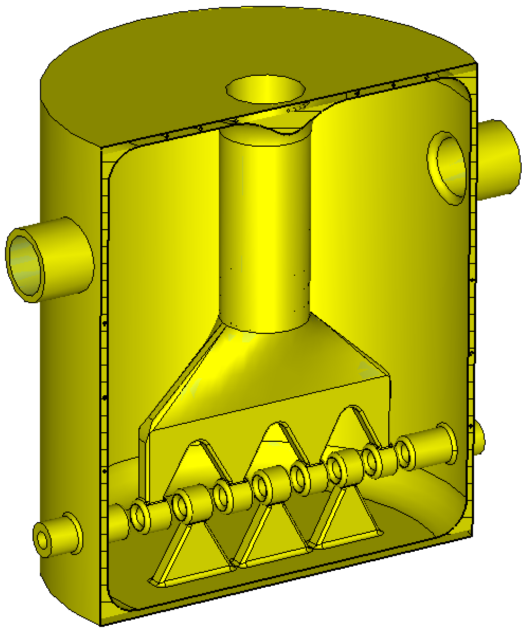
Normal or Superconducting Linac?



- Transition energy between normal- and super-conducting sections in a CW linac depends from the mass-tocharge ratio of the beam
- Our comparison of NC and SC versions in the energy range from 300 keV/u to 1.2 MeV/u for A/Q=5 shows
  - Wall plug power is comparable
  - The capital cost is much lower for a NC linac
  - Operational costs are less for a NC linac
- Normal conducting linac in this energy range is much more cost-efficient

High shunt impedance NC CW structures

- Efficient multi-gap QWRs were designed
- Similar accelerators were built at RIKEN and TRIUMF



Accelerator	XMAT	RIKEN	TRIUMF
Type	QWR	QWR	IH
Frequency, MHz	60.625	36.5	105
Number of cavities (+ bunchers)	4 (+1)	3 (+1)	5 (+7)
Voltage gain, MV	4.5	4.06	8.37
Total RF power, kW	56.7	34.9	117.6
Length*, m	3.1	3.5	5.9

* Total length of RF cavities

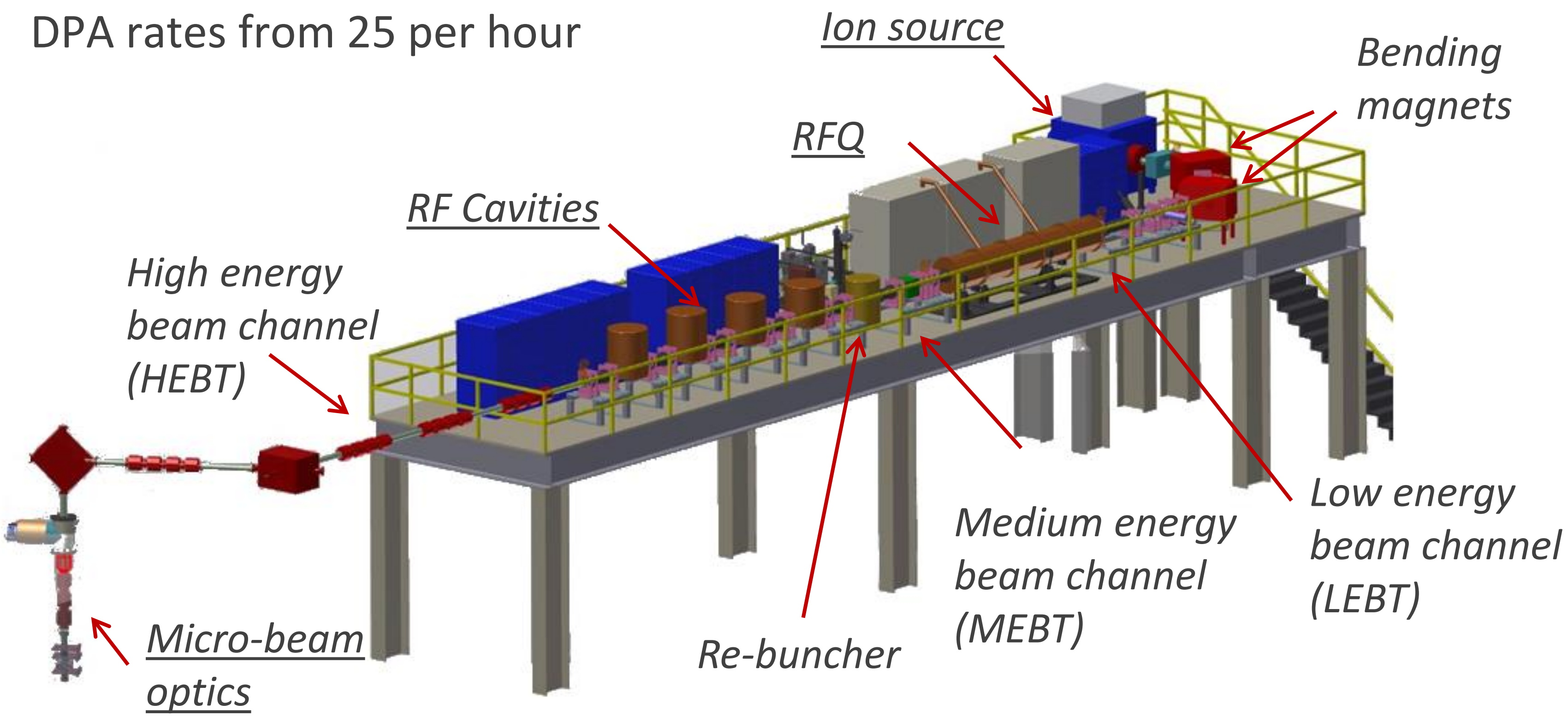
- Normal conducting cavities are very efficient for heavy ion acceleration in CW regime for energies up to ~1.5 MeV/u

Ref: K. Suda et al. “Drift tube linac cavities with space-saving amplifier coupling of new injector for RIKEN RI-beam factory”, IPAC’10, Kyoto

Ref: R.E. Laxdal et al. “A separated function drift-tube linac for the ISAC project at TRIUMF”, PAC’97, Vancouver

Accelerator layout

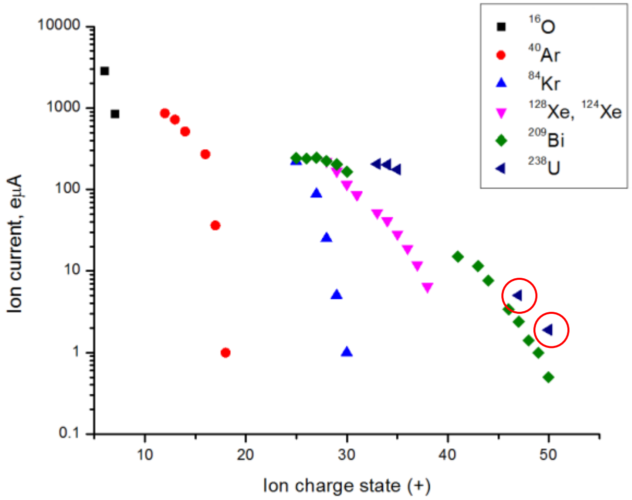
- CW heavy-ion accelerator for any ion from protons to uranium
- Mass-to-charge ratios from 1 (protons) to 5 (50+ uranium)
- Beam energies 1.2 MeV/u (uranium) to 1.6 MeV/u (helium)
- Ion range ~10 microns for all elements
- DPA rates from 25 per hour



Ion source

- Using uranium beam with mass-to-charge ratio of ~5 instead of 7 reduces the facility cost as it requires shorter RFQ and less cavities

VENUS (LBNL)

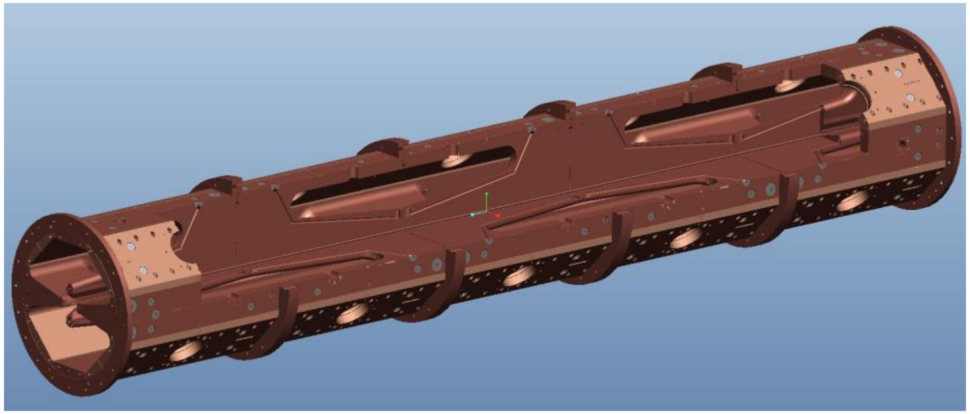


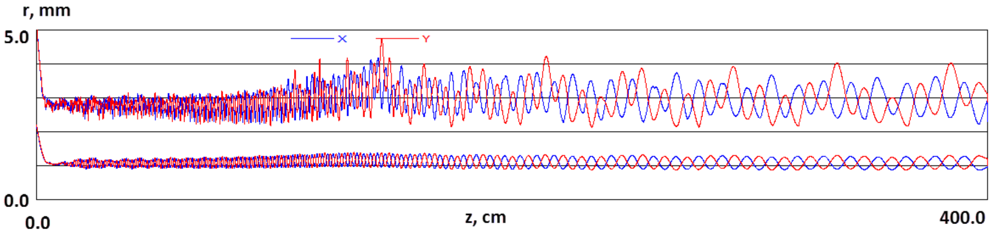
- The recent success in ECR ion source developments, in particular the VENUS source in LBNL, has practically solved this problem
- VENUS-type source can provide 5 eμA of U^{48+} which is enough to provide 10^7 particles/second in a 10 micron diameter spot

Ref: http://ecrgroup.lbl.gov/venus.htm

Radio Frequency Quadrupole

- XMAT RFQ will accelerate any ion from protons to U^{50+}
- 4-vane, 4-segments, 4 meter long
- Conventional RFQ design without a multi-harmonic buncher, provides almost 100% particles transmission at a cost of larger longitudinal emittance

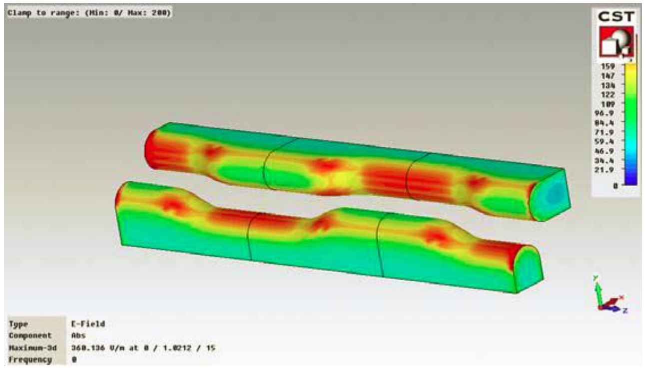


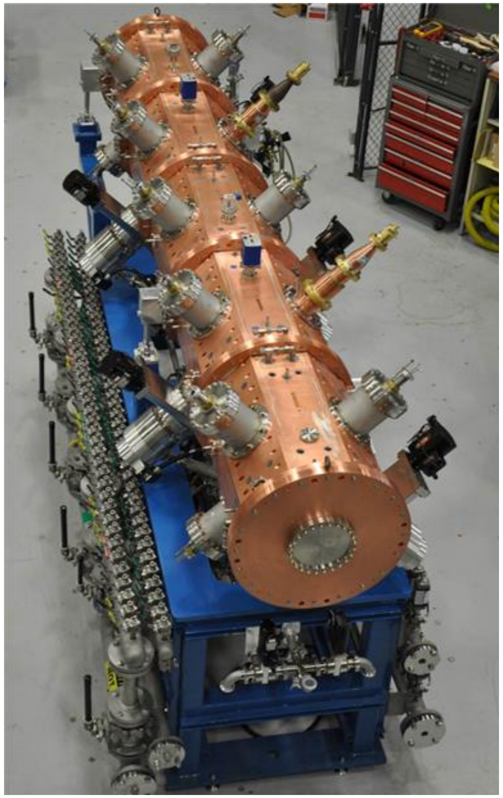


Parameter	Value
Frequency, MHz	60.625
Mass to charge ratio	5
Input energy, keV/u	5.0
Output energy, keV/u	302.5
Particles captured, %	>95%
Energy spread, %	1.07
Inter-vane voltage, kV	70
RFQ length, m	4.04

Existing RFQ technology

- Recently a new RFQ was built at Argonne for the ATLAS Upgrade
- Accelerated ions with mass-to-charge ratios up to 7 from 30 to 295 keV/u
- 80% beam transmission efficiency
  - Multi-harmonic buncher
  - Low longitudinal emittance
- Inter-vane voltage ~70 kV (60 kW surface power loss)
- Excellent agreement with simulations



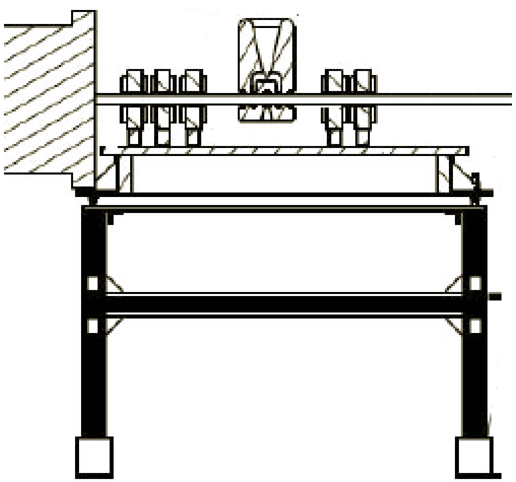


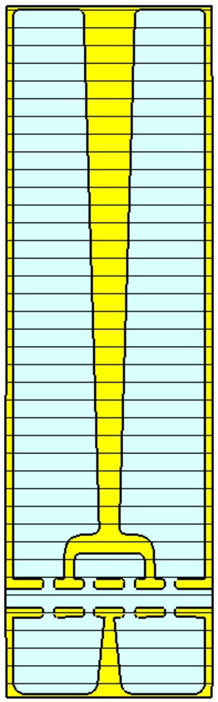
Ref: P.N. Ostroumov et al. “Development and beam test of a continuous wave radio frequency quadrupole accelerator”, Phys. Rev. STAB, 2012

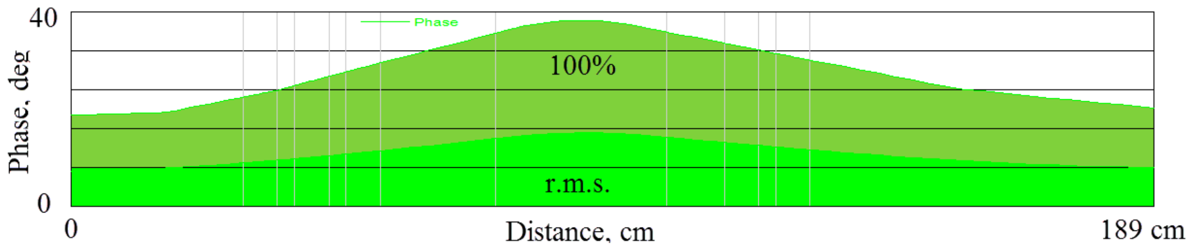
MEBT

- MEBT is 1.89 m long, consists of 1 re-buncher, 1 quadrupole triplet, 1 doublet and beam dagnostics
- Rebuncher frequency is the same - 60.625 MHz
- Optimum β = 0.025
- RF losses at optimal 0.25 MV voltage are 2.75 kW
- We chose 4 gaps because 2 gap cavity has higher losses

due to the higher surface to volume ratio

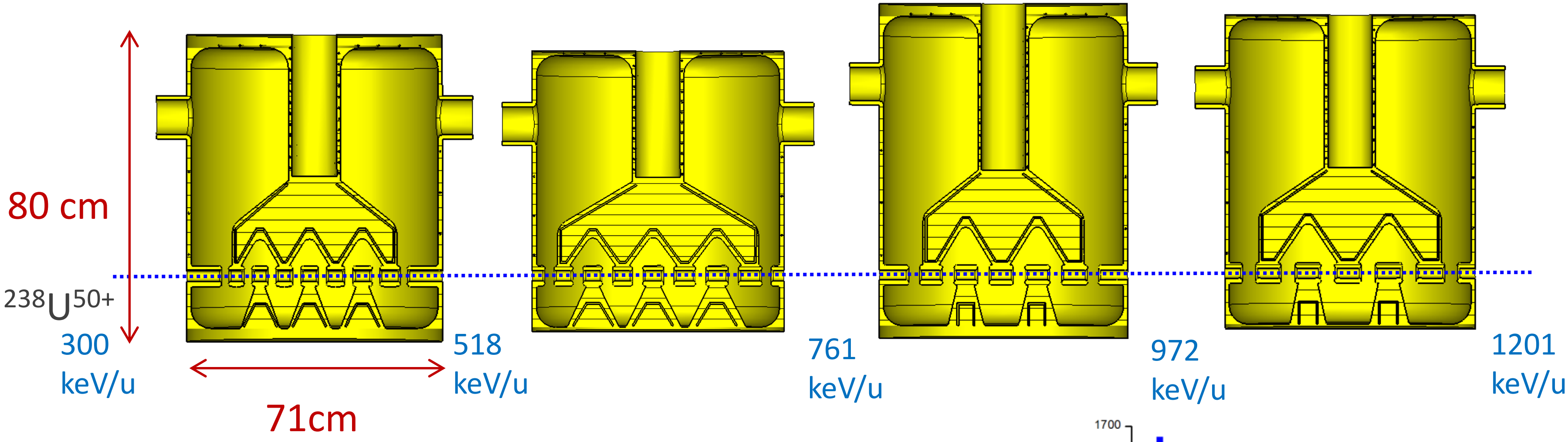




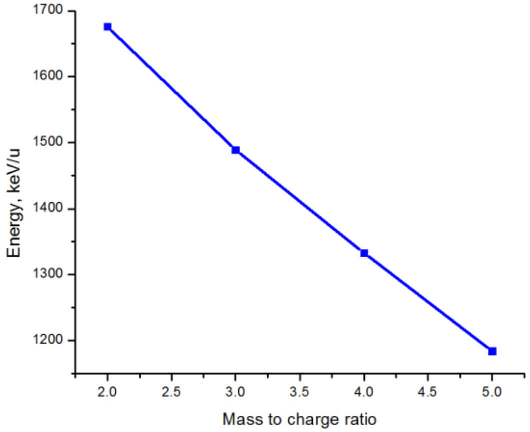


Accelerating cavities

- Four multi-gap coaxial copper resonators were designed to accelerate $^{238}U^{50+}$ ions from 300 keV/u (71 MeV) to 1.2 MeV/u (285 MeV)
- Two 8-gap QWRs and two 6-gap QWRs.

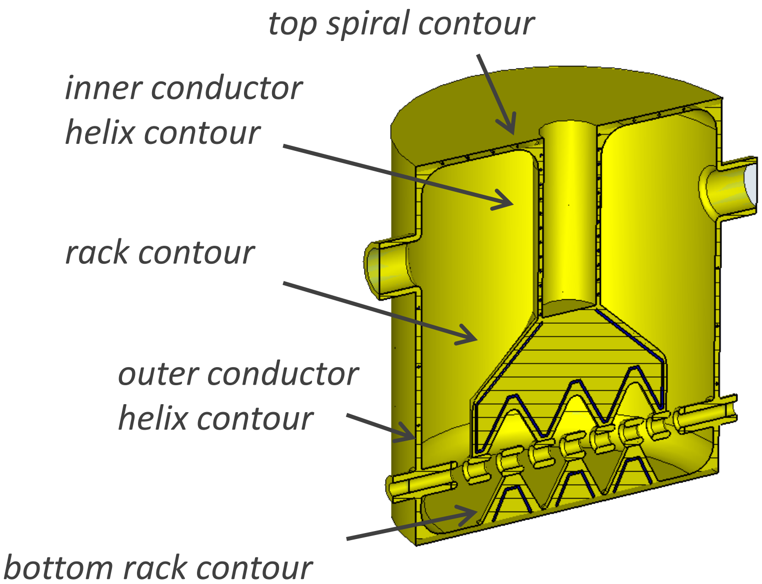


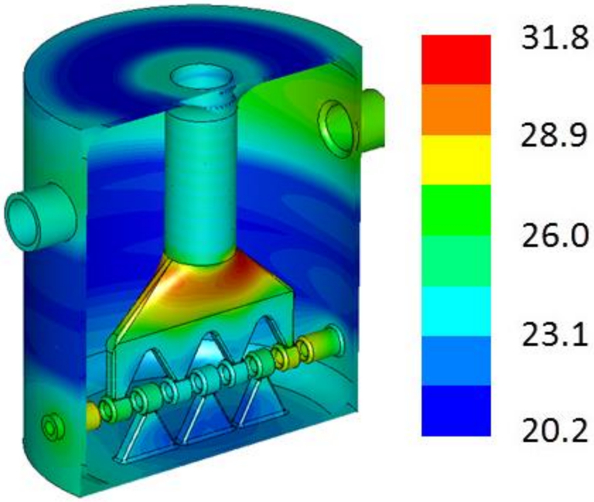
- Gap widths were optimized to flatten the field
- Peak fields are less than 1.5 Kp
- Beam focused using quadrupole doublets
- No beam loss during acceleration in simulations



Development of the cavity prototype

- A cavity prototype is planned to be built
- Complete engineering design and analysis was done
- 6 water contours are used to cool the cavity

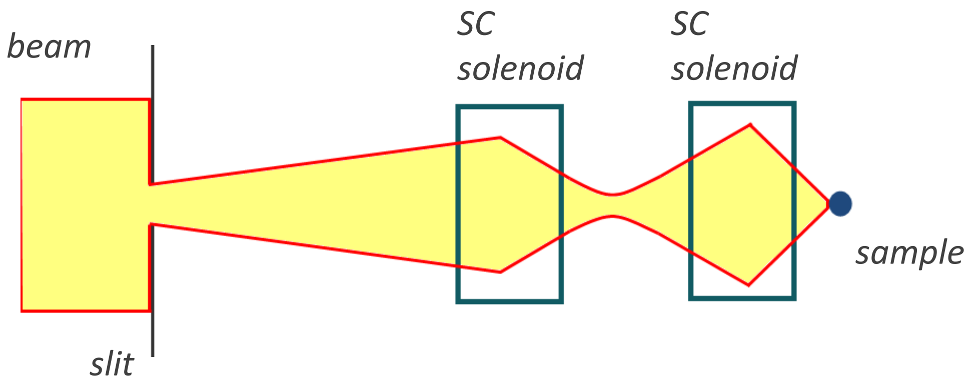




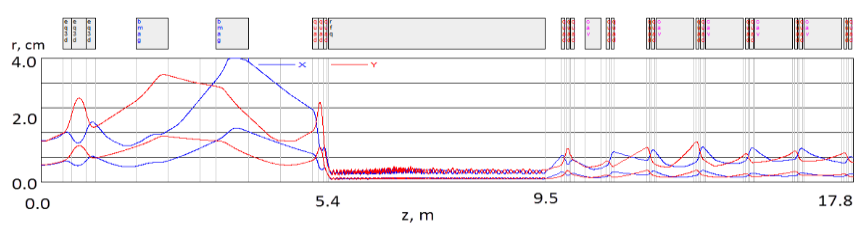
- No significant overheating or deformations
- Stresses are within yield safety limits

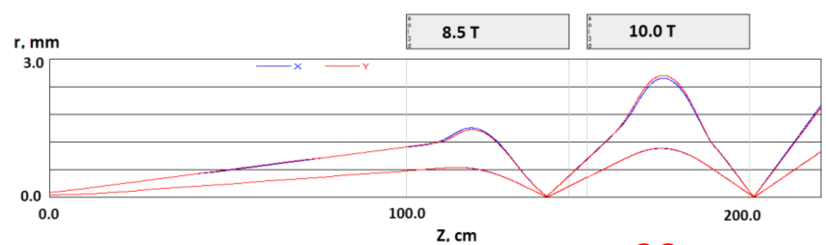
Micro-beam optics

- The beam should pass through a 100 microns diameter slit in order to be focused on microscopic samples
- Two superconducting solenoids will then be used to focus the beam to a 20 microns spot.
- The rest of the beam is not wasted!
- Material samples that doesn’t require in-situ analysis with X-rays can be put around the slit



- Aberrations limit the spot size
- We are working to improve focusing system





33 µm

Summary

- Concept design for XMAT is ready
- Highly efficient room temperature CW linac is designed
- High damage rates from 25 dpa/hour can be provided
- Any types of ion beams from protons to uranium can be accelerated to energies up to 1.2 MeV/u
- Ion beams can be focused to 30 microns diameter and penetrate 10 microns into sample
- Ion species, beam energy, size and current can be adjusted according to experiment requirements
- APS provides a unique opportunity for in-situ material studies