Design of a Ring for Bunch Compression of Heavy Ion Beams at the MSU NSCL

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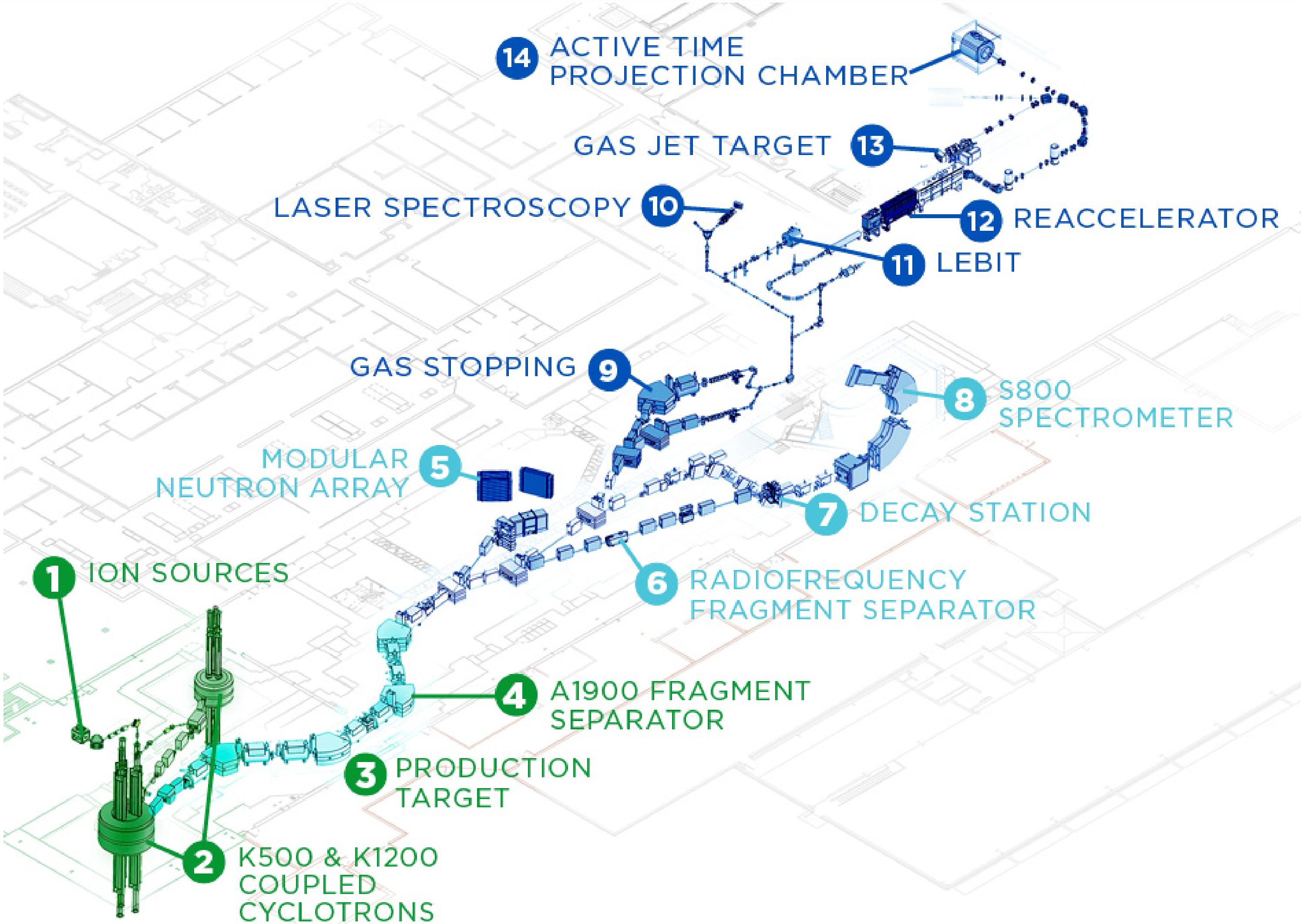
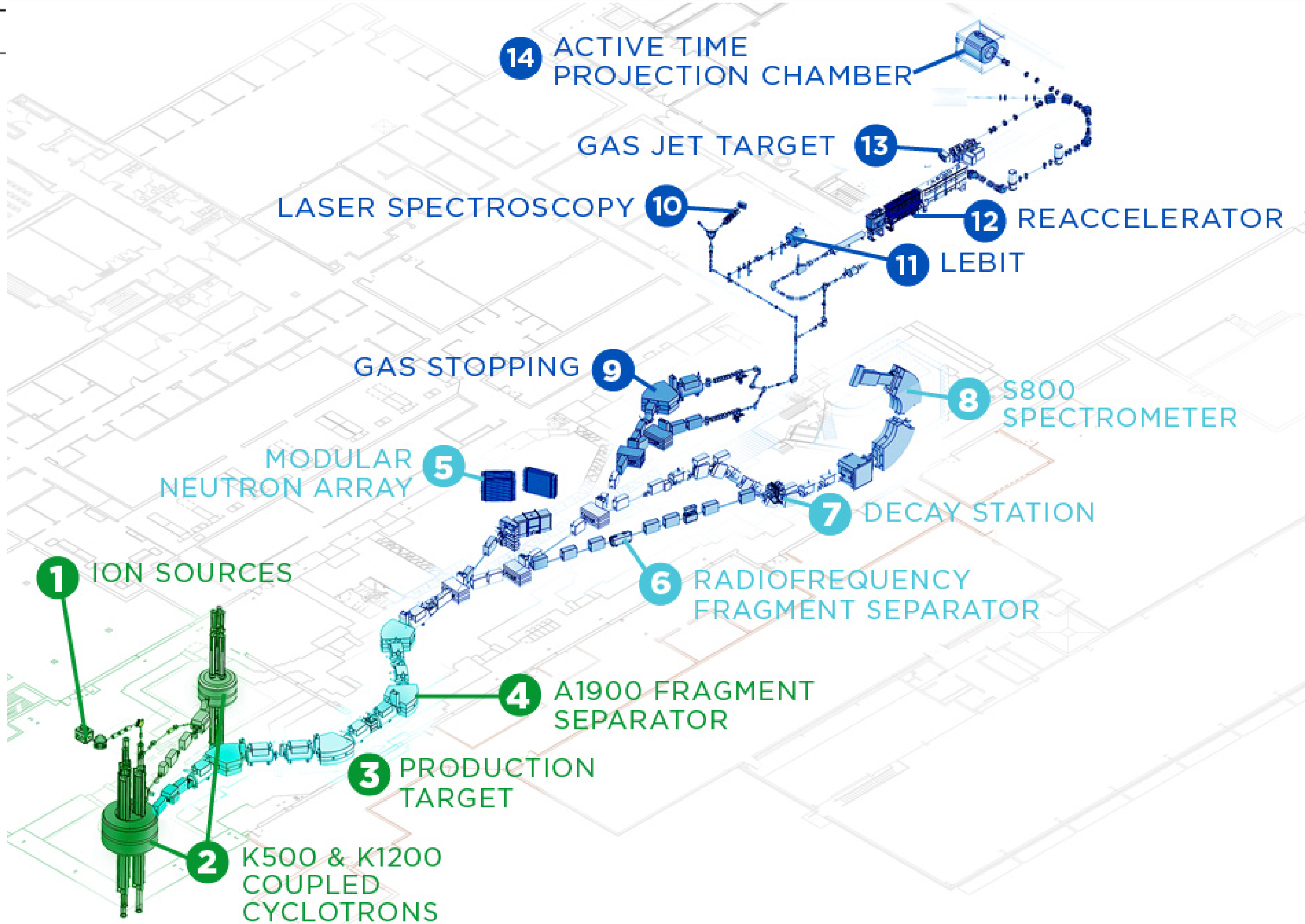
Coupled–Cyclotron Facility @ NSCL



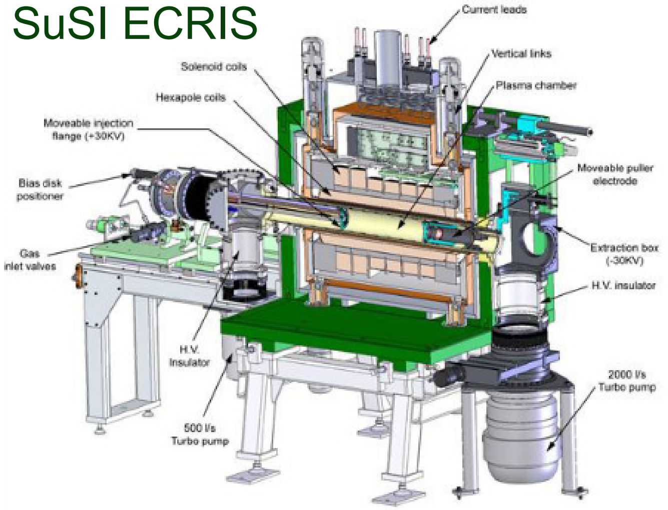
Coupled–Cyclotron Facility @ NSCL

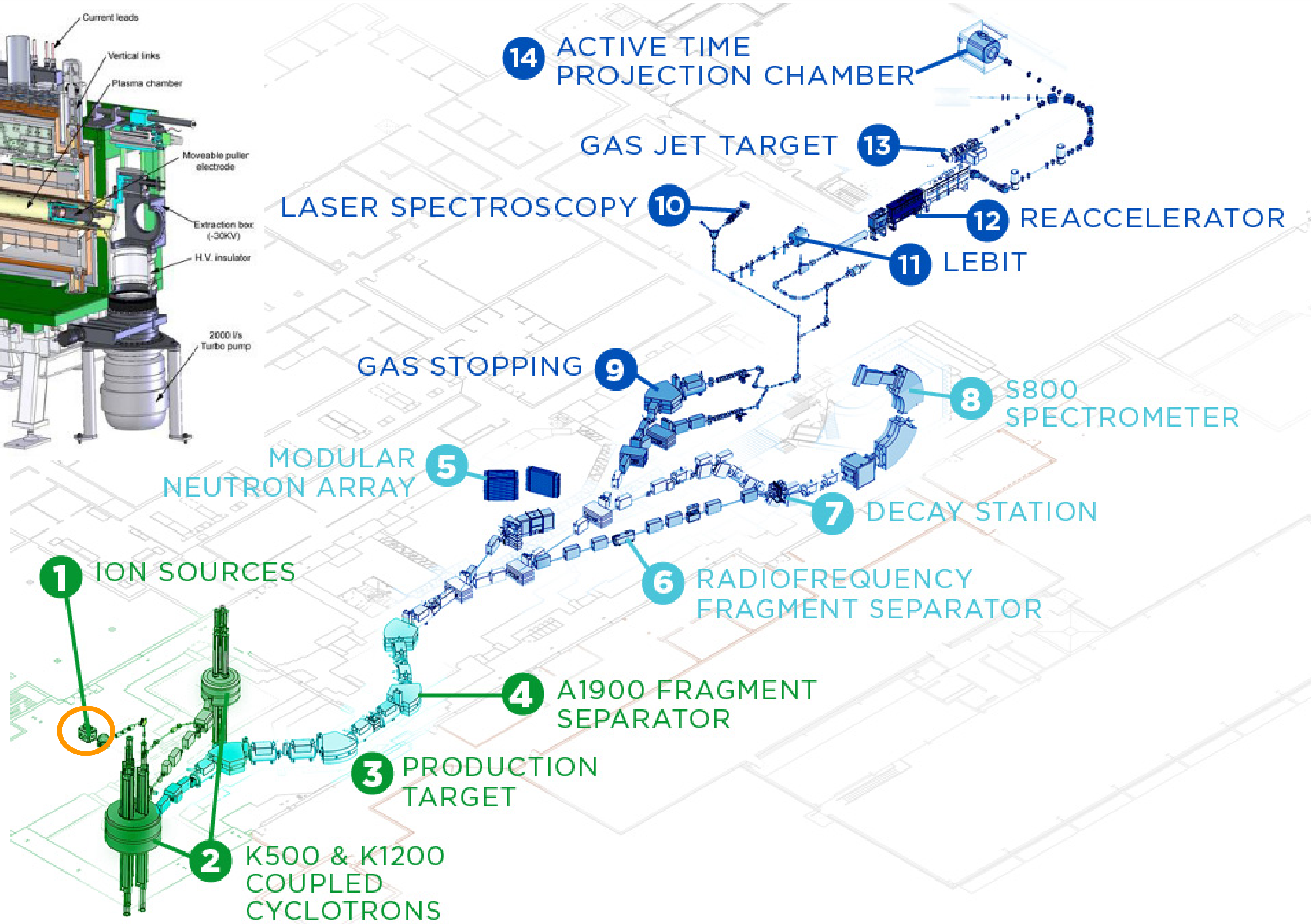
Particle
^{16}O
^{18}O
^{20}Ne
^{22}Ne
^{22}Ne
^{24}Mg
^{36}Ar
^{40}Ar
^{40}Ca
^{48}Ca
^{48}Ca
^{58}Ni
^{64}Ni
^{76}Ge
^{82}Se
^{78}Kr
^{86}Kr
^{86}Kr
^{96}Zr
^{112}Sn
^{118}Sn
^{124}Sn
^{124}Xe
^{136}Xe
^{208}Pb
^{209}Bi
^{238}U
^{238}U



Coupled–Cyclotron Facility @ NSCL

SuSI ECRIS





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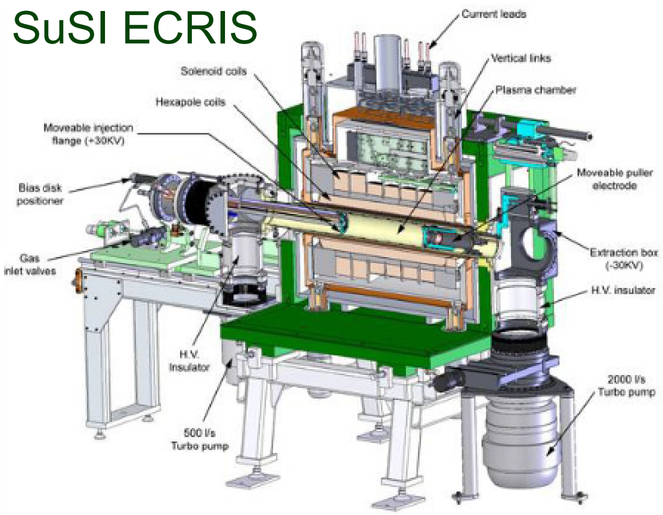

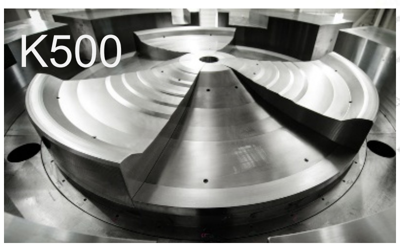

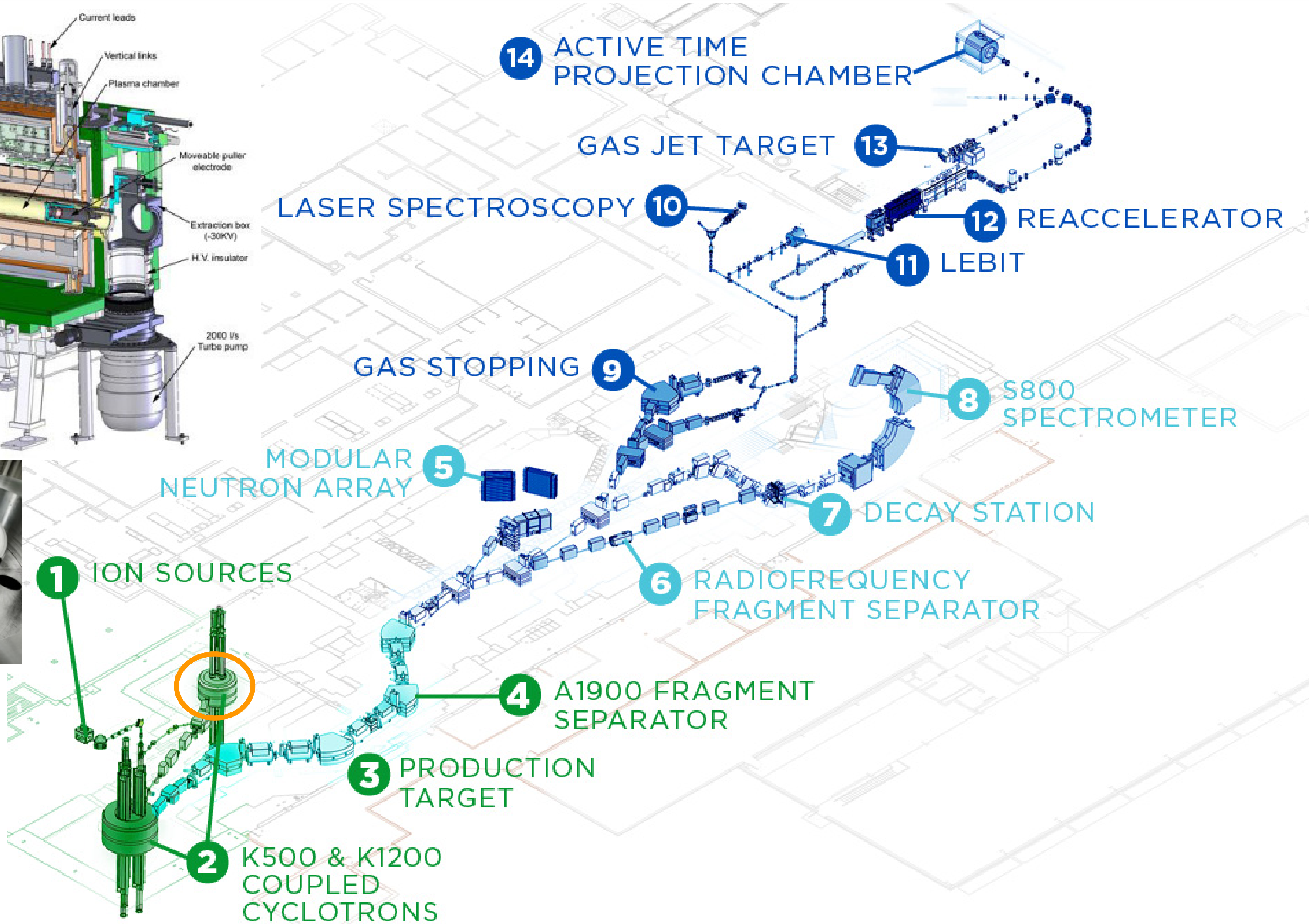

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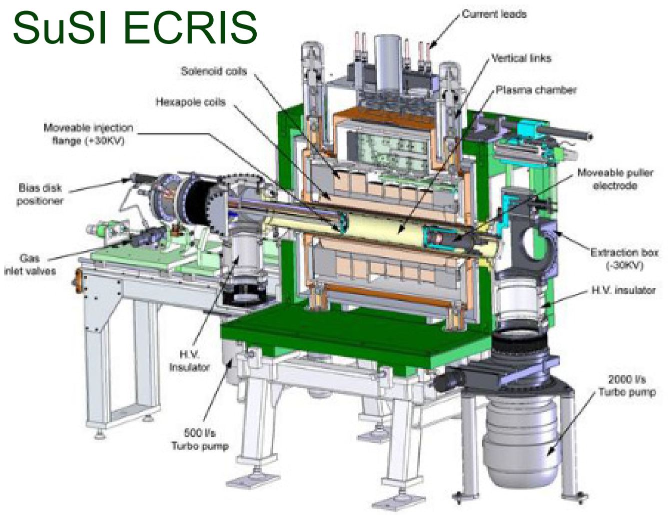

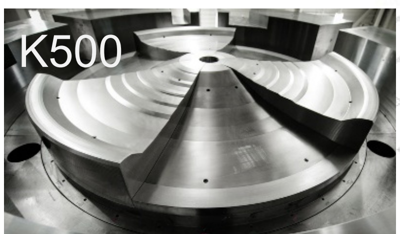

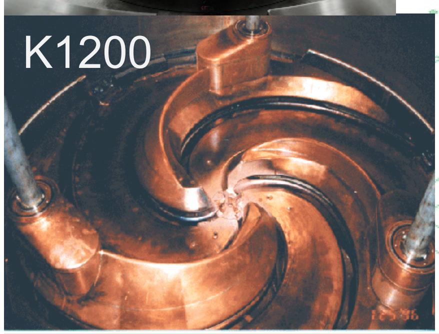

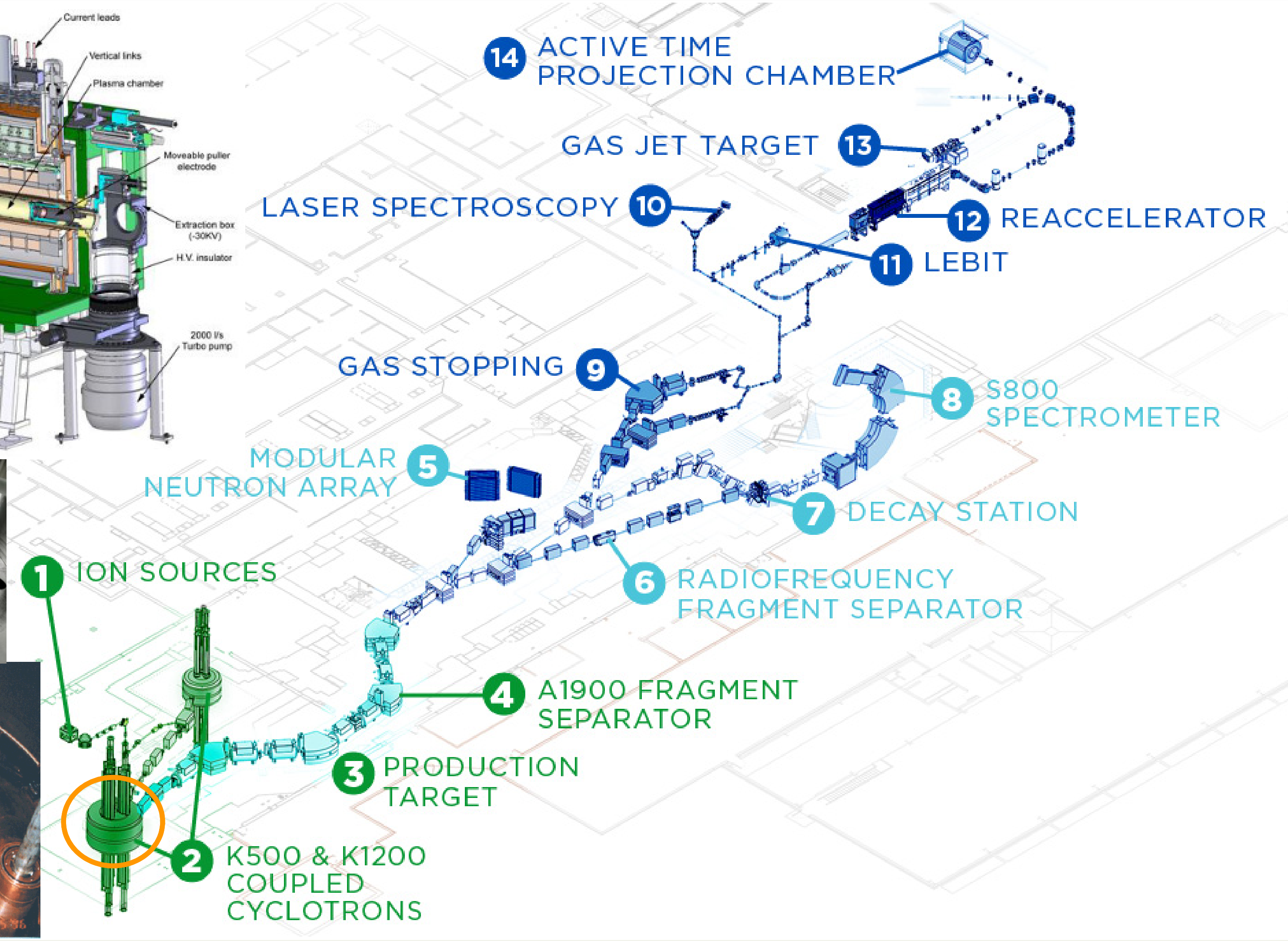

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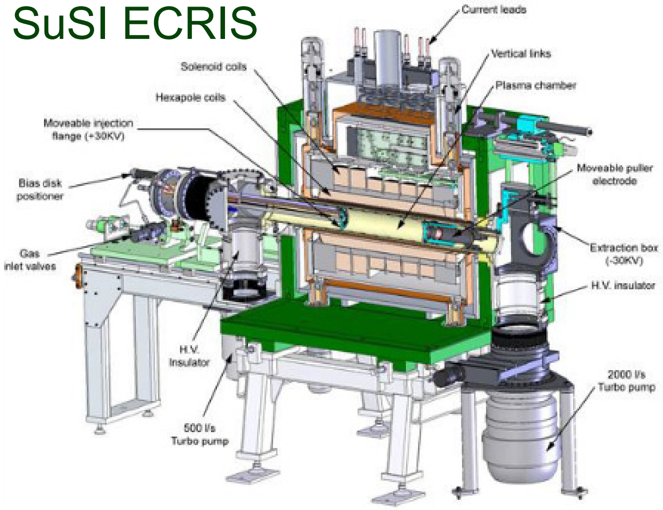

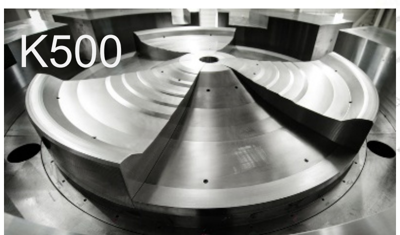

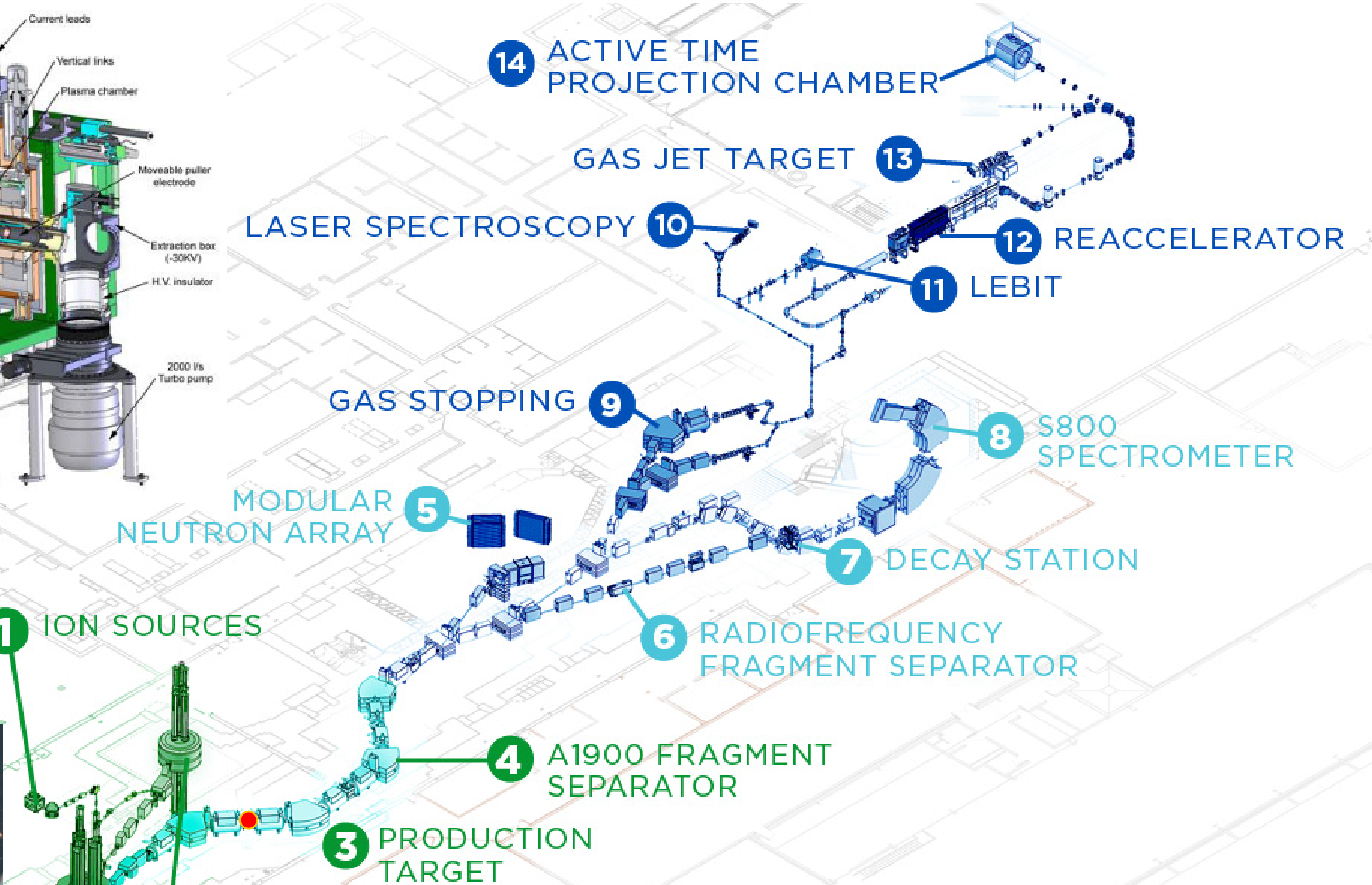

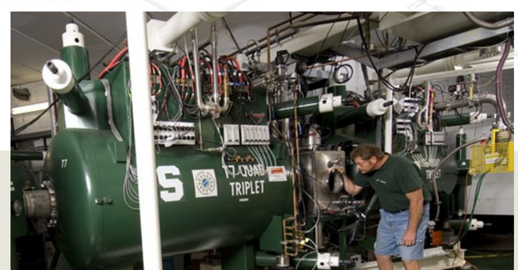

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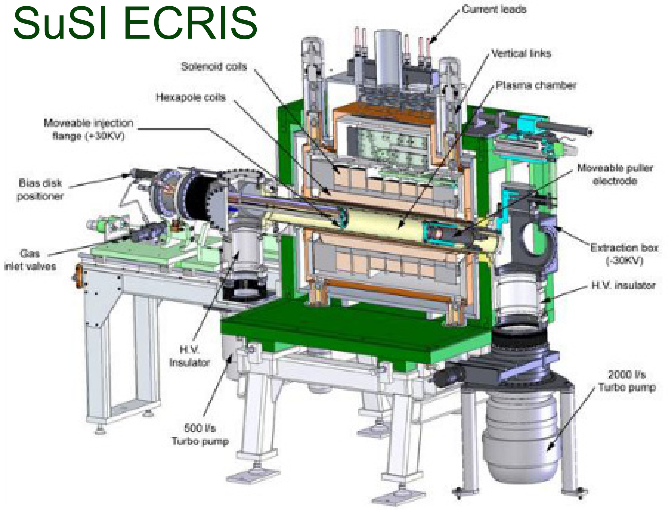
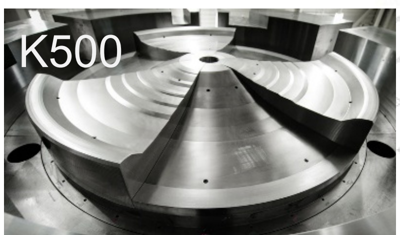
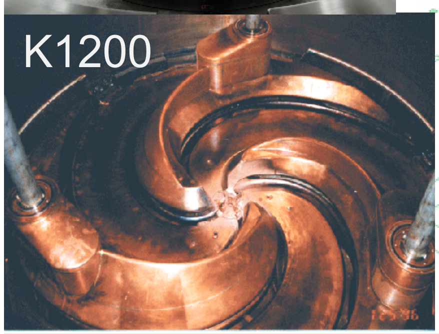
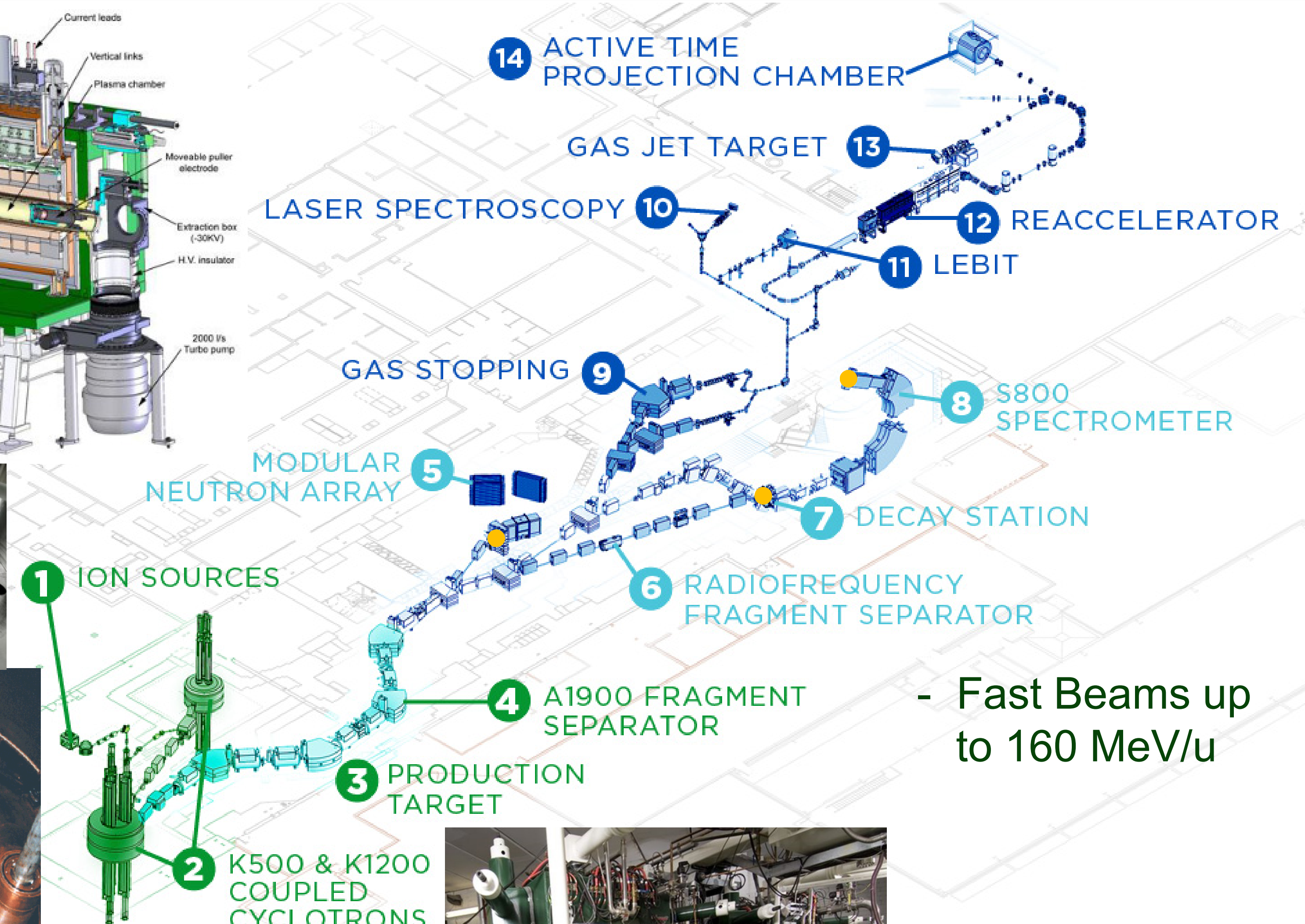
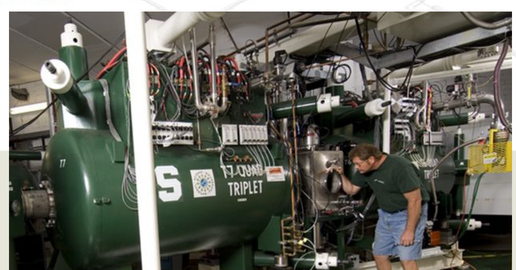








- Fast Beams up to 160 MeV/u



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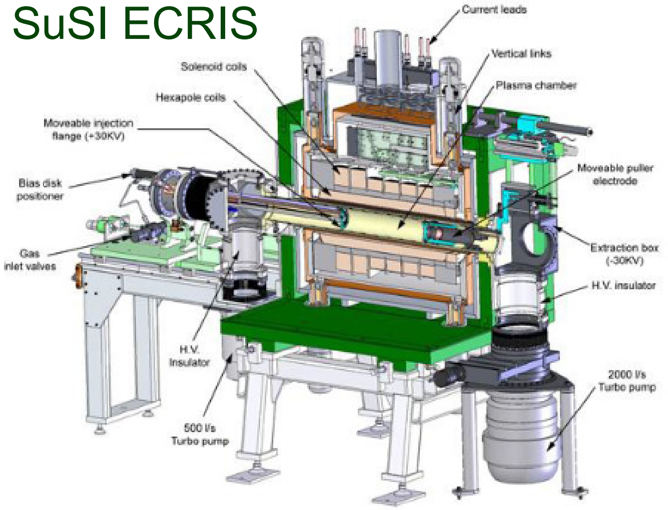
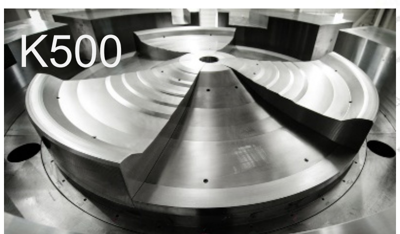
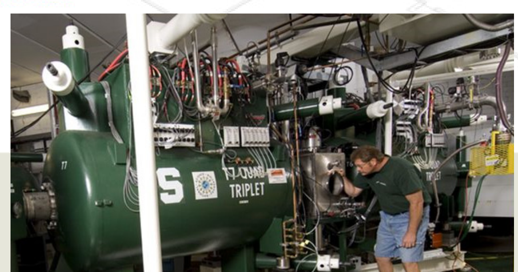


K500



K1200

- Fast Beams up to 160 MeV/u
- Stopped Beams in the eVs



Coupled–Cyclotron Facility @ NSCL

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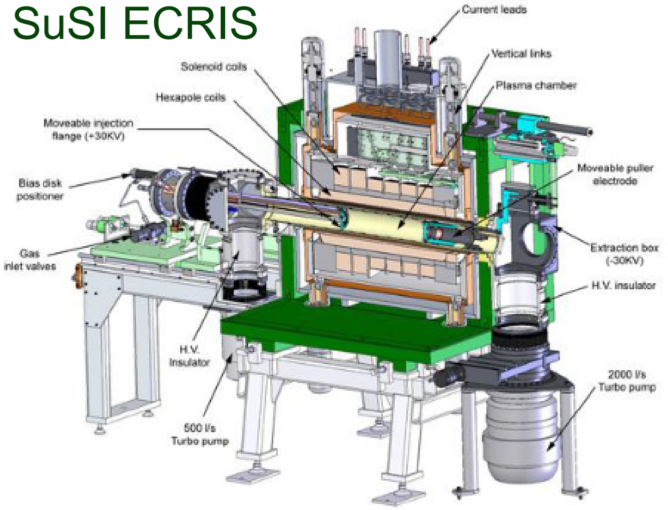

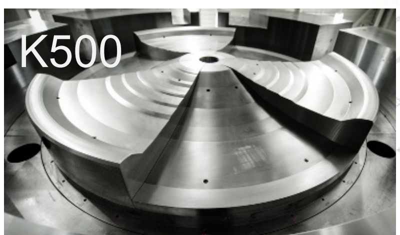

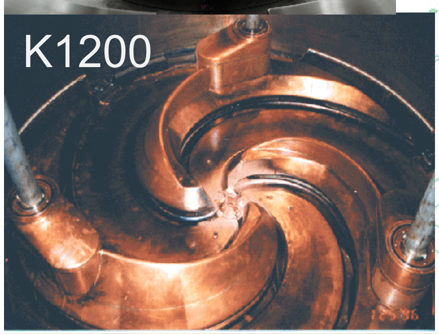

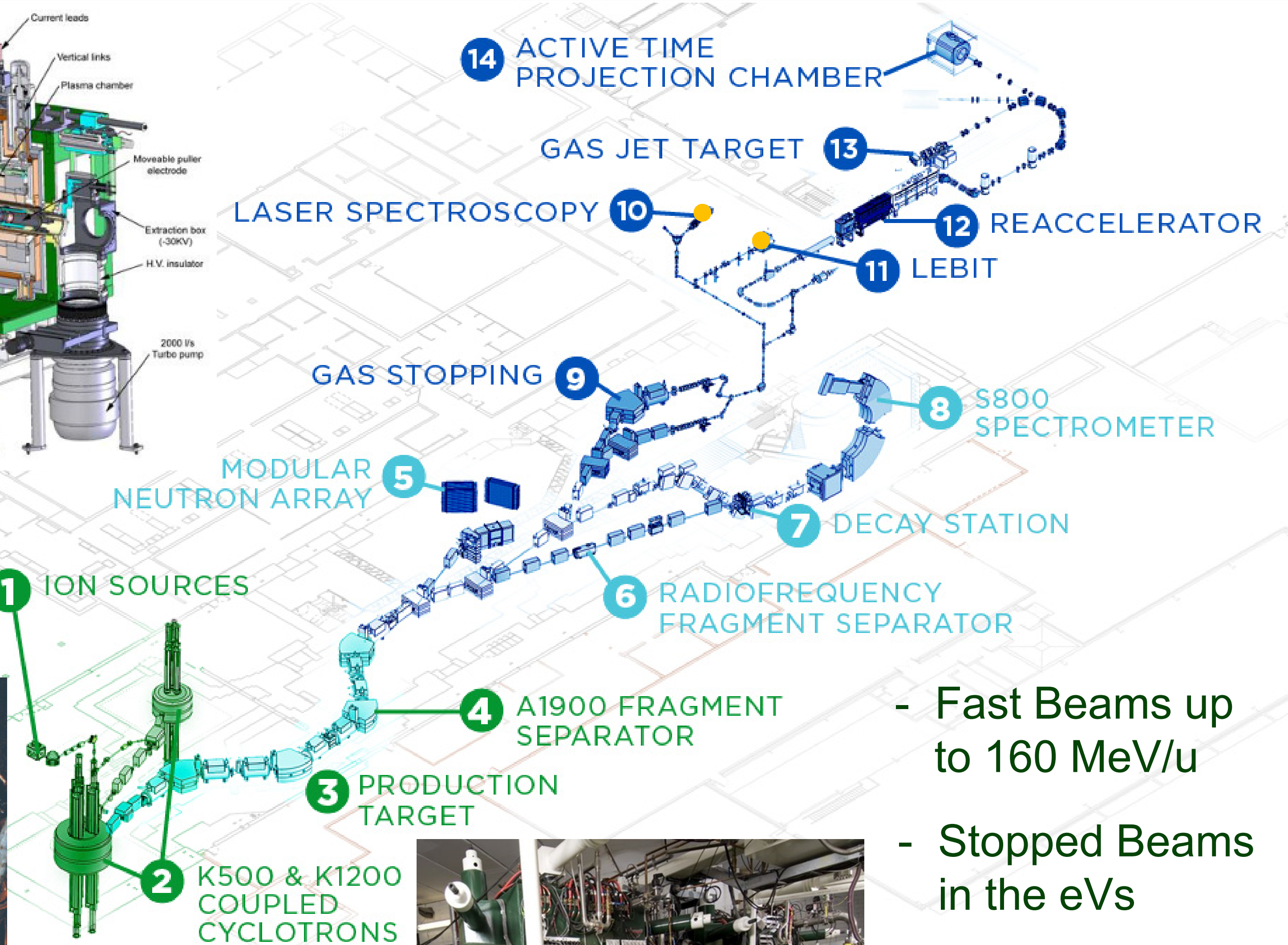

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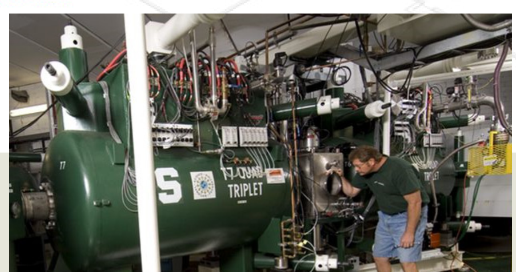

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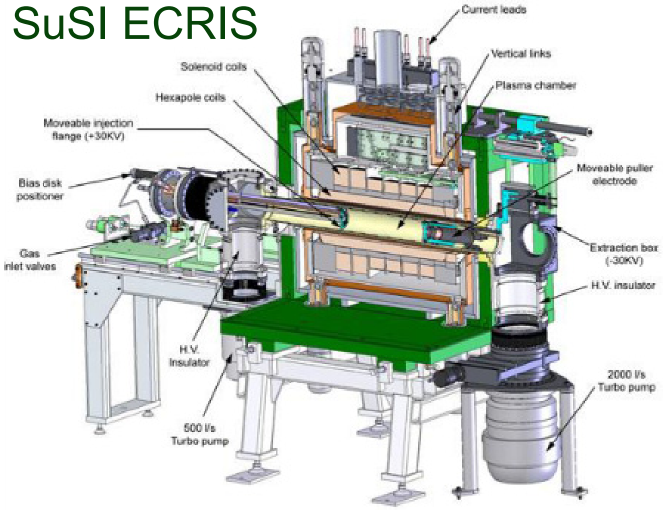

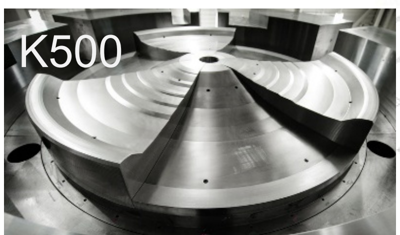

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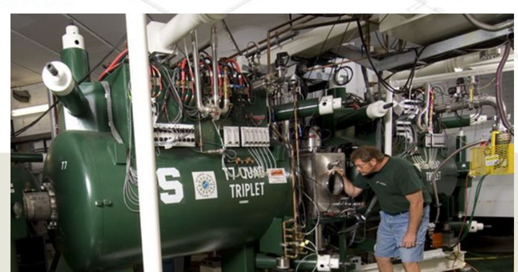

ReAccelerator @ NSCL

- Currently, ReA3 re-accelerates stopped ion beams to variable energies ~0.3–3 MeV/u for Uranium (upgrade to 12 MeV/u)
- ReA3 commissioning completed in 2015, currently delivering beam
- ReA serve as a test bed for FRIB Front End and SRF technology

X. Wu, *et al.*, *Proc. SRF2007*, paper MO304, Beijing, China.
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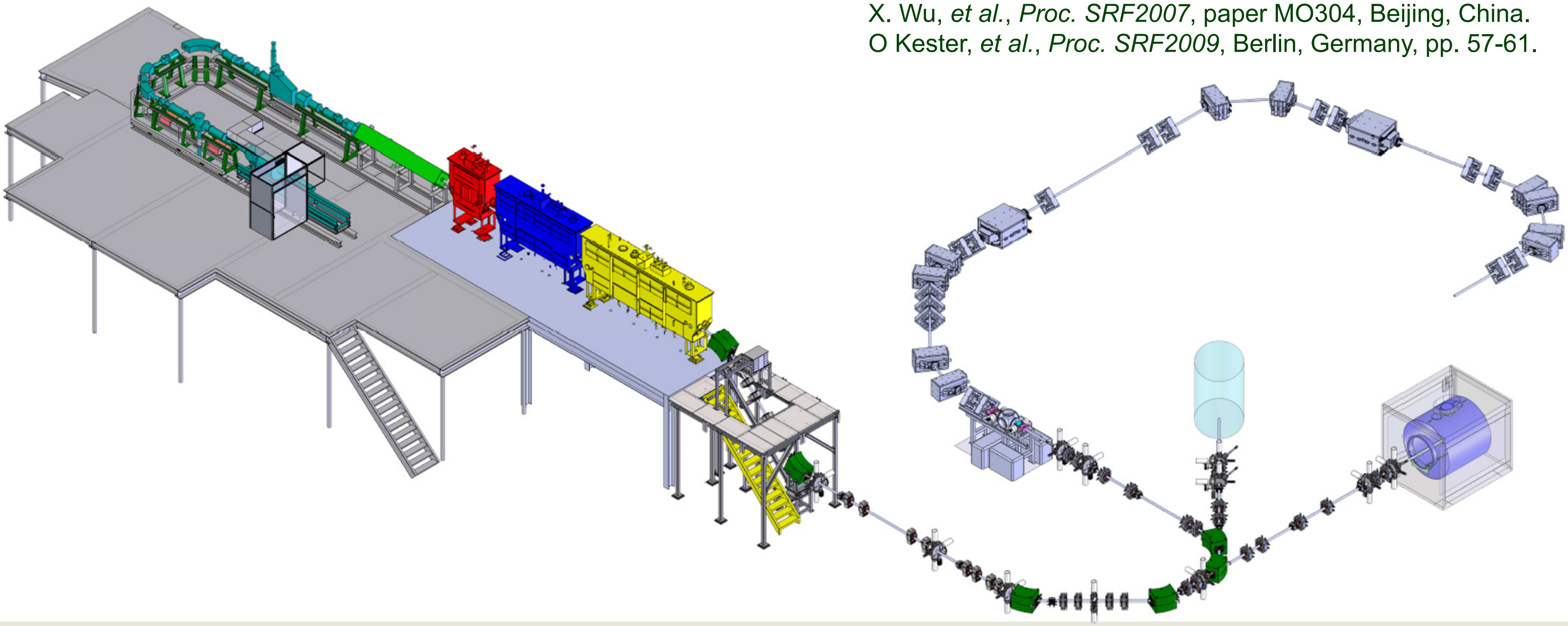

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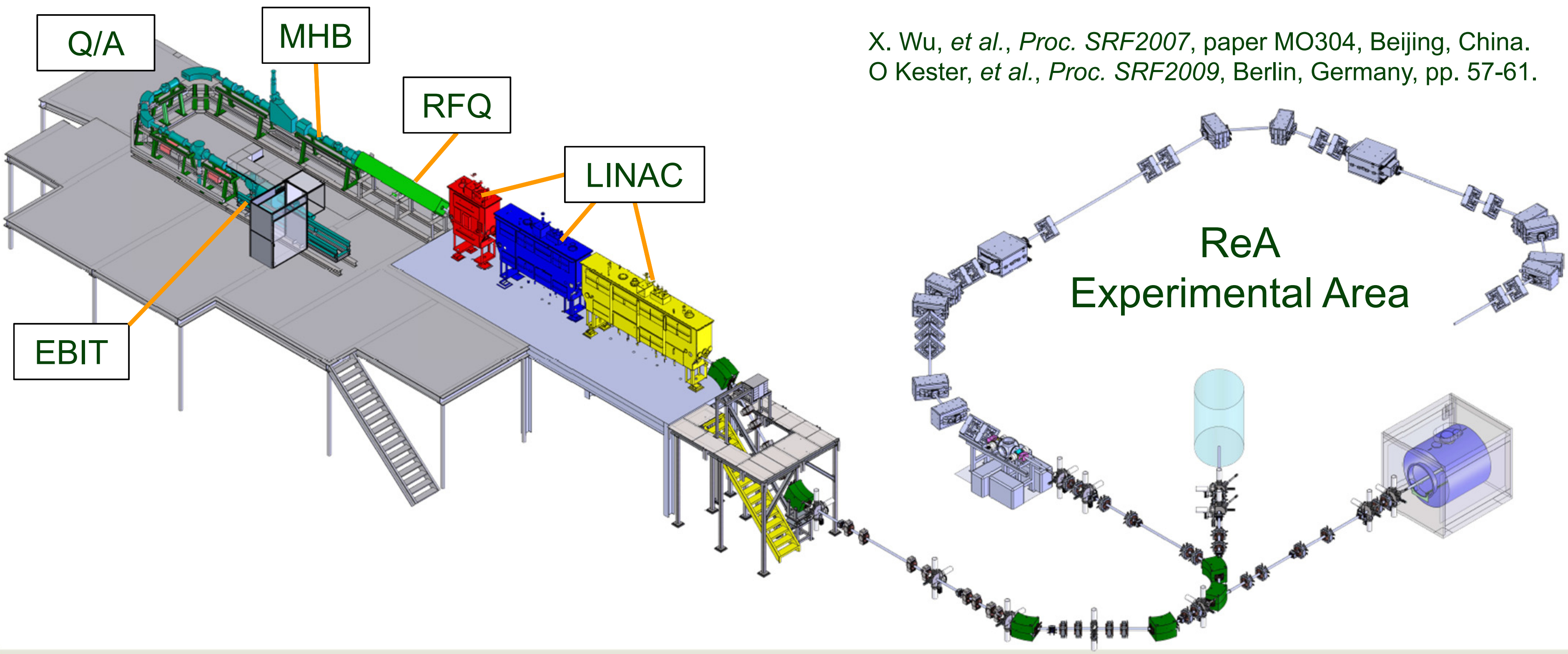

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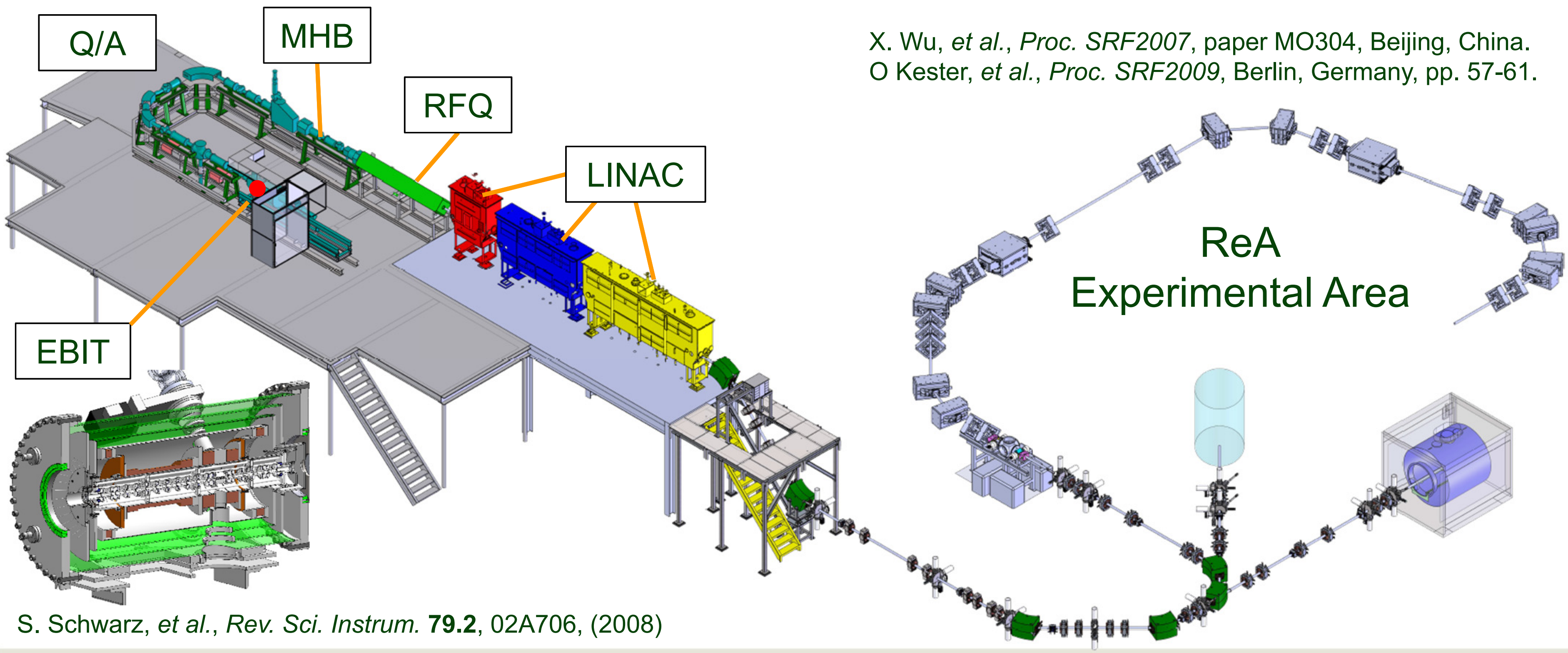

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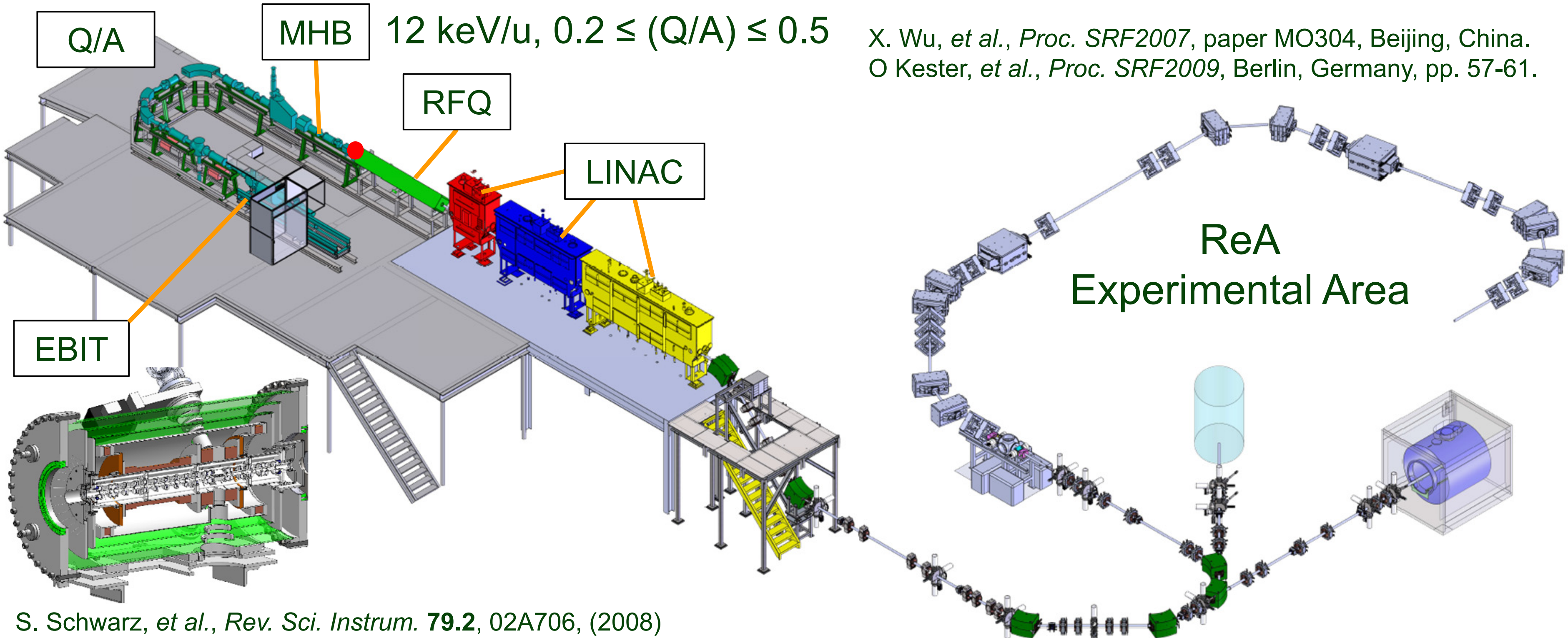

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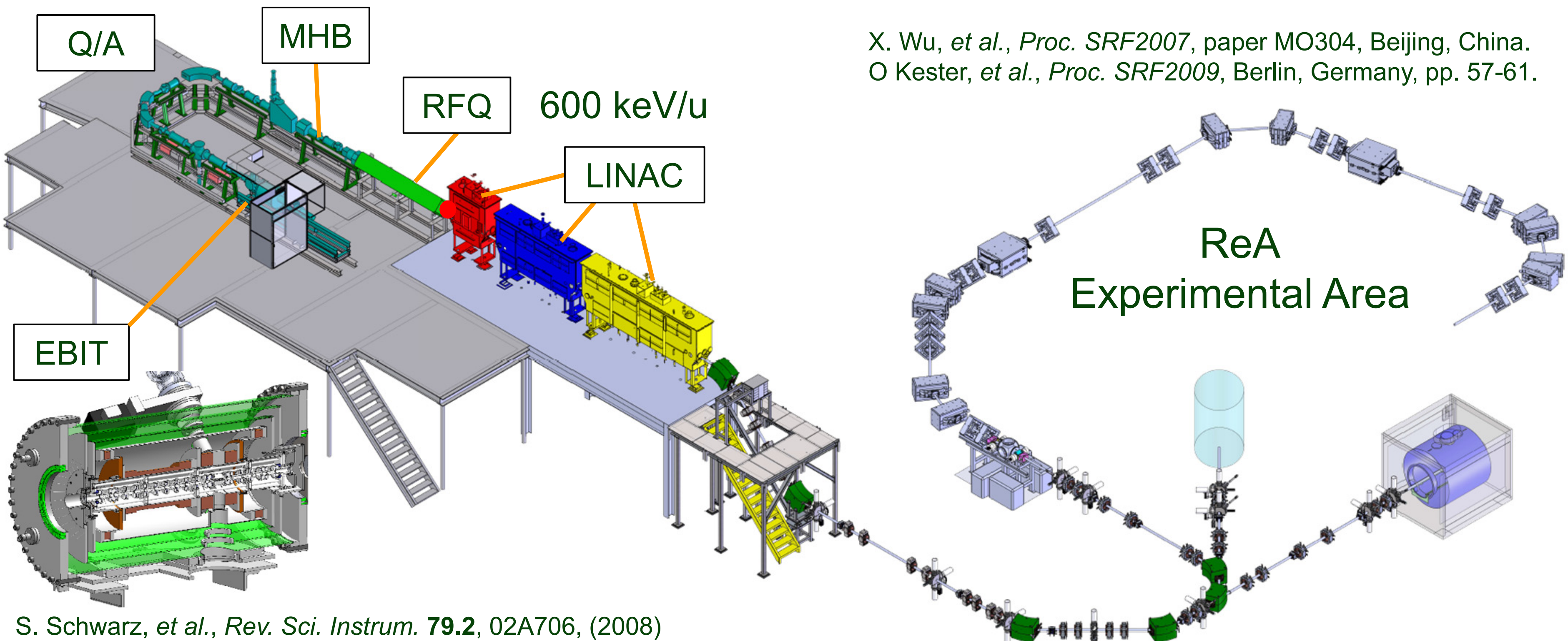

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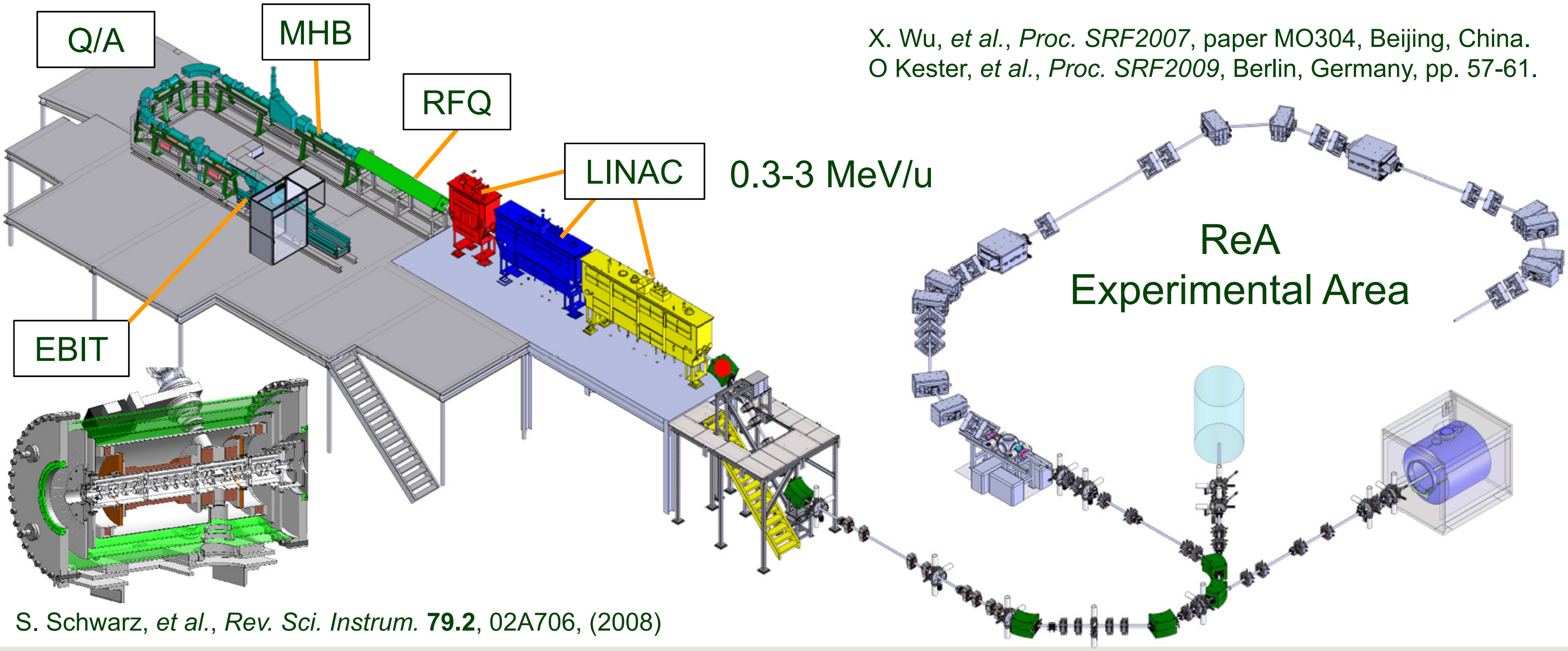

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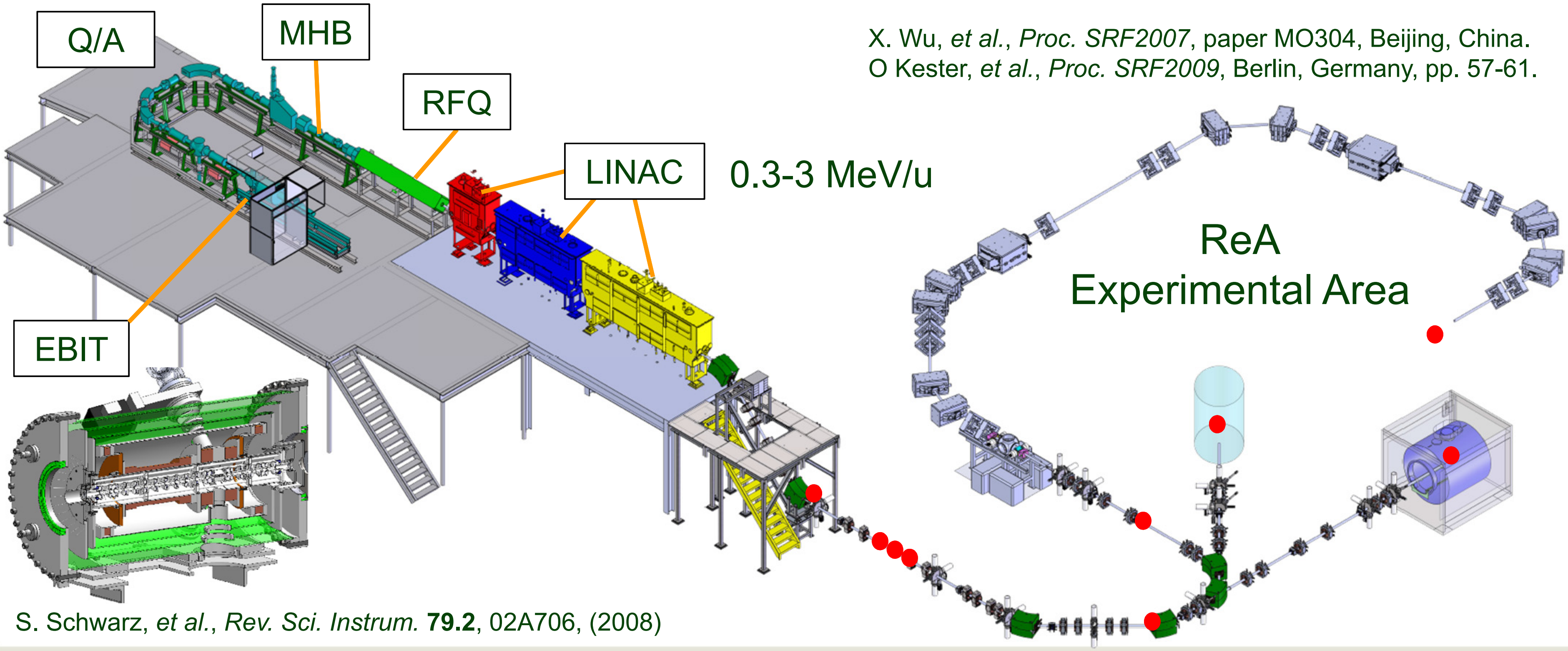

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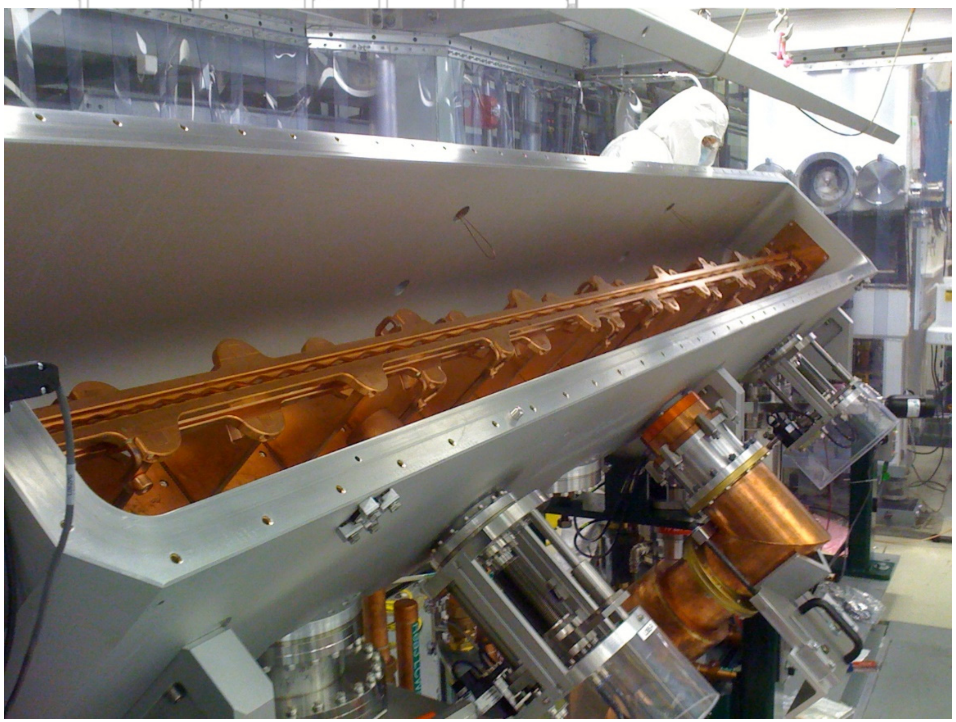
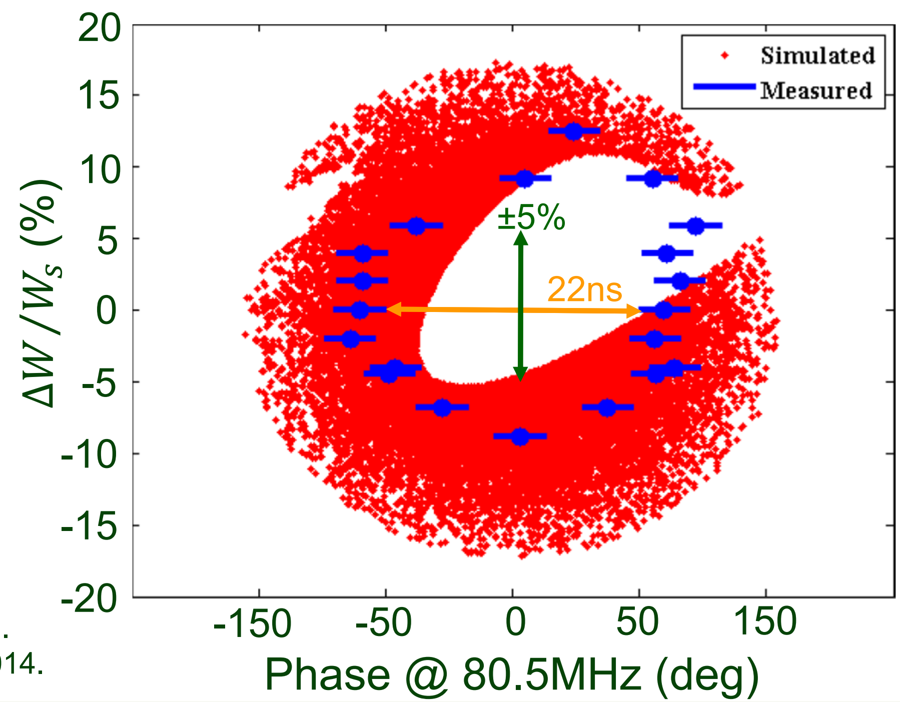
ReA Radio Frequency Quadrupole



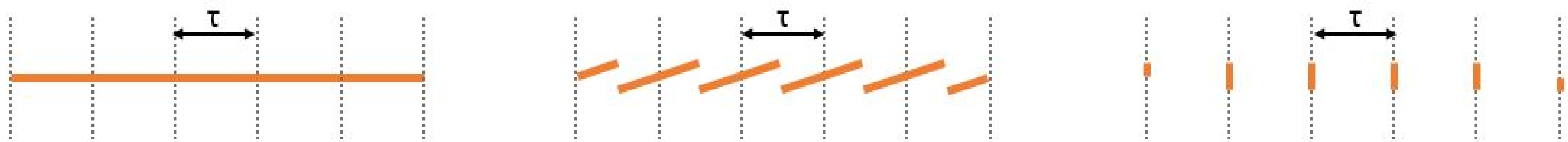
RFQ Parameters	Values
RF Frequency f_{RFQ}	80.5 MHz
RF Frequency Tuning Range Δf_{RFQ}	300 kHz
Q/A Operational Range	0.2–0.5
Kinetic Energy Acceptance W_{RFQ}	12 keV/u
Kinetic Energy Acceptance Range ΔW_{RFQ}	±5%
Bunch Length Acceptance σ_{RFQ}	±11 ns



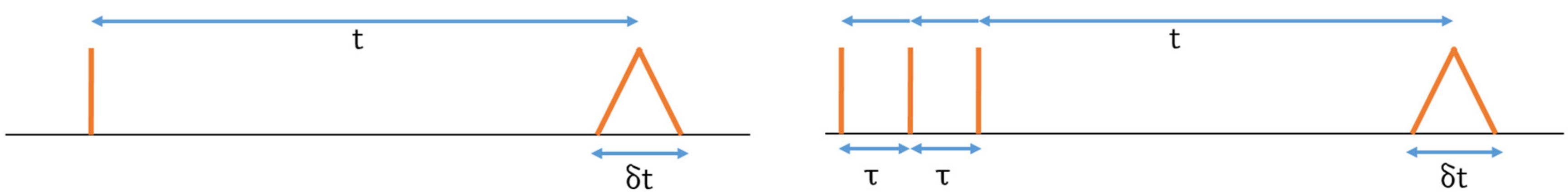
D. Leitner, *et al.*, *Proc. PAC*, paper WEP226, New York, USA, Mar. 2011.
D. Alt, *et al.*, *Proc. IPAC*, paper THPME052, Dresden, Germany, Jun. 2014.

ReA Bunch Time Structure

- ReA RFQ and LINAC designed to operate at 80.5 MHz
  - Corresponding to $\tau = 12.4$ ns between buckets
- Pre-bunching (longitudinal matching) is required for optimal beam transmission through RFQ and LINAC
- For Pre-bunching at 80.5 MHz

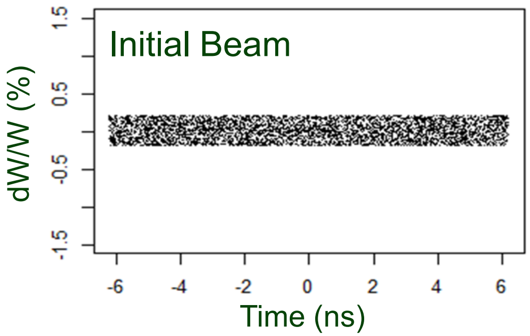


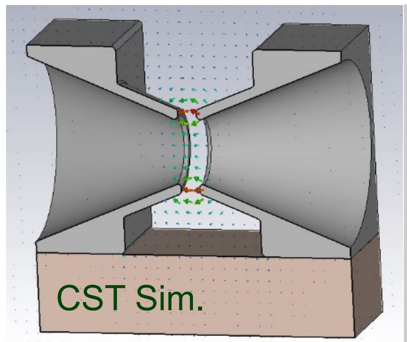
- $\tau = 12.4$ ns bunch separation is much too short for accurate time-of-flight (TOF) measurements at the NSCL
  - TOF measurement uncertainty not only a function of bunch time spread, but also ambiguity in bunch-bunch detection

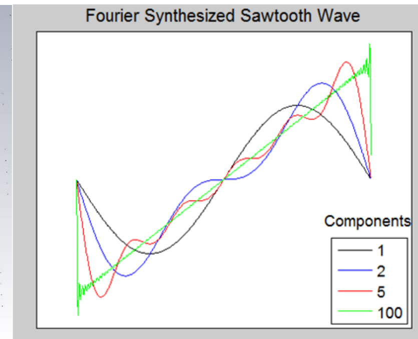


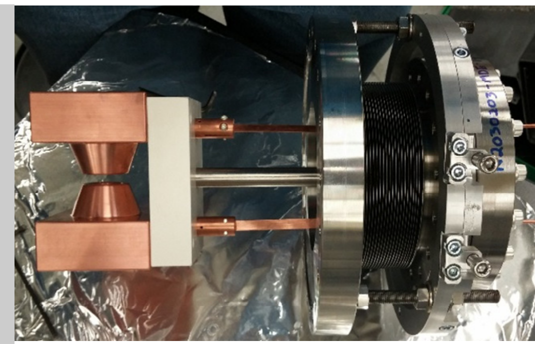
16.1 MHz Multi-Harmonic Buncher

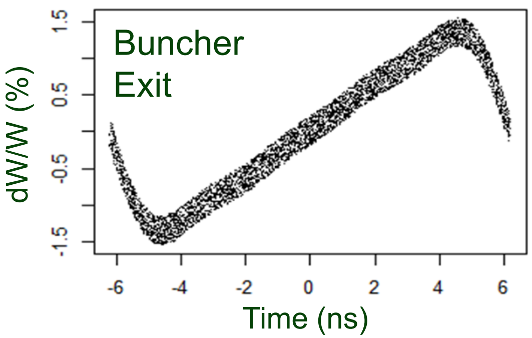
MHB at 16.1, 32.2, 48.3 MHz sub-harmonics to generate saw-tooth waveform with 62.1ns period

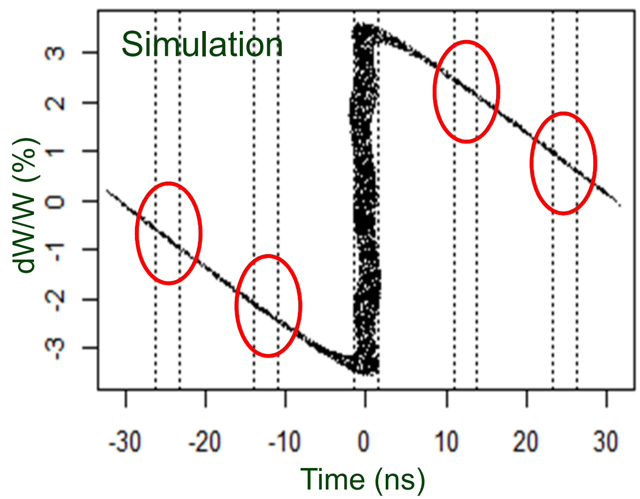


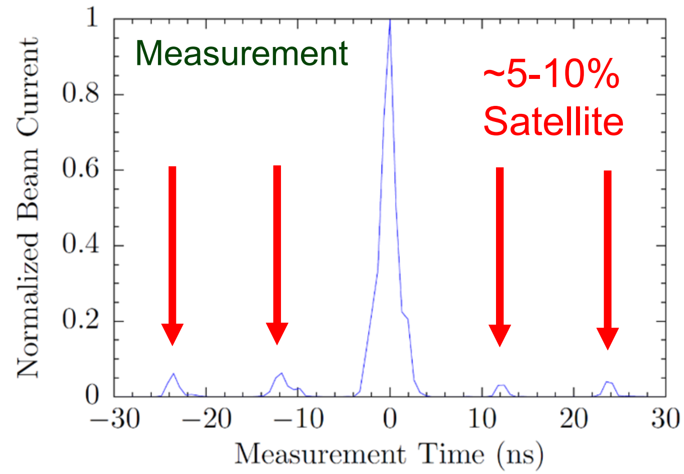


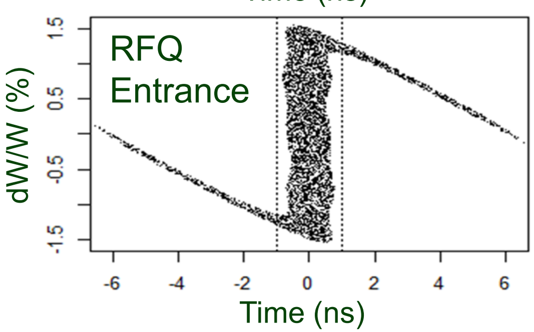












D. Alt, *et al.*, *Proc. IPAC2014*, paper THPME051 Dresden Germany.

D. Alt, *Ph.D. Dissertation, Phys. Astron. Dept*. East Lansing, Michigan, USA

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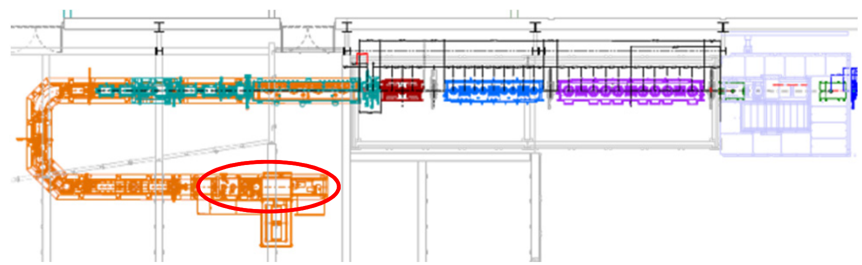
Why a Buncher Ring?

- Satellite bunches can be cleaned using a beam chopper
  - However 5-10% of RIBs produced are thrown away
- Configure EBIT to provide shorter pulses avoiding non-linear tails in the bunching process
  - <50ns pulses are required, unfortunately the shortest pulse measured from the EBIT is about 100-150ns

EBIT Parameters	Values
Extraction Kinetic Energy W_s	12 keV/u
Total Bunch Length σ_z	100 ns - 10s μs
Energy Spread $\Delta W/W_s$	$<$ 0.5%
RMS Transverse Emittance ϵ_x, ϵ_y	$<$ 10 mm·mrad



- More complicated MHB schemes using many Fourier components can be developed
  - Small fraction of the RIBs will still be lost

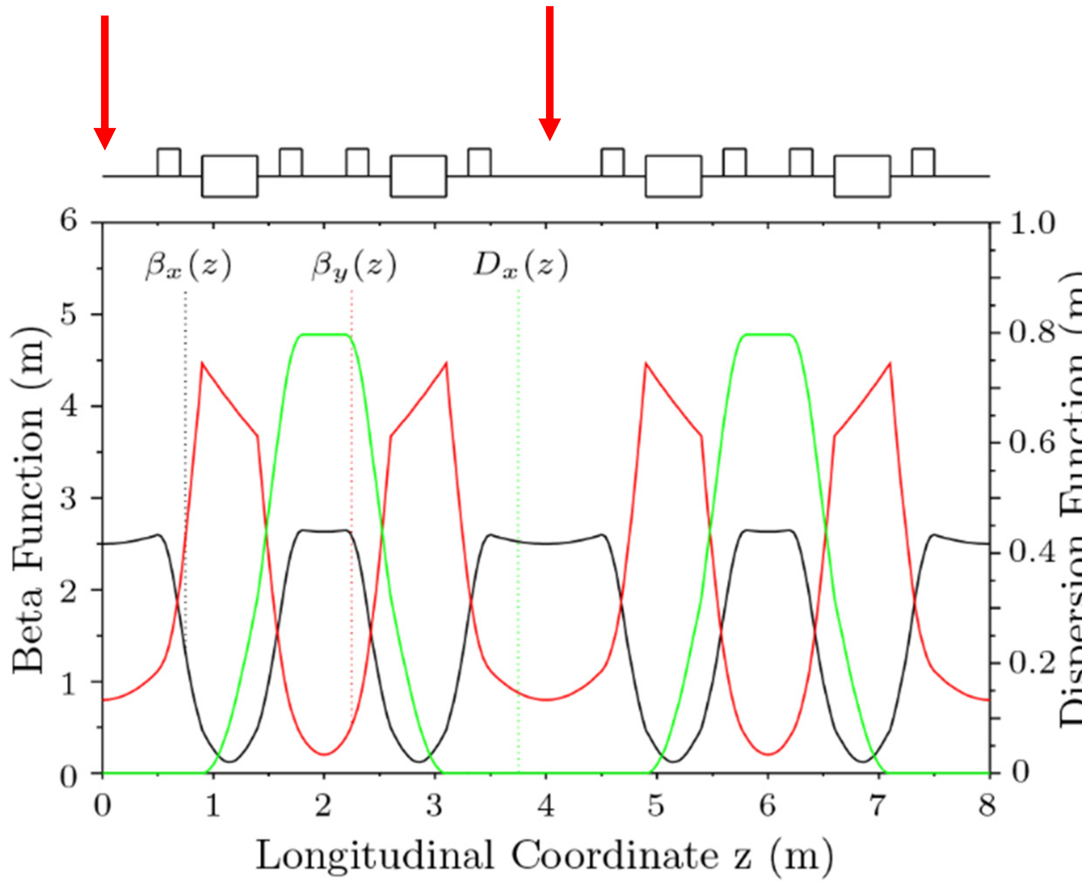
ReA Buncher Ring

- Buncher Ring for ReA can provide lossless injection into RFQ
  - A nominal 200ns pulse from the EBIT can be transported into the ring with large longitudinal acceptance
  - An accelerating structure with harmonic number $h = f_{RF}/f_o$ and peak voltage V can rotate the pulse in phase-space
  - To produce a pulse, after n revolutions, that is matched to the RFQ acceptance
- Ring can be configured in a wide variety of ways to manipulate the pulse structures of delivered beams
- Electron cooling channel for enhancing mass resolution
- Allows for the implementation of isomeric separation techniques to explore the metastable state of an atomic nucleus

Transverse Considerations of ReA Ring

Lattice Parameters	Values
Circumference C	8 m
Beam Kinetic Energy W_o	12 keV/u
Dipole Bending Radius ρ	0.318 m
Dipole Edge Angles ϵ_1, ϵ_2	30°
β_x, β_y at Injection Point	2.5 m, 0.8 m
α_x, α_y at Injection Point	0, 0
Betatron tunes ν_x, ν_y	0.11, 0.31
Momentum Compaction Factor α_c	0.091

- Dipole edge angles provide vertical focusing
- Quadrupole magnets provide horizontal focusing
- Dispersion Function and derivative of Beta Function minimize at injection point and location of accelerating structure



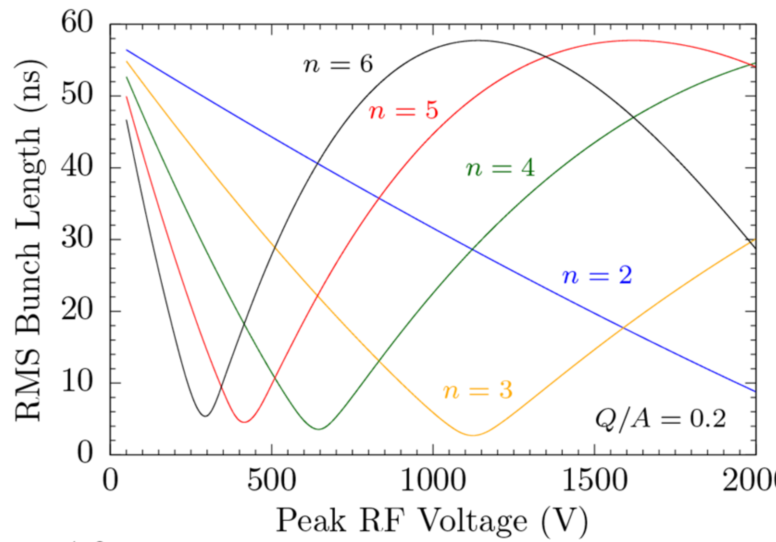
Longitudinal Considerations of ReA Ring

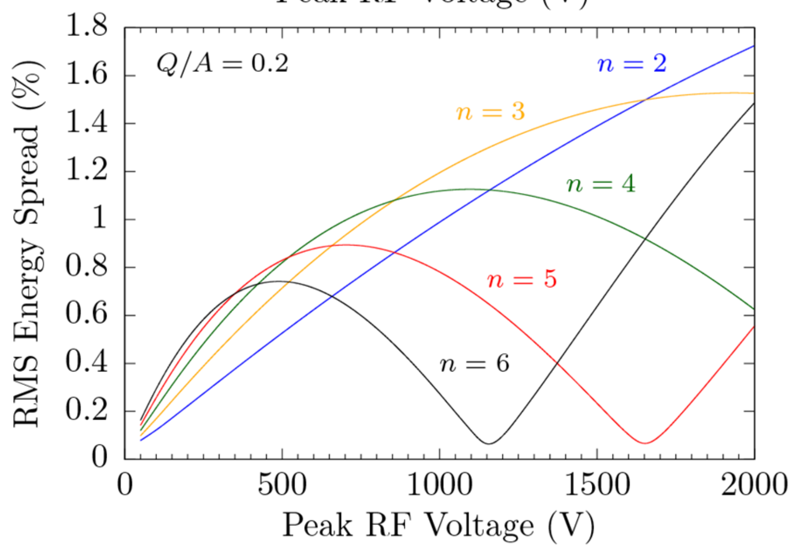
Radio Frequency Parameters	Values
Revolution Frequency f_o	190.2 kHz
Revolution Period T_o	5.3 μs
RF Harmonic Number h	5
RF Frequency f_{rf}	951.1 kHz
RF Phase Slip Factor η	-0.909

$$H = \frac{eV}{2\pi}\left(\frac{Q}{A}\right)\left[\cos(\phi_s + \Delta\phi) + \Delta\phi \sin\phi_s\right] + \frac{1}{2}\frac{h\eta\omega_o^2}{\beta^2 W_s}\left(\frac{\gamma - 1}{\gamma}\right)\left(\frac{\Delta W}{\omega_o}\right)^2$$

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta}{\beta^2 W_s}\left(\frac{\gamma - 1}{\gamma}\right)\Delta W_n$$

$$\Delta W_{n+1} = \Delta W_n + eV\left(\frac{Q}{A}\right)\left[\sin\phi_{n+1} - \sin\phi_s\right]$$

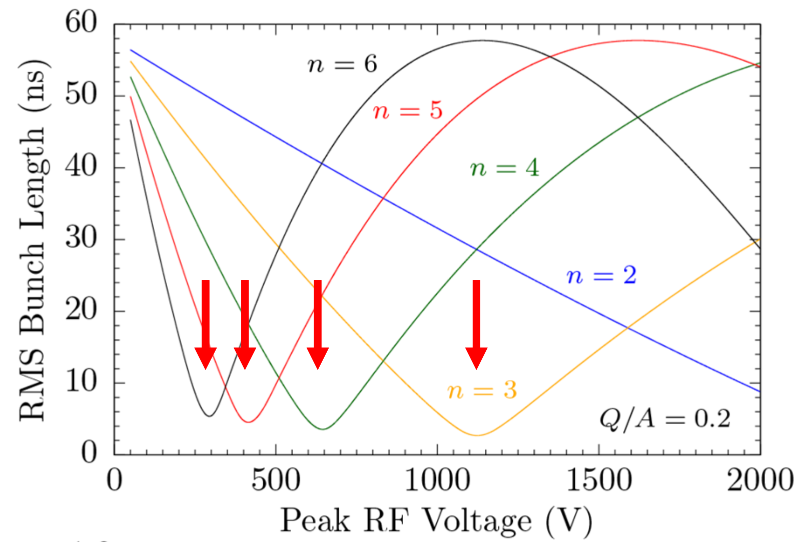


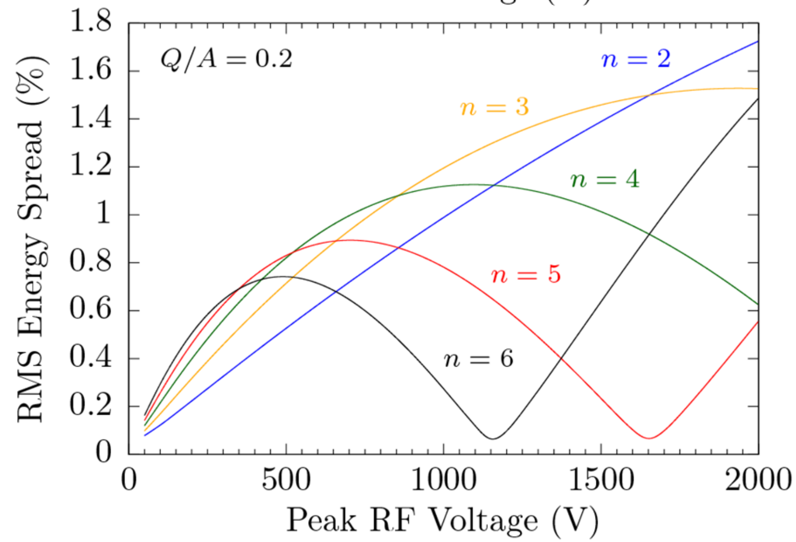


Longitudinal Considerations of ReA Ring

Radio Frequency Parameters	Values
Revolution Frequency f_o	190.2 kHz
Revolution Period T_o	5.3 μs
RF Harmonic Number h	5
RF Frequency f_{rf}	951.1 kHz
RF Phase Slip Factor η	-0.909

- Longitudinal tracking of beams into RFQ explored assuming initial 200ns bunch with energy spread of 0.5% from the EBIT
- Peak RF voltage requirement decreases with n revolutions in the ring





Longitudinal Considerations of ReA Ring

Radio Frequency Parameters	Values
Revolution Frequency f_o	190.2 kHz
Revolution Period T_o	5.3 μs
RF Harmonic Number h	5
RF Frequency f_{rf}	951.1 kHz
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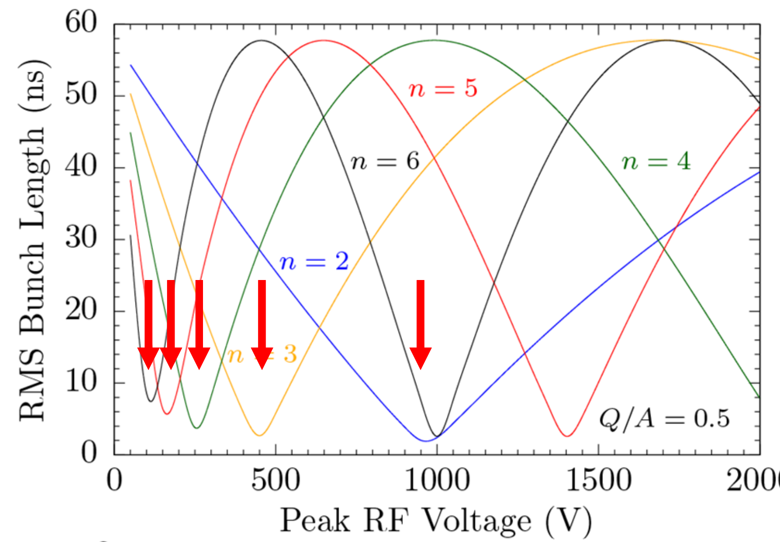
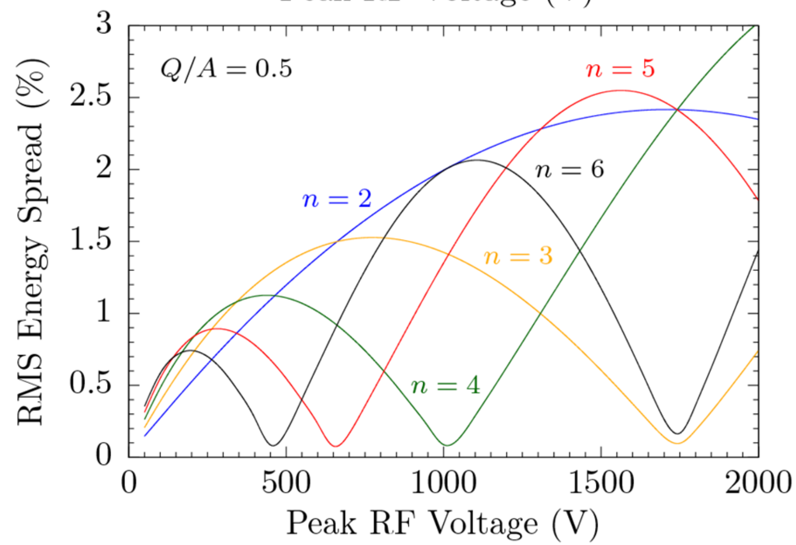
- Longitudinal tracking of beams into RFQ explored assuming initial 200ns bunch with energy spread of 0.5% from the EBIT
- Peak RF voltage requirement decreases with n revolutions in the ring
- Resulting energy spreads at RFQ entrance are well below energy acceptance range
- Smaller bunch lengths with increasing Q/A with slight increase in energy spreads





Ongoing Research

- Design of Injection and Extraction beam transport lines
- Explore more useful modes of storage ring operation
- MAD-X lattice simulation results are currently being benchmarked against COSY Infinity and WARP
- Find suitable option for low frequency accelerating structure
- Explore the possibility of electron cooling capabilities for enhanced mass resolution during mass separation
- Explore nuclear isomeric separation capabilities

Thank you for your time!

Feel free to contact me
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