EuCARD 2013

Nuclear Physics Accelerators - Accelerator Perspectives for Nuclear Physics

P.N. Ostroumov

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Content

- NSAC and NuPECC long range plans
- RHIC performance upgrades
  - High luminosity Run-II
- Low energy Ion-Ion and Electron-Nucleon Colliders
- EIC: BNL proposal, JLAB proposal, LeHC
- High current, high energy SC ERL
- Cooling of hadron beams: new ideas
- Radioactive ion beam facilities
- Driver and post accelerators
- SRF for nuclear physics
- Advanced concepts for MW-scale targets
- R&D on ion, electron sources including polarized beams
- Charge breeders for radioactive ions
- Applications
- Summary

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  - Thomas Roser (BNL)
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  - Paolo Giubellino (CERN)
  - Frank Zimmermann (CERN)

  Web-sites: Accelerators for America's Future: http://www.acceleratorsamerica.org/

  NSAC long range plan:

  http://science.energy.gov/~/media/np/nsac/pdf/docs/nuclear_science_low_res.pdf

  NUPECC long range plan:

  http://www.nupecc.org/lrp2010/Documents/lrp2010_booklet_final.pdf

  Town meeting “Relativistic Heavy-Ion Collisions”

  http://indico.cern.ch/conferenceDisplay.py?confId=192371

Nuclear Physics Research Frontiers-1, *NSAC LRP*

- QCD and its implications and predictions for the state of matter in the early universe, quark confinement, the role of gluons, and the structure of the proton and neutron
  - What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
  - What is the internal landscape of the nucleons?
  - What does QCD predict for the properties of strongly interacting matter?
  - What governs the transition of quarks and gluons into pions and nucleons?
  - What is the role of gluons and gluon self interactions in nucleons and nuclei?
  - What determines the key features of QCD, and what is their relation to the nature of gravity and space-time?
- Existing and future accelerators:
  - High-energy CW electron Linac –JLAB
  - Ion-ion collider – BNL, heavy-ion LHC
  - **Electron Ion Collider (EIC), FAIR, ENC&FAIR, HL-LHC, LHeC**

Nuclear Physics Research Frontiers-2, *NSAC LRP*

- The structure of atomic nuclei and nuclear astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos
  - What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
  - What is the origin of simple patterns in complex nuclei?
  - What is the nature of neutron stars and dense nuclear matter?
  - What is the origin of the elements in the cosmos?
  - What are the nuclear reactions that drive stars and stellar explosions?
- Existing and future accelerators:
  - Accelerator facilities – ATLAS, ISOLDE, NSCL, LBNL,TRIUMF, GSI, COSY, RIKEN, GANIL, INFN-Catania, INFN-LNL-Legnaro, IUAC-New Delhi, Many Universities Labs, JYFL (Finland), CIAE (China), HIF at IMP (China, Lanzhou), JINR (Dubna, Russia), SARAF (Israel)
  - **Upgrades: RIKEN, HIE-ISOLDE, SPES at INFN-LNL**
  - **New Projects: Spiral2 at GANIL, FRIB (USA), FAIR (Germany), RAON (S. Korea),ISOL@ MYRRHA**
  - **Future Projects: EURISOL**

Nuclear Physics Research Frontiers-3, *NSAC LRP*

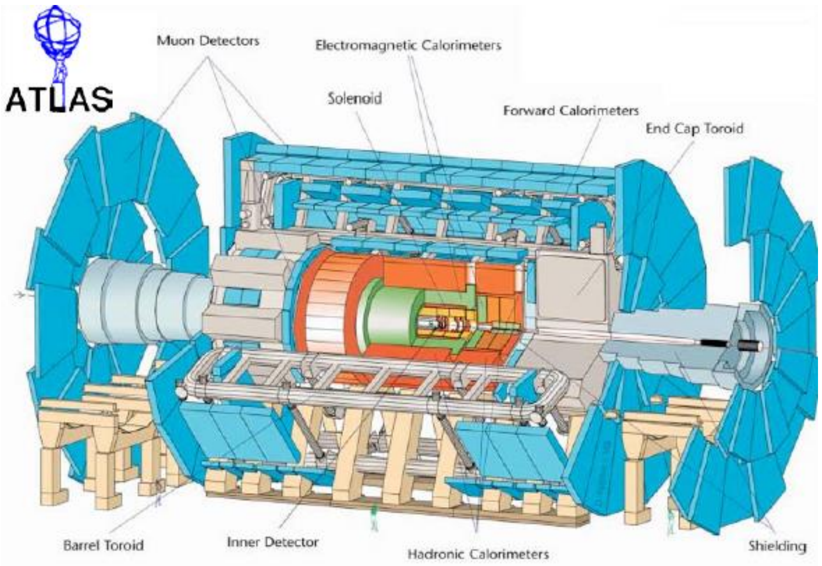
- Developing a New Standard Model of nature's fundamental interactions, and understanding its implications for the origin of matter and the properties of neutrinos and nuclei
  - What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?
  - Why is there now more visible matter than antimatter in the universe?
  - What are the unseen forces that were present at the dawn of the universe but disappeared from view as the universe evolved?
- Existing and future accelerators:
  - Accelerator facilities – JLAB, SNS
  - **JLAB 12 GeV Upgrade**
  - **High-intensity proton accelerators (Project X)**
  - **Neutrino Factories**
  - **Beta beams**

NSAC and NuPECC Long Range Plans

- Near term
  - Complete 12 GeV CEBAF Upgrade, Spiral2 at GANIL
  - RHIC-II luminosity upgrade and detector improvements
  - Construction of the Facility for Rare Isotope Beams, FRIB
  - Construction of FAIR
  - ISOL@MYRRHA
  - Luminosity increase of colliding heavy ions at LHC
- Long term
  - High-luminosity Electron-Ion Collider (EIC)
  - LHeC
  - Electron Nucleon collider, FAIR Upgrade
  - EURISOL

Relativistic Heavy Ion Physics at LHC

- The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC



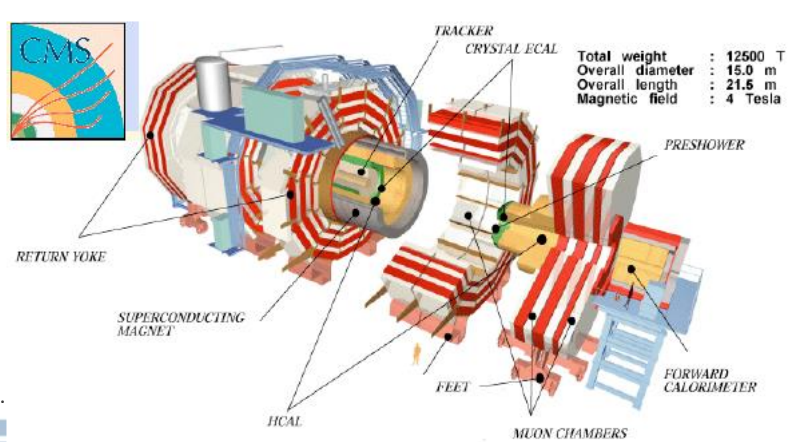
Design

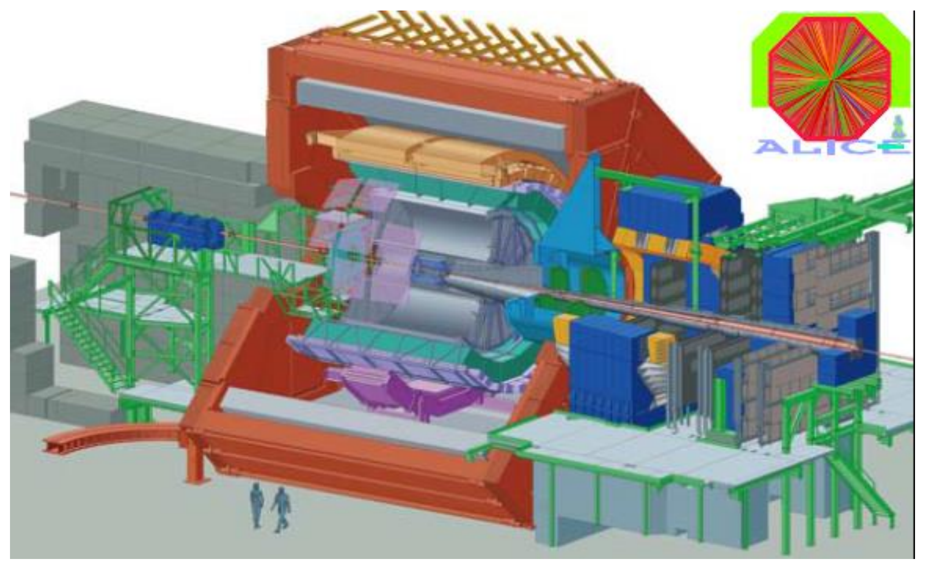
C.m. energy 5.5 TeV per nuclear pair

Luminosity – 10^{27} cm^{-2} s^{-1}

Achieved peak luminosity at lower energies

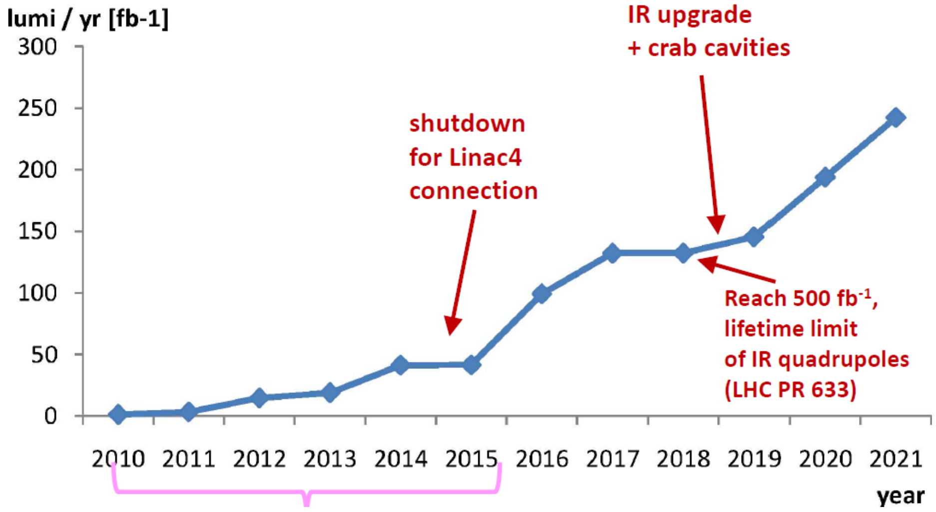
5×10^{26} cm^{-2} s^{-1}





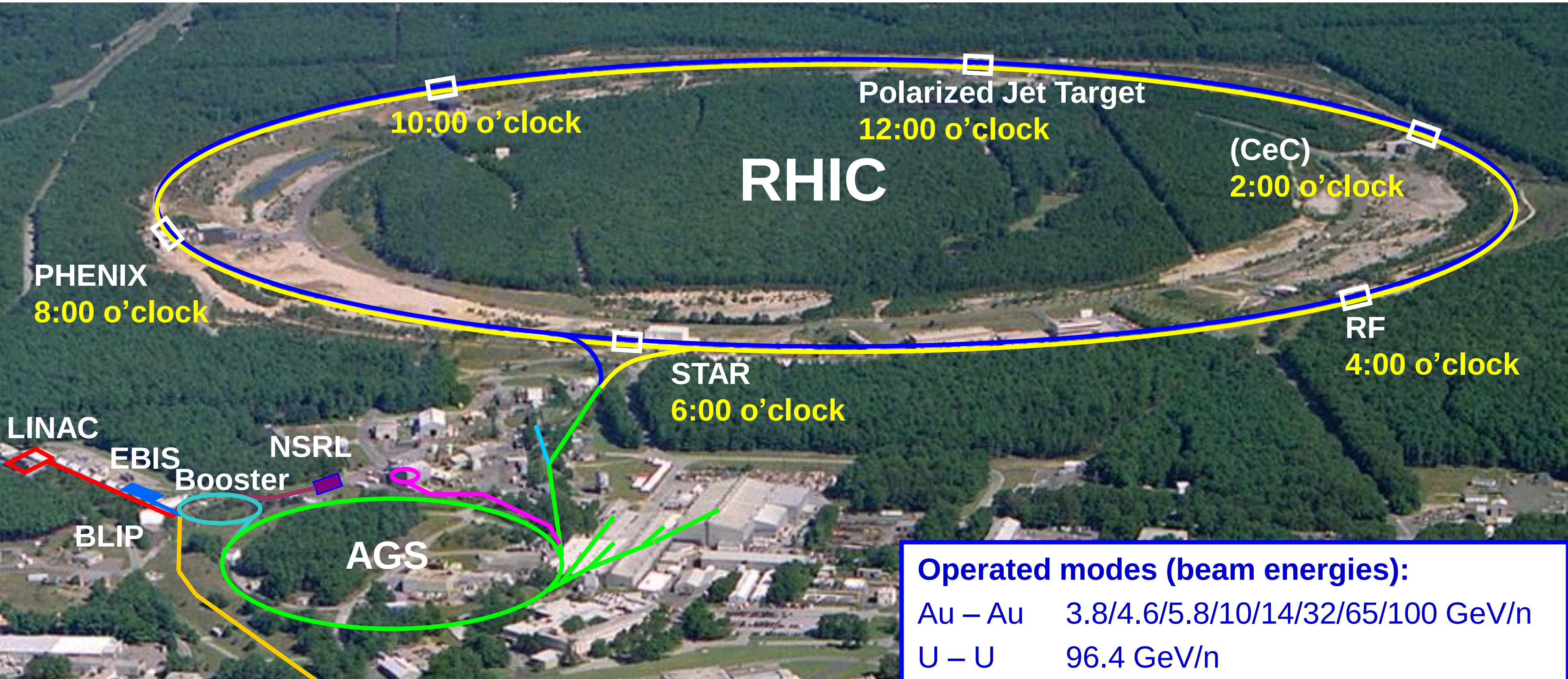
LHC Luminosity Upgrade with Heavy Ion Beams

- LINAC3
  - Number of ions accelerated per pulse
  - Increase the Linac3 repetition rate
  - Modify Linac3 for multiple charge acceleration



- LEIR: reduce beam losses
- PS: reduce bunch spacing, batch compression
- SPS: improve injection system, reduce RF noise in high harmonic cavities
- Crab cavities in the LHC
- Interaction region upgarde
- Stochastic cooling in the LHC?
- Design luminosity can be increased by an order of magnitude
- Upgrade detectors to accept higher luminosity

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au – Au (100 GeV/n) 195×10^{30} cm^{-2} s^{-1}

p↑ – p↑ (255 GeV) 165×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar) 110×10^{30} cm^{-2} s^{-1}

LHC (p – p) 430×10^{30} cm^{-2} s^{-1}

Center-mass energies: 7-500 GeV

Operated modes (beam energies):

Au – Au 3.8/4.6/5.8/10/14/32/65/100 GeV/n

U – U 96.4 GeV/n

Cu – Cu 11/31/100 GeV/n

p↑ – p↑ 11/31/100/205/250/255 GeV

d – Au* 100 GeV/n

Cu – Au* 100 GeV/n

Planned or possible future modes:

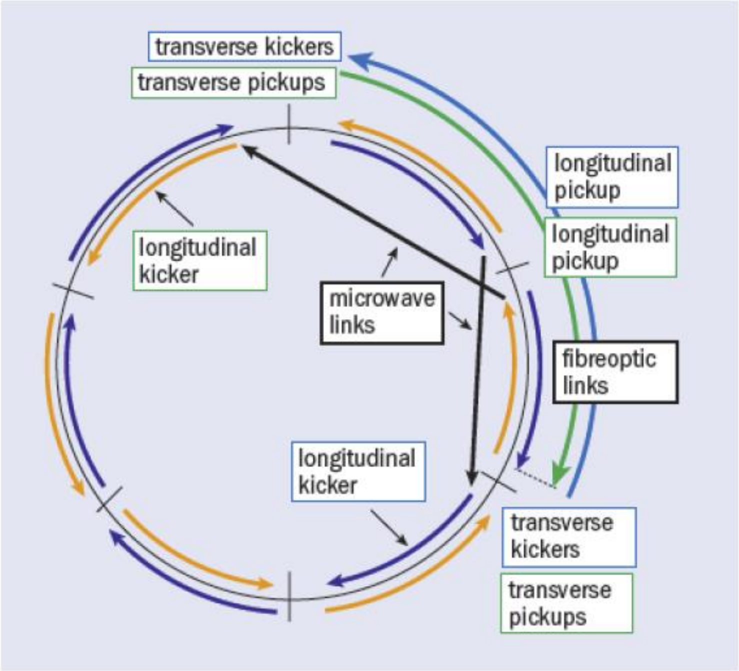
Au – Au 2.5 GeV/n

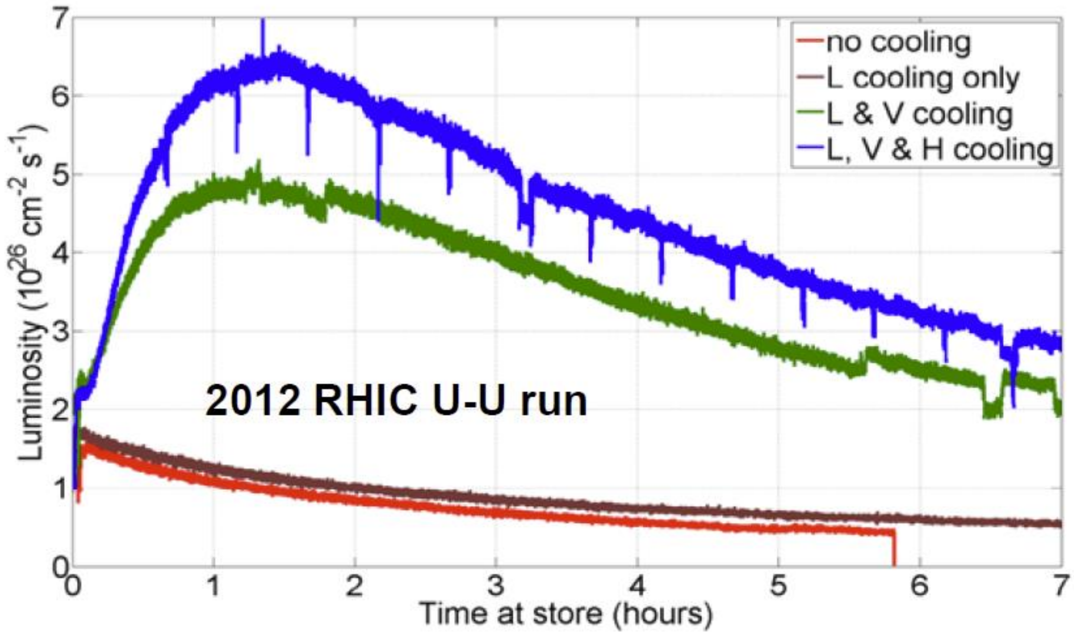
p↑ – Au* 100 GeV/n

p↑ – ^{3}He↑* 166 GeV/n (*asymmetric rigidity)

RHIC – II, Ongoing Upgrades

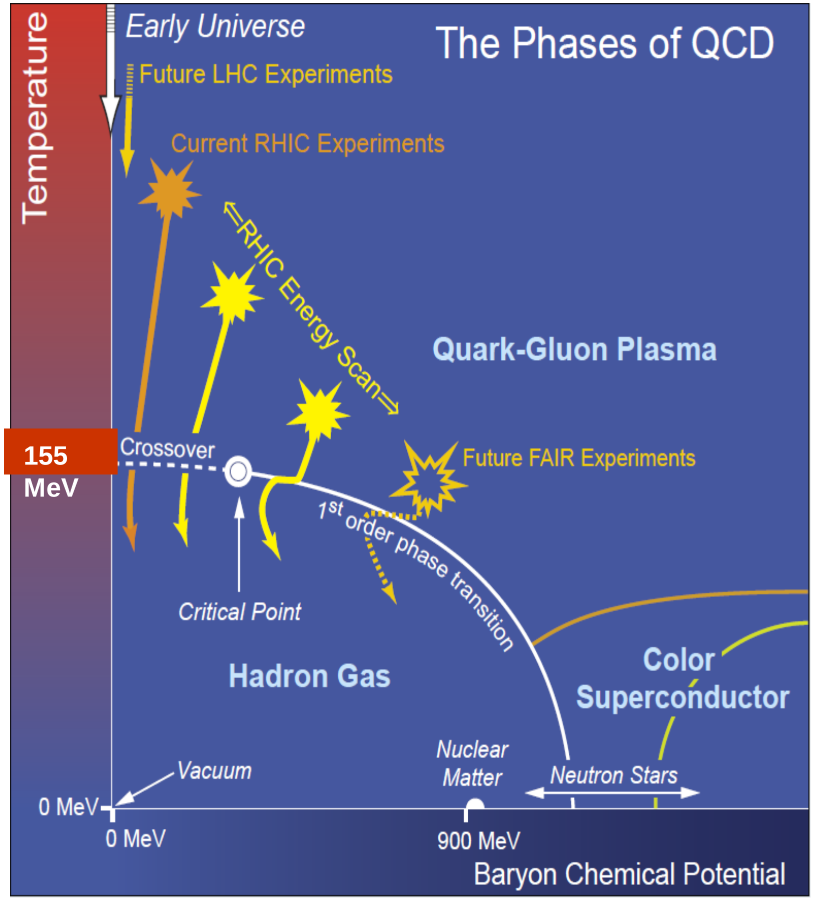
- Significant luminosity increase by bunched-beam stochastic cooling
- EBIS injector can provide most ion species, two different species for asymmetric ion-ion collisions
- Head-on beam-beam (p-p) compensation with the help of electron beam lenses - 2014
- 56 MHz storage cavity to reduce vertex length - 2014

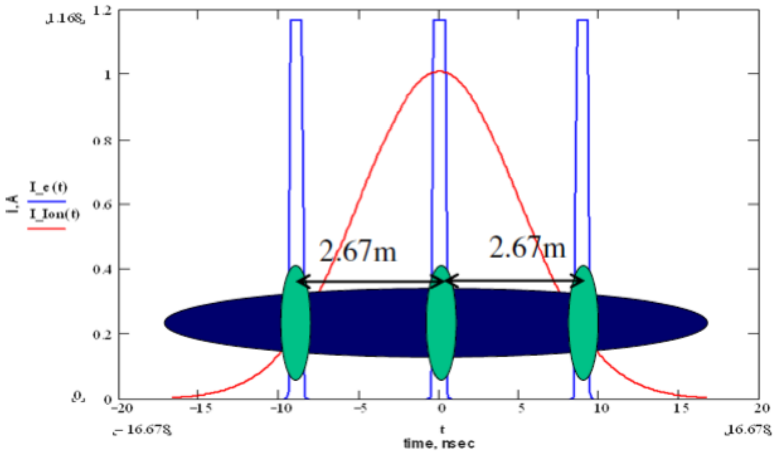


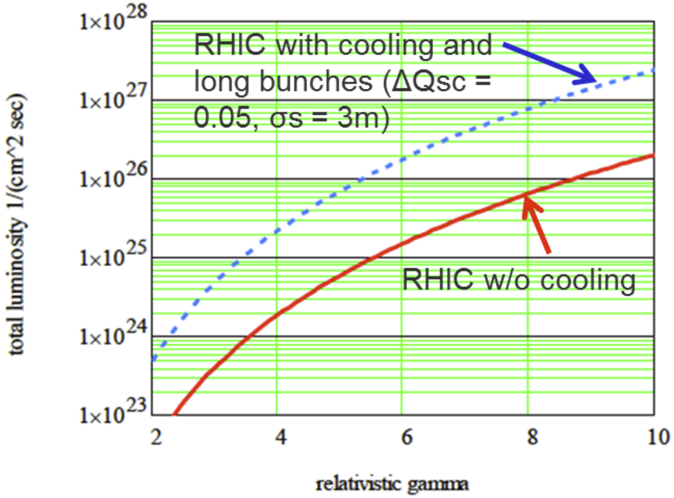


RHIC – II, Future Upgrade

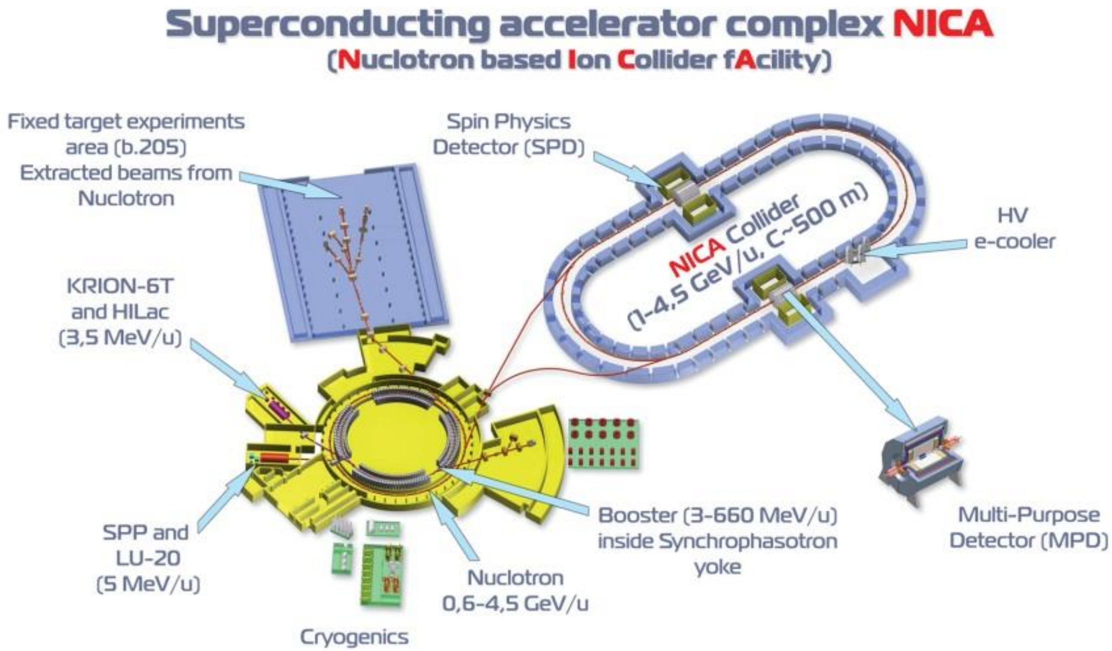
- Search for the Critical Point in the phase diagram
- Simulation of the anticipated order of magnitude improvement in low-energy Au+Au collision luminosity by the addition of low-energy electron cooling and the use of lengthened beam bunches in RHIC





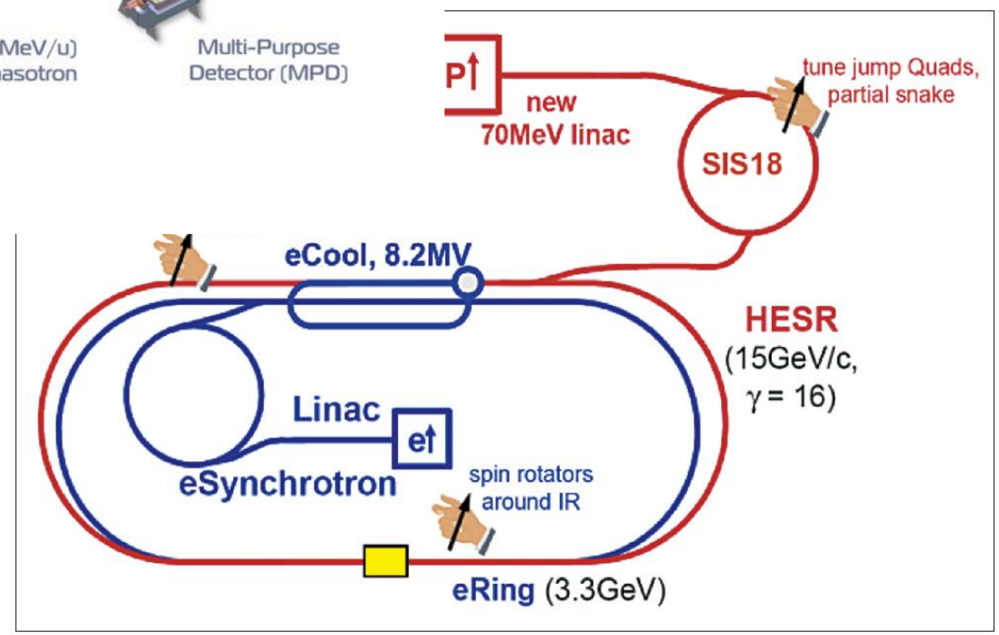


Low-Energy Ion-Ion and Electron Nucleon Collider



NICA at Dubna

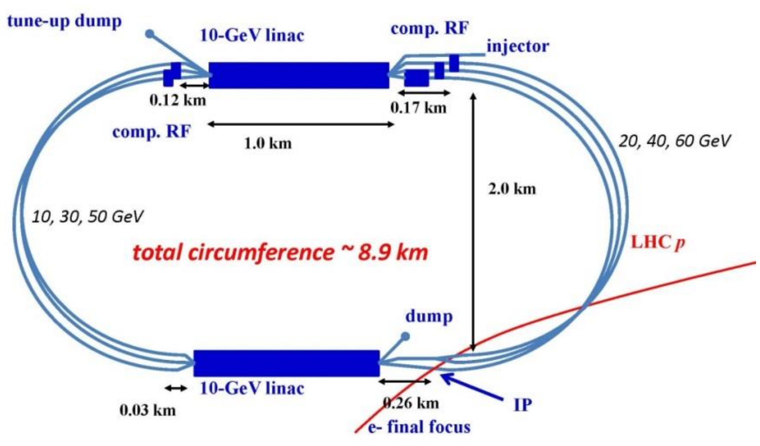
FAIR Upgrade



Layout of ENC@FAIR.

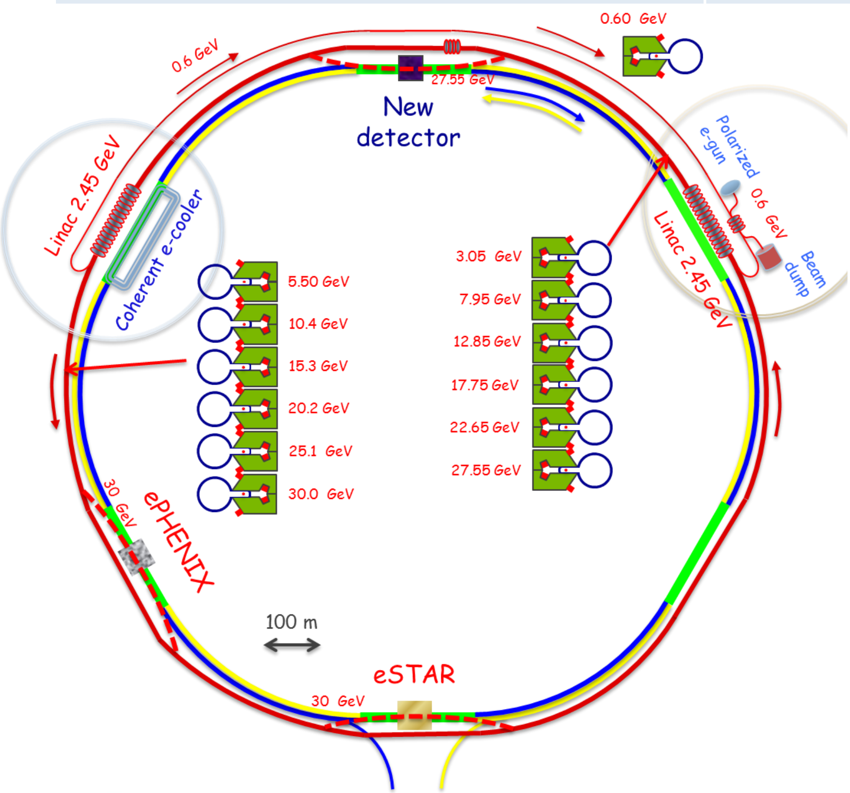
Electron Ion Colliders

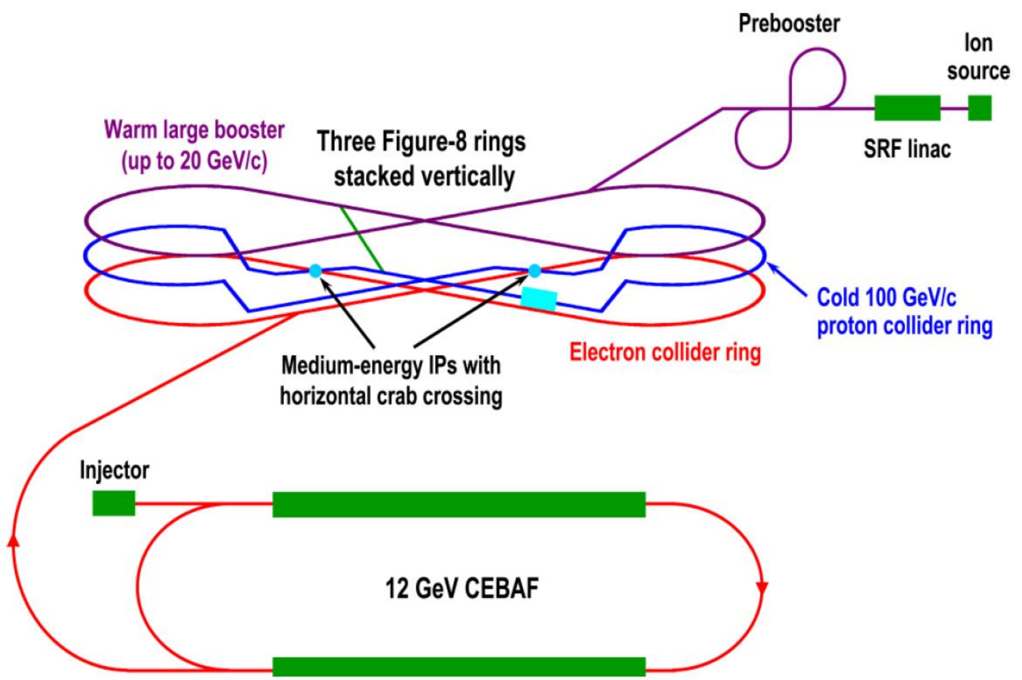
- While the HERA collider at DESY provided electron-proton collisions at energies e-27.5 GeV, p-920 GeV, the performance needed at a future electron-ion collider relies on three major advances over HERA:
  - Beams of heavy nuclei, at least up to gold, are essential to access the gluon saturation regime under conditions of sufficiently weak QCD coupling, and to test the universality of the CGC (Color Glass Condensate);
  - Collision rates exceeding those at HERA by at least two orders of magnitude;
  - Polarized light-ion beams, in addition to the polarized electrons available at HERA, are mandatory to address the central question of the nucleon's spin structure in the gluon-dominated region.
- The LHeC is an LHC upgrade to electron-ion collider at ≥ 1 TeV center-mass energy. Two options for electron accelerator
  - A ring accelerator for electrons, 70 GeV
  - ERL with ILC type cavities, 140 GeV
  - Luminosities are ~100 times larger than HERA
  - Each electron accelerator option has own challenges



Plans for an Electron-Ion Collider in the USA

	eRHIC	MEIC	ELIC
Energy, GeV e/p/HI	30/250/100	20/100/40	20/250/100
Luminosity, 10^{33} $cm^{-2}s^{-1}$	~1	~1	~2
Polarized beams	e, p	e, p, Li	e, p, Li



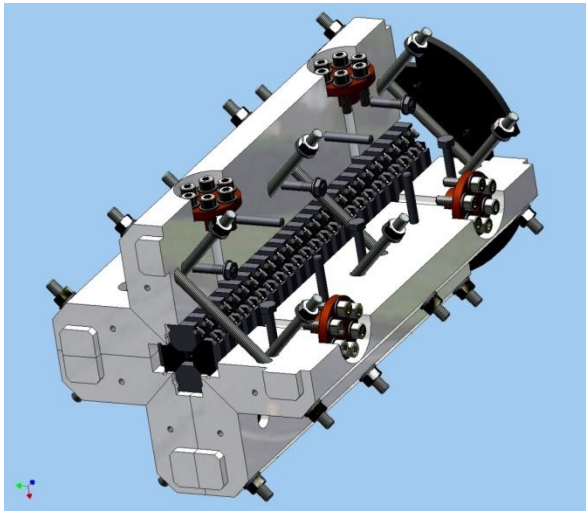


EIC: Accelerator Challenges Beyond State of the Art

- Polarized electron gun – factor of 10 higher intensities, up to 50 mA
- Coherent Electron Cooling – New concept
- Electron cooling based on SRF linac and recirculating electron beam
- Multi-pass 30-GeV SRF ERL: 5x increase in current,30x increase in energy
- Crab crossing: new for hadron colliders
- Understanding of beam-beam effects
- New type of collider, β^*=5 cm, 5x reduction, strong magnets
- Feedback for kink instability suppression: novel concept
- Small aperture strong focusing magnets for electron beam rings
- Effective synchronization of the colliding beams at different energies
- Mitigate effect of electron clouds
- Preservation of beam polarization
- Ion sources: high-intensity polarized light ion sources

Coherent Electron Cooling - I

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high-brightness electron beams and FEL technology
- Being developed for eRHIC
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (~ 2015)

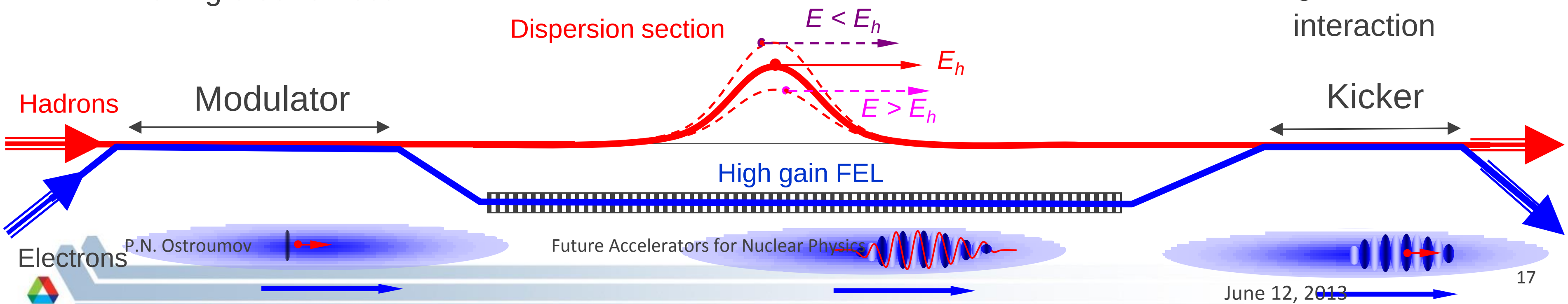


Helical wiggler prototype

Pick-up: electrostatic imprint of hadron charge distribution onto co-moving electron beam

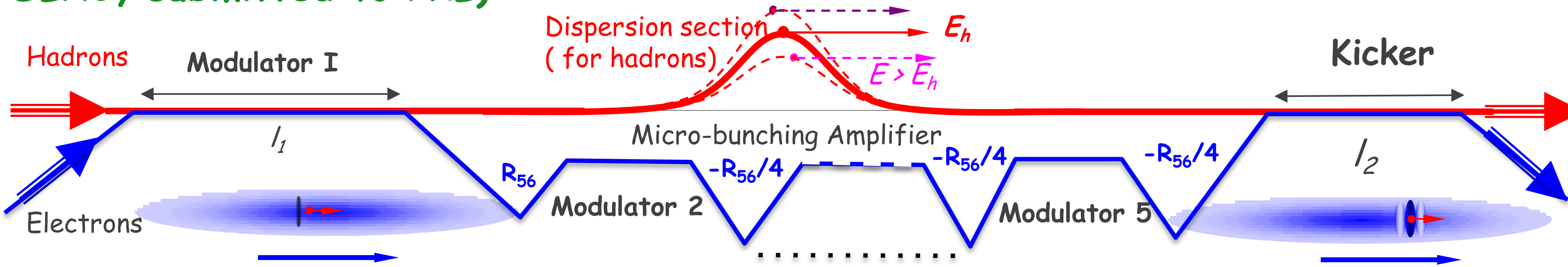
Amplifier: Free Electron Laser (FEL) with gain of 100 -1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

Kicker: electron beam corrects energy error of co-moving hadron beam through electrostatic interaction



Coherent Electron Cooling – II

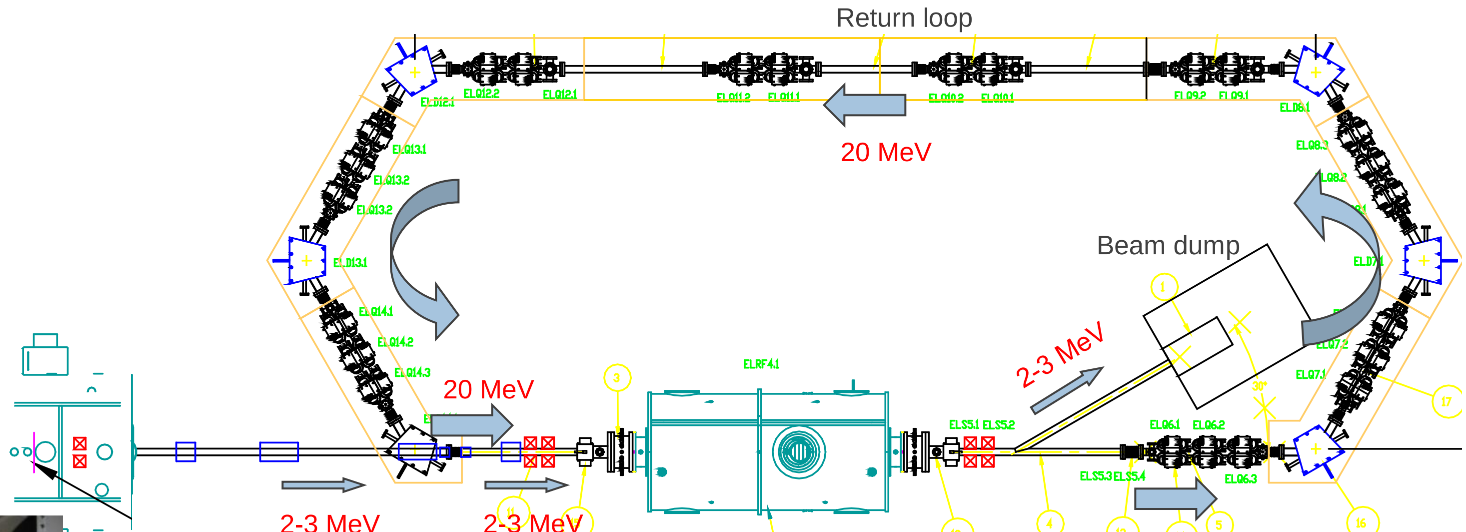
Enhanced bunching (single stage 2007 - VL, Multi-stage 2013, D. Ratner, SLAC, submitted to PRL)



Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, Long/trans, hrs	Trad. Electron cooling, hrs	Coherent Electron Cooling, hrs
RHIC PoP	***Au***	***40***	**-**	**-**	**~ 1**	***0.02/0.06***
eRHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
eRHIC	**p**	**325**	**~100**	**40,246 ∞**	**> 30**	**~0.1**
LHC	p	7,000	~ 1,000	13/26	∞ ∞	~1

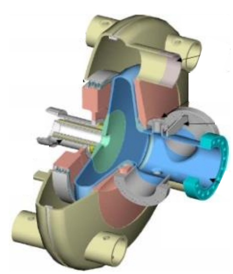
Energy Recovery Linac (ERL) Test Facility

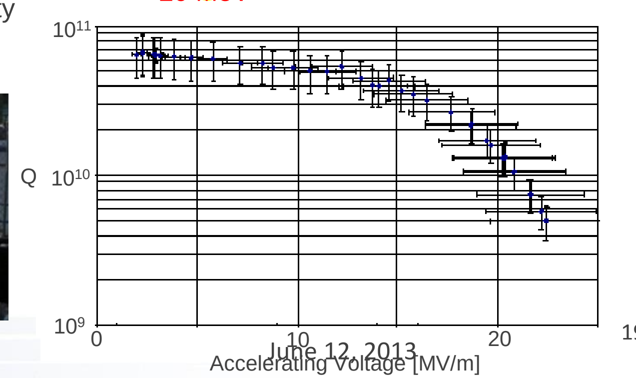
- Test of high current (0.3 A, 6-passes eRHIC), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Gun rf tested at 2 MV; recirculating beam is expected in 1-2 years
- Test bed for high-intensity/brightness ERL and linac applications



SRF Gun
2MV, 0.5A

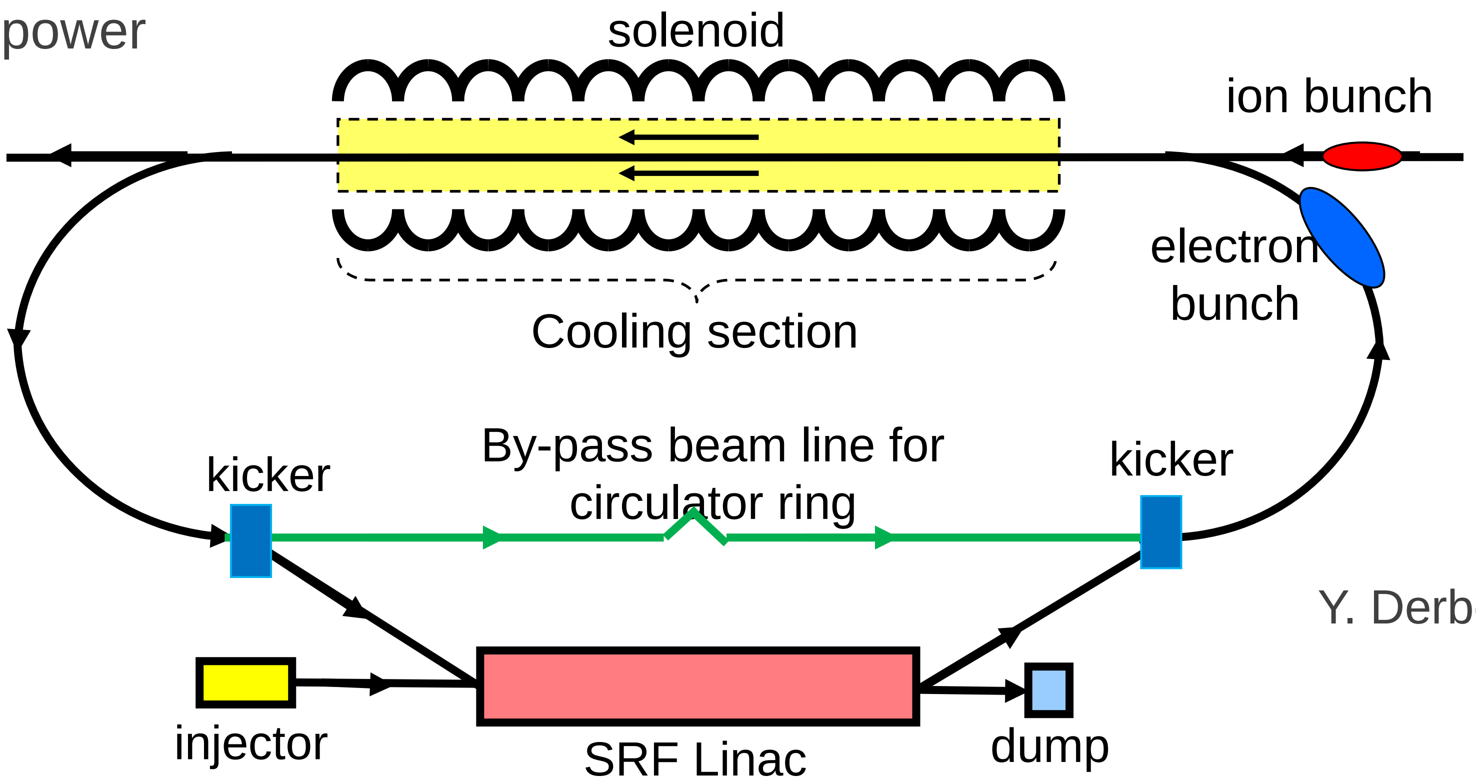
5 Cell SRF "single mode" cavity
Q > 10^{10} @20 MV/m CW





SRF Linac for Electron Cooling in the MEIC collider

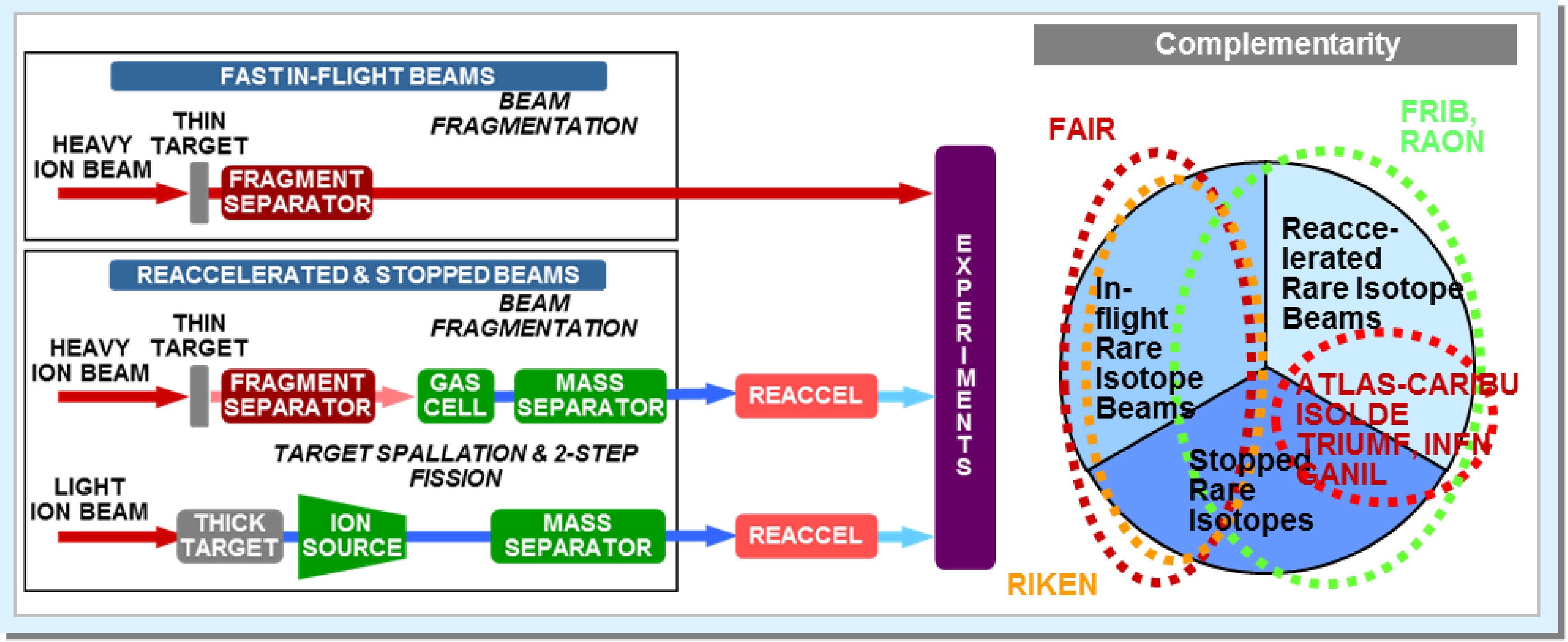
- Multi-stage electron cooling is proposed in MEIC
- Last stage: cooling during the collisions. Single pass linac can not be used: 81 MW for a 1.5 A electron beam with 55 MeV.
- Use ERL and pulsed e-gun, circulate about ~100 turns, average current from the gun is 15 mA: tremendous reduction in average power



Y. Derbenev

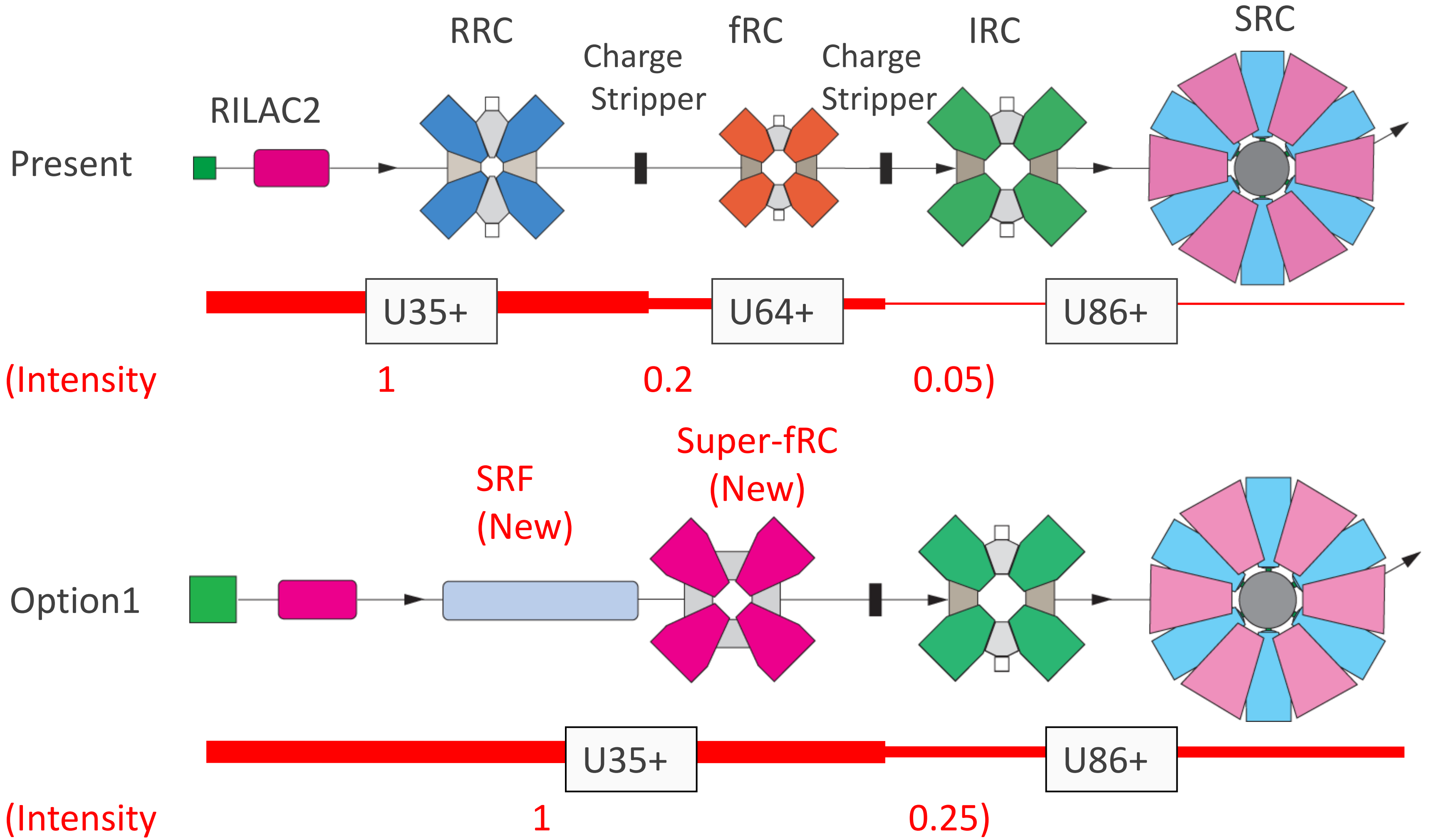
Radioactive Ion Beam Facilities

- Existing large facilities: ISOLDE, GSI, NSCL, RIKEN,GANIL and TRIUMF
- Funded large facility projects: GANIL-SPIRAL2, FAIR, FRIB, RAON (Korea)
- Many smaller facilities: ATLAS-CARIBU (ANL), SPES, EXCYT, many University facilities,…
- Proposals: EURISOL

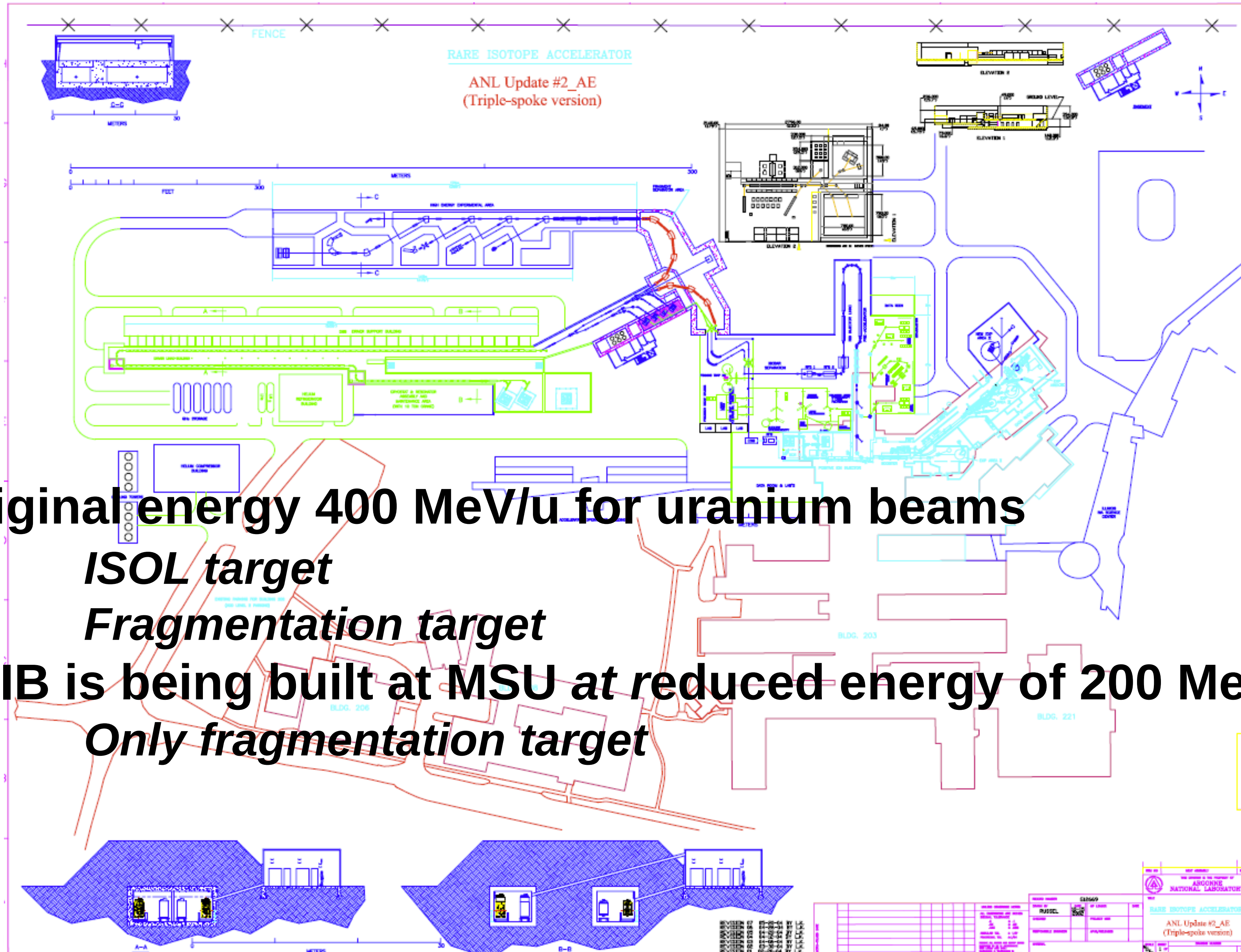


Intensity Upgrade of RIKEN RI Beam Factory

- Presently RIKEN provides 350 MeV/u uranium beam with very low intensity ~50 pnA



Original Rare Isotope Accelerator Proposal in the USA



Original energy 400 MeV/u for uranium beams

ISOL target

Fragmentation target

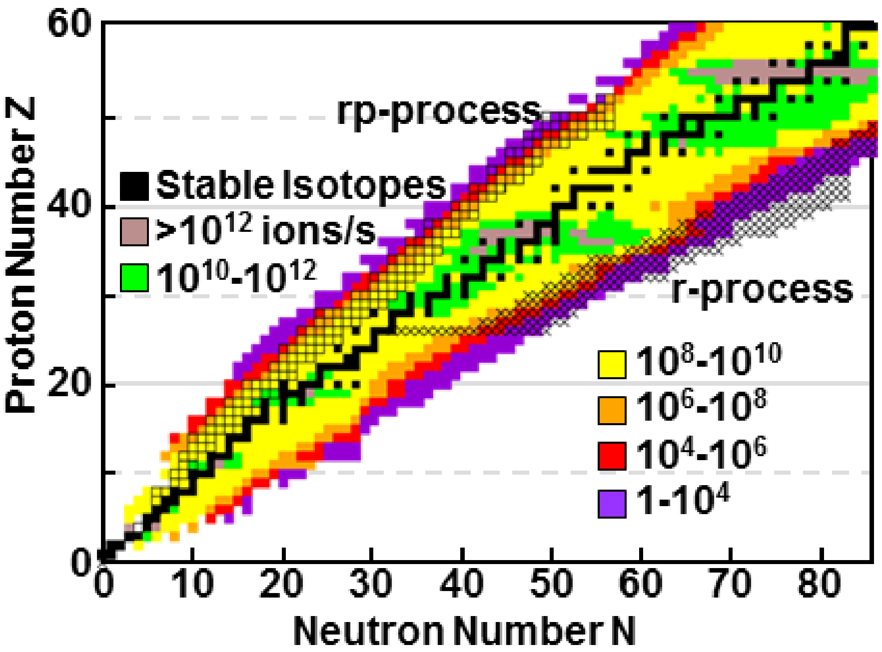
FRIB is being built at MSU *at reduced energy of 200 MeV/u*

Only fragmentation target

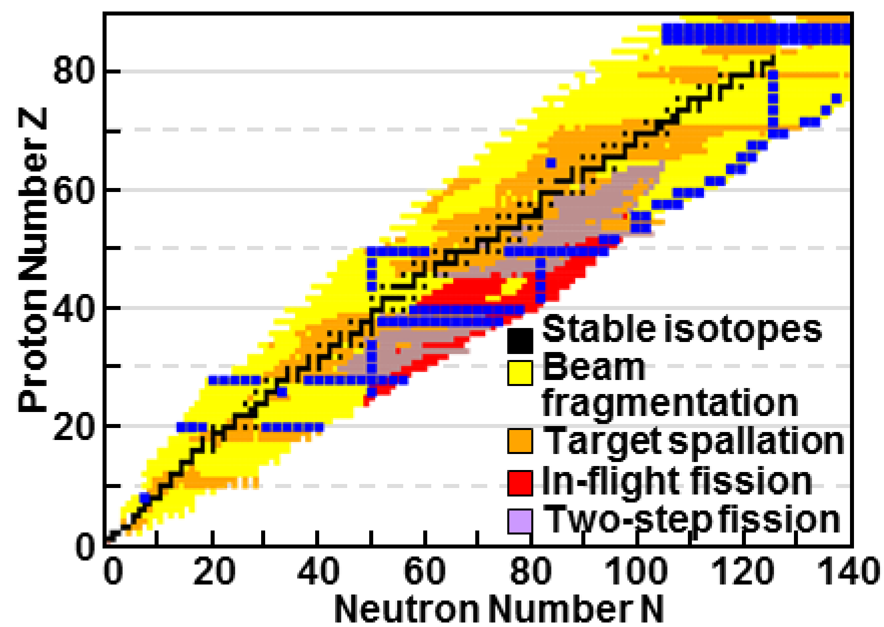
Original US Rare Isotope Accelerator Proposal

- Did not get funded due to the cost considerations
- CW SRF accelerator with capability to accelerate multiple charge state uranium beams
- Included ISOL (thick) and in-flight (thin) targets

Intensities of isotopes in 400 MeV/u, 400 kW RIA

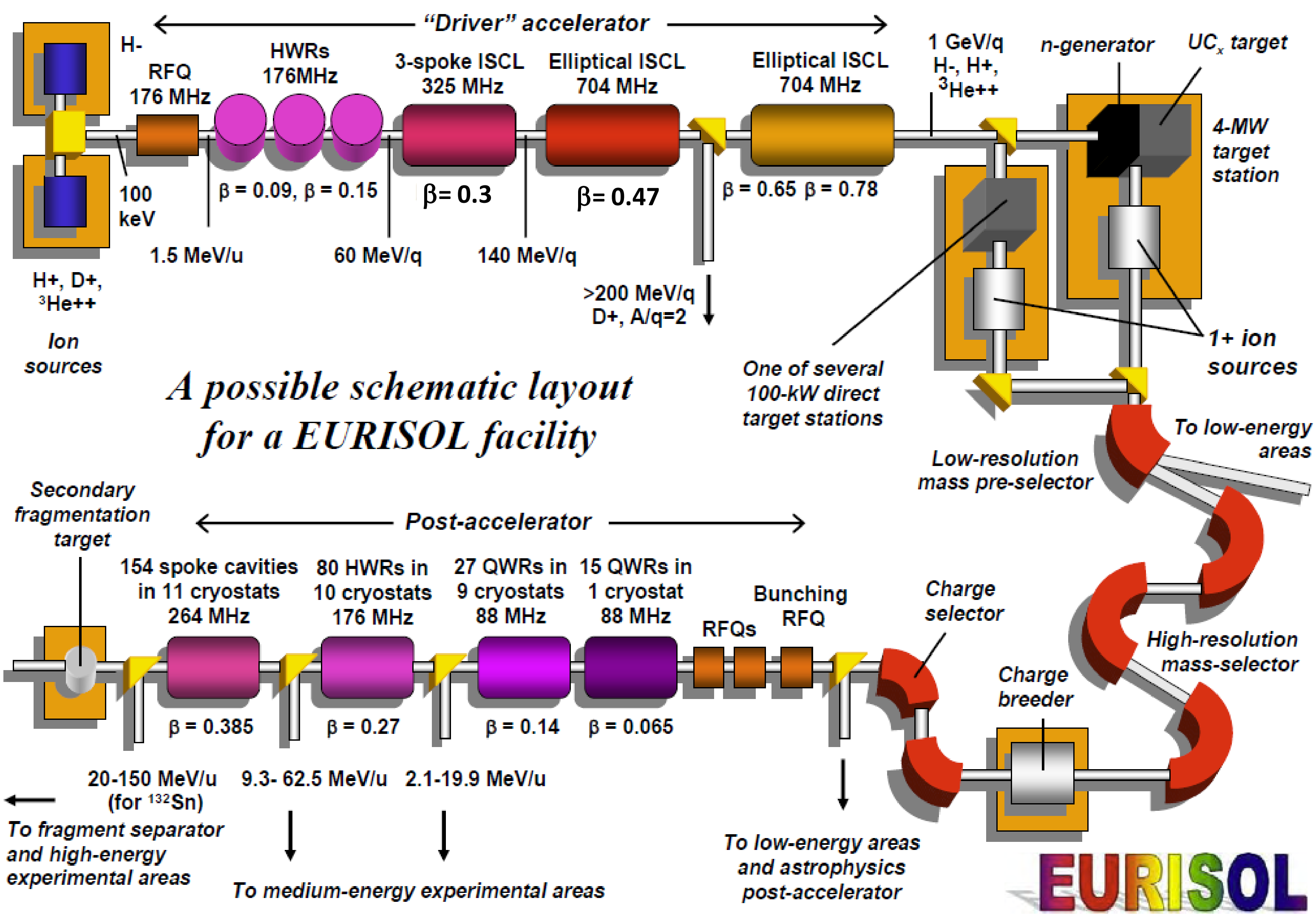


Production mechanisms



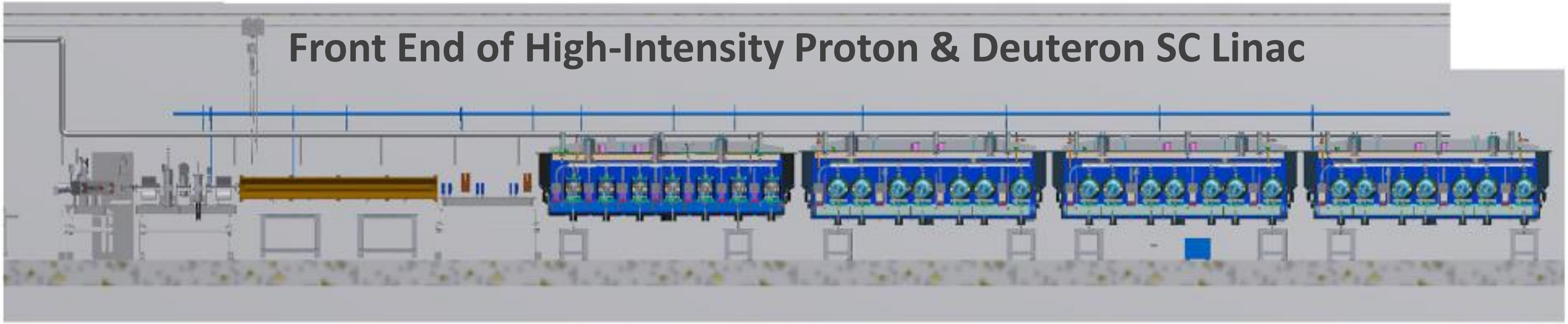
EURISOL Proposal

- Driver linac: 5 MW beam power



Future Driver Accelerators, Light and Heavy Ions

- CW operation for maximum beam power – SRF linac
- High-intensity high charge state DC ion source
- ~2 GeV/u fully-stripped uranium beam is required for best yields from fragment separators, total linac voltage is ~6 GV
- Stripper technology for high-power heavy ion beams
  - Liquid metal films
- New technologies for cost-effective acceleration of ion beams are required
  - More efficient superconducting cavities
  - New high-gradient CW accelerating structures for full velocity range

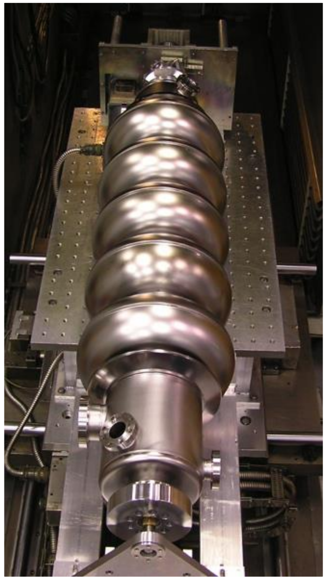


Future Post Accelerators for Radioactive Beams

- CW accelerators with similar voltage, ~6 GV, as in the driver linac for the best yield of new isotopes; SRF technology
- 1+ post-accelerator in the front end to increase the intensity and eliminate contamination of reaccelerated beams
- High-intensity beta-beams for neutrino factories
- The addition of a storage ring, providing opportunities for mass measurements and detection of isomers as well as for charge radius measurements via electron scattering on the stored ions: electron-radioactive beam collider

SRF Accelerators

- Various types of SC cavities are required to cover full velocity range from ~0.025c to 1.0c
  - Technology is available, but expensive
- ERL: high-current SC electron linac
- Cost of bulk niobium for accelerating cavities and cryomodules is high and is continuously going up in the last decade
- Cost of cryoplants and liquid helium is increasing
- Cost of operation is high
- Roadmap:
  - New SRF materials
    - Thin films on copper substrate
    - Multi-layer coating
    - Atomic layer deposition
  - Increase cryogen temperature
  - Increase efficiency of cryoplants



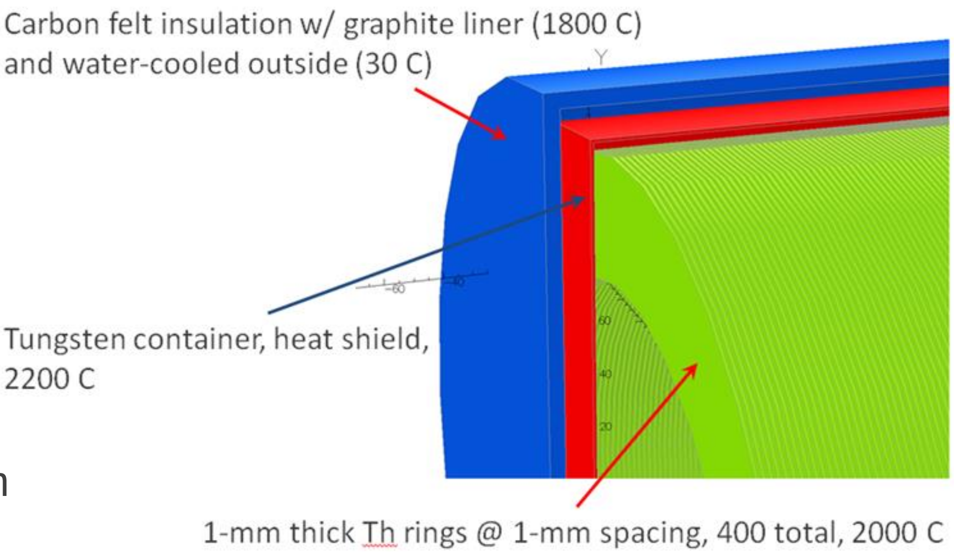
Advanced Concepts for MW-Scale Heavy Ion Facilities

MW-scale ISOL-type targets for next generation sources of isotopes for fundamental symmetry physics

Extrapolation to 1-GeV, 500 μA for Project X: Rn, Fr

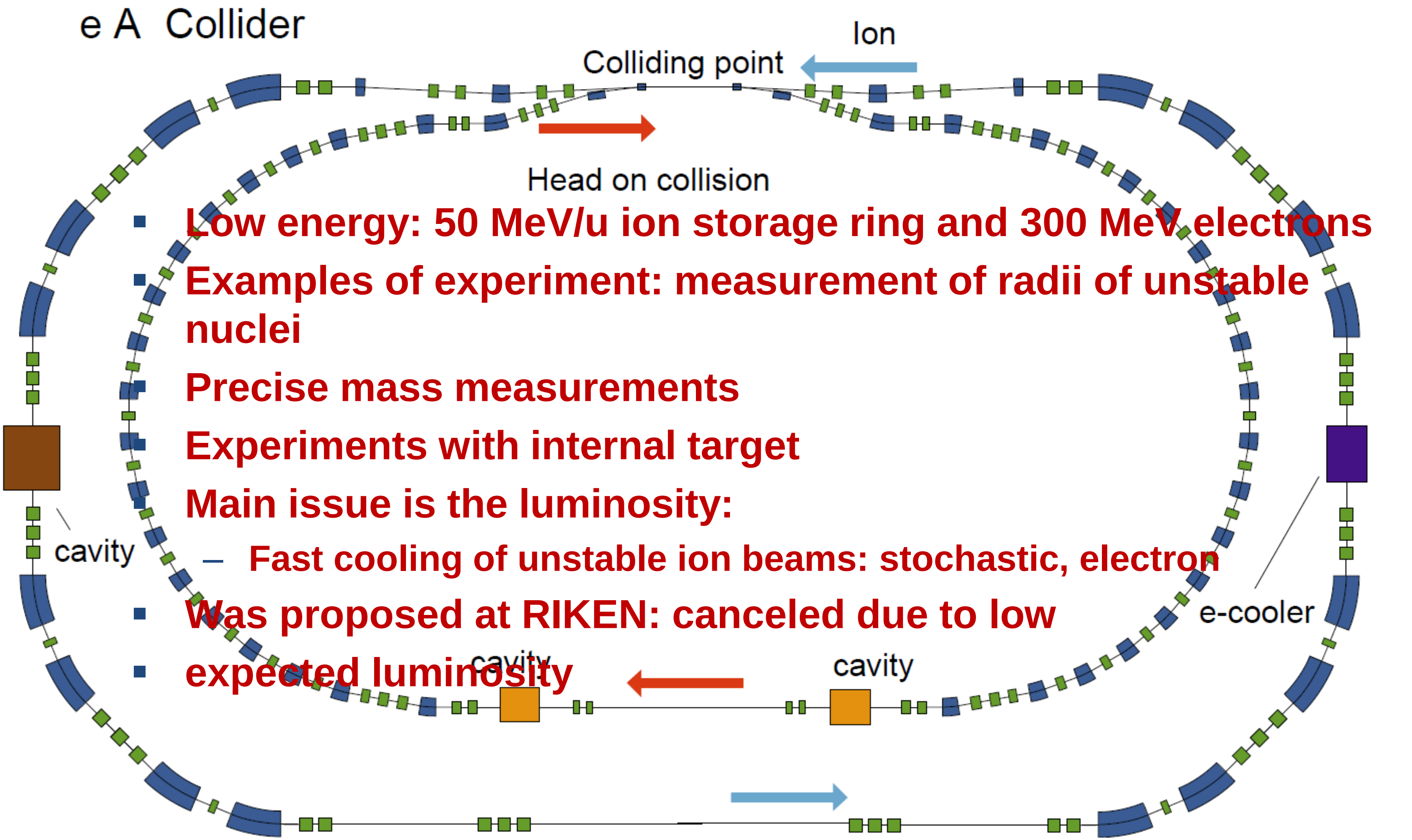
- Operating temperature ~2000 C to release isotopes
- Must radiate ~120 W/cm^2 at this T
- Power loss ~1500 W/cm -> diameter ~25 cm
- Optimum thickness ~200 g/cm^2 thorium (~1 radiation length)
- Average density ~2.5 g/cm^3 (1-mm thick disks 5 g/cm^2 with 1-mm spacing) -> target length ~80 cm, 400 disks
- Annular target, 1-cm diameter beam spot at ~12-cm radius; rotation > 1 kHz
- Insulation by 1 tungsten heat shield and 5-mm graphite felt
- Water cooling on outside surface

500-kW thorium target concept - close-up



MW-scale infrastructure for heavy ion beams, e.g. liquid tin beam dumps for uranium beams.

Electron – Radioactive Ion Colliders

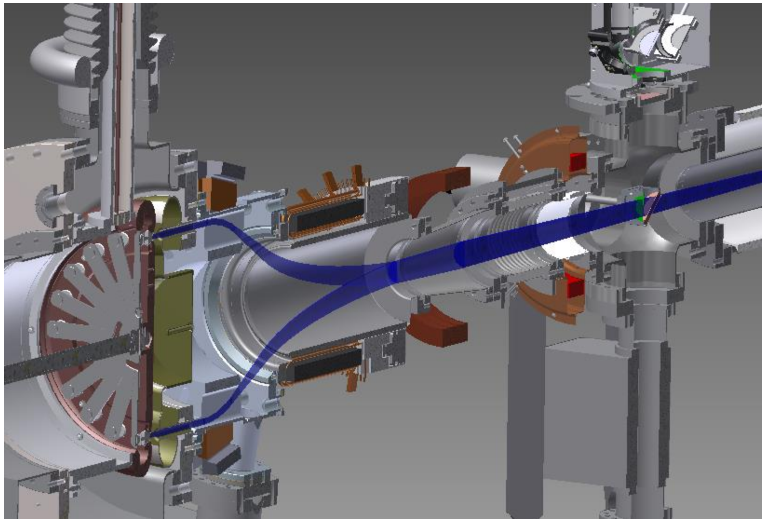


- **Low energy: 50 MeV/u ion storage ring and 300 MeV electrons**
- **Examples of experiment: measurement of radii of unstable nuclei**
- **Precise mass measurements**
- **Experiments with internal target**
- **Main issue is the luminosity:**
  - **Fast cooling of unstable ion beams: stochastic, electron**
- **Was proposed at RIKEN: canceled due to low**
- **expected luminosity**

Electron Sources

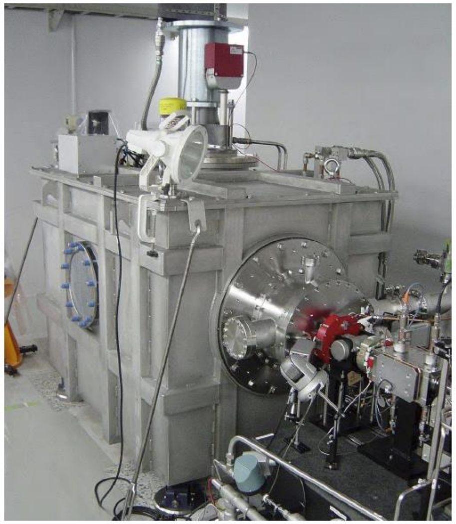
- High-current, low-emittance DC electron guns
  - Electron cooling
  - Energy recovery linacs
- High current (>50 mA) polarized electron sources for EIC

BNL's Gatling Gun project
for polarized election beams

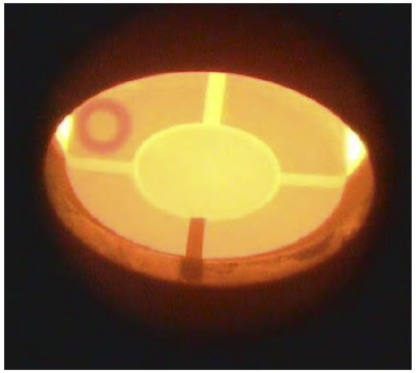


SPRING-8 (Japan) thermal cathode,
1 A very low emittance pulsed beam

500 kV Electron Gun



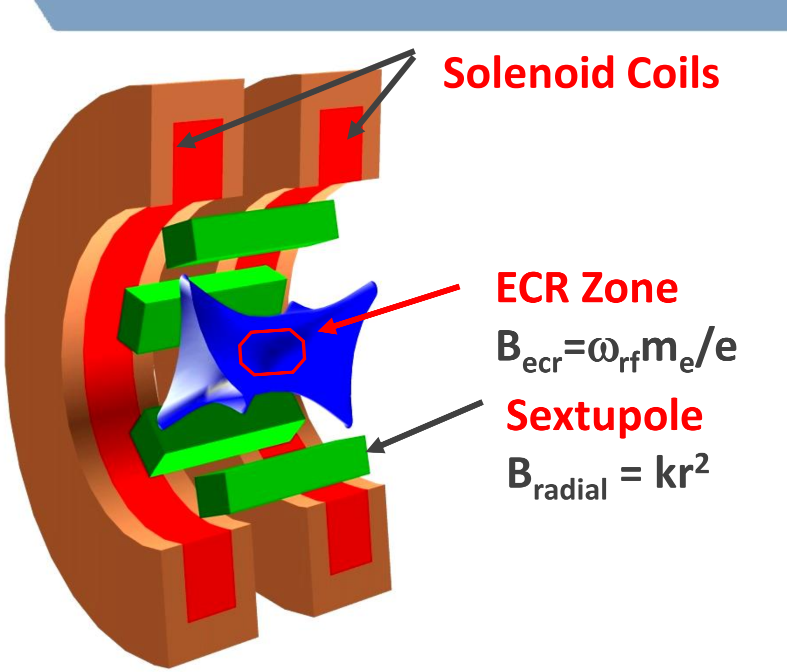
Heating Cathode



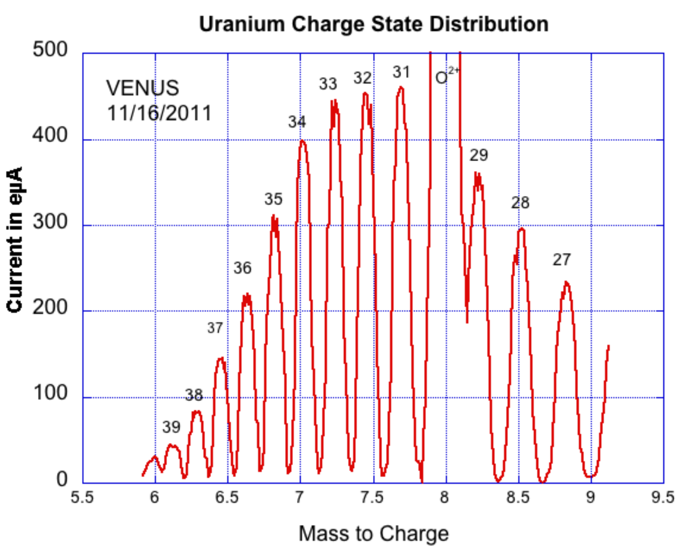
Diameter : ϕ3 mm
Temperature : ~1500 deg.C
Beam Voltage : 500 kV
Peak Current : 1 A
Pulse Width : ~2 μs

Ion Sources

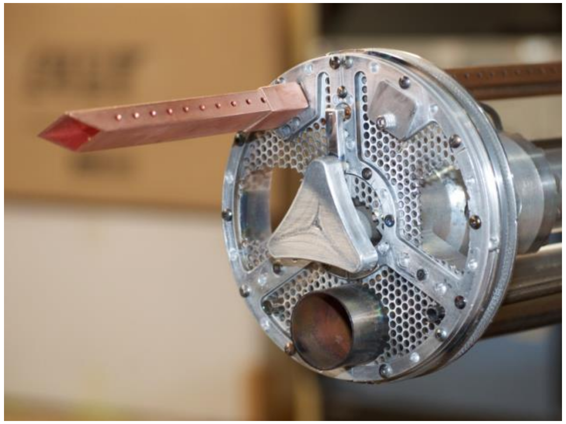
- High intensity DC and pulsed ion sources
  - High charge state to reduce required accelerating voltage of the linac
  - Heavy element synthesis
  - Pulsed: injection to synchrotrons



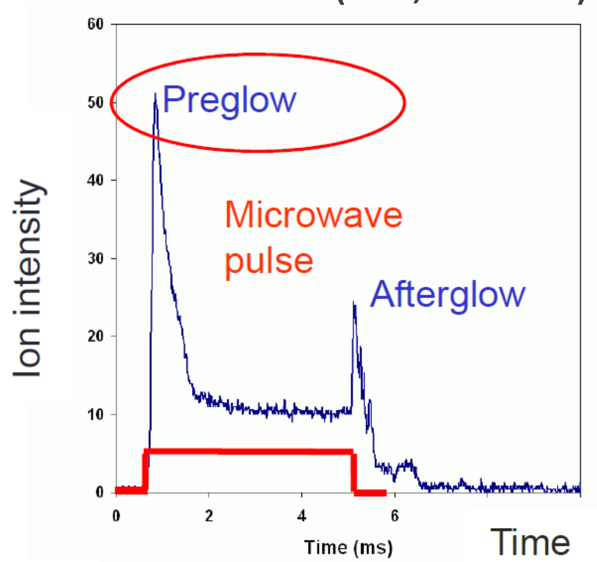
Modern DC ECR (LBNL, USA)



RF antennas



Pulsed ECR (IAP, Russia)

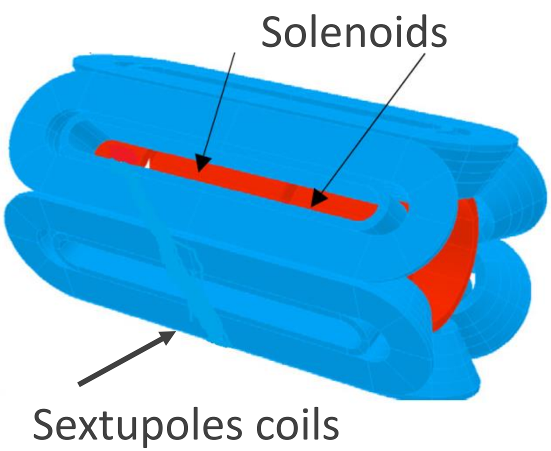


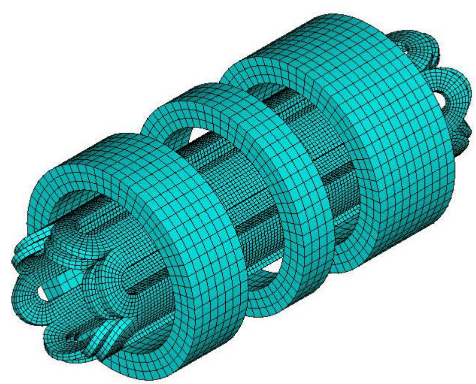
4th Generation ECR Sources

- Factor 4 gain in intensities of high charge states
- RF frequency is 50-60 GHz up to 35 kW. Very high density of RF power for plasma heating is required. CW RF power sources are needed
- Nb_3Sn SC solenoid and sextupole coils
- Issue: intense parasitic X-ray flux, generated by bremsstrahlung
- How to manage space charge for ~50 mA current from ECR ?

IMP-Lanzhou Design
SECRAL

LBNL Design: Sextupole and solenoids
Deformation of sextupole coils
due to EM forces: support system

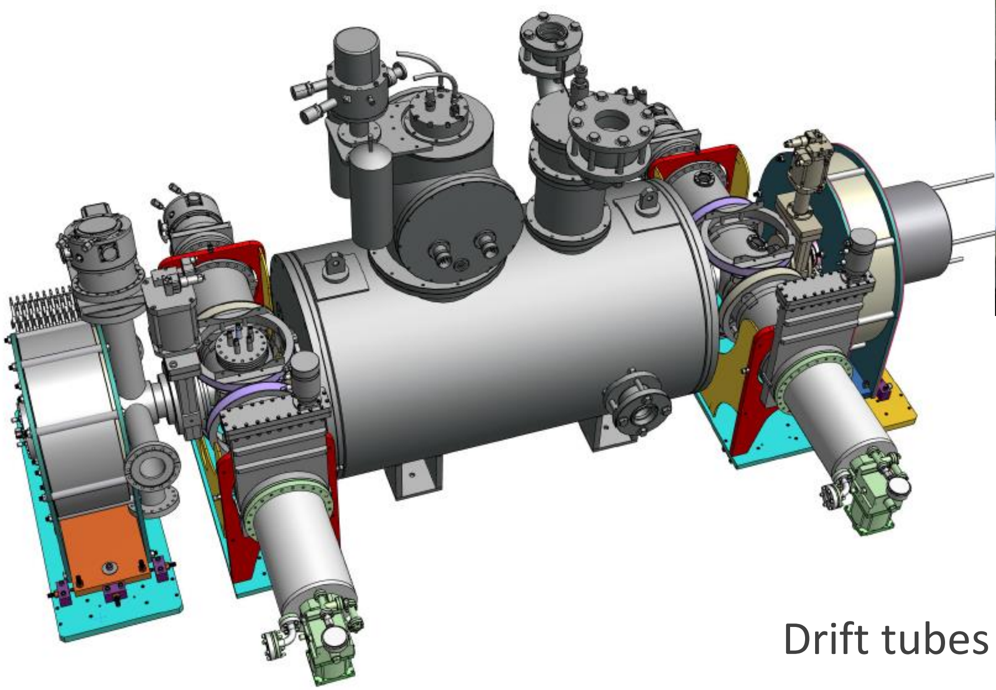




Radioactive Ion Charge Breeders

- Intensity of radioactive ions in the cooler-buncher is limited by space charge to ~10^6 ions/bunch, 4-5 order of magnitude increase is required
- EBIS: high efficiency, low contamination

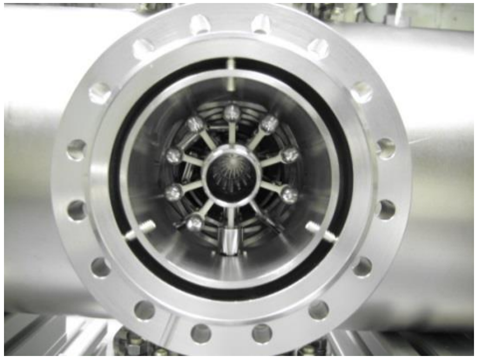
EBIS



E-collector

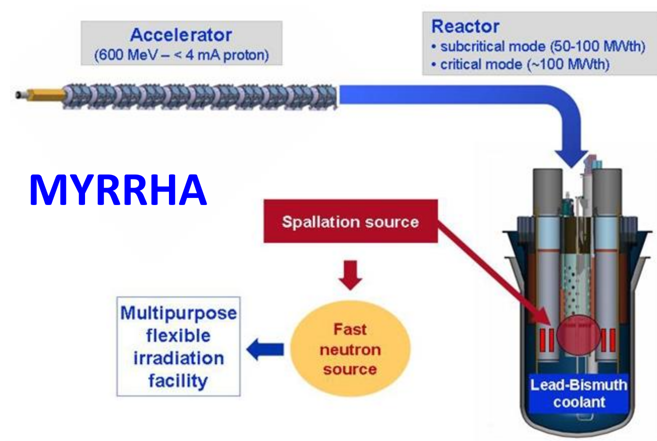
E-gun

Drift tubes



Applications, Some Examples

- The society receives significant benefits from accelerator R&D
- Light sources, neutron sources, FEL
- Accelerators for power generation and nuclear waste transmutation (ADS): technology is available
- Heavy-ion inertial fusion: extended R&D is required
- Developing materials for advanced nuclear power systems (IFMIF)
- Accelerators for medicine: radioisotopes, therapy, pharmaceutical developments
- Accelerators for industry: electron beam welding, ion beams for non-destructive elemental analysis of materials; semiconductor industry;…
- Accelerator mass spectroscopy
- **Future R&D: compact accelerator systems, low cost, small size, energy efficient, high reliability and performance**



Summary

- Strong R&D is taking place in many fronts:
  - Electron, ion sources, polarized sources
  - SRF technology, ERLs
  - Increased luminosity, beam cooling, small beta-function in EICs
  - Increased intensity of radioactive beams
- The next large machine for Nuclear Physics is a high-luminosity electron-ion collider
  - Polarized electrons, protons, light ions
  - Various heavy-ion species
- Beyond EIC
  - Much higher intensity radioactive beam facilities
  - Electron-radioactive ion colliders
  - Neutrino factories
- Successful accelerator R&D for Nuclear Physics generated wide applications for the society needs:
  - Accelerators for medicine, biology, material science, energy and industry