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Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Accelerator Physics Developments for Rare Isotope Facilities

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Outline

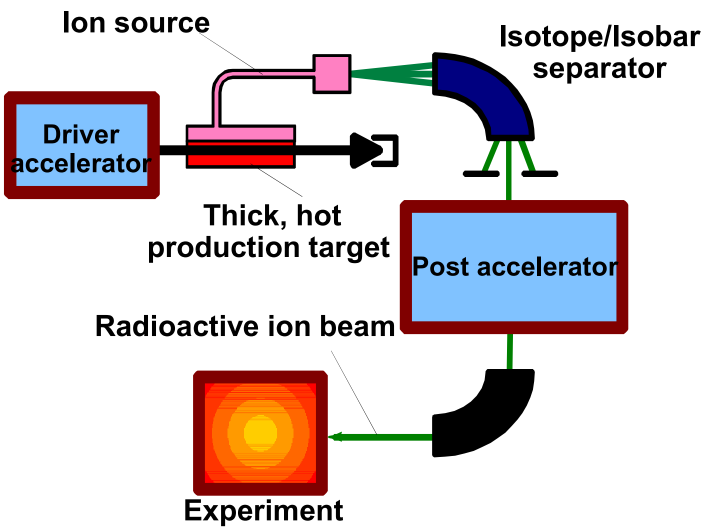
- Overview particle accelerators for RIB production
  - Challenges of RIB production
  - Particle accelerators for ISOL and fragmentation facilities

- Some accelerator developments
  - Ion source - charge state booster
  - Vacuum effects
  - Accelerator cavities – superconducting
  - Beam instrumentation and beam dynamics

Overview particle accelerators for RIB production

Production of rare isotopes

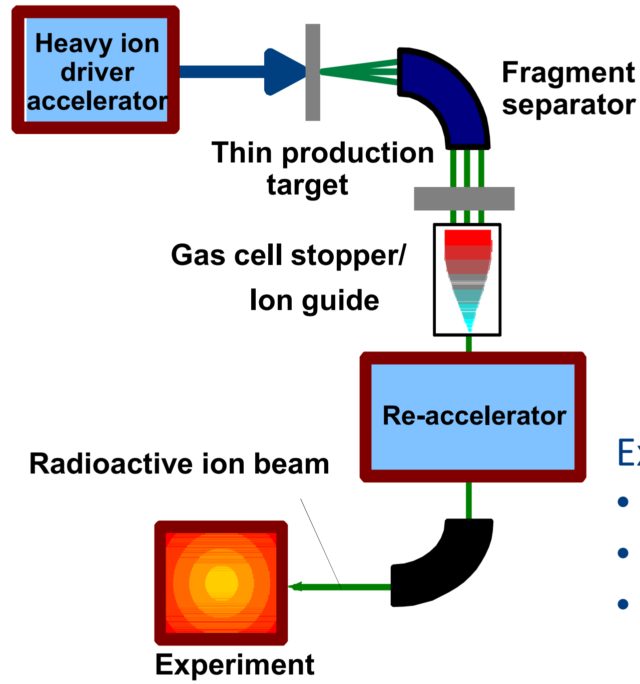
Ion Separation OnLine (ISOL)



Examples:

- ISOLDE (CERN)
- TRIUMF
- GANIL

Projectile Fragmentation (PF) and stopped beams

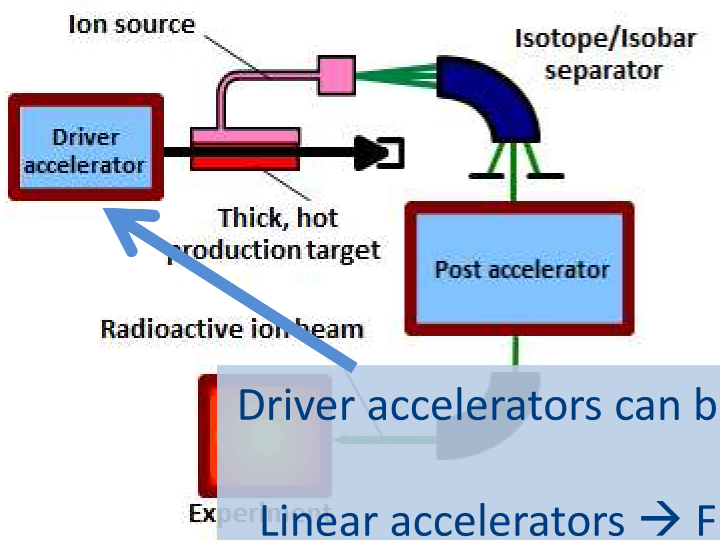


Examples:

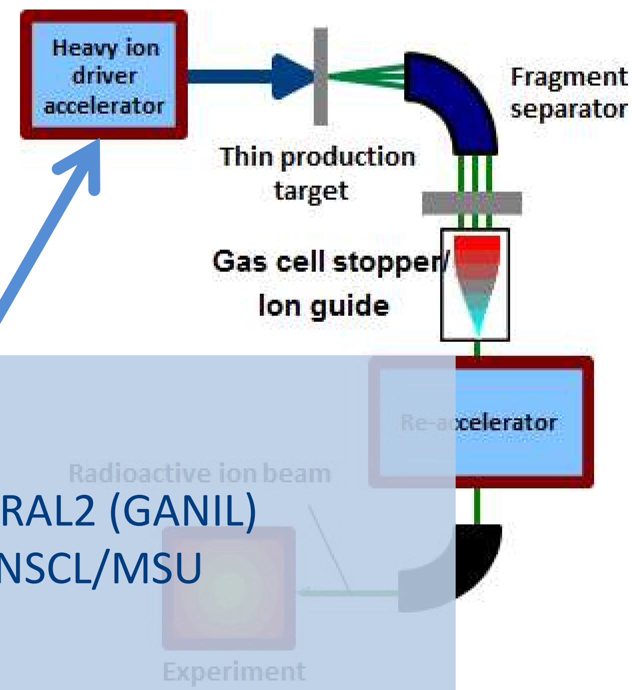
- NSCL/MSU
- GSI
- RIKEN

Driver accelerators

Ion Separation OnLine (ISOL)



Projectile Fragmentation (PF) and stopped beams

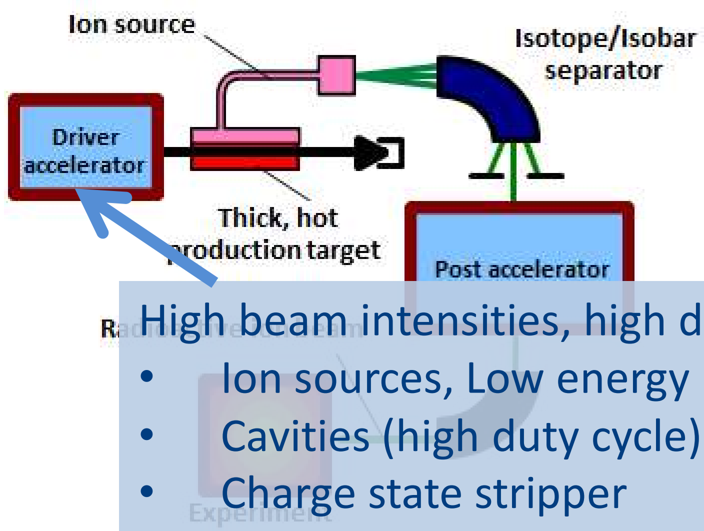


Driver accelerators can be:

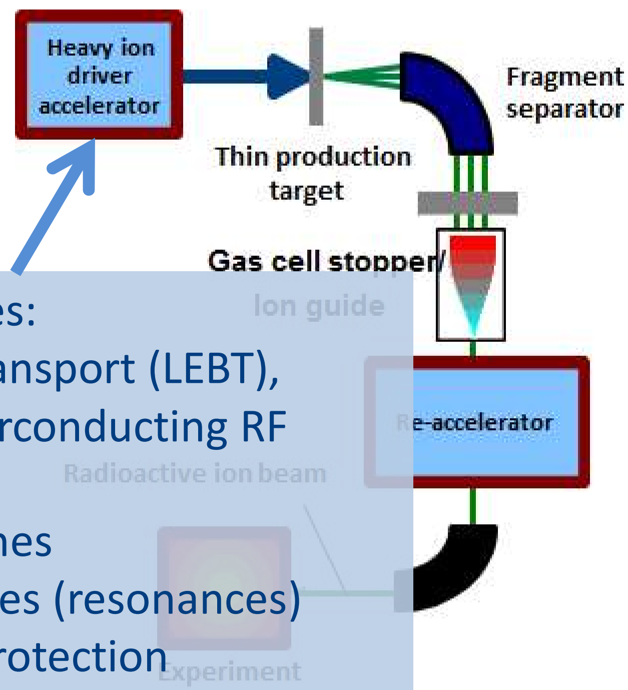
- Linear accelerators → FRIB, SPIRAL2 (GANIL)
- Cyclotrons → TRIUMF, RIKEN, NSCL/MSU
- Synchrotrons → ISOLDE, GSI
- Electron linac → TRIUMF

Driver accelerator challenges

Ion Separation OnLine (ISOL)



Projectile Fragmentation (PF) and stopped beams



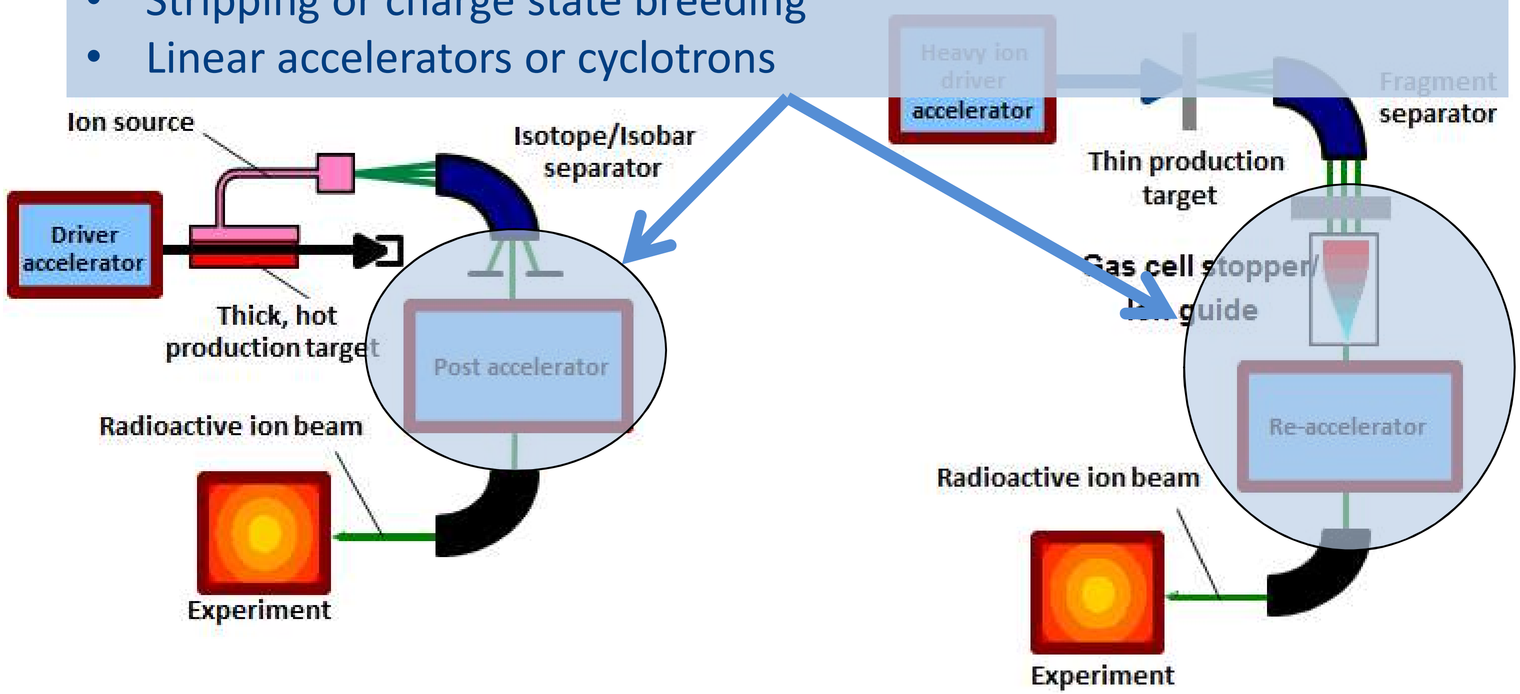
High beam intensities, high duty cycles:

- Ion sources, Low energy beam transport (LEBT),
- Cavities (high duty cycle) → superconducting RF
- Charge state stripper
- Quality of magnets in ring machines
- Highest intensities in ring machines (resonances)
- Beam diagnostics and machine protection
- Beam losses and activation

Post or re-accelerator

Post acceleration of ISOL beams, beam stopping and re-acceleration of beams from fragmentation

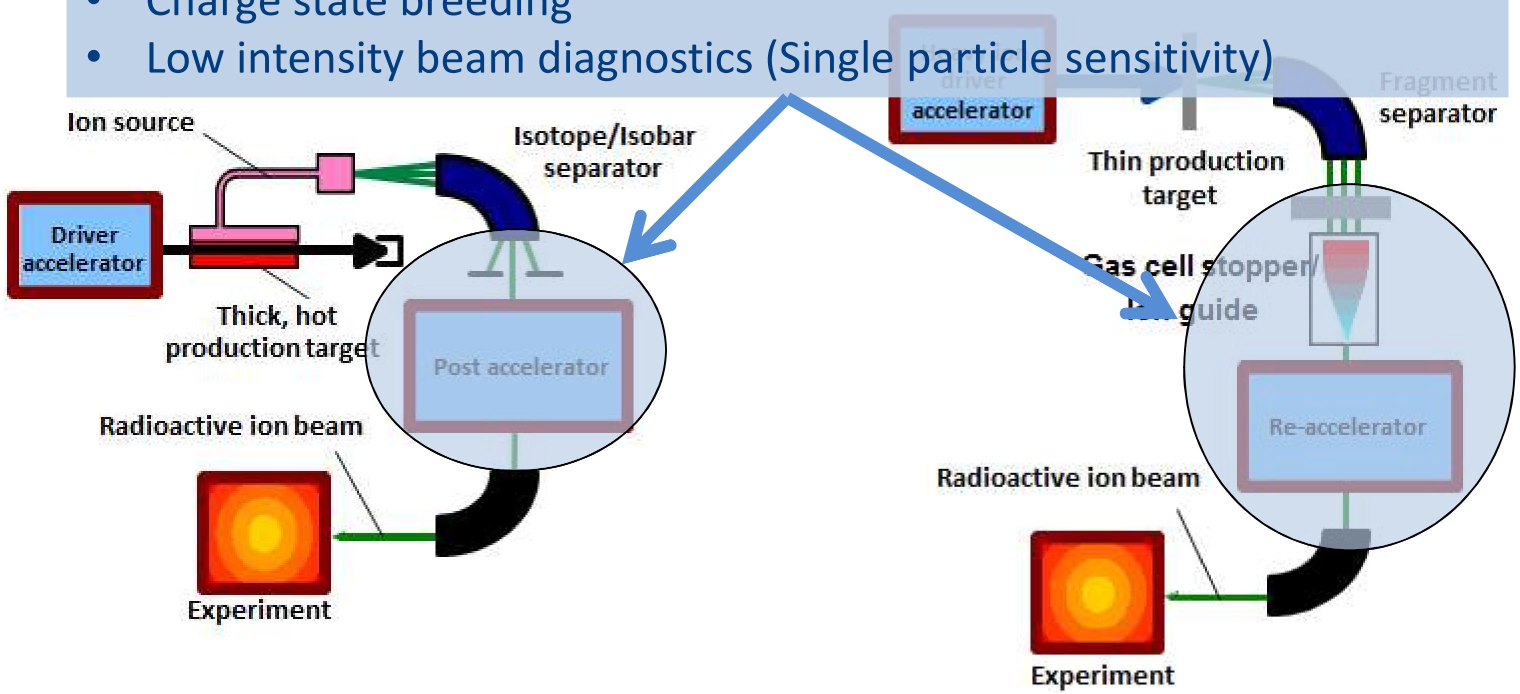
- Stripping or charge state breeding
- Linear accelerators or cyclotrons



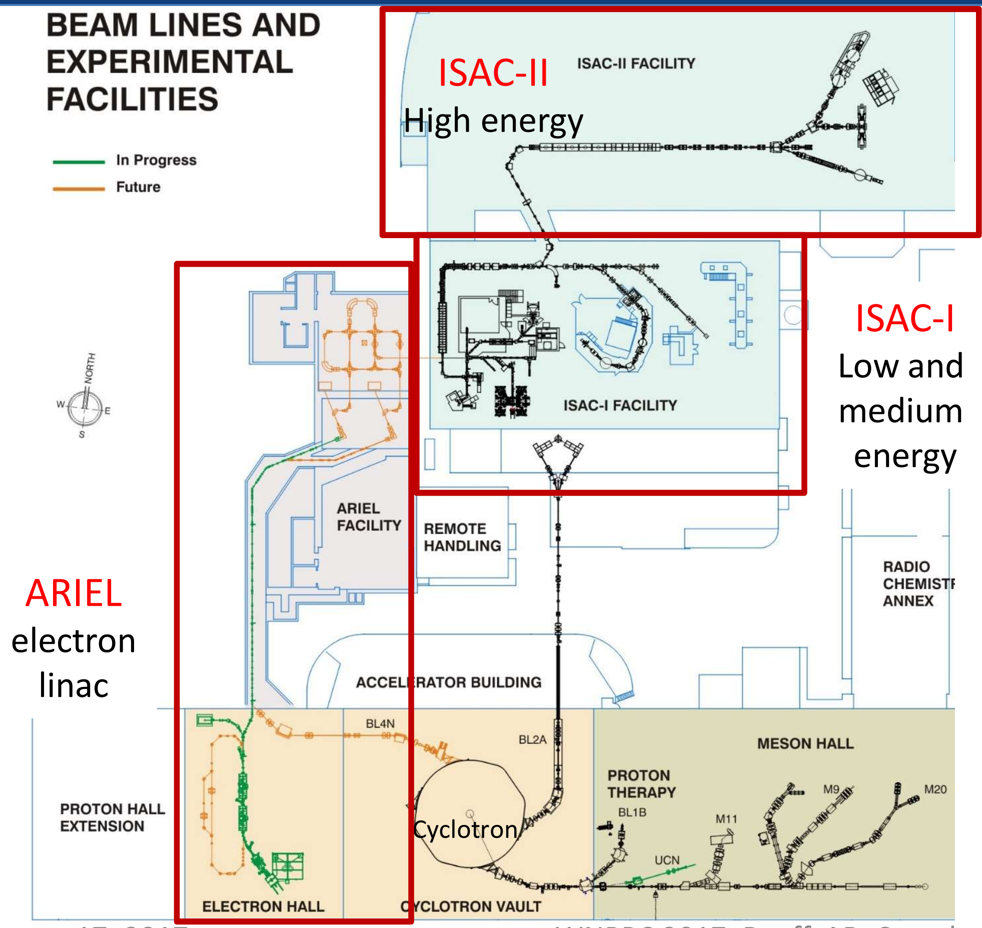
Post or re-accelerator challenges

Efficiency in each step, beam energy variation

- Beam stopping (in case of PF)
- Charge state breeding
- Low intensity beam diagnostics (Single particle sensitivity)



Example ISOL: TRIUMF facilities



Primary beam driver:
Cyclotron, 500 MeV, H^-
ISOL facility with highest power driver beam

Isotope Separator and Accelerator facility - ISAC

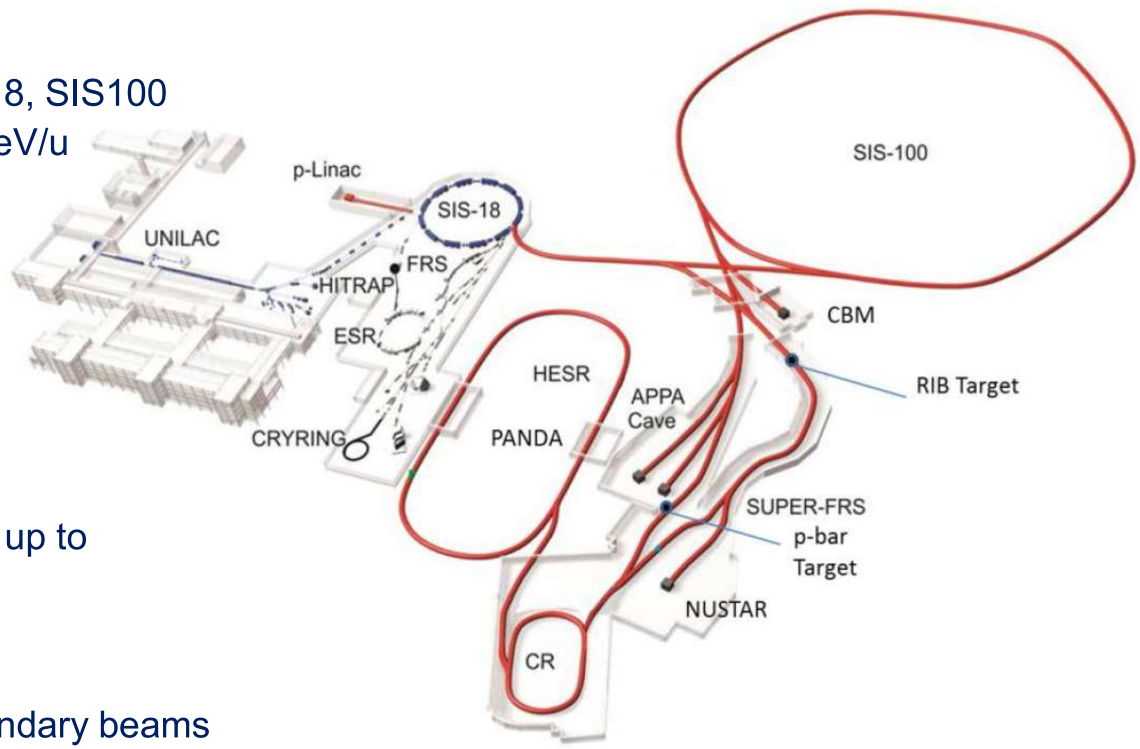
ISAC-I: Normal conducting-linac, 0,15-1,5 MeV/u
ISAC-II: Superconducting-linac, 5-11 MeV/u

Advanced rare isotope laboratory - ARIEL:
Superconducting electron linac
50 MeV, 10 mA, cw

Example PF: Facility for Antiproton and Ion research - FAIR

Primary Beam driver:
Linac injectors, Synchrotrons SIS18, SIS100

- 4.5×10^{11} U^{28+} ions/spill; 1.5 GeV/u
- 2×10^{13} protons/spill; 29 GeV



Secondary Beams

- range of radioactive ion beams up to 1.5 - 2 GeV/u
- antiprotons 1.5 - 14.1 GeV

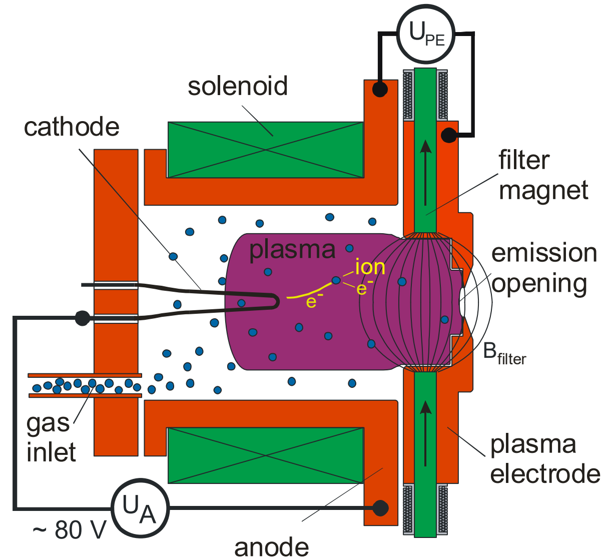
Storage and Cooler Rings for secondary beams

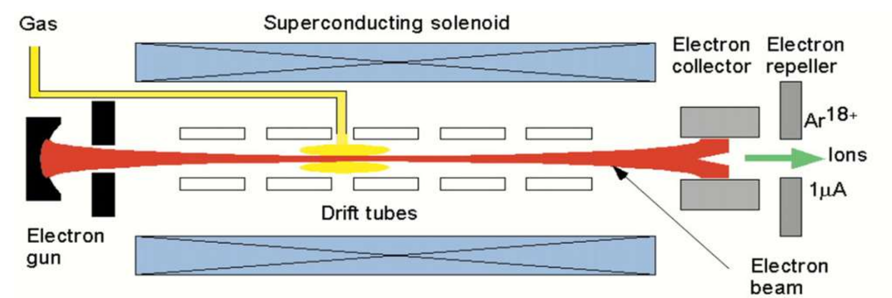
CR: 10^8 antiprotons; 3 GeV HESR: 10^{10} antiprotons; 1.5 - 14.1 GeV

Some accelerator developments

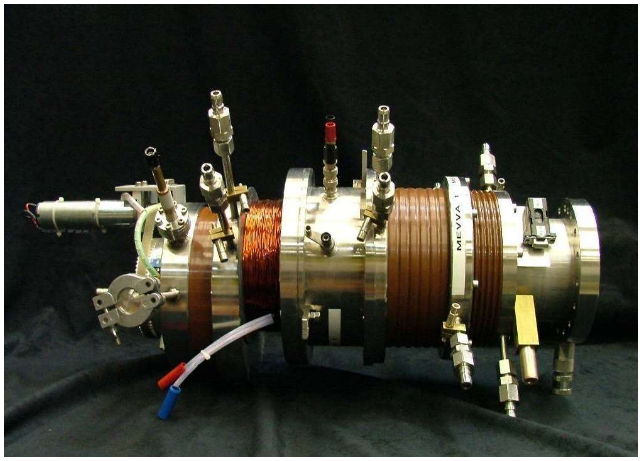
- Ion sources that deliver high current (mA to A), but low charge states
  → high current sources
  (Penning source, plasmatron sources, MEVVA, volume sources)

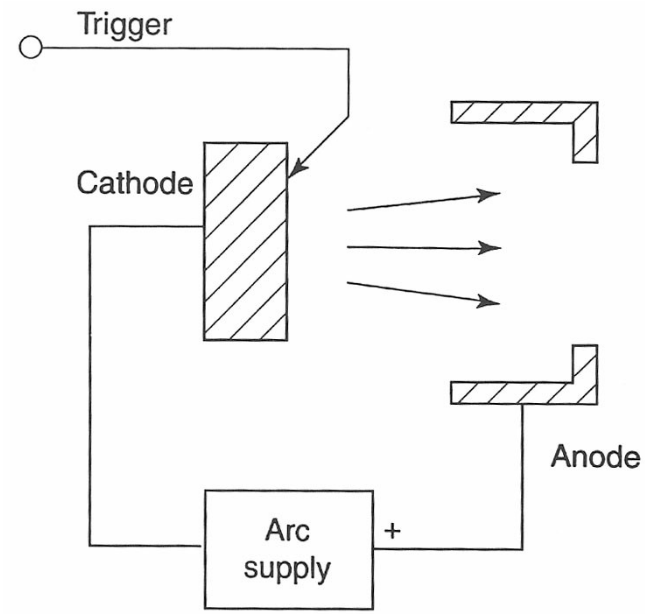
- Ion sources that deliver high charges states (up to U^{92+}), but low intensities
  → high charge state sources
  (Electron Cyclotron Resonance Ion Source - ECRIS, Electron Beam Ion Source - EBIS



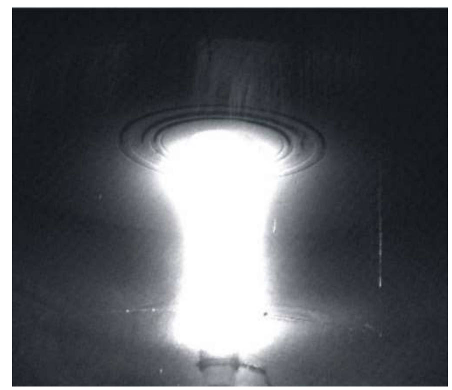


Metal Vapor Vacuum Arc (MeVVA)





New cathode materials required (alloys)
→ avoid to melt cathodes

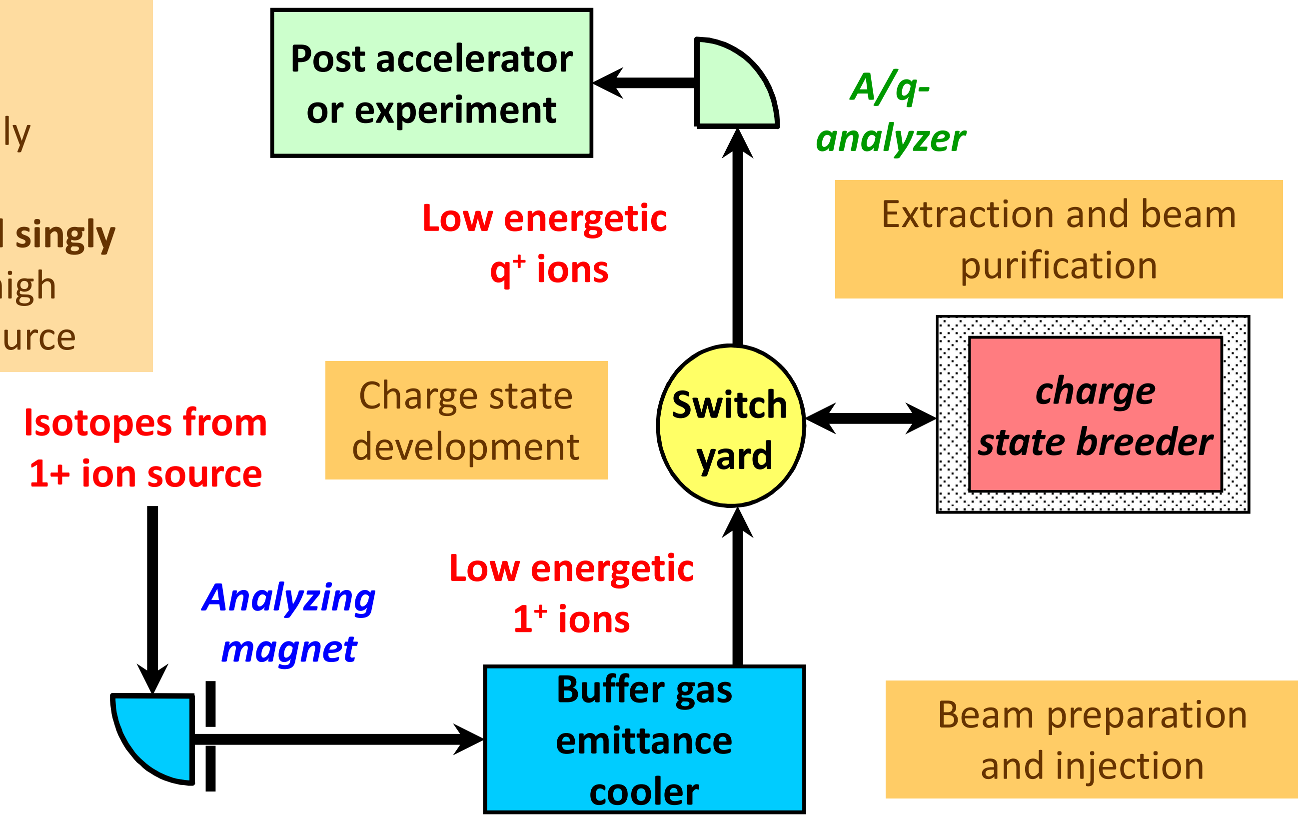


Discharge power: 50 kW
(13,3 MW/cm^2)
Discharge current: ~1 kA
Duty Cycle: 1 Hz, 1 ms

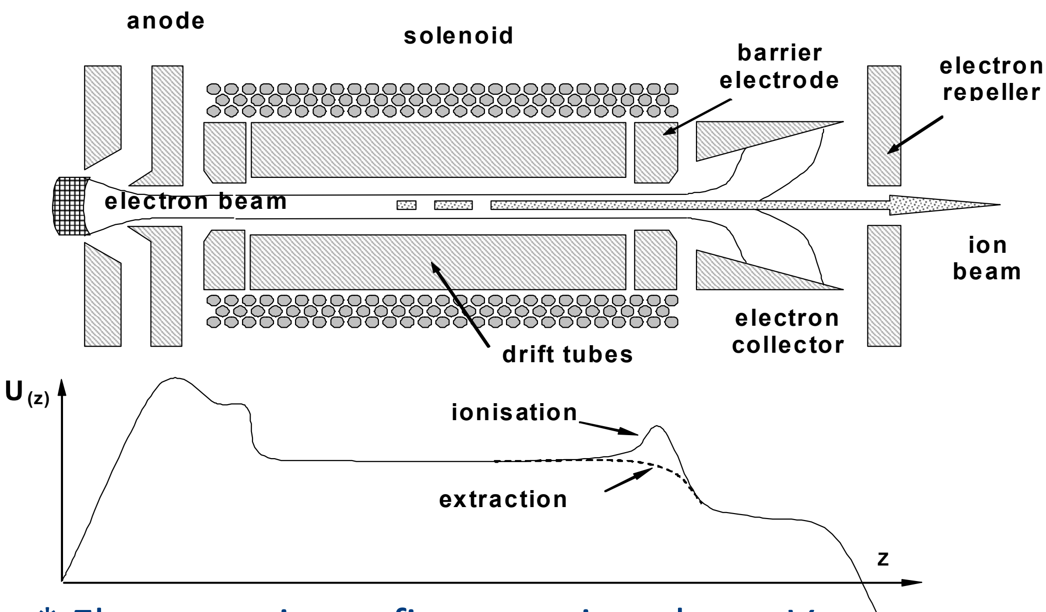
Charge state breeding

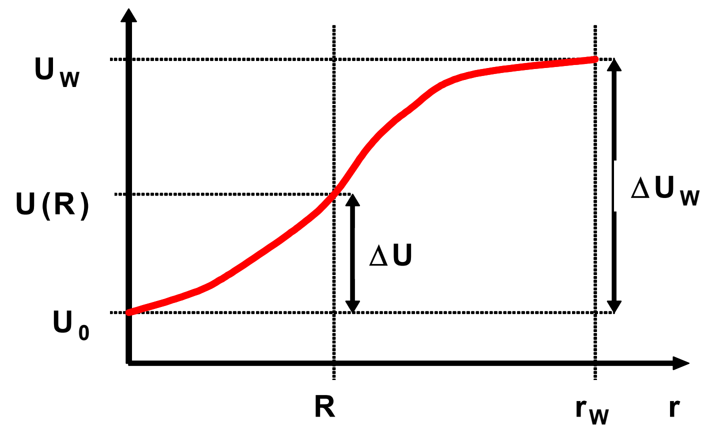
Charge breeding =

Generation of highly charged ions from **externally injected singly charged ions** in a high charge state ion source



Electron Beam Ion Source (EBIS)





Potential distribution inside and outside the electron beam

- * Electrostatic confinement in volume *V* between barrier electrodes (distance *l*)
- * Intense electron beam (current density, up to 10^4 A/cm^2)
- * Tunable electron beam energy

$$N^- = \sqrt{\frac{m_e}{2e^3}} \cdot l \cdot \frac{I_e}{\sqrt{U_e}}$$

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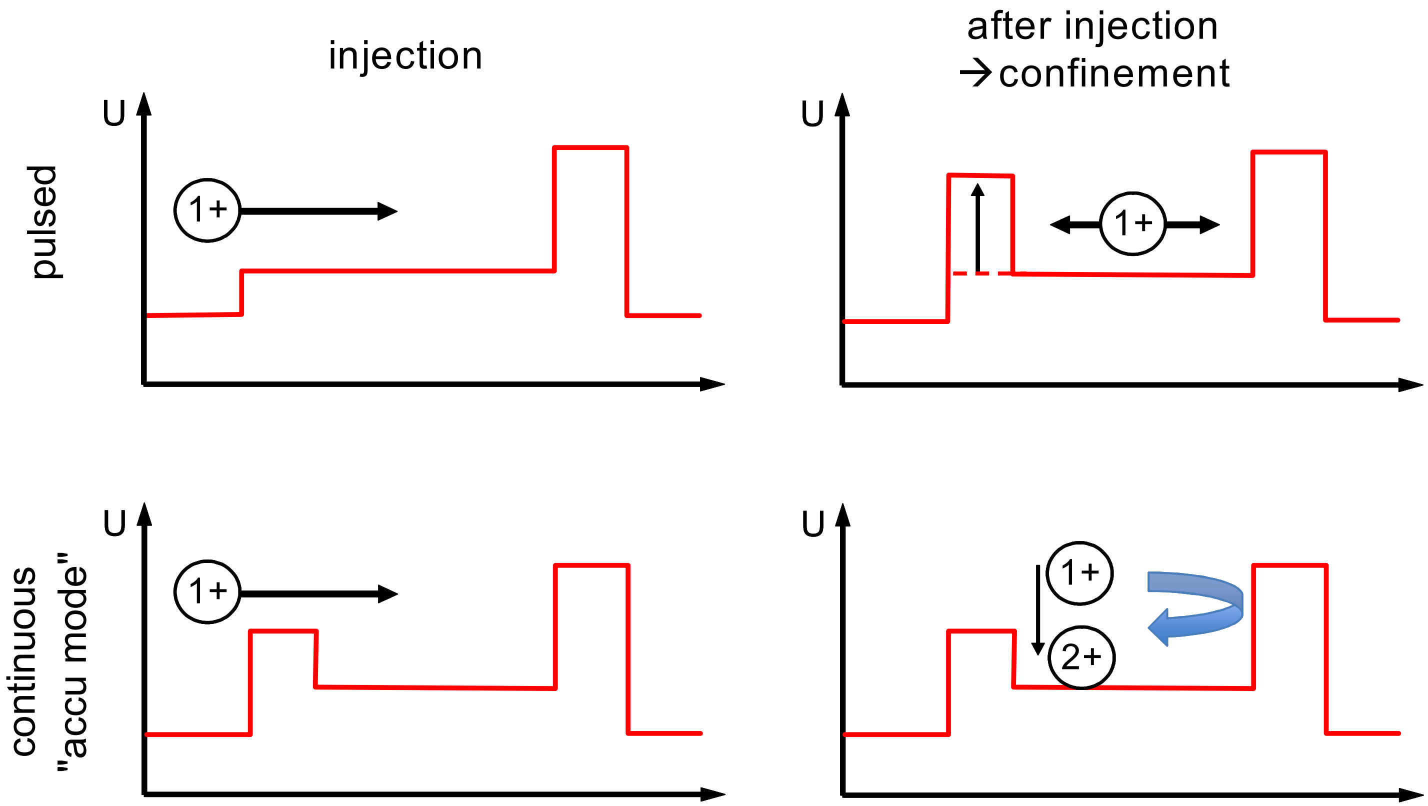
Injection of 1+ ions into EBIS/T

Pulsed injection:

- TRIUMF CANREB EBIS
- REX-EBIS at ISOLDE/CERN

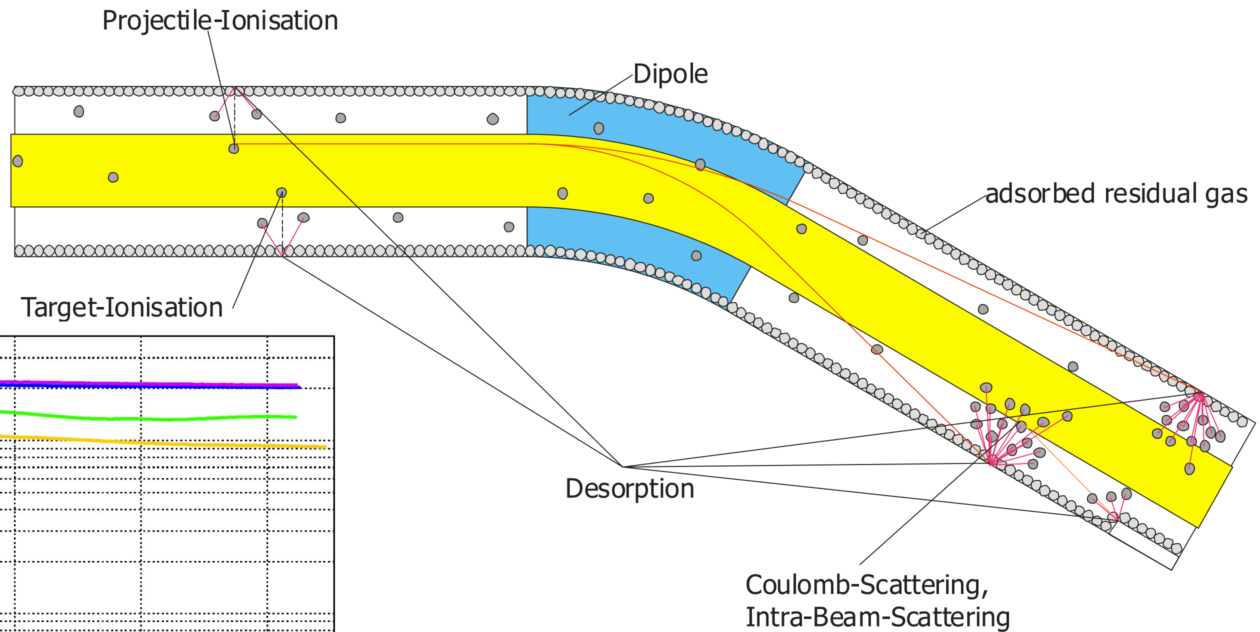
Continuous injection:

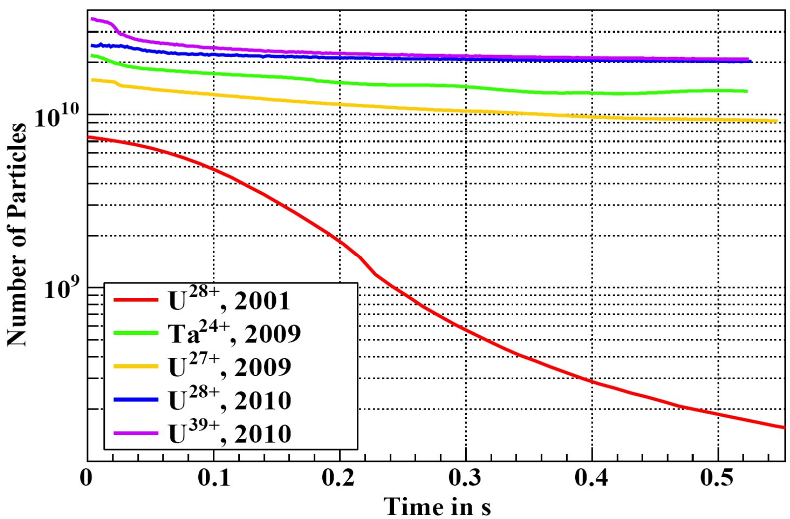
- ReA3 EBIS at MSU



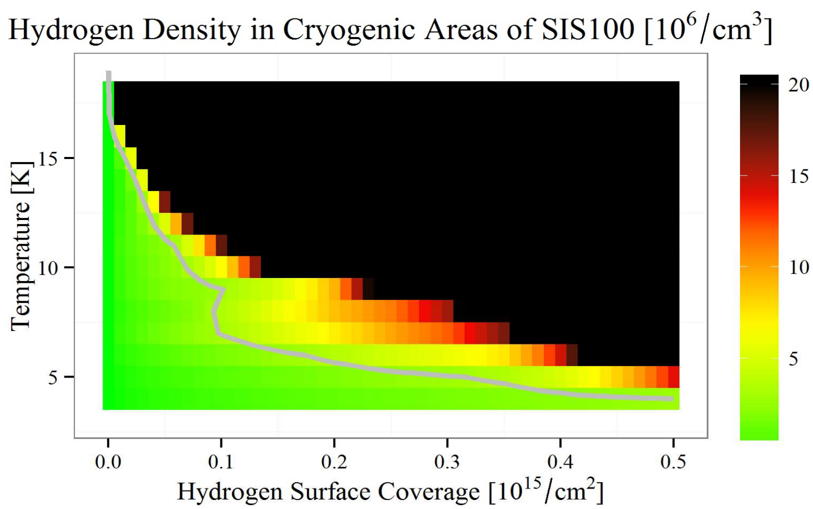
Dynamic Vacuum effect and collimation

- Beam losses induce local pressure bumps
- Ions get stripped



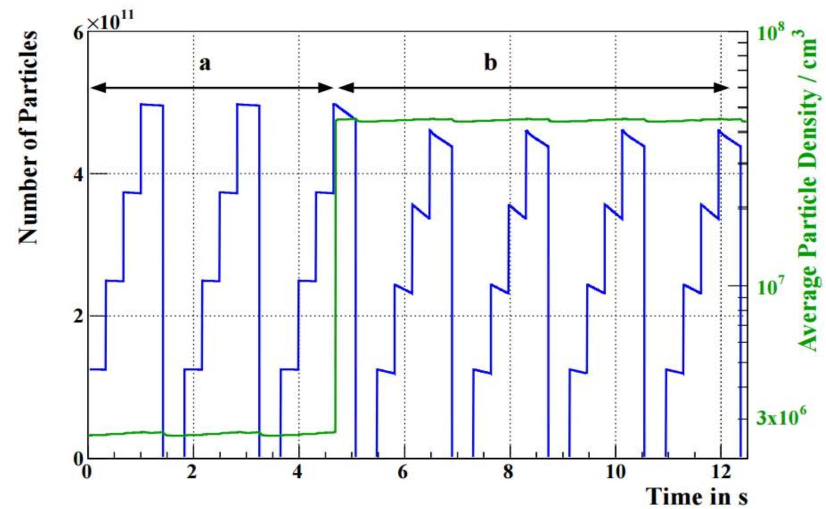


Cryogenic Surface Pumping

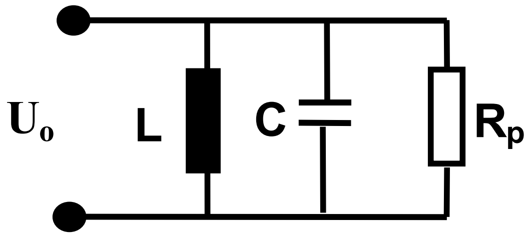


Surface coverage and temperature has been linked to residual gas density

- Long term density stays low enough for stable operation
- Equilibrium density is very sensitive to temperature rises

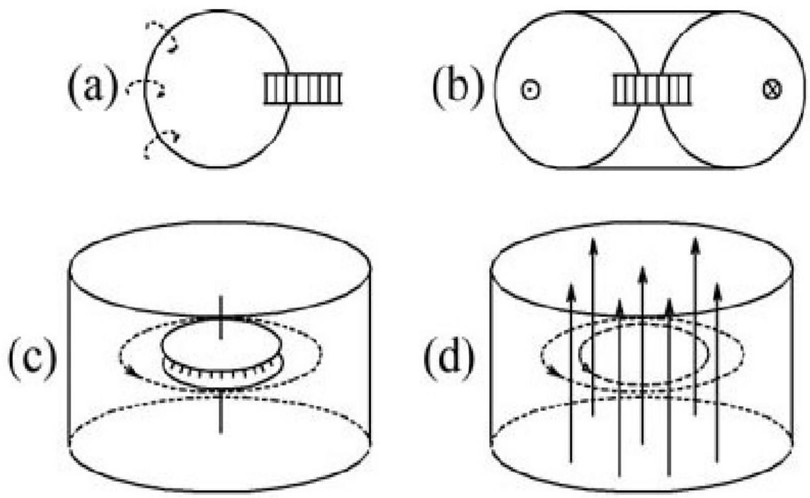


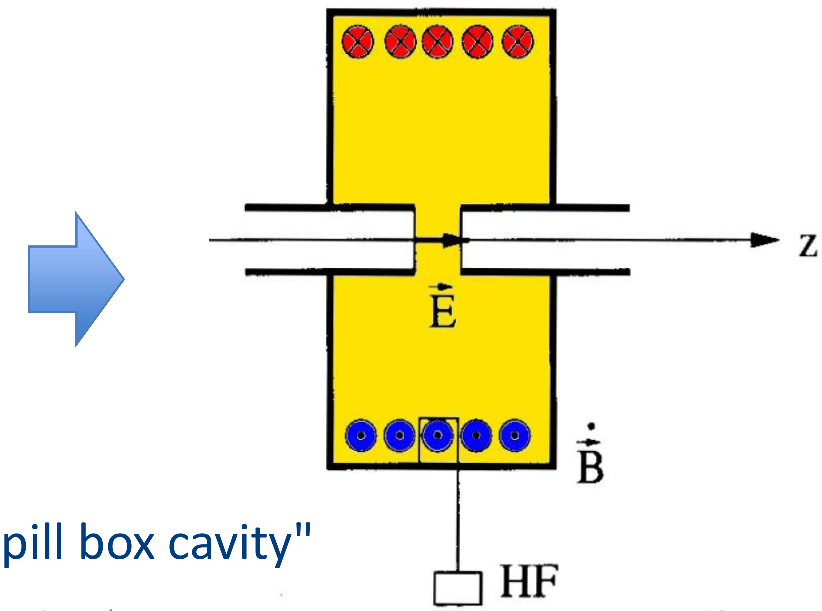
Transformation from a resonance circuit to a cavity



$$f = \frac{1}{2\pi\sqrt{L \cdot C}}$$

Thomson formula
→ resonance frequency

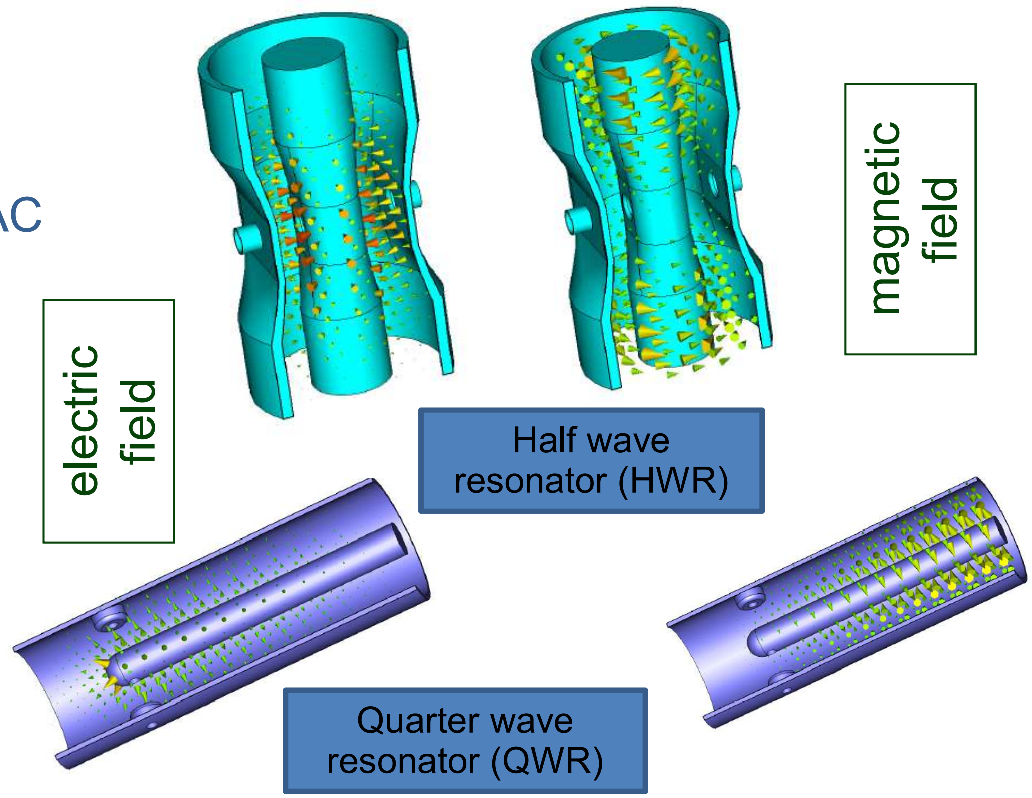




"pill box cavity"

SRF cavity examples

- Quarter wave and half wave resonators (QWR/HWR)
- Coaxial resonators used at ISAC and REX-ISOLDE

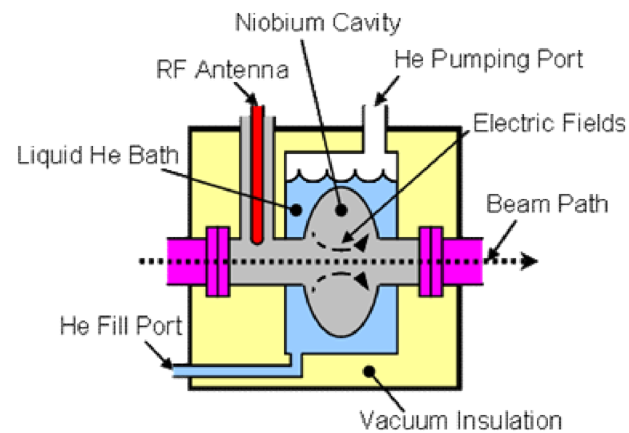


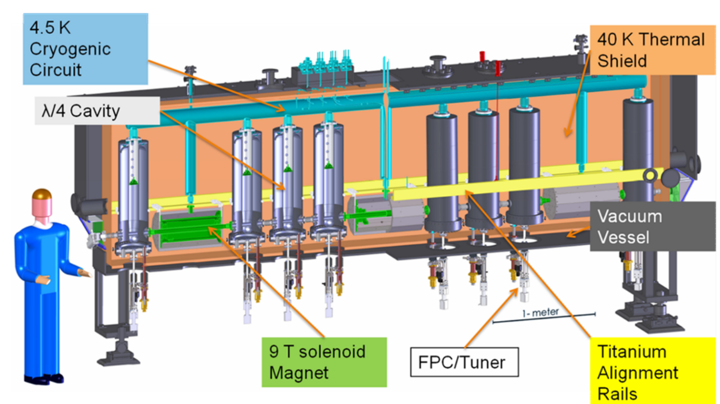
Superconducting cavities have been pursued since ~1960 in the hope of reducing the power dissipation in the walls to zero.

Success came in the 70s and 80s using niobium:

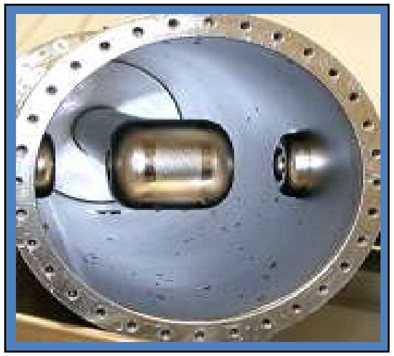
- first heavy ions (few cavities – ATLAS at ANL, now ISAC-II)
- then electrons (many cavities same size – Cornell, CEBAF, LEP)
- now protons (many cavities – 1-GeV at SNS)

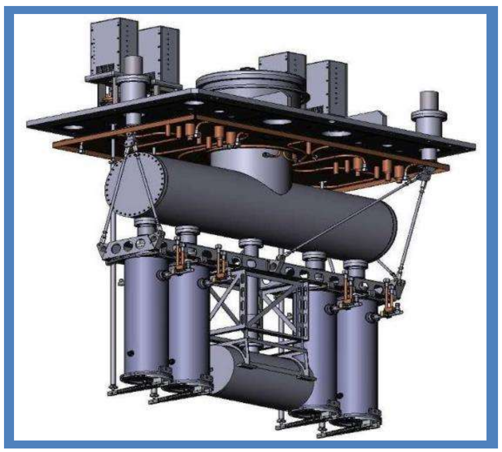
Furthermore, much higher fields can be produced – up to 30-50 MV/m.

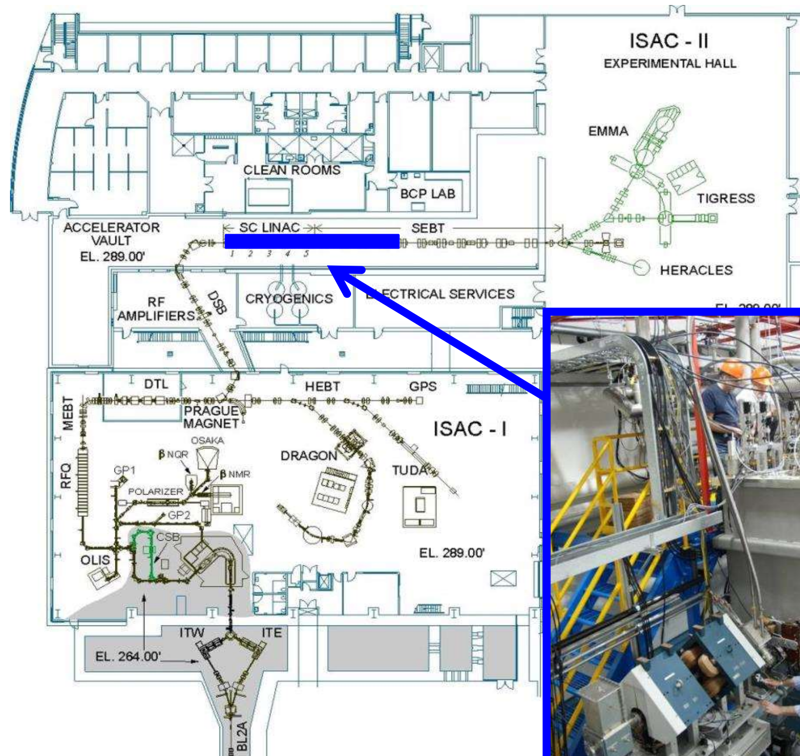




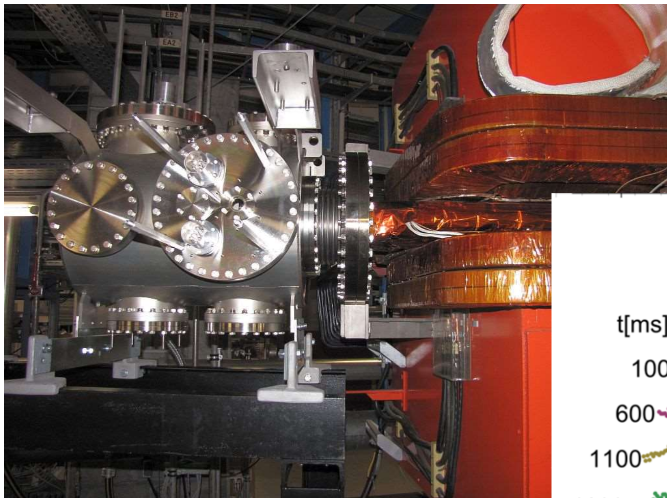
Example: ISAC II SRF linac

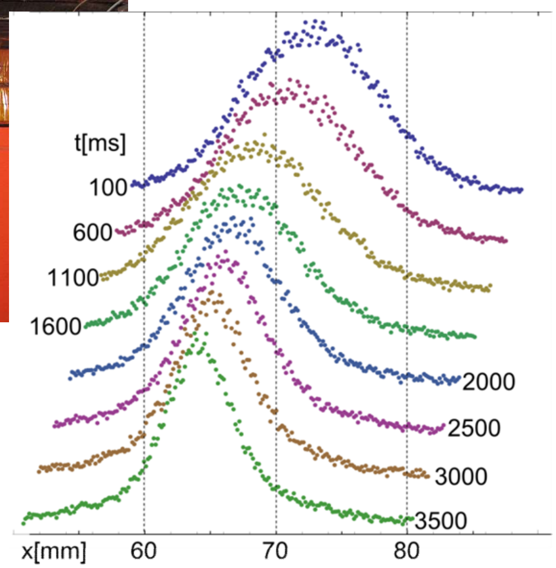






New Beam Profile Monitor in ESR

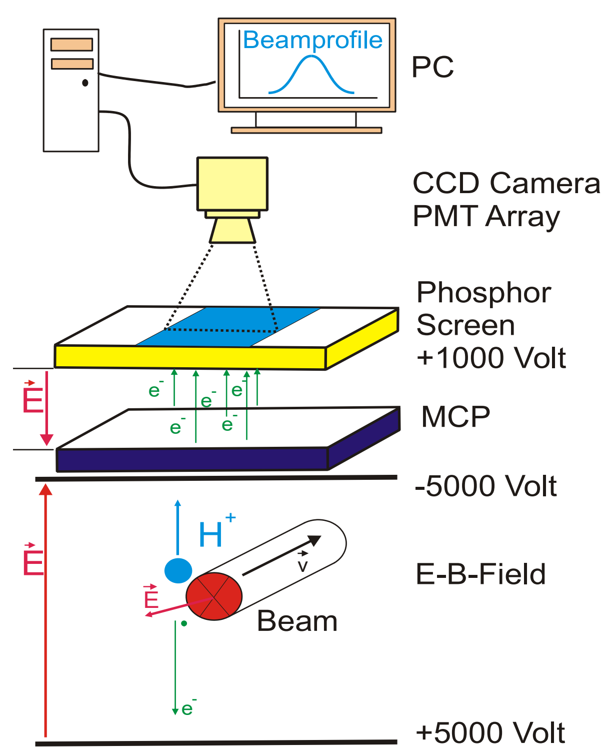




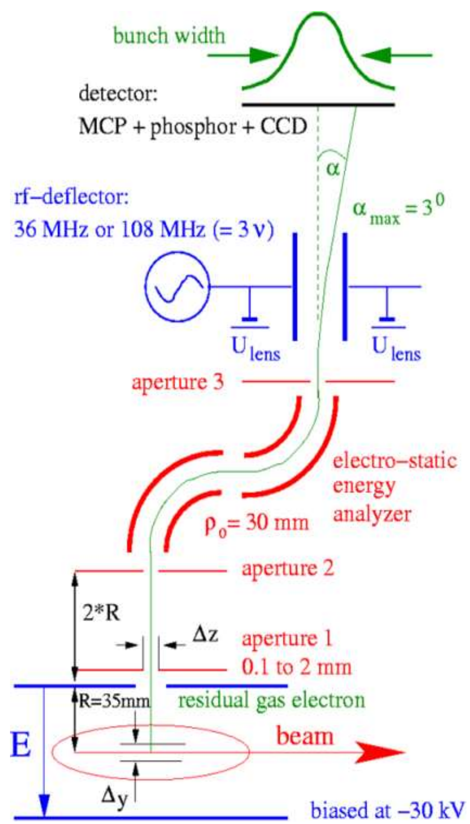
- Non destructive!
- ions detection:
- MCP readout

Cooling after injection into a storage storage ring

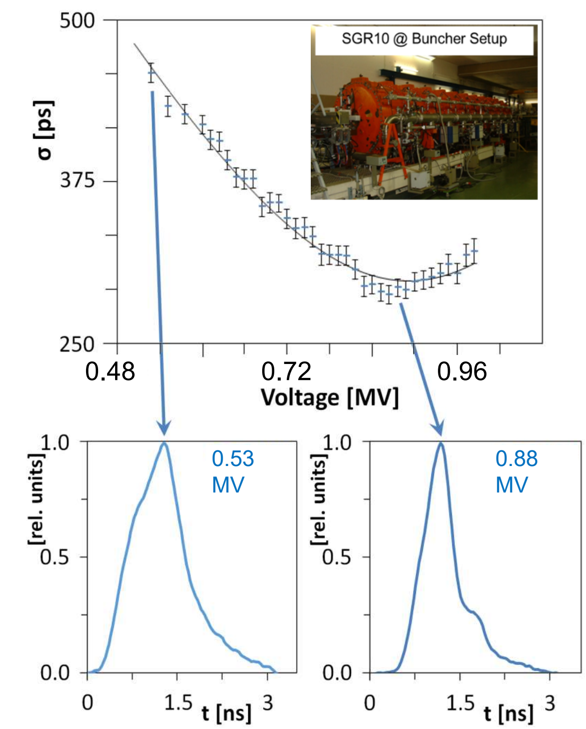
Detector principle



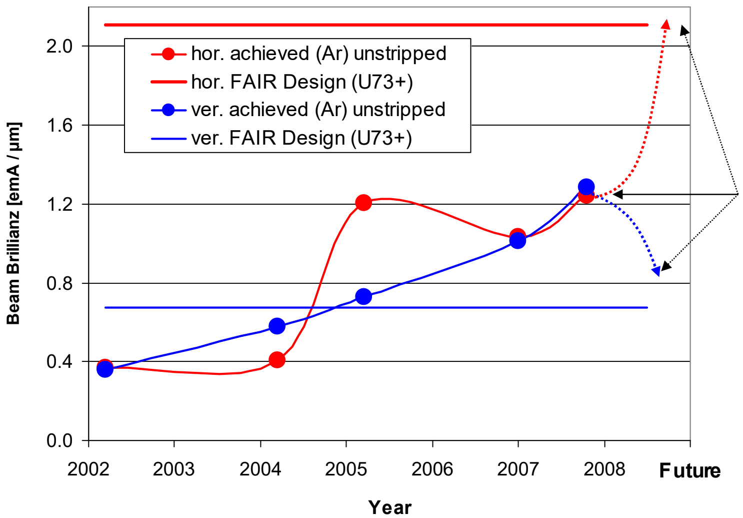
Non-intercepting bunch shape monitor



- Bunch shape monitor uses secondary electrons produced by the ion beam
- Simulation confirm the measurements and reveal the time resolution of 5 ps
- Bunch shape can be used to determine the long. emittance

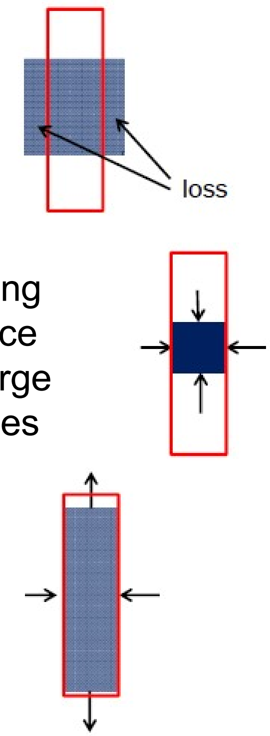


Emittance transfer experiment (EMTEX)



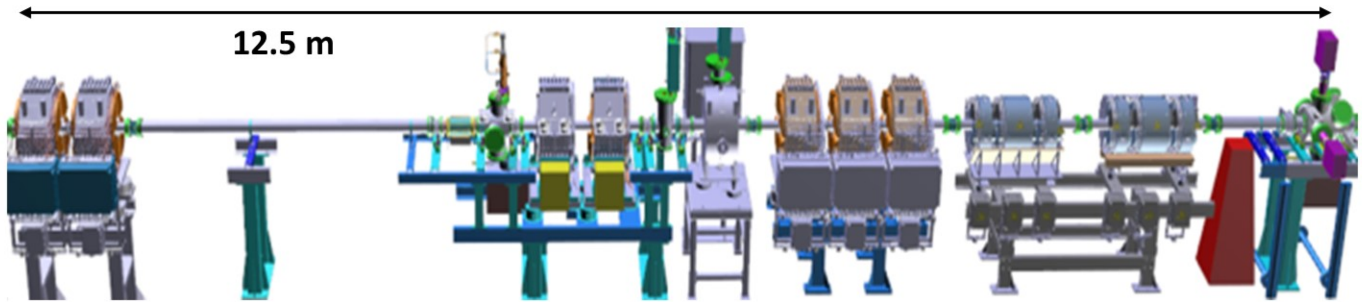
Emittance transfer via Eigen-emittance manipulation

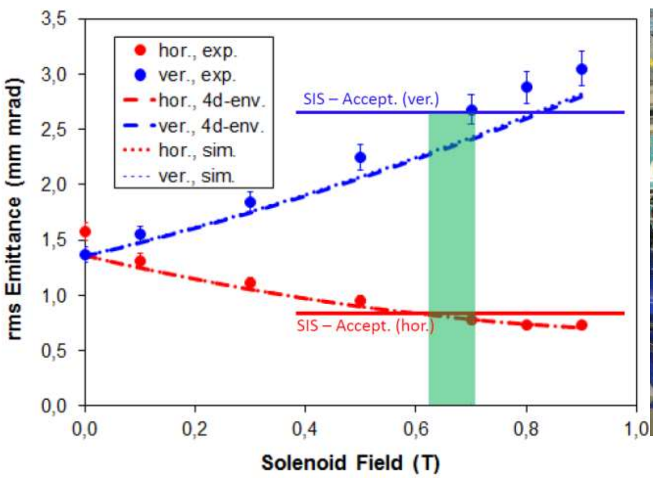
$$brilliance = \frac{I}{\varepsilon_x \cdot \varepsilon_y}$$

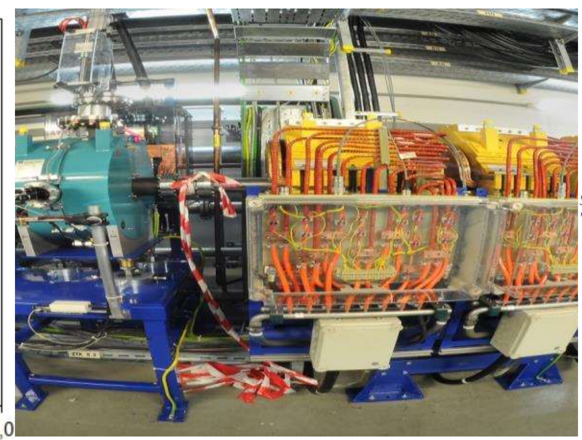


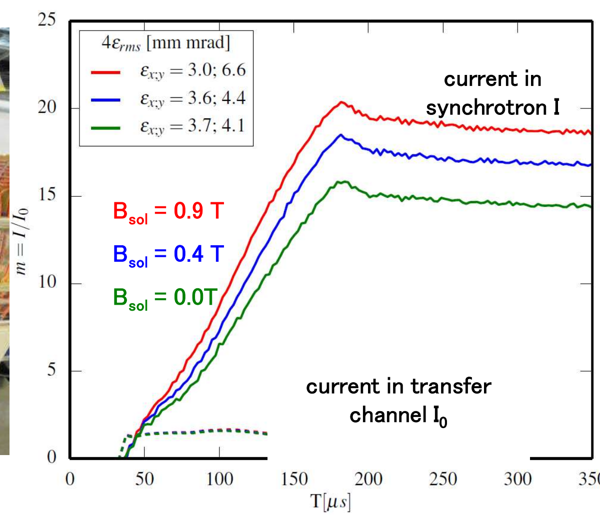
strong space charge forces

EMTEX-beam line and first results









Summary

- RIB facilities
  - Challenges of RIB production -ISOL and fragmentation
  - High intensity primary beam driver
  - High efficiency post accelerator
- Research in
  - ion sources - charge state booster
  - vacuum effects → dynamic
  - accelerator cavities – superconducting
  - beam instrumentation
    → non destructive
  - sophisticated beam dynamics

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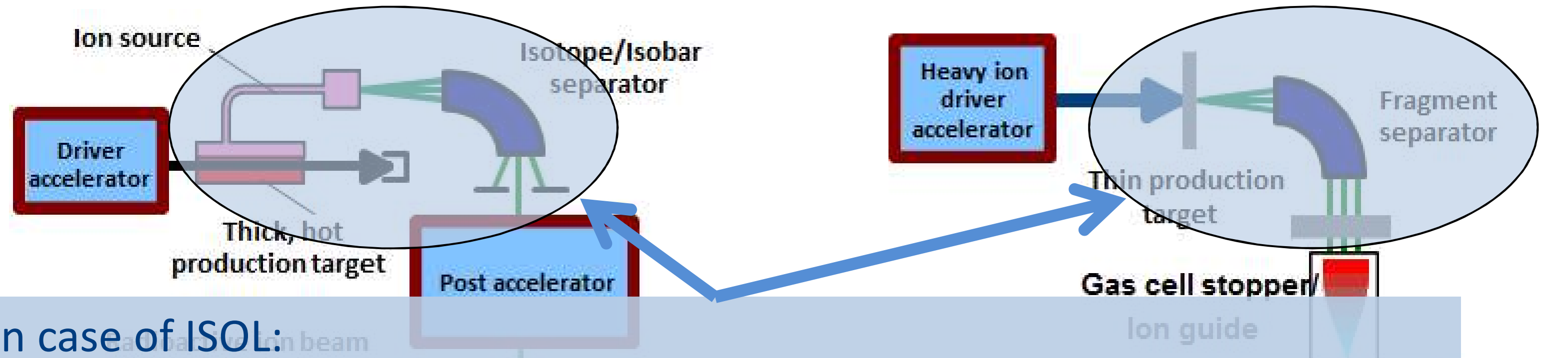
Targets and separators

Ion Separation OnLine (ISOL)

Projectile Fragmentation (PF) and stopped beams



In case of ISOL:

- Thick target using fragmentation, fission and spallation of target nuclei → light ions or electrons as projectiles
- Low energy, high resolution separators (20-100 keV)

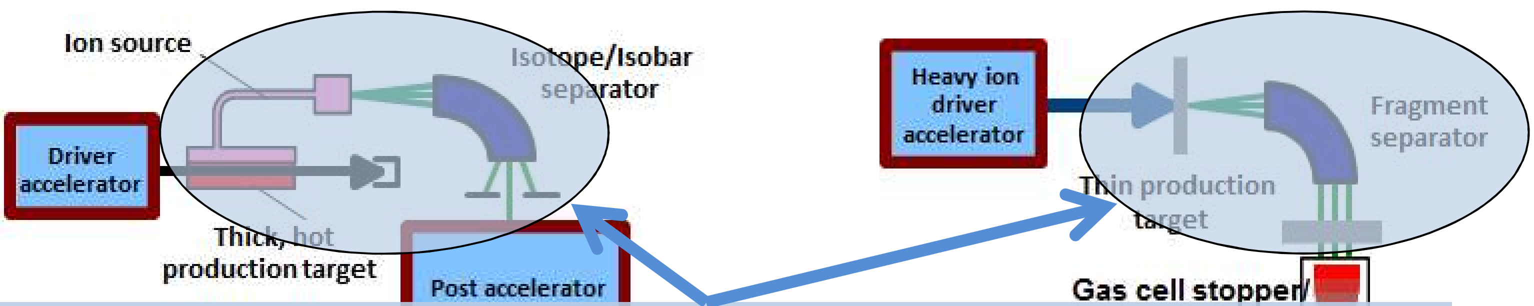
In case of fragmentation:

- Thin target, using fragmentation of projectiles
- High energy (>50 MeV/u), large acceptance separators

Target and separator challenges

Ion Separation OnLine (ISOL)

Projectile Fragmentation (PF) and stopped beams



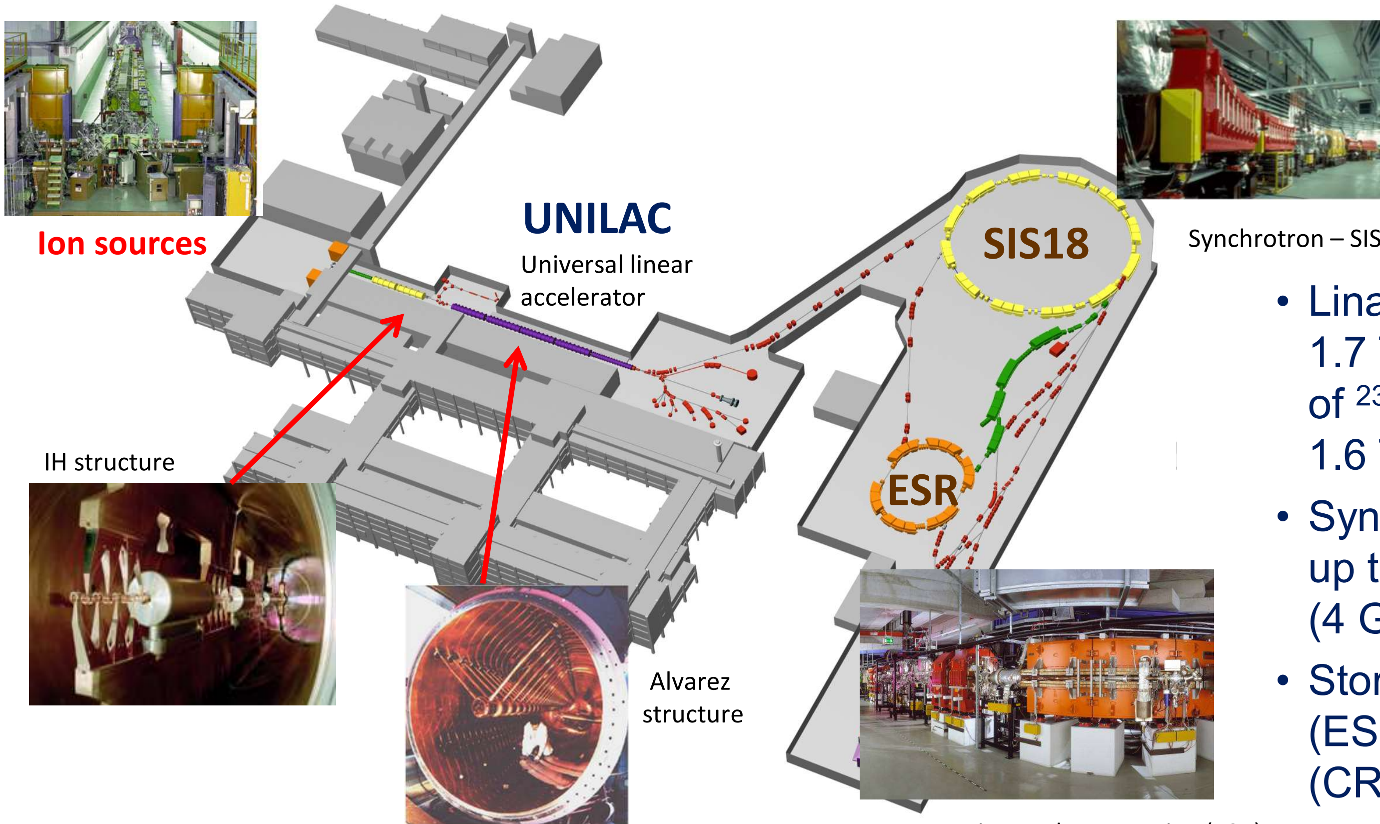
Targets:

- Beam power deposition in the targets and lifetime of the targets (similar to charge state stripper)
- Activation and target handling

Separators:

- Phase space acceptance, resolution → Magnet size
- Activation of components, Suppression of background contamination

Existing GSI accelerator facility



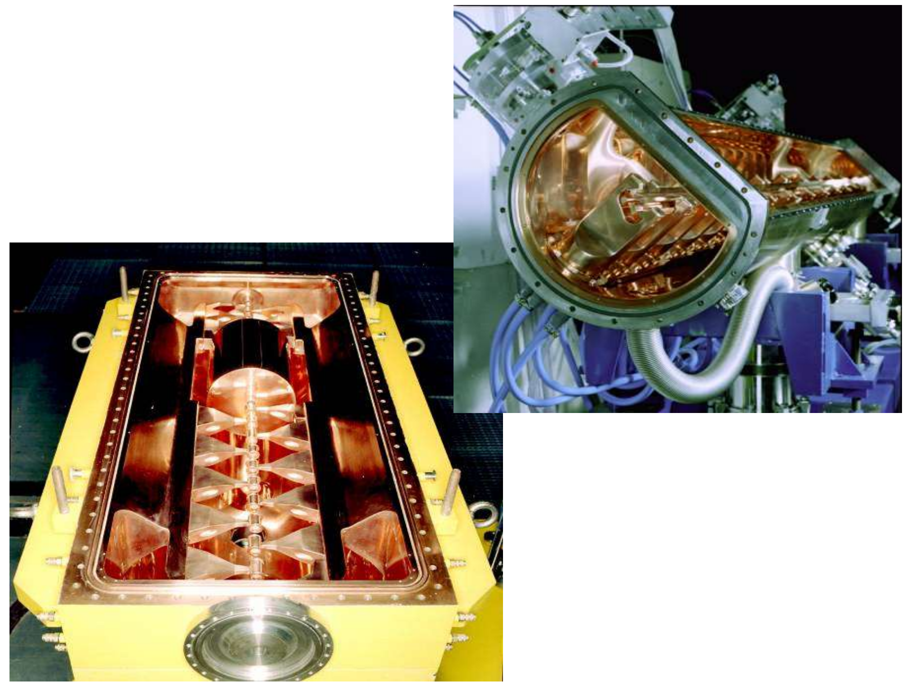
- Linac for beams up to Bρ = 1.7 Tm (for comparison Bρ of $^{238}U^{73+}$ @11.4 MeV/u = 1.6 Tm)
- Synchrotron delivers beams up to 18 Tm (4 GeV protons)
- Storage rings with 10 Tm (ESR) and 1.44 Tm (CRYRING)

What is a „particle accelerator“?

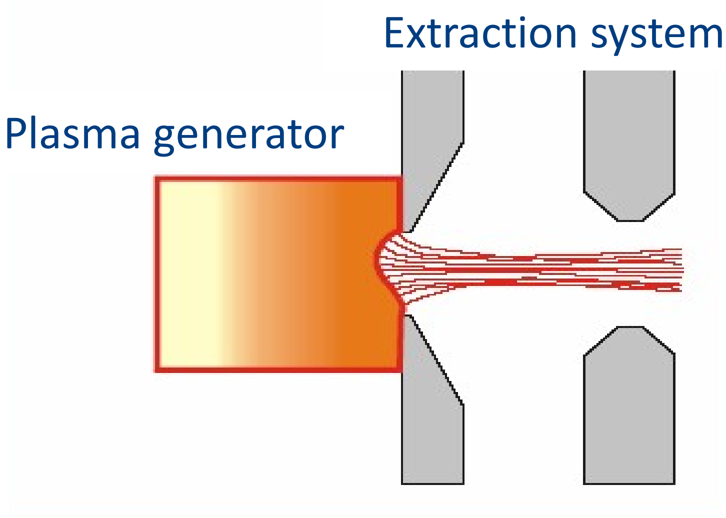
An accelerator is a device that uses electromagnetic forces to accelerate and guide charged particles.

THE ESSENTIALS;

- Particle source (electrons, protons, ions)
- Vacuum
- Electric field for acceleration
- Magnetic and/or electric fields for focusing and steering
- Controls

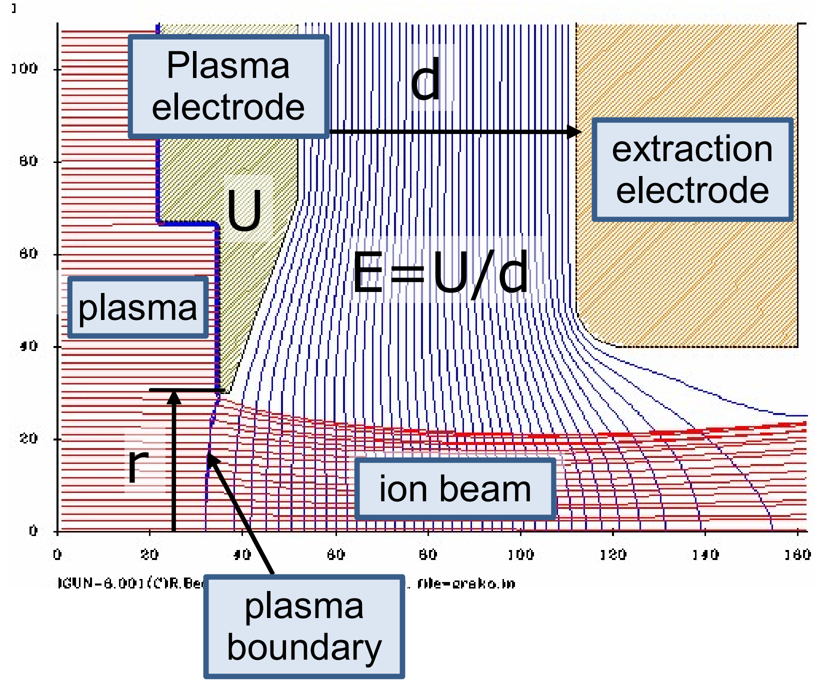


Principle of plasma ion sources



- Production of charged particles (Electrons, Ions) → Production of a plasma via discharge
- Ionisation of atoms → Electron impact ionisation

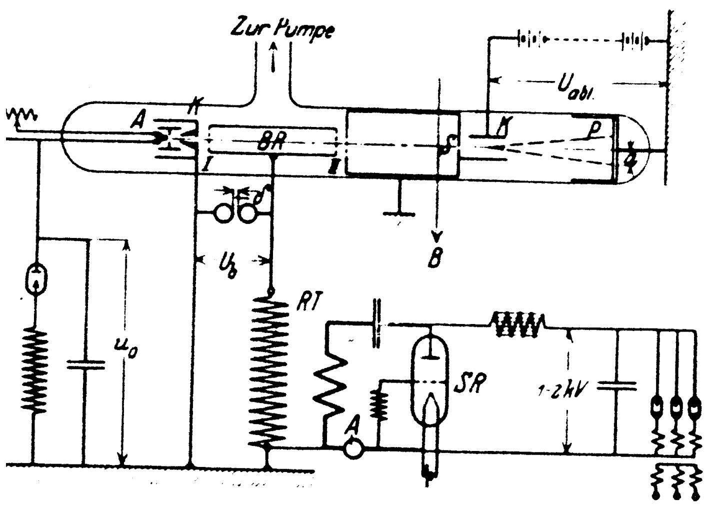
Plasma extraction = Beam shaping and transport

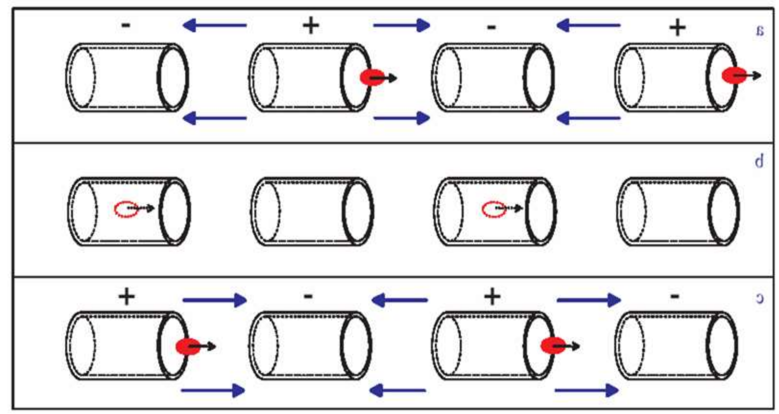


RF-accelerator principle

Multiple use of the same alternating voltage

→ Wideroe principle!





1928 proof of the rf- acceleration principle by Rolf Wideroe in Berlin

Frequency: 1 MHz

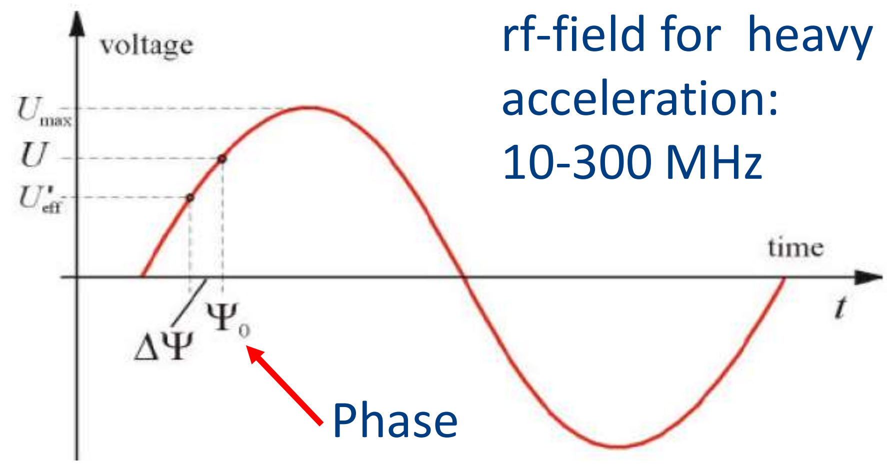
Electric Field = 25000 V

Phase focusing

The electric fields in an RF-accelerator are time dependent. The field strength depends on the time a particle enters the acceleration gap.

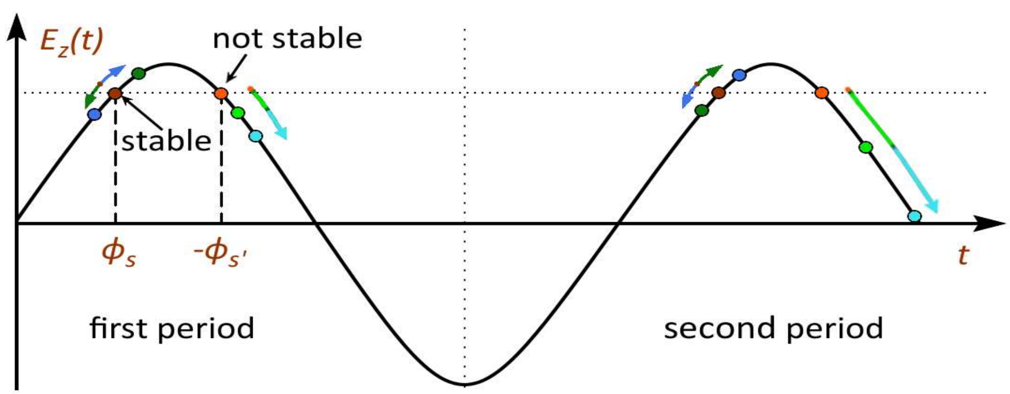
$$eU(t) = eU_{max} \sin\Psi_0$$

is the energy gain in the gap if the particle arrives in gap center at Ψ_0



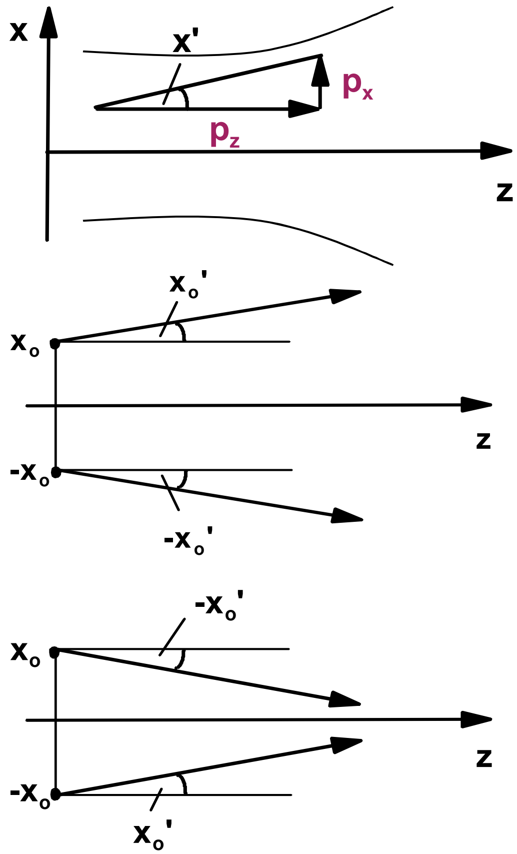
rf-field for heavy ion acceleration:
10-300 MHz

Synchronous phase in front of the crest (negative synchronous phase) → longitudinal focusing



Synchronous (perfect) particle → perfect synchronism in the linac

Beam phase space ellipse



$$x' = \frac{p_x}{p_z}$$