AN OVERVIEW OF LINAC ION SOURCES

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Scope Limitations for this Presentation

- **Sources for high-duty-factor rf Linacs**
  - 5% - cw
- **Tutorial character**
  - Taking the ‘Sourcery’ out of Ion Sources
- **No attempt at encyclopedic format**
  - Fundamentals
  - Major lines of development
  - Key operational parameters
  - General and type-specific limitations and problems
- **Peak sample results included**
- **Not included**
  - Penning (PIG)
  - Duoplasmatrons
  - Duopigatrons
  - Beam formation issues in detail
  - LEBTs

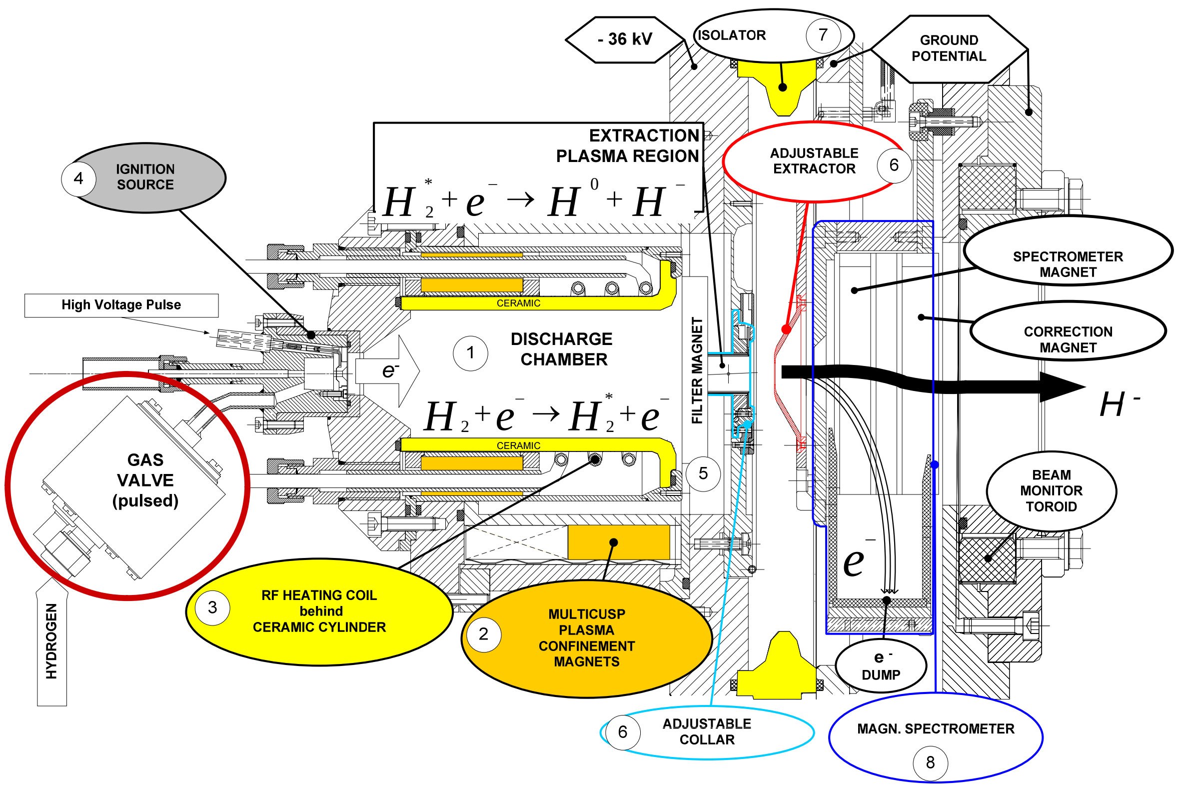
Contents

- **Introduction** *(already given)*
- **Particle feeding methods**
- **Plasma generation**
  - Filament driven
  - Rf driven
- **Multicusp sources**
  - Filament driven
  - Rf driven
- **ECR Ion Sources**
  - ECRIS for Highly charged Ions
  - ECRIS as Charge Breeders
  - ECRIS for High-current Beams

Particle Feeding Methods (1)

Materials in pure, gaseous form

- **Needle valve**
- **Regulated valve**
  - May need fast-pulsed valve to reduce average pressure in LEBT



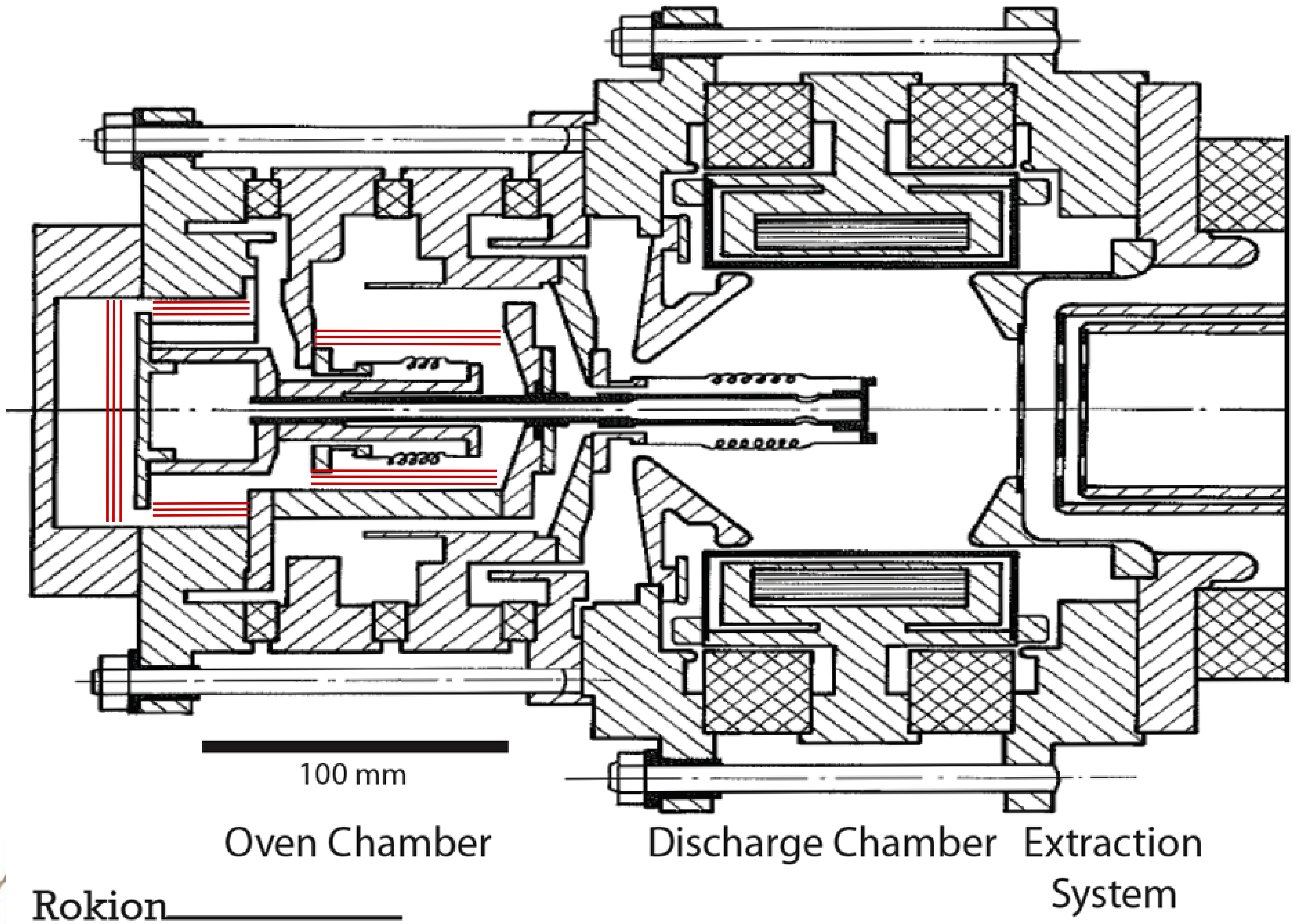
Particle Feeding Methods (2)

Non-gaseous elements

- **Gaseous compounds**
  - e. g., **C** from CO_2
- **Liquid compounds with sufficient vapor pressure**
  - e. g., **B** from BF_3
  - Many compounds contain an **aggressive component**
    - **Erosion** of source parts, especially hot filaments
    - Increased **sparking** rate in extraction system
- **Oven**
  - Need to limit re-condensation material fed into source
    - **Oven should be coldest of internal source parts**
    - Dual heating systems
  - Might benefit from auxiliary gas to stabilize discharge

Particle Feeding Methods (3)

CHORDIS with oven



Rokion IONENSTRAHL-TECHNOLOGIE

R. Keller & F. Nöhmayer, GSI Darmstadt

Particle Feeding Methods (4)

Cathode sputtering

- **Technique well suited for high-melting materials**
  - Dedicated sputtering electrode
  - Biasing existing electrode
    - Made from, or coated with, material of interest
  - Needs auxiliary gas to release desired particles from electrode
    - Self-sputtering does occur but is not a stable process
  - **Sputtering current regulates share** of desired species in plasma
    - Maximum 10-20%
  - Need to limit re-condensation of sputtered material
    - Similar solution as with oven

Plasma Generation (1)

Creating and maintaining a discharge (NOT: arc)

- **Sustained by dc power and thermionic cathodes (filaments)**
  - Continuous (dc)
  - Pulsed
- **Sustained by rf power**
  - Continuous (cw)
  - Pulsed (modulated)
- **Choice of discharge voltage and current values influences plasma composition**
  - Total beam current
  - Singly or multiply charged ions
- **Cathode filaments**
  - Tungsten, tungsten/rhenium or tantalum wire
    - Lifetime limitations
    - Resistance-increase data for diagnostics
  - Earth-alkaline oxide paste on nickel or platinum mesh
    - Used for hydrogen feeding gas (low sputtering rate)

Plasma Generation (2)

Filament lifetime assessment for dc discharges, *R. Keller et al., NIBS Conf. 2008*

'Creep' phenomenon for material under stress

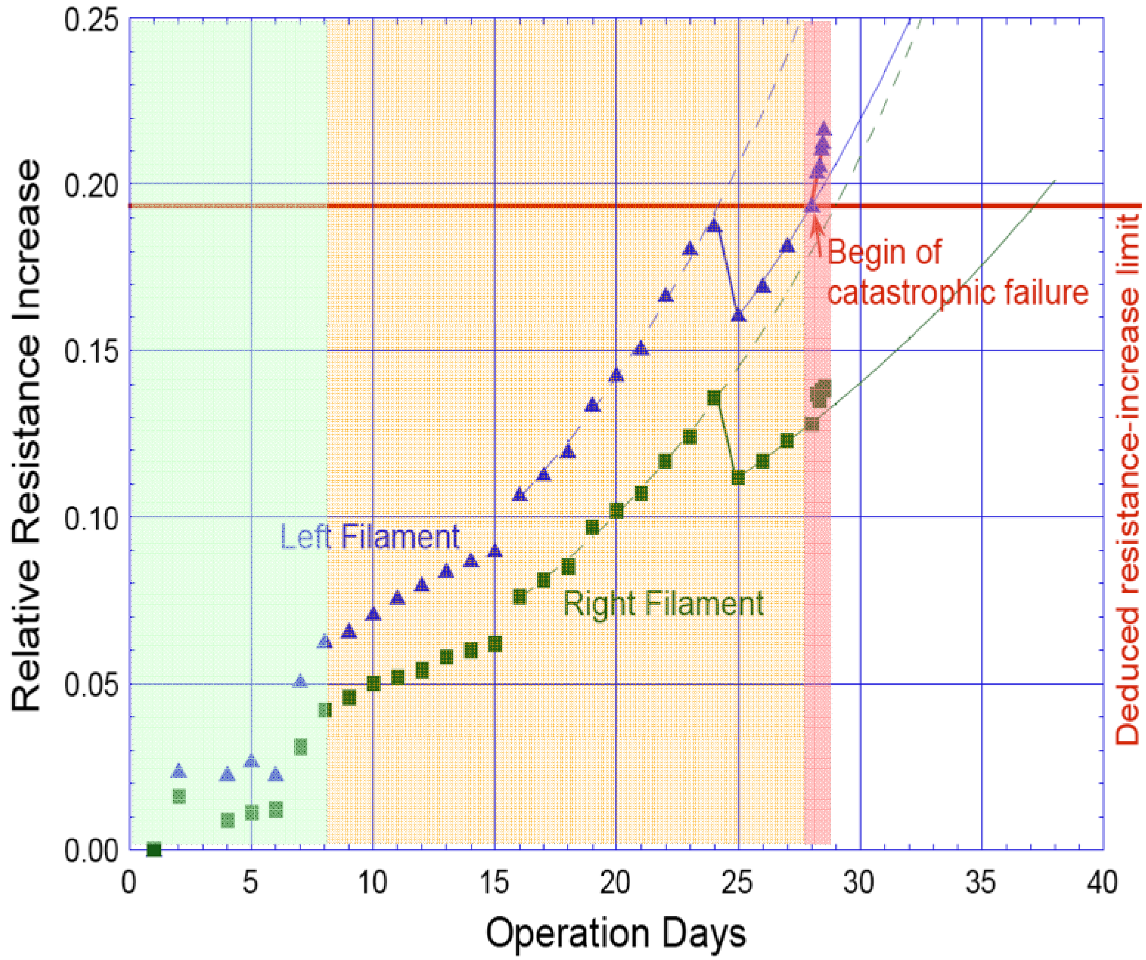
Data can be used to predict time of failure

-> Adjust filament heating power

Approach supported by analytical/computational model

Model shows **exponential growth and catastrophic failure**

0.05-mm 'nick' reduces lifetime by factor of 2



Typical resistance-increase plot – heating power was varied twice

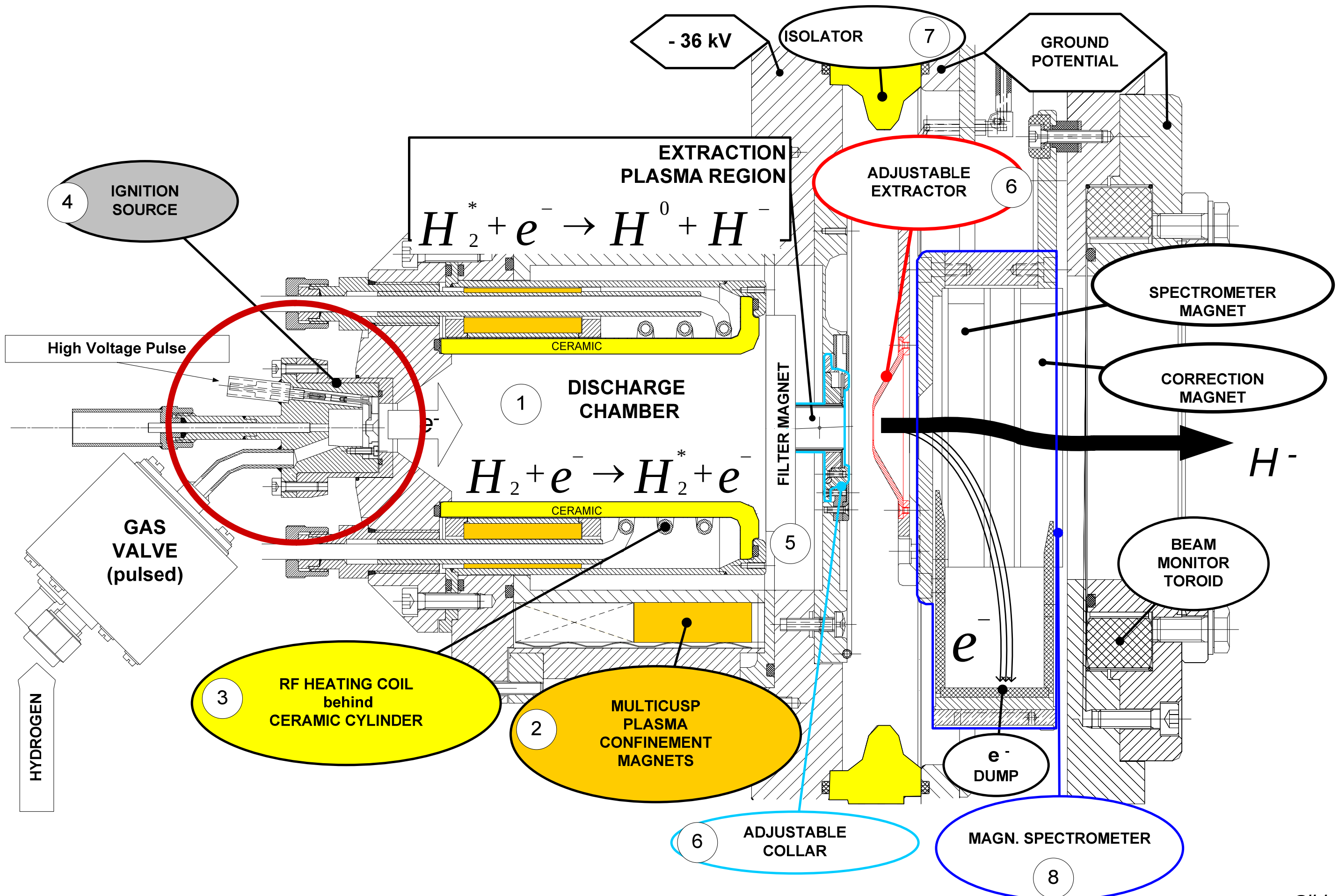
Rf Sustained Discharges (1)

Fundamentals

- **Typical frequencies 1-13.56 MHz**
- **No fast-eroding components such as filaments**
- **Need impedance matcher**
  - Amplifier typically 50 Ohm
  - Plasma about 1 Ohm
- **Ignition poses a problem**
  - Cw operation mode: Raise gas pressure for ignition
  - Pulsed operation mode: several options
    - Add low-power cw amplifier
      - Decouple power flow
      - Protect cw amplifier from reflected power as plasma impedance changes
    - Add spark-gap chamber or ‘plasma gun’ combined with pulsed gas valve

Rf Sustained Discharges (2)

‘High’ pressure discharge chamber added to facilitate ignition



Rf Sustained Discharges (3)

Antenna options

- **Antenna needs to be insulated from plasma**
  - Avoid arcing, meltdown
- **Internal antenna**
  - Porcelain coated
    - Single- or multi-layer
  - Incompatibility of thermal expansion coefficients leads to **cracks**
    - **Water/vacuum accident waiting to happen**
- **External antenna**
  - Major part of discharge chamber made from Al_2O_3 or, better AlN
  - Needs to be engineered for desired duty factor
    - Heat transfer
    - Maximum temperature gradient
    - May have to be protected from discharge heat load by Faraday shield

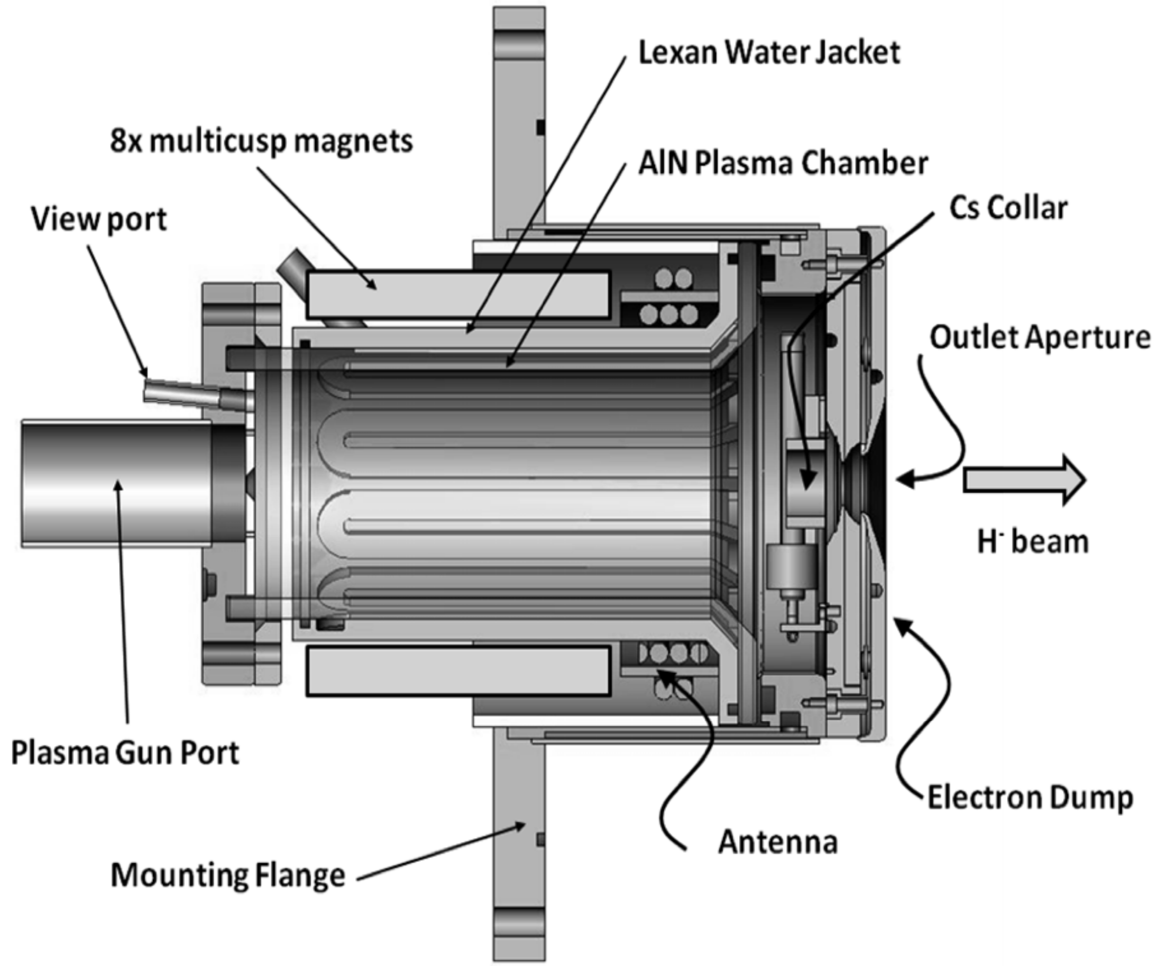
Rf Sustained Discharges (4)

Ion source with external antenna

SNS H^- Ion Source

1 ms/60 Hz pulsed operation

100 mA beam current
from 7-mm aperture

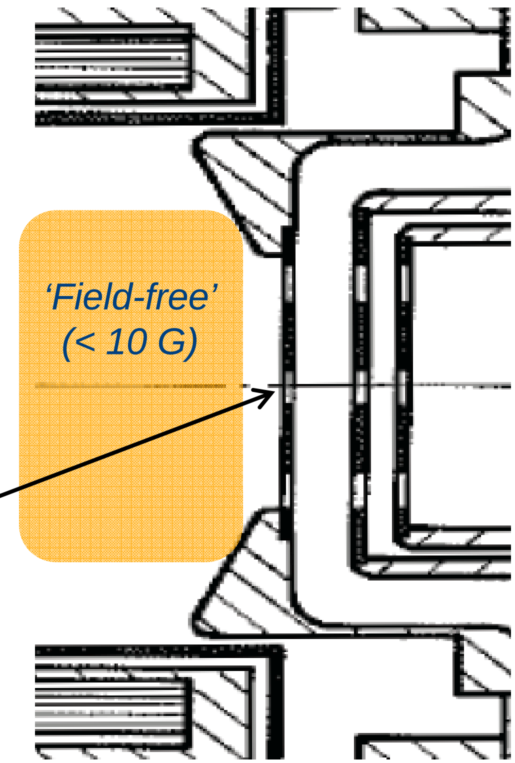


R. F. Welton et al., SNS-ORNL Oak Ridge

Multicusp ('Bucket') Sources (1)

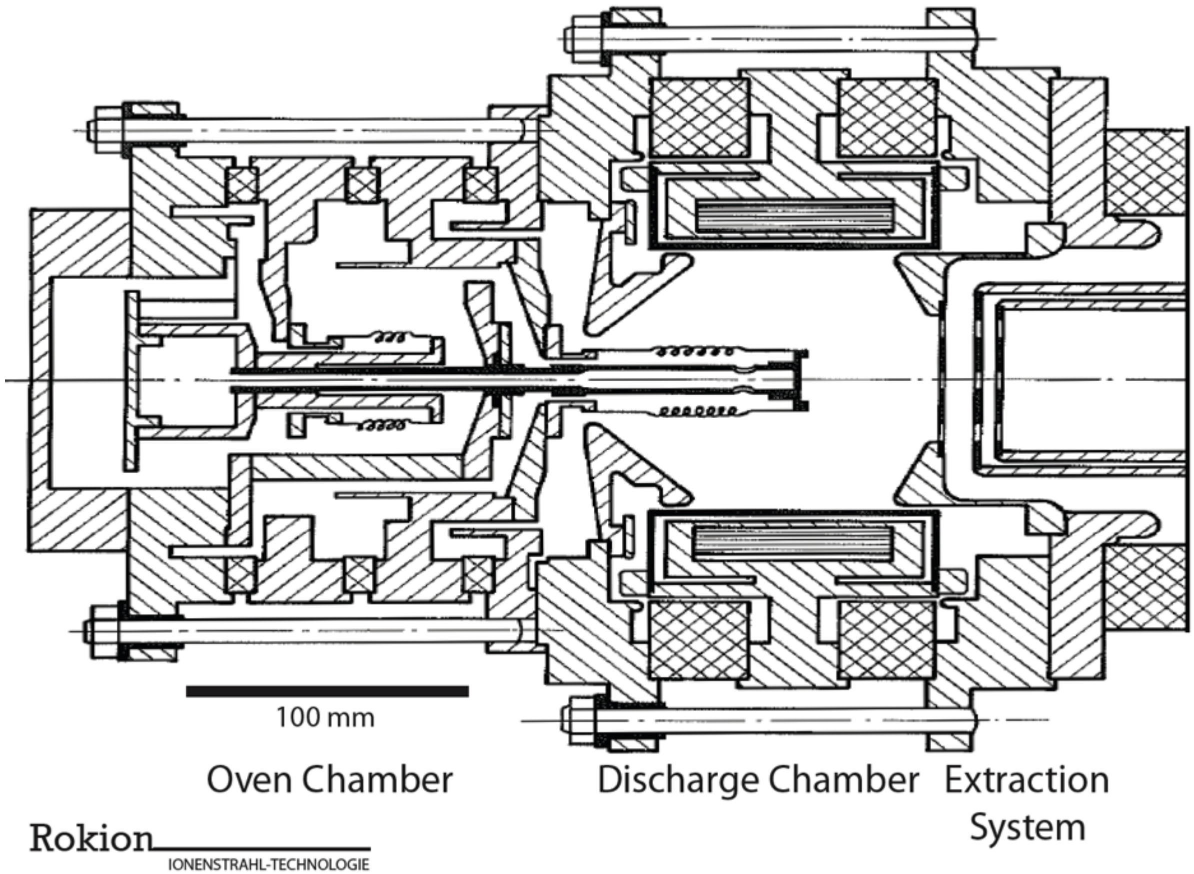
Fundamentals

- **Stable plasma confinement achieved by minimum-B configuration**
  - Magnetic fields increase with increasing distance from discharge center
  - Increases ionization probability for electrons
    - Significantly reduces plasma-loss area
  - Facilitates space-charge compensation of extracted beam (no oscillations)
  - Realized by lining discharge chamber with permanent magnets
    - High-current sources (8 – 20 magnets around)
  - Permanent-magnet or electro-magnet sextupoles
    -> ECR sources
  - Higher number of magnets enlarges 'field-free' cross-sectional area
    - Uniform plasma density allows use of wide multi-aperture extraction systems



Multicusp Sources (2)

Heavy ions



Conservative formula for single aperture, single ion species, single charge state:

$$I\ [\text{mA}] = 0.5\ A^{-1/2}\ U^{3/2}\ [\text{kV}^{3/2}]$$

See: *R. Keller, 1984 Linac Conf.*

Multicusp Sources (3)

H^+/D^+ generation fundamentals

- **Need to be optimized for atomic ion (H^+/D^+) production**
- **Molecular ions compete for share in plasma**
- **Cannot simply push discharge voltage to optimum value as with multi-charged (heavy) ions**
- **Need to excite vibrational states of H_2/D_2 molecules**
  - Requires low-energy electrons
- **Install hot liner or BN liner**
  - Creates 'pre-dissociation'
- **Install magnetic dipole filter across discharge chamber**
  - Keeps energetic electrons from penetrating across filter field into secondary chamber
  - Low-energy electrons pushed through by elastic collisions, ExB drift
- **Alternative: ECR source (see below)**

Multicusp Sources (4)

H^-/D^- generation fundamentals

- **Volume- and surface production,** *see M. Bacal, Nucl. Fusion (2006)*
- **Volume production issues similar to (H^+/D^+) ion production**
  - Install magnetic dipole filter across discharge chamber
    - Keeps energetic electrons from penetrating across filter field into secondary chamber
    - Low-energy electrons pushed through by elastic collisions, ExB drift
  - Need to excite ro-vibrational states of H_2/D_2 molecules
    - Requires even lower low-energy electrons
- **Even 10-eV electrons and neutrals can destroy H^-/D^-**
  - Provide short paths to outlet aperture
  - Less-than-proportional scaling of beam current vs. aperture area
- **Surface production relies on resonant-tunneling charge-exchange of H^-/D^- from surface with low work function**
  - Cesiated Mo etc.
  - Barium

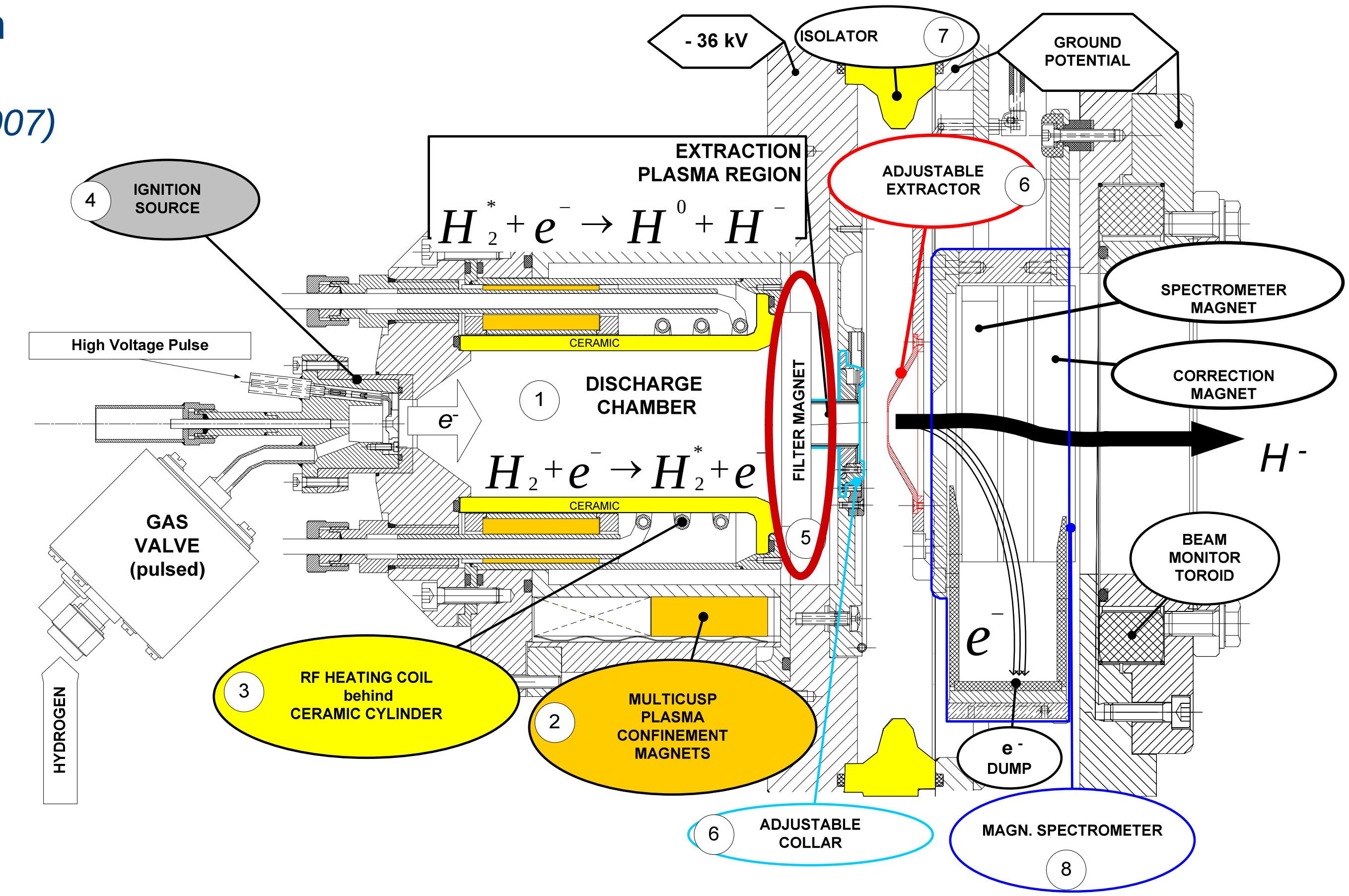
Multicusp Sources (5)

H^-/D^- generation by volume production

Multicusp source with magnetic dipole filter
(J. Peters, ICIS Conf. 2007)

Peak result

40 mA of H^- over 3 ms
Cesium-free



Multicusp Sources (6)

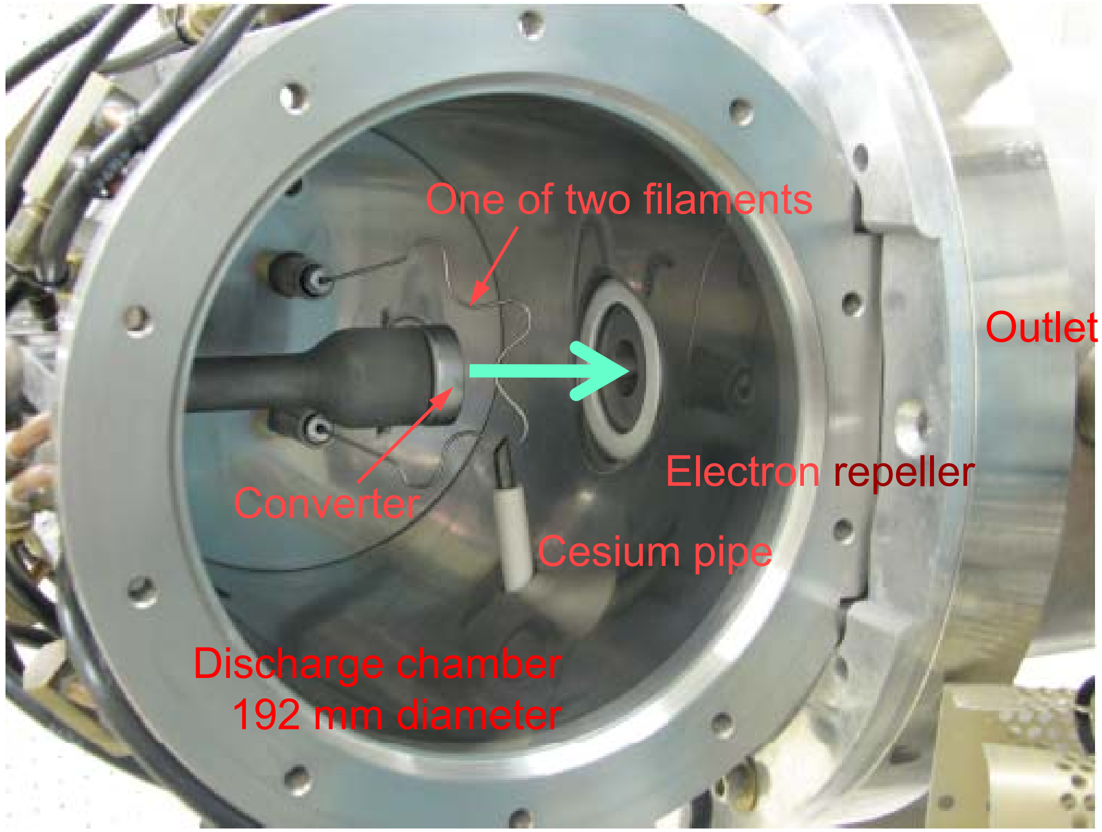
H^-/D^- Generation by surface production

LANSCE H^- Ion Source with cesiated, biased converter

0.8 ms-60/120 Hz operation

Up to 25 mA beam current from 9.8-mm aperture

300-eV beam energy inside source



R. L. York, R. R. Stevens et al., LANL Los Alamos

Electron Cyclotron-Resonance Sources (1)

Fundamentals, *see R. Geller, ECRIS Workshop (1987)*

- **Filament-free**
  - Very long times-between-services even at cw conditions
- **Microwave driven in 2.45-28 GHz frequency range**
- **Longitudinal magnetic mirror field**
- **Resonance condition** B_{res} [T] = 0.0354 f [GHz]
- **Highly charged ions**
  - Low gas pressure $< 10^{-6}$ Torr
  - High density
  - **High** magnetic field for plasma confinement
  - **Low** magnetic field better for extracting more beam current
  - Transverse confinement by sextupole
  - Cut-off electron density $n_e\ [cm^{-3}] \leq 1.25 \times 10^{10}\ f^2\ [GHz^2]$
- **High-current beams**
  - Higher gas pressure $\sim 10^{-3}$ Torr
  - Overdense wave penetration mode

Electron Cyclotron-Resonance Sources (2)

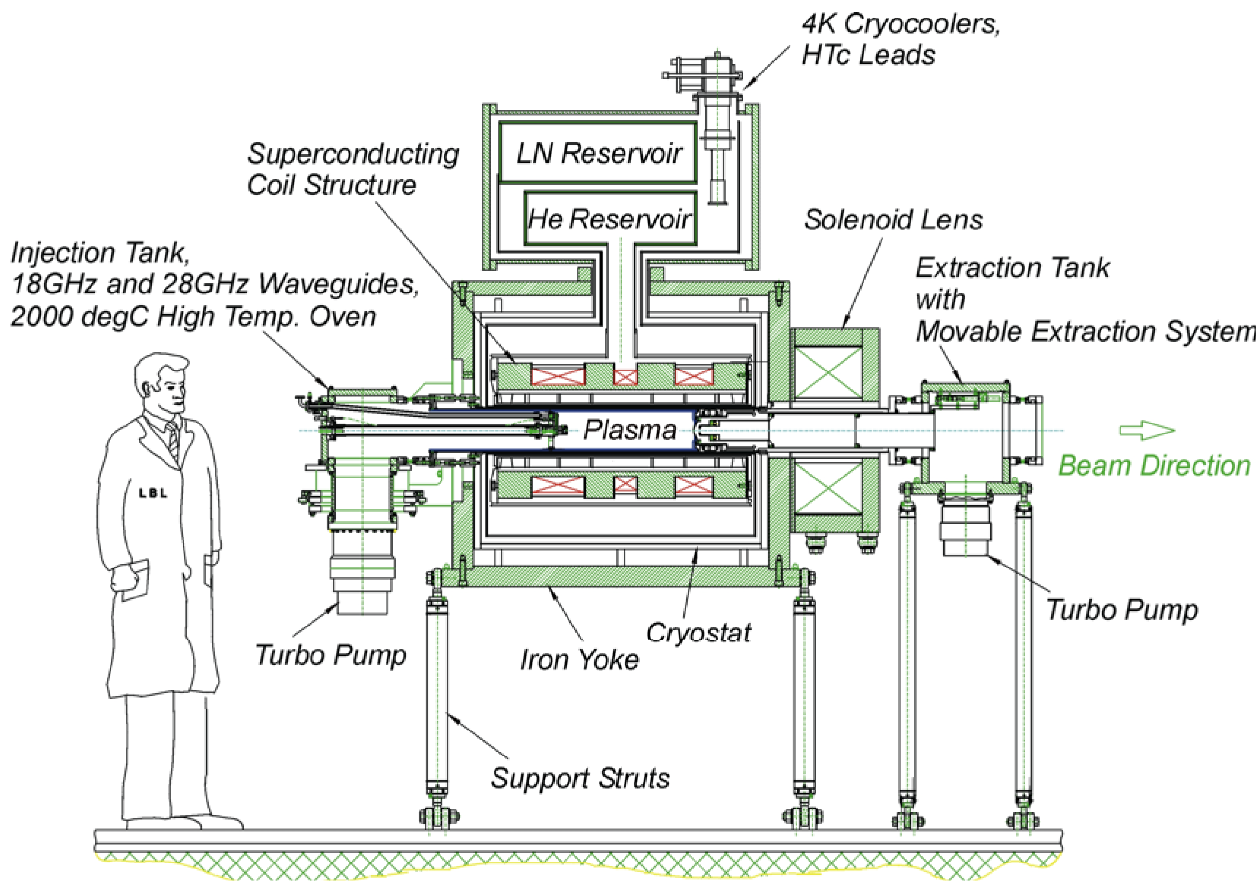
VENUS ECR Source for highly charged ions

Solenoid field 3.4 T peak
  1 T resonance at 28 GHz

Sextupole field 2.1 T at
  chamber wall

Peak results [electr. μ A]

$^{16}O^{6+}$	2850
$^{16}O^{7+}$	85
$^{129}Xe^{28+}$	222
$^{129}Xe^{38+}$	7
$^{238}U^{34+}$	202
$^{238}U^{35+}$	175
$^{238}U^{47+}$	5
$^{238}U^{50+}$	1.9



D. Leitner et al., LBNL Berkeley

Electron Cyclotron-Resonance Sources (3)

Issues and trends with ECR Sources for highly charged ions

- **Hollow-beam formation often noted**
  - Poor transport properties
- **X-ray generation becomes increasingly severe issue as plasma density, frequency and microwave power increase**
  - Requires external radiation shielding
  - Jeopardizes internal equipment (superconducting coils)
- **Ion production appears to depend on resonance volume**
  - Surface area of ‘resonance cigar’ times electron Larmor radius
  - Two-frequency microwave power
  - Broadband amplifier with Traveling-Wave Tube
  - **Small frequency adjustments beneficial** - *L. Celona et al., ECRIS Conf. (2008)*
  - Improves microwave mode selection
  - Increased power efficiency, about 30%
  - Improved beam profile
    - Hollow triangle -> solid ‘star’

Electron Cyclotron-Resonance Sources (4)

Charge Breeders

- **Serving Secondary Beam Facilities**
  - FAIR, RIA/FRIB
- **Collects radioactive ions from primary target**
- **Ionizes captured ions to higher charge states**
  - Improve efficiency of secondary accelerator
- **Main aspects**
  - Modular design minimizes radioactive waste upon turnover
  - Beam-current output depends on primary accelerator and target
  - Particle efficiency critical

Peak result from ANL Argonne, *see G. Savard et al., ECRIS Conf. 2008*

$^{133}Cs^{20+}$ at 3%
$^{85}Rb^{15+}$ at 3.6% particle efficiency

Electron Cyclotron-Resonance Sources (5)

High-current ECR Sources

- **Penetration of microwaves into overdense plasma**
  T. Taylor and J. S. C. Wills, Nucl. Instrum. Methods Phys. Res. A 309 (1991)
  - Utilized by microwave driven proton source
    - 2.45 GHz frequency
    - About 1 kW cw power
    - 0.0875 T ECR resonance field
      - Solenoids or permanent magnets used
      - Beam optics similar to 'field-free' extraction systems
    - No transverse plasma-confinement configuration

Peak result from LEDA project, Los Alamos

120 mA transportable dc beam with 90% proton share from 8.6-mm outlet aperture

See J. D. Sherman et al., ICIS Conf. (2001)

Recent Ion Source Information

Meetings and Journals

- **International Conference on Ion Sources**
  - Rev. Scientific Instrum. 79 (2008, latest published issue)
- **International Workshop on ECR Ion Sources**
  - AIP Conf. Proceedings 749 (2005, latest published issue)
  - Latest workshop held 2 weeks ago in Chicago
- **International Conference on Negative Ions, Beams and Sources**
  - AIP Conf. Proceedings 925 (2007, latest published issue)
    Meeting formerly called
    Int. Symp. on Production and Neutralization of Negative Ions and Beams

- **Nucl. Instrum. Methods in Phys. Research A and B**
- **Physical Review Special Topics - Accelerators and Beams**
- **IEEE Transactions on Plasma Science**
- **Applied Physics Letters**