H^-, D^- & He^{++} Source Developments for Medical Isotope Production Cyclotrons

Accelerator Development and Technology (ADT-1)
Tuesday, March 19, 2024.

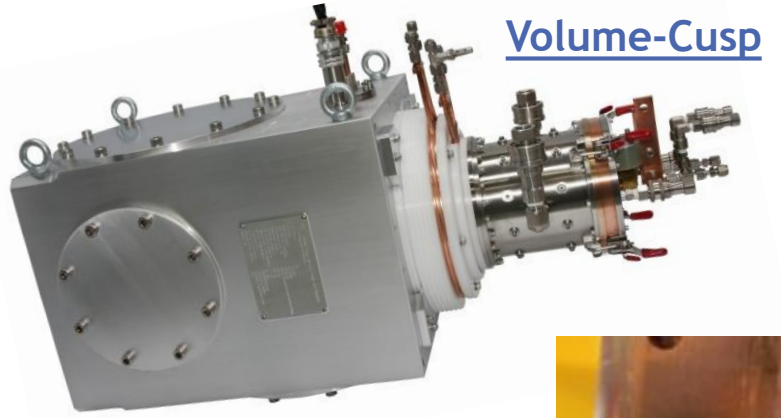
Thank You Very Much:

- Dr. Oliver Kester
- Dr. Brahim Mustapha

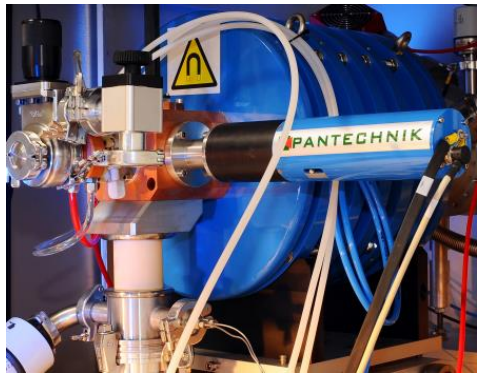
Presenter: Morgan Dehnel, Ph.D., Founder D-Pace, Inc.

Co-Authors: C. Hoehr, TRIUMF; S. Melanson, A. George, N. Savard D-Pace, Inc.

Monday, March 18, 2024



Volume-Cusp



ECR

Penning

[1] https://www.d-pace.com/?e=304
[2] D. Potkins, M. Dehnel, S. Melanson, T. Stewart, P.Jackle, J. Hinderer, N. Jones, L. Williams, “Improvements to Siemens Eclipse PET Cyclotron Penning Ion Source”, AIP Conference Proceedings, Vol. 2052, No. 1, P. 050016, AIP Publishing, 2018.
[3] https://www.pantechnik.com/wp-content/uploads/2020/07/Supernanogan.pdf

Norfolk, Virginia
AccelApp'24

Cyclotron Radioisotope Production: Topic Areas

- **Category 1**: Low Energy Cyclotron (Signpost: Proton 7 – 19 MeV, Typ. PET)
  - Internal Penning Ion Gauge (PIG) Ion Sources: $H^+/H^-/D^-$
    - Present Status & Developments
  - External Volume-Cusp Ion Sources: H^-/D^-
    - Present Status & Developments
- **Category 2**: Medium Energy Cyclotron (Signpost: Proton 20 – 45 MeV, Typ. SPECT, Therapeutic)
  - External Volume-Cusp Ion Sources: H^-/D^-
    - Present Status & Developments
  - ECR or Penning Source: $^4He^{++}$
    - Present Status & Developments
- **Category 3**: High Energy Cyclotron (Signpost: Proton 45+ MeV, Typ. SPECT, Therapeutic)
  - External Volume-Cusp Ion Sources: H^-/D^-
    - Present Status & Developments
  - ECR or Penning Source: H^+, H_2^+, $^3He^{++}$, $^4He^{++}$
    - Present Status & Developments

PRESENT STATUS

Internal Penning Ion Source

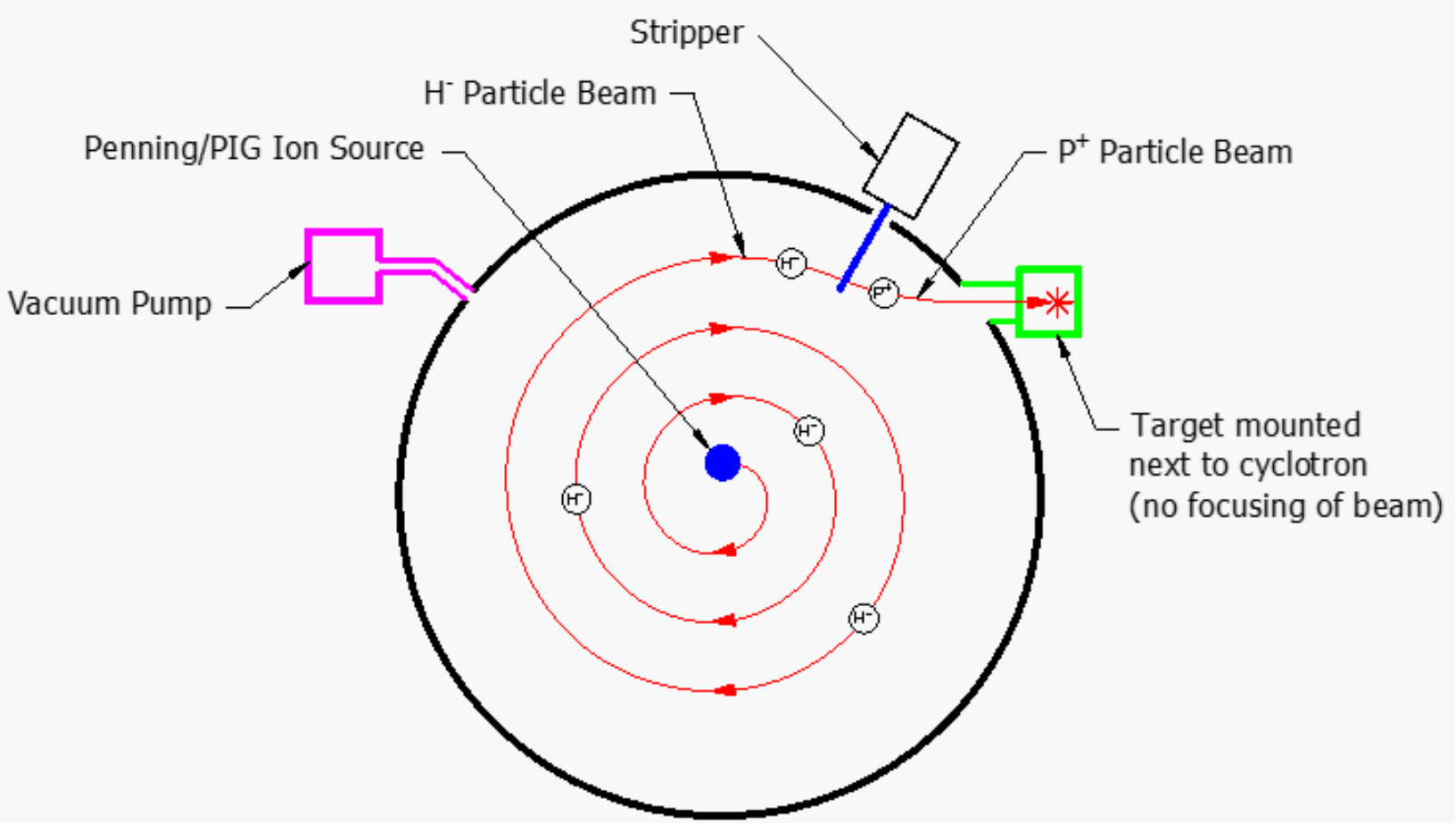
- BEST/ABT:	Canada/USA	BG-75
- GE:	Sweden	PETtrace™ 800, MINItrace™ Qilin
- IBA:	Belgium	KIUBE, Cyclone 18/9, Cyclone 18 HC
- Samyoung Unitech Co.	South Korea	Kotron-13
- Siemens:	USA	Eclipse
- SHI:	Japan	CYPRIS HM12, CYPRIS HM20

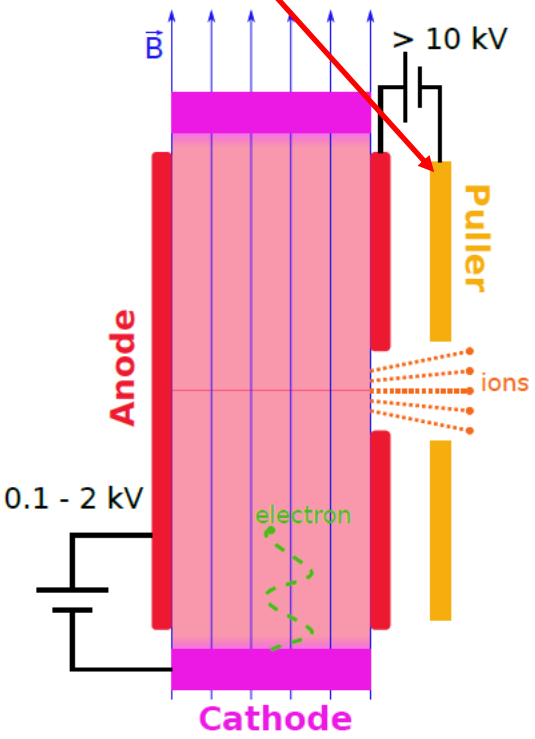
External Volume-Cusp Ion Source

- ACSI	Canada	TR19, TR19/9
- BEST	Canada	B15P
- PMB-Alcen	France	iMiTRACE

Category 1: Low Energy Cyclotron - Internal Penning Ion Source - Review

Can also be an RF Dee.



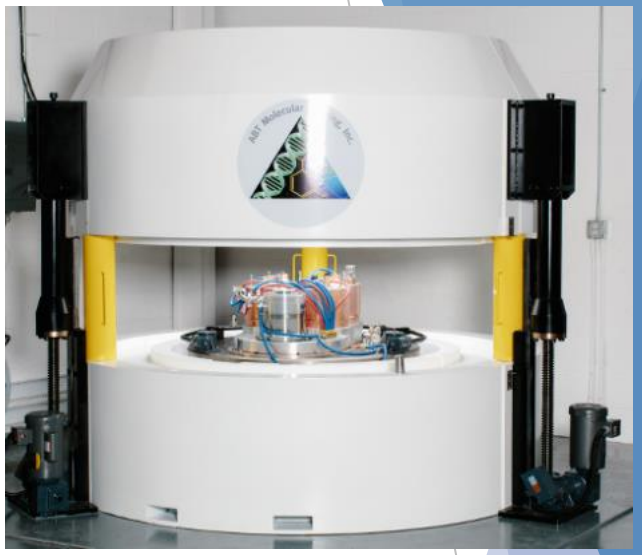


[1] Nicolas Savard, "Development and Characterization of a Penning Ion Source Using Helium", UBC PhD Dissertation, February 2022.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

BEST/ABT

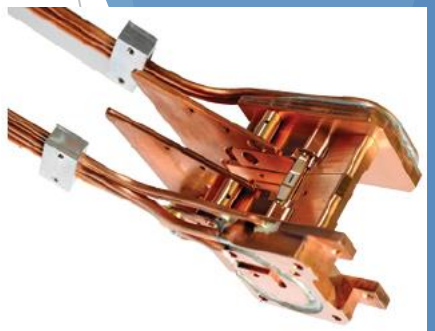
- **BG-75:** Max. Current: **H^+ 5 µA @ 7.5 MeV (internal target)**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^+
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. Arc Current: 400 mA
  - Steady State Arc Power: 60 W
  - Arc Current/Voltage: 72 mA/832 V
  - Gas Flow: 4-5 sccm
  - Cathode Lifetime: Unreported



[1] http://www.bestabt.com/our-solutions/overview/
[2] Private Communication: Darrell McCroskey, Director – Manufacturing Services, BEST ABT Inc., Data by Email March 14, 2024.

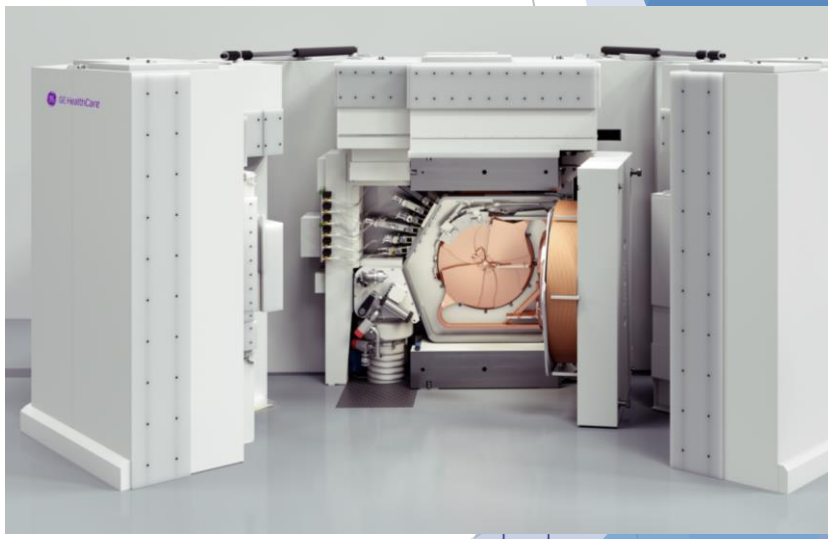
Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

GE



PETtrace 800 ion source

- **PETtrace™ 800:** Max. Extracted Current: **H^+ 160 µA @ 16.5 MeV; D^+ 60 µA @ 8.4 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-, D^-
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. H^-/D^- Current: Not Measured
  - Steady State Arc Power: ~100 W
  - Arc Current/Voltage: 300 mA/300V
  - Gas Flow: H^- 5 sccm; D^- 3.5 sccm
  - Cathode Lifetime: 35 mA.hrs on target, >219 hrs @ Max



[1] Private Communication – Tomas Eriksson, Chief Engineer Cyclotrons, GE Healthcare – Data by email February 5, 2024.
[2] Private Communication – Tomas Eriksson, Chief Engineer Cyclotrons, GE Healthcare – Photo by email February 12, 2024.
[3] PT800 Cyclotron System Data Sheet rev6.pdf

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

GE

- **MINItrace™ Qilin:** Max. Extracted Current: **H^+ 50 µA @ 9.6 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. H^- Current: Not Measured
  - Steady State Arc Power: ~125 W
  - Arc Current/Voltage: 500 mA/250V
  - Gas Flow: 5 sccm
  - Cathode Lifetime: 10 mA.hrs on target, >200 hrs @ Max

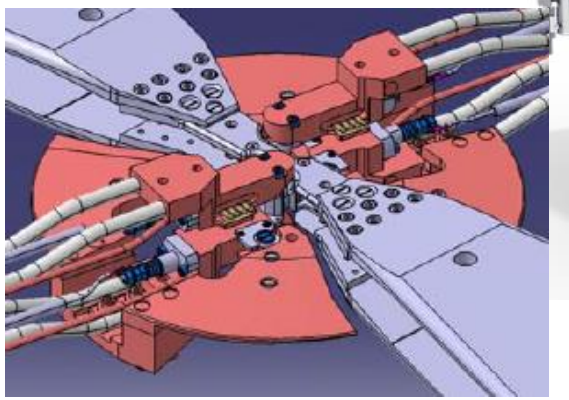
MINItrace Qilin ion source

[1] Private Communication – Tomas Eriksson, Chief Engineer Cyclotrons, GE Healthcare – Data by email February 5, 2024.
[2] MT QILIN Cyclotron System Data Sheet rev4.pdf

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

IBA

- **Cyclone®KIUBE 300 (Twin Source):** Max. Extracted Current: **H^+ 300 µA @ 18 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. H^- Current: N/A
  - Steady State Arc Power: 325W
  - Arc Current/Voltage: 1.25A/260V
  - Gas Flow: 2.5 -> 3.7 sccm
  - Cathode Lifetime: ~600 hrs



[1] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email January 17, 2024.
[2] Private Communication – Benoit Nactergal, Director R&D; Eric Kral, Systems Engineer, IBA RadioPharma Solutions, Data received by email March 1, 2024.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

IBA

- **Cyclone18/9 (Twin Source):** Max. Extracted Current: **H^+ 80 µA @ 18 MeV; D^+ 40 µA @ 9 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-/D^-
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. H^- Current: N/A
  - Steady State Arc Power: 325W
  - Arc Current/Voltage: 1.25A/260V
  - Gas Flow: 2.5 -> 3.7 sccm
  - Cathode Lifetime: ~600 hrs

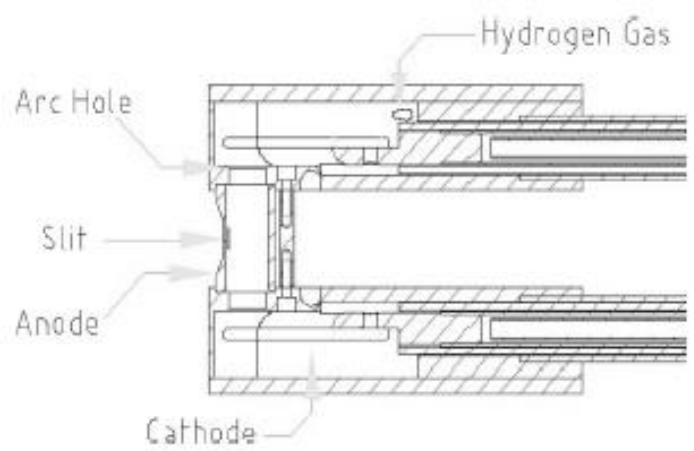
Cyclone® 18/9 Standard

[1] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email January 17, 2024.
[2] Private Communication – Benoit Nactergal, Director R&D; Eric Kral, Systems Engineer, IBA RadioPharma Solutions, Data received by email March 1, 2024.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

SAMYOUNG-UNITECH

- **Kotron-13:** Max. Extracted Current: H^+ 120 µA @ 13 MeV
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: Grounded, RF Dee Extraction
  - Source Max. H^- Current: Not Known
  - Steady State Arc Power: Not Known
  - Arc Current/Voltage: 2.8 A/2.5 kV* Ignition
  - Gas Flow: 6.5 sccm
  - Cathode Lifetime: >83 hours

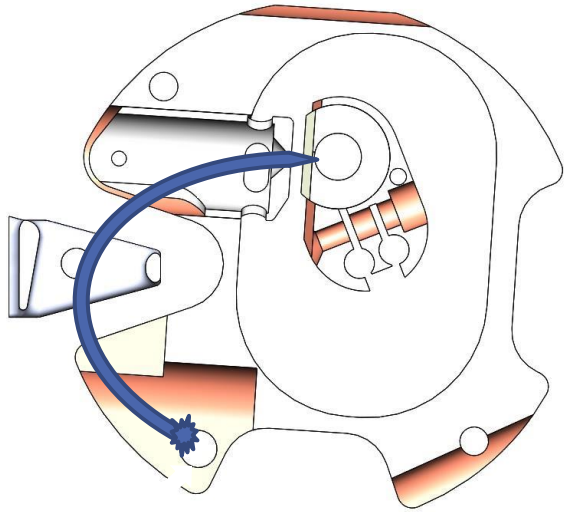


[#] http://samyoungunitech.com/doc/en/sb2_2.php
[#] B.C. Lee, H.J. Lee, J.H. Park, B.S. Moon, S.E. Kim, W. K. Lee, K.I. Jung, S. K. Chae, J.H. Kim, "Intensification of the KOTRON-13 Cyclotron by Optimizing the Ion Source", Journal of the Korean Physical Society, Vol. 57, No. 6, December 2010, pp. 1376-1380.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

Siemens

- **Eclipse:** Max. Extracted Current: **H^+ 150 µA @ 11 MeV (Dual 75 µA)**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: -15 kV, Puller Grounded, then RF Acceleration
  - Source Max. H^- Current: 1.5 mA DC (on Post Beam Stop)
  - Steady State Arc Power: 244 W
  - Arc Current/Voltage: 325 mA/750V
  - Gas Flow: 5 -> 9 sccm
  - Cathode Lifetime: >246 hrs



[1] Private Communication – Logan Williams, Cyclotron Engineer, Siemens Medical Solutions USA, Inc., Data provided in email January 29, 2024.
[2] Private Communication – J. Bret Miller, CCS Engineering Manager, Siemens Medical Solutions USA, Inc., Data provided in email January 30, 2024.
[3] D. Potkins, M. Dehnel, S. Melanson, T. Stewart, P.Jackle, J. Hinderer, N. Jones, L. Williams, "Improvements to Siemens Eclipse PET Cyclotron Penning Ion Source", AIP Conference Proceedings, Vol. 2052, No. 1, P. 050016, AIP Publishing, 2018.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source – Present Status

SHI

- **Cypris HM12:** Max. Extracted Current: **H^+ 50 µA @ 12 MeV; D^+ 30 µA @ 6 MeV**
- **Cypris HM20:** Max. Extracted Current: **H^+ 150 µA @ 20 MeV; D^+ 50 µA @ 10 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-/D^-
  - Source Bias: Grounded, RF Extraction from Dees
  - Source Max. H^- Current: Not Provided
  - Steady State Arc Power: Not Provided
  - Arc Current/Voltage: Not Provided
  - Gas Flow: Not Provided
  - Cathode Lifetime: Not provided

[1] CYRIC Annual Report 1998.
[2] https://www.shi.co.jp/industrial/en/product/medical/pet-radiopharmacy/cyclotron-hm12.html
[3] https://www.shi.co.jp/industrial/en/product/medical/pet-radiopharmacy/cyclotron-hm20.html
[4} H. Tsutsui et al, "Current Status of Sumitomo's Superconducting Cyclotron Development for Proton Therapy", Cyclotrons 2019 Conference, Cape Town, South Africa.

Developments

- **BEST/ABT BG-75**
  - Upgrade: H^+ beam, 20 micro-amperes @ 9.5 MeV internal targets [1].
- **GE MINItrace™ Qilin** the Penning ion source slit location in relation to the puller opening is remotely adjustable [2].
- **GE PETtrace™**
  - In-the-field cathode lifetime ranges 16-26 weeks at 55-60 hrs/week (880 hrs – 1560 hrs) [3].
  - Cathodes working surface at changeout are normally flat with mirror finish unless there is contamination such as an air leak [3].
  - Typical reason for changeout is reduced output due to slit erosion on Penning anode chamber (known as a “chimney”) [3].
  - Cathodes at some sites are re-used for 2-3 chimney change-outs. Insulators normally reused unless broken from over-tightening [3].

[1] Private Communication: Vasile Sabaiduc, Director of Cyclotron Operations, BEST Cyclotron Systems, Data by Email February 13, 2024.
[2] Private Communication – Tomas Eriksson, Chief Engineer Cyclotrons, GE Healthcare – Data by email March 5, 2024.
[3] Private Communication – Marty Magerl, Director of Cyclotron Services, North America SOFIE – Data by email February 16, 2024.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source

Developments

- **Siemens Eclipse**
- Recent developments [1]:
  - Improved vacuum integrity at the hydrogen line & ion source itself. Improvements in serviceability.
- Future developments [1]:
  - The focus is on improved heat transfer at the upper cathode.
  - Mitigate a glow discharge phenomenon in the hydrogen feed line (at times).
  - Long-term goal is still to test for increased, persistent ion production using caesium.
- Caesium getters. SAES Group: 2.7mg, Ø1mm x 0.8mm pills (0.6 mg Cs). Released from Cs-Al-Zr salt >550 C [2]

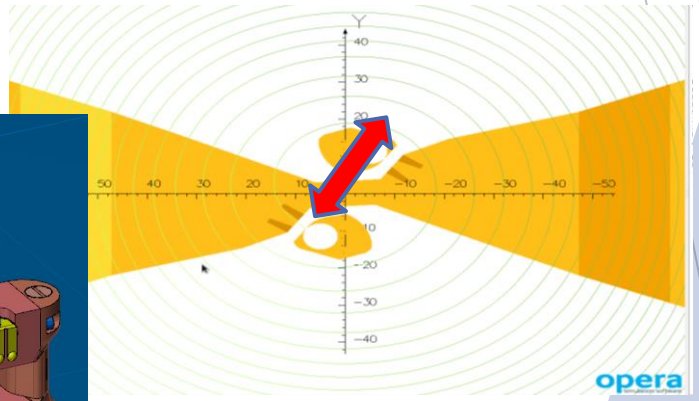
	Arc I	Arc Power	Beam @ Post	Beam @ 11 MeV	
Baseline	0.27 A	174 W	740 µA	128 µA	[2]
Cs Pill in Lower Cathode	0.27 A	116 W	925 µA	155 µA	[2]

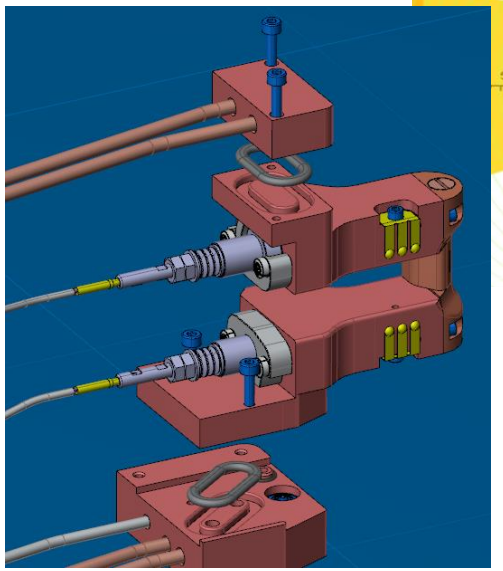
[1] Private Communication – Logan Williams, Cyclotron Engineer, Siemens Medical Solutions USA, Inc., Data provided in email January 29, 2024 .
[2] D. Potkins, M. Dehnel, S. Melanson, T. Stewart, P.Jackle, J. Hinderer, N. Jones, L. Williams, "Improvements to Siemens Eclipse PET Cyclotron Penning Ion Source", AIP Conference Proceedings, Vol. 2052, No. 1, P. 050016, AIP Publishing, 2018.

Category 1: Low Energy Cyclotron - Internal Penning Ion Source

Developments

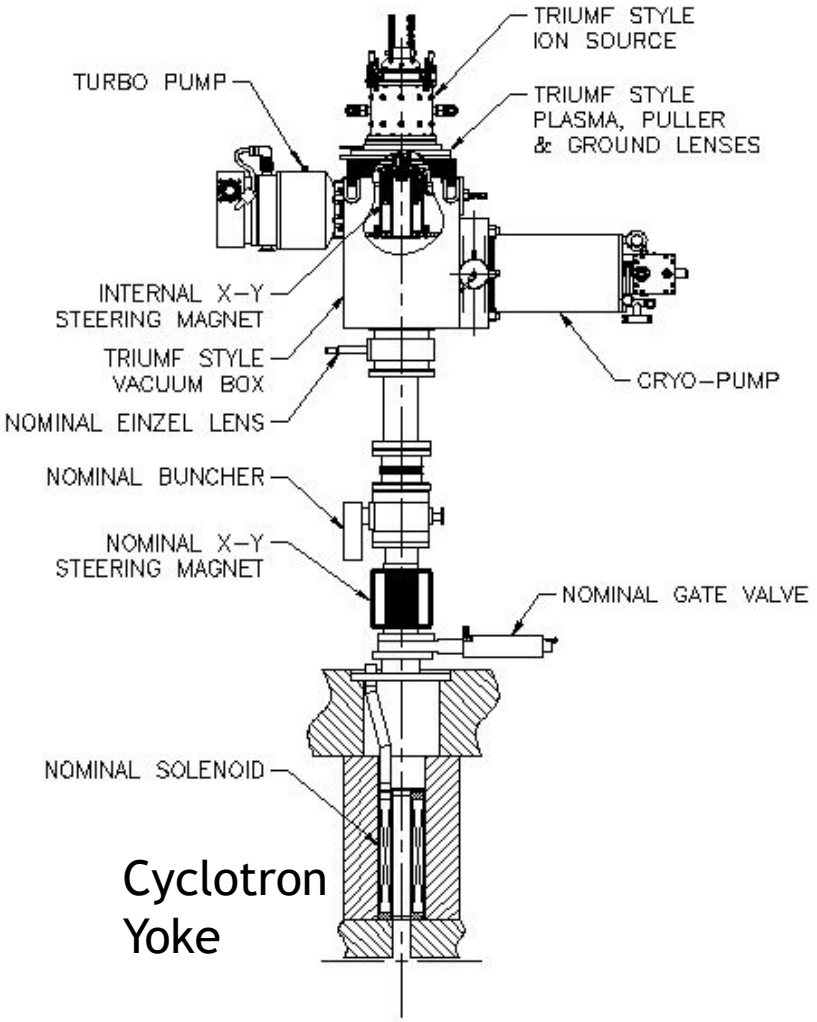
- **IBA [1]**
  - Twin Ion Sources:
    - Switching to second source is automated.
    - Global source lifetime significantly increased.
  - Kiube Motorized Source:
    - Azimuthal/Radial .
    - Global source lifetime significantly increased.
  - Kiube Easy Access:
    - Source body/cathodes, maintenance.
    - 300 µA extracted at 18 MeV, H^+

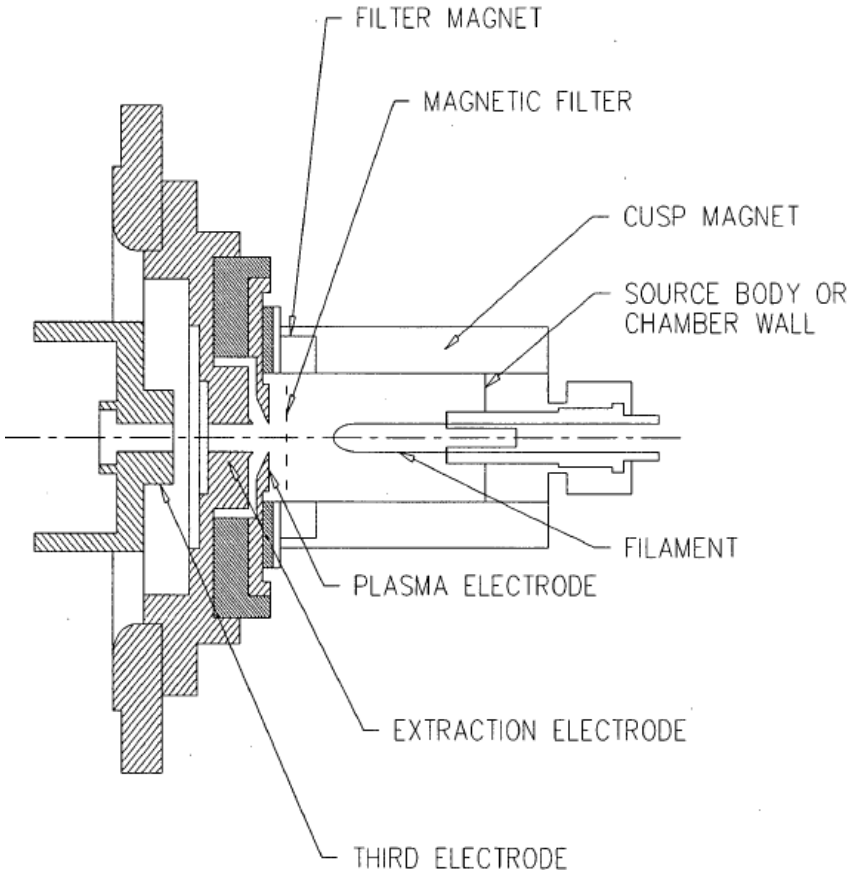




[1] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email January 17, 2024.

External Volume-Cusp Ion Source Review





[1] M. Dehnel et al, "An Ion Source Upgrade for an Axial Injection Based Commercial Cyclotron", NIMB, Vol. 241, Issues 1-4, pp. 896-900, 2005.
[2] M. Dehnel, "The Development of an Injection System for a Compact H- Cyclotron, the Concomitant Measurement of Injected Beam Properties, and the Experimental Characterization of the Spiral Inflector", UBC, PhD thesis, 1995.

Category 1: Low Energy Cyclotron – External Volume-Cusp Ion Source – Present Status

BEST

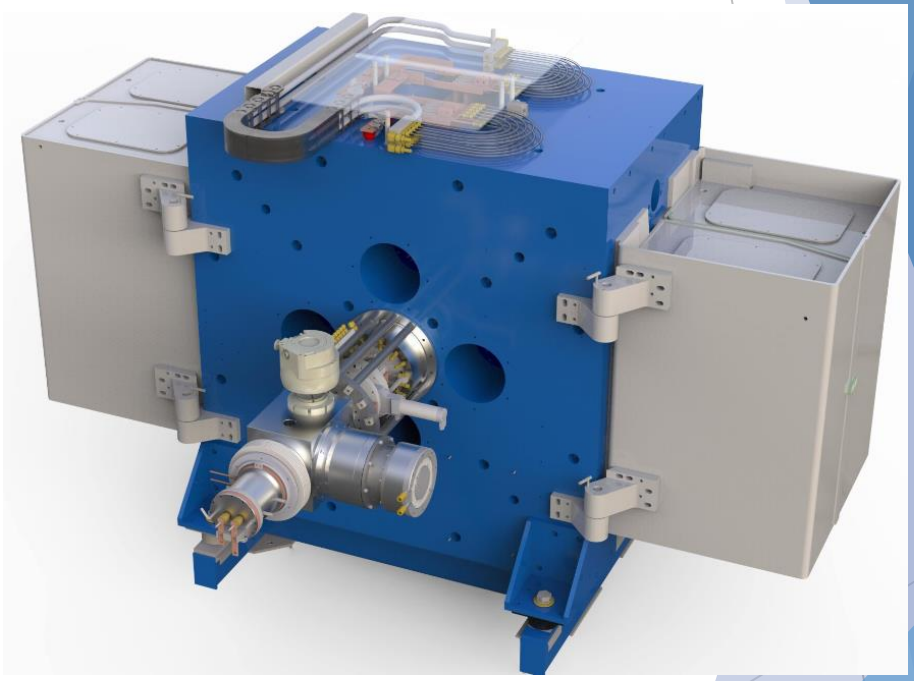
- **B15P:** Max. Extracted Current: **H^+ 400 µA @ 15 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: −25 kV
  - Source Max. H^- Current: 5 mA
  - Steady State Arc Power: 2.8 kW
  - Arc Current/Voltage: 20 A/140 V
  - Gas Flow: 12 sccm
  - Filament Lifetime: >500 hrs

[1] Private Communication: Vasile Sabaiduc, Director of Cyclotron Operations, BEST Cyclotron Systems, Data by Email February 13, 2024.

Category 1: Low Energy Cyclotron – External Volume-Cusp Ion Source – Present Status

ACSI

- **TR-19, TR-19/9:** Max. Extracted Current: **H^+ 400 µA @ 19 MeV; D^+ 75 µA @ 9 MeV**
- Cyclotron Parameters for Max. Extracted Current
  - Accelerated Particle: H^-, D^-
  - Source Bias: −28 kV, −13 kV
  - Source Max. H^- Current: 5 mA, 2.6 mA
  - Steady State Arc Power: 1.5 kW
  - Arc Current/Voltage: 15 A/100 V
  - Gas Flow: 10 sccm, 5 sccm
  - Filament Lifetime: >1500 hrs



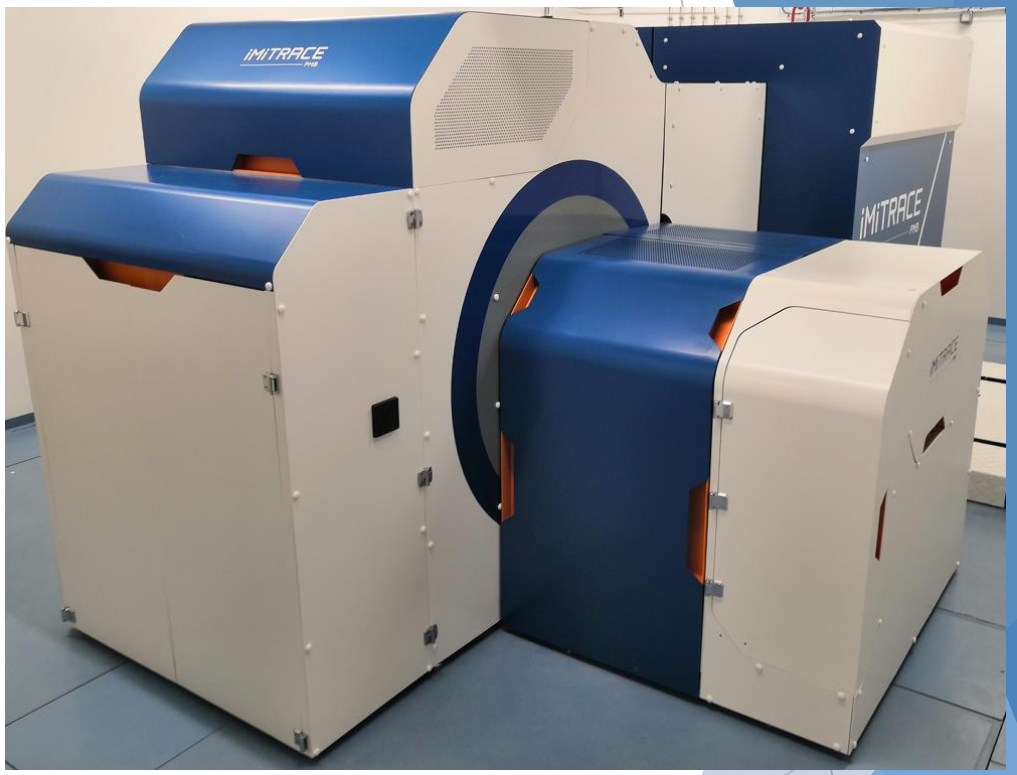
[1] Private Communication: Russell Watt, Chief Cyclotron Engineer, ACSI, Data by Email January 19, 2024.
[2] https://advancedcyclotron.com/our-cyclotrons/tr19/

Category 1: Low Energy Cyclotron – External Volume-Cusp Ion Source – Present Status

PMB-Alcen

- **iMiTRACE:** Max. Extracted Current: **H^+ 50 µA @ 12 MeV**
- Cyclotron* Parameters for Max. Extracted Current
  - Accelerated Particle: H^-
  - Source Bias: −25 kV
  - Source Max. H^- Current: 1.5 mA
  - Steady State Arc Power: 2 kW
  - Arc Current/Voltage: 20 A/100 V
  - Gas Flow: 10 sccm
  - Filament Lifetime: >800 hrs

*Super-Conducting



[1] Private Communication: Gaëtan Carreno, Cyclotron Engineer, PMB-Alcen, Data by Email January 19, 2024.

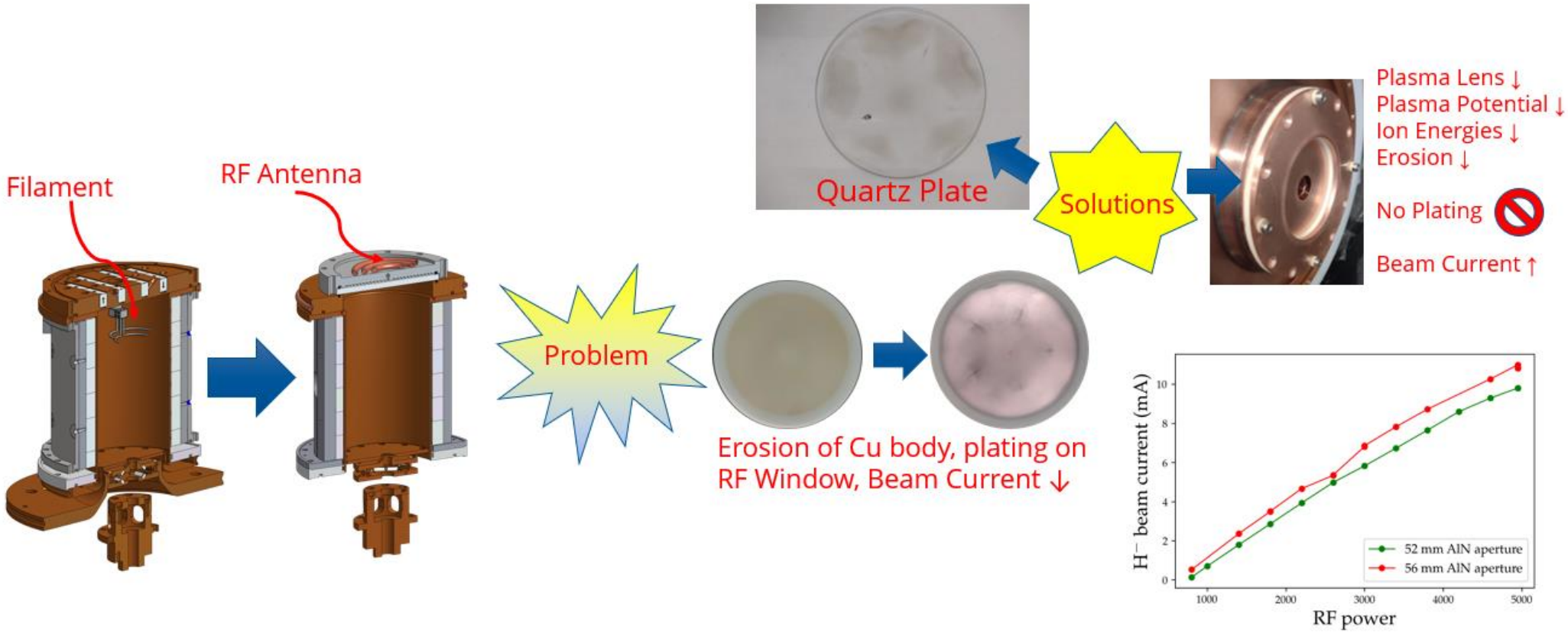
Developments

- **PMB-Alcen, iMiTRACE** [1]
  - Enameling of ceramic parts for easier cleaning.
  - Feasibility study on moving to simpler, less expensive Penning System.
- **ACSI TR19** [2]
  - Converted from cryo-pumps to Turbo pumps many years ago (avoids cryo-regeneration).
  - Filament failure occurs when filament heating current (not arc current) is ~90A, so filament replacements are scheduled when filament heating current ~120A.
  - Source cleaning of only major flakes with lint free cloth. Retain sputtered tantalum surface. If source inner chamber cleaned to copper surface, then it can take a few days to get current production back up to normal.
  - Keep source running at low current to source beam stop between runs. Do not “turn off” source as then thermal cycling of the filament will reduce lifetime.

[1] Private Communication: Gaëtan Carreno, Cyclotron Engineer, PMB-Alcen, Data by Email March 7, 2024.
[2] Private Communication: Leonard Popa, Senior Principal Product Engineer, Cardinal Health, March 3, 2024.

Developments

- **D-Pace RF Ion Source** [1] PostDoc with TRIUMF; hybrid TRIUMF & U. Jyväskylä licenses:
  - Aim is to avoid filament changeouts, maintenance interval 1-2 years.



[1] A. George et al, "Investigation of Plasma Chamber Erosion in an RF Ion Source", International Conference on Ion Sources, Victoria BC Canada, September 2023, in press.

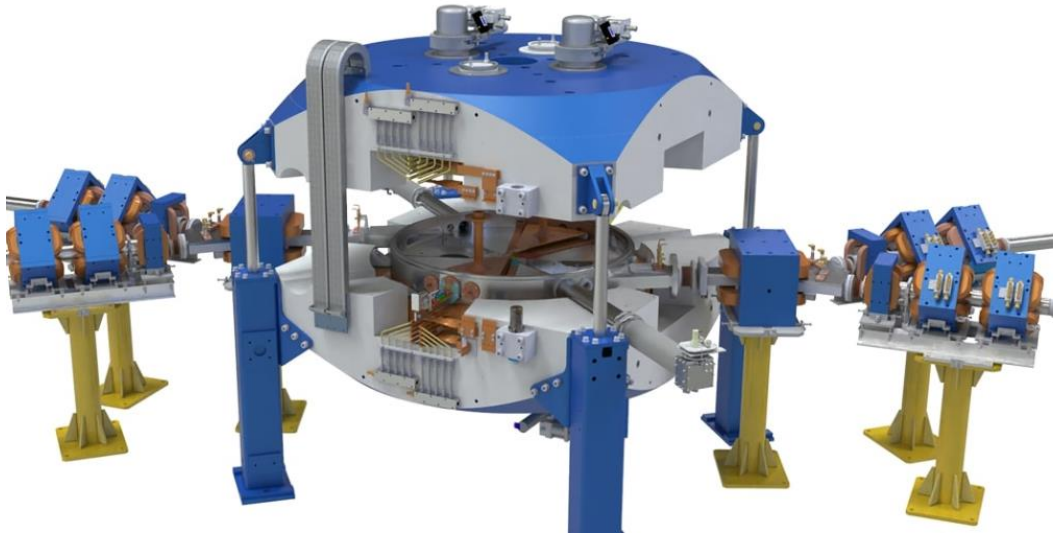
PRESENT STATUS

- **External Volume-Cusp Ion Source**
  - ACSI — Canada — TR-24, TR-FLEX, TR-30, TR-30/15
  - BEST — Canada — B25P, B35P
  - IBA — Belgium — C30, C30-HC
- **External Volume-Cusp Ion Source & ECR**
  - IBA — Belgium — C30XP
- **External Volume-Cusp Ion Source & Penning**
  - SHI — Japan — MP-30

Category 2: Medium Energy Cyclotron – External Volume-Cusp – Present Status

ACSI

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
TR-24	$H^- \rightarrow H^+$	**1000 µA/24 MeV**	15 mA	−28 kV	1.5 kW	15A/100V	8 sccm	1500 hours
TR-FLEX	$H^- \rightarrow H^+$	**1000 µA/30 MeV**	15 mA	−28 kV	1.5 kW	15A/100V	8 sccm	1500 hours
TR-30	$H^- \rightarrow H^+$	**1800 µA/30 MeV**	15 mA	−28 kV	3.5 kW	35A/100V	12 sccm	1500 hours
TR-30/15	$D^- \rightarrow D^+$	**150 µA/15 MeV**	5 mA	−13 kV	2.0 kW	20A/100V	7 sccm	1500 hours

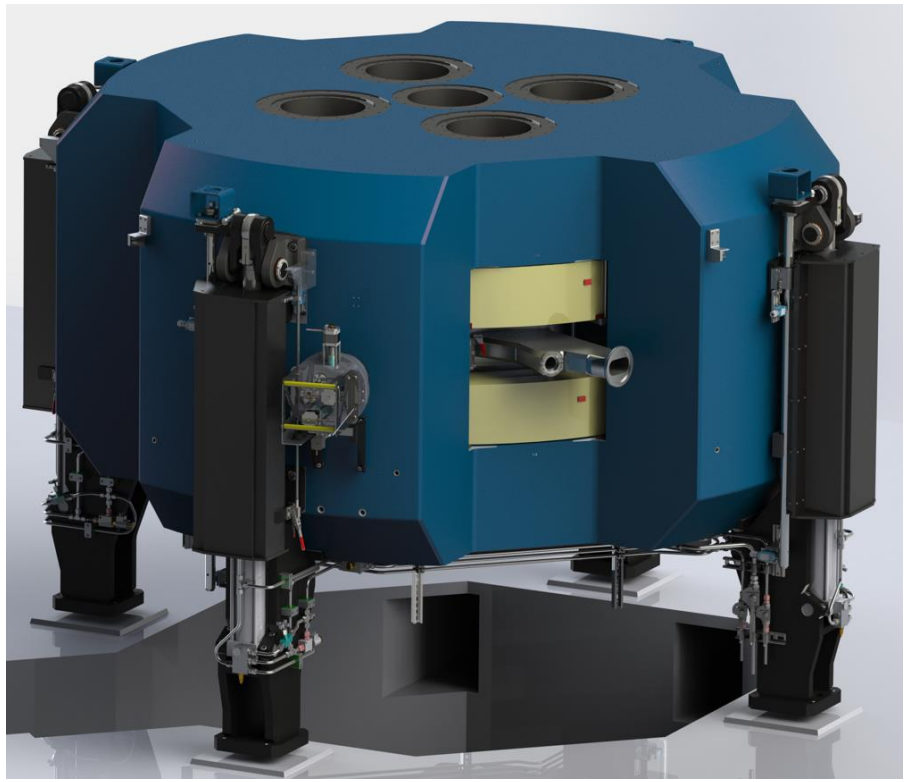


[1] Private Communication: Russell Watt, Chief Cyclotron Engineer, ACSI, Data by Email January 19, 2024.
[2] https://advancedcyclotron.com/our-cyclotrons/tr30/

Category 2: Medium Energy Cyclotron – External Volume-Cusp – Present Status

BEST

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
B25P	$H^- \rightarrow H^+$	**1000 µA/25 MeV**	10 mA	−28 kV	4 kW	28A/143V	12 sccm	>500 hours
B35P	$H^- \rightarrow H^+$	**1200 µA/35 MeV**	12 mA	−28 kV	4 kW	28A/143V	12 sccm	>500 hours



[1] Private Communication: Vasile Sabaiduc, Director of Cyclotron Operations, BEST Cyclotron Systems, Data by Email February 13, 2024.

Category 2: Medium Energy Cyclotron – External Volume-Cusp – Present Status

IBA

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
C30	$H^- \rightarrow H^+$	**750 µA/30 MeV**	5 mA	−31 kV	2.0 kW	25A/80V	12 sccm	500 hours
C30-HC	$H^- \rightarrow H^+$	**1200 µA/30 MeV**	10 mA	−31 kV	2.5 kW	20A/120V	12 sccm	800 hours
IKON	$H^- \rightarrow H^+$	**1200 µA/30 MeV**	10 mA	−40 kV	2.5 kW	25A/100V	12 sccm	800 hours

[1] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[2] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email March 4, 2024.

Category 2: Medium Energy Cyclotron – External Volume-Cusp & ECR – Present Status

IBA

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
C30xp	$H^- \rightarrow H^+$	**350 µA/30 MeV**	5 mA	–40 kV	2.0 kW	25A/80V	12 sccm	500 hours
C30xp	$D^- \rightarrow D^+$	**100 µA/15 MeV**	1.2 mA	-20 kV	2.5 kW	15A/167V	12 sccm	500 hours
C30xp*	$^4He^{++}$	**50 µAe/30 MeV**	1.2 mAe	+20 kV	0.5 kW RF	N/A	12 sccm	15000 hours

*** ECR for $^4He^{++}$**

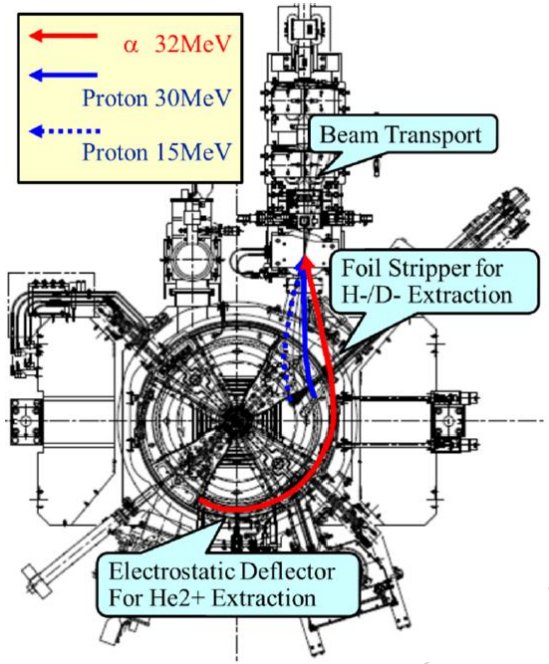
[1] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[2] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email March 4, 2024.

Category 2: Medium Energy Cyclotron – External Volume-Cusp & Penning – Present Status

SHI

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
MP-30	$H^- \rightarrow H^+$	**400 µA/30 MeV**	N/A	−30 kV	N/A	N/A	N/A	N/A
MP-30	$D^- \rightarrow D^+$	**100 µA/15 MeV**	N/A	-16 kV	N/A	N/A	N/A	N/A
MP-30*	$^4He^{++}$	**30 µAe/32 MeV**	N/A	+16 kV	N/A	N/A	N/A	N/A

***Penning for $^4He^{++}$**



[1] M. Taniguchu et al, "Sumitomo Multi-Purpose Cyclotron MP-30", Proceedings of the 14th Annual Meeting of Particle Accelerator Society of Japan, August 1-3, 2017, Sapporo, Japan.

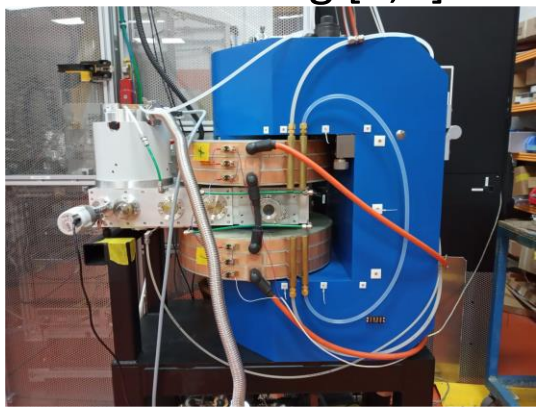
Category 2: Medium Energy Cyclotron – External Volume-Cusp/ECR/Penning

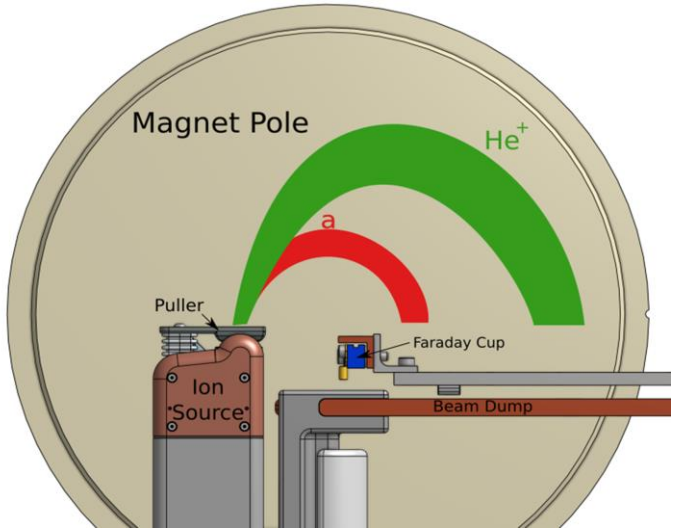
Developments

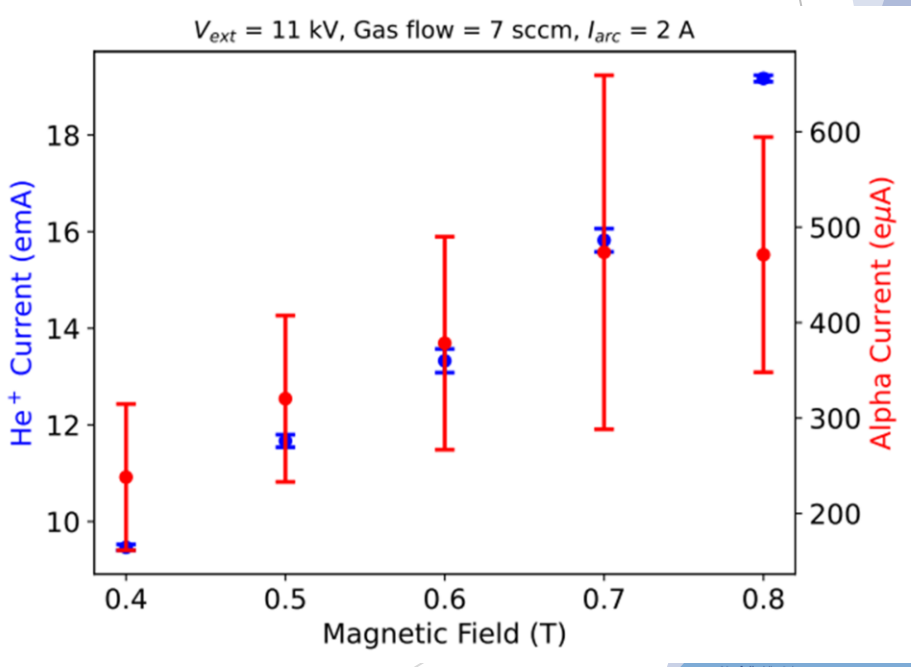
	Source	Particle	Extraction	Max IS	IS Bias	RF Power	Gas Flow	Lifetime
TR-Alpha [1]	**ECR**	$^4He^{++}$	**NA/30 MeV***	N/A	30 kV	N/A	N/A	N/A
C30-Alpha [2]	**PIG**	$^4He^{++}$	**150 eμA/29 MeV**	150 eμA	RF ext.	N/A	N/A	100 hours

* Internal Target

- D-Pace Penning [3,4]







[1] Private Communication: Russell Watt, Chief Cyclotron Engineer, ACSI, Data by Email March 13, 2024.
[2] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[3] N. Savard et al, "Extraction of High-Charge State Argon and Alpha Particles from D-Pace Penning Ion Source Test Stand", Proc. 13th IPAC, Bangkok, 12-17 June 2022. JACoW Publishing, 2022 pp. 1816-1818.
[4] N. Savard, "Development and Characterization of a Penning Ion Source Using Helium", UBC PhD, Thesis, 2022.

PRESENT STATUS

- **External Volume-Cusp Ion Source**
  - BEST Canada B70P
  - IBA Belgium C70P
- **External Volume-Cusp & ECR Ion Source**
  - IBA Belgium C70XP
- **Internal Penning Ion Source**
  - Scanditronix Sweden MC50

Category 3: High Energy Cyclotron – External Volume-Cusp – Present Status

BEST

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
B70P	$H^- \rightarrow H^+$	**1000 µA/70 MeV**	12 mA	−40 kV	4.0 kW	28A/143V	12 sccm	500 hours

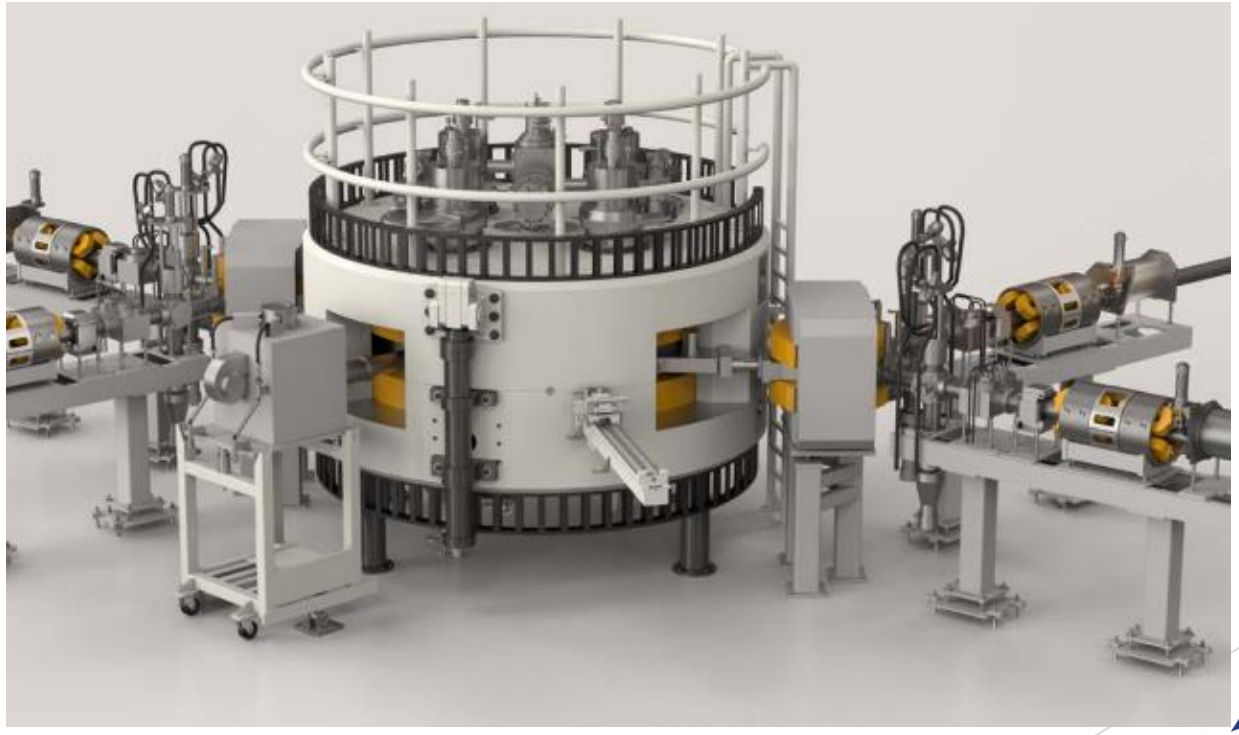
[1] Private Communication: Vasile Sabaiduc, Director of Cyclotron Operations, BEST Cyclotron Systems, Data by Email February 13, 2024.

Category 3: High Energy Cyclotron – External Volume-Cusp – Present Status

IBA

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
C70p	$H^- \rightarrow H^+$	**350*µA/70 MeV**	5 mA	–40 kV	2.0 kW	25A/80V	12 sccm	500 hours

* Did 700 µA 35-70 MeV, and also 750 µA in single beam mode with D-Pace's TRIUMF licensed multi-cusp, filament-powered H^- source 10 mA.



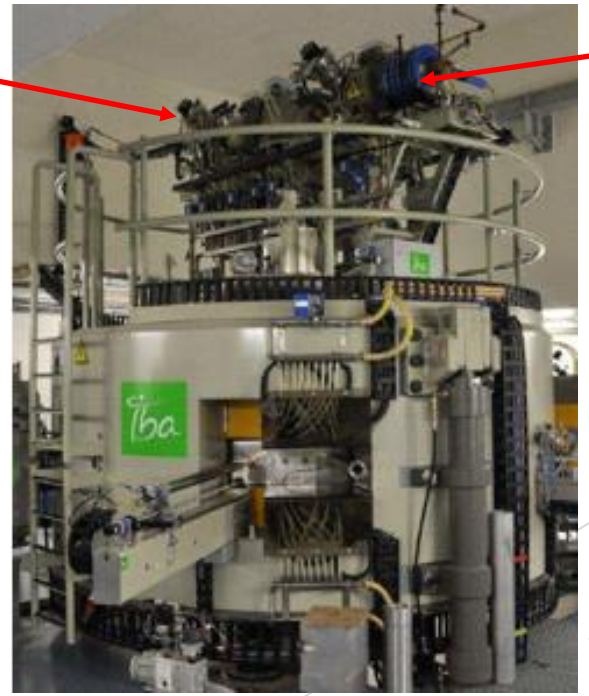
[1] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[2] https://hm-offload.s3.eu-west-3.amazonaws.com/iba/2023/04/cyclone_70_web.pdf
[3] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email March 4, 2024.

Category 3: High Energy Cyclotron – External Volume-Cusp & ECR – Present Status

IBA

	Particle	Extraction	Max IS	IS Bias	Arc Power	Arc I/V	Gas Flow	Filament Lifetime
C70xp	$H^- \rightarrow H^+$	**1000*µA/70MeV**	10 mA	–40 kV	2.0 kW	25A/80V	12 sccm	500 hours
C70xp	$D^- \rightarrow D^+$	**100 µA/35 MeV**	1.2 mA	-20 kV	2.5 kW	15A/167V	12 sccm	500 hours
C70xp	$^4He^{++}$	**70 eµA/70 MeV**	1.2 mAe	+20 kV	0.5 kW RF*	N/A	12 sccm	15000 hours
C70XP	H_2^+	**50 µA/15 MeV**	1 mAe	+20 kV	0.5 kW RF*	N/A	12 sccm	15000 hours

Volume-Cusp **ECR**



* Did 750 µA 35-70 MeV at Arronax.

[1] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[2] Private Communication - Jean-Michel Geets, IntegraLab Business Developer – IBA Fellow, IBA RadioPharma Solutions – Data by email March 4, 2024.

Category 3: High Energy Cyclotron – Penning – Present Status

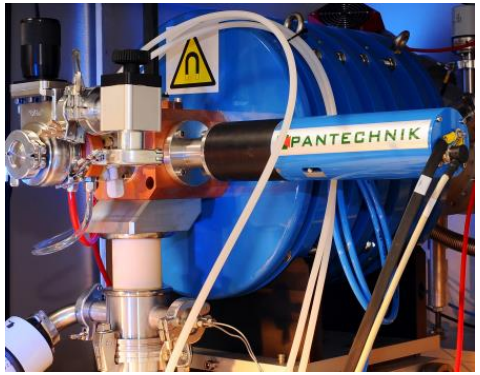
Scanditronix (UWMCF)

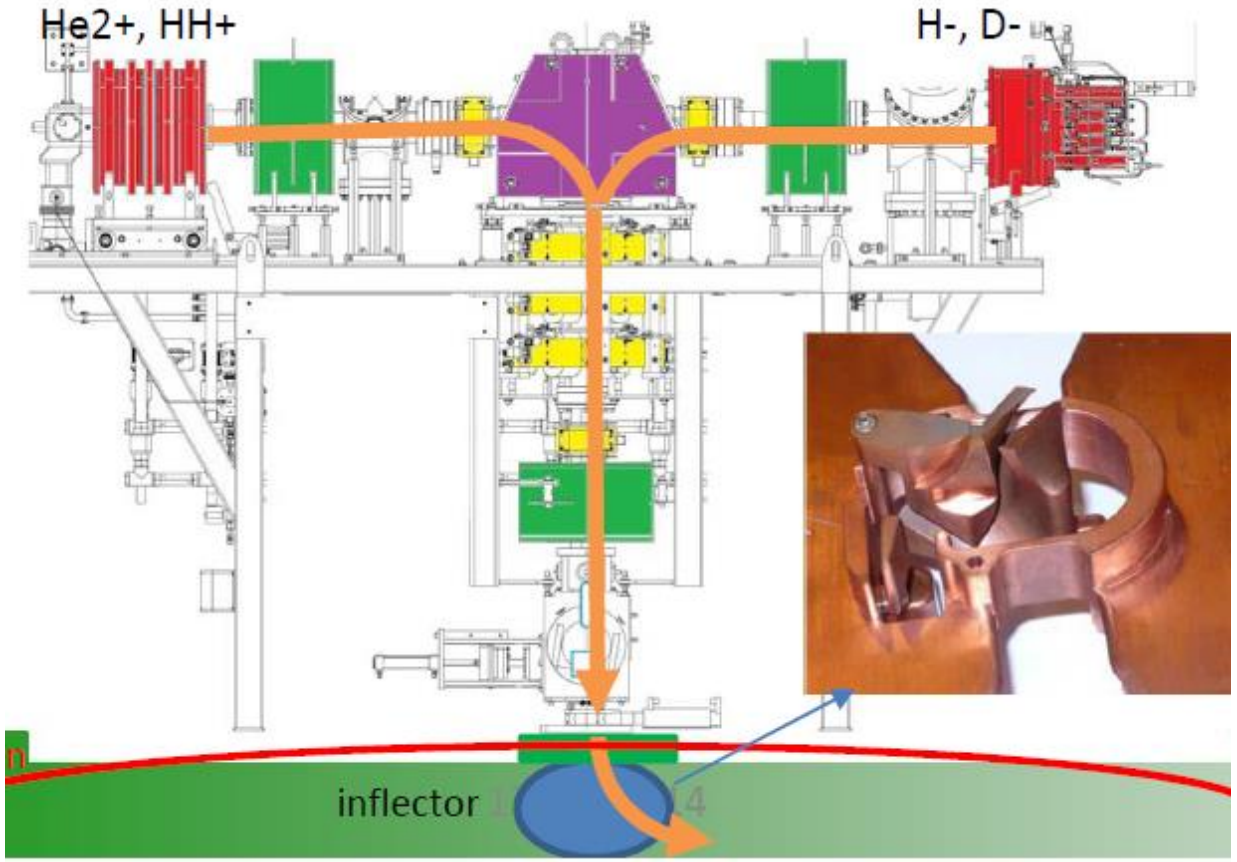
	Particle	Extraction	Max IS (r17 cm)	IS Bias	ArcPower	Arc I/V	Gas Flow	Cathode Lifetime (buttons)
MC50	H^+	**50 µA/50.5 MeV**	70 µA	Ground	106 W	85mA/1.25kV	3 sccm	>120 hours
MC50	$^4He^{++}$	**70µAe/47.3 MeV**	80 µA	Ground	750 W	0.5A/1.5 kV	3 sccm	4-8 hours
MC50	D^+	**35 µA/23.8 MeV**	N/A	Ground	45 W	50mA/0.9kV	3.7 sccm	>120 hours
MC50	$^3He^{++}$	**2 µAe/35.7 MeV**	N/A	Ground	280 W	0.2A/1.4kV	3.5 sccm	4-8 hours

[1] Private Communication: Marissa Kranz, Facility Director, University of Washington Medical Cyclotron Facility, Data by Email February 29, 2024.
[2] Private Communication: Marissa Kranz, Facility Director, University of Washington Medical Cyclotron Facility, Photo by Email March 13, 2024.

Developments

- **IBA C70P** [1]

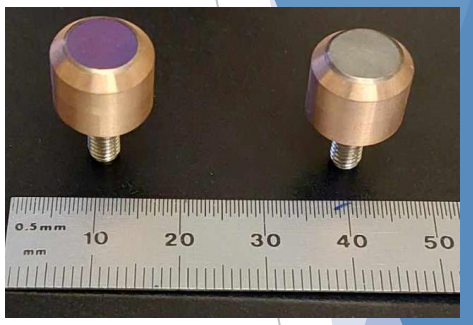




[1] Private Communication: Jean-Luc Delvaux, Honorary Fellow, IBA, Data by Email January 18, 2024.
[2] https://www.pantechnik.com/wp-content/uploads/2020/07/Supernanogan.pdf
[3] https://www.d-pace.com/?e=304

Developments

- **Scanditronix MC50 UWMCF** [1]
  - 2 Cu pieces form two chimneys. Replace every 150-200 hrs. Cathode material shorts.
  - Chimney 1: Purple Button Cathode LaB_6 used for proton and deuteron source, 120+ hrs
  - Chimney 2: Grey Button Cathode HfC used for Alpha and He-3, 4-8 hours
  - Molybdenum Penning Exit slits known as windows were Molybdenum, but are now tungsten, for much reduced slit widening due to erosion. Especially important in Chimney 2 with the more massive particles.



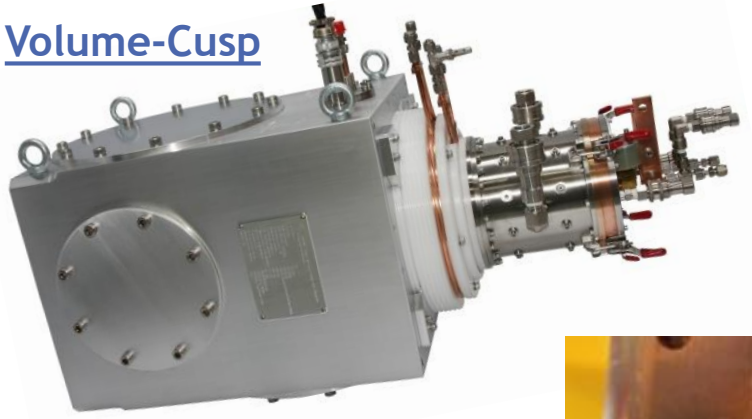
[1] Private Communication: Marissa Kranz, Facility Director, University of Washington Medical Cyclotron Facility, Data by Email February 29, 2024.

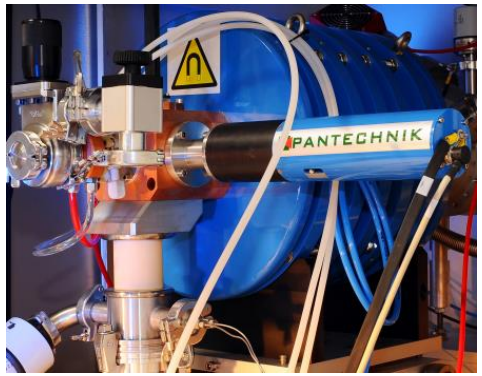
H^-, D^- & He^{++} Source Developments for Medical Isotope Production Cyclotrons

Accelerator Development and Technology (ADT-1) Tuesday, March 19, 2024.

QUESTIONS?

Volume-Cusp





ECR

Penning

Monday, March 18, 2024

[1] https://www.d-pace.com/?e=304
[2] D. Potkins, M. Dehnel, S. Melanson, T. Stewart, P.Jackle, J. Hinderer, N. Jones, L. Williams, “Improvements to Siemens Eclipse PET Cyclotron Penning Ion Source”, AIP Conference Proceedings, Vol. 2052, No. 1, P. 050016, AIP Publishing, 2018.
[3] https://www.pantechnik.com/wp-content/uploads/2020/07/Supernanogan.pdf