# $H^-$ ion source caesiations at other labs

180th Machine Protection Panel Meeting, Continuous caesiation at Linac 4
CERN, 30.08.2019

## $H^-$ ion source types

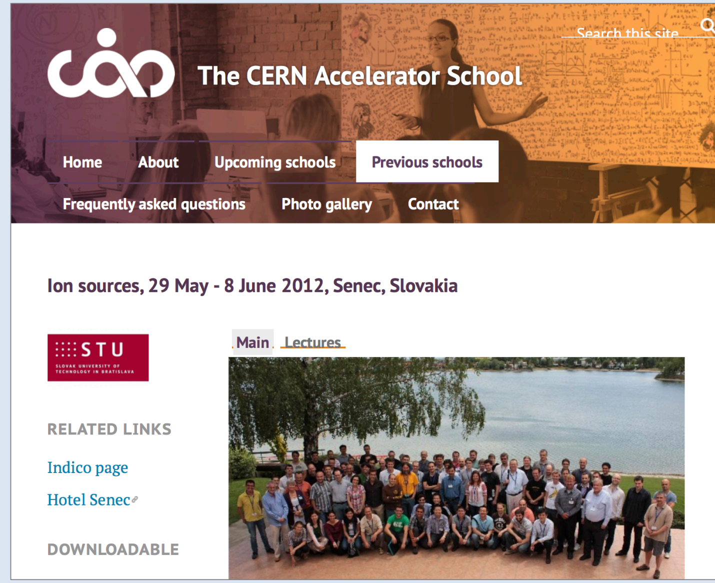
## Caesiation hardware and methods

- BNL
- FNAL
- J-PARC
- RAL
- ORNL

## Summary

Acknowledgements
Deepak Raparia (BNL), Daniel Bollinger (FNAL), Dan Faircloth (RAL)
Akira Ueno (J-PARC), Martin Stockli (ORNL)

# Ion sources for particle accelerators


## Bibliography

D. Küchler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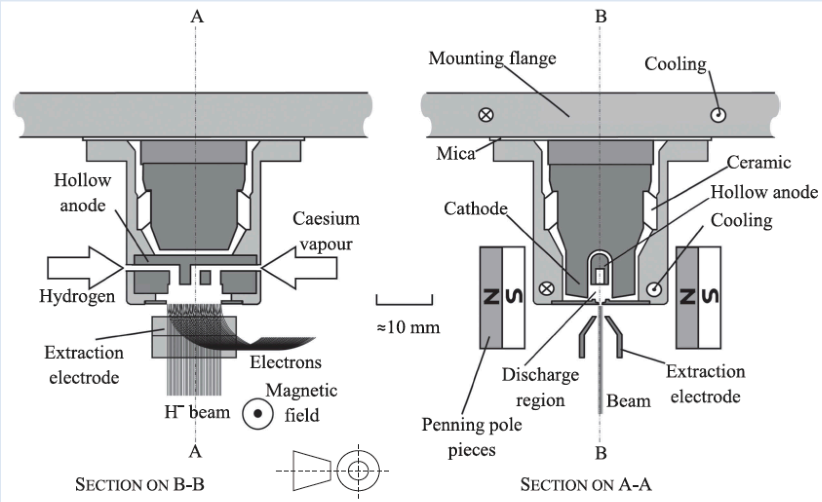
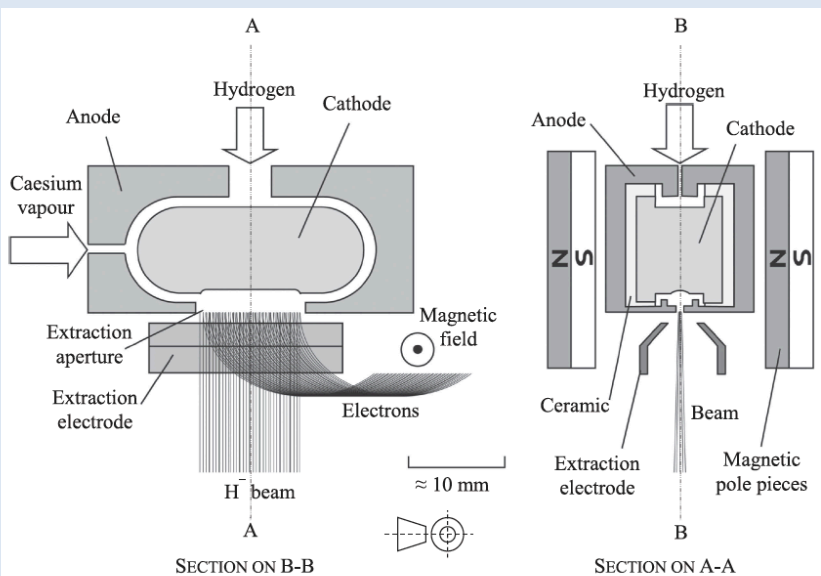
# $H^-$ ion sources types (1)




**Penning surface plasma ion source**

*ISIS, STFC Rutherford Appleton Laboratory (RAL), UK*



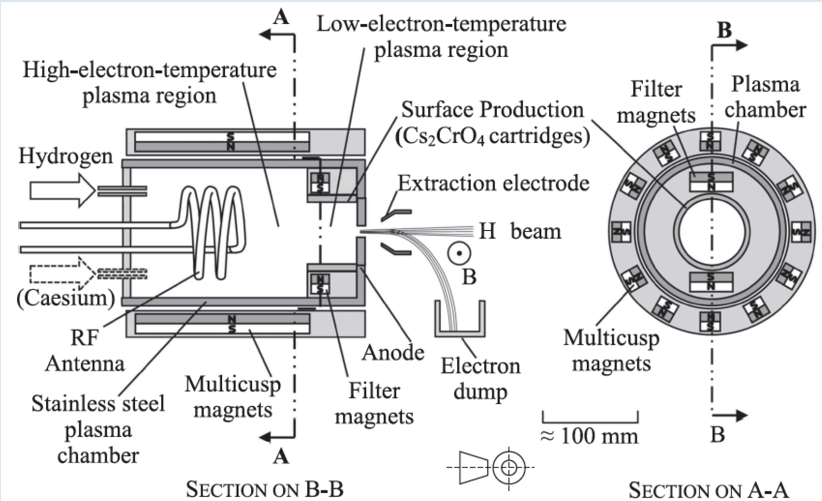

**Magnetron surface plasma ion source**

*Brookhaven National Laboratory (BNL), USA*

*Fermi National Accelerator Laboratory (FNAL), USA*

D. Faircloth, S. Lawrie, New J. Phys. **20** (2018) 025007

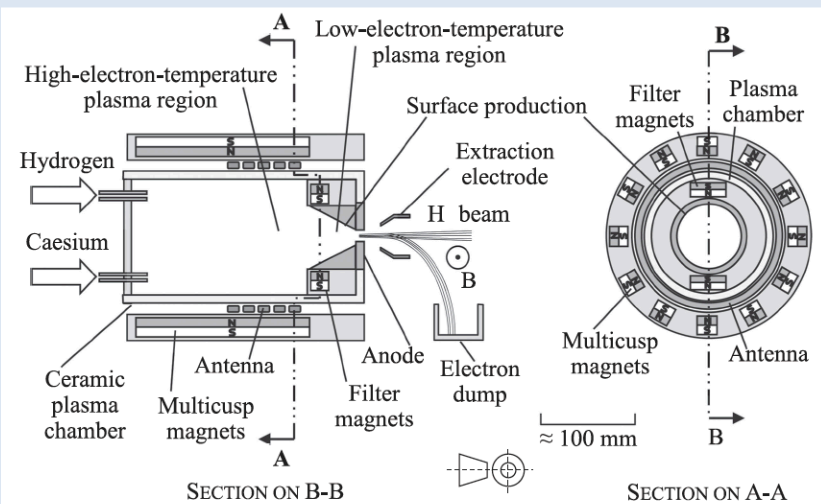
# $H^-$ ion sources types (2)




**Internal RF solenoid antenna driven volume & surface plasma ion source**

*Japan Proton Accelerator Research Complex (J-PARC), Japan*

*SNS, Oak Ridge National Laboratory (ORNL), USA*




**External RF solenoid antenna driven volume & surface plasma ion source**

*LINAC4, CERN, Switzerland*

D. Faircloth, S. Lawrie, New J. Phys. **20** (2018) 025007

# Comparison of sources currently operating on accelerator facilities or accelerator test stands

| Source | Variant | Technology | Caesium | Beam current |
|---|---|---|---|---|
| D-Pace | Filament | Filament-driven volume | No | 18 mA |
| D-Pace | RF | External planar antenna RF-driven volume | No | 8 mA |
| ISIS | Operations | Penning surface plasma | Yes, elemental | 55 mA |
| ISIS | FETS | Penning surface plasma | Yes, elemental | 80 mA |
| BINP | CW | Penning surface plasma | Yes, caesium chromate | 25 mA |
| FNAL | Operations | Magnetron surface plasma | Yes, elemental | 80 mA |
| BNL | Operations | Magnetron surface plasma | Yes, elemental | 100 mA |
| LANL | LANSCE | Filament-driven surface convertor | Yes, elemental | 18 mA |
| SNS | Operations | Internal solenoid antenna RF-driven volume and surface | Yes, caesium chromate | >60 mA |
| J-PARC | Operations | Internal solenoid antenna RF-driven volume and surface | Yes, elemental | 45 mA (test stand 66 mA) |
| CERN | Linac4 | External solenoid antenna RF-driven volume and surface | Yes, elemental | 45 mA |

D. Faircloth, S. Lawrie, New J. Phys. **20** (2018) 025007

# Other labs

- ○ Five accelerator laboratories contacted (24 July 2019) for up-to-date ion source and caesiation system information, contacted experts:

- ○ Deepak Raparia (BNL), Daniel Bollinger (FNAL), Akira Ueno (J-PARC),
- ○ Dan Faircloth + Oli Tarvainen (RAL), Robert Welton + Martin Stockli (ORNL)

- *The Linac4 team would highly appreciate if you could prepare and send me a few slides summarizing your ion source caesition system, which is presently in accelerator use. The following specific points are very welcome:*

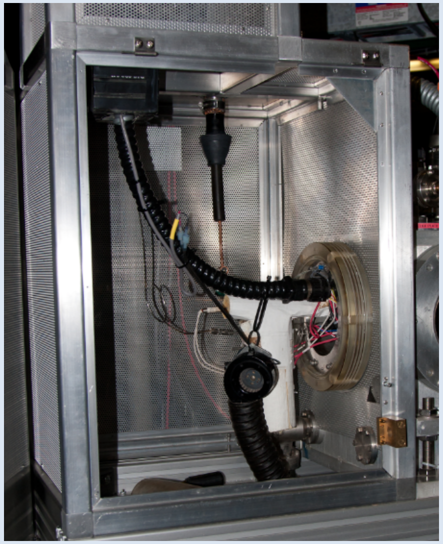
- *a brief **description** of your Cs hardware system, preferably with some photos,*
- ***temperatures, durations, and repetition(s)** applied during caesiation,*
- *approximate **Cs consumption** per month or per year,*
- *the **total amount** of Cs in your oven/system,*
- ***measures** and/or equipment **to protect the lina**c - especially the RFQ - **against Cs**,*
- *observed/solved **problems in the past**, either associated with your Cs system or in the beamline.*

Remark: On the following slides all expert replies are quoted with blue text

# BNL

## Magnetron, continuous caesiation

D. Raparia




### Cs hardware system for BNL source

- Cs oven heated up to 100-120 °C
- Valve and feed line up to 300 °C
- It is covered by insulator

Temperatures, durations, and repetition(s) applied during caesiation?

- At start up **125-130** °C for about **8 hours**, then reduce to **90-110** °C for rest of the operation (**> 6 months**)

Approximate Cs consumption per month or per year? **~ 0.5 mg/hour**

Total amount of Cs in your oven/system? **5 g**

Measures and/or equipment to protect the linac - especially the RFQ - against Cs?

- **None**; LEBT with 45 degree bend is about 2 meter, **never had any issues with Cs in RFQ**

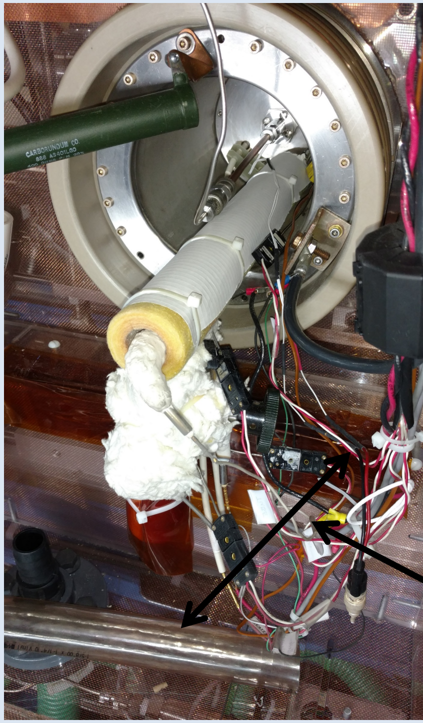
Observed / solved problems in the past, either associated with your Cs system or in the beamline.

- **Cs valve** failure **once in last 25 year**, clogging at opening of feed line in the source once in 25 years

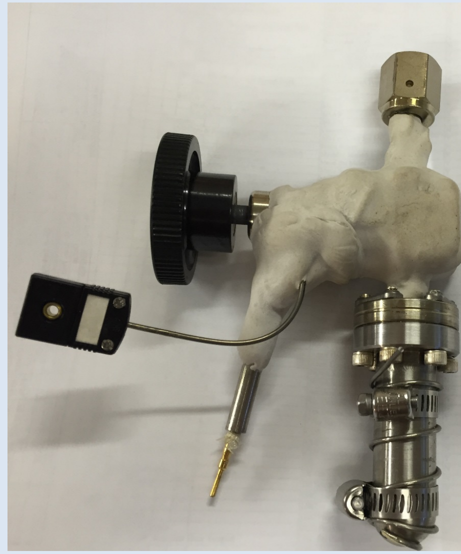
# FNAL

## Magnetron, continuous caesiation

D. Bollinger



Cesium tube:
- Delivers cesium into source
- 27.30 5cm
- Temperature 200 °C



### Cs delivery system

Cesium system valve:
- Isolates cesium boiler
- 7.14375 cm
- Temperature 200 °C

Cesium boiler (oven):
- 5.3975cm
- 5g cesium
- Temperature 110 °C

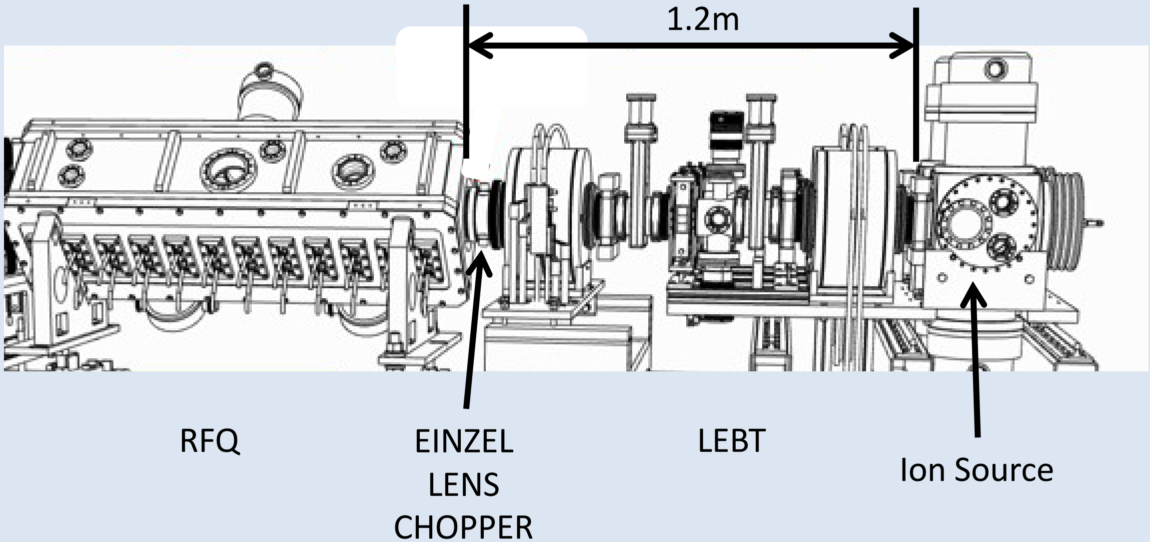
Oven contains 5g of elemental cesium

- Typical cesium system temperatures: **oven 110 °C**, **valve 200 °C**, **tube 200 °C**
- Cesium consumption is **5g/600days**, note: the cesium **oven** is **typically not completely empty** after 600 days
- No machine protection to address cesium in beamline and RFQ
- **No issues with cesium in RFQ** or HV element in LEBT since RFQ upgrade in 2012
- **No method of trapping cesium** coming out of the source
- Current FNAL ion source annual operations: 9 months continuous running, 3 months summer shutdown

# FNAL

## Magnetron, continuous caesiation

D. Bollinger




Ion source facing side of the extractor after 9 months operation does have cesium deposits

- The **RFQ** is about **1.2m from** the **ion source**
- There is an Einzel Lens at the entrance to the RFQ. It operates at 38kV. There have been **no issues with cesium deposits on the lens**
- The only time that we see the entrance to the RFQ is when the Einzel Lens is removed due to failure. We have not had an Einzel Lens failure in 2 years (the lens was redesigned due to previous failures)
- We have **never seen any signs of cesium deposits at the entrance to the RFQ**
- We do not have any machine protection addressing the possibility of cesium in the beamline

# FNAL

## Magnetron, continuous caesiation

D. Bollinger

Pictures from the last time the Einzel Lens Chopper was replaced (7/15/2015)

Source facing side of Einzel Lens

Blue tint has not been analyzed, likely not a cesium compound

Inside of Einzel Lens

Einzel Lens operates at 38kV, located U.S. of the RFQ. The lens has failed in the past due to insufficient design. Latest design has not failed in over 2 years.

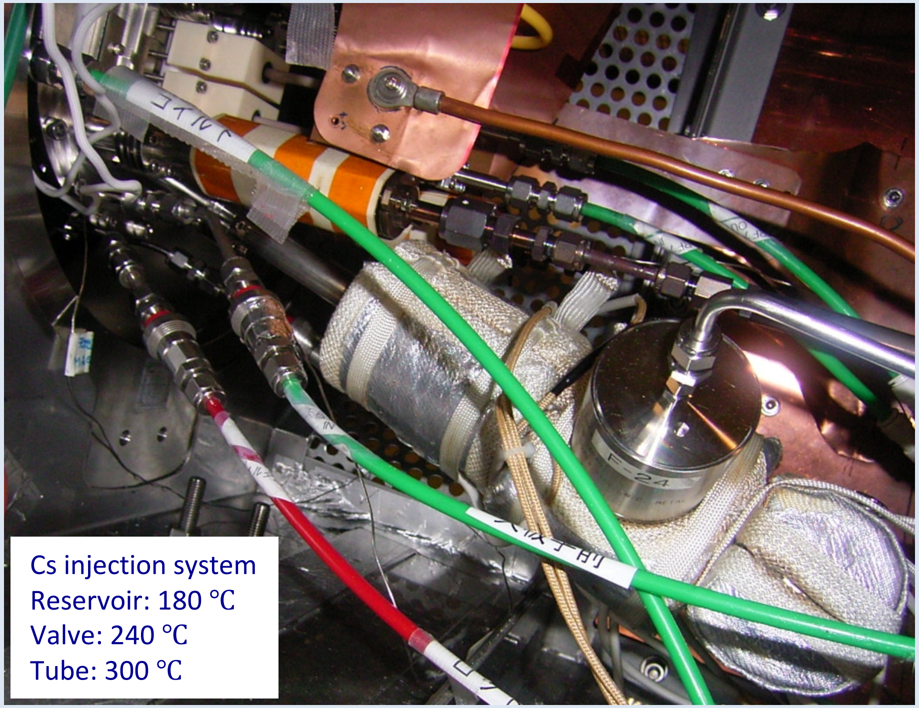
RFQ entrance

The only time we see the source facing side of the RFQ is when Einzel Lens is removed due to failure. It has been over 2 years since we had to change the lens

# J-PARC

## RF source, very frequent caesiations

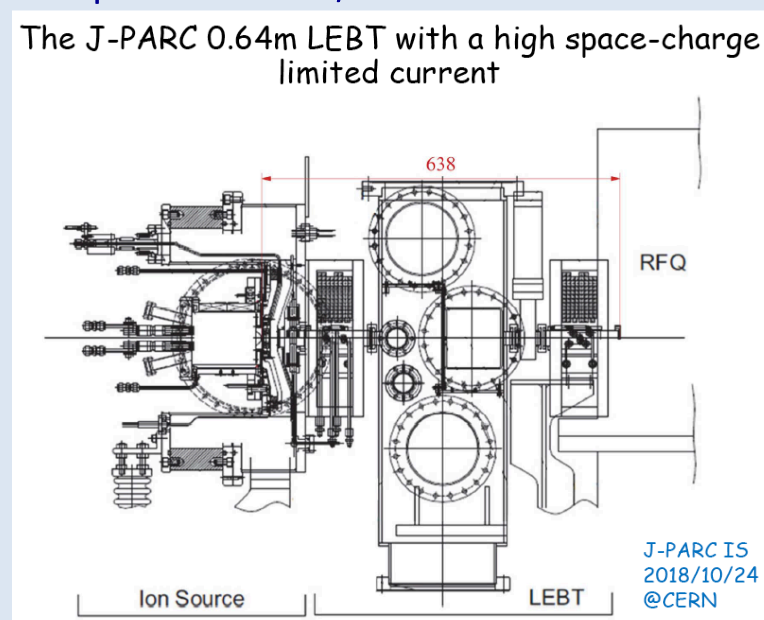
A. Ueno




J-PARC IS Cs Injector installed on Plasma Chamber with 3 mantle heaters for Reservoir, Valve (Fujikin FWBR-71-9.52#A) and Tube.

**Valve** is **remotely opened/closed** by compressed air on/off.

J-PARC IS Cs Injector without mantle heaters



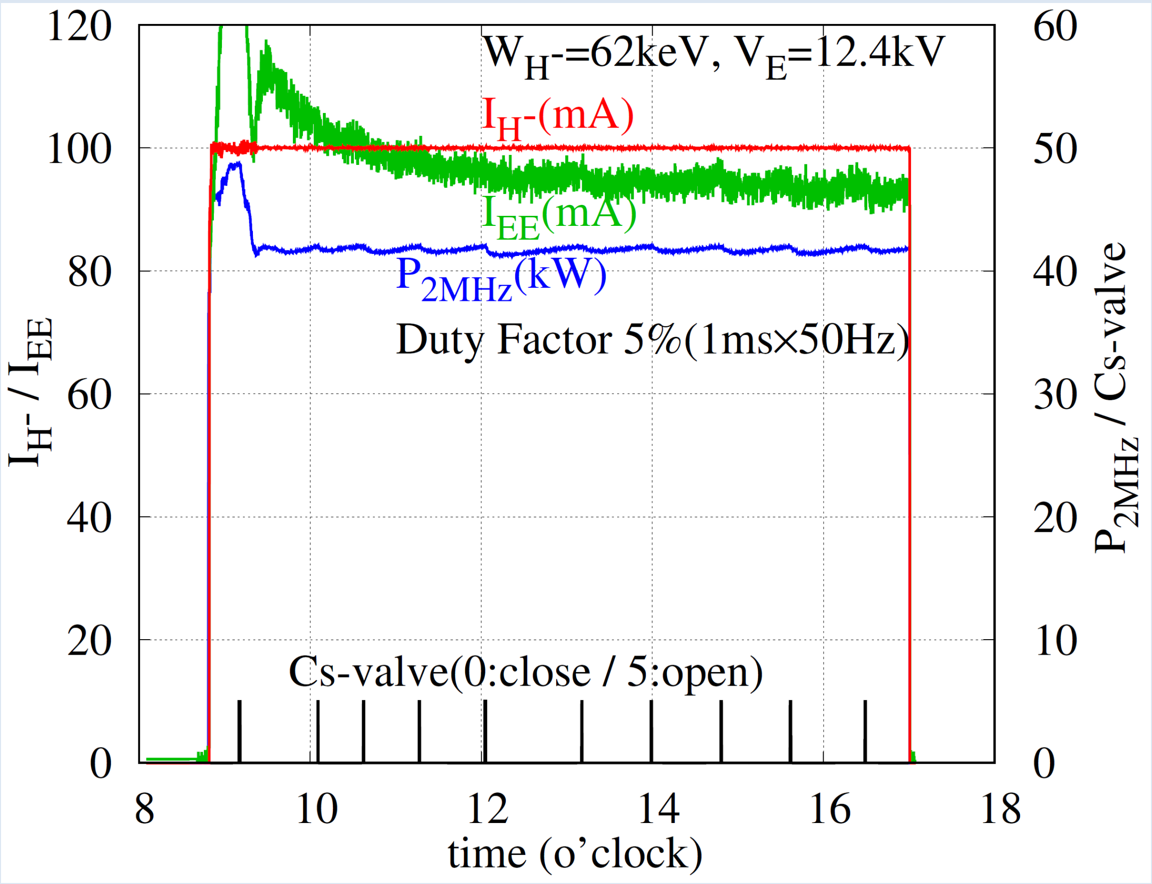

Source - RFQ distance is 64 cm

# J-PARC

## RF source, very frequent caesiations

A. Ueno

J-PARC H⁻ IS Continuous Caesiation Example




For 5% duty (1 ms x 50 Hz) and 100 mA operation on **test-stand**, Cs density on plasma electrode was feedbacked by automatic opening Cs valve for about 40 s, which was estimated as 38.8 µg per opening with 180 ℃ reservoir, to keep 2 MHz RF power lower than 42 kW.

For **J-PARC operation** steady state {1.75%(0.7 ms x 25Hz) RF-duty and 50 mA@LINAC exit ($P_{2MHZRF}$~24 kW)}, typically **Cs valve opens for about 45 s** (43.7µg @$T_R$=180 ℃) **each 70 minutes.**

# J-PARC

## RF source, very frequent caesiations

A. Ueno

Approximate Cs consumption per month or per year?

- The estimated Cs consumption rate (with accuracy between 50%~200%) is
  **43.7 µg/70 minutes** = 26.9 mg/month = 216 mg/year (8 months)

Do you also perform some Cs measurements or calibration tests?

- Based upon very old experimentally measured time to empty 1 g Cs from 200 ℃ reservoir, it is calculated. The **Cs consumption** itself is **not so important**. The **amount of the Cs leakage** from the plasma electrode aperture **determine** the **stability** of the **high voltage gaps** and **RFQ**.

The total amount of Cs in your oven/system?

- **3g Cs** is installed **in the reservoir**, since some of it seems to combine with impurities inside Cs injector and air.

Measures and/or equipment to protect the linac - especially the RFQ - against Cs?

- **Cs 852 nm spectrum** is **observed**. If it exceeds the threshold value, then $T_{Rset}$=0 ℃ (not used)
- **No issue** observed **in** the **beam line and/or RFQ**
- The amount of the **Cs leakage** was drastically **decreased** by decreasing the **plasma electrode temperature from** about **200 ℃ to 70 ℃**

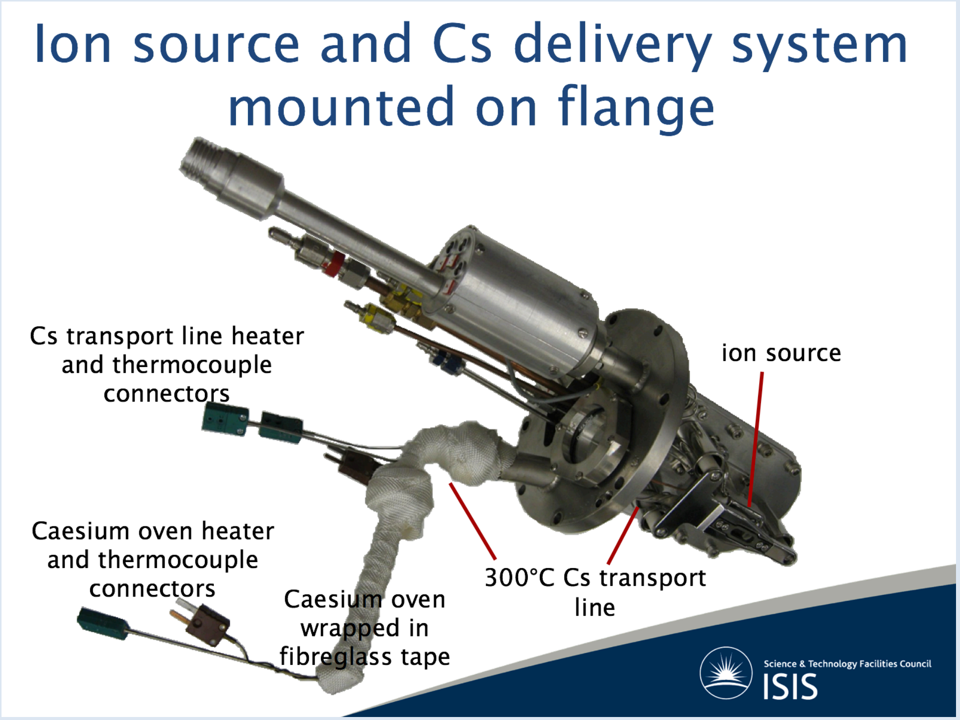
Observed / solved problems in the past, either associated with your Cs system or in the beamline.

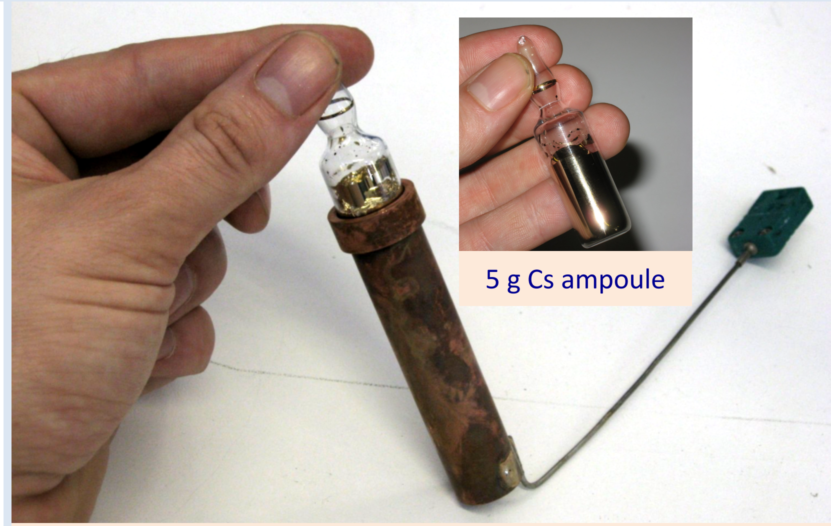
- **Cs valve maker**: Swagelok -> Fujukin

# RAL

## Penning, continuous caesiation

D. Faircloth




Caesium ampoule being inserted into copper oven with thermocouple silver soldered to the bottom of oven
When we are ready to run the copper oven and Cs ampoule are crushed with a tool

In normal operation the **Cs oven** is held **between 155 °C and 170 °C**. The Caesium temperature is slowly increased during the lifetime of the source (2-3 weeks)

Cs consumption is **3 g/month**. The total amount of Cs in the oven/system is **5 g**

Measures and/or equipment to protect the linac - especially the RFQ - against Cs?

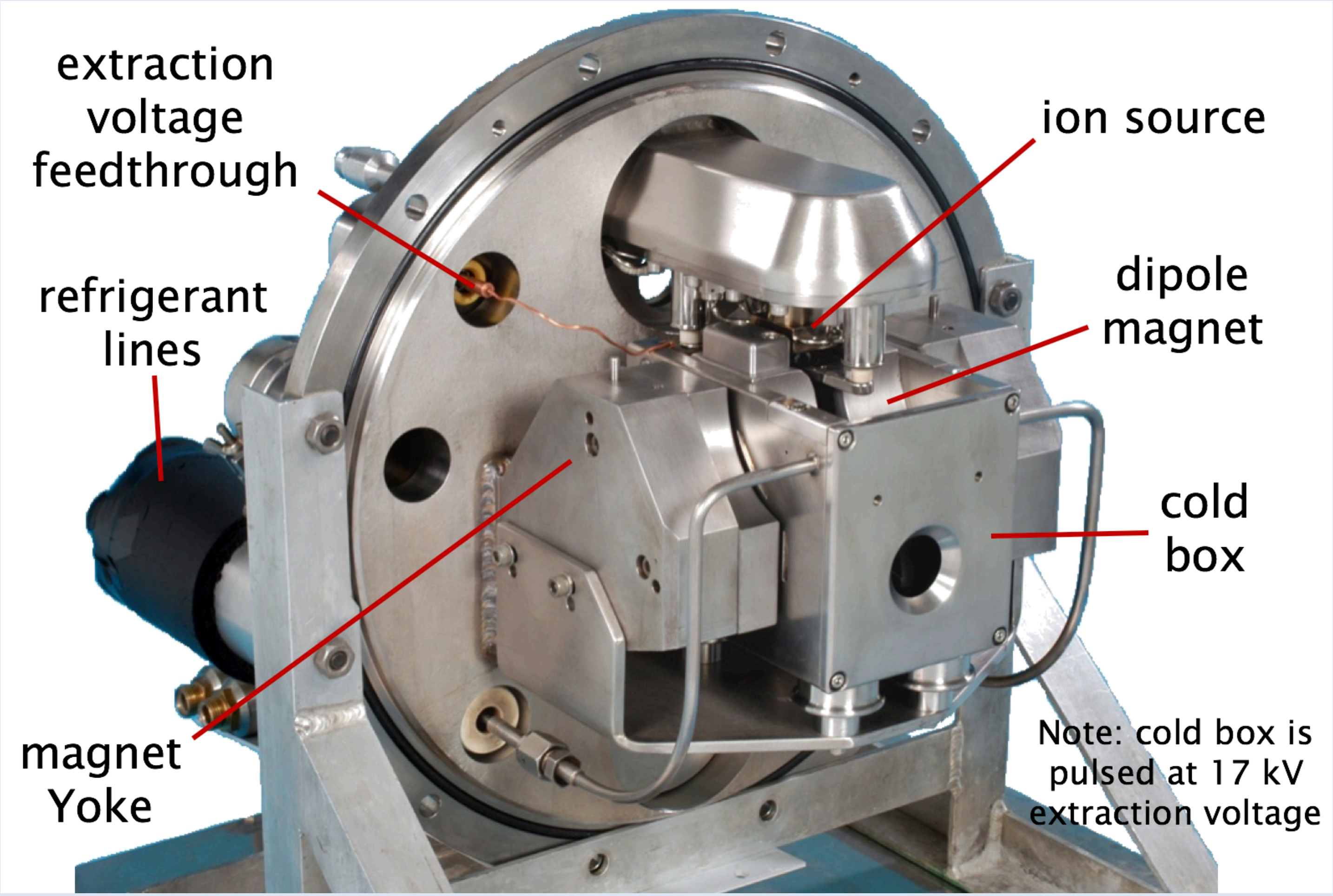
Beam comes out of the source then passes though a **90 degree dipole** in a **cold box** held at about **-5 °C**

# RAL

## Penning, continuous caesiation

D. Faircloth

## Caesium Trapping: ‘Cold Box’

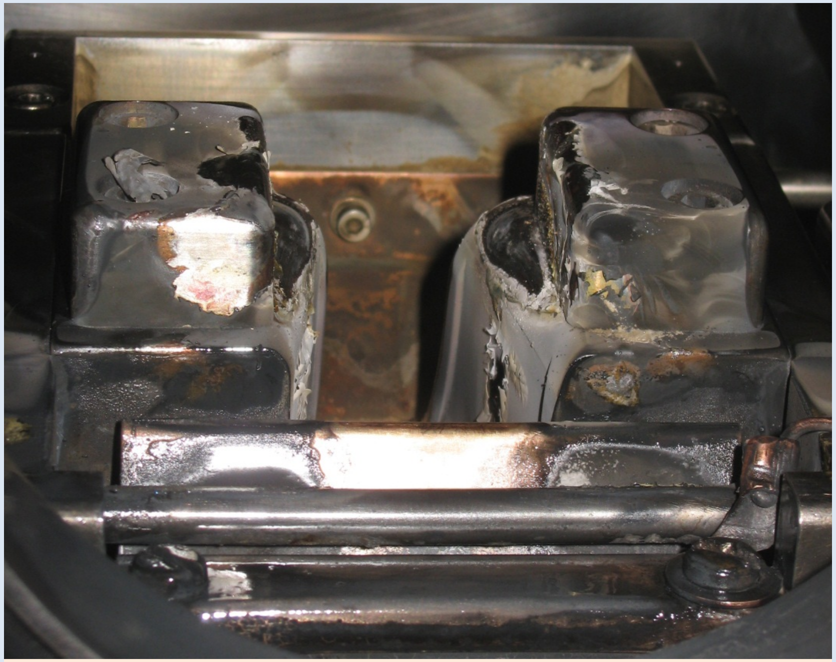


# RAL

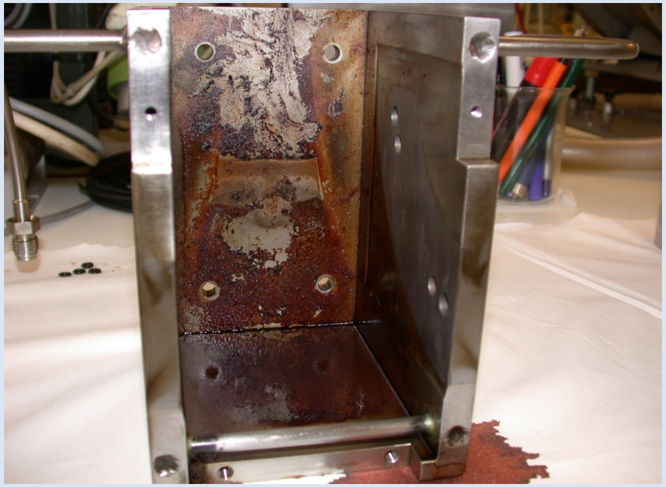
## Penning, continuous caesiation

D. Faircloth

## Cold Box After Several Months' Use



- Maintain a positive nitrogen pressure in vessel during source changes
- Acetone wipe to remove excess Cs
- Ensure all cold box surfaces clean before installing new ion source
- Thorough cold box removal & maintenance every ~6 months



# RAL

## Penning source, continuous caesiation

D. Faircloth

Observed / solved problems in the past, either associated with your Cs system or in the beamline.

- **No problem with beamline in 35 years**.
- First 20 years running directly into a 665 kV accelerating column.
- Second **15 years running into** a 3 solenoid LEBT and **RFQ**.

Various **problems** with Cs system **solved** over the years:

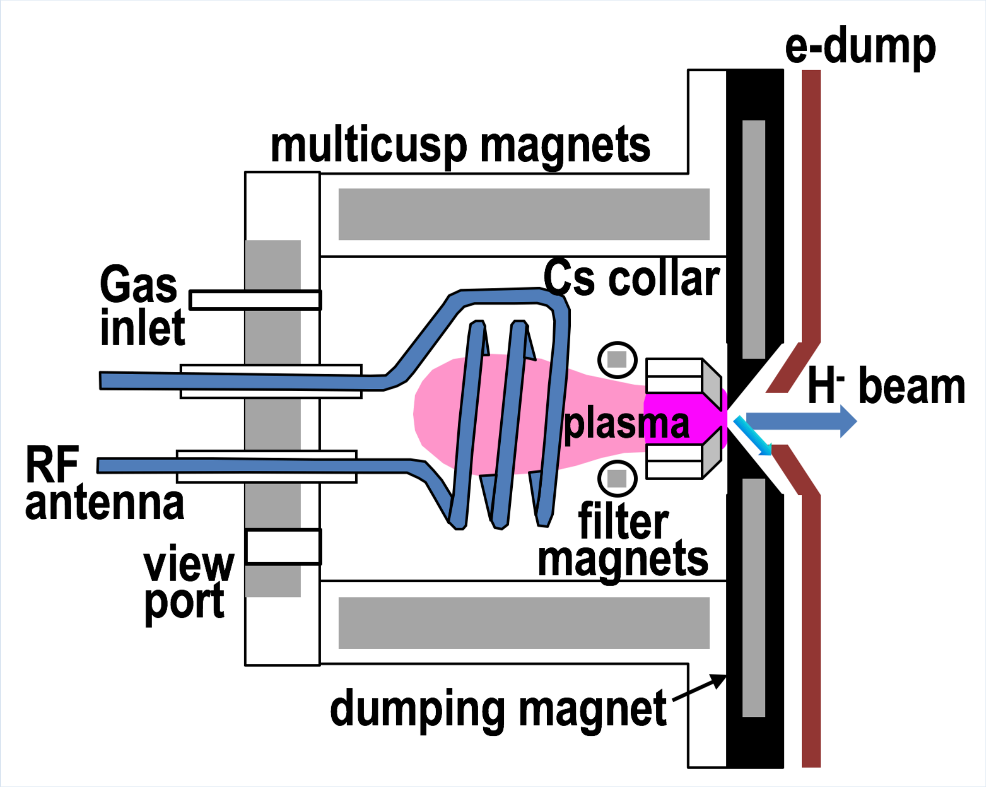
- Cs oven over-temperature prevented with inline thermal cut-out switches
- Cs purity increased to 99.99 %
- Tried pouring Cs directly into oven but reliability improvements not worth the increased handling precautions

# ORNL

## RF source, heated Cs collar

M. Stockli

### The SNS Baseline Ion Source




**LBNL developed** and SNS improved the cesium-enhanced, RF-driven multicusp $H^-$ ion source, which delivers ~1-ms long $H^-$ current pulses at 60 Hz.

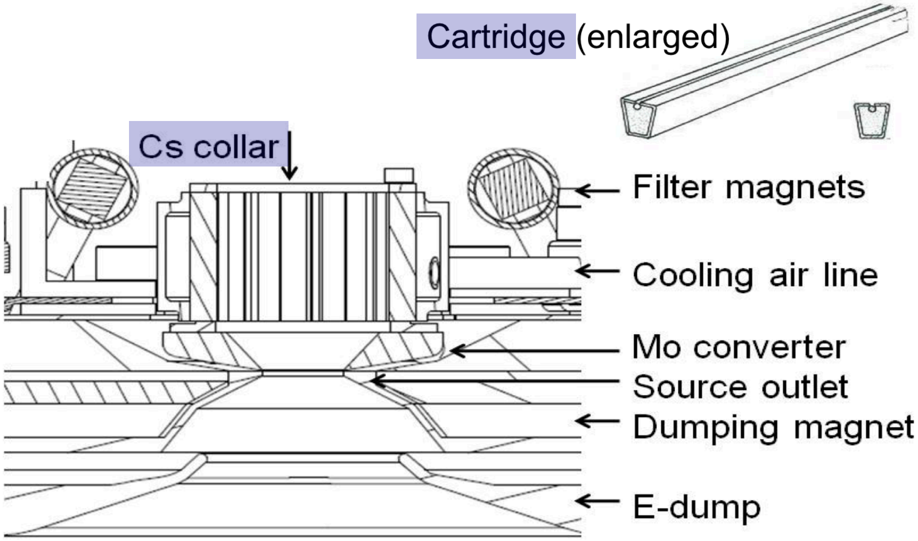
# ORNL

## RF source, heated Cs collar

M. Stockli

### The Magic 30 mg Cs System:

- To minimize Cs-induced arcing in the SNS LEBT and nearby RFQ, LBNL implemented 8 $Cs_2CrO_4$ cartridges from SAES Getters, which together contain <30 mg Cs. They are integrated into the Cs collar. The system compactness allows for rapid startups!
- The Mo ion converter is electrically and thermally attached to the Cs Collar. Heated air controls their temperature.




- Just after being evacuated, the Cs system is outgassed at 170°C and the Mo converter is sputter-cleaned with 6%, 50 kW, 2 MHz H plasma for 3 hours. Then the collar is heated for ~12 min. to 550°C to release ~4 mg of Cs*. Then the temperature is lowered to ~180°C, with the converter remaining near 400°C, yielding a ~0.5 Cs layer.
- Normally the $H^-$ beam grows for a few days by 1 or 2 mA.
- Then normally the $H^-$ beam becomes persistent, free of decay!

***Over 7 A·h of $H^-$ ions have been produced without any $H^-$ beam decay, maintenance or adding additional Cs!***

# ORNL

## RF source, heated Cs collar

M. Stockli

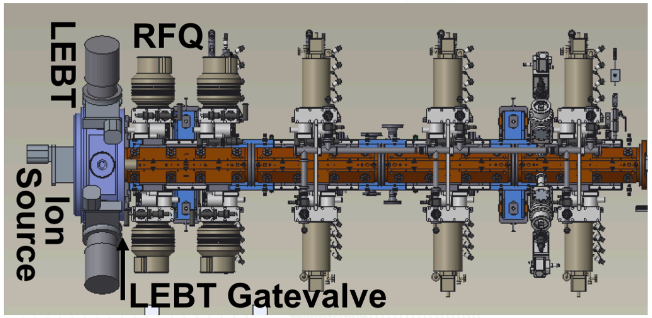
### The Numbers*, Protections, and Precautions

*In the early days before our cesiations were optimized, 2-3 successful 30 min-long cesiations at 550°C could be executed with a single set of 8 cartridges. Apparently at 550°C the cartridges emit Cs for ~90 minutes. Having been able to reduce the cesiations to ~12 minutes, we appear to release only 4 mg in each cesiation.

Typically we use about 3-6 sources per year on the production frontend. Recesiations are very rare occurrences, mostly happing at the end of a run as a part of a ion source study.

This is a total yearly consumption of **~40 mg.**

For the last year or so, there is a gate valve between the LEBT and the RFQ. This is closed, whenever we cesiate.




During cesiations in-line-of-sight surfaces get coated with Cs. This are issues with the 1st lens, which can draw excessive corona and the e-dump that can arc. However it appears that 3 hours of delay dissipates enough Cs to practically eliminate the e-dump arcing and overheating of the 1st lens.

# Summary ion sources comparison (1/2)

| Status August 2019 | BNL | FNAL | RAL |
|---|---|---|---|
| $H^-$ source type | Magnetron | Magnetron | Penning |
| Caesiation method | continuous | continuous | continuous |
| Cs oven fill | 5 g | 5 g | 5 g |
| Cs system temperatures | oven: 125-130 ℃ (8h) then 90-110 ℃<br>valve, tube: 300 ℃ | oven: 110 ℃<br>valve: 200 ℃<br>tube: 200 ℃ | oven: 155-170 ℃<br>tube: 300 ℃ |
| Cs consumption | 0.5 mg/h<br>4.38 g/year<br>measured by left over | < 5 g/600 d<br>< 3.0 g/year<br>no measurements, 600 d based on experience, weighing oven foreseen | 3 g/month<br>36 g/year |
| Valve between Cs oven and ion source | manual valve<br>Opened/closed only for source start/removal | manual valve<br>Only time that they need to close that is when they let up the vacuum and remove the ion source | no valve<br>Transport line as short as possible, could collect Cs and get blocked |
| Measures to protect the linac against Cs | none; LEBT with 45 degree bend | no method of trapping cesium coming out of the source | 90 degree dipole, cold box |
| Observed issues with beamline, RFQ | never had any issues with Cs in RFQ | no issues with cesium in RFQ or HV element in LEBT | no problem with beamline in 35 years |
| Source-RFQ distance | 2 m | 1.2 m | 1.5 m |

All numbers and information kindly provided in July/August 2019 by D. Raparia (BNL), D. Bollinger (FNAL), D. Faircloth (RAL)

# Summary ion sources comparison (2/2)

| Status August 2019 | J-PARC | ORNL |
|---|---|---|
| $H^-$ source type | RF | RF |
| Caesiation method | not continuous,<br>very frequent (with beam)<br>45 s each 70 min | not continuous,<br>once per ~100 day long run |
| Cs oven fill | 3 g | 30 mg Cs in Cs collar as $Cs_2CrO_4$ |
| Cs system temperatures | oven: 180 ℃<br>valve: 240 ℃<br>tube: 300 ℃ | Normally ~200 °C and raised to 550℃ for ~12 min to activate St101 getter |
| Cs consumption | 43.7 µg/70 min<br>0.328 g/year<br>no measurements, estimated values | ~40 mg/year<br>including Cs for frontend R&D |
| Valve between Cs oven and ion source | pneumatic valve<br>Opened/closed remotely by compressed air on/off | not applicable because Cs collar is an integral part of the ion source |
| Measures to protect the linac against Cs | Cs 852 nm spectrum observation | gate valve next to RFQ is closed during caesiations |
| Observed issues with beamline, RFQ | no issue in the beam line and/or RFQ observed | arcing problems resolved after introducing a 3-hour wait between caesiation and applying high voltages |
| Source-RFQ distance | 0.64 m | 0.1 m |

All numbers and information kindly provided in July/August 2019 by A. Ueno (J-PARC), M. Stockli (ORNL)

# 2018 CERN Linac 4 ion source review – final report

*Olli Tarvainen, Ursel Fantz, Dan Bollinger, Martin Stockli and Akira Ueno*
*November 16th, 2018*

Full report: EDMS 2048831 v.1

*Continuous caesiation is seen important for the reliability of the 25 mA beam and the ultimate goal of 45 mA*. These experiments directly support reaching the 25 mA goal.

page 5

The work at the test stand after 2019 should concentrate on long-term experiments with the highest possible current using the RFQ box as a monitor. This allows the CERN team to master the caesium delivery process – in particular to determine whether occasional or continuous caesiation is the preferred choice for the high current operation. The committee is leaning towards continuous caesiation as it has better potential for maintaining the current over the foreseen 10 month run cycle. CERN should also investigate possibilities to determine the caesium consumption and leakage from the source under the high-current operation.

page 6

Caesiation should not be seen as a risk but as an opportunity. Several labs run routinely in the caesiated mode and demonstrate reliable performances.

page 4

# Summary

- For different ion source types (Magnetron, Penning, RF), presently in accelerator operation at BNL, FNAL, RAL, J-PARC, ORNL, five different Cs hardware installations and methods are summarized and compared in an up-to-date review based on inputs (July/August 2019) from various lab experts.
- **Continuous caesiations** are done at BNL, FNAL, RAL, which are compared with the **very frequent caesiations** (without beam interruption) at J-PARC. A **single shot caesition** is performed at ORNL where the Cs source is an integral part of the ion source.
- Independent of the different methods applied, all other labs use caesiation temperatures **$T_{Cs}$ (oven) > 100** ℃.
- **No** lab reported any **operational issues** (beamline and/or RFQ) **related to Cs**.
- There is **little** to no **machine protection** applied (and needed) **at other labs**.
- **Continuous caesiation** was supported and **recommended** by **external ion source review committee** (Nov. 2018 report).