Modeling filaments in H^- ion source from the first principles

Nikolai Yampolsky
Larry Rybarcyk
Enrique Henestroza
David Kleinjan
Ilija Draganic

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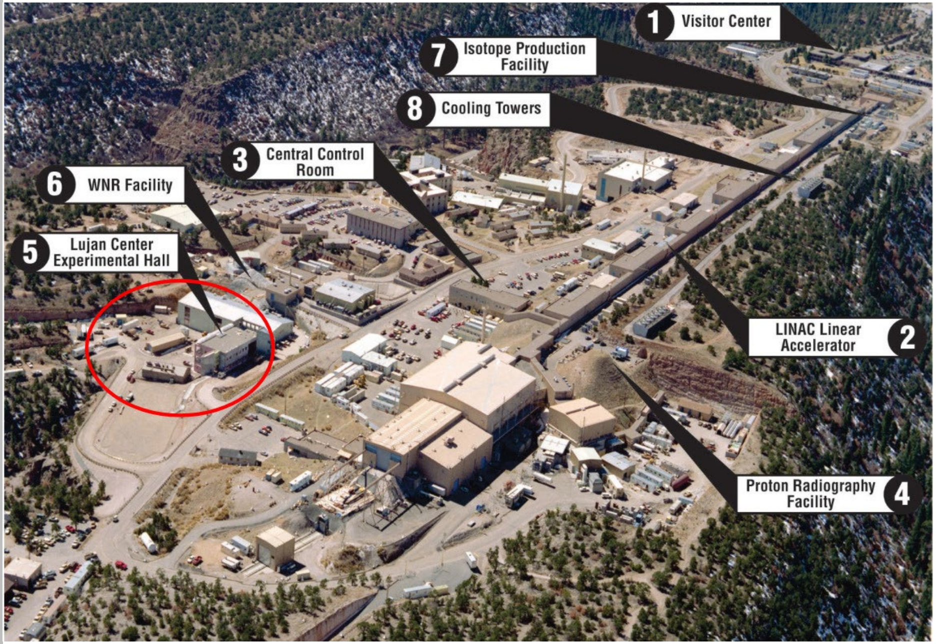
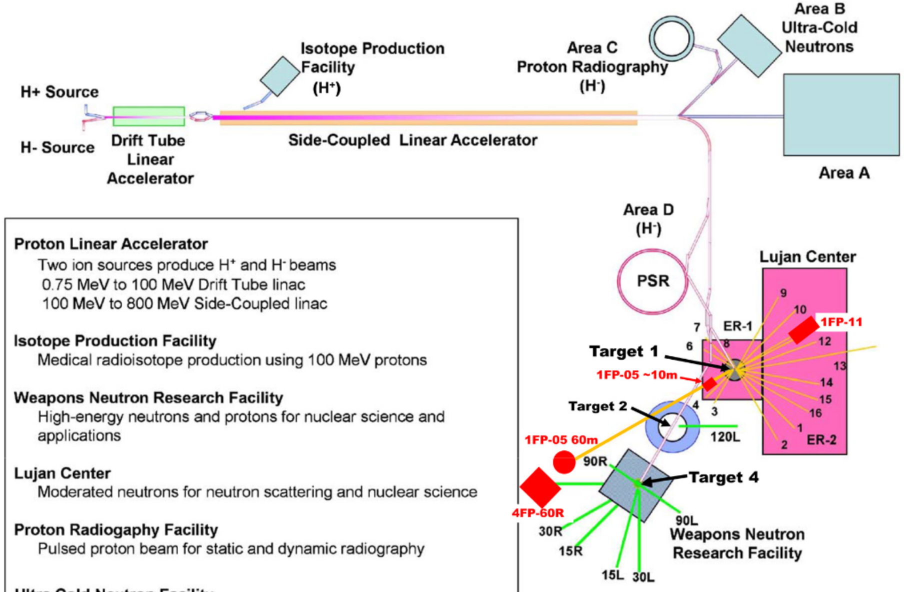
Los Alamos Neutron Science Center (LANSCE)



Operates since 1972
LANSCE is being constantly upgraded and new facilities are added
(UCN – 1997, IPF – 2003, pRad – 2003)

H^+ and H^- are accelerated simultaneously



Proton Linear Accelerator
Two ion sources produce H^+ and H^- beams
0.75 MeV to 100 MeV Drift Tube linac
100 MeV to 800 MeV Side-Coupled linac

Isotope Production Facility
Medical radioisotope production using 100 MeV protons

Weapons Neutron Research Facility
High-energy neutrons and protons for nuclear science and applications

Lujan Center
Moderated neutrons for neutron scattering and nuclear science

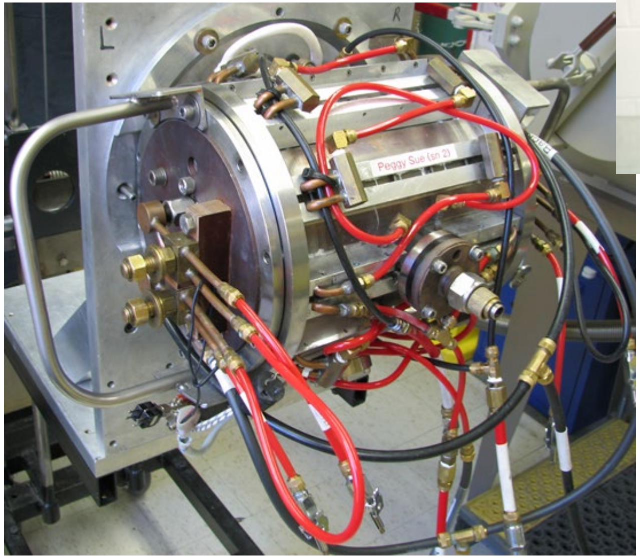
Proton Radiography Facility
Pulsed proton beam for static and dynamic radiography

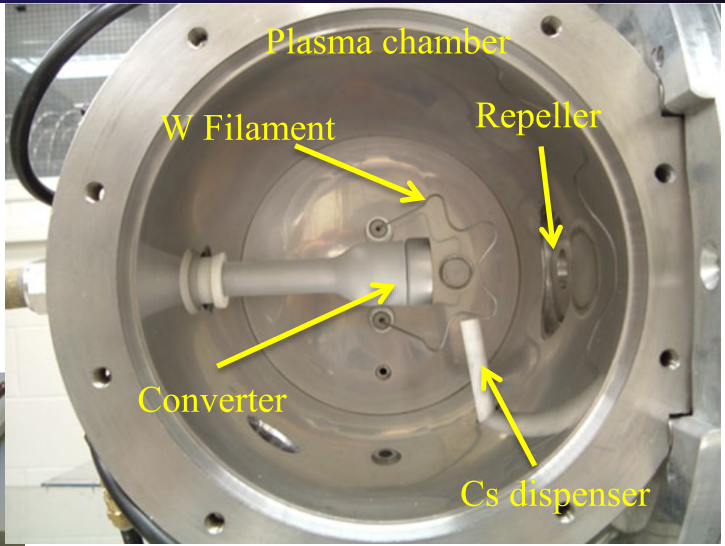
Ultra Cold Neutron Facility
Fundamental physics experiments with UCN

LANSCE H^- ion source

Multi-cusp magnetic structure
Surface H^- production

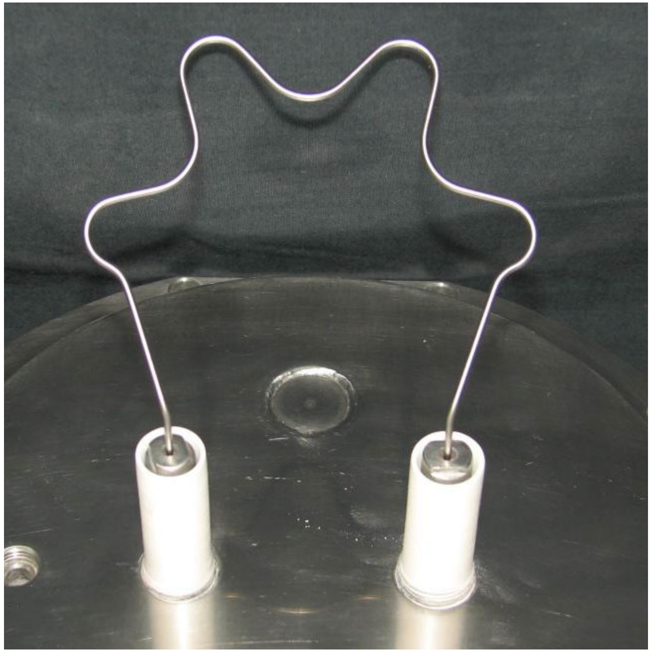
<u>Beam parameters:</u>
120 Hz repetition rate
10% duty factor
14-16mA of H^- current
4-5 weeks recycle



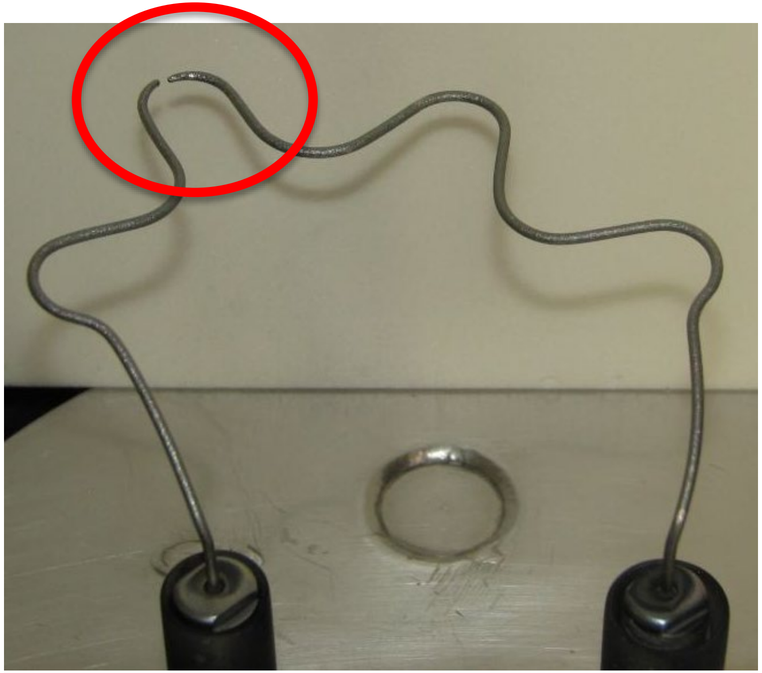


Filament damage

Ion source operation time is limited by the lifetime of tungsten filaments. They are heated to 2600-2700K to large thermionic current during arc discharge, producing plasma.

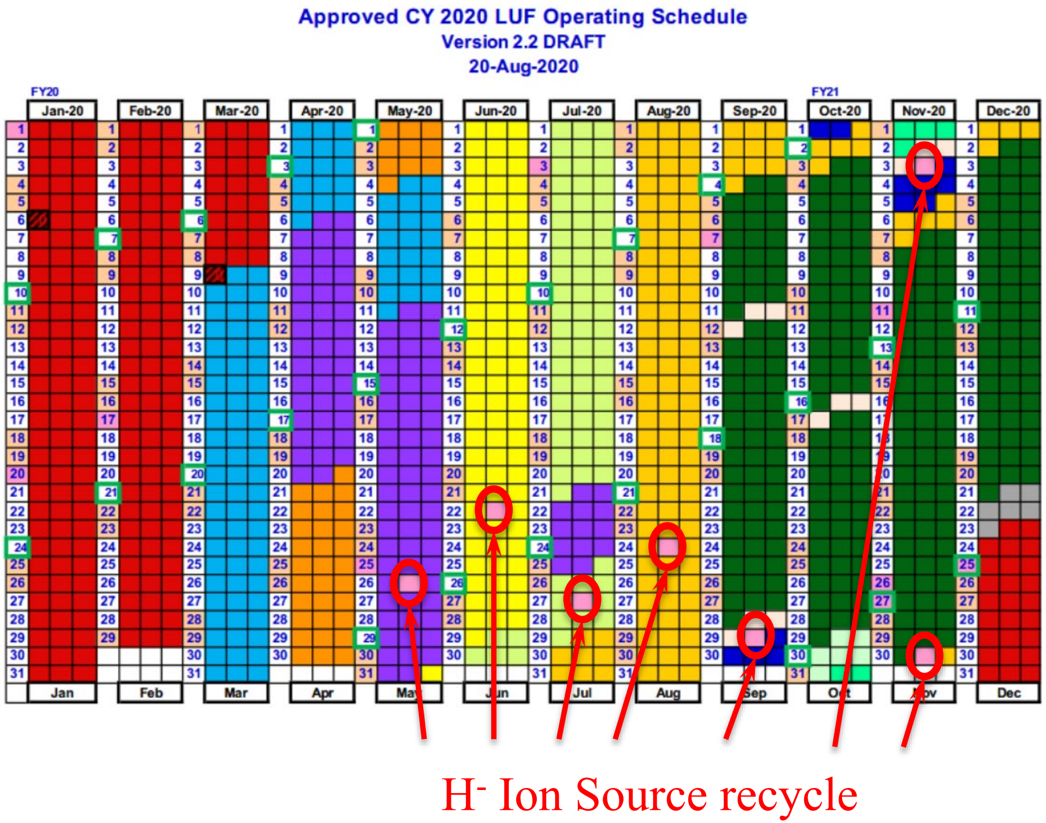


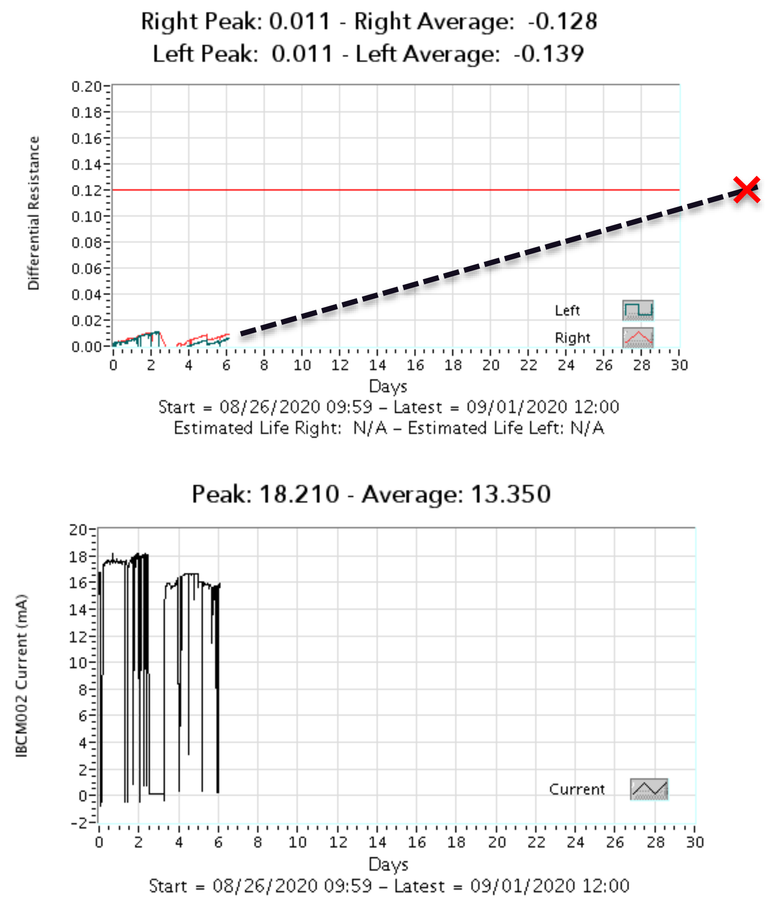
Initial filament



Filament at the end of production

Planning and scheduling

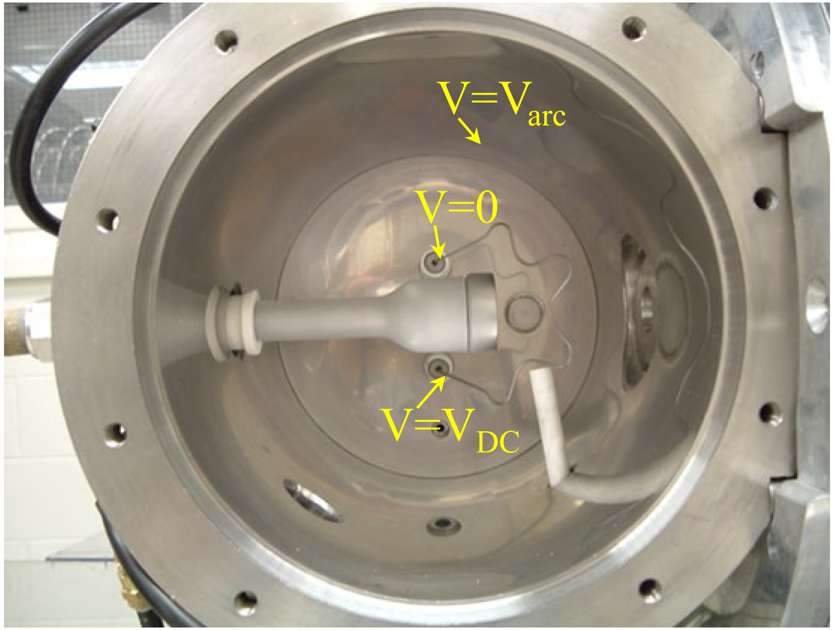




Filament operation

DC voltage ~11V is applied to each filament to drive ~100A DC current which heats the filament

~150-200V arc voltage is applied with respect to the chamber wall (120Hz, 10% duty factor) to initiate 20-40A arc current and create plasma



Essential physics

- Ohm's law
- Energy balance equation
- Filament degradation

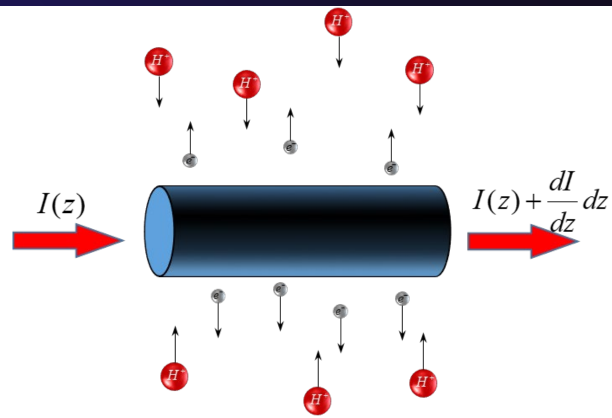
Parameters of the model

$d(z)$ distribution of the wire diameter along the filament

$T(z)$ distribution of temperature along the filament

$I(z)$, $Iarc(z)$ distributions of current along the filament during the phases of operation when the arc is off and on

$U(z)$, $Uarc(z)$ distributions of potential along the filament during when the arc is off and on



$\rho(T)$ the resistivity of the filament material

$\kappa(T)$ the thermal conductivity of the filament material

$\epsilon(T)$ the emissivity of the filament material

$C_E(T)$ evaporation rate

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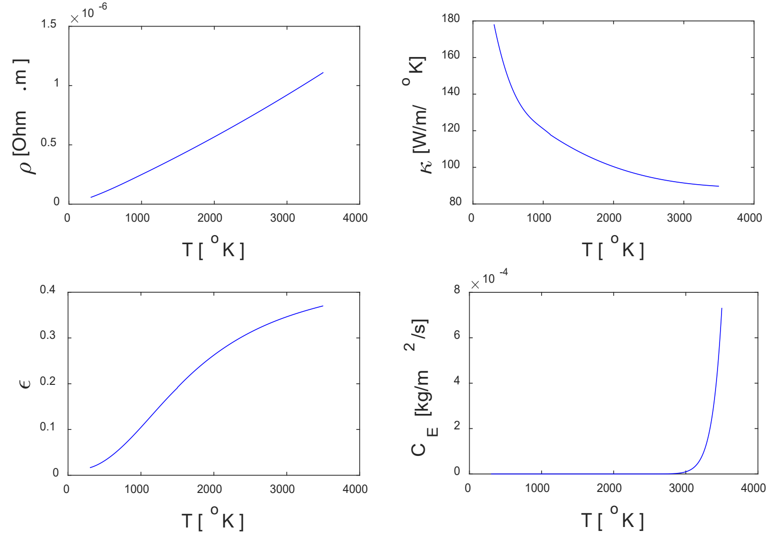
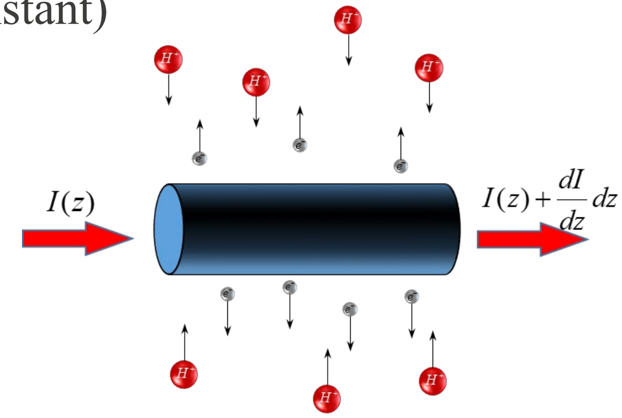


Ohm's law

Voltage drop along the filament is defined by the distribution of current and resistivity (diameter and temperature of the filament are not constant)

$$\frac{dU}{dz} = I\frac{dR}{dz} \qquad \frac{dR}{dz} = \frac{\rho(z)}{\pi d^2(z)/4}$$



$$\frac{dI_{arc}}{dz} = (j_e + j_i)\frac{\pi d(z)}{2}$$

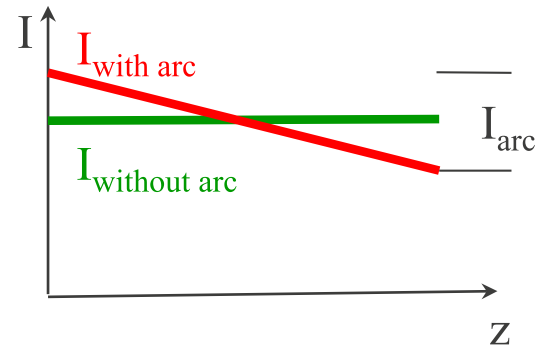
Current along filament changes due to arc discharge

$$j_e = AT^2 \exp\left(-\frac{\phi}{T}\right)$$

Richardson's law for thermal emission

$$j_i = 0.6 n_e e\left(\frac{T_e}{m_i}\right)$$

Plasma sheath current



Energy balance equation

$$\frac{d}{dz}\left(\kappa\frac{\pi d^2}{4}\frac{dT}{dz}\right)-\varepsilon\sigma(T^4-T_{env}^4)+\frac{\pi d^2}{4}\sum\dot{q}_i=0$$

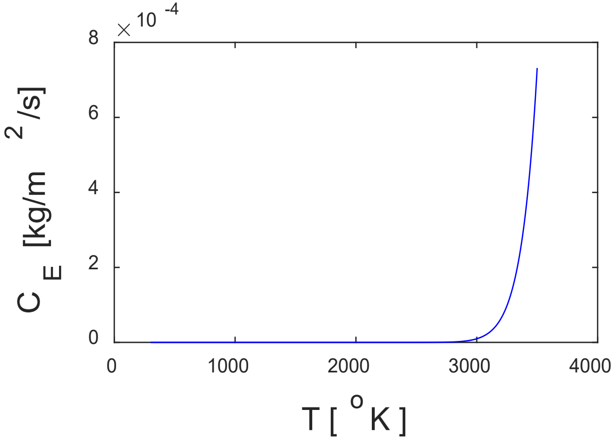
Physical effect	Power
Radiation losses (black body radiation)	~1100W
DC Ohmic heating	~1000W
AC Ohmic heating	~40W
Thermal conductivity	~80W
Ion heating	~20W
Electron cooling	~5W
Heat exchange with neutrals	~15W

Process	Volumetric power flow
Ohmic heating	$[(1-f)I^2+fI_{arc}^2]\frac{dR}{dz}$
Ion heating	$fj_i\pi d(\phi_{arc}-U)$
Electron cooling	$-fj_e\pi d\phi_W$
Cooling by neutrals	$\sqrt{\frac{9}{2\pi}\frac{T_{gas}}{m_{gas}}}\frac{4n_{gas}}{d}(T_{gas}-T)$

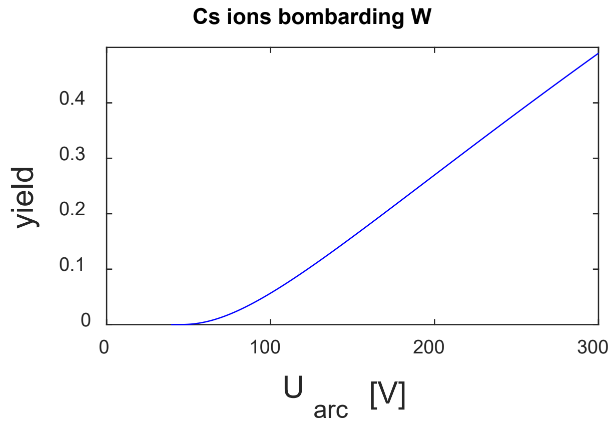
Ohmic heating and radiation losses are the main two mechanisms, which define the filament temperature. Other mechanisms need to be accounted for since evaporation and thermionic emission are highly sensitive to temperature.

Degradation of filament

$$\frac{\partial}{\partial t} d = -2\frac{C_E}{D} - 2Yj_i\delta_{Cs}\frac{m_{Cs}}{-eD}$$



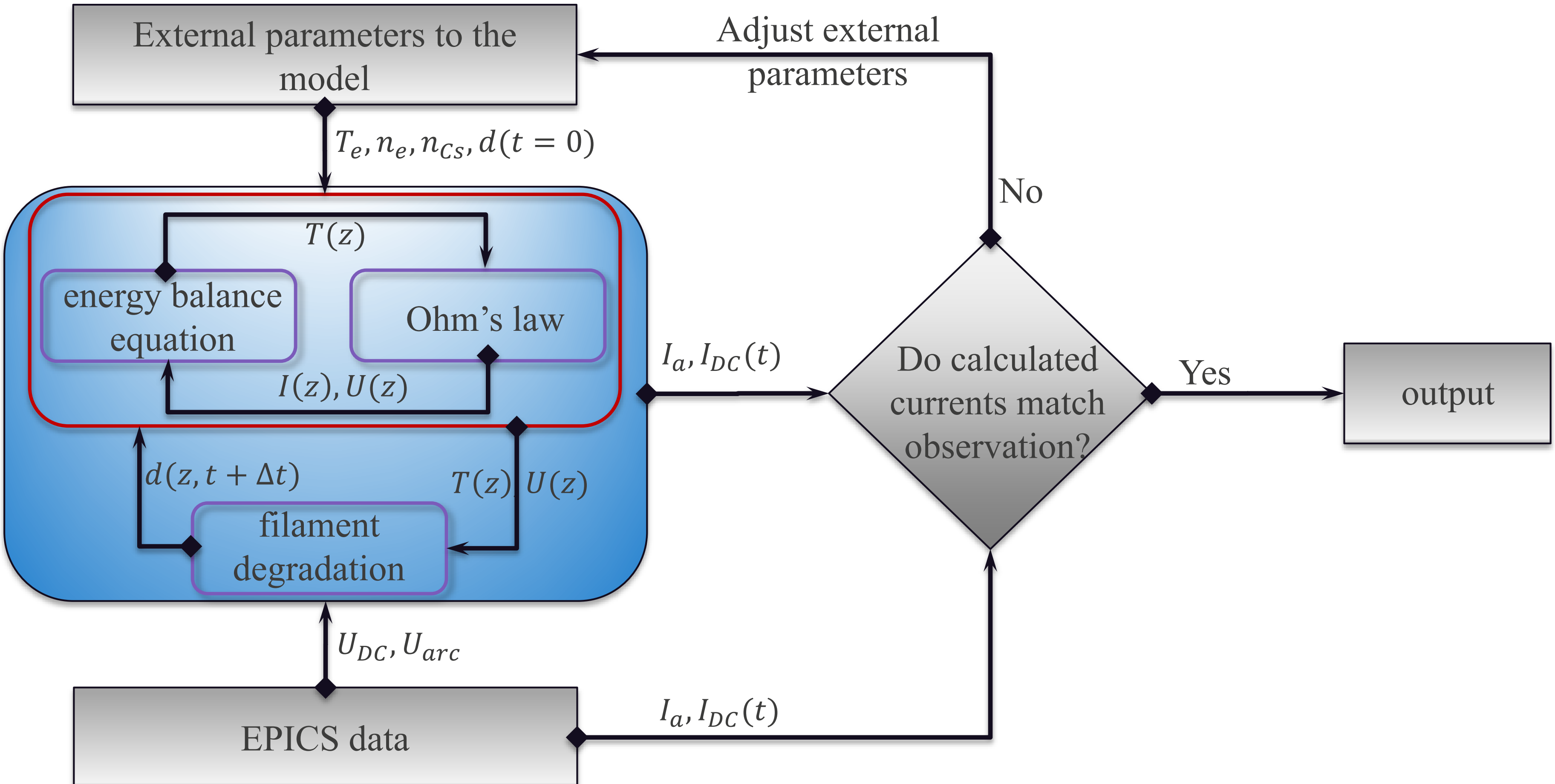
Filament slowly degrades over time due to evaporation of material and sputtering by Cs ion, which are accelerated in the sheath.



Physics included in filament model

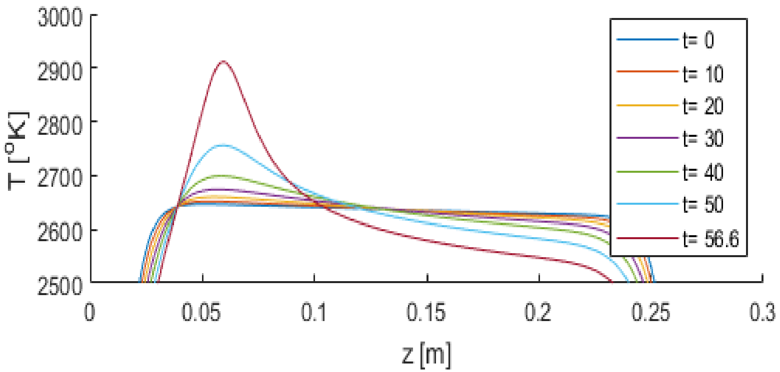
1. Energy balance equation
    - Nonuniform heating due to Ohmic losses
    - Different Ohmic heating during “arc on” and “arc off” phases
    - Radiation heat losses
    - Thermal conductivity
    - Ion heating
    - Electron cooling
    - Heat exchange with surrounding gas
2. Ohm’s law
    - “Arc on” and “arc off” phases of operation are treated separately
    - Self-consistent evaluation of electron arc current based on Richardson’s law
    - Ion current is calculated from plasma sheath problem.
3. Degradation of filament
    - Evaporation of tungsten due to heating
    - Sputtering due to inflow of Cs ions

Structure of the code

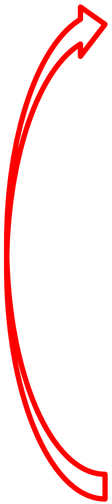


Hot spot

Typical simulation shows more or less uniform distribution of temperature along the filament. The hot spot starts to develop due to slightly higher temperature of the filament on one end (higher current during the arc)



Formation of the hot spot



Temperature distribution is slightly asymmetric

⇓

Evaporation in that spot is higher

⇓

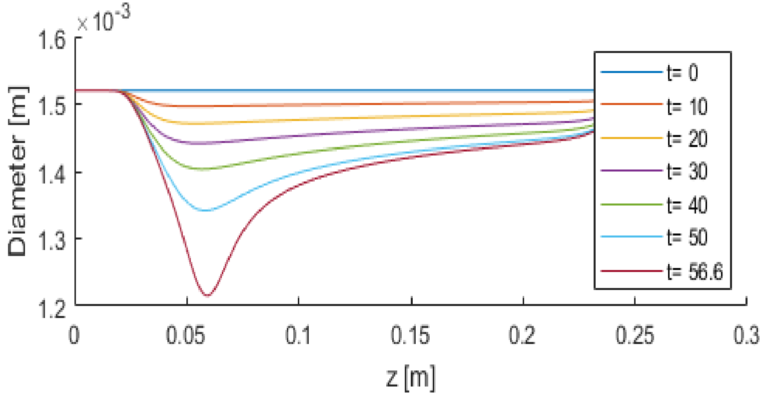
Diameter is reduced faster

⇓

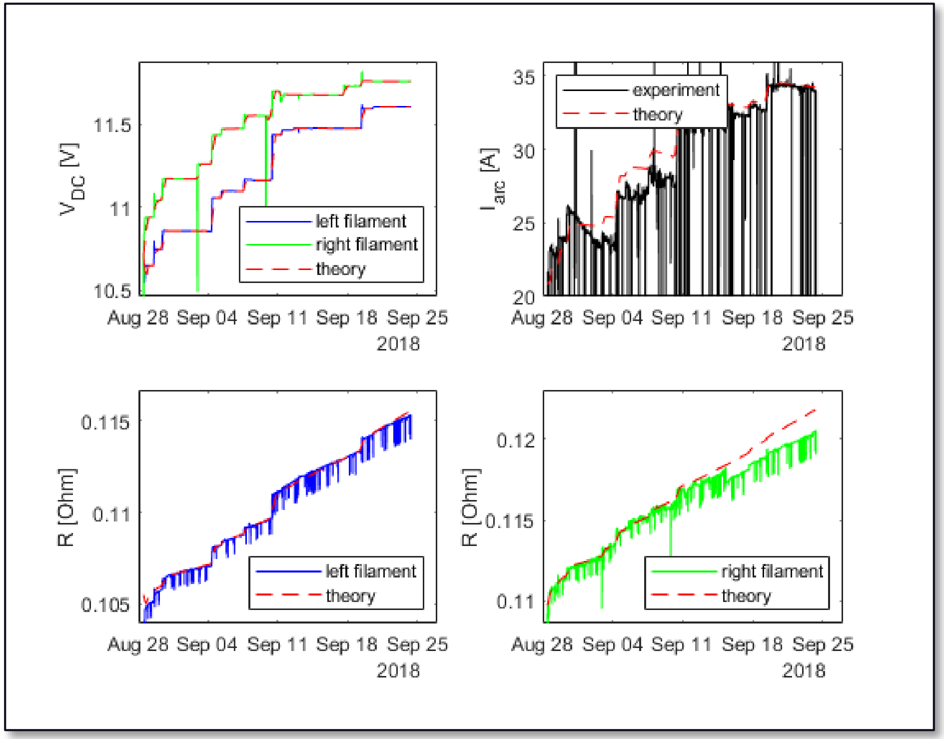
Local resistance increases faster

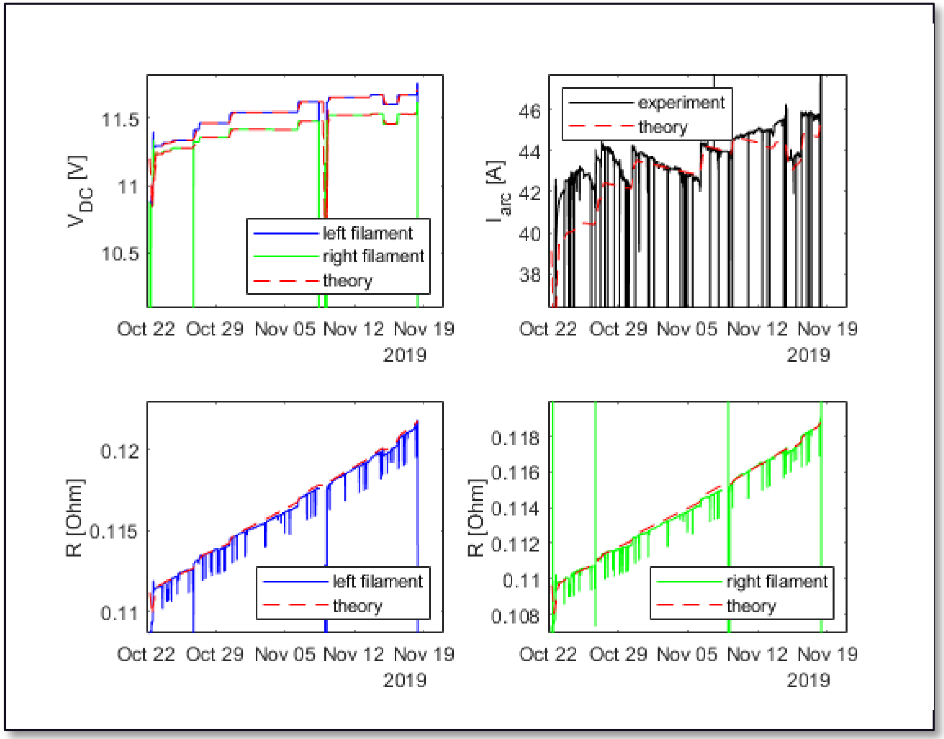
⇓

Ohmic losses increase

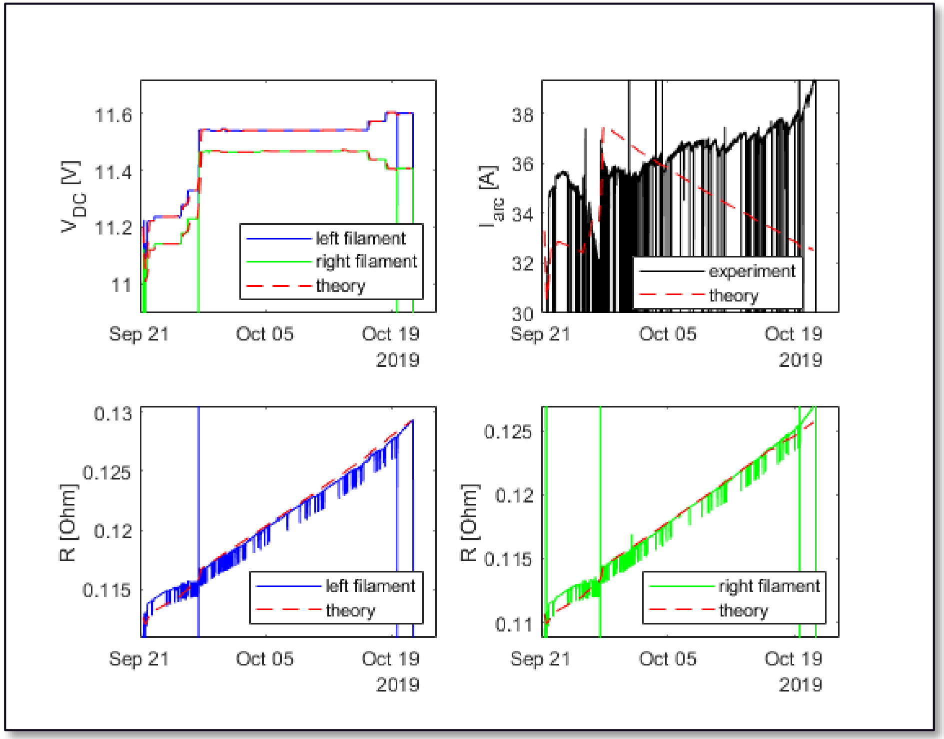


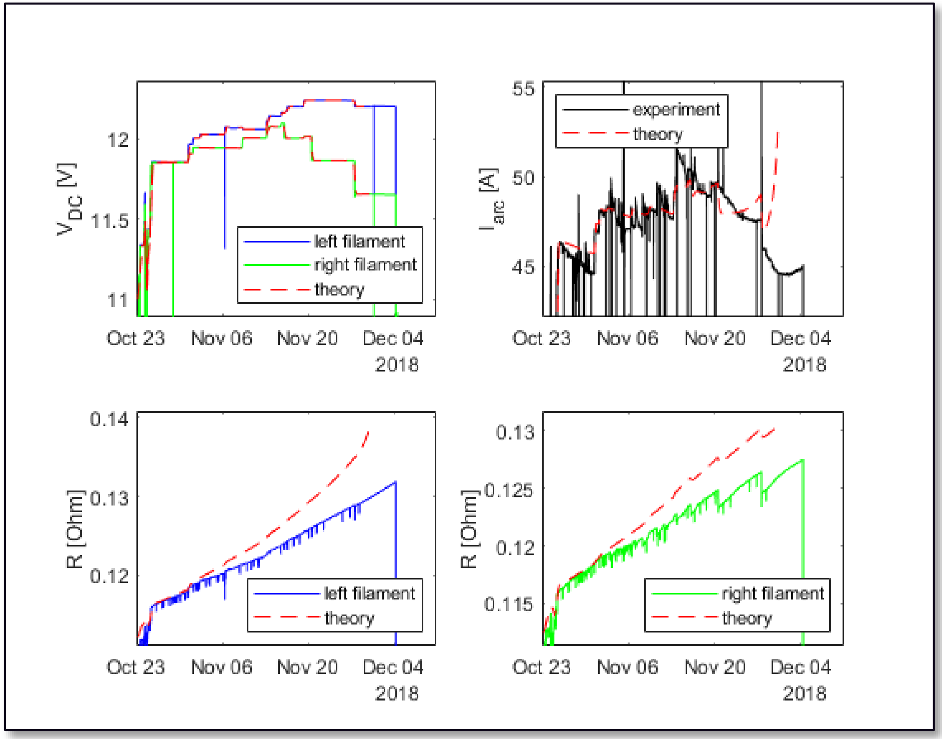
Typical good experiment/theory agreement





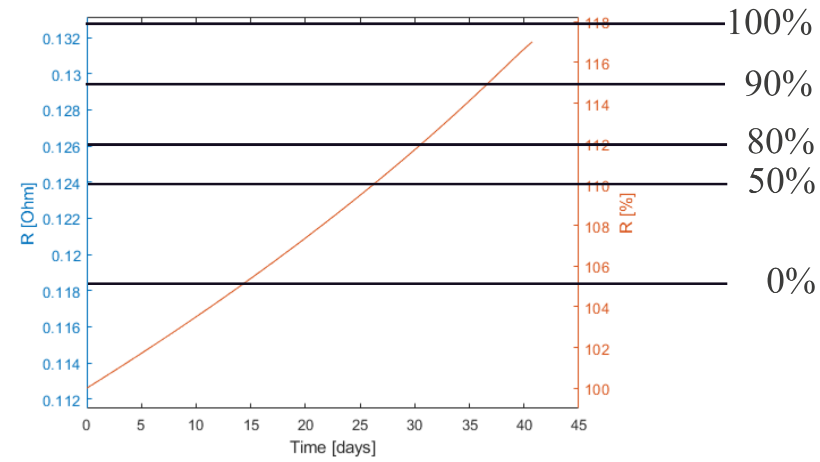
Typical bad experiment/theory agreement



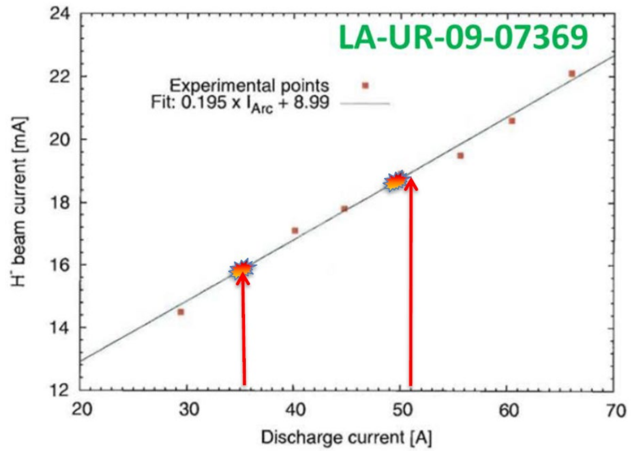


Model driven risk assessment for filament life time

Based on operation experience, we have rough statistics of probability of filament failure based on increase in relative resistance. This statistics is not available for every regime of operation. We can fill the gap with the model to estimate the lifetime based on the delivered H^- current.



H^- current / chance of failure	0%	50%	80%	90%	100%
14mA	29	54	63	76	88
16mA	18	34	39	47	55
18mA	14	25	29	35	36
20mA	10	19	22	26	26



Summary

• Self-consistent model describing the change of filament parameters over time has been developed.

• There are no empirical parameters introduced to match experimental data. All the physics is accounted for from the first principles.

• Model explains a large number of trends in filament performance

• The model is capable of providing quantitative predictions on lifetime and arc current.

• Verification with experiment has been done. The model shows reasonable agreement with LANSCE H^- ion source data. Agreement is reasonable across different regimes of operation (arc current has been varied within 25-45A range, 60Hz and 120Hz repetition rates).

• Proper verification allows to apply the developed model to other ion sources.

Thank you