Oak Ridge National Laboratory

H^- injectors for accelerators - status and future prospects

International Conference on Ion Sources 2025

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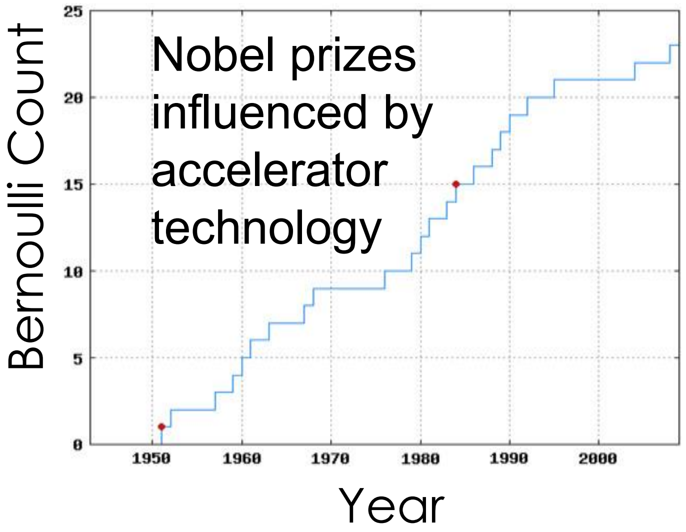
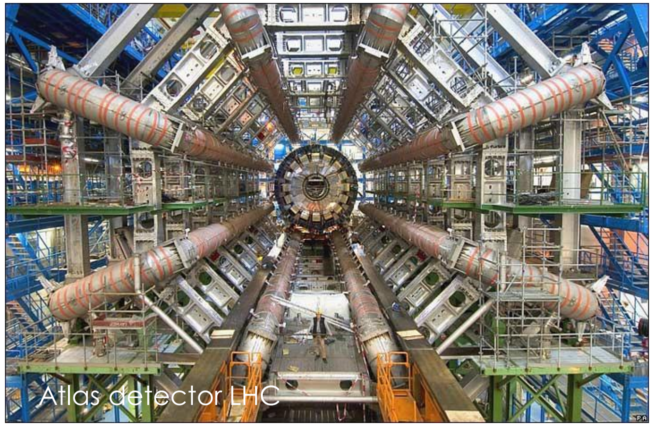
Outline

- **Particle accelerator-based user facilities and their impact on society**
- **Working principle of a typical H^- beam injector**
- **Survey of ion sources and Low Energy Beam Transports (LEBTs)**
  (system description, current operational parameters, future requirements and R&D efforts)
  - **Brookhaven National Laboratory (BNL)**
  - **CERN (LHC)**
  - **Chinese Spallation Neutron Source (CSNS)**
  - **D-Pace (licensed by TRIUMF) ion sources used mainly with cyclotrons**
  - **Fermi National Accelerator Laboratory (FNAL)**
  - **Los Alamos Neutron Science Center (LANSCE)**
  - **Japan Proton Accelerator Research Complex (J-PARC)**
  - **Rutherford Appleton Laboratory (RAL-ISIS)**
  - **Oak Ridge National Lab (Spallation Neutron Source)**
  - **Future Circular and Muon Colliders**
- **The big picture - current state of the art, overall goals and summary of R&D efforts**

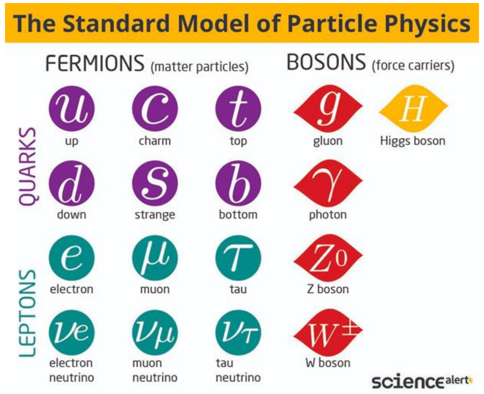
Particle accelerators and their impact on society

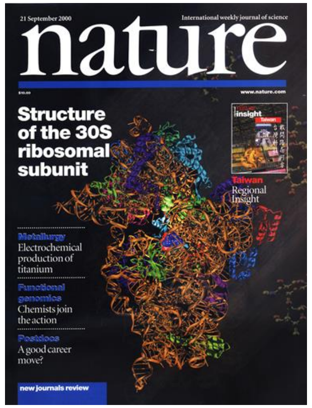
- Since the early 20th century particle accelerators and their associated user facilities have been engines of science and innovation worldwide. One measure of the impact of accelerators on physics can be seen through contributions to Nobel prize awards-
- Since their establishment (1930's) accelerator technology has contributed to ~28% Nobel prize in physics awards – Haussecker and Chao
- More recent accomplishments include completion of the standard model of particle physics by the discovery of the Higgs particle at the LHC (2013 Nobel Prize), structure of the ribosome (2009) and Nobels in biology and chemistry (1997, 2003, 2006, 2009 and 2012).
- These facilities are some of the most complex and sophisticated scientific instruments of our time




Atlas detector LHC

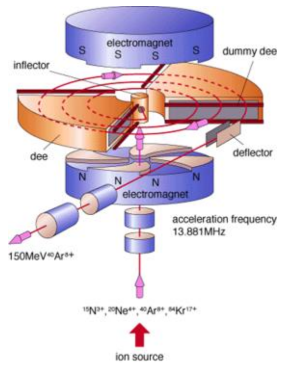

CMS detector LHC



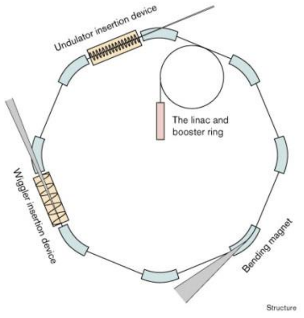


Large particle accelerator-based user facilities

- Can be categorized as follows-

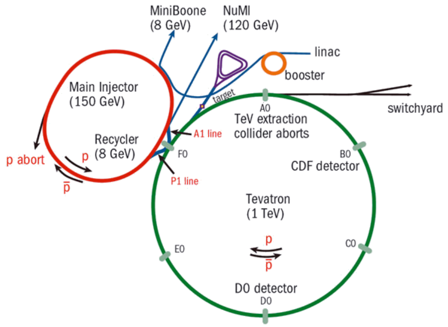


Heavy ion accelerators- cyclotrons, linacs, tandems, used in nuclear physics, radioactive beams, isotope production

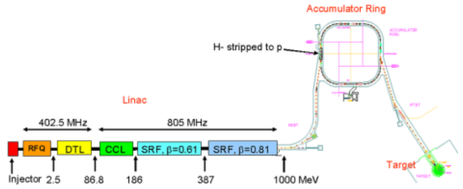


Coherent light sources- FEL, linacs, synchrotrons, storage rings, structural biology (2 recent Nobels), condensed matter, brightness frontier

Colliders-chains of accelerators, synchrotrons, linacs, used in high energy physics, early universe, energy frontier

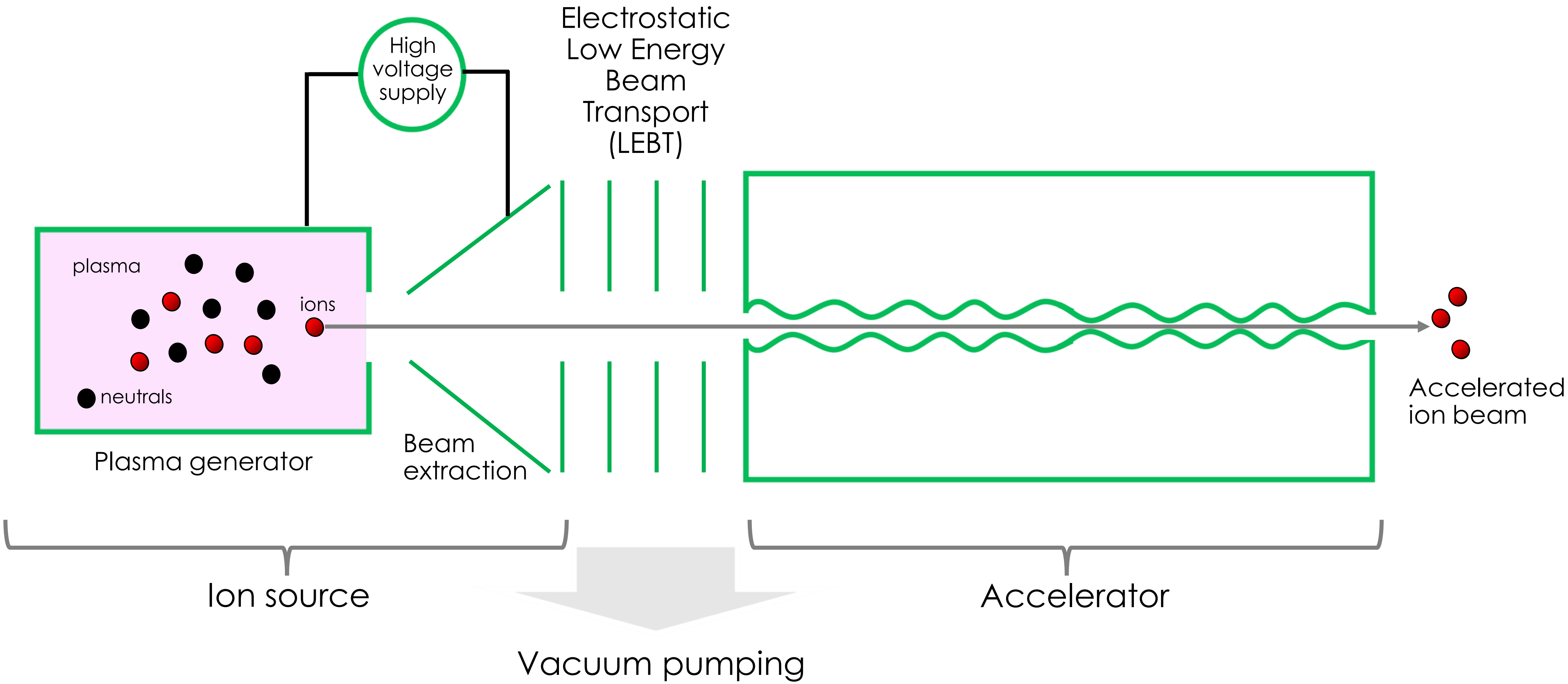


Proton drivers- produces neutrons, muons, mesons, neutrinos for particle and condensed matter physics, intensity frontier (MW-class)



Cheat sheet: Hadrons are protons, heavy ions, neutrons, mesons and Antiprotons. Leptons are electrons, positrons, photons, neutrinos, gammas and muons

Simplified Illustration of a hadron beam injector



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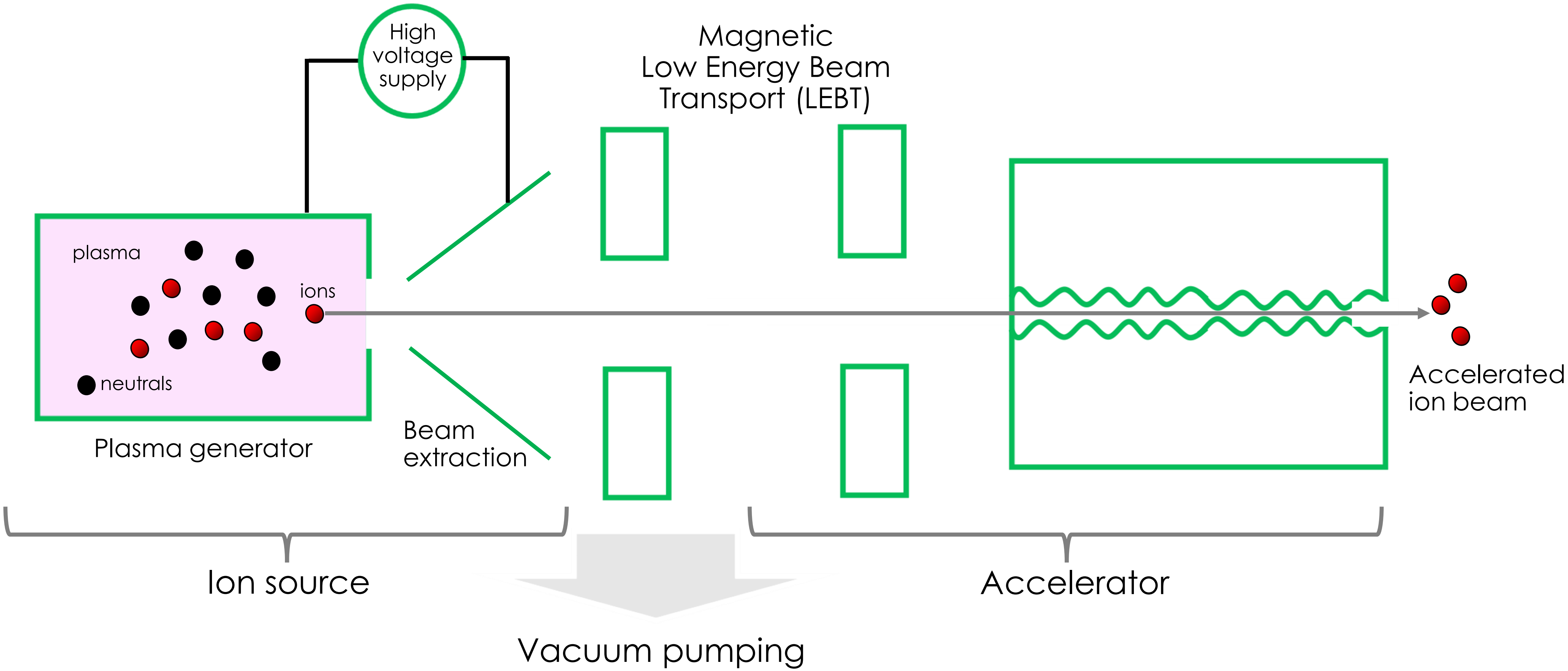
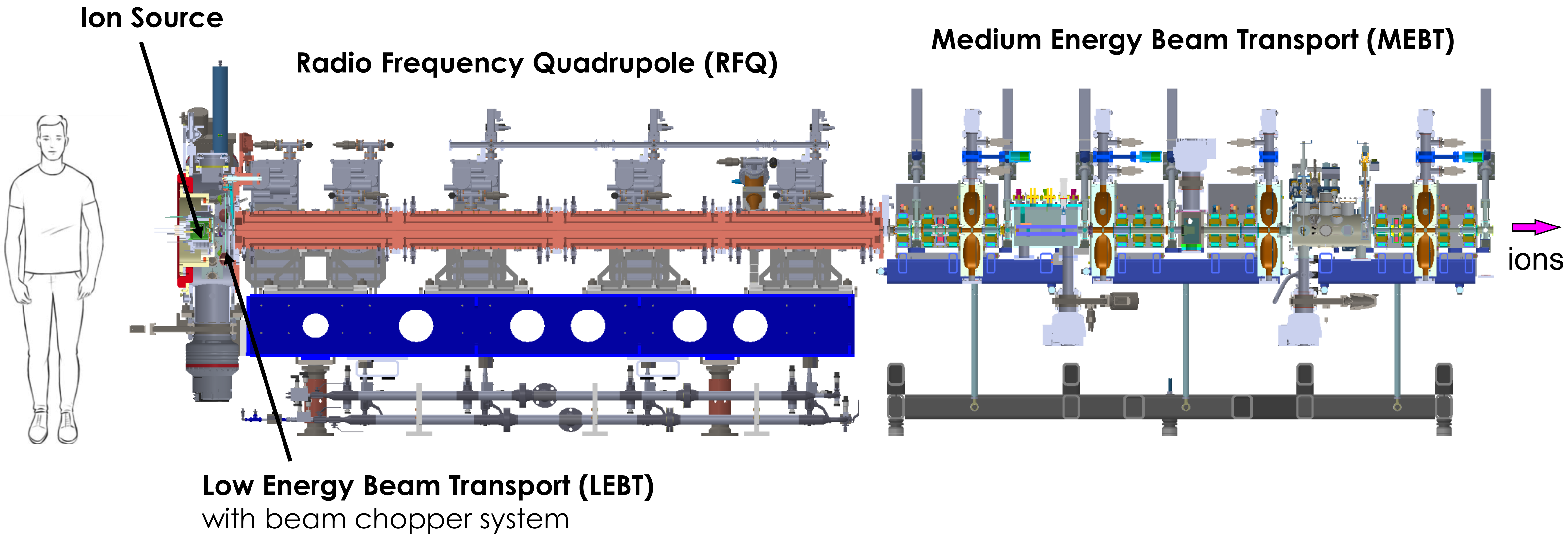


Typical Modern Hadron Injectors

- Typically delivers milliamperes of MeV beams into an accelerator

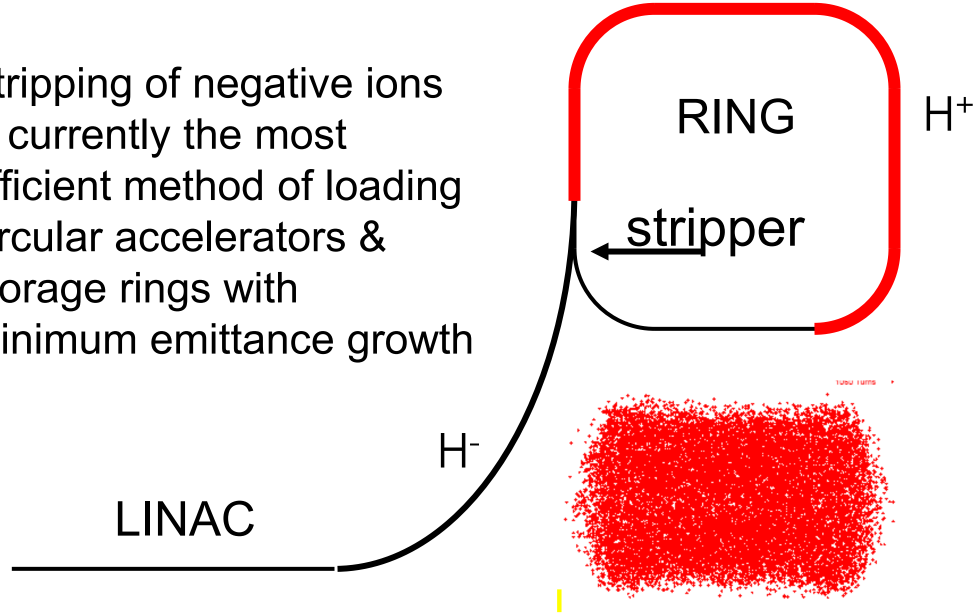
SNS front end system

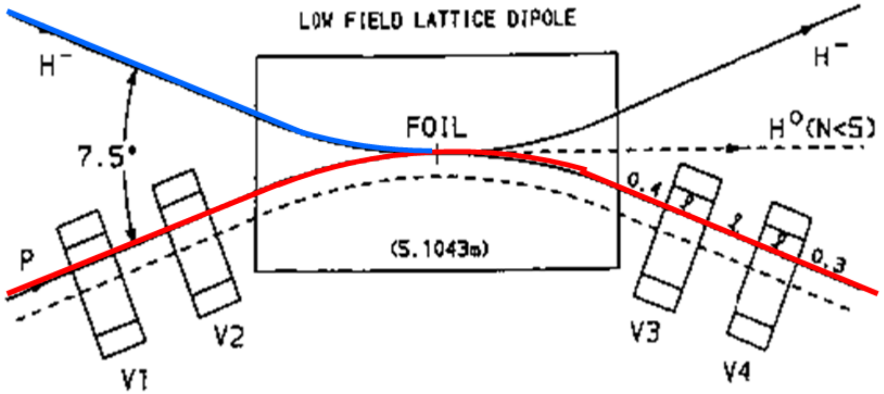


We focus on H⁻ ions, why?

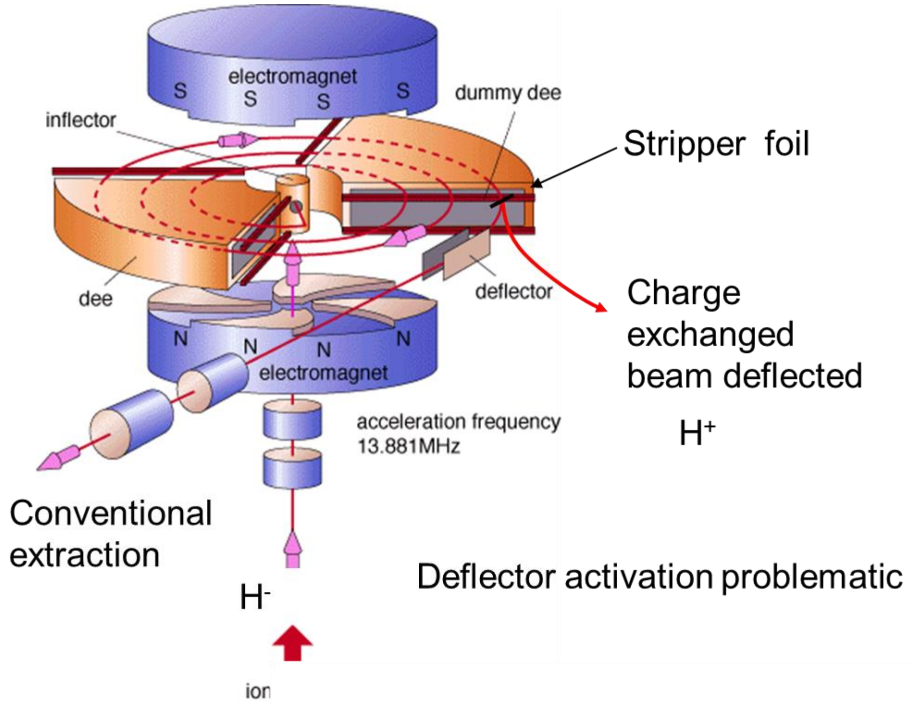
Efficient charge exchange injection into rings

- Stripping of negative ions is currently the most efficient method of loading circular accelerators & storage rings with minimum emittance growth

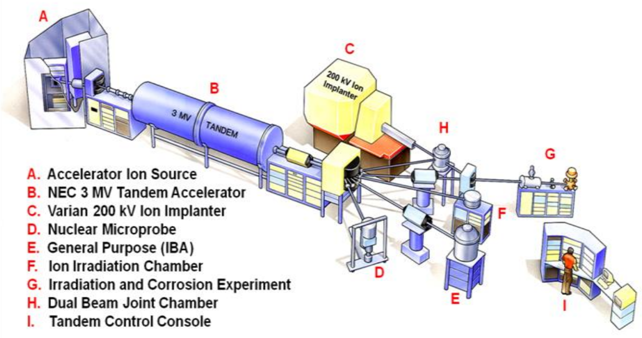




Efficient extraction from Cyclotrons



Negative ions in general are also needed for tandem accelerators

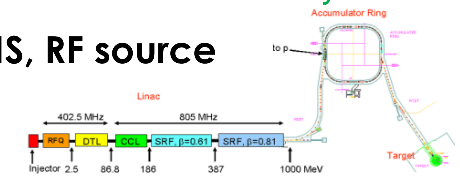


The H$^-$ accelerator facilities that participated in this study

- These facilities require H$^-$ beams ranging from 1-120 mA, 1μs-cw pulse lengths, with an RMS normalized emittance of around 0.25 π mm mrad
- These facilities operate over decades span decades and 10,000's of scientific users

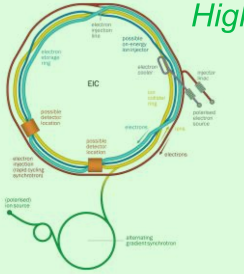
MW-class Neutron facility

SNS, RF source

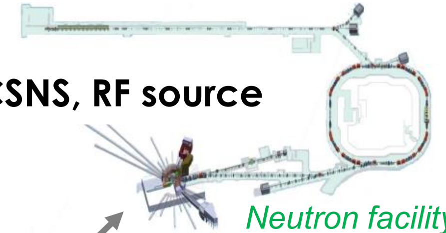


High Energy Physics

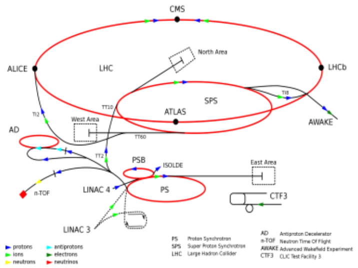
BNL Magnetron source



CSNS, RF source

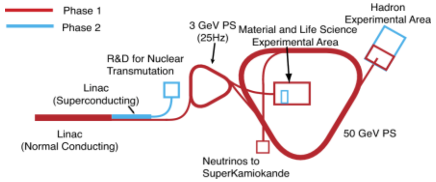


Neutron facility



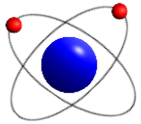
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



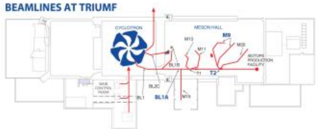
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

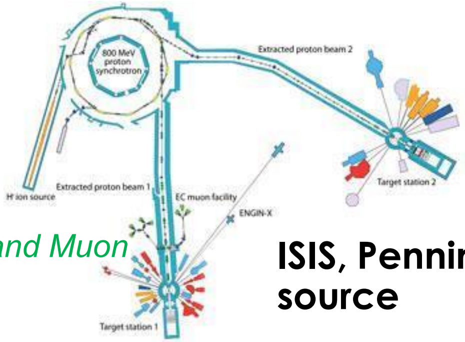


H$^-$

D-Pace, filament sources



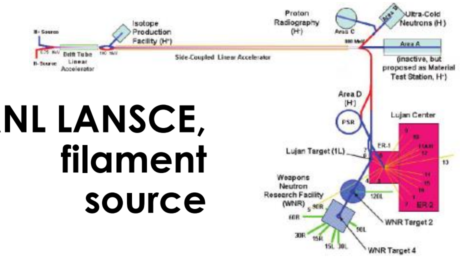
Many cyclotron facilities worldwide



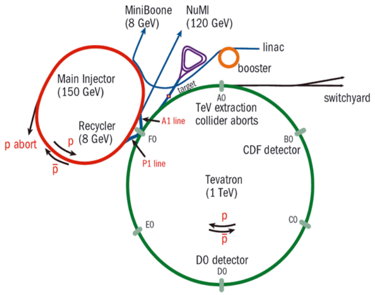
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility

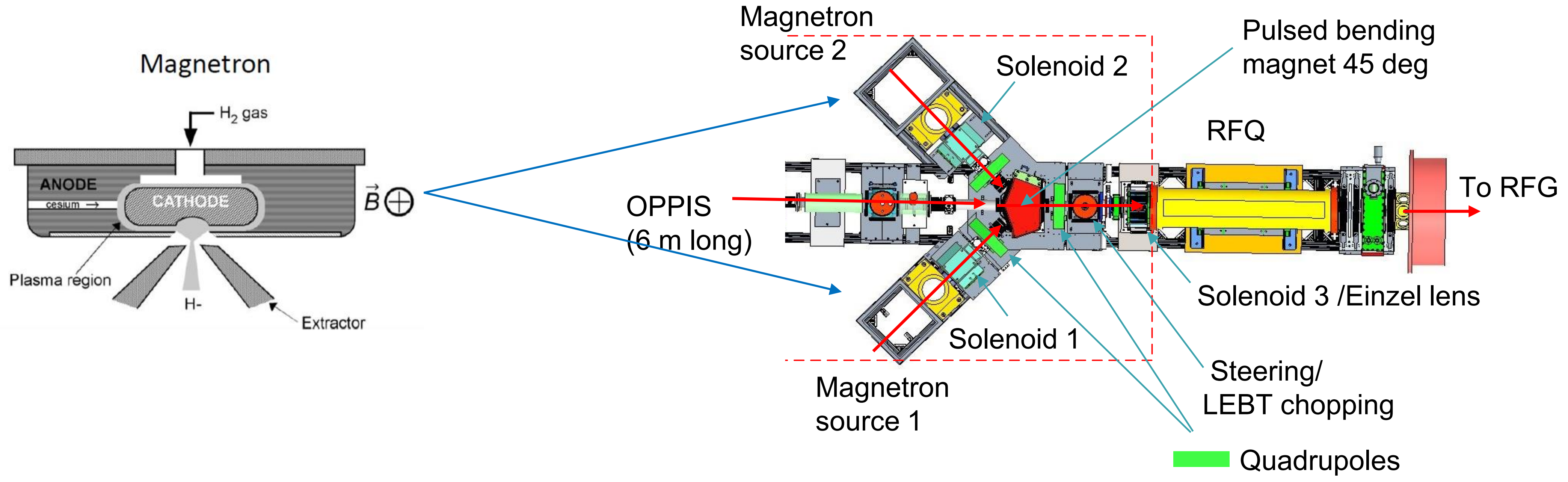


TeV-class high energy physics, neutrinos facility

FNAL, Magnetron source

BNL H$^-$ magnetron ion source and magnetic /electric LEBT

~85 mA, 750 us, 7 Hz, 6-9 months, >99.6% available



- Ion source(s)- 2x magnetron (~125 mA, pulsed arc source, Cs) and an optically pumped polarized source based on a proton source +Rb + Na cells, ~3m long (~400uA)
- LEBT: Electromagnetic (solenoids + quads +einzel lens), 3 meter long, active gas **Xe** (~3x10^{-6} Torr) neutralization, chopper: 2 us to 600 us

Contact: Deepak Raparia– raparia@bnl.gov
Anatoli Zelenski

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

H^- Ion Source R&D at BNL

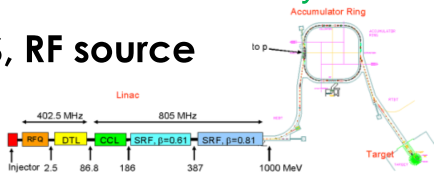
- **Motivation**
  - Higher duty factor for facility upgrades **0.525 →1.1 %** (7→10 Hz, 0.75 → 1.1 ms) (achieved on test stand)
  - Higher polarization >400uA (routine) Improve Cs control
  - Improve Plasma arc stability
  - Lower spark frequency
- **Capabilities**
  - 2x magnetron test stands
  - diagnostic apparatus
  - modeling software, etc.
  - OPPIS test Lab
- **Current efforts**
  - Improved heating system for the source and Cs supply to ensure steady Cs flow and minimum consumption while keeping the source body 160-180C range (unable to be heated by arc power alone)
  - Improved power supplies reducing footprint and achieving better arc stability with reduced noise.
  - Improved ceramic supports for the ion optics: reducing Cs and W deposition on insulators and consequent spark frequencies.
  - Significant improvements were also made to the pulsed gas valve

Current injection parameters delivered to the main accelerator complex at each facility

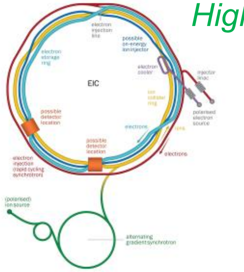
Operational injector	BNL
Type of ion source	Magnetron
H^- beam current injected into accelerator	80-90 mA
Beam energy	35 keV
Beam pulse length	750 us
Beam repetition rate	7 Hz
Typical beam emittance normalized RMS	0.4 π mm mrad
Cesium (Y/N)	Yes
Extraction aperture diameter	2.8 mm
Typical discharge power	2 kW
Typical source availability	> 99.6%
Typical source service period	6-9 Months
HV supply (cw vs pulsed)	Pulsed
Type of LEBT (mag, ele)	Mag/Ele
# of solenoids / Einzel lenses	2/1 (active gas neutralization)
Length of LEBT	3/6 meters
Type of chopper(s)	pulses
Location of chopper (LEBT, MEBT)	LEBT
Chopping period / fraction chopped	10us/10-90%

MW-class Neutron facility

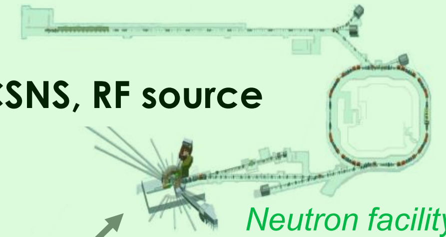
SNS, RF source



High Energy Physics

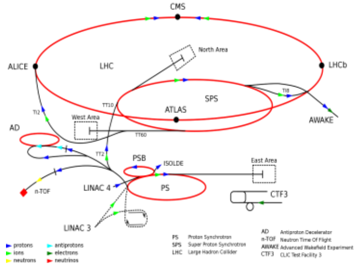


BNL Magnetron source



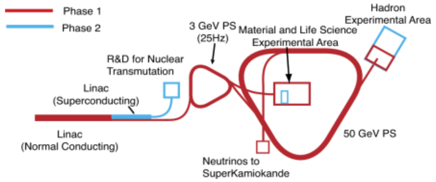
CSNS, RF source

Neutron facility



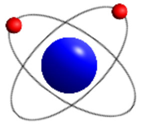
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



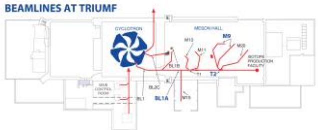
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

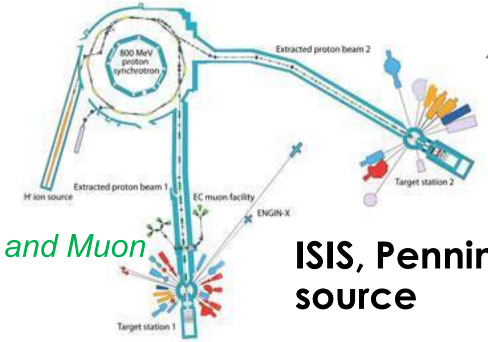


H⁻

D-Pace, filament sources



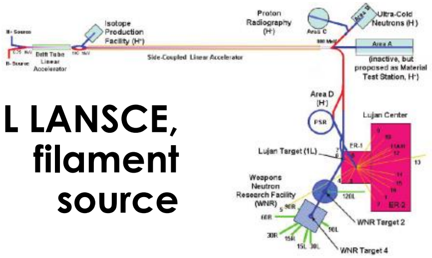
Many cyclotron facilities worldwide



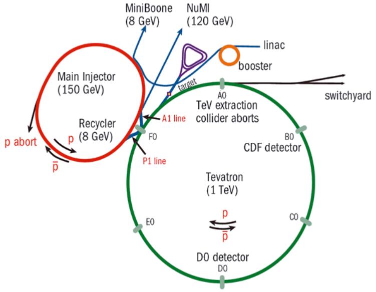
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility

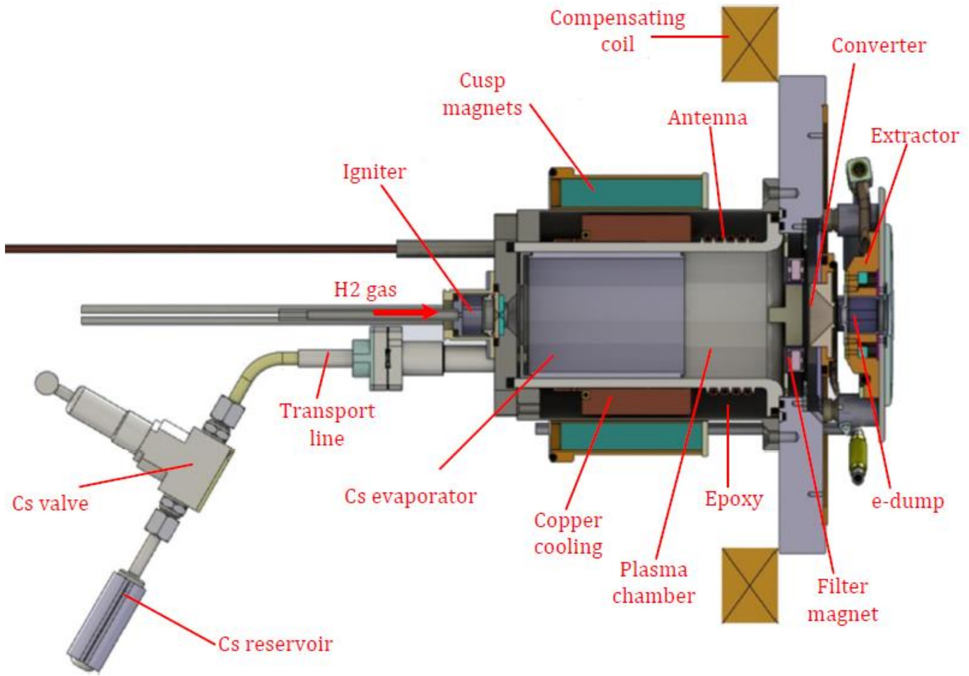


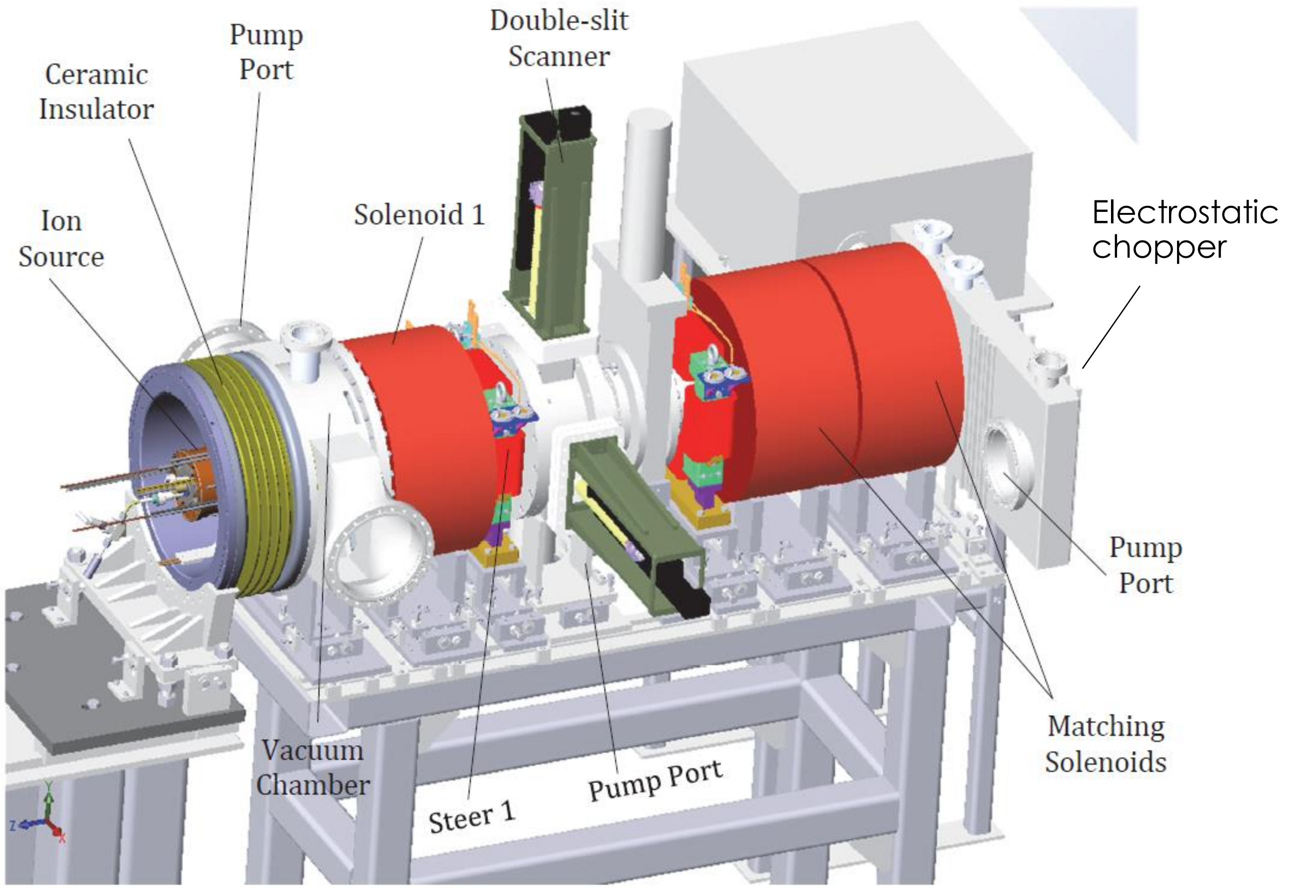
TeV-class high energy physics, neutrinos facility

FNAL, Magnetron source

CSNS RF H^- Ion Source and magnetic LEBT

15-42 mA, 570 us, 25 Hz, >11 months, ~100% available





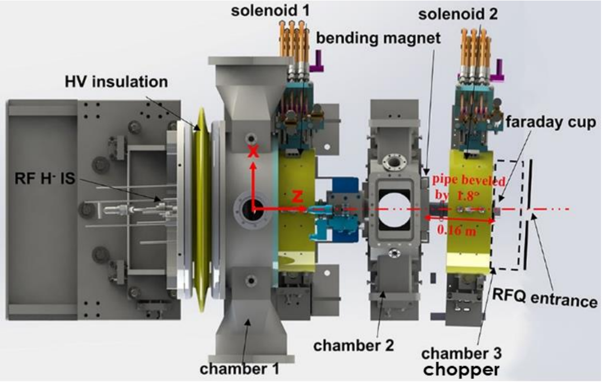
- RF source with external coil, Cs
- Silicon Nitride chamber
- 3 solenoid LEBT

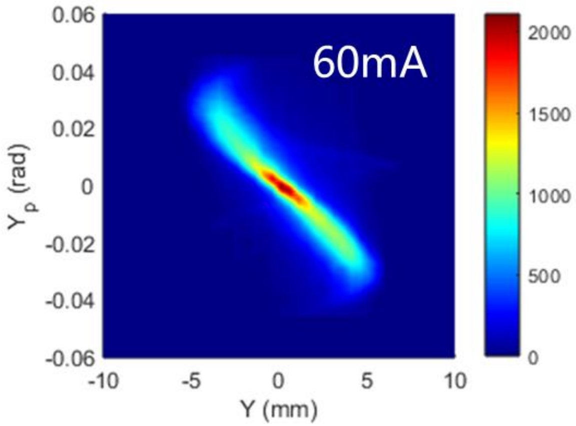
Silicon Nitride chamber

Contact: Weidong Chen – chenwd@ihep.ac.cn

H^- Ion Source R&D at CSNS

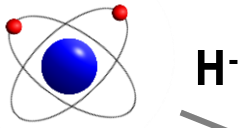
- **Motivation**
  - Repetition rate increases from 25 to 50 (75) Hz, >40mA for CSNS-II (5y construction period CSNSII)
  - Suppress stripped proton beam injection into the RFQ ($H^+/H^- < 0.01\%$)
  - Address emittance growth from beam chopping
- **Capabilities**
  - Ion source /experimental LEBT test stand, software, diagnostic apparatus
- **Current efforts**
  - New bent (1.8 deg) LEBT configuration is being used to measure and filter stripped protons is being tested
  - CSNS II beam currents and duty-factor have been achieved on the test stand





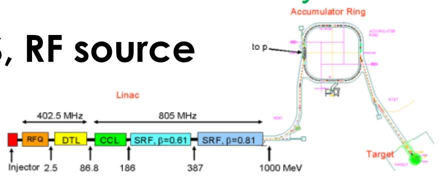
$\varepsilon(95\%)\sim0.25$ mm mrad

Operational injector	CSNS
Type of ion source	RF (2 MHz)
H^- beam current injected into accelerator	15~42mA
Beam energy	50kV
Beam pulse length	570us
Beam repetition rate	25Hz
Typical beam emittance (normalized RMS)	0.26 π mm mrad
Cesium (Y/N)	yes
Extraction aperture diameter	8mm
Typical discharge power	30kW
Typical source availability	100%
Typical source service period	>11months
HV supply (cw vs pulsed)	cw
Type of LEBT (mag, ele)	mag
# of solenoids / Einzel lenses	2
Length of LEBT	1.65 m
Type of chopper(s)	Ele def
Location of chopper (LEBT, MEBT)	End of LEBT
Chopping period / fraction chopped	1us/42%



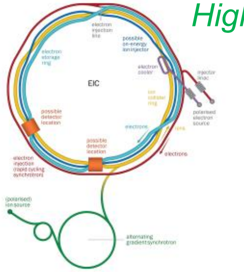
MW-class Neutron facility

SNS, RF source

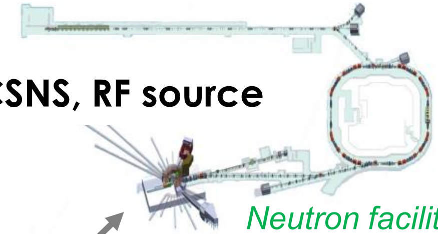


High Energy Physics

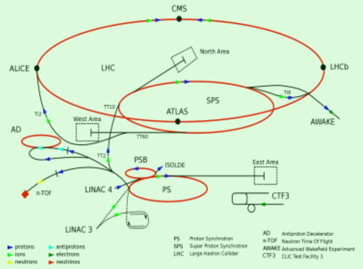
BNL Magnetron source



CSNS, RF source

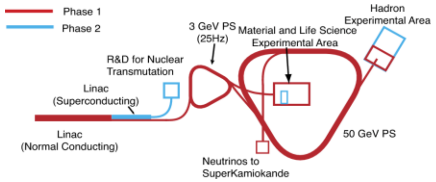


Neutron facility



TeV-class high energy physics, multipurpose laboratory

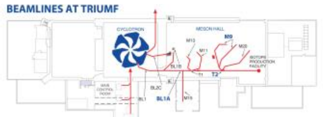
CERN LINAC-4, RF source



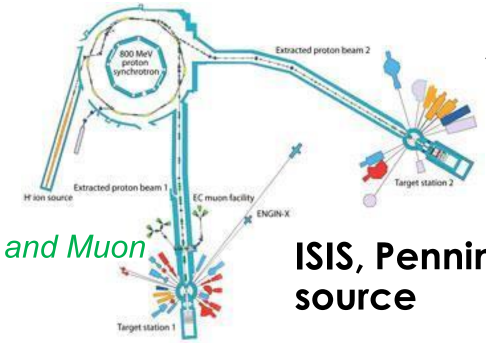
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

D-Pace, filament sources



Many cyclotron facilities worldwide



Neutron and Muon facility

ISIS, Penning source

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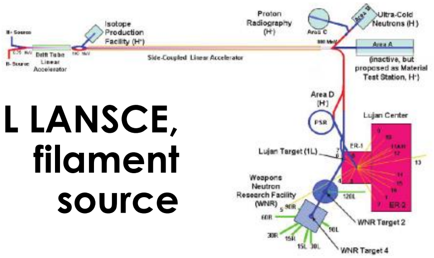
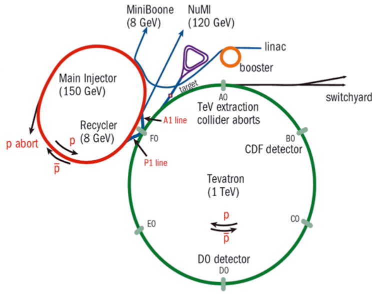


MW-class multipurpose facility

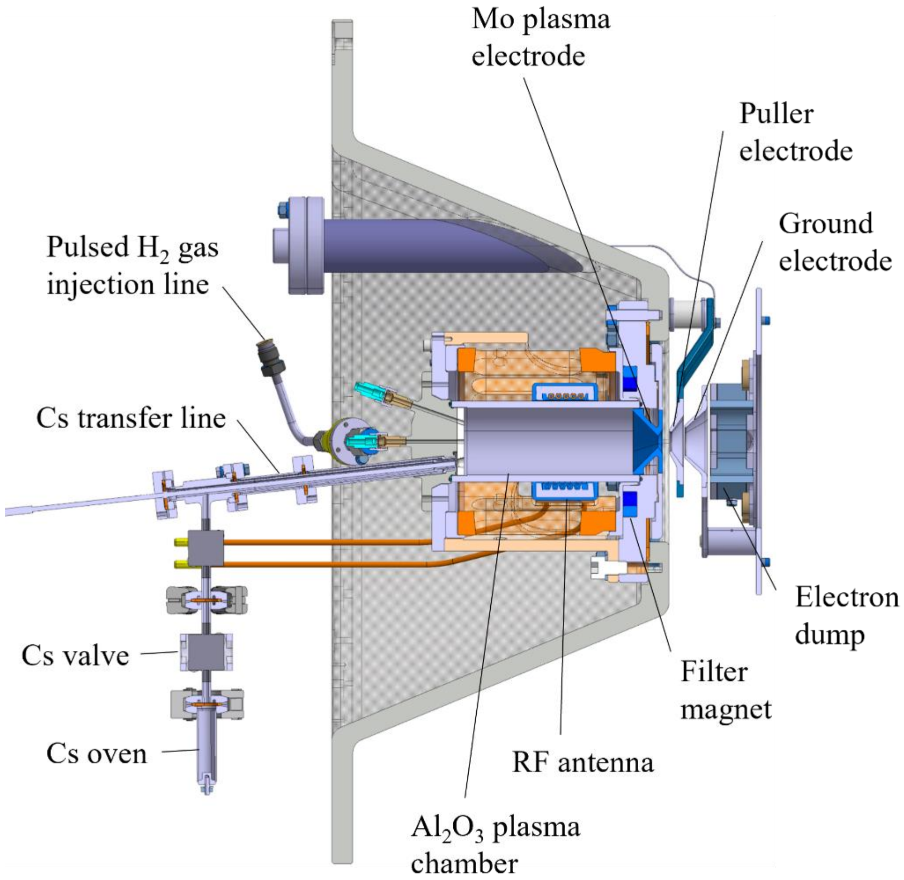


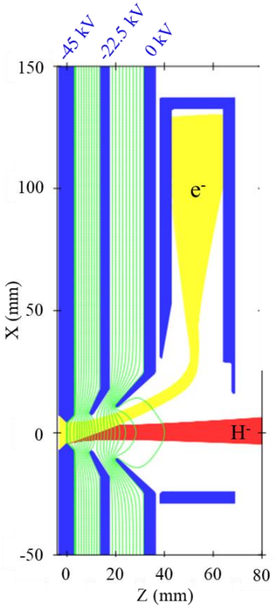
TeV-class high energy physics, neutrinos facility

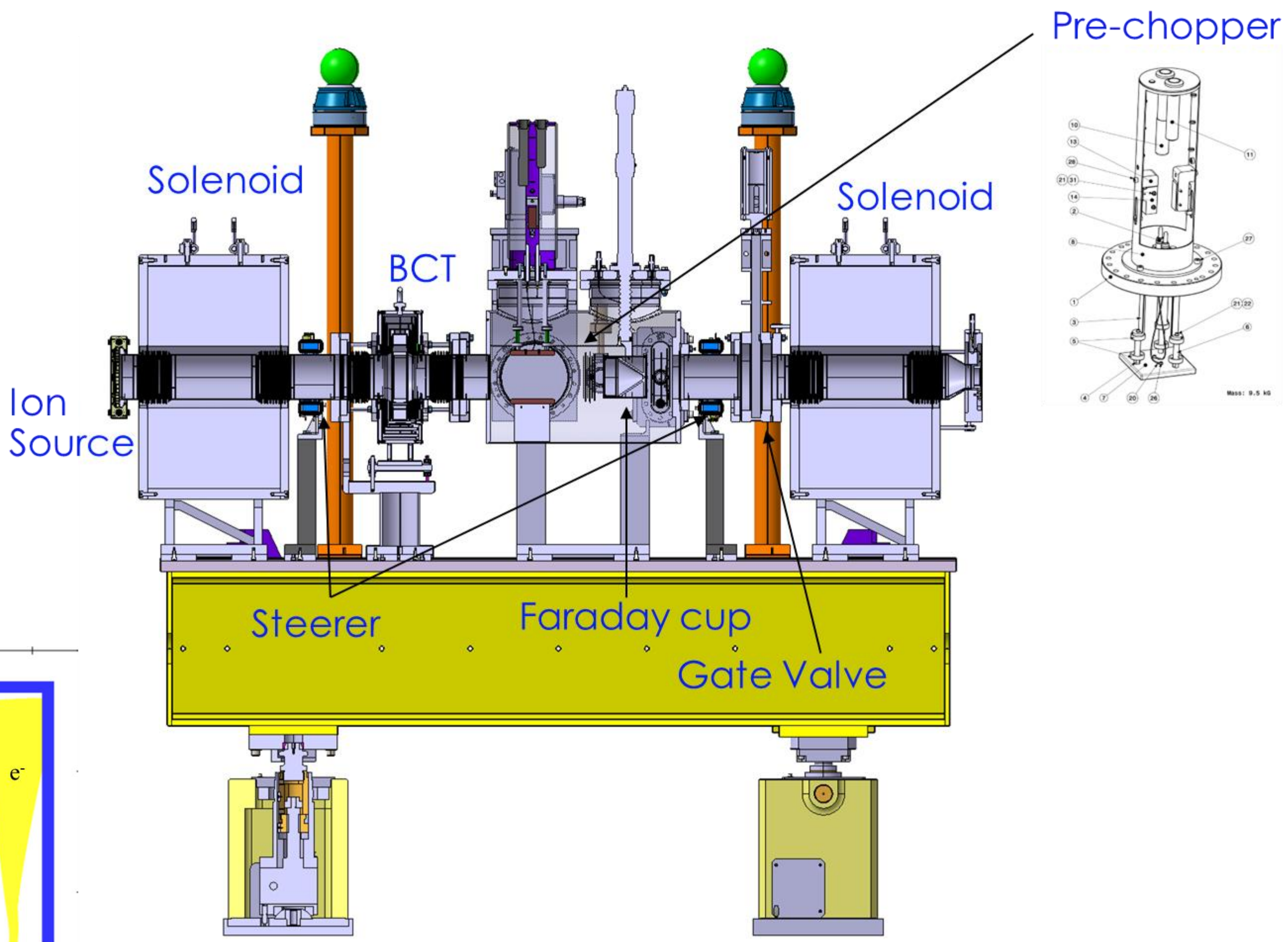
FNAL, Magnetron source

CERN RF H$^-$ Ion Source and magnetic LEBT

35 mA, 850 us, 0.83 Hz, ~10 months, >99.6% available







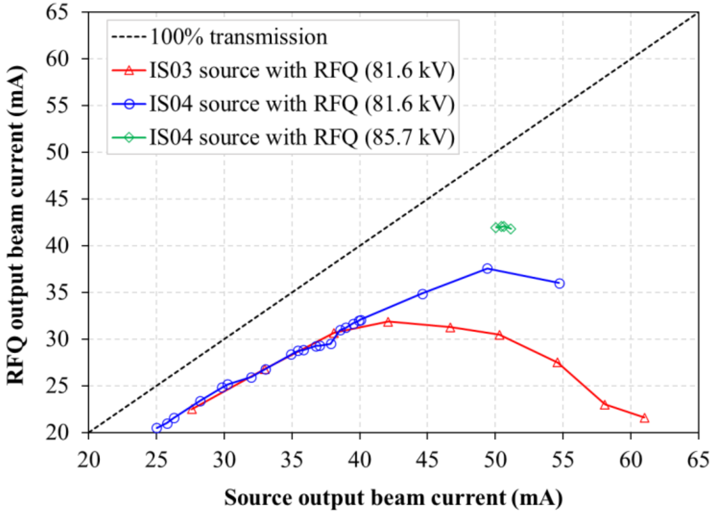
- RF source with external coil, Cs
- Aluminum oxide chamber
- 2 solenoid LEBT

Contact: Edgar Sargsyan – edgar.sargsyan@cern.ch

H^- Ion Source R&D at CERN

- **Motivation**
  - Increase beam current out of the RFQ to ~45 mA from the demonstrated 35-40 mA
  - Reduce emittance to improve the beam transmission through the RFQ. Original requirement was 0.25 π.mm.mrad; presently ~0.4 π.mm.mrad.
  - Improve the stability of the pulsed gas injection valve
- **Capabilities**
  - Ion source/LEBT test stand, RFQ mask, software, diagnostic apparatus, spare RFQ test stand being commissioned
- **Current efforts**
  - Recently developed IS04 which had better RFQ transmission
  - It Features e-dumping on ground
  - Eliminated LEBT einzel lens

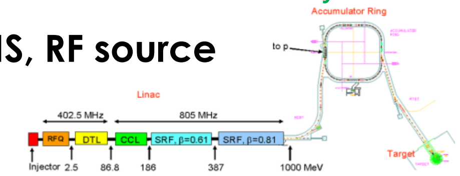
Nominal RFQ vane voltage: 81.6kV



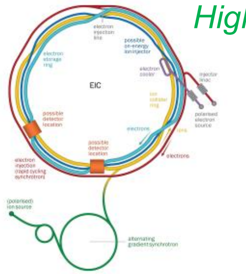
Operational injector	CERN
Type of ion source	RF (2 MHz)
H^- beam current injected into accelerator	35 mA
Beam energy	45 keV
Beam pulse length	0.85 ms
Beam repetition rate	0.83 Hz
Typical beam emittance Normalized RMS	~0.4 π mm mrad
Cesium (Y/N)	yes
Extraction aperture diameter	8 mm
Typical discharge power	~27 kW
Typical source availability	>99.6%
Typical source service period	~10 months
HV supply (cw vs pulsed)	pulsed
Type of LEBT (mag, ele)	mag.
# of solenoids / Einzel lenses	2
Length of LEBT	~2 m
Type of chopper(s)	Ele. def.
Location of chopper (LEBT, MEBT)	Pre-chop. in LEBT & fast chop. In MEBT
Chopping period / fraction chopped	LEBT: 1.2s/~6-76% MEBT: 1us/35-40%

MW-class Neutron facility

SNS, RF source

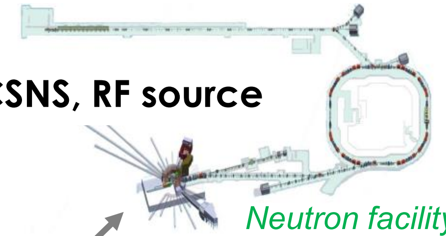


High Energy Physics

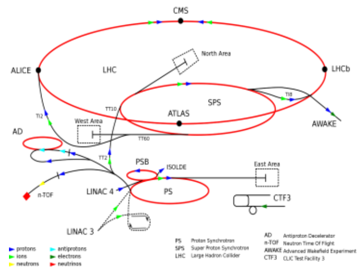


BNL Magnetron source

CSNS, RF source

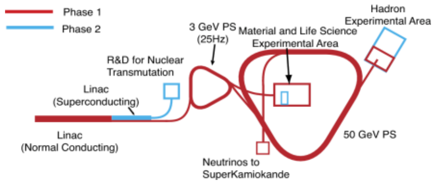


Neutron facility



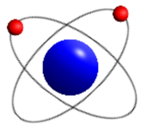
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



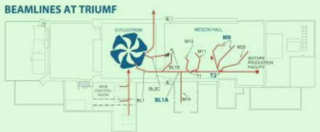
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

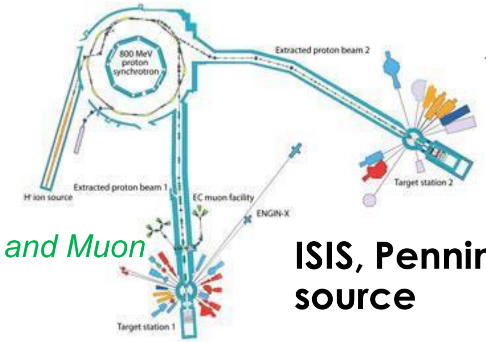


H$^-$

D-Pace, filament sources



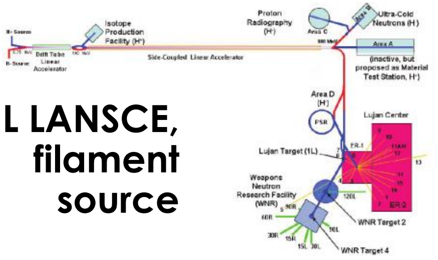
Many cyclotron facilities worldwide



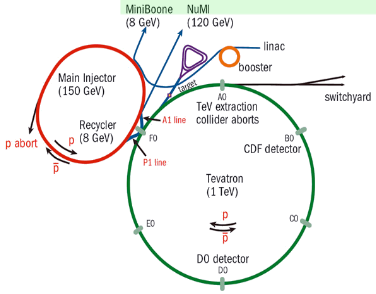
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility



TeV-class high energy physics, neutrinos facility

FNAL, Magnetron source

Operational injector	D-Pace
Type of ion source	Filament
H^- beam current injected into accelerator	15 mA DC
Beam energy	30 keV
Beam pulse length	N/A
Beam repetition rate	N/A
Typical beam emittance (RMS, normalized)	< 1π mm mrad
Cesium (Y/N)	N
Extraction aperture diameter	9.5 mm
Typical discharge power	4.5 kW
Typical source availability	>99.5%
Typical source service period	5250 mA-hrs
HV supply (cw vs pulsed)	DC
Type of LEBT (mag, ele)	mag
# of solenoids / Einzel lenses	varies
Length of LEBT	varies
Type of chopper(s)	N/A

D-Pace Filament-driven multicusp H^- ion Source
(TRIUMF licenced)

15 mA, CW, 5250 A hrs, >99.5% available

- In 2001, D-Pace licensed the 15 mA TRIUMF H^- source.
- These sources are now utilized worldwide:
  - Commercial axial injection type cyclotrons for medical radioisotope production
  - Boron Neutron Capture Therapy (BNCT) applications in tandem accelerators and cyclotrons

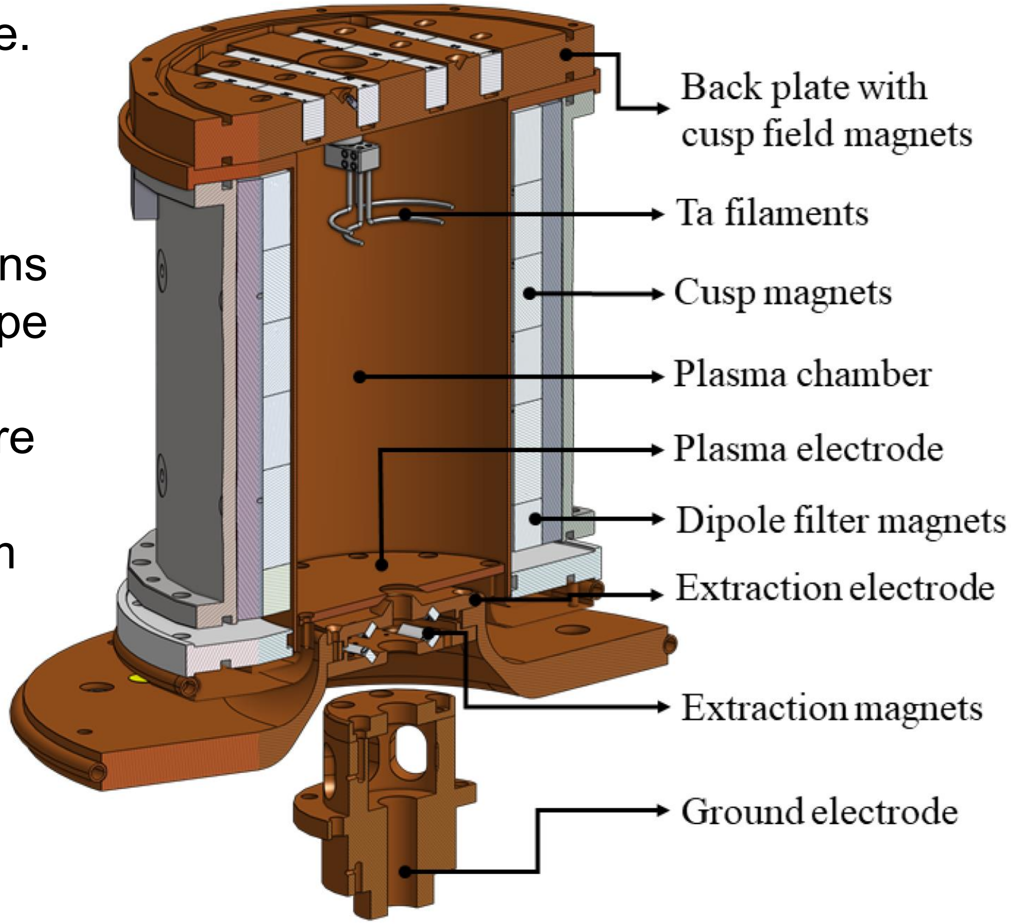
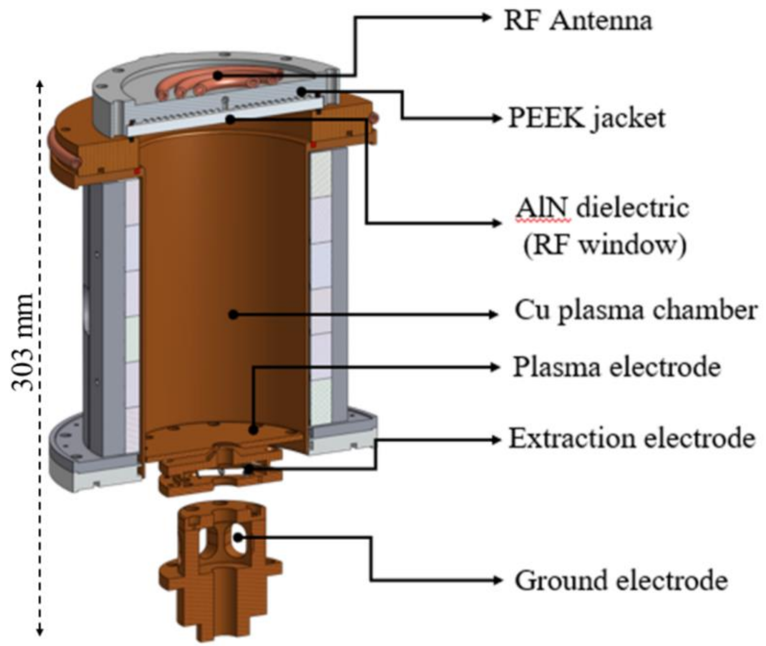


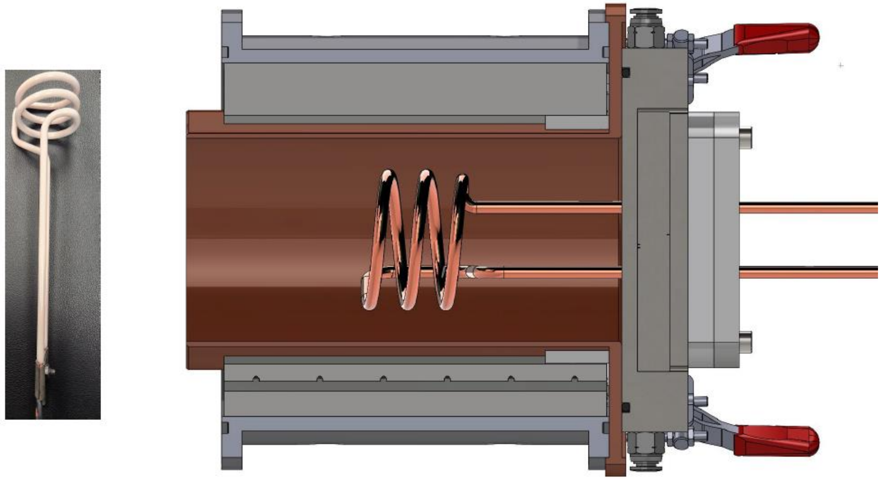
Figure by Anand George

Contacts: Morgan Dehnel – morgan@d-pace.com
Anand George - anand@d-pace.com

H$^-$ Ion Source R&D at D-Pace

- **Motivation**
  - Increase source lifetime > 5250 mA-hrs (~15 days at 15mA)
  - Increase beam current >15mA for isotope production and BNCT utilizing medical cyclotrons and tandem accelerators (BNCT desires ~30mA)
- **Capabilities**
  - Ion source/LEBT test stand, emittance and phase space scanner, Faraday cup, mass spectrometer, etc.
  - Software- IBSIMU, implicit PIC, COMSOL, etc.
- **Current efforts**
  - Lifetime extension project retrofitting RF coils (Jyväskylä and SNS) benefits all goals
  - Continuous interaction with customers, addressing new areas as they emerge



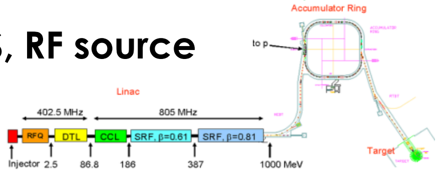


A picture of the Porcelain-coated copper antenna and design view of the internal antenna RF ion source

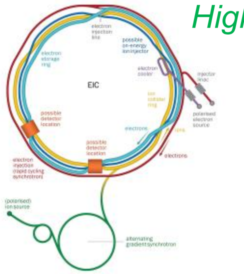
See poster by Anand George

MW-class Neutron facility

SNS, RF source

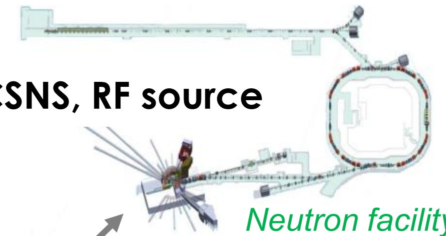


High Energy Physics

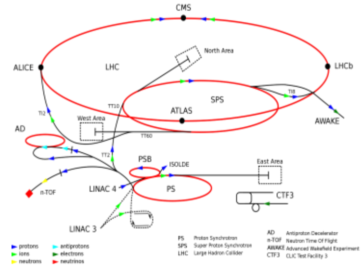


BNL Magnetron source

CSNS, RF source

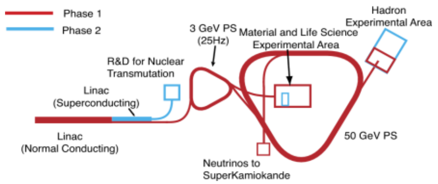


Neutron facility



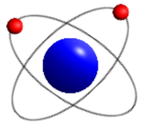
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



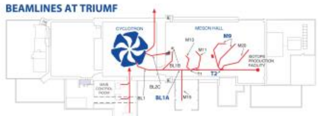
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

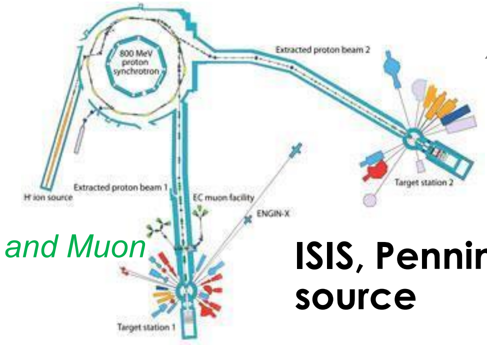


H$^-$

D-Pace, filament sources



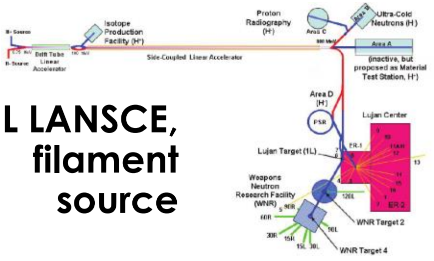
Many cyclotron facilities worldwide



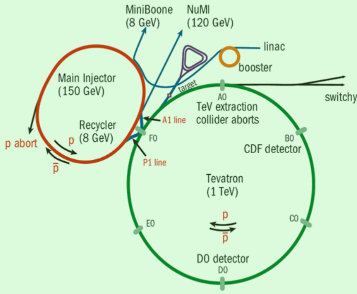
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility

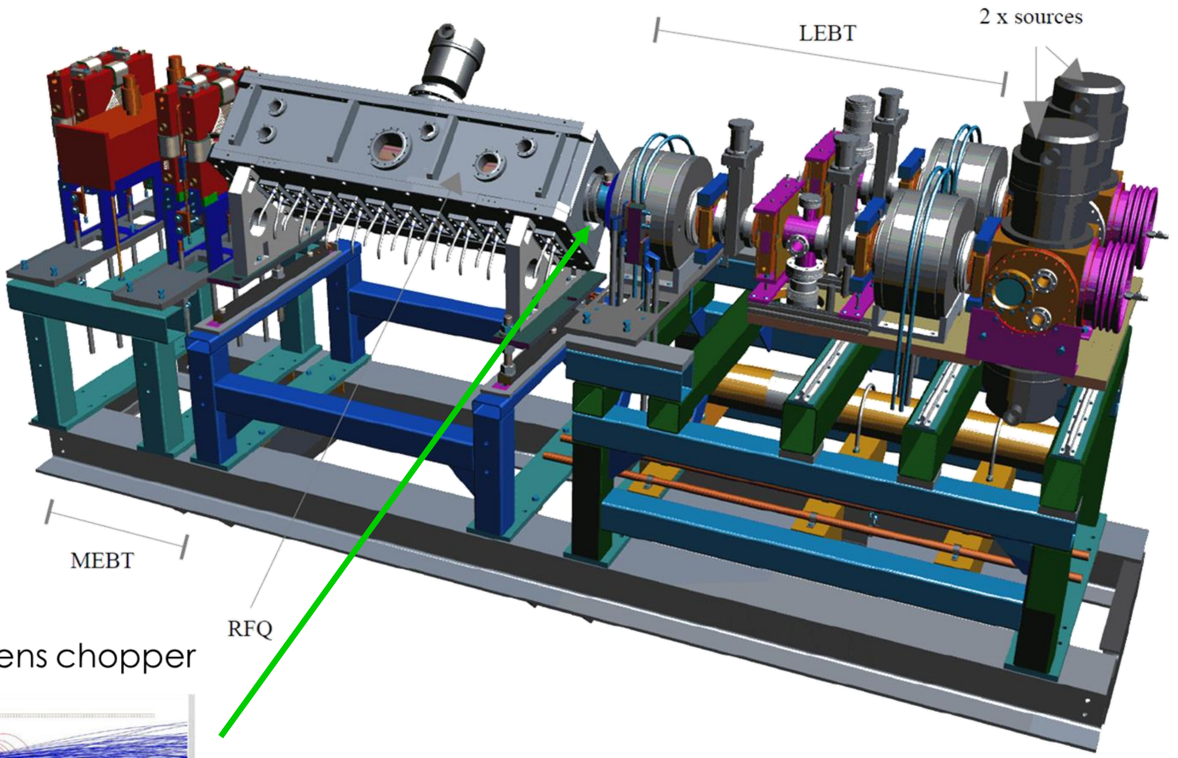


TeV-class high energy physics, neutrinos facility

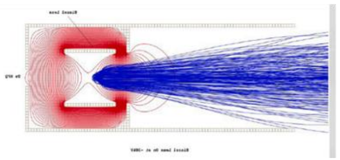
FNAL, Magnetron source

FNAL H$^-$ magnetron ion source and magnetic LEBT

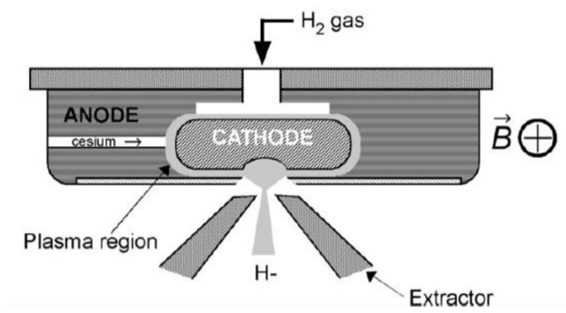
~60 mA, ~160 us, 15 Hz, > 9 months



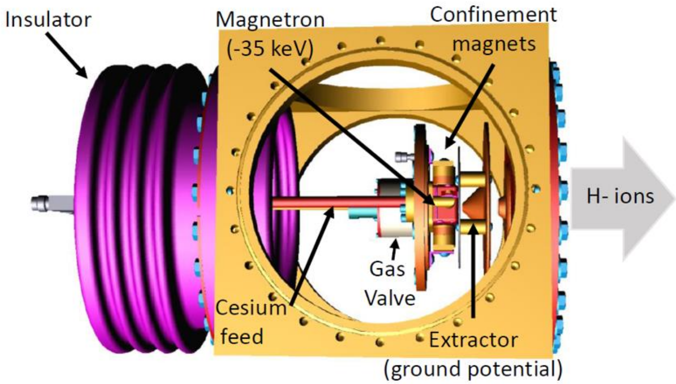
Einzel lens chopper



Magnetron



Operational Ion source



- The source pulses continuously for at least 9 months
- Low arc power (~4 W) have made for a very reliable source
- Arc: ~150V, ~10A

Contact: Dan Bollinger – bollinger@fnal.gov

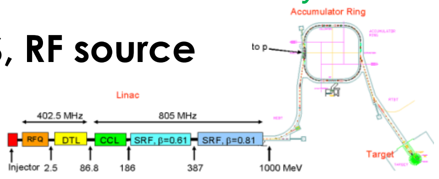
H^- Ion Source R&D at FNAL

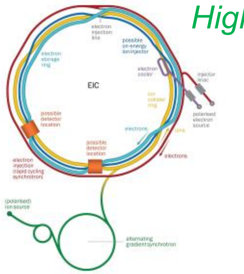
- **Motivation**
  - Fermilab PIP II (Proton Improvement Plan) utilizes an 800 MeV LINAC, replacing current DTL
  - Need a ~5mA cw H- source, 30kV, 1-100% duty-factor, emittance 0.15mm-mrad with a lifetime > 24 days, initial operation at 20 Hz.
- **Capabilities**
  - Test stands to test magnetron, penning and D-Pace sources are being built, diagnostic equipment, modelling software
- **Current efforts**
  - Current plan is to test and use a D-Pace 15 mA H^- Volume Cusp Source for PIP II
  - Other back up plans include demonstrating that the magnetron (1.3% duty-factor) or Penning sources can operate a useful duty-factor with a much longer lifetime than the D-Pace source

Operational injector	FNAL
Type of ion source	SPS
H^- beam current injected into accelerator	~60mA
Beam energy	35kV
Beam pulse length	~160μs
Beam repetition rate	15Hz
Typical beam emittance (RMS, normalized)	y~0.7 π, x~0.5 π mm mrad
Cesium (Y/N)	yes
Extraction aperture diameter	~3mm
Typical discharge power	~1.6kW/pulse (~4W ave)
Typical source availability	
Typical source service period	>9 months
HV supply (cw vs pulsed)	pulsed
Type of LEBT (mag, ele)	mag
# of solenoids / Einzel lenses	2
Length of LEBT	~1.2m
Type of chopper(s)	Ele Einzel Lens
Location of chopper (LEBT, MEBT)	End of LEBT
Chopping period / fraction chopped	~48us/22-32%

MW-class Neutron facility

SNS, RF source

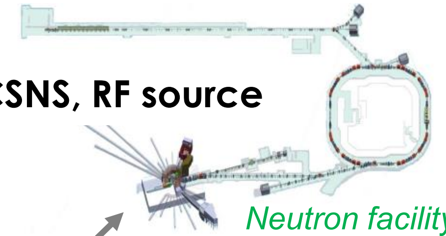




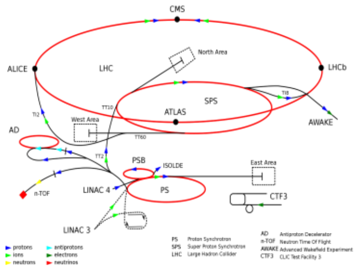
High Energy Physics

BNL Magnetron source

CSNS, RF source

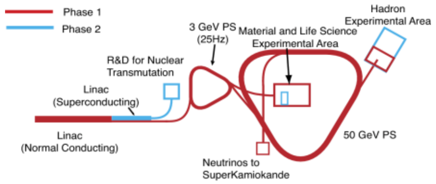


Neutron facility



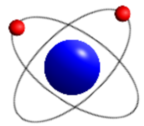
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



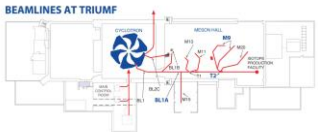
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

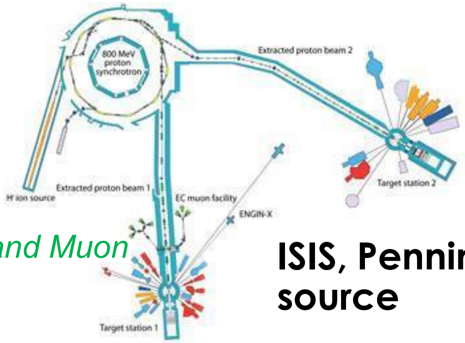


H$^-$

D-Pace, filament sources

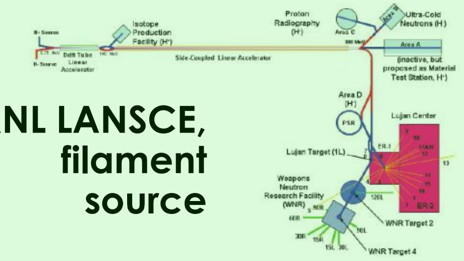


Many cyclotron facilities worldwide



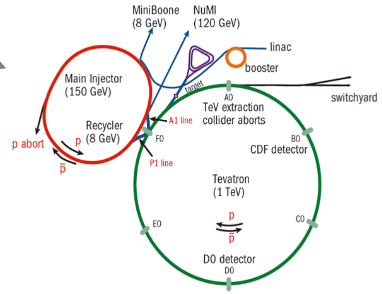
Neutron and Muon facility

ISIS, Penning source



LANL LANSCE, filament source

MW-class multipurpose facility



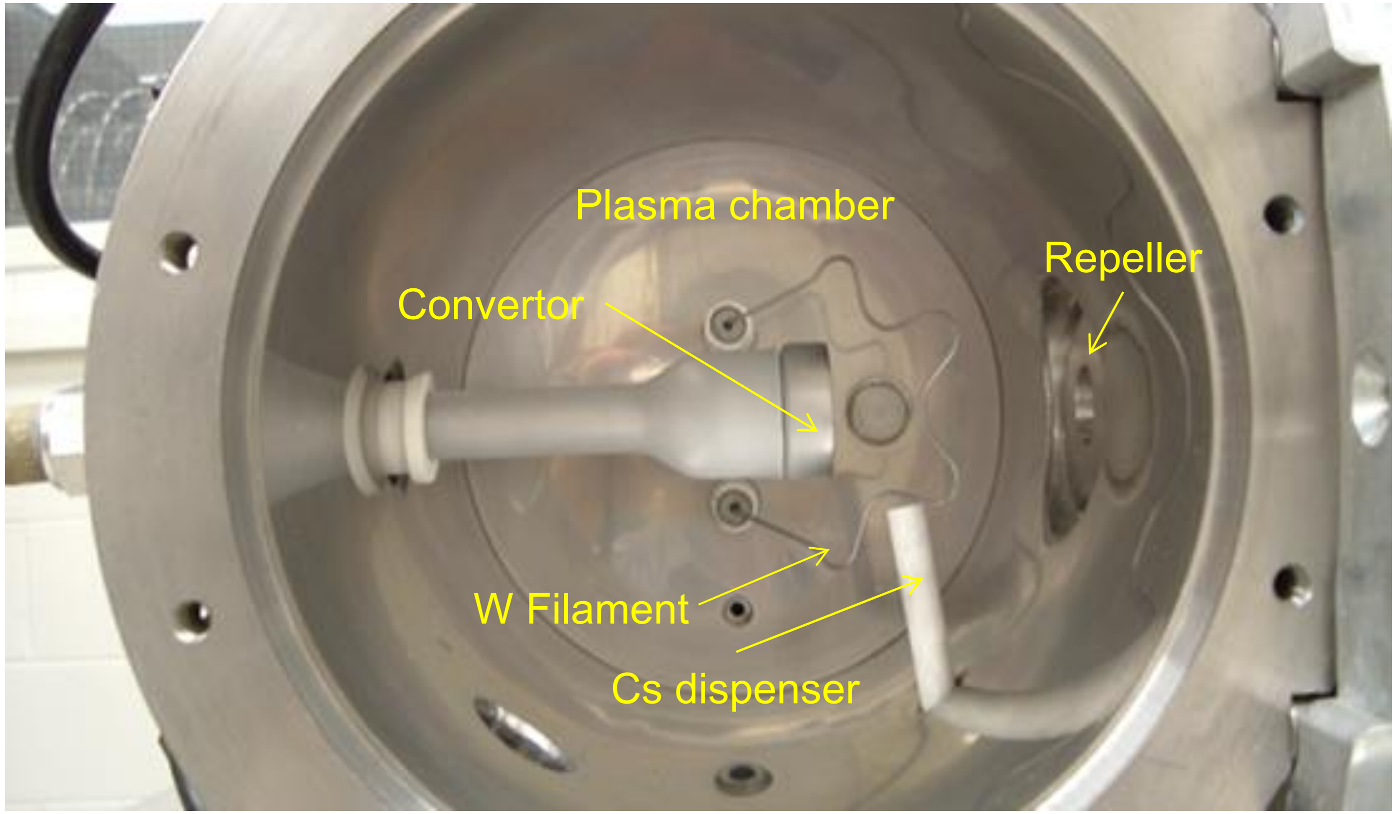
TeV-class high energy physics, neutrinos facility

FNAL, Magnetron source

Operational injector	LANL
Type of ion source	Multi cusp surface conversion (filament based)
H^- beam current injected into accelerator	14.5 mA
Beam energy	80kV
Beam pulse length	835 us
Beam repetition rate	120 Hz
Typical beam emittance (normalized RMS)	0.19 π mm mrad
Cesium (Y/N)	Y
Extraction aperture diameter	10 mm
Typical discharge power	8kW
Typical source availability	90%
Typical source service period	1 month
HV supply (cw vs pulsed)	Cw
Type of LEBT (mag, ele)	Mag
# of solenoids / Einzel lenses	2
Length of LEBT	2.5 m
Type of chopper(s)	Ele hel trav wave
Location of chopper	MEBT
Chopping period / fraction	1ns-500us/25%-99%

LANSCE filament-driven ion source

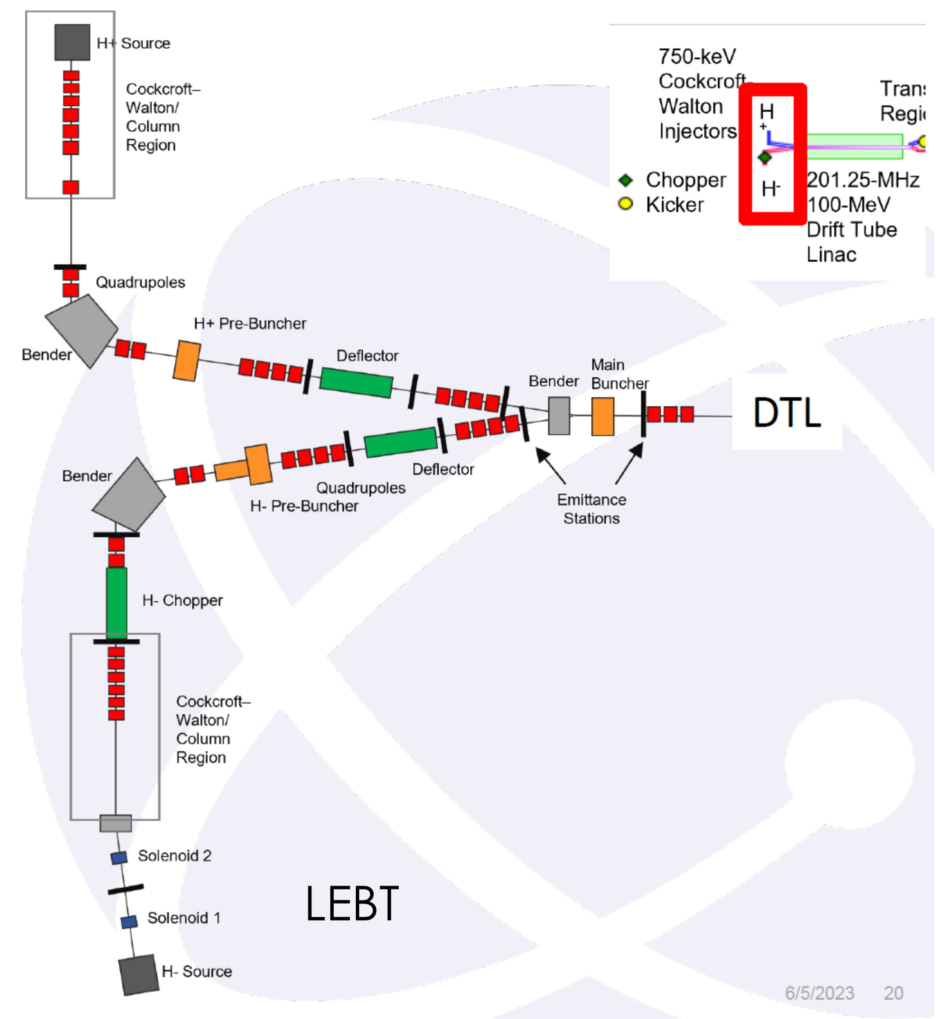
~15 mA, 835 us, 120 Hz, 1 month, ~90% available, magnetic LEBT



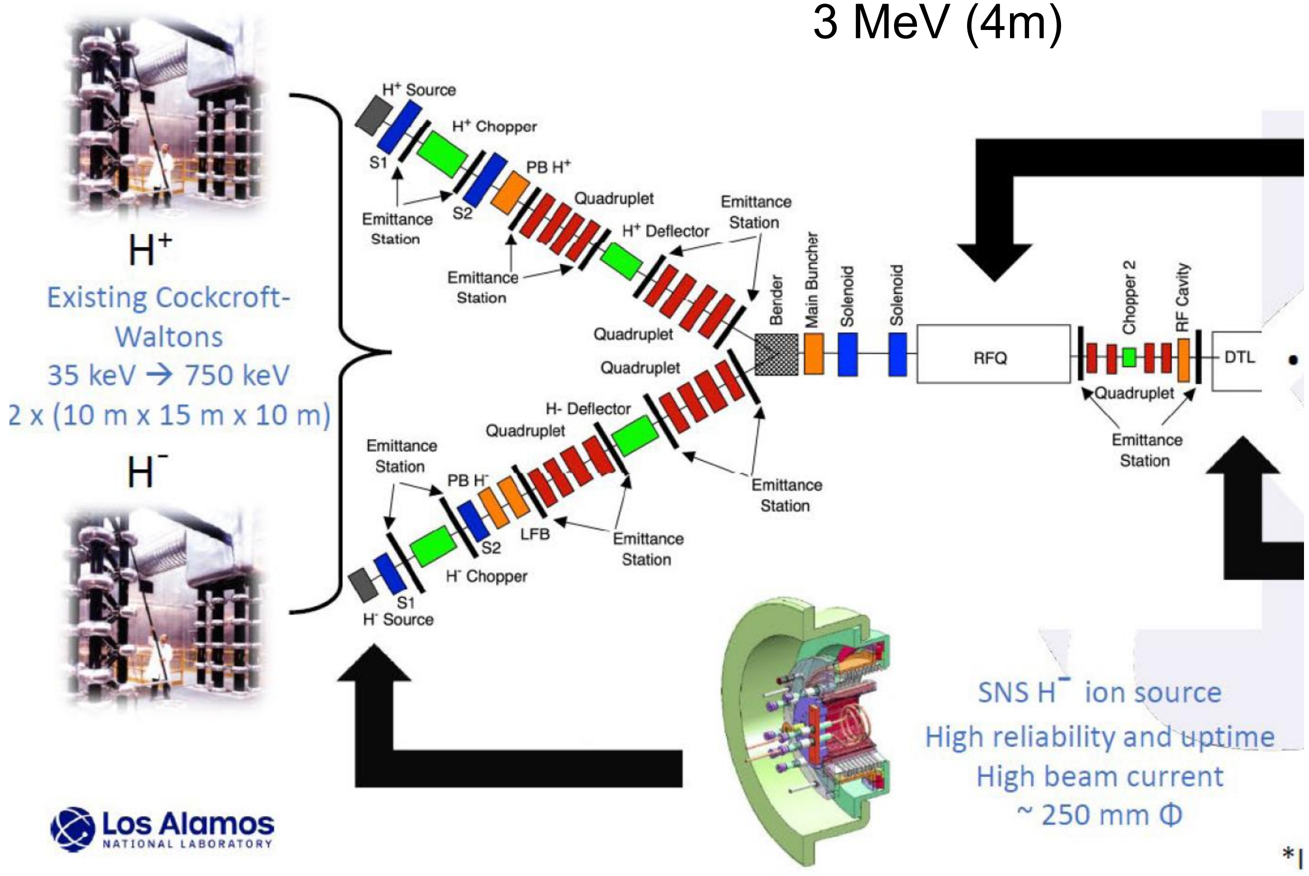
Contact: Anna Alexander (LAMP) – aalexander@lanl.gov
David Kleinjan (LANSCE) – Kleinjan@lnal.gov

LANSCE Modernization Project (LAMP)

- Replace Cockcroft-Walton H^- and H^+ injectors with single RFQ
- Replace ageing DTL
- Modernize PSR
- Replace H^- source with SNS source

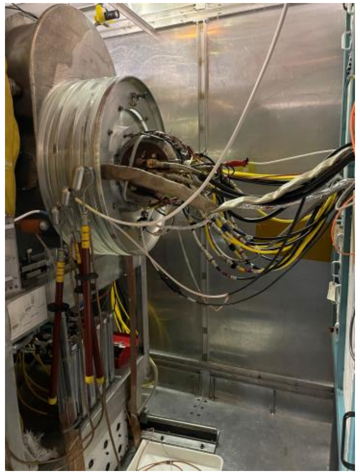


Proposed RFQ 80keV→ 3 MeV (4m)

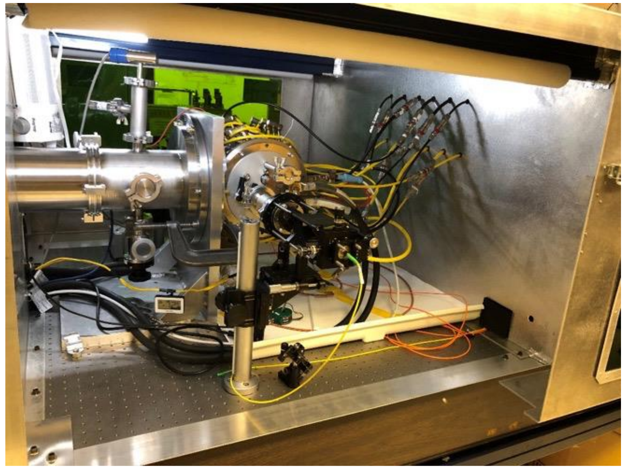


H^- Ion Source R&D at LANL

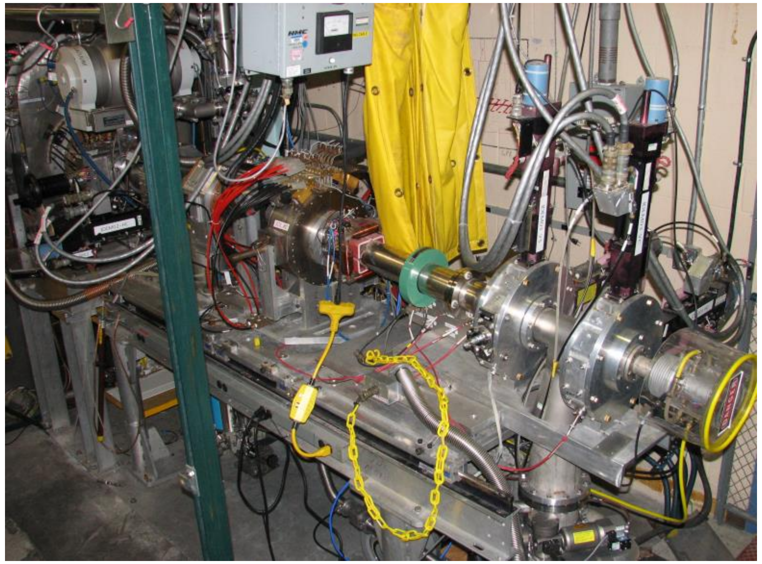
- **Motivation**
  - Front end part of LAMP CD-0
  - **35 mA current required**
  - **SNS RF ion source** (design source mounting, extraction and coupling to LEBT)
  - **~10 years**
- **Capabilities**
  - **HLDS**: enclosed class IV laser system for optical diagnostics for Cs measurement-no extraction
  - **ISTS**: includes beam extraction
  - **LANSCE**: long downtimes ~1-3 ion sources/yr testing on the production machine
  - **Modelling**, COMSOL, etc.
- **Current efforts**
  - LAMP design work
  - reducing arcs and improving cesiation process
  - Cs diagnostics / modeling



LANSCE H- Ion Source



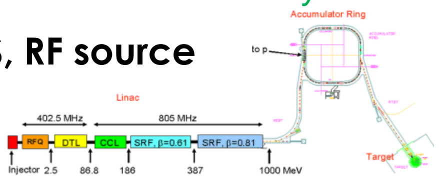
H^- Ion Source Laser Diagnostic Stand (HLDS)



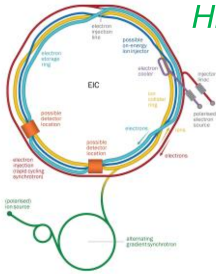
H- Ion Source Test Stand (ISTS)

MW-class Neutron facility

SNS, RF source

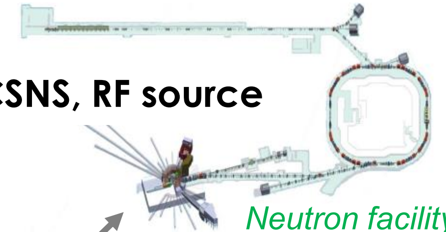


High Energy Physics

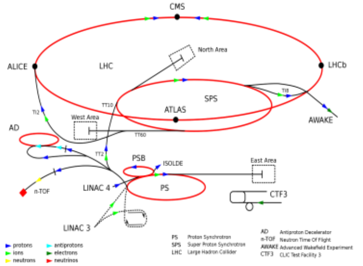


BNL Magnetron source

CSNS, RF source

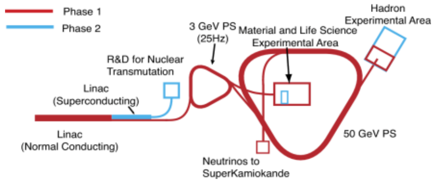


Neutron facility



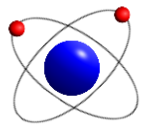
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



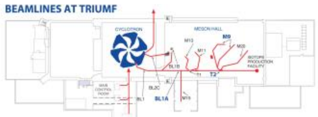
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

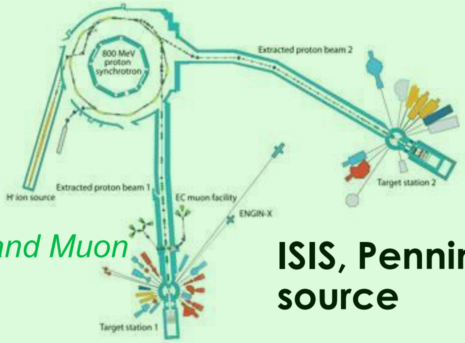


H^-

D-Pace, filament sources



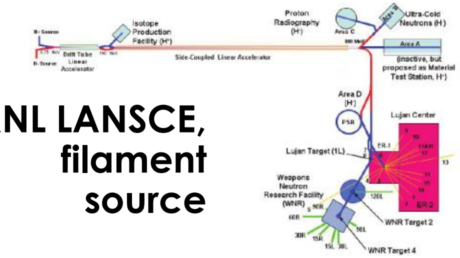
Many cyclotron facilities worldwide



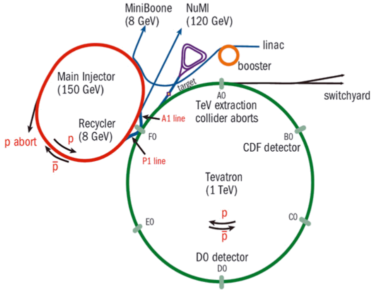
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility



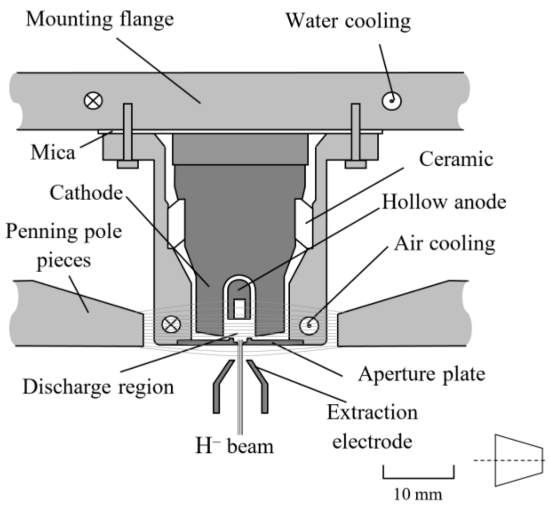
TeV-class high energy physics, neutrinos facility

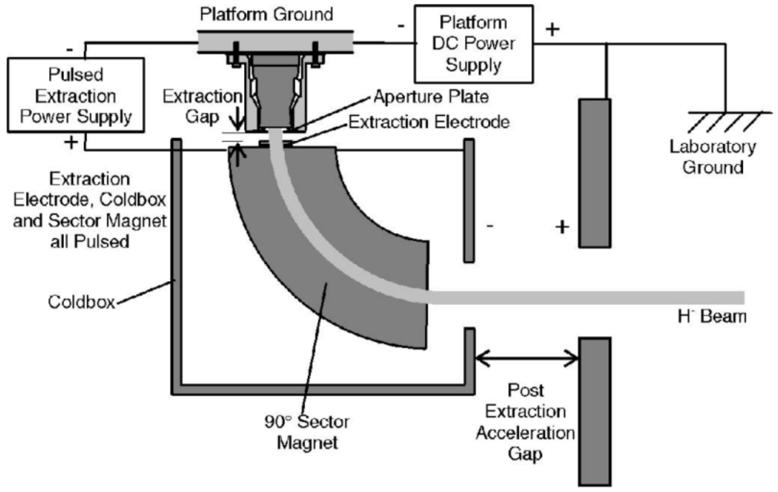
FNAL, Magnetron source

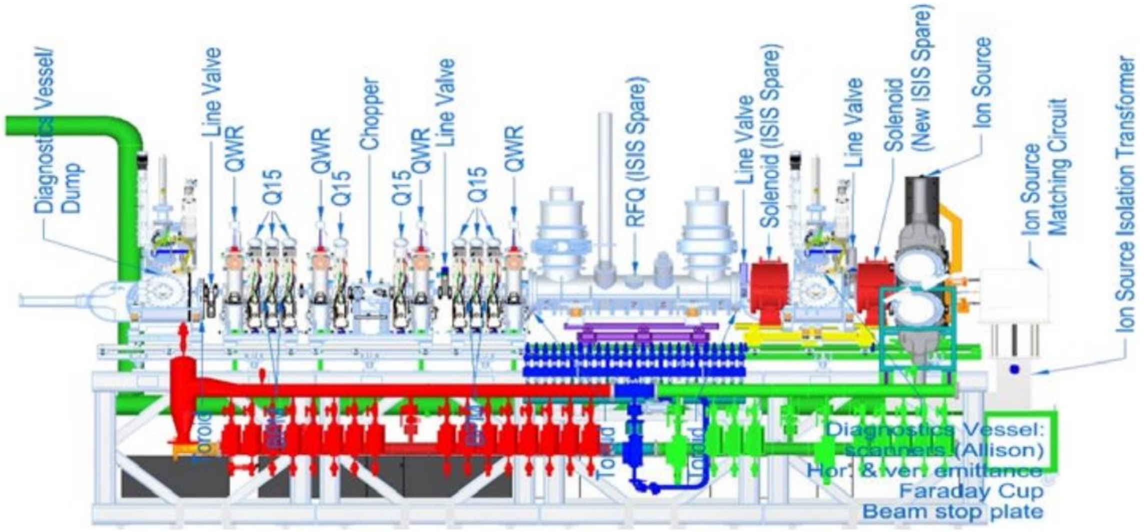
ISIS H$^-$ penning ion source and LEBT

~55 mA, ~215 us, 50 Hz, 3 weeks, >98% available, magnetic LEBT

Operational injector	ISIS
Type of ion source	**Penning**
H$^-$ beam current injected into accelerator	**50-60 mA**
Beam energy	**36 keV**
Beam pulse length	**200-230 us**
Beam pulse repetition rate	**50 Hz**
Typical beam emittance (normalized RMS)	**0.5 π mm mrad**
Cesium (Y/N)	**Yes**
Extraction aperture	**10 mm x 0.6 mm**
Typical discharge power	**3 kW (0.7 ms)**
Typical source availability	**>98% (2h change out)**
Typical source service period	**3 weeks**
HV supply (cw vs pulsed)	**Pulsed**
Type of LEBT (mag, ele)	**Magnetic**
# of solenoids	**3**
Length of LEBT	1.2 m
Type of chopper(s)	**None**







Contact: Dan Faircloth – dan.faircloth@stfc.ac.uk

H^- Ion Source R&D at ISIS

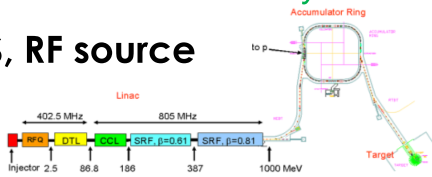
- **Motivation**
  - **Reduce beam losses** at the synchrotron injection by installing a MEBT & chopper
  - **Increase source lifetime** by installing an RF source
  - **Demonstrate longer term ISIS-II plans**: ~60mA, 50 Hz, 600μs
  - **Improve thermal control and diagnostics of the Penning ion source**
  - **Eliminate 90° magnet** and cold box

- **Capabilities**
  - 3x test stands (ISDR, RF source, FETS), HV development rig, diagnostic apparatus, modeling and simulations (PIC, analytical, beam extraction and transport)

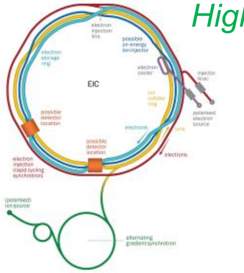
- **Current efforts**
  - **Develop the RF source** (SNS-type Cs delivery system)
  - **Commission the 665kV RFQ & MEBT** test stand to allow 1-year of soak-testing before use on ISIS.
  - Discharge monitoring / optical diagnostics for the operational penning source
  - **Active commissioning of FETS** 3.5 MeV RFQ and 2X Penning source.
  - Development of **diagnostics for space charge compensation.**
  - **Additive manufacturing** techniques including refractory metals for plasma facing components.

MW-class Neutron facility

SNS, RF source

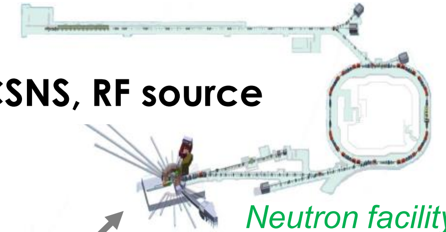


High Energy Physics

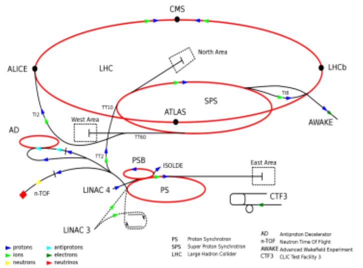


BNL Magnetron source

CSNS, RF source

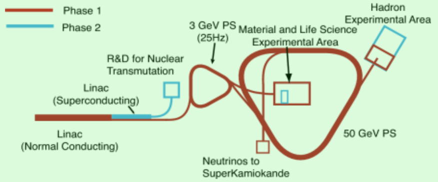


Neutron facility



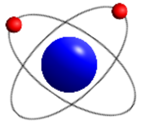
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



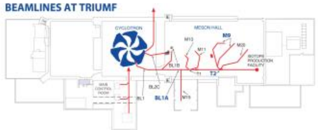
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

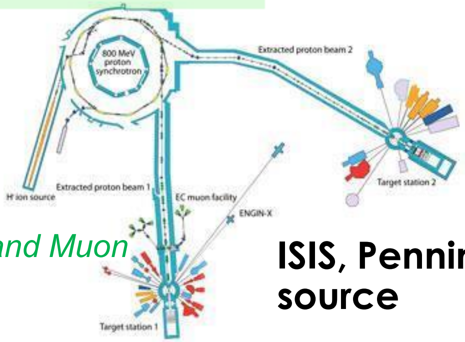


H$^-$

D-Pace, filament sources



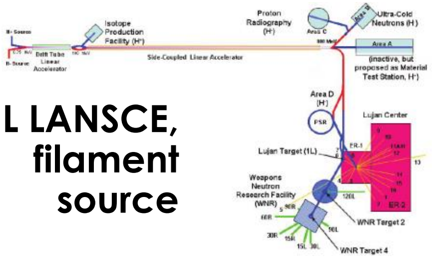
Many cyclotron facilities worldwide



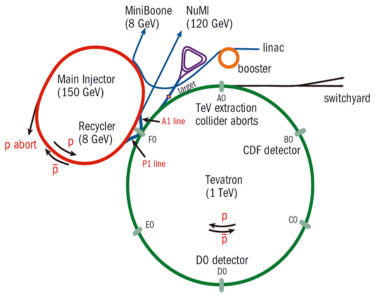
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility



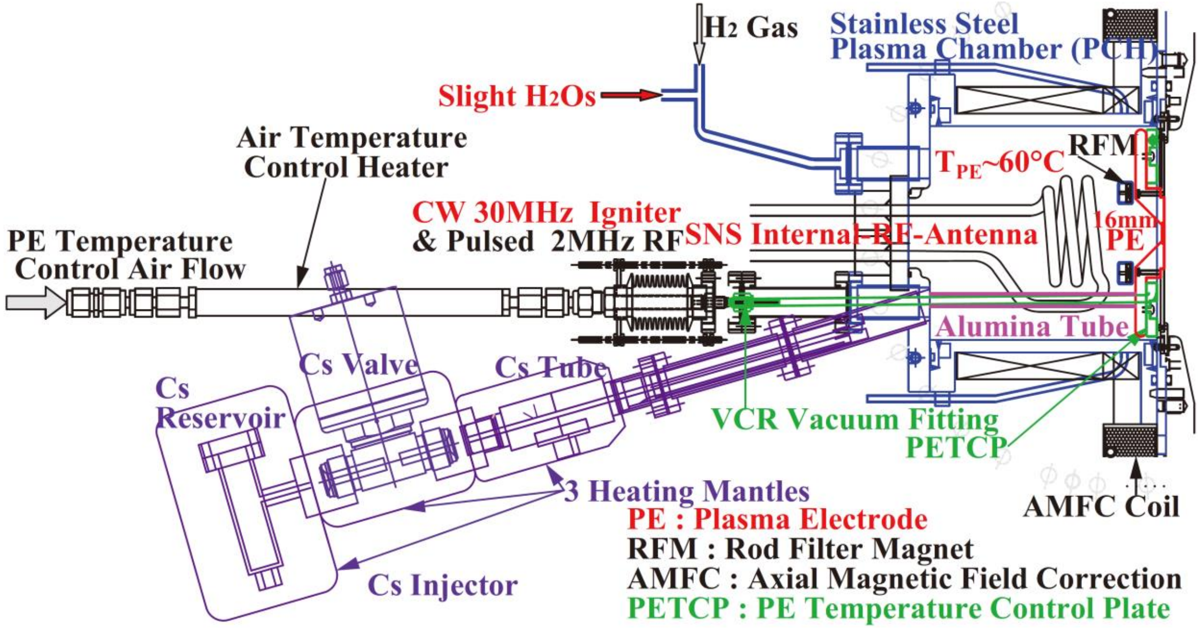
TeV-class high energy physics, neutrinos facility

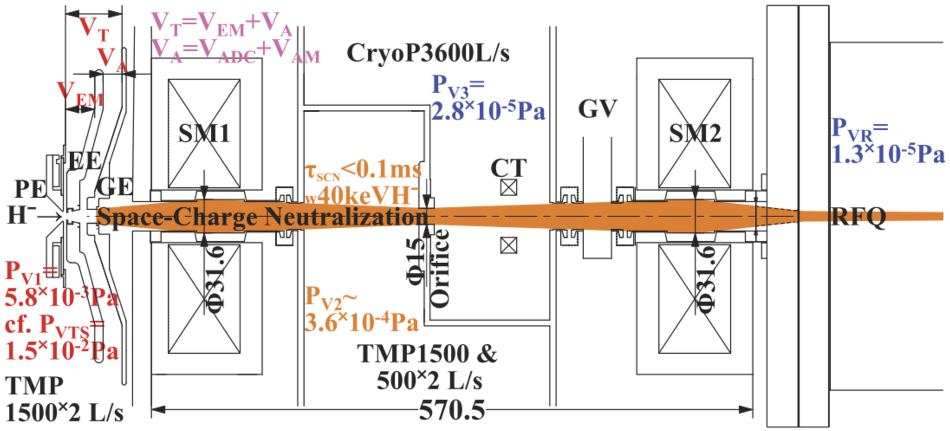
FNAL, Magnetron source

Operational injector	J-PARC
Type of ion source	RF
H^- beam current injected into accelerator	60 mA
Beam energy	52.5 kV
Beam pulse length	~0.5 ms
Beam repetition rate	25 Hz
Typical beam emittance	~0.25 π mm mrad 95% n-RMS
Cesium (Y/N)	Yes
Extraction aperture diameter	9 mm
Typical discharge power	< 35 kW
Typical source availability	> 99.5 %
Typical source service period	~7 months
HV supply (cw vs pulsed)	1st gap: Pulsed 2nd gap: Pulsed+CW
Type of LEBT (mag, ele)	
# of solenoids / Einzel lenses	2 solenoids
Length of LEBT	< 700 mm*
Type of chopper(s)	RF deflector
Location of chopper (LEBT, MEBT)	In the MEBT
Chopping period / fraction chopped	813ns/ 56.0~56.5%

JPARC ion source& LEBT

~60 mA, ~500 us, 25 Hz, ~7 months, >99.5% available, magnetic LEBT





*from the ground electrode to the entrance of the RFQ

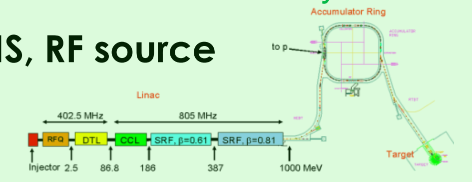
Contact: Katsuhiro Shinto – kshinto@post.j-parc.jp

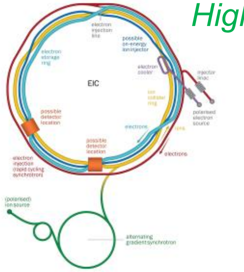
H^- Ion Source R&D at J-PARC

- **Motivation**
  - Neutrino upgrade 0.8 →1.3 MW → **present source**
  - Hadron upgrade 80 → 100kW → **present source**
  - Neutron/muon upgrade and 2nd target station 1→ 1.5 MW → requires higher source output **60 → ~75 mA**.
  - Aternative injection schemes and Irradiation/transmutation → **25 →50 Hz**
- **Capabilities**
  - Several ion source and RFQ test stands, diagnostic apparatus, modeling software, etc.
- **Current efforts**
  - Demonstrate **75 mA** H- beams for several months (**~7 months**) – upgrade extraction PS 10-15kV
  - Construct a new RFQ test stand for the injection energies of **70 ~ 80 keV** for ~ 100 mA of H-
  - A. Ueno showed **145 mA** of H- beam extraction. (J. Phys. Conf. Series, 2743, 012001, 2024)
  - **50-Hz operation** of RF plasma ignition has already been achieved without any serious issues.

MW-class Neutron facility

SNS, RF source

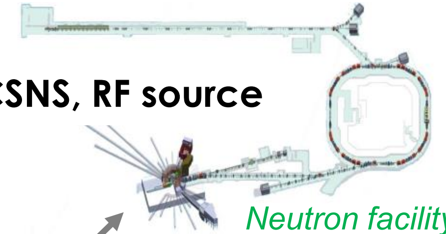




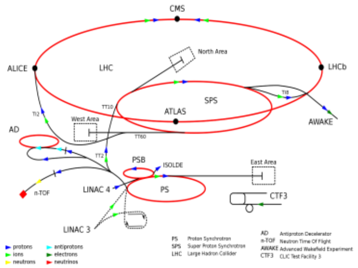
High Energy Physics

BNL Magnetron source

CSNS, RF source



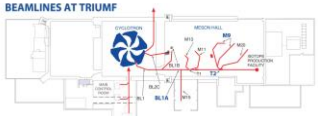
Neutron facility



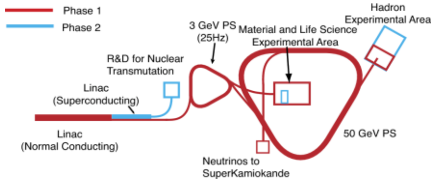
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source

D-Pace, filament sources

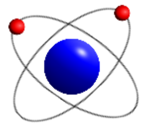


Many cyclotron facilities worldwide

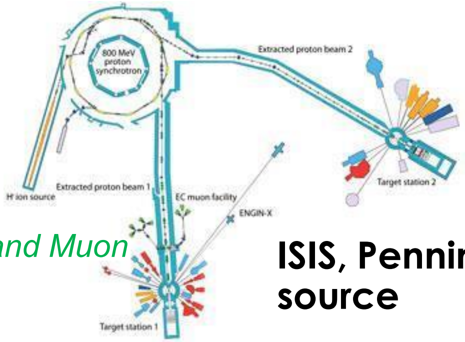


J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

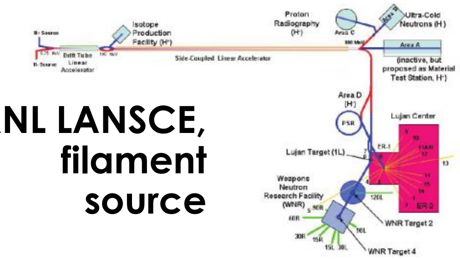


H⁻



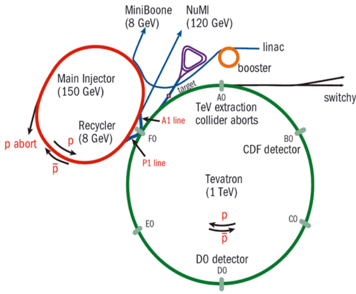
Neutron and Muon facility

ISIS, Penning source



LANL LANSCE, filament source

MW-class multipurpose facility



TeV-class high energy physics, neutrinos facility

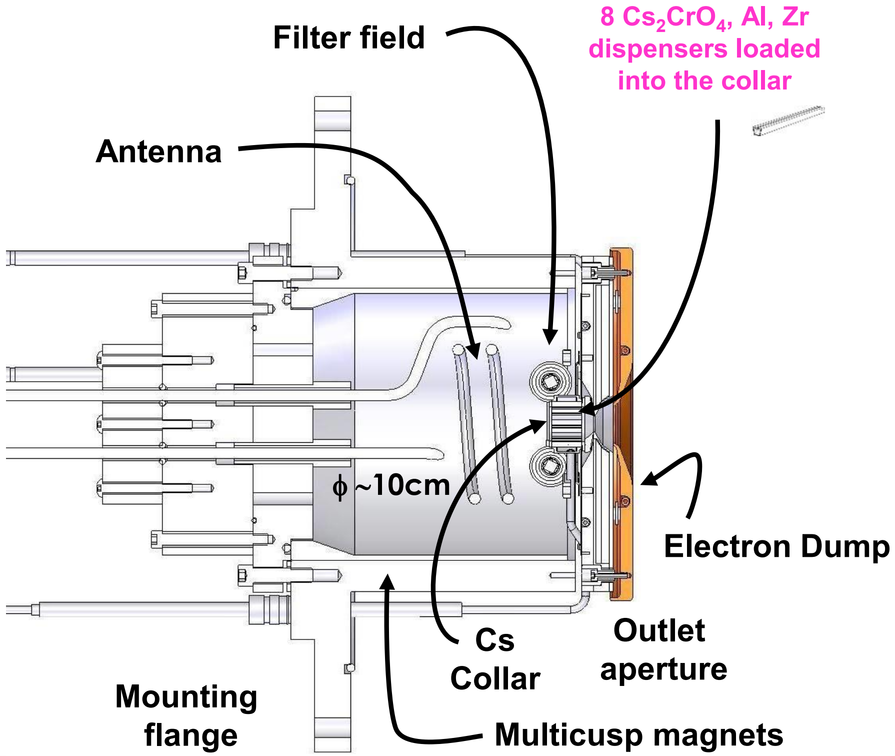
FNAL, Magnetron source

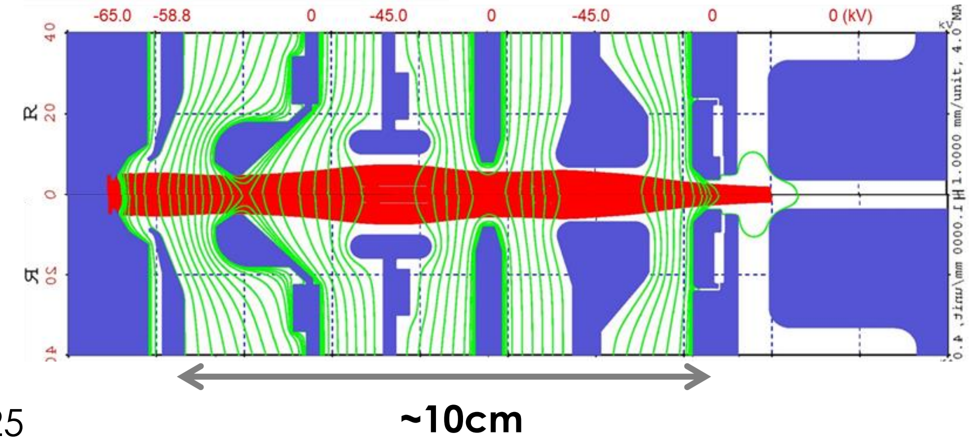
The SNS RF ion source and electrostatic LEBT

~55 mA, ~1 ms, 60 Hz, ~4 months, >99.5% available, electrostatic LEBT

	SNS
Type of ion source	RF
H^- beam current to accel	~55 mA
Beam pulse length in LEBT	~1 ms
Beam repetition rate in LEBT	60 Hz
Typ. beam emittance (π mm mrad,normalized,RMS)	~0.25
Cesium (Y/N)	yes
Outlet aperture diameter	7 mm
Typical discharge power	~50 kW
Typical source availability	>99.5%
Typical source service period	~4 months
Type of LEBT	Ele
Beam energy	65 keV
HV supply (cw vs pulsed)	cw
# of solenoids / Einzel lenses	2
Length of LEBT	~10 cm
Type of chopper(s)	Ele def
Location of chopper	End of LEBT
Chopping period / fraction chopped	~1us/30-40%

2 MHz
(1ms, 60Hz)
+
13 MHz cw





Contacts:
Baoxi Han – hanb@ornl.gov
Rob Welton – welton@ornl.gov

H^- Ion Source R&D at SNS (ORNL)

- **Motivation**
  - Support operations through continuous improvements
  - Support future 2.8 MW SNS operations → up to **80 mA** may be needed from the source
  - Exploration of beam **intensity frontiers** with experiments and modeling
- **Capabilities**
  - Ion source, LEBT and RFQ test stands, emittance analyzer, BCMs, faraday cup, optical and photo emission (laser) spectroscopy, Langmuir probe, thermal cameras and probes
  - Coupled multi-physics simulations (COMSOL, PBGuns, Simion and IBSIMU)
- **Current efforts**
  - H- injector **frontier demonstrations ~150 mA, 1ms, 60Hz**
  - Optimization and modeling of the extraction (larger apertures), Cs, chopping and filter field systems
  - Test electrostatic and magnetic LEBT
  - First Langmuir probe and photoemission spectroscopy (direct work function) measurements on an SNS-type H^- ion source
  - **Ongoing collaborations** include **LANL** (implementation of the SNS source on LAMP, Cs modeling), **ISIS** (implementation of an SNS-type Cs system), **D-Pace** (implementation of an SNS-type internation antenna), **IPP** (modelling), **Avalanche Fusion, Siemens**, etc.

Future potential large H⁻ accelerator projects: Muon and Future Circular Collider (FCC)

- **FCC** will rely on the existing LHC injector chain
- Recently completed LHC Injector Upgrade **exceeds FCC requirements**
- Currently operates with 27 mA peak current after the RFQ
- Source tested with a peak current of up to 50 mA resulting in 35 mA at PSB injection
- Focus on improving the pulse-to-pulse beam stability, reliability, and availability
- Flexible source pulsing with a variable cycle period of 0.9-2.5 s being considered

- **Muon collider** requirements being discussed:
- ~80 mA peak current (assuming 100% RFQ transmission), 2.5 – 5 ms pulse length, 5 Hz repetition rate, duty-factor: 2.5%
- SNS source with a 9mm aperture should meet this

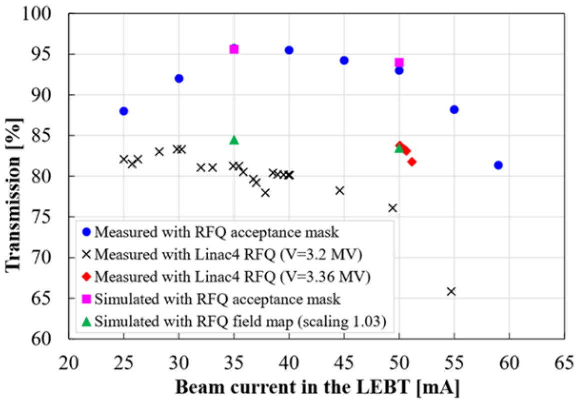
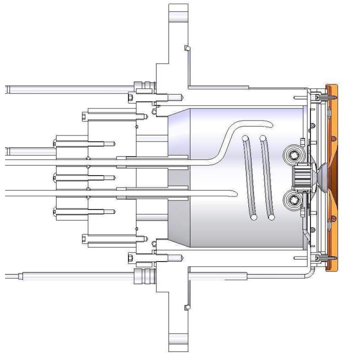
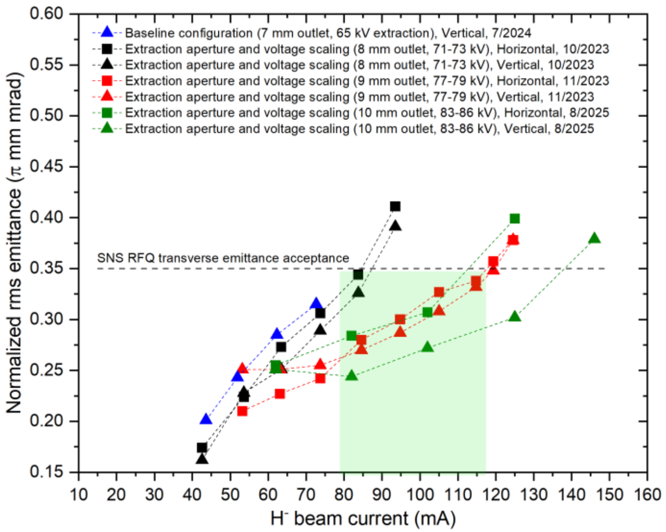
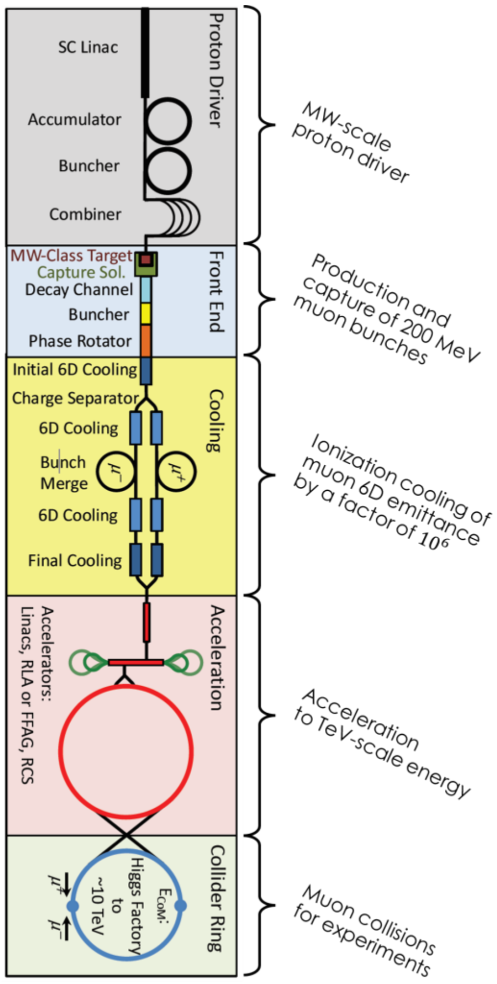


Figure 8: Simulated and measured beam transmission through RFQ acceptance mask and Linac4 RFQ.



SNS Source

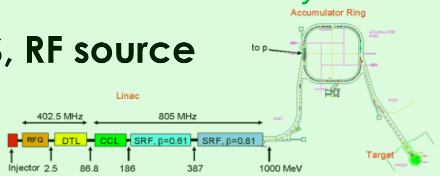


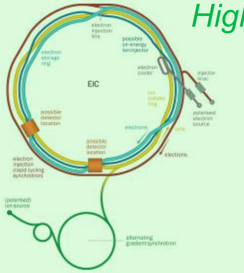


The Big Picture….

MW-class Neutron facility

SNS, RF source

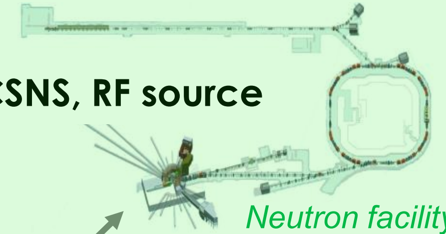




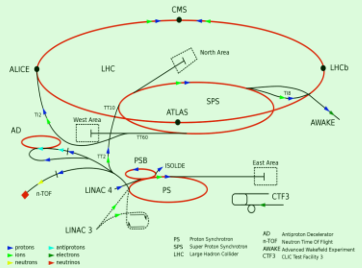
High Energy Physics

BNL Magnetron source

CSNS, RF source

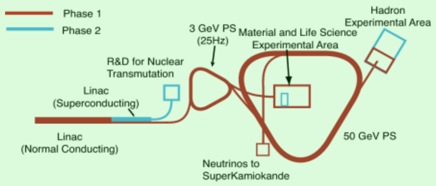


Neutron facility



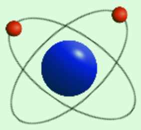
TeV-class high energy physics, multipurpose laboratory

CERN LINAC-4, RF source



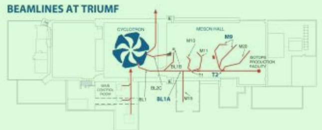
J-Parc, RF source

Multi purpose MW-class neutrons and meson facility

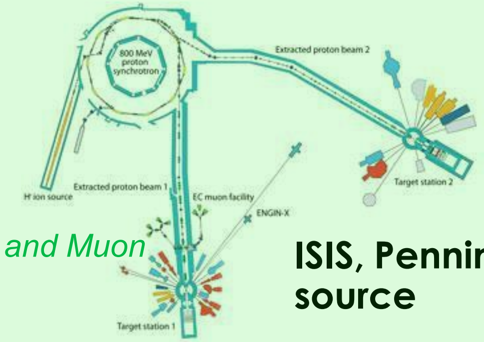


H^-

D-Pace, filament sources



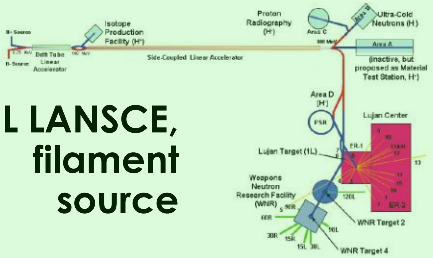
Many cyclotron facilities worldwide



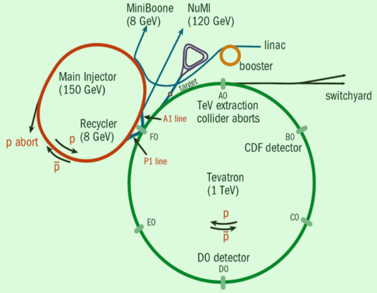
Neutron and Muon facility

ISIS, Penning source

LANL LANSCE, filament source



MW-class multipurpose facility



TeV-class high energy physics, neutrinos facility

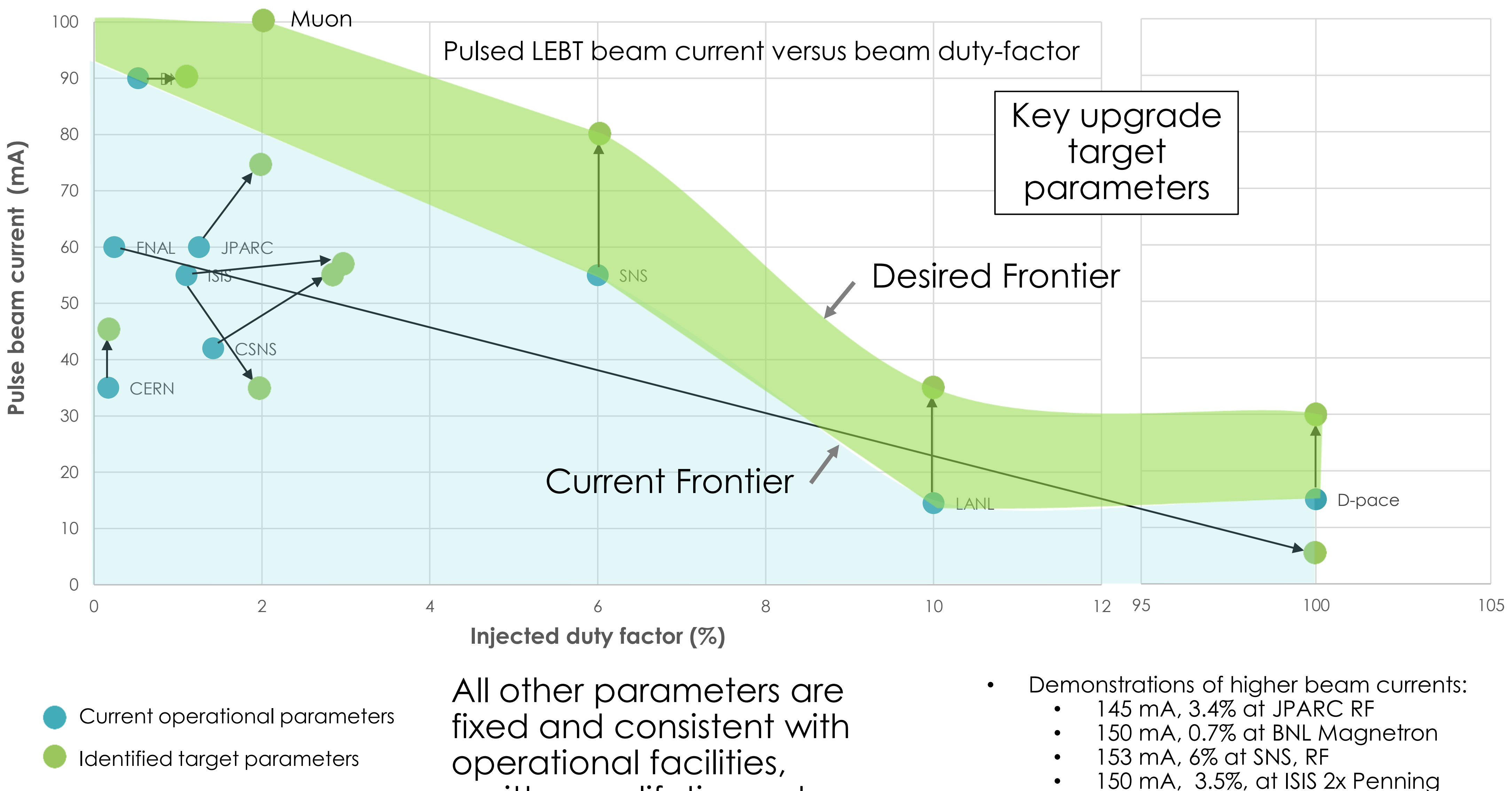
FNAL, Magnetron source

The current state of the art

(operating parameters for H^- on sources & LEBTs at operational facilities)

Operational parameters	JPARC	LANL	BNL	D-Pace	ISIS	CERN	CSNS	SNS	FNAL
Type of ion source	RF	Multicusp filament	Magnetron	Filament	Penning	RF	RF	RF	Magnetron
H^- beam current to accel	60 mA	14.5 mA	90 mA	15 mA	50-60 mA	35 mA	15-42 mA	~55 mA	~60 mA
Beam pulse length in LEBT	~0.5 ms	835 us	750 ms	CW	200-230 us	0.85 ms	570 us	1 ms	~160 μs
Beam repetition rate in LEBT	25 Hz	120 Hz	7 Hz	CW	50 Hz	0.83 Hz	25 Hz	60 Hz	15 Hz
Typ. beam emittance (π mm mrad, normalized, RMS)	~0.25	0.19	0.4	< 1	0.5	~0.4	0.26	~0.2	y~0.7, x~0.5
Cesium (Y/N)	yes	yes	yes	no	yes	yes	yes	yes	yes
Outlet aperture diameter	9 mm	10mm	2.8 mm	9.5 mm	10 x 0.6 mm	8 mm	8 mm	7 mm	~3mm
Typical discharge power (per pulse)	< 35kW	8 kW	2 kW	4.5 kW	3 kW	~27 kW	30 kW	~50 kW	~1.6 kW/pulse (~4W ave)
Typical source availability	>99.5%	90%	>99.6%	>99.5%	>98%	>99.6%	100%	>99.8%	~99.8%
Typical source service period	~7 M	1 M	6-9 M	5250 mA-hrs	3 weeks	~10 M	>11 M	~4 M	>9 M
Type of LEBT	Mag	Mag	Mag	Mag	Mag	Mag	Mag	Ele	Mag
Beam energy	52.5 kV	80 kV	35 keV	30 keV	36 keV	45 keV	50 kV	65 keV	35 keV
HV supply (cw vs pulsed)	1st gap pulsed 2nd gap pulsed +cw	cw	pulsed	cw	pulsed	pulsed	cw	cw	pulsed
# of solenoids / Einzel lenses	2	2	2/1 (active gas neutralization)	varies	3	2	2	2	2
Length of LEBT	< 0.7 m	2.5 m	3/6 m	varies	1.2 m	~2 m	1.65 m	~10 cm	~1.2 m
Type of chopper(s)		Trav wav	pulsed	N/A	none	Ele def	Ele def	Ele def	Ele Einzel Lens
Location of chopper	MEBT	MEBT	LEBT	N/A	NA	Pre-chop. in LEBT & fast chop. In MEBT	End of LEBT	End of LEBT	End of LEBT
Chopping period / fraction chopped	813ns/ 56%	1ns,500us 25-99%	10us/ 10-90 %	N/A	NA	LEBT: 1.2s/~6-76% MEBT: 1us/35-40%	1us/ 42%	~1us/ 30-40%	~48us/ 22-32%

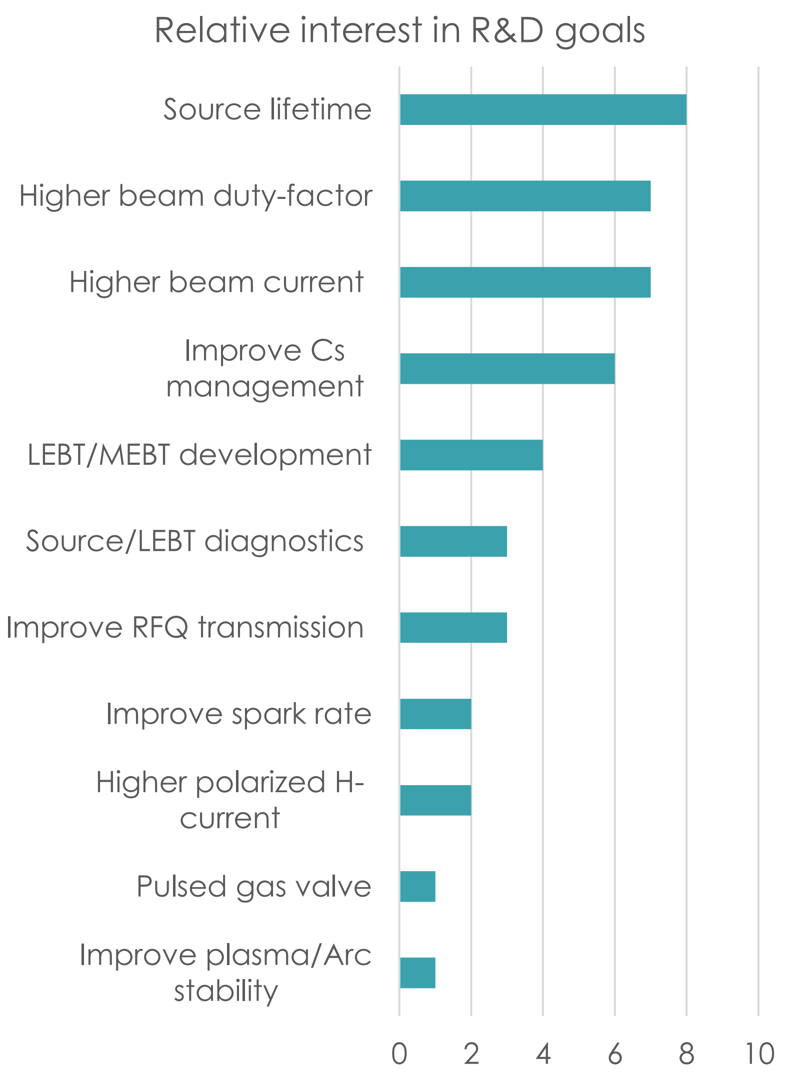
Trends in future H^- ion source / LEBT requirements



All other parameters are fixed and consistent with operational facilities, emittance, lifetime, etc.

- Demonstrations of higher beam currents:
  - 145 mA, 3.4% at JPARC RF
  - 150 mA, 0.7% at BNL Magnetron
  - 153 mA, 6% at SNS, RF
  - 150 mA, 3.5%, at ISIS 2x Penning

Key drivers of H⁻ ion source / LEBT R&D at facilities



key drivers of R&D	BNL	CERN	CSNS	D-Pace	FNAL	LANSCE	ISIS	J-PARC	SNS	Interest Score
Higher beam duty-factor	**x**		x		**x**	**x**				**7**
Higher beam current		**x**		**x**			**x**		x	**7**
Higher polarized H^- current	**x**									**2**
Improve Cs management	x			x		x	**x**		x	**6**
Improve plasma/Arc stability	x									**1**
Improve spark rate	x					x				**2**
Pulsed gas valve		x								**1**
Improve RFQ transmission, beam emittance		**x**						x	x	**3**
Source lifetime				**x**	**x**	**x**	x	x		**8**
LEBT/MEBT development			x				**x**		x	**4**
Source/LEBT diagnostics						x	x		x	**3**
Using or pursuing an RF source		**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	

x – major focus (2 pts), x normal - (1 pts)

Summary and Outlook

- Overall, the H^- ion sources and LEBTs for accelerators operate quite well with most having an availability >99% and lifetimes usually measured in months

- Most facilities have demonstrated their upgrade requirements on test stands often with some with modifications to their original operational sources.

- The initial requirements of future Muon and FCC facilities can be with existing sources (SNS, CERN)

- LANSCE (LAMP) and FNAL (PIPII) are both planning to switch to sources which have been essentially proven to meet the requirements.

- The CERN RF source has already been proven operationally but they still desire a modest increase in beam current out of the RFQ.

- D-Pace has identified a target beam currents and lifetimes which should, at least in principle, be attainable with proven SNS internal antenna technology and possible Cs usage.

- Source lifetime, beam current, duty-factor and Cs management were identified as most important drivers of R&D worldwide.

- Arc sources with high duty-factors have significantly shorter life spans and alternatives are being considered

2026 Symposium on Negative Ions, Beams and Sources (NIBS2026)
hosted by Selkirk College's 'Selkirk Ion-source Research Centre' (SIRC)
September 20 - 25, 2026
Nelson, BC, Canada
TRIUMF, University of Victoria, and University of Saskatchewan.
First announcement to be issued in late 2025
Contact- Morgan Dehnel mdehnel@selkirk.ca