Fusion Prototypic Neutron Source

(FPNS)

Yash Pise

Varun Chinchalkar

Vidisha Bardekar

Nikhil Bhuta

Abhijeet Patil

Introduction

- To realize fusion energy, it is essential to build a neutron source that can replicate the extreme conditions of fusion energy devices, including **atomic displacements**, **transmutation production**, and **high operating temperatures**
- There are still fundamental knowledge gaps regarding the materials used in fusion energy devices
- Fusion Prototypic Neutron Source (FPNS), could be constructed soon at a moderate cost
- A FPNS will help build the scientific foundation required to enable design of a next step fusion device

Design Requirements

The primary mission of FPNS is to establish the materials science knowledge base to understand materials degradation in a D-T fusion environment. To achieve these goals a set of key parameters were considered.

Parameter	Guideline
Damage rate	~8-11 dpa/calendar year (Fe)
Spectrum	~10 appm He/dpa (Fe)
Sample volume in high flux zone	$\geq 50\ cm^3$
Temperature range	~300-1000°C
Temperature control	3 independently monitored and controlled regions
Flux gradient	$\leq 20\%/cm$ in the plane of the sample

Cost Estimate

Ion Source Systems: High intensity ion sources are considered in various stages of design, construction, operation of FPNS system

Cost: $7M

Accelerator Systems : Several past accelerator system design studies were reviewed, and an analysis of alternatives was completed to assess the range of accelerator parameters and accelerating structure types that can potentially meet the requirements. Alternatives were used to develop two options for consideration based on a common set of accelerator system parameters

Cost: $75M

Lithium Target Systems: The members of the group performed a bottom-up estimate for the lithium target system based upon designs that have been published previously. The design includes three sets of master-slave manipulators, three shield windows, a bridge crane with a servo manipulator, a 30-ton bridge crane for handling large components, a beam dump with a vault-like facility, and resources to detail the facility and integrate it with the building.

Cost: $33M

Conventional Facilities: Conventional facilities includes the site preparation; buildings that contain the accelerator and target system; electric power for the system and the need for a new electrical substation; heat exchangers to remove the waste heat from the accelerator and the target; fees for the general contractor who will execute this work.

Cost: $173M

Contingency and cost range: This is the cost range for a D-Li stripping version of FPNS

Cost: $471M-$1179M

Detailed Cost Estimate

		Cost Scaling Factors		Point estimate [$M]
Accelerator Systems				**220**
	Ion Source Systems			7
	Accelerator Systems			75
	Li target and sample handling systems			33
	Project Management		12% of system cost	14
	Design		25% of system cost	29
	Instrumentation and Controls		15% of system cost	17
	Commissioning		5% of system cost	6
	As-built drawings		4% of system cost	5
	Fees, overhead, etc.		30% of system cost	34
Conventional Facility				**173**
	Facility buildings	$1000 to 1300 per sqft	35000 sqft	42
	Li building with steel liner	$1075 to 1375 per sqft	6000 sqft	8
	Site Preparations	$1M per acre	4 acres	4
	Utilities extensions	$250/linear foot/utility	1500 ft x 3 utilities	1
	Shop and Operator Building	$600/sqft	10000 sqft	6
	Central Utilities Building		50 MW thermal	30
	Electrical Substation		50 MW electric	25
	General Contractor Fee		15% of facility cost	17
	Design		15% of facility cost	17
	Contractor management and integration		20% of facility cost	23
Project Subtotal				**393**
Project contingency			50% of total project	196
Total Project Cost				**589**

Preliminary cost and TRL estimate of the ion source and LEBT for the Fusion Prototypic Neutron Source

Abstract

- The development of a fusion prototypic neutron source (FPNS) to evaluate materials exposed to fusion reactor environments has been a long-standing goal of the fusion community
- It explains that D-T fusion plasmas emit intense fluxes of ~14 MeV neutrons which create unique damage profiles within structural wall materials that cannot be studied using neutrons from fission reactors nor conventional spallation neutron sources
- A dedicated FPNS could be used to simultaneously irradiate many candidate sample materials with the correct neutron energies having a flux intensity sufficiently high to allow material evaluations to occur much more rapidly than in actual fusion reactors.+
- The cost estimate was based on the cost of the ion source and LEBT delivered to the ESS (European Spallation Neutron Source). It includes labor and materials needed for design integration, construction, installation and commissioning of the system while neglecting licensing costs of the design as well as the cost of implementing beam diagnostics and controls hard- and software

CONCEPT OF THE D-Li FUSION NEUTRON FACILITY AND REQUIREMENTS

Materials used in fusion devices have received comparatively little attention than fission, despite their critical importance

The energy spectrum of neutrons emitted from a fission reactor is 2 MeV while that emitted from D-T fusion plasmas is 14 MeV thereby inducing unprecedented levels of dislocation damage (100-200 dpa) to materials as well as significant transmuted He production

To produce neutrons with intensities that of a fusion reactor, an accelerator-based approach is under consideration which utilizes the Li reaction as a source of neutrons

CW beams of deuterons (~125 mA) can be accelerated to relevant energies by an RFQ and a 40 MeV LINAC and then collided with Li to produce sufficiently intense neutron beams

A $1B International Fusion Materials Irradiation Facility project is now being constructed and commissioned in Rokkasho, Japan

CONCEPT OF THE D-Li FUSION NEUTRON FACILITY AND REQUIREMENTS

- Recently, the US Department of Energy (DOE) Office of Fusion Energy Sciences (FES) has asked ORNL to provide an estimated cost, timeframe and TRL (Technical Readiness Level) of constructing a scaled down version of IFMIF facility, presumably in the United States

- The proposed facility will require the ion source and LEBT parameters to be essentially the same as IFMIF: ~140 mA of D^+ CW/DC extracted and transported through the LEBT at ~100 keV with an RMS normalized emittance $\varepsilon < 0.25\ \pi$ mm mrad). The beam from the RFQ that will be transported through the LINAC to target would be ~125 mA

COST ESTIMATE BASED ON THE EUROPEAN SPALLATION SOURCE ION SOURCE / LEBT SYSTEM

MATERIAL	Cost (k€)	Company
Insulating transformer (100kV - 30kW)	35	*GUTH*
HV platform + GND shields + Insulators	70	*UMAS*
Magnetron + ATU + Fast shutdown unit	50	*SAIREM*
Microwave line with passive diagnostics	32	*ATM, R&S*
19inch racks for HV platform	14	*SCHROFF*
PS source coils	35	*TDK-LAMBDA*
D2 Gas system (valves, flow meter, gauges)	30	Sigma Aldrich
Body source with support	52	*COMEB*
Source coils	53	*SIGMAPHI*
Extraction column	91	*Intellion*
Extraction electrodes unit	42	*ANDALO'*
First Element LEBT	45	*FANTINI*
LEBT support	25	ITEM
LEBT solenoids & steerers	80	SEF
Vacuum equipment (pumps, gauges)	200	Pheiffer
Iris (chamber + motors)	72	VCS+Laser Energy
Diagnostics (EMUs, FC, DCCT,…)		***provided by others***
RFQ Input Collimator	19	VCS
Beam stop	18	UMAS
Chopper + electronics	62	
FUG 100kV 200mA and ancillaries	220	FUG
FUG 3.5kV 10 mA	10	FUG
Power supply LEBT solenoids	55	SORENSEN
Power supply LEBT steerers	25	SORENSEN
HV+ GND controls		***provided by others***
EMI controls subracks protected and assembled	45	SIATEL
X-ray shielding	20	ITECO
Local consolle equipment (PCs, oscilloscope…)	40	
Misc, Installation, cabling	60	

TOTAL (2016 k€) **1500** ***<u>(except material to be provided by others)</u>***

Inflation/dollar adjusted total (in kilo USD) **1800**

Table III. Project cost in kilo USD. Estimate does not include diagnostics, controls and collaboration costs of using CEA or INFN designs.

	Cost in Kilo-USD
Total equipment cost	$1,800
Needed spares	$1,800
Initial design effort (1yr, 3 FTE)	$1,000
Receiving, assembly and initial testing effort (2 yr, 4 FTE)	$2,640
Effort to commission system bring to an operational state (1yr, 3 FTE)	$1,000
Contingency and misc expense 20%	$1,640
	$9,880
FTE/year assumed to be $330	

ESTIMATED TRL LEVEL OF THE D-LI FUSION NEUTRON FACILITY ION SOURCE / LEBT

❖ The technical Readiness Level TRL is defined as follows:

- TRL 1 - When a technology is at TRL 1, the scientific research is just beginning, and those results are being used to plan future research and development. Basic principles are observed and reported.
- TRL 2 - TRL 2 occurs once the basic principles have been studied and those results can be applied to practical applications. TRL 2 technology is very speculative, with little to no experimental proof of concept for the technology. The technology concept and/or application have been formulated.
- TRL 3 - When active research and design begin, a technology is elevated to TRL 3. Generally, both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. A proof-of-concept model is developed.
- TRL 4 – Component or breadboard validation in the laboratory environment.
- TRL 5 - TRL 5 is a continuation of TRL 4. Component or breadboard validation in a relevant environment.
- TRL 6 – System/subsystem model or prototype demonstration in a relevant environment.
- TRL 7 - Working model or prototype demonstrated in a relevant operational environment.
- TRL 8 – Actual system completed and qualified through test and demonstration.
- TRL 9 – Actual system proven through successful mission operations.

Current state for High intensity sources for High energy accelerators

The **CRNL** team demonstrated that an over-dense plasma may be achieved by axially injecting 1 kW of microwaves into a tiny plasma chamber with an axial magnetic field.

This arrangement was proved to be capable of delivering **90% proton fractions** with CW current densities of 120 mA/cm2, and it will be the basis for all **high-intensity proton sources utilized for high energy accelerator injection** during the next 30 years.

Since then, a range of other projects have used **proton sources and LEBTs mainly provided by CEA or INFN**. This source, together with LEBT and an RFQ, will eventually serve as one of the IFMIF project's two accelerators.

INFN has produced a very comparable version of the **CEA / IFMIF source and LEBT to be utilized as the H+ injector** for the ESS in parallel with the IFMIF/CEA project.

Various variants of these sources have been tested in pulsed and CW/DC modes, yielding H+/D+ beam currents ranging from 50 to 130 mA, as well as dependable operation and adequate beam emittance.

This data will be used as our rough cost estimate of implementing an ion source and LEBT in the proposed **FPNS**.

Different Projects and their Ion source Origin comparisons

Project	Ion source origin	Beam Current	ε rms norm (π mm mrad)	Duty Factor	Species	LEBT Energy	Ref	Notes
LEDA	LANL/ CRNL	100 mA	0.25	100%	H^+	75kV	6	Was operational, 100 mA/CW/6.7MeV
ESS	INFN	40-125 mA	0.25	4%	H^+	75 kV	12	4% duty factor
IFMIF	CEA	150 mA	0.25	100%	D^+ H^+	100 kV	11	~10 h, 100 mA
IPHI	CEA	100 mA	0.25	100%	D^+ H^+	95 kV	14	60mA, 1%
FAIR	CEA	80 mA	0.3	<1%	H^+	95 kV	15	Testing CEA
TRASCO	INFN	30 mA	0.2	100%	H^+	80 kV	13	INFN testing
MYRRHA/ LPSC	CEA	30 mA	0.2	100%	H^+		16	
Pantechnik	CEA	120 mA	0.2	1-100%	D^+ H^+	100 kV	9	Commercially available

ORNL D-Li Fusion Neutron Facility

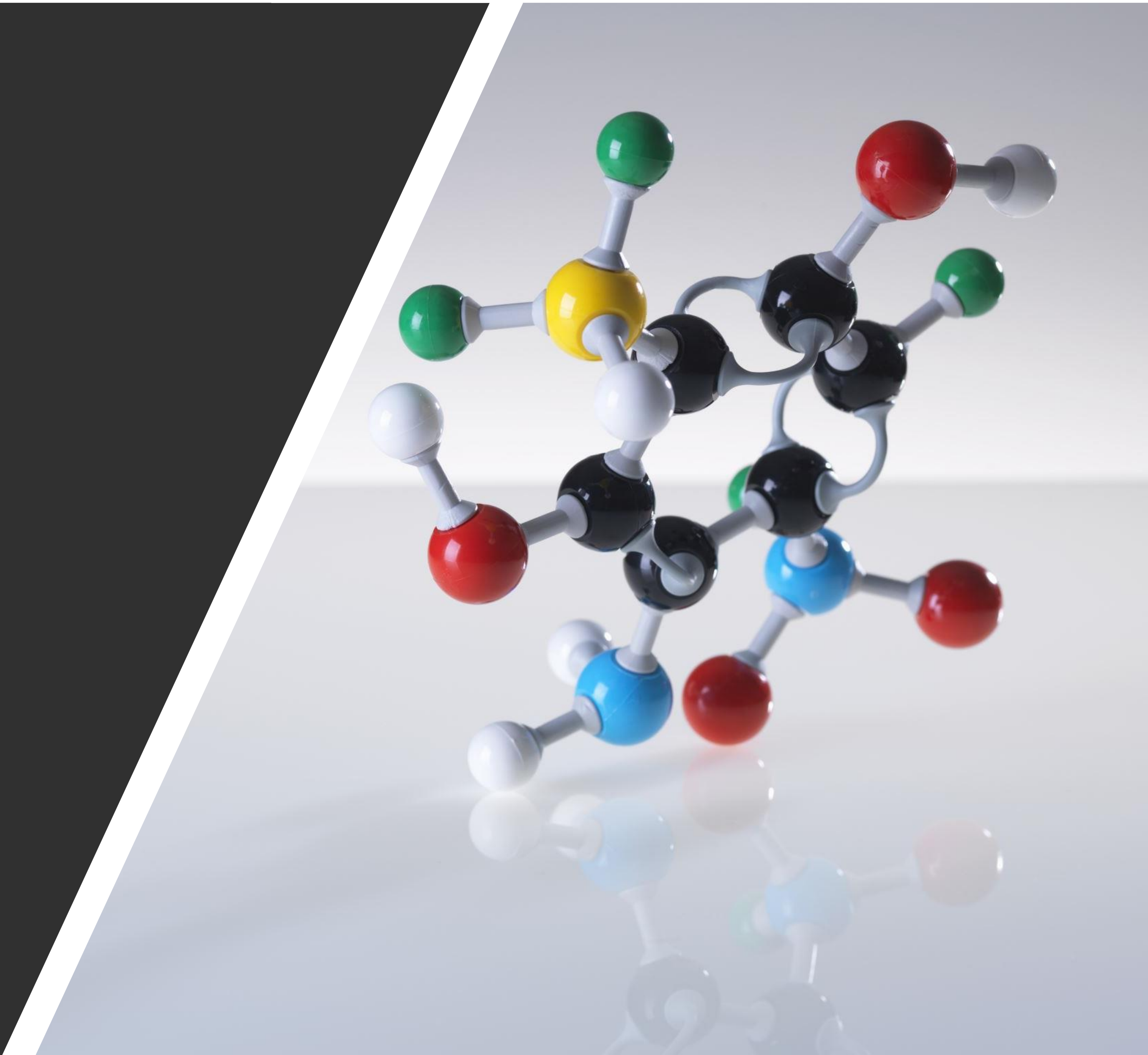
Accelerator Systems alternatives and Cost Report

- An analysis of alternatives completed to assess the range of accelerator parameters and accelerating structure types that can potentially meet the requirements of a 125- mA, 40-MeV, D-Li Fusion Neutron Facility
- Results of the analysis of alternatives were used to develop two options for consideration based on a common set of accelerator system parameters:

- Ion Source and Injector – 140 mA D^+, DC/CW operation (pulsed capability for tuning), 100 keV, transverse output emittance <0.25 π-mm-mrad.
- Low-Energy Beam Transport (LEBT) – 2 solenoid, gas neutralization, electron trap
- RFQ – 100 keV to 5 MeV, 125 mA CW
- Medium-Energy Beam Transport (MEBT) – 4-5quadrupoles, 2 multi-gap buncher cavities
- Main Linac – 5 MeV to 40 MeV, 125 mA CW (superconducting or normal conducting)
- High-Energy Beam Transport (includes beam expander optics) – quadrupole magnet focusing lattice for beam transport, multipole magnets for beam expansion and 2D uniform distribution, final configuration TBD based on Li target geometry.

Abstract

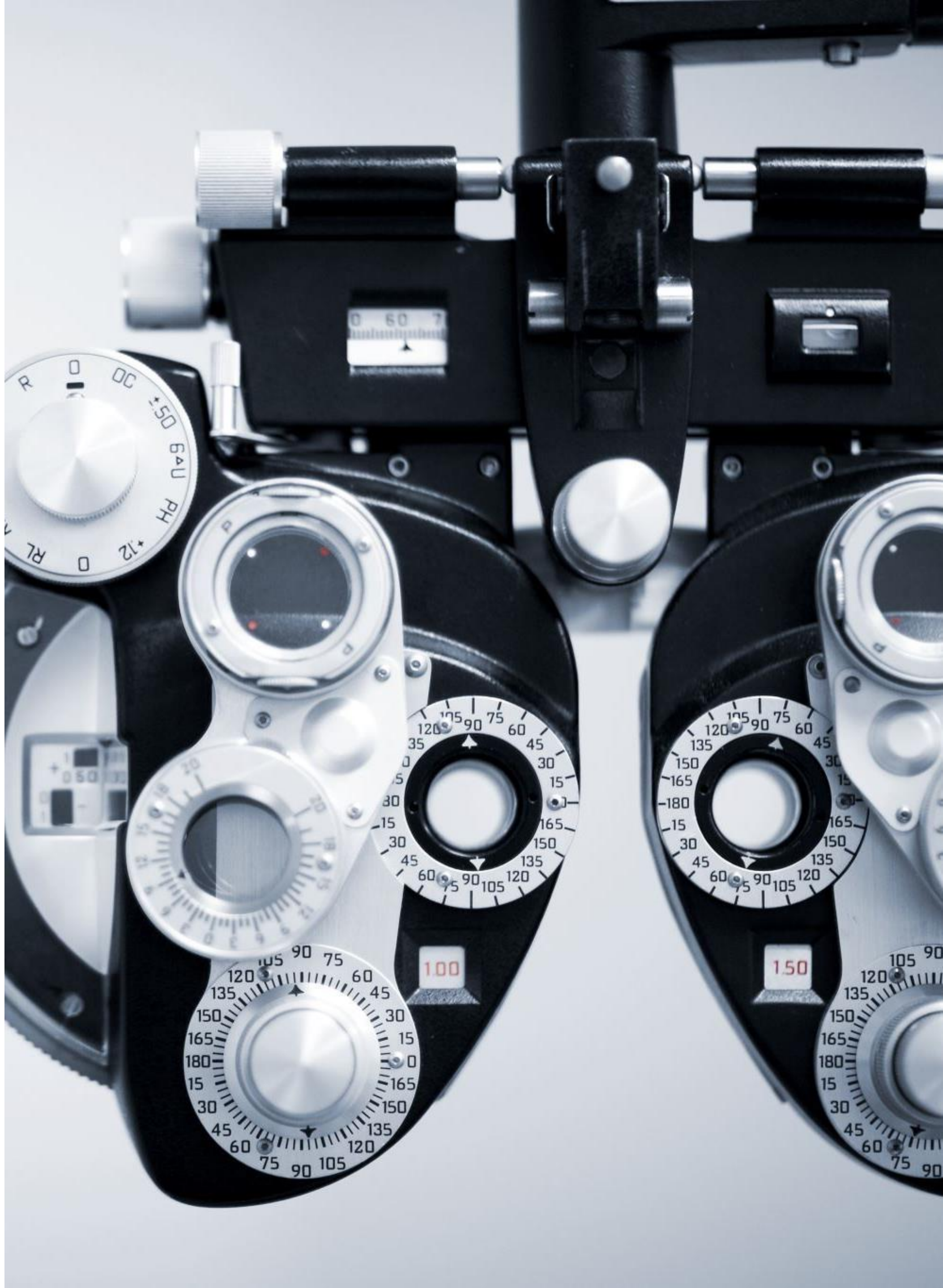
- In 2018 a community workshop was held by the US fusion materials community to assess the value of a Fusion Prototypic Neutron Source (FPNS)
- It was focused on understanding material degradation in a fusion environment
- The workshop concluded that, moderate cost FPNS would advance the current state of scientific understanding of materials degradation in the intense fusion neutron environment and that such a facility would be an asset to the US fusion program
- The primary goal of building a FPNS is to provide a source of neutrons at relevant energies and fluxes in a test station in the next 5-10 years, in a cost-effective manner
- Options such as 40 MeV D-Li Fusion Neutron are being explored



- Ion Source and Injector reproduces the 40-MeV IFMIF-EVEDA-LIPAc design based on an RFQ and a SCRF HWR-based main linac
- Low-Energy Beam Transport (LEBT) is an alternative 40-MeV design based on an RFQ followed by a normal-conducting (NC) DTL main linac
- Both of them meet the accelerator requirements
- Ion Source and Injector is complex to build while, LEBT is simple but will be more costly as it needs additional electrical power
- Technology readiness levels (TRLs) of RFQ has been recently demonstrated at the prototype level in a relevant operational environment for the proposed application
- The TRL level range from TRL 6 to TRL 7
- Cost scaling factors were developed and used to estimate the accelerator system costs
- Both Ion Source and Injector and LEBT have a similar cost estimate
- Ion Source and Injector costs $74 Million and LEBT costs $70 Million
- These include only the major accelerator system
- Total Project cost estimate goes upto $100 million which includes design, management and other project costs

Analysis of Alternative (AOA)

- Several accelerator designs were proposed for D-Li fusion neutron facility to generate 14-MeV neutrons.
- Design includes both normal-conducting and superconducting main accelerators following RFQ accelerator for initial acceleration of D beam.
- Major goal is to develop a cost-effective solution that also meets the performance requirement for moderate-energy D-Li fusion.
- initial designs proposed at LANL including modification and reuse of the Low-Energy Demonstration Accelerator (LEDA), an early design agreed to by consensus of the fusion and accelerator communities (FMIF), and the presently accepted IFMIF design.



LANL High-Flux Accelerator-Based Neutron Source for Fusion Materials and Technology Testing (1989)

- Workshop in San Diego, CA
- based on the Fusion Materials Irradiation Test (FMIT)
- improvements incorporated since FMIT include:
- a. A better analytical understanding
- b. Use of ramped linac accelerating gradients
- c. Use of permanent-magnet quadrupoles
- d. Use of higher RF frequencies to reduce beam emittance growth
- e. Use of improved beam-dynamics and high-order optics codes for simulating high-current beams and for controlling the spatial intensity of the beam

LANL High-Flux Accelerator-Based Neutron Source for Fusion Materials and Technology Testing (1989)

- The 1989 report highlights several accelerator technical issues:
- a. Beam losses in the accelerator and HEBT – activation levels need to allow for hands-on maintenance
- b. Accelerator Efficiency – RF costs dominant overall accelerator costs.
- c. Beam Energy Variability – Design uses a DTL as the main accelerating structure.
  - Cost information was provided, and the estimated cost of the full fusion materials and technology facility is $352M (2019$) based on escalating the cited costs in Ref. 6 by 3% per year.
  - Estimated cost of the accelerator system is $85M (2019$).

Table 1 – Accelerator specifications for the proposed High-Flux Accelerator-Based Neutron Source for Fusion Materials and Technology Testing.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	Not available
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	3.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.36
Structure Power (MW)	0.3
Total RF Power (MW)	0.66
Beam Loading (%)	55
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.27
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	0.46
Structure Length (m)	5.4
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz multi-gap cavities
MEBT Length (m)	Not available
Main Accelerator	
Structure Type	DTL
RF Frequency (MHz)	350
Input Energy (MeV)	3.0
Output Energy (MeV)	35.0
No. Structure Segments	4
Input Beam Current (mA)	125
Output Beam Current (mA)	125
Beam Power (MW)	4.0
Structure Power (MW)	3.3
Total RF Power (MW)	7.3
Beam Loading (%)	55
Transverse Focusing Type	Quadrupole magnets
Quadrupole Gradients (T/m)	120.0-100.0
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	0.51
Accelerating Gradient (MV/m)	3.0-4.0
Structure Length (m)	13
High-Energy Beam Transport (HEBT)	Beam Expander - Octupole, D-quad, F-quad
RF Systems	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystron

Fusion Materials Irradiation Facility (FMIF 1992)

- accelerator design specifications for a 14-MeV fusion materials irradiation facility capable of providing a neutron flux equivalent to a neutron wall loading of 2 MW/m2 to a 1-liter irradiation volume.
- specifications proposed are very similar to those proposed by LANL in 1989 with a few differences.
- assumes 100-keV injection into a 2-MeV 175-MHz RFQ followed by a hybrid NC-SCRF 40-MeV, 350-MHz DTL.
- DTL design uses four tanks that allow energy variations in discrete steps of the final output beam energy
- DTL is divided into two major sections: Section 1 is a NC 350-MHz DTL accelerating the beam to 8 MeV. Section 2 contains three 350-MHz SCRF DTL sections accelerating the beam to the final 40-MeV energy.
- The accelerator design specifications presented are not supported by beam physics or engineering design calculations.

Table 2 – Accelerator specifications for the proposed 1992 Fusion Materials Irradiation Facility.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.075-0.125
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.2-0.8
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.075-0.125
Output Energy (MeV)	2.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.24
Structure Power (MW)	TBD
Total RF Power (MW)	TBD
Beam Loading (%)	TBD
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.4
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	Not available
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz multi-gap cavities
MEBT Length (m)	Not available
Main Accelerator	
Structure Type	DTL (RT + SCRF)
RF Frequency (MHz)	350
Input Energy (MeV)	2.0
Output Energy (MeV)	40.0
No. Structure Segments	4
Input Beam Current (mA)	125
Output Beam Current (mA)	125
Beam Power (MW)	4.75
Structure Power (MW)	Not available
Total RF Power (MW)	Not available
Beam Loading (%)	Not available
Transverse Focusing Type	Quadrupole magnets
Quadrupole Gradients (T/m)	Not available
Output Transverse Emittance (π-mm-mrad, rms, norm)	Not available
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	Not available
Accelerating Gradient (MV/m)	Not available
Structure Length (m)	Not available
High-Energy Beam Transport (HEBT)	Not available
RF Systems	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystron