IFMIF: the INFN contribution

International Fusion Materials Irradiation Facility

Andrea Pisent
INFN Laboratori Nazionali di Legnaro
Istituto Nazionale di Fisica Nucleare (Italy)

outline

- IFMIF in the contest of Nuclear Fusion Plans
- IFMIF EVEDA project in construction
- INFN contribution with the Radio Frequency Quadrupole
- Beam operation issues for a high intensity machine
- Beam commissioning plans
- Conclusions
International Road Map
Advanced Materials are at a critical path

ITER
1-3 dpa/lifetime

DEMO
< 150 dpa

IFMIF
20-40 dpa/year

Dpa: displacement per atom: measure the integral of received radiation

International Fusion Materials Irradiation Facility
Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

Typical reactions:

\(^7\text{Li}(d,2n)^7\text{Be}, \quad \text{\ }^6\text{Li}(d,n)^7\text{Be}, \quad \text{\ }^6\text{Li}(n,T)^4\text{He}

Beam footprint on Li target
20cm wide x 5cm high (1 GW/m^2)
Beam-target choice for neutron production

- 40 MeV deuterons with Li target nuclear stripping reaction

- 10 MW about $10^{17}$ n/s and $10^{10}$ n/s per W or 0.2 n/d
- Vs spallation sources less production but softer spectrum
- Typical reactions $^7$Li(d,2n)$^7$Be and $^6$Li(d,n)$^7$Be

Istituto Nazionale di Fisica Nucleare (Italy)
Example of after irradiation test of small specimens

Fatigue:

<table>
<thead>
<tr>
<th>φ [mm]</th>
<th>1.25</th>
<th>1.25</th>
<th>1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ [mm]</td>
<td>10</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>φ/ρ</td>
<td>0.125</td>
<td>0.500</td>
<td>1.000</td>
</tr>
<tr>
<td>K_t</td>
<td>1.03</td>
<td>1.11</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Different shape specimens for fatigue tests
IFMIF facility: two, high power CW drivers, each delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target in order to yield neutrons \(10^{17} \text{s}^{-1}\) via nuclear stripping reactions.
IFMIF EVEDA
(IFMIF Engineering Validation and Design Activities)

• Within the BA (Broader Approach to fusion agreement, 2008) the IFMIF EVEDA activities have been launched with and agreement between Europe (represented by F4E) and Japan (represented by JAEA)

• The Validation activities follows three programs (Systems)
  – Prototype Accelerator (LIPAc Linear IFMIF Prototype Accelerator)
  – Prototype of the Lithium target circuit
  – Experimental facility definition

• Design activities concern the design of IFMIF facility (preliminary, interim or detailed, is under further definition)
• Recently funded within the Broader Approach to Fusion: construction of a 9 MeV 125 mA cw deuteron accelerator (to be built in Rokkasho, Japan) based on a high power RFQ followed by a superconducting linac
IFMIF EVEDA

Recently funded within the Broader Approach to Fusion: construction of a 9 MeV 125 mA cw deuteron accelerator (to be built in Rokkasho, Japan) based on a high power RFQ followed by a superconducting linac.
Istituto Nazionale di Fisica Nucleare (Italy)

IFMIF EVEDA

• Recently funded within the Broader Approach to Fusion: construction of a 9 MeV 125 mA cw deuteron accelerator (to be built in Rokkasho, Japan) based on a high power RFQ followed by a superconducting linac

The accelerator components are in kind contribution from European countries
### RFQs general parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Lab</th>
<th>ion</th>
<th>energy</th>
<th>vane</th>
<th>beam</th>
<th>RF Cu</th>
<th>Freq.</th>
<th>length</th>
<th>Emax</th>
<th>Power density</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFMIF-EVEDA</td>
<td>LNL</td>
<td>d</td>
<td>2.5</td>
<td>79-132</td>
<td>130</td>
<td>650</td>
<td>585</td>
<td>175</td>
<td>9.8</td>
<td>5.7</td>
<td>1.8</td>
</tr>
<tr>
<td>IFMIF-EVEDA</td>
<td>LNL</td>
<td>p</td>
<td>0.75</td>
<td>178</td>
<td>200</td>
<td>150</td>
<td>440</td>
<td>202</td>
<td>1.8</td>
<td>1.2</td>
<td>2.5</td>
</tr>
<tr>
<td>SNS</td>
<td>LBNL</td>
<td>H-</td>
<td>2.5</td>
<td>83</td>
<td>70</td>
<td>175</td>
<td>664</td>
<td>402.5</td>
<td>3.7</td>
<td>5.0</td>
<td>1.85</td>
</tr>
<tr>
<td>CERN linac 3</td>
<td>LNL</td>
<td>A/q=8.3</td>
<td>0.25</td>
<td>70</td>
<td>0.08</td>
<td>0.04</td>
<td>300</td>
<td>101</td>
<td>2.5</td>
<td>0.8</td>
<td>1.9</td>
</tr>
<tr>
<td>CW</td>
<td>LEDA</td>
<td>p</td>
<td>6.7</td>
<td>67-117</td>
<td>100</td>
<td>670</td>
<td>1450</td>
<td>350</td>
<td>8</td>
<td>9.3</td>
<td>11.4</td>
</tr>
<tr>
<td>high</td>
<td>IPHI</td>
<td>p</td>
<td>3</td>
<td>87-123</td>
<td>100</td>
<td>300</td>
<td>750</td>
<td>352</td>
<td>6</td>
<td>7.0</td>
<td>15</td>
</tr>
<tr>
<td>TRASCO</td>
<td>LNL</td>
<td>p</td>
<td>5</td>
<td>68</td>
<td>30</td>
<td>150</td>
<td>847</td>
<td>352</td>
<td>7.3</td>
<td>8.6</td>
<td>6.6</td>
</tr>
<tr>
<td>mid</td>
<td>SARAF</td>
<td>d</td>
<td>1.5</td>
<td>65</td>
<td>4</td>
<td>12</td>
<td>250</td>
<td>176</td>
<td>3.8</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>SPIRAL2</td>
<td>CEA</td>
<td>A/q=3</td>
<td>0.75</td>
<td>100-113</td>
<td>5</td>
<td>7.5</td>
<td>170</td>
<td>88</td>
<td>5</td>
<td>1.5</td>
<td>1.65</td>
</tr>
<tr>
<td>ISAC TRIUMF A/q=30</td>
<td>0.15</td>
<td>74</td>
<td>0</td>
<td>0</td>
<td>150</td>
<td>35</td>
<td>8</td>
<td>0.9</td>
<td>1.15</td>
<td>- -</td>
<td></td>
</tr>
<tr>
<td>lp</td>
<td>PIAVE</td>
<td>A/q=6</td>
<td>0.58</td>
<td>280</td>
<td>0</td>
<td>0</td>
<td>8e-3 (SC)</td>
<td>80</td>
<td>2.1</td>
<td>0.5</td>
<td>- - -</td>
</tr>
</tbody>
</table>

The RFQ is INFN Italy responsibility

LNL
Padova
Torino
..Bologna

**IFMIF-EVEDA RFQ**
- 18 modules 9.8 m
- Powered by eight 220 kW rf chains and 8 couplers
- High availability 30 years operation.
- Hands on maintenance
- First complete installation in Japan
RFQ system organization

- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti

About 30 persons involved, 20 FTE, 10 dedicated contracts

The participation of INFN to IFMIF-EVEDA includes
- RFQ construction
- Participation to final IFMIF design activity
- Participation to the man power of the project team in Japan
- Participation to beam commissioning in Japan
INFN group for RFQ realization

- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti
  - Planning: J. Esposito
- Physical design: M. Comunian
  - Radio frequency: A. Palmieri
  - High power tests: E. Fagotti
  - Computer Controls: M. Giacchini
  - Vacuum system and technological processes C. Roncolato
- Mechanics design and construction A. Pepato
  - Engineering integration P. Mereu
  - Modules alignment D. Dattola
  - Quality assurance: R. Dima
  - Module production follow up M. Benettoni
  - Stainless steel components production A. Margotti
  - Cooling system integration G. Giraudo
Elements of the IFMIF prototype accelerator

125 mA 9 MeV deuteron beam
i.e. 1.1 MW beam power
16 RF chains 200 kW each
RFQ normal conducting
HWR linac superconducting
Injector 3D mockup V4.3
RF system 3D mockup V1.0

- TH781 Tetrode
- TH561 Tetrode
- 19" cubicle
- 50 kW Load
- 135 kW Circulator
Subsystems mockup
F4E integrates the different mockups sent by all subsystems
Integration realized by the Projet Team in Rokkasho
IFMIF/EVEDA
Accelerator building by JAEA
In Rokkasho (Aomori)
IFMIF EVEDA intensity 125 mA = 25*ongoing projects

SARAF (Israel)
40 MeV
4 mA d and p
176 MHz
Status: beam test up to the first cryomodule

SPIRAL2 driver (France)
5 mA d and ions up to A/q=3
40 MeV
80 MHz
Status: in construction
Beam dynamics in IFMIF linac

Figure 3: Tune depression in the RFQ and the SRF-Linac
IFMIF EVEDA RFQ challenges

- **650 kW beam** should be accelerated with **low beam losses and activation** of the structure so as to allow hands-on maintenance of the structure itself (Beam losses $<10$ mA and $<0.1$ mA between 4 MeV and 5 MeV). (Tolerances of the order of 10-50 um)

- **600 kW RF dissipated** on copper surface: necessity to keep geometrical tolerances, to manage hot spots and counteract potential instability.

- The RFQ will be the **largest ever built**, so not only the accelerator must be reliable, but also the production, checking and assembling procedure must be reliable
  - Fully exploit **INFN internal production capability** (design machining, measurement and brazing)
  - Make production accessible for different industrial partners

- At present and **we are in the production of the modules phase**.
IFMIF RFQ modulation design

<table>
<thead>
<tr>
<th>Ions</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>0.1-5 MeV</td>
</tr>
<tr>
<td>input-output nom emit</td>
<td>0.25 mmmrad (rms)</td>
</tr>
<tr>
<td>Output long emit</td>
<td>0.2 MeV deg (rms)</td>
</tr>
<tr>
<td>Output current</td>
<td>0.2</td>
</tr>
<tr>
<td>Transmission</td>
<td>98 % WB distr.</td>
</tr>
<tr>
<td></td>
<td>95 % Gaussian distr.</td>
</tr>
</tbody>
</table>

- The voltage is increased (79-132 kV) following an analytic law.
- The focusing in the Gentle Buncher is strong (B=7) so to keep the tune depression above 0.4 for the best control of space charge.
- Main resonances are avoided in the accelerator section.
- The focusing in the shaper raises from 4 to 7 to allow an input with smaller divergence.
Beam losses

- To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to $w^2$

$$n = 5.15 \times 10^{-7} N w^{2.1}$$

WB distribution 0.25 mm mrad rms norm
RF cavity design
Cavity cross section

Operating Frequency: 175 MHz
Length: 9.78 m
Vg (min – max): 79 – 132 kV
R0 (min - max): 0.4135 - 0.7102 cm
Total Stored Energy: 6.63 J
Max. RF power to the cavity (beam+SF*1.3*1.21): 1345 kW
Number of slug tuners: 96
Frequency tuning: Water temp.

$TE_{21n}$
Field Error < 4% in the initial path. $F = 174.097$ MHz (600000 mesh tetrahedra).
Geometrical tolerances

- The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE21n (spurious quadrupoles) and TE11n (dipole) modes, whose frequencies can be very close to the operating mode.

Perturbation to the nominal geometry $\rightarrow$ Accelerating mode is not pure

$TE_{21n}$

$TE_{11n}$
(dipole modes)
**Geometrical tolerances**

- The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE21n (spurious quadrupoles) and TE11n (dipole) modes, whose frequencies can be very close to the operating mode.

  Perturbation to the nominal geometry  \(\iff\)  Accelerating mode is not pure

\[ TE_{21n} \]

No resonant coupling

\[ TE_{11n} \]

(dipole modes)

No PILS dipole stabilizers

Yes  
Dipole rod termination
The aluminum real-scale RFQ model (9.8 meters long)

- Tunable end cell
- Dummy tuners
- Dielectric Bead pulling
9.8 m model: tuning results

After 4 iteration we can achieve a voltage error of +/- 1%
Modules construction
RF cavities built in three supermodules (6 modules each)

- High energy SM in construction at Cinel, Padua (Italy), Intermediate energy in INFN Padova, Low energy by RI Koln (Germany)
Mechanical design

• Based on vacuum brazing, LNL experience with TRASCO, CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry (up to now three modules brazed at CERN, Cinel and LNL respectively)

• Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length 550 mm).

• To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, a rough-cut of the shape of the module components from a starting block of about 500x280x570 mm will be performed, by using a EDM (wire electroerosion).

• The accelerator is composed by 18 of these modules.
Mechanics details

Head flange

Vacuum grids machined from bulk
Cooling circuit

- About **600 kW RF power** are removed by means of **28 channels** longitudinally drilled along the RFQ modules; the water velocity is approximately 3 m/s,
- **12 channels at fixed low temperature** on the **vanes**
- **16 channels on the cavity wall** with variable temperature for **frequency tuning**
  - the temperature of the channels on the vane and on the cavity wall can be separately tuned so to achieve a tuning range of ±100kHz.
- **3 modules are in series** (**supermodule**)
3D details

- Dummy tuners, vacuum grids and end cells
- In the end cell the 45° angle of the undercut guarantees the access of the cooling channel as close as possible to the hot spot at the electrode base (~80 W/cm²*), which is the most severe of the entire RFQ
- Deformations of 70 um and field perturbation less than 1%

*with margin of 10% higher field
First construction step module n0 16

- Rough machining of block 550 mm long via EDM for minimal stresses and deformations during annealing and brazing.
Finishing

• 0.7 um roughness
• 3d modulation
• 20 um tolerances on vane tip geometry
Four electrodes of module #16 electrodes (machined by Cinel) in specs

Max Deviation: 18.6 \( \mu \text{m} \)

Max Deviation: 10.5 \( \mu \text{m} \)

Max Deviation: 6.1 \( \mu \text{m} \)

material stock
Module 16 construction
Istituto Nazionale di Fisica Nucleare (Italy)
3300x900x1700 mm [LxWxH];

Dedicated lifting equipment (under study) to be coupled with the supporting frame;

Update characteristics of the crane in the accelerator vault.

Temporary vertical shock absorbers on the mechanical supporting frame

4000 kg;

N.B. Lifting equipment and elastic supports are conceptual

0.35 m/s

0.047 m/s

0.167 m/s
Istituto Nazionale di Fisica Nucleare (Italy)

- Module #16,17 and 18 of the RFQ
- Technological prototype module #2 as RF plug.
- Power coupler by JAEA
- 16 loop-equipped tuners for field sampling

IFMIF HIGH POWER TESTS in LNL (2013)

- IFMIF-RFQ test skid
- Vacuum system (test manifolds)
- Control system

f = 175 MHz
L = 2.02 m (2/9 of the overall length)
P(L) = 200 kW (V=132 kV, Es=1.8 Kp)
1 loop power coupler
RF Power Amplifier + Control

Power Supply

RF Cooling SKID
Within IFMIF program the RFQ of TRASCO has been tested at Saclay (CEA) stable condition cw nominal field 80kW/m, 1.8 Ekp
Beam operation aspects

- PPS (personal protection system)
- The beam hall is of course close during operation
- Activation after beam stop has to be evaluated in the various cases (see for example RFQ activation after 6 months operation)
Machine Protection System:  
600 kW beam from the RFQ into the cryostat, 1 MW into the beam dump

Purpose of the MPS system:
• Protect the accelerator (beam pipes, cavities, beam dump…) from any damages that could occur, due to the malfunction of a component or due to the mistuning/misalignment of the beam

Inputs:
• All relevant status/interlock signals from the subsystem LCSs (vacuum, temperature, cooling, RF, LVPS, valves, slits, BLOMs…)

Means of action:
• Stop the beam (pulse reset, fast, slow, CF)
• Close the valves (in line, fast)
Local control system

- Based on EPICS and PLC
- Controls Cooling system, Vacuum system, RF signals, interfaces with MPS, PPS and timing
- The group (head by Mauro Giacchini, poster this week)

EPICS Vacuum Control System (Simulation)
Beam commissioning phases

Note 2: In stage 2 and 3, the maximum duty cycle in pulsed mode must be determined from activation calculations. Meanwhile, it is arbitrarily fixed to 0.1 % in this document.

The 5 MeV beam is stopped by the LPBD (Low Power Beam Dump)
Conclusions (1/2)

• IFMIF is a high intensity neutron source, based on two high intensity accelerators and a 10 MW liquid lithium target.
• The neutron spectrum is optimized to simulate the spectrum in a fusion reactor (up to 14 MeV)
• Within the Broader Approach agreement (complementary research programs approved together with ITER) the project IFMIF-EVEDA has been launched.
• This program includes a prototype accelerator (1.2 MW) and INFN Italy has the responsibility for the first accelerating structure, the RFQ
• IFMIF EVEDA RFQ is under construction, (12 modules given to industry, 6 modules will be machined at INFN PD and brazed at LNL).
• 4 modules for 200 kW power tests should be ready for the end of 2012
Conclusions (2/2)

• This accelerator development is done in good part within Accelerator division, the same group of people is involved in development an operation of PIAVE-ALPI, and in IFMIF.

• This can create some organization and logistic problem sometimes, but it is at the end a very strong point both for LNL complex operation (young people, up-to-date tools) and for new accelerators development (practical experience in the design).