A Cost-Effective Energy Upgrade of the ALPI Linac at INFN-Legnaro

1. Bird’s eye view: present status of INFN-LNL accelerating facilities
2. Next goal on the stable beam front (with very limited resources...) – RIBs being the priority
3. Recent progress on: ECR, cryogenic plant, cavities
4. Proposal for a cost-effective energy upgrade for very heavy ion beams
A User-oriented Lab, in a EU framework

INFN offers LNL and LNS infrastructures jointly

2010-2014
Funded by the European Commission within its Seventh Framework Programme (FP7) under the specific programme 'Capacities'. It provides coordinated access to the EU NP Facilities: GANIL (F), GSI (D), joint LNL-LNS (I), JYFL (FI), KVI (NL), CERN-ISOLDE (CH) and ALTO (F).
15 MV VdG Tandem (HV Corp),
H-\(^{100}\)Mo beams, \(E = 30 \div 1.5\) MeV/A,
CW or pulsed (1984)
SC Linac with QWRs (Nb, Nb/Cu) at 4.5K in 19 cryostats $V_{eq} \sim 48$ MeV/q, beams from $^{12}\text{C}$ to $^{197}\text{Au}$, injected by Tandem or PIAVE (1994)
Supernanogan ECR on 350 kV platform
SC-RFQs and QWRs, $V_{eq} \sim 8$ MV
$^{12}$C – $^{197}$Au (higher q and $I_{beam}$)
(2006)
T-A and P-A Typical Beams
Beam Hours Available for Experiments

AGATA Demonstrator Campaign

(1) Supernanogan ECRIS installation and Special XTU Maintenance
(2) Special Maintenance on the Cryogenic Plant
The innovative use of detectors in position-sensitive mode (combining digital DAQ, pulse shape analysis, γ-ray tracking) will result in high efficiency (~40%) and excellent energy resolution, making AGATA the ideal device for spectroscopic studies of weak channels.
The innovative use of detectors in position-sensitive mode (combining digital DAQ, pulse shape analysis, γ-ray tracking) will result in high efficiency (~40%) and excellent energy resolution, making AGATA the ideal device for spectroscopic studies of weak channels.
The Experimental Campaign at INFN-LNL (2010-2011)
What are the next steps?

**Radioactive Ion Beams**

The Lab priority is the **SPES project**

1. **Driver**: 70 MeV, 700 uA proton cyclotron (purchased, in construction)

2. Multi-slice UC\(_x\) direct **target-ion-source station**, followed by HRMS, beam cooling systems

3. **RIB acceleration**: charge breeding, CW NC RFQ injection into ALPI

**ALPI refurbishment**: replace and modernize old components, accelerate ultra-low-I mid-A exotic beams beyond Coulomb barrier with typical U-targets (specific diagnostics)

**Stable Ion Beams**

- **Increase** trasmission and \(I_{\text{exp}}\) AMARP
- **Especially for** very heavy ones
- Further **increase the final energy** for all ions (good for SPES too)

**Target**: \(^{208}\text{Pb}\) at \(~10\) MeV/A and \(I \geq 1\) pnA

Three MUSTS:
(since this not the top priority):

- **COST-EFFECTIVE**
- **WORKLOAD-EFFECTIVE**
- **(BEAM)TIME-EFFECTIVE**

M. Comunian (14.00 today!)
The very-heavy stable beam option

208Pb projectile

Isospin Mixing in 80Zr
Neutron-rich nuclei in the vicinity of 208Pb
Pygmy and GQR states
High-lying states in 124Sn and 140Ce
Molecular structure of 21Ne
Coulex of 42Ca
Proton drip-line
50
20
28
20
28
50
28
20
n-rich nuclei
82
Order-to-chaos transition in 174W
Shape transition in 196Os
Lifetime of 136Te
N=84 isotope 140Ba
N=51 nuclei
Neutron-rich nuclei populated by fission
Lifetimes of the n-rich Cr isotopes
Lifetimes near the island of inversion
Lifetimes in n-rich Ni, Cu and Zn isotopes
Lifetime of the 6.792MeV state in 18O
20(+3) exp.
148 days
Ingredients for the $^{208}$Pb 10 MeV/A – 1 pnA recipe

1. **ECRIS**: good \((l,q)\) performance \((q \geq 30+)\)

2. **Ancillary Systems**: adequate performance \((\text{He refrigerator})\)

3. **ALPI**: Higher equivalent voltage \((\text{higher } E_a \text{? More resonators?})\)

   \textit{We can’t violate the cost+workload effectiveness...}

4. **Beam transmission**: overall improvement
Ingredients for the $^{208}$Pb 10 MeV/A – 1 pnA recipe

1. **ECRIS**: good $(I,q)$ performance $(q \geq 30+)$

2. **Ancillary Systems**: adequate performance (He refrigerator)

3. **ALPI**: Higher equivalent voltage (higher $E_a$? More resonators?)
   
   *We can’t violate the cost+workload effectiveness...*

4. **Beam transmission**: overall improvement
ECR Ion Source Status

A high $V_{eq}$ linac is fully exploited with adequate ECRIS performance

- Since 2009: **LEGIS**, an all-permanent-magnet Supernanogan source (Pantechnik)
- **Ar**, **Kr**, **Xe**, **Ag**, **Ta**, **Au** readily available in the source acceptance tests
- **Metal beams** of specific interest to the EU nuclear physics community were developed in the time left available by the official beam time schedule
- Presently available beams: **C**, **N**, **O**, **Mg**, **Ar**, **Zn**, **Kr**, **Nb**, **Sn**, **Sm**, $^{197}$Au$^{30+}$
- Next planned developments: **Mo**, **Ca**, **Pb**, (Dy, Pd)

- **Spring 2012**: $I_{\text{max}}$ through PIAVE 1$\rightarrow$2 euA (tests with a $^{16}$O$^{3+}$ beam).
- **OK** $\rightarrow$ **5 euA** at least (from T-sensors on SC resonators and locking)
- **ALPI diagnostics** must be upgraded: 2 euA is present practical limit
Ingredients for the $^{208}$Pb 10 MeV/A – 1 pnA recipe

1. **ECRIS**: good $(l,q)$ performance $(q \geq 30+)$

2. **Ancillary Systems**: adequate performance *(He refrigerator)*

3. **ALPI**: Higher equivalent voltage *(higher $E_a$? More resonators?)*
   
   *We can’t violate the cost+workload effectiveness...*

4. **Beam transmission**: overall improvement
Air Liquide-based on a **Claude cycle** processing up to 150 g/s He.

Liquid He production:

- **2 gas bearing turbines** (used for cooling cryostats shields too)
- **a JT expansion valve** (**alternatively**: a reciprocating wet expander - **WE**)

**Commissioning result (with WE) -1991:**

3900W (60K) + **1180W (4,5K)**

**Noisy WE** soon abandoned – **with JT**: **only ~ 700W @4,5K** - **NO redundancy**: barely enough for shield cooling and for cryostats and cavities installed – **cavities working at 6 W instead of 7 W** since 2010.

**2012**: 3rd **supercritical turbine** in place of WE, to increase refrigeration capacity at 4,5K **with the JT expansion valve**
Measured increase in the refrigeration capacity: 360 W (predicted 300W): +51%
Ingredients for the $^{208}$Pb 10 MeV/A – 1 pnA recipe

1. **ECRIS**: good (l,q) performance ($q \geq 30+$)

2. **Ancillary Systems**: adequate performance (He refrigerator)

3. **ALPI**: Higher equivalent voltage (higher $E_a$? More resonators?)
   
   *We can’t violate the cost+workload effectiveness...*

4. **Beam transmission**: overall improvement
QWR Families in ALPI

\[ \beta_{\text{opt}} = 0.13 \]
\[ \text{Nb/Cu, 160 MHz} \]

\[ \beta_{\text{opt}} = 0.11 \]
\[ \text{Nb/Cu, 160 MHz} \]

\[ \beta_{\text{opt}} = 0.56 \]
\[ \text{Full Nb, 80 MHz} \]
ALPI – An open workshop on QWR performance

... despite the flat top, the quest for higher $E_{\text{acc}}$ continues...
Low-β Resonator Upgrade

Thin wall Nb cavities are less stable mechanically.
Upgrade: Liquid-N cooling of input RF power coupler, to increase $P_{RF,in}$ from 0.15 to 1 kW - QWR $\phi$&A locking from 3 to 5 MV/m (or more)
Low-β Resonator Upgrade

Thin wall Nb cavities are less stable mechanically. Upgrade: Liquid-N cooling of input RF power coupler, to increase $P_{RF,\text{in}}$ from 0.15 to 1 kW - QWR φ&A locking from 3 to 5 MV/m (or more)

Reliable locking at 5 MV/m for days was demonstrated on CR03
Status: CR03, CR02-P, CR05 completed and mounted; CR01-P and CR06 presently in maintenance; CR04 will be upgraded in 2013
Medium-β Resonator Improvements

Cu base for presently installed Nb/Cu QWRs $E_a \sim 4.8 \text{ MV/m}$

PROTOTYPE CRYOSTAT CR15

Rounded-off shorting plate & beam ports, $E_a \sim 5.5 \text{ MV/m}$

Measured in 02/2012

Further margins of improvement are possible ...

A.M. Porcellato et al., Poster PO10
High-β Resonator Improvements

Removal of the In gasket, replaced by a high pressure gasket-less joint is beneficial to the Q, removing a source of dissipation. 

Q improves, Q-slope does not change, $\Delta E_a = +1$ MV/m
Ingredients for the $^{208}$Pb 10 MeV/A – 1 pnA recipe

1. **ECRIS**: good (I,q) performance ($q \geq 30+$)

2. **Ancillary Systems**: adequate performance (He refrigerator)

3. **ALPI**: Higher equivalent voltage (higher $E_a$? More resonators?)

   *We can’t violate the cost+workload effectiveness...*

4. **Beam transmission**: overall improvement
Ingredients for the $^{208}\text{Pb}$ 10 MeV/A – 1 pnA recipe

1. ECRIS: good (l,q) performance ($q \geq 30+$)
2. Ancillary Systems: adequate performance (He refrigerator)
3. ALPI: Higher equivalent voltage (higher $E_a$? More resonators?)
   
   We can’t violate the cost+workload effectiveness...

4. Beam transmission: overall improvement

Full refurbishment of low and medium $\beta_{opt}$ resonators can provide the required energy increase for beams such as $^{208}\text{Pb}^{30+}$

Or: addition of two more cryostats on the high energy side
Reshuffling ALPI Cryostats

Could house 4 QWR, has 2, uses 1 with $E_{a,\text{max}} \sim 0.54 \text{ MV/m}$

Could house 4 QWR, has 2, uses 1 with $E_{a,\text{max}} \sim 0.3 \text{ MV/m}$ (used when injecting into CR07)

Could house 4 QWR, has 2, uses 1 with $E_{a,\text{max}} \sim 1.8 \text{ MV/m}$
Reshuffling ALPI Cryostats

Could house 4 QWR, has 2, uses 1 with $E_{a,\text{max}} \sim 0.54 \text{ MV/m}$

Could house 4 QWR, has 2, uses 1 with $E_{a,\text{max}} \sim 1.8 \text{ MV/m}$ (used when injecting into CR07)
New bunchers

CR10 ← CR07  4,8 MV/m
CR06 ← CR03  5 MV/m

CR12 → CR18  6,5 MV/m
CR19-22

CRB3

3,6 MV/m

CRB4 (1 QWR)

E_{a,max} \sim 0,3 MV/m
NC 160 MHz QWR

E_{a,max} \sim 0,54 MV/m
NC 80 MHz QWR

Its need is being calculated
$^{208}\text{Pb}^{30+}$ (A/q~7) up to CR22

Assumptions: 4,5 MV/m from CR03 to CR18; 6,5 MV/m for CR19-CR22

Final energy (CR20→CR22): 7,5 → 9,8 MeV/A

37% beam loss (only 0,5% beam loss due to addition of CR21 and CR22)

Zooming in» shows loss location

Losses (37% in total) are located on the first and last cavities, in a row of 8 with no quads in between.
Losses Budget

- ALPI has a «loose» lattice, justified $E_{a,\,des} \approx 3$ MV/m
- In the present conditions, losses are inevitable, unless a different layout is well enough motivated in the SPES project framework

Moreover, **poor alignment in general** and a missing «on-purpose» **displacement between cavity axis and beam axis** increase loss budget by another $20\div25\%$

M. Comunian, Physical Design of the SPES Facility, today at 2.00 pm
ALPI Alignment Campaign

- Correction of the QWR beam steering effect by offset beam axis
  

A laser tracking campaign just started, with the supervision of D. Bianculli (CNAO Foundation)

June 14, 2012
Outlook

- Increase ALPI refrigeration capacity by 50% (turbine T3) provides proper redundancy and leaves margin for more RF dissipation.

- Recent progress on medium-high $\beta_{opt}$ QWR $E_a$ is promising, but applying it to the whole linac violates LABOUR-EFFECTIVENESS.

- Reshuffling of «bunching» cryostats provides same energy increase, COST-EFFECTIVELY.

- Beam losses budget is comparable to present one, will be improved by Laser Tracking alignment.

- Provided that the ECR does its part, 10 MeV/A $^{208}$Pb is within reach.
TTF along ALPI

![Graph showing Transit Time Factor (TTF) along progressive cavity number for different ions: 104Ru14+, 70Zn12+, 58Ni13+, and 28Si10+.

- **Transit Time Factor (Y-axis):** Ranges from 0.75 to 1.00.
- **Progressive cavity number (X-axis):** Ranges from 0 to 60.
- **Optimum values:** β_{opt} 0.56, β_{opt} 0.11, β_{opt} 0.13.