An overview of the research activities and perspectives: From stable (high Intensity) to radioactive nuclear beams

Giacomo de Angelis

Nuclear Physics

Accelerator technologies

Gravitational waves and General Physics

Interdisciplinary researches
Infrastructures of LNL

Interdisciplinary activities and applications

4500

46% non-INFN
INFM, ENEA, ISS, Universities

5500

10,000

hours of beam on target
P → Au / from AkeV → 20 AMeV
from few pnA → few pμA

High intensity beams of stable heavy elements
Individual users asking for access to the Research Installations

![Graph showing the number of Italian and foreign guests over the years from 1998 to 2003. The graph includes data points for each year, with a bar for Italian guests and another for foreign guests.](image-url)
“Transnational Access to major Research Infrastructures” Improving the Human Research Potential and Socio-economic Knowledge Base

MAN-DAYS (2000/2003) DISTRIBUTED BY THE COUNTRY OF ORIGIN OF USERS

总工作日数 2981

Belgium: 873
Denmark: 52
Germany: 144
Greece: 11
Spain: 368
France: 123
Italy: 247
Netherlands: 275
Portugal: 258
Sweden: 12
United Kingdom: 267
Bulgaria: 199
Cyprus: 13
Hungary: 16
Israel: 9
Poland: 5
Romania: 76
Slovakia: 28
Other: 5

Belgium
Denmark
Germany
Greece
Spain
France
Italy
Netherlands
Portugal
Sweden
United Kingdom
Bulgaria
Cyprus
Hungary
Israel
Poland
Romania
Slovakia
Other
Nuclear Structure at LNL

- Clustering and reflection asymmetric shapes
- Collectivity and shell model
- Isospin symmetries and mirror pairs
- Isospin mixing in N=Z nuclei
- Spectroscopy at the dripline

- New symmetries at the critical point
- Rotational damping

- High spin states and superdeformation
- Chiral Symmetry in Nuclei

- Shell stability and shell evolution

High intensity (100 pnA) beams of stable heavy ions complementary to RIBS
Transition Matrix Elements in mirror pairs

Effective Charges in the $fp$ Shell

$$\epsilon_p = 1 + e_{pol}^{(0)} - e_{pol}^{(1)}, \quad \epsilon_n = e_{pol}^{(0)} + e_{pol}^{(1)}.$$

Isospin Mixing and Mirror Simmetries

Unusual Isospin-Breaking and Isospin-Mixing Effects in the $A = 35$ Mirror Nuclei

Electromagnetic spin-orbit term?

$$C_{ls} = \left( g_s - g_l \right) \frac{1}{2m^2_{\text{nucleon}}} \frac{1}{c^2} \langle \frac{1}{r} \frac{dV_C(r)}{dr} \rangle \langle \vec{l} \cdot \vec{s} \rangle,$$

Quasi-molecular states in nuclei

Thummerer et al.

\[ \langle \Psi \rangle = \left| \Psi \right| \]
\[ R(\omega) \langle \Psi \rangle = \left| \Psi \right| \]
\[ R(\omega) \langle \Psi \rangle \neq \langle \Psi \rangle \]

Gamma-Ray Spectrum

Counts

Energy (keV)

Thummerer et al.

\[ \langle \Psi \rangle = \left| \Psi \right| \]
\[ P \langle \Psi \rangle = \left| \Psi \right| \]
\[ P \langle \Psi \rangle \neq \langle \Psi \rangle \]
Critical-Point Symmetries

Observed in $^{134}\text{Ba}$

Observed in $^{152}\text{Sm}$
Comparison of the Excitation Energy Ratios for the N=90 Rare earth isotones $^{150}$Nd, $^{152}$Sm, $^{154}$Gd and $^{156}$Dy with the prediction of the X(5) symmetry

Extended Casten symmetry triangle

$$R_{0/2} = \frac{E(0^+_2)}{E(2^+_2)}$$

$$R_{4/2} = \frac{E(4^+_1)}{E(2^+_1)}$$

$$R_{4_2/2} = \frac{E(4^+_2) - E(0^+_2)}{E(2^+_2) - E(0^+_2)}$$

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Comparison of the experimental level scheme of $^{154}$Gd with the X(5) predictions. The $E(2_{1}^{+})$ value (in keV) and the $B(E2; 2_{1}^{+} \rightarrow 0_{1}^{+})$ value (in W.u.) are normalized to the experimental data.


Does Chiral symmetry exists in nuclei?

“\text{I call any geometrical figure, or group of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself.}” - Lord Kelvin 1904

Examples of chiral systems are found in:

- Chemistry: molecules with opposite handedness react differently in similar environments
- Biology: DNA has right and left-handed “screws”
- Particle Physics
Nuclear Physics: Current distributions in nuclei

Triaxial odd-odd nuclei result in 3 perpendicular angular momenta for p-h configurations built on high-j orbitals.

The energies of the excited states for the left-handed and right-handed systems should be identical.

\[ \mathcal{P} = 1 \]

\[ 8^+, 7^+, 6^+, 5^+, 4^+ \]

The energies of the excited states for the left-handed and right-handed systems should be identical.

V. I. Dimitrov et al, PRL 84 (2000) 5732
Does Chiral symmetry exists in nuclei?

Planar to a-planar phase transition?

S. Brant et al, PRC 69 (2004) 017304
High Intensity Stable Beams and Neutron Rich Nuclei

Stable nuclei:

- \( N/Z \approx 1 - 1.5 \), \( S_n \approx 6 - 8 \text{ MeV} \)
- Homogeneously mixed protons and neutrons
- Good mean-field description
- Good "single-particle" picture (magic numbers)
- Large gaps between major shells
- Empirical shell-model interactions

Very neutron-rich nuclei:

- \( N/Z \approx 2 - 2.5 \), \( S_n \ll 1 \text{ MeV} \)
- Diffuseness of neutron distribution (neutron skins & halos)
- More states near the Fermi surface
- Breakdown of the single-particle description
- Redefinition or disappearance of magic numbers
- Unknown shell-model interactions
- Reduction of spin-orbit potential

\[ V_{s.o.} \approx \frac{1}{r} \frac{\partial}{\partial r} V_{ls}(r) \]
\[ V_{ls} = \frac{m}{m_{eff}} (V - S) \]

\[ \Delta E_{ls} = E_{n,l,j=l-1/2} - E_{n,l,j=l+1/2} \]

The Properties of Nuclei with Extreme N/Z-Ratios

- Basic nuclear properties of rare isotopes (e.g., masses, half-lives, ...) determine element formation in the cosmos

Element formation in r-process: quenching of shell-structure?

Pfeiffer et al., Z. Phys. A357 (1997) 235

Disappearance of Shell Structure?
Cautions in jumping to conclusions about shell modifications related to diffuse density distribution:

“Single particle” orbitals are dressed even in semi-magic nuclei

- **Effective single-particle energy (ESPE)**

  ESPE is changed by $N\cdot v_m$

  Monopole interaction, $v_m$

  $N$ particles

  **ESPE**: Total effect on single-particle energies due to interaction with other valence nucleons

  T. Otsuka et al. Zakopane 2004
Detecting $\gamma$-ray emitted at rest: no Doppler correction! Sensitive to the decay of levels which live longer then the stopping time.

\[
\text{Populate high spin states}
\]
\[
\text{Rolling limit:}
L_{TLF} = \frac{2}{7}\left(\frac{1}{1+(A_B/A_T)^{1/3}}\right)L_{MAX}
\]
\[
L_{MAX} = \sqrt{\frac{2\mu R^2}{\hbar^2}(E_{CM} - V_C)}
\]

Deep inelastic reactions - a tool for nuclear spectroscopy
higher selectivity strongly needed

angular acceptances $\Delta \theta \sim 12^\circ$ $\Delta \phi \sim 22^\circ$
solid angle $\Delta \Omega \sim 80$ msr
d. target-focal plane 7 m
energy acceptance $\pm 20\%$
max rigidity 70 MeV amu
dispersion $\sim 4$ cm/%
mass resolution $\sim 1/300$ FWHM
Clover Ge detectors from EUROBALL
First experimental campaign just started

82Se + 238U $E = 505$ MeV $64^\circ$ deg

- Fission events
- Proton pick-up channels
- Proton stripping channels

Z = 50
Z = 34

LNL – APRIL 2004
γ-spectroscopy of neutron rich nuclei
Mass distribution of 505 MeV $^{82}\text{Se} + ^{238}\text{U}$

Preliminary
$^{82}\text{Se} + ^{238}\text{U} \ E=505\text{ MeV}$

455 keV $23/2^{(+)} \rightarrow 21/2^{(+)}$

$^{87}\text{Rb}$

$^{+3p+2n}$

$^{84}\text{Se}$

PRC70, 024301 (2004)
Research activities of Prisma-Clara in 2004

- Spectroscopy of $^{54}\text{Co}$, Isospin non-conserving part of the effective interaction
- Multi-nucleon transfer
- $^{90}\text{Zr} + ^{208}\text{Pb}$
- Shell closure evolution at the magic number $N=50$
- Shell model $A\sim 60$
- Large-angle scattering
- $^{64}\text{Ni} + ^{238}\text{U}$
- Pairing-vibration states in $^{40}\text{Ca}$
- $^{40}\text{Ca} + ^{208}\text{Pb}$
- $^{36}\text{S} + ^{208}\text{Pb}$
- $^{32}\text{S} + ^{58}\text{Ni}$
- Shell model in $^{37}\text{P}$ and $^{39}\text{P}$, Breaking of a semi-magic shell closure far from stability

Heavy ion beams from PIAVE-ALPI strongly needed
E(5) critical point symmetry

vibrator to γ-unstable rotor

$E_{4+}/E_{2+} = 2.20$
$E_{6+}/E_{2+} = 3.65$

$58^{\text{Cr}}$

<table>
<thead>
<tr>
<th>$KB3G$</th>
<th>$FPD6$</th>
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<tbody>
<tr>
<td></td>
<td>(10$^+$)</td>
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<tr>
<td></td>
<td>(8$^+$)</td>
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<tr>
<td></td>
<td>(6$^+$)</td>
</tr>
<tr>
<td></td>
<td>(4$^+$)</td>
</tr>
<tr>
<td></td>
<td>2$^+$</td>
</tr>
<tr>
<td></td>
<td>0$^+$</td>
</tr>
</tbody>
</table>

$E_{4+}/E_{2+} = 2.20$

$E_{6+}/E_{2+} = 3.65$

TABLE 1. Excitation energies of the E(5) symmetry.

<table>
<thead>
<tr>
<th>$\xi$ = 1</th>
<th>$\xi$ = 2</th>
<th>$\xi$ = 3</th>
<th>$\xi$ = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ = 0</td>
<td>0</td>
<td>3.03</td>
<td>7.58</td>
</tr>
<tr>
<td>$\tau$ = 1</td>
<td>1</td>
<td>4.80</td>
<td>10.11</td>
</tr>
<tr>
<td>$\tau$ = 2</td>
<td>2.20</td>
<td>6.78</td>
<td>12.86</td>
</tr>
<tr>
<td>$\tau$ = 3</td>
<td>3.59</td>
<td>8.97</td>
<td>15.81</td>
</tr>
</tbody>
</table>

Dynamic Symmetries at the Critical Point

P. Iachello

Center for Theoretical Physics, Sloan Laboratory, Yale University, New Haven, Connecticut 06520-8120

Received 8 May 2000
Identification of new states based on $\gamma$-coincidences (cross-coincidences)

Neutron rich heavy projectiles allow to use transfer reactions as a $\Delta N-\Delta Z$ filter for driving the multi-nucleon transfer flux to exotic regions.
Transfer induced by Neutron Rich (radioactive) Beams

Driving the multi-nucleon transfer flux to very exotic regions

Coupled channel calculations (Grazing).
G. Pollarolo

Understand the relative weight of the sequential transfer of single nucleons, of pair transfer or the more complex transfer of clusters.

Enhancement of the pair-transfer mode due to the dropping of the two-neutron separation energy as a function of the neutron excess.
Gamma Arrays based on Compton Suppressed Spectrometers

\[ \varepsilon \sim 10 - 5\% \quad (M_{\gamma}=1 - M_{\gamma}=30) \]
Gamma Arrays based on Compton Suppressed Spectrometers

\[ \varepsilon \sim 10 \text{ -- } 5\% \quad (M_\gamma = 1 \text{ -- } M_\gamma = 30) \]

Tracking Arrays based on Position Sensitive Ge Detectors

\[ \varepsilon \sim 40 \text{ -- } 20\% \quad (M_\gamma = 1 \text{ -- } M_\gamma = 30) \]

Intermediate step \(\rightarrow\) Exogam, Miniball, SeGa: optimized for Doppler correction at low \(\gamma\)-multiplicity
**Ingredients of Gamma Tracking**

1. **Highly segmented HPGe detectors**

2. **Digital electronics to record and process segment signals**

3. **Pulse Shape Analysis to decompose recorded waves**

4. **Identified interaction points**

\[ (x, y, z, E, t)_i \]

**Reconstruction of tracks evaluating permutations of interaction points**

**Reconstructed gamma-rays**
AGATA/GRETA Prototypes 2

May, 2004

Courtesy J. Eberth, IKP Cologne

April, 2004

Courtesy I-Yang Lee, LBNL
First phase of AGATA
15 clusters ($1\pi$)
4 x efficiency

Solid Angle = 80 msr  Energy accept. 20%
$\Delta m/m = 1/300$  $\Delta E/E=1/1000$

$^{64}\text{Ni} (390 \text{ MeV}) + ^{238}\text{U}$

With present ALPI beam

With the PIAVE Xe beams
Reaction Mechanisms at LNL

Sub-barrier fusion:
Fusion dynamics and nuclear structure

Break-up of
Exotic light nuclei

Fission dynamics
Symmetry energy and stellar collapse

GDR response probing shapes and non uniform charge and mass distributions in nuclei

Multifragmentation at low excitation energy

Deformed proton emitters
Fission dynamics in the super-heavy mass region

Influence of Q.F. on fusion process
Fission dynamics in Super-Heavy region

$^{80}\text{Se} + ^{208}\text{Pb}$ 470 MeV

**Neutrons**
12 scintillators 2m from the target

**Fission Fragment**
PPAC 5 x 4 cm$^2$ for TOF, 2 MWPC 13 x 13 cm$^2$

No evidence for symmetric splitting events, corresponding to Fusion-Fission reactions Nevertheless:

Evidence of a long transient delay in asymmetric splitting (DIC-like) suggesting the formation of a composite Super-heavy system
SHE - Instrumentation

Competition between the Quasi-Fission and Fusion-Fission mechanisms

DEMON: Détecteur Modulaire de Neutrons
(belgian-french collaboration: ULB, UCL, LPC, IReS + LNL)

40 NE513 + FF + BaF$_2$
Multi-source fit to the experimental neutron and a energy spectra pre- and post-scission multiplicities Fission delay time \( t_D \)

Comparing neutron prescission multiplicities with Statistical Model a \( t_D \approx 5 \times 10^{-20} \) s is obtained.
Gas

Liquid

Density $\rho/\rho_0$

Big Bang

Neutron Stars

Temperature 20200 MeV

1

5?

Plasma of Quarks and Gluons

Dense matter EOS

Crab nebula

July 5, 1054

Collisions

Heavy Ions

Nuclei

Plasma of Quarks and Gluons

Dense matter EOS

Crab nebula

July 5, 1054

Collisions

Heavy Ions

Nuclei
Evaporation residues and fragments measurement: from fusion to multifragmentation

With the last upgrade → also Isotope identification:

- 3rd coordinate in the phase space
- Temperature information of the emitting source

To be checked:
- same charge of the emitting systems formed through the different entrance channels through comparison to models (charge correlations, charge distributions etc.)
- same temperature of the emitting sources
- same volume (through correlation functions)

Signals already at lower energy 11AMeV
Interdisciplinary Researches

- Surface analysis
- MOT traps
- High reflectance mirrors for solar corona
- Tissue equivalent proportional counters
- Radiation biology
- Nb sputtering into Cu cavities
- Detector technology
- Images of seven holes 300 µm in diameter and 100 µm spaced

Zoom effect as function of the drift voltage

<table>
<thead>
<tr>
<th>$V_{\text{drift}}$</th>
<th>50 V</th>
<th>100 V</th>
<th>200 V</th>
<th>500 V</th>
</tr>
</thead>
</table>

Spatial resolution < 100 µm
Tests of the Standard Model - Atomic Parity violation

- Precision tests of CP, P violation and unitarity of CKM matrix;
- Physics beyond VA;
- Measurements of $\sin^2 \Theta_W$ at low $q$

215Fr: CN* formed in $^{18}$O+$^{197}$Au

Parity violation studies in Francium

Weak interaction studies in N=Z nuclei

EDM search in Radium

Proton number $Z$

Neutron number $N$
TRAPPING OF 85RB
Interdisciplinary & Biomedical Physics Facilities

Nanodosimetric structure of hadron tracks

DNA

Ionization events

Microbeam facility for single cell irradiation

Biological sample holder

Cooled-CCD

Beam extraction window

Beam-pipe

Tissue equivalent proportional counters

Radiation biology
Radiobiological studies:

- Light ion broad-beam irradiation facility at the 7MV Van de Graaff CN electrostatic accelerator (protons, deuterons, helium-3 and helium-4 ions; E: 0.8-12 MeV)

- Heavy ion broad-beam facility at the Tandem-ALPI accelerator complex (A>4; E: 5-26 MeV/amu)

- Light single-ion microbeam facility for single-cell irradiation at the 7MV Van de Graaff CN electrostatic accelerator (protons, deuterons, helium-3 and helium-4 ions; E: 0.8-12 MeV)

- Fully equipped biology Laboratory

Main Activities at LNL

- Cell inactivation
- Gene mutation
- Mutation characterization
- Chromosome aberration
- Influence of chromosome architecture in aberration formation
- Protein expression in normal and tumoral cells.

...Particular emphasis on the low-dose and low-dose rate effects...
...bystander effects and cell-to-cell communication.

Mainly performed in the framework of INFN and EU Contract projects.
Relative Biological Effectiveness (RBE) vs Linear Energy Transfer (LET) of light ions for cell inactivation in V79 cells.
• ADVANCED THIN FILM MATERIALS

Synthesis and Process Development

• Plasma Sputtering Deposition
• Plasma Diagnostics
• Ion Implantation

• Low Friction, High Hardness Nanoscaled Materials and Multilayers

• Extreme UV and soft X-ray optics development

• Insulating Oxides and High Performance Plastics
characterization of physical properties

composition

- ion beam analysis (rbs, nra, erda, pixe)
- microbeam (micro-pixe 2-d trace element analysis)

mechanical characterization

- nano hardness / stress
- adhesion (micro scratch)
- atomic force microscopy
Nuclear Physics Perspectives at LNL

Tandem+Alpi

A Superconductive Linac as a test bench for Eurisol

Nuclear Structure and Dynamics at the limits (spin and isospin)

High intensity stable beams

Moderately neutron rich nuclei by means of high intensity stable beams

Multi-nucleon transfer and deep-inelastic collisions as a way to access n-rich nuclei: The Clover array + PRISMA

from SPES to Eurisol

Medium size next generation RIB facility, a way to Eurisol

Advanced Gamma-ray Tracking Array and other Integrated Infrastructure Initiatives
PIAVE first beams in Dec 2004
$^{16}O^{3+}$: $I = 430$ pna; transmission 40-50%
$^{129}Xe^{18+}$: $I = 5.5$ pna; transmission 25-30%
Injection Test in ALPI: since Feb 2005

First superconduttive RFQ in operation in the world
Larger Beam Intensities
Superconductive LINAC with Nb/Cu resonators

Intensities ~ 100 pnA

Pb/Cu
2.3 MV/m

Nb/Cu
4.4 MV/m
Test of the standard model

Test of the trapping efficiency

On-Line Trap for Fr

Trapping of Francium atoms
Production reactions

- $p(^{17}\text{O, }^{17}\text{F})n$
- $^{3}\text{He}(^{6}\text{Li, }^{8}\text{B})n$
- $^{7}\text{Li}(^{9}\text{Be, }^{6}\text{He})^{10}\text{B}$
- $p(^{7}\text{Li, }^{7}\text{Be})n$
- $p(^{14}\text{N, }^{14}\text{O})n$
- $^{3}\text{He}(^{16}\text{O, }^{18}\text{Ne})n$
Neutron rich unstable beams

Starting construction 2005

ISOL facility

SPES p and d driver
Ep,d=100 MeV I~1-10 mA

Primary p beam

238U

Fission fragments

$1 \text{ mA} \times 100 \text{ MeV} = 100 \text{ kW}$

$10^{13-14} \text{ f/s}$

$10^8 \text{ }^{132}\text{Sn} / \text{s}$

$0.02 \text{ pnA}$

$^{132}\text{Sn at 16 MeV/u}$

ALPI

Supercond. p linac
100 MeV

Be or $^{13}\text{C}$
100 kW

4 Kg UCx

ALPI
Fragments produced by each proton (in the Ucx target)

The nominal beam is of $1.7 \times 10^{16}$ p/s
Multinucleon transfer and DIC in the $^{132}$Sn region

- Topics: residual interactions: SPE and TBME, core and particle-core excitations, high spin with DIC
- $-4p$ transfer estimated $\delta\sigma/\delta\Omega \sim 100$ to 500 $\mu$b/sr, Ge efficiency $\sim 3\%$.
  Prisma acceptance $\sim 80$msr,
  Beam: 10 pmA $^{134,136}$Xe.
  Target 300mgr/cm$^2$ $^{208}$Pb or $^{238}$U,
  $\gamma$-Multiplicity 5: 10 to 50 $\gamma-\gamma$-Prisma coin./hour


Neutron Skin Oscillations: Pygmy Resonance


Use of DIC to study GDR
Tetrahedral symmetry in nuclei?

The lowest order: $\lambda = 3$

Shells at $Z,N =$
16, 20, 32, 40, 56, 70

J. Dudek et al., PRL 88 (2002) 252502

Quasi-elastic reactions?
Summary

- LNL as a multidisciplinary nuclear physics based user oriented laboratory
  - Nuclear Structure and Reaction based facilities
  - Infrastructure for applied physics
  - Interdisciplinary and biomedical physics facilities

- LNL as an high intensity stable heavy beam facility: a short term perspective

- Neutron rich radioactive beams at LNL: the SPES project

- New detectors (Prisma-Clara) and powerful Ge detectors based on gamma ray tracking
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<th>Category</th>
<th>Number</th>
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<td>Guests</td>
<td>129</td>
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<tr>
<td>Fellowships and grants</td>
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<tr>
<td>Students and Ph.D. Students</td>
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<tr>
<td>Italian researcher</td>
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<td>EU researcher</td>
<td>126</td>
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<tr>
<td>Non EU researcher</td>
<td>119</td>
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<tr>
<td>Workshops and meetings</td>
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<tr>
<td>Publications in Journals</td>
<td>74</td>
</tr>
<tr>
<td>International Conferences</td>
<td>20</td>
</tr>
</tbody>
</table>
Present ALPI output energy – Tandem injector

ALPI 2003 (low beta not included)
ALPI 2003 (low beta included)
ALPI Dec 1998

Tandem 15 MV; F,F
1998: 11 Pb/Cu cryostats
2003: 13 Nb/Cu cryostats
Near future switching from a Tandem to a q+ injector (PIAVE)

ALPI Output with the two Injectors

- MORE CURRENT
- HEAVIER MASSES
- MORE BEAM TIME AVAILABLE (TWO INJECTORS)
PIAVE: - 2 SRFQs at the design accelerating fields
    - 8 low β resonators at 5 MV/m

ALPI - 12 low β resonators operating at 4.4 MV/m
    - 44 medium β resonators operating at 4.4 MV/m
    - 8 high β resonators operating at 5.5 MV/m