Recent results in the field of High Intensity CW linac development for RIB production

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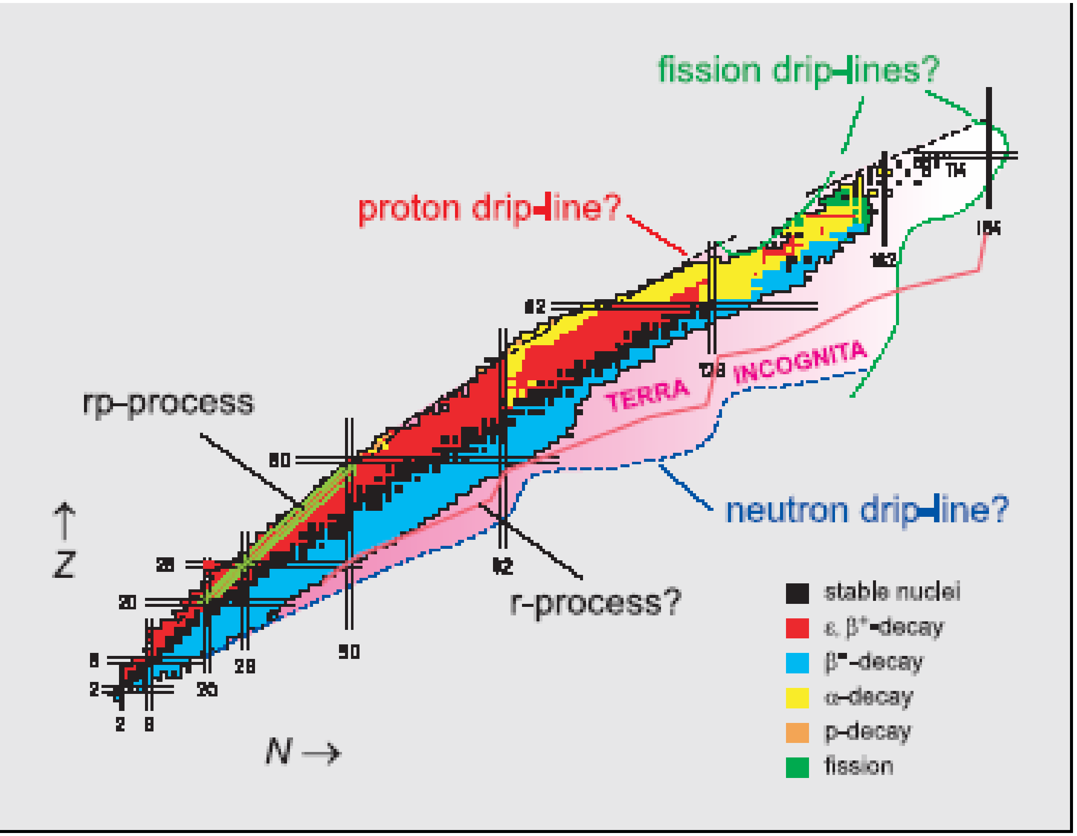
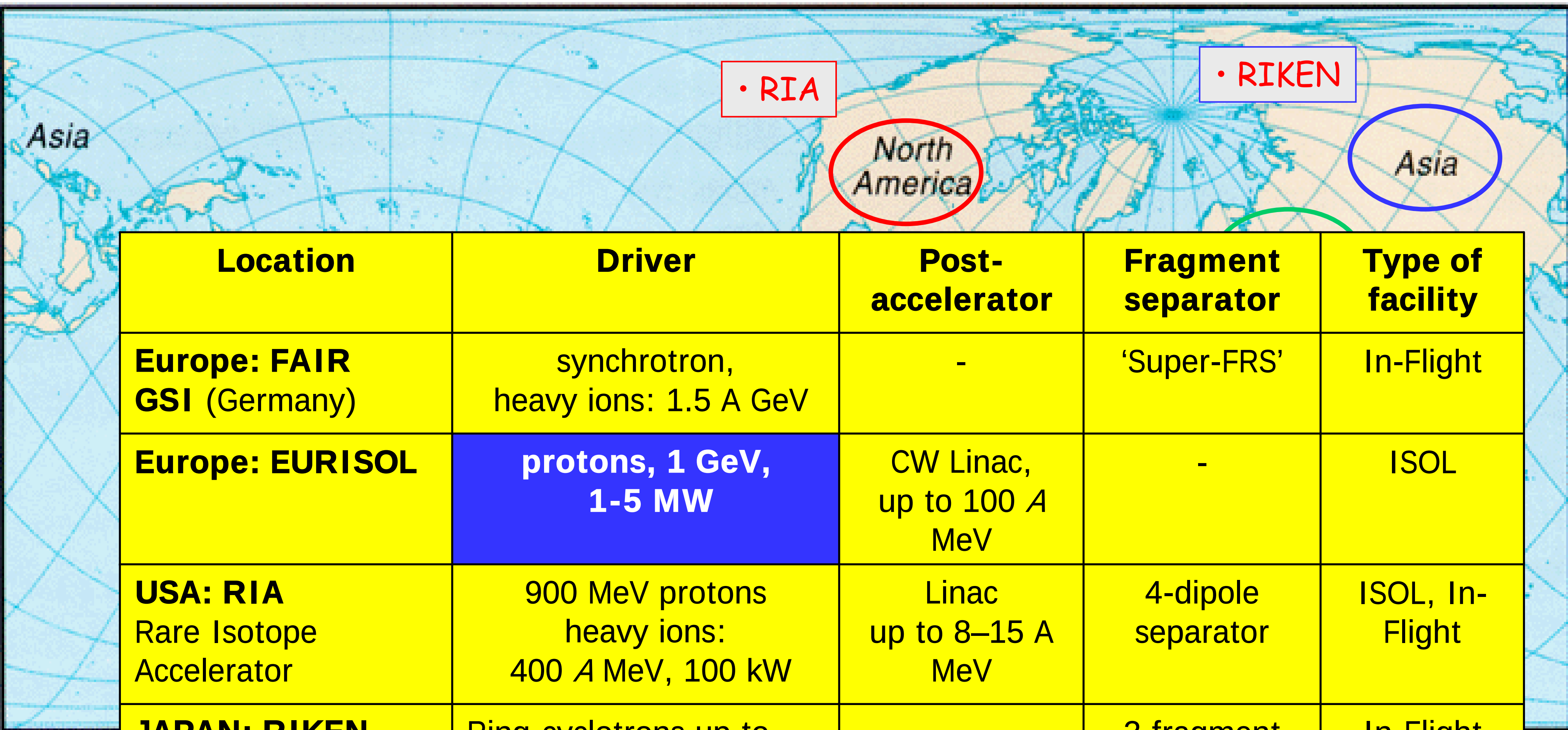


By means of RIBs (Radioactive Ion Beams) it is possible to study the properties of nuclei that, due to their short life-time, cannot be used as a target.

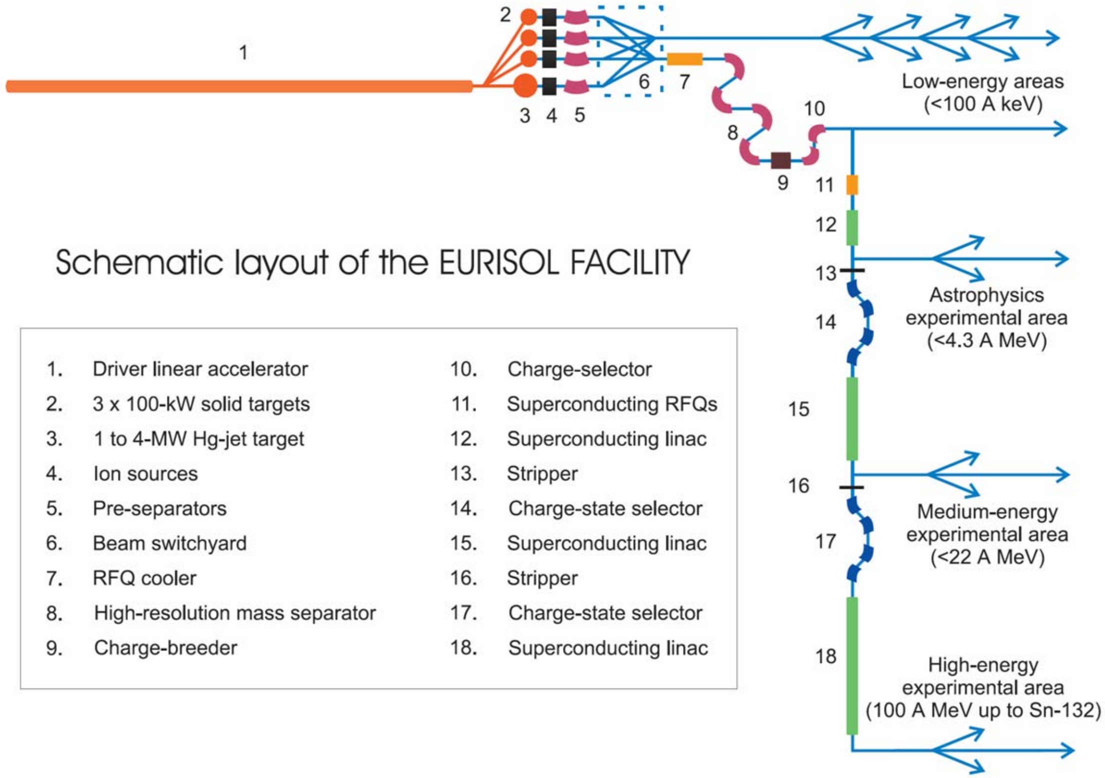
Therefore RIBs allow to extend the knowledge of nuclear structure to exotic compounds and to study conditions that are relevant for the understanding of the early stage of the Universe and for the nucleus-synthesis.

New generation RIB facilities



Location	Driver	Post-accelerator	Fragment separator	Type of facility
Europe: FAIR GSI (Germany)	synchrotron, heavy ions: 1.5 A GeV	-	'Super-FRS'	In-Flight
Europe: EURISOL	**protons, 1 GeV, 1-5 MW**	CW Linac, up to 100 *A* MeV	-	ISOL
USA: RIA Rare Isotope Accelerator	900 MeV protons heavy ions: 400 *A* MeV, 100 kW	Linac up to 8–15 A MeV	4-dipole separator	ISOL, In-Flight
JAPAN: RIKEN RIB Factory	Ring-cyclotrons up to 400 *A* MeV (light ions); up to 150 *A* MeV (heavy ions)	-	3 fragment separators storage & cooler rings	In-Flight

EURISOL report facility

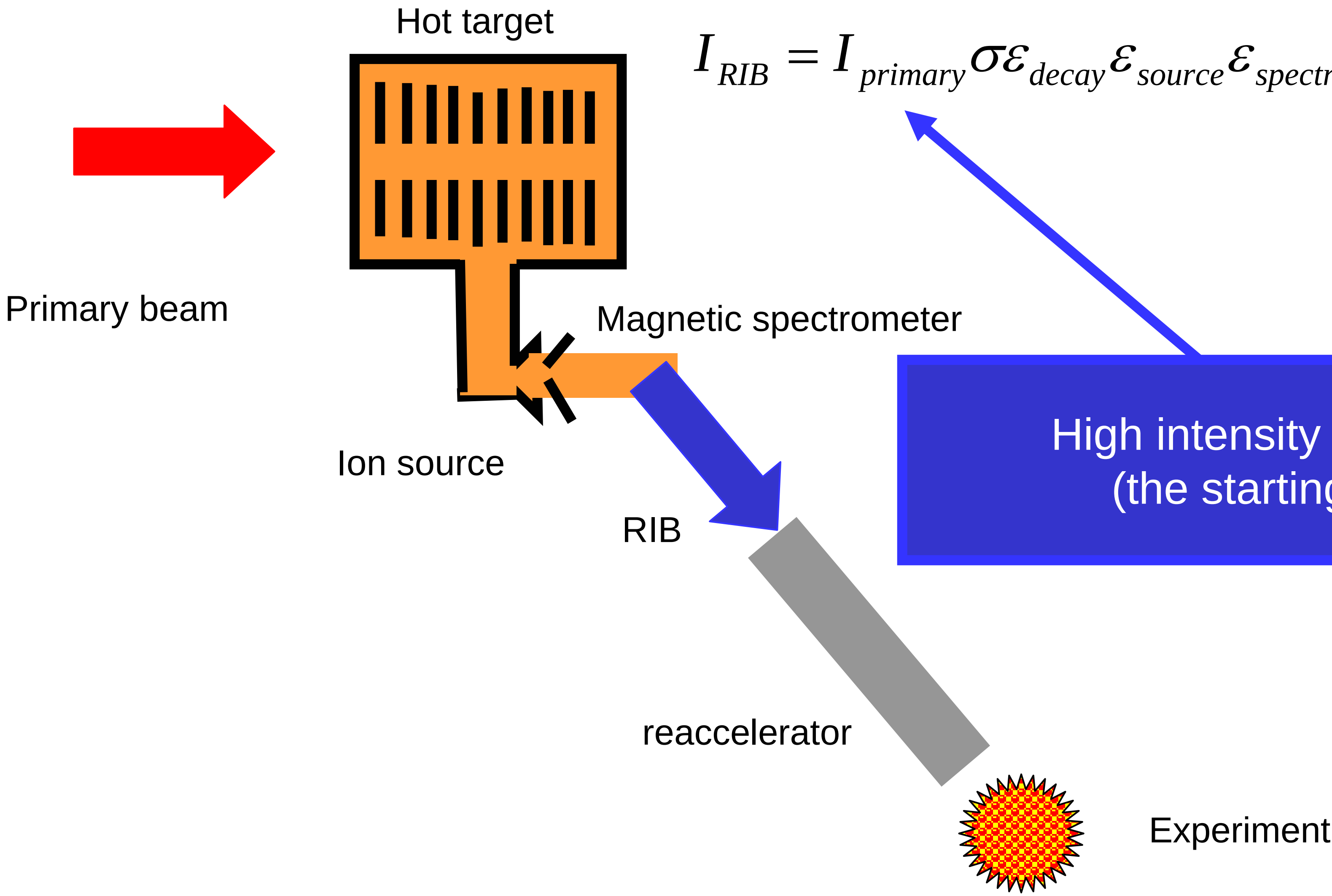


Schematic layout of the EURISOL FACILITY

- EURISOL project funded by EU (large group of research institutions, including the major Nuclear Physics laboratories). TDR last year
- EURISOL-DS, under negotiation with EU
- Thanks to the complementarity with FAIR, EURISOL is mainly concentrated on the use of a 1 GeV high power proton linac.

Scheme of principle of an ISOL facility

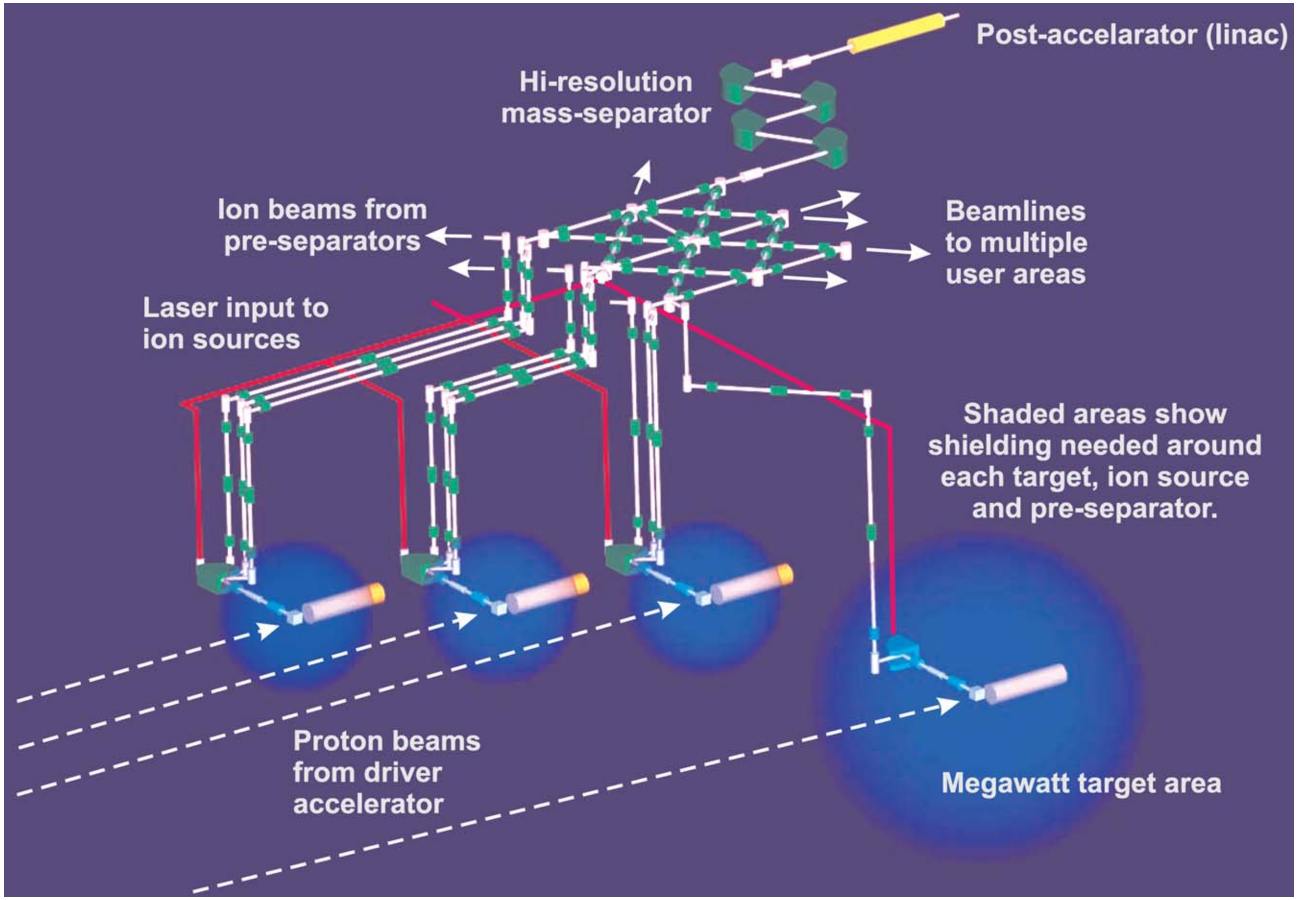
$$I_{RIB} = I_{primary} \sigma \varepsilon_{decay} \varepsilon_{source} \varepsilon_{spectrometer} \varepsilon_{accelerator}$$



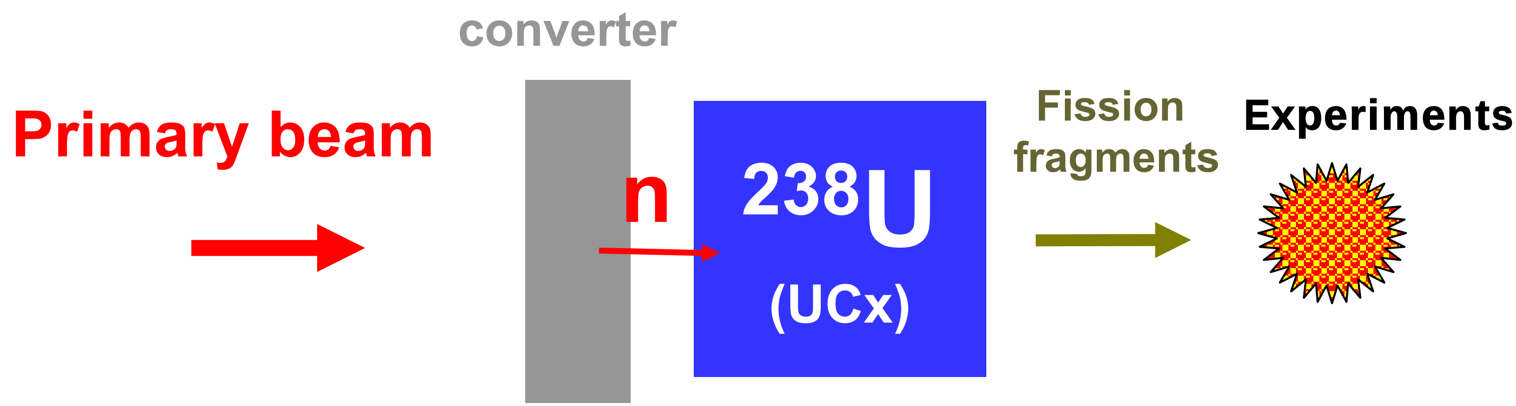
High intensity is just one (the starting) factor

Target region and operation modes

- EURISOL reference facility foresees three 100 kW targets (100 μA beam) stations and one 5 MW target (5 mA).



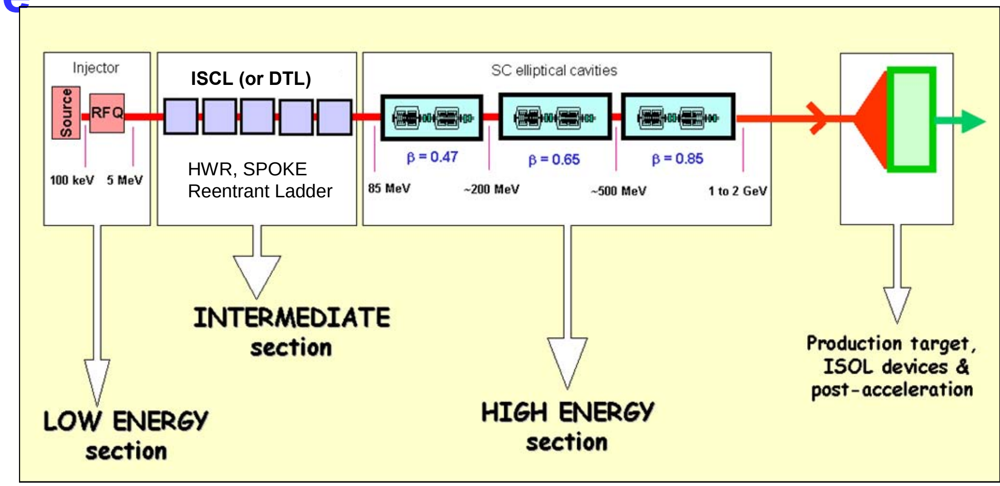
Production of n-reach isotopes by fission of ^{238}U

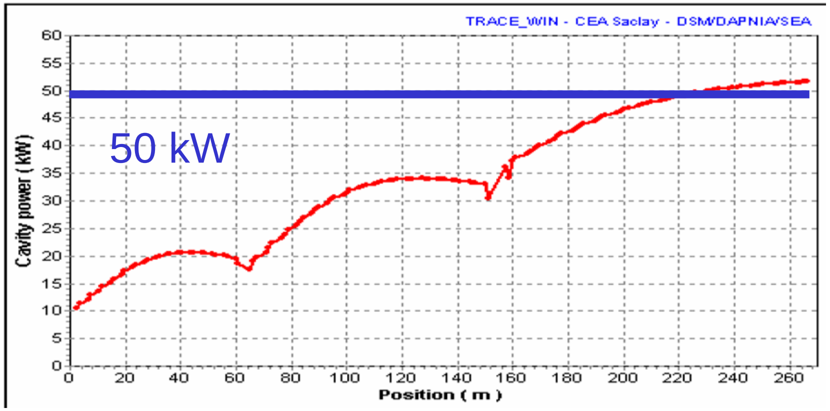


EURISOL	protons	5 mA *1GeV = 5 MW	10^{15} f/s 30 kW	10^{10} ^{132}Sn/s 2 pnA,100 MeV/u

EURISOL Linac layout (5 mA cw)

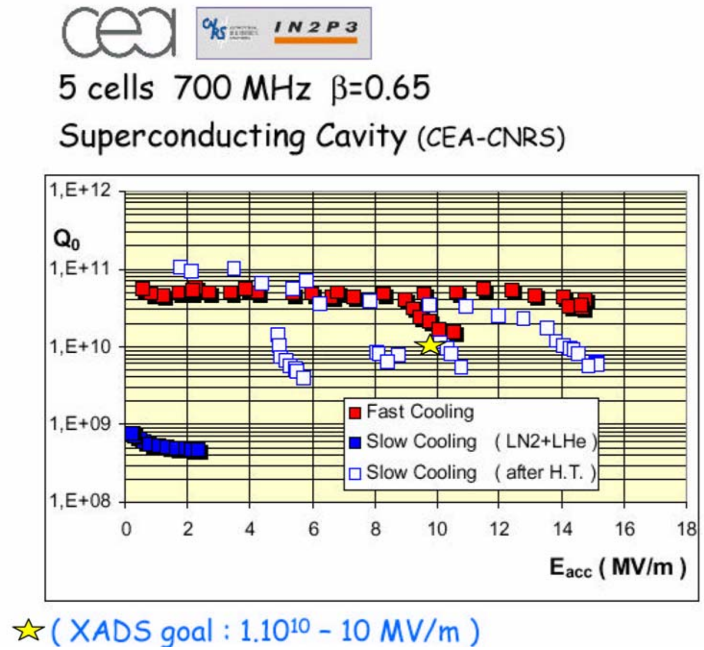
- For RIB users the **time structure of the primary beam is not a requirement** since they see the continuous beam after thermal effusion from the target.
- It is convenient to build a **CW linac** since,
  - It avoids thermal shocks in the target,
  - The linac operation is simplified due to the absence of Lorenz force detuning in the transient.
  - The RF power per cavity is minimized (about 50 kW), the **couplers** can be easily developed and **low power RF units** can be installed for each cavity, with an important simplification of phase control.

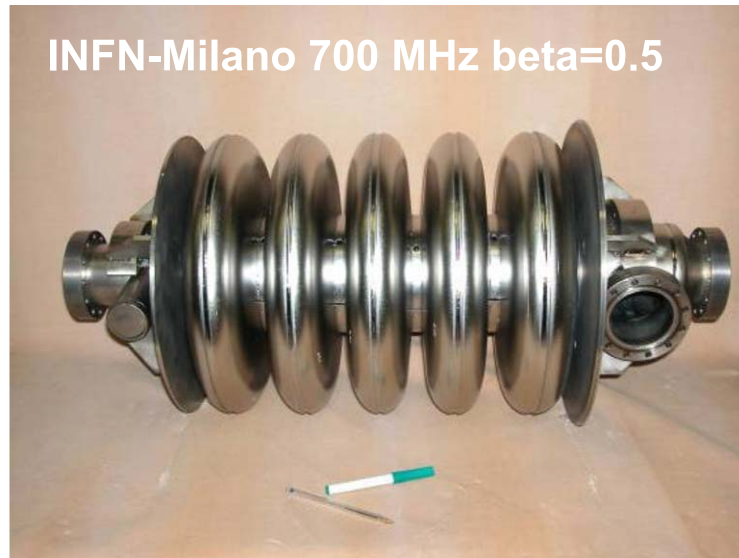


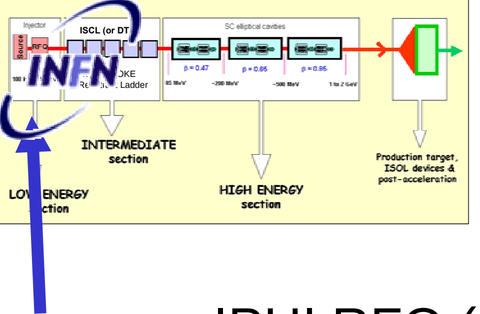


Mode of operation

- On the other hand, the analysis done by EURISOL target working group shows that a pulsed linac, with **repetition rate higher than 50 Hz, is acceptable for the high power target**. As a consequence, if EURISOL **shared** the driver with other applications (SPL at CERN), **the driver could be pulsed**.
- This also means that it is preferable that all the superconducting cavities developed for RIB production have the capability to work in pulsed mode.

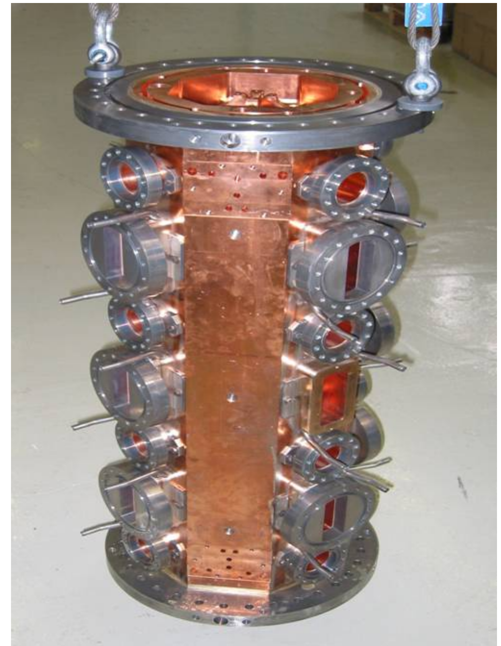




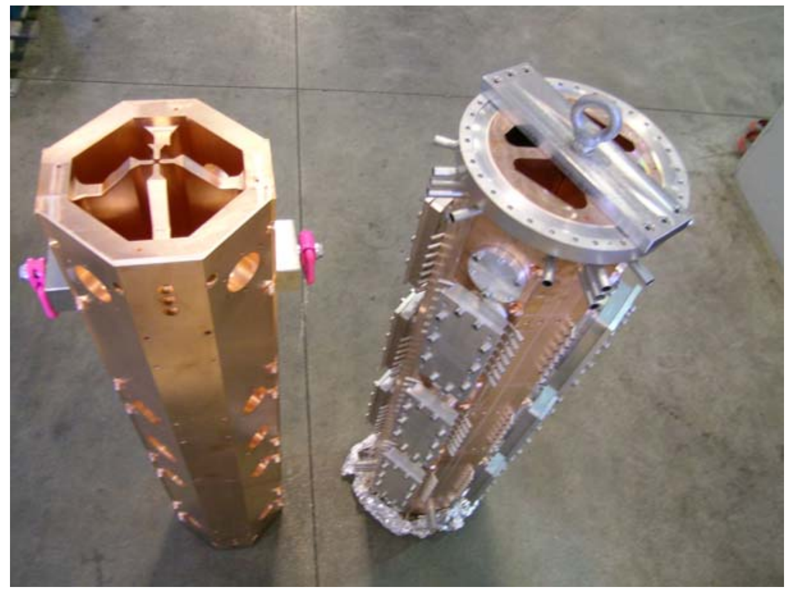


European 352 MHz cw RFQs

- IPHI RFQ (5 MeV 100 mA) will be built up to 3 MeV (first module brazed) and, after being tested cw at CEA Saclay, it will operate at CERN (Linac4) in pulsed mode.



- TRASCO RFQ (5 MeV, 30 mA) will be used as injector (10mA) of SPES at LNL (two modules brazed) and will be used at full current for interdisciplinary applications.



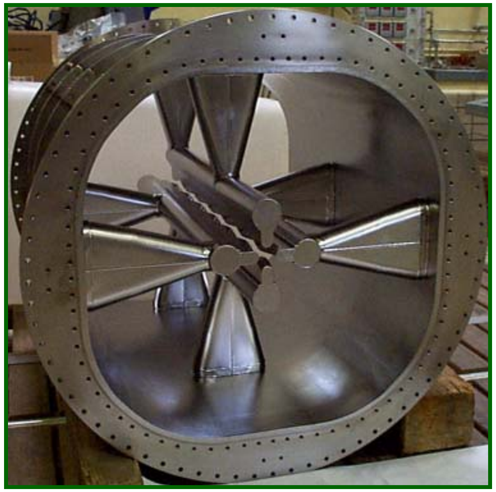
RF power considerations

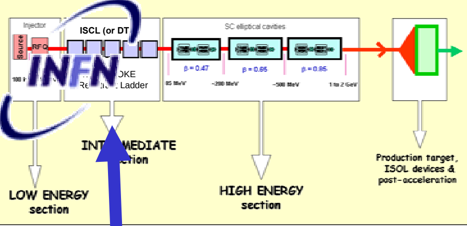
- The beam **loading in RIB case is rather small (25 kW**), and this makes the RFQ rather inefficient from an energy consumption point of view.
- Thus a lower intervane voltage structure like TRASCO RFQ suits better

	TRASCO	IPHI	
Intervane voltage	68	87-123	kV
RF dissipation	800	1200	kW
nominal beam load	150	500	kW
5 mA beam power	25		kW
beam losses (1%)	250		W

•It has also been considered, and excluded, the possibility to use a **superconducting RFQ** for this **cw low beam loading application.**

  •**It is very difficult to envisage beam losses lower than 1% (approx. 250W @ 4.2 K) in a RFQ**, with the mechanical tolerance achievable in a Nb construction.

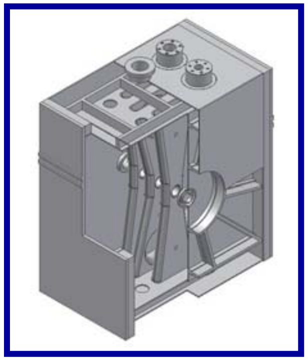




ISCL (352 MHz)
(Independent Superconducting Cavity Linac)

1 gap reentrant cavity LNL

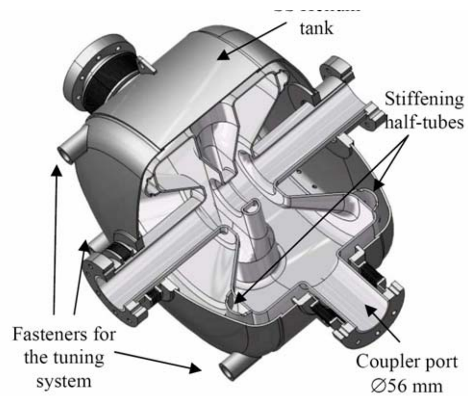
4 gap ladder cavity LNL beta=0.12



HWR LNL beta=0.31

5 MeV — **20 MeV** — **100 MeV**

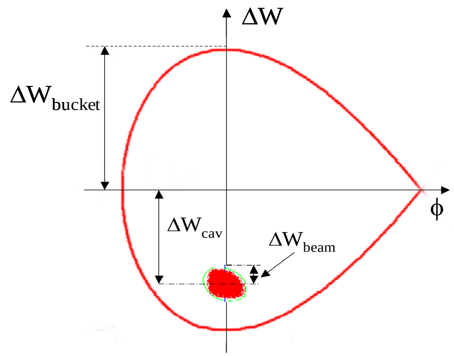
IPN Orsay beta=0.15



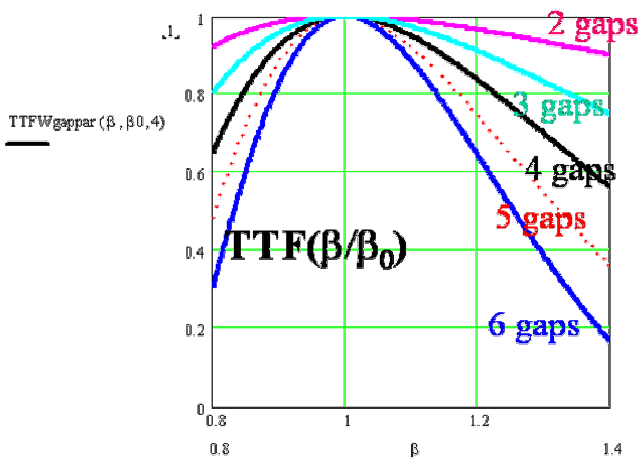
2 gap spoke- IPN Orsay
352 MHz, β=0.36

Advantages of ISCL

- Room temperature (DTL) and superconducting option have been compared. ISCL (ispired to the existing HI linacs) has the main advantages:
- **lower operating cost**
  - DTL and ISCL options seem to have similar costs, but with an important difference in AC power (8.8 MW compared with less than 1.5 MW) and it makes a big difference in the operating cost – of the order of **2 M€ per year**
- **Potential high reliability:**
  - it is possible to design a linac so that the beam survives in target if one cavity is off due to a fault
- **Heavy ion capability:**
  - changing the independent phases it is possible to accelerate (with full gradient) ions with different q/A



$$\Delta W_{bucket} > \Delta W_{beam} + \Delta W_{cavity}$$



Beam dynamics issues: DTL quality beams

- **DTL** guarantees a high quality beam in the main linac thanks to a **compact focusing structure**, important for a low $(\sigma - \sigma_0)/\sigma_0$ and for a smooth matching RFQ-DTL
- In a ISCL the focusing structure is the key choice, capable of allowing the efficient use of high performance cavities (Typical values for *ΔW,* energy gain par cavity, go from the 0.6 MeV of re-entrant cavities, to 1-1.5 MeV for multi gap structures).
- Low order resonances and envelope instability are avoided if

$$\sigma_{0L} \leq \sigma_{0T} \leq \pi/2 \qquad \text{with} \qquad \sigma_{0L} = L\sqrt{\frac{eE}{mc^2}\frac{2\pi\sin(-\phi_s)}{\beta^3\gamma^3\lambda}} \approx \sqrt{\frac{n\Delta WL}{\lambda}}\sqrt{\frac{2\pi\sin(-\phi_s)}{mc^2\beta^3\gamma^3}}$$

- **This limits the period length *L*, *n* cavity per period and *ΔW*** , since (in non rel approx):

$$\frac{n\Delta W}{W}\frac{L}{\beta\lambda} < \frac{\pi}{4\sin(-\phi_s)} \approx 1.5$$

Therefore high performance cavities need a compact lattice!

Beam dynamics in ISCL

- consequences
  - the use of **superconducting quadrupoles** to be installed **inside the cryomodule** is almost necessary at low energy (even if the solution with many short cryostats has been considered);
  - the **doublet lattice** is preferable with respect to the FODO lattice, allowing a larger space for cavities during each period.
  - **very compact cavities** in longitudinal direction are needed, even when this has to be compromised with smaller beam bore aperture.

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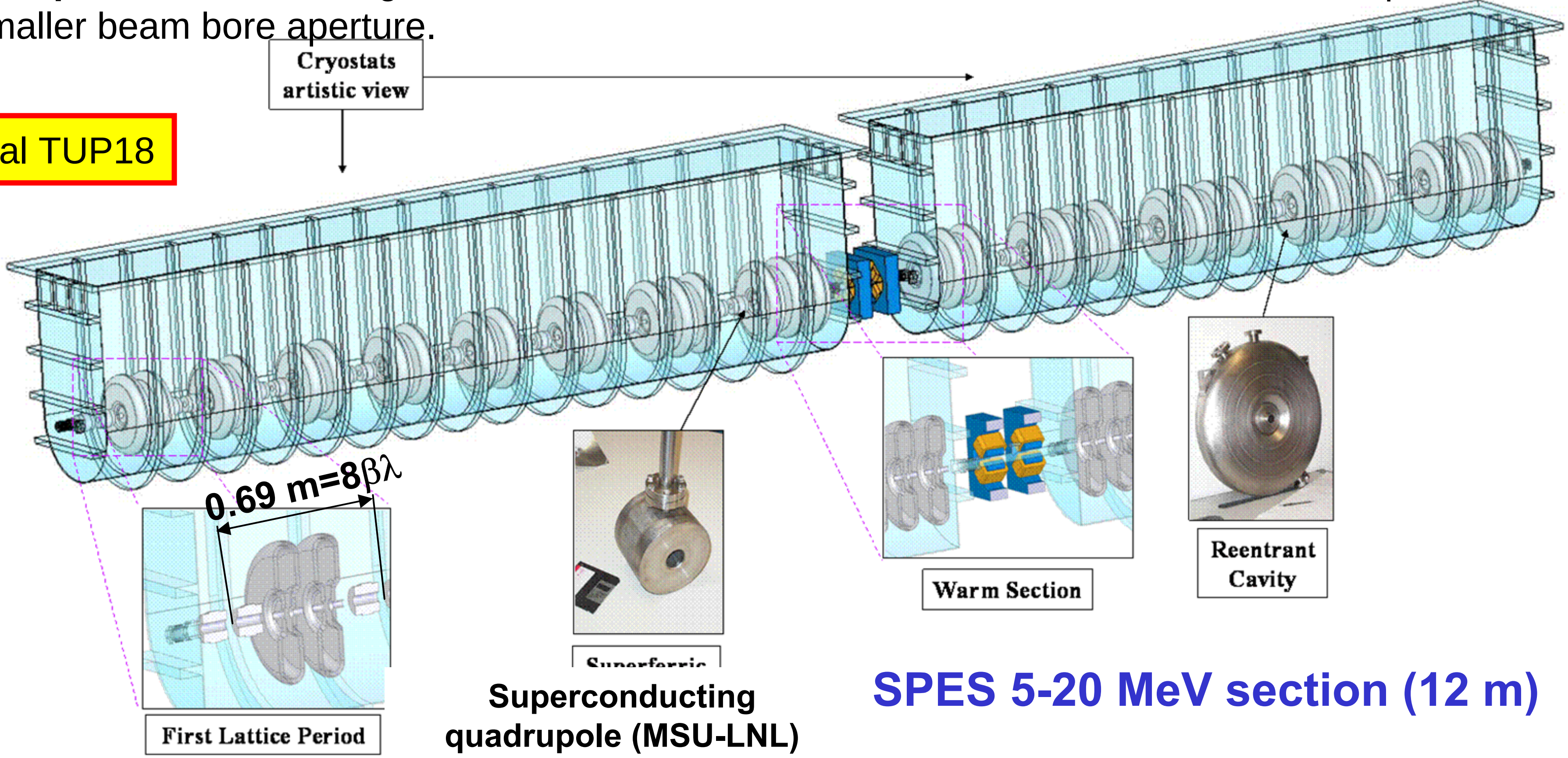
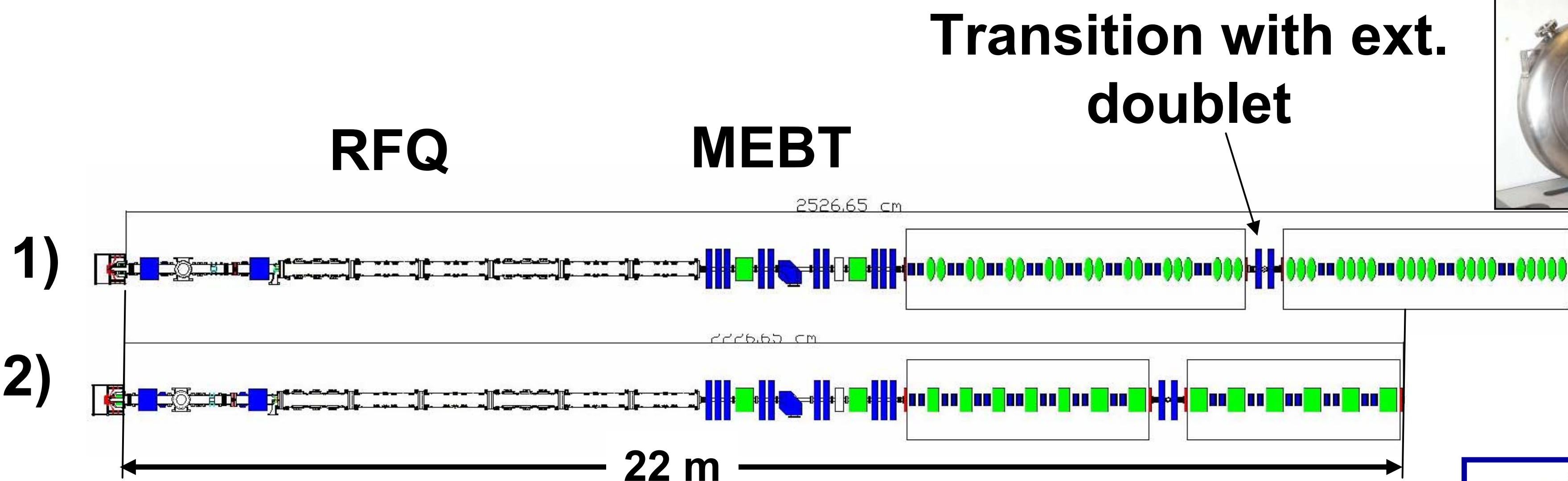


Superconducting quadrupole (MSU-LNL)

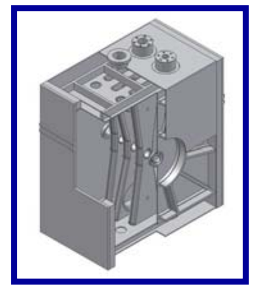
SPES 5-20 MeV section (12 m)

The 20 MeV 10 mA linac (alternatives)

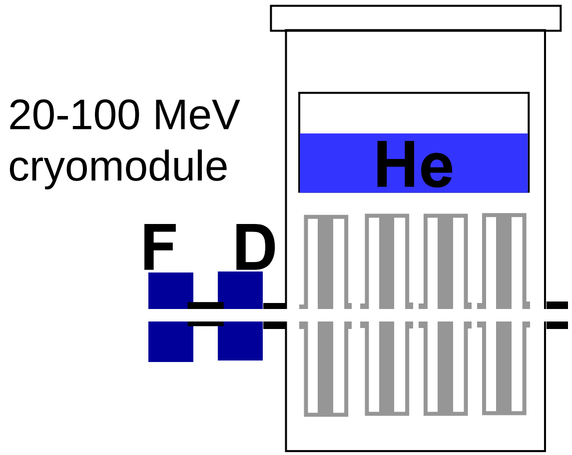


Straight linac with dipole for BNCT line (38 reentrant or 13 ladder)

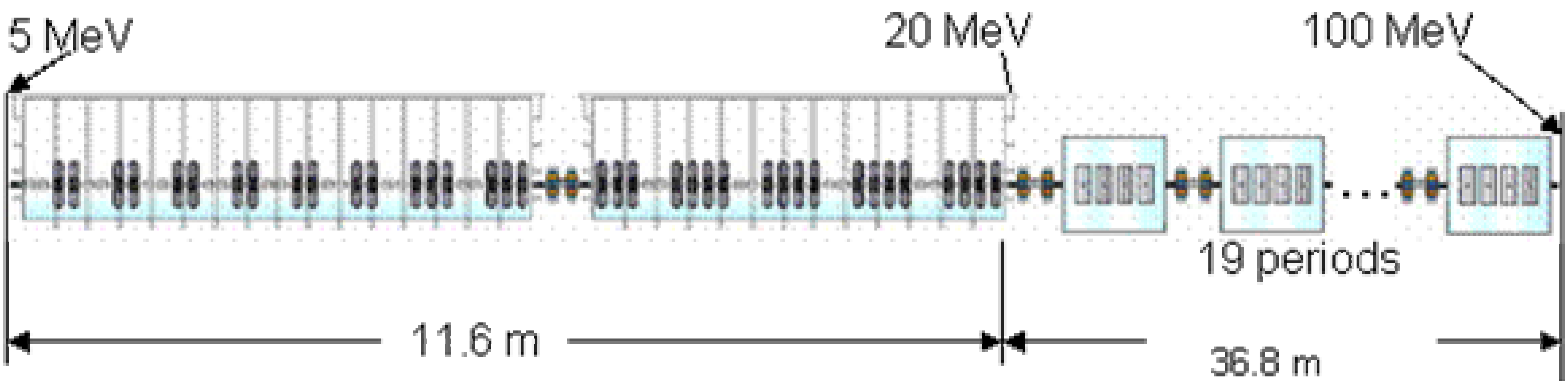
- **Full transmission (100K)**
- **<5% emittance increase**



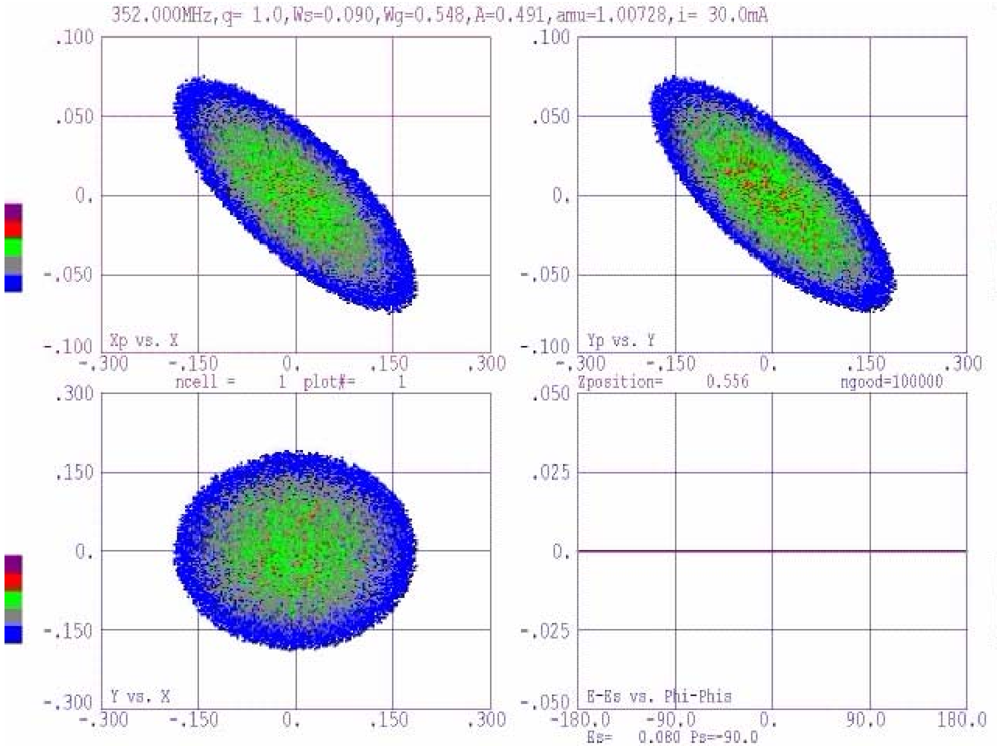
LNL 352 MHz, β=0.3 HWR

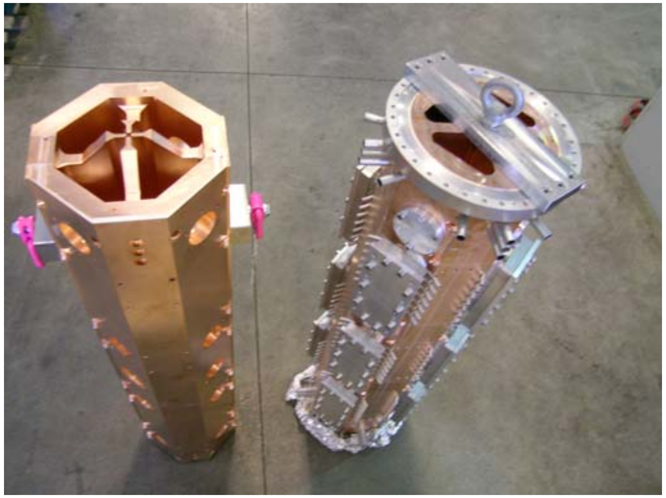


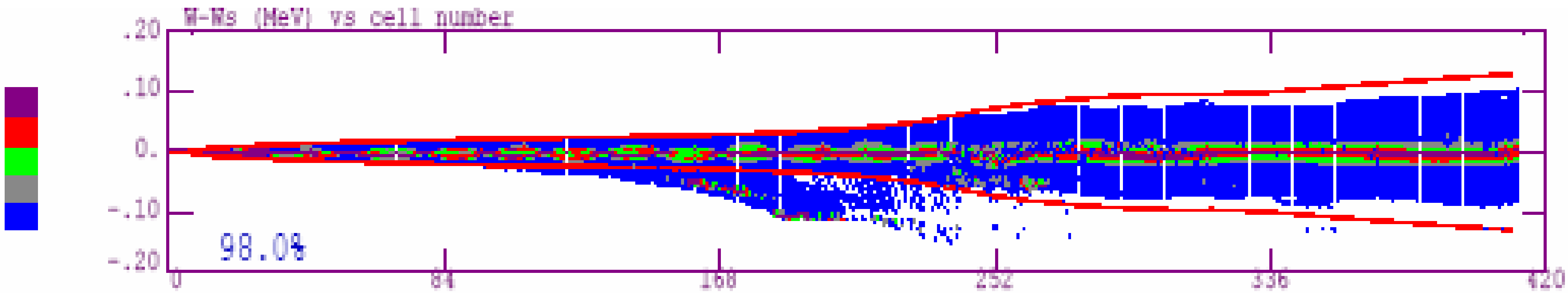
- Side tuner insensitive to He pressure changes
- Real estate length: 286 mm; active length: 224 mm, $\beta\lambda$=256 mm)



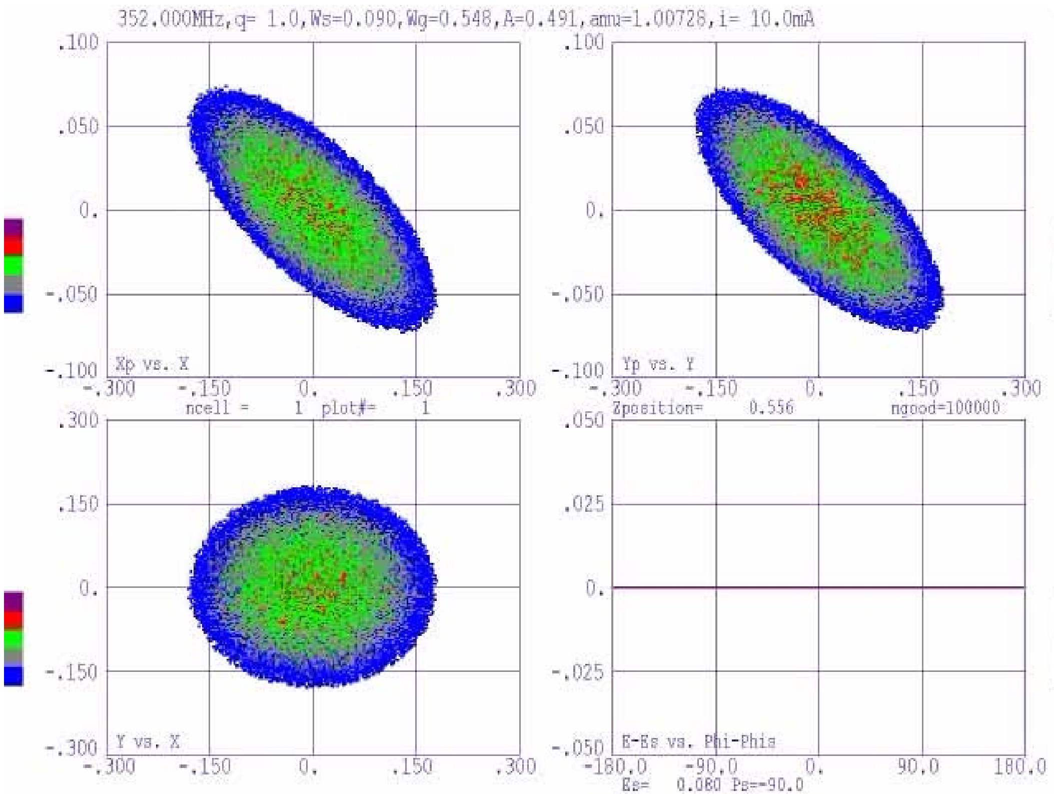
Beam dynamics in TRASCO RFQ (30 mA)

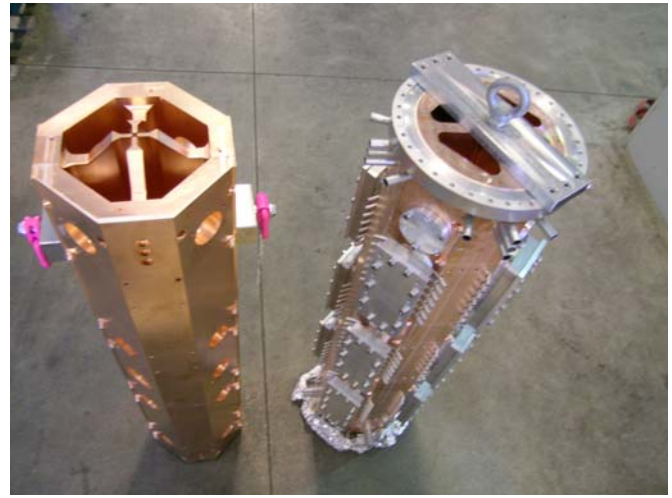


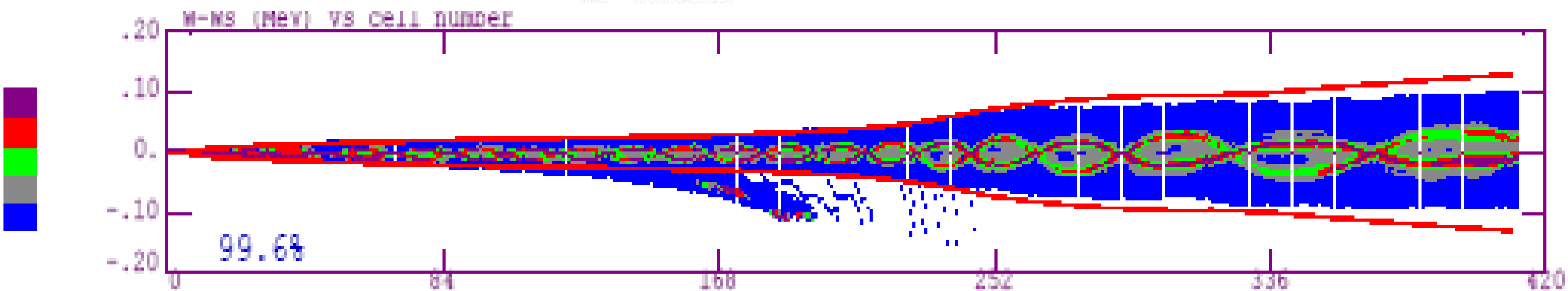




Beam dynamics in TRASCO RFQ (10 mA)







Beam Parameters vs. input current

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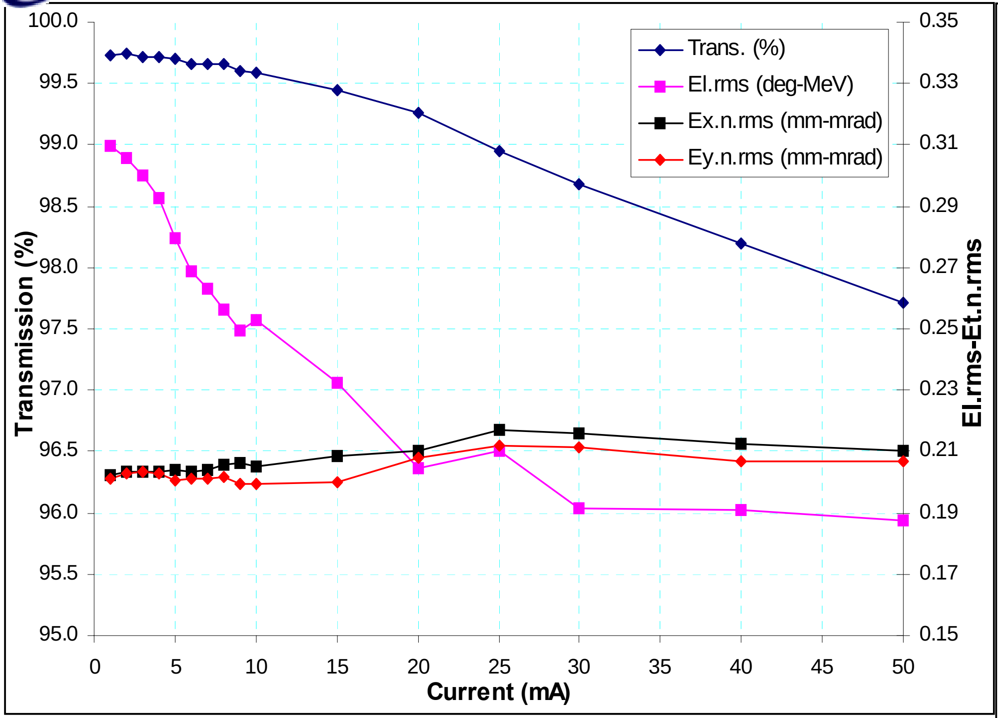
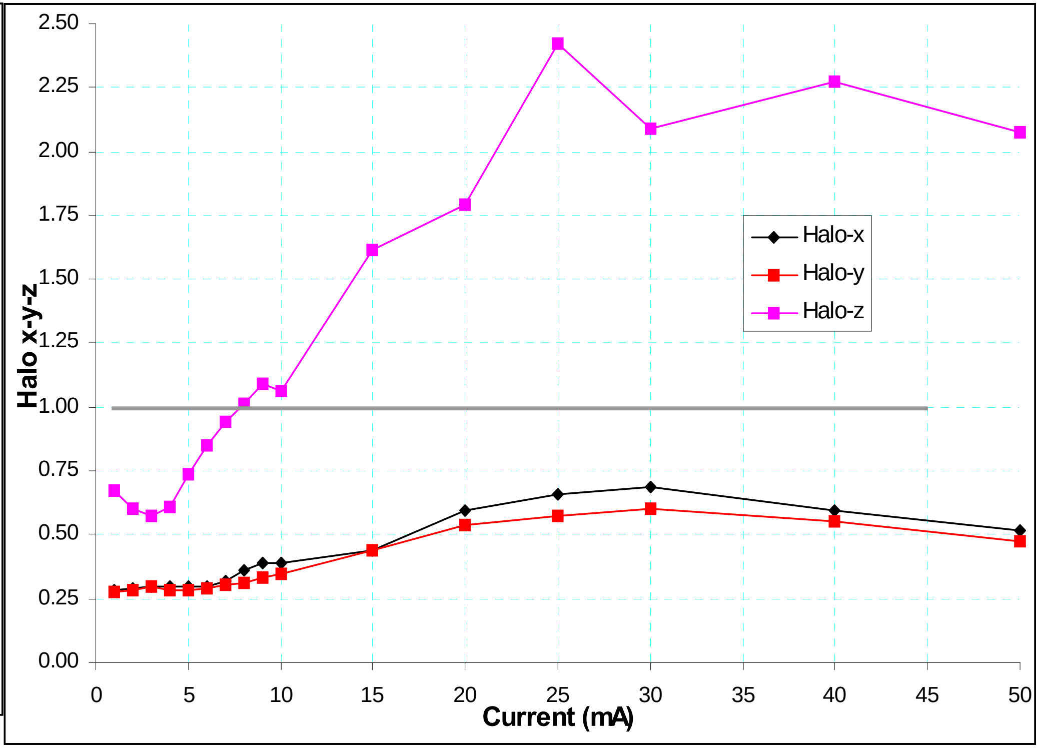




$$I_2 = \langle q^2\rangle\langle p^2\rangle - \langle qp\rangle^2$$

$$I_4 = \langle q^4\rangle\langle p^4\rangle + 3\langle q^2 p^2\rangle^2 - 4\langle q p^3\rangle\langle q^3 p\rangle$$

$$H = [(3 I_4)^{1/2} / 2 I_2] - 2$$

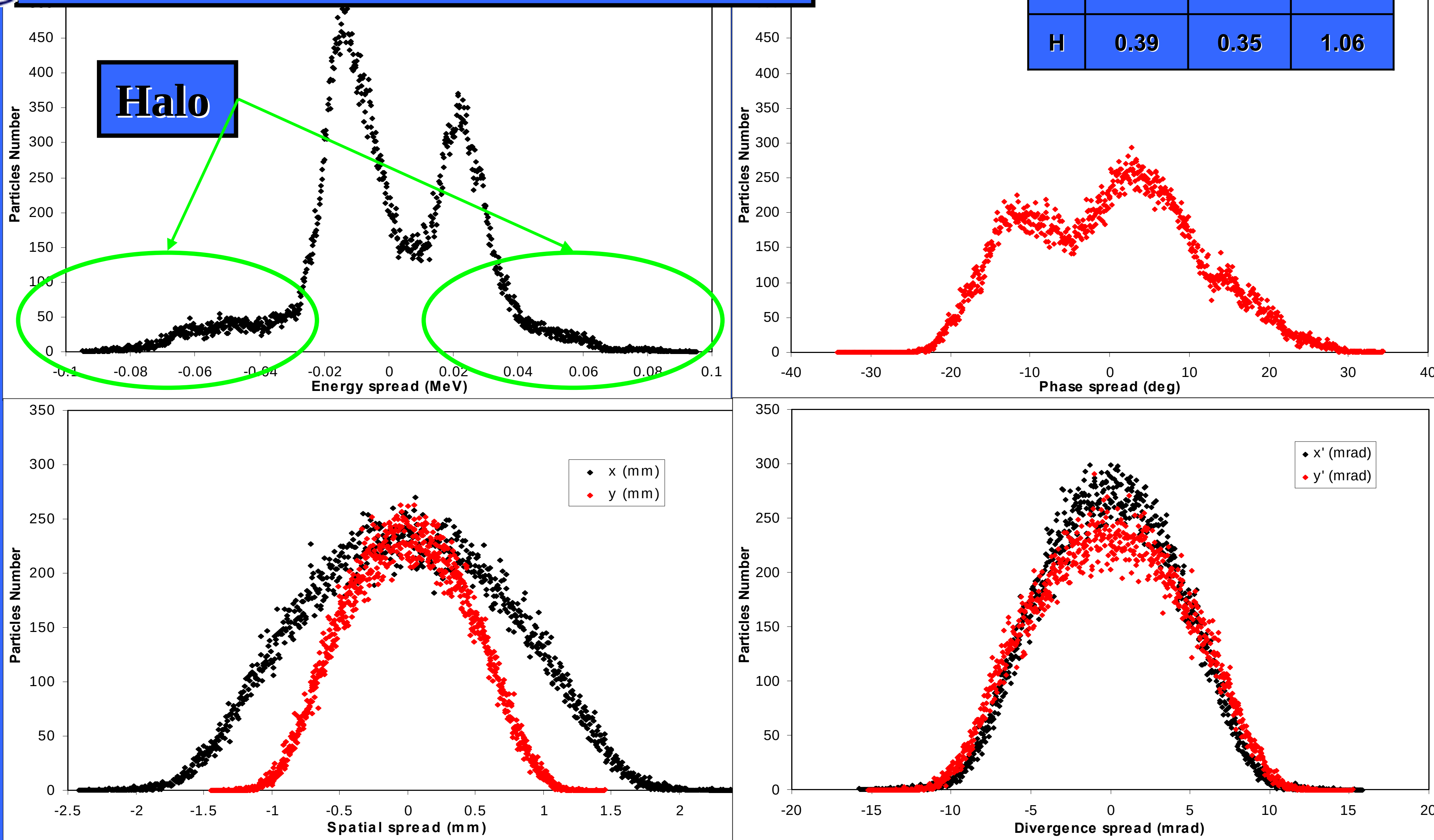
Halo Limit ~ 1 for gaussian beams

Transversal phase-space may be considered halo free for all currents

Longitudinal phase-space presents a halo structure increasing with current

Halo parameters for a 10 mA beam

	X	Y	Z
h	0.35	0.36	0.35
H	0.39	0.35	1.06

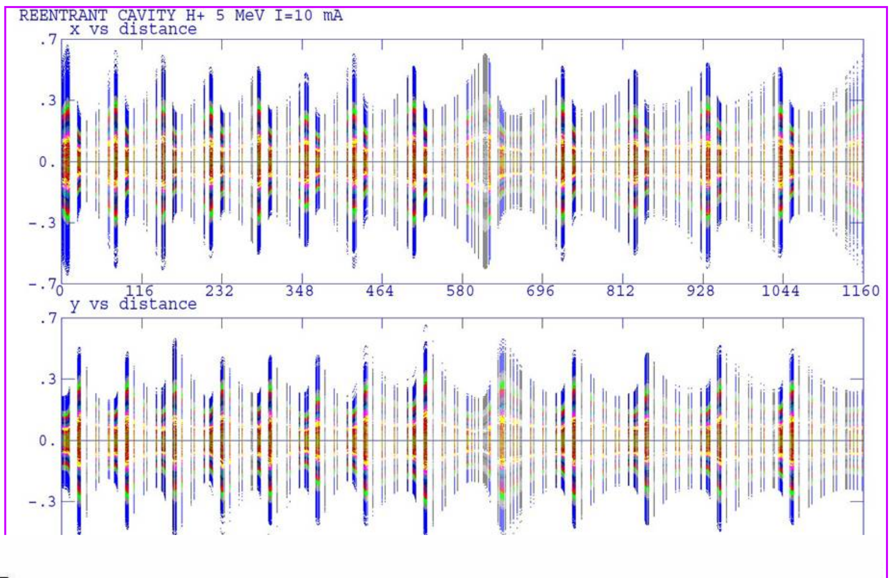


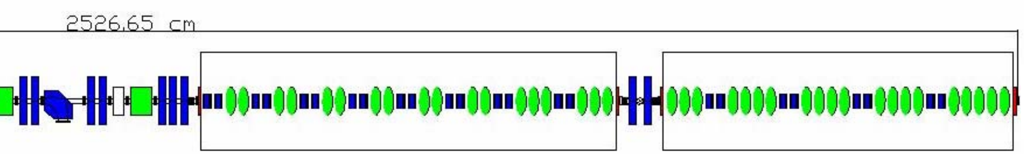
Beam distribution at RFQ out for 10 mA input current

Beam dynamics with construction errors (20 MeV)

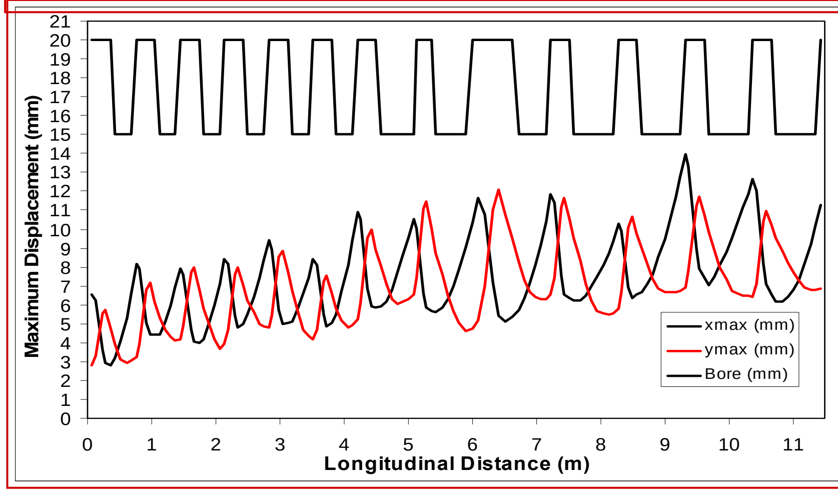
Input conditions (actual RFQ distribution)

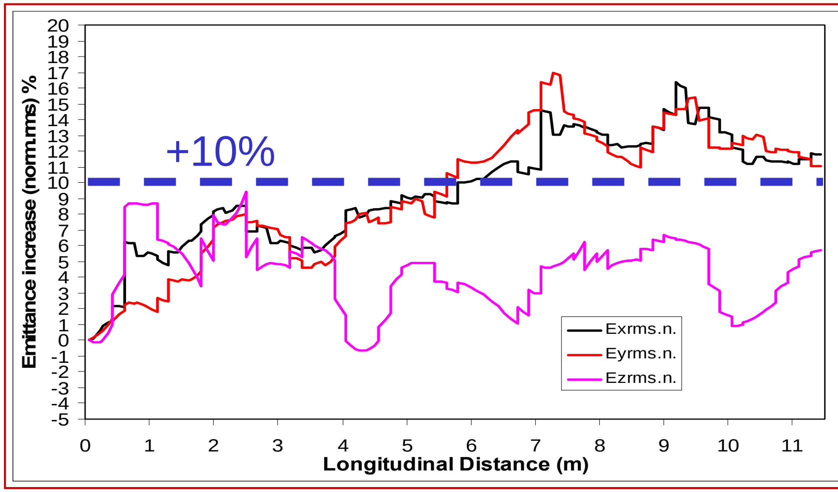
Current	**10 mA**	
Energy	**5 MeV**	
Emit. norm. rms	**x**	**0.208 mm-mrad**
	y	**0.204 mm-mrad**
	z	**0.240 deg-MeV**





Maximum rms emittances increase versus longitudinal length for 200 independent with about 100000 macroparticles (2W a 20 MeV).





errors

Quadrupole transverse displacements	**0.2 mm**
Quadrupole tilt	**3.5 mrad**
Quadrupole roll	**3.5 mrad**

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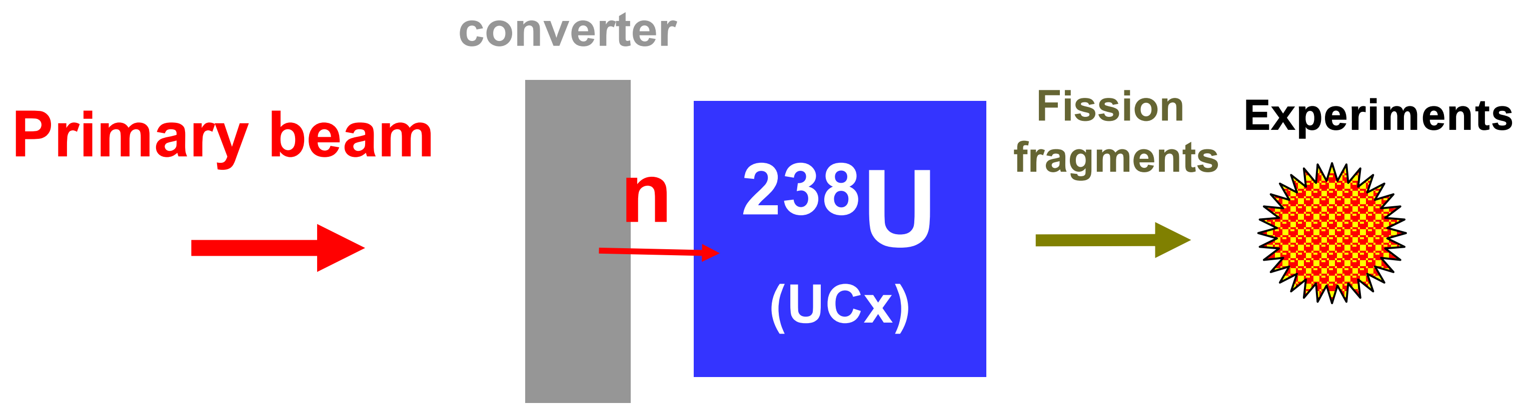
New ISOL facilities in EUROPE

- Some new ISOL facilities have been proposed in Europe for the next decade. In EURISOL-DS proposal and in NuPECC Long Range Plan a road map with the realization of these new facilities on national laboratory scale is described.

Location	RIB Starting Date	Driver	Post-accelerator
SPIRAL-II: GANIL Caen, France	2008	SC linear accelerator LINAG deuterons up to 40 MeV heavy ions up to 15 *A* MeV	cyclotron CIME *K* = 265, 2–25 *A* MeV
MAFF Munich, Germany	2008	reactor 10^{14} $n/cm^2.sec$	linac up to 7 *A* MeV
SPES Legnaro, Italy	2008 (Initial phase funded: SPES-1)	SC proton linac 100 *MeV* SPES-1 20 *MeV*	ALPI linac 15-20 *A MeV*
ISOLDE upgrade CERN	2008	PS booster p, 1.4 GeV, 10 μA	linac up to 5 *A* MeV

Production of n-reach isotopes by fission of ^{238}U



EURISOL	protons	5 mA *1GeV = 5 MW	10^{15} f/s 30 kW	10^{10} ^{132}Sn/s 2 pnA, 100 MeV/u

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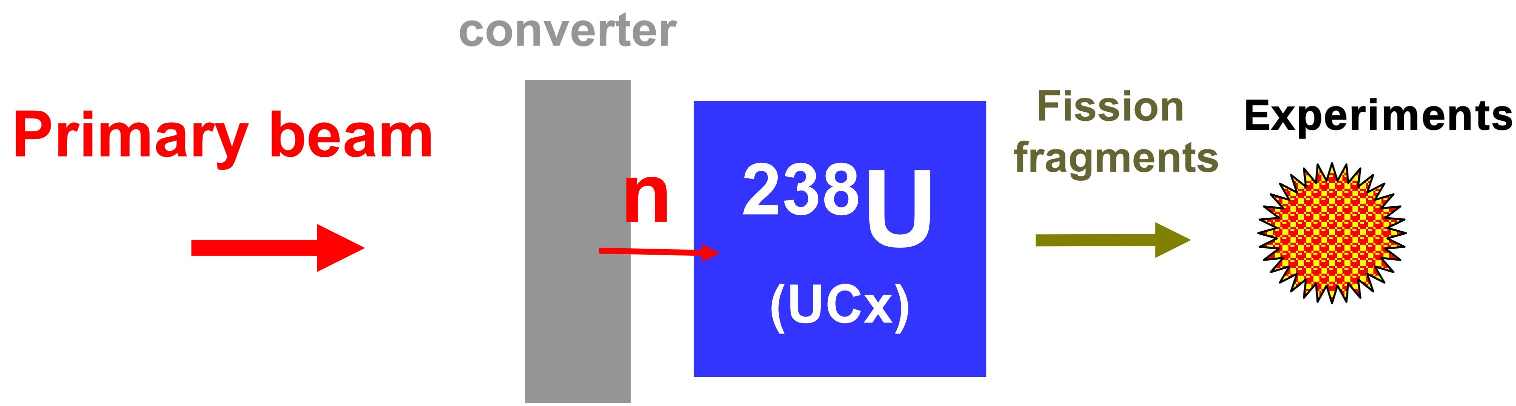
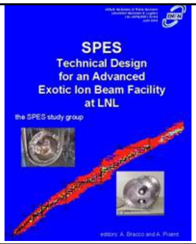
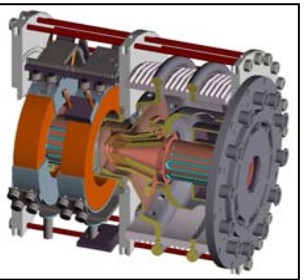
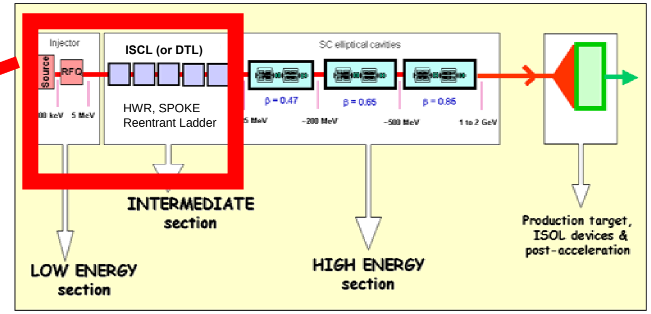


EURISOL	protons	5 mA *1GeV = 5 MW	10^{15} f/s 30 kW	10^{10} ^{132}Sn/s 2 pnA, 100 MeV/u
 SPES	protons	1 mA *100 MeV = 100 kW Be or ^{13}C	10^{13} f/s 300 W	10^{8} ^{132}Sn/s 0.02 pnA, 16 MeV/u
Spiral2	deuterons	5 mA *40 MeV = 200 kW ^{12}C	10^{13} f/s 300 W	cyclotron CIME K = 265, 2–25 A MeV





SPES driver

Source TRIPS

BNCT

5 MeV

RFQ

ISCL

Be converter

U target

Ion source

100 MeV

Pre-separator

Charge breeder

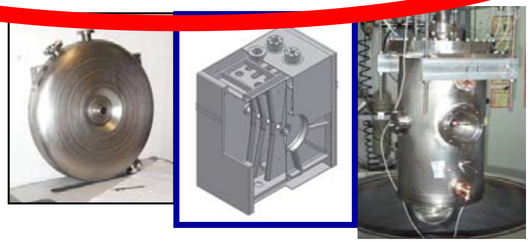
Isotope separator

High resolution spectrometer

SRFQ

ALPI

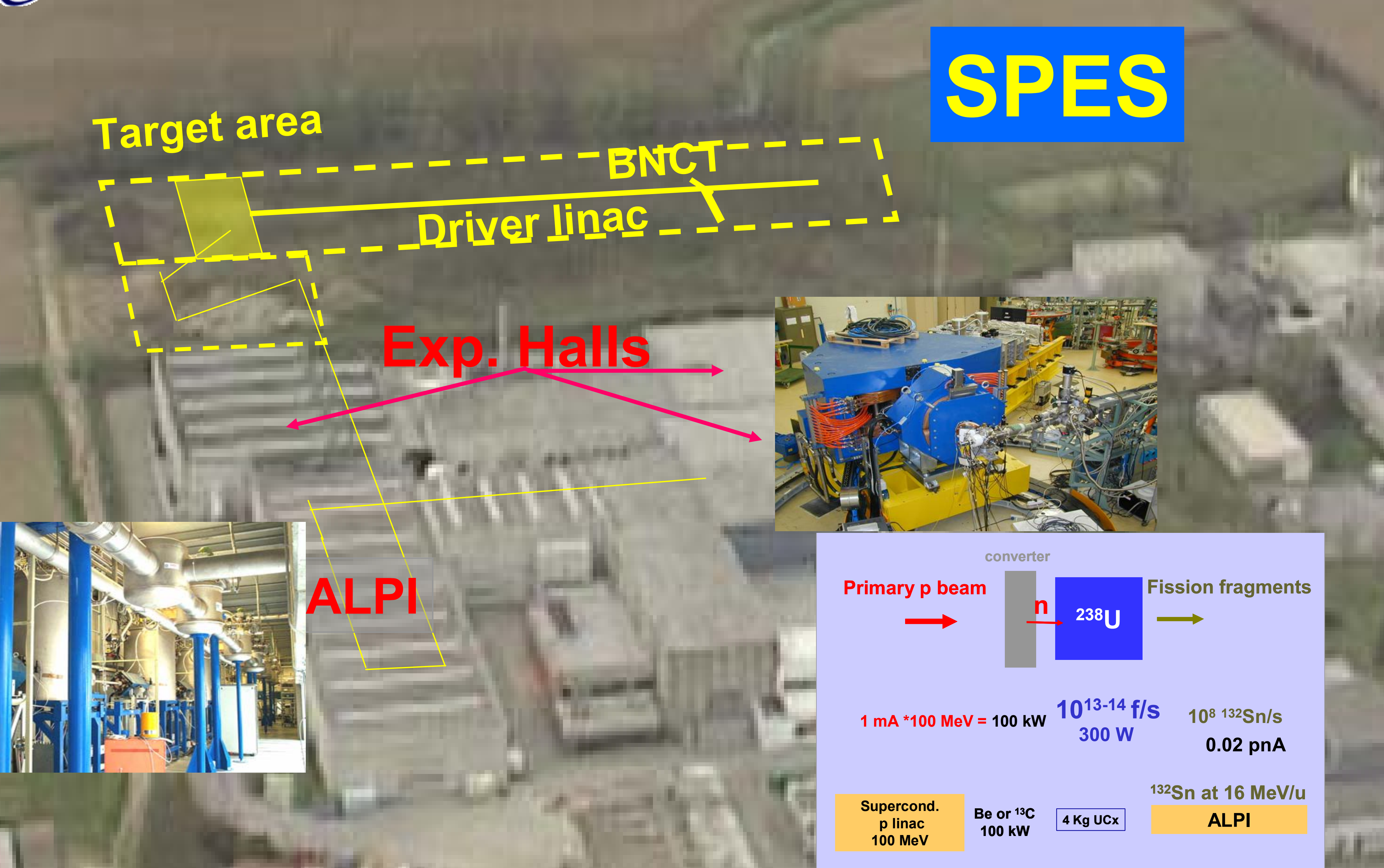
Exp.



SPES block diagram

(Study and Production of Exotic Species)

Legnaro National Laboratory aerial view

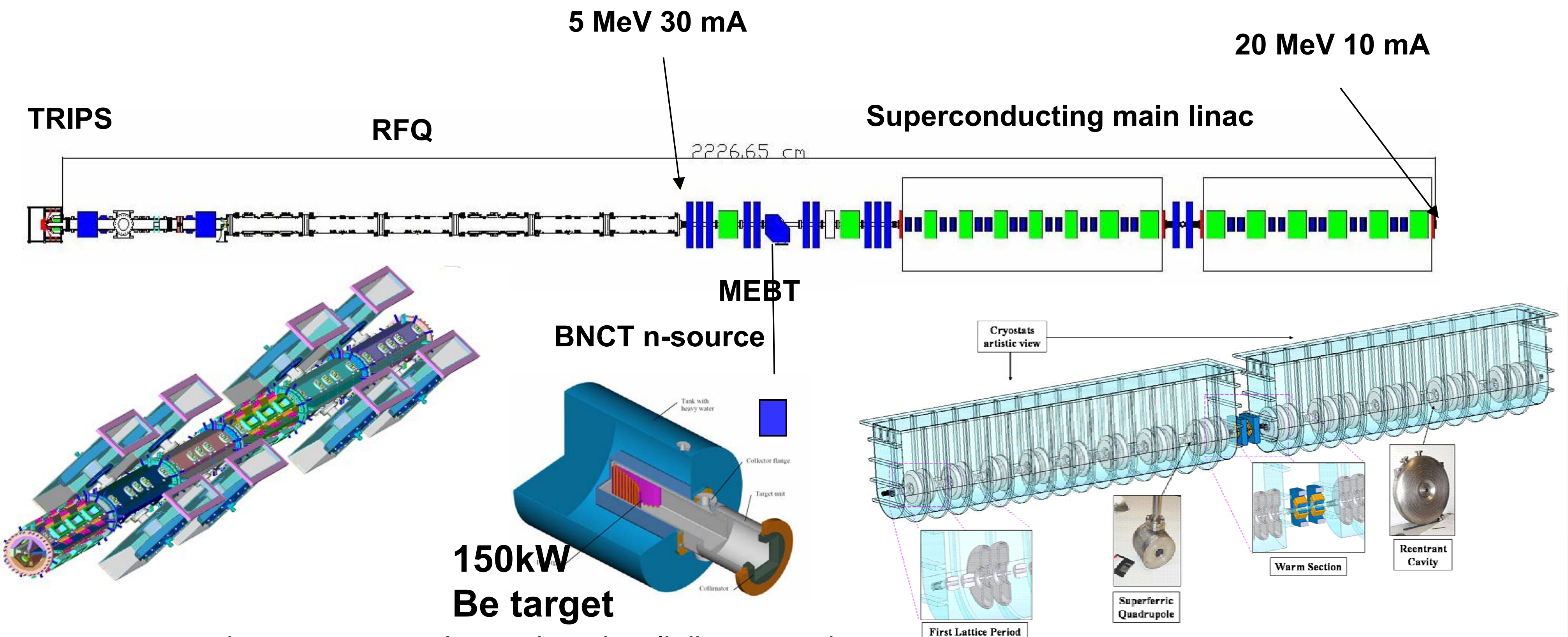


SPES-1 approved at LNL:

1. Realization of the 5 MeV 30 mA p injector (based on TRASCO technology)
2. Development and construction of the thermal neutron facility (10^9 cm^{-2} s^{-1} using 30 mA 5 MeV) for BNCT (Boron Neutron Capture Therapy)
3. Development and construction of the superconducting p linac, for a maximum current of 10 mA, up to 20 MeV
4. Further development of the R&D program on RIB production targets

Since Jan '04 SPES-1 is a funded INFN Special Project

(18.6M€, five years)



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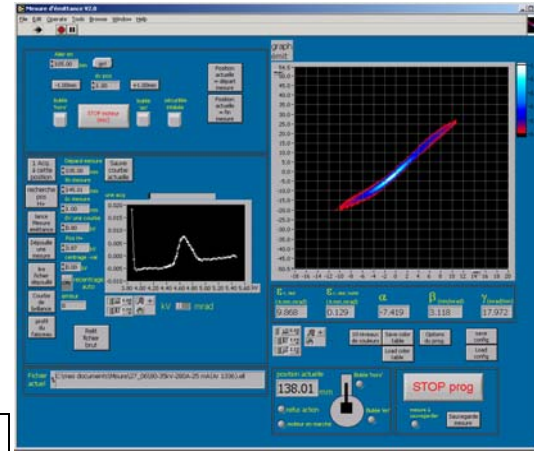
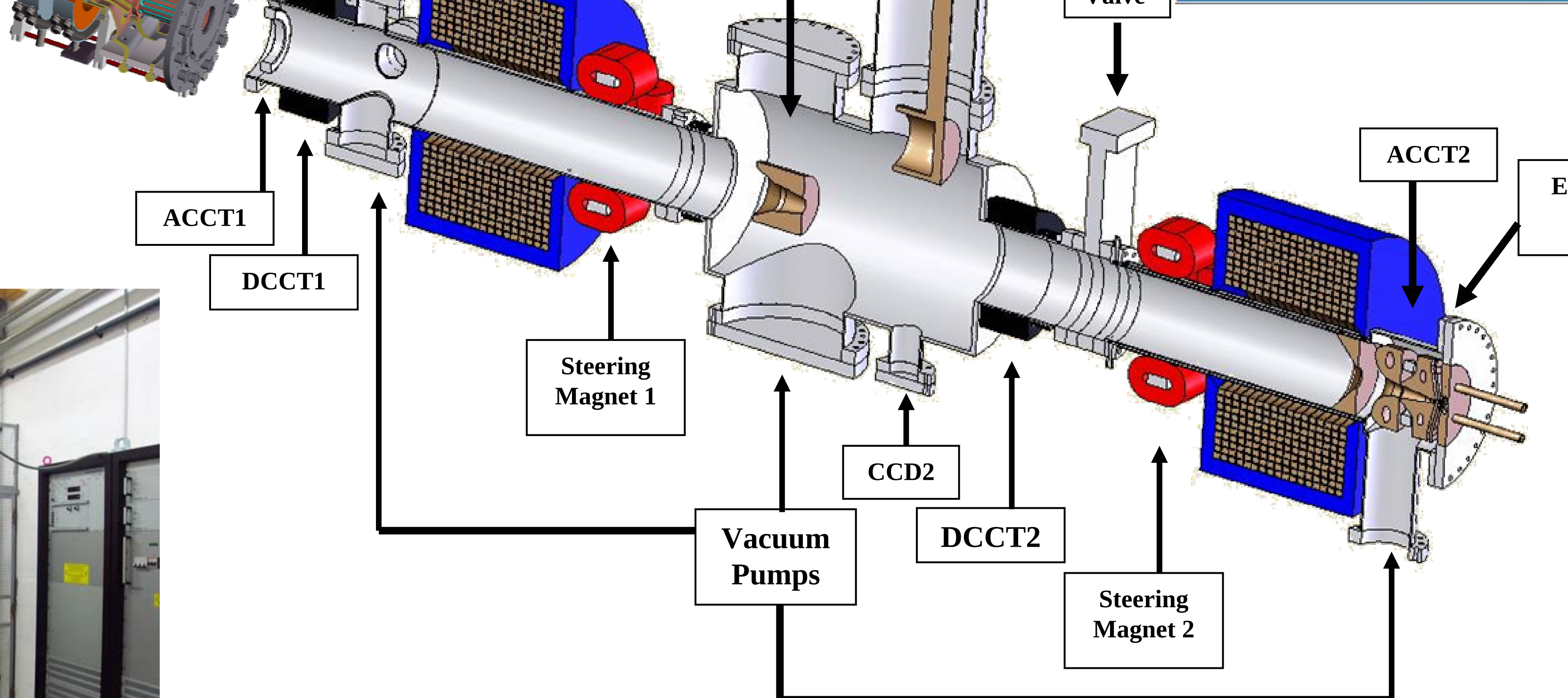
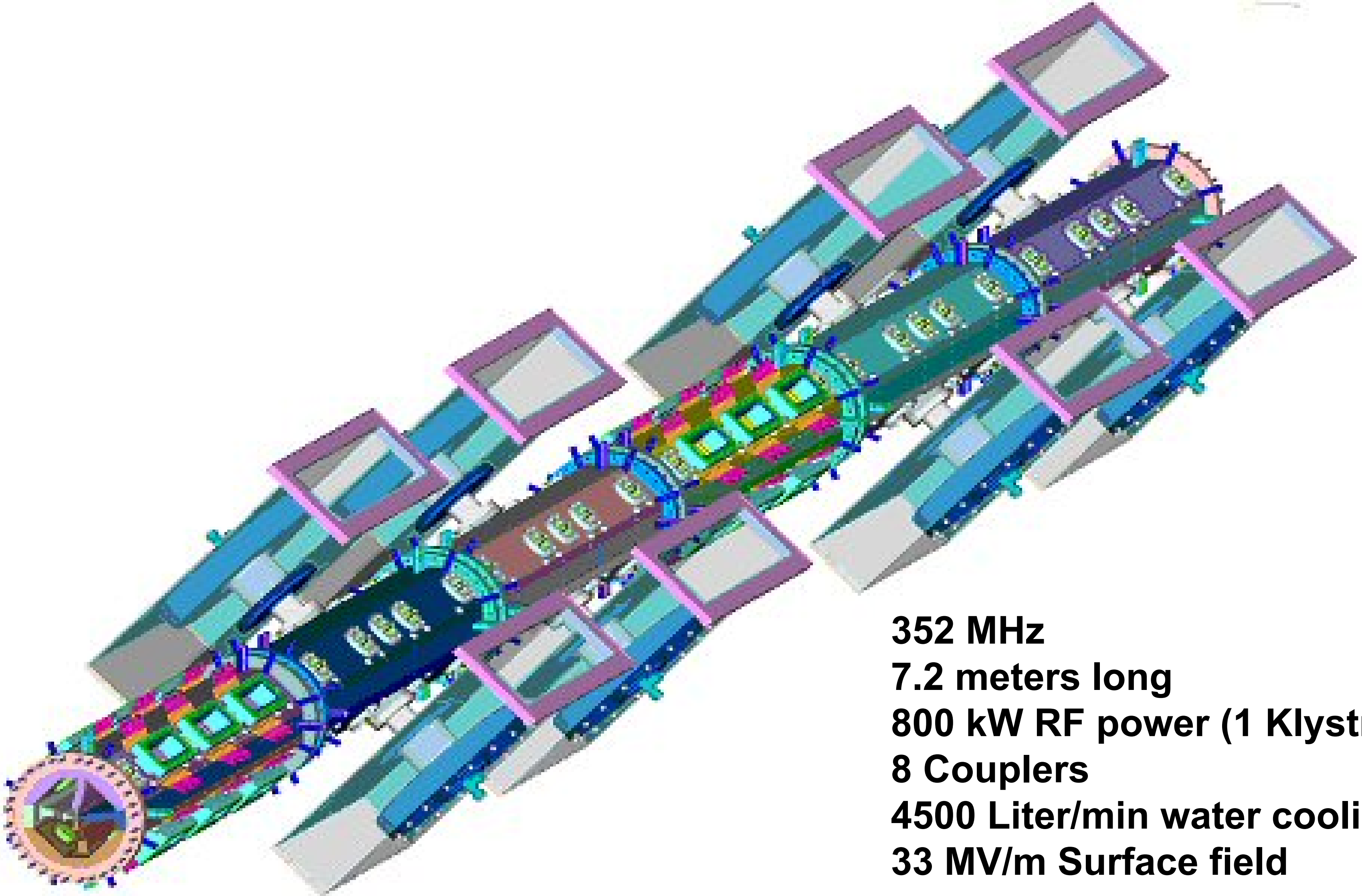
TRIP source and LEBT

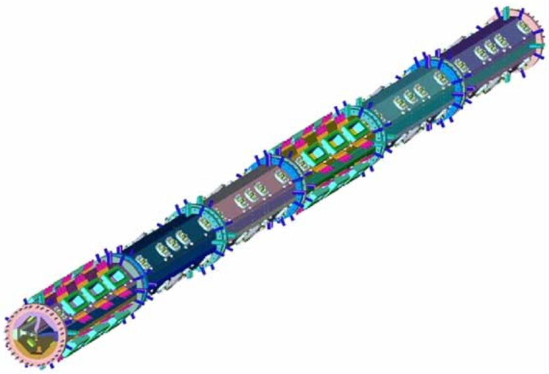




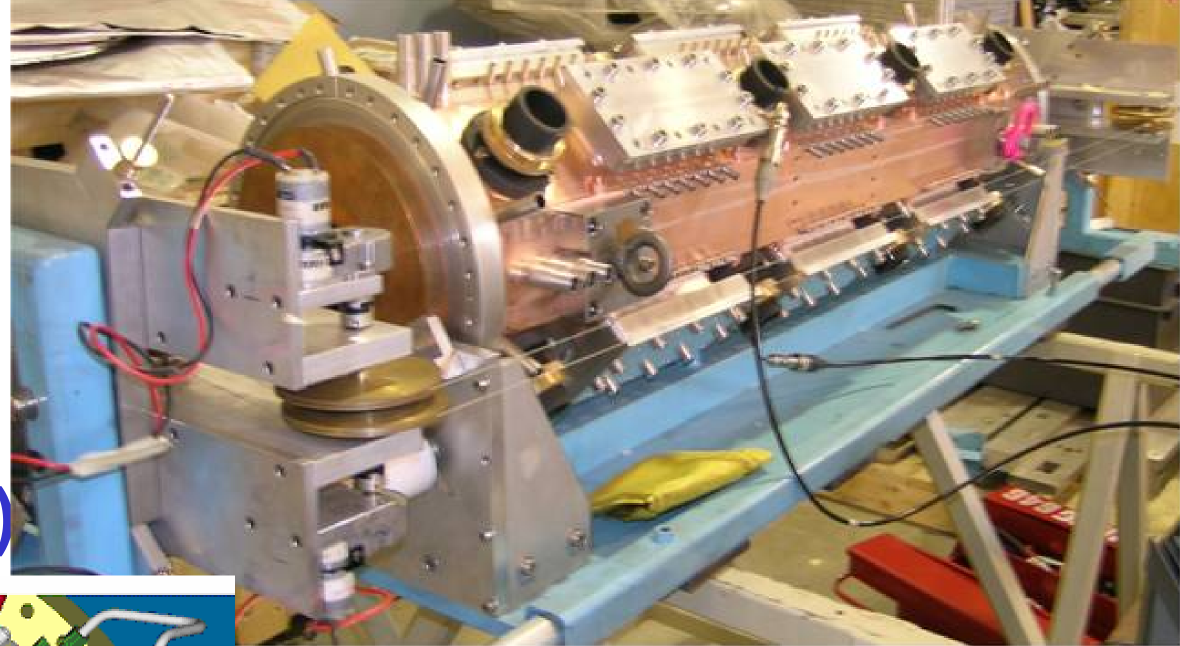
TRASCO-SPES 5 MeV 30 mA CW RFQ

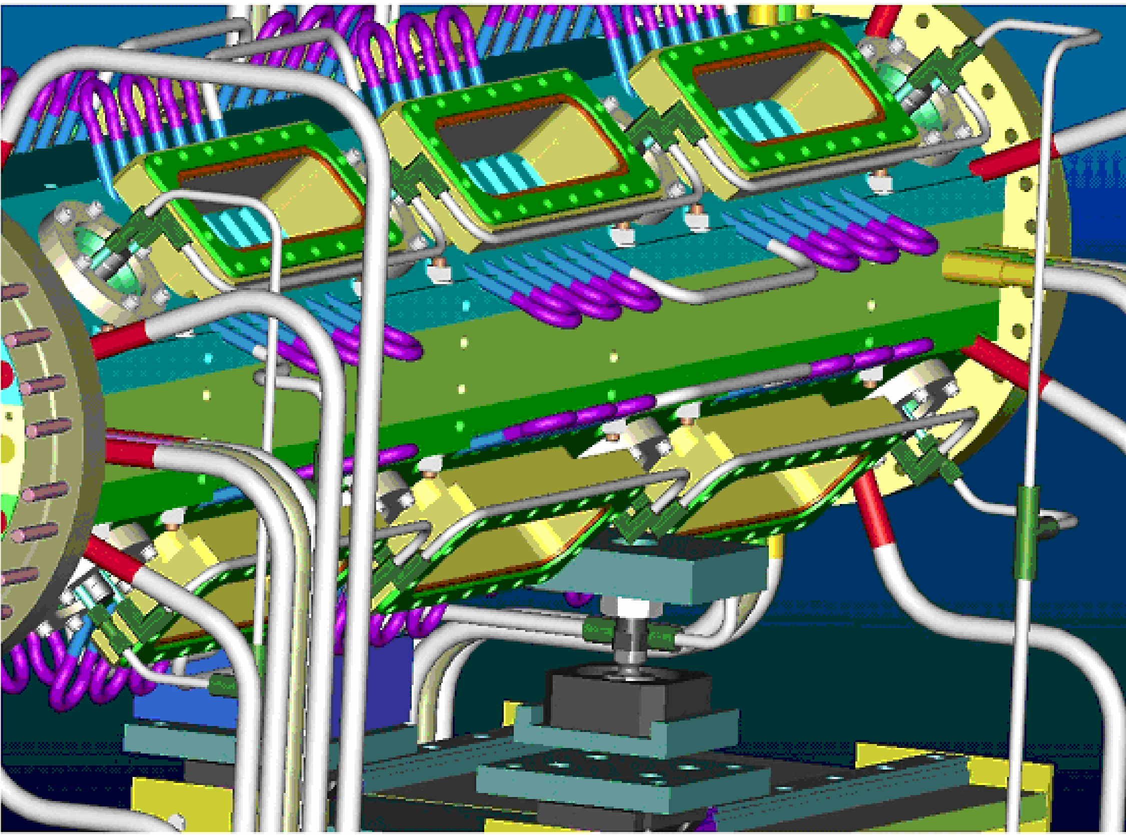


352 MHz
7.2 meters long
800 kW RF power (1 Klystron)
8 Couplers
4500 Liter/min water cooling
33 MV/m Surface field



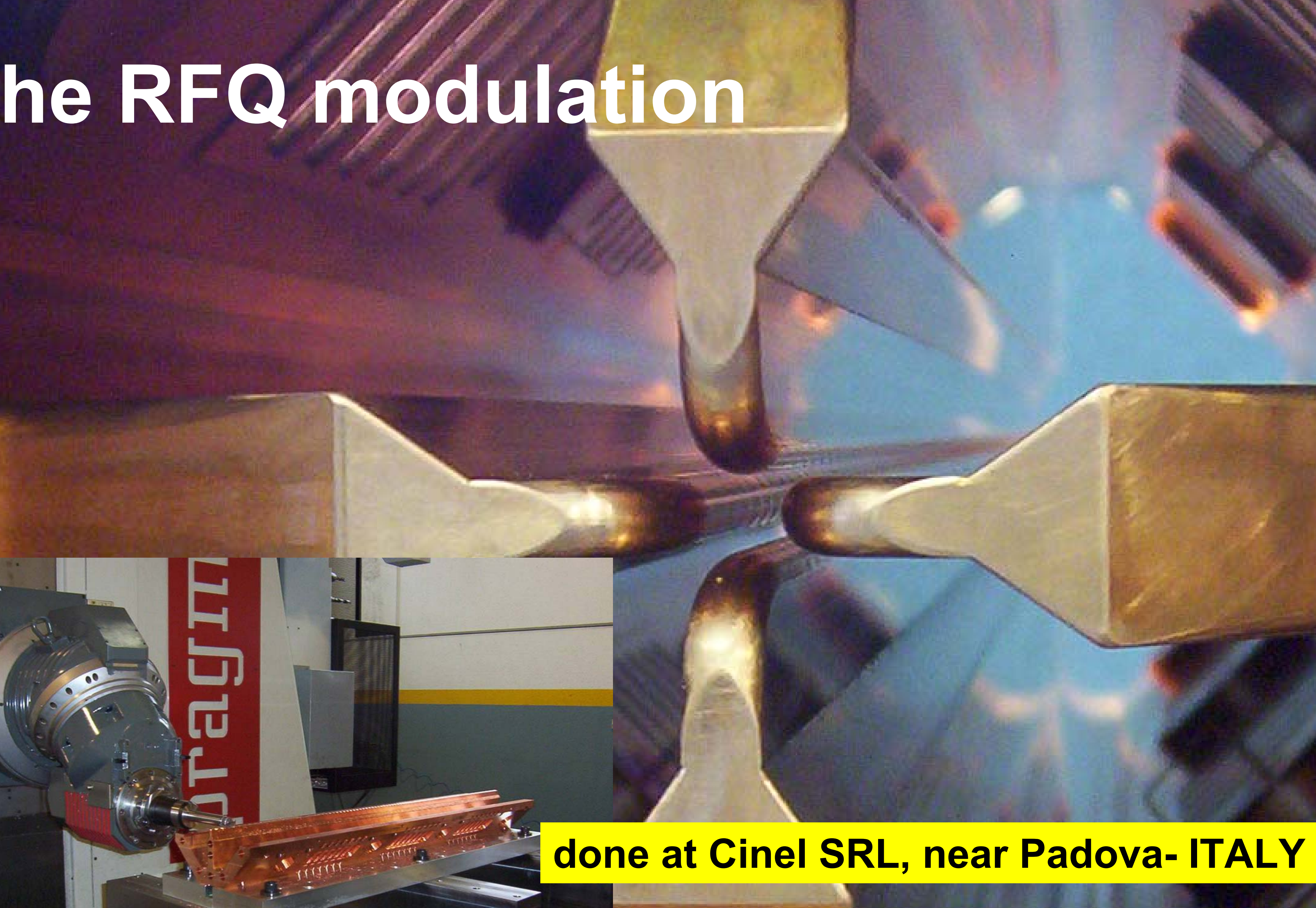
TRASCO RFQ construction (Cinel, Italy)





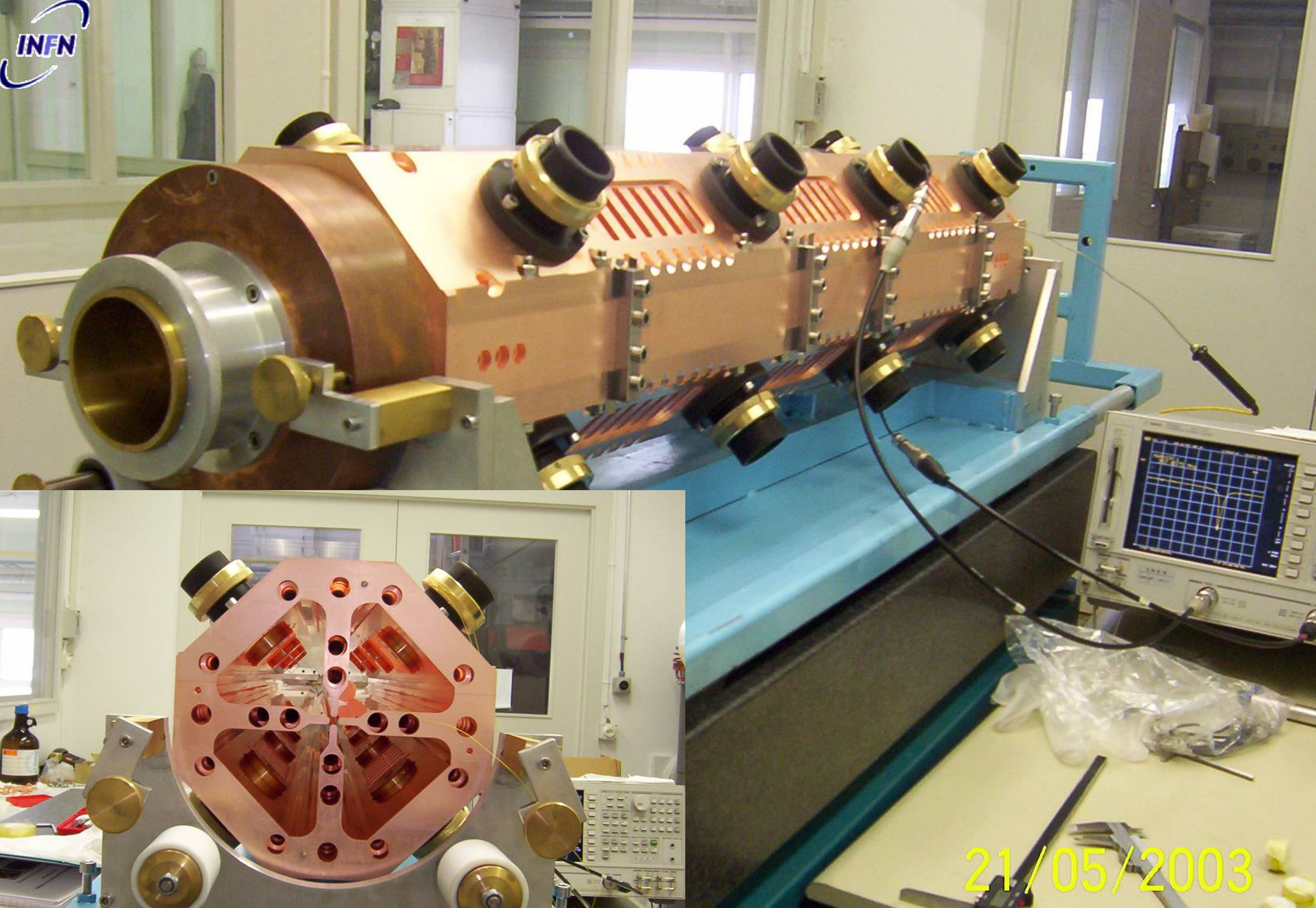
Italy)

he RFQ modulation

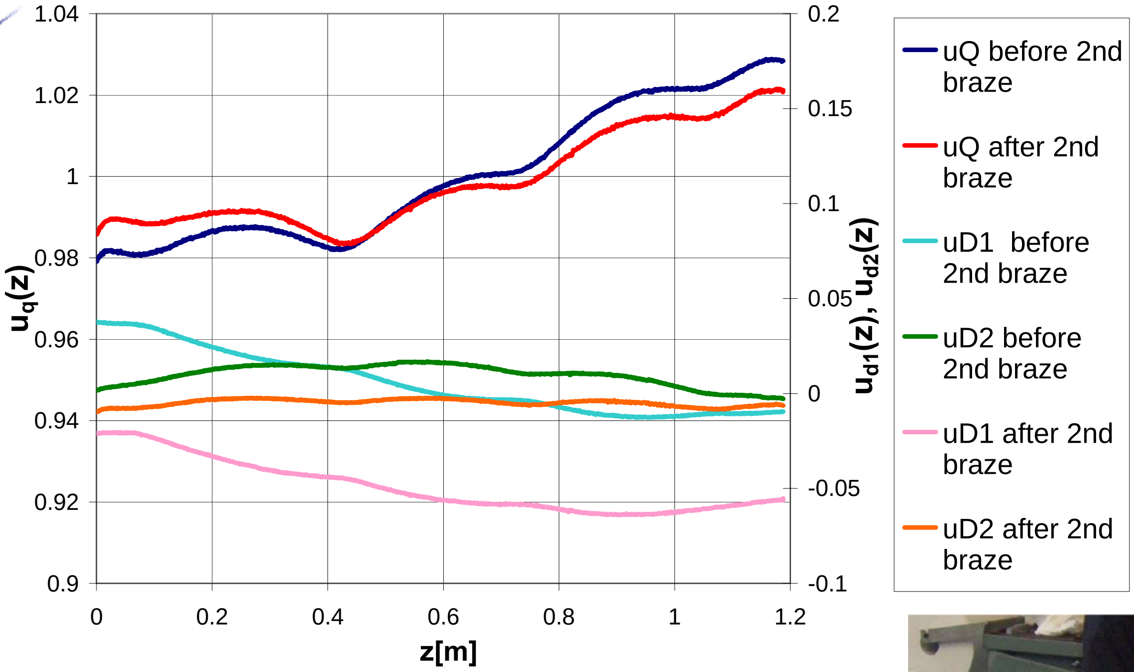


done at Cinel SRL, near Padova- ITALY

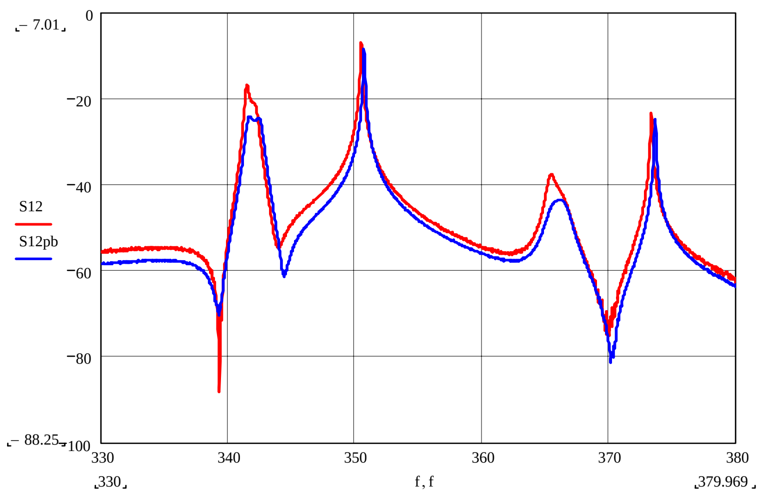

Piccola industria veneta: alta competenza in meccanica, flessibilità

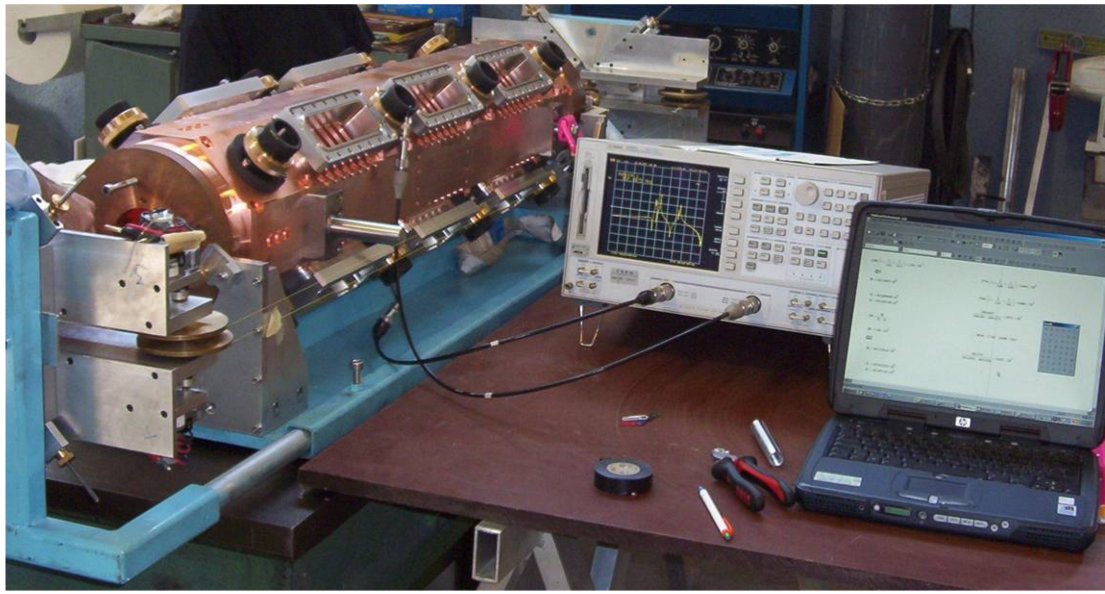

INFN
21/05/2003

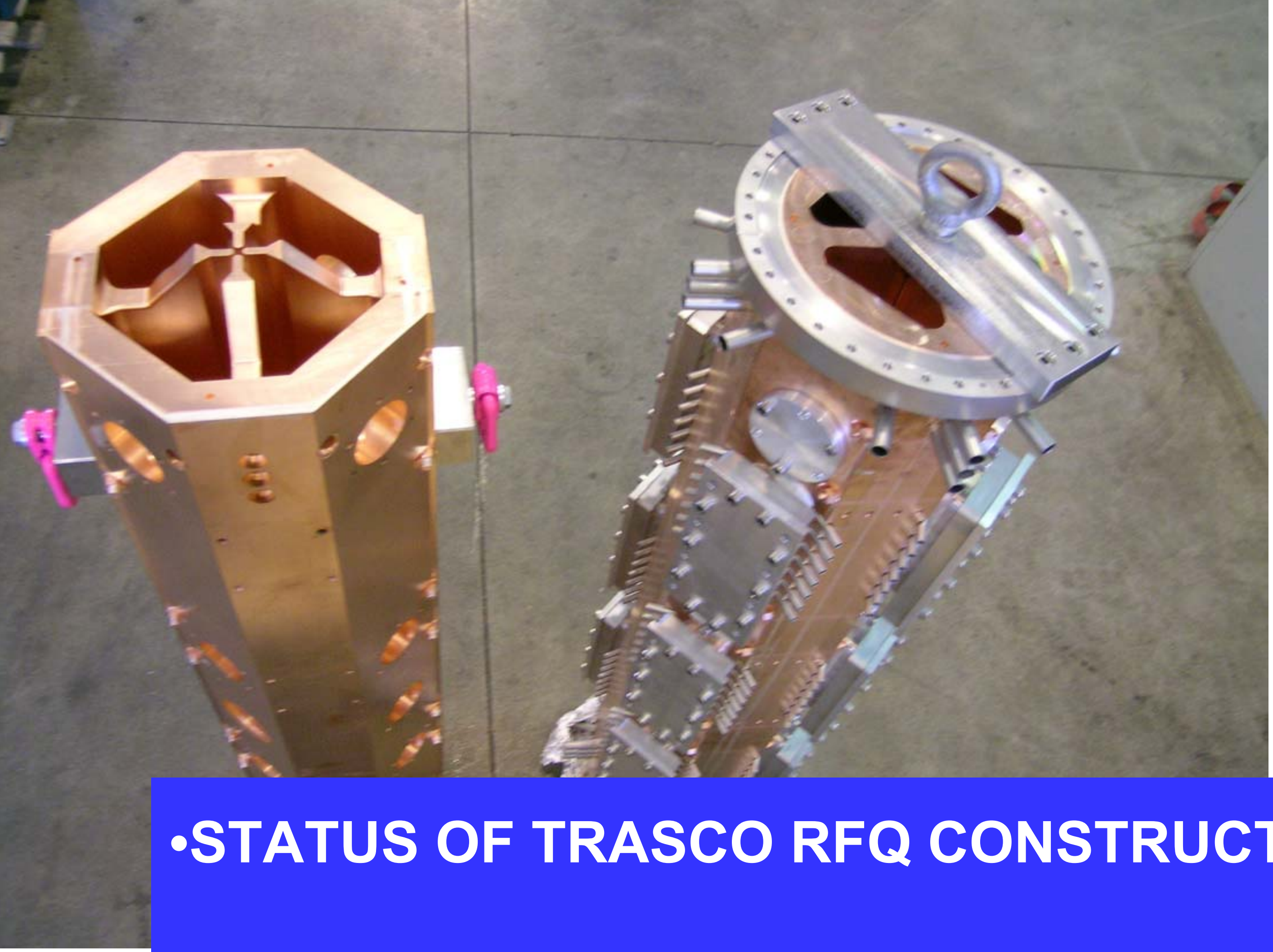
RF measurements of the first module



field variation before and after 2nd braze







A. Pisent et al MOP16

•STATUS OF TRASCO RFQ CONSTRUCTION

The first RFQ module has been built and brazed
The second RFQ module has passed the first brazing
The last four modules have been ordered

Conclusions

- The long range ISOL facility will necessarily be on European scale (**EURISOL**), based on a high intensity linac as driver and a superconducting linac for the reacceleration.
- **The technology of the driver (and of the converter) is common to other applications** like spallations sources for material science, nuclear waste transmutation and High Energy Physics.
- There is an intermediate phase with an essential role for National Laboratories, like **SPES project at LNL**, and **SPIRAL2 at GANIL**. There is therefore an integrated plan for the development of ISOL facilities in Europe, and good perspectives for the implementation of the relative Physics programs.
- The first step in Italy will be the construction of **SPES-1** (20 MeV 10mA) in the next five years.

Acknowledgements

- **EURISOL** driver study group
- Eric Baron[2], Jean-Luc Biarrotte[1], Jean-Louis Coacolo[1], Michele Comunian[3], John Cornell[2], Alberto Facco[3], Shinian Fu[6], Roland Garoby[4], Tomas Junquera[1], Jean-Michel Lagniel[5], Marie-Hélène Moscatello[2], Guillaume Olry[1], Andrea Pisent[3], Henri Safa5 and André Tkatchenko[1] **Coordinated by A. Mueller[1]**

[1] *IPN Orsay, France*

[2] *GANIL, France*

[3] *INFN, Laboratori Nazionali di Legnaro, Italy*

[4] *CERN, Geneva, Switzerland*

[6] *CEA Saclay, France*

[6] INFN LNL, permanent address *IHEP Beijing, China*

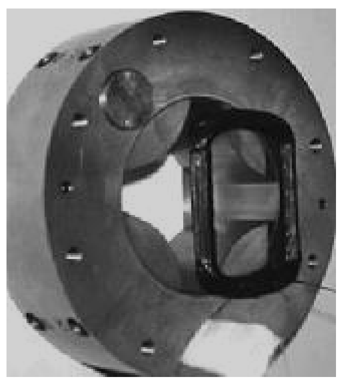
- **SPES**
- A. Pisent, M. Comunian, E. Fagotti, G. Lamanna, A. Lombardi, G. Bisoffi, A. Facco, A. Palmieri, F. Scarpa, V. Zviaginziev, P.A. Posocco, V. Andreev, J. Esposito, P. Favaron.
- **SPIRAL2** M.H. Moscatello

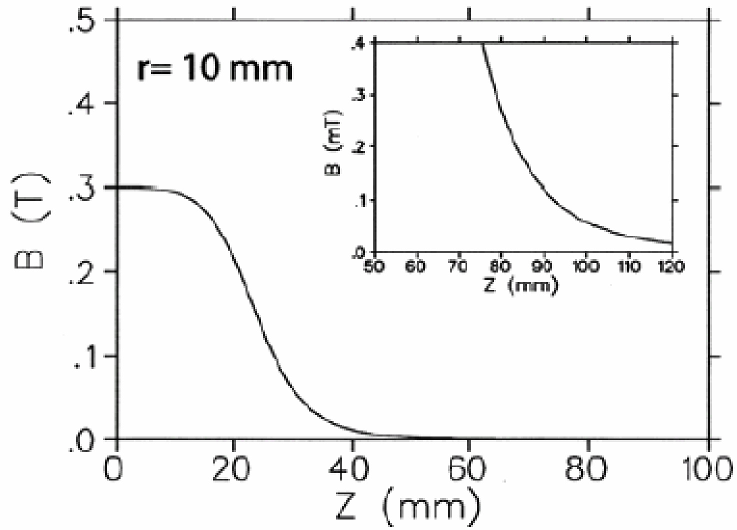
LNL-MSU Superferric quadrupole magnet

- **Developed at MSU-NSCL in collaboration with INFN-LNL for superconducting linacs**
- **Very compact, to be used inside cryostats-magnetic shielding required**
- **tested at 300K; test at 4.2 K to be done**

TABLE I
PHYSICAL PARAMETERS

Property	Specification
Effective length	50 mm
Radius	20 mm
Gradient	31 T/m
Turns of 0.431 mm wire	78
Current (2-D calculation)	63 A





EXCYT,TRIUMF,
GANIL
ORNL,REX ISOLDE,
LOUVAIN LA NEUVE

UPGRADING

THERE IS STILL A ROLE
FOR THE EUROPEAN
NATIONAL LABS (GANIL
LNL)

?

EURISOL

RIA

GSI, RIKEN

~10^5 p/s	~10^6 p/s	~$10^{8,9}$ p/s	~pnA
some M€ tens	tens of M€	≤ 100 M€	~400 M€ - 800 M€
few kW	10-20 kW	100kW	up to 5 MW
2003	2005-8	2010?	2012-15

We think YES

NETWORKING of complementary
projects (SPES, SPIRAL II)

By G. Fortuna