Technical highlights and status of future project of stable ions beams

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Disclaimer

This review is covering a wide range of stable ion beam facilities in Europe, excepted the 2 following facilities/project which have dedicated talks further away in the session:

Refer to these 2 others talks to have a complete picture:

- ✓ ***Status and Future Experiments with S3,*** **Hervé Savajols**
- ✓ ***The LINCE Project at Huelva,*** **Ismaël Martel**

Acknowledgement

Many thanks to the people who sent me information and slides for this review:

- ✓ ***Adam Maj ,*** **IFJ Krakow**
- ✓ ***Santo Gammino,*** **LNS Catania**
- ✓ ***Krzysztof Rusek,*** **HIL Warsaw**
- ✓ ***Rauno Julin,*** **JYFL, Jyväskylä**
- ✓ ***Giovanni Bisoffi,*** **LNL Legnaro**
- ✓ ***Giuseppe Verde,*** **IPN Orsay**

Outlook

- **Facilities based on cyclotrons**
  - **CCB (Krakow) and HIL (Warsaw)**
  - **JYFL Jyväskylä**
  - **Flerov Laboratory - Dubna**
  - **LNS Catania**
- **Facilities based on linacs**
  - **LNL Legnaro**
  - **GSI Darmstadt**

- **Facilities based on cyclotrons**
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National Cyclotron Center in Poland

National Cyclotron Laboratory is composed of two centers:

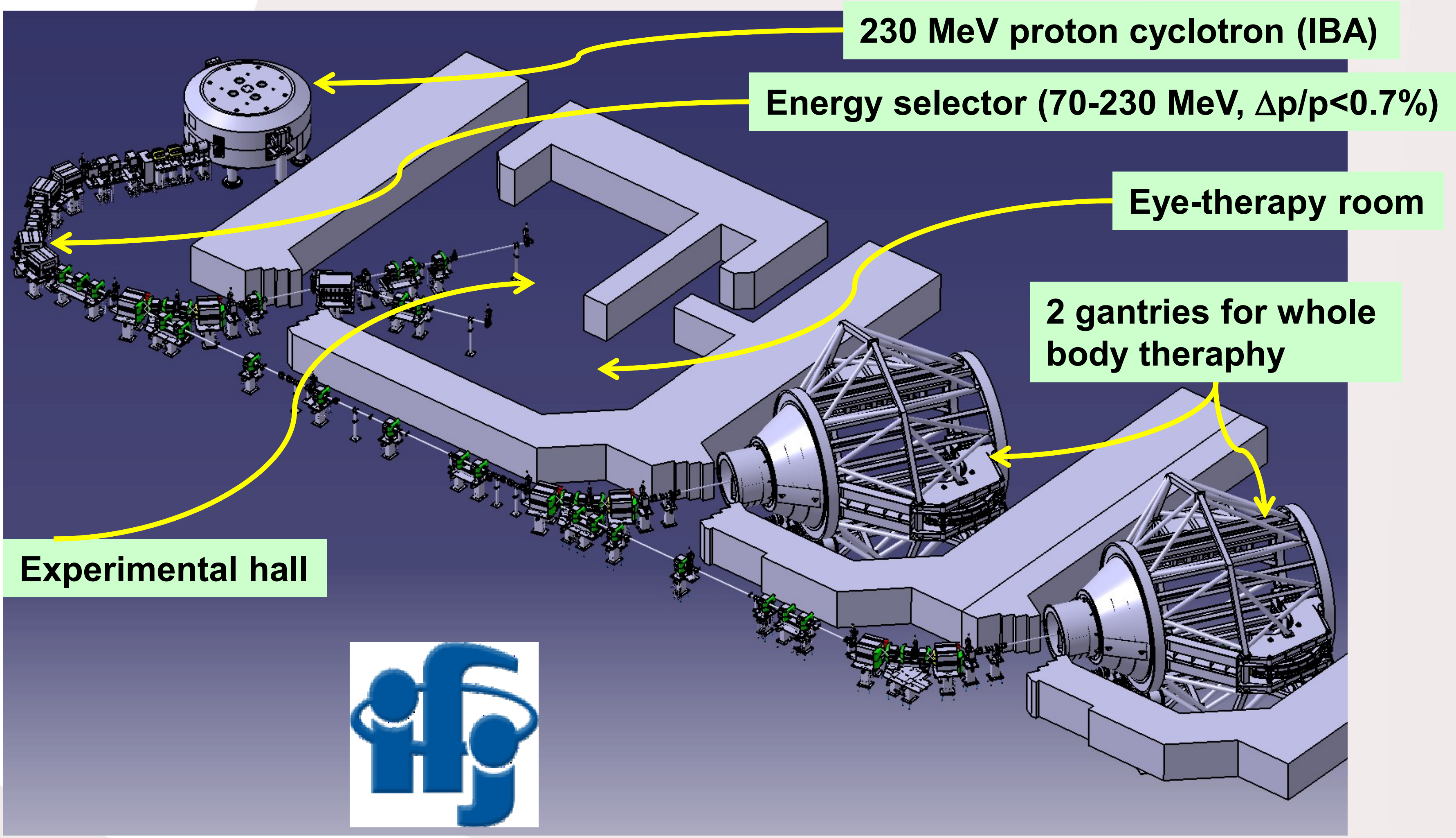
CCB in Krakow and HIL in Warsaw

Based on nuclear physics institutions, operating 4 cyclotrons and involved in medical applications – production of radiopharmaceuticals and hadron therapy.

CCB Krakow and HIL Warsaw are in the ENSAR2 H2020 project as a TNA facility

Cyclotron Center Bronowice - Krakow

2 cyclotrons: AIC-144 (homemade) and the new Proteus C235 from IBA

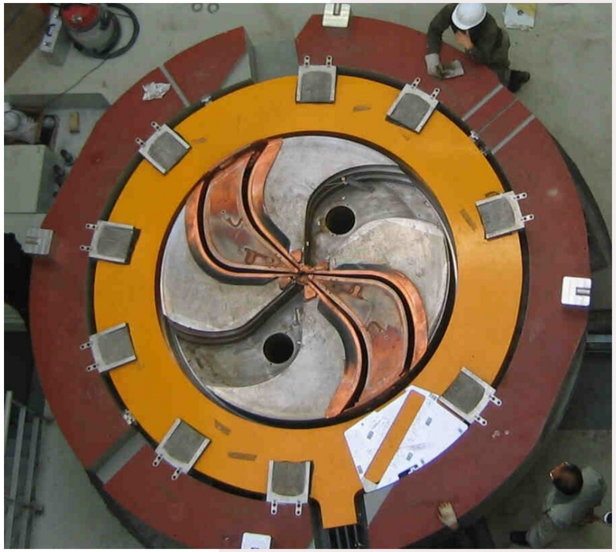


Courtesy A. Maj

Cyclotron Center Bronowice - Krakow

The new cyclotron:

C 235 Proteus



Courtesy K. Gugula

Magnet Length Diameter	435 cm
Magnetic Structure	4 spiral sectors
Deep valley design	
Magnetic Field	1,75 ÷ 2,35 T
Main Coil Current	0 ÷ 850 A
Number of Harmonic Coils	4
Cental region Number of Dees	2 (α=30º)
RF Generator Frequency	106 MHz
RF Generator Power	100kW
Dee voltage Central region	50 kV
Extraction region	100 kV
Emittance 1σ	E_x=11mm mrad, E_z=12mm mrad

A physics program is being built (instruments recommended by IAC), and a detector (BINA) for light nuclei reactions studies was already moved from KVI Groningen

Heavy Ion Laboratory - Warsaw

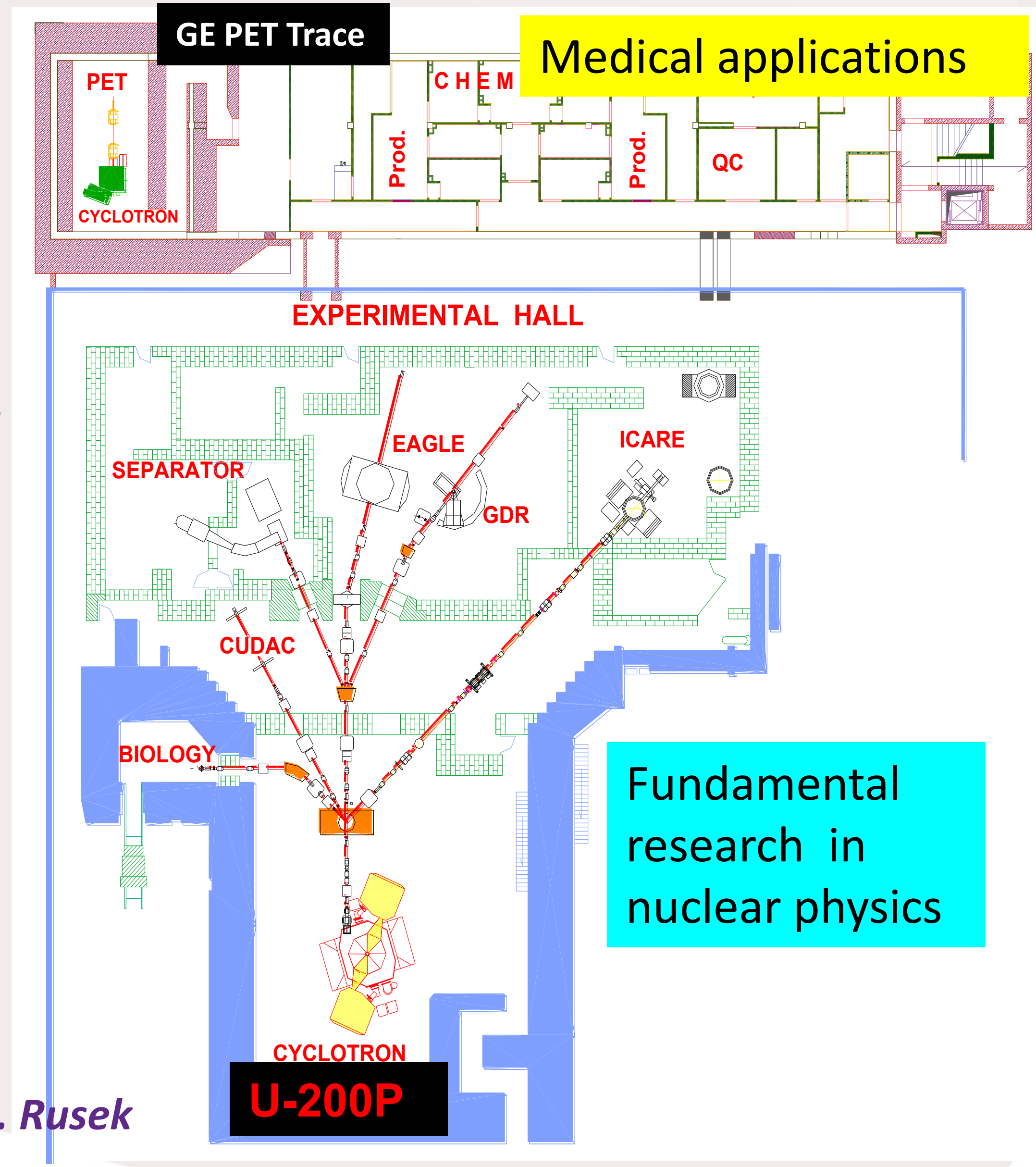
The HIL Facility

User Facility: ~ 100 users per year

Staff: 35 technicians, 13 scientists

Two cyclotrons:

- U-200P heavy-ion cyclotron, up to 10 MeV*A, two ECR ion sources
- GE PET Trace, high intensity p/d cyclotron (16/8 MeV)



Courtesy K. Rusek

Heavy Ion Laboratory - Warsaw

Recent achievements and plan:

- 2014: the spiral inflector and the new ECR source coupled with the U-200P cyclotron, possible beams from He – Xe

- 2015:

- replacement of the HF generators (U-200P)
- installation of the new solid target station for the isotope production (GE PET Trace cyclotron)
- PIXE laboratory eq. with the NEC 1.7 MV tandem

- From 2016 work on:

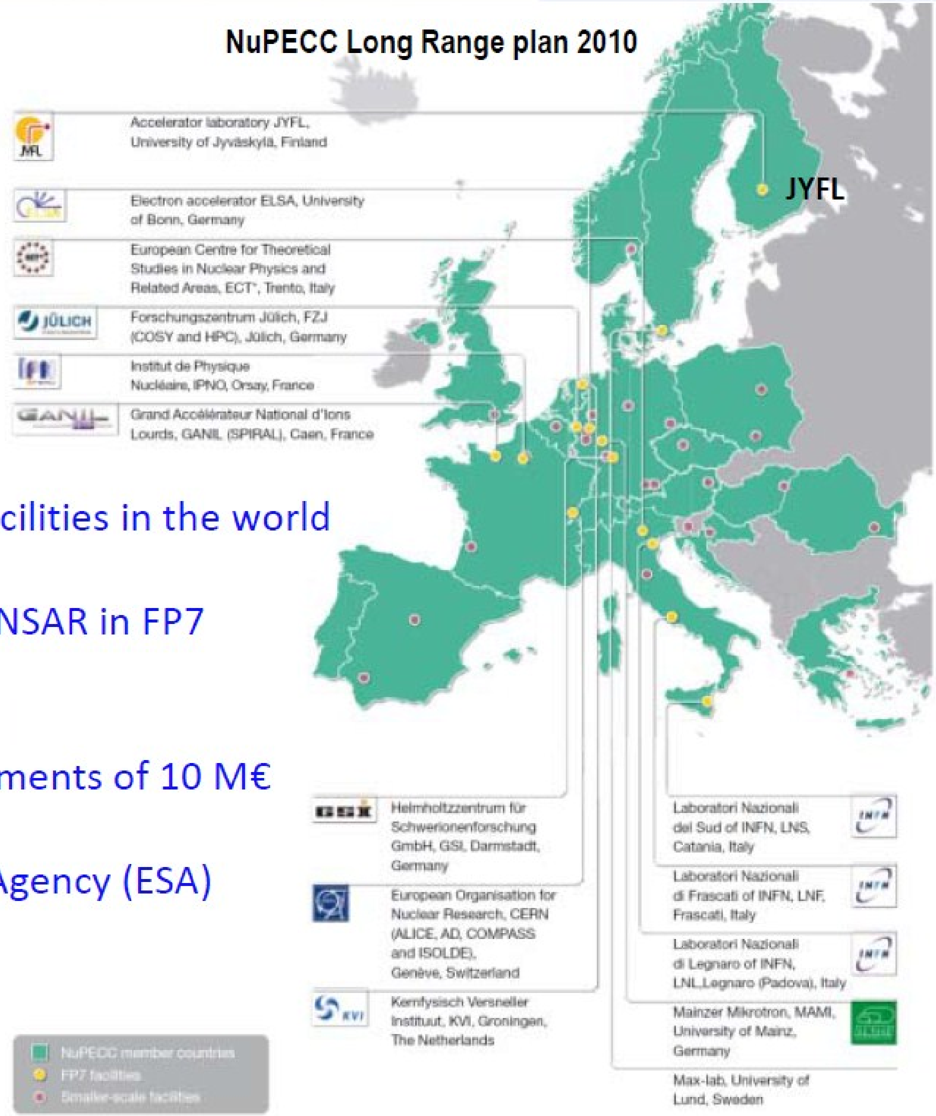
- upgrade of the U-200P in order to increase the beam intensity,
- ^{11}C and ^{15}O radioactive beams

JYFL Accelerator Laboratory

JYFL Acclab: principal infrastructure

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

- Part of the Department of Physics
- Centre for Excellence (2012 – 2017)
- Over 6000 beam time hours a year
- One of the leading stable-ion beam facilities in the world
- EU- Access Laboratory since FP4 - ENSAR in FP7
- International infrastructure in Finland
  - over 200 users a year, foreign investments of 10 M€
- One of 3 accredited European Space Agency (ESA) test facilities

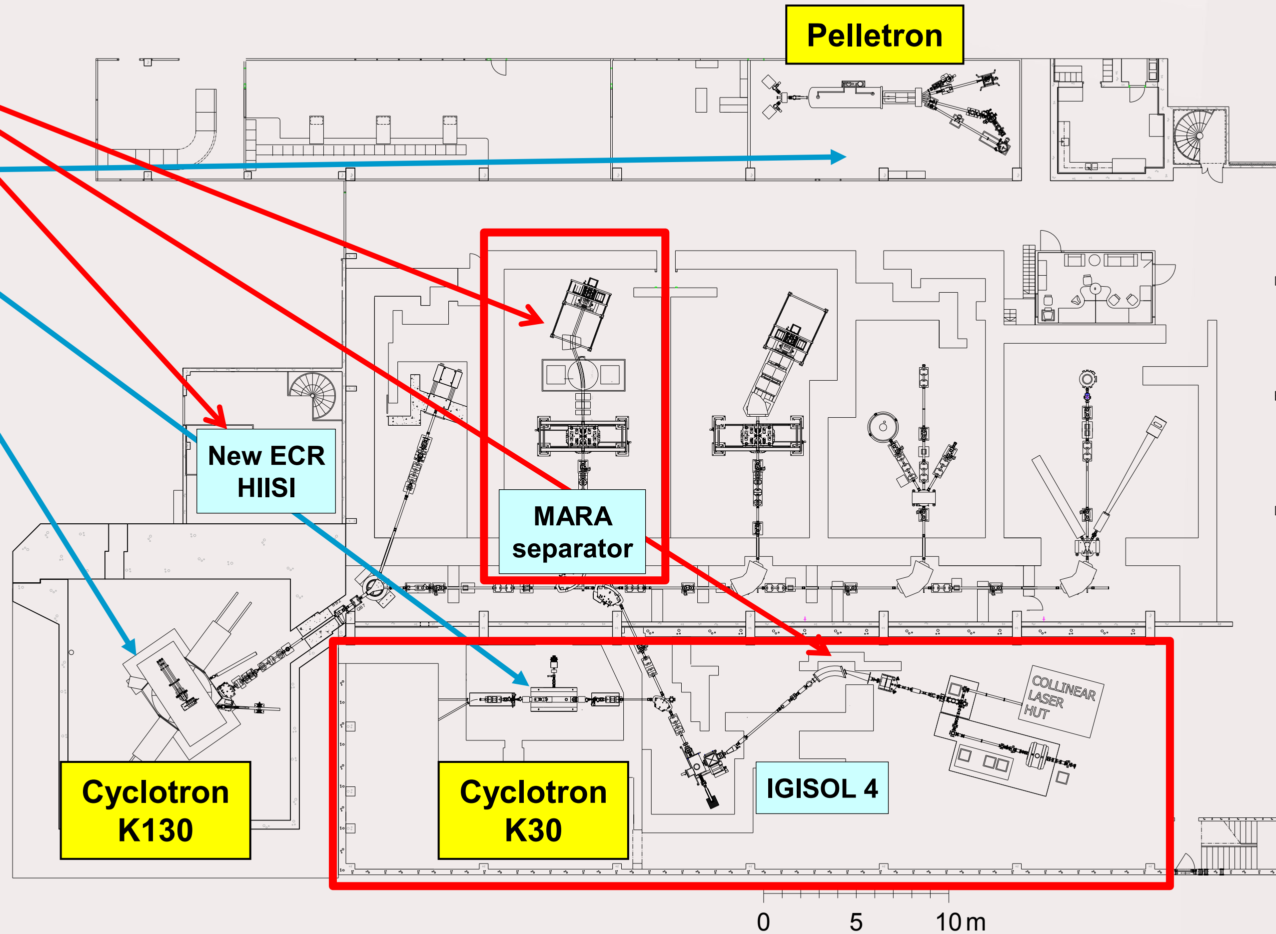


JYFL Accelerator Laboratory

At JYFL: Upgrades and developments are on-going

New instrumentation

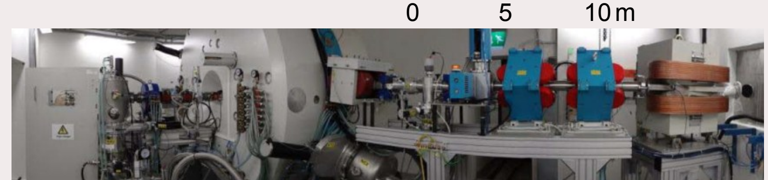
Three accelerators



→ More beam time for difficult experiments and new applications

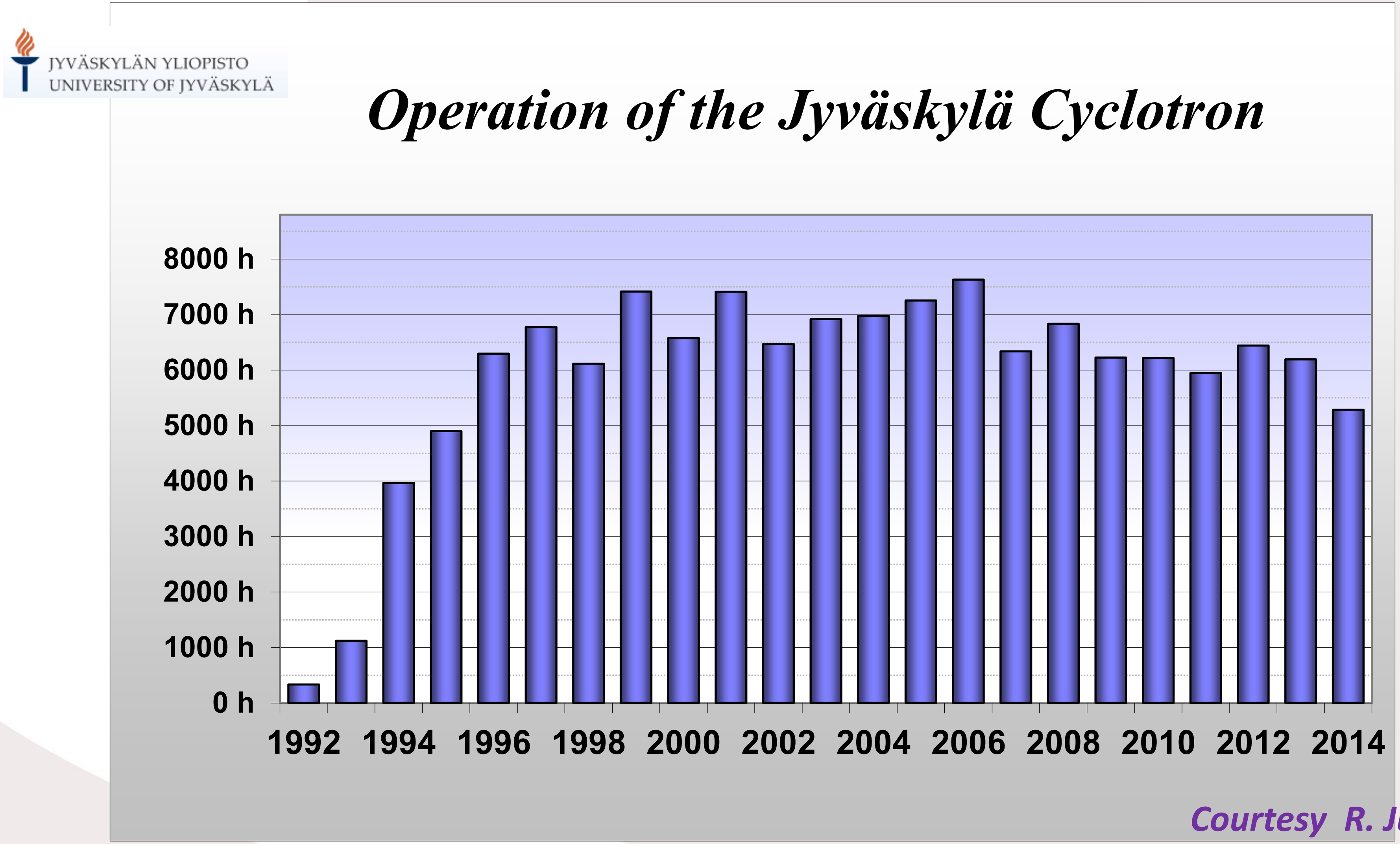
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Courtesy R. Julin



JYFL Accelerator Laboratory

In spite of the upgrades going on, the K130 cyclotron is in heavy use



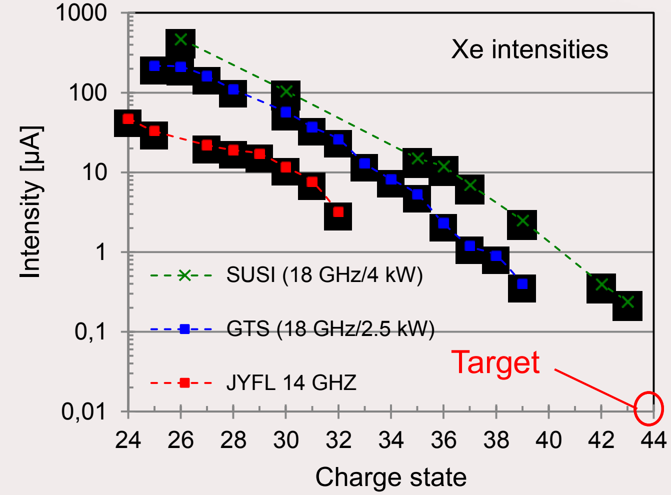
Courtesy R. Julin

JYFL Accelerator Laboratory

Main development: HIISI, New 18 GHz ECRIS for the K130 cyclotron

Academy of Finland granted funding for a new 18 GHz ECRIS HIISI (Heavy-Ion Ion-Source Injector). Source has to provide adequate ion beam intensities for the nuclear physics program and applications.

- Nuclear physics: ×10 present intensity at medium charge states (Ar^{8+}, Xe^{26+}, energy > 5 MeV/u). Low injection voltage for K130 cyclotron is challenging.
- Radiation effects facility: Ion beam cocktail energy increased from current 9.3 MeV/u to 15 MeV/u (Xe^{44+} required).
- As graph shows SUSI (@ NSCL) can meet the requirement when operated at 18 GHz frequency.



ECRIS	B_{rad}	B_{inj}	B_{ext}	B_{min}	∇B_{inj}	∇B_{exr}	Length
SUSI	1.35	2.81	1.56	0.46	6.6	5.9	115
HIISI	1.24	2.51	1.52	0.43	6.3	6.3	132

HIISI can reach almost the same magnetic field configuration as SUSI → high performance can be expected.

Courtesy R. Julin

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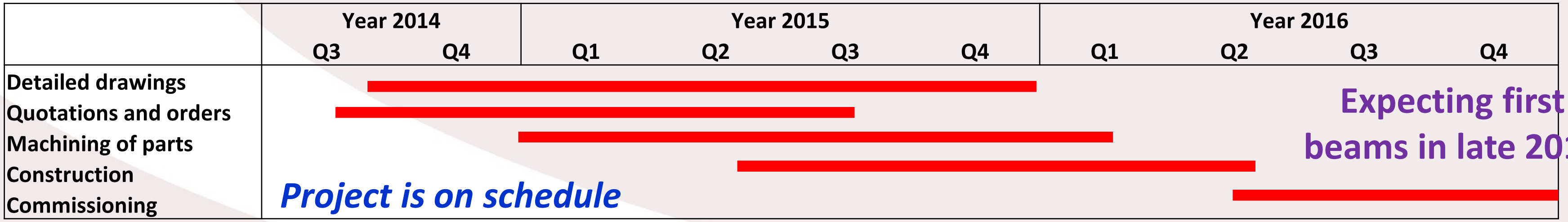


Expecting first beams in late 2016

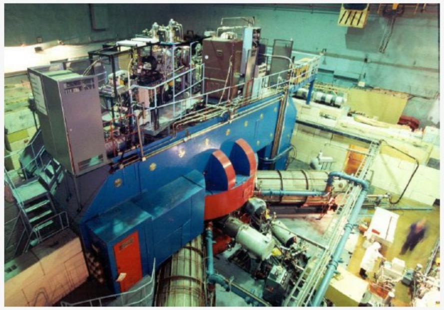
FLEROV Laboratory - Dubna

- **U400 (1979) - Accelerator complex for synthesis of new elements.**
- **U400M (1993) - In 2002, this cyclotron was included in DRIBs accelerator complex designed for production of radioactive ion beams.**
- **DRIBs - DRIBs-I accelerator complex (130m long) is designed for production of radioactive ion beams and combines constructively U400 and U400M cyclotrons. Was put into operation in 2002.**
- **U200 (1968)- At present used for production of ultraclean radioisotopes for ecology and nuclear medicine.**
- **MT-25 - Microtron electron accelerator (1973), upgraded in 1980 (MT-22) and in 1986 (MT-25). Used for study and production of ultraclean radioisotopes.**
- **DC-40 (IC-100) - Cyclotron complex is the full-scale upgrade of IC-100 cycle implanter. Designed for high technology and applied research**

FLEROV Laboratory - Dubna

The two main isochronous cyclotrons

U400M - stand-alone & driving accelerator



- Properties and structure of light exotic nuclei;
- Astrophysics;
- Reactions with exotic nuclei;
- Light neutron-rich nuclei;
- Deep inelastic scattering;
- Producing of RIBs.

U400M
E=30 50 MeV/A
E=4.5 9 MeV/A

Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	35	6 10^{13}
^{18}O	33	1 10^{13}
^{40}Ar	40	1 10^{12}
^{48}Ca	5	6 10^{12}
^{54}Cr	5	3 10^{12}
^{58}Fe	5	3 10^{12}
^{124}Sn	5	2 10^{11}
^{136}Xe	5	4 10^{11}
^{238}U	7	2 10^{10}

Courtesy S. Dmitriev

U400 → U400R GOALS

- Increasing the beam intensity A ≈ 50 ions up to 2.5 pμA;
- Smooth ion energy variation on the target within a factor 5;
- Reducing the ion's energy spread on the target up to 10^{-3};
- Improvement of the beam emittance on the target up to 10 π mm · mrad;
- Reducing the main magnet average field level from 1.8 to 0.8 T.

U400R (expected)

Ion	Ion energy [MeV/A]	Output intensity
^{6}He	2.8 ÷ 14	10^{8}
^{8}He	1.6 ÷ 8	10^{5}
^{7}Li	2-17	1 10^{14}
^{16}O	6,4 -27	1 10^{14}
^{40}Ar	1-5,1	6 10^{13}
^{48}Ca	1,6-11	1.5 10^{13}
^{50}Ti	4,1-21	6 10^{12}
^{58}Fe	1,2-7,5	6 10^{12}
^{84}Kr	0,8-3,5	2 10^{12}
^{132}Xe	0,8-3,5	3 10^{12}
^{238}U	1,5- 8	5 10^{11}

FLEROV Laboratory - Dubna

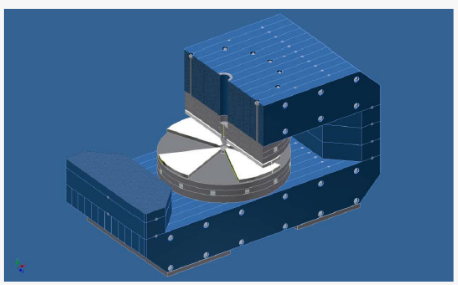
DRIB-III : The on-going project of SHE facility

- Completion of modernization of cyclotrons U400 and U400M

- Creation of SHE factory based on the high-intensity universal DC280 cyclotron (A≤238, E≤10 MeV•A , I≤ 20 pμA) in a new separate experimental building

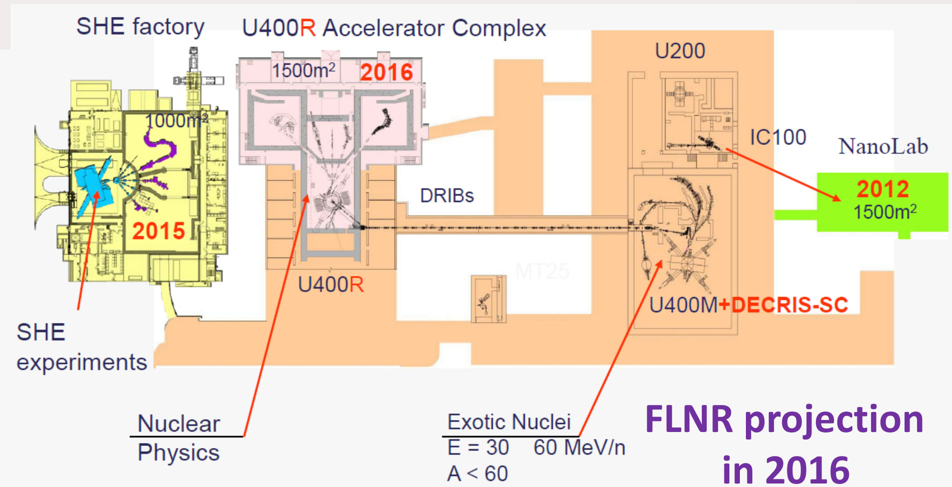
- Total reconstruction of the U400 experimental hall, including 6 radiation safe experimental caves

DC280 - stand-alone SHE-factory



- Synthesis and study of properties of superheavy elements;
- Search for new reactions for SHE-synthesis
- Chemistry of new elements;

DC280 (expected) E=4 8 MeV/A		
Ion	Ion energy [MeV/A]	Output intensity
^{7}Li	4	1 10^{14}
^{18}O	8	1 10^{14}
^{40}Ar	5	6 10^{13}
^{48}Ca	5	0,6-1,2 10^{14}
^{54}Cr	5	2 10^{13}
^{58}Fe	5	1 10^{13}
^{124}Sn	5	2 10^{12}
^{136}Xe	5	1 10^{14}
^{238}U	7	5 10^{10}

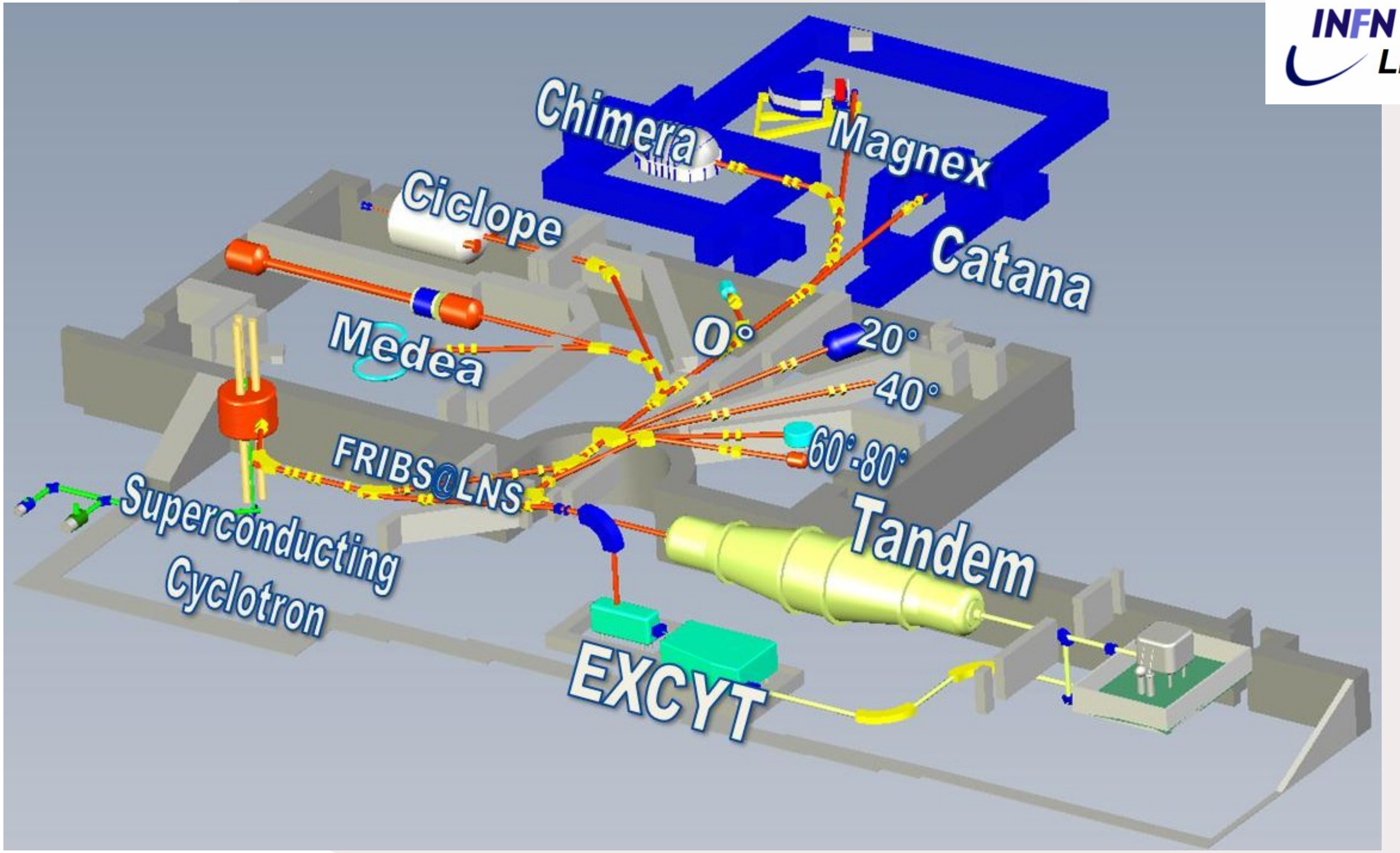


Courtesy S. Dmitriev

Unfortunately, no recent update to report on.

LNS Catania

2 accelerators (tandem, SC Cyclotron) and experimental halls

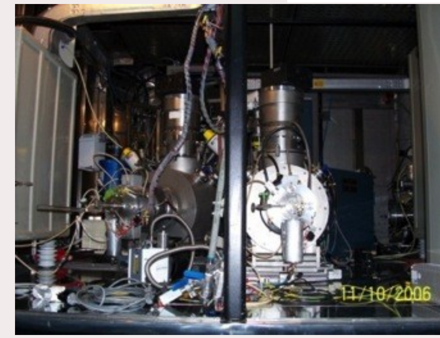


Courtesy G. Cuttone & S. Gammino

LNS Catania

2 accelerators (tandem, SC Cyclotron) and ion sources

450 KV injector
2 sputtering sources



Courtesy G. Cuttone & S. Gammino

Superconducting
ECR source SERSE

Normal conducting
ECR source
CAESAR

LNS Catania

Improvements on ECR sources: cryogenics of Serse and new injection system of Caesar

Limited availability of SERSE due to cryogenic problems

Autonomous system based on Helium recondensation

- **Dimensioned and designed - cost defined to be around 300 k€ : project LNS Nuclear Astrophysics**
- **Realization : a) purchase of cryocoolers just done 128 k€ b) assembling of cryocoolers and high T_C current leads → second half of 2014**

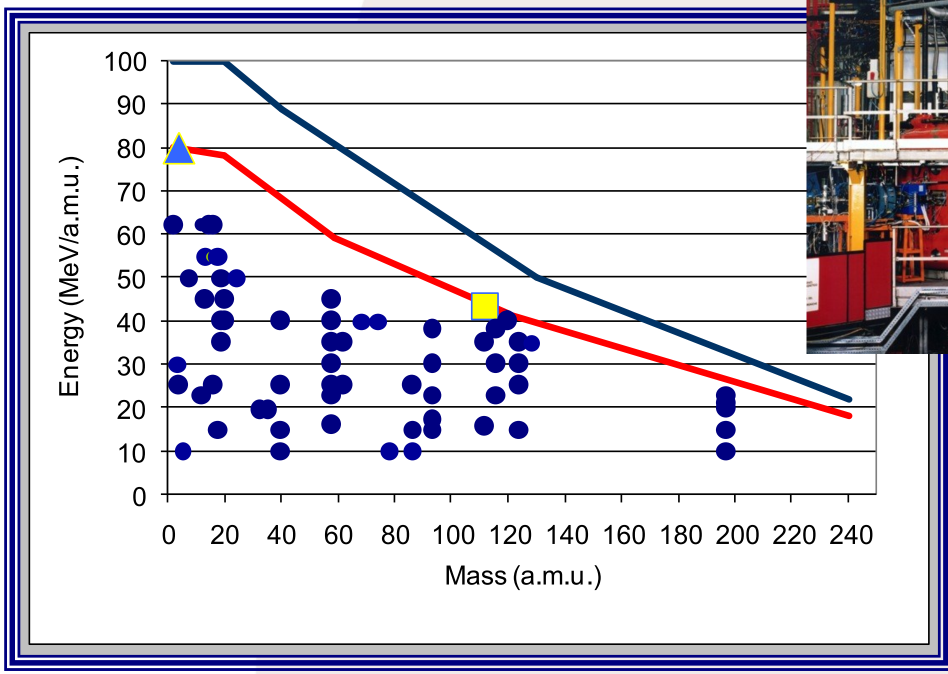
New beams with CAESAR new injection system

- **metallic species through the installation of an oven: in 2014 after the implementation of the new control system**
- **MIVOC technique for "difficult beams", for instance ^{11}B for production of ^{8}He at FRIBS@LNS tests done – feasibility demonstrated**

Courtesy G. Cuttone & S. Gammino

LNS Catania

Beams produced with SC cyclotron



^{4}He 80 AMeV

^{112}Sn 43.5 AMeV

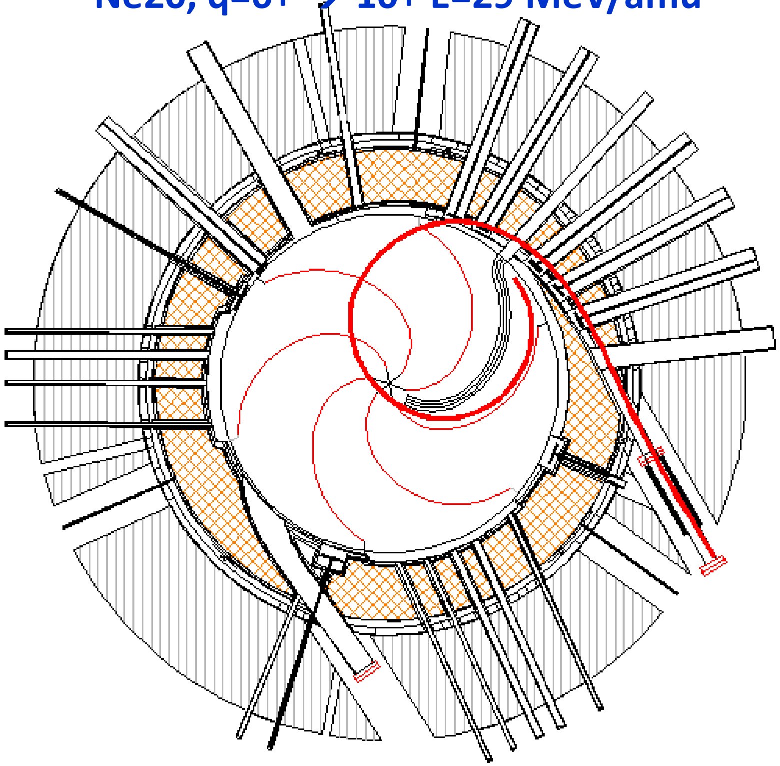
In red beams with intensity 10^{12} pps

^{A}X	E (AMeV)
H_2^+	62,80
H_3^+	30,35,45
$^{2}D^{+}$	35,62,80
^{4}He	25,62,80
He-H	10, 21
^{9}Be	45
^{11}B	55
^{12}C	23,62,80
^{13}C	45,55
^{14}N	62,80
^{16}O	21,25,55,62,80
^{18}O	15,55
^{19}F	35,40,50
^{20}Ne	20,40,45,62
^{24}Mg	50
^{27}Al	40
^{36}Ar	16,38
^{40}Ar	15,20,40
^{40}Ca	10,25,40,45
^{42,48}Ca	10,45
^{58}Ni	16,23,25,30,35,40,45
^{62,64}Ni	25,35
^{68,70}Zn	40
^{74}Ge	40
^{78,86}Kr	10
^{84}Kr	10,15,20,25
^{93}Nb	15,17,23,30,38
^{107}Ag	40
^{112}Sn	15.5,35,43.5
^{116}Sn	23,30,38
^{124}Sn	15,25,30,35
^{129}Xe	20,21,23,35
^{197}Au	10,15,20,21,23
^{208}Pb	10

LNS Catania

Need for higher intensities: extraction by stripping

Extraction trajectory
Ne20, q=6+ → 10+ E=29 MeV/amu



INFN LNS

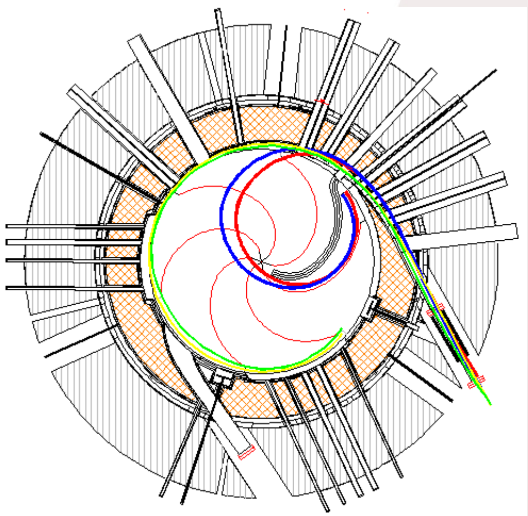
Extraction by stripping is based on the reduction of magnetic rigidity of the accelerated ion, caused by an increase of charge state or decrease of mass, after crossing a thin carbon foil (stripper).

For light ions at high energies the charge state fraction for q=Z after a stripper with thickness bigger than the equilibrium thickness is >99%

Beam dynamics calculations are necessary to check the feasibility of extraction by stripping. In particular the beam envelope has to be evaluated.

LNS Catania

From electrostatic extraction to extraction by stripping



A new cryostat is required:

A conceptual design study is being accomplished in collaboration with MIT

A new SC magnet is required

The whole upgrade:

Looking for intensity

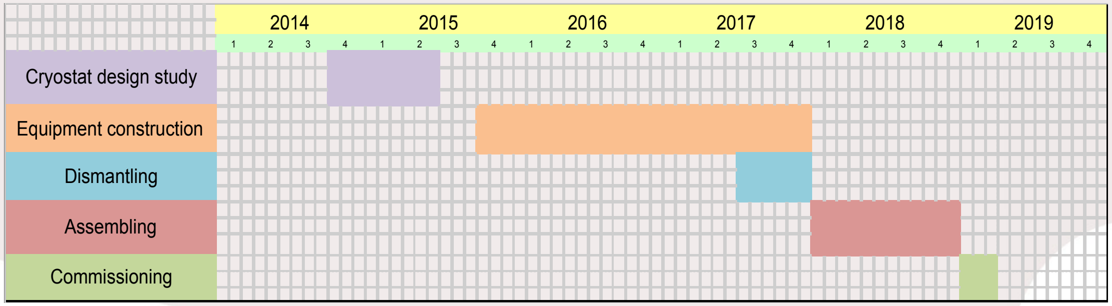
- New s.c. magnet: cryostat with coils
- Stripper system
- Magnetic channels
- New liner
- Source-Cyclotron matching
- Cyclotron-Magnex beam line

Looking for reliability

- New trim coils
- RF cavities insulators
- New power supplies
- New Helium liquefier

Roughly estimated cost

Superconducting magnet	6 M€
"Intensity" equipment	2.2 M€
"Reliability" equipment	4.5 M€
Total	12.7 M€



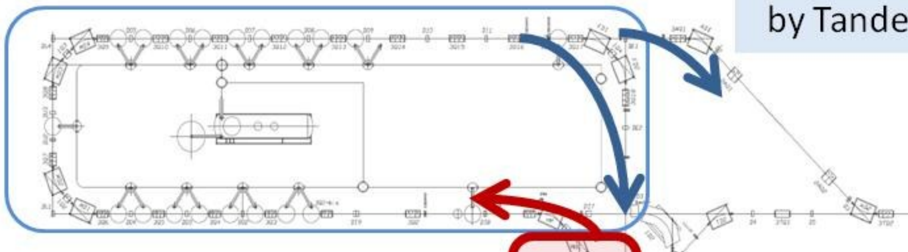
- Facilities based on cyclotrons
  - CCB (Krakow) and HIL (Warsaw)
  - JYFL Jyväskylä
  - Flerov Laboratory - Dubna
  - LNS Catania
- **Facilities based on linacs**
  - **LNL Legnaro**
  - **GSI Darmstadt**

LNL - Legnaro

SC Linac with **QWRs** (Nb, Nb/Cu) at 4,5K in 19 cryostats $\mathbf{V_{eq}}$ **~ 48 MeV/q**, beams **from ^{12}C to ^{197}Au**, injected by Tandem or PIAVE (**1994**)

SC Linac

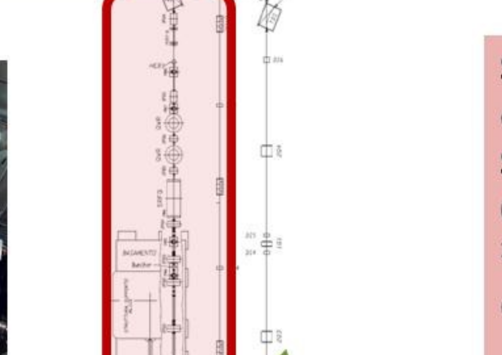
ALPI

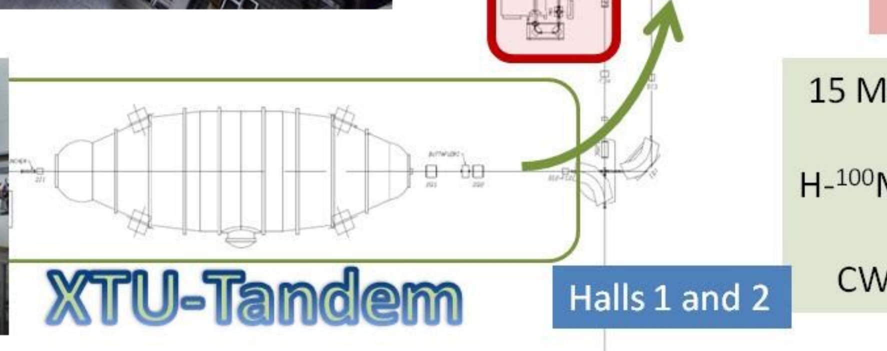


INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Legnaro

PIAVE





Hall 3

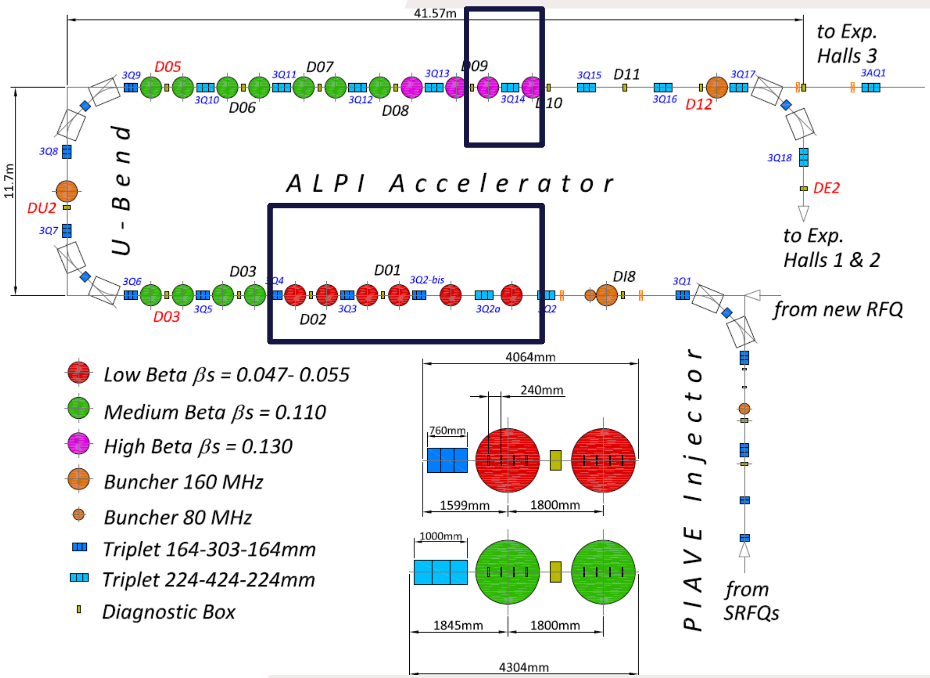
Supernanogan ECR on 350 kV platform **SC-RFQs** and **QWRs**, $\mathbf{V_{eq}}$ **~ 8 MV** **^{12}C – ^{197}Au** (higher q and I_{beam}) (**2006**)

15 MV VdG Tandem (HV Corp), H-^{100}Mo beams, E = **30 ÷ 1.5 MeV/A**, CW or pulsed (**1984**)

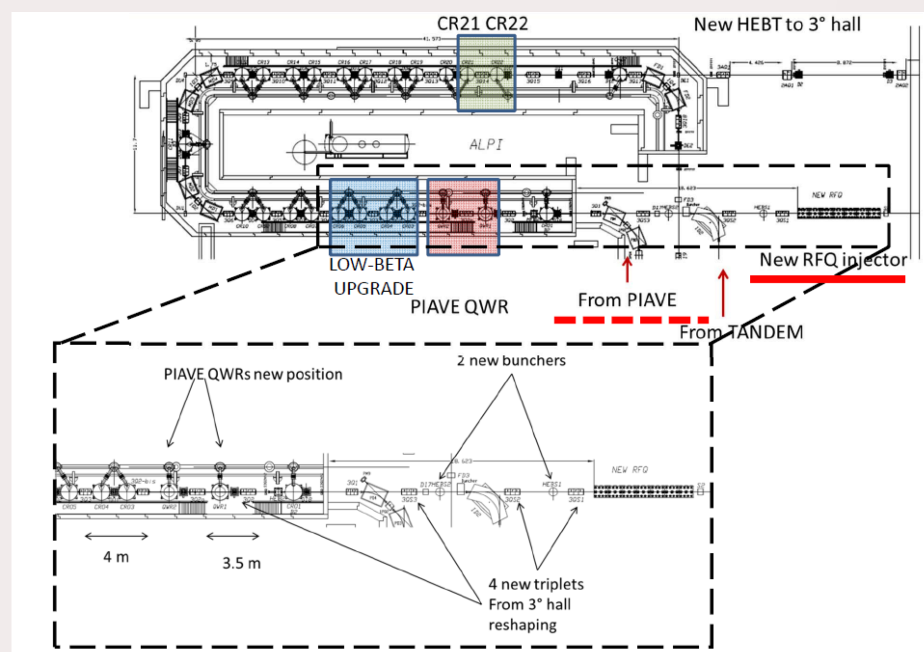
Courtesy G. Bisoffi

LNL - Legnaro

SPES Upgrades on ALPI, impacting on stable and rare beams



- **Larger cryoplant cooling power** (available)
- More and better performing **low-beta cavities**, for higher E_{fin} and I_{fin} (done, flaws to be fixed)
- **Two more cryomodules on the high-E ALPI branch** to achieve 10 MeV/A with exotic ^{132}Sn, e.g., (rescheduled due to changing teams)



- **New diagnostic stations**, lodging devices for stable and rare beam features (will be available in stages 2016-2018)
- **Higher gradient magnetic quads** for better beam transmission (to be purchased in 2015)
- **Control systems** upgrade (next slide)

Courtesy G. Bisoffi

LNL - Legnaro

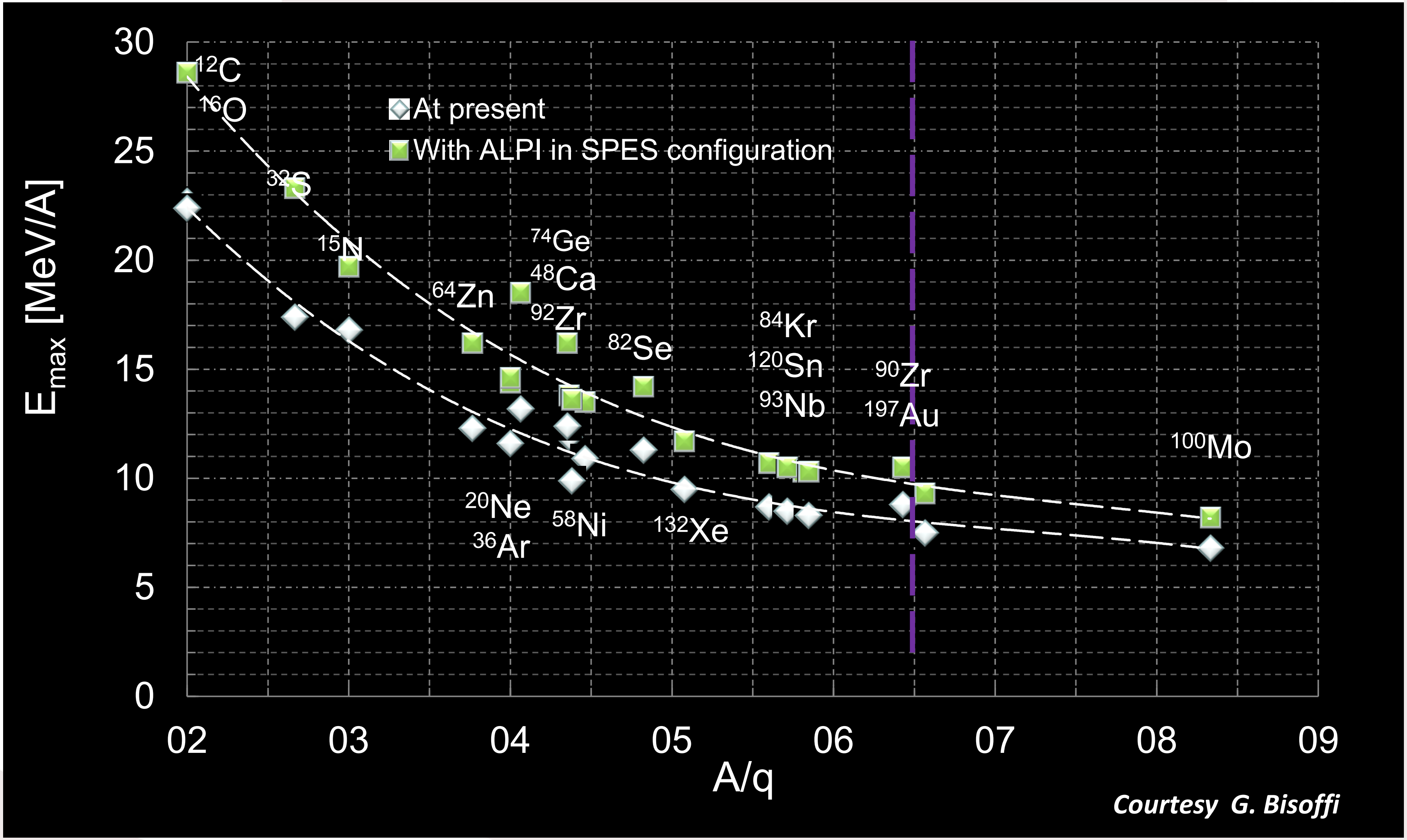
SPES Upgrades on ALPI, impacting on stable and rare beams:
Upgrade of the ALPI control system

Courtesy G. Bisoffi

- Diagnostics control for P and A was upgraded (photo), completed
- Control Upgrade of:
- Magnets, started
- ECR ion source, started
- Cryoplant (planned) and cryostats (on-going)
- radiofrequency (digital controllers) on-going

LNL - Legnaro

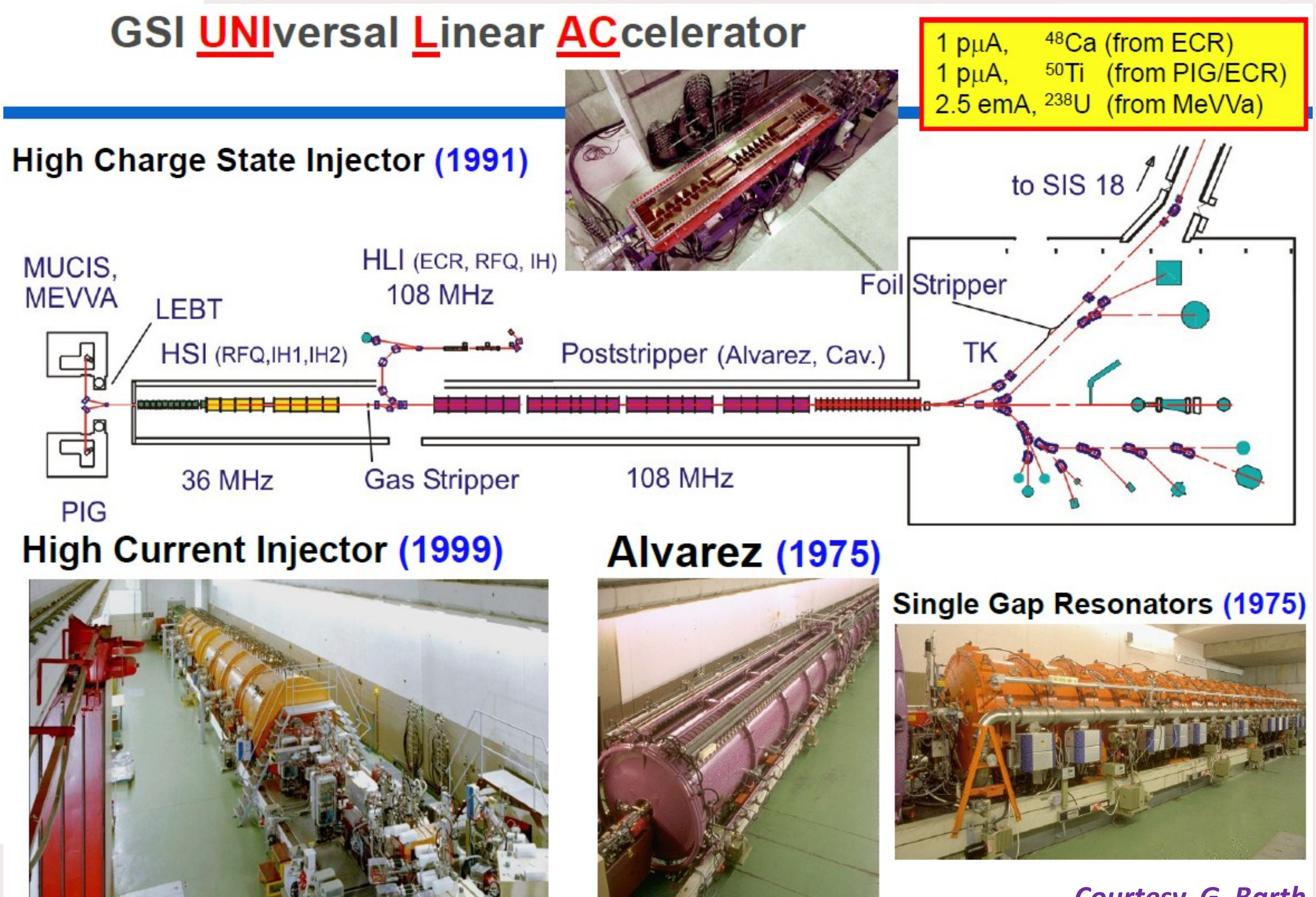
Immediate visible effect on stable beam energy !



A/q=6,5 is realistic in that case, with the present ECR ion source

GSI - Darmstadt

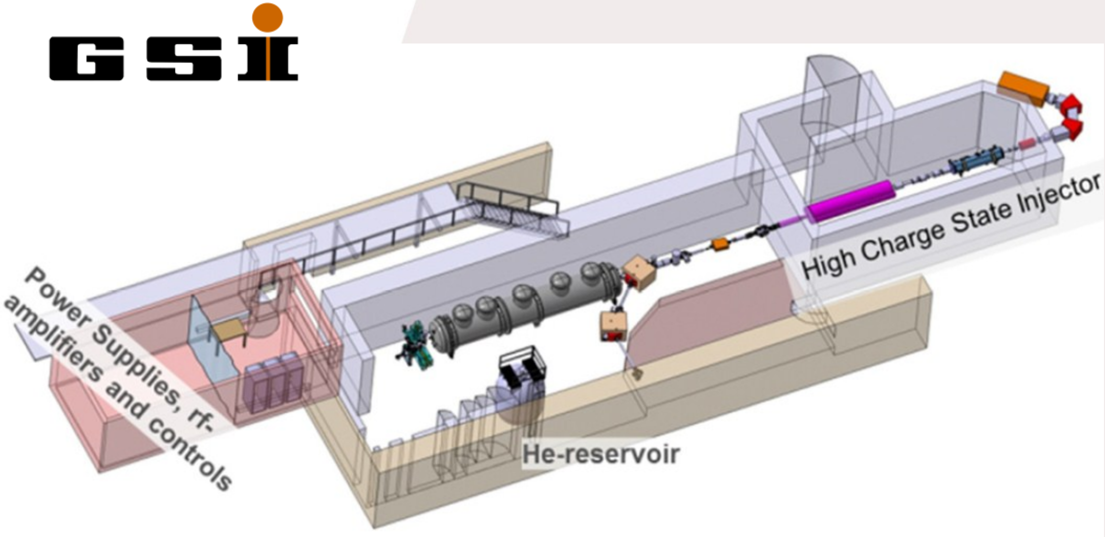
UNILAC @ GSI:



Courtesy G. Barth

GSI - Darmstadt

Project: CW heavy ion linac dedicated to SHE experimental program



Courtesy G. Barth

Table 1: Design Parameters of the Cw-LINAC

Mass/Charge		6
Frequency	MHz	217
Max. beam current	mA	1
Injection Energy	AMeV	1.4
Output energy	AMeV	3.5 – 7.3
Output energy spread	AMeV	±3
Length of acceleration	m	12.7
Sc CH-cavities		9
Sc solenoids		7

Conceptual design:

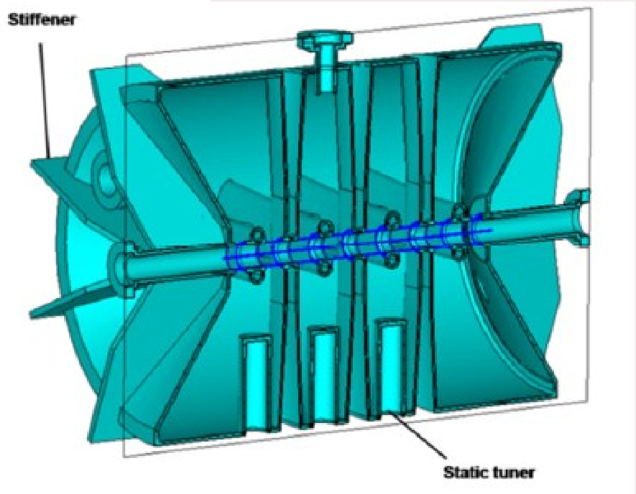
- Acceleration of highly charged ions (mass to charge ratio of 6) at 1.4 MeV/u from the upgraded HLI.
- Nine superconducting CH-cavities operated at 217 MHz accelerate the ions to energies between 3.5 MeV/u and 7.3 MeV/u,
- Energy spread should < ±3keV/u.
- Beam focusing with super-conducting solenoids mounted between the cavities

GSI - Darmstadt

Project: CW heavy ion linac dedicated to SHE experimental program

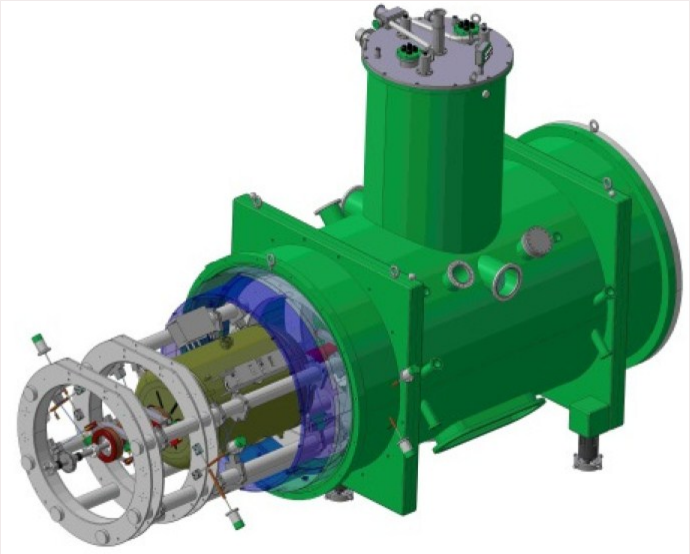
The project development plan is well defined and an intense R&D program has started:

- **a first linac section (one CH cavity embedded by 2 solenoids) will be tested**
- **then, an advanced cryomodule hosting 4 CH will be constructed**
- **Intermediate steps on CH cavities developments are foreseen: a 15-gaps CH cavity @217 MHz is presently under fabrication, and a demonstrator cryomodule is being fabricated.**



The short 8 gaps CH cavity @ 217 MHz

Courtesy G. Barth



Demonstrator cryomodule: 1 CH, 2 solenoids

Conclusion

- **All cyclotrons-based facilities have upgrade plans for their accelerator facilities, either to increase performances (intensities), or enlarge beam production capability.**

- **High intensities is the main objective of future accelerators for physics with stable beams -> recent project based their design on superconducting cavities, a technology of choice for this application.**

THANK YOU FOR YOUR ATTENTION!