Overview of the
World-wide RIB Facilities - Status and Challenges

(RIB: Radioactive Isotope Beam or Rare Isotope Beam)

Contents

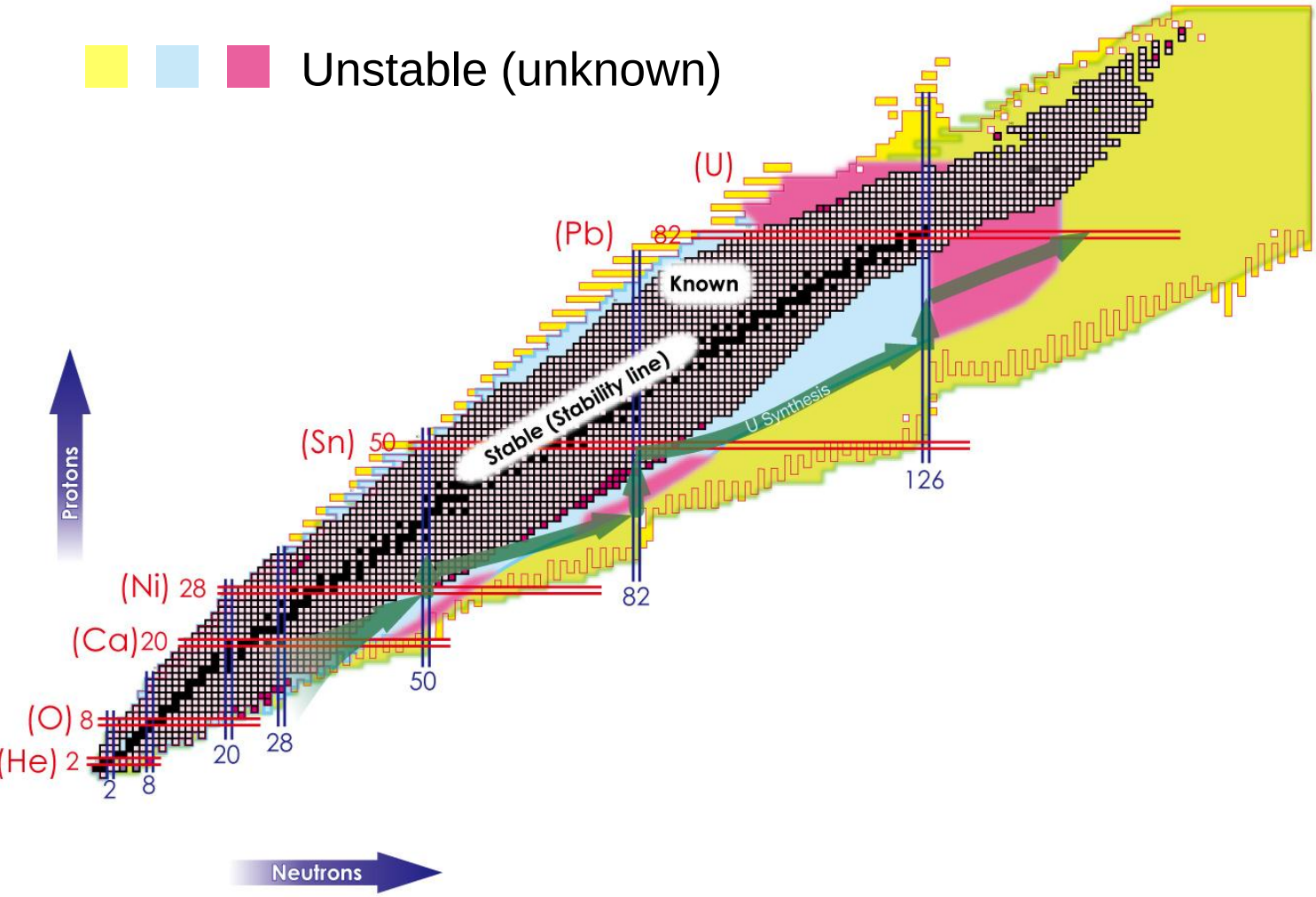
Osamu Kamigaito
RIKEN Nishina Center

1. Introduction – Nuclear chart

Stable

Unstable (known)

Unstable (unknown)



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Stable

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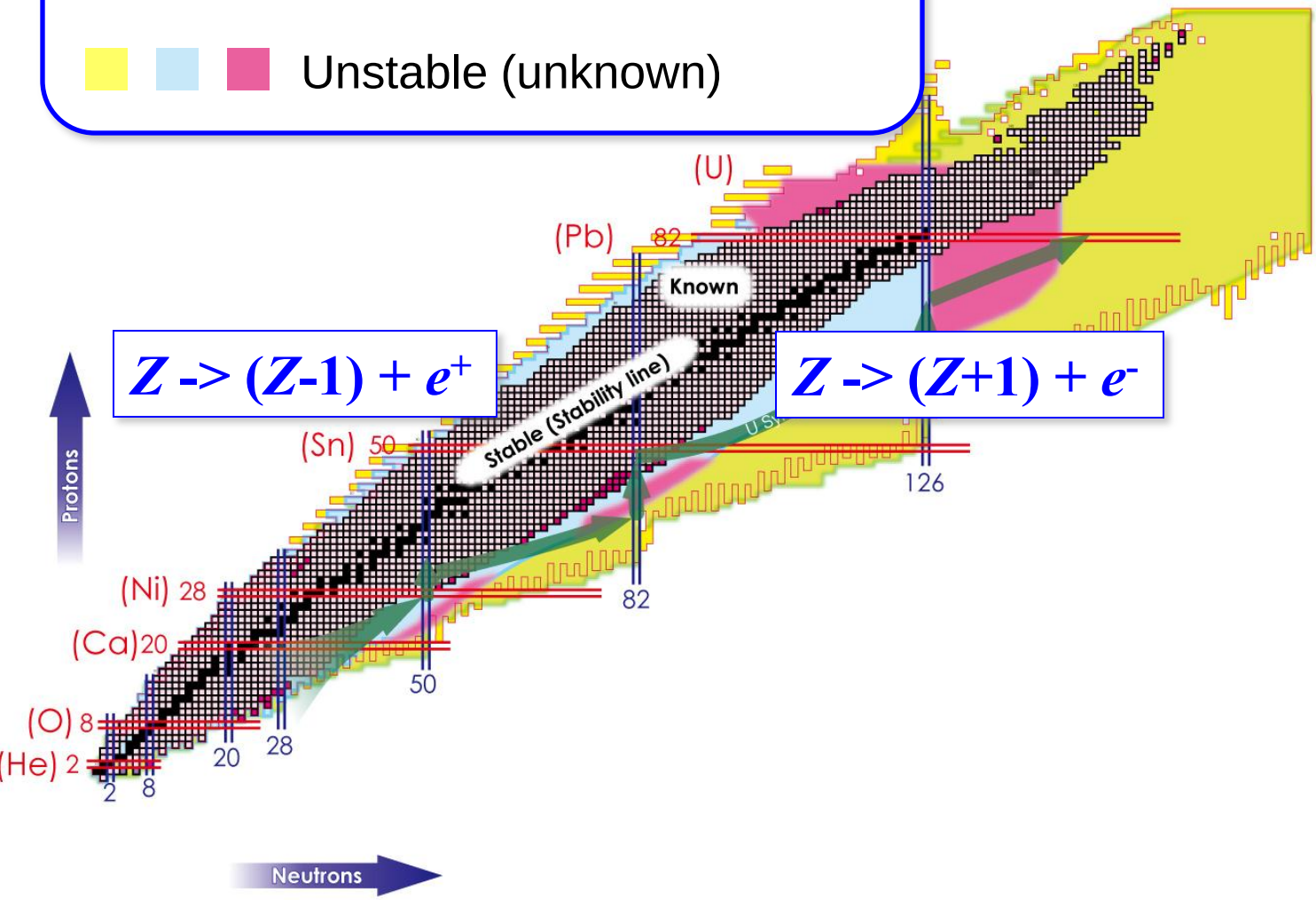
Unstable (unknown)

against ***beta-decay***

Lifetime ~ ms



$Z \rightarrow (Z\text{-}1) + e^{+}$

$Z \rightarrow (Z\text{+}1) + e^{-}$

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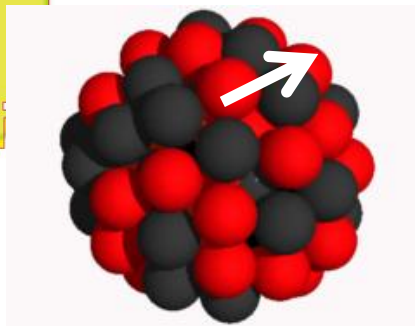
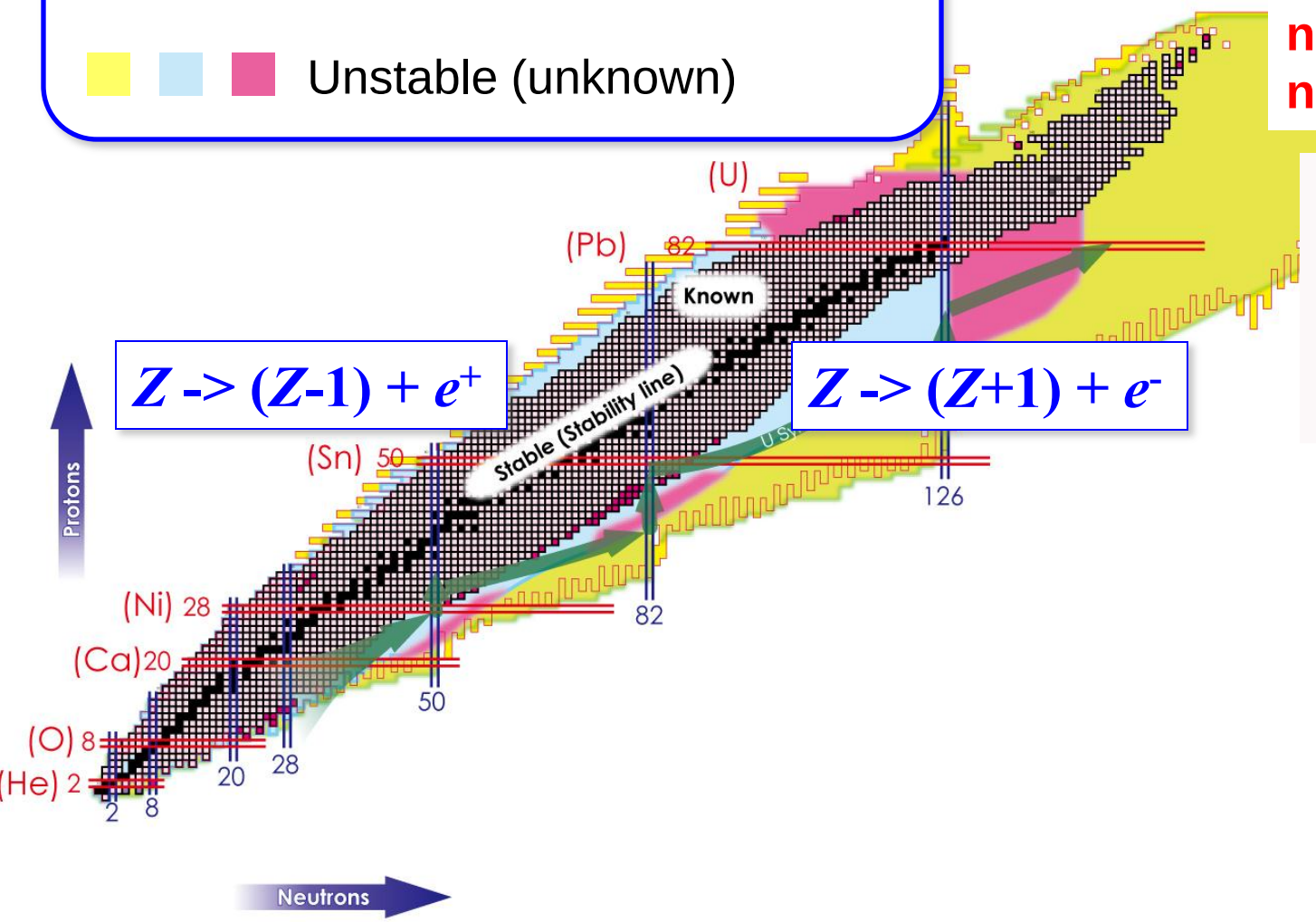
Stable against ***beta-decay***

Unstable (known)

Unstable (unknown)

Lifetime ~ ms >> Time scale of nucleon motion in nuclei ~ 10^{-22} s





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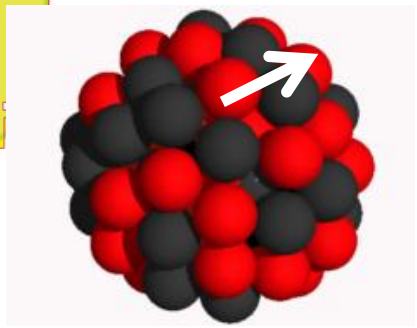
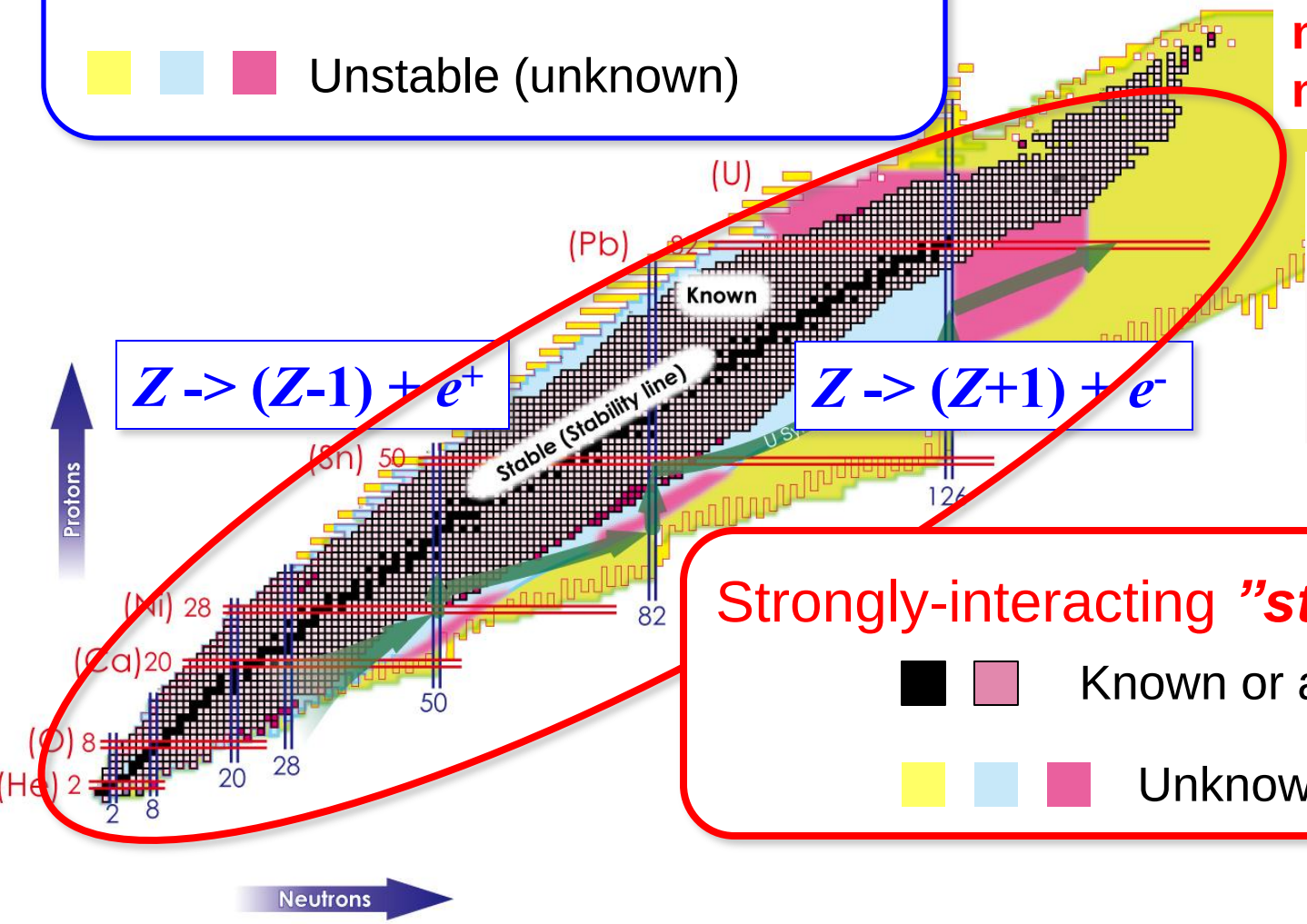




$Z \rightarrow (Z-1) + e^{+}$

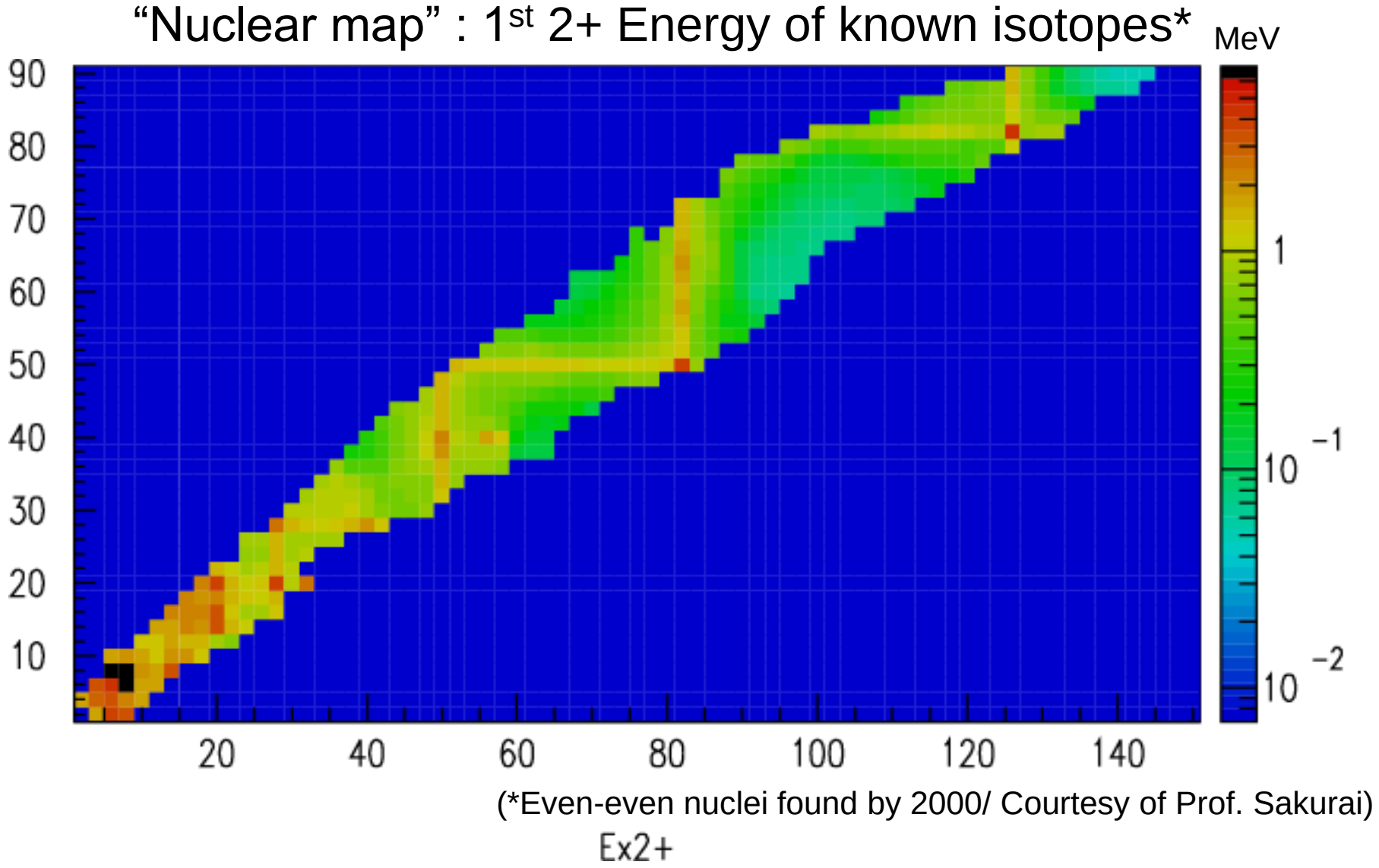
$Z \rightarrow (Z+1) + e^{-}$

Strongly-interacting ***"stable"*** systems

Known or accessed

Unknown

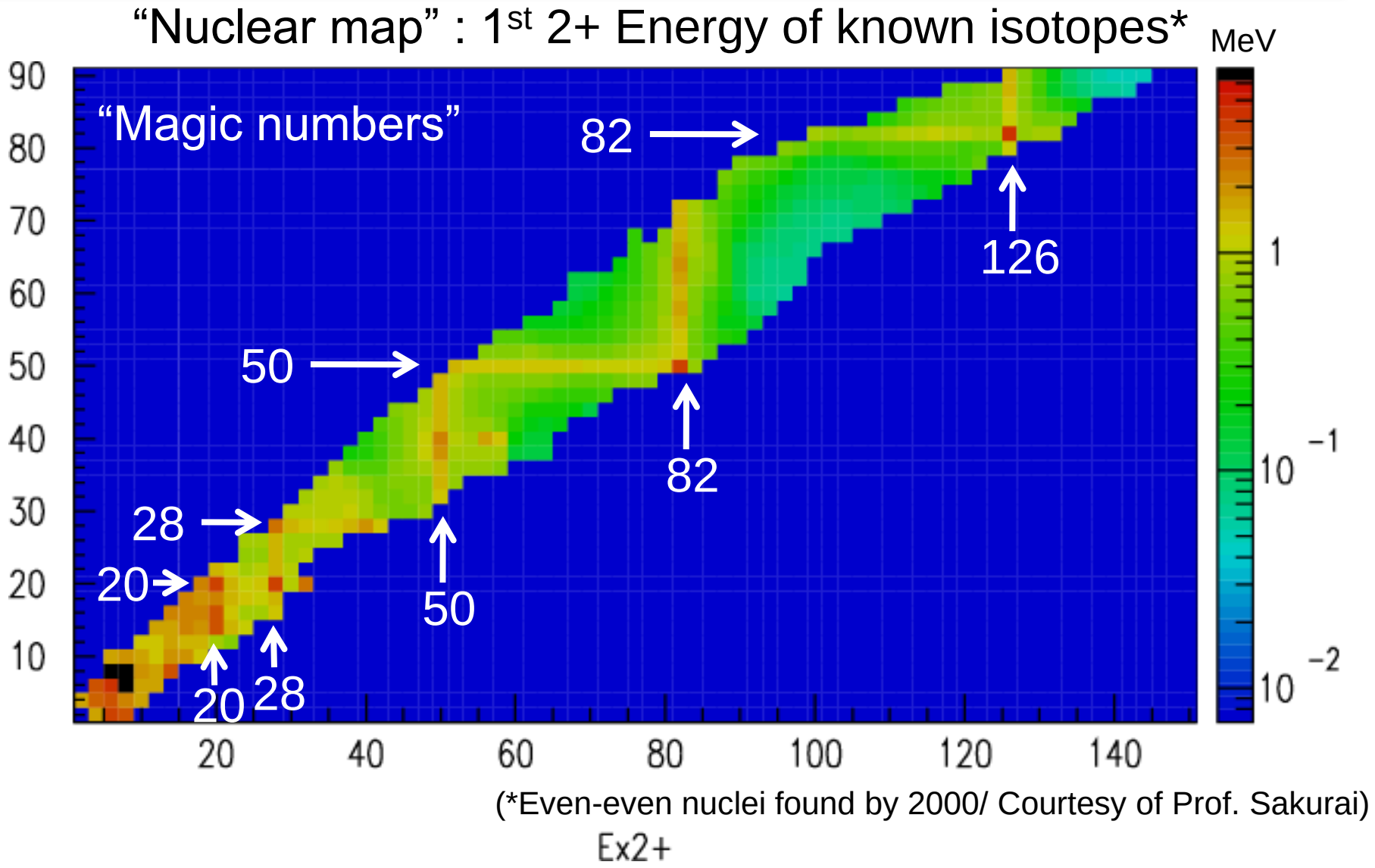
Toward comprehensive understanding of nuclear structure



(*Even-even nuclei found by 2000/ Courtesy of Prof. Sakurai)

(RIs are also important in astrophysics and various applications.)

Toward comprehensive understanding of nuclear structure



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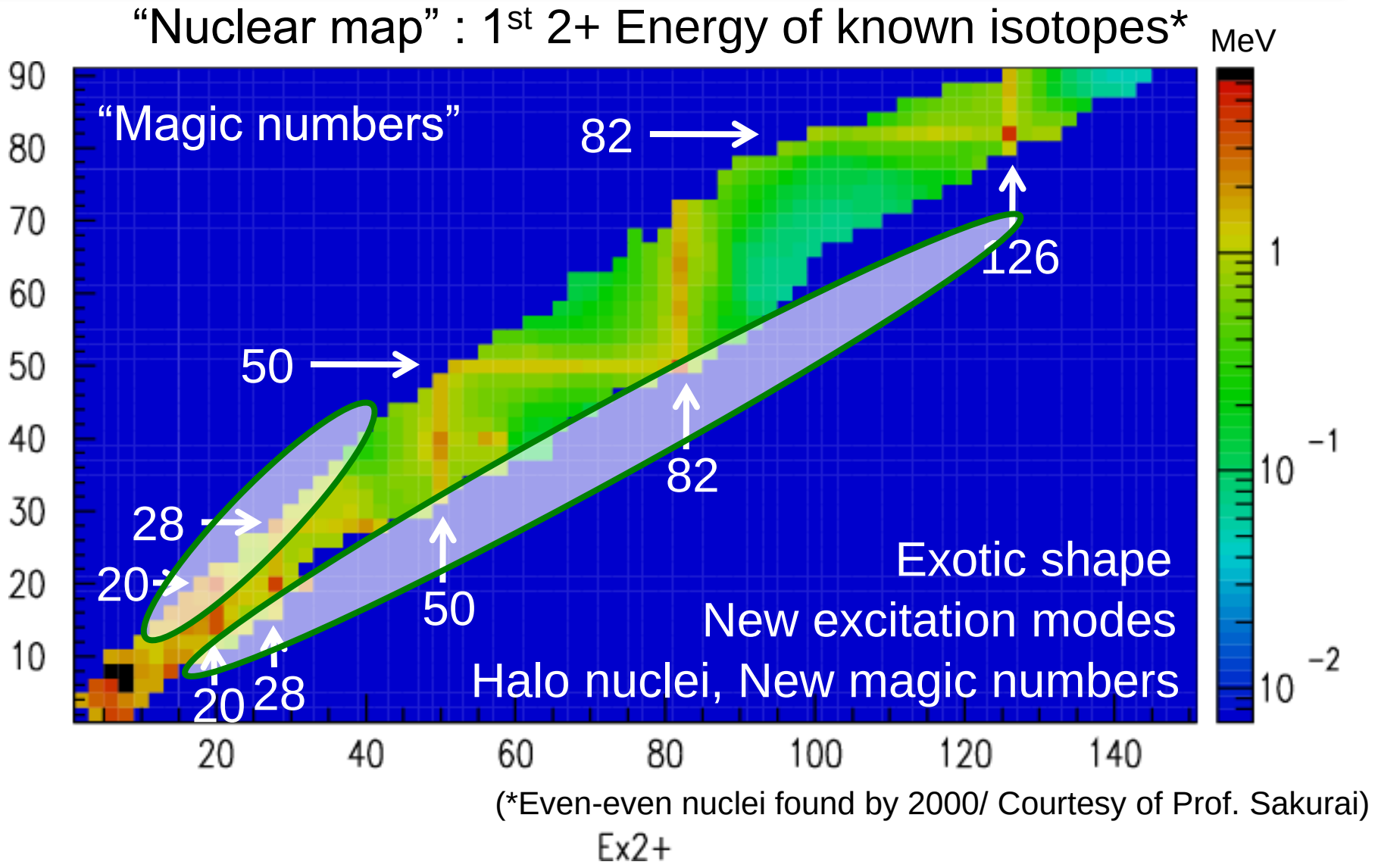

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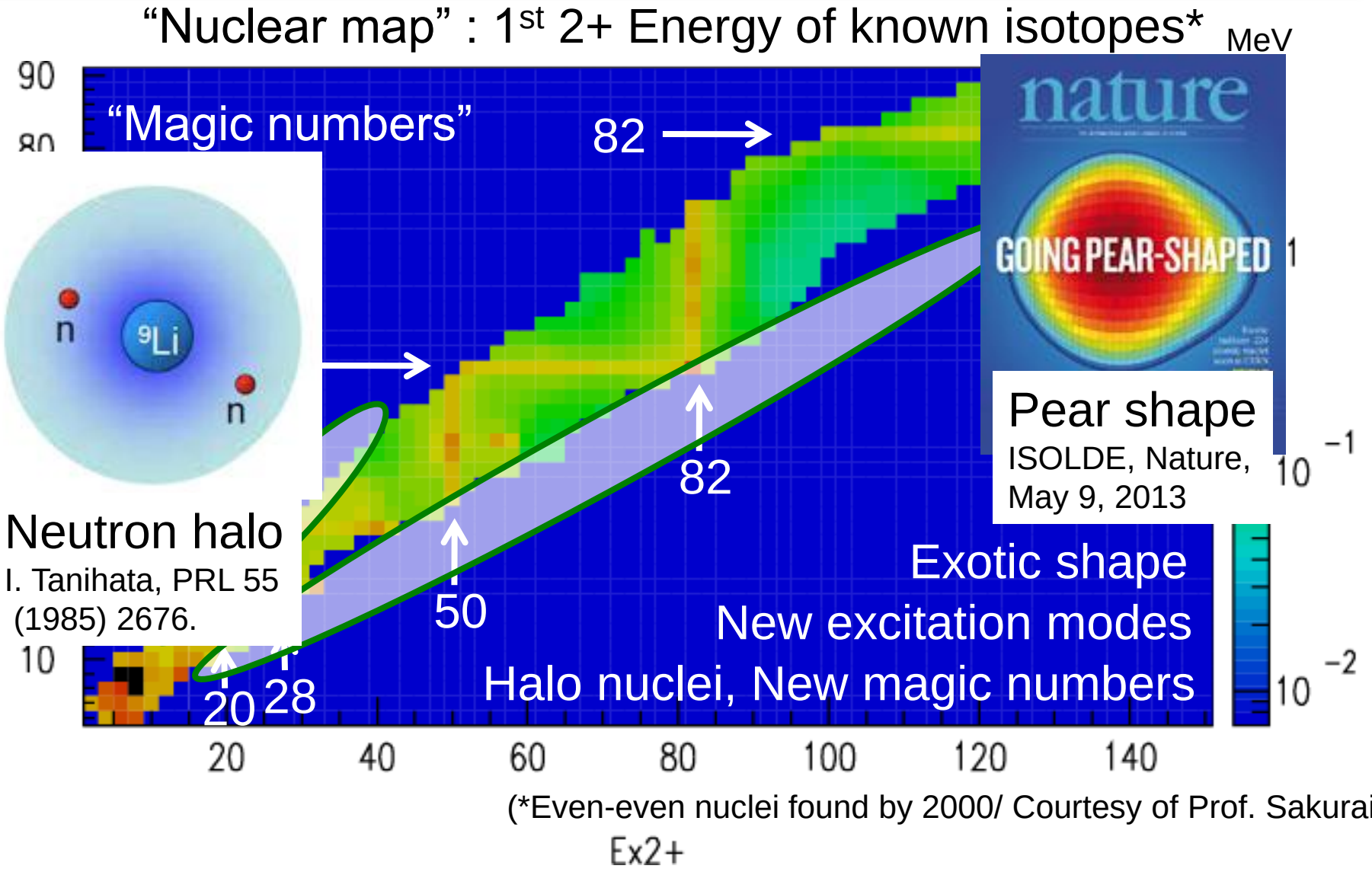

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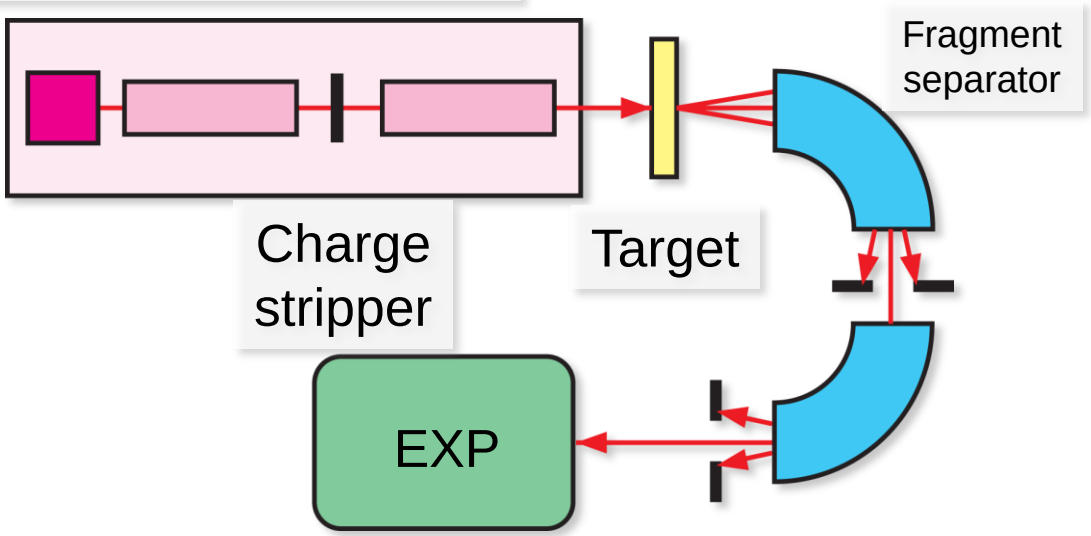
(RIs are also important in astrophysics and various applications.)

2. How to make RIB

In-flight



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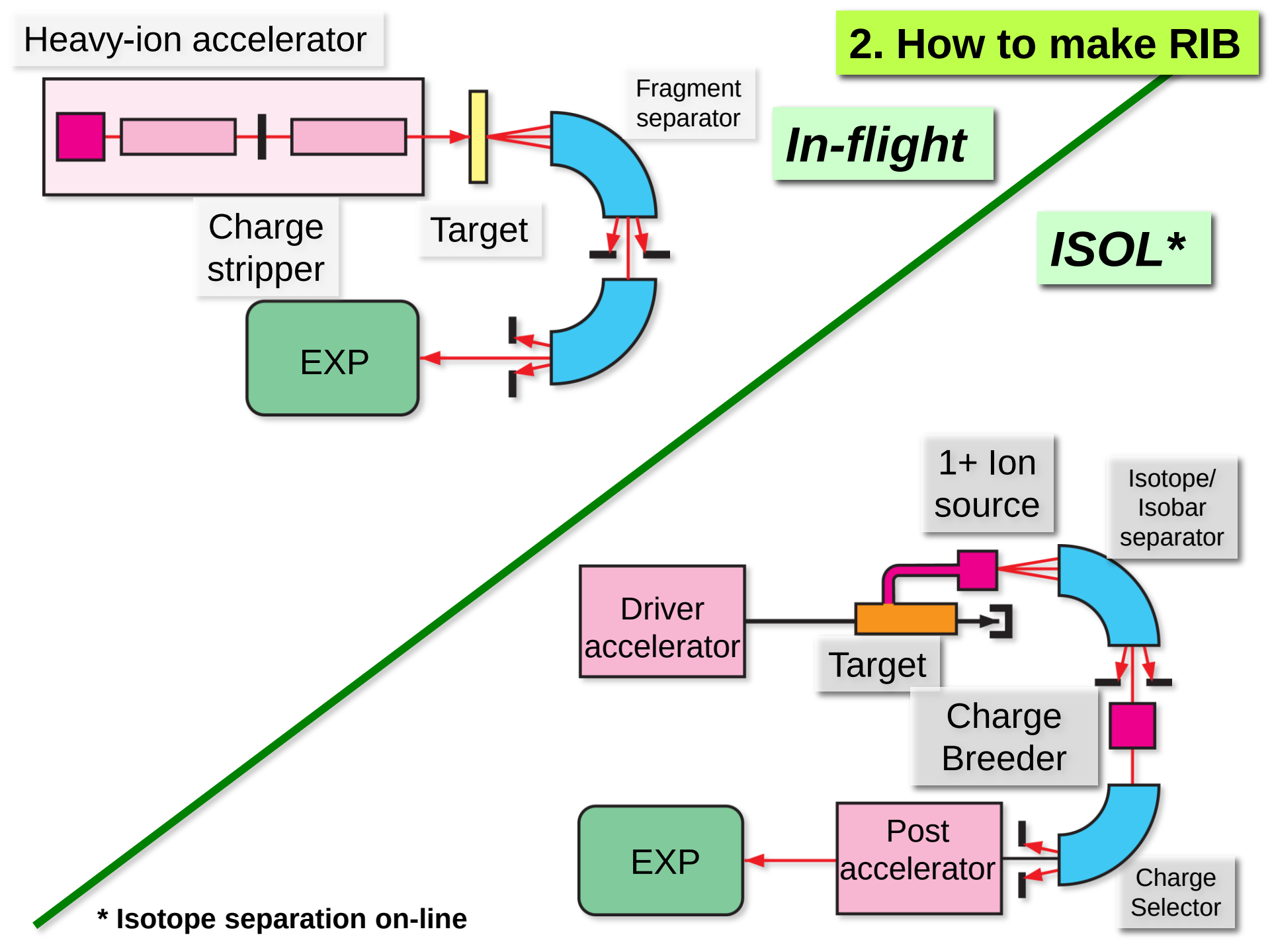

* Isotope separation on-line

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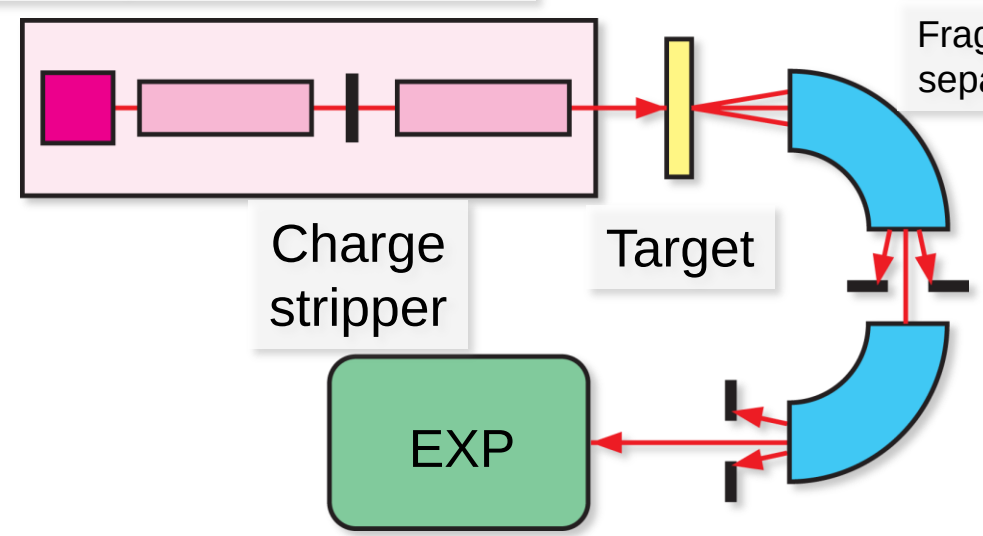


In-flight

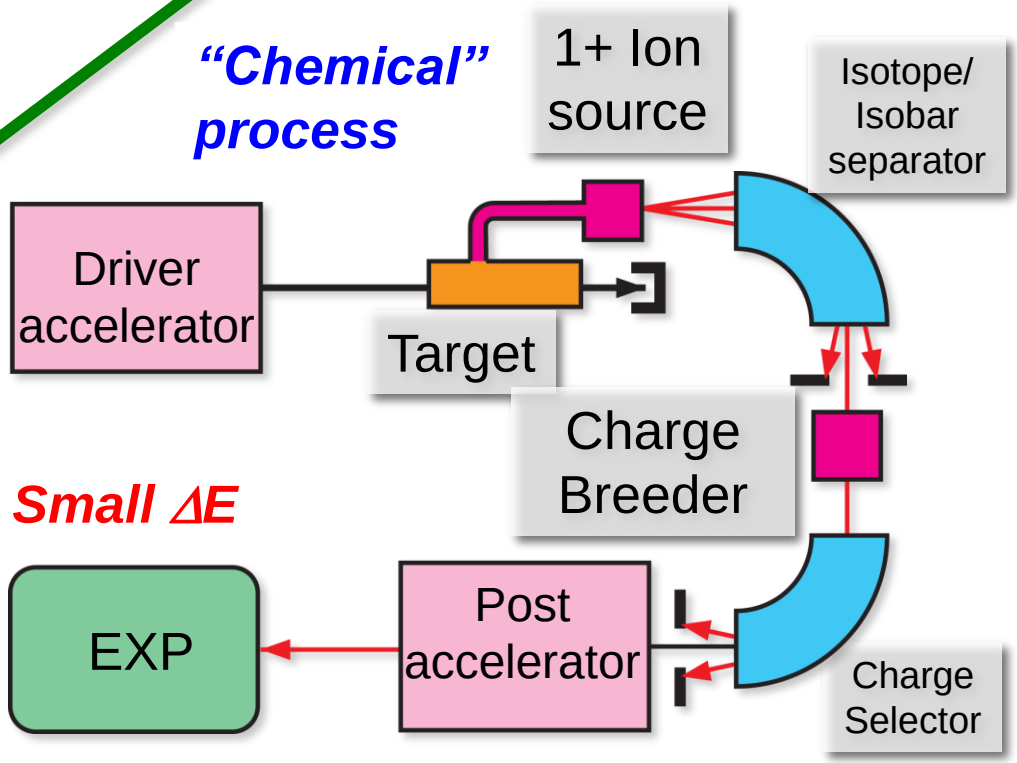
Large ΔE

ISOL*

Pros

Cons

"Chemical" process



Long lived RI

* Isotope separation on-line

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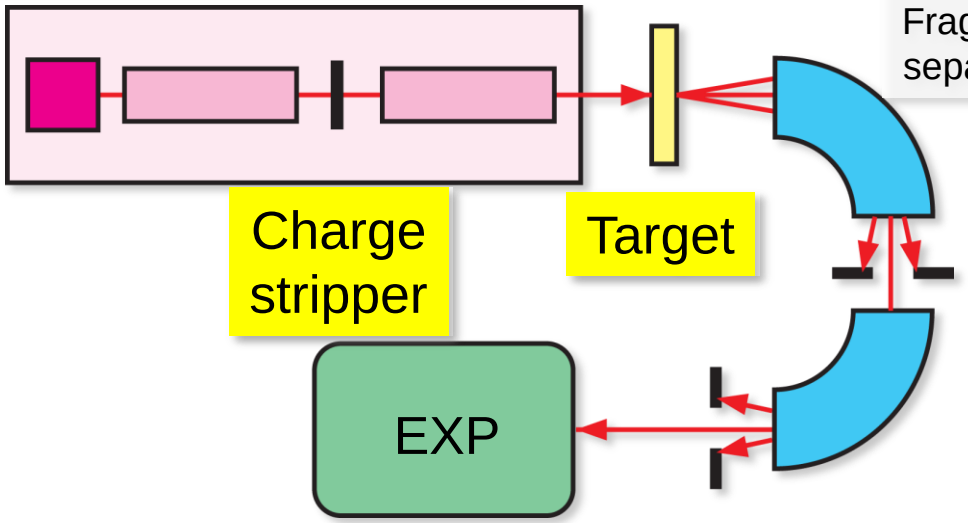


In-flight

Large ΔE

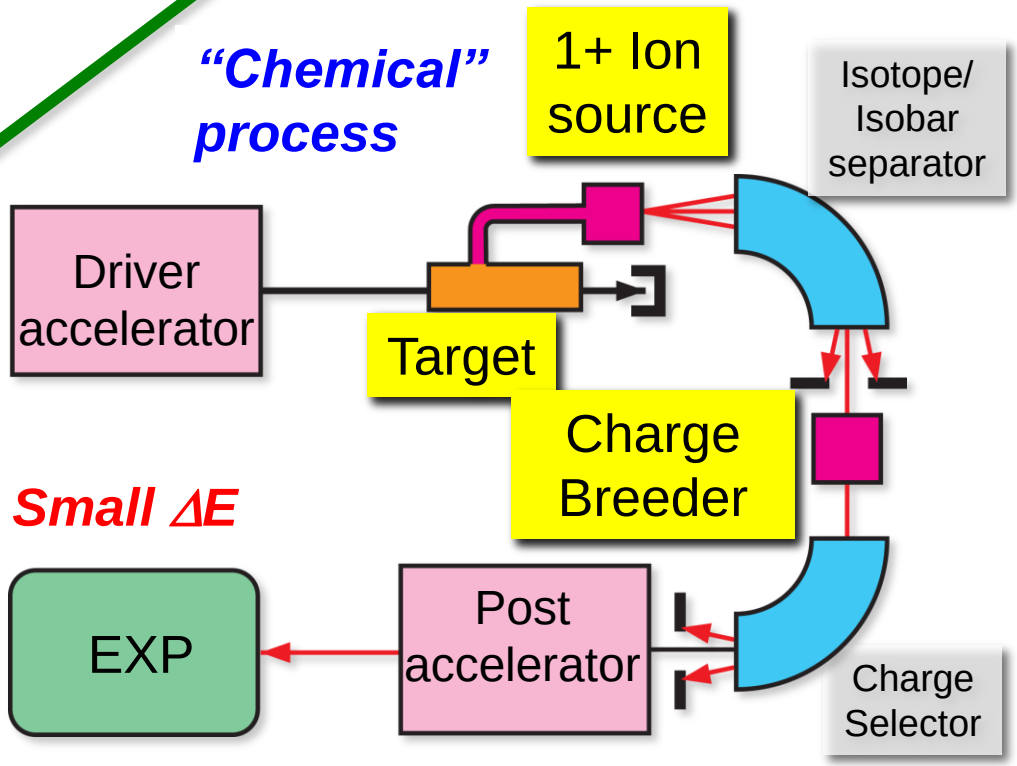
(Challenging issues!!)

Long lived RI

ISOL*

Pros

Cons



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3. RIB facilities in the world

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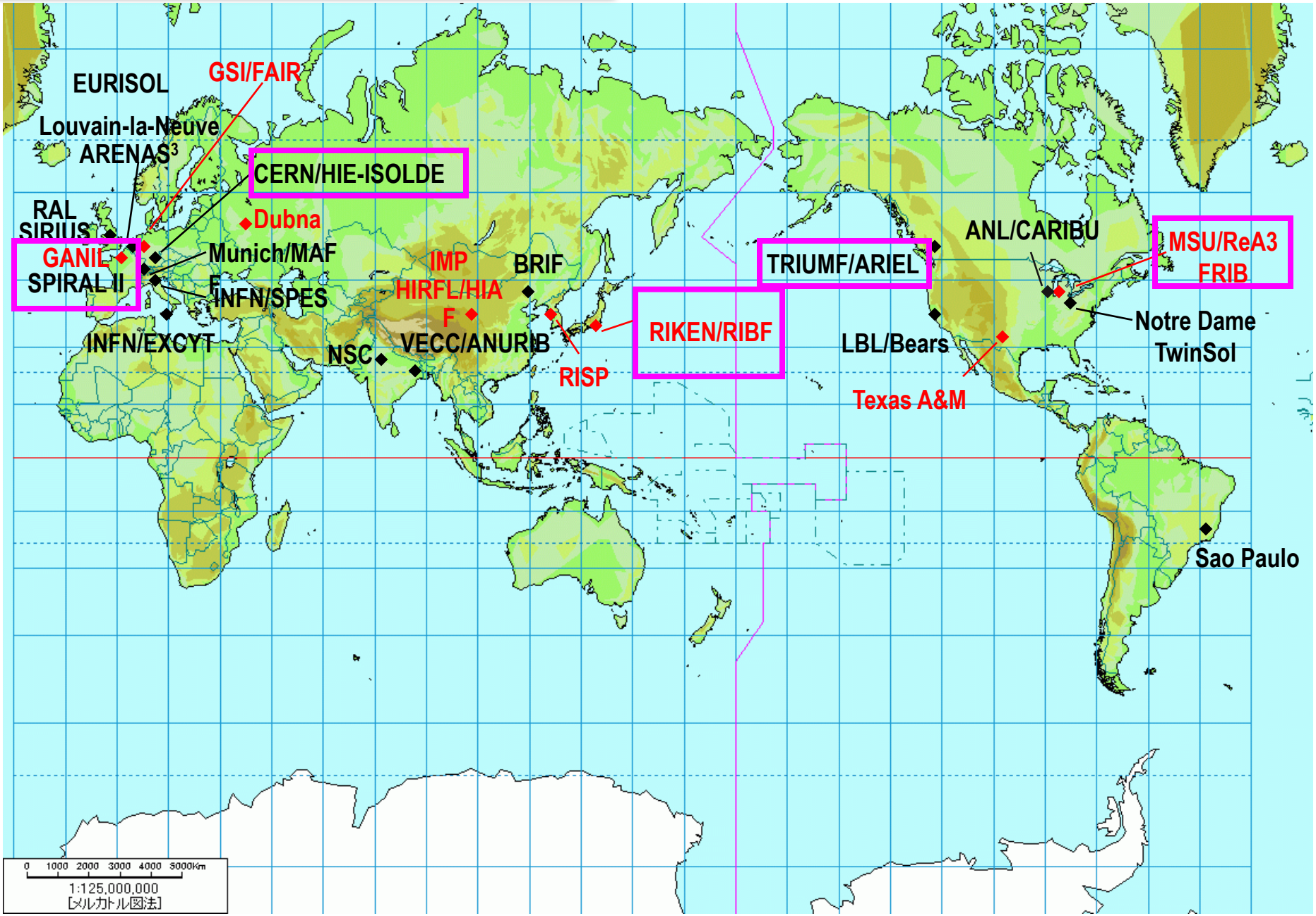
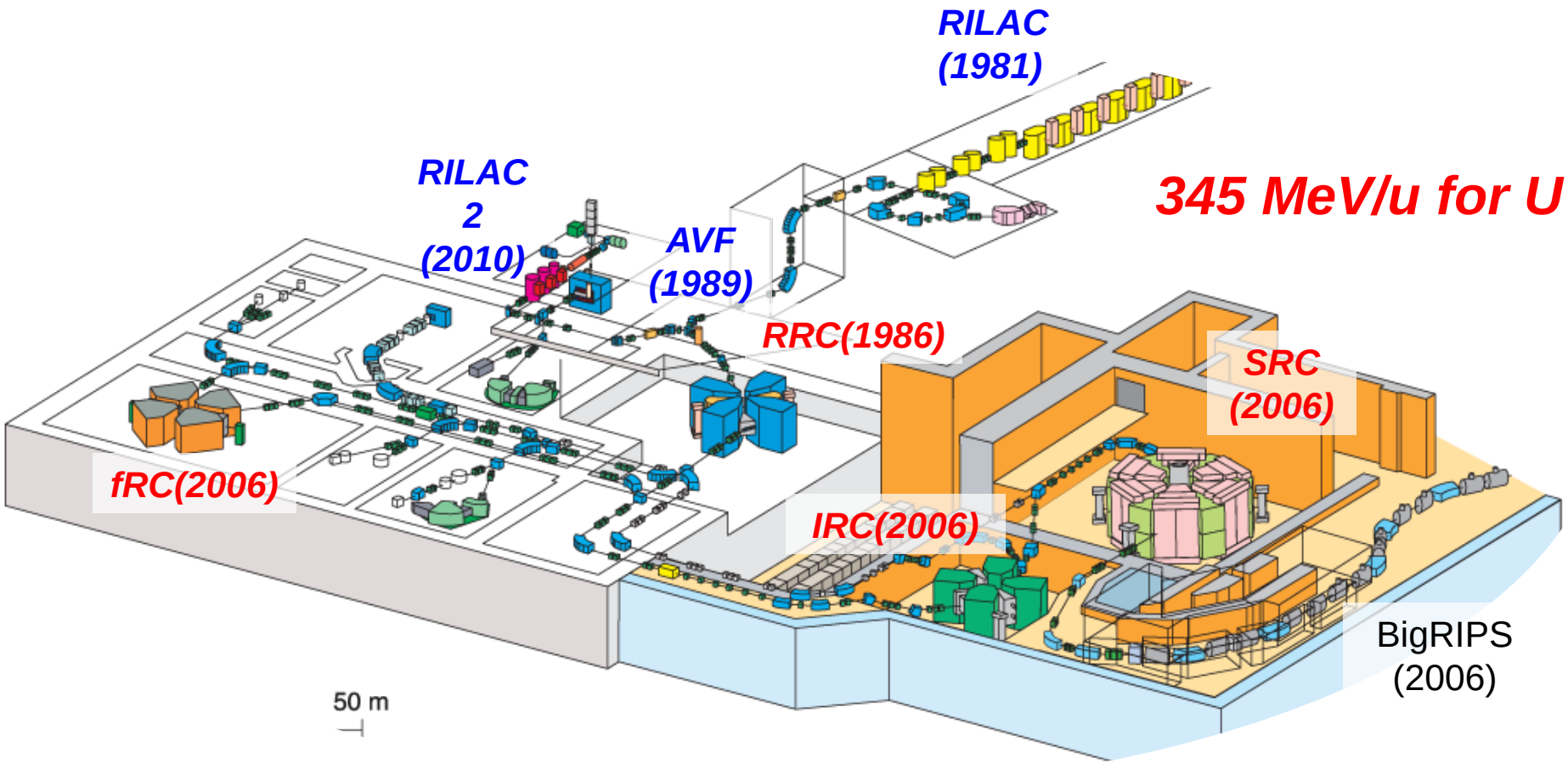


RIKEN RI Beam Factory

(RIBF=Radioactive Isotope Beam Factory)

Y. Yano, NIM B261 (2007) 1009

- 3 injectors and 4 booster cyclotrons
- 3 acceleration modes to accommodate all ion species
- 3 simultaneous users (RILAC2-RIBF, RILAC-GARIS, AVF)



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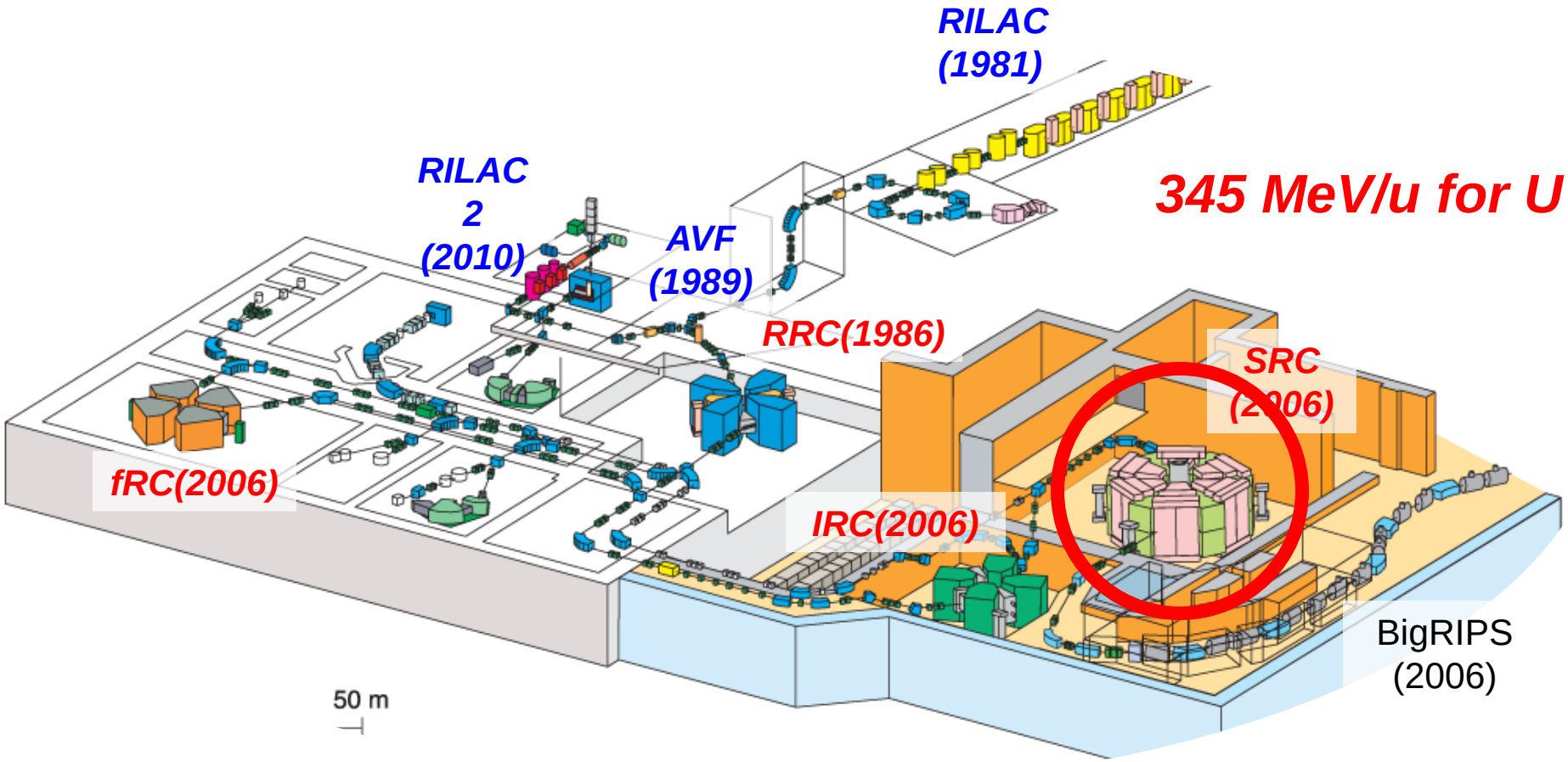
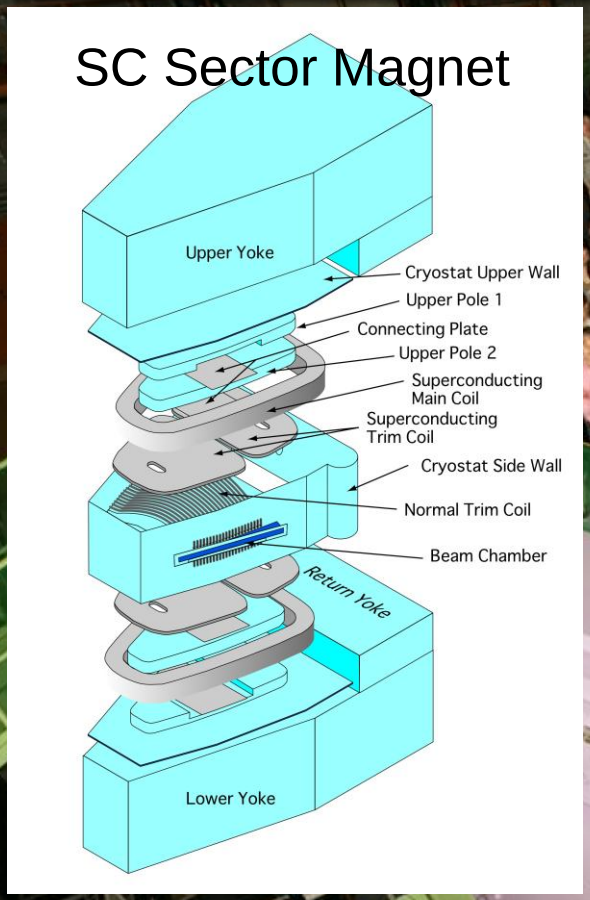



RIKEN RIBF, Japan
K2600-MeV SRC

RIKEN RIBF, Japan

K2600-MeV SRC



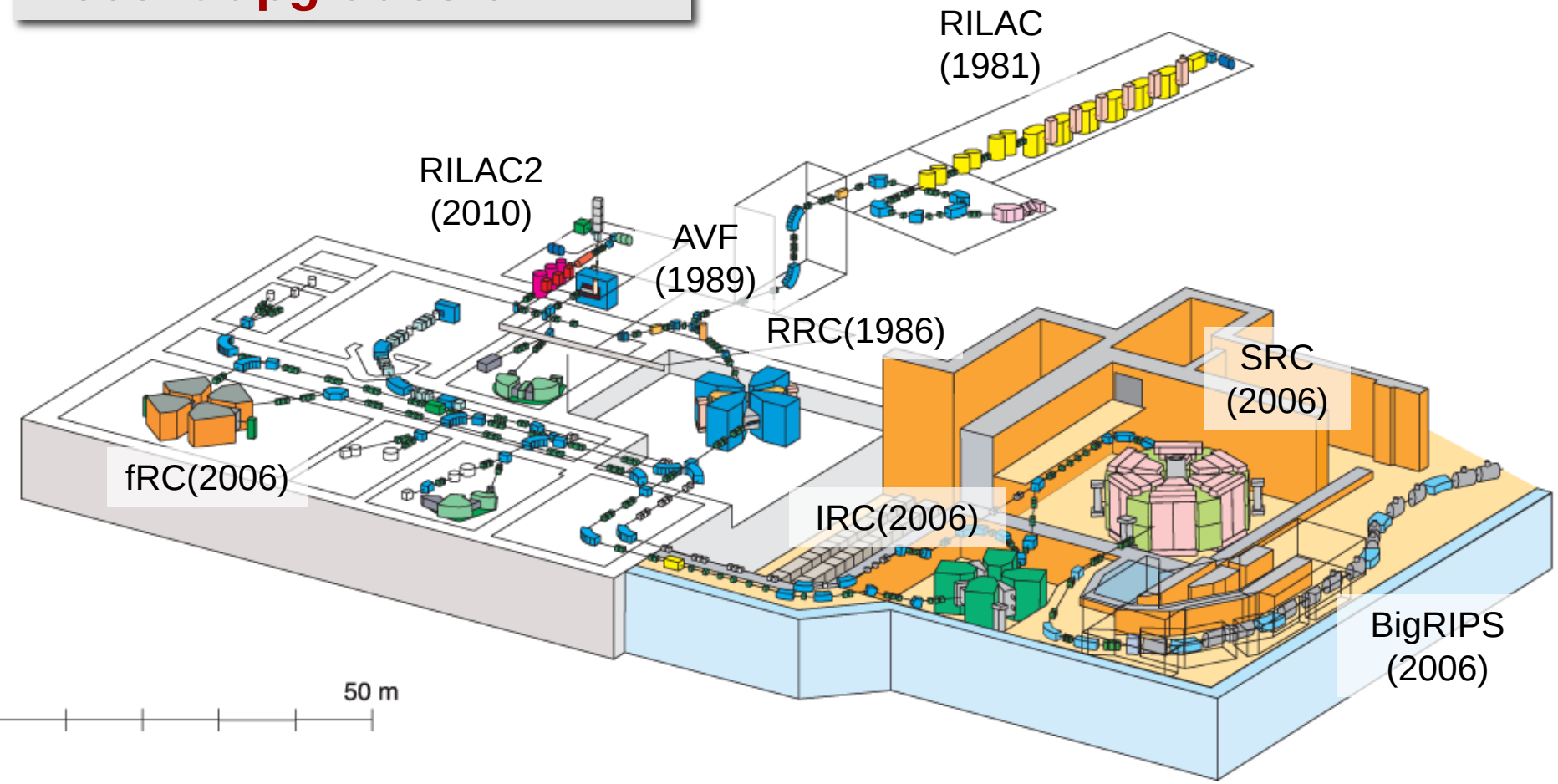
World's first superconduting RING cyclotron

B_{max}= 3.8 T, Voltage gain = 640 MV (cw)

Total weight = 8,300 tons

H. Okuno et al., IEEE Trans. Applied Superconductivity, 17 (2007) 1063

Recent upgrades of RIBF



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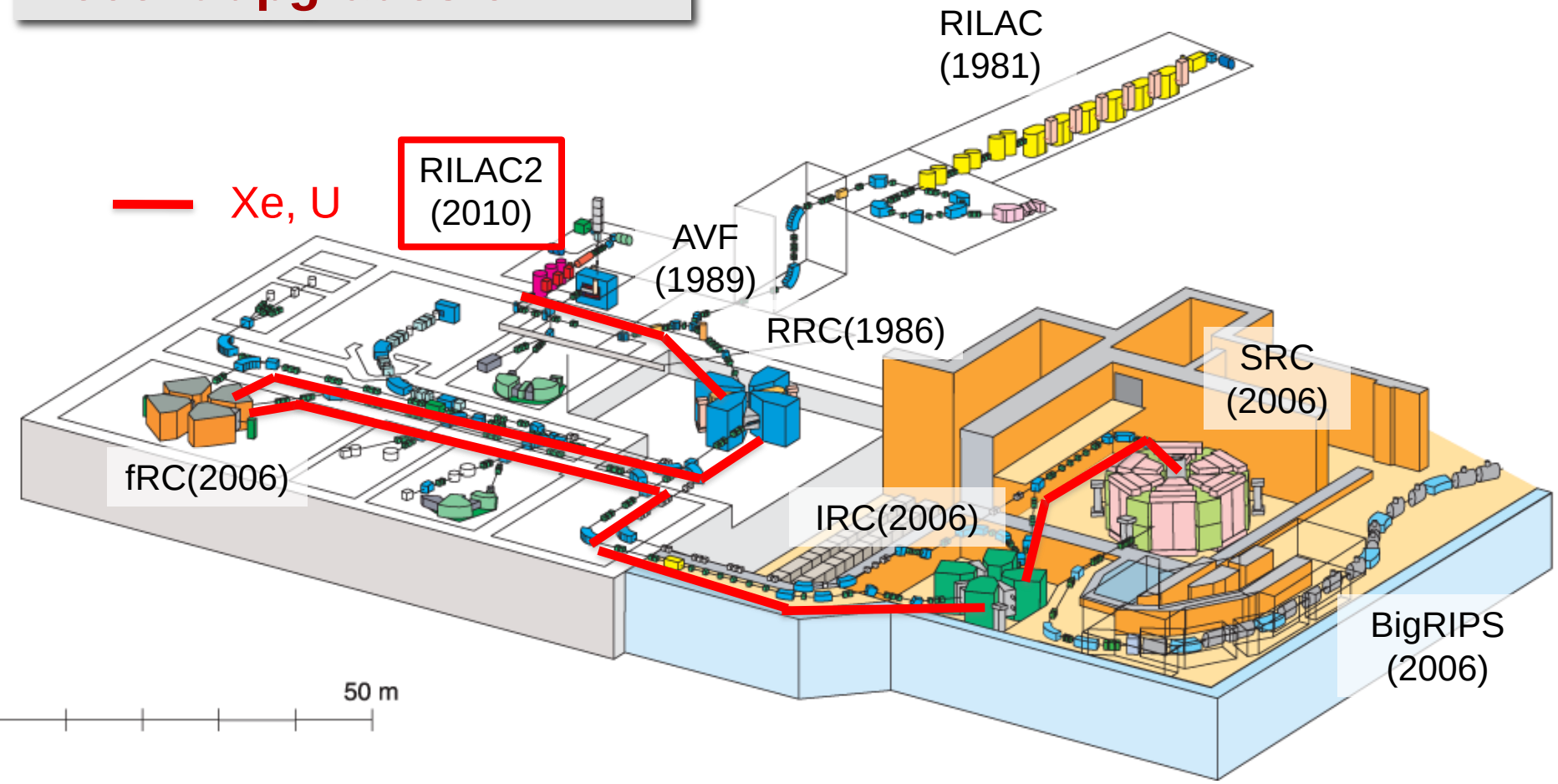

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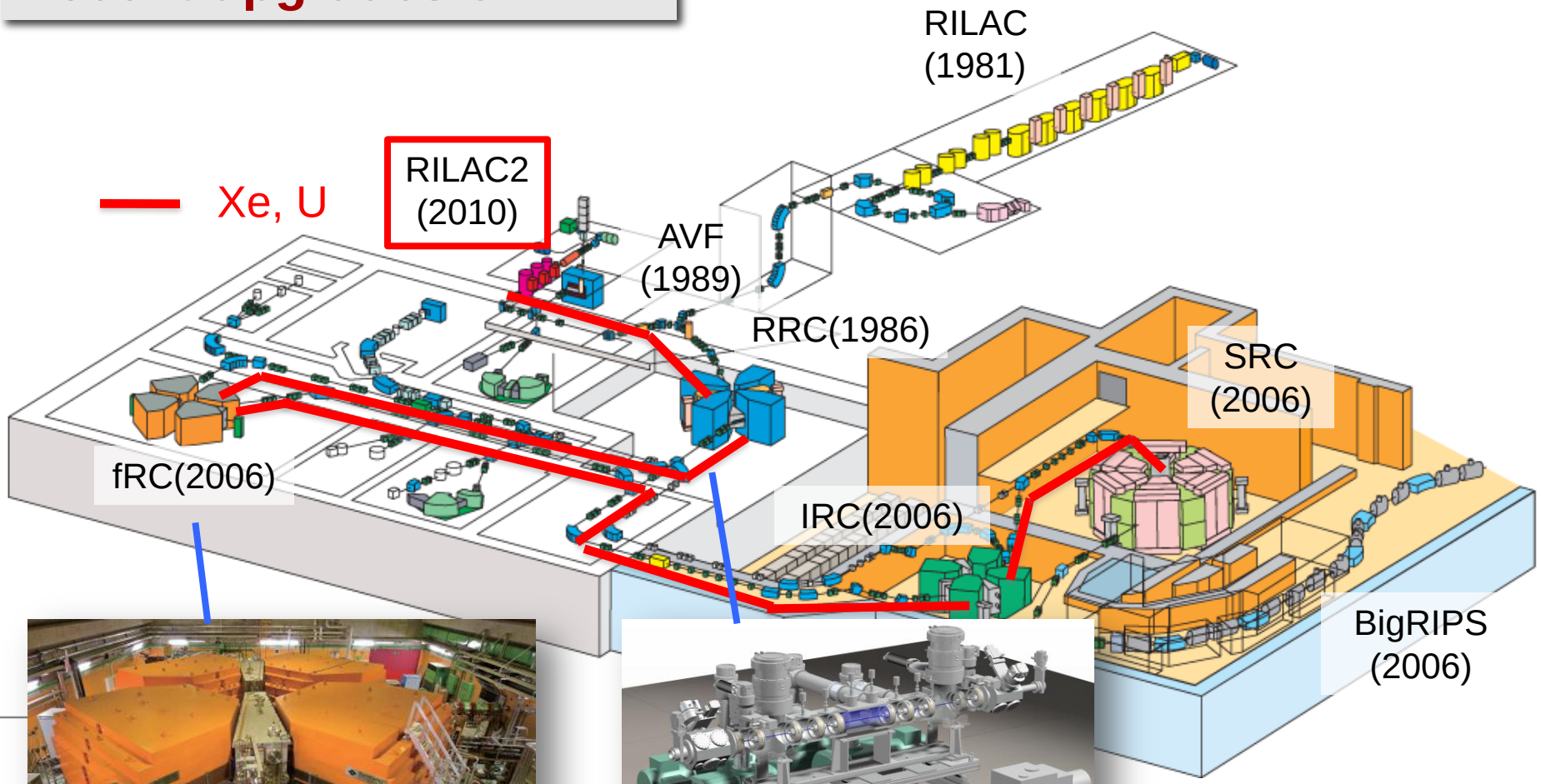
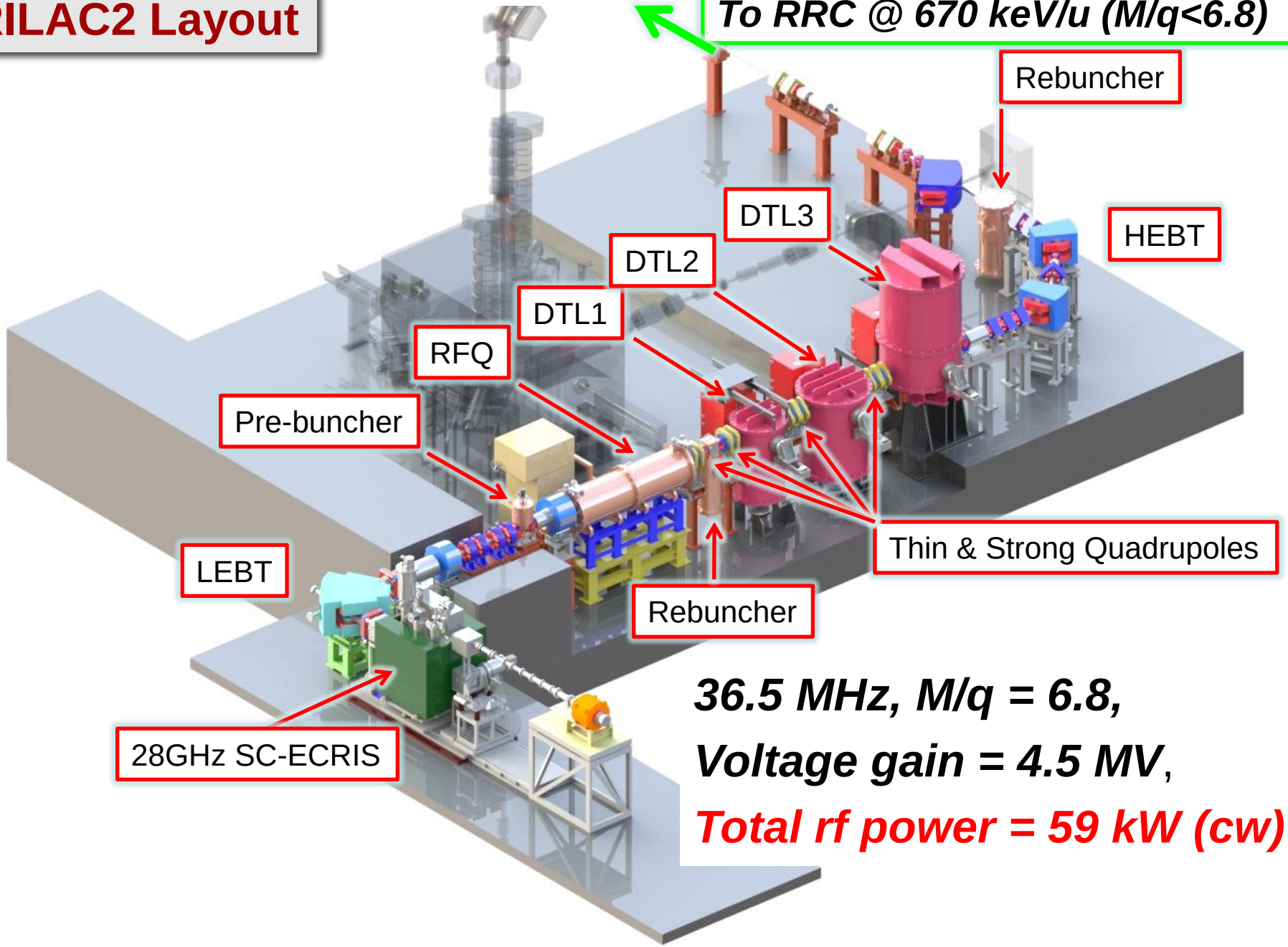


fRC upgraded (2012)
K570 => K700 MeV

He-gas stripper (2012)
(Imao, ACFA/IPAC'13 prize)

RILAC2 Layout



36.5 MHz, M/q = 6.8,

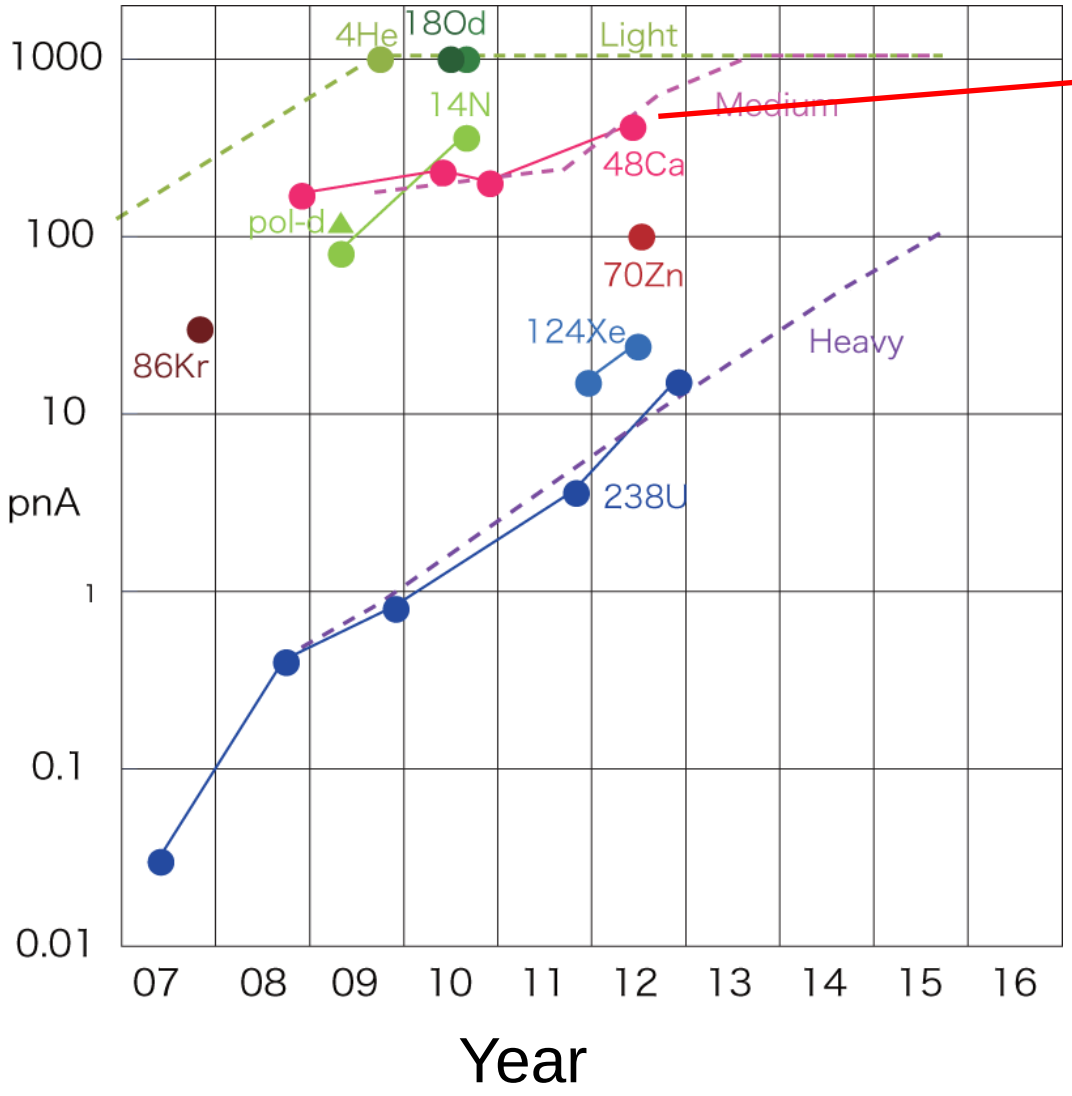
Voltage gain = 4.5 MV,

Total rf power = 59 kW (cw)

K. Yamada, IPAC'12, K Suda, NIMA in press

Evolution of beam intensities at RIBF

H. Okuno, N. Fukunishi, O. Kamigaito, Prog. Theor. Exp. Phys. 03C002 (2012).



Max. beam power: 7 kW

← 10^{11} pps

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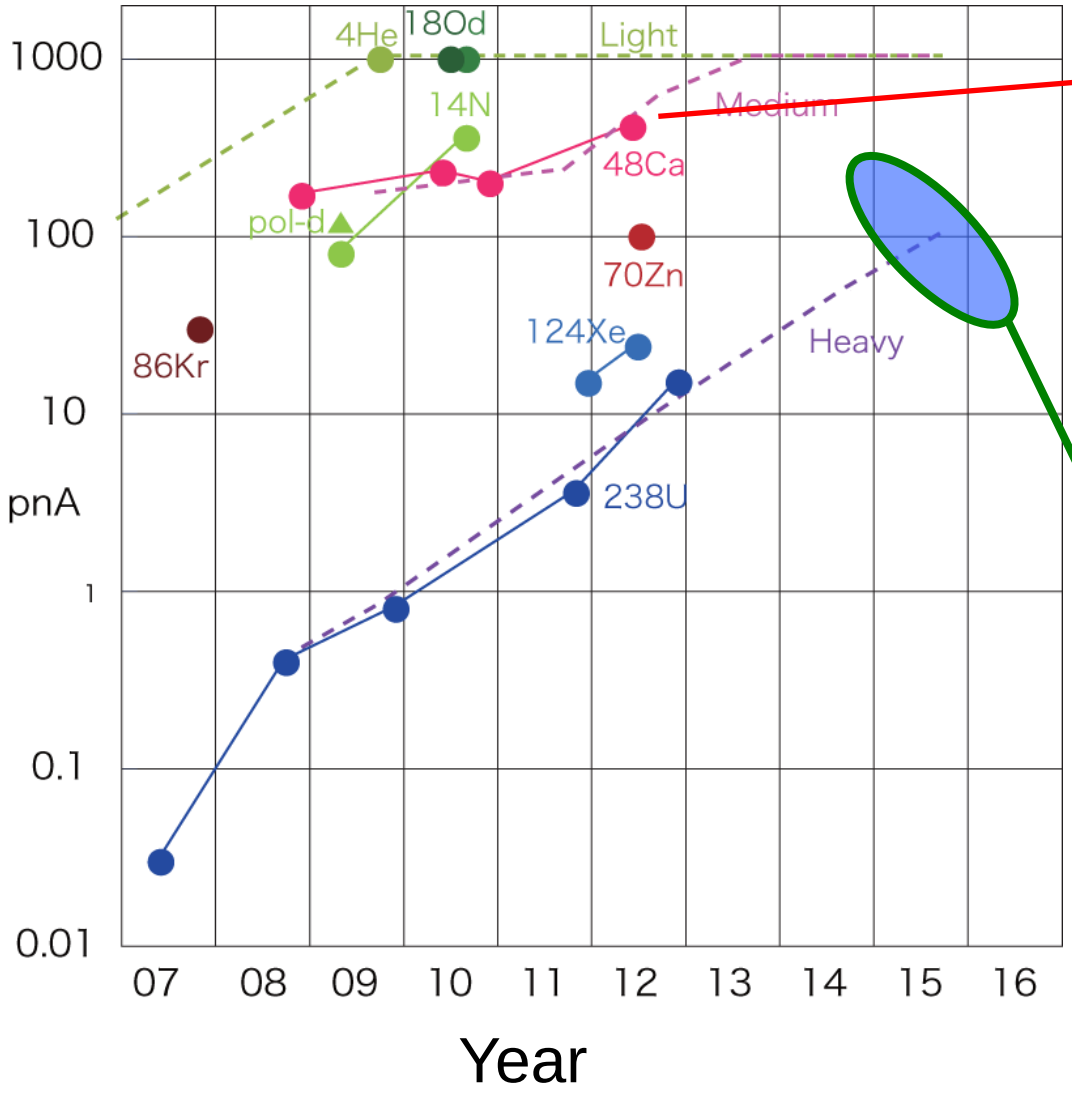
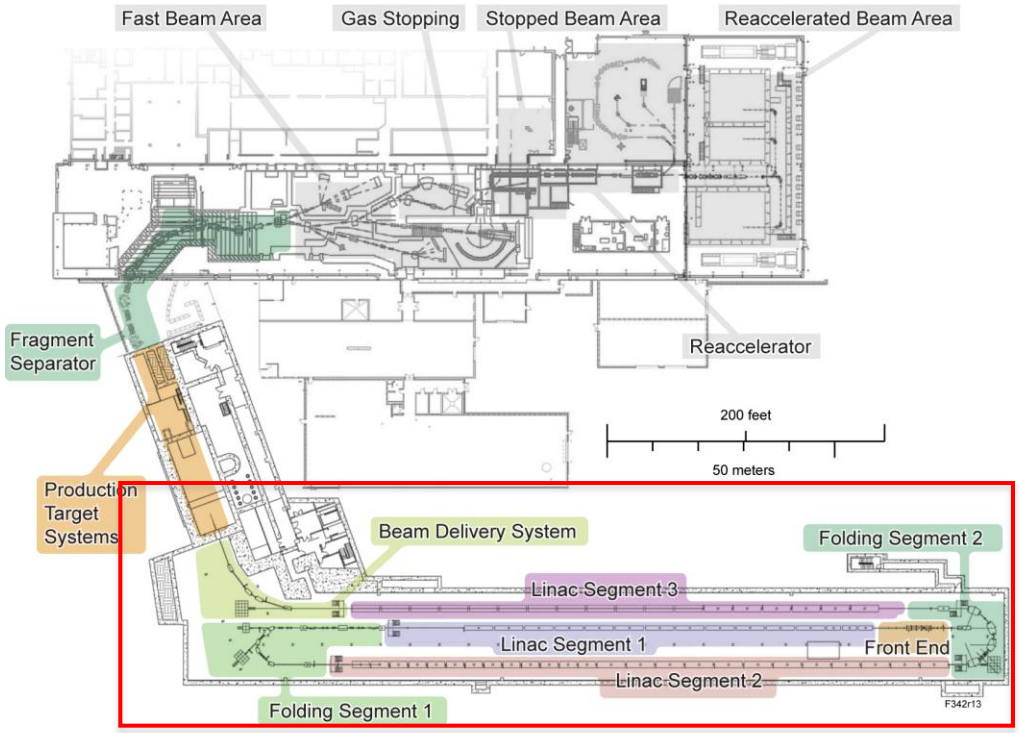


Max. beam power: 7 kW

10^{11} pps

5 - 10 kW in 3 - 5 years

FRIB Accelerator Design Requirements

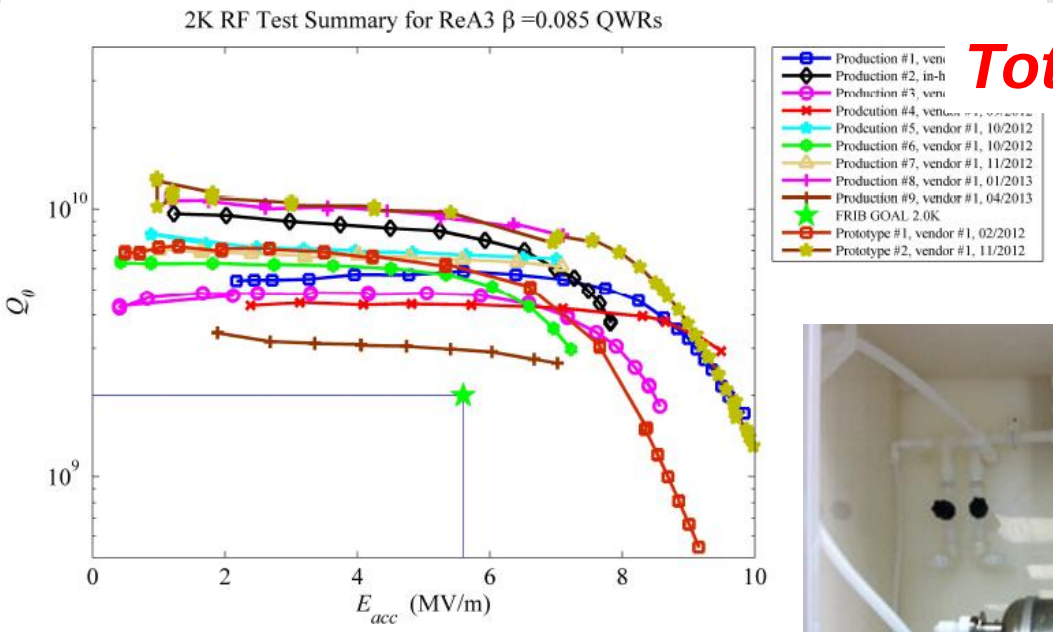


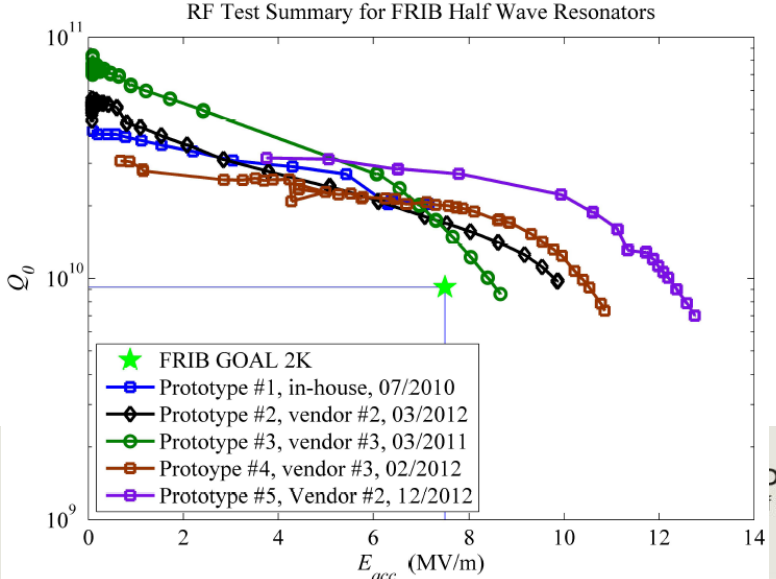
- Delivers FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than ***200 MeV/u***
- Provide beam power up to ***400 kW <= multi charge***
- Satisfy beam-on-target requirements

- ***Energy upgrade*** by filling vacant slots with 12 SRF cryomodules
- Maintain ***ISOL option***
- Upgradable to ***multiuser*** simultaneous operation of light/heavy ions with addition of a light-ion injector

(Courtesy of Dr. Wei)

Quarter-wave (β=0.085) and Half-wave (β=0.53) Resonators Qualified for FRIB Production



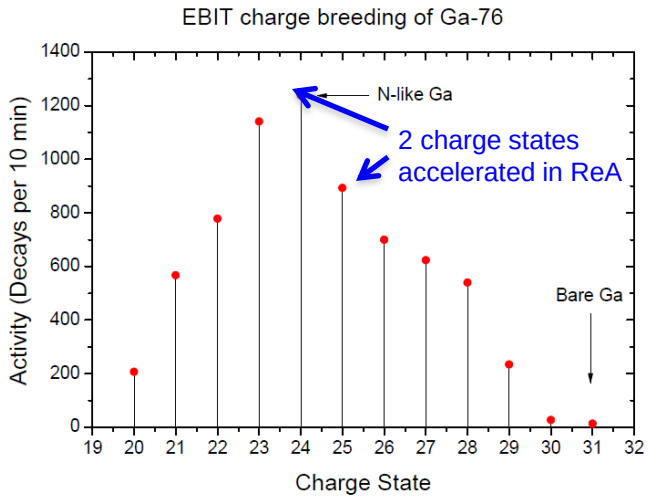


Total: 330 resonators (4 types)

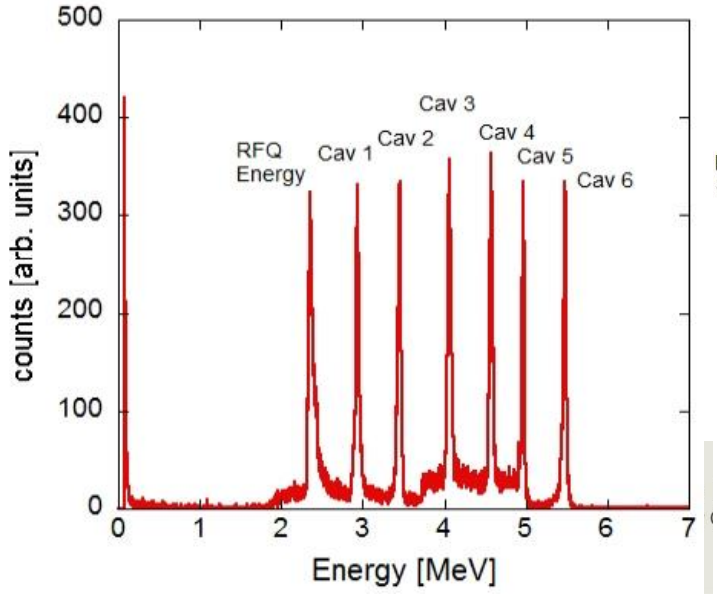
ope Beams
Science

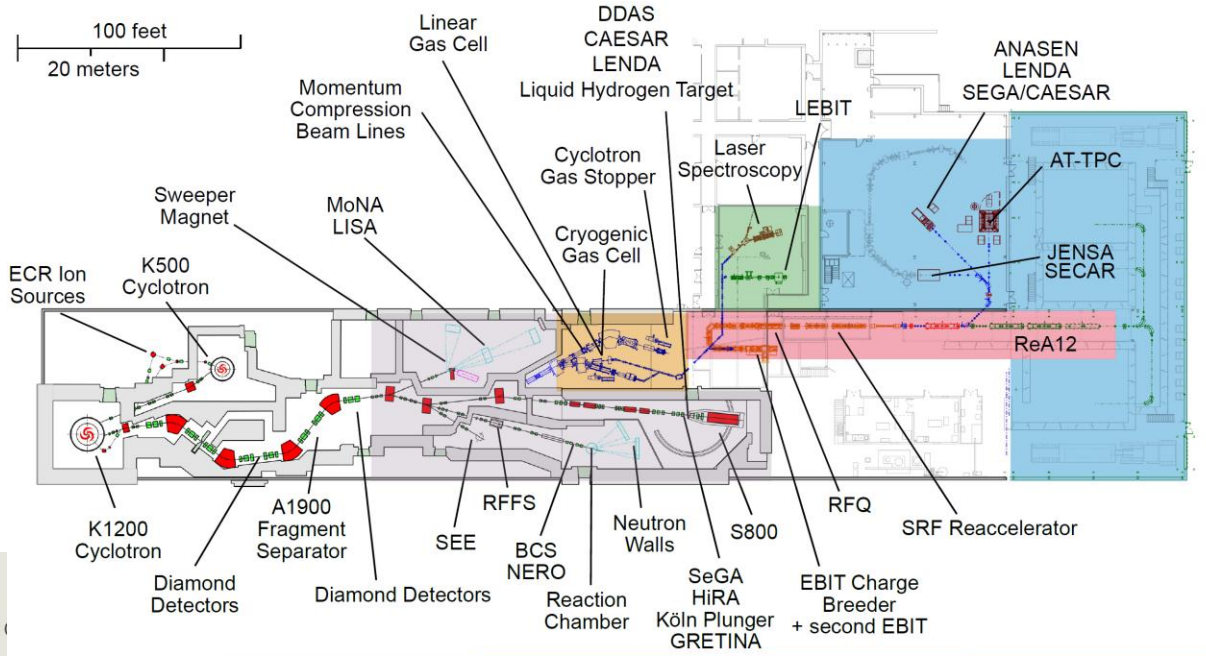
(Courtesy of Dr. Wei)

Rare Isotope ^{76}Ga Produced and Accelerated
Acceleration Using RFQ and β=0.041 Cryomodules



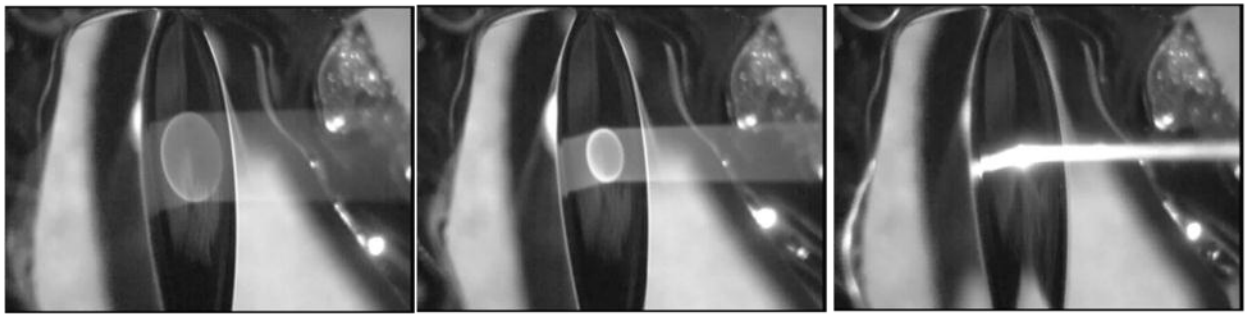
- Superconducting cyclotrons accelerate ^{76}Ge beam to 130 MeV/u
- ^{76}Ga produced and ***stopped in gas cell***
- ***Charge Breeding*** in the EBIT Source
- ***Re-acceleration*** in the ReA accelerator





Liquid Lithium Stripping Film Successfully Tested with Twice FRIB Beam Power Density

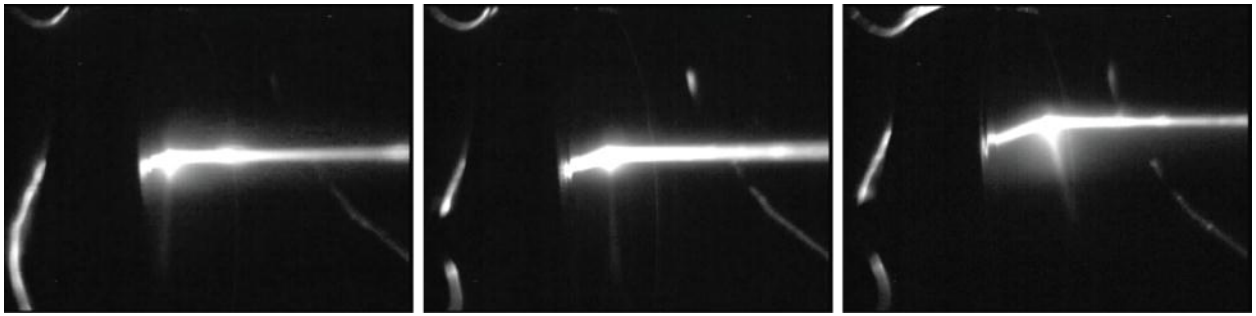
- LEDA ion source from Los Alamos restored at MSU; ***lithium film sustained*** beam power test at Argonne using the ***proton beam from the LEDA***



Argonne NATIONAL LABORATORY

Los Alamos NATIONAL LABORATORY EST.1943

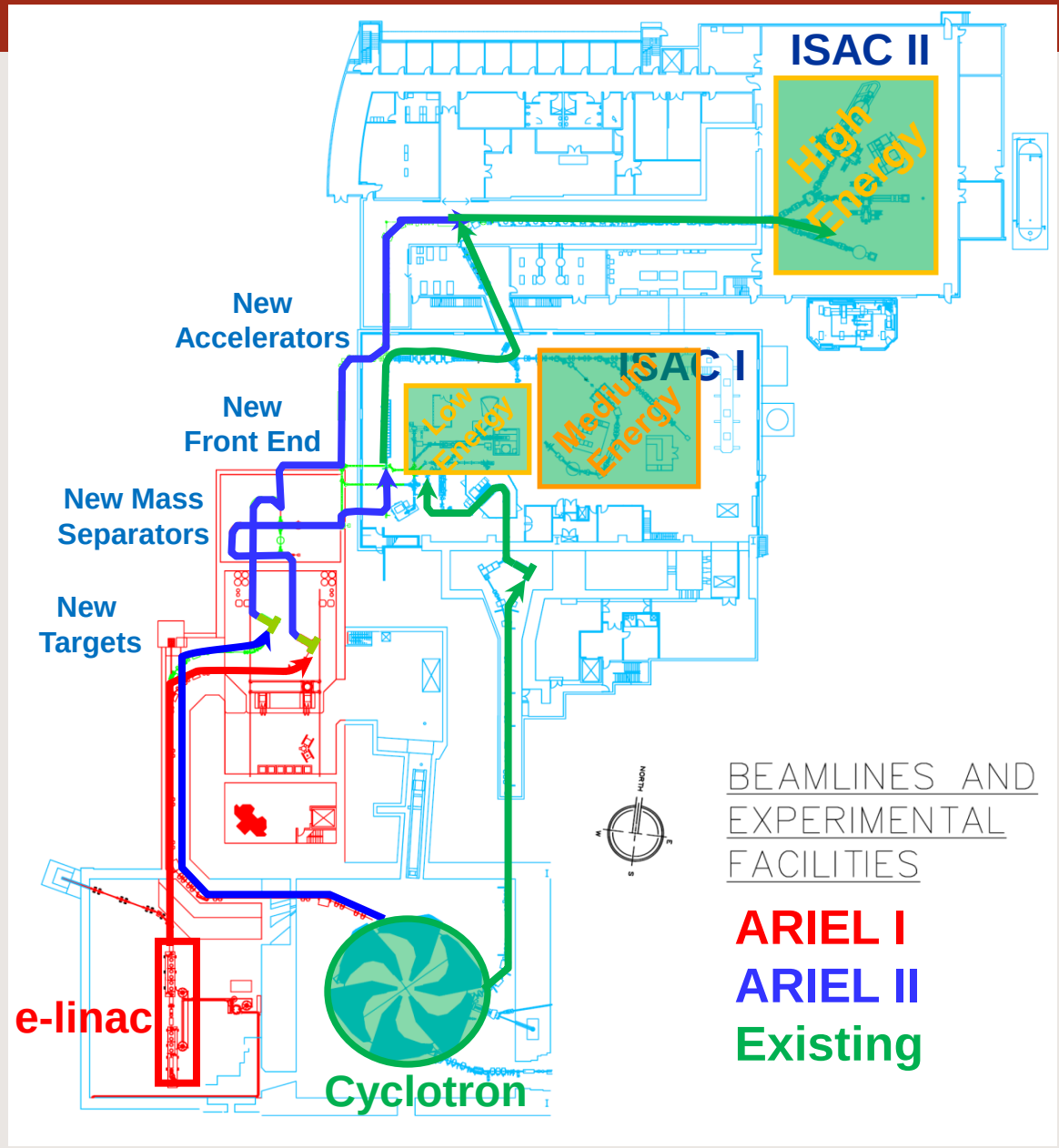
Proton beam (65 kV, 4 mA, σ = 0.7 mm in the best focused condition) impinging on the liquid lithium film, ~ 10 μm thick, moving at 50 m/s.



Photos showing the trail of heated lithium flow lines. By moving the impact point from left to right, the flow lines can be visualized.

(Courtesy of Dr. Wei)

ARIEL Project: 10-Year Vision



Substantially expand RIB program with:

- ***three simultaneous beams***
- increased number of hours delivered per year
- new beam species
- increased beam development capabilities

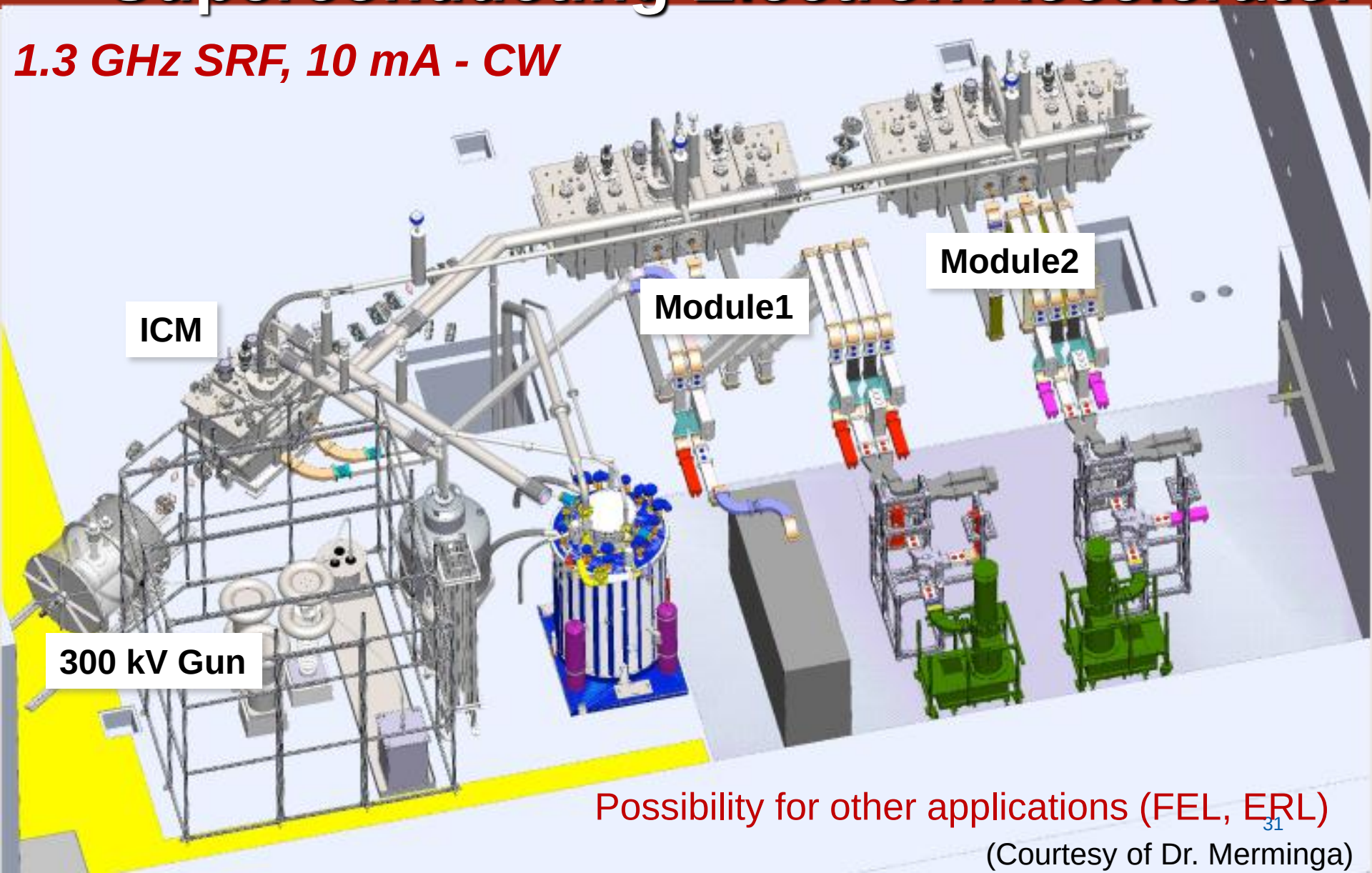
Implementation:

- Complementary ***electron linac*** driver for photo-fission
- ***New target stations*** and front end
- ***New proton beamline***
- Staged installation

(Courtesy of Dr. Merminga)

ARIEL e-Linac : MW-class Superconducting Electron Accelerator

1.3 GHz SRF, 10 mA - CW



Possibility for other applications (FEL, ERL)

(Courtesy of Dr. Merminga)

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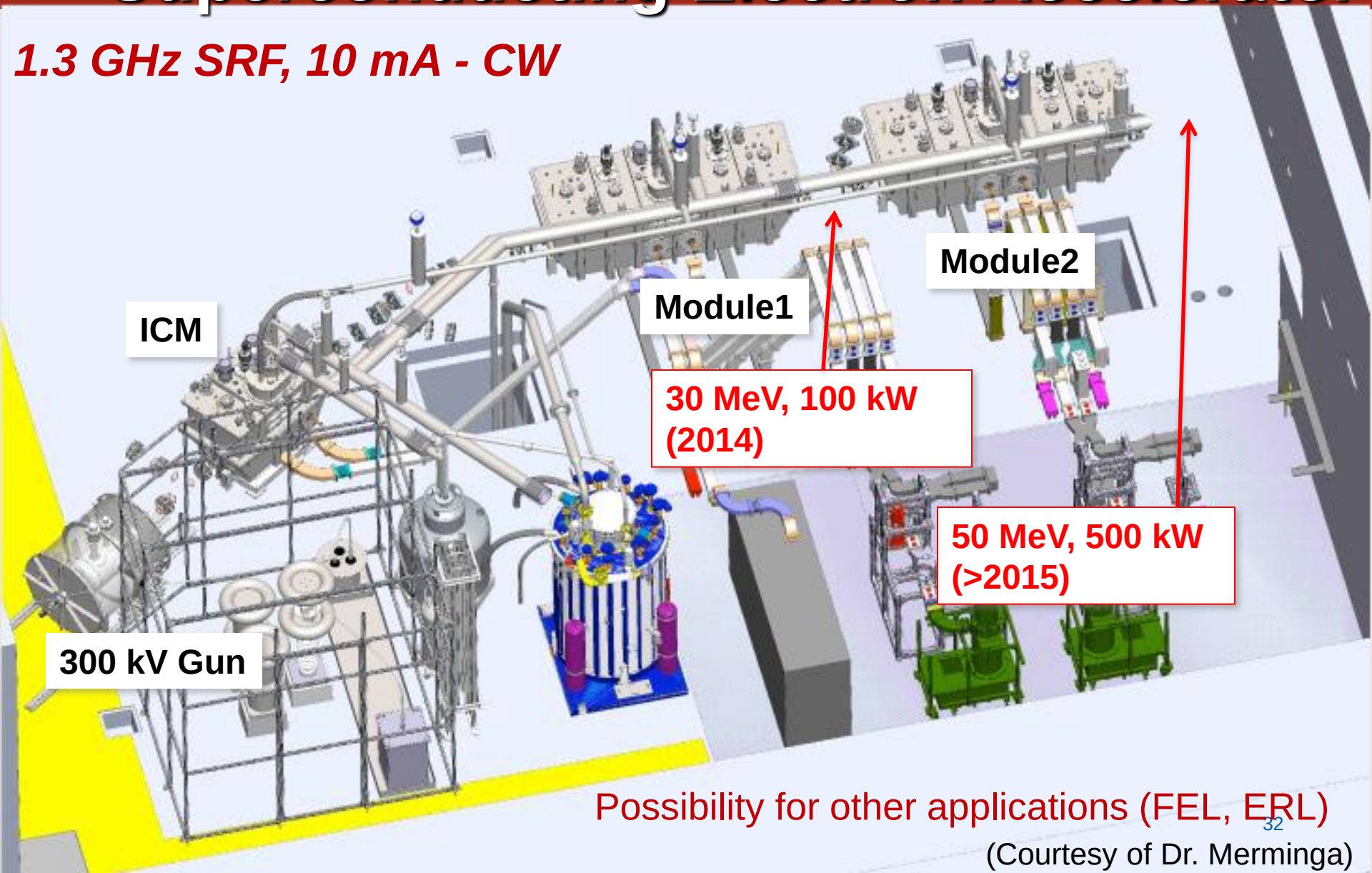

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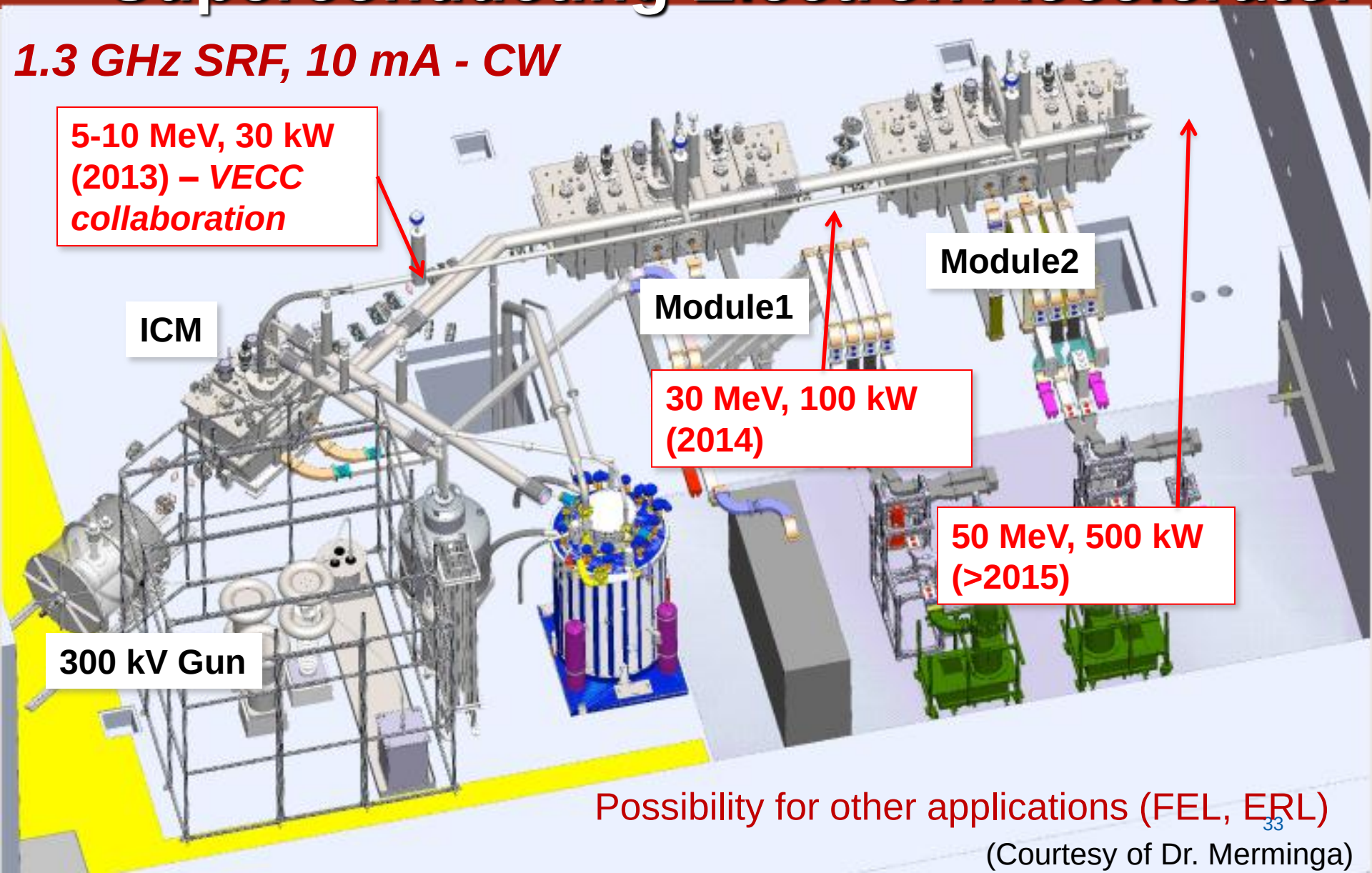
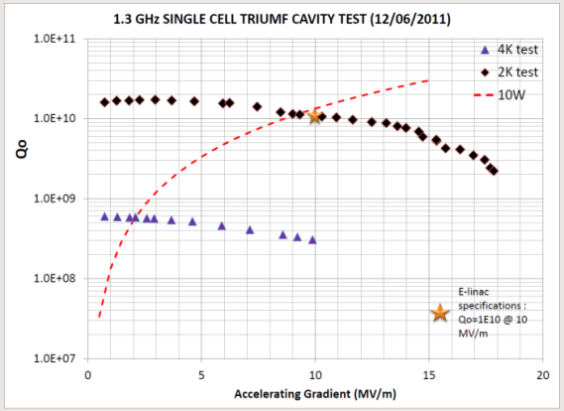


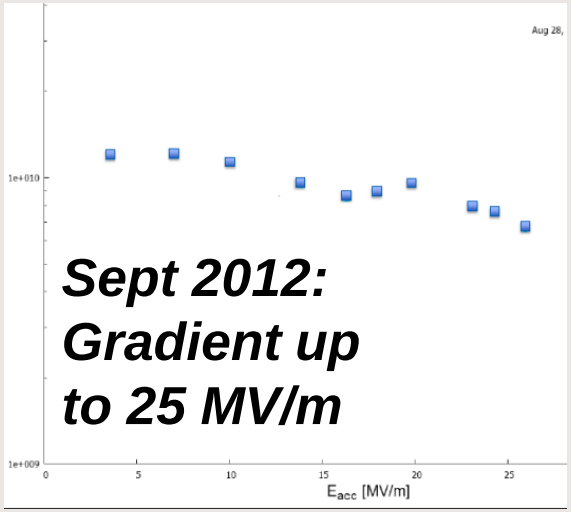
SRF Cavities

(Courtesy of Dr. Merminga)

Single-cell cavity status:

Dec 2011: 7 out of 7 **PAVAC**/TRIUMF single-cells meet Q_0 requirements

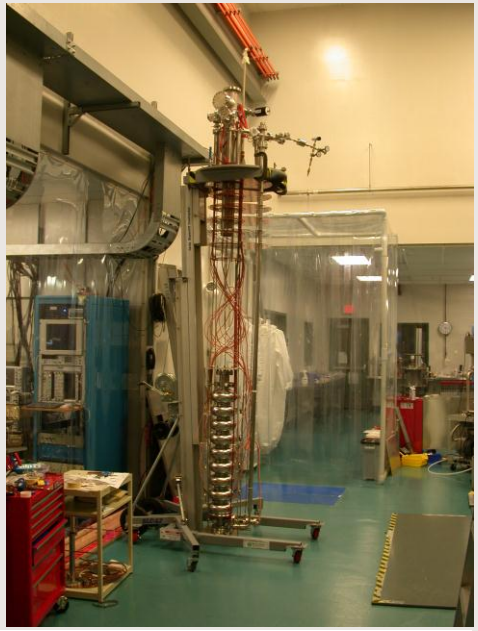


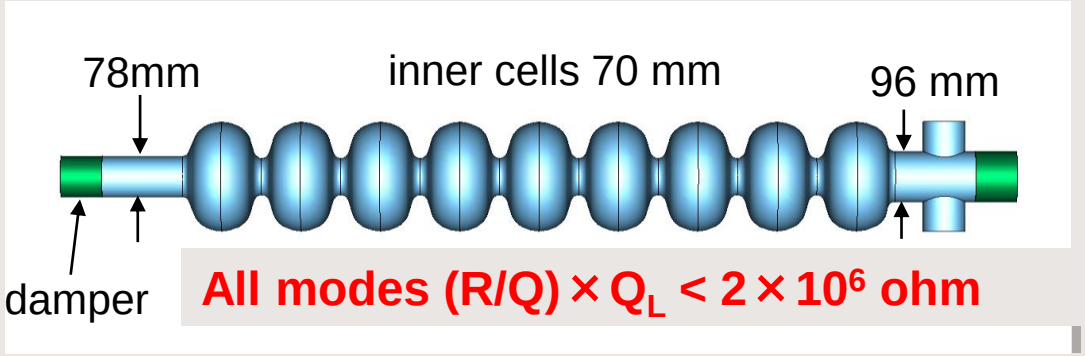


Multi-cell cavity fabrication by PAVAC (BC):

7-cell Cu cavity delivered Feb 2012

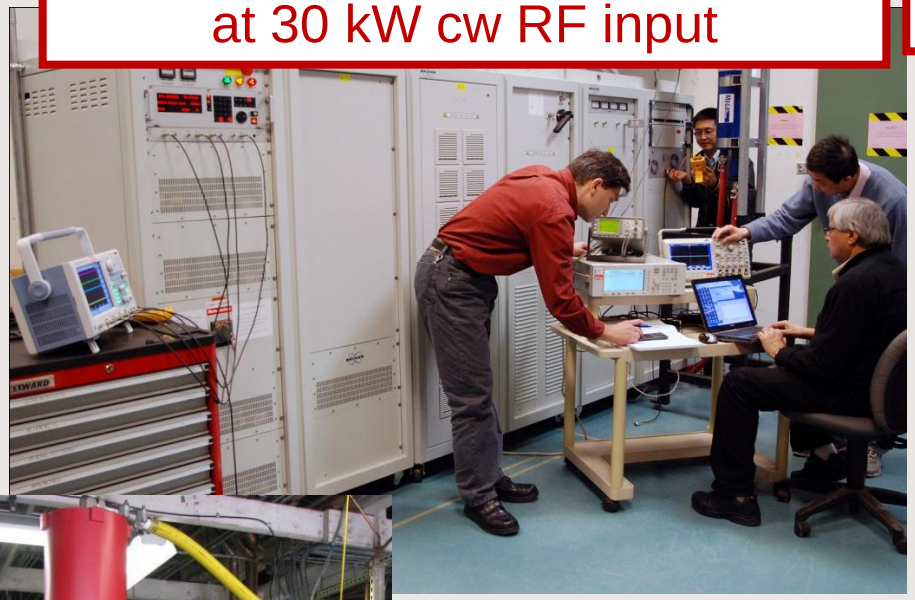
9-cell Nb cavity delivery May 2013





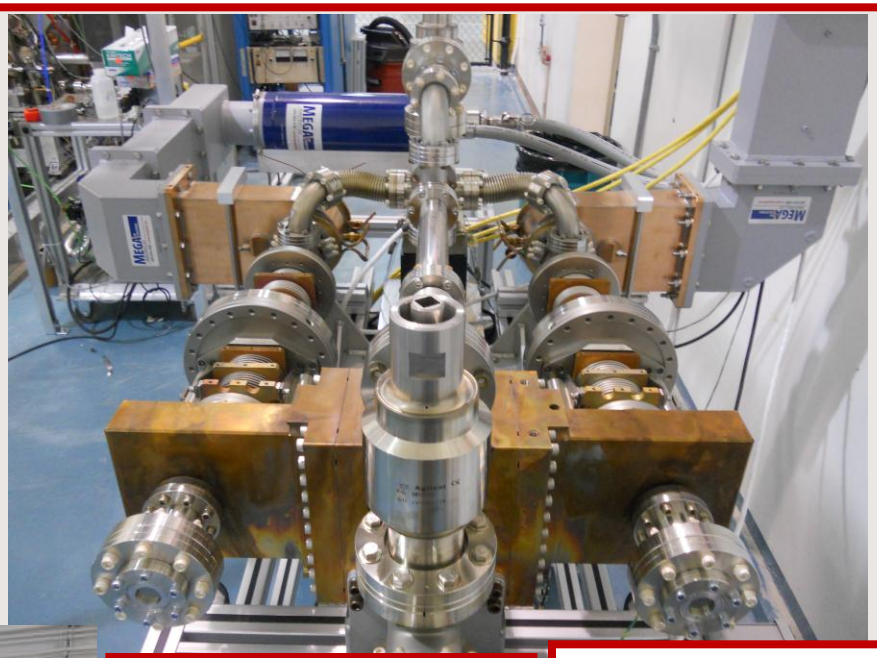
High Power RF Systems

IOT transmitter routine operation at 30 kW cw RF input



(Courtesy of Dr. Merminga)

HP Coupler Conditioning Station: reached 8 kW cw, up to 10kW peak 500µs



1.3 GHz 300 kW klystron purchase from CPI in coordination w/ HZB. Delivered 3/2013

600kW 65kV HVPS awarded to Thomson Broadcast. Delivery 7/2013

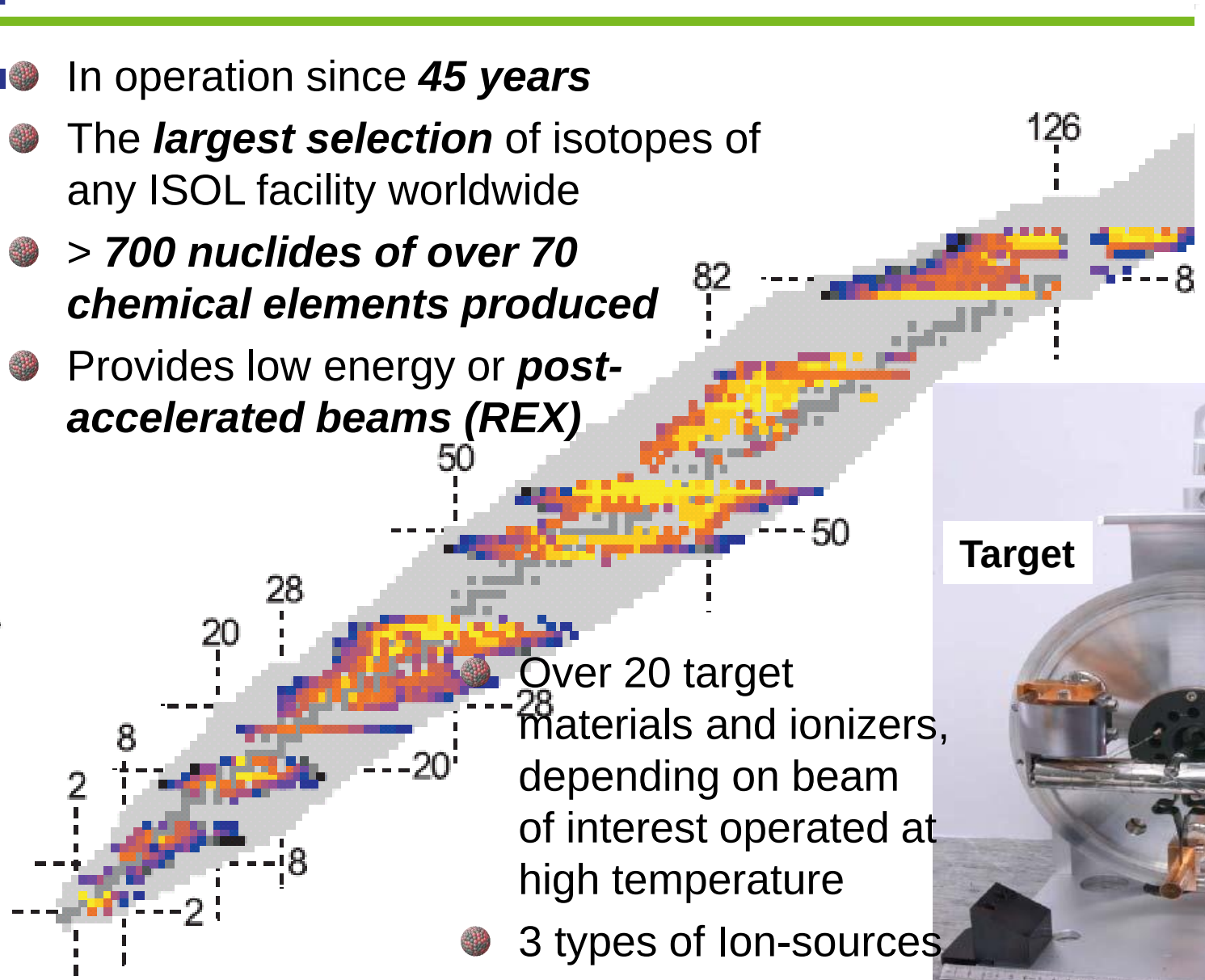
ARIEL Construction – April 2013

(Courtesy of Dr. Merminga)

RIB Annex

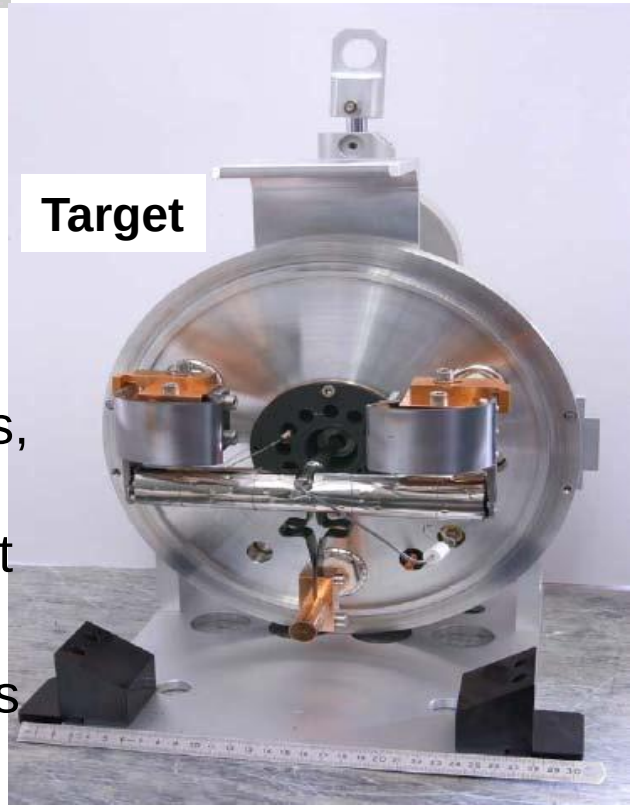
CERN ISOLDE

- In operation since ***45 years***
- The ***largest selection*** of isotopes of any ISOL facility worldwide
- > ***700 nuclides of over 70 chemical elements produced***
- Provides low energy or ***post-accelerated beams (REX)***



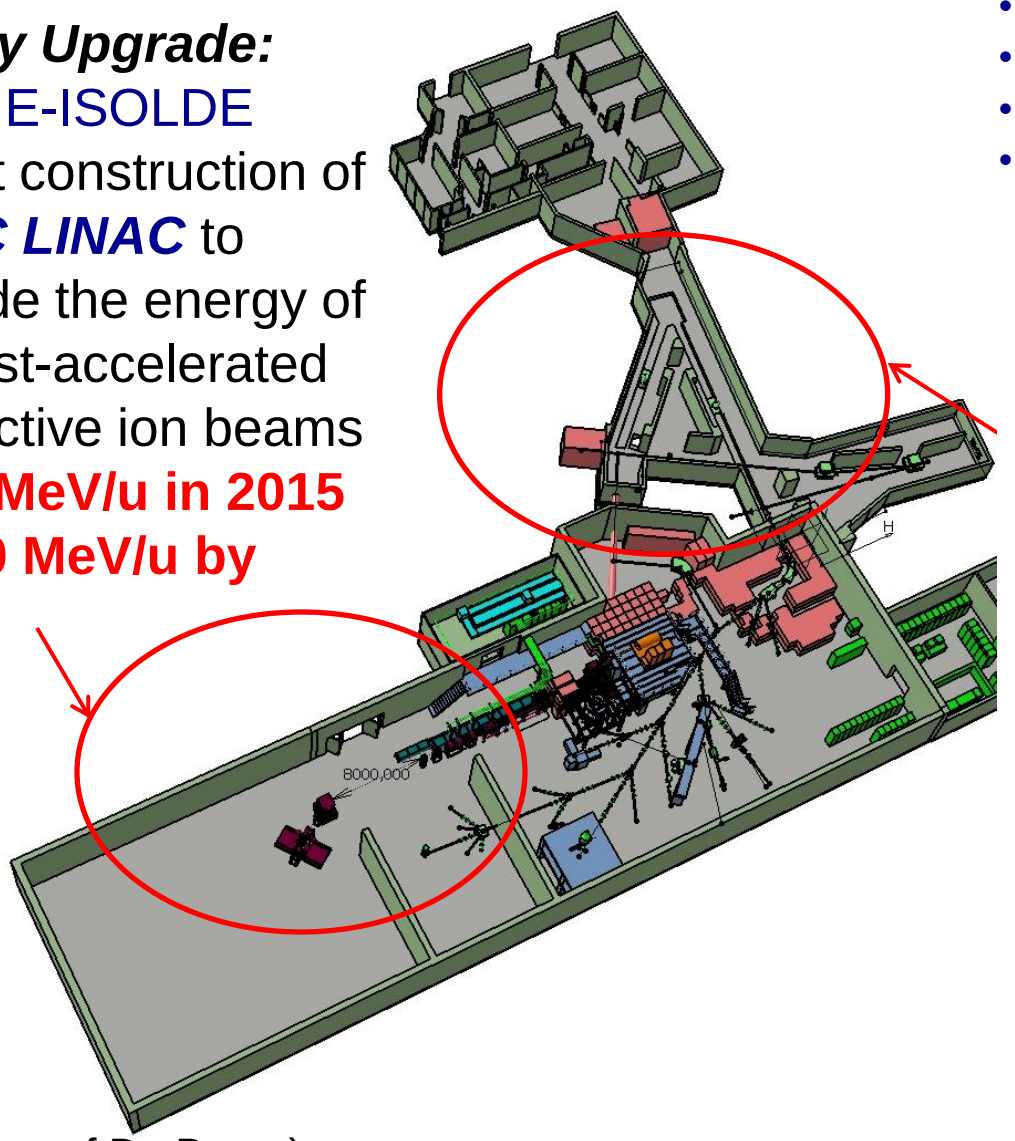
(Courtesy of Dr. Borge)

- Over 20 target materials and ionizers, depending on beam of interest operated at high temperature
- 3 types of Ion-sources



Near Future: HIE-ISOLDE project

Energy Upgrade:
The HIE-ISOLDE project construction of the ***SC LINAC*** to upgrade the energy of the post-accelerated radioactive ion beams to **5.5 MeV/u in 2015** and **10 MeV/u by 2017**

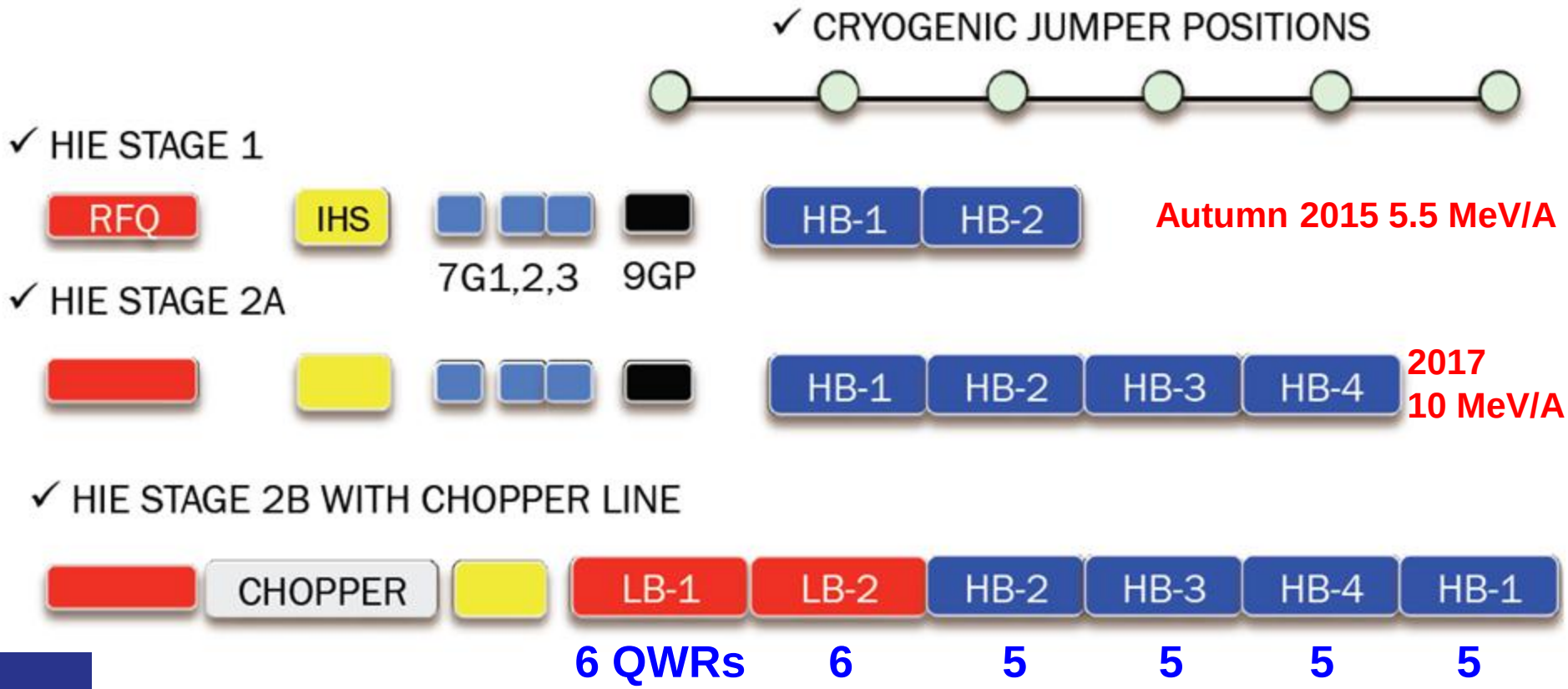


(Courtesy of Dr. Borge)

- Approved Dec 2009
- Offically started Jan 2010
- Yacine Kadi project Leader
- Budget 40 M$

Intensity Upgrade:
The design study for the intensity upgrade, also part of HIE-ISOLDE, **started in 2011**, and addresses the technical feasibility and cost estimate for operating the facility at ***10 kW*** once LINAC4 and PS Booster are online.

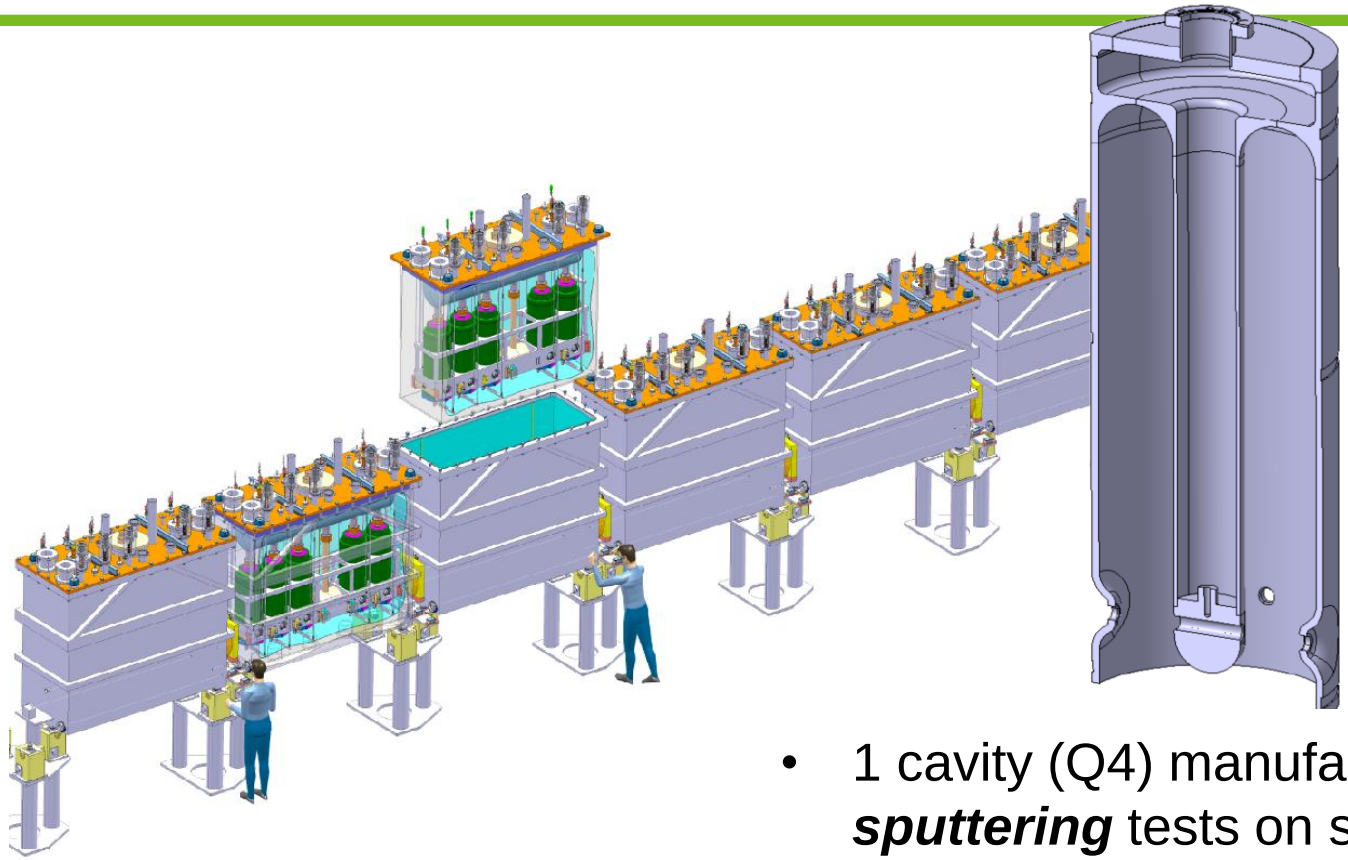
SC-LINAC Installed in 3-phases



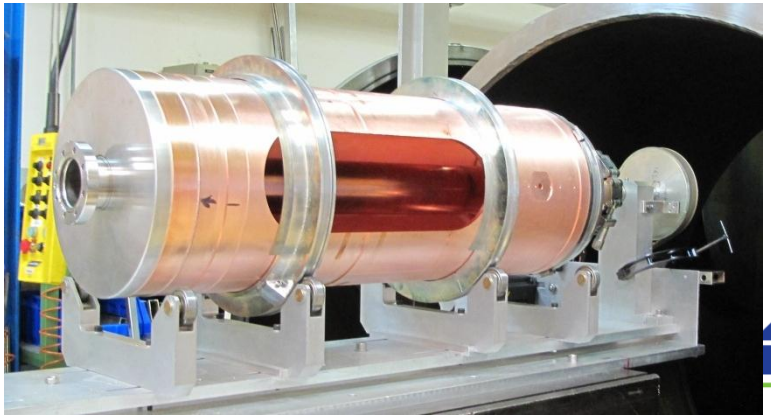
Period 100ns
Resolution 1-2 ns
Background < 1%

(Courtesy of Dr. Borge)

Cavity prototypes designed & built @ CERN

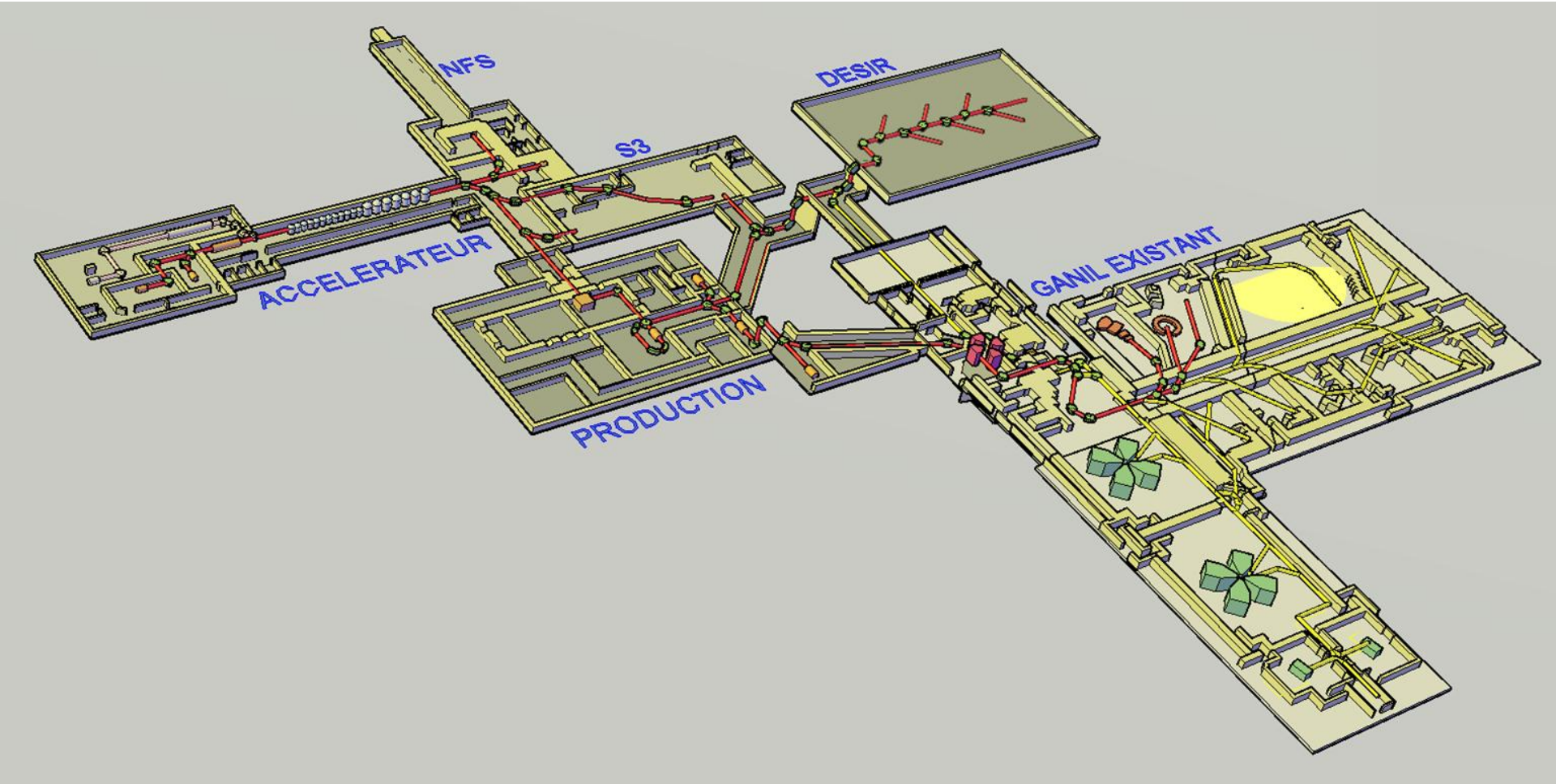


- 1 cavity (Q4) manufactured for ***sputtering*** tests on samples



(Courtesy of Dr. Borge)

SPIRAL2-GANIL Layout



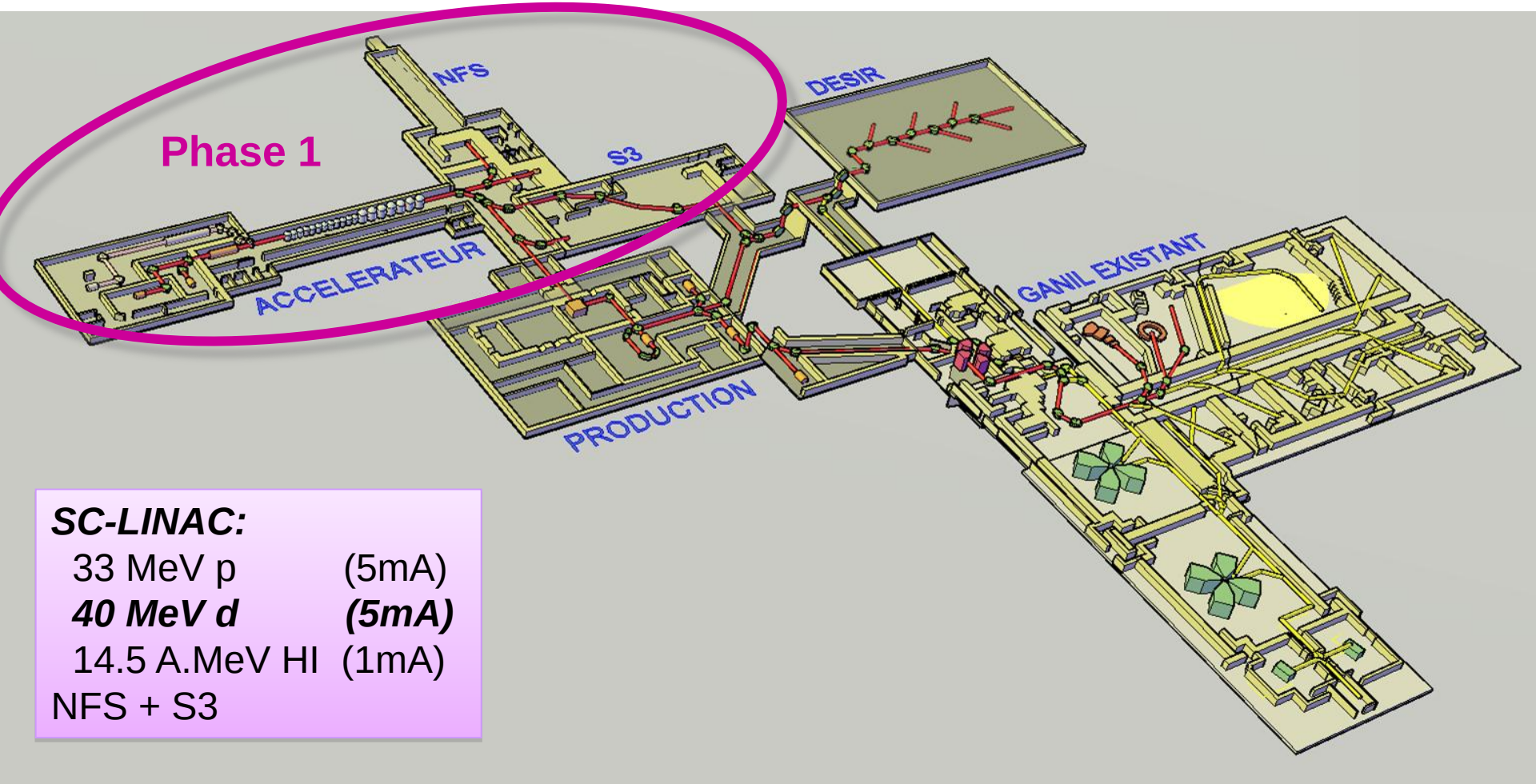
(Courtesy of Dr. Lagniel)

SPIRAL2-GANIL Layout

SPIRAL2 under construction:

Phase 1: High intensity ***stable*** beams in 2014 + Experimental rooms (S^3 + NFS)

Phase 2: High intensity ***Radioactive*** Ion Beams (RIBs)



SC-LINAC:

33 MeV p	(5mA)
40 MeV d	***(5mA)***
14.5 A.MeV HI	(1mA)

NFS + S3

(Courtesy of Dr. Lagniel)

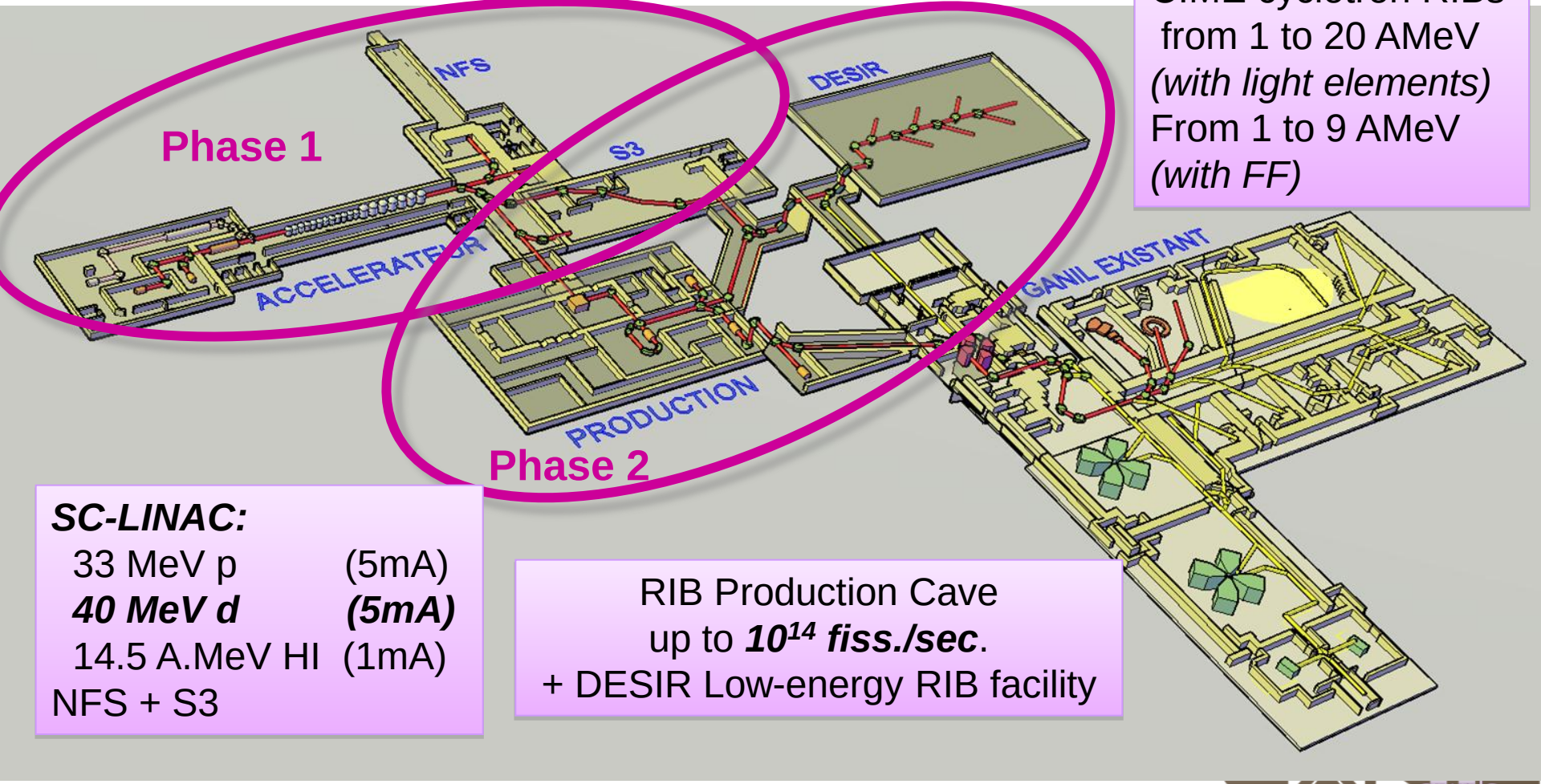
SPIRAL2-GANIL Layout

SPIRAL2 under construction:

Phase 1: High intensity ***stable*** beams in 2014 + Experimental rooms (S^3 + NFS)

Phase 2: High intensity ***Radioactive*** Ion Beams (RIBs)

CIME cyclotron RIBs
from 1 to 20 AMeV
(with light elements)
From 1 to 9 AMeV
(with FF)



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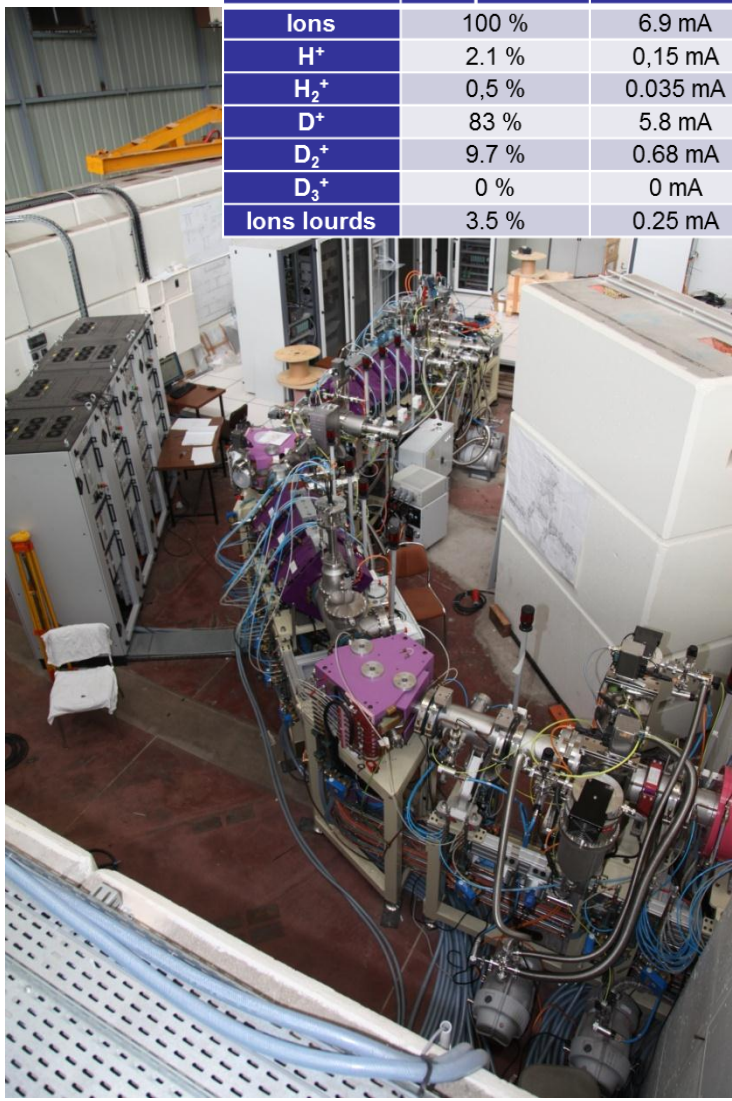
RIB Production Cave
up to ***10^{14} fiss./sec***.
+ DESIR Low-energy RIB facility

(Courtesy of Dr. Lagniel)

Light ion source performances

- Up to 14.5 mA at the source exit, 12mA @ the LEBT end, 79% D^+
- 90 µA also measured, stable, with source tuning (9->2.4mA) without gas injection, then line tuning and the use of slits
- Measurement at RFQ injection point

Ion	Proportion	Courant
Ions	100 %	6.9 mA
H^+	2.1 %	0,15 mA
H_2^+	0,5 %	0.035 mA
D^+	83 %	5.8 mA
D_2^+	9.7 %	0.68 mA
D_3^+	0 %	0 mA
Ions lourds	3.5 %	0.25 mA



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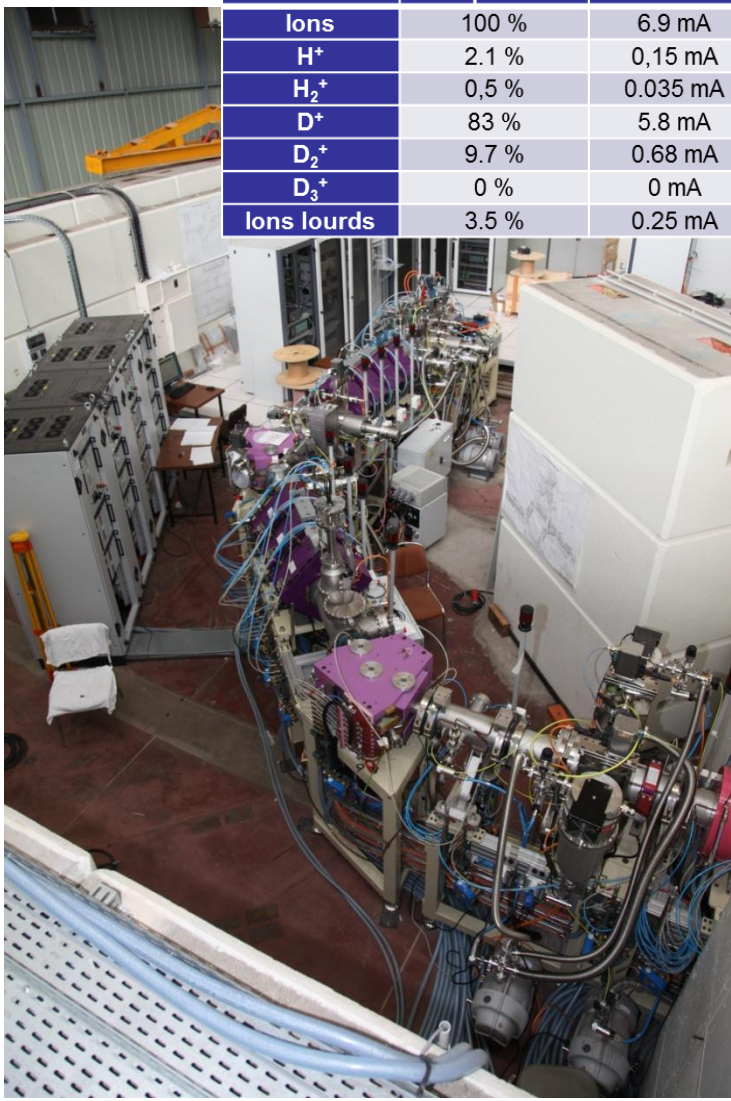
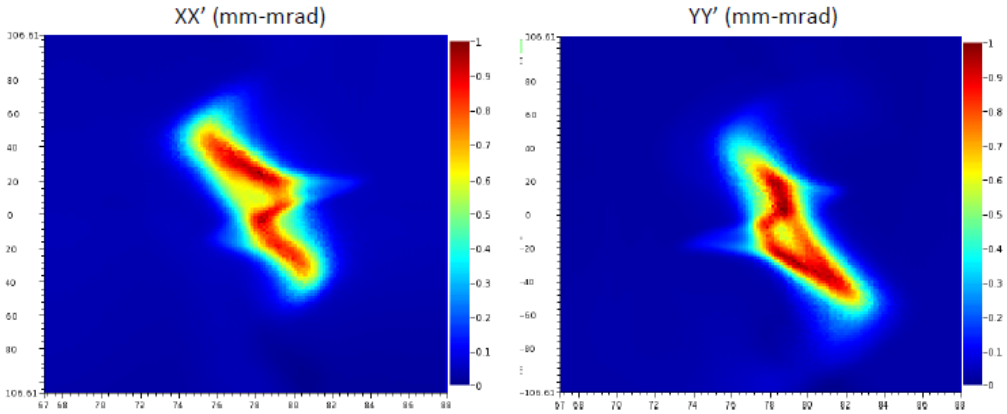




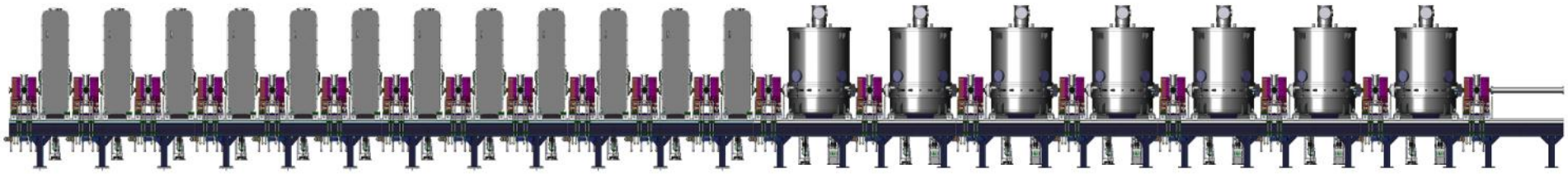
Nominal:
0.22 π.mm.mrad

$\varepsilon_{xx'}$	0.23 π.mm.mrad
$\beta_{xx'}$	0.095 π.mm/mrad
$\alpha_{xx'}$	0.99
$\varepsilon_{yy'}$	0.22 π.mm.mrad
$\beta_{yy'}$	0.10 π.mm/mrad
$\alpha_{yy'}$	1.17

Beam measured numerically transported through RFQ with no losses nor emittance growth

(Courtesy of Dr. Lagniel)

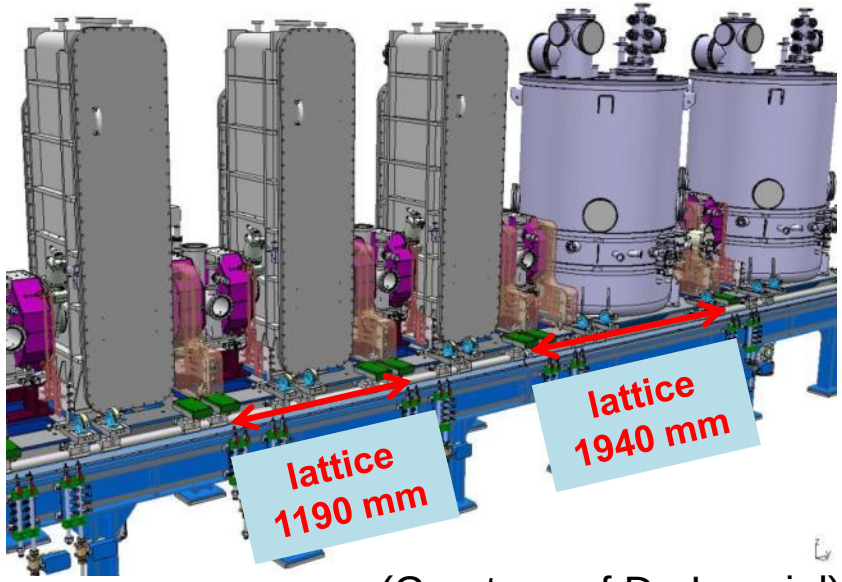
SC LINAC



Beta 0.07 energy section — Beta 0.12 energy section

L=29.8 m

Cryomodule A	Cryomodule B	Power coupler
CEA Saclay	IPN Orsay	LPSC Grenoble

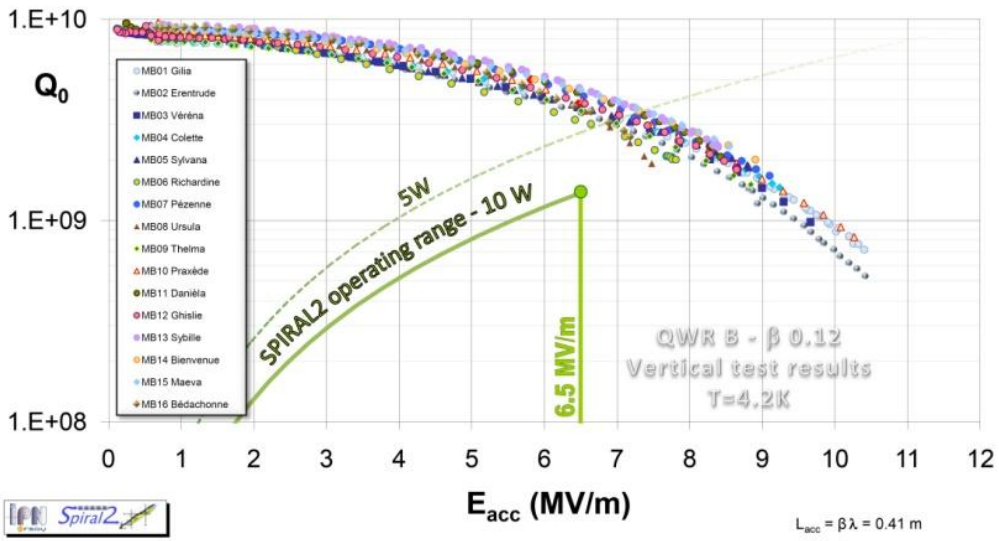


(Courtesy of Dr. Lagniel)

Cryomodule	A	B
Valve-to-valve length [mm]	610	1360
# cavities	12	14
f [MHz]	88.05	88.05
β_{opt}	0.07	0.12
Epk/Ea	5.36	4.76
Bpk/Ea [mT/MV/m]	8.70	9.35
r/Q [Ω]	599	515
Vacc @ 6.5 MV/m & β_{opt}	1.55	2.66
Lacc [m]	0.24	0.41
Beam tube ∅ [mm]	38	44

High beta cavity status

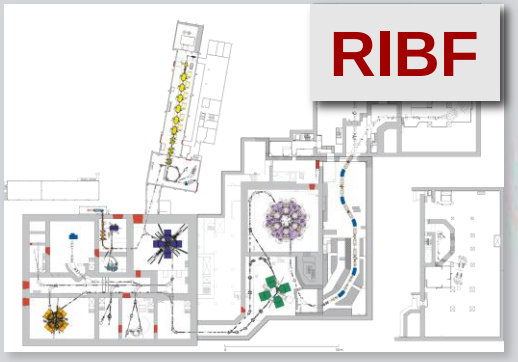
- Company RI GmbH (ACCEL) selected for the 16 series cavities (14 needed at first)
  - **All** cavities delivered
  - **All** cavities tested, with specs OK
  - Chemistry done in Orsay
  - Only one cavity needed repair (too high in frequency at first, local chemistry in H field area)
- Cryostats all manufactured by SDMS
- Pressure sensitivity : < 8 Hz/mbar



(Courtesy of Dr. Lagniel)

Construction

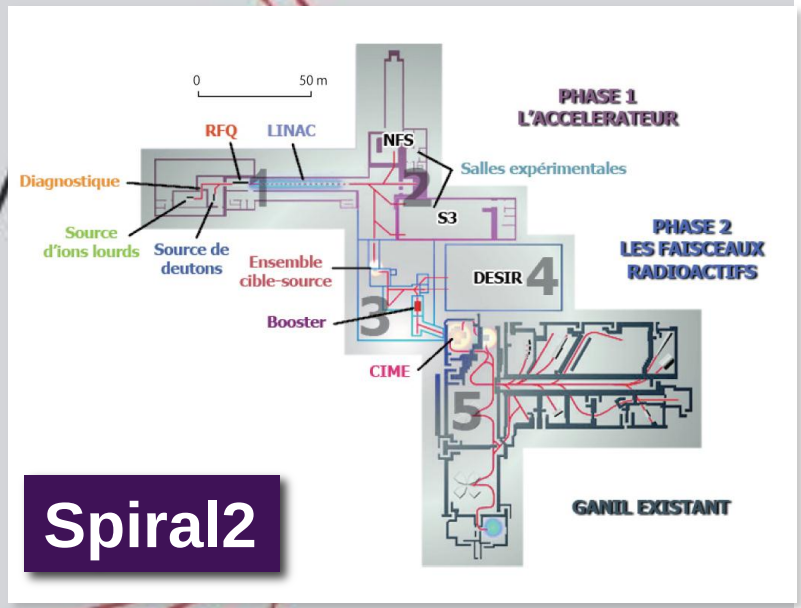
(Courtesy of Dr. Lagniel)

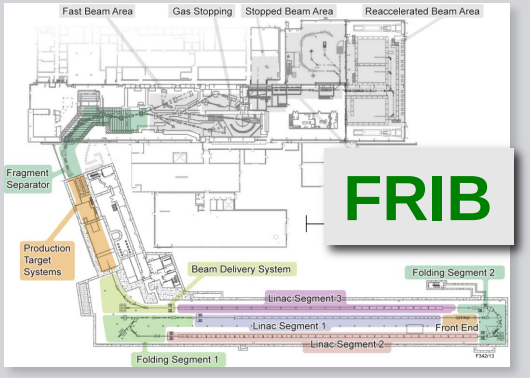


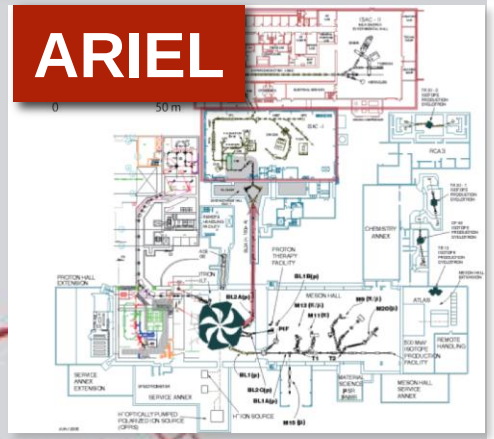
100 m

SIS 100/

FAIR







SIS

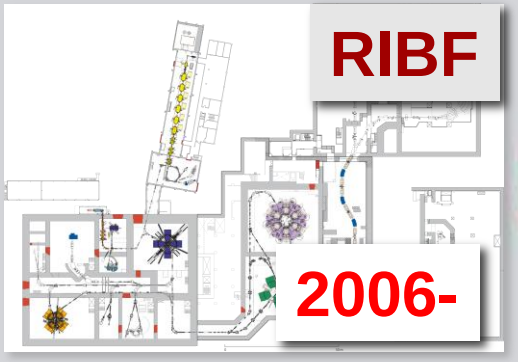
FRS

ESR

UNILAC

HESR

Super FRS

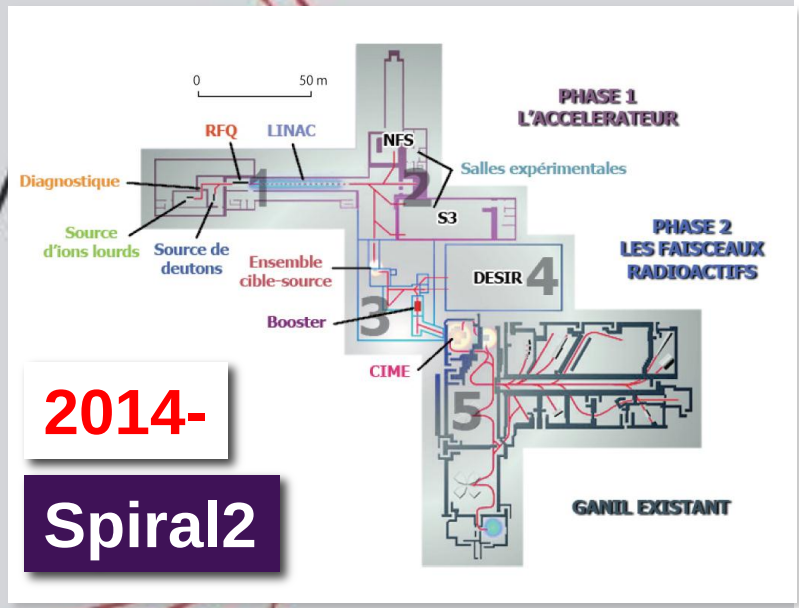


100 m

SIS 100/

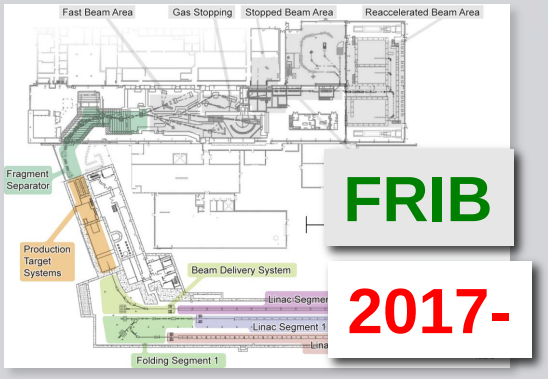
FAIR

2018-



2014-

Spiral2

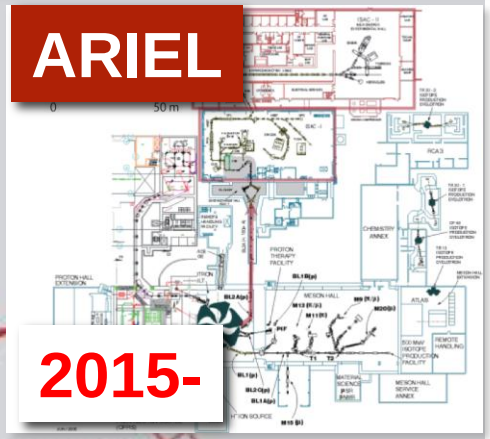


FRIB

2017-

HIE-ISOLDE/CERN

2015-



ARIEL

2015-

SPES

2014-

SIS

FRS

ESR

UNILAC

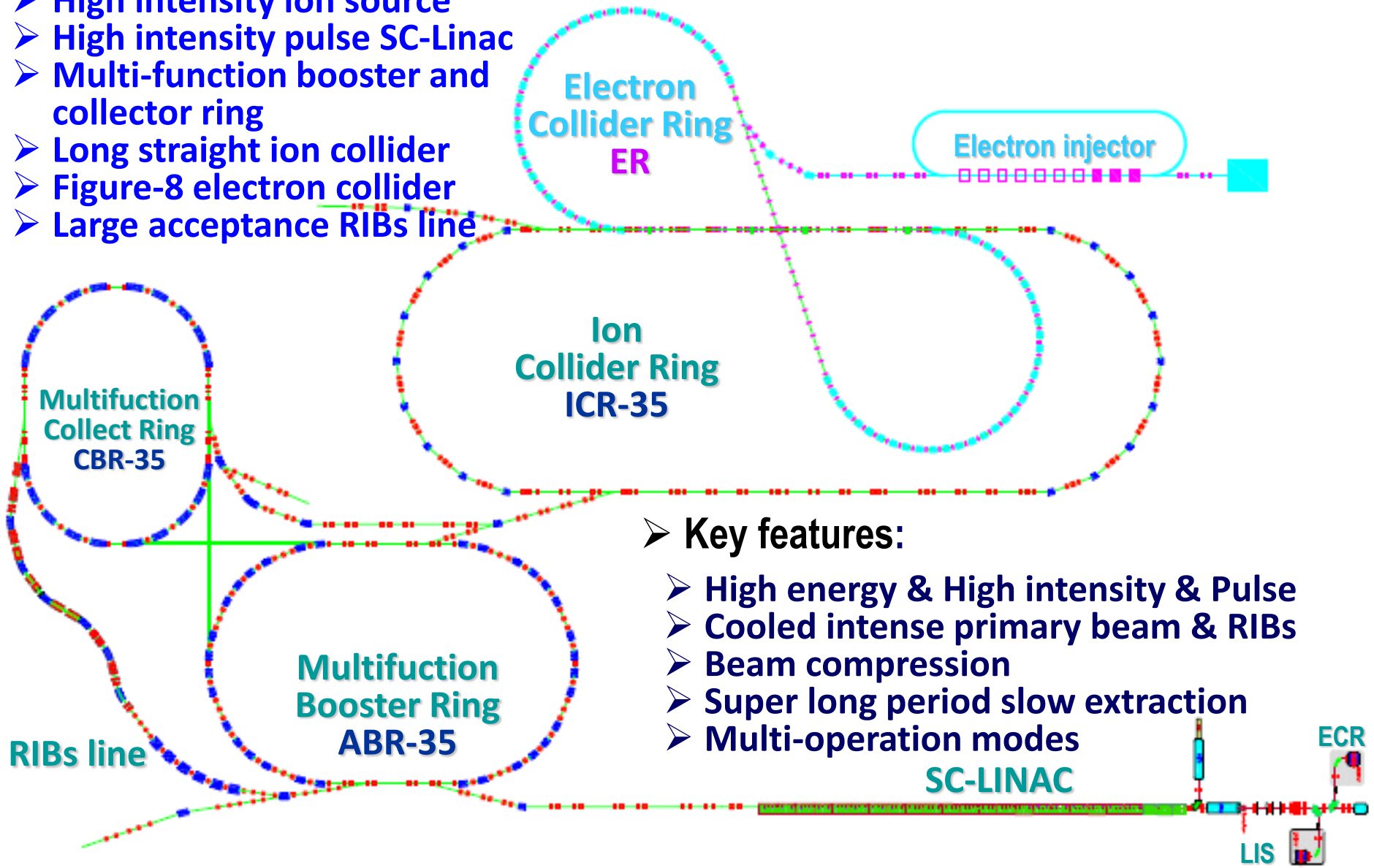
HESR

Super
FRS

The Layout of HIAF Complex

Courtesy of Prof. Zhao

- **Main Components:**
  - High intensity ion source
  - High intensity pulse SC-Linac
  - Multi-function booster and collector ring
  - Long straight ion collider
  - Figure-8 electron collider
  - Large acceptance RIBs line



- **Key features:**
  - High energy & High intensity & Pulse
  - Cooled intense primary beam & RIBs
  - Beam compression
  - Super long period slow extraction
  - Multi-operation modes

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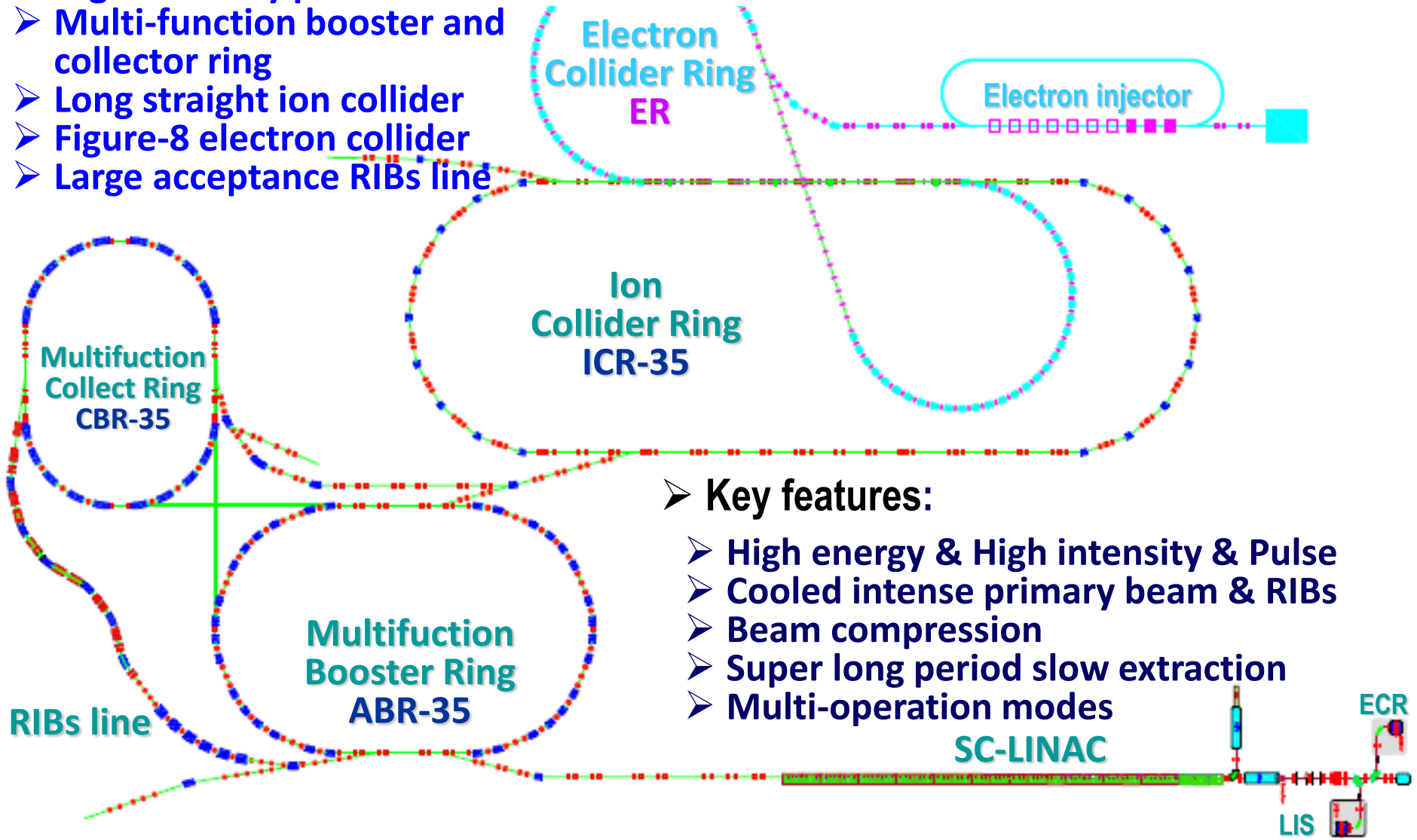
Courtesy of Prof. Zhao

Asian activities: RISP(Korea), ANURIB(India), …



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Acknowledgements

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