Nucleosynthesis in Explosive Astrophysical Sites

Lecture 2

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Saha Institute. Kolkata, India

Let's think of a typical reaction, say alpha burning on carbon

$\alpha + {}^{12}\text{C} > {}^{16}\text{O} + \gamma$

As the nuclei approach they run up against the Coulomb barrrier

So how close do the nuclei get?

$z_1 z_2 e^2 / 4\pi\varepsilon_0 r_{close} = E$ (the kinetic energy)

But the kinetic energy is related to the temperature

$E \sim kT$

So what is r_{close} if T is, say, 10^9K?

And how close are the nuclear surfaces?

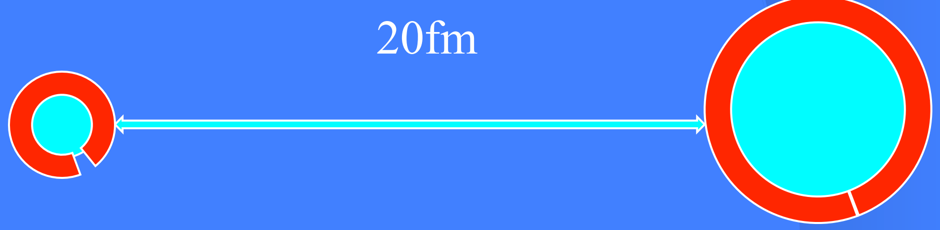
$r = 1.2\ A^{1/3}$ fm

How does this compare with the range of the nuclear force?

Answer: For nuclei with average energy (E ~ kT ~ 0.1 MeV) R~ 200fm

For nuclei in Gamow window (E ~ 1.0 MeV) R ~ 20fm

Surfaces are 15.4fm apart while range of force 1fm



In the last lecture we discussed the astrophysical objects where explosive nucleosynthesis occurs Novae, X-ray Bursters and Supernovae).

We saw how the nucleosynthesis in these site is dominated by reactions between exotic (short lived) nuclei.

This creates difficulties in measuring the reaction cross sections, unless we can get beams of radioactive nuclei.

In this lecture we will looks at how this is done and at examples of some of the facilities that have been (and will be) built to provide these.

Lecture 2

Producing radioactive beams

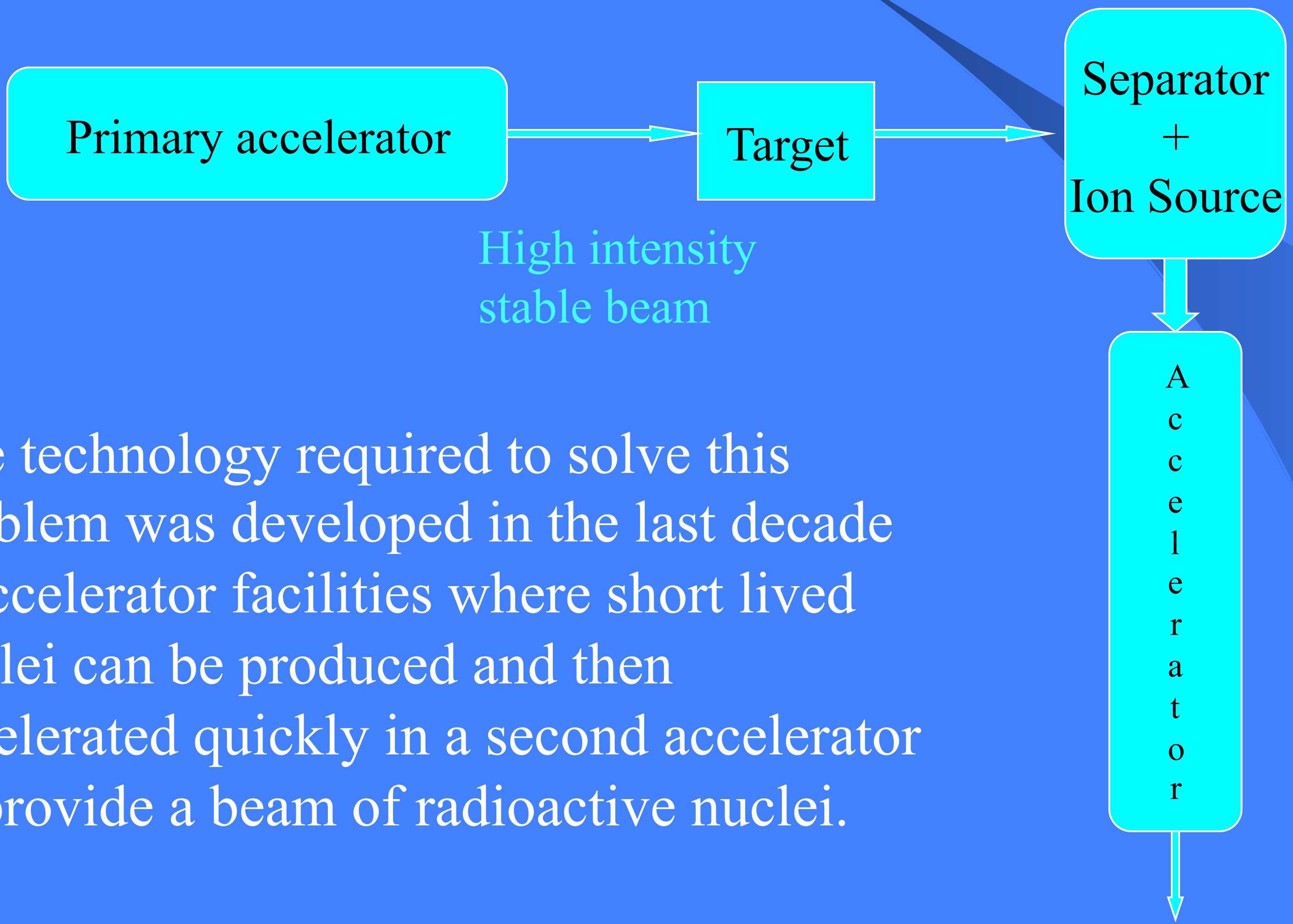
Existing and planned facilities

Lecture 3

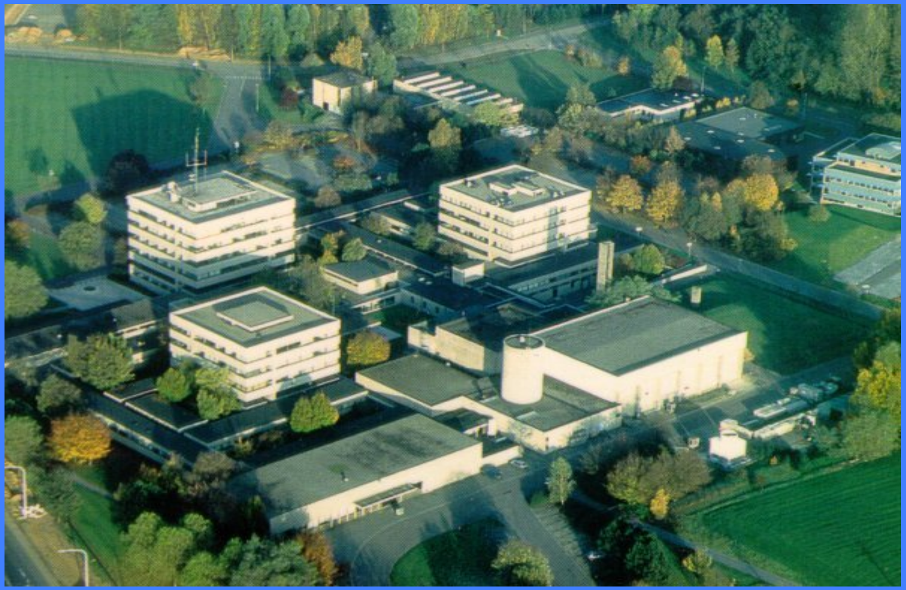
Detection systems for experiments

Stable beam measurements:	Problems are targets and background
Radioactive beam measurements:	Problam is usually "not enough beam"!

Start where we left off– the nuclei we need for our cross section measurements don't live long enough for us to make a target out of them to use in experiments



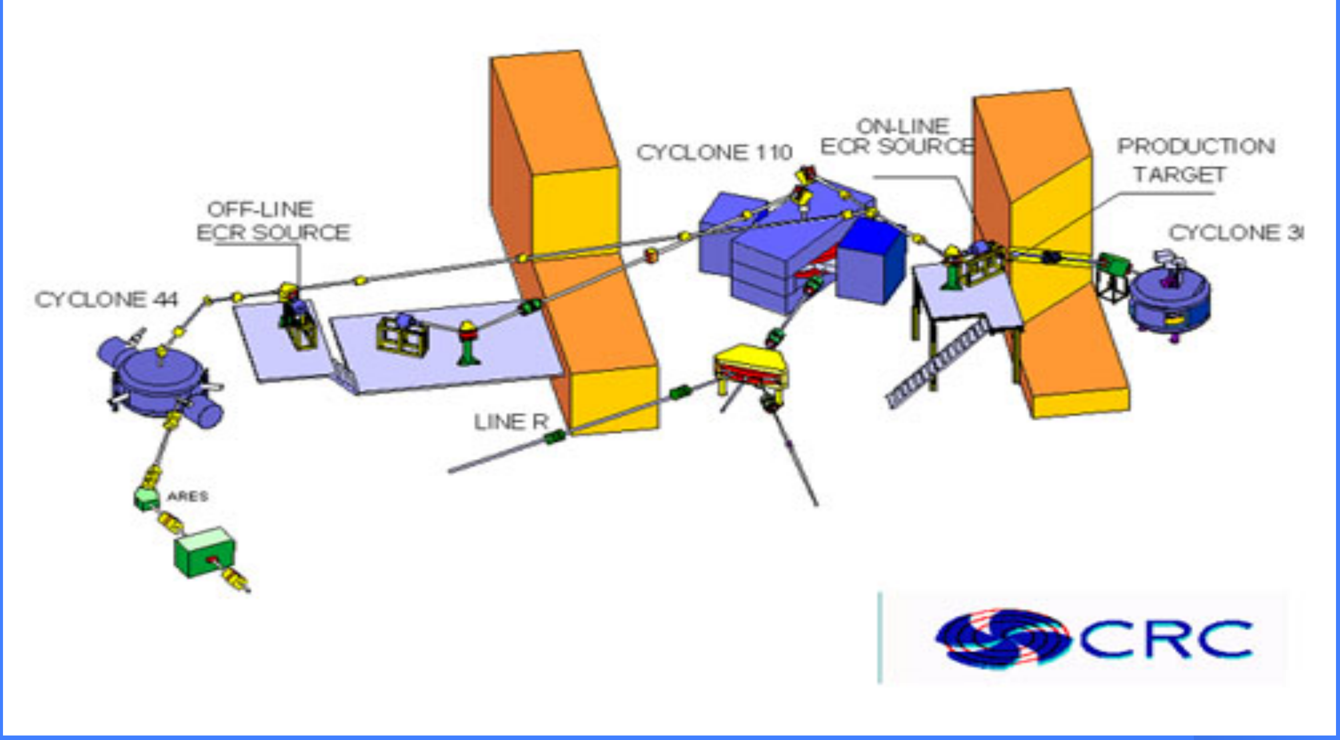
The technology required to solve this problem was developed in the last decade – accelerator facilities where short lived nuclei can be produced and then accelerated quickly in a second accelerator to provide a beam of radioactive nuclei.



Louvain-la-Neuve

The first two-stage radioactive beam facility

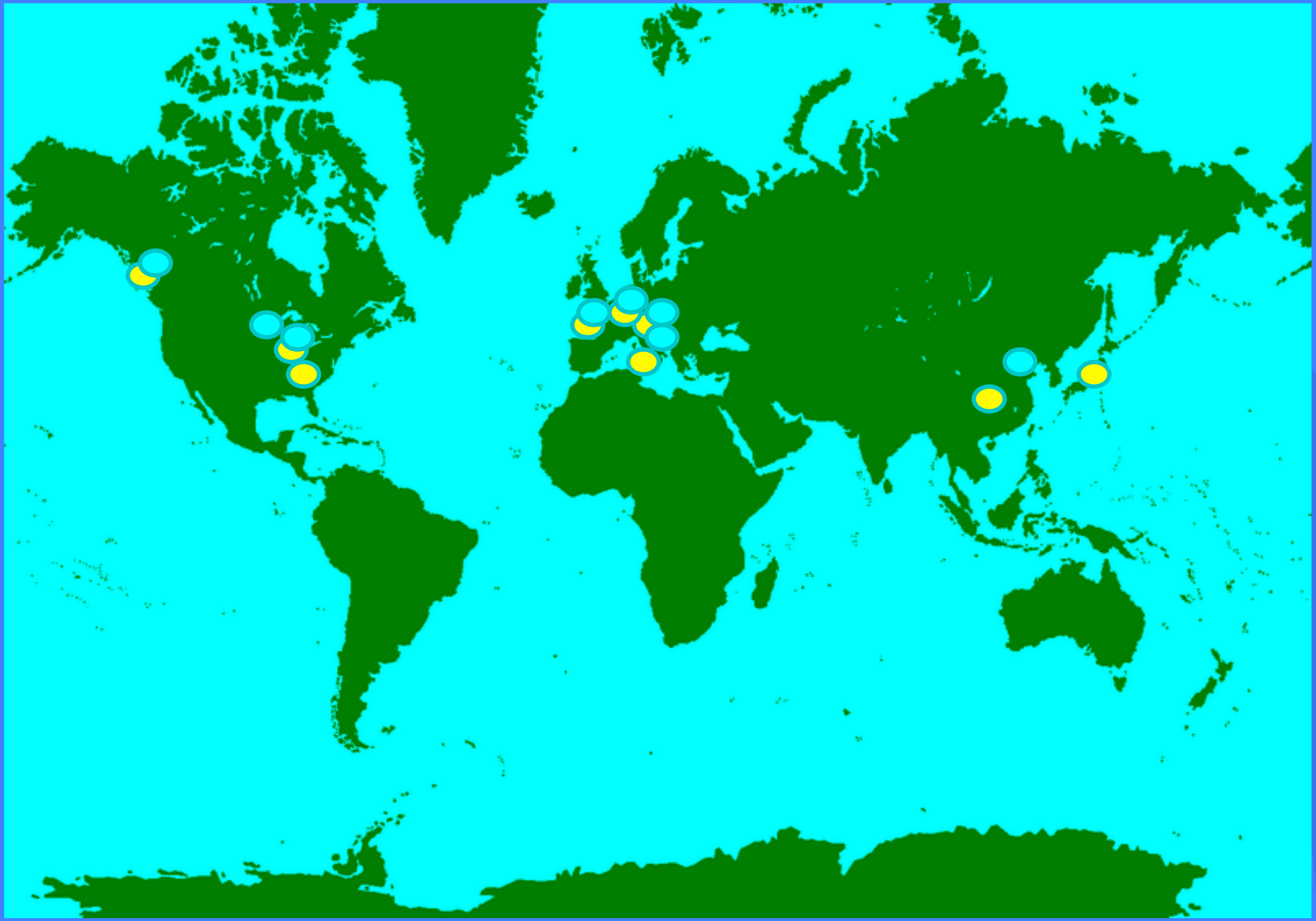
New generation now available, e.g. TRIUMF (Canada), SPIRAL, REX-ISOLDE where we can do more complex measurements



Current operating facilities and those under construction or approved

Operating

Construction/approved

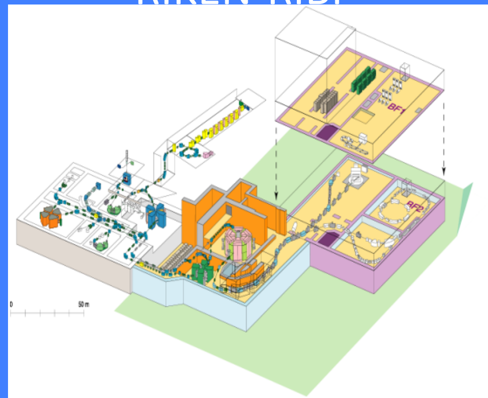


OPERATING

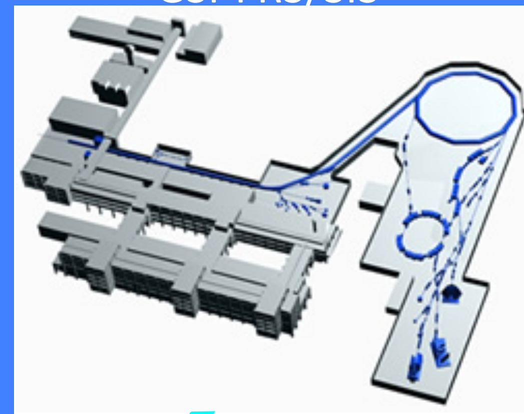
In-flight

ISOL

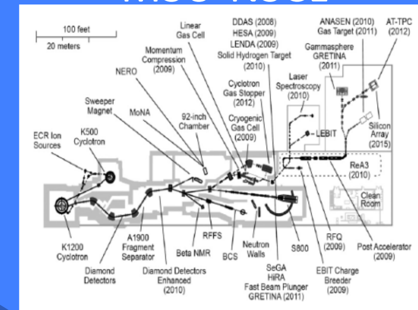
RIKEN-RIBF



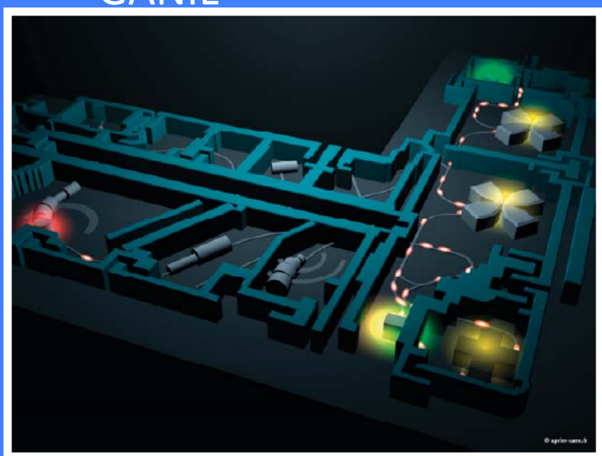
GSI-FRS/SIS



MSU-NSCL

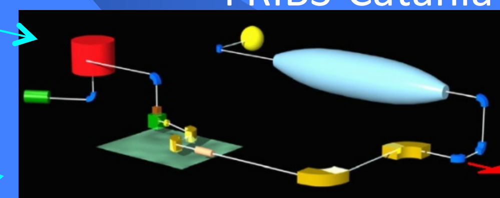


GANIL

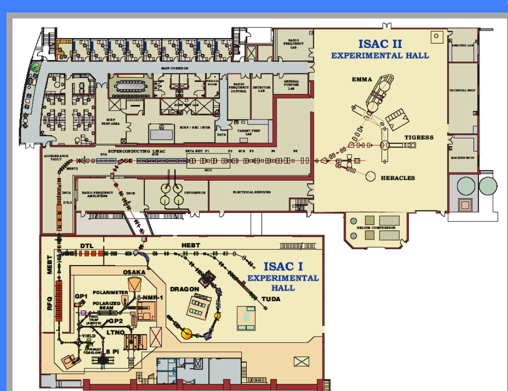


SIRAL

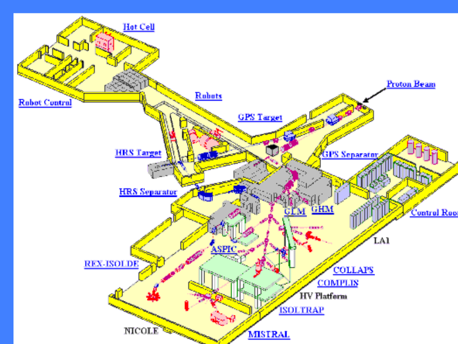
FRIBS-Catania



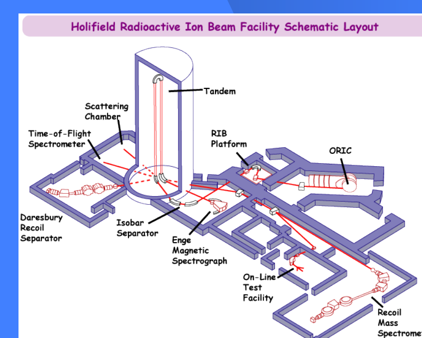
EXCYT-Catania



TRIUMF_ISAC-2

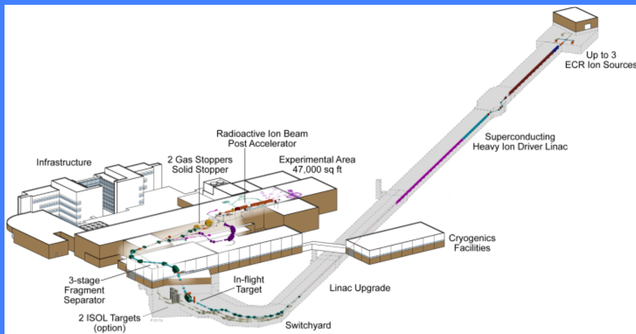


CERN-ISOLDE

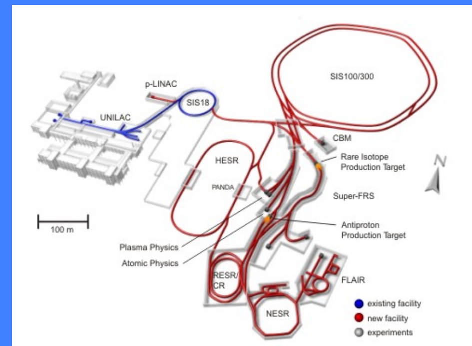


ORNL-HIRF

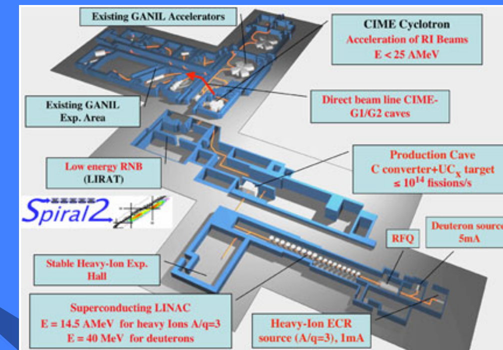
FRIB-MSU



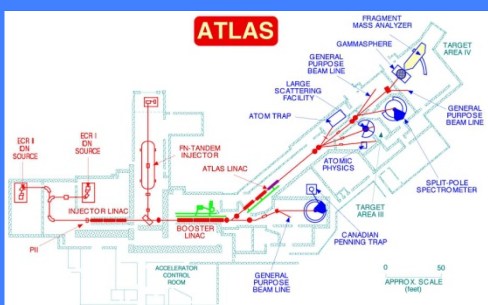
FAIR-GSI



SPIRAL2-GANIL



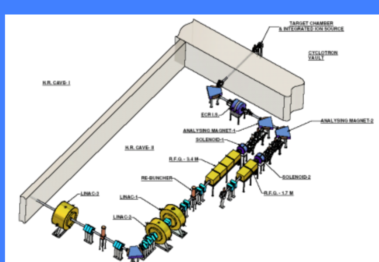
New Facilities



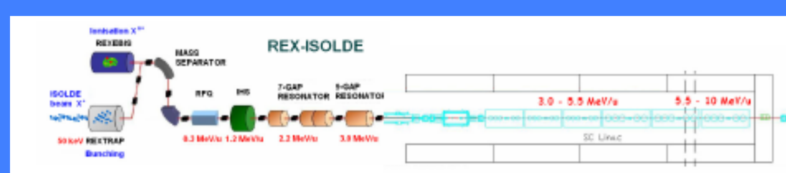
CARIBU (Argonne)

UNDER CONSTRUCTION

Upgrades



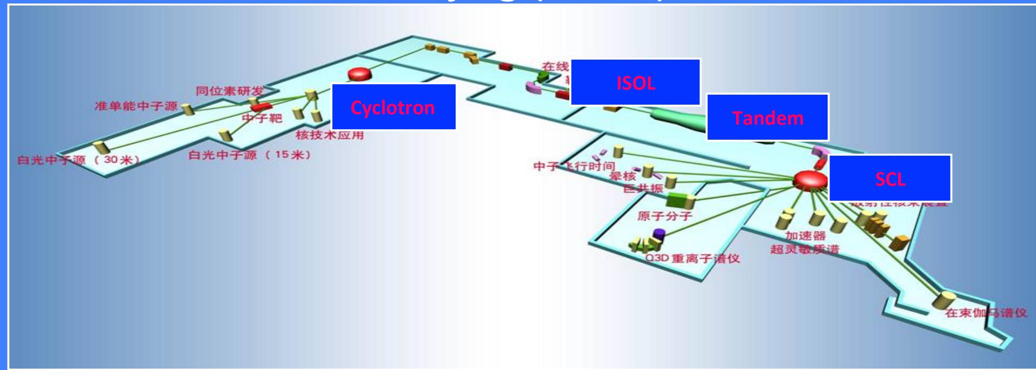
VECC-RIB (Calcutta)



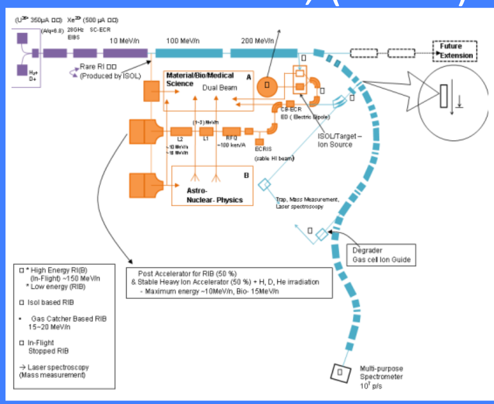
HIE-ISOLDE (CERN)

E-fission (TRIUMF)

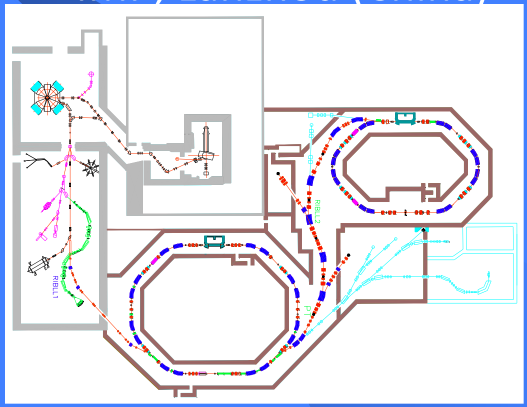
CIA Beijing (China)



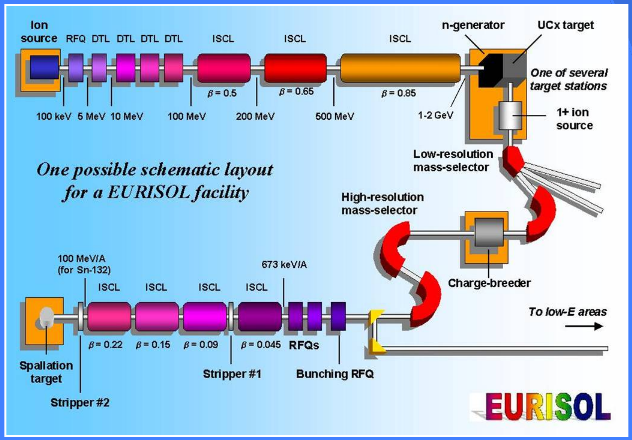
HI Accelerator, (Korea)



IMP, Lanzhou (China)

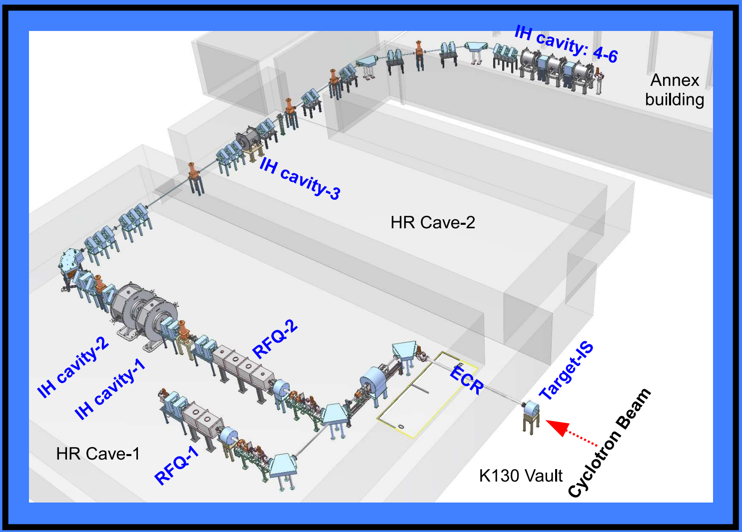


FUTURE PROJECTS

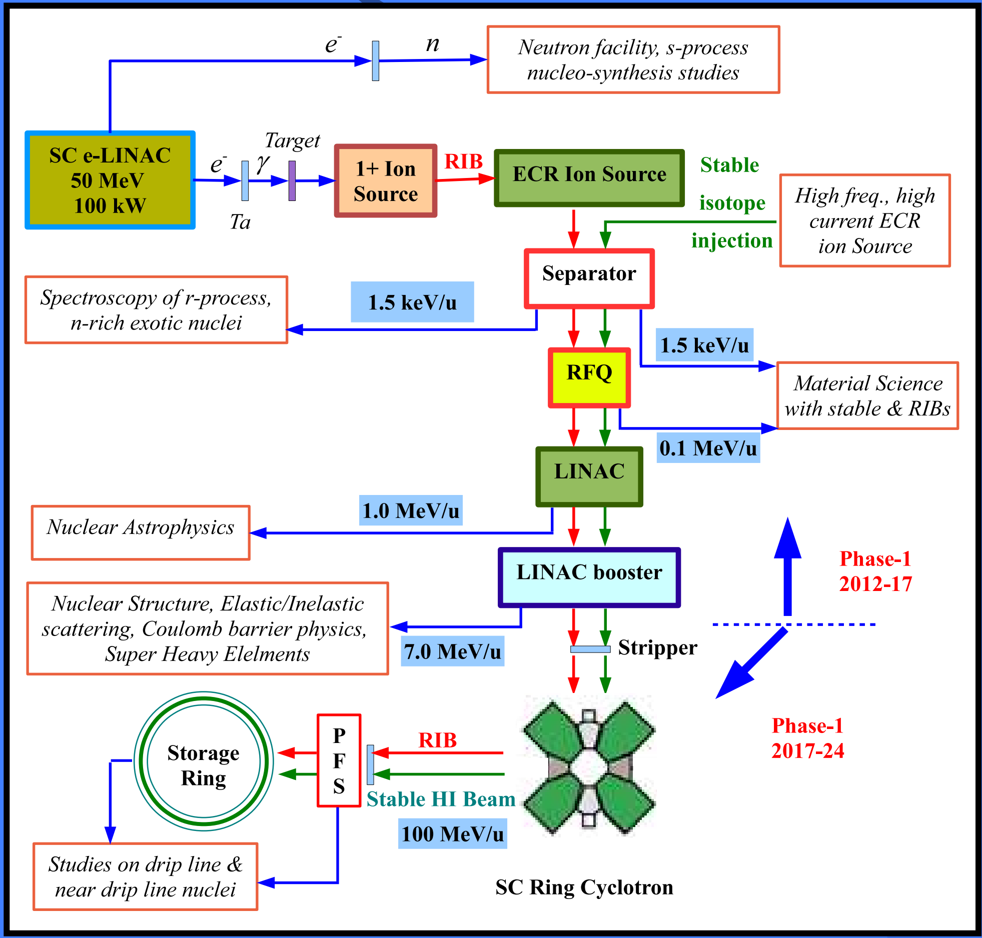


Radioactive beams in India

Under development
RIB facility at VEC



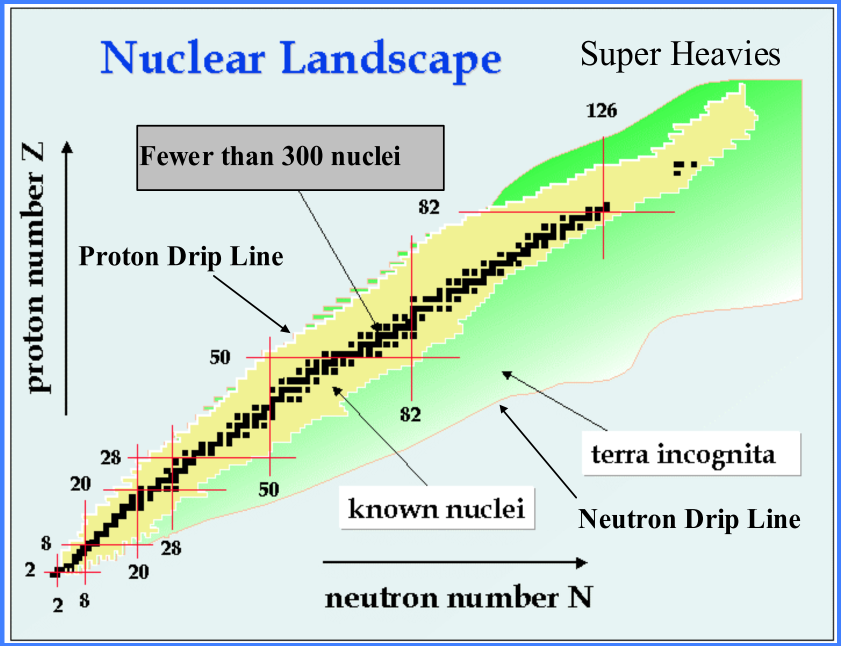
Concept
ANURIB project

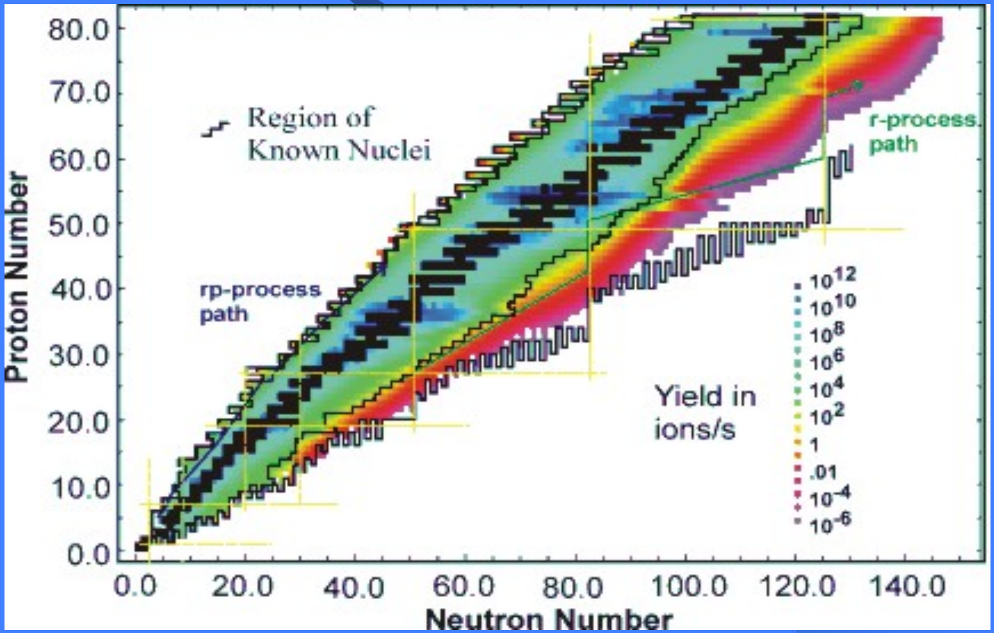


Similar to ARIEL project at TRIUMF

The development of Radioactive Beam Facilities (RBFs)

A defining feature of our field over the last two decades has been the development of facilities where short-lived nuclear species can be created, separated and reaccelerated to provide beams of radioactive nuclei.



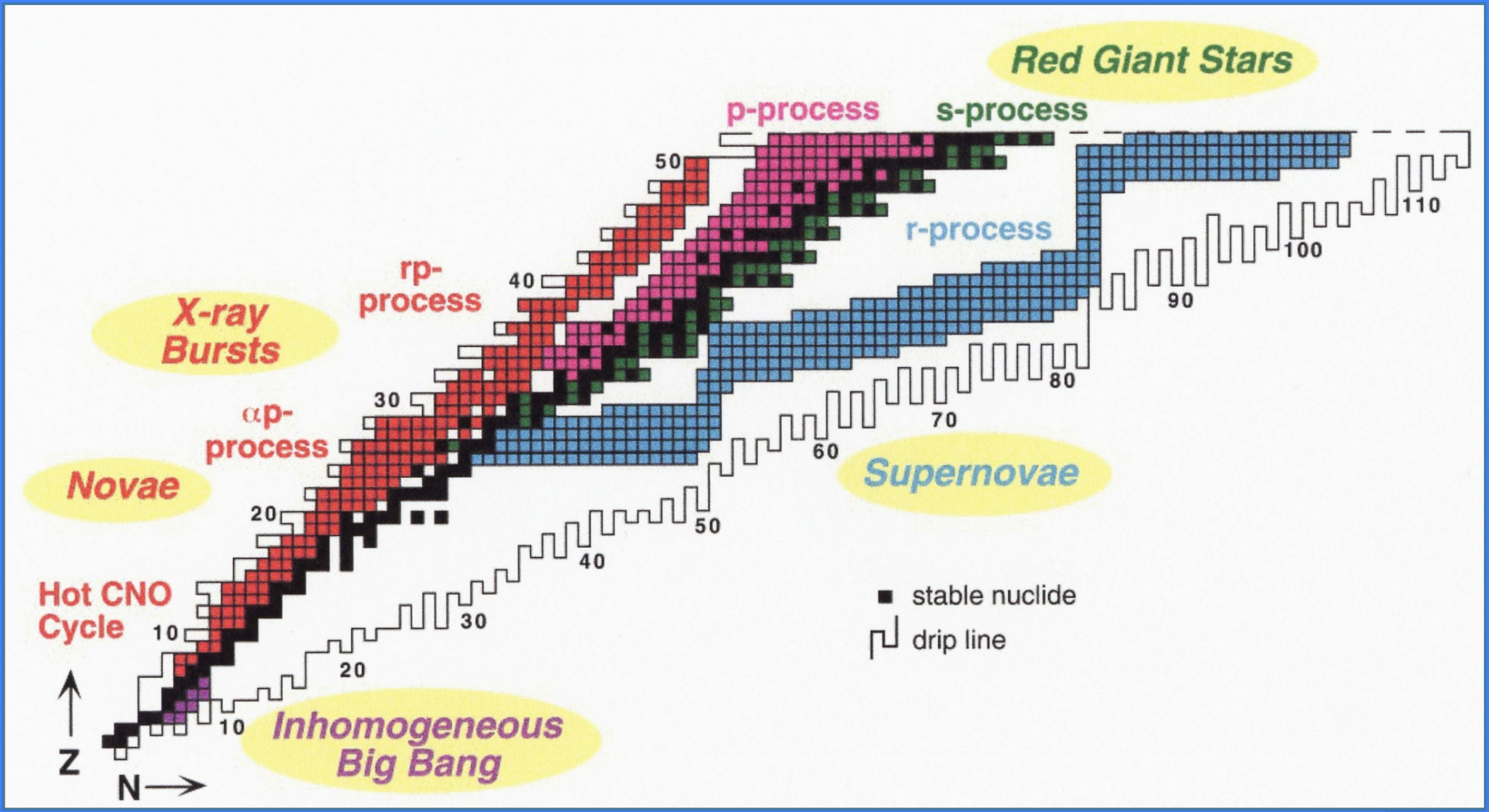


First 70 years of research seriously constrained as only had beams of stable nuclei (~300)

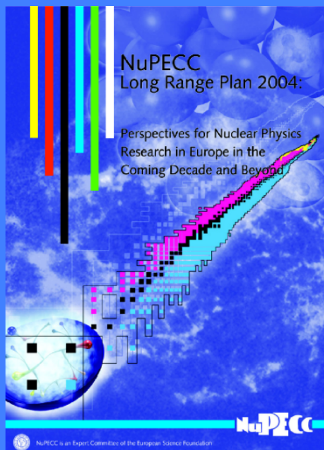
Now facilities coming on line which can produce and accelerate unstable (radioactive) nuclei (~6000)

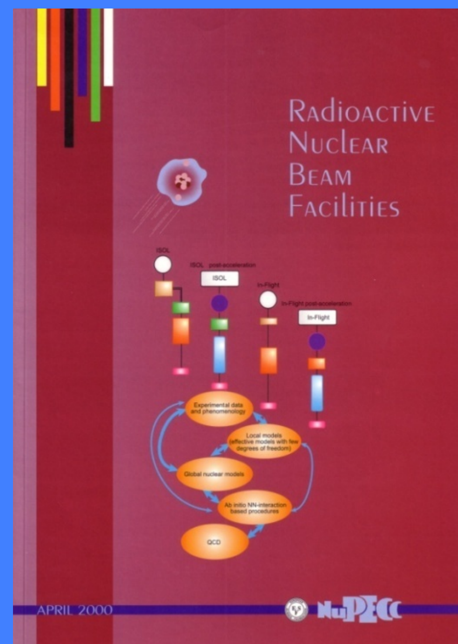
But note beam intensities 10^3/s-10^{12}/s compared to 10^{16}/s Christian mentioned

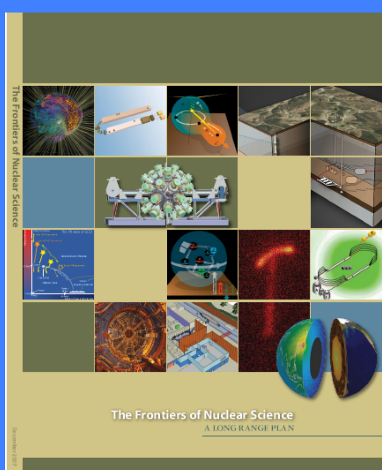
For nuclear astrophysics, the "playground" for these new, and existing, facilities is nicely illustrated on a chart of the nuclei prepared by Mike Smith and Ernst Rehm for their review article (Ann. Rev. Nucl. Part. Sci. 51 (2001) 91-130



This worldwide network of RBF’s has not evolved by accident, but has emerged within a planning context created by Long Range Plans produced by the international community







Plus occasional International reports carried out under the auspices of the OECD Global Science Forum, most recently in 1999 and 2008

Note Asia now has it's community - ANPhA - to match Europe and North America

You might be interested to note some of the statistics found in these reports

"There is a significant global effort in basic nuclear physics research, involving around 13,000 scientists and support staff, with funding of approximately two billion dollars per year."

OECD Global Science Forum Working Group on Nuclear Physics 2008

3,000 young people are trained to PhD level each year taking high tech skills into the global workforce

There are billion dollar industries in power, medicine, defence, and applications to numerous other sciences and applications.

Back to the beams - how do we produce these

Concept is simple

Use a high power accelerator to bombard a target and produce lots of reactions creating lots of new nuclei

Devise a way to get these out of the target quickly (before they decay) and use them as a beam for your experiment

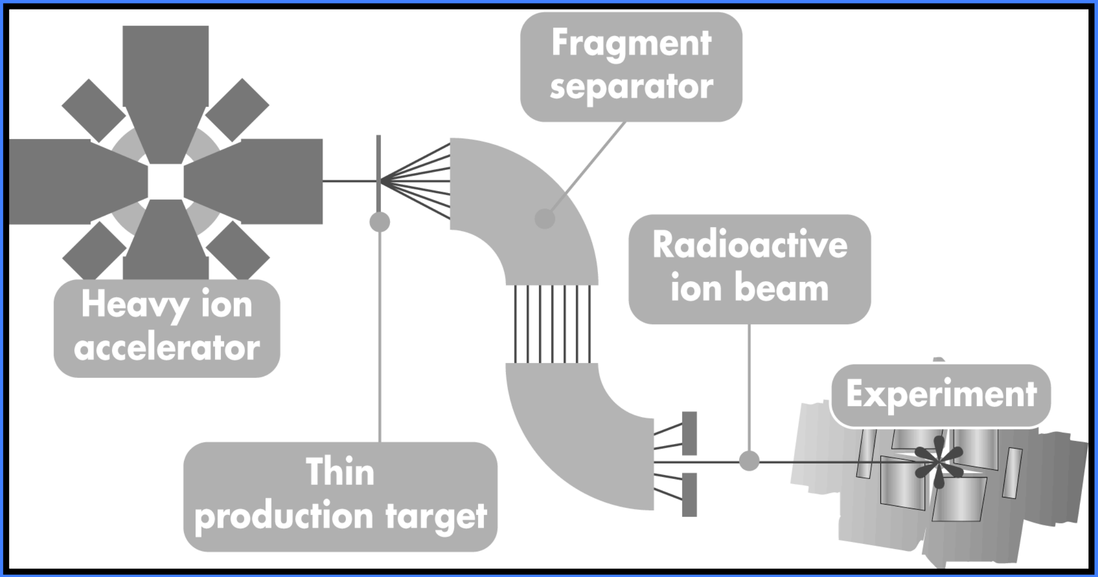
First part is relatively easy - accelerators are a mature technology

The second part is the hard bit

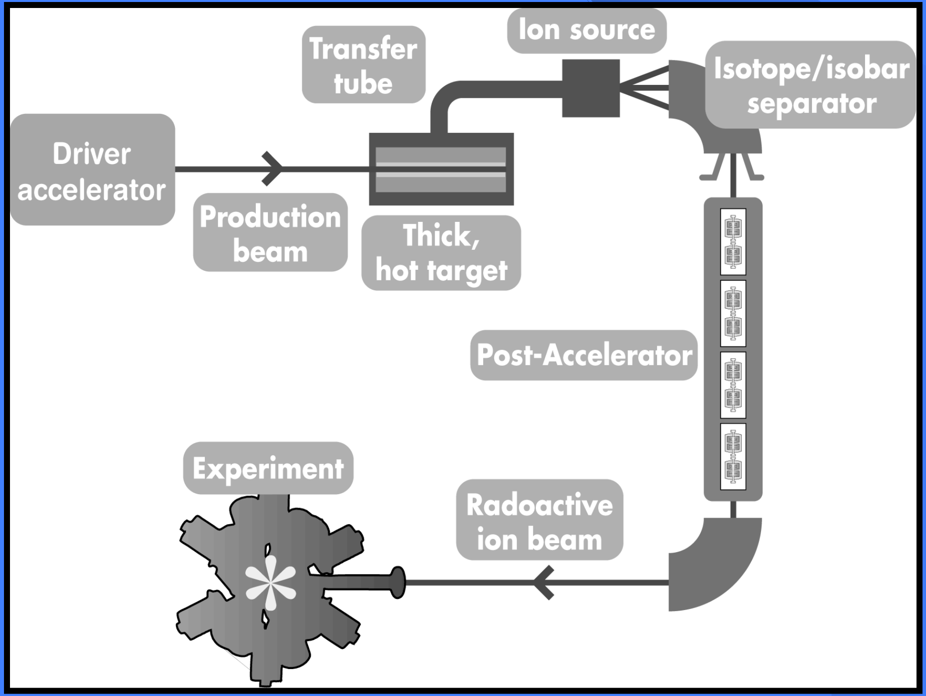
Two approaches:

- In-flight (sometimes called "Fragmentation")
- ISOL (Isotope Separator On Line)

In-flight



ISOL

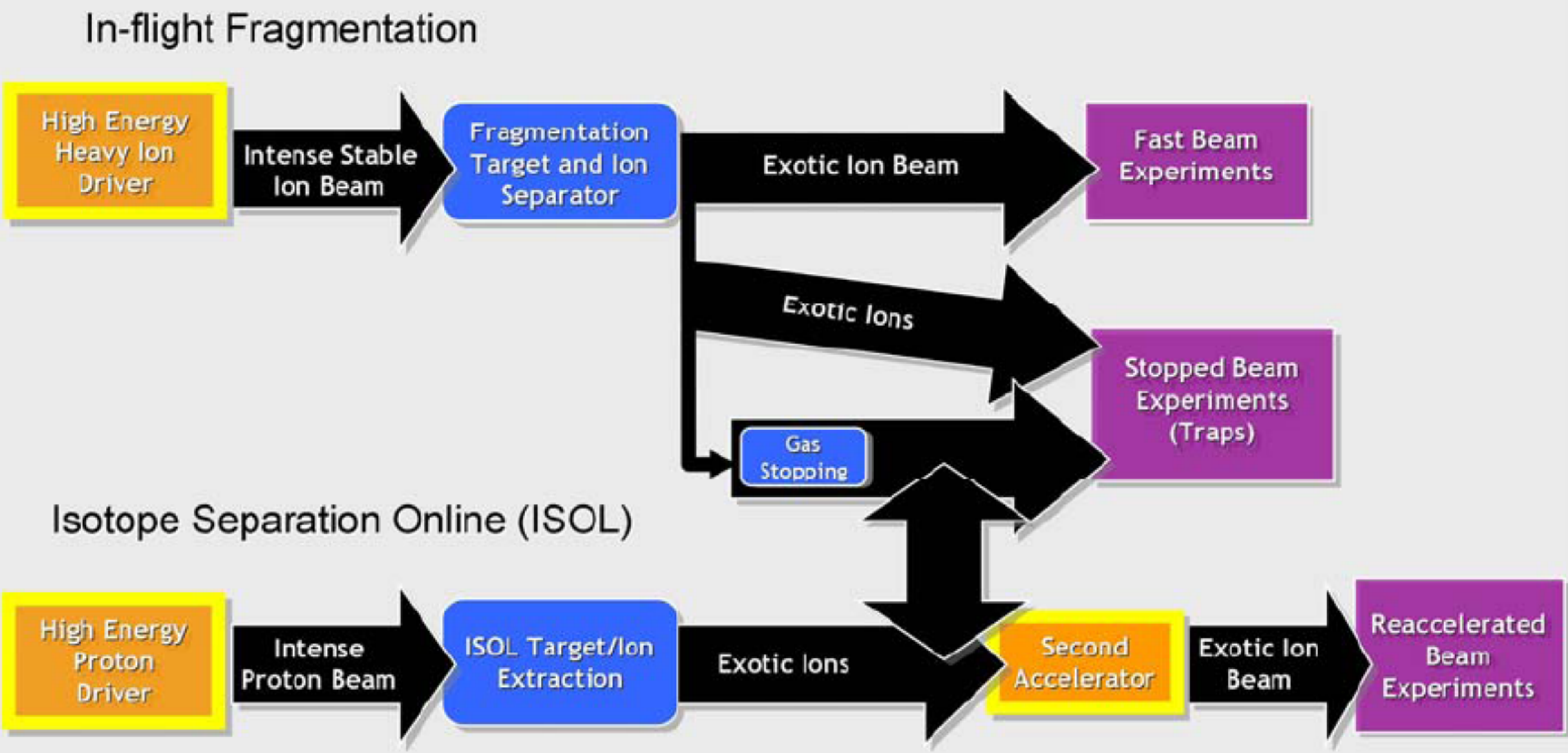


	Advantages	Disadvantages
ISOL	Variable energy beams Good quality beams	Huge target problems Chemical selectivity Long release times
In-Flight	Short half-lives No chemical selectivity	Limited energy variability Complex separation optics Poor resolution

In-flight: Great for "frontier studies" as able to produce lots of beams quickly for survey type studies.

ISOL: Great for follow up precision studies where good resolution is needed

"Hybrid" approaches now emerging



Picture from Peter Butler

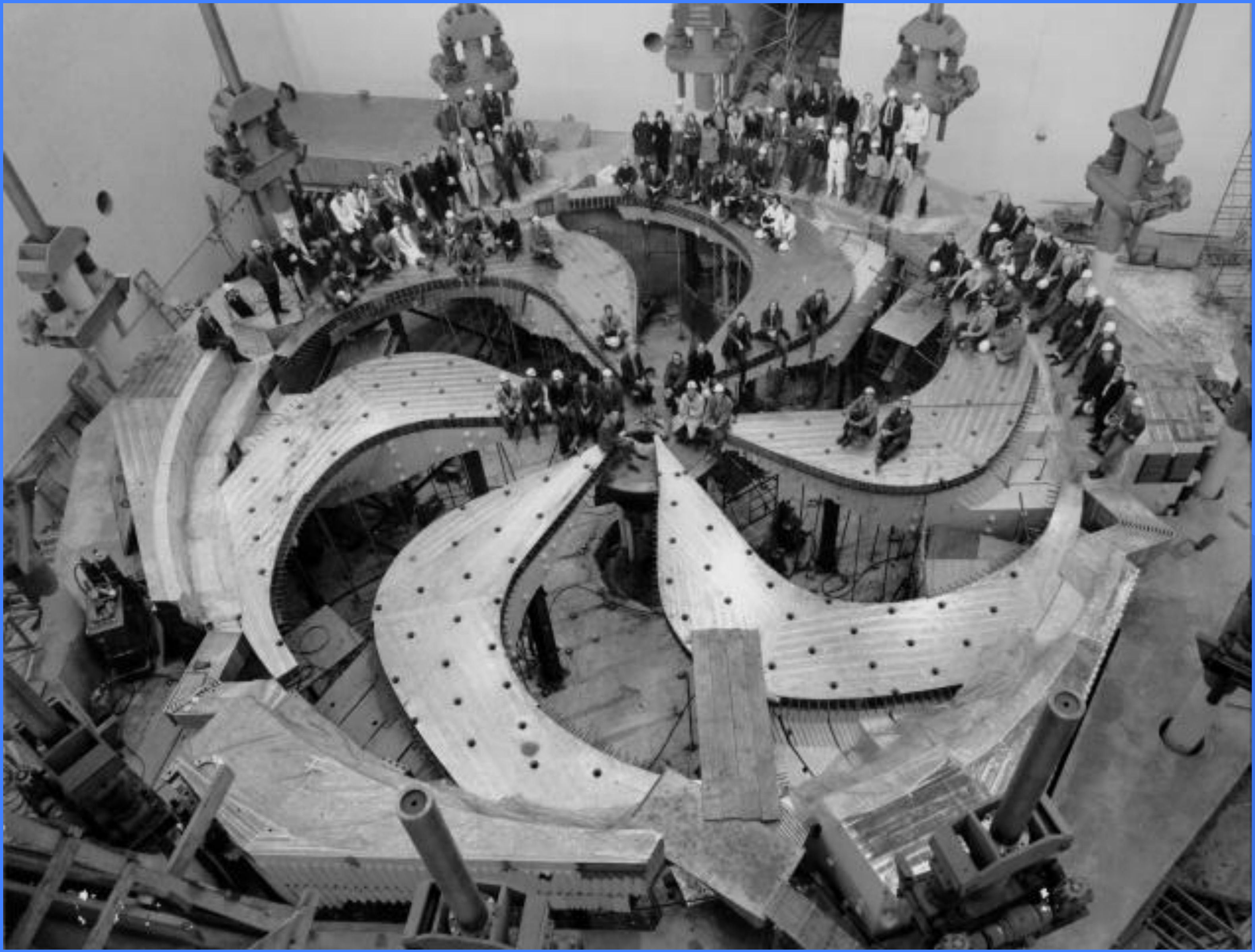
A closer look at an ISOL facility TRIUMF Laboratory (Vancouver, Canabera

History

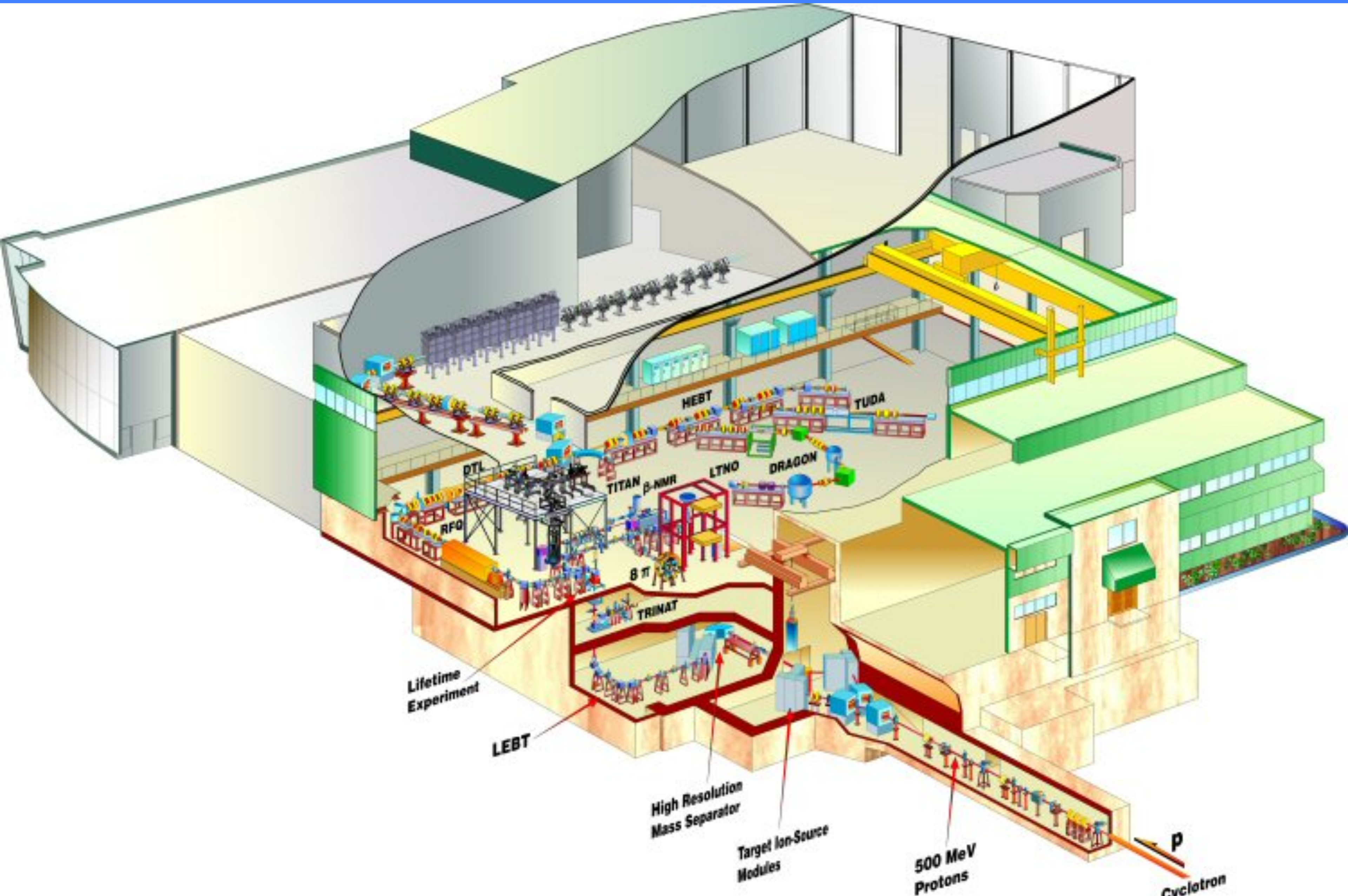
Originally Canada's High Energy Laboratory running a 500MeV cyclotron

ISAC facility built in 2000 using cyclotron beam as driver for ISOL target

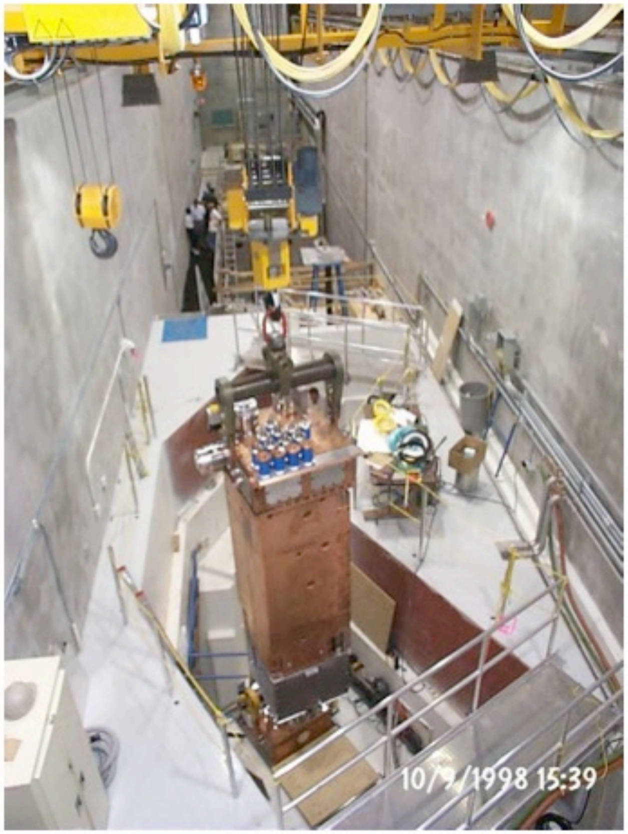
Extended in 2010 to ISAC-2 by adding larger post accelerator

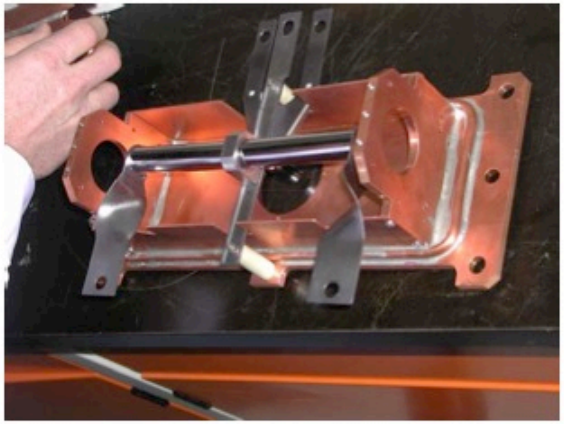


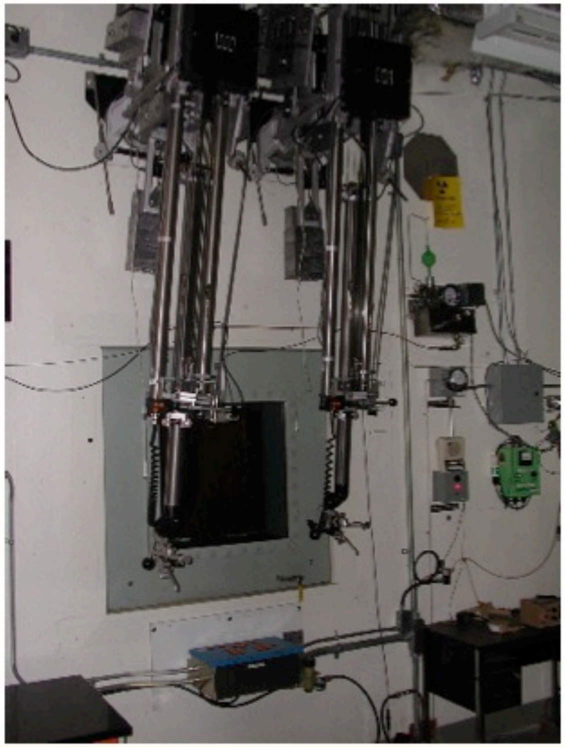
Worlds largest cyclotron - 500MeV protons at up to 200µA

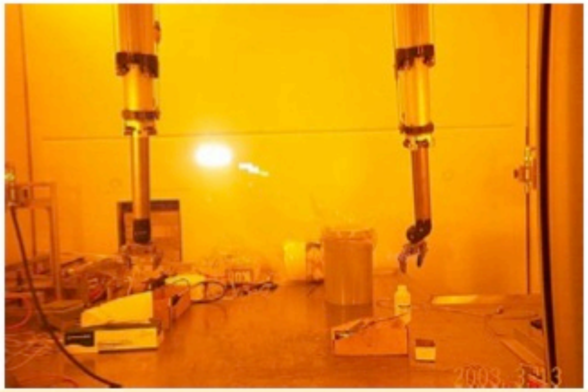

HEBT
TUDA
DTL
TITAN
β-NMR
LTNO
DRAGON
RFQ
8 π
TRINAT
Lifetime Experiment
LEBT
High Resolution Mass Separator
Target Ion-Source Modules
500 MeV Protons
p
Cyclotron

Enormous technological, radiological and safety issues in the targetry





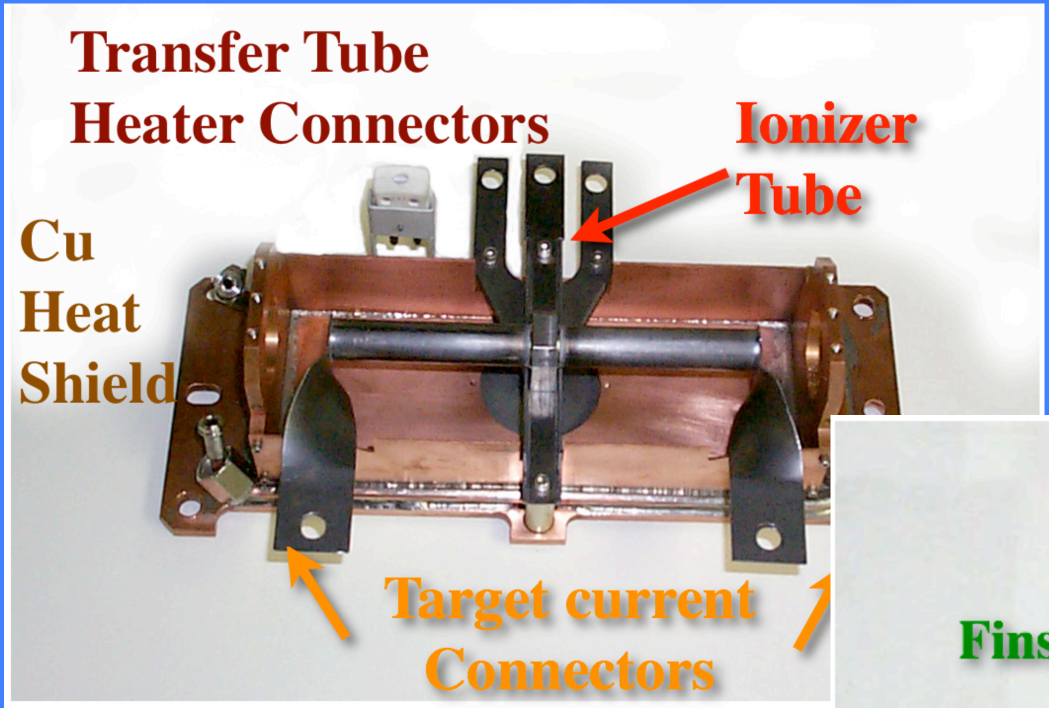




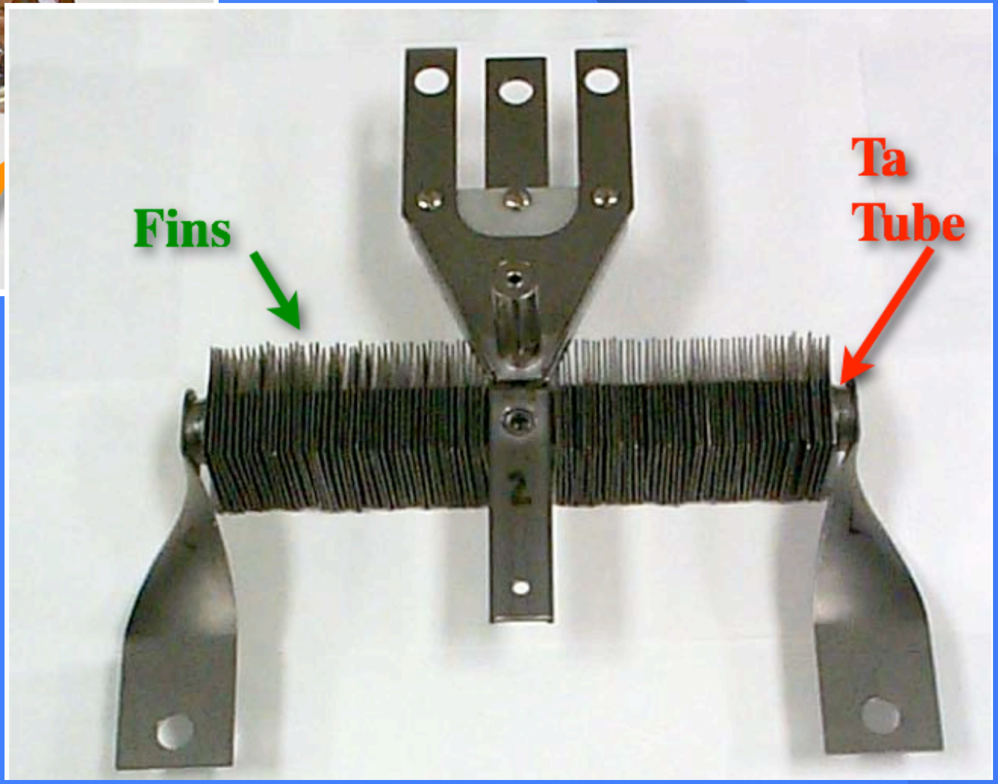
Christian described the problems with 100W on target.......

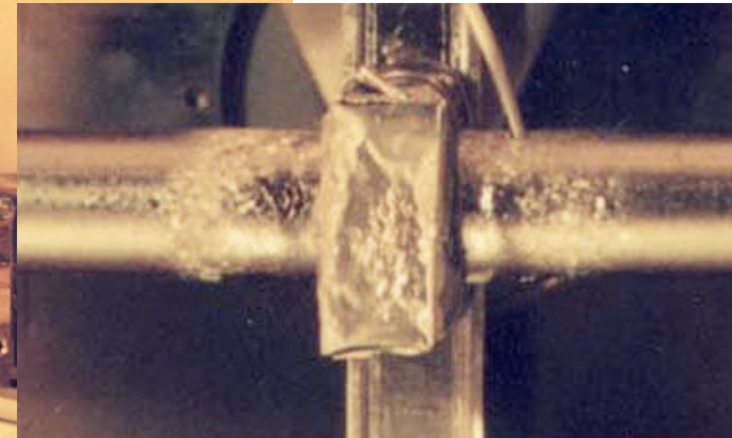
......this is 50kW!

Low power target
up to 7μA



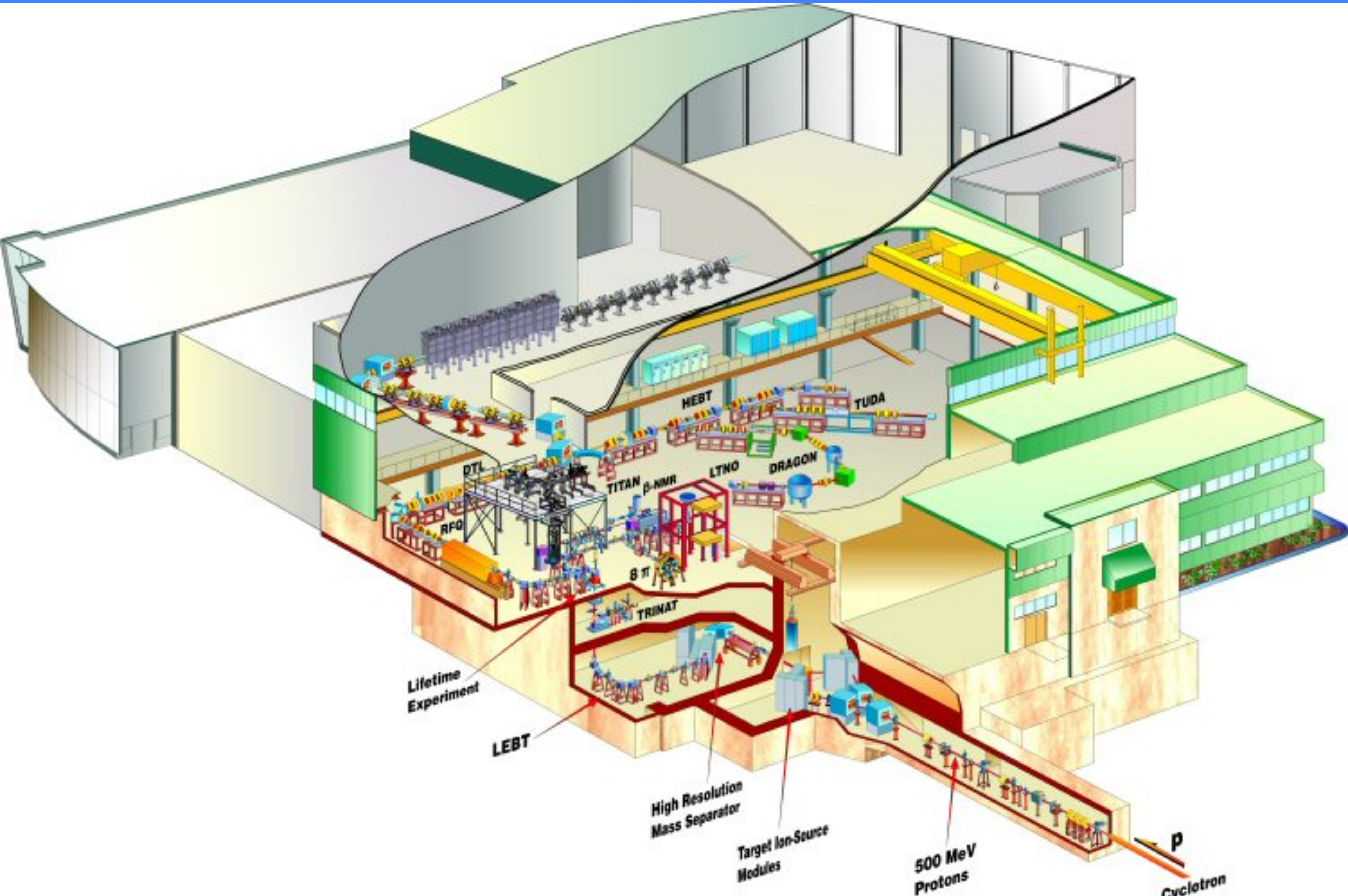
High power target
up to 100μA





Ta target after receiving 3.2×10^{20} protons

X50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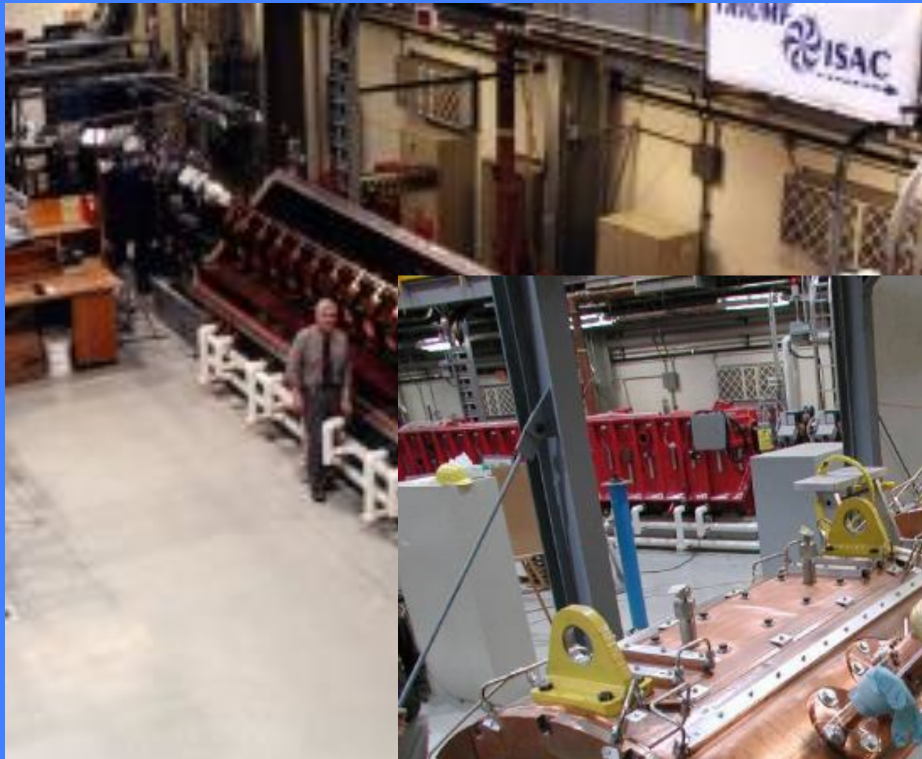
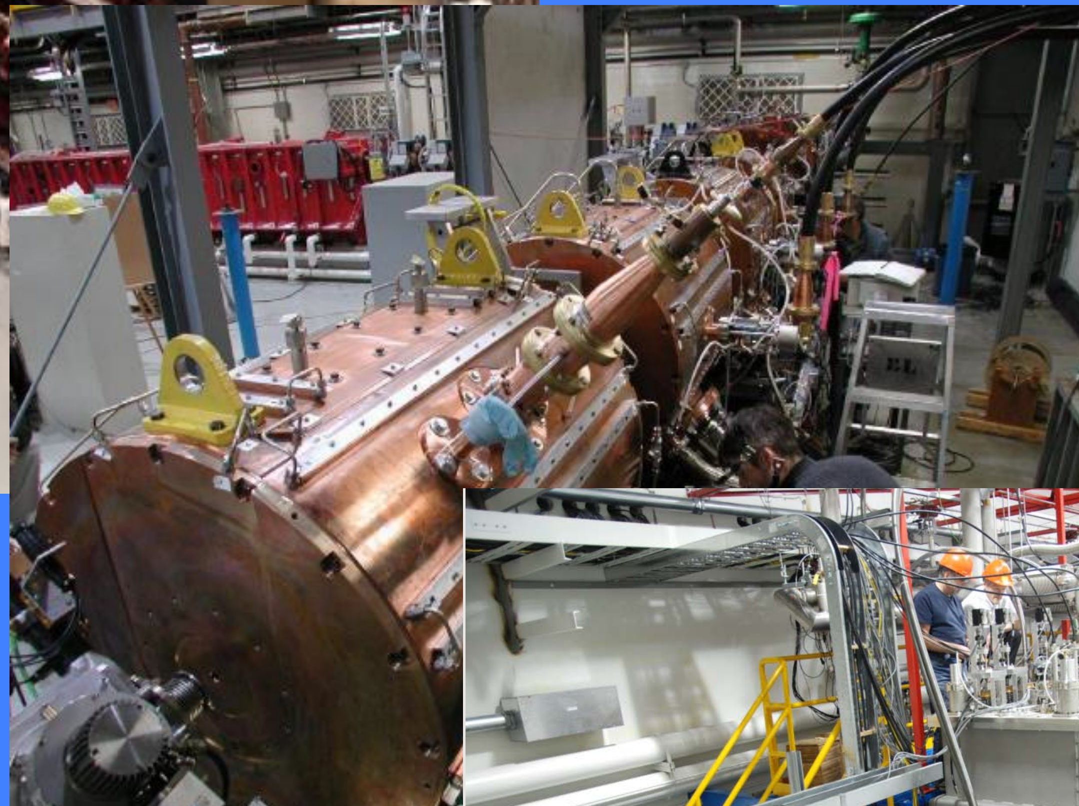
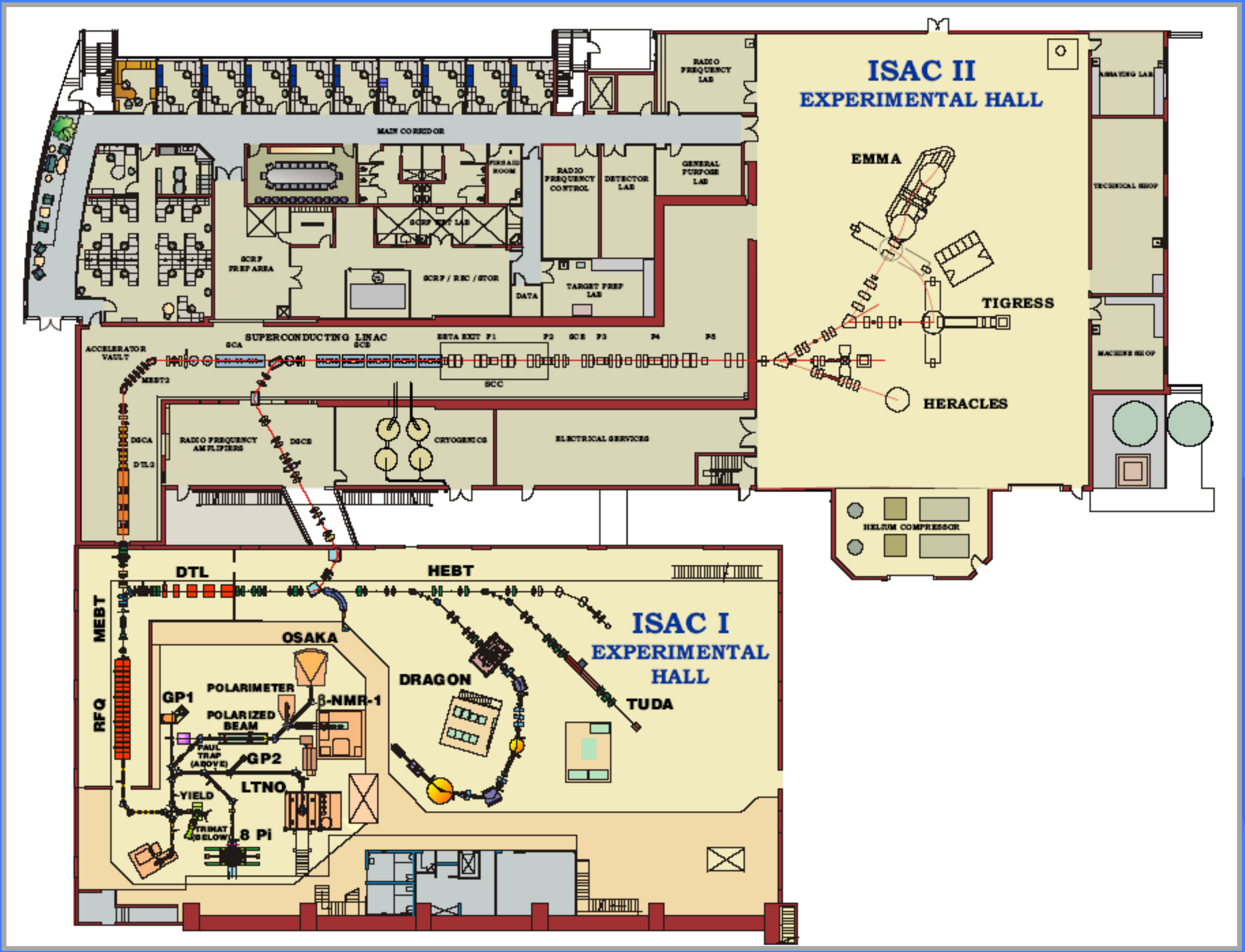
Lifetime Experiment
LEBT
High Resolution Mass Separator
Target Ion-Source Modules
500 MeV Protons
p
Cyclotron

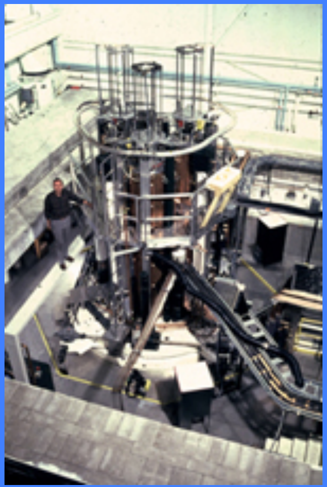
The radioactive beam accelerators





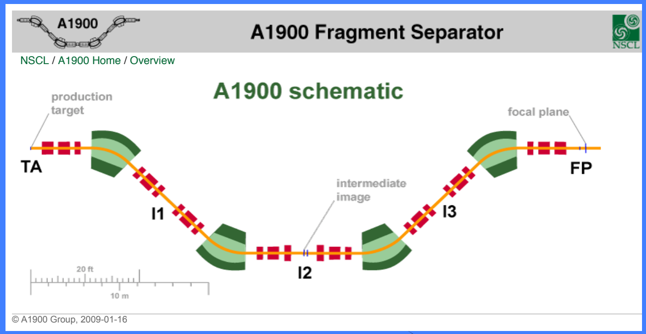

ISAC II
EXPERIMENTAL HALL
EMMA
TIGRESS
HERACLES
MAIN CORRIDOR
SUPERCONDUCTING LINAC
ACCELERATOR VAULT
RADIO FREQUENCY AMPLIFIERS
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
DTL
HEBT
MEBT
RFQ
OSAKA
POLARIMETER
β-NMR-1
GP1
POLARIZED BEAM
PAUL TRAP (ABOVE)
GP2
LTNO
YIELD
8 Pi
DRAGON
ISAC I
EXPERIMENTAL
HALL
TUDA

A closer look at an in-flight facility   NSCL, Michican State University, USA

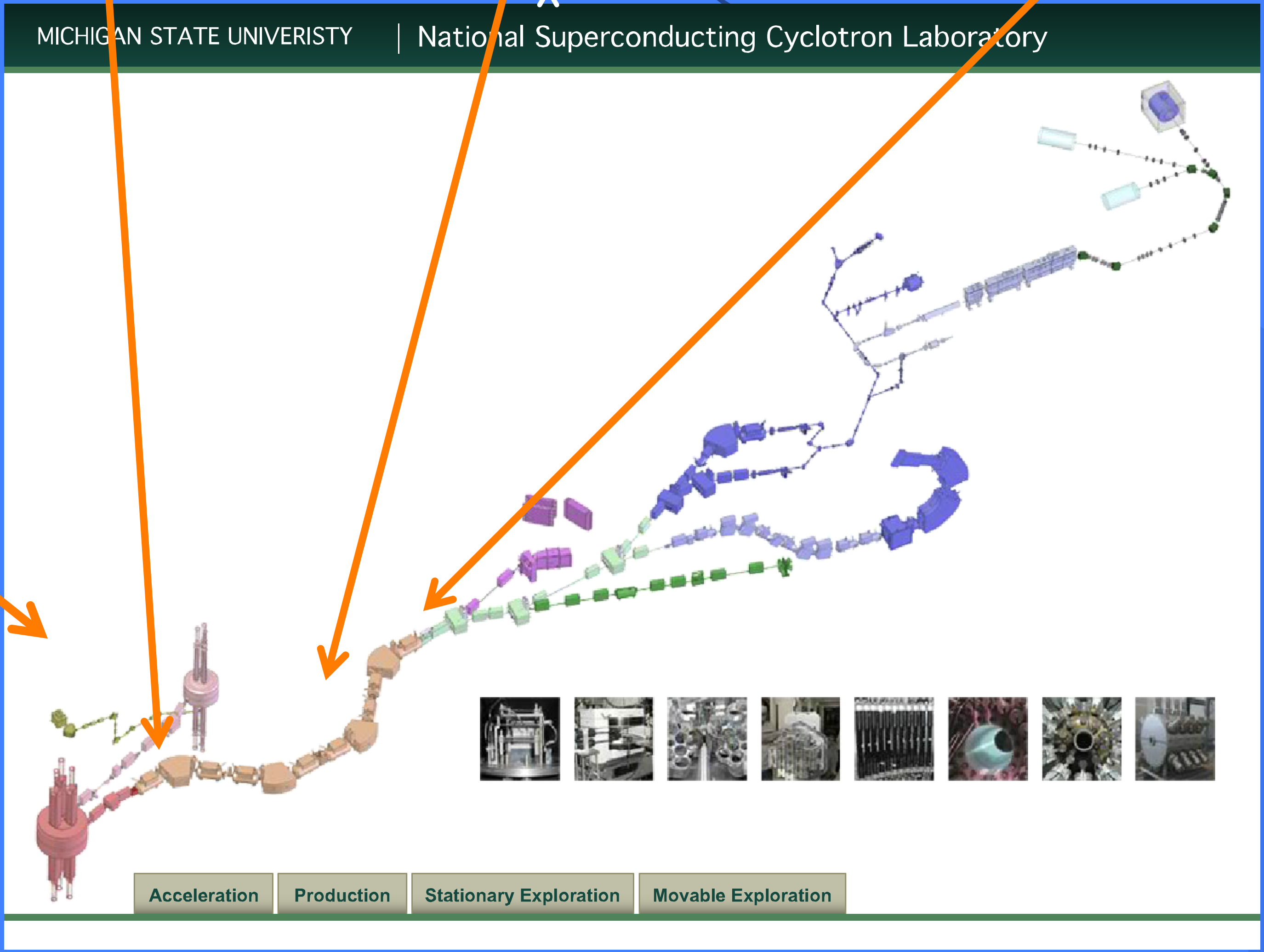


Two coupled superconducting cyclotrons

Primary Target



Secondary Target



The incident beam from the cyclotrons is very high energy so all the exotic nuclei produced by collisions in the target fly forward a zero degrees with essentially the same momentum as the beam

The magnets in the A1900 separate according to momentum

$F_{centripetal} = mv^2/r$

$F_{magnetic}$ - Bqv

$mv^2/r = Bqv$

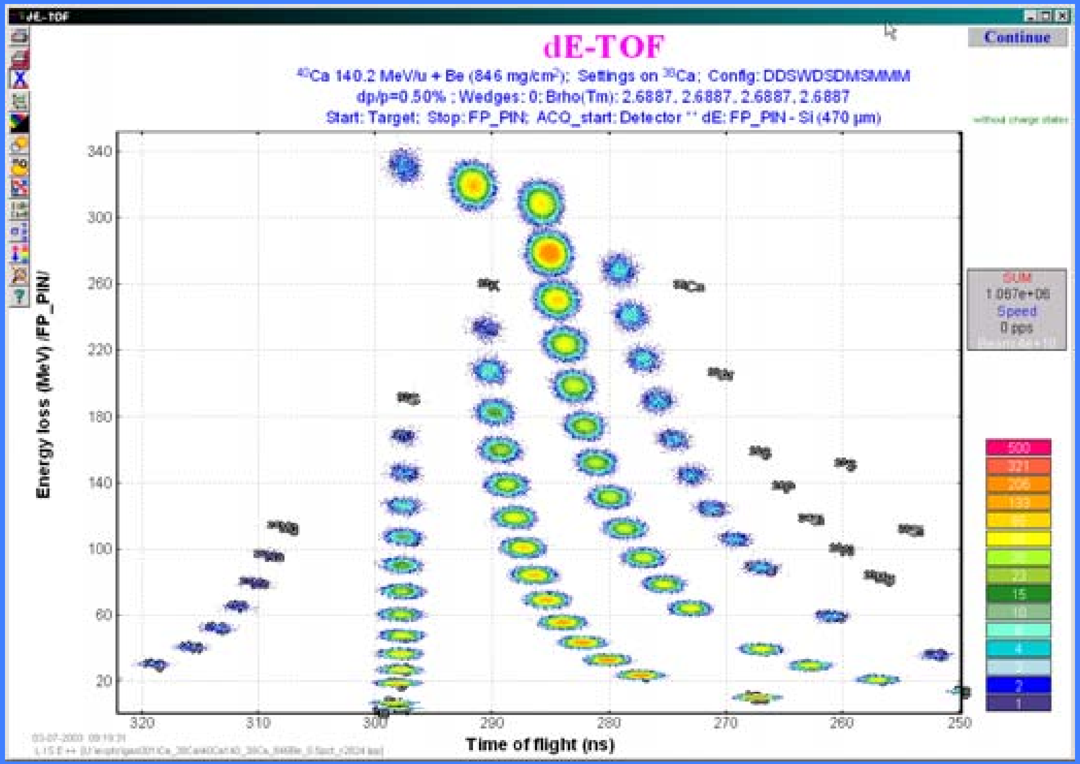
$p/q = Br = constant$

So the only nuclei that we see at the end of the separator are those with the p/q we selected

We identify these by combining two measurements

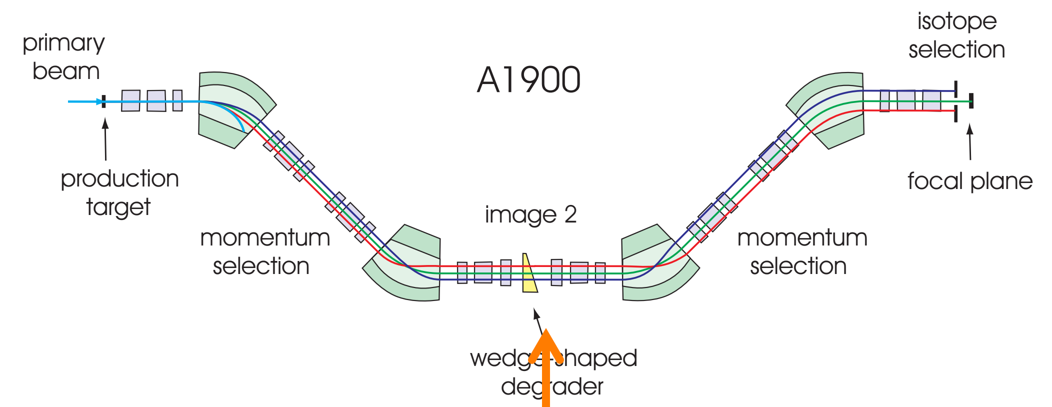
Energy the deposit in a detector

Time they have taken to get through the device



But this results in many different nuclei arriving at the end of the separator as well as the ones we want

This results in a background of reactions which we can't distinguish from the ones we want



	p/p	d	B max	rel. accept.
A1200 (1991-99)	3%	0.8 msr	5.4 Tm	1
A1900 (2001-)	5%	8 msr	6 Tm	18.3
RIA (HR)	6%	10 msr	~8 Tm	25

stolz@nscl.msu.edu 2002-

The trick is to put a thick "degrager" foil at the intermediate focus

As the nuclei pass through the foil the lose energy, the amount of which depends on the Z of the nucleus

So now the different elements has different momenta in the second stage and we can adjust the magnetic fields to just let through the nucleus of interest

END OF LECTURE 2

However, you have homework for the break!

We have noted that beam intensities from radioactive beam facilities are low and that this means measurements take longer

.........let's work out just how long

Let's take a reaction this is important for observing gamma rays from novae

$p + {}^{18}F > \alpha + {}^{15}O$

Using a radioactive beam of ^{18}F, so low intensity - let's take 10^6/s

Target of plastic has hydrogen (protons) and has 10^{18} /cm^2

Cross section is small as low energy - let's say 1mb

Detector for the α particles is 5x5 cm and is a distance 25cm from the target

How many a particles are emitted per second?

How long would it take to measure this cross section to an accuracy of 10%?