Next steps reaching the horizon

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革新的研究開発推進プログラム ImPACT Impulsing Paradigm Change through Disruptive Technologies Program

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Nuclear Reactor

Enrico Fermi

Thermal neutron capture
Chain reactions

ImPACT

Radioactive isotope free nuclear energy

- more safe
- less waste production
- sustainable
- …

Accelerator Transmutation System for LLFP

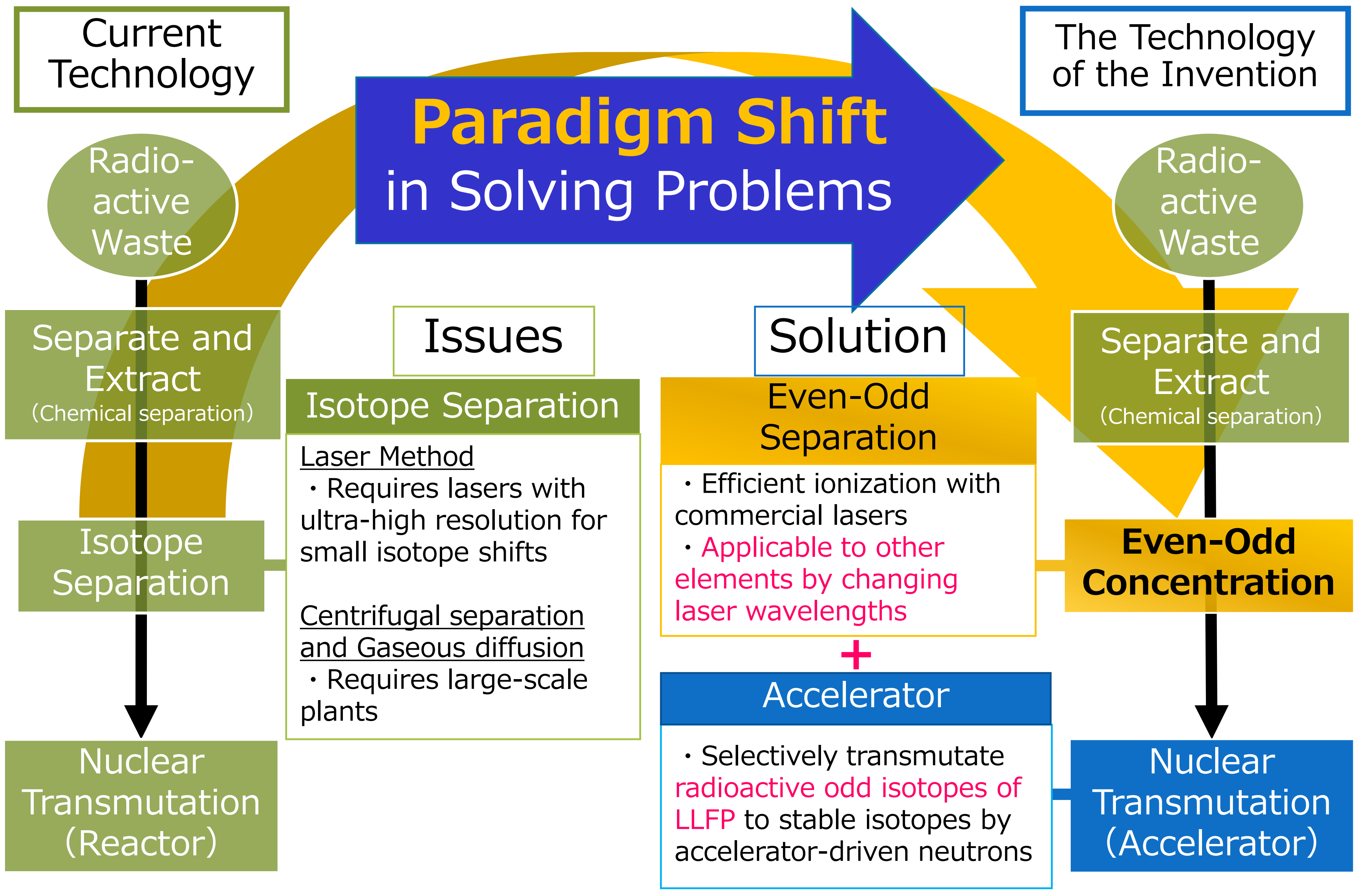
R&D efforts to minimize risk of radioactive materials

Transmutation System for Minor Actinide (MA)
has been well studied;
Accelerator-Driven System and Fast Breeder Reactor

<u>How about accelerator system to reduce radioactivity of LLFP?</u>
At reactors, transmutation reactions are limited to
neutron-induced reactions at energy of thermal to MeV.
In addition, such reactors produce LLFP further.

Compared with reactors,
A variety of reactions are applied at accelerator system
for nuclear transmutation;
spallation reaction, incomplete fusion,
muon capture, (n,2n), etc…

Paradigm Shift of the Invention



The 21st Century Invention Award, Japan Institute of Invention and Innovation (2018)

Important Parameters for Transmutation

Y: throughput (yield of reaction products)

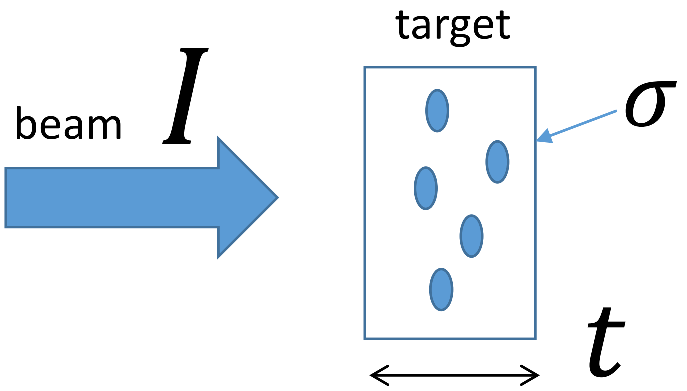
$$Y = I\sigma t$$

How to maximize Y ?

I: number of energetic particles ((2ndary) beam intensity)

σ: reaction probability (cross section)

t: number of target nuclei (target thickness)



Organization of the ImPACT program

Partitioning

To enrich nuclides for transmutation
  Chemical separation
  (Even-odd) isotope separation

Nuclear Reaction Data

To predict cross section
  experimental data for reactions
  Theoretical models
  Database for engineering

t

σ

System design

I

Accelerator system

To provide intense beams
  acceleration scheme
  target for high-power beams

Partitioning: Chemical Separation

Matsumura

simulated HLLW

real HLLW

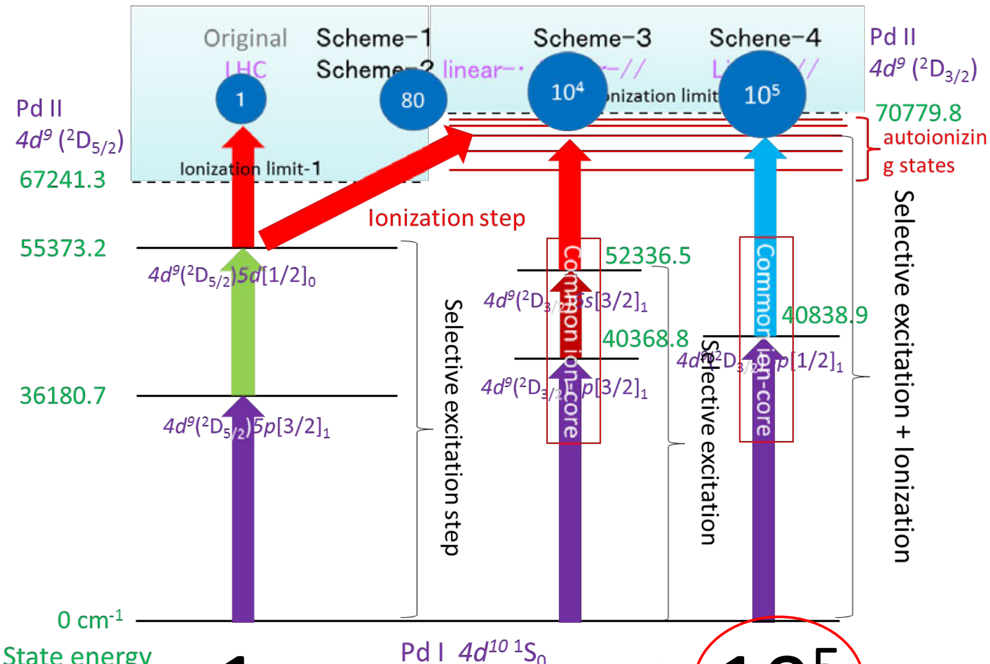
Separating technologies with limited secondary wastes are proposed by PJ1

Small-scale Test with real HLLW is necessary for the proposed process

Partitioning: Even-Odd Isotope Separation

Kobayashi

Comparison in ion yield



1 → 10^5

3 lasers (circular) 2 lasers (linear)

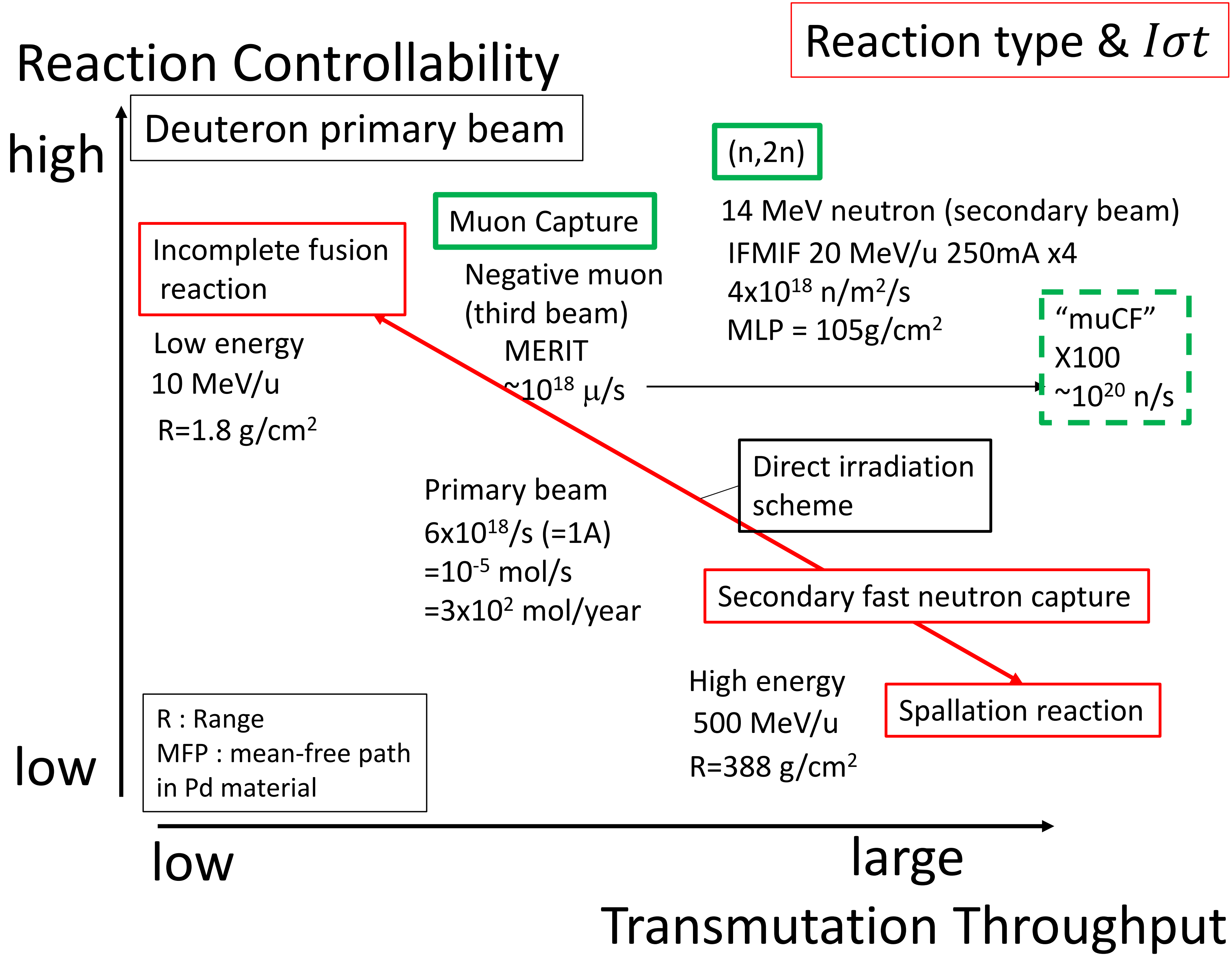
High-level nuclear waste (HLW) 20 ton/year

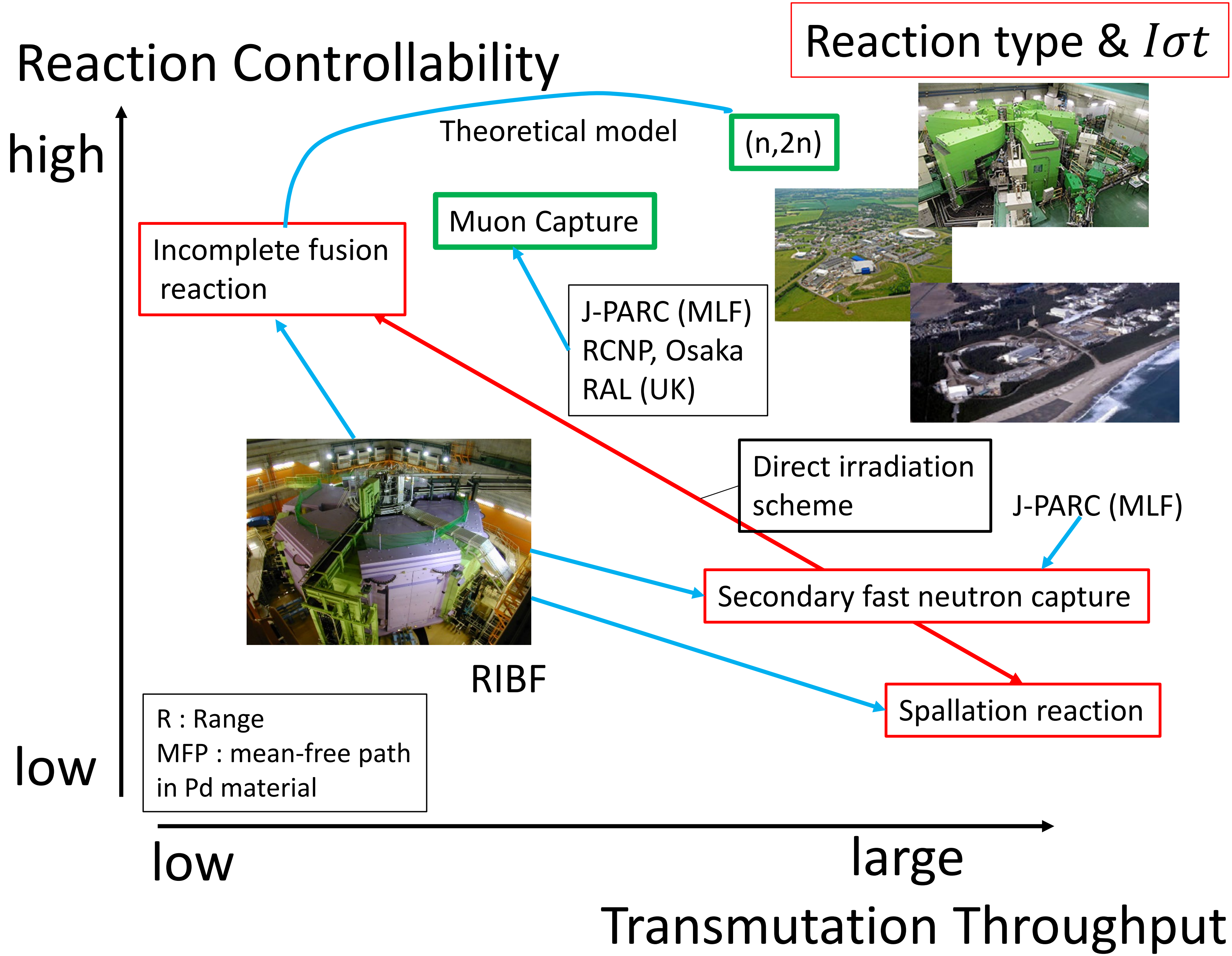
Pd 27 kg/year

× 350

Our value 77 g/year

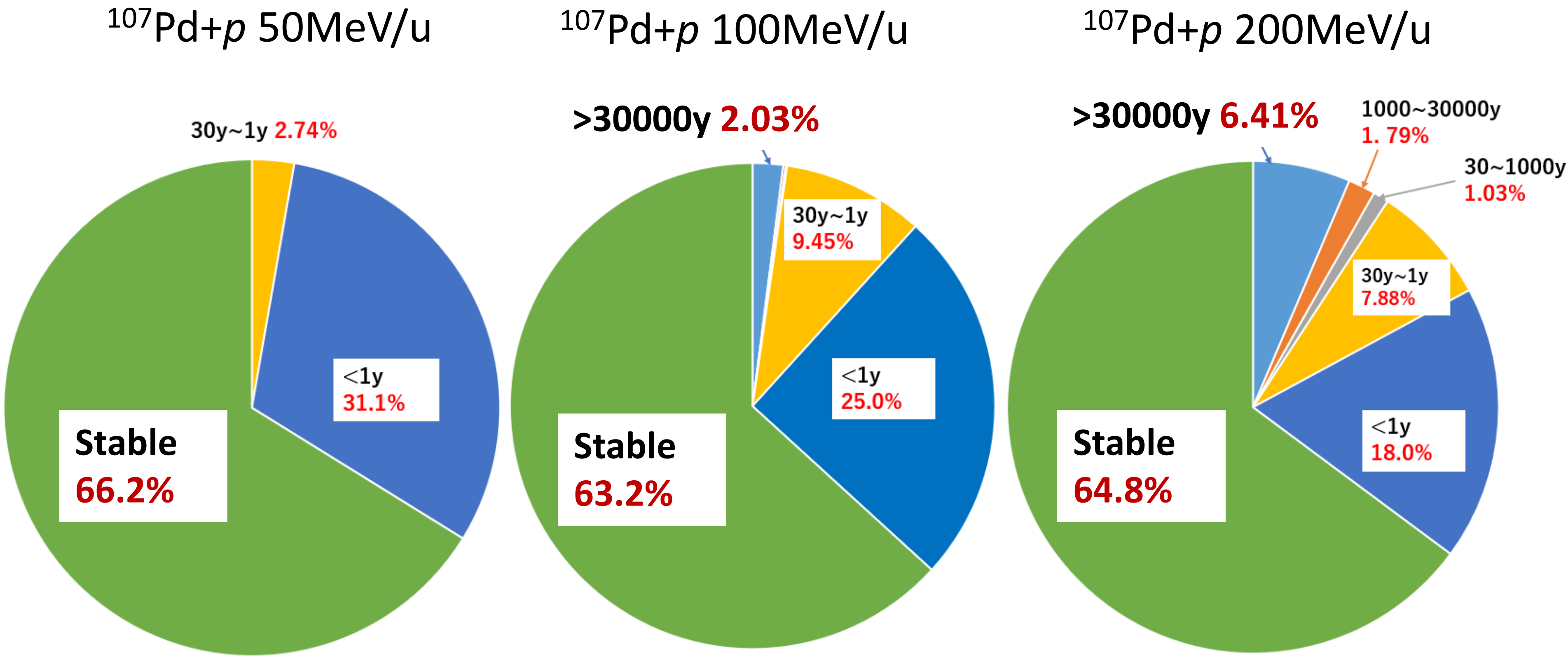
- High power lasers
- Large volume multi-pass optics


Reaction Controllability
Reaction type & $I\sigma t$
high
Deuteron primary beam
(n,2n)
Muon Capture
14 MeV neutron (secondary beam)
IFMIF 20 MeV/u 250mA x4
$4x10^{18}$ n/m²/s
MLP = 105g/cm²
Incomplete fusion reaction
Negative muon
(third beam)
MERIT
~10^{18} μ/s
"muCF"
X100
~10^{20} n/s
Low energy
10 MeV/u
R=1.8 g/cm²
Direct irradiation scheme
Primary beam
$6x10^{18}$/s (=1A)
=10^{-5} mol/s
=$3x10^{2}$ mol/year
Secondary fast neutron capture
High energy
500 MeV/u
R=388 g/cm²
Spallation reaction
R : Range
MFP : mean-free path
in Pd material
low
low
large
Transmutation Throughput


Reaction Controllability
Reaction type & $I\sigma t$
high
Theoretical model
(n,2n)
Muon Capture
Incomplete fusion reaction
J-PARC (MLF)
RCNP, Osaka
RAL (UK)
Direct irradiation scheme
J-PARC (MLF)
Secondary fast neutron capture
RIBF
Spallation reaction
R : Range
MFP : mean-free path
in Pd material
low
low
large
Transmutation Throughput

Experimental Reaction Data

Half life distributions of reaction products



Preliminary

Experimental Reaction Data

Shimoura

Reaction data with LLFPs by RIBF-ImPACT

Experiments	Beam lines	Settings	Purpose	Energy [MeV/u]
Pre-ImPACT	BigRIPS+ZeroDegree	^{137}Cs	Fragmentation/ spallation	190
		^{90}Sr		
ImPACT in 2015 spring	BigRIPS+ZeroDegree	^{107}Pd	Fragmentation/ Spallation/Coulomb	100/200
		^{93}Zr/^{90}Sr		
		^{135}Cs		
ImPACT in 2015 autumn	BigRIPS+SAMURAI	^{93,94}Zr	Exclusive measurements	100/200
		^{79,80}Se		100/200
ImPACT in 2016 autumn	BigRIPS+ZeroDegree	^{107}Pd	Spallation	50
		^{93}Zr	Spallation	50
		^{126,127}Sn	Spallation/Coulomb	100/200
ImPACT in 2017 autumn	BigRIPS+OEDO/SHARAQ	^{107}Pd	p/d induced reaction	24/30
		^{93}Zr		30
		^{79,77}Se	(d,p) for (n,γ) surrogate	20

	20-30 MeV/u	50 MeV/u	100, 200 MeV/u
^{107}Pd	✓	✓	✓
^{93}Zr	✓	✓	✓
^{79}Se	✓		✓
^{126}Sn			✓
^{135}Cs			✓

Neutron capture data for ^{135}Cs
Muon capture data for ^{107}Pd

more data for energy dependence
more data for other nuclides
^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs
new data for n-induced reaction at high energy
new data for MA

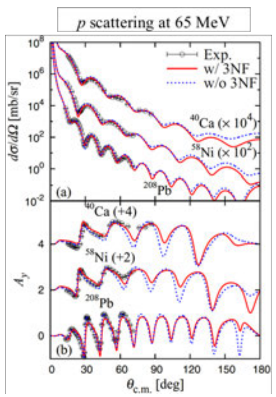
Higher intensity beam at RIBF to take more data in shorter periods

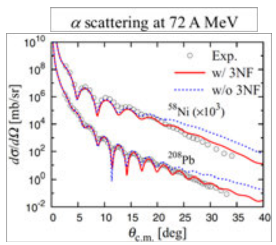
Theory and Database

Ogata and Kunieda

Development of new theoretical treatments and models
Improvement of accuracy for evaluated data
by taking into account experimental data and microscopic theory

Success of microscopic optical potential





No free parameter (“prediction”)

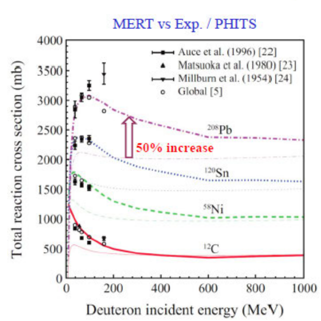
M. Toyokawa, Yahiro, Matsumoto, Minomo, O, Kohno, PRC **92**, 024618 (2015).

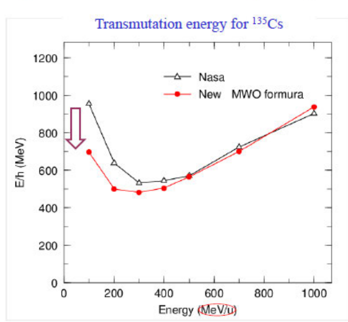
Evaluated data sets are produced for both neutron- and proton-induced reactions up to 200 MeV (JENDL/ImPACT-2018)

DEURACS code for deuteron-induced reactions are newly developed.

MERT evaluation for deuteron reaction cross sections

K. Minomo, K. Washiyama, and K. Ogata, Journal of Nuclear Science and Technology, 54, 127 (2017).





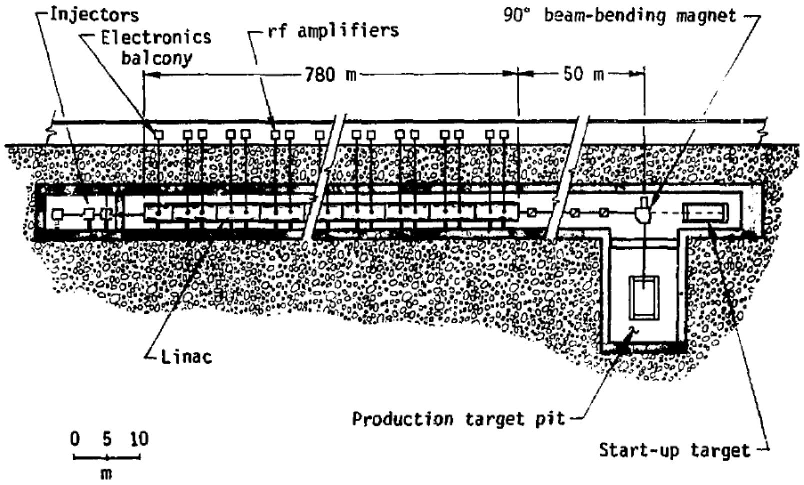
-> Database for deuteron-induced reactions

Material Testing Accelerator (MTA)

E.O. Lawrence + Univ of California Radiation Lab
(-> Lawrence Berkeley Lab)

1949-1954
To develop a deuteron accelerator and target assembly appropriate for
nuclear breeding of ^{239}Pu, ^{233}U and Tritium by irradiation of depleted uranium
with accelerator-produced neutrons.
Terminated in the mid of 50's with the discovery of ample uranium deposits

250 mA 500-MeV Deuteron Linac



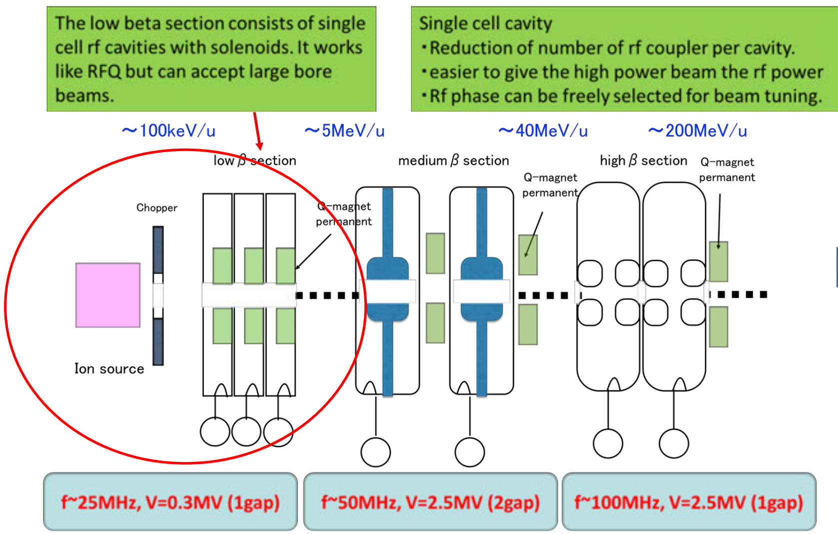
ImPACT 2017 Model

1A deuteron linac

Accelerator

H. Okuno

1A deuteron linac
Single cell linac with magnetic focusing

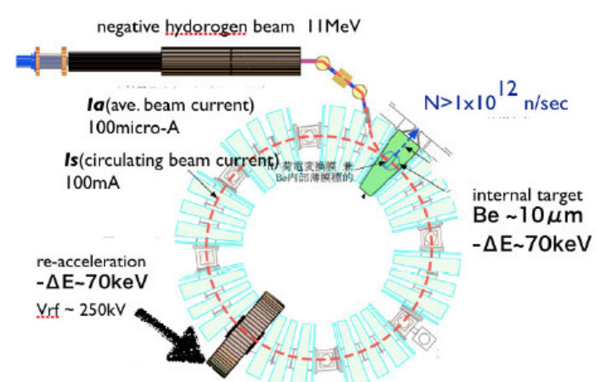


Developing "proof of concept" prototype

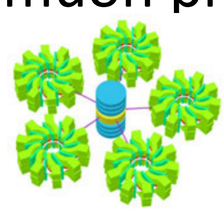
Constructions for
- ion source
- a part of low-beta,
- rf cavities in medium and high beta
- ……

R&D for super conducting cavity

Multiplex Energy Recovery Internal Target (MERIT) (linac+FFAG) for muon production



Multi-cyclotron system



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Enrico Fermi

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Aiming to construct a pilot plant 10 years later

Many R&D works and challenges in each of I, σ, t
Scheme to invite new ideas
More collaborations with univ., institutes, and industries
New applications
International alliances