Radioactive Ion Beams

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Solid ground for Science

Abstract Landscapes

Summary

- Context: What – Why - How
- RIB production: full chain
- RIB development

Clarification

RIB: **R**adioactive **I**on **B**eam!

What – Why - How

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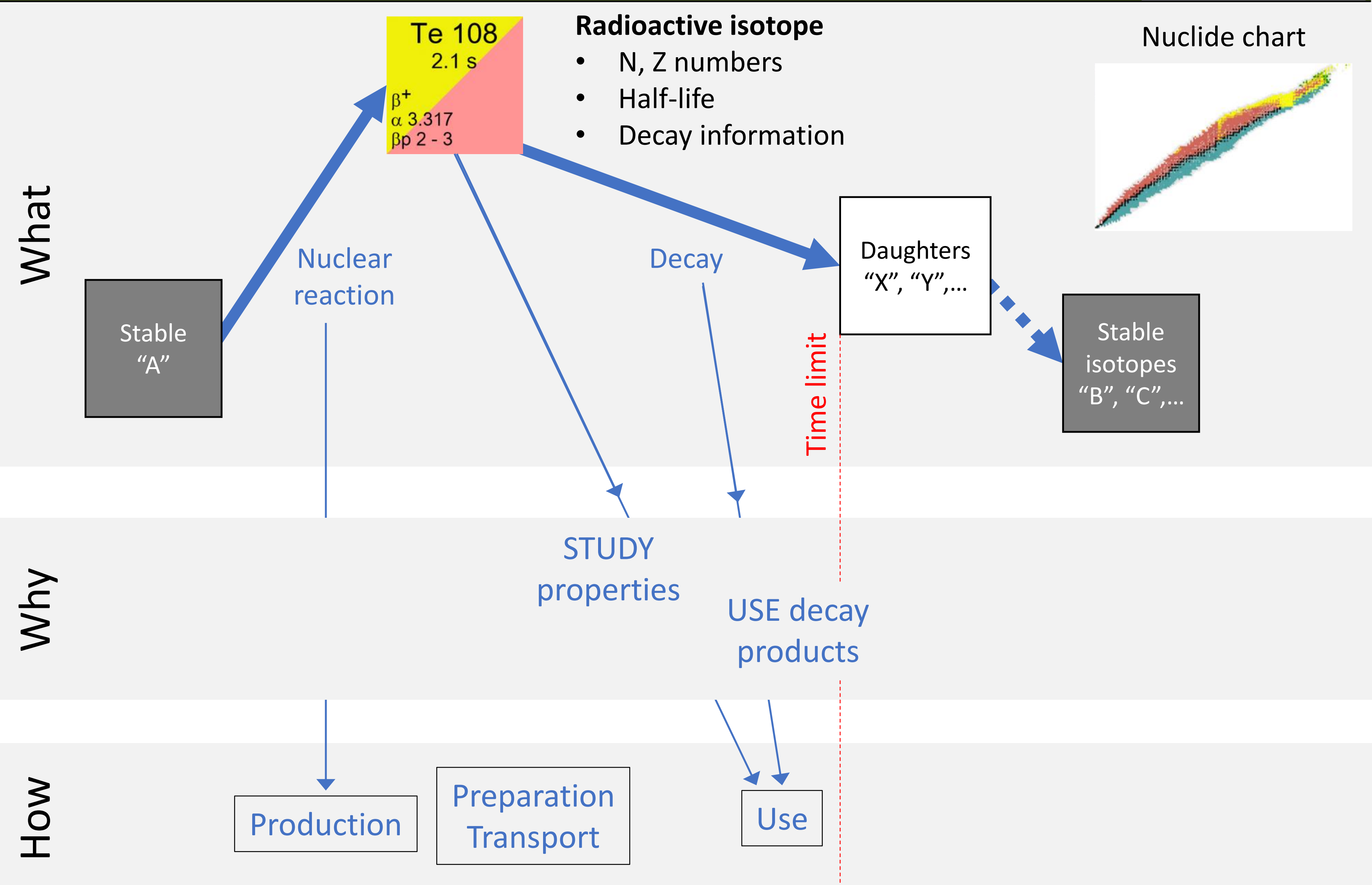
Abstract Landscapes



Reactions and Decays

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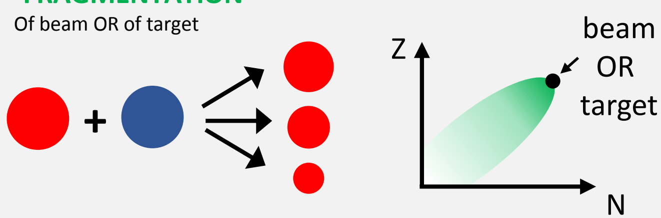
Main reaction types

Reaction	$a + {}^{Z+N}X \rightarrow {}^{Z'+N'}Y + b$
Notation	${}^{Z+N}X\ (a,\ b)\ {}^{Z'+N'}Y$

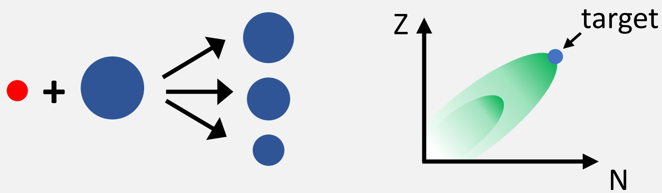
FRAGMENTATION

- Of beam OR of target



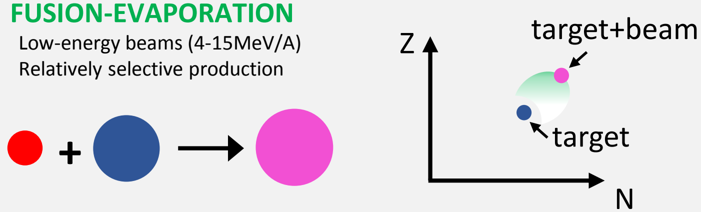
SPALLATION

- 2 channels: spallation-evaporation and spallation-fission
- Accompanied by neutrons (from thermal up to ~10MeV)



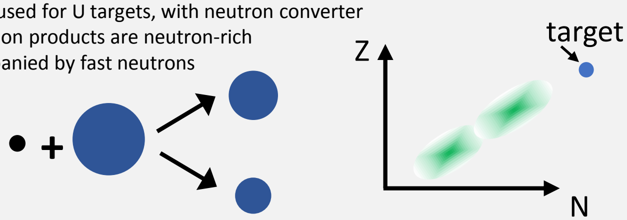
FUSION-EVAPORATION

- Low-energy beams (4-15MeV/A)
- Relatively selective production

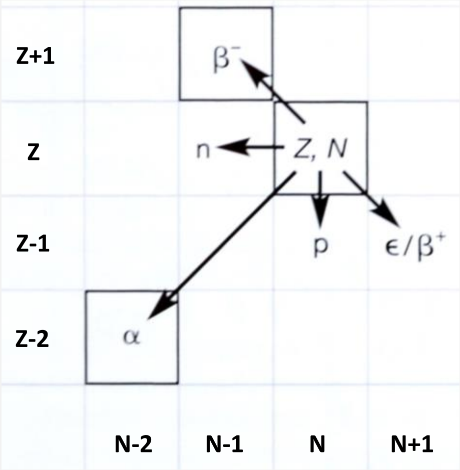


NEUTRON-INDUCED FISSION

- Mostly used for U targets, with neutron converter
- The fission products are neutron-rich
- Accompanied by fast neutrons



Main decay types



α decay

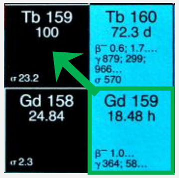
- α: particle energies [MeV]; order: decreasing probability
- γ energies"[keV]; order: decreasing intensity

Positron emission (β⁺)

- β+: Endpoint energies [keV] (cont.spectrum)
- γ energies"[keV]; order: decreasing intensity

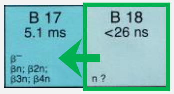
β- decay

- β-: Endpoint energies [keV] (cont.spectrum)
- γ energies"[keV]; order: decreasing intensity



p decay

n emission



The uses of RIBs

- Imaging
- Treatment
- Research

Medicine

Radioactive Isotopes

RIBs

Fundamental & Applied Sciences

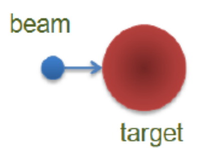
- Nuclear physics
- Atomic physics
- Solid state physics
- Materials science
- Life sciences

Half-life ←

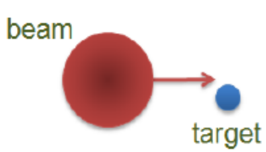
Industry

- Flow tracing
- Mixing measurements
- Neutron imaging
- Gamma sterilization

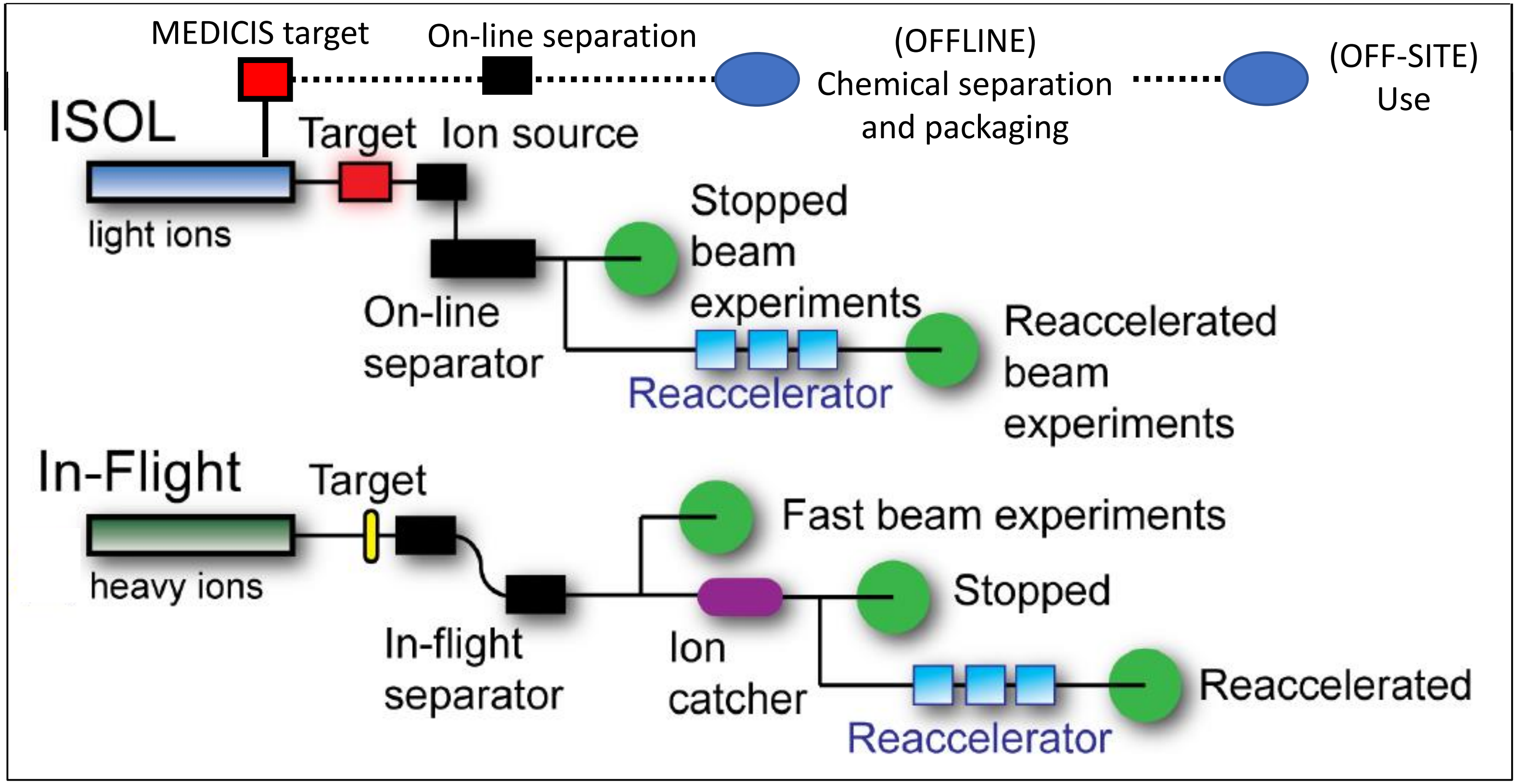
RIB production methods



- ✓ Spallation
- ✓ Fragmentation
- ✓ Fission



- ✓ Fragmentation
- ✓ Fusion-evaporation

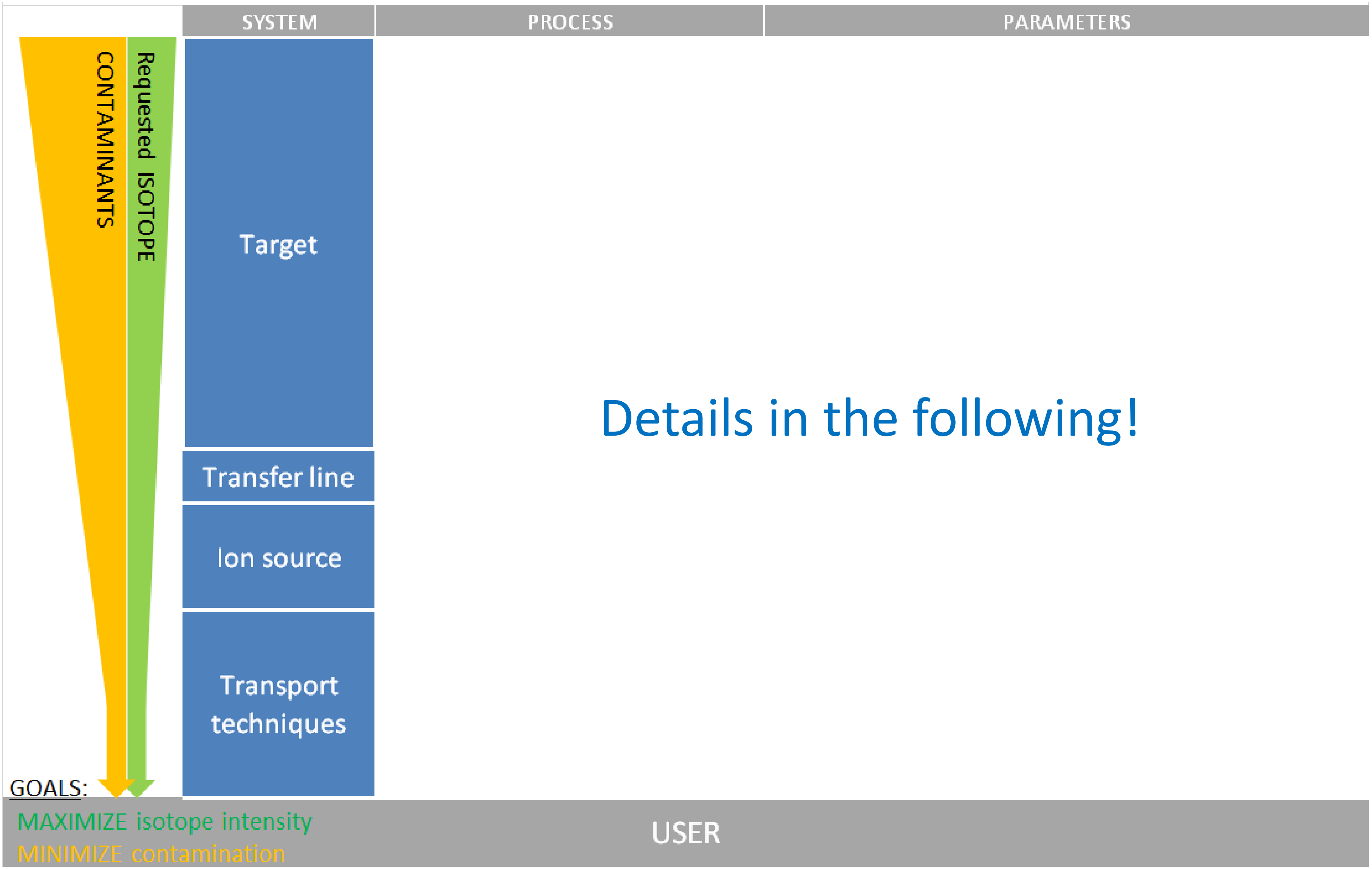


O.Tarasov

COMPARISON	ISOL	In-Flight
Projectile	light	heavy
Target	thick	thin
Release from target	slow	fast
RIB intensity	high	low
RIB quality	good	poor
RIB energy	low	high

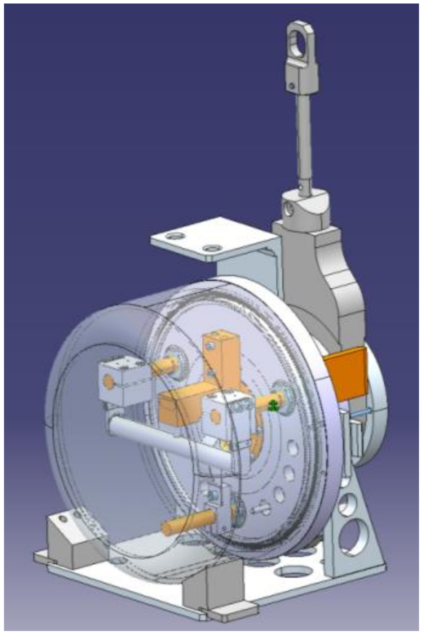
M. Kowalska

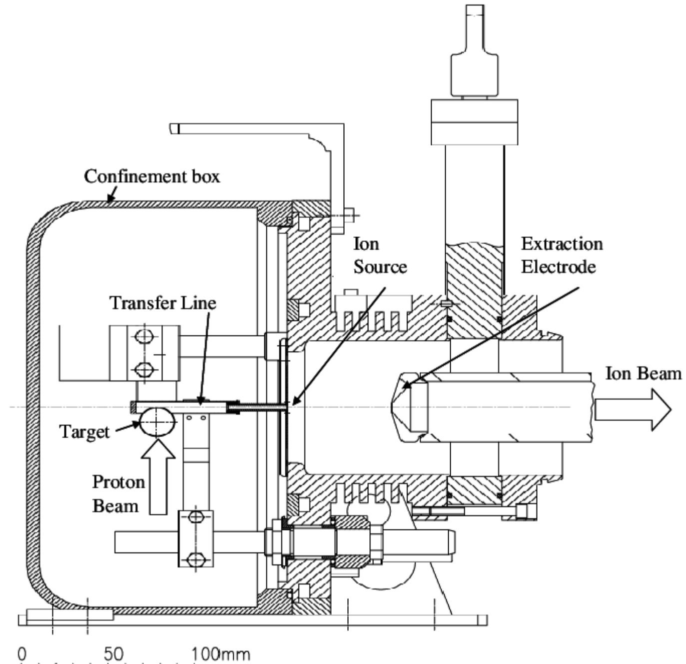
ISOL – method overview



Targets

ISOLDE target





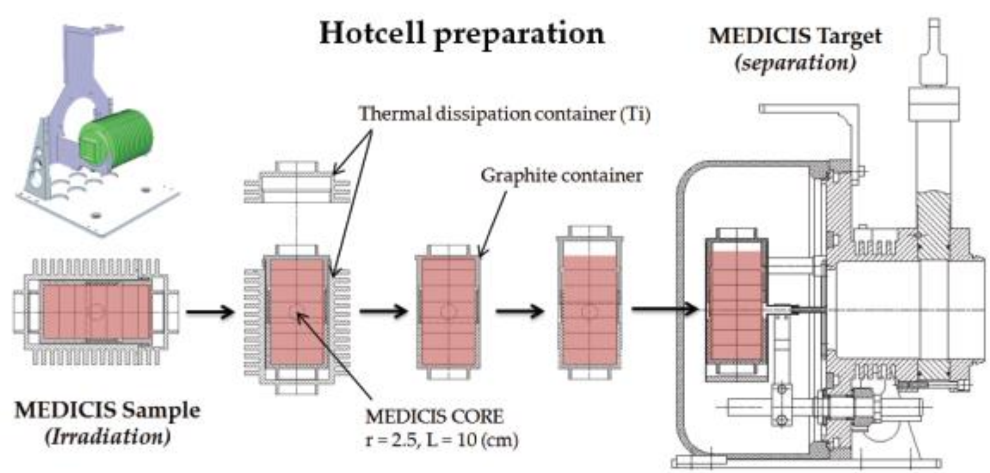
Target types:

- Solid metals
- Oxides
- Carbides
- Molten materials

MEDICIS target

Beam scattered by primary target, so:

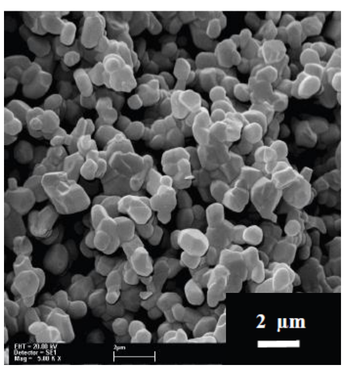
- Volume increase (4x ISOLDE target)
- Density increase



Targets

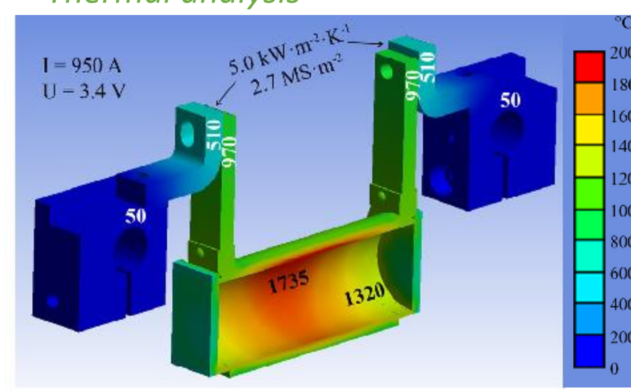
SYSTEM	PROCESS	PARAMETERS
Target	Manufacturing	Target type, composition, density and dimensions
		Particle radius; open porosity
		Melting point; phase diagrams
	Isotope production	Reaction type; cross section
		Particle conversion (p -> n; e ->γ)
	Chemistry	Chemical compatibility; temperature stability
		Molecular sideband
	Calorimetry / heat management	Deposited power; heat transfer; thermal stability
		Thermal conductivity, emissivity; cooling
	Diffusion	Arrhenius parameters; temperature
		Radiation-enhanced diffusion
		Shockwave effects (pulsed beam)
	Ageing	Target sintering; grain growth; radiation damage
		Acumulated dose

Al_2O_3 - SEM



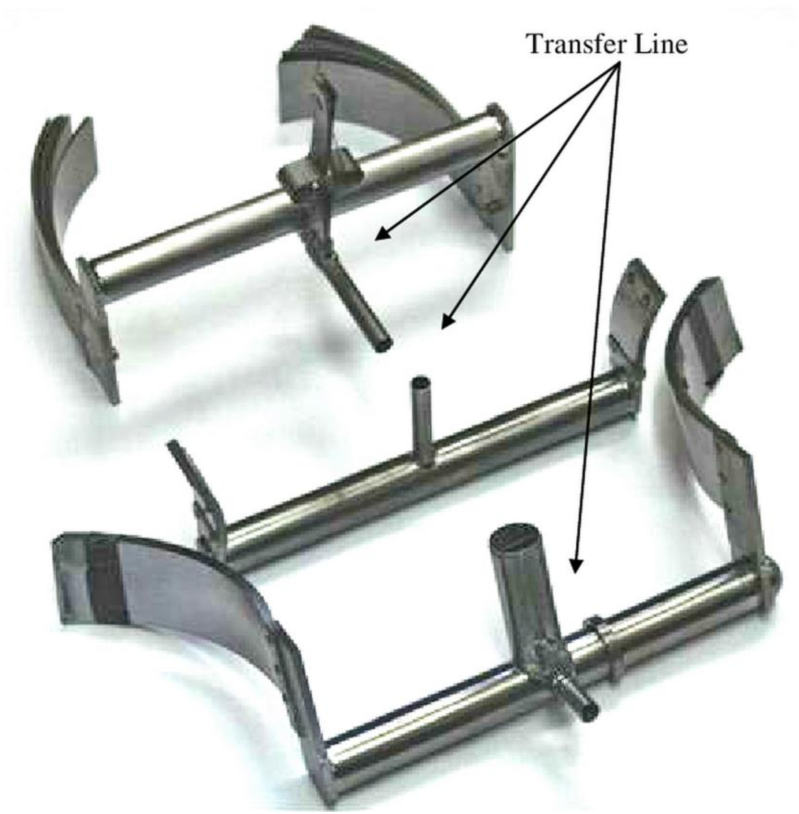
Nanometric CaO powder

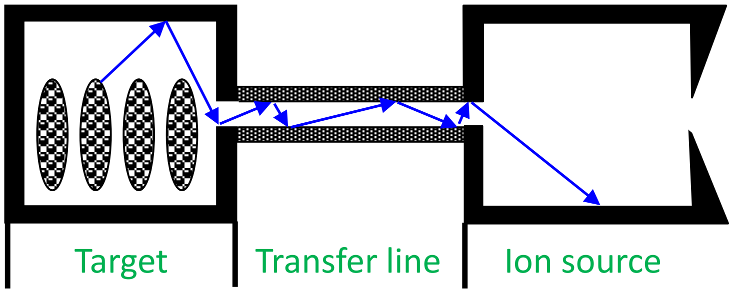
Thermal analysis

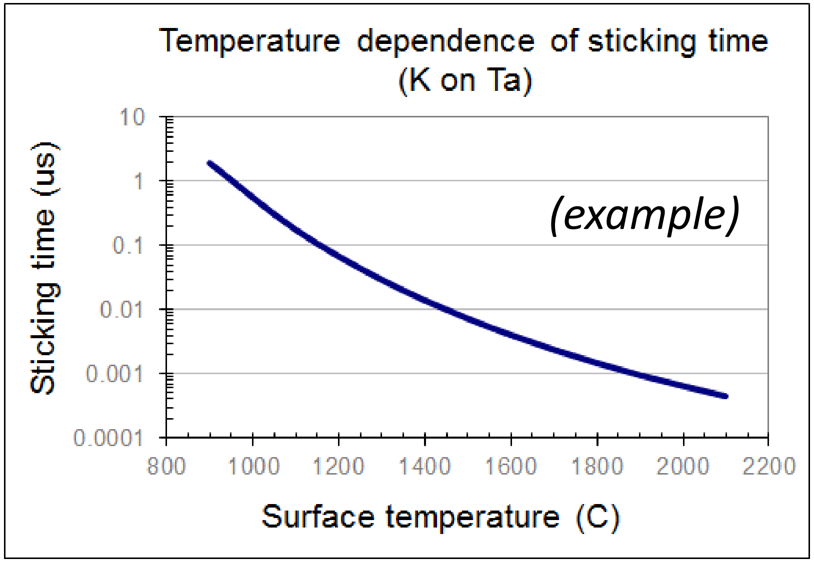


Transfer lines

SYSTEM	PROCESS	PARAMETERS
Transfer line	Effusion	Adsorption enthalpy; sticking time
		Number of wall collissions; flight time







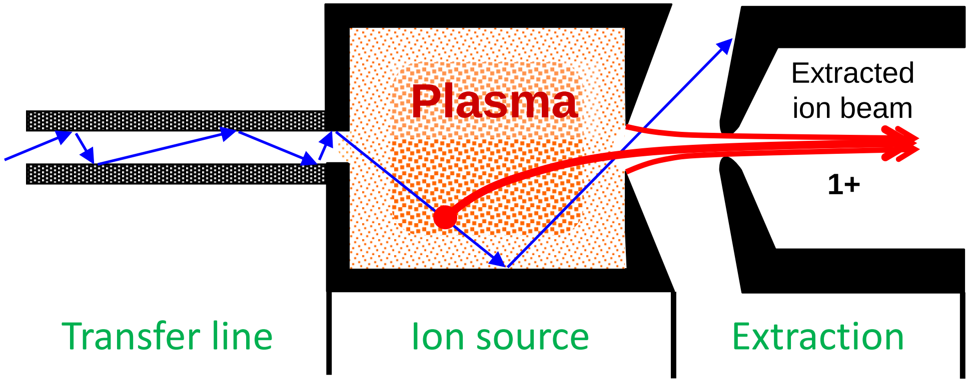
GOALS: fast, selective, (efficient)

Ion sources

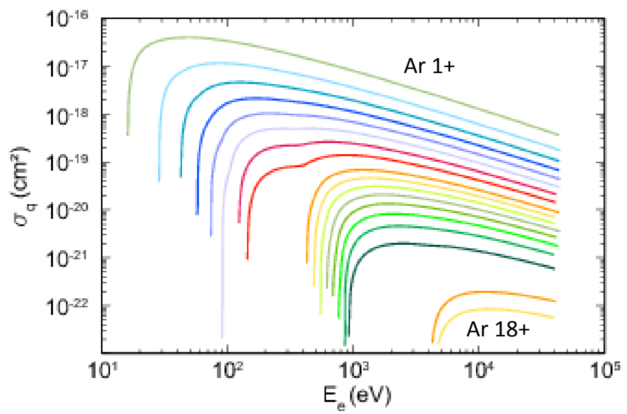
SYSTEM	PROCESS	PARAMETERS
Ion source	Ionization	Ionization mechanism; cross sections; confinement; recombination
	Neutral flow	Gas pumping; material evaporation; support gas
	Extraction	Electrical field; magnetical field; space charge; emittance

Ion source types

1+	1+ → N+
➢ Surface ionization ➢ Laser ionization (e.g. RILIS) ➢ Electron beam impact ionization (e.g. VADIS) ➢ RF heated plasma sources (e.g ECR, Helicon, COMIC)	➢ EBIS (electron beam ion source) ➢ ECR (electron cyclotron resonance)
GOALS: efficient, selective, (fast)	**GOALS**: efficient, (fast)



Example: Argon ionization cross sections (stepwise)

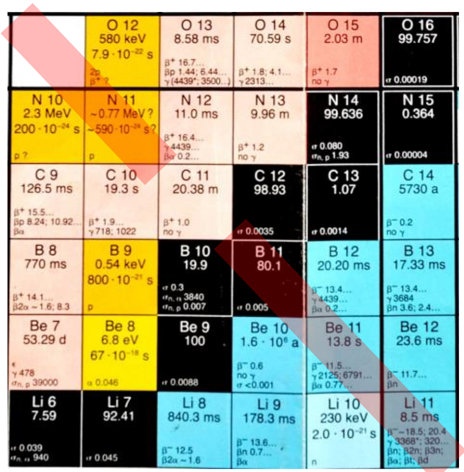


Transport techniques

GOALS:

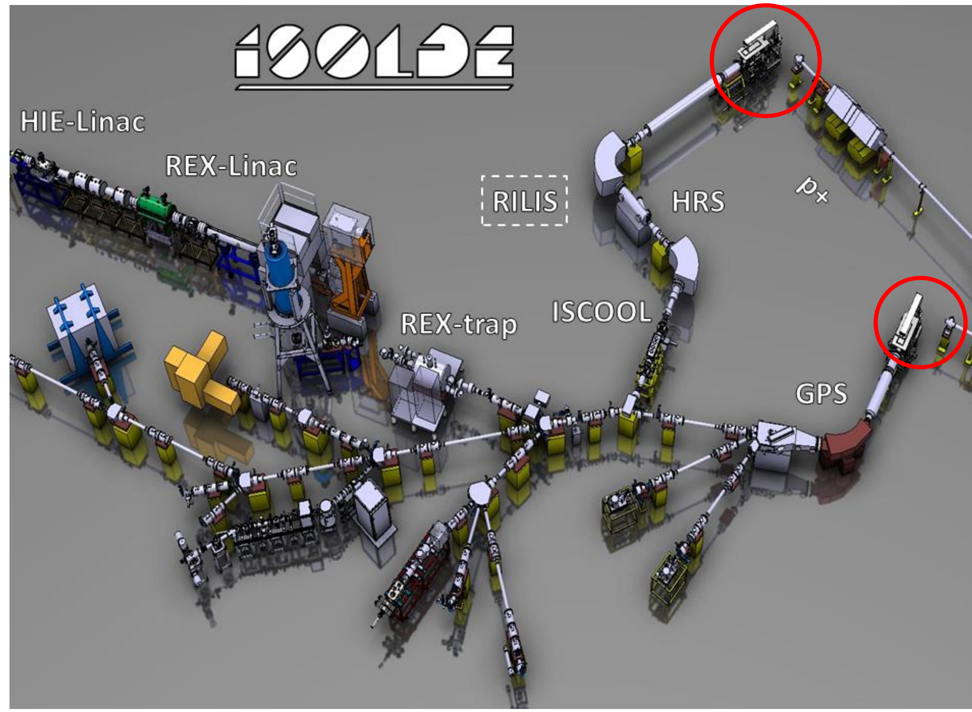
- RIB characterization
- Selectivity
- Accumulation
- Preparation (energy, size)
- Efficiency

Isobaric contamination



Example: ISOLDE facility

Targets



INPUT

1+ ions, low energy (≤60keV)/u)
Isobaric contaminants
Energy and angular spread

Transport techniques

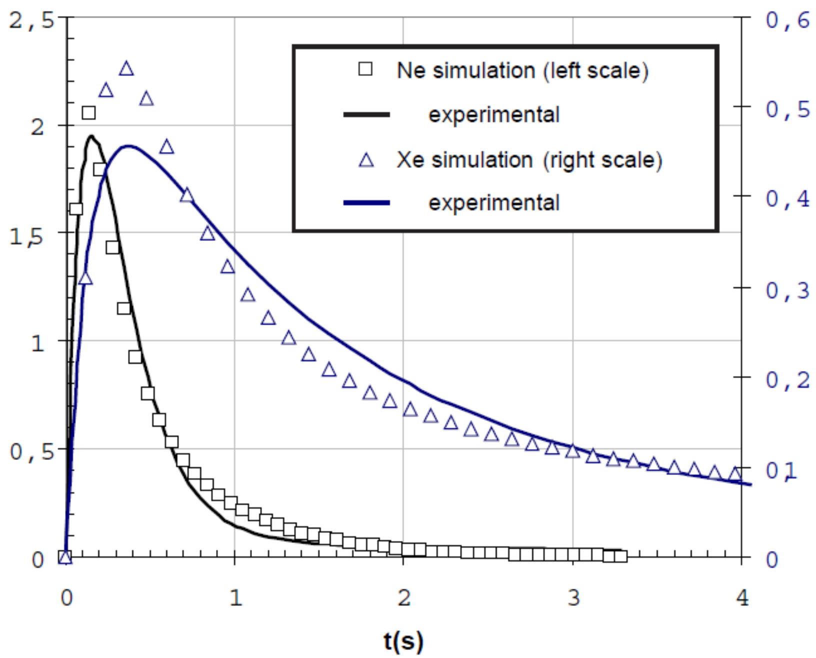
OUTPUT

Yield specification
Purity specification
Delivery specification (time structure, energy, charge state, size)

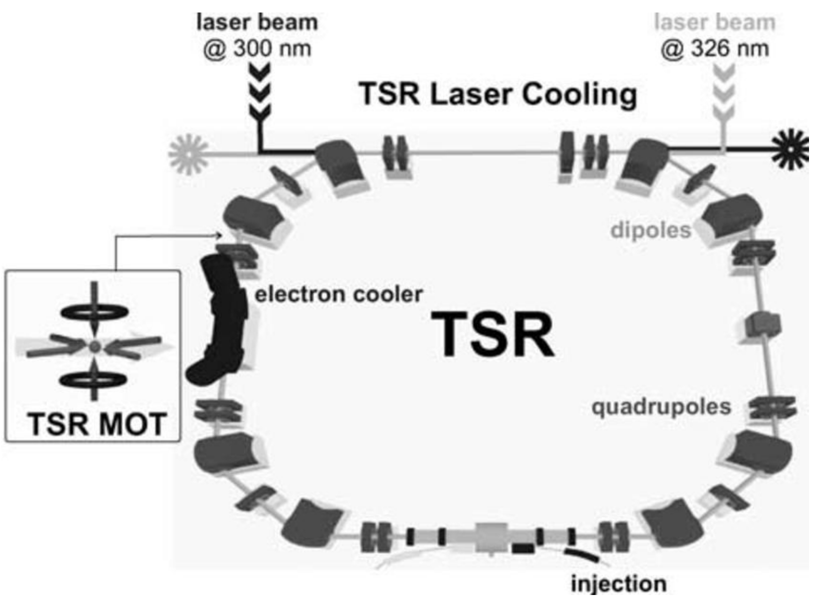
Transport techniques

SYSTEM	PROCESS	PARAMETERS
Transport techniques	High-resolution separator (e.g. HRS)	Mass resolution
	Gating for release curve (slow)	Release curves (comparative)
	Gating for ion source (fast, e.g. RILIS)	Selective ionization; extraction curves
	Selective accumulation (e.g. ISOLTRAP)	Space charge limit; accumulation time; extraction time; efficiency
	Post-acceleration (e.g. REX-ISOLDE)	Energy; efficiency (N+)
	Storage ring (e.g. TSR)	Injection efficiency

Example: comparative release curves



Example: storage ring for accumulation and cooling



ISOL – method overview

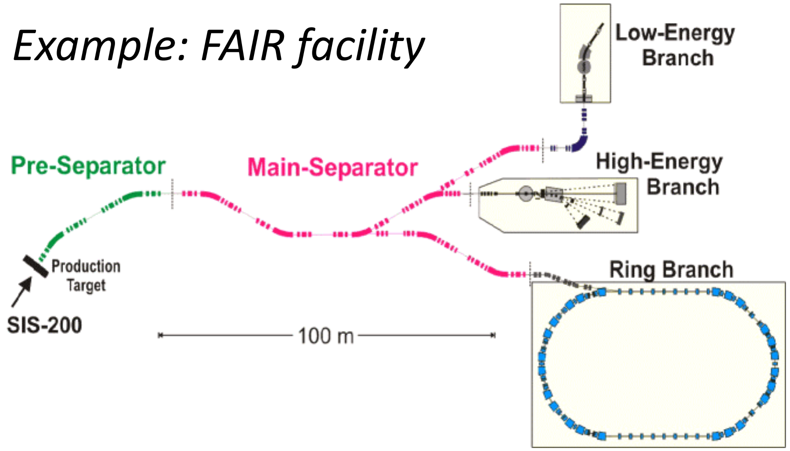
SYSTEM	PROCESS	PARAMETERS
Target	Manufacturing	Target type, composition, density and dimensions
		Particle radius; open porosity
		Melting point; phase diagrams
	Isotope production	Reaction type; cross section
		Particle conversion (p -> n; e ->γ)
	Chemistry	Chemical compatibility; temperature stability
		Molecular sideband
	Calorimetry / heat management	Deposited power; heat transfer; thermal stability
		Thermal conductivity, emissivity; cooling
	Diffusion	Arrhenius parameters; temperature
		Radiation-enhanced diffusion
		Shockwave effects (pulsed beam)
	Ageing	Target sintering; grain growth; radiation damage
		Acumulated dose
Transfer line	Effusion	Adsorption enthalpy; sticking time
		Number of wall collissions; flight time
Ion source	Ionization	Ionization mechanism; cross sections; confinement; recombination
	Neutral flow	Gas pumping; material evaporation; support gas
	Extraction	Electrical field; magnetical field; space charge; emittance
Transport techniques	High-resolution separator (e.g. HRS)	Mass difference
	Gating for release curve (slow)	Release curves (comparative)
	Gating for ion source (fast, e.g. RILIS)	Selective ionization; extraction curves
	Selective accumulation (e.g. ISOLTRAP)	Space charge limit;accumulation time; extraction time
	Post-acceleration (e.g. REX-ISOLDE)	Energy; efficiency (N+)
	Storage ring (e.g. TSR)	Injection efficiency

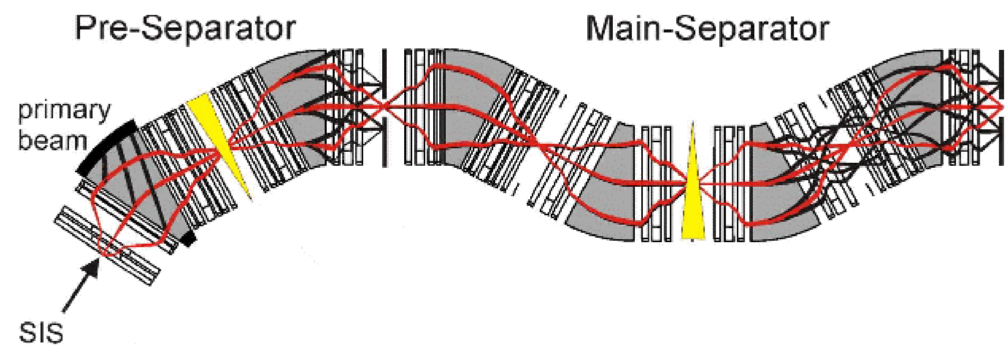
GOALS:
MAXIMIZE isotope intensity
MINIMIZE contamination

USER

In-Flight method overview

Example: FAIR facility



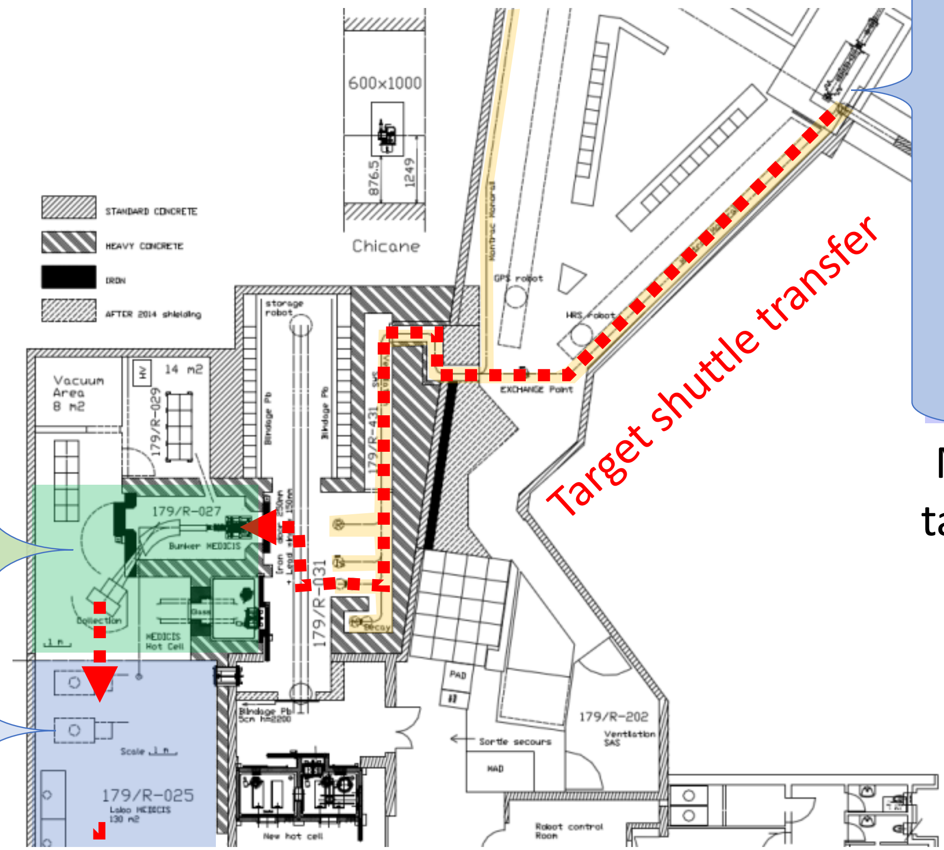


SYSTEM	PROCESS	PARAMETERS
Beam	Production	Element, energy, intensity
	Delivery	Size, shape, time structure
Target	Manufacturing	Target type, composition, density and dimensions
		Melting point; phase diagrams
	Isotope production	Reaction type; cross section
		Particle conversion (p -> n)
	Calorimetry / heat management	Deposited power; heat transfer; thermal stability
		Thermal conductivity, emissivity; cooling
		Rotation/circulation speed
	Ageing	Acumulated dose
Transport techniques	High-resolution separator (including dipoles, degraders and Wien filters)	Mass and energy resolution
	Ion catcher (=compact TIS unit)	Parameters of diffusion + effusion + ionization + extraction
	Beam cooling	Space charge limit; cooling time; bunch width; transmission
	Selective accumulation	Space charge limit; accumulation time; extraction time; efficiency
	Post-acceleration	Energy; efficiency (N+)
	Storage ring	Injection efficiency

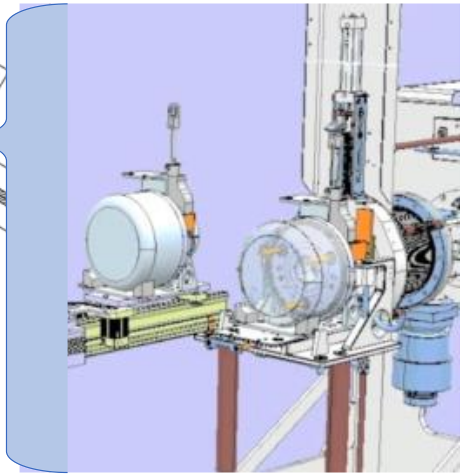
MEDICIS – method overview

MASS SEPARATOR
- Isobaric selection
- Products implanted on: metallic foils, polymeric supports with salt layers, or ice samples.

CHEMICAL LAB
- Chemical purification (cation-exchange chromatography)



Single-isotope batches sent to hospitals



MEDICIS target unit

Production of medical isotopes

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SYSTEM	PROCESS	PARAMETERS
Beam	Choice of driver	Large accelerator (e.g. ISOLDE MEDICIS), cyclotron*, nuclear reactor
	Production	Particle, energy, intensity
	Delivery	Size, shape, time structure
Target	Manufacturing	Target type, composition, density and dimensions
		Grain size; open porosity
		Melting point; phase diagrams
	Isotope production	Reaction type; cross section
		Particle conversion rate (p -> n; e ->γ)
	Chemistry	Chemical compatibility; temperature stability
		Molecular sideband
	Calorimetry / heat management	Deposited power; heat transfer; thermal stability
		Thermal conductivity, emissivity; cooling
	Diffusion	Arrhenius parameters; temperature
		Radiation-enhanced diffusion
		Shockwave effects (pulsed beam)
	Ageing	Target sintering; grain growth; radiation damage
		Acumulated dose
Transfer line	Effusion	Adsorption enthalpy; sticking time
		Number of wall collissions; flight time
Ion source	Ionization	Ionization mechanism; cross sections; confinement; recombination
	Neutral flow	Gas pumping; material evaporation; support gas
	Extraction	Electrical field; magnetical field; space charge; emittance
Transport techniques	Mass separation	Mass resolution
	Sample implantation/irradiation	Sample type; amount of contaminants; implantation time
	Chemical purification	Resin type, eluent type
	Radiopharmaceutical synthesis	Bioconjugate type, chelator type

If driver=cyclotron jump directly here

Production of a RIB

PROCEDURES

Preparation of:

- ❑ Components
- ❑ Systems

Verifications:

- ❑ Parameters
- ❑ Full performance

DEVELOPMENT of a new RIB

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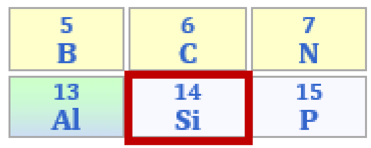
Development CATEGORIES



1) ISOTOPE already produced
2) ELEMENT already produced
3) ELEMENT not produced

LIMITATION analysis

a) Higher INTENSITY required?
b) FASTER production required?
c) Higher PURITY required?
d) Higher RELIABILITY required?
e) Apply technology from OTHER FACILITY?
f) NEW TECHNOLOGY required?

Choice of BASELINE

QA of existing knowledge

Isotope	Half life	Yield (at/µC)	Target	Driver
C 9	126.5 ms	2.0E+03	CaO	PSB
C 9	126.5 ms	4.0E+02	CaO	PSB

(example)

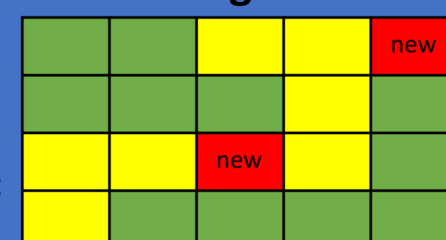
- Stability?
- Reproducibility?
- Knowledge of all parameters?
- Modeling status?

CONSOLIDATION activities

IMPLEMENTATION and TESTS

- Validation of PHENOMENA and PARAMETERS
- Model BENCHMARKING for used range
- Refine the ENGINEERING solutions
- Manufacturing and control PROCESSES
- Dedicated tests of EXISTING SYSTEMS
- Tests of NEW COMPONENTS (separated)
- INTEGRATION tests
- Tests of COMPLETE LAYOUT (integrated): offline characterization, RIB production

"Knowledge matrix"



Discussion

You are the experts!

- Discussion on specific examples
- Missing parameters?
- Observed limitations
- Side results and possible applications
- Follow-up interests