BigRIPS Separator at RIKEN

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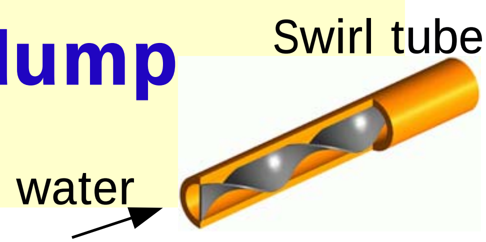
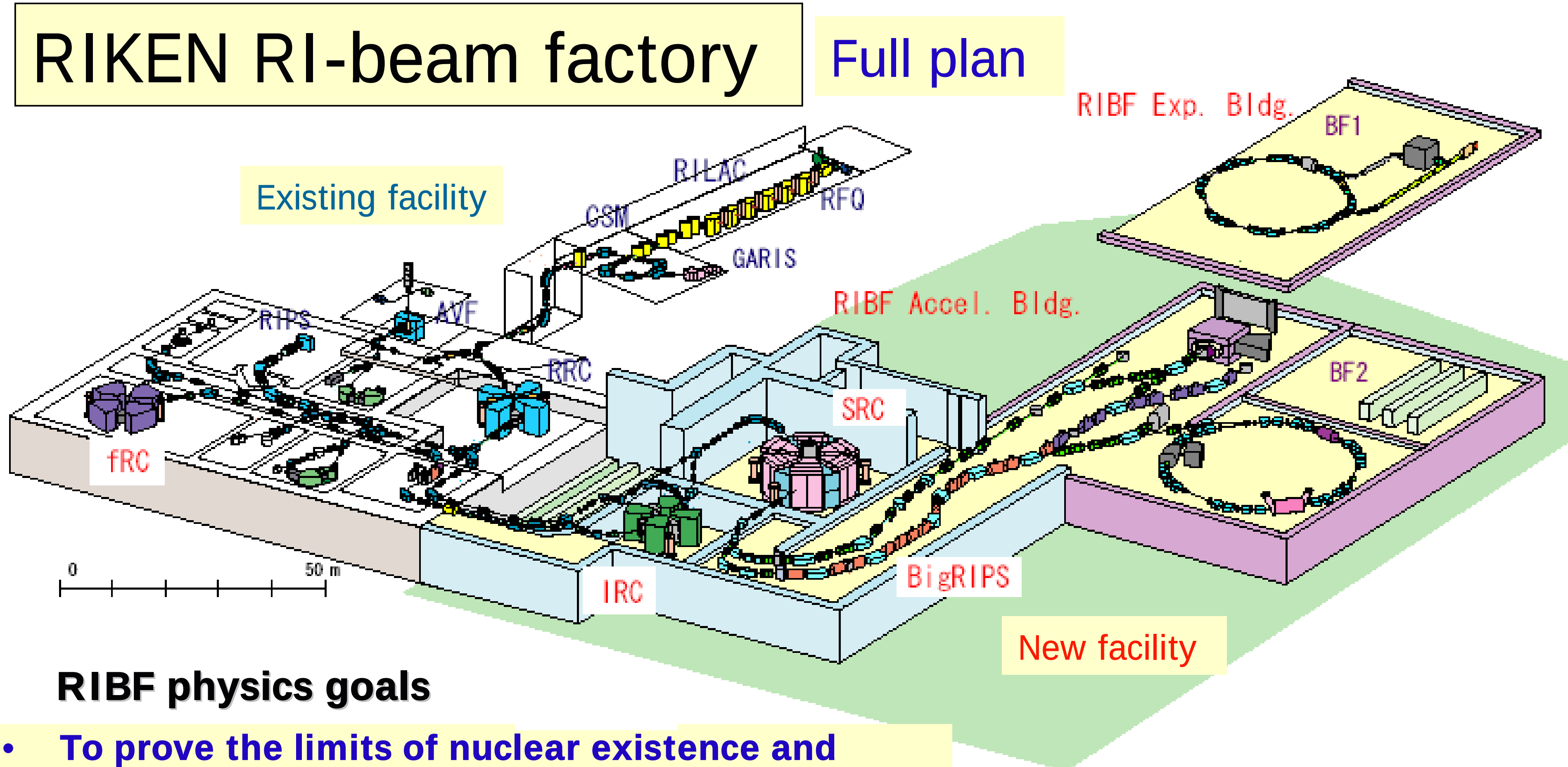
- Currently being built for the production of radioactive/rare isotope beams at RIKEN RI-beam factory (RIBF).
- BigRIPS: In-flight RI-beam separator.

1. **Outline of RIKEN RI-beam factory project**
   (being built, first beam acceleration in 2006)
2. **Outline of BigRIPS separator**
   (being built, first RI-beam production in 2006)

   High beam power
   ~100 kW max.
3. **High-power water-cooled rotating target**
   (being developed)
4. **High-power water-cooled beam dump using swirl tubes** (being designed)



RIKEN RI-beam factory

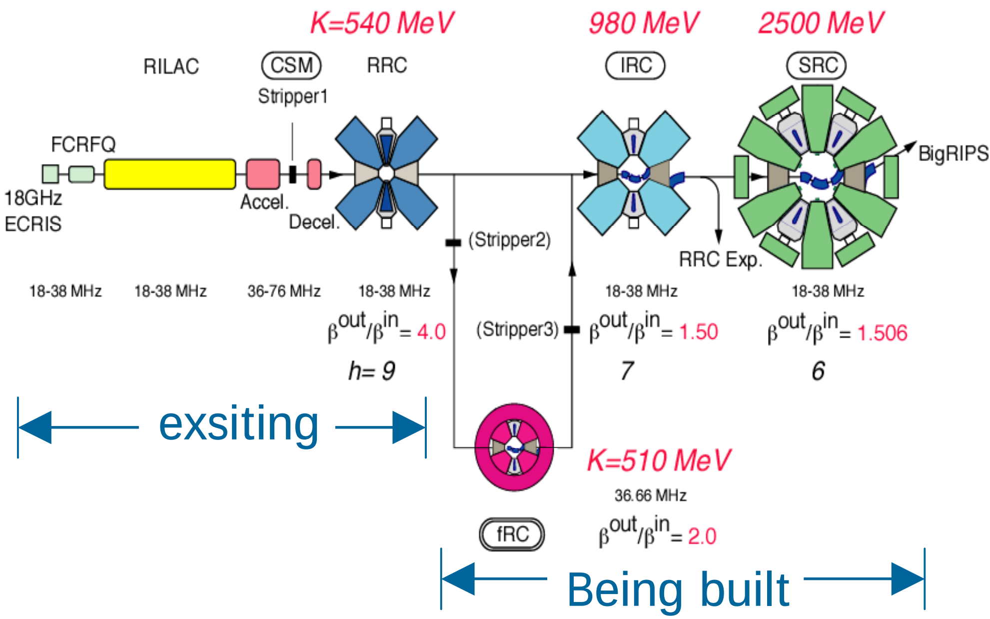


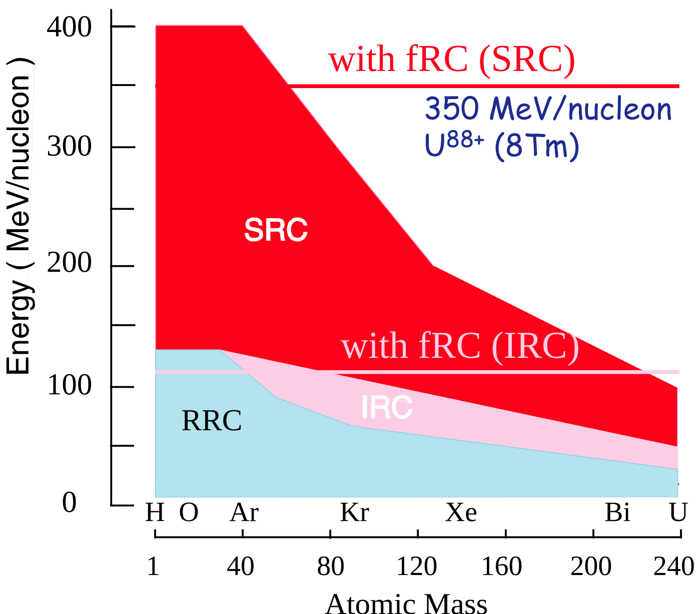
RIBF physics goals

- **To prove the limits of nuclear existence and to understand the basic physics of the nuclear landscape**
  - Exploration of the limit of existence
  - Magic numbers far from stability
- **To explore the new forms and dynamics of nuclei**
  - Neutron skin and halo
  - Exotic shapes
- **To provide the basic data of nuclear astrophysics**
  - Stellar evolution and the rp-process
  - The r-process
  - Equation of state of asymmetric matter and neutron stars

Outline of RIKEN RI-Beam Factory (RIBF)

- Three new cyclotrons (fRC, IRC and SRC) are being built as an extension of the existing cyclotron facility.
- SRC: a superconducting cyclotron with K = 2500 MeV. 7800 tons.
- Cascade of the cyclotrons accelerates heavy ions up to 400 MeV/u for light A (< 40), 350 MeV/u for heavy A up to ^{238}U.
- Expected max. beam intensity: ~1 pμA (6 X10^{12} pps).
- Max. beam power: ~100 kW (^{238}U 350 MeV/u ~1 pμA: goal)
- BigRIPS: production, separation and tagging of RI beams.
- RI-beam delivery lines and several experimental setups downstream of BigRIPS

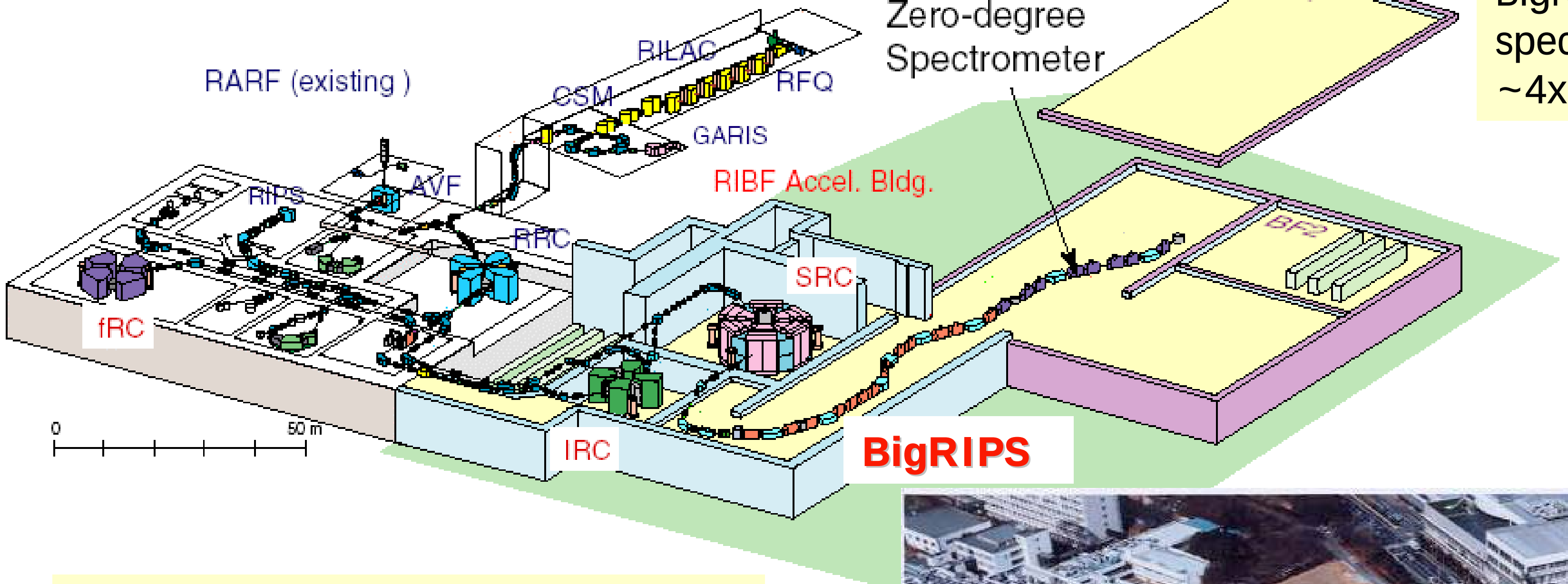




RIBF layout in 2006

~40x10⁹ yen
~3.3X10⁸ USD

BigRIPS+0-deg spectrometer: ~4x10⁹ yen



First beam acceleration & first RI-beam production: scheduled in 2006

Building construction →

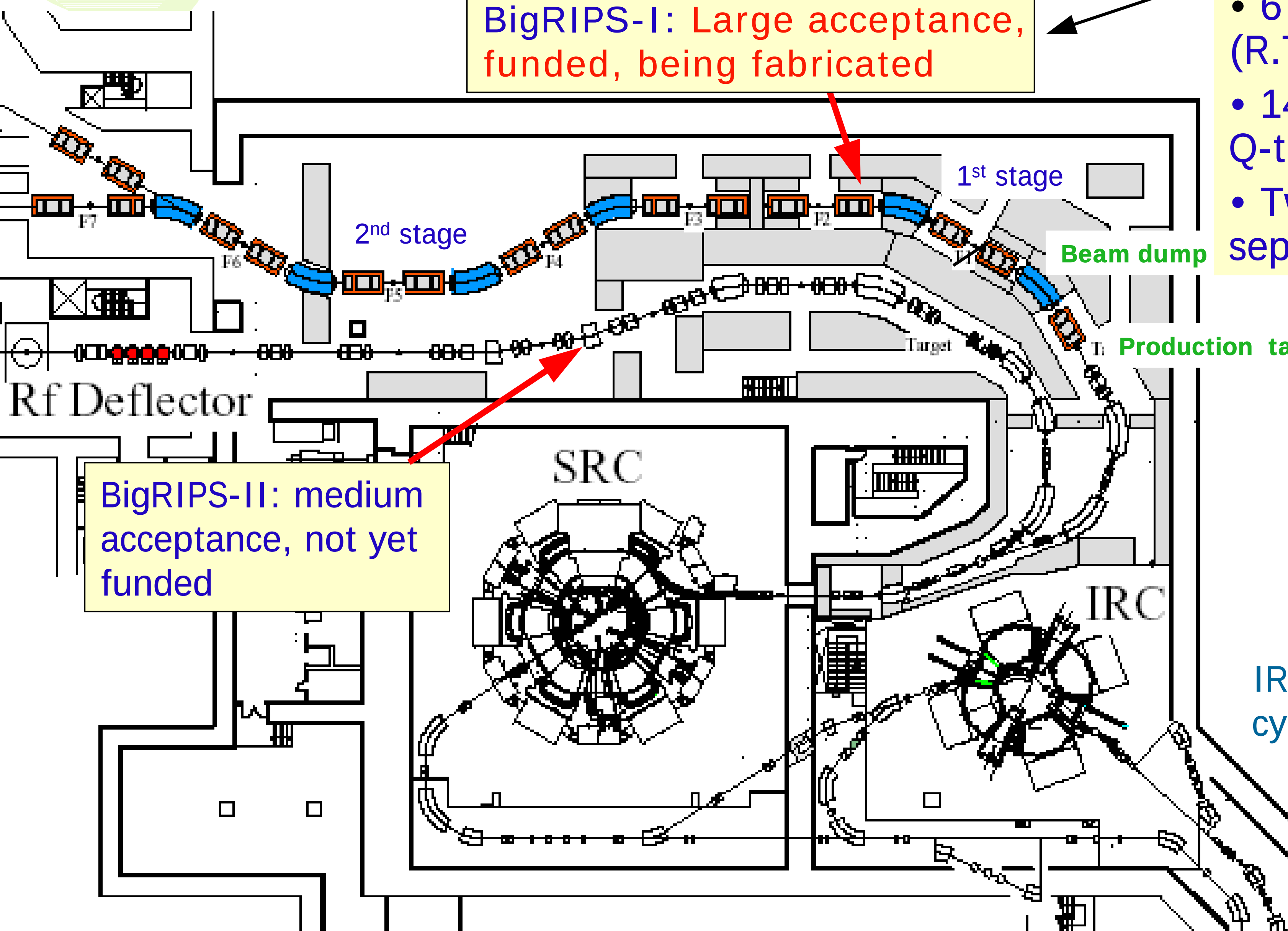
Feb. 2003

Layout of BigRIPS separator

Superconducting quadrupole triplets with large apertures

- 6 dipoles (R.T.)
- 14 super Q-triplets
- Two-stage separator

BigRIPS-I: Large acceptance, funded, being fabricated



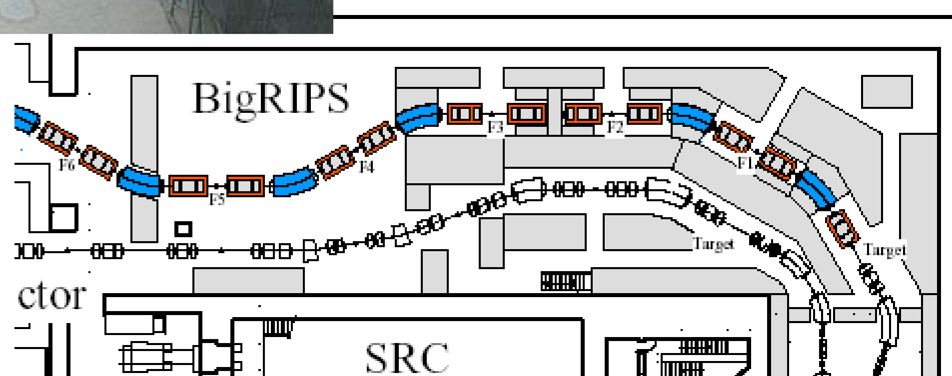
BigRIPS-II: medium acceptance, not yet funded

IRC, SRC: cyclotrons

The Building for BigRIPS

Feb. 27th, 2002

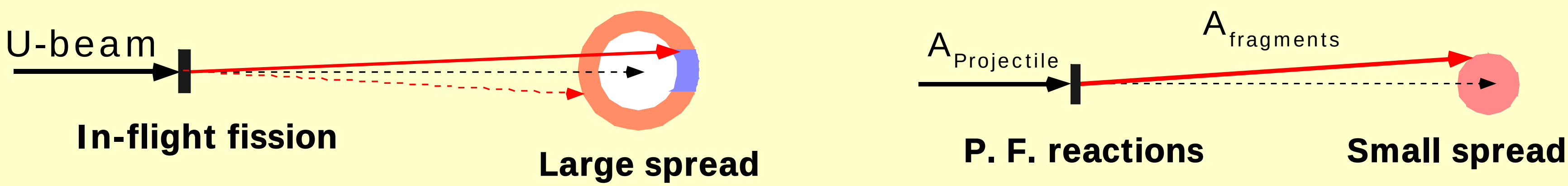
The photo taken from this direction



Features of the BigRIPS separator

BigRIPS-I

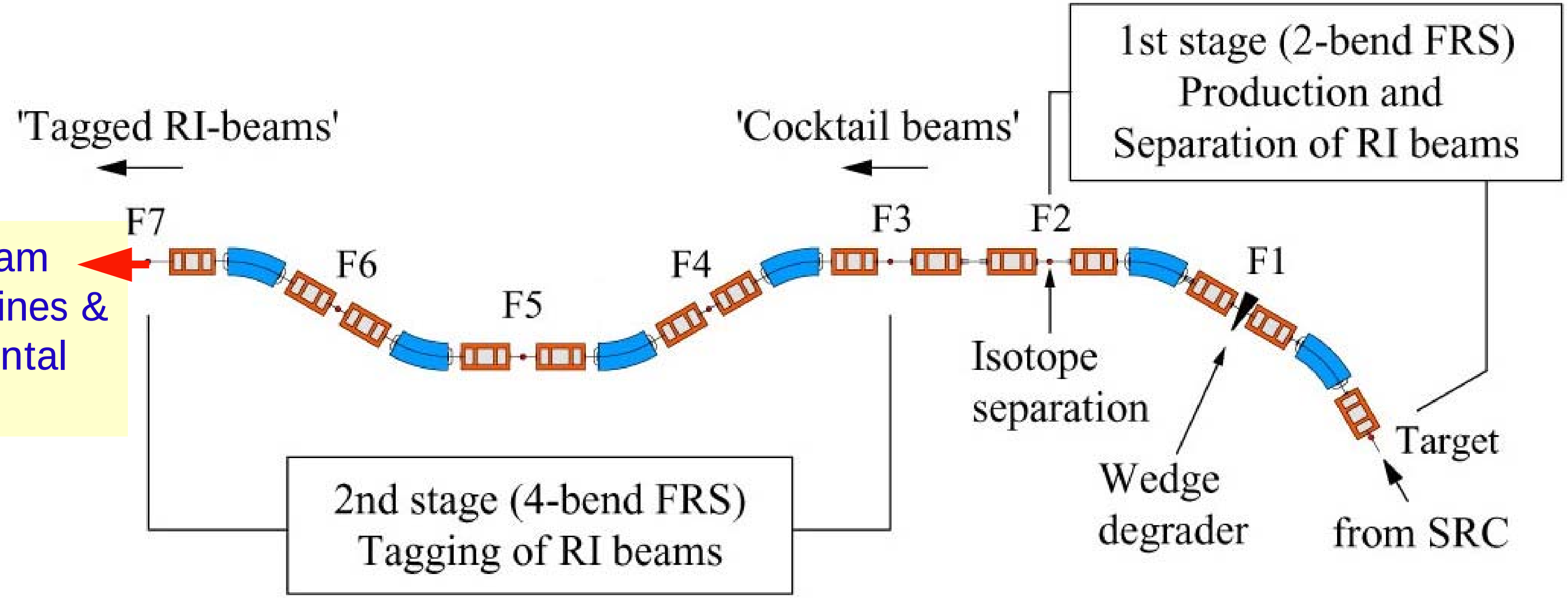
- In-flight fission of ^{238}U beams is used, as well as projectile fragmentation.
  -> Large cross section for medium heavy neutron-rich isotopes.
- Large acceptance: 80 – 100 mr, 6 %,
  allowing efficient collection of fission fragments which have
  large spreads at our energy, e.g. ~100 mr, ~10 % at 350 MeV/u.



- The large acceptance is achieved by using
  superconducting quadrupoles with a large aperture.
- RI-beam purity is still not so good at our energies:
  sometimes called 'Cocktail beams'.
- Two-stage separator scheme is adopted to overcome this difficulty:
  allows to deliver Tagged RI beams, and
  facilitates RI-beam experiments such as secondary reaction studies.
- Followed by RI-beam delivery lines and experimental setups.

Delivery of tagged RI beams

BigRIPS: Two-stage (or tandem) separator



To RI-beam delivery lines & experimental setups

TOF, Bρ, ΔE → Z, A/Q (A, Q), P

Identify RI-beam species in an event-by-event mode

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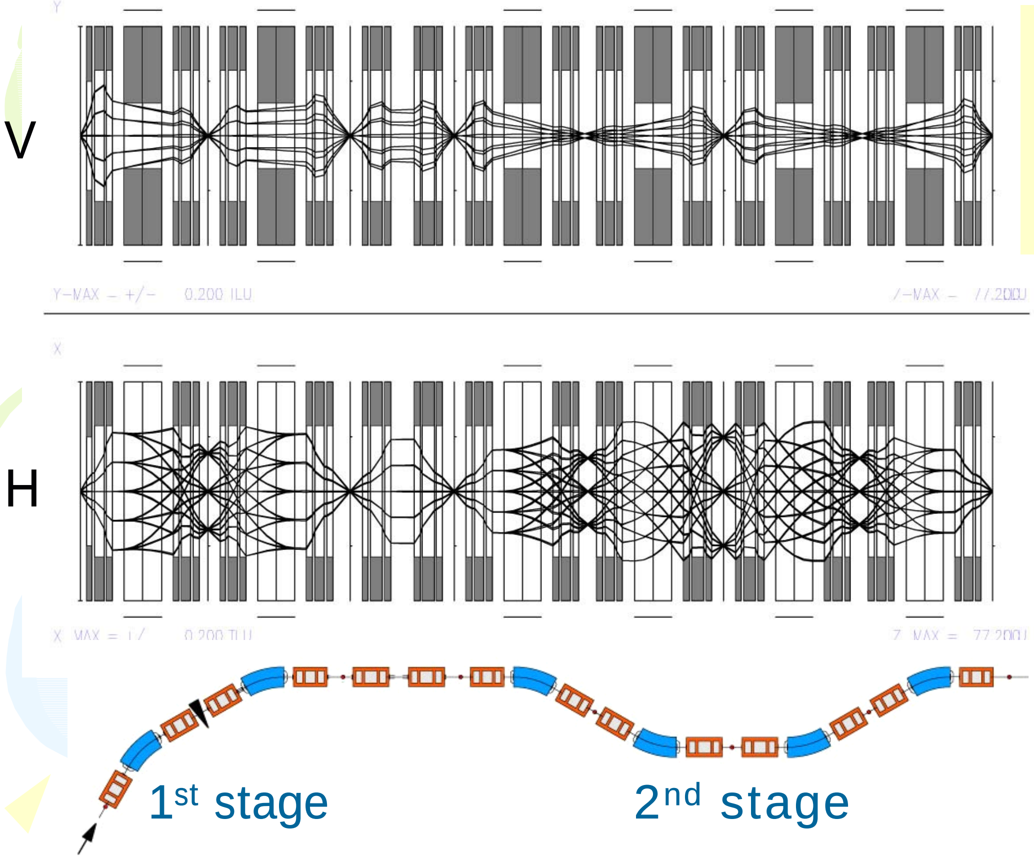
First-order ion optics of BigRIPS-I (large acceptance)



~100 mr
~ 10 %

In-flight fission of ^{238}U beams at 350 MeV/u

BigRIPS specifications

	BigRIPS-I
Configuration	Tandem se
First stage	Two bends
Second stage	Four bends
Energy degrader	Achromati
Quadrupoles	Superconducting F
Angular acceptance[mr]	
Horizontal	80
Vertical	100
Momentum acceptance[%]	6
Maximum magnetic rigidity[Tm]	9
Total length[m]	77
Momentum dispersion* [cm/%]	
First stage	−2.31
Second stage	3.3
Momentum resolution**	
First stage	1290
Second stage	3300

* At the mid focus of the stage.

** First-order momentum resolution at the mid focus for which object size is assumed to be 1 mm.

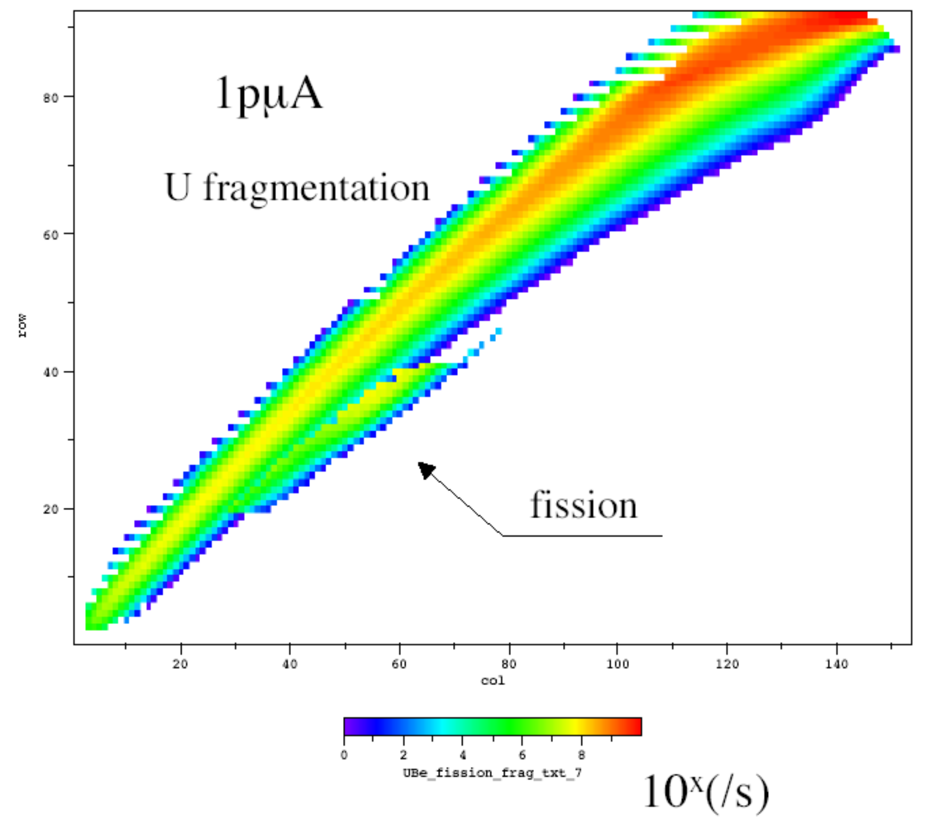
Expected RI-beam intensity

^{78}Ni	~10 pps	(^{238}U)
^{132}Sn	~10^7 pps	(^{238}U)
^{100}Sn	~1 pps	(^{124}Xe)

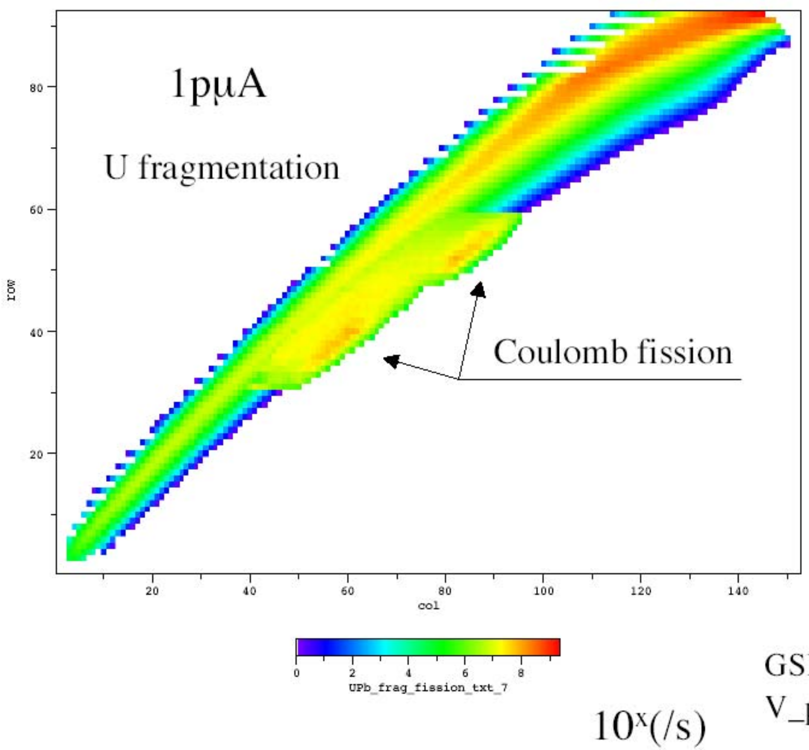
I(primary beam) = 1 pμA.

Estimated based on the GSI data and the EPAX formula

RI bema intensity(^{238}U+^{9}Be)

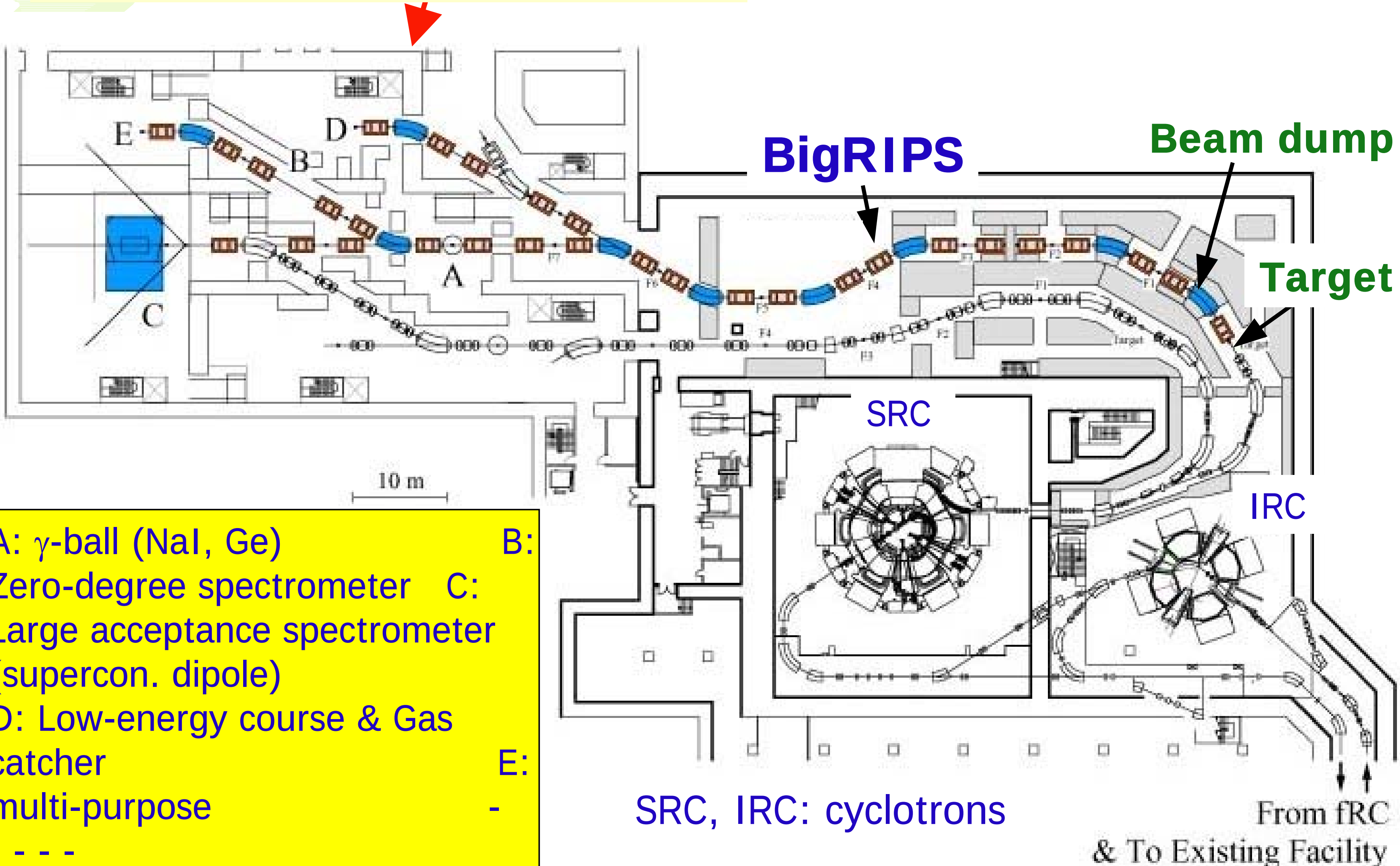


RI bema intensity(^{238}U+^{208}Pb)



GSI xsection
V_photon 補正無し

RI-beam delivery lines & experimental devices

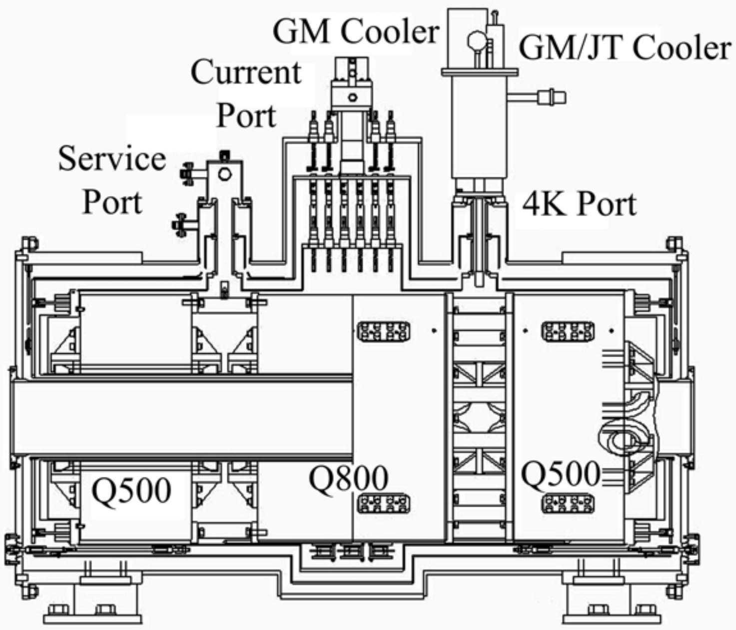


A: γ-ball (NaI, Ge) B: Zero-degree spectrometer C: Large acceptance spectrometer (supercon. dipole)
D: Low-energy course & Gas catcher E: multi-purpose - - - - -

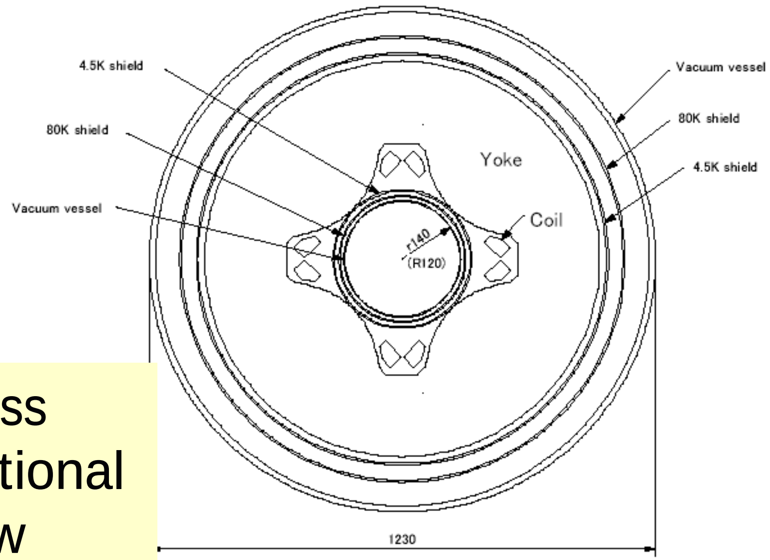
SRC, IRC: cyclotrons

Superconducting quadrupole for BigRIPS, features

- Quadrupole triplet:
  three quadrupoles are installed in a single cryostat.
- Large aperture:
  warm bore radius of 120 mm, -> large acceptance
- Iron-dominated type: STQ2-14, partly air-core type: STQ1
- Thin NbTi wire: 1.1 mmϕ
- Impregnated coils with epoxy
- Epoxy with a filler
- Wet and orderly winding
- Flat coil, a racetrack shape
- A prototype: successfully tested



Iron-dominated superconducting quadrupole



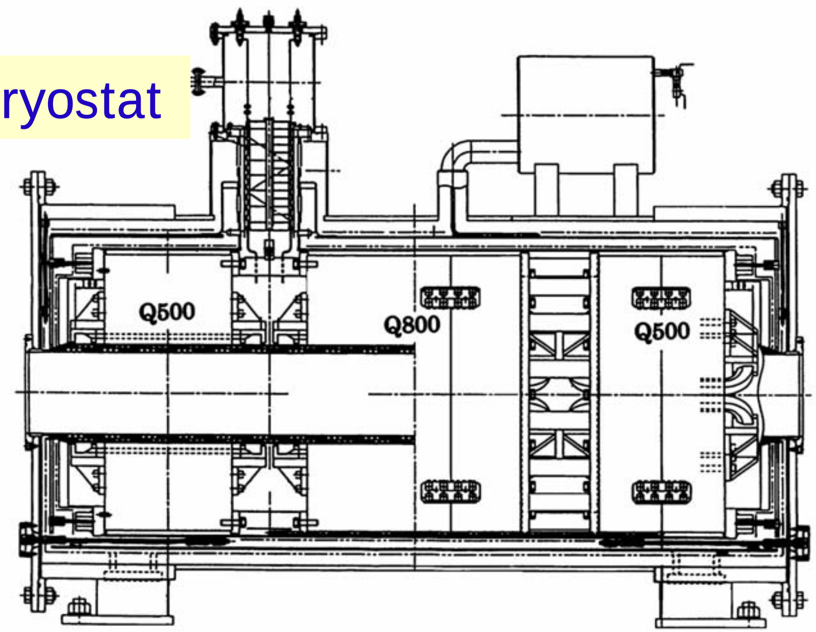
Cross-sectional view of prototype quadrupole magnet

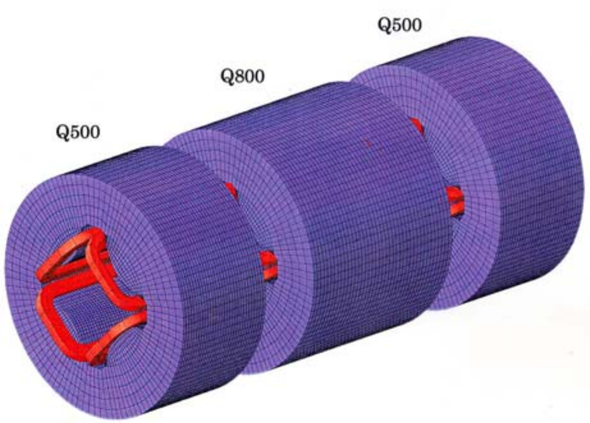
Cross sectional view

One quadrupole

Super-conducting coils

Cryostat



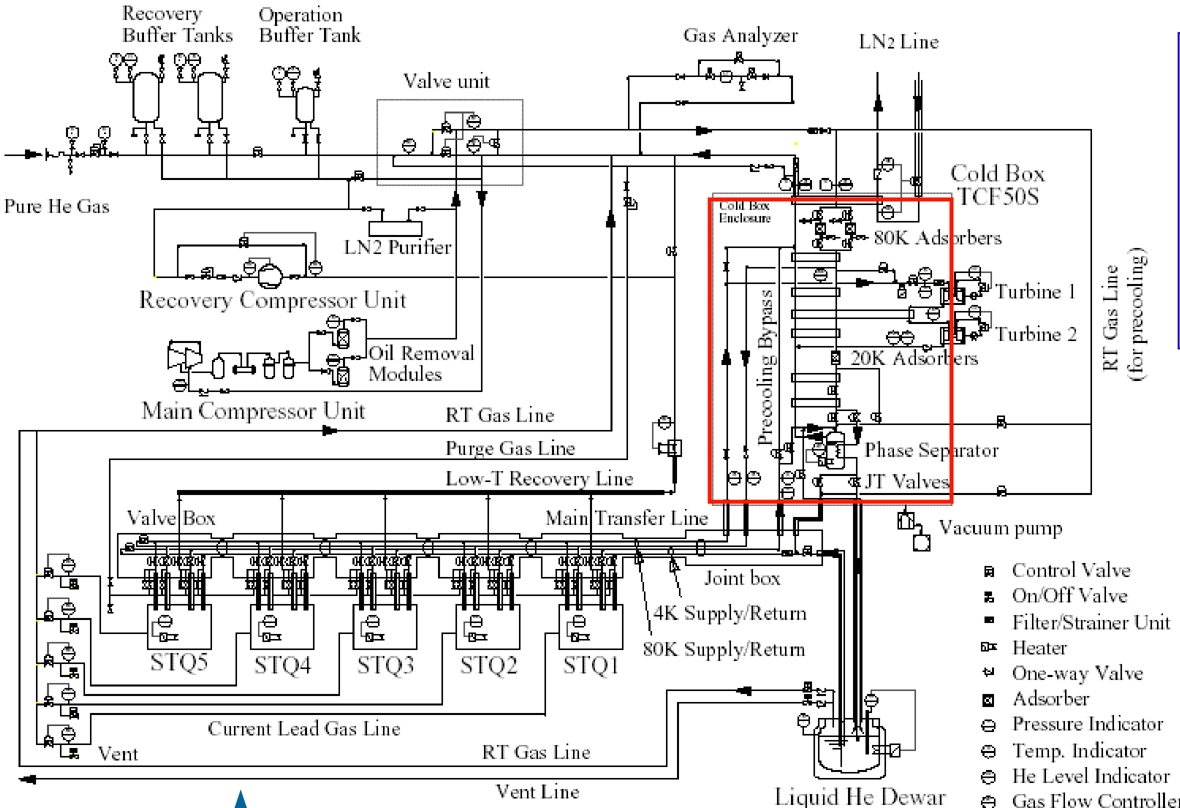


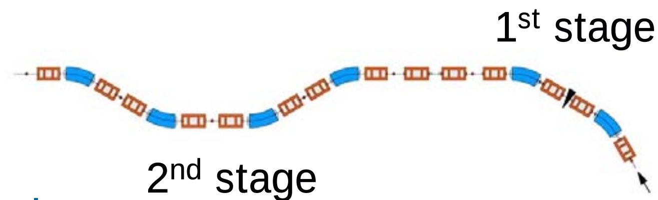
Schematic view of the prototype quadrupole triplet

Q triplet

Based on MSU design

Cryogenic system for BigRIPS quadrupole triplets (two kinds of scheme)





First stage (STQ1-5): Integrated cryogenic system

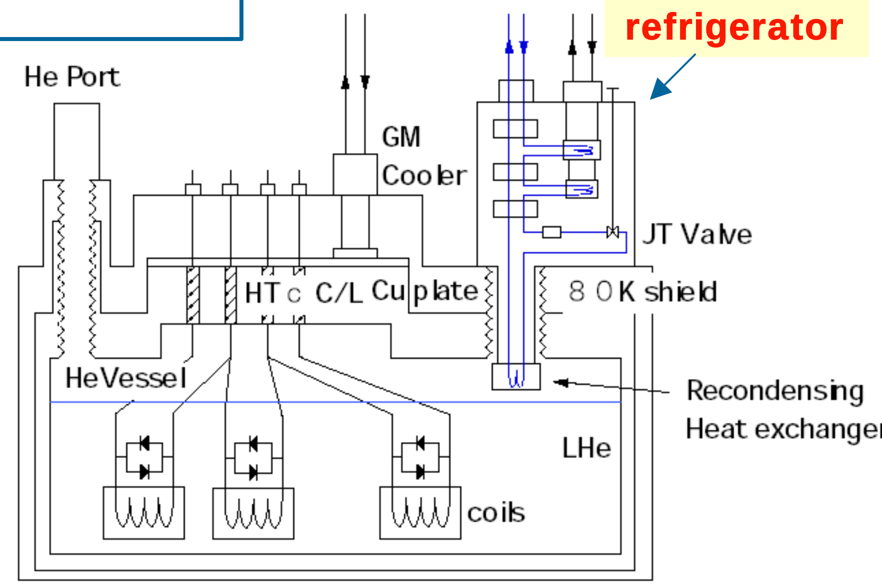
320 W at 4.5 K
420 W (with liquid N_2)

For large radiation heat loads

Second stage: Small GM-JT refrigerator (STQ6-14)

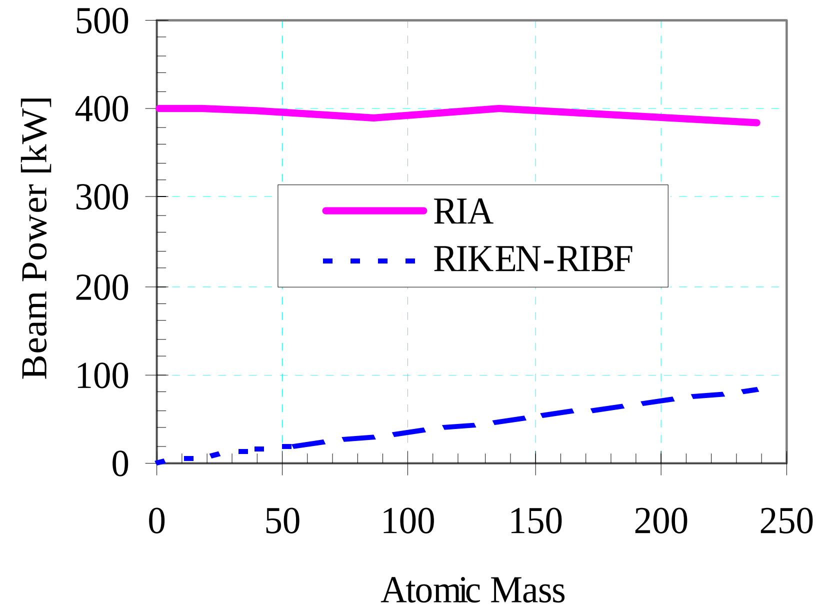
2.5 W at 4.3 K (for each STQ)

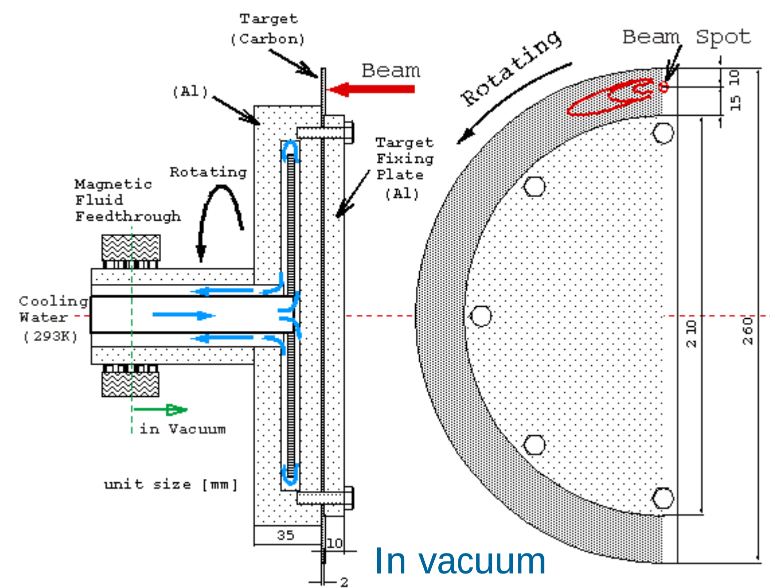
GM-JT refrigerator



High-power water-cooled rotating-disk target

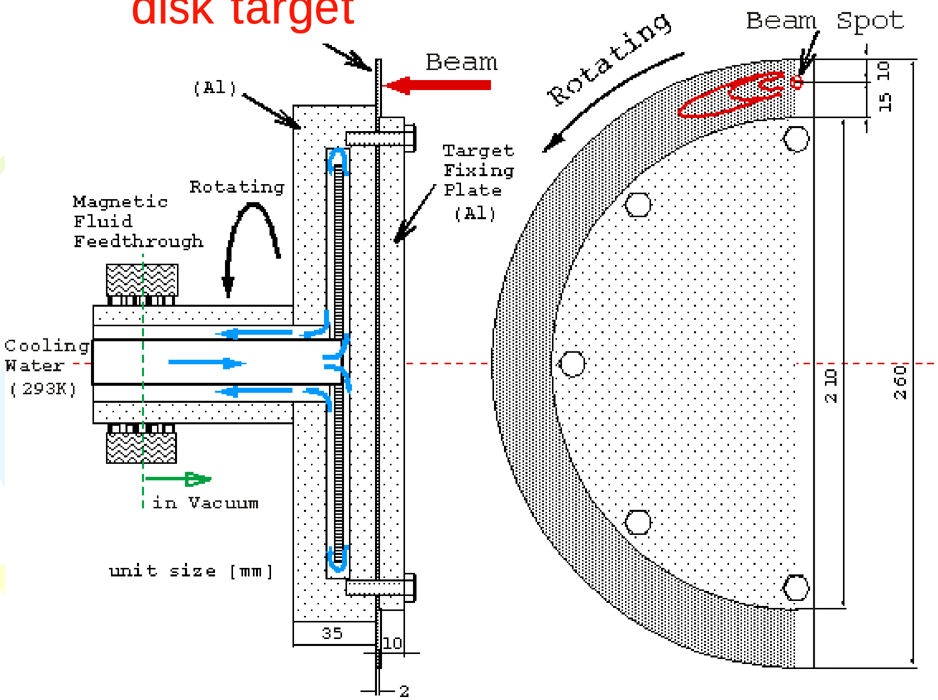
1. Max. beam power: ~100 kW (goal)
   ^{238}U 350 MeV/u ~1 pμA
2. Target material: C, Be, Ta
3. Max. energy loss in target: ~25 kW
   In-flight fission of ^{238}U at 350 MeV/u
   Thickness: ~1 g/cm^2 (C 5.6 mm)
   Beam spot size: 1 mmϕ
   -> Max. power density: ~30 GW/m^2, ~5.7 kW/mm^3
4. A wide range of thickness up to ~30 mm for projectile fragmentation.
5. Water-cooled rotating disk target:
   Disk size ~260 mmϕ or smaller
   Rotation speed: > 200 rpm
   Water cooled (& partially radiation)
   <- supplied through a rotation shaft





Prototype of the rotating C target

Carbon disk target



Testing with ^{40}Ar beam

E= 24 MeV/u, I=1.9 pμA

Beam spot : **< ϕ 3mm**

Target: Carbon disk, 2 mm thick

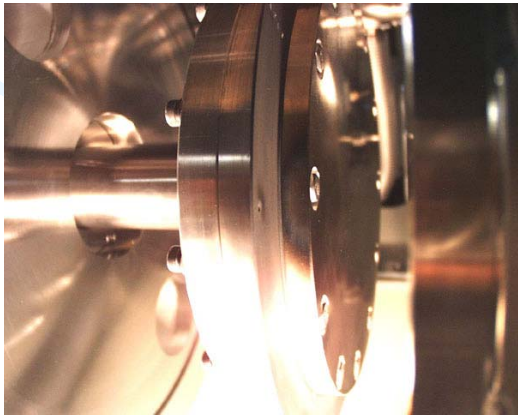
^{40}Ar beam range: 430 μm

Energy loss : **full stop 1.8 kW**

Measured beam-spot Temp.

Cooled by water flow

Rotate in vacuum



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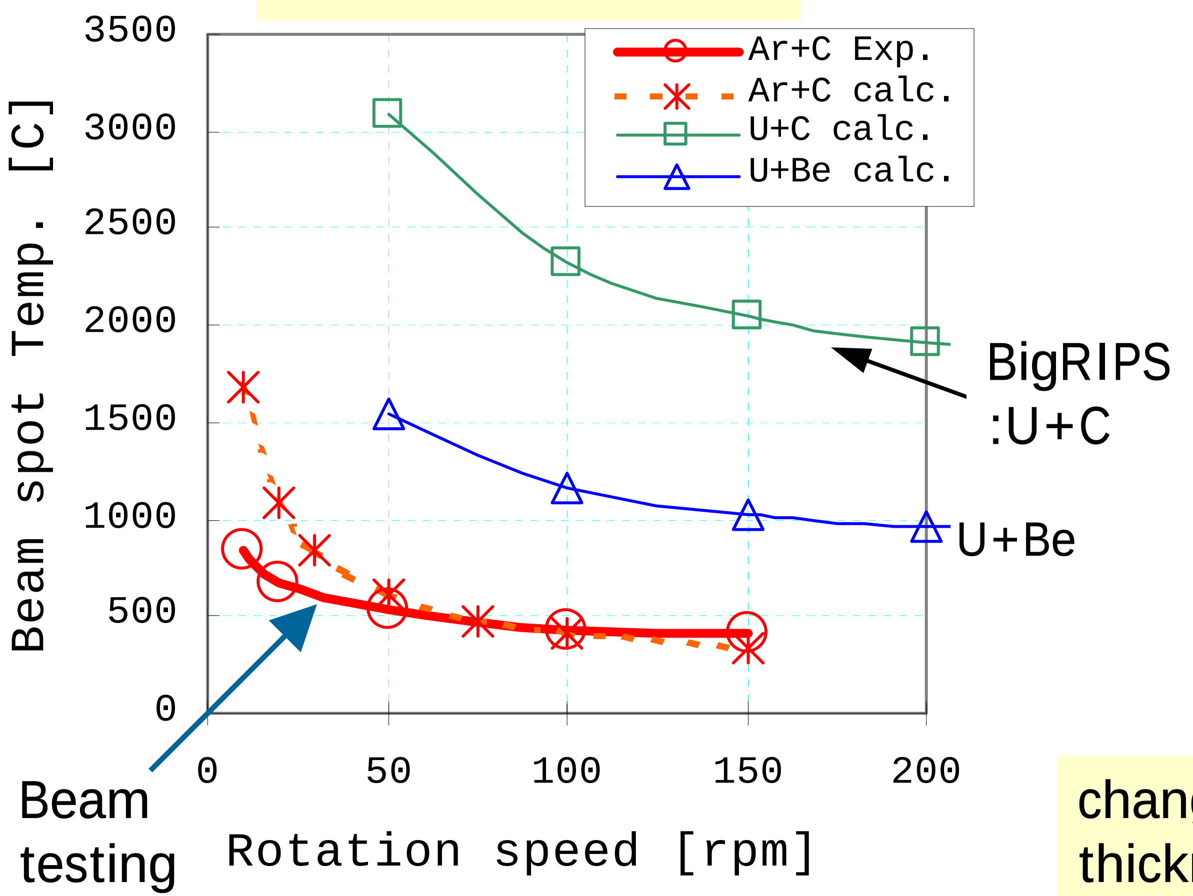
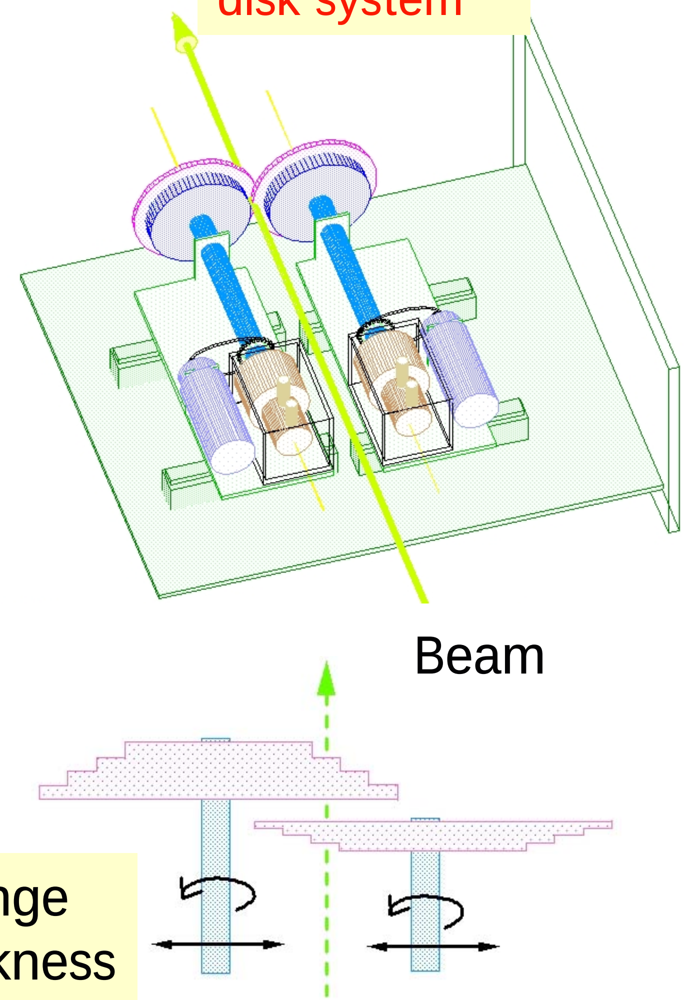
Simulation for the U beam at RIBF and a Target System for BigRIPS





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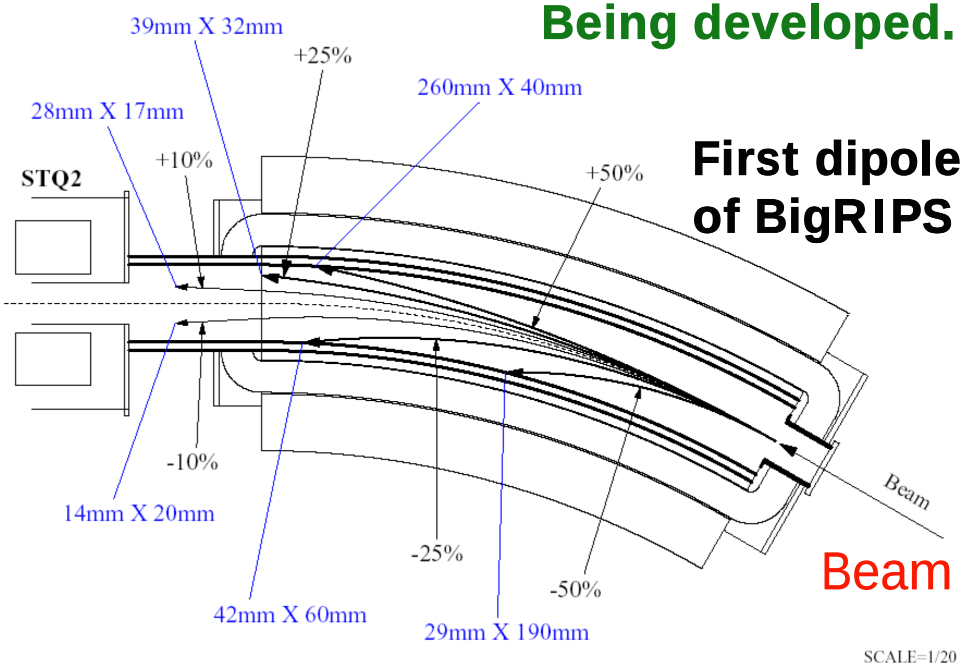
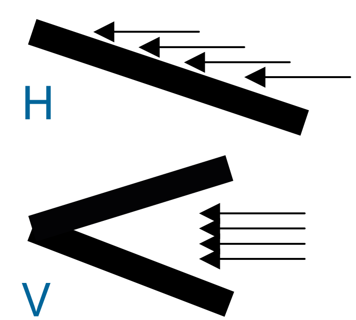
High-power water-cooled beam dump

- Beam power: ~100 kW max., ^{238}U 350 MeV/u 1 pμA.
- Beam stops at the beam dump wall placed inside the first dipole.
- Stopping position and beam size changes depending on Bρ setting.
- Power density amounts to ~ several hundreds MW/m^2, if the beam is injected perpendicularly to the wall. Too high to cool!

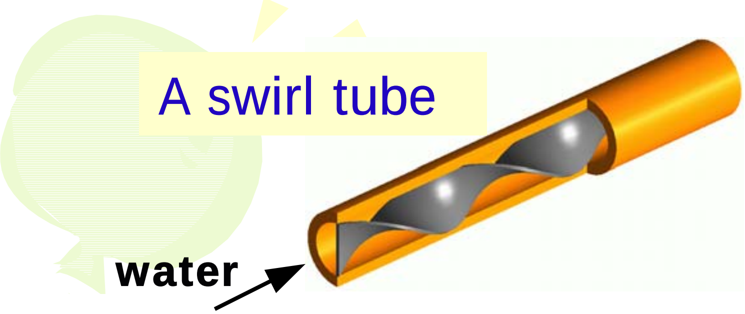
Being developed.

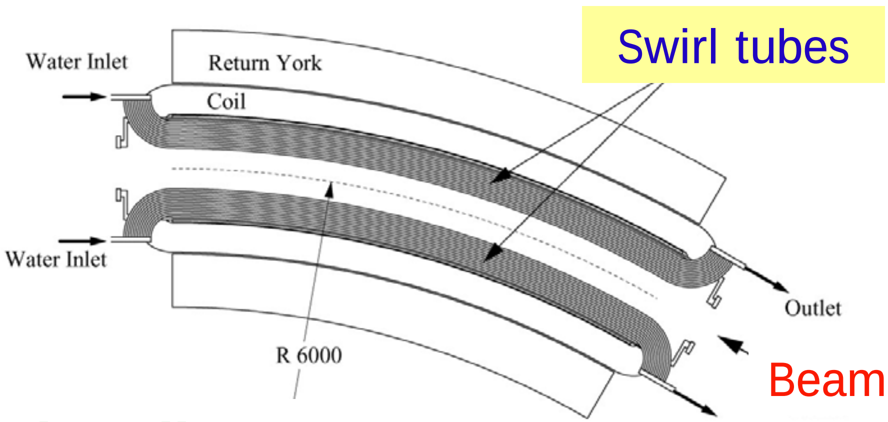


The power density can be reduced down to ~20-50 MW/m^2 in our case, because the beam is injected at small angles to the beam-dump wall and if the wall is vertically tilted like a V shape. This increases the projected beam-spot size. But still quite high density!

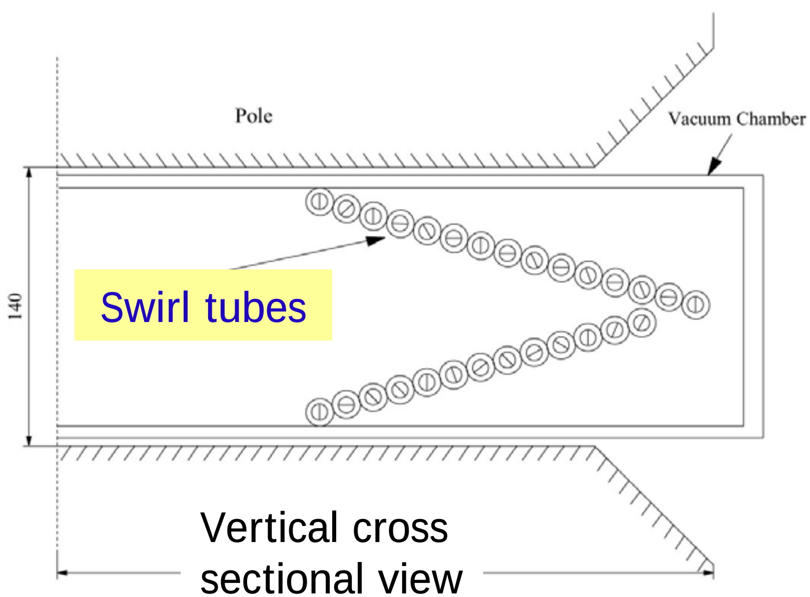


Water-cooled beam dump using a Cu **swirl tube**





First dipole



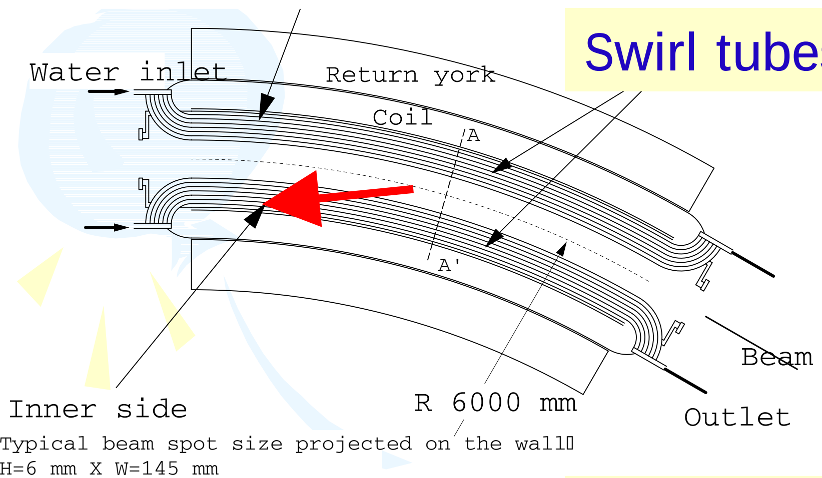
- Use swirl tubes for the beam-dump wall to improve the heat transfer coefficient h[W/m^{2}K] of water by a factor of 2, allowing to lower the beam-dump temperature.
- Cooled by forced convection of pressurized water flow and latent heat of sub-cooled boiling.
- Swirl tubes promote turbulence flow, increasing h[W/m^{2}K].
- Increase water pressure to increase the temperature margin.
- Material of tubes: CuCrZn alloy. Enhance the strength at high T, keeping heat conductivity the same. Material of swirl ribbon : INCONEL

ANSYS simulation for the Cu swirl-tube beam dump

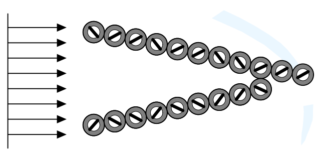
Swirl tube conditions:
ϕ(out)= 14 mm, ϕ(in)= 8 mm;
material CuCrZn alloy (λ=351 W/mK).
Water conditions:
flow speed= 10 m/s; pressure= 10 atoms; boiling temp.= 180 degree C.

The beam hits the inner side:
production of neutron-rich RI beams

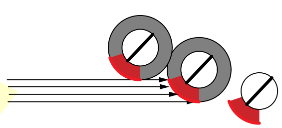
Swirl tubes



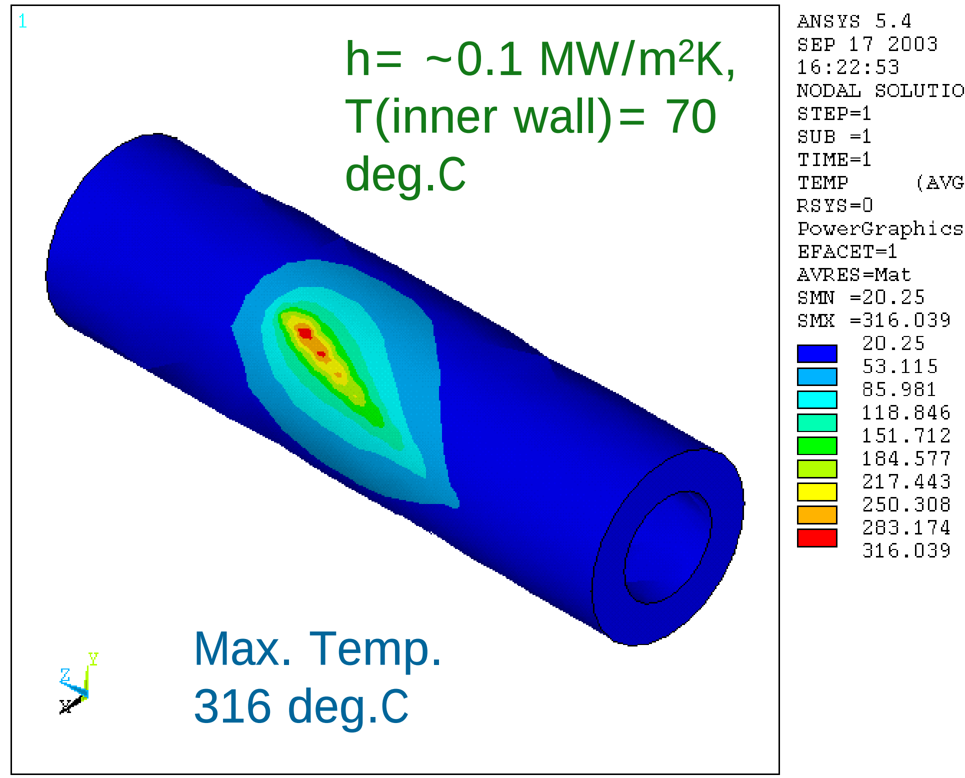
~115 MW/m²



Vertically tilted angle: +- 9.8 deg.



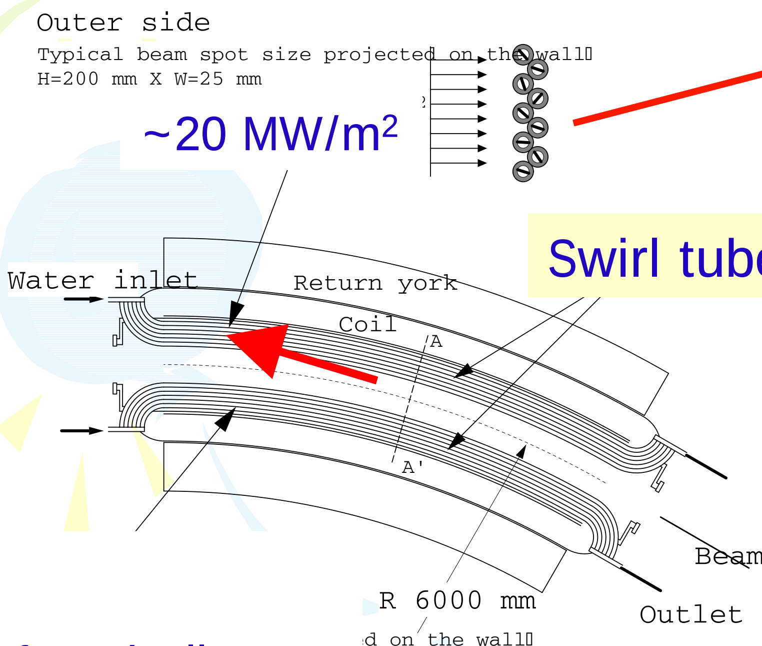
Average density: ~ 46 MV/m²

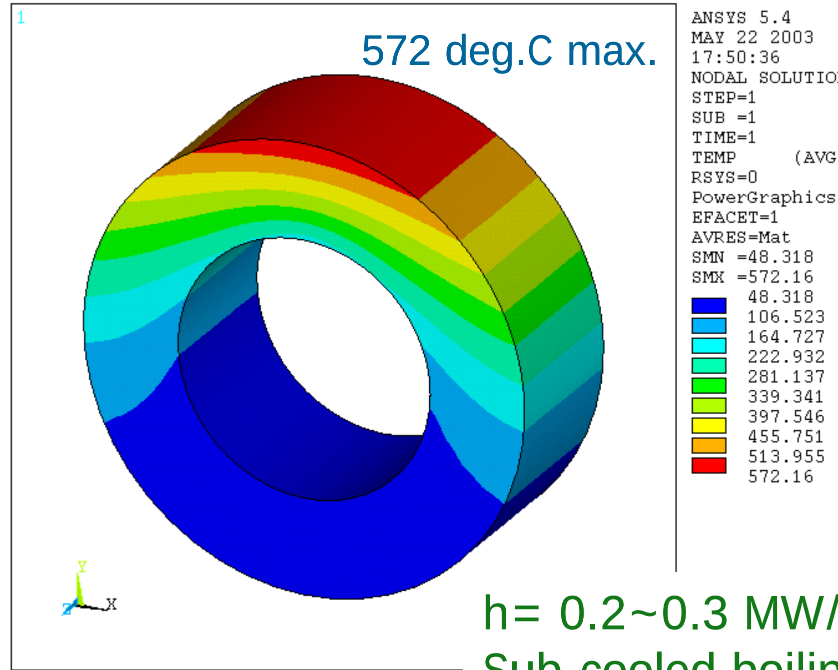


Well below the melting temp. of Cu.
(1083 degree C)

ANSYS simulation for the beam dump

The beam hits the outer side:
production of proton-rich RI beams

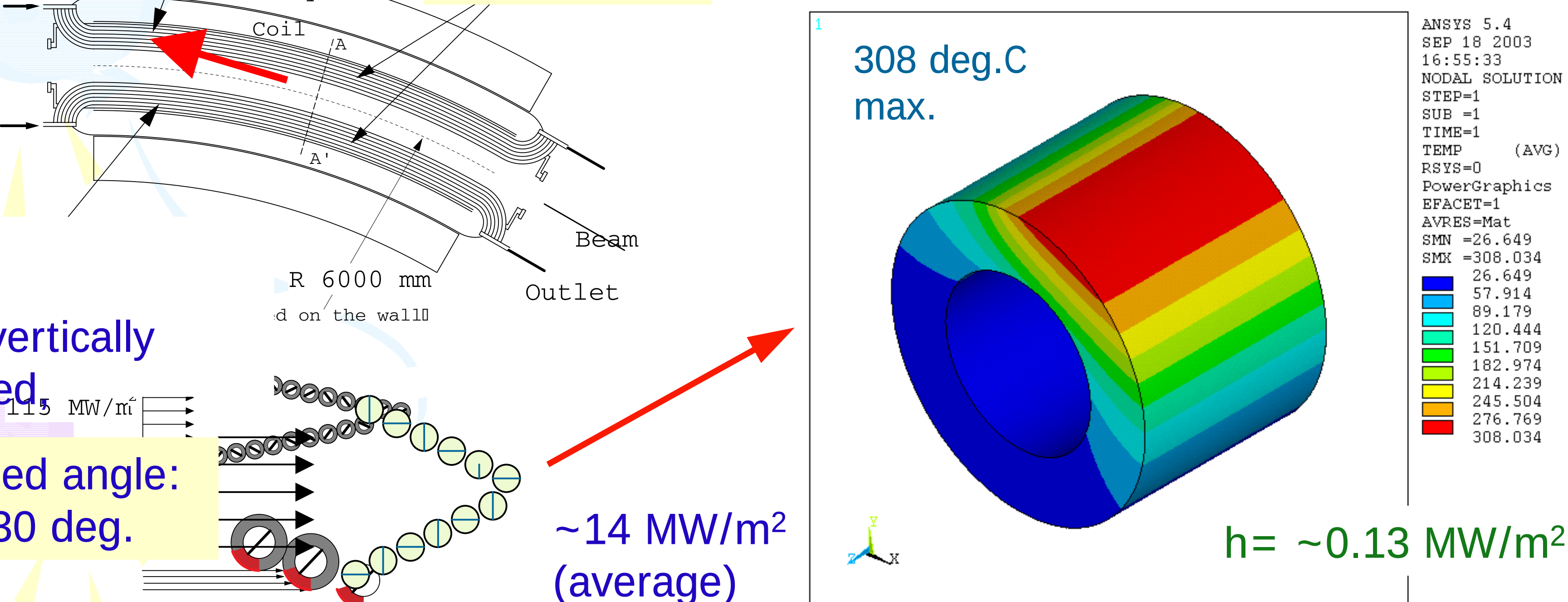




$h = 0.2 \sim 0.3$ MW/m^{2}K
Sub-cooled boiling

If vertically tilted,

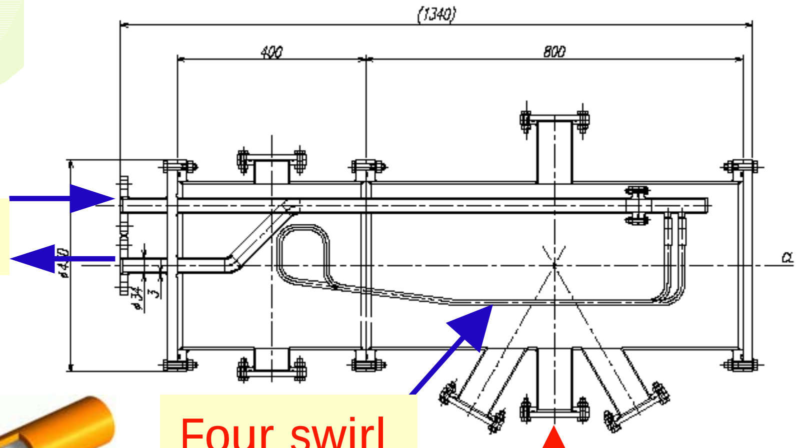
Tilted angle: +-30 deg.



~14 MW/m² (average)

$h = \sim 0.13$ MW/m^{2}K

Prototype of the swirl-tube beam dump for testing



Recently built.

- Goal power density: ~20-50 MW/m^2.
- Use of Cu swirl tube. ϕ(out) and ϕ(in) diameters: 14 mm and 8 mm. Swirl pitch; 16 mm. tube material: CuCrZn alloy (λ=351 W/mK). Swirl ribbon material: INCONEL (Ni+Cr+etc).
- Water flow conditions: flow speed 10 m/s; pressure 10 atoms; boiling temp. 180 degree C; in sub-cooled boiling phase.
- Under these conditions, heat transfer coeff. h= 0.1-0.3 MW/m^{2}K.
- Simulation by ANSYS shows it can withstand 20-50 MV/mm^2.
- Plan to test the prototype with a 6kW CW laser beam and ion beams at RIKEN. e.g. 1.8 kW Ar beams: beam size 1 cm x 1cm -> 18 MW/m^2.

Summary

1) RIKEN RI-beam factory (RIBF)   First beam in 2006

Three new cyclotrons are being built. E = 400 MeV/u for A <40 and 350 MeV/u for heavier A up to U. I = 1 pμA.

2) In-flight RI beam separator BigRIPS First RI beam in 2006

> Large acceptances: efficient RI beam production for in-flight fission

> Two-stage separator scheme: delivery of tagged RI beams

> Large-aperture superconducting quadrupoles

> etc.

3) High-power water-cooled rotating disk target

being developed.   ~25 KW, 5.7 kW/mm^3, 30 GW/m^2 at max.

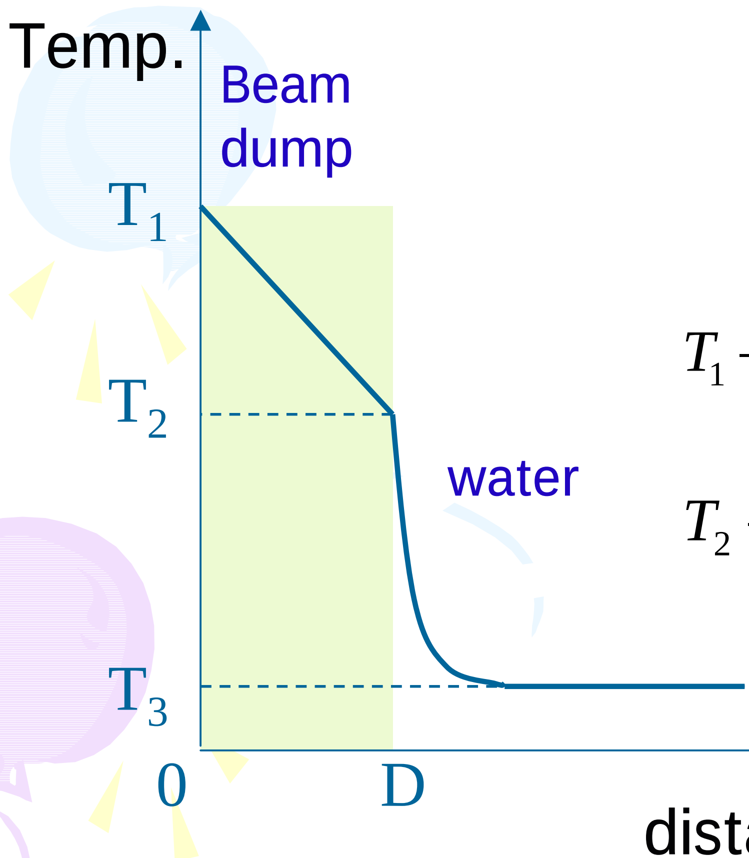
ANSYS simulation and beam testing show that this type of target can withstand the beam heat loads of ~25kW.

4) High-power water-cooled beam dump using a swirl tube

being developed. ~100 kW, ~20-50 MW/m^2 at max.   A prototype using has been built recently and is to be tested soon.

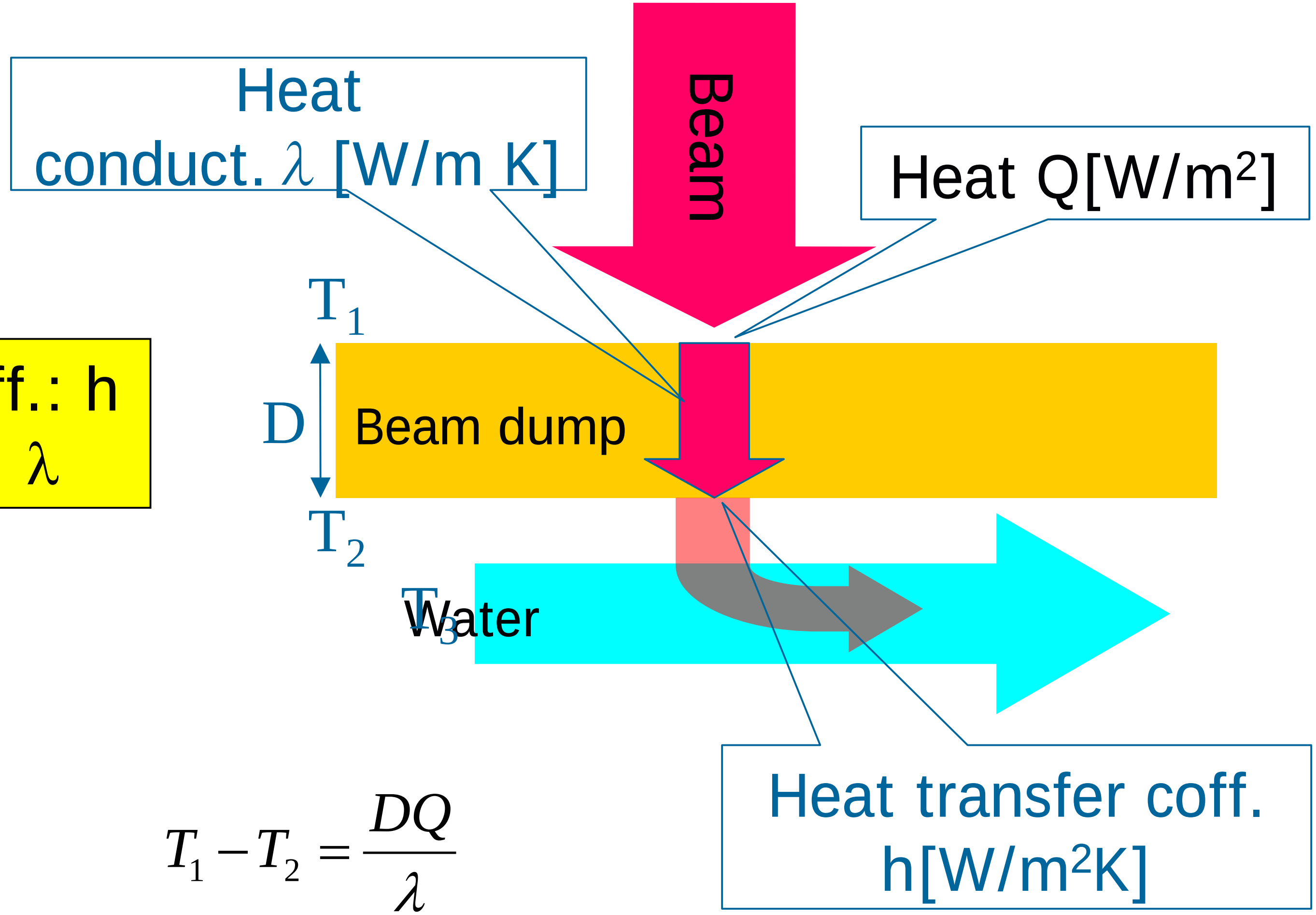
ANSYS simulation shows it can withstand the expected power density.

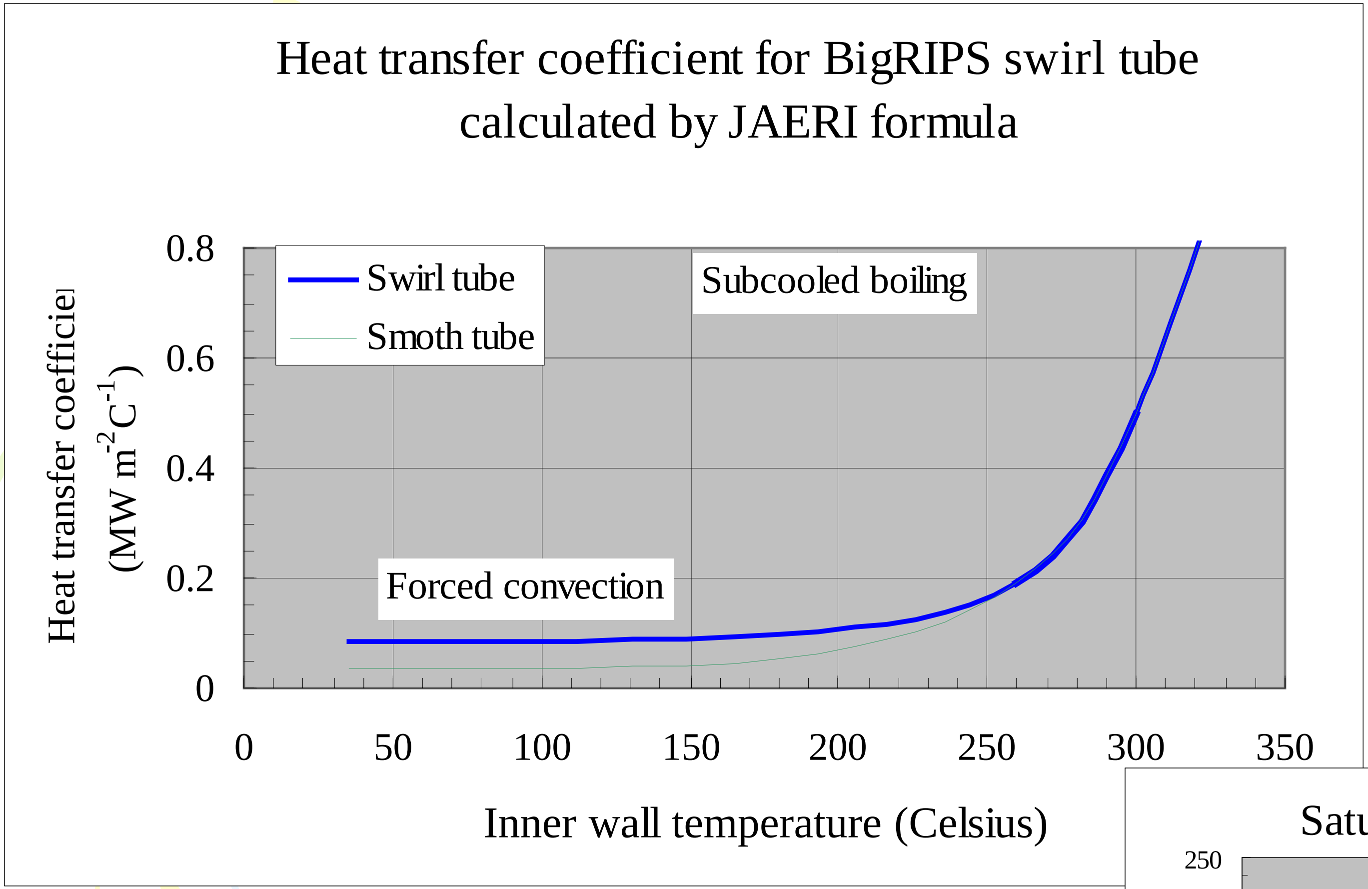
Heat transfer coeff.: h
Heat conductivity: λ



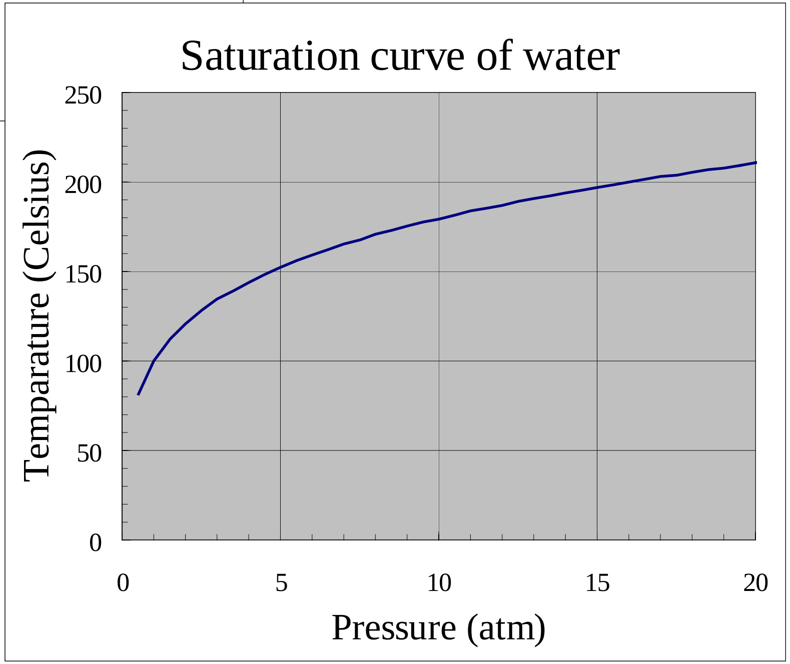
$$T_1 - T_2 = \frac{DQ}{\lambda}$$

$$T_2 - T_3 = \frac{Q}{h}$$



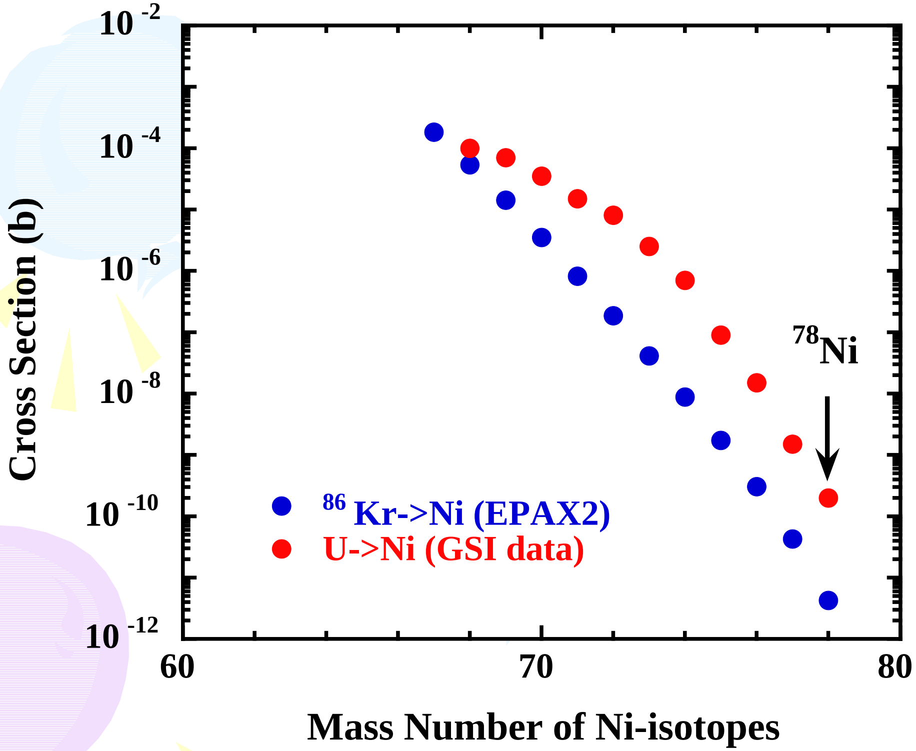


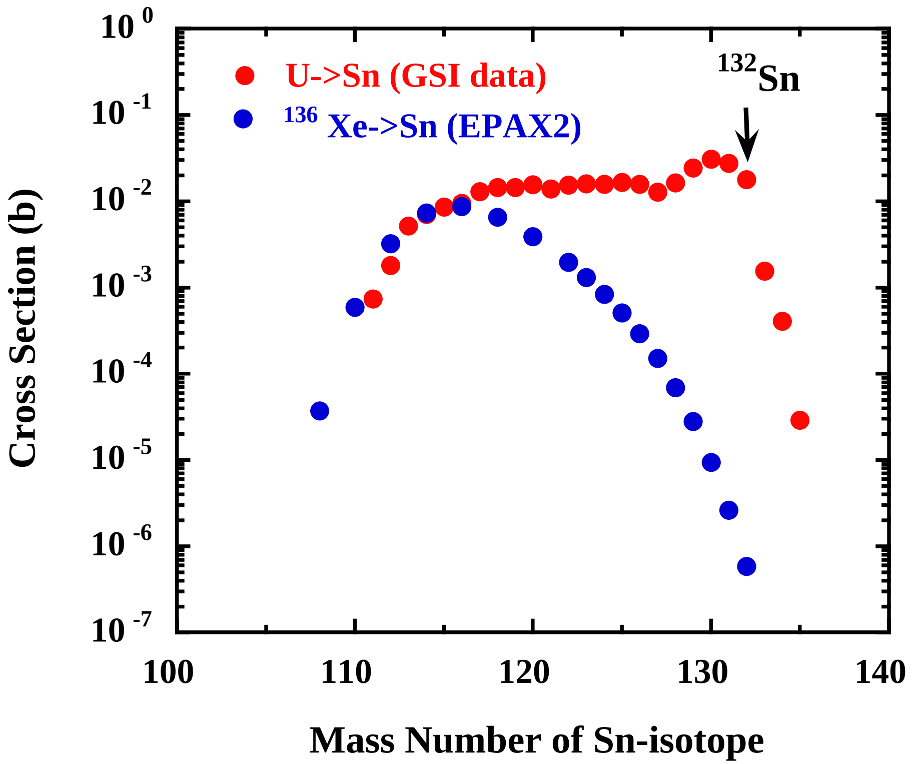
Heat transfer coefficient: h v.s. Inner wall temp. of tube



Swirl tube parameters:
ϕ(out)= 14 mm, ϕ(in)= 8 mm;
material CuCrZn alloy (λ=351 W/mK).
Water conditions:
flow speed= 10 m/s; pressure= 10 atoms; boiling temp.= 180 degree C.

Productin cross section of Ni and Sn isotopes





Radiation damages caused by fast neutrons from the target and beam dump

- **Radiation damages** to the components closely located.

  avoid using weak materials and choose stronger or the strongest ones that are currently available.

  e.g. polyimid coating for the NbTi wire, a polyimid super-insulator foil, full mineral insulated r.t. coils for the first dipole and so on.

- The first two quadrupole triplets (STQ1 and STQ2) may be destroyed in a few years mainly due to the damage to coil epoxy.

  Replace them by new one. Designing BigRIPS so that the replacement can be made as easily as possible under high residual radiation.

Radiation heat loads to the cryogenic system of STQ1-5

Particularly the first two quadrupole triplets STQ1 and STQ2.

(STQ1: an air-core type reduces the heat loads.)

Extra-cooling capacity: 270 W at 4.5 K v.s. normal loads: 150 W

Total cooling capacity: 420 W at 4.5 K with liquid nitrogen.

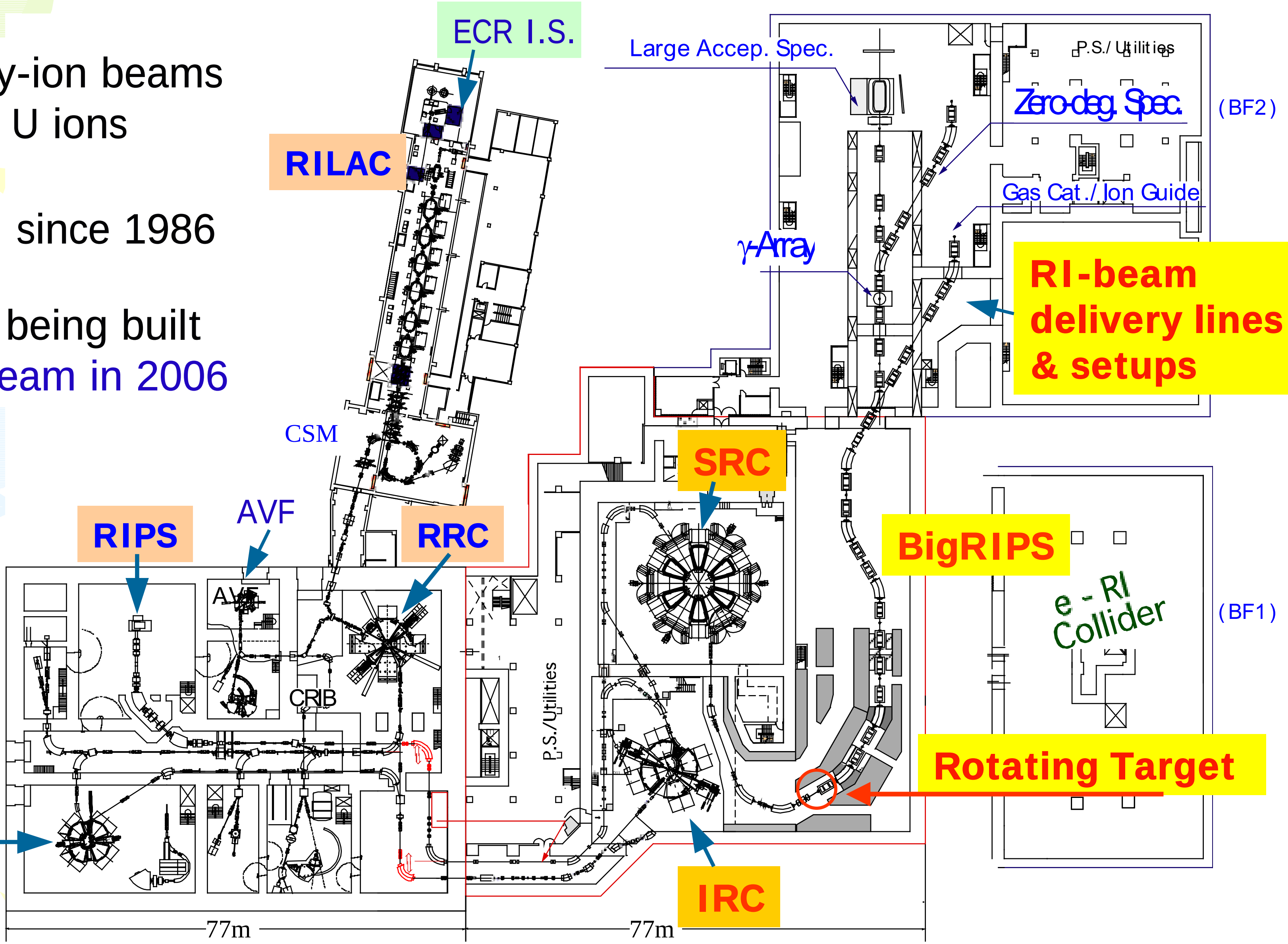
Heaters compensate the changes of radiation heat loads.

RIKEN Accelerator Facility: RARF & RIBF

Heavy-ion beams
up to U ions

RARF: since 1986

RIBF: being built
first beam in 2006



T. Kubo, RIKEN

Physics goal of RIKEN RI-beam Factory

- **To prove the limits of nuclear existence and to understand the basic physics of the nuclear landscape**
  - Exploration of the limit of existence
    - Drip-line nuclei: new-isotope search, mass
    - Nuclei outside the drip lines: (d, p), (p, ^{2}He)
  - Magic numbers far from stability
    - mass, $\beta-\gamma$, $\beta-\gamma$-n, moments (μ, Q)
    - Coulomb excitation, transfer reactions (d, p), (d, n)
    - nucleon knockout reactions (p, 2p), (p, pn)
    - charge exchange reactions (p, n), (d, 2n)
- **To explore the new forms and dynamics of nuclei**
  - Neutron skin and halo
    - total cross section, laser spectroscopy, elastic scattering
    - giant resonances: Coul. ex., (p, p'), (α, α')
  - Exotic shapes
    - mulitiple-Coulomb excitation

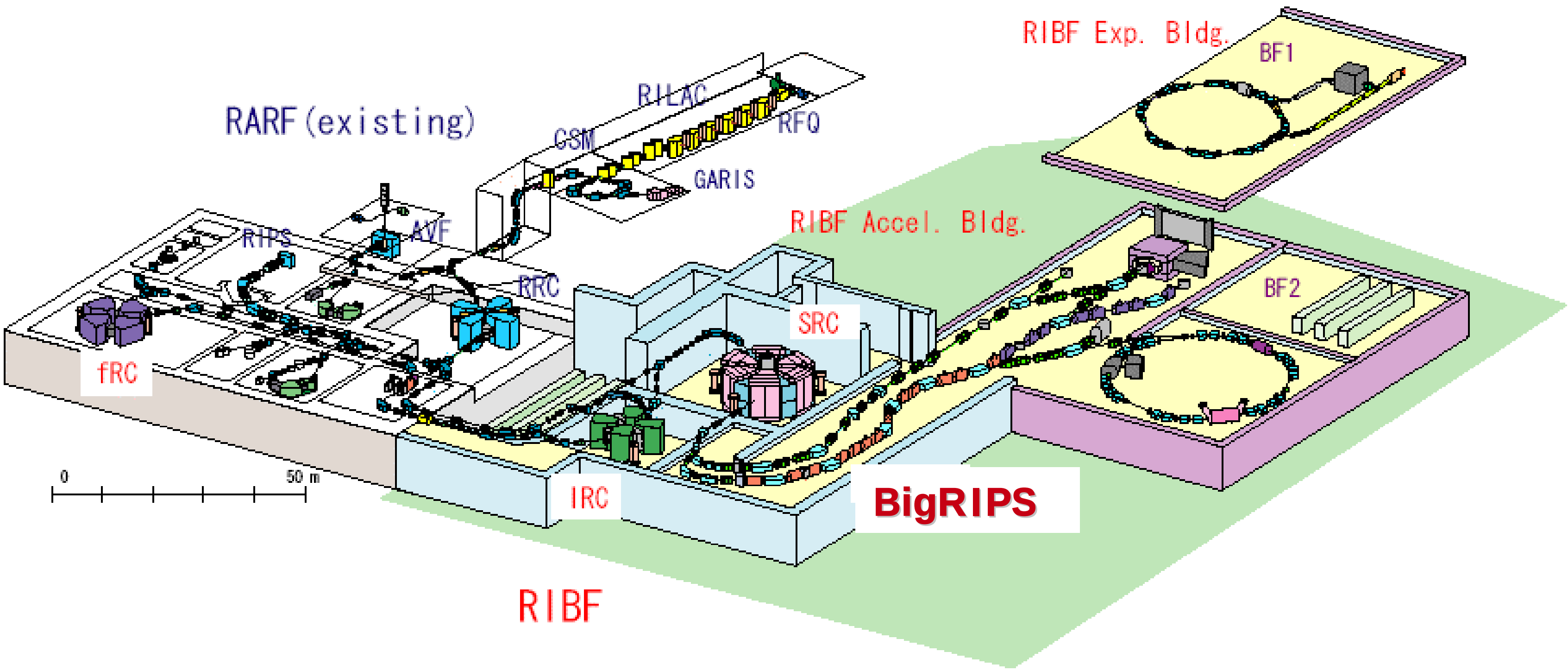
Physics goal of RIKEN RI-beam Factory
(continued)

- **To provide the basic data of nuclear astrophysics**
  - Stellar evolution and the rp-process
    - Coulomb breakup (γ, p),
    - transfer reaction (d, n)
  - The r-process
    - mass, T1/2, Pn, β–γ-n,
    - transfer reaction (d, p),
    - Coulomb dissociation (γ, n)
  - Equation of state of asymmetric matter and neutron stars
    - Total cross section
    - mono-pole giant resonace

Challenge toward the drip-lines

- How do nuclear properties change in large isospin asymmetry?
  - Location of the drip-lines
  - Shell structure, effective interactions
    - magicity loss at N= 8, 20, 28, 50?, 82?, ---
    - new magic number at N= 16, 34?, ?, ---
    - Odd-odd N=Z nuclei, T=0, T=1
    - ---
  - Nuclear matter and dynamics
    - Halo, skin
    - Exotic-cluster formation
    - EOS
    - ----
- Challenge in predictions
  - Enhancement of prediction power
  - Exotic phenomena
- Challenge in measurements
  - Efficient production RI beams
  - New methods to overcome difficulties caused by low-yield rates

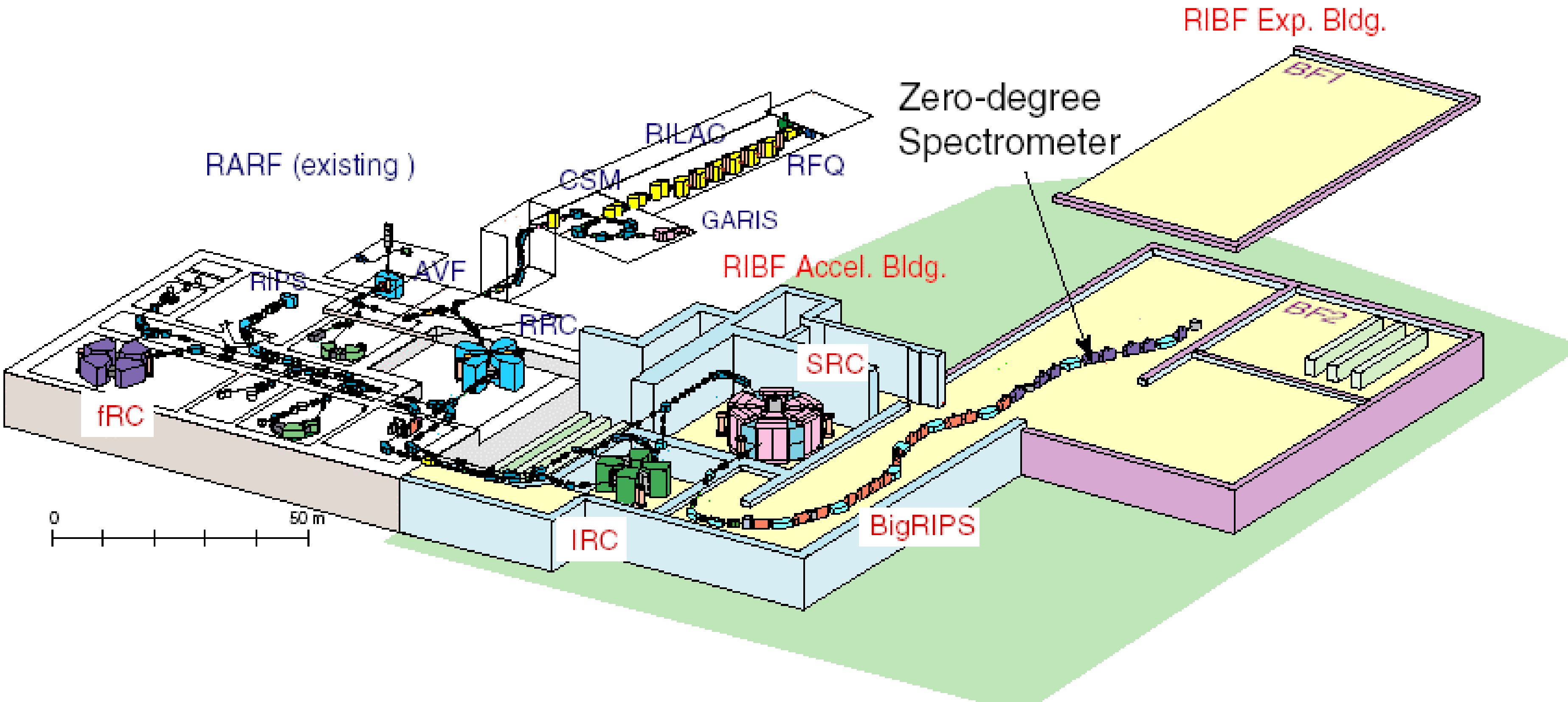
RIKEN RI-beam Factory (RIBF) Project



First beam and first RI-beam production: scheduled in 2006

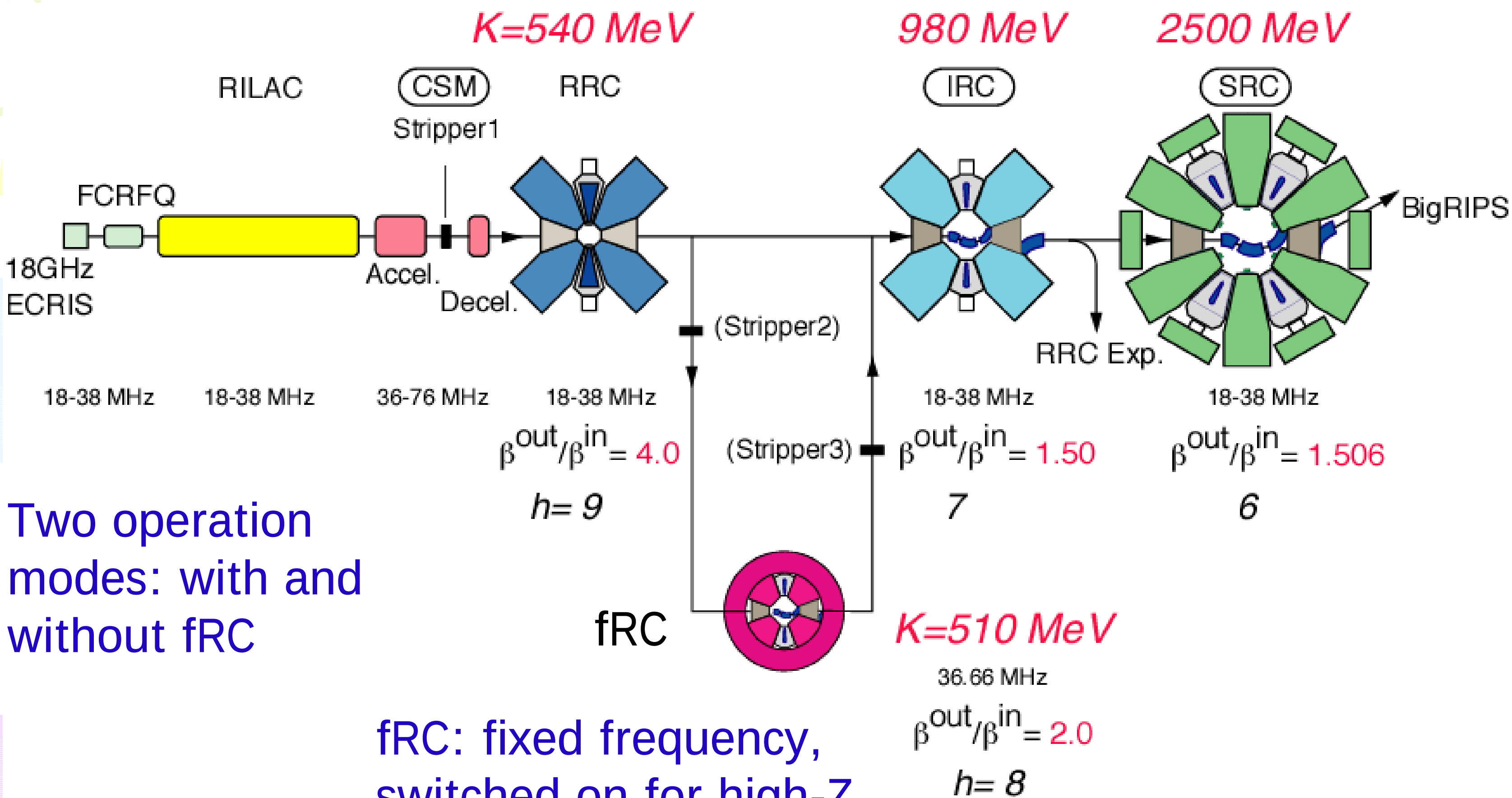
Feb. 2003

RIKEN RIBF in 2006



First beam acceleration and first RI-beam production: scheduled in 2006

Configuration of RIBF accelerators



Two operation modes: with and without fRC

fRC: fixed frequency, switched on for high-Z heavy ions

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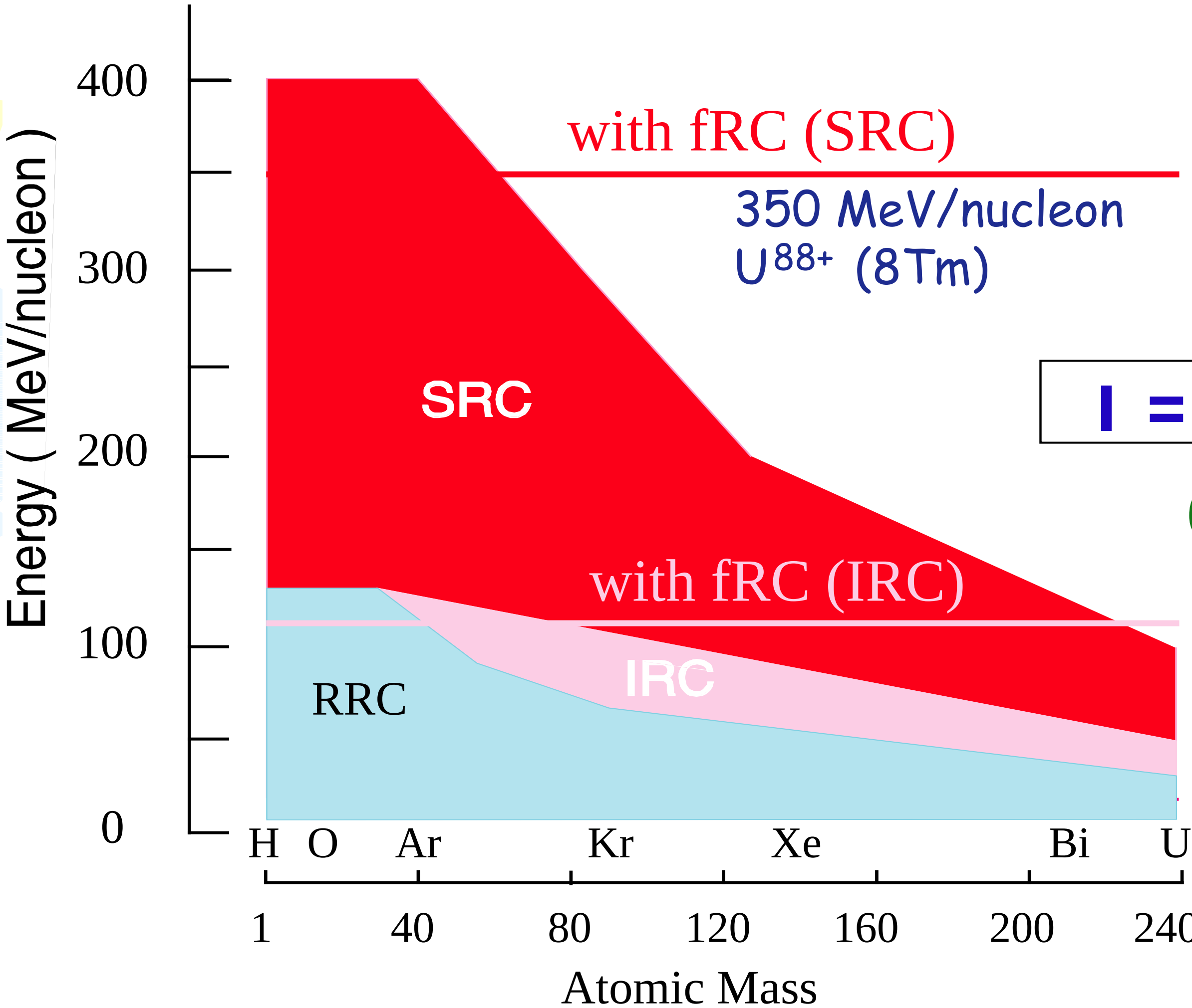
Beam energy and intensity at RIBF/RIKEN



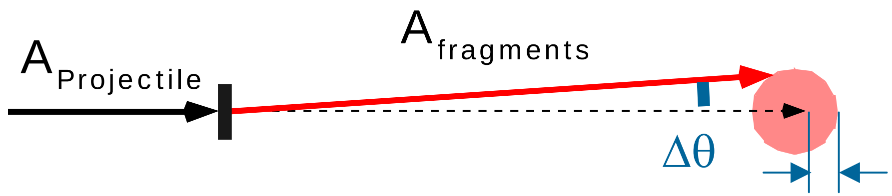
I = 1 pμA

6 x 10^{12} pps

T. Kubo, RIKEN

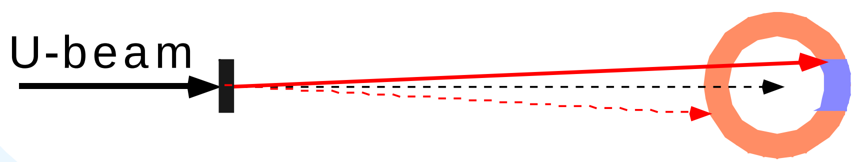
Production reactions

1) Projectile Fragmentation



small Δθ ,
small Δp/p

2) In-Flight Fission of ^{238}U beam



350MeV/u
Δθ~ ±50mrad
Δp/p ~±5%

For neutron-rich RI beams

σ(fission) > σ(fragmentation)

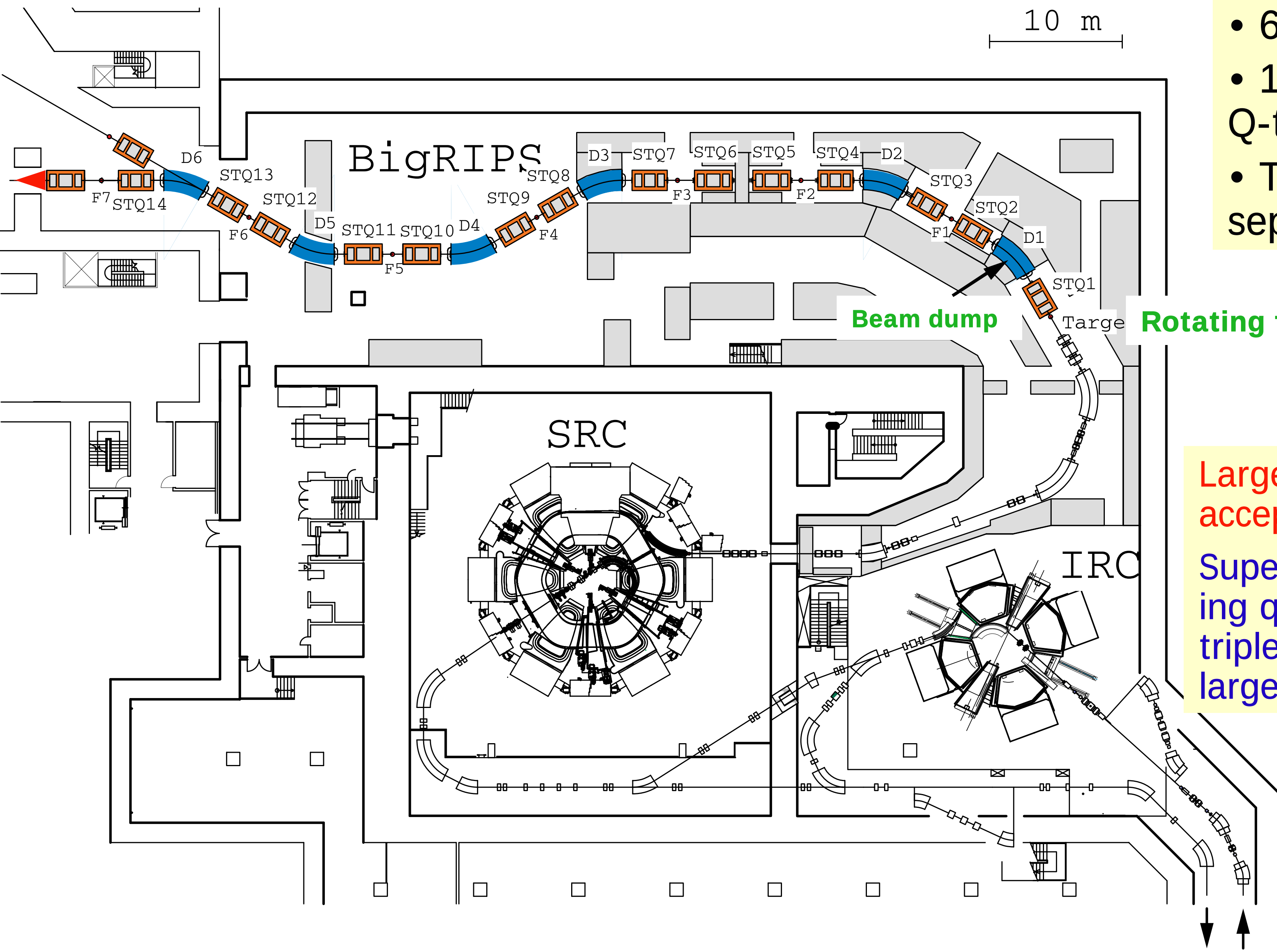
Large spreads ▶
Large acceptance separator

T. Kubo, RIKEN

Layout of BigRIPS separator

Based on the in-flight separation scheme

- 6 dipoles
- 14 super Q-triplets
- Two-stage separator

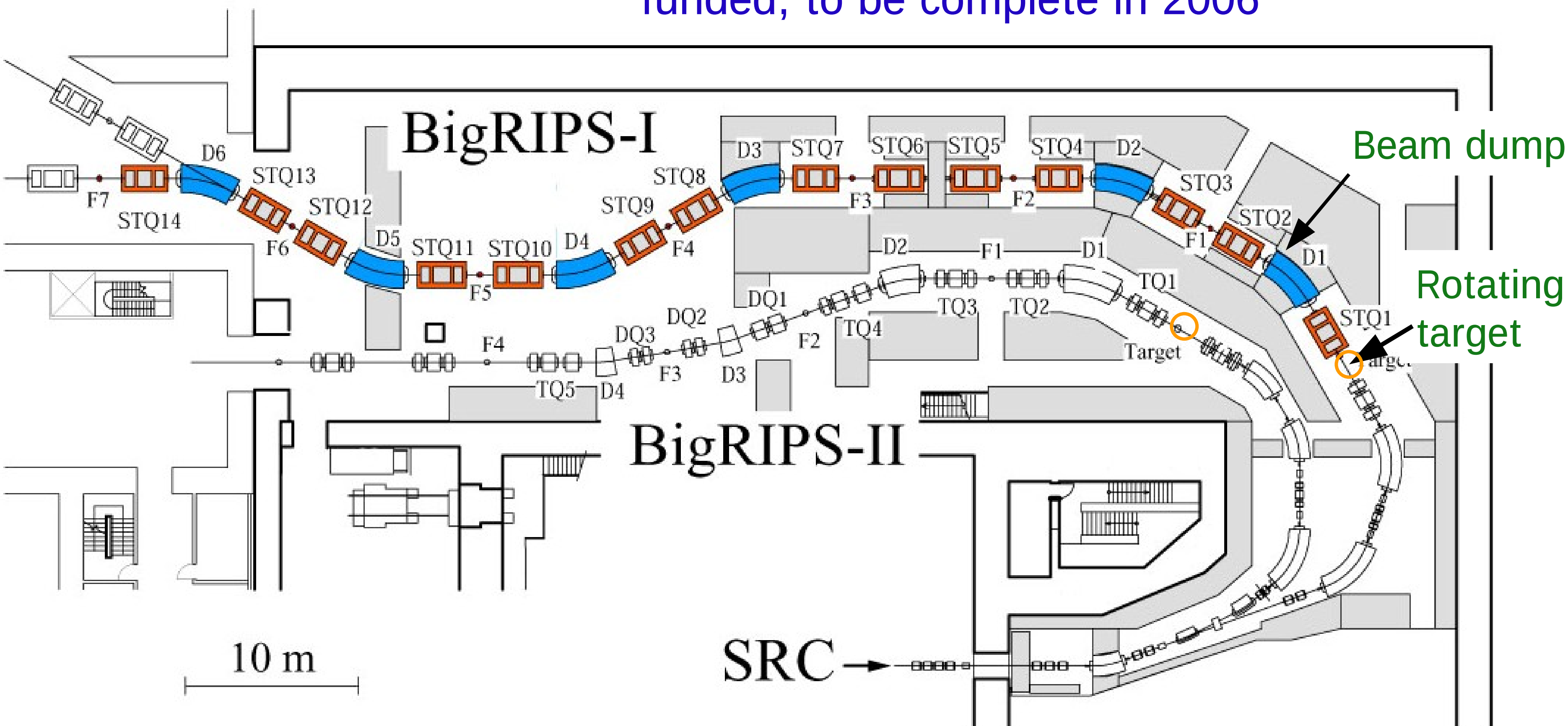


Large acceptance

Superconducting quadrupole triplets with large apertures

Layout of BigRIPS separator

BigRIPS-I: large acceptance, super-conducting quads, funded, to be complete in 2006



BigRIPS-II: medium acceptance, not yet funded

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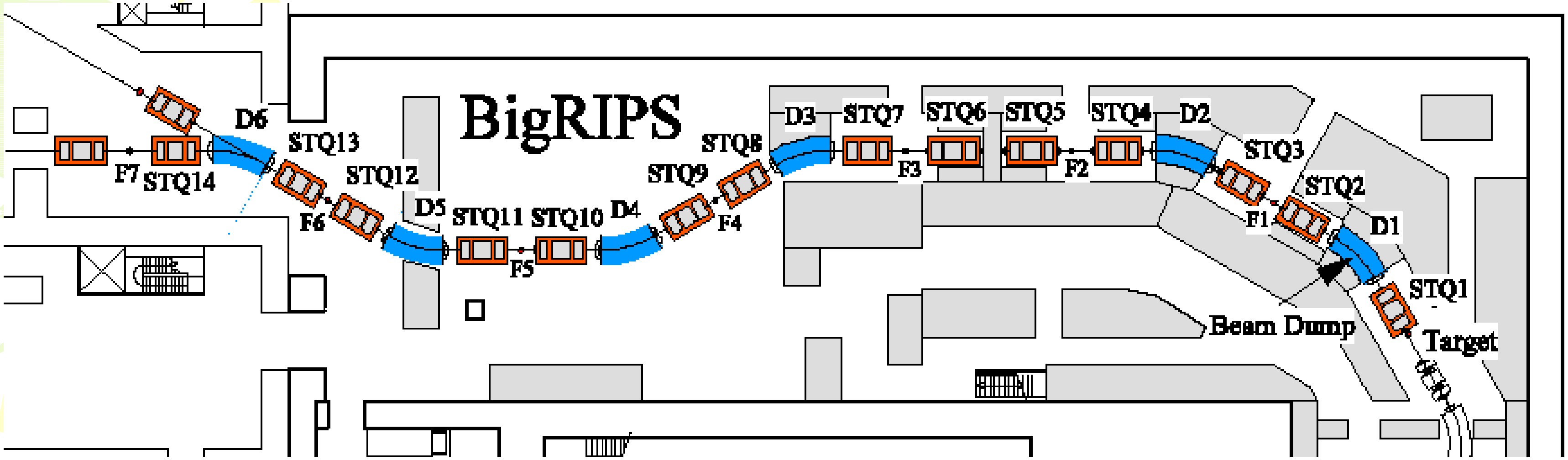
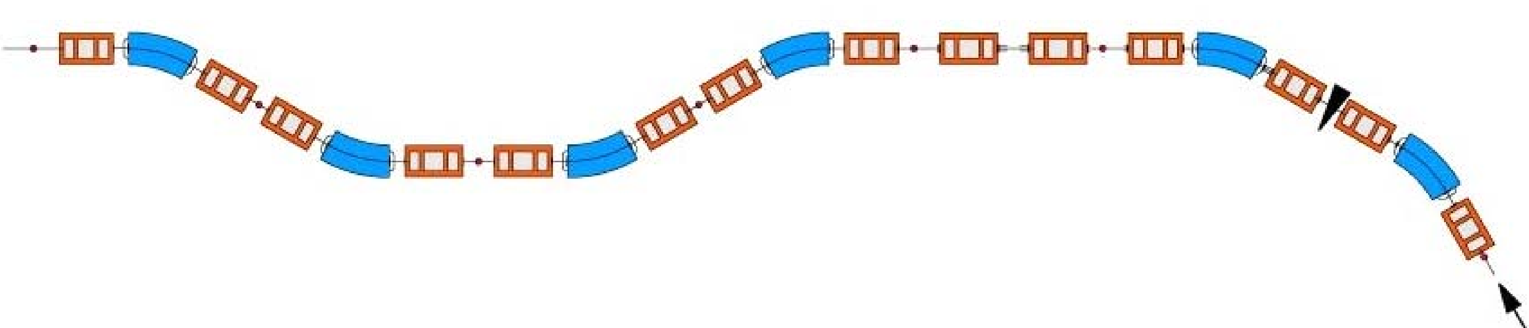
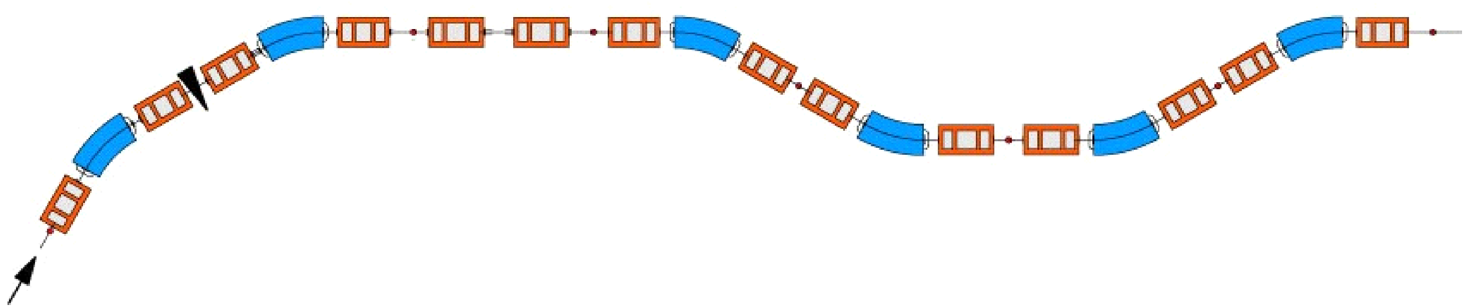
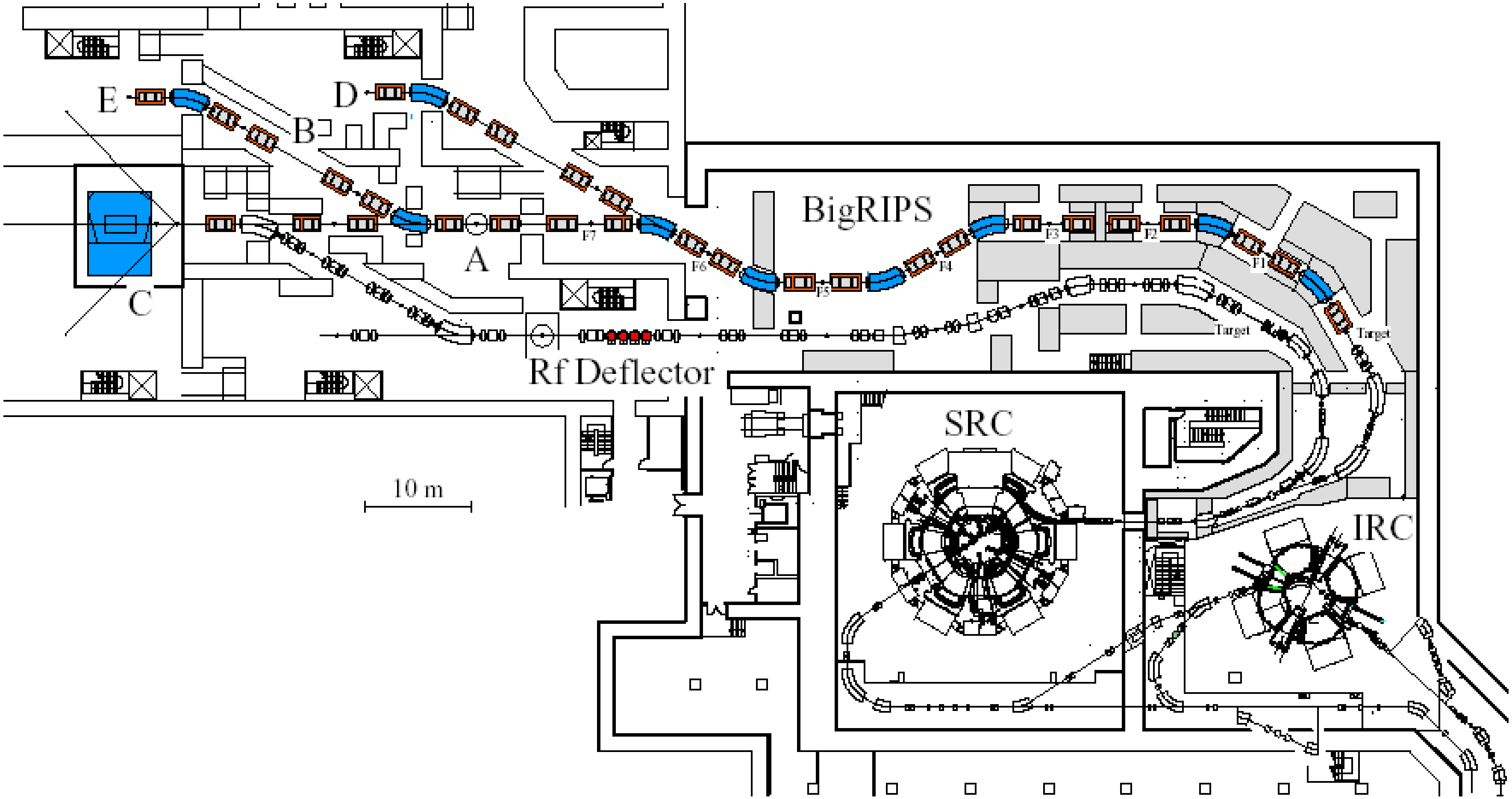
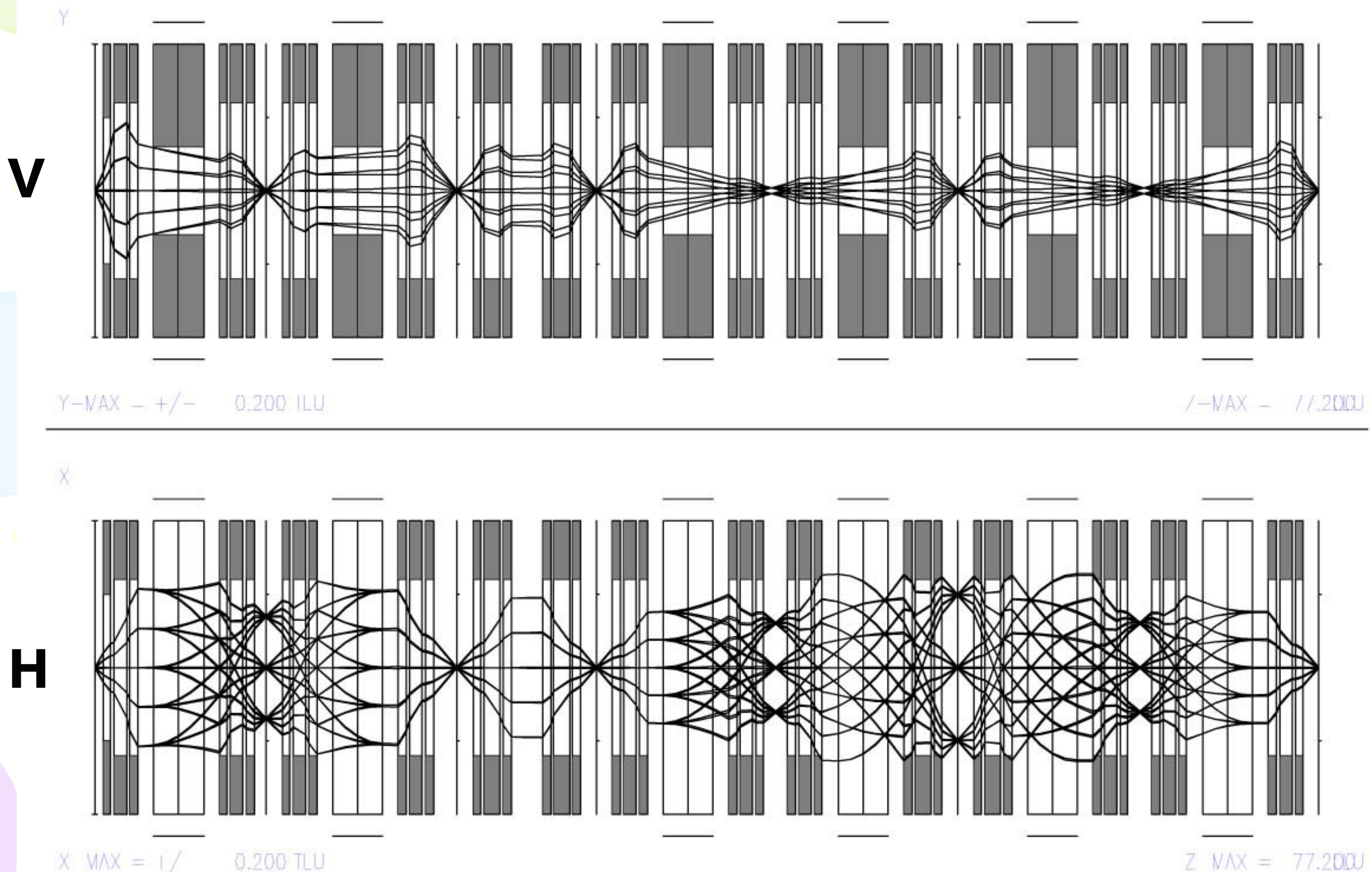

BigRIPS
D6
STQ13
STQ12
F7
STQ14
F6
D5
STQ11
STQ10
D4
F5
STQ9
STQ8
F4
D3
STQ7
F3
STQ6
STQ5
F2
STQ4
D2
STQ3
STQ2
F1
D1
STQ1
Beam Dump
Target

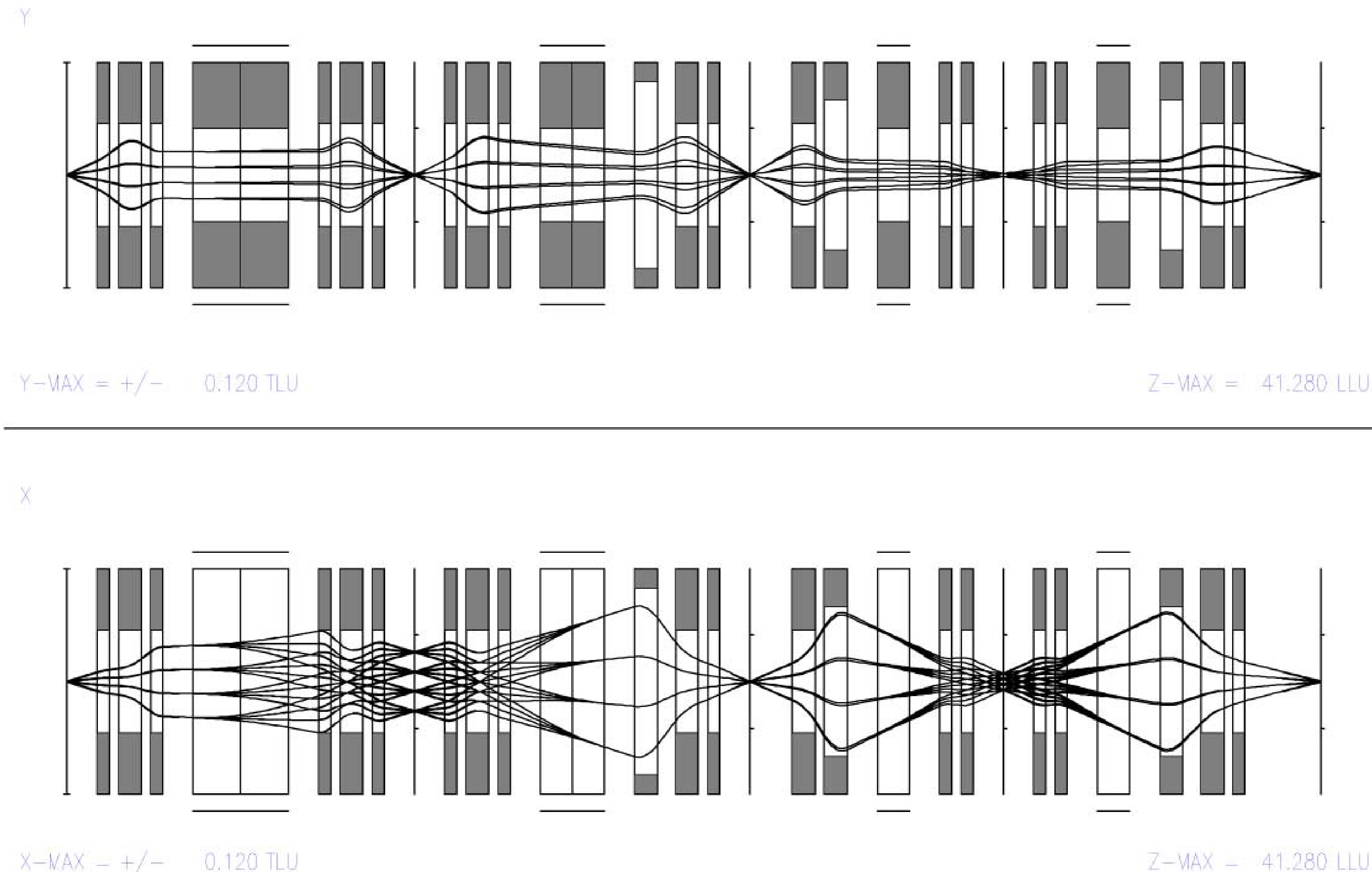





E
B
D
C
A
BigRIPS
F7
F6
F5
F4
F3
F2
F1
Target
Target
Rf Deflector
SRC
IRC
10 m

First-order ion optics of BigRIPS-I




Y
Y-MAX = +/- 0.120 TLU
Z-MAX = 41.280 LLU
X
X-MAX = +/- 0.120 TLU
Z-MAX = 41.280 LLU

Specifications of BigRIPS separator

	BigRIPS-I	BigRIPS-II
Configuration	Tandem separator	
First stage	Two bends	Two bends
Second stage	Four bends	Two bends
Energy degrader	Achromatic wedge	
Quadrupoles	Superconducting	Room temperature
Angular acceptance[mr]		
Horizontal	80	20
Vertical	100	30
Momentum acceptance[%]	6	3
Maximum magnetic rigidity[Tm]	9	9
Total length[m]	77	41
Momentum dispersion* [cm/%]		
First stage	−2.31	−2.1
Second stage	3.3	0.57
Momentum resolution**		
First stage	1290	2000
Second stage	3300	590

* At the mid focus of the stage.

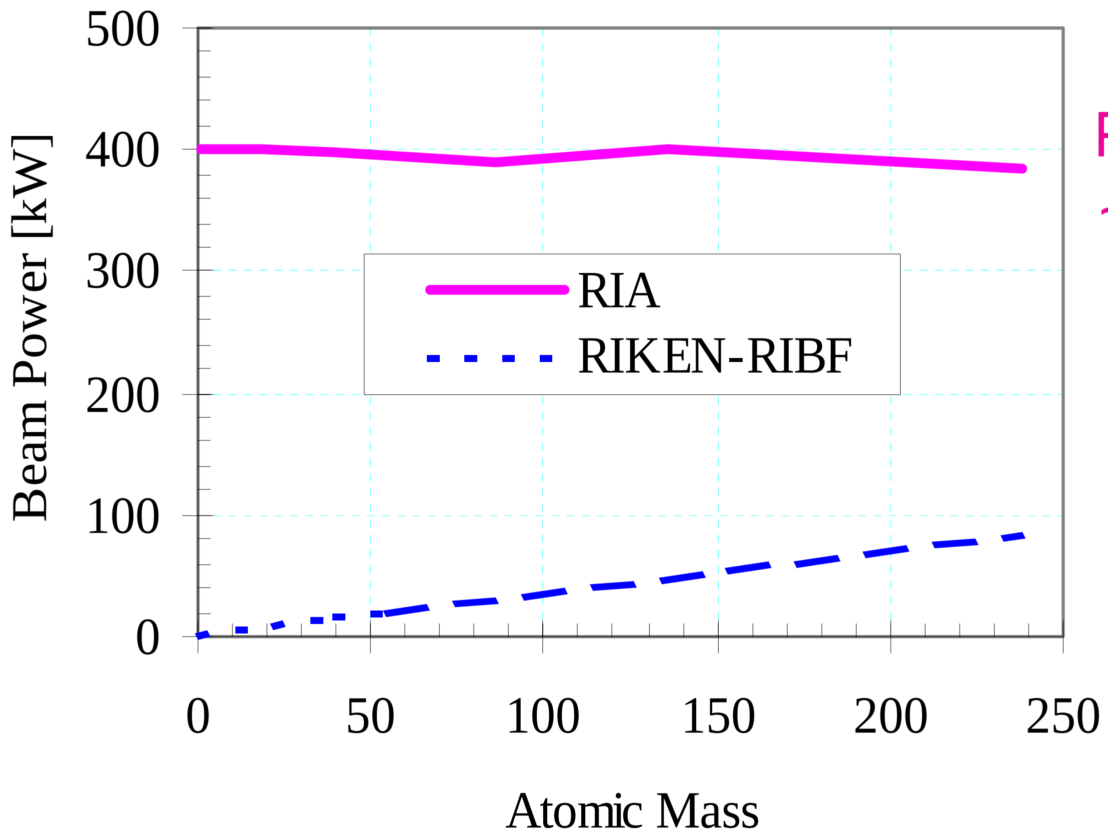
** First-order momentum resolution at the mid focus, for which object size is assumed to be 1 mm.

In-flight fission of ^{238}U beams at 350 MeV/u

~100 mr

~ 10 %

Beam power at RIBF/RIKEN



RIA/USA
~400 kW

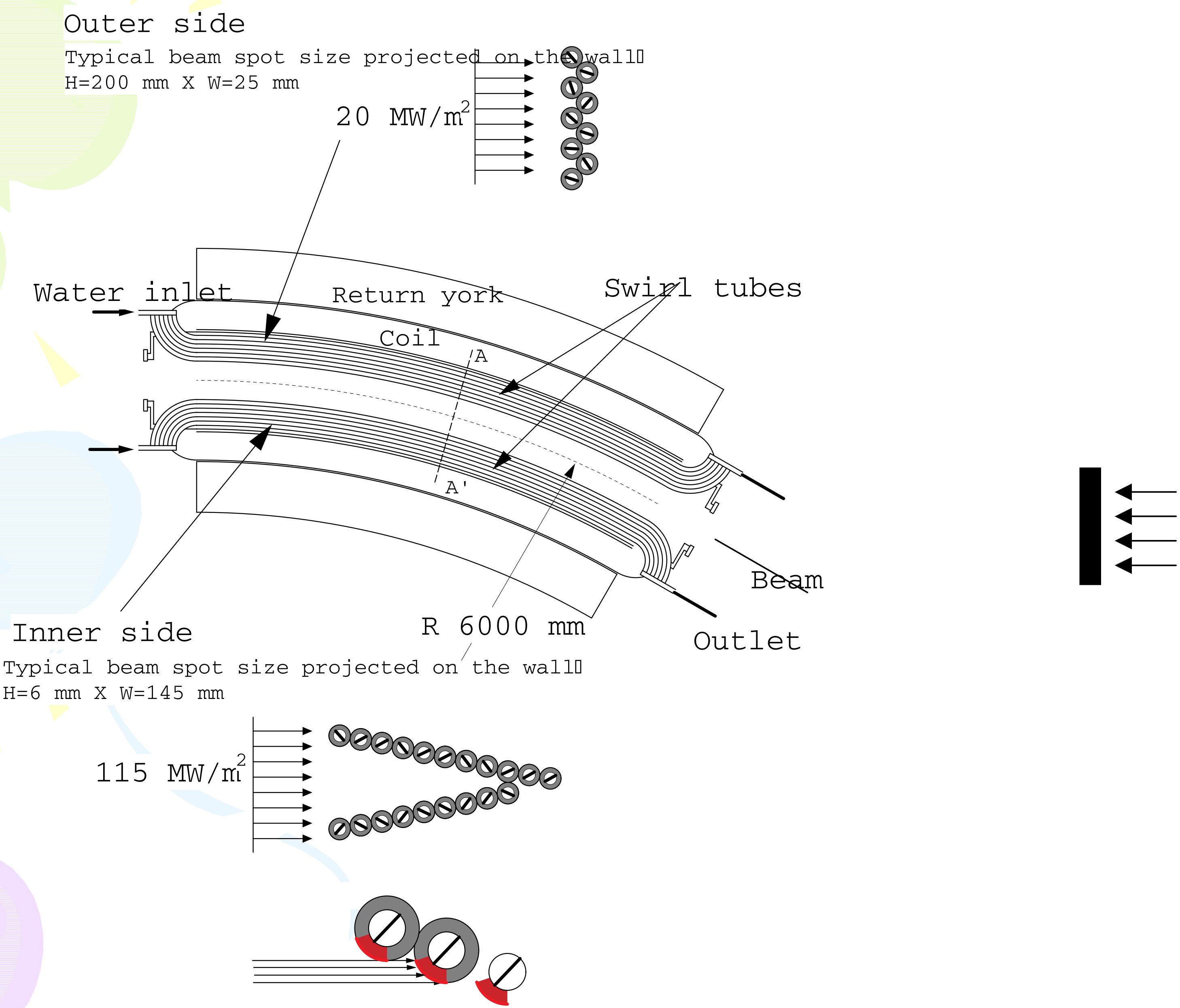
RIBF/RIKEN
~100 kW
max.

^{238}U 350 MeV/u 1 pμA; C target ~1 g/cm^2 (5.6 mm); Energy loss ~24 kW; Beam size 1 mmϕ; Power density ~30 GW/m^2, ~5.5 kW/mm^3

T. Kubo, RIKEN

RIBF building, Feb. 2003

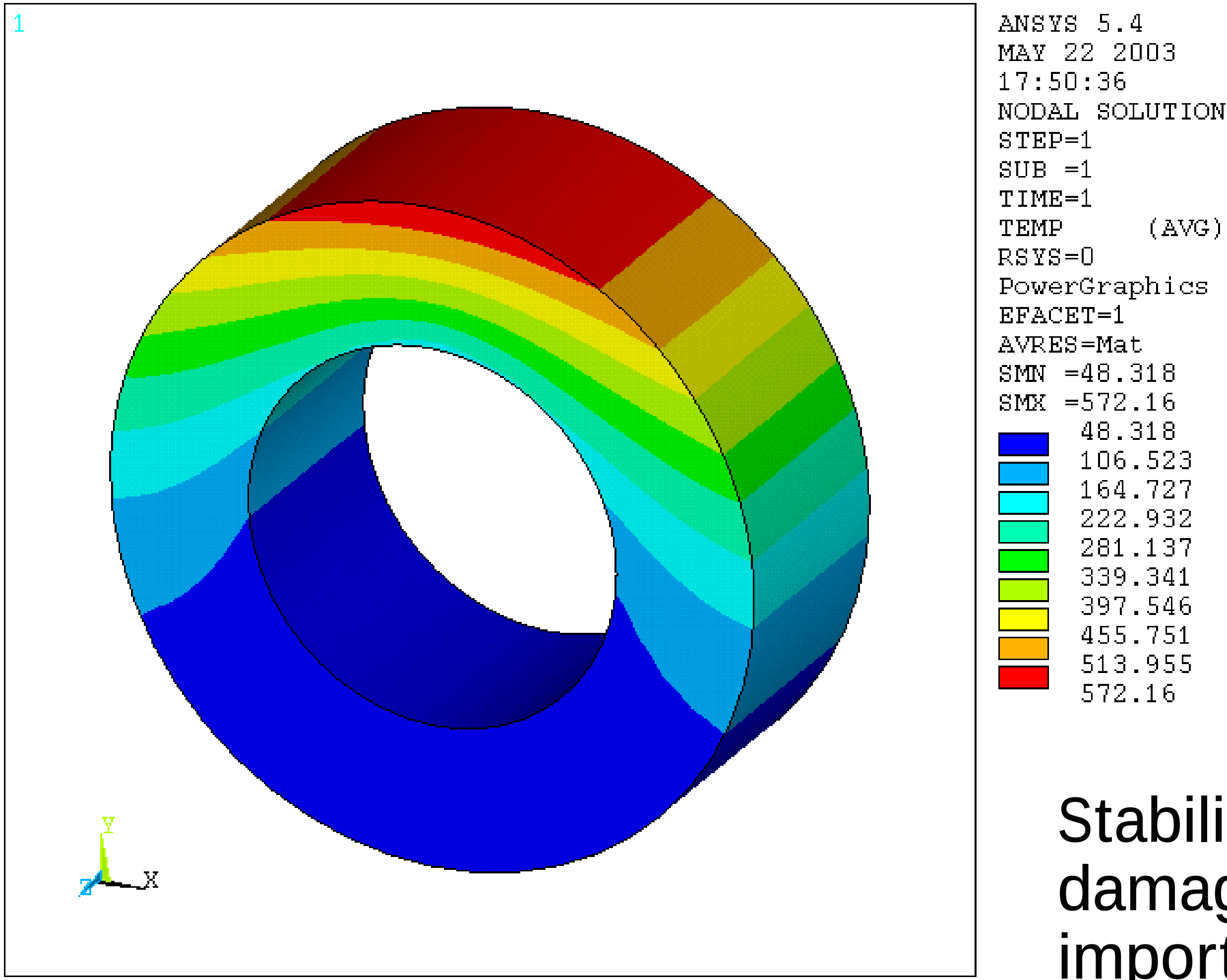
Assembling SRC cyclotron at RIKEN



Outer side
Typical beam spot size projected on the wall
H=200 mm X W=25 mm
20 MW/m2
Water inlet
Return york
Swirl tubes
Coil
A
A'
Beam
Outlet
R 6000 mm
Inner side
Typical beam spot size projected on the wall
H=6 mm X W=145 mm
115 MW/m2

ANSYS simulation for the prototype beam dump

Power density 20 MW / m²



The beam hits the upper half of tube.

Sub-cooled boiling,
h = 0.2~0.3 MW/m^2K

Well below the melting temp. of Cu.
(1083 degree C)

Stability of cooling and damage to tubes will be the important issues.

T. Kubo, RIKEN

Collaborators (BigRIPS team)

- **In-flight RI beam separator BigRIPS**
  K. Kusaka, Y. Mizoi, K. Yoshida, A. Yoshida, N. Kakutani, and T. kubo, RIKEN and H. Sakurai, U. of Tokyo.
- **High-power rotating disk target**
  A. Yoshida, T. Kubo and I. Tanihata, RIKEN
- **High-power beam dump**
  Y. Mizoi, K. Kusaka, K. Yoshida, A. Yoshida and T. Kubo, RIKEN