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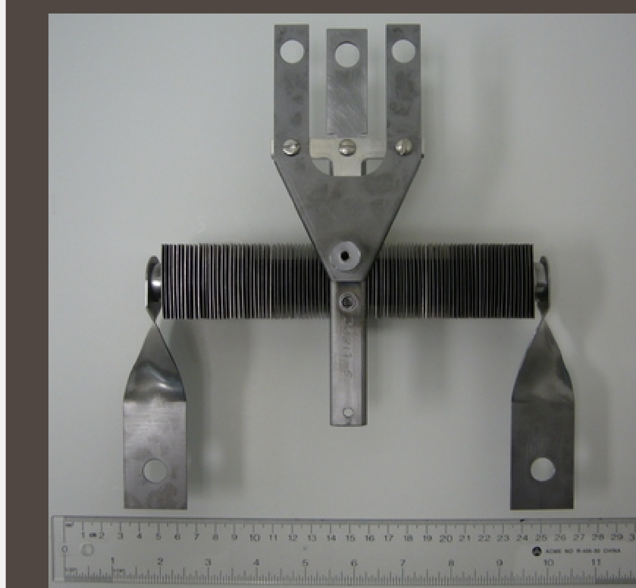
Canada’s national laboratory for particle and nuclear physics

FLUKA Simulations of ISAC Targets

2nd FLUKA Advanced Course & Workshop
Sep 20, 2012

Mina Nozar, TRIUMF



Outline

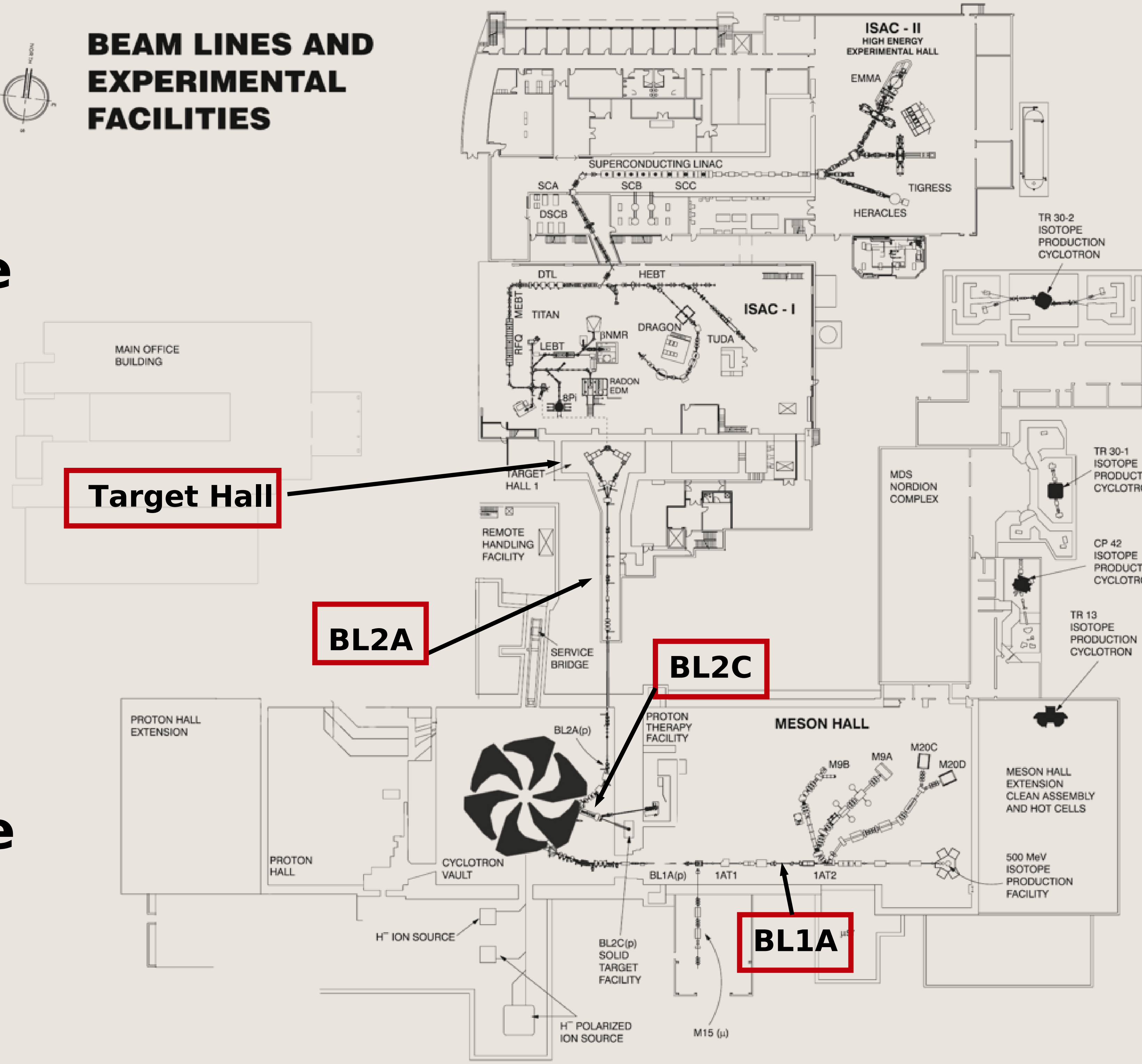
- Overview of ISAC Targets
  - Target location in the hall
  - Target components
  - Target life cycle
- FLUKA simulations
  - Time evolution of radio-nuclide inventory
  - Time evolution of dose rate
  - Shielding assessment for spent targets

General Layout of the ISAC Facility (present)

- **500 MeV, 100 μA proton beam from the BL2A port of the H^- cyclotron**

- **Two Target Stations, one operating at a time**

- **One Hot Cell and one Conditioning Station in use at the moment**

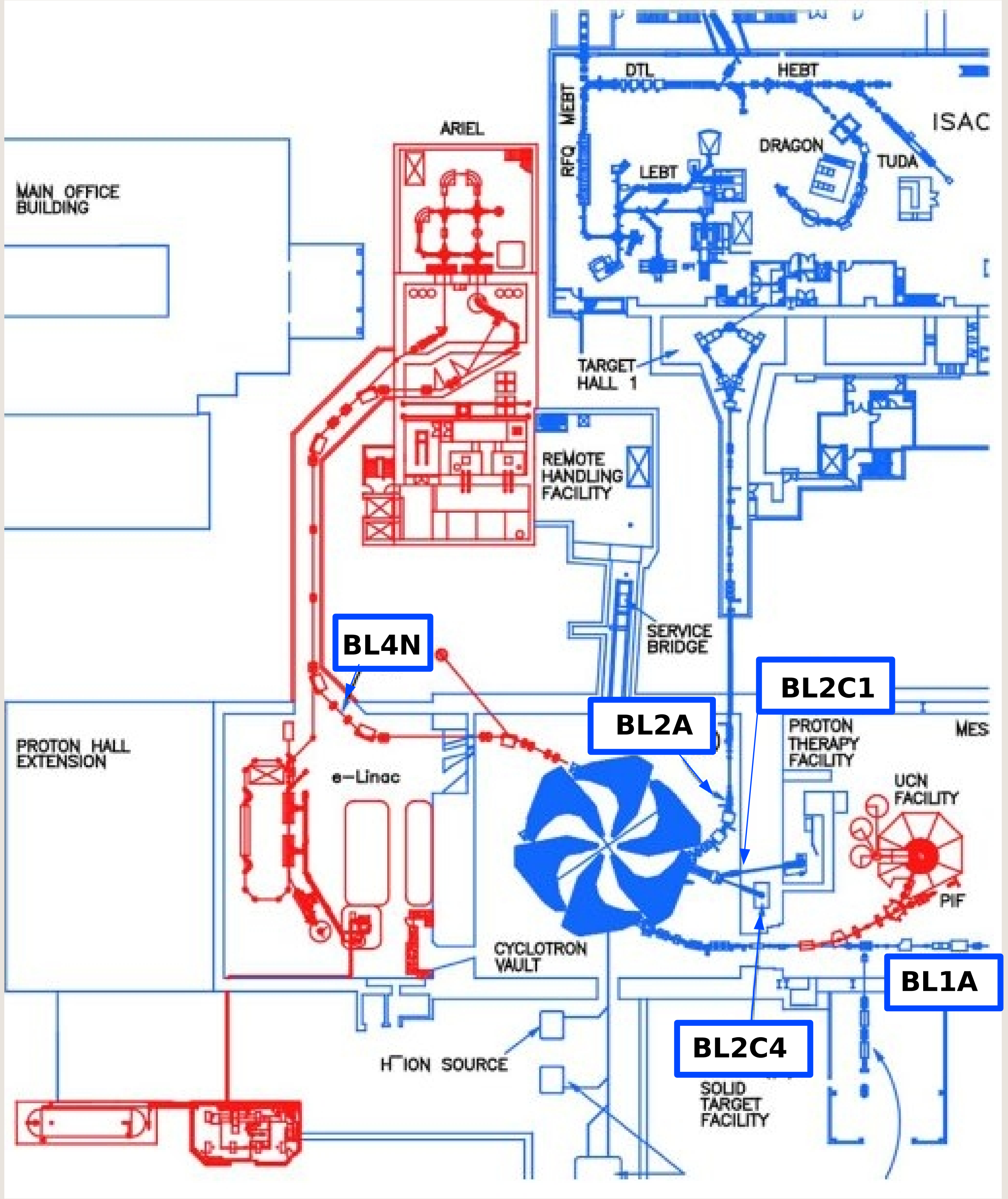


General Layout of the ISAC & ARIEL (upcoming)

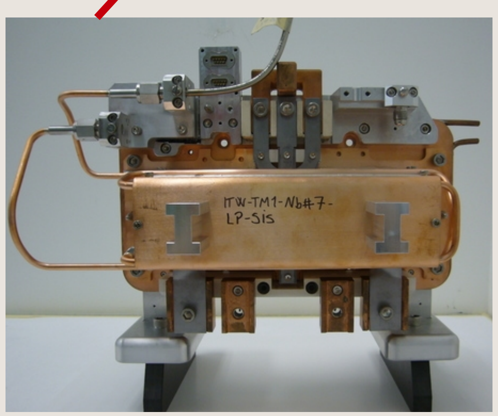
- New **Electron beam** via a Superconducting LINAC
25 MeV, 4 mA
50 MeV, 10 mA

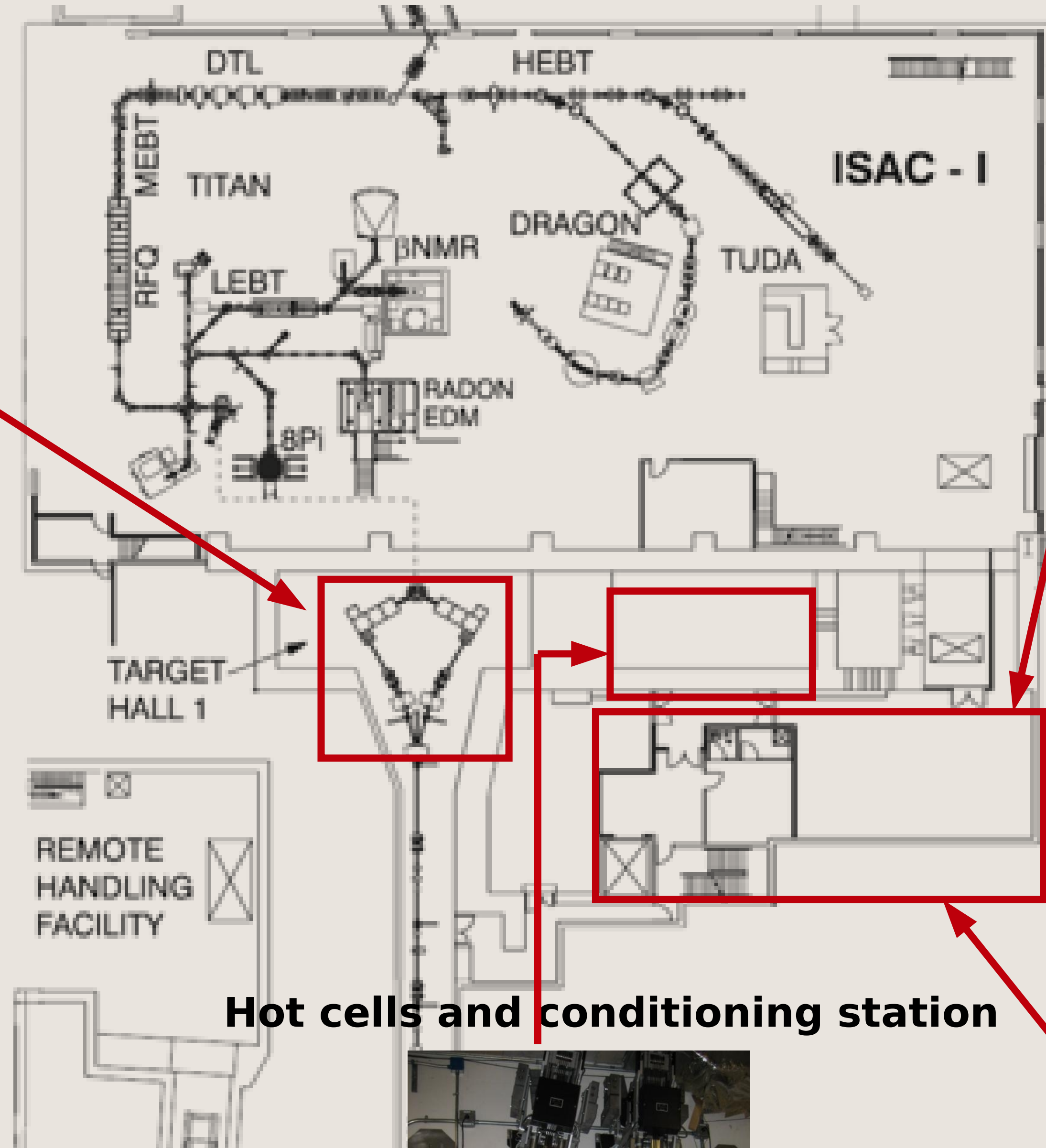
- New **Proton beam** via the BL4N port of the existing Cyclotron
500 MeV, 200 μA

- Addition of two new Target Stations, Hot cells, Target Conditioning Stations, Storage area



Location of things

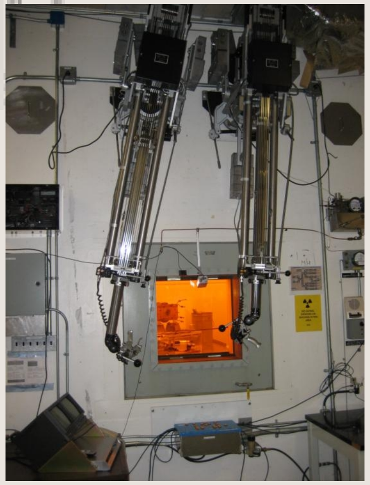




Conventional Chemistry Lab

Radio-chemistry Lab

Hot cells and conditioning station



Crane Control Room

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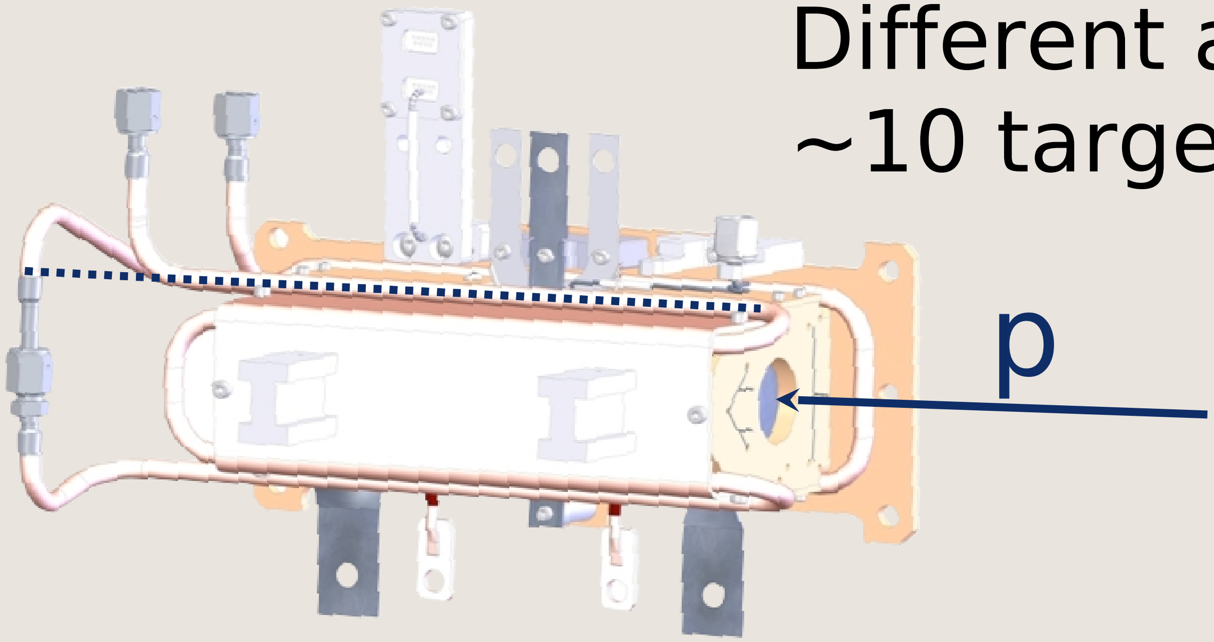
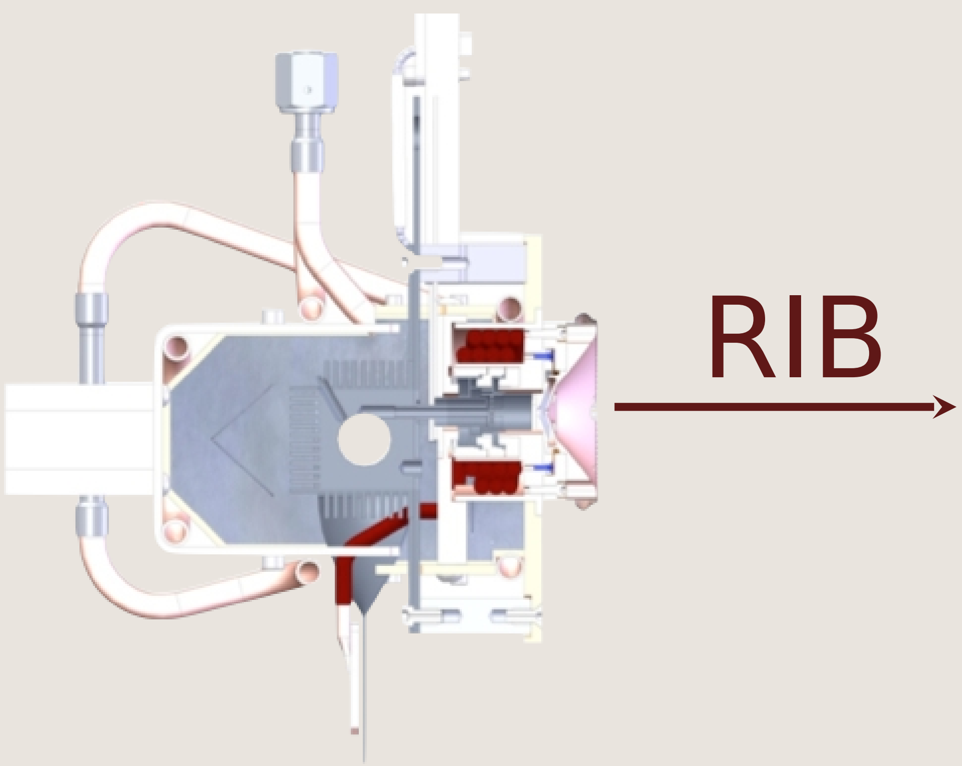
Target function

Different target materials to produce RIBs
Different assembly configurations
~10 targets irradiated per year

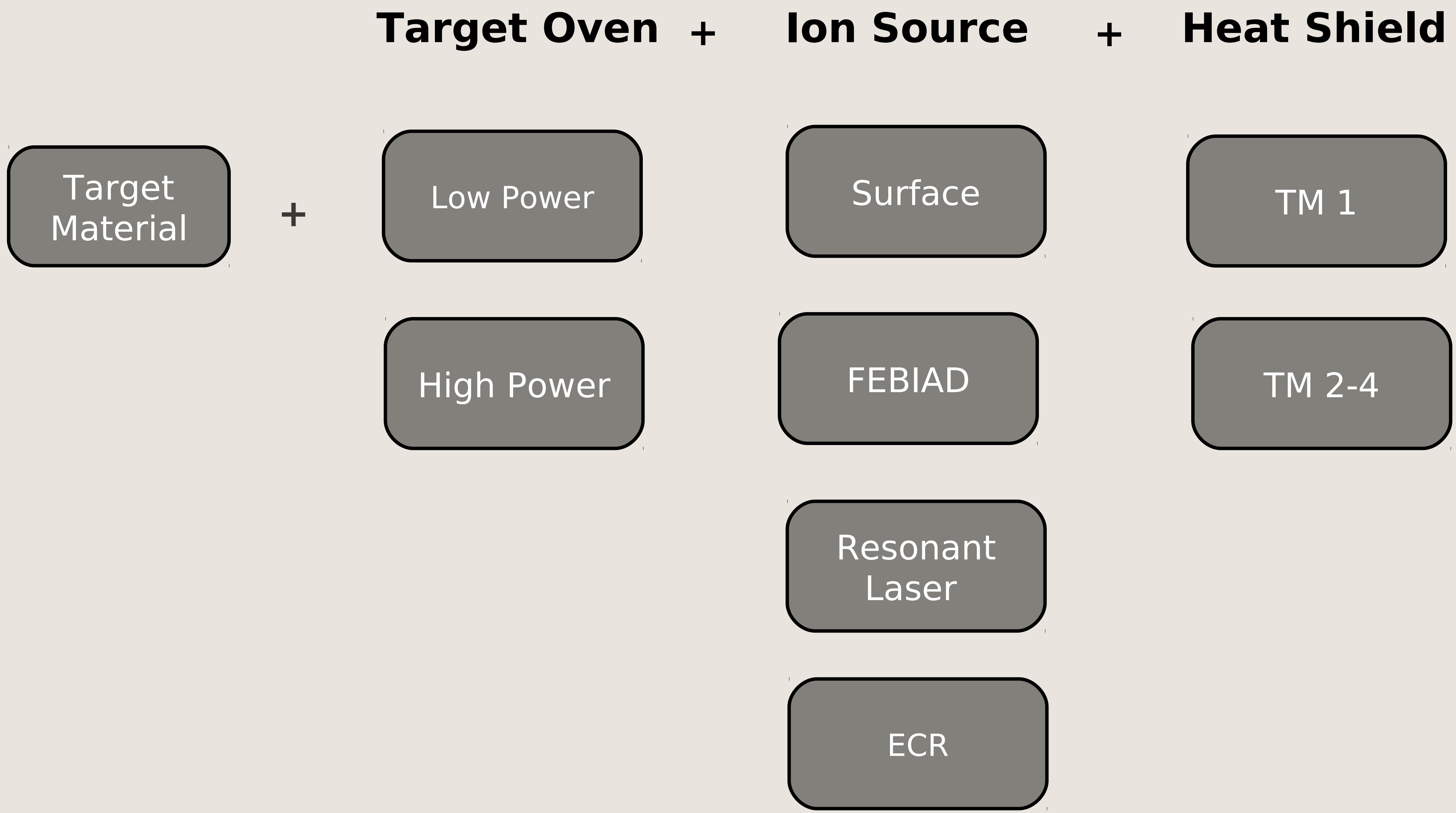




Mass separator, beam transport system, and RFQ

ISACI or ISACII experimental stations for nuclear structure and astrophysics

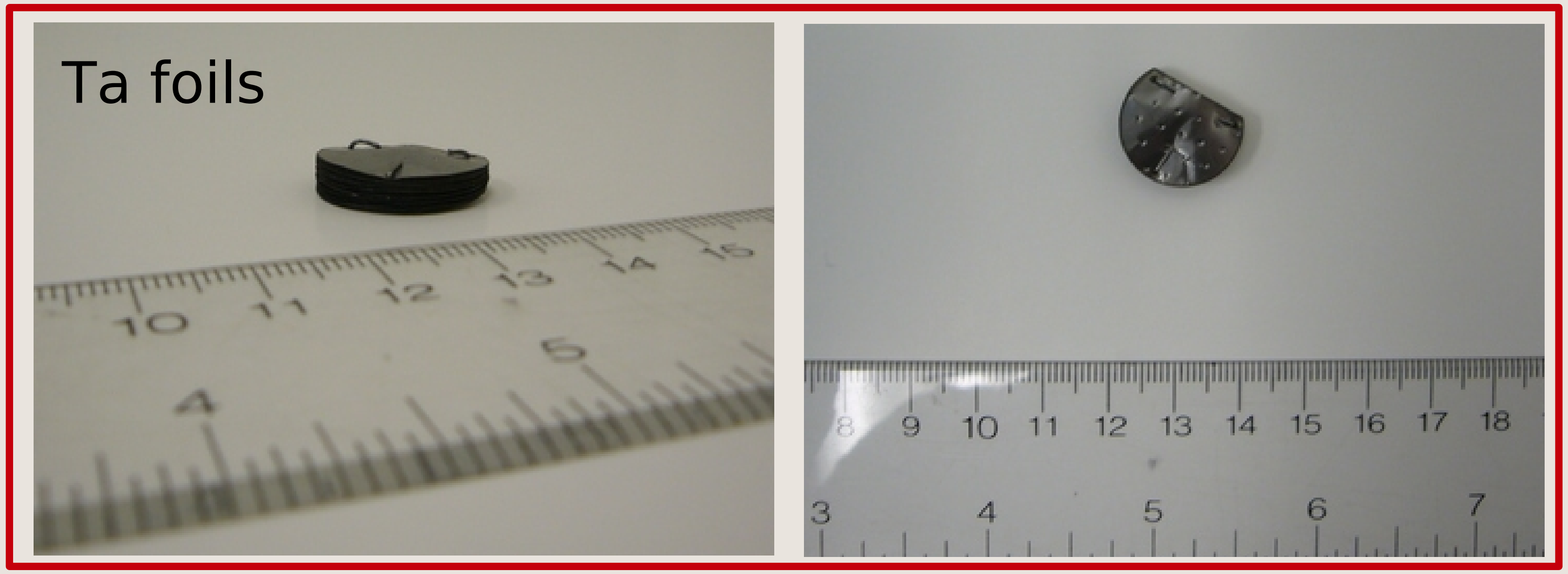
Target Components



Target Components - Target Material

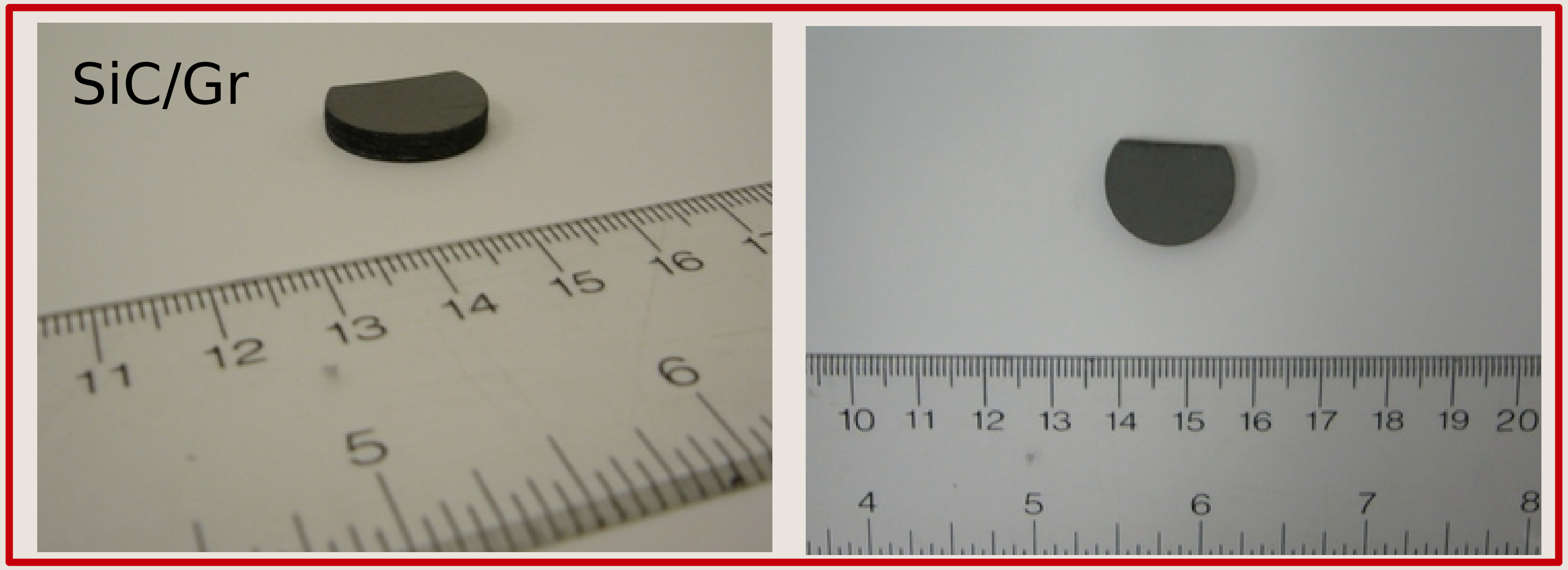
Different materials, depending on the radionuclide of interest
Heat dissipation through radiative cooling and conduction

Refractory target foils:
Nb, Ta



Compound targets:
TaC/Gr, TiC/Gr, SiC/Gr,
ZrC/Gr, UO, Ucx/Gr, ...

Carbides bound onto a graphite foil to achieve higher thermal conductivity



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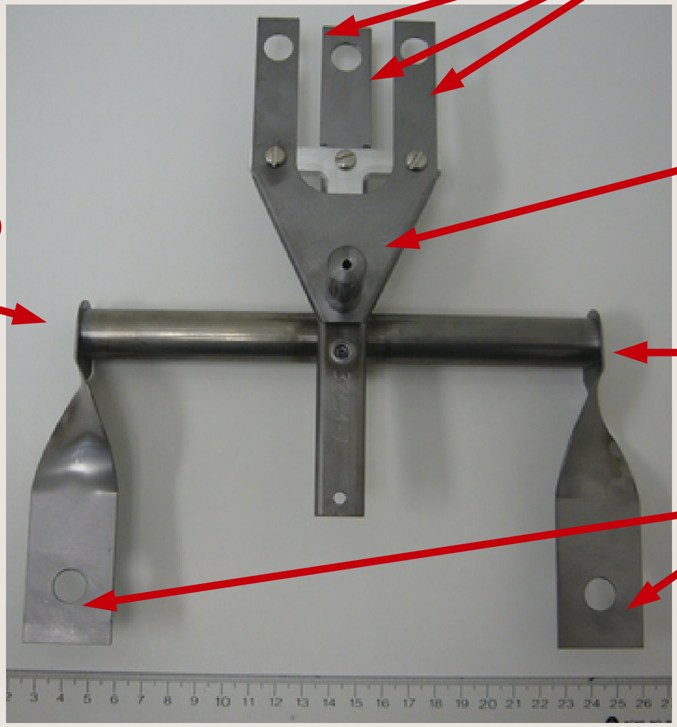
Target Components: Target Oven

Low Power

High Power

End cap

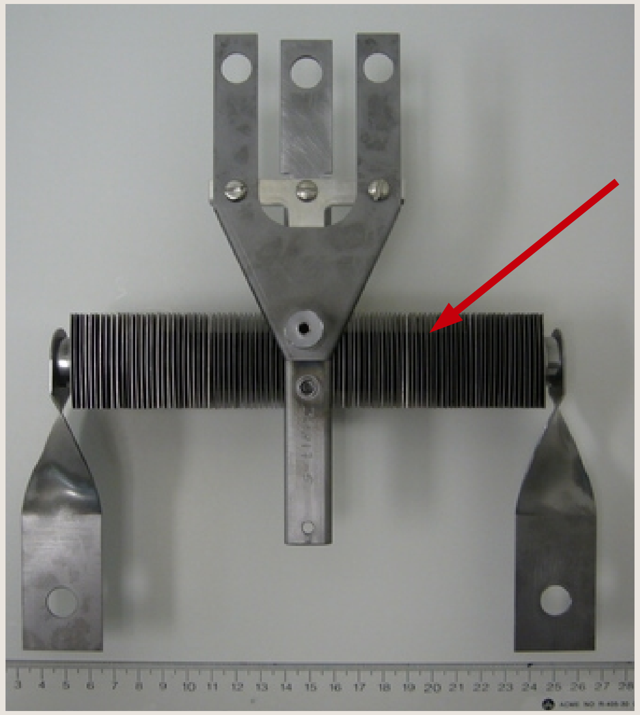


Transfer Tube heating terminals

Transfer Tube

Target Oven

Target Oven heating terminals



Cooling Fins

$I_P \leq 40\ \mu A$

Dissipates up to 5 kW
of power deposited by beam

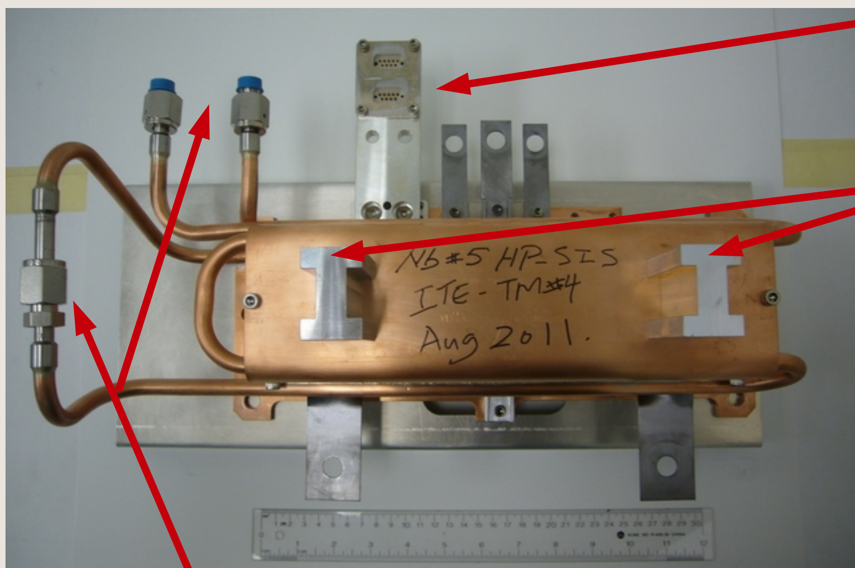
$55\ \mu A \leq I_P \leq 100\ \mu A$

Dissipates up to 25 kW
of power deposited by beam

Target Components – Heat Shield

TM 4

Front View



Plug connector mounting plate

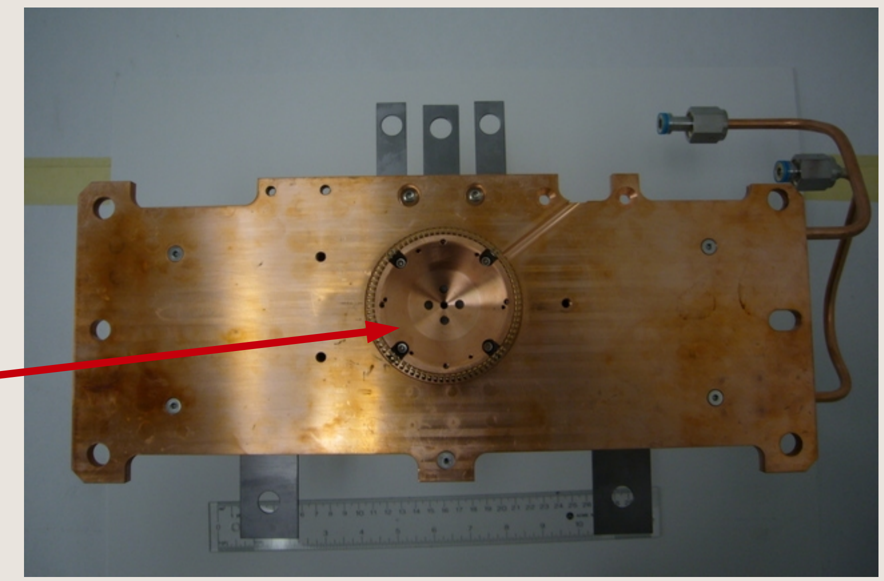
Gripper Arms

Ion source

VCR water connections

TM 1

Back View



Beam's eye View

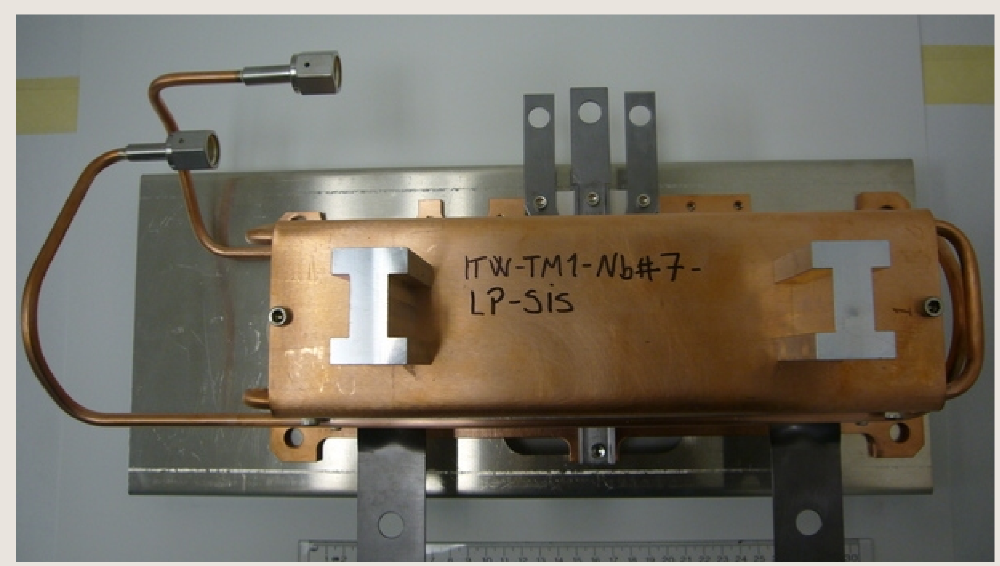
Target Life Cycle

- Raw material and Commercial Components
- Machine Shop
- Assembly
- Test & Inspection
- Target Exchange
- Conditioning
- RIB Production
- Storage & Disposal

Chemistry labs & Machine shop

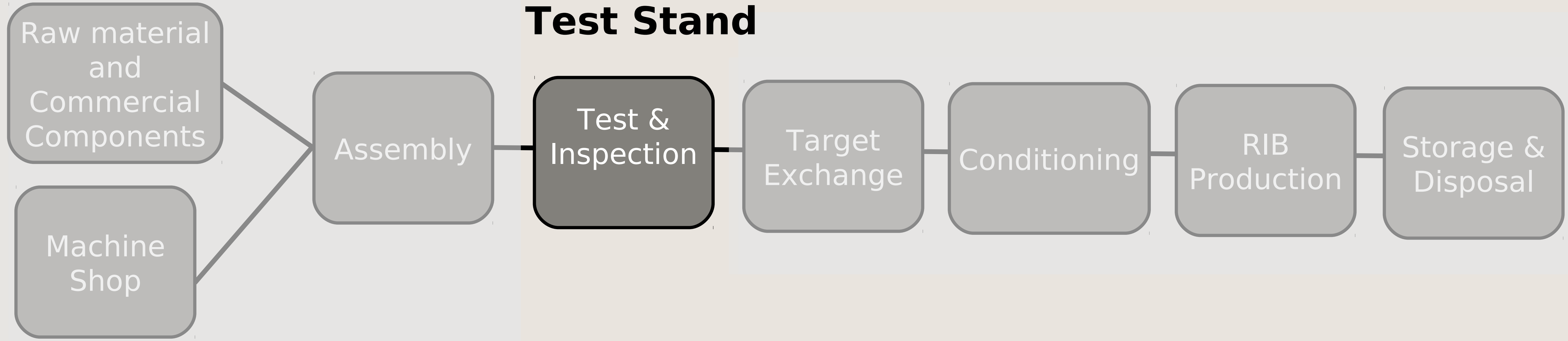


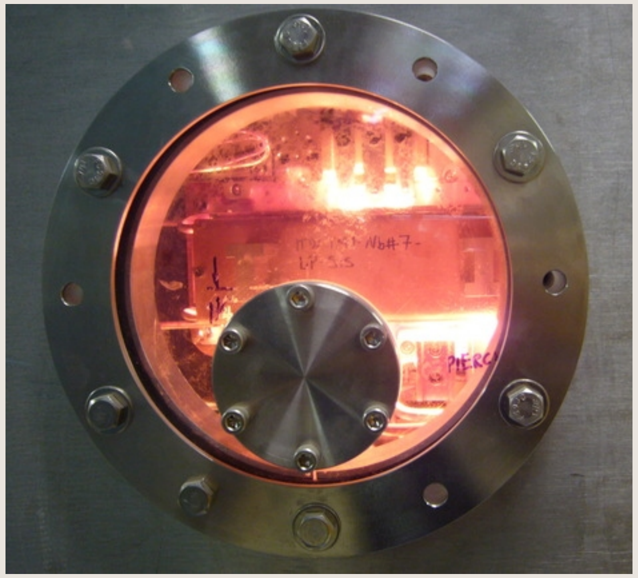


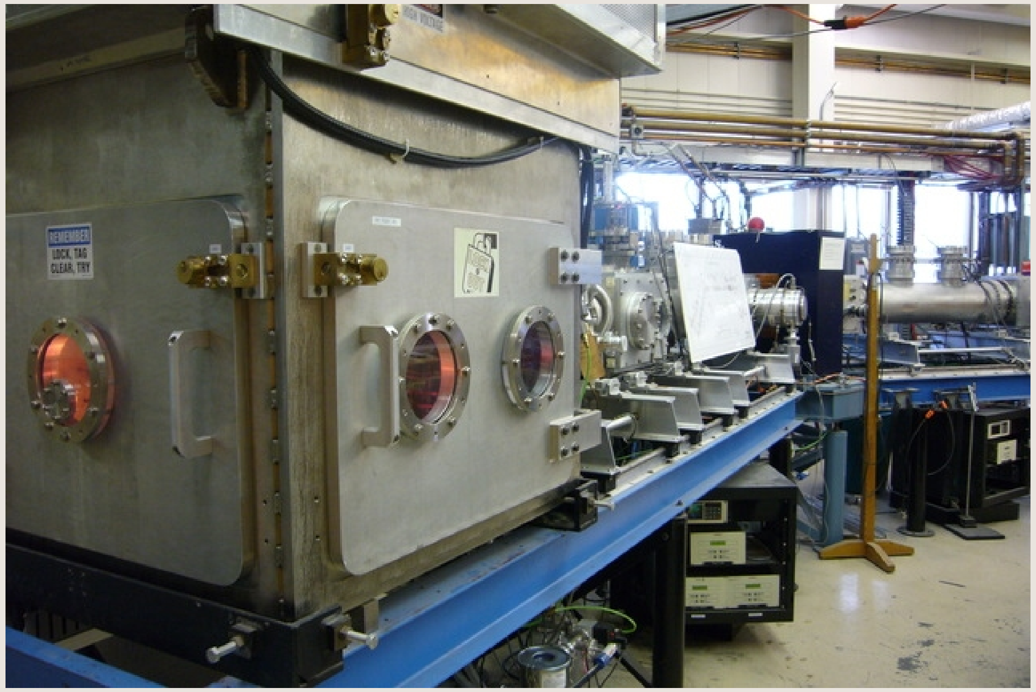



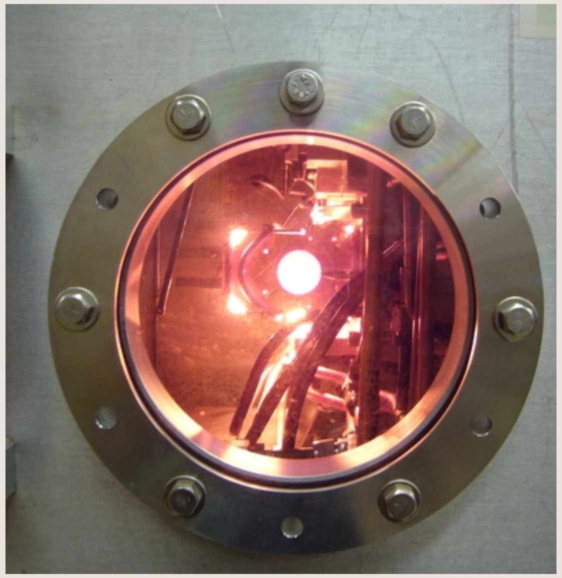
Target Life Cycle

Test Stand









Target Life Cycle

Raw material and Commercial Components

Machine Shop

Assembly

Test & Inspection

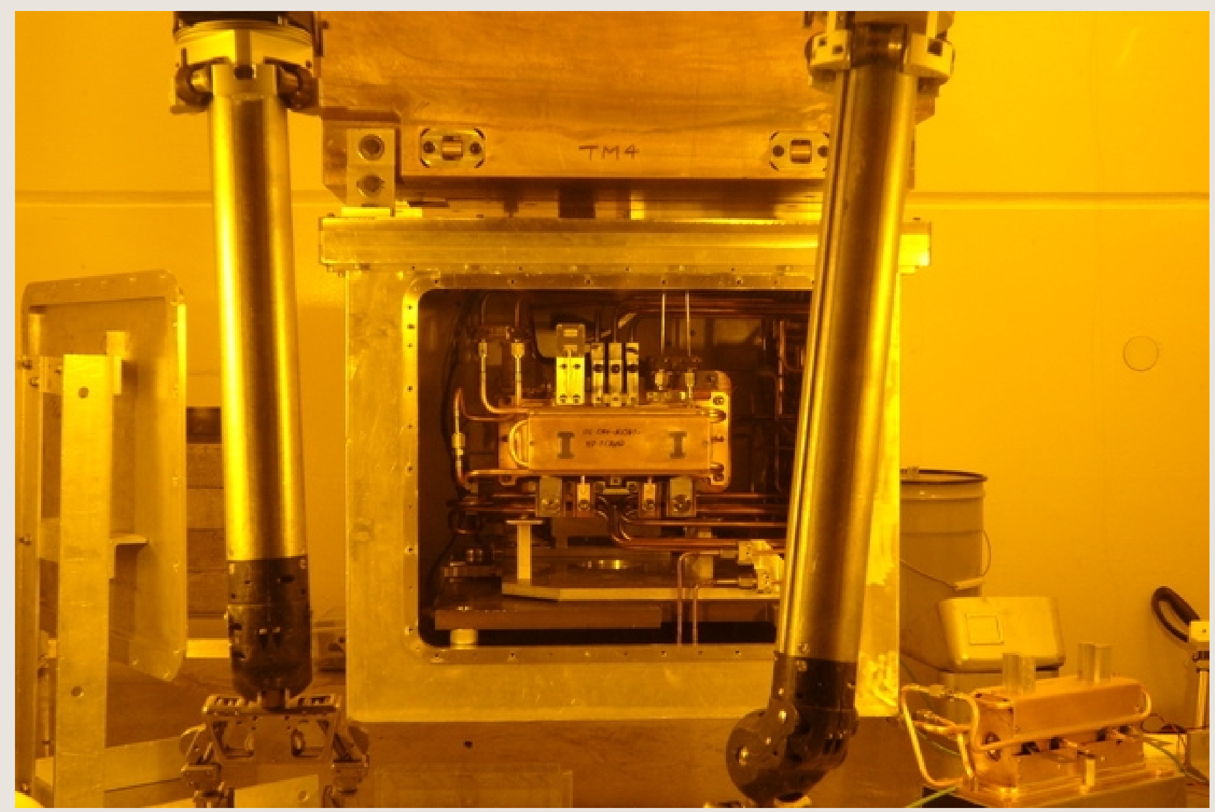
Hot Cell

Target Exchange

Conditioning

RIB Production

Storage & Disposal



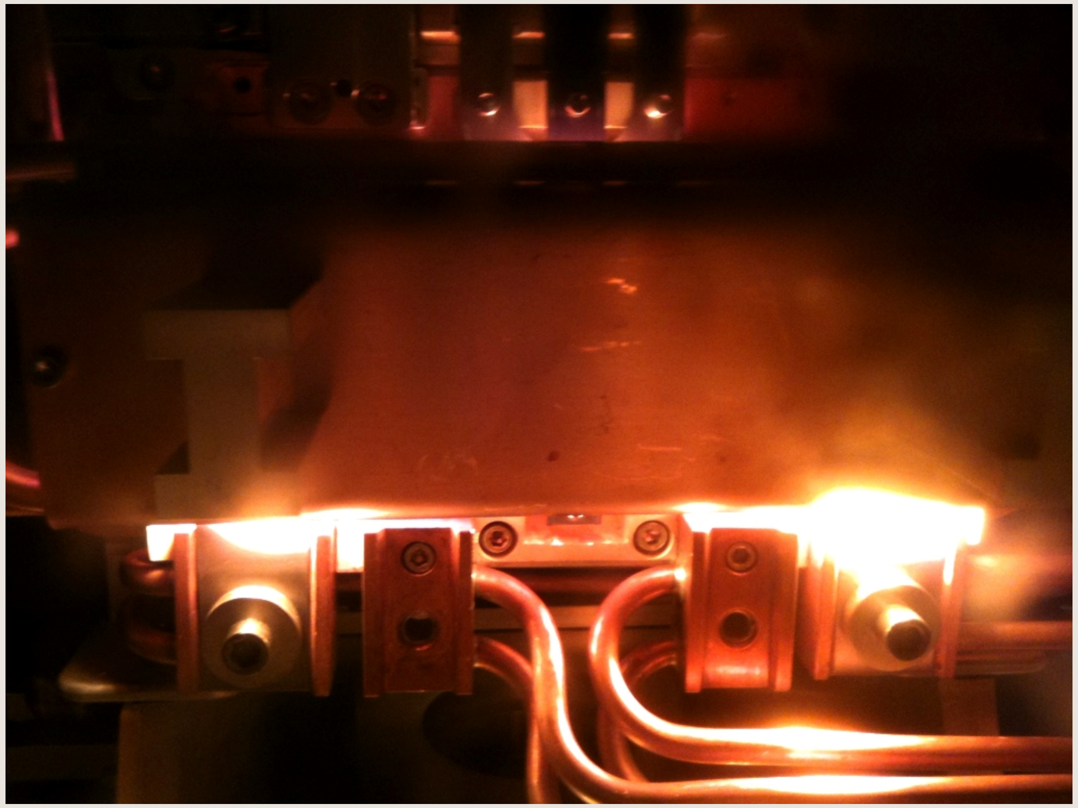
Target Life Cycle

Raw material and Commercial Components

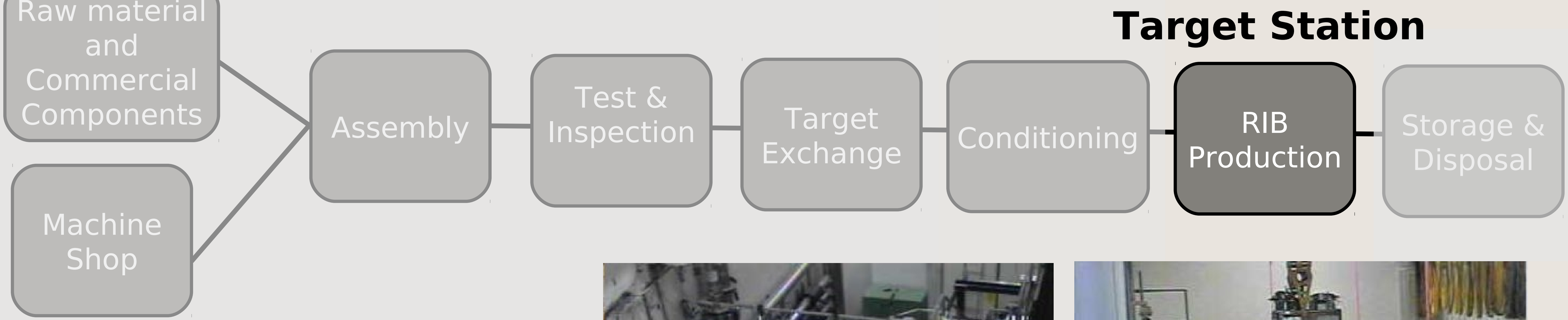
Machine Shop

Assembly → Test & Inspection → Target Exchange → **Conditioning** → RIB Production → Storage & Disposal

Conditioning Station



Target Life Cycle



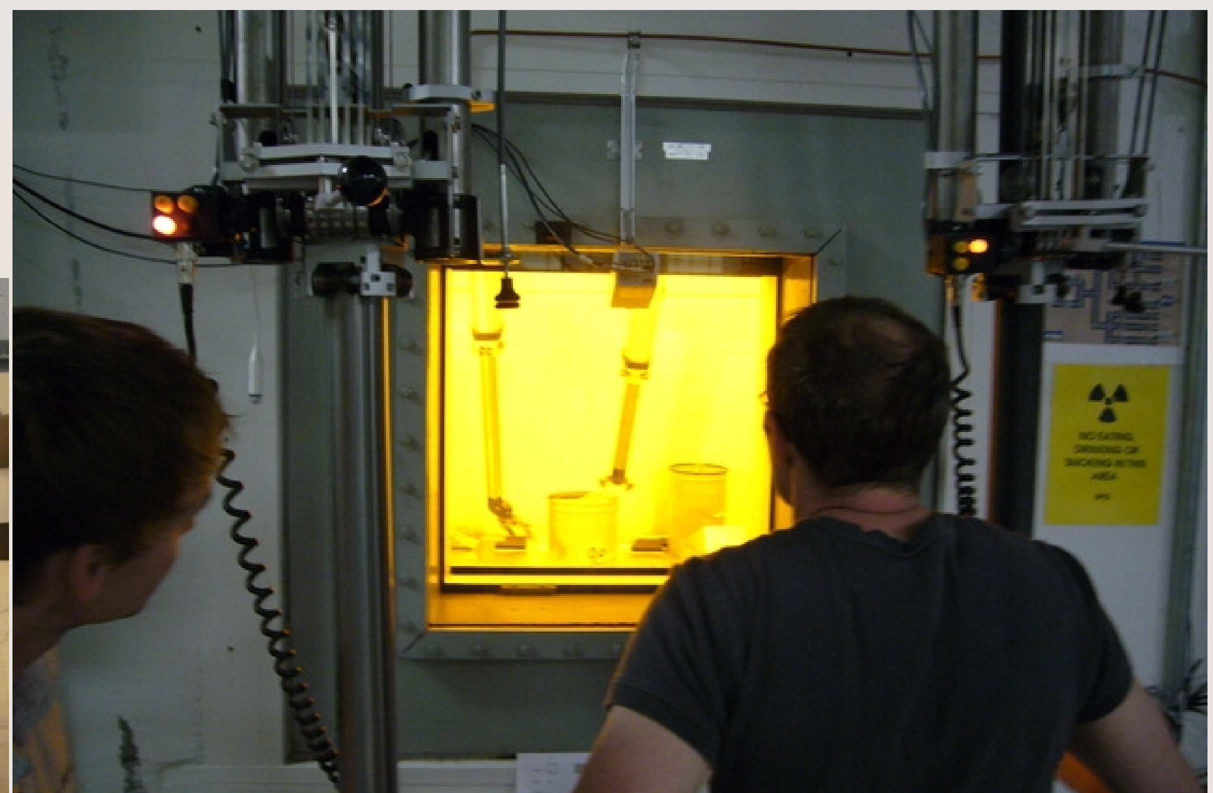
Target Life Cycle

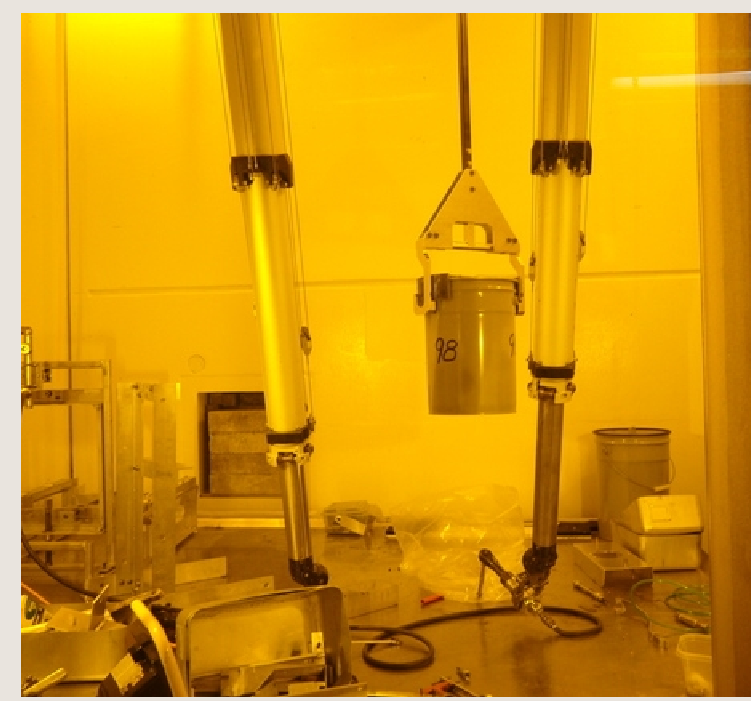
Raw material and Commercial Components → Assembly

Machine Shop → Assembly

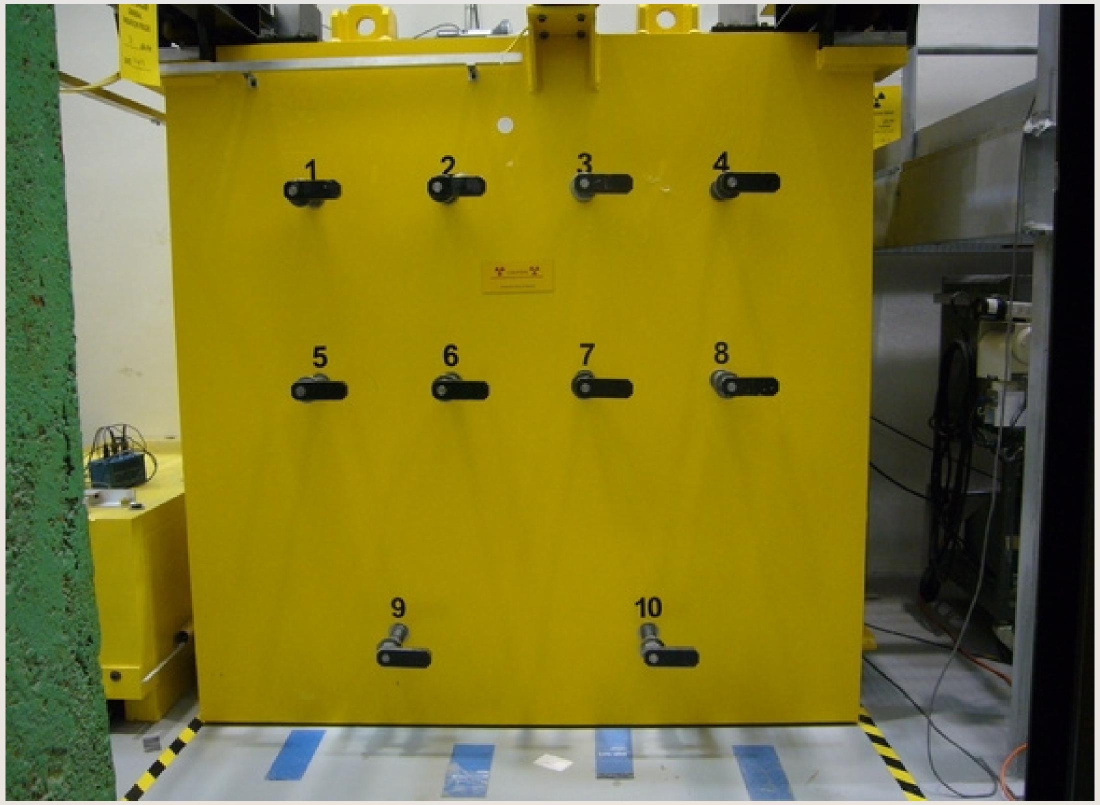
Assembly → Test & Inspection → Target Exchange → Conditioning → RIB Production → Storage & Disposal

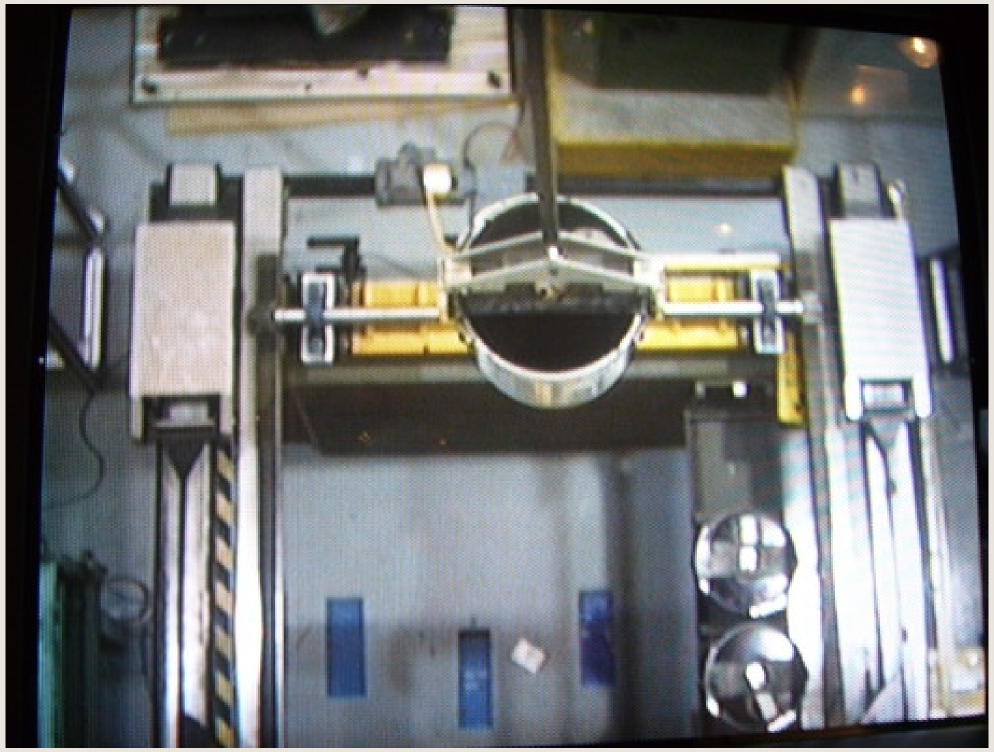
Hot cell





Target Life Cycle





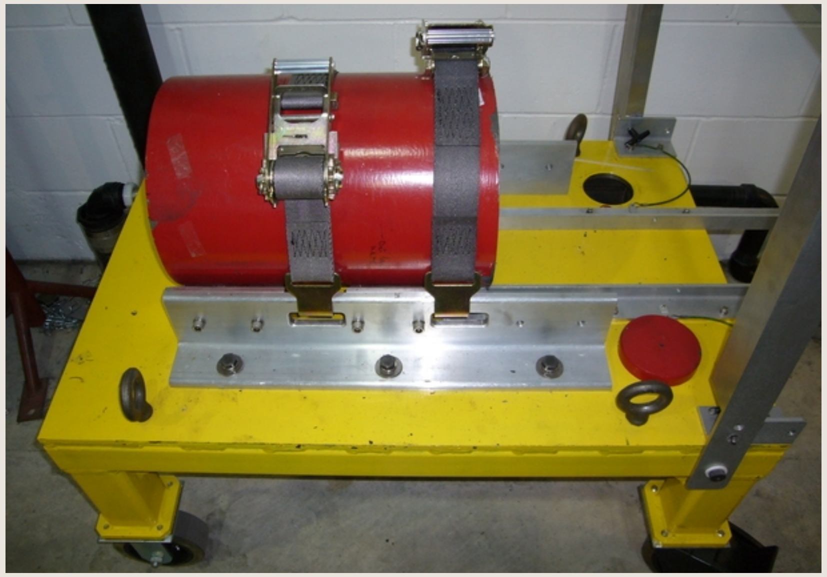
Target Life Cycle

Raw material and Commercial Components → Assembly
Machine Shop → Assembly
Assembly → Test & Inspection → Target Exchange → Conditioning → RIB Production → **Storage & Disposal**

Radiation field and activity measurements

Portable HPGe detector

Collimation & shielding



RAM R-200

Target Life Cycle

Raw material and Commercial Components → Assembly

Machine Shop → Assembly

Assembly → Test & Inspection → Target Exchange → Conditioning → RIB Production → **Storage & Disposal**

Mini storage &Transport Flask

FLUKA SIMULATIONS
Standard (single step) FLUKA run

- Using standard FLUKA (single FLUKA simulation)
  - Production of radioactive isotopes in the target material
  - Time evolution of the radionuclide inventory and their activity
  - Time evolution of residual dose rate, 1 m from the target
  - Contribution of back-scattered neutrons to activation and dose rate

- Using Stefan Roesler's two-step method
  - First-step: Production of radio-nuclides at given cooling times for a given irradiation profile, in different regions
  - Second-step: Assessing shielding for dose rates calculated from transport of the β^+, β^- , γ emitted from radio-nuclides of the first-step

FLUKA SIMULATIONS – Targets simulated

Studied six ISAC targets used between 2008 and 2010

Beam energy: 480 MeV

Beam profile: Gaussian with 7 mm FWHM

Target	Target Oven		Ion Source	Heat Shield		Beam Intensity (μA)	Irradiation time (h)
	LP	HP	SIS	TM1	TM4		
Ta#27	x		x	x		40	705
SiCGr#24	x		x	x		35	286
Ta#26		x	x		x	70	578
SiCGr#25		x	x		x	68	247
Nb#4		x	x		x	98	416
Nb#5		x	x		x	98	537

FLUKA SIMULATIONS – Material description

- Target Material
  - Single elements: Ta and Nb

    Volume = total length * disc area

    Effective Density = (total mass) / volume

  - Compounds: SiC bounded onto graphite (SiC/Gr)

    Find fractional masses:

    Mass(SiC): # SiC discs * t_SiC * ρ_SiC * disc area

    Mass(Gr): # gr discs * t_gr * ρ_gr * disc area

    Find compound effective density:

    Effective Density = (total mass) / volume

- Target Oven + Heat Shield + Ion Source

  Ta, Cu, AlN, Al alloy 6061-T6, and SST

FLUKA SIMULATIONS – Targets simulated

Six regions for activation study:

Target material + Ta + Cu + 6061-T6 + AlN + SST

Target	Length (cm)	Mass (g)	Effective Density (g/cm^3)
Ta#27	7.5	46.19	2.89
SiCGr#24	18.4	55.46	1.36
Ta#26	7.2	46.19	2.78
SiCGr#25	18.5	54.63	1.33
Nb#4	8.6	23.85	1.25
Nb#5	4.0	18.7	2.05

FLUKA SIMULATIONS – Targets simulated

Six regions for activation study:

Target material + Ta + Cu + 6061-T6 + AlN + SST

Target Module	Quantity	Region				
		Ta	Cu	6061-T6	AlN	SST
TM1	Volume (cm^3)	29.4	461.3	109.3	19.8	28.6
	Density (g/cm^3)	16.7	9.0	2.7	3.3	8.0
	Mass (g)	489.2	4133.3	295.2	64.8	228.6
TM4	Volume (cm^3)	62.9	711.4	164.4	19.8	32.6
	Density (g/cm^3)	16.7	9.0	2.7	3.3	8.0
	Mass (g)	1047.0	6374.4	443.9	64.8	260.9

FLUKA SIMULATIONS – Geometry description

- Target material

  Solid cylinder inside the Target Oven with top cut off

- Target Oven

  Inf. Cylinders + planes + RPPs to mimic geometry in the drawings as closely as possible (fins' tot. Volume added to the T.O. tube)

- Heat Shield + Ion Source

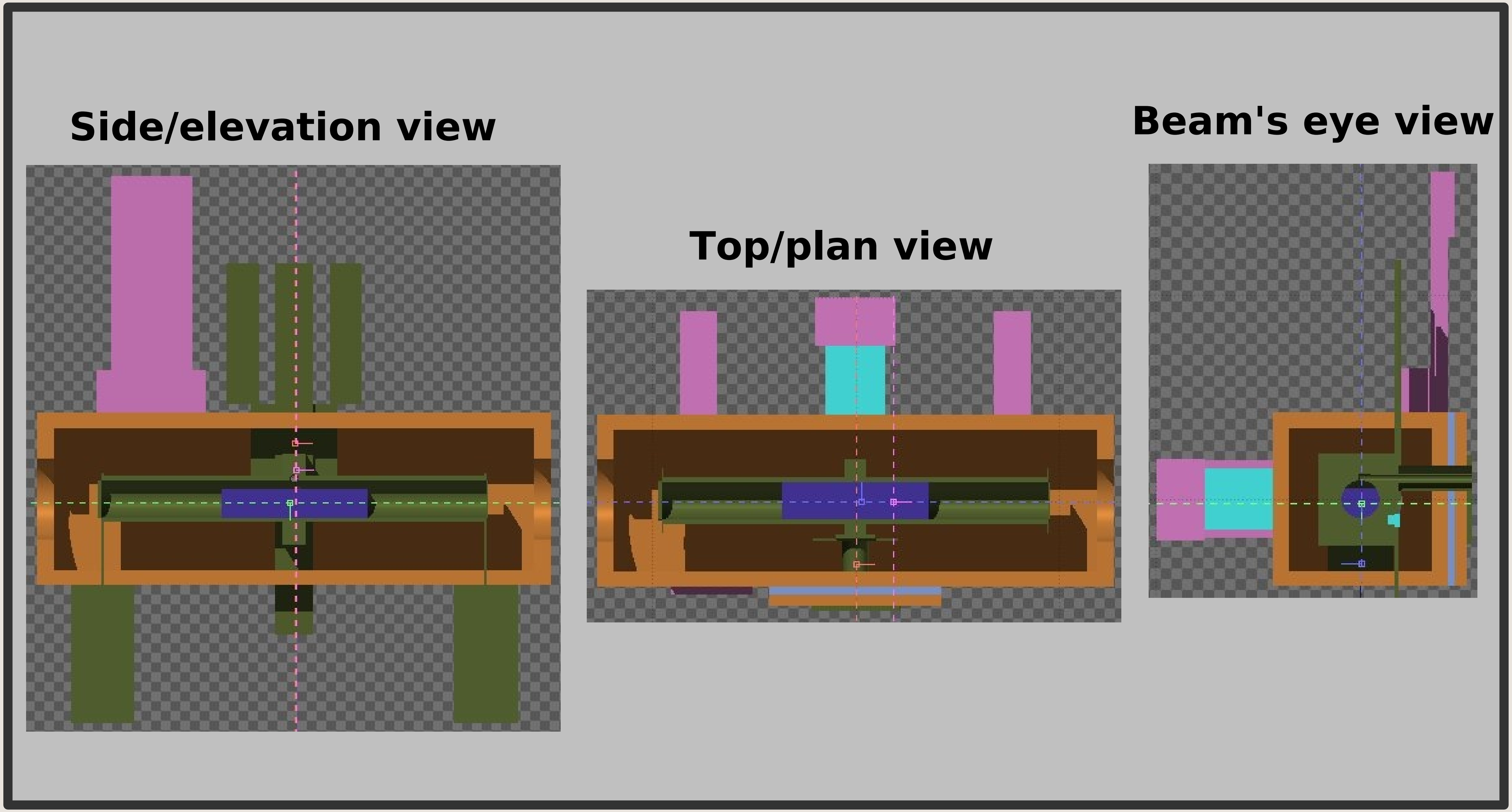
  RCCs to describe cover, cover plate, and base for Heat Shield

  Copper tubes added into the above volume, using volumes from solid works

  All remaining components of H.S. And Ion Source, were added as simple geometrical shapes, using volume and material info. From solid works

FLUKA SIMULATIONS – Geometry

Ta#26



FLUKA Physics settings

Activated:

- Evaporation of heavy fragments

  PHYSICS   SDUM=EVAPORAT WHAT(1)=3

- Coalescence mechanism

  PHYSICS   SDUM=COALESCE   WHAT(1)=1

FLUKA Transport settings (1)

Set:

- Production thresholds for e^+, e^-, γ in all materials to 20 keV (KE)

  EMFCUT SDUM=PROD-CUT WHAT(1)=2E-5 WHAT(2)=2E-5
  WHAT(4) and WHAT(5) to cover all materials

- Transport threshold for e^+, e^-, γ in all regions to 20 keV (KE)

  EMFCUT SDUM='empty' WHAT(1)=2E-5 WHAT(2)=2E-5
  WHAT(4) and WHAT(5) to cover all regions

- Proton transport cut-off for protons to 1 keV

  PART-THR SDUM=Energy WHAT(1)=1E-6 WHAT(2)=PROTON

FLUKA Transport settings (2)

Radioactive decays

- Activate radioactive decays for build-up and cool-down times
- Set transport energy cut-off for β^+,β^-,γ to 20 KeV
- Set transport energy cut-off mult. factor to 99999
  (kill electromagnetic cascade in the prompt part)

RADDECAY SDUM=PROD-CUT WHAT(1)=Active WHAT(2)=On
WHAT(3)=3 WHAT(4)=0 WHAT(5)=1099999

FLUKA Transport settings (3)

- Define irradiation profile

  Irradiation time: 578 hours , Beam Intensity: 70 μA

  IRRPROFI WHAT(1)=2080800 WHAT(2)=4.3694E14

- Set build-up times

  Build-up times (4): 1 h, 1 d, 3 d, 10 d after SOB

  DCYTIMES WHAT(1)=-2.0772E6 WHAT(2)=-1.9944E6
  WHAT(3)=-1.8216E6 WHAT(4)=-1.2168E6

- Set cool-down times

  Cool-down times (9): 0 s, 1 h, 1 d, 10 d, 40 d, 1 y, 2y, 3y, 5y after EOB

  DCYTIMES WHAT(1)=0 WHAT(2)=3600 WHAT(3)=86400
  WHAT(4)=864000 WHAT(5)=3.456E6 WHAT(6)=3.154E7
  WHAT(7)=6.307E7 WHAT(8)=9.461E7 WHAT(9)=1.577E8

FLUKA Scoring (1)

Looked at:

- Isotope production rate (nuclei/prim) in each of the 6 regions (6 RESNUCLE cards)

  Ex: Isotope production rate in the Tantalum target region

```
RESNUCLE    3.    -21.    74.    49.    rTgtTa26    1.RNTgt
```

- Time evolution of activities (Bq) in each of the 6 regions (78 RESNUCLE plus 13 DCYSCORE cards)

  Ex: Activity in the Tantalum target region, 1 hour after EOB

```
RESNUCLE          3.      -31.       74.       49.  rTgtTa26        1.SOB1hTgt
DCYSCORE          1.      SOB1hTgt        RESNUCLE
```

FLUKA Scoring (2)

Looked at:

- Time evolution of residual dose rate (pSv/s) in a cylindrical detector (1m long x 10 cm thick) filled with air, placed 1 m away from the center of the beamline

  Ex: Residual dose rate, 1 hour after SOB

```
USRTRACK          -1.   DOSE-EQ      -47.     rDet    65973.46    100.DEDetSB1h
USRTRACK  0.010010          1E05                                          &
```

Used the default AMB74 fluence to dose equivalent conversion coefficients

FLUKA simulation results (1)

- Based on 100 M primaries (20 M prim/run * 5 runs)

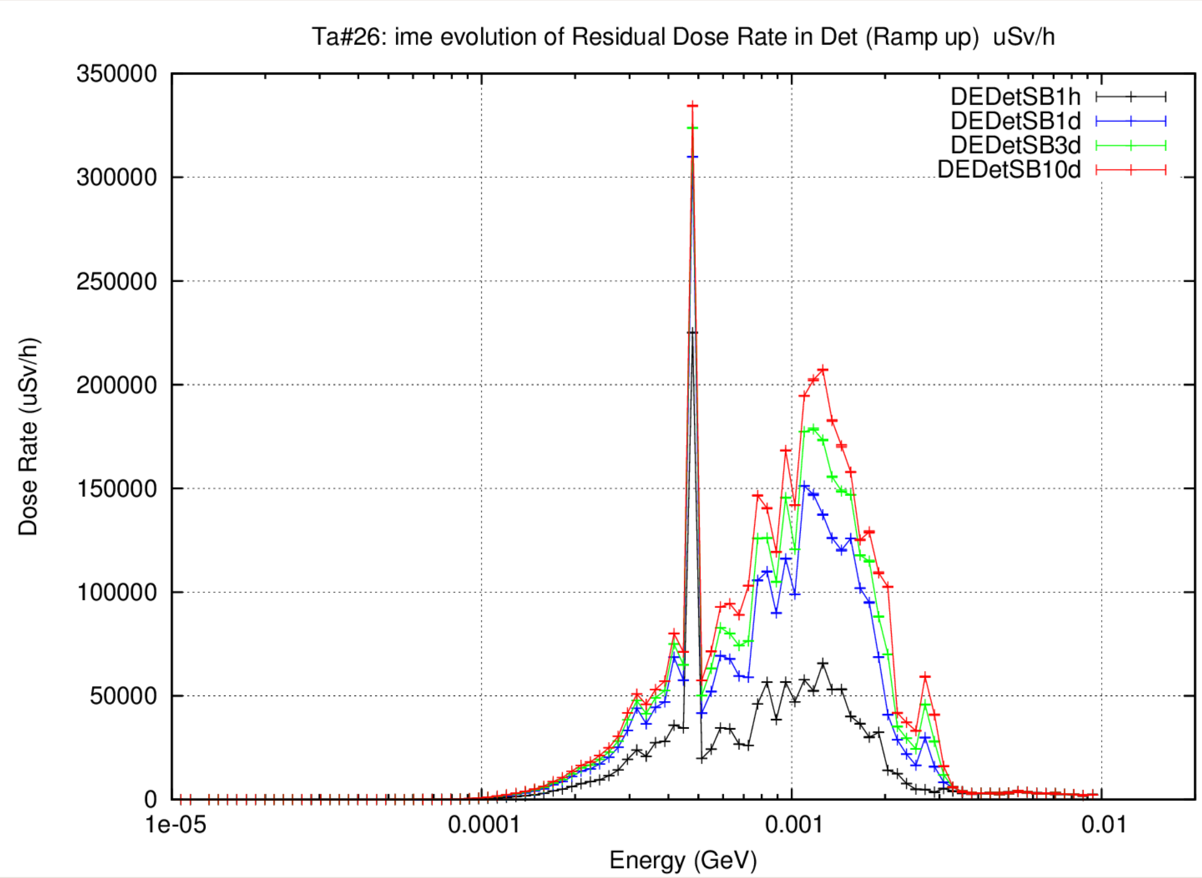
- Post-processing:
  - Used flair to combine results of multiple runs
  - Used python, shell, and awk scripting to extract relevant information from “tab” and “sum” files for comparison purposes

FLUKA simulation results

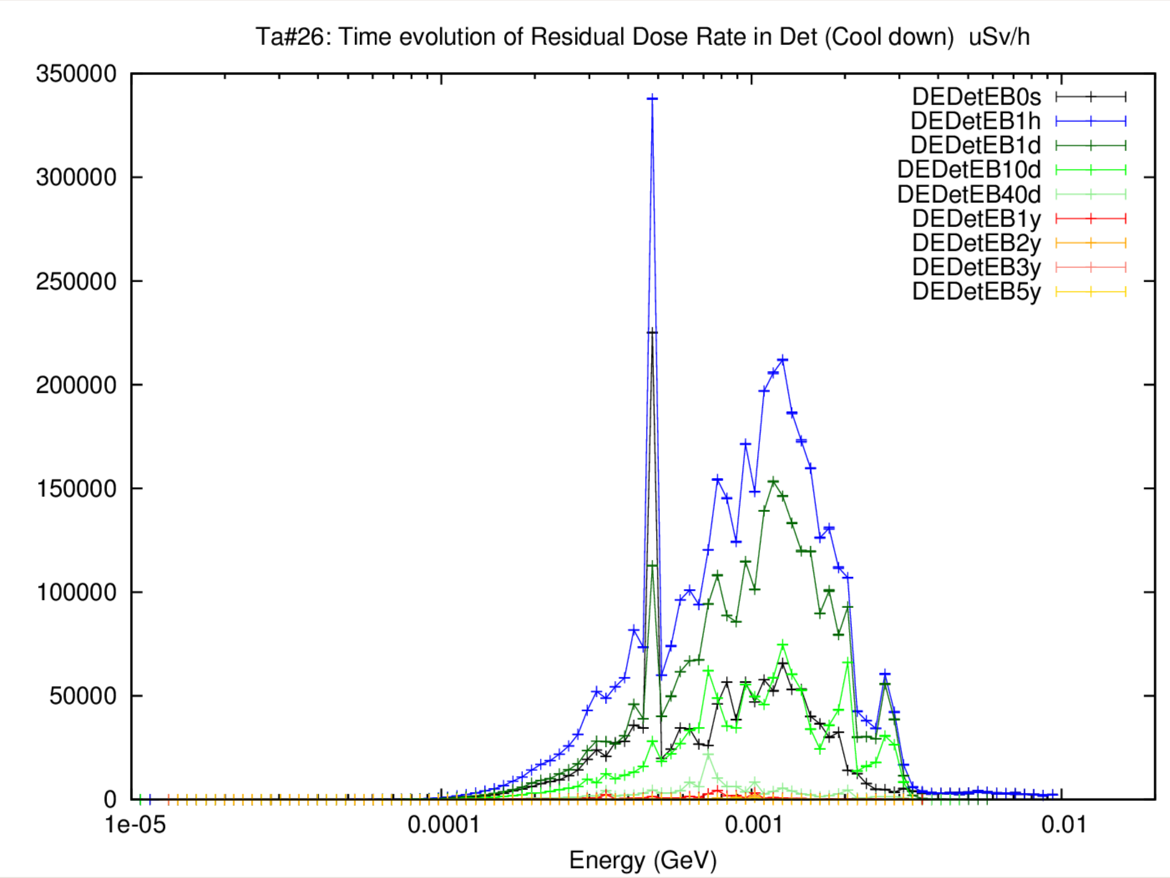
Time evolution of residual dose rates in the detector

As a function of energy for Ta#26

Build-up times



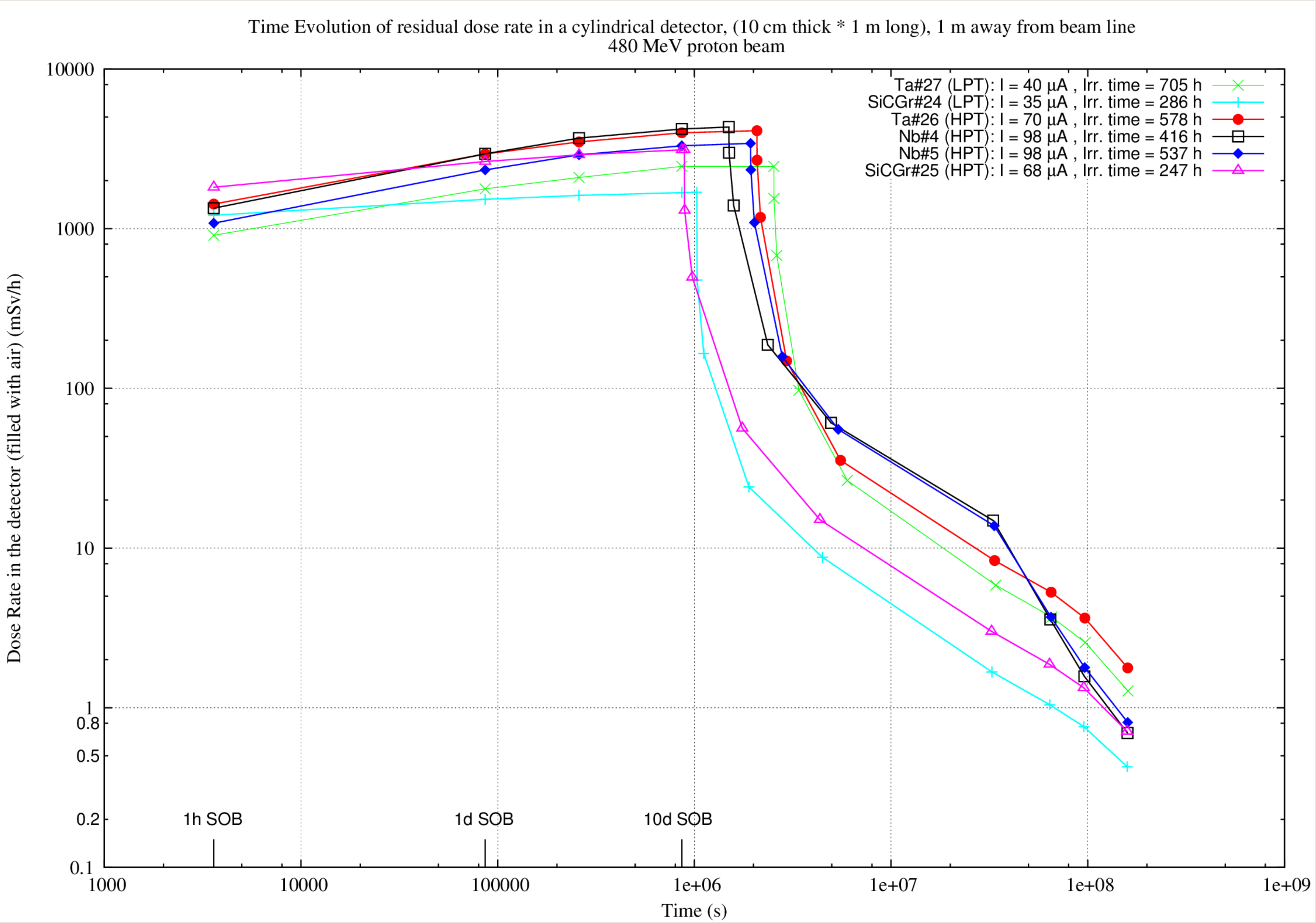
Cool-down times



Detector placed 1 m away from the target (1m long x 10 cm thick)

FLUKA simulation results (3)
Time evolution of residual dose rates in the detector

Total dose rates for the 6 targets studied



FLUKA simulation results (4)

Residual dose rates – comparison B/N FLUKA and measurement

Target	Measurement time after EOB (years)	Dose Rate (mSv/h)		FLUKA/Measurement
		Measurement +/- 10%	FLUKA +/- < 0.5%	
Ta#27	2.65	2.71	2.96	1.09
SiCGr#24	1.20	1.99	1.55	0.78
Ta#26	3.14	3.34	3.51	1.05
Nb#4	2.13	3.89	3.31	0.85

FLUKA simulation results (5)

Total activities: Comparison between FLUKA & measurement

γ-emitting Isotopes		Total activity (Bq), 3 years after EOB							
Isotope	$T_{1/2}$ (y)	Ta#27		SiCGr#24		Ta#26		Nb#4	
		FLUKA	Assay	FLUKA	Assay	FLUKA	Assay	FLUKA	Assay
Na-22	**2.60**	**6.37e+7**	**7.43e+7**	**2.43e+9**	**4.08e+9**	**6.05e+7**	**3.21e+7**	**4.54e+7**	**1.16e+8**
Mn-54	**0.86**	**4.09e+8**	**3.58e+8**	**2.69e+8**	**3.74e+8**	**6.76e+8**	**3.23e+8**	**5.00e+8**	**3.50e+8**
Co-56	**0.21**	**7.28e+5**		**5.66e+5**	**4.25e+5**	**1.15e+6**		**9.11e+5**	
Co-57	**0.74**	**8.94e+8**	**2.83e+8**	**6.04e+8**	**2.82e+8**	**1.42e+9**	**6.05e+8**	**1.04e+9**	
Co-58	**0.19**	**1.34e+6**	**1.78e+8**	**8.41e+5**	**9.53e+5**	**2.23e+6**	**1.63e+9**	**1.62e+8**	**1.47e+7**
Co-60	**5.28**	**8.93e+8**	**6.09e+8**	**3.29e+8**	**4.84e+8**	**7.75e+8**	**1.05e+9**	**5.37e+8**	**6.22e+8**
Zn-65	**0.67**	**4.11e+7**		**2.81e+7**	**4.41e+7**	**5.43e+7**		**2.02e+8**	**1.52e+8**
Se-75	**0.33**	**4.99e+5**	**2.17e+7**	**4.43e+4**		**8.18e+5**		**7.63e+7**	**4.55e+7**
Y-88	**0.29**	**9.19e+5**	**1.89e+6**	**6.96e+4**	**3.65e+5**	**1.62e+6**	**2.74e+9**	**9.27e+8**	**5.87e+8**
Lu-172	**0.02**	**1.63e+10**		**1.56e+9**		**3.15e+10**		**1.07e+10**	
Lu-173	**1.37**	**1.64e+10**		**1.61e+9**		**3.22e+10**	**3.66e+8**	**1.12e+10**	
Hf-172	**1.87**	**1.61e+10**	**7.77e+9**	**1.54e+9**	**2.98e+9**	**3.12e+10**	**6.31e+9**	**1.06e+10**	**3.14e+9**
Hf-175	**1.19**	**9.24e+6**	**5.30e+6**	**1.04e+6**	**1.3e+9**	**1.94e+7**		**7.20e+6**	**2.48e+6**
Ta-182	**0.31**	**1.28e+4**	**1.80e+8**	**1.00e+3**	**3.09e+7**	**1.95e+4**	**5.56e+8**	**8.02e+3**	**1.72e+8**

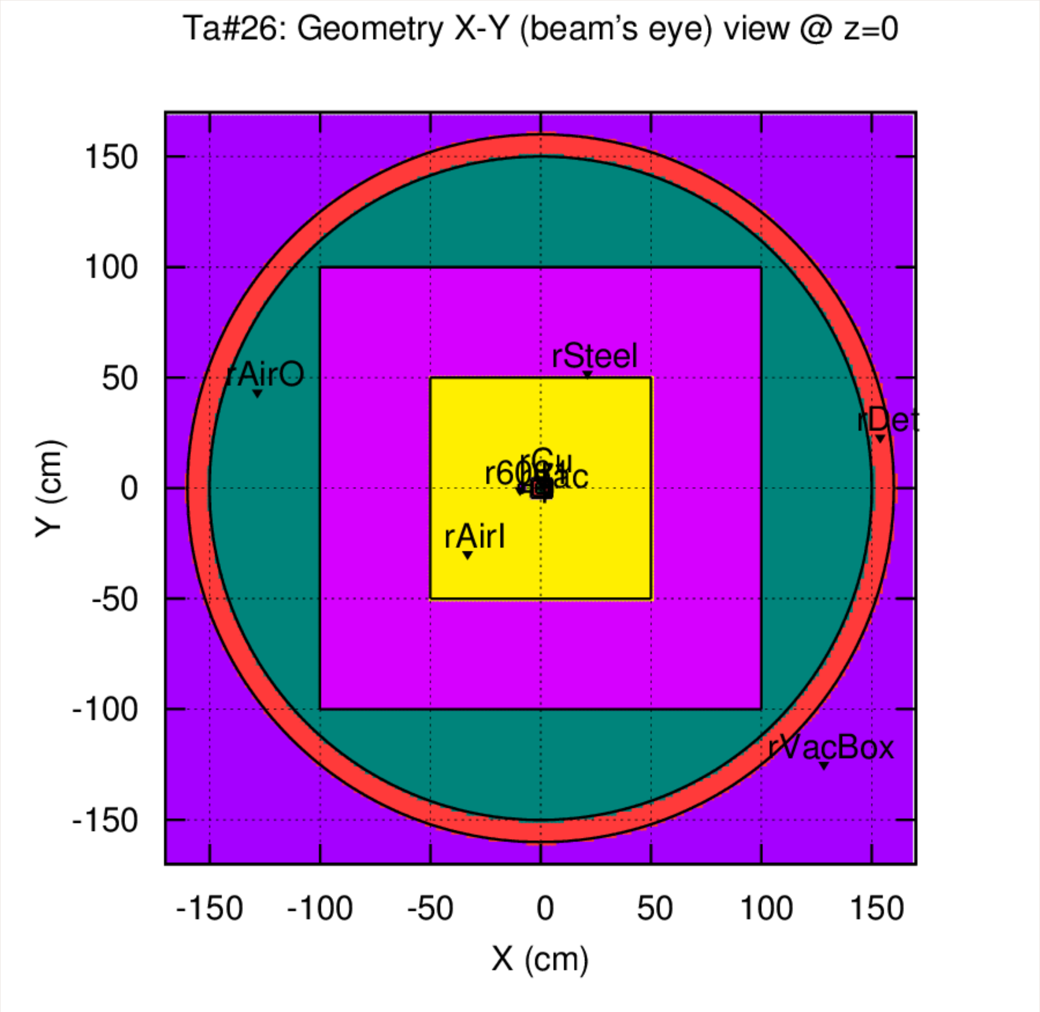
FLUKA simulation results (6)
Residual dose rates calculated from activities and h*10

Target	Dose Rats, 3 y after EOB (mSv/h)		FLUKA/Measurement
	Measurement	FLUKA	
Ta#27	2.56	5.50	2.15
SiCGr#24	2.43	1.46	0.60
Ta#26	3.63	10.2	2.81
Nb#4	1.47	4.01	2.73

Gamma factors from document 814.501 (Data for Operational Radiation Protection)

FLUKA simulation results (7)
Contribution from back-scattered neutrons

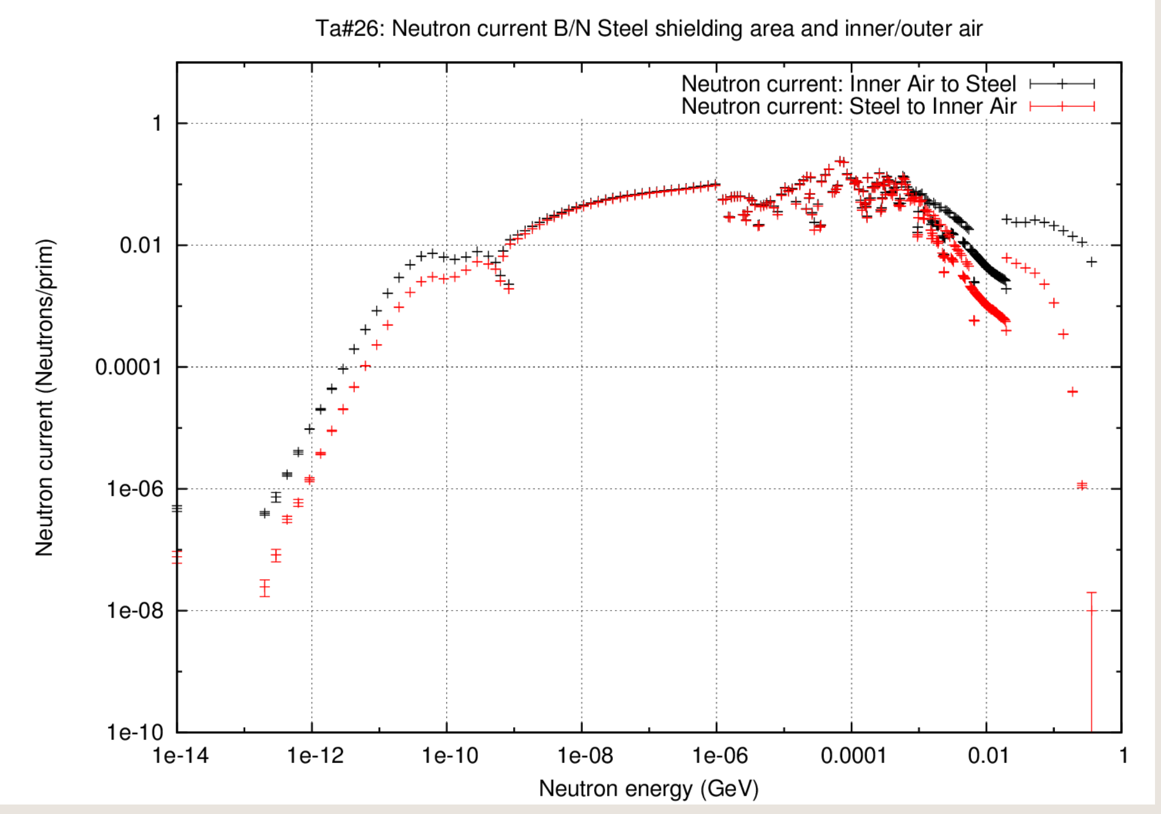
Added 50 cm steel outside the target assembly to assess contribution to activation from back-scattered neutrons

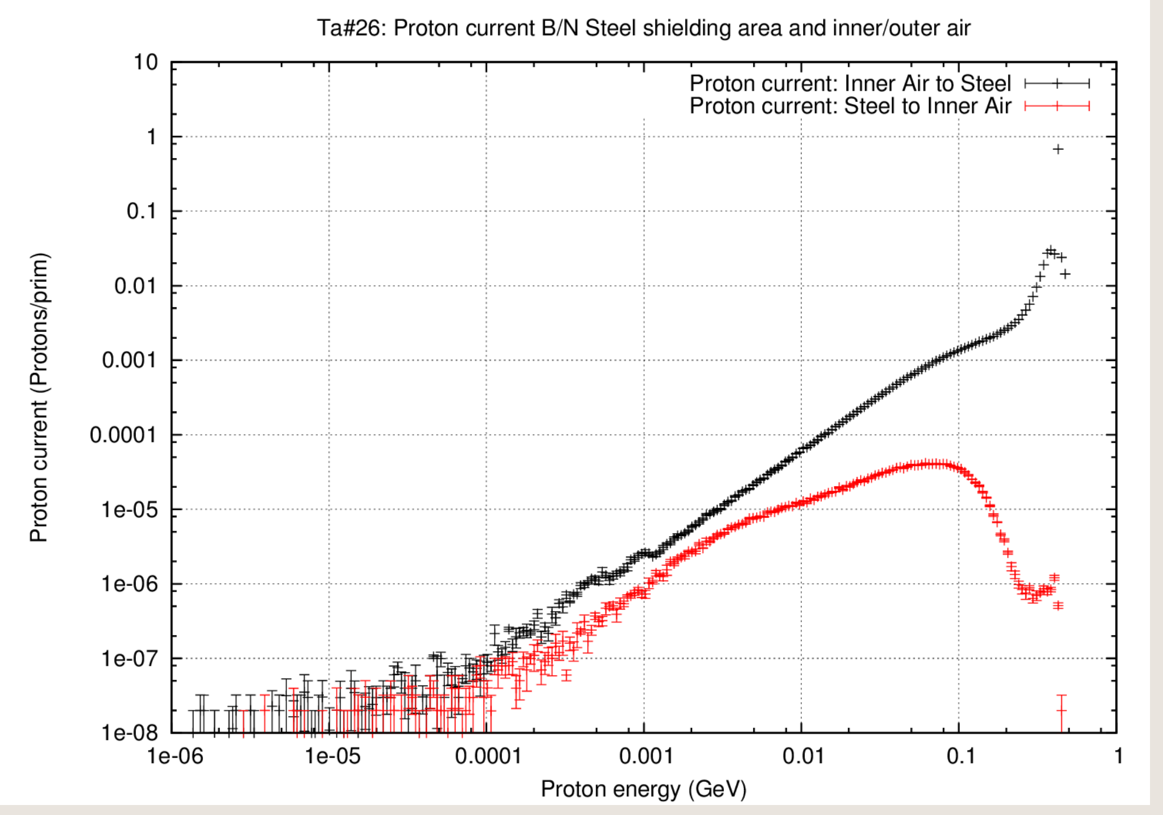


FLUKA simulation results (8)
Neutron and proton currents

Neutrons
crossing the 'inner Air' and 'steel' boundary

Protons
crossing the 'inner Air' and 'steel' boundary





FLUKA simulation results (7)
Contribution from back-scattered neutrons

γ-emitting Isotopes		Total activity for Ta#26, 3 years after EOB	
Isotope	$T_{1/2}$ (y)	FLUKA	
		No shielding	Steel shielding
Na-22	**2.60**	**6.05e+7**	**5.96e+7**
Mn-54	**0.86**	**6.76e+8**	**6.74e+8**
Co-56	**0.21**	**1.15e+6**	**1.18e+6**
Co-57	**0.74**	**1.42e+9**	**1.43e+9**
Co-58	**0.19**	**2.23e+6**	**2.22e+6**
Co-60	**5.28**	**7.75e+8**	**7.89e+8**
Zn-65	**0.67**	**5.43e+7**	**5.48e+7**
Se-75	**0.33**	**8.18e+5**	**7.86e+5**
Y-88	**0.29**	**1.62e+6**	**1.63e+6**
Lu-172	**0.02**	**3.15e+10**	**3.15e+10**
Lu-173	**1.37**	**3.22e+10**	**3.23e+10**
Hf-172	**1.87**	**3.12e+10**	**3.12e+10**
Hf-175	**1.19**	**1.94e+7**	**1.93+7**
Ta-182	**0.31**	**1.95e+4**	**2.19e+4**

FLUKA SIMULATIONS
Stefan Roesler's two-step method

First-step: Production of radio-nuclides at given cooling times for a given irradiation profile in different regions

- Geometry, material, physics, biasing, same as in the standard run
- Took out RADDECAY, IRRPROFI, DCYTIMES under Transport

Additional files:

Fortran file: doserate11.2.f

Contains: usrini.f, usrout.f, usrrnc.f → 1st step (usrini.f, usrrnc.f)

source.f → 2nd step

Data files:

Irrcyc.inp	irradiation cycle	→ 1st step
glines.dat	γ emitters	→ 2nd step
plines.dat	β^+ emitters	
eiclines.dat	β^- emitters	
ICRP38.BET	β energy spectra	→ 2nd step

FLUKA SIMULATIONS

Stefan Roesler's two-step method – First Step

Define irradiation cycle and cooling times in irrcyc.inp

4.369e14	Beam intensity (protons/sec for I = 70 μA)
h600.	Irradiation time (600 hours)
s0	
1	→ Not used, don't change!
s1	

Input settings (1)

- Under Scoring:

  - A single RESNUCLE card for a region in which nuclides are produced

  - A USERWEIG card to activate a call to usrrnc routine

```
RESNUCLE    3.    -21.    74.    49.    rTgtTa26    1.RNTgt
USERWEIG                                        1.0
```

Input settings (2)

- Under General:

  - Defined cooling times in units of days (1 week and 3 years)

    USRICALL SDUM=TCOOLD WHAT(1)=7 WHAT(2)=1095

  - Chose which emitters to save (gamma rays and positrons only)

    USRICALL SDUM=DUMPING WHAT(1)=4

  - Chose regions to save emitters from
    (Six regions: Ta:3, Cu:6, 6061: 7, AlN:8, SST:9, Tgt:11)

```
USRICALL   SDUM=DUMPREG  WHAT(1)=3    WHAT(2)=3
                         WHAT(3)=6    WHAT(4)=6
                         WHAT(5)=7    WHAT(6)=7
USRICALL   SDUM=DUMPREG  WHAT(1)=8    WHAT(2)=8
                         WHAT(3)=9    WHAT(4)=9
                         WHAT(5)=11   WHAT(6)=11
```

Input settings (3)

- Under General:

  - Chose biased isotope dumping

    Set number of entries in dump file used for adjusting biasing set to 200 (default)

    Set maximum fraction of abundance of an isotope within the 200 entries for applying biasing to 20%

```
USRICALL   SDUM=BIASING WHAT(1)=200  WHAT(2)=0.2
```

  - Chose regions for biasing

```
USRICALL   SDUM=BIASREG  WHAT(1)=3    WHAT(2)=3
                         WHAT(3)=6    WHAT(4)=6
                         WHAT(5)=7    WHAT(6)=7
USRICALL   SDUM=BIASREG  WHAT(1)=8    WHAT(2)=8
                         WHAT(3)=9    WHAT(4)=9
                         WHAT(5)=11   WHAT(6)=11
```

Input settings (4)

- Under General

  - Chose ascii file format for the output (isotope dump) file

    USRICALL   SDUM=OUTPUT WHAT(1)=1

  - Chose to actually write the dump file!

    USROCALL

Compilation and Running

- Compiled dorerate11.2.f and linked with fluka.o to make a new executable
- Used a modified rfluka script with the following piece added in to link additional files from running directory to the temporary fluka_##### directories

```
MYDATAFILES="irrcyc.inp"
for i in $MYDATAFILES ; do
    if [ -r ${CURDIR}/${i} ] ; then
       ${ECHOE} "\nFile ${CURDIR}/${i} exists and it is not a link!"
       ln -s -f ${CURDIR}/${i} ${i}
    else
       ln -s -f ${FTOP}/${i} ${i}
    fi
done
...
for i in \
  $DATAFILES  $MYDATAFILES $neuxsc.bin $XNLOANFIL xnloan.dat
```

Output file

Can not concatenate output files, one output file per run. Need to run multiple runs.

Name: <run>-001_isodump.out

Format:

```
  4  2
tc   1   6.0480000E+05
tc   2   9.4608000E+07
#1  1  73 178 2    3 -4.27468E-01 -9.50193E-02 -9.69216E+00  1.00000E+00
  9.29319E-08
#1 -1  73 178 2   11 -4.83913E-01 -2.88948E-01 -2.38690E+00  1.00000E+00
#1  1  73 176 1   11  1.06143E-01 -5.15467E-01 -1.76789E+00  1.00000E+00
 2.79992E+08
#1  1  73 177 1   11 -4.31354E-02  3.19773E-01 -2.25109E+00  1.00000E+00
 6.36827E+13
#2  1  74 176   11  6.31583E-01  4.97915E-01 -7.46459E-01  1.00000E+00
  2  0  0  0  0  0  0  0
  1  73 176 1 0.40521E+09  74 176 1 0.29460E-05
```

FLUKA SIMULATIONS
Stefan Roesler's two-step method

Second Step: Assessment of shielding for dose rates calculated from transport of the β^+, β^-, γ emitted from radio-nuclides of the first-step

- Need a different input file for each cooling time since the shielding geometry is different for each:

  - 1 week cooling time: Shielding to represent the Storage Vault (25 cm thick steel box)

  - 3 year cooling time: Shielding to represent the F308 transport flask (5 cm lead box encased in 0.8 cm steel)

FLUKA SIMULATIONS

Stefan Roesler's two-step method – Second Step

General preparation

For each cooling time and shielding scenario:

- Set up 10 directories (A001 ... J001)
- Make symbolic links to the data files the isodump.out files generated from first step: *<run>-<A-J>001_isodump.out* to *isodump.out in each dir*
- *Add the shielding structure to the geometry in the input file*

Wrote a script to automate the process!

General preparation (2)

- Need weight information from standard output file of 1st step, (*<run>-<A-J>001.out)* as input parameters for 2nd step:

Parameters for USRICALL: **Weights for the two cooling times**

- all regions
9.304E-02 2.710E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 3
4.118E-02 1.270E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 6
8.405E-04 2.840E-04 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 7
1.040E-04 3.200E-05 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 8
1.650E-05 9.000E-06 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 9
1.079E-03 1.022E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00
- regions no. 11
4.981E-02 1.306E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00

Input settings (1)

- Under General:

  - Weight factors for the two cooling times

    USERICALL SDUM=WCOOL WHAT(1)=9.304E-02 WHAT(2)=2.710E-02

  - Set format of the input isodump.out file to ascii

    USRICALL SDUM=OUTPUT WHAT(1)=1

  - Regions to consider for tracking of emitted radiation
    (Six regions: Ta:3, Cu:6, 6061: 7, AlN:8, SST:9, Tgt:11)

    USRICALL SDUM=SAMPREG WHAT(1)=3 WHAT(2)=3
    WHAT(3)=6 WHAT(4)=6
    WHAT(5)=7 WHAT(6)=7

  - Read in isodump.out as input source file

    USROCALL

Input settings (2)

- Under Source:

  - Set isotopes for which cooling time to consider for tracking
    and which radio-nuclides to consider
    Ex: 1st cooling time and gamma ray and positron emitters only
    SOURCE WHAT(1)=4 WHAT(2)=4

Input settings (3)

- Under Scoring:

  - Use USRBIN to look at spacial distribution of dose rate

```
USRBIN 10. DosE-EQ   -94.  120 120. 55.DEDist
USRBIN -120. -120. -55.  120. 55.&
```

  - Use USRBIN to look at the dose rate in the detector (reg binning)

```
USRBIN 10. DosE-EQ   -94.   rDet  DEDistReg
USRBIN  rDet      1.    &
```

  - Use USRTRACK to look at the total dose rate in the detector

```
USRTRACK         -1.   DOSE-EQ      -40.      rDet 659734.46      100.DEinDet
USRTRACK     .010010      1E-5                                          &
```

Compilation and Running

- Compiled dorerate11.2.f and linked with fluka.o to make a new executable
- Used a modified rfluka script with the following piece added in to link additional files from running directory to the temporary fluka_##### directories

```
MYDATAFILES="glines.dat plines.dat eiclines38.dat ICRP38.BET irrcyc.inp isodump.out"
for i in $MYDATAFILES ; do
   if [ -r ${CURDIR}/${i} ] ; then
      ${ECHOE} "\nFile ${CURDIR}/${i} exists and it is not a link!"
      ln -s -f ${CURDIR}/${i} ${i}
   else
      ln -s -f ${FTOP}/${i} ${i}
   fi
done
...
for i in \
   $DATAFILES  $MYDATAFILES $neuxsc.bin $XNLOANFIL xnloan.dat
```

Stefan Roesler's two-step method – Second Step

Results based on:

- First Step:

  1M primaries, 10 independent runs, each producing an isodump file

- Second step:

  10 runs with 20M primaries

  Each run using isodump.out file of one of the 10 runs in the first step

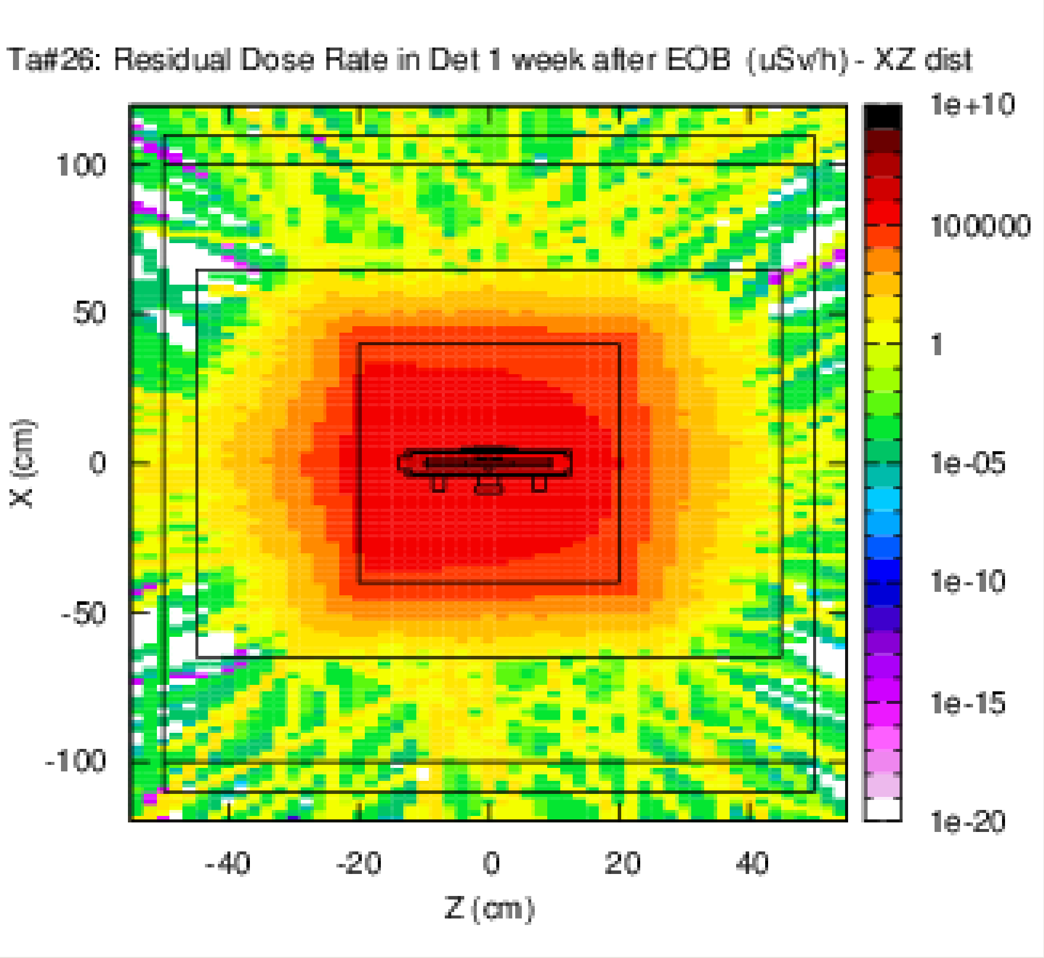
For proton beam energy of 115.7 MeV, not 480 MeV (an unintended mistake from setting beam momentum of 480 MeV)

FLUKA SIMULATIONS

Stefan Roesler's two-step method – Results (1)

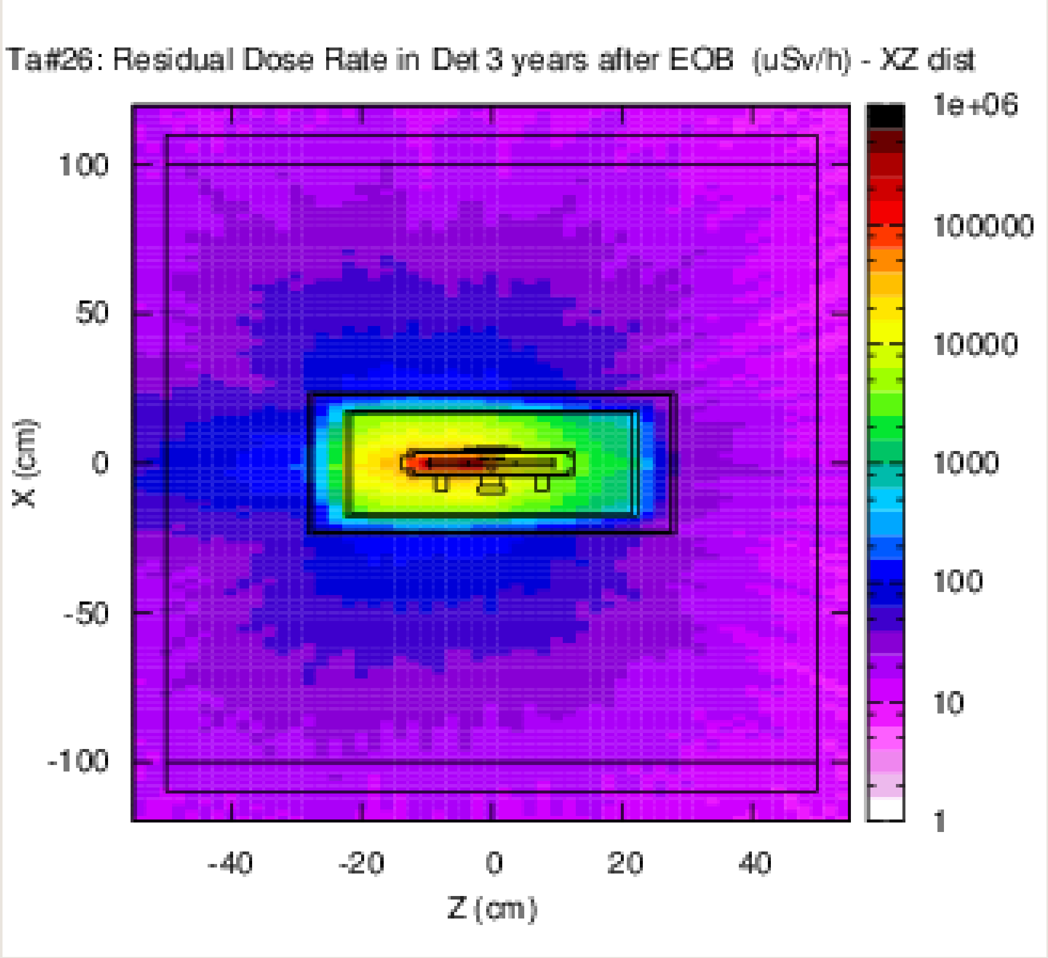
Residual rate distribution for Ta#26

1 week after EOB



25 cm steel

3 years after EOB



5 cm lead encased in 0.8 cm steel

FLUKA SIMULATIONS

Stefan Roesler's two-step method – Results (2)

Target	Residual dose rate @ 1m (µSv/h)	
	Spent Target Storage Vault 1 week after EOB	Target Transfer Flask 3 years after EOB
Ta#27	2.79 +/- 8.3 %	15.2 +/- 1.7 %
SiCGr#24	0.78 +/- 13.3 %	14.84 +/- 0.49 %
Ta#26	4.08 +/- 14.3 %	22.86 +/- 0.74 %
SiCGr#25	1.51 +/- 9.6 %	27.47 +/- 0.99 %
Nb#4	4.95 +/- 5.4 %	24.41 +/- 0.97 %
Nb#5	7.1 +/- 11.0 %	22.65 +/- 0.94 %

* Results need to be repeated with the correct beam energy of 480 MeV

Questions & thoughts

- How does Stefan's two-step method compare with the standard run?
  - Check using no shielding (i.e. same geometry in the second step as in the first)
- FLUKA version where prompt material can be set to vacuum and decay to shielding material?
  - Can this serve our needs to assess shielding for spent target material at different cooling times using the standard FLUKA run? (geometry constrains)
- Can the two-step method become integrated into the current version of FLUKA?

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Special Thanks & credits

FLUKA/FLAIR Community

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Alfredo Ferrari
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Chad Fisher
Travis Cave
Daniel Rowbotham
Stuart Austen
...

Slides 5-20 inspired/contributed by Anders Mjos from the TRIUMF Target group to provide background
For Stefan Roesler's two-step method, see: "Radioactive Isotopes – Production and Decay", Stefan Roesler, 15 March 2007

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