DAPNIA visit of SARAF

- **October 24th:**
  09:00 arrival at Soreq
  09:10 welcome (Dr. Yair Yariv)
- 09:20 SARAF presentation (Dr. Ami Nagler)
  10:30 break
  10:45 The operation concept of SARAF linac (Dr. Israel Mardor)
  11:15 Safety and shielding calculations (Dr. Israel Mardor)
  11:45 First front-end beam test results (Dr. Dan Berkovits)
  12:15 Solid and liquid targets cooling (Dr. Ido Silverman)
  13:00 lunch
  14:00 tour of the target cooling lab (Dr. Ido Silverman)
  15:00 The RF and LLRF systems (Eng. Israel Fishman)
  15:30 the cryogenic system and LHe stability measurements (Dr. Ido Silverman)
  16:00 evening tour of Jerusalem old city
  23:00 back to the hotel

  October 25th :
  08:20 arrival at Soreq
  08:30 tour of the linac and auxiliaries (Dr. Dan Berkovits)
  10:00 beam loss simulation along the SC linac (Dr. Jacob Rodnizki)
  10:30 beam diagnostic (Dr. Leo Weissman)
  11:00 discussion and summary (possibility of extra tour of RF and cryogenic plant)
  12:00 lunch
  13:00 transfer to the airport

SARAF – Soreq Applied Research Accelerator Facility

Presentation to DAPNIA

October 24th, 2007

Ami Nagler on behalf of SARAF team


Angel

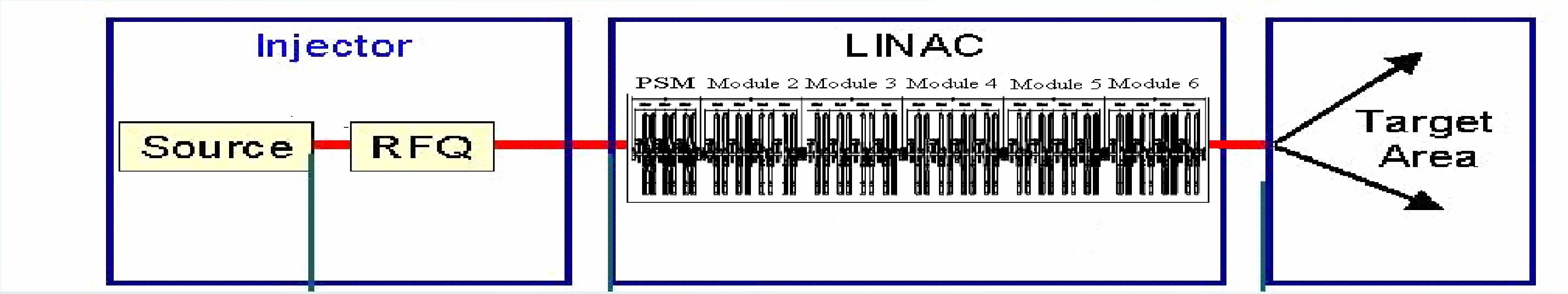

SARAF Snake

Soreq NRC

24/10/07

Content of the talk

1. Introduction
2. SARAF accelerator technologies
3. Some SARAF applications



Why SARAF?

- To modernize the source of neutrons at Soreq and extend neutron based research and applications.
- To develop and produce radioisotopes primarily for bio-medical applications.
- To enlarge the experimental nuclear science infrastructure and promote the research in Israel.

The Project Objective

To enable the continuous, reliable and safe operation and **applications** of a proton/deuteron accelerator of 40 MeV and 2 mA at Soreq during the year 2013

Phase I Task

Physical and technical feasibility of the accelerator and its applications at the mid of 2008

Initial Technical Decisions (1/3)

1. **RF linac (vs. Cyclotron)**
    1. **accelerating different ions with single frequency.**
    2. **Current upgrade to 4 mA and beyond.**
    3. **Energy can be increased modularly.**
    4. **Beam quality can be reached which will enable hands-on maintenance.**

Initial Technical Decisions (2/3)

2. **Super-Conducting Cavities (vs. NC)**
   1. Less electrical power consumption
   2. An independently RF phase to each cavity
   3. Enables CW with high beam current
   4. Allow a bore radius significantly larger than that of a NC cavity.

Initial Technical Decisions (3/3)

3. **NC RFQ and SC linac** (no DTL in between in order to minimize operation cost at 2 mA)
4. **p (and d) SC linac → HWR** (QWR at that time (Aug. 01) didn't have a solution for the dipole steering)
5. **HWR → 176 MHz** (to moderate cavity size)
6. **176 MHz → HWR $\beta_0 \geq 0.09$** (conditioning)
7. **high initial β_0 → long RFQ** (β_{exit}=0.056 (1.5 MeV/u) > the d+Cu activation threshold (~1 MeV/u))
8. **176 MHz → 4-rod RFQ** (tuning and cavity size)

A RF Superconducting Linear Accelerator

Accelerator Basic Characteristics

Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	
Current Range	0.04 – 2 mA	Upgradeable to 4 mA
Operation mode	CW and Pulsed	PW: 0.1-1 ms; rep. rate: 0.1-1000 Hz
Operation	6000 hours/year	
Reliability	90%	
Maintenance	Hands-On	Very low beam loss

The SARAF Operation Program

A Sample operation plan for a typical week

Subject	Beam on Target (hr)	Beam tune (hr)	Beam off (hr)	Ion	Energy (MeV)	Current (mA)
^{103}Pd	36	~3		d	20	2
TNR	14	~3		d	40	2
Basic Research	27	~3		d	20	2
Basic Research	16	~3		d	40	2
^{18}FDG	8	~3		p	18	0.2
^{201}Tl	14	~3		p	29	0.25
שבת			28			

- **Accelerator will not operate on Weekends**

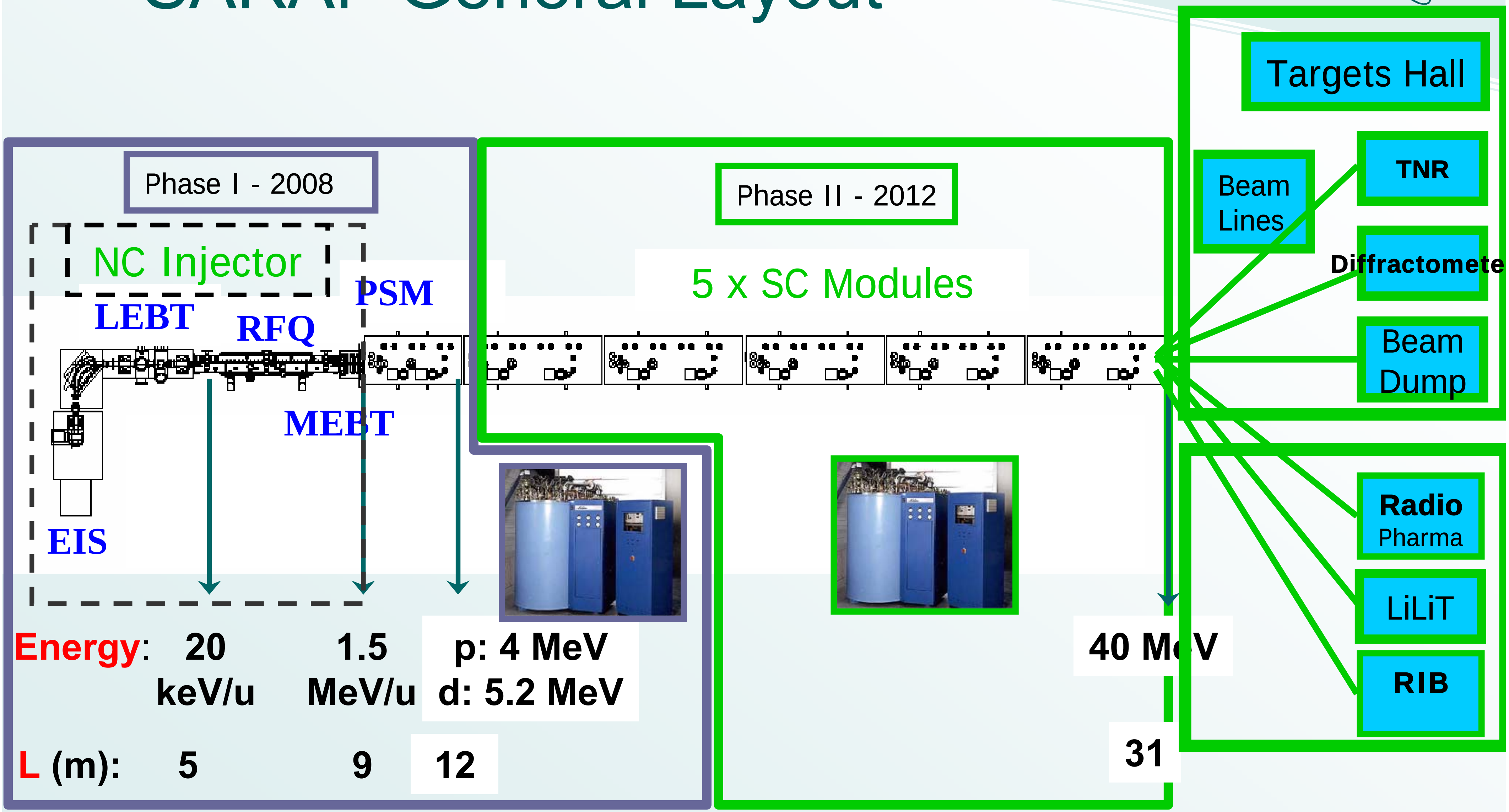
- **Total BOT for this week = 105 hr**
- **Total Beam available = 151 hr**

The Planned Facility Group

	Design	Design & Construction	Commissioning Phase I	Construction & Commissioning Phase II	Start operation
	2001-4	**2004-6**	**2007-8**	**2008-10**	**2011▯**
Management & Researchers	5.5	5.5	5.5	6.5	5.5
Engineers	2	5	5	5	4
Technicians	1.5	1.5	1.5	4	6.5
Total	9	12	12	15.5	16

Operators will come mainly from Engineers and Technicians groups

SARAF General Layout



Targets Hall

Phase I - 2008

Phase II - 2012

NC Injector

5 x SC Modules

Beam Lines

TNR

Diffractomete

Beam Dump

LEBT

RFQ

PSM

MEBT

EIS

Radio Pharma

LiLiT

RIB

Energy:	20 keV/u	1.5 MeV/u	p: 4 MeV d: 5.2 MeV	40 MeV
L (m):	5	9	12	31

Accelerator Building and Infrastructure

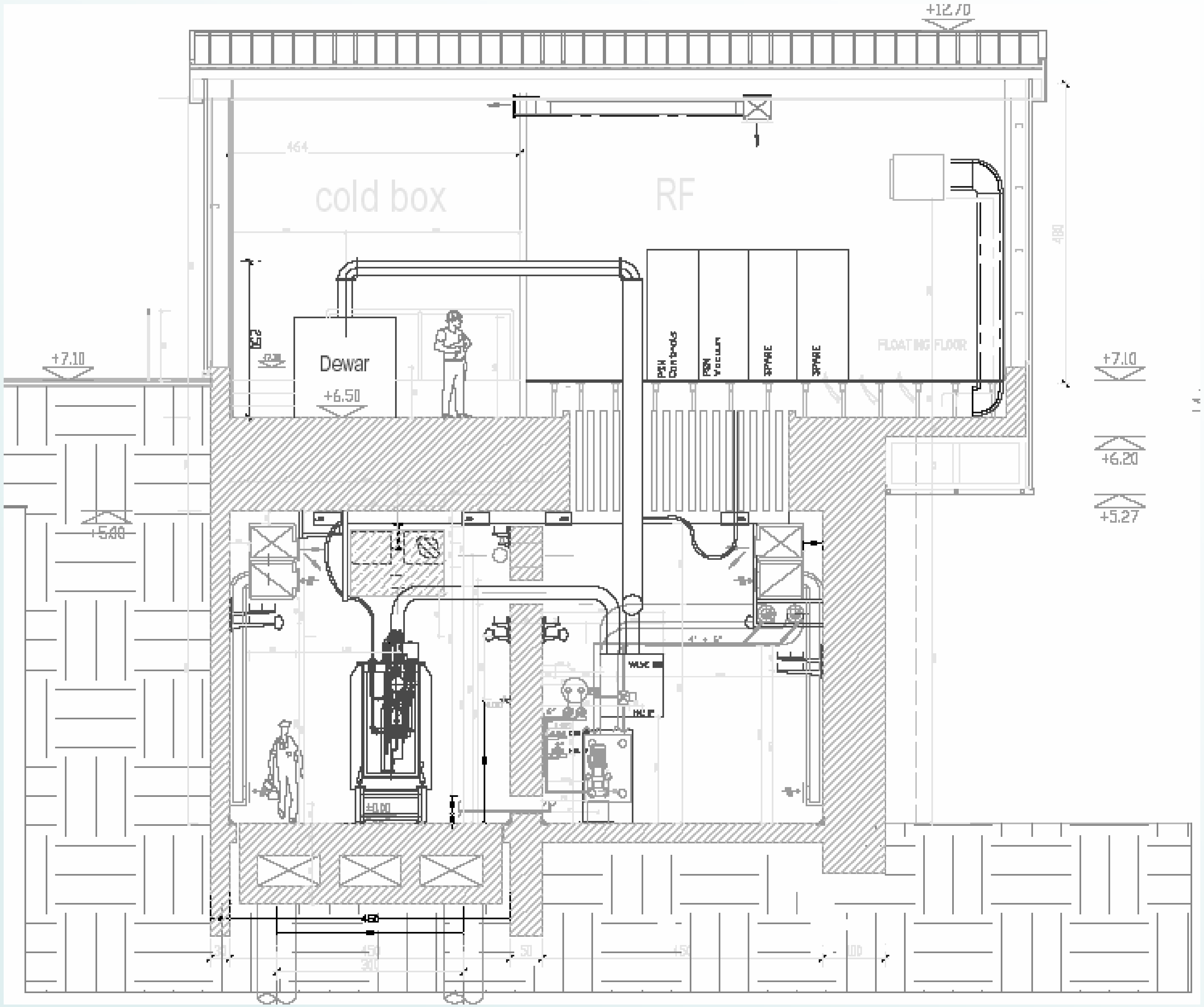
Cryogenics

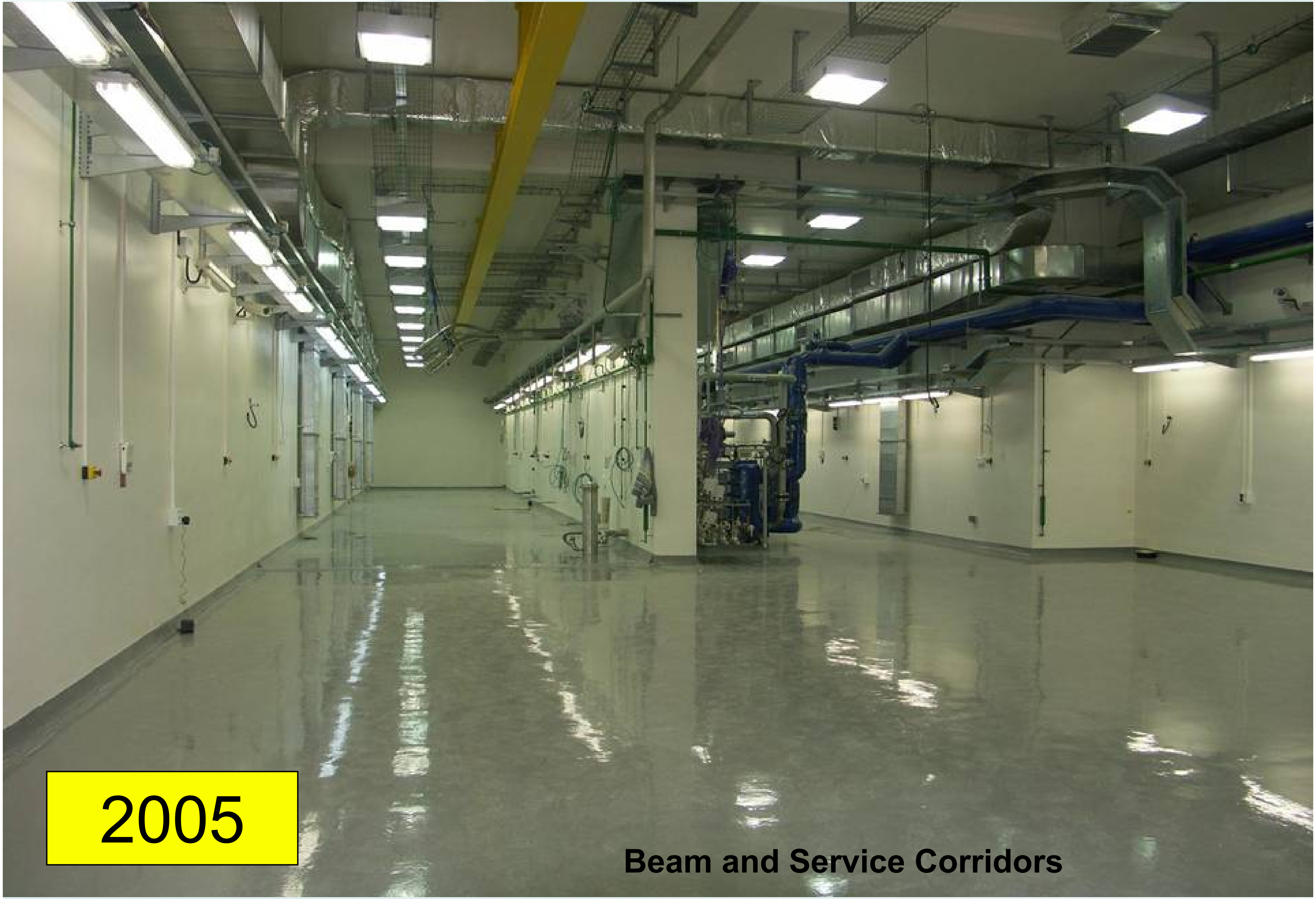
Major Systems – Phase I

- Accelerator – Accel Instruments (Germany)
- Cryogenics – Linde Kryotechnik (Switzeraland)
- Building and Infrastructure – U. Doron (Israel)
- Beam Halo Monitor, Beam dump, Control - Soreq
- **Applications** – Soreq
- Beam dynamics – Accel & Soreq

General Integration – Soreq

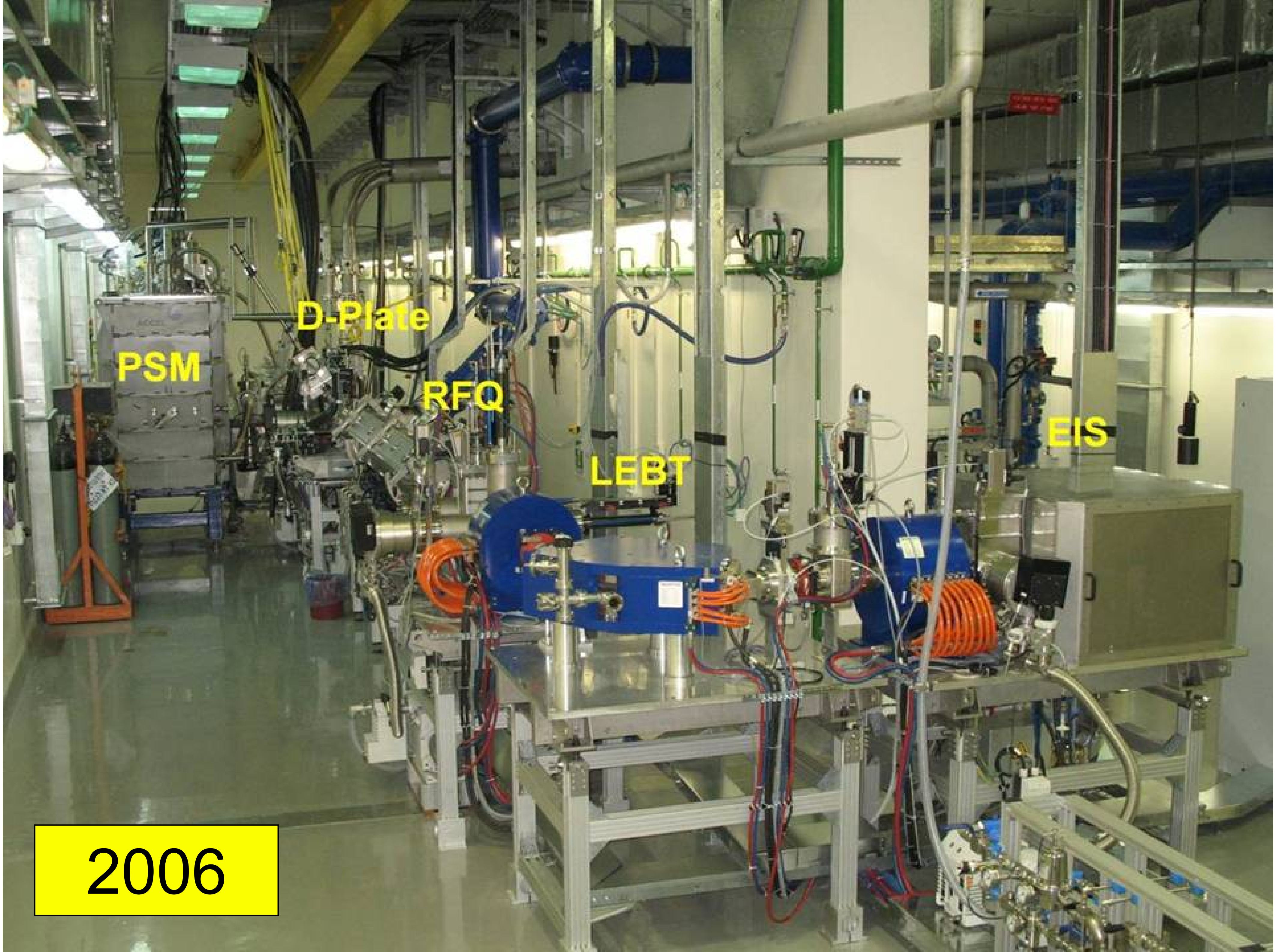
Corridors' vertical cross section





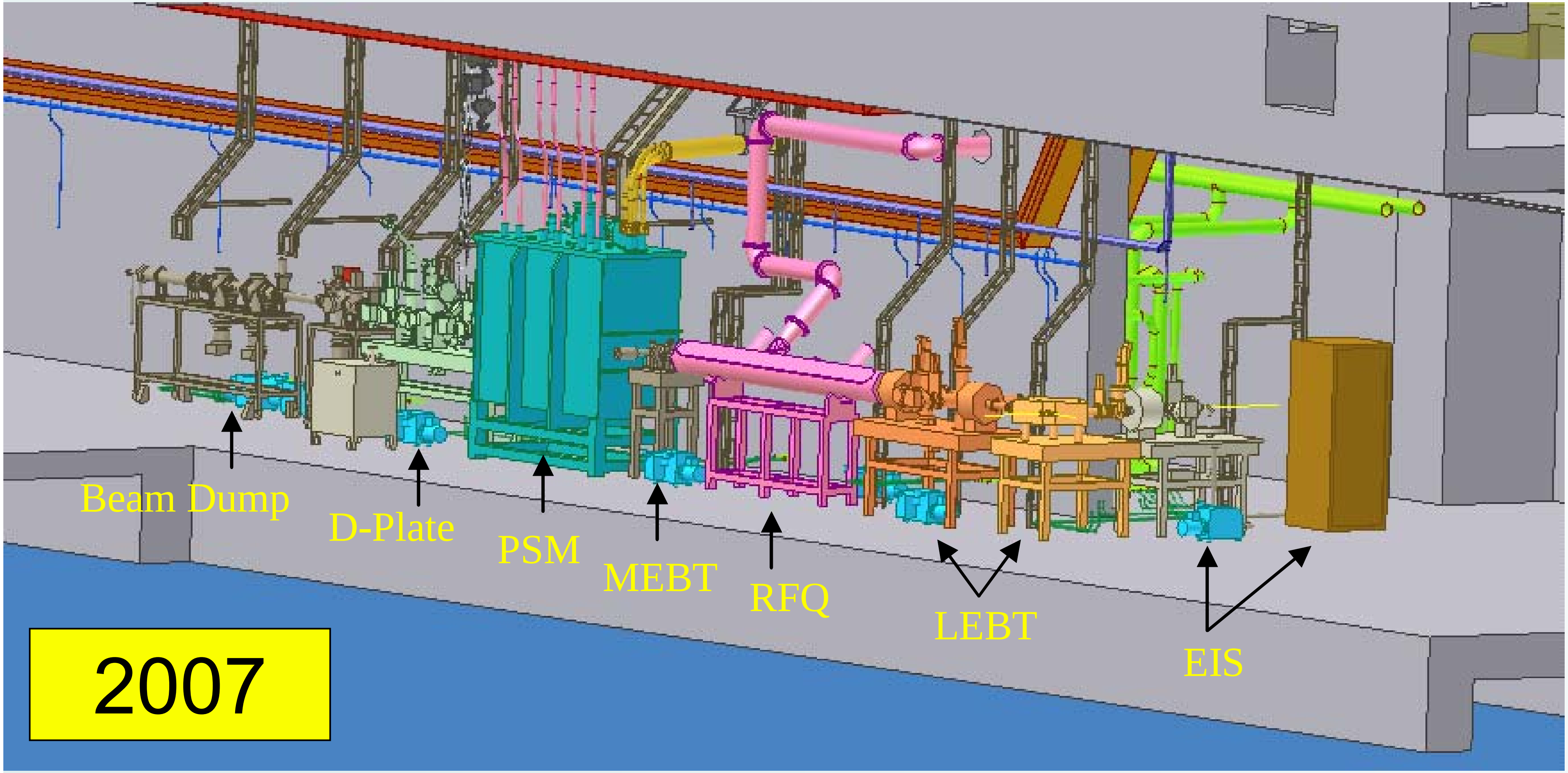
2005

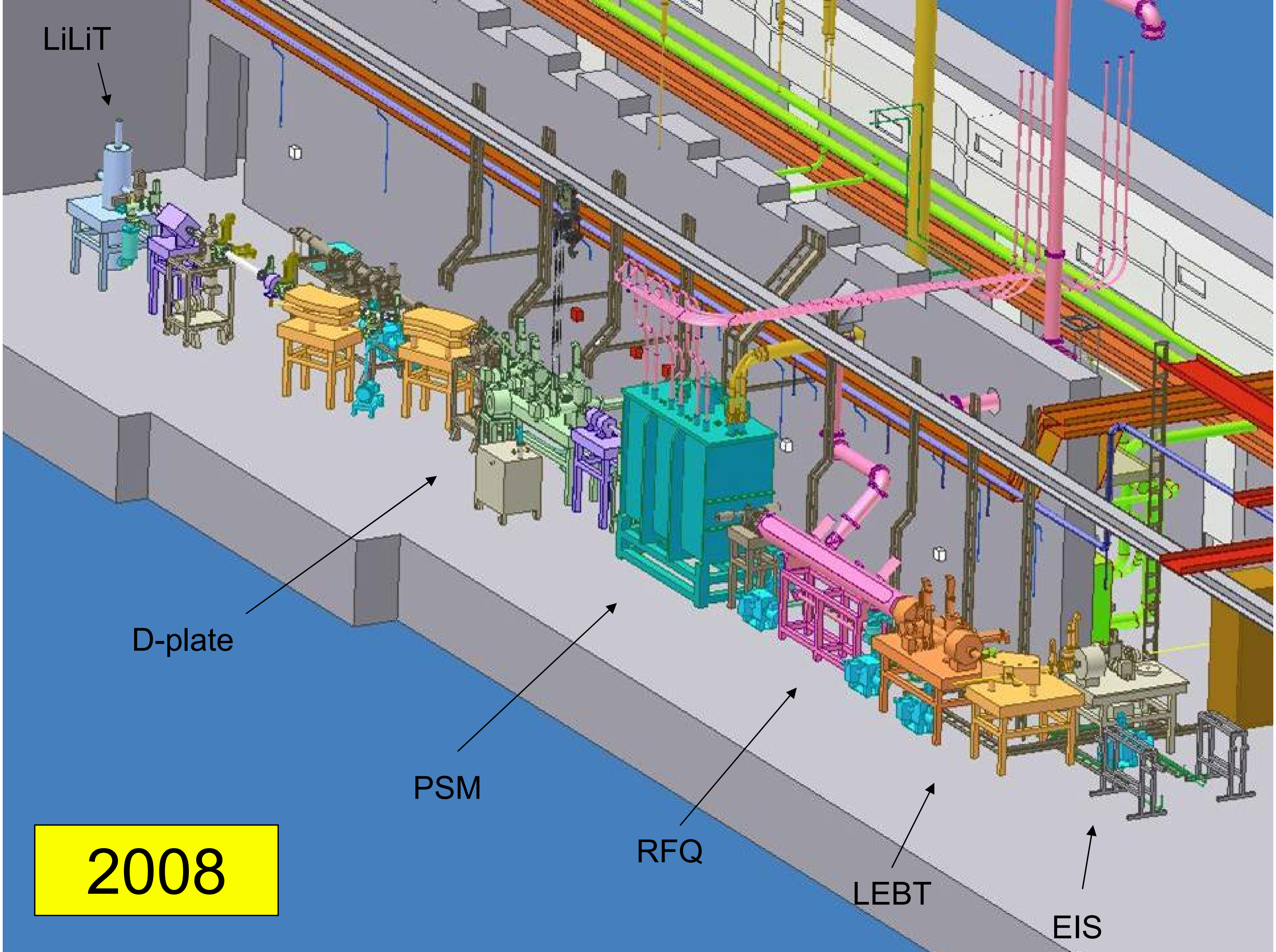
Beam and Service Corridors



2006

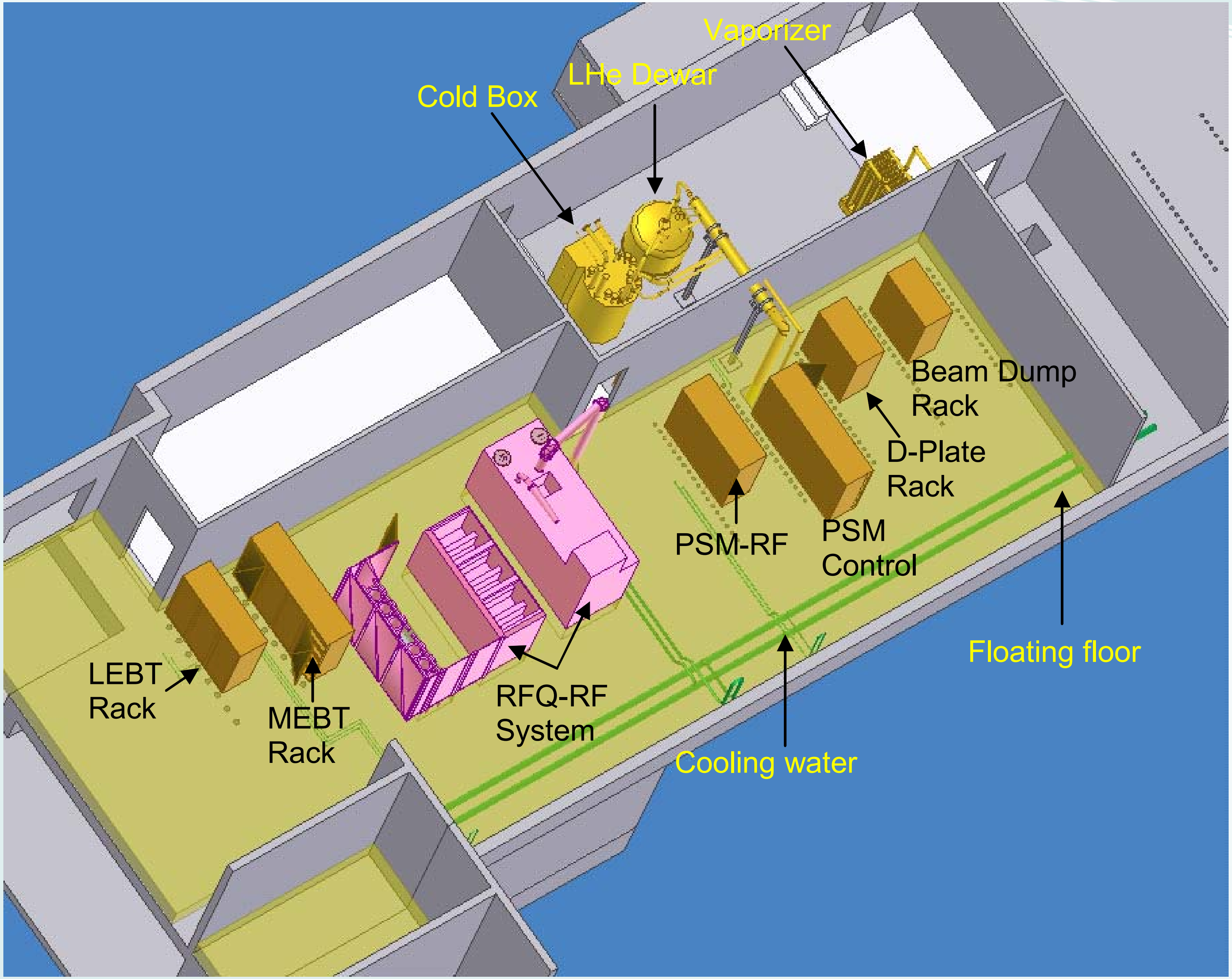
Set up for beam characterization



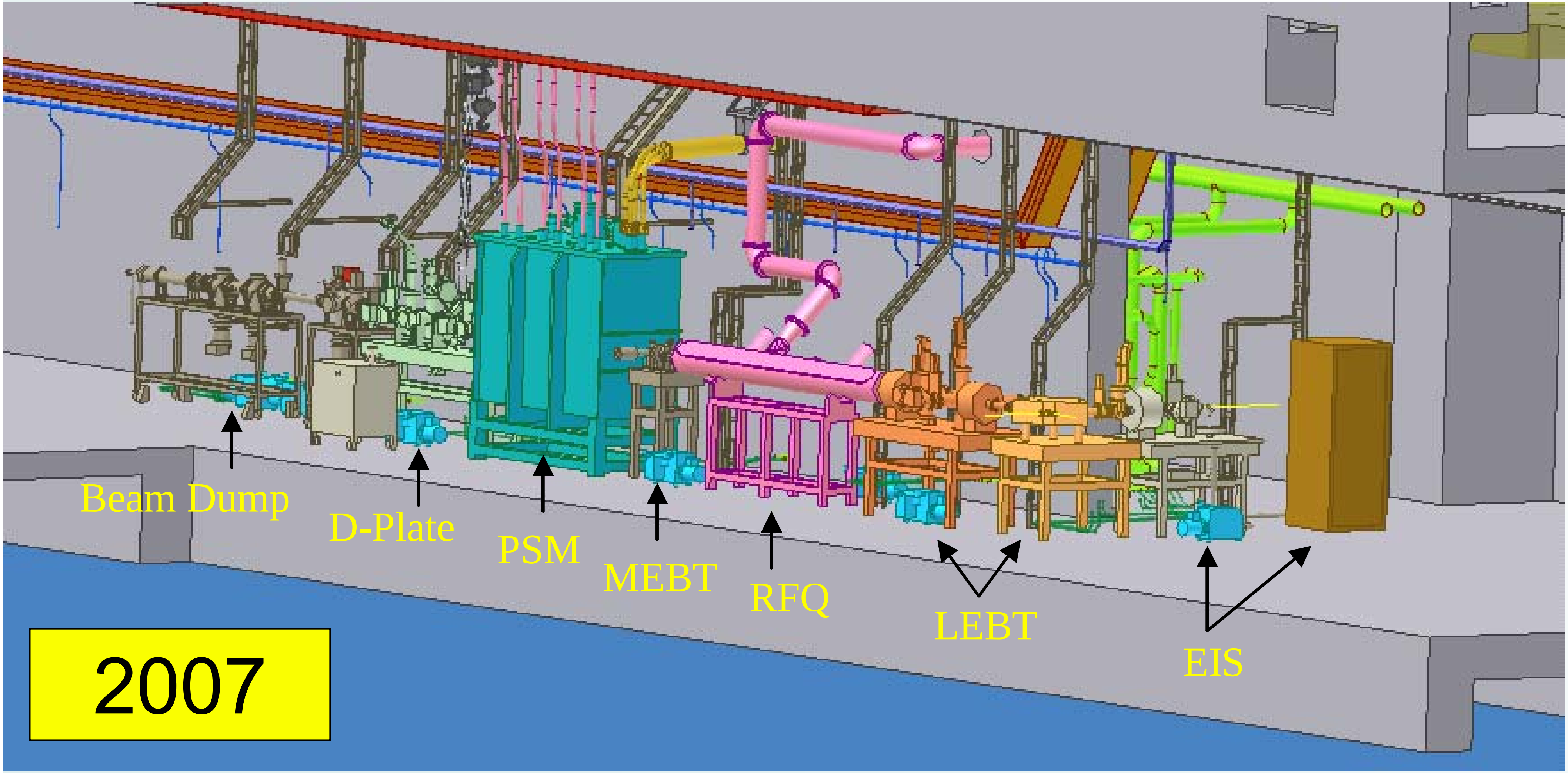


2008

Phase-I upper floor overview



Set up for beam characterization

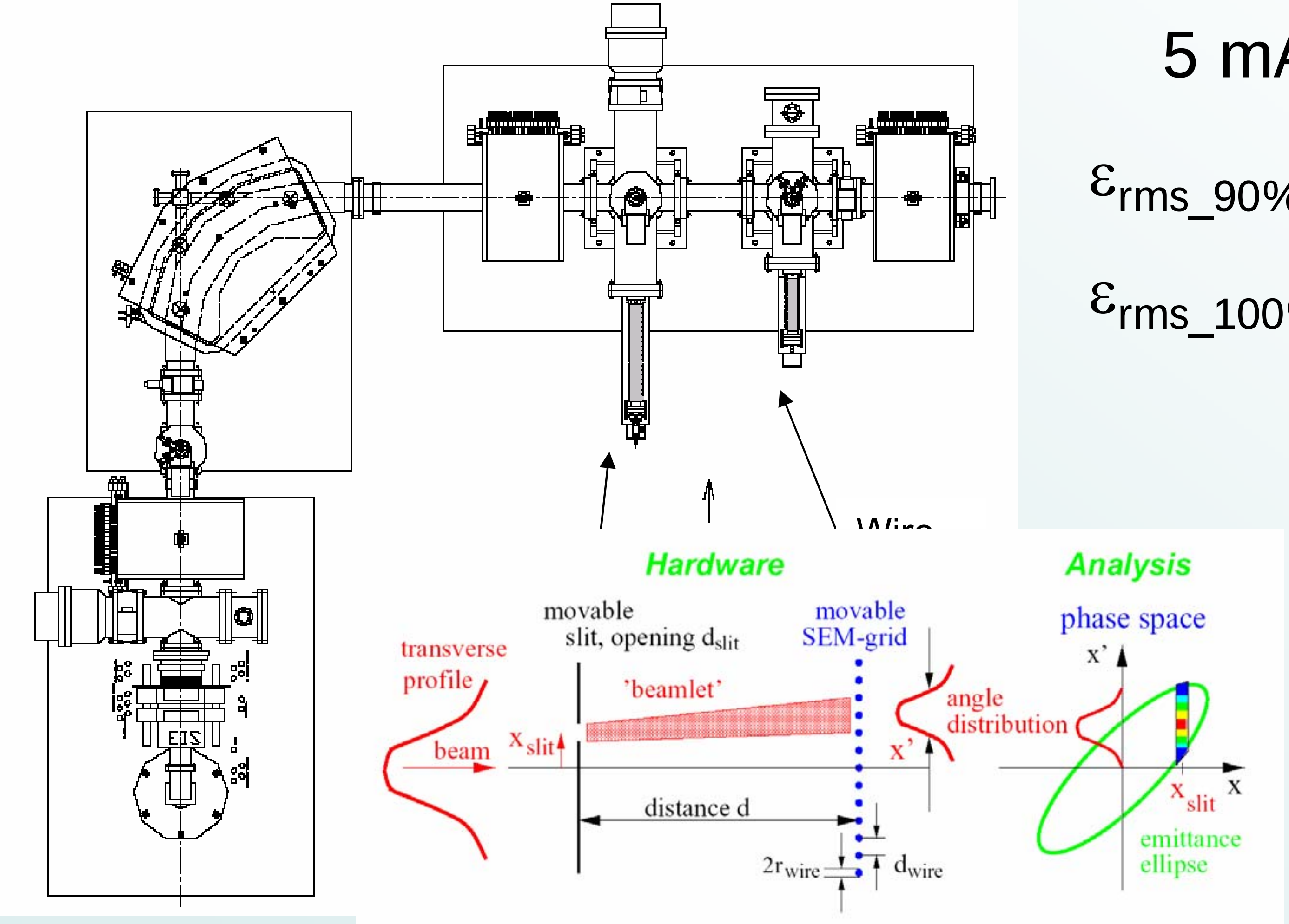


SARAF Electron Cyclotron Resonator Ion Source (ECRIS) Design Parameters

Ion Species	p, d, H_2^+
Extraction Energy	20 keV/u
Energy ripple	±0.03 keV/u
Current range	0.04 – 5 mA
Current ripple (max current)	±2%
Transverse emittance (norm, r.m.s.)	0.2 π·mm·mrad

ECRIS: Emittance measurement

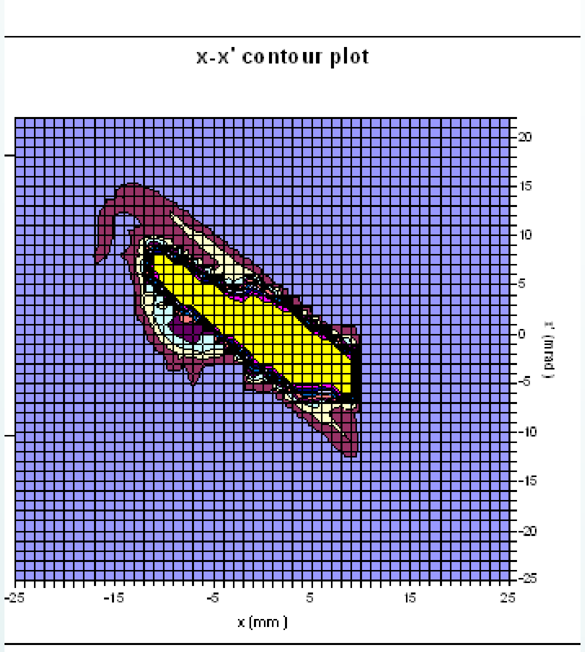
The emittance of the beam has been measured by scanning the beam channel with slit and wire.



5 mA p norm. emittance

$$\varepsilon_{rms\_90\%} = 0.10\ \pi\ \text{mm mrad}$$

$$\varepsilon_{rms\_100\%} = 0.17\ \pi\ \text{mm mrad}$$

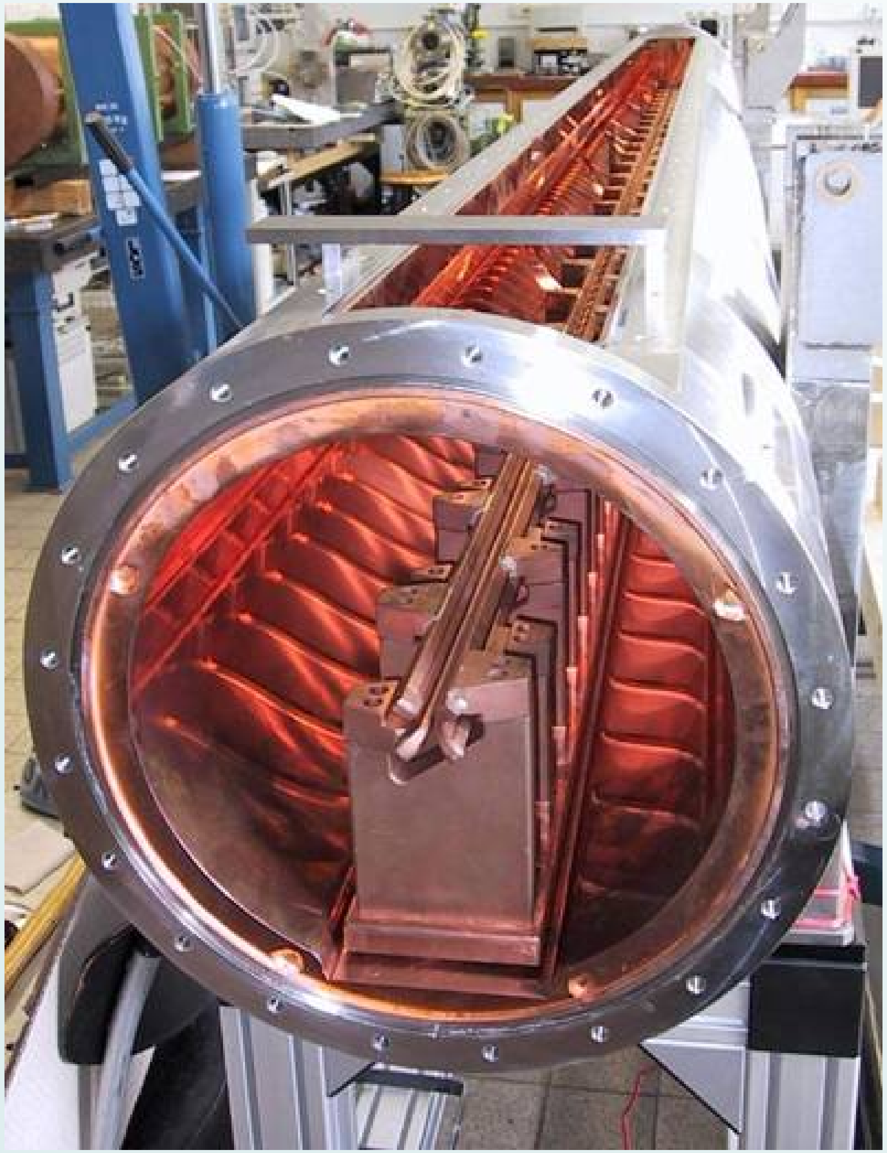


SARAF Radio Frequency Quadrupole (RFQ) Parameters

Output Energy	1.5 MeV/u
Energy ripple	±0.03 MeV/u
Maximal Current	4 mA
Transverse emittance (norm, r.m.s.)	0.3 π·mm·mrad
Longitudinal emittance (r.m.s.)	120 π·keV·deg/u
Transmission	90% (70%)
Length	3.8 meters
RF Power (p,d)	55, 220 kW (60,240)
Quality factor	2000 (3600)

Radio Frequency Quadrupole (RFQ)

In factory 2005

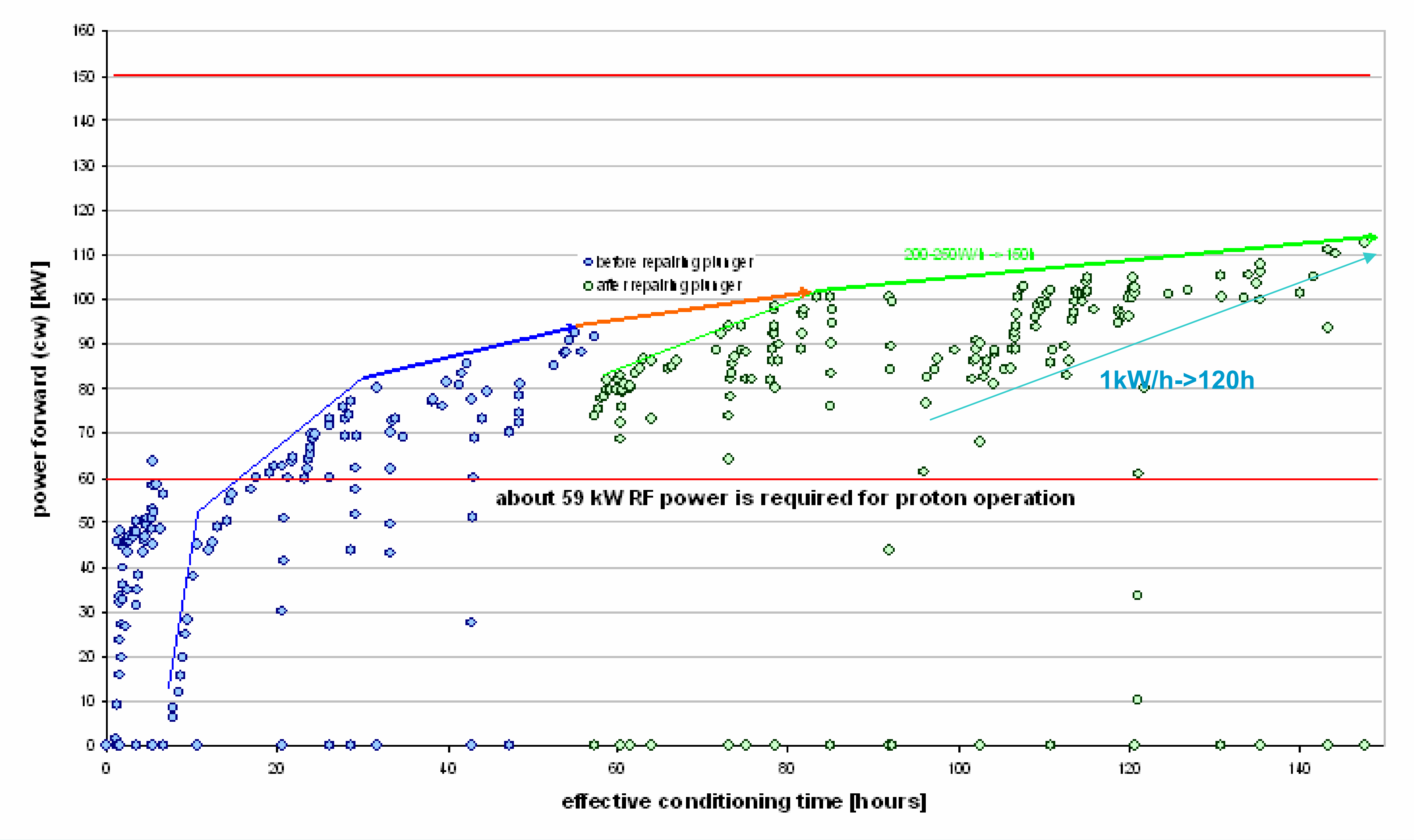


On site 2006

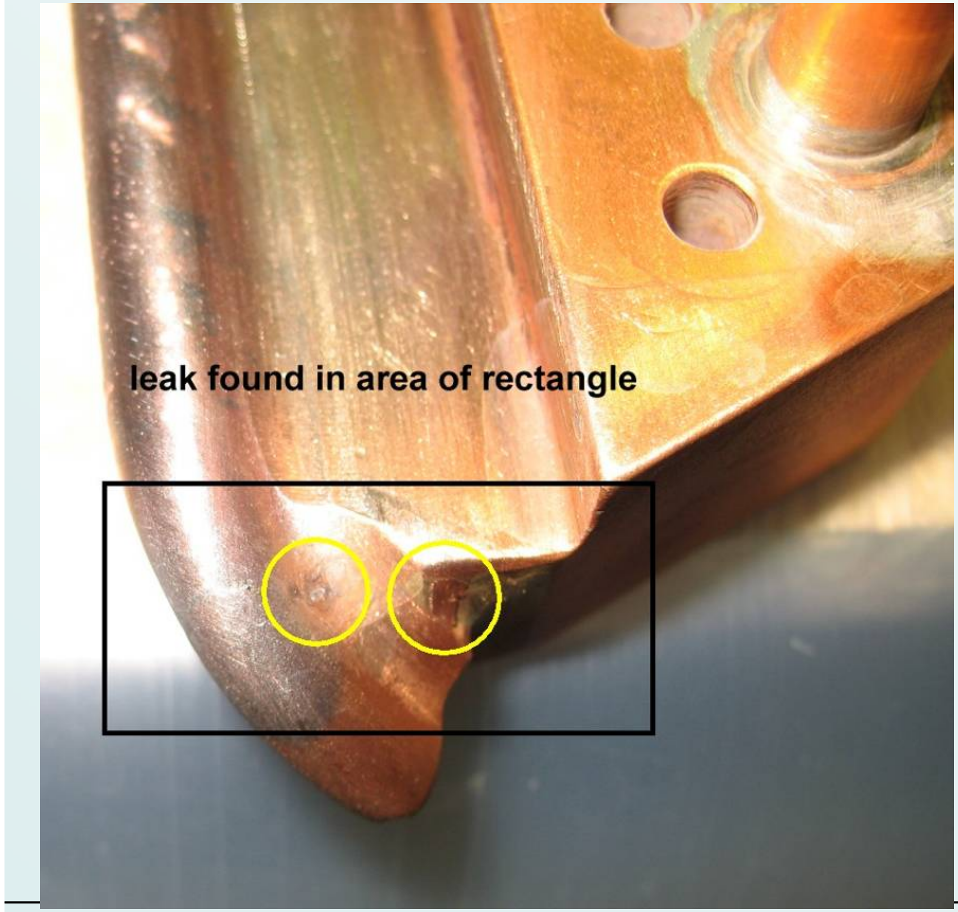
P. Fischer EPAC 2006

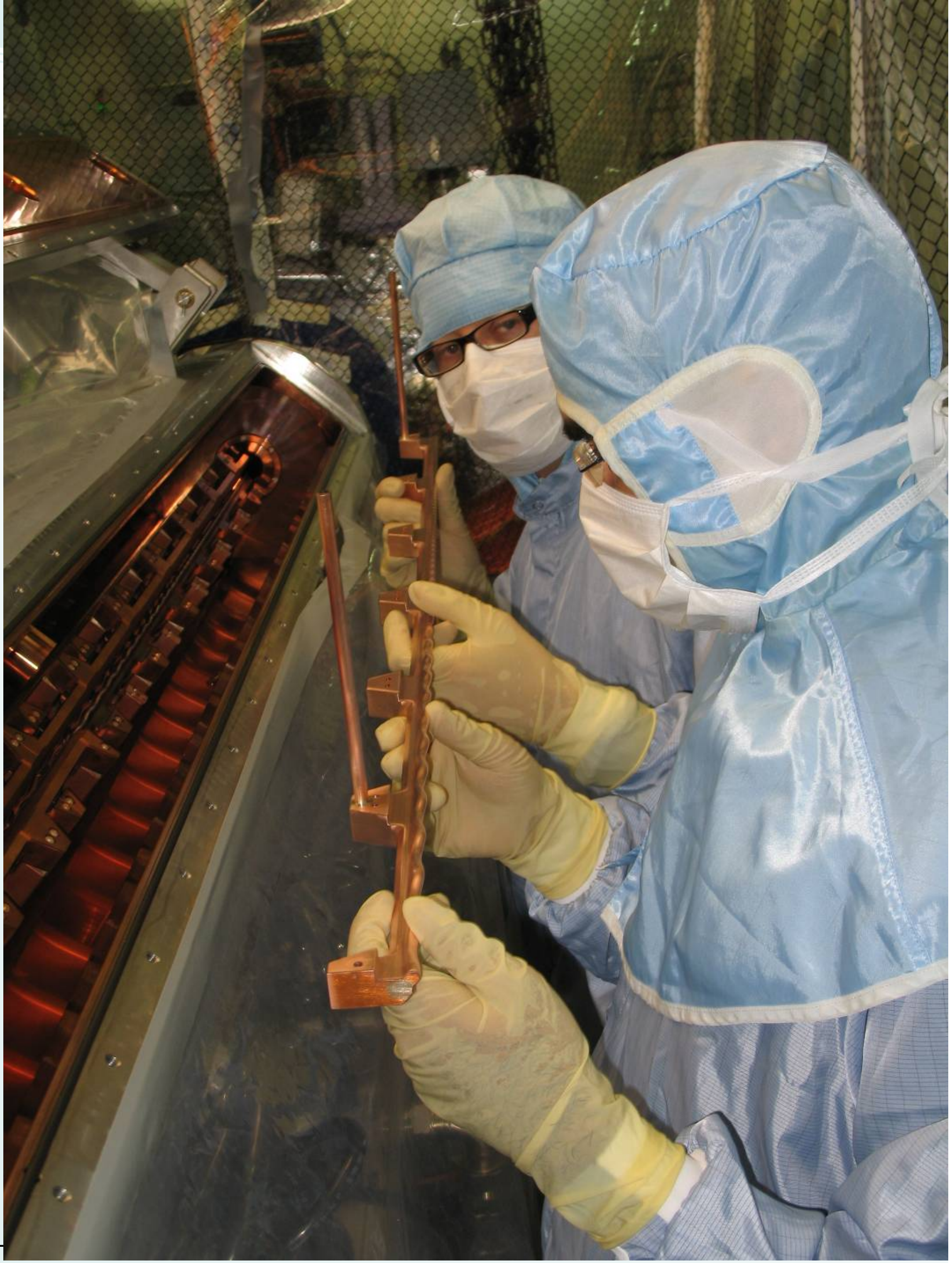
RFQ-RF

RFQ: Status conditioning



RFQ rod water leak to vacuum



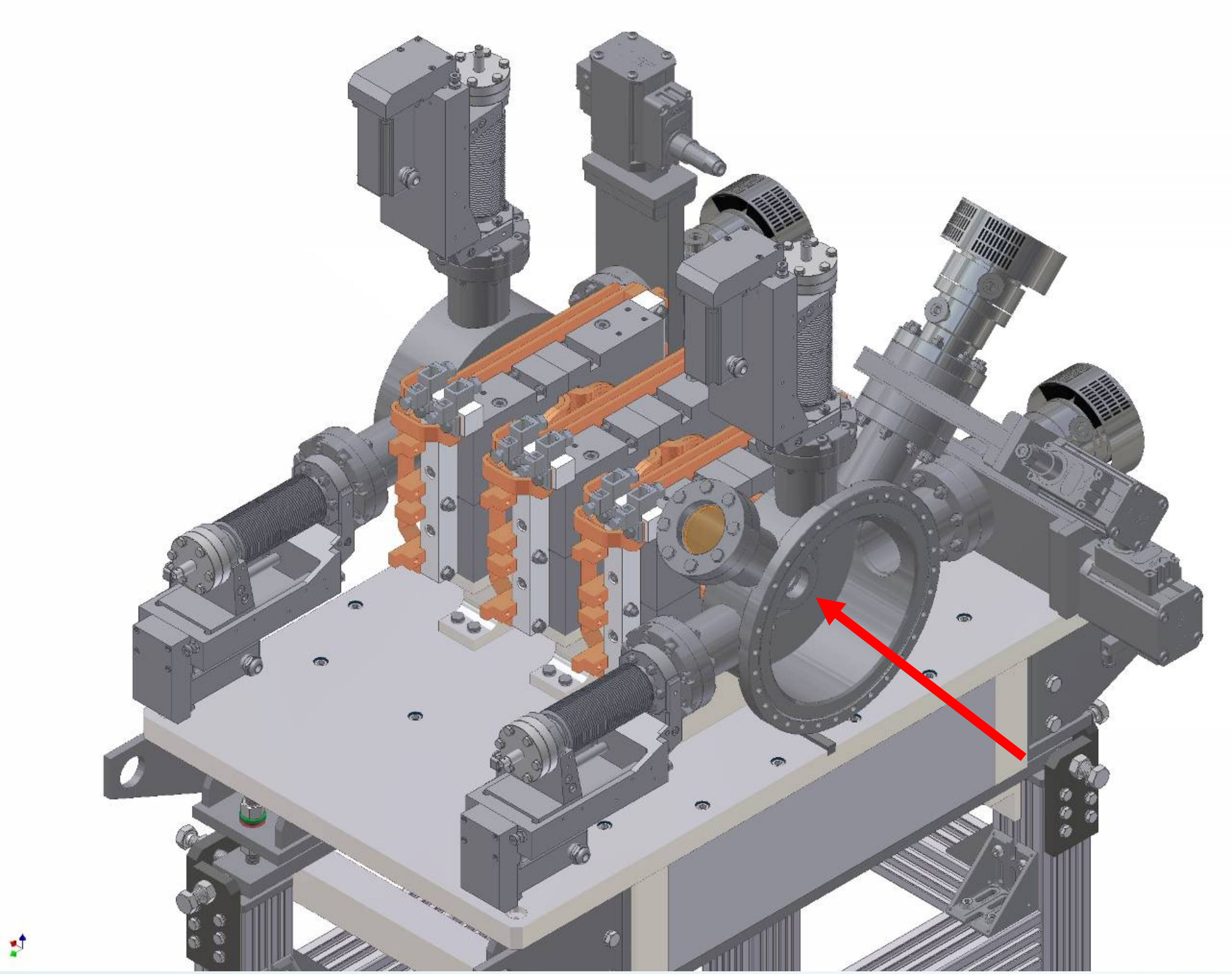


MEBT

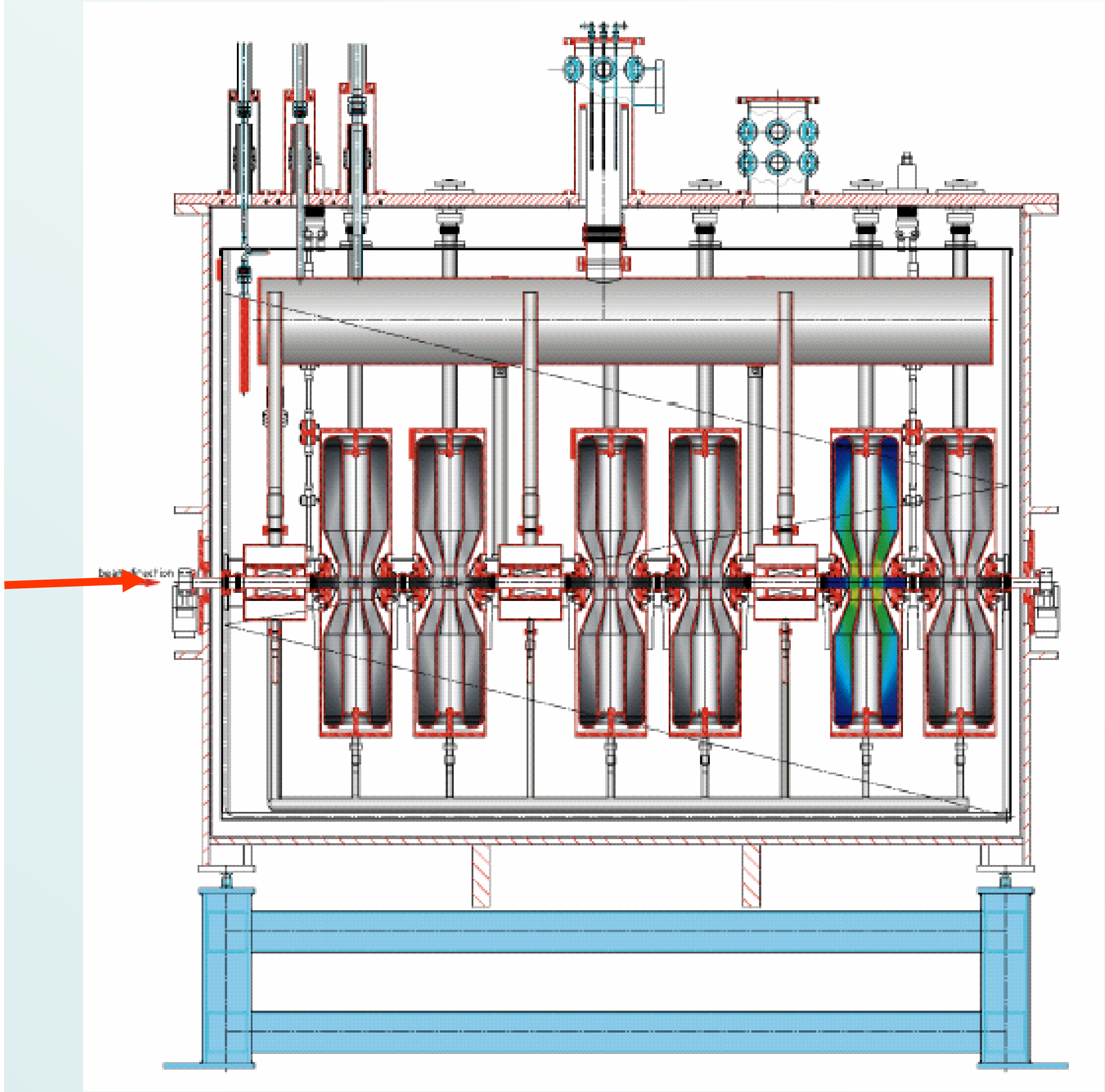
Main components:

- Quadrupole lenses
- Beam diagnostics
- Vacuum pumps

- 65 cm long

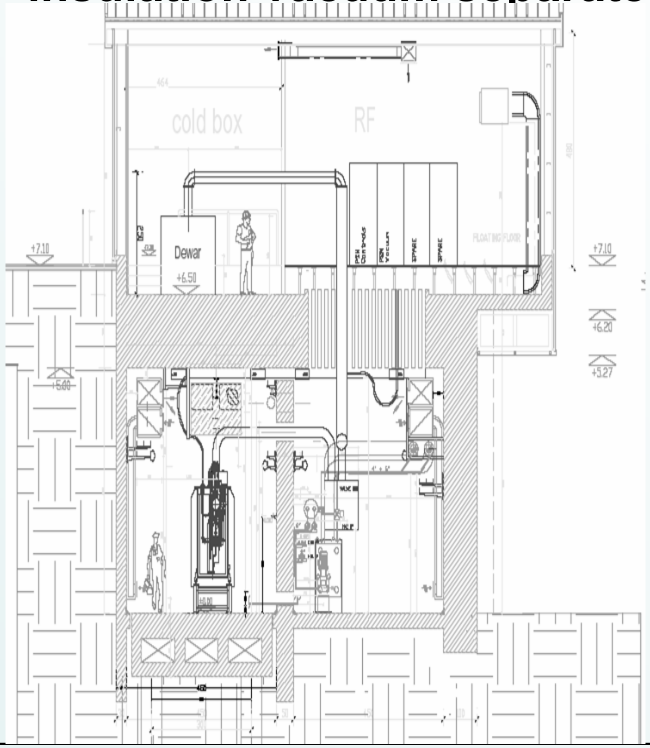


Prototype SC Module (PSM) developed by ACCEL

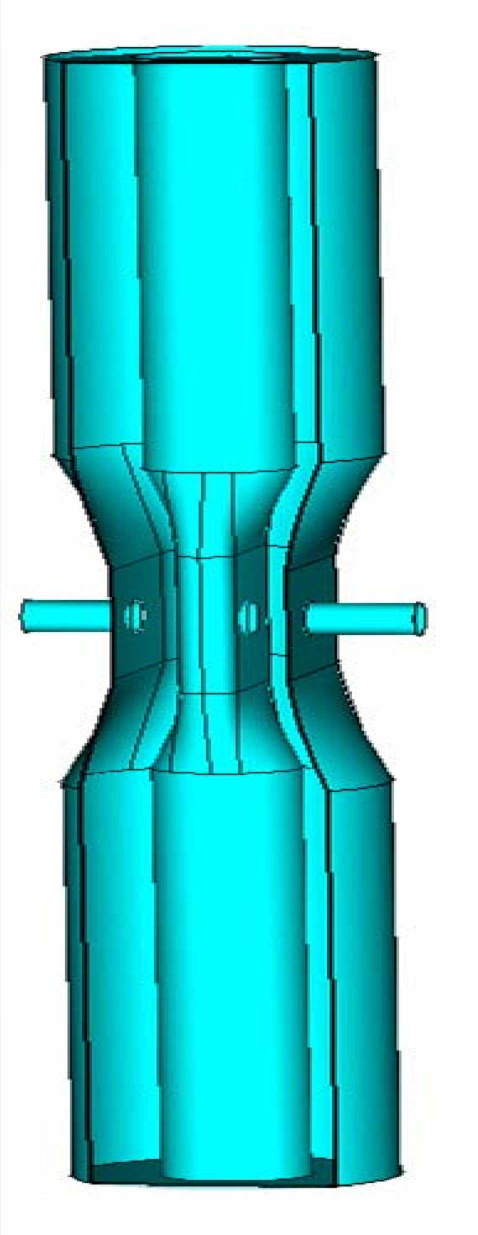


General Design:

- Houses 6 HWR and 3 superconducting solenoids
- Accelerates protons and deuterons from 1.5 MeV/u on
- Very compact design in longitudinal direction
- Cavity vacuum and insulation vacuum separated



Half Wave Resonator (HWR)

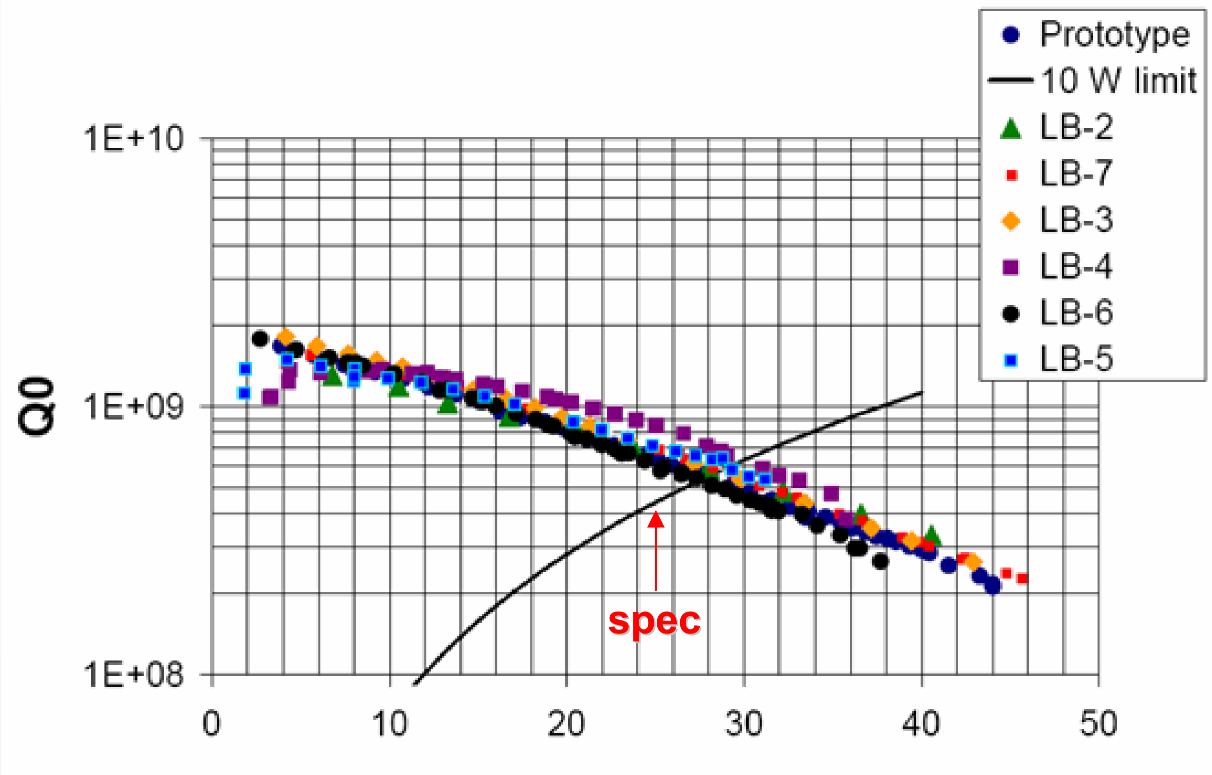


- f = 176 MHz & bandwidth ~ 100 Hz
- height ~ 85 cm high
- Optimized for

  β=0.09 @ first 12 cavities (2 modules)

  β=0.15 @ 32 cavities (4 modules)
- Bulk Nb 3 mm @ 4.45 K
- $E_{peak, max}$ = 25 MV/m & E_{peak}/E_{acc} ~ 2.5
- $Q_0 \sim 10^9$
- Cryogenic Load < 10 W

Summary of cavity test results (vertical dewar)



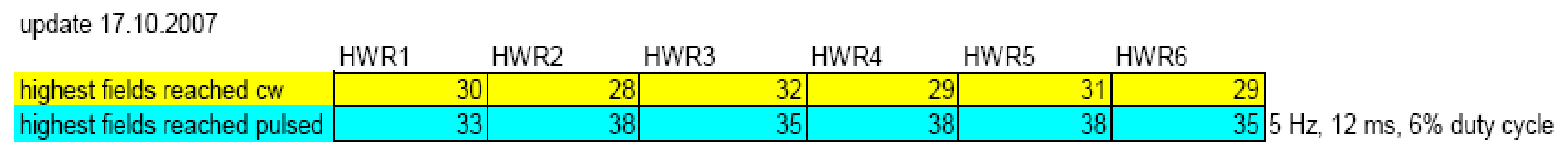
Cavity performance:

- LB-2, LB-7, LB-3, and LB-4 tested before helium vessel welding
- LB-6 and LB-5 tested after helium vessel welding
- In all test of series cavities, multipacting was much reduced compared to the prototype cavity
- Field emission only seen at very high field levels

PSM: RF fields reached so far

No coupler heating is limiting the cavity performance so far. Only mild warming of couplers up to 7 K are observed with Rf power of 1 kW cw.

Cavity one could be processed successfully. First lots of xrays were observed at 18 MV/m. After processing in pulsed operation, no more xrays are seen.



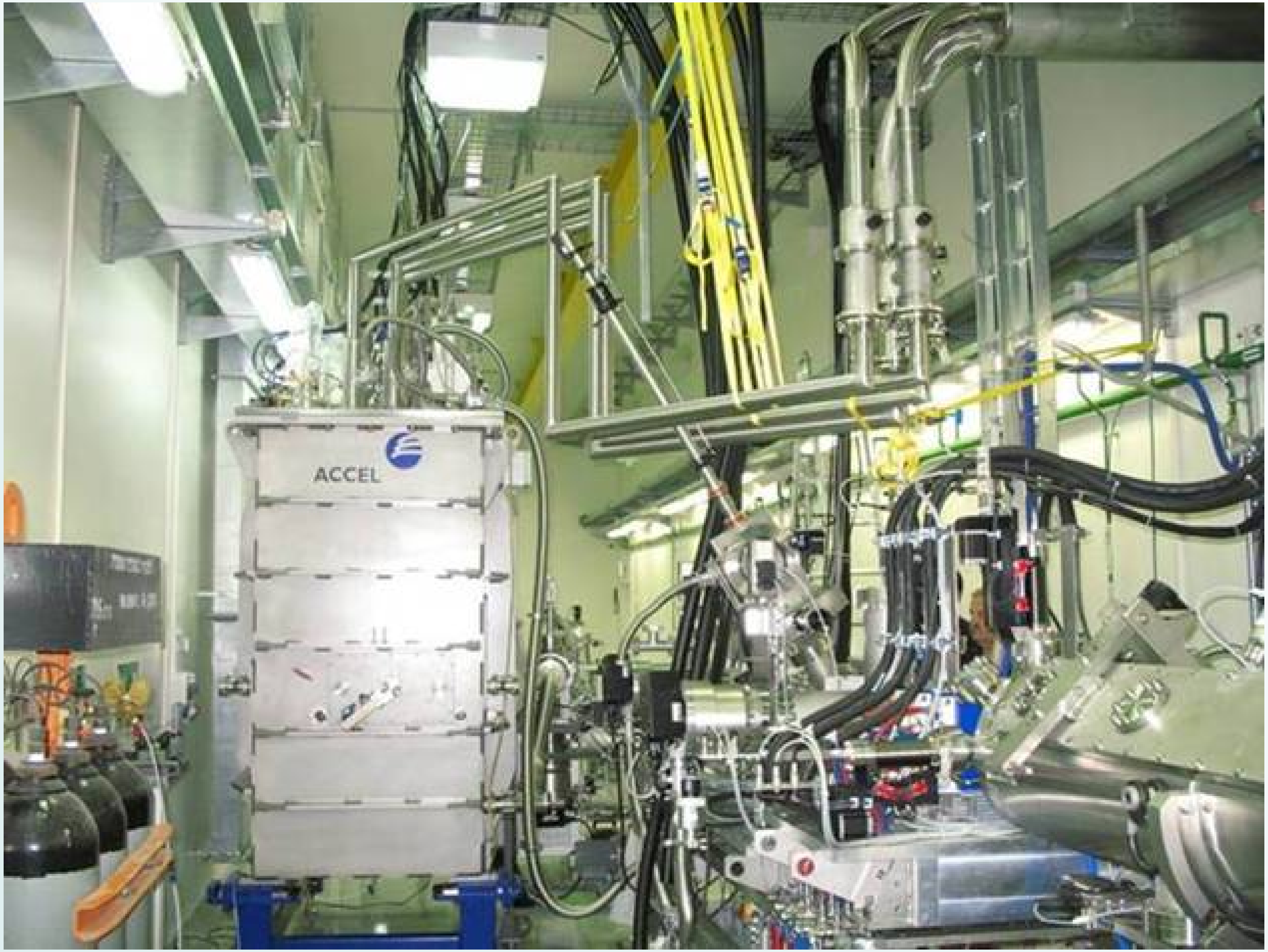
update 17.10.2007

	HWR1	HWR2	HWR3	HWR4	HWR5	HWR6	
highest fields reached cw	30	28	32	29	31	29	
highest fields reached pulsed	33	38	35	38	38	35	5 Hz, 12 ms, 6% duty cycle

For comparison, fields reached at ACCEL in 2006

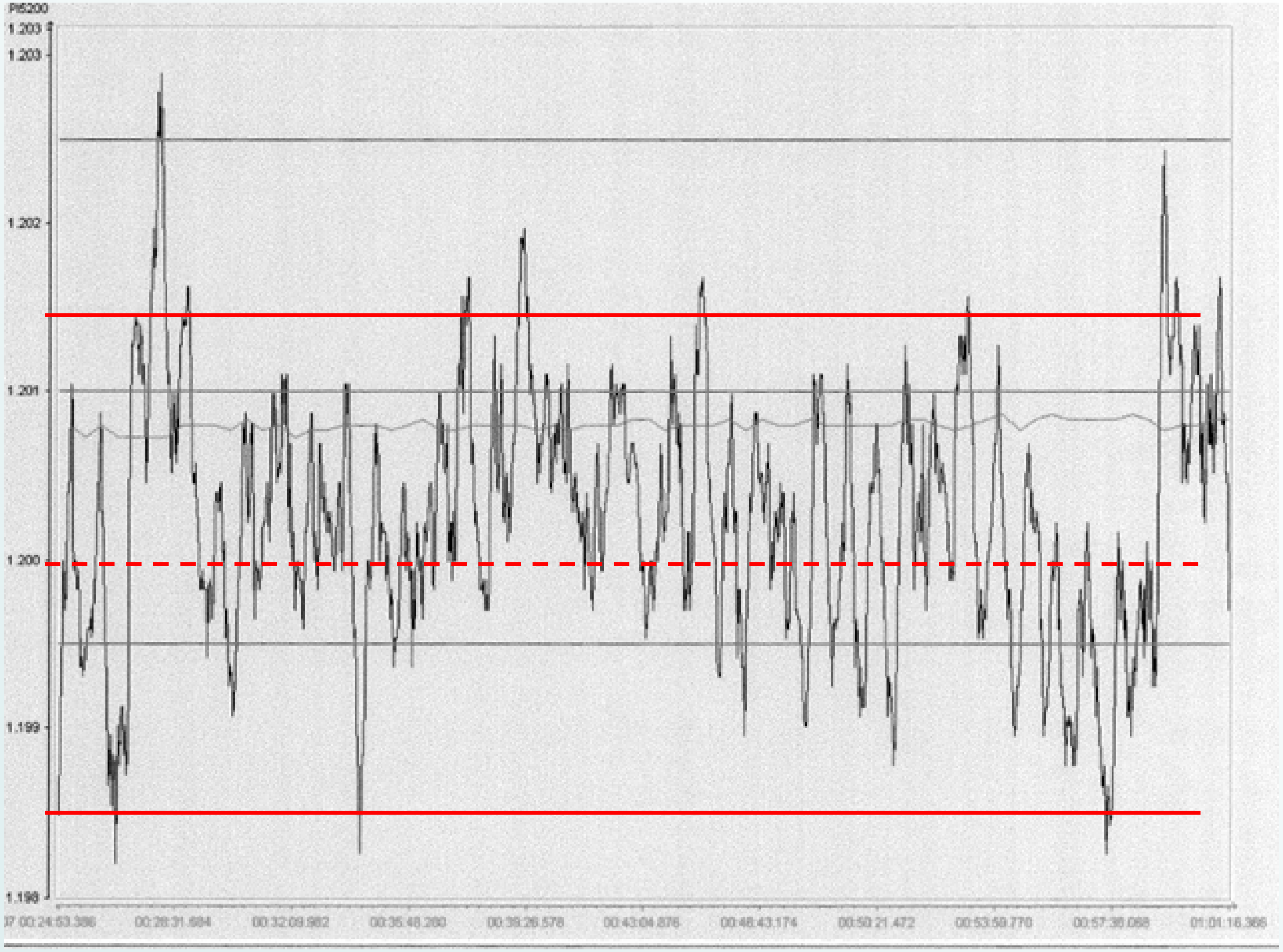
Cavities	Maximum gradient	limitation
Cavity 1	18.2 MV/m	Xrays
Cavity 2	21.2 MV/m	Coupler temperature
Cavity 3	24.8 MV/m	None
Cavity 4	26.4 MV/m	None
Cavity 5	19.7 MV/m	Xrays
Cavity 6	22.4 MV/m	Coupler temperature

Prototype SC Module (PSM)



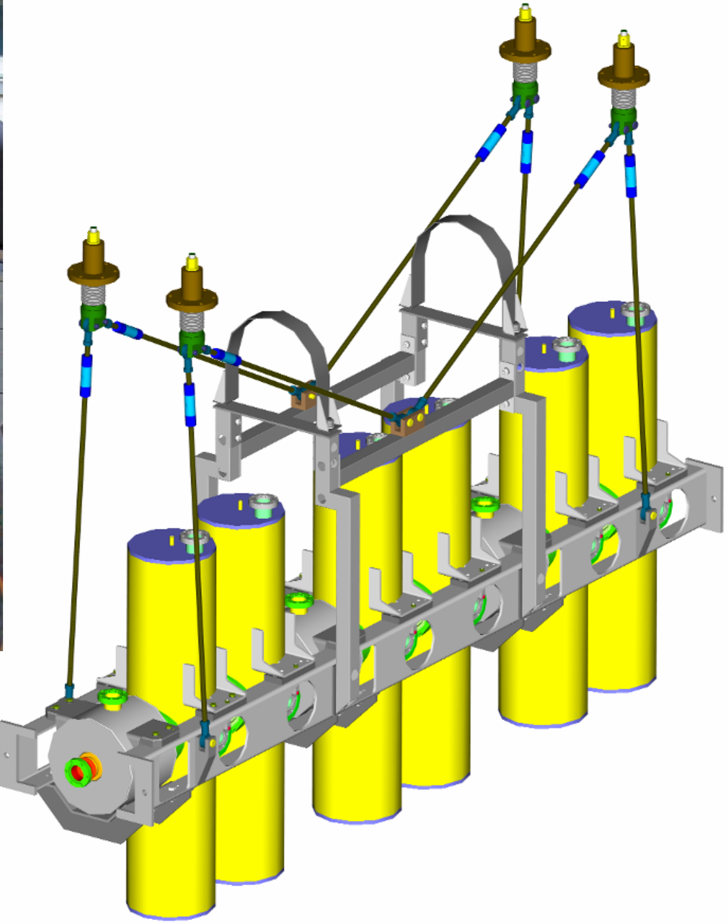
PSM installed out of beam line to allow D-plate being used at PSM location

Operation of cryoplant with intermediate transfer lines



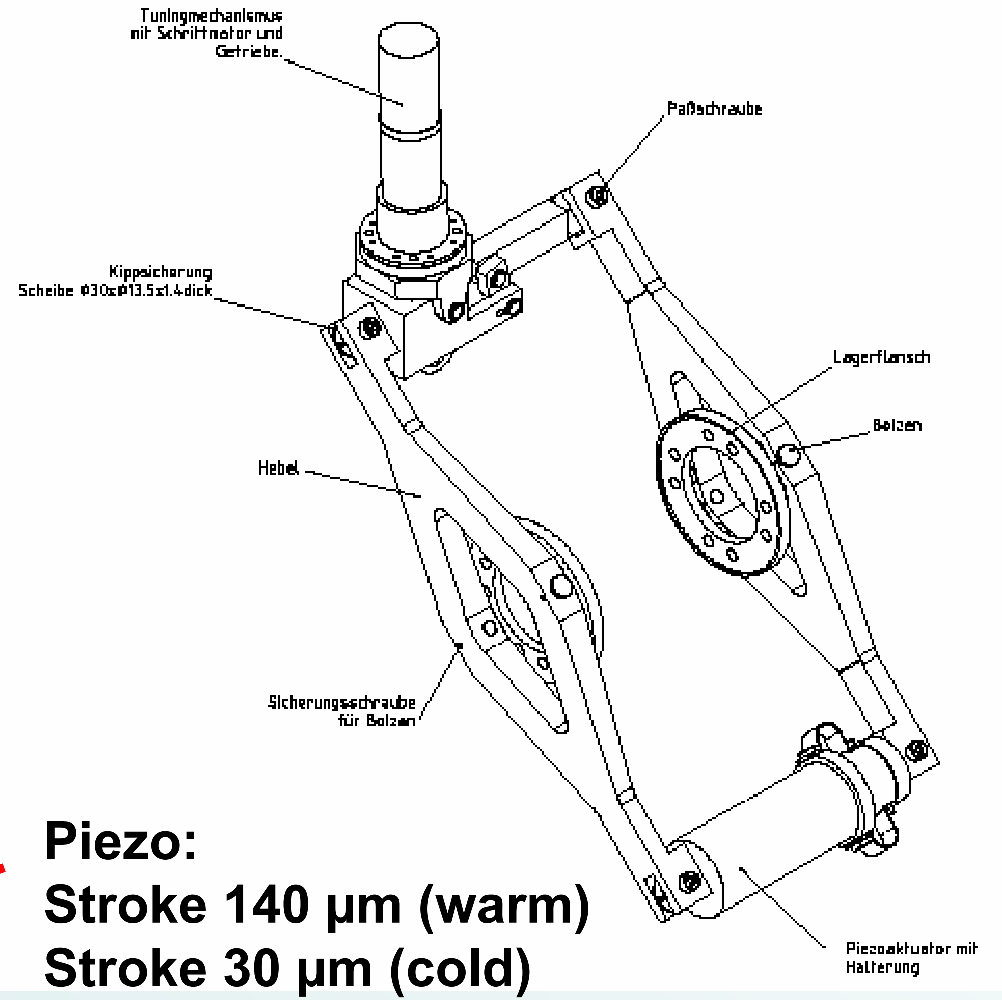
Helium bath pressure over night without load changing over a time of half an hour, certainly above +/- 1.5 mbar as specified. We need to find out the influence of the intermediate transfer lines and hopefully will improve at original location of PSM

Cryostat and Cavities' Assembly

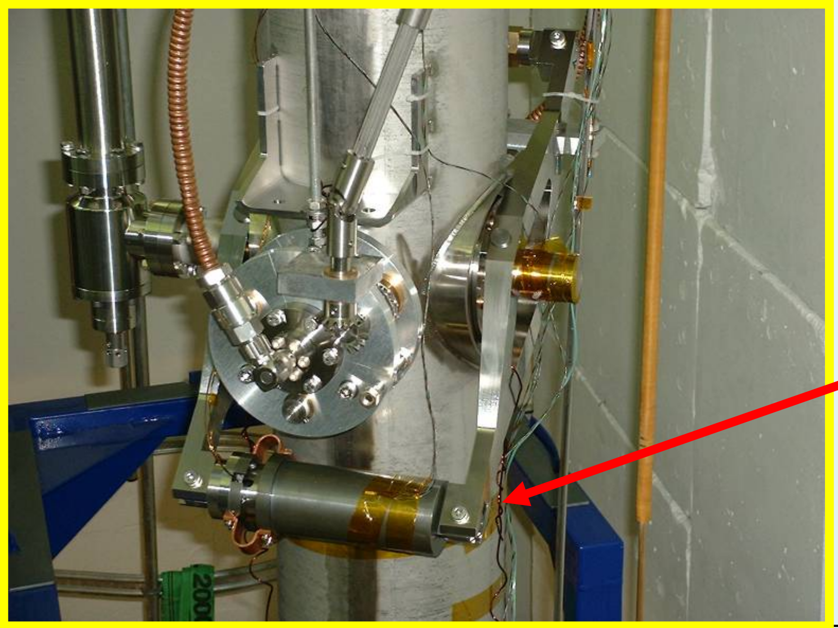


Tuners

Mechanical: Warm & Cold
Sensitivity: 0.2 Hz/step



Piezo:
Stroke 140 µm (warm)
Stroke 30 µm (cold)
Usable stroke (+/-3 µm)
-> +/- 450 Hz tuning range

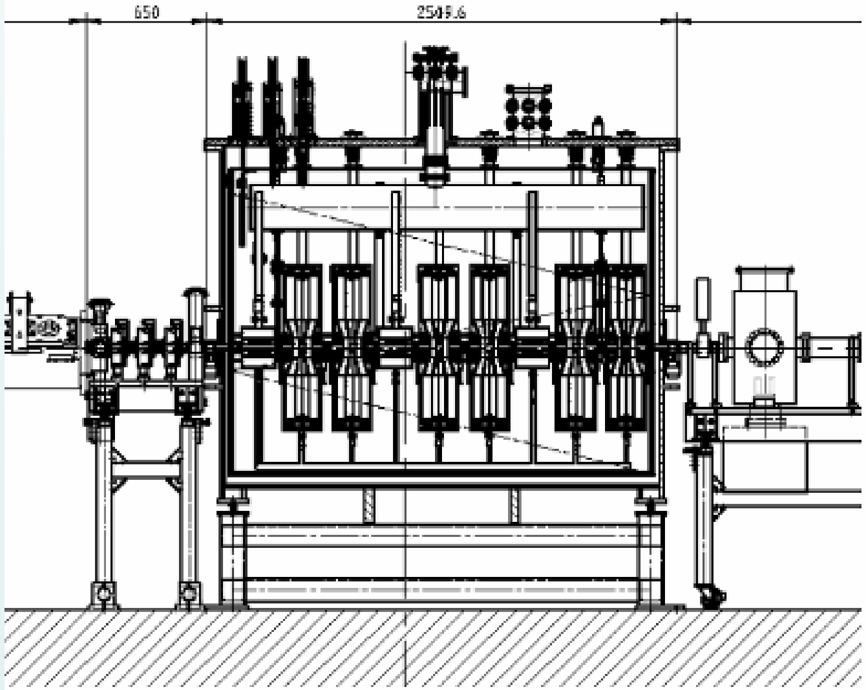


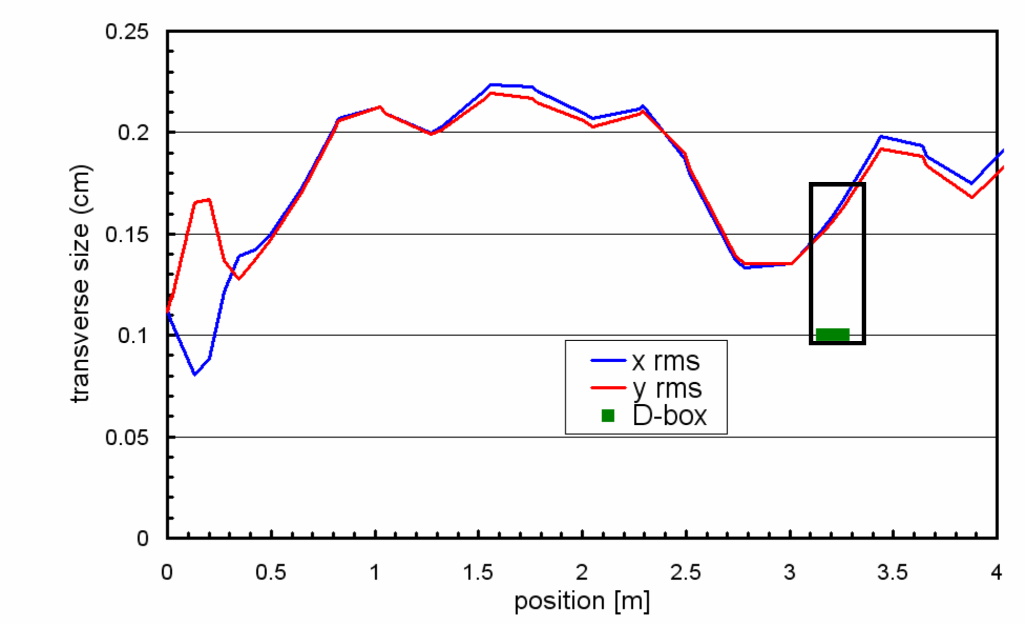
Cryogenic system (Phase-II)

- Linde TCF50 x 2 Liquid He refrigerator
- Cryogenic power load:
  - 900 W @ 4.5 K
  - 1150 W @ 70 K
- 700 kW mains power

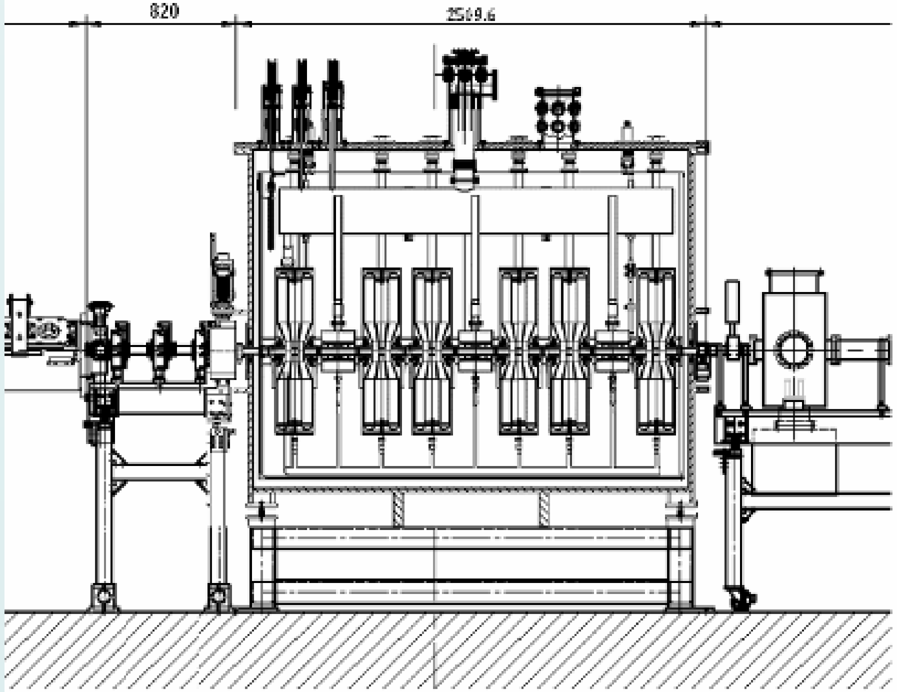
- Pressure
  - 1250 mbar at a cavity
  - Stability ±1.5 mbar

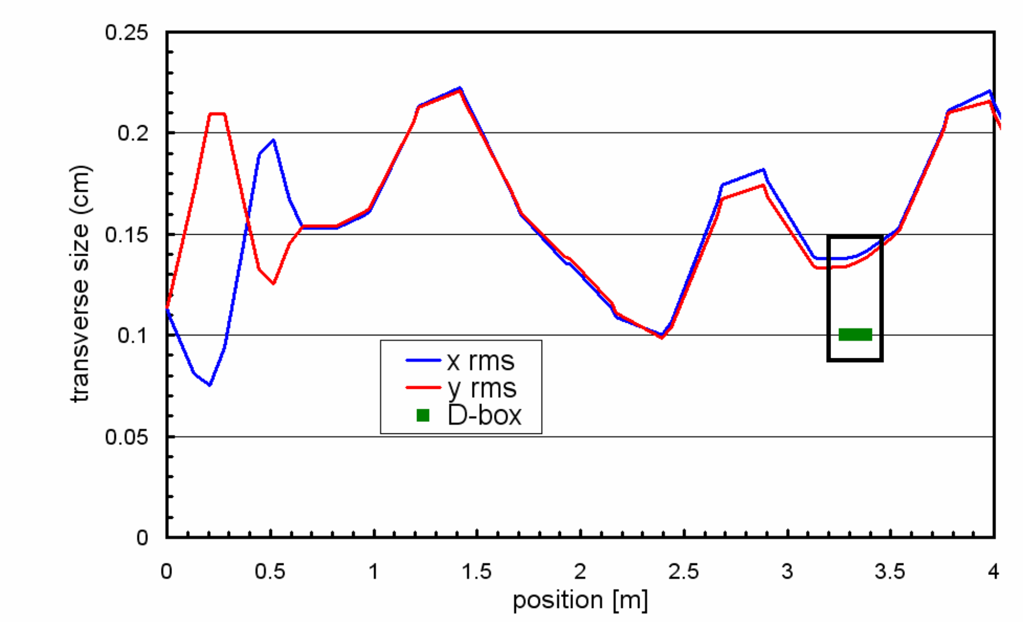
Cold box Phase-I in situ



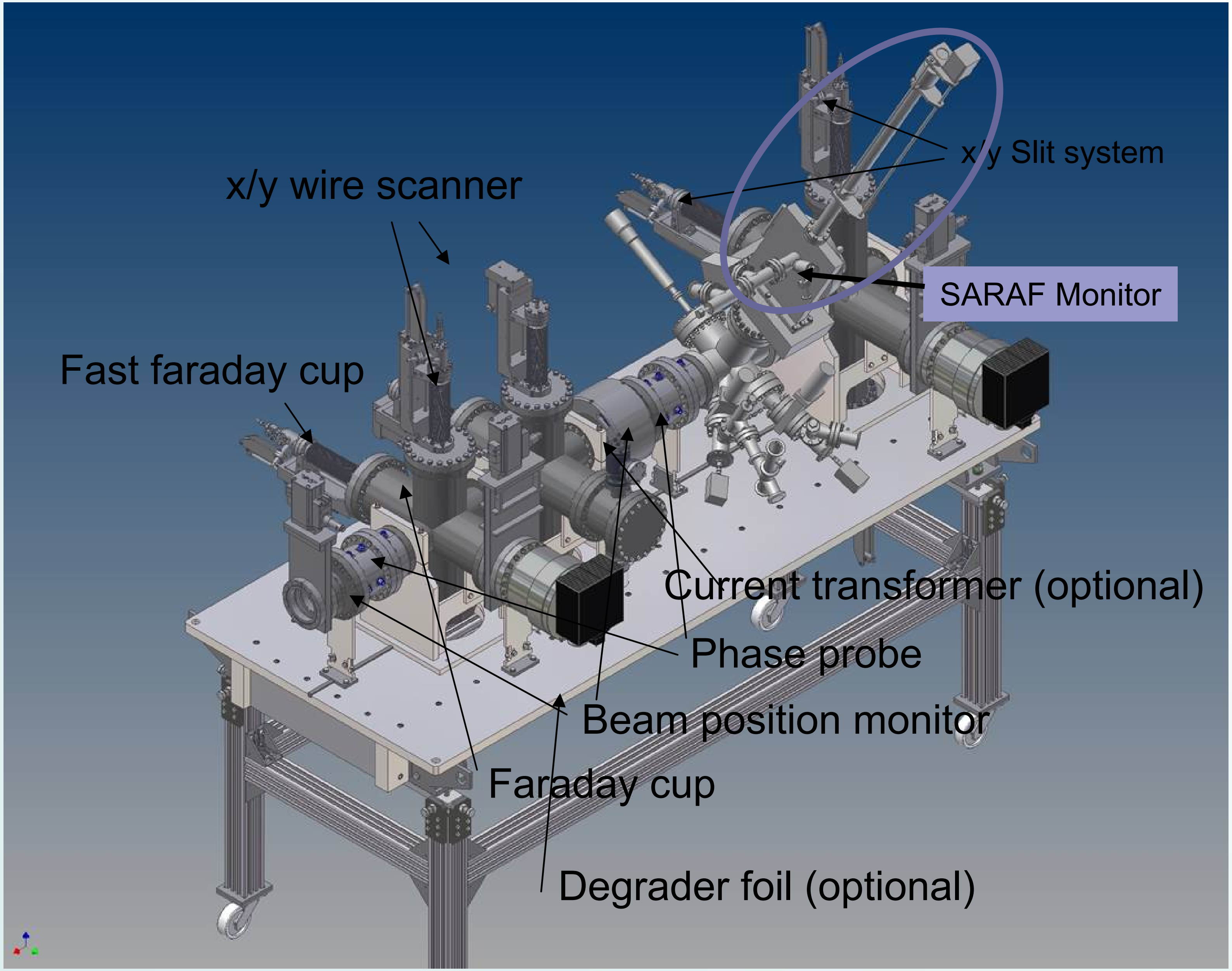


Symmetric versus Asymmetric lattice





D-Plate design modified to 40MeV



Transversal Emittance

Energy

Current

Longitudinal Emittance

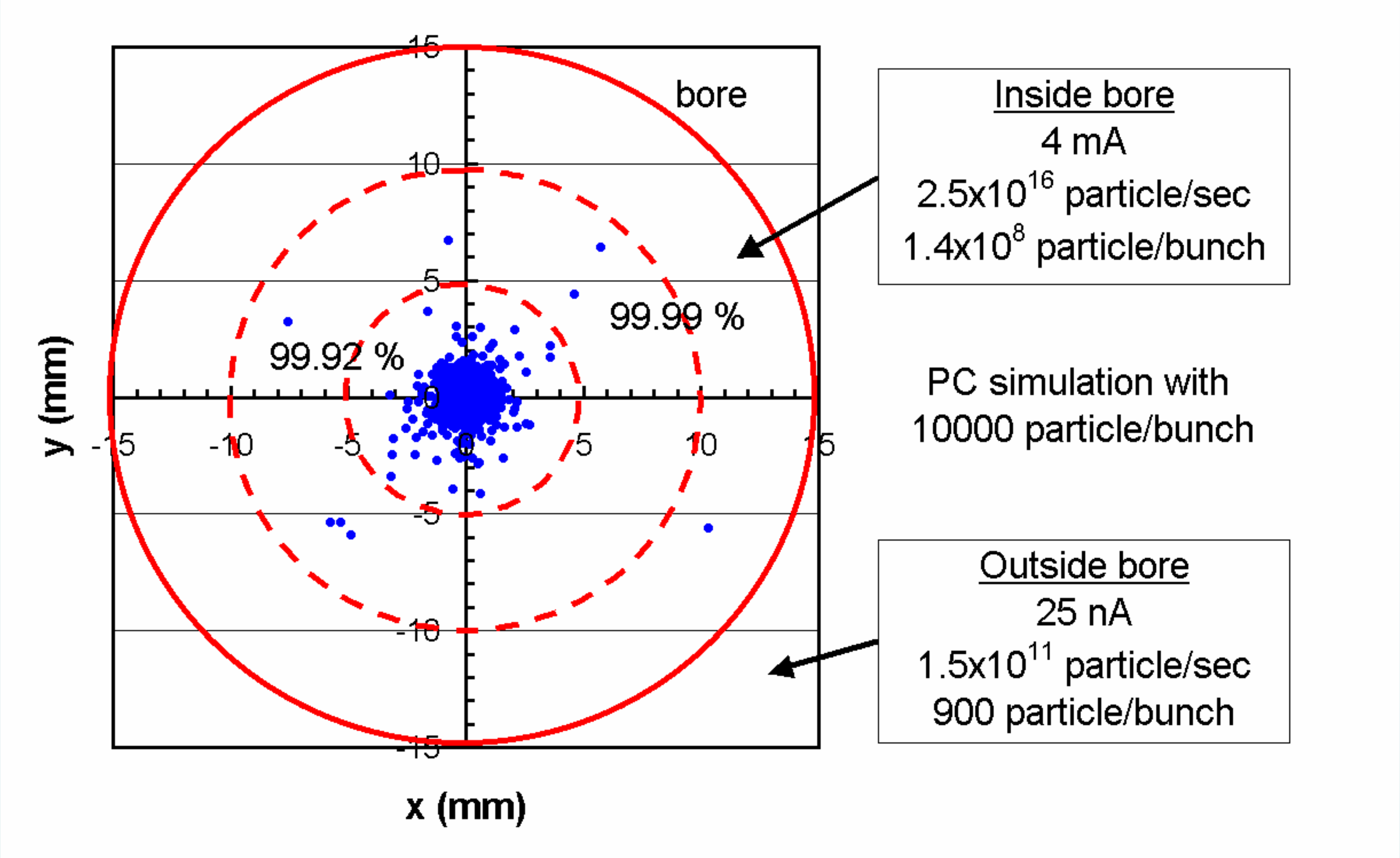
Beam Halo

Hands-On maintenance criterion

Beam loss along the linac

< 20 mSv/h at a distance of 30 cm from the beam line and 4 hour after shutdown

(< 1 nA/m for 6000 hour/y operation with 50 MeV deuteron)



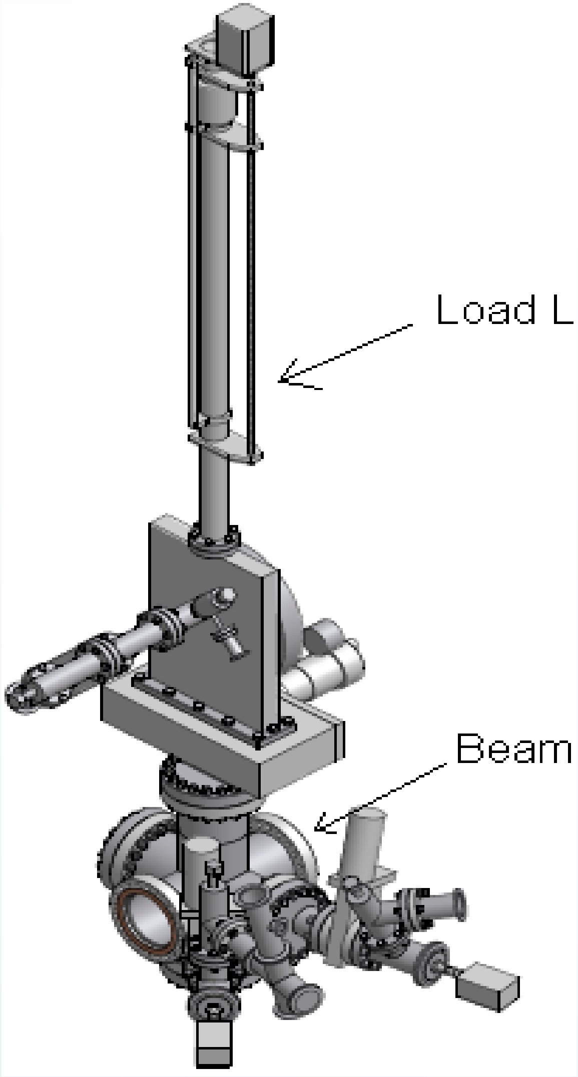
Inside bore
4 mA
2.5×10^{16} particle/sec
1.4×10^{8} particle/bunch

PC simulation with
10000 particle/bunch

Outside bore
25 nA
1.5×10^{11} particle/sec
900 particle/bunch

Beam Halo measurement

1. Electric methods (FC or MCP)
2. Nuclear reactions 2.5 - 4 MeV p on LiF
    - On-line $^{19}F(p,\alpha\gamma)^{16}O$ resonance → γ @ 7 MeV
    - Off-line 2.5 or 4 MeV pulsed beam
      $^{7}Li(p,n)^{7}Be(T_{1/2}=53\text{ d})$
3. Rutherford scattering (on a gold foil using a Si detector)



Summary

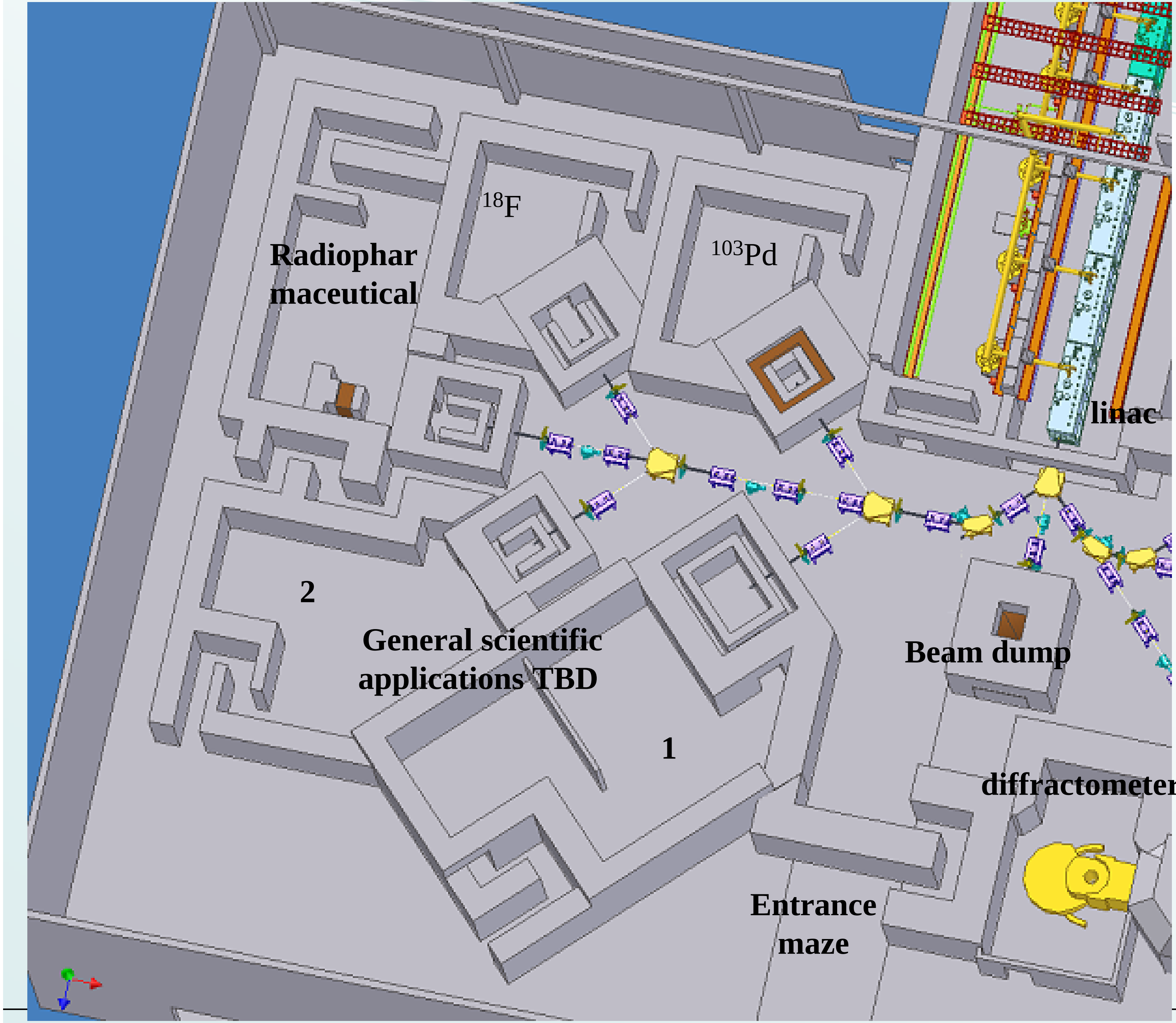
SARAF Innovated technologies

- CW RFQ with power dissipation of 60 kW/m
- Light-ion low-beta superconducting linac
- Superconducting HWR at 176 MHz
- Separated vacuums in the cryostat
- Linac beam loss of the order of 10^{-6}

Applications

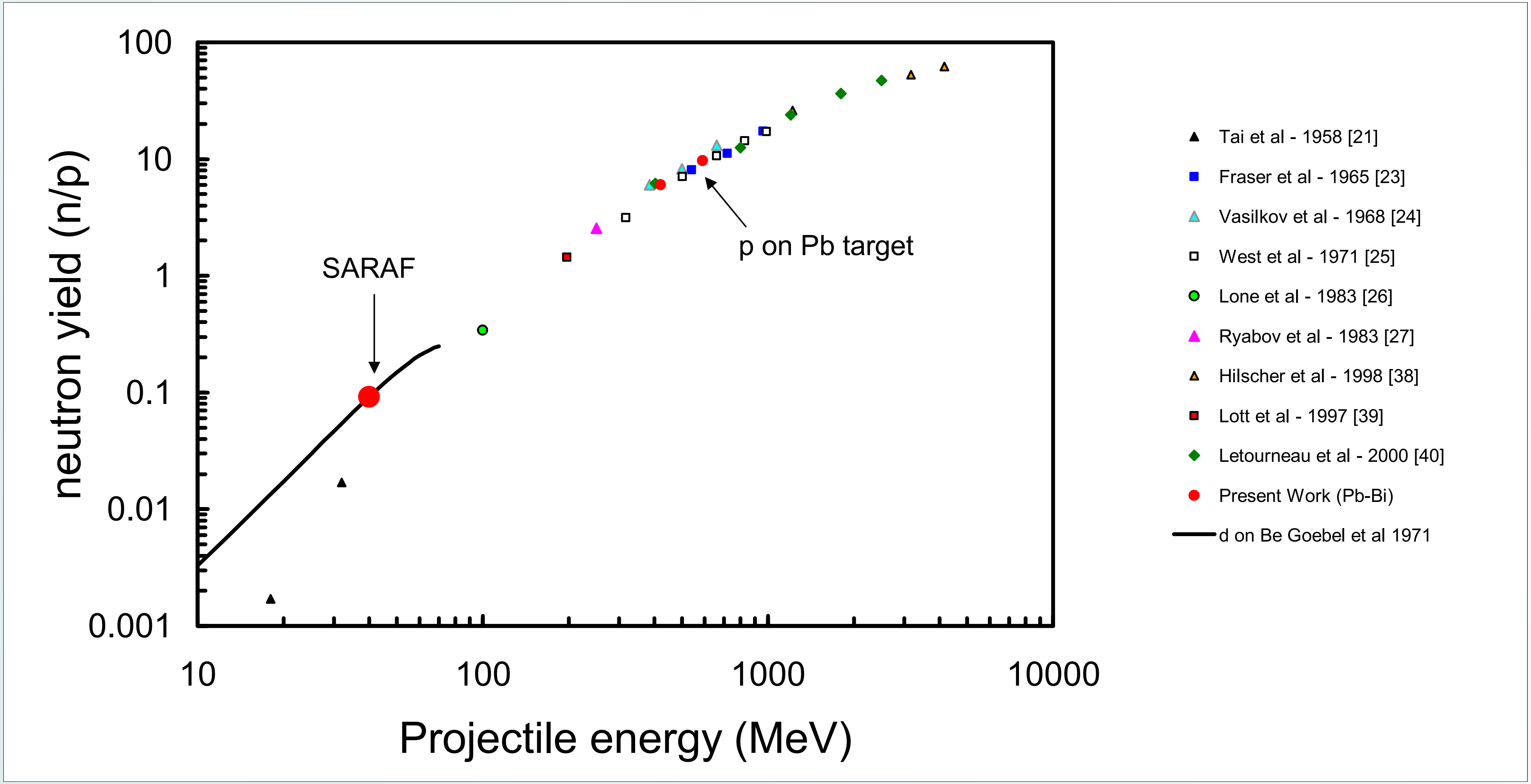
1. Neutron Generator for:
    1. Thermal Neutrons for Non Destructive Tests
    2. Monochromatic Neutron Diffractometer
2. Direct Radioisotope Production for:
    1. Radio pharmaceutical isotopes
    2. Basic research in nuclear physics

Target Hall (2013)

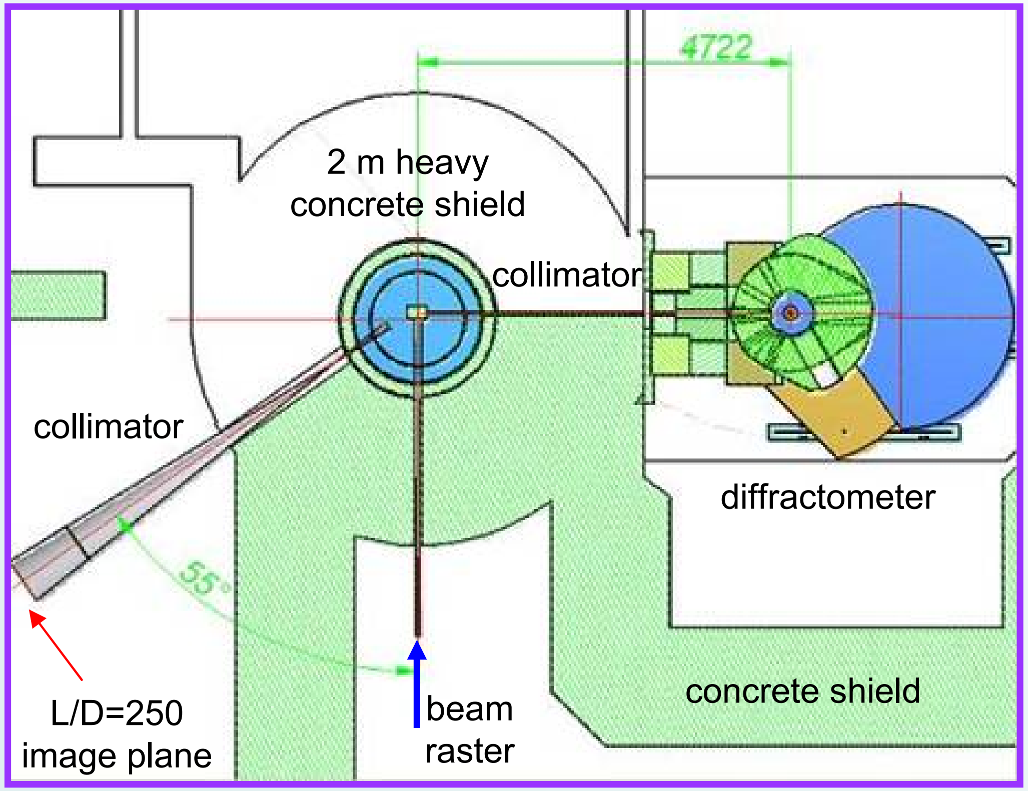


Neutron yield

K. van der Meer, M.B. Goldberg *et al.* NIM B (2004)



Thermal neutron source



2 m heavy
concrete shield

collimator

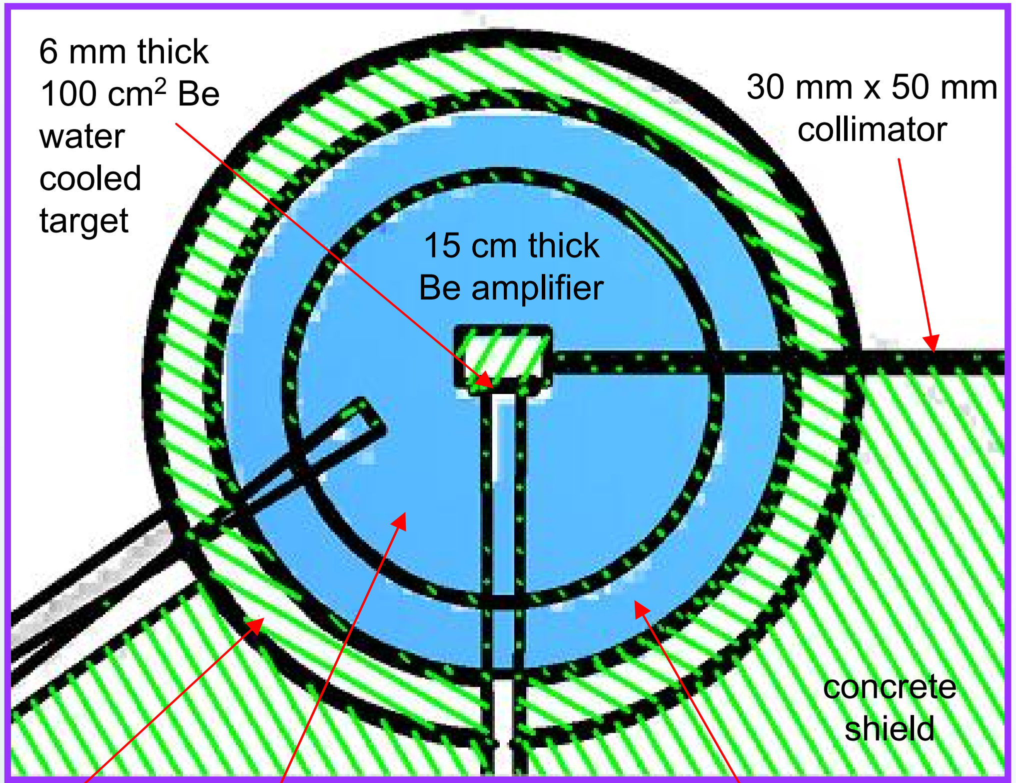
collimator

diffractometer

concrete shield

L/D=250
image plane

beam
raster

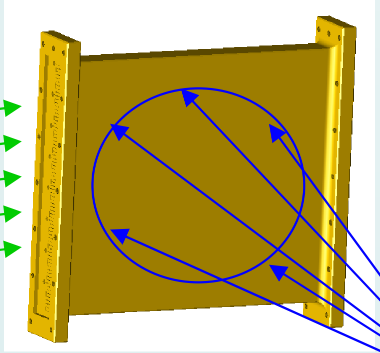


6 mm thick
100 cm^2 Be
water
cooled
target

30 mm x 50 mm
collimator

15 cm thick
Be amplifier

concrete
shield



water
cooling

6 mm thick 100
cm^2 Be target

40 MeV x 2 mA
d beam

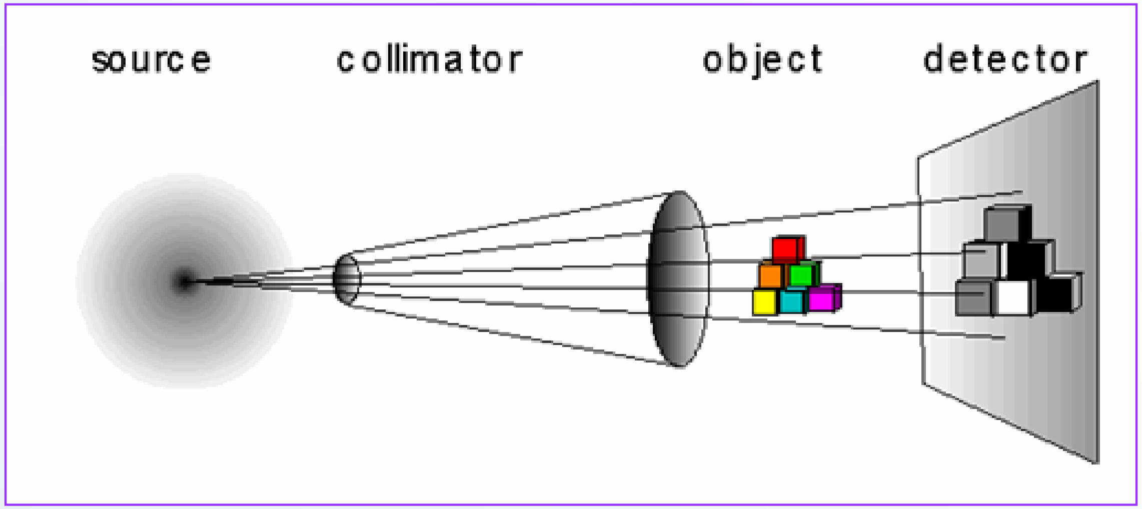
thermal Pb+Fe
water cooled shield

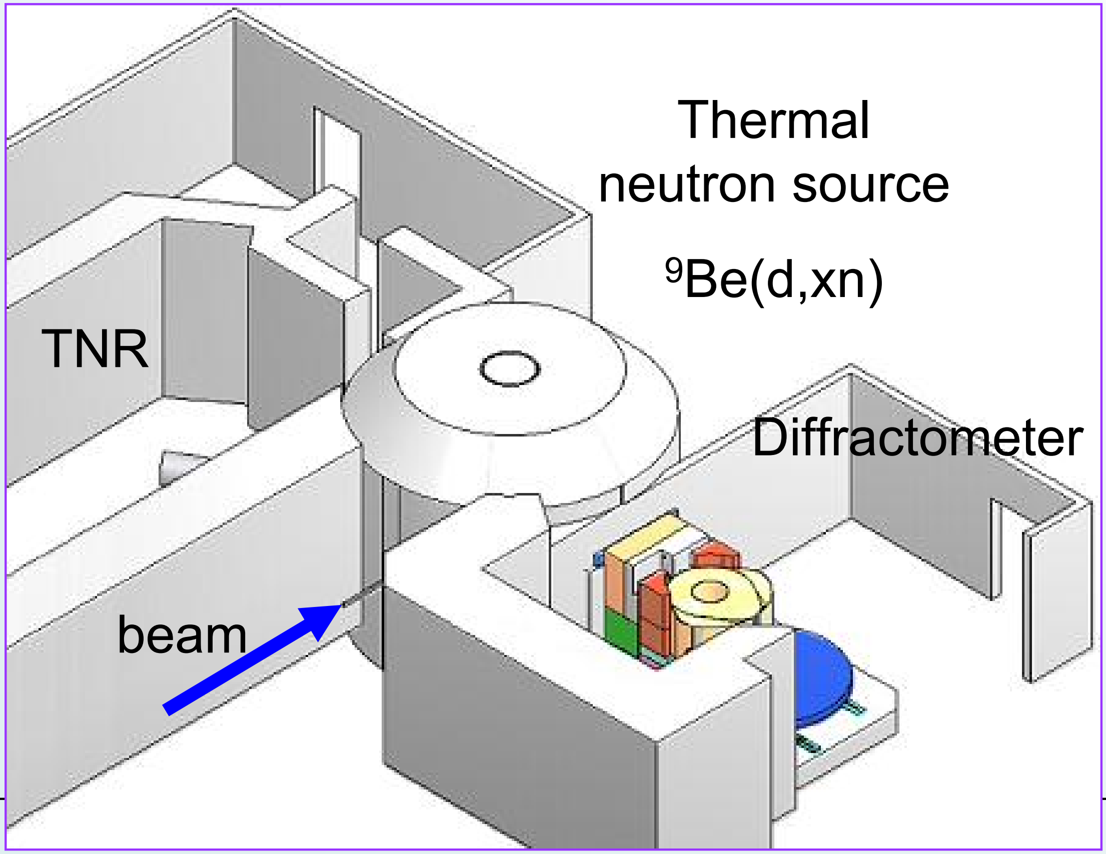
Φ=120 cm
D_2O moderator

beam

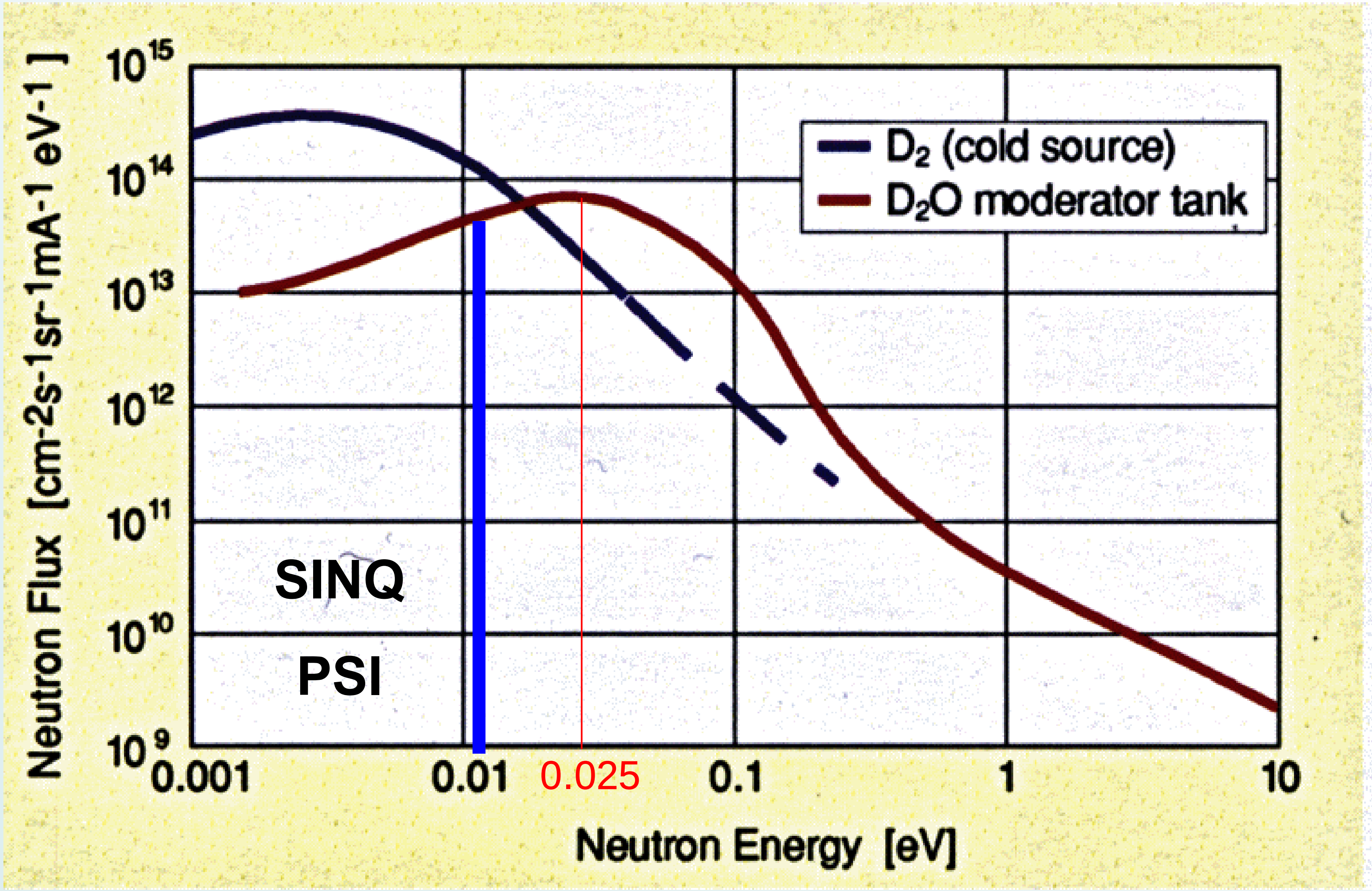
20 cm H_2O reflector

(1) Thermal Neutron Radiography (TNR)





Diffractometer neutron energy



Summary of Neutronic calculations

Values at the extraction point

radius (cm)	Φ_{th}/Φ_f	current ($n/cm^2\ s$)	th. flux ($n/cm^2\ s$)
33	14	0.87×10^{12}	1.43×10^{12}
25	4	1.40×10^{12}	2.30×10^{12}

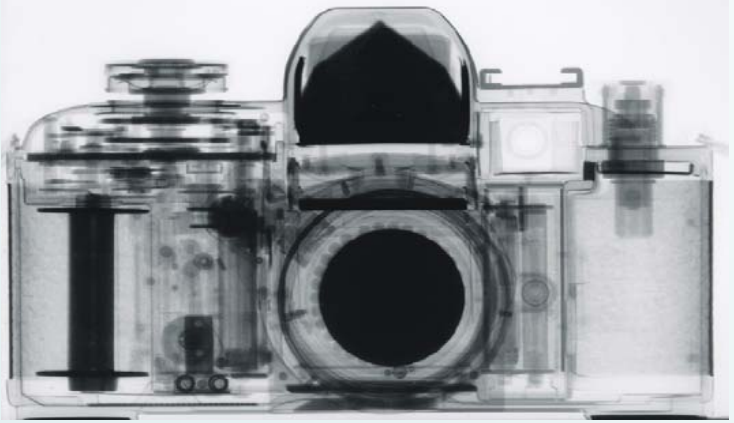
Thermal Flux ($n/cm^2\ s$) at the target

- Image plane > 6×10^5
- Entrance to monochromator of the diffractometer ~2.4×10^7 (L/D = 57)

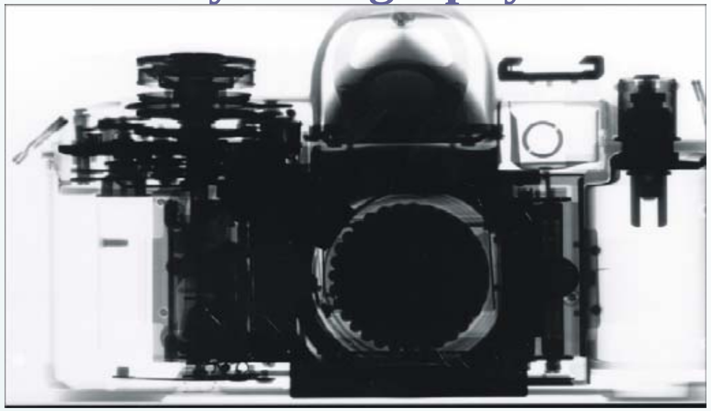
Neutron Radiography

- Powerful non destructive imaging technique.
- Provides images in the same manner as x-ray radiography.

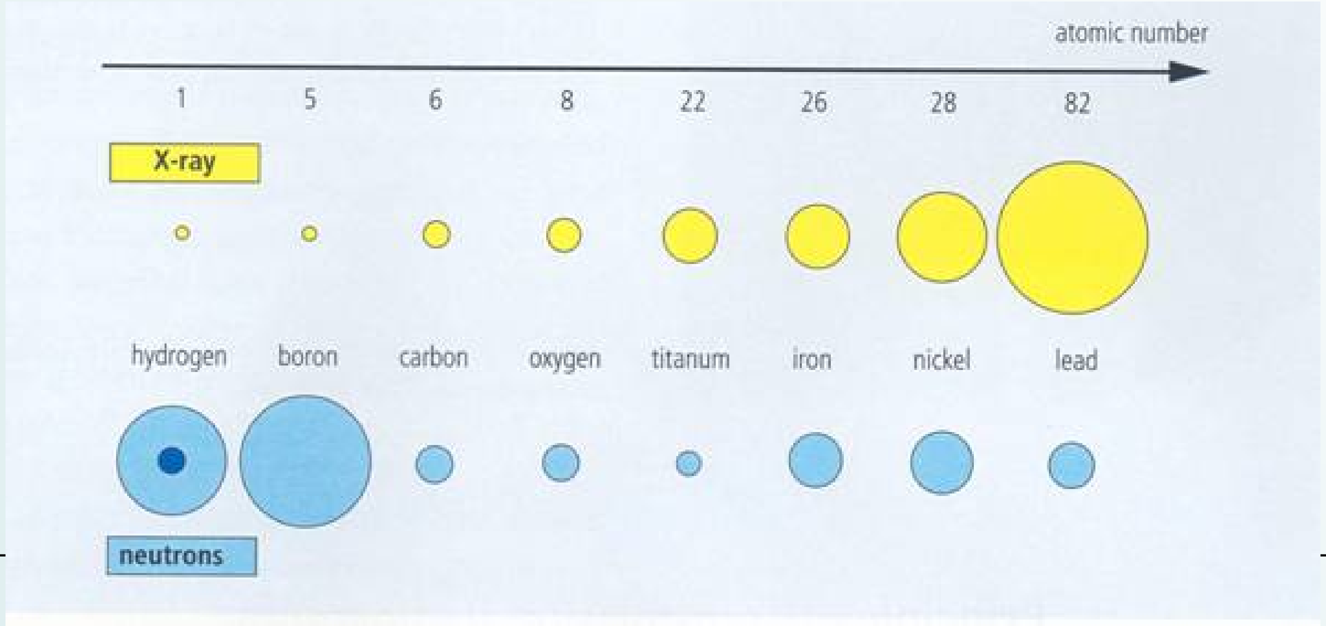
neutron radiography



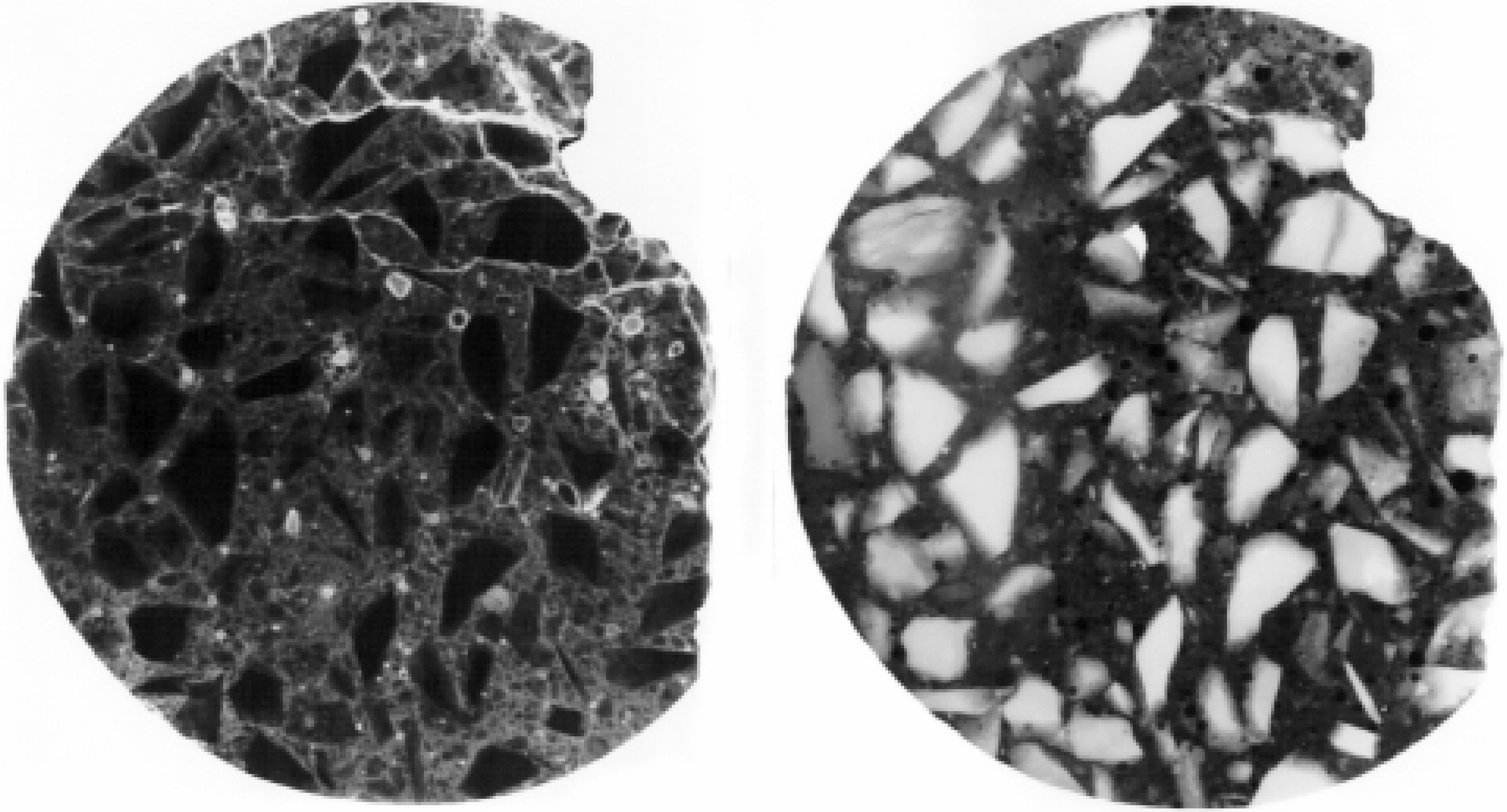
x-ray radiography



Differences in interaction probability are particularly marked at lower neutron energies



n-Ray vs. X-Ray of concrete



Neutron Radiograph
(N-Ray)

"X-Ray" Radiograph

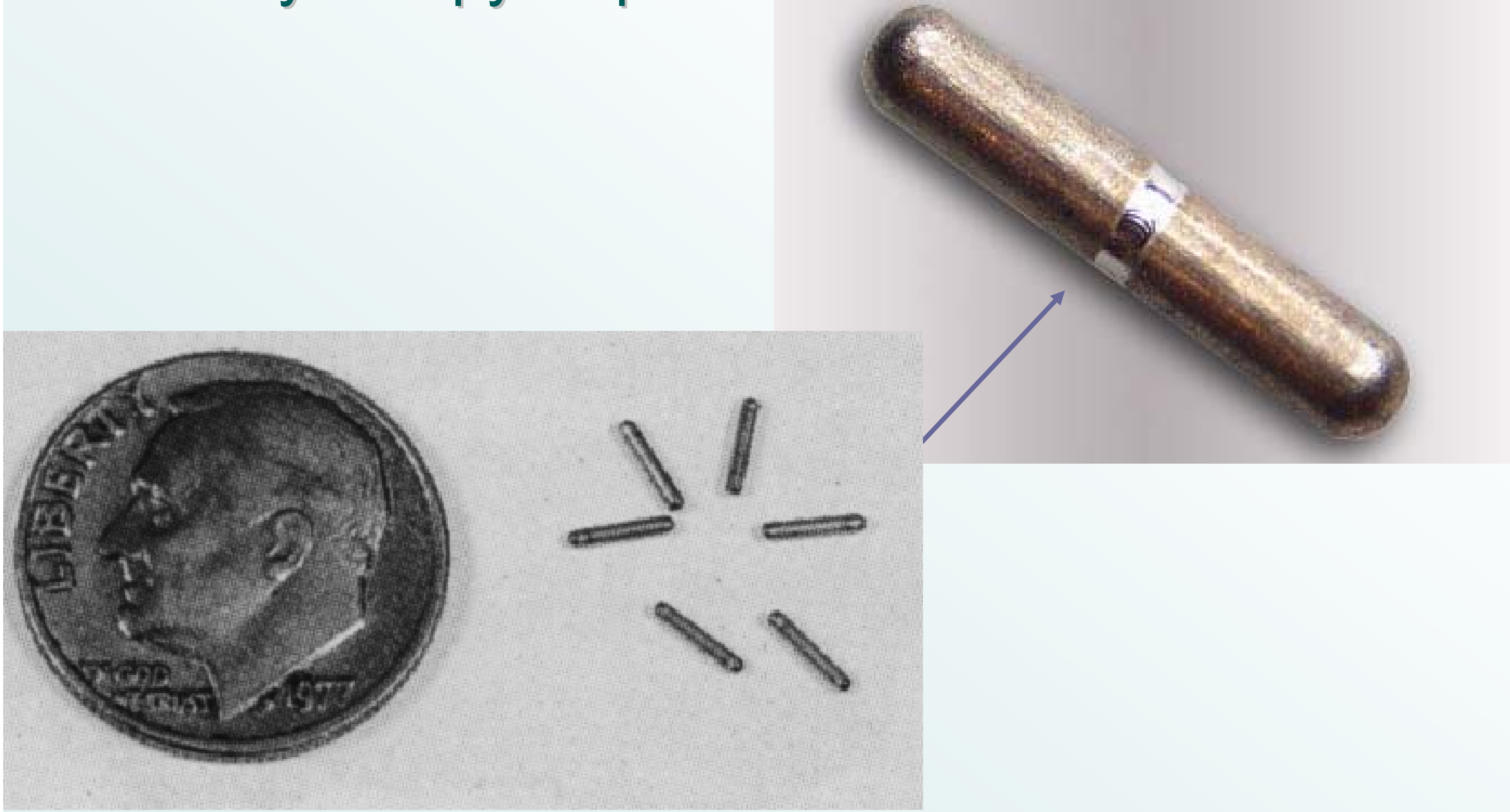
(2) Accelerator-Based Radio Pharmacy Isotopes

Isotope / usage	Target (% abund.) (type)	Energy (MeV)	Reaction
^{201}Tl / SPECT	^{203}Tl (29.5) (S)	30 p	p,3n
^{123}I / SPECT	^{124}Xe (0.094) (G)	30 p	p,2n
^{103}Pd / Therapy	^{103}Rh (100) (S)	12-14 p 17 d	p,n d,2n
^{111}In / SPECT	^{112}Cd (24.0) (S)	18 p	p,2n
^{18}F^{-} / PET	^{18}O (0.2) (L)	18 p	p,n
^{186}Re	^{186}W (29.0) (S)	16 d	d,2n

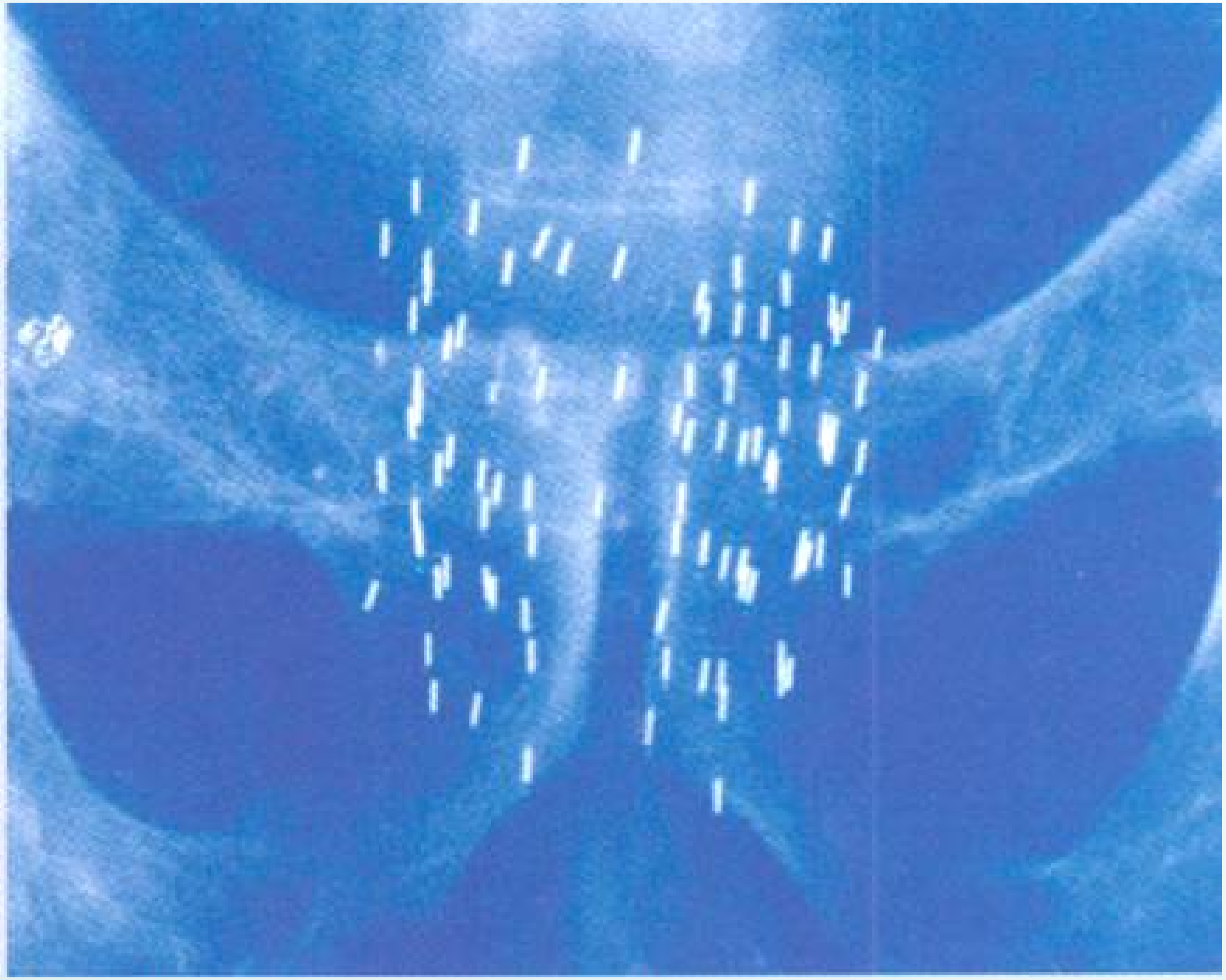
Palladium (^{103}Pd) for Brachytherapy

- Irradiate ^{103}Rh with protons or deuterons to generate ^{103}Pd
- Low energy (20 keV gamma), long half-life (17 days) – advantages for local tumor treatment and for world wide distribution
- ^{103}Pd inserted into capsules which are planted in tumor

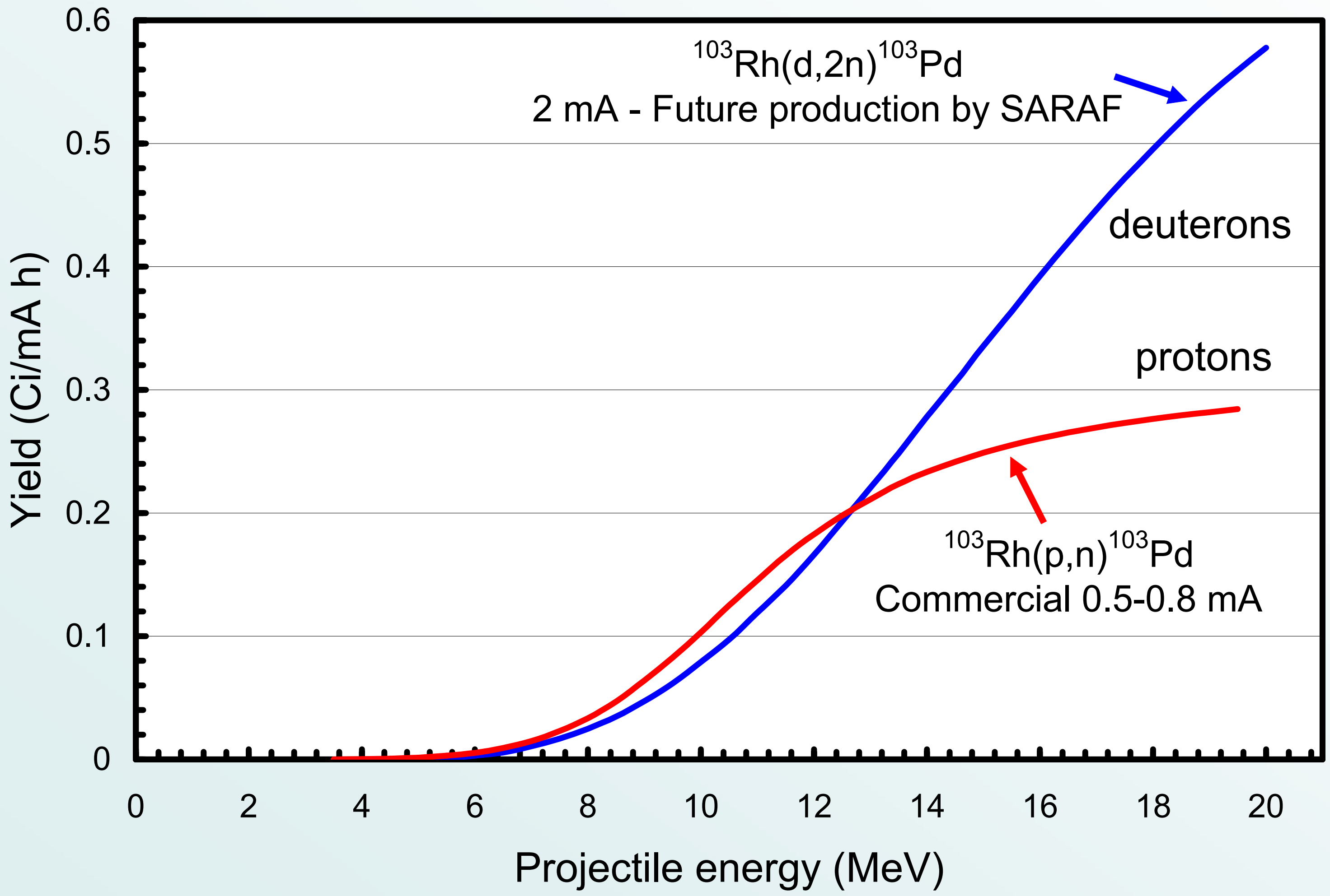
Brachytherapy Capsule



Treatment Illustration



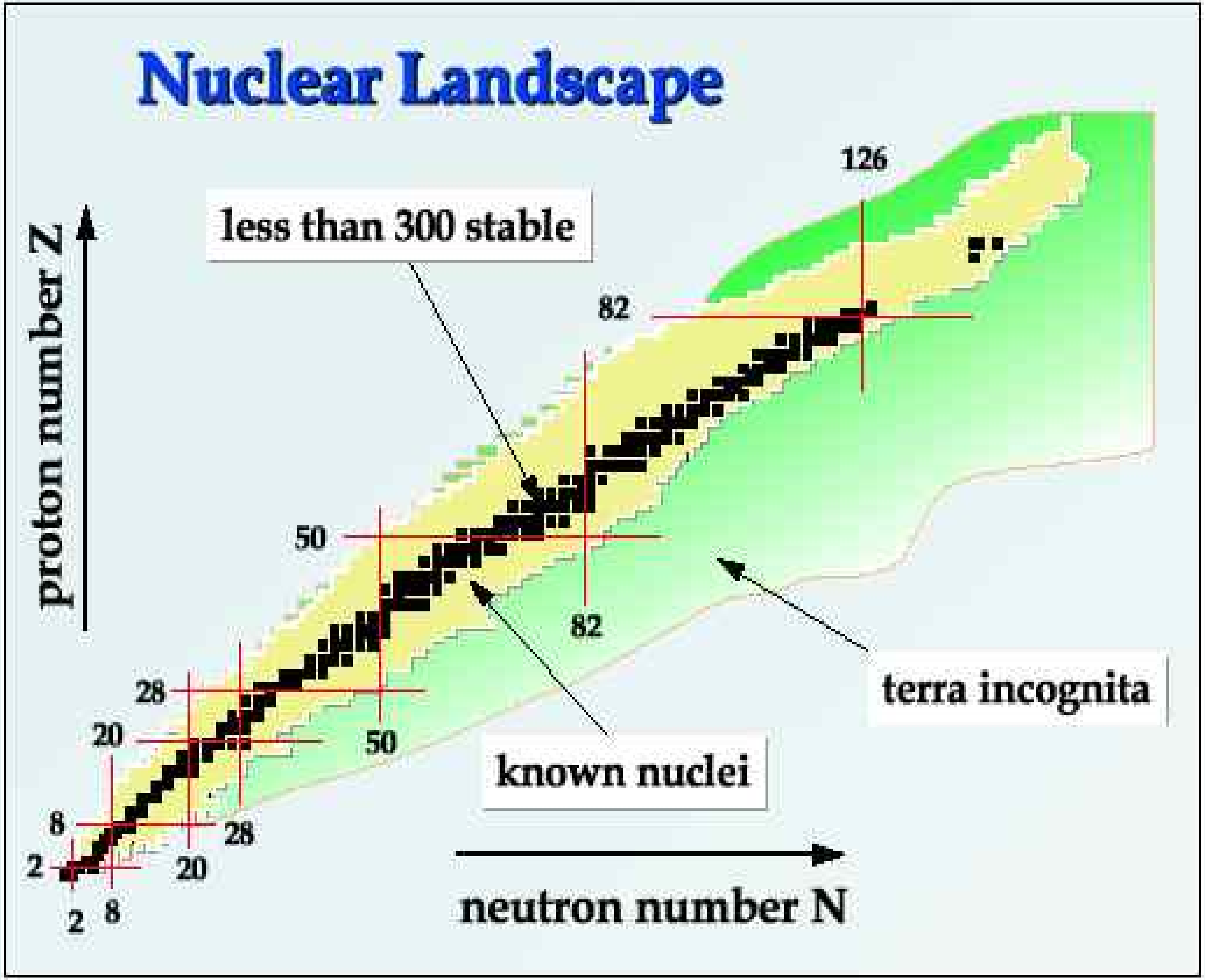
^{103}Pd production yield



(3) Radioactive Nuclear Beam

Goal:

To explore, study and understand the phenomena that nuclei present near the limits of nuclear existence.



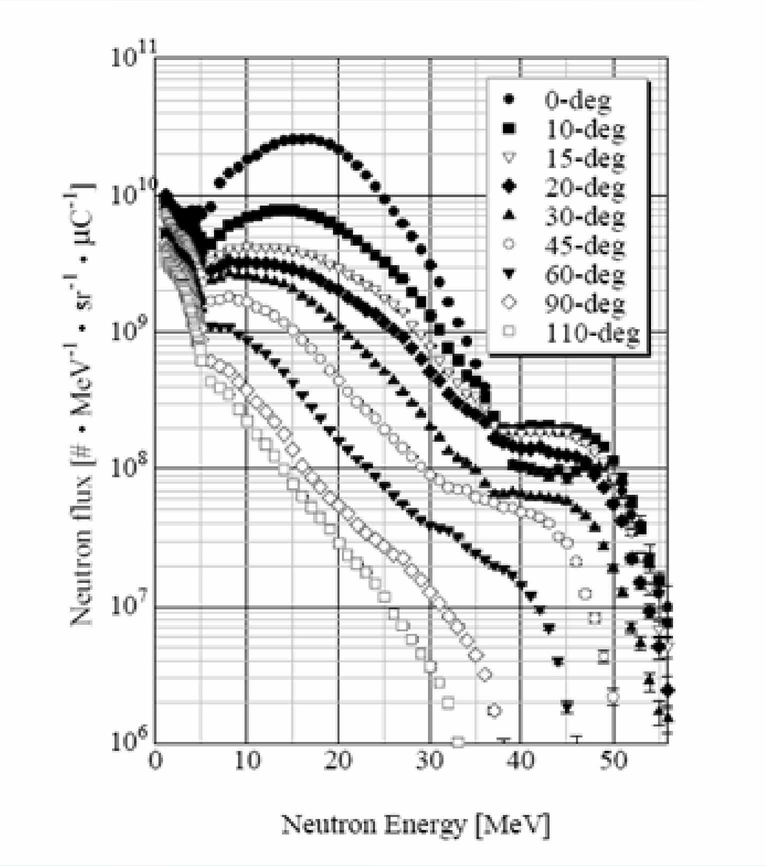
^{6}He ($t_{1/2}$=807 ms)

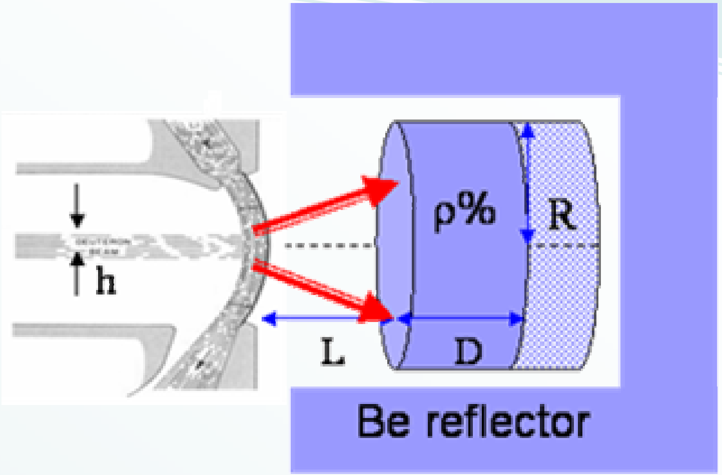
Two-stage production

$^{9}Be(d,xn) \rightarrow {}^{9}Be(n,\alpha){}^{6}He$

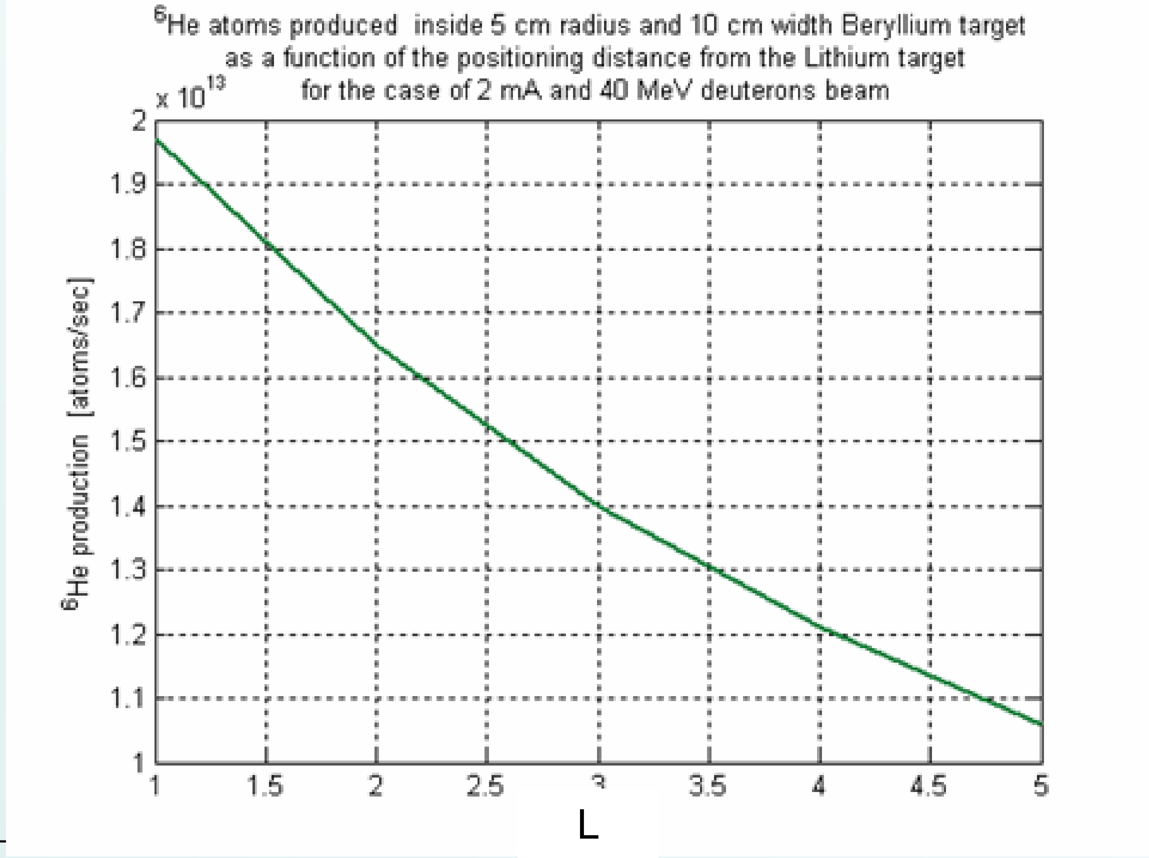
$^{9}Be(d,xn) \rightarrow {}^{9}Be(n,2n) \rightarrow {}^{9}Be(n,\alpha){}^{6}He$

Yield optimization





^{nat}Li(d@40MeV,xn)



M. Hagiwara et al.,
J. Nuc. Sci. Tech., **41**, Issue.4,
p.399, (2004).

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