The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1858-28

School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

19 - 30 November 2007

Accelerators for ADS: Science, Technology and Design
Part II

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DESIGN OF ACCELERATORS FOR ADS

4th Lecture

The ADS Accelerator

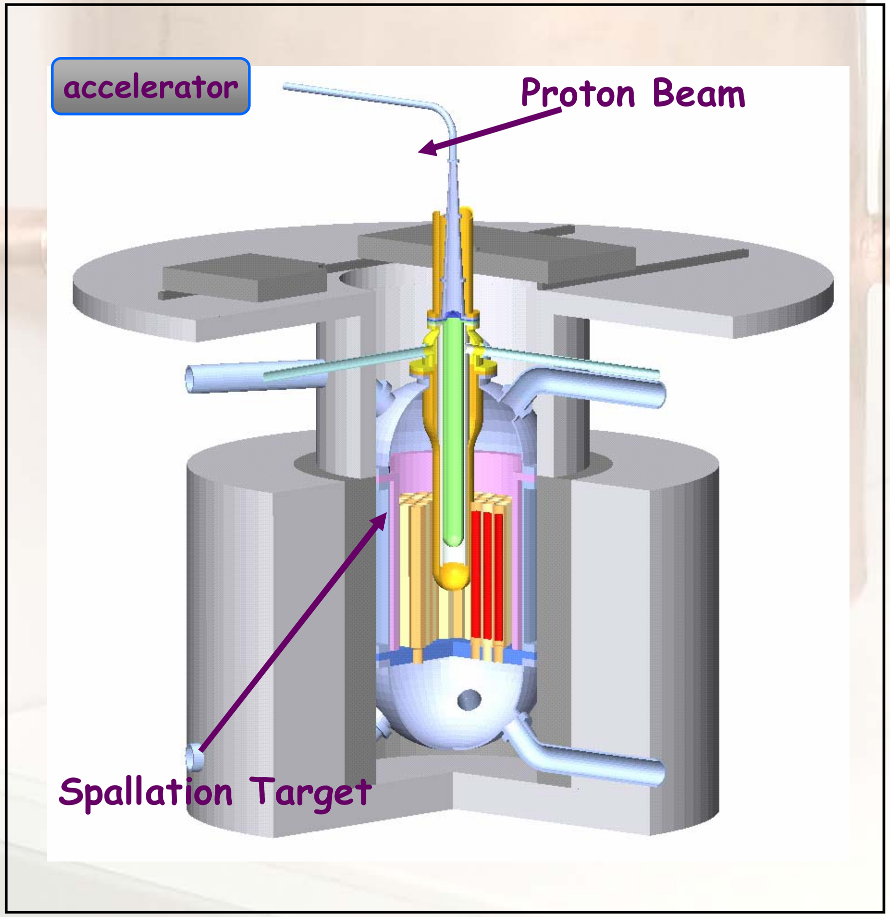
- Specifications for the XADS, a HPPA
- High-power proton accel. presently under construction
- The reference linac developed within PDS-XADS
  - R&D efforts
  - Maintenance & radioprotection
  - Costing & roadmap
- The reliability issue
- EUROTRANS
- The accelerator WP within EUROTRANS

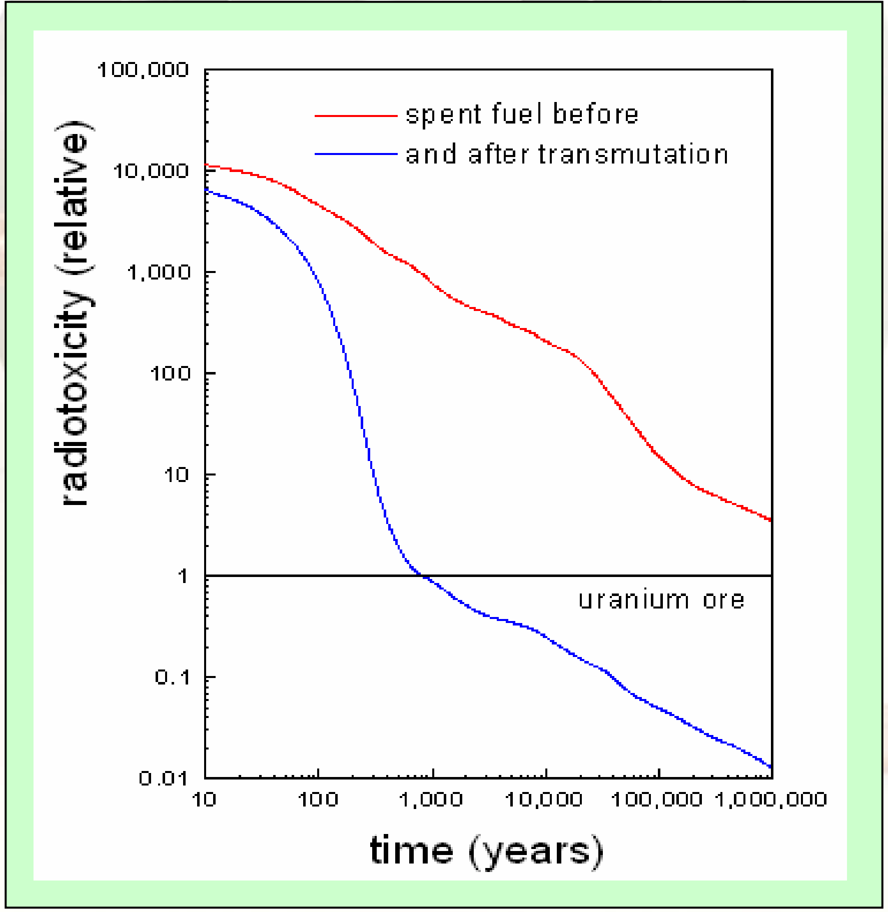
ADS: Accelerator Driven (subcritical) System for transmutation of nuclear waste

Both critical reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems.

Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction.

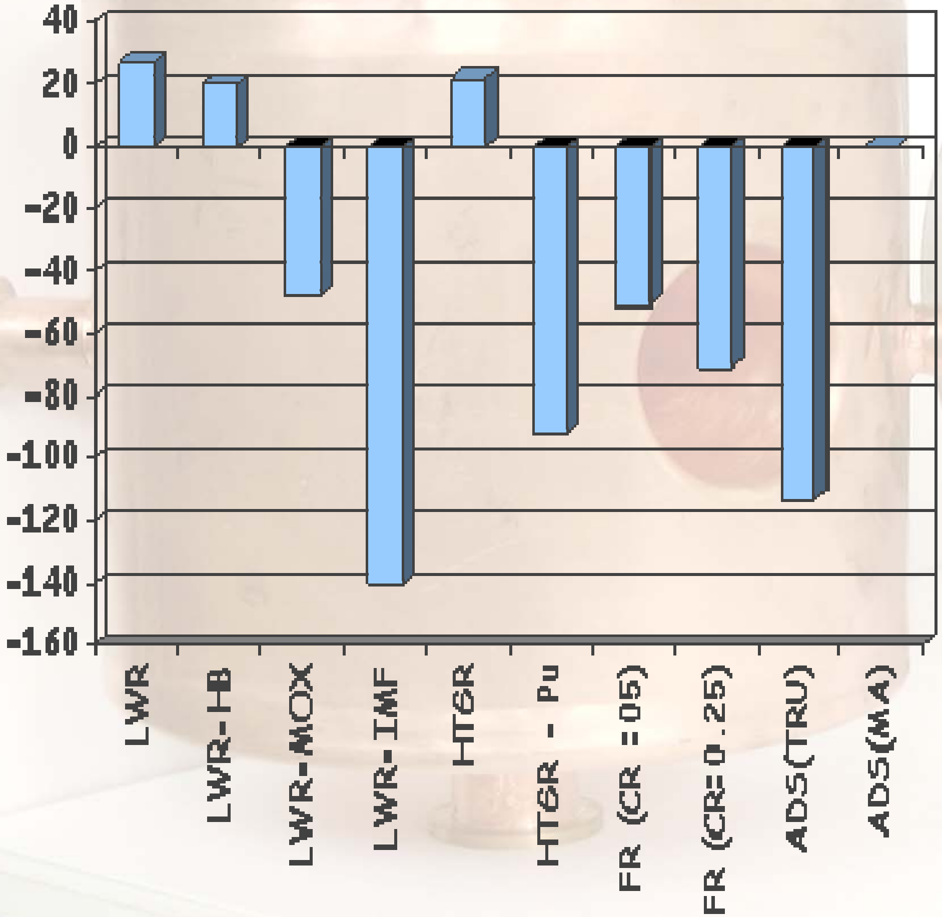
ADS operates flexible and safe at high transmutation rate (sub-criticality not virtue but necessity!)



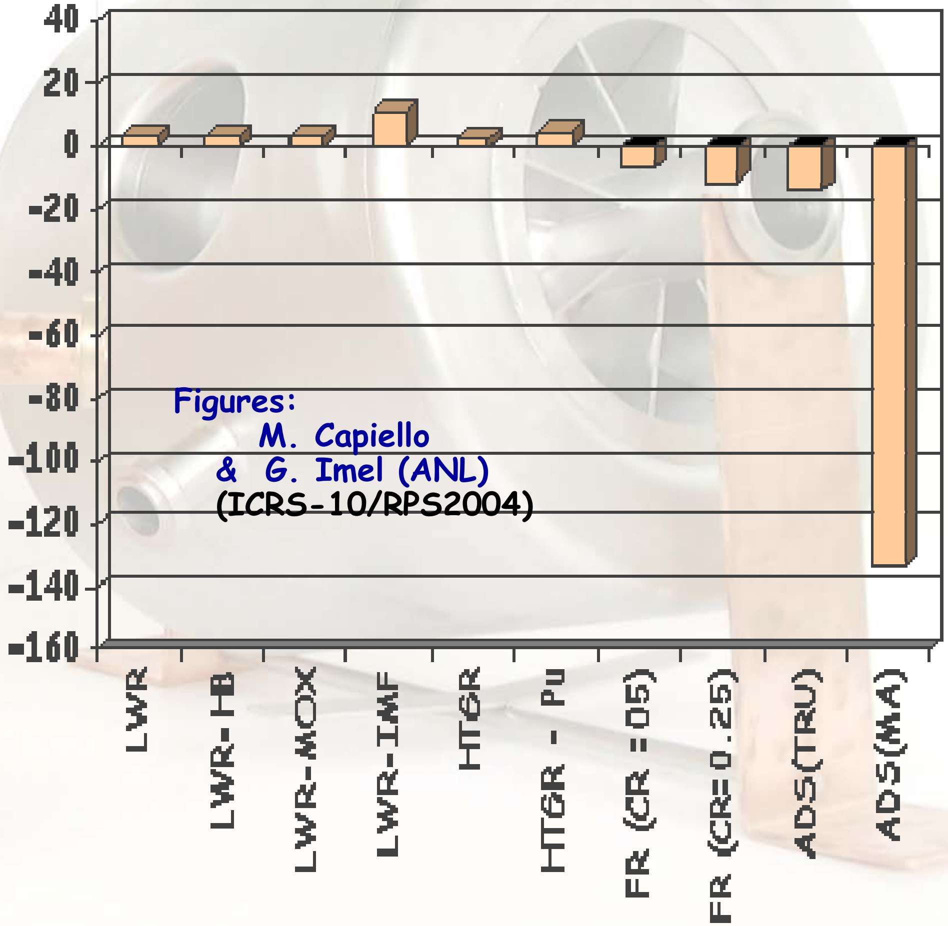


Burning (Breeding) Efficiency of different reactor types

- **The ADS is most efficient at Minor Actinide Transmutation**



Pu Production Rate (grams / GWh)



MA Production Rate (grams / GWh)

TWG: a European ADS Roadmap

A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration

April 2001

The European Technical Working Group on ADS

The European Technical Working Group (members see below) issued in 2001 a Roadmap for Developing ADS (see left), with the propasal for a 100 MWth demonstrator.

Carlo Rubbia
ENEA, Italy, Chair

Hamid Ait Abderrahim
SCK-CEN, Belgium

Mikael Börnberg
VTT, Finland

Bernard Carluec
Framatome ANP, France

Guiseppe Gherardi,
ENEA, Italy

Enrique Gonzalez Romero
CIEMAT, Spain

Waclaw Gudowski
Royal Institute, Sweden

Gerhard Heusener
FZK, Germany

Helmut Leeb
Atominstitut, Austria

Werner von Lensa
FZJ, Germany

Joseph Magill
JRC, European Union

José Martinez-Val
Madrid Polytech, Spain

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Alex C. Mueller
CNRS-IN2P3, France

Marco Napolitano
INFN, Italy

Angel Pérez-Navarro
LAESA, Spain

Massimo Salvatores
CEA, France

José Carvalho Soares
ITN Lisboa, Portugal

Jean-Baptiste Thomas
CEA, France

TWG Report: Roadmap & Cost estimate

Table 2.3. Time schedule and milestones for the development of ADS technology in Europe

Year 2000+	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	25	30	40	50
Phase-1 XADS/XADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■												
Choices of Options	■	■	■	■																				
Preliminary design			■	■																				
Design + Licensing					■	■	■	■	■															
Construction								■	■	■	■	■												
Low power testing													■	■										
Full power testing														■										
XADS Operation															■	■	■	■	■	□				
XADT Conversion																	■	■	■					
XADT Operation																				■	■	■	■	
Phase-2 Prototype ADT																								
Basic R&D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Constr., Operation																				■	■	■	■	■
Phase-3																								
Industr. Application																								■

Roadmap for the 100 MW_{th} demonstrator (left) and budget estimates (below).

A TWG subgroup elaborated the project PDS-XADS (see next slide) which was funded by the EU.

Table 2. Estimated costs (M€) for the development of a 100 MW_{th} accelerator driven system

Year 2000+	1 – 2	3 – 6	7 – 10	11 – 12	**Total**
	5^{th} FP	6^{th} FP	7^{th} FP		
Basic & Support R&D	30	90	70	10	200
Engineering Design	5	75	60	10	150
Construction	0	80	300	70	450
Fuel	0	10	120	50	180
Total	**35**	**255**	**550**	**140**	**980**
R&D for Dedicated Fuel	5	70	70	35	180*

* Estimated cost to 2012 for development of dedicated fuel & fuel processing

2001-2004: PDS-XADS as central P&T project

European Commission Research

Projects on ADvanced Options for Partitioning and Transmutation (ADOPT)

PARTITIONING *(5 MEuro)*
PYROREP
PARTNEW
CALIXPART

TRANSMUTATION *(3.9 MEuro)*
Fuels:
CONFIRM
THORIUM CYCLE
FUTURE

TRANSMUTATION *(6 MEuro)*
Preliminary Design Studies for an Experimental ADS:
PDS-XADS

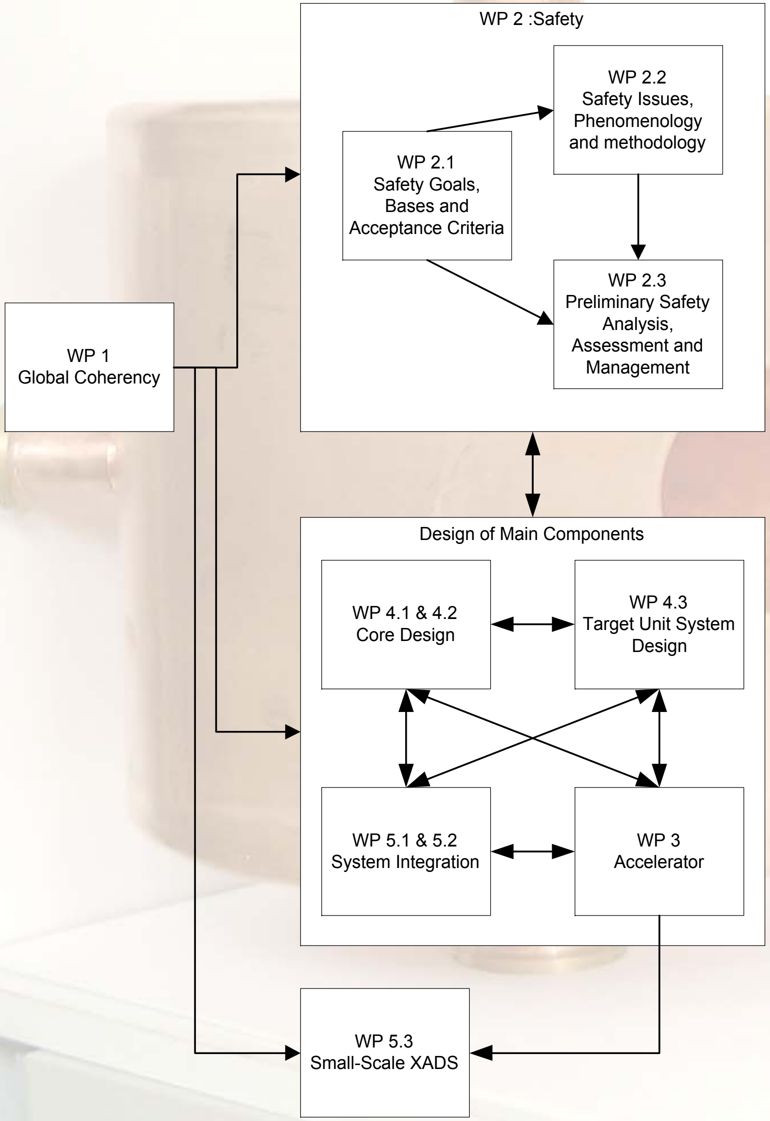
TRANSMUTATION *(6.5 MEuro)*
Basic Studies:
MUSE
HINDAS
N-TOF_ND_ADS

TRANSMUTATION *(7.2 MEuro)*
Technological Support:
SPIRE
TECLA
MEGAPIE - TEST

EURATOM

06.09.2001- Slide 1

FP5 PDS-XADS*: Working Packages



*Contract N° FIKW-CT-2001-00179 (2001-2004)

A collaboration between Industrial Partners and Research Organisations

F: Framatome-F CNRS CEA
I: Ansaldo INFN ENEA CRS4
RFA: Framatome-D FZK FZJ UFra
Esp: CIEMAT Empresarios UPM
B: SCK IBA Tractebel
UK: NNC BNFL
Pt: ITN
S: KTH
Sui: PSI
Pl: UMM
NL: NRJ
Eur: JRC

coordinateur général : Framatome (B.Carluec, B.Giraud)
coordinateur accélérateurs: CNRS-IN2P3 (A.C. Mueller)

The PDS-XADS Accelerator Group (WP3)

- **WP3 partners**
  - Coordinator: CNRS-IN2P3 (F)
  - Participants: Ansaldo (I), CEA (F), ENEA (I), FANP (F), F GmbH (D), IBA (B), INFN (I), ITN (Pt), U. Frankfurt (D)

- **Main WP3 objectives**
  - Investigation of linac and cyclotron types with the main emphasis on the XADS requirements
  - Examination of the XADS accelerator characteristics: reliability, availability, stability, power control & maintainability
  - Definition of the R&D needs
  - Choice of the reference accelerator type for XADS and for a long-term extrapolated industrial transmuter
  - Definition of the road mapping of the ADS-class accelerators

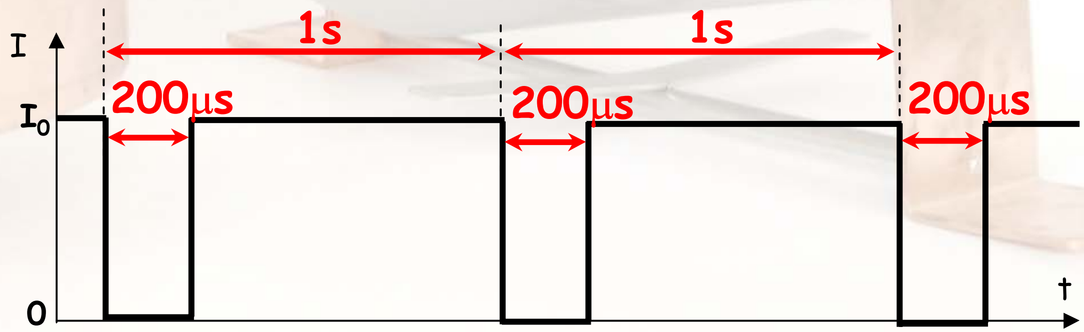
- **6 Deliverables**
  - D9 – D47 – D48 – D57 – D63 – D80

XADS Accelerator Requirements

- **Proton Beam Specifications**
  - Defined by WP1
  - **600 MeV, 6 mA max**. for operation
  - 10 mA for the demonstration of concept
  - 350 MeV for the smaller scale XADS MYRRHA
  - **High reliability requirement**: less than 5 beam trips > 1 sec per year

Accelerator requirements	
Max. Beam Intensity	6 mA
Proton Energy	600 MeV
Beam entry	To be defined
Beam trip number	Less than 5 per year for the accelerator design Less than 50 per year for the reactor design
Beam type	CW, best solution Pulsed, back-up solution
Beam power stability	± 2 %;
Beam energy stability	± 1 %;
Beam intensity stability	± 2 %;
Beam footprint dimensions	± 10 %.

- **Additional requirements**
  - 200 μs beam « holes » for on-line sub-criticality measurements
  - Safety grade shutdown



Specifications for different HPPA

HPPA = High Power Proton Accelerator

>1

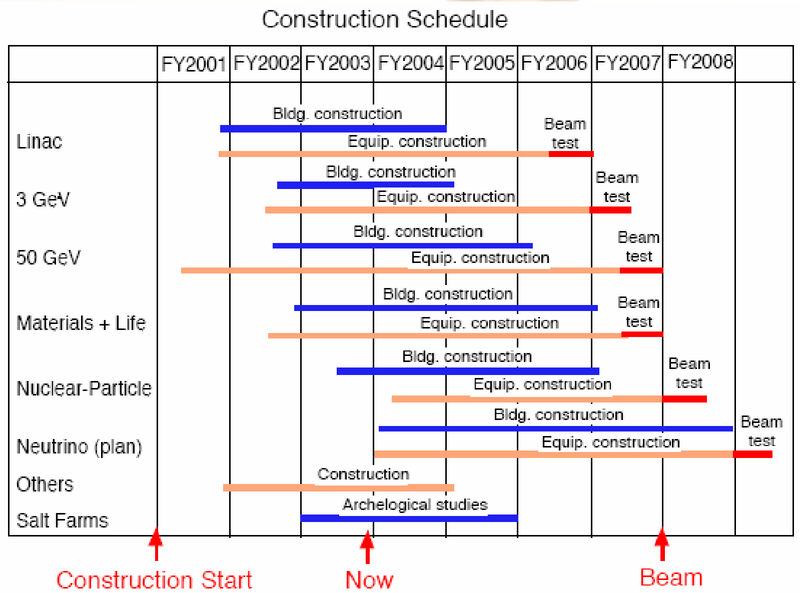
		Puissance [MW]	Énergie [GeV]
Faisceaux secondaires	Neutrinos, muons	4	2
Ions radioactifs	avec des protons	.2	>.2
	avec des neutrons	5	1
Irradiation des matériaux	par spallation	10	1
	par break-up ("IFMIF")	2 × 5.4	.04
Matière condensée	avec des neutrons	5	1.3
Transmutation	Démo 100 MW thermique	5	.6
	Système industriel	10 à 20	.8 à 1

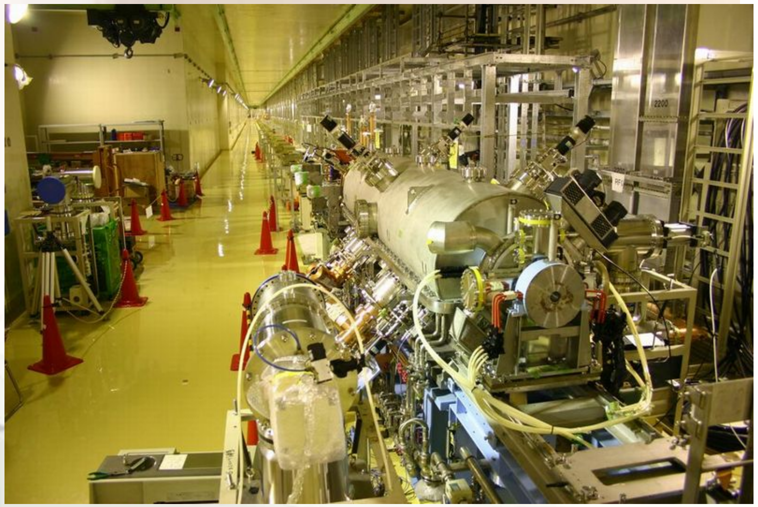
≈ 1

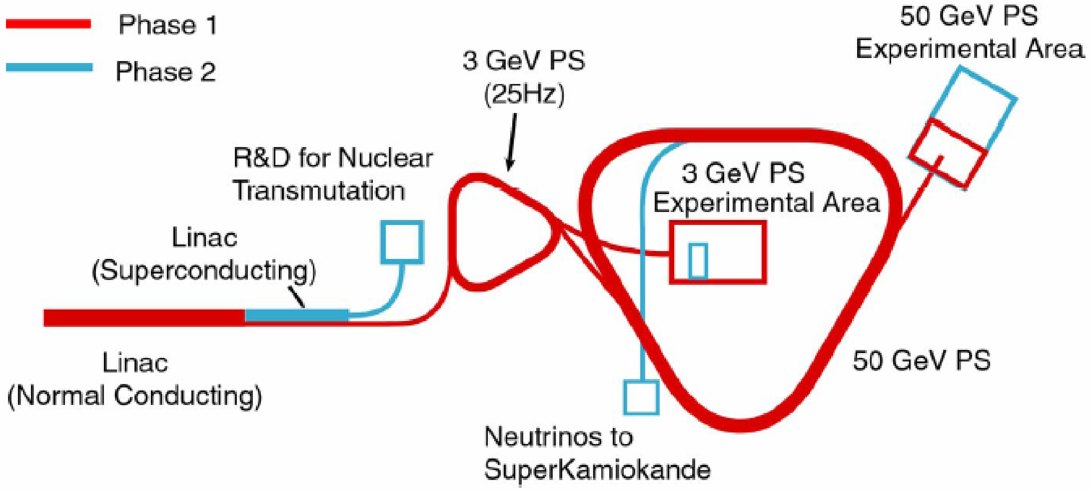
HPPA under Construction/commissioning: J-PARC

une "multi-purpose" Facility

J-PARC







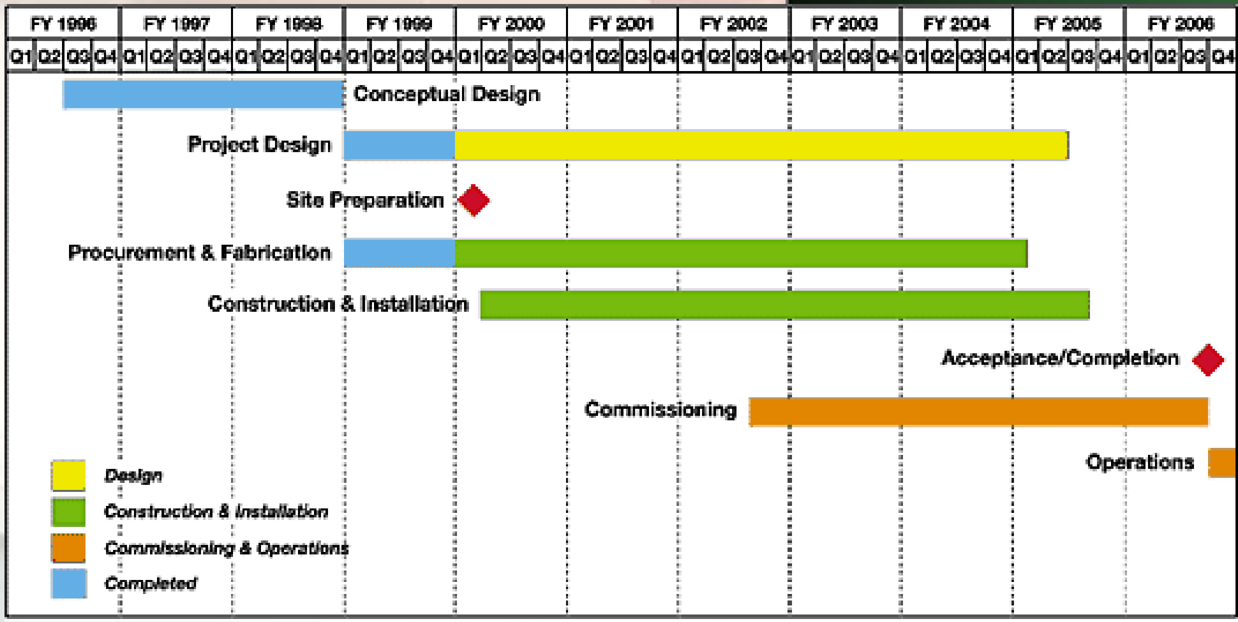
- Phase 1 + Phase 2 = 189 billion Yen (= $1.89 billion if $1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

A second brand-new HPPA: SNS

SNS at Oak-Ridge, beam since2006

SNS

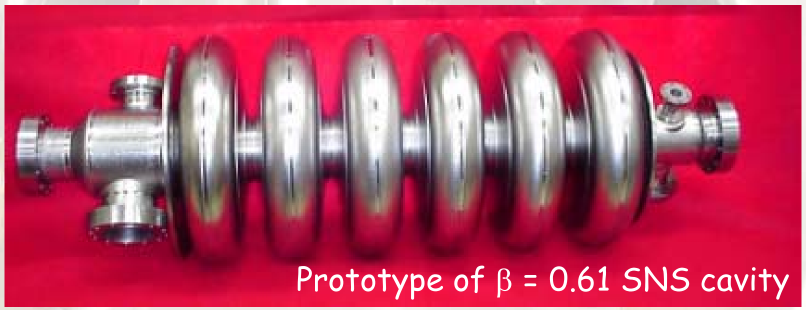
161-kV Substation
Cooling Towers
Front End Building
Water Tower
Ring
Ring Service Building
Central Utilities Building
Linac
RTBT (Ring to Target Beam Transport)
Klystron Hall
CHL and SRF
(Central Helium Liquefaction Building and Superconducting Radio Frequency Shop)
Dumps
HEBT
(High Energy Beam Transport)
Target
Central Lab and Office Building



FY 1996
FY 1997
FY 1998
FY 1999
FY 2000
FY 2001
FY 2002
FY 2003
FY 2004
FY 2005
FY 2006
Q1 Q2 Q3 Q4
Conceptual Design
Project Design
Site Preparation
Procurement & Fabrication
Construction & Installation
Acceptance/Completion
Commissioning
Operations
Design
Construction & Installation
Commissioning & Operations
Completed

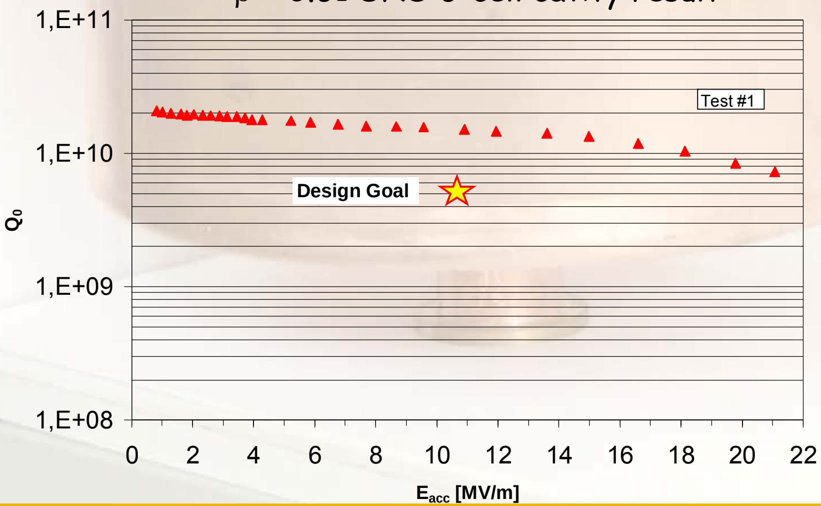
The SNS Example

- **Multicell structures have been built for the SNS project, for both the β=0.61 and the β=0.81 cavities**
  - All tests reached the design goals with good margins
  - Industrial fabrication for all the SNS cavities is in progess
  - The actual RIA linac proposed design uses the SNS cavities adding a β=0.47 6-cell cavity section, as in the European scheme

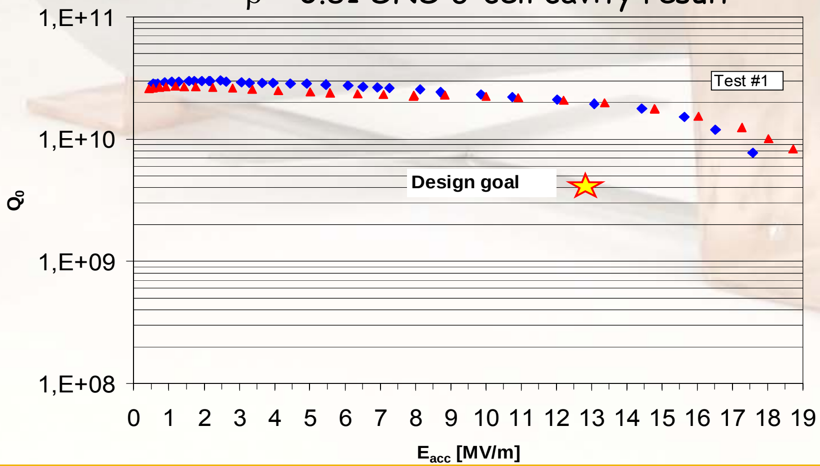


Prototype of β = 0.61 SNS cavity

β = 0.61 SNS 6-cell cavity result



β = 0.81 SNS 6-cell cavity result

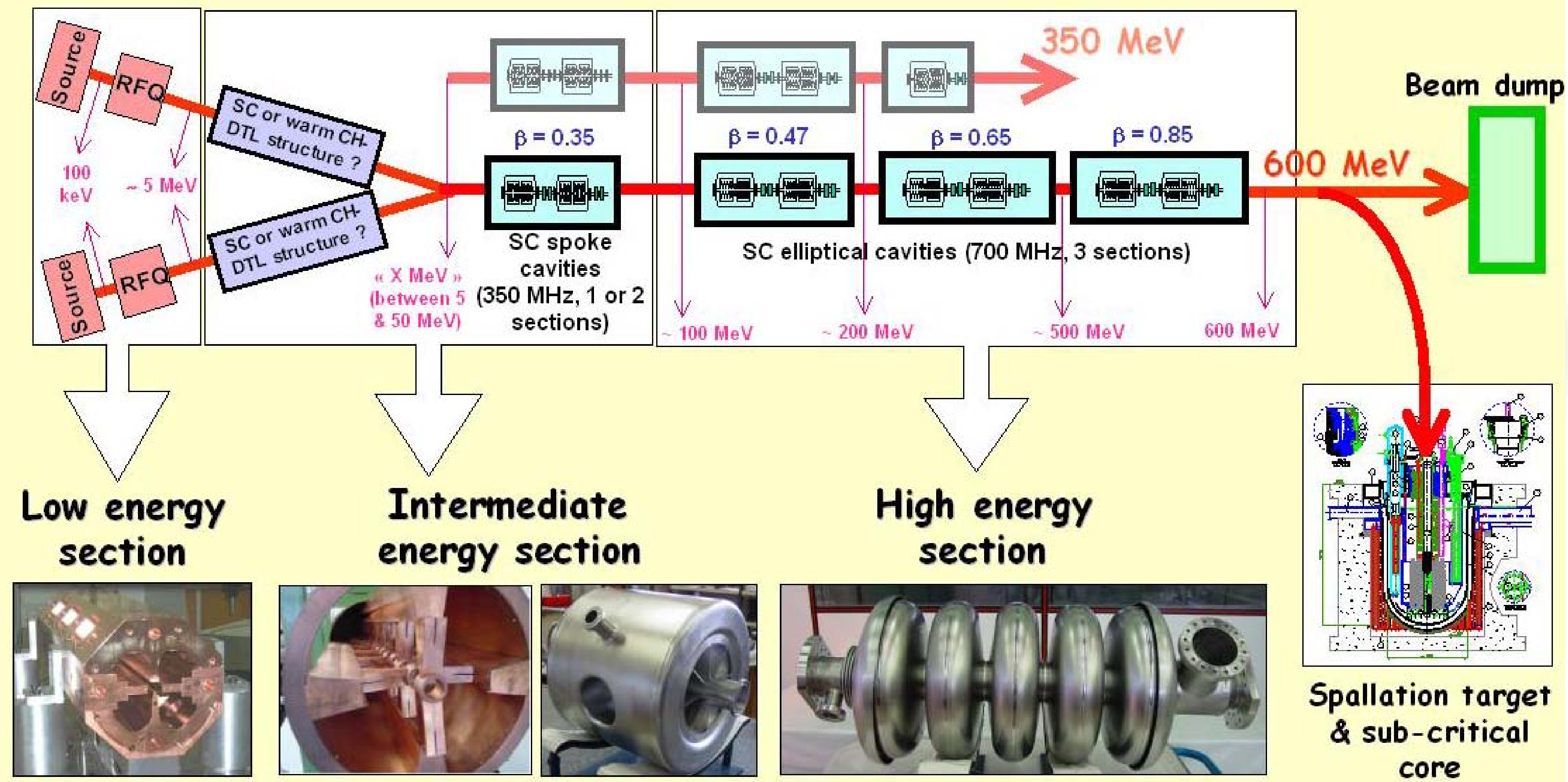


Choice of the Generic Accelerator Type

- **Main technical answers**
  - Superconducting linac
    - No limitation in energy & in intensity
    - Highly modular and upgradeable (industrial transmuter)
    - Excellent potential for reliability (fault-tolerance)
    - High efficiency (optimized operation cost)
  - Cyclotron
    - Attractive (construction) cost (?)
    - Required parameters at limits of feasibility ("dream machine")
    - Compact, but therefore not modular

- **In complete agreement with findings of the NEA report:**
  - **Cyclotrons of the PSI type** should be considered as the natural and cost-effective choice **for preliminary low power experiments**, where availability and reliability requirements are less stringent.
  - **CW linear accelerators must be chosen for demonstrators and full scale plants**, because of their potentiality, once properly designed, in term of availability, reliability and power upgrading capability.

PDS-XADS Reference Accelerator Layout



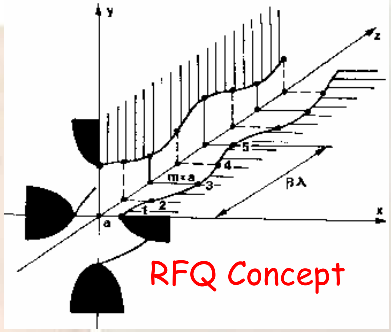
Strong R&D & construction programs for LINACs underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Injector: LEDA at LANL

Source & RFQ were operational in 1999 !

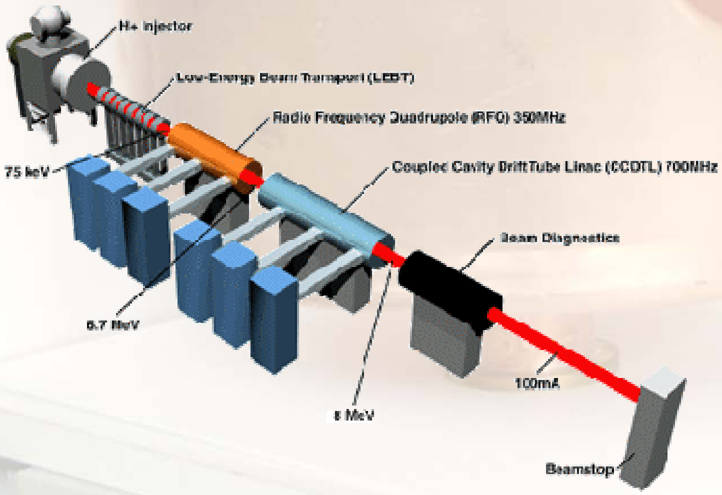
LEDA Source:	
Proton Beam current	**110 mA**
Total Beam current	**130 mA**
Beam emittance	**0.2 π mm mrad**
Operating voltage	**75 kV**



RFQ Concept

$$\vec{F}_{Lorentz} = \frac{d\vec{p}}{dt} = q \cdot (\vec{E} + \vec{v} \times \vec{B}) = \vec{F}_{el} + \vec{F}_{mag}$$

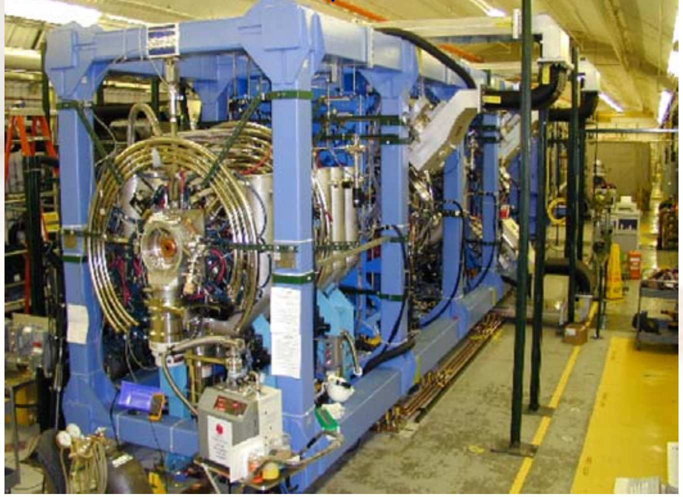
LEDA RFQ:	
Beam current	**100 mA (95 %)**
Beam emittance	**0.22 π mm mrad**
	0.17 π deg MeV
Final Energy	**6.7 MeV**
Length	**8 m (4 sections)**
RF Power	**670 kW (beam)**
	1.2 MW (structure)
Peak Field	**1.8 Kilpatrick**



One Section of LEDA-RFQ

Beam halo tests have been performed on the LEDA HEBT to compare simulation codes with experimental results

The LEDA-RFQ fully installed

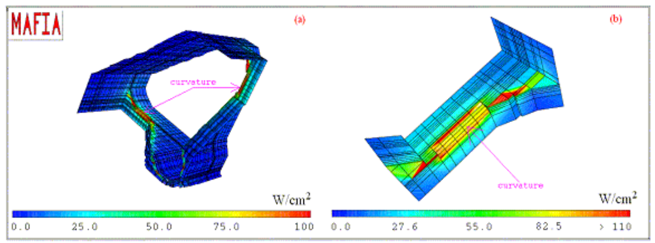


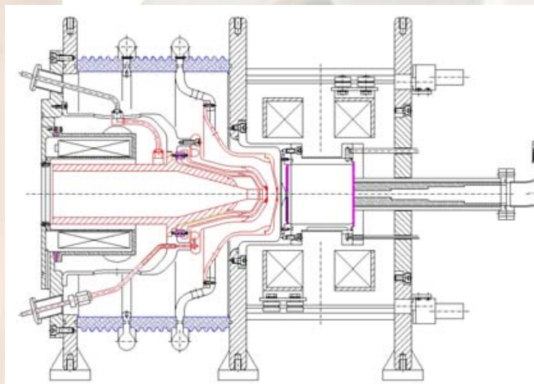
Linac Injector: TRASCO at INFN

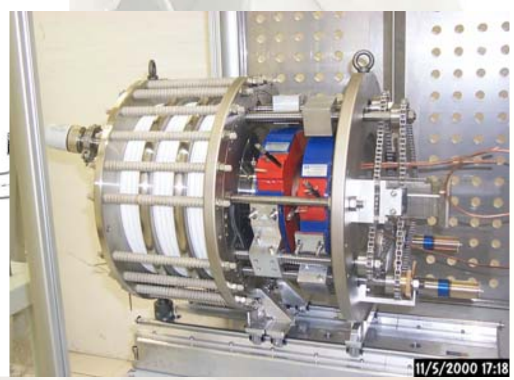
- Different optimization w/respect to LEDA
  - Limit to 1 klystron (1.3 MW CERN)
  - Lower design current: 30 mA
  - Peak field limited to 33 MV/m
  - Lower power dissipation: ~ 600 kW

- TRIPS, similar to SILHI with some extraction improvement and overdesign for reliability
- ECR source: 35 mA, 80 keV (operating)

RFQ e.m. simulations



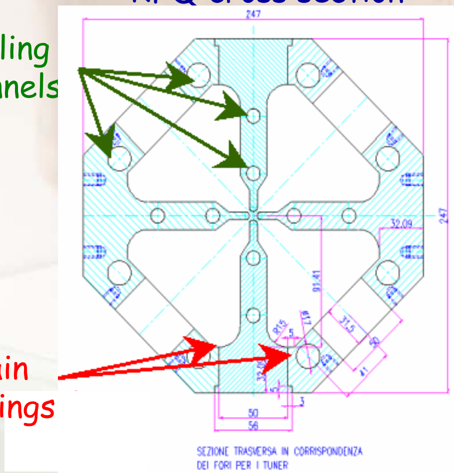




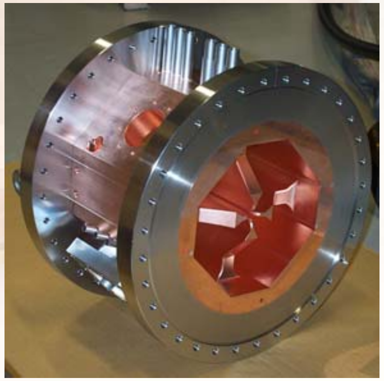
RFQ cross section

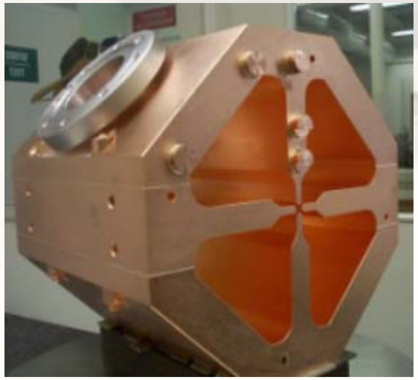
Cooling channels

Main brasings

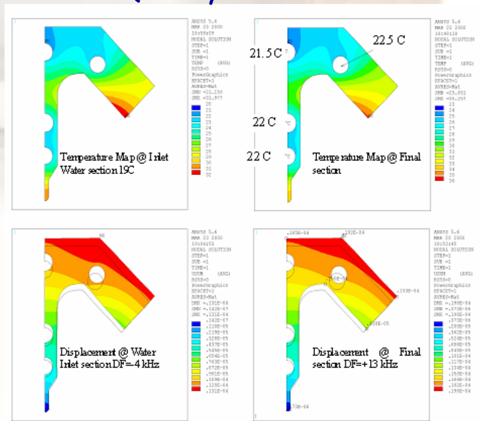


RFQ short models to set technology





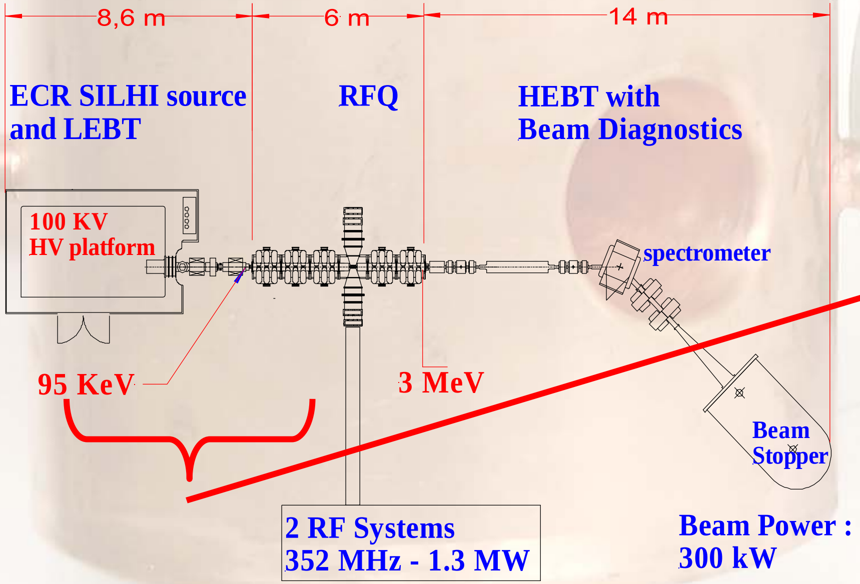
RFQ Ansys simulations



Injector: SILHI at Saclay

SILHI Goals:		Achievements
Beam current	110 mA (90 % p.f.)	157 mA (~83 % p.f.)
Beam emittance	0.2 π mm mrad	0.11 π mm mrad
Operating voltage	95 kV	95 kV
Beam noise (rms)	2 %	1.2 %

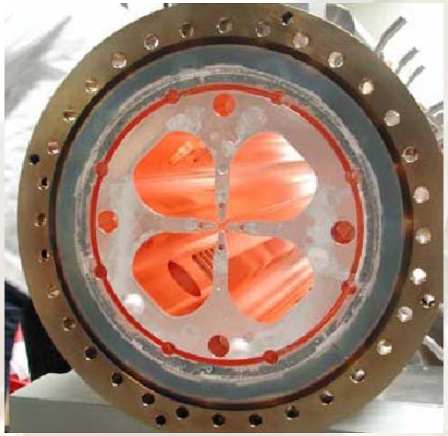
- The SILHI source is fully operationl
- ECR type: 110 mA, 95 keV



- Several reliability tests were performed on the source
  - 3 before extraction system changes: 99.96% availability (1 stop in 104 hours of operation)
  - 2 with new extraction system:
    99.8% availability (8 stops in 162 hours, automatic restarting in 2.5 min, MTBF=23.1 hours)

Injector: IPHI RFQ at Saclay

- IPHI RFQ under fabrication
- Two 1.3 Mw klystrons required
- First RFQ beam expected in 2008

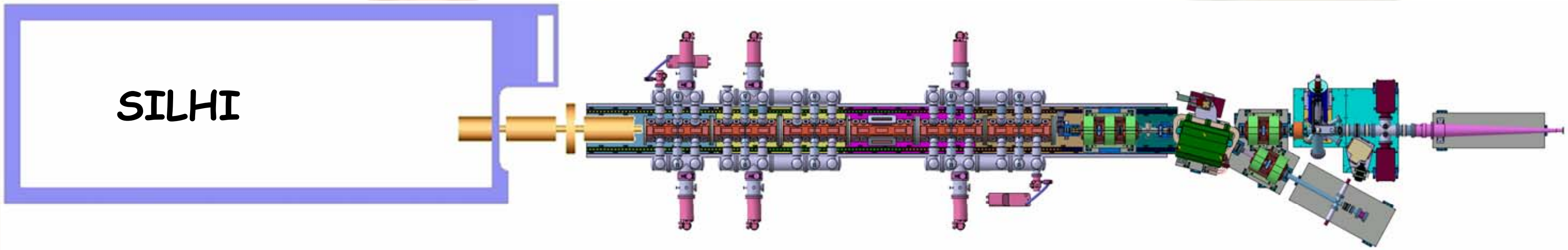


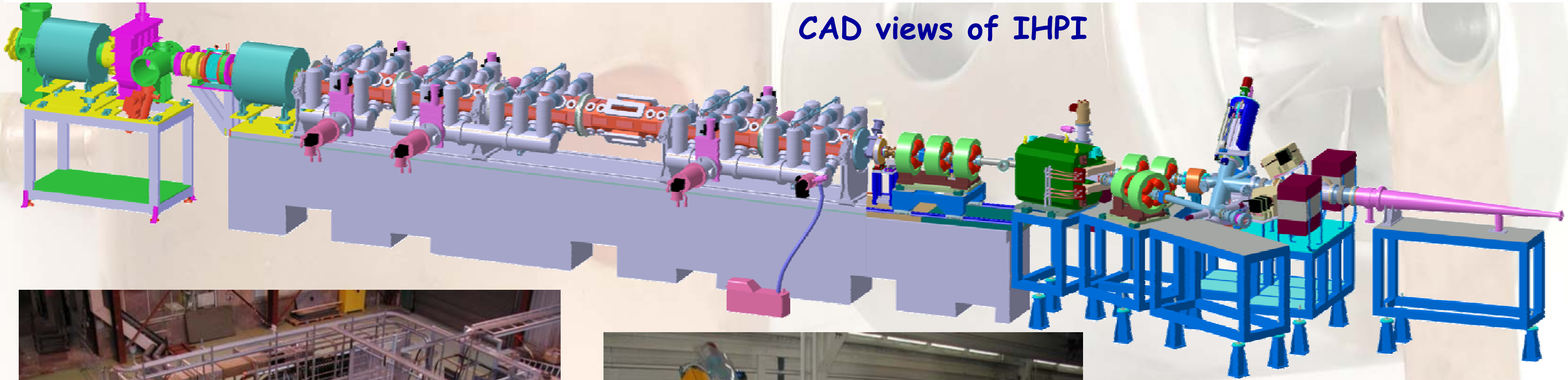
Picture of the first IPHI RFQ section ready for brasing

View of the vanes from the low energy side

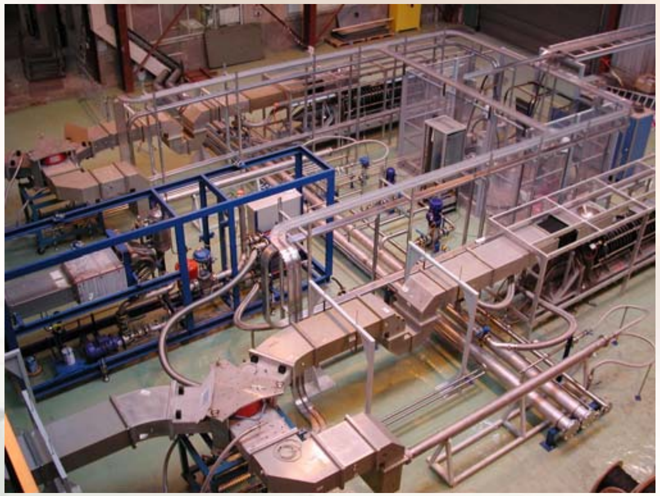
IPHI RFQ parameters:	
Beam current	100 mA (99.2%)
Beam emittance	0.2 π mm mrad T
	0.2 π deg MeV L
Final Energ	5 MeV
Length	8 m (3 sections)
RF Power	500 kW (beam)
	1.2 MW (structure)
Peak field	1.7 Kilpatrick

IPHI (collaboration CEA-CNRS-CERN)





CAD views of IHPI



IPHI RF installation (left)

IPHI Diagnostics:
Wire Scanner (center)

Reference Accelerator: Low Energy Section

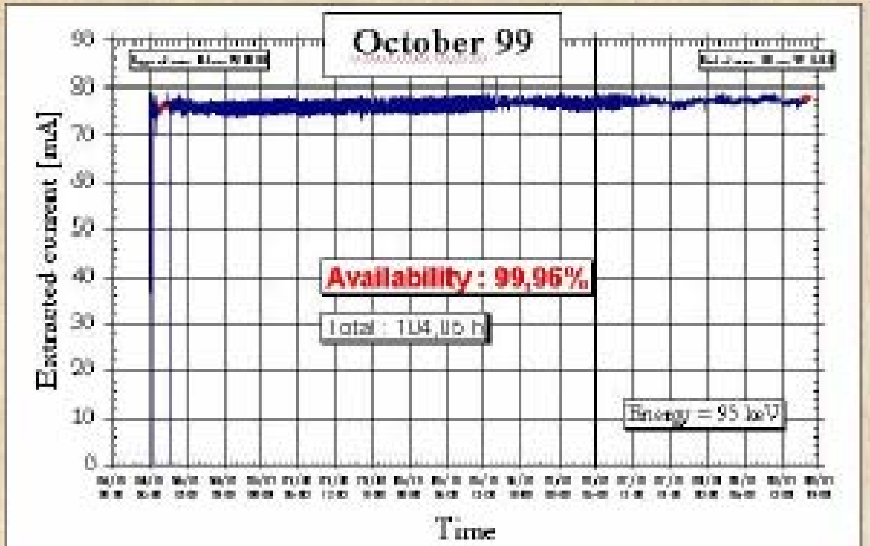
Reliability tests

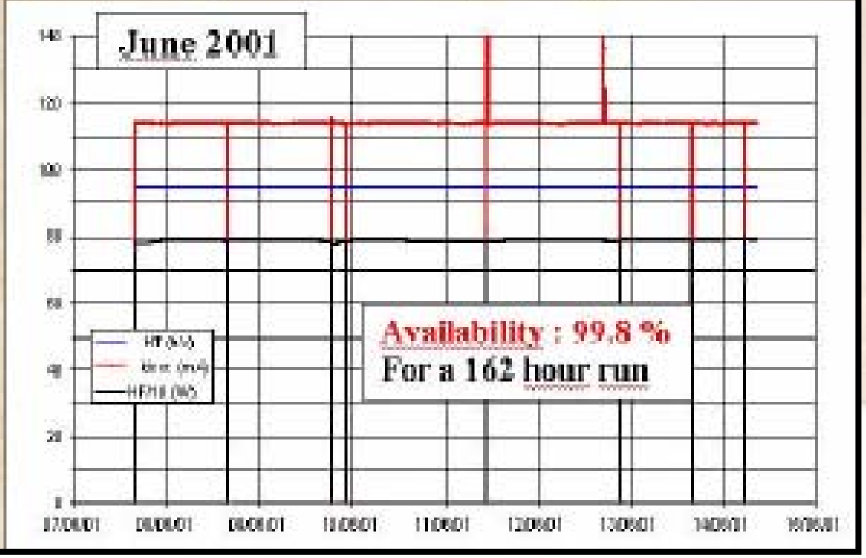
Parameters	Déc. 97	Mai 99	Oct. 99	March 01	June 01
Energy (keV)	80	95	95	95	95
Intensity (mA)	100	75	75	118	114
Duration (h)	103	106	104	336	162
Beam off number	53	24	1	53	7
MTBF (h)	1.75	4	n. appl.	≈ 6	23.1
MTTR (mn)	6	5.3	2.5	≈ 18	2.5
Uninterrupted beam (h)	17	27.5	103	25	36
Availability (%)	94.5	97.9	99.96	95.2	99.8

5 reliability tests have been performed :

3 with a limited extracted beam (old extraction system) and the 2 last ones with the new system which limits beam losses on the electrodes.

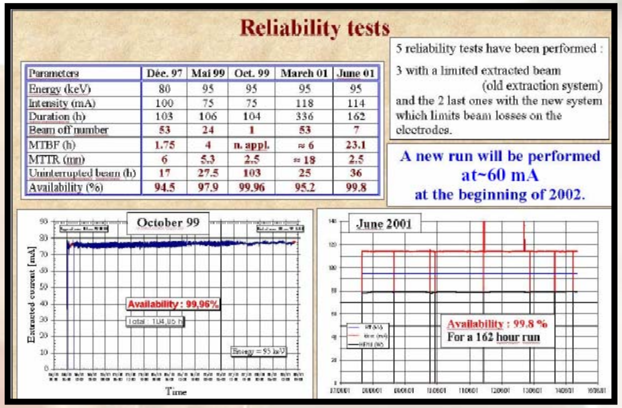
Future test within EUROTRANS within the complete IPHI system (SILHI + RFQ) at 10 & 40 mA





Reference Accelerator: Low Energy Section

- **R&D on the injector part by the WP3 partners**
  - « IPHI » ECR Source & Normal Conducting RFQ (CEA-CNRS)
  - « TRASCO » ECR Source & Normal Conducting RFQ (INFN)
  - Normal Conducting IH-DTL Structure (IBA)
  - Superconducting CH-DTL Structure (U. Frankfurt)



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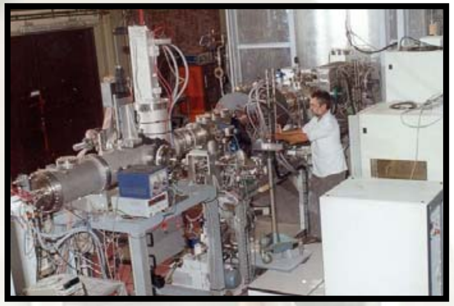
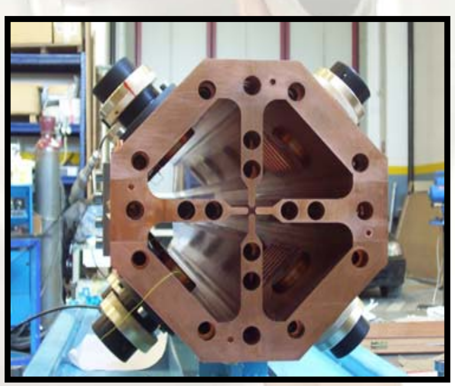
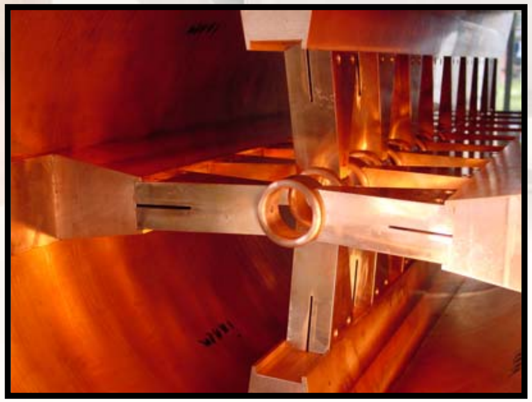
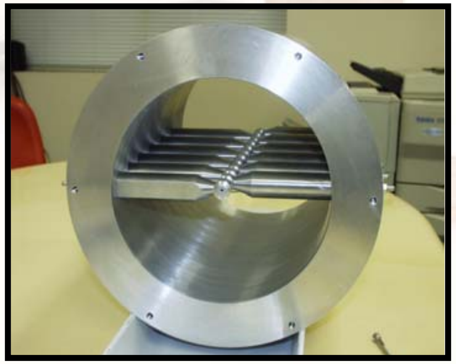
3 with a limited extracted beam (old extraction system)
and the 2 last ones with the new system which limits beam losses on the electrodes.

A new run will be performed at~60 mA at the beginning of 2002.







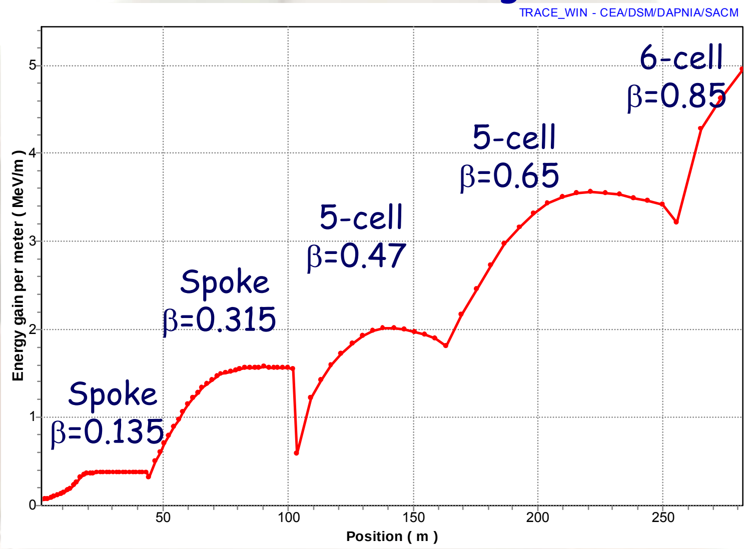


The 0-order Design for PDS-XADS

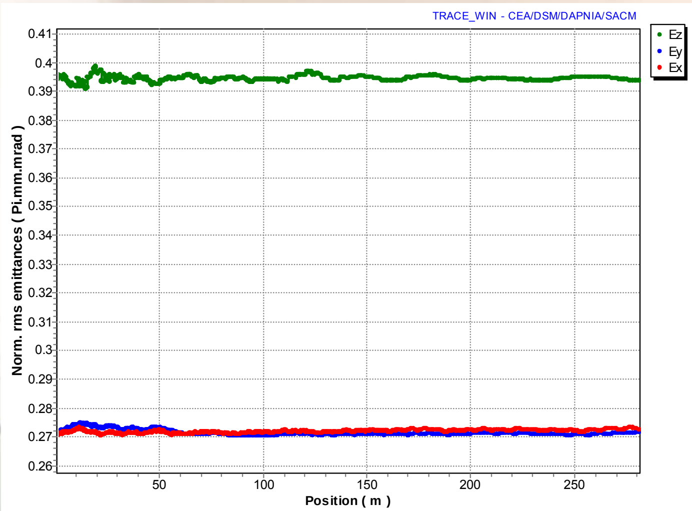
SC Linac Section Parameters

	Section number				
	1	2	3	4	5
Input Energy [MeV]	5	17	95	200	490
Output Energy [MeV]	17	95	200	490	600
Cavity Technology	Spoke		Elliptical		
Structure β_g	0.135	0.314	0.47	0.65	0.85
Number of cavity cells	2	2	5	5	6
Number of cavities	34	64	28	48	12
Focusing type	SC quad doublet		NC quad doublet		
Cavities/Lattice	1	2	2	3	4
Synch Phase [deg]	-65 to -30	-30	-25		
Lattice length [m]	1.3	1.9	4.2	5.8	8.5
Number of lattices	34	31	14	16	3
Section Length [m]	44.2	59.9	60.8	92.8	25.5
<gradient> [MV/m]	0.3	1.3	1.8	3.1	4.3

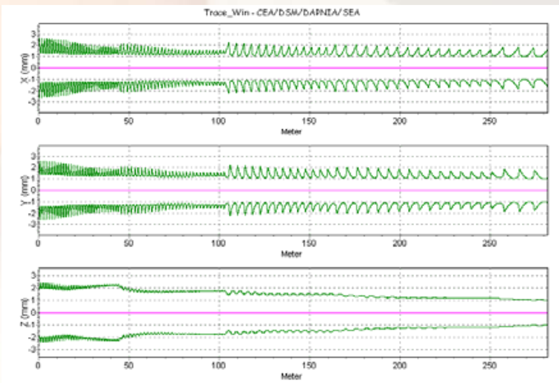
Real Estate ΔE/m along the linac



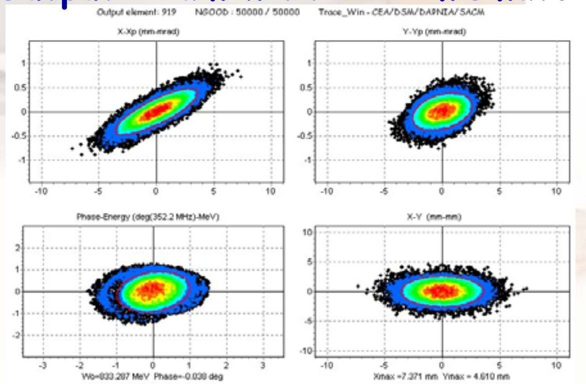
rms emittances in the whole linac



rms beam size along the linac

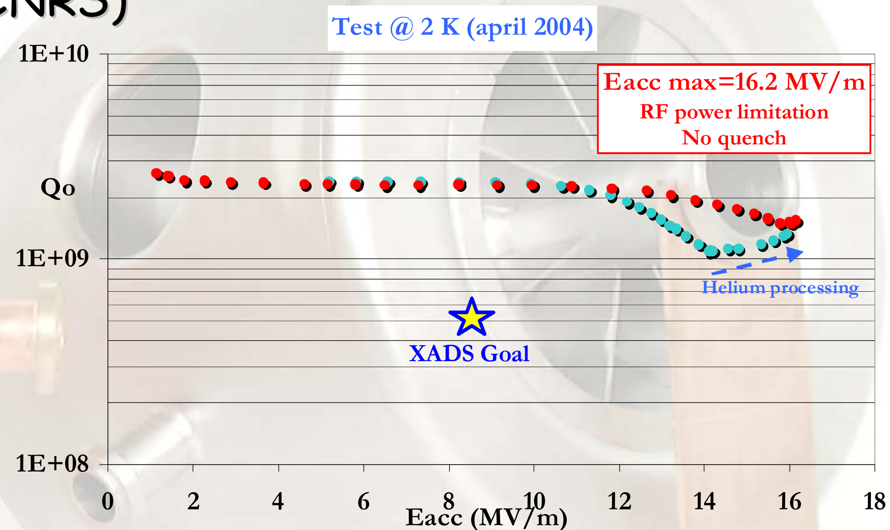


Output beam with 30% mismatch

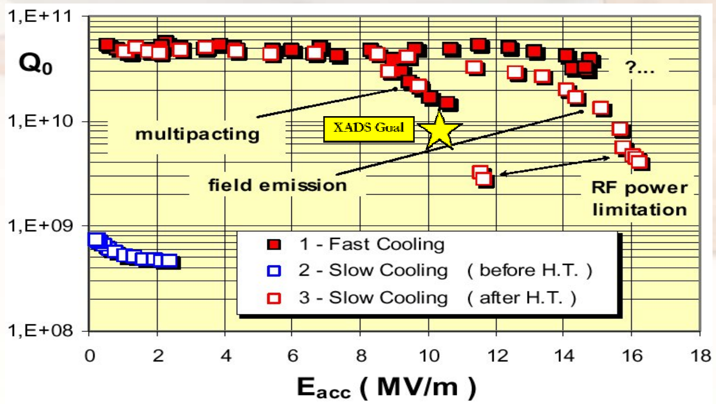


Reference Accelerator: High Energy Section

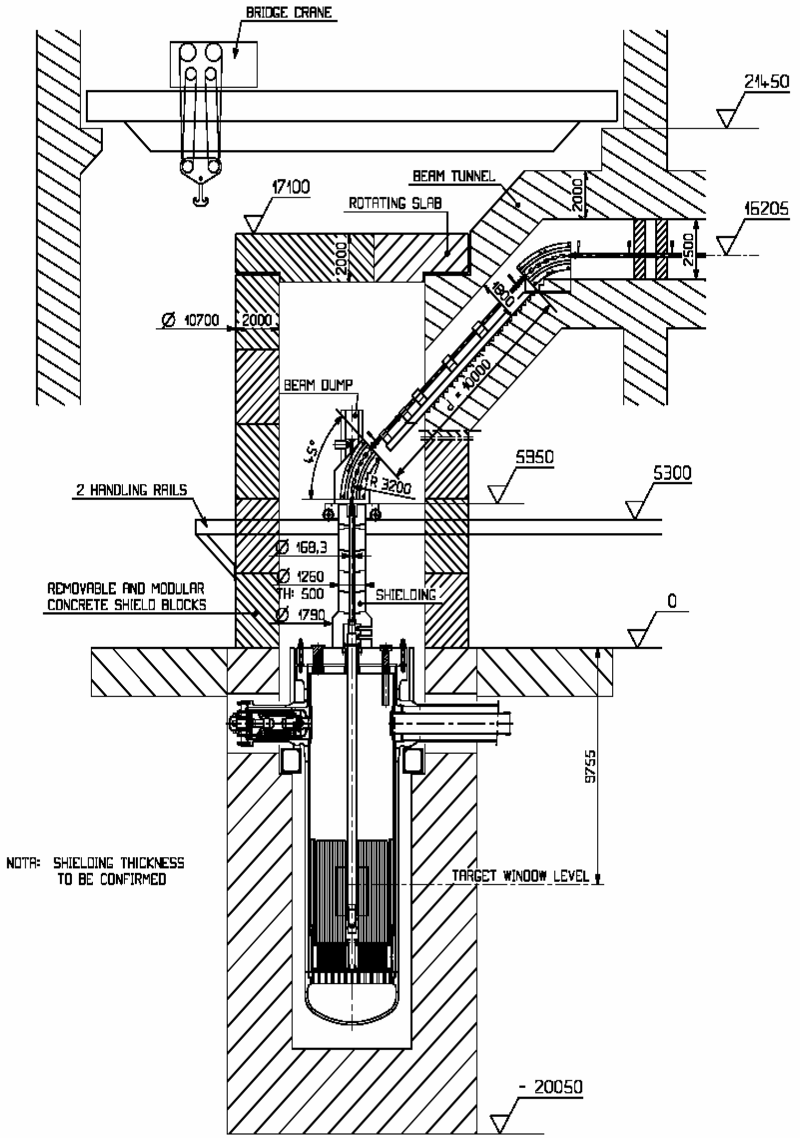
- R&D on SC prototypical cavities by the WP3 partners
  - Spoke cavities β = 0.15 & β = 0.35 (CNRS)



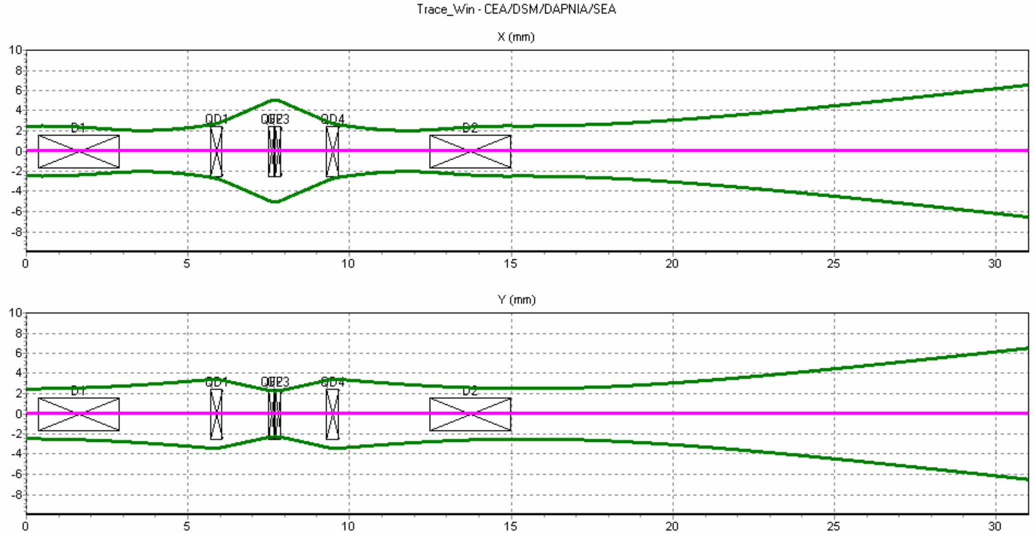
  - Elliptical cavities β = 0.5 & β = 0.65 (CEA-CNRS-INFN)



Reference Accelerator: Beam Line Transport

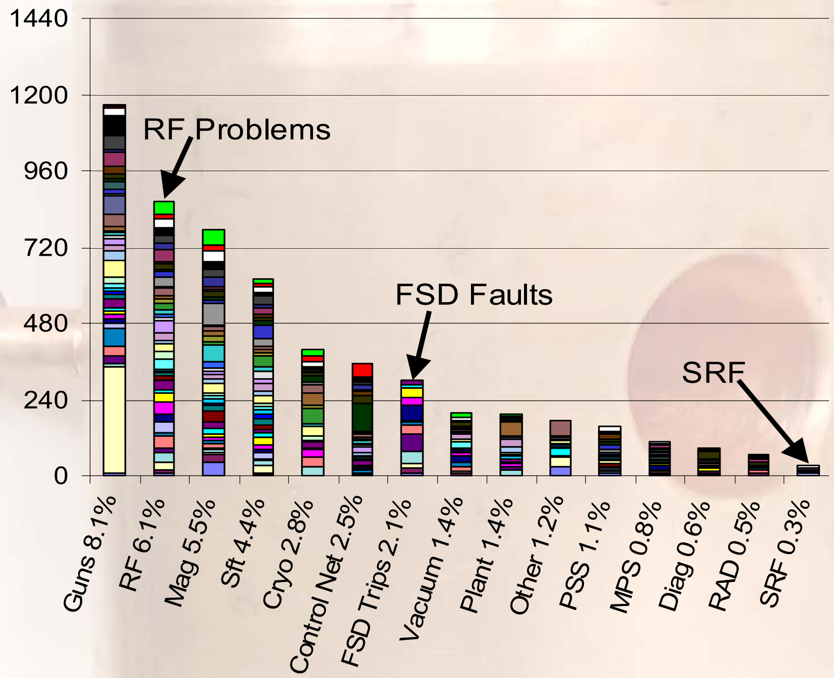


- **The doubly achromatic beam line concept + beam scanning method meets the specifications:**
  - of the Gas-cooled XADS
    (circular footprint, ∅160)
  - of the LBE-cooled XADS
    (rectangular footprint, 10×80)
  - of MYRRHA
    (quasi-circular footprint, ∅72)

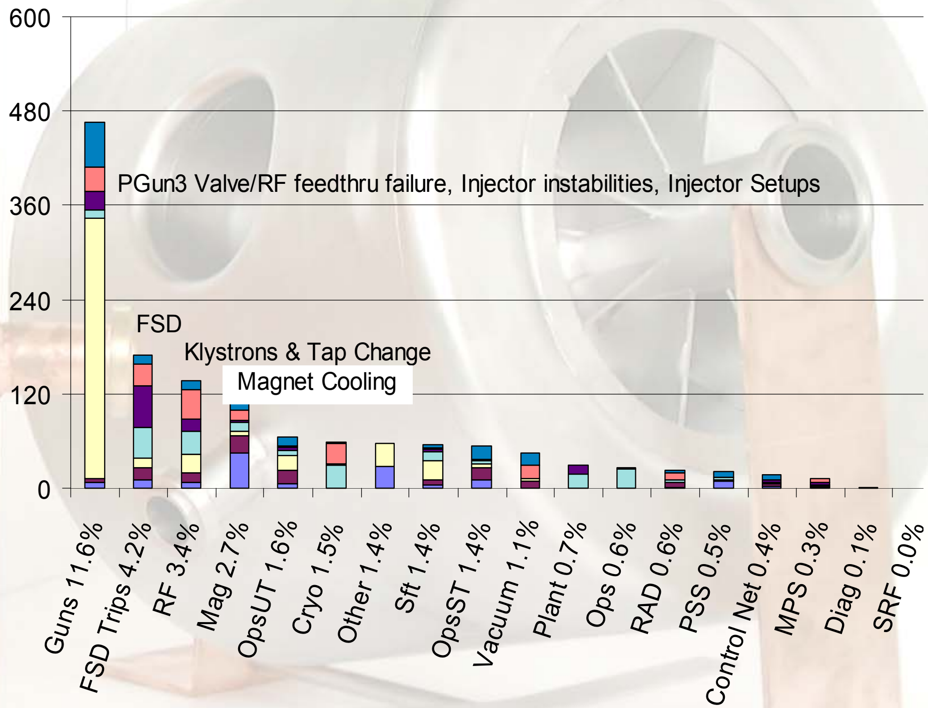


Reliability Example - CEBAF

Lost Time Totals June'97-May'01



Lost Time Totals FY 2001



- Reliability must be improved for ADS applications
- The SC linac is modular and allows: overdesign, redundancy and "spare-on-line"
- Fast dedicated control electronics is crucial
- Beam can stay "on" when the linac is resetting itself to use spere-on line
- SC cavity technology proved to be the minor concern

Reliability Analysis

FP5

CONTRACT N°: FIKW-CT-2001-00179

ISSUE CERTIFICATE

PDS-XADS
Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/03/057 **Revision: 0**

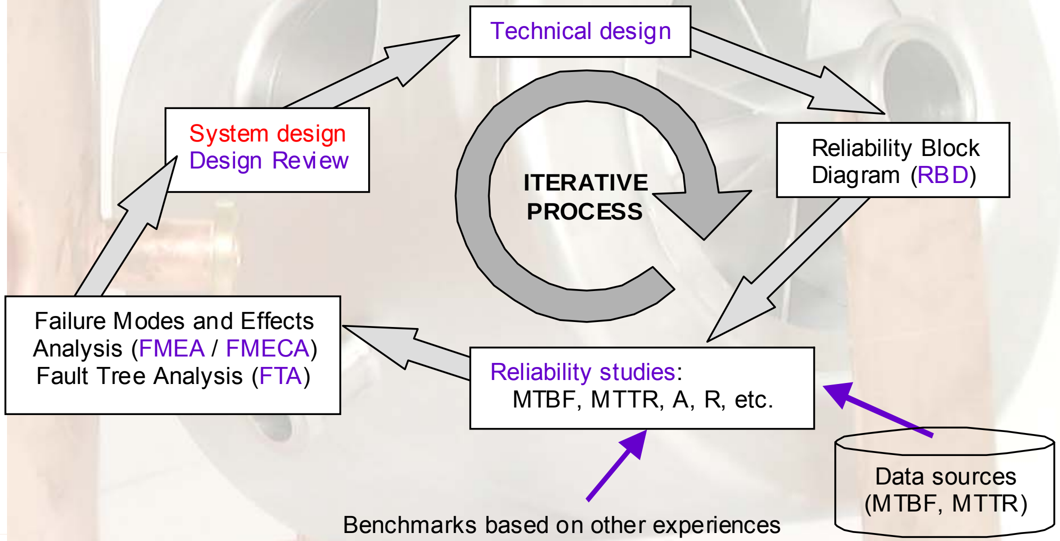
Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators

Dissemination level: *RE*
Issued by: *INFN*
Reference: **INFN/TC_03/9 (July, 23rd, 2003)**
Status: *Final*

Summary:
This document identifies the suitable design strategies that have been followed in order to meet the reliability and availability specifications for the XADS accelerator outlined in Deliverable 1. The document describes also how these strategies can be applied in the different components of the XADS accelerator design, and how design iterations can lead to reliability improvements. The Failure Mode and Effect Analysis (FMEA) methodology has been used on the suggested design for highlighting the reliability critical areas. Finally, a first rough cost estimation of the XADS accelerator is also provided.

23/07/2003	Paolo Pierini, INFN	Alex C. Mueller, CNRS	Bernard Carluec Framatome ANP SAS
	[signature]	[signature]	[signature]
DATE	RESPONSIBLE Name/Company Signature	WP LEADER Name/Company Signature	COORDINATOR Name/Company Signature

- Assessments using the « Failure Modes and Effects Analysis » (FMEA) method



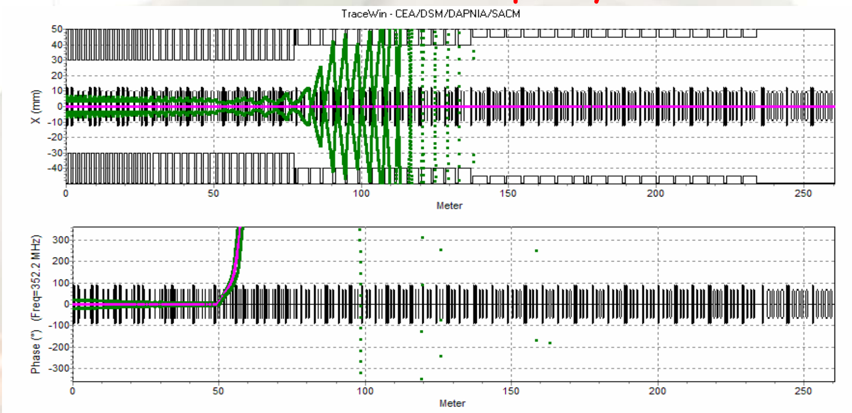
- Reliability engineering is a discipline for estimating, predicting and controlling the probability of occurrence of system faults

Main Conclusions on Reliability

- The cyclotron option for PDS-XADS does not seem to offer a sufficient perspective of reaching the requested reliability level
- No showstopper to reach high availability & high reliability with the XADS reference linac if over-design & redundancy are used
- Fault tolerance has been identified as key element in order to guarantee reliability by design and operation
  - Identification of the main component faults & estimate of their effect on the beam (not always straightforward)
  - Identification of strategies (and proper hardware systems) to deal with faults
  - Plans for the accelerator commissioning and maintenance
  - Reliability/availability allocation need to be examined with the constraints of legislation (safety aspects) & radioprotection

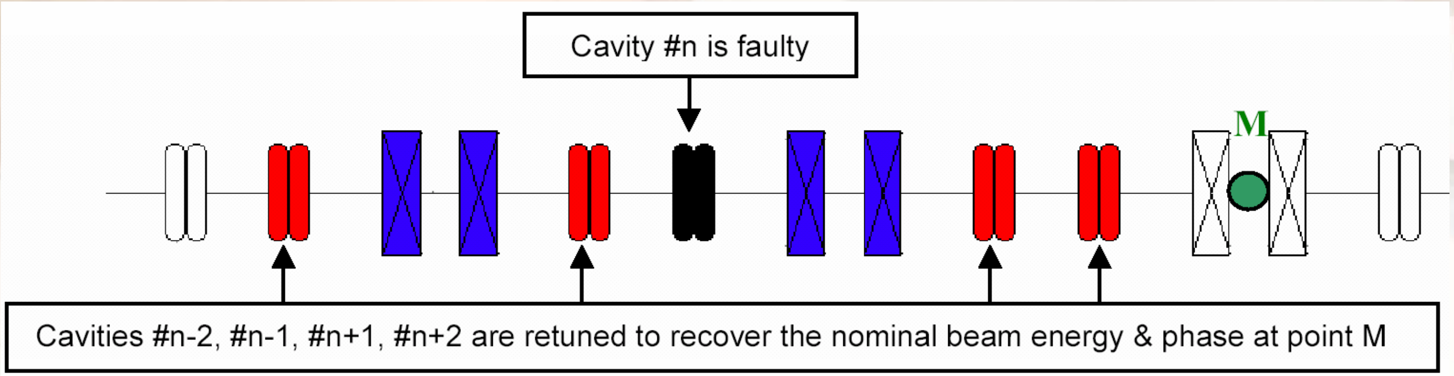
Fault Tolerance, a new concept uniquely applicable in a modular super conducting Linac

Fault tolerance in the independently phased SC sections is a crucial point because a few tens of RF systems failures are foreseen per year.



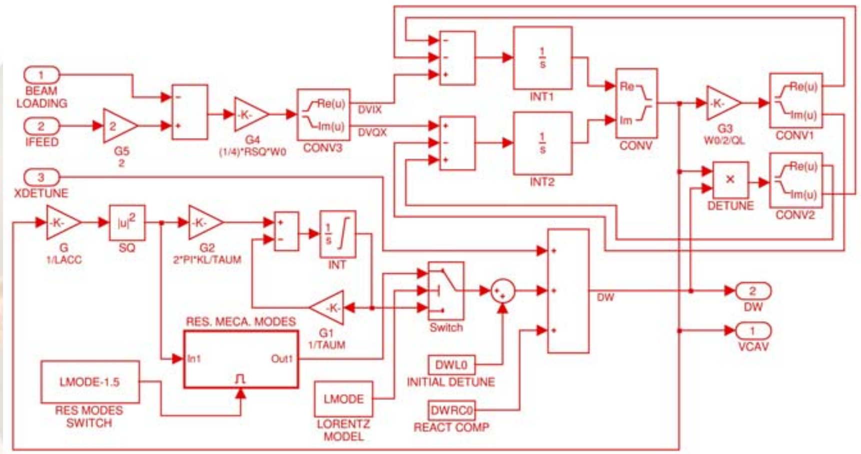
1. Consequences of the failure of a superconducting RF cavity
→An RF system failure induces phase slip (non relativistic beam)
→ If nothing is done, the beam is always LOST

2. Linac retuning after the failure of a RF cavity or of a quadrupole
→ Local compensation philosophy is used
→ In every case, the beam can be transported up to the high energy end without beam loss



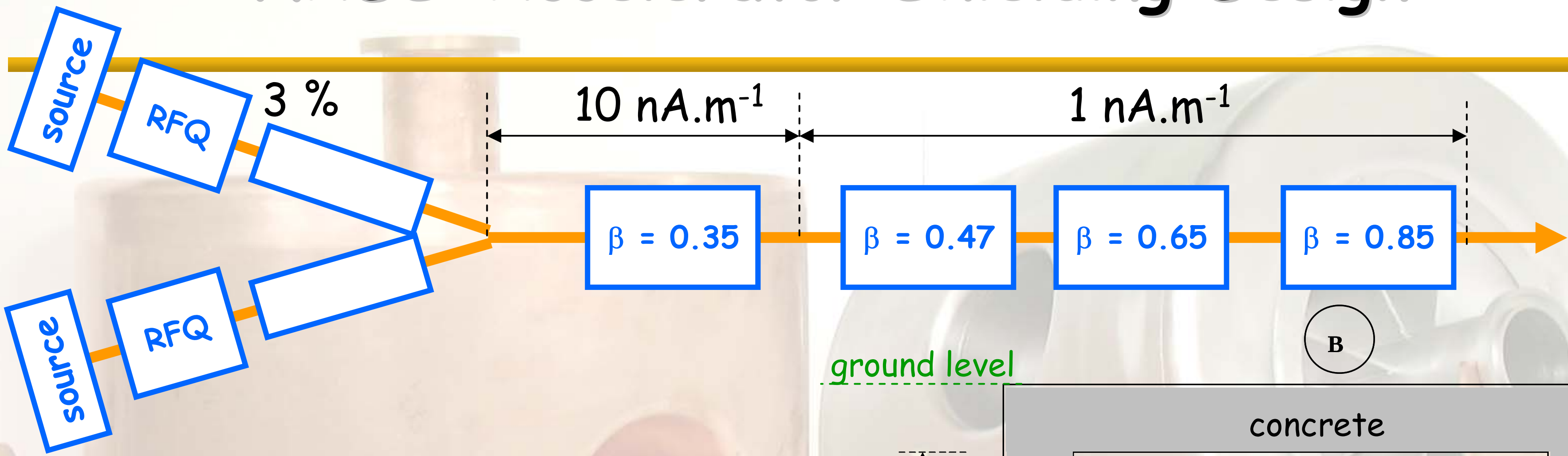
Reliability, Feedback Systems & Maintenance

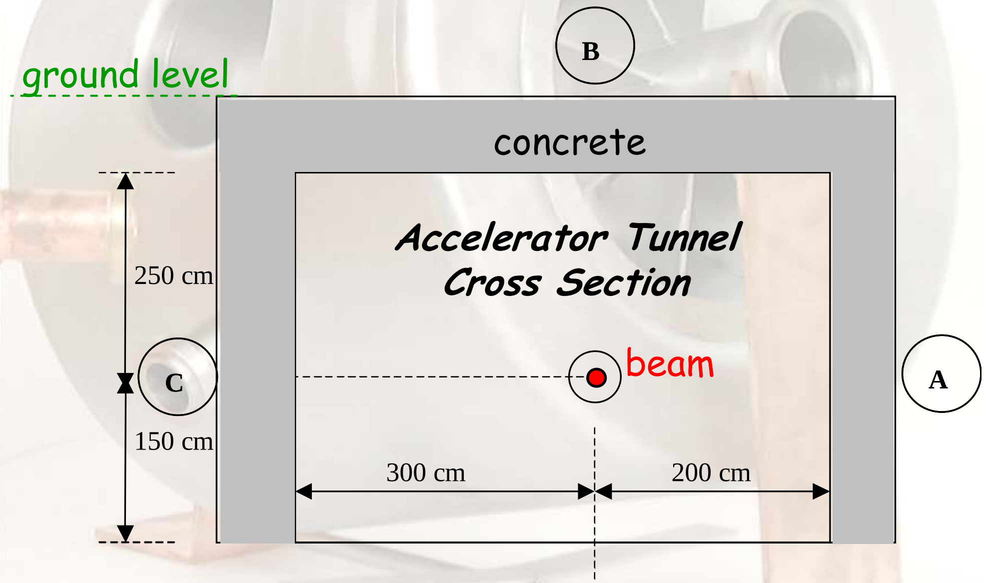
- **The feedback systems has to provide the necessary energy stability, dealing with faults in order to reach the project goals** *(less than 5 beam trips per year)*
  - **Fast digital RF system** can implement fault tolerance with respect to cavity fault by dealing fault set tables
  - **Beam diagnostics** is also an area of prime importance



- **The maintenance strategy has to guarantee the reliability of the machine for more than 20 years**
  - It should guarantee the long-term validity of the linac prime criteria:
    - Over-Design / Redundancy / Fault Tolerance
  - Need for an expert system :
    - Detecting faulty or out-of-order equipment
    - Planning of subsequent maintenance & management of the intervention time according to radioprotection

XADS-Accelerator Shielding Design





- **Conservative beam losses assumptions**
  - Normal beam losses
    - RFQ: 3%
    - Intermediate energy: 10 nA/m
    - High energy: 1 nA/m
  - Unwanted beam trips
    - P > 1. 10^{-2} $year^{-1}$ → included in the normal beam losses
    - P < 1. 10^{-2} $year^{-1}$ → "accidental beam losses" case

- **ALARA shielding design criteria**
  - < 1 mSv/year
  - I.e. **< 0.5 µSv/h** (2000 h/year)
  - Occupancy factor = 1

600 MeV XADS:
Shielding for Normal Operation and for Commissioning

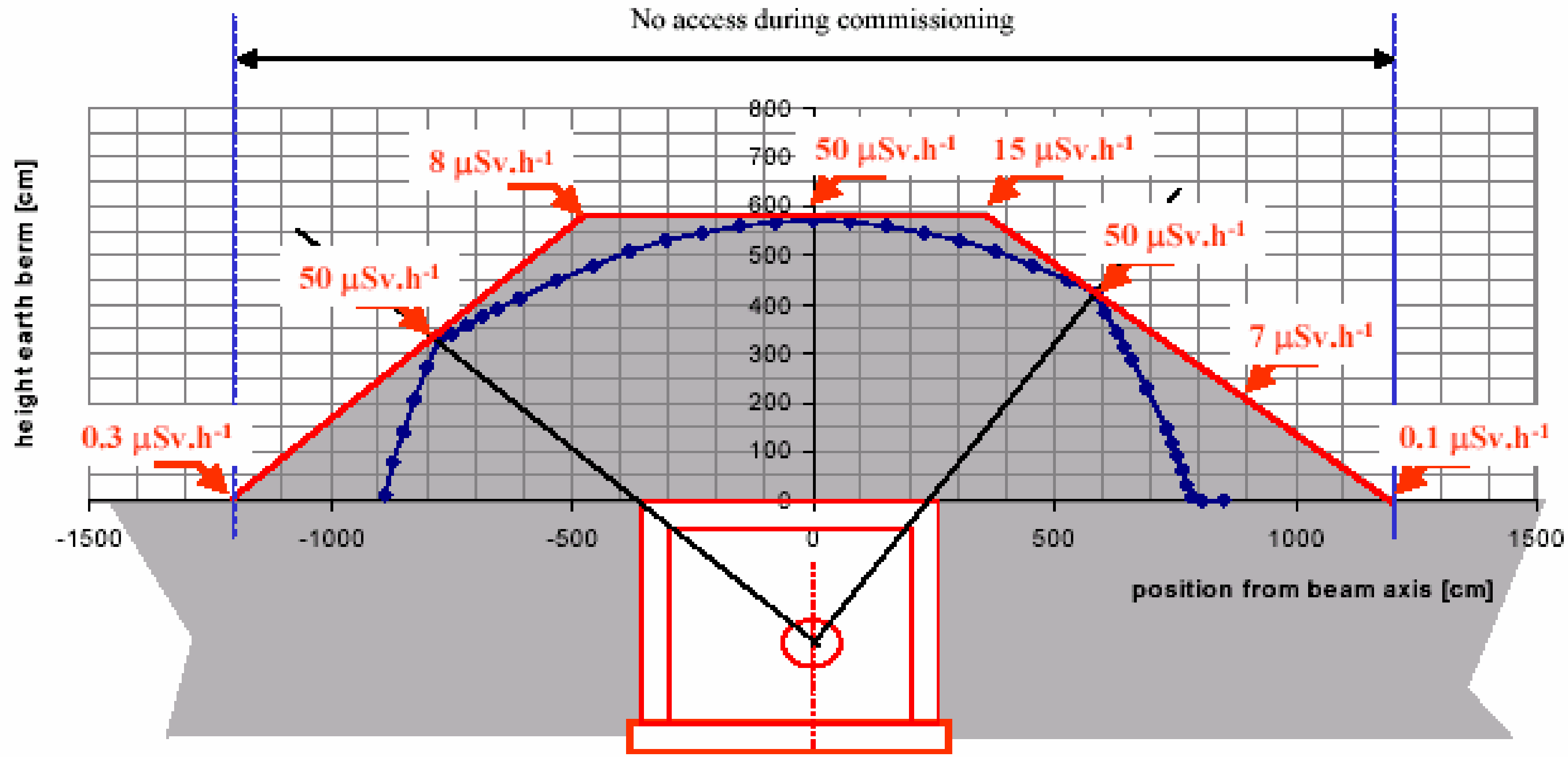
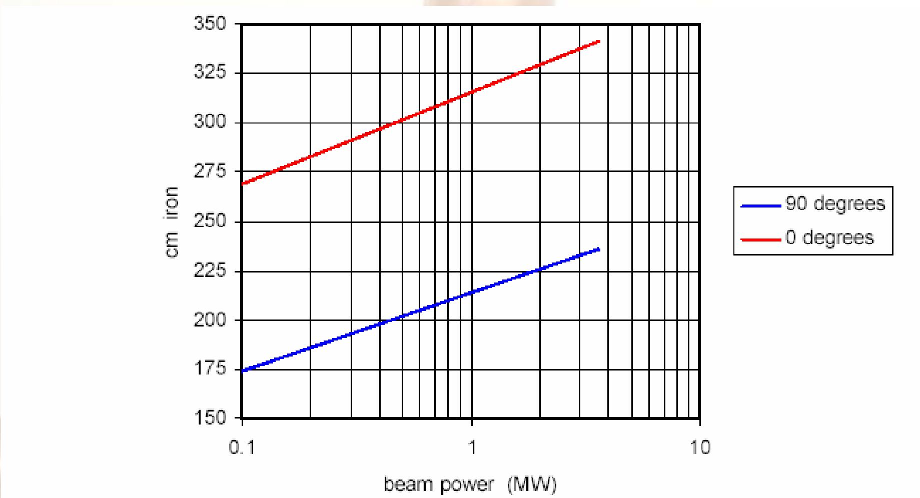
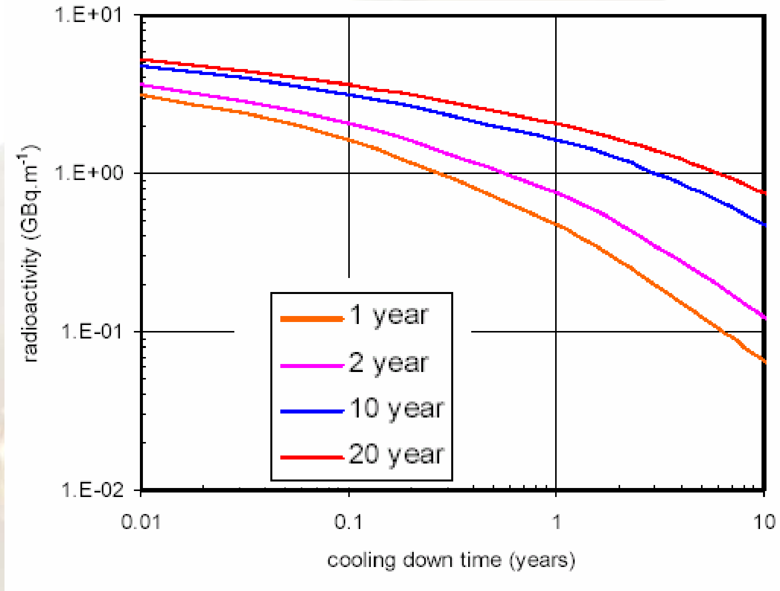


Figure 6.1 – Minimum earth profile above a 60 cm concrete tunnel (blue curve) corresponding to a beam loss rate of 1 nA.m^{-1} at 600 MeV for a residual dose rate of 0.5 □Sv.h^{-1}. Red curve: corresponding realistic earth profile. Dose rates are calculated for a beam loss rate of 100 nA.m^{-1} at 600 MeV.

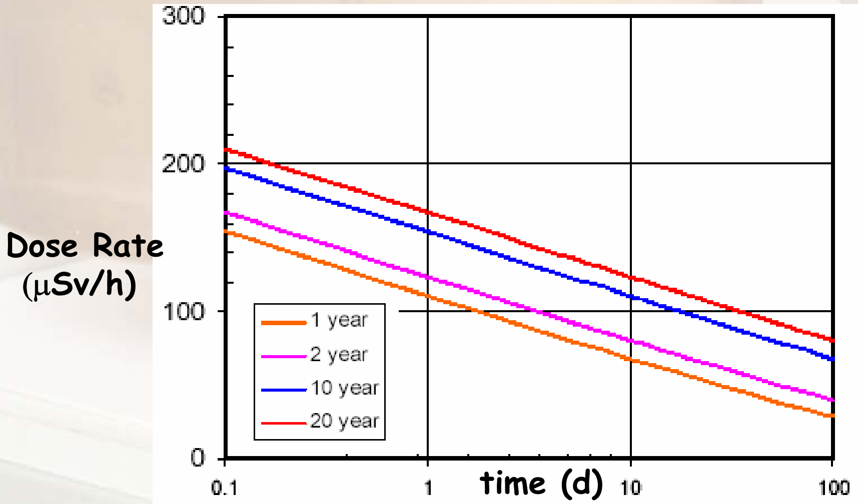
600 MeV Beam Stop and Accelerator Activation



Iron shielding for a 600 MeV beam dump as a function of the beam power, required to reduce the dose rate outside a 60 cm concrete building, covered with 550cm of earth, below 0.5 $\mu Sv.h^{-1}$.



Radioactivity produced per meter along the high-energy part of the accelerator for a 1 $nA.m^{-1}$ beam loss, as a function of the decay time, for 4 different values of the irradiation time.



Dose rates at 50 cm from the beam axis, along the high-energy part of the accelerator for a 1 $nA.m^{-1}$ beam loss, as a function of the decay time, for 4 different values of the irradiation time.

Extrapolation to a 1 GeV industrial transmuter

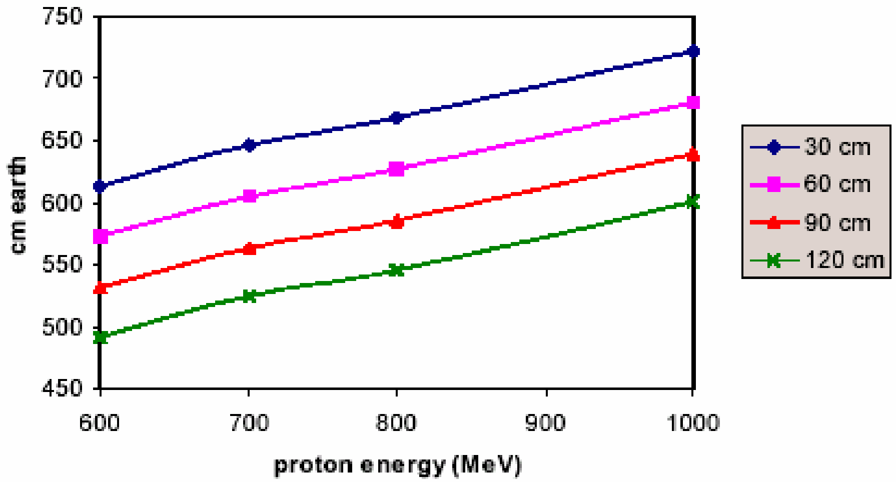


Figure 10.1 - Required earth thickness between 600 MeV and 1 GeV for four different values of the concrete shield wall thickness (30 cm, 60 cm, 90 cm and 120 cm respectively), for a linear beam power loss of 1 $nA.m^{-1}$.

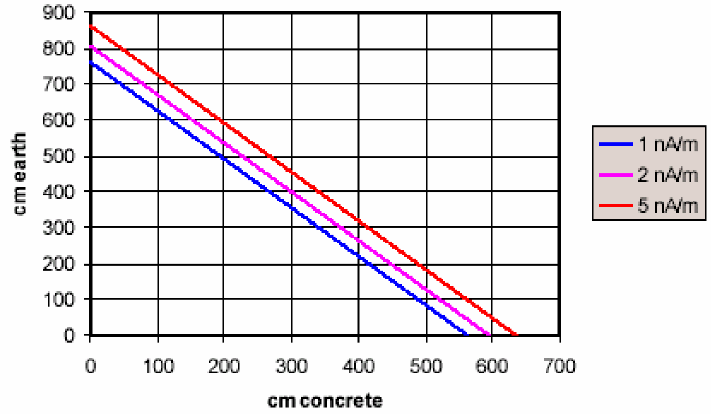


Figure 10.4 - Required concrete / earth combined thickness at 1 GeV, for a distance between the beam axis and the inner shield wall of 200 cm, for three values of the linear beam power loss: 1 $nA.m^{-1}$, 2 $nA.m^{-1}$ and 5 $nA.m^{-1}$.

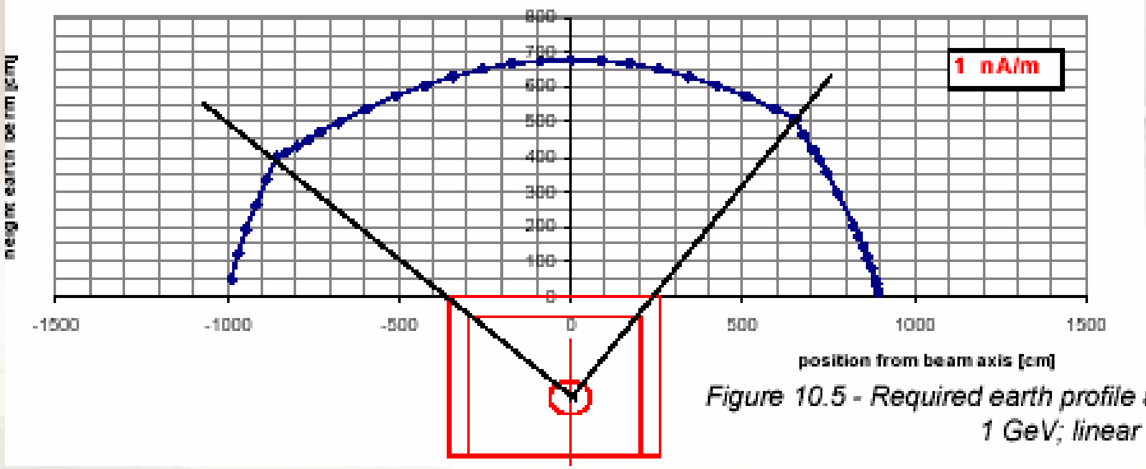
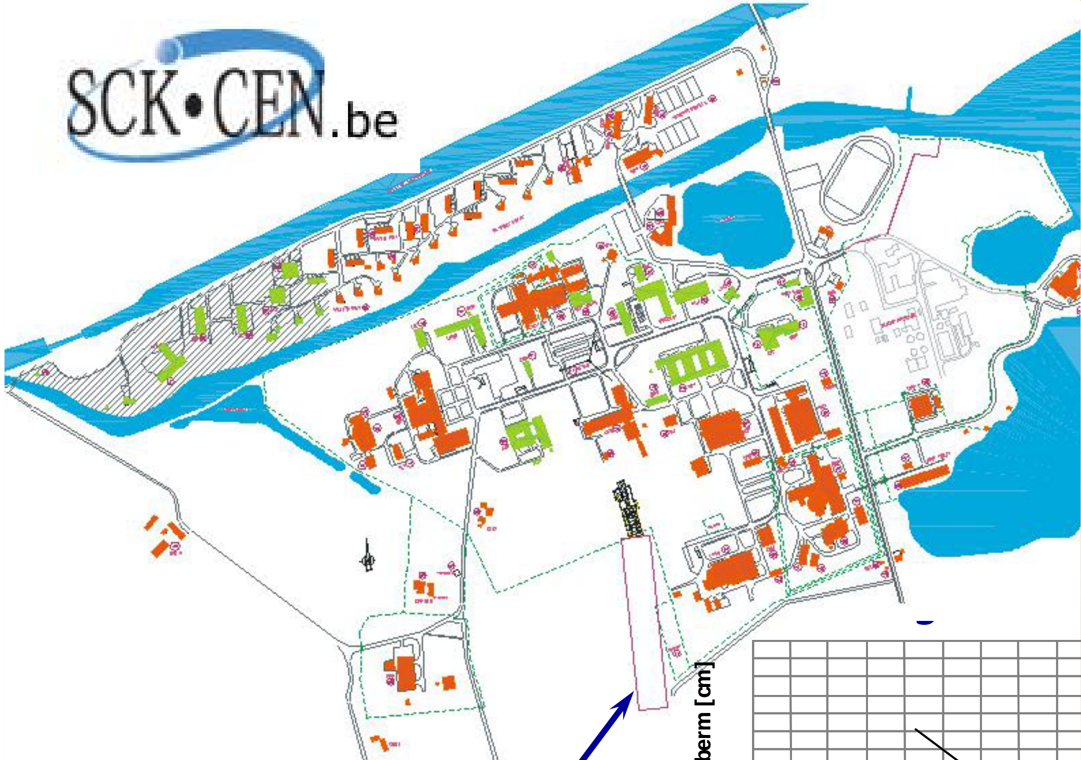


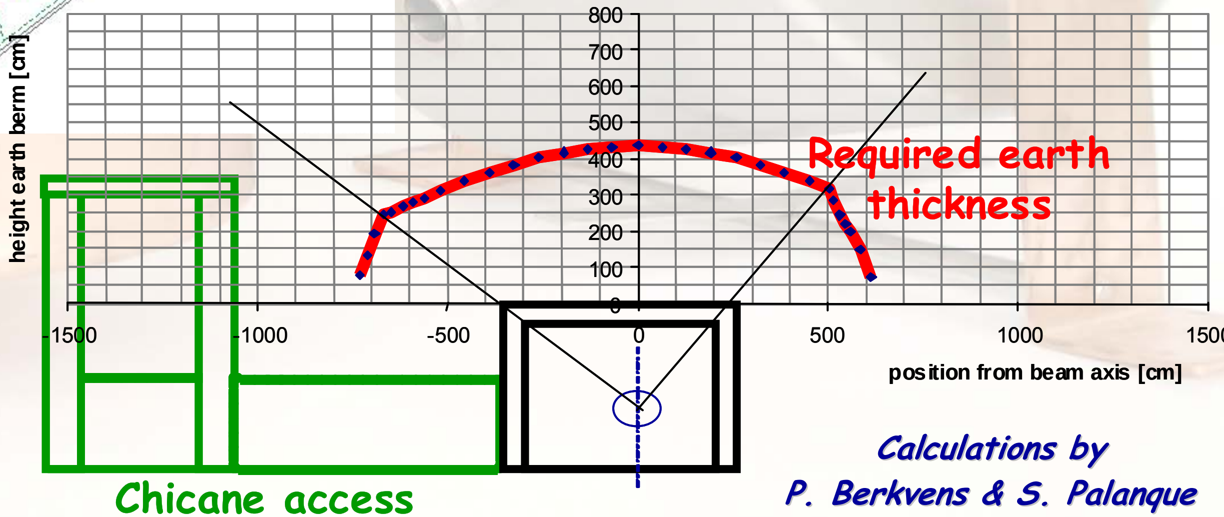
Figure 10.5 - Required earth profile above 60 cm concrete linac tunnel; proton energy: 1 GeV; linear beam loss power: 1 $nA.m^{-1}$.

Safety Aspects: Application to MYRRHA @ Mol



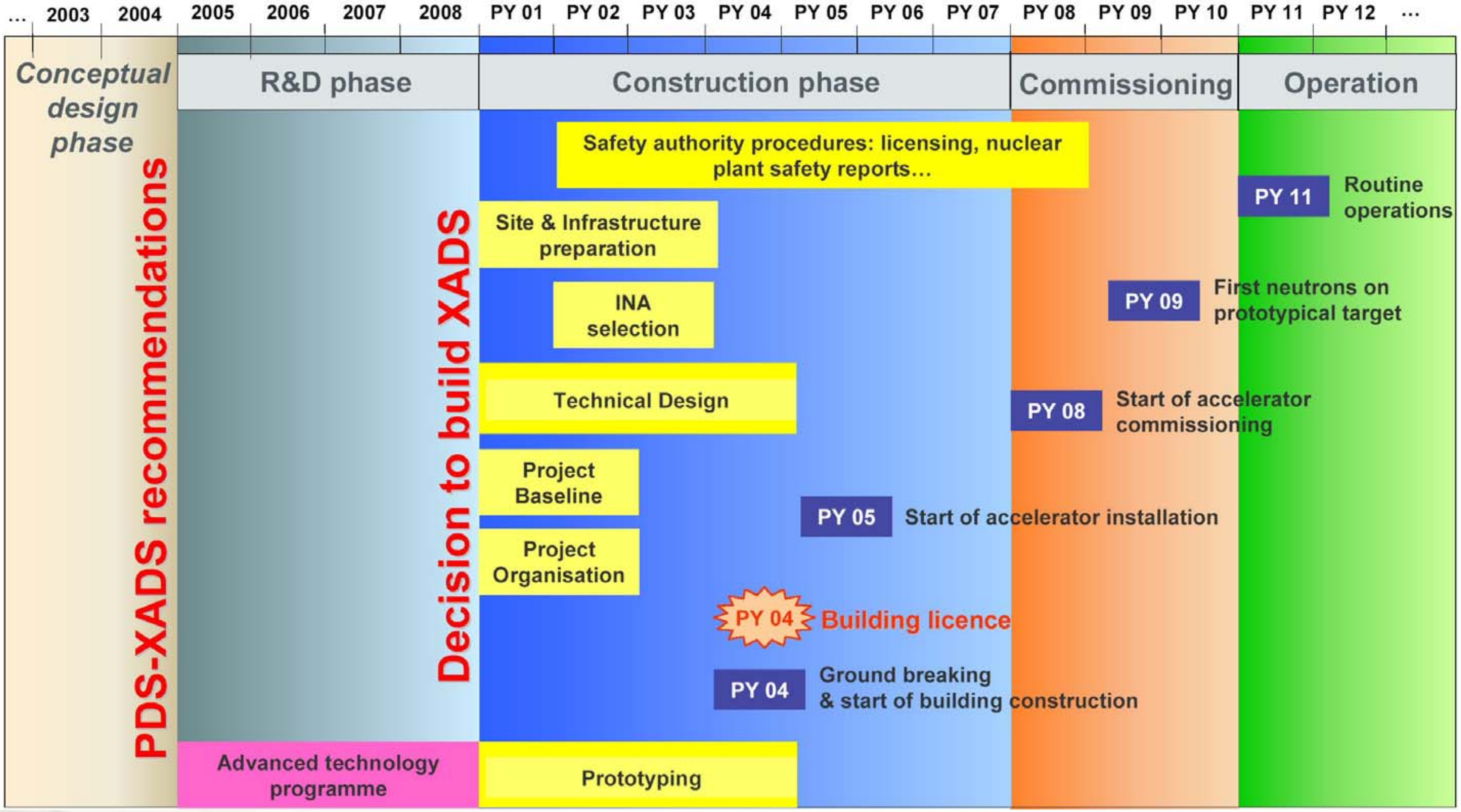
- **The 350 MeV MYRRHA machine**
  - Location on the SCK•CEN site, Mol, Belgium

- **Tunnel design for a 350 MeV XADS linac**
  - **Shielding calculations @ 350 MeV**, 1 nA/m, 0.5 μSv/h
  - Chicane access design
  - Shielding for normal losses also copes with « accidental losses »



Calculations by P. Berkvens & S. Palanque

Roadmap for the XADS-Accelerator (D63)



Cost Estimates for the Accelerator

Major sub-systems	Costs (M€)
Low Energy *	46
Intermediate Energy	18
High Energy	57
RF Power System	45
HEBT + Beam dump (500 kW)	21
Diagnostics + Vacuum + Control System	54
Cryogenic plant	20
Production assembly Hall of cavities	12
Total Estimated Costs (M€)	**273**

* including 2 Injector lines

- Includes internal and external man-power
- does not include purchase of land, basic infrastructures (roads, office buildings, cantine, water and electricity to the boundary of the site……)

Buildings	Civil Engineering	Electricity & HVAC distrib.	Total
Front - End	7 000	3 000	**10 000**
Linac tunnel	4 500	1 500	**6 000**
Klystron Hall	3 000	7 000	**10 000**
Central Liquifier	600	900	**1 500**
Production assembly Hall	1 250	1 250	**2 500**
Total (k€)	**16 350**	**13 650**	**30 000**

Remarks:

1) 350 MeV cheaper

2) does an XT-ADS need double injector?

3) Possible savings from a well suited site

Optimisation of Accelerator Reliability for ADS

RF systems have been identified as one of the critical areas*:

- Uncertainties on MTBF (most by engineering judgement)
- Not enough operation of 700 MHz CW RF sources
- Several subcomponents with low MTBF
- High "parts count"

1 RF system each cavity.
Redundancy (at expenses of operational cost and complexity)

If all are in series $MTBF_{series} = MTBF_{comp}/N$

Need to achieve fault tolerance to RF faults

*nb: this is true for all RF accelerators

Optimisation of Accelerator Reliability for ADS

Critical area: the RF system

Group	Components	Typical MTBF
Tubes (power amplifier)	Klystrons, IOT, Solid State	~ 50 000 h
RF power components	Windows, waveguides, circulators, loads	50 000…150 000 h
Low Level RF	Pre-amps, VCO, mixers, phase shifters	100 000 h
Transmitters	Auxiliary PS, interlocks, monitoring	5 000 … 10 000 h
HVPS	Oil tanks, HV passive components	20 000…50 000 h

Component SNS	Number	MTBF, khr	Failures year	MTTR, hr	Down Time/ year, hr
Klystron	81	50	9.72	4.5	43.7
Wave Guide	81	150	3.24	3.0	9.72
Load	81	75	6.48	3.0	19.4
Circulator	81	50	9.72	3.0	29.2
Converter/ Modulator	7	22.6	1.86	4.0	7.43
Transmitter	14	5.6	15	3.0	45.0
Window	81	100	4.68	24.0	116.6
LLRF	81	100	4.68	2.0	9.73
Totals			55.7		280.8

Table 4. Down time allocation for the 805 MHz, Super Conducting (SRF) RF System.

Optimisation of Accelerator Reliability for ADS

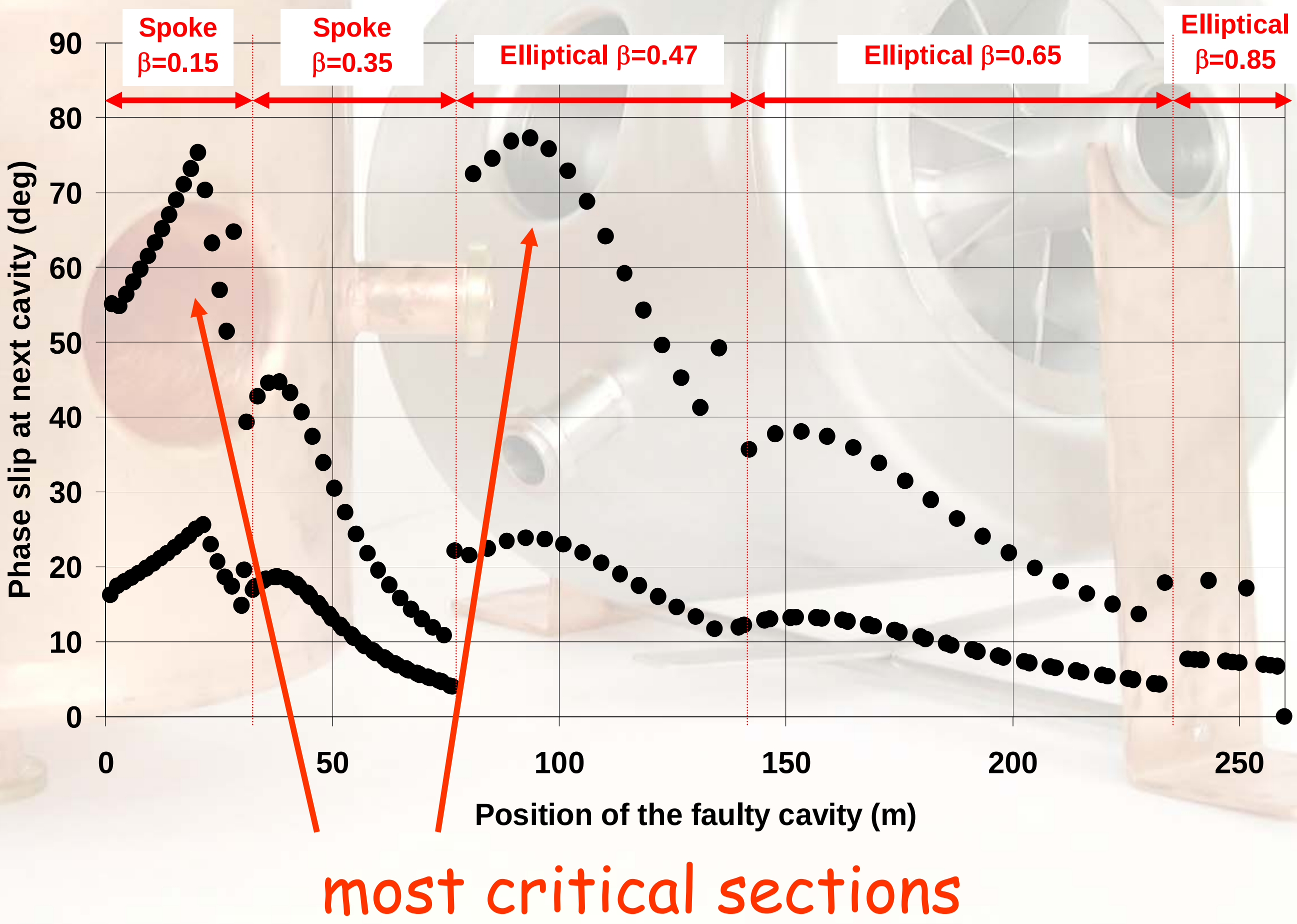
Consequences of cavity failure

We have a non-relativistic proton beam

Any energy loss will imply a phase slip along the linac increasing with the distance, beam can get out of stability region

$$\delta\varphi = 2\pi\left(\delta z/\lambda\right)\left(\delta\beta/\beta^2\right)$$

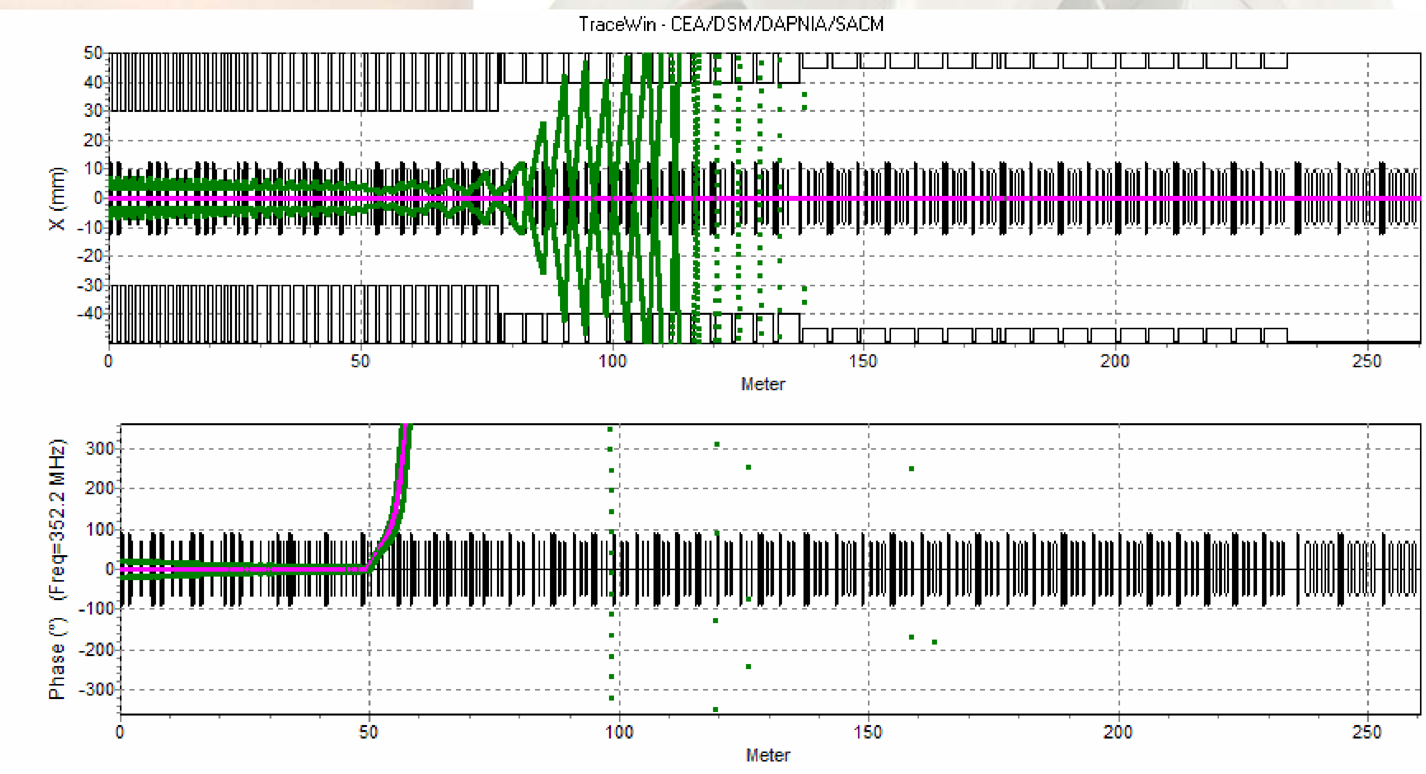
β is the beam velocity
λ the RF wavelength
$\delta\beta$ the velocity loss at δz



Optimisation of Accelerator Reliability for ADS

Consequences of cavity failure

If the synchronous phase or/and the accelerating field is too high, the beam is TOO LATE & leaves the stability region: the beam is lost



Beam dynamics simulation with TraceWin

Optimisation of Accelerator Reliability for ADS

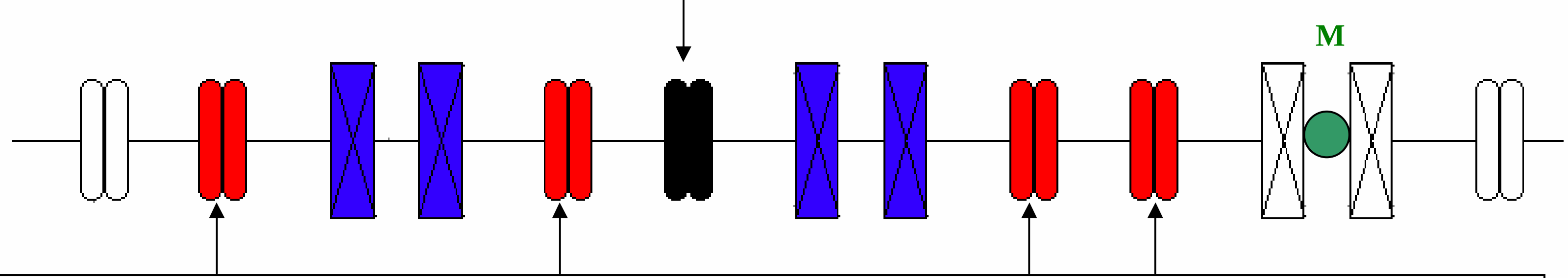
Need to have linac design that can handle the loss of one or several cavities

The modularity of our LINAC makes this possible because we have INDEPENDENTLY PHASED structures

We need to find procedure that use the neighbouring cavities to compensate phase/energy beam offset

These procedures should then be integrated in RF control system

Cavity #n is faulty



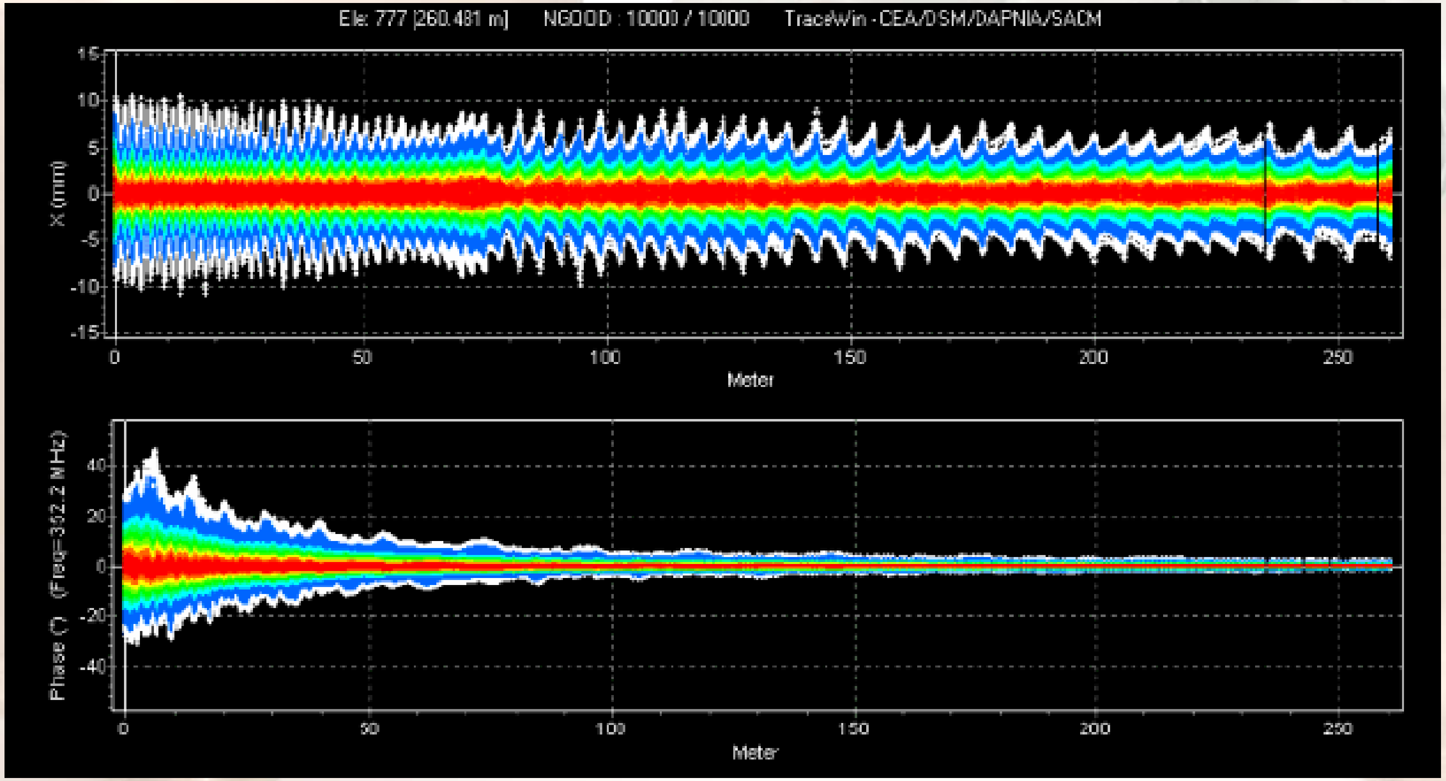
Cavities #n-2, #n-1, #n+1, #n+2 are retuned to recover the nominal beam energy & phase at point M

Optimisation of Accelerator Reliability for ADS

After retuning correct number of neighboring cavities

Amplitude

Phase



Fault-tolerance: Cavity retuning (Biarrotte & thesis Lukovac)

Study has been applied to **most representative cavities in all in all sections** (beginning, half and end of each section)

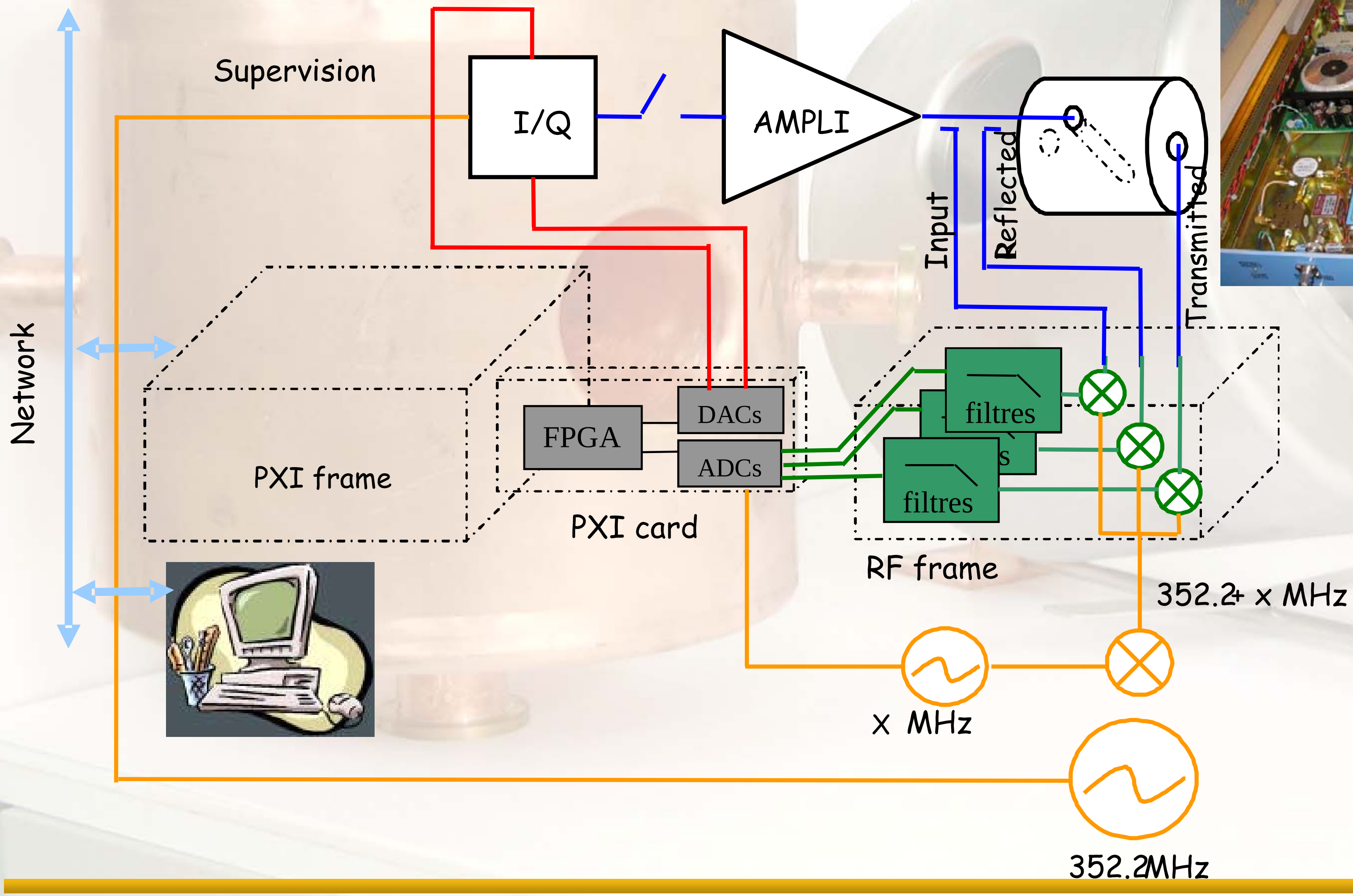
In every case, the beam can be transported up to high energy with 100% transmission, small emittance growths, nominal parameters

Only for E < 10 MeV increase above 30% is necessary

# faulty cavity	section	Final energy	Emittance growth (%) Transv.	Emittance growth (%) Long.	# of retuned cavities (bef + aft)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	# retuned quads (bef + aft)
0	-	Nominal	+ 5 %	0 %	-	-	-	-	-
1	SP 0.15	Nominal	+ 7 %	+ 4 %	0 + 4	+ 67 %	19 MV/m	+ 67 %	0 + 4
2	SP 0.15	Nominal	+ 9 %	+ 12%	1 + 3	+ 90 %	19 MV/m	+ 68 %	0 + 4
3	SP 0.15	Nominal	+ 10%	+ 12%	2 + 3	+ 94 %	21 MV/m	+ 56 %	4 + 2
4	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 3	+ 46 %	15 MV/m	+ 35 %	2 + 4
19	SP 0.15	Nominal	+ 6 %	+ 6 %	2 + 3	+ 38 %	24 MV/m	+ 48 %	2 + 2
20	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 2	+ 37 %	26 MV/m	+ 58 %	2 + 2
35	SP 0.15	Nominal	+ 6 %	0 %	2 + 3	+ 20 %	32 MV/m	+ 27 %	2 + 2
36	SP 0.15	Nominal	+ 7 %	+ 4 %	3 + 3	+ 22 %	34 MV/m*	+ 32 %	2 + 2
37	SP 0.35	Nominal	+ 6 %	0 %	3 + 2	+ 22 %	35 MV/m*	+ 34 %	2 + 2
38	SP 0.35	Nominal	+ 7 %	+ 6 %	3 + 4	+ 29 %	31 MV/m	+ 26 %	2 + 2
39	SP 0.35	Nominal	+ 5 %	+ 5 %	4 + 2	+ 24 %	36 MV/m*	+ 35 %	4 + 2
61	SP 0.35	Nominal	+ 6 %	+ 2 %	2 + 3	+ 25 %	31 MV/m	+ 26 %	2 + 2
62	SP 0.35	Nominal	+ 6 %	0 %	2 + 2	+ 26 %	31 MV/m	+ 28 %	2 + 2
63	SP 0.35	Nominal	+ 5 %	+ 1 %	3 + 2	+ 25 %	31 MV/m	+ 27 %	2 + 2
94	SP 0.35	Nominal	+ 6 %	+ 2 %	3 + 3	+ 16 %	29 MV/m	+ 18 %	4 + 2
95	SP 0.35	Nominal	+ 7 %	- 1 %	3 + 3	+ 22 %	31 MV/m	+ 29 %	4 + 2
96	SP 0.35	Nominal	+ 5 %	+ 1 %	4 + 2	+ 21 %	30 MV/m	+ 25 %	4 + 2
97	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 18 %	59 mT	+27 %	4 + 2
98	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 23 %	62 mT	+ 31 %	4 + 2
109	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 20 %	60 mT	+ 28 %	4 + 2
110	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 20 %	60 mT	+ 29 %	2 + 2
123	EL 0.47	Nominal	+ 6 %	0 %	2 + 4	+ 20 %	60 mT	+ 26 %	4 + 2
124	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 19 %	60 mT	+ 28 %	4 + 2
125	EL 0.65	Nominal	+ 5 %	0 %	2 + 3	+ 18 %	59 mT	+ 27 %	4 + 2
126	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 21 %	61 mT	+ 20 %	4 + 2
127	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 21 %	61 mT	+ 25 %	4 + 2
146	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
147	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 4	+ 19 %	60 mT	+ 22 %	4 + 2
148	EL 0.65	Nominal	+ 6 %	- 1 %	3 + 3	+ 20 %	60 mT	+ 22 %	4 + 2
173	EL 0.65	Nominal	+ 5 %	0 %	3 + 4	+ 17 %	59 mT	+ 19 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
175	EL 0.65	Nominal	+ 5 %	0 %	4 + 4	+ 17 %	59 mT	+ 18 %	4 + 2
176	EL 0.85	Nominal	+ 5 %	0 %	3 + 5	+ 18 %	59 mT	+ 22 %	4 + 2
177	EL 0.85	Nominal	+ 5 %	0 %	4 + 4	+ 18 %	59 mT	+ 20 %	4 + 2
178	EL 0.85	Nominal	+ 5 %	0 %	5 + 4	+ 18 %	59 mT	+ 19 %	4 + 2
179	EL 0.85	Nominal	+ 5 %	0 %	6 + 4	+ 17 %	59 mT	+ 16 %	4 + 2
184	EL 0.85	Nominal	+ 5 %	0 %	4 + 3	+ 17 %	59 mT	+ 29 %	2 + 2
185	EL 0.85	Nominal	+ 6 %	0 %	5 + 2	+ 19 %	60 mT	+ 30 %	2 + 2
186	EL 0.85	Nominal	+ 7 %	0 %	6 + 1	+ 21 %	61 mT	+ 33 %	2 + 2
187	EL 0.85	Nominal	+ 6 %	0 %	7 + 0	+ 25 %	63 mT	+ 37 %	2 + 2

Fault tolerance: Low Level RF Fast Feedback System

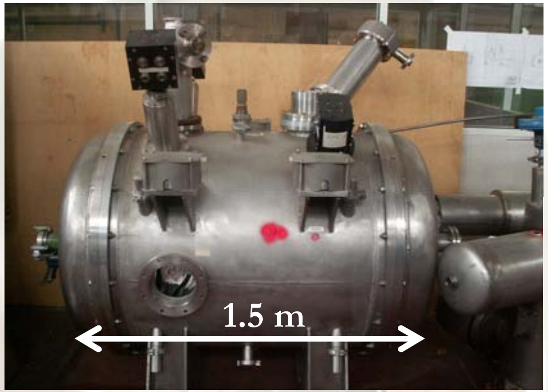
Collaboration IPN Orsay and LPNHE Paris

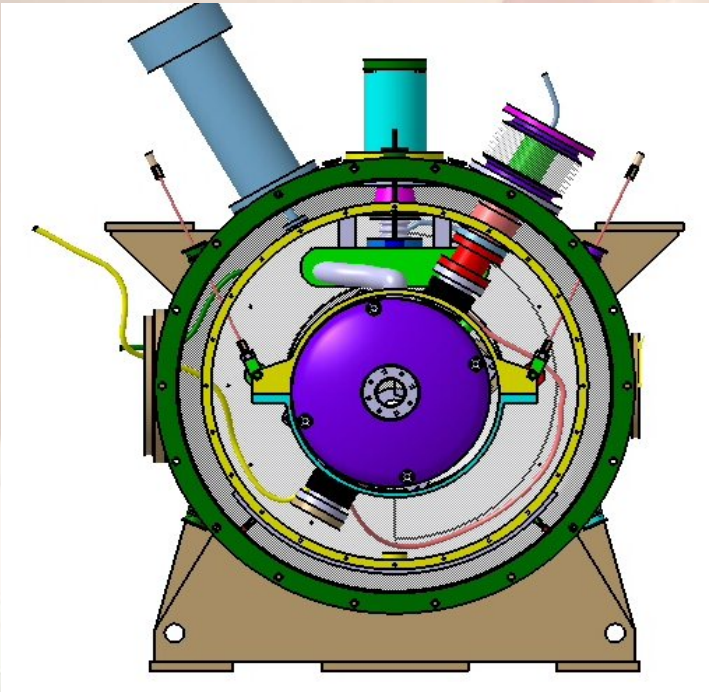


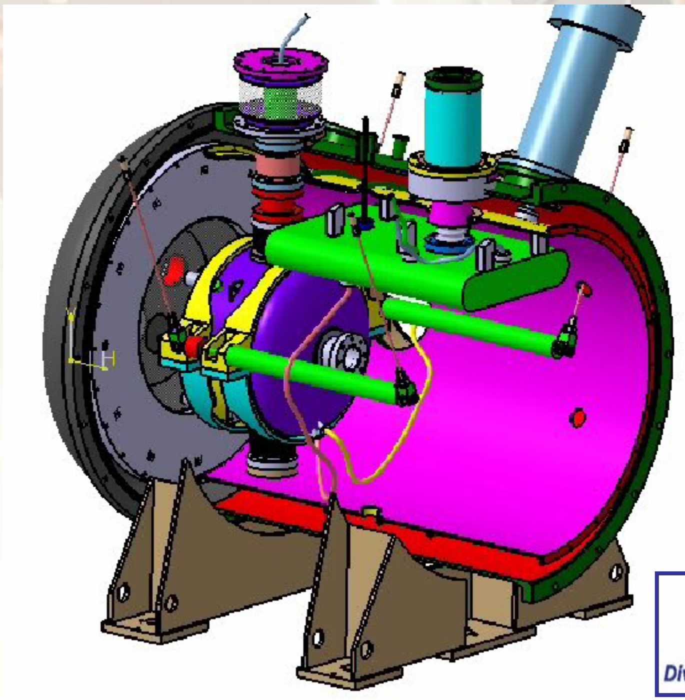
Optimisation of Accelerator Reliability for ADS

one selected example:

Tests of all components for a cryomodule :
LLRF digital system + RF power coupler + SPOKE cavity
in horizontal cryostat foreseen for beginning 2007

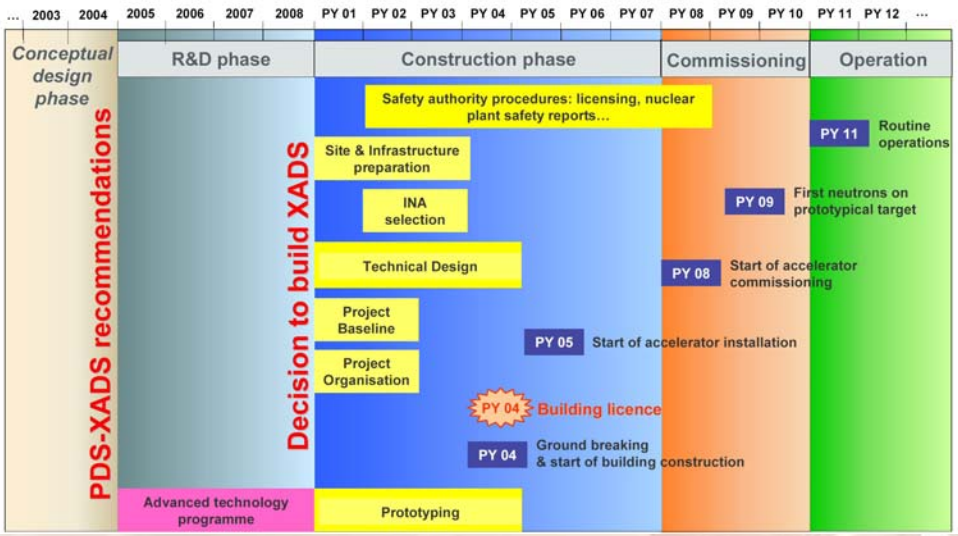






IPN Orsay Division Accélérateurs

From FP5 PDS-XADS to FP6 EUROTRANS



done within →

FI6W-CT-2004-516520
Integrated Project
On European Transmutation
(EUROTRANS)

EUROTRANS
- EUROPEAN RESEARCH PROGRAMME FOR THE TRANSMUTATION OF HIGH LEVEL -
NUCLEAR WASTE IN AN ACCELARATOR DRIVEN SYSTEM

FZK
AAA
ANSALDO
Nexia Solutions
CEA
CIEMAT
CNRS
CRS4
CSIC
EA
ENEA
ENEN
FANP SAS
FZJ
FZR

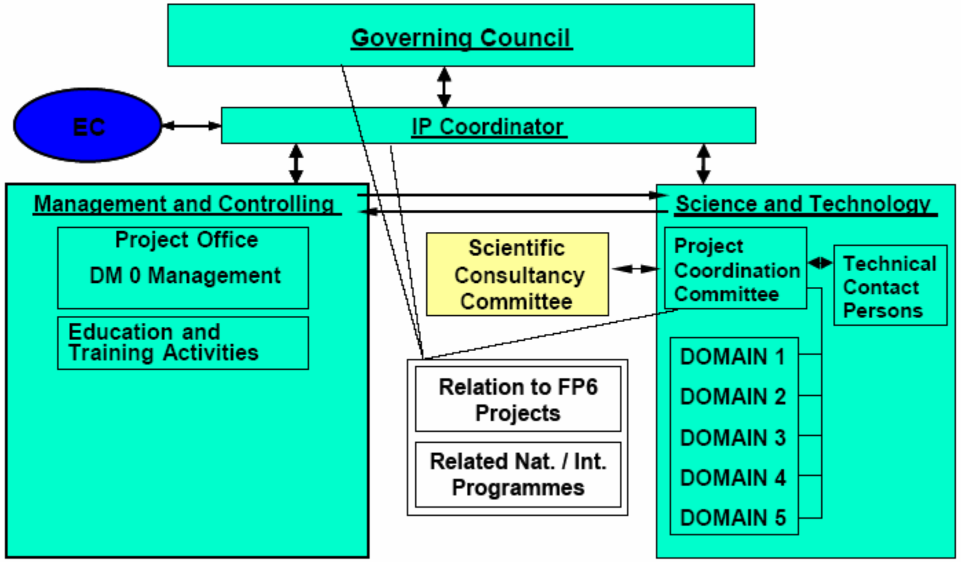
GSI
IBA
INFN
INRNE
ITN
JRC
NRG
NRI
OTL
PSI
SCK-CEN
Suez-Tractebel
FANP GmbH
NNC

From FP5 PDS-XADS to FP6 EUROTRANS

FP	Design Concepts			Objectives
FP5	**XADS (Pb-Bi)** 80 MW(th) 110 W/cm single batch loading	**XADS (Gas)** 80 MW(th) 250 W/cm single batch loading	**MYRRHA (Pb-Bi)** 50 MW(th) 500 W/cm multi batch loading	**XADS** Demonstration of technological feasibility of an ADS system
FP6	**European Transmutation Demonstration (ETD)** advanced design	**XT-ADS** < 100 MW(th) 250 - 300 W/cm multi batch loading		**XT-ADS** Short-term demonstration of transmutation on a sizable scale and of the ADS behaviour
	conceptual design, economics, scalability	**EFIT** Several 100 MW(th) 250 - 300 W/cm multi batch loading		**EFIT** Long-term transmutation on an industrial scale

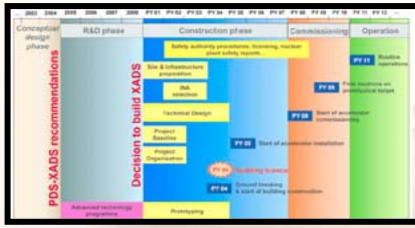
EUROTRANS-PCC: Tasks & Members

J.U. Knebel (FZK), coordinator
H.A. Abderrahim (SCK), DM1 Design
S. Monti (ENEA), DM2 ECATS
S. Pillon (CEA), DM3 AFTRA
C. Fazio (FZK), DM4 DEMETTRA
E. Gonzalez (CIEMAT), DM5 NUDATRA
B. Giraud (FANP), Industry
L. Cinotti (ANSALDO), Industry
A.C. Mueller (CNRS), Accelerator
M. Giot (ENEN), Universities



- Technical co-ordination of the project work programme,
- Preparation, where necessary, of revisions to the detailed work programmes,
- Approval of the IP Instruction Book and the QA Guidelines,
- Preparation of the updated Implementation Plan and associated financial plan for the EC,
- Identification of technical and scientific problems and/or issues,
- Identification of technical developments, which are related to patents and the development of design, component or process issues,
- Review and approve the contractually required interim and progress reports,
- Proposing technical workshops, technical meetings, etc.

The accelerator within EUROTRANS-DM1



WP1.3: ACCELERATOR

GOAL:

HPPA development, and in particular, qualification of the reliability of the prototypical components

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Alex C. Mueller*

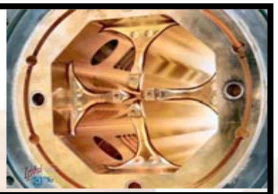
DM1 DESIGN WP1.3 - Accelerator	TOTAL WP1.3			
	Cons. k€	PM	Total k€	*EU request k€*
P5-CEA (F)	170	67	840	*420.0*
P8-CNRS (F)	180	138	1560	*780.0*
P13.4-IAP-FU (D)	75	27	345	*172.5*
P13.12-UPM (SP)	3	4	43	*21.5*
P18-IBA (B)	182	20	382	*191.0*
P19-INFN (I)	480	65	1130	*565.0*
P21-ITN (P)	10	10	110	*55.0*
P31-FANP GmbH (D)	3	2	23	*11.5*
Total WP1.3	1103	333	4433	*2216.5*

1 PM = 10k€

RED: *Leading Organization in this Work Package*

Injector Reliability

TASK 1.3.1



GOAL:

The injector IPHI, developed by CEA and CNRS, will be used for a long run test to demonstrate on a real scale the reliability of the injector part.

CO-ORDINATING CONTRACTOR:

CEA (F) – *Raphaël Gobin*

MILESTONES:

M1.3.1: Specifications for the long test run (+9)

M1.3.2: Injector operational for test (+18)

M1.3.3: Experimental tests accomplished (+36)

M1.3.4: Final report: results and analysis (+39)

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.1 Experimental evaluation of the proton injector reliability		
	Cons. k€	PM	Total k€
P5-CEA (F)	140	38	520
P8-CNRS (F)	0	15	150
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	0	0
P19-INFN (I)	0	0	0
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	140	53	670

DELIVERABLES:

D1.3.1: Preliminary short report. Specifications of the long test runs (CEA, +9)

D1.3.2: Intermediate progress report on injector status and proposed test schedule (CEA, +18)

D1.3.3: Final report on results and analysis (CEA, +39)

Intermediate-energy Section

TASK 1.3.2

GOAL:

Evaluation of room-temperature cavities and superconducting cavities performances, reliability and cost. Determination of the energy transition from where on doubling of the injector is no longer required for reliability.

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Tomas Junquera*

MILESTONES:

M1.3.5: Specifications for prototypes (+6)

M1.3.6: Prototypes ready for test (+27)

M1.3.7: Experimental results of prototypes performances (+39)

M1.3.8: Final report: synthesis and design proposals (+42)

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.2 Assessment of the reliability performances of the intermediate energy accelerating components		
	Cons. k€	PM	Total k€
P5-CEA (F)	0	1	10
P8-CNRS (F)	**50**	**24**	**290**
P13.4-IAP-FU (D)	70	24	310
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	170	15	320
P19-INFN (I)	0	0	0
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	**290**	**64**	**930**

DELIVERABLES:

D1.3.4: Preliminary report. Specifications of the prototypes (IAP_FU, +6)

D1.3.5: Intermediate report on prototype test schedules (IBA, +18)

D1.3.6: Final report: tests results, synthesis and design proposals (CNRS, +42)

High-energy Section

TASK 1.3.3

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.3 Qualification of the reliability performances of a high energy cryomodule at full power and nominal temperature		
	Cons. k€	PM	Total k€
P5-CEA (F)	0	1	10
P8-CNRS (F)	100	80	900
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	0	0
P19-INFN (I)	440	60	1040
P21-ITN (P)	0	5	50
P31-FANP GmbH (D)	0	0	0
Total WP1.3	**540**	**146**	**2000**

GOAL:

Design, construction and test of a full prototypical cryomodule of the high energy section of the proton linac.

CO-ORDINATING CONTRACTOR:

INFN (I) – *Paolo Pierini*

MILESTONES:

M1.3.9: Preliminary cryomodule specifications (+9)

M1.3.10: Cryomodule design finalized (+15)

M1.3.11: Cryomodule is ready for test (+30)

M1.3.12: Exptl. results of cryomodule performances (+39)

M1.3.13: Final report: synthesis and design proposals (+42)

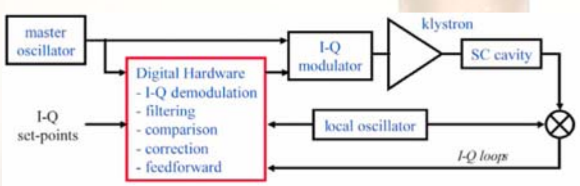
DELIVERABLES:

D1.3.7: Preliminary report: specifications for the cryomodule (INFN, +9)

D1.3.8: Report on cryomodule design and schedule (CNRS, +15)

D1.3.9: Final report: test results, synthesis and design proposals (INFN, +42)

Digital RF Control



TASK 1.3.4

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.4 Conceptual design of an RF control system for fault tolerant operation of the linear accelerator		
	Cons. k€	PM	Total k€
P5-CEA (F)	10	15	160
P8-CNRS (F)	0	5	50
P13.4-IAP-FU (D)	0	0	0
P13.12-UPM (SP)	0	0	0
P18-IBA (B)	0	1	10
P19-INFN (I)	10	0	10
P21-ITN (P)	0	0	0
P31-FANP GmbH (D)	0	0	0
Total WP1.3	**20**	**21**	**230**

GOAL:

Modelling and VHDL analysis of a digital RF control system for fault tolerant operation of the linear accelerator. *(Prototyping of an RF control unit is strongly recommended)*

CO-ORDINATING CONTRACTOR:

CEA (F) – *Michel Luong*

MILESTONES:

M1.3.14: Preliminary RF control system specifications (+6)

M1.3.15: RF control system modelling (+24)

M1.3.16: Final report: VHDL architecture and synthesis (+42)

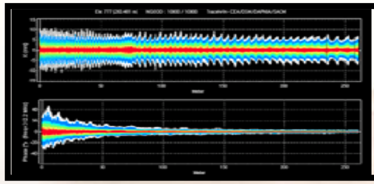
DELIVERABLES:

D1.3.10: Preliminary specifications of the RF control system (CEA, +6)

D1.3.11: Report on RF control system modelling (CEA, +24)

D1.3.12: Final report: VHDL architectures and synthesis (CEA, +42)

Beam Dynamics and Overall Coherence



TASK 1.3.5

GOAL:

Overall coherence of the accelerator design, including beam dynamics simulations, integrated reliability analysis, and cost estimation.

CO-ORDINATING CONTRACTOR:

CNRS (F) – *Jean-Luc Biarrotte*

MILESTONES:

M1.3.17: General specifications (+6)
M1.3.18: WP1.3 overall task review (+18)
M1.3.19: Results of beam dynamic simulations (+30)
M1.3.20: Reliability study experimental results (+39)
M1.3.21: Integrated reliability analysis (+45)
M1.3.22: Cost Analysis (+45)
M1.3.23: Final report (+48)

DM1 DESIGN WP1.3 - Accelerator	Task 1.3.5 Overall coherence of the accelerator design, final reliability analysis, cost estimation of XT-ADS and EFIT		
	Cons. k€	PM	Total k€
P5-CEA (F)	20	12	140
P8-CNRS (F)	30	14	170
P13.4-IAP-FU (D)	5	3	35
P13.12-UPM (SP)	3	4	43
P18-IBA (B)	12	4	52
P19-INFN (I)	30	5	80
P21-ITN (P)	10	5	60
P31-FANP GmbH (D)	3	2	23
Total WP1.3	113	49	603

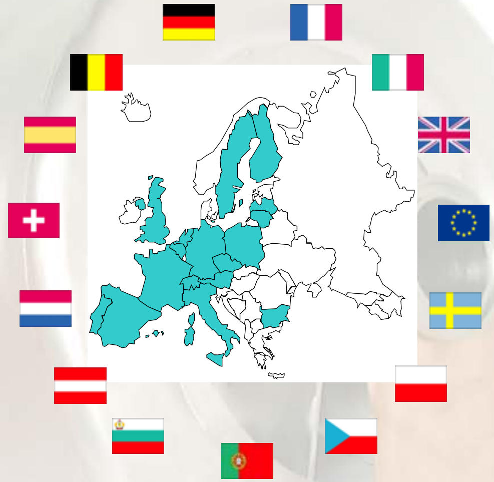
DELIVERABLES:

D1.3.13: General specifications for all the tasks (CNRS, +6)

D1.3.14: Beam dynamics simulations for fault tolerance (CNRS, +30)

D1.3.15: Report on integrated reliability analysis of the accelerator (INFN, +48)

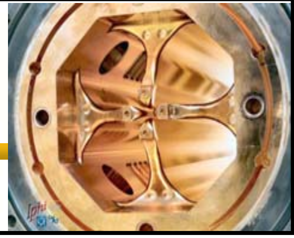
D1.3.16: Final report: accelerator design, performances, costs for XT-ADS and EFIT and associated road map (CNRS, +48)



EUROTRANS DM1

WP 1.3 Accelerator

TASK 1.3.1



Objectives

Prepare the IPHI injector long test run

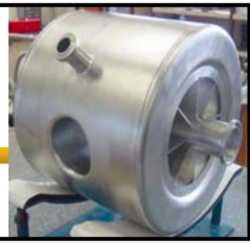
PROGRESS ACHIEVED

- Fabrication of RFQ sections 2 to 6 still on-going (CEA)
- Installation of RFQ environment 90% completed (CEA)
- Installation of diagnostic beam line in progress (CNRS)
- First beam planned in October 2008
- Eurotrans tests planned in January / March 2009

PROBLEMS ENCOUNTERED

- Important shift (9 months at least) in the schedule due to RFQ fabrication difficulties

TASK 1.3.2



Objectives

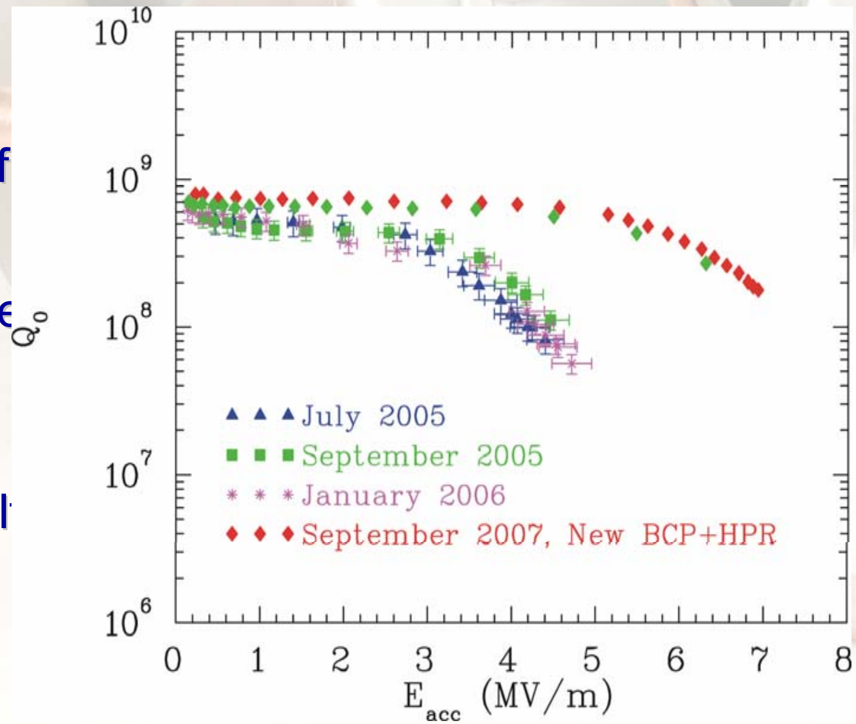
Prepare the final EUROTRANS experimental tests for the 3 different structures of the intermediate energy section

PROGRESS ACHIEVED

- New EXCELLENT experimental results of the SC CH cavity (IAP-FU)

- Very promising first test of the CM0 Spoke cryomodule at low power with LLRF loop and Cold tuning system (CNRS)

- CM0 High power test scheduled in 1st hal 2008 (CNRS)



PROBLEMS ENCOUNTERED

- None

TASK 1.3.3

Objectives

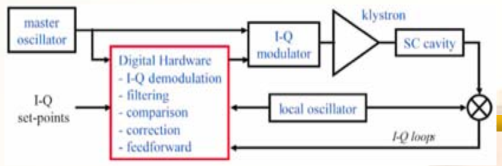
Finalize the design of the high-energy test cryomodule and start the call for tender procedures

PROGRESS ACHIEVED

- Cavity + cold tuning system under final assembling & preparation (INFN)
- Vacuum vessel under final design phase (INFN)
- Coupler design under final design phase (CNRS)
- Call for tender for the cryomodule planned before end 2007 (INFN + CNRS)
- Most of the RF power system elements already ordered (CNRS)
- Eurotrans High power tests foreseen beginning 2009

PROBLEMS ENCOUNTERED

- None, but we have 9 months delay on the initial roadmap because of the complexity of the task



TASK 1.3.4

Objectives for the period

Achieve the RF system modelling and start of the DSP implementation study

PROGRESS ACHIEVED

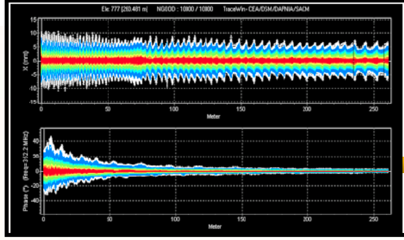
- System modelling achieved (CEA)

- First experimental test results at low temperature in a horizontal cryostat on a spoke cavity with very good stability results (CNRS)

- Investigations on an alternative solution for control (UNED)

PROBLEMS ENCOUNTERED

- None up to now



TASK 1.3.5

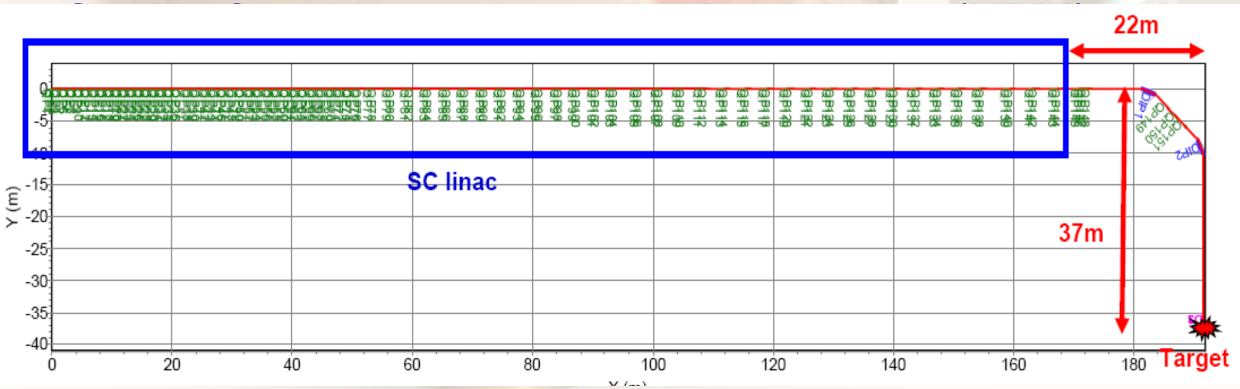
Objectives for the period

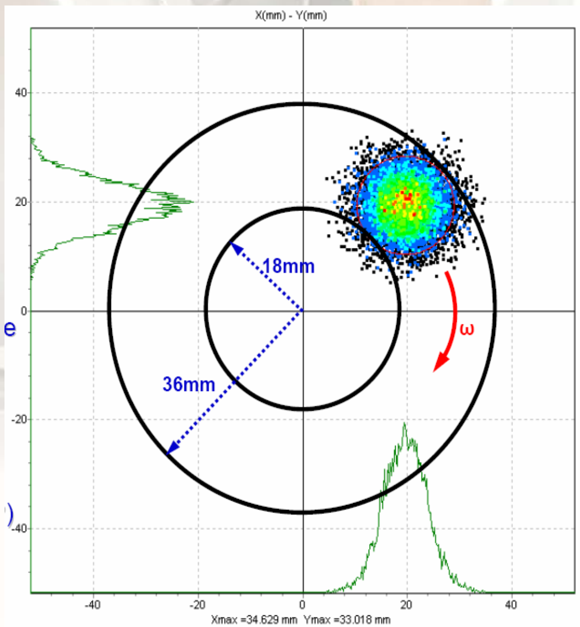
Pursue the different studies going on beam dynamics & global coherence

PROGRESS ACHIEVED

- Achievement of the beam dynamics calculations for fault-tolerance analysis (CNRS/CEA)

- Optical design of the final beam line (CNRS)





PROBLEMS ENCOUNTERED

- None