High Power CW Superconducting Linacs for EURISOL and XADS

PDS-XADS

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The EURISOL & XADS European projects

<u>EURISOL = "EURopean Isotope Separation On-Line"</u>

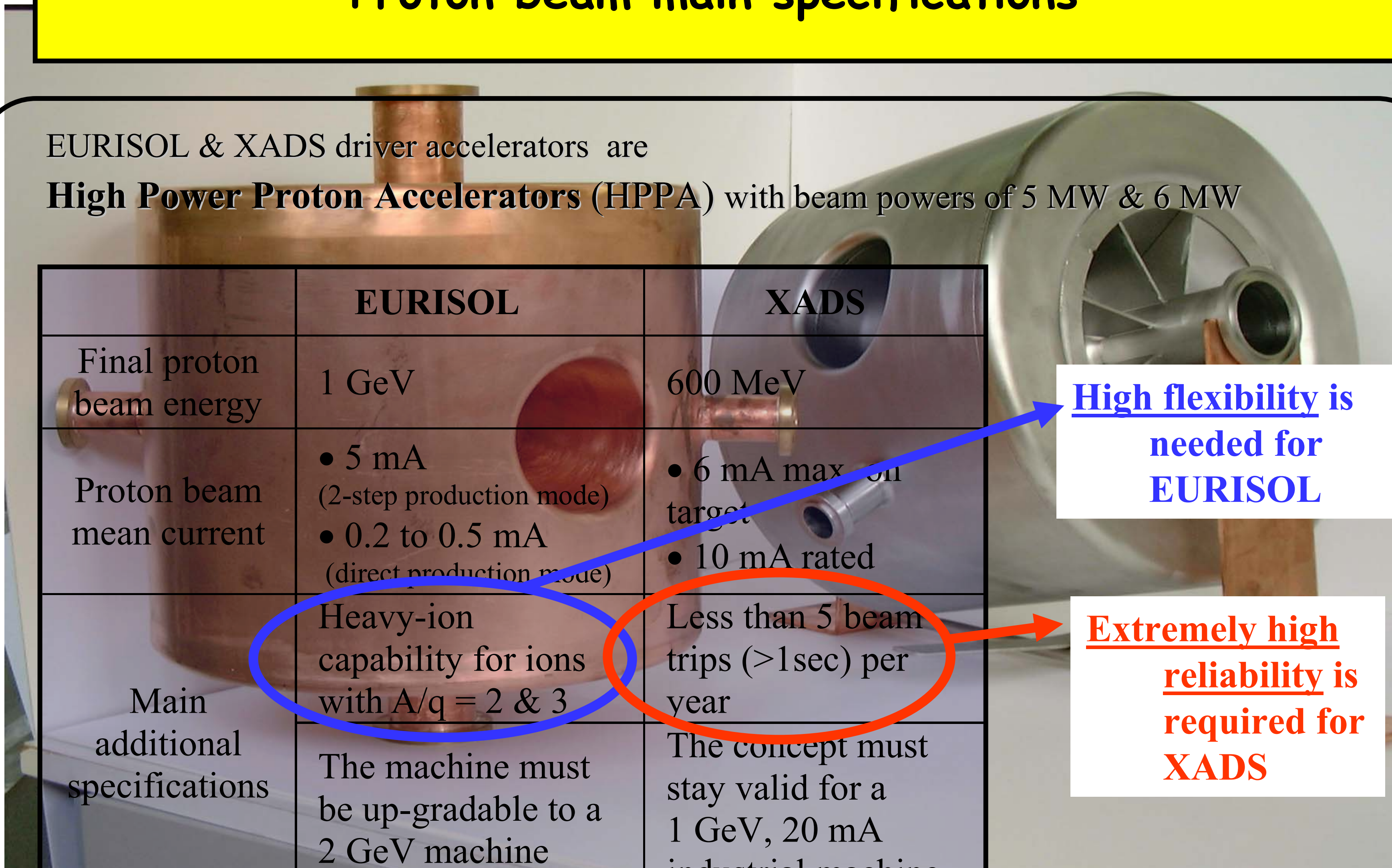
- Feasibility Study for the next generation European ISOL radioactive ion beam facility
- The 3-year Preliminary Design Study (European Commission Contract n° HPRI-CT-1999-500001) is achieved. See the "EURISOL report" (Dec. 2003) on www.ganil.fr/eurisol/
- Driver Accelerator Group = CEA Saclay, CERN, GANIL, INFN Legnaro, CNRS/IPN Orsay
- To be pursued within FP6 with the 4-year "EURISOL Design Study" (2004-2008)

PDS-XADS

<u>XADS = "eXperimental Accelerator Driven System "</u>

- Feasibility study of an experimental ADS for Nuclear Waste Transmutation
- The 3-year Preliminary Design Study (European Commission Contract n° FIKWW-CT-2001-00179) is close to the end (end = Nov. 2004)
- WP3 "Accelerator" group = Ansaldo, CEA Saclay, CNRS/IPN Orsay (coordinator), ENEA, Framatome ANP, Fram. GmbH, FZ Jülich, IBA, INFN Milano, ITN Lisboa, Univ. Frankfurt
- To be pursued within FP6 with a 4-year "EUROTRANS" IP project (2004-2008)

Proton beam main specifications



EURISOL & XADS driver accelerators are

High Power Proton Accelerators (HPPA) with beam powers of 5 MW & 6 MW

	EURISOL	**XADS**
Final proton beam energy	1 GeV	600 MeV
Proton beam mean current	• 5 mA (2-step production mode) • 0.2 to 0.5 mA (direct production mode)	• 6 mA max on target • 10 mA rated
Main additional specifications	Heavy-ion capability for ions with A/q = 2 & 3	Less than 5 beam trips (>1sec) per year
	The machine must be up-gradable to a 2 GeV machine	The concept must stay valid for a 1 GeV, 20 mA industrial machine

High flexibility is needed for EURISOL

Extremely high reliability is required for XADS

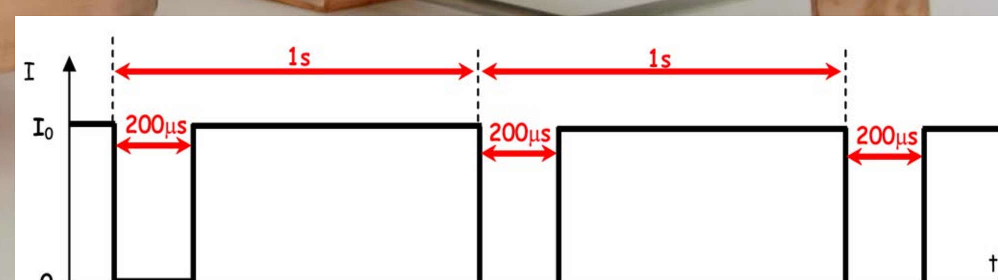
J-L. BIARROTTE, XXII Int. LINAC Conf., Lübeck, Germany, August 17th, 2004.

Proton beam time structure

- **A CW beam is favoured** to avoid thermal stresses on the ADS beam window, target and sub-critical assembly, or in the radioactivity-releasing ISOL target.
- **A "pulsed beam mode"** (sharp & short beam interruptions) is also needed:
  - in EURISOL for measurements of target release properties
  - in XADS to enable the in-line measurement of the sub-criticality level
- **A CW RF operation is preferred for the accelerator** (maximum reliability, lower R&D effort - see the EURISOL report)

A simple & natural choice is **CW accelerator + CW-based beam time structure**

… but the beam current can still be arbitrary shaped !



XADS beam time structure during normal operation

Superconducting LINAC Vs Cyclotron

Superconducting linac:

- No limitation in energy & in intensity
- Highly modular and upgradeable
- Excellent potential for reliability (fault-tolerance)
- High efficiency (optimized operation cost)

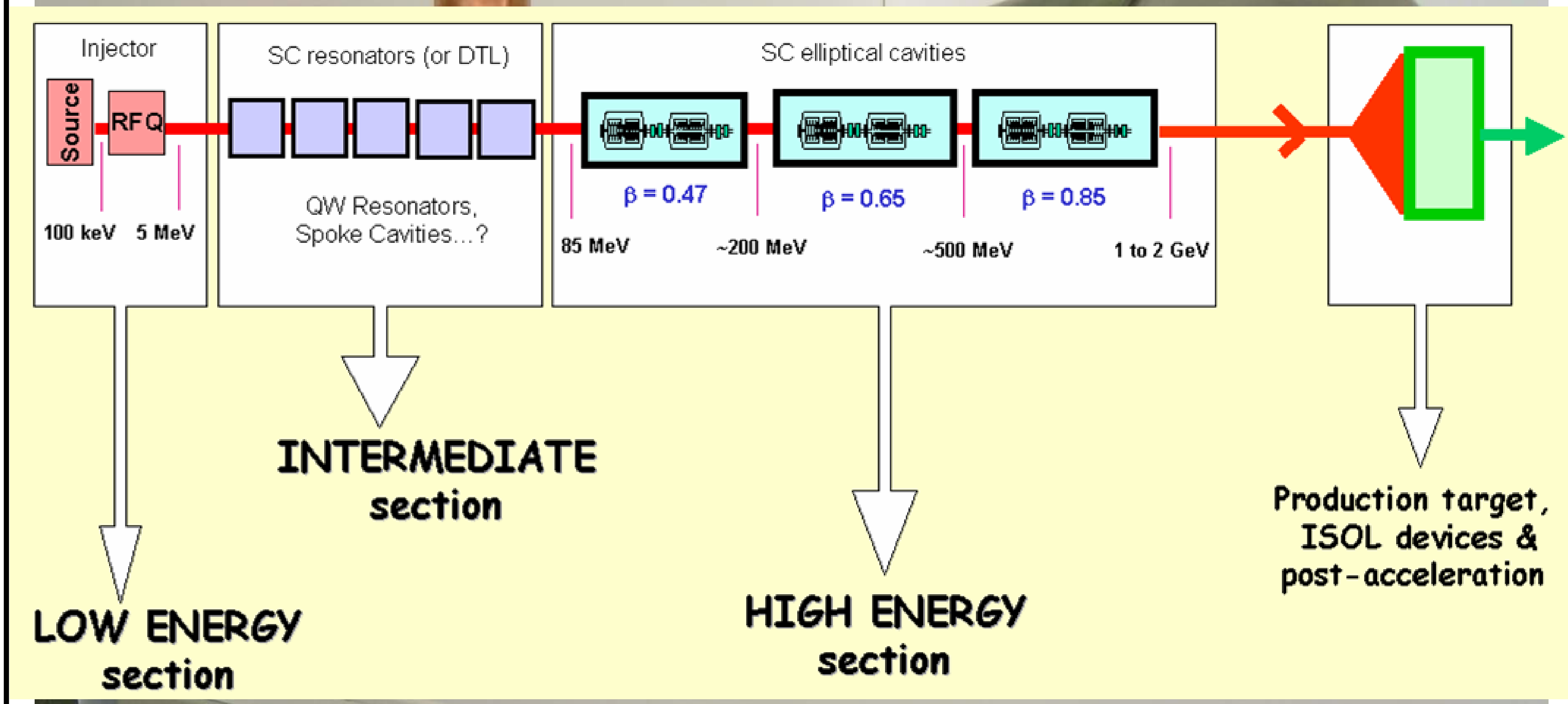
Cyclotron:

- 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.*

General layout of a SC high power proton LINAC



Layout of the EURISOL proton linac

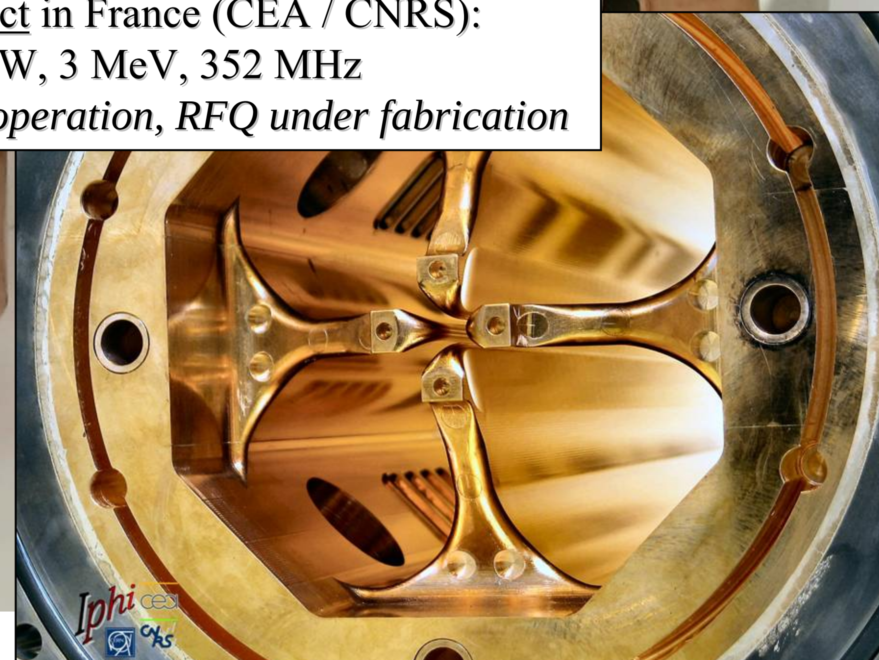
The low-energy section (the injector)

High-intensity proton injectors are quite straightforward: ECR source + RFQ

<u>TRASCO project</u> in Italy (INFN):
30 mA CW, 5 MeV, 352 MHz
source in operation, RFQ under fabrication

<u>LEDA project</u> at Los Alamos:
100 mA CW, 6.7 MeV, 350 MHz
in full operation (now stopped)

<u>IPHI project</u> in France (CEA / CNRS):
100 mA CW, 3 MeV, 352 MHz
source in operation, RFQ under fabrication

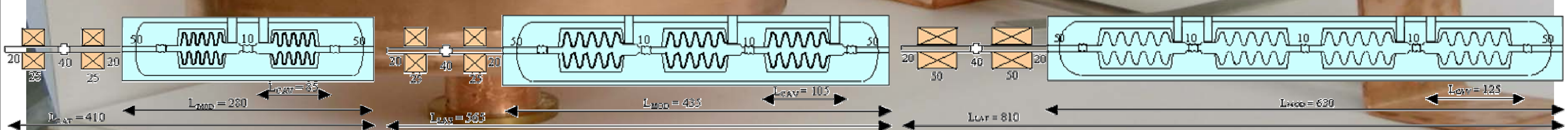


The high-energy section (1)

General agreement for using **SC multi-cell elliptical cavities** @700 MHz:

- High performance (high gradients, high efficiency, security, reliability…)
- "Well-established" solution (TTF, SNS…)
- Comfortable margins can be chosen on critical values to ensure a design as robust as possible: it consists in limiting, in a reasonable way, the minimum beam apertures, the fields in the cavities, the phase advances along the linac, the sensibility to beam mismatch, or the possibility of halo creation.

EURISOL high-energy section:



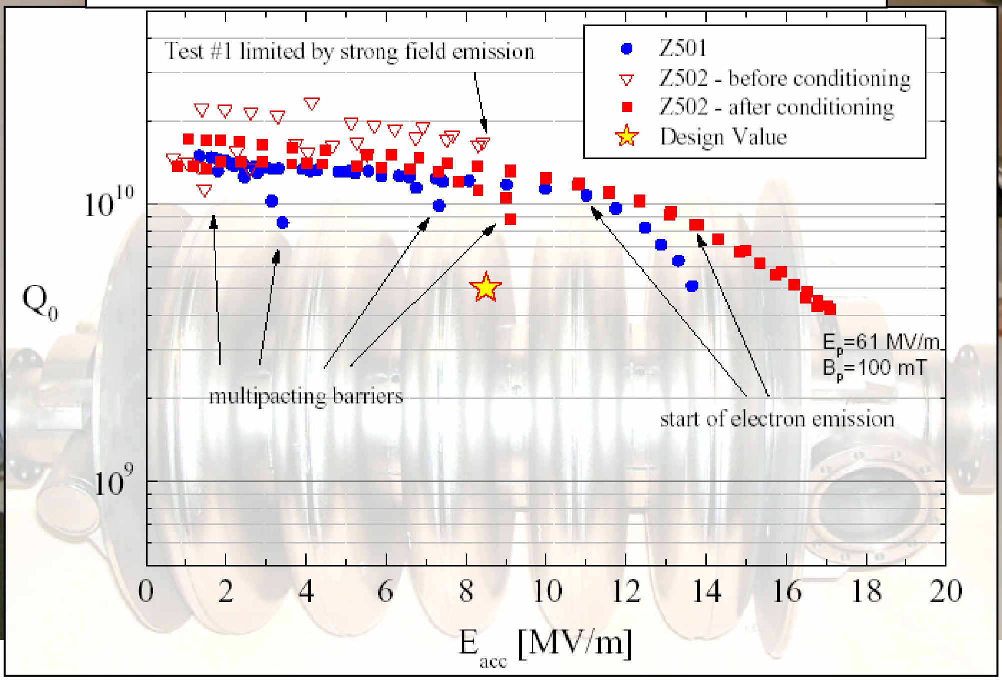
β=0.5 (85-192 MeV), β=0.65 (192-481 MeV) & β=0.85 (481 MeV – 1 or 2 GeV) lattices

(15 modules / 62 m) (16 modules / 90 m) (14 or 39 modules / 113 or 316 m)

The high-energy section (2)

Active R&D and prototyping are going on successfully at CEA Saclay, CNRS / IPN Orsay & INFN Milano

Test results @2K of 5-cell β=0.5 prototypes (INFN Milano)



A 5-cell
(CEA Sa

The intermediate section

Two concepts have been retained:

1. Extend the injector philosophy towards high energies using **DTL-type structures**
2. Extend the high-energy SC linac philosophy towards low energies using **low-beta superconducting resonators**

<u>The SC cavities solution</u> <u>as compared to</u> **<u>a room-temperature DTL solution</u>**

- Roughly same length & construction cost
- Excellent “RF to beam” efficiency

  => **Significant operation cost savings (7 MW AC, i.e. 2M€/year for EURISOL)**
- Very large beam aperture => **High safety** (less structure activation)
- Independant RF structures => **High flexibility** (power adjustments, heavy-ion acceleration)

  => **High reliability** (low power RF components, fault tolerance capability)
- **Poor real estate gradient at very low energies** (< 20 MeV)

The EURISOL intermediate section

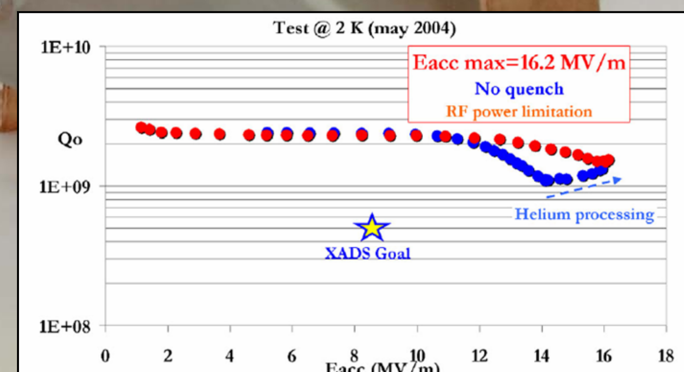
- **The independently-phased SC option is preferred,** especially because it allows to fullfill **the heavy-ion capability requirement** (e.g. 500 MeV/u for A/q=2 ions): small number of gaps + independent phasing = large ion velocity acceptance !
- Two different preliminary designs have been proposed for the 5-85 MeV section:
  - 1 using 352 MHz re-entrant (or 4-gap ladder) cavities and HWR (INFN Legnaro)
  - 1 using 352 MHz spoke cavities (CNRS / IPN Orsay)

352 MHz prototyping for the EURISOL intermediate section (INFN Legnaro, CNRS / IPN Orsay)

The XADS intermediate section

- **The independently-phased SC option** is agreed from at least 50 MeV, especially because of it allows to implement the **fault-tolerance concept** *(see later)*
- **352 MHz β=0.35 spoke cavities,** developed by CNRS / IPN Orsay, are used in this region (high shunt impedance, good mechanical stability & tunability, no steering effect, possibility to design multi-gap structures if needed, excellent test results)
- Between 5 MeV and 20 MeV, the β=0.15 spoke solution is not so efficient in terms of real estate gradient; DTL-type solutions are explored: **room-temperature IH-DTL structure**, developed by IBA, & **superconducting CH-DTL structure**, developed by IAP Frankfurt

Prototyping on SC CH-DTL & IH-DTL (U.Fra & IBA)



Test result on a spoke cavity (IPN Orsay)

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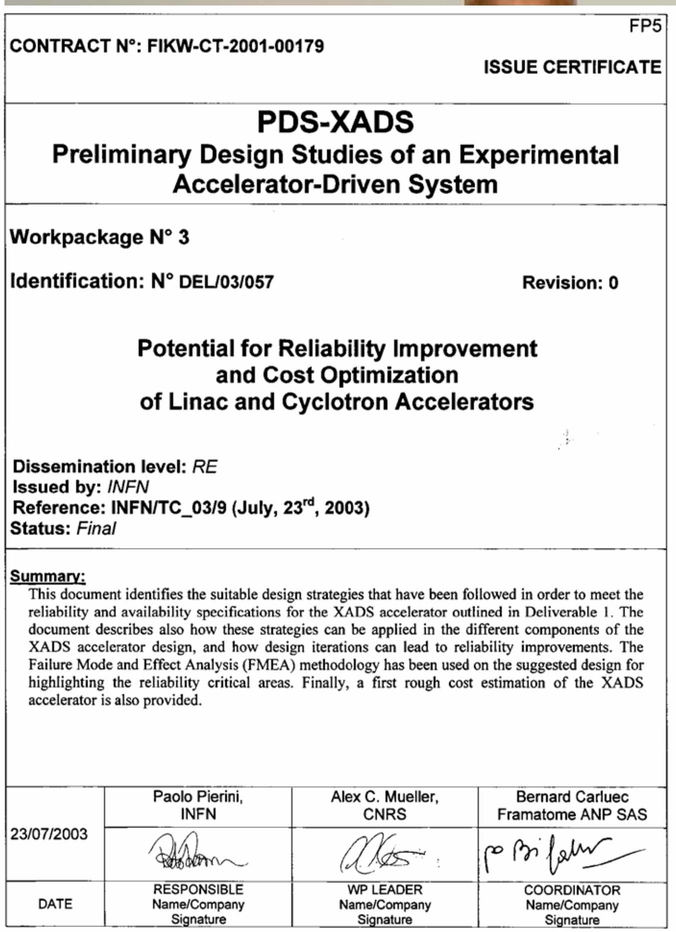
The XADS reliability analysis



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.

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

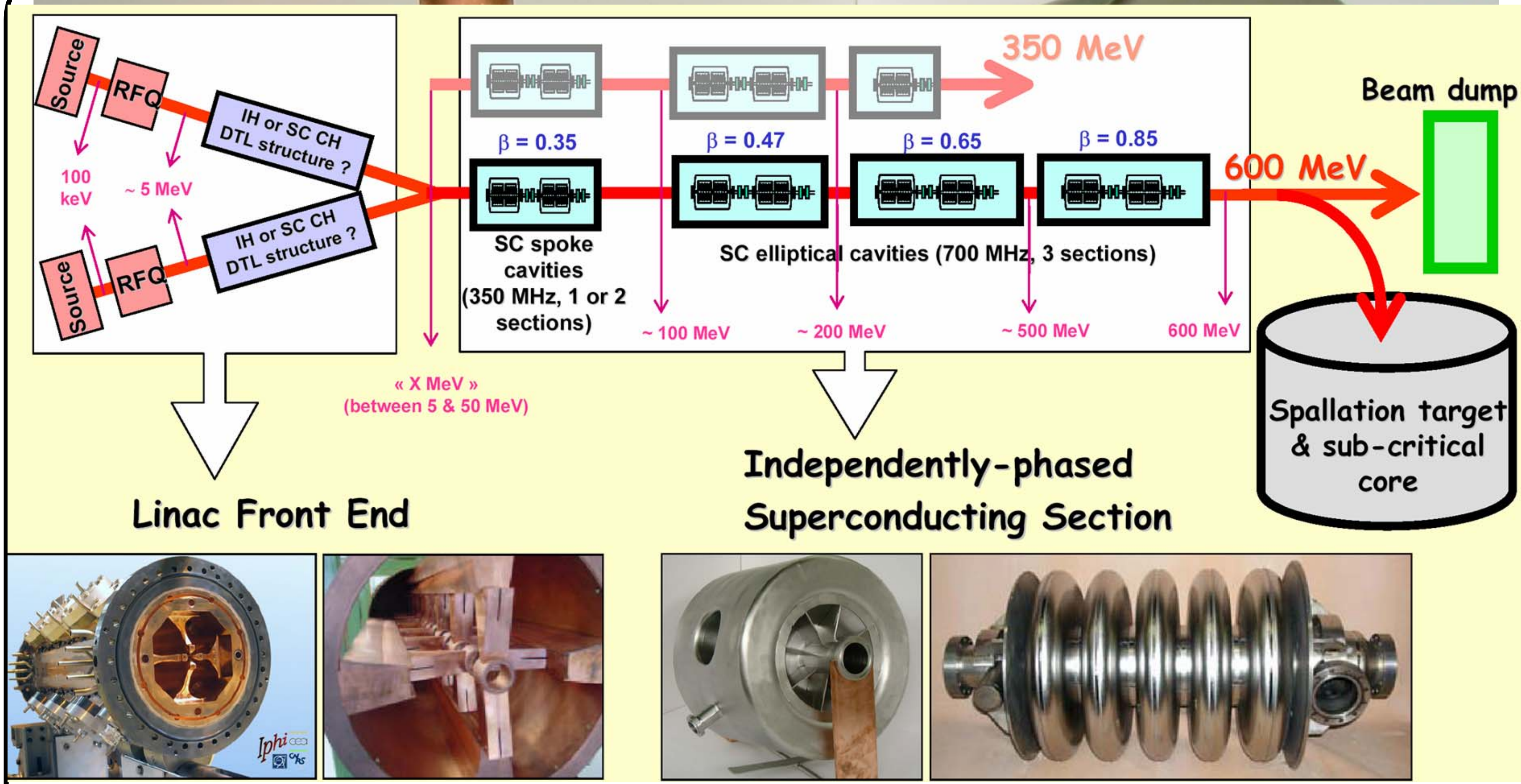
Main conclusions of the reliability analysis performed within the XADS project

- 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 a key element in order to guarantee reliability by design and operation (as an example, several tens of RF failure are foreseen per year …)

The XADS accelerator, optimized for reliability



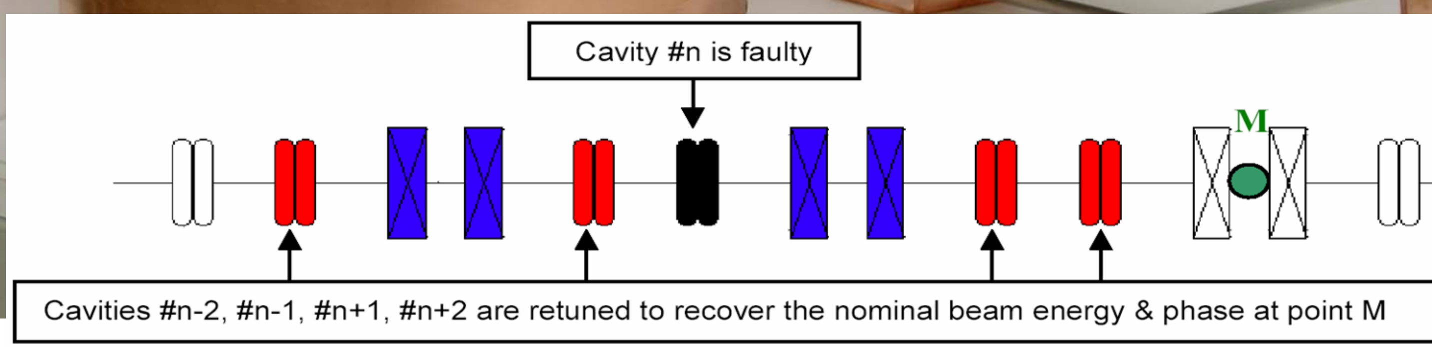
Fault tolerance calculations for XADS (1)

Fault tolerance = ability to loose a cavity or a Q-pole on line without loosing the beam

- **A systematic study** has been performed to analyse the fault tolerance capability of the XADS SC linac (5 – 600 MeV)

SC linac sections	Energy range	Nb of cavities
Spoke 2-gap, 352.2 MHz, β=0.15 (~30 metres)	5 - 17 MeV	36 (2 per lattice)
Spoke 2-gap 352.2 MHz, β=0.35 (~50 meters)	17 - 91 MeV	63 (3 per lattice)
Elliptical 5-gap, 704.4 MHz, β=0.47 (~60 meters)	91 - 192 MeV	28 (2 per lattice)
Elliptical 5-gap, 704.4 MHz, β=0.65 (~100 meters)	192 - 498 MeV	51 (3 per lattice)
Elliptical 6-gap, 704.4 MHz, β=0.85 (~25 meters)	498 - 615 MeV	12 (4 per lattice)

- The **“local compensation method”** has been used



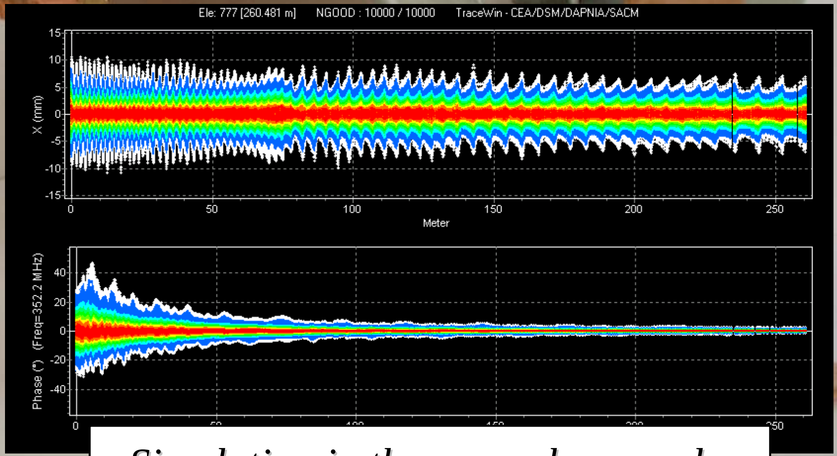
Fault tolerance calculations for XADS (2)

- The conclusion of the study is that in every case, **with an appropriate retuning, the beam can be transported up to the high energy end without any beam loss** (100 % transmission, reasonable emittance growth), and within the nominal target parameters. It is also recommended to switch off the whole quadrupole doublet if one quadrupole fails.

- An adequate fast LLRF control system is required, margins of at least 30% are needed on the Eacc operating point of the cavities, and the energy gain per resonator can not be too high

# faulty cavity	section	Final energy	Emittance growth (%)		Number of retuned cavities (before + after)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	Nb of retuned quads (before + after)
			Transv.	Long.					
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	Nomi							
146	EL 0.65	Nomi							
147	EL 0.65	Nomi							
148	EL 0.65	Nomi							
172	EL 0.65	Nomi							

Sample of the retuning values for each cavity failure



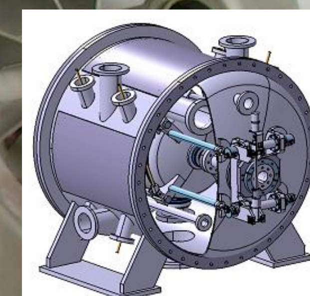
Simulation in the case where spoke cavity #4 is lost (5.5 MeV), and proper retuning is performed

R&D for the FP6 (2004-2008)

● Prototyping for the intermediate energy section (5 MeV – 100 MeV)

- Construction and test of HWR, ladder resonators (INFN Legnaro), of spoke cavities (IPN Orsay), of a SC CH-DTL (IAP Frankfurt), of a normal conducting IH-DTL (IBA), and of their associated equipments (coupler, tuner, cryostat, LLRF system...)

- Qualification of the reliability of these different components



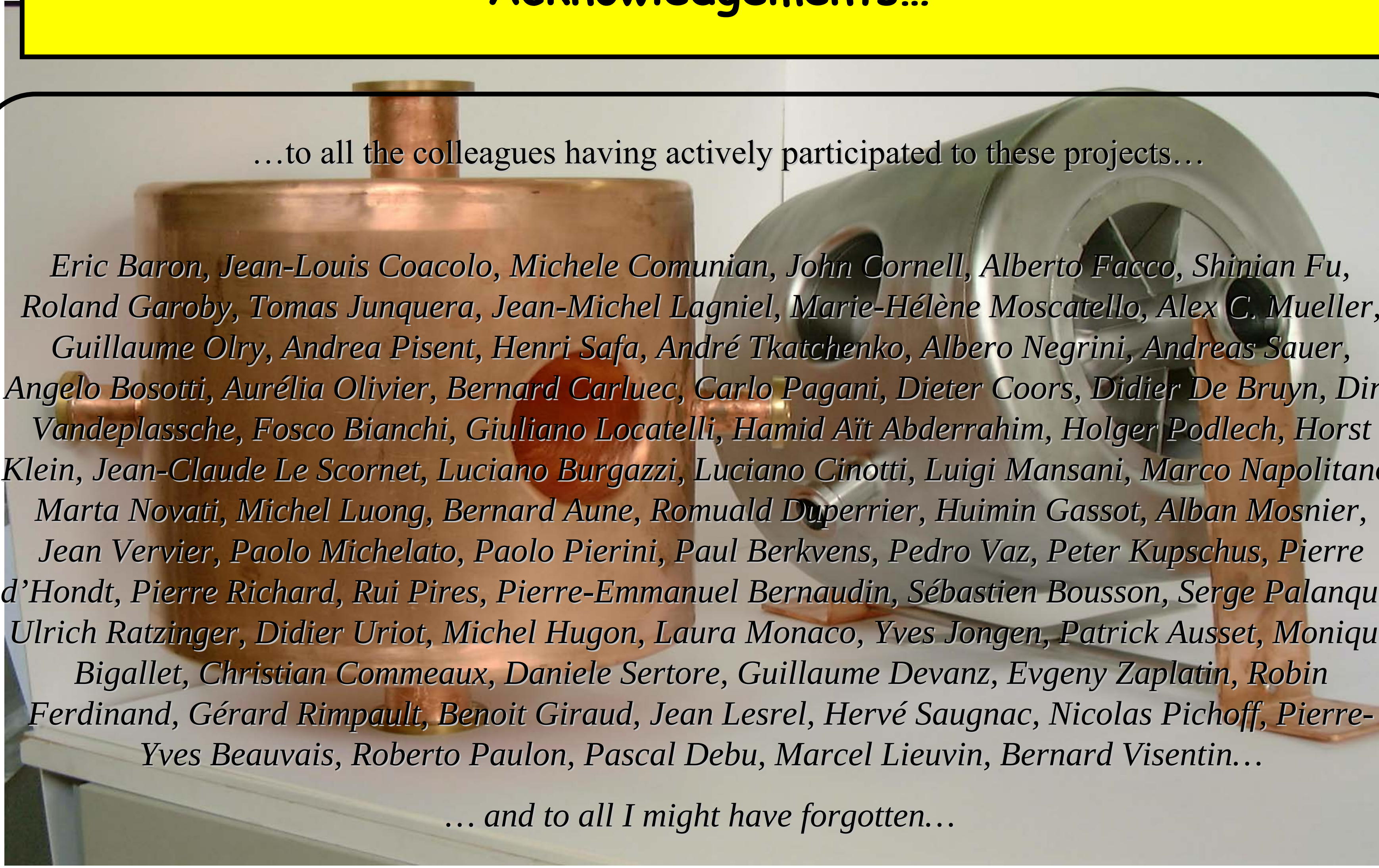
● R&D focused on reliability

- Long test run of the 3 MeV, 100 mA accelerator IPHI @ CEA Saclay

- Construction & test, by INFN Milano and IPN Orsay, of a complete elliptical cryomodule with all subsystems running at rated power and nominal temperature

- Development of a fast LLRF system adapted to fault tolerance, able to handle beam trips as quickly as possible using the local compensation method.

This R&D program should finally lead to a frozen design of the XADS and EURISOL linacs, with assessed reliability and costing



Acknowledgements…

…to all the colleagues having actively participated to these projects…

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… and to all I might have forgotten…