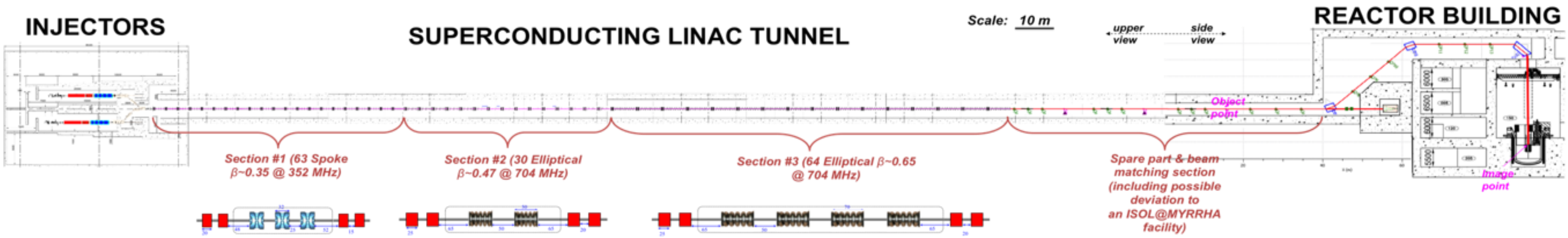
MYRRHA

Multipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications



MYRRHA: a polyvalent research project around an ADS nuclear reactor

The 600 MeV, 2.4 MW superconducting proton LINAC

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

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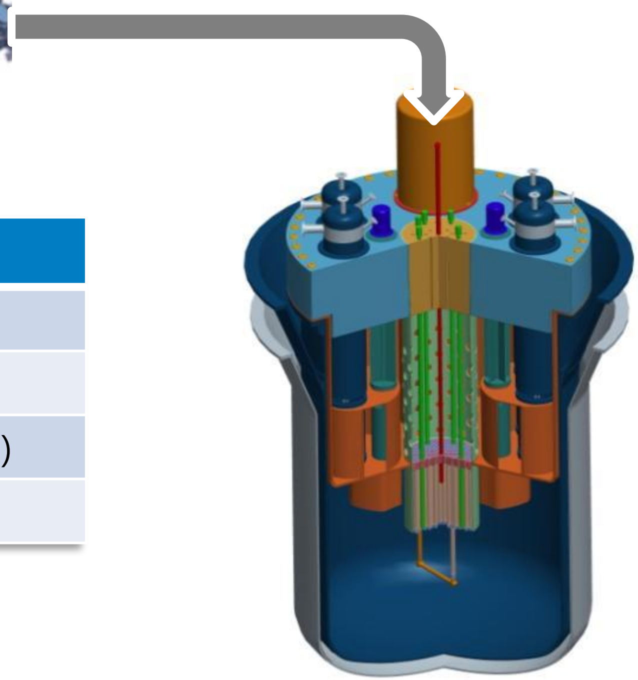
NSP - SCK•CEN

MYRRHA - Accelerator Driven System

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA
mode	CW
MTBF	> 250 h

Reactor	
power	~85 MW_{th}
k_{eff}	0.955
spectrum	fast (flexible)
fuel	high-enriched MOX
coolant	LBE

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)
power	2.4 MW



MYRRHA accelerator: background...

- **90's**: collaborative R&D activities worldwide on ADS accelerators
  (Energy Amplifier, TRASCO)
- **2001**: "The European roadmap for developing ADS for Nuclear Waste Incineration", European Technical Working Group on ADS *(chaired by C. Rubbia, ENEA)*
- **2002**: pre-design "**MYRRHA Draft 1**" *(cyclotron 350 MeV)*
- **2002-2004:** MYRRHA is studied as one of the 3 reactor designs within the **PDS-XADS FP5 project** (coord. Framatome/AREVA)
  (cyclotron turns into linac, first reliability analyses show a need for fault-tolerance capability)

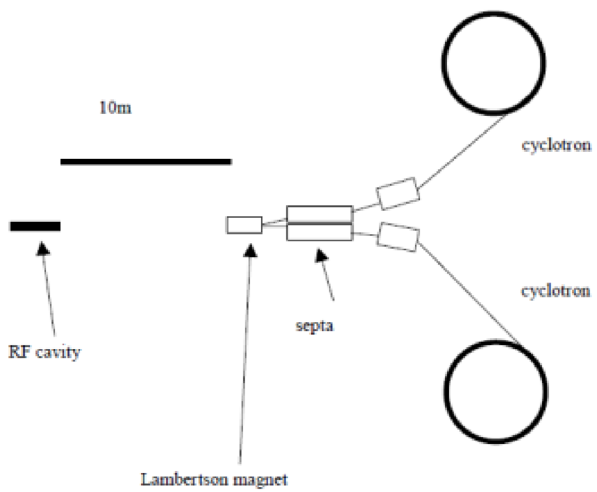


Figure 40 – Overall Layout for the Cyclotron XADS option.

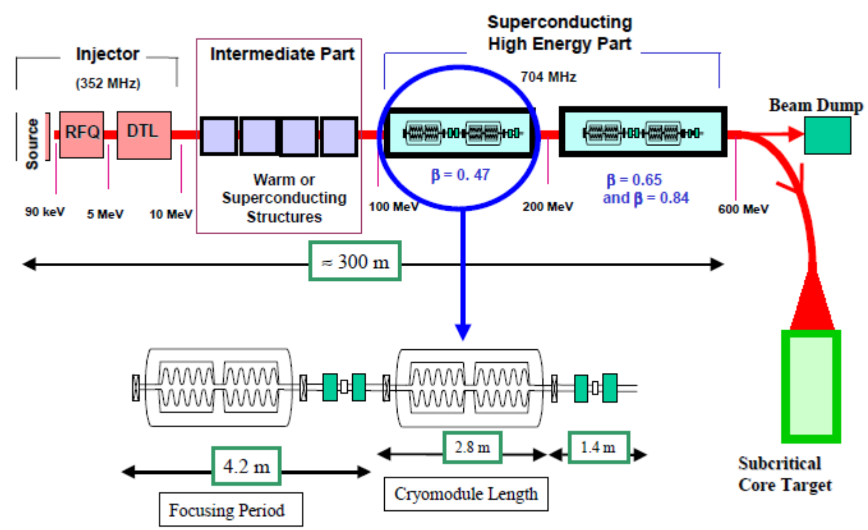
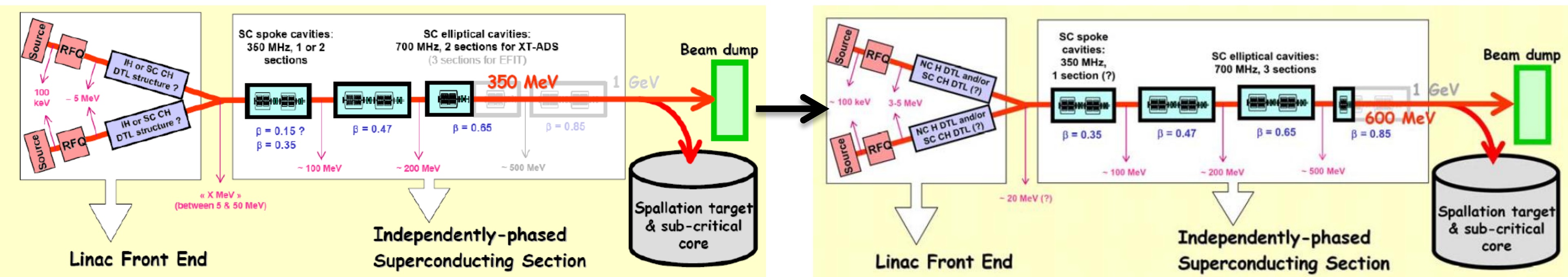


Figure 1 – Schematic layout of the XADS accelerator in the linac option.

MYRRHA accelerator: background…

- **2005**: updated pre-design "**MYRRHA Draft 2**" *(linac 350 MeV)*
- **2005-2010:** MYRRHA is studied as the XT-ADS demo within the **EUROTRANS FP6 project** (coord. FZK)
  (600 MeV linac conceptual design, R&D activities w/ focus on reliability)



- **2010:** MYRRHA is on the ESFRI list, and officially supported by the Belgium government at a 40% level *(384M€, w/ 60M€ already engaged)*
- **2010-2014:** MYRRHA accelerator advanced design phase w/ support from the **EURATOM FP7 projects** *(CDT, FREYA, MAX especially)*

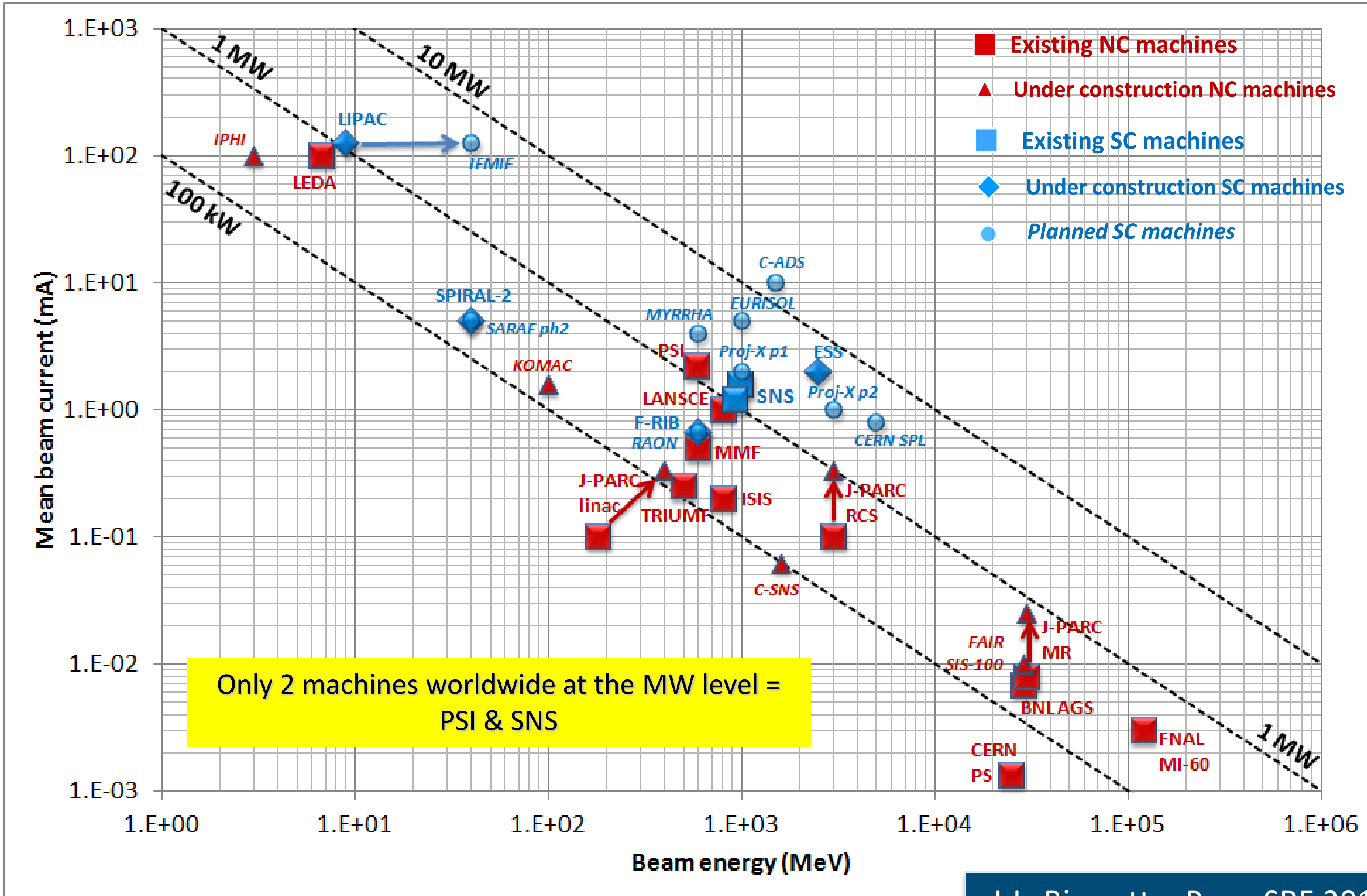
MYRRHA Accelerator: current characteristics

High power proton beam (up to 2.4 MW)

Proton energy	600 MeV
Beam current	0.1 to 4.0 mA
Repetition rate	CW, 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
Beam footprint on reactor window	Circular ∅85mm
Beam footprint stability	< ± 10% on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

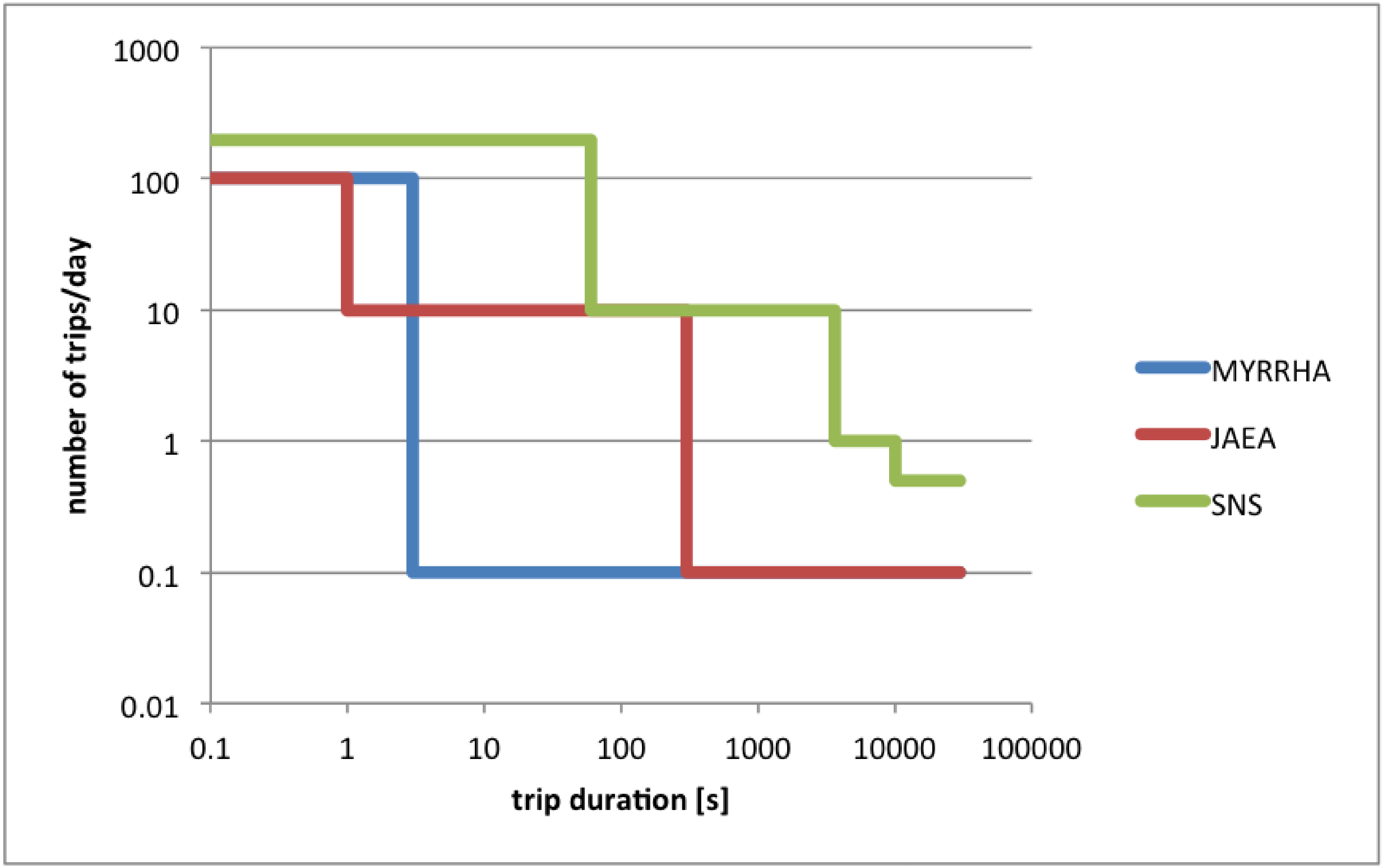
Extreme reliability level: MTBF > 250 hrs

Beam power: comparison



J-L. Biarrotte, Proc. SRF 2013

Beam trips rate: comparison



D. Vandeplassche, Proc. IPAC 2012

MYRRHA Accelerator: design key-points

- *Reliable*: extremely high Mean Time Between Failures (MTBF) > 250 hrs
- *Continuous*: CW beam delivery
- *Powerful*: 1 to 4 mA beam current, high power

"It's not that I'm so smart, it's just that I stay with problems longer."

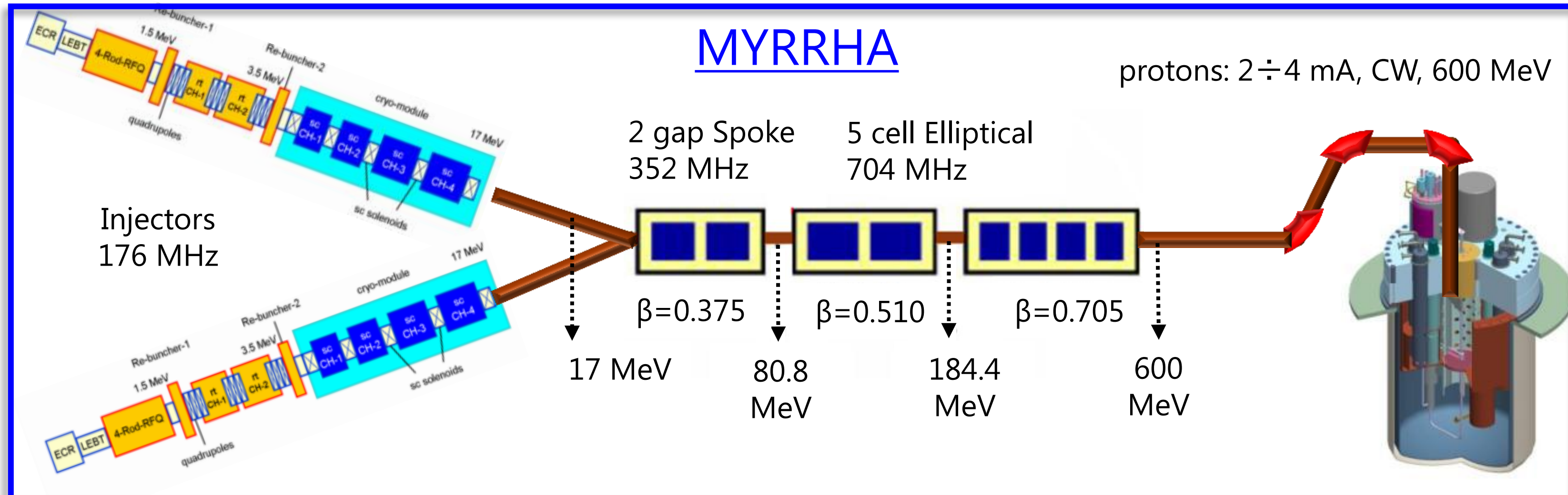
A. Einstein

- **Superconductivity**:
  - access to large accelerating gradients (operation margins)
  - large beam apertures with small losses
  - lower power consumption in CW
  - high beam current handling
  - compact machine

D. Vandeplassche, Proc. IPAC 2011

- **Fault Tolerance**:
  - Solid design: robust optics, use components far from their technological limits, modularity
    - Solid State (SS) RF amplifiers
    - Modular DC power supplies
    - Digital Low Level RF (LLRF) control
  - Redundancy, with
    - Parallel scheme in the injector: frozen optics
    - Serial scheme in the High Energy LINAC: modular structures
  - Reparability (short MTTR) to guarantee high availability

MYRRHA Accelerator: design choices and machine layout



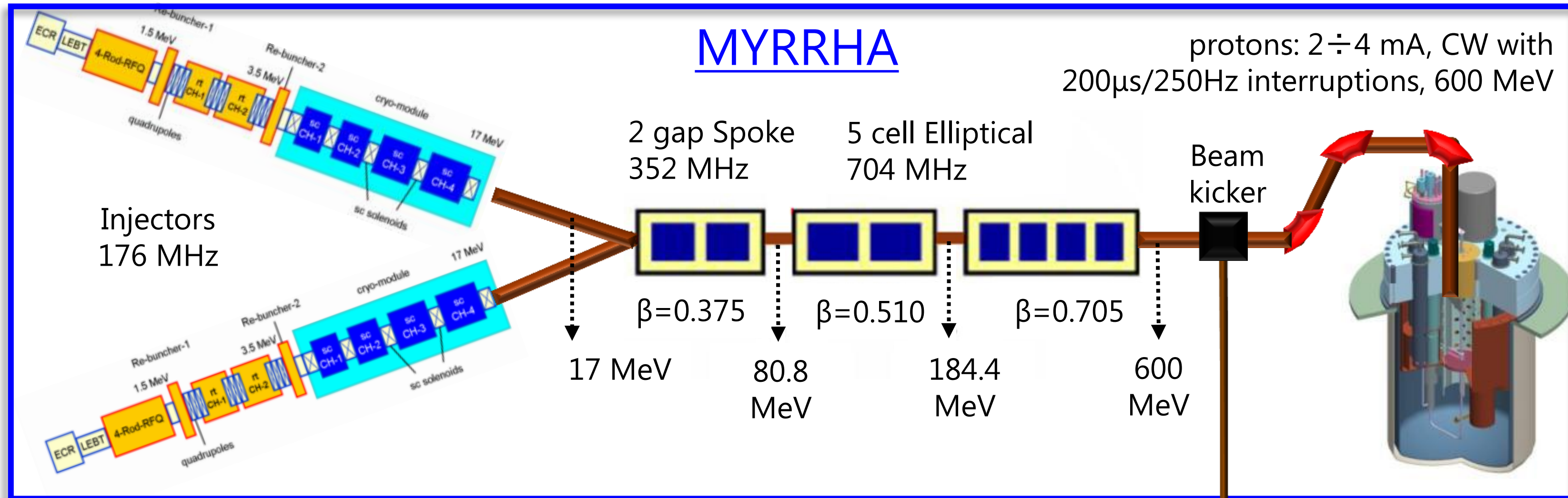
- Doubled Injector, multicell structures, up to 17 MeV @ 176.1 MHz:
  - ECR ion source, 30 keV
  - LEBT
  - 4-rod RFQ, 1.5 MeV
  - RT-CH, 3.5 MeV
  - SC-CH, 17 MeV

- Superconducting LINAC, modular, individually controlled cavities, warm quadrupoles doublets and diagnostics:

E_{in} [MeV]	*Cavity*	f_{RF} [MHz]	β	$\frac{cav.}{CM}$	*n. CM*	E_{out} [MeV]
17.0	spoke	352.2	0.375	2	24	80.8
80.8	elliptical	704.4	0.510	2	17	184.4
184.4	elliptical	704.4	0.705	4	15	600.0

CM: Cryomodule; $\beta = v/c$: cavity geom. value

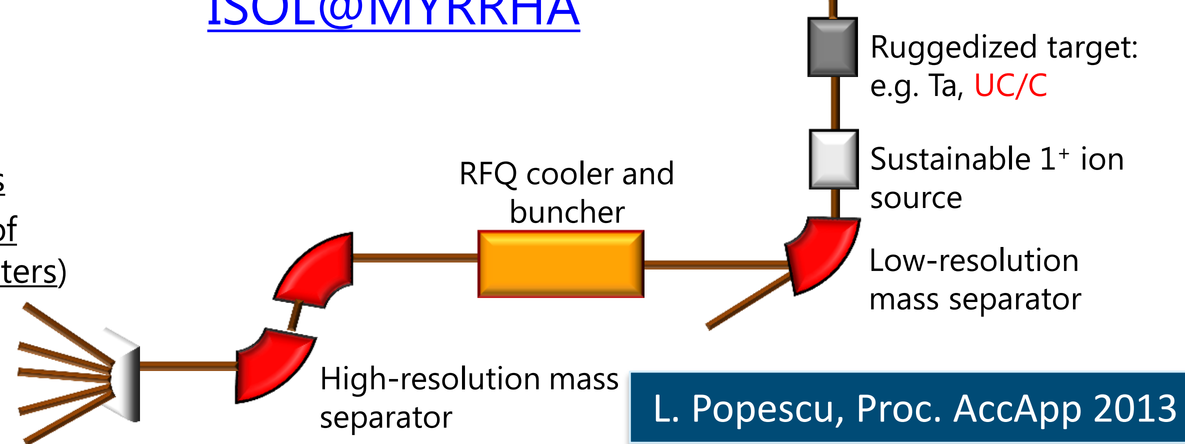
MYRRHA + ISOL@MYRRHA



ISOL@MYRRHA

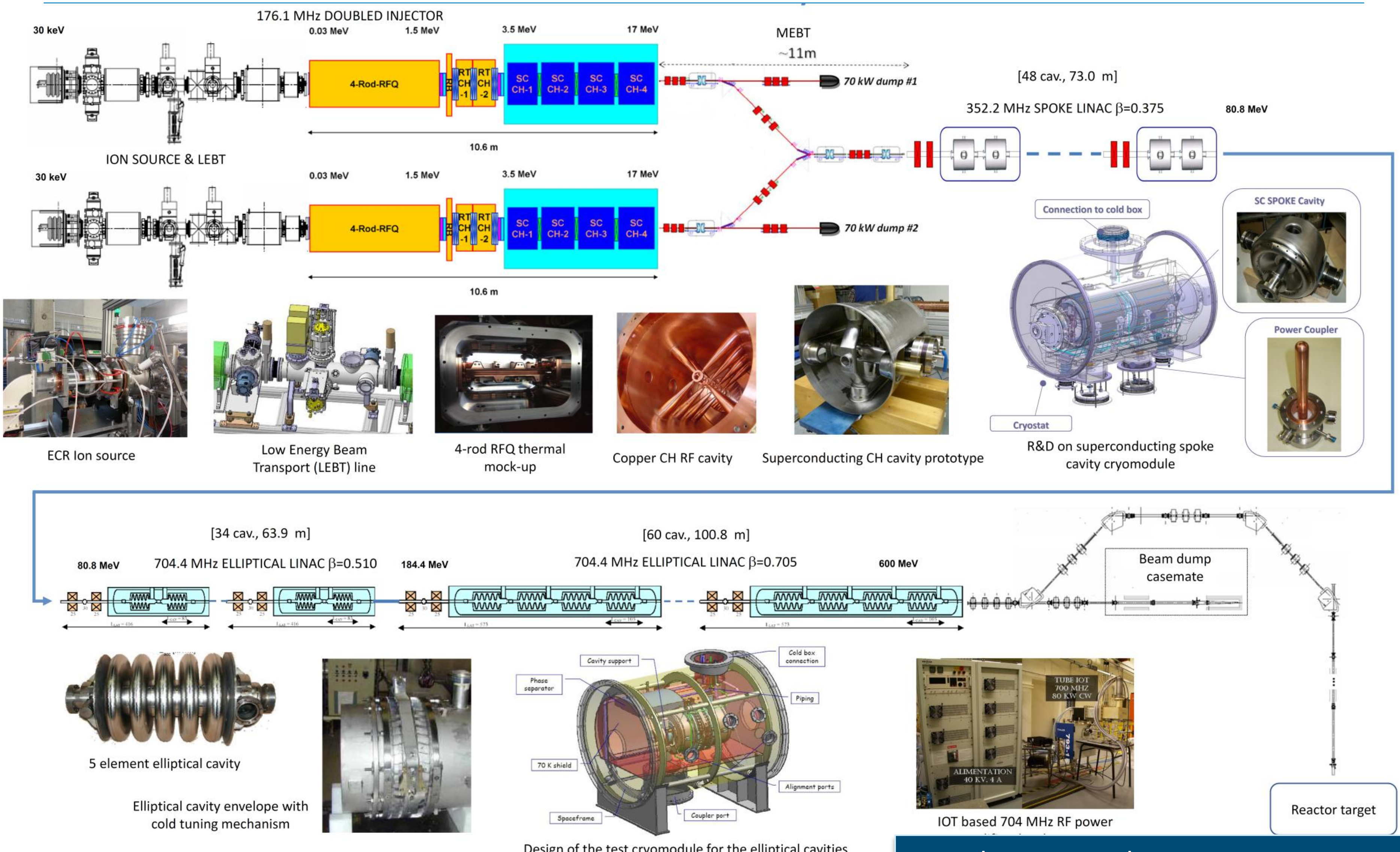
Experiments:

- nuclear physics
- condensed matter
- atomic physics
- fundamental Interactions
- life science (production of radioisotopes alpha emitters)



L. Popescu, Proc. AccApp 2013

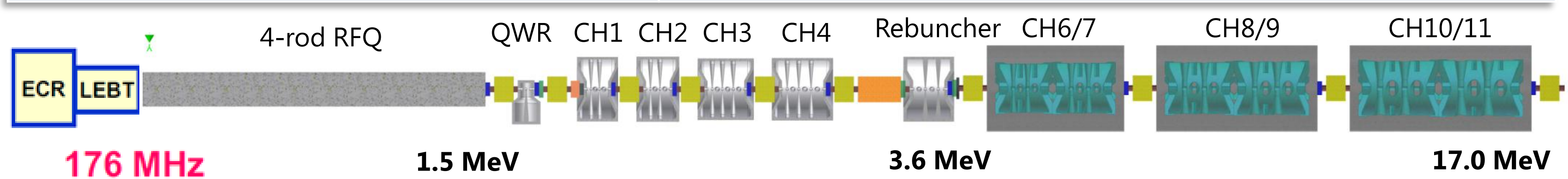
MYRRHA Linear Accelerator: R&D fields



R. Salemme et al., Proc. AccApp 2013

R&D line – Injector@UCL

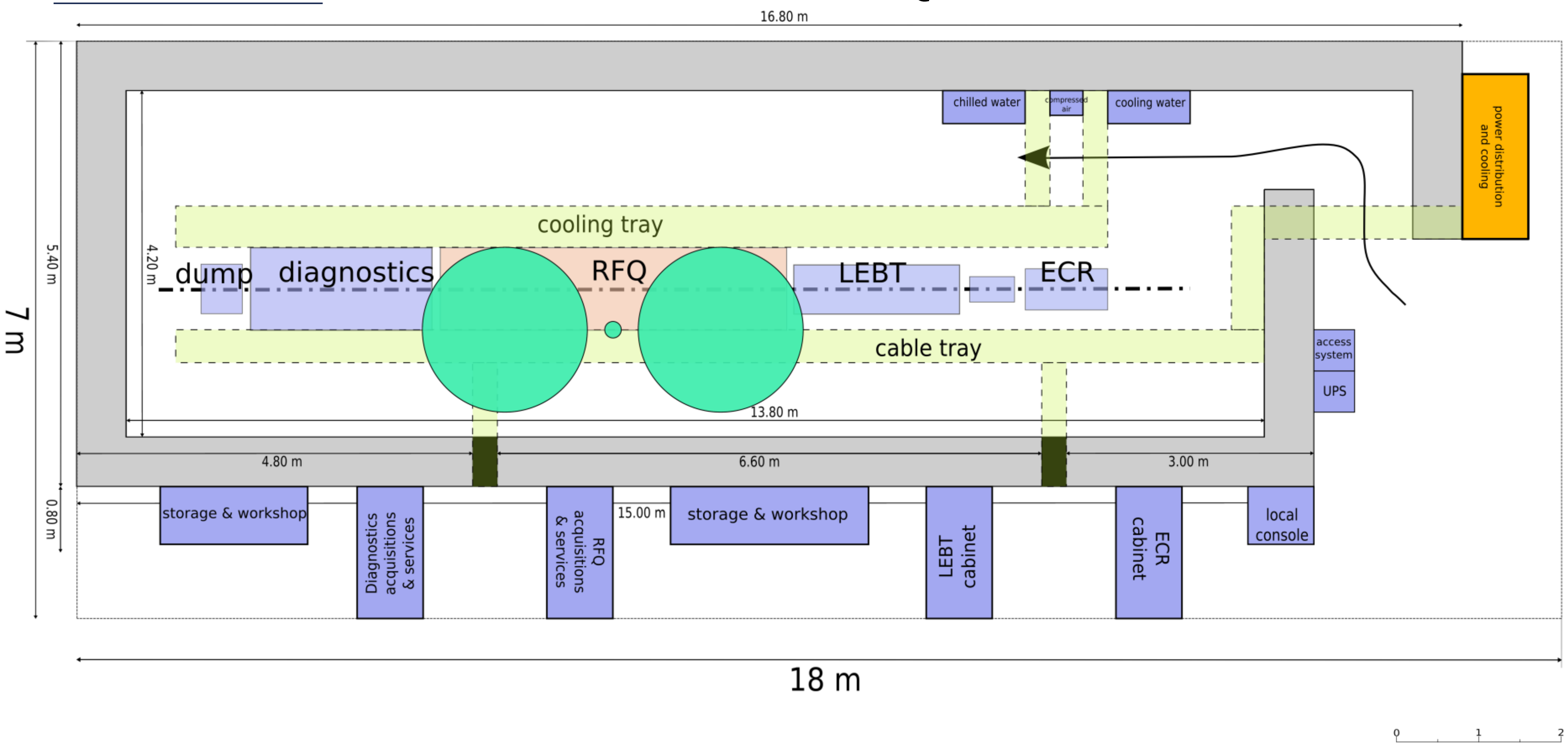
INJECTOR@UCL	
Up to 2014 and beyond - led by SCK•CEN	
Goals	• Test platform: experimentally address the injector design though prototyping • tool for relevant reliability minded experience
Main topics: • Beam characterization • CW operation of the 4-rod RFQ • SS RF amplifier @ 176.1 MHz–160kW • Diagnostics for high current beams • 3-tier Control System • Long reliability runs	Principal partners: • MAX Collaboration (especially WP1 and WP2) • research institutes: IPNO, LPSC, IAP, UCL/CRC, soon CERN • industries: Pantechnik, Cosylab



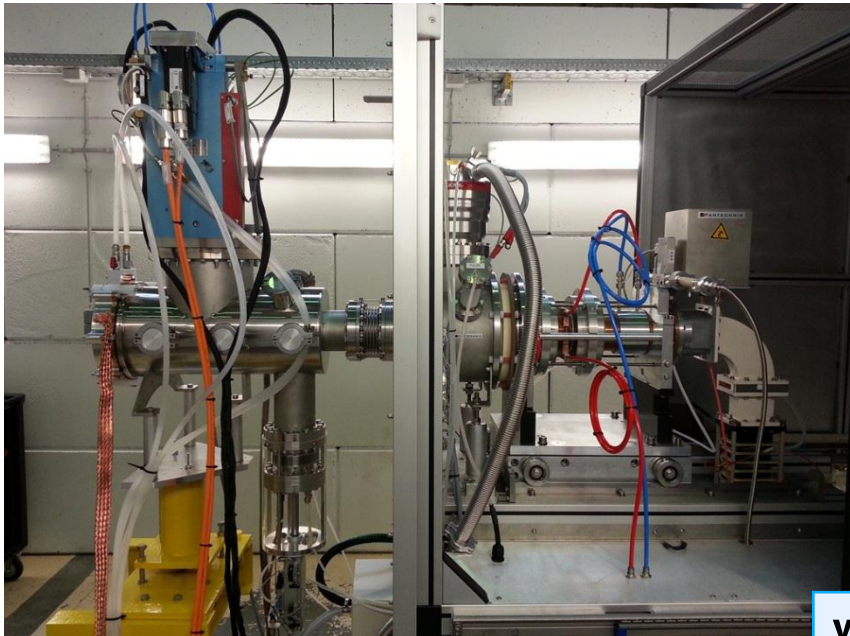
UCL Université catholique de Louvain

General layout of the experimental test stand in UCL/Centre de Ressources du Cyclotron (CRC) at Louvain-la-Neuve, Belgium:

RFQ@UCL



The ECR proton source

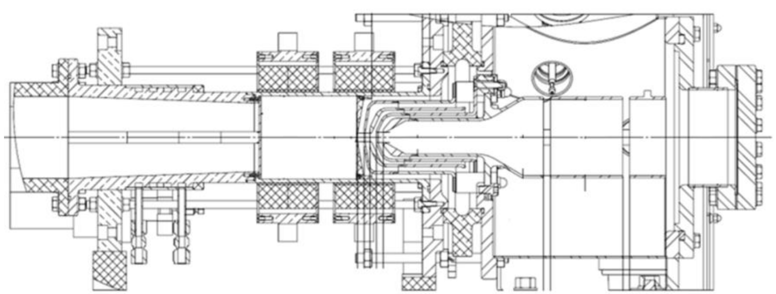


PANTECHNIK

Monogan 1000

ECR Ion souce – 30keV, 20mA

- Electron Cyclotron Resonance, 2.45 GHz
- multi-electrodes extraction system
- flat magnetic profile configuration by PMs
- tapered axial RF injection
- Einzel electrostatic focusing lens



voltage	**30 kV** (40 kV capable)
beam current	20 mA DC
RF	2.45 GHz, 1200 W
transverse emittance @ 5 mA	**0.1 π·mm·mrad RMS norm.**
magnetic system	Permanent Magnets
autonomous control system	NI CompactRIO
provisions for reliability/repairability	
beam diagnostics devices incl.: Faraday Cup, Allison scanner	

The Low Energy Beam Transport (LEBT) line

LPSC Grenoble 30 keV magnetic LEBT

2-axis collimation slits

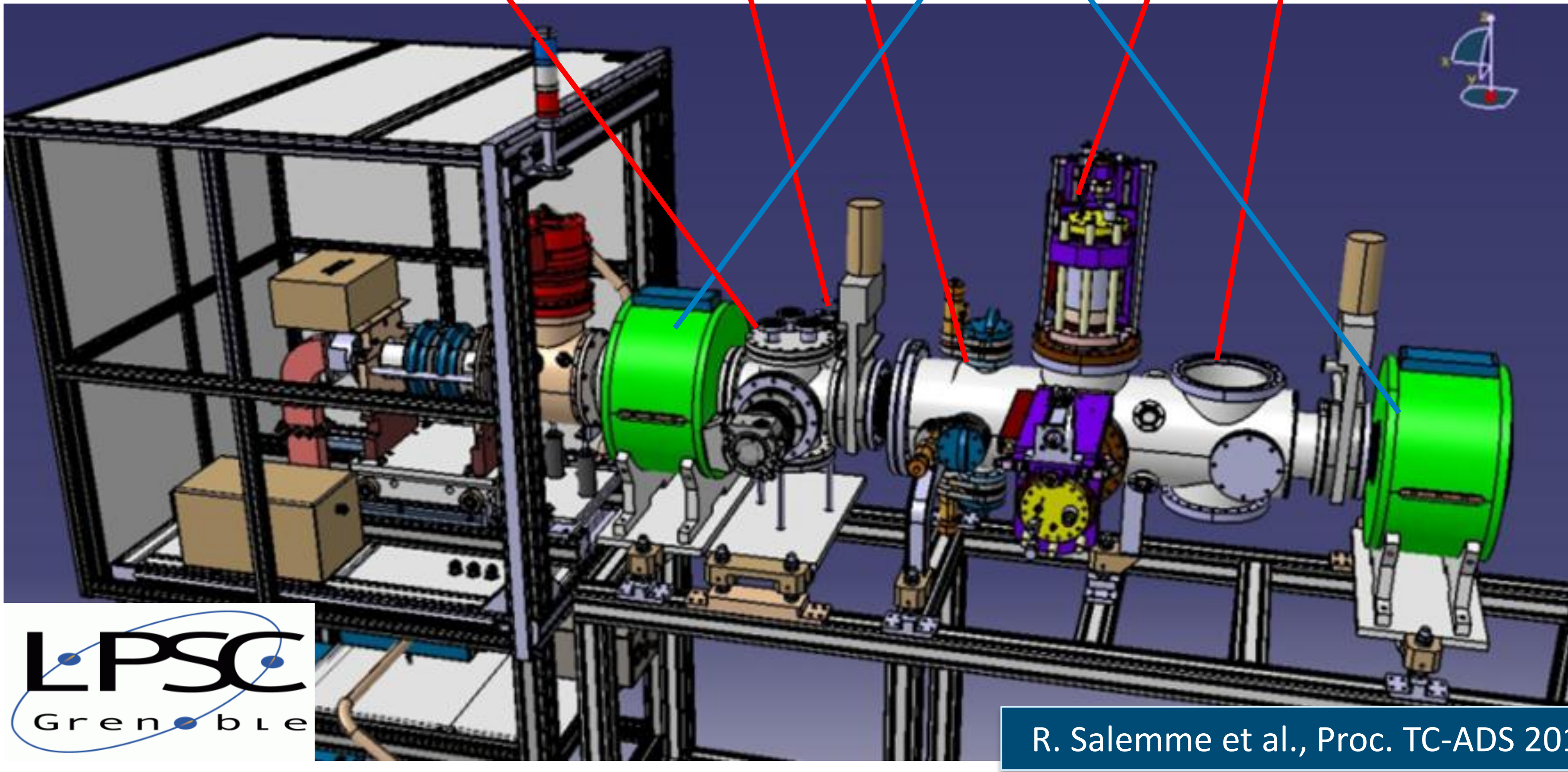
Solenoids + H/V steerers

Allison scanners and beam profiler

Gas injection ports

Faraday cup

Beam chopper back-up port



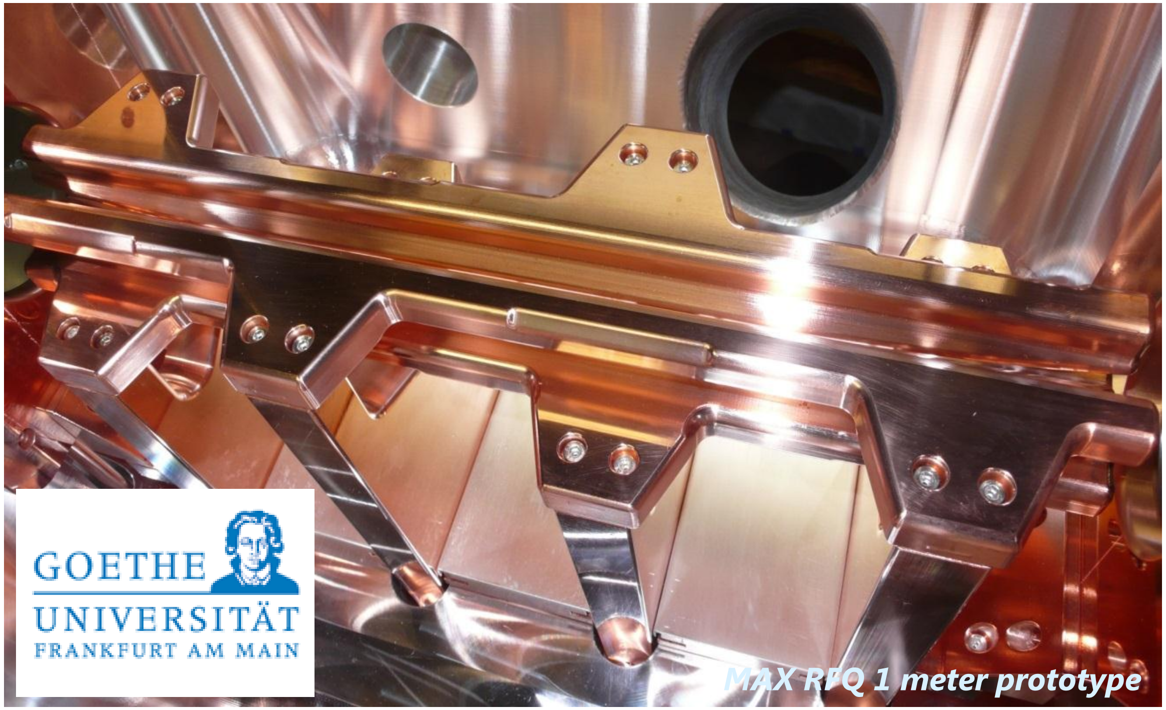
R. Salemme et al., Proc. TC-ADS 2013

The 4-rod 176 MHz CW RFQ

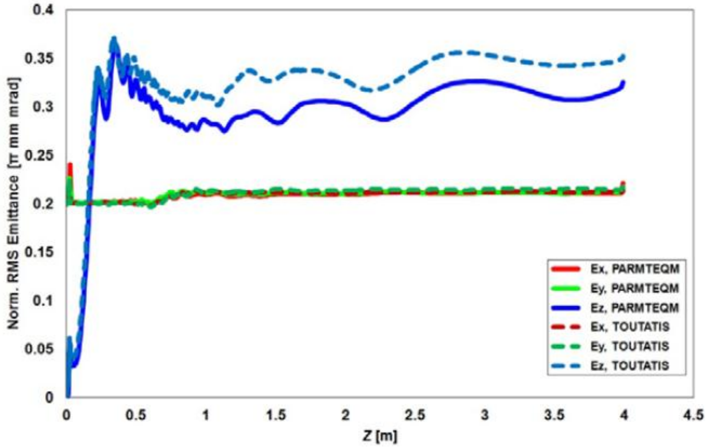
- 4-rod structure at 176.1 MHz
- **R&D at IAP Frankfurt on thermal effects**
- Construction of RFQ 1-m prototype achieved (ready for high-power RF test)
- Next step: procure the full RFQ

Parameter	EUROTRANS	MYRRHA	SARAF
f [MHz]	352	**176**	176
W_{in} [MeV] / W_{out} [MeV]	0.05 / 3	**0.03 / 1.5**	0.02 / 1.5
U [kV]	65	**40**	32.5
$E_{s,\,max}$ / E_k	1.7	**1**	0.8
a_{min} [mm]	2.3	**2.9**	2.7
m_{max}	1.8	**2.3**	2.7
g_{min} [mm]	2.6	**3.6**	3.7
$\varepsilon_{in}^{t.,\,n.,\,rms}$ [π mm-mrad]	0.2	**0.2**	0.175
$\varepsilon_{out}^{t.,\,n.,\,rms}$ [π mm-mrad]	0.21 / 0.20	**0.22 / 0.22**	0.19* / 0.19*
$\varepsilon_{out}^{l.,\,rms}$ [π keV-deg]	109	**64.6**	36*
L [m]	4.3	**4.0**	3.8
T [%] / T_{10mA} [%]	~100 / ~100	**~100 / ~100**	95.5* / 92.3*
R_p [kΩm]	61 (MWS)	**67 (after SARAF)**	67 (meas.)
P_c [kW/m]	69.8 (MWS, +20%)	**23.5**	15.8

** Simulated by A. Bechtold using the RFQSim code without image effects or multipole effects.*



MYRRHA RFQ parameters & emittance evolution



M. Zhang et al., Proc. LINAC 2012

M. Vossberg et al., Proc. LINAC 2012

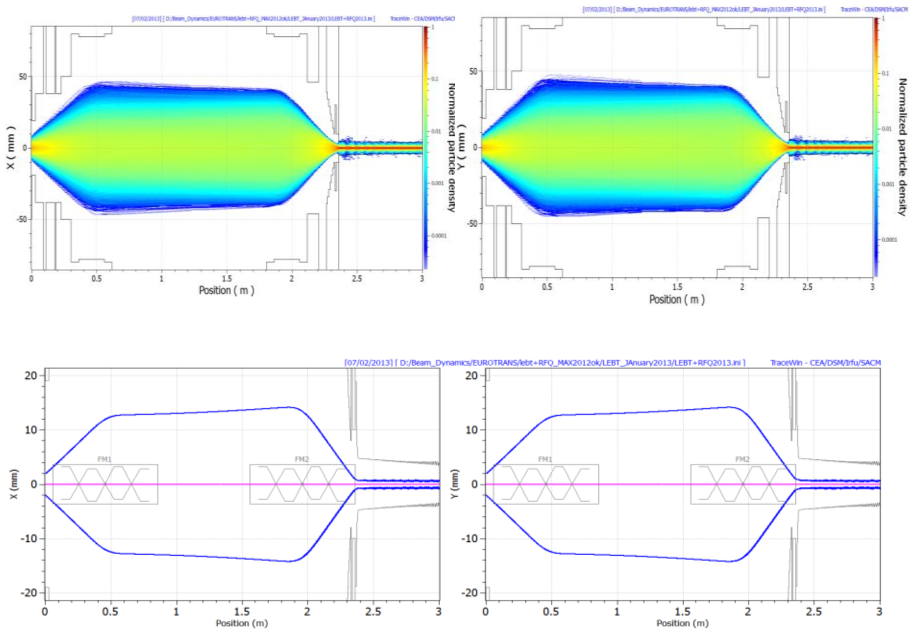
R&D line – the MYRRHA Accelerator eXperiment

FP7 - MAX

3 ½ years- coordinated by IPNO

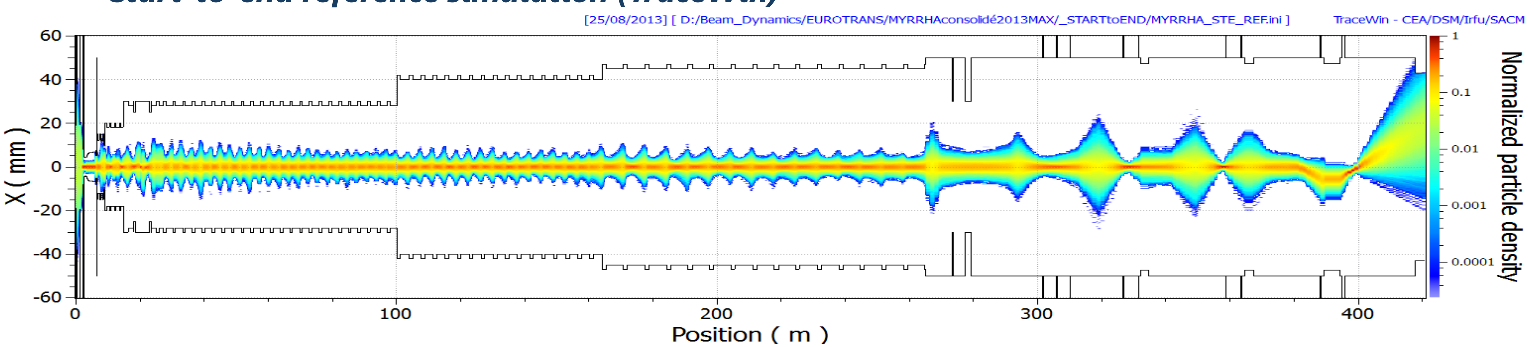
Goal	coherent concept of the MYRRHA accelerator
Technical Work Packages (WPs)	1. Global design coherence 2. Injector design 3. Main linac design 4. System optimisation
Main topics: • Simulations (beam and reliability) • Injector consolidated design • Design of spoke cryomodule • Tests with elliptical cryomodule • Perspectives for 704 MHz SS RF amplifier	Principal partners: • IN2P3 - IPN Orsay • IAP Frankfurt • INFN Milano • CEA • SCK•CEN

MYRRHA Accelerator eXperiment



- Design of the 230 m SC LINAC incl. fault-tolerance capabilities and fault recovery schemes
- Reference source-to-target beam simulation
- Benchmarking activities (TraceWin, Track)
- Monte Carlo error studies

Start-to-end reference simulation (TraceWin)



Superconducting LINAC: fault recovery scheme

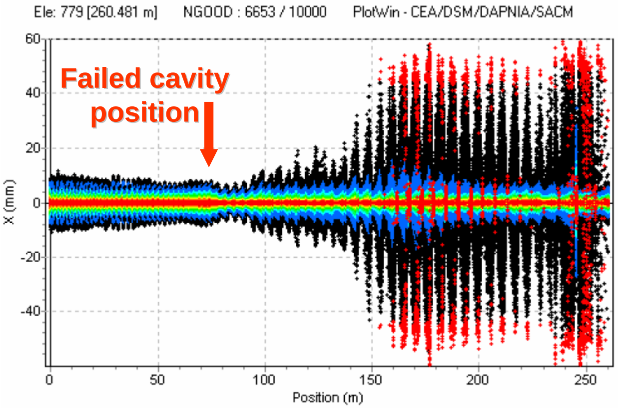


Figure 12 : Transverse beam distribution at 220 μs, in red are plotted the losses

1) A failure is detected somewhere

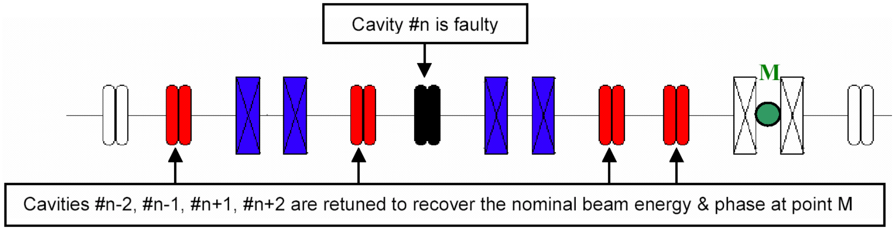
→ Beam is stopped by the MPS in the injector at t_0

2) The fault is localized in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

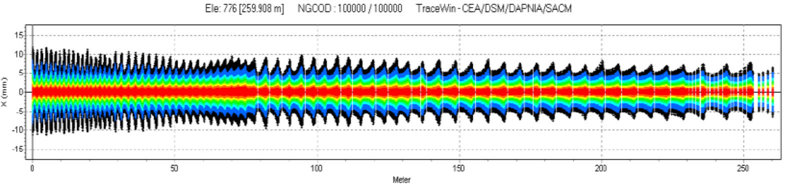
3) New V/φ set-points are updated to cavities adjacent to the failed one

→ Set-points determined via virtual accelerator application and/or at the commissioning phase



4) The failed cavity is detuned (to avoid the beam loading effect)

→ Using the Cold Tuning System



5) Once steady state is reached, beam is resumed at $t_1 < t_0 + 3$sec

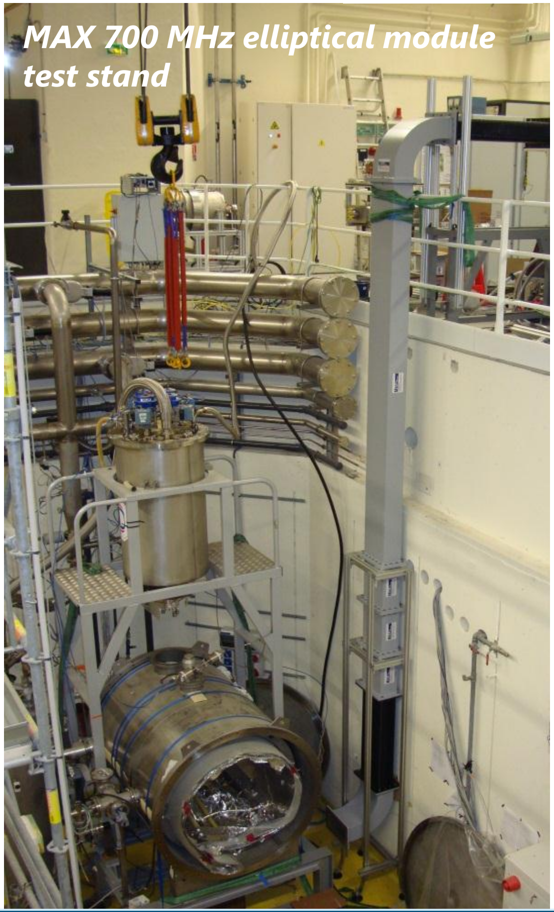
→ Failed RF cavity system to be repaired on-line if possible

J-L. Biarrotte, Proc. TC-ADS2, 2013

MYRRHA Accelerator eXperiment

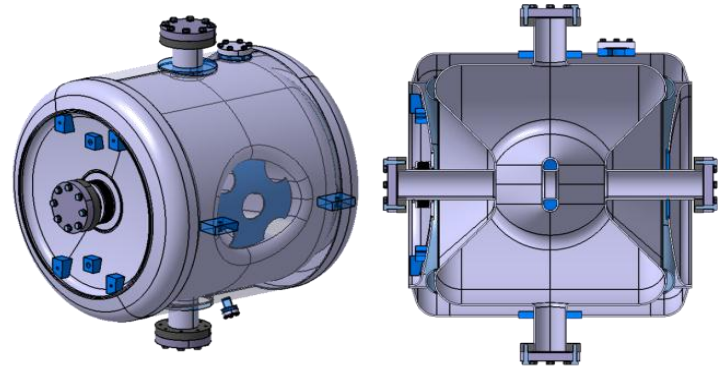
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

INFN Istituto Nazionale di Fisica Nucleare

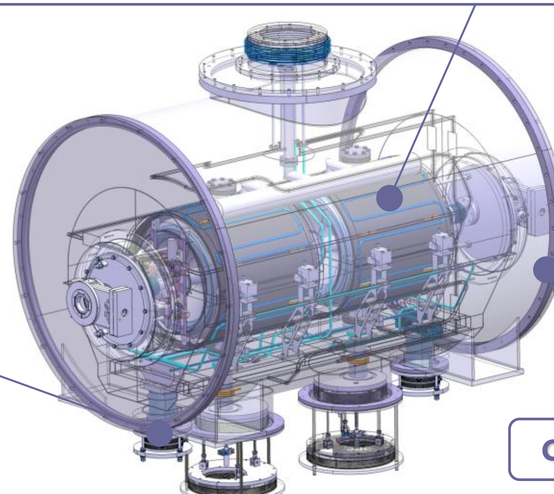


- R&D on **SC Spokes cavities and cryomodule** investigation
- Demonstration of **700 MHz elliptical cavity CW RF fault tolerant operation with LLRF control**

SC SPOKE Cavity



Power Coupler

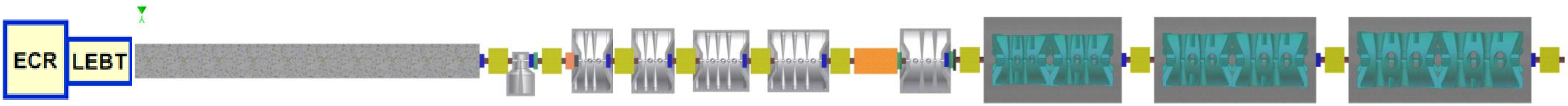


Cryostat

F. Bouly, M. El Yakoubi, et al., Proc. SRF 2013

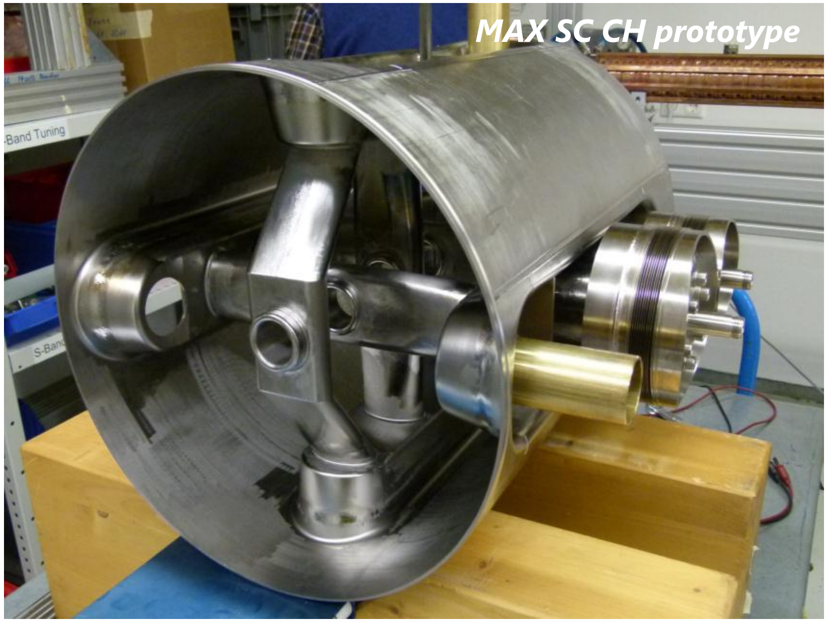
MYRRHA Accelerator eXperiment

- Optimization of the **injector design**



- Construction of **176 MHZ RT and SC CH cavities prototypes** achieved (ready for tests)

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



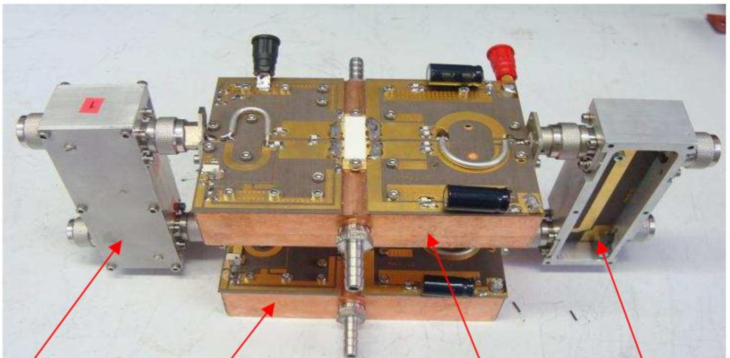
M. Bush et al., Proc. SRF 2013

D. Mäder et al., Proc. SRF 2013

MYRRHA Accelerator eXperiment

THALES ELECTRON DEVICES

R&D on **Solid State 700MHz RF amplifiers**



3dB coupler Input printed

Amplifier N°1

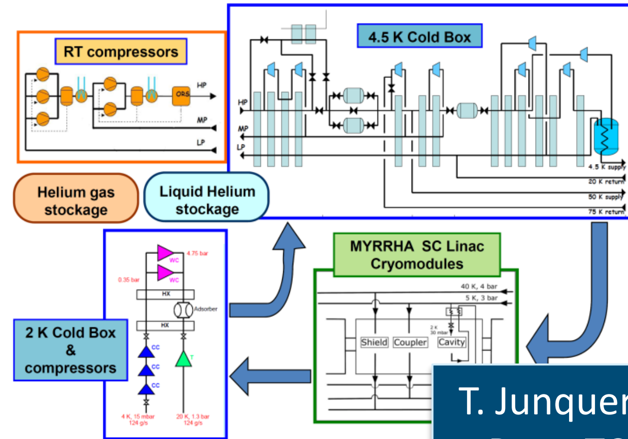
Amplifier N°2

3dB coupler Output printed

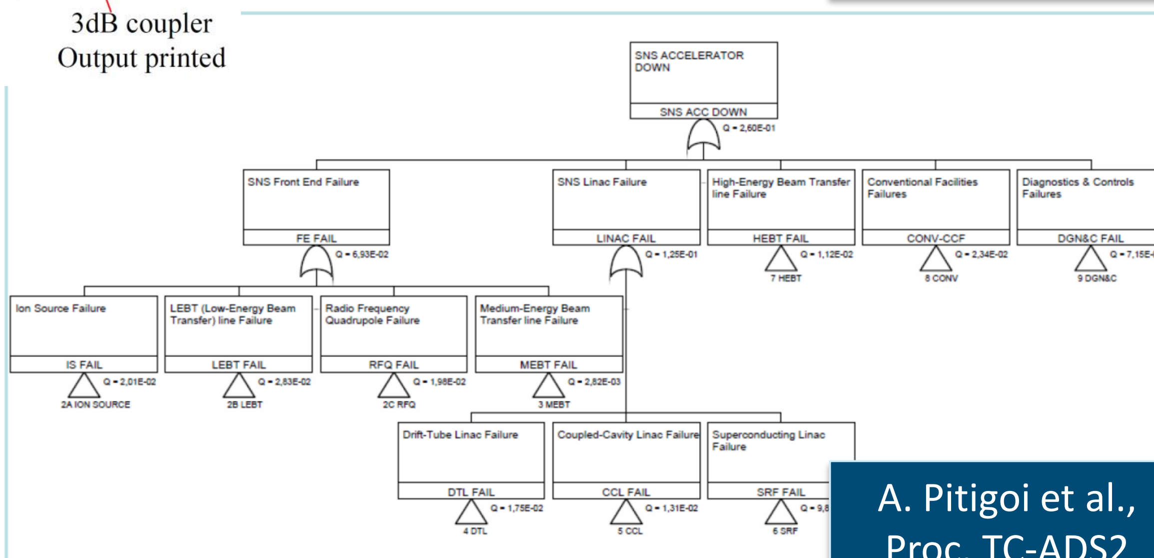
EMPRESARIOS AGRUPADOS

ORNL SNS **accelerator reliability model and benchmarking** with operational data

ACCELERATORS AND CRYOGENIC SYSTEMS **Cryogenic system**

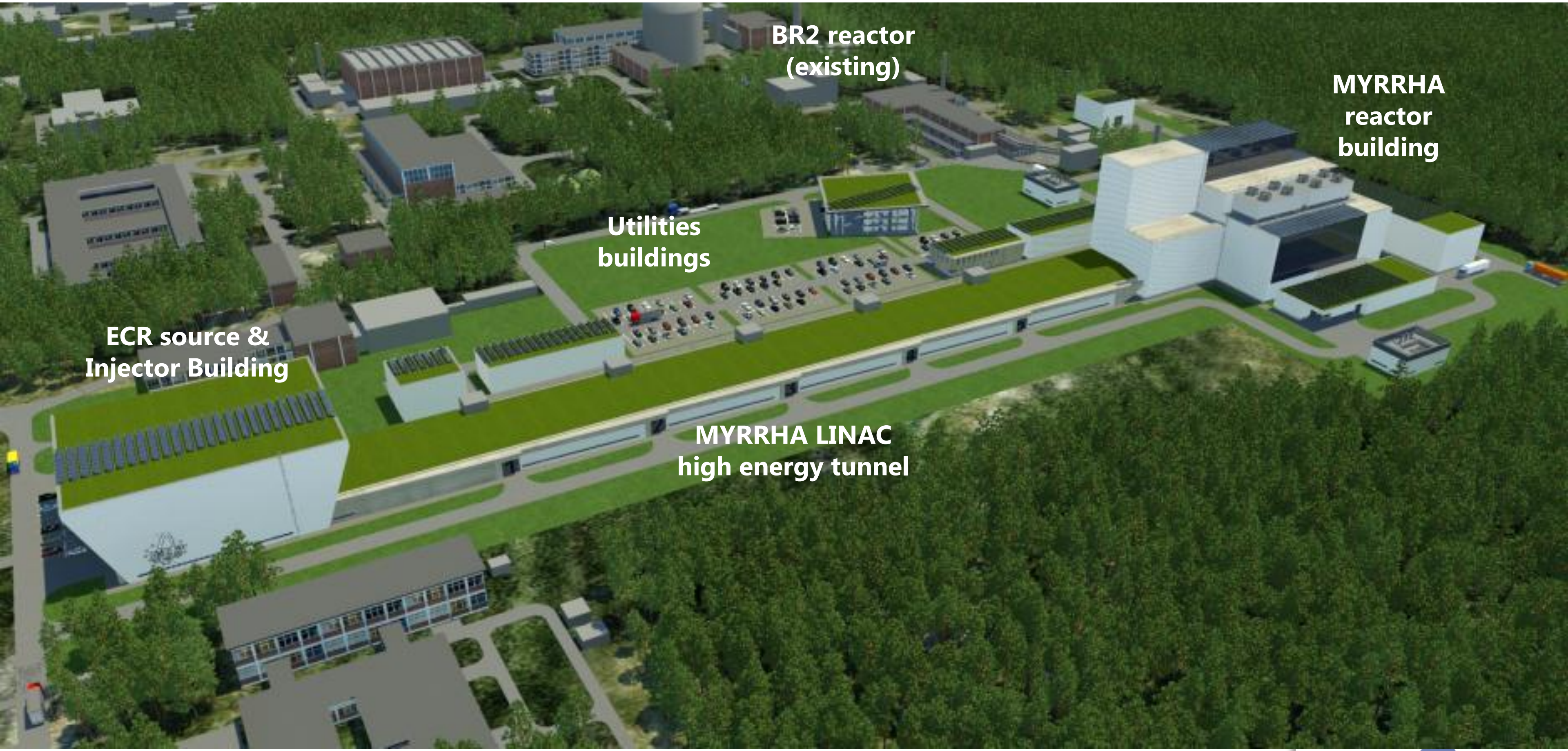


T. Junquera et al., Proc. TC-ADS2



A. Pitigoi et al., Proc. TC-ADS2

A glance into the future…



http://myrrha.sckcen.be

SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

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Foundation of Public Utility

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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE