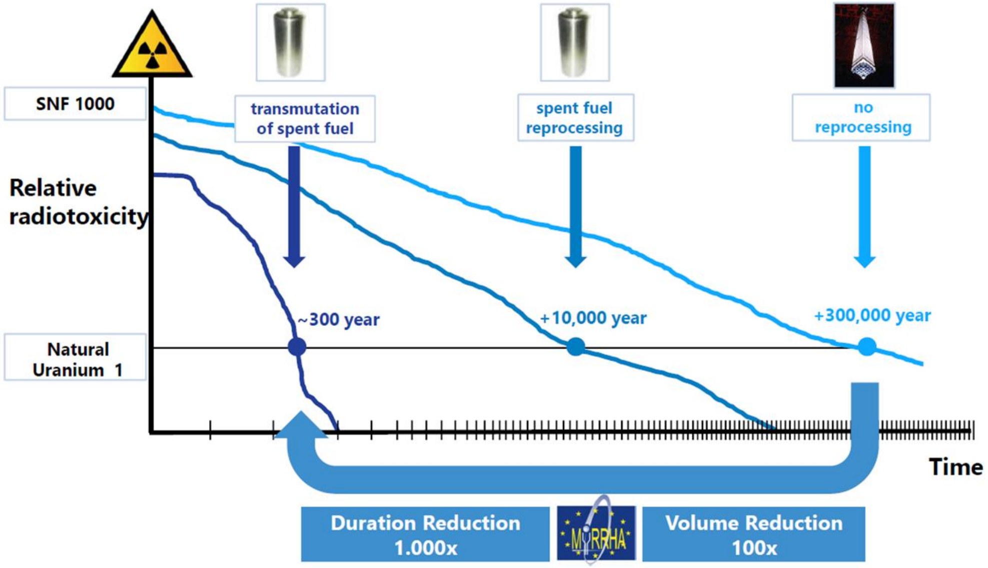
sck cen
Belgian Nuclear Research Centre

CWRF22-September 2022

RF Solid State Amplifiers for MINERVA General Architecture and Main Challenges

MYRRHA – Applications

*SNF = Spent Nuclear Fuel



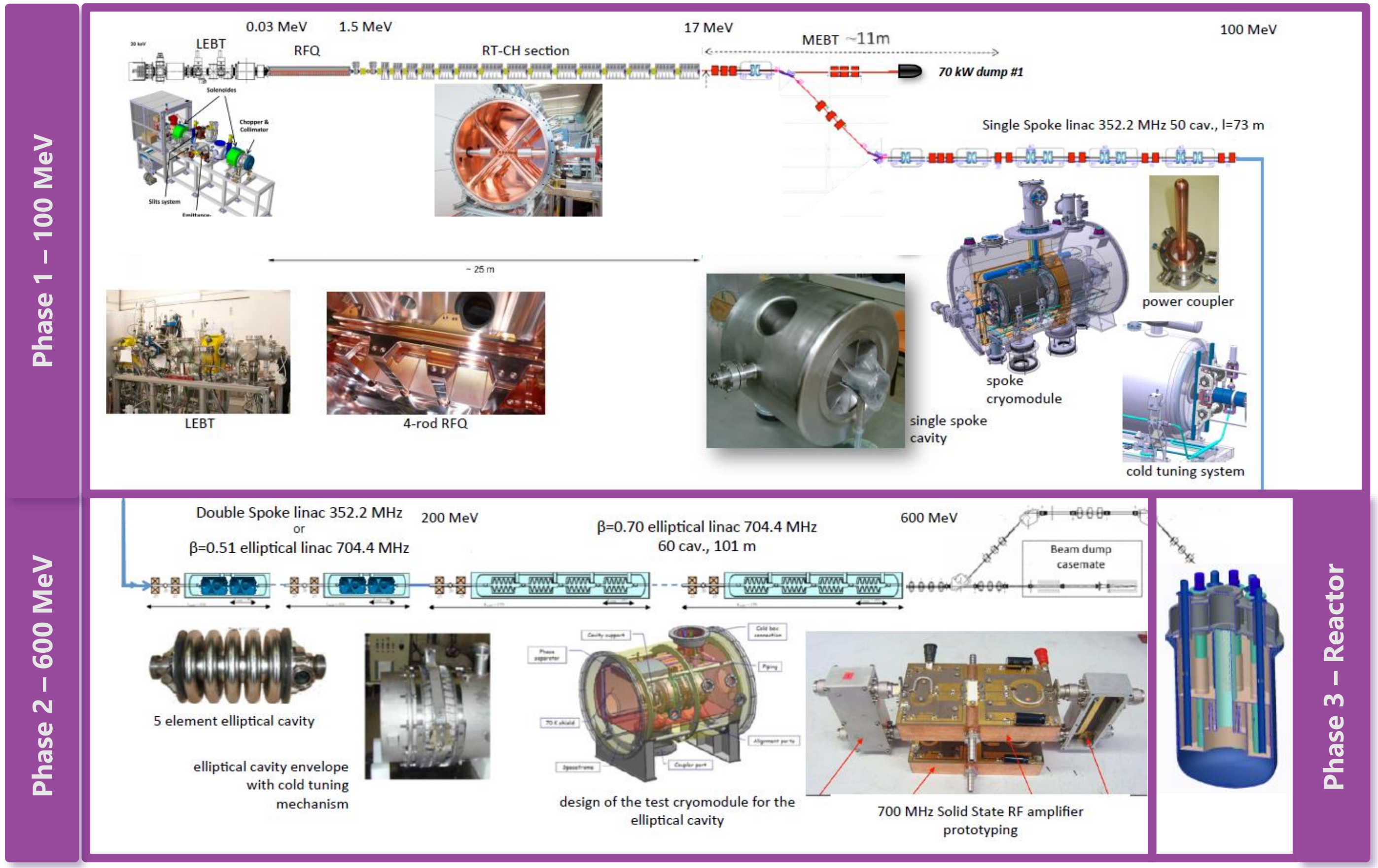
*SNF = Spent Nuclear Fuel

- Demonstrate ADS concept at pre-industrial scale
- Transmutation demonstration
- Multipurpose & flexible irradiation testing facility

- An attractive tool for education and training of young scientists and engineers
- A medical radioisotope production facility

MYRRHA – Phases

- **Phase 1** (approved, financed by Belgium Govt.)
  - 100 MeV LINAC + PTF & FPF implementation
  - Design and pre-licensing of the reactor
  - R&D for 600 MeV linac



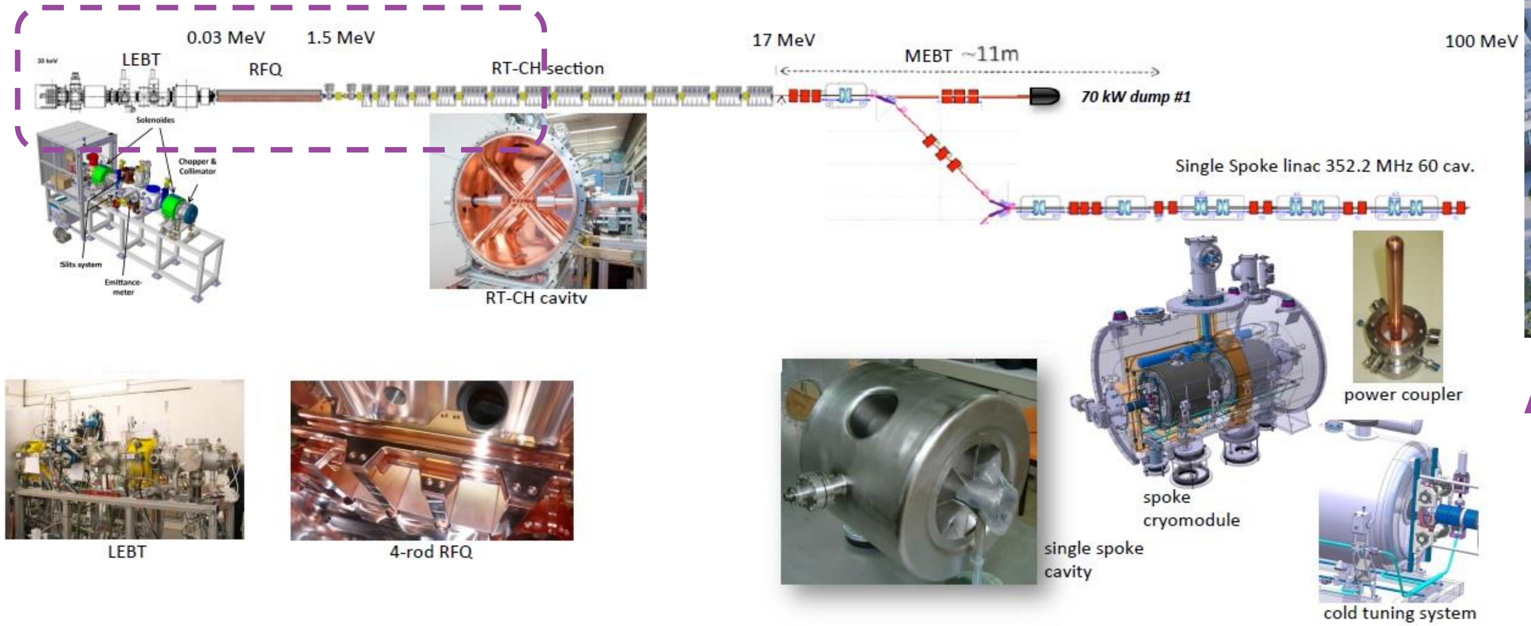
Phase 2: extension of the LINAC to 600 MeV

Phase 3: reactor implementation (2034 = start)

Phase 1 – MINERVA

Objectives

- Demonstrate reliability as required for ADS
- Reliability goal evaluation
- Fault tolerant schemes implementation



---- Existing inject test stand

Applications

- Fundamental research
- Develop new medical isotopes
- Include design considerations for upgrade use with fusion material research

MINERVA LINAC - Requirements

- **High reliability** requirements ***(*)***
  - Mean Time Between Failures (MTBF) > 250hrs
    - Allowed beam trips > 3 sec – Max. 10 per 90 day operation
    - Allowed beam trips > 100 ms – Max. 100 per day
    - Allowed beam trips < 100 ms – “unlimited”

Achieving reliability

- Conservative design: Use mature technologies and components, not pushing their technological limits
  - Solid State (SS) RF amplifiers
  - Modular DC power supplies
  - Digital Low Level RF (LLRF) control
- Serial redundancy in the main LINAC

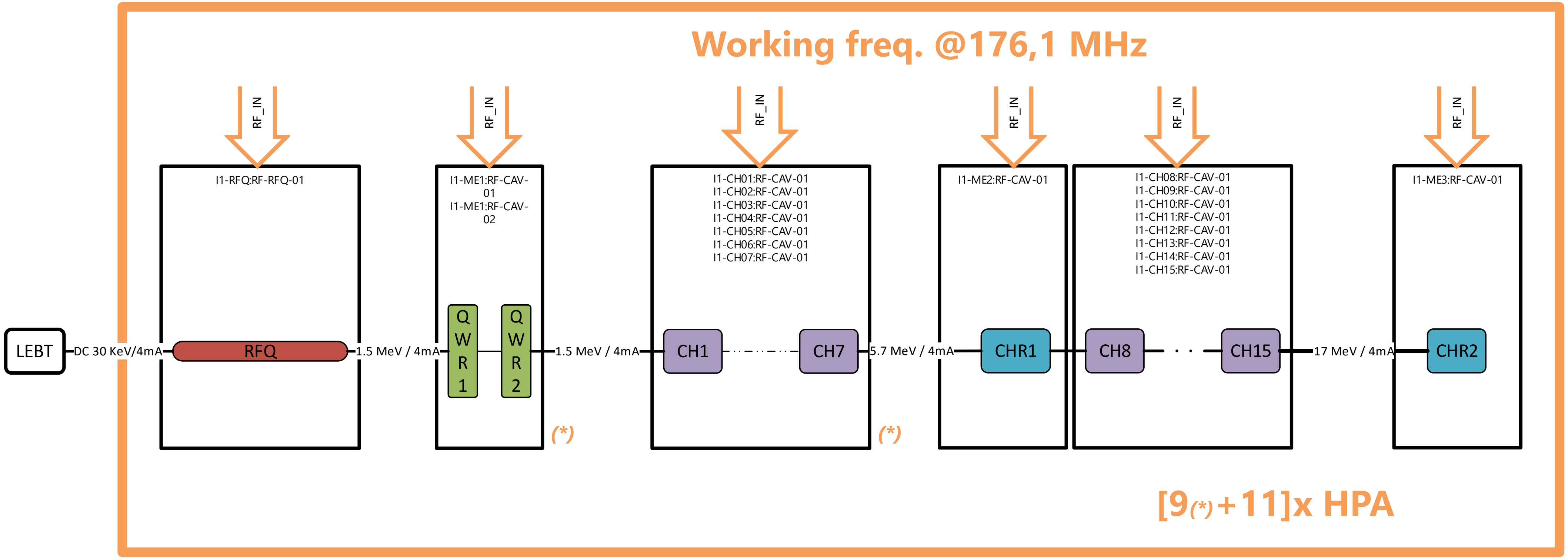
- **High availability** requirements
  - Low Mean Time To Recover (MTTR)
  - Failure detectability mechanisms

Achieving availability

- Modular design for key elements
  - Solid State (SS) RF amplifiers
  - Modular DC power supplies
  - Digital Low Level RF (LLRF) control
- Hot swappable elements
- Low average corrective maintenance time
- Predictive maintenance

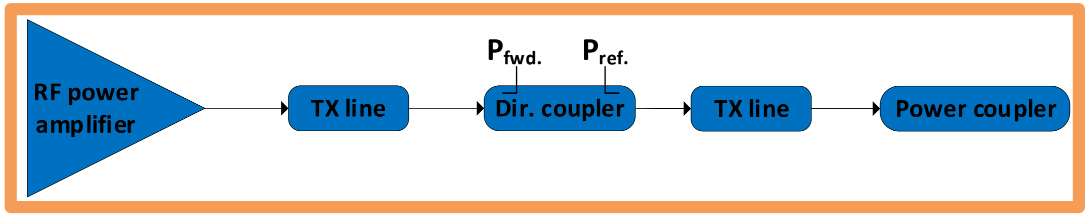
(*) MYRRHA requirements

HP RF System – 17MeV Injector architecture



Additional system elements

- RF distribution system -> Coaxial rigid line
- Monitoring elements -> RF monitoring Couplers



RFQ: **R**adio-**F**requency **Q**uadrupole

QWR: **Q**uarter **W**ave **R**esonator

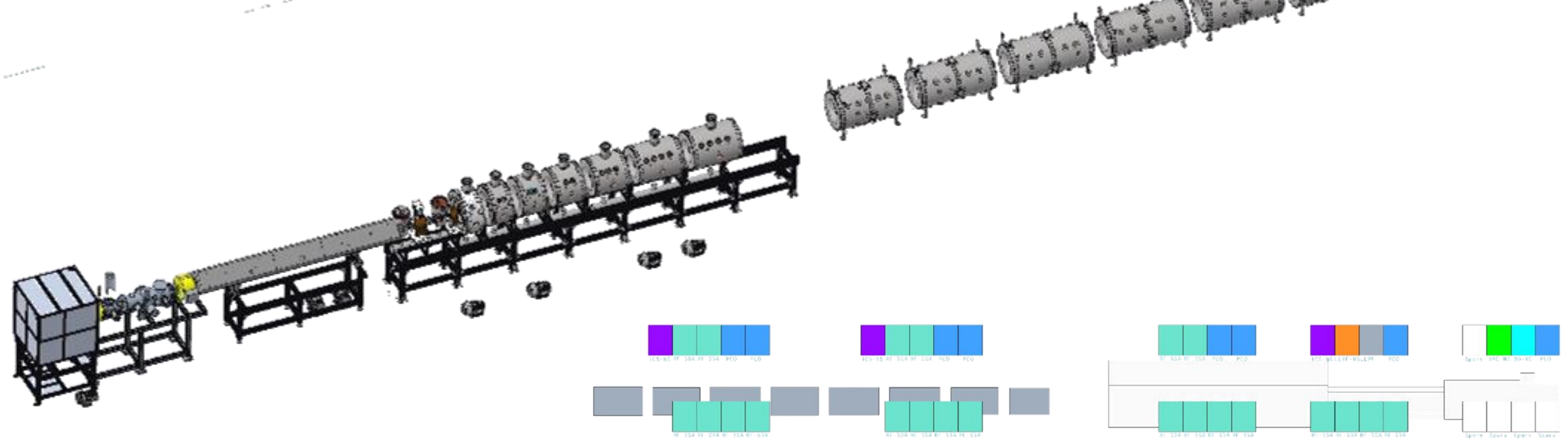
CH: **C**ross-bar **H** mode cavity

CHR: **CH** cavity used for **R**ebunching

HP RF System – 17MeV Injector architecture

RF Gallery to injector

- Up to 22 SSA racks distributed along the RF gallery
  - Freedom on rack distribution
  - Coaxial rigid line used as TXL

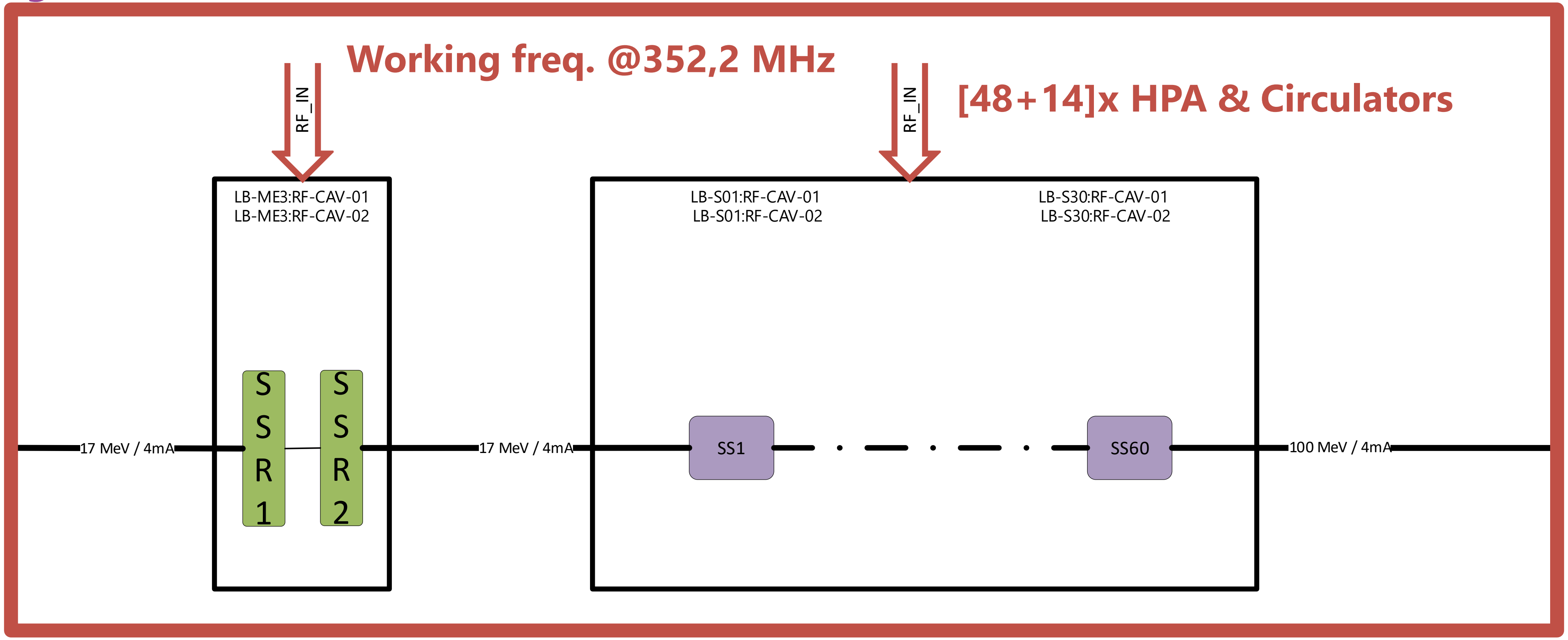


HP RF System – 17MeV Injector Power Needs

	Driving cavity	Quantity	Single P_{out} range Min-Max[kW](*)	Estimated # of cabinets
176,1 MHz	RFQ	1	168	3
	QWR1 & QWR2(**)	2	6	4
	CH1 & CH2(**)	2	24	
	CH3&CH4(**)	2	36	
	CH5&CH7(**)	2	48	
	CH6(**)	1	60	
	CH8-CH15	8	59-62	15
	CHR1 & CHR2	2	13-15	
	Amplifiers to be newly procured	11	---	18

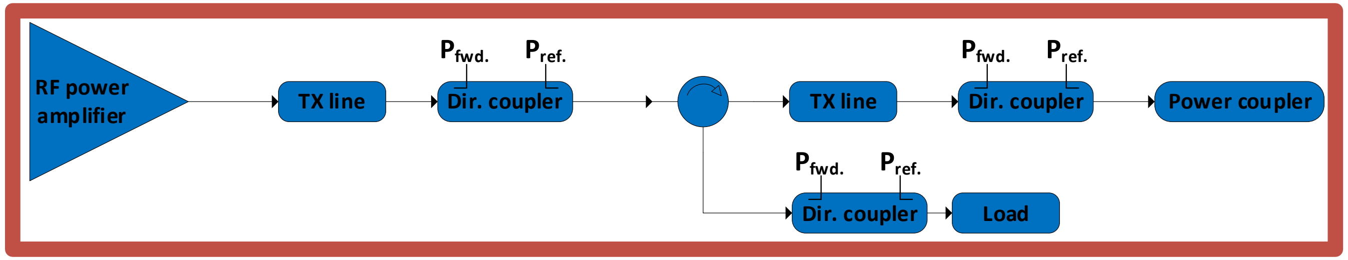
(*) Peak power at the output combiner connector on the rack.
(**) Already procured
Amplifiers should support operation on both CW and CW_P

HP RF System – 100MeV LINAC Architecture



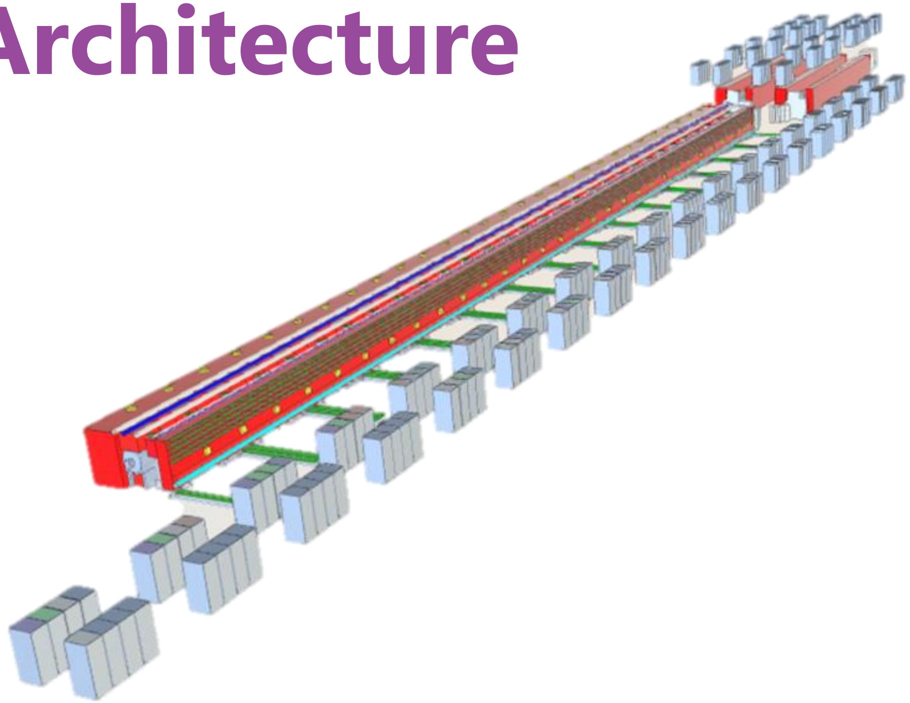
Additional system elements

- **High power RF circulators + Loads**
- RF distribution system -> Coax rigid line
- Monitoring elements -> RF monitoring Couplers



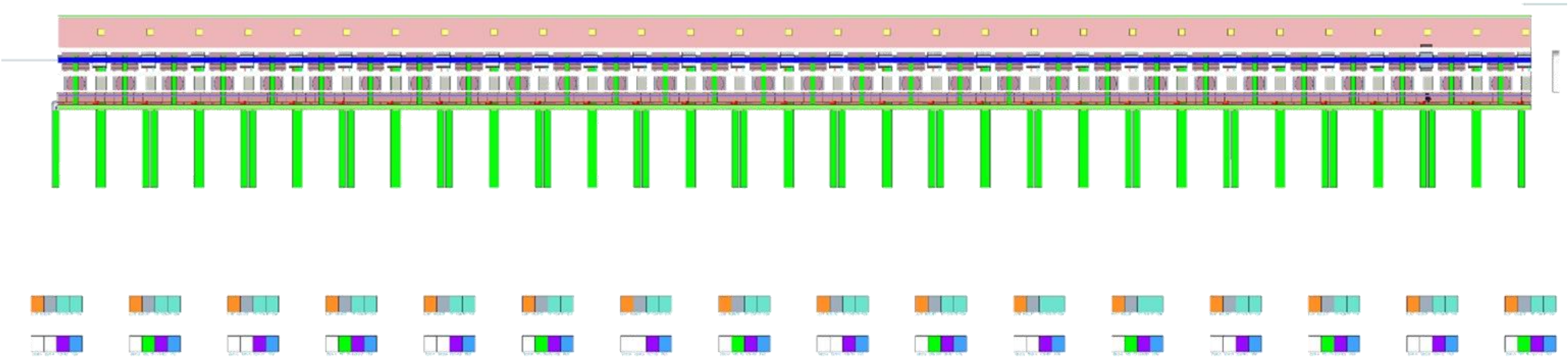
SS: **S**ingle **S**poke cavity **SSR**: **S**ingle **S**poke cavity used for **R**ebunching

HP RF System – 100MeV LINAC Architecture



RF Gallery to the tunnel

- Up to 32 racks distributed along the RF gallery
  - About one rack each two cavities
- 62 circulators distributed along the gallery
  - One circulator per cavity
  - Coaxial rigid line used as TXL



HP RF System – 100MeV LINAC Power Needs

	Driving cavity	Quantity	Single P_{out} range Min-Max[kW]*(*)*	Estimated cabinet availability #
352,2 MHz	SSR1-2 & SS1-14	16	4-9	25
	SS15-22	8	10-12	
	SS23-46	24	13-14	
	SS47-60*(**)*	14	15-20	7
	Total amplifiers to be procured without options	48	---	25
	Total amplifiers to be procured with options	62	---	32
	(*) Peak power at the output combiner connector on the rack. *(**) Option amplifiers* *Amplifiers should support operation on both CW and CW_P*			

- Two operation modes, two nominal powers @352 MHz-> Efficiency must be maximized for both operation modes

HP RF System –Specifications & Requirements

Design

- Reliable design ensuring high MTBF figures
- Stable design for any Gamma, P_{OUT} & V_D
- High efficiency over large P_{OUT} range
- Custom design
- Modular & redundant

Serialization

- Quality assurance plan
- Quality control plan
- High volume production capability

Installation & Commissioning

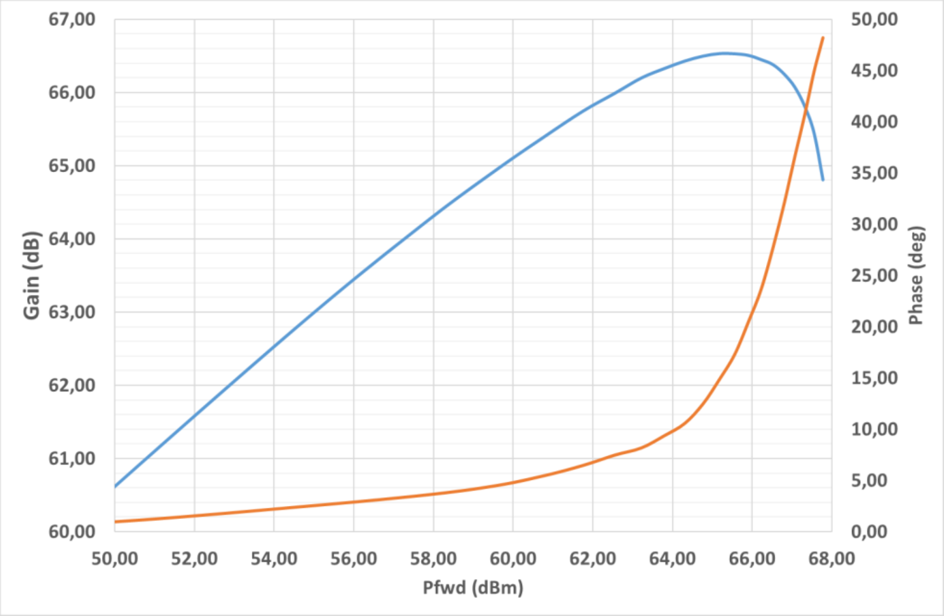
- Final on-site installation will also be within the scope of the delivery

O&M

- Full documentation package to ensure maintenance, repair and amplifier upgrades
- Dedicated hands-on trainings on operation and maintenance
- Spare parts long term availability

HP RF System – NCRF/SRF allowed PxdB

Gain & Phase variation over P_{fwd}

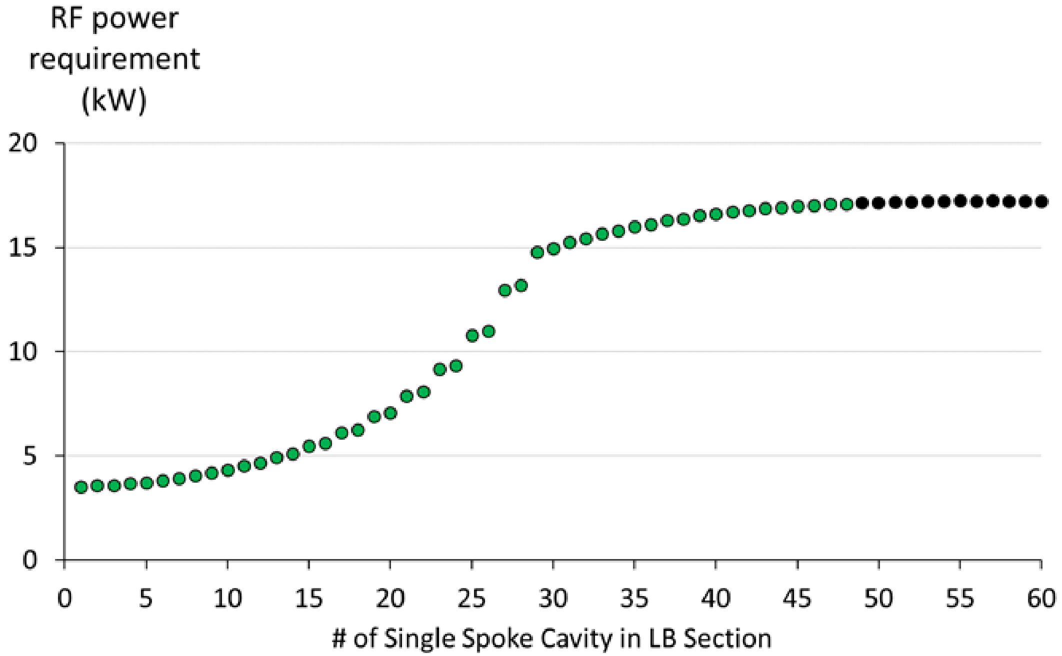


Maximum PxdB allowed

- Impact on Gain and phase linearity AM/AM & AM/PM
  - Investigating impact on LLRF regulation loop
  - Exploring use of Digital Pre-Distorsion (DPD)
- Impact on RF power provision

HP RF System – SRF series redundancy

FFT estimated RF power levels

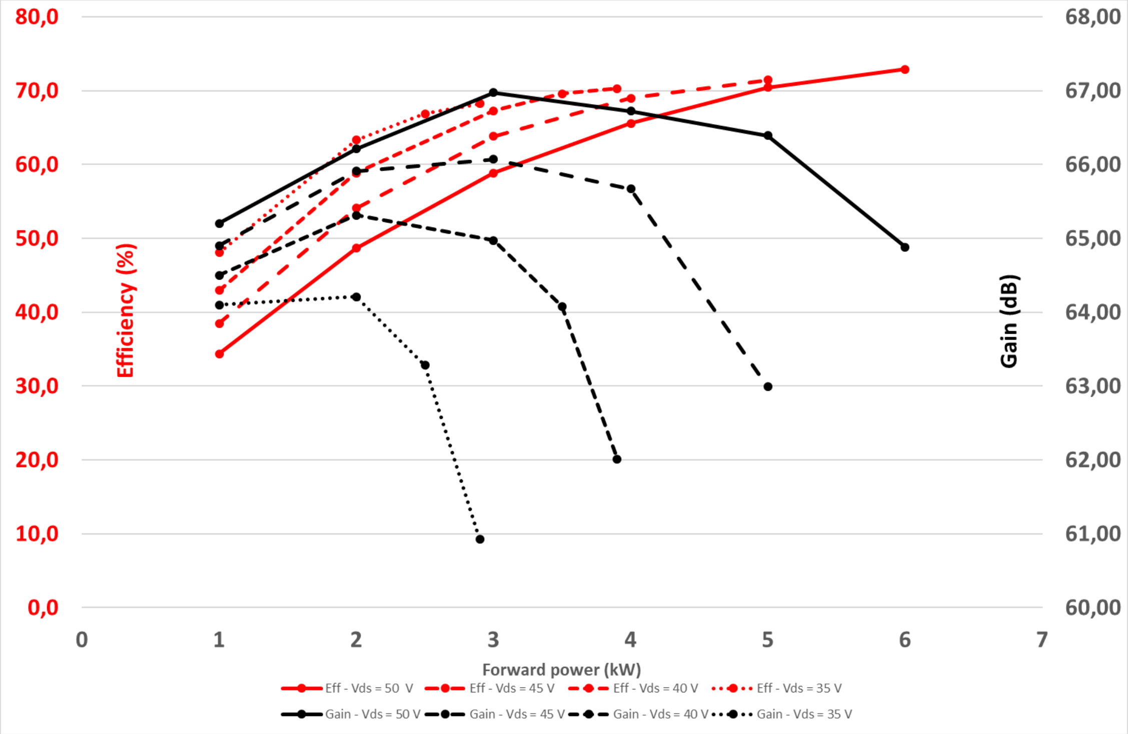


SRF Series redundancy

- Adjacent cavities compensating for the failure of one cavity.
- SSAs will operate at 2 different power levels:
  - Standard Fault Tolerance (SFT)
  - Full Fault Tolerance (FFT)
- SFT 3dB Back Off (BO) from FFT!
  - Degraded Drain efficiency (Deff) of about 15%

HP RF System – SRF BO Efficiency Optimization

Drain voltage impact on efficiency and gain

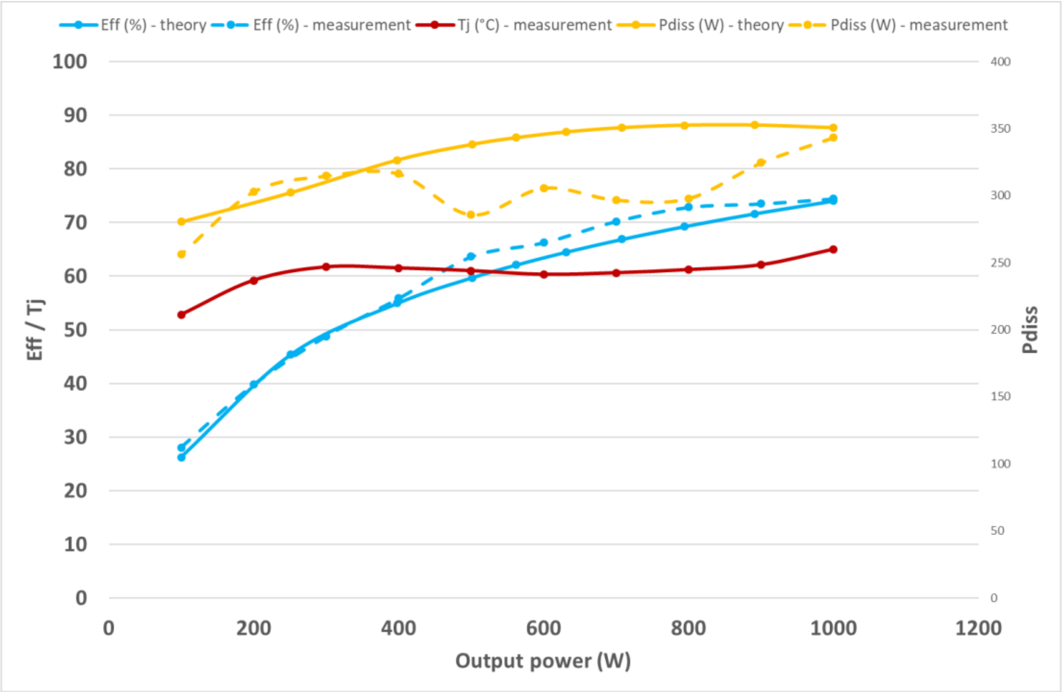


Vds Efficiency optimization is the current path

- Two different setting modes FFT and SFT
  - Investigating feasibility and integration with LLRF
  - Assessing operational concept
- But still few question marks
  - Can be done without stopping RF?
  - What is the impact on the gain variation?
  - How to deal with internal SSA failures?
  - Stability across all voltage range

HP RF System – SRF BO MTBF

Efficiency/Junction Temp/P_{diss}



Thermal resistance $$R_{THj\_c} = \frac{Tjunction - Tcase}{Pdiss}\ [K/W]$$

MTBF at SFT

- Without efficiency optimization MTBF will only be better
  - Junction temperature does not increase
  - Breakdown voltage much lower (Lower RF power)
  - Rest of components working at conservative ratings e.g. combiners, PSUs
- With efficiency optimization MTBF will only be better
  - Junction temperature will be drastically reduced
  - Breakdown voltage much lower (Lower RF power + Lower DC voltage)
  - Rest of components working at conservative ratings e.g. combiners, PSUs like without efficiency optimization

HP RF System – Other Challenges

NCRF SSA without circulators

- Proof of concept had been carried for the RFQ at the Injector Test Stand (ITS)
  - Due to the small beam loading on NCRF cavities in combination with CW operation not high VSWR expected
  - Cavity filling and “discharge” time plays a crucial role and needs to be further investigated
  - For CW_P operational mode cavity filling and “discharge” times needs to be carefully investigated
  - Output impedance load pull

Conclusions

- MINERVA is the 1st phase of MYRRHA implementing a 100 MeV SRF linac
- MINERVA requires 20 SSAs at 176.1 MHz and 60 SSAs at 352.2 MHz CW and CW_P capable.
- Experience from available SSAs@ITS is the basis for the technical specifications
- Technical specifications for the SSAs are being prepared.
- High availability requirement, SFT & FFT, is THE main challenge for the SSA specification
- Drain voltage control impact is under investigation.

SCK CEN
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL