Neutrino Beams @ CERN

...with feedback from many colleagues - thanks!

I. Efthymiopoulos — CERN

ν-activities at CERN - Europe

- Operational ν-beam : **CNGS**
- Design Studies
  - **EUROν**/FP7 (2008-2012) : SuperBeams - BetaBeams - NeutrinoFactory (IDS-NF)
  - **LAGUNA**/FP7 (2008-2011) : Far detector for astroparticle and beam physics
  - **LAGUNA_LBNO**/FP7 (20011-2014) : LAGUNA + Beam from CERN
    - Incremental Approach towards a ~2MW ν-beam facility
  - R&D activities for HP-SPL
- ν-experiment proposals
  - **Short-baseline** neutrino Beam at CERN/PS - sterile neutrinos

CERN Neutrinos to Grand Sasso - CNGS LBL beam

- Long-baseline ν beam designed for ν oscillation studies via **ν_τ appearance**
  - two optimized detectors at LNGS : **OPERA** (1.2kt) - **ICARUS** (0.6kt)

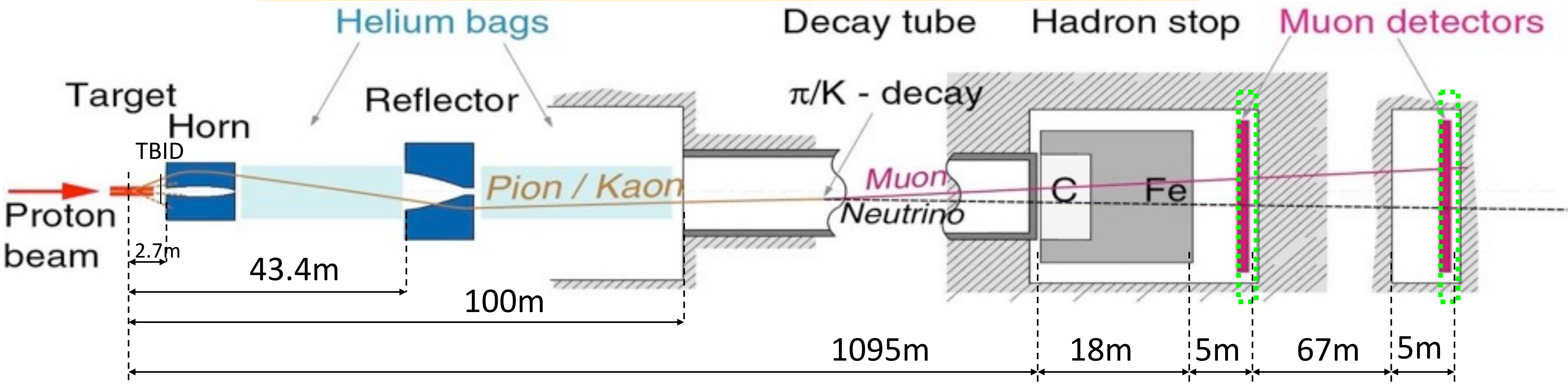
Approved program:

- **4.5×10^{19} protons/year** - 5 year program
- ~3.5×10^{11} ν_μ/year at Grand Sasso
- ~3000 CC ν_μ interactions/kt/year at the experiment
- **~2÷3 ν_τ interactions detected/year** (OPERA)
- Construction completed in **2006**, physics since **2008**

Beam parameters	Nominal beam
Nominal energy [GeV]	400
Normalized emittance [μm]	H: 12 V: 7
Emittance [μm]	H: 0.028 V: 0.016
Momentum spread Δp/p	0.07% ± 20%
# extractions per cycle	2 separated by 50 ms
Batch length [μs]	10.5
Cycel length [s]	6
# of bunches per pulse	2100
Intensity per extraction	**$2.4\ 10^{13}$**
Beam power [100%df]	**510 kW**
Bunch length [ns] (4σ)	2
Bunch spacing [ns]	5
Beta at focus [m]	H: 10 V: 20
Beam sizes at 400 GeV [mm]	0.5 mm
Beam divergence [mrad]	H: 0.05 V: 0.03

CNGS : Conventional long-baseline ν beam

$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+, K^+ \rightarrow \text{(decay)} \rightarrow \mu^+ + \nu_\mu$



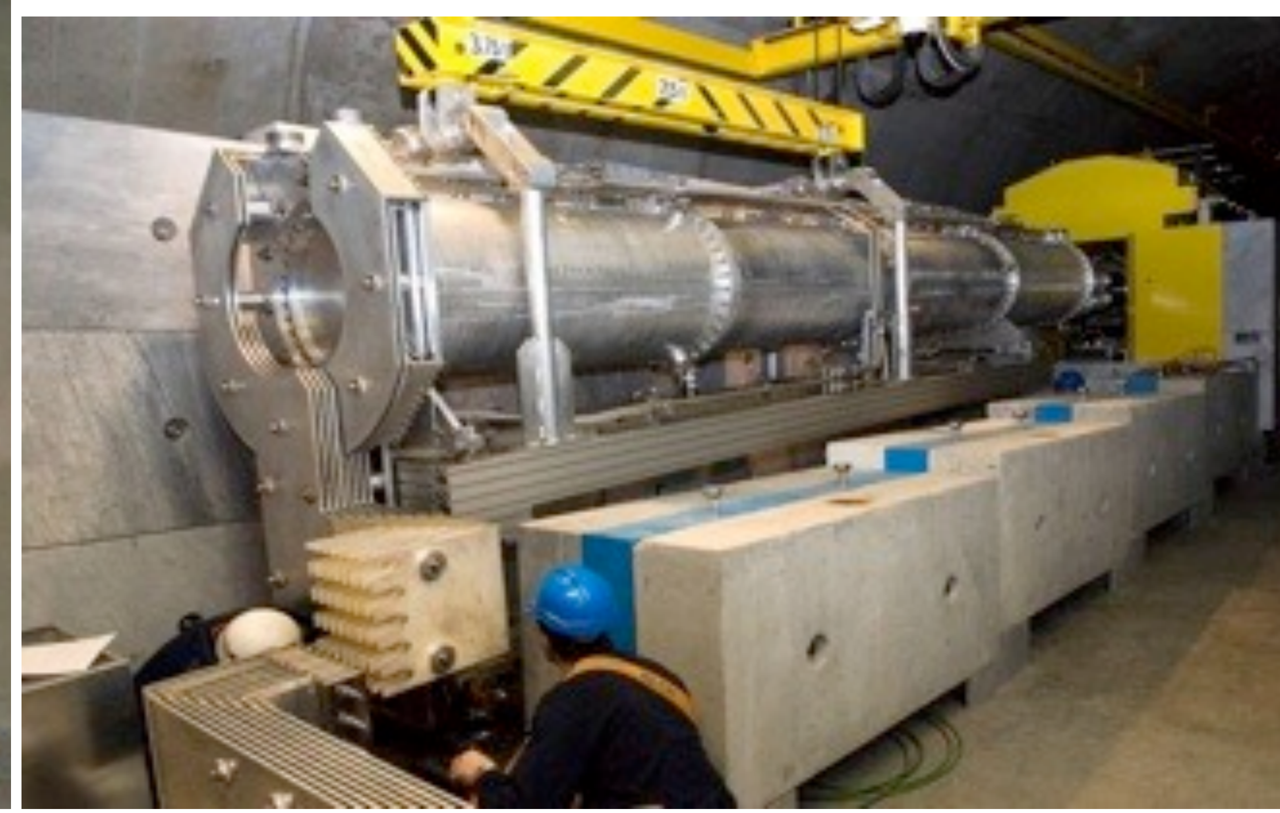
Target Unit

- C rods
- 5(4) mm Ø
- 5 in-situ spares

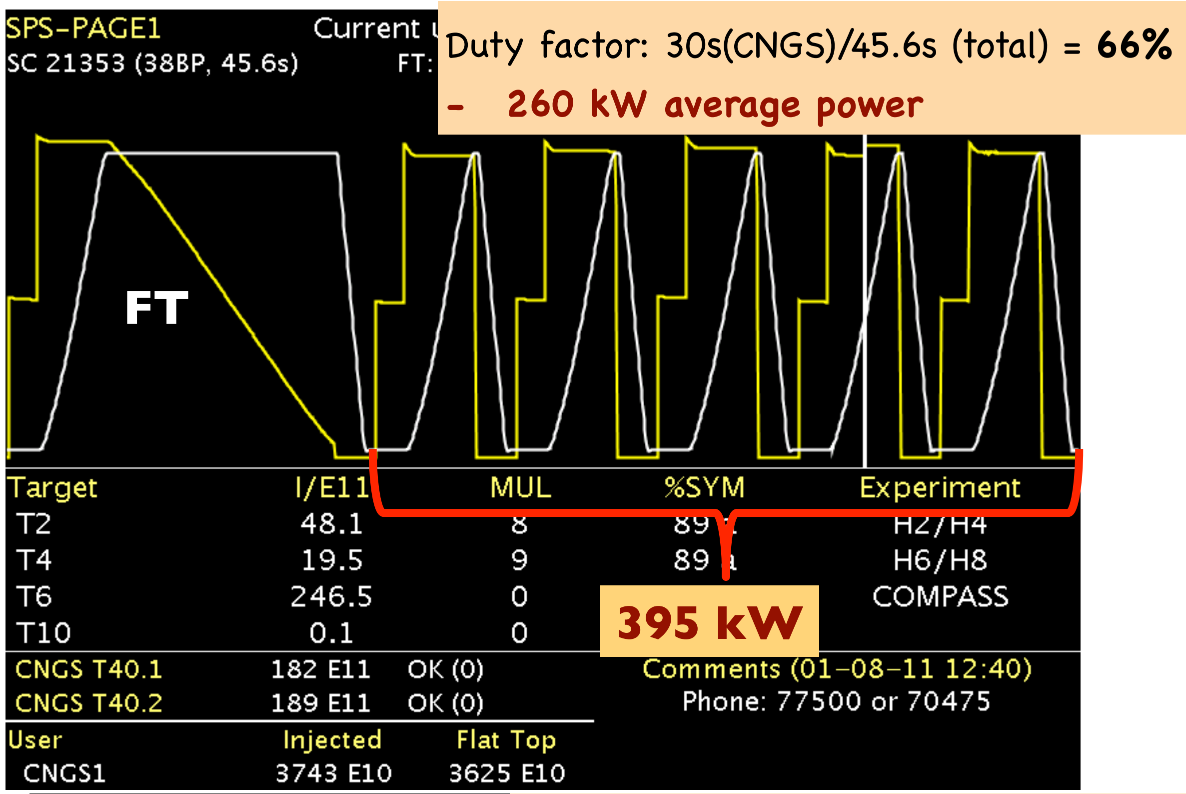
Muon detectors

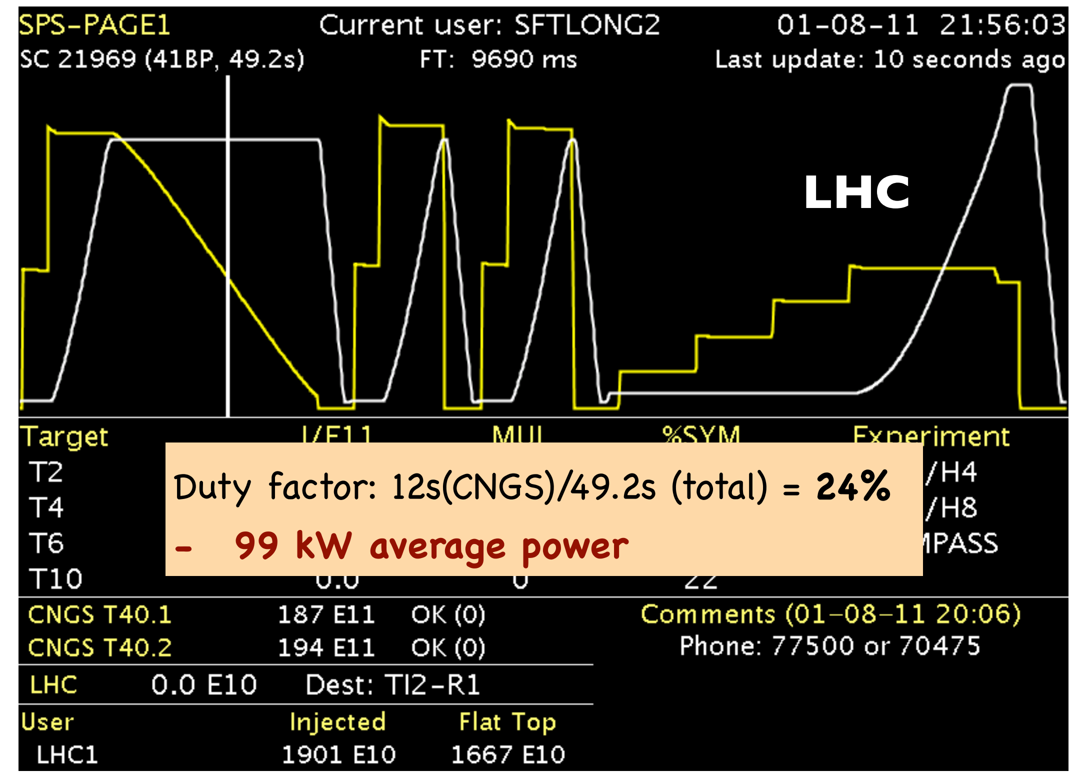
- 2 × 41 fixed monitors
- 2 × 1 motorized monitor

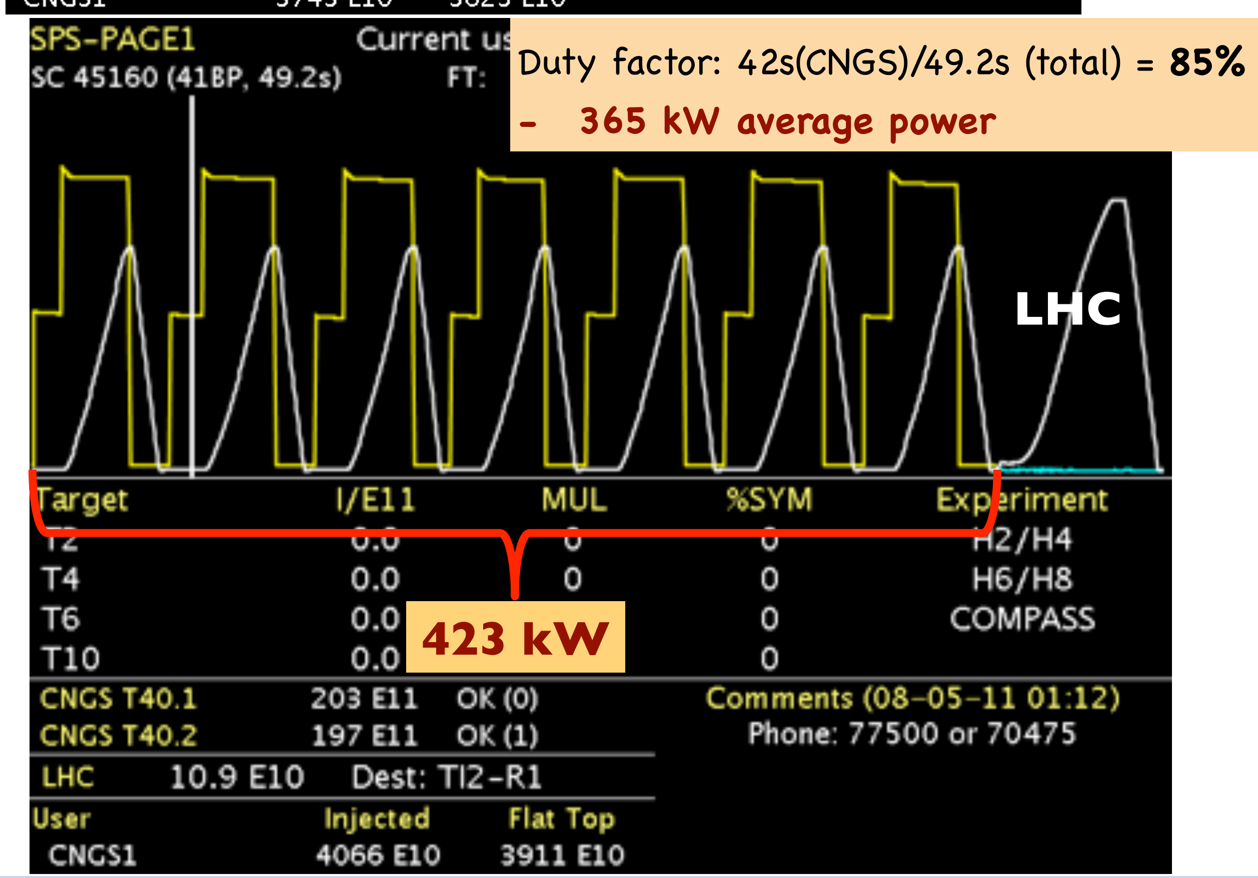
Magnetic Horns

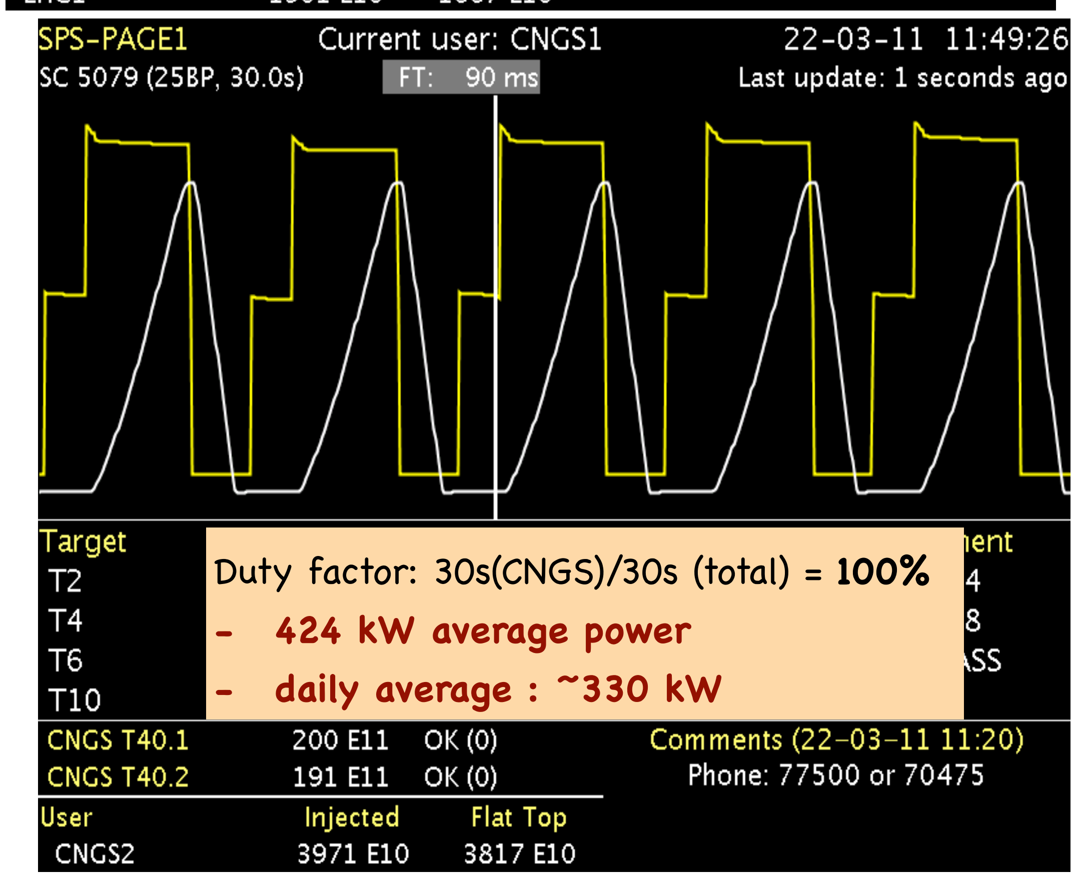


CNGS : Operation









CNGS : Operation history

- construction
- beam commissioning
- beam commissioning with high intensity
- physics run
- physics run MTE tests
- physics run MTE tests
- physics run MTE tests, bunched beam

2001 | | | | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011

- leak in the reflector cooling circuit : repair and improvements
- broken stripline cable : repair and improvements

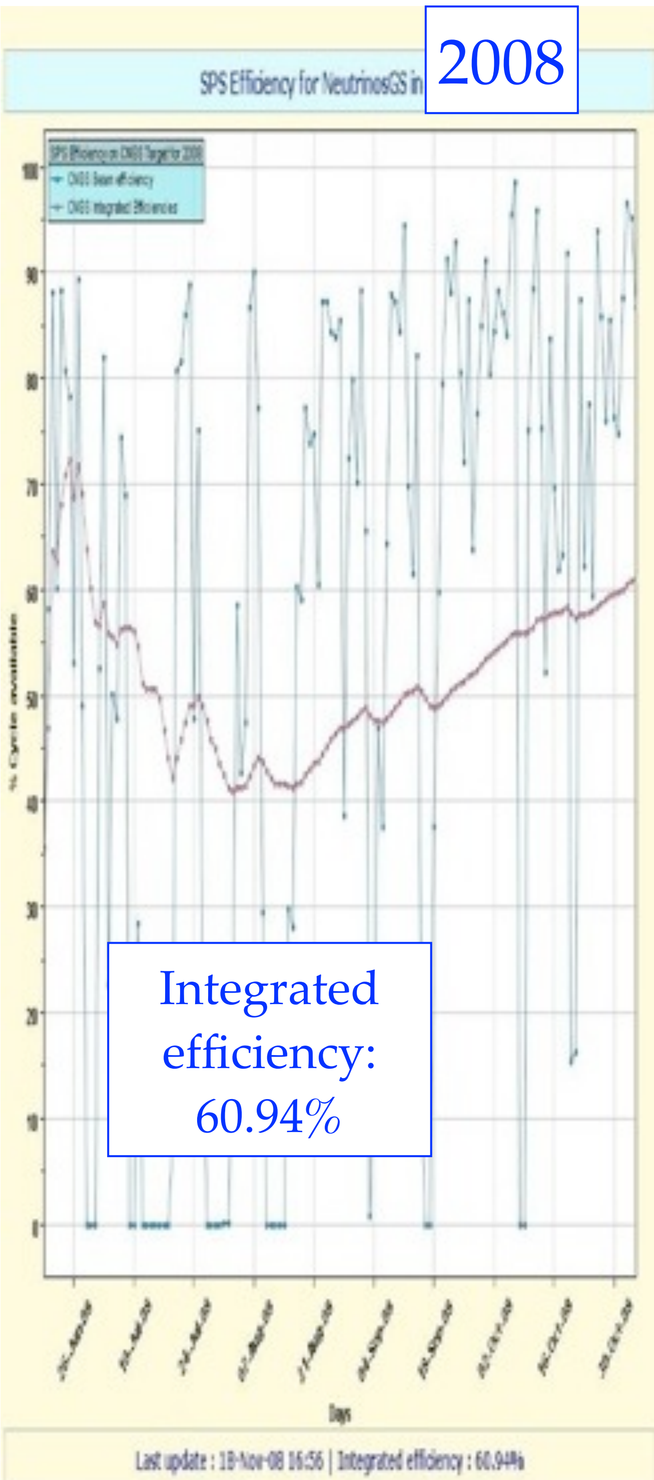
- radiation effects in proximity electronics
  - additional shielding, reconfiguration

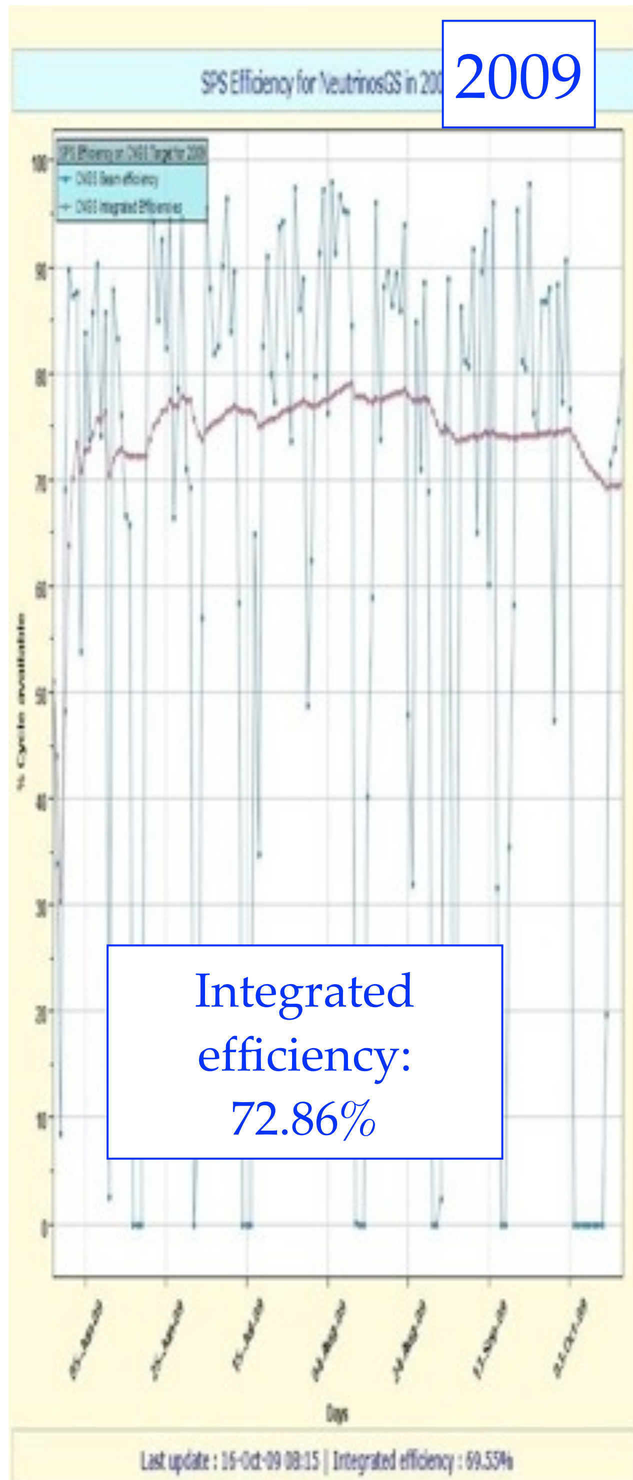
- damaged target rotation mechanism : inspection

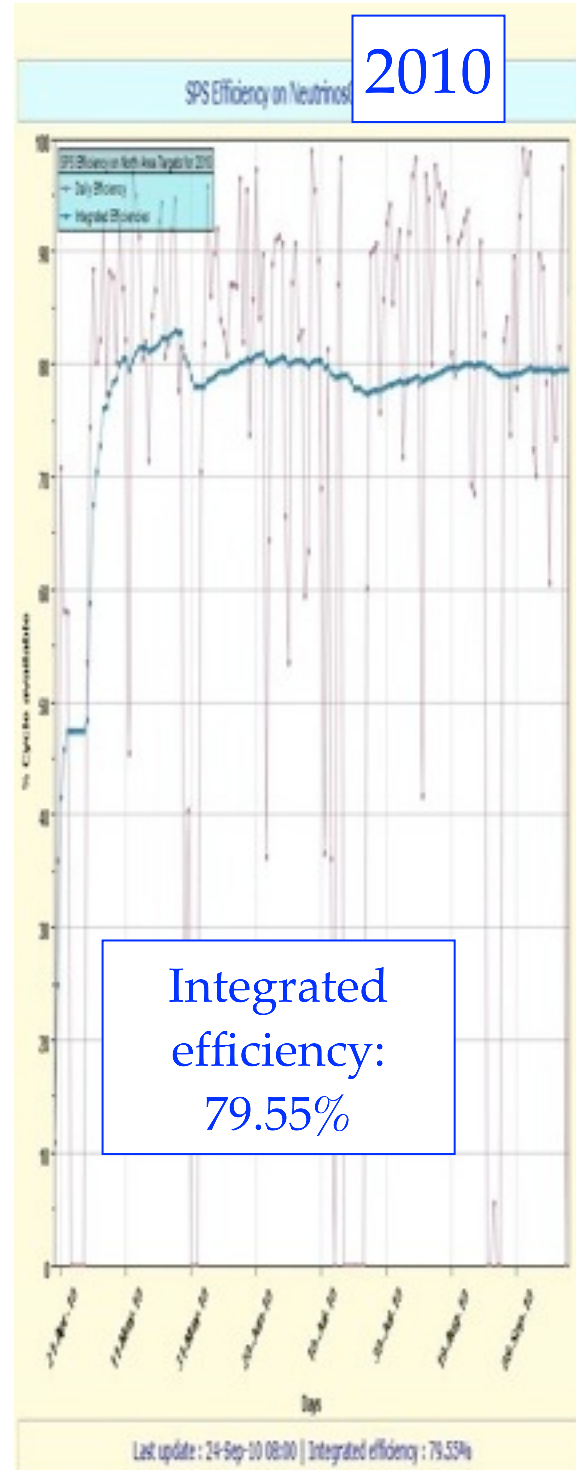
- tritium issue : civil engineering works, new configuration of the drain water circuit

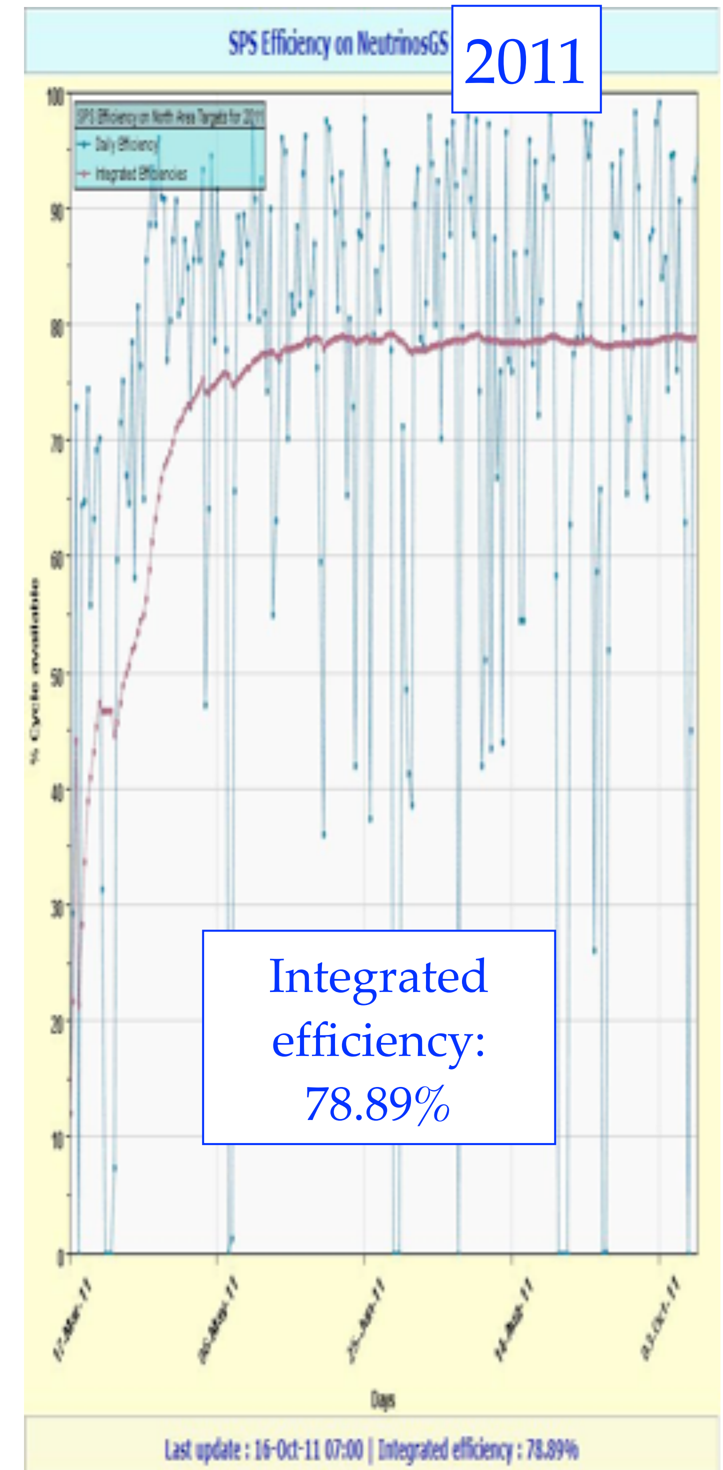
- tritium issue : reconfiguration of ventilation system

CNGS : Operation





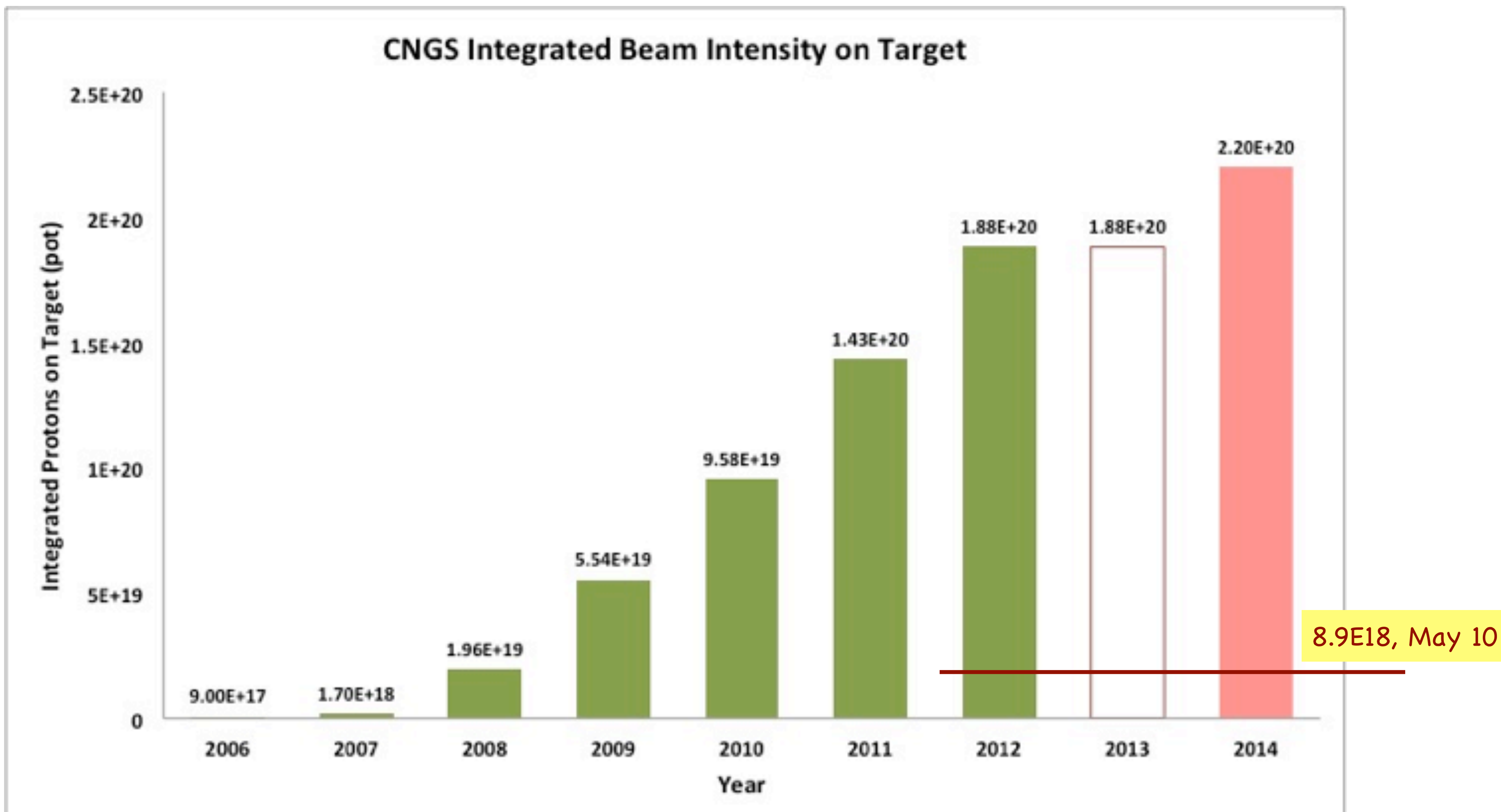




Courtesy : Edda Gschwendtner

Operational ν-beam : CNGS - Status & Plans

- At the end of 2012 CNGS should reach **1.88 × 10^{20} pot**
  - to complete the presently approved program **(5y × 4.5 10^{19} pot/y = 2.2 10^{20} pot)** running in 2014 will be required
- decision to continue or not beyond LS1 still pending



Lessons learned - CNGS Technology

- The design and operation of a high-intensity, high-power beam facility is always very challenging

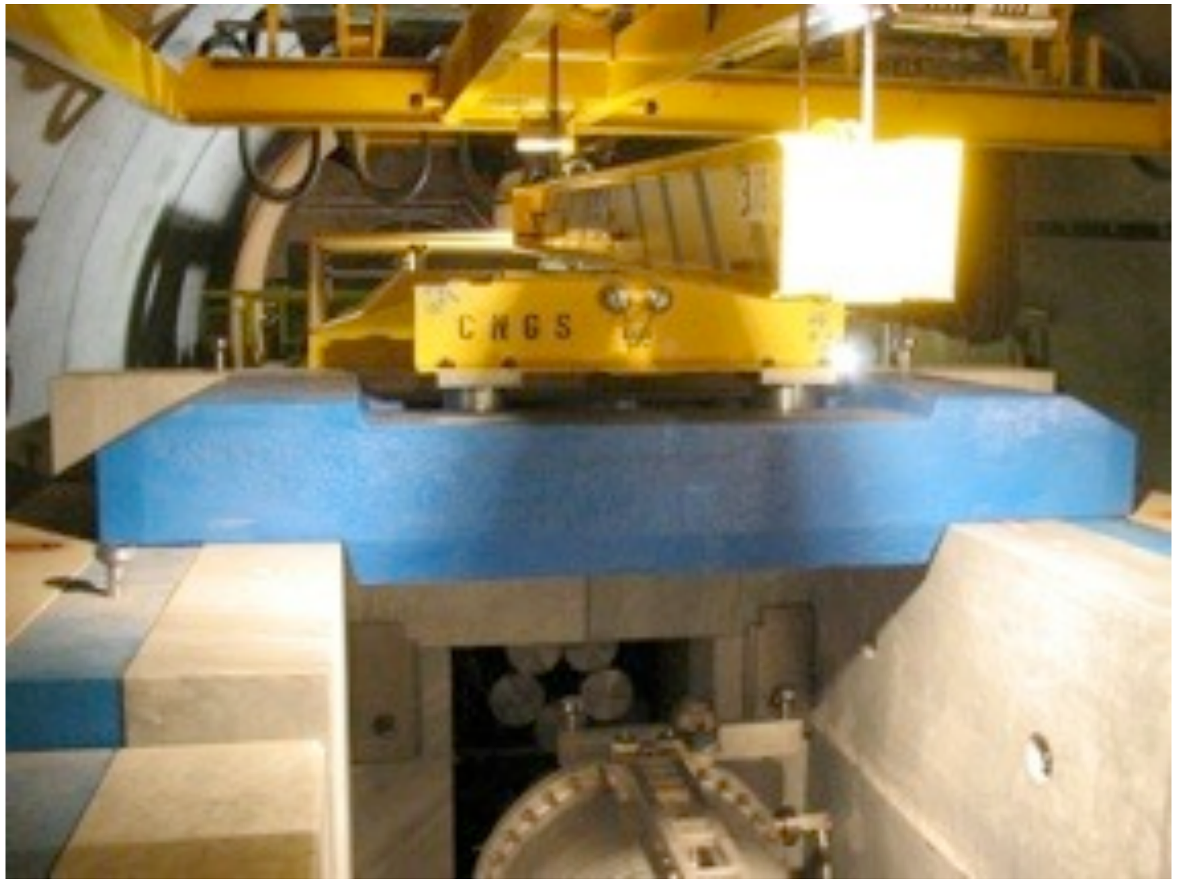
- **Design**
  - choice of **materials**, **layout**, **shielding**, **radiation** environment
  - technical challenges during **construction**

- **Operation**
  - possibility for **early repairs** must be included in the design
  - radiation effects on **proximity electronics** should not be ignored
  - the target area **ventilation system** is a key element with double challenge:
    - temperature/humidity control and management of the radioactive air
  - **H-3 creation** (air, water) should not be forgotten
    - **civil engineering & layout** are key elements for the operation of the facility

- **Important lessons learned, in view of future facilities with (M)MW of beam power**

CNGS upgrades ? (1)

- Target station design with large cavern
- Optimized shielding and services (crane, etc.)
- However difficult to imagine could suffice for MW class beams
  - lot of air volume around the target --> H3 production is a time bomb!
  - still lot of equipment in a very "hot" environment



CNGS Upgrades ? (2)

- **Limitations:**
  - key elements of the secondary beam line to increased beam power: **target**, **horns**, **beam windows**
  - **layout** and **RP** considerations (impact to environment - beam permit?), SPS RF and beam extraction system

- **Considerations:**
  - target/horn optimization for new (lower) energy
  - no near detector, decay pipe length, beam dump

Int. per PS batch	# PS batches	Int. per SPS cycle	200 days, 100% efficiency, no sharing	200 days, 55% efficiency, no sharing	200 days, 55% efficiency, 60% CNGS sharing
		[prot./6s cycle]	[pot/year]	[pot/year]	[pot/year]
2.4×10^{13} - Nominal CNGS	2	4.8×10^{13}	**1.38×10^{20}**	**7.6×10^{19}**	**4.56×10^{19}**
3.5×10^{13} - Ultimate CNGS	2	**7.0×10^{13}**	2.02×10^{20}	1.11×10^{20}	6.65×10^{19}

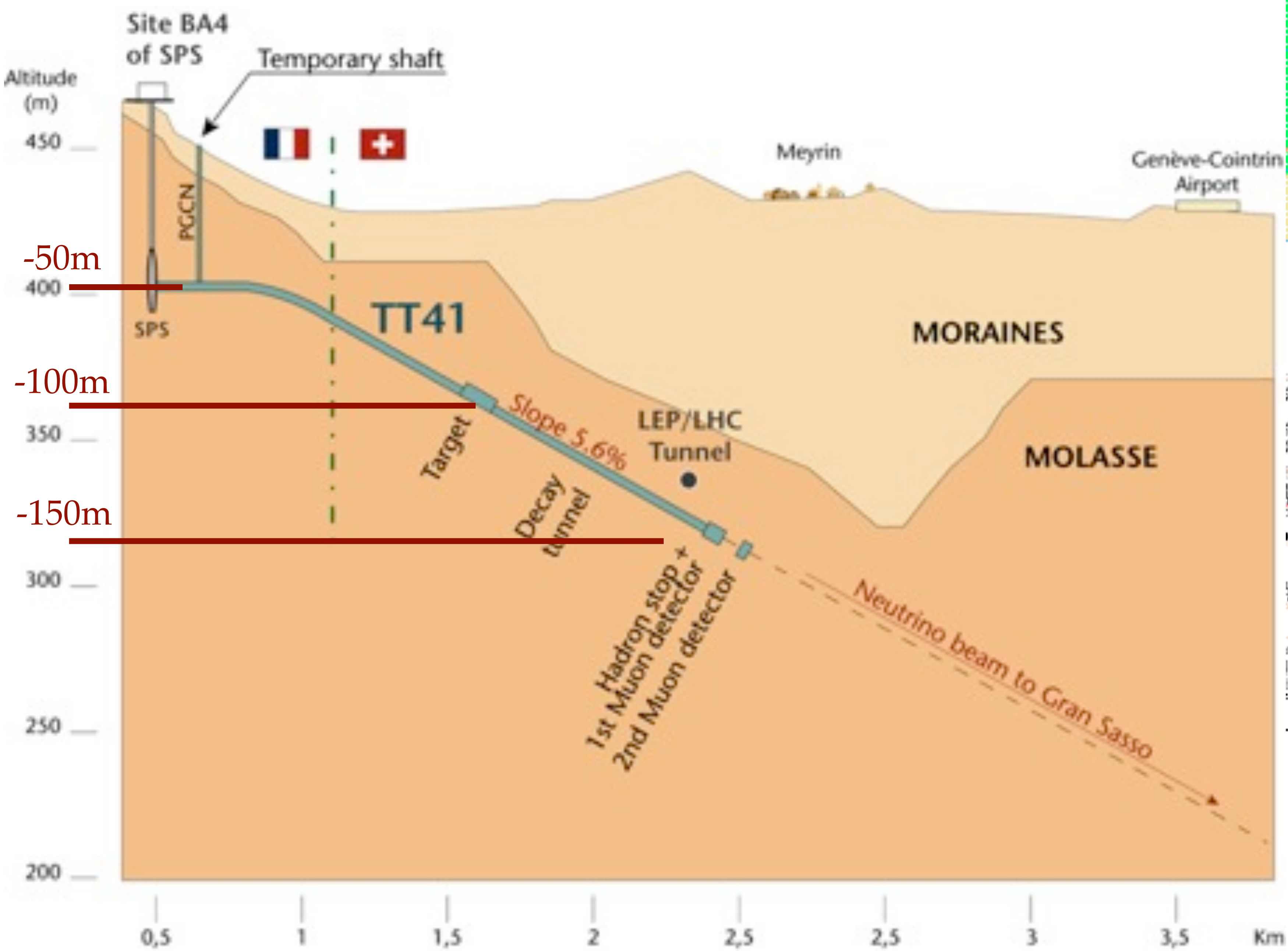
M.Meddahi, E.Schaposnicova - CERN-AB-2007-013 PAF

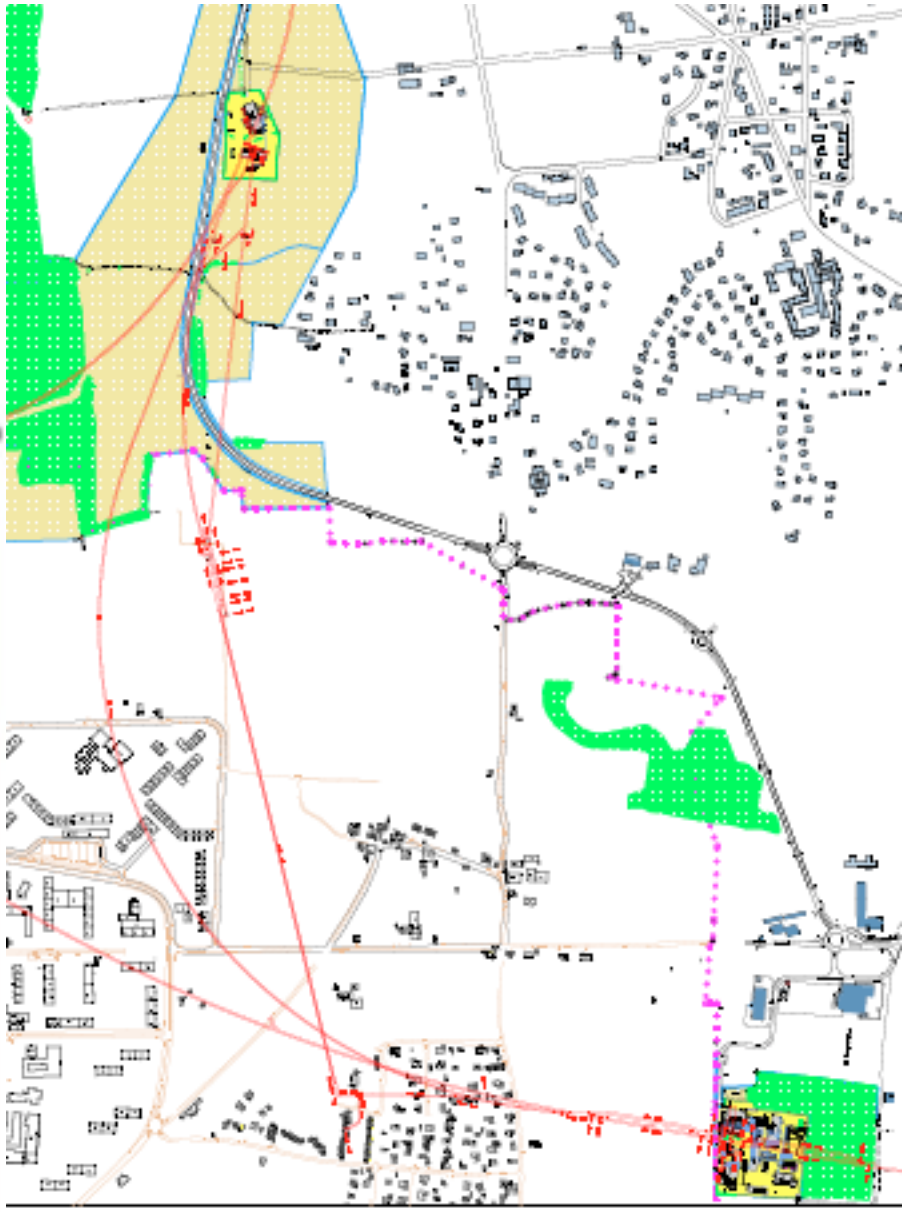
750kW design limit for the target head (rods only!)

working hypothesis for RP calculations

CNGS Upgrades ? (3)

- Near detector location under Meyrin/Airport
- Access via LHC/Point-8





CNGS Upgrades ? (4)

Summary

- Extending the lifetime of present CNGS looks tempting
  - at the same time
    - difficult to modify the layout (if requested) of highly radioactive facilities not designed to retrofit; it will be costly in dose and money, and will take time
    - the present installation may reach its limits (H3, environment impact) even before the intensity limits (~700kW) from SPS !!
    - in all cases would be a single step upgrade without long-term possibilities

- If the **CERN-LNGS** baseline represents a **solid physics case for neutrino physics today**, with **short** and **long-term** perspectives, building a new optimized target station and secondary beam with a ND is probably a better alternative
  - this is also considered for other ν-installations - NuMI

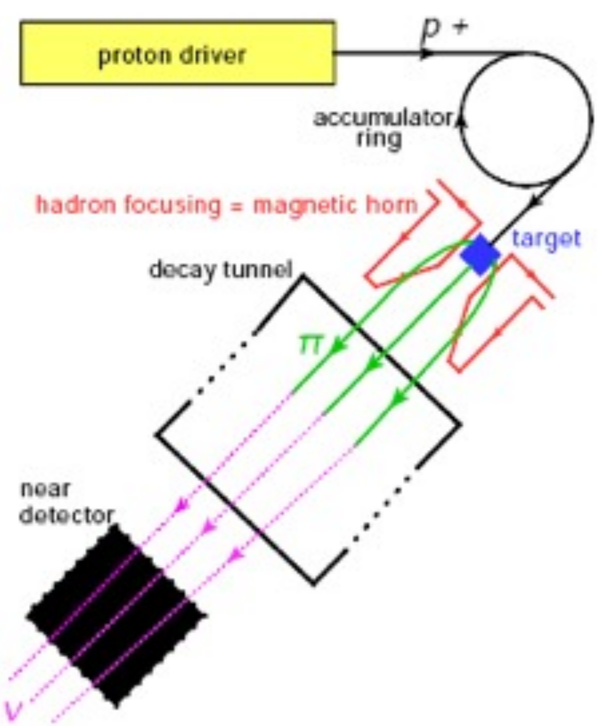
- Alternatively, the **experience gained** by CNGS in the design and operation of high-power neutrino beams (and **detectors**), can be **capitalized** in future projects

EUROnu / FP7 - Design Study (2008-2012)

- Three neutrino beam facilities under study

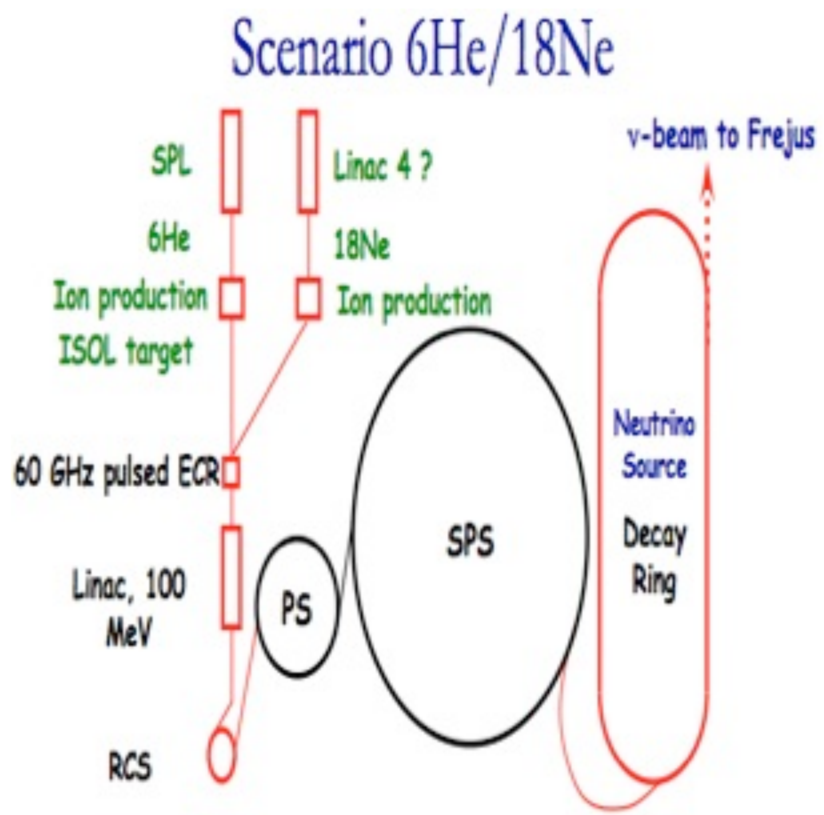
- Super beam : CERN ⇒ Frejus(FR)

- **4MW** proton beam from CERN HP-SPL @ 5 GeV
- **130 km** baseline
- **440 kT** fm detector



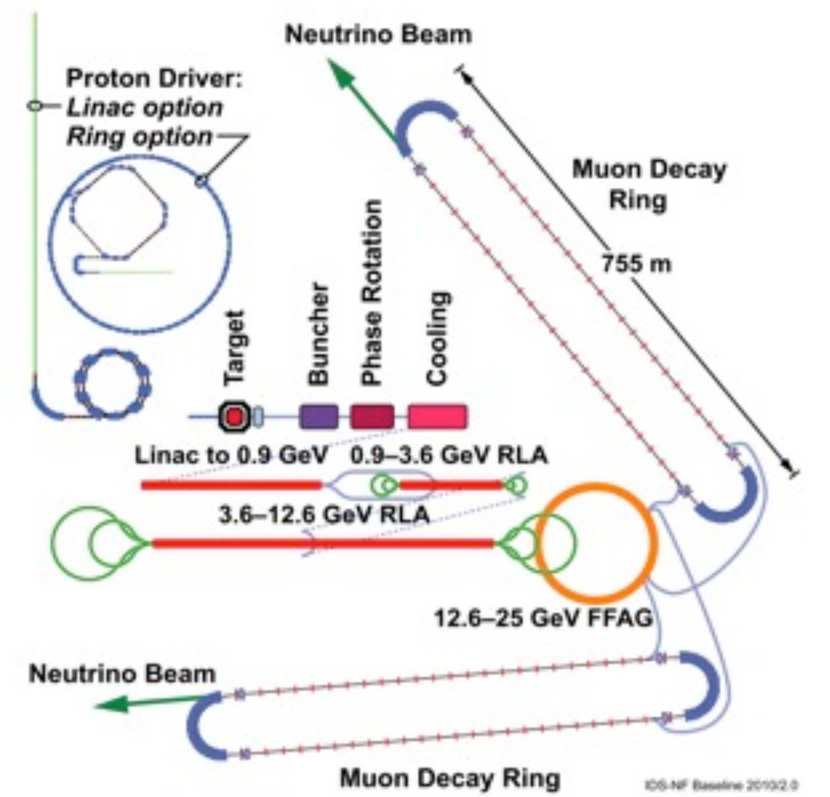
- β-beam : CERN ⇒ Frejus(FR)

- ion production options:
  - **He^6/Ne^{18}** - Li^8/B^8
- γ=100



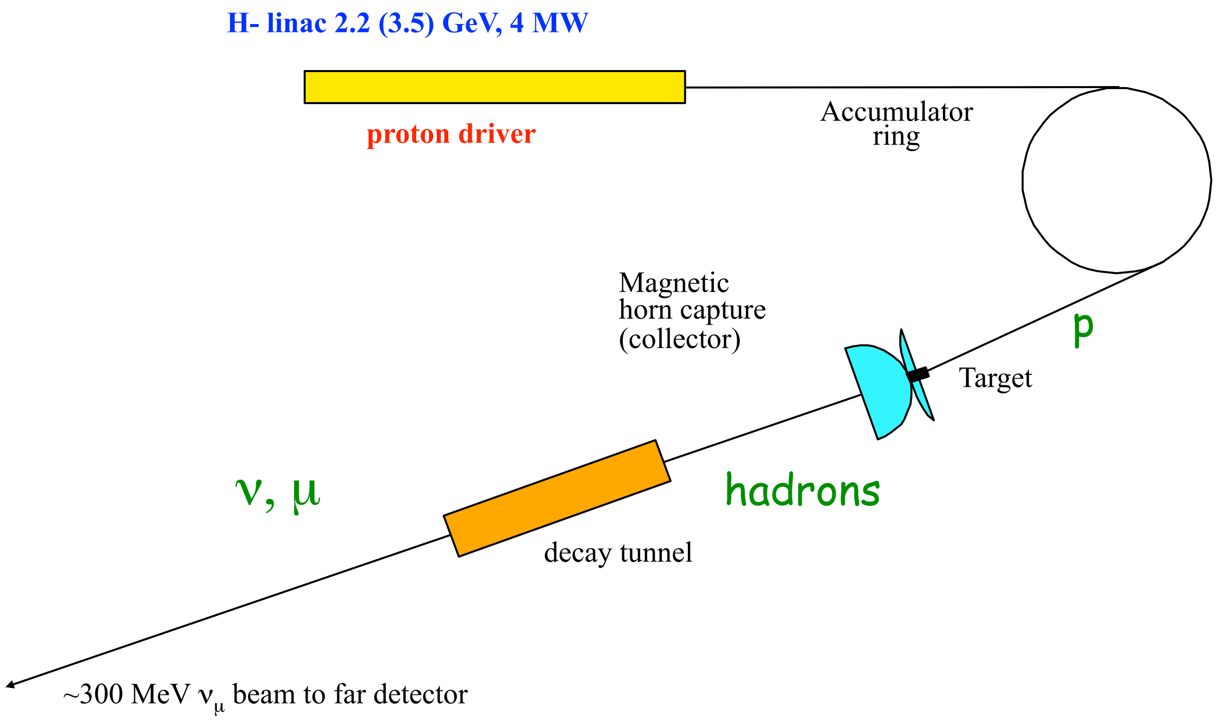
- Neutrino Factory - IDS/NF

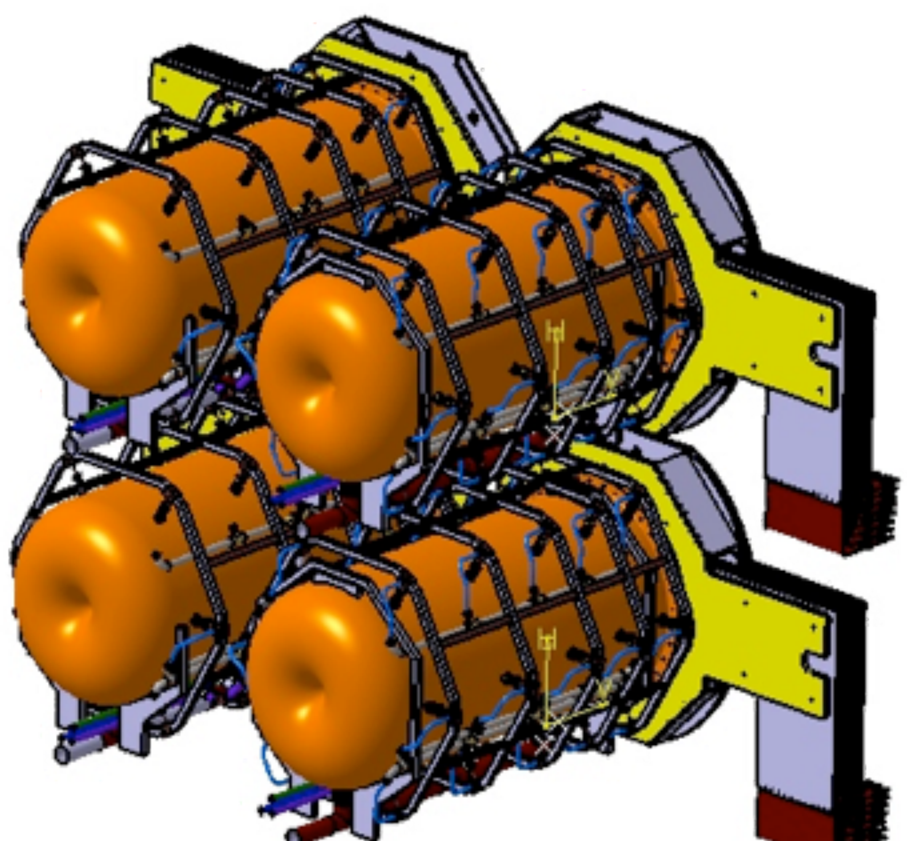
- **4MW** proton driver
- **target station** and **cooling** channel
- muon acceleration to 25 GeV or
- **low-energy NF** based on θ_{13} value



- Deliverable : comparison evaluation based on **cost, physics reach**
  - use CERN as example site for localization dependent costs

EUROnu : CERN Super-beam to Frejus





Courtesy : M. Dracos - EUROnu

Technical Challenges

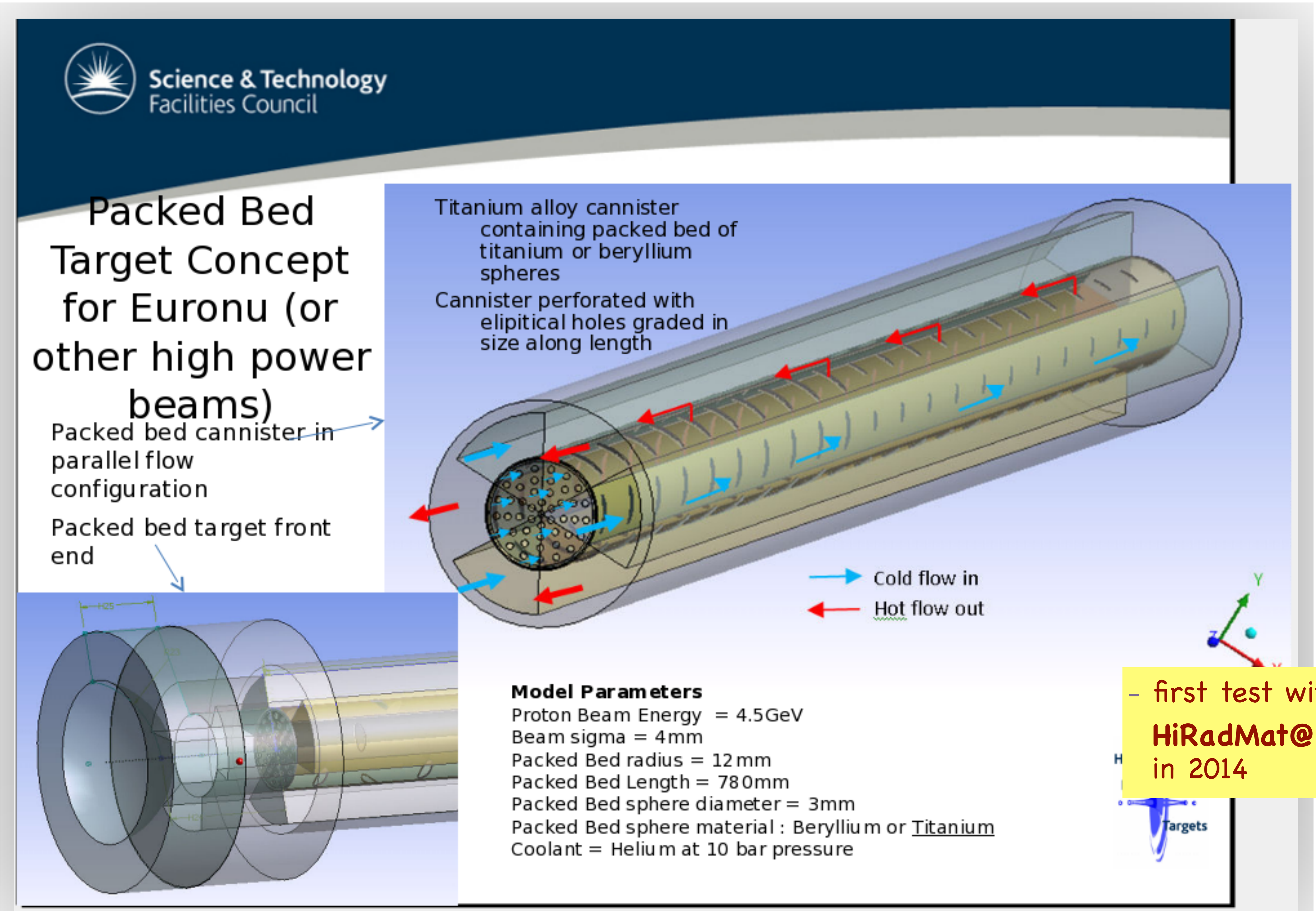
- Target design
  - impact of the 4 MW beam
  - 50 Hz operation
- Horn design
  - high-current, mechanical constraints due to physics requirements, radiation, heating (Joule effect + radiation), pulsing

Solution

- **4 × 1 MW = 4 MW !!**
- four target/horn assemblies mounted on a common mechanical structure
- 12.5 Hz operation, beam delivery ???

EUROnu : CERN Super-beam to Frejus

- **Target baseline :** packed bet with Ti spheres



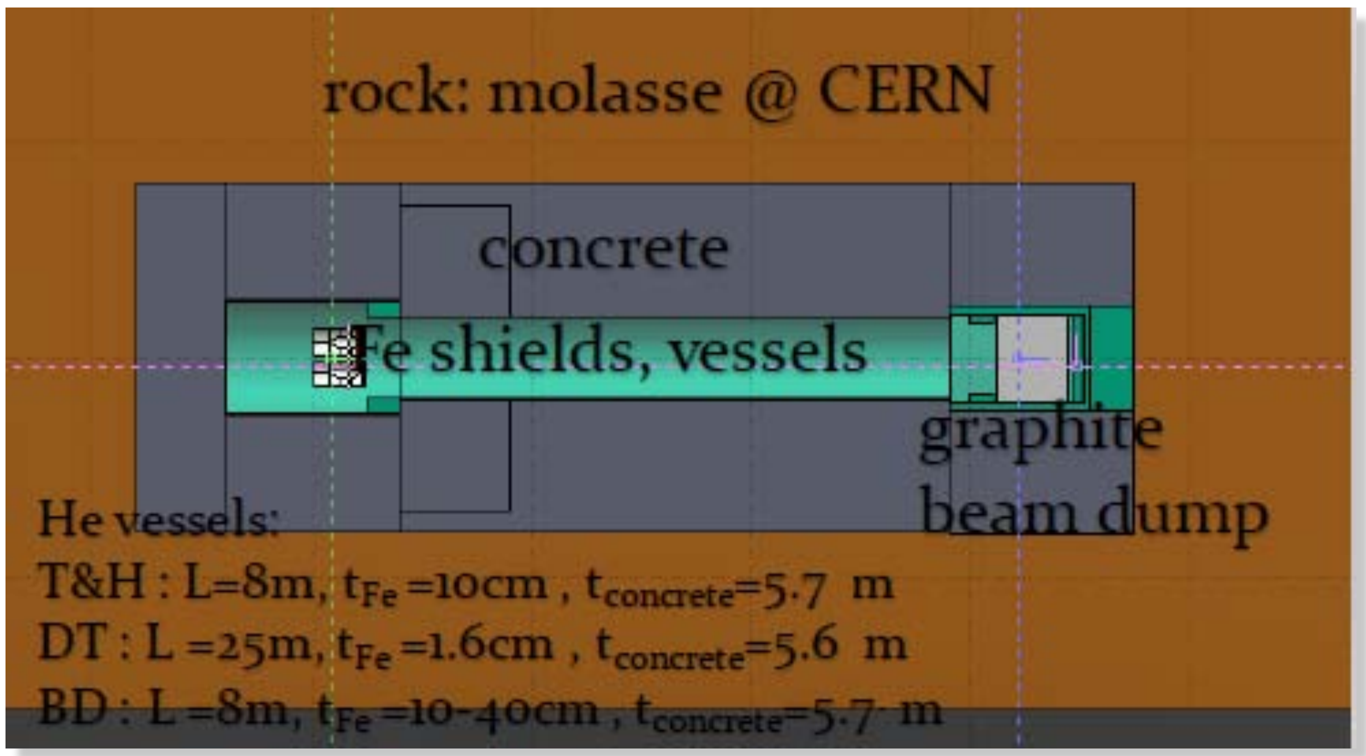
- first test with beam in the new **HiRadMat@SPS** facility at CERN in 2014

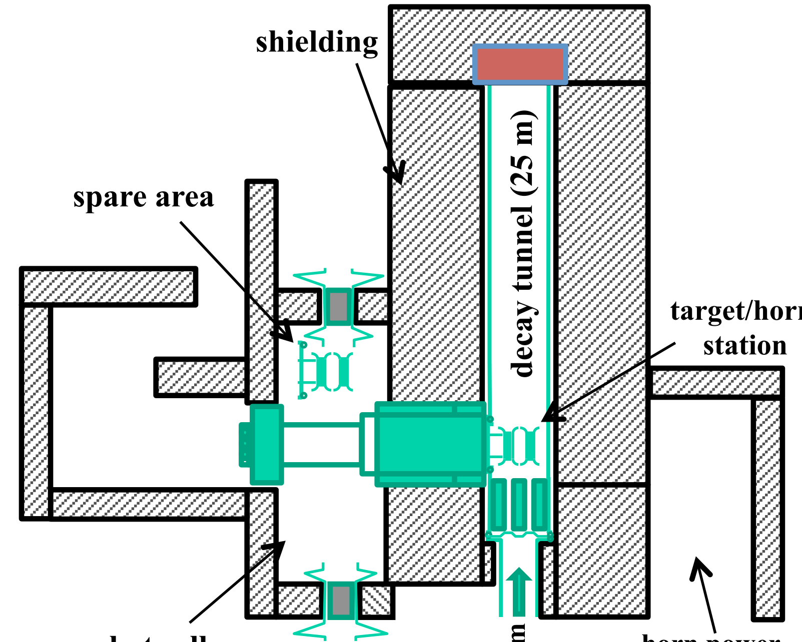
Courtesy : Chris Densham - EUROnu

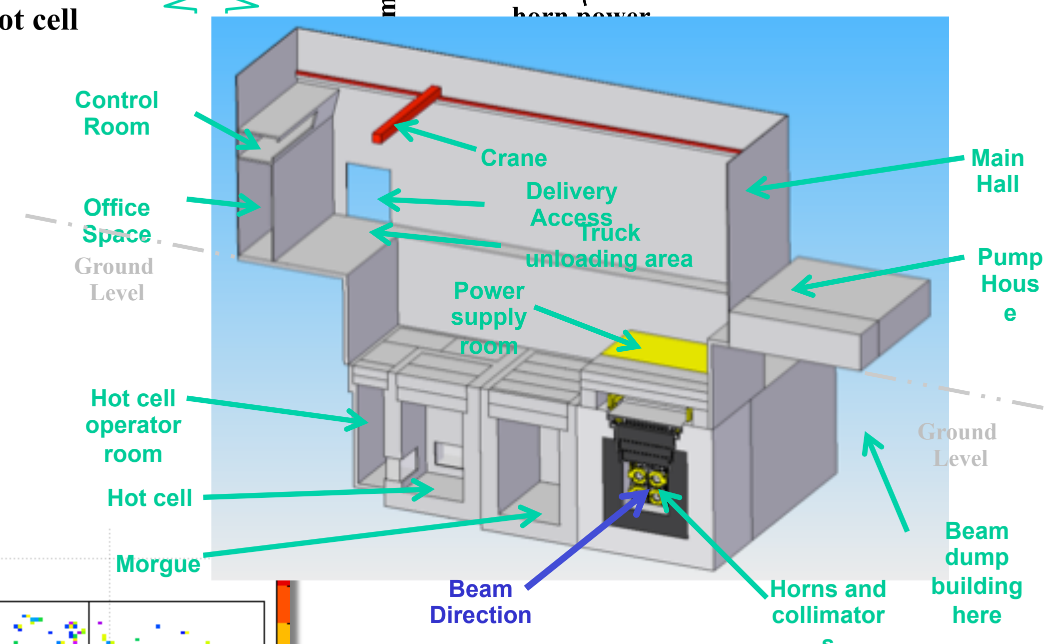
EUROnu : CERN Super-beam to Frejus

Courtesy : M. Dracos - EUROnu

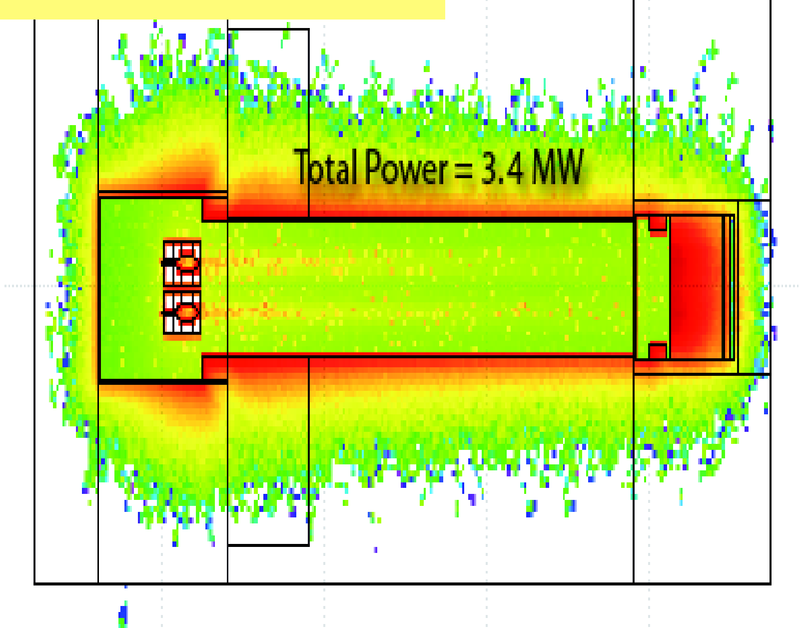
Layout and RP studies



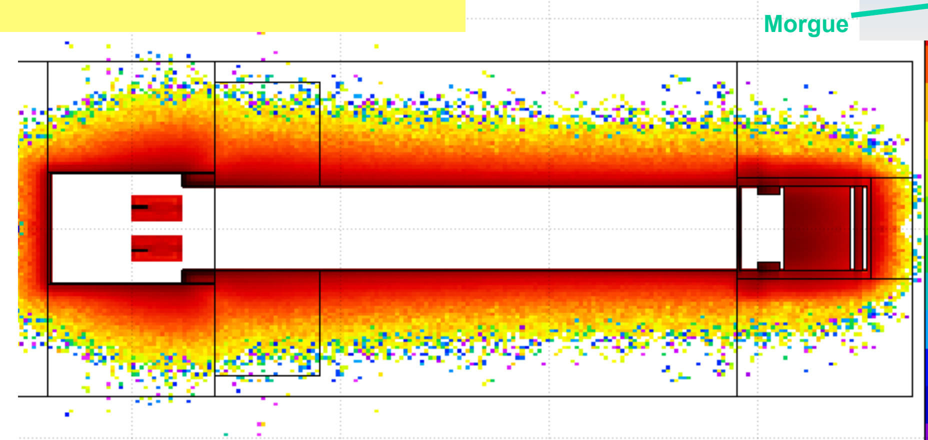




- Energy deposition



- Activation studies



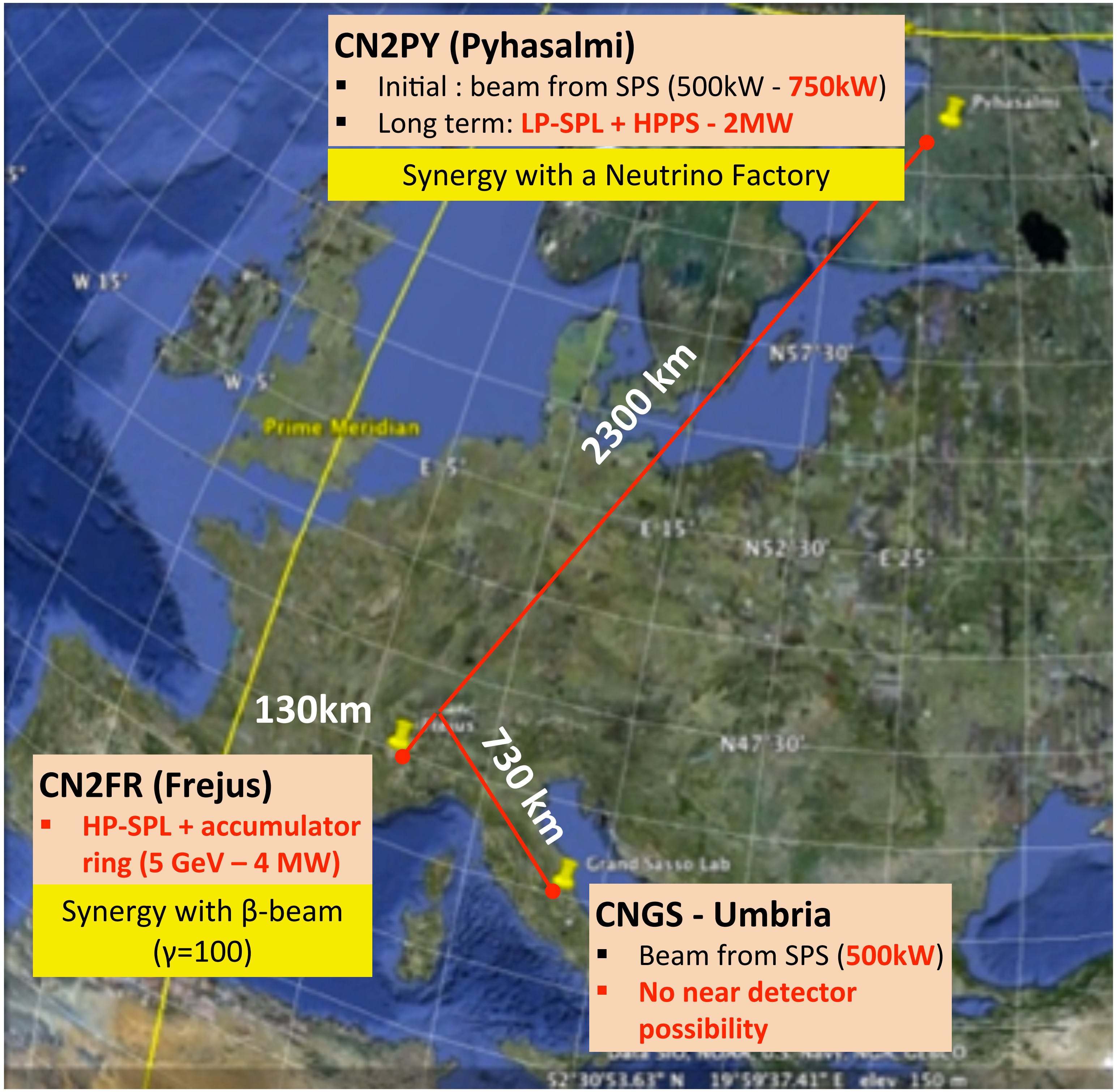
- A **6m thick concrete wall** surrounding all the layout is sufficient to limit the production of radionucleides in the molasse.
- expected horn lifetime : **80÷200 days !!!**

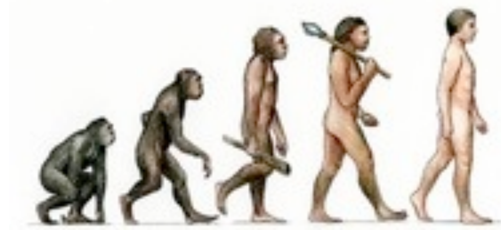
LAGUNA_LBNO / FP7 Design Study (2011-2014)

- New design study, extending that of LAGUNA, **including the neutrino beams from CERN**
- Beam options for **unique physics** opportunities in Europe

  ☞ Talk A. Rubbia, S. Pascoli

- Profit from **experience** gained with the CNGS operation
- **Incremental** approach with competitive physics goals at each stage
- **Synergy** with other ν-beam options
  - CN2FR : β-beam
  - CN2PY : Neutrino Factory
- Collaboration in a **global** scale, profit from know-how in other ν-beam facilities in US and Japan



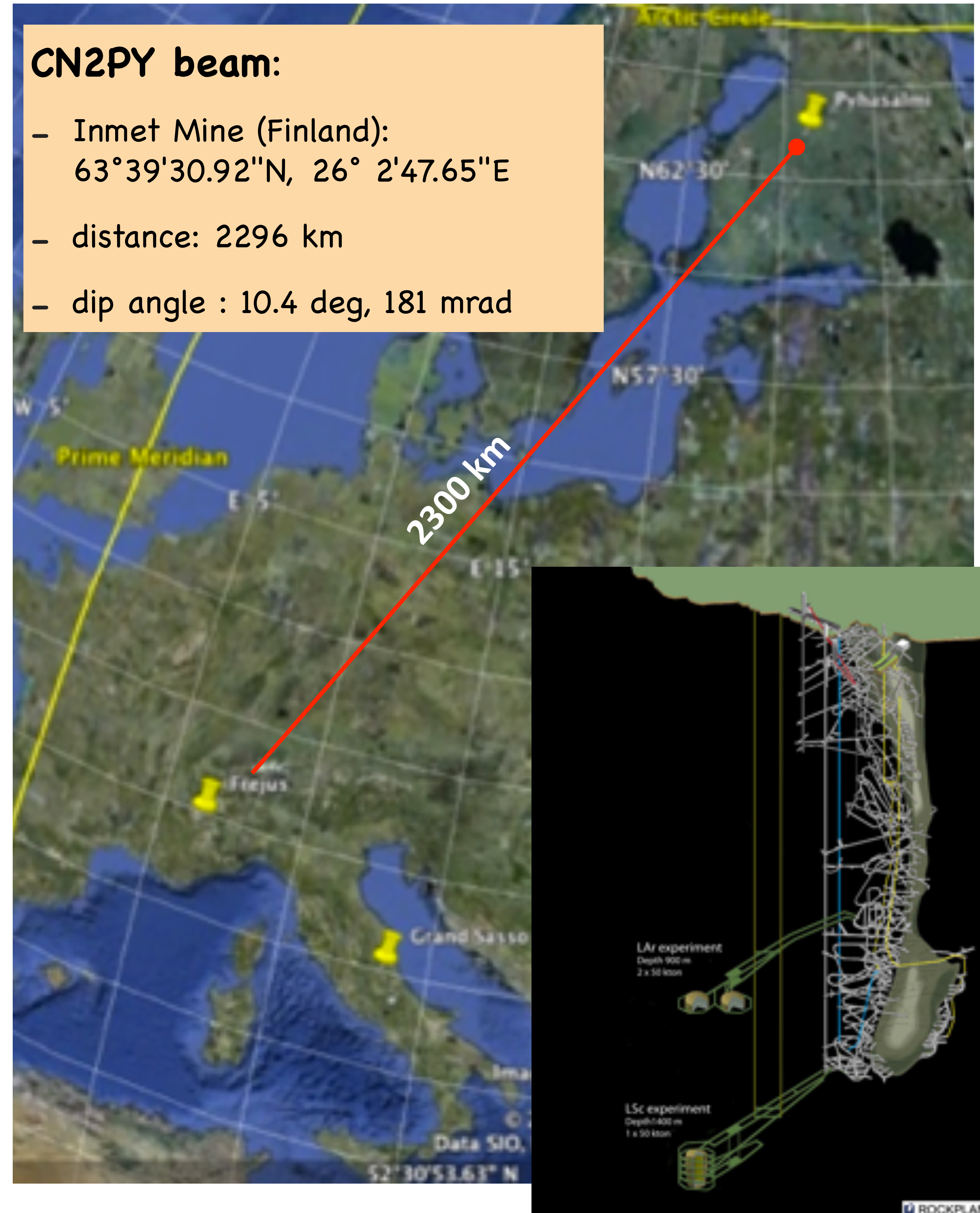


CN2PY LBL ν-beam

- A Long-baseline Neutrino Beam for unique physics opportunities in Europe
- **Incremental** approach for beam intensity
  - Initial phase: **400 GeV** protons from **SPS**
    - present **500kW** beam operation (CNGS)
    - future **~700kW** profiting form injector upgrades
  - Second phase: **30-50 GeV** protons from a new **HP-PS**
    - Use the (LP)-SPL as injector (4 GeV ?)
    - Fast acceleration reaching **~2MW**
- ..and detector size
  - Phase 1: 20kT LAr + 25kT LSc + Fe detector
  - Phase 2(add): 50kT LAr + 25kT LSc + Fe detector
  - Phase 3 : replace 20kT by 50 kT LAr + Fe detector
- Clear physics opportunities for each stage, flexible program that can adopt to physics requirements and possible funding profile

CN2PY beam:

- Inmet Mine (Finland): 63°39'30.92"N, 26° 2'47.65"E
- distance: 2296 km
- dip angle : 10.4 deg, 181 mrad



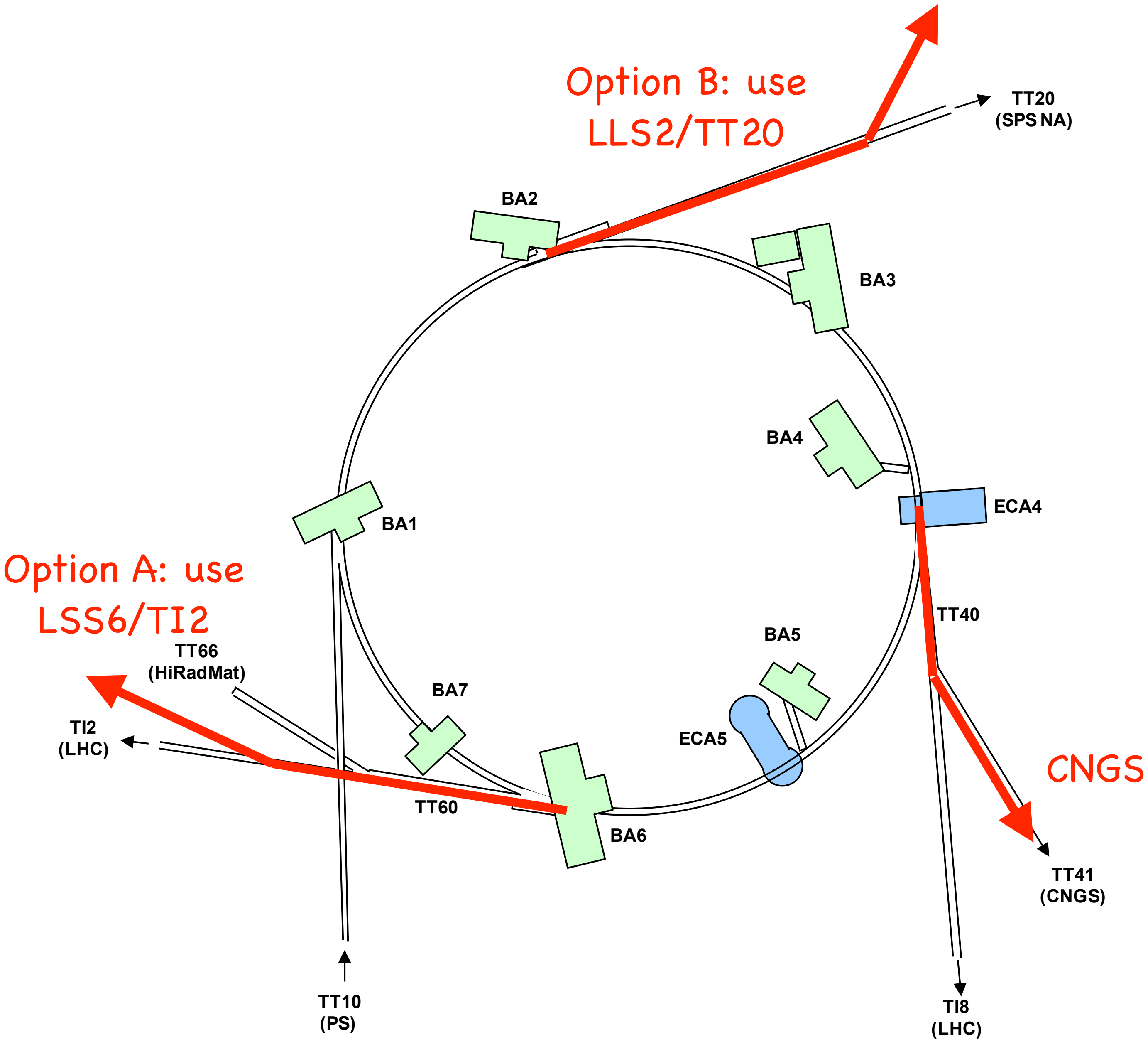
CERN ν-beam to Pyhasalmi - CN2PY

- Phase 1 layout using the 400 GeV beam from SPS

Possibilities:

- **Option A**: LSS6 extraction, target near BA2
  - LSS6 fast extraction and TT60 beam line exists
  - New switch to direct the proton beam towards North
  - Long (~1.6km) proton tunnel to bring the beam towards BA2

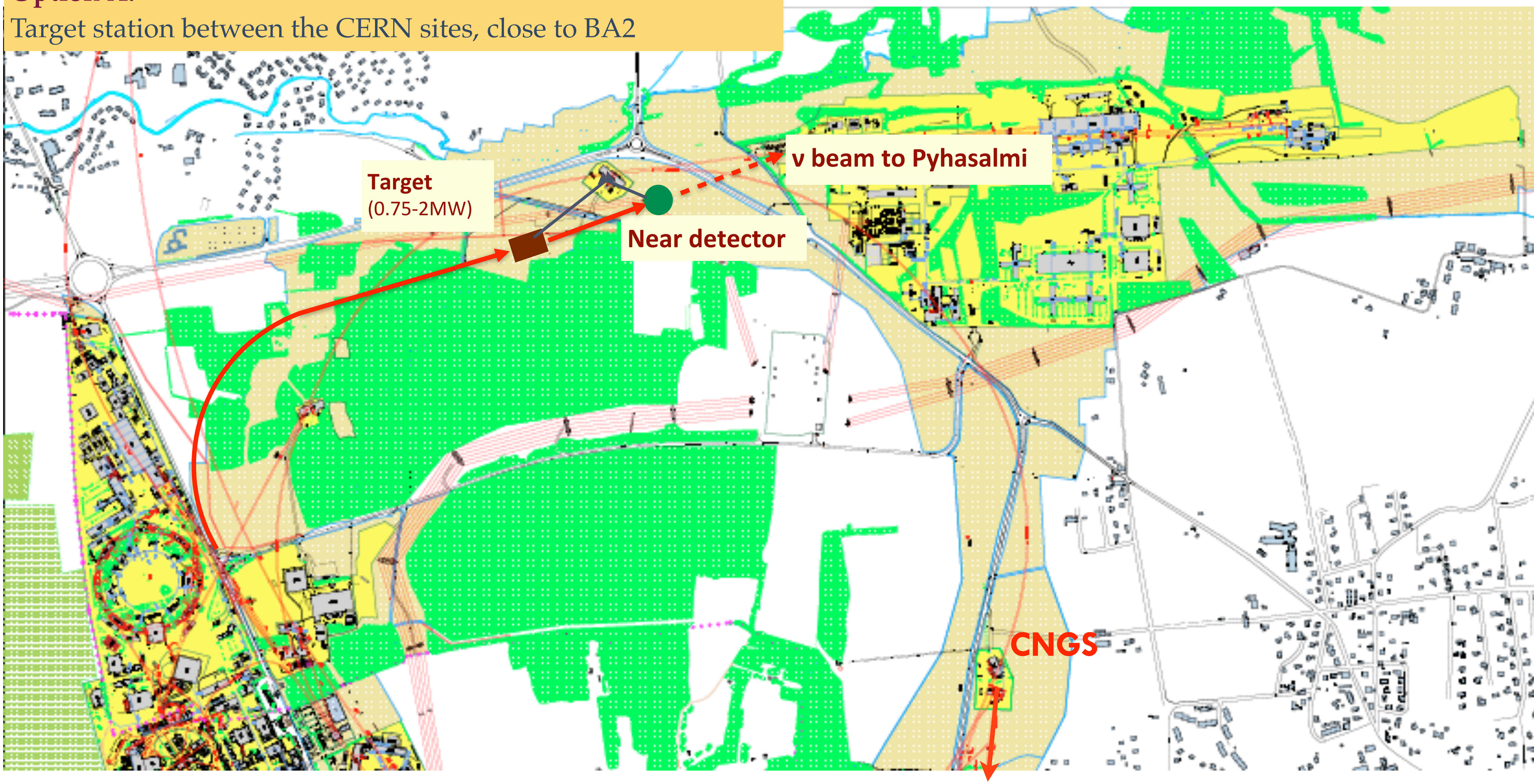
- **Option B** : LSS2 extraction, target near TCC2
  - new fast extraction system in LSS2
  - TT20 beam line exists
  - Target area near existing TCC2



Courtesy : B. Goddard - LLBNO

CERN ν-beam to Pyhasalmi - CN2PY

Option A:
Target station between the CERN sites, close to BA2



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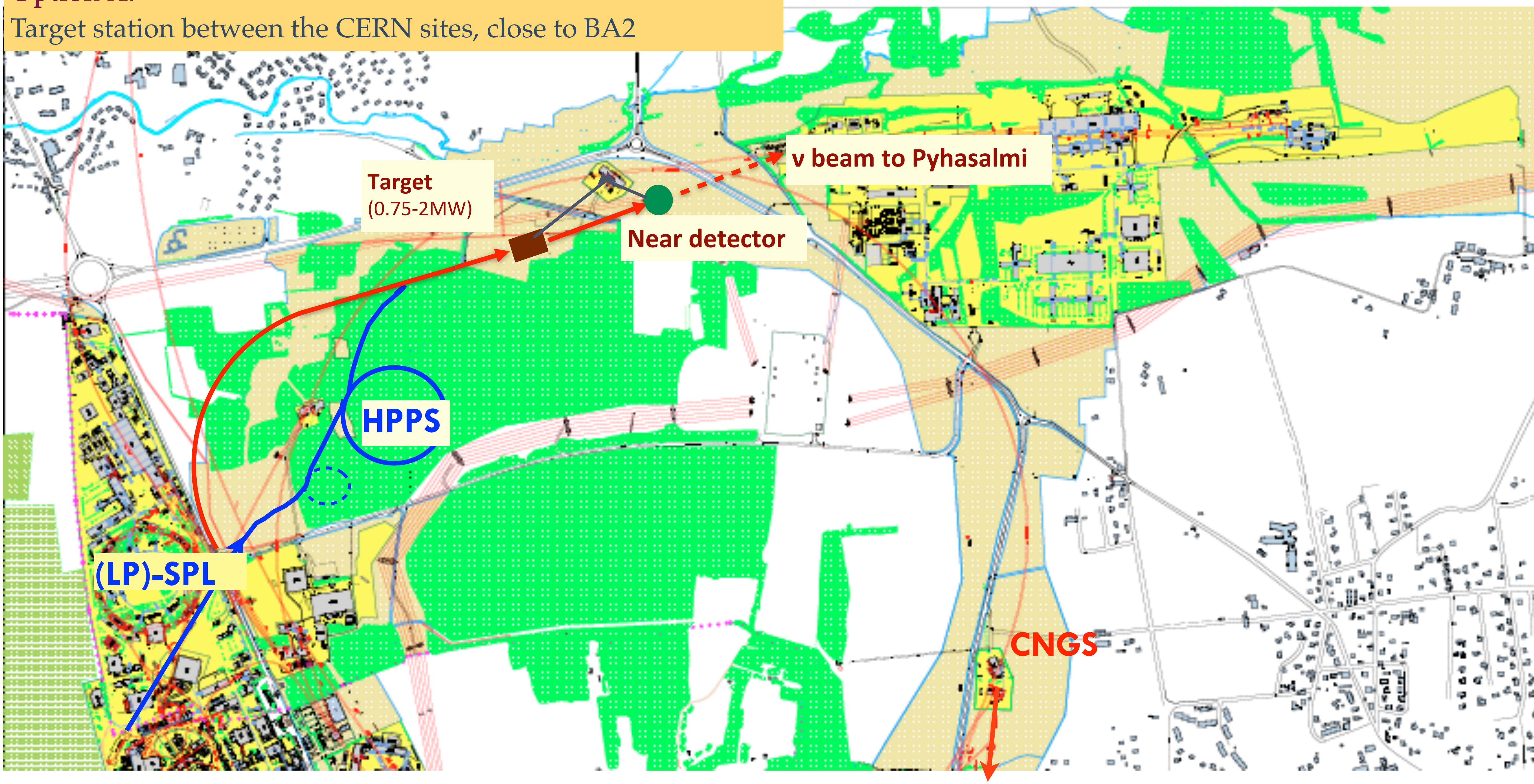
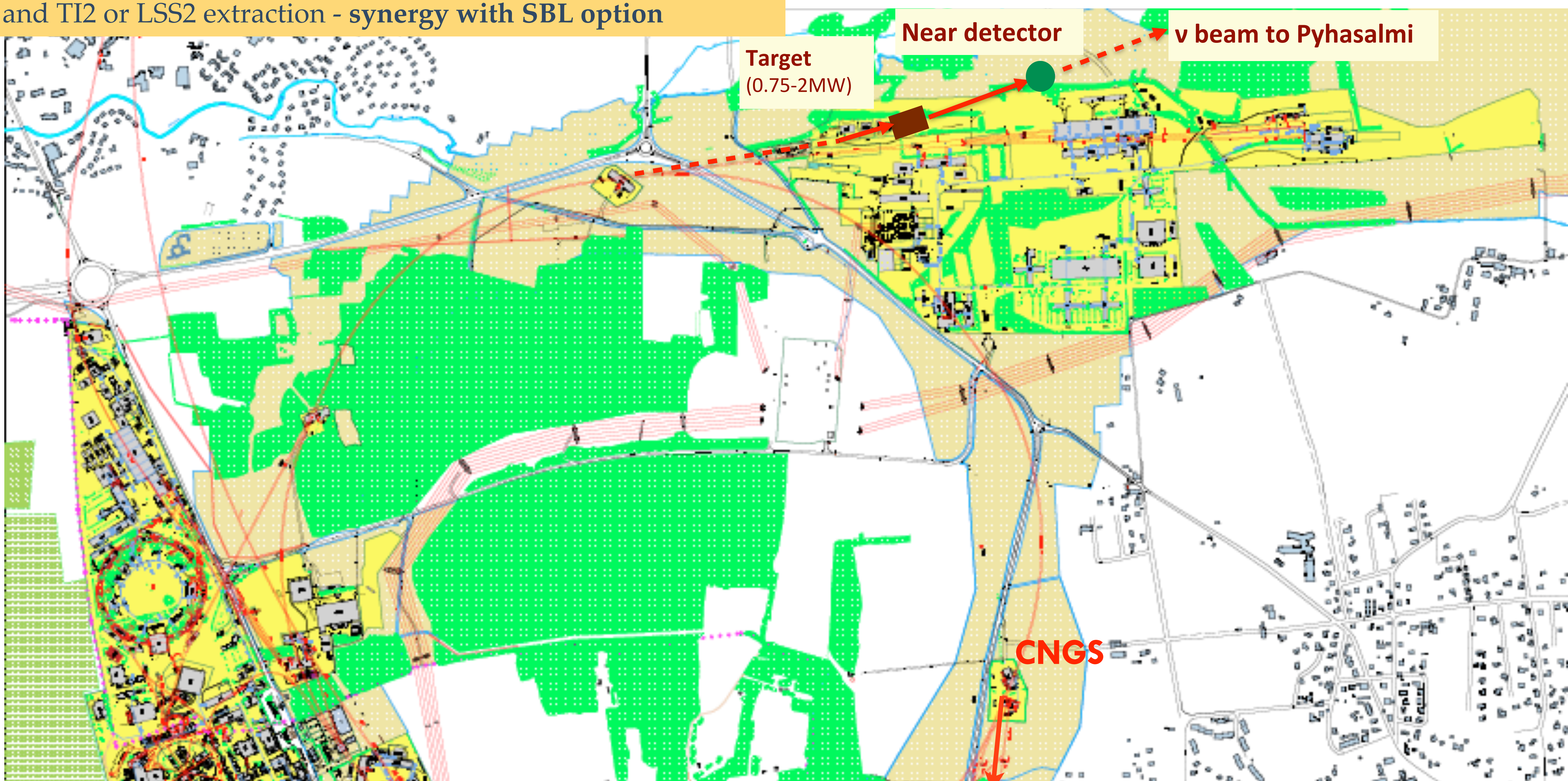


CERN ν-beam to Pyhasalmi - CN2PY

Option B:
Target station and ND in the North Area, use existing TT20 line and TI2 or LSS2 extraction - **synergy with SBL option**



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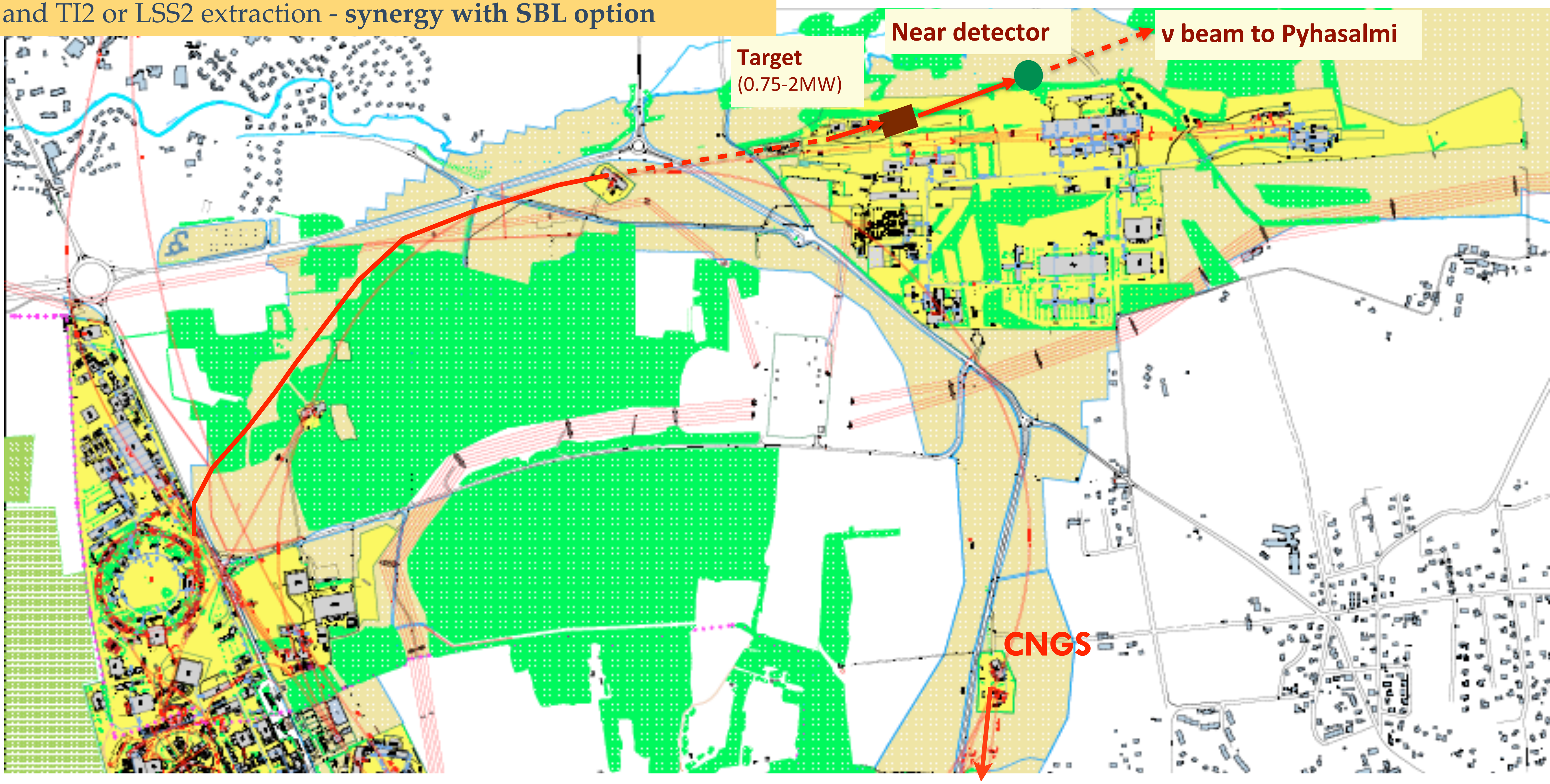

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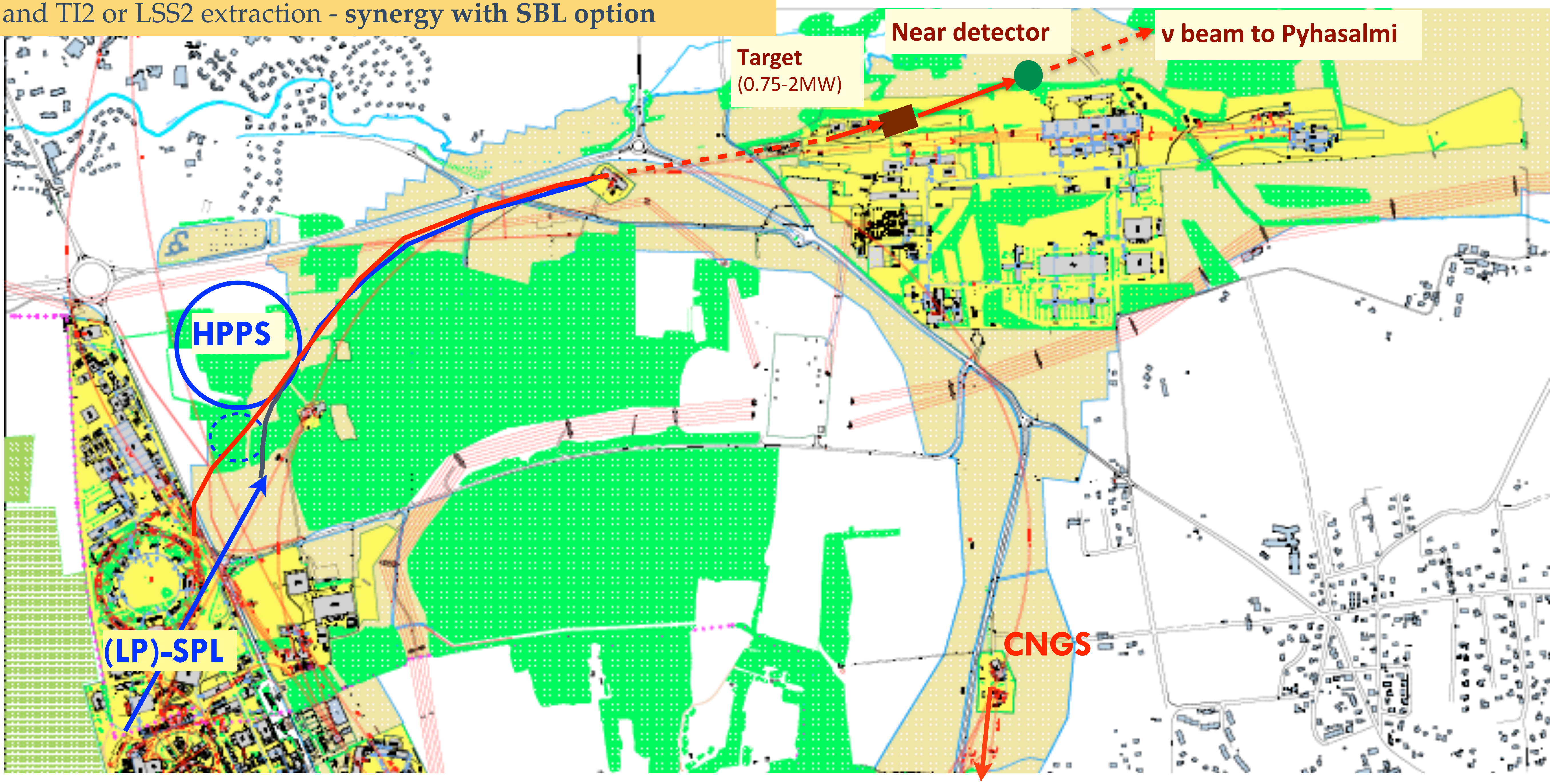
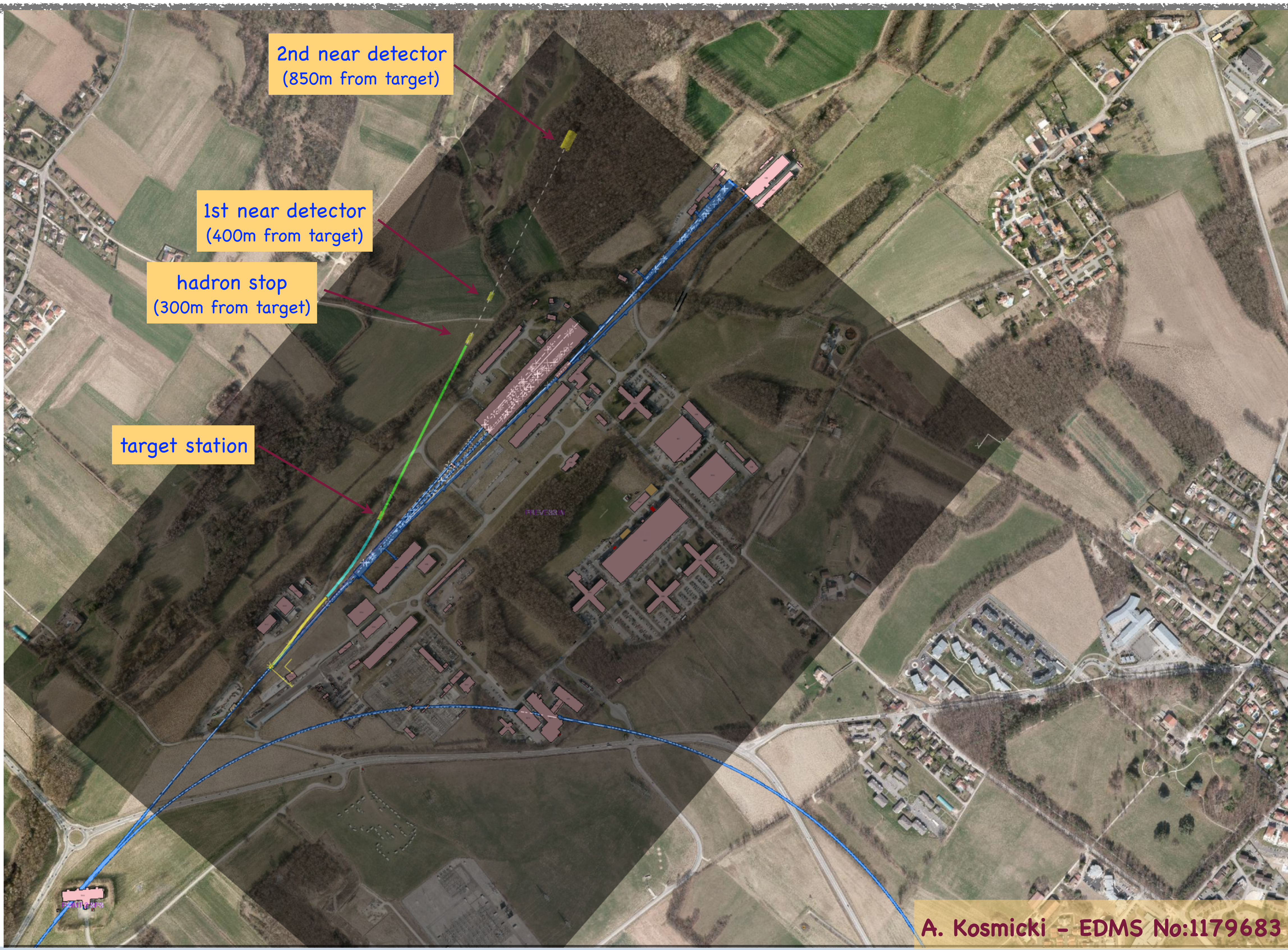
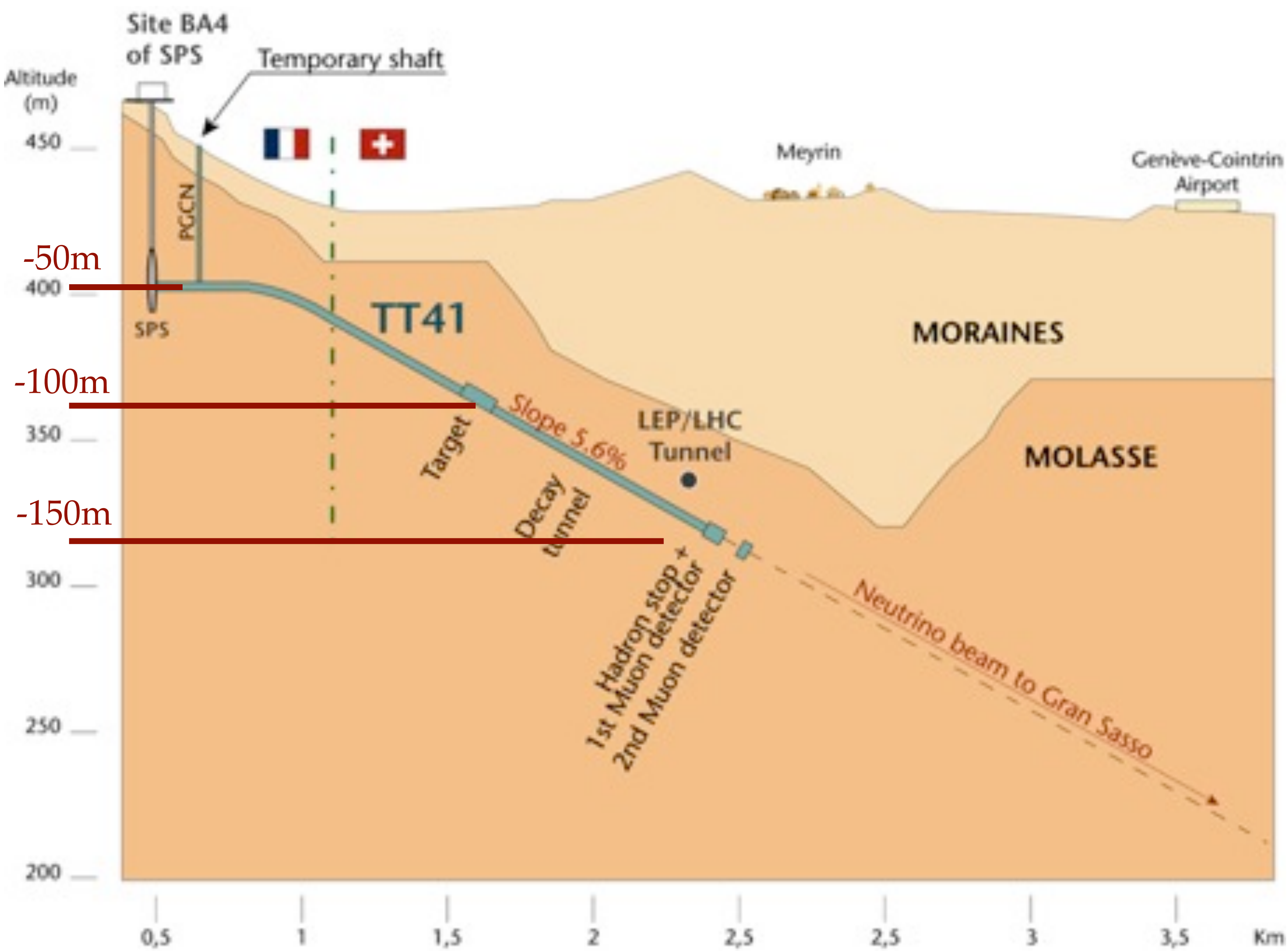


CN2PY Option-B Layout study



CN2PY - Layout considerations

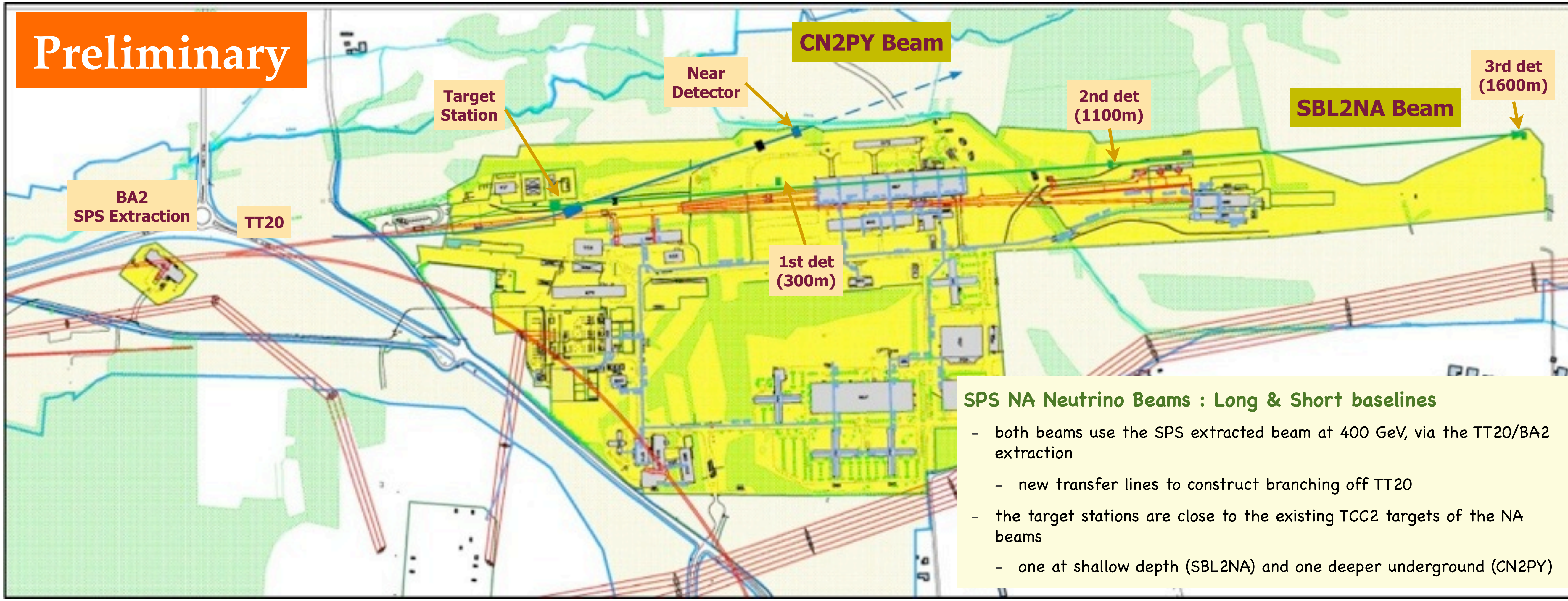
- The depth for the installations is the major concern
  - 18% slope compared to 5.6% for CNGS



CN2PY Beam - Generic Layout		
	Distance	**Depth**
Target	-	0 m
Hadron stop	300 m	-54.3 m
Muon station	330 m	-59.8 m
Near detector	400 m	-72.6 m
Middle detector	830 m	-150.6 m

- Starting the beam from the SPS level adds **~100m** to the depth of the installations
- Staying in the **molasse layer** has quite some advantages for the CE (stability) and radiation to environment (underground water activation issues) issues

NA Long & Short Baseline ν beams



- **CN2PY Beam layout parameters**
  - 10.4 deg downwards slope to point to Finland
  - 15.1 deg angle wrt North Area beams
  - target station at ~34m underground
    - 20 m deeper than the existing TCC2 targets
    - ~6m of concrete shielding around to allow 2MW operation
  - decay pipe ~300-400m long
  - near detector at ~500m, 116m underground, within the CERN area

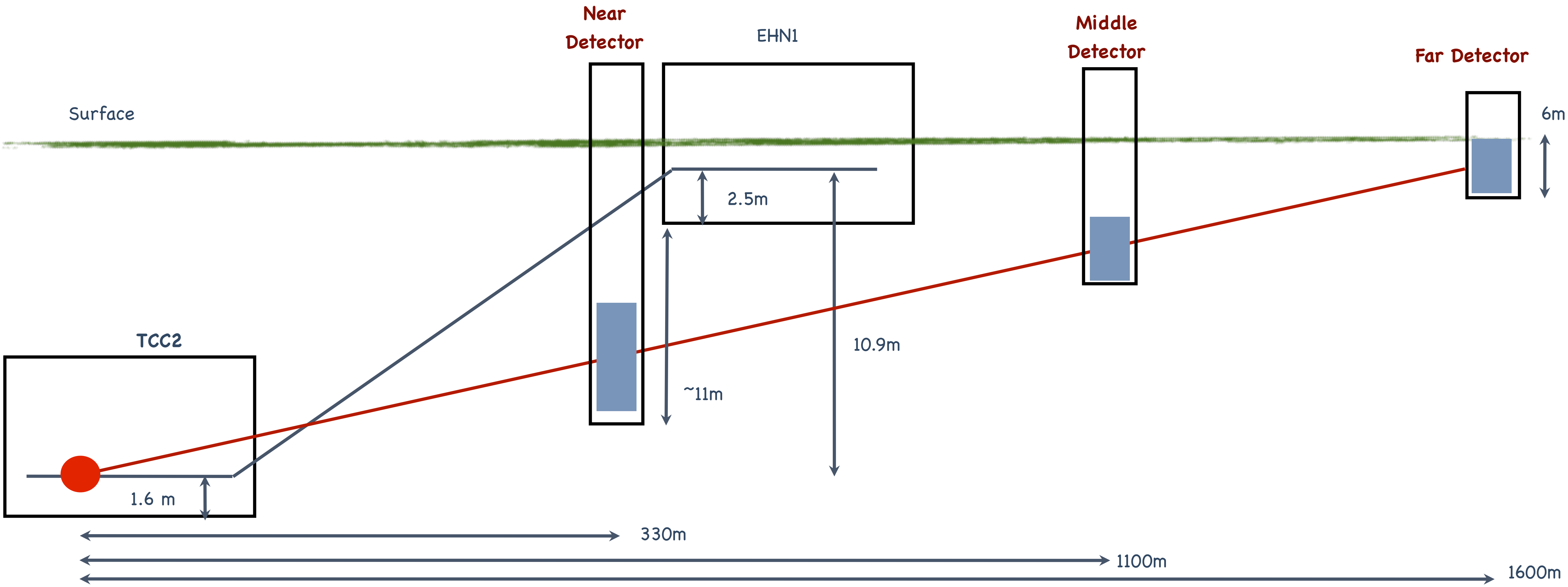
- **Short-Baseline beam (SBL2NA)**
  - horizontal (or slightly upwards) beam line
  - short decay pipe (~50m) followed by the beam dump
  - target station at ~10m underground, adjacent to existing TCC2 target station
  - possibilities for detectors at 300, 1100, or 1600m
    - profit from existing infrastructure, including cryogenics
  - detector position and on/off axis location depending on physics

Short Baseline ν beam in the SPS North Area

Layout parameters

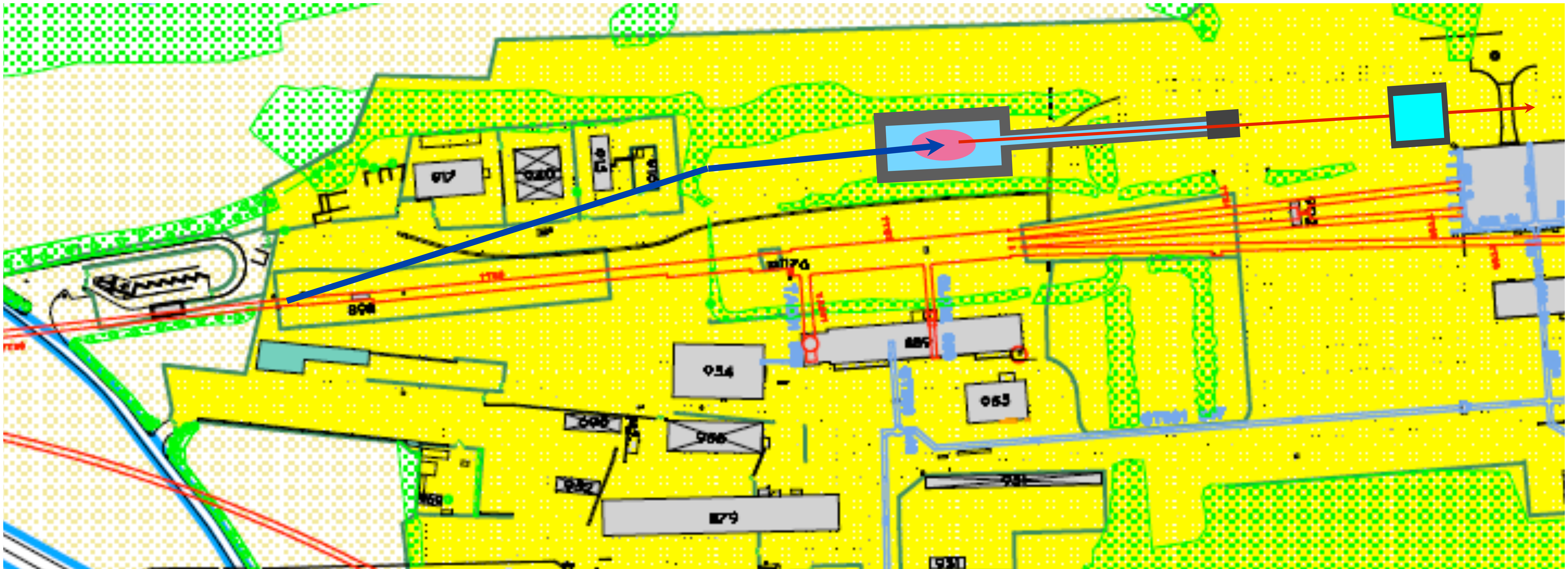
- primary beam : **100 GeV**, ν-beam : **~2 GeV**
- target station at the TCC2 level (**~11m underground**)
  - Lateral distance defined by the location of the near&far detectors
  - sufficient distance from TCC2 to allow works during NA operation
    - not really mandatory but better if we can, at least for civils
  - Cavern design like NuMI (LBNE)
- decay pipe : **80m, 3m** diameter
- beam dump : **15m of Fe** with graphite core, followed by μ stations
- ν-beam angle : pointing upwards
  - at -3m in the far detector --> **~5mrad slope**

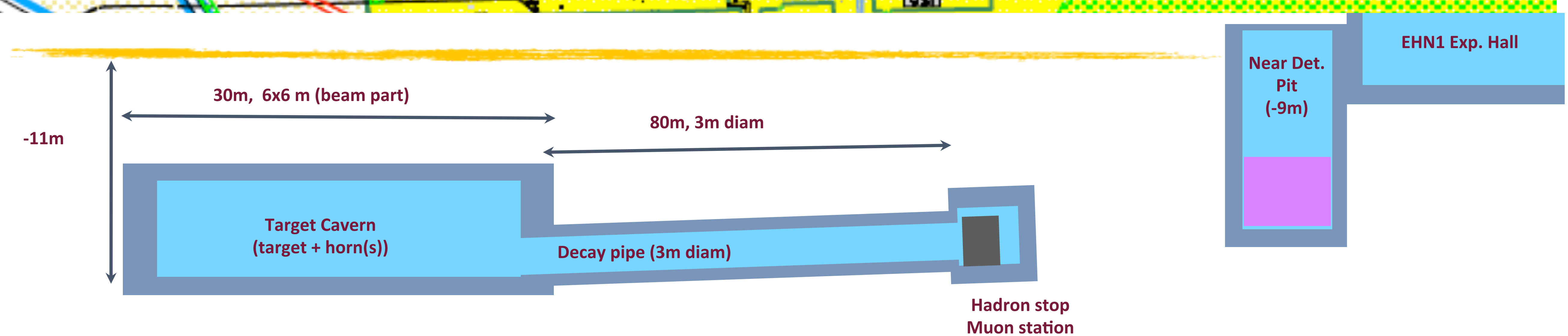
SBL2NA Layout - Vertical plane



- Neutrino beam slope : 8m/1600m = 5mrad
- Depths :
  - near detector : -9.3m, or ~11m below the EHN1 level
  - middle detector : -5.5m
  - far detector : -3m

SBL2NA Layout – Target station and Near Detector





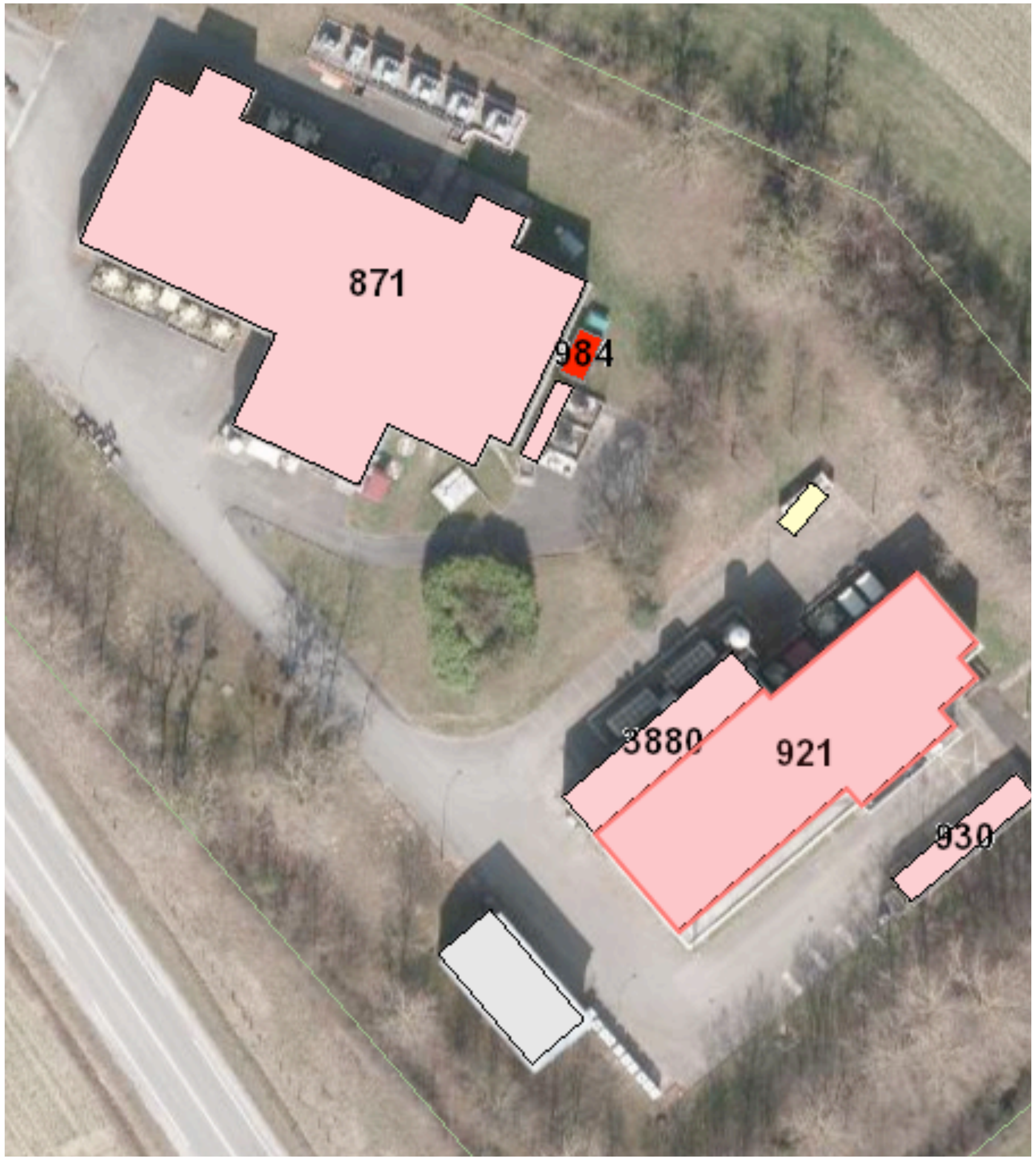
Short Baseline ν beam in the SPS North Area

Variant - "Saleve" side

- tuned for the 100 GeV primary beam
- has a shorter primary proton beam
- better (cheaper) detector locations, could profit from the muon/neutrino beam of COMPASS

NA ν-beam facility - Civil Engineering Works

- Primary beam
  - 300m of beam tunnel (4.5m diameter ?)
  - Connection to TT20
- Target station + Secondary beam
  - Target station
  - Decay pipe
  - Hadron stop
- Detector pits
  - Near detector
  - Far detector
- Buildings
  - Primary beam services
  - Target station services



BB4 (b.921,3880): surface service building for TT41/CNGS (should also count the equipment installed in ECA4 [horn-PS]!

CN2PY/SBL2NA - A 3rd Generation ν-beams

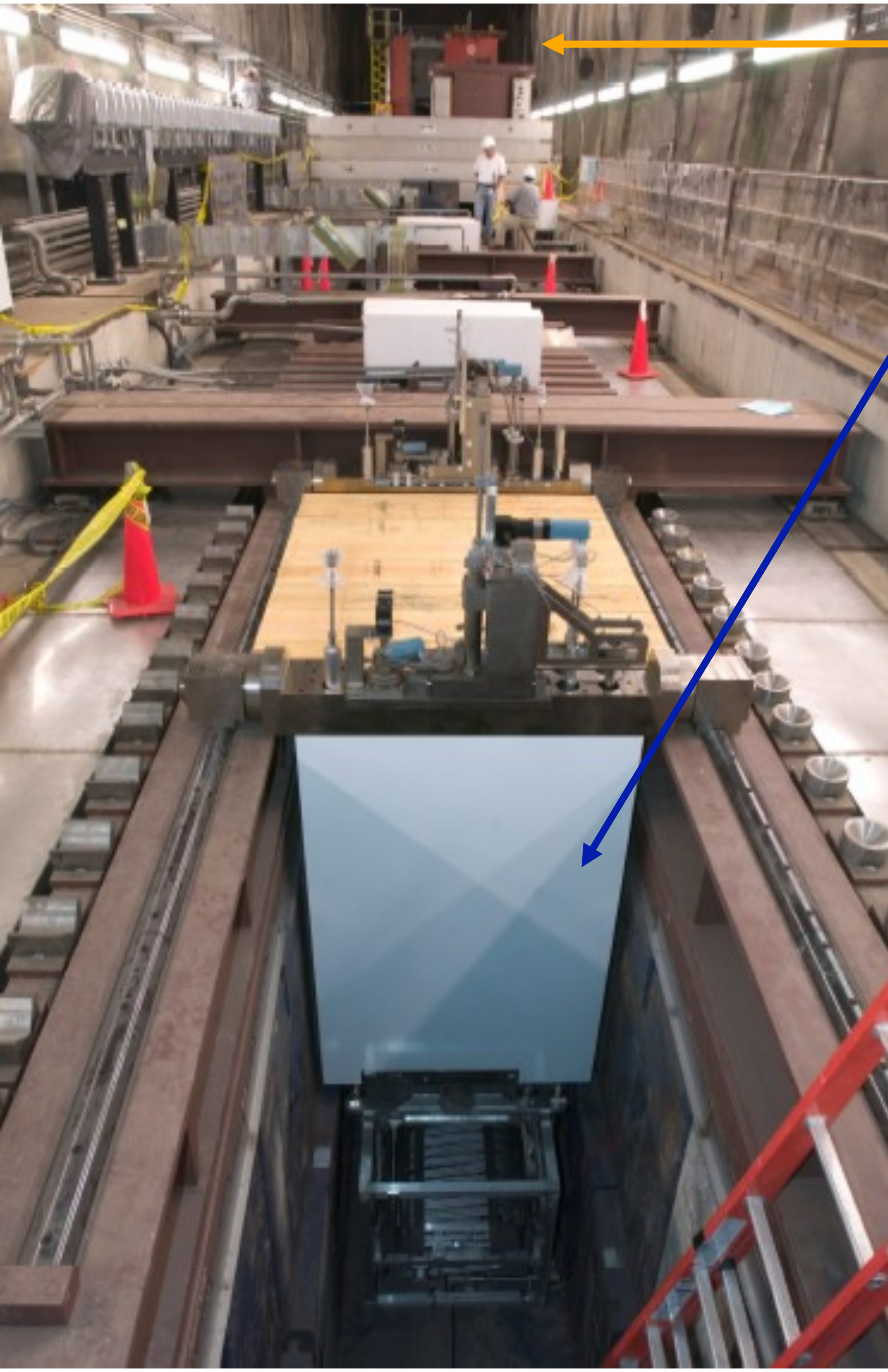
- Profit from the existing experience from the other installations:
  - **CNGS** : radiation, tritium issues, target lifetime/operation
  - **T2K** : high-power design, He vessel for target and decay pipe, remote handling
  - **NuMI** : layout design access and repair of "hot" equipment
- .. and the design options for future projects
  - **LBNE** : target station layout options
  - **Neutrino Factory** : target station design

MINOS Target Chamber

Work cell

Target module in beam-line

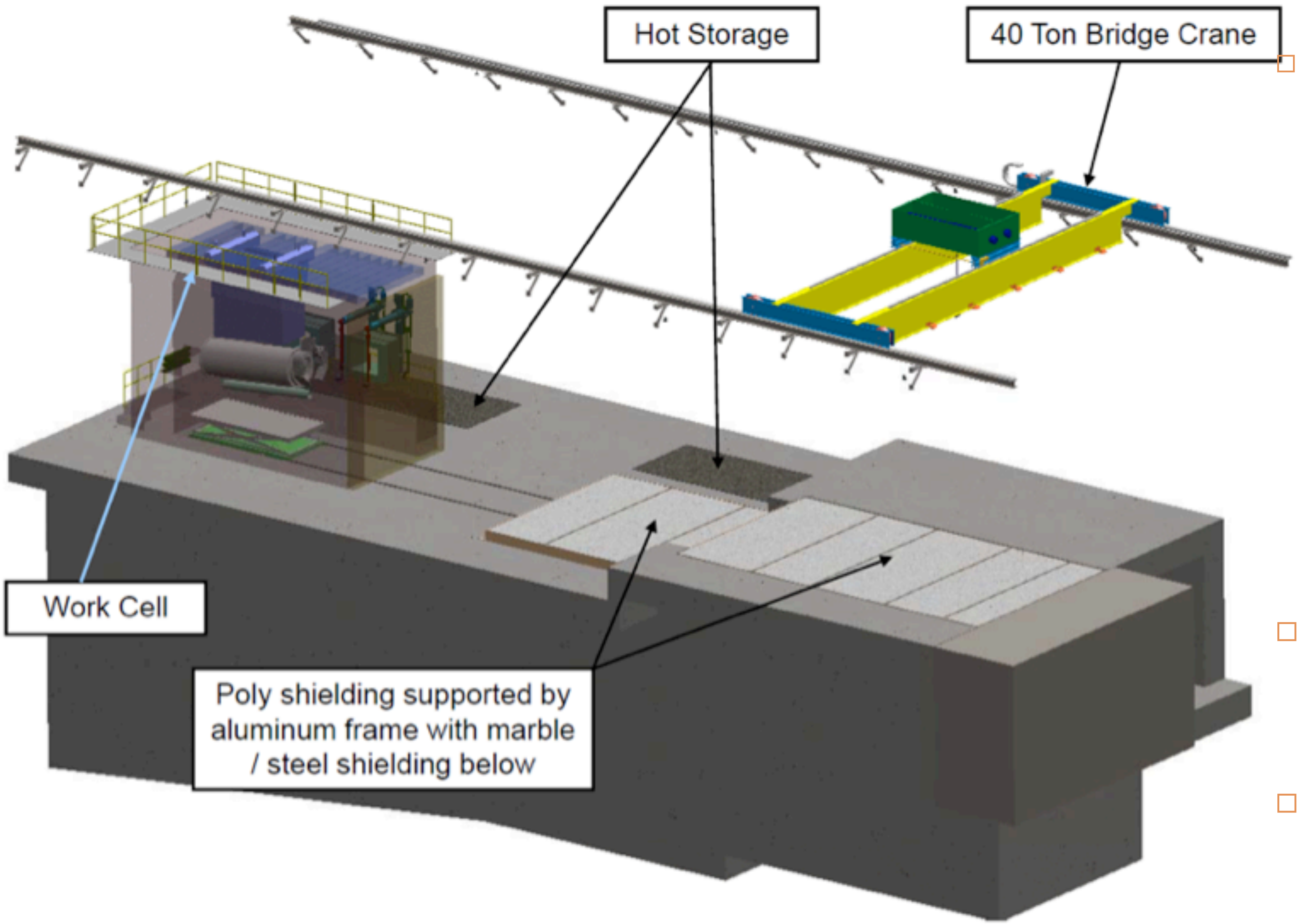
1st target being removed



J. Hylen/FNAL - NBI10

3

LBNE - Target Chamber

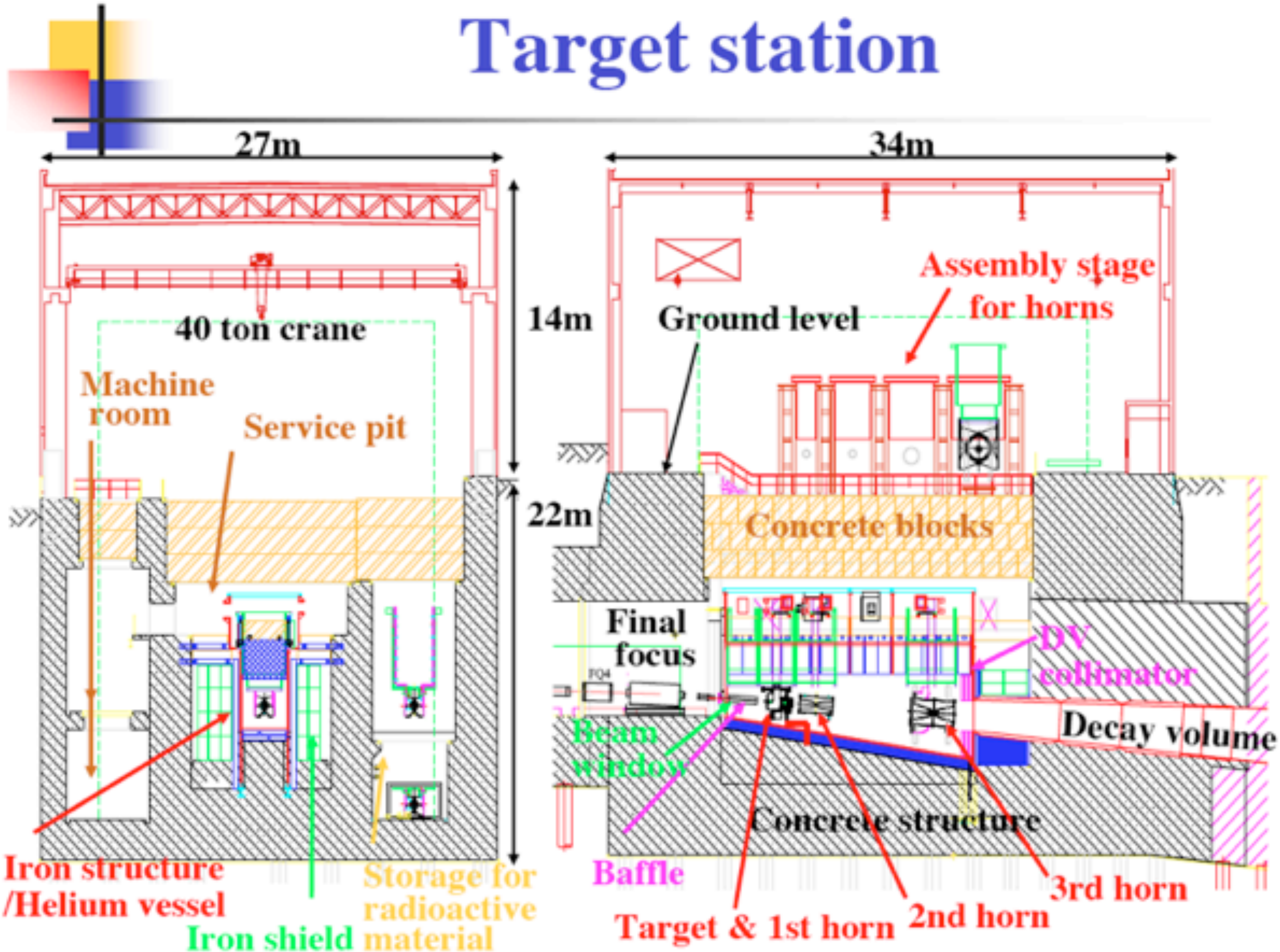


P. Hurh: LBNE Remote Handling Overview for NBI 2010

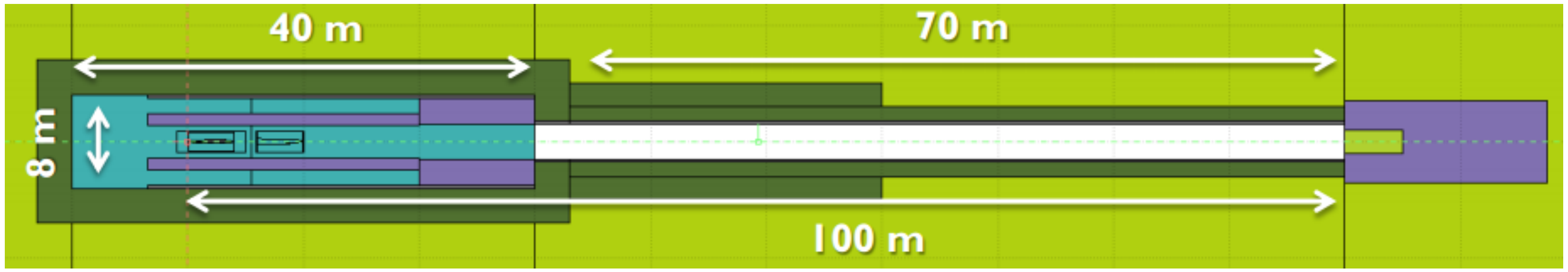
- ORNL Remote Systems Group enlisted to develop conceptual designs of remote handling equipments and systems
  - Tom Burgess
  - Van Graves
  - Adam Carroll
  - Tim Lessard
- 40 ton remotely operated bridge crane
- Full vision system (mounted video cameras removed during beam on)

T2K Target Chamber

Y. Yamada/KEK - NBI10

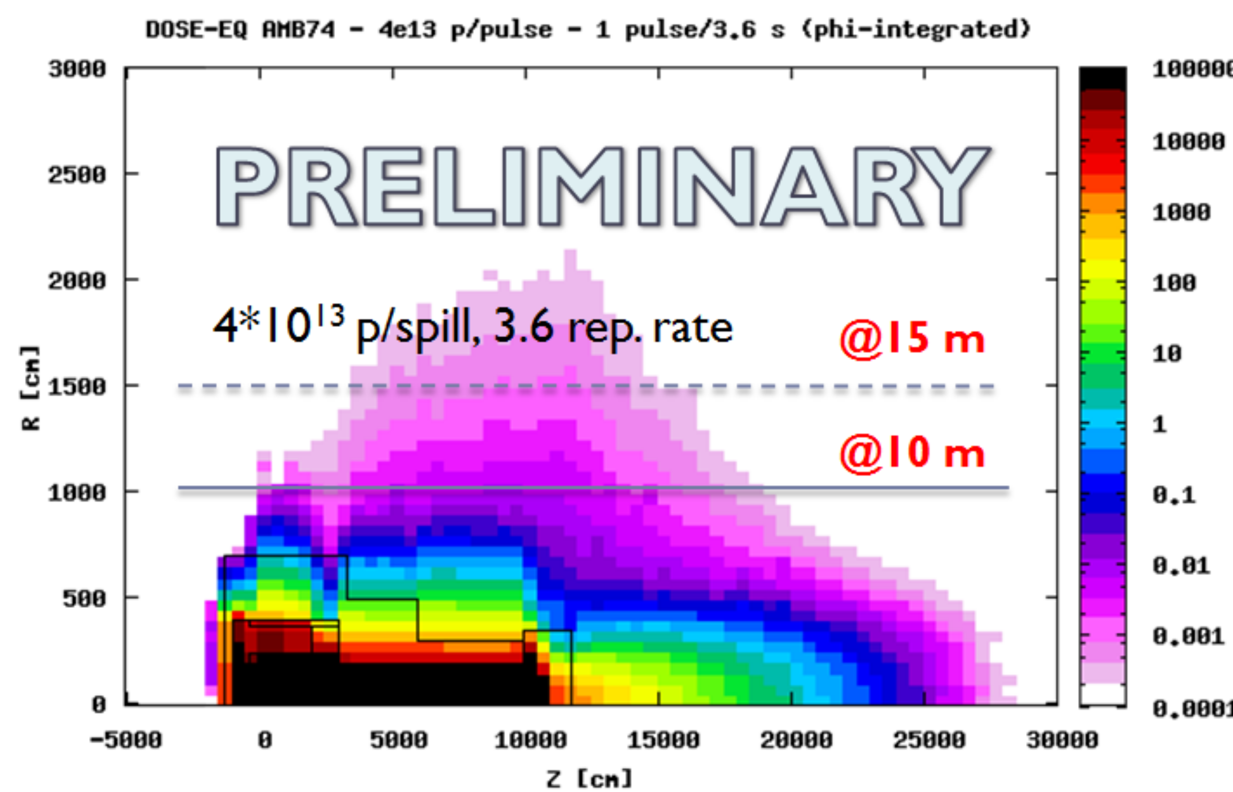


SBL2NA – RP considerations



Element	kJ/spill	kW avg.
Dump core (C)	162.29	45.08
DP inner Fe lining	139.50	38.75
Target Fe sh.	130.15	36.15
Dump (Fe)	79.01	21.95
Target Fe sh. (down)	37.87	10.52
DP upper Fe lining	10.29	2.86
DP concrete shielding	6.40	1.78
Horn inner conductor	2.39	0.66
Target	1.97	0.55
Reflector inner conductor	1.48	0.41

- In a first approximation the SBL2NA beam can receive the same beam intensity presently delivered to CNGS
  - $4\div5\ 10^{19}$ pot/year
  - further increase can come as by-product of the SPS upgrades, and a possible shorter SPS cycle (3.6s instead of 6s for CNGS) due to the lower beam energy
- Preliminary FLUKA studies
  - RP issues can be easily mitigated with appropriate shielding
  - Muons rate to near detector (330m) can be kept low: 1 μ/spill
  - Soil activation (^{3}H, ^{22}Na) and RP to environment can be under control with appropriate design



M. Calviani, A. Ferrari – CERN

New fast extraction in SPS LSS2?

B. Goddard - CERN

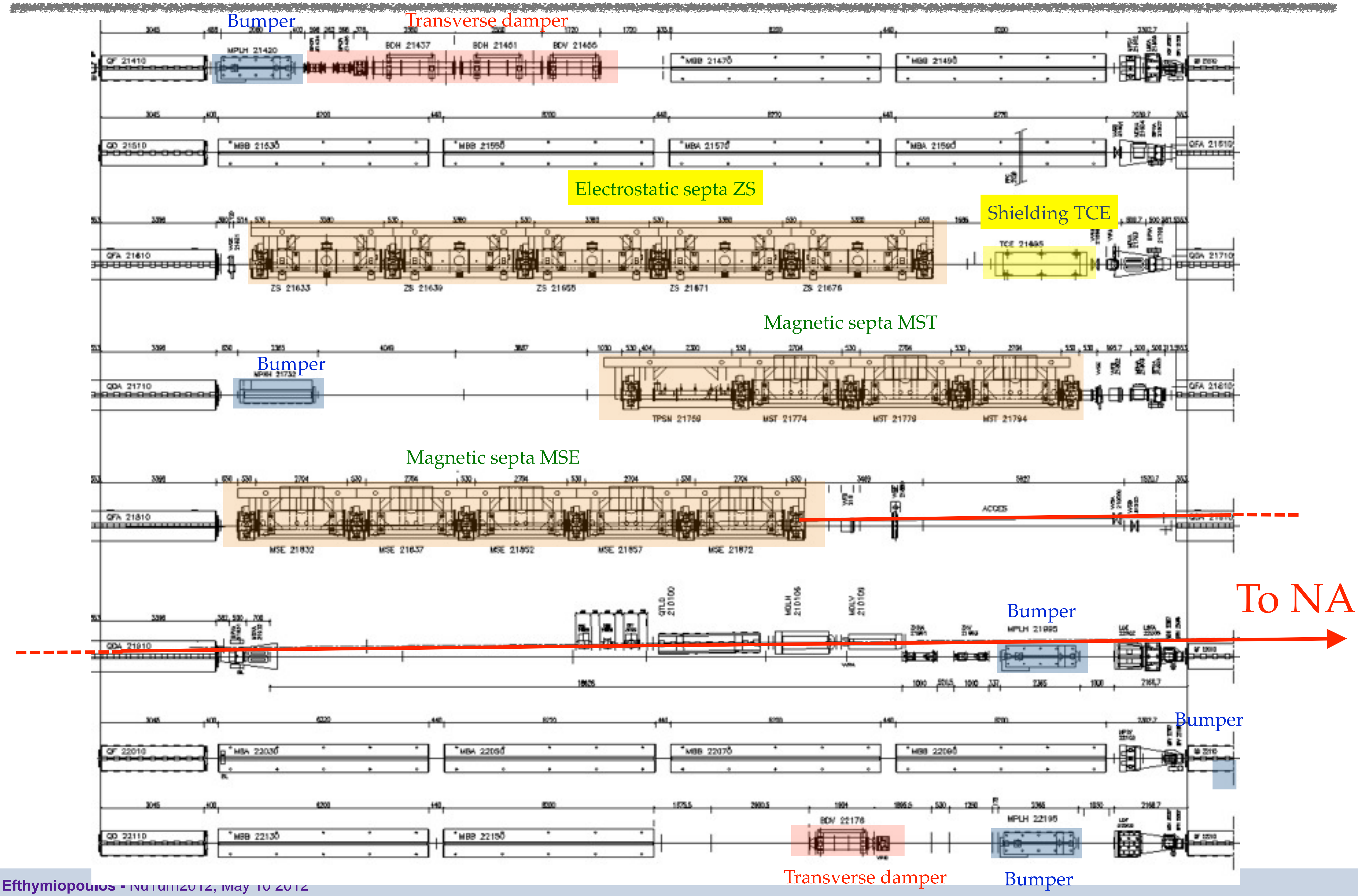
- Constraints : must keep slow extracted beam capability to North Area
  - Hybrid extraction needed for slow and fast extracted beams

First preliminary feasibility study

- Solution found with displacement of ZS girder and TCE downstream by 3m
  - Two new MKEX kickers – [larger H aperture version than MKE]
  - Extraction energy limited to 100 GeV with 1μs kicker rise time
    - Can be later modified to extract 400 GeV, with a rise time 3-4μs
  - Emittance limited to about 8 π.um in H, and 5 π.um in V

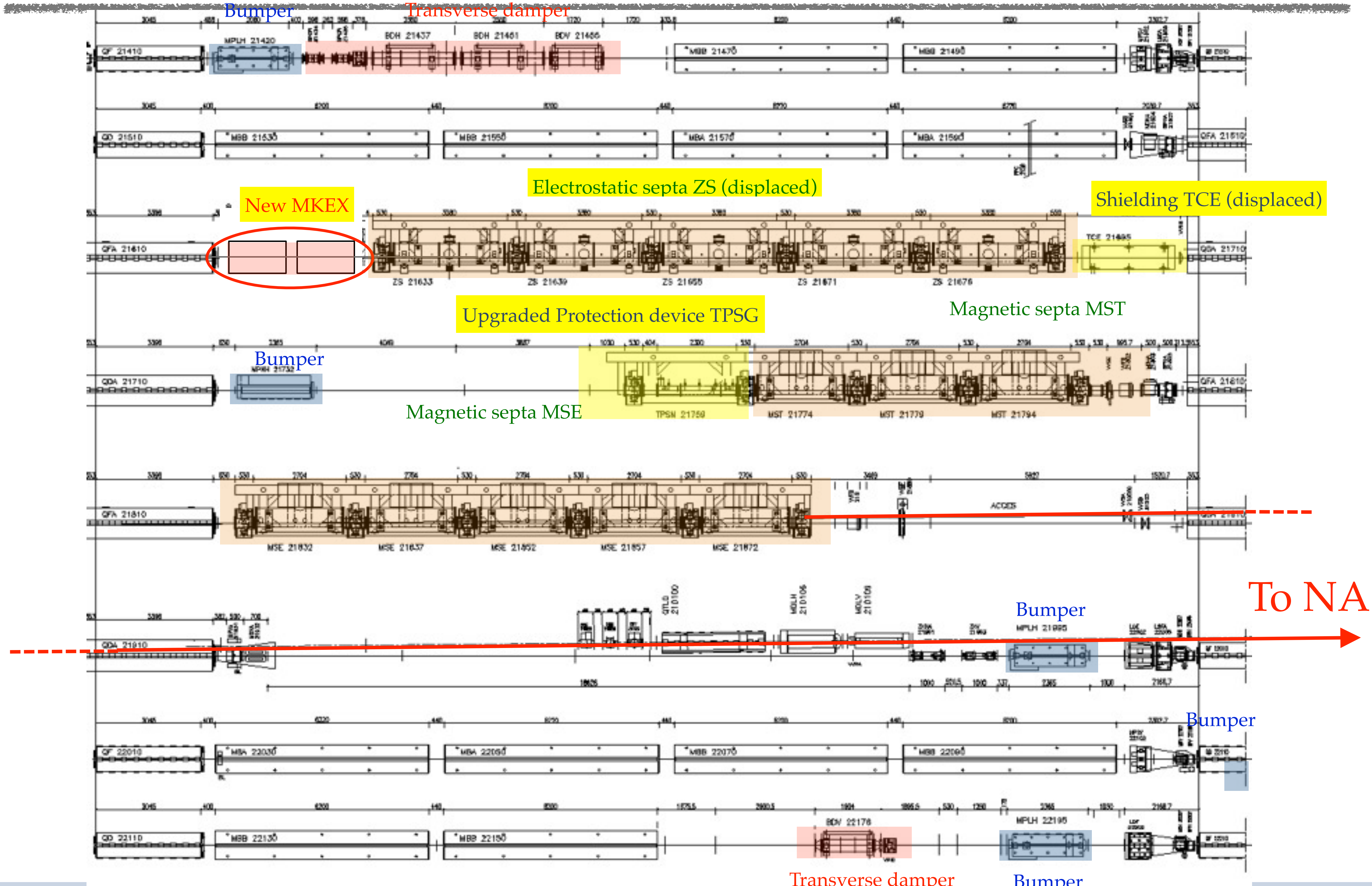
LSS2 Present Layout

B. Goddard - CERN



LSS2 Possible Layout

B. Goddard - CERN



Beam Intensity Upgrades - Injectors (PSB, PS, SPS)

E. Shaposhnikova, R. Garoby - LiU-LLBNO/CERN

- **Present limitations:**
  - PSB-to-PS injection, losses
    - controls
  - PS-to-SPS extraction, losses
    - MTE, bunch to bucket injection
  - SPS RF power
    - additional RF cavities
    - injection beyond transition
  - Shielding in PS
    - ongoing

Parameters	SPS record at 450 GeV		HL-LHC at 450 GeV	
	LHC	CNGS	I	II
bunch spacing [ns]	25	5	25	50
bunch intensity /10^{11}	1.3	0.13	2.2	3.6
number of bunches	288	4200	288	144
total intensity /10^{13}	3.7	**5.3**	**6.3**	5.2
long. emittance [eVs]	0.7	0.8	0.8	0.9
norm. H/V emitt. [μm]	3.0	8/5	2.5	3.0

- Studies ongoing to understand the limits and identify possible upgrade options
  - constraint : keep the machine performance for LHC beams

- Aim to reach **~750kW** of nominal beam power (7.0E13, 6s cycle)

Beam Intensity Upgrades - HP-PS

Y. Papaphilippou, M. Benedikt, R. Steerenberg - LLBNO/CERN

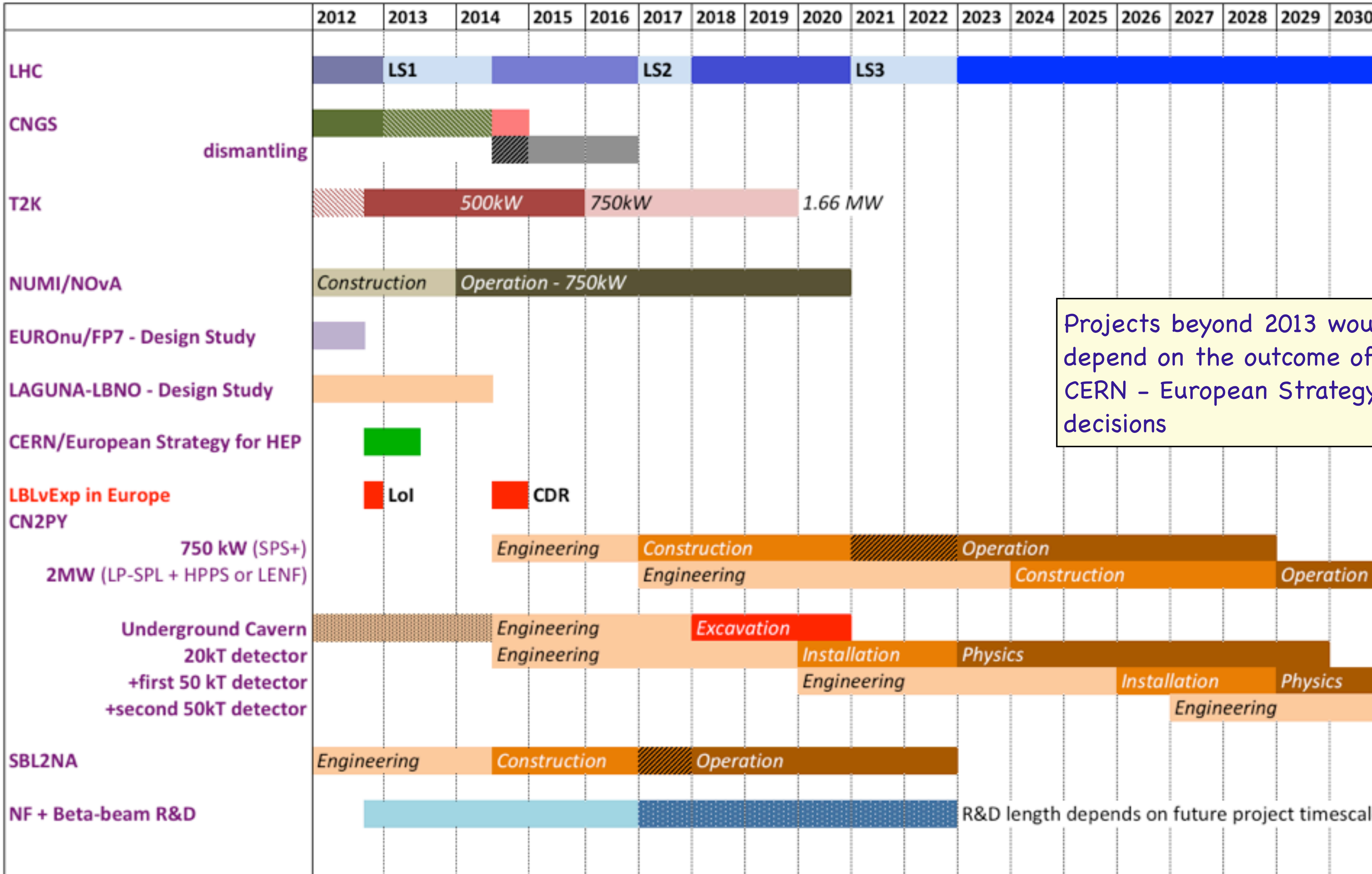
Preliminary !

$$P = qf_rN_pE_k$$

Parameters	PS2	HP-PSa	HP-PSb	HP-PSc	HP-PSd
Circumference [m]	1346.4	**1256**	1009	763	**1256**
Symmetry	2-fold	**3 / 4-fold**			
Beam Power [MW]	0.37	**2.0**			
Repetition rate [Hz]	0.42	**2**	2	2.6	**1.3**
Kinetic Energy @ inj./ext. [GeV]	4/50	**4/50**	4/40	4/30	**4/50**
Protons/pulse [10^{14}]	1.1	**1.25**	1.6	1.6	**1.9**
Dipole ramp rate [T/s]	1.4	**6.1**	6.0	7.5	**4.0**
Bending field @ inj/ext. [T]	0.17/1.7	**0.17/1.7**	0.21/1.7	0.27/1.7	**0.17/1.7**
Fractional beam loss [10^{-4}]	35.1	**6.5**	5.0	4.0	**6.5**
Space-charge tune-shift H/V	-0.13/-0.2	**-0.2/-0.2**			
Lattice type	NMC arc, doublet LSS and DS	**Resonant NMC arc, doublet LSS**			
Norm. emit. H/V [µm]	9/6	**6.8/6.7**	8.6/8.5	11/11	**10.5/10.3**
Max. beta H/V [m]	**60/60**				
Max. dispersion [m]	3.2	**5**			

- Getting 2MW of beam power is not straight-forward
  - ramp rate, space-charge, losses, acceptance, space(circumference), **cost!**

Future Neutrino Beams - possible timeline



Projects beyond 2013 would depend on the outcome of the CERN – European Strategy decisions

Summary

- The newly obtained results enhanced the interest for ν-physics, changed the landscape and will help to better define a future ν-program among the all possible options currently under study
  - **T2K :** θ_{13} non-zero and **large**
  - **NuMI/MINOS :** θ_{13} , $\nu \leftrightarrow$ anti-ν results
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  - **Reactor experiments :**
    - θ_{12}, θ_{13} measurement indeed **very large**!!!

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    - broad physics potential (CP-violation, mass hierarchy,..)
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    - for an independent physics program and detector R&D

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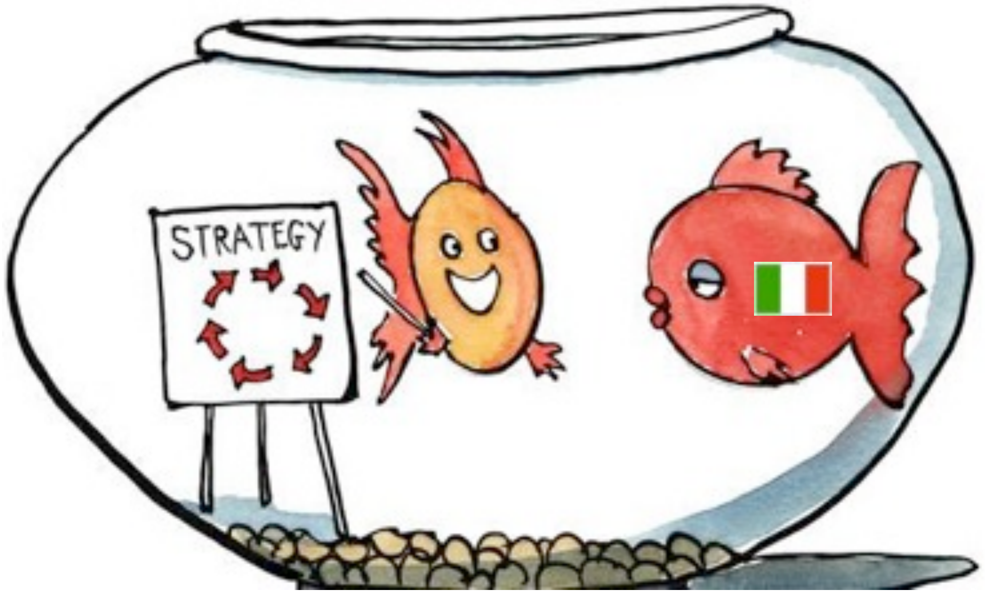

Courtesy : HRN Europe blog (http://www.hrneurope.com/blog/?p=206

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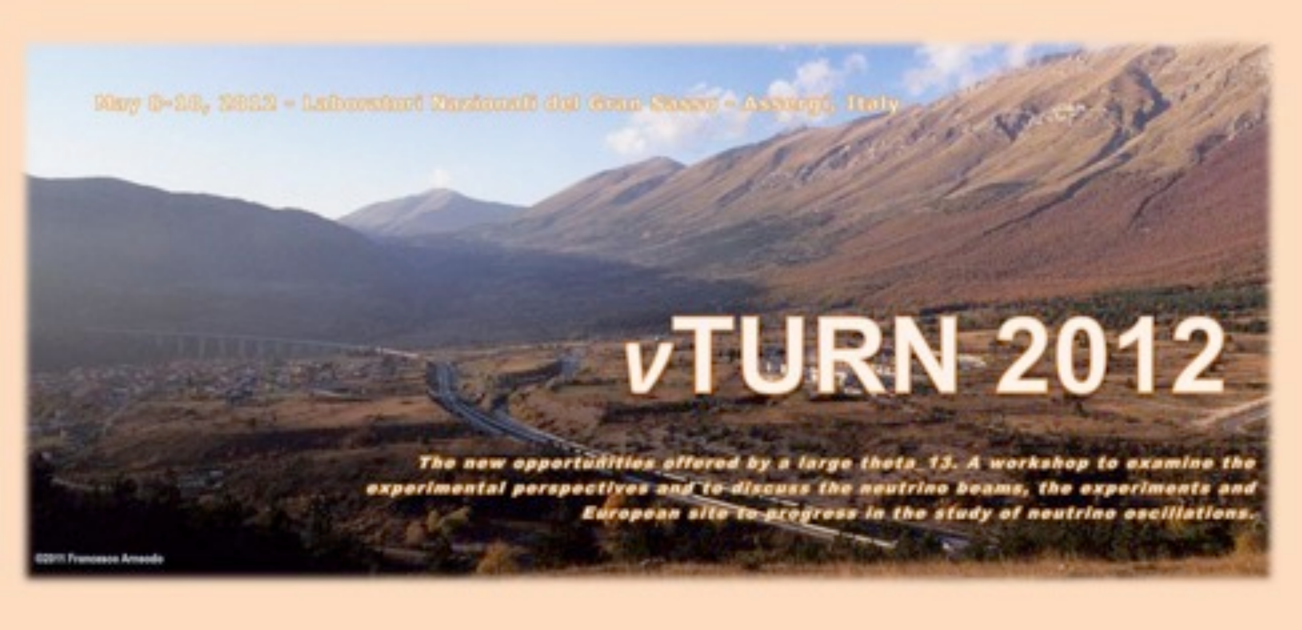
The future?

...with feedback from many colleagues - thanks!

The future?



from South ...

...with feedback from many colleagues - thanks!

The future?

to North?

from South ...

...with feedback from many colleagues - thanks!

The future?

to North?

from South ...

any colleagues -

As Greek, I would certainly prefer South than North, but life these days for Greeks is tough!