TARGETRY FOR HIGH POWER MUON FACILITIES

- Reminder : design parameters & constraints
- R&D Needs
- Synergies

I. Efthymiopoulos - *CERN*

HIGH POWER MUON FACILITIES

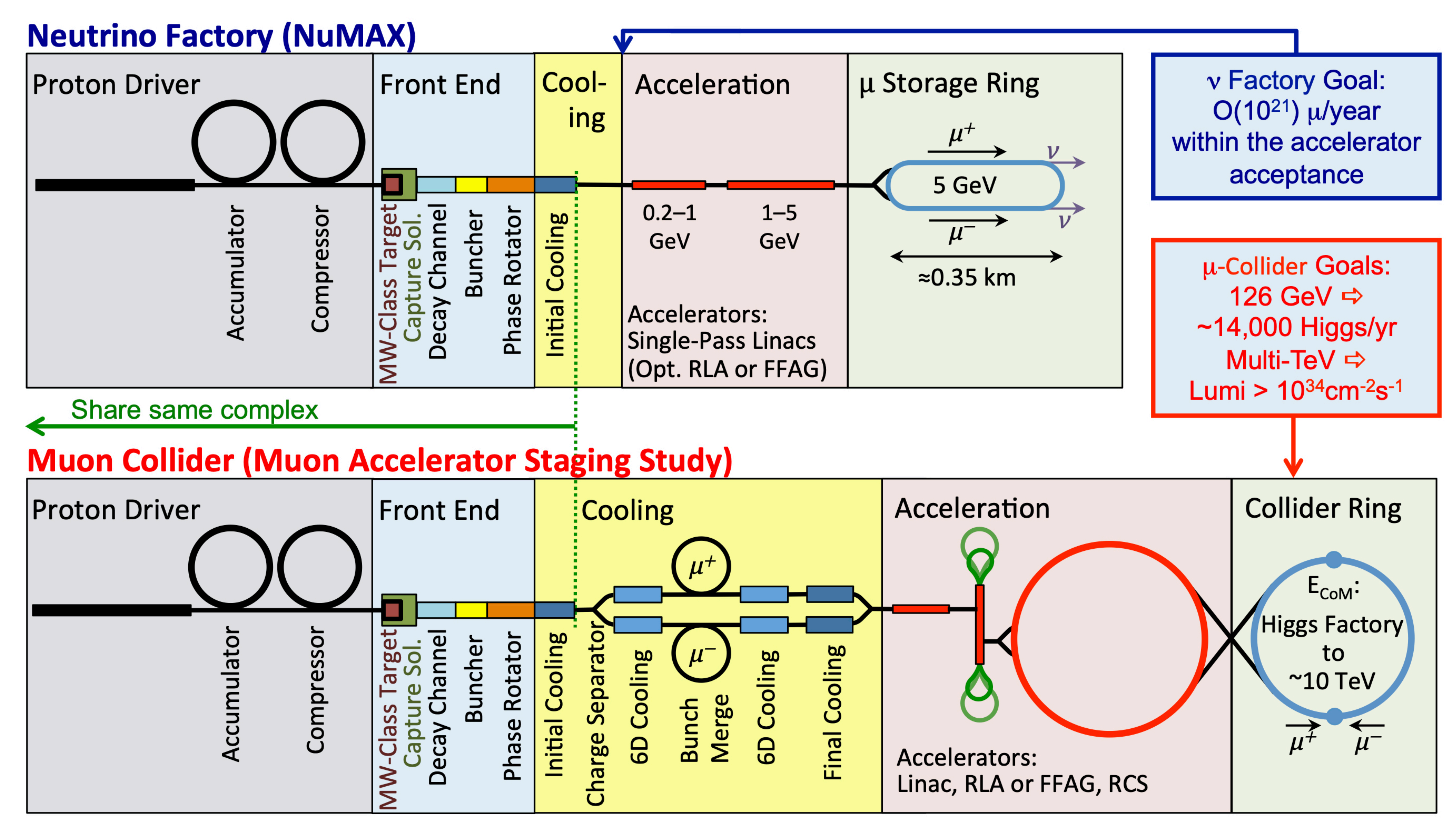
- Muon Facilities considered since long as attractive alternatives to study particle physics in
  - the neutrino sector : Neutrino Factory
    - high-energy, narrow-band ν_e , ν_μ neutrinos from stored muon decays
      - decay kinematics well, known – study $\nu_e \rightarrow \nu_\mu$ oscillations, superior reach in CPV, MH, …
  - the energy frontier : Muon Collider
    - $\mu+\mu-$ collisions at high-energy to explore new physics, but also tuned to Higgs production
    - as point-like particles full beam energy available for particle production, absence of synchrotron radiation thus small footprint, narrow energy spread at IP, but also come with challenges like electron and neutrino irradiation at IP
- Intensive R&D effort for many years at a national and international level : IDS-NF, MuonColl, EU projects, Japan NF group…
- Study of Muon Facilities included as path for R&D in the recent European Strategy Update…

HIGH POWER MUON FACILITIES

MAP : Muon Collider – Neutrino Factory

MAP web : https://map.fnal.gov

- R&D in synergy for the two facilities
- Share ~identical Proton driver & Front-End



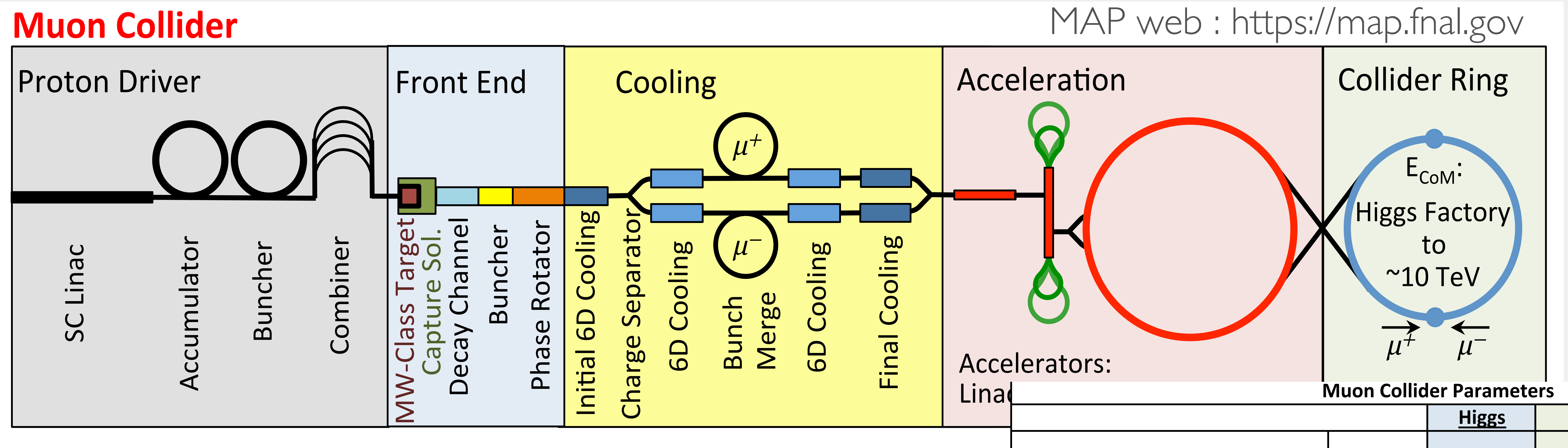
MUON BEAM CHALLENGES

Creating intense muon beams represents several major challenges on:

- production: muons are produced as tertiary particles through $p \rightarrow \pi \rightarrow \mu$ (baseline)
  - implies using **high intensity proton source** ➟ **MW proton pulsed LINAC**
  - target head that can sustain the impact of multi-MW beam ➟ High-Power Targetry
  - high-capture efficiency, handling of energy spread and transverse phase space ➟ **Emittance Cooling**, large acceptance accelerator system
  - Alternative proposal : muons from positron beam – LEMMA scheme, with its advantages and challenges
- acceleration and beam handling due to short muon lifetime (*2.2μs at rest*)
  - rapid beam manipulations, high-gradient RF, fast acceleration, collision ring

THE MUON COLLIDER

The Ultimate option for a high-energy collider



	Units	Higgs	M-TeV	
CoM Energy	TeV	0.126	1.5	3.0
Colliding beam μ/bunch	μ/s	$6.0\ 10^{13}$	$3.0\ 10^{13}$	$2.4\ 10^{13}$
		$\sim 4.0\ 10^{13}$		
Production: μ/bunch		$\sim 4.0\ 10^{14}$		
Protons on Target (POT)	p/s	$\sim 4.0\ 10^{15} \rightarrow$ $\sim 8\ 10^{13}$ ppp @ 50 Hz, 8 GeV 4 MW proton beam		

Muon Collider Parameters

		Higgs	Multi-TeV		
Parameter	*Units*	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

THE MUON COLLIDER TARGET

Target system requirements

- The target material must withstand the impact of the intense proton focused beam
  - high energy density deposition - ~80 kJ/pulse
  - ~20% of the proton beam power would be deposited in the target material: 0.8 MW for a 4 MW beam!
  - Issues to consider:
    - Thermal management : melting, vaporization, shock wave
    - Radiation management : DPA, change of material properties
- Need to capture both signs of pions(muons) to a sizeable volume as input to the front-end channel - solenoid
- Use of a high-Z material to promote the creation of secondaries
- Optimized target geometry to allow separating the captured beam from the remnant proton beam, and..
  - don't forget the beam dump! A sizeable fraction of the proton beam will arrive to the dump (depends on the exact parameters of the target) plus, the dump must be able to withstand the full beam in case of an accident
- Robust design for all systems to assure long (>10-year?) lifetime, foresee remote handling with associated labs for exchanges or repairs

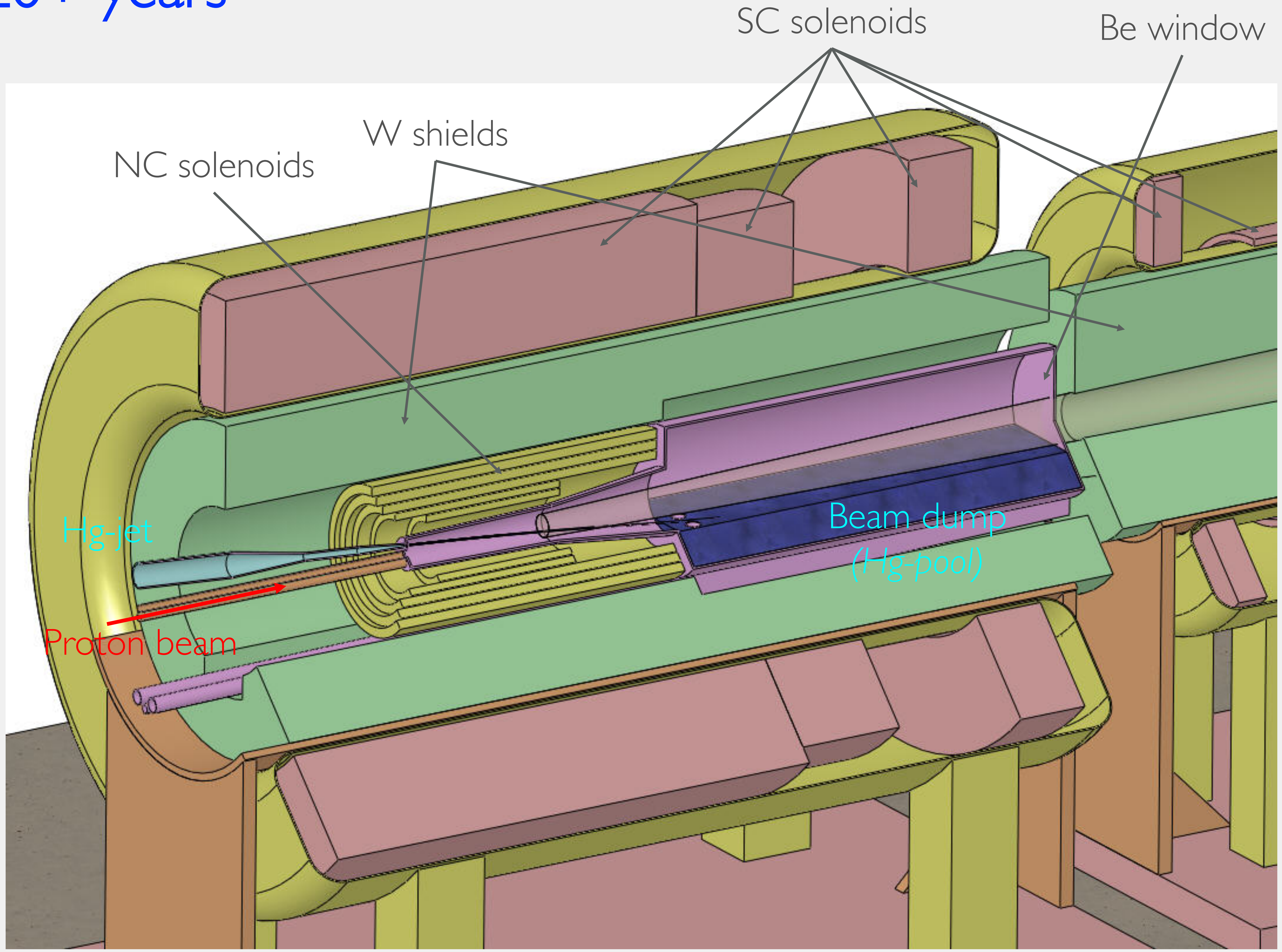
THE MUON COLLIDER TARGET STATION

Rigorous R&D program for the last ~20+ years

- extensive study on materials (solid, liquid, granular,…),
- capture options (solenoid, toroids,…),
- topology

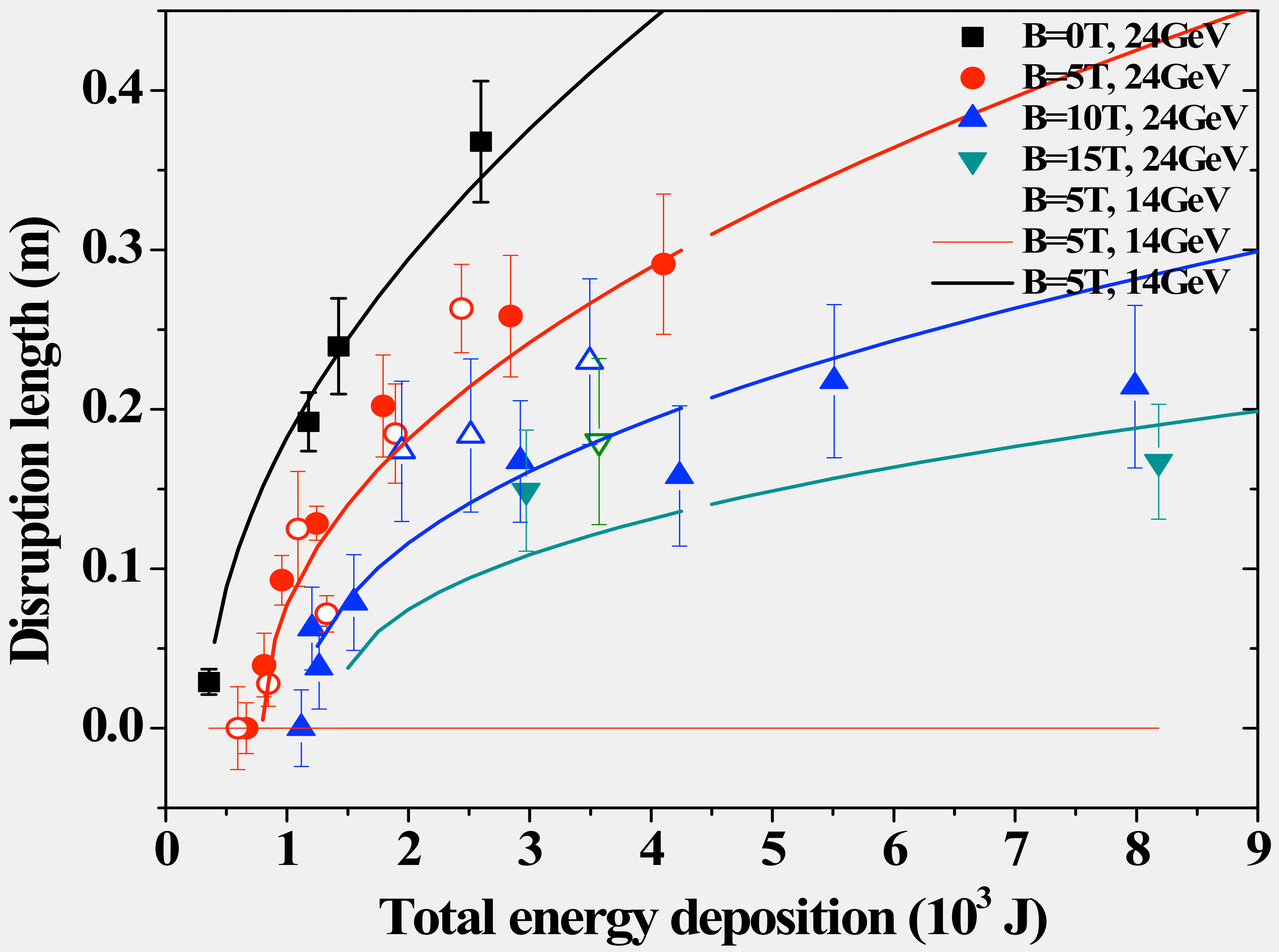
Final baseline :

- Hg-jet target
  - fast-moving 20m/s, regenerates after each pulse
- Solenoid capture (sc + nc magnets)
  - high-field around the target 20T
  - tapering system to 2T
- Tilt angle of the proton beam to solenoid axis
  - proton beam direction towards the dump (Hg-pool), out of the capture beam path



THE MERIT EXPERIMENT @ CERN-PS

- Proof-of-principle experiment of a high-power target for NF/MC based on a free Hg-jet



Key results #1 :

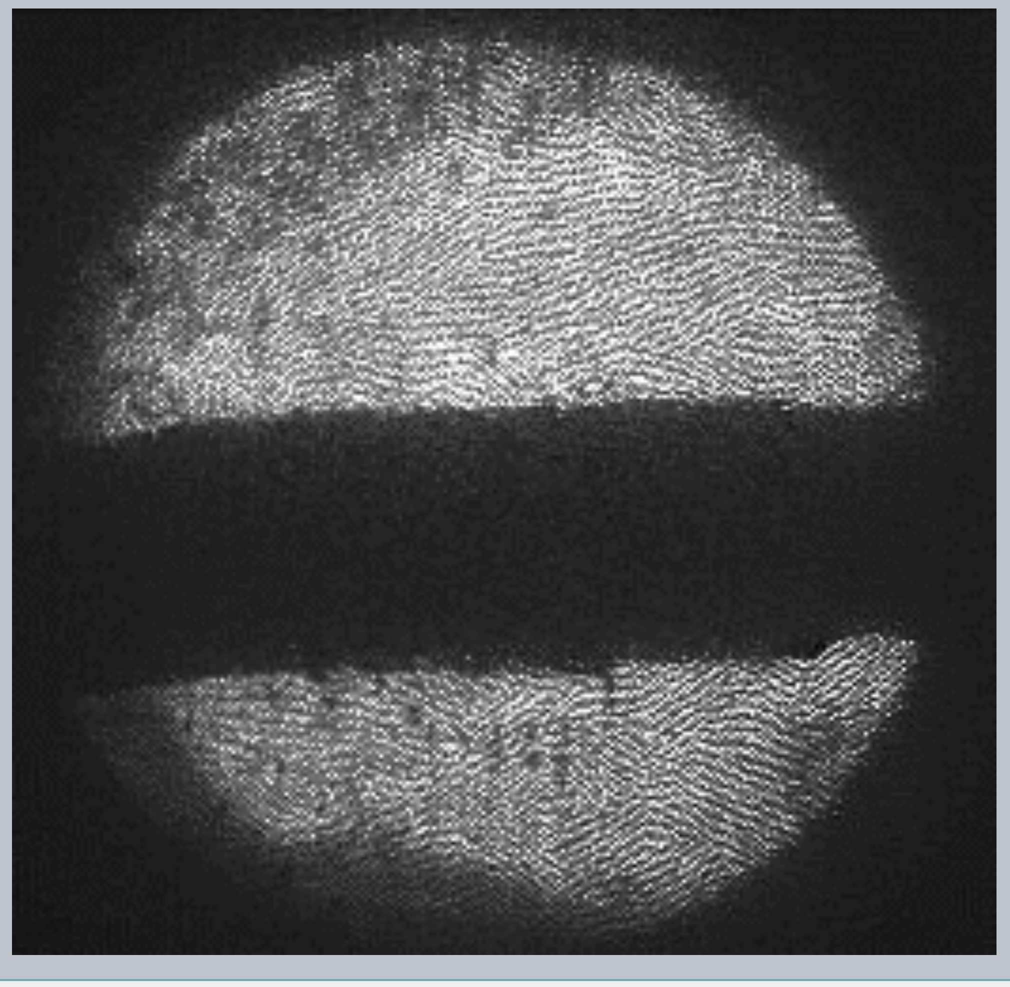
- Hg-jet disruption mitigated by magnetic field
- 20 m/s jet operation allows up to 70Hz operation with beam

Key results #2 :

- Disruption threshold: >4×10[12] protons @14 GeV, 10T field
  - 115kJ pulse containment demonstrated
  - 8 MW capability demonstrated

Hg-jet - beam impact

4×10^{12} protons, 10T field



- The MERIT experiment validated the baseline option, and remains so far, the only option for a multi-MW target system. However, it comes with a great safety challenge from the use of Hg.

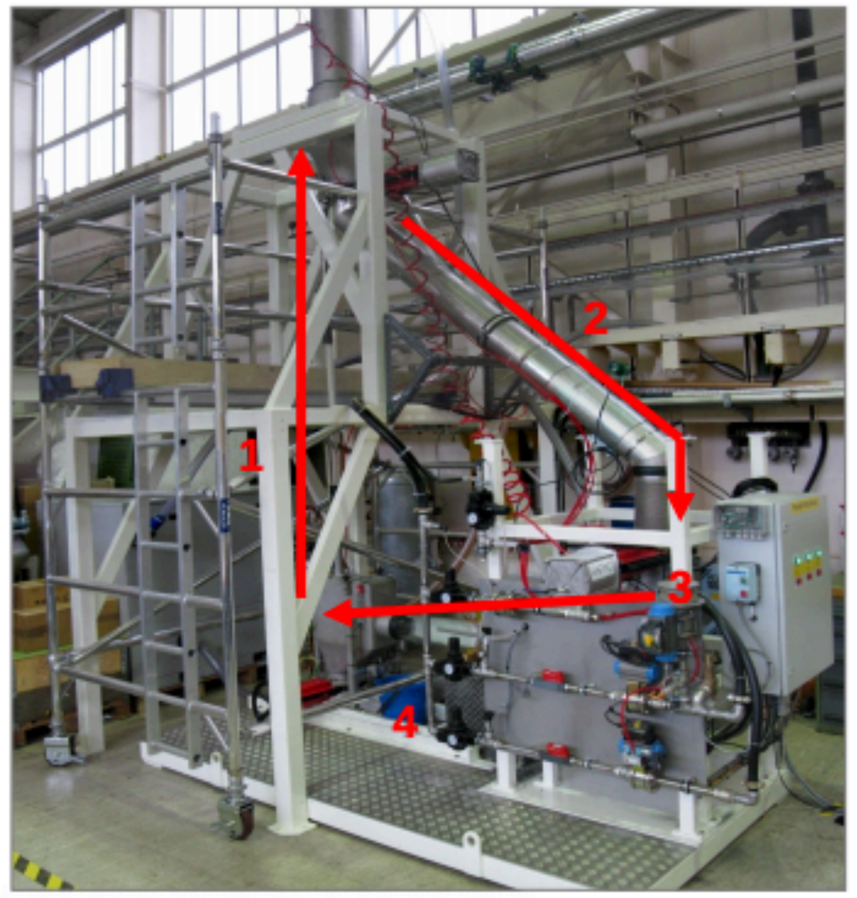
Alternatives?

MULTI-MW TARGET - ALTERNATIVES

- Fluidized granular target C. Densham et. al – RAL High-power Target Group

Fragmented high Z flowing target: W powder rig @RAL

- Offline testing
- Pneumatic conveying
  - (dense-phase and lean-phase)
  - Containment / erosion
  - Heat transfer and cooling of powder



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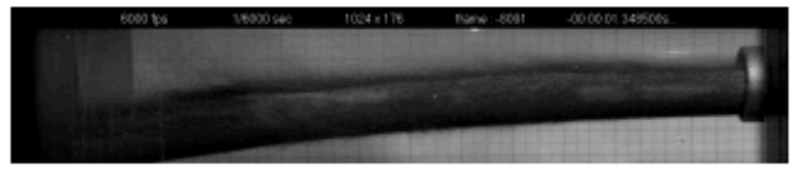
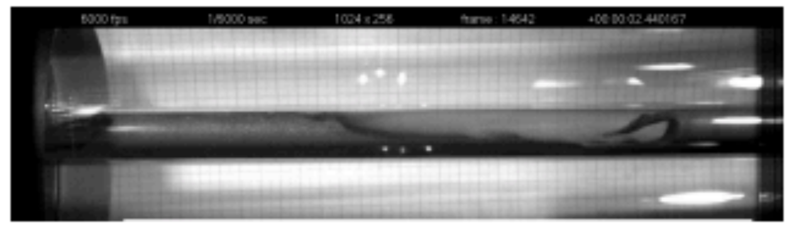
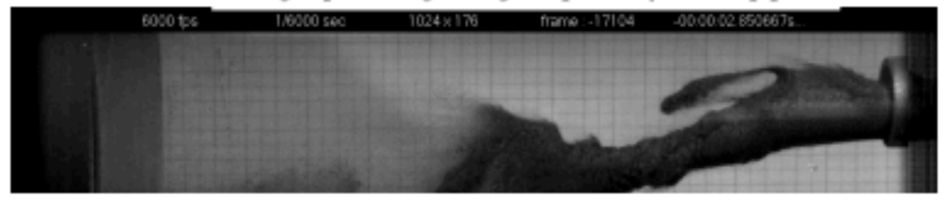
Dense-phase delivery



High speed image: tungsten powder jet

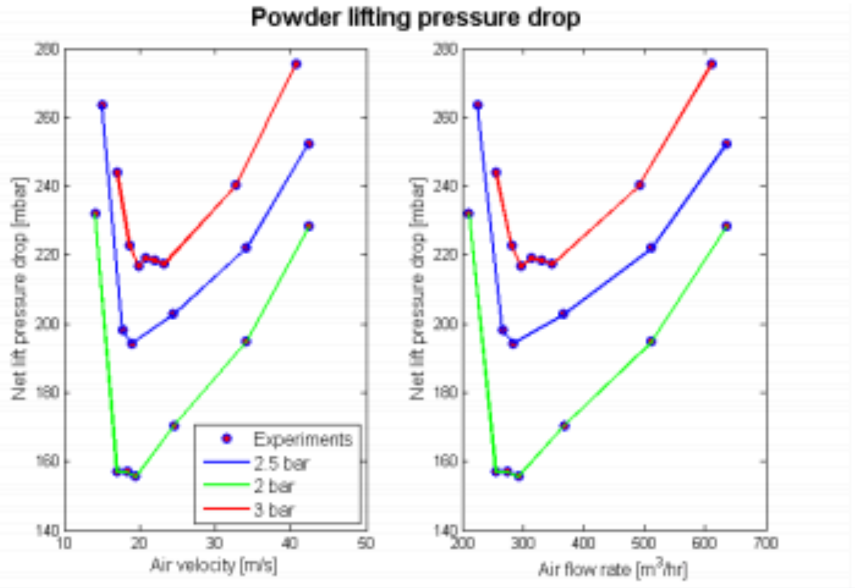


High speed image: tungsten powder flow in a pipe

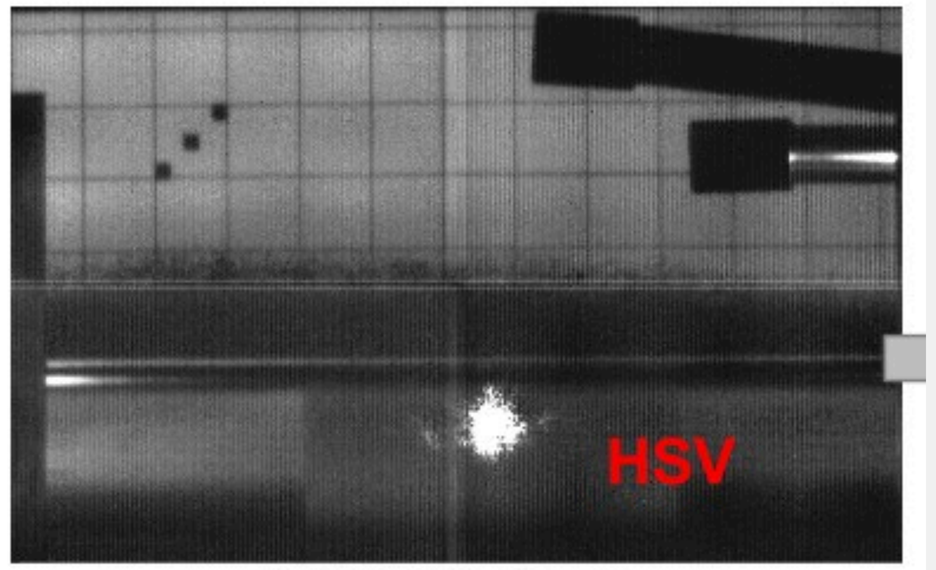


Unstable tungsten powder jet

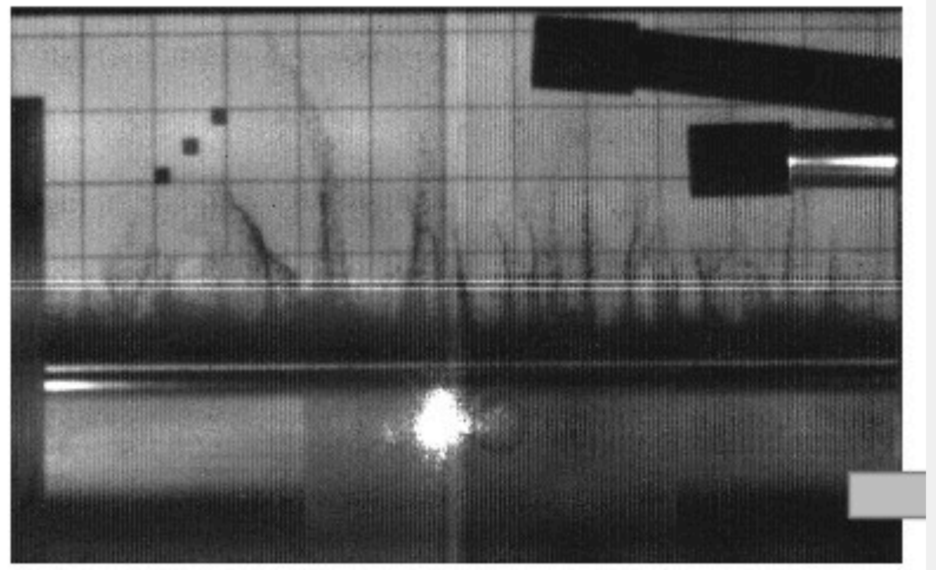
Lean-phase lift



- Single pulse tests - HiRadMat@CERN facility



Shot #8, 1.75e11 protons
Note: nice uniform lift



Shot #9, 1.85e11 protons
Note: filaments!

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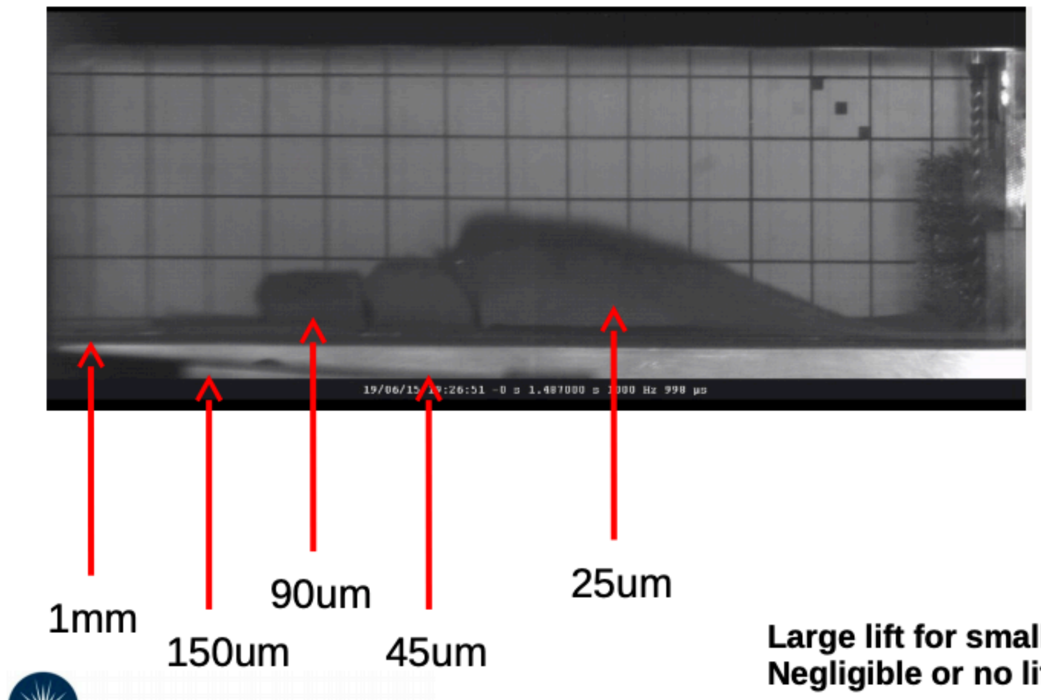

- Shot 1-28
- Several sizes
- 2e11 PoT

Large lift for small grains.
Negligible or no lift for larger particles

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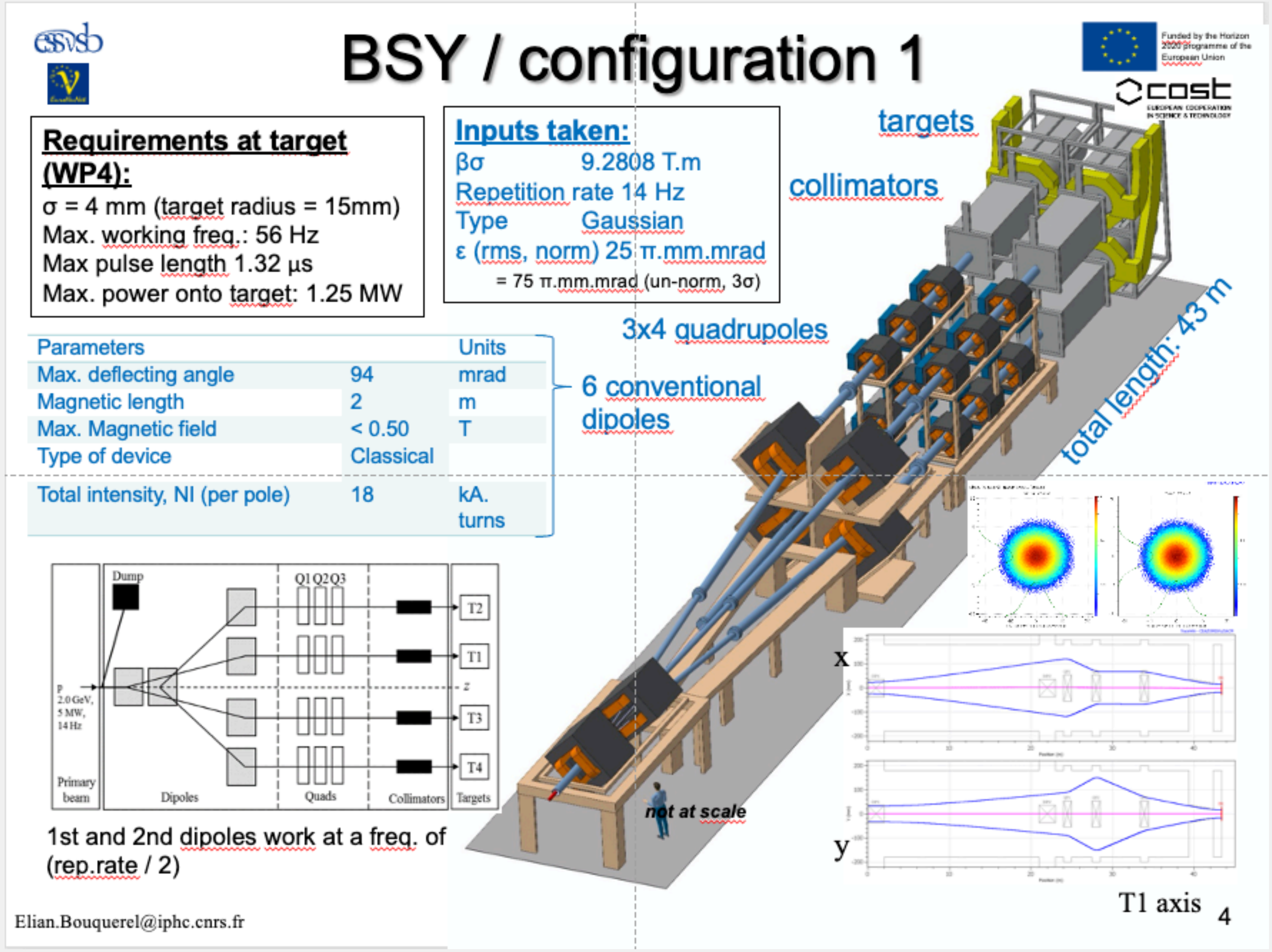
- At ~NUFACT peak energy deposition (~130J/g) the 45um spheres (which have an average size distribution ~20um) lift with a velocity of approx 3m/s
- Notice that at this energy deposition the whole rig (rather heavy and stiffly supported) seems to shudder!

- Shot 2-43
- 45um
- 3.1e12 PoT

- Active R&D continues, studies for LBNF, T2K, …

MULTI-MW TARGET - ALTERNATIVES

- 4 MW = 4×1MW – **EUROν**, and recently **ESSnuSB** neutrino super beam
  - Not a "real" multi-MW option
  - Shares the constraints between:
    - the target,
    - the switchyard and,
    - the dump
  - Works well for a long-baseline ν-beam, not easy to extend the concept to an accelerator muon beam
    - could imagine the four beam segments are not // but tilted pointing to a common center
      - provides the needed tilt angle with the target,
      - possibly use a single beam dump at the center
    - numerous challenges: the four solenoids of high-field, fast pulsing magnets (~25 Hz) and the front-end to merge the four beam segments



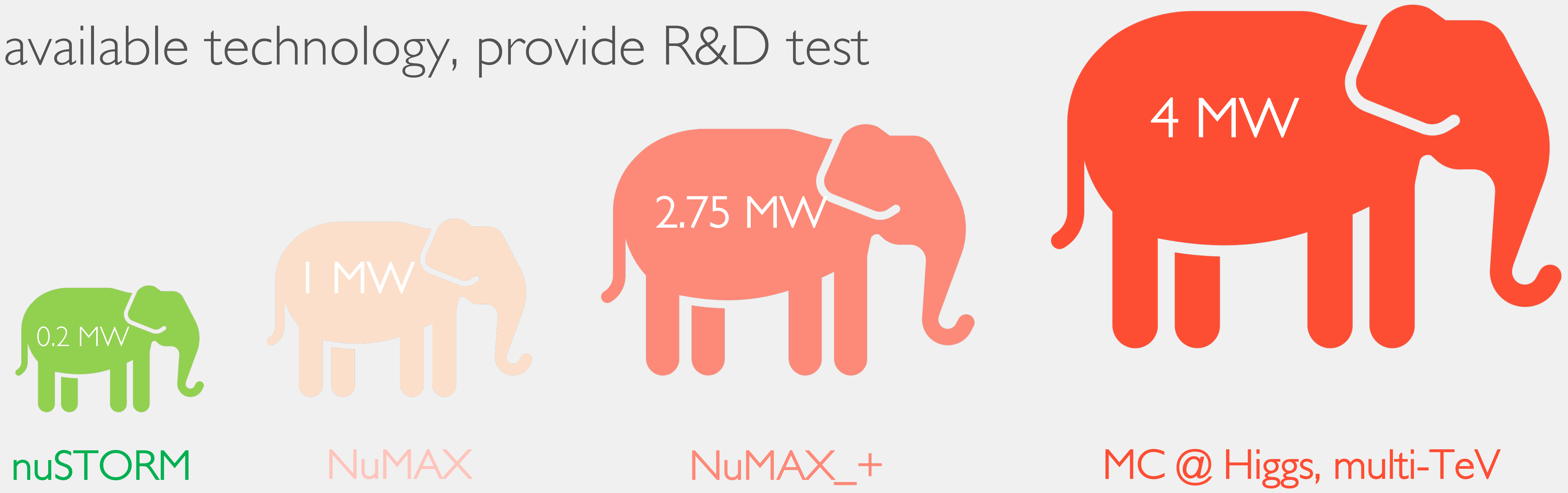
HPT FACILITIES – STAGED APPROACH?

Multi-MW HPT installations extremely challenging to design and operate

- present operational installations approach the range of ~0.7-1.0 MW (T2K, NuMI), with design capabilities to reach ~1.5 MW. New facilities under design for LBL neutrino beam to reach ~2.5 MW (LBNF)
- going beyond requires a) finding technical solutions and b) building operational experience in a high-radioactive environment

MAP considered a staged approach towards the final NF/MC installation

- profit from synergies, start from available technology, provide R&D test bed for the next stages



NUSTORM @ CERN-SPS

nuSTORM : proposed and currently under study @ CERN

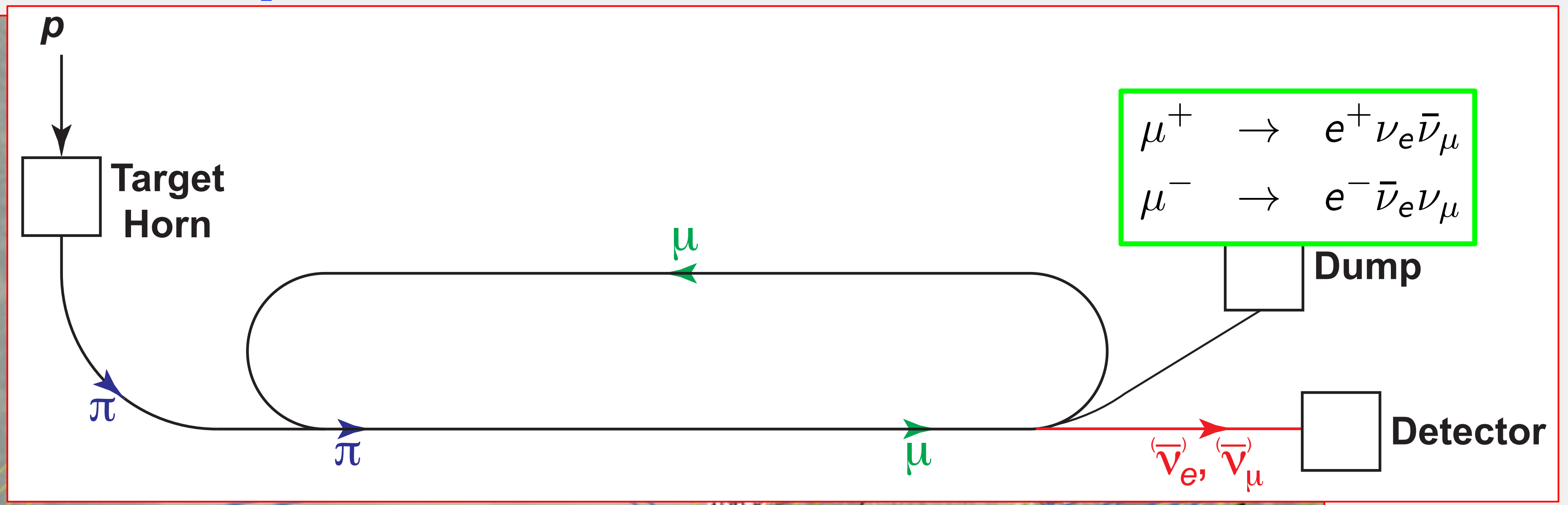


Table 1: Key parameters of the SPS beam required to serve nuSTORM.

Momentum	100 GeV/c
Beam Intensity per cycle	4×10^{13}
Cycle length	3.6 s
Nominal proton beam power	156 kW
Maximum proton beam power	240 kW
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}
Nominal / short cycle time	6/3.6 s
Max. normalised horizontal emittance ($1\,\sigma$)	8 mm.mrad
Max. normalised vertical emittance ($1\,\sigma$)	5 mm.mrad
Number of extractions per cycle	2
Interval between extractions	50 ms
Duration per extraction	10.5 μs
Number of bunches per extraction	2100
Bunch length ($4\,\sigma$)	2 ns
Bunch spacing	5 ns
Momentum spread (dp/p)	2×10^{-4}

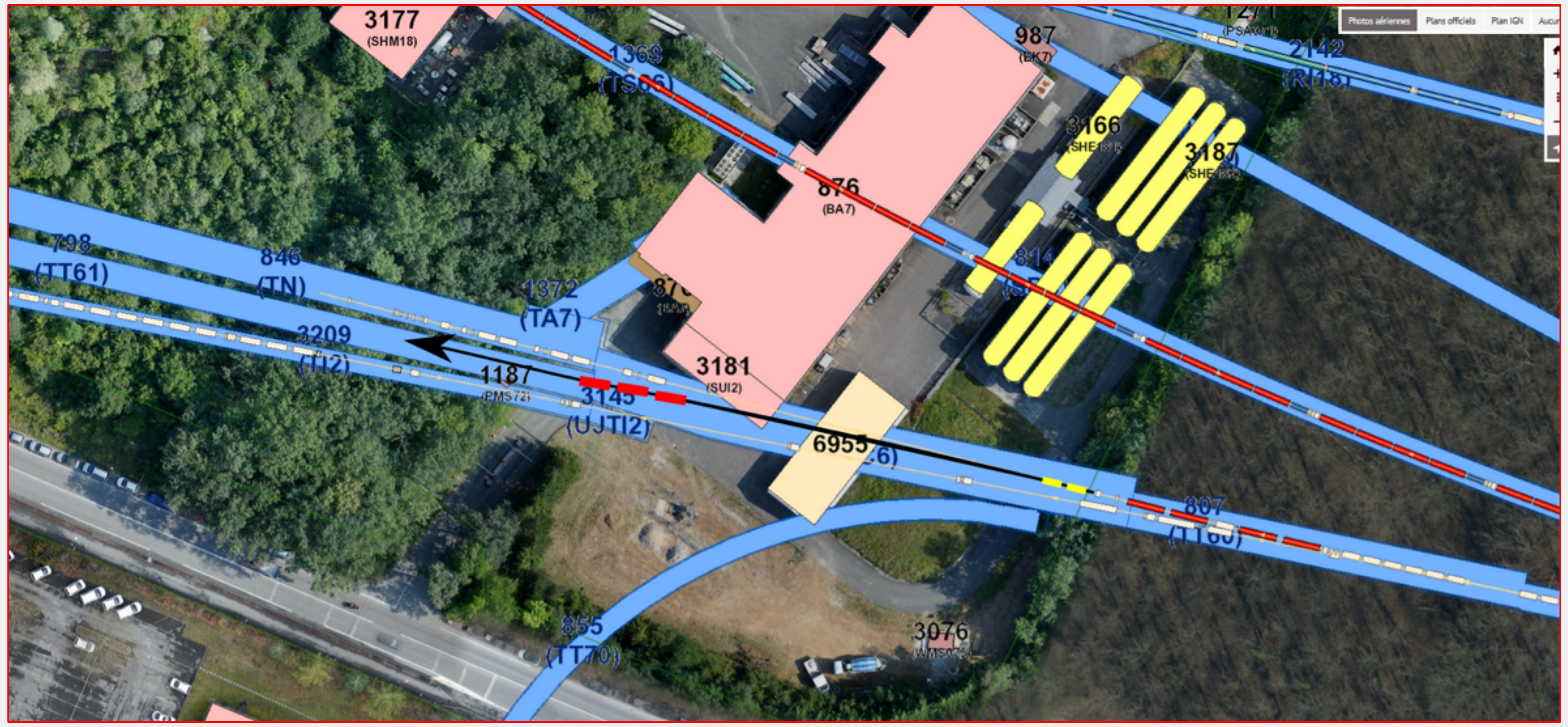
- The beam : collect single-charge pions(π) from the target (horn capture) → select momentum bite with conventional magnets → inject to the ring → pions decay in first straight section to muons → accumulate to produce intense muon/neutrino beam
- Layout study using a fast extracted proton beam from SPS

In parallel to its own physics program, the facility, can offer a unique opportunity for **R&D towards high-power targetry and front-end** (..and with **muons** – Chris's talk), but also to develop synergies other neutrino or muon programs

NUSTORM @ CERN-SPS

Beam extraction and transfer

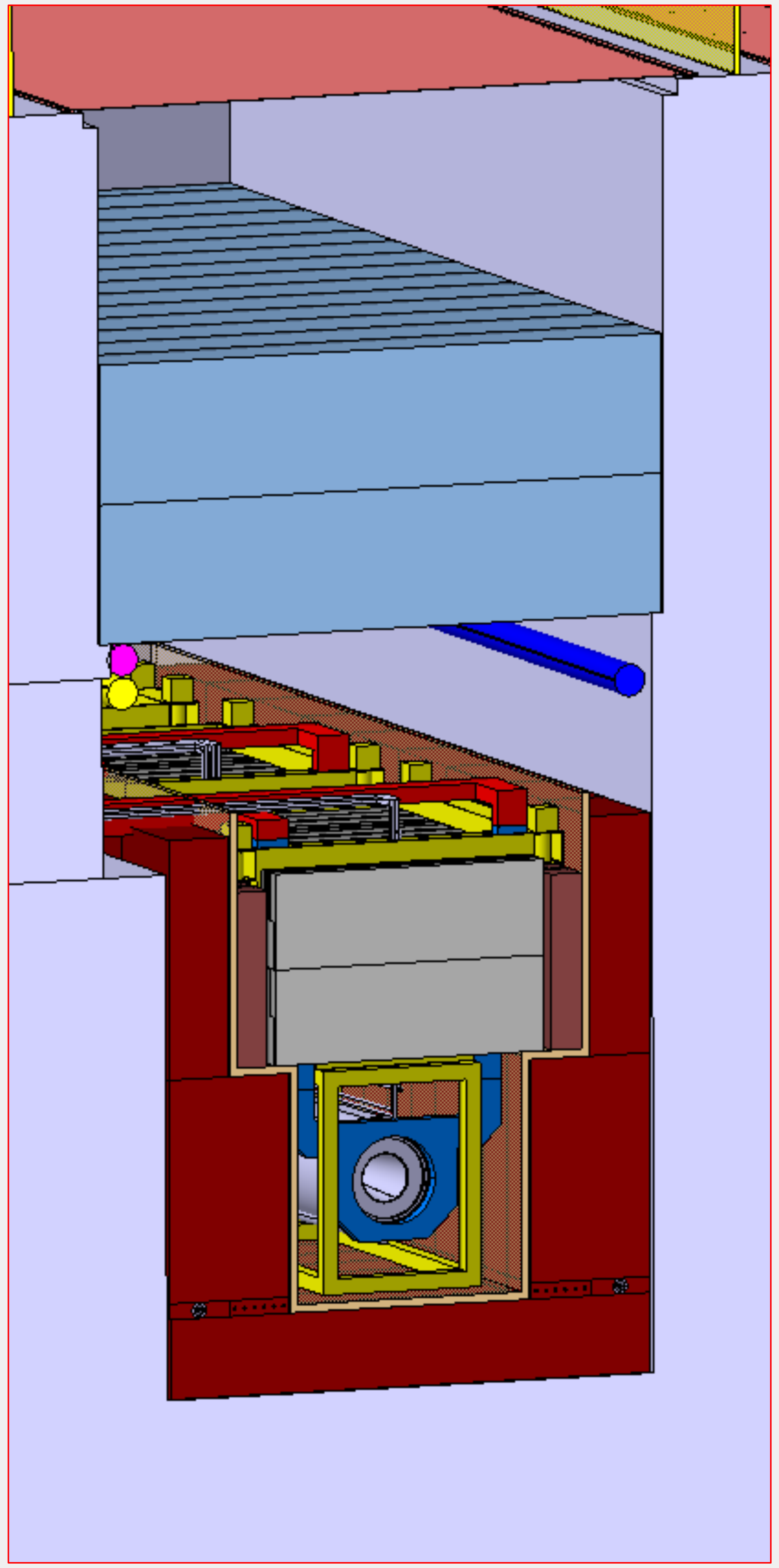
- fast extraction @ 100 GeV – like CNGS 2×10.5 μs pulses, ~20 Tppp



nuSTORM@CERN – W. Bartmann, CERN

Target station

- Baseline : FNAL scheme, graphite target like CNGS
- Horn and quads to select the pion beam



nuSTORM@CERN – M.Calviani, CERN

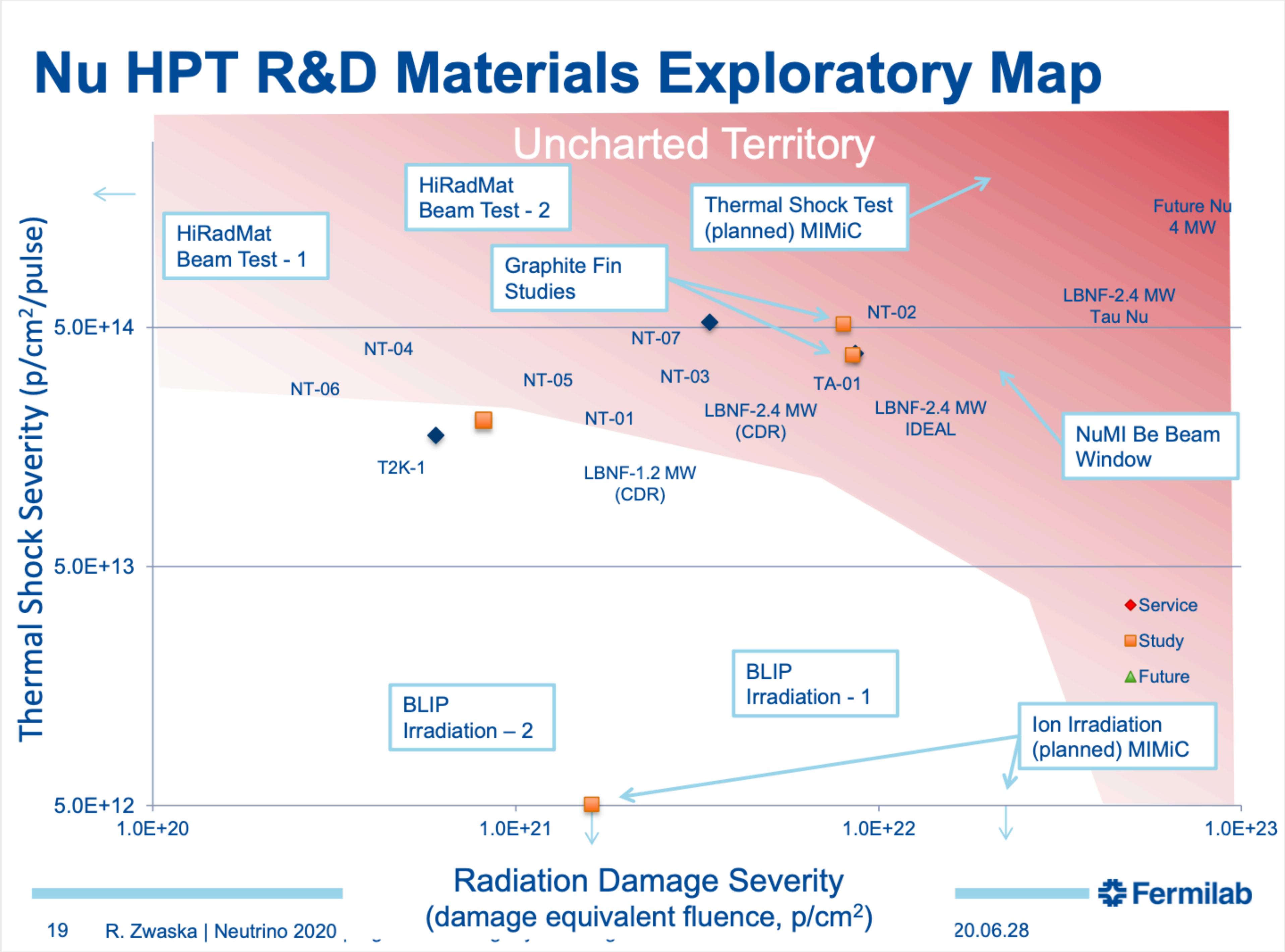
NUSTORM @ CERN – HPT R&D SYNERGIES

Target material R&D

- The operational target of nuSTORM would be a low-power target ~200kW. However, for R&D tests, the full beam of SPS could be used like in HiRadMat. Combined with a low emittance can emulate the parameters in a NF/MC multi-MW operation.

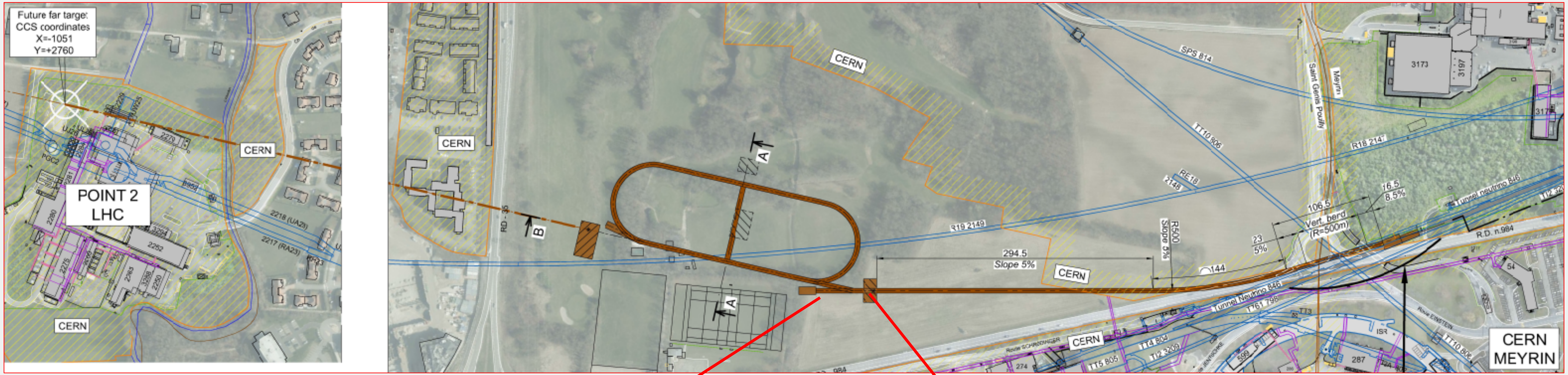
Themes:

- evaluate alternative material to Hg – synergy with RADIATE collaboration – single pulse ⟺ long-term irradiations
- examples:
  - further investigate and optimize the design of granular or fluidized targets for mMW operation
  - perform tests to compare and validate simulation codes, related to the dynamics of the target materials in pulsed beams; evaluate threshold effects on damage to determine lifetime of components



NUSTORM @ CERN – HPT R&D SYNERGIES

Target head R&D - implementation



Option B: create a new test stand upstream or downstream of the operational target
pros :
- separated from the operational target, can switch back/forth relatively fast

cons:
- need to control the beam shape to the sample maybe install additional magnets?
- need remote handling in that area – should exist anyhow
- must install additional instrumentation to monitor the beam to the samples

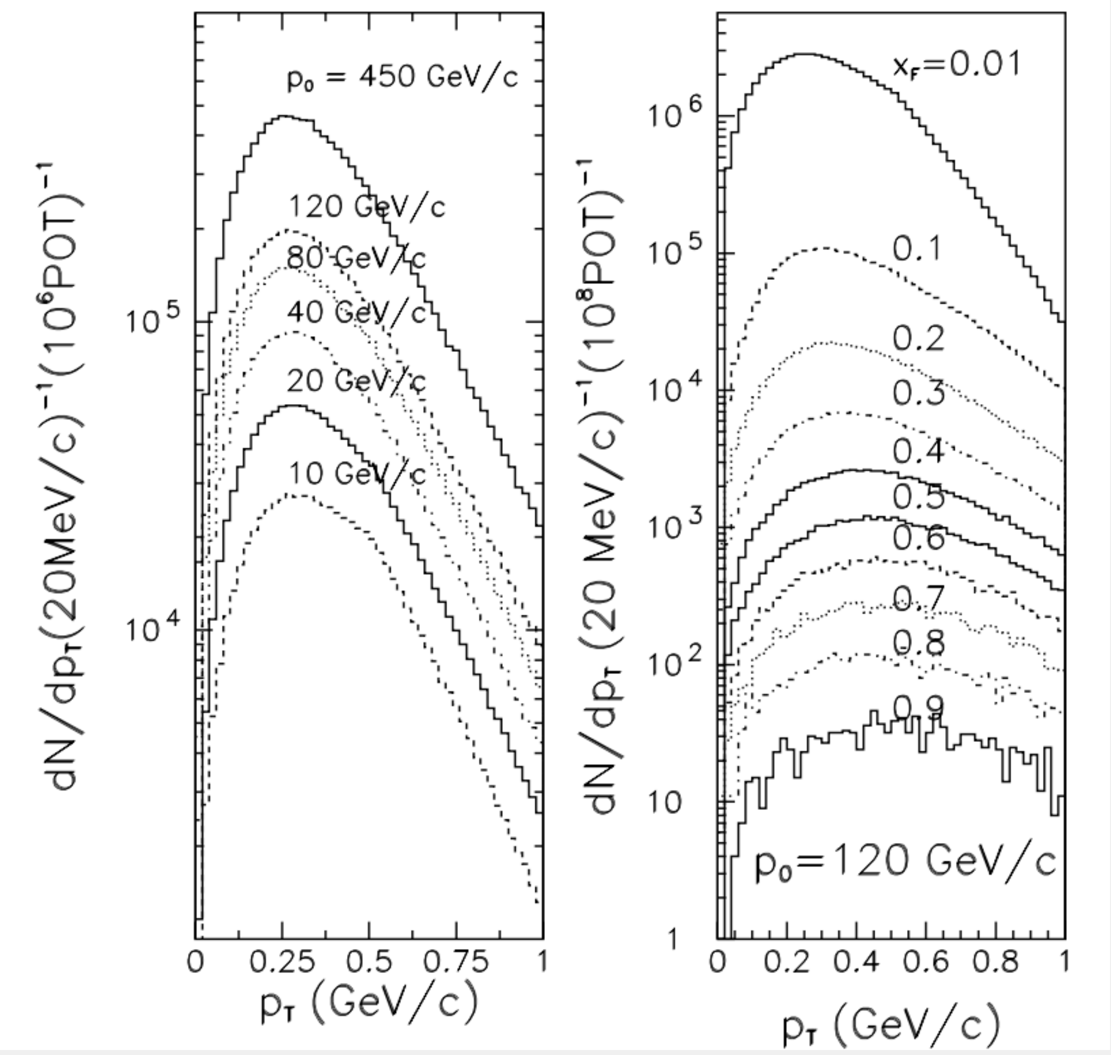
Option A: Use the operational target location for the tests
pros:
- easy to implement, has all the instrumentation before to monitor the beam (position and shape)

cons:
- must remove operational target$_{\text{and horn}}$ (remote anyhow) – long stop of operations
- needs temp. storage for horn/target

NUSTORM @ CERN – HPT R&D SYNERGIES

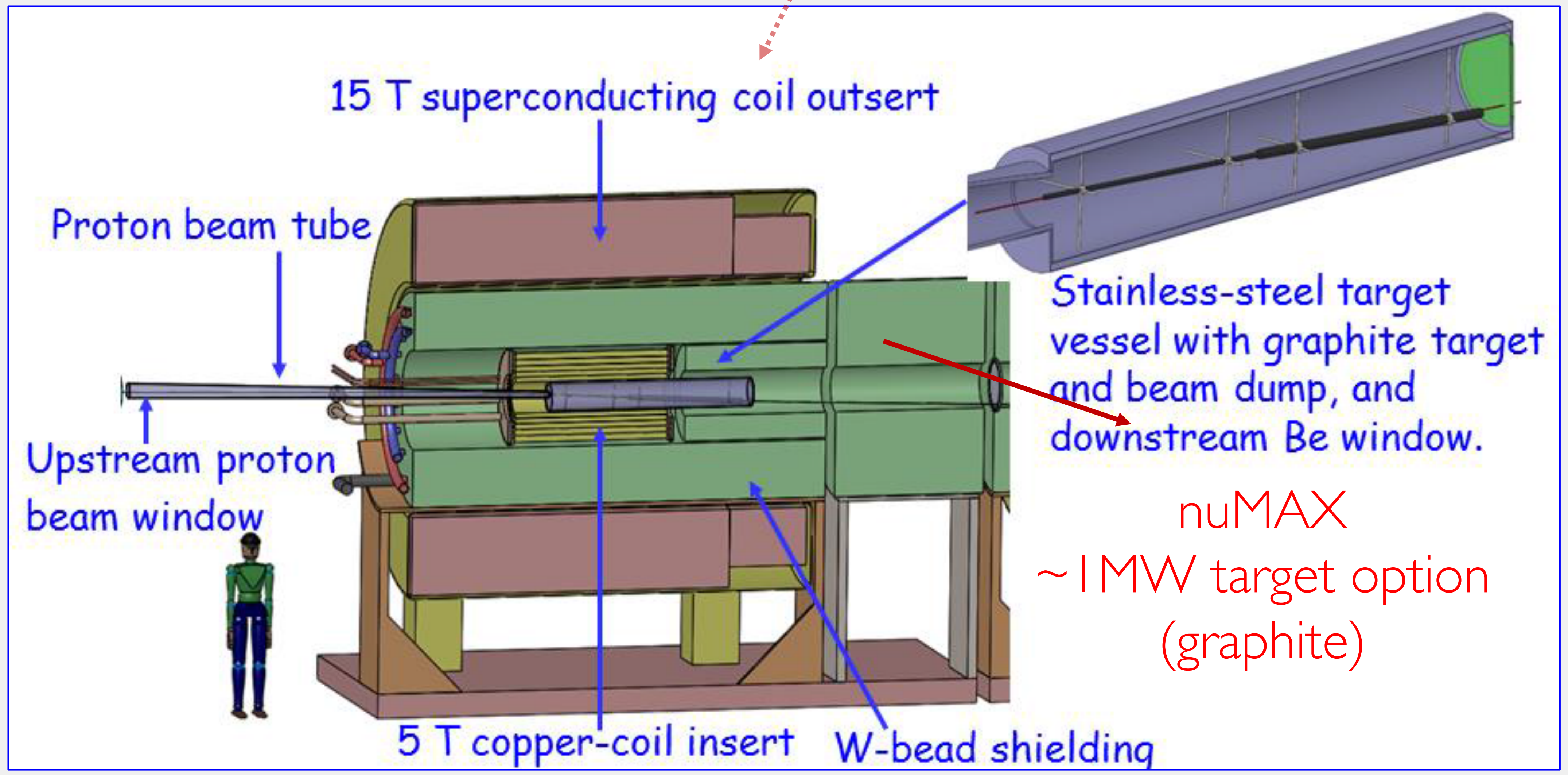
NF/MC Front-end R&D

- profiting from the higher beam energy of SPS (100-400 GeV) and by properly adjusting the beam intensity, the production of secondaries from the target can be made to match that of a NF/MC at a single pulse level

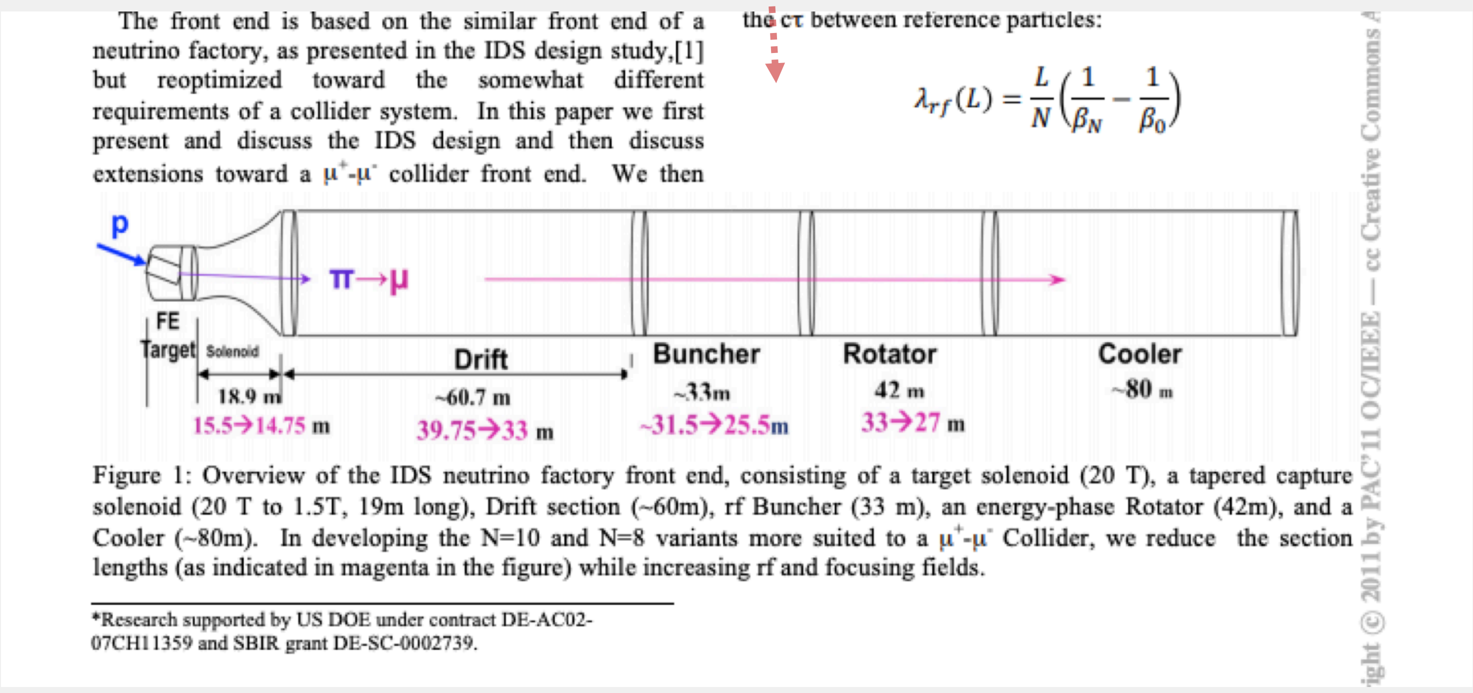


P. Sala – 2nd NBI, FNAL 2000

- this opens the possibility to
  - test the full target-capture system with solenoids
  - gradually build up the full front-end of a NF/MC installation pion-muon separation, background, buncher (RF?)
    - then inject directly muons into the ring that would open a variety of studies with μ-beams



nuMAX
~1MW target option
(graphite)



The front end is based on the similar front end of a neutrino factory, as presented in the IDS design study,[1] but reoptimized toward the somewhat different requirements of a collider system. In this paper we first present and discuss the IDS design and then discuss extensions toward a μ^+-μ^- collider front end. We then

the cτ between reference particles:

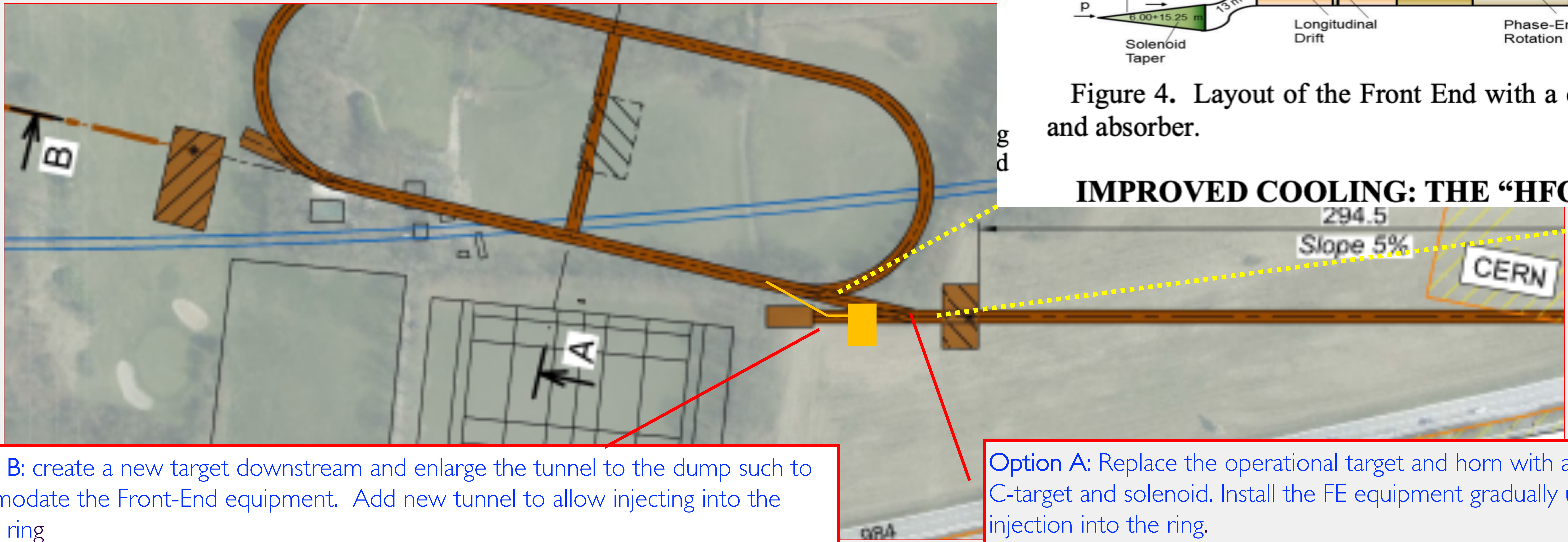
$$\lambda_{rf}(L) = \frac{L}{N}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$$

Figure 1: Overview of the IDS neutrino factory front end, consisting of a target solenoid (20 T), a tapered capture solenoid (20 T to 1.5T, 19m long), Drift section (~60m), rf Buncher (33 m), an energy-phase Rotator (42m), and a Cooler (~80m). In developing the N=10 and N=8 variants more suited to a μ^+-μ^- Collider, we reduce the section lengths (as indicated in magenta in the figure) while increasing rf and focusing fields.

*Research supported by US DOE under contract DE-AC02-07CH11359 and SBIR grant DE-SC-0002739.

NUSTORM @ CERN – HPT R&D SYNERGIES

Frond-end R&D - implementation



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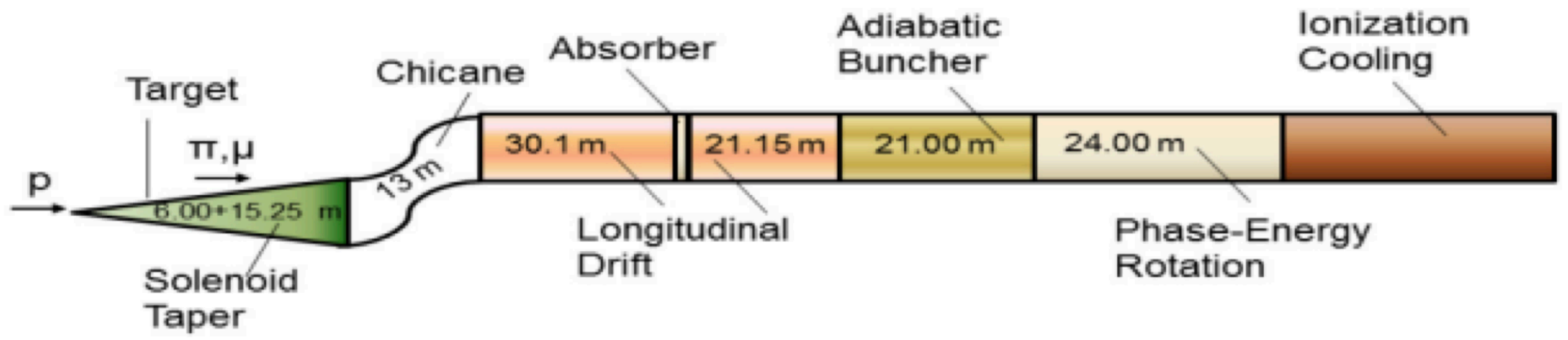


Figure 4. Layout of the Front End with a chicane and absorber.

IMPROVED COOLING: THE "HFOFO

Option B: create a new target downstream and enlarge the tunnel to the dump such to accommodate the Front-End equipment. Add new tunnel to allow injecting into the storage ring

pros:

- separated from the operational target, can switch back/forth relatively fast
- maintain original option of nuSTORM with pion capture/injection

cons:

- need remote handling in that area – should exist anywhow

Option A: Replace the operational target and horn with a NF-type C-target and solenoid. Install the FE equipment gradually until the injection into the ring.

pros:

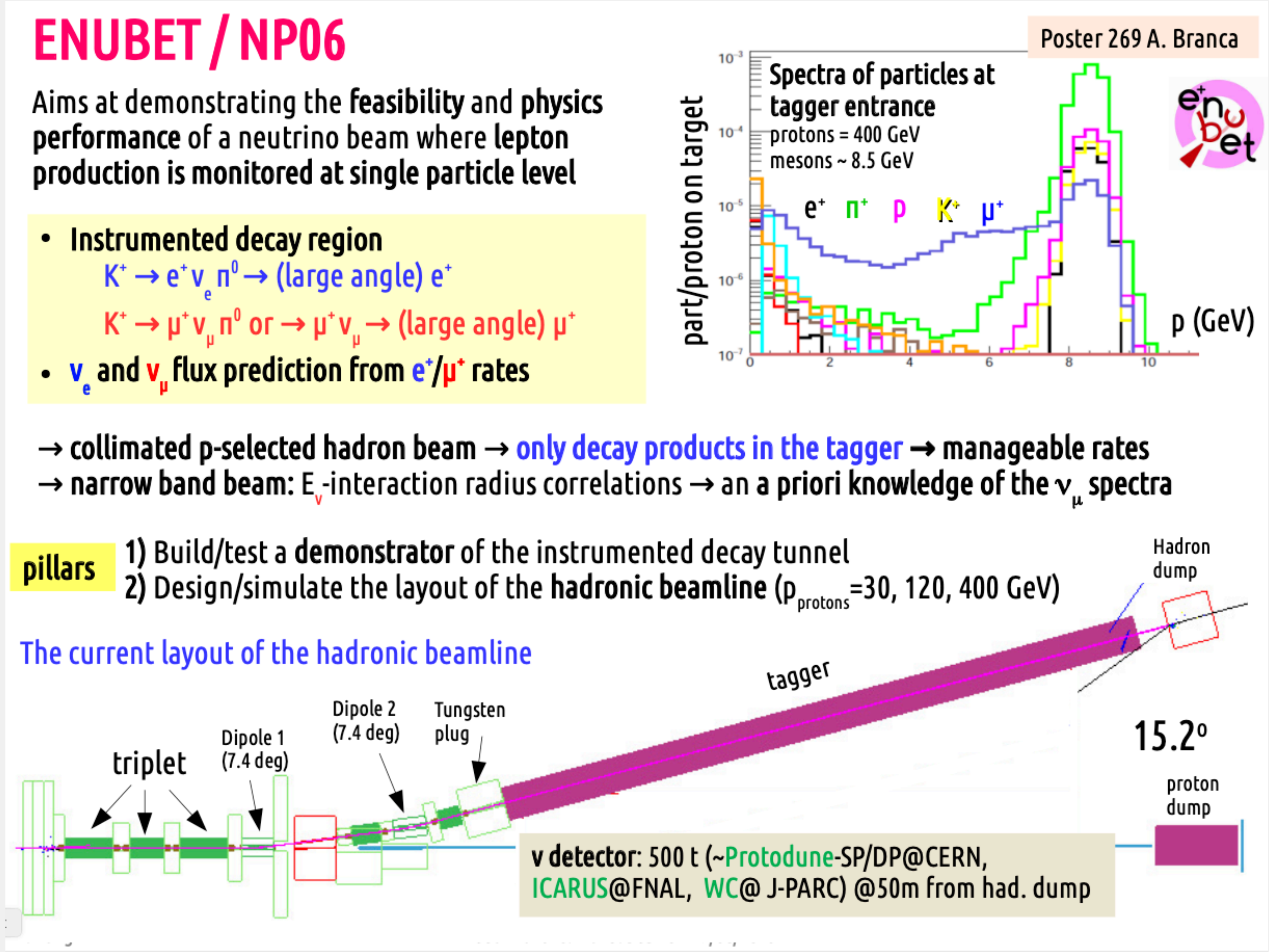
- straight forward to implement

cons:

- requires removing target head and horn
- not compatible with normal nuSTORM operation

NUSTORM @ CERN –SYNERGIES

- ENUBET /NP06 – Enhanced NeUtrino BEams from Kaon Tagging



A.Longhin – Neutrino 2020

The beam layout looks like nuSTORM – room for synergies !

…but the devil is in the details !

Issues to consider:

- Beam **capture** from the target: horns, dipoles, etc..
- **Layout** : use same detector locations?

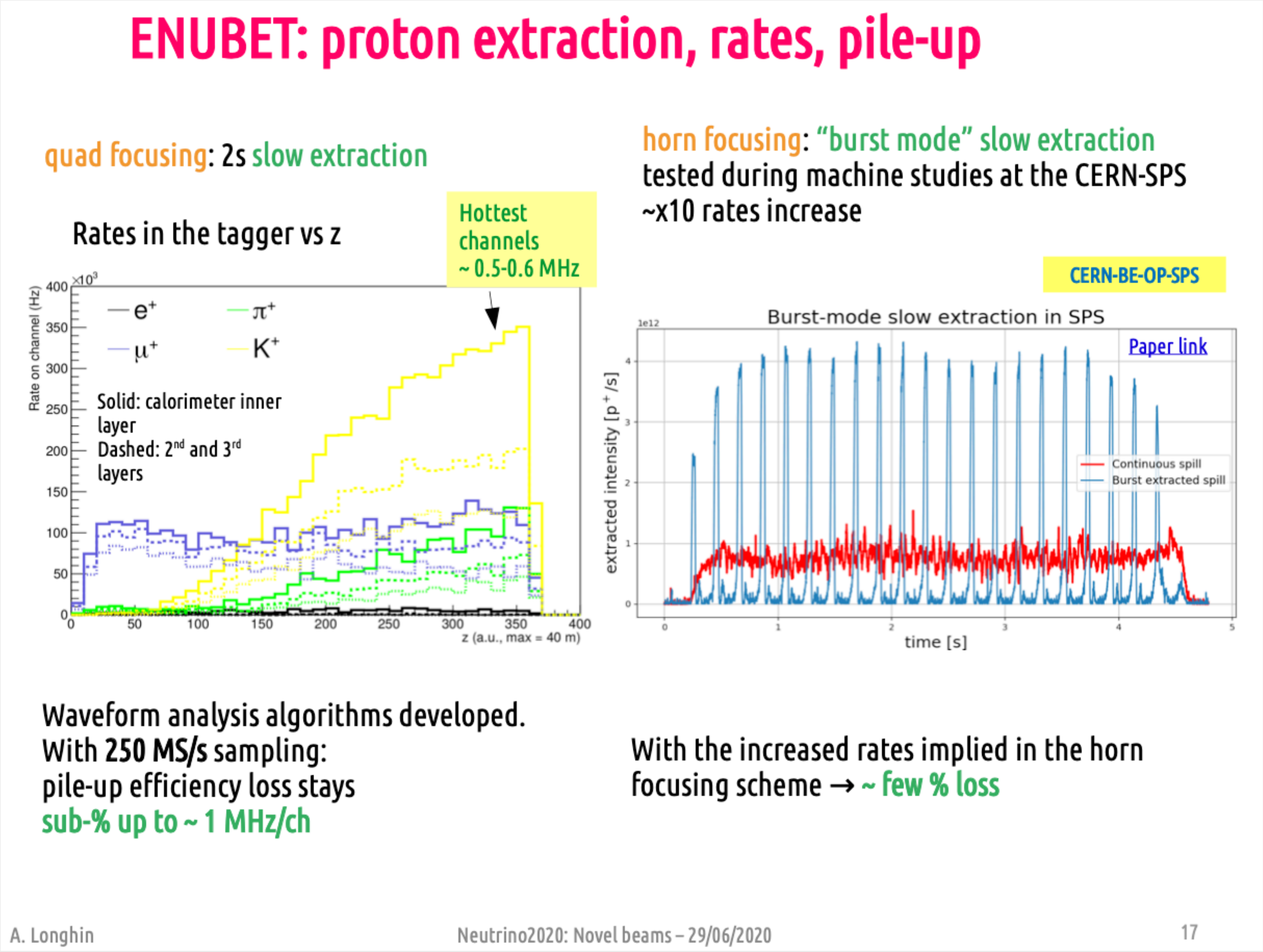
Note : narrow band beams were made in the past at CERN and FermiLab in two configurations:

- **horn focusing** with "**plug**" or **dipole** for momentum selection
- **dichromatic** NBB without horn and only magnetic elements

See: Sascha E. Knopp, Phys.Rept.439:101-159, 2007

NUSTORM @ CERN –SYNERGIES

- ENUBET /NP06 – Beam Extraction

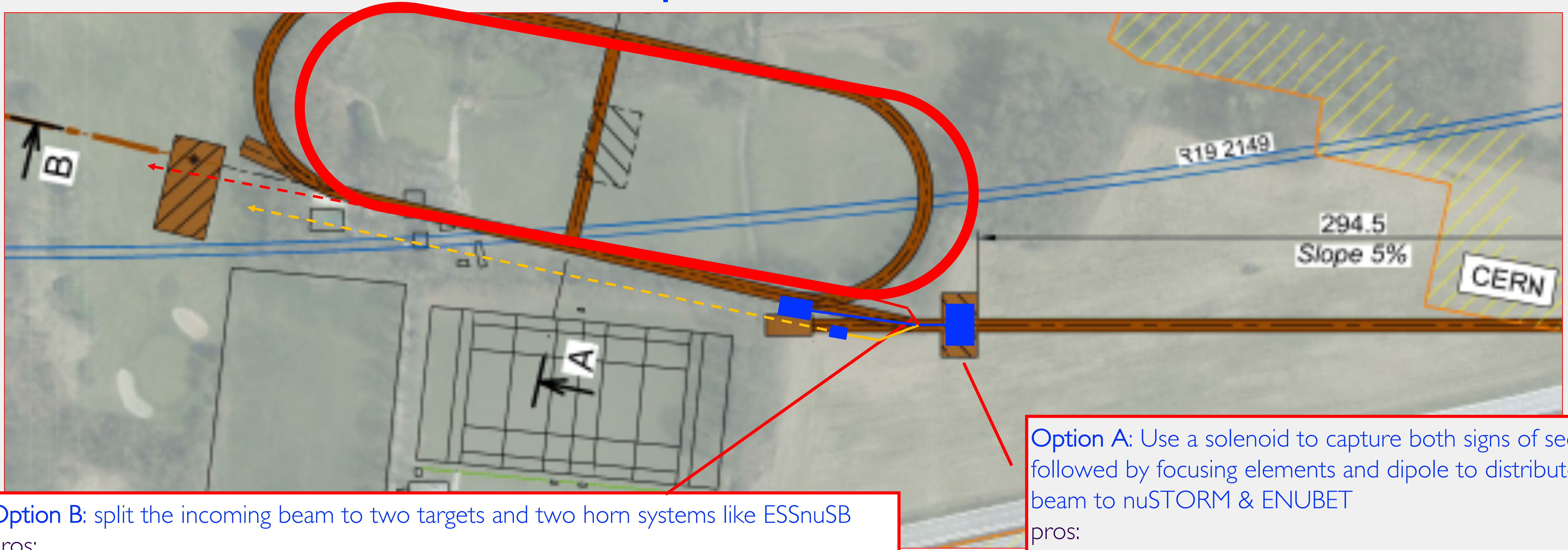


- The slow-extraction option, if preferred and possible at the foreseen installation of nuSTORM, could be accommodated by a fast + slow extraction from SPS as was done for years for WANF

- The burst mode could be accommodated in the decay ring design
  - didn't have the time to look at it…

NUSTORM @ CERN – HPT R&D SYNERGIES

ENUBET & nuSTORM - implementation



Option B: split the incoming beam to two targets and two horn systems like ESSnuSB

pros:

- separated target/capture system for each project, possibly tuned to its needs

cons:

- beam sharing, reduced flux to each project
- requires development of fast cycling magnets, 0.25Hz

Option A: Use a solenoid to capture both signs of secondaries, followed by focusing elements and dipole to distribute the charged beam to nuSTORM & ENUBET

pros:

- Easy solution can allow // operation of the two projects
- The layout can be adjusted to allow pointing the neutrinos to the same detector
- The solenoid option can work at any pulse duration

cons:

- requires development of a solenoid solution!

SUMMARY

- High-power Targetry in application to Muon Beams is a very challenging but at the same time a very exciting R&D subject

- Thanks to the long-running R&D studies for ~30 years already, a conceptual baseline option for a multi-MW NF/MC application emerged.
  - Unfortunately, this solution comes with important safety and operational concerns, therefore, the need to continue, investigate alternatives, perform detailed studies and gain experience

- The nuSTORM proposal, valid on its own by an appealing physics program, can serve as test bed for HPT and Front End R&D studies for muon beams, and to build synergies with other projects in the field.

An opportunity to carefully value and not miss!

HIGH POWER TARGETRY

NoVa ν target – High Power Targets Group STFC

Big Canon in Moscow Kremlin

maybe indeed the future in high-power is in granular pebble bed targets!