Physics Beyond Colliders

LHC Injectors Upgrade

CERN

Proton throughput in the LHC Injectors Upgrade (LIU) era

Giovanni Rumolo

Special thanks to: H. Bartosik and R. Steerenberg

With the input of: G. Arduini, M. Calviani, C. Carli, R. Catherall, E. Chiaveri, H. Damerau, A. Fabich, M. Fraser, L. Gatignon, S. Gilardoni, M. Giovannozzi, B. Goddard, E. Gschwendtner, K. Hanke, M. Lamont, M. Meddahi, E. Métral, B. Mikulec, E. Shaposhnikova

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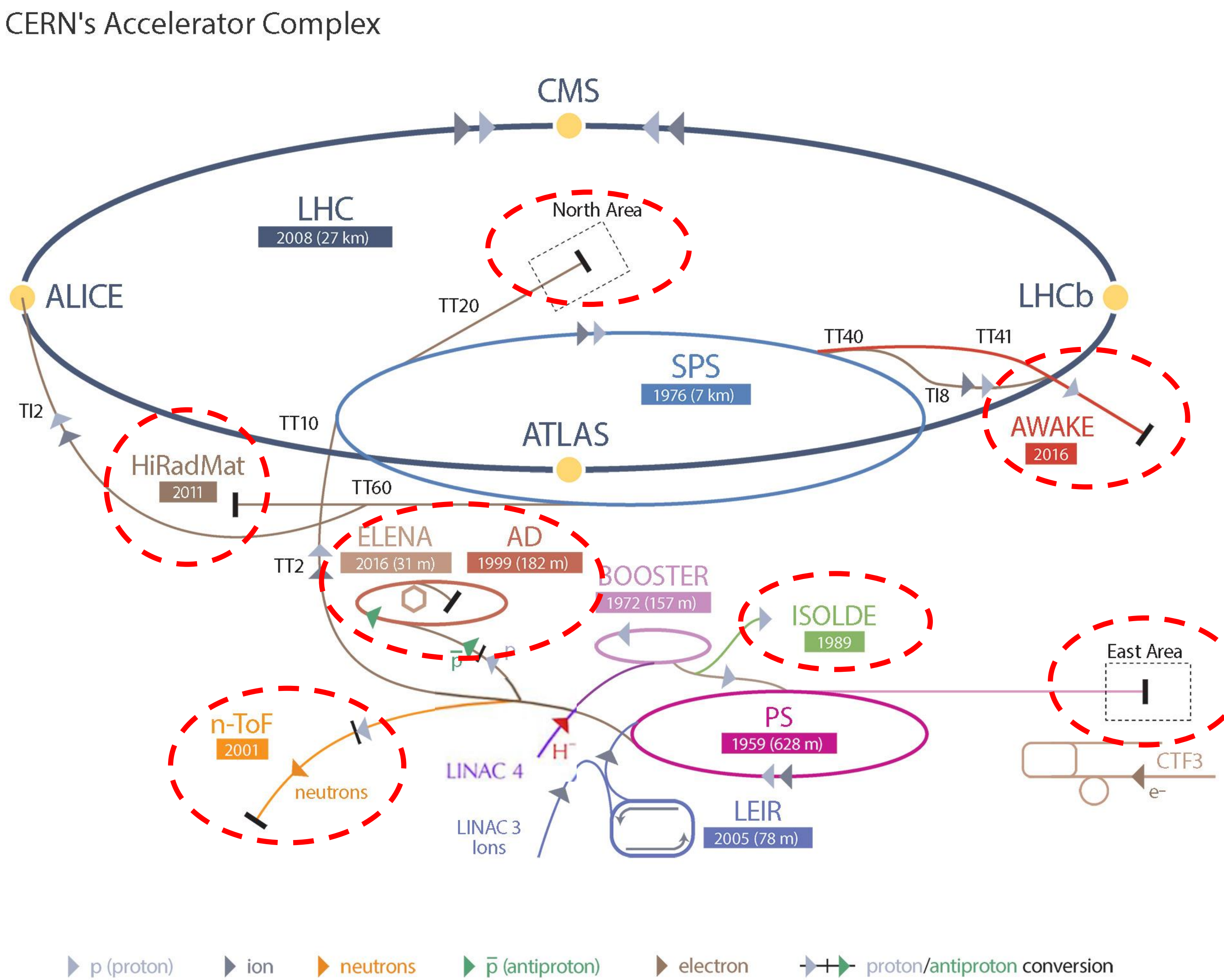
http://indico.cern.ch/event/523655/

Outline of the talk

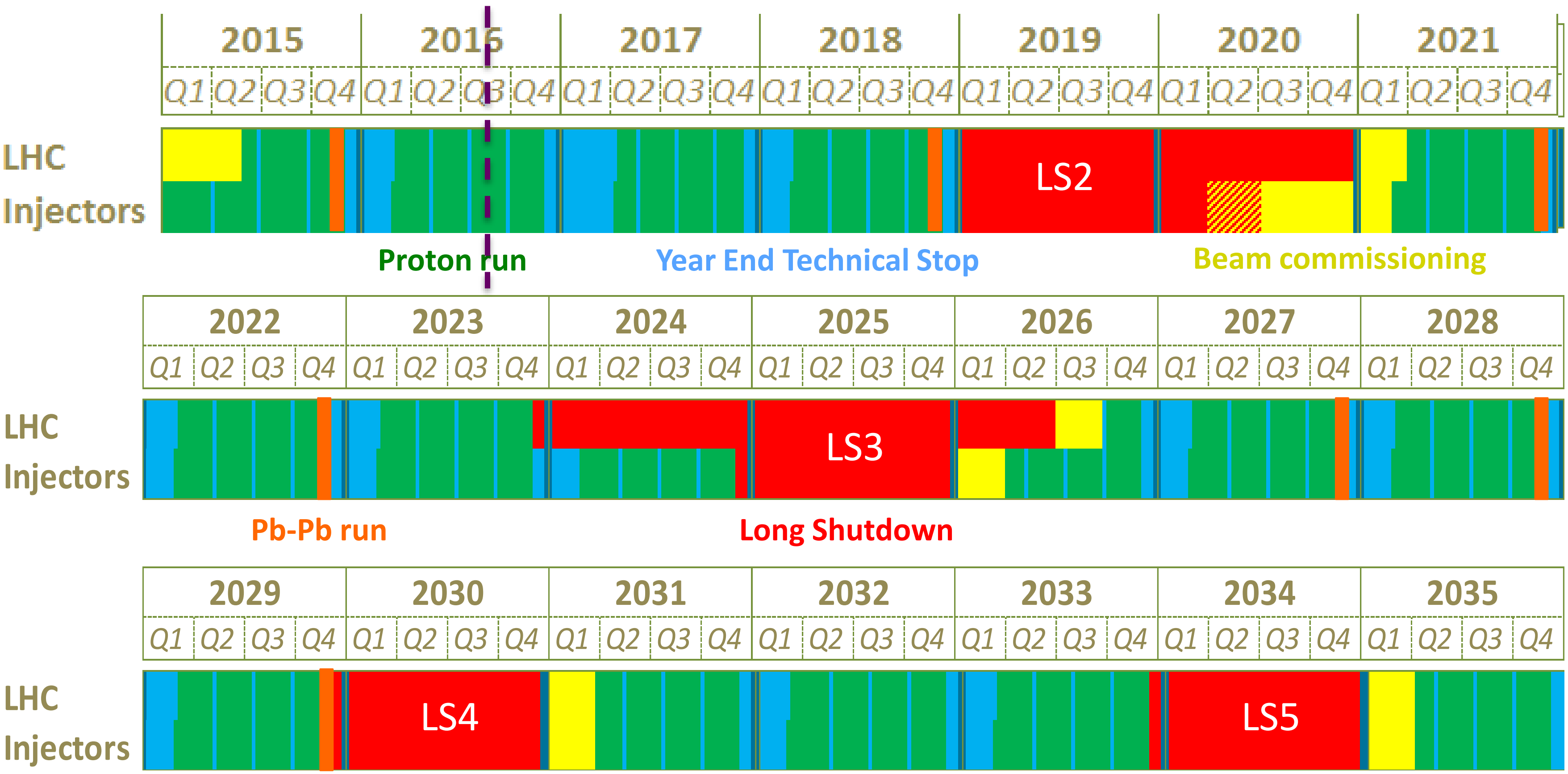
- **CERN's accelerator complex**
  - Overview
  - Timeline out to 2035 and LHC Injectors Upgrade (LIU)
- **Foreseen proton throughput including LIU upgrades**
  - Outlook for non-LHC physics users (existing and future?)
  - General considerations
    - Optimisation of the delivery rates
    - Limitations and challenges
- **Conclusions**

CERN accelerator complex



Timelines up to 2035

- **LHC Injectors Upgrade (LIU) installations during Long Shutdown 2**
  - Preparation (studies, hardware design/production) until LS2
  - LIU beam commissioning during Run 3
- **High Luminosity LHC (HL-LHC) installations during Long Shutdown 3**



LHC Injectors Upgrade (LIU)

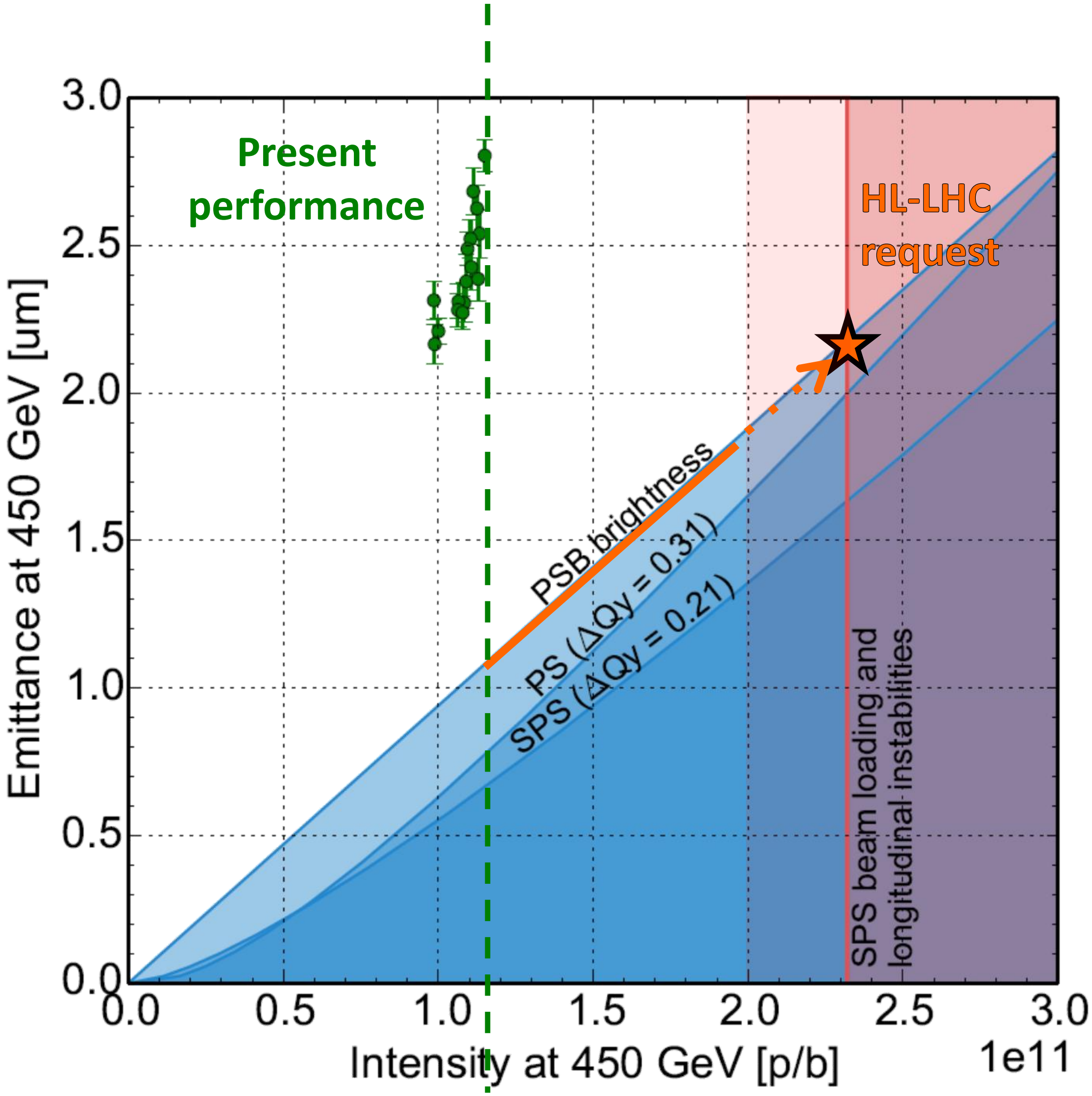
⇒AIM of the project

- Increase intensity/brightness in the injectors for **LHC beams** to match High Luminosity LHC (HL-LHC) requirements
- Increase **injector reliability and lifetime** to cover HL-LHC run (until ~2035)

• Main baseline items

- Replace Linac2 with **Linac4** → H^- charge exchange injection at 160 MeV into the PS-Booster
- **2 GeV** PS-Booster to PS transfer
- **Upgrade of main RF system** in SPS

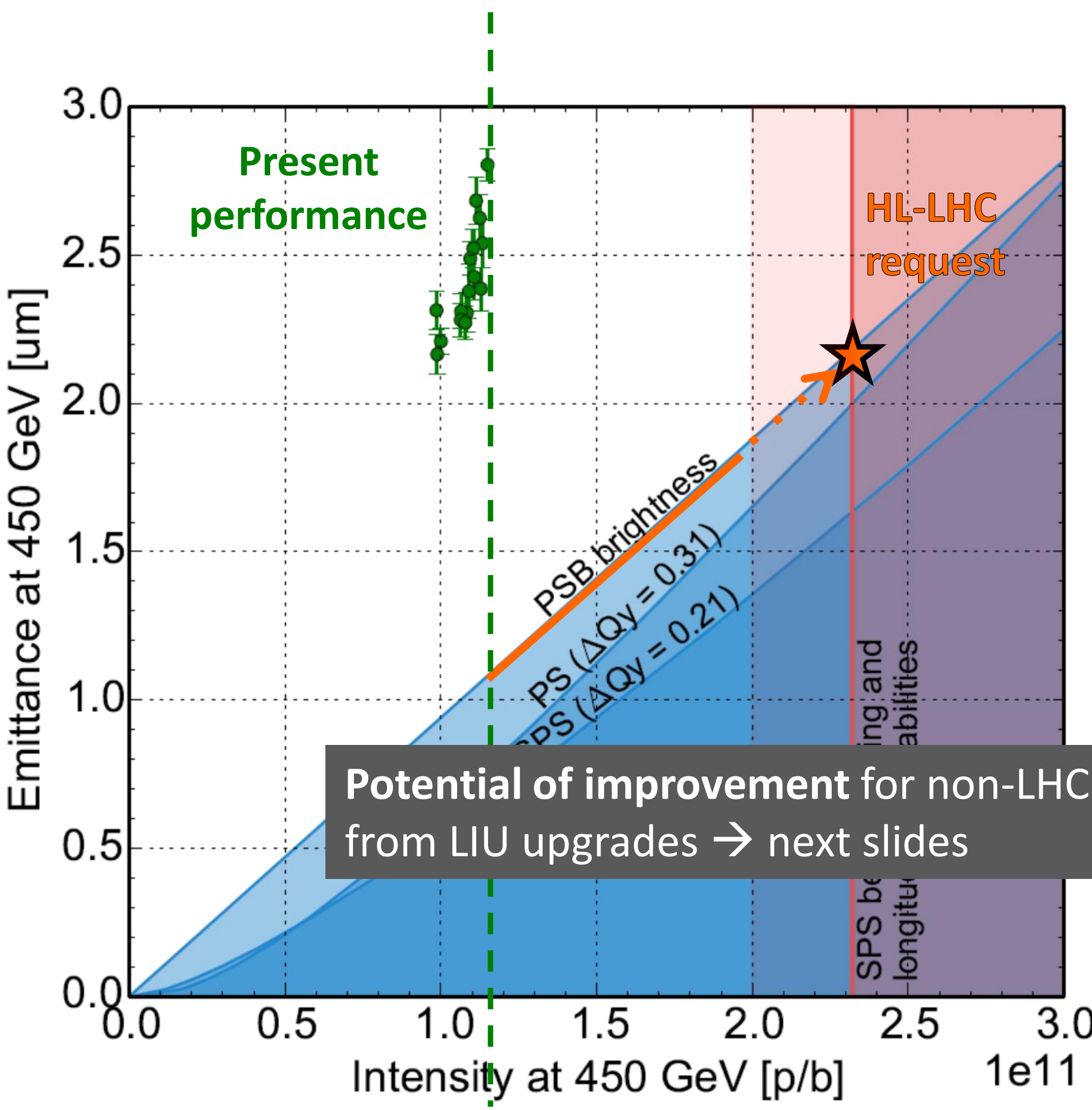
LHC Injectors Upgrade (LIU)



	$\mathcal{N}$ (x 10^{11} p/b)	ε (μm)
HL-LHC	2.3	2.1

- **LIU era**: beam commissioning towards the ultimate goal of matching the desired (HL-LHC) parameters at LHC injection
- After LS3 proton delivery rate to LHC of about **3 x 10^{17} p/year** (and a similar, probably higher, number dumped in SPS for beam preparation)

LHC Injectors Upgrade (LIU)



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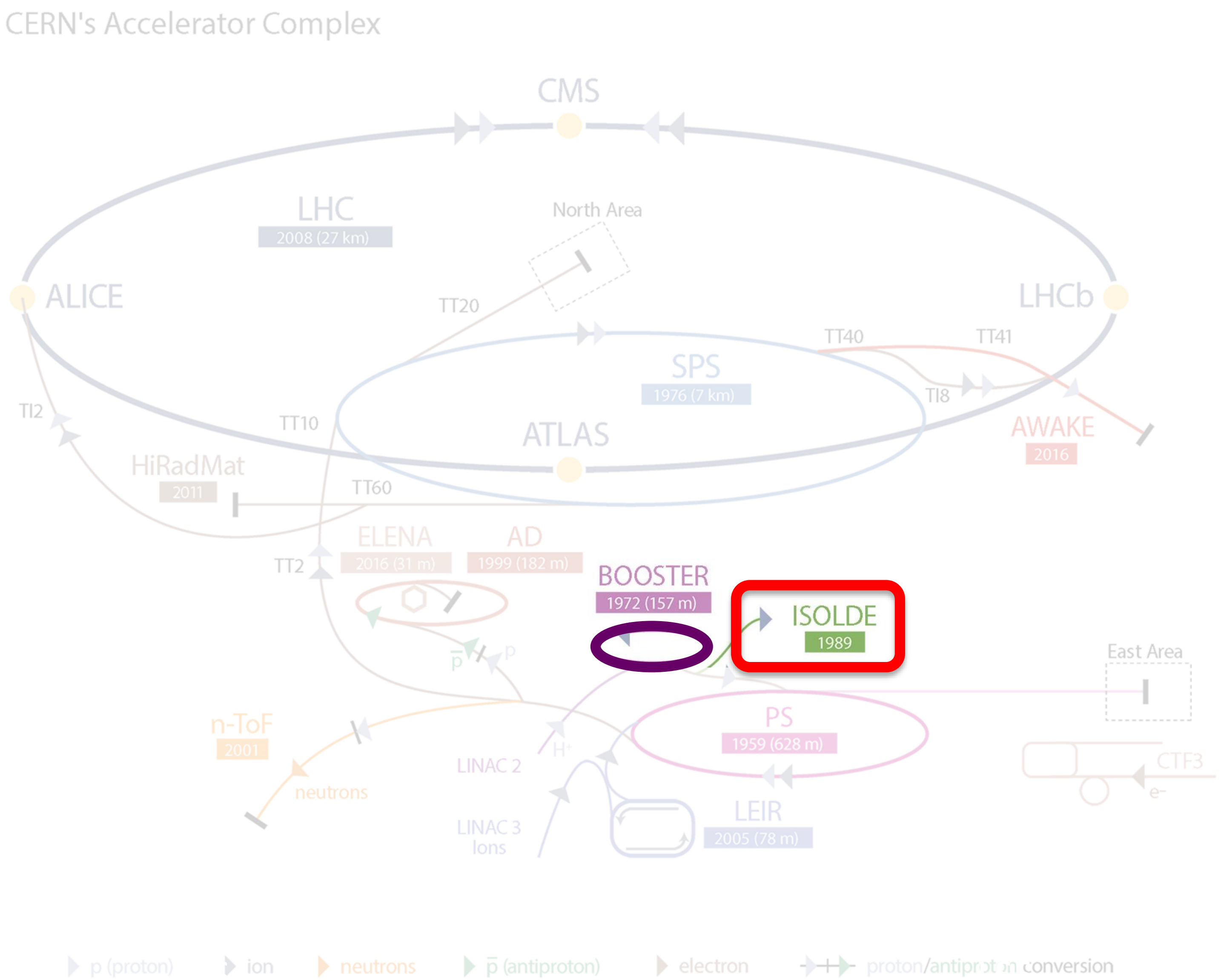
Potential of improvement for non-LHC physics beams from LIU upgrades → next slides

PSB & ISOLDE


CERN's Accelerator Complex
CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
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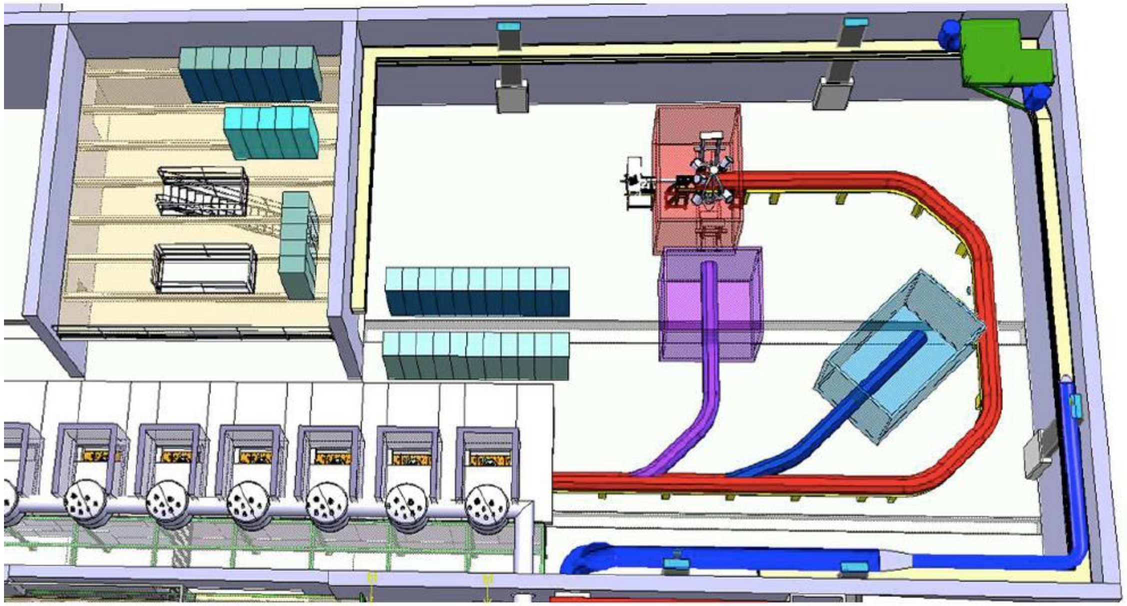
ISOLDE

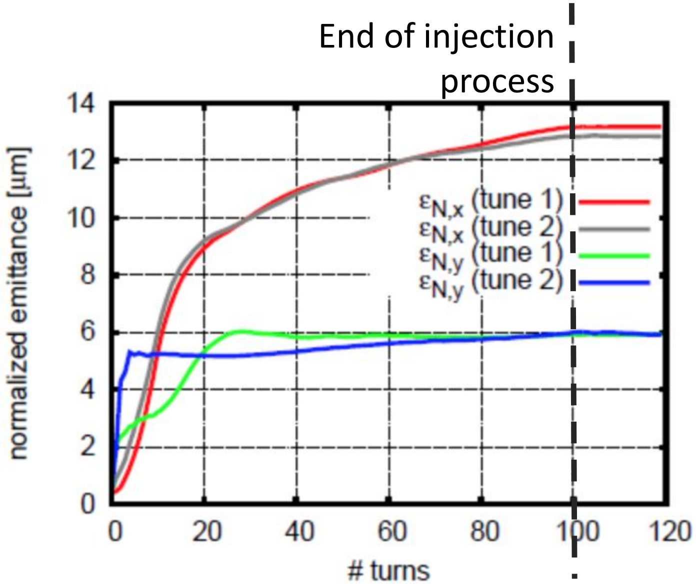
- **Perspectives for the Medium Term**
  - HIE being implemented (SC linac for post-accelerated beam to 10 MeV/u)
  - Higher intensity available from PSB after connection to Linac4 (LS2)
  - Option: Upgrade of extraction energy of beams to ISOLDE to 2 GeV (post-LS2)



A post-accelerator after REX-ISOLDE

ISOLDE

- **Future beam to ISOLDE after LIU upgrades**
  - Higher intensity thanks to
    - H^- charge exchange injection at 160 MeV
    - Increased RF power with new RF system
  - Limitations
    - Current at the end of Linac4
    - Injection and extraction losses

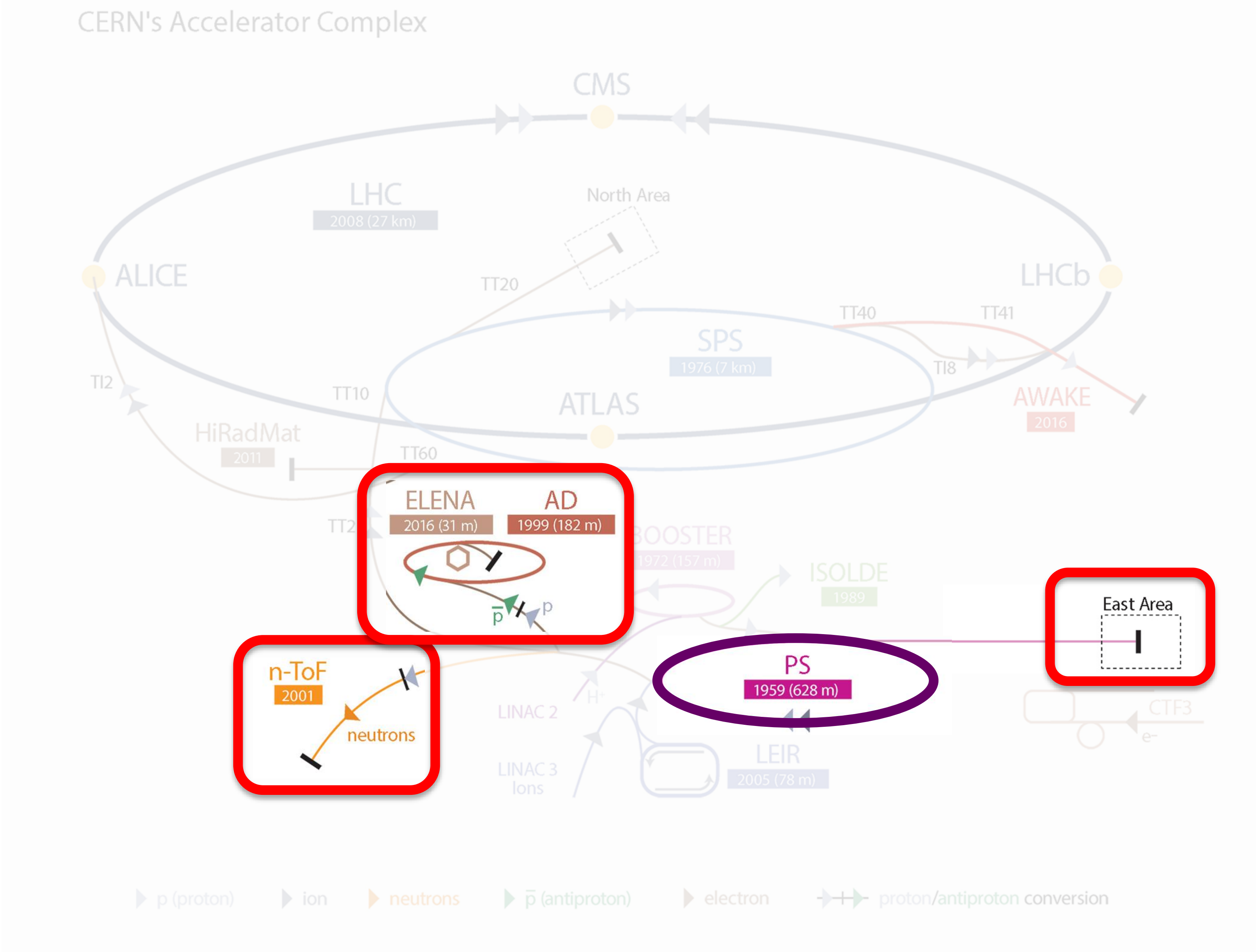


1.6 x 10^{13} p per pulse and per ring
with 40 mA (unchopped) from Linac4 and 100 turns injection

Twice as much as available today from PSB

J. Abelleira et al, in LIU-PSB Injection meetings

PS & users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nTOF

- **Expected to run until 2030 and beyond**
  - Target exchange during LS2
    - To increase present limit of 1.66 x 10^{12} pot/s to 3 x 10^{12} pot/s
    - To accept up to 1.5 – 2 x 10^{13} pot/pulse
  - Expected lifetime of target ~10 years, many clients

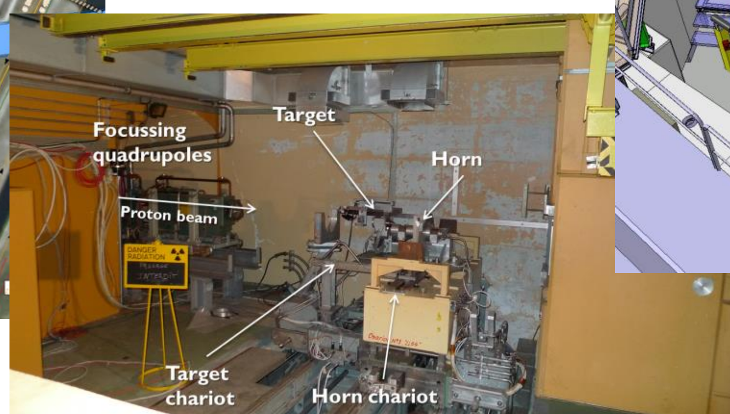
- **Protons to nTOF: present and future**
  - 8 x 10^{12} pot/pulse (17% of supercycle dedicated, 17% parasitic with half intensity)
    - RF power for acceleration and bunch rotation before extraction
    - Transverse instability
    - Losses at extraction septum

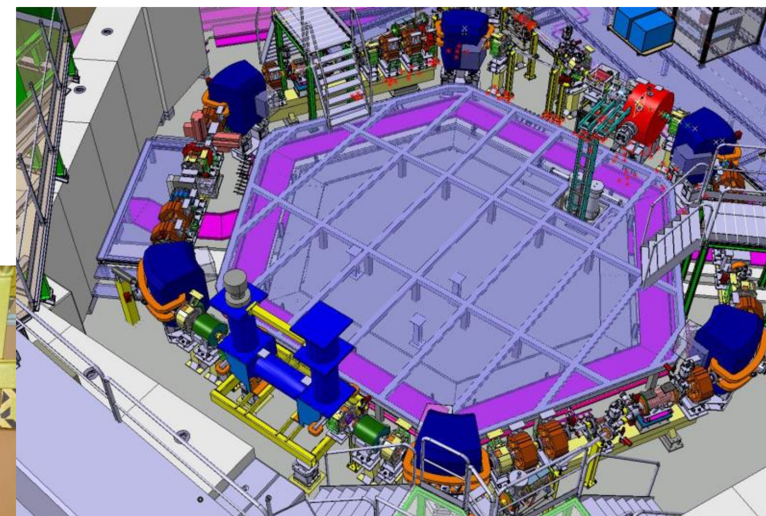
  → This results in the delivery of **1.9 x 10^{19} pot/year**

  - Beam after LS2 and LIU upgrades (>10^{13} pot/pulse?)
    - More intensity from the PS-Booster
    - Enhanced beam stability
    - Lower transverse emittance

AD, ELENA

- **Expected to run until 2030 and beyond**
  - Major renovation of AD target area during LS2. Main items
    - New air-cooled target and magnetic horn
    - Ventilation system and consolidation of buildings/tunnels
  - ELENA expected to start commissioning with beam (from external source) at the end of 2016
    - After commissioning with beam from AD, most experiments will connect to ELENA





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    - After commissioning with beam from AD, most experiments will connect to ELENA

- **Protons to AD/ELENA: present and future**
  - ~1.5 x 10^{13} pot/pulse – mainly limited by shielding in AD ring
  - Beam on AD target every ~100 s
  - Similar AD beam request in the future (increase depends on improvement of AD shielding)
    - Higher proton rate for stacking (9.6 sec period after upgrade) and high energy antiprotons

→ **2 – 4 x 10^{18} pot/year** limited mainly by the repetition rate

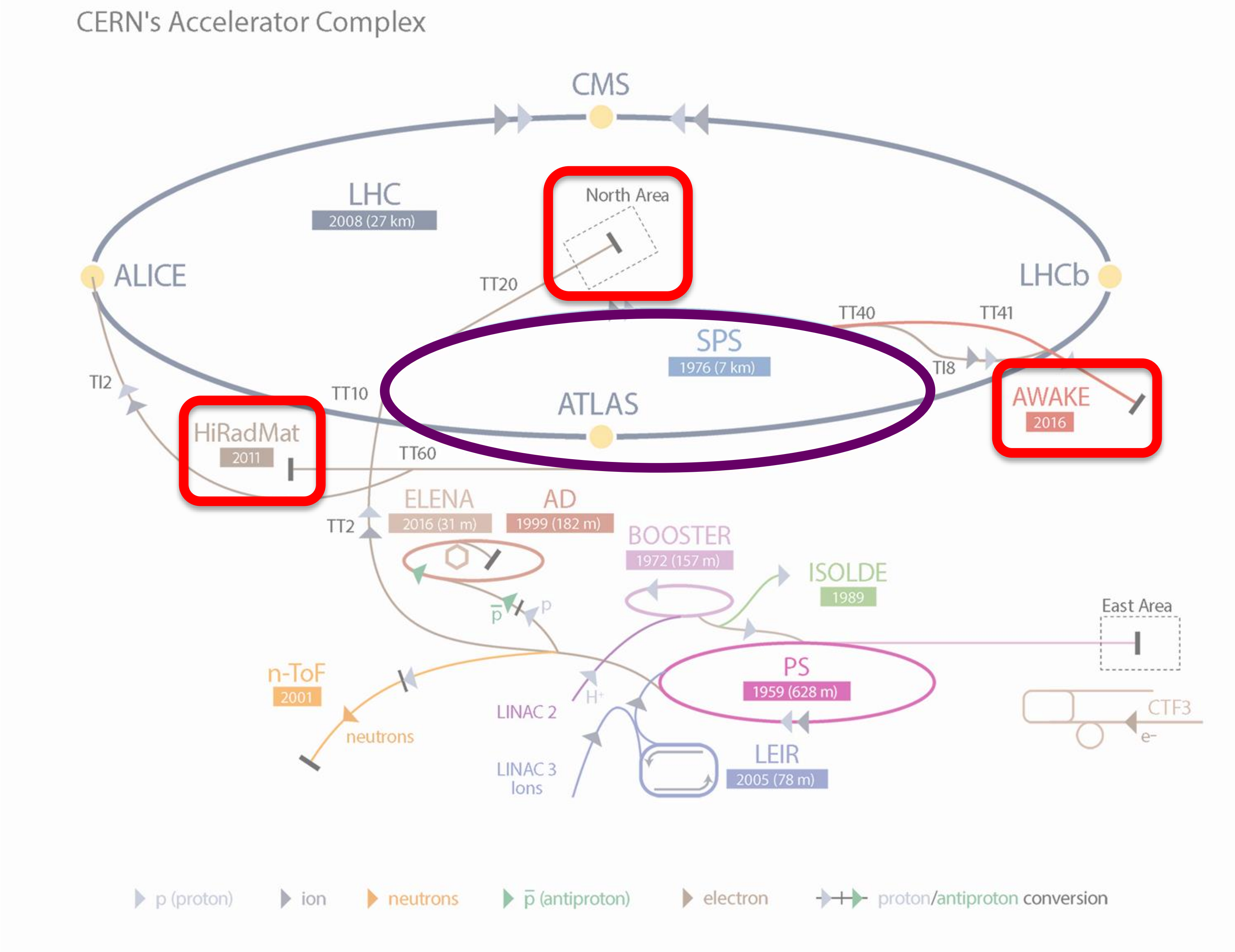
East Area

- **Expected to run until 2030 and beyond**
  - Test beams and irradiation facility
  - Major renovation plans during LS2
    - Redesign and renovation of transfer lines during LS2
    - Improvement of RP aspects, consolidation of infrastructure

- **Protons to East Area: present and future**
  - Low intensity: 1 – 5 x 10^{11} p/spill
  - 17% of cycles in supercycle
  - No change expected in the East beam request in the future, maybe ion beams should be also included for irradiation tests

→ ~10^{18} pot/year

SPS & users



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HiRadMat & AWAKE

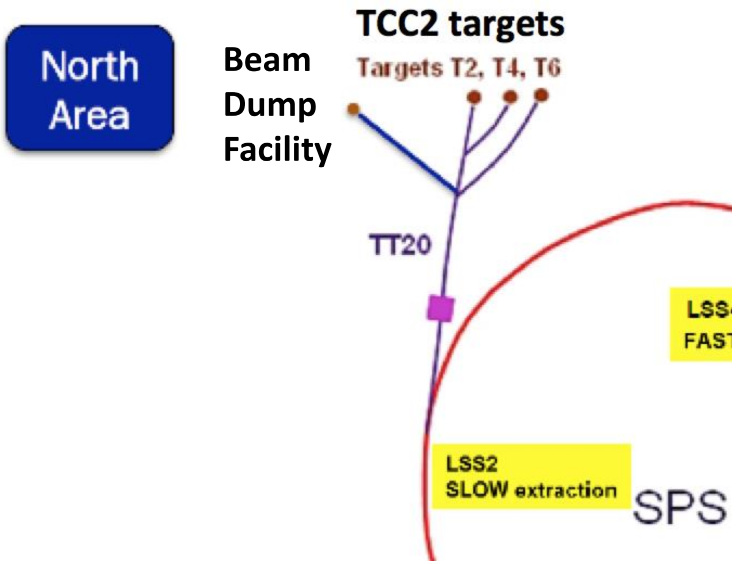
- **Plans for the Medium Term and beyond**
  - Both experiments will be active until LS3 and beyond
    - Several clients for **HiRadMat** to test accelerator components
    - **AWAKE**: proof of concept for plasma wake acceleration (<LS2), demonstration of plasma wake acceleration with good beam quality, scalability and applications (>LS2)

- **Protons to AWAKE and HiRadMat: present and future**
  - HiRadMat: Single bunches (10^{11} p/pulse) to full LHC beams (pulses of 288 bunches with 1.2×10^{11} p/b) for ~10 experiments/year mainly limited by environmental impact
    - Double intensity expected after LIU upgrades
  - AWAKE: Bright intense short single bunches (~3.5×10^{11} p/pulse). With LIU:
    - RF power upgrade and longitudinal impedance reduction (stability, bunch shortening)
    - Lower transverse emittance

→ **2×10^{16} pot/year for HiRadMat and 10^{17} pot/year for AWAKE**

North Area (and BDF scenario)

- **Expected to run until 2030 and beyond**
  - Several clients
    - T2, T4, T6 (TCC2) beam line users
    - Request for ions to TCC2 for about four weeks/year, expected to continue until 2030
    - Possible future scenario: Beam Dump Facility to share protons to North Area
  - Some improvements planned if BDF
    - Replace existing splitter magnet with bipolar version and pulsed TT20 optics
    - Beam instrumentation (e.g. BLMs in area of splitter)



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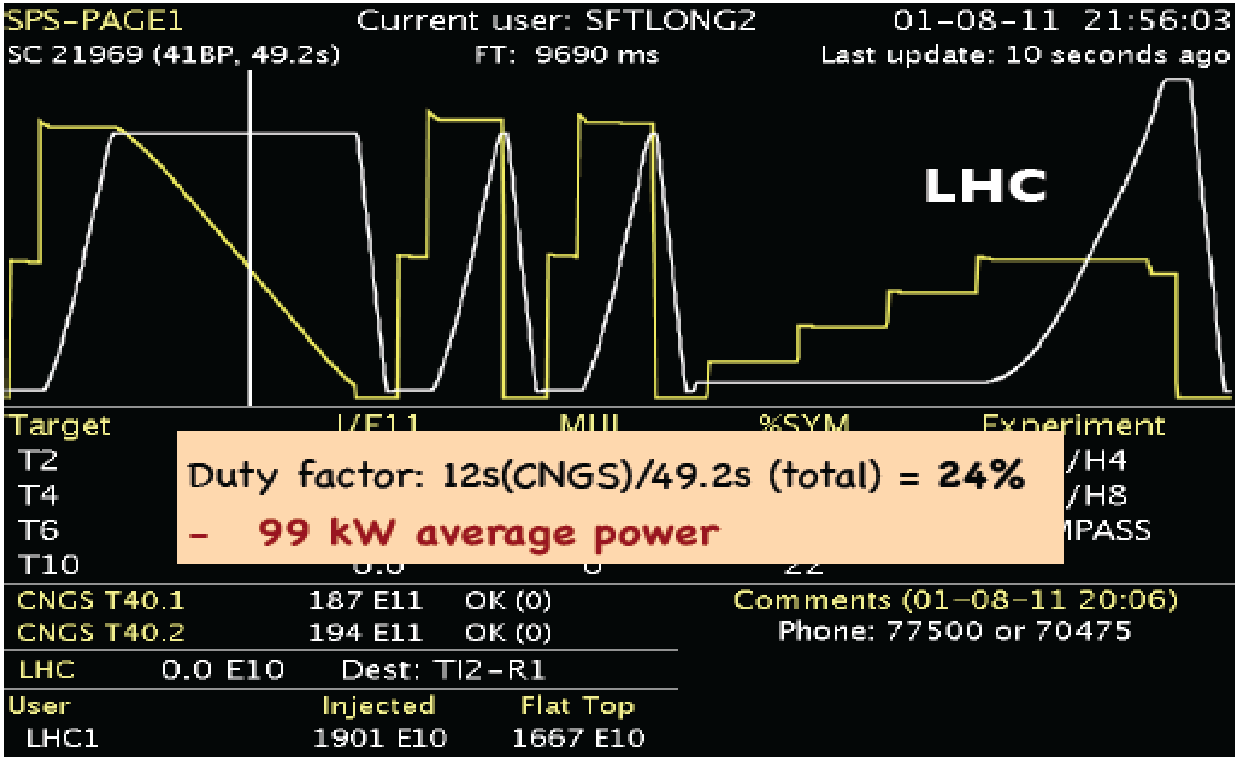
- **Protons to North Area: estimates from past experience**
  - 4×10^{13} p/spill to TCC2
  - 4.2×10^{13} p/spill to BDF
  - Both limited by losses and machine activation, margin to improve with smaller LIU beams and RF upgrade in SPS

→ Target for BDF is **4×10^{19} pot/year** – how much available to TCC2 targets?

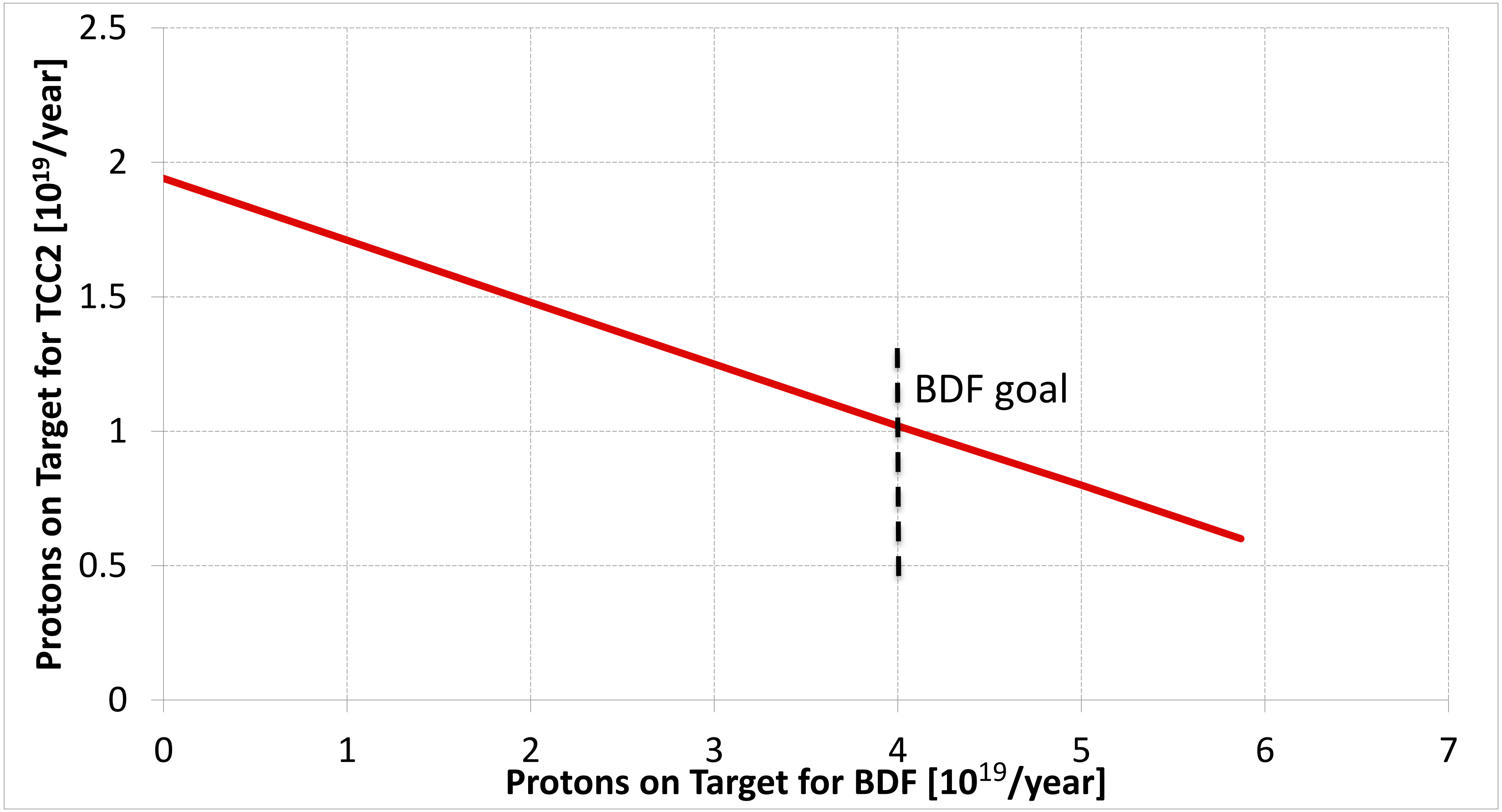
BDF scenario

- **Assumptions**
  - Running scenario based on SPS operational experience in 2011-2012
  - Spill of 9.7 s for beam to TCC2, 1 s for beam to BDF
  - Several supercycle compositions considered (e.g. day and night, during LHC set up and filling)



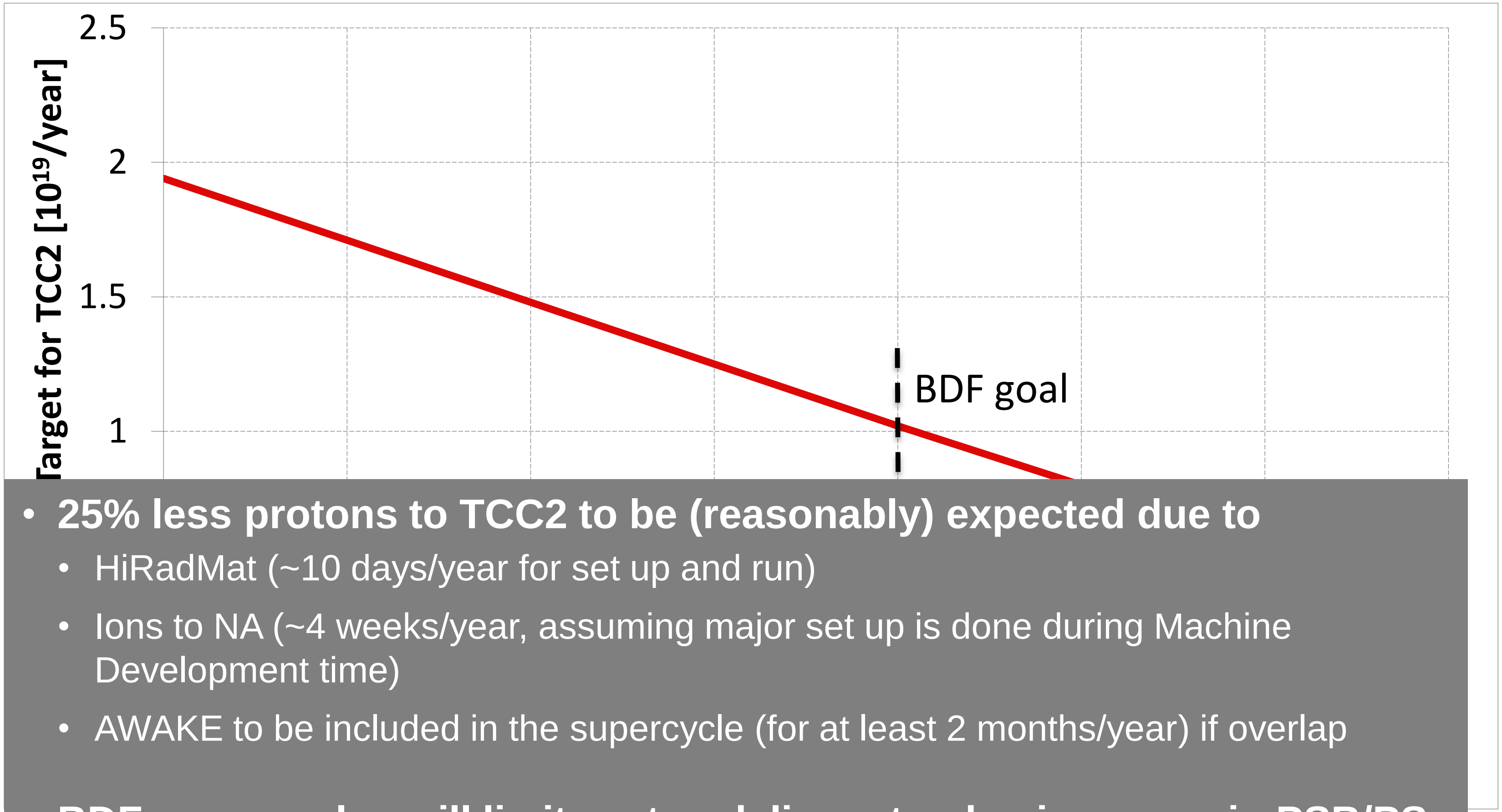
Example of supercycle with CNGS, NA and LHC filling (2011)

BDF scenario: proton sharing



G. Arduini, B. Goddard, L. Gatignon, K. Cornelis, CERN-SHiP-NOTE-2015-004

BDF scenario: proton sharing



- **25% less protons to TCC2 to be (reasonably) expected due to**
  - HiRadMat (~10 days/year for set up and run)
  - Ions to NA (~4 weeks/year, assuming major set up is done during Machine Development time)
  - AWAKE to be included in the supercycle (for at least 2 months/year) if overlap
- **BDF supercycles will limit proton delivery to physics users in PSB/PS**

G. Arduini, B. Goddard, L. Gatignon, K. Cornelis, CERN-SHiP-NOTE-2015-004

Optimisation of delivery rates

- **Increase limits of proton delivery rates on target**
  - Better compensation of the time distribution to users on timescale of weeks
  - Ex. nTOF/ISOLDE could increase the number of cycles in supercycle when other not online
- **Normal/spare mechanism in supercycle driven by direct request from users**
  - When one user’s request off, play spares to increase number of other physics users in supercycle compatibly with limitations
  - Concept already applied to AD due to its ‘sparse’ repetition rate
  - Avoid manual readjustments from the CCC and use all available time
- **Fully use the potential of the four PS-Booster rings**
  - Concept already applied when playing parasitic nTOF with EAST users
  - Whenever users needing one PS-Booster ring are served, other three rings could serve ISOLDE
    - Fast pulsing of the switching magnet

Outstanding intensity limitations for non-LHC beams

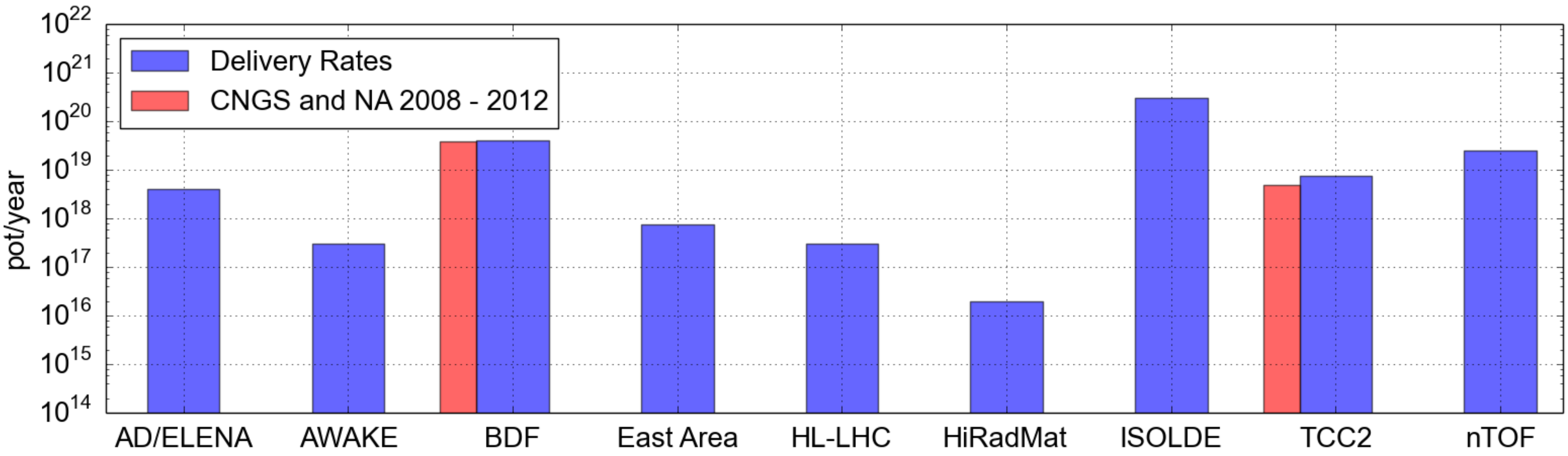
- **Beam losses in all accelerators → machine activation**
  - PSB: Losses at recombination septum limit vertical emittance of high intensity beams
  - PS: Losses at extraction → With currently operational Multi Turn Extraction (MTE) islands are extracted without need of intercepting device and losses are controlled
  - SPS:
    - Losses due to limited vertical acceptance
    - Losses on electrostatic septum (ES) during slow extraction – might pose in the future a serious limit on the maximum number of protons per year that can be extracted to the North Area
    - Capture losses

- **Other intensity limitations**
  - PS & SPS
    - RF power
    - Beam instabilities
    - Heating/outgassing/sparking of sensitive elements, stress on beam dump

Conclusions

- **LIU upgrades implemented in LS2**
  - Goal is to double intensity and brightness of LHC beams
  - Benefits for non-LHC physics beams
    - ISOLDE, HiRadMat, AWAKE
    - Potential for nTOF and SPS Fixed Target
    - Still limitations from beam loss and machine activation

- **Future scenario with BDF at SPS**
  - Will constrain proton delivery to TCC2 targets and physics users upstream
  - Options available to increase proton delivery in LIU era



LHC Injectors Upgrade

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THANK YOU FOR YOUR ATTENTION!

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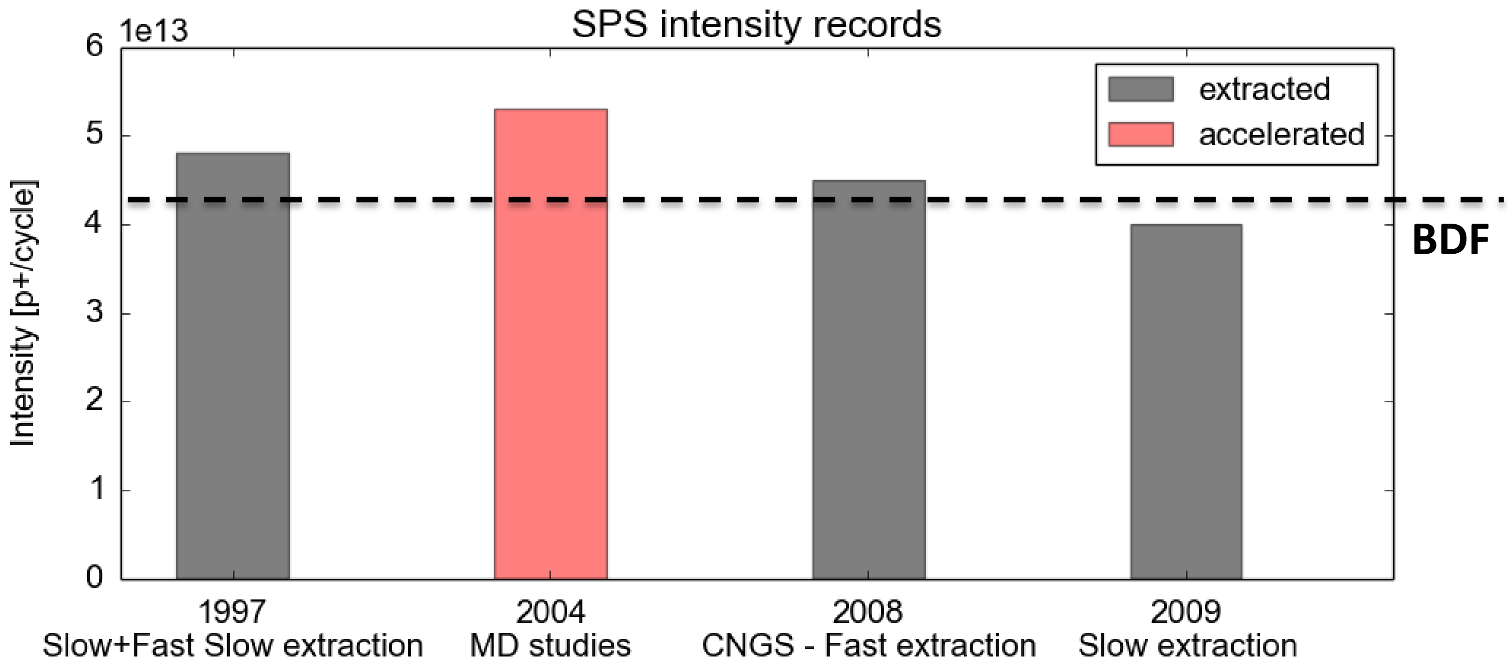
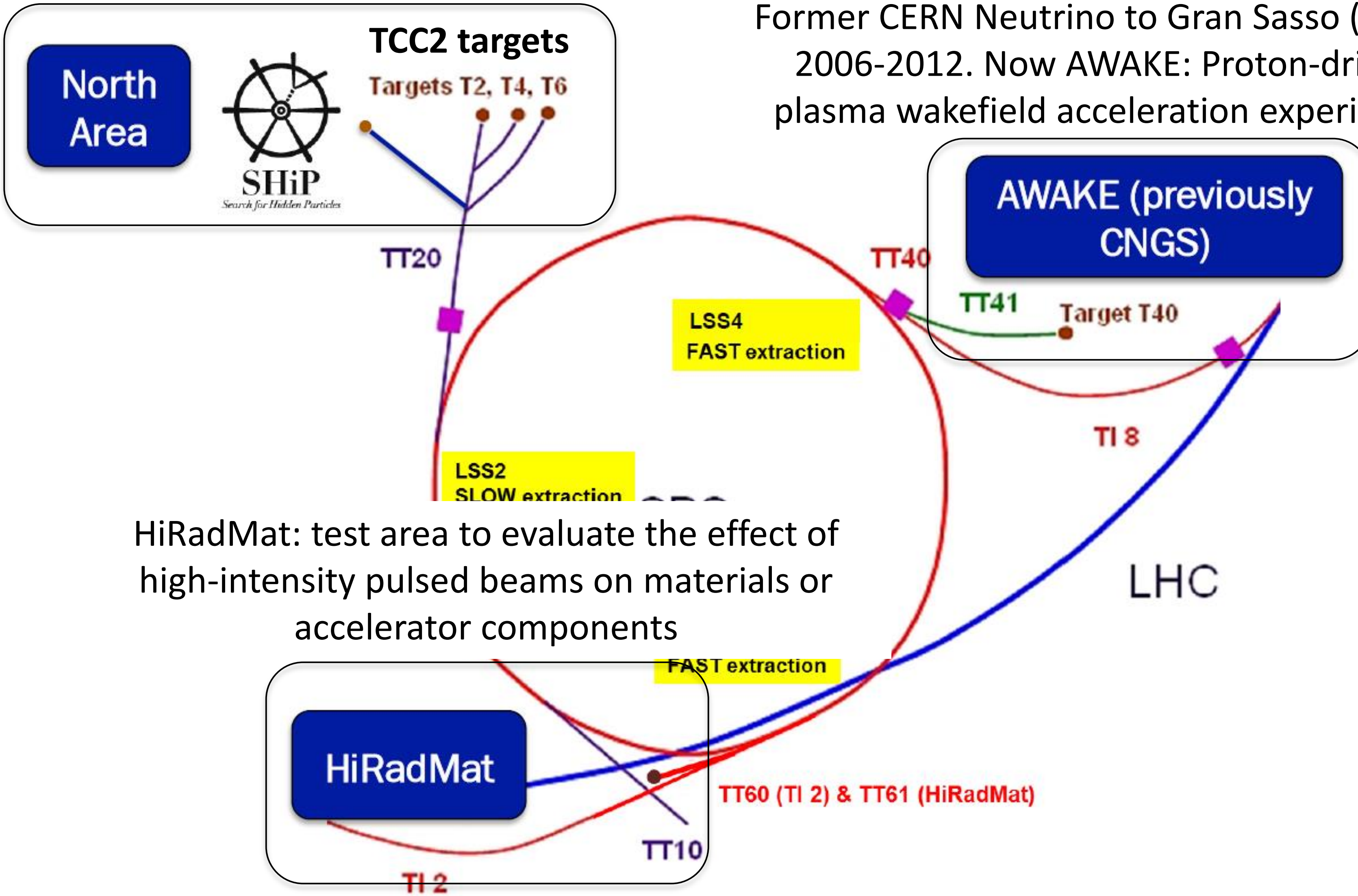
BDF running scenario

- **Beam parameters**
  - Based on operationally demonstrated fixed target beam intensity
    - Room for improvement thanks to LIU upgrades (smaller emittance, SPS RF upgrade)



TCC2 target experiments and SHiP (general-purpose fixed target facility to search for hidden particles)

Former CERN Neutrino to Gran Sasso (CNGS) 2006-2012. Now AWAKE: Proton-driven plasma wakefield acceleration experiment



HiRadMat: test area to evaluate the effect of high-intensity pulsed beams on materials or accelerator components

Typical PSB cycles (currently)

User	Kinetic energy (GeV)	Intensity (10^{10} p/ring)	Duration (s)	
ISOLDE	1.4	800	1.2	40% of cycles in supercycle
LHCPROBE/LHCINDIV		1 – 50		Typically only Ring 3
LHC25		160		4 + 2 rings
TOF		800		Only Ring 2
AD		360		
SFTPRO		400		
EAST		10 – 50		Only Ring 3 (with possible parasitic TOF)
MD	0.05, 0.16, 1.4	1 – 900		

ISOLDE

CERN Physics Beyond Colliders

- **Plans for the Medium Term**
  - HIE being implemented (SC linac for post-accelerated beam to 10 MeV/u)
  - Higher intensity available from PSB after connection to Linac4 (LS2)
  - Upgrade of extraction energy of beams to ISOLDE to 2 GeV? (post-LS2)

	ppp	Current	Power
MT Target**	**6.4 x 10^{13}**	**6 μA**	**13 kW**

** assumes 50% of the cycles to ISOLDE

- **Beyond MT**
  - Will be steered also by potential clients and new facilities coming online in the next years (SPES@LNL, Spiral2@GANIL), however it is reasonable to assume long term running
  - A long term option is Eurisol with the construction of the “next-generation” European ISOL radioactive ion beam (RIB) facility (~100 kW, will require new injector)

HIE: 10 MeV/u upgrade with SC linac → **LS2: LIU upgrades** → **Run 3: ISOLDE 2 GeV upgrade** → **LS3** → // →

TSR, Eurisol ??

BDF running scenario

- **Example of impact of BDF supercycle on other physics users in PSB and PS**
  - FT + BDF during day time (i.e. including an MD cycle in all machines)
  - TOF runs in dedicated and parasitic on East cycles (half intensity)
  - Intensity to ISOLDE assumed to be doubled (6.4e13 p/pulse)

SPS

NA fixed target (12s with 6.1s FT)	1 2 3 4 5 6 7 8 9 10
SHiP	11 12 13 14 15 16
MD-X (7.2s)	17 18 19 20

PS

SFTPRO SPS	1
SFTPRO SPS	2
EAST_IRRAD FTN/T8	3 4
EAST_IRRAD FTN/T8	5 6
TOF nTOF	7
	8
PS-MD/SU TT2-D3	37 38
SHiP SPS	11
SHiP SPS	12
EAST_NORTH FTN / N	13 14
TOF nTOF	15
	16
MD-X SPS	17 18
TOF nTOF	19
	20

PSB

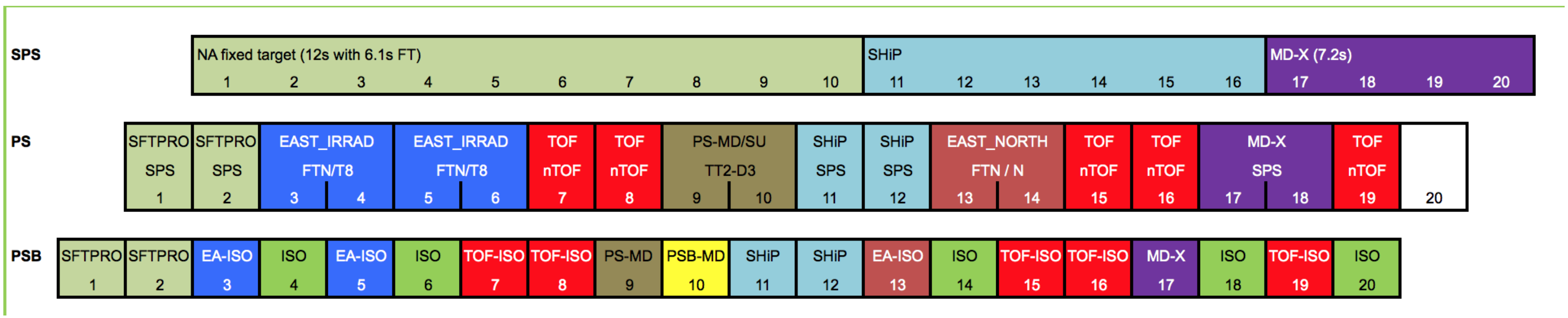
SFTPRO	1
SFTPRO	2
EASTB	3
ISO	4
EASTB	5
ISO	6
TOF	7
ISO	8
PS-MD	37
PSB-MD	10
SHiP	11
SHiP	12
EASTA	13
ISO	14
TOF	15
ISO	16
MD-X	17
ISO	18
TOF	19
ISO	20

3 µA to ISOLDE
(50% above present limitation, half of future limitation)

1.65 x 10^{12} p/s for TOF
(just compliant with present limitation and 55% of future limitation)

BDF running scenario – improved

- **Example of impact of BDF supercycle on other physics users in PSB and PS**
  - Implementing the optimisation on the PSB rings, i.e. combining three rings to ISOLDE with both TOF and East users
  - Immediate gain by >50% on ISOLDE, ~15% on TOF – could be redistributed



4.7 µA to ISOLDE
(80% of future limitation)

1.9 x 10^{12} p/s for TOF
(65% of future limitation)

Challenges and areas of further exploration for non-LHC beams

- **PSB**
  - ❑ Full potential for high intensity beams will be determined by
    - Linac4 current depending on source performance – present assumption is 40 mA unchopped
    - Range of energy sweep of the debuncher for longitudinal painting

- **PS**
  - ❑ Explore intensity limitation after LIU upgrade and impedance reduction
  - ❑ Extraction beam loss reduction
    - Test MTE with high intensity (2.4×10^{13} p/pulse and above)
    - Barrier bucket or bunched beam with MTE to avoid kicker rise time
    - Higher extraction energy, possible with MTE → new kickers required + impact on duty cycle
    - Three injections into SPS (two 3-turn and one 4-turn extractions from PS) → increase of cycle time

- **SPS**
  - ❑ Beam loss reduction and extension of intensity reach
    - Voltage modulation for individual capture of each batch with new LLRF
    - Use 800 MHz cavity during the cycle to improve beam stability
    - Higher injection energy (smaller beam size + avoid transition crossing)
    - Possibility of gamma jump quadrupoles for transition crossing with high intensity
    - Extraction beam loss on-line monitoring and control (ZS alignment, extraction orbit control)
    - Collimation system to control/localize losses

Conclusions

- **LIU upgrades implemented in LS2**
  - Goal is to double intensity and brightness of LHC beams, which will remain below 0.1% of the total proton delivery of the CERN complex even in the HL-LHC era
- **Perspectives for most of the present physics users up to 2030+**
  - Some of the beams will clearly benefit from LIU upgrades (e.g. ISOLDE)
  - Increase of target limitations is the key to improve throughput
    - Make a better use of potential higher intensity for non-LHC beams
    - Optimise time distribution between users on timescale of weeks and through normal/spare mechanism driven by user request
- **Beam Dump Facility scenario?**
  - Target is 4 x 10^{19} pot/year
  - SPS: Proton delivery to TCC2 users likely to be limited below 10^{19} pot/year
  - PSB and PS: physics users also well below future target limits with BDF supercycles
    - Potential to improve by optimising the use of the four PSB rings
- **Main limitations and challenges**
  - Machine activation especially due to (extraction) losses in all machines
  - Several ideas to be tested to reduce losses