



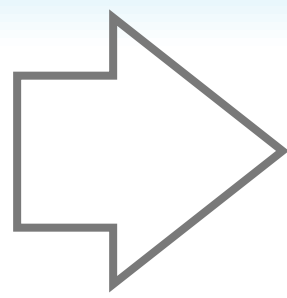
# HIGH POWER HADRON ACCELERATORS

Mamad Eshraqi  
2015 June 1-2

Sponsored by EuCARD2 WP5 (XBEAM), a project supported by European Commission under the Capacities 7th Framework Programme, Grant Agreement 312453.

## Design Drivers:

|                         |        |
|-------------------------|--------|
| High average beam power | 5 MW   |
| High peak beam power    | 125 MW |
| High availability       | >95 %  |



## Key parameters:

|                 |         |
|-----------------|---------|
| Energy          | 2.0 GeV |
| Current         | 62.5 mA |
| Repetition rate | 14 Hz   |
| Pulse length    | 2.86 ms |
| Losses          | <1 W/m  |
| Ions:           | p       |

Flexible/Upgradable design  
Minimize energy consumption



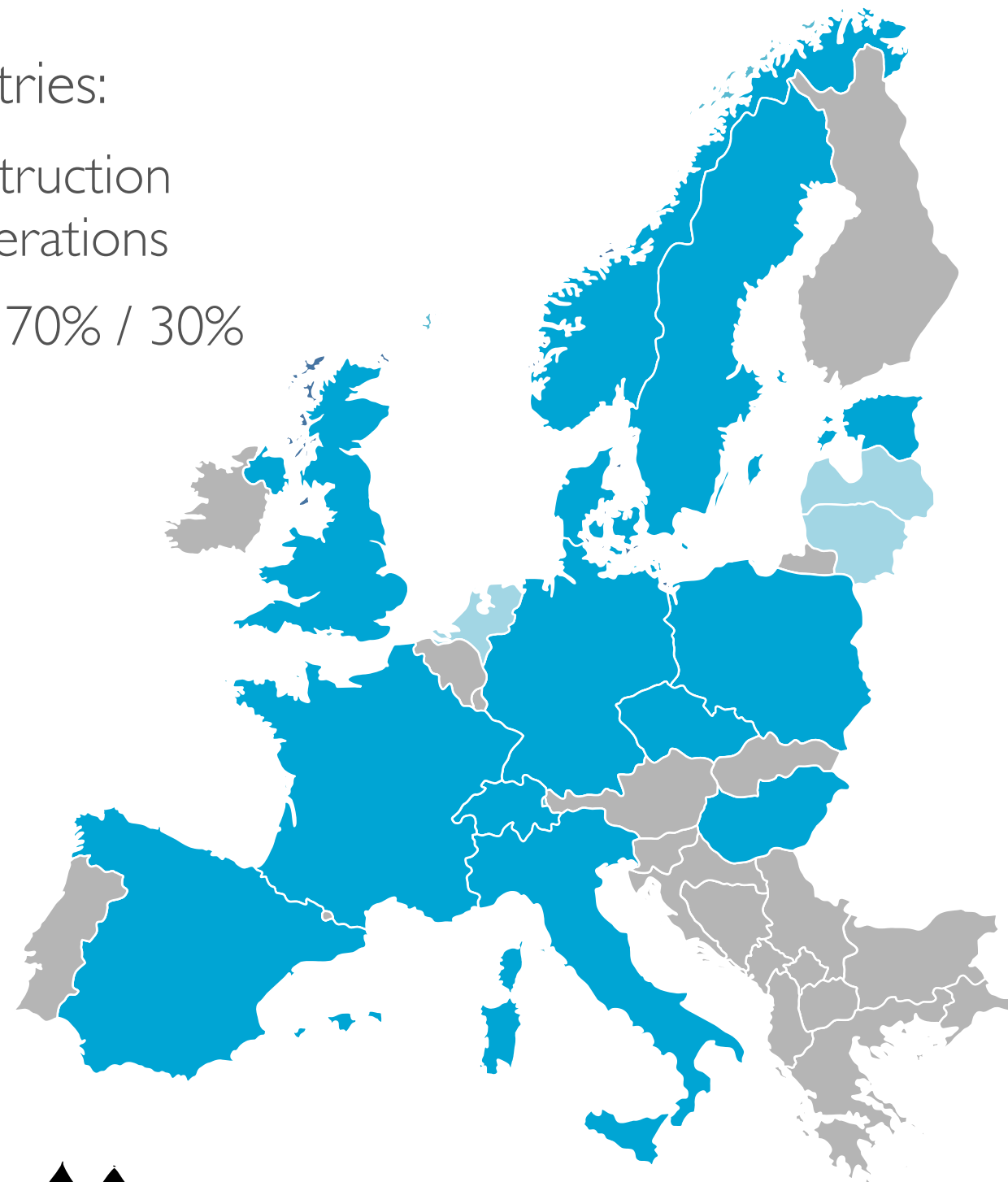
# FUNDING AND PARTNERS

## ► Sweden and Denmark:

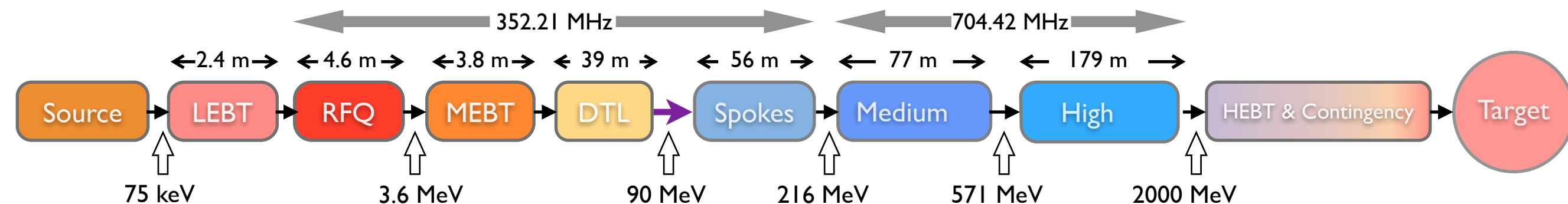
- ◉ 47,5% Construction  
15-20% Operations
- ◉ Cash ~ 100%

## ► Partner Countries:

- ◉ 52,5% Construction  
80-85% Operations
- ◉ IKC/Cash ~ 70% / 30%







|                    | Length | No. Cavs | No. Magnet           | No. Steerers  | $\beta$ | No. Sections | Power (kW) |
|--------------------|--------|----------|----------------------|---------------|---------|--------------|------------|
| LEBT               | 2.38   | —        | 2 Solenoids          | $2 \times 2$  | --      | 1            | —          |
| RFQ                | 4.6    | 1        | —                    | —             | --      | 1            | 1600       |
| MEBT               | 3.83   | 3        | 11 Quads             | $10 \times 2$ | --      | 1            | 15         |
| DTL                | 38.9   | 5        | PMQs                 | $15 \times 2$ | --      | 5            | 2200       |
| LEDP + Spoke       | 55.9   | 26       | 26 Quads             | 26            | 0.50    | 13           | 330        |
| Medium Beta        | 76.7   | 36       | 18 Quads             | 18            | 0.67    | 9            | 870        |
| High Beta          | 178.9  | 84       | 42 Quads             | 42            | 0.86    | 21           | 1100       |
| Contingency + HEDP | 130.4  | —        | 32 Quads             | 32            | (0.86)  | 15           | —          |
| DogLeg             | 66.2   | —        | 12 Quads + 2 Dipoles | 14            | —       | 1            | —          |
| A2T                | 46.4   | —        | 6 Quads + 8 Raster   | —             | —       | 1            | —          |



EUROPEAN  
SPALLATION  
SOURCE

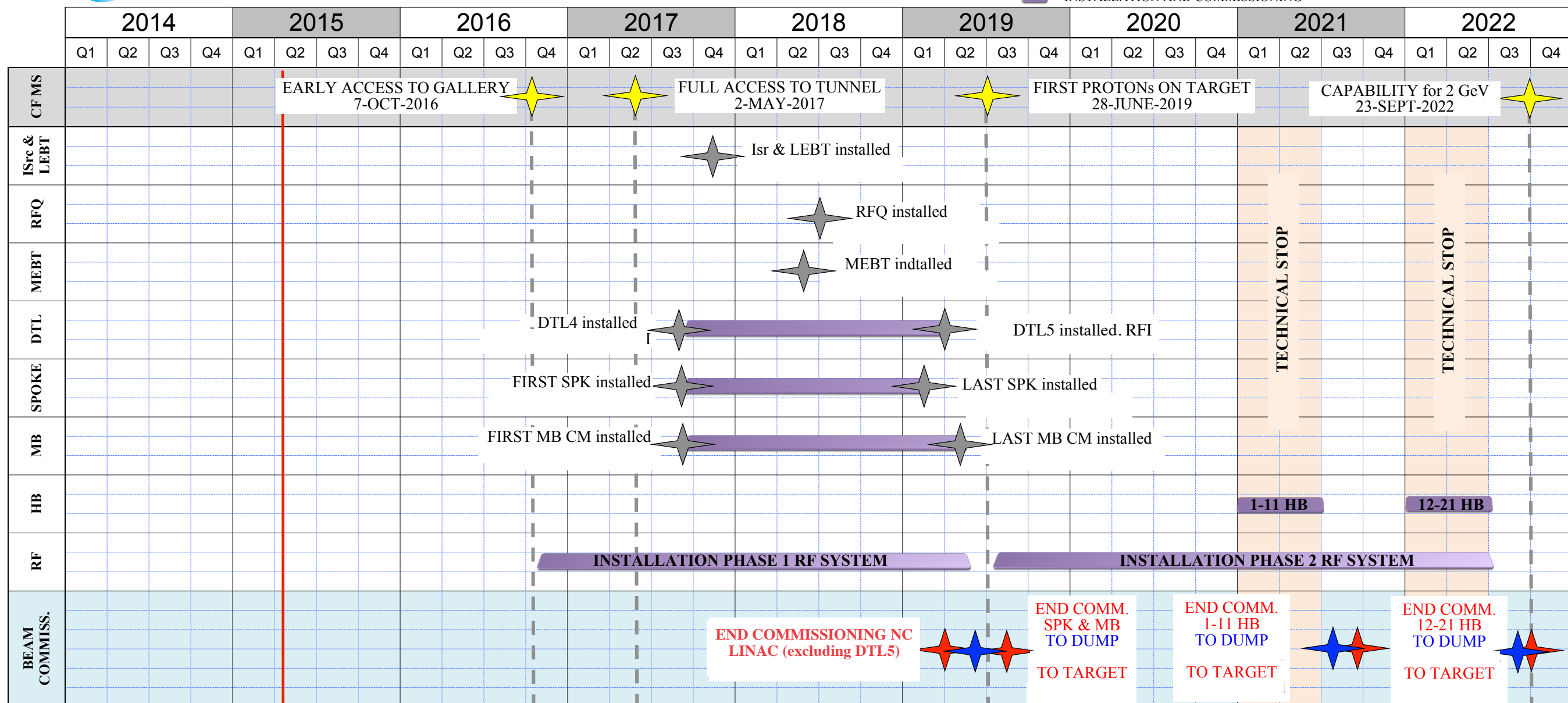
## MASTER SCHEDULE - WP02 COMMISSIONING



MILESTONES



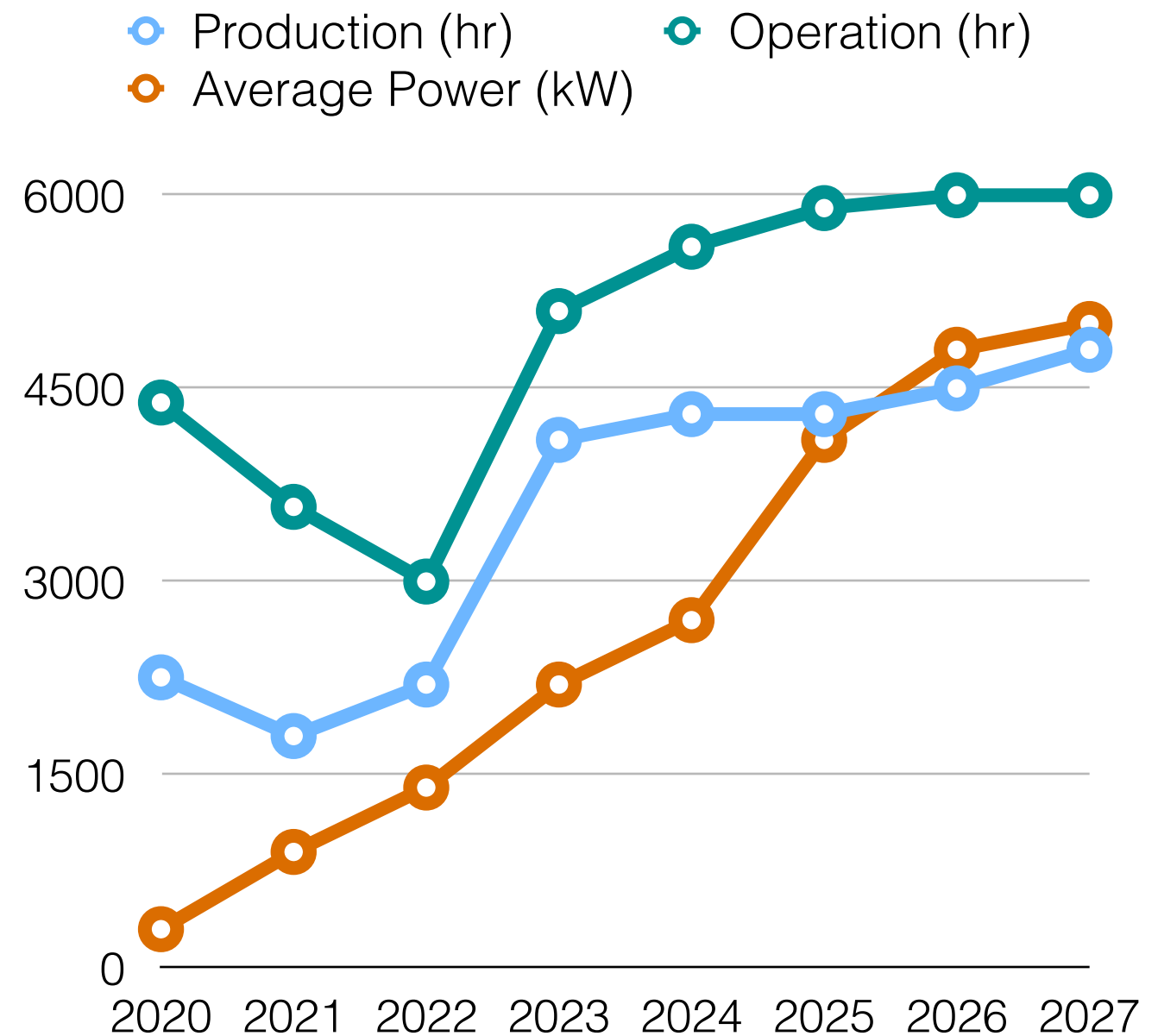
INSTALLATION AND COMMISSIONING



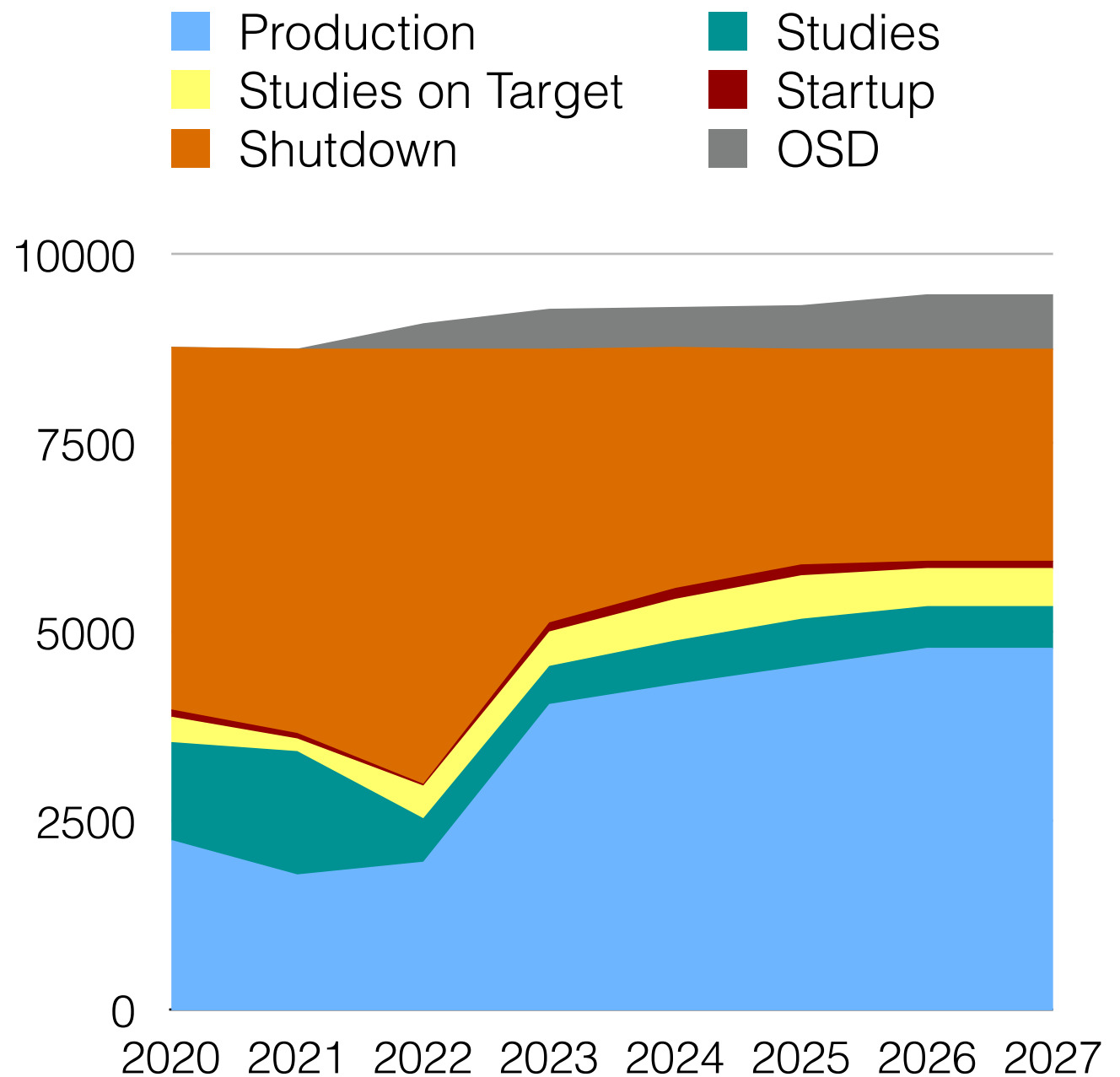
DATA EXTRACTED BY P6 PLANNING - APRIL 2015

PREPARED BY M. ESHRAQI, L. LARI  
CHECKED BY J. WEISEND  
APPROVED BY M. LINDROOS

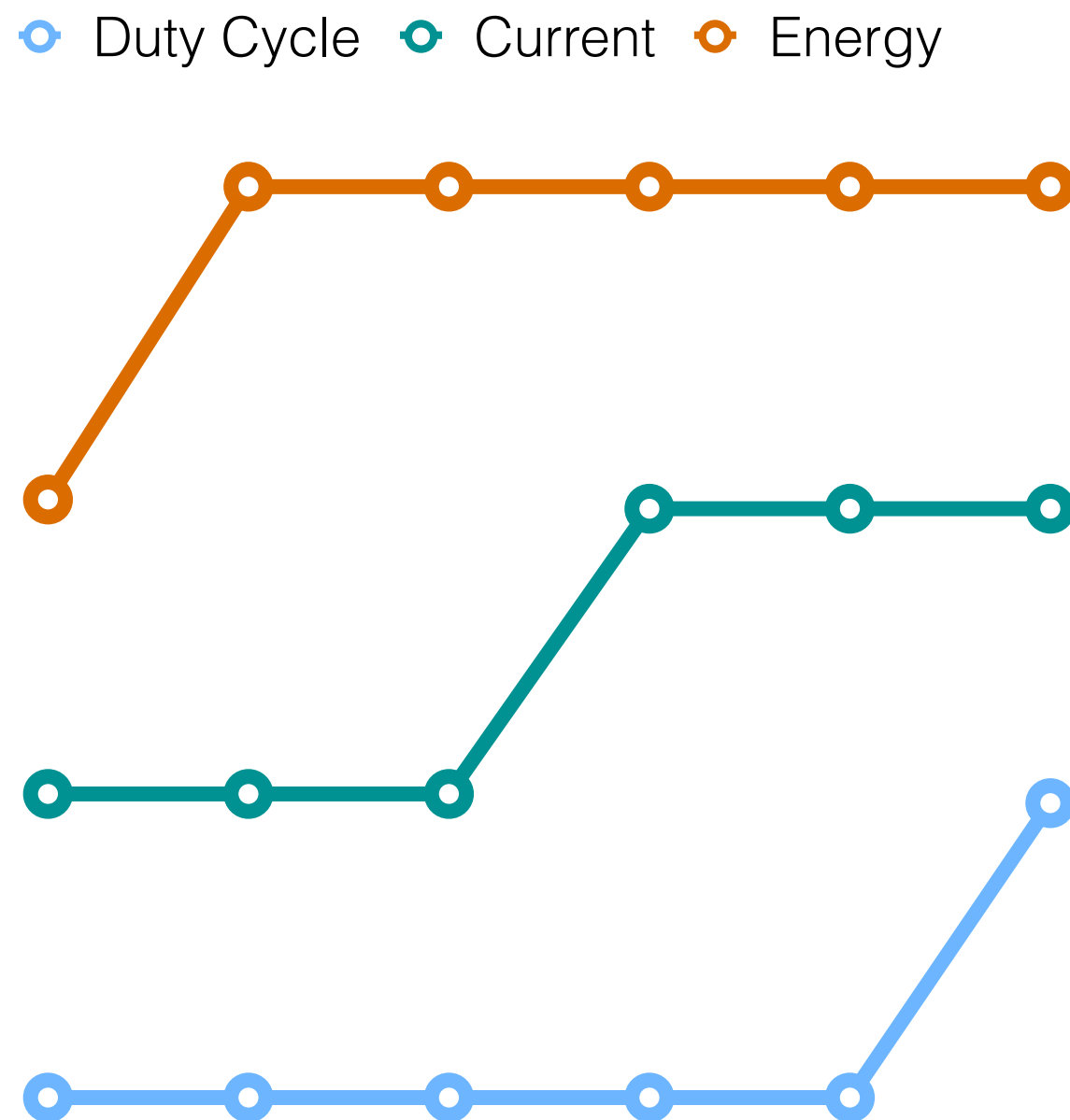
- The planned (annual averaged) power ramp up increases monotonically from ~300 kW in 2019 to 5 MW in 2026.
- The power could be adjusted through changing the energy, beam current, pulse length and repetition rate.



- Two long shutdowns are foreseen for years 2021 and 2022, permitting the installation of high beta cryomodules in two phases.
  - In phase one the beam energy can reach 1370 MeV by installing 11 high beta cryomodules
  - In phase two the accelerator is fully installed and can bring the beam energy to 2 GeV

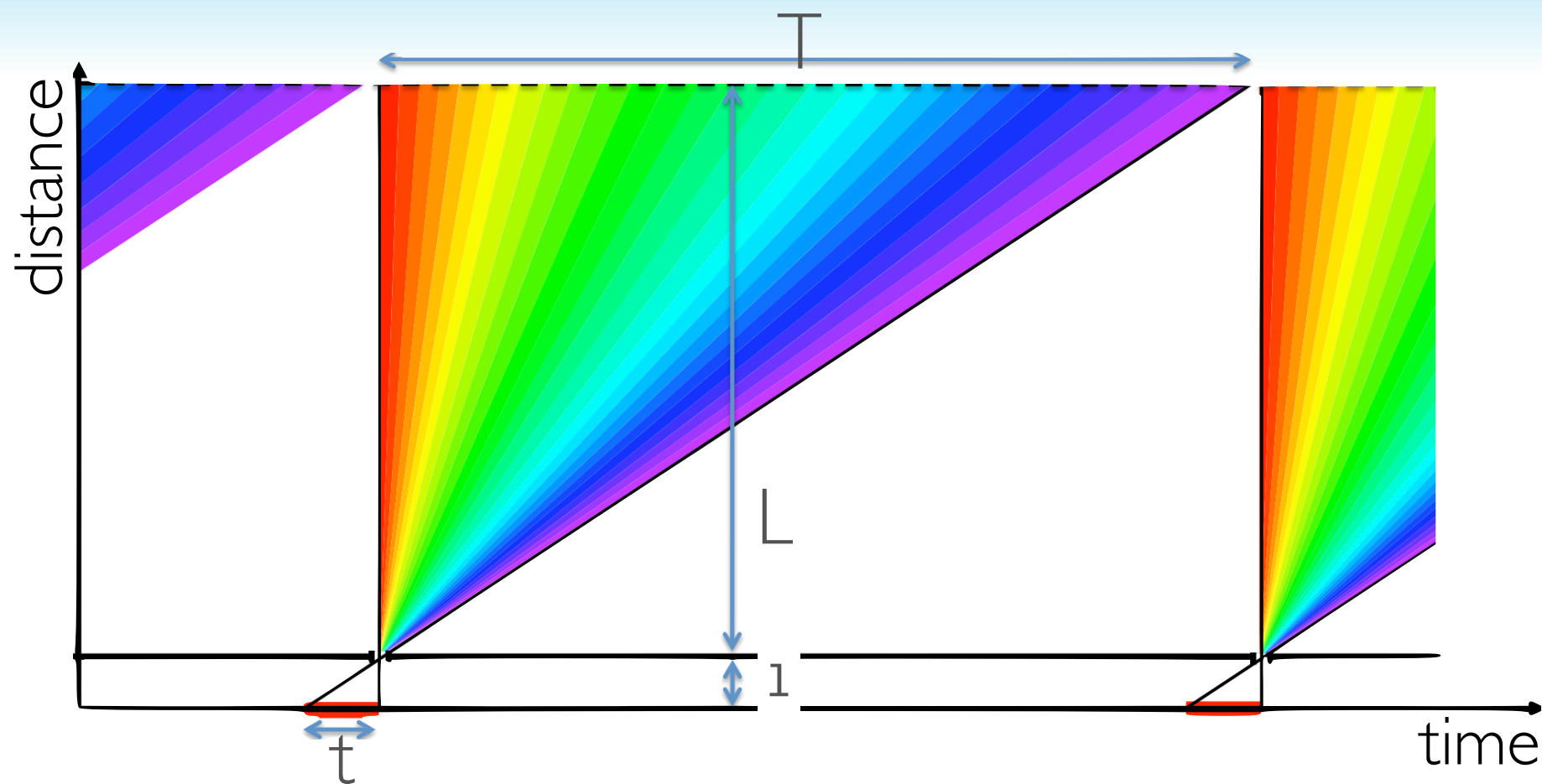


- Initially the cavities are ramped to their nominal (maximum possible), gradient to reach the max energy
- After a period of test the current will be increased to check the sensitivities to space charge and losses as a function of that
- Finally the rep rate is raised to increase the power





# DUTY CYCLE



- Instruments require the full pulse length, however, one wants to ramp up the power gradually
- most efficient way is to ramp the rep rate instead of beam current



# CONSTRUCTION TO OPERATION

| Dec 2019 | Jan 2020 | Feb 2020 | Mar 2020 | Apr 2020 | May 2020 | Jun 2020 | Jul 2020 | Aug 2020 | Sep 2020 | Oct 2020 | Nov 2020 | Dec 2020 |
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| Sun 18   | Wed 18   | Sat 18   | Sat 18   | Tue 18   | Thu 18   | Sat 18   | Tue 18   | Fri 18   | Mon 18   | Wed 18   | Sat 18   | Tue 18   |
| Mon 19   | Thu 19   | Sun 19   | Sun 19   | Fri 19   | Sat 19   | Mon 19   | Wed 19   | Tue 19   | Sun 19   | Thu 19   | Mon 19   | Wed 19   |
| Tue 20   | Fri 20   | Mon 20   | Mon 20   | Thu 20   | Sat 20   | Tue 20   | Tue 20   | Sun 20   | Wed 20   | Fri 20   | Mon 20   | Wed 20   |
| Wed 21   | Sat 21   | Tue 21   | Tue 21   | Fri 21   | Sun 21   | Wed 21   | Fri 21   | Mon 21   | Sat 21   | Sat 21   | Tue 21   | Thu 21   |
| Thu 22   | Sun 22   | Wed 22   | Wed 22   | Sat 22   | Mon 22   | Thu 22   | Tue 22   | Mon 22   | Tue 22   | Mon 22   | Fri 22   | Fri 22   |
| Fri 23   | Mon 23   | Thu 23   | Thu 23   | Sun 23   | Tue 23   | Fri 23   | Sun 23   | Wed 23   | Sat 23   | Mon 23   | Thu 23   | Sat 23   |
| Sat 24   | Tue 24   | Fri 24   | Fri 24   | Mon 24   | Wed 24   | Sat 24   | Mon 24   | Tue 24   | Sun 24   | Tue 24   | Fri 24   | Sun 24   |
| Mon 25   | Wed 25   | Sat 25   | Sat 25   | Tue 25   | Thu 25   | Sun 25   | Tue 25   | Wed 25   | Thu 25   | Wed 25   | Mon 25   | Mon 25   |
| Mon 26   | Thu 26   | Sun 26   | Sun 26   | Wed 26   | Fri 26   | Mon 26   | Mon 26   | Wed 26   | Sat 26   | Tue 26   | Sun 26   | Tue 26   |
| Fri 27   | Mon 27   | Tue 27   | Tue 27   | Sat 27   | Sun 27   | Tue 27   | Tue 27   | Thu 27   | Sat 27   | Fri 27   | Mon 27   | Wed 27   |
| Sat 28   | Wed 28   | Thu 28   | Thu 28   | Fri 28   | Sun 28   | Wed 28   | Sun 28   | Mon 28   | Thu 28   | Mon 28   | Thu 28   | Thu 28   |
| Tue 29   | Sun 29   | Fri 29   | Fri 29   | Sat 29   | Mon 29   | Tue 29   | Sat 29   | Tue 29   | Fri 29   | Sun 29   | Tue 29   | Fri 29   |
| Mon 30   | Tue 30   | Sat 30   | Sat 30   | Sun 30   | Wed 30   | Sun 30   | Sun 30   | Mon 30   | Sat 30   | Mon 30   | Wed 30   | Mon 30   |
| Sat 31   | Tue 31   | Wed 31   | Fri 31   | Sun 31   | Wed 31   | Mon 31   | Mon 31   | Tue 31   | Tue 31   | Tue 31   | Thu 31   | Sun 31   |

- How high availability affects losses
  - A defined number operating hours
    - Samples / Users
  - Fast repair and maintenance requirement
    - Activation of the components
    - Cool down time and hands-on maintenance

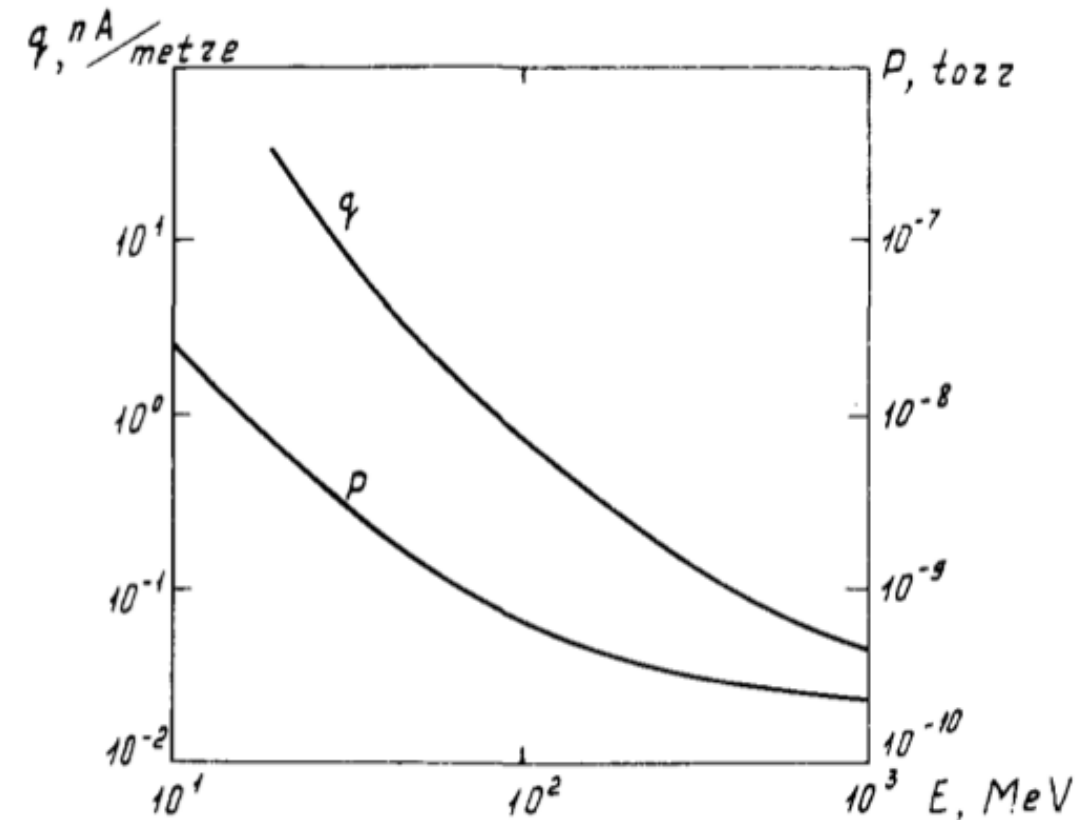
- ING: Intense Neutron Generator, 65 MW (1968)
- APT: Accelerator Production of Tritium, 200 MW (1991)
- CONCERT: A High Power Proton Accelerator Driven Multi-Application Facility, 25 MW (2000)
- ISIS: ————, 350kW (1980)
- SNS: Spallation Neutron Source, 1 MW (1993) - [PSS]
- IFMIF: International Fusion Materials Irradiation Facility, 10 MW (1994)
- ESS: European Spallation Source, 5 MW (1988)



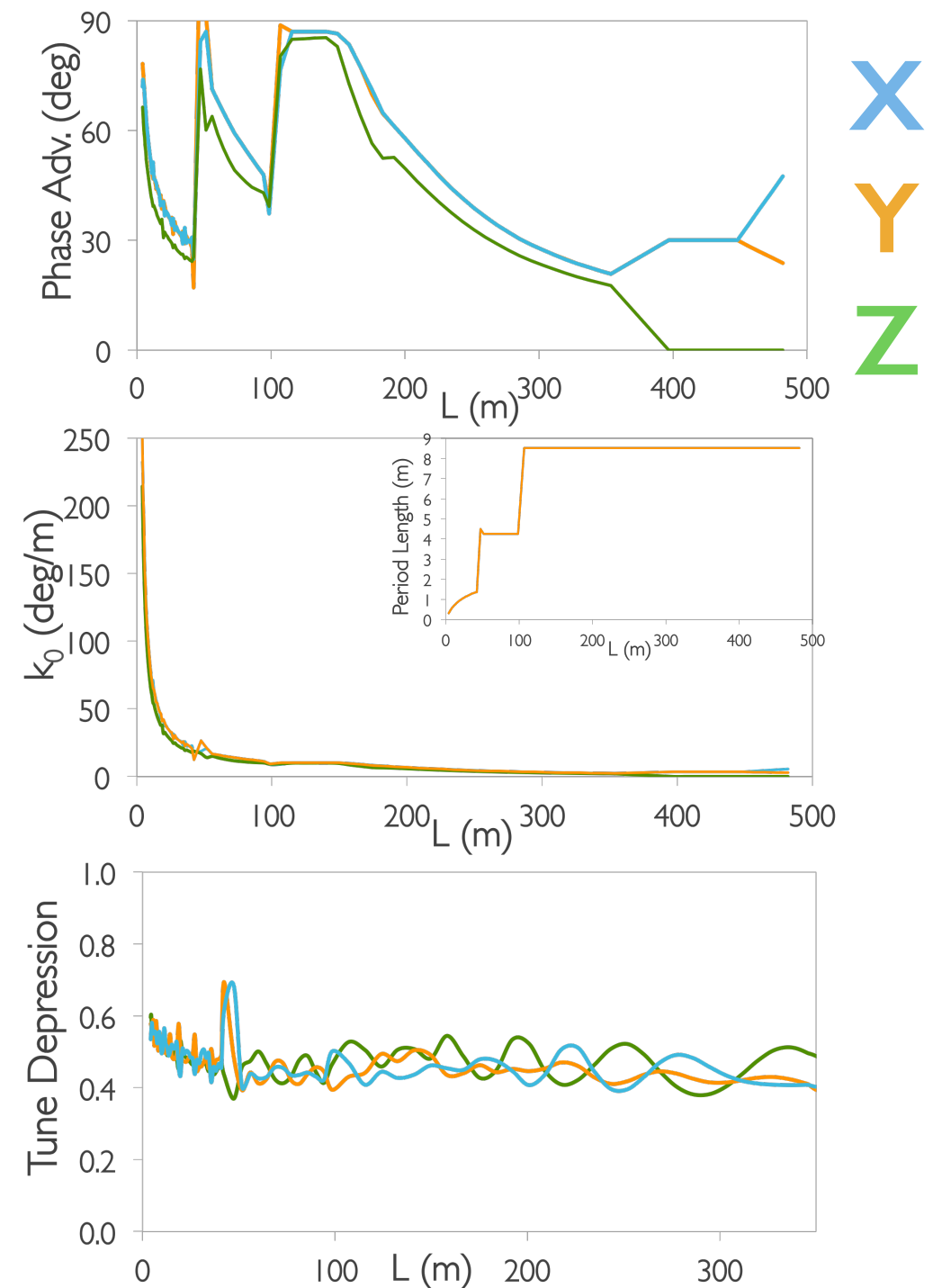
- At 5 MegaWatt:
  - 14 pulses a second
    - ▶ Has the same energy as a discus (2 kg) flying at ~2150 kph (Mach 1.76)
  - Has the same energy as a 1 ton car which travels at ~110 kph
  - Or you can melt +8 (+5) kg of copper (niobium) starting from room temperature



- “The linac can be considered as radiation-free, provided that the gamma dose at one-metre distance from the linac does not exceed the professional dose of  $28 \mu\text{Gy/hr}$  one hour after the linac has been stopped after a long operation”  
A. P. Fedotov
  - This translates to few tens of a watt/meter
- This value could be relaxed by looking at the linac few hours after such a shutdown, maybe that is where this  $1 \text{ W/m}$  comes from!



- Phase advance per period  $< 90$  degrees
- Smooth average phase advance
- Avoiding strong tune depression



- Ion source: current stability
- RFQ: Phase and amplitude stability
  - The phase of the linac is dictated by RFQ
- Errors in phase and amplitude and static errors in the rest of the linac



# LLRF FOR LLRF

- Phase and amplitude error in RFQ causes beam arrival error in the rest of the linac
  - This adds/creates additional errors - to be compensated(?) - by the LLRF
  - This adds to the power needed by the buncher cavities (if not compensated)
    - ▶ Since buncher cavities work at  $-90^\circ$  (quadrature wrt beam), the power needed by this cavities is only to compensate the ohmic losses. A shift in the arrival time adds to the load.

- Transient behaviour of the linac is an issue that needs further study.
- A heavily beam loaded accelerator operating at such high power can only be operated with a complex set of sensors and multiple, interacting feedback and feedforward control loops.
- In particular, start-up and recovery from safety trips or routine klystron trips ...

- We are entering the era of – operational – high power accelerators, where beam losses should be controlled to few parts in  $10^7$ .
- This is mainly caused by high availability demanded by users of this machines.
- Though a robust beam physics design could reduce the risk of beam losses, with such high power machines the LLRF is as important and plays a major rule in the success of the accelerator.

THANK YOU!

