Future high-intensity proton accelerators

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SRF'07, 15-19 October 2007

Outline

- Introduction,
- Classification of facilities according to P_{beam}, rep-rate, energy, and pulse length,
- Examples of applications and proposed machines,
- Focus on the staged construction of a linac-based proton driver (CERN SPL),
- Summary.

What is high-intensity?

in general:

$$Intensity = \frac{Energy}{Time \times Area}$$

in proton accelerators:

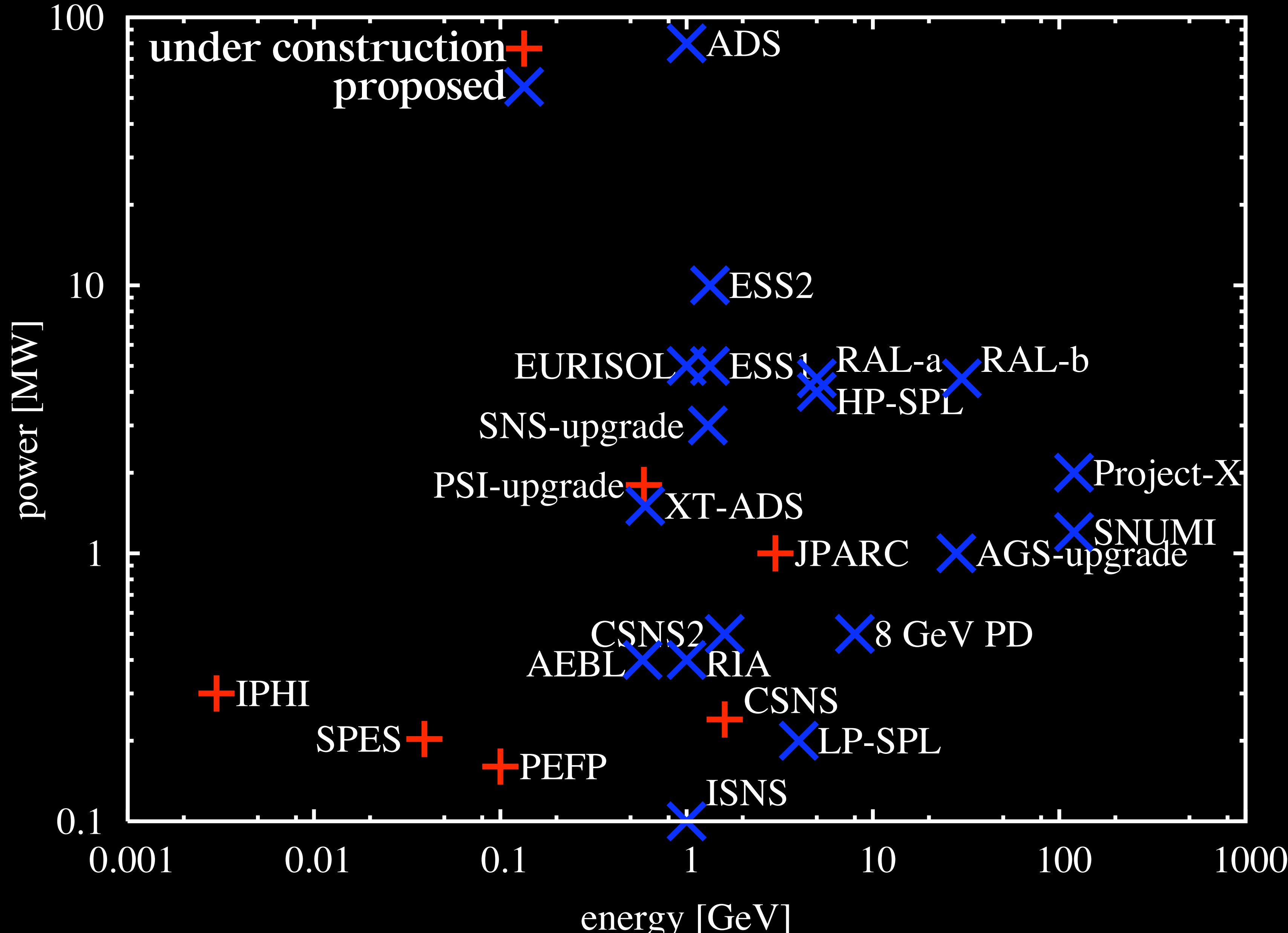
high power beams with small emittances

in this talk:

future proton machines with $P_{beam} > 100$ kW

counting facility upgrades as “future machines”

Beam power & energy



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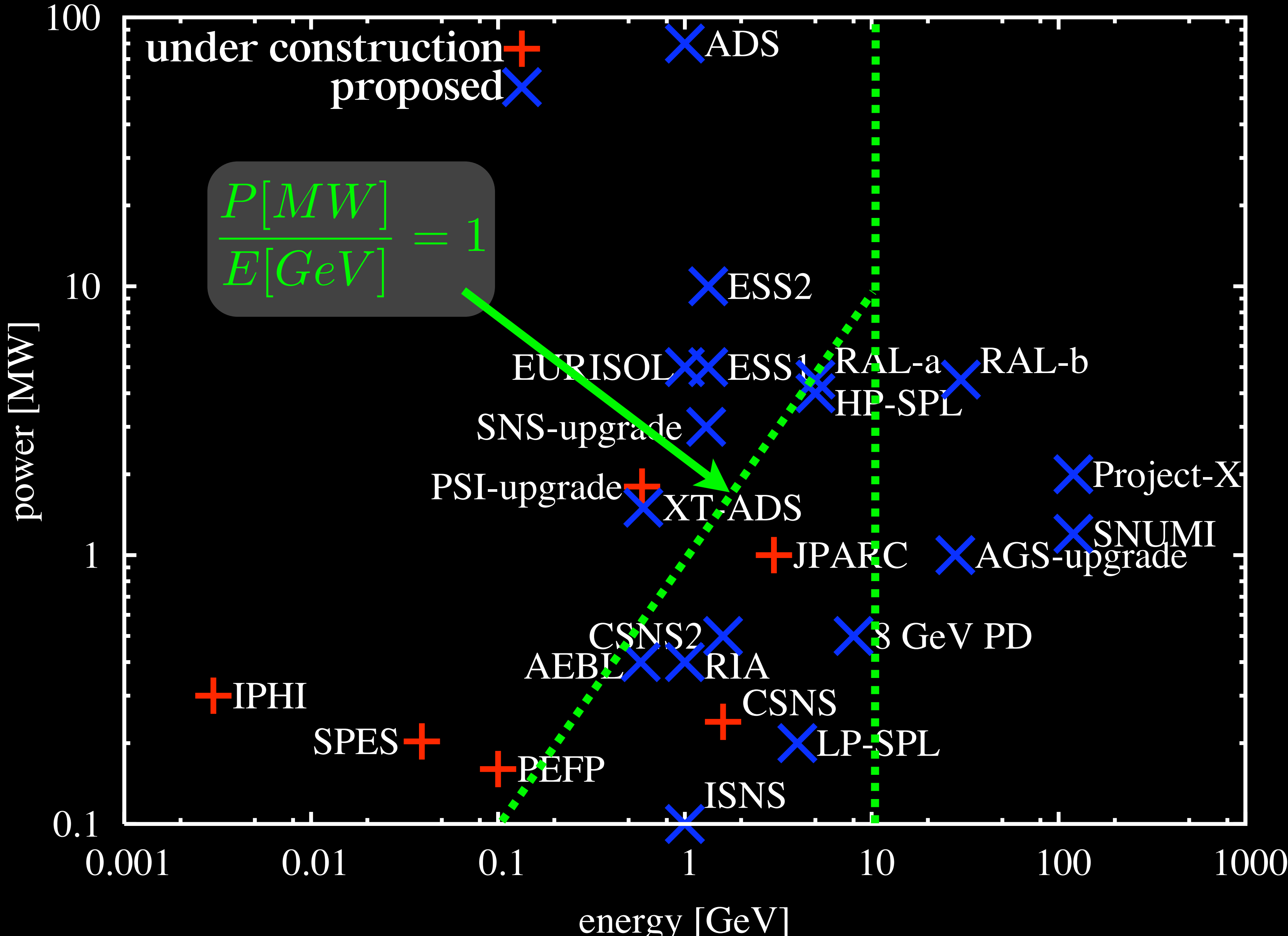
Beam power & energy



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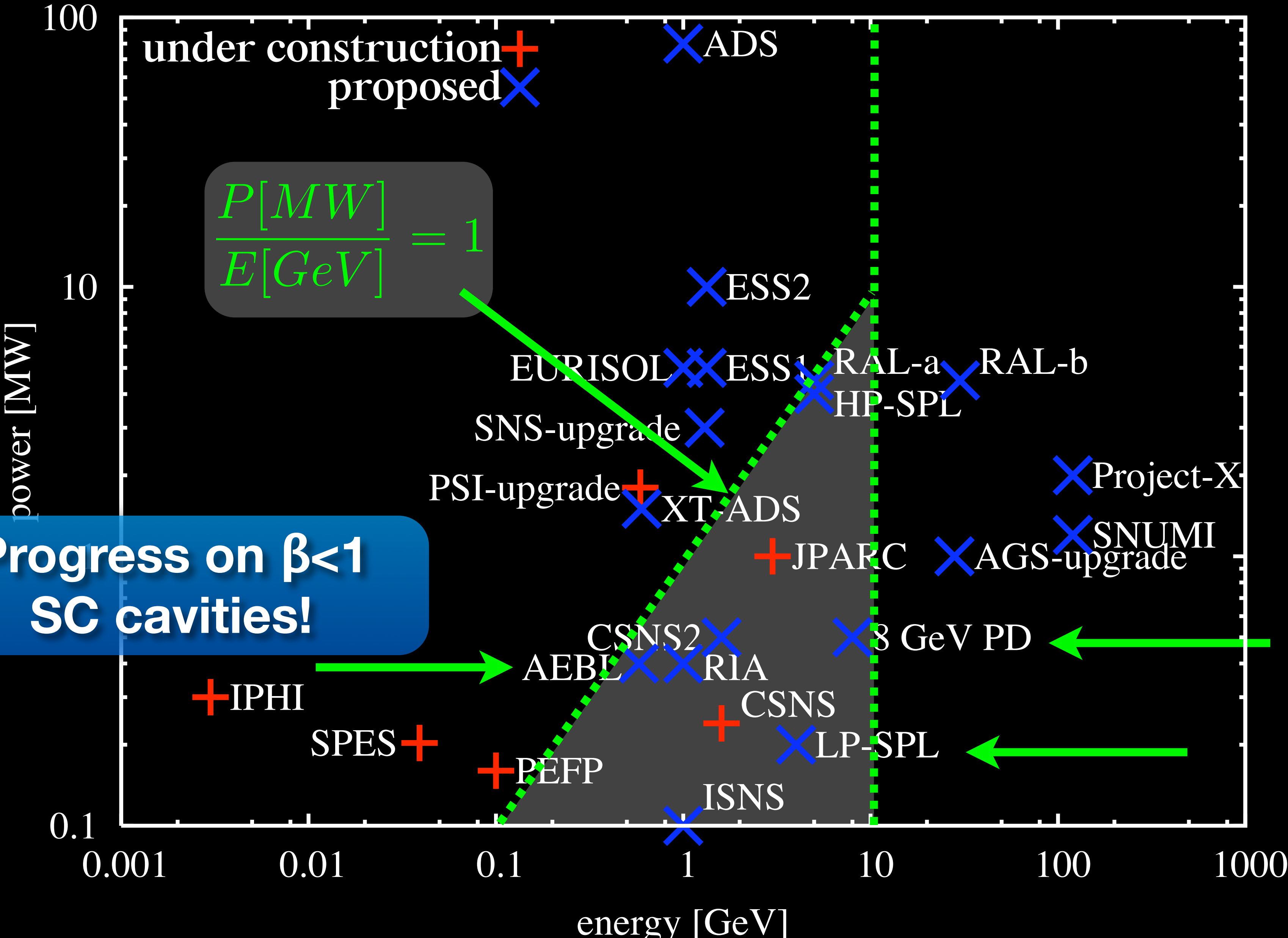
Beam power & energy



Progress on β<1 SC cavities!

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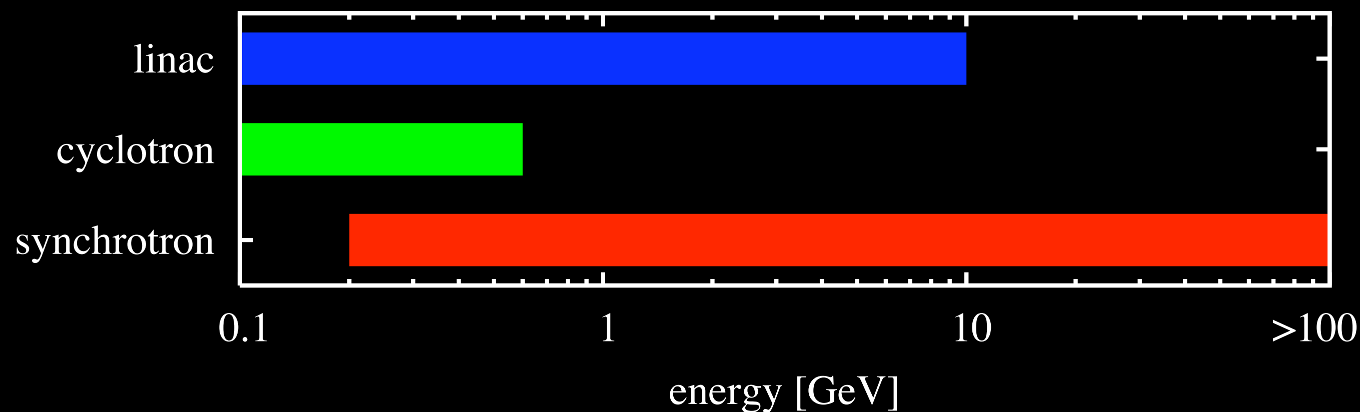
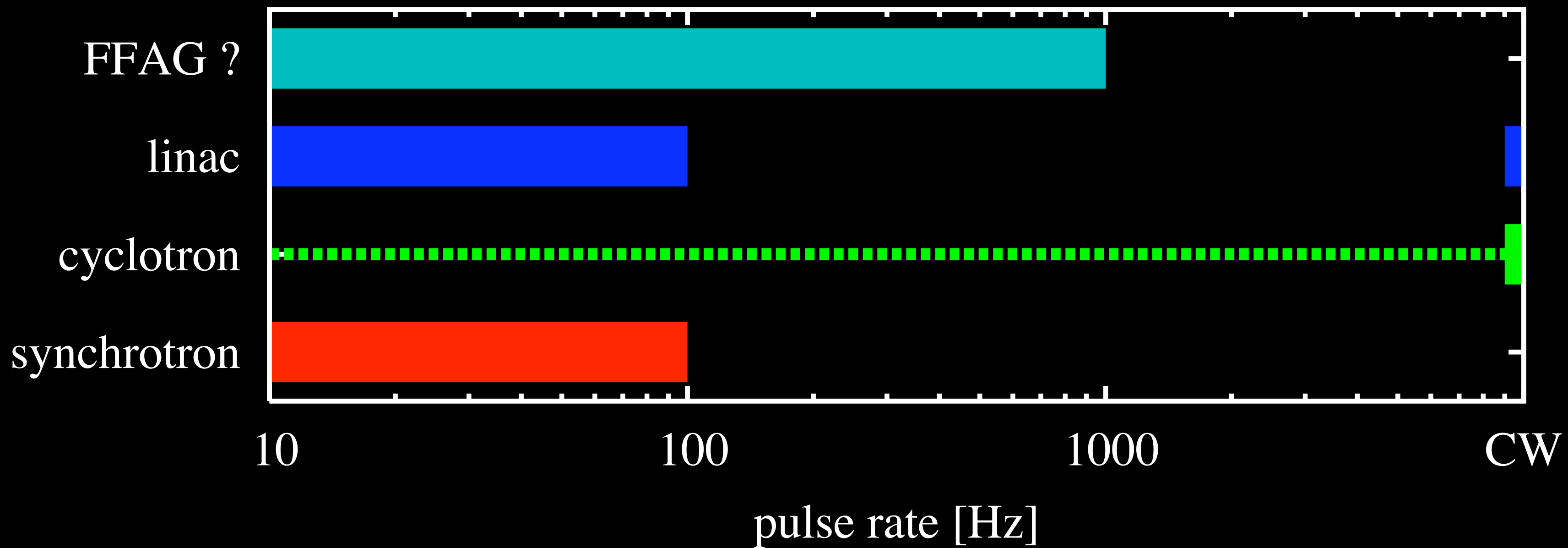
Energy



presently planned high-power machines suggest:

- > 10 GeV synchrotrons are the only suitable machines,
- < 1 GeV linacs or cyclotrons have demonstrated MW beams,
- between 1 - 10 GeV linacs or synchrotrons are possible, choice depends on beam power, time structure of beam, and preference (or experience) of the designers,
- linacs are reaching for higher energies!

Repetition rate



- so far no pulsed linac or synchrotron has >> 100 Hz rep rate,
- FFAGs have the potential to go to kHz, but they have not demonstrated high-power proton beams yet.

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CW operation

- provided by linacs or cyclotrons,
- usually not beyond 1 GeV,
- efficient use (SC) RF power: no wasted power during the filling time,

Proposed applications:

- Radioactive Ion Beams (e.g. Eurisol, RIA),
- Accelerator Driven Systems (e.g. XT-ADS),
- neutrons (PSI upgrade),
- material irradiation,

CW operation: cyclotrons

PSI in Switzerland:

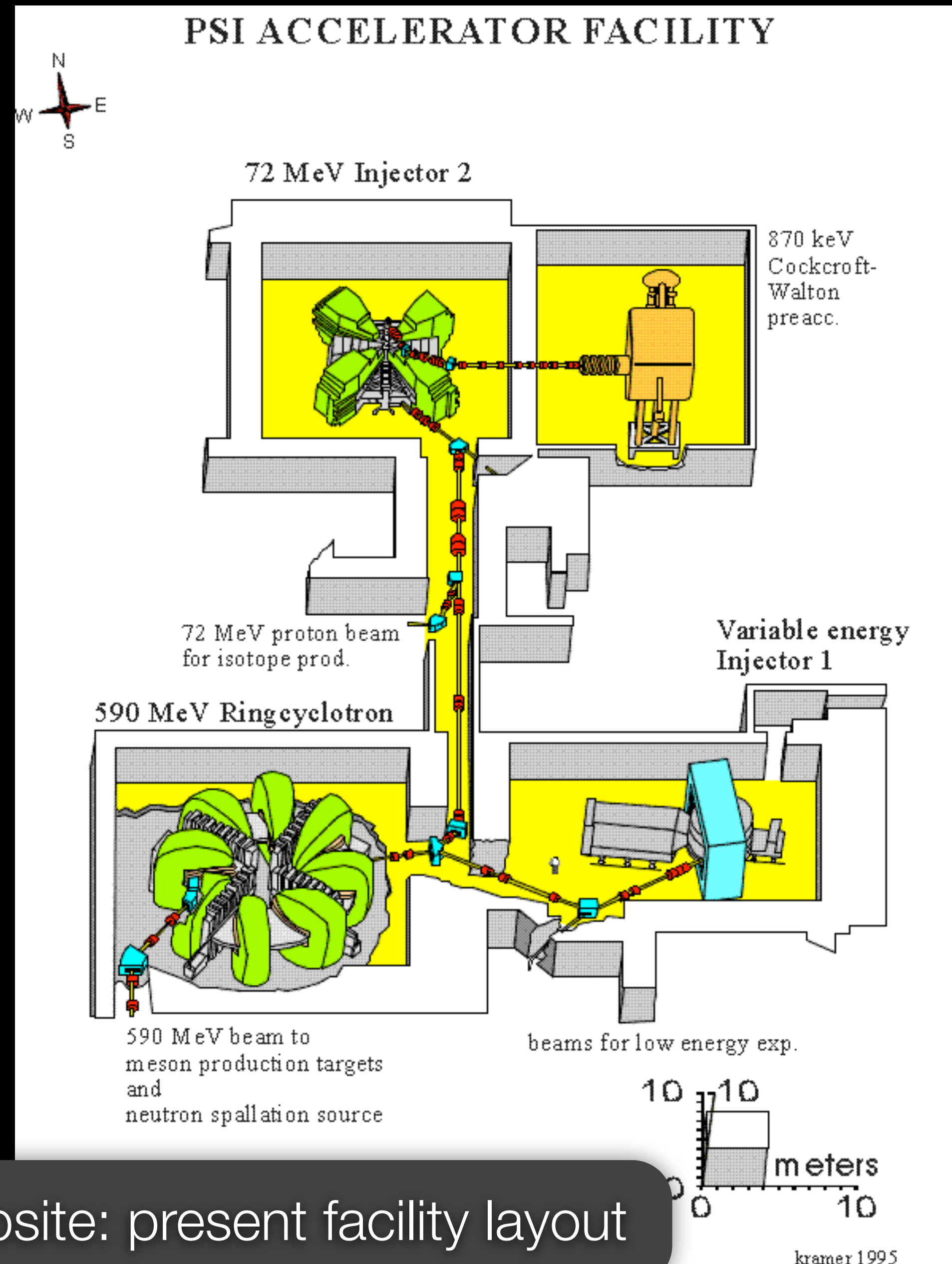
- 1.2 MW @ 590 MeV have already been demonstrated!
- 1.8 MW are planned for 2012 (in progress),

Applications:

- neutrons, pions, muons,

Upgrade program:

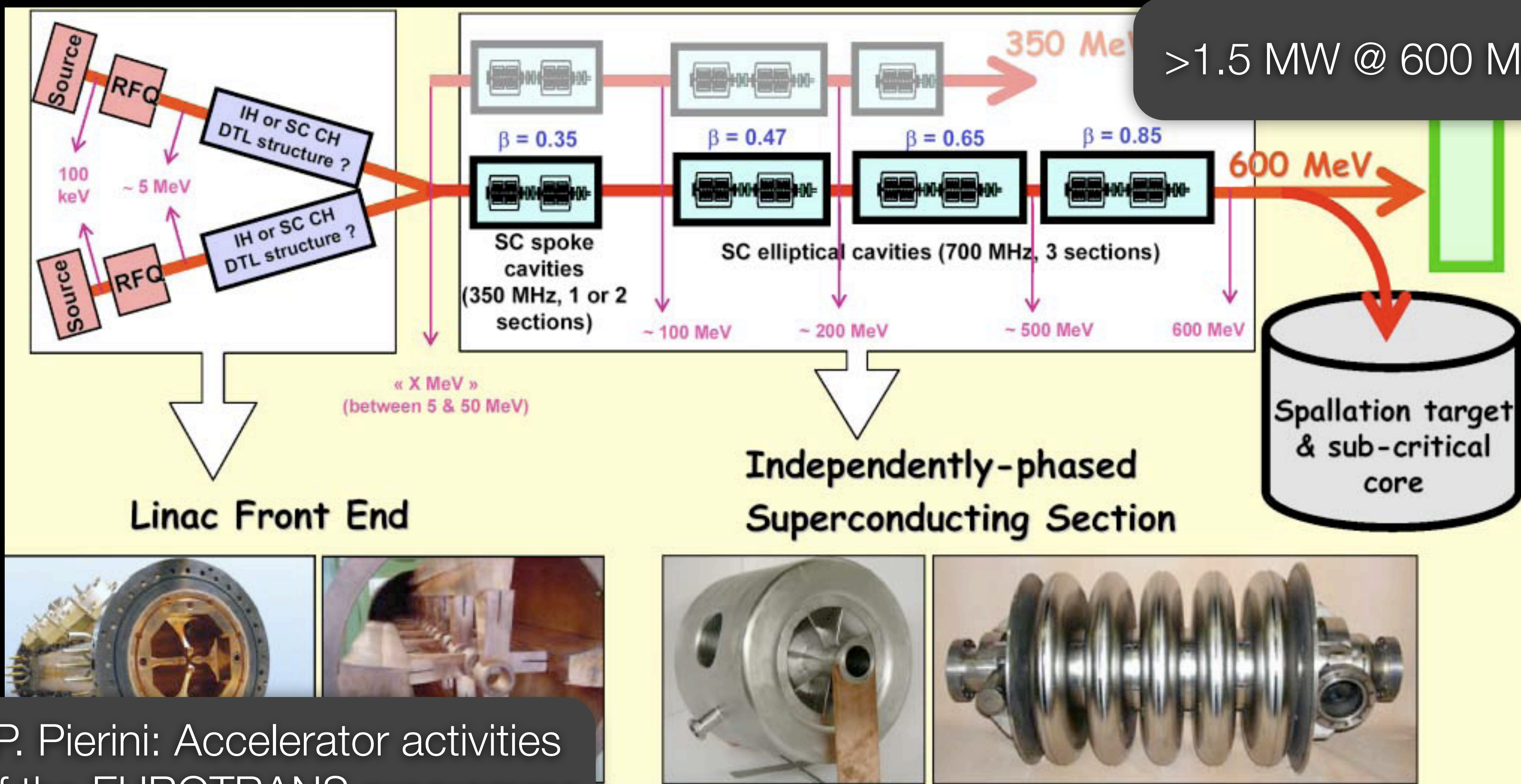
- new RF system, new bunchers, targets,



GSI website: present facility layout

CW operation: linacs, XT-ADS

eXperimental facility demonstrating the feasibility of Transmutation in an Accelerator Driven System



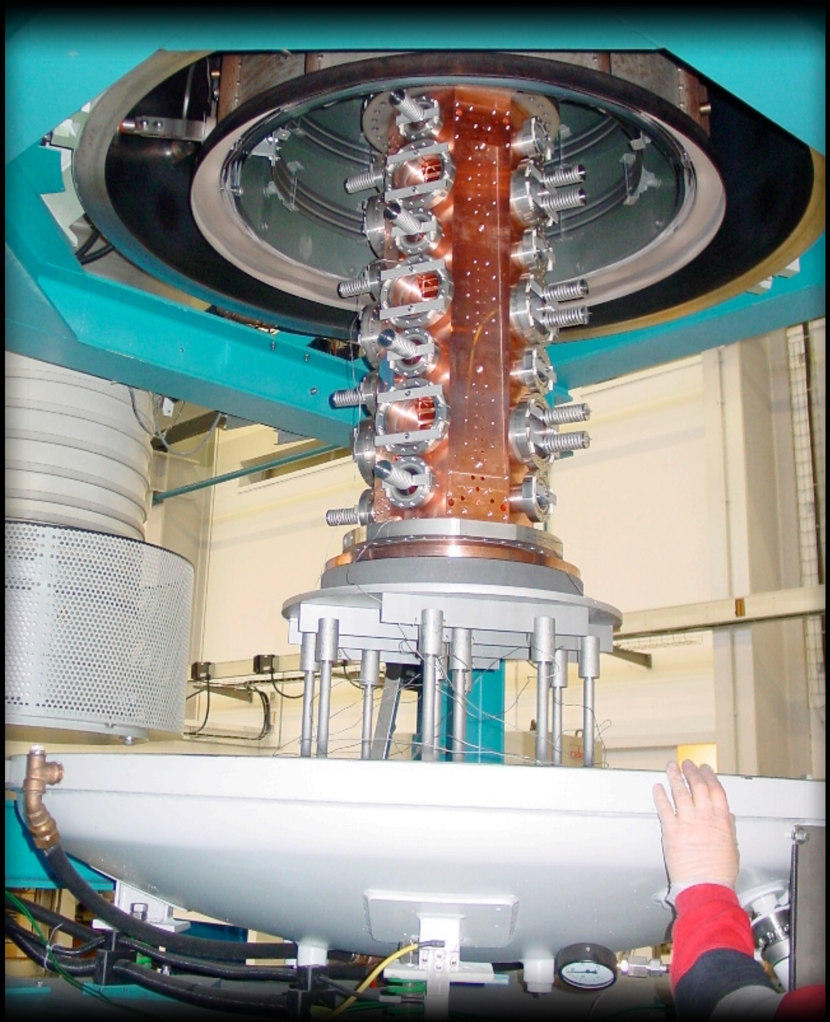
>1.5 MW @ 600 MeV

P. Pierini: Accelerator activities of the EUROTRANS programme

CW operation: IPHI

IPHI RFQ is conceived as generic CW injector (e.g. ADS)

- IPHI is designed as 3 MeV, 352 MHz, CW injector with E_{inj} = 95 kV, 6 metre long, optimised for low-loss operation at 100 mA, modulated vane voltage, **P_{beam} = 300 kW**.
- under construction at Saclay, France (CEA & IN2P3), beam expected in 2008/9.



Long-pulse operation

- typically linacs without subsequent accumulator/ compressor rings,
- pulse length < ms range, energies: MeV - GeV,

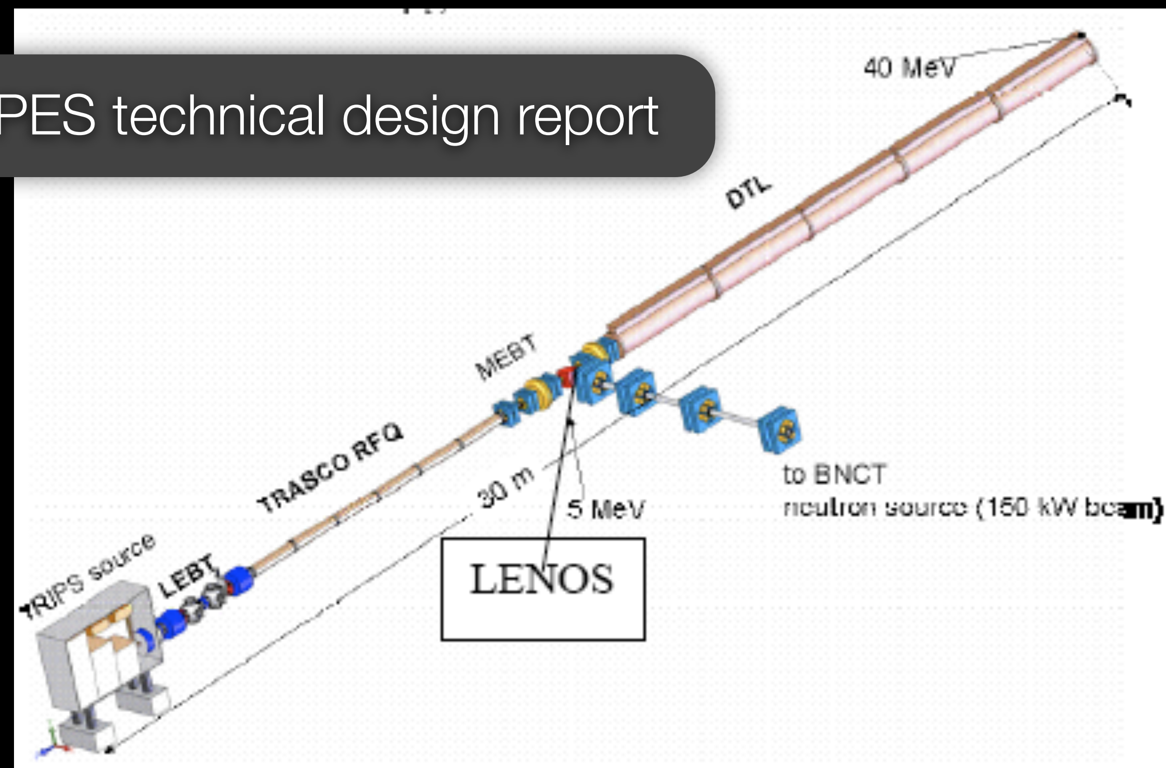
Applications:

- long-pulse spallation sources (ESS “long-pulse”),
- material irradiation (PEFP),
- Radioactive Ion Beams (SPES),
- ν beta-beams,

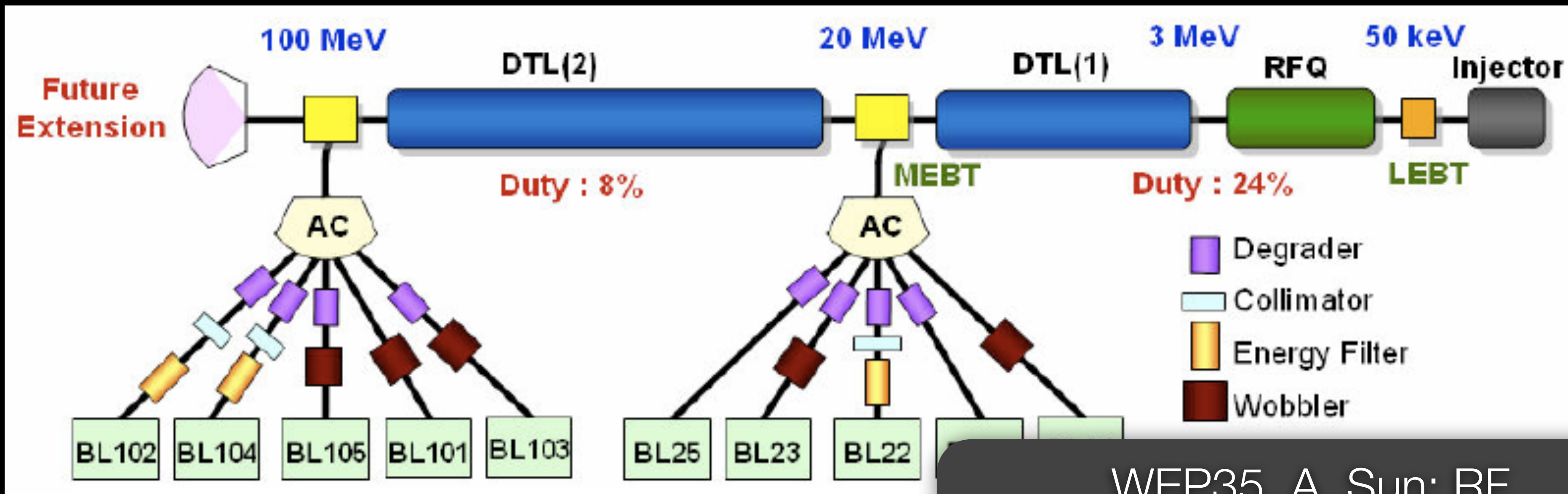
Long-pulse operation: SPES

Study & Production of Exotic Species (SPES), Legnaro, Italy

- Possible pulsed front-end for EURISOL,
- CW RFQ + pulsed DTL,
- DTL development together with Linac4 (CERN),
- application: RIB,
- 200 kW @ 40 MeV (50 Hz) or 150 kW @ 5 MeV,
- under construction.



Long-pulse operation: PEFP



WEP35, A. Sun: RF Superconducting Acitivities of PEFP

- Proton Engineering Frontier Project (PEFP): under construction in Gyengju, Korea,
- 160 kW @ 100 MeV, 130 kW @ 20 MeV,
- operational in 2012.

Short-pulse operation

- pulse length: ~μs, (bunch length with compression: ~ns),
- synchrotrons (with final bunch-rotation scheme) or linacs plus accumulator (and compressor) rings,
- > 10 GeV only synchrotrons, 1-10 GeV synchrotron- or linac-based solutions in competition,

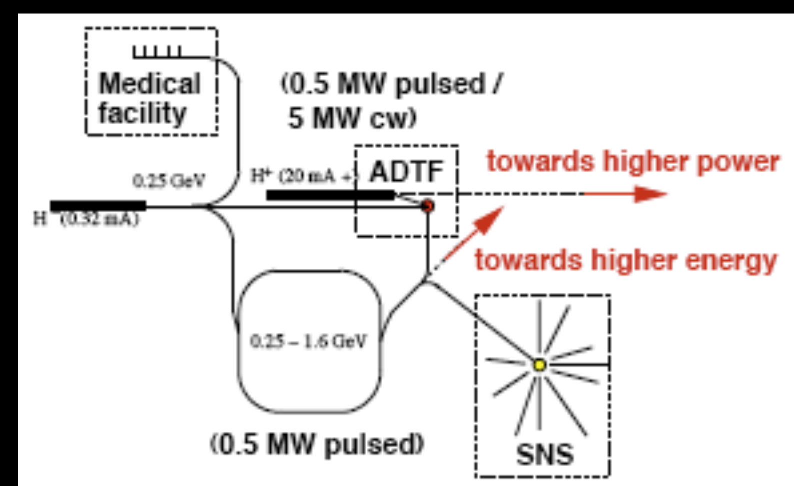
Applications:

- short-pulse neutron spallation sources: < 3 GeV for optimum beam power to neutron conversion efficiency,
- tendency so far: i) linac based: ~1 - 1.3 GeV, 1-10 MW, or ii) synchrotron based: 1-3 GeV, ~0.1 - 1 MW, are proposed,
- neutrino factory.

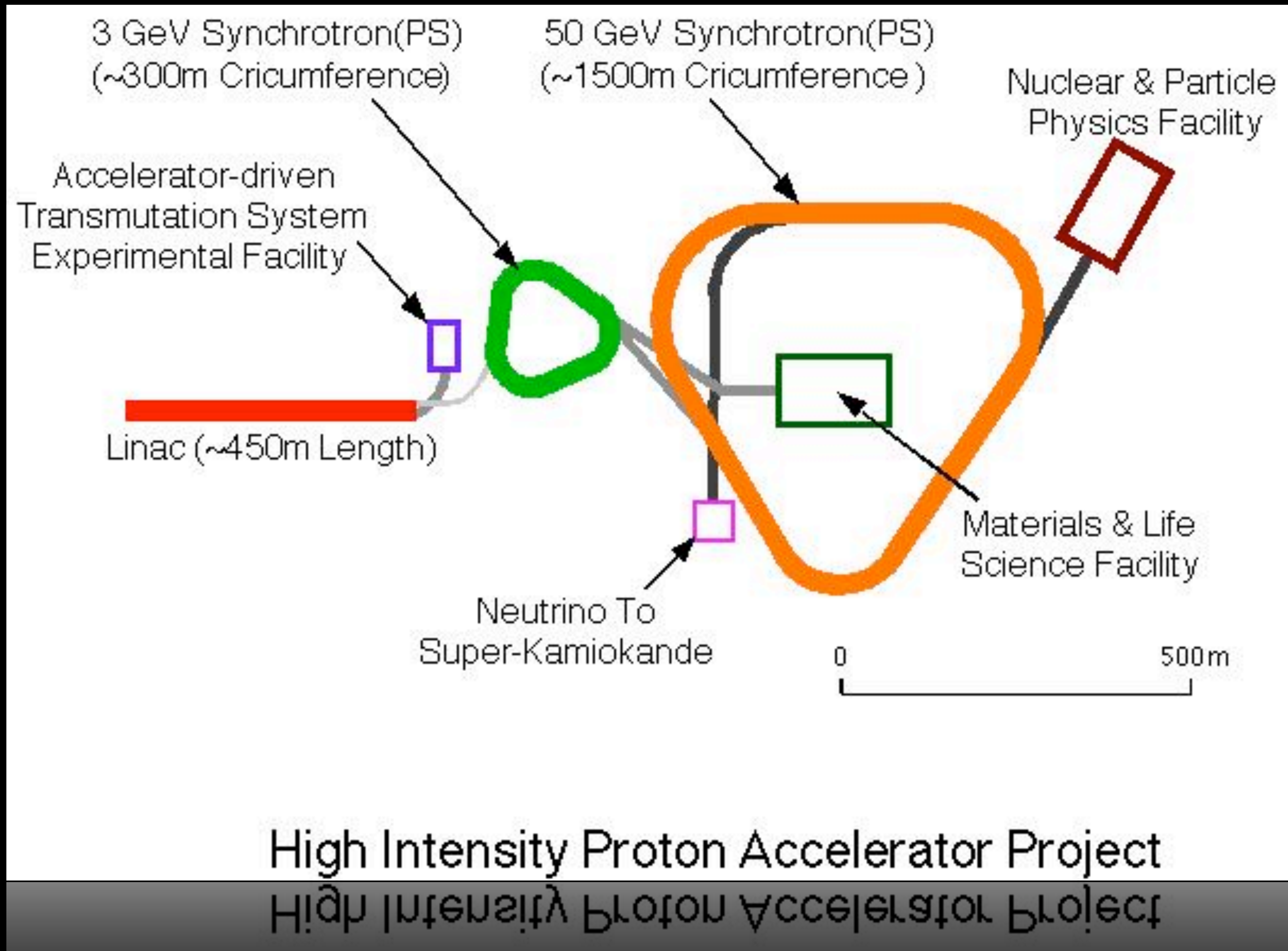
Short-pulse operation: CSNS

- Chinese Spallation Neutron Source (CSNS),
- 120 - 500 kW @ 1.6 GeV, linac energy: 81 - 230 MeV,
- approved in 2005 and under construction.

J.Wei *et al*: China spallation neutron source accelerators: design, research, and development



JPARC



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JPARC

- 200 kW @ 600 MeV for Transmutation Experimental Facility (TEF),
- 1 MW @ 3 GeV for neutrons, nuclear physics,
- 0.75 MW @ 50 GeV for nuclear physics, neutrinos,
- facility is nearing completion,
- upgrade program to 5 MW in preparation.

SNS-upgrade


Front-End Building
Klystron Building
Central Helium Liquefaction Building
Linac Tunnel
Ring
Radio-Frequency Facility
Target
Future Target Building
Support Buildings
Central Laboratory and Office Complex
Center for Nanophase Materials Sciences
Joint Institute for Neutron Sciences

SNS-upgrade

- nominal beam: 1.3 MW @ 1 GeV,
- upgrade: 3 MW @ 1.3 GeV (increased energy and increased current),
- energy upgrade is trivial,
- current upgrade is possible from the RF point of view, adequate source is needed,
- ring and target are designed for 2 MW,
- loss control!

Which machine to choose between 1 and 10 GeV for moderate beam power (< 1 MW)?

RCS versus linac I

2 studies have been made to compare costs and performance:

8 GeV proton driver (FNAL) vs RCS

- 8 GeV linac, 0.5 MW, 10 Hz,
- 600 MeV linac + 8 GeV synchrotron,

LP-SPL (CERN) vs RCS

- 4 GeV linac, 0.2 MW, 2 Hz,
- 400 MeV linac + 4 GeV synchrotron,

Both studies concluded that the linac solution is ~30% more expensive.

RCS versus linac II

Nevertheless, both studies preferred the linac option!

8 GeV proton driver (FNAL):

- upgrade potential for future physics needs,
- test bench for ILC cavities,

LP-SPL:

- upgrade potential,
- performance advantage.

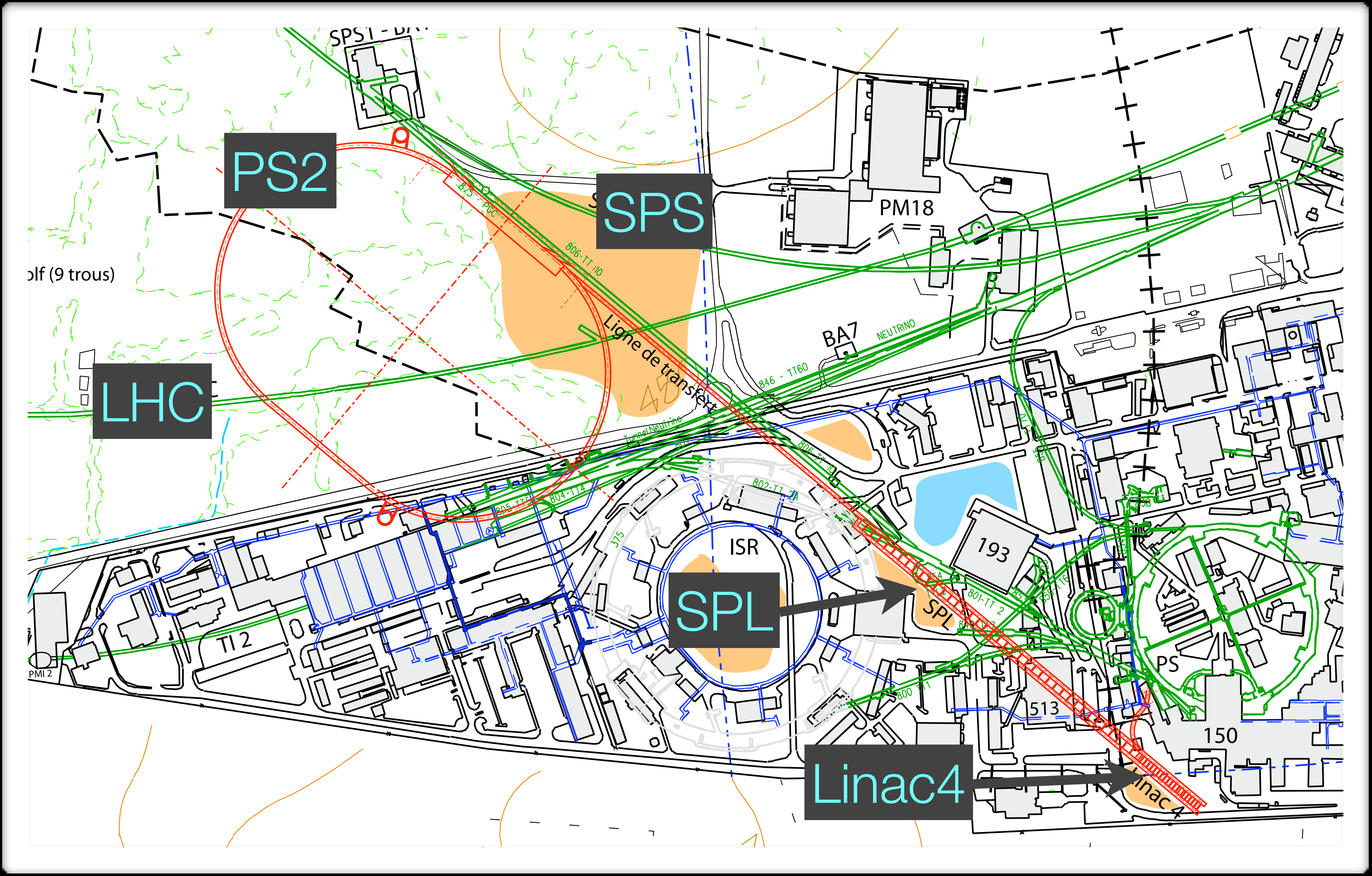
	LP-SPL	RCS	Advantage
Filling time PS2	1.2 ms	1.3 s	SPL
Proton rate	2.5	1	SPL
Fixed target physics	ideal	acceptable	SPL
Ions	acceptable	ideal	RCS
Upgrade potential	high	low	SPL
Relative cost	1.28	1	RCS

The linac + acc./compr. solution

Example: the SPL project at CERN

- one facility to produce short (us) and long (ms) pulses,
- use unmodified linac pulses for RIB production, and
- in case of CERN to drive the LHC injector chain,
- use accumulator/compressor rings to modify the pulse structure for neutrino physics (superbeam, neutrino factory),
- staged construction and adaptation to needs as the facility grows.

New proton injector complex at CERN



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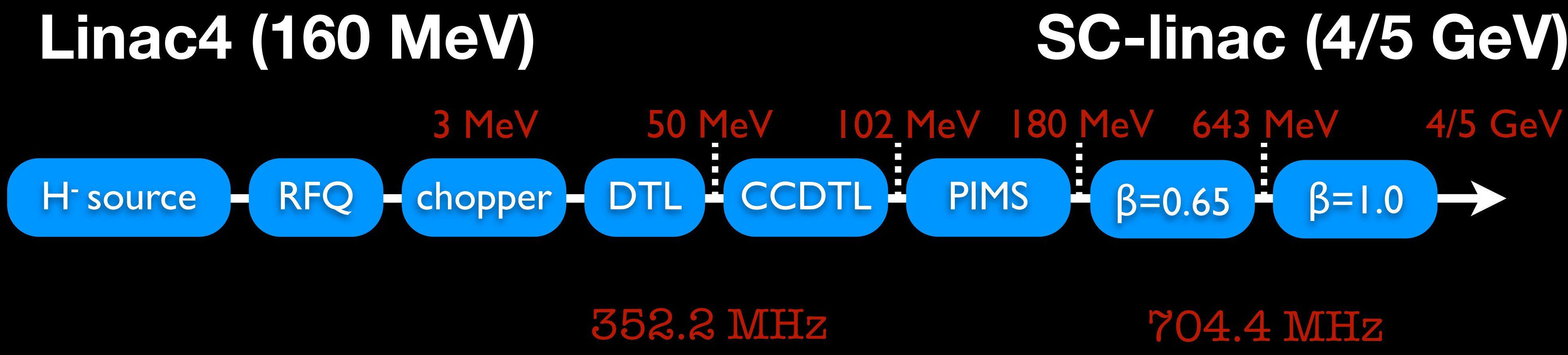
SPL machine layout

- During construction and commissioning of the LPSPL, Linac4 will continue as PSB injector and provide beam to commission SPL/ PS2,
- when PS2 is running, the “switching” area will be replaced with a 160-180 MeV normal conducting linac.



Stage 1: installation of Linac4

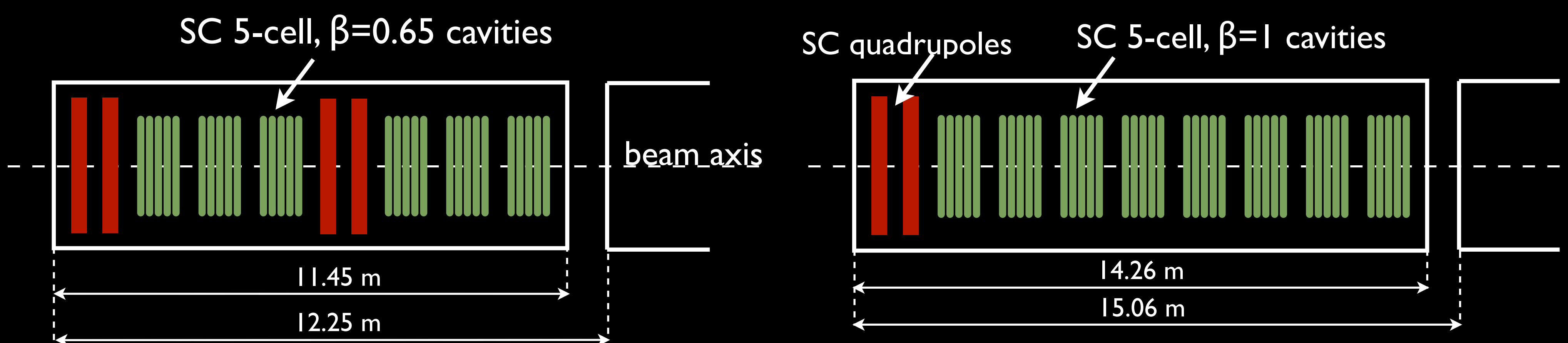
- 160 MeV normal conducting front-end of the SPL,
- replacing the ageing Linac2 (50 MeV),
- operating at 0.08% duty cycle but designed as front-end of the SPL (up to 5% duty cycle),
- first step towards LHC luminosity upgrade,
- project is approved and beam is expected in 2012.

Stage 2: installation of LP-SPL

- 4 GeV, 2 Hz, 0.2 MW, 20 mA pulse current: LP Low-Power,
- replaces the PS-booster and is constructed together with PS2,

Applications:

- LHC luminosity upgrade, injection into PS2 (1.2 ms, 1.5 10^{14} ppp)
- increasing the reliability of the CERN proton injector complex.



19 MV/m

25 MV/m

Stage 3: upgrade to HP-SPL

- 4 → 5 GeV, 2 → 50 Hz, 20 → 40 mA, 0.2 → 4 MW,
- replace all klystron modulators and power supplies,
- double the number of klystrons,
- new infrastructure for electricity, water, cryogenics, surface buildings.

Applications:

- PS2/SPS/LHC,
- neutrino beta beam,
- EURISOL, ISOLDE upgrade.

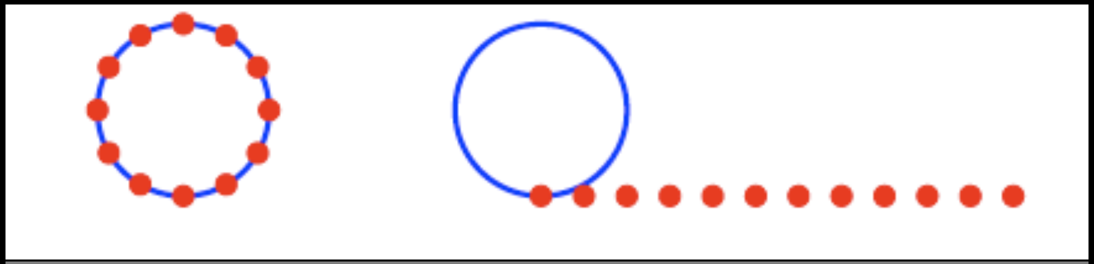
Stage 4/5: accumulator/compressor

Accumulator ring

- neutrino superbeam,

Compressor ring:

- neutrino factory.



Only at this stage one has to fix the time structure of the beam:

circumference = pulse length

harmonic number = number of bunches

bunch length = RF gymnastics

main parameters

SPL type	Linac4	low-power	full-power
E [GeV]	0.16	4.0	5.0
P_{beam} [MW]	0.005	0.192	>4
f_{rep} [Hz]	2	2	50
$I_{average}$ [mA]	40	20	40
t_{pulse} [ms]	0.4	1.2	0.4-0.6
$n_{protons/pulse}$ [10^{14}]	1.0	1.5	1-1.5
$n_{klystron}$ (Linac4 + SPL)	19	19+24	19+53
$n_{SC\ cavities}$	-	194	234
inst. $P_{RF(peak)}$ [MW]	24	100	220
$P_{facility}$ [MW]	≈ 1	4.5	38.5
$P_{cryo,\ electric}$ [MW]	-	1.5	4.5
T_{cryo} [K]	-	2	2
length [m]	80	459	534

Summary I

- Traditionally high-intensity linacs where only proposed for energies around 1-2 GeV (neutron sources, APT, ADS, RIB).
- Driven by the "neutrino factory" demand for high beam power at 5-10 GeV, linac designs are now going up to ~10 GeV!
- The advancement of SC RF technology makes it now possible to build multi-GeV linacs with a reasonable footprint (several 100 m), even for low beam power (LP-SPL: 0.2 MW).
- CERN and FNAL chose linac designs over RCS solutions despite the 30% cost difference.

Summary II

- Cyclotrons seem to have a “niche-existence” even though they have demonstrated the highest CW proton beam power (1.2 MW, PSI).
- Very few RCS designs aim at MW beam power below 10 GeV (JPARC, RAL proposals), breakthrough with magnetic alloy cavities (JPARC) and/or fast cycling SC magnets.
- High-energy (>10 GeV) high-intensity beams will remain synchrotron dominated.
- MW beam power has been demonstrated by the LAMPF linac (0.8 GeV) and PSI (0.6 GeV), or by synchrotrons (NuMI: 120 GeV, CNGS: 400 GeV). In the lower GeV range ISIS remains the record RCS (160 kW @ 0.8 GeV).