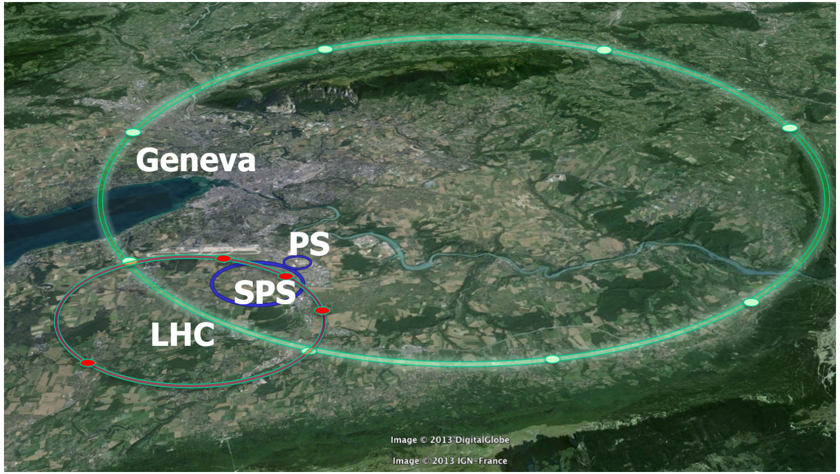


[FCC Study]

Mike Seidel :: Paul Scherrer Institut & École polytechnique fédérale de Lausanne

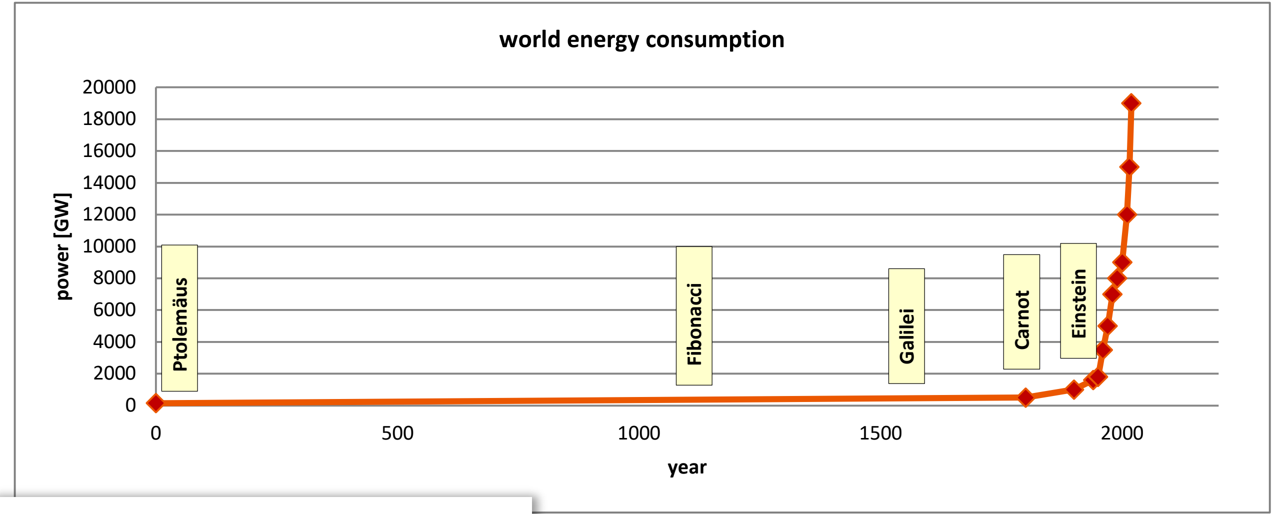
Energy Efficiency of Accelerator driven Research Infrastructures

Workshop Sustainable HEP :: 28-30 June 2021, CERN

Context - The Energy Problem

climate change causes critical reflections on non-sustainable energy carriers and irresponsible consumption of energy and resources

→ With our research we must contribute to solutions and should not be part of the problem.



includes all carriers, today ≈ 18TW

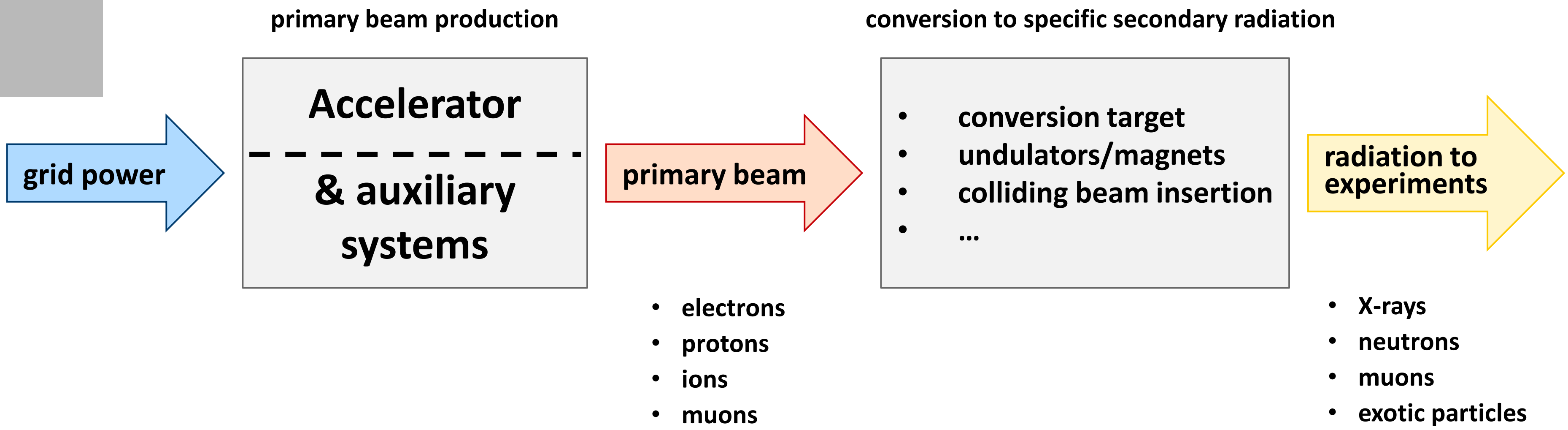
School Strike for Climate

Wikipedia

Categories of RI Sustainability

- energy related research
- mobility & business travel
- research infrastructure system efficiency
- efficient technologies
- water consumption
- waste management & recycling
- office/lab energy consumption
- energy procurement
- grid energy consumption
- heating & waste heat recycling
- use of materials and ressources

Accelerator based RI – the abstract view

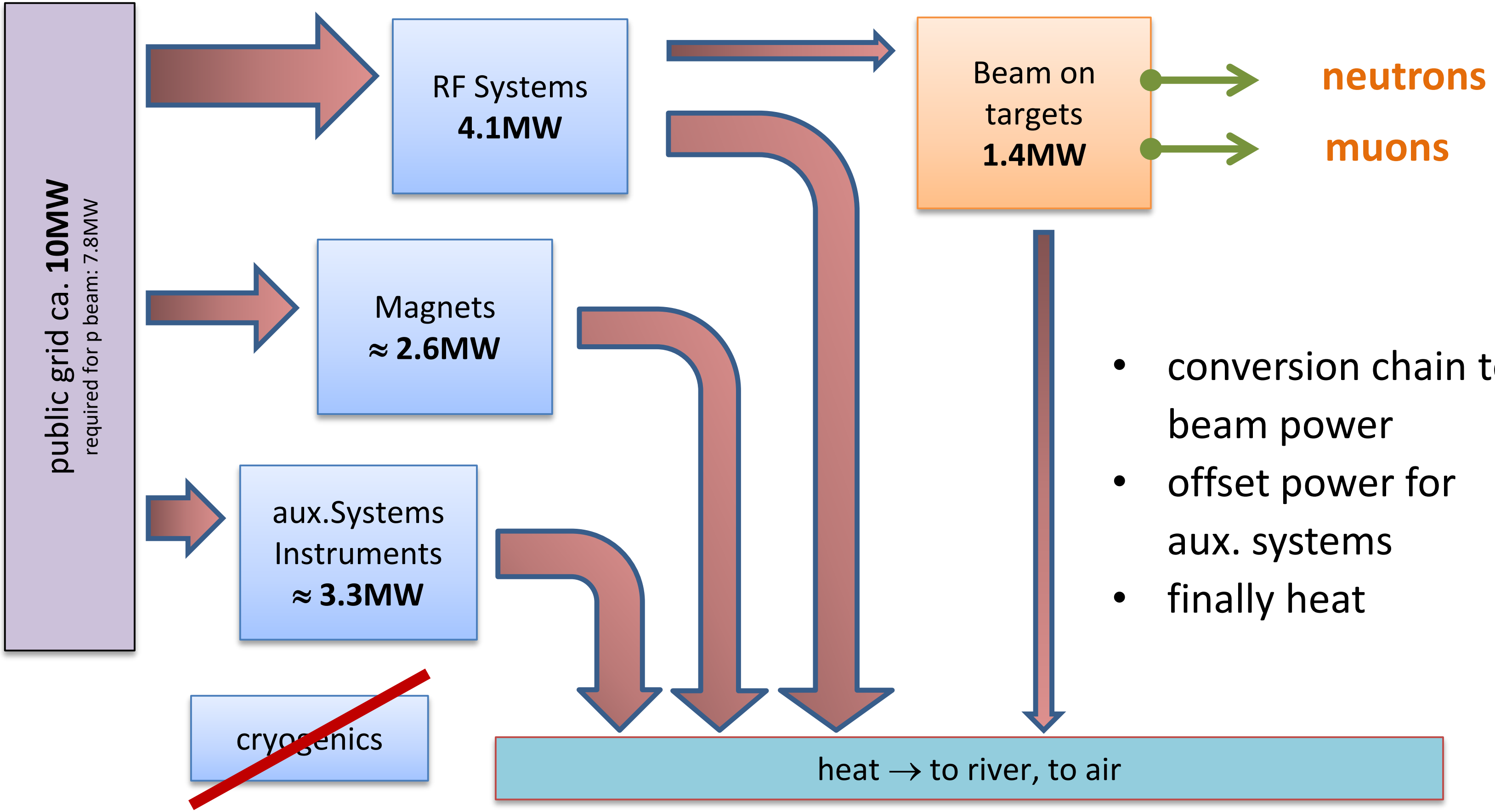


quantitative: rate of events; perhaps enabling thresholds

qualitative: energy reach, energy spread, polarization etc.

collider figure of merit: **Integrated Luminosity / Grid Energy**

Example: Power flow in PSI's Proton Accelerator



- conversion chain to beam power
- offset power for aux. systems
- finally heat

Large Hadron Collider LHC

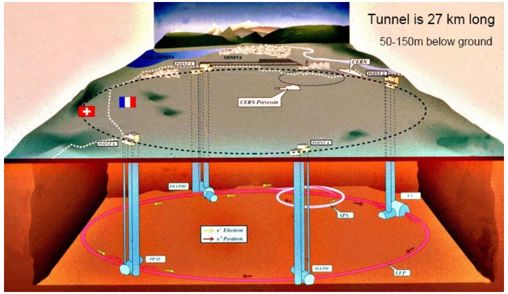
largest accelerator and highest particle energy
27km circumference (the LEP tunnel)

CM energy:	14TeV (7 + 7)
Luminosity:	$10^{34} cm^{-2}s^{-1}$
circulating beam power:	4 TW
synchrotron radiation:	0.22 W/m
wall plug power:	**≈ 120 MW**
yearly grid energy:	**≈ 1 TWh**

Higgs production:

70 fb^{-1} / year, σ_H = 50pb → 3.500.000 H/year

$M_H = 2 \cdot 10^{-8}$ J, Grid: 10^{+9} J/H (15€)



EPFL PAUL SCHERRER INSTITUT PSI

Particle Species and Synchrotron Radiation

	mass	lifetime	P_γ rel.
electron	0.511 MeV	stable	1
muon	106 MeV	2.2 μs	$5\cdot10^{-10}$
proton	938 MeV	stable	10^{-13}

accelerated charges radiate, SR power scales with 4´th power of rest mass:

$$P_\gamma \propto \frac{1}{\rho^2} \cdot \frac{E_k^4}{(m_0 c^2)^4}$$

impact of SR in accelerators:

- power loss of a beam must be compensated → grid power consumption

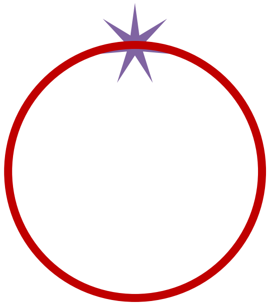
  example LEP top energy: 104.5GeV, ρ = 3km, $\Delta E_{SR}/E_k$ = 3% per turn, $P_{loss}\approx$20MW

- in storage rings beam assumes equilibrium size, hardly modified in longitudinal plane → linear colliders can generate much higher particle density

Accelerators for Particle Physics

Ring Collider

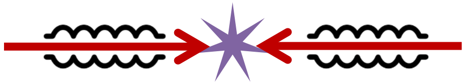
beams circulate



- beam reused
- synchrotron radiation dominated
- equilibrium beamsize $\rightarrow$ collision parameters limited

Linear Collider

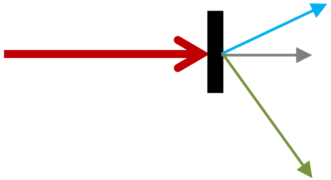
beams collide once



- beam used only once
- no synchrotron radiation
- ambitious collision parameters possible (no ring dynamics)

Particle Source (μ, ν, n, …)

high flux



- primary beam power
- conversion & capture efficiency
- emittance & other quality parameters

Proposed HEP Projects and Grid Power

	ECM [TeV]	L / IP [$10^{34} cm^{-2}s^{-1}$]	P_{Grid} [MW]	power driving effects
FCC-ee (Z)	0.091	230	**259**	SR Power: 50MW/beam
FCC-ee (t)	0.365	1.5	**359**	SR power: 50MW/beam
FCC-hh	100	30	**580**	SR power: 2.4MW/beam @ 50K, cryogenics
ILC	1	4.9	**300**	beam power: 13.6 MW/beam, cryogenics
CLIC	3	5.9	**582**	beam power: 14 MW/beam
muon coll.	6	12	**270**	mu decay, 1.6MW/drive beam, cycling magnets, but scaling advantages, least developed

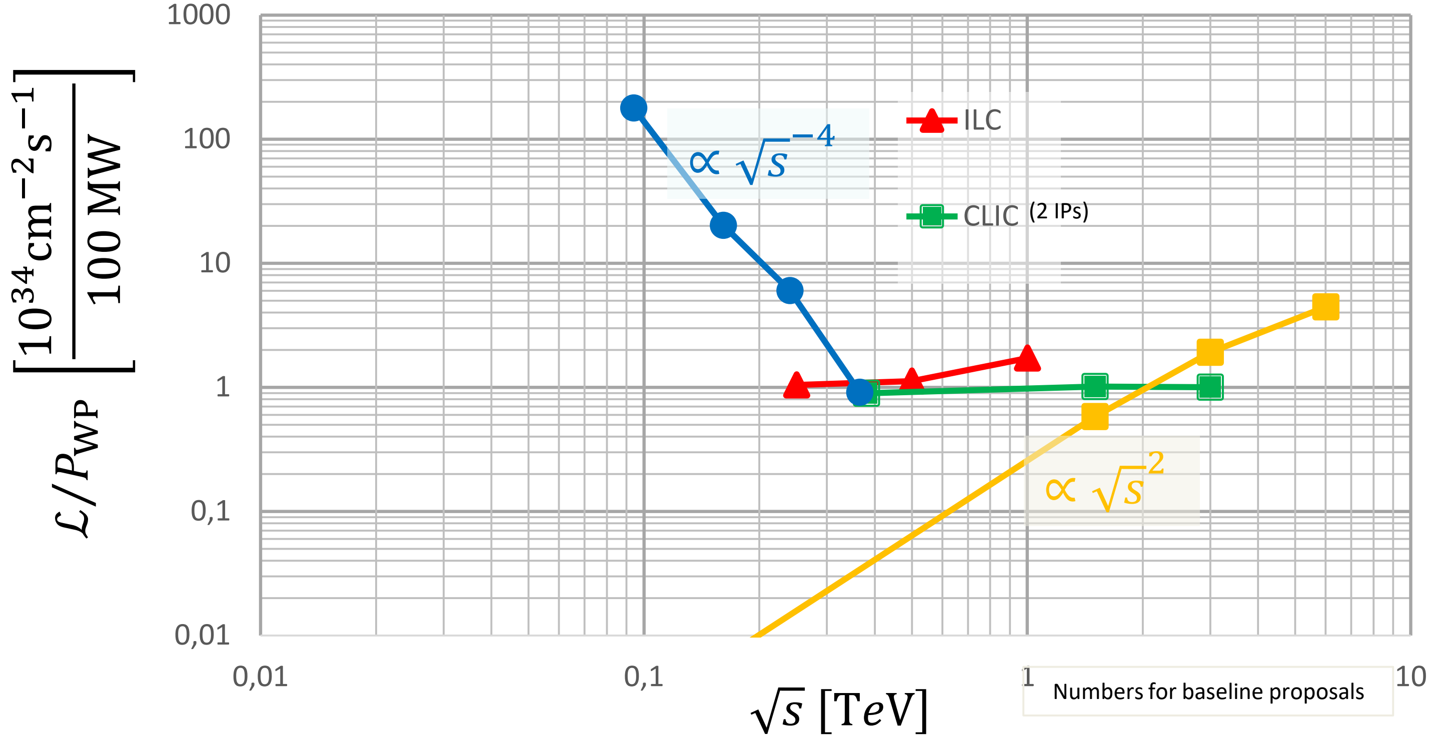
$$P_{\mathrm{SR}} \propto \left(\frac{E}{E_0}\right)^4 \frac{1}{R}$$

$$L_{\mathrm{lin.col.}} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\mathrm{beam}}$$

$$L_{\mathrm{mu.col.}} \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\mathrm{beam}}$$

Significant energy cost: 4TWh ~ 200M€, and sustainability concerns.
→ need more R&D towards efficient concepts & technology, energy management

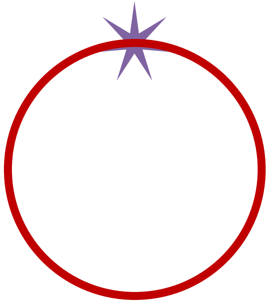
Collider Proposals: Luminosity per Grid Power



[E.Jensen, Granada 2019, Strategy Update]

Ring Collider vs. Linear Collider

Ring Collider
beams circulate

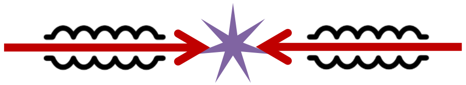


- beam reused
- synchrotron radiation dominated
- equilibrium beamsize → collision parameters limited

attainable collision parameters
[taken from design studies]

	$FCC\text{-}ee_{365GeV}$	$CLIC_{380GeV}$
σ_x [nm]	38'000	150
σ_y [nm]	68	3
σ_z [μm]	2'500	70
N [10^9]	230	5,2
f_b [kHz]	17,6	147

Linear Collider
beams collide once



- beam used only once
- no synchrotron radiation
- ambitious collision parameters possible (no ring dynamics)

The path to higher efficiency

Concept Ideas

- energy recovery linac (ERL)
- energy management

Technological Advancements for Efficient Accelerators

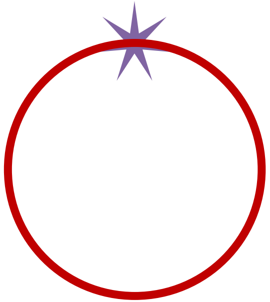
- efficient RF systems
- s.c. RF, high Tc
- permanent magnets

General Considerations

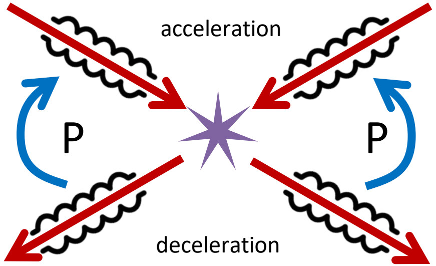
- potential spin-offs
- CERN utilizing its networking for international solutions

Energy Recovery Linac (ERL)

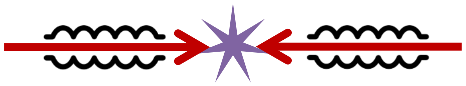
Ring Collider
beams circulate



ERL
power re-cirulated



Linear Collider
beams collide once



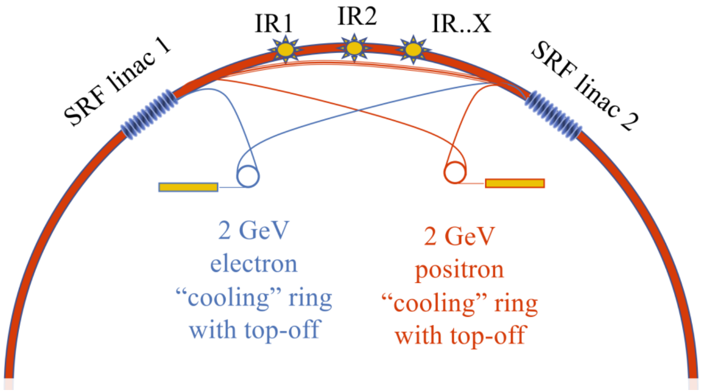
- beam used once
- but power recirculated
- ambitious collision parameters → low beam intensity

→ **overall low energy consumption, but high investments**

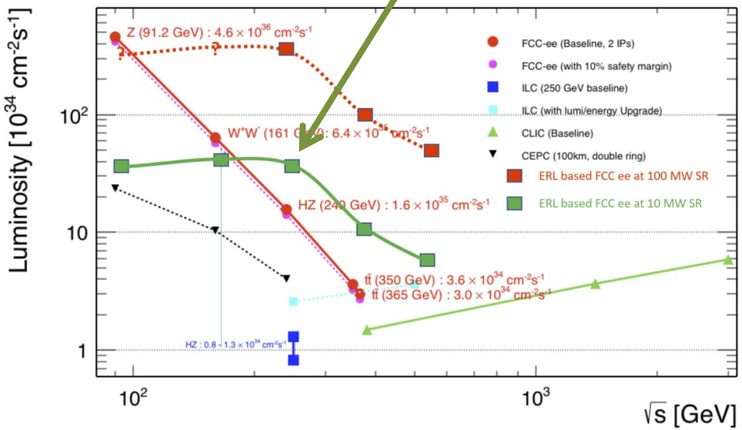
ERL concept for an e^+/e^- collider?

M.Llatas, V.N.Litvinenko, T.Roser et al (BNL)

- 4/6 pass linear accelerator / decelerator
- reduction of SR 50MW → 5MW per beam
- higher investment cost not evaluated!



performance compared to FCC-ee low power variant



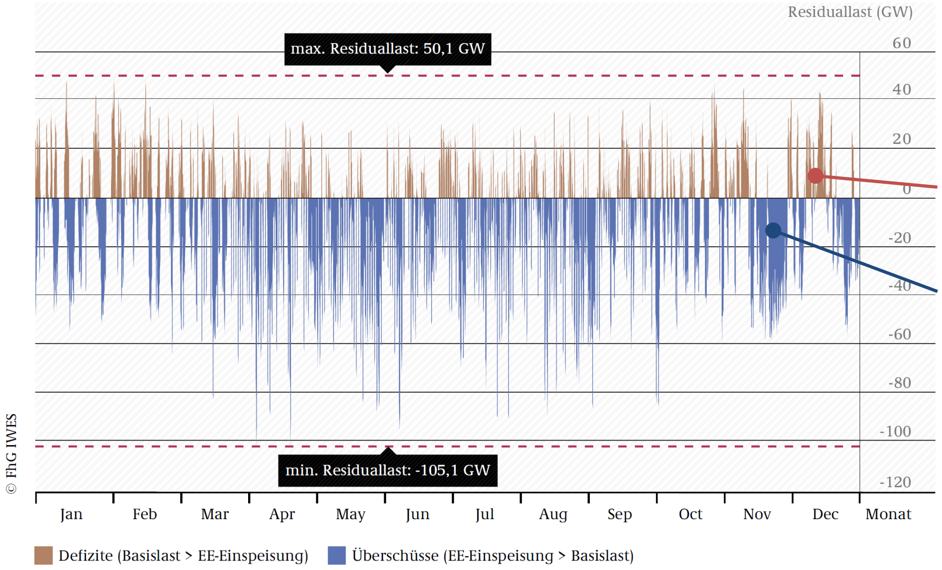
- ERL concept & performance evaluation
- quality of decelerated beam
- optimisation of economy

Energy Management

impact of RI energy consumption on the society can be minimized by smart energy management

- avoid times of high load / low energy production
- use energy storage technology, perhaps in synergy with available cryogenics
- use dynamic operation schemes, minimize luminosity recovery times

simulation Germany 2050, fluctuating E production, without E storage



deficit: 53 TWh/y

surplus: 154 TWh/y

FCC-hh: 4 TWh/y

[courtesy : Fraunhofer Gesellschaft]

Energy management example: CLIC Study on standby modes

CLIC project predicts large power for 3TeV case: 580MW

idea:

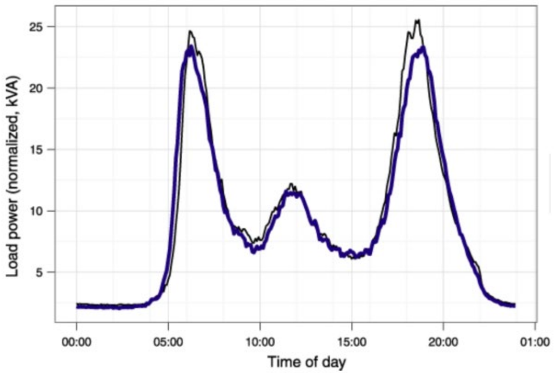
- prepare standby modes for high consumption times during day; relatively fast luminosity recovery from standby (challenging)
- model calculation includes standby power, startup times

result of model with 2 standbys during day:

- 1 day with 2 × standbys:
  $E_{standby}$ = 582 MW × 14 hours + 2 × (4 × 268 MWh + 1 × 425 MWh) = 11.14 GWh
  $L_{standby}t = 2.0\times10^{34}\ cm^{-2}s^{-1} \times (14 + 2 \times ½)$ hours = 1.08 fb^{-1}

Energy consumed is reduced by **18% (-2.826 GWh)**
Luminosity delivered is reduced by **37% (-0.648 fb^{-1})**

Energy consumption per day



We could go to stand-by mode during the most critical (i.e. expensive) hours of the day...

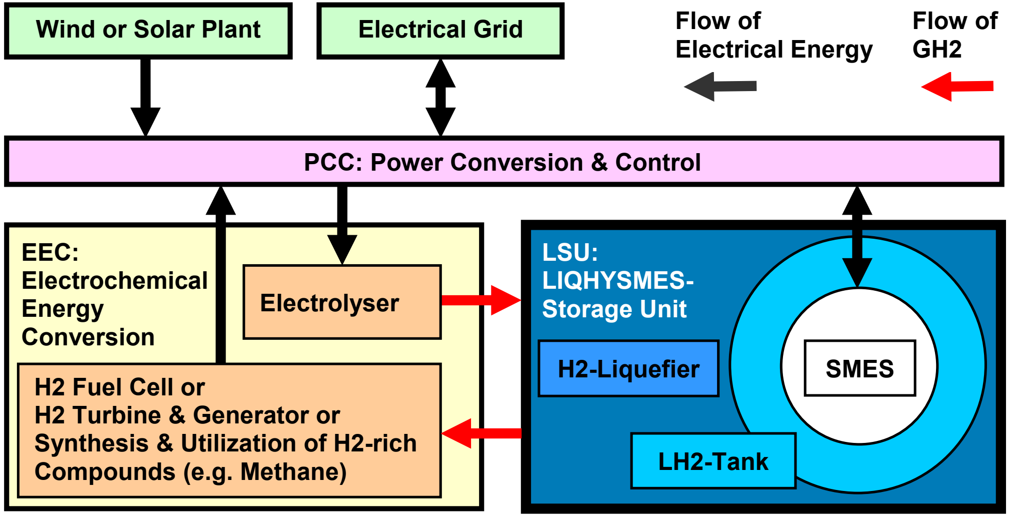
Andrea Latina, CERN

Energy Storage for Accelerators ?

development by KIT for general purpose: hybrid SMES/LH2
[M.Sander, R.Gehring, KIT]

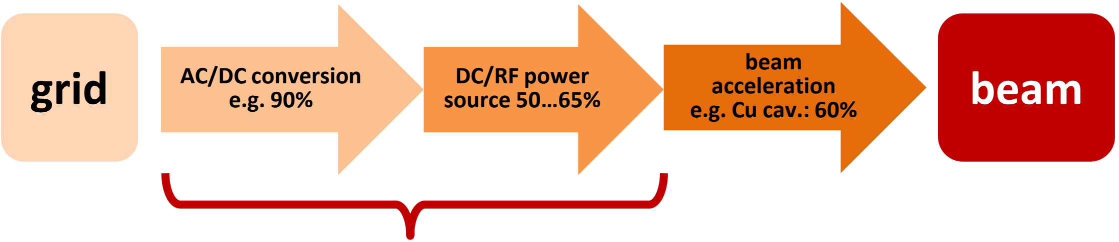
- large power ..100 MW
- capacity to ~70 GWh
- SMES to ~10 GJ
- synergy with existing cryogenics?
- capacity: ≈ 8.25 €/kWh
- but power is cost driver, ≈1.9k€/kW, **≈1B€/500MW**

Large capacity technology: LIQuid HYdrogen & SMES



energy storage at large is an option, but requires major investments

Efficient RF Sources



RF generation efficiency is key for many accelerator applications

technology topics:

- klystron development (major focus, LHC upgr, potential gain: 10..20%)
- phase stable magnetrons (e.g. JLAB, Fermilab, η≈90%)
- solid state amplifiers (potentially better than klystrons)

EU co-funded workshops Efficient RF sources:

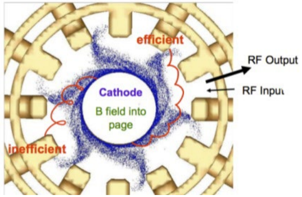
2014, Daresbury: https://indico.cern.ch/event/297025/

2019, Uppsala: https://indico.uu.se/event/515/

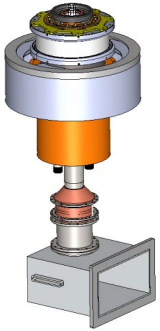
2022, planned for I.FAST

THALES: multi-beam klystron

SIEMENS: solid state amplifier



magnetron, court. A.Dexter



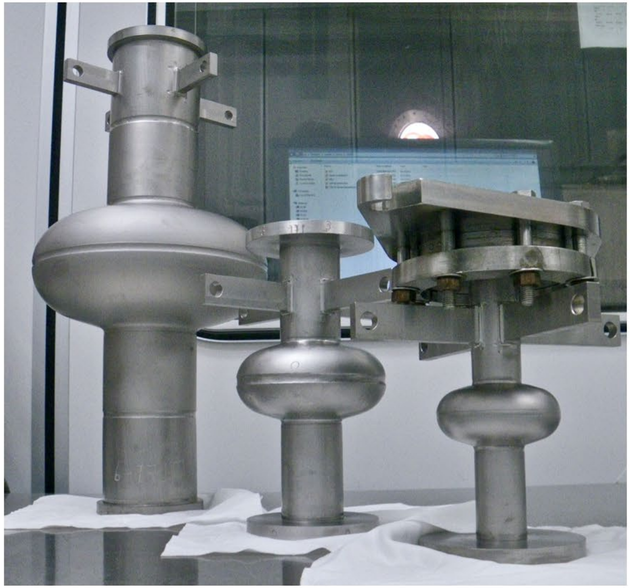
CPI: multi-beam IOT

E2V: magnetron

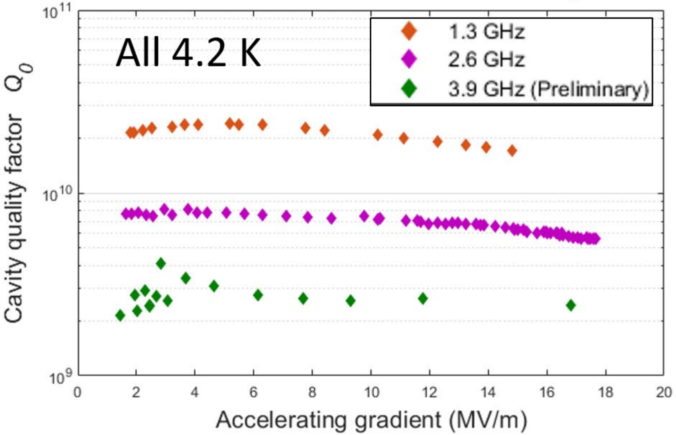
Superconducting RF at Higher Temperature

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

High Frequency Nb_3Sn



Q vs E for Different Frequencies of Nb_3Sn Cavity



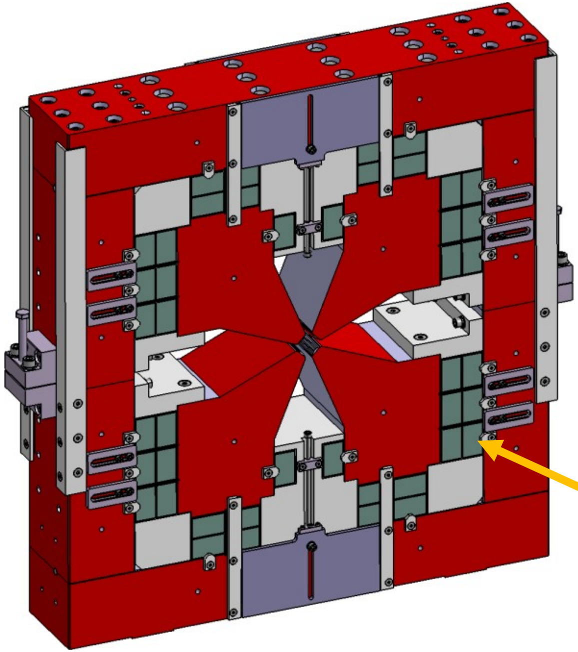
Great first results!

cryogenic efficiency x3 at 4.2K vs. 2.0K !

Ryan Porter, Matthias Liepe et al. (Cornell)
ESSRI 2019

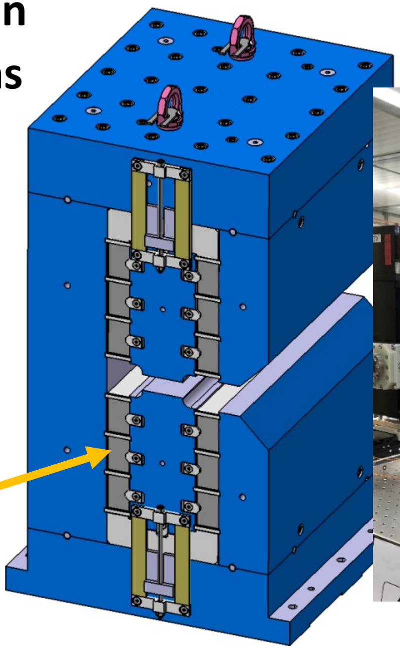
efficient technology example: Permanent Accelerator Magnets for SLS2.0

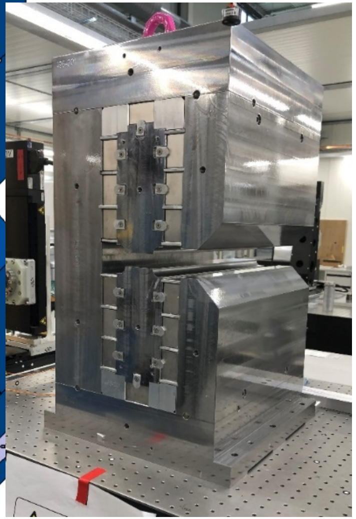
quadrupole



+ compact design
+ zero power consumption
+ no cooling, no vibrations
- no remote tunability
- rare earth materials

dipole





NdFeB
+ NiFe wrapping

Spin-offs of Accelerator & HEP Development

knowledge from HEP + accelerator R&D is can be utilized for adressing energy related problems:

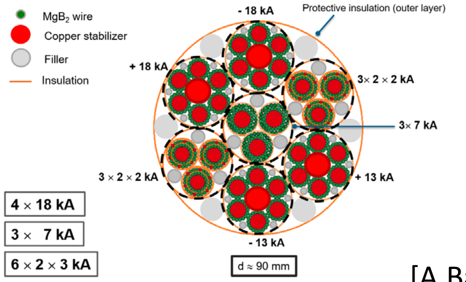
- high temperature superconducting cables
- accelerator driven subcritical reactors
- … potentially many more topics.

TRANSMUTEX
Nuclear Waste to Green Energy

ABOUT TRANSMUTEX

Transmutex is a revolutionary nuclear technology for the transmutation of long-lived nuclear waste. It was developed and tested at CERN in Geneva. We believe nuclear waste to be our generation's problem, not the next one. It must be dealt with today, not to be forgotten in the day to day political maelstrom.

MgB_2 Cables



[A.Ballarino et al]

Extrapolation at higher currents and energies

10 mA at 1 GeV = 10 MWatt
Efficiency of conversion from AC to beam ≈ 50 %
Injection energy 120 MeV

Potential of Cyclotron based Accelerators for Energy Production and Transmutation

Th. Stammbach, S. Adam, H.R. Fitze, W. Joho and U. Schryber
Accelerator Division, Paul Scherrer Institute
CH–5234 Villigen-PSI, Switzerland

Abstract. PSI operates a 590 MeV-cyclotron facility for high intensity proton beams for the production of intense beams of pions and muons. The facility, commissioned in 1974, has been partially upgraded and is now operated routinely at a beam current of 1 mA, which corresponds to a beam power of 0.6 MW. At this current, the beam losses in the cyclotron are about 0.02%. By the end of 1995 we expect to have 1.5 mA of protons. Extensive theoretical investigations on beam current limitations in isochronous cyclotrons were undertaken. They show that the longitudinal space charge effects dominate.
Based on our experience we present a preliminary design of a cyclotron scheme that could produce a 10 MW beam as a driver for an "energy amplifier" as proposed by C. Rubbia and his collaborators. The expected efficiency for the conversion of AC into beam power would be about 50% (for the RF-systems only). The beam losses in the cyclotron are expected to be a few μA, leading to a tolerable activation level.

A PSI study

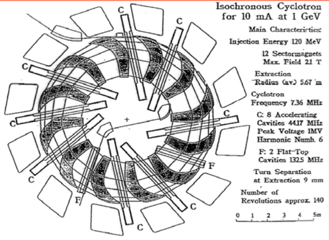


Fig. 4. Layout of the proposed high power cyclotron.

Maximum fission driving power: 2.4 GWth for k_{eff}= 0.99

Sweden, June 2005

[C.Rubbia]

Renewable power for CERN, DESY, …

How to avoid the 50% power loss?

„DESERTEC“ solution:

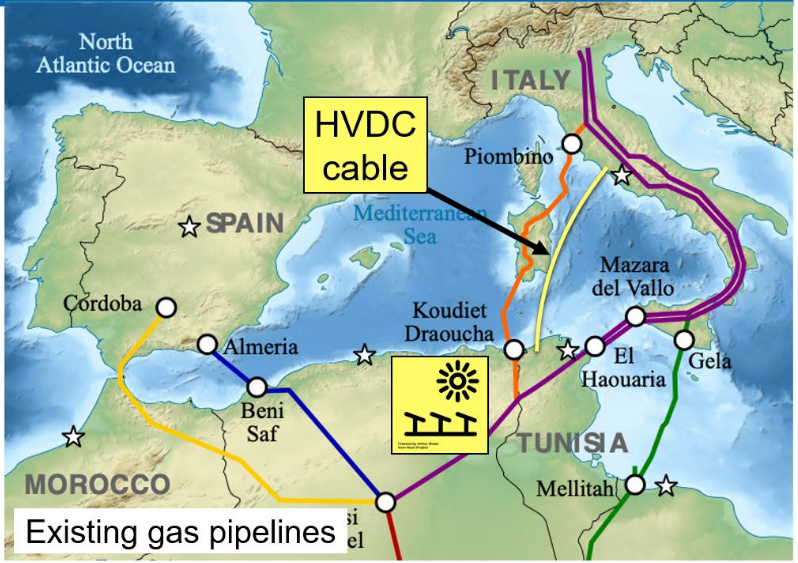
day: PV ~1 ct/kWh (1,5 ct/kWh today)

night: CSP with Thermal Storage ~4 ct/kWh

cable: HVDC e.g. Tunisia-Italy <1 ct/kWh

Connection to European power market

Total cost ~ 4 ct/kWh ?



Why CERN?

- political and financial situation is not a show stopper
- all involved countries are members or associates of CERN
- experience with SESAME in Jordan as peace-promoting project

M.Düren, ESSRI (2019, PSI)

→ **flash talk this conference**

Efficient Accelerators - Conclusions

- next generation **collider facilities need significant grid power** to deliver required luminosity
- **conceptual advancements** are aimed at increasing specific luminosity, e.g. energy recovery linac, in principle all beam dynamics measures to maximize L/P
- **technological advancements** in accelerators include: efficient RF sources, permanent magnets, HTC s.c. cables and cavities, efficient cryogenics + other subjects
- another strategy is to accept high power consumption but to minimize the impact on society $\rightarrow$ **dynamic operation, energy management incl. energy storage**
- **our community can contribute to the solution of the global energy problem** through spin-offs of our R&D and through international networking

Discussion Questions

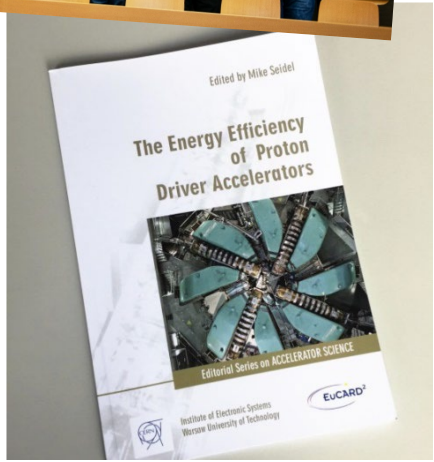
1.) What future power consumption is appropriate for a HEP RI (LHC today 1TWh/y)?

2.) Considering cost vs. energy consumption – what is more relevant when optimizing a collider design?

2.) Would you accept compromises for science work:
- lower event statistics to limit power consumption?
- less predictable operating schedule for dynamic operation?

3.) Should CERN / the HEP community engage with their intl. networks to help establishing sustainable energy supply solutions?

Programs and Workshops related to Accelerator Sustainability



EUCARD-2 (2013), ARIES (2017), I.FAST (2021) Programs co-funded by EC

- **≈ 15 workshops on efficient concepts & technologies 2013-2020**
- topics: heat recovery, s.c. cavities, efficient magnets, efficient RF systems, proton driver accelerators, energy storage, high brightness neutron production
- **≈10 selected development & survey projects,** master, PhDs, Postdocs
- http://www.psi.ch/enefficient , http://www.psi.ch/aries-eem