Sustainability of Particle Accelerators

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Paul Scherrer Institute and EPFL, Switzerland

CERN Accelerator School – Introductory Course

September 30, 2024

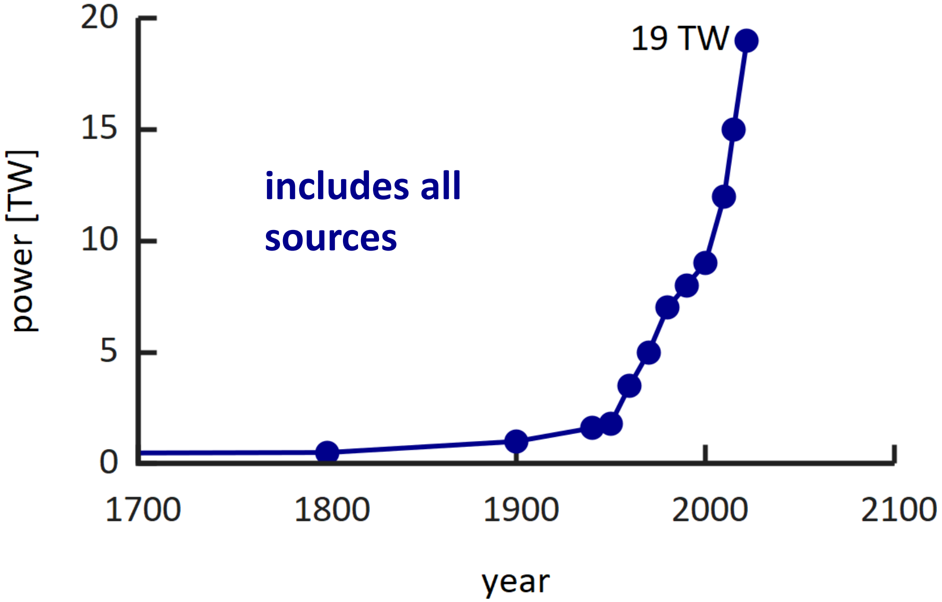
Santa Susanna

Sustainability = Meeting the needs of the present without compromising the ability of future generations.

(one of many debated formulations)

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

Energy Consumption - Motivation

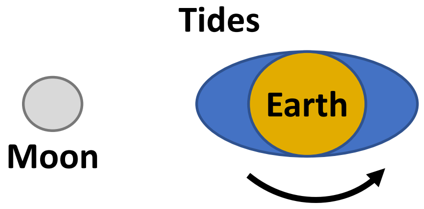


The world energy consumption has been continuously rising, reaching ca **19 TW** today.

As a science community we rather want to contribute to solutions and not be part of the problem.

<u>example from nature</u>:
the Earth-Moon system dissipates **3.8 TW** power from the rotation energy of earth

[Williams, Boggs, 2016]



School Strike for Climate Wikipedia

Community Activities on Sustainability

2014-17: EUCARD-2, WP Energy Efficient Accelerator Technologies

https://www.psi.ch/enefficient

2017–21: ARIES, Work Package Efficient Energy Management

https://www.psi.ch/aries-eem

2021–25: I.FAST, Work Package Sustainable Concepts

https://www.psi.ch/scat

EuCARD² Enhanced European Coordination for Accelerator Research & Development

ARIES Accelerator Research and Innovation for European Science and Society

iFAST Innovation Fostering in Accelerator Science and Technology

→ consult websites for link collection to workshops and documentation

ICFA

- ICFA panel on sustainable accelerators, chair: Thomas Roser (BNL)
- https://icfa.hep.net/icfa-panel-on-sustainable-accelerators-and-colliders/

Accelerator driven Research Infrastructures (RI)

grid power → **accelerator** / **auxiliary systems** → **primary beam** →

- **conversion target**
- **undulators/magnets**
- **colliding beam insertion**
- **…**

→ **radiation to experiments**

primary beam production

- **electrons**
- **protons**
- **ions**

conversion to specific secondary radiation

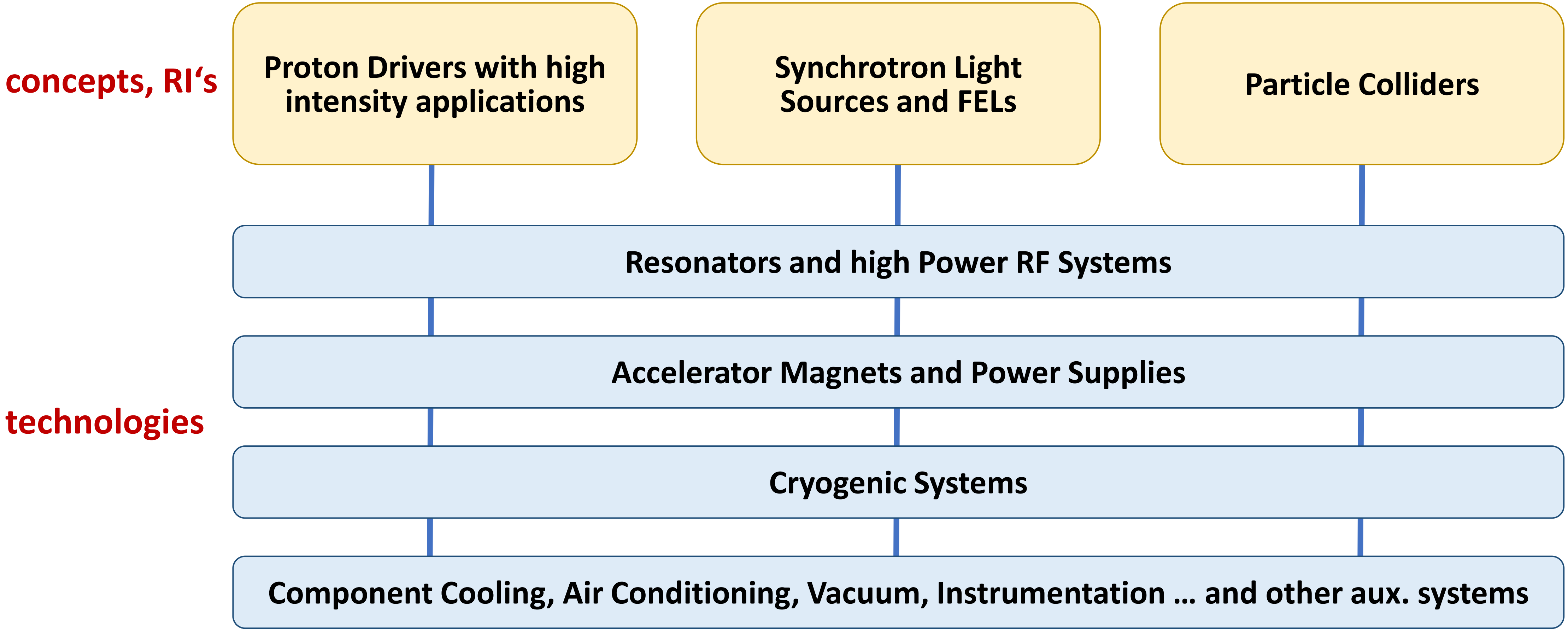
- **X-rays**
- **neutrons, muons, neutrinos**
- **exotic particles**

high level goal:

Science output per grid power, per operating/investment cost.

Accelerator Concepts and Technologies

[with emphasize on energy efficiency]



Efficient Accelerator Technologies

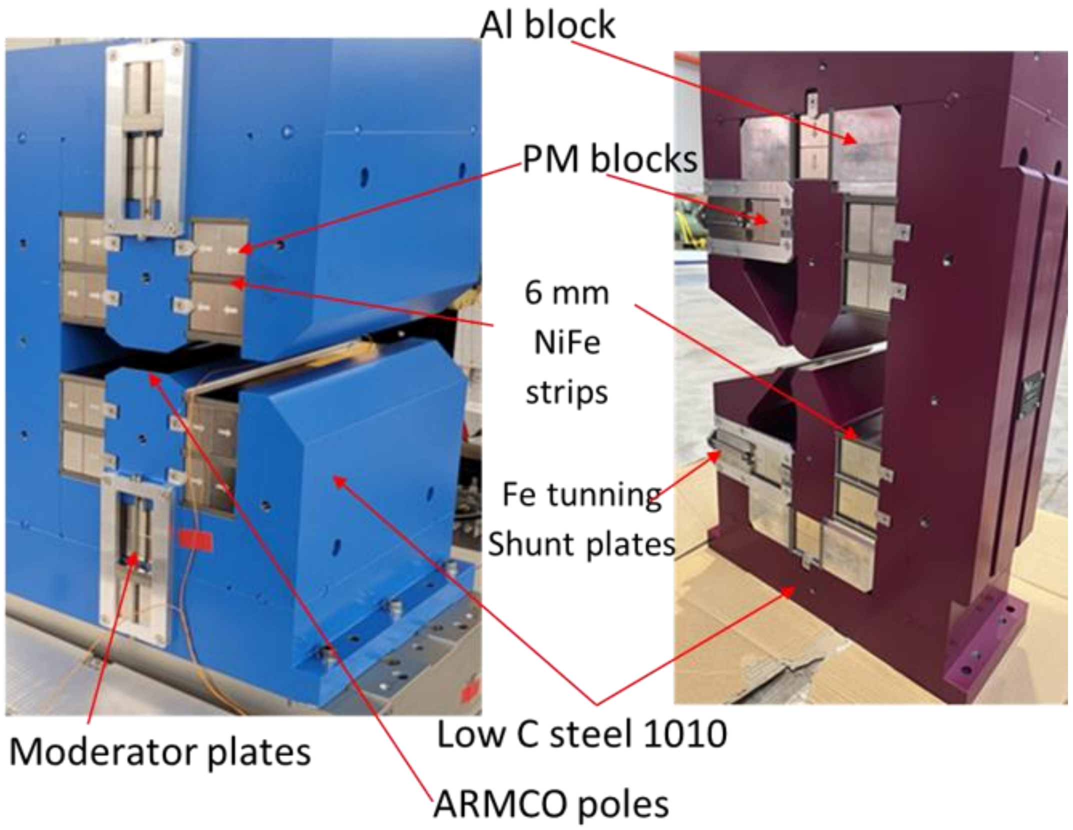
Accelerator Magnets with Permanent Magnet Material

permanent magnets:

+ extremly compact → low emittance lattices
+ no power consumption
+ no cooling, thus no heat introduced, no vibrations from cooling loop

- field tuning difficult
- use of rare earth materials

Dipole and Quad for SLS2.0, S.Sanfilippo et al (PSI)



B = 1.35 T

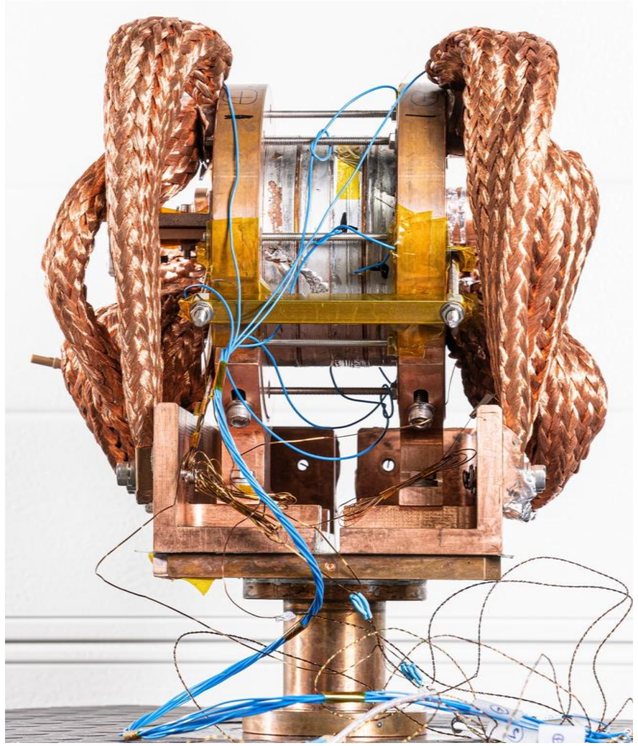
g = -40.6 T/m

Accelerator Magnets with High Temperature Superconductor Coils

magnets with High Temperature Superconductor (HTS) coils:

+ medium fields for all applications (high fields in block config.)
+ ReBCO and Bi-2212 materials are studied
+ no ohmic losses, can replace power hungry large aperture dipoles/quads
+ cryogen free conduction-cooling possible (no He)
+ much improved cryogenic efficiency at elevated temperatures (e.g. 4.5K…15K instead 2K)

- today expensive materials
- field ramping and field quality difficult (wide tapes)



solenoid test magnet, 18T @ 12K
PSI/CHART, B.Auchmann et al

Efficient RF Power Sources

- **Klystrons**, η>70% within reach
  e.g. CLIC two stage multi-beam klystron, J.Cai, I.Syratchev, IEEE Trans, 2020

- **Magnetron**, R&D at various groups, η=60-80% within reach
  e.g. Wang et al, J-Lab, IPAC 2019; A.Dexter, Lancaster U., LINAC-2014; B.Chase, Fermilab, JINST-2015

- **Solid state amplifiers (SSA)** at various groups, η=60-90% depending of freq.

3362 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 67, NO. 8, AUGUST 2020

Modeling and Technical Design Study of Two-Stage Multibeam Klystron for CLIC

Jinchi Cai and Igor Syratchev

Example: study 1GHz for CLIC drive beam; 6 cavities, 30 beamlets; 25+140kV; η_{sat}=82%

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 70, NO. 2, FEBRUARY 2022 1401

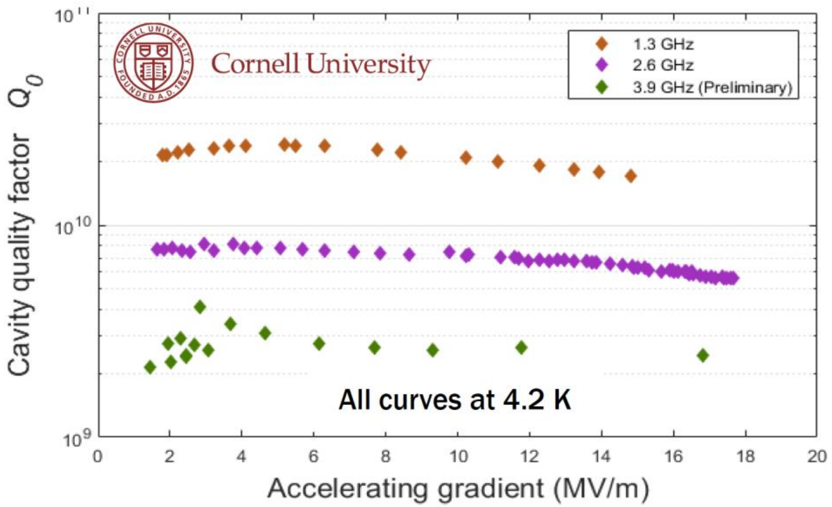
Kilowatt Power Amplifier With Improved Power Back-Off Efficiency for Cyclotron Application

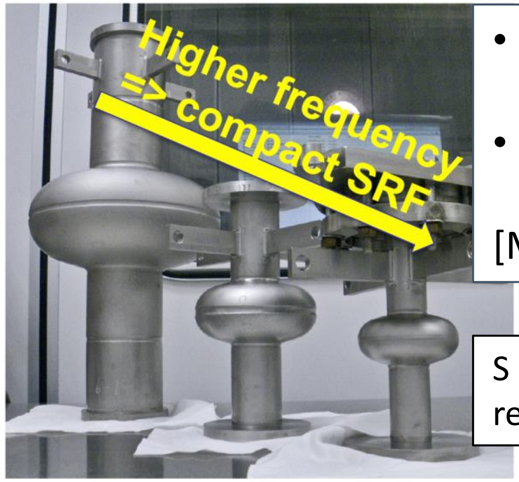
Renbin Tong, Olof Bengtsson, *Senior Member, IEEE*, Jörgen Olsson, *Senior Member, IEEE*, Andreas Bäcklund, and Dragos Dancila

Example: SSA for Isotope production Cyclotron, 98.5MHz, 12x1kW units, η_D=93% (90% with regulation overhead)
Uppsala group, WP in I.FAST program

I.FAST efficient RF workshop, July 23-25, 2025, Toledo: https://indico.cern.ch/event/1407353/

Technology R&D: Superconducting RF at higher temperature





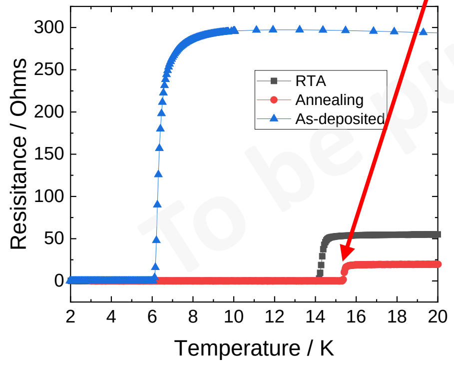
- promising R&D: Nb_3Sn coated cavities at Cornell
- 4.2 vs. 2.0K → efficiency

[M.Liepe, Cornell, IPAC'19]

Cornell, FERMILAB
→ simplicity, cost, efficiency, smaller size

S Posen et al 2021 Supercond. Sci. Technol. 34 025007
record cw gradient in Nb_3Sn-coated, E_{acc} = 24 MV/m

SMART recipe leads to a T_c of 15.4 K on Nb-samples coated with 15 / 25 nm of AlN / NbTiN



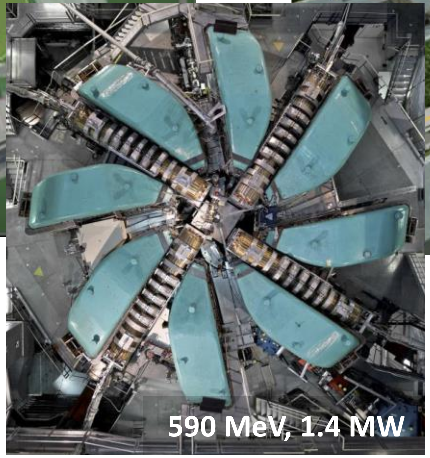
DESY, Hamburg U.
aim for sustained SRF accelerator technology
10y Goal: >70 MV/m with a Q_0 of $1x10^{10}$ and at 4K
contact: M.Wenskat, DESY

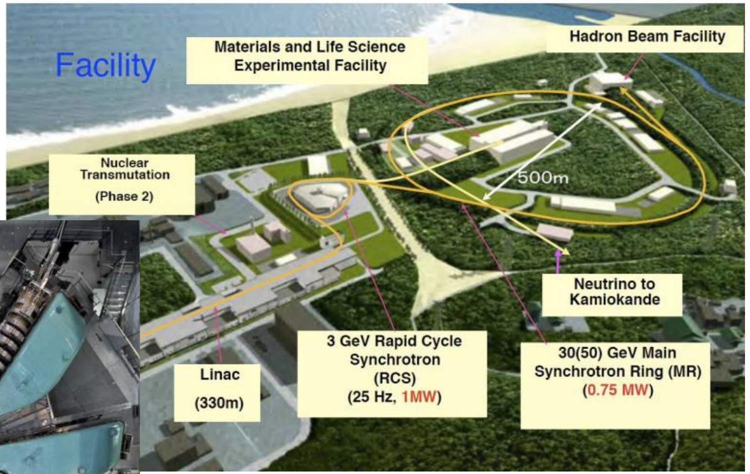
G. Deyu et al., „Al_2O_3 coating of Superconducting Niobium Cavities with thermal ALD", in preparation

Proton Driver Accelerators

or: Best attainable Grid-to-Beam efficiency?

Comparison: Megawatt p-Drivers





Workshop: Efficiency of Proton Driver Accelerators, 2016, PSI
https://indico.psi.ch/event/3848/

Yakovlev, FNAL, invited talk, IPAC 2017

FRXCB1 Proceedings of IPAC2017, Copenhagen, Denmark

THE ENERGY EFFICIENCY OF HIGH INTENSITY PROTON DRIVER CONCEPTS*

J. K. Grillenberger, Paul Scherrer Institut, 5232 Villigen, Switzerland,
S-H. Kim, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
M. Yoshii, KEK and JAEA J-PARC Center, 2-4 Shirakata-Shirane, Tokai, Ibaraki 319-1195, Japan
M. Seidel, Paul Scherrer Institut, 5232 Villigen, Switzerland
V.P. Yakovlev†, Fermi National Accelerator Laboratory, Batavia, Il 60510, USA

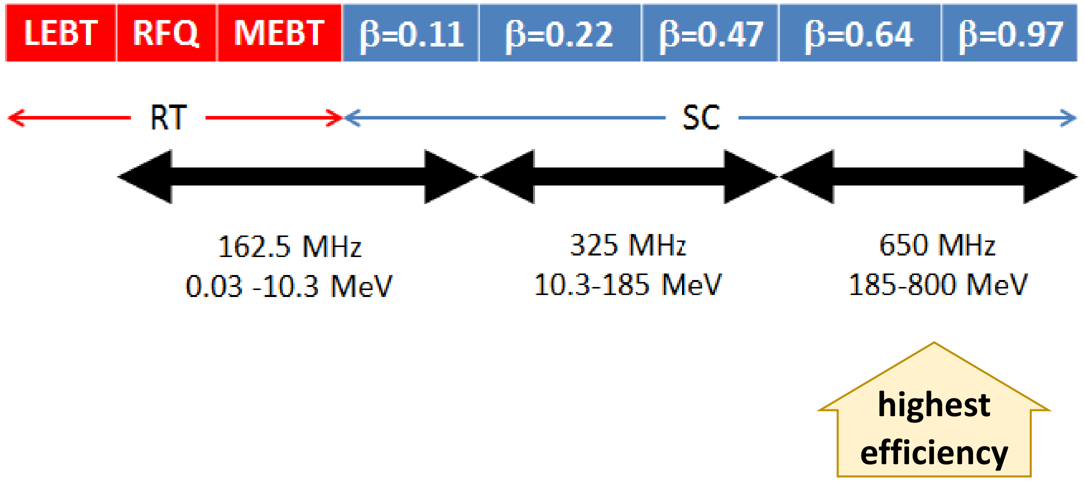
Megawatt class facilities operating today:

optimized for application, not efficiency

facility	accelerator type	Economy	Energy Reach	Power Reach	operational complexity	grid-to-beam Efficiency
SNS	superconducting linac	--	++	++	++	**9%**
J-PARC	rapid cycling synchrotron	++	++	-	-	**3%**
PSI	isochronous cyclotron	+	--	+	-	**18%**

Superconducting Linac : High Efficiency Potential

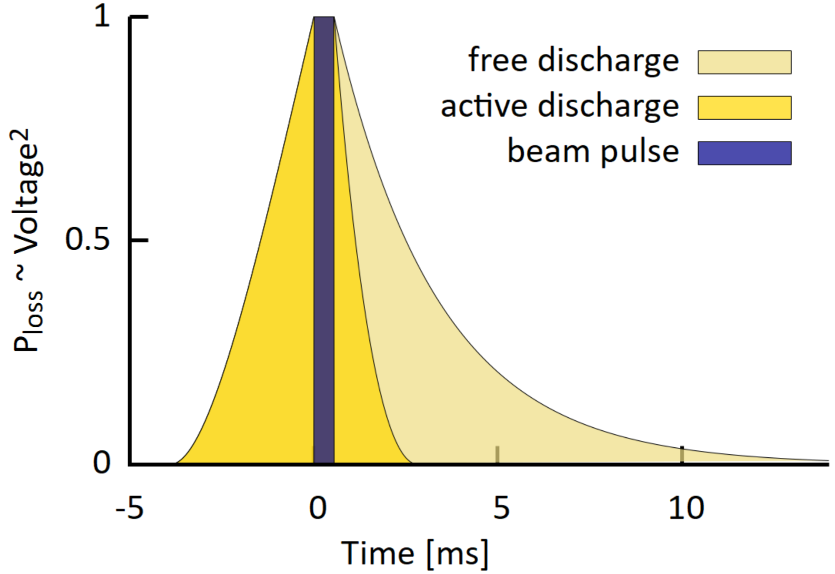
example: PIP-II design of Fermilab



PIP-II base parameters:

- **H^-, 800MeV, 2.0mA**, part of Fermilab complex
- aim: neutrino production (1MW @ 60..120GeV)
- CW operation as upgrade path

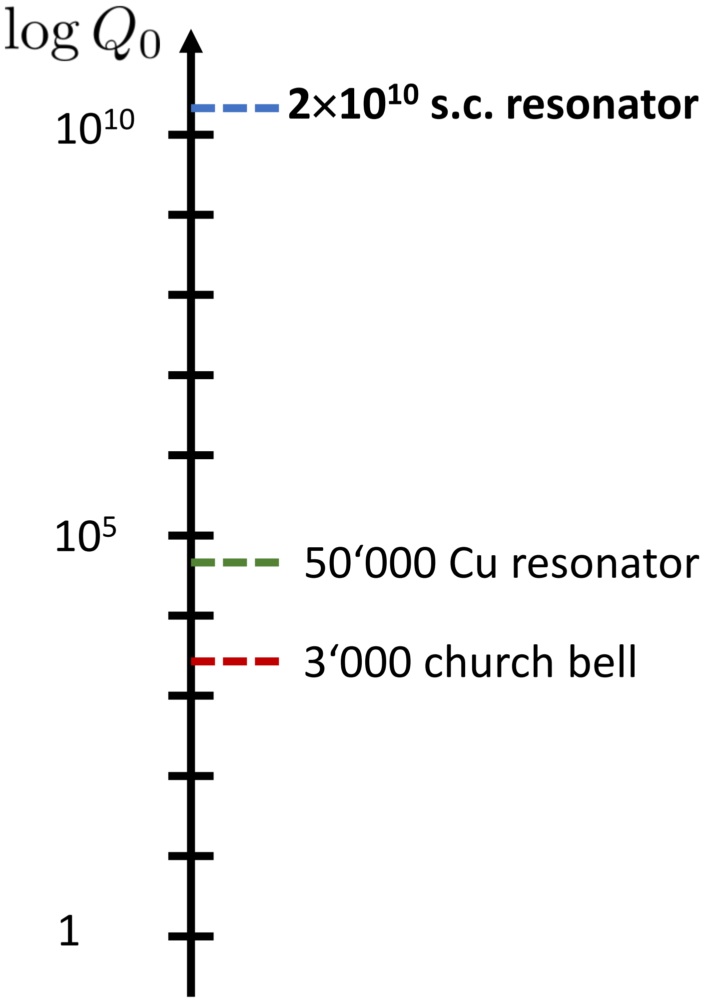
not efficient in pulsed operation:



operating regime	avg. RF power	cryogenic power	avg. beam power	grid-to-beam Efficiency
PIP-II pulsed operation	**1.44MW**	**1.19MW**	**17.6kW**	**0.7%**
PIP-II CW operation	**9.10MW**	**1.83MW**	**1.60MW**	**15%**

[from presentation B.Chase, Y.Yakovlev, 2018]

Low Loss Superconducting Resonators

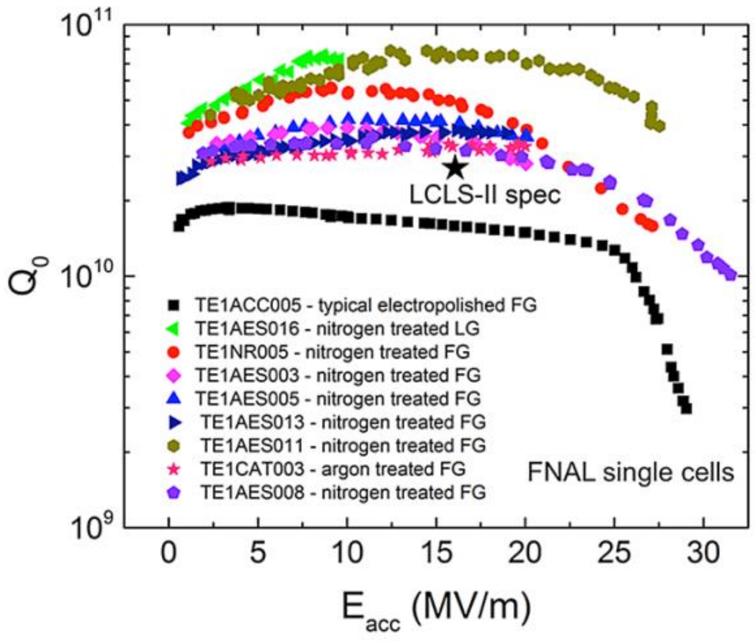


Q_0 = quality factor
→ e-folding decay and resonance width

dissipated power:

$$P_{\rm dissip} = \frac{U_a^2}{\left(\frac{R}{Q}\right) Q_0}$$

high Q resonators, 1.3GHz, 2K, FNAL
[A.Grassellino, A.Romanenko et al, 2013]

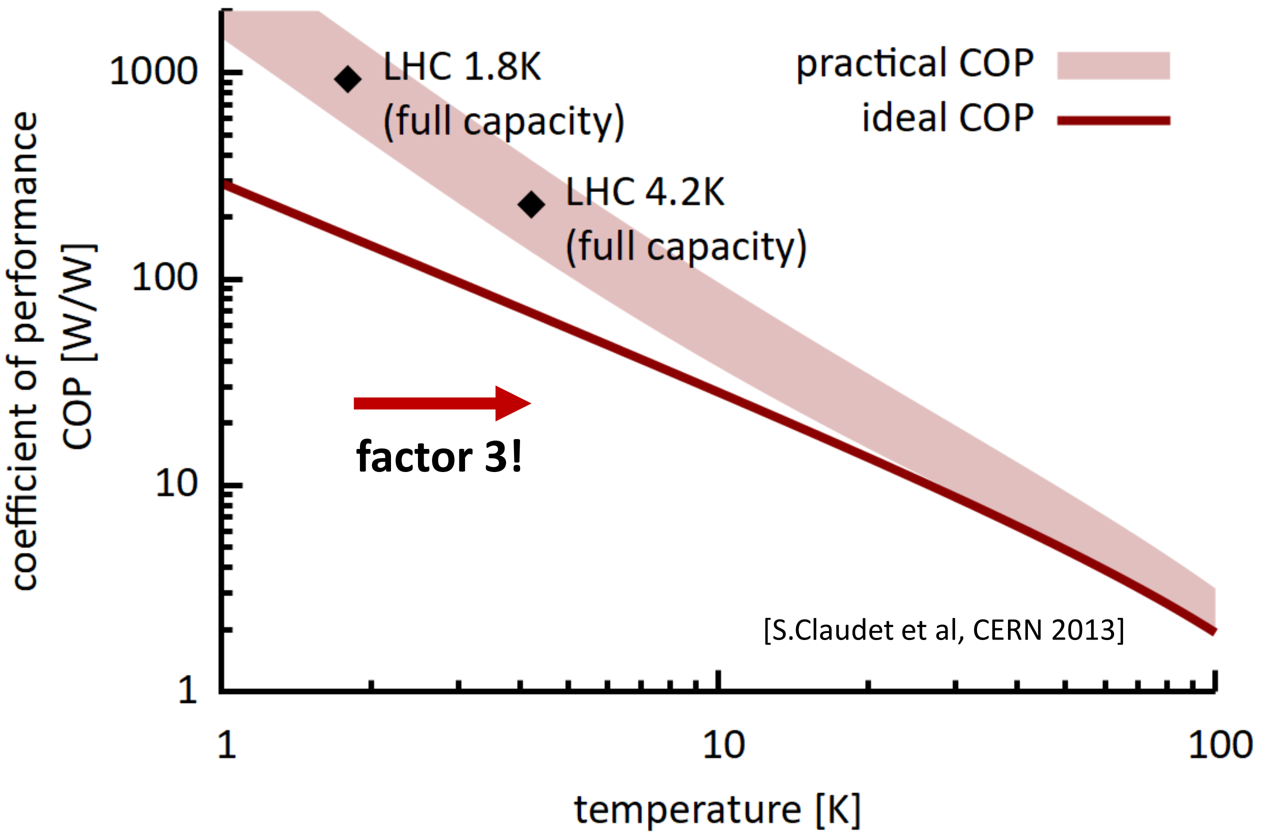


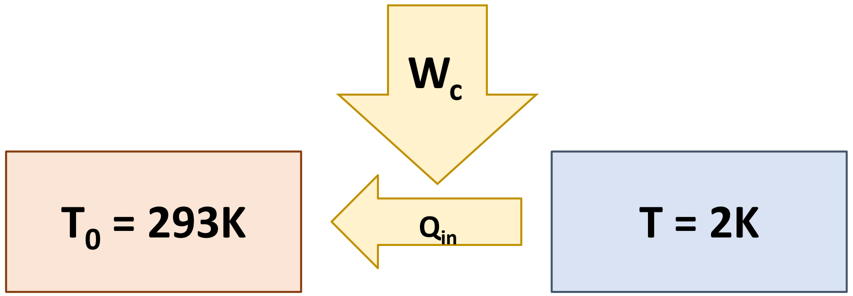
example:
U_a = 20MV, (R/Q) = 609Ω, $Q_0 = 2\times10^{10}$, I_b=2mA

→ P_{dissip} = 33 W
→ P_{beam} = 40.000 W

but: cryogenic efficiency!

Cryogenic Efficiency





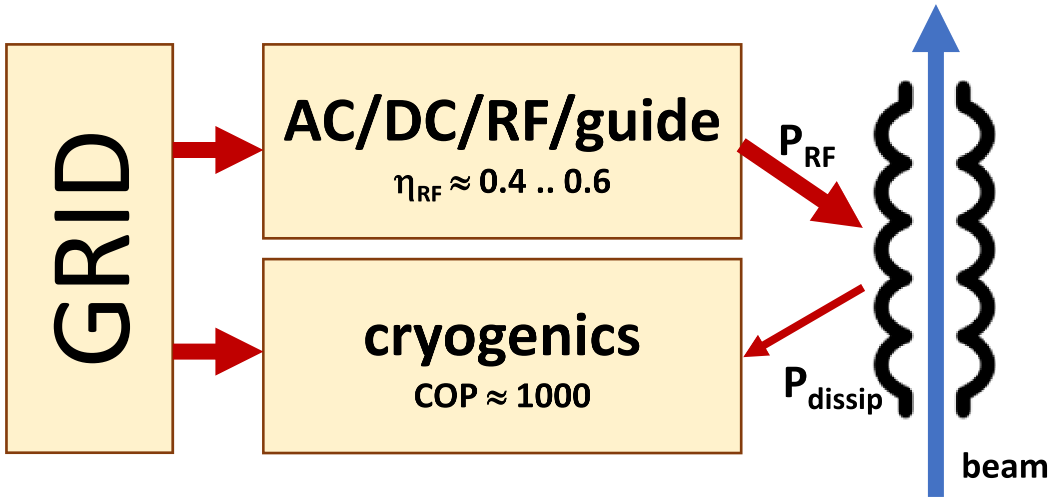
best possible coefficient of performance (COP):

$$\mathrm{COP} = \left(\frac{W_c}{Q_\mathrm{in}}\right)_\mathrm{Carnot} = \frac{T_0 - T}{T}, \quad T_0{=}293\,\mathrm{K}$$

W_c = amount of work required to remove heat Q_{in} at cold temperature T

$$P_\mathrm{cryo} = \mathrm{COP} \cdot P_\mathrm{dissip}$$

Powerflow s.c. Linac – Minimum System Example for a Single Cavity



power balance:

$$P_{\text{grid}} = P_{\text{cryo}} + P_{\text{RF}}$$
$$= \text{COP} \cdot P_{\text{dissip}} + \frac{1}{\eta_{\text{RF}}} \Delta P_{\text{beam}}$$

$$\eta_{\text{total}} = \frac{\Delta P_{\text{beam}}}{P_{\text{grid}}}$$

considered:
- one 650MHz cavity
- U_a = 20MV
- l = 1.1m

ignored: cavity detuning, β<1, regulation overhead, aux. systems …

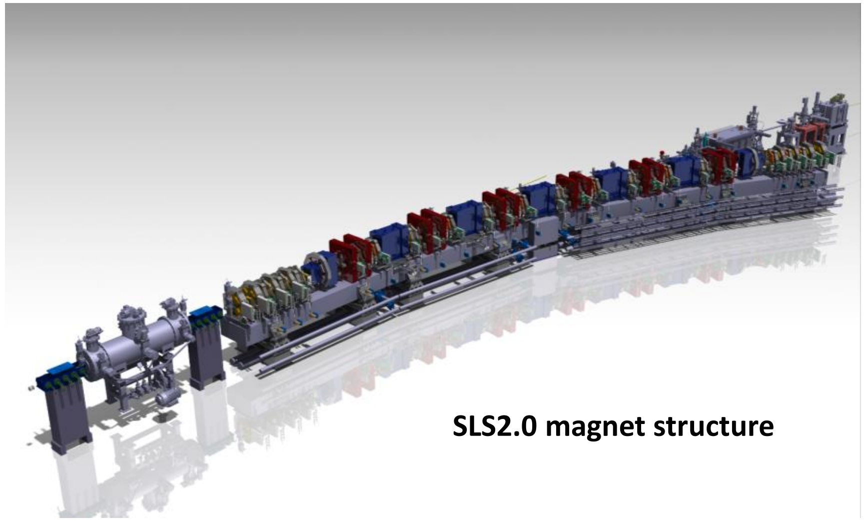
regime	I_b [mA]	Q_0	η_{RF}	ΔP_{beam} [kW]	grid-to-beam Efficiency
TDR, CW	2.0	$2 \cdot 10^{10}$	0.44	40.0 kW	30%
high Q	2.0	$3 \cdot 10^{10}$	0.44	40.0 kW	33%
high current	4.0	$3 \cdot 10^{10}$	0.65	80.0 kW	50%

extrapolation (high Q, high current)

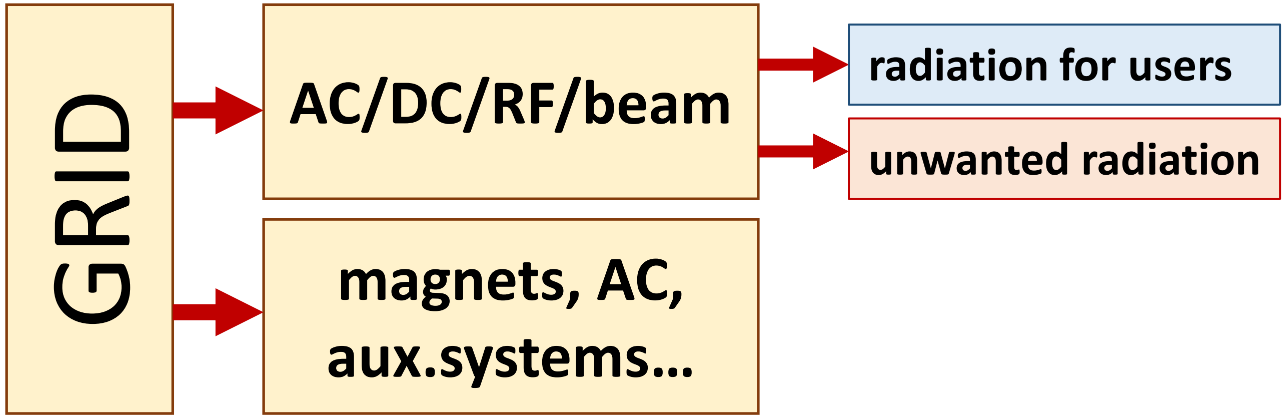
Light Sources

Synchrotron Light Sources and Free Electron Lasers

- over the history ring light sources have improved the brilliance by more than 10 orders of magnitude, the last step is made using **multi bend achromat lattices** and miniaturization using permanent magnets
- **power consumption** of ring light sources is in the range of a few Megawatt and **often not a critical factor**; however, s.c. FELs might use O(20MW)
- the production of tailored radiation – spectral distribution, coherence, ultrashort pulses etc. is in the focus today



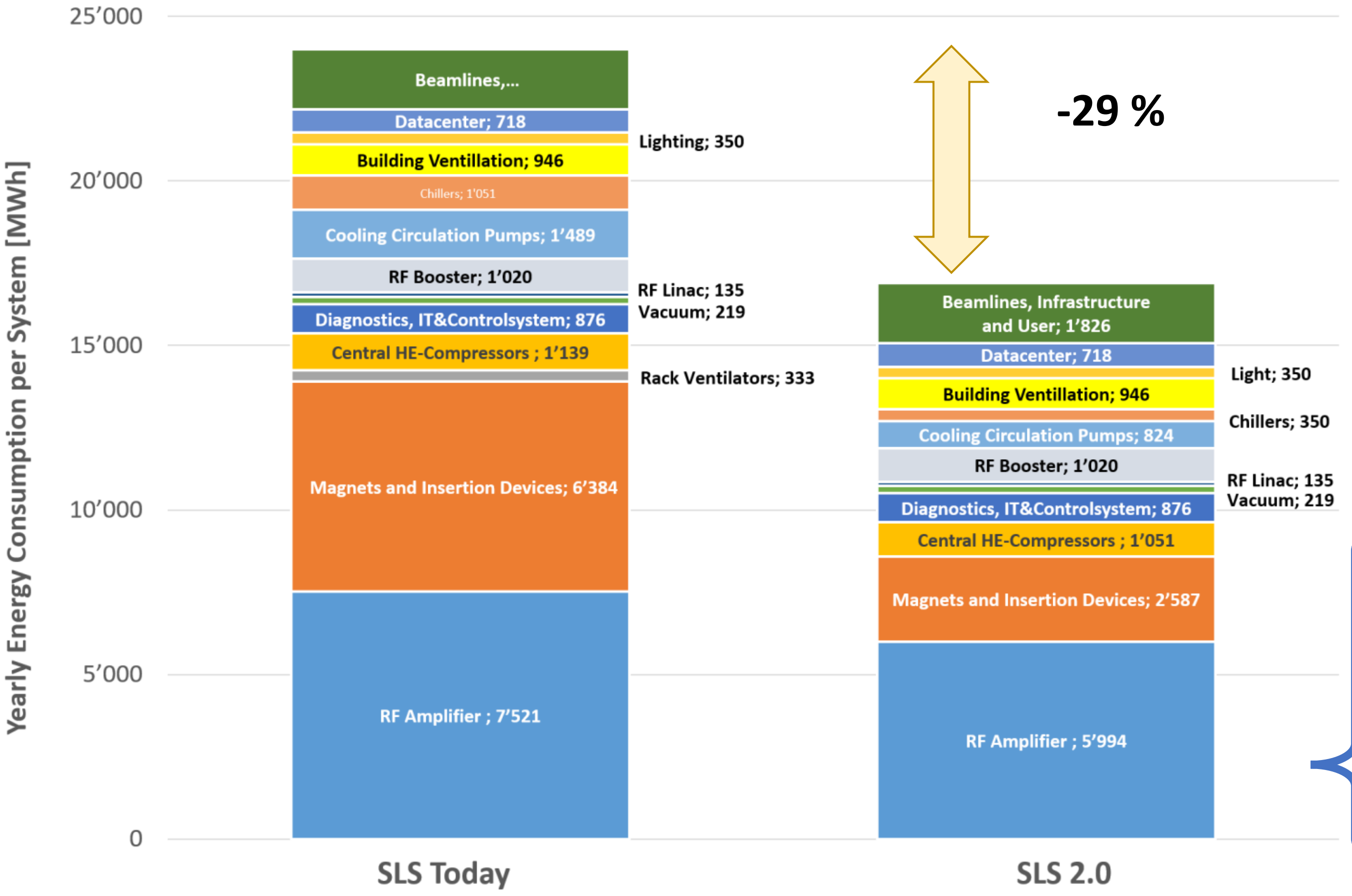
SLS2.0 magnet structure



possible efficiency measure:

$$\eta_{\text{total}} = \frac{P_{\gamma,\text{users}}}{P_{\text{grid}}}$$

Example Swiss Light Source SLS and its Upgrade



[M.Jörg, PSI]

More radiated X-ray power for users
Less electricity consumption

	SLS → SLS2.0
E_{e^-}	2.4 GeV → 2.7 GeV
P_{SR}	310 GeV → 365 kW
W_{elec}/y	24 GWh → 17 GWh

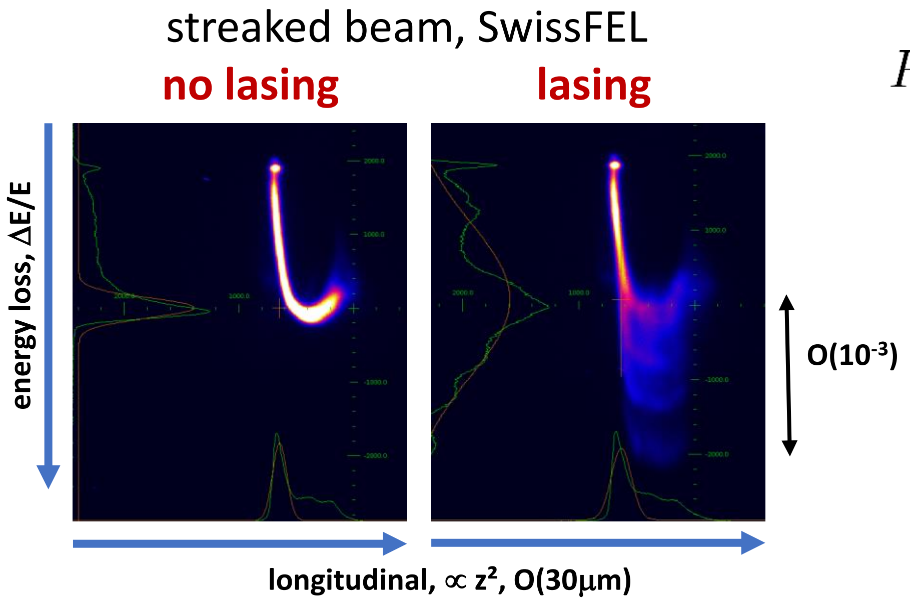
Key savings:
- Electromagnets → Permanent magnets
- Klystrons → Solid state amplifiers
- standard pumps → modern pumps for cooling

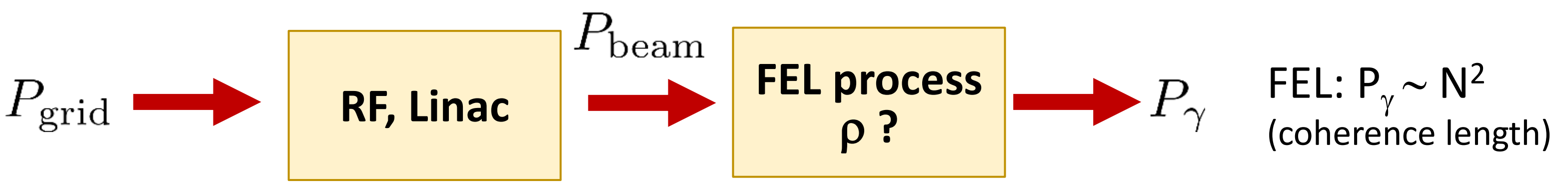
main RF power flow SLS2.0

AC power	816 kW
DC power	772 kW
RF power to beam	488 kW
power to beam	366 kW
dipole/undulator radiation	275 kW / 91 kW

95%
63% SSA
75%

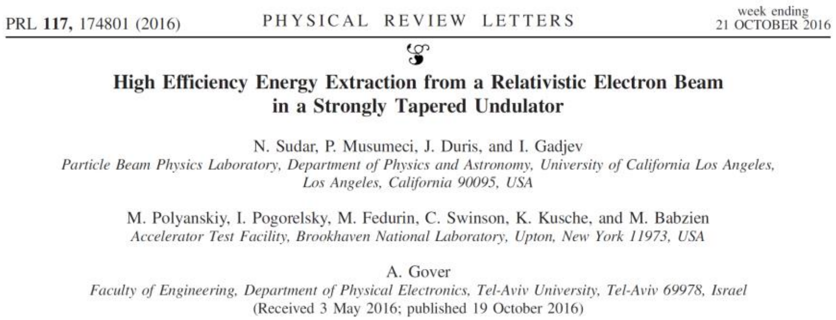
Free Electron Laser





best demonstrated energy extraction: $\Delta E/E = 30\%$

(E_k=65MeV, Laser seeded FEL)


PRL **117,** 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

N. Sudar, P. Musumeci, J. Duris, and I. Gadjev
Particle Beam Physics Laboratory, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA

M. Polyanskiy, I. Pogorelsky, M. Fedurin, C. Swinson, K. Kusche, and M. Babzien
Accelerator Test Facility, Brookhaven National Laboratory, Upton, New York 11973, USA

A. Gover
Faculty of Engineering, Department of Physical Electronics, Tel-Aviv University, Tel-Aviv 69978, Israel
(Received 3 May 2016; published 19 October 2016)

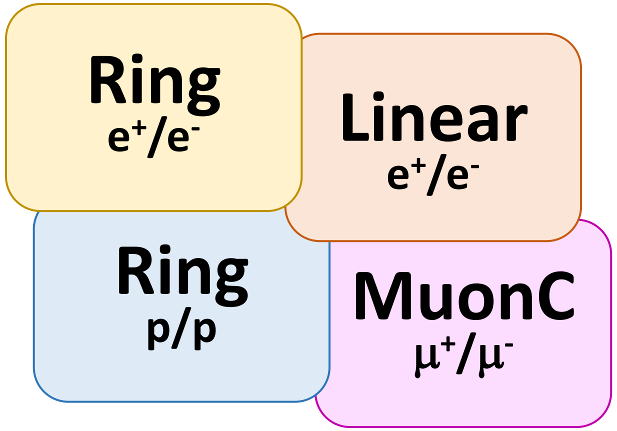
Grid Power Consumption (order of magnitude) examples: n.c. / s.c.

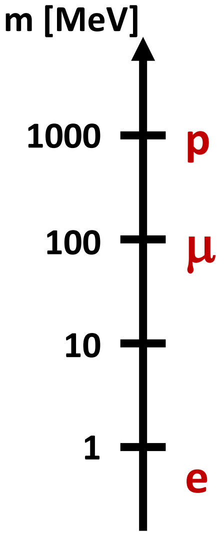
Facility	Technology	P_{grid} (typ)	P_{beam} (typ)	Photon Power
SwissFEL	n.c., 6 GHz, pulsed	≈ 3.0 MW	100 W	up to 0.2 W
EXFEL	s.c., 1.3 GHz, pulsed	≈ 10 MW	40‘000 W	up to 40 W

Particle Colliders

Colliders - Concepts

Next generation: high Luminosity, high Energy reach needed
Energy Efficiency: Luminosity per Grid Power





particle mass impacts synchrotron radiation and beamstrahlung (collision)

→ scaling laws and grid power drivers are quite different for the concepts under discussion

Colliders Types and Power Drivers

Collider	Example	Pros/Cons	Scaling
Ring e^+/e^-	FCC-ee 240GeV: P_{grid} = 273MW	+ beam recirculation - synchrotron radiation	$P_{\rm SR} \propto I_{\rm beam} \left(\frac{E}{m_0}\right)^4 \frac{1}{R}$
Linear e^+/e^-	CLIC 380GeV (3.0TeV): P_{grid} = 252MW (589MW) ILC 250GeV (1TeV): P_{grid} = 111MW (300MW)	+ no synchrotron radiation - no recirc., small beam needed **power drivers**: cryo (ILC) vs RF (CLIC)	$L_{\rm lin.col.} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\rm beam}$
MuonC μ^+/μ^-	MAP 6.0TeV: P_{grid} = 270MW	+ no Beamstrahlung-Limitation - inefficient RCS, complexity	$L_{\rm mu.col.} \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\rm beam}$
Ring p/p	FCC-hh 100TeV: P_{grid} = 580MW	+ high energy reach - SR deposited @50K, cryogenics	$P_{\rm SR} \approx 5\,{\rm MW}$ $\rightarrow P_{\rm grid,SR} \approx 100{\rm MW}\ (17\%)$

Ring Collider

- energy recirculated, thus efficient concept
- however, SR losses at higher energies
- comment: for LHC burnup dominates beam loss (no SR)

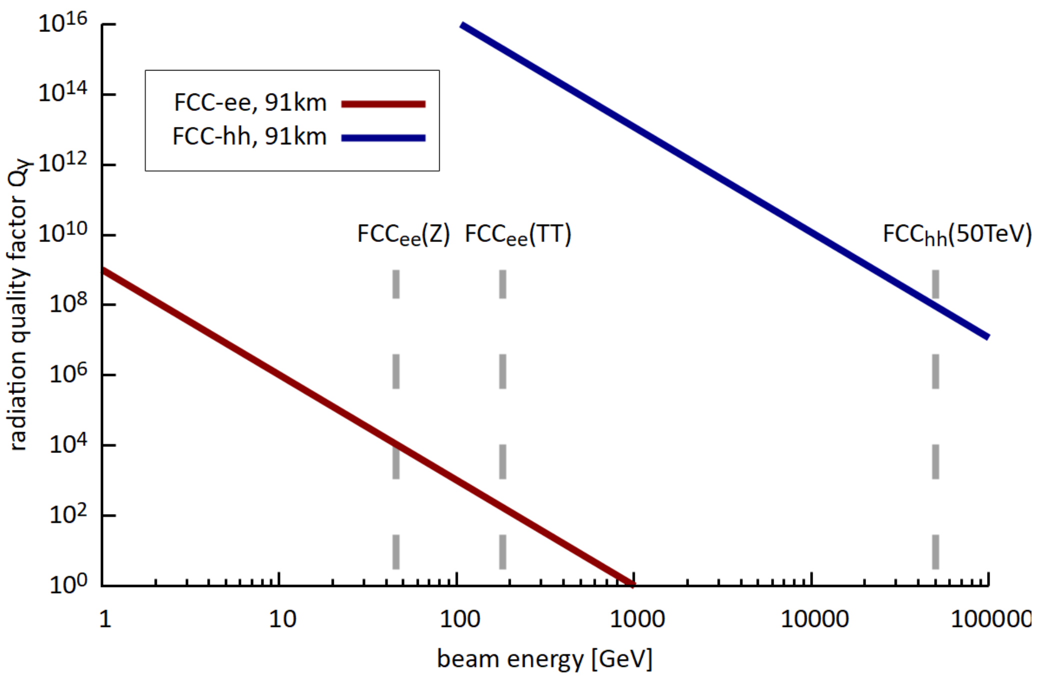
quality factor storage ring: $$Q_\gamma = \omega \frac{E_{\text{stored}}}{P_{\text{dissipated}}} = 2\pi \frac{E}{\tau P_\gamma} = 2\pi \frac{E}{U_0} \gg 1$$

= „decay time of beam energy in number of turns due to SR“

bending radius

$$Q_\gamma = \frac{3}{2} \frac{\rho}{r_c} \gamma^{-3}$$

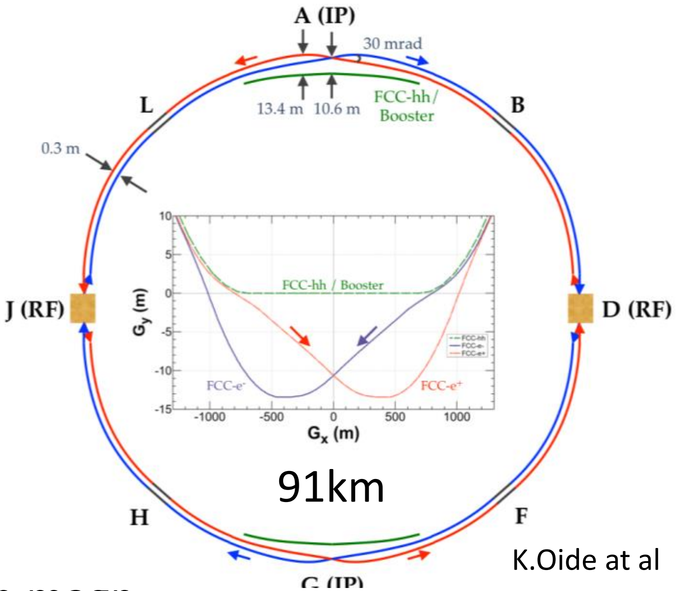
classical particle radius



FCC-ee – Optimized Lepton Ring Collider

conceptual measures:
- crab waist scheme (specific luminosity)
- 4 IP's instead 2
- maximise bending field fill factor (next talk)

technology measures:
- high-efficiency klystrons (HEIKA collaboration)
- 4.5 K s.c. cavities, high Q (400 MHz Nb/Cu)
- twin apertue dipoles (50% savings of bends)
- HTS quads and sextupoles, nested combined function magn.



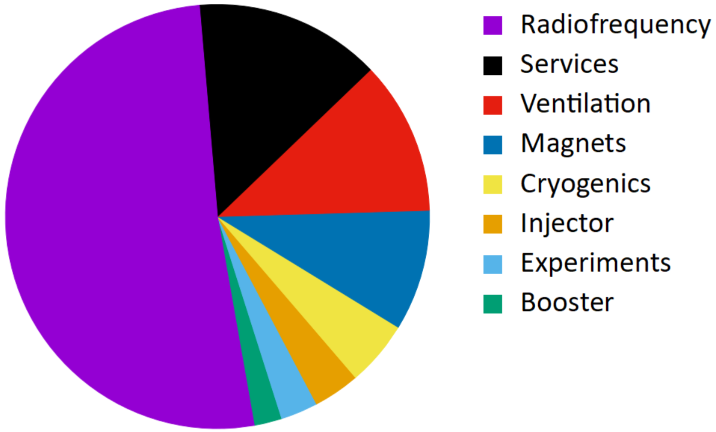
K.Oide at al

A. Milanese, Efficient twin aperture magnets for the future circular e^+/e^- collider, Phys. Rev. Accel. Beams 19, 112401 (2016)

similar as CERN total today

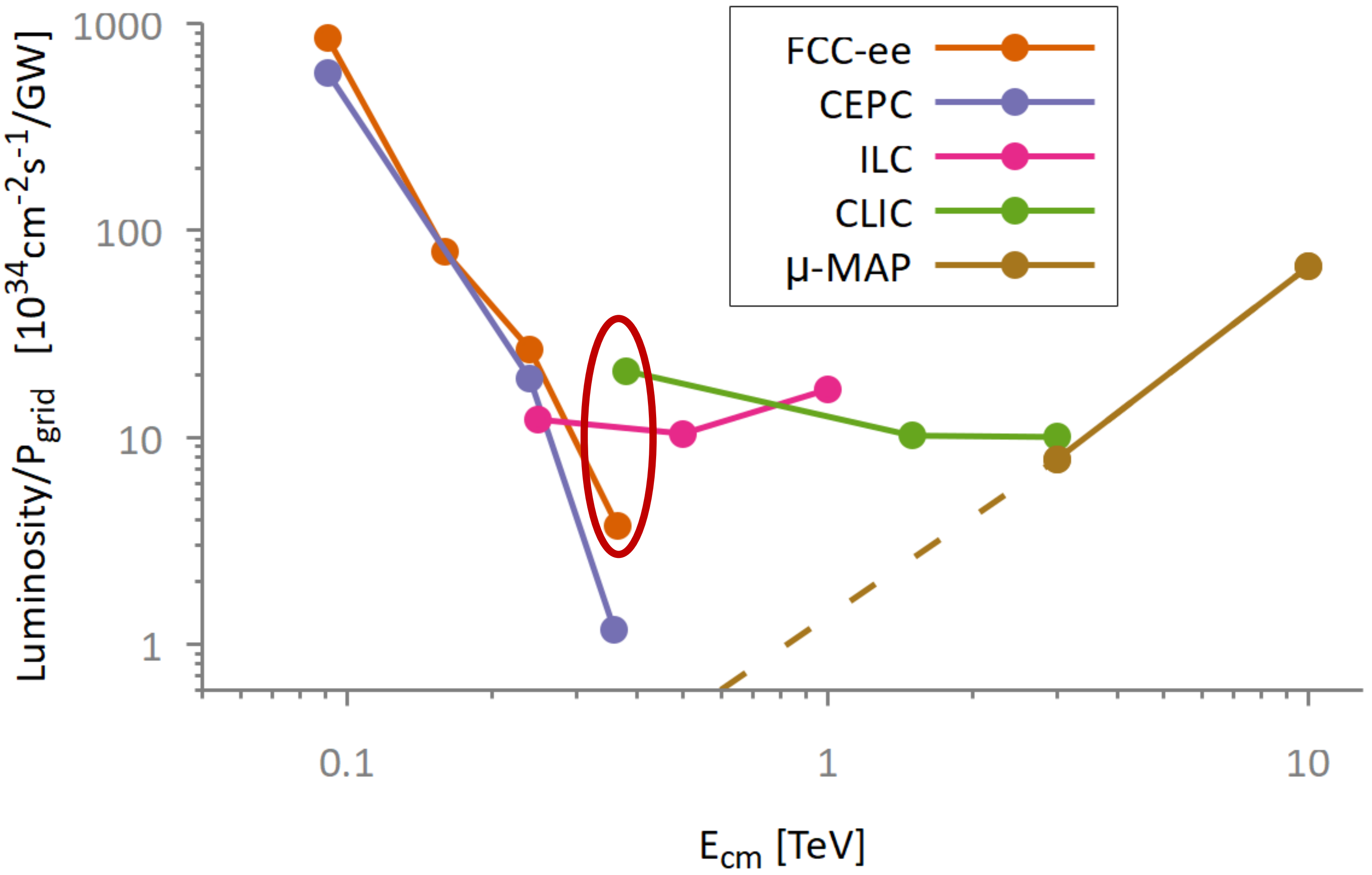
E_{cm} = 240 GeV (H)
P_{grid} = 273 MW
E_{grid}/y = 1.33 TWh

→ dominated by RF (compensating SR losses)



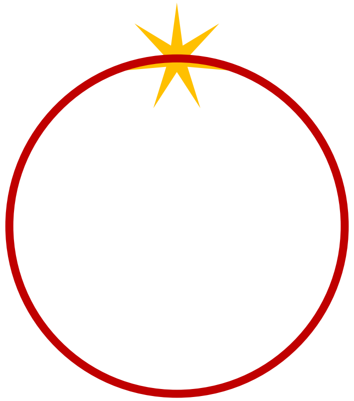
Overview Lepton Proposals

energy specific
luminosity production:



Ring vs. Linear Collider

Ring Collider
beams circulate



	FCC-ee 365GeV	**CLIC** 380GeV
σ_x [nm]	39‘000	150
σ_y [nm]	69	2
σ_z [μm]	2‘950	70
N [10^9]	264	5,2
f_b [kHz]	118	17,6
P_b[MW]	912	2.8

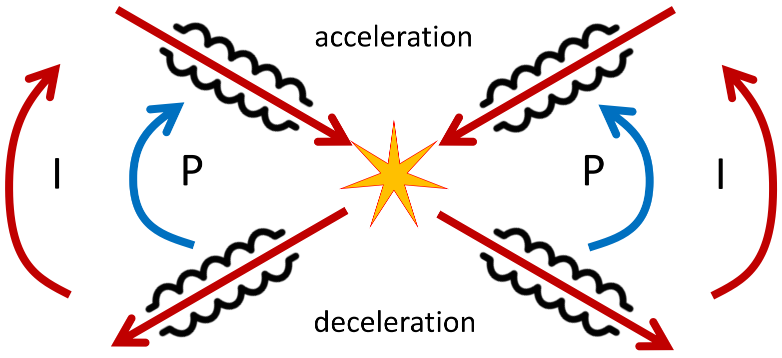
Linear Collider
beams collide once

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

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

Combining Linear- and Ring-Collider using the ERL Concept

ERL
power circulates



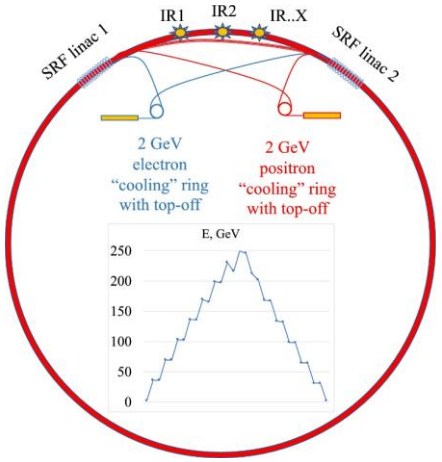
- power recirculated, beam recirc. at low E
- benefit from better collission parameters

→ high L per grid power, but higher investments & complexity

two ERL proposals published:

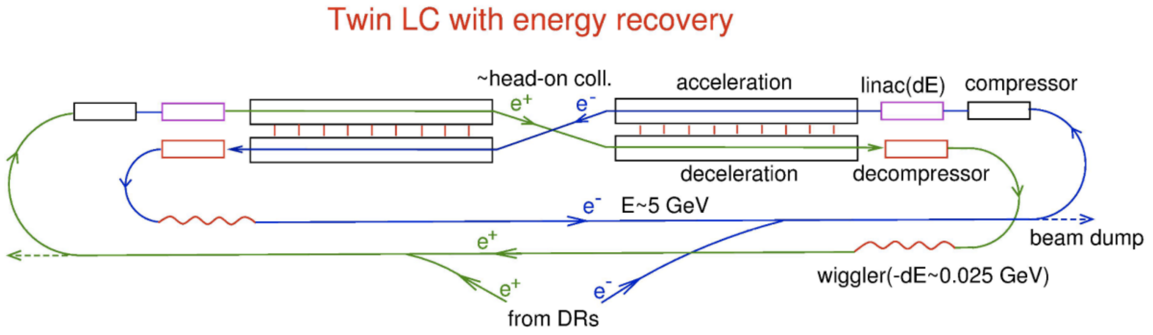
1) Circular Energy Recovery Collider
V. Litvinenko, T. Roser, M. Llatas, Physics Letter B 804 (2020) 135394

multi turn ERL, modification FCC-ee



2) Energy Recovery Linear Collider
V.I. Telnov 2021 *JINST* **16** P12025

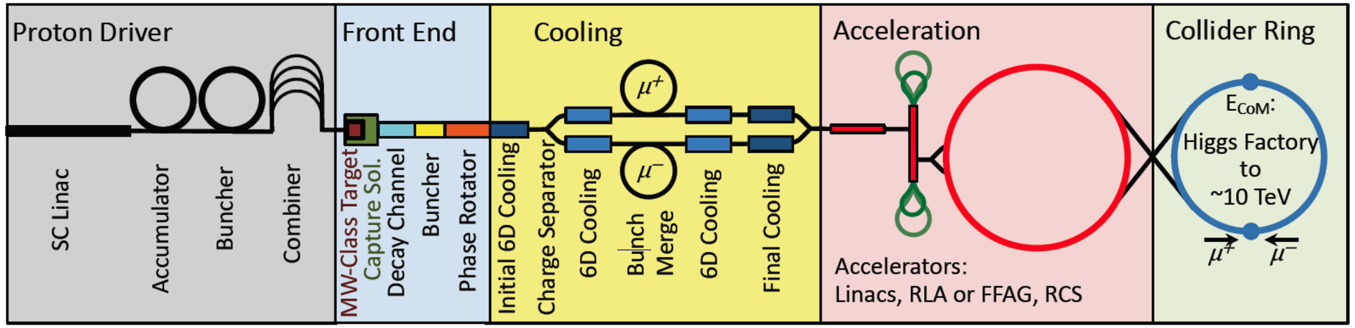
twin s.c. linacs, beam recirculation, wiggler damping



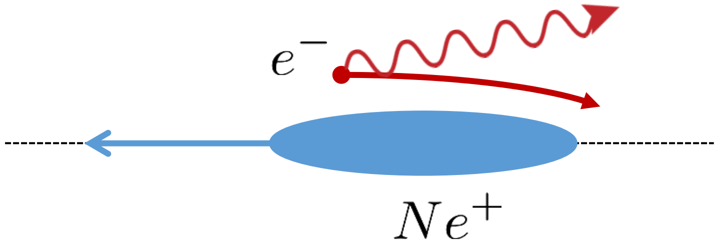
Muon Collider – Efficient at Highest Energies

Muon: E_0 = 106 MeV, τ_μ = 2.2 μs

mass x 200 compared to electrons:
low SR, low beamstrahlung during collisions!



Beamstrahlung in e+/e- collider, mitigation results in limitation of IP beam parameters and flat beams: $\sigma_x >> \sigma_y$



Energy scaling of the Muon Collider

1) particle physicists demand a fixed relative energy spread during collisions, across varying collision energies → $\frac{\delta E}{E} \approx 10^{-3}$
2) with given longitudinal emittance the product of bunch length and energy spread is constant across energies → $\sigma_z \propto \frac{1}{\delta E}$
3) hourglass effect: length of IP waist and bunch length are of same order of magnitude (beta-function at IP) → $\beta^*_{x,y} \propto \sigma_z$
4) the beam can be made smaller with increasing energy → $\beta^*_{x,y} \propto \frac{1}{\gamma}$

thus L/P is increasing with energy*:

$$\mathcal{L} \propto \frac{N^2}{\sigma_x \sigma_y} \propto \frac{N^2}{\sqrt{\varepsilon_x \beta^*_x \varepsilon_y \beta^*_y}} \propto \frac{N^2}{\varepsilon_n}\gamma^2 \propto \frac{N}{\varepsilon_n}\gamma P_{\text{beam}}$$

* the grid power is assumed roughly proportional to beam power

other aspects of sustainability

- rare earths, critical materials
- carbon footprint of components, construction, operation
- heat recovery
- carbon footprint of tunnel dominates

iFAST

Critical Materials and Life Cycle Management: The Example of Rare Earths – curse or blessing?

6.–8. Feb. 2023
Hamburg
Europe/Berlin Zeitzone

Orga

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Life Cycle Assessments get more and more in the focus in industry and also in science. iFAST presents a platform for discussing and finding solutions in these topics.
In our workshop we want to focus on the Life Cycle Management using the example of Rare Earths Elements (REE), the key material in permanent magnets used in a variety of fields like accelerator, turbines, hard drives and many more.

On the workshop we will discuss the following points:

- Life cycle management
  Consider entire life cycle of technical component using critical materials:
  construction – operation – deconstruction
- Mining and processing of REE
  a socio-ecological approach – energy savings versus destructive mining and processing
- Using permanent magnets
  Examples of the use of permanent magnets and its Pro and Con
- Certification for mining and processing of REE
  How to force more sustainable thinking in the production of REE
- Recycling of permanent magnets
  New processes for the re-use and recycling of permanent magnets
- Alternatives for permanent magnets with REE
  New magnetic materials as well as improved electromagnets

Science, industry, politics and NGO in cooperation can forces to tackle the problem – we can develop solutions together.

SUSTAINABLE DESY.

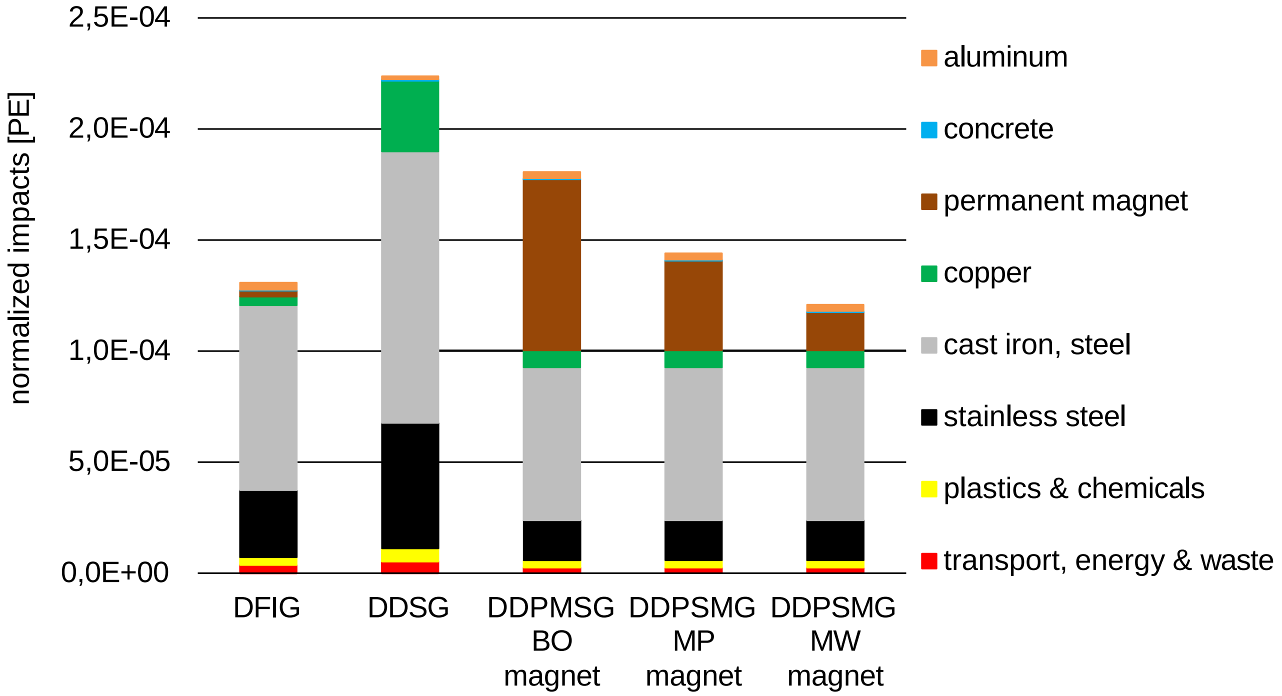
Topics:

- rare earths: benefits and issues
- assessing carbon footprint, env. impact, societal impact …
- supply chains and certification
- recycling

https://indico.desy.de/event/35655/

Petra Zapp (IEK-STE), excerpt: Comparison of Wind Generator Types

Influence of RE origin (ore type, mining location, specific site conditions) on environmental impacts per 1 kWh electricity generated by 3 MW wind power plant



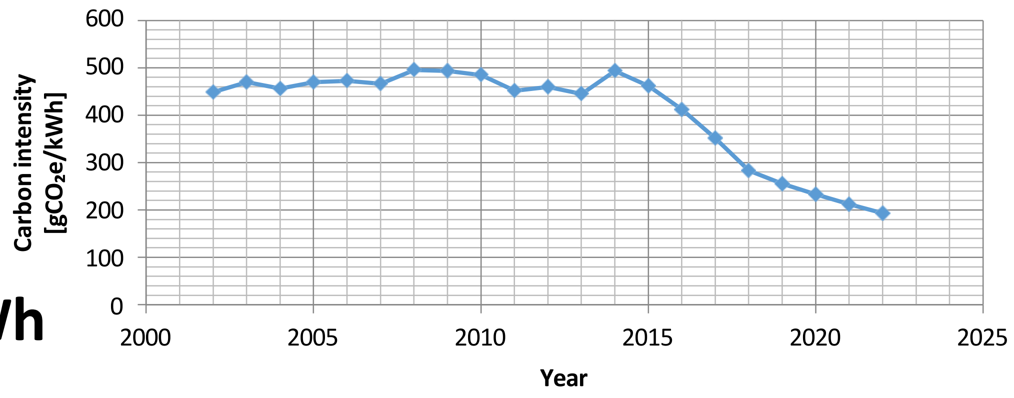
- Electricity generation by DDPMSG with permanent magnet produced from Chinese RE (Bayan Obo) has higher normalized environmental impacts compared to
  - U.S. Mountain Pass (→ 20%)
  - Mt. Weld (Aus) (→ 33%)
- Electricity generation by Australian DDPMSG is 8% better than by DFIG

DFIG: doubly-fed induction generator
DDSG: direct driven synchronous generator

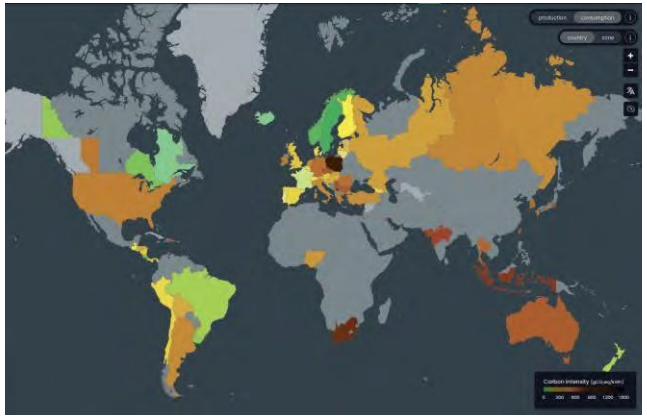
DDPMSG: electrically excited and direct drive permanent magnet synchronous generator

A. Schreiber, J. Marx and P. Zapp: **Comparative life cycle assessment of electricity generation by different wind turbine types;** Journal of Cleaner Production ***2019*** Vol. 233 Pages 561-572

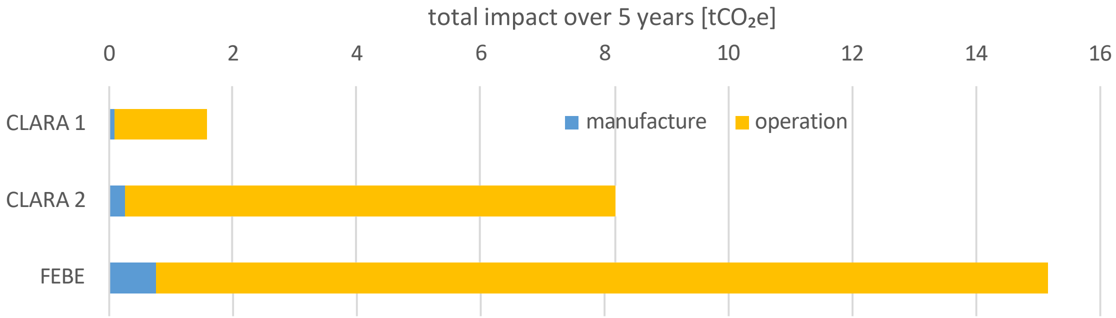
B.Shepherd (STFC): Electromagnet Operation vs. Manufacturing Footprint



- Power usage at nominal operating point
  - CLARA 1: **385 W**
  - CLARA 2: **2.01 kW**
  - FEBE: **3.72 kW**
- UK electricity carbon intensity 2022: **193 gCO_2e / kWh** (and improving every year!)
  - Highly dependent on fuel mix:
    Sweden 21g; France 102g; USA 432g; Germany 481g; Switzerland 153g
    (source: Electricity Maps)

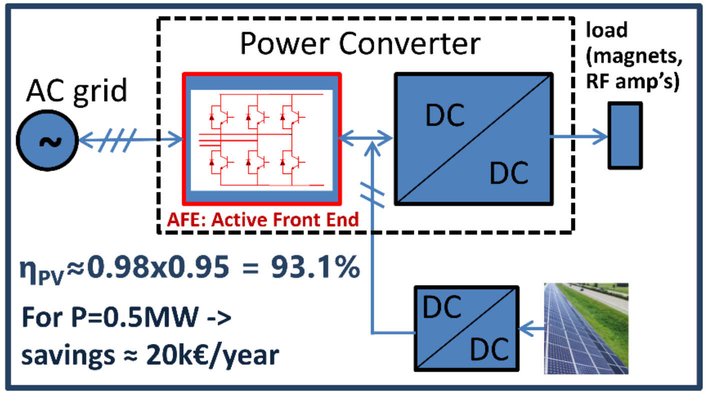


- Assume operated for 5 years, 250 days per year, 16 hours per day
- Total impact of operation *(note: cooling not included)*
  - CLARA 1: **1.49 tCO_2e**
  - CLARA 2: **7.76 tCO_2e**
  - FEBE: **14.4 tCO_2e**
- Much greater than manufacture impact



Supporting measures to increase sustainability of accelerators

photovoltaic energy production
Option: direct injection of DC power for accelerator systems

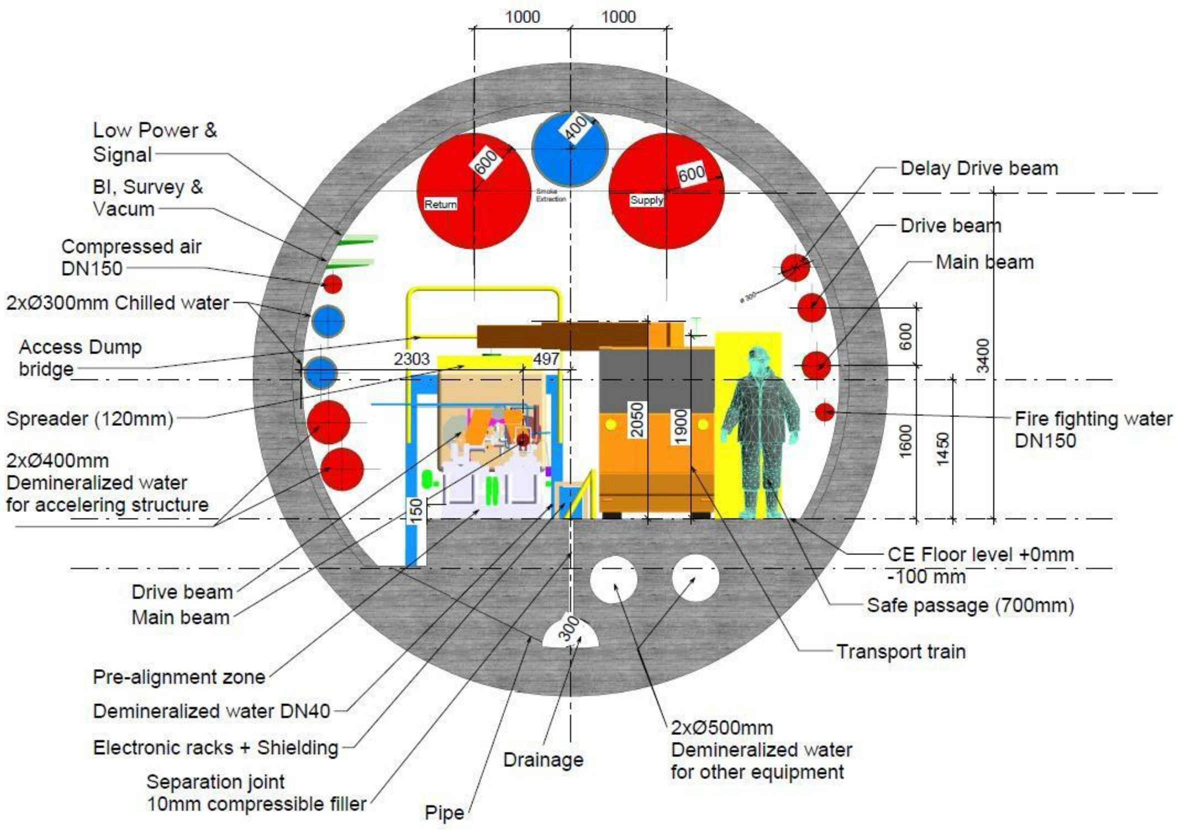


concept idea
DC injection of PV power
[C.Martins, ESS, I.FAST]

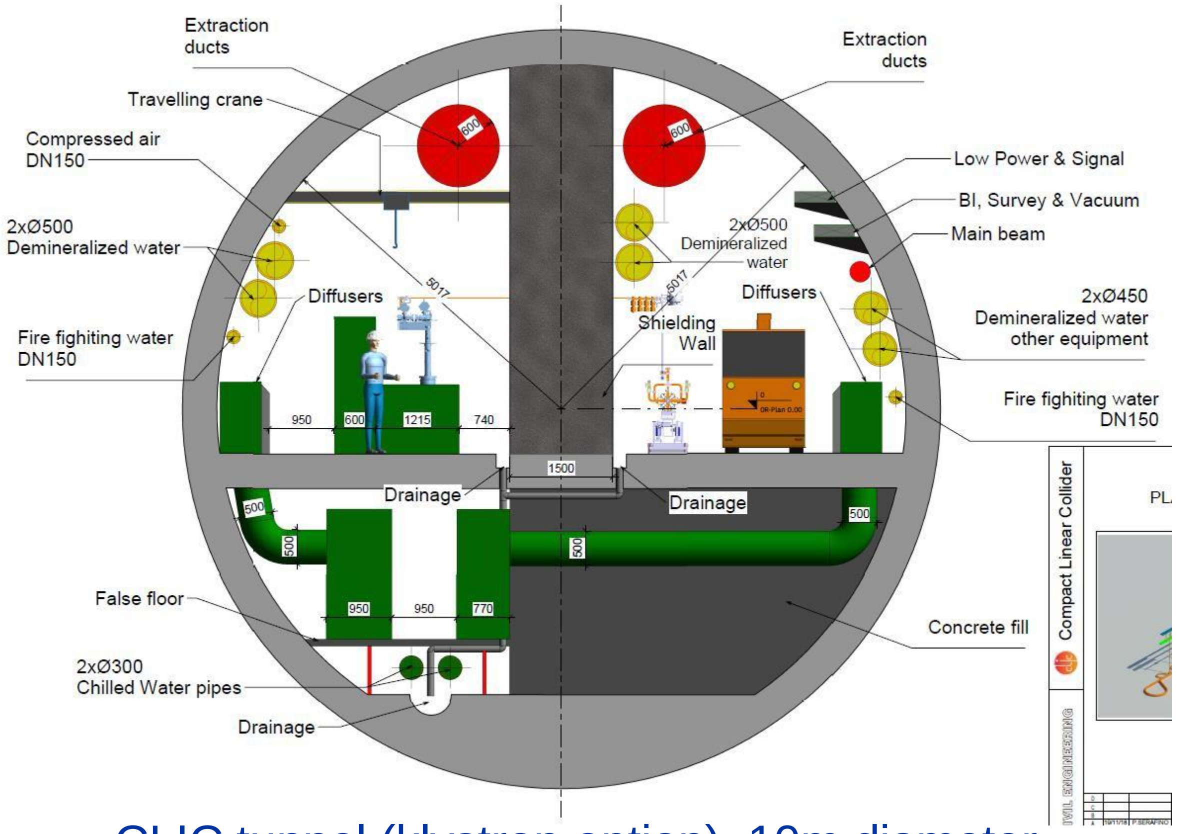
use of **waste heat for heating**, often limited by low temperature of cooling water
→ Use heat pumps to provide higher T at the expense of some additional grid power

heat pumps at MAX-4
[Björn Eldvall / E.ON,
Martin Gierow / Kraftringen]

B.List et al: CLIC CO_2 Footprint, Tunnel Cross Sections



CLIC tunnel (drive beam option), 5.6m diameter



CLIC tunnel (klystron option), 10m diameter

My estimate: 12.4m² concrete
-> 31 t/m concrete

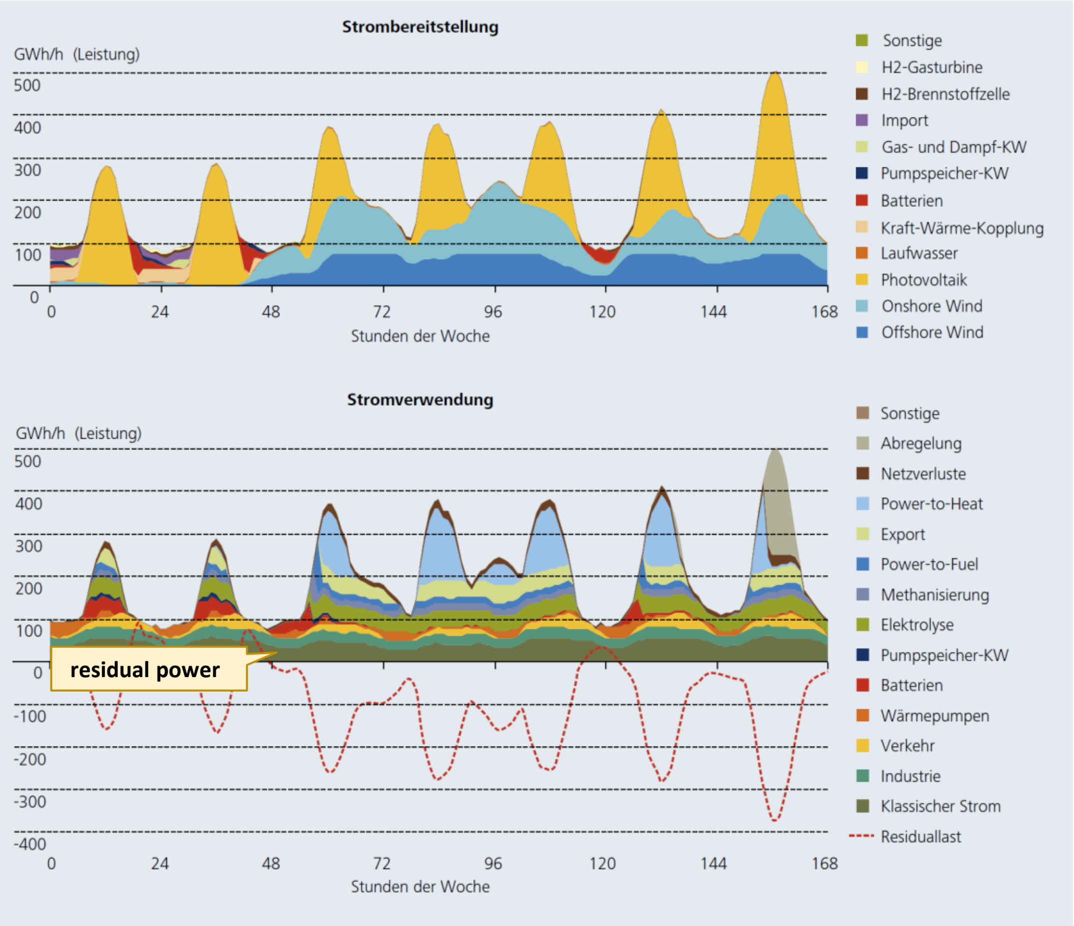
My estimate: 44.8m² concrete
-> 112 t/m concrete

The Future – Fluctuating Energy Sources

simulation: April 2050, **sustainable energy system, Germany**

production of power
- **solar, wind**
- **release from storage**
- **variation: x5!**

use of power
- **industry, traffic etc**
- **energy storage**

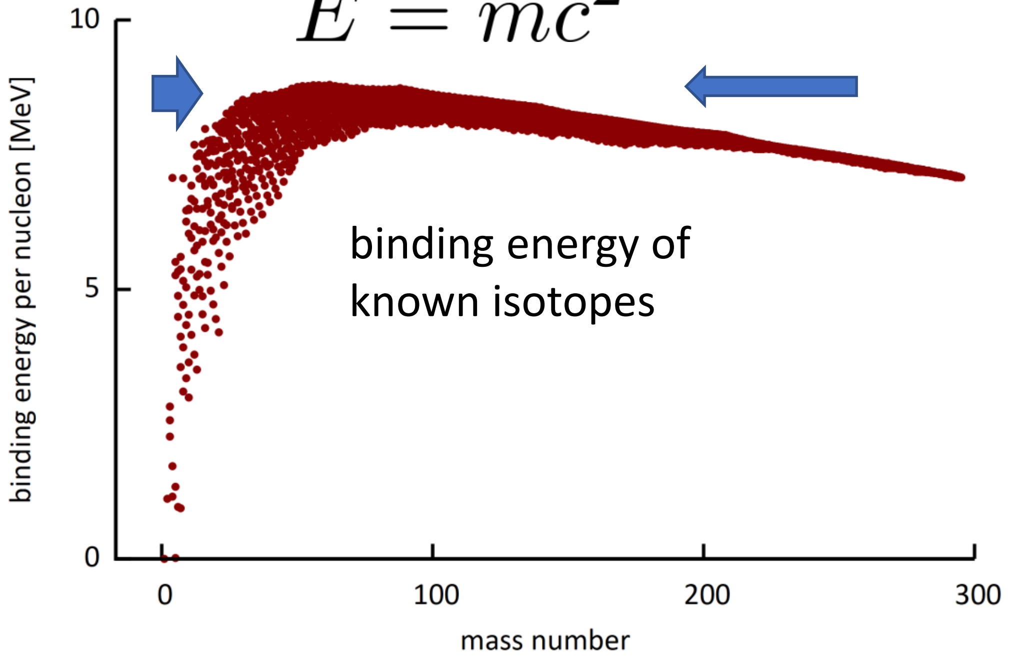


- full collider operation at times of high grid production
- reduced operation or standby modes with fast L recovery otherwise

courtesy: FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME ISE, Karlsruhe (2020)

Comment on Energy Production (actually Conversion)

$$E = mc^2$$



- **The Sun** (:: wind, PV)
- fusion reactor

- fission reactor
- radioactive decays (geothermal energy)

With accelerator driven systems (ADS) nuclear power can be made safer and more sustainable.

For fusion reactors synergetic R&D in the field of accelerators, like RF power generation, s.c. magnet - and vacuum technology.

Summary Particle Accelerators

Grid to Beam

- State of the art 20%, up to 50% reachable for s.c. linacs & high beam power; cyclotrons provide solutions for E<1GeV, e.g. ADS systems

Colliders

- e+/e- ring collider is a powerful yet simple scheme; advanced efficient schemes include energy recovery collider and muon collider
- fluctuating sustainable energy: E management / dynamic operation

  → **use surplus energy for RIs**

Technology

- **s.c. magnets & high Q cavities** are efficient, **higher temperature operation (HTS)**
- **efficient RF sources, permanent magnets,** heat recovery & photovoltaics
- other: water & He consumption, critical materials, managed lifecycle, carbon footprint, energy procurement, advanced energy production

Thank you for your attention.

Many thanks for discussions and input:

V.Yakovlev (Fermilab), V.Ziemann (U.Uppsala),
M.Jörg (PSI), D.Schulte, F.Zimmermann (CERN).