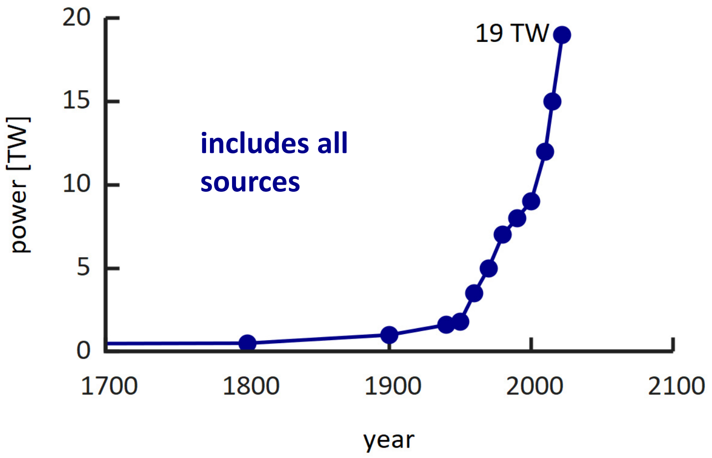
Towards Efficient Particle Accelerators – a Review

Mike Seidel

Paul Scherrer Institute and École polytechnique fédérale de Lausanne

Work supported by the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Energy Consumption - Motivation

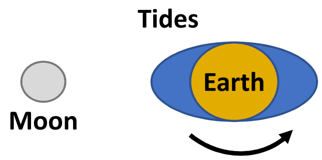


The world energy consumption has been continuously rising, reaching **19 TW** today, 2022.

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

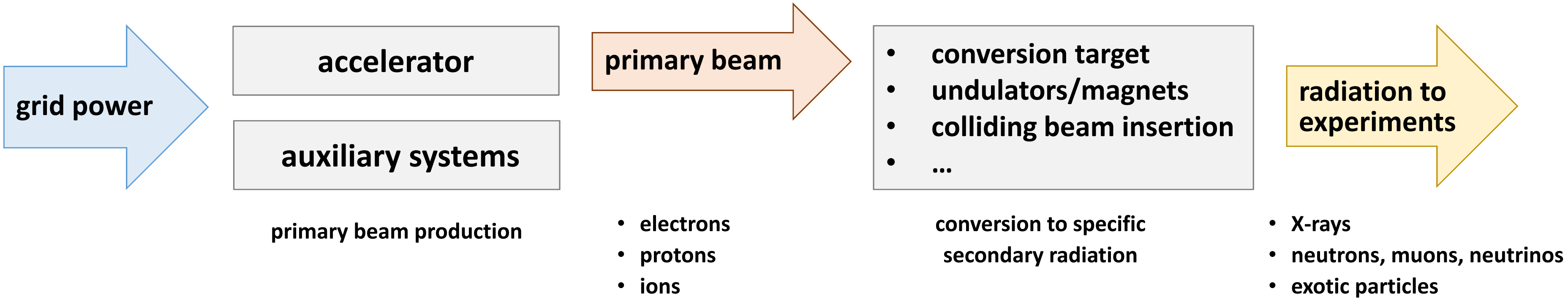
iFAST Innovation Fostering in Accelerator Science and Technology

→ 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)

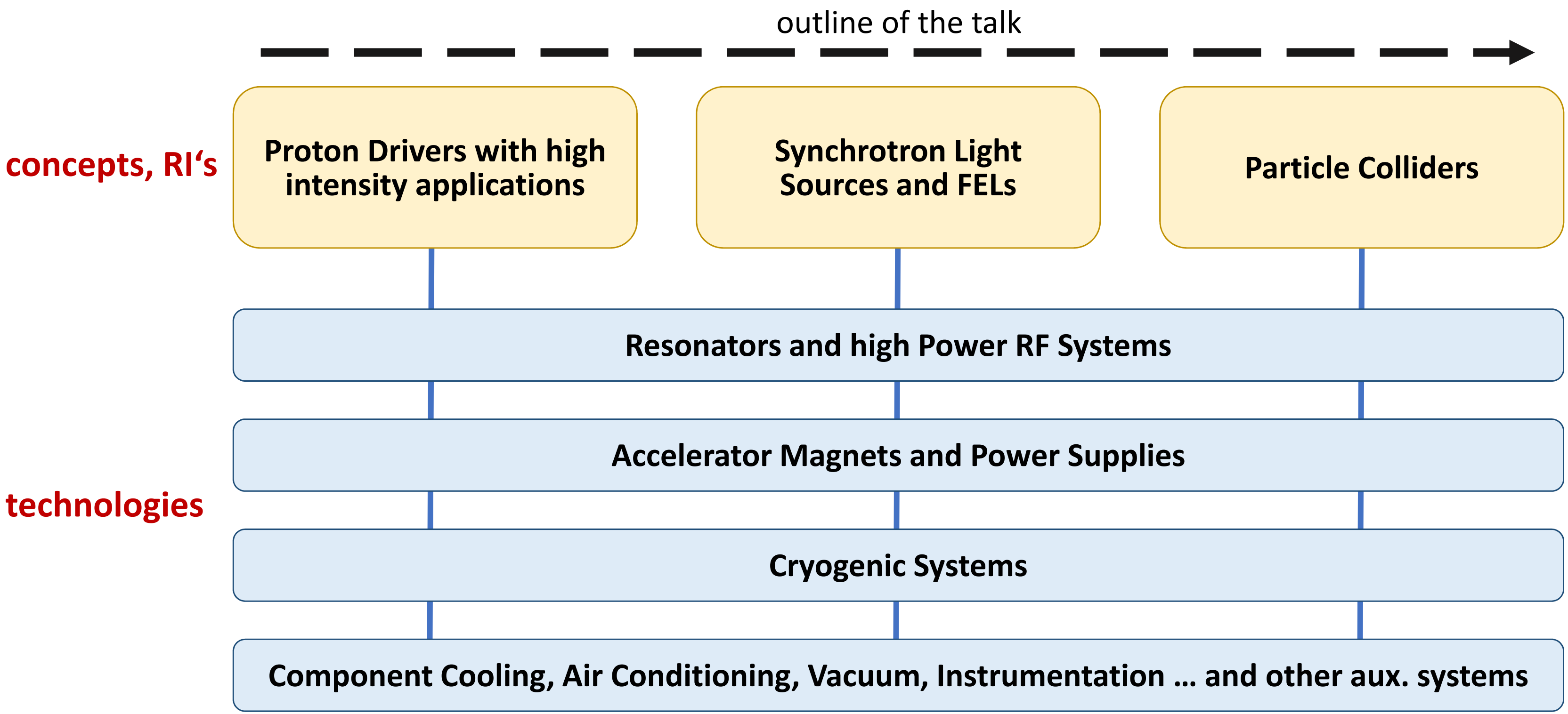


high level goal:

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

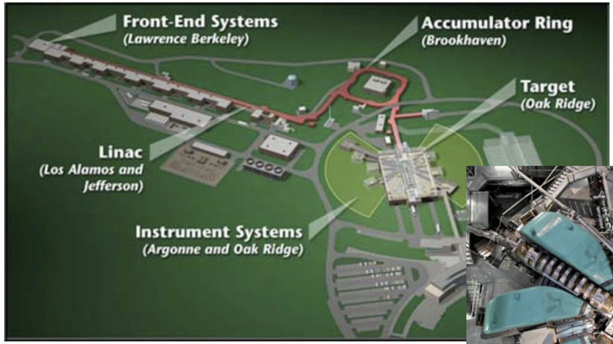
Accelerator Concepts and Technologies

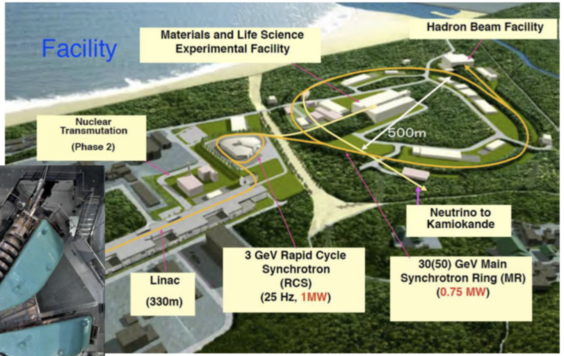
[with emphasize on energy efficiency]

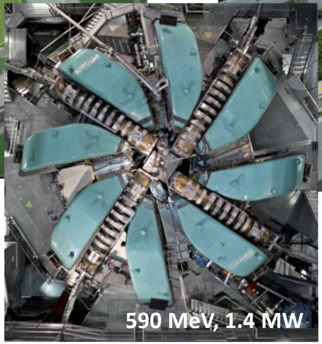


Proton Driver Accelerators

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

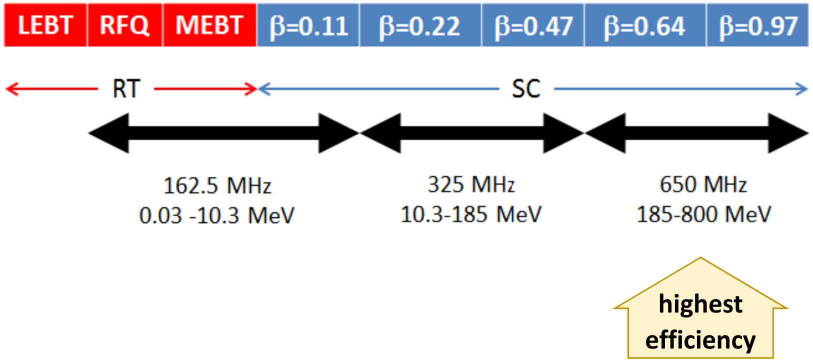
Megawatt class facilities operating today:

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%**

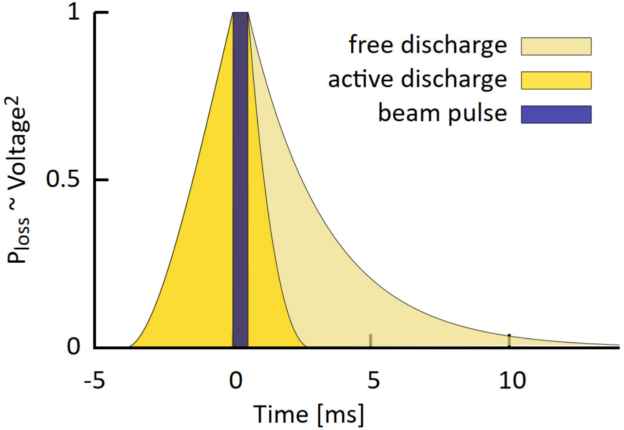
Superconducting Linac : High Efficiency Potential

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

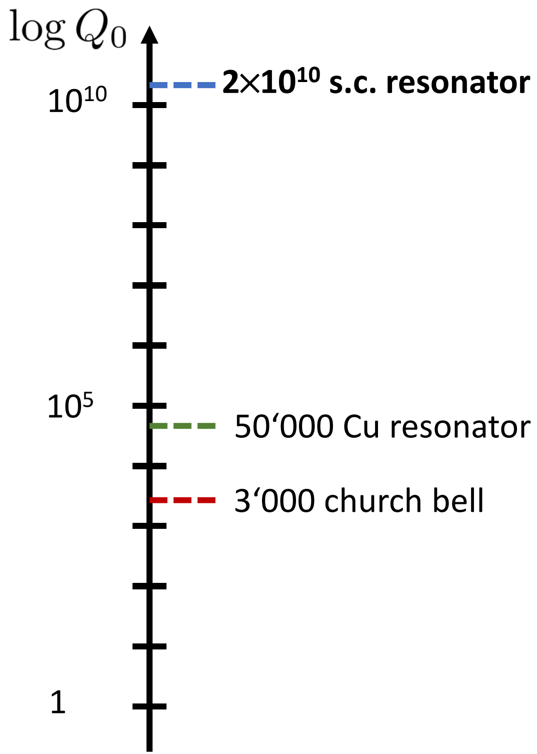
not efficient in pulsed operation:



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

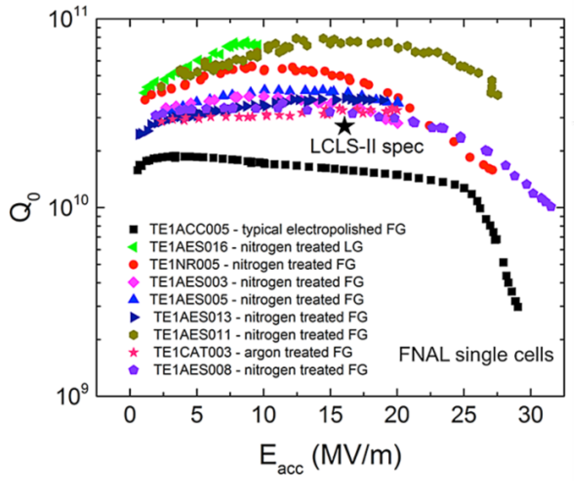


Q_0 = quality factor
$\rightarrow$ e-folding decay and resonance width

dissipated power:

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

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

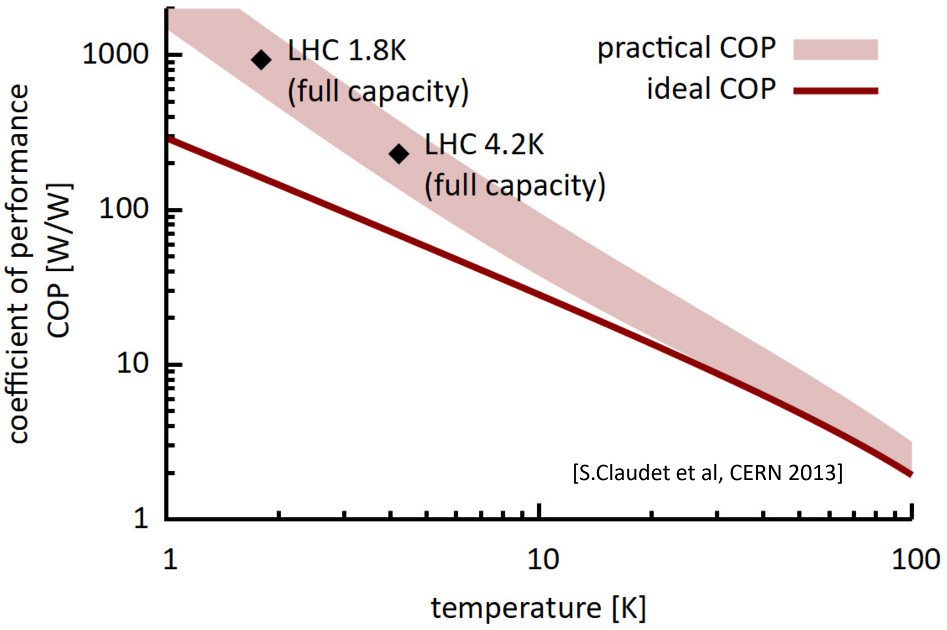


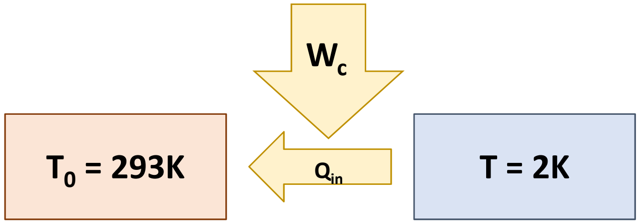
example:
U_a = 20MV, (R/Q) = 609Ω, Q_0 = 2×10^{10}, I_b=2mA

$\rightarrow$ P_{dissip} = 33 W
$\rightarrow$ P_{beam} = 40.000 W

but: cryogenic efficiency!

Cryogenic Efficiency





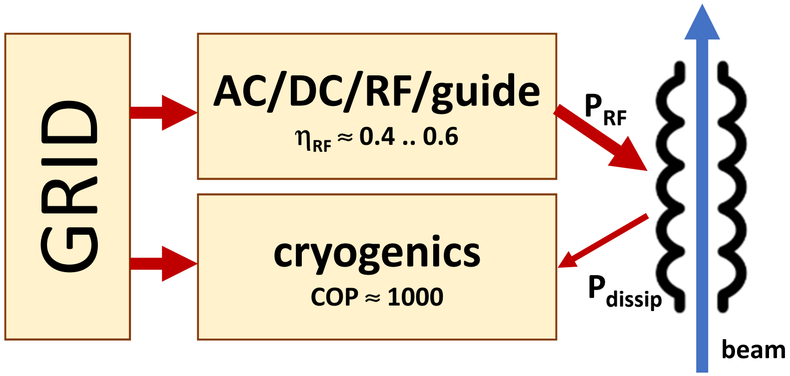
best possible coefficient of performance (COP):

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

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)

Technology R&D: 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

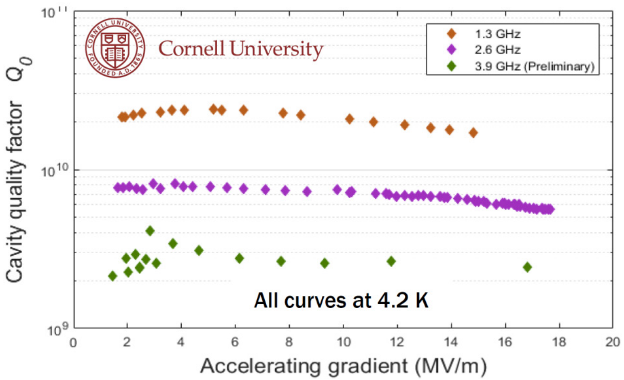
Kilowatt Power Amplifier With Improved Power Back-Off Efficiency for Cyclotron Application

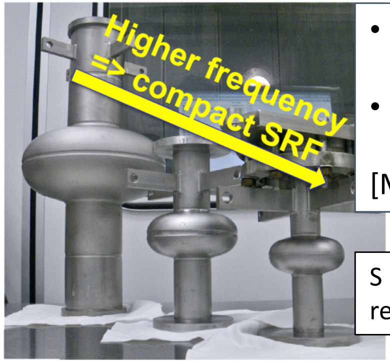
Renbin Tong, Olof Bengtsson, *Senior Member, IEEE*, Jörgen Olsson, *Senior Member, IEEE*, Andreas Bäcklund, and Dragos Dancila

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

upcoming I.FAST efficient RF workshop, July 4-6, Switzerland: https://indico.cern.ch/event/1138197/

Technology R&D: Superconducting RF at higher temperature





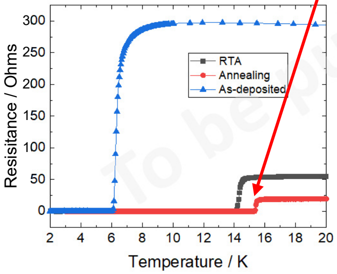
- promising R&D: Nb_3Sn coated cavities at Cornell
- 4.2 vs. 2.0K → efficiency

[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



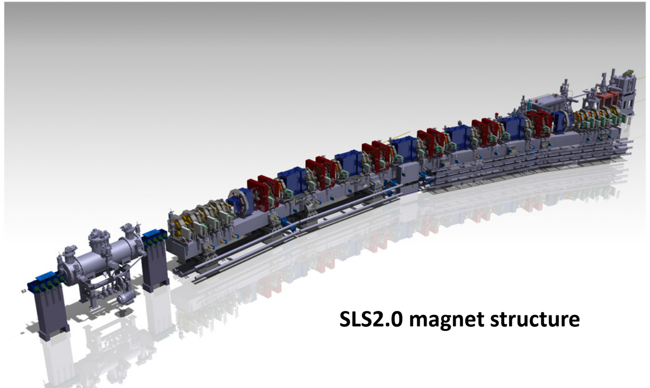
DESY, Hamburg U.
aim for sustained SRF accelerator technology
10y Goal: >70 MV/m with a Q_0 of $1x10^{10}$ and at 4K
contact: M.Wenskat, DESY

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

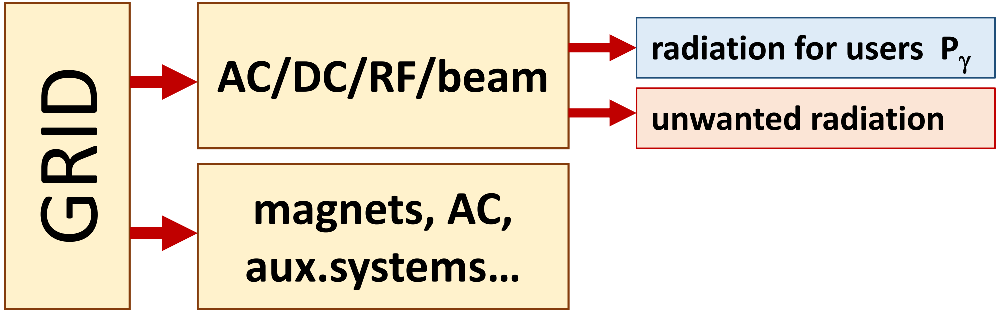
Light Sources

Synchrotron Light Sources and Free Electron Lasers

- **low emittance lattices** (MBA) $\rightarrow$ much better brilliance per grid power
- power consumption of ring light sources is in the range of a **few Megawatt**

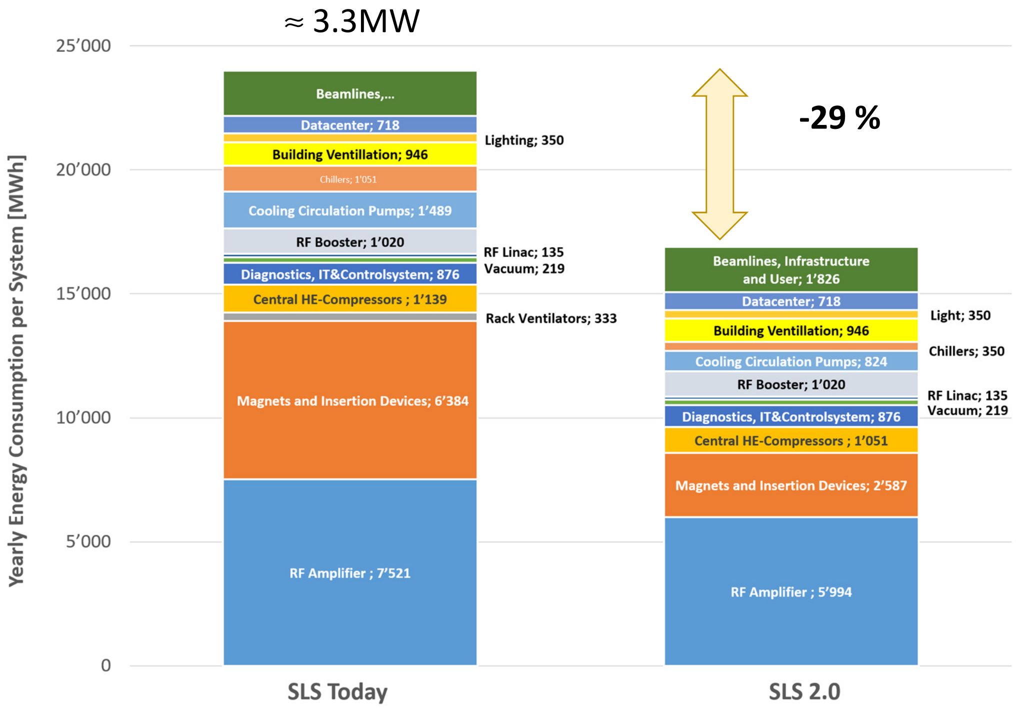


SLS2.0 magnet structure



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

Example Swiss Light Source SLS and its Upgrade



More radiated X-ray power for users
Less electricity consumption

Key savings:

Electromagnets → Permanent magnets
Klystrons → Solid state amplifiers (63%)
standard pumps → modern pumps for cooling

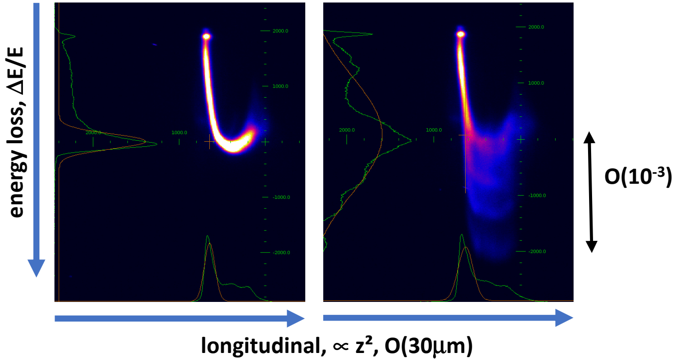
SLS2.0

P_{tot} = 2.4MW
P_{RF} = 0.82MW
$P_{\gamma\,(undulators)}$ = 91kW

Free Electron Laser

streaked beam, SwissFEL

no lasing **lasing**

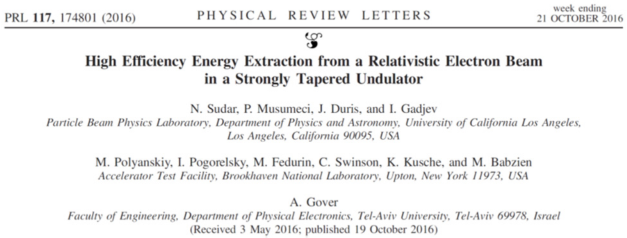


P_{grid} → **RF, Linac** → P_{beam} → **FEL process ρ ?** → P_{γ}

FEL: $P_{\gamma} \sim N^2$
(coherence length)

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 examples: (order of magnitude)

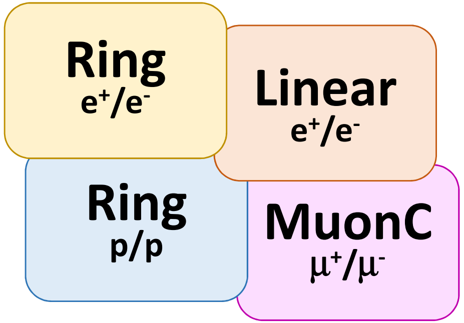
Facility	Technology	P_{grid} (typ)	P_{beam} (typ)	Photon Power
SwissFEL	n.c., 6 GHz, pulsed	≈ 3.0 MW	100 W	up to 0.2 W
EXFEL	s.c., 1.3 GHz, pulsed	≈ 10 MW	40‘000 W	up to 40 W

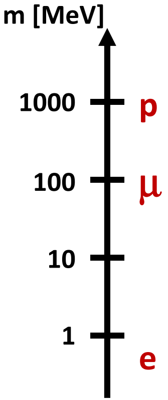
Particle Colliders

Colliders - Concepts

Next generation: high Luminosity, high Energy reach needed

Energy Efficiency: Luminosity per Grid Power





particle mass impacts synchrotron radiation and beamstrahlung (collision)

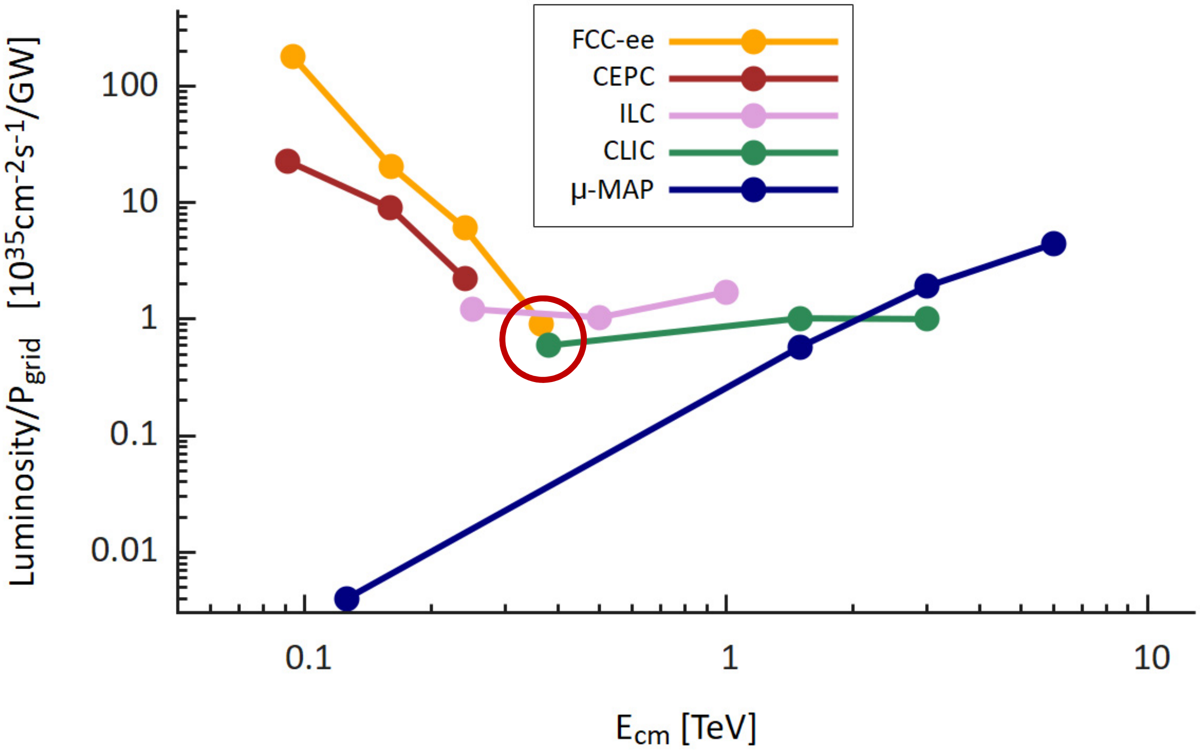
→ scaling laws and grid power drivers are quite different for the concepts under discussion

Colliders Types and Power Drivers

Ring e^+/e^-	FCC-ee 240GeV: P_{grid} = 282MW	+ beam recirculation - synchrotron radiation	$P_{\mathrm{SR}} \propto I_{\mathrm{beam}} \left(\frac{E}{m_0}\right)^4 \frac{1}{R}$
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)	$L_{\mathrm{lin.col.}} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\mathrm{beam}}$
MuonC μ^+/μ^-	MAP 6.0TeV: P_{grid} = 270MW	+ no Beamstrahlung-Limitation - inefficient RCS, complexity	$L_{\mathrm{mu.col.}} \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\mathrm{beam}}$
Ring p/p	FCC-hh 100TeV: P_{grid} = 580MW	+ high energy reach - SR deposited @50K, cryogenics	$P_{\mathrm{SR}} \approx 5\,\mathrm{MW}$ $\rightarrow P_{\mathrm{grid,SR}} \approx 100\mathrm{MW}\ (17\%)$

Overview Lepton Proposals

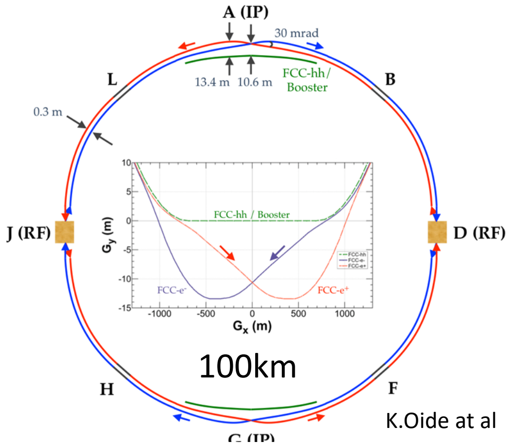
energy specific
luminosity production:



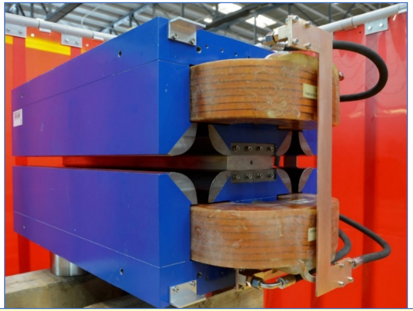
FCC-ee – Optimized Lepton Ring Collider

conceptual measures:
- crab waist scheme (specific luminosity)
- 4 IP‘s instead 2
- optimized beam dynamics and working point

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)



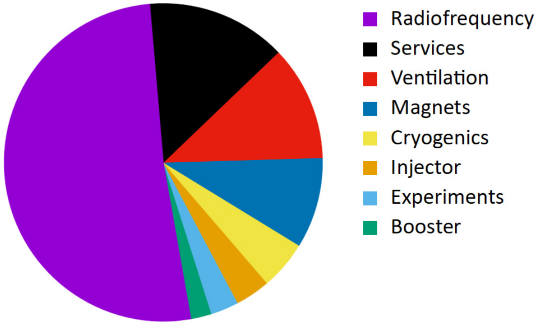
K.Oide at al



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

E_{cm} = 240GeV (H)
P_{grid} = 282MW

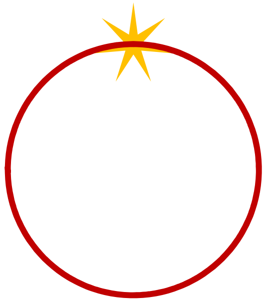
→ dominated by RF



Ring vs. Linear Collider

Ring Collider
beams circulate

Linear Collider
beams collide once



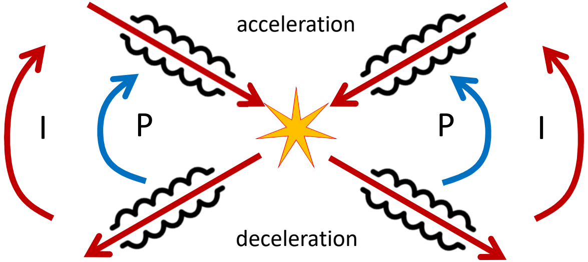
	FCC-ee 365GeV	**CLIC** 380GeV
σ_x [nm]	38‘000	150
σ_y [nm]	68	3
σ_z [μm]	2‘500	70
N [10^9]	230	5,2
f_b [kHz]	147	17,6
P_b[MW]	988	2.8

- beam reused
- synchrotron radiation dominated
- equilibrium beamsize $\rightarrow$ 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



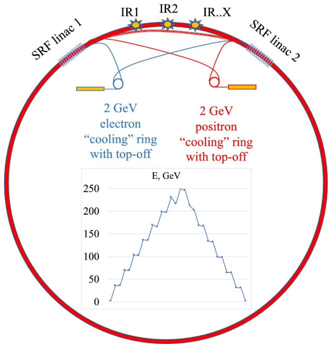
- power recirculated, beam recirc. at low E
- benefit from better collission parameters

→ 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

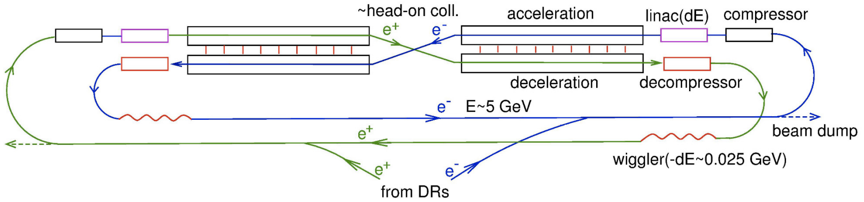
multi turn ERL, modification FCC-ee



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

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

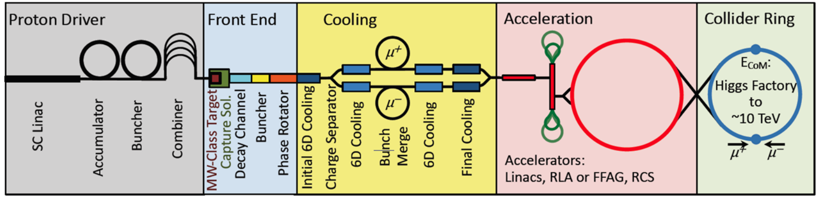
Twin LC with energy recovery



Muon Collider – Efficient at Highest Energies

Muon: E_0 = 106 MeV, τ_μ = 2.2 µs

low SR, low beamstrahlung during collisions!
scaling laws for muon collisions at varying E:



MAP design, see also D.Schulte this conference

$$\frac{\delta E}{E} \approx 10^{-3} \rightarrow \sigma_z \propto \frac{1}{\delta E} \rightarrow \beta^*_{x,y} \propto \sigma_z \rightarrow \beta^*_{x,y} \propto \frac{1}{\gamma}$$

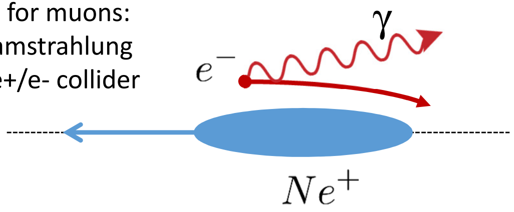
thus L/P is increasing with energy:

unique for muons

$$\mathcal{L} \propto B \frac{N_0}{\varepsilon_n} \gamma P_{\text{beam}}$$

smaller ring → more collisions during τ_μ

not for muons:
Beamstrahlung
in e+/e- collider

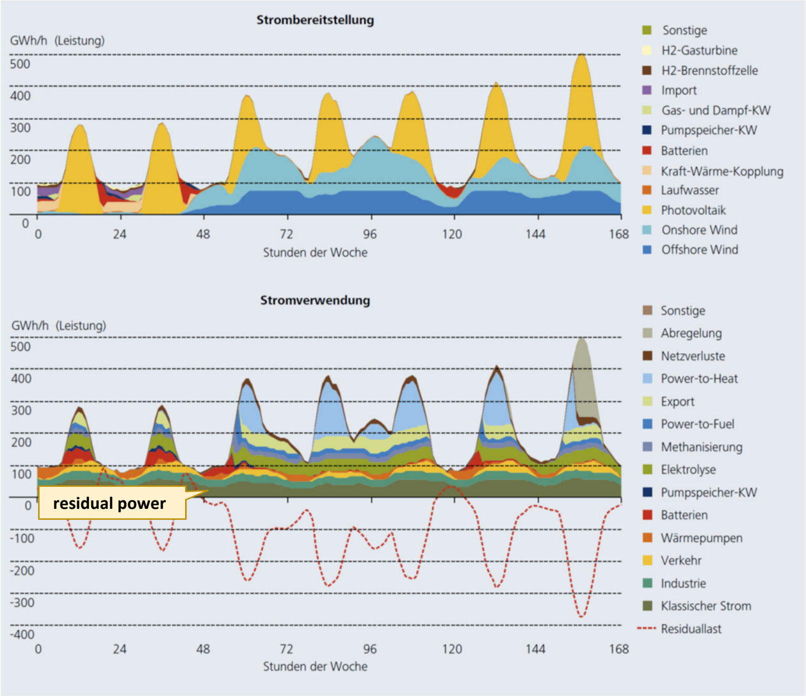


The Future – Fluctuating Energy Sources

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)

Summary: Concept Efficiency

high intensity proton drivers

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

light sources

- many technical advancements: permanent magnets, RF sources, conventional cooling etc.; MBA: boost of brilliance per grid power

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**

Summary: Efficient Technologies

- **s.c. magnets & high Q cavities** provide efficient solutions, **higher temperature operation (HTS)**; perhaps the most important development
- **efficient RF sources**: klystrons, solid state amps, magnetrons
- **permanent magnets** (light sources, FFA [S.Brooks this IPAC])
- heat recovery & photovoltaics
- other sustainability: water & He consumption, critical materials, lifecycle management, carbon footprint, energy procurement

Thank you for your attention.

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