

Towards Efficient Particle Accelerators – a Review

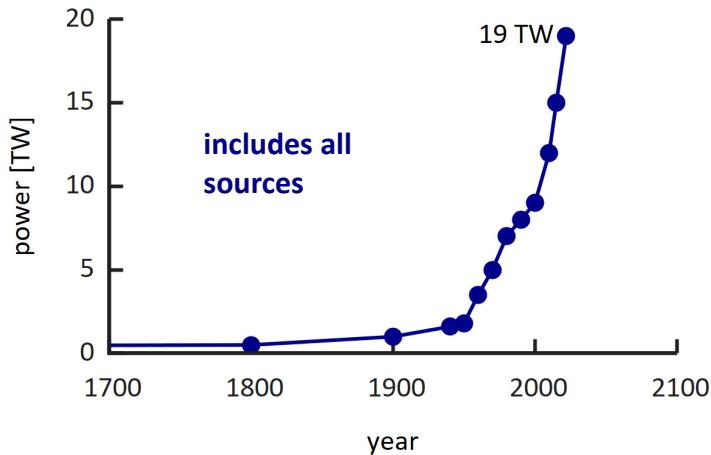
Mike Seidel

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



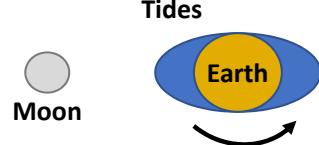
The world energy consumption has been continuously rising, reaching **19 TW** today, 2022.

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

example from nature:

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>



Enhanced European Coordination for Accelerator
Research & Development

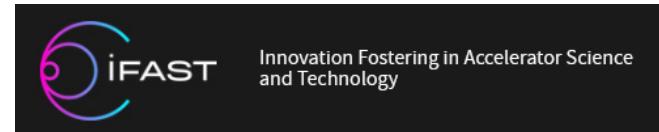
2017–21: ARIES, Work Package Efficient Energy Management

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

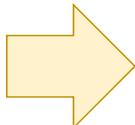


2021–25: I.FAST, Work Package Sustainable Concepts

<https://www.psi.ch/scat>

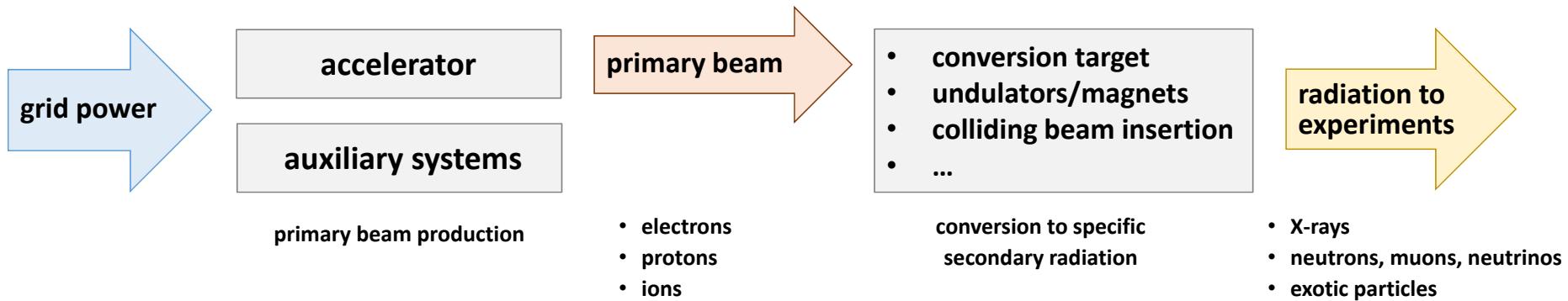


→ consult websites for link collection to workshops and documentation



- 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]

outline of the talk

concepts, RI's

Proton Drivers with high intensity applications

Synchrotron Light Sources and FELs

Particle Colliders

technologies

Resonators and high Power RF Systems

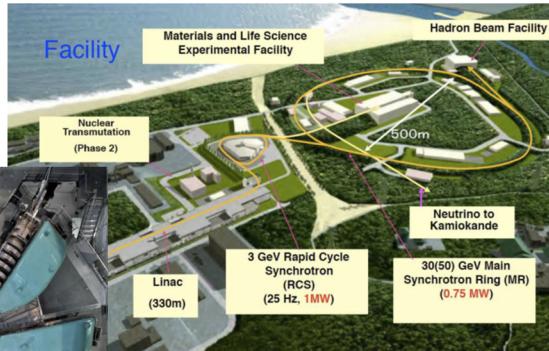
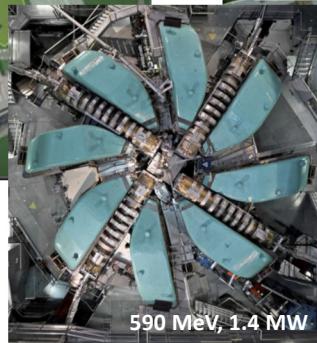
Accelerator Magnets and Power Supplies

Cryogenic Systems

Component Cooling, Air Conditioning, Vacuum, Instrumentation ... and other aux. systems

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*

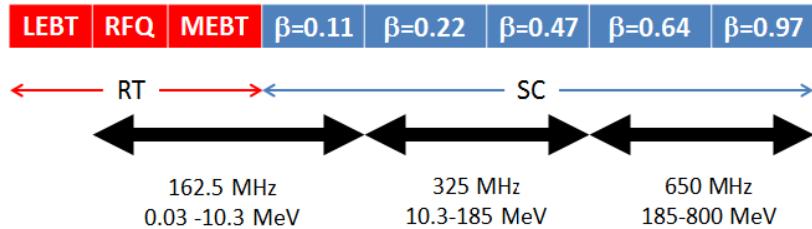
J. K. Grillenberger, Paul Scherer Institut, 5232 Villigen, Switzerland,
 S.-H. Kim, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
 M. Yoshii, KEK and JAEA J-PARC Center, 2-4 Shirakata-Shirane, Tokai, Ibaraki 319-1195, Japan
 M. Seidel, Paul Scherer Institut, 5232 Villigen, Switzerland
 V.P.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



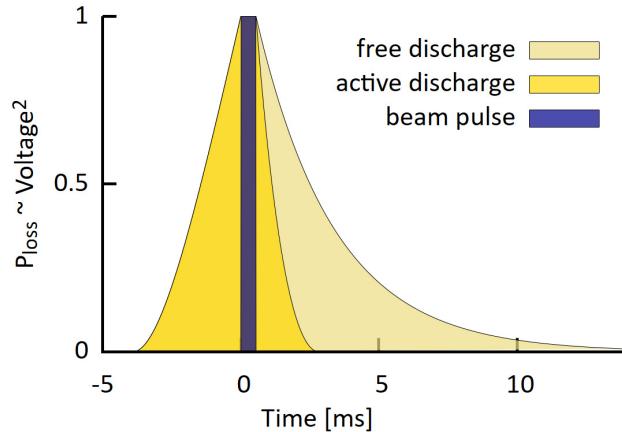
PIP-II base parameters:

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

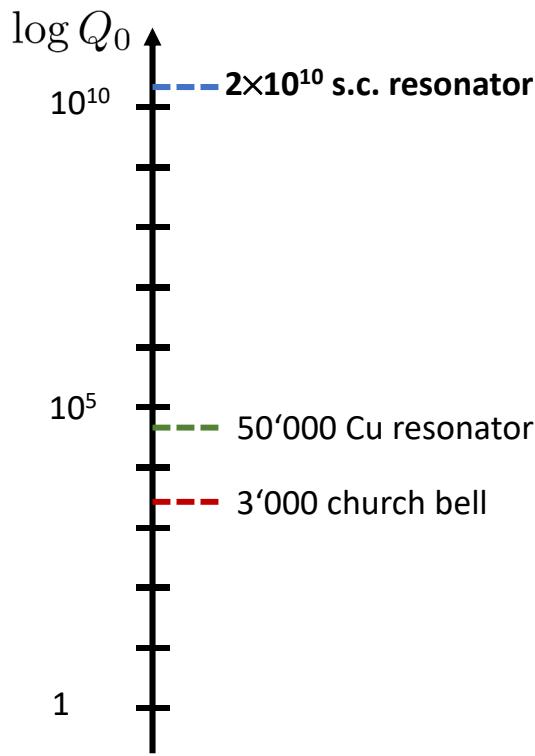
not efficient in pulsed operation:

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



Q₀ = quality factor
→ e-folding decay and resonance width

dissipated power:

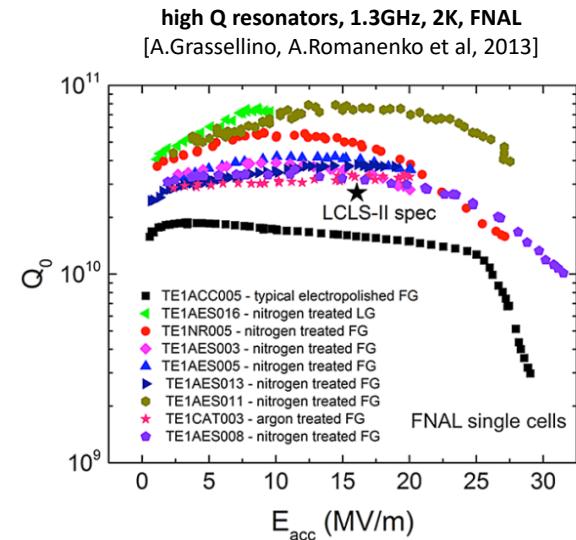
$$P_{\text{dissip}} = \frac{U_a^2}{\left(\frac{R}{Q}\right) Q_0}$$

example:

$$U_a = 20\text{MV}, (R/Q) = 609\Omega, Q_0 = 2 \times 10^{10}, I_b = 2\text{mA}$$

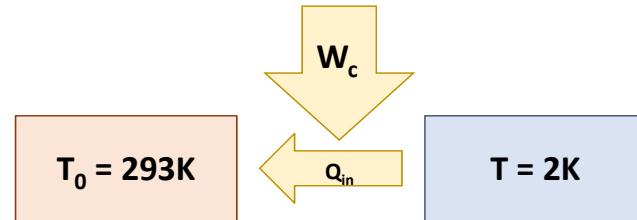
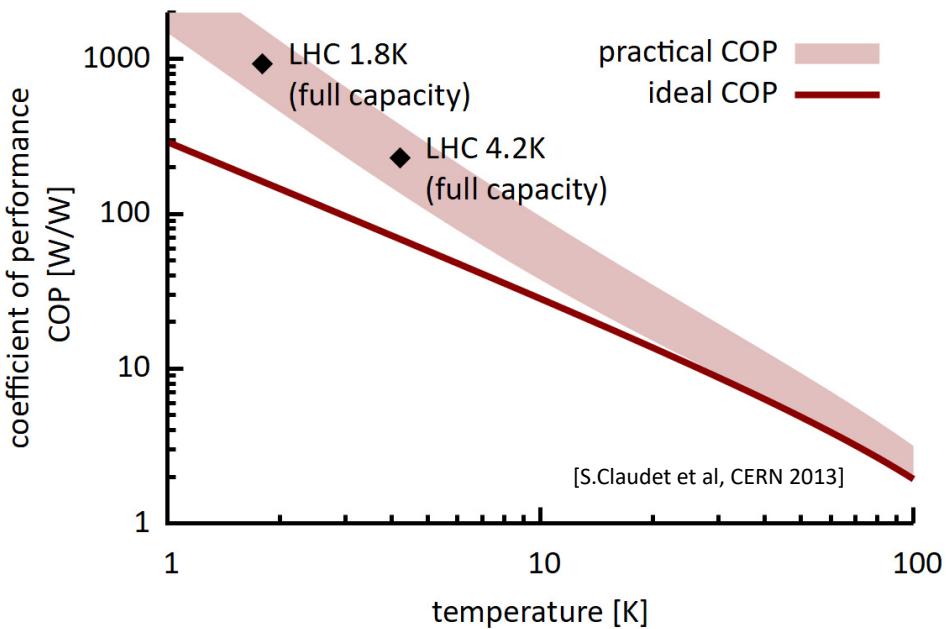
$$\rightarrow P_{\text{dissip}} = 33\text{ W}$$

$$\rightarrow P_{\text{beam}} = 40.000\text{ W}$$



but: cryogenic efficiency!

Cryogenic Efficiency



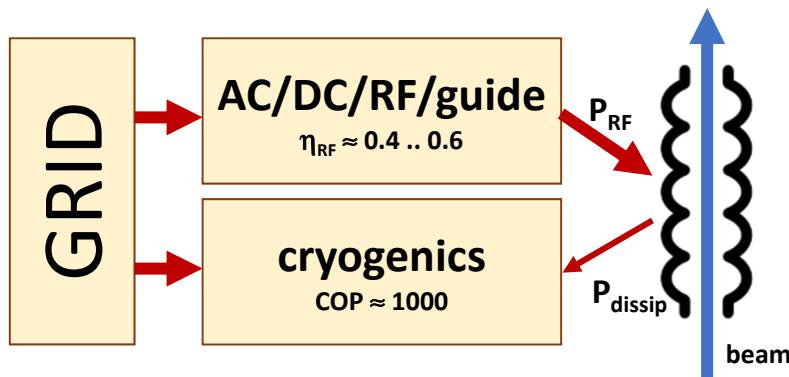
best possible coefficient of performance (COP):

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

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

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

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



power balance:

$$P_{\text{grid}} = P_{\text{cryo}} + P_{\text{RF}}$$

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

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

considered:

- one 650MHz cavity
- $U_a = 20\text{MV}$
- $I = 1.1\text{m}$

ignored: cavity detuning,
 $\beta < 1$, 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

Technology R&D: Efficient RF Power Sources

- **Klystrons**, $\eta > 70\%$ within reach

e.g. CLIC two stage multi-beam klystron, J.Cai, I.Syratchev, IEEE Trans, 2020

- **Magnetron**, R&D at various groups, $\eta = 60-80\%$ 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, $\eta = 60-90\%$ 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; $\eta_{sat}=82\%$

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

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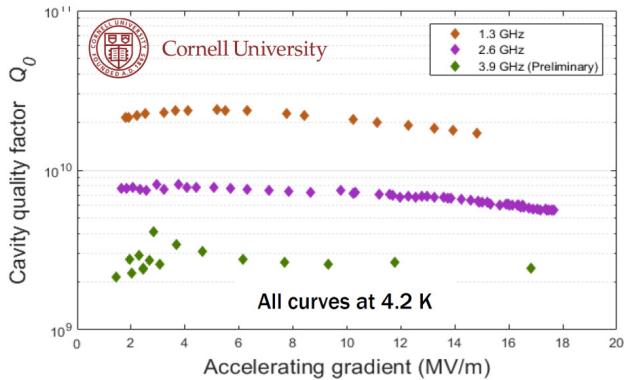
Kilowatt Power Amplifier With Improved Power Back-Off Efficiency for Cyclotron Application

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, $\eta_D=93\%$ (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

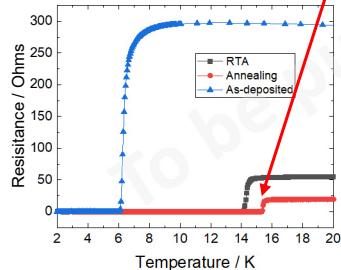


- promising R&D: Nb₃Sn coated cavities at Cornell
- 4.2 vs. 2.0K → efficiency

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

S Posen et al 2021 Supercond. Sci. Technol. 34 025007
record cw gradient in Nb₃Sn-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



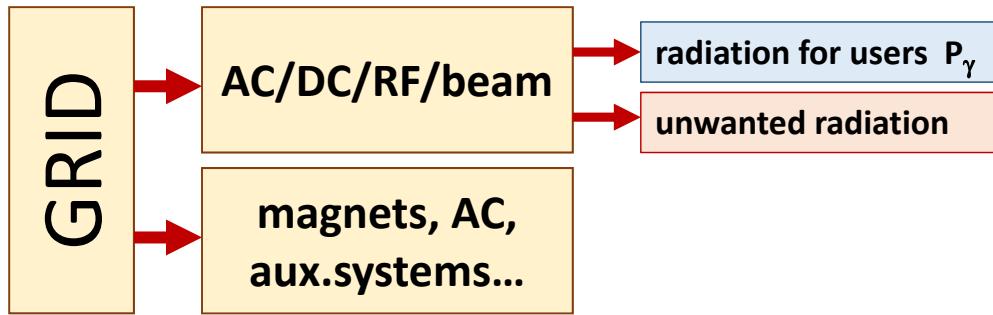
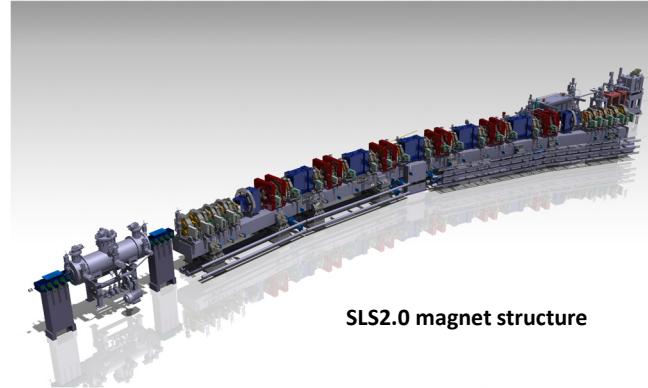
DESY, Hamburg U.
aim for sustained SRF accelerator technology
10y Goal: >70 MV/m with a Q_0 of 1×10^{10} and at 4K
contact: M.Wenskat, DESY

G. Deyu et al., „Al₂O₃ coating of Superconducting Niobium Cavities with thermal ALD“, in preparation

Light Sources

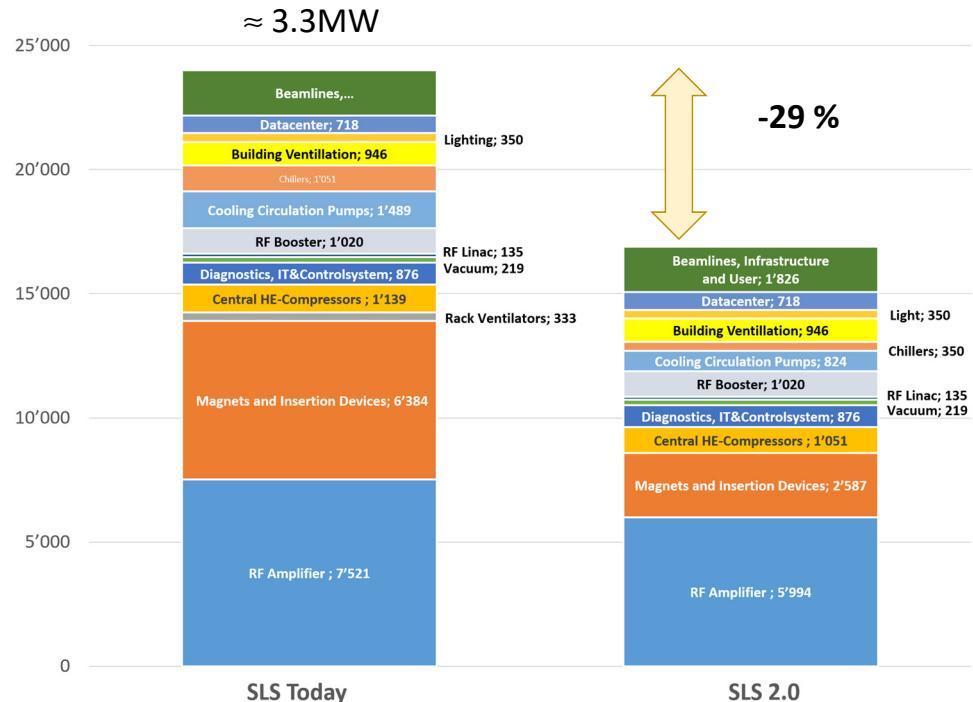
Synchrotron Light Sources and Free Electron Lasers

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



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**

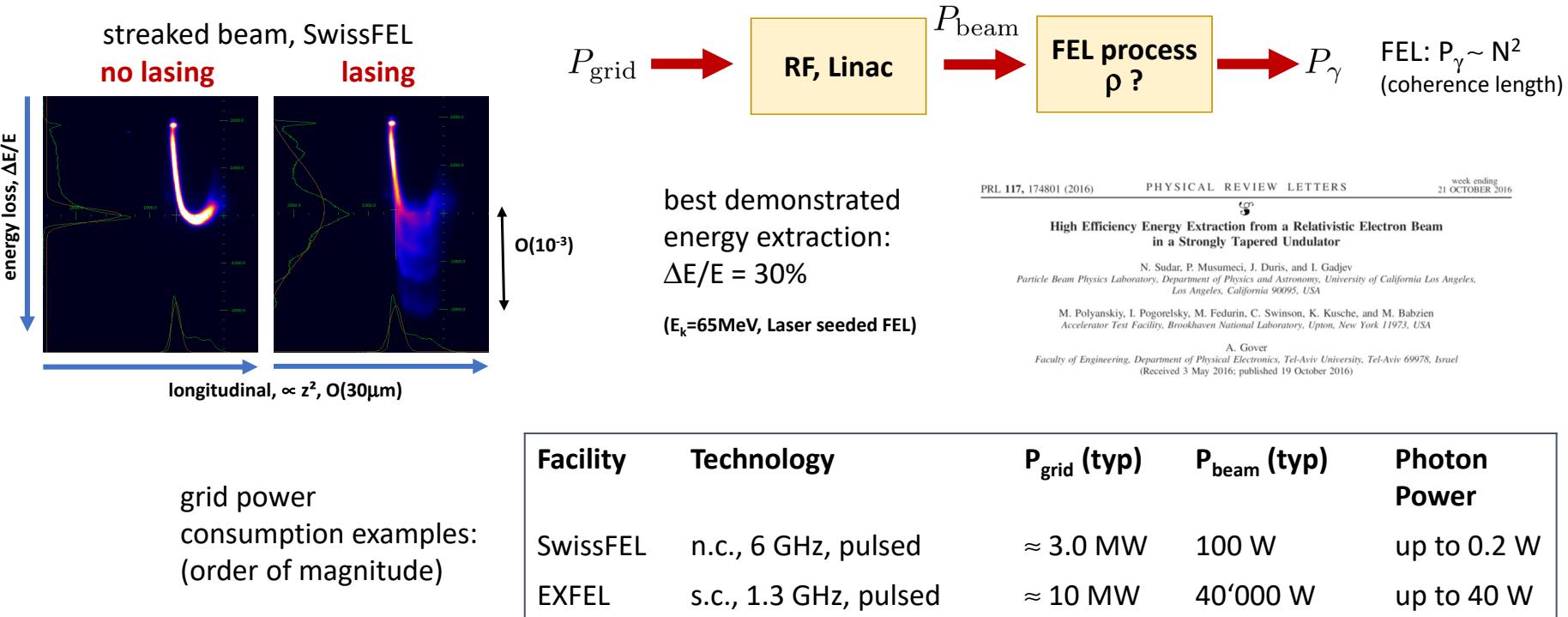
Key savings:

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

SLS2.0

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

Free Electron Laser

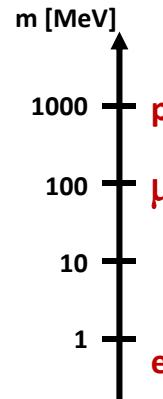
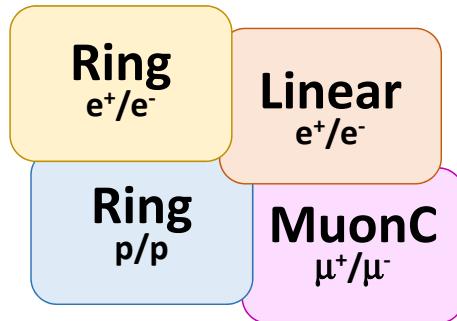


grid power consumption examples:
(order of magnitude)

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:

$P_{\text{grid}} = 282\text{MW}$

+ beam recirculation

- synchrotron radiation

Linear e^+e^-

CLIC 380GeV (3.0TeV):

$P_{\text{grid}} = 252\text{MW} (589\text{MW})$

ILC 250GeV (1TeV):

$P_{\text{grid}} = 111\text{MW} (300\text{MW})$

+ no synchrotron radiation

- no recirc., small beam needed

power drivers: cryo (ILC) vs RF (CLIC)

MuonC $\mu^+\mu^-$

MAP 6.0TeV:

$P_{\text{grid}} = 270\text{MW}$

+ no Beamstrahlung-Limitation

- inefficient RCS, complexity

Ring p/p

FCC-hh 100TeV:

$P_{\text{grid}} = 580\text{MW}$

+ high energy reach

- SR deposited @50K, cryogenics

$$P_{\text{SR}} \propto I_{\text{beam}} \left(\frac{E}{m_0} \right)^4 \frac{1}{R}$$

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

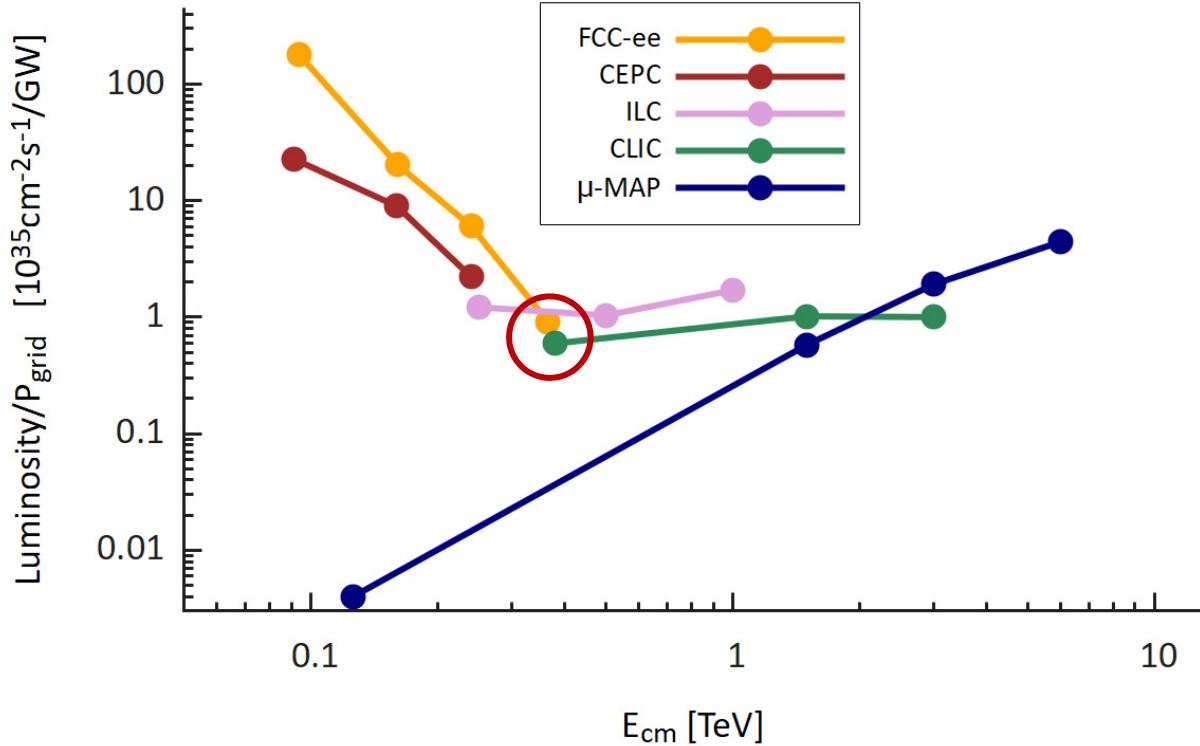
$$L_{\text{mu.col.}} \propto B \frac{N_0}{\varepsilon_{xy,n}} \cancel{\gamma} P_{\text{beam}}$$

$$P_{\text{SR}} \approx 5\text{ MW}$$

$$\rightarrow P_{\text{grid,SR}} \approx 100\text{MW (17\%)}$$

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

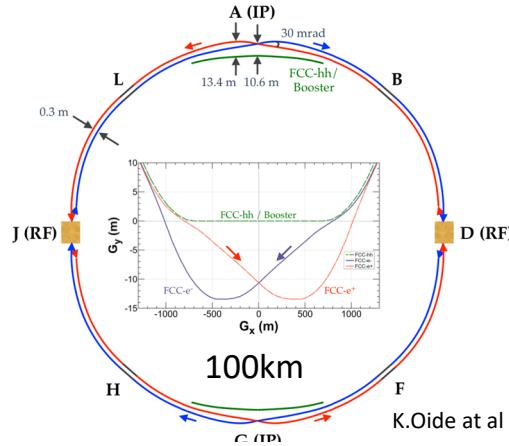
technology measures:

- high-efficiency klystrons (HEIKA collaboration)
- 4.5 K s.c. cavities, high Q (400 MHz Nb/Cu)
- twin aperture dipoles (50% savings of bends)

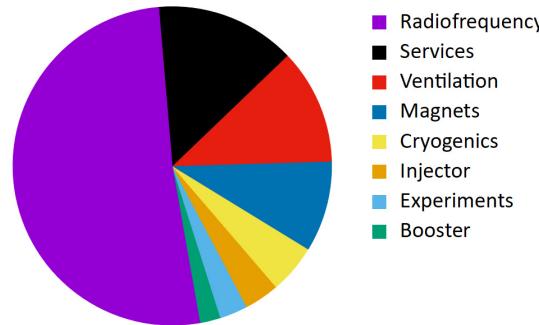
$$E_{cm} = 240\text{GeV (H)}$$

$$P_{grid} = 282\text{MW}$$

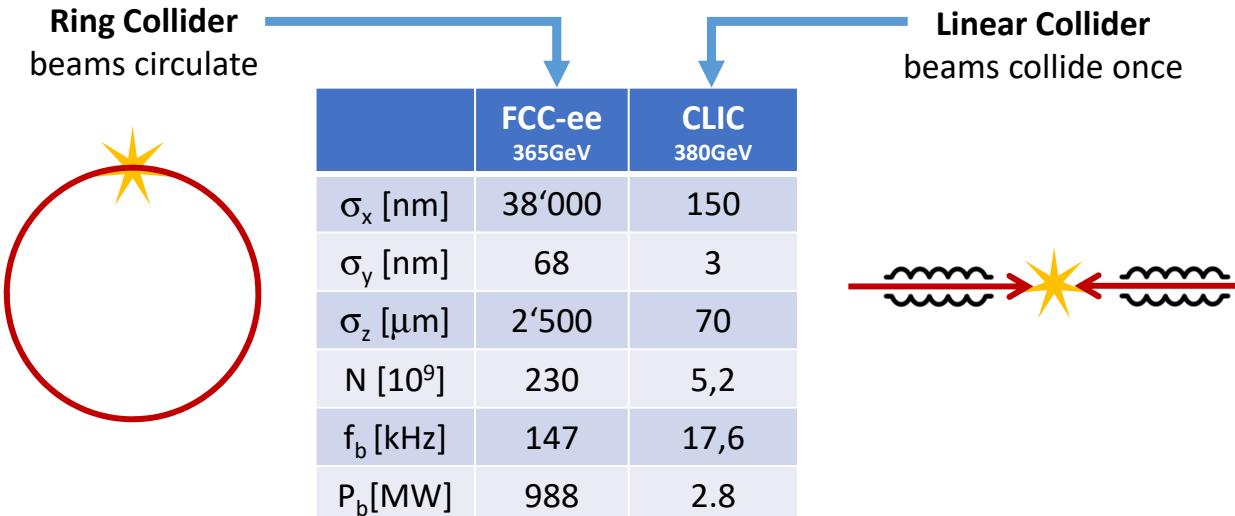
→ dominated by RF



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



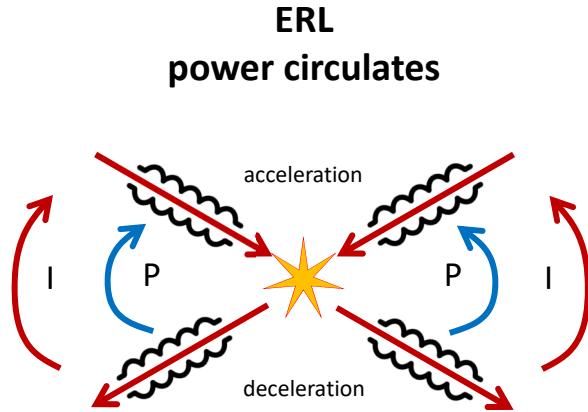
Ring vs. Linear Collider



- 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



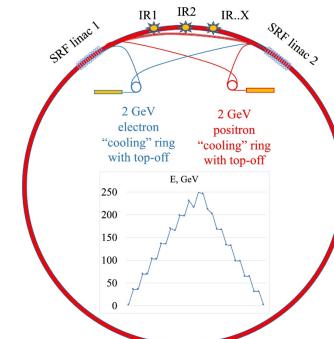
- power recirculated, beam recirc. at low E
 - benefit from better collision parameters
- **high L per grid power, but higher investments & complexity**

two ERL proposals published:

1) Circular Energy Recovery Collider

V. Litvinenko, T. Roser, M. Llatas, Physics Letter B 804 (2020) 135394

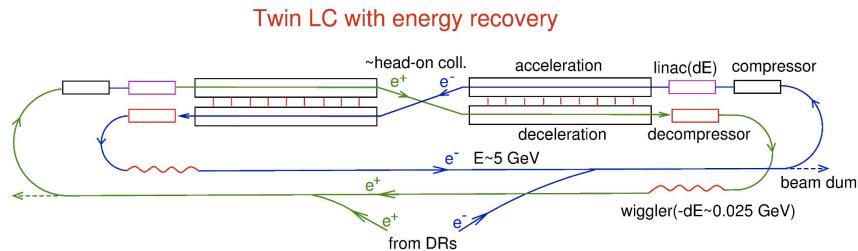
multi turn ERL, modification FCC-ee



2) Energy Recovery Linear Collider

V.I. Telnov 2021 JINST 16 P12025

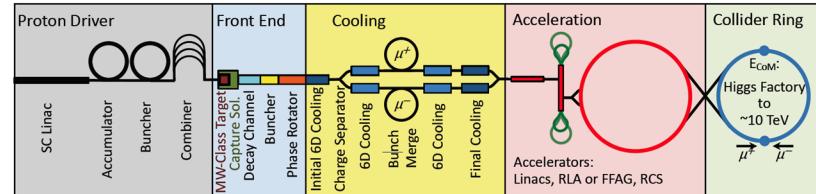
twin s.c. linacs, beam recirculation, wiggler damping



Muon Collider – Efficient at Highest Energies

Muon: $E_0 = 106 \text{ MeV}$, $\tau_\mu = 2.2 \mu\text{s}$

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



MAP design, see also D.Schulte this conference

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

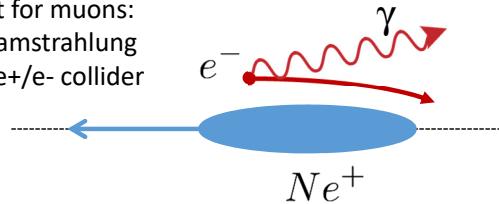
thus L/P is increasing
with energy:

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

unique for muons

smaller ring \rightarrow more collisions during τ_μ

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

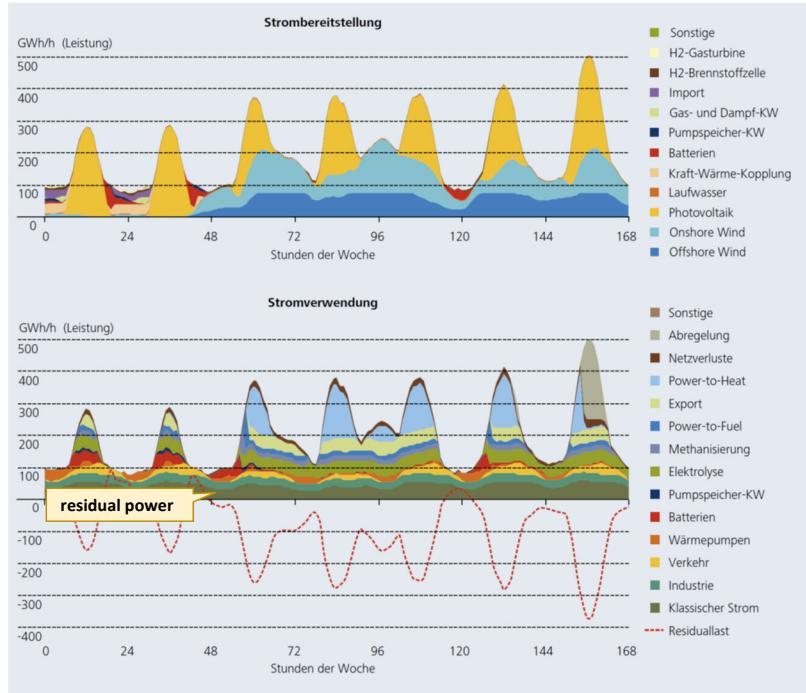


The Future – Fluctuating Energy Sources

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 $E < 1\text{GeV}$, 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.

Many thanks for discussions and input:

V.Yakovlev (Fermilab), V.Ziemann (U.Uppsala),
W.Decking (DESY), S.Reiche (PSI),
D.Schulte, F.Zimmermann (CERN).