Energy Efficiency of Particle Accelerator driven Research Infrastructures

CHIPP/CHART Workshop on Sustainability in Particle Physics
June 14, 2023, Sursee

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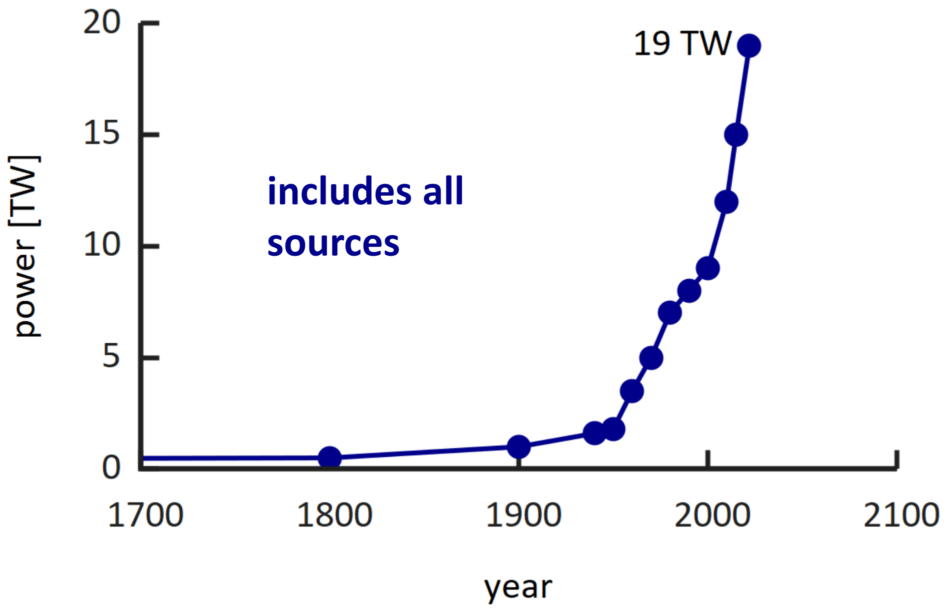
Paul Scherrer Institute and École polytechnique fédérale de Lausanne

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

Energy Consumption - Motivation

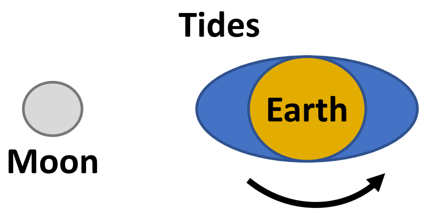


The world energy consumption has been continuously rising, reaching ca **19 TW** today.

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

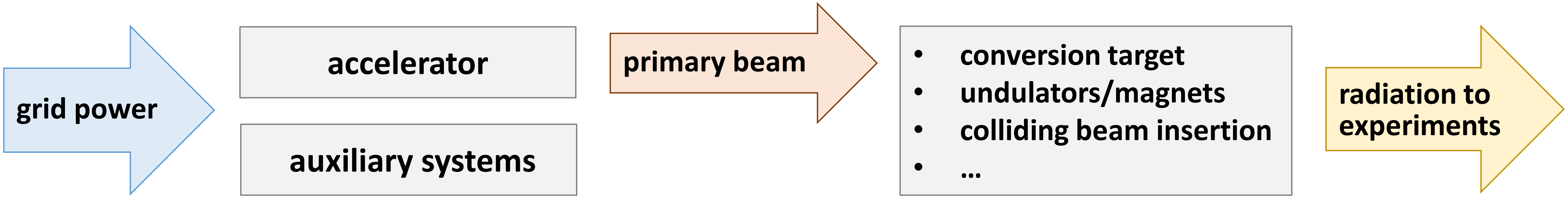
iFAST Innovation Fostering in Accelerator Science and Technology

→ 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)



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]

outline of the talk →

concepts, RI‘s

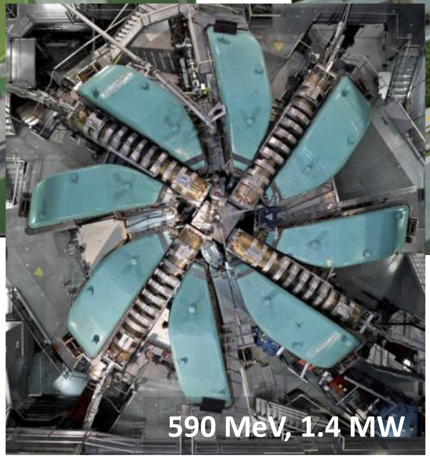
- **Proton Drivers with high intensity applications**
- **Synchrotron Light Sources and FELs**
- **Particle Colliders**

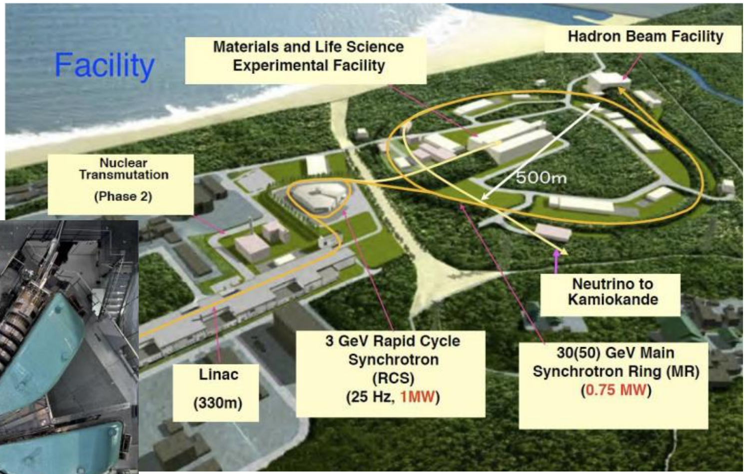
technologies

- **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 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

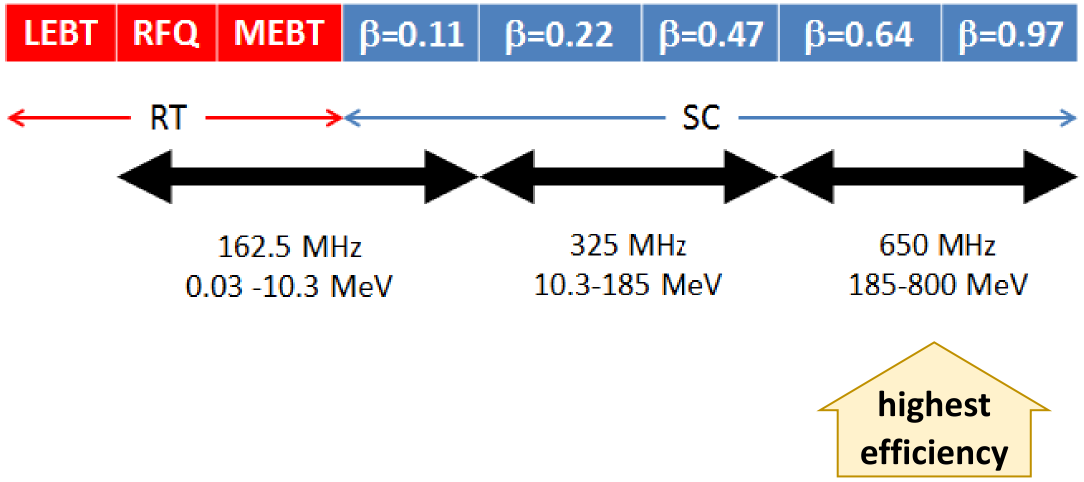
Megawatt class facilities operating today:

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

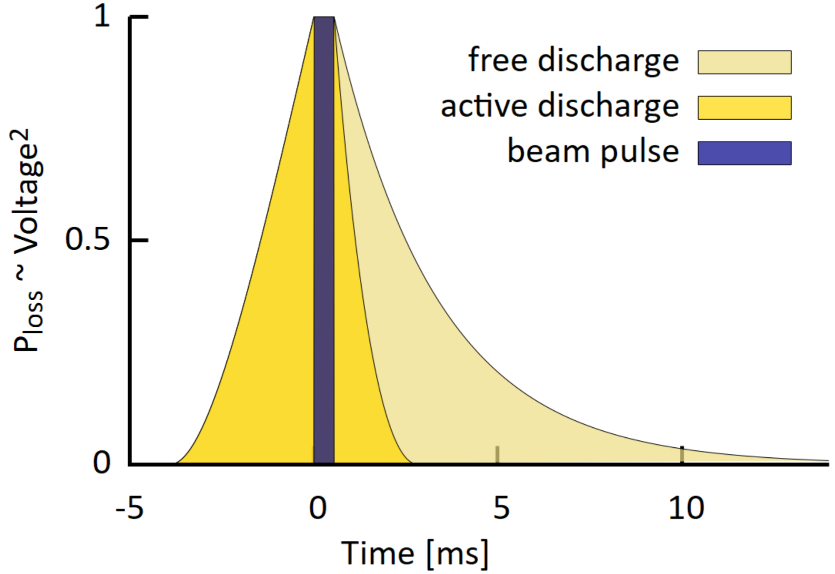
example: PIP-II design of Fermilab



PIP-II base parameters:

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

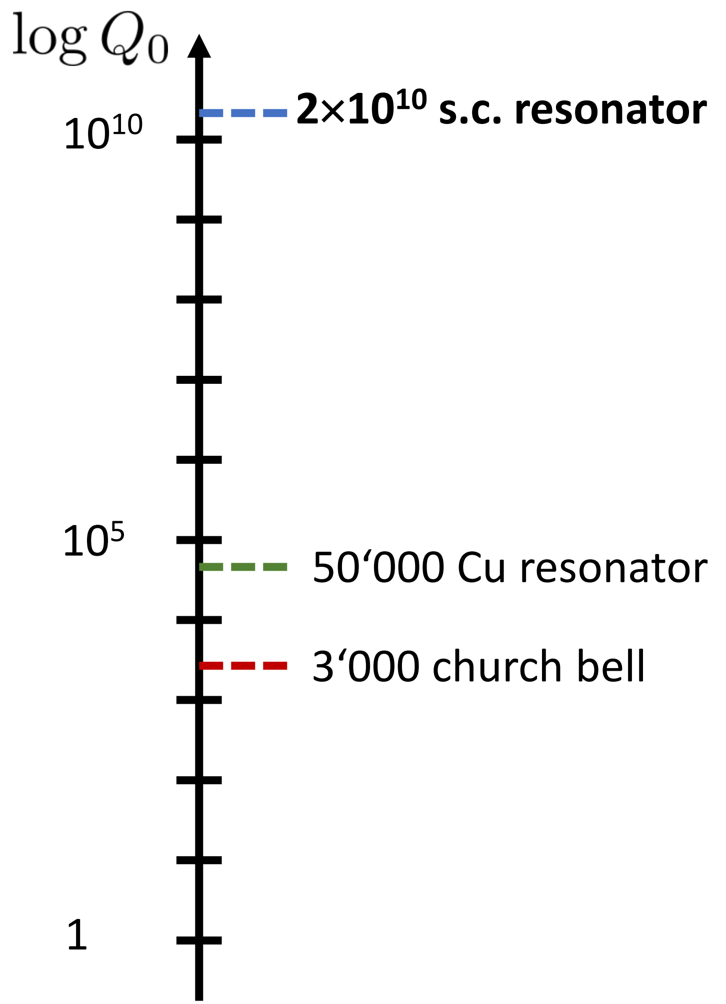
not efficient in pulsed operation:



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

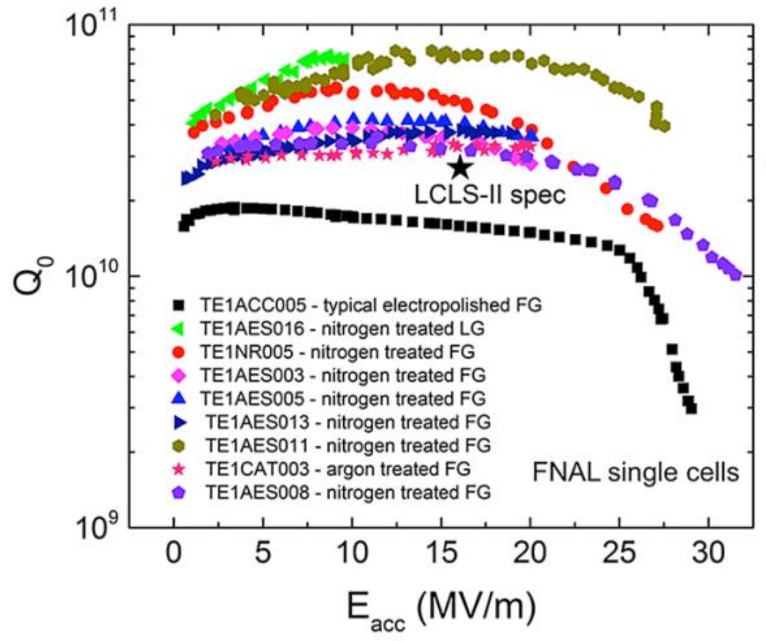
dissipated power:

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

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

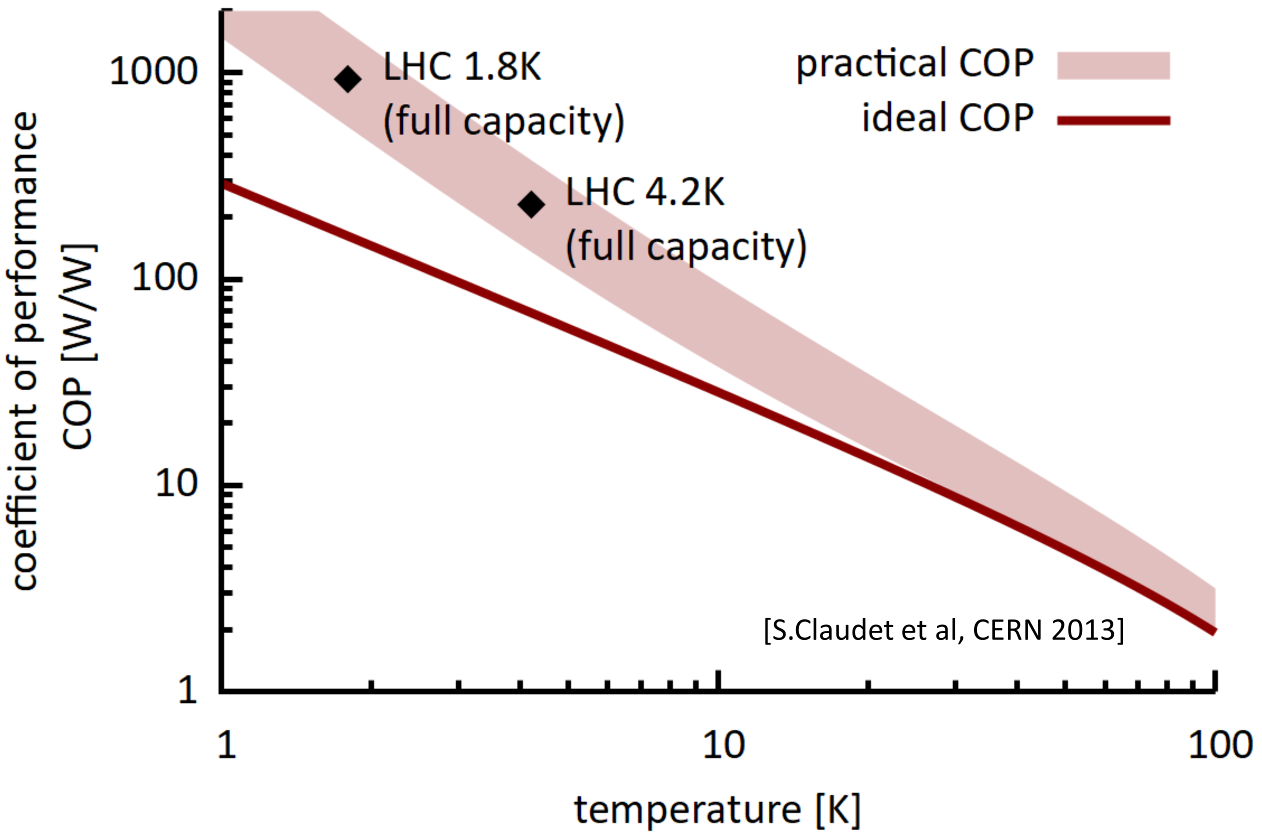
→ P_{dissip} = 33 W
→ P_{beam} = 40.000 W

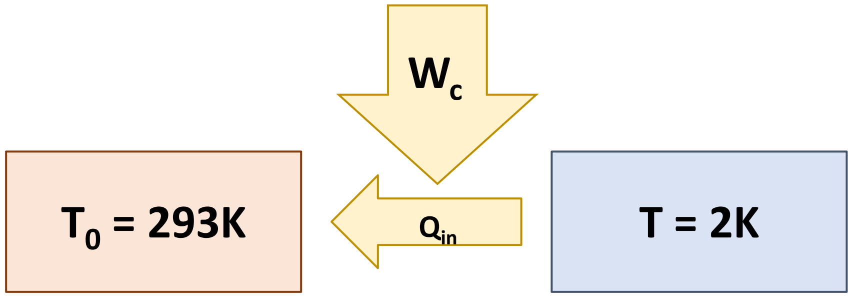
high Q resonators, 1.3GHz, 2K, FNAL
[A.Grassellino, A.Romanenko et al, 2013]



but: cryogenic efficiency!

Cryogenic Efficiency





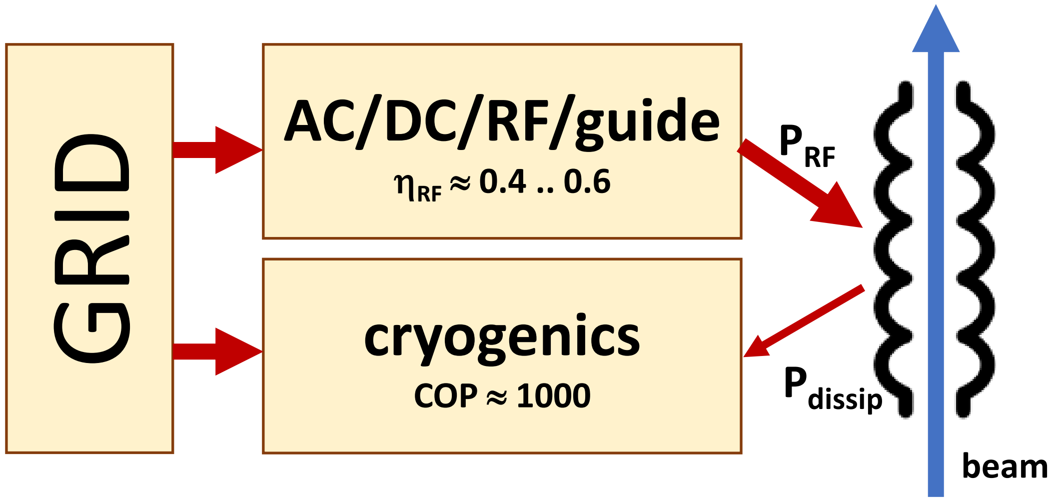
best possible coefficient of performance (COP):

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

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

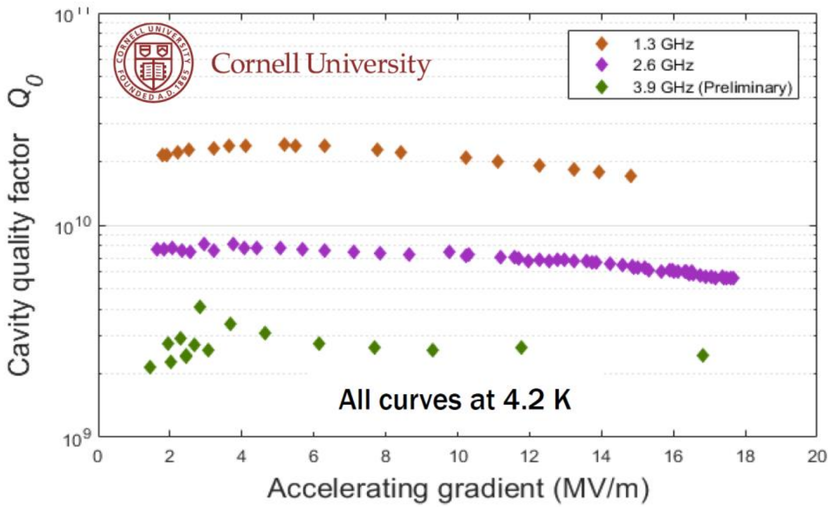
Kilowatt Power Amplifier With Improved Power Back-Off Efficiency for Cyclotron Application

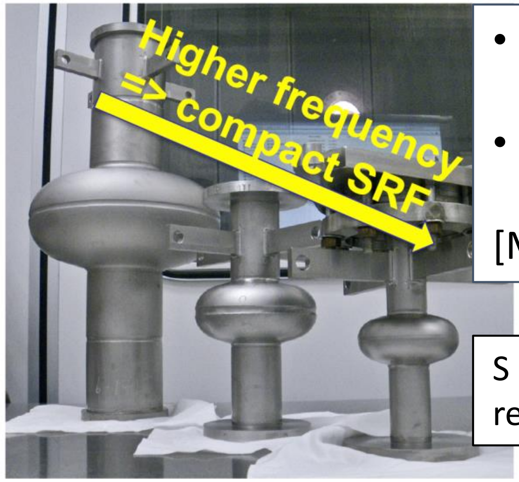
Renbin Tong, Olof Bengtsson, *Senior Member, IEEE*, Jörgen Olsson, *Senior Member, IEEE*, Andreas Bäcklund, and Dragos Dancila

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

I.FAST efficient RF workshop, July 4-6, 2022, Switzerland: https://indico.cern.ch/event/1138197/

Technology R&D: Superconducting RF at higher temperature





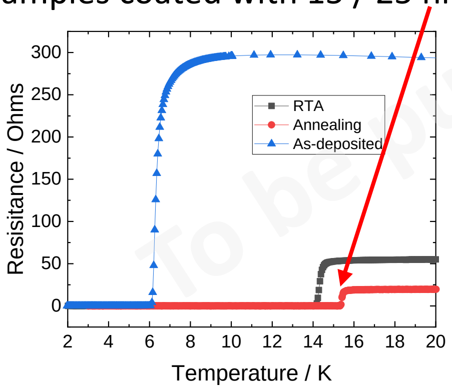
- promising R&D: Nb_3Sn coated cavities at Cornell
- 4.2 vs. 2.0K → efficiency

[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

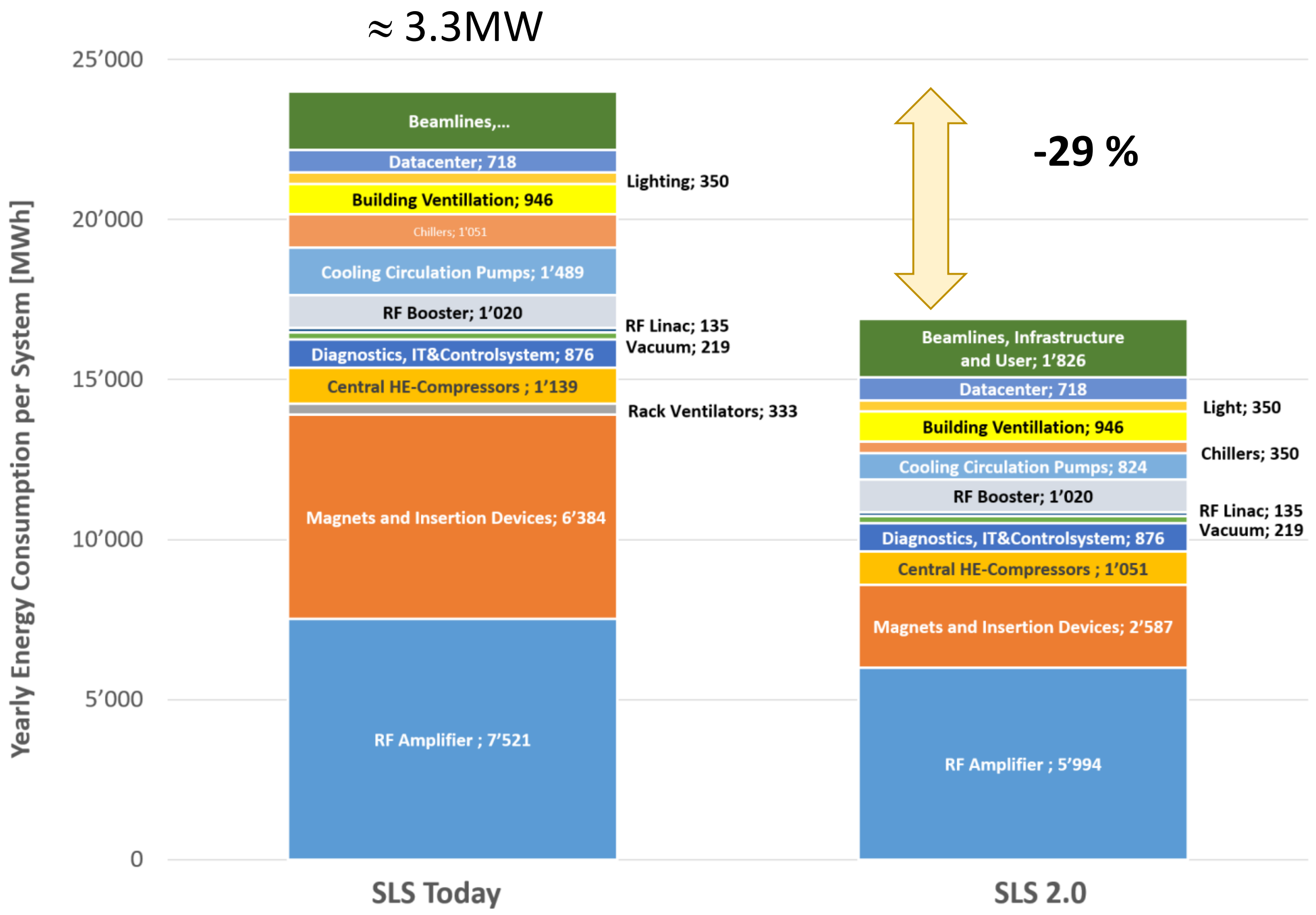


DESY, Hamburg U.
aim for sustained SRF accelerator technology
10y Goal: >70 MV/m with a Q_0 of $1x10^{10}$ and at 4K
contact: M.Wenskat, DESY

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

Light Sources

Example Swiss Light Source SLS and its Upgrade



[M.Jörg, PSI]

Brilliance x 35 for users
Less electricity consumption

Key savings:

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

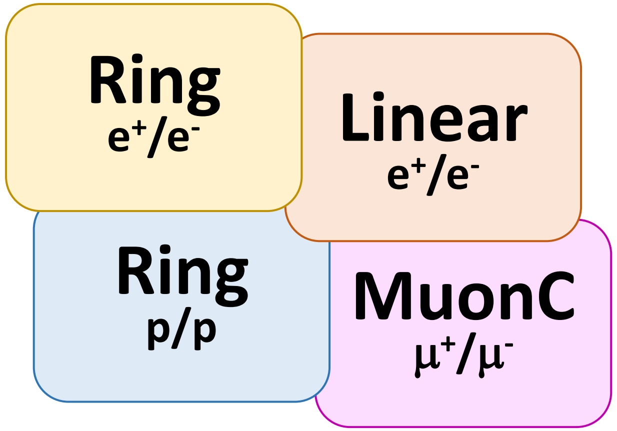
SLS2.0

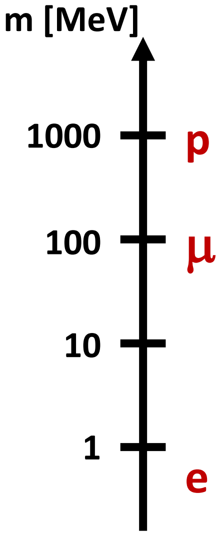
P_{tot} = 2.4MW
P_{RF} = 0.82MW
$P_{\gamma\text{ (undulators)}}$ = 91kW

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} = 273MW	+ 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	$P_{\mathrm{SR}} \approx 5\,\mathrm{MW}$ $\rightarrow P_{\mathrm{grid,SR}} \approx 100\mathrm{MW}\ (17\%)$

Ring Collider

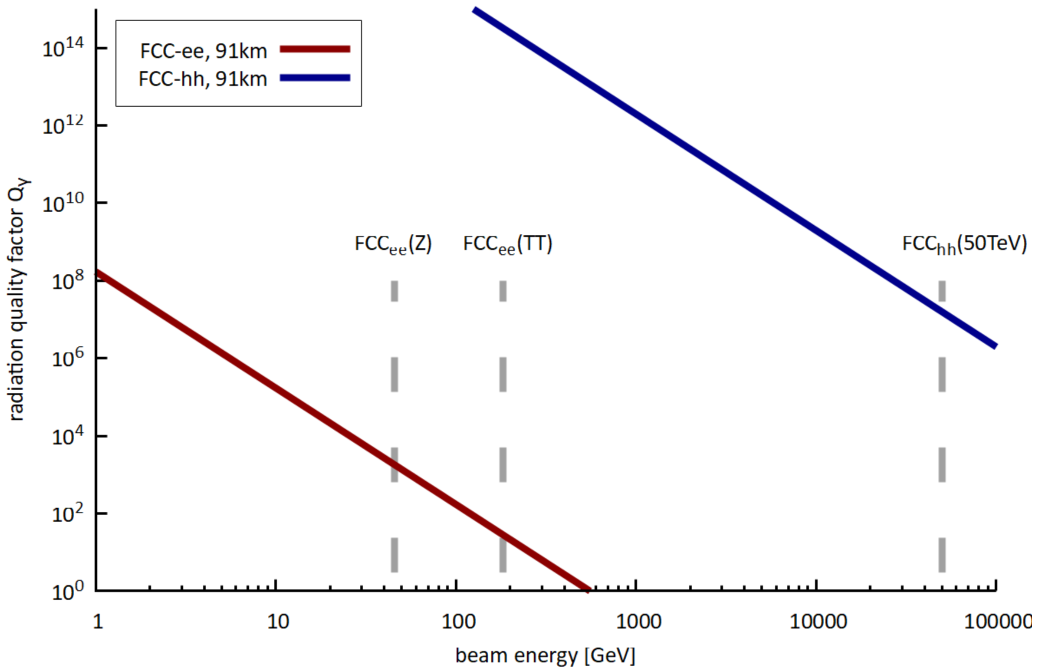
- energy recirculated, thus efficient concept
- however, SR losses at higher energies
- LHC: burnup dominates beam loss

quality factor of a storage ring: $$Q_\gamma = \frac{P_{\text{stored}}}{P_{\text{dissipated}}} = \frac{E/\tau}{P_\gamma} = \frac{E}{U_0} \gg 1$$ = „decay time of beam energy in number of turns due to SR“

bending radius

$$Q_\gamma = \frac{3}{4\pi}\frac{\rho}{r_c}\gamma^{-3}$$

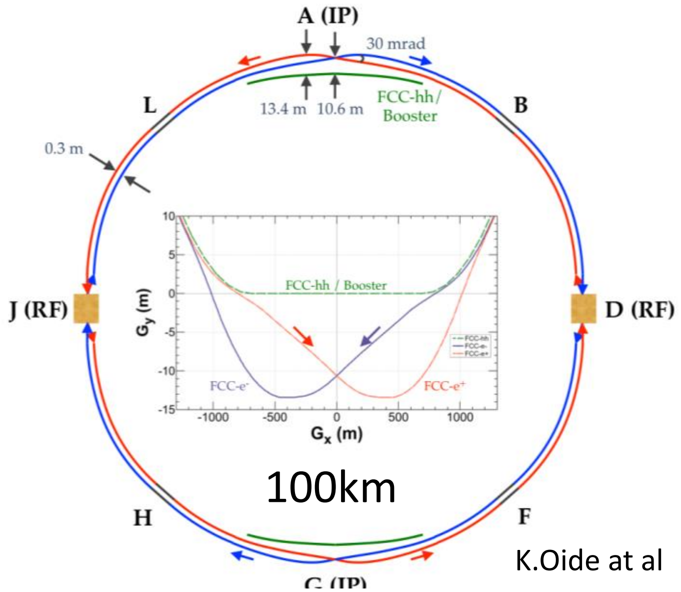
classical particle radius



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



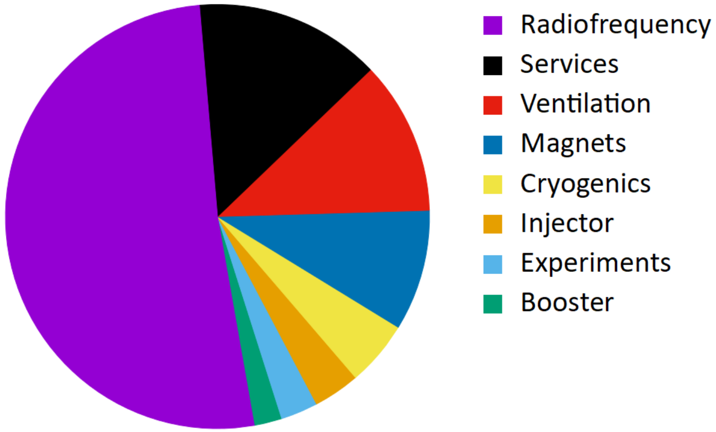
K.Oide at al

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

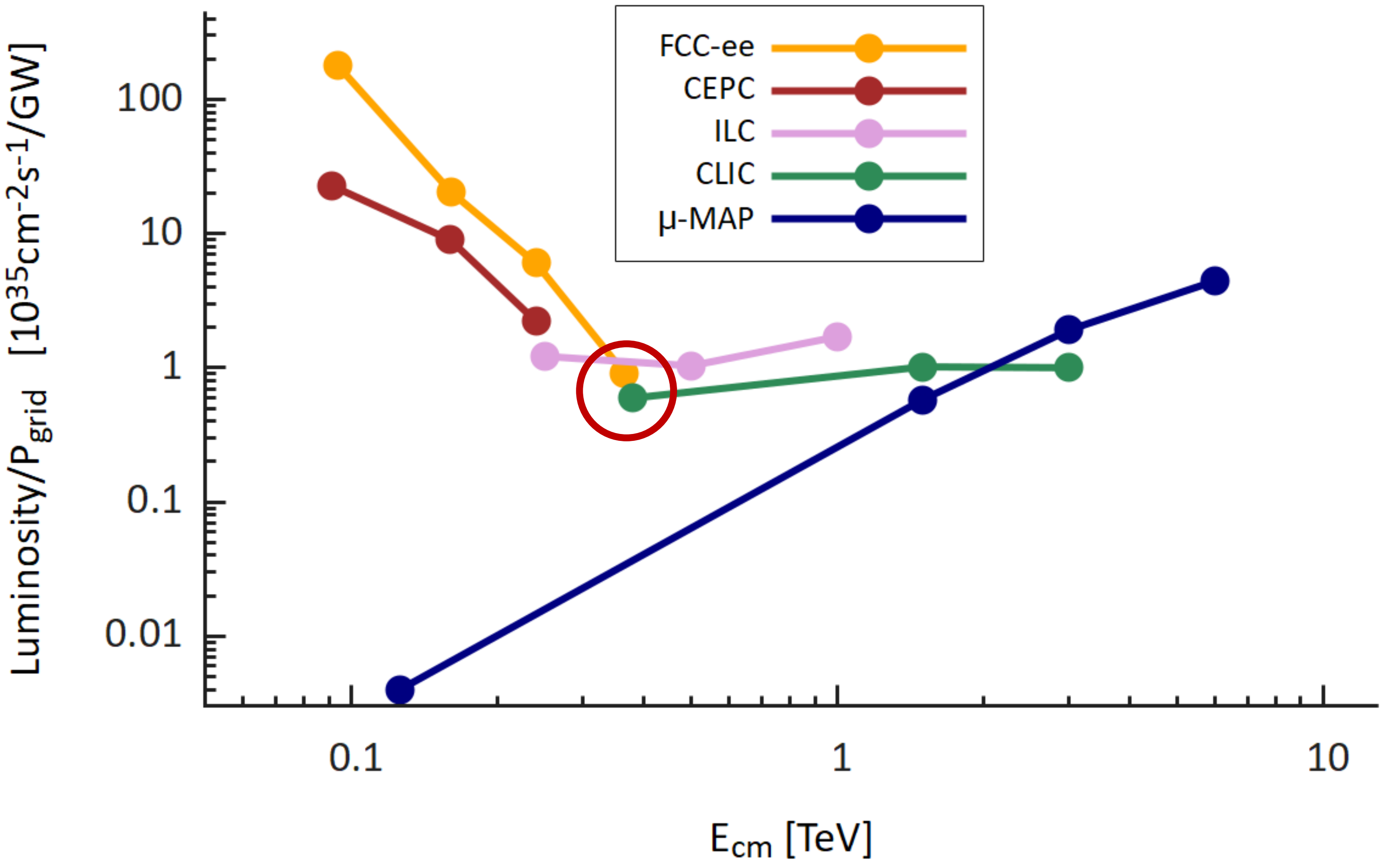
E_{cm} = 240 GeV (H)
P_{grid} = 273 MW
E_{grid}/y = 1.33 TWh

→ dominated by RF (compensating SR losses)



Overview Lepton Proposals

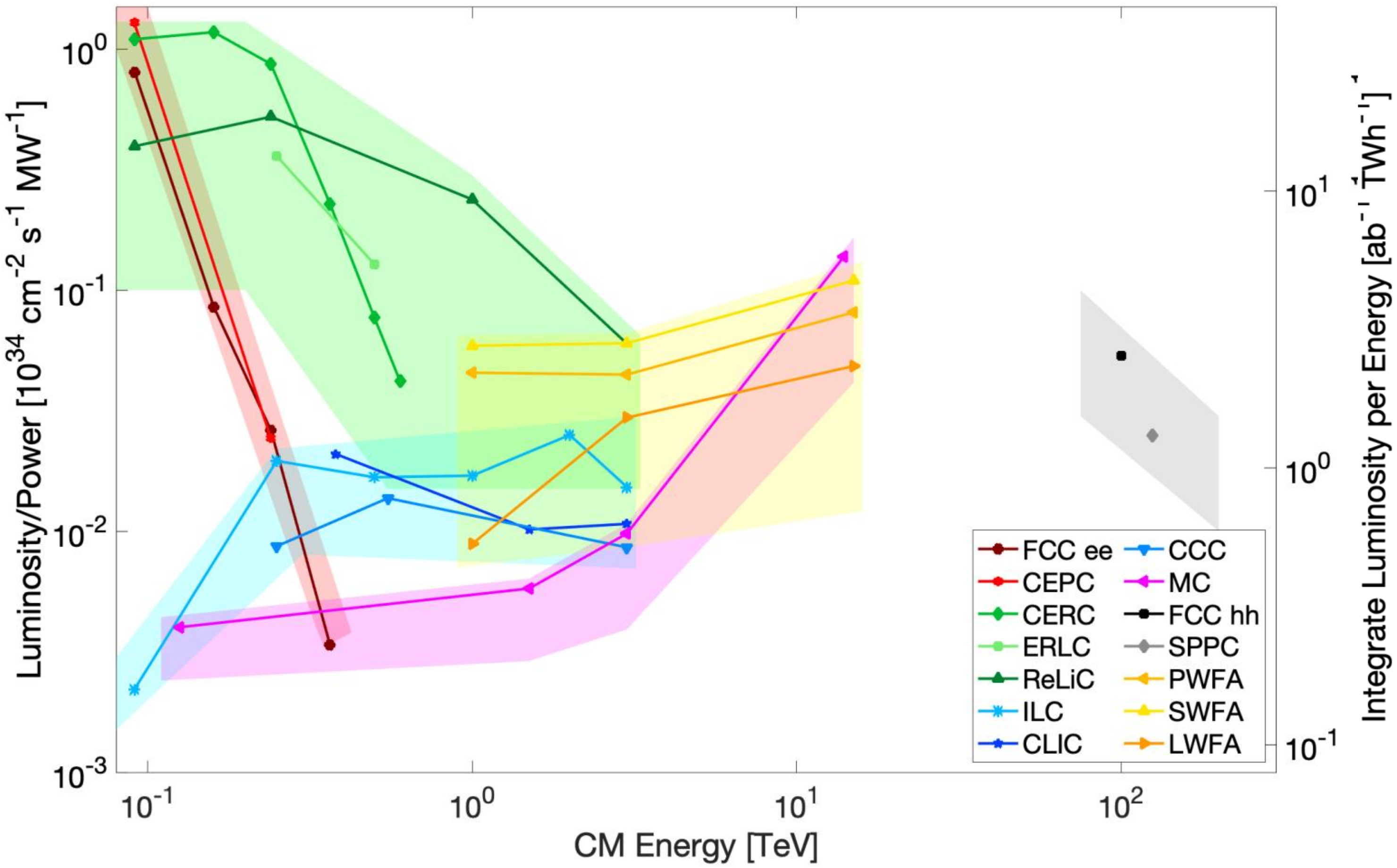
energy specific
luminosity production:



Snowmass Implementation Task Force – Assessment of 24 Collider Proposals

- includes **energy recovery concepts** and **advanced acceleration concepts**
  - PWFA = plasma wake field
  - SWFA = structure wake field
  - LWFA = laser wakefield accelerator
- includes uncertainties and integrated luminosity per energy scale

full report: **arXiv:2208.06030v2**



Assessing „Maturity“

[Snowmass, Th.Roser et al]

Technical risk categories (darker blue is higher risk).

Design status:

1. **TDR complete**
2. **CDR complete**
3. **substantial documentation**
4. **limited documentation and parameter table**
5. **parameter table**

“Overall risk tier”:

1 – lower overall technical risk

…

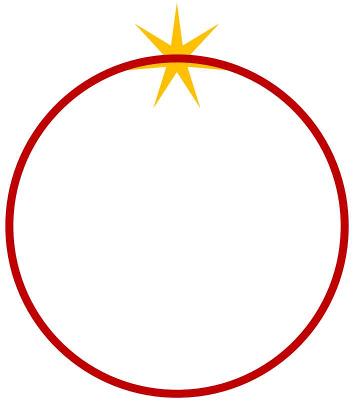
4 – multiple technologies require further R&D

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

Ring vs. Linear Collider

Ring Collider
beams circulate

Linear Collider
beams collide once



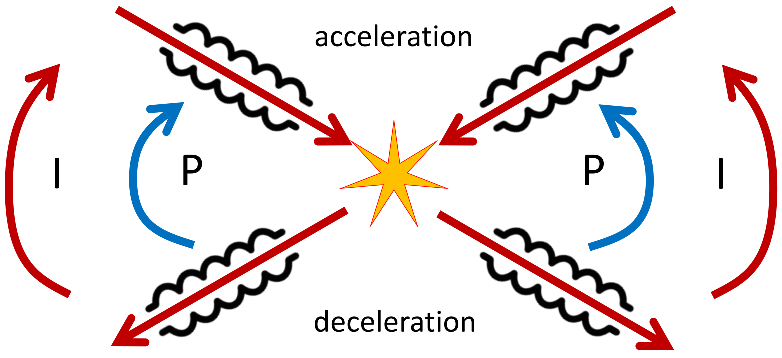
	FCC-ee 365GeV	**CLIC** 380GeV
σ_x [nm]	38‘000	150
σ_y [nm]	68	3
σ_z [μm]	2‘500	70
N [10^9]	230	5,2
f_b [kHz]	147	17,6
P_b[MW]	988	2.8

- beam reused
- synchrotron radiation dominated
- equilibrium beamsize → 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

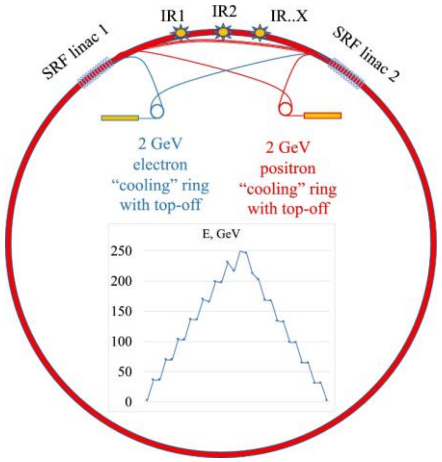
ERL
power circulates



- 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:

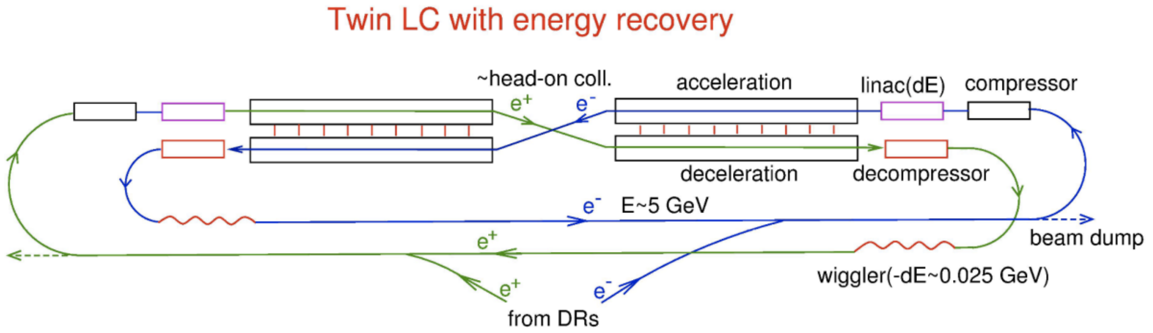


1) Circular Energy Recovery Collider
V. Litvinenko, T. Roser, M. Llatas, Physics Letter B 804 (2020) 135394

multi turn ERL, modification FCC-ee

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

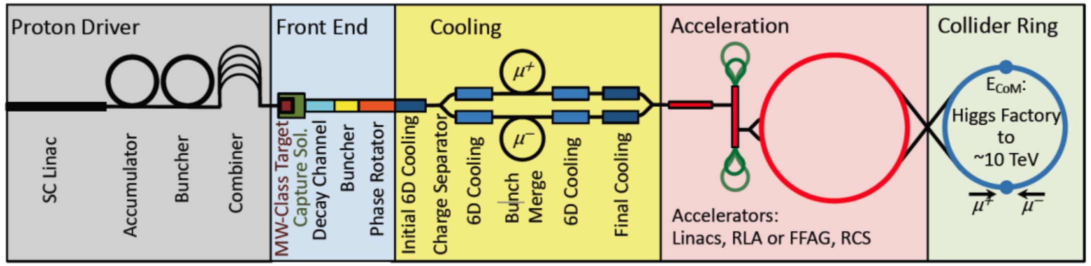
twin s.c. linacs, beam recirculation, wiggler damping



Muon Collider – Efficient at Highest Energies

Muon: E_0 = 106 MeV, τ_μ = 2.2 μs

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

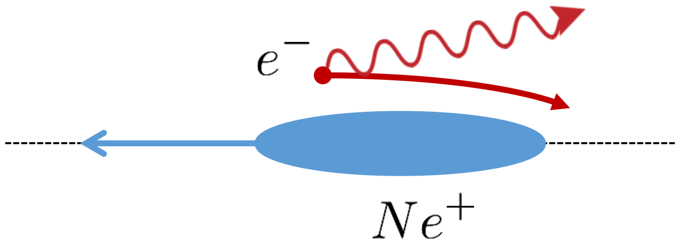


$$\frac{\delta E}{E} \approx 10^{-3}\ \text{(design)},\ \ \sigma_z \propto \frac{1}{\delta E}\ \text{(long.emittance)},\ \ \beta_{x,y} \propto \sigma_z\ \text{(hourglass)},\ \ \rightarrow \beta_{x,y} \propto \frac{1}{\gamma}$$

thus L/P is increasing with energy:

$$\mathcal{L} \propto \frac{N^2}{\sigma_x \sigma_y} \propto \frac{N^2}{\sqrt{\varepsilon_x \beta_x \varepsilon_y \beta_y}} \propto \frac{N^2}{\varepsilon_n}\gamma^2 \propto \frac{N}{\varepsilon_n}\gamma P_{\text{beam}}$$

Beamstrahlung in e+/e- collider:

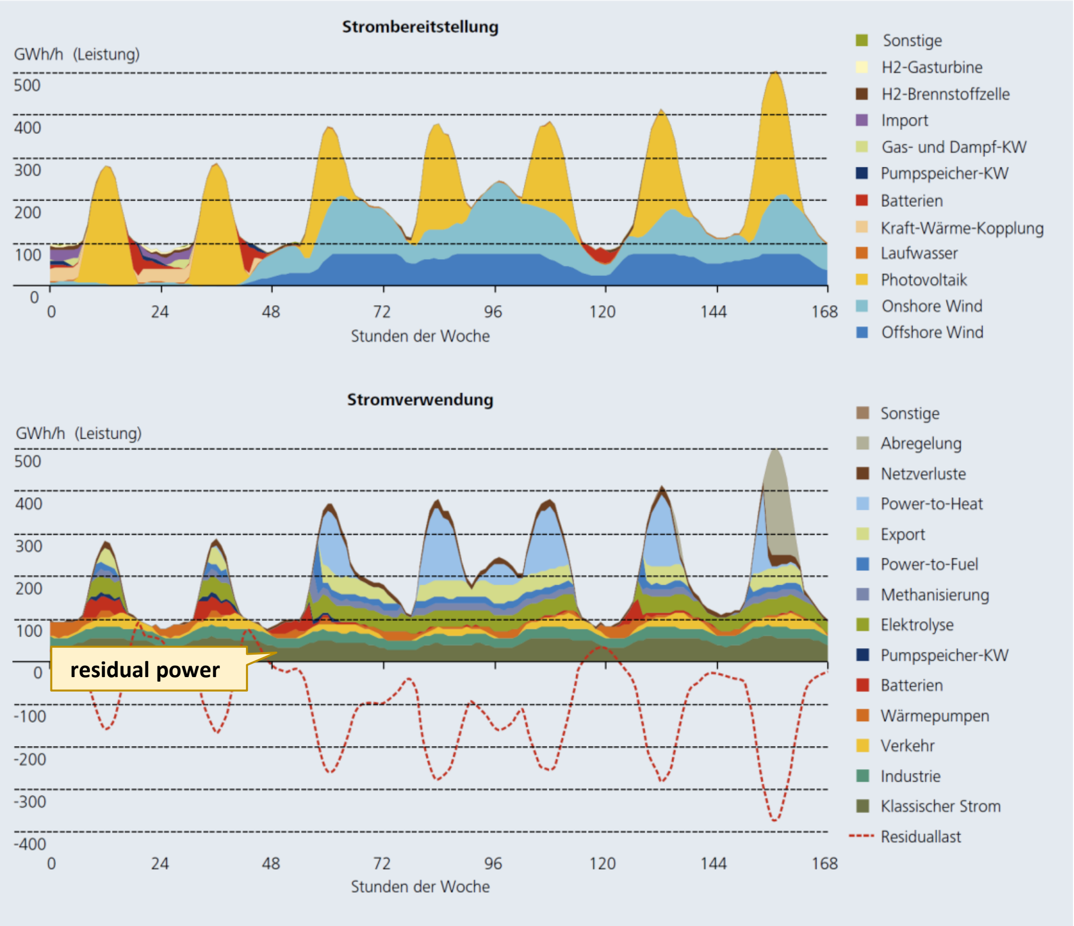


The Future – Fluctuating Energy Sources

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**

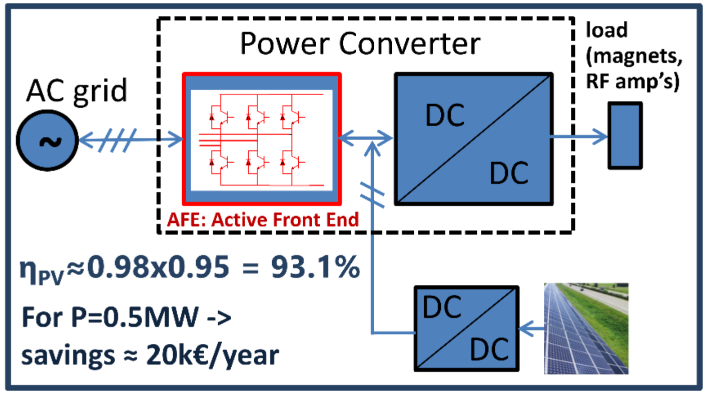


- full collider operation at times of high grid production
- reduced operation or standby modes with fast L recovery otherwise

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

Supporting measures to increase sustainability of accelerators

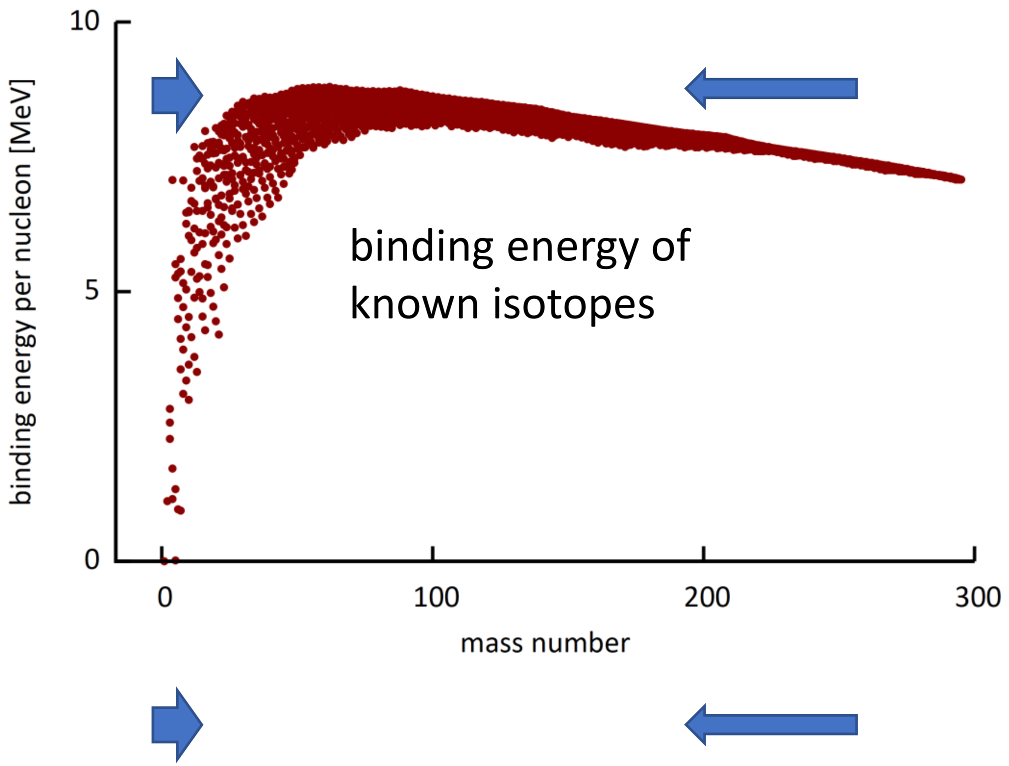
- use of waste heat for heating, heat pumps
- photovoltaic energy production
- careful management of resources like He, water
- thoughtful acquisition of critical materials, e.g. rare earth mats.



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

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

Comment on Energy Production (actually Conversion)



- **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.

Also for fusion reactors we have synergetic technologies 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.

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