Beam Physics Frontier Problems

in 25 minutes

Frank Zimmermann
eeFACT’22 ICFA Workshop
13 September 2022

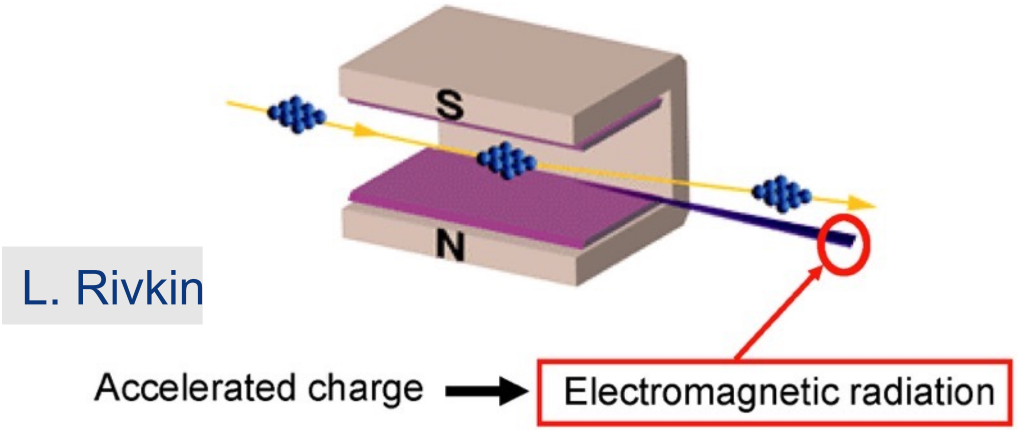
many thanks to Prof. Jie Gao and the Program Committee

major beam frontier challenges

1. synchrotron radiation
2. bending magnetic field
3. accelerating gradient
4. (rare) particle production – e^+ and μ
5. cost and sustainability
6. exploring novel directions

challenge #1: synchrotron radiation (SR)

circular colliders



energy loss per particle per turn

$$U_0 = \frac{e^2}{3\varepsilon_0} \frac{\gamma^4}{\rho}$$

SR power

$$P_{SR} = \frac{I_{beam}}{e} U_0$$

e±: P_{SR} = 23 MW for LEP (former e+e- collider in the LHC tunnel),
100 MW for FCC-ee (imposed as design constraint),

protons: P_{SR} = 0.01 MW for LHC,
5 MW for FCC-hh – this requires >100 MW cryoplant power

SR in the arcs: possible mitigations (challenge #1)

mitigations:

- **large bending radius ρ**

  → large circular collider → *next slide*

- **linear collider**

  - ”almost” no arcs, but beamstrahlung → *next next slides*

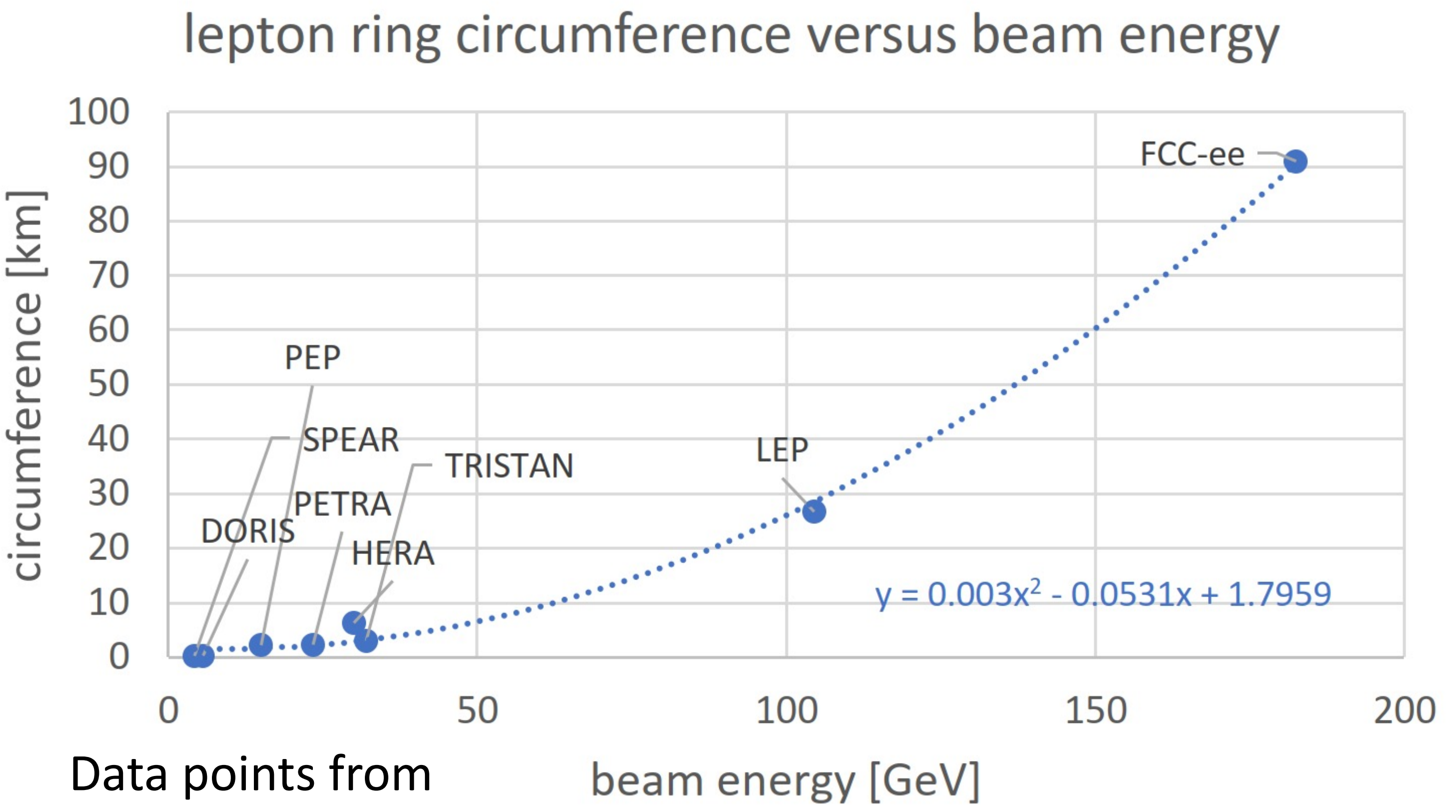
- **muon collider**

  - μ ~200 heavier than $e^{\pm}$ → ~10^9x less radiation at same energy and radius, but μ's decay → *later*

- **shaping beam vacuum chamber or the beam itself**

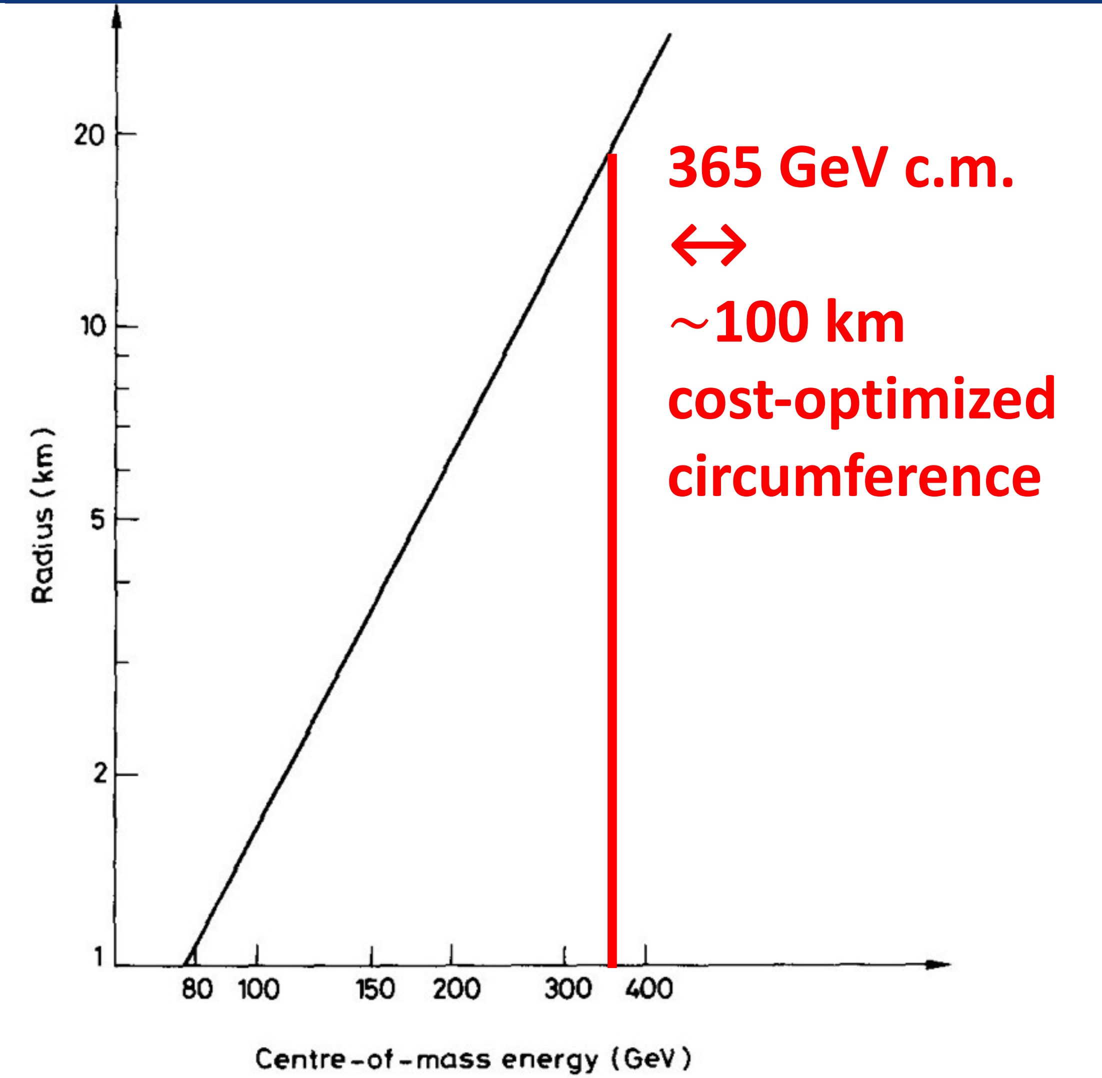
  - tiny vacuum chamber in large ring, $\lambda_{sh} \approx 2\sqrt{d^3/\rho}$ with *d:* pipe diameter
  - beam shaping to suppress radiation; a DC beam does not radiate! explored in EU projects ARIES & I.FAST → *later*

SR → size of circular e^+e^- colliders (challenge #1)



Data points from S. Myers, “*FCC - Building on the Shoulders of Giants*”, submitted to EPJ+ (2021)

Serendipitously, 90-100 km is exactly the size required for a 100 TeV hadron collider and optimum tunnel size in the Lake Geneva basin !



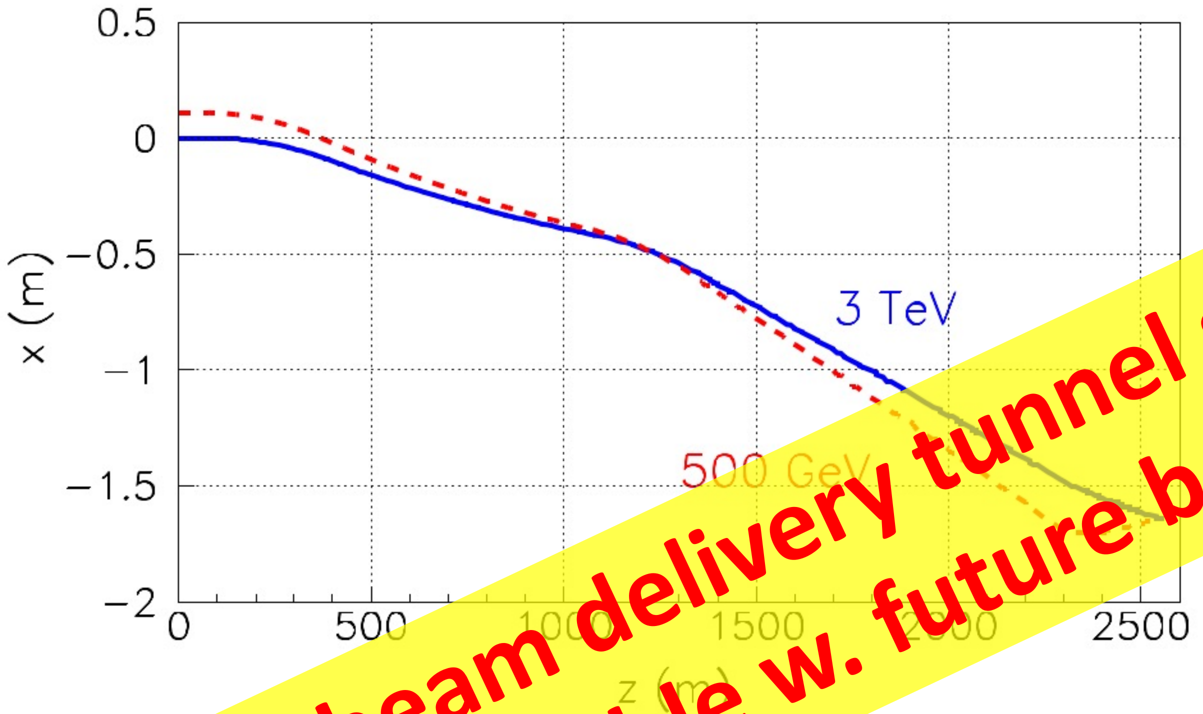
B. Richter, “*Very High Energy Electron-Positron Colliding Beams for the Study of Weak Interactions*”, NIM 136 (1976) 47-60

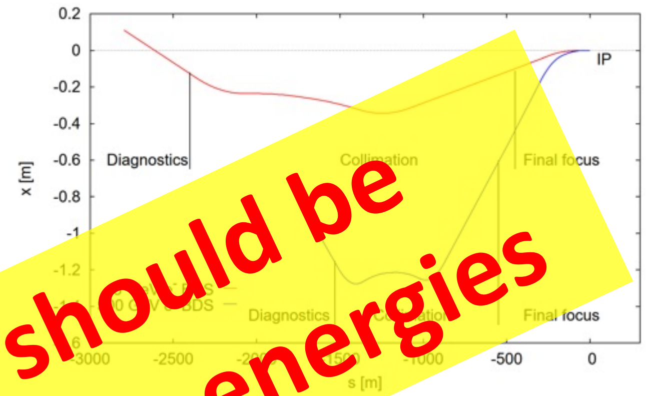
circular colliders

SR → linear collider beam delivery (challenge #1)

linear colliders

SR in bending magnets of the beam-delivery system





Other footprints of CLIC 3-TeV and 500-GeV beam delivery systems (G. Zamudio, R. Tomas, 2011, CLIC-Note-882)

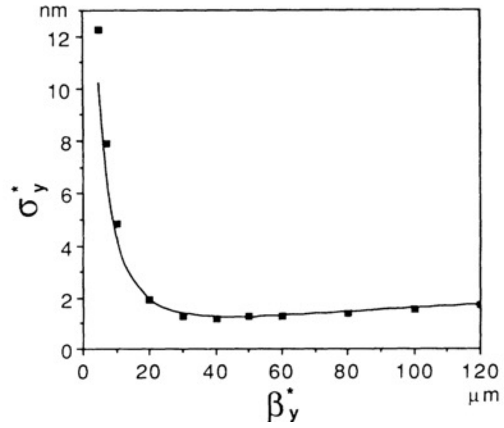
beam delivery tunnel should be compatible w. future beam energies

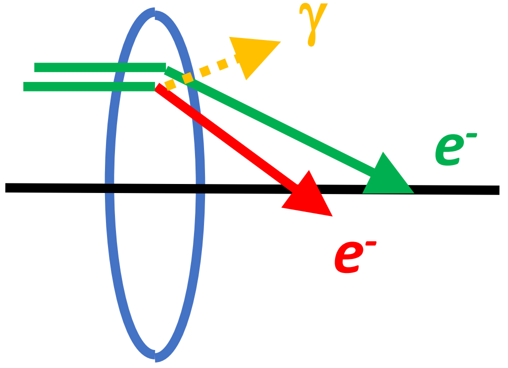
SR in final quadrupole magnet ("Oide effect") limits collision spot size

K. Oide, Phys. Rev. Lett. 61, 1713 (1988)

Historical footprints of CLIC 3-TeV and 500-GeV beam delivery systems (M. Aleksa et al., 2003, CLIC-Note-551)

SR in bending magnets caused a factor ~2 loss in luminosity in 2003 CLIC BDS design at 3 TeV; similarly for the SLC at 91 GeV c.m. (!)



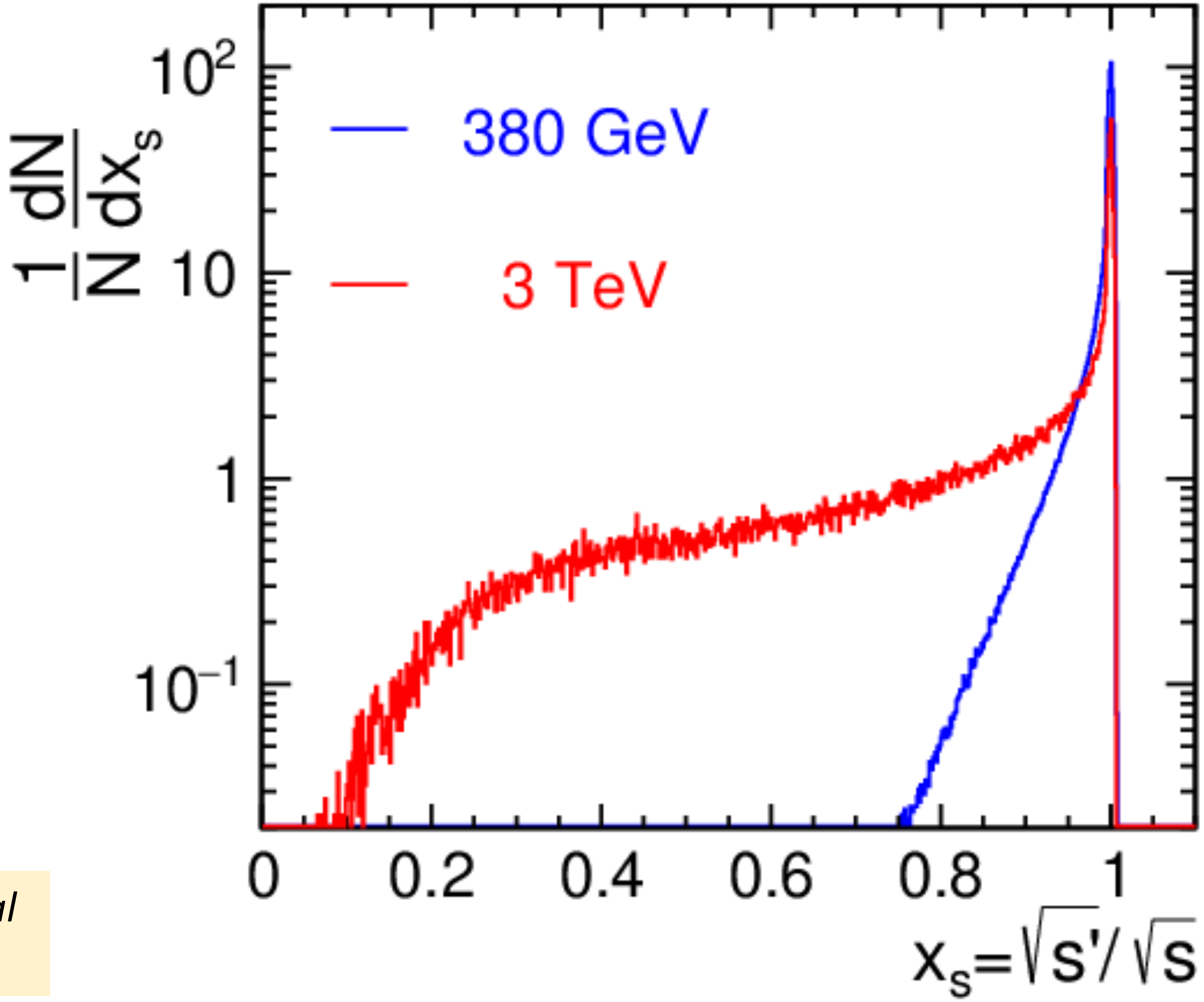


final quadrupole lens

challenge #1: synchrotron radiation - cont'd

linear colliders

synchrotron radiation in the strong field of the opposing beam (="**beamstrahlung**") degrades the luminosity spectrum



CLIC at 380 GeV: 60% of total luminosity within 1% of target energy

CLIC at 3 TeV: only 33% of total luminosity within 1% of target

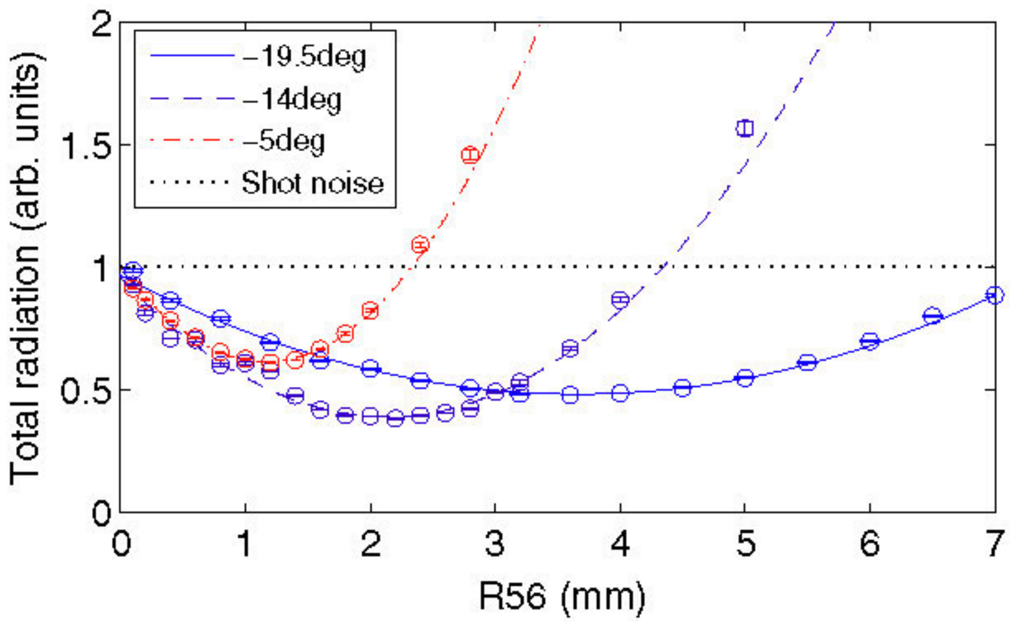
e^+e^- collisions in linear colliders lose their distinct energy precision

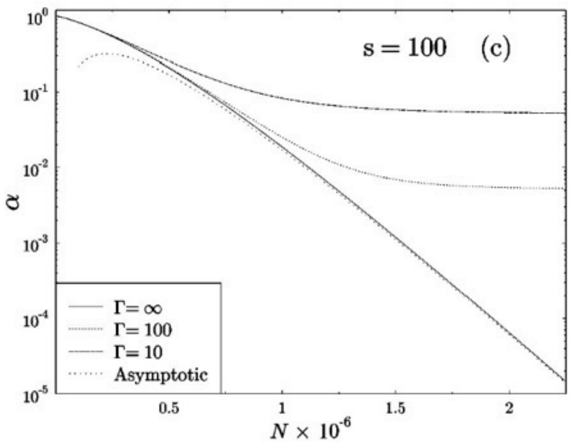
D. Schulte

H. Abramowicz, *et al* - arXiv:1807.02441

suppressing synchrotron radiation: shaping the beam?

- **DC beam does not radiate**
- suppression of shot noise and reduced radiation demonstrated at SLAC NLCTA, D. Ratner et al., PRST-AB 18, 050703 (2015)
- 1 D crystalline beam (acceleration by induction acceleration)?





***N*~10^6**
particles uniformly distributed
→
factor 50 reduction in total SR power

Synchrotron radiation of crystallized beams, Harel Primack and Reinhold Blümel, Phys. Rev. E 60, 957 (1999)

suppressing synchrotron radiation: tailoring boundary?

tailoring the boundary

- large bending radius + small chamber size provide shielding
  - *effect seen at RHIC*
- HTS coating for small (mm/micro/nano-) chamber?
- hollow channel shield?

$$\lambda \geq 2\sqrt{h^2\, w/\rho}$$

h: full chamber height

w: full chamber width

ρ: bending radius

Examples:

h=*w*=1 cm, ρ=1 km → λ >600 nm (2 eV)

***h*=*w*=1 mm, ρ=10 km → λ >0.6 nm (2 keV)**

***h*=*w*=0.1 mm, ρ=10 km → λ >2 pm (600 keV)**

parameters	particle		Au^{79+}		d
	E_0	GeV/n	70	100	101.9
	γ		75.2	107.4	108.7
Synch. rad. free space	U_s	eV/turn	4.95	20.6	0.003
Synch. rad. reduced	U_s	eV/turn	0.3	9.1	0.0
Impedance	σ_w	mm	0.383	0.268	0.265
	k_{diff}	V/pC	4744	4777	4778
	k_{rw}	V/pC	230	394	401
	$U_{imped.}$	eV/turn	4.97	5.17	0.8×10^{-3}
Ionization	P	nTorr	1	1	1
	U_{ion}	meV/turn	9.3	9.7	9.7
Total Calculated	U_{total}	eV/turn	5.3	14.3	0.02
Total Measured	U_m	eV/turn	7	12	0.5
	δU_m	eV/turn	1	2	1

first experimental evidence for suppression of incoherent synchrotron radiation,

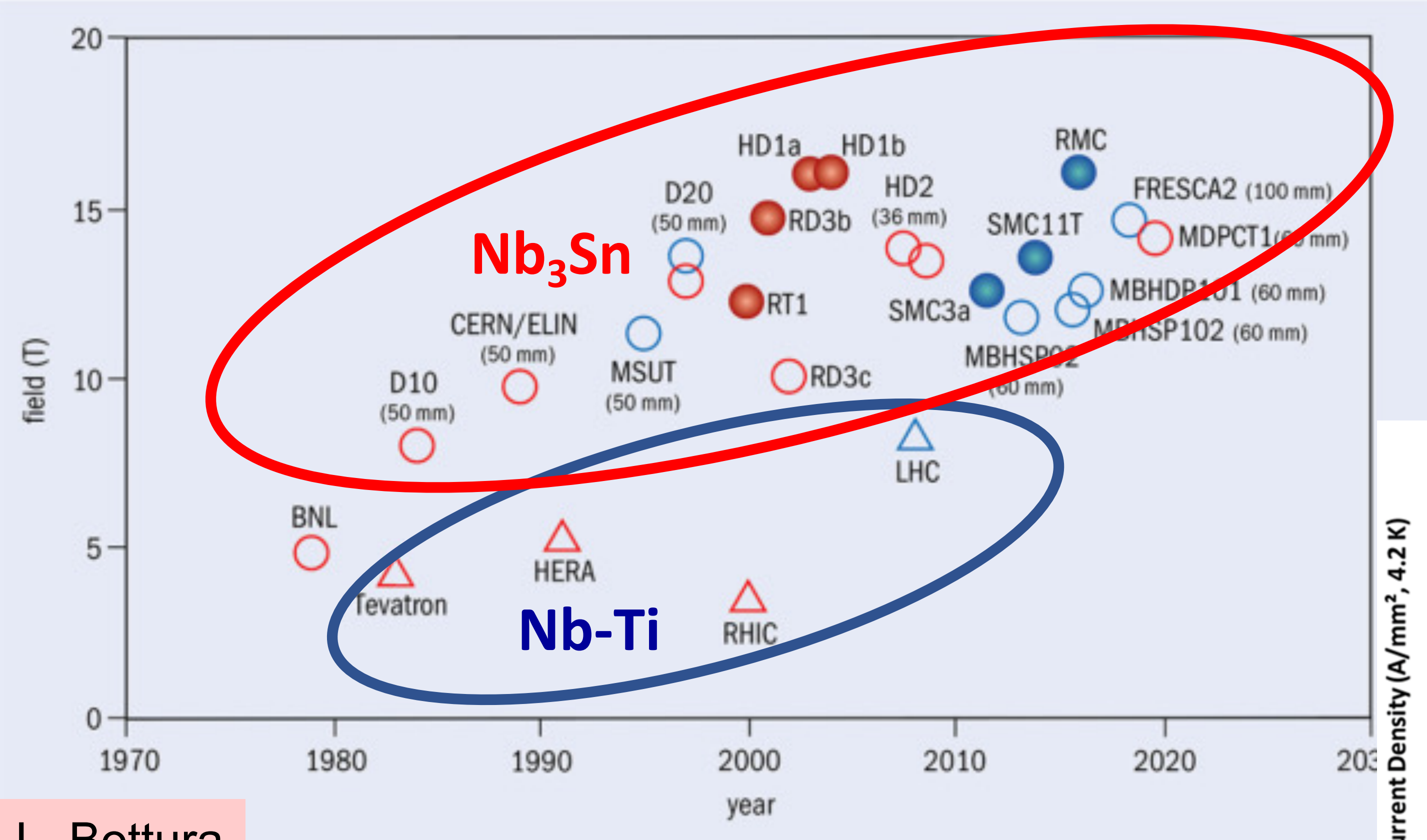
N. P. Abreu et al., EPAC'08

SR suppression in plasma

above plasma frequency: index of refraction < 1 : phase velocity of light > 1 → suppression of synchrotron emission

"Razin-Tsytovich effect"

challenge #2: bending magnetic field



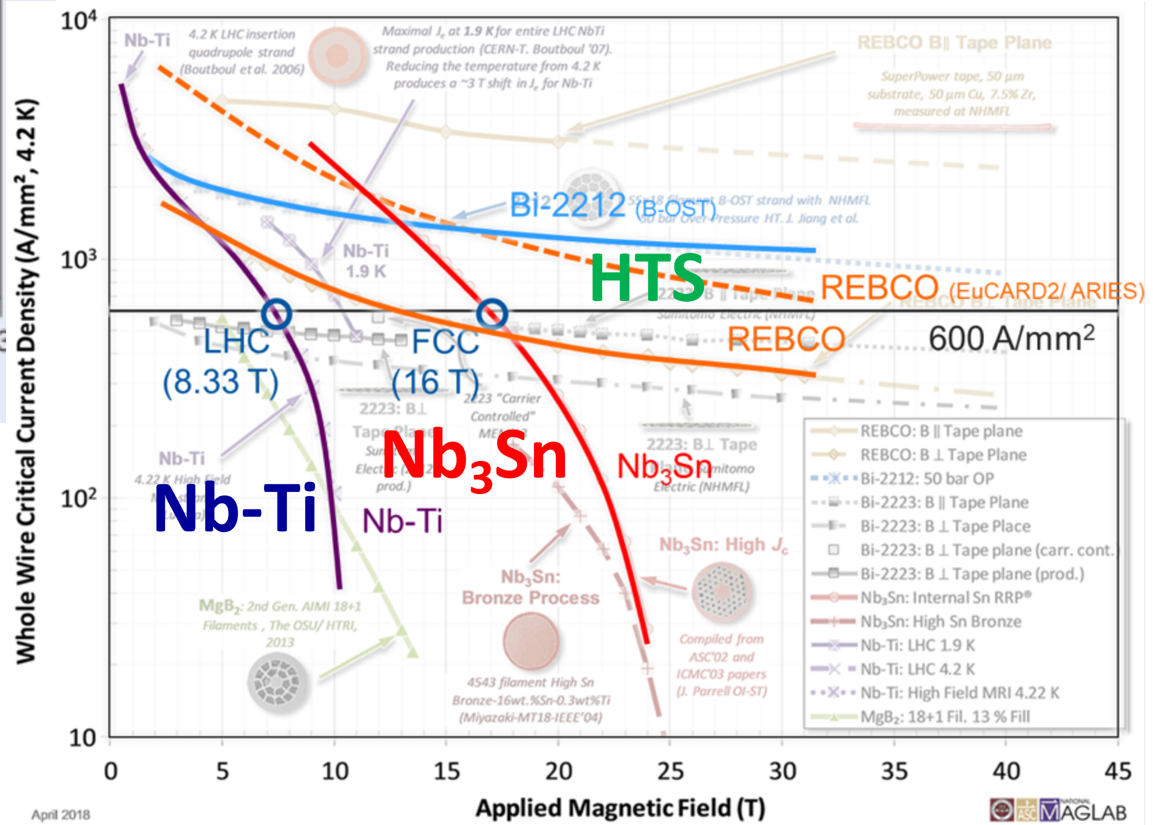
L. Bottura

Record fields attained with dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature.

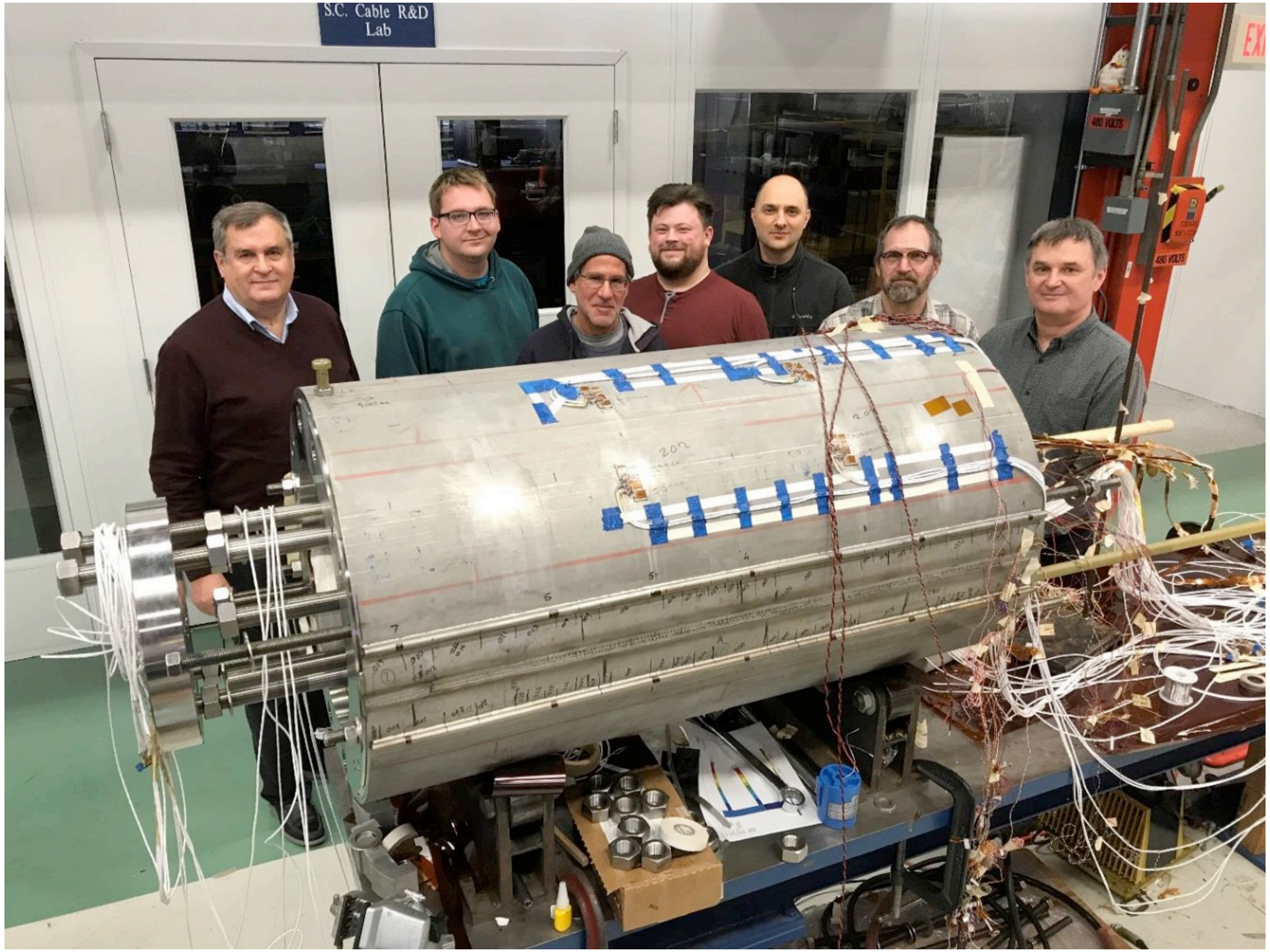
→ hadron collider energy reach

Superconducting wire critical current density versus magnetic field.

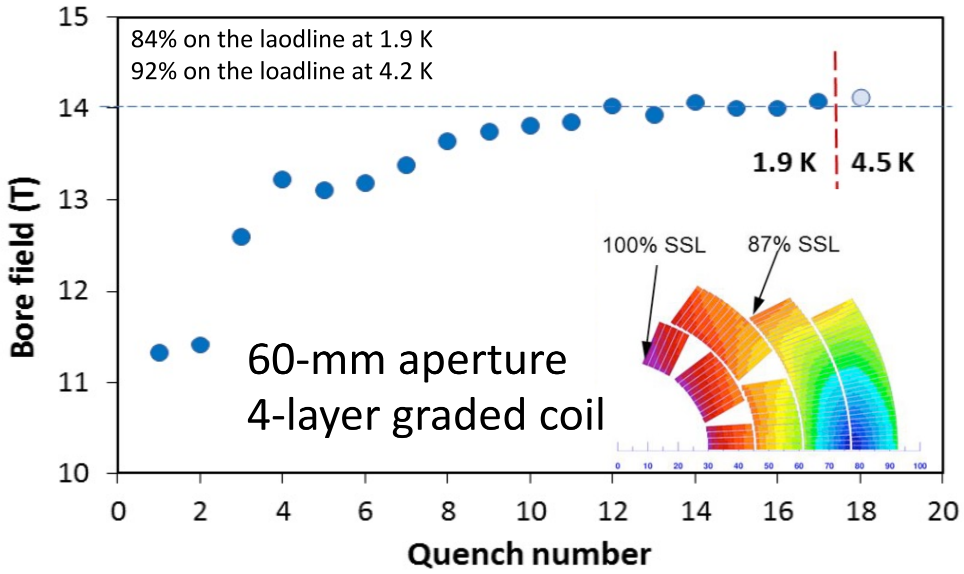
P. Lee



US – MDP: 14.5 T magnet tested at FNAL

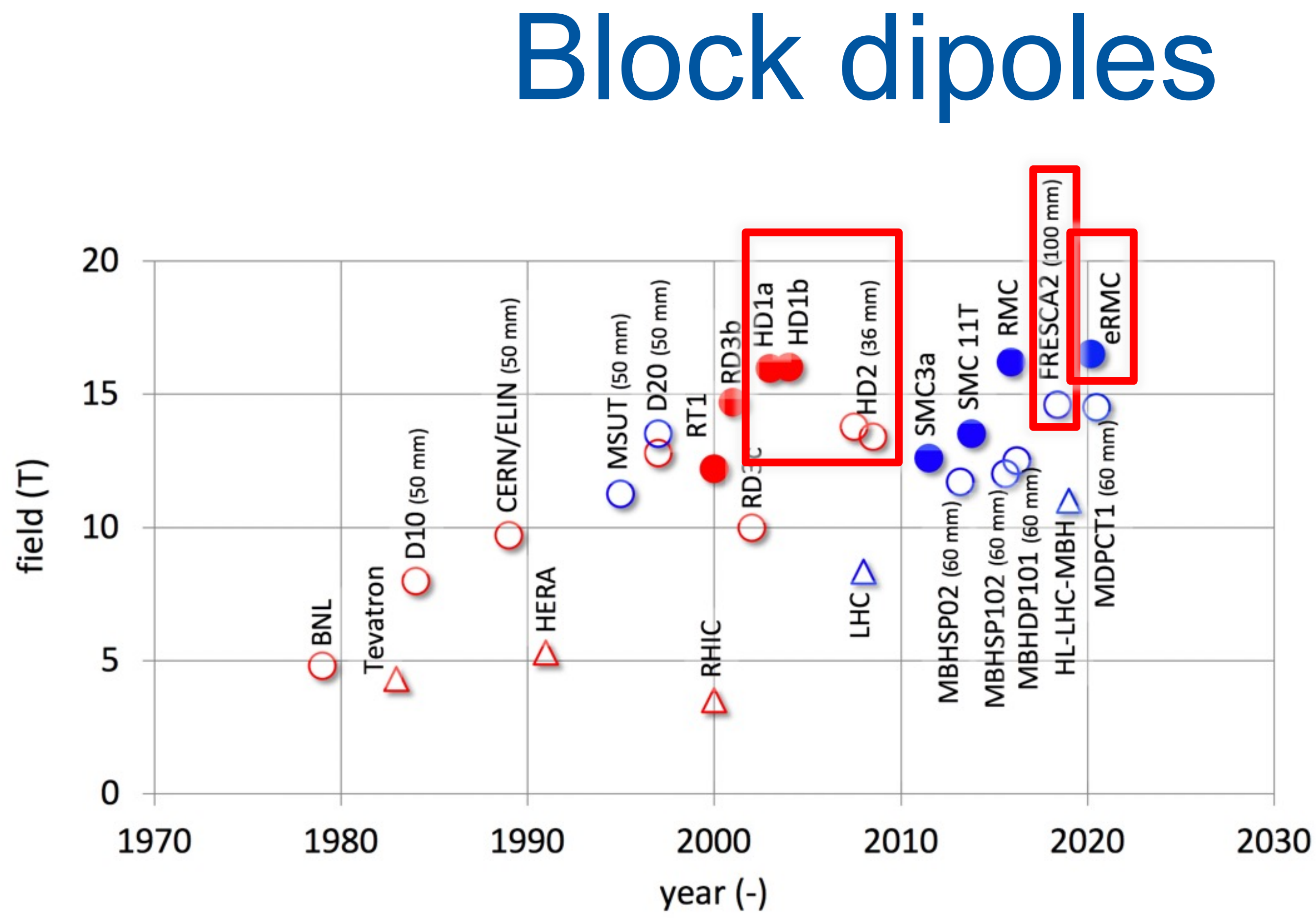


cosθ dipole

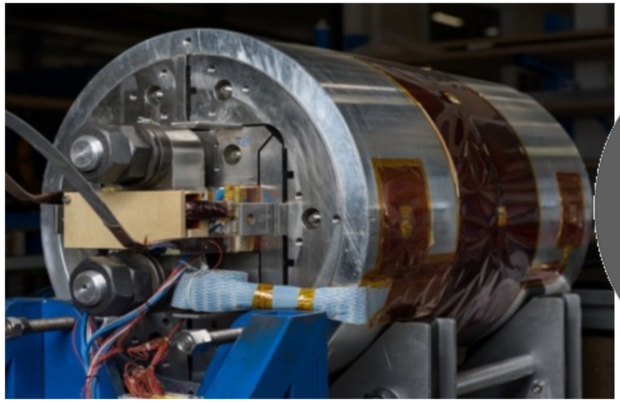


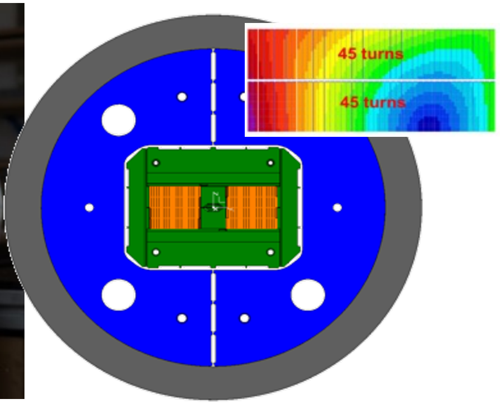
- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

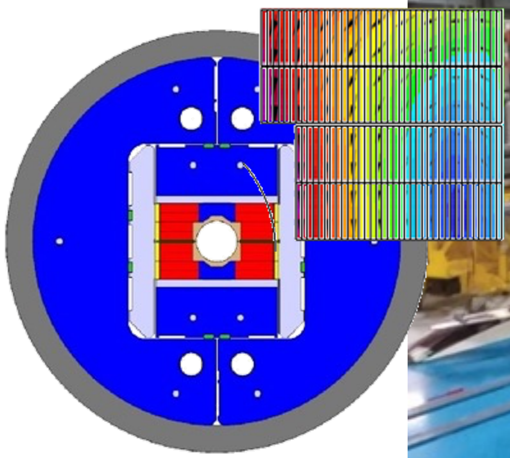
CERN Nb_3Sn progress: FRESCA2 & eRMC



RMC/eRMC (2-decks, no aperture), 16.5 T



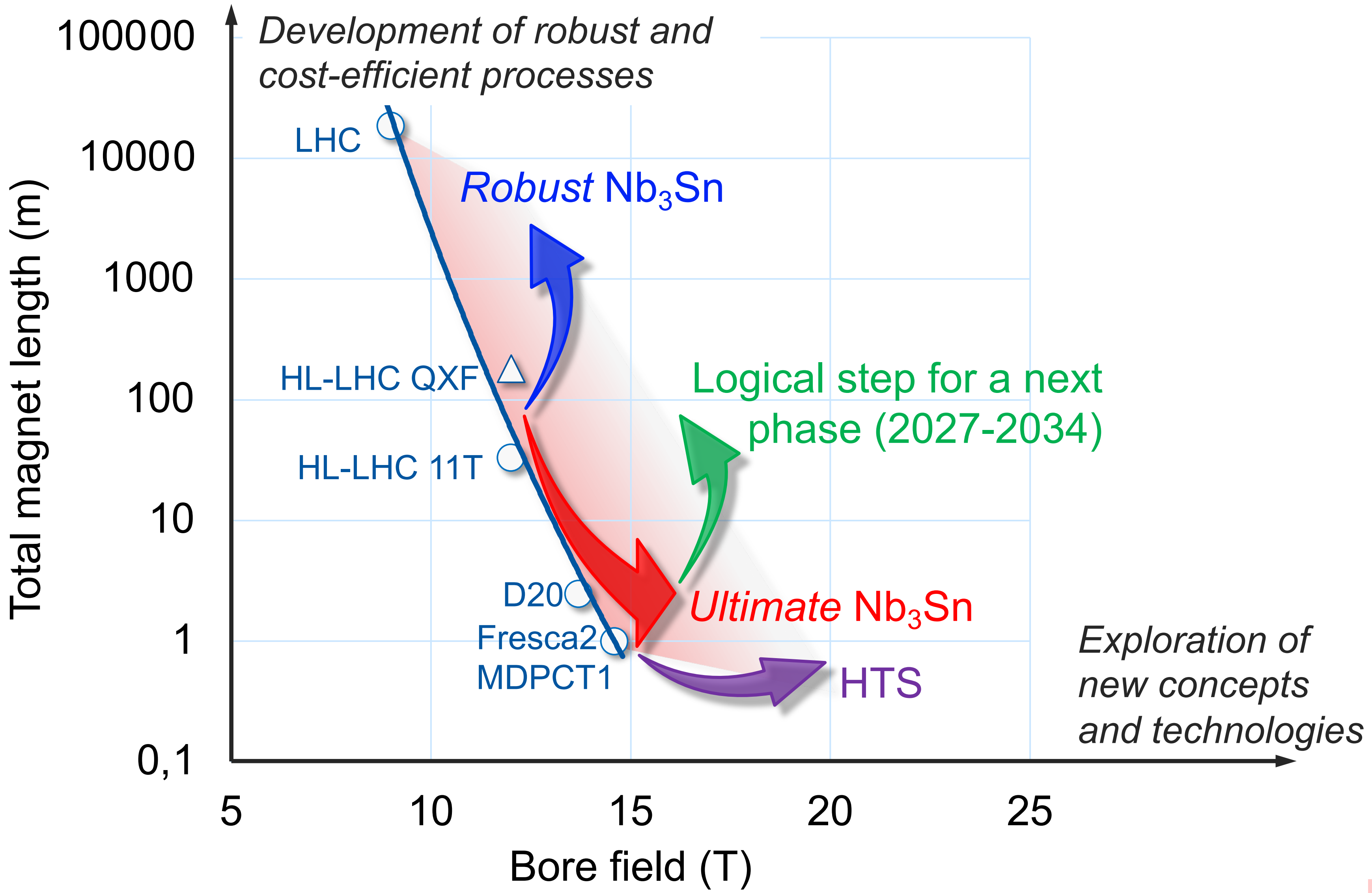




FRESCA2 (4-decks, 100 mm), 14.6 T

Luca Bottura

High-Field Magnets - R&D Program Goals



Luca Bottura

Nuclear Fusion Magnet R&D Progress

RESEARCH & APPLICATIONS

MIT ramps 10-ton magnet up to 20 tesla in proof of concept for commercial fusion

Fri, Sep 10, 2021, 6:59PM | Nuclear News

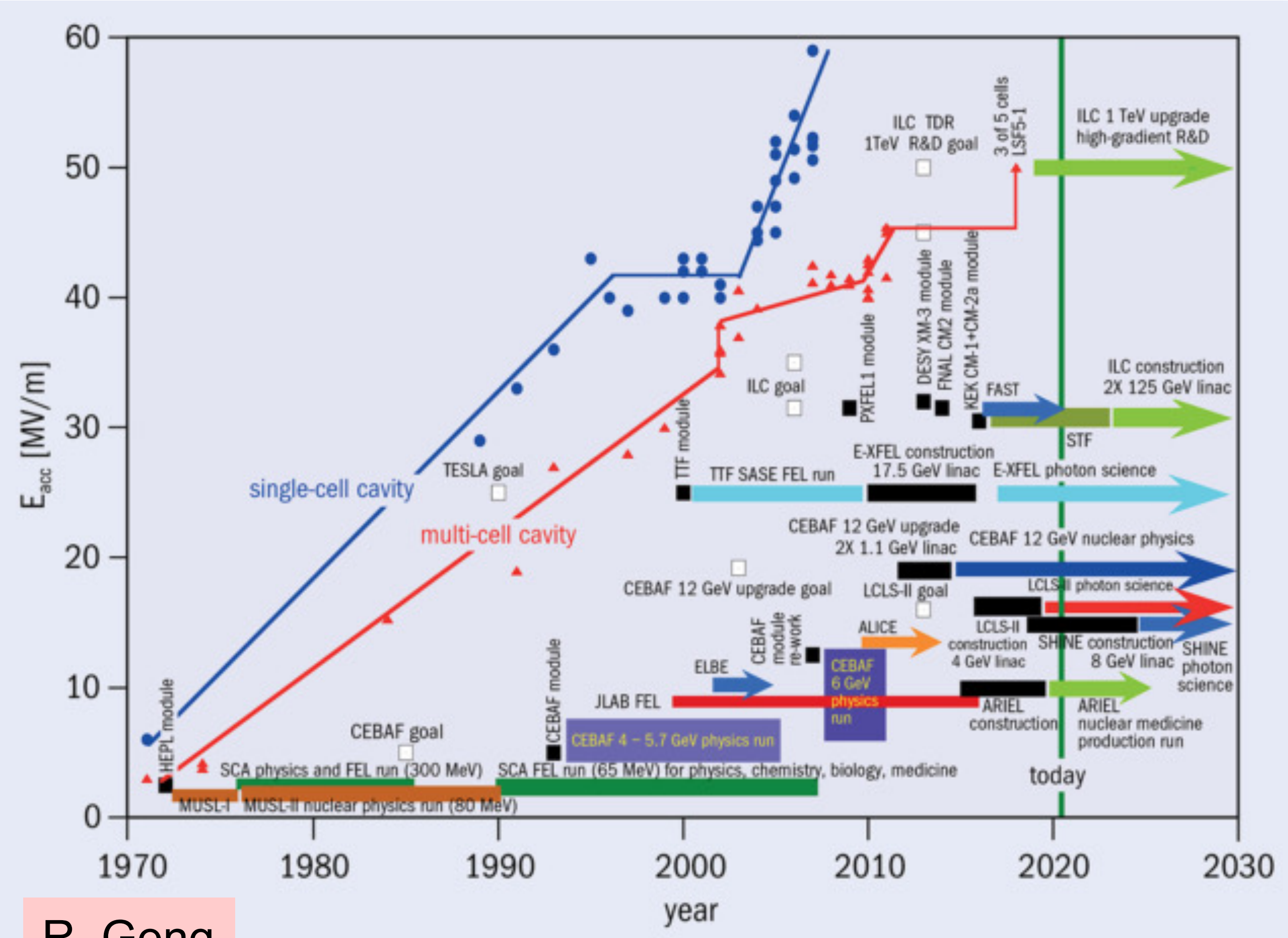
September 2021

toroidal model coil

This large-bore, full-scale high-temperature superconducting magnet designed and built by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center is the strongest fusion magnet in the world. (Photo: Gretchen Ertl, CFS/MIT-PSFC)

challenge #3: accelerating gradient

Gradient growth Superconducting RF linac accelerating gradient achievements and applications since 1970. CERN Courier 2020



R. Geng

RF Accelerators

R. Aßmann

> 30,000 operational – many serve for Health

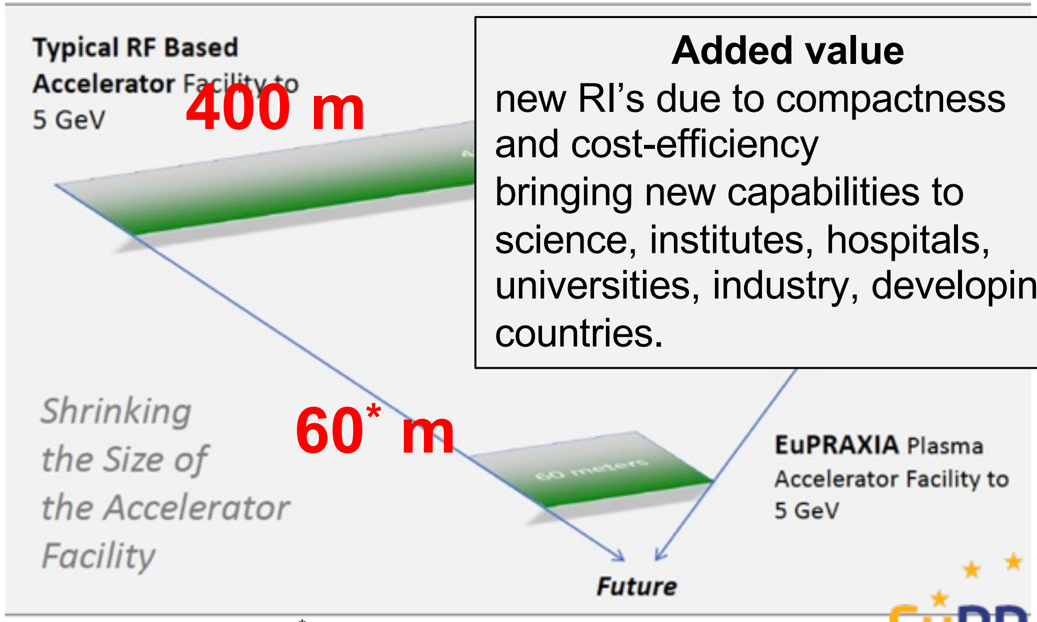
30 million Volt per meter

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt per meter



Added value

new RI's due to compactness and cost-efficiency

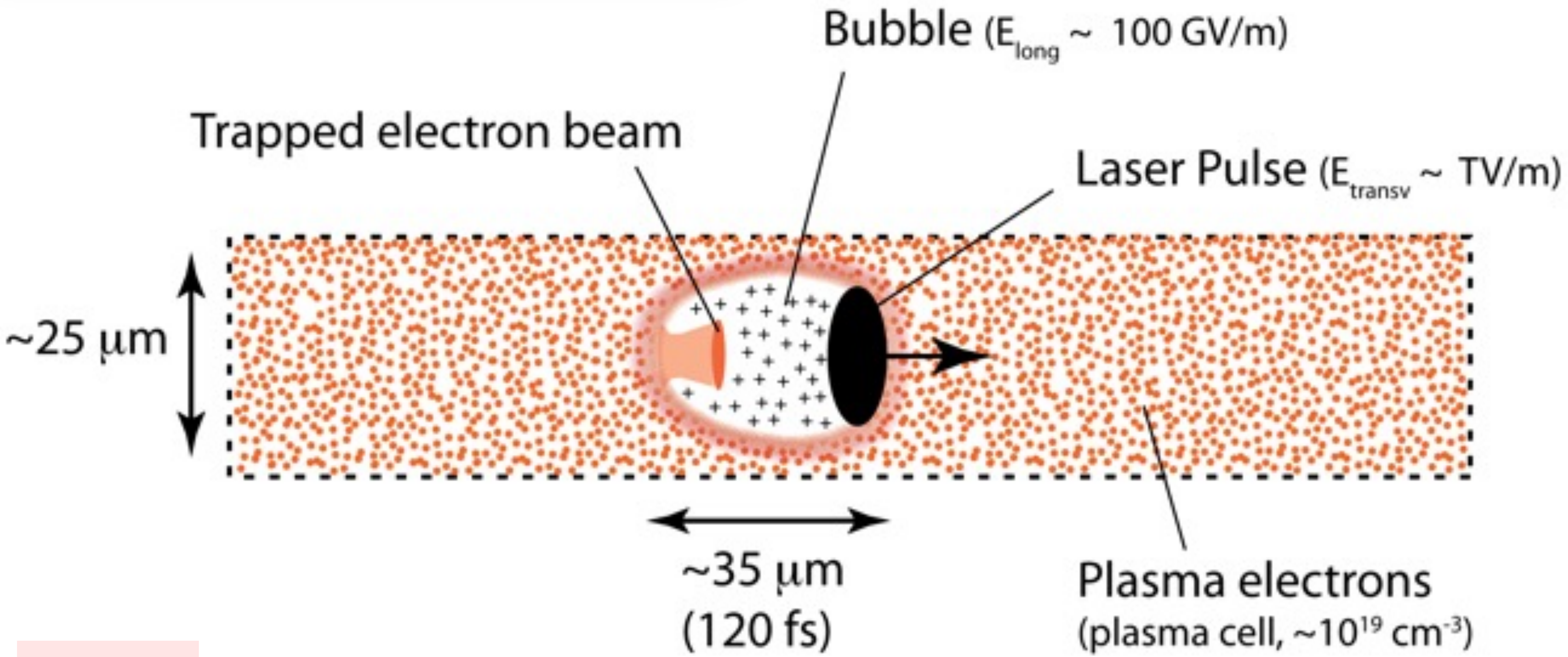
bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

*realistic design including all required infrastructure for powering, shielding,

EuPRAXIA

High-Gradient Acceleration (Plasma/Laser)

This accelerator fits into a human hair



R. Assmann

plasma acceleration of positrons ? (required for e^+e^- collider)

"ballistic injection": a ring-shaped laser beam and a coaxially propagating Gaussian laser beam are employed to create donut and center bubbles in the plasma, resp.

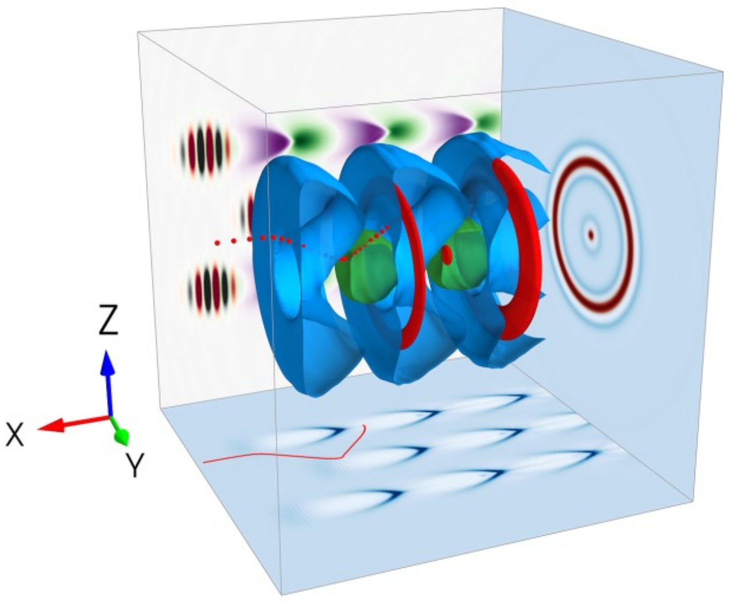
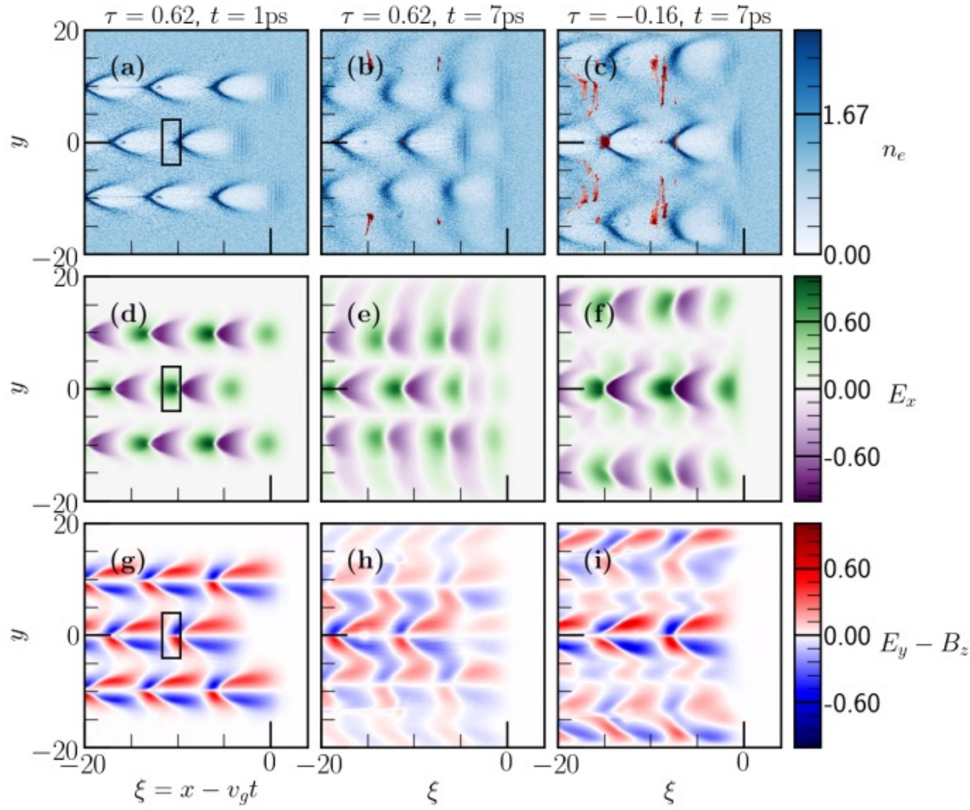


FIG. 1. The concept of the positron ballistic injection scheme. The blue and green colors are contour surfaces of electron densities of donut and center bubbles, respectively. The red color represents injected positrons. The x–y and x–z planes are transverse slices of the density distribution and the longitudinal electric field E_x. The red curve in the x–y plane is the trajectory of an injected positron (corresponding to the projection of red balls in the 3D model). The leading oscillating colors (amber and grey) denote the laser beams in the x–z plane. The y–z plane is the projection of electron density (blue) and injected positron density (red).



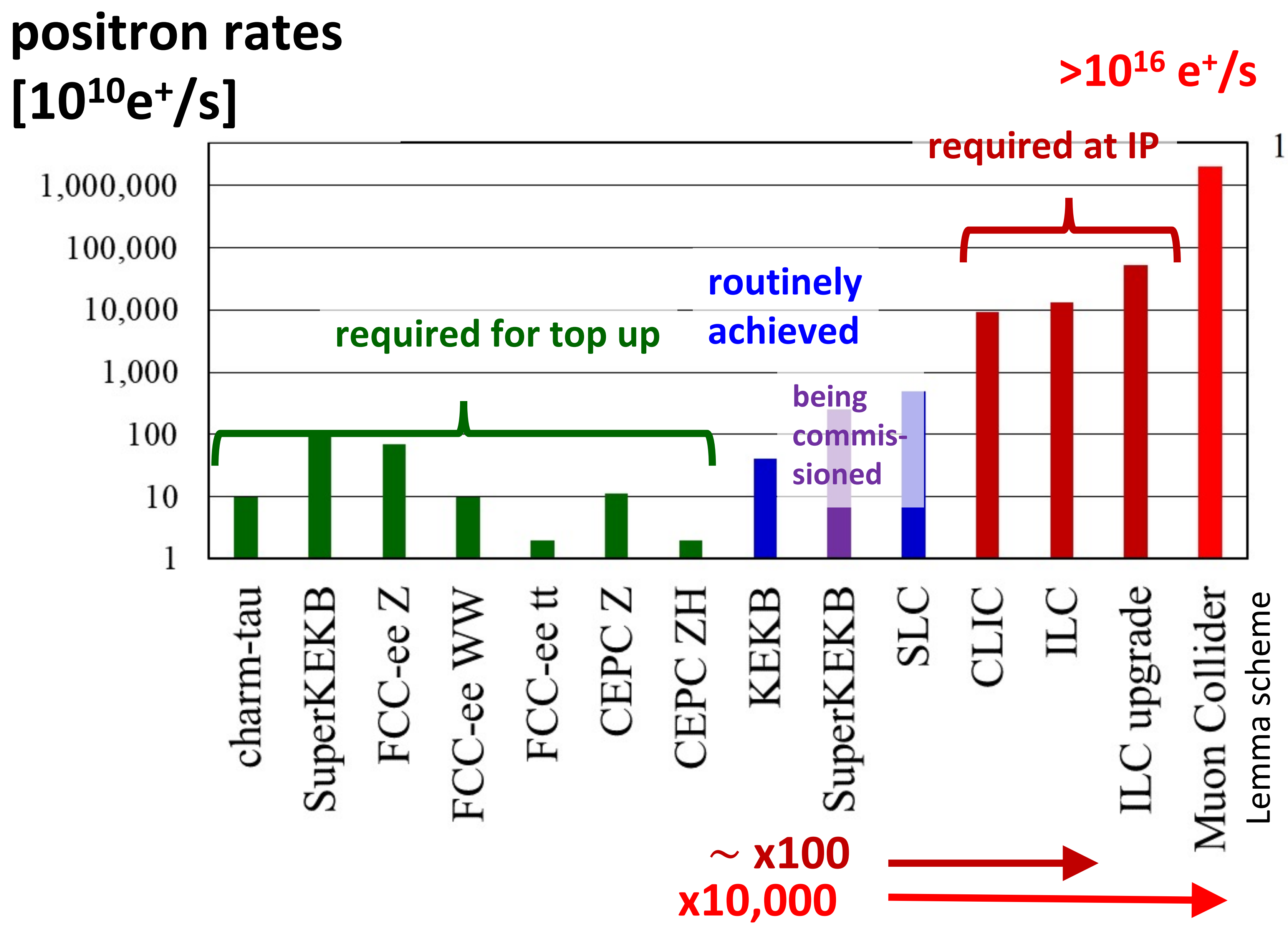
PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 091301 (2020)

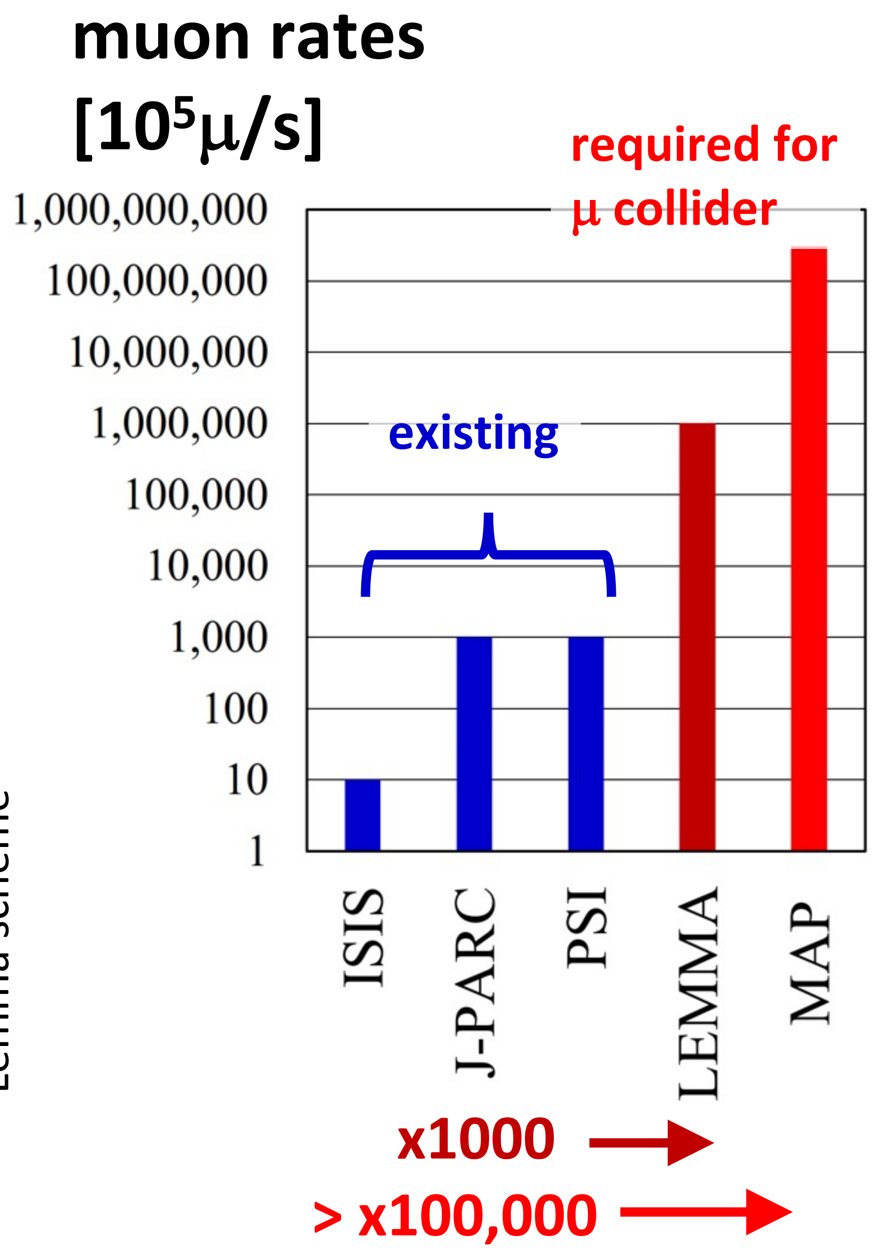
New injection and acceleration scheme of positrons in the laser-plasma bubble regime

Z. Y. Xu,[1] C. F. Xiao,[1] H. Y. Lu,[1,2,3,*] R. H. Hu,[1,†] J. Q. Yu,[1,‡] Z. Gong,[1] Y. R. Shou,[1] J. X. Liu,[1] C. Z. Xie,[1] S. Y. Chen,[1] H. G. Lu,[1] T. Q. Xu,[1] R. X. Li,[4] N. Hafz,[5] S. Li,[5] Z. Najmudin,[6] P. P. Rajeev,[7] D. Neely,[7] and X. Q. Yan[1,3]

Z.Y. Xu

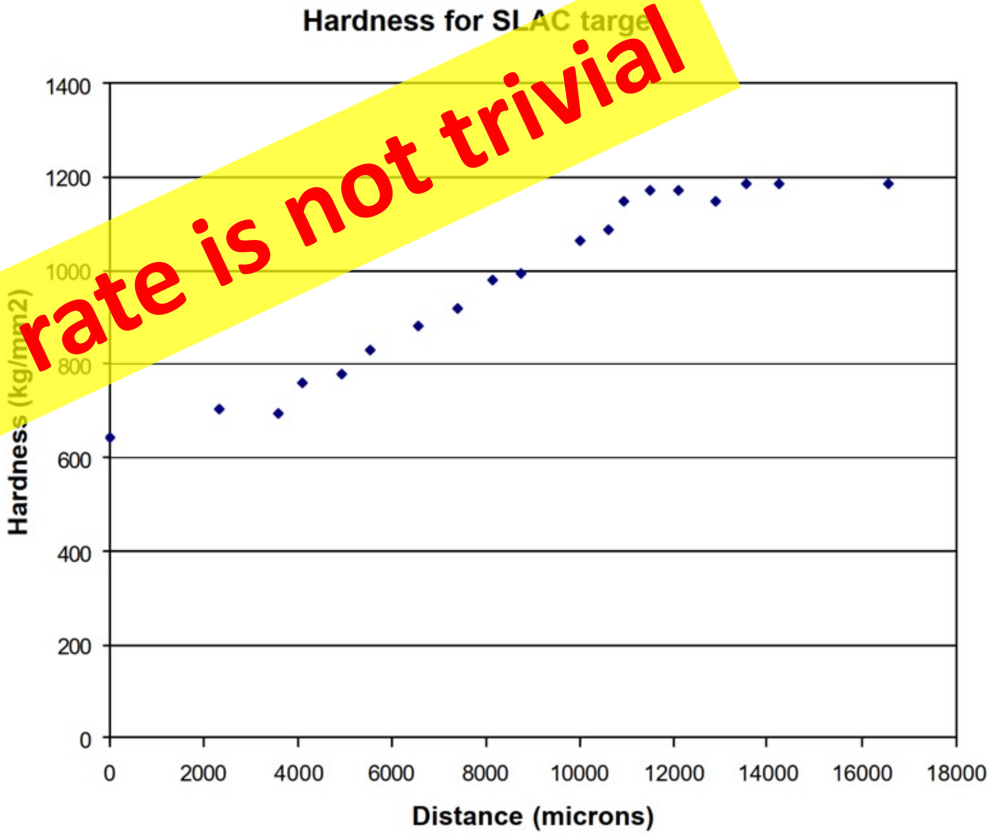
challenge #4: particle production – e^+, μ





failure of SLC e^+ target after 5 years of operation (challenge #4)

SLC target analysis at LANL: Failed SLC positron target was cut into pieces and metallographic studies were carried out to examine level of deterioration of material properties due to radiation exposure.



even achieving SLC e^+ rate is not trivial

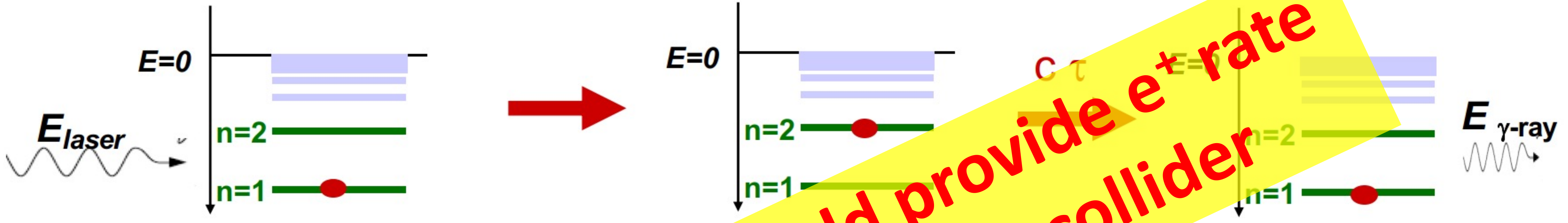
Radiation damage, work hardening, or temperature cycling?

David Schultz

Snowmass, July 10, 2001

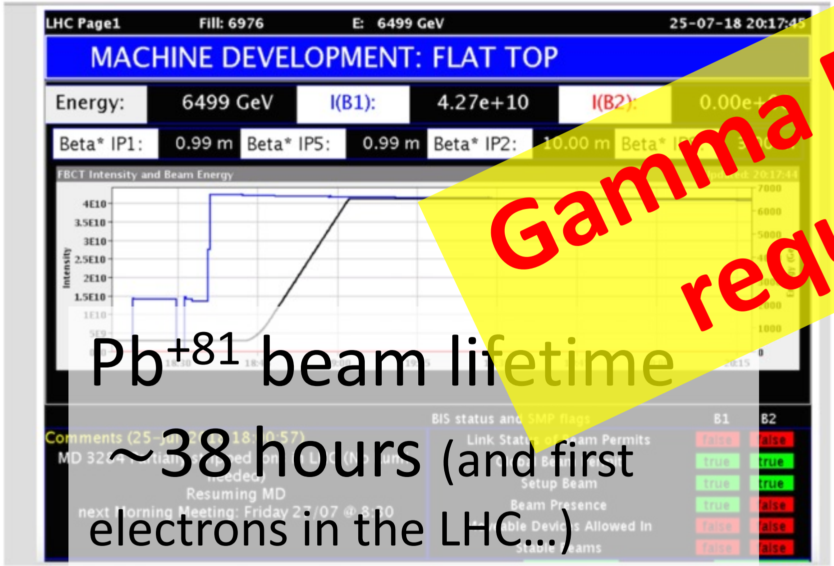
particle production: Gamma factory (challenge #4)

resonant scattering of laser photons off partially stripped heavy-ion beam in LHC (or FCC): high-stability laser-light-frequency converter



$$\nu^{max} \rightarrow (4\gamma_L^2)\,\nu_{laser}$$

Gamma Factory could provide e$^+$ rate required for LEMMA μ collider



Pb^{+81} beam lifetime ~38 hours (and first electrons in the LHC…)

<u>proposed applications:</u>

intense source of **e$^+$ (10^{16}-10^{17}/s) , μ (10^{11}-10^{12}/s)**, π, etc. – **sufficient for LEMMA type μ collider**

doppler laser cooling of high-energy beams

HL-LHC w. laser-cooled isocalar ion beams

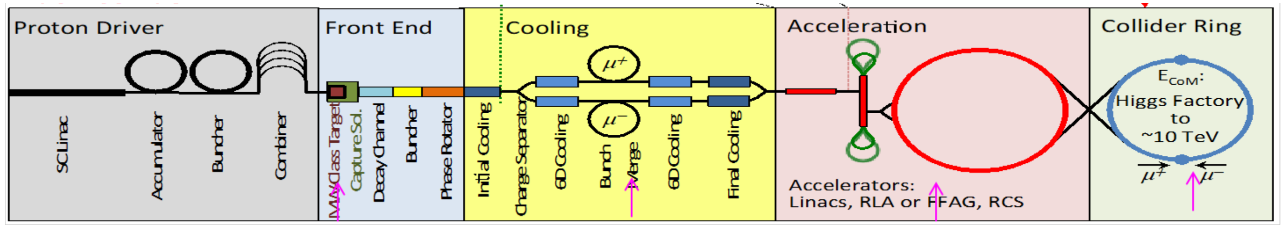
W. Krasny

Muon Collider schemes & challenges

~1.6x10^9 x less SR than e$^+$e$^-$, no beamstrahlung problem

two production schemes proposed

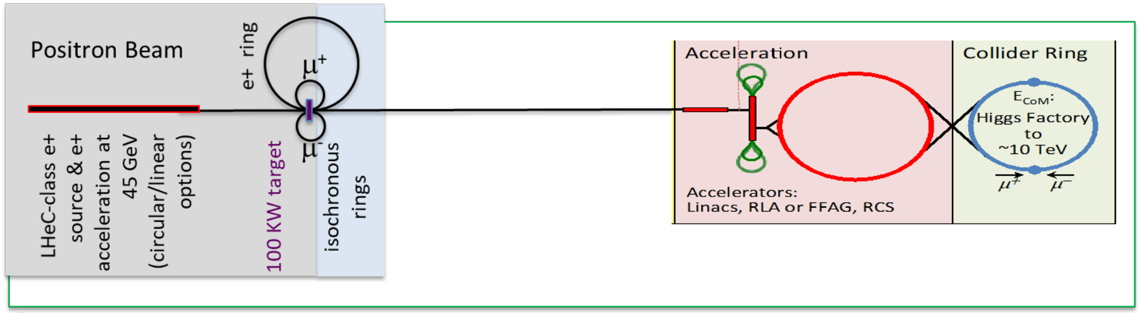
US-MAP (2015) *p*-driven



key challenges

~10^{13}-10^{14} μ / sec tertiary particle $p \to \pi \to \mu$:	fast cooling (τ=2μs) by 10^6 (6D)	fast acceleration mitigating μ decay	background from μ decay

Italian LEMMA (2017) *e*$^+$-annihilation



key challenges: ~10^{11} μ / sec from $e^+e^- \to \mu^+\mu^-$

key R&D: 10^{15} e$^+$/sec, 100 kW class target, NON destructive process in e+ ring

needs large 45 GeV e$^+$ ring like FCC-ee, possible upgrade path to **FCC-μμ**

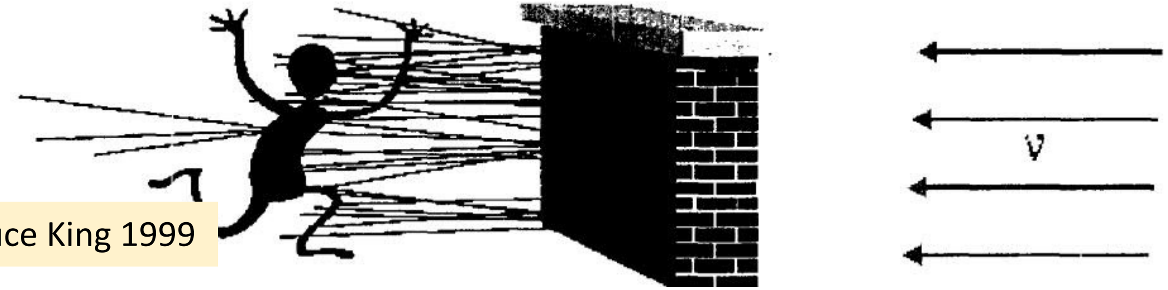
μ's decay within a few 100 - 1000 turns:

→ rapid acceleration

(perhaps plasma?)

→ ν radiation hazard

(limits maximum μ energy)



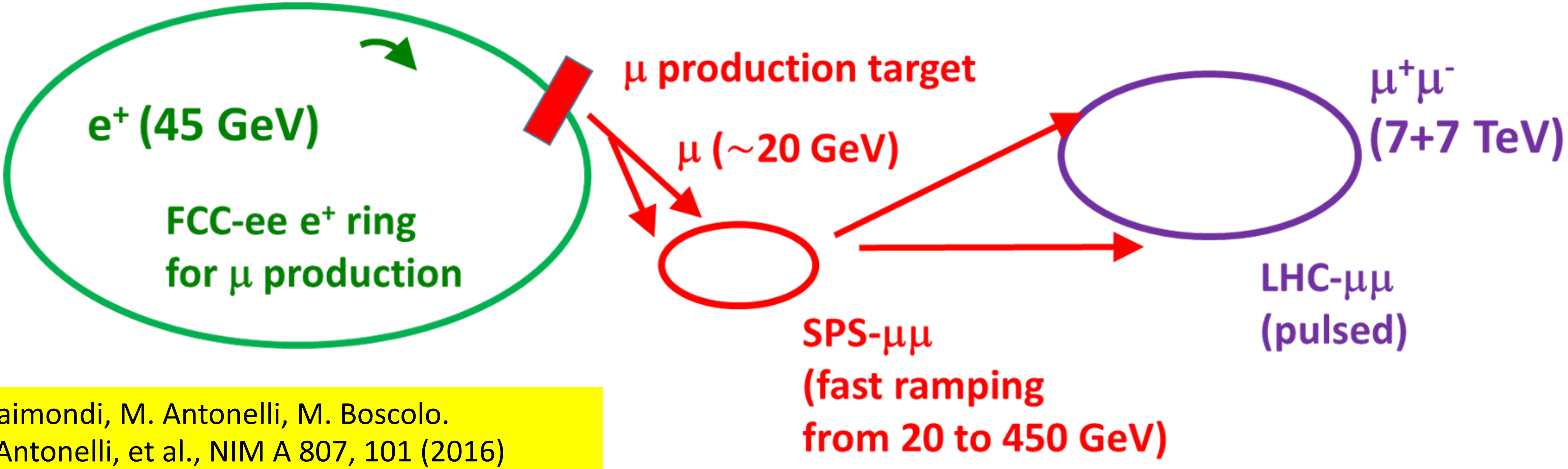
Bruce King 1999

$\sigma_\nu \propto E$, flux $\propto E^2$ (Lorentz boost)

solution beyond 10 TeV unclear

post FCC-ee option: feeding 14 TeV μ collider

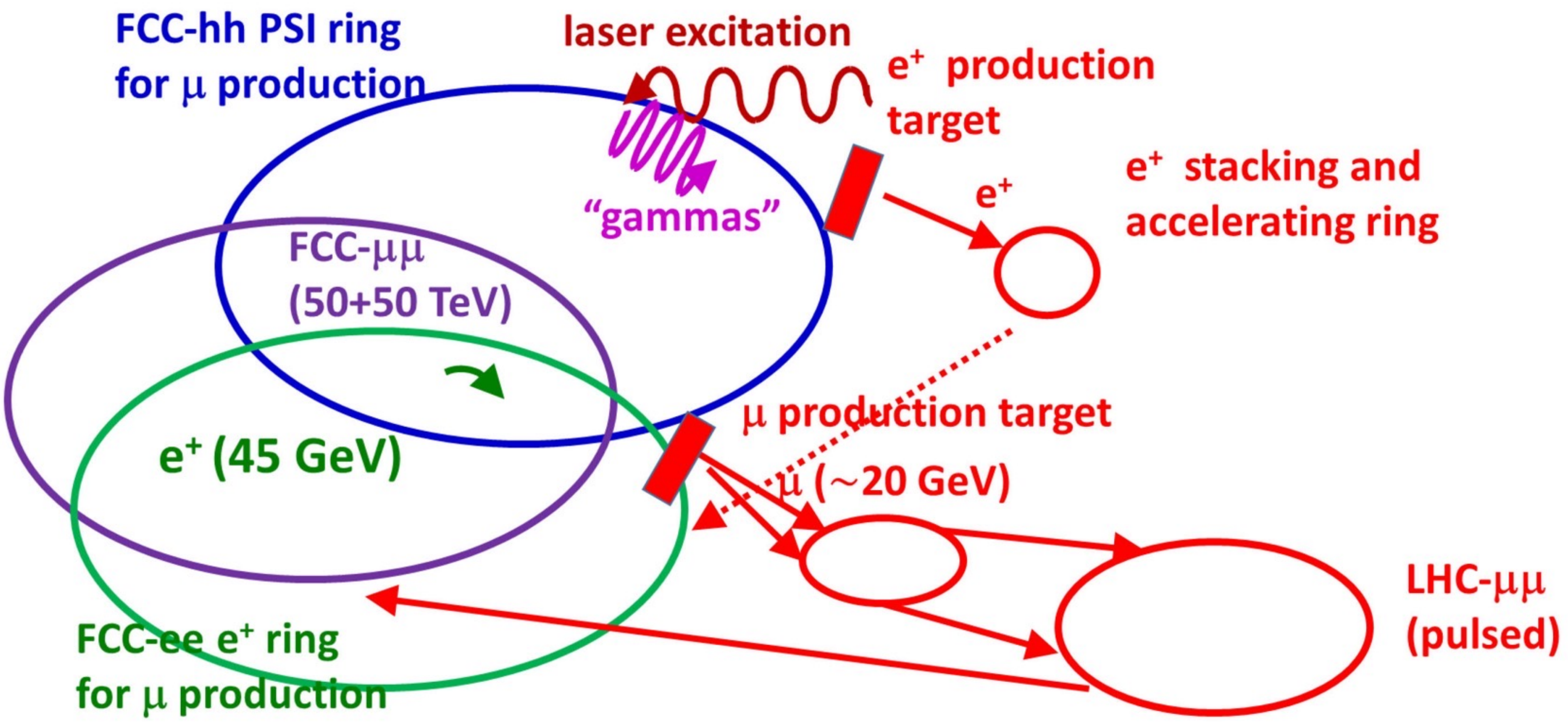
14 TeV μ collider LHC-μμ with FCC-ee $\mu^\pm$ production



P. Raimondi, M. Antonelli, M. Boscolo.
M. Antonelli, et al., NIM A 807, 101 (2016)
M. Boscolo et al., PRAB 23, 051001 (2020)

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

after FCC-hh: FCC-μμ, a 100 TeV μ collider?

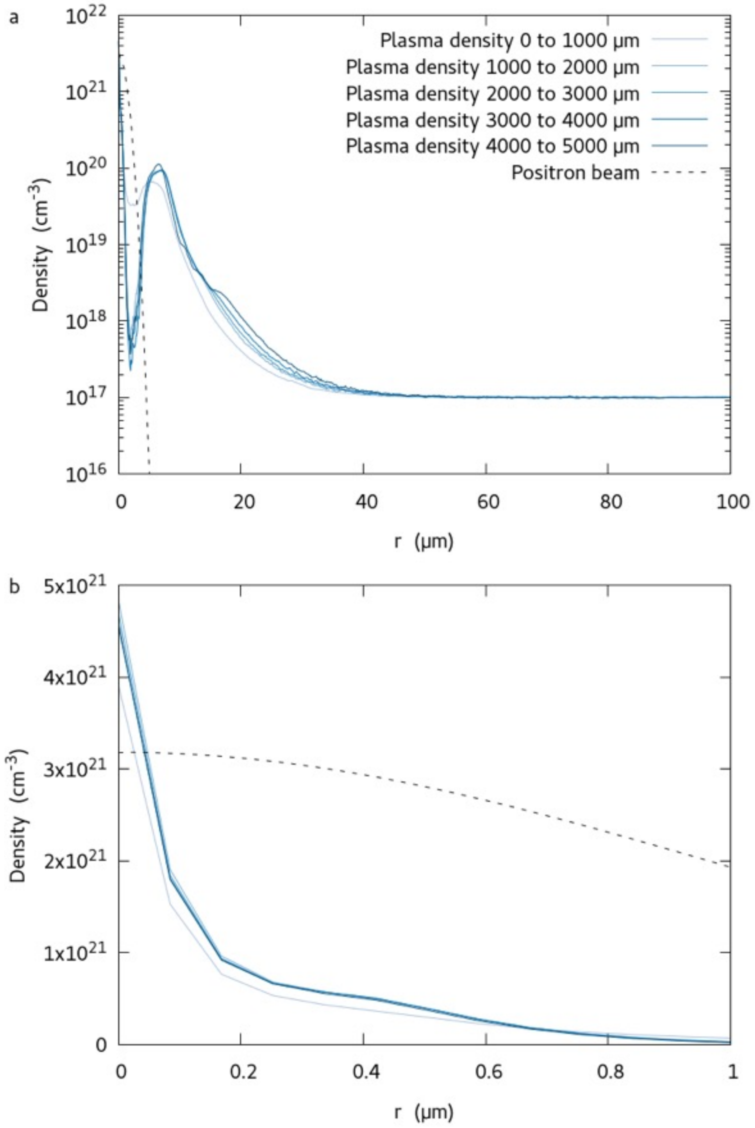


W. Krasny, https://arxiv.org/abs/1511.07794

PSI: partially stripped ion ("Gamma Factory")

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

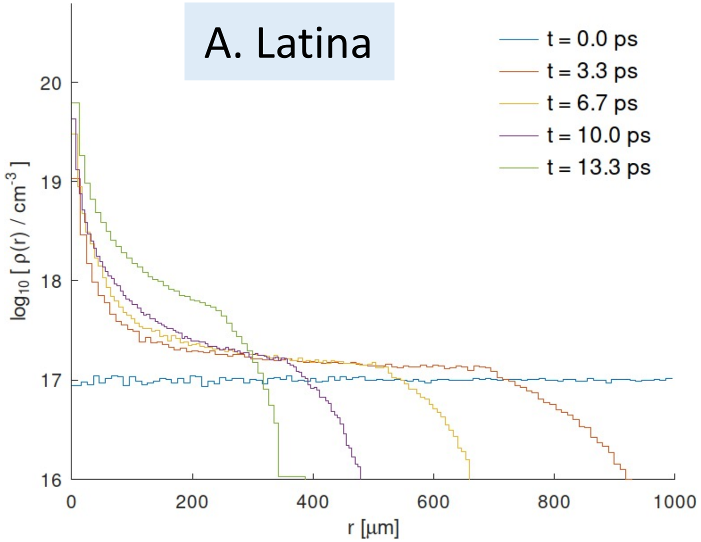
simulated of plasma target response for FCC-μμ



J. Farmer

Transverse profiles of the plasma electron density as the positron bunch passes through the plasma, simulated with LCODE (K.V. Lotov) for the initial bunch distribution. The mean density over different distances behind the head of the beam are shown over a radial distance of up to 100 μm from the beam (a) and a zoom over 1 μm around the beam (b).

F. Zimmermann et al., Proc. IPAC'22, p. 1691



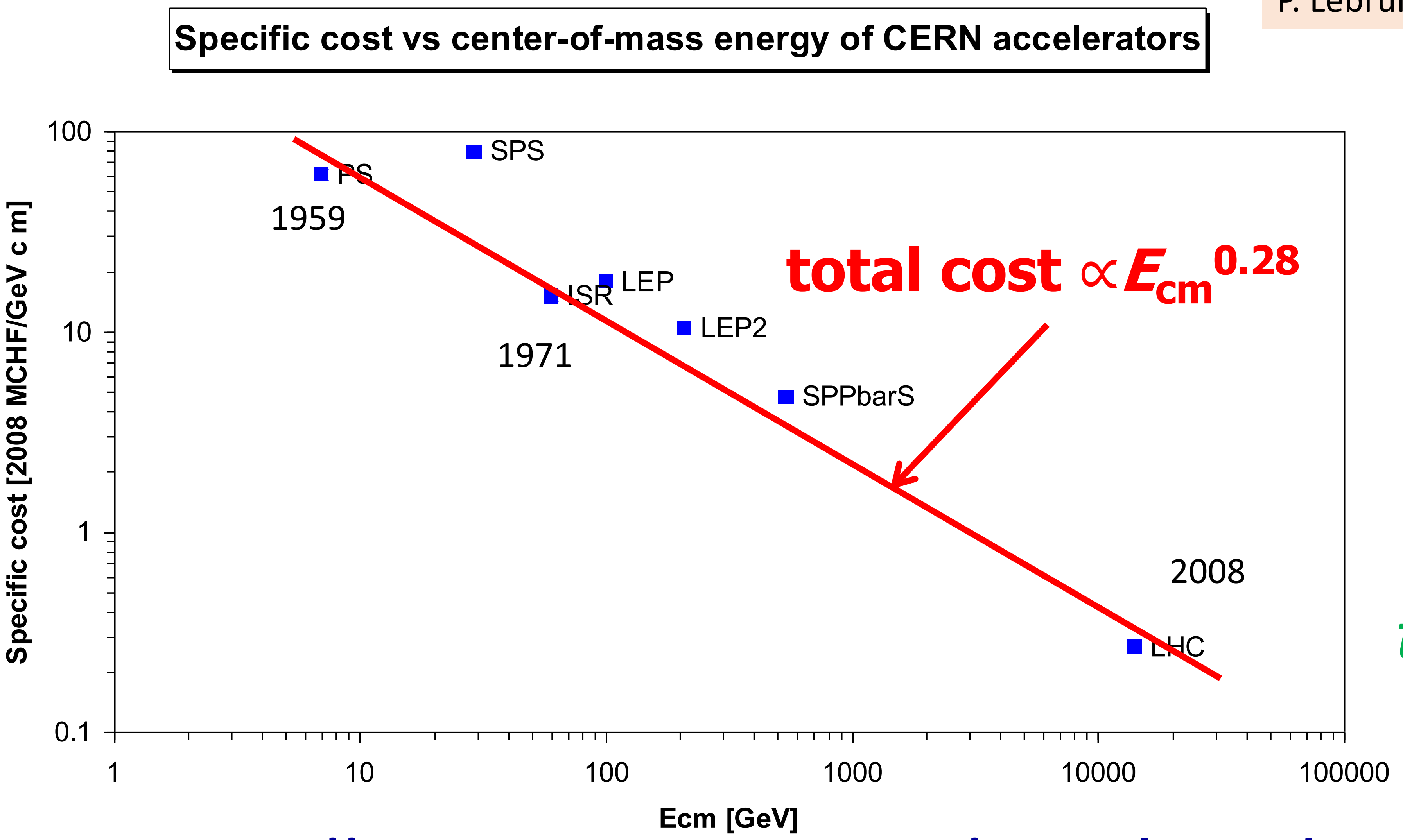
A. Latina

Electron density at the entrance of the plasma as a function of radial position for different time steps, simulated by RFTRACK, with only positron fields acting on electrons; during 3.3 ps the positron bunch advances by 1 mm.

energy loss mechanisms inside the plasma ?

challenge #5: cost / sustainability

P. Lebrun, RFTech 2013

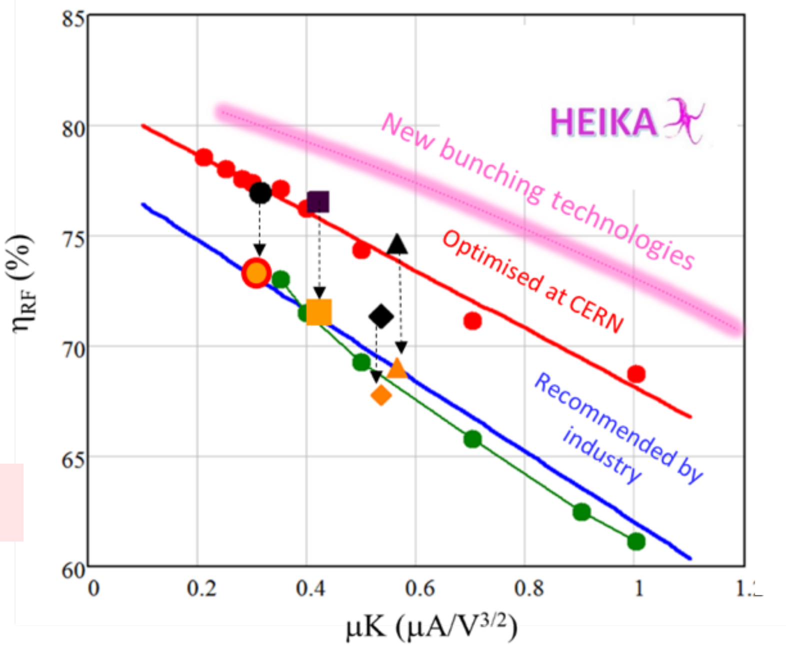


new concepts and new technologies

cost per collision energy greatly reduced

“green” energy efficient technologies

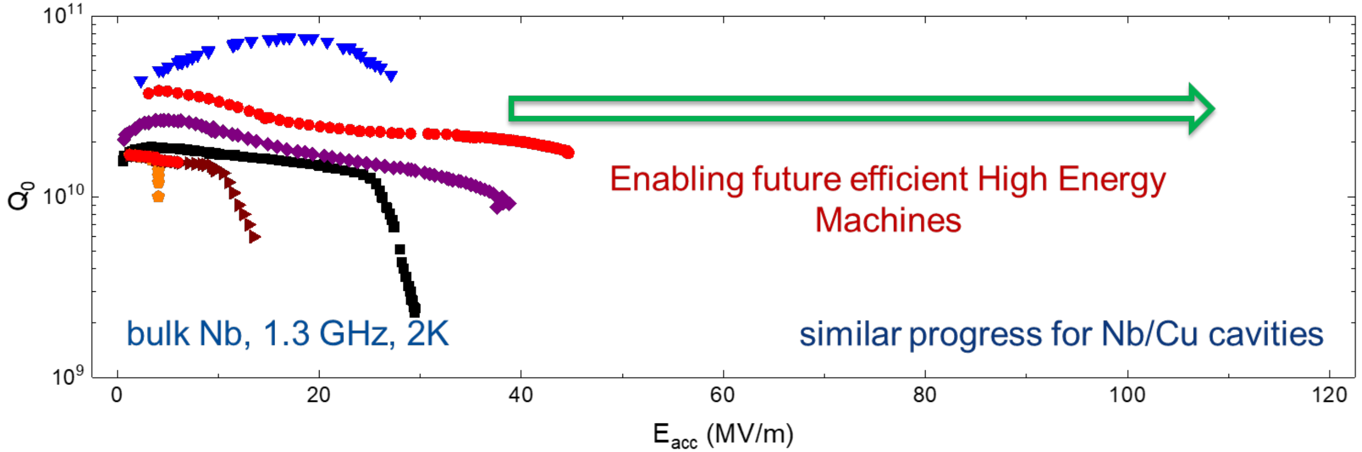
more efficient RF power sources



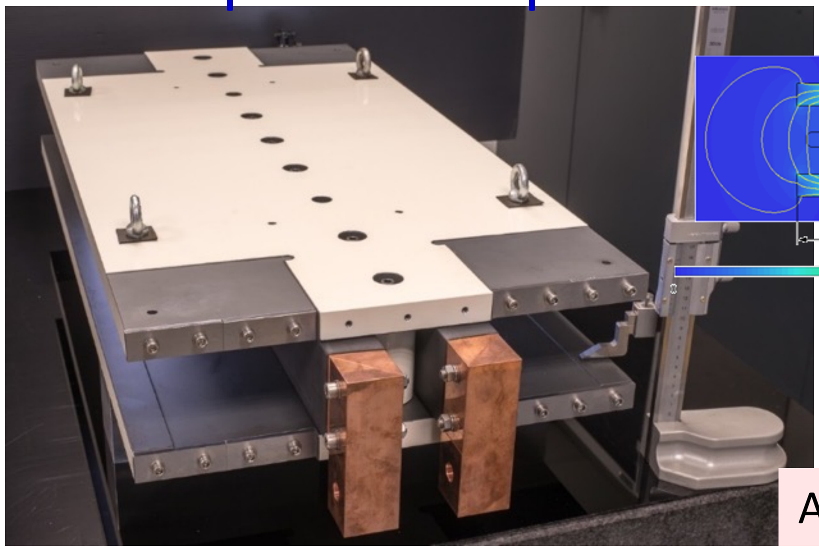
I. Syratchev

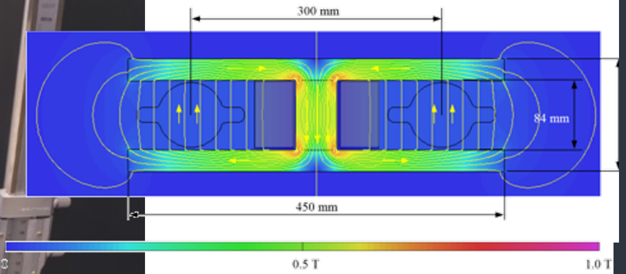
more efficient SC cavities

A. Grasselino

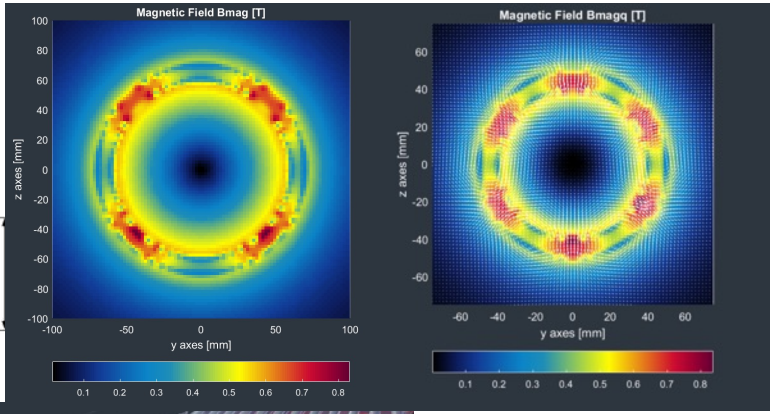


twin aperture dipoles for FCC-ee

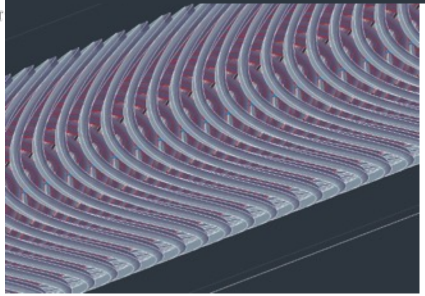




A. Milanese

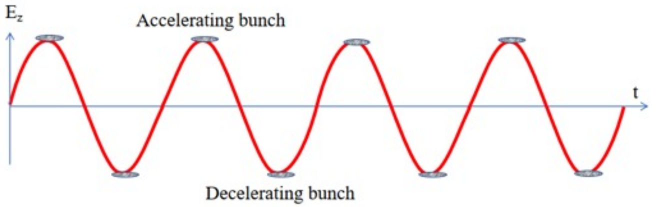


M. Koratzinos

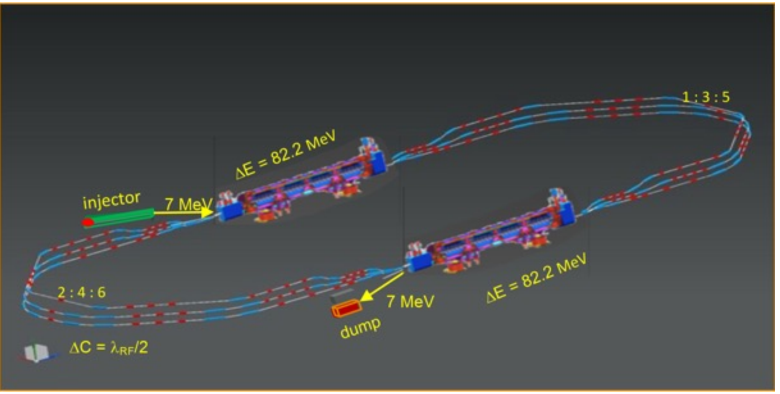


CCT HTS quadrupoles & sextupoles for FCC-ee

Energy Recovery Linacs (ERLs) – Landscape

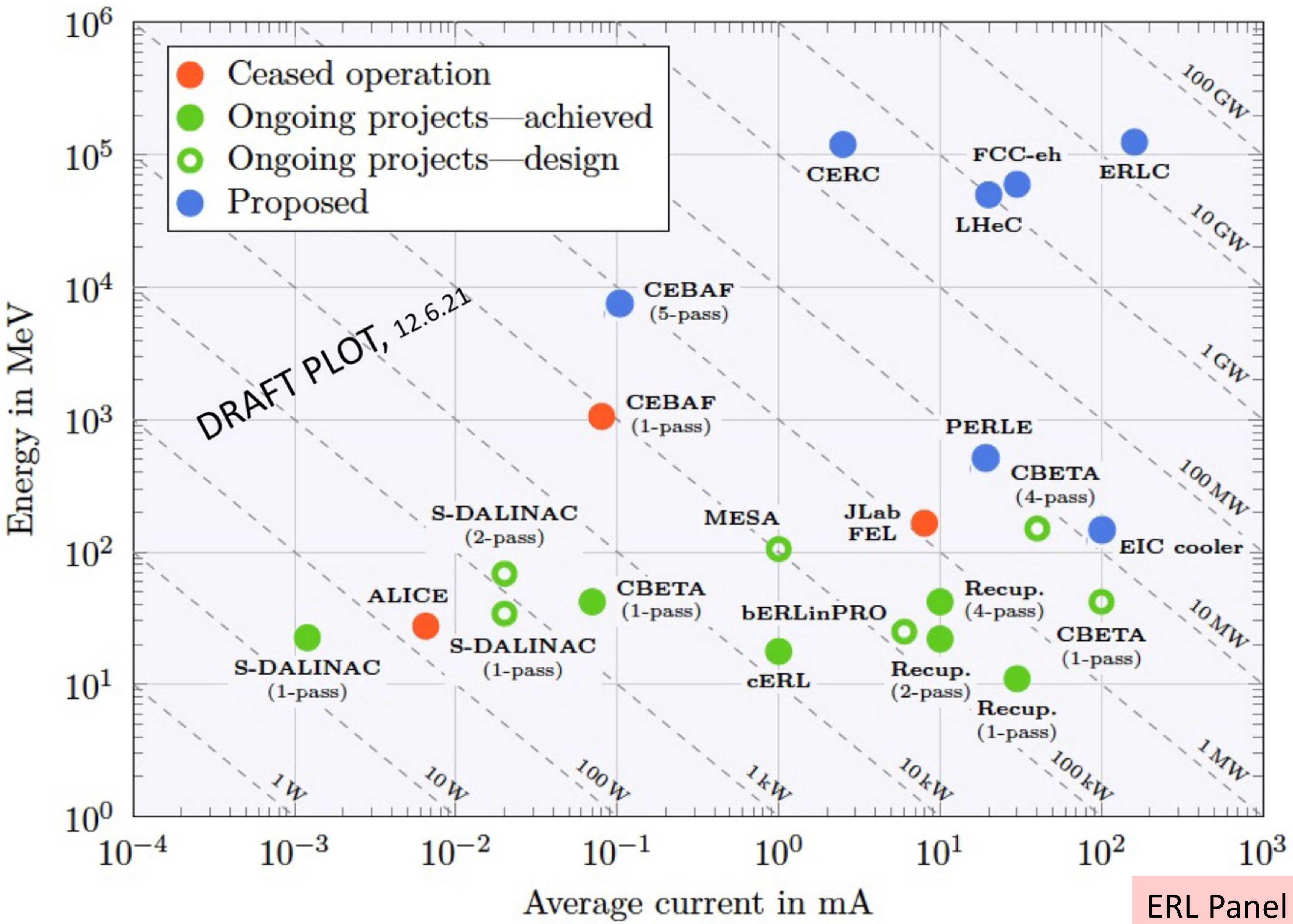


V. Litvinenko, T. Roser, M. Chamizo



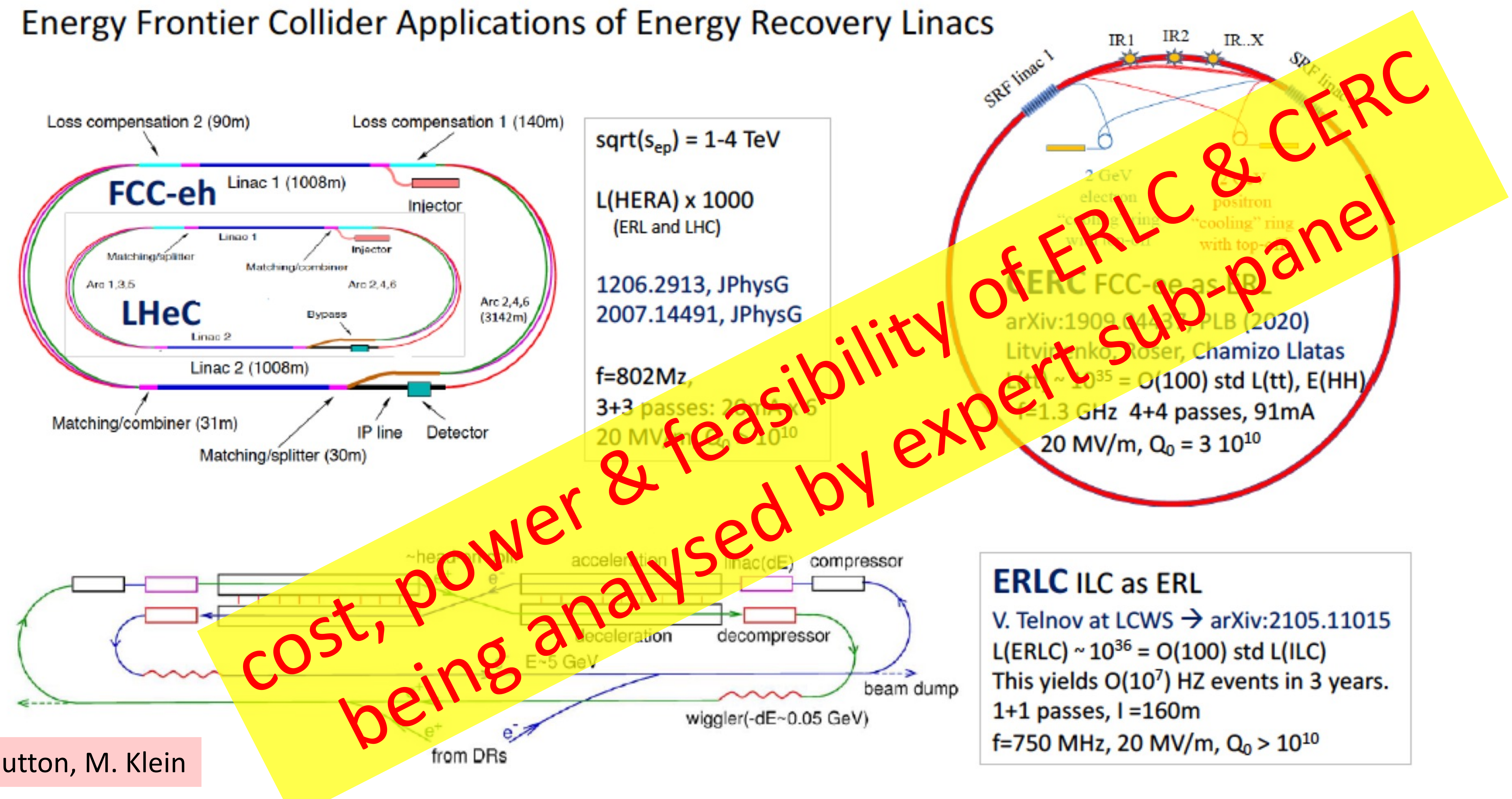
test Facility PERLE at IJClab
(high current, multi-turn)
would complement MESA, CBETA, bERLinPRO and EIC cooler

M. Klein, A. Hutton, et al.



ERL Panel

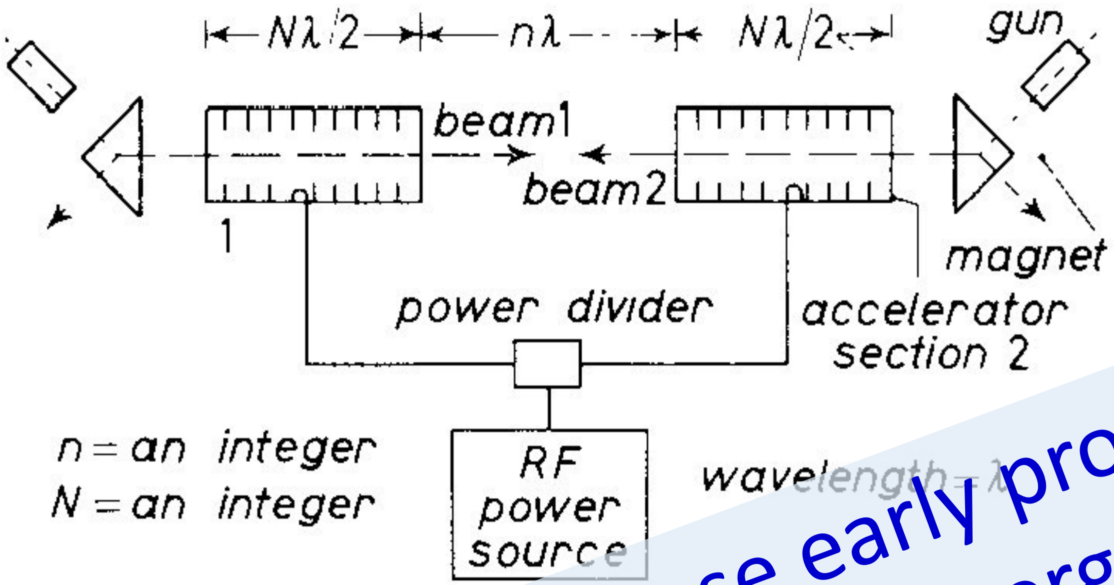
Possible Future Colliders based on ERLs



A. Hutton, M. Klein

reappraisal of historical ERL collider proposals

early linear-collider proposals

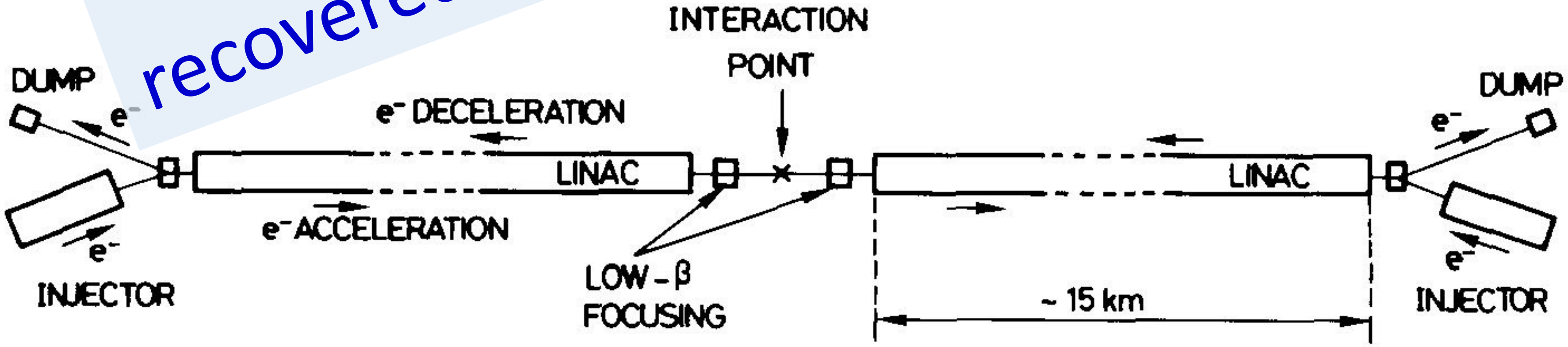


1-6 GeV c.m.

Maury Tigner, "*A Possible Apparatus for Clashing-Beam Experiments*", Nuovo Cimento 37, 1228 (**1965**)

these early proposal always recovered the energy of the spent beam!

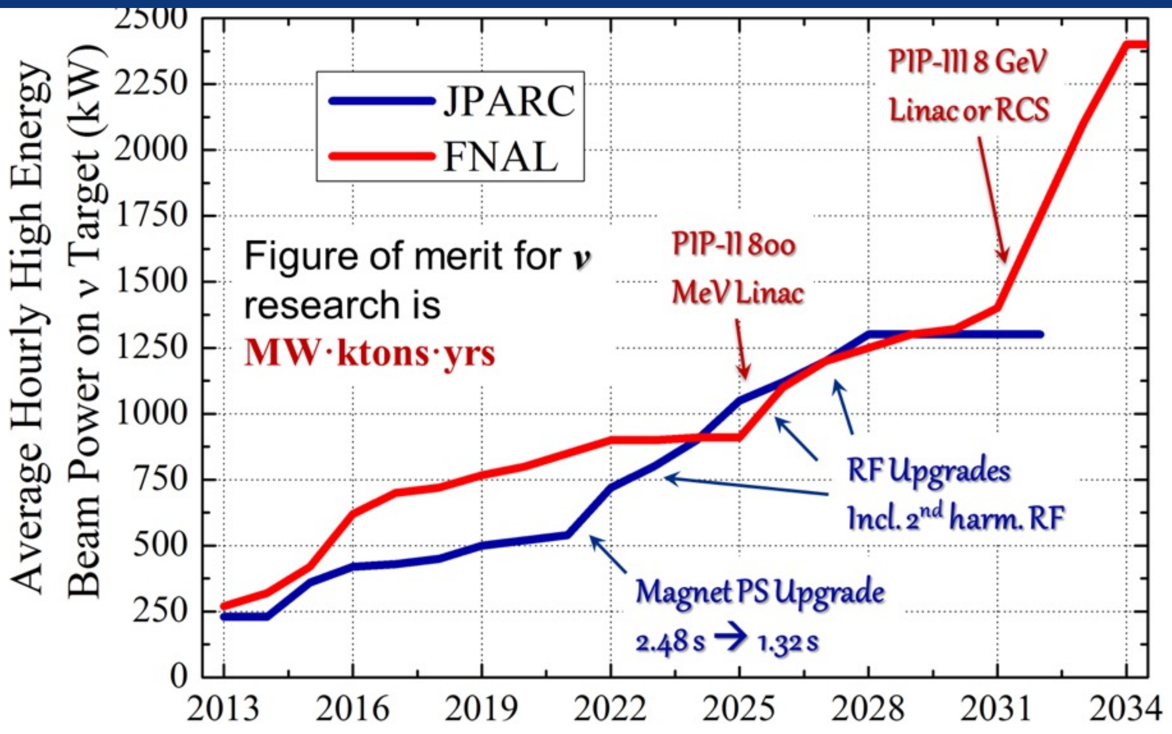
Ugo Amaldi, "*A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV*", Physics Letters B61, 313 (**1976**)



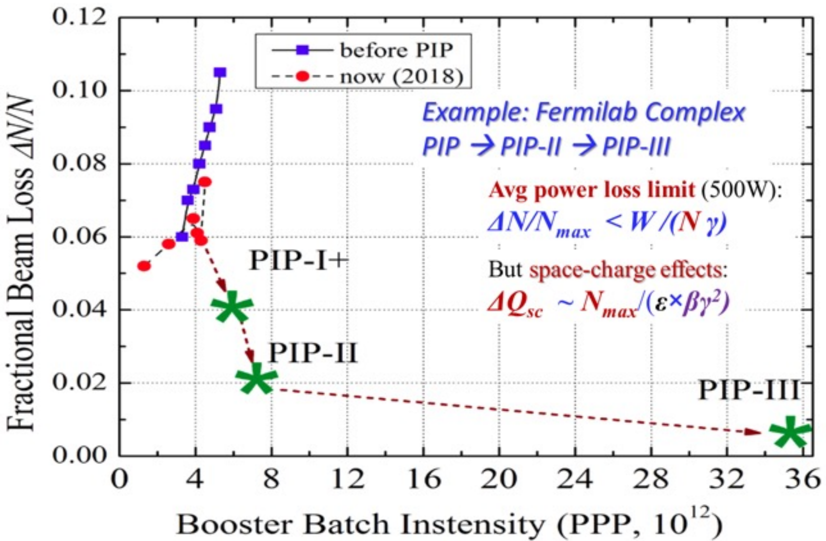
300 GeV c.m.

efficiency and upgrade of super-beam facilities

Fermilab & J-PARC Power Upgrades

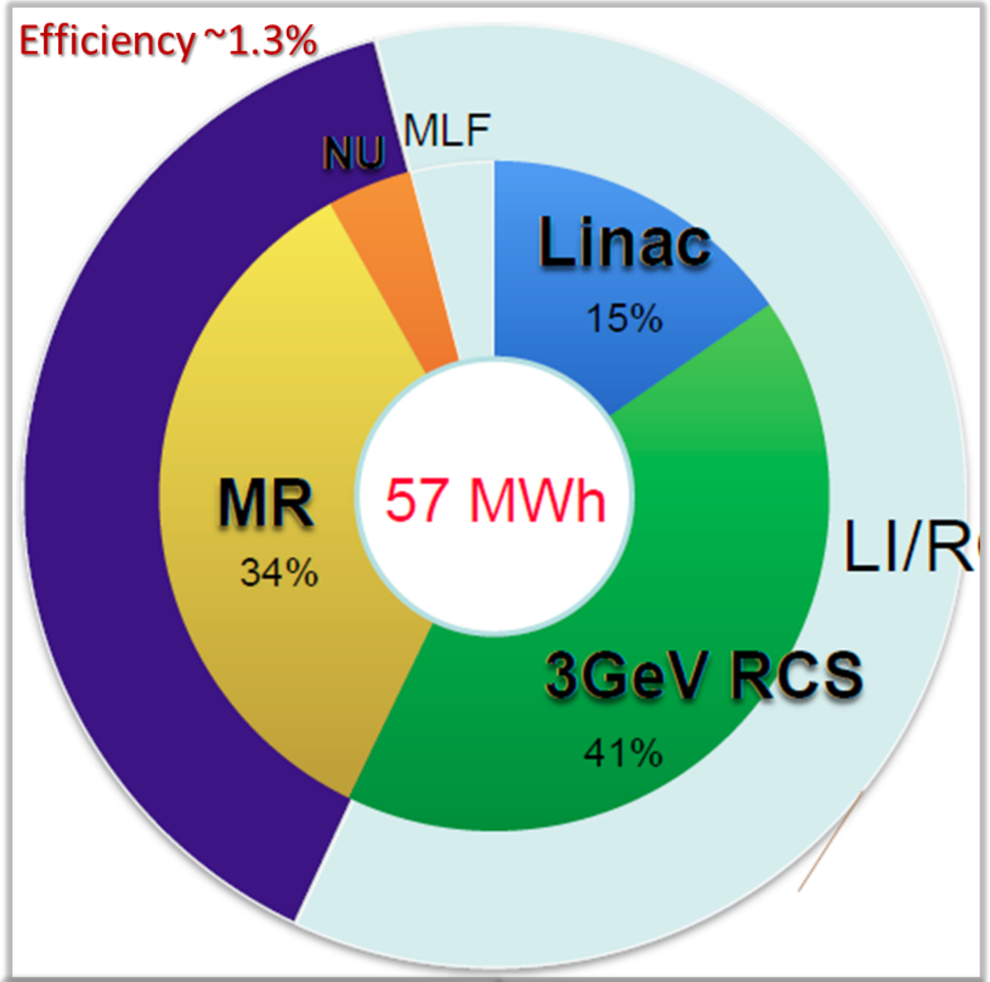


protons per pulse challenge



power efficiency challenge

J-PARC : 0.5 MW beams vs ~40 MW site power



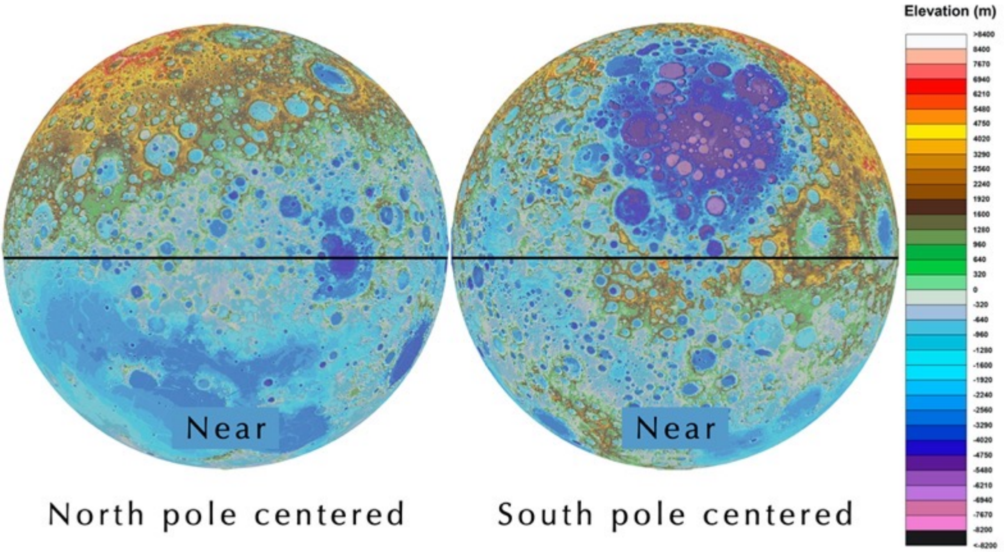
- MR Magnets: **10.4 MWh** per hour
- MR RF: **3.8 MWh** per hour

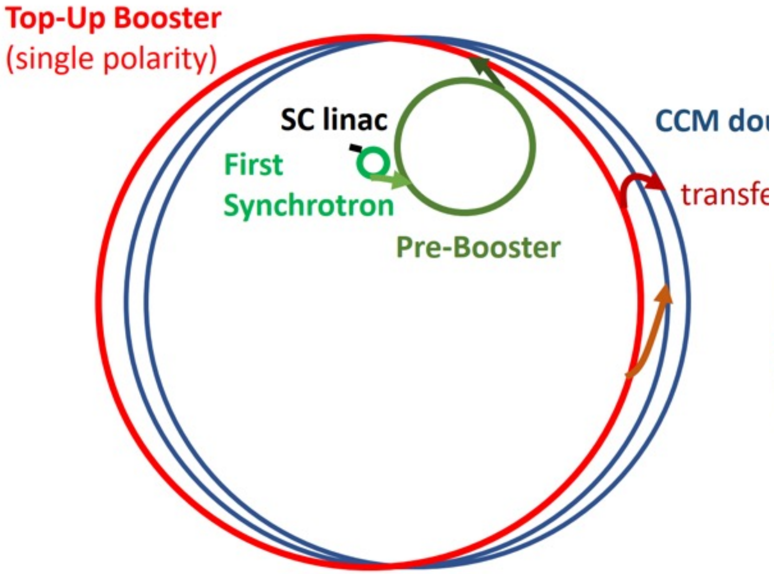
- RCS Magnets: **9.6 MWh** per hour
- RCS RF: **7 MWh** per hour

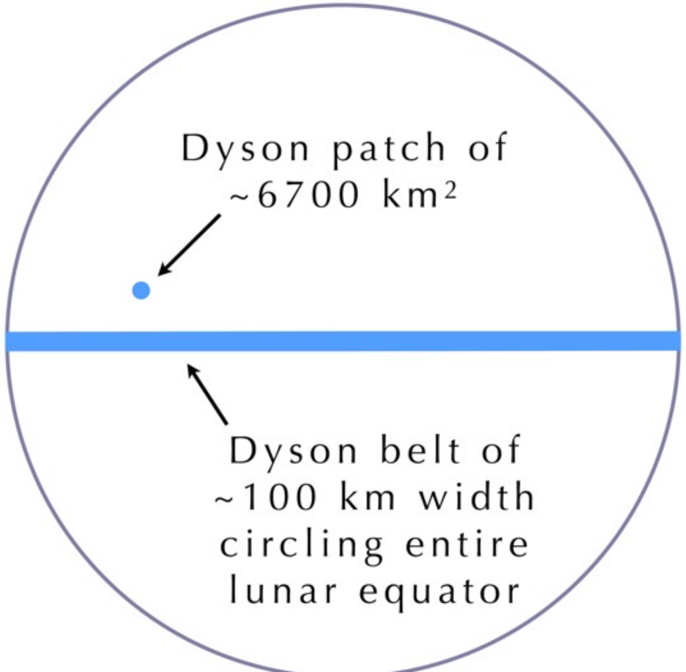
V. Shiltsev

challenge #6: exploring novel directions

Very large hadron collider on the Moon (CCM), $C \sim 11$ Mm, $E_{c.m.} \sim 14$ PeV (1000x LHC's), 6×10^5 dipoles with **20 T field**, either ReBCO, requiring ~7-13 k tons rare-earth elements, or IBS, requiring ~a million tons of IBS. **Many of the raw materials required to construct machine, injector complex, detectors, and facilities can potentially be sourced directly on the Moon. 11000-km tunnel a few 10 to 100 m under lunar surface** to avoid lunary day-night temperature variations, cosmic radiation damage, and meteoroid strikes. **Dyson band or belt to continuously collect sun power.** Required: <0.1% sun power incident on Moon surface.







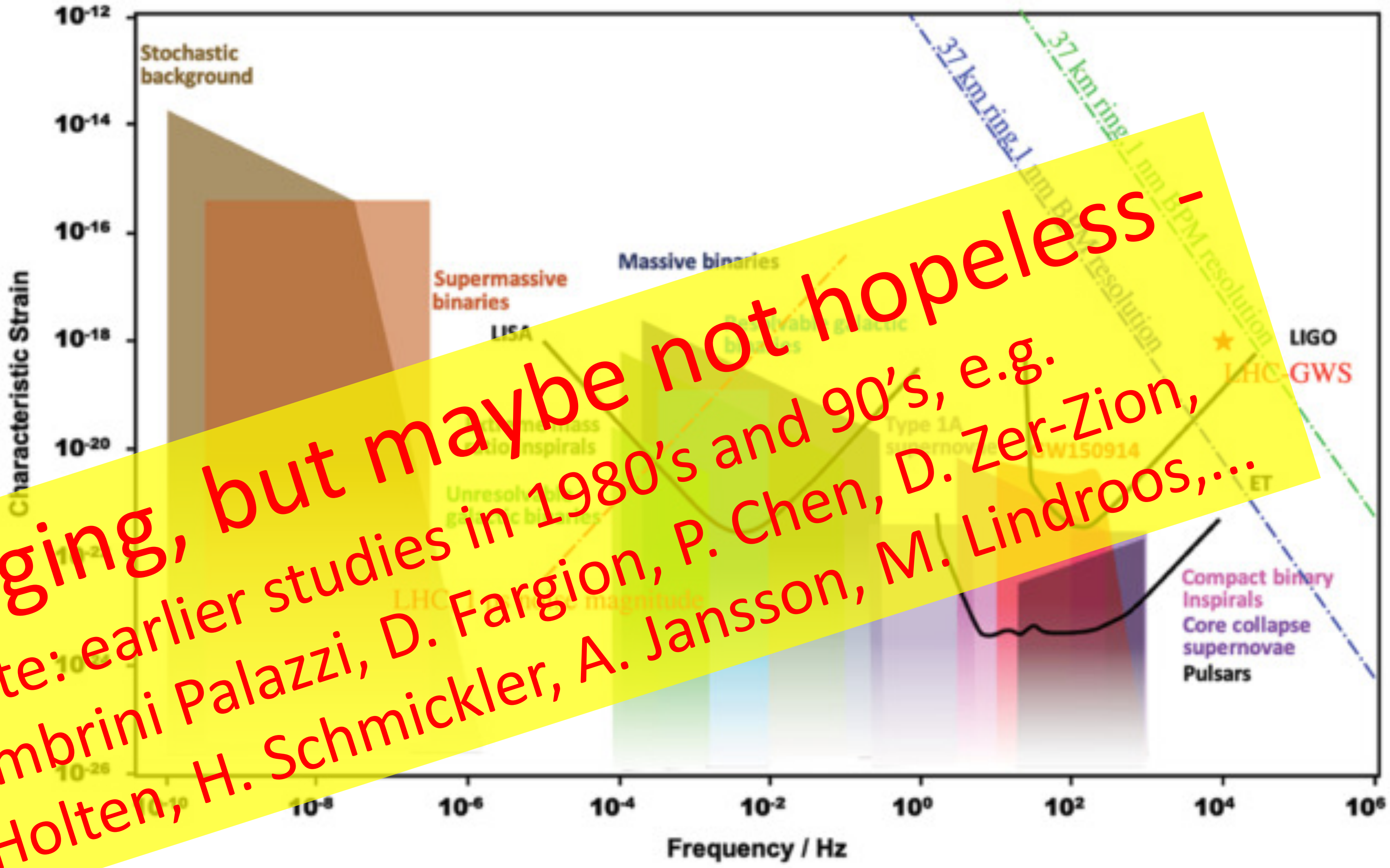
J. Beacham, F. Zimmermann, 2022 *New J. Phys.*, https://doi.org/10.1088/1367-2

storage rings as tools to detect or generate gravitational waves

ARIES workshop 2021

Accelerators meet gravitational waves
Courier

J. Ellis et al (2021),
https://arxiv.org/abs/2105.00992



Sources and sensitivities GW sources (shaded) and detector sensitivities (lines), incl. space-based interferometer LISA, ground-based LIGO and Einstein Telescope. Accelerator-based detection methods and sources are superimposed based on optimistic assumptions.

challenging, but maybe not hopeless -

note: earlier studies in 1980's and 90's, e.g.
G. Diambrini Palazzi, D. Fargion, P. Chen, D. Zer-Zion,
J. Van Holten, H. Schmickler, A. Jansson, M. Lindroos,...

This is the place to make progress !

Marcus Tullius Cicero, 106-43 BC

Tusculanae Disputationes, 45 BC: series of dialogues that take place during **five days** at Cicero’s villa **at Tusculum (now the town of Frascati** near Rome) – Might the Frascati eeFACT’22 proceedings (5 days of talks!) become equally famous?!