ENERGY RECOVERY LINACS

Virtual Beam Power for a multitude of Application

Andreas Jankowiak
Technical Director BESSY II

Advanced Accelerator Physics Course
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Content

Energy Recovery Linacs – Why and How ?

storage ring versus linac (real ↔ virtual power, equilibrium ↔ control)
the ERL principle and its promises

History

first idea, first tests, first projects

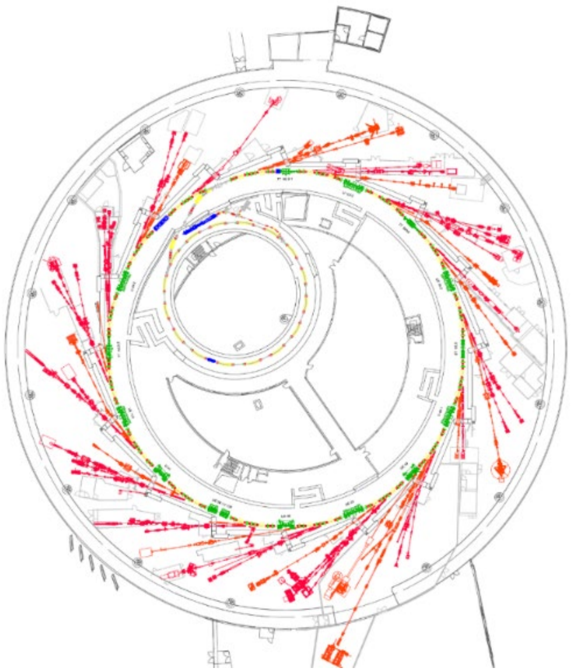
Applications

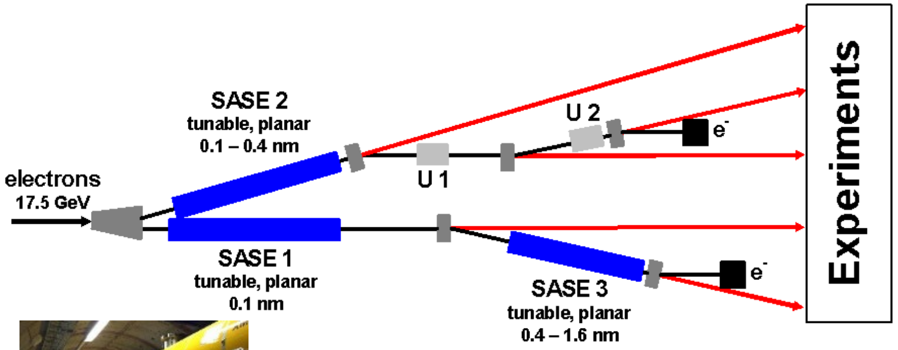
multi-user light sources, collider, cooler, compact sources, …

Challenges

electron source, SRF technology, beam losses
at the example of the Berlin Energy Recovery Linac Project bERLinPro

Storage ring ↔ linac / virtual ↔ real power





synchrotron radiation source, collider

$$P_{virtual}[W] = E[eV] \cdot I[A]$$

$$E_{stored}[J] = E[eV] \cdot I[A] \cdot T_{rev}[s]$$

e.g. BESSY II, 3rd generation light source

1.7 GeV, 300 mA = 510 MW virtual beam power, thereof ca. 90 kW used synchrotron radiation power (and only 408 J stored energy)

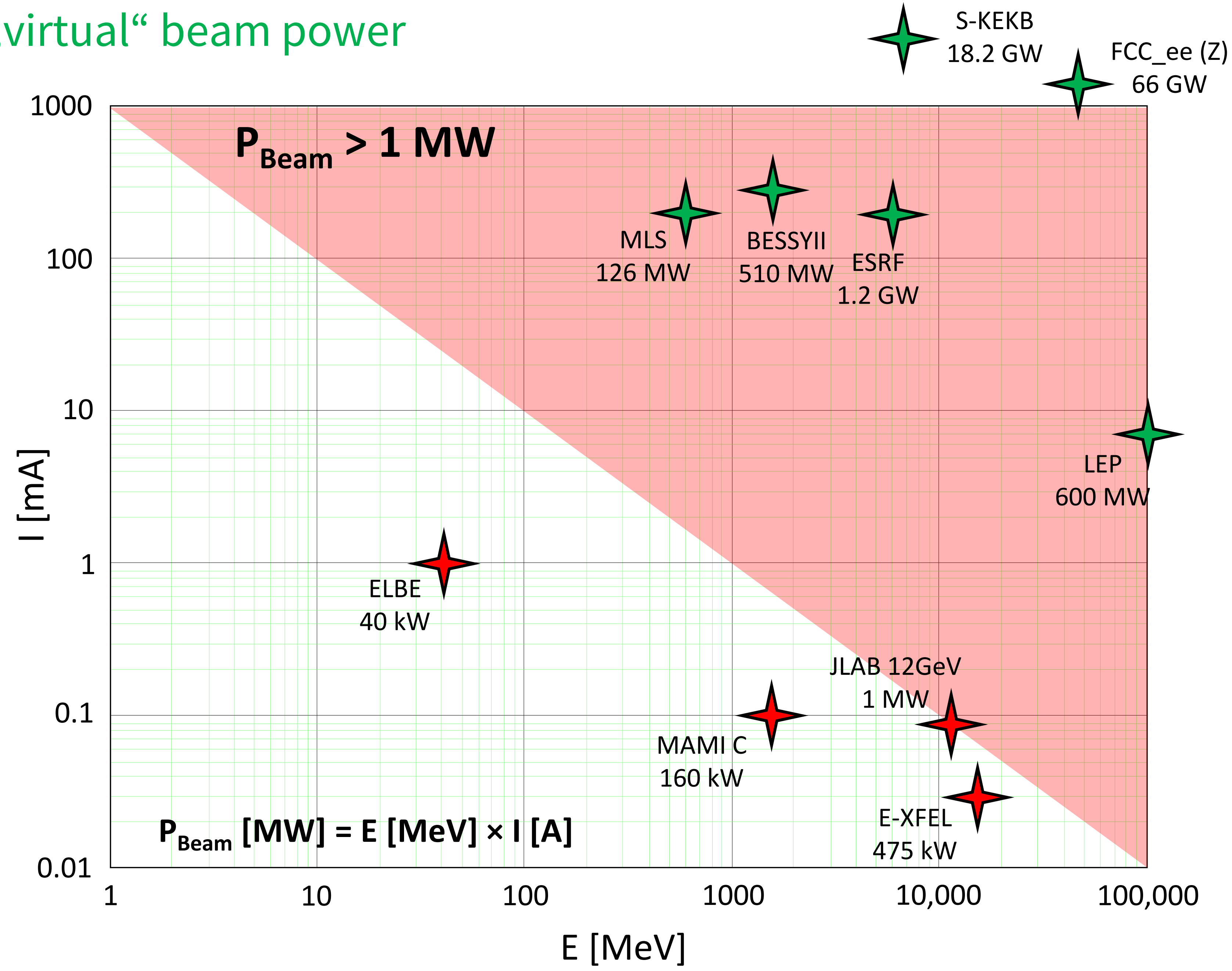
free electron laser, collider, fixed target

$$P_{real}[W] = E[eV] \cdot I[A]$$

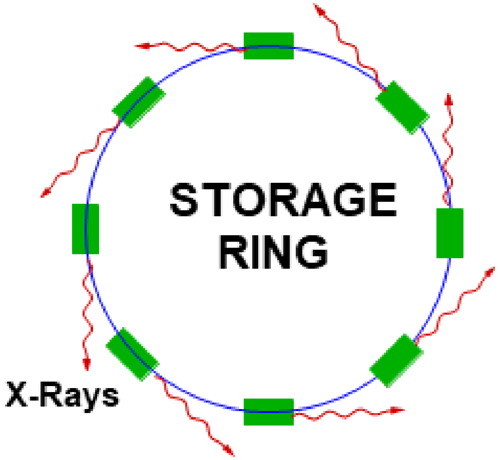
e.g. European XFEL, 1 Å hard X-ray source

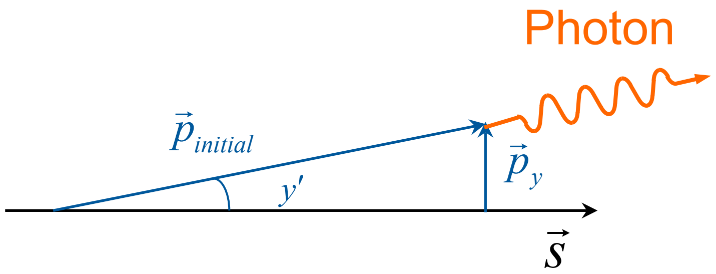
17.5 GeV, 0.027 mA = 475 kW real beam power, ca. 100 GW peak power in 100 fs, 10 x 2700 pps, used FEL power ca. 300 W

real ↔ „virtual“ beam power

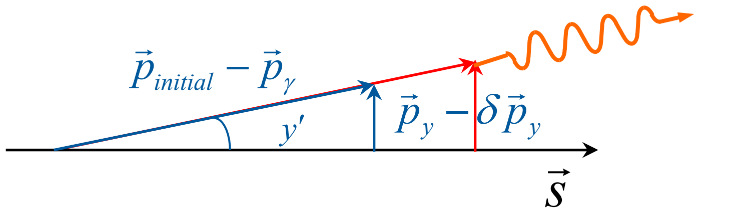


Storage ring – governed by equilibrium processes

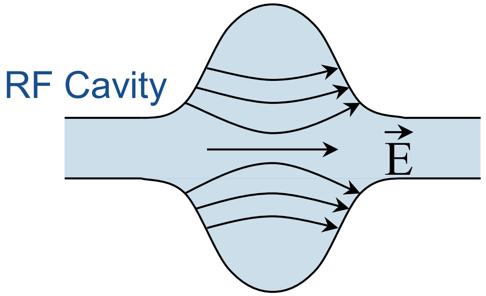




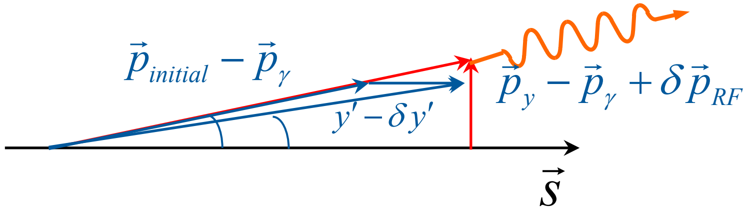
electron emits photon



looses momentum (also transversal)



longitudinal momentum restored
in acceleration cavity

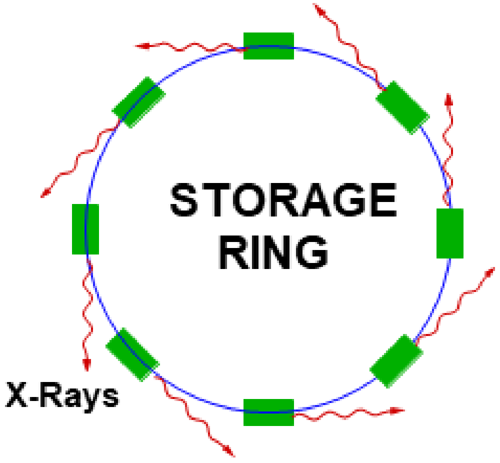


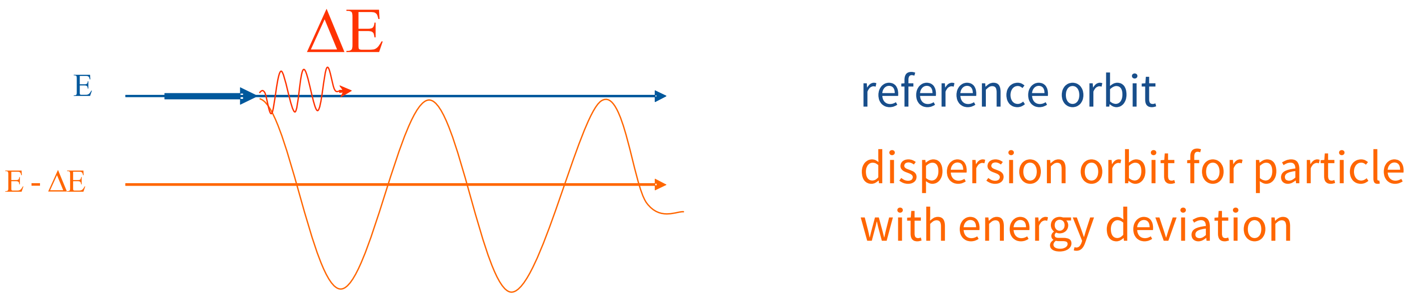
angle and displacement reduces
→ emittance shrinks

“damping” by synchrotron radiation

Storage ring – governed by equilibrium processes

emission of photon at position with dispersion (e.g. in dipole, where transversal position is energy dependent)
electron starts oscillating around dispersion orbit → emittance increase

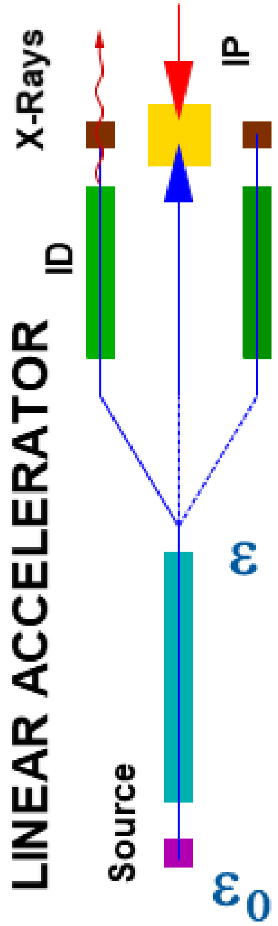




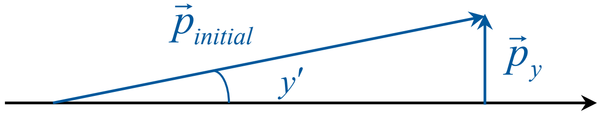
“heating” by synchrotron radiation

Emittance is defined by an **equilibrium** between these two processes (damping and heating). As there is no “vertical dispersion” in storage rings, normally we have “flat” beams with vertical emittance being 1/100 or less of horizontal. Similar processes defines energy-spread (and pulse length).

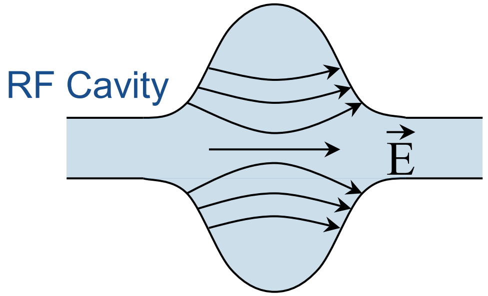
Linac – governed by adiabatic damping and control



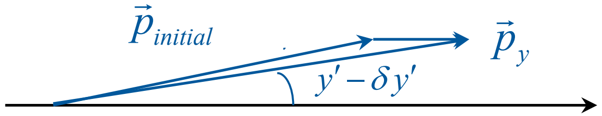
„adiabatic“ damping



electron has transversal momentum

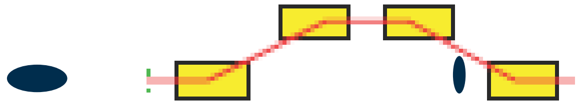


longitudinal component increases during acceleration



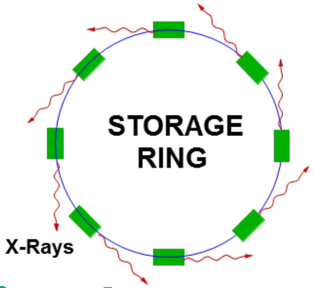
angle reduces with acceleration, emittance shrinks $\varepsilon = \dfrac{\varepsilon_0}{\gamma}$

additional: bunch-length control by applying correlated energy chirp (off crest) and magnetic chicane with longitudinal dispersion

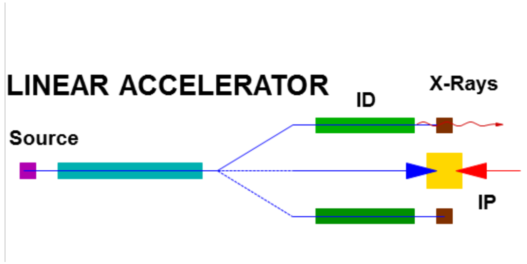


The quality of the beam is defined by the source, the rest is proper acceleration and phase space control!

Storage ring versus Linac



equilibrium beam parameters



adiabatic damping + control

$\varepsilon_x = C_\gamma \cdot \frac{\gamma^2}{J_x} \cdot \frac{\left\langle \frac{1}{R^3} H(s) \right\rangle}{\left\langle \frac{1}{R^2} \right\rangle} \sim \frac{\gamma^2}{N^3}, \varepsilon_y = \kappa \cdot \varepsilon_x$	$\varepsilon_{x,y} = \frac{\varepsilon_0}{\gamma}$
$\frac{\sigma_E}{E} \sim \frac{\gamma}{\sqrt{\rho}}$	$\left(\frac{\sigma_E}{E}\right)_0 \sim \frac{1}{\gamma}$
$\sigma_s \sim \sqrt{\frac{\alpha}{V'}} \cdot \sigma_E$	$\sigma_s = f(\sigma_0)$ plus bunch manipulation

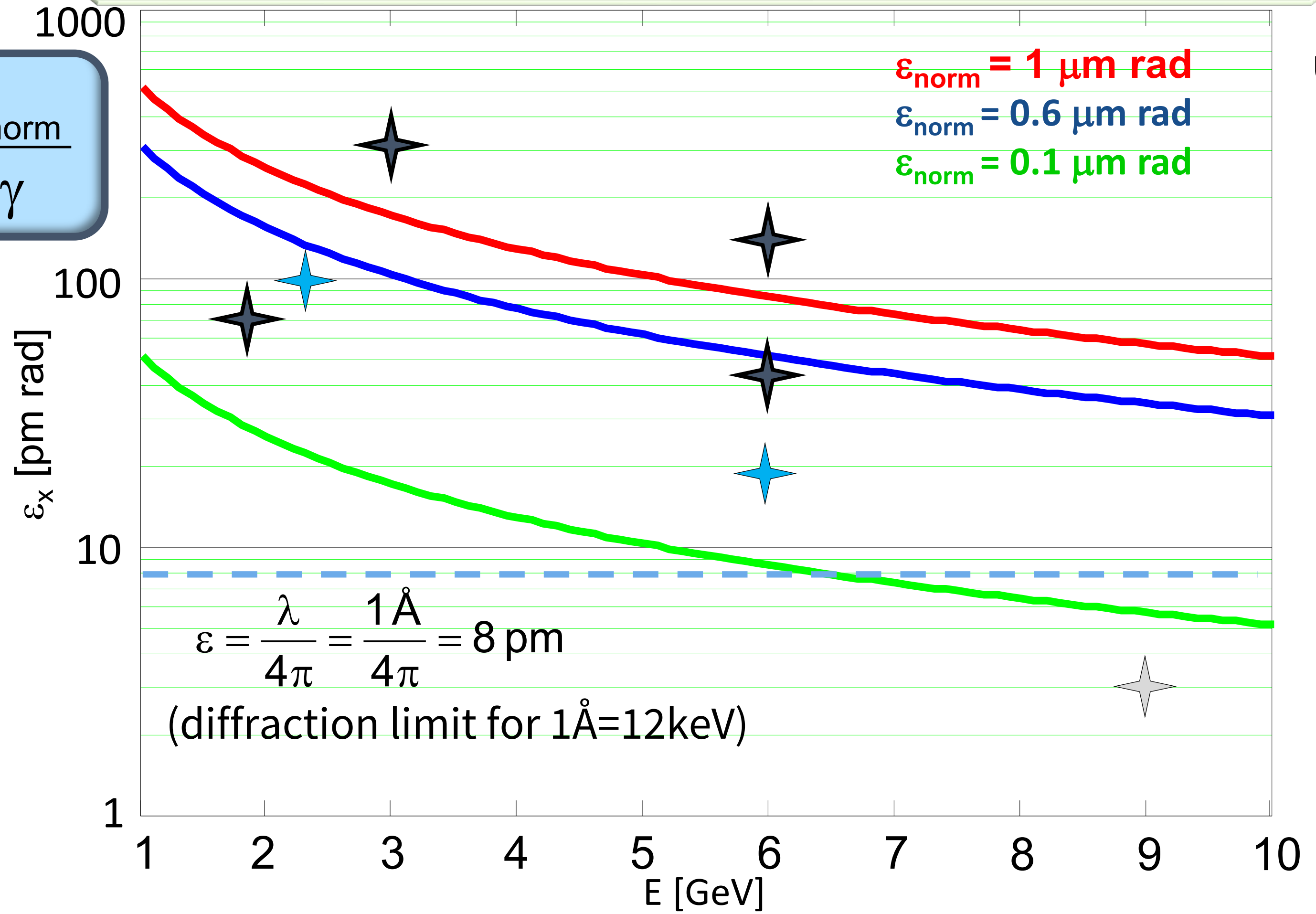
“virtual” (internal) power

real (external) power

Beam emittance – single pass machine ↔ storage ring

3rd generation light sources in operation (selection):
ALBA (5 nm@3 GeV), SOLEIL (4 nm@2.7 GeV), DIAMOND (3 nm@3 GeV),
ESRF (4 nm@6 GeV), APS (3 nm@7 GeV), SPring8 (3nm@8 GeV)
ALS (2.2 nm@1.9 GeV), PETRAIII (1 nm@6 GeV / 0.16nm@3GeV)

$$\varepsilon = \frac{\varepsilon_{norm}}{\gamma}$$



MBA ultra low emit. lattices:

320 pm, MAX IV
(in operation since 2016)
135 pm, ESRF EBS
(in operation scince 2020)
46 pm, APS-U
(in operation since 2024)
< 85 pm, ALS-U
(realisation phase, CD03A decision)

100 pm, BESSY III
(TDR 2028)
< 20 pm, PETRA IV
(EDR 2026)

3 pm, tUSR
(design study)

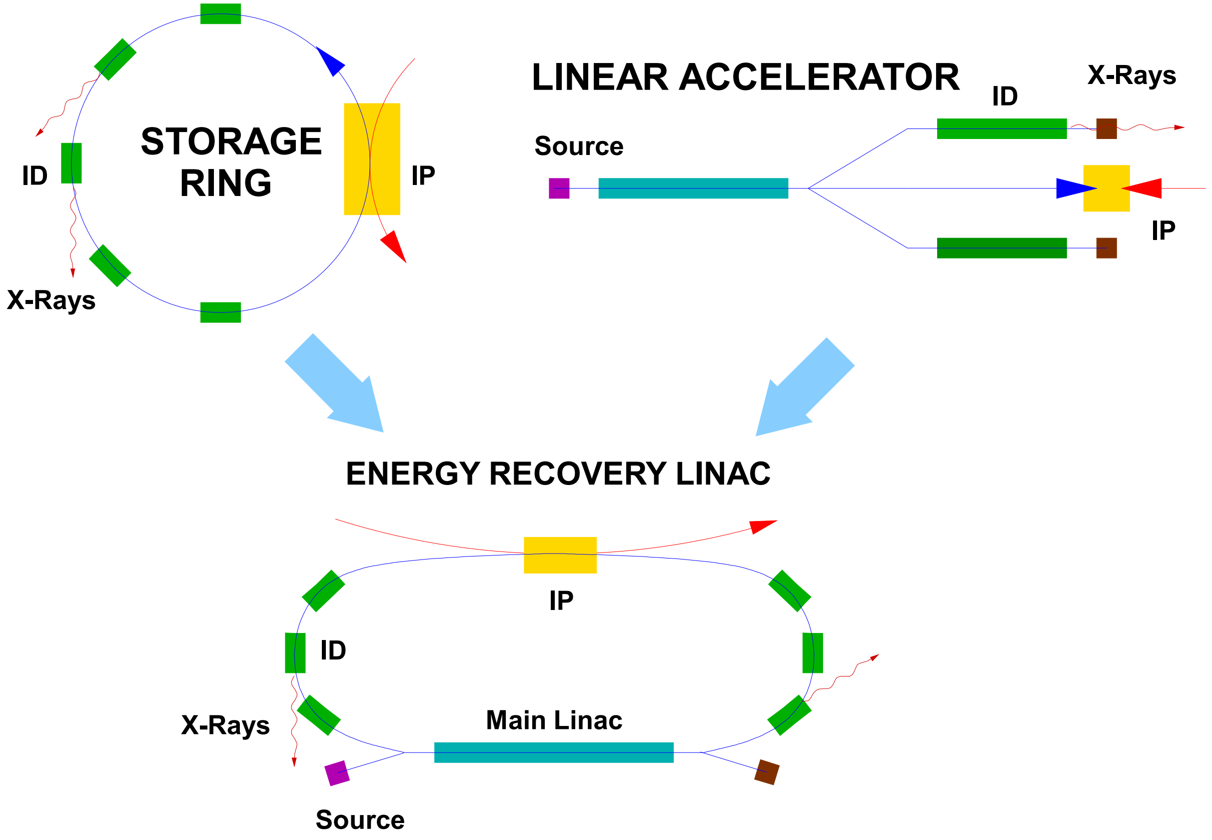
Storage rings: low emittance goes hand in hand with necessity to operate with long bunches (up to some 100 ps) to reduce Touschek and IBS scattering!

Energy Recovery Linacs – The idea

- high average („virtual“) beam power (up to A, many GeV)
- many user stations
- beam parameter defined by equilibrium
- typical long bunches (20 ps – 200 ps)

- outstanding beam parameter
- single pass experiments
- high flexibility
- low number of user stations
- limited average beam power (<<mA)

e.g. ESRF:
6 GeV, 200 mA
1.2 GW
virtual power,
stored energy
only 3380 J



e.g. XFEL:
17.5GeV, 30 μA
“only” ~ 500 kW,
but real power

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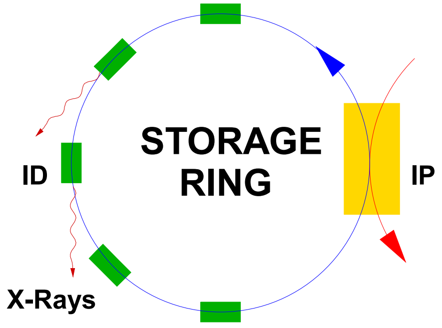
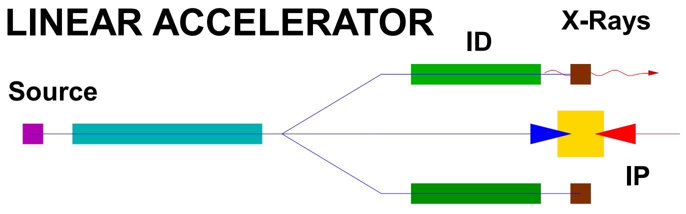
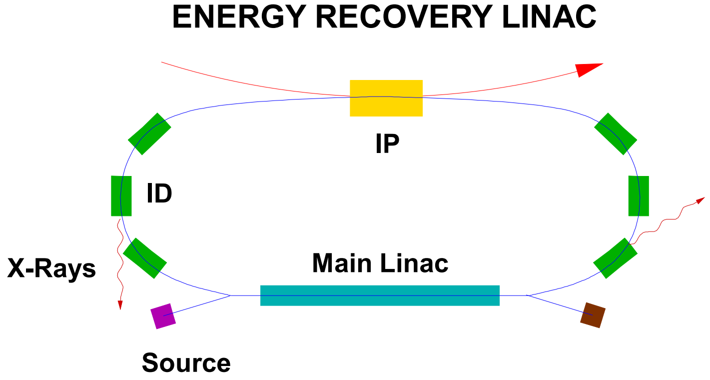




e.g. XFEL:
17.5GeV, 30 μA
“only” ~ 500 kW,
but real power

$$\varepsilon \sim \frac{1}{\gamma} \cdot \varepsilon_{source}$$

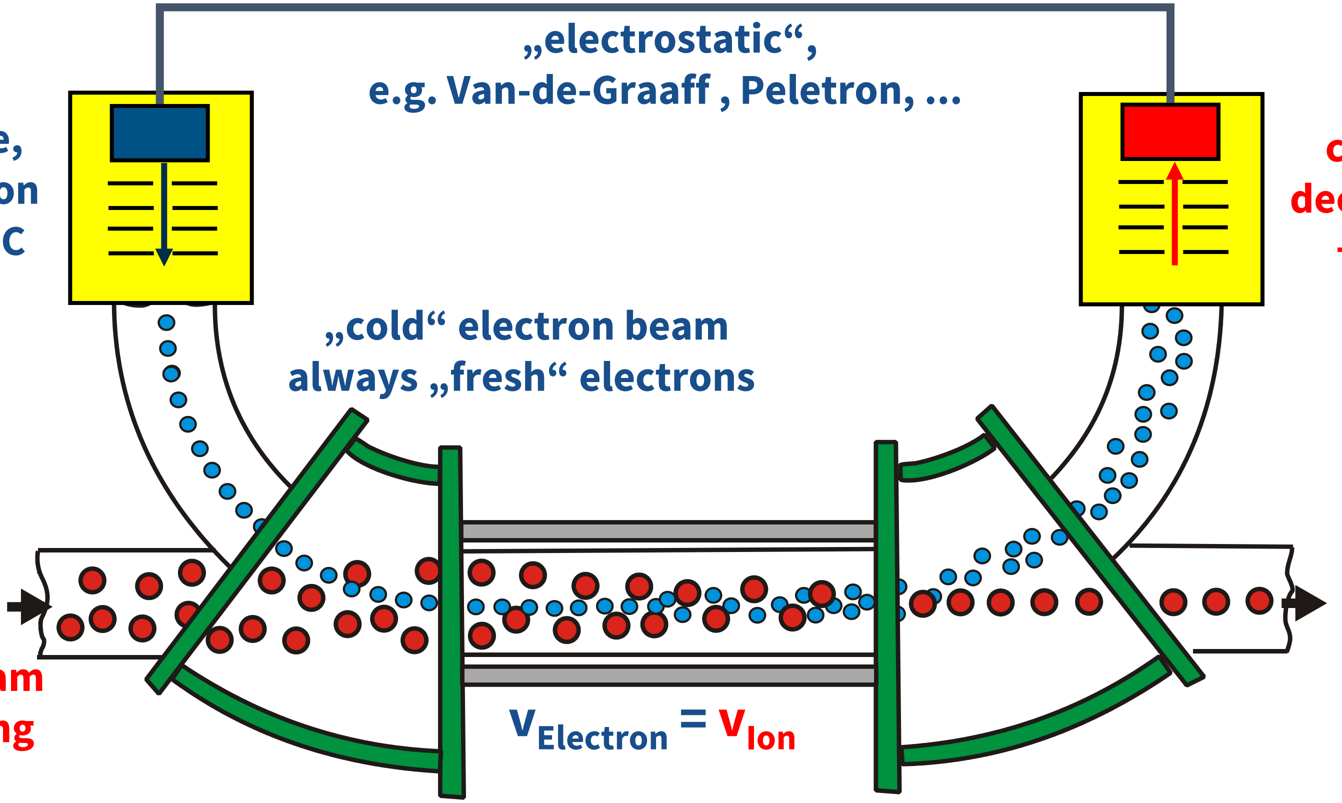
intrinsic short bunches, high current



high average beam power (multi GeV @ some 100 mA) for single pass experiments, excellent beam parameter, high flexibility, multi user facility

Energy recovery (nothing spooky and not a perpetuum mobile)

e.g. „electron cooler“ for ion beams, first devices in the 70ies

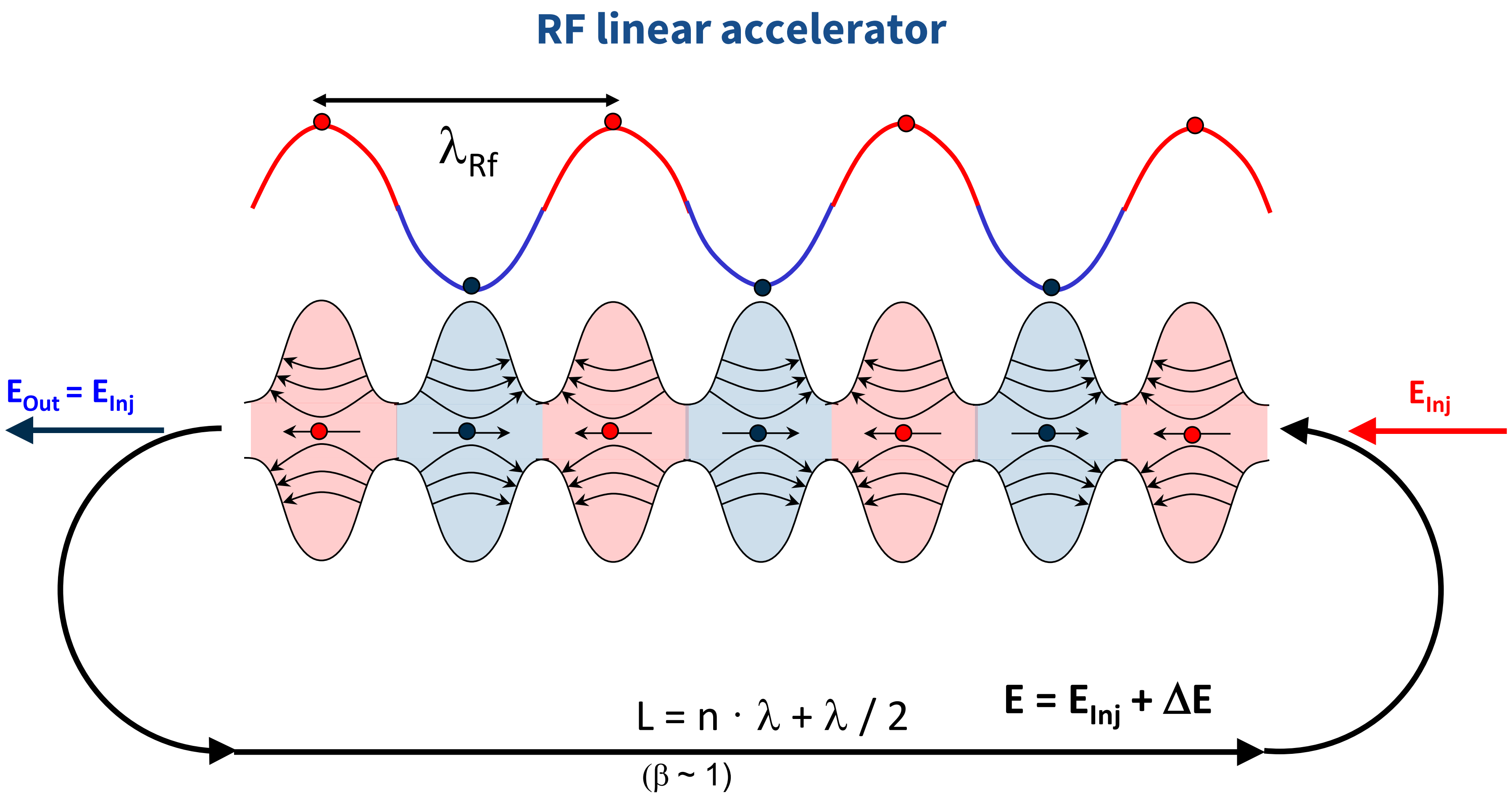


e.g. FermiLab recycler ring (Tevatron)

anti protons:	E = 9 GeV	$\rightarrow \beta = 0.995$
electrons:	E = 4.9 MeV	$\rightarrow U_{Cooler} = 4.39$ MV ($\beta = 0.995$)
	I = 0.5A (DC)	$\rightarrow$ **P = 2.2 MW**

„virtual“

Energy recovery in RF-fields – braking the DC limit



Energy supply = acceleration

→ „loss free“ energy storage (in the beam)

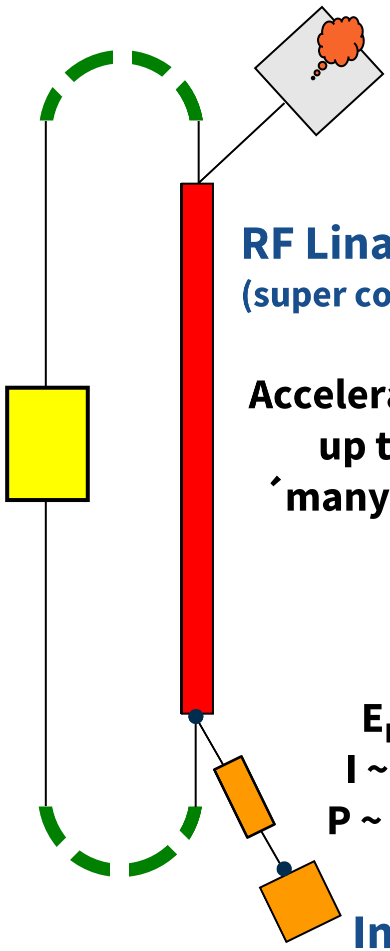
→ Energy recovery = deceleration

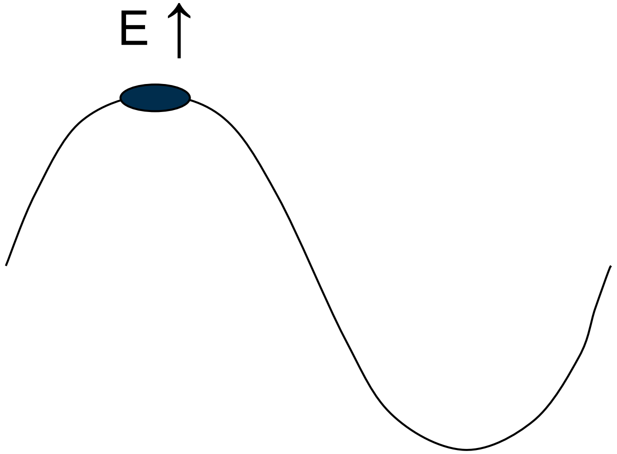
The Energy Recovery Linac Principle

„experiment“ needs „virtual“ power MW to GW

and

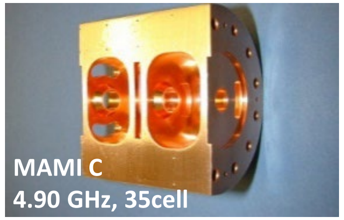
an always „fresh“ beam





ERLs are in favor of superconducting RF

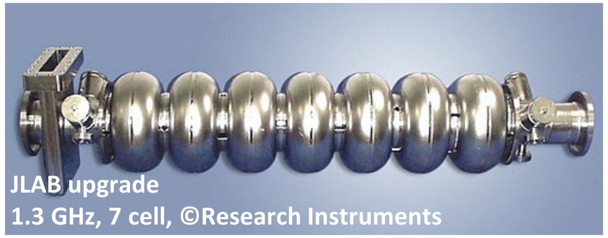
normal conducting (Cu) RF
(typical S/C-Band, ~2 – 6 GHz)



ΔE ~ 1 MV/m / P_{RF} ~ 15 kW/m (CW)
(in short structures 210 kW/m reached = 3.8 MV/m)
pulsed operation allows ~ 50 MV/m, but duty cycle reduced by $1/50^2$ = 0.4 ‰

cw high current operation hampered by limited HOM damping capabilities
(efficiency needs long structures with many cells, apertures typical only 10-20mm)

super conducting (Nb) RF
(L-Band, ~ 1 – 2 GHz)



ΔE ~ 20 MV/m / P_{RF} ~ 20 W/m (CW)
(JLAB upgrade: 19.2 MV/m)
large apertures (70mm+) and low number of cells allows efficient HOM damping

SC RF allows to built an ERL “compact” (high gradient)
for high current cw operation (large apertures, strong HOM damping)
Wall plug power consumption shifts from RF to Cryo (2K efficiency ~ 1/1000)
ERL is not necessarily a “green machine”

History – First idea

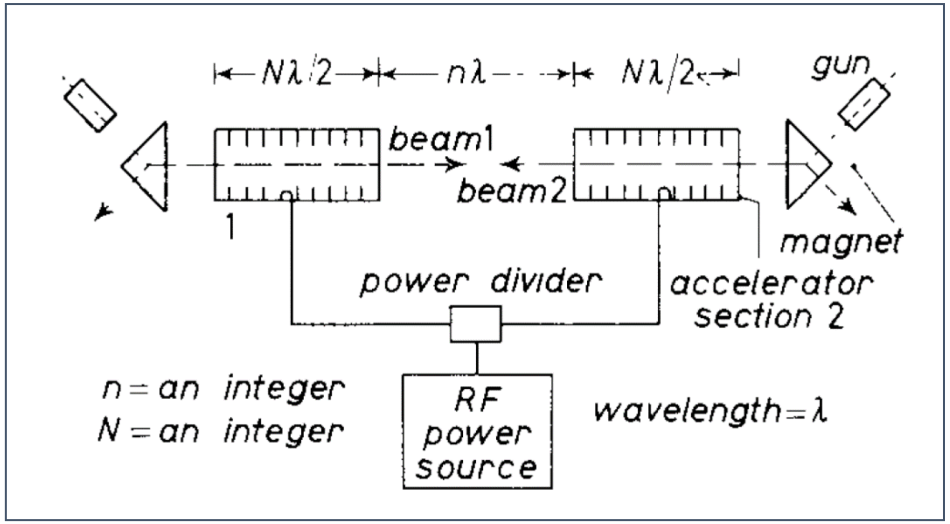
First idea: M. Tigner, Nuovo Cimento 37 (1965) 1228

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

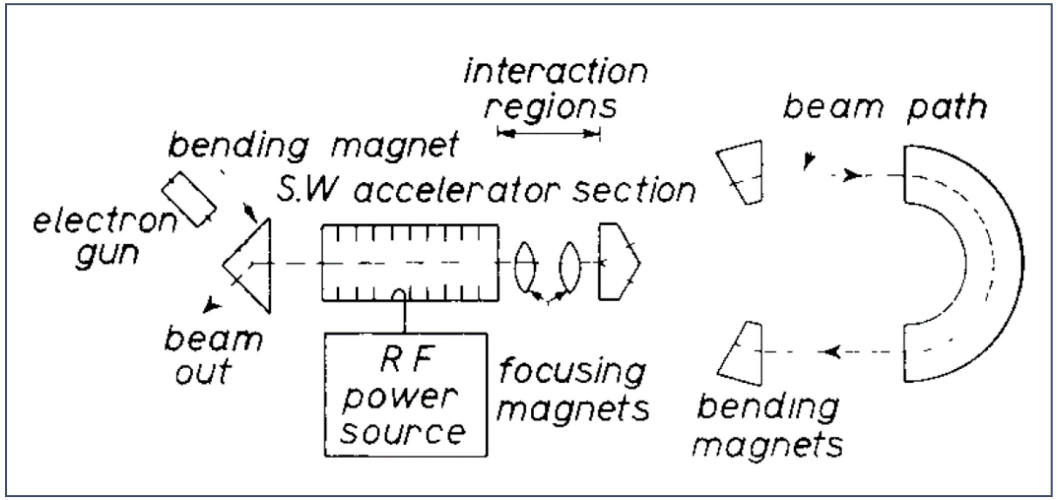
(ricevuto il 2 Febbraio 1965)



History – First idea

First idea: M. Tigner, Nuovo Cimento 37 (1965) 1228

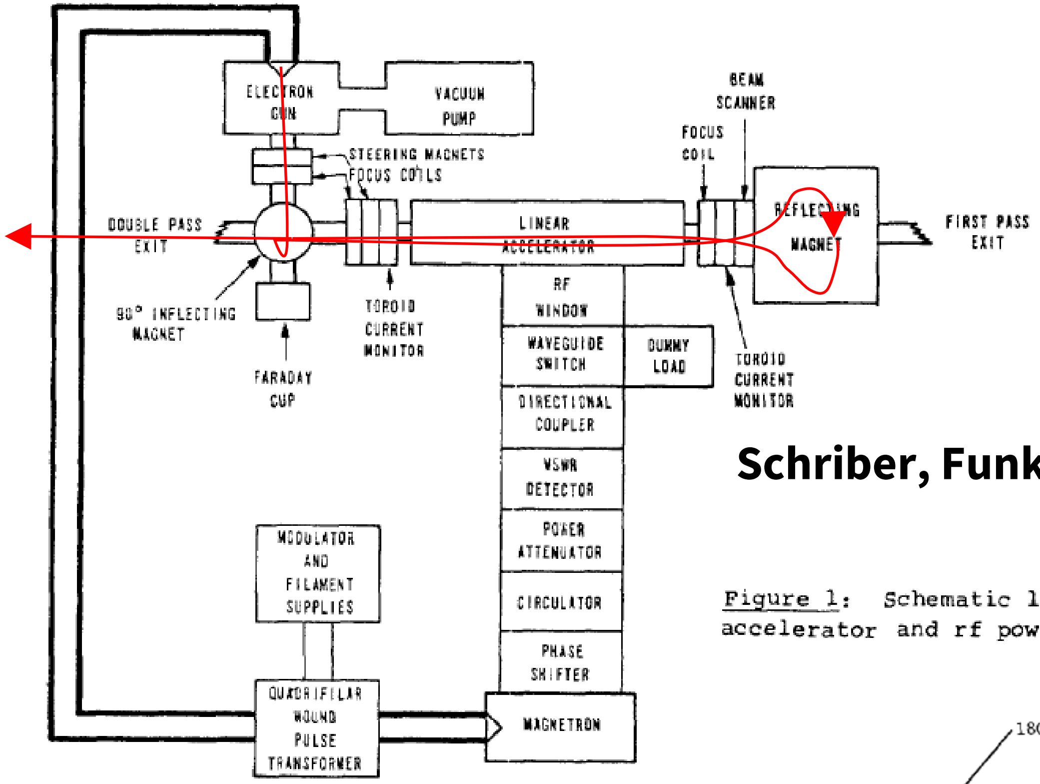
Beam energy (GeV)	0.5	3
Length (m)	47	275
Beam current (A)	0.120	0.120
Luminosity ($cm^{-2}\ s^{-1}$)	$3 \cdot 10^{30}$	$3 \cdot 10^{30}$
RF power to establish accelerating field in absence of beam (kW) (1000 MHz operation)	.55	3.3
Refrigerator power (MW)	0.92	5.5
Synchrotron radiation loss in magnets (kW)	—	14 (30 m) bending radius)



- stability issues (need same current in both linacs for efficient energy recovery) solved
- one linac only

Maybe first realisation
(1977, without taking attention to it):
Reflexotron (two pass linac) for
medical application
(Chalk River, Canada)
S.O. Schreiber, IEEE NS-22 (1975) (3) 1060-1064

History – The Chalk River Reflexotron



Schriber, Funk, Hodge, Hucheon, PAC1977, 1061-1063

Figure 1: Schematic layout of accelerator and rf power system.

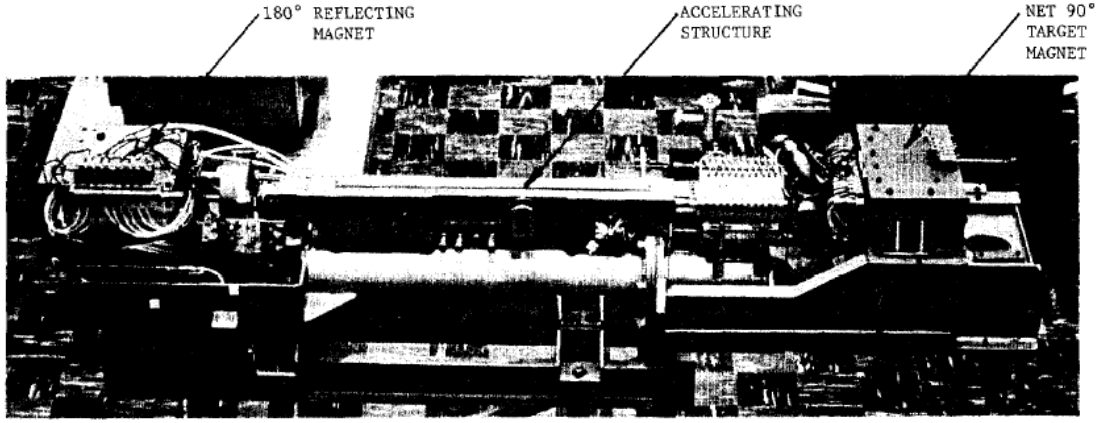
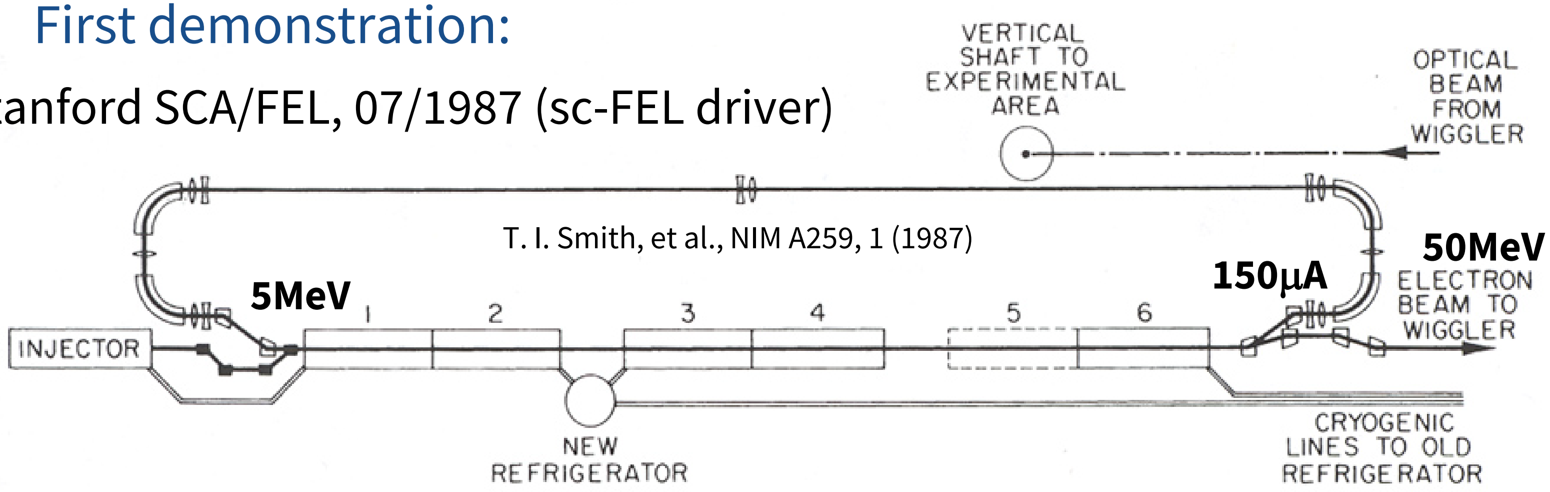


Figure 1. The 25 MeV electron accelerator attached to its strongback.

History – First demonstration

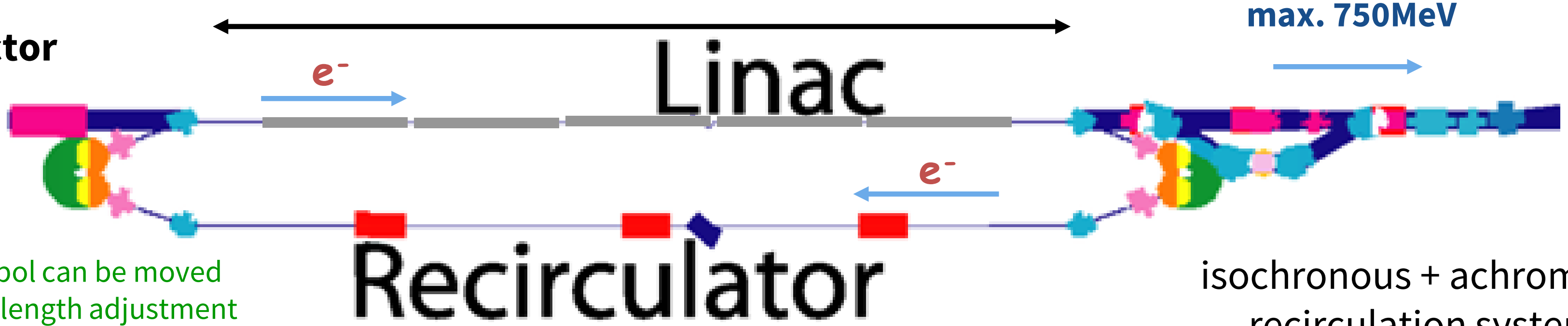
First demonstration:

Stanford SCA/FEL, 07/1987 (sc-FEL driver)



T. I. Smith, et al., NIM A259, 1 (1987)

MIT Bates Recirculated Linac (2.857GHz, nc, pulsed), 1985



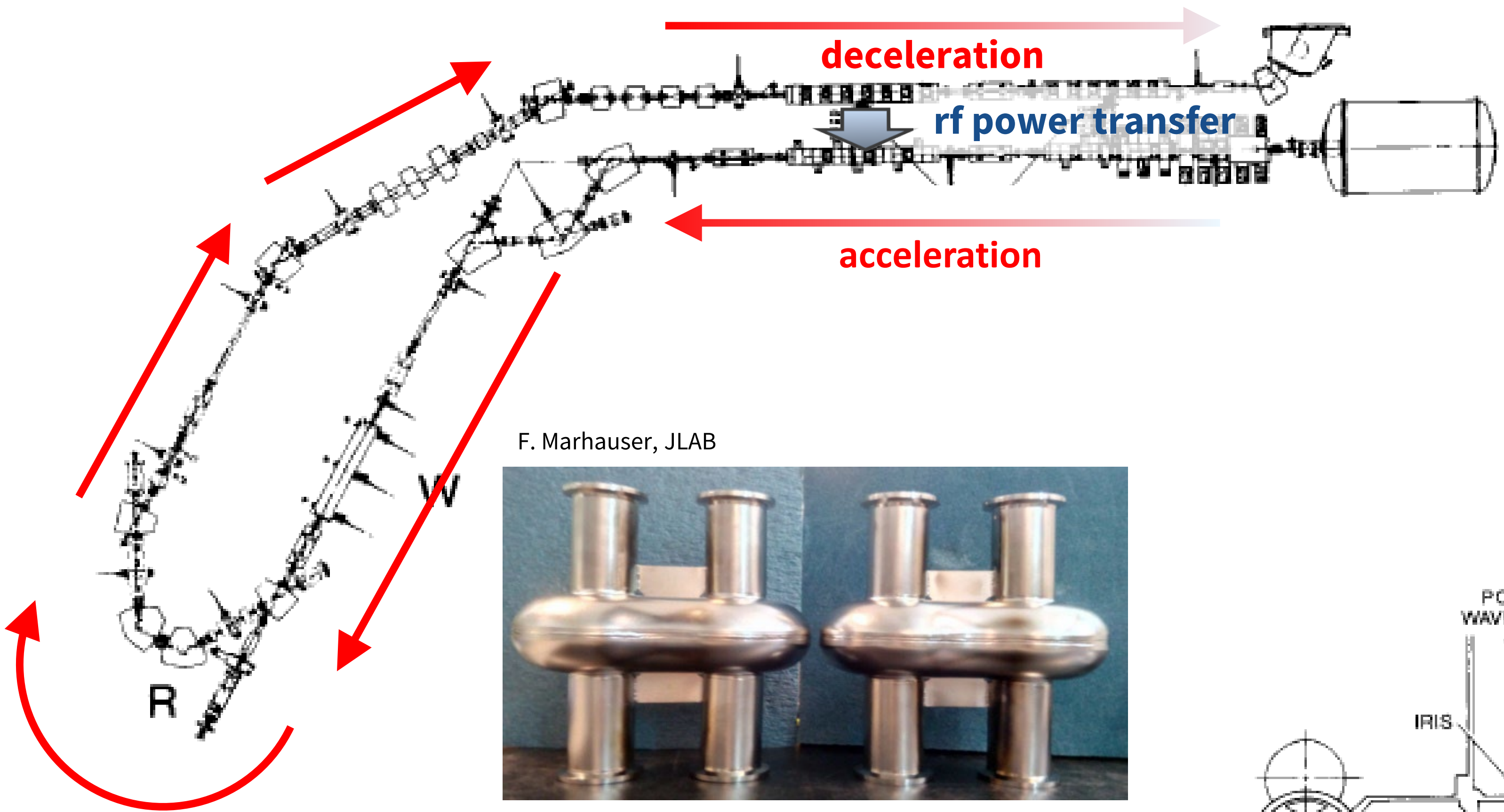
180° dipol can be moved for path length adjustment

isochronous + achromatic recirculation system (energy bandpass: 6%)

J.B. Flanz et al., IEEE Trans. Nucl. Sci., NS-32, No.5, p.3213 (1985)

History – A Little Different Concept

D.W. Feldman et al. / Energy recovery in the Los Alamos FEL



F. Marhauser, JLAB

rf power transfer

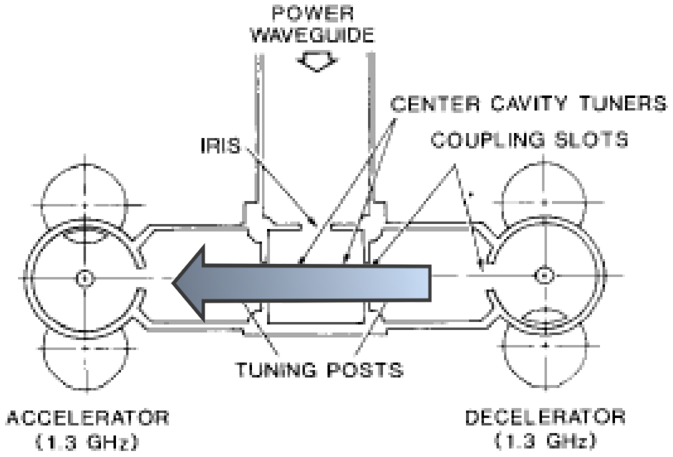
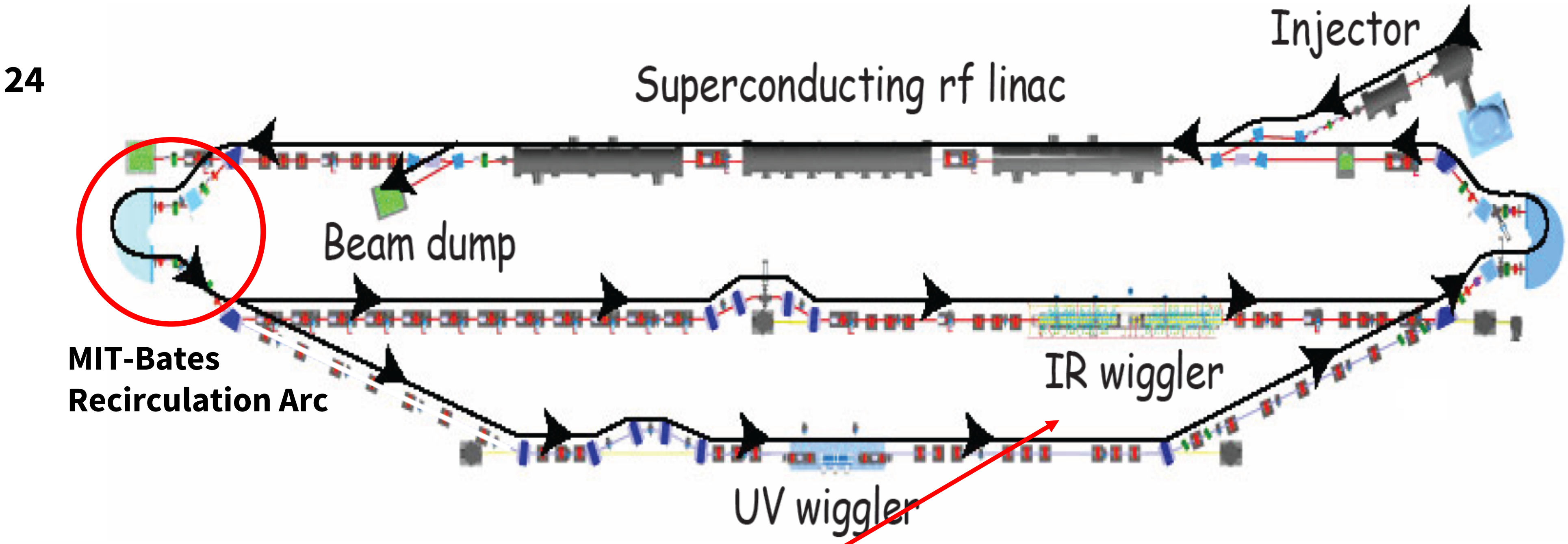


Fig. 2. Resonant bridge-coupler cross section.

First facilities – JLAB FEL

G.R. Neil, et al., Nucl. Instr. & Methods **A557** (2006) 9.



up to 14 kW cw laser power
@ 1.6 µm wavelength

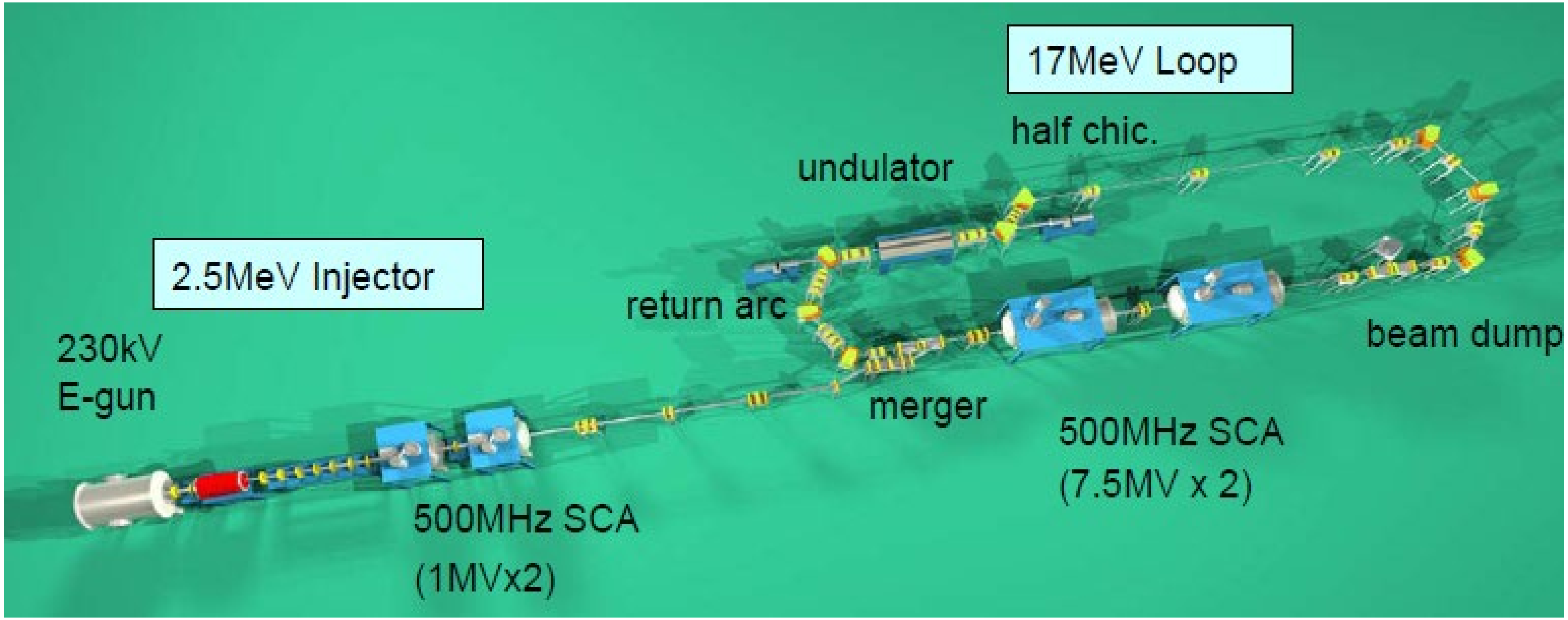
Parameter achieved:

Energy: **160 MeV**
Current: **9.1 mA**
(135 pC @ 75 MHz)
beam power: 1.5 MW

emittance (norm.): **7 mm**
min. pulse length: **150 fs**

First facilities – KEK / JAEA ERL FEL

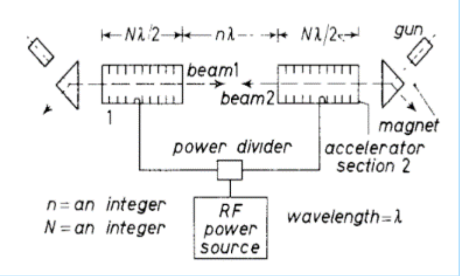
JAEA IR-FEL (starts 1987, JAERI):
500 MHz sc cavities, 15 – 20 MeV, 8 mA → 2 kW cw laser power @ 22 μm
at the beginning single pass → 2002 upgrade to energy recovery setup



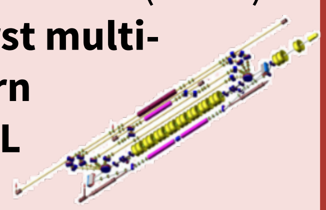
Around 2005: KEK and JAEA proposes ERL based light sources (5 GeV)
Decision to built in an common effort: Compact ERL !

Overview on projects and facilities

First idea:
M. Tigner (1965)



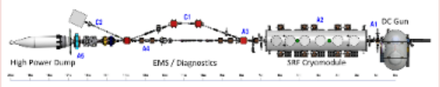
BINP FEL (2004):
First multi-turn ERL



JAERI FEL (2002):
17 MeV, 5 mA

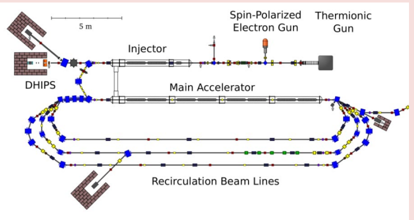
CBETA (2019)
FFAG ERL
(with BNL)

Cornell University
Injector Teststand



BNL R&D ERL
Beijing ERL-FEL

S-DALINAC ERL
Single- / Multi-Turn
(2017) (2021)

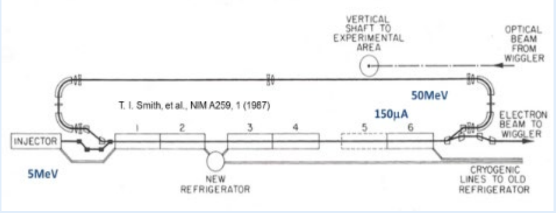


1960 1980 2000 2020

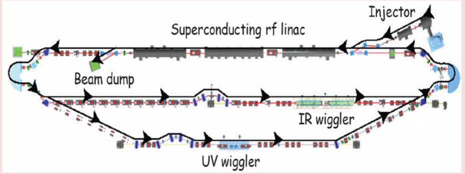
ALICE, Daresbury

PERLE@ORSAY
CERN, JLAB, Daresbury, BINP, LAL

First energy recovery:
Stanford SCA/FEL (1987)

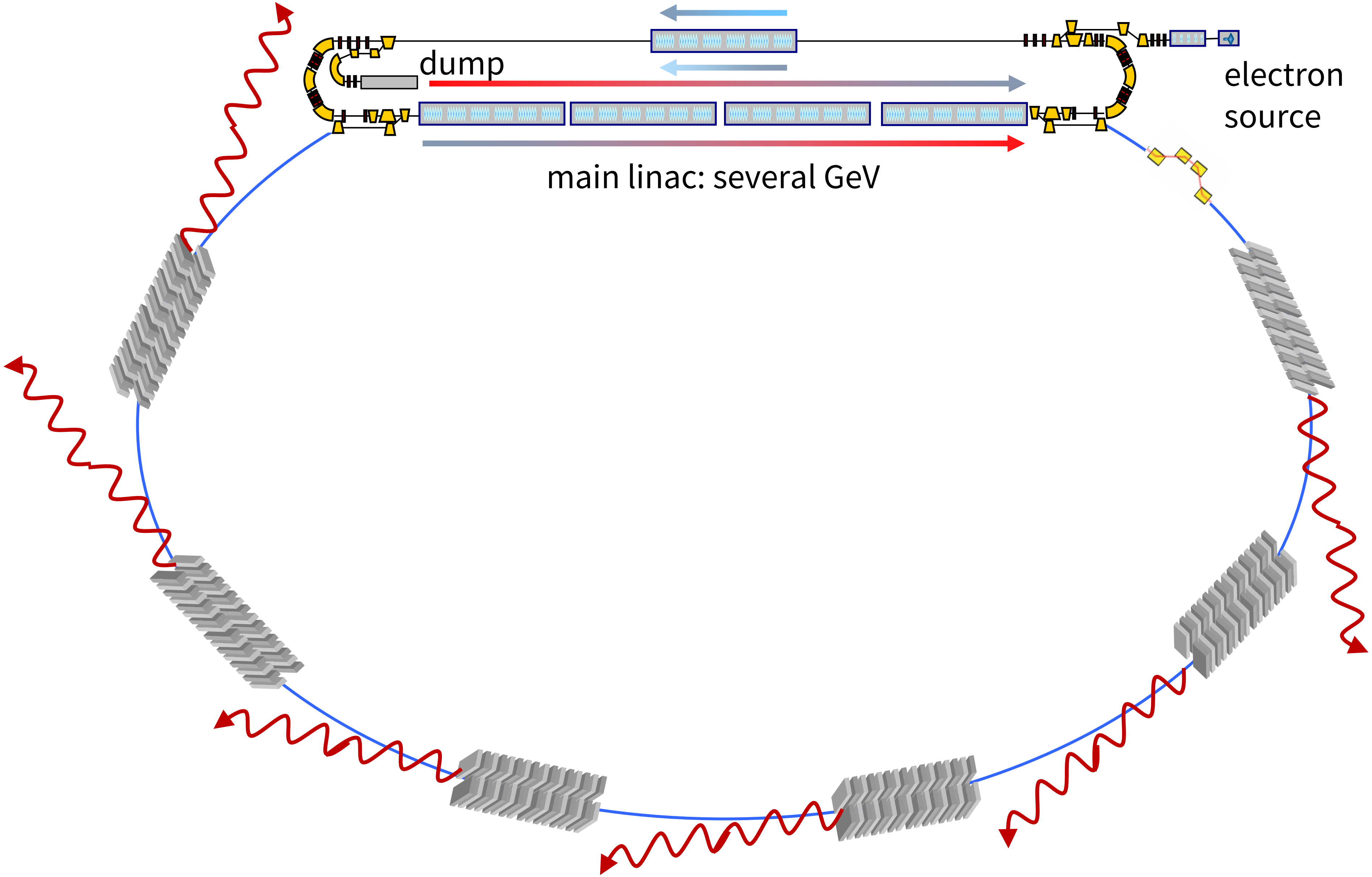


JLAB-FEL: Demo-FEL (1999) &
FEL Upgrade (2004)



KEK cERL (2014):
recirc. & energy recovery

ERL as next Generation Multi-GeV, Multi-User SR-Source



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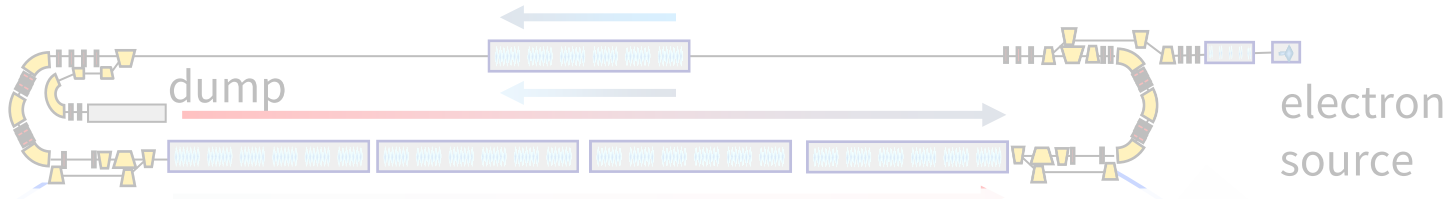


Combines the two worlds of storage rings and linacs

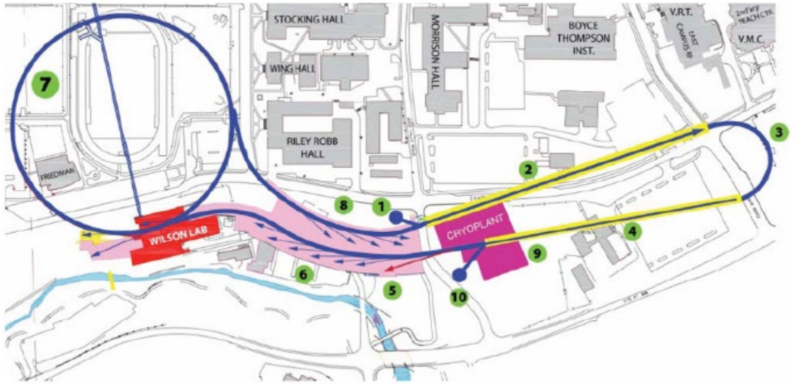
- with energy recovery: some 100mA @ many GeV possible
- always “fresh” electrons (no equilibrium)
  - → small emittance (~ 0.1 μm rad norm. = 10 pm rad@6GeV)
  - → very high brilliance
  - → short pulses (ps down to 10 – 100 fs)
- free choice of polarisation
- 100% coherence up to hard X-rays
- real multi-user operation at many beam lines
- tailored optics at each ID

Flexible modes of operation (high brilliance, short pulse, different pulse patterns)

adaptable to user requirements!

ERL light source design studies

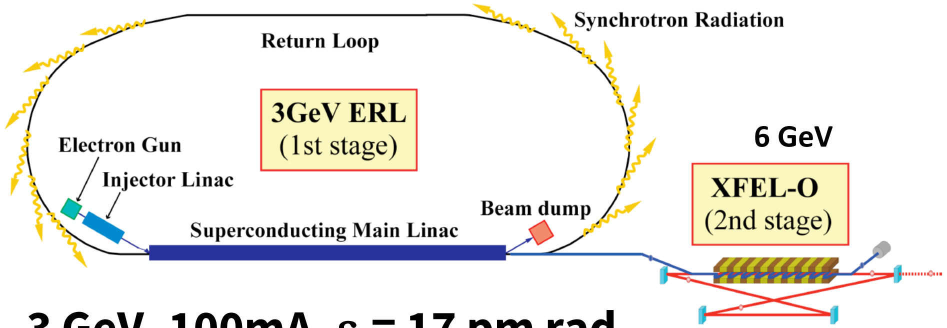
Cornell ERL



5 GeV, 100mA, ε = 8 pm rad

(ε_{norm} = 0.08 μm (@77pC) , 2ps)

KEK ERL

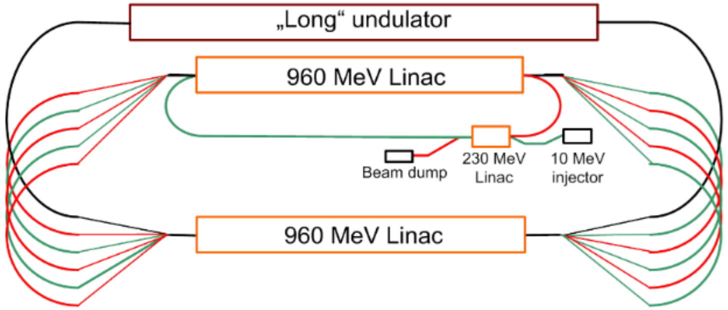


3 GeV, 100mA, ε = 17 pm rad

(ε_{norm} = 0.1 μm (@77pC) , 2ps)

Femto Science Facility (FSF)

(multi turn, split linac), A. Matveenko et al.



6 GeV, 20/5 mA, ε = 8/40 pm rad

(ε_{norm} = 0.1/0.5 μm (@15/4 pC), < 1 ps / 10 fs)

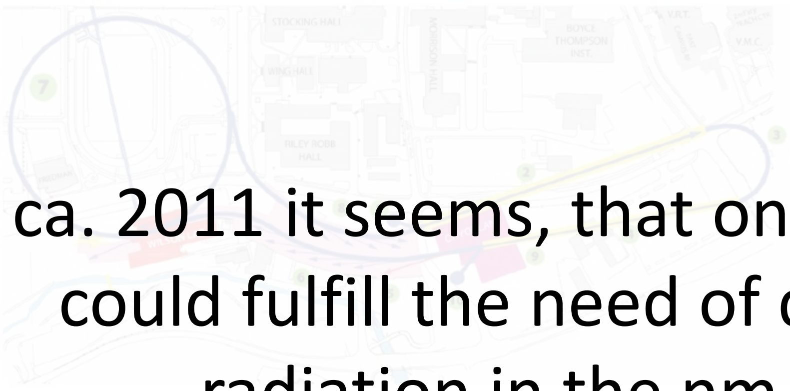
ERL light source design studies

Up to ca. 2011 it seems, that only high energy, high current (~100mA class) ERL could fulfill the need of diffraction limited (transverse coherent) radiation in the nm, down to the Å, wavelength range!

But: The concept of “Multi-Bend-Achromat Lattices” for 4th generation light sources took over!
(near to requested performance, known technology, less risk)

Will there be an “come back” of the ERL for light sources?

Cornell ERL



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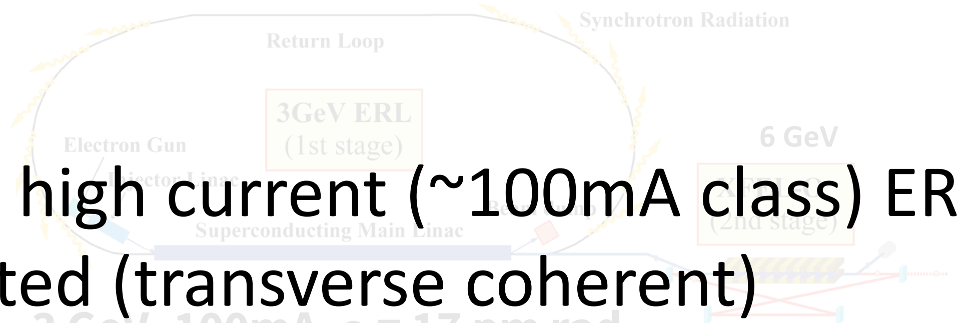
KEK ERL



3 GeV, 100mA, ε = 17 pm rad

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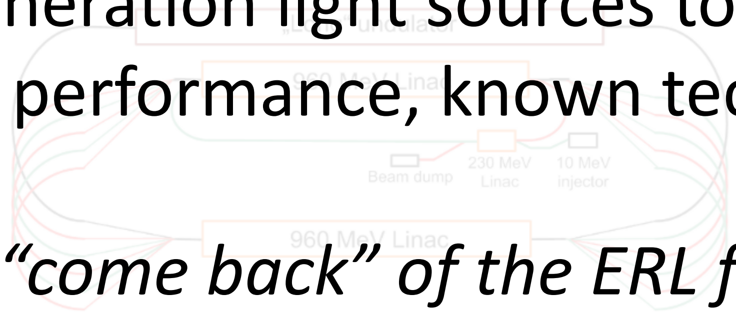


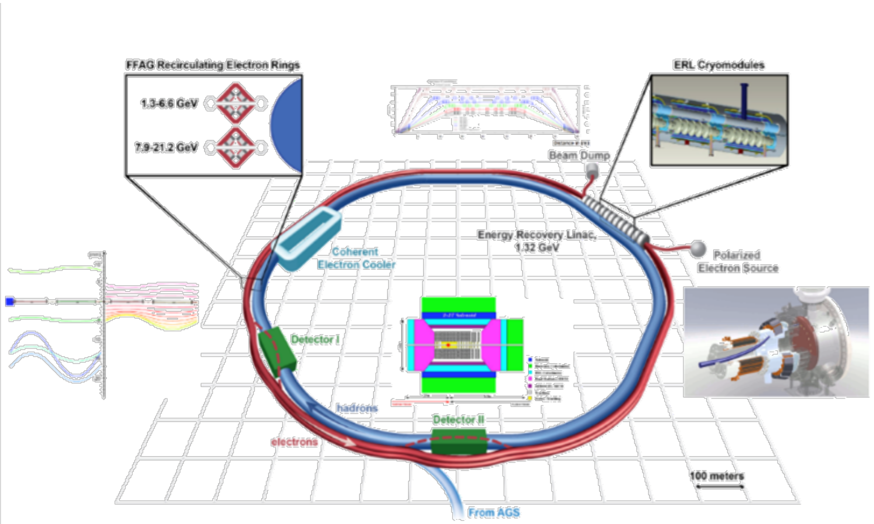
6 GeV, 20/5 mA, ε = 8/40 pm rad
(ε_{norm} = 0.1/0.5 μm (@15/4 pC), < 1 ps / 10 fs)

ERL as electron part of Electron Ion Collider

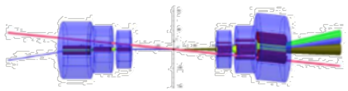
e.g. addition of an ERL to an Hadron Collider (Electron-Ion-Collider)

250 GeV polarised protons ↔ 20GeV polarised electrons, $L=10^{33\text{-}34}\ cm^{-2}\ s^{-1}$

(415 mA) (10 mA) (β^*=5cm, 6μm spot size @ IP)



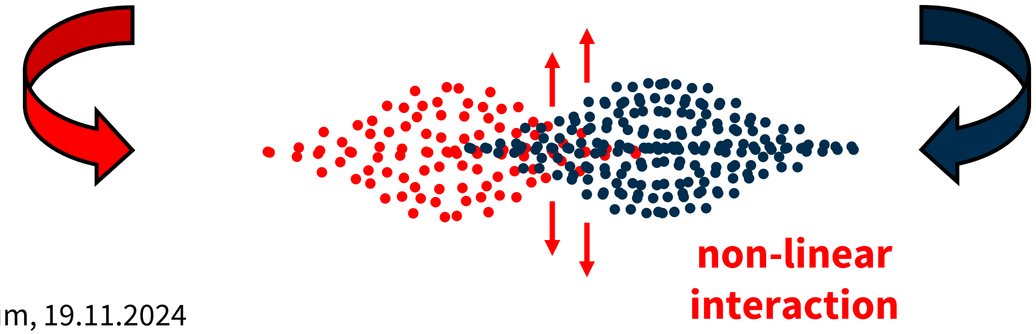
Why ERL and not storage ring?



Luminosity

$$L = f_{coll} \cdot \frac{n_{Ion} \cdot n_e}{4 \cdot \pi \cdot \varepsilon \cdot \beta} \cdot F_{HGR}$$

Limit: beam-beam parameter electrons (!)



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ERL compared to storage ring

- electron beam needs to pass the interaction zone only once
- disturbance of electron beam by proton beam can be up to 20x stronger
- higher number of hadrons/Ions with high density possible
  → drastic increase in luminosity
- higher flexibility in interaction region design
- spin transparency (free choice to arrange spin orientation at IP)

Why ERL and not storage ring?

Luminosity

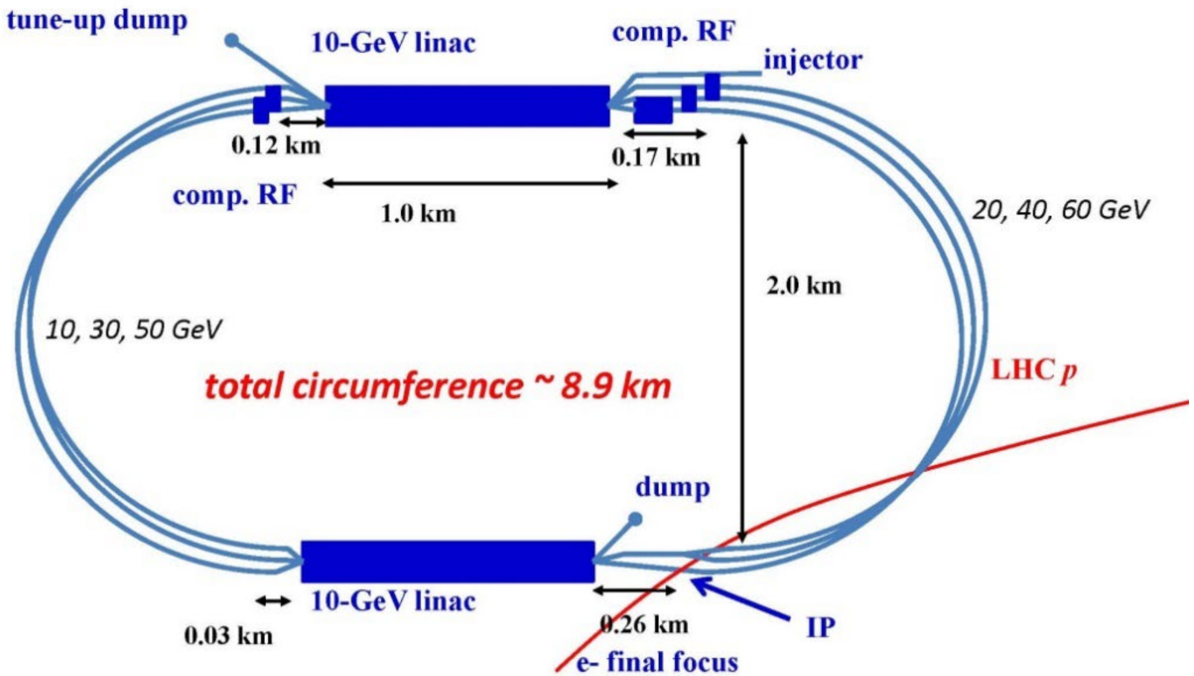
$$L = f_{coll} \cdot \frac{n_{Ion} \cdot n_e}{4 \cdot \pi \cdot \varepsilon \cdot \beta} \cdot F_{HGR}$$

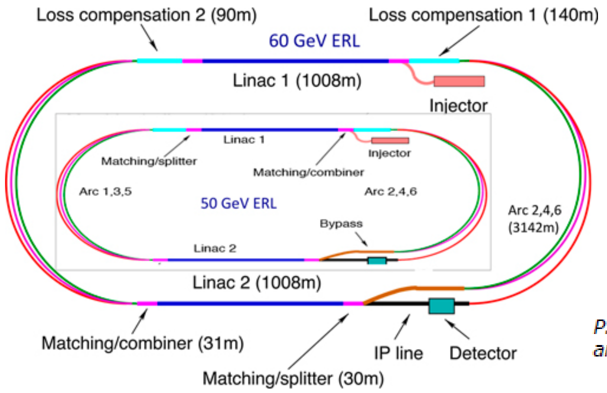
Limit: beam-beam parameter electrons (!)

$$\xi^e = \frac{r_{0,e}}{4\pi} \cdot \frac{n_{Ion}}{\gamma_e} \cdot \frac{\beta_e^*}{\varepsilon_{Ion} \cdot \beta_{Ion}^*} < 0.1$$

ELR as electron part of Electron Ion Collider

60 GeV (e) x 7 TeV (p)



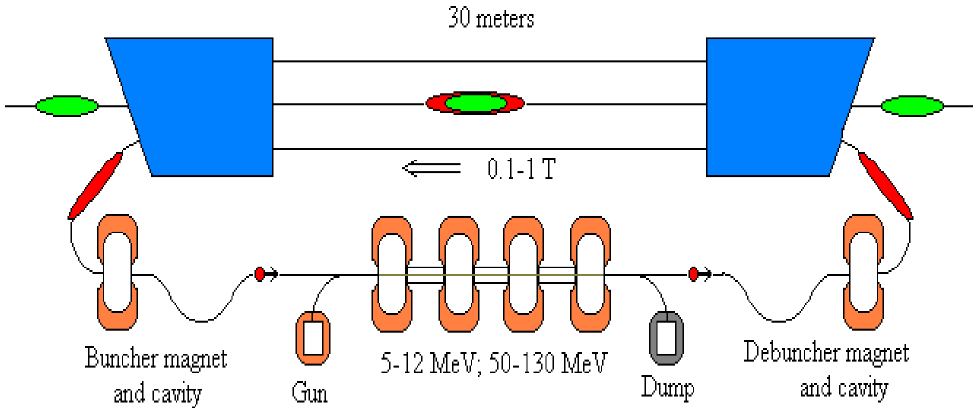


Parameters	LHeC	
	e	p
Energy (GeV)	60	7000
Bunch spacing (ns)	25	
Intensity, 10^{11}	0.01	1.7
Current (mA)	6.4	860
rms norm. emit. (mm-mrad)	50	3.75
$\beta_{x/y}^{*}$ (cm)	12	10
rms bunch length (cm)	0.06	7.6
IP rms spot size (μ m)	7.2	
Beam-beam parameter		0.0001
Disruption parameter	6	
Polarization, %	90	None
Luminosity, $10^{33} cm^{-2} s^{-1}$	1.3	

P. Agostini et al., The Large Hadron-Electron Collider at the HL-LHC, subm. to J. Phys. G, arXiv:2007.14491, 2020. https://arxiv.org/abs/2007.14491.

ELR as electron cooler

e.g. RHIC
Cooling of 100GeV/u Au



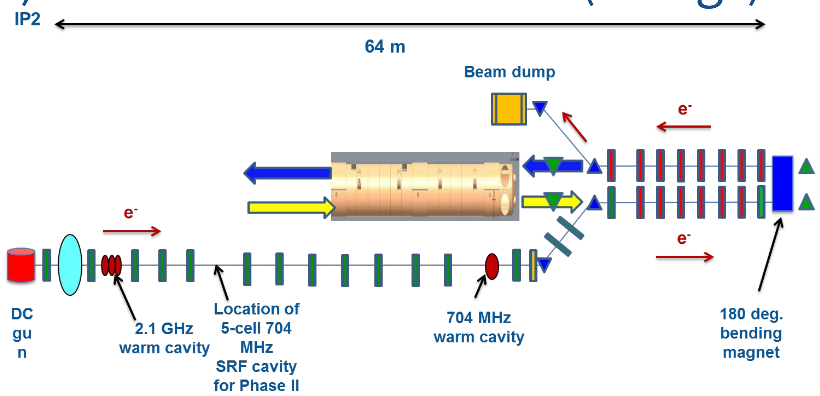
Efficient cooling needs

- $\gamma_{ion} = \gamma_{electron}$, e.g. 100 GeV protons needs 54.5 MeV electrons
- low emittance of electron beam (ε_{norm} ~ μm rad)
- low energy spread of electron beam ($\delta_{E,rel}$ ~ 0.05%)
- high electron beam current

54.5 MV and Ampere class currents not feasible with electrostatic accelerators

ERL cooler needs overlap of (many "short") electron bunches with ("long") ion bunches

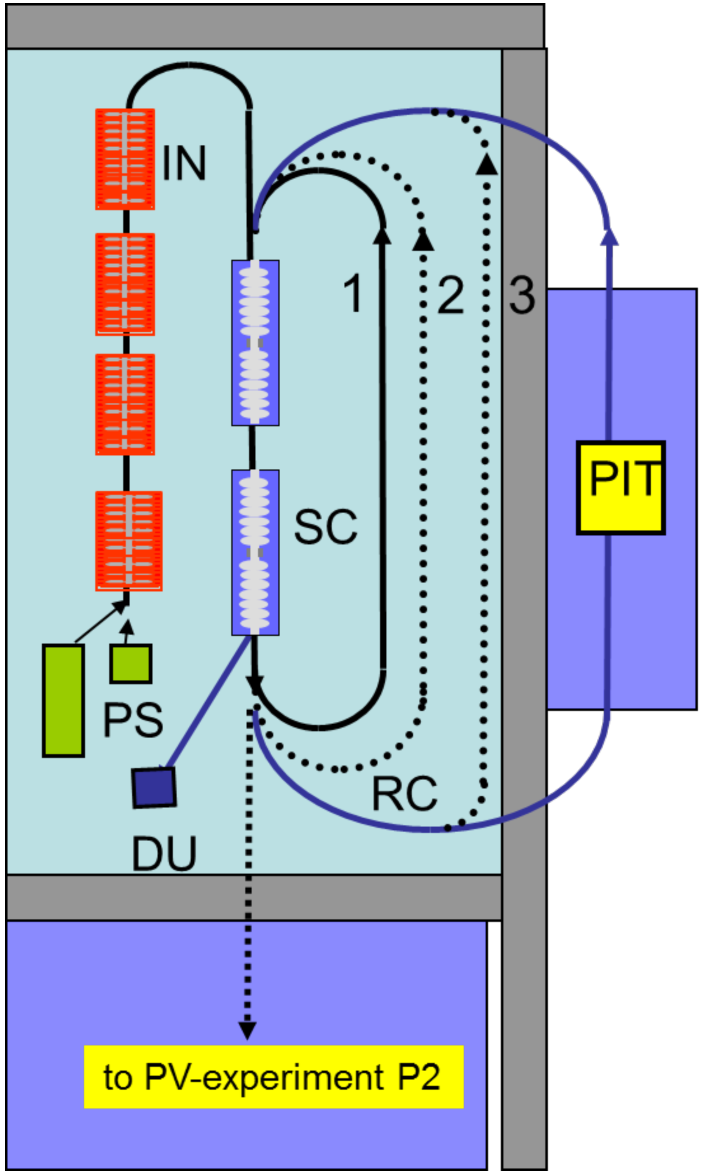
(LEReC Phase-I project@BNL,
up to 2 MeV, gun2dump approved)



for ultra high ion energies
Coherent Electron Cooling
("stochastic cooling")

- ion beam imprints modulation on electron beam
- modulation on electron beam amplified by FEL
- electron beam acts back on ion beam

Compact ERL for low energy, high luminosity internal target experiments



First sketch (2009)

MESA @ Mainz University

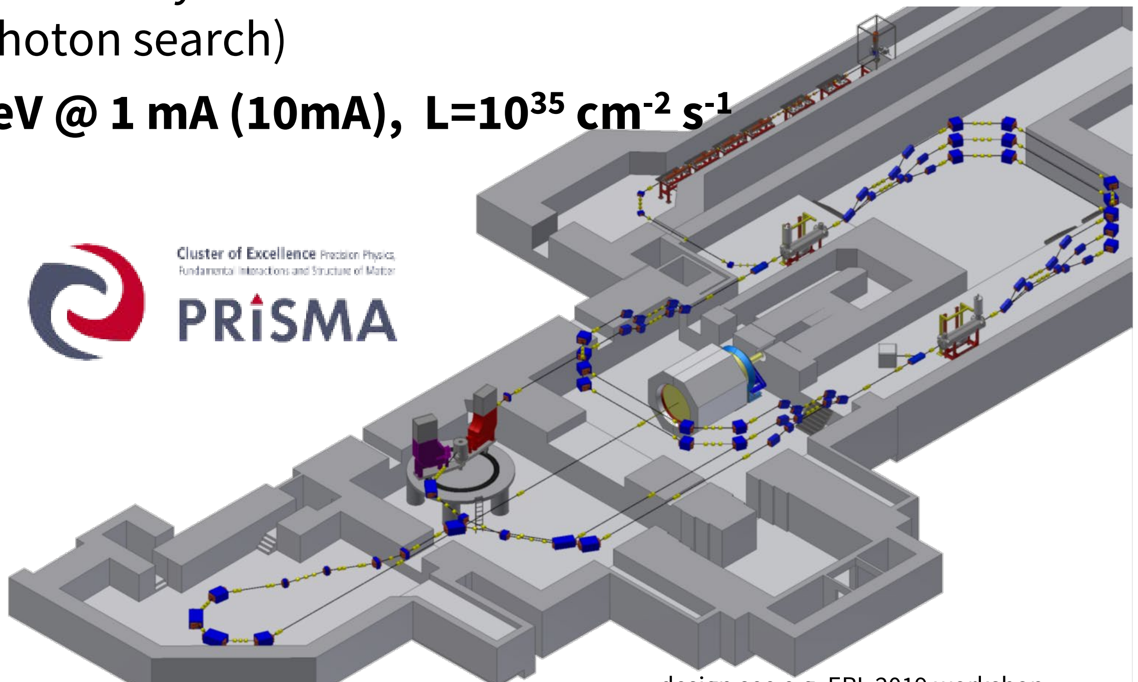
Multi turn ERL for

1) External beams for precision measurements (weak mixing angle)

E=155 MeV @ 150 μA, polarized e^-, $L=10^{39}\ cm^{-2}\ s^{-1}$

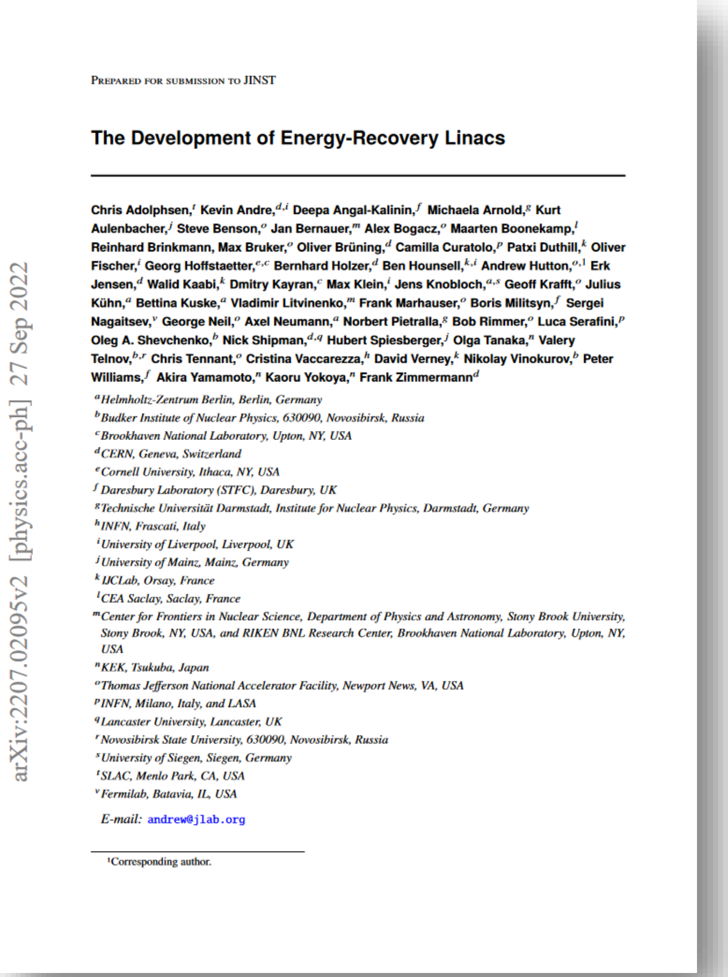
2) Pseudo Internal Target (PIT) experiments in Energy Recovery mode (dark photon search)

E=105 MeV @ 1 mA (10mA), $L=10^{35}\ cm^{-2}\ s^{-1}$



design see e.g. ERL 2019 workshop

Landscape of past, present and future ERL



arXiv:2207.02095v2 [physics.acc-ph] 27 Sep 2022

Prepared for submission to JINST

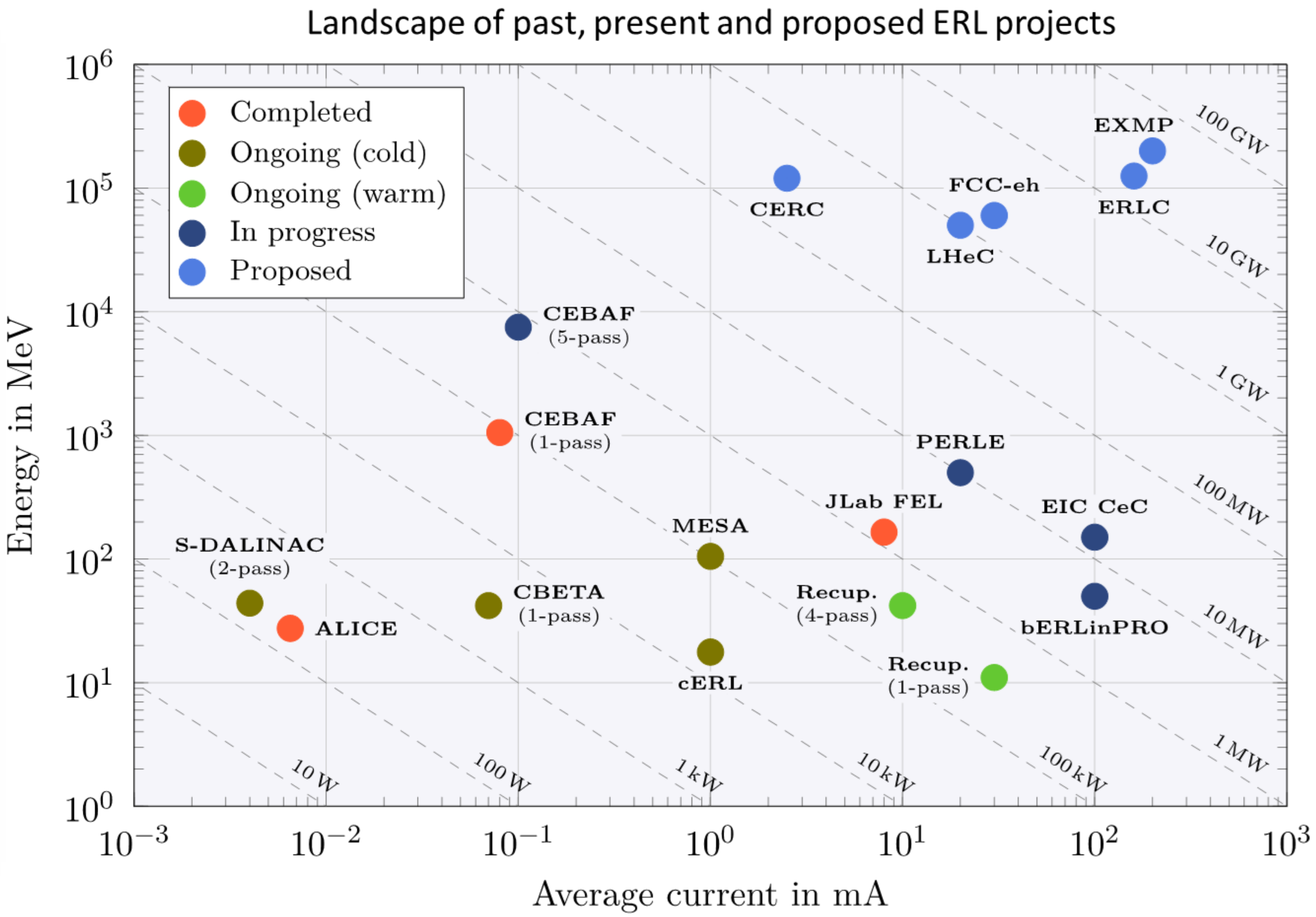
The Development of Energy-Recovery Linacs

Chris Adolphsen,[t] Kevin Andre,[d,i] Deepa Angal-Kalinin,[f] Michaela Arnold,[g] Kurt Aulenbacher,[j] Steve Benson,[o] Jan Bernauer,[m] Alex Bogacz,[o] Maarten Boonekamp,[l] Reinhard Brinkmann, Max Bruker,[o] Oliver Brüning,[d] Camilla Curatolo,[p] Patxi Duthill,[k] Oliver Fischer,[i] Georg Hoffstaetter,[e,c] Bernhard Holzer,[d] Ben Hounsell,[k,i] Andrew Hutton,[o,1] Erk Jensen,[d] Walid Kaabi,[k] Dmitry Kayran,[c] Max Klein,[i] Jens Knobloch,[a,s] Geoff Krafft,[o] Julius Kühn,[a] Bettina Kuske,[a] Vladimir Litvinenko,[m] Frank Marhauser,[o] Boris Militsyn,[f] Sergei Nagaitsev,[v] George Neil,[o] Axel Neumann,[a] Norbert Pietralla,[g] Bob Rimmer,[o] Luca Serafini,[p] Oleg A. Shevchenko,[b] Nick Shipman,[d,q] Hubert Spiesberger,[j] Olga Tanaka,[n] Valery Telnov,[b,r] Chris Tennant,[o] Cristina Vaccarezza,[h] David Verney,[k] Nikolay Vinokurov,[b] Peter Williams,[f] Akira Yamamoto,[n] Kaoru Yokoya,[n] Frank Zimmermann[d]

[a] *Helmholtz-Zentrum Berlin, Berlin, Germany*
[b] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[c] *Brookhaven National Laboratory, Upton, NY, USA*
[d] *CERN, Geneva, Switzerland*
[e] *Cornell University, Ithaca, NY, USA*
[f] *Daresbury Laboratory (STFC), Daresbury, UK*
[g] *Technische Universität Darmstadt, Institute for Nuclear Physics, Darmstadt, Germany*
[h] *INFN, Frascati, Italy*
[i] *University of Liverpool, Liverpool, UK*
[j] *University of Mainz, Mainz, Germany*
[k] *IJCLab, Orsay, France*
[l] *CEA Saclay, Saclay, France*
[m] *Center for Frontiers in Nuclear Science, Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA, and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY, USA*
[n] *KEK, Tsukuba, Japan*
[o] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[p] *INFN, Milano, Italy, and LASA*
[q] *Lancaster University, Lancaster, UK*
[r] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[s] *University of Siegen, Siegen, Germany*
[t] *SLAC, Menlo Park, CA, USA*
[v] *Fermilab, Batavia, IL, USA*

E-mail: andrew@jlab.org

[1] Corresponding author.



Application of ERLs

Next generation multi-user light source

(diffraction limited, short pulses, ID tailored beam parameters)

High energy electron cooling of bunched proton/ion beams

(Energy ~ 100 MeV + high current → rules out VdG or SR)

Ultra high luminosity electron – ion collider (EIC, LHeC)

(overcoming beam-beam effect electron ring)

Compact radiation sources

(FEL, Compton sources,
next generation lithography)

and more …

Challenges

Electron source:

high current, low emittance (100 mA – A cw with ε_{norm} < µm rad) not yet demonstrated

(big step forward: Cornells 80 mA, dc gun)

Injector/Booster:

100 mA @ 5 – 15 MeV = 500 – 1500 kW beam loading (coupler, HOM damper, beam dump)

Main-Linac:

100 mA recirculating beam → beam break up (BBU), higher order modes (HOM),
highest cw-gradients (>15 MV/m) with quality factor > 1010 → reduce cryo costs

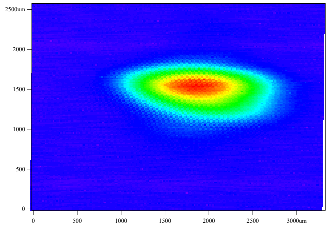
Beam dynamics / optics:

recirculation, flexible optics, bunch compression schemes = flexibility

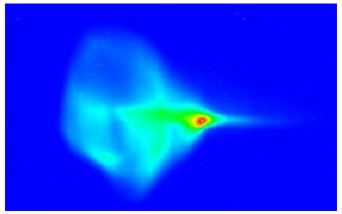
Control of beam loss

unwanted beam = dark current from cathode, gun, cavities due to field emission,
stray light / halo cathode laser beam, collimation schemes (at low beam energy)

Storage ring:
nearly Gaussian distribution
~ pA losses typical
~ 10 nA maximum



ERL:
no dead mathematician distribution
~ 100 µA losses possible (multi kW and more)



The "hummingbird"
P. Evtushenko, JLAB

Comparison Storage Ring <-> ERL (used charge / losses)

Let us assume 6000h/a operation @ 1.7 GeV

ERL parameter:
(10 MeV dump energy, 10^{-6} loss rate)

I_{Beam} = 100 mA
→ 0.1 C / s
→ 2.2 10^6 C / a = $1.4\cdot10^{25}$ electrons / a

BESSY II parameter (adjusted for comparison):
(τ = 15 h beam lifetime, $\eta_{inj.}$ = 90% injection eff., T_{circ} = 800 ns)

I_{Beam} = 100 mA
→ Q_{Beam} = 80 nC circulating "forever"
→ 80 nC = $0.5\cdot10^{12}$ electrons "forever"

$$I(t) = I_0 \cdot e^{-\frac{t}{\tau}}, \qquad Q(t) = Q_0 \cdot e^{-\frac{t}{\tau}}$$

$$\dot{Q}(t=0) = -\frac{Q_0}{\tau}, \quad Q_{loss}/s = \frac{\dot{Q}}{\eta_{eff}} = \frac{Q_0}{\eta_{eff}\cdot\tau}$$

assume a lossrate of 10^{-6}

99.9999 mA dumped @ 10 MeV = 1 MW
(easily shielded, as mostly Gammas and *no* neutrons)

100 nA dumped @ 1.7 GeV = 170 W
→ 100 nC / s
→ 2.16 C / a = $1.34\cdot10^{19}$ electrons / a

losses are governed by lifetime and injection

maintaining I_{Beam} = 100 mA / Q_{Beam} = 80 nC
→ 1.65 pC / s

1.65 pA dumped @ 1.7 GeV = 0,0028 W
→ 1.65 pC / s
→ 35.6 µC / a = $2.2\cdot10^{14}$ electrons / a

Demonstrator projects world-wide

cERL, KEK + JAEA

35 MeV, 10 mA

- 1 mA reached 2016 –

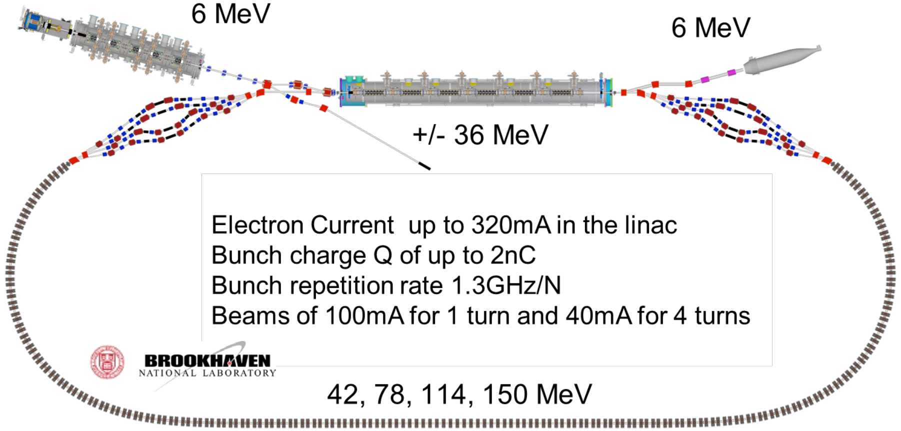
discontinued

CBETA FFAG ERL, Cornell/BNL

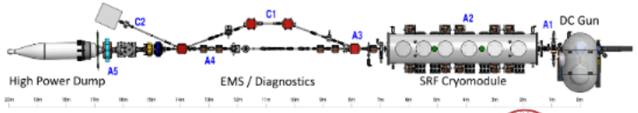
150 MeV (4 turns), 40 mA

- construction started 2016

- four-turn ER demonstrated in 2019



ERL Injector, Cornell



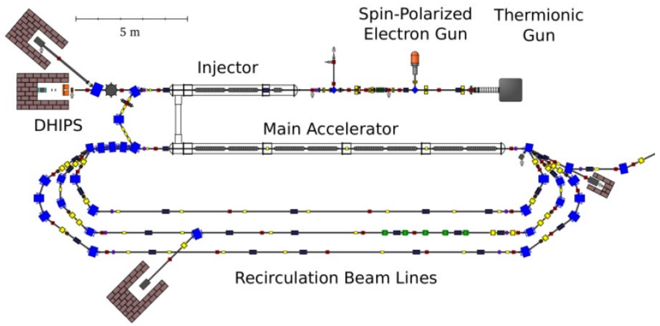
5 – 15 MeV, 100 mA

- 80 mA max. demonstrated -

S-DALINAC

2 turns, 40 MeV, ~2.3 μA

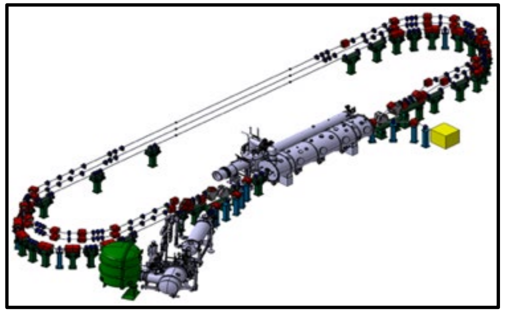
TECHNISCHE UNIVERSITÄT DARMSTADT



PERLE@ORSAY (CNRS)

250 MeV, 20 mA (3 turns, 802 MHz)

(TDR 2025, stepwise installation and commissioning till 2031)



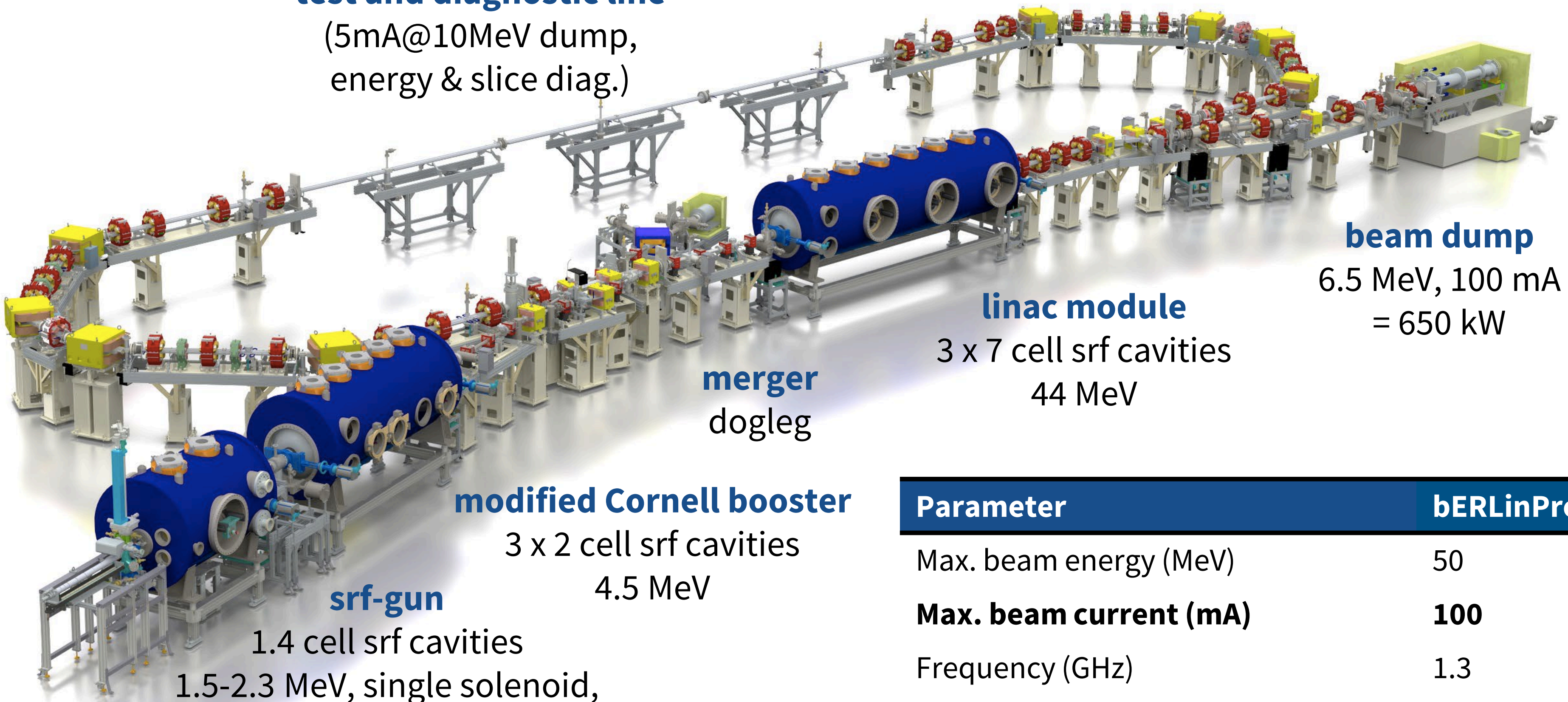
CERN
STFC, U Liverpool, ESS Bilbao
BINP, an-Najah University
contribution of iSAS EU project

all based on DC photo electron sources

bERLinPro – Berlin Energy Recovery Linac Project

bERLinPro = Berlin Energy Recovery Linac Project

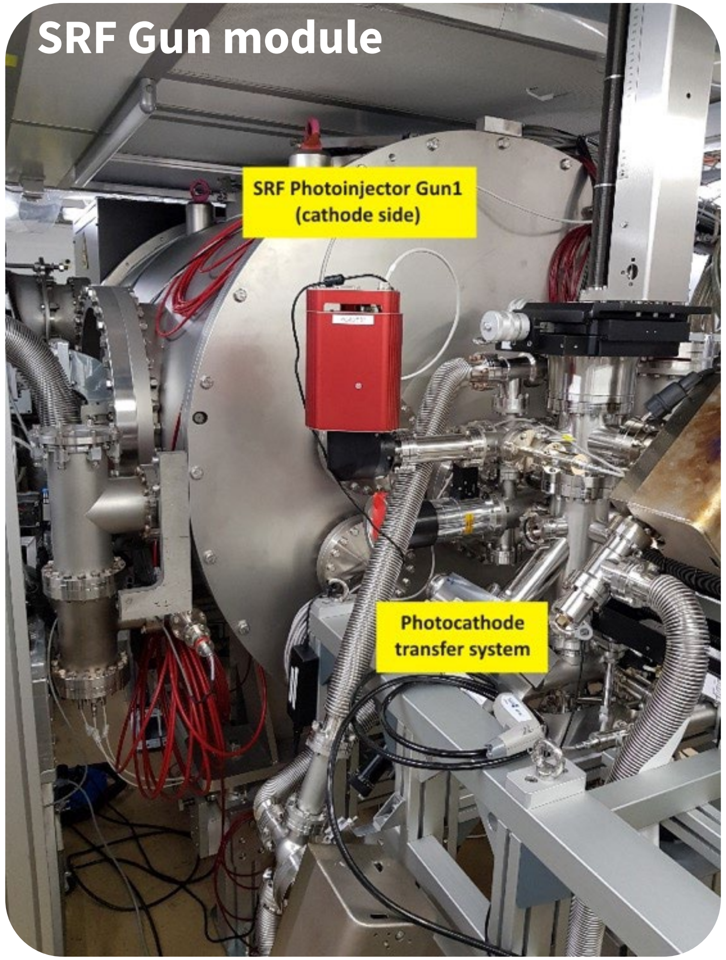
100 mA / low emittance technology demonstrator (covering key aspects of large scale ERL)

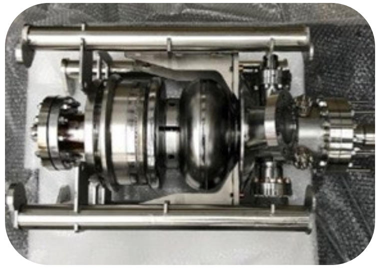


Parameter	bERLinPro
Max. beam energy (MeV)	50
Max. beam current (mA)	**100**
Frequency (GHz)	1.3
Normalized emittance (mm mrad)	**1 (< 0.6 in simulations)**
Bunch length (ps)	**< 2 ps (100 fs @ 10mA)**
Beam losses	<< 10^{-5} @ 100 mA

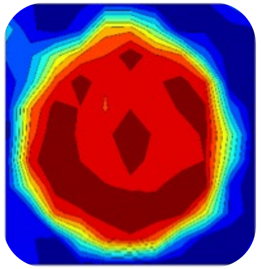
project started 2011
building ready 2017, first SRF photo gun electrons 2017 (Teststand)
Installation infrastructure / warm parts completed 2021
SRF Gun RF tested 2024 / First beam expected 12/2024

First beam tests of the bERLinPro SRF photo-injector





First beam 12/2017



QE map Cu cathode

First 1.6 cell SRF Gun
with exchangeable high-QE cathode

01/2018 Operation with high QE cathode failed,
as cathode plug „dropped“ into Gun cavity ☹

HZDR

MAX-BORN-INSTITUT

LOMONOSOV MOSCOW STATE UNIVERSITY

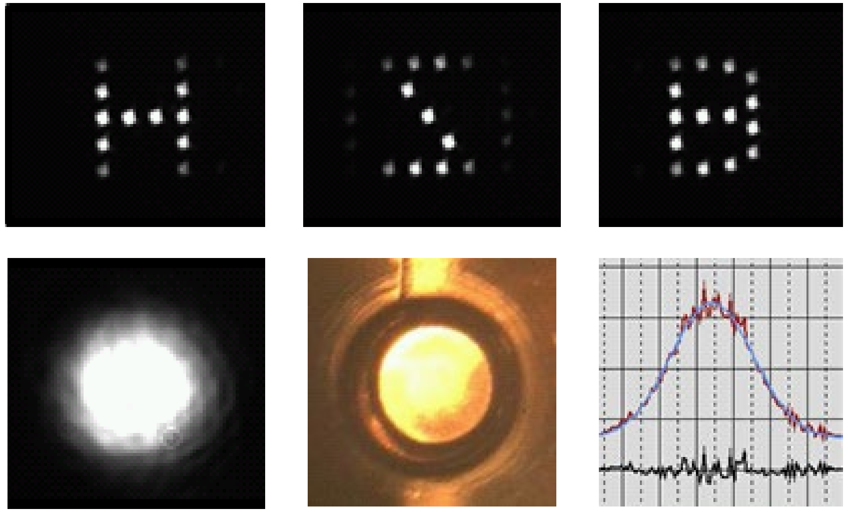
Jefferson Lab
Thomas Jefferson National Accelerator Facility

High QE photo cathodes & drive laser development

Klemz, Ohm-Krafft

Drive laser development:

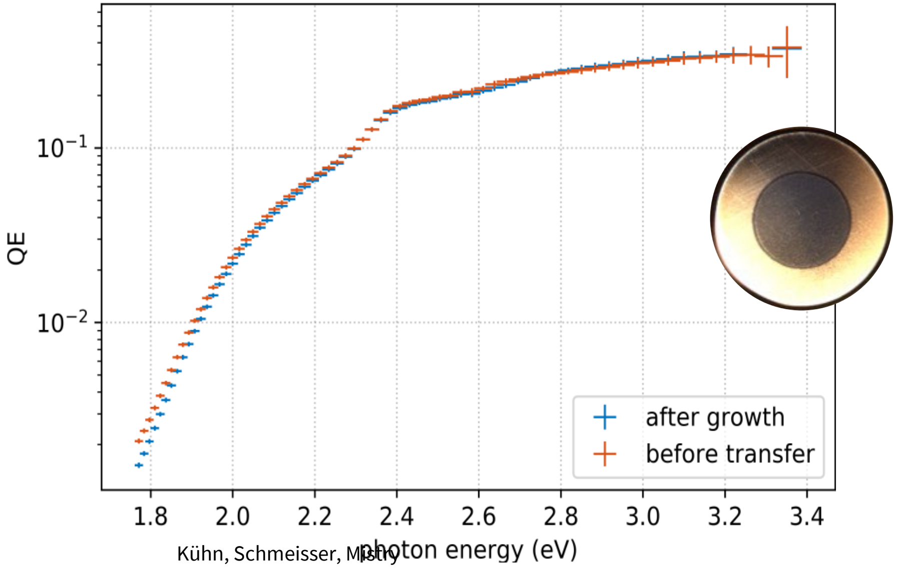
- online control of laser parameters (transverse shape and pulse length)
- tools to monitor photocathode
- high power (> 40 W @ 515 nm) 1.3 GHz laser with 3 to 12 ps pulse length



Virtual cathode **Real cathode** **Laser pulse length**

BROOKHAVEN NATIONAL LABORATORY · CORNELL UNIVERSITY FOUNDED A.D. 1865 · MAX-BORN-INSTITUT

Sepctral response photocathode P017



Kühn, Schmeisser, Mistry

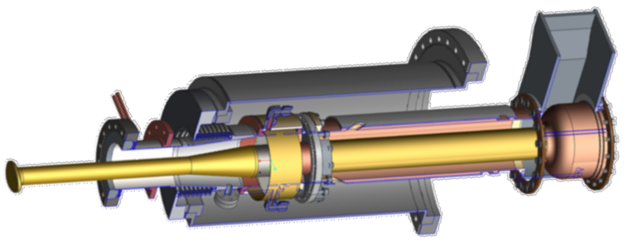
Photocathode preparation and analysis laboratory up and running since 2015

- insight into growth process with material science studies in parallel
- achieved quantum efficiency of 16.8% at 515 nm (spec is 1%) with CsKSb / recently 8% with Na_2KSb (much higher stability)
- successful transfer from cathode lab to SRF gun
- demonstrated, that cooling of cathode to 120 K do not harm quantum efficiency (unlike prediction by other researchers!)

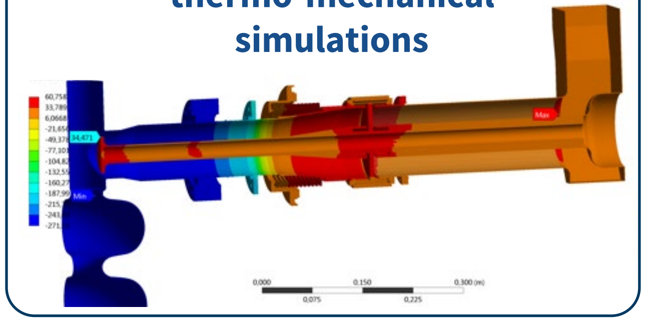
Technological Challenges - high current booster module

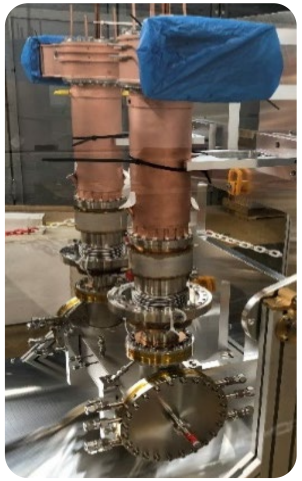
- Pre-accelerator for highest beam power: up to 500 kW_{CW}, max. 240 kW/cavity
- Collaboration Cornell University (USA), Jefferson Lab (USA), KEK (Japan)
- Cavity design: Cornell / production: Jefferson Lab (USA) (4 x 2 cell)
- High power RF coupler for up to 120 kW CW
- Coupler production: warm parts - FMB (Berlin) / cold part – Toshiba/Canon (Japan)

RF coupler design @ HZB

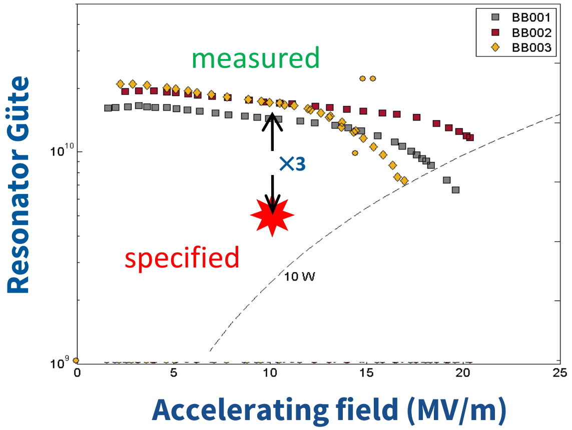


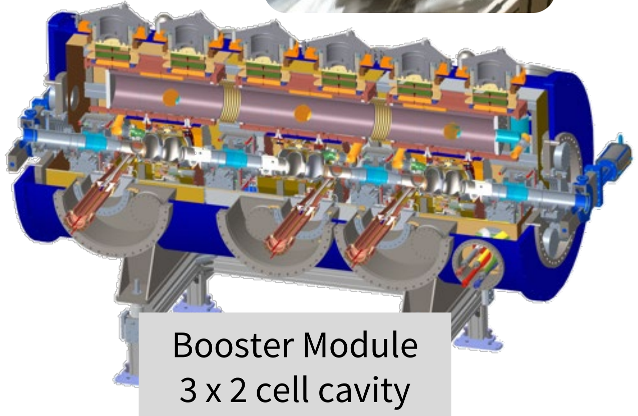
thermo-mechanical simulations





2 cell SRF booster cavity

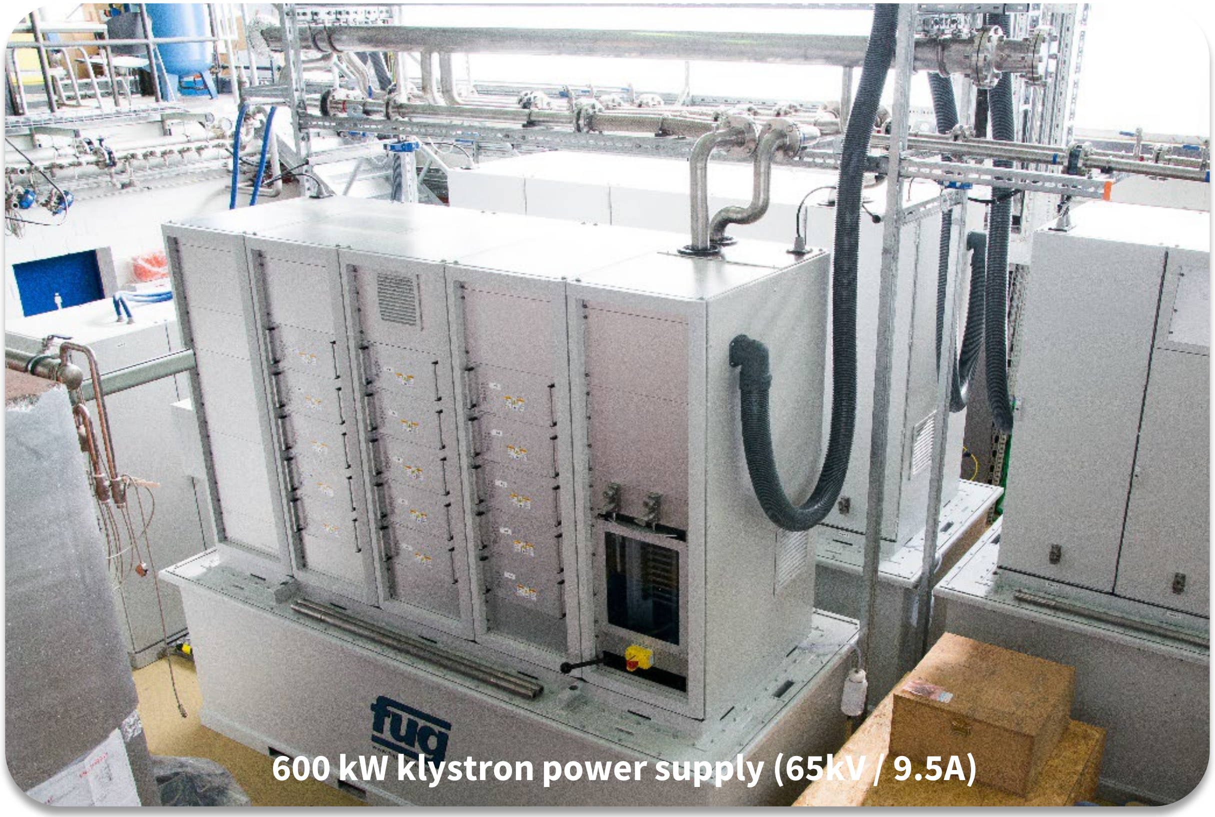




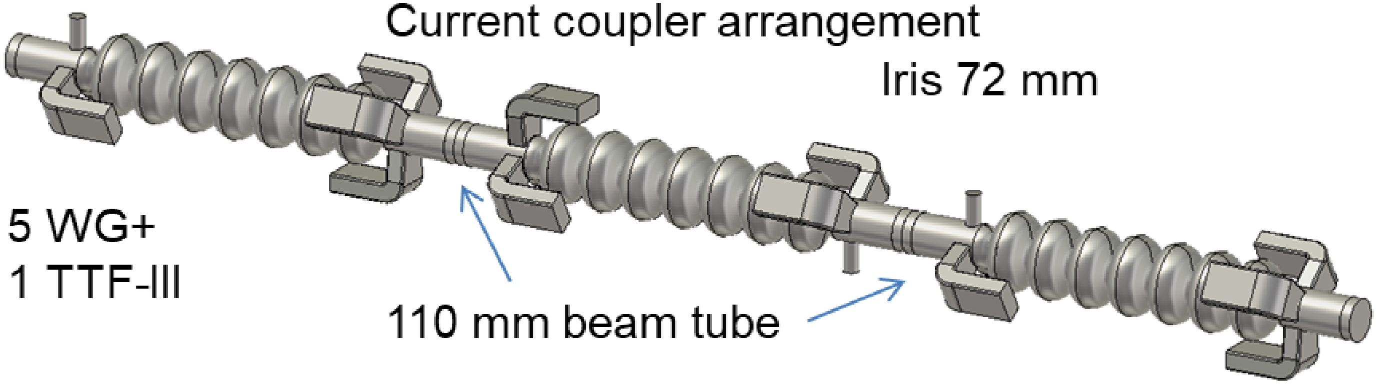
Booster Module
3 x 2 cell cavity

Technological challenges - CW high power klystrons & auxillaries

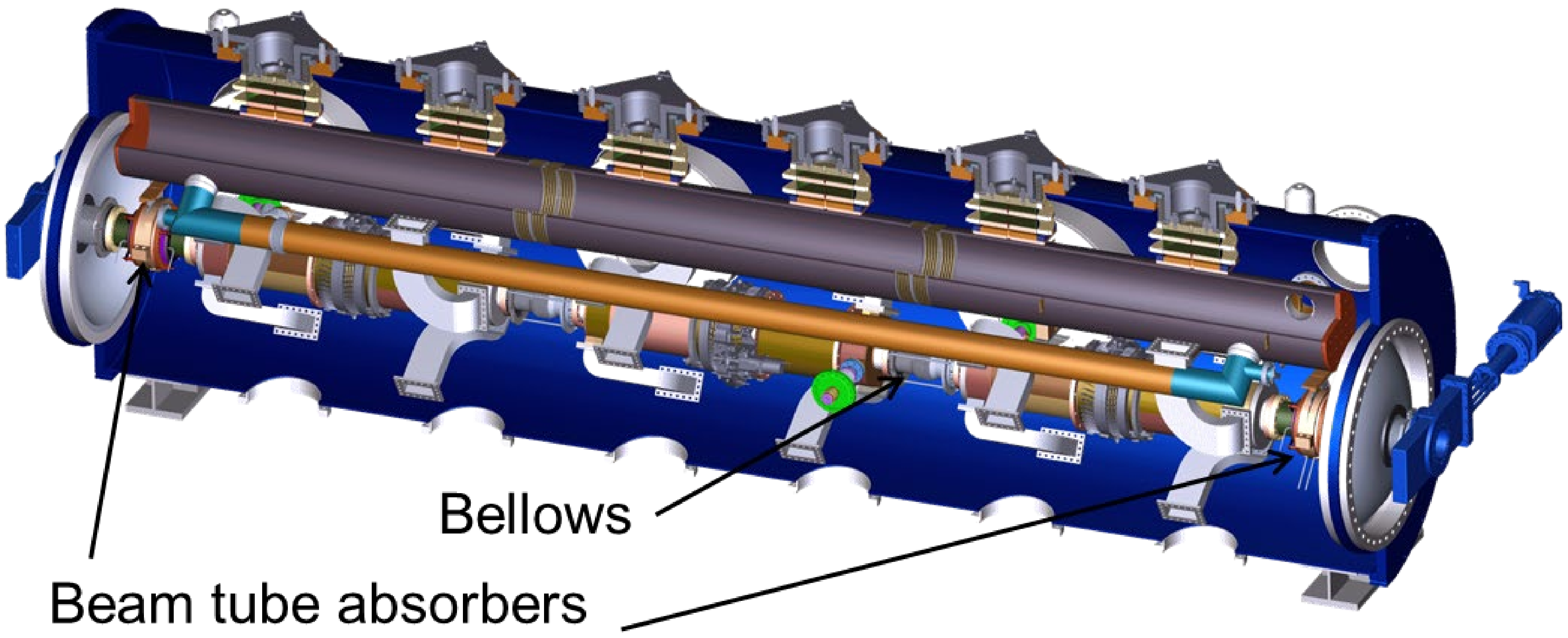
- Developed at CPI (USA) together with HZB and TRIUMF (Canada)
- 270 kW_{CW} @ 1.3 GHz at present only available @ HZB, TRIUMF
- Essential part of future SupraLab@HZB infrastructure
- First klystron tested up to max power @ bERLinPro



Technological Challenges – HOM damped, high current linac module



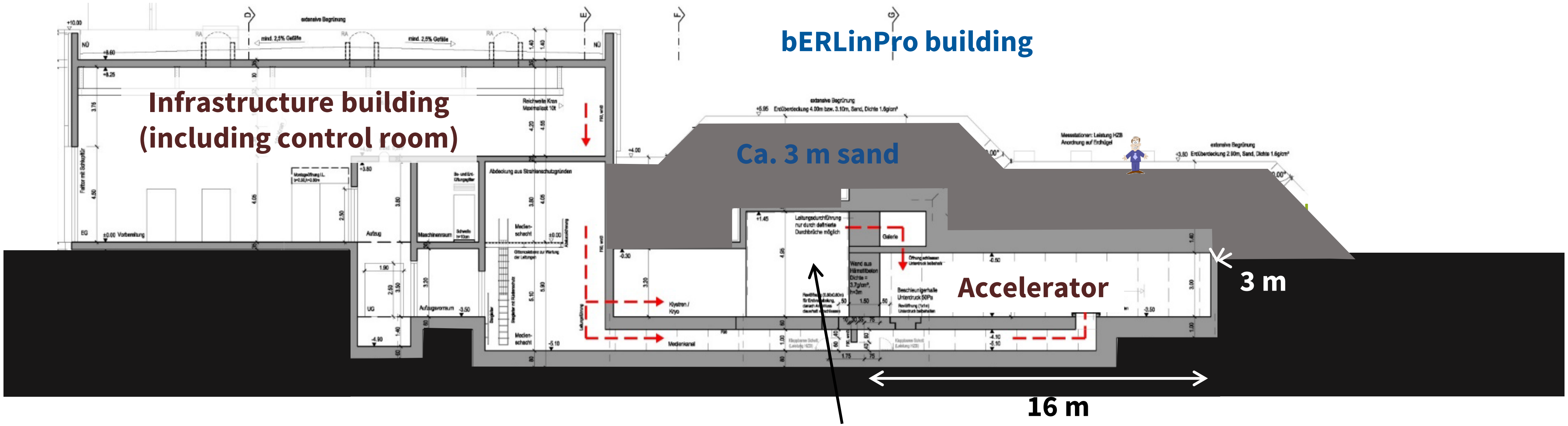
- 3 x 7 cell SC linac module
- 1.3 GHz CW operation
- ΔE = 44 MeV ~ 20 MV/m
- strong HOM damping with attached waveguide groups



And here we run out of money ☹

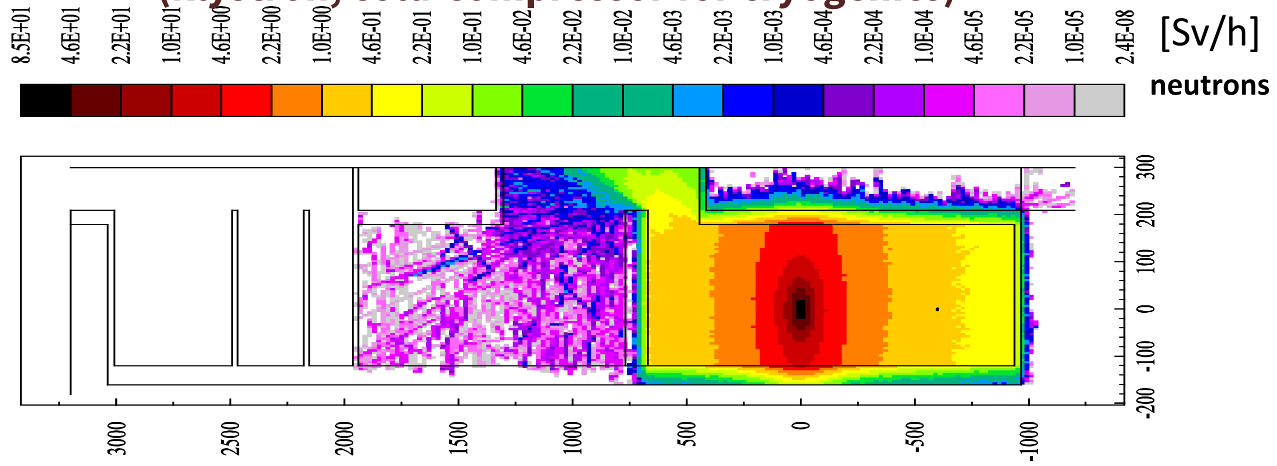
Full design available!

Radiation protection for ERL – shielding neutrons

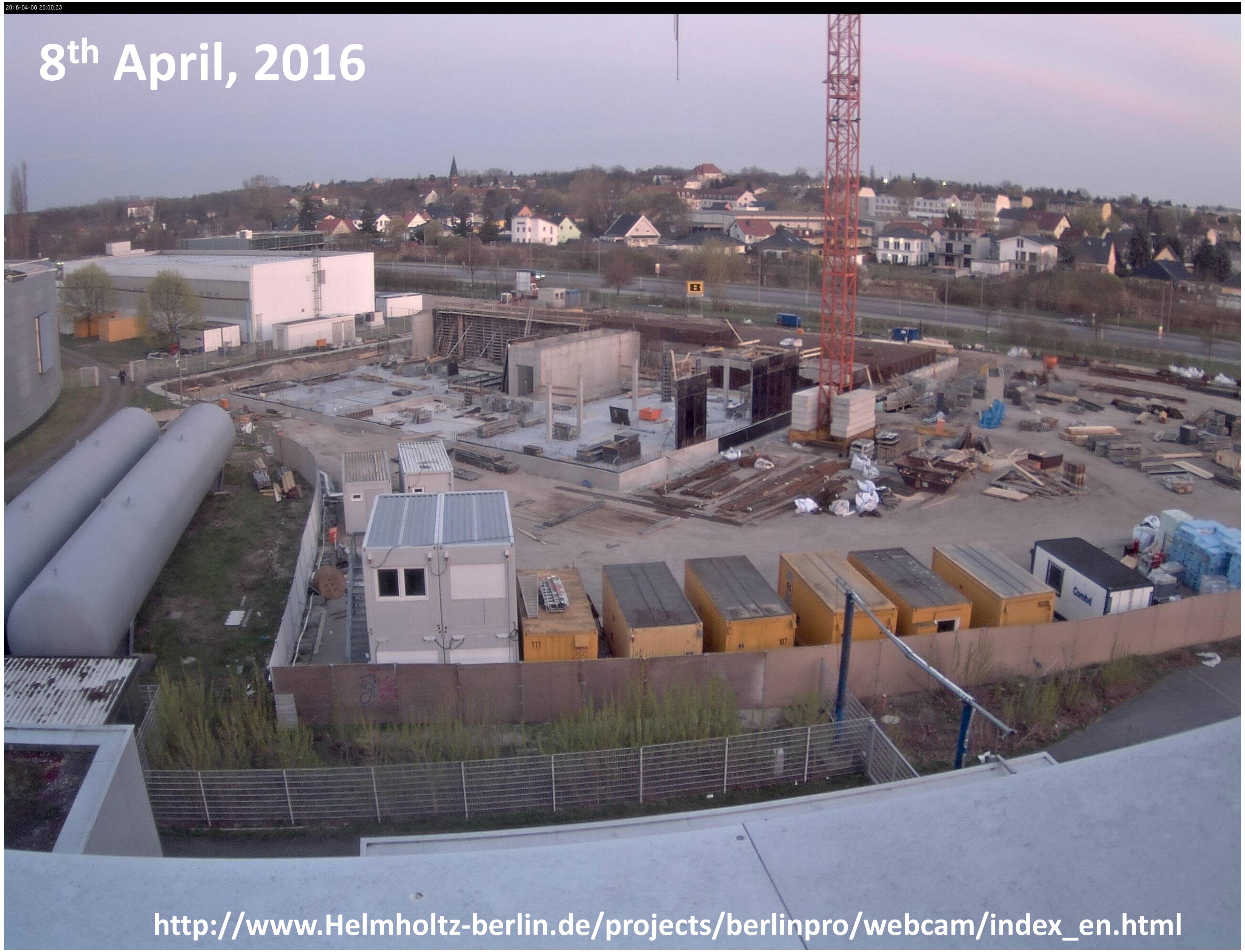


Fluka calculations
(K. Ott, HZB)

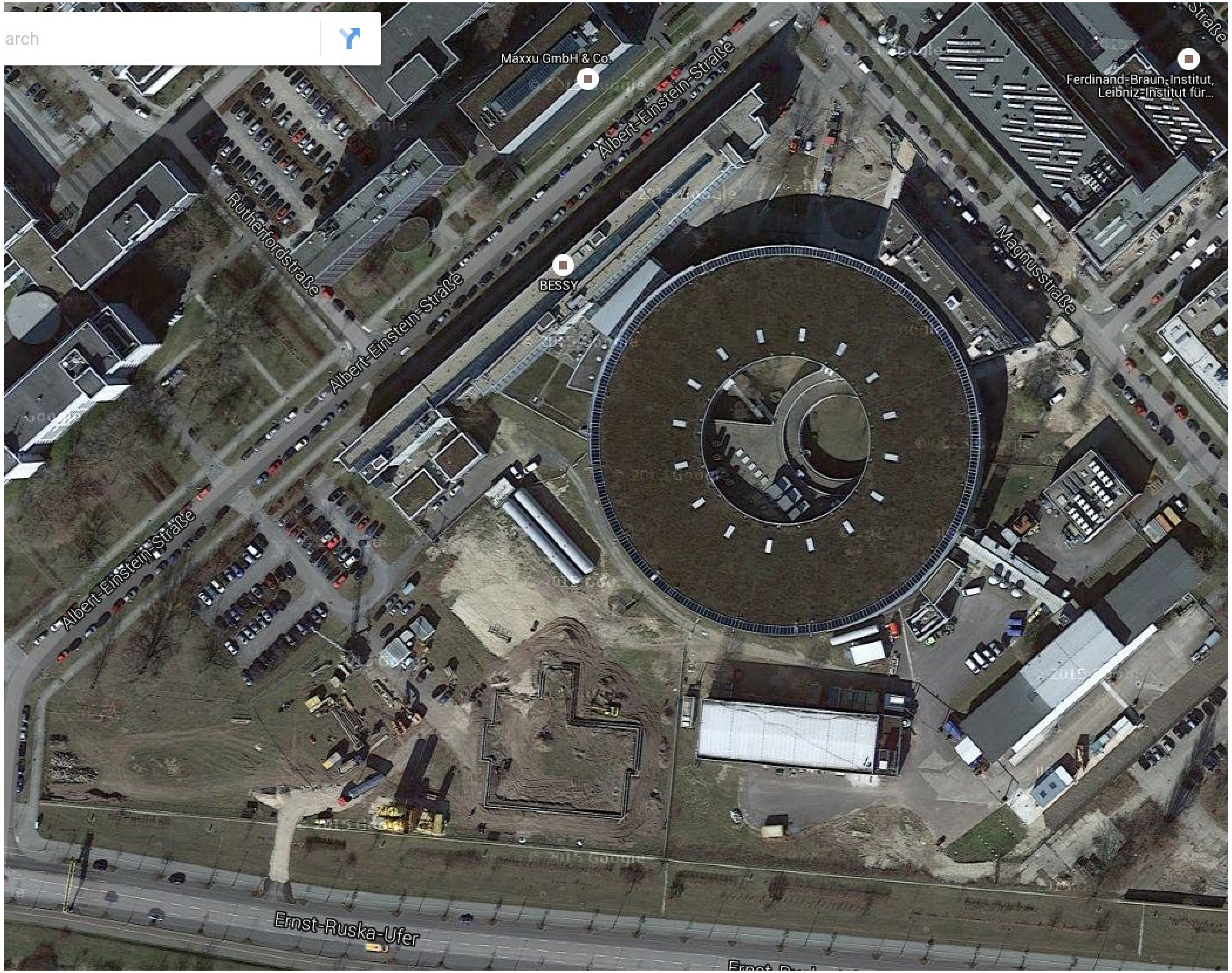
50 MeV, 100 mA = 5 MW
→ kW losses easily possible



bERLinPro building

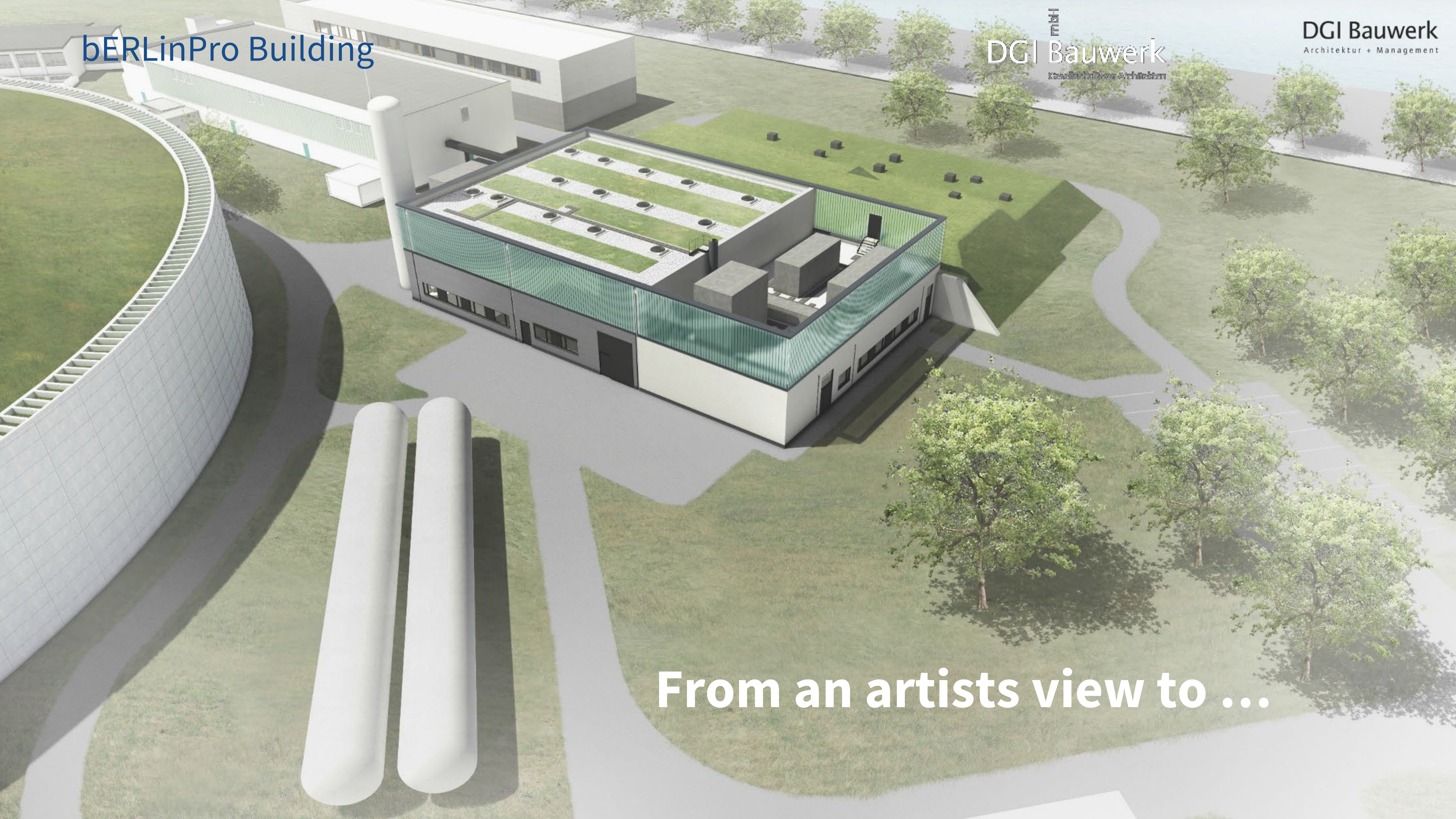


bERLinPro building



bERLinPro building

bERLinPro Building



bERLinPro Building

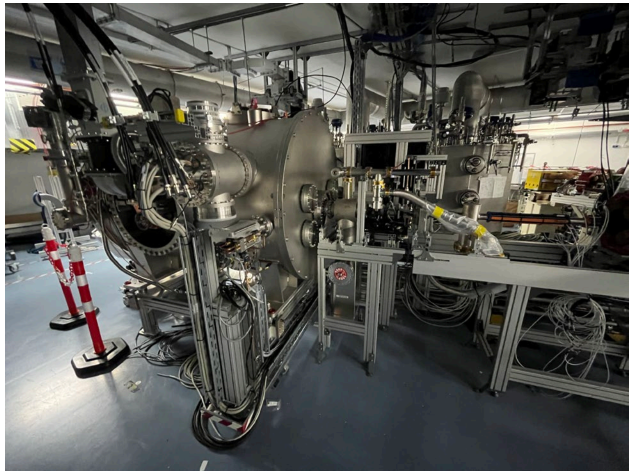
view north-west

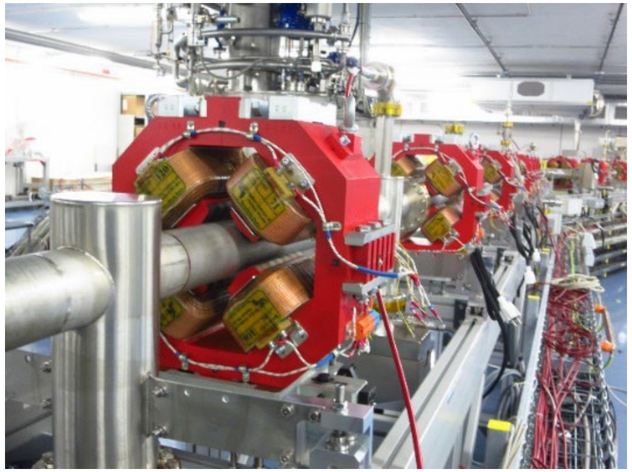
bERLinPro Building

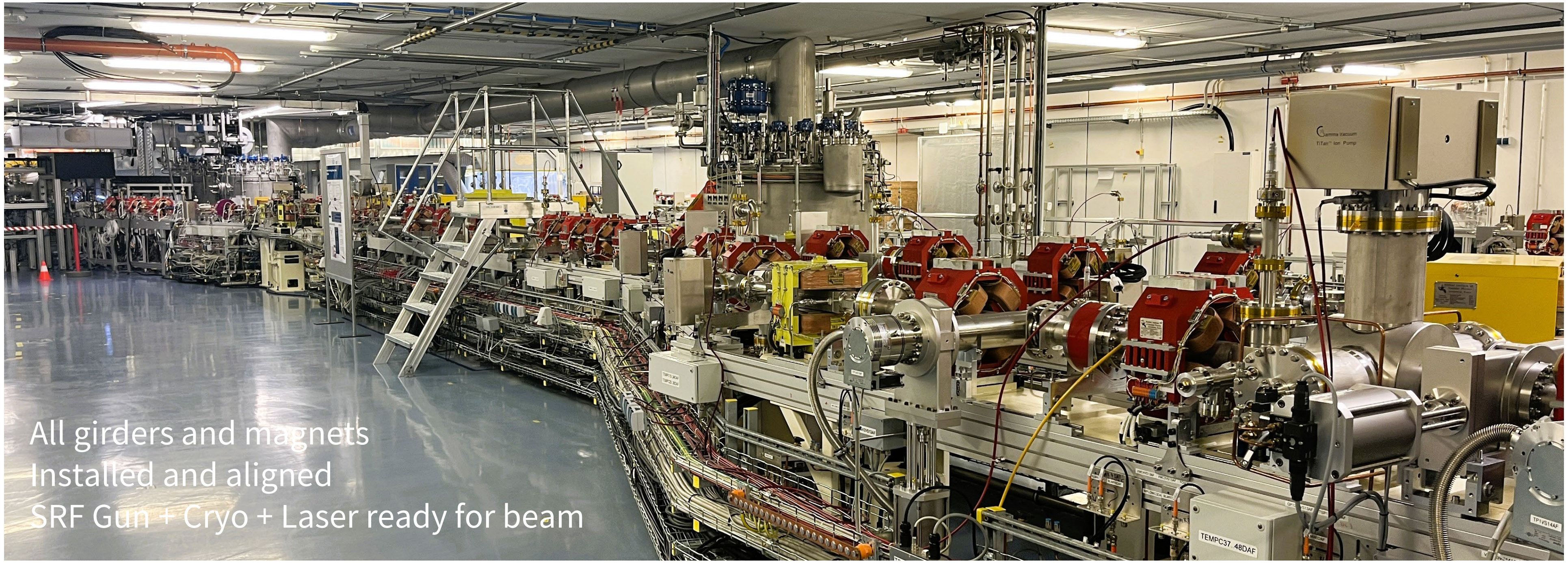
view south-east

Underground accelerator hall – 12/2016

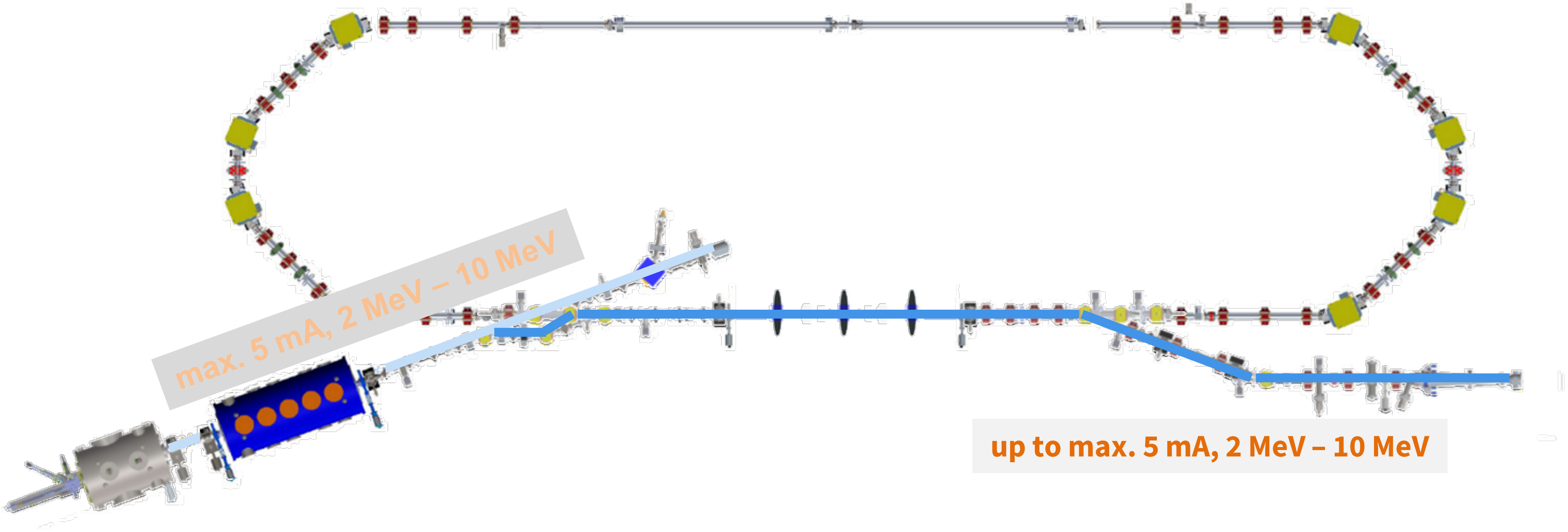
Underground accelerator hall – machine installation in full swing







Present planning and next steps

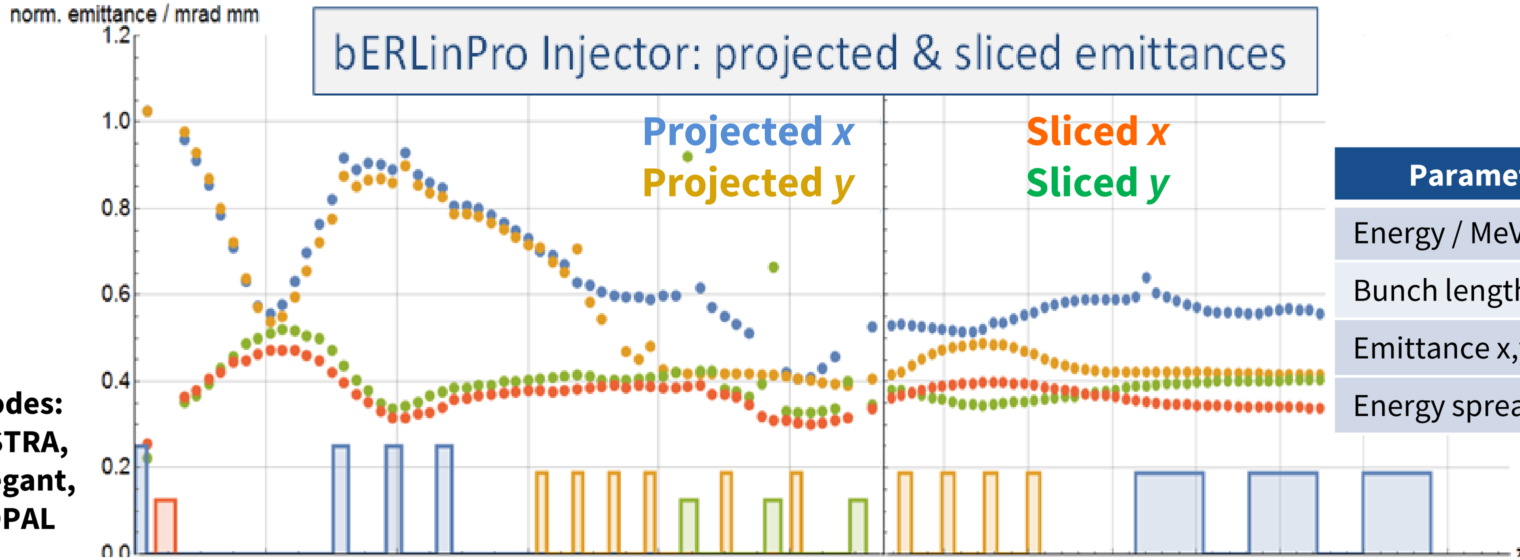


05/2024 SRF Gun cool down and RF commissioning (no beam tests)
12/2024 First electrons SRF Gun expected
12/2025 booster module installed
From 2026 very versatile SRF Photo Injector (SRF Gun & 3x2cell Booster)

What about re-circulation? We are much too late and run out of money!

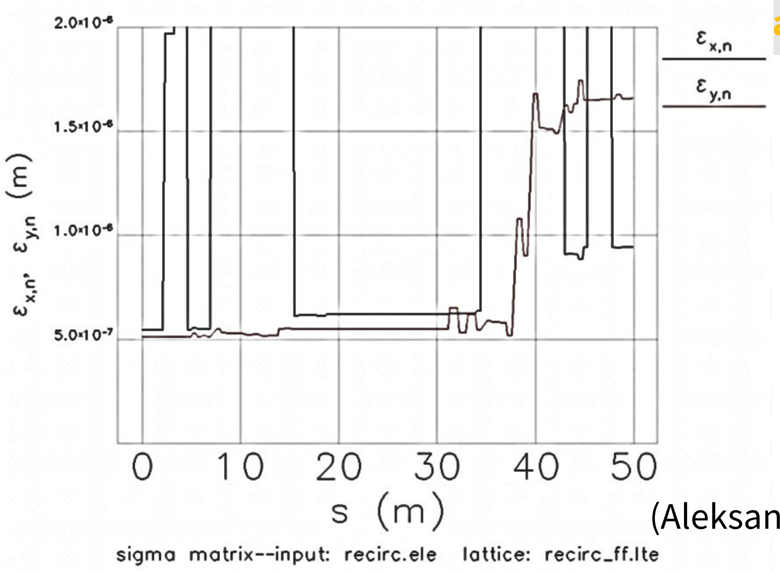
bERLinPro – performance parameter (simulations)

codes:
ASTRA,
elegant,
OPAL

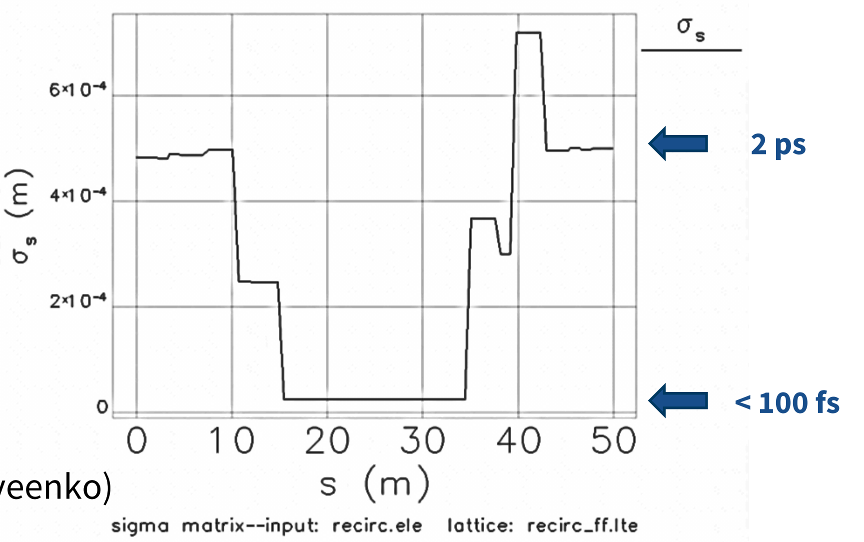


Parameters at LINAC exit	
Energy / MeV	50.1
Bunch length / ps	4.65
Emittance x,y / µm	0.58/0.41
Energy spread / keV	254

Optics (Short Bunch Mode, 10 pC): Bunch size & Emittance



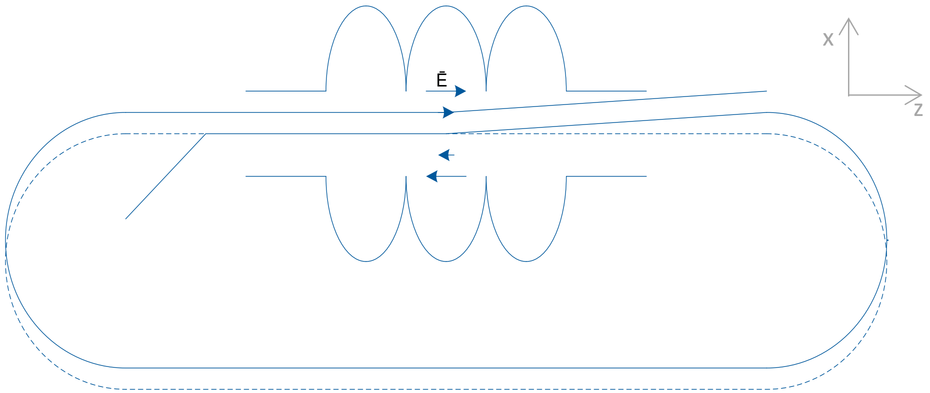
(Aleksandr Matveenko)

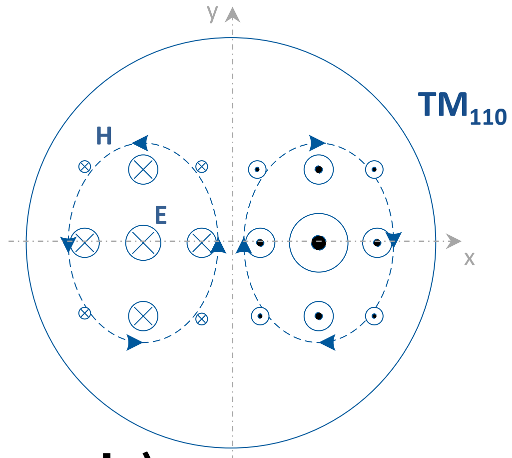


ERL Beam Dynamics – Beam Break Up

Beam Break Up: resonant interaction of short & long range cavity wake fields with the generating bunch or subsequent bunches → **instability & beam loss**

e.g. Multibunch BBU: many flavours: cumulative / regenerative, transverse / longitudinal, single-/multi-cavity, single-/multiple-turn





regenerative transverse BBU (single cavity, single turn, one mode):

1. bunch passes cavity "off axis" during accelerating passage → induce HOM voltage & transverse kick due to HOM
2. after recirculation kick transforms to an offset & HOM damp according to its Q
3. bunch passes cavity with varied offset on decelerating passage → induce HOM voltage & transverse kick due to HOM

BBU: HOM excitation exceeds HOM damping → kick strength growth up to loss

ERL Beam Dynamics – Beam Break Up

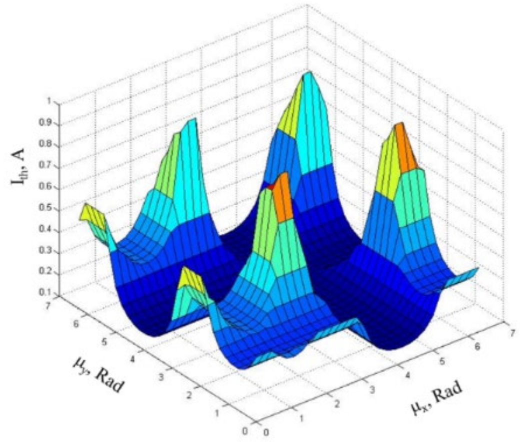
BBU threshold current

$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

valid for:
- $m^* \sin(\omega_\lambda T_{rec}) < 0$
- $\omega_\lambda \neq n^* \omega_{rf}$

Countermeasures: $m^* = m_{12}\cos^2(\alpha) + (m_{14} + m_{32})\sin(\alpha)\cos(\alpha) + m_{34}\sin^2(\alpha)$

1. cavity design:
   - HOMs: small R/Q, varying ω_λ at fixed ω_0 → multi cavity BBU thresholds increase
   - no HOM on a fundamental's harmonics: $\omega_\lambda \neq n^*\omega_{rf}$
   - low Q for HOM → HOM dampers (ferrites, waveguides, …)
2. recirculator beam optics:
   - for α=0 & uncoupled beam transport → $m^* = m_{12} = (\beta_1\beta_2)^{1/2} \sin(\Delta\varphi_x)$
     → stable for $\Delta\varphi = n\pi$
   - adjust $\sin(\omega_\lambda T_{rec}) = 0$ for worst HOM
     large path length change → inpractical ☹



Y. Petenev

E. Pozdeyev et al.: Multipass beam breakup in energy recovery linacs, NIM-A 557 (2006) 176–188
G. Hoffstaetter et al.: Beam-breakup instability theory for energy recovery linacs, PRST-AB 7, 054401 (2004)
G. Hoffstaetter et al.: Recirculating beam-breakup thresholds for polarized higher-order modes with optical coupling, PRST-AB 10, 044401 (2007)

ERL Beam Dynamics – Unwanted Beam

Unwanted Beam

Halo

generated by / together with wanted beam

- scattered particles (residual gas, IBS)
- laser stray light on cathode
- laser: limited extinction ratio
- … (?)

moving together with wanted beam at design rf phases → same energy, no dispersive separation

Dark Current

generated independently of wanted beam (laser off)

- field emission in rf cavities
- ghost pulses from laser
- … (?)

beside Dark Current from the gun → lower energy than wanted beam → lost in dispersive regions

UBW 2012: https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2

ERL Beam Dynamics – Unwanted Beam

Amount:

- not reliably predictable for most sources

Loss positions:

- with initial beam parameter (place of origin, momenta) loss position along the machine can be calculated for the various generation processes
  → loss probability (to be weighted with unknown loss current ☹)

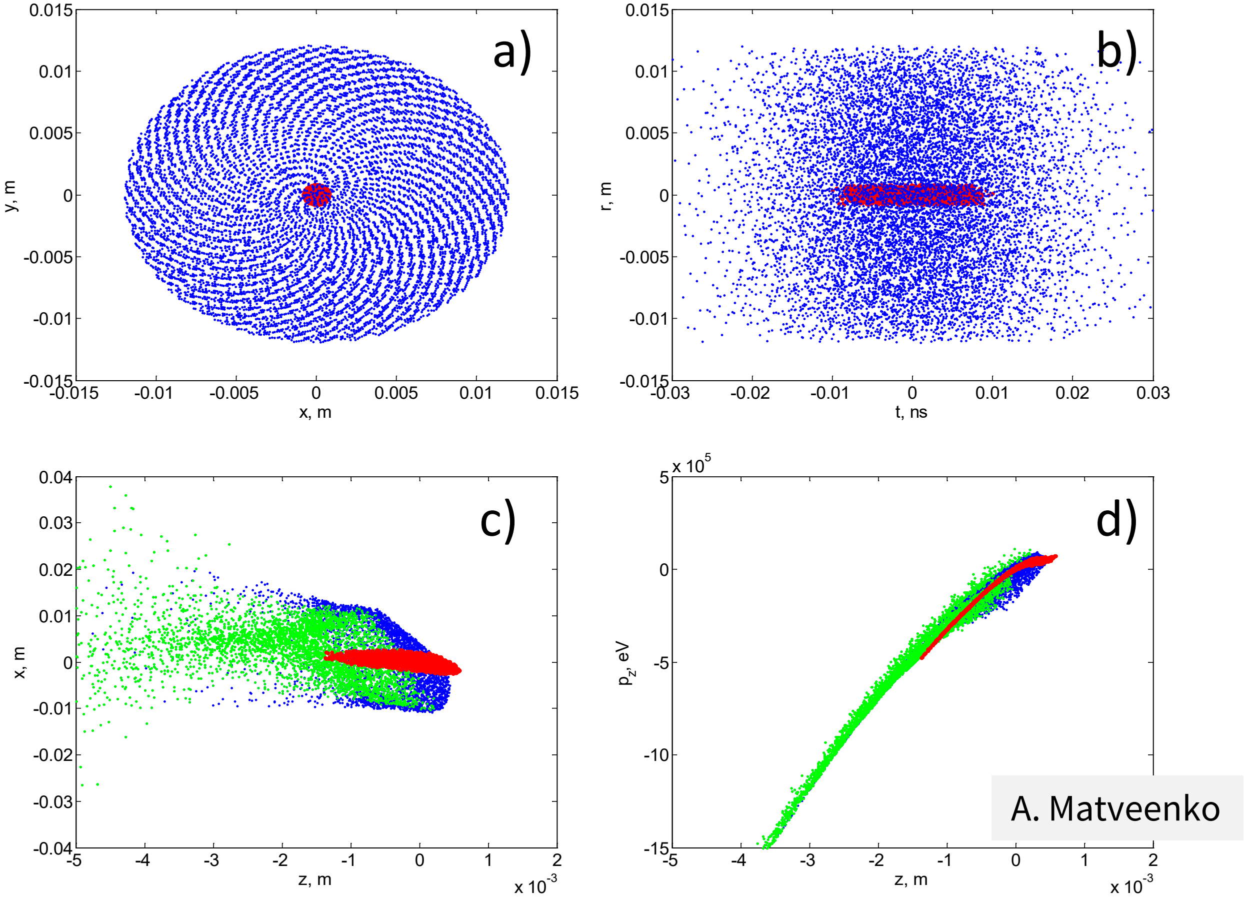
source	generating process	loss positions	amount
Halo	scattered Particles		
	stray light – laser halo		
Dark Current	field emission gun cath & plug		
	field emission booster & linac		

UBW 2012: https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2

ERL Beam Dynamics – Unwanted Beam / Halo

Halo:

1. **residual gas scattering**
2. **intra beam scattering → Touschek losses**
3. **laser stray light from cathode**



Beam halo modeling:
particle distribution from ASTRA.

red – active beam particles,
blue – passive halo particles,
green – particles lost in collimators.

Initial distribution on the cathode in
a) *x-y* plane,
b) *x-t* plane.

Particle distribution after the merger section in
c) *x-z* plane,
d) p_z-*z* plane.

→ **Collimation of large fraction of halo particles, but not 100%.**

bERLinpro: one testing collimator in the merger section

ERL Beam Dynamics – Unwanted Beam / field emission

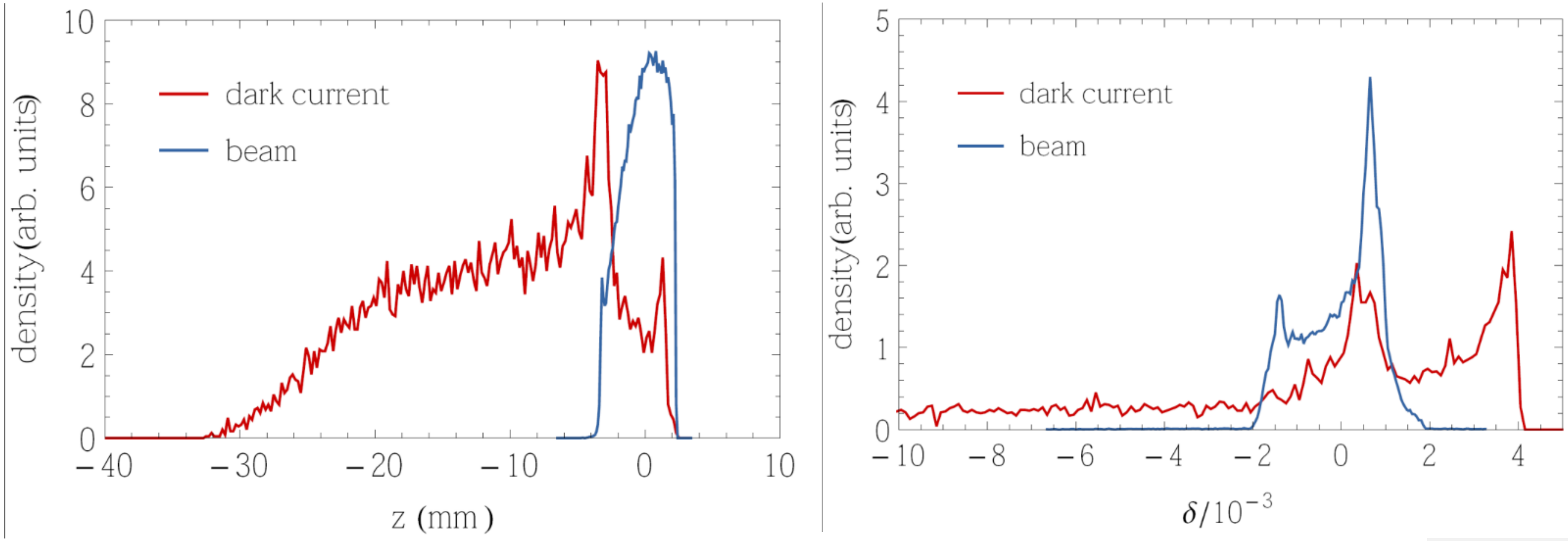
Dark Current: field emission from gun cathode

Field Emission from gun cathode

- Fowler Nordheim: φ = 1.9 eV, β = 200, E_{max} = 30 MV/m
- tracking trough merger incl. SC of reference bunch
- x-y apertures in booster & merger → loss distribution

$$j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\varphi} \exp\left(-\frac{B_{FN}\varphi^{\frac{3}{2}}}{\beta_{FN}E}\right)$$

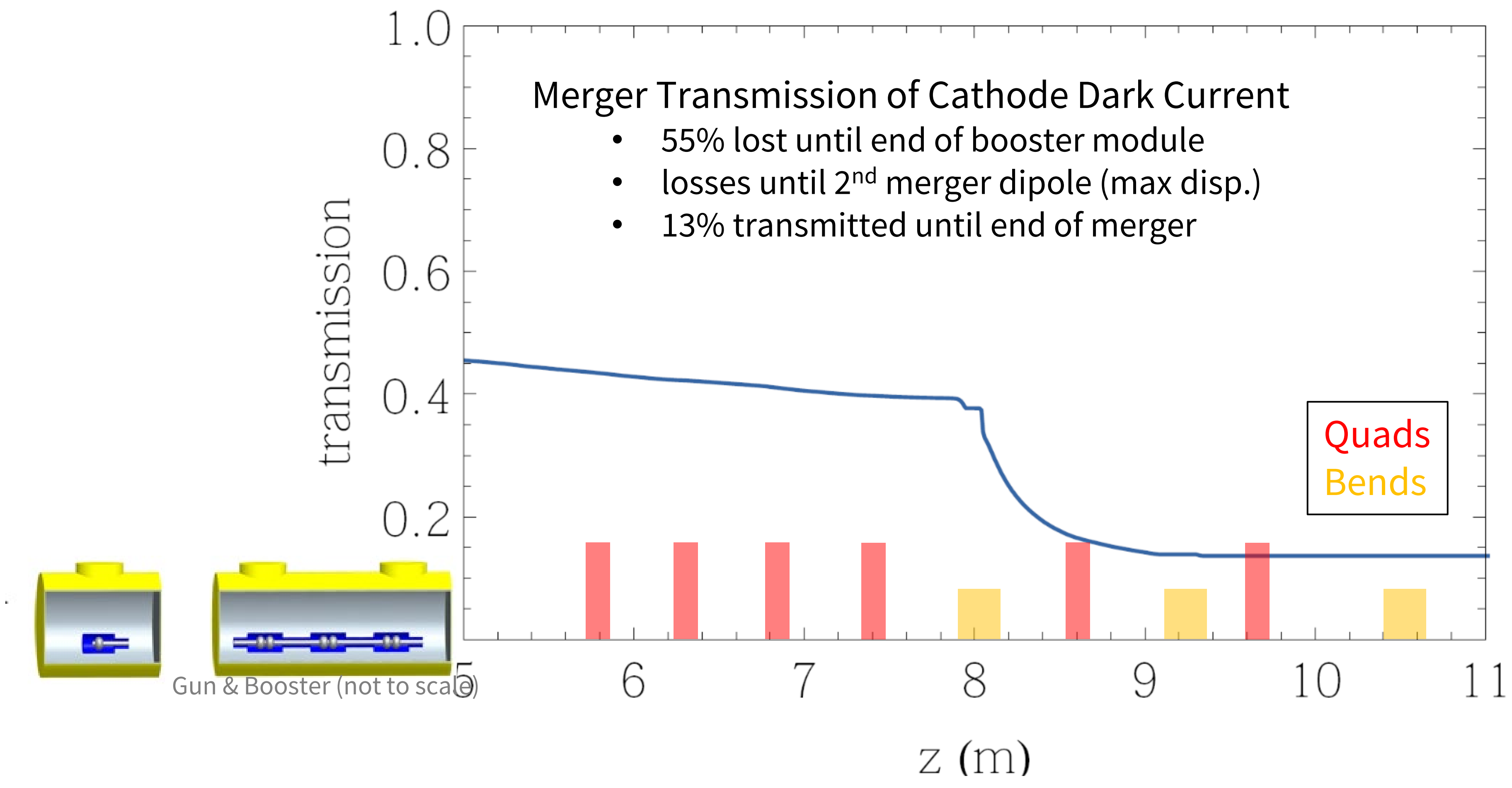
E – electric field, φ – work function



S. Wesch

ERL Beam Dynamics – Unwanted Beam / field emission

Dark Current: field emission from gun cathode



S. Wesch

Summary

Energy Recovery Linacs can provide high current, high quality beams for single-pass-experiments in flexible setups

multi user light sources, **collider**, cooler, compact sources, …

cw superconducting RF is the enabling technology

high gradient, large apertures

many challenges to be addressed

low emittance/high current sources, HOM damped cavities (BBU), flexible bunch compression, control of unwanted beam, optimising SRF efficiency (high gradient, high Q0)

ongoing, worldwide effort to push ERL technology

cERL, BNL ERL, CBETA Cornell Injector + FFAG ERL, JLAB ERL-FEL, **Bejing University & IHEP**, **NovoERL BINP**, **MESA, S-DALINAC ERL, PERLE@ORSAY**, **LHeC**, FCCeh

Thanks to many of my colleagues providing me data and information!
Special thanks to my colleague Michael Abo-Bakr for transparencies on beam dynamic issues.

Some historical facts taken from G. Kraffts talk “What is an ERL, and why there might be one in your future”, ERL Symposium, DPG Frühjahrstagung Darmstadt, 03/2016


Many thanks for your attention!


Its all about teamwork!