Energy Recovery Linacs

Virtual beam power for a multitude of applications

Andreas Jankowiak
Helmholtz-Zentrum Berlin and
Humboldt-Universität zu Berlin

The CERN Accelerator School
Advanced Accelerator Physics
Egham, 07.09.2017

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

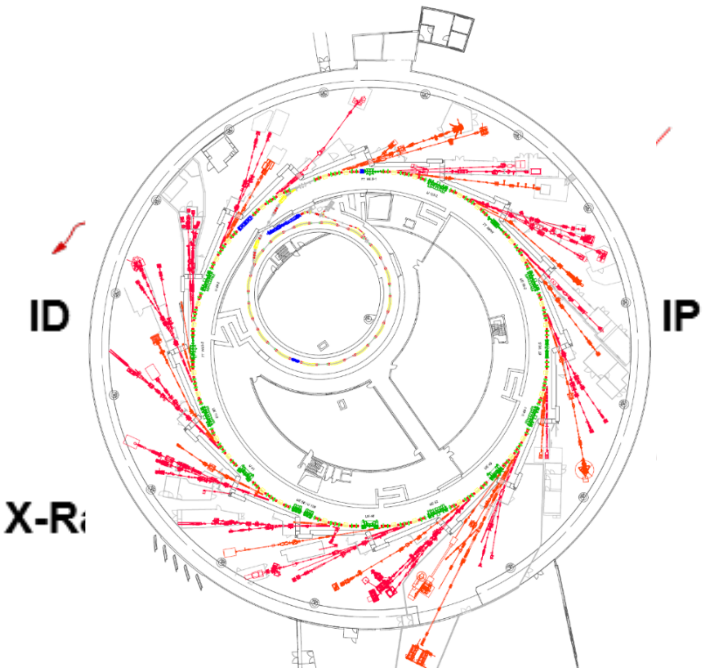
Applications

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

more details on many aspects e.g.:
https://indico.cern.ch/event/470407/
ERL2017, ICFA Workshop
CERN, Genf

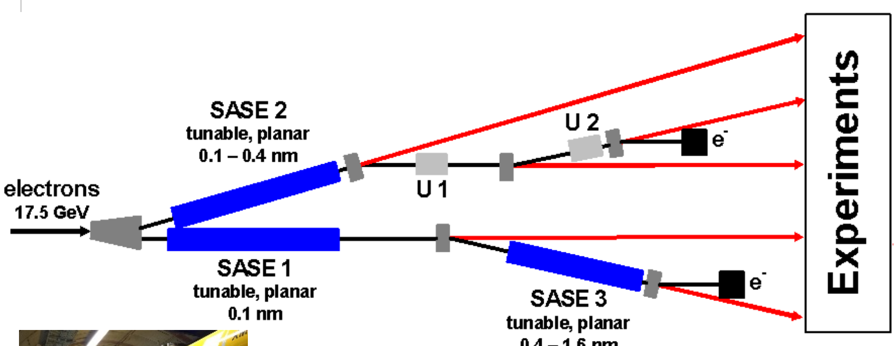


synchrotron radiation source, collider

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

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

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)

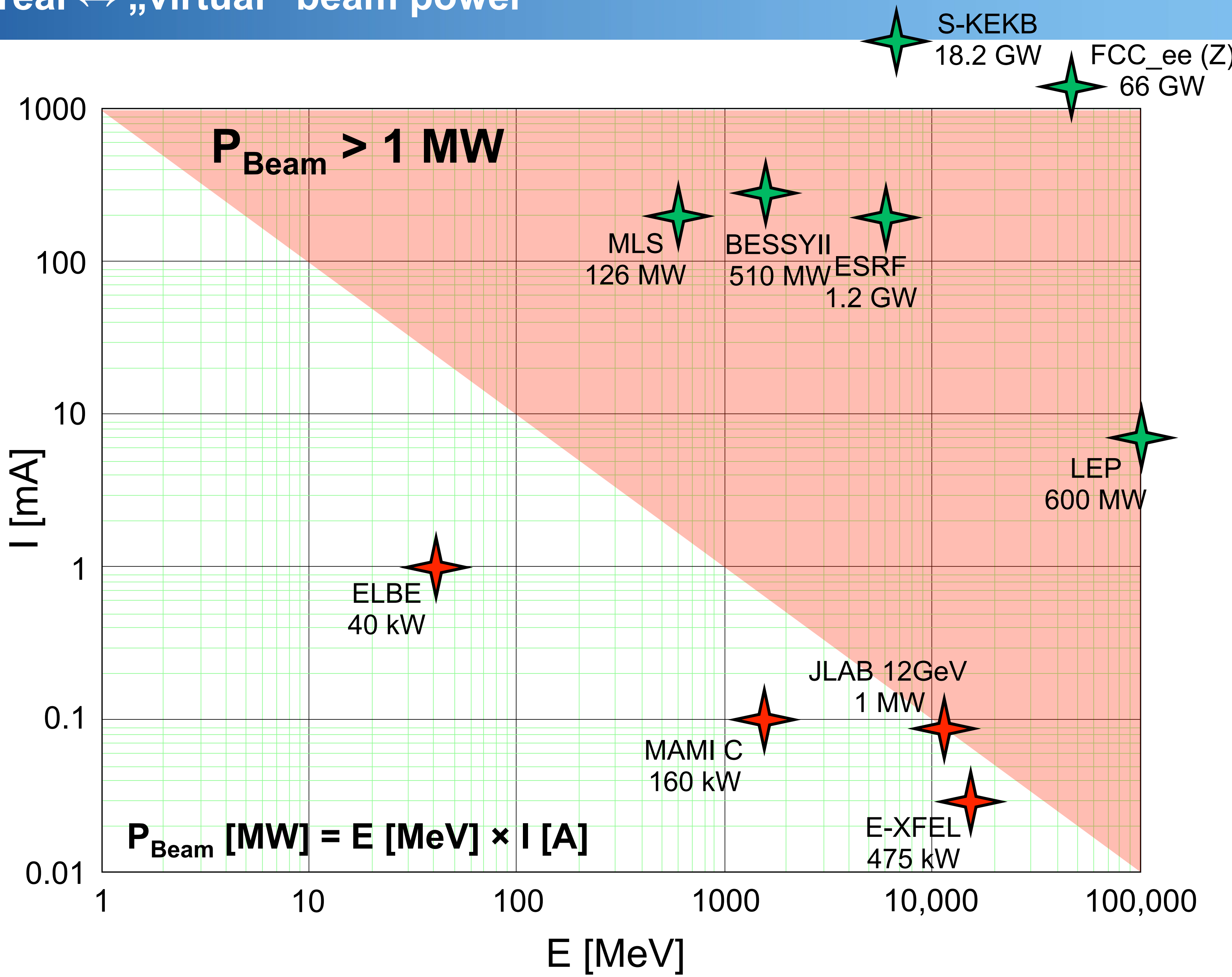


free electron laser, collider, fixed target

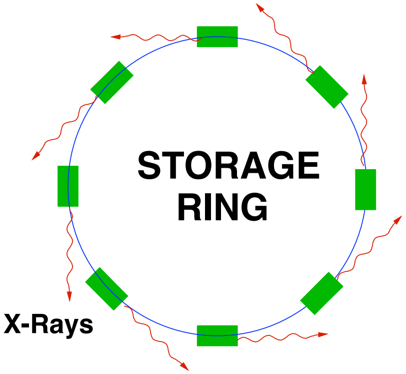
$$P_{real}[W] = E[eV] \cdot I[A]$$

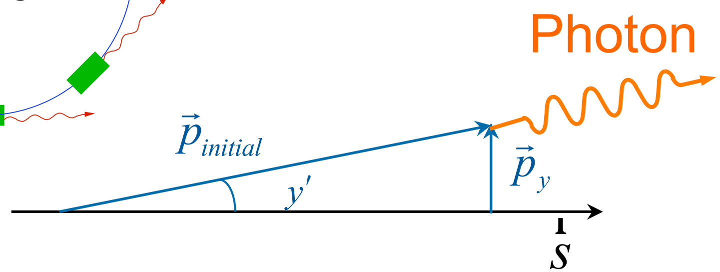
e.g. European XFEL, 1 Å hard X-ray source
17.5 GeV, 0.027 mA = 475 kW real beam power,
ca. 100 GW peak power in 100 fs, 10 x 2700 pps,
used FEL power ca. 300 W

real ↔ „virtual“ beam power

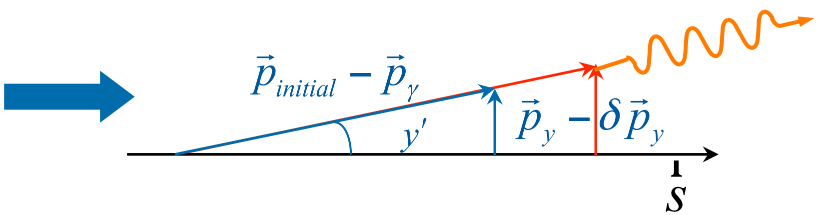


Storage ring – governed by equilibrium processes

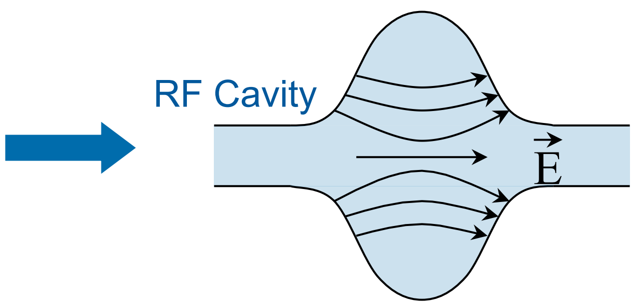




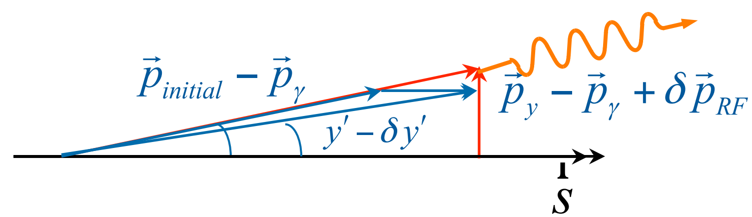
electron emits photon



looses momentum (also transversal)



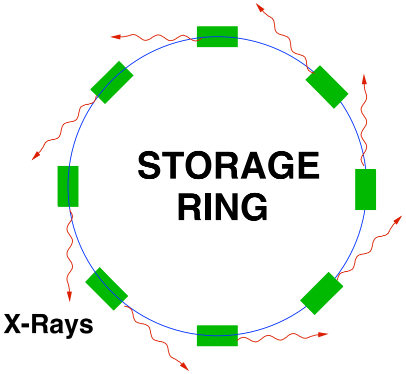
longitudinal momentum restored
in acceleration cavity



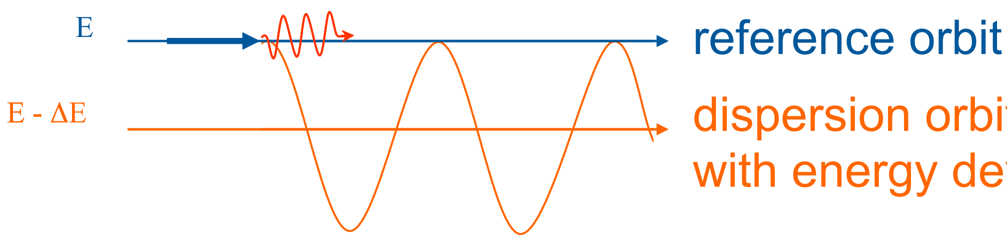
angle and displacement reduces
→ emittance shrinks

“damping”

Storage ring – governed by equilibrium processes

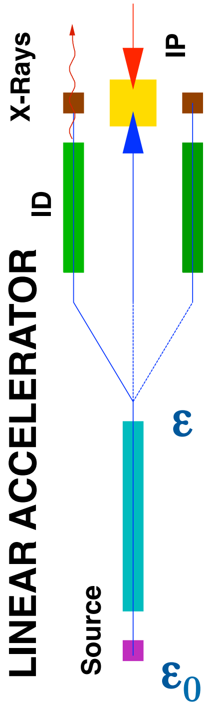


emission of photon at position with dispersion (e.g. in dipole, where transversal position is energy dependent)
electron oscillates around reference orbit
→ emittance increase

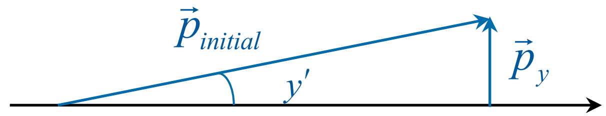


“heating”

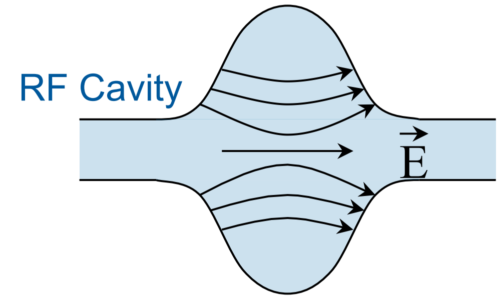
emittance is defined by an equilibrium between these two processes (damping and heating)
typical order: some nm rad horizontal (1/100 vertical)
similar process defined energy-spread and pulse length



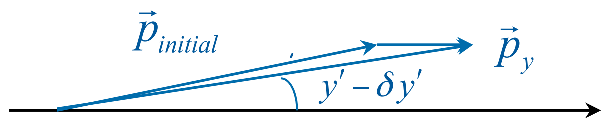
„adiabatic“ damping



electron has transversal momentum

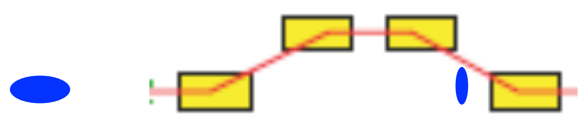


longitudinal component increases during acceleration

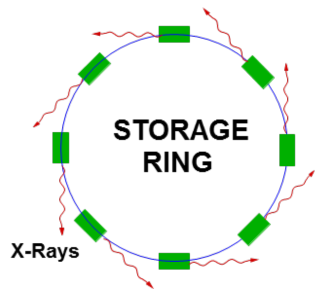


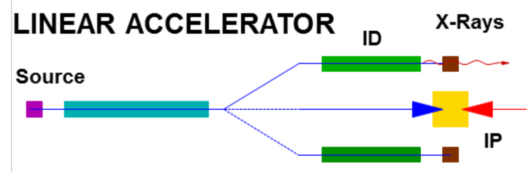
angle reduces with acceleration, emittance shrinks $\varepsilon = \frac{\varepsilon_0}{\gamma}$

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 !





equilibrium beam dimensions	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

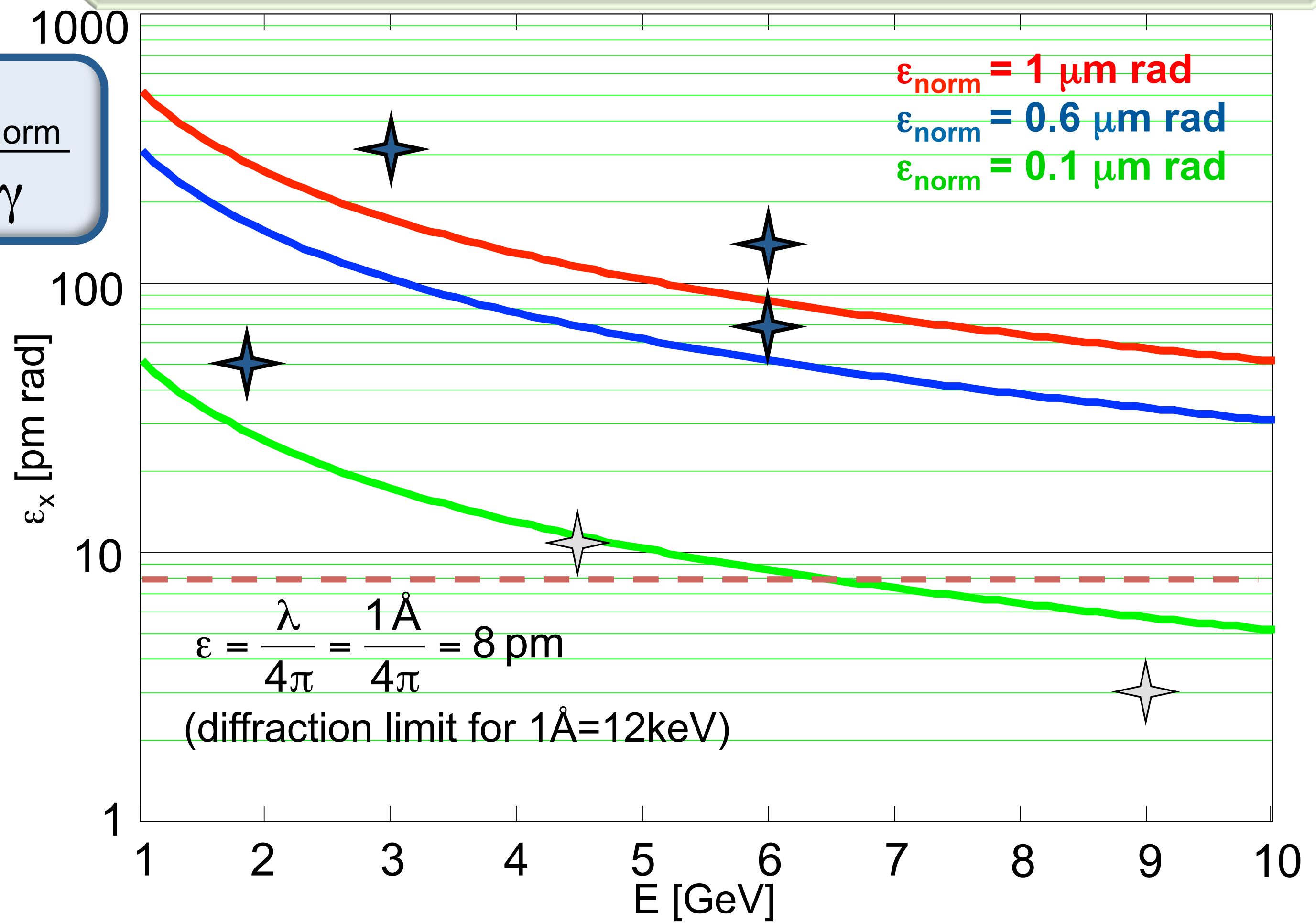
“virtual” (internal) power

real (external) power

Beam emittance – single pass machine ↔ storage ring

3[rd] 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)
147 pm, ESRF II (upgrade 2018 - 2020)
65 pm, APS (design phase)
~50 pm, ALS-U (design phase)

11 pm, PEPX (design study)

3 pm, tUSR (design study)

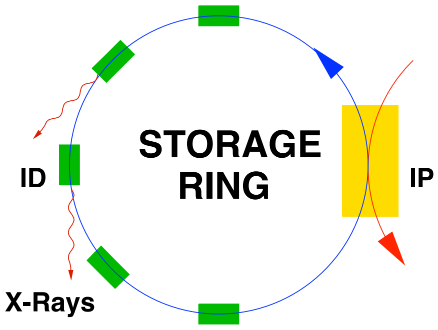
Storage rings: low emittance goes hand in hand with necessity to operate with long bunches (up to some 100 ps) to reduce Touschek and IBS scattering!

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, short bunches (~ 10 fs)
- 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

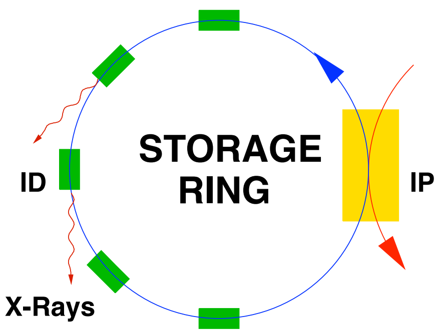


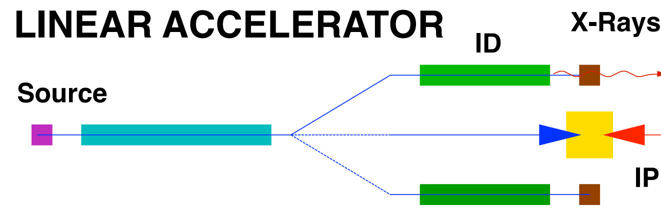
Energy Recovery Linacs – The idea

- 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, short bunches (~ 10 fs)
- 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

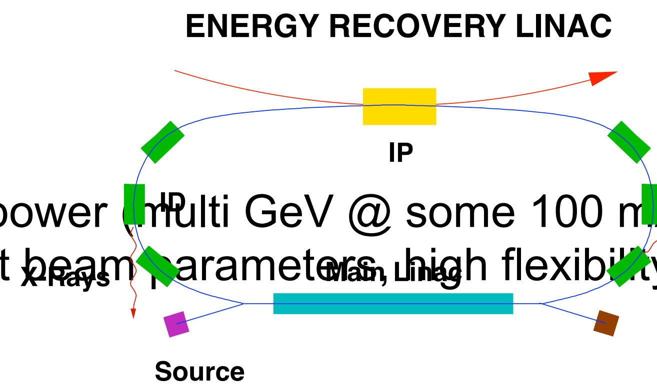




e.g. XFEL:
17.5GeV, 30 μA
“only” ~ 500 kW,
but real power

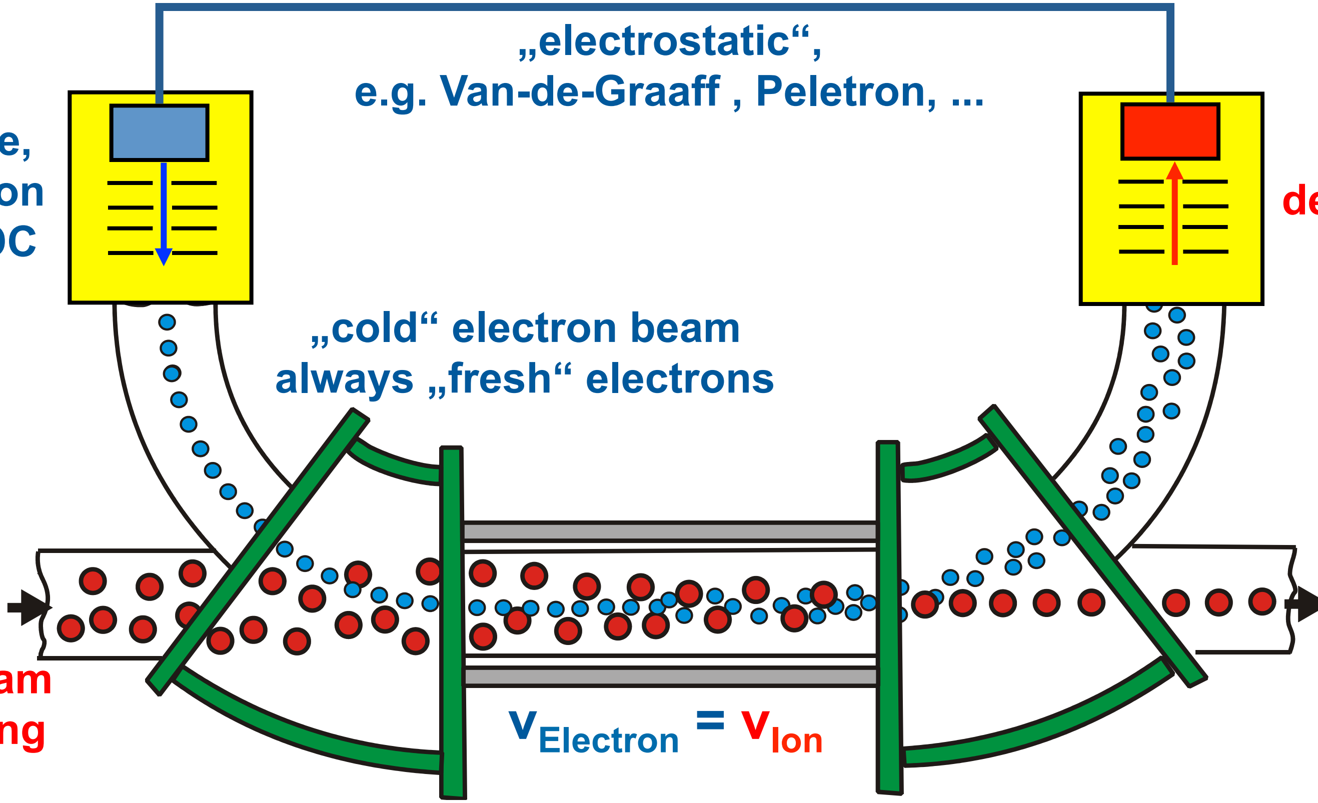
$$\varepsilon \sim \frac{1}{\gamma} \cdot \varepsilon_{source}$$

intrinsic short bunches, high current



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

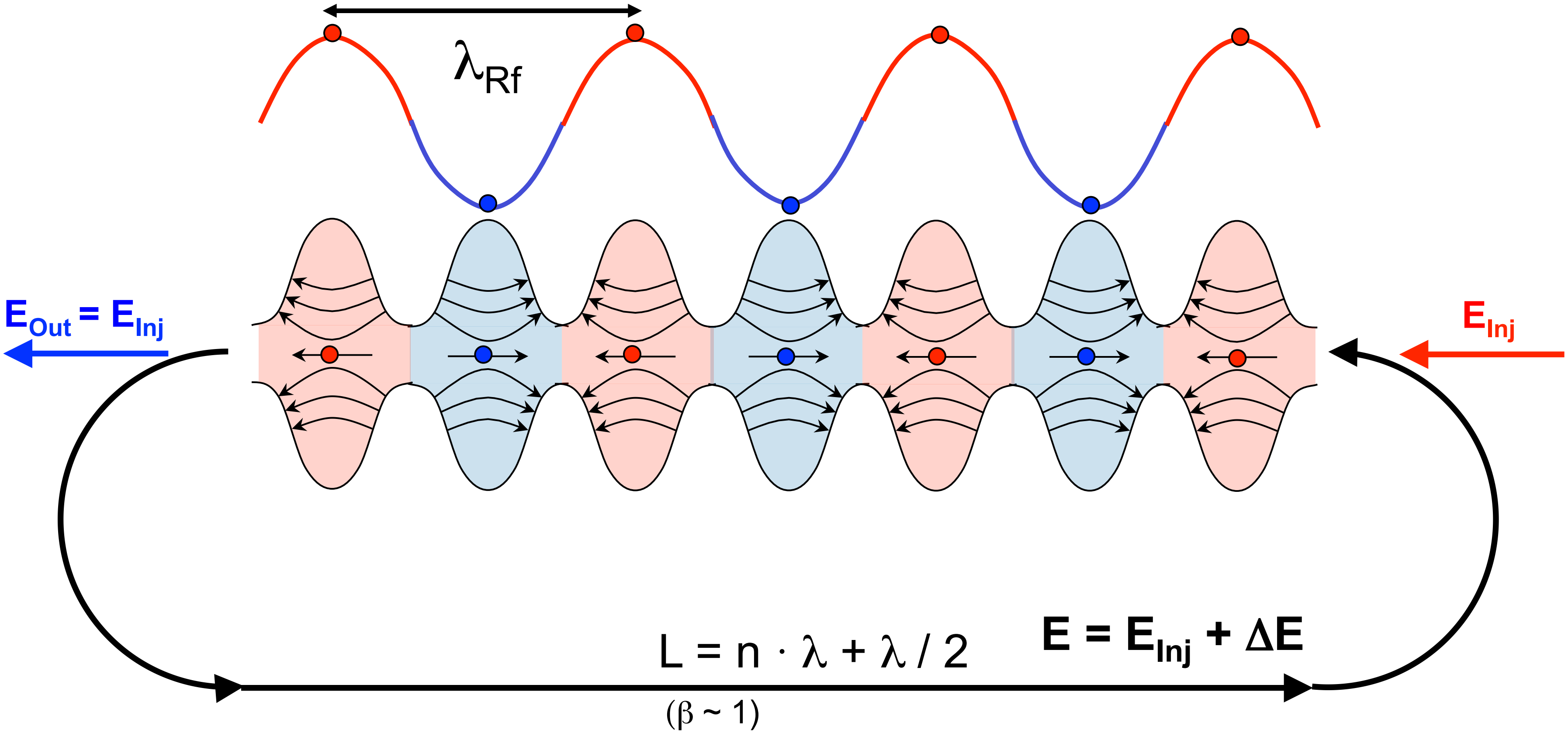
e.g. „electron cooler“ for ion beams, first devices in the 70ies



e.g. FermiLab recycler ring (Tevatron)

anti protons:	E = 9 GeV	→ β = 0.995
electrons:	E = 4.9 MeV	→ U_{Cooler} = 4.39 MV (β = 0.995)
	I = 0.5A (DC)	→ **P = 2.2 MW**
		„virtual“

RF linear accelerator



Energy supply = acceleration

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

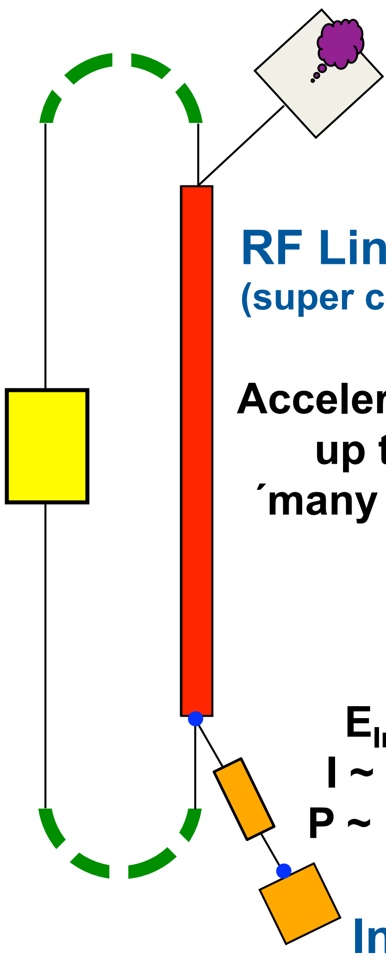
→ **Energy recovery = deceleration**

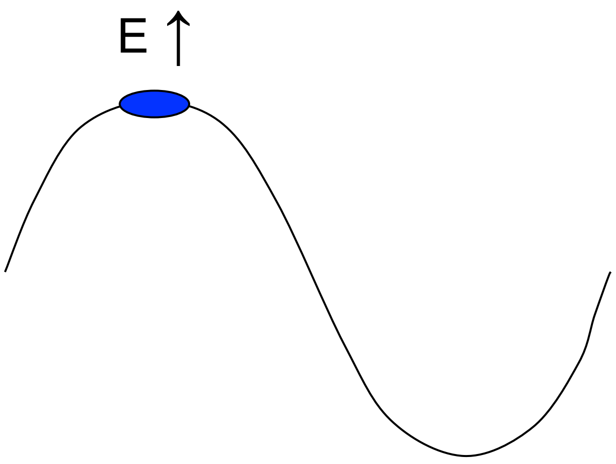
The Energy Recovery Linac Principle

„experiment“
needs
„virtual“ power
MW to GW

and

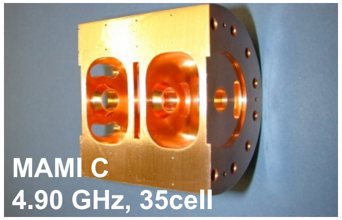
an always
„fresh“ beam





ERLs are in favor of superconducting RF

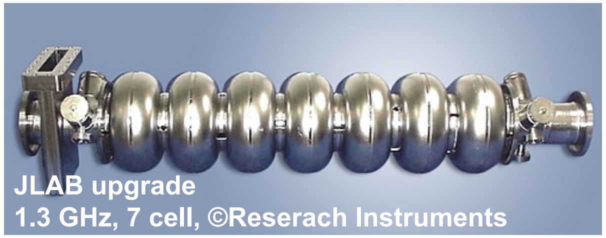
normal conducting (Cu) RF
(typical S/C-Band, ~2 – 6 GHz)



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"

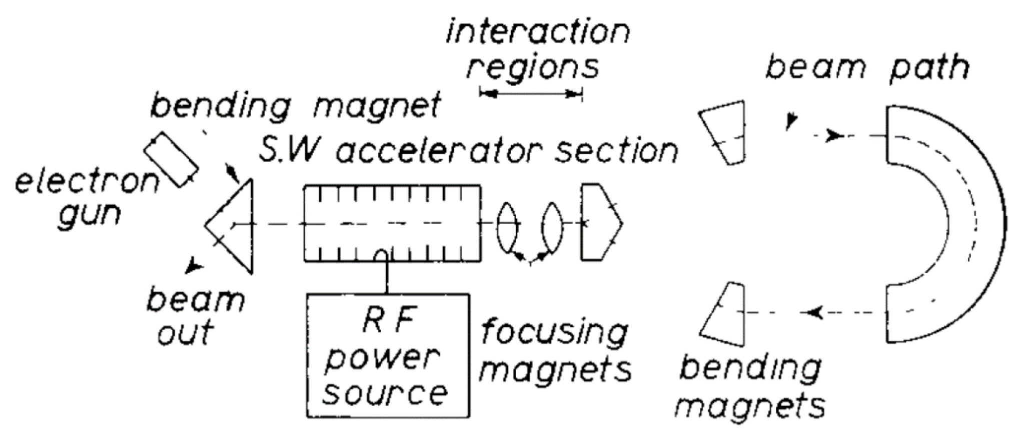
First idea: M. Tigner, Nuovo Cimento 37 (1965) 1228

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)

g-Beam Experiments (*).

rsity - *Ithaca, N. Y.*

65)

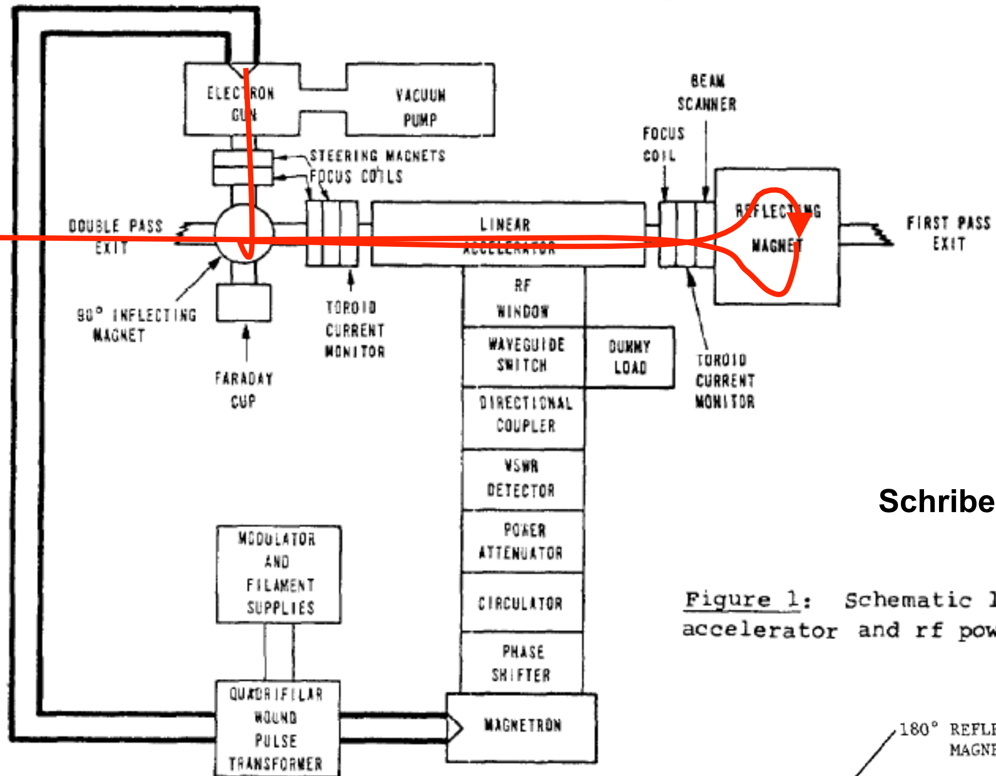


- stability issues (charge) solved
- one linac only

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.

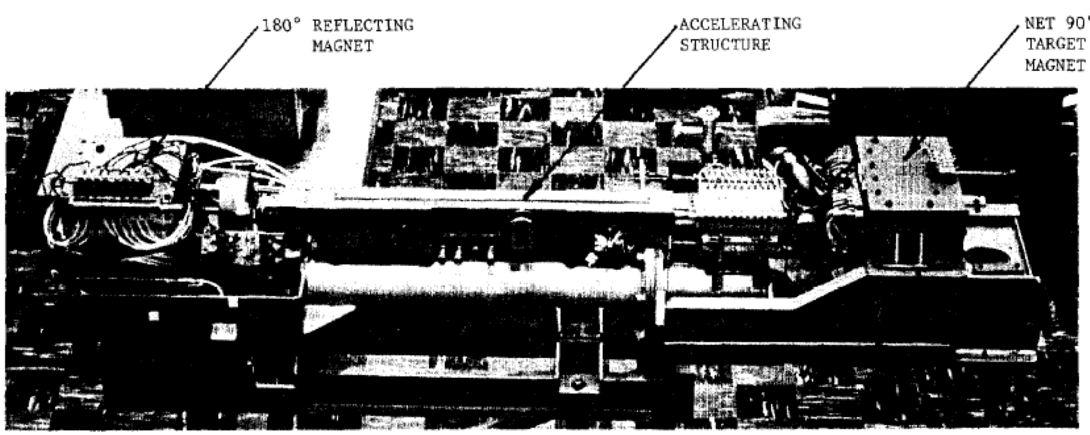
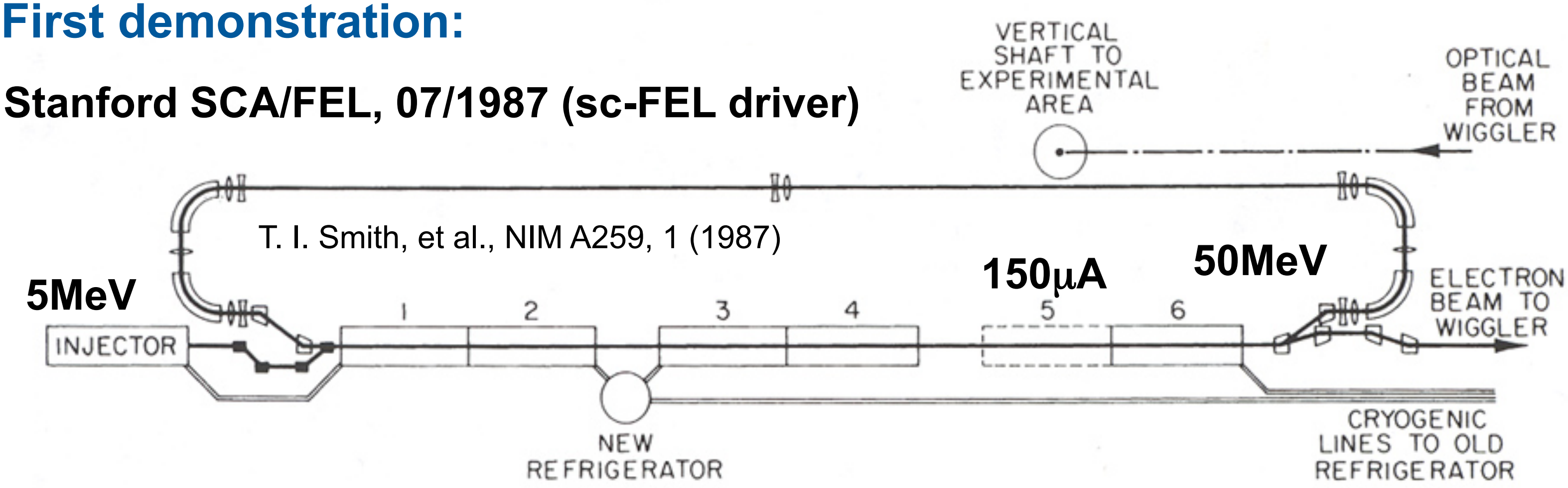


Figure 1. The 25 MeV electron accelerator attached to its strongback.

First demonstration:

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

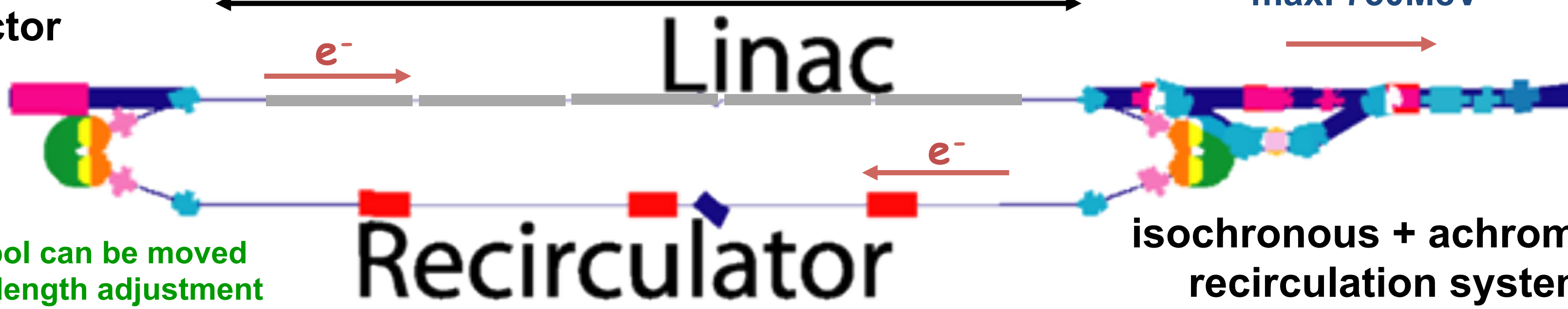


MIT Bates Recirculated Linac (2.857GHz, nc, pulsed), 1985

200m, max. 400MeV

max. 750MeV

Injector



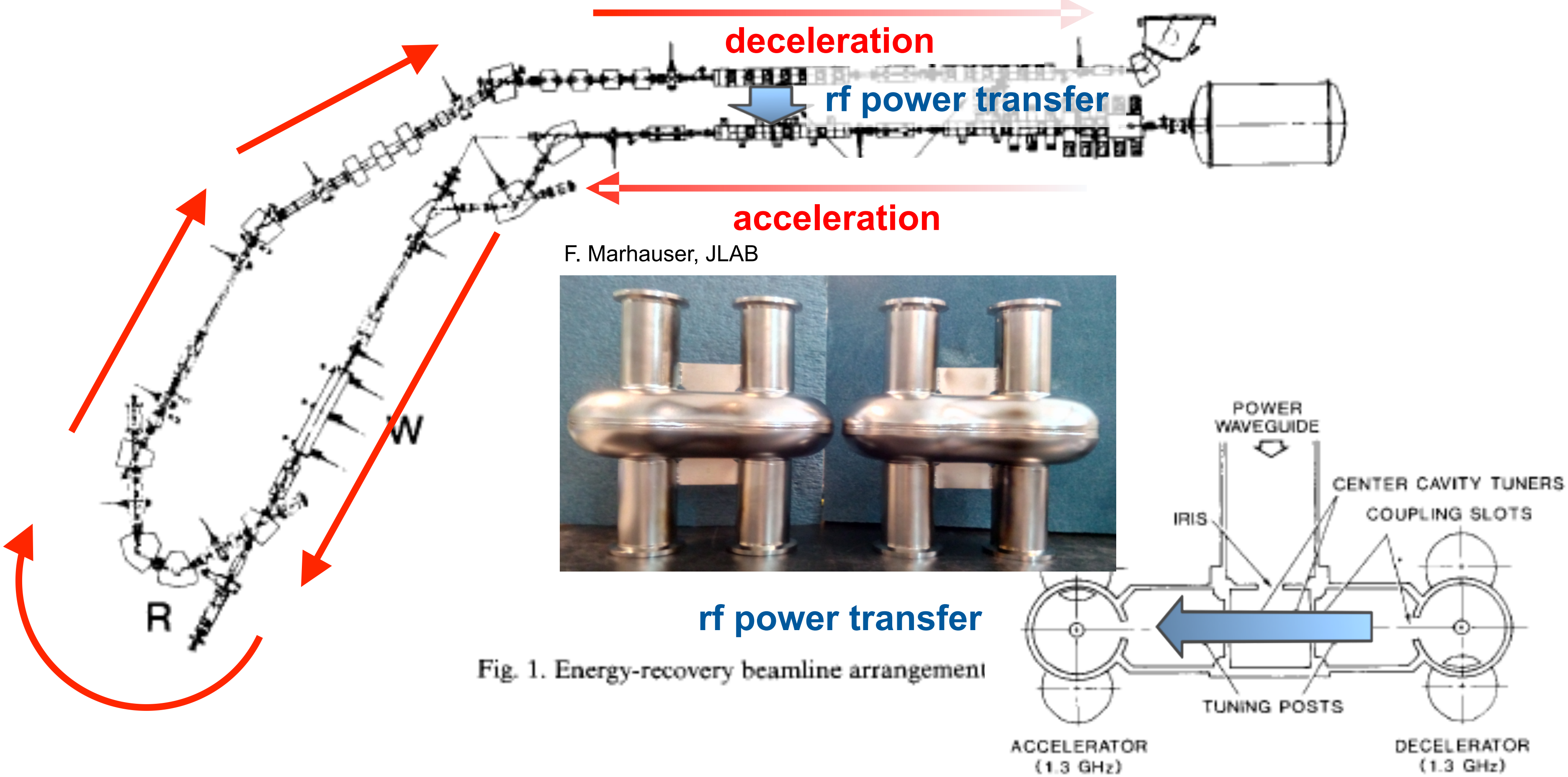
180° dipol can be moved
for path length adjustment

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



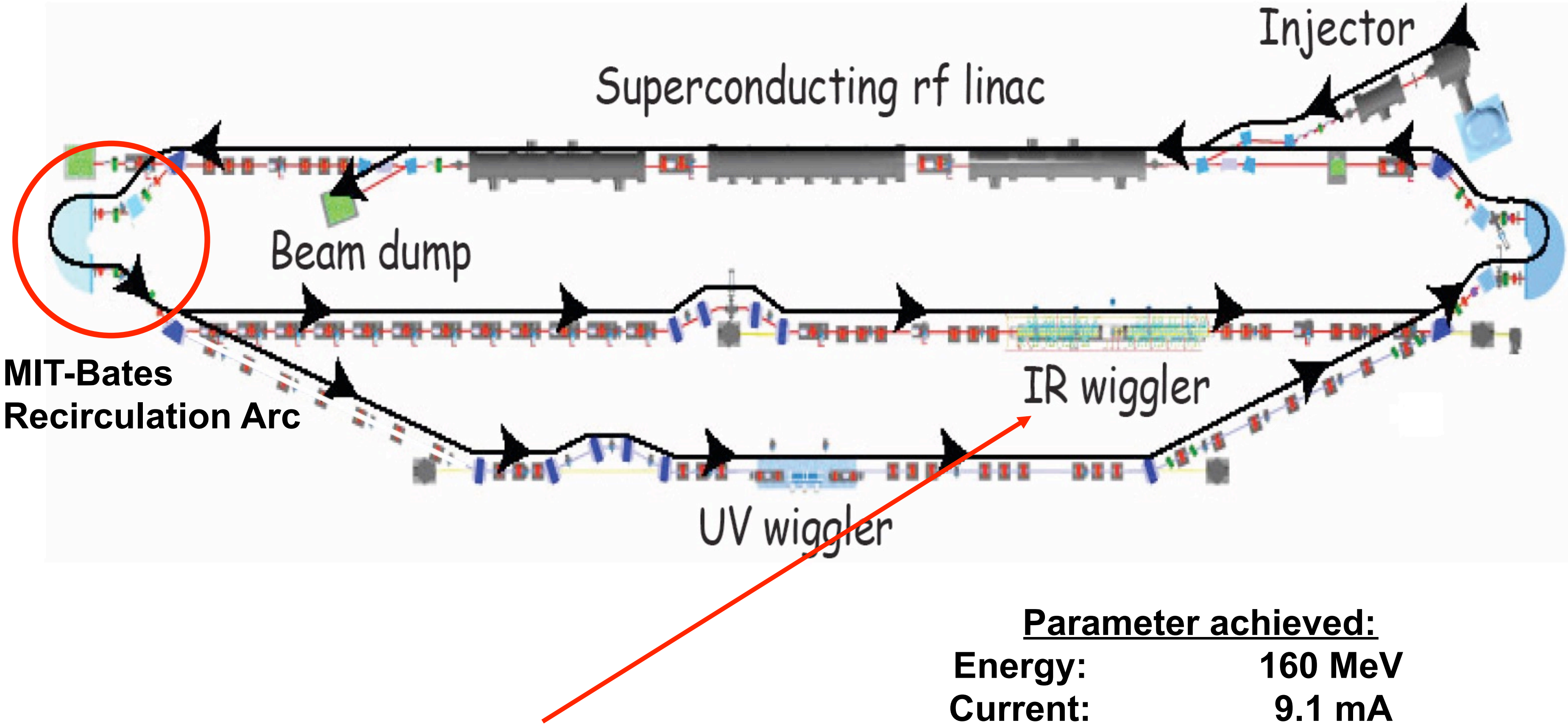
F. Marhauser, JLAB

Fig. 1. Energy-recovery beamline arrangement

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

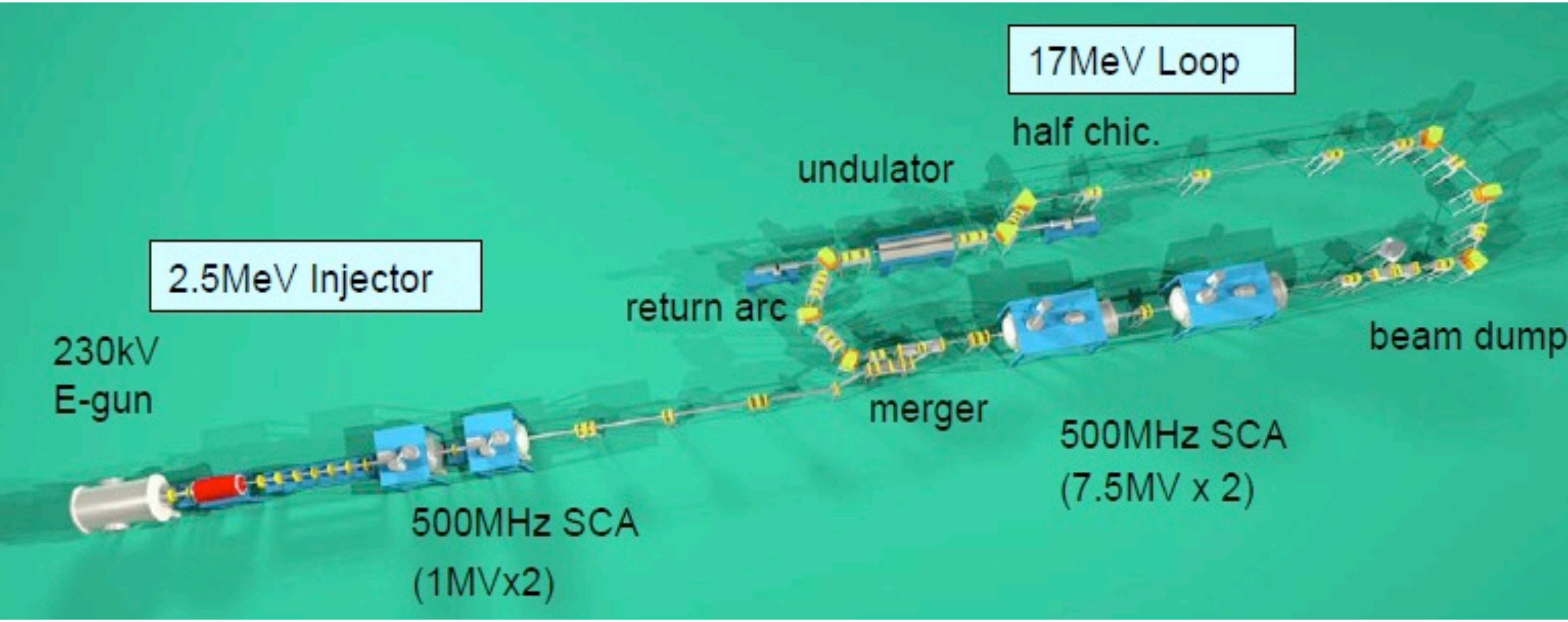
Parameter achieved:

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

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

First facilities – KEK / JAEA ERL FEL

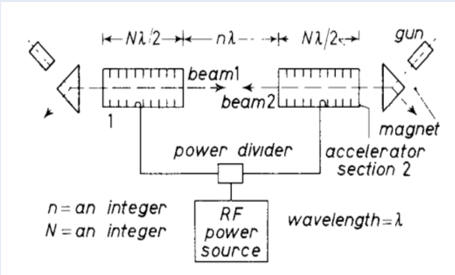
JAEA IR-FEL (starts 1987, JAERI):
500 MHz sc cavities, 15 – 20 MeV, 8 mA → 2 kW cw laser power @ 22 μm
at the beginning single pass → 2002 upgrade to energy recovery setup



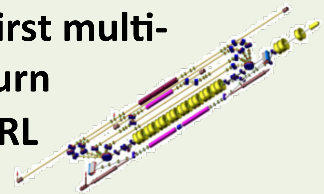
Around 2005: KEK and JAEA proposes ERL based light sources (5 GeV)
Decision to built in an common effort: Compact ERL !

Overview on projects and facilities

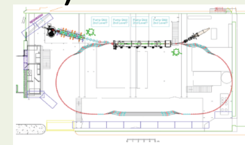
First idea:
M. Tigner (1965)



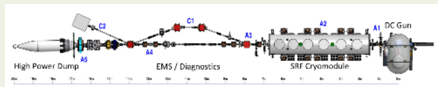
BINP FEL (2004):
First multi-turn ERL



CBETA (2016)
FFAG ERL
(with BNL)



Cornell University
Injector Teststand



BNL R&D ERL
Beijing ERL-FEL

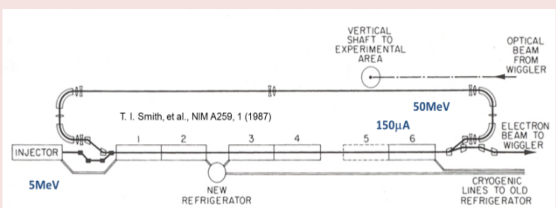
JAERI FEL (2002):
17 MeV, 5 mA

1960
1980
2000
2020

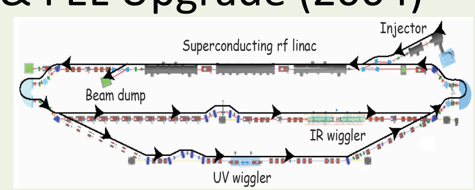
ALICE, Daresbury

PERLE@ORSAY (?)
CERN, JLAB, Daresbury, BINP, LAL

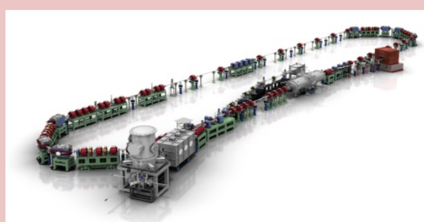
First energy recovery:
Stanford SCA/FEL (1987)



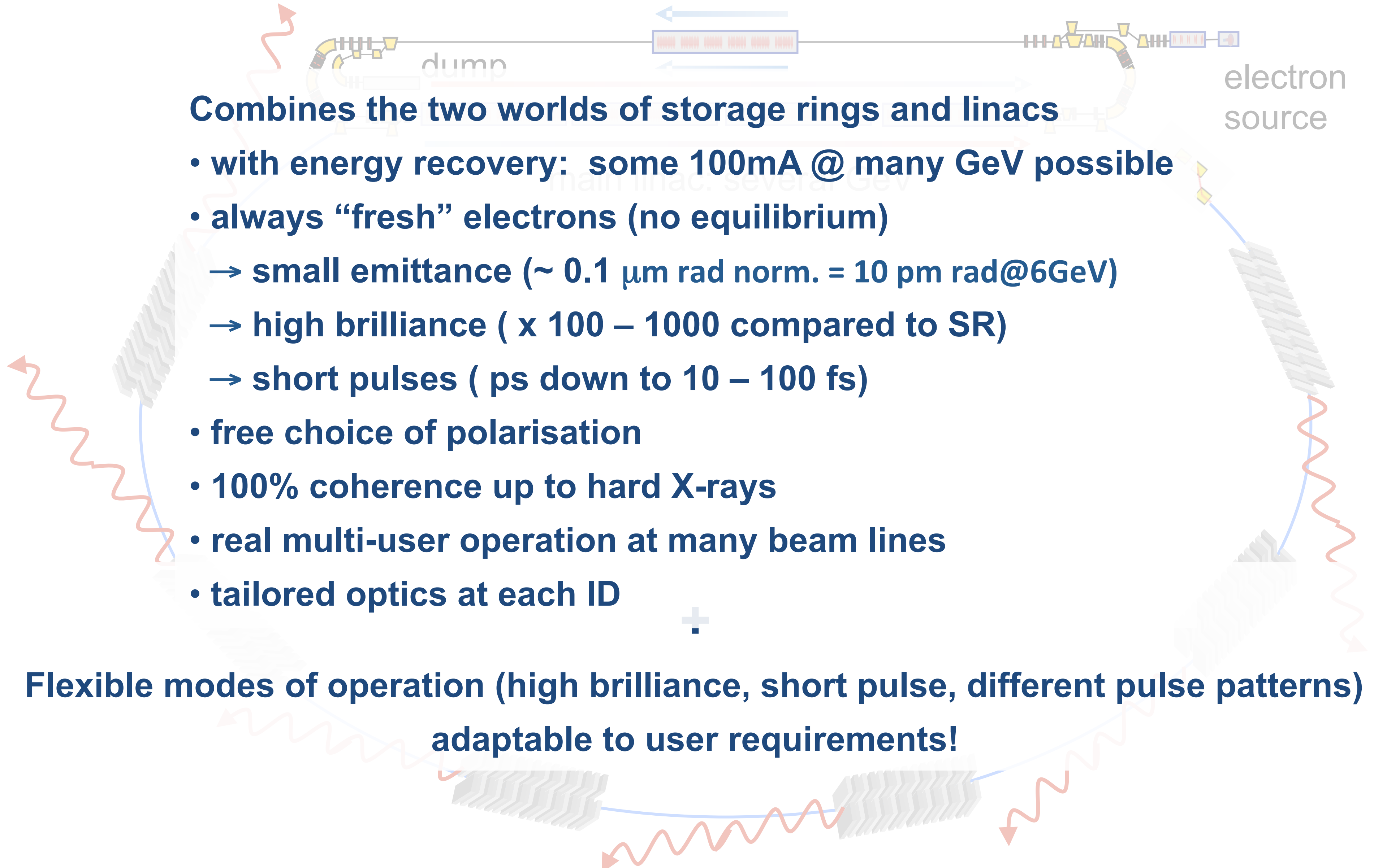
JLAB-FEL: Demo-FEL (1999)
& FEL Upgrade (2004)



KEK cERL (2014):
recirc. & energy recovery



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



Combines the two worlds of storage rings and linacs

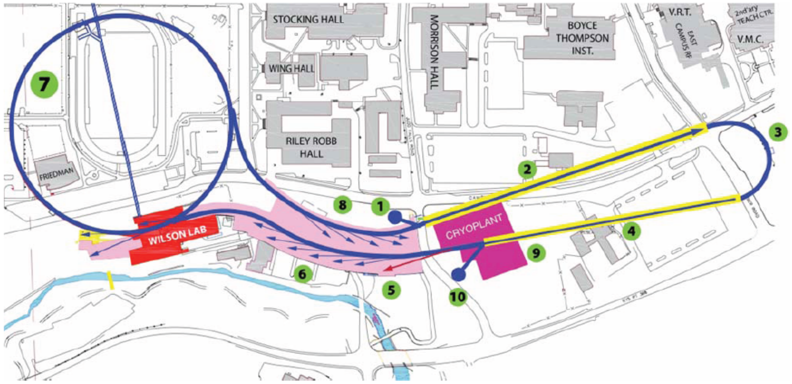
- with energy recovery: some 100mA @ many GeV possible
- always "fresh" electrons (no equilibrium)
  - → small emittance (~ 0.1 μm rad norm. = 10 pm rad@6GeV)
  - → high brilliance (x 100 – 1000 compared to SR)
  - → short pulses (ps down to 10 – 100 fs)
- free choice of polarisation
- 100% coherence 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

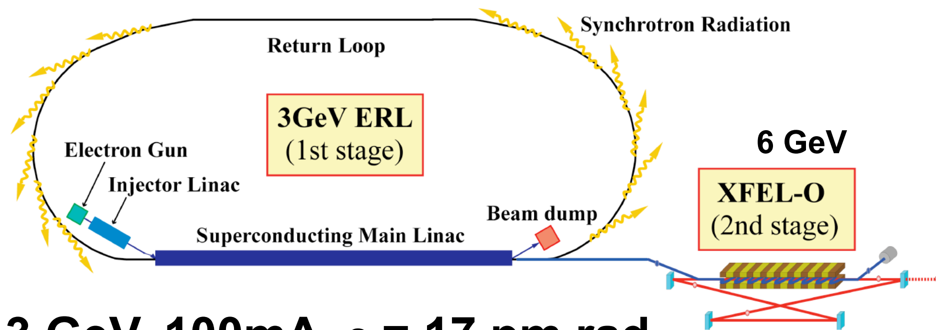
Cornell ERL



5 GeV, 100mA, ε = 8 pm rad

(ε_{norm} = 0.08 μm (@77pC) , 2ps)

KEK ERL

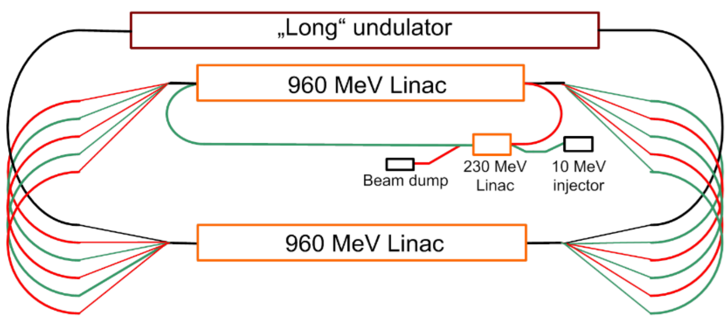


3 GeV, 100mA, ε = 17 pm rad

(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)

e.g. eRHIC: addition of an ERL to RHIC / BNL = Electron Ion Collider

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

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

ERL compared to storage ring

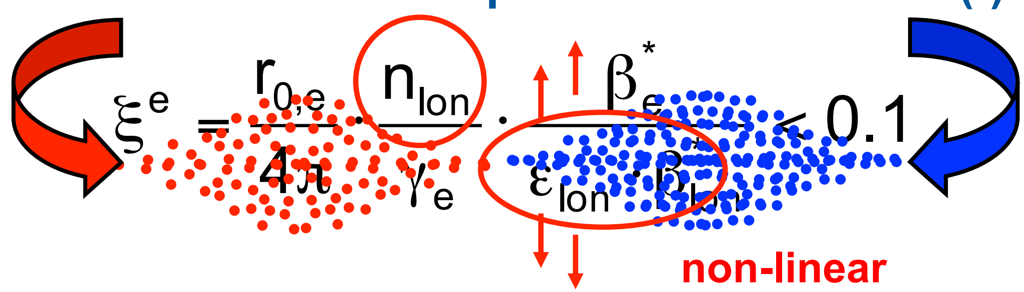
- electron beam needs to pass the interaction zone only once
- disturbance of electron beam by proton beam can be up to 20x stronger
- higher number of protons with high density possible
  → drastic increase in luminosity
- higher flexibility in interaction region design
- spin transparency (free choice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

Why ERL and not storage ring?

Luminosity

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

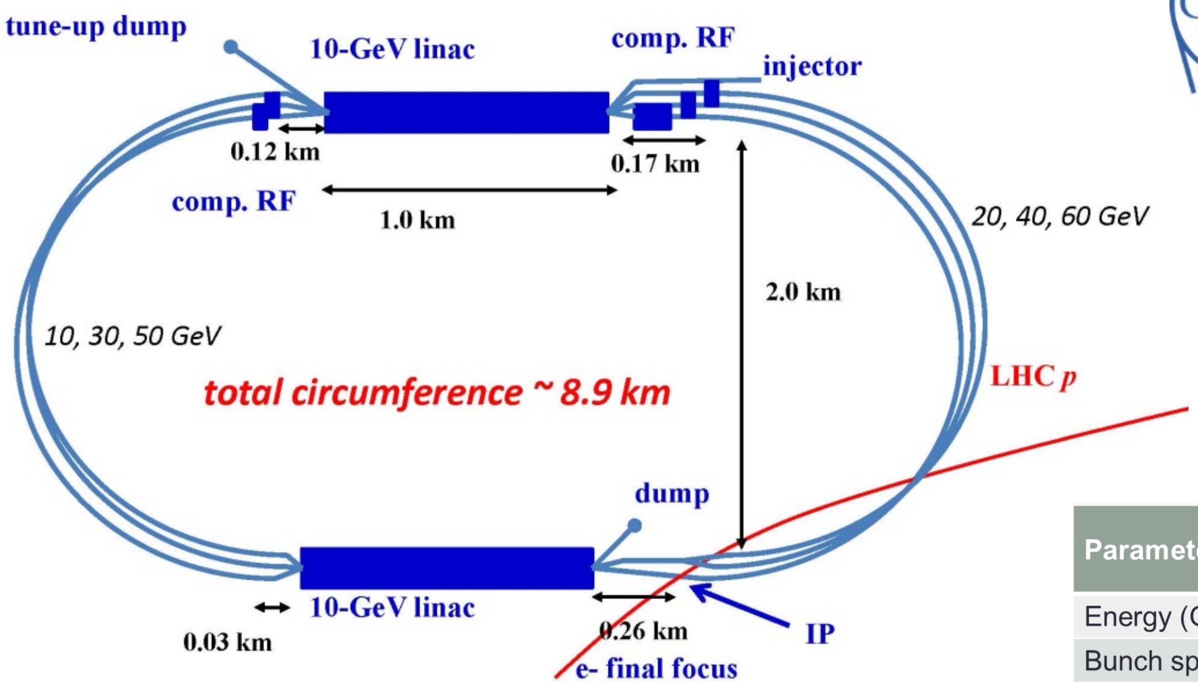
Limit: beam-beam parameter electrons (!)



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

ELR as electron part of Electron Ion Collider

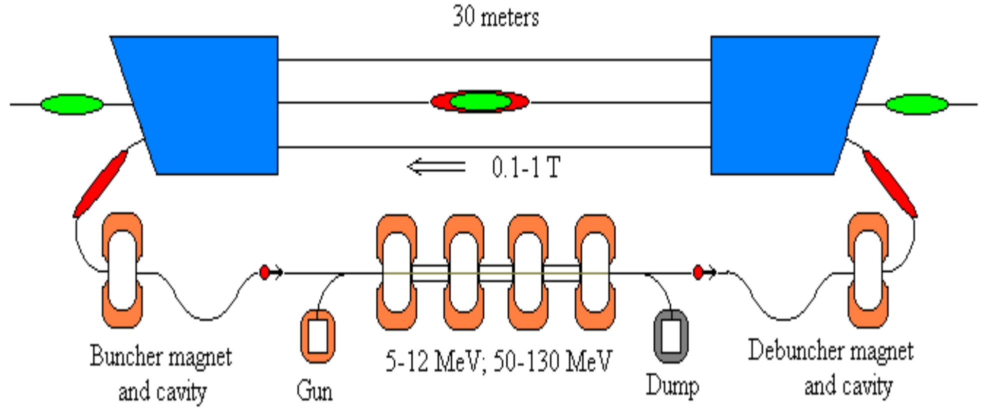
60 GeV (e) x 7 TeV (p)



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	

ELR as electron cooler

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

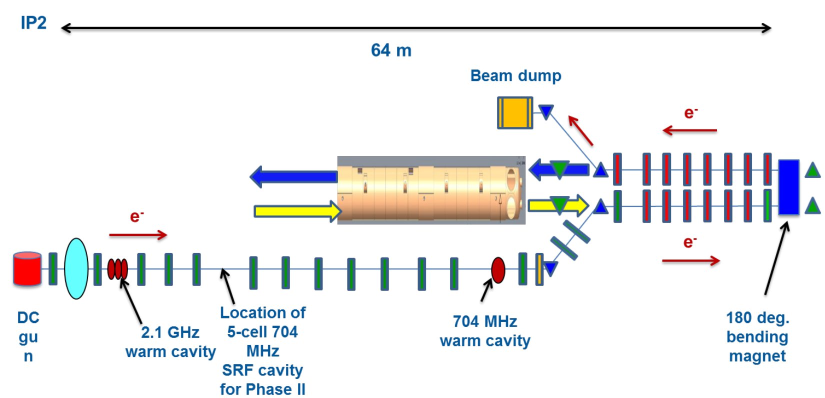


Efficient cooling needs

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

54.5 MV and A 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)

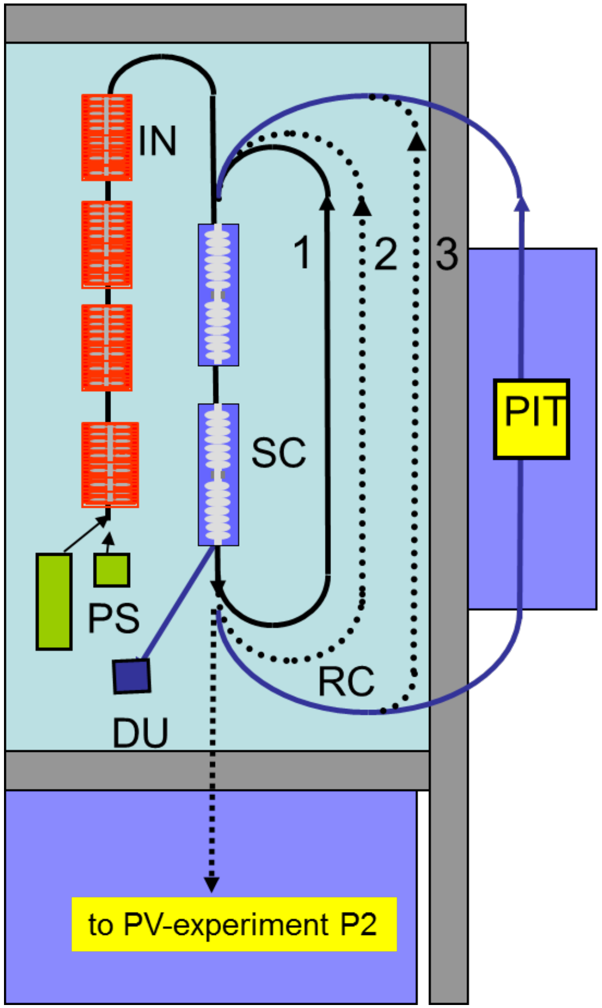


for ultra high ion energies
Coherent Electron Cooling
("stochastic cooling")

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

Compact ERL for high luminosity, low energy internal targets

First
sketch
(2009)



MESA @ Mainz University

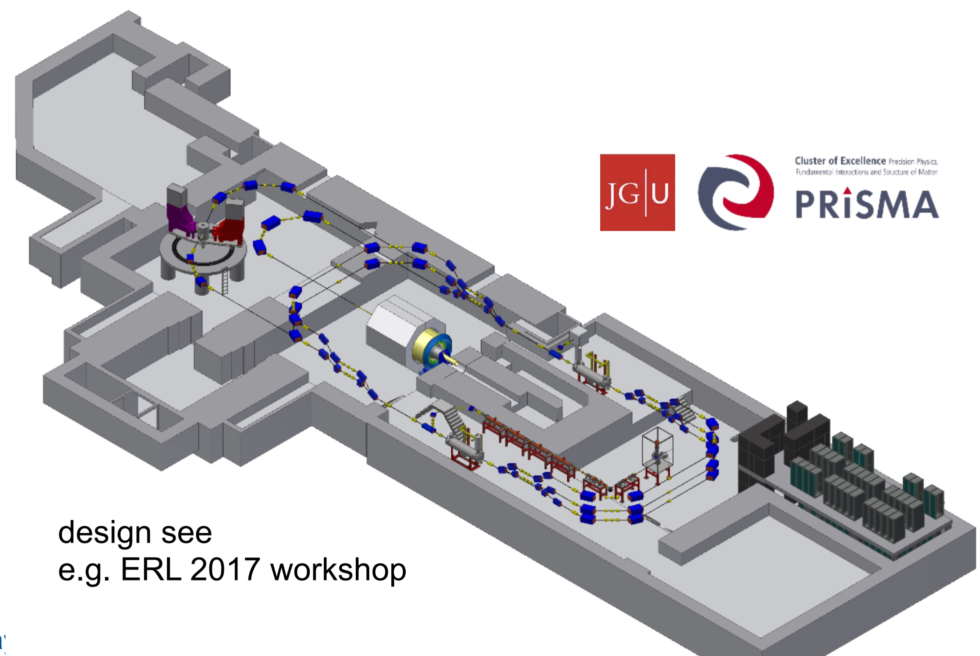
Multi turn ERL for

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 2017 workshop

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 > 10^{10} → reduce cryo costs

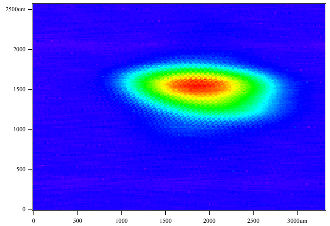
Beam dynamics / optics:

recirculation, flexible optics, bunch compression schemes = flexibility

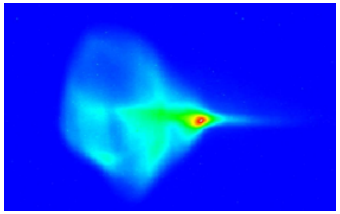
Control of beam loss

unwanted beam = dark current fromcathode, gun, cavities due to field emission, stray light laser
beam halo, collimation schemes !?

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



ERL:
no dead mathematician
~ 100 μA losses possible



The "hummingbird"
P. Evtushenko, JLAB

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 = $1.4 \cdot 10^{25}$ electrons / a

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 = $1.34 \cdot 10^{19}$ 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 = $0.5 \cdot 10^{12}$ electrons "forever"

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

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

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 = $2.2 \cdot 10^{14}$ electrons / a

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 = $1.4 \cdot 10^{25}$ electrons / a

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 = $1.34 \cdot 10^{19}$ electrons / a

BESSY II operation parameter:
(**τ = 5 h** beam lifetime, $\eta_{inj.}$ = 90% injection eff., T_{circ} = 800 ns)

I_{Beam} = 300 mA
→ Q_{Beam} = 240 nC circulating forever
→ 240 nC = $1.5 \cdot 10^{12}$ electrons forever

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

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

losses are governed by lifetime and injection

maintaining I_{Beam} = 300 mA / Q_{Beam} = 240 nC
→ 13.3 pC / s

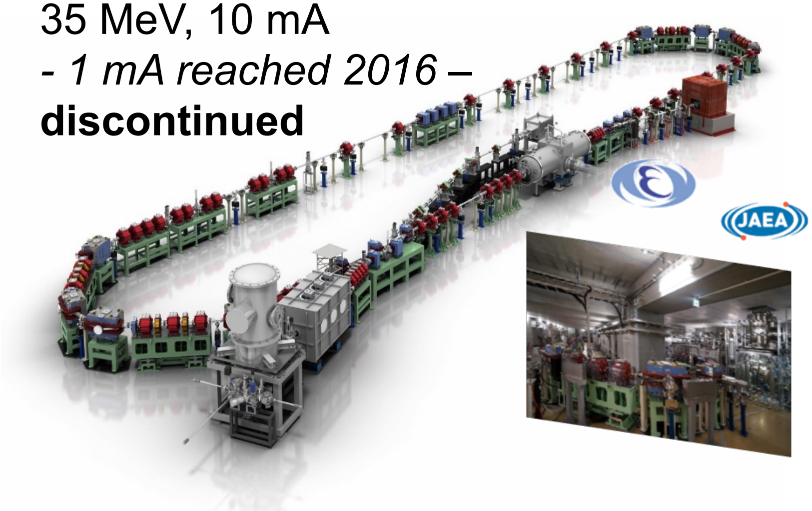
15 pA dumped @ 1.7 GeV = 0,025 W
→ 15 pC / s
→ 320 μC / a = $2 \cdot 10^{15}$ electrons / a

cERL, KEK + JAEA

35 MeV, 10 mA

- 1 mA reached 2016 –

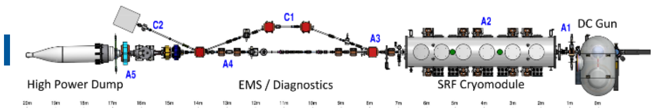
discontinued



ERL Injector, Cornell

5 – 15 MeV, 100 mA

- 80 mA max. demonstrated -



BNL ERL

20 MeV, 30 mA

- first electrons from gun 2014 –

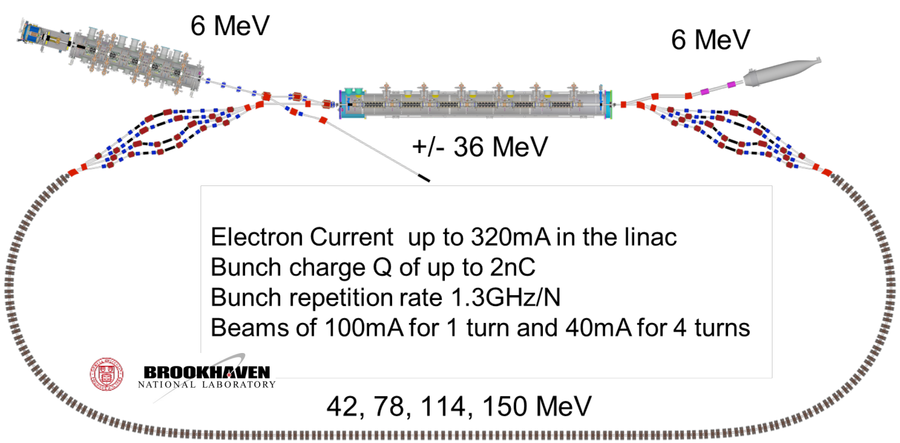
discontinued

CeC project

CBETA FFAG ERL, Cornell/BNL

150 MeV (4 turns), 40 mA

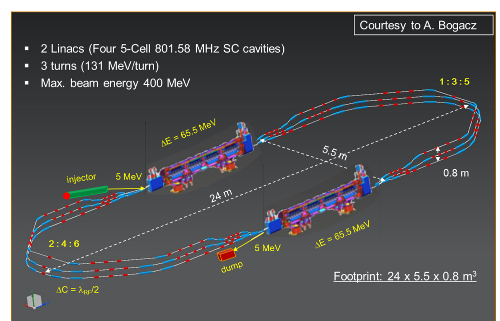
- funded, under construction since 2016 -



PERLE@ORSAY

max. 400 MeV, 15 mA (3 turns, 2 linacs, 802 MHz)

- CDR in 2017, to be funded –



CERN

JLAB,

Daresbury / U Liverpool

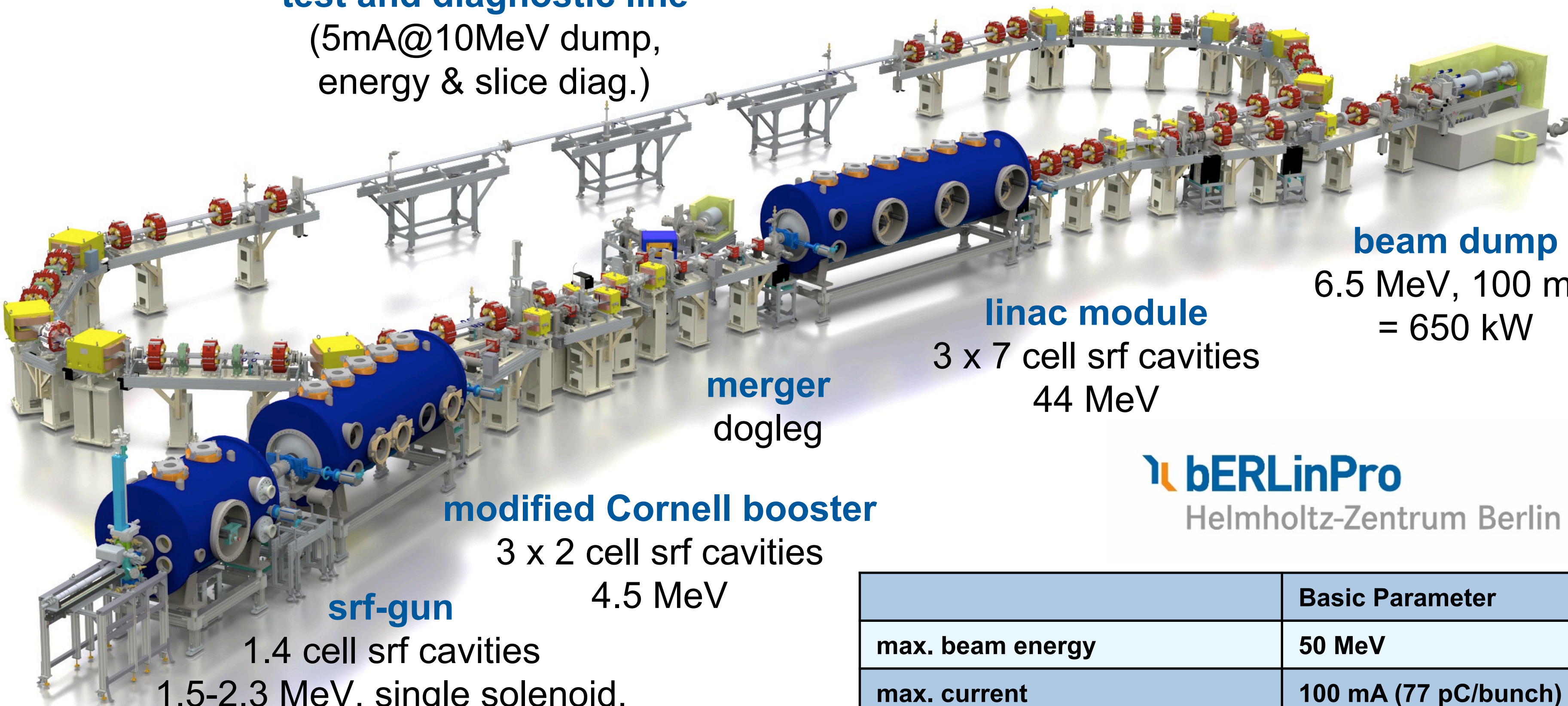
BINP

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)



test and diagnostic line
(5mA@10MeV dump,
energy & slice diag.)

beam dump
6.5 MeV, 100 mA
= 650 kW

linac module
3 x 7 cell srf cavities
44 MeV

merger
dogleg

modified Cornell booster
3 x 2 cell srf cavities
4.5 MeV

srf-gun
1.4 cell srf cavities
1.5-2.3 MeV, single solenoid,

bERLinPro
Helmholtz-Zentrum Berlin

	Basic Parameter
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 µm (0.5 µm)
bunch length (straight)	2 ps or smaller (100 fs)
rep. rate	1.3 GHz
losses	< 10^{-5}

project started 2011, fully funded
building ready 2017
first electrons 2018
recirculation 2019/2020

bERLinPro – Technological challenges I

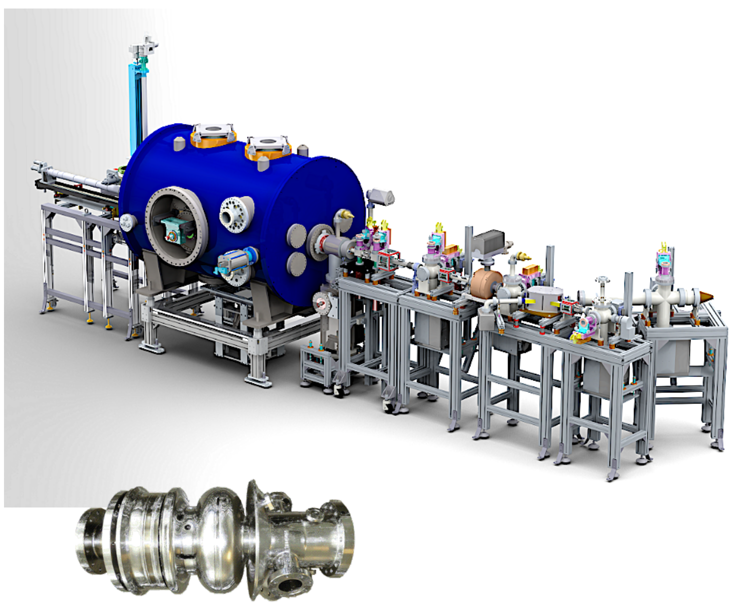
High current, GeV range ERLs

- massive virtual (x 100 MW) and real (x 100 kW) power
  - RF generator & amplifier, RF control: transient beam loading

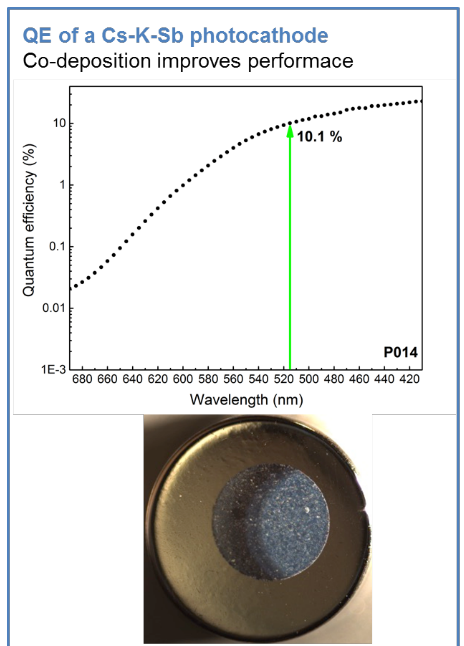
    3 x 270 kW klystron based cw transmitter / 600 kW wall plug power

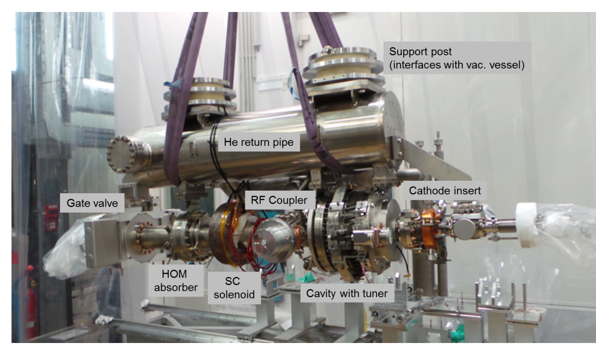
High current, GeV range ERLs

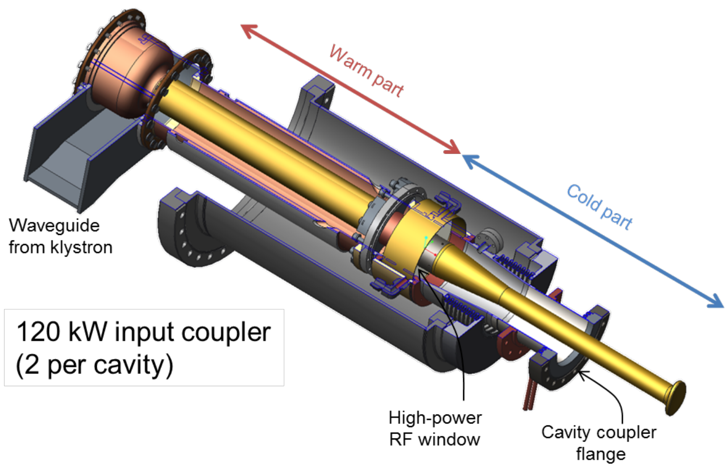
- massive virtual (x 100 MW) and real (x 100 kW) power
    - RF generator & amplifier, RF control: transient beam loading
- high current source
    - nc (Cornell: 80 mA DC-gun (2014)) vs. sc (Elbe/HZDR, bERLinPro/HZB, BNL)
    - cathode: material, handling & insertion, QE, lifetime, …
    - laser: power, wavelength, pattern, …

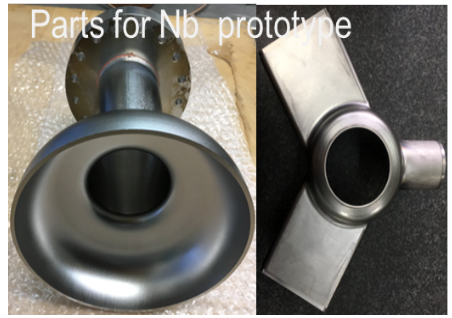


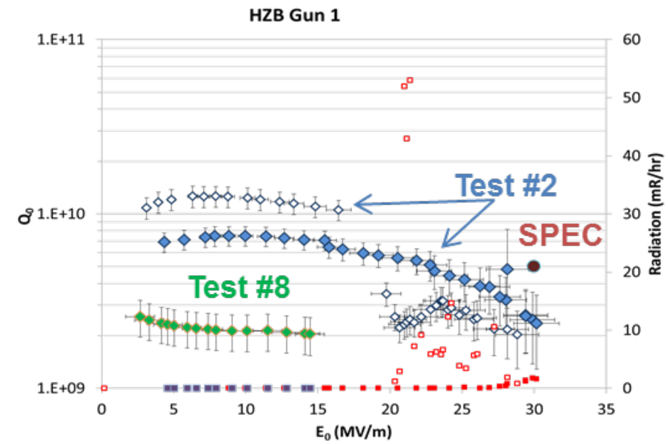
1.4-cell SRF injector



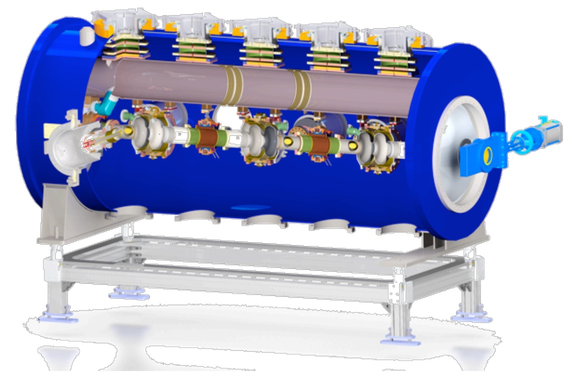








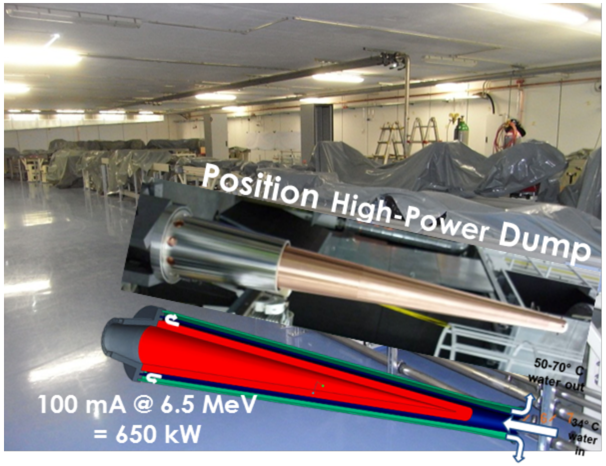
- sc technology
  - high fields / gradients, high Q(uality)
  - fieldemission (dark current), multipacting
  - cavity treatment (forming & welding, HPR, ECP, BCP, ..), module assembly (clean room, …)
  - high power coupler



bERLinPro – Technological challenges I

High current, GeV range ERLs

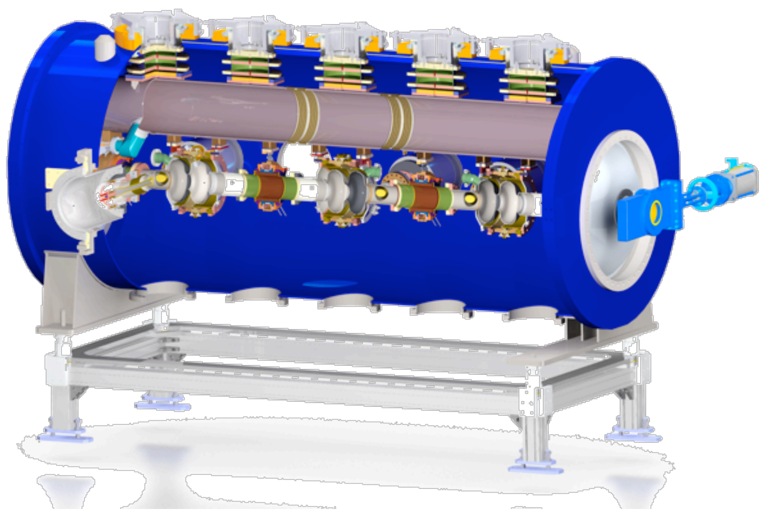
- massive virtual (x 100 MW) and real (x 100 kW) power
  - RF generator & amplifier, RF control: transient beam loading
- high current source
  - nc (Cornell: 80 mA DC-gun (2014)) vs. sc (Elbe/HZDR, bERLinPro/HZB, BNL)
  - cathode: material, handling & insertion, QE, lifetime, …
  - laser: power, wavelength, pattern, …
- sc technology
  - high fields / gradients, high Q(uality)
  - fieldemission (dark current), multipacting
  - cavity treatment (forming & welding, HPR, ECP, BCP, ..), module assembly (clean room, …)
  - high power coupler
- radiation & machine safety
  - fast MPS
  - high power beam dump



bERLinPro – Technological challenges II

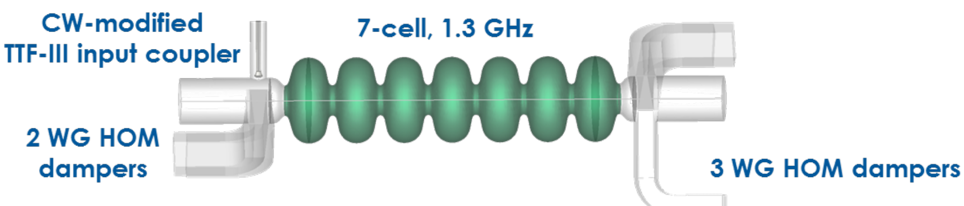
Booster cavities and module are based on the Cornell design

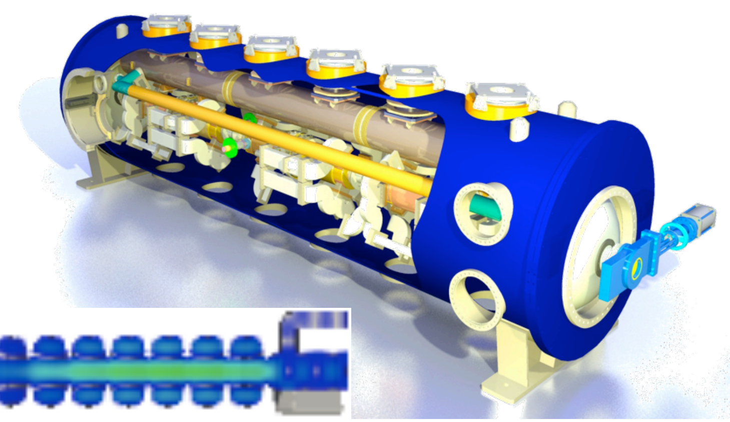
(3 x 2 cell, 1.8 K, 4 MeV@100 mA = 400 kW real beam power, 2 x 230 kW klystron)



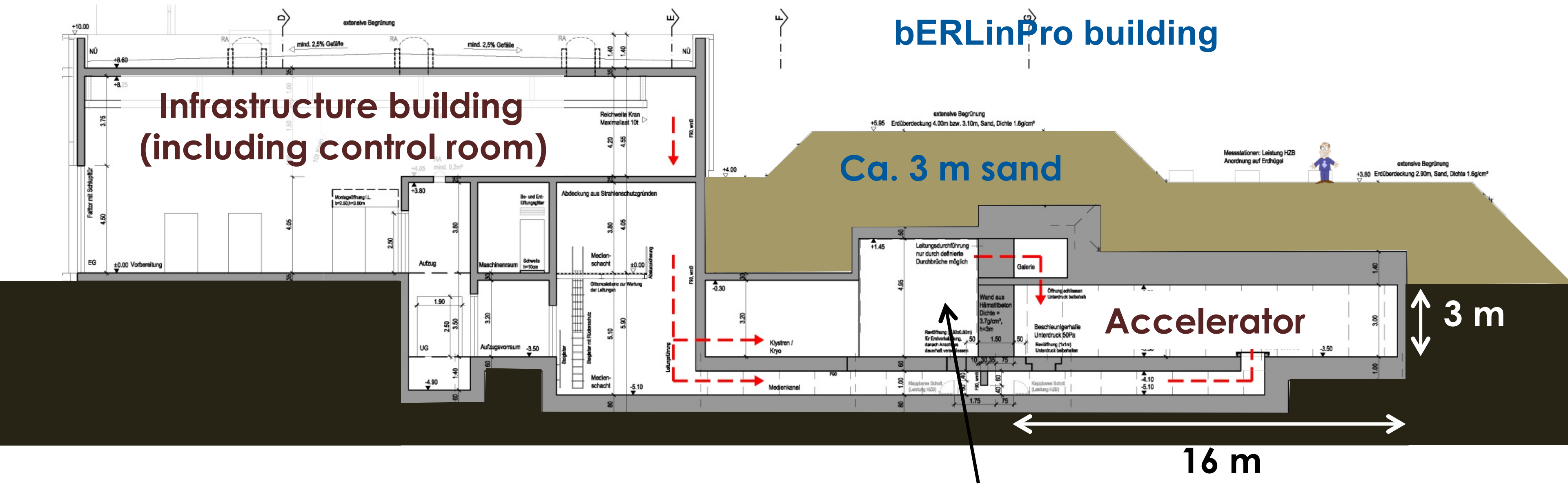
Linac cavities and module (HZB design)

(3 x 7 cell, 1.8 K, 44 MeV@2x100 mA, zero net beam-loading, 3 x 10 kW SSA)





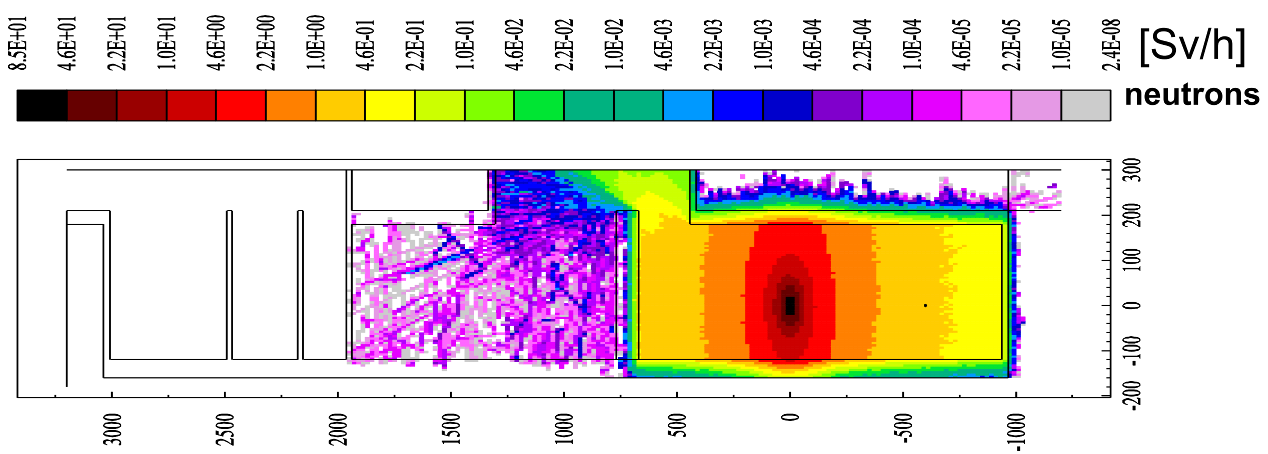
Radiation protection for ERL – shielding neutrons



Partially shielded ante-room for equipment close to the accelerator (klystron, cold-compressor for cryogenics)

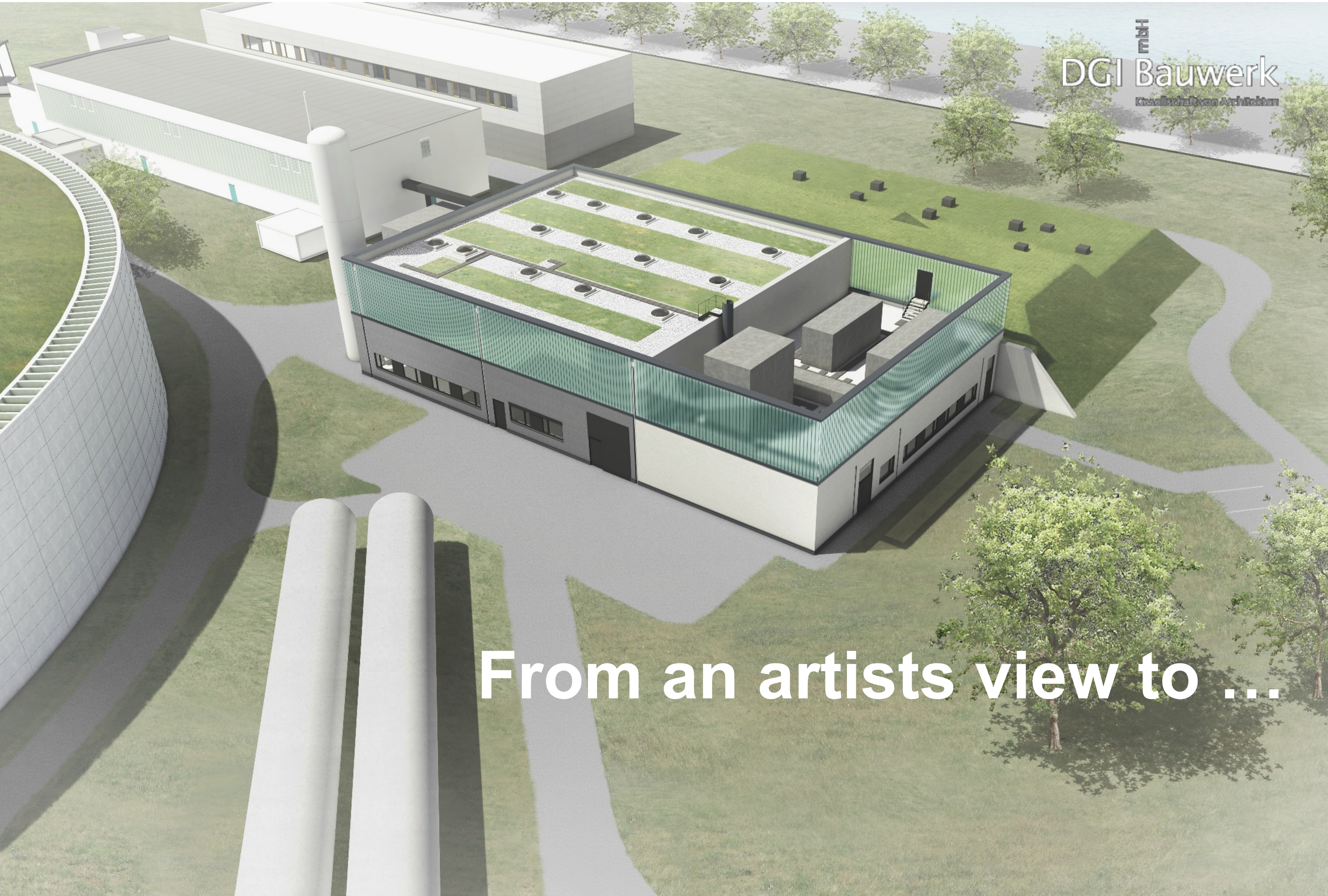
Fluka calculations
(K. Ott, HZB)

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



bERLinPro Building construction started 02/2015

bERLinPro Building



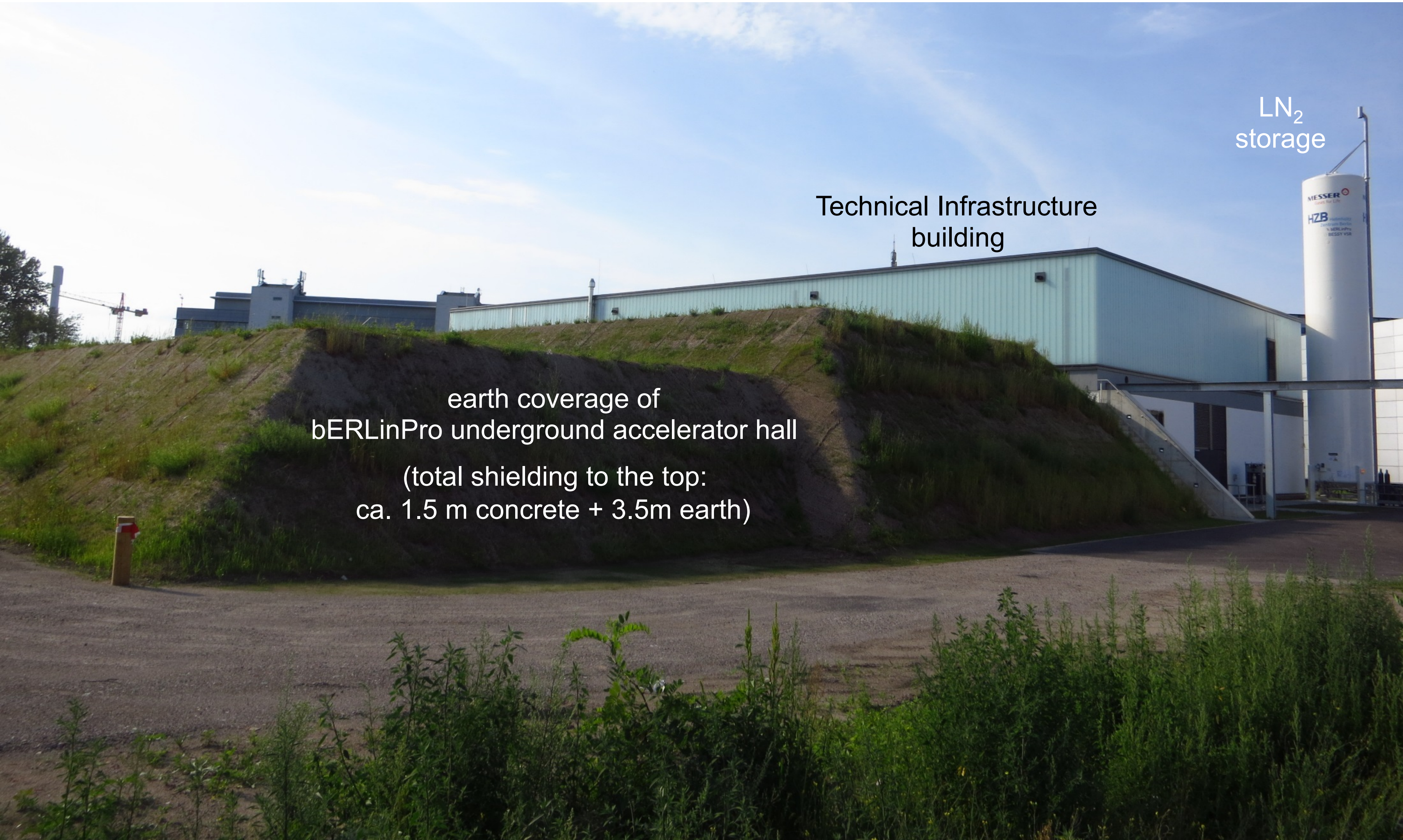
From an artists view to …

bERLinPro Building

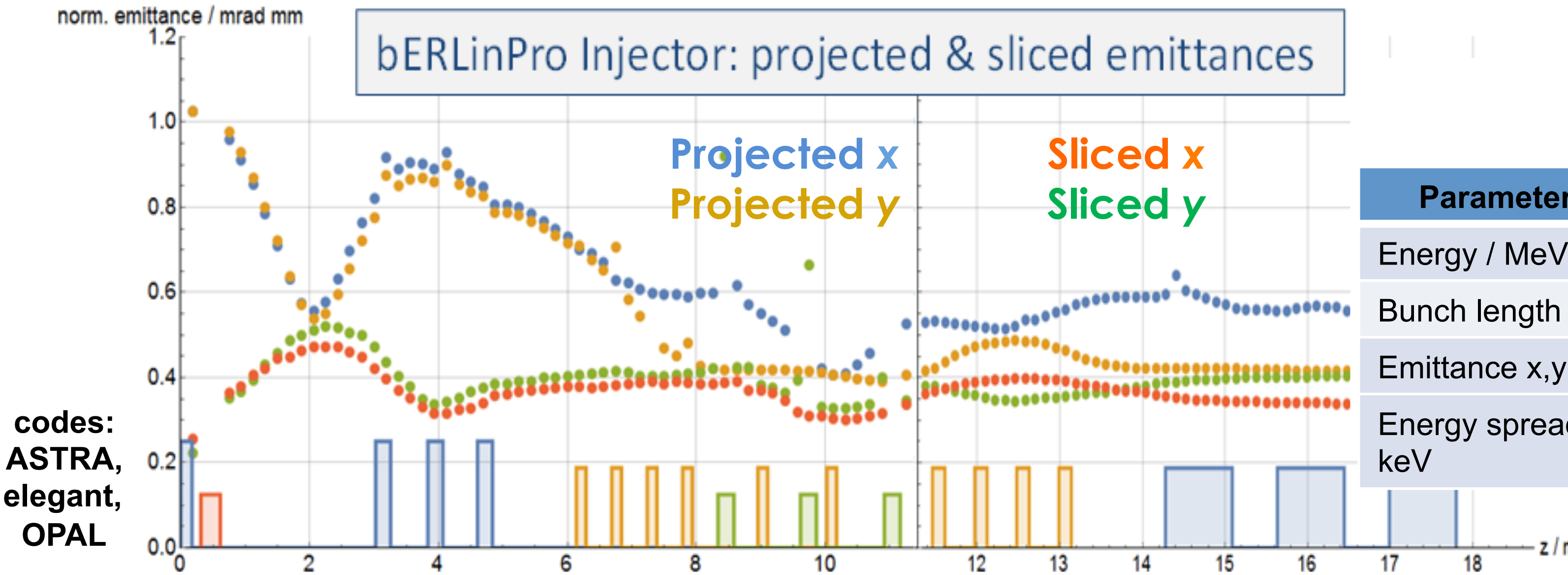
view north-west

bERLinPro Building

view south-east

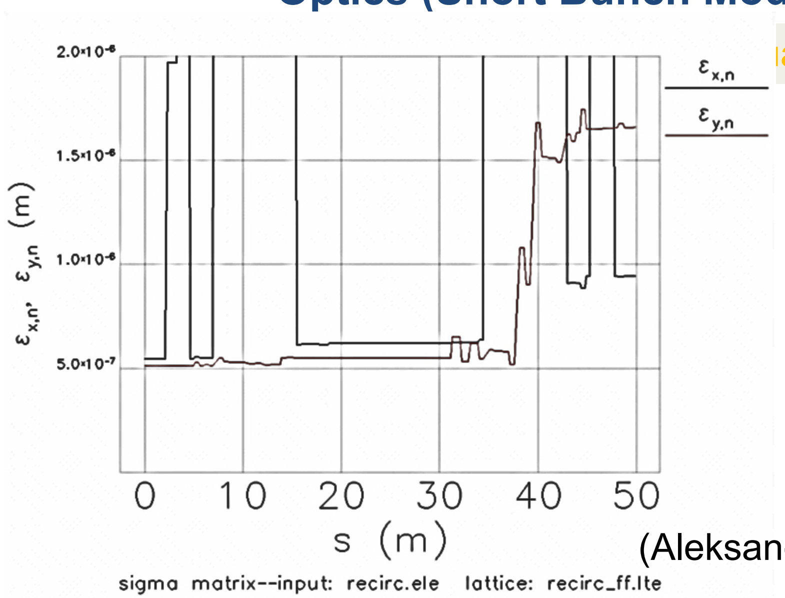


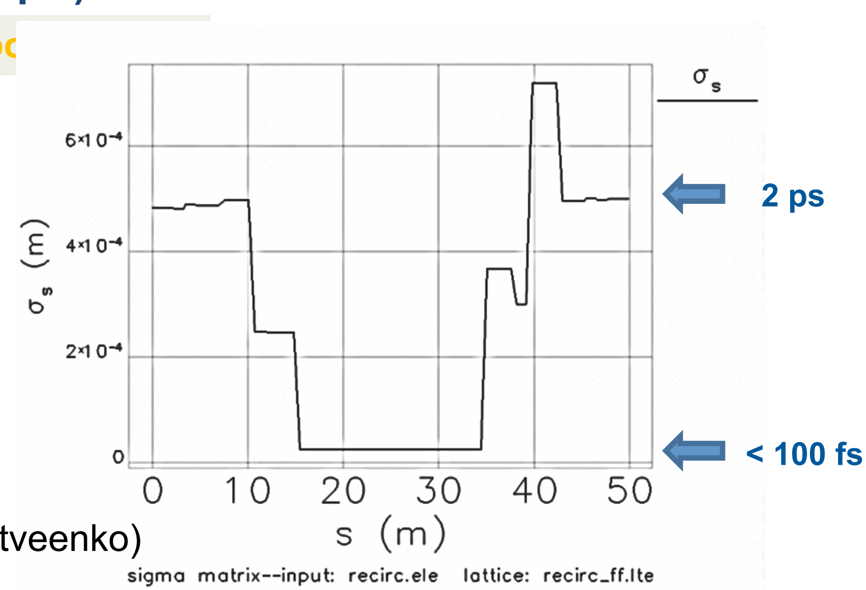
bERLinPro – performance parameter (simulations)



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

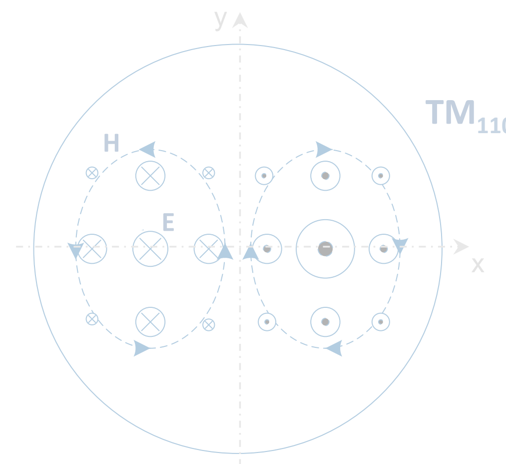




(Aleksandr Matveenko)

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

BBU threshold current

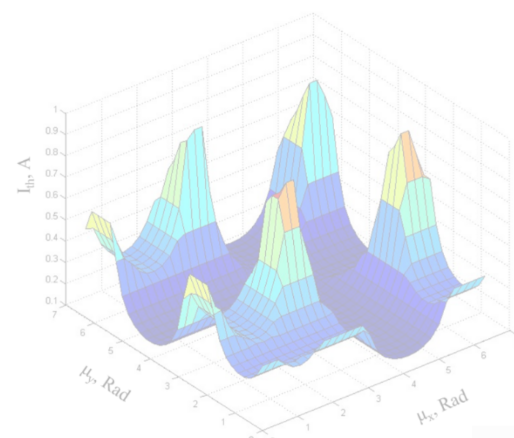
$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

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

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

Countermeasures:

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

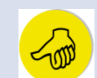
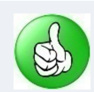
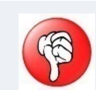
Unwanted Beam

Amount:

- not reliably predictable for most sources

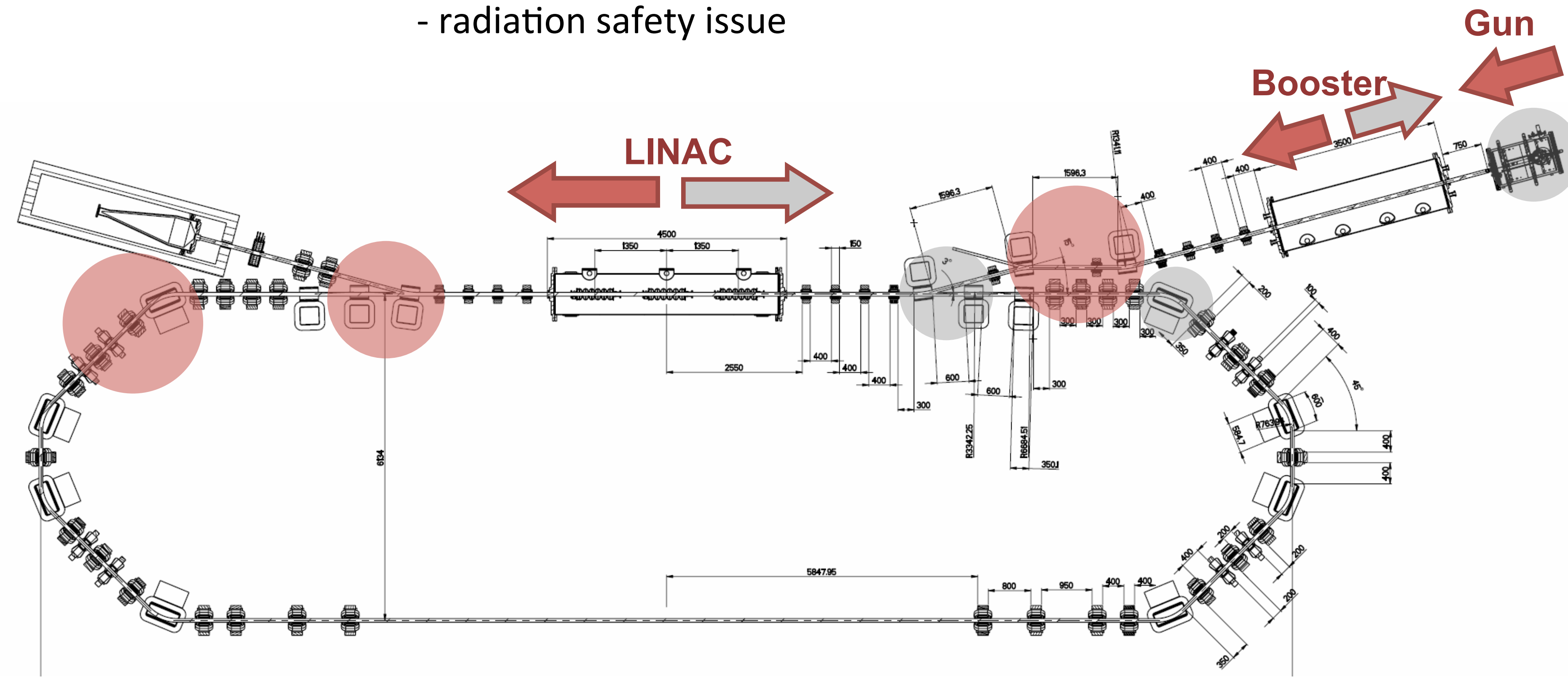
Loss positions:

- 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

Dark Current: - consuming rf power (linac)
- MPS relevant: μA @ tens of MeV → $10^2 \ldots 10^3$ W/??
- radiation safety issue



- dark current from booster (E_{max} = 4.5 MeV → ΔE > 30%) will be lost in merger
- dark current from linac (E_{max} = 44 MeV → ΔE > 13%) will be lost in the 1st arc bend

Only dark current from gun will potentially reach the recirculator!

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 Q_0)

ongoing, worldwide effort to push ERL technology

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

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

Finis