Energy Recovery Linacs

Virtual beam power for a multitude of applications

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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

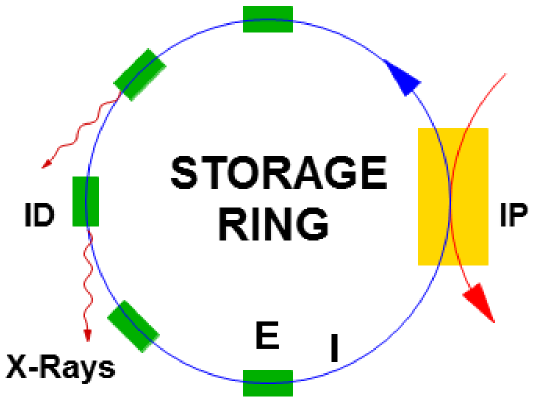
multi-user light sources, collider, cooler, compact sources

Challenges

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

more details on many aspects e.g.:
https://www.helmholtz-berlin.de/events/erl19/index_en.html
ERL2019, ICFA Workshop
HZB, Berlin & Jacow Proceedings on ERL Workshops

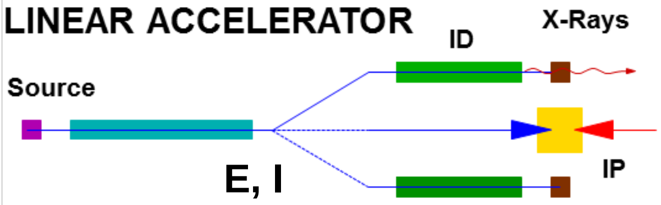
Storage ring ↔ linac / virtual ↔ real power



synchrotron radiation source, collider

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

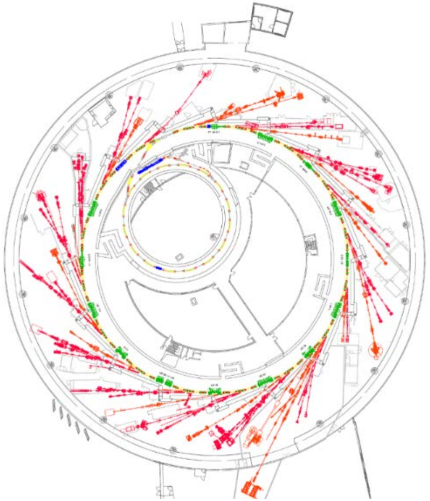
$$E_{\text{stored}}[\text{J}] = E[\text{eV}] \cdot I[\text{A}] \cdot T_{\text{rev}}[\text{s}]$$



free electron laser, collider, fixed target

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

Storage ring ↔ linac / virtual ↔ real power

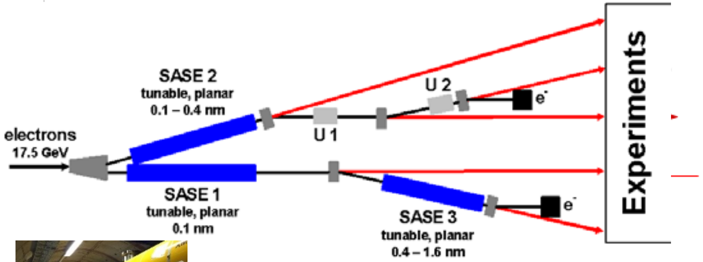


synchrotron radiation source, collider

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

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

e.g. BESSY II, 3rd generation light source, 240m circumference
1.7 GeV, 300 mA = 510 MW **virtual beam power**,
thereof ca. 90 kW used synchrotron radiation power
(and only 408 J stored energy)

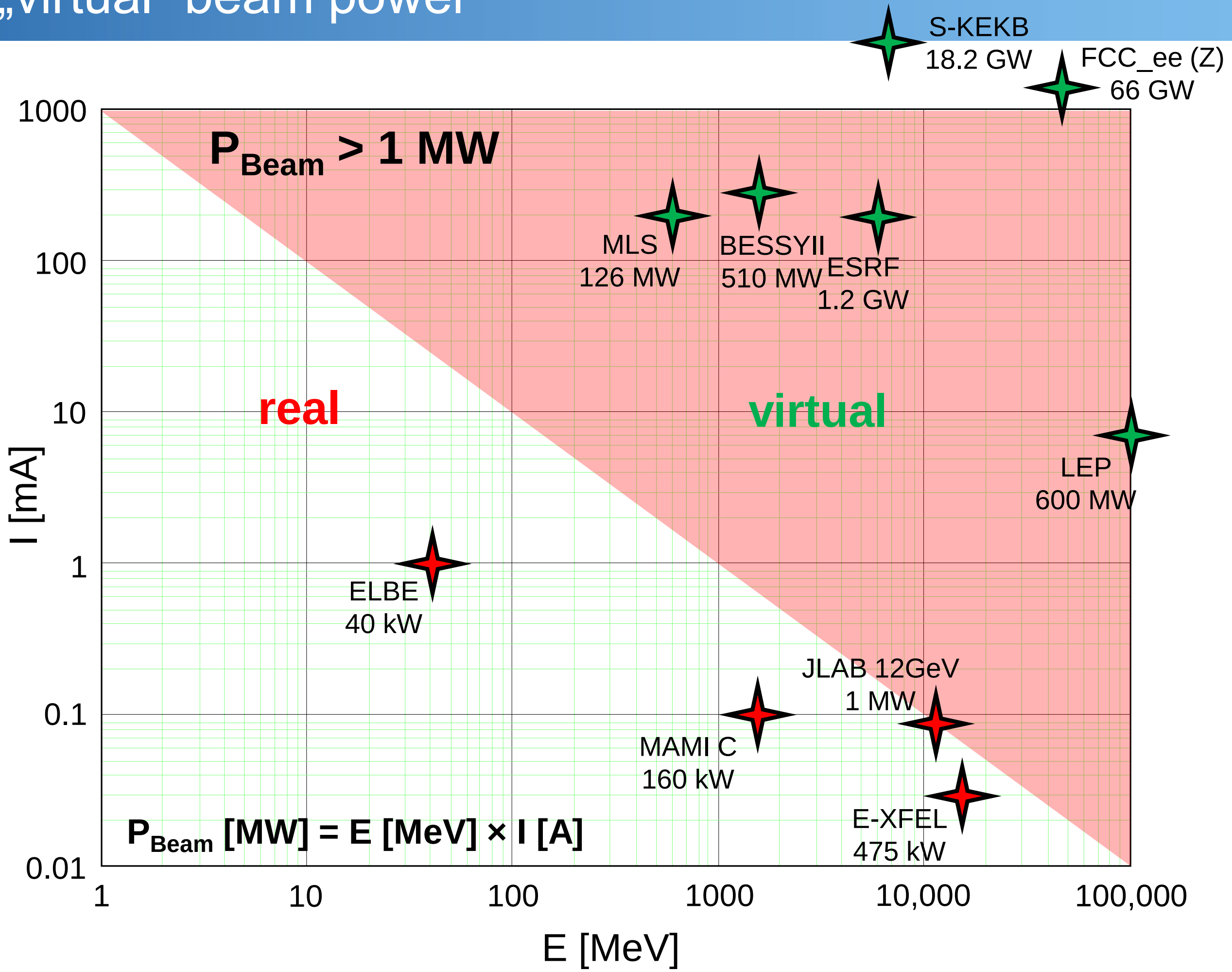


free electron laser, collider, fixed target

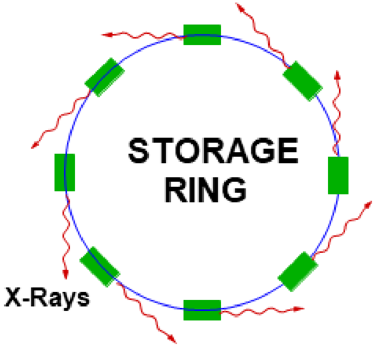
$$P_{real}[W] = E[eV] \cdot I[A]$$

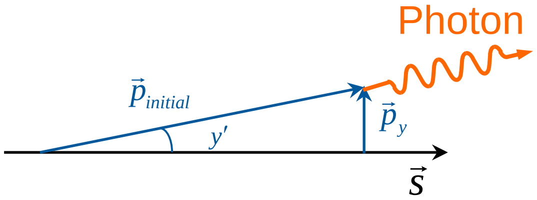
e.g. European XFEL, 1 Å hard X-ray source, ca. 3km length
17.5 GeV, 0.027 mA = 475 kW **real beam power**,
ca. 100 GW peak power in 100 fs, 10 x 2700 pps,
used FEL power ca. 300 W

real ↔ „virtual“ beam power

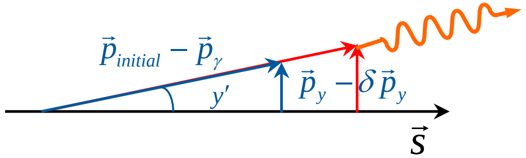


Storage ring – governed by equilibrium processes

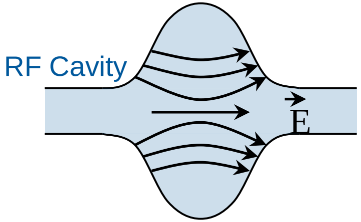




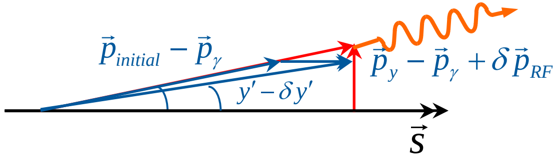
electron emits photon



looses momentum (also transversal)



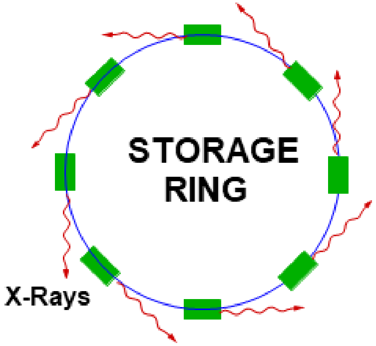
longitudinal momentum restored
in acceleration cavity



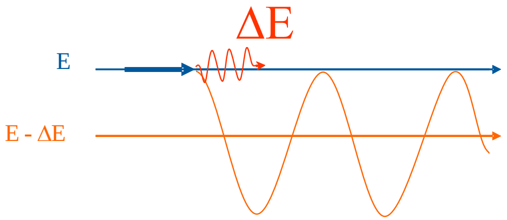
angle and displacement reduces
→ emittance shrinks

“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**



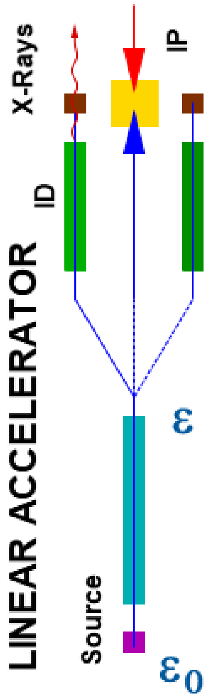
reference orbit

dispersion orbit for particle with energy deviation

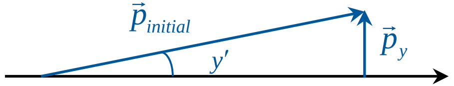
“heating” by synchrotron radiation

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).

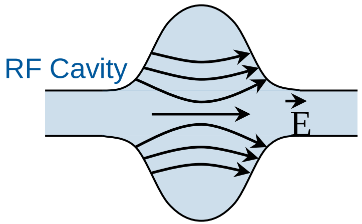
Linac – governed by adiabatic damping and control



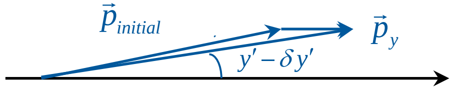
„adiabatic“ damping



electron has transversal momentum

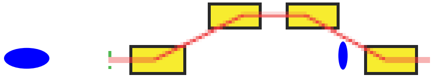


longitudinal component increases during acceleration



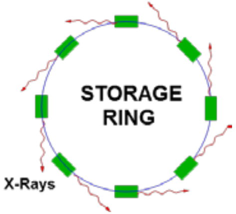
angle reduces with acceleration, emittance shrinks $\varepsilon = \frac{\varepsilon_0}{\gamma}$

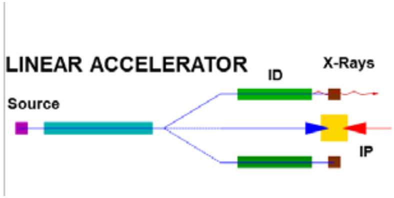
additional: bunch-length control by applying correlated energy chirp (off crest) and magnetic chicane with longitudinal dispersion



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

Storage ring versus Linac





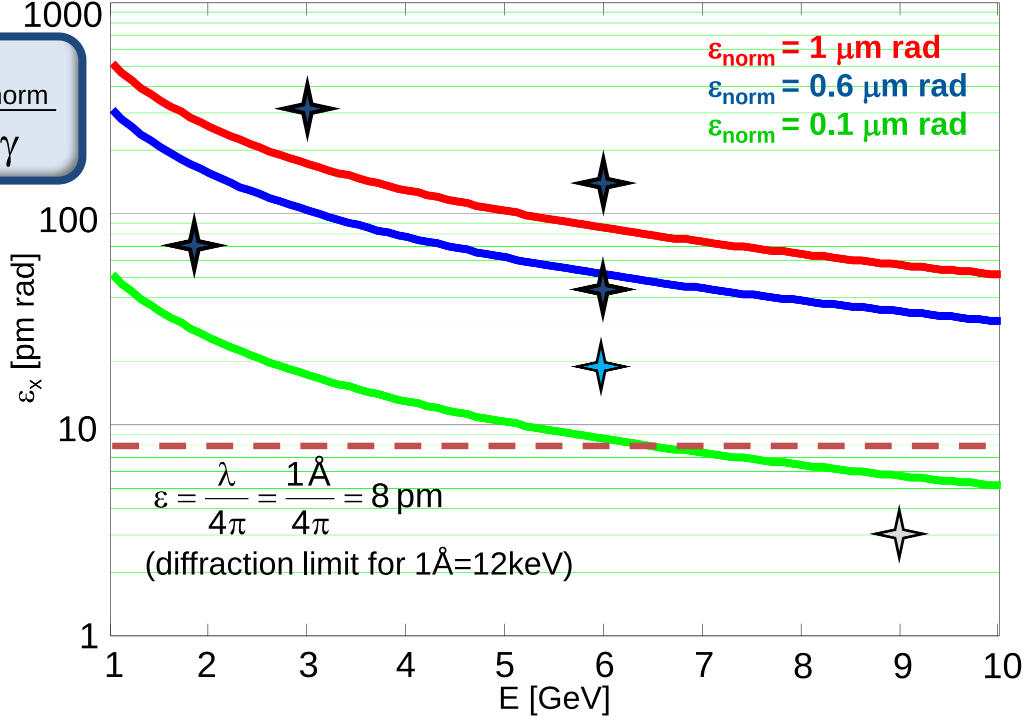
equilibrium beam parameters	**adiabatic damping + control**
$\varepsilon_x = C_\gamma \cdot \frac{\gamma^2}{J_x} \cdot \frac{\left\langle \frac{1}{R^3} H(s) \right\rangle}{\left\langle \frac{1}{R^2} \right\rangle} \sim \frac{\gamma^2}{N^3}, \varepsilon_y = \kappa \cdot \varepsilon_x$	$\varepsilon_{x,y} = \frac{\varepsilon_0}{\gamma}$
$\frac{\sigma_E}{E} \sim \frac{\gamma'}{\sqrt{R}}$	$\left(\frac{\sigma_E}{E}\right)_0 \sim \frac{1}{\gamma}$
$\sigma_s \sim \sqrt{\frac{\alpha}{V'}} \cdot \sigma_E$	$\sigma_s = f(\sigma_0)$ 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)

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



$$\varepsilon = \frac{\lambda}{4\pi} = \frac{1\text{Å}}{4\pi} = 8\,\text{pm}$$

(diffraction limit for 1Å=12keV)

MBA
ultra low emit.
lattices:

320 pm, MAX IV
(in operation since 2016)

135 pm, ESRF II
(commissioning started 2019)

46 pm, APS-U
(realisation phase, CD03 decision)

< 85 pm, ALS-U
(realisation phase, CD03A decision)

< 20 pm, PETRA IV
(CDR 2019)

3 pm, tUSR
(design study)

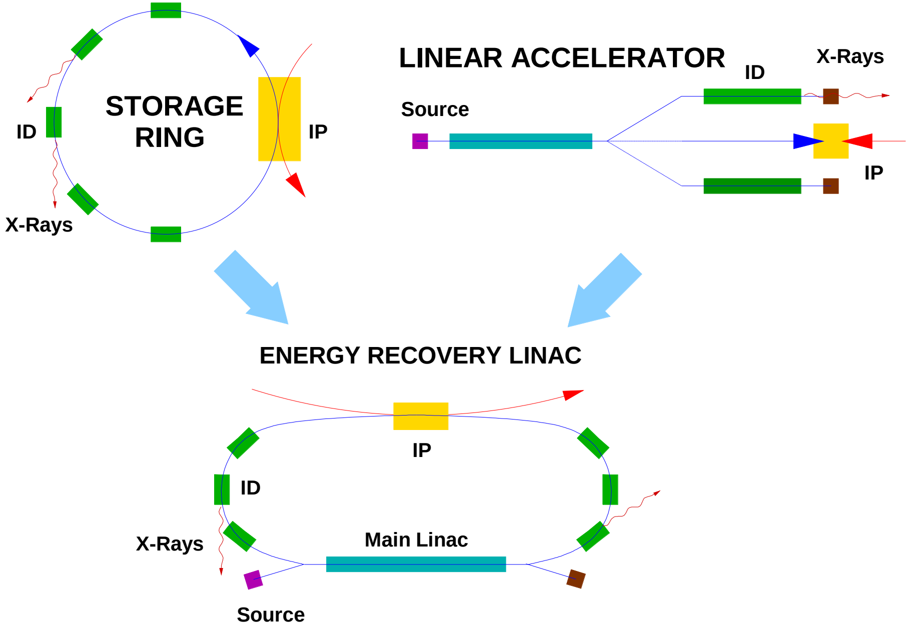
Storage rings: low emittance goes hand in hand with necessity to operate with long bunches (up to some 100 ps) to reduce Touschek and IBS scattering!

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)

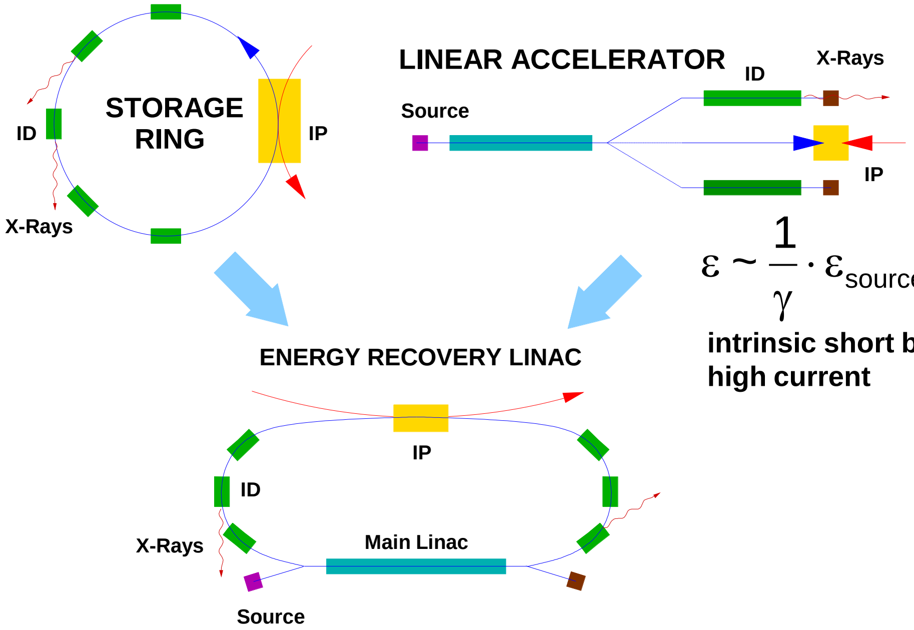
- outstanding beam parameter
- single pass experiments
- high flexibility
- low number of user stations
- limited average beam power (<<mA)

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

Energy Recovery Linacs – The idea



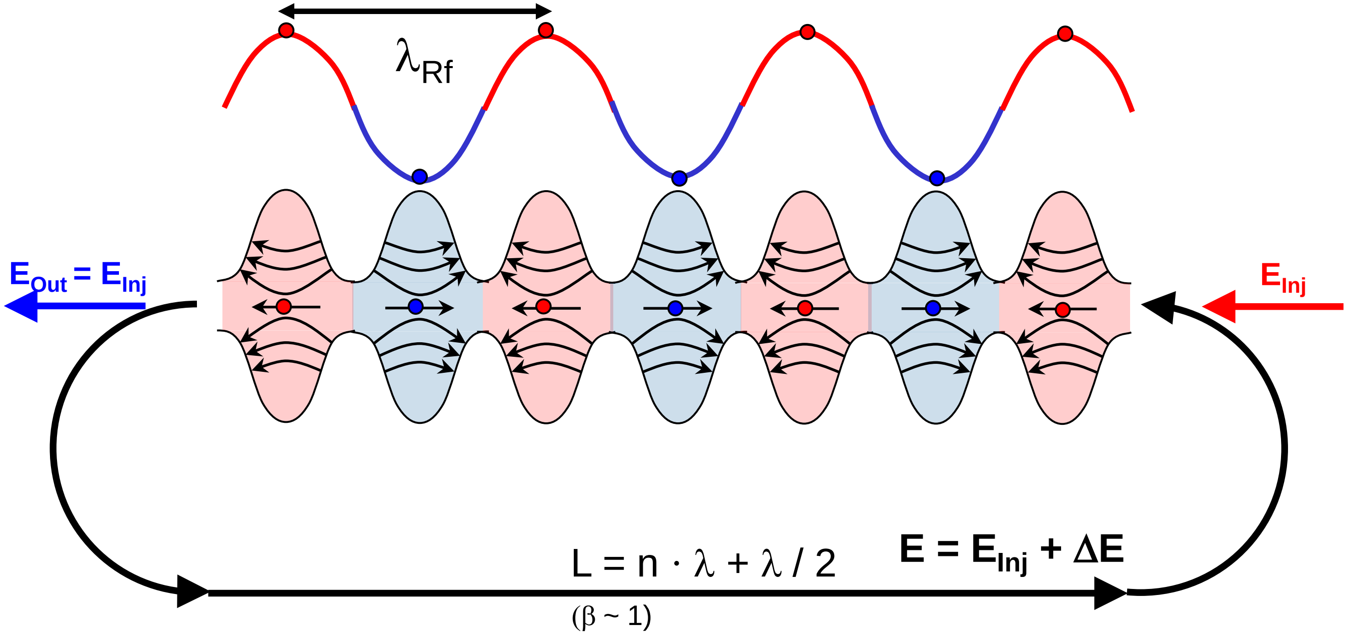
$$\varepsilon \sim \frac{1}{\gamma} \cdot \varepsilon_{\text{source}}$$

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 in RF-fields

RF linear accelerator



Energy supply = acceleration

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

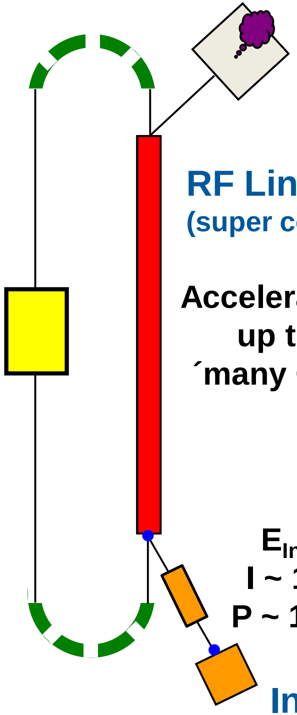
→ Energy recovery = deceleration

The Energy Recovery Linac Principle

**„experiment“
needs
„virtual“ power
MW to GW**

and

**an always
„fresh“ beam**



Dump

**E_{dump} ~ 10 MeV
I ~ 10 mA – 1 A
P ~ 100 kW - MW**

**RF Linac
(super conducting)**

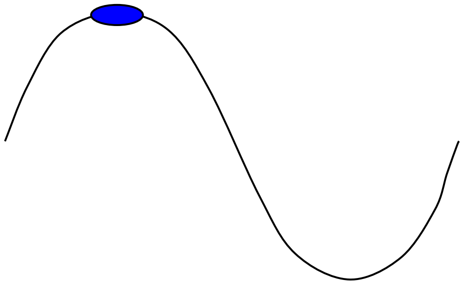
**Acceleration
up to
´many GeV**

**E_{Inj} ~ 10 MeV
I ~ 10 mA – 1 A
P ~ 100 kW - MW**

Injector

**acceleration
energy transfer**

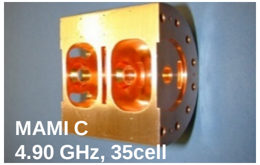
E ↑



E ↓

**deceleration
energy recuperation
transfer to accelerated beam**

ERLs are in favor of superconducting (SC) RF (or SRF)

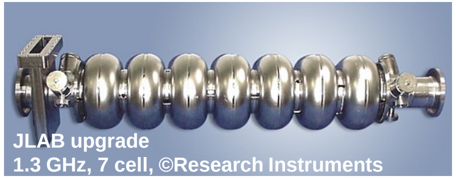


MAMI C
4.90 GHz, 35cell

normal conducting = NC (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)



JLAB upgrade
1.3 GHz, 7 cell, ©Research Instruments

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

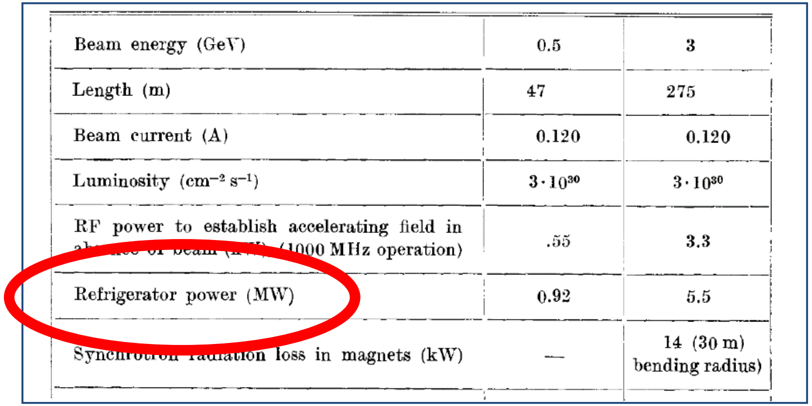
ΔE ~ 20 MV/m / P_{RF} ~ 20 W/m (CW)
(JLAB upgrade: 19.2 MV/m)
large apertures (70mm+) and low number of cells allows efficient HOM damping

SC RF allows to built an ERL “compact” (high gradient)
for high current cw operation (large apertures, strong HOM damping)

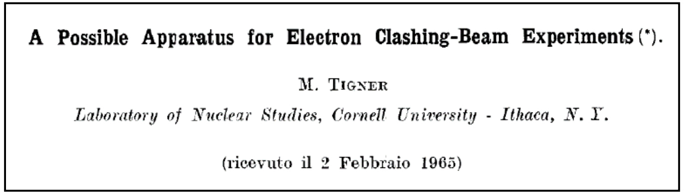
Wall plug power consumption shifts from RF to Cryo (2K efficiency ~ 1/1000)
ERL is not necessarily a “green machine”

History – First idea

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



Beam energy (GeV)	0.5	3
Length (m)	47	275
Beam current (A)	0.120	0.120
Luminosity (cm^{-2} s^{-1})	$3\cdot10^{30}$	$3\cdot10^{30}$
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)

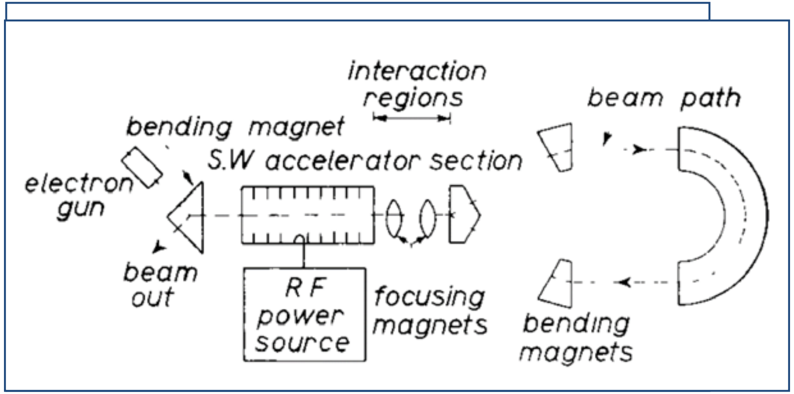


A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

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

(ricevuto il 2 Febbraio 1965)



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

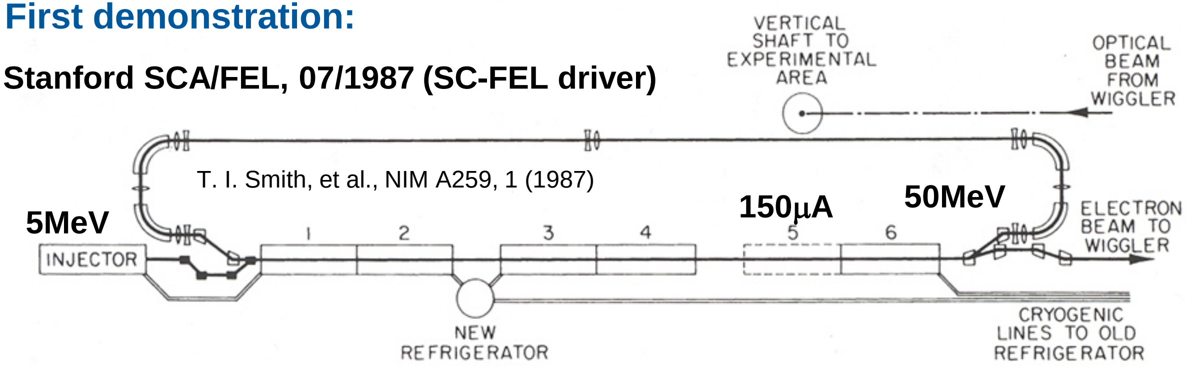
Maybe first realisation
(1977, without taking attention to it):
Reflexotron (two pass linac) for
medical application
(Chalk River, Canada)

S.O. Schreiber, IEEE NS-22 (1975) (3) 1060-1064

History – First demonstration

First demonstration:

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



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

5MeV

150μA

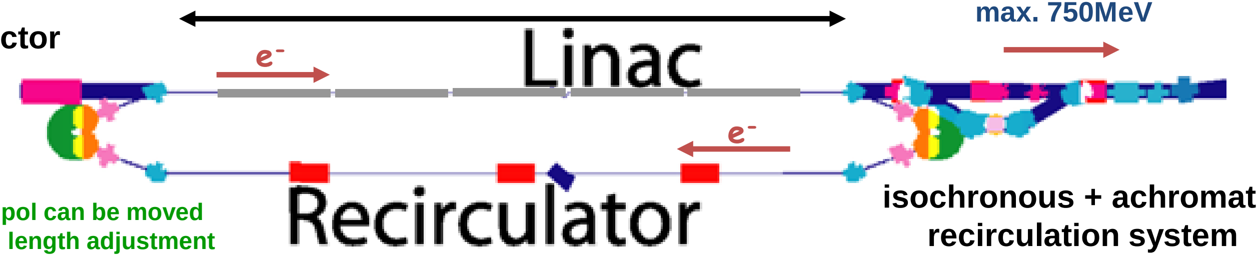
50MeV

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

200m, max. 400MeV

Injector

max. 750MeV



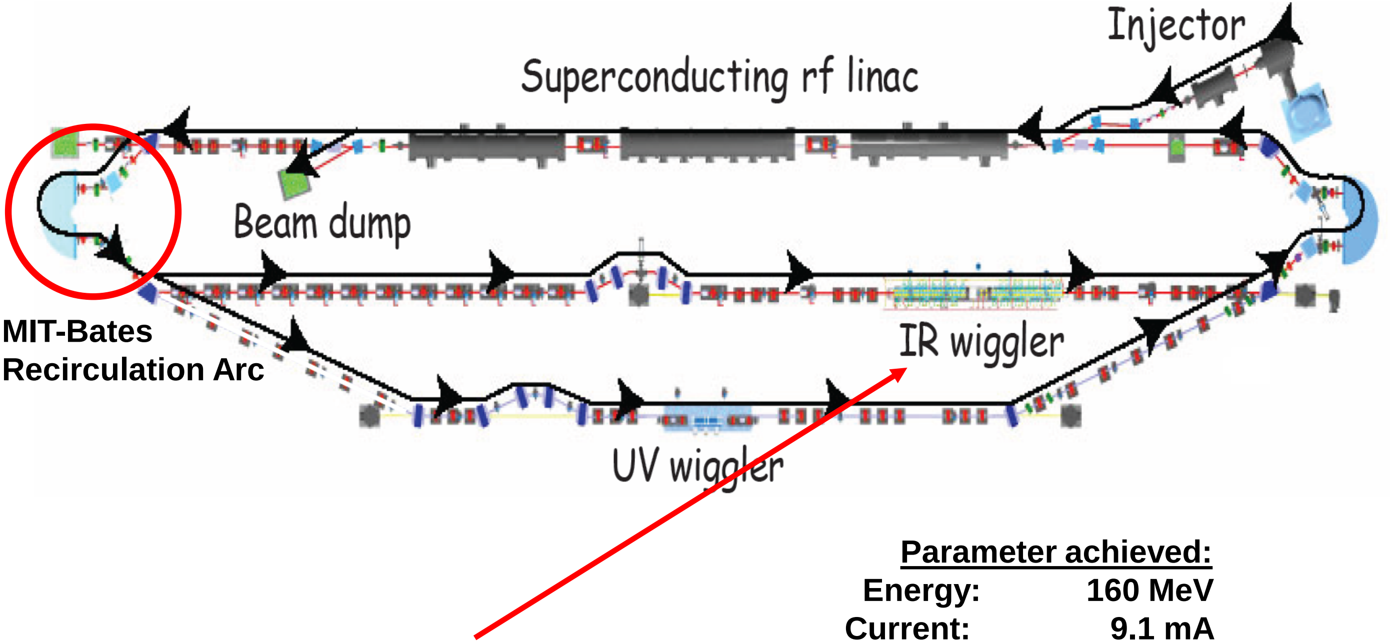
180° dipol can be moved for path length adjustment

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

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

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

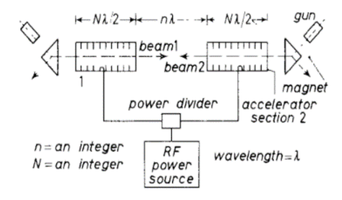
Parameter achieved:

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

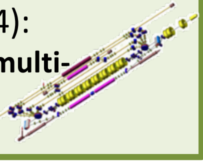
emittance (norm.): 7 μm
min. pulse length: 150 fs

Overview on projects and facilities

First idea:
M. Tigner (1965)

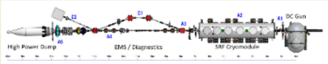


BINP FEL (2004):
First multi-turn ERL



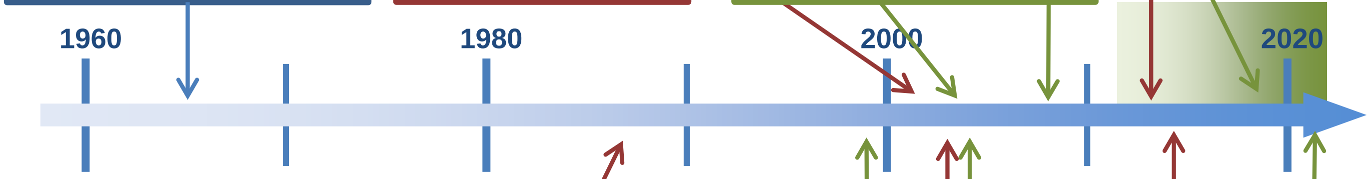
CBETA (2016)
FFAG ERL
(with BNL)

Cornell University
Injector Teststand



BNL R&D ERL
Beijing ERL-FEL

JAERI FEL (2002):
17 MeV, 5 mA

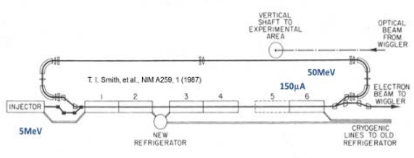


ALICE, Daresbury

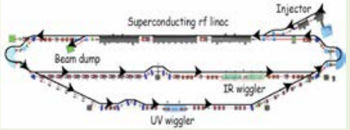
PERLE@ORSAY (?)

CERN, JLAB, Daresbury, BINP, LAL

First energy recovery:
Stanford SCA/FEL (1987)

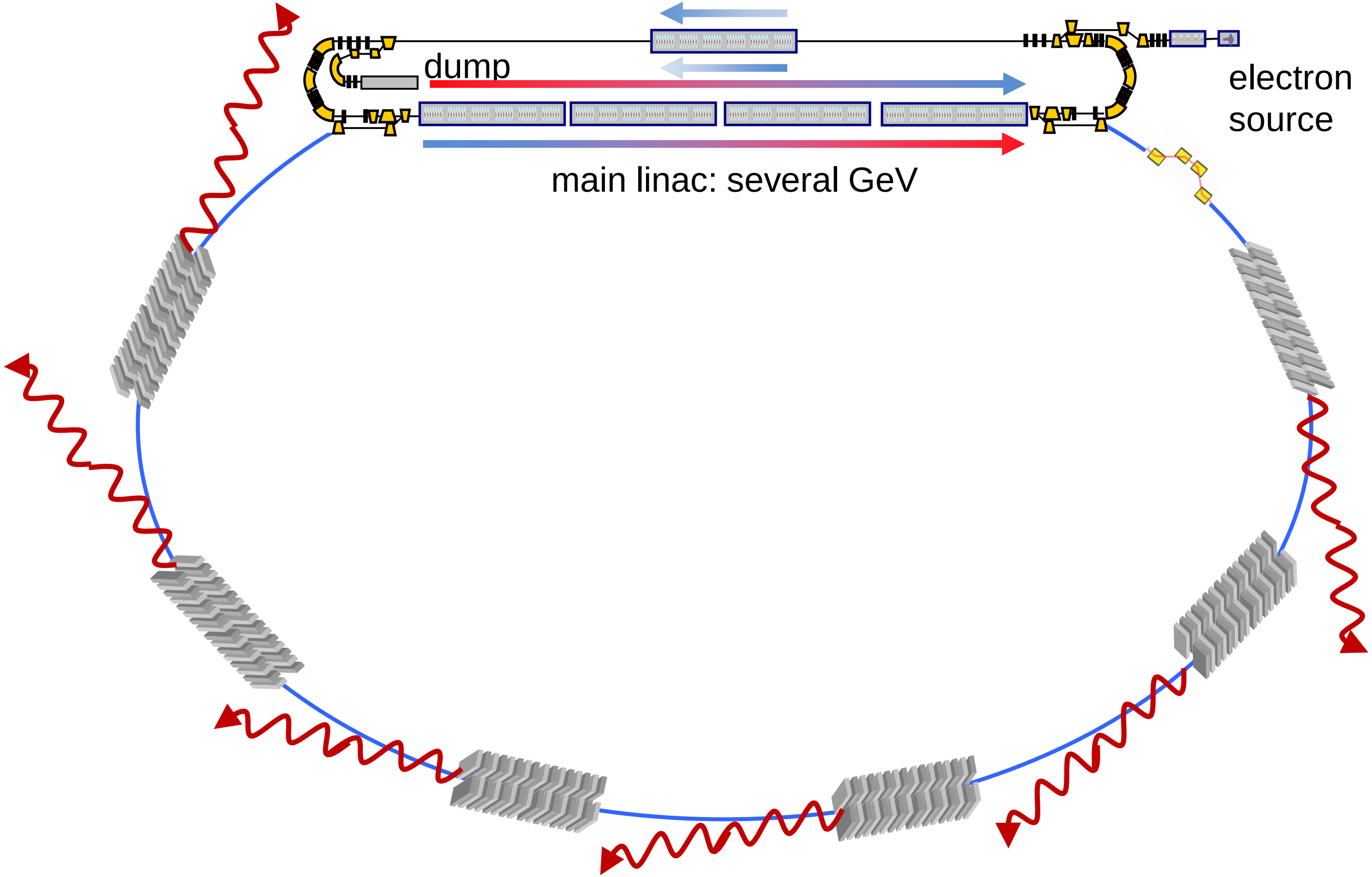


JLAB-FEL: Demo-FEL (1999)
& FEL Upgrade (2004)

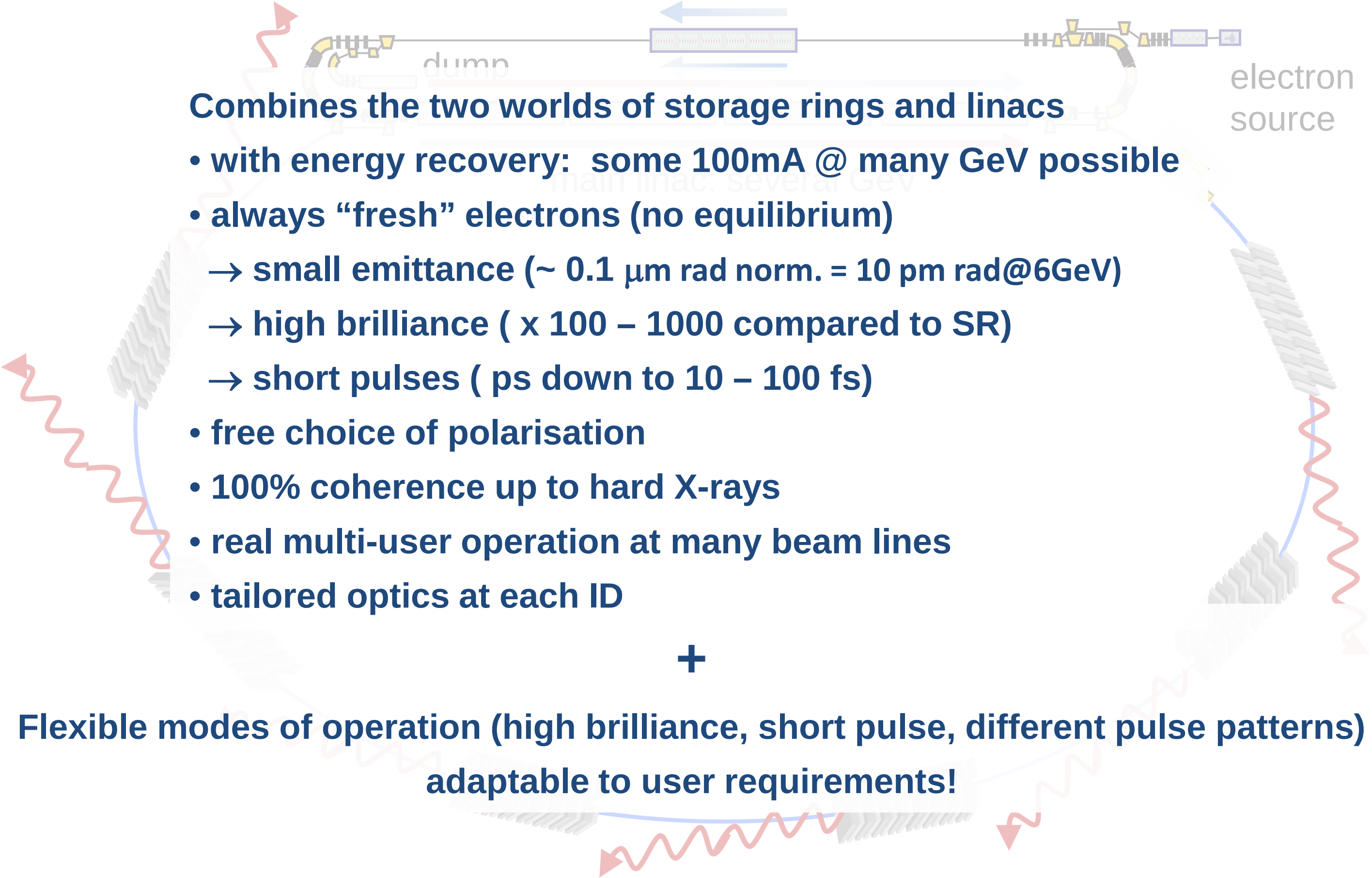


KEK cERL (2014):
recirc. & energy recovery

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



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



Combines the two worlds of storage rings and linacs

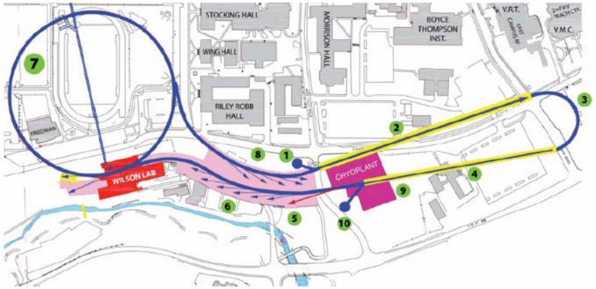
- **with energy recovery: some 100mA @ many GeV possible**
- **always “fresh” electrons (no equilibrium)**
  - **→ small emittance (~ 0.1 μm rad norm. = 10 pm rad@6GeV)**
  - **→ high brilliance (x 100 – 1000 compared to SR)**
  - **→ short pulses (ps down to 10 – 100 fs)**
- **free choice of polarisation**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

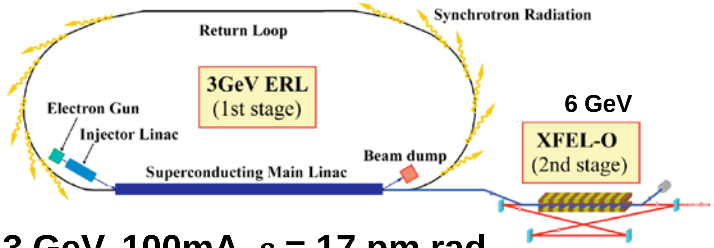
Cornell ERL



5 GeV, 100mA, ε = 8 pm rad

(ε_{norm} = 0.08 μm (@77pC) , 2ps)

KEK ERL

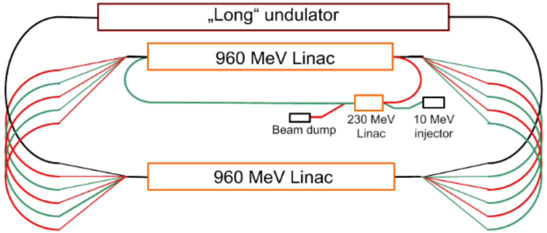


3 GeV, 100mA, ε = 17 pm rad

(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

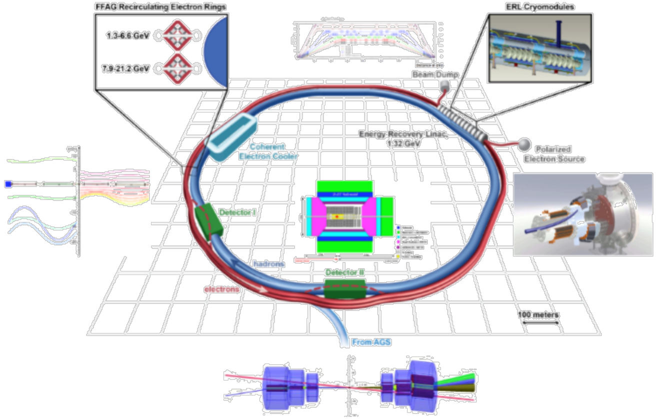
(ε_{norm} = 0.1/0.5 μm (@15/4 pC), < 1 ps / 10 fs)

ELR as electron part of Electron Ion Collider

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

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

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

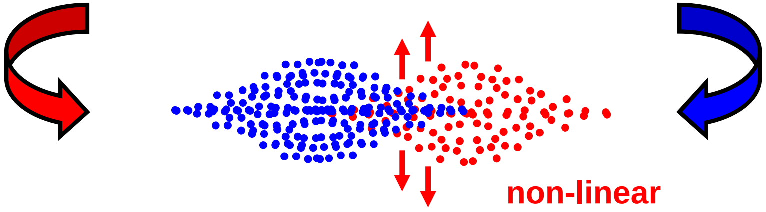


Why ERL and not storage ring?

Luminosity

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

Limit (in storage rings): beam-beam parameter electrons (!)



non-linear interaction

ELR as electron part of Electron Ion Collider

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

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

(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

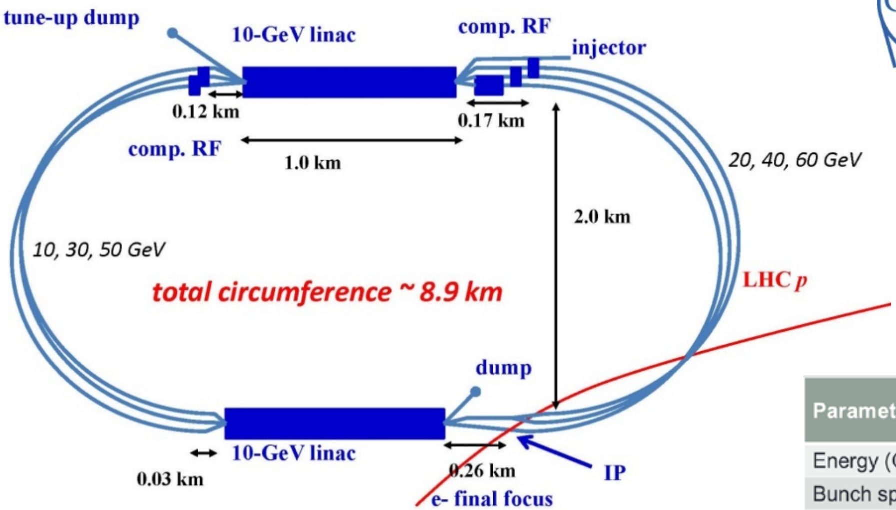
$$L = f_{\mathrm{coll}} \cdot \frac{n_{\mathrm{Ion}} \cdot n_e}{4 \cdot \pi \cdot \varepsilon \cdot \beta} \cdot F_{\mathrm{HGR}}$$

Limit (in storage rings): beam-beam parameter electrons (!)

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

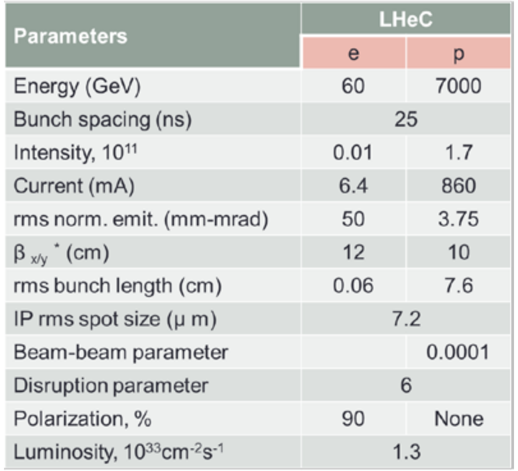
ELR as electron part of Electron Ion Collider

60 GeV (e) x 7 TeV (p)



CERN

LHeC

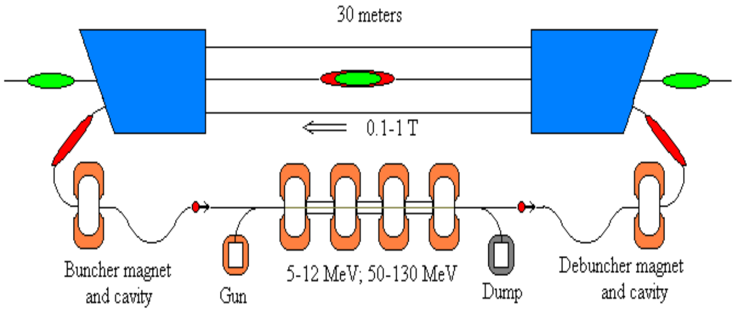


Parameters	LHeC	
	e	p
Energy (GeV)	60	7000
Bunch spacing (ns)	25	
Intensity, 10^{11}	0.01	1.7
Current (mA)	6.4	860
rms norm. emit. (mm-mrad)	50	3.75
$\beta_{x/y}^{*}$ (cm)	12	10
rms bunch length (cm)	0.06	7.6
IP rms spot size (μ m)	7.2	
Beam-beam parameter		0.0001
Disruption parameter	6	
Polarization,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

ELR as electron cooler

BROOKHAVEN NATIONAL LABORATORY

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



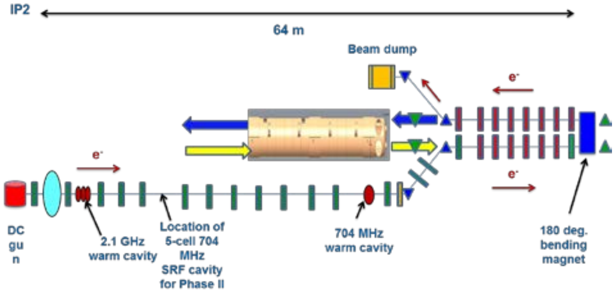
Efficient cooling needs

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

54.5 MV and A class currents not feasible with electrostatic accelerators

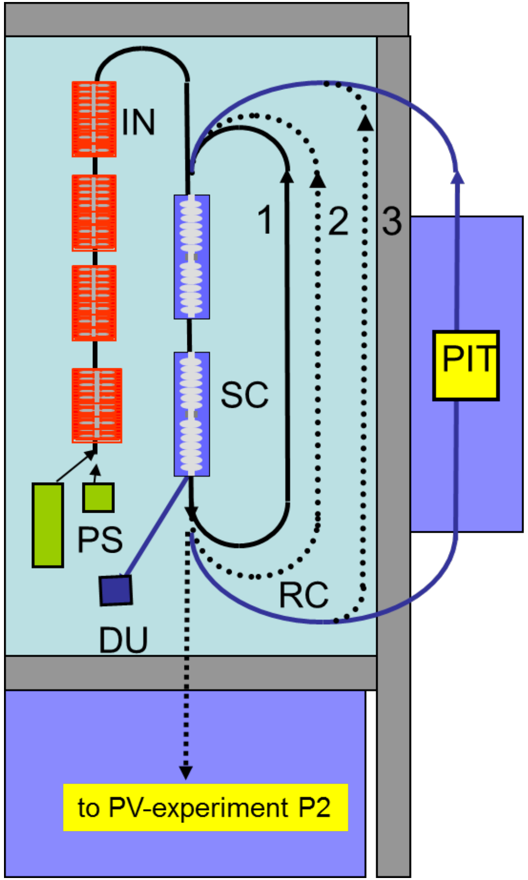
ERL cooler needs overlap of (many “short”) electron bunches with (“long”) ion bunches

(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

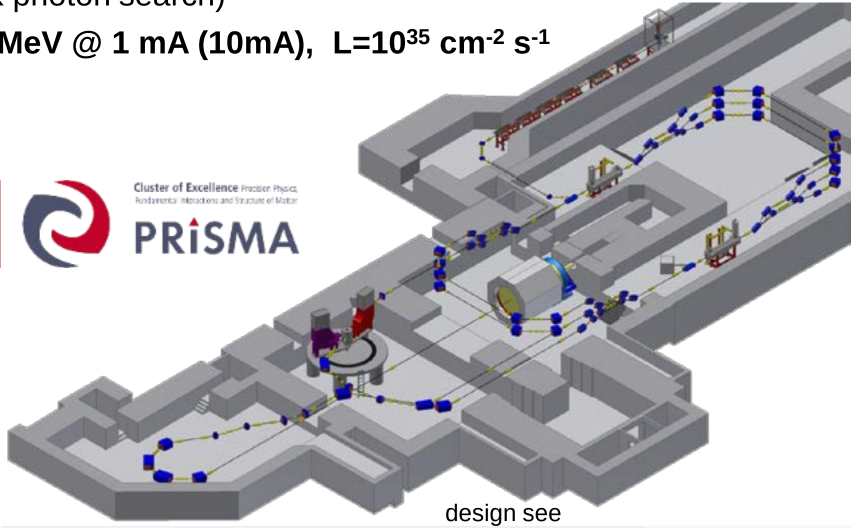
Multi turn ERL for

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 2019 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

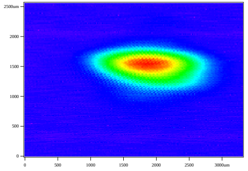
Beam dynamics / optics:

recirculation, flexible optics, bunch compression schemes = flexibility

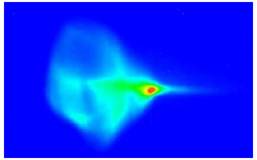
Control of beam loss

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

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



ERL:
no dead mathematician
distribution
~ 100 μA losses possible



The “hummingbird”
P. Evtushenko, JLAB

Demonstrator projects world-wide

cERL, KEK + JAEA

35 MeV, 10 mA

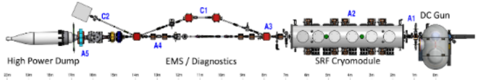
- 1 mA reached 2016 –

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

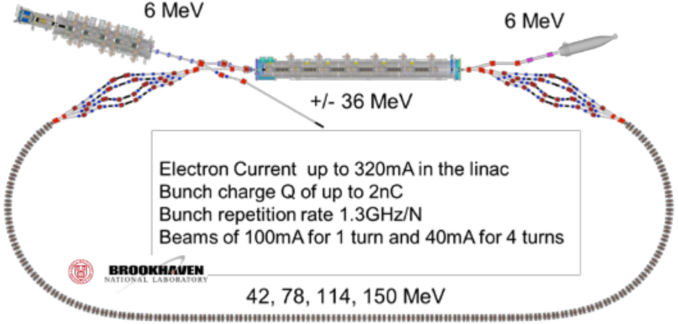
CeC project

CBETA FFAG ERL, Cornell/BNL

150 MeV (4 turns), 40 mA

- funded, under construction since 2016

- four-turn ER demonstrated in 2019

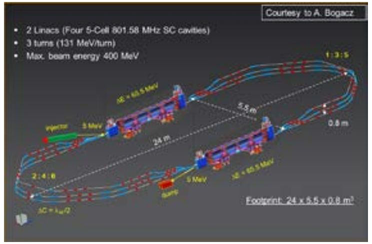


Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

PERLE@ORSAY

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

- CDR in 2017, to be funded –



Courtesy to A. Bogacz

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (131 MeV/turn)
- Max. beam energy 400 MeV

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

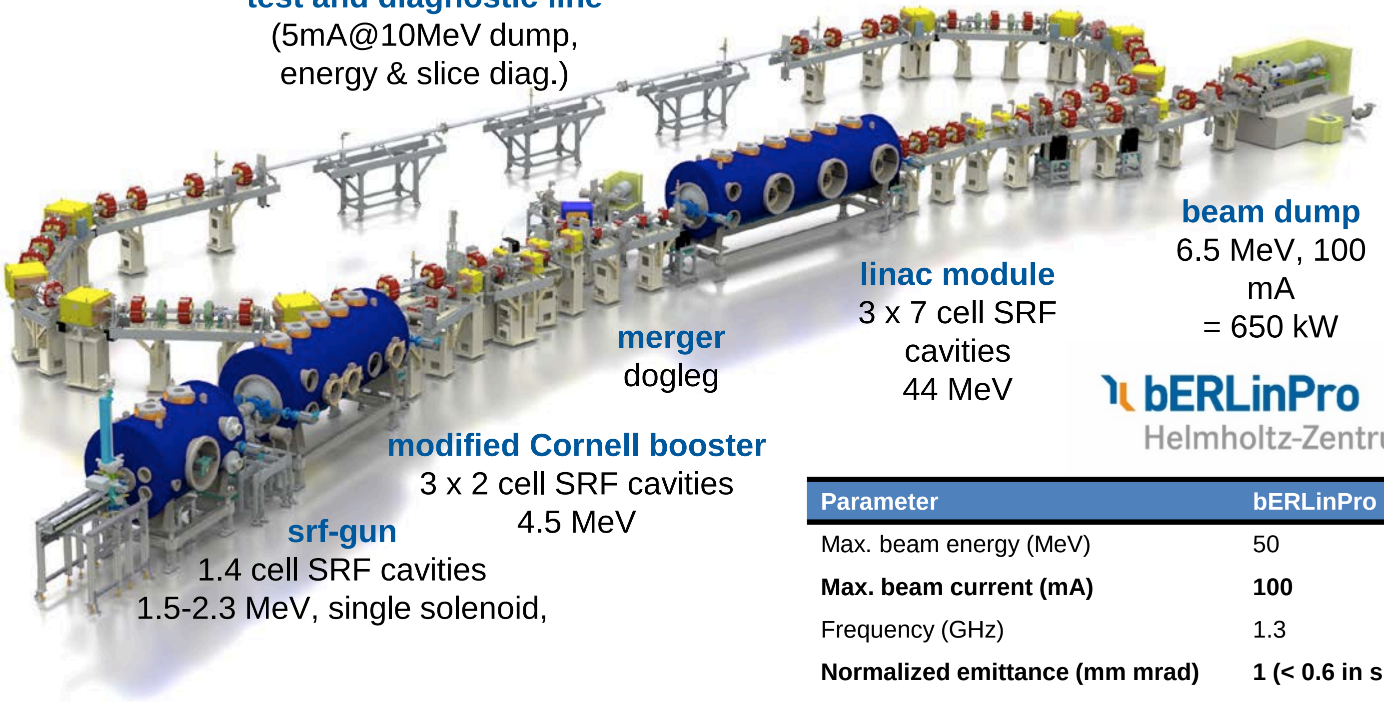
CERN
JLAB,
Daresbury / U Liverpool
BINP

all based on DC photo electron sources

bERLinPro – Berlin Energy Recovery Linac Project (fully SC)

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

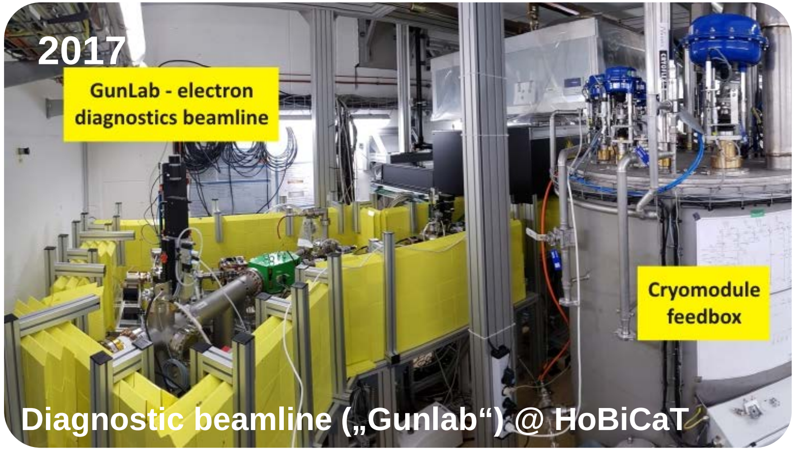
modified Cornell booster
3 x 2 cell SRF cavities
4.5 MeV

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

bERLinPro
Helmholtz-Zentrum Berlin

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

First beam tests of the bERLinPro SRF photo-injector

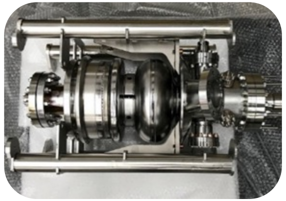


2017

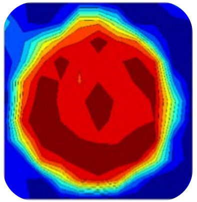
GunLab - electron diagnostics beamline

Cryomodule feedbox

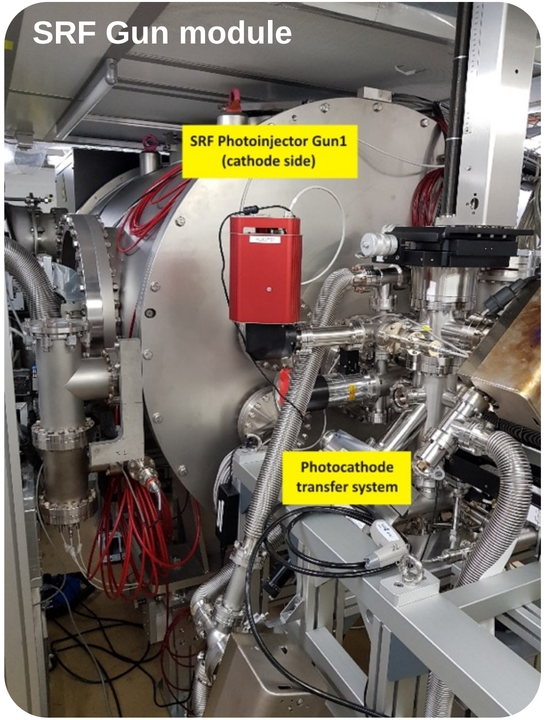
Diagnostic beamline („Gunlab“) @ HoBiCaT



First beam 12/2017



QE map Cu cathode



SRF Gun module

SRF Photoinjector Gun1 (cathode side)

Photocathode transfer system

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 ☹

High QE photo cathodes & drive laser development

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

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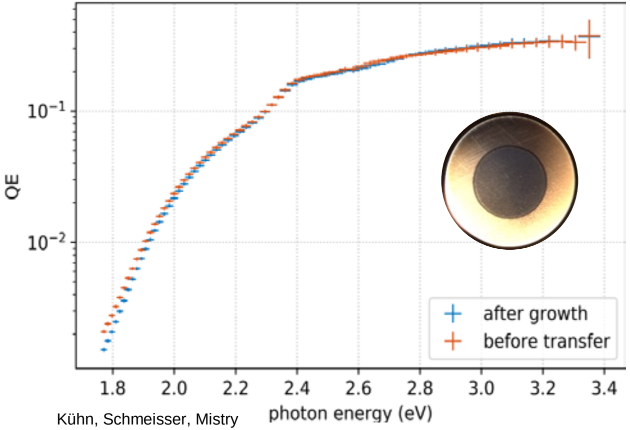
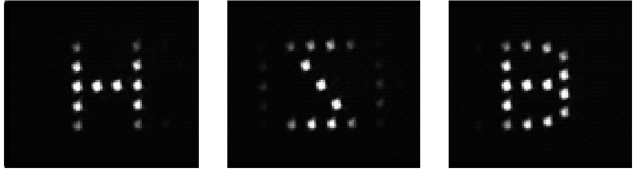
MAX-BORN-INSTITUT

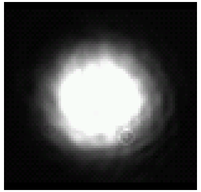
Sepctral response photocathode P017



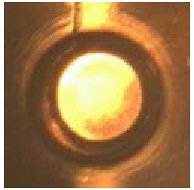
Kühn, Schmeisser, Mistry

Klemz, Ohm-Krafft

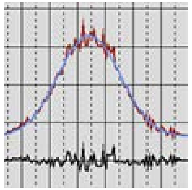




Virtual cathode



Real cathode



Laser pulse length

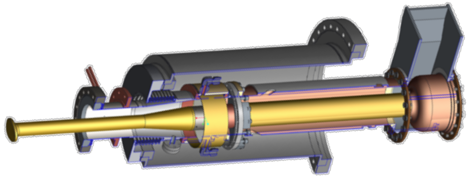
Photocathode preparation and analysis laboratory up and running since 2015

- insight into growth process with material science studies in parallel
- **achieved quantum efficiency of 16.8% at 515 nm (spec is 1%) with CsKSb**
- 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!)

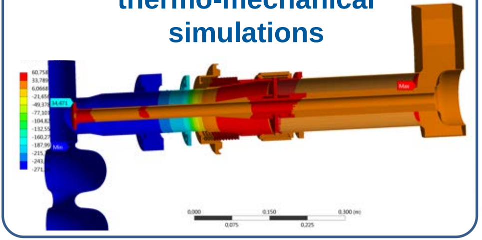
Technological Challenges - high current booster module

- 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) / strong HOM damping
- High power RF coupler for up to 120 kW CW
- Coupler production: warm parts - FMB (Berlin) / cold part – Toshiba/Canon (Japan)

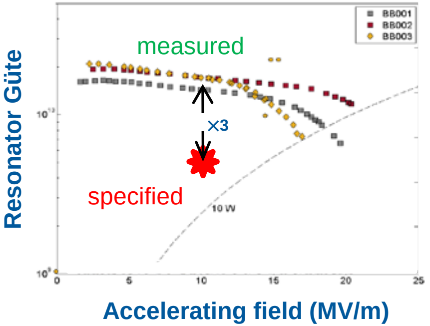
RF coupler design @ HZB

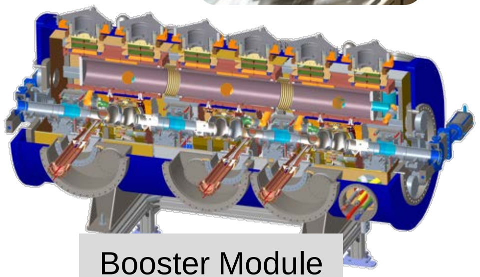


thermo-mechanical simulations




2 cell SRF booster cavity





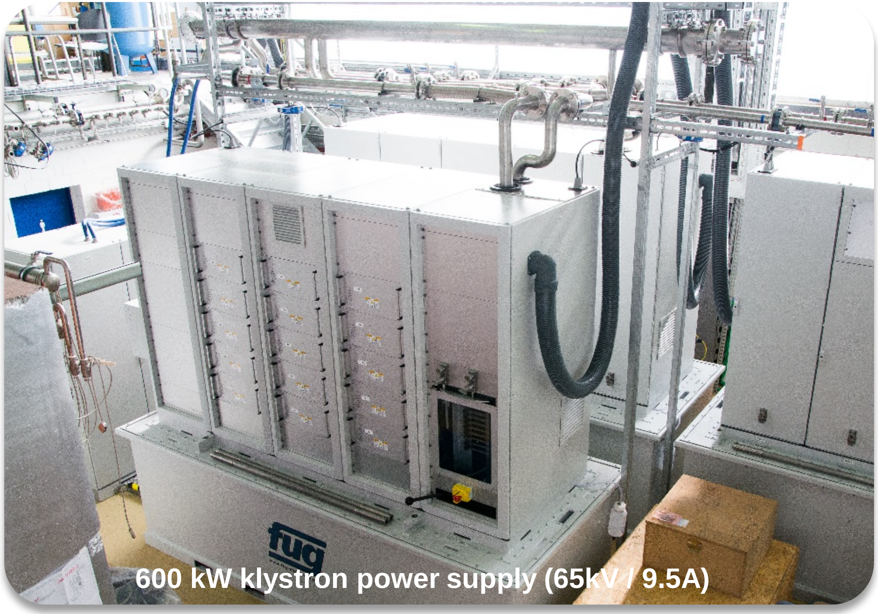
Booster Module
3 x 2 cell cavity

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 out future SupraLab@HZB infrastructure
- klystrons tested up to max power @ bERLinPro

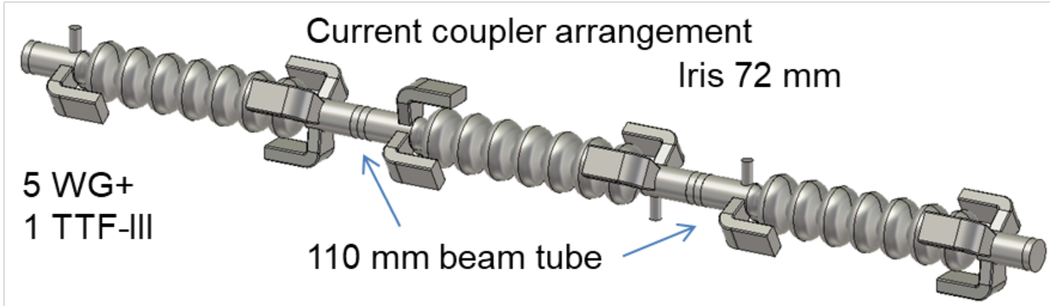
270 kW klystron

(incl. Circulator + load)

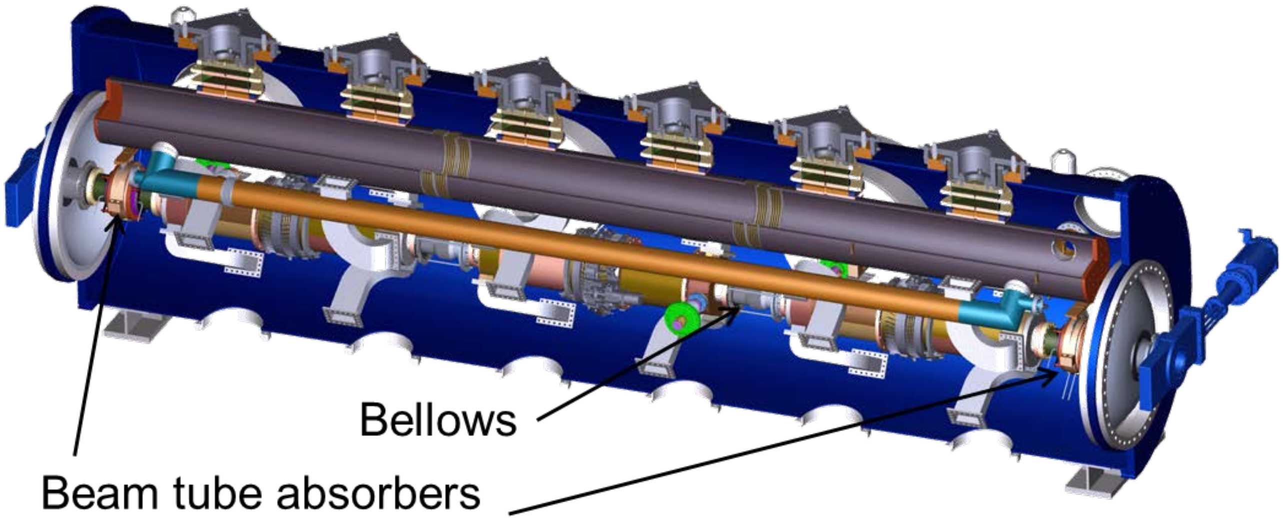


600 kW klystron power supply (65kV / 9.5A)

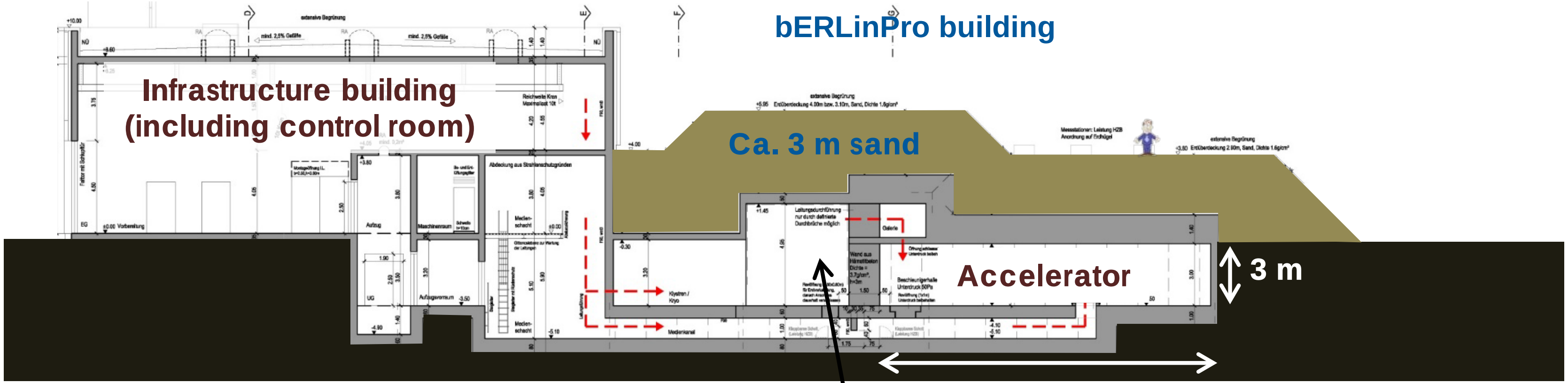
Technological Challenges – HOM damped, high current linac module



- 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



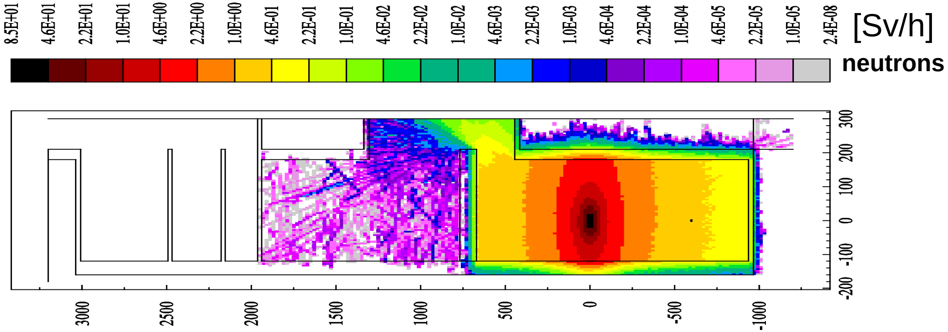
Radiation protection for ERL – shielding neutrons



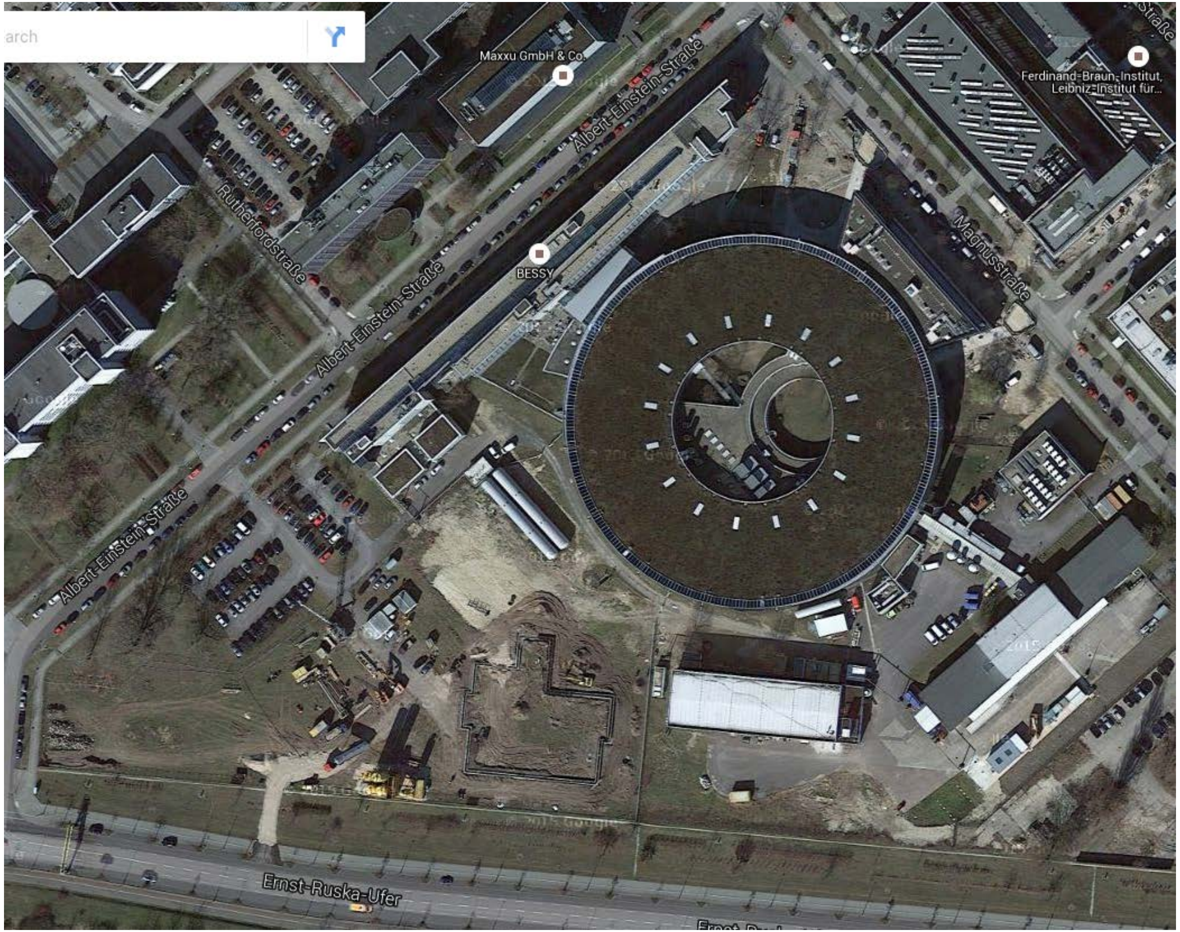
Partially shielded ante-room for equipment close to the accelerator (klystron, cold-compressor for cryogenics)

Fluka calculations (K. Ott, HZB)

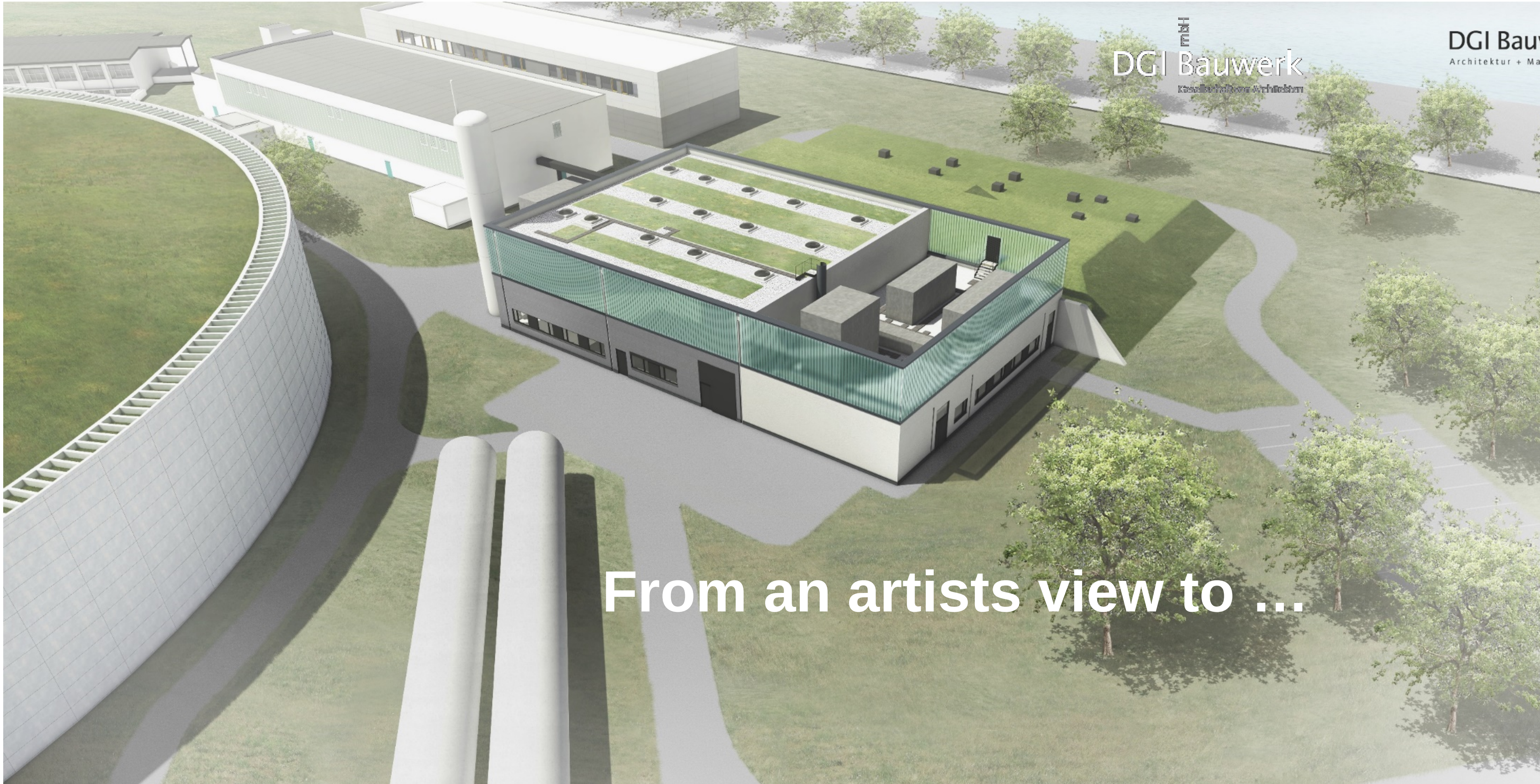
50 MeV, 100 mA = 5 MW
→ kW losses easily possible



bERLinPro building construction started 02/2015



bERLinPro Building



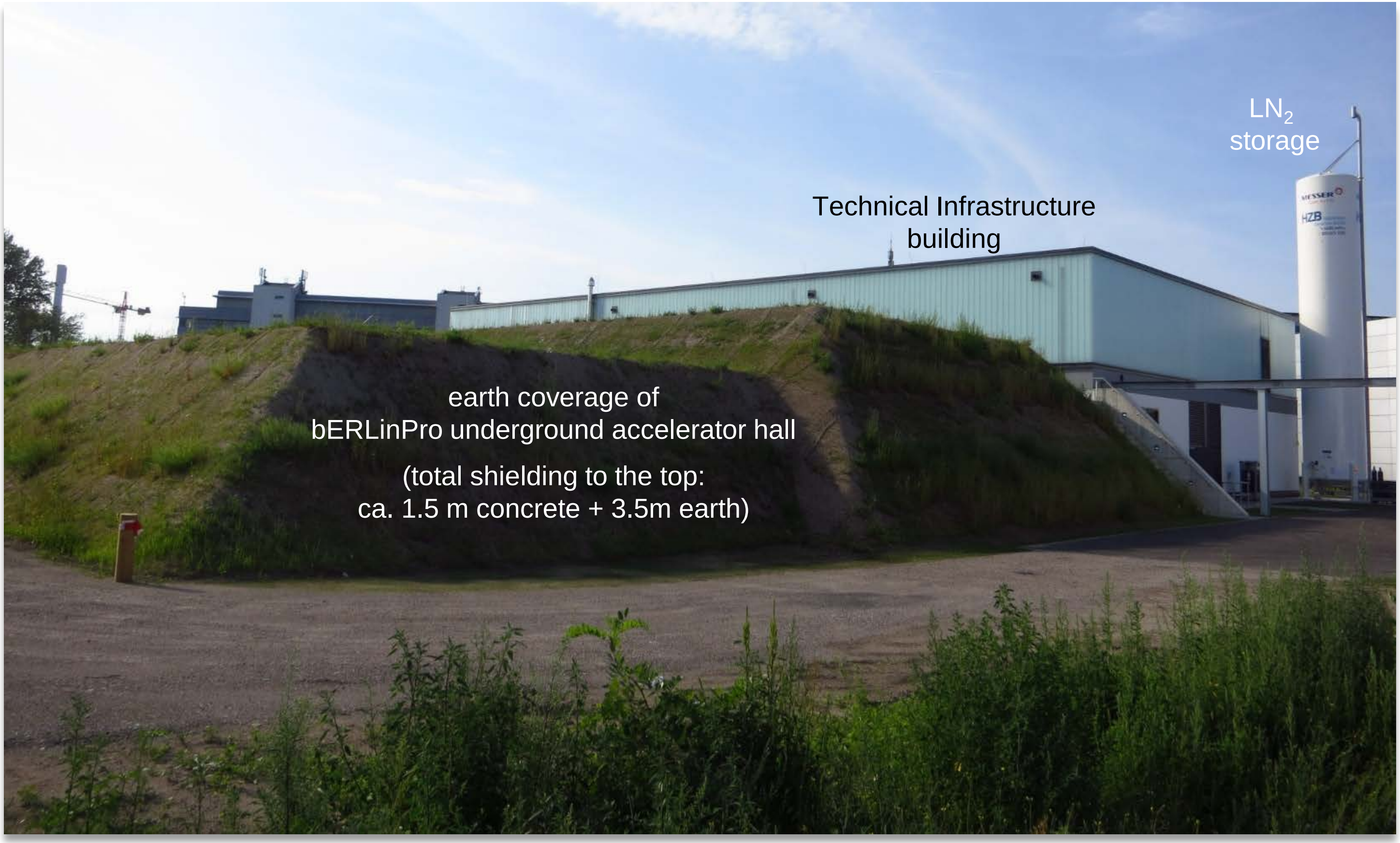
From an artists view to …

bERLinPro Building

view north-west

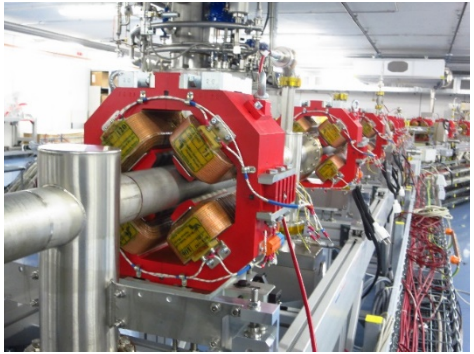
bERLinPro Building

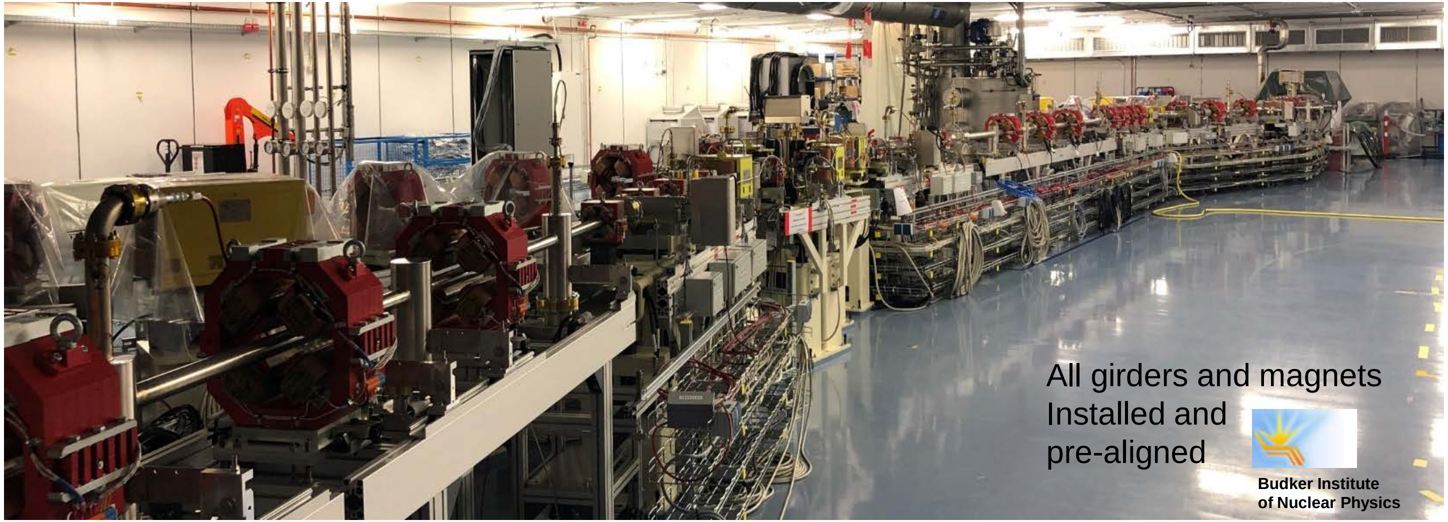
view south-east



Underground accelerator hall – 12/2016

Underground accelerator hall – machine installation in full swing

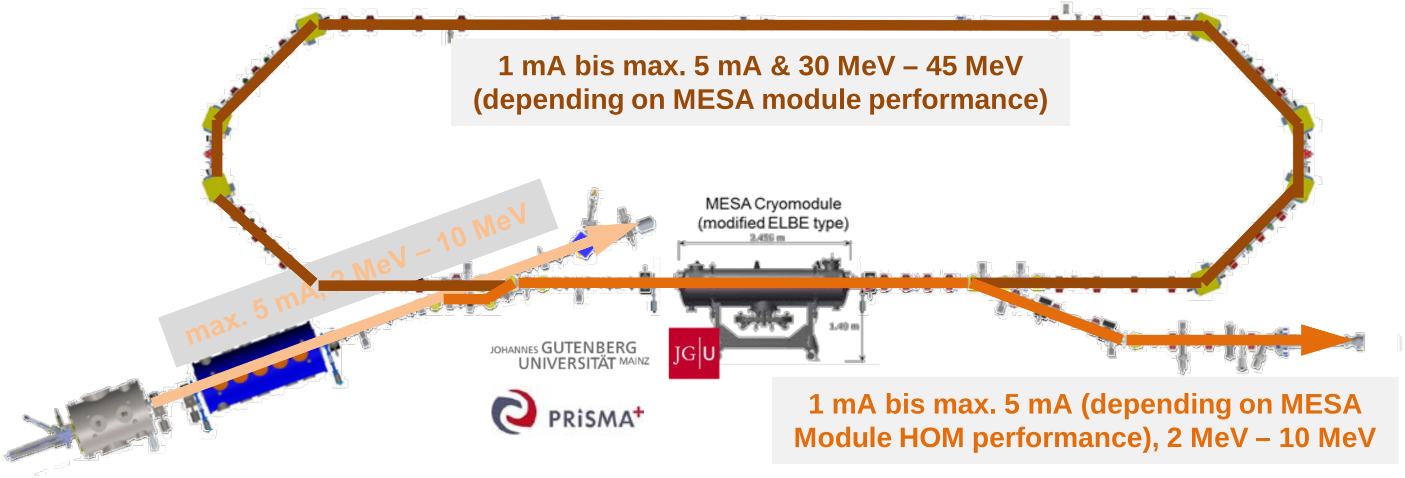




All girders and magnets
Installed and
pre-aligned

Budker Institute
of Nuclear Physics

Present planning – recirculation in collaboration with MESA@JGU



11/2020 Gun1 cool down and RF commissioning

11/2020 start installation of re-circulator vacuum (to be finished 03/2021)

04/2021 booster module installed

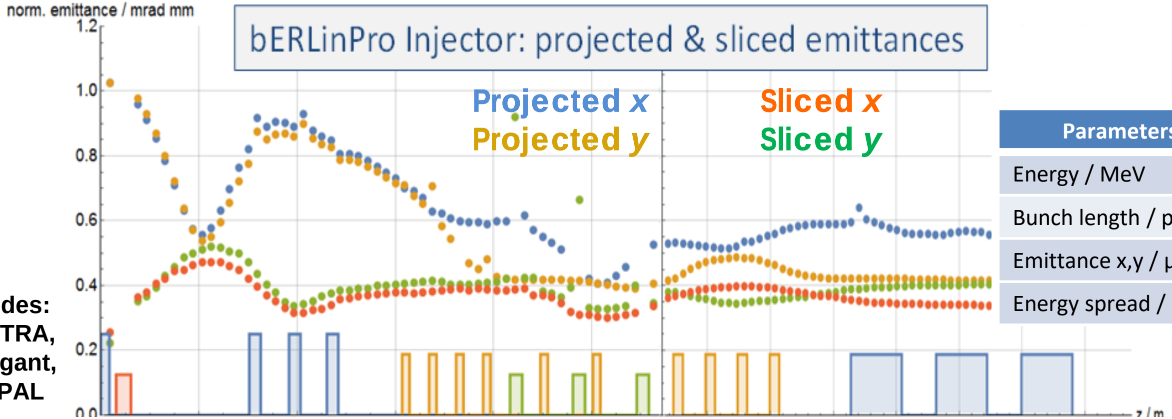
06/2021 MESA module installed (collaboration JGU Mainz, 2 x 9 cell)

09/2021 First beam possible, with subsequent re-circulation + recovery

Re-circulation test period limited, as MESA module need to be back in Mainz 12/2022
Funding for 2000 h / a of operation secured till end of 2022.

And suddenly all of our time planning became obsolete!

bERLinPro – performance parameter (simulations)

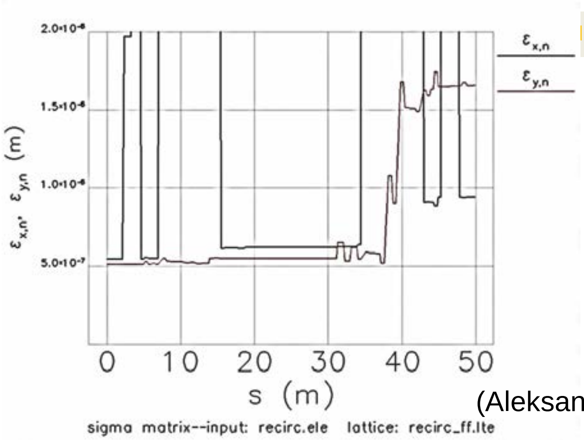


Parameters at LINAC exit	
Energy / MeV	50.1
Bunch length / ps	4.65
Emittance x,y / µm	0.58/0.41
Energy spread / keV	254

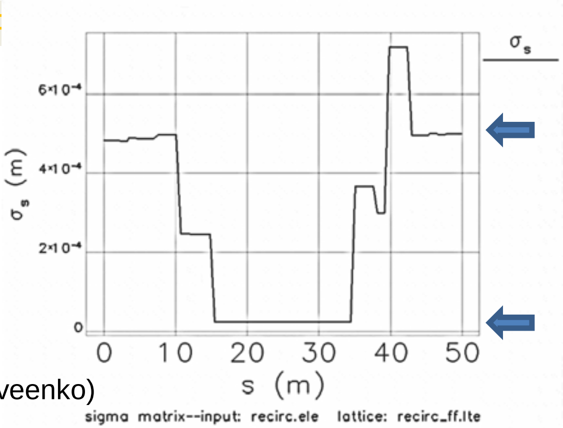
codes: ASTRA, elegant, OPAL

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

adrupc



(Aleksandr Matveenko)



2 ps (=0.6 mm)

< 100 fs (=0.03 mm)

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

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

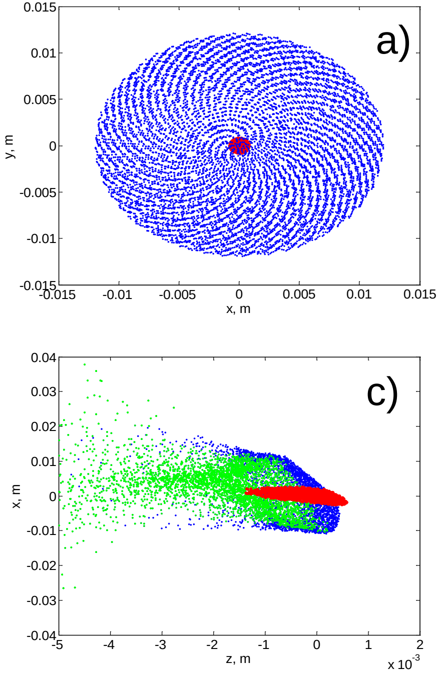
Unwanted beam workshop, Helmholtz-Zentrum Berlin, 2012

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,

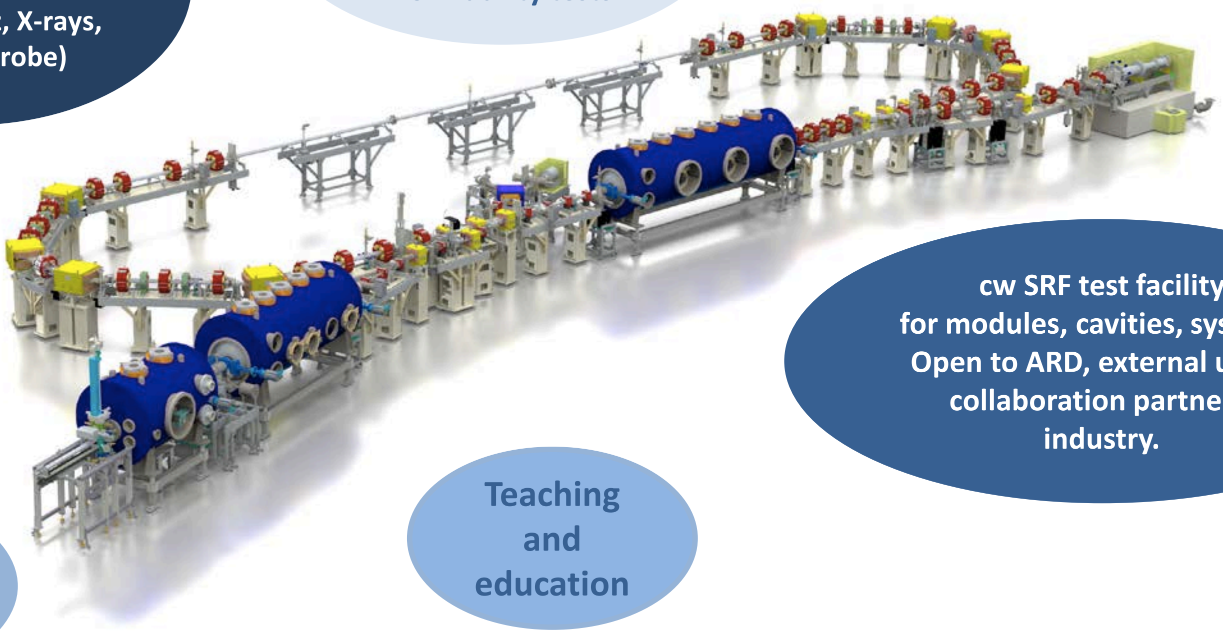
Particle distribution after the merger section in
c) *x-z* plane

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

bERLinpro: one testing collimator in the merger section

A. Matveenko

bERLinPro as an R&D test facility in the future ...



THz pilot facility,
High quality, high
power radiation
schemes (THz, X-rays,
e- pump/probe)

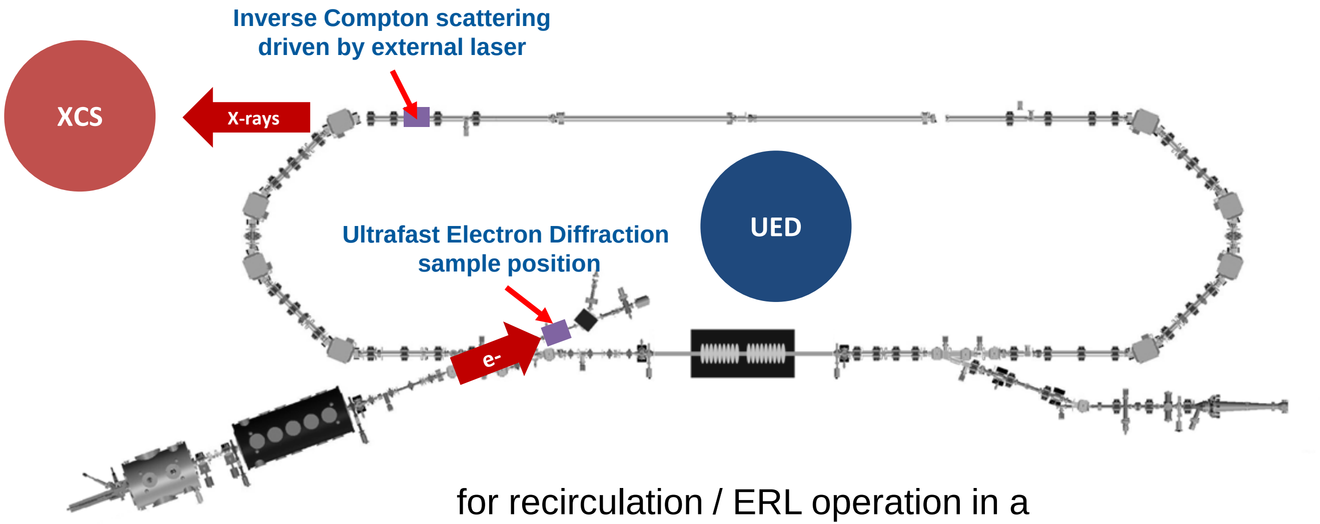
Exotics
Dark matter search,
Isotope production,
EUV facility tests

cw SRF test facility
for modules, cavities, systems.
Open to ARD, external users,
collaboration partners,
industry.

ERL / Gun test
accelerator, test
bed for undulators,
impedance tests, …

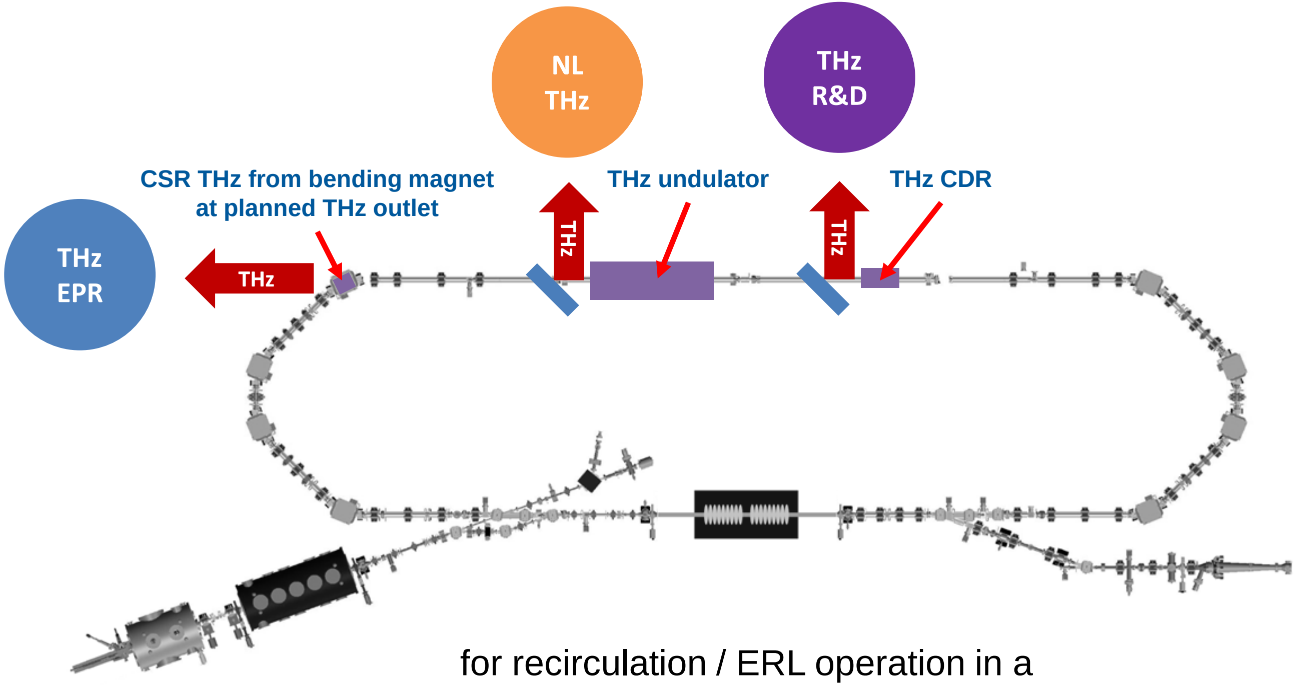
Teaching
and
education

Some first ideas – X-ray/e- opportunities at THz@SupraLab/bERLinPro



for recirculation / ERL operation in a
“post MESA@bERLinPro time” (from 2022/23 on)
we need a “linac module”

Some first ideas - THz opportunities at THz@SupraLab/bERLinPro



for recirculation / ERL operation in a
“post MESA@bERLinPro time” (from 2022/23 on)
we need a “linac module”

Summary

Energy Recovery Linacs can provide high current, high quality beams for single pass experiments in flexible setups, which only needs a low fraction of the available beam power
(ERLs favours experiments with a low efficiency in using the beam 😉)

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

cw superconducting RF is the enabling technology

large cw accelerating 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 Michael Abo-Bakr (bPro theory) 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

Thank you very much for you attention and patience!
I wish you, your families and friends all the best! Stay healthy!

There is always light behind the dark!