State of the Art and Expected/Desirable Evolution of Energy Recovery Linacs

Florian Hug

Introduction

Possible ERL Applications

- Internal target Experiments for dark matter searches
- Linac-Ring hadron-electron colliders

Challenges in ERL Operation

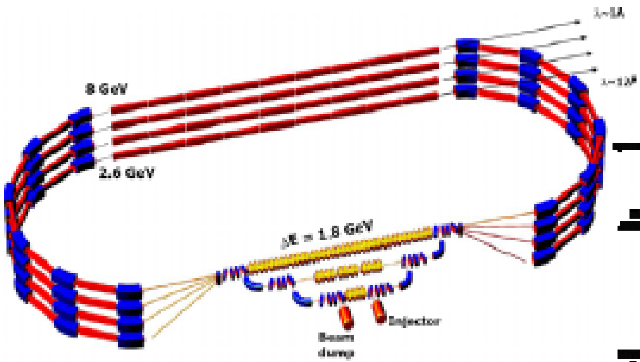
- Energy spread optimization
- RF control

Summary and Outlook

When does it make sense to built a new type of accelerator? … taking into account risks of new concepts

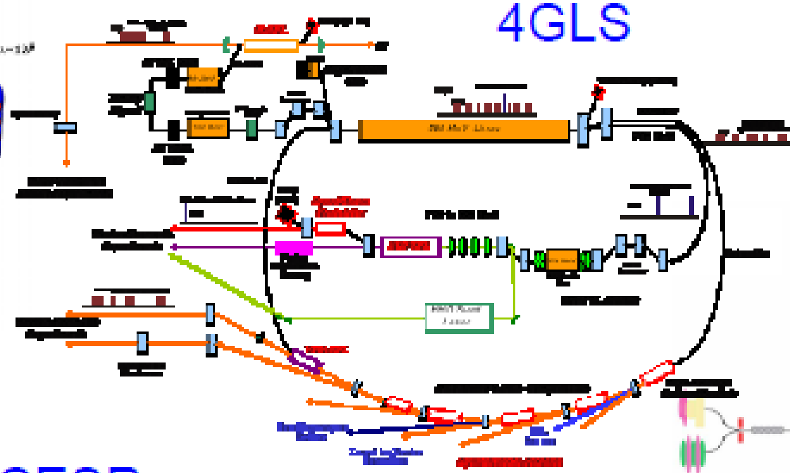
One promise (argument):
If experiments become possible that have not been possible before

~10 years before: ERL seen most likely as 4th generation radiation source

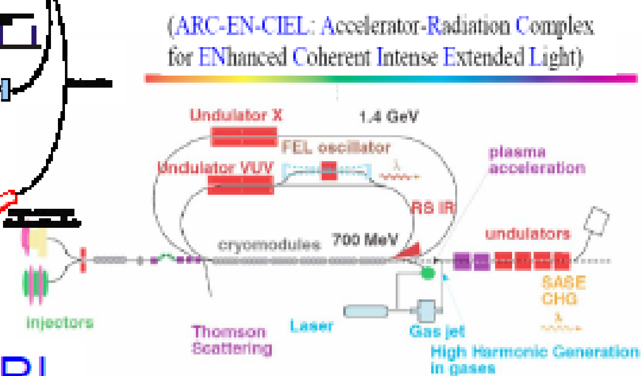


BINP MARS

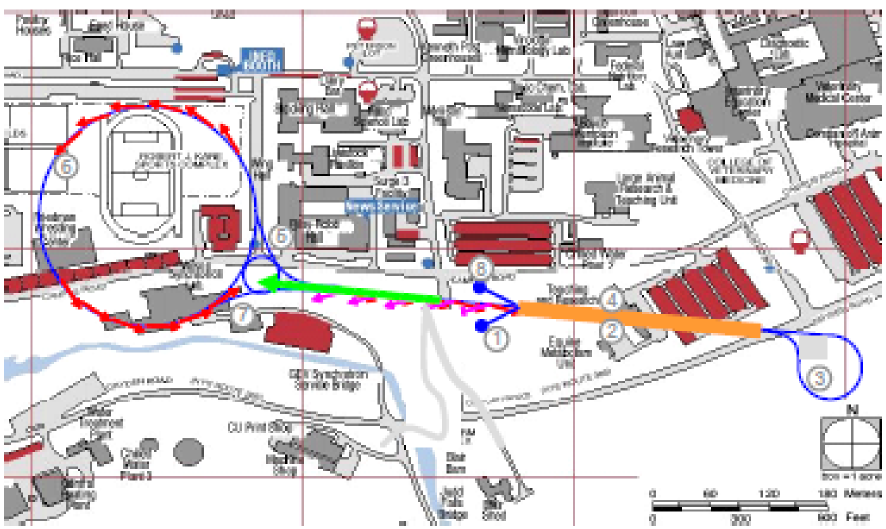
4GLS



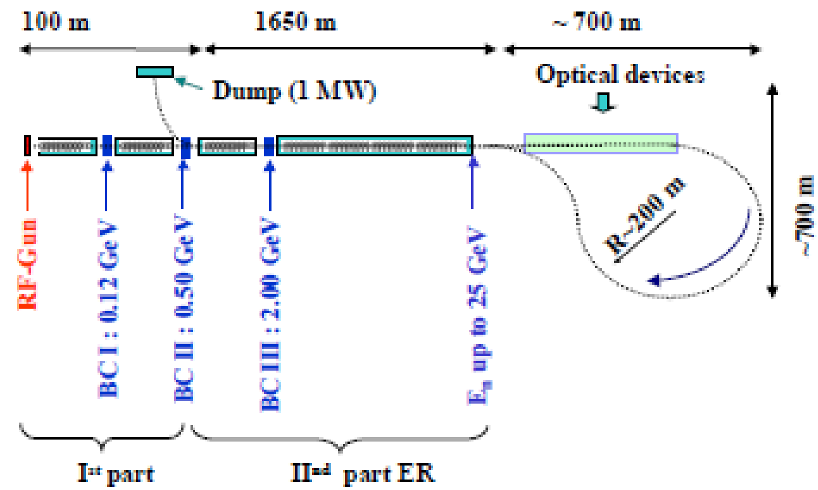
ARC-EN-CIEL



ERL@CESR



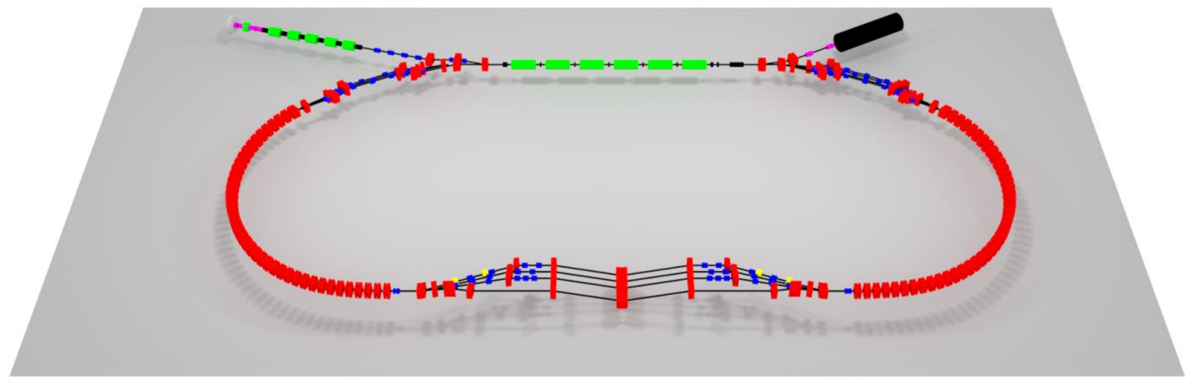
XFEL ERL



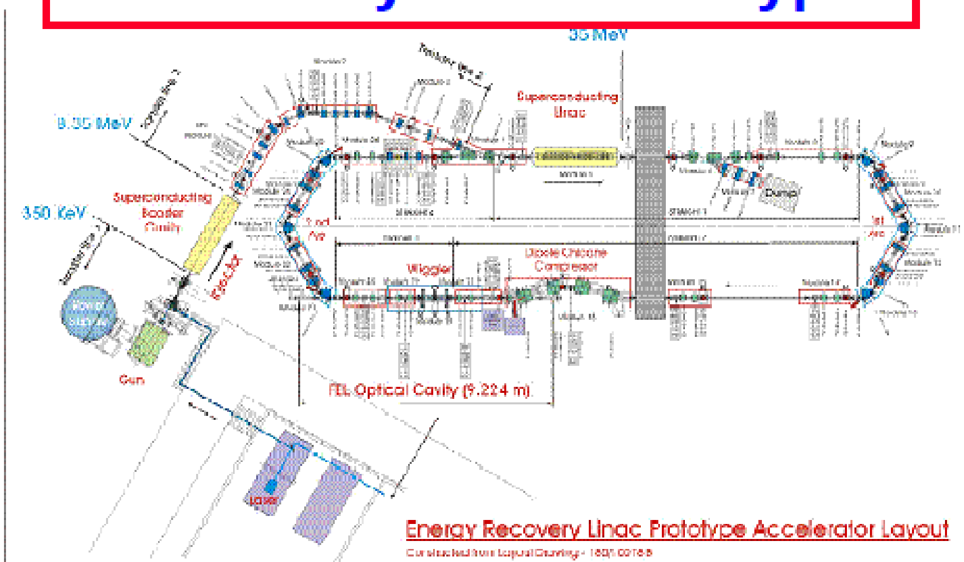
L Merminga, FEL 2005

b*ERL*in Pro:

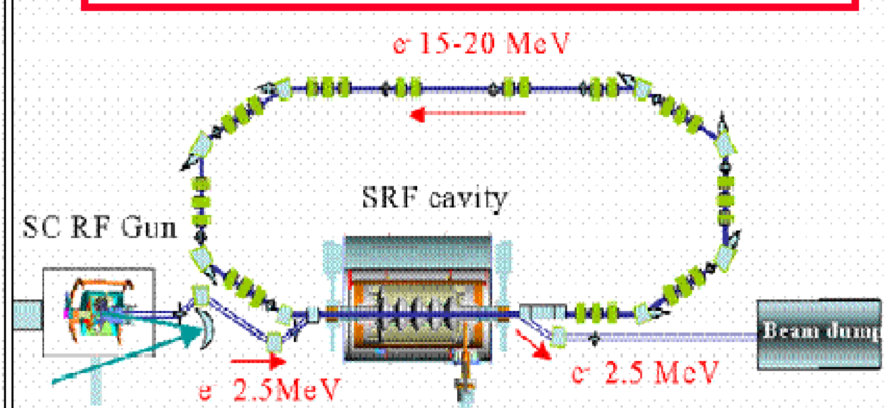
CBETA @ Cornell (FFAG Demonstrator):



Daresbury ERL Prototype

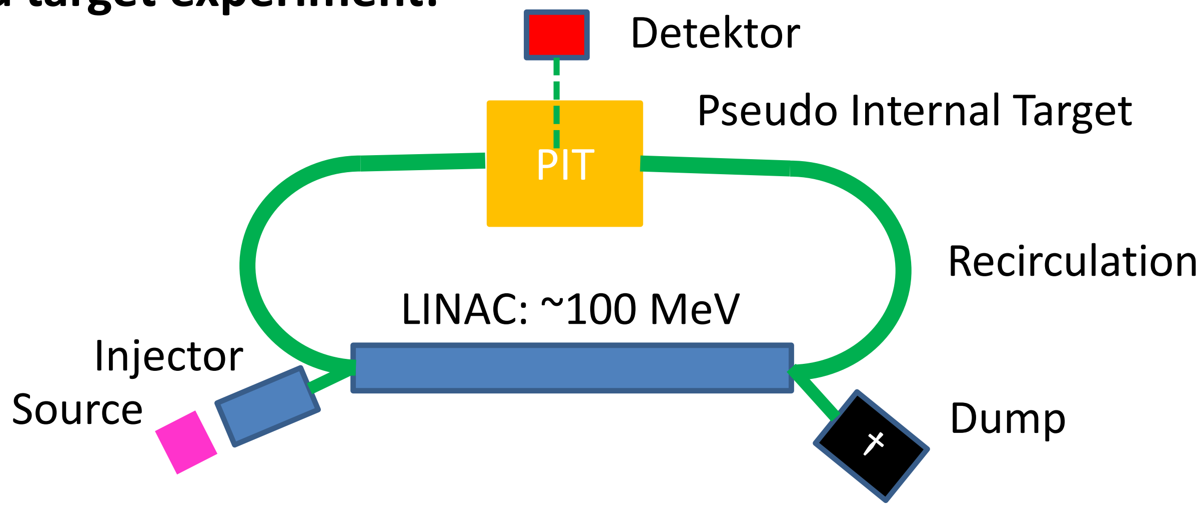


BNL R&D ERL



L Merminga, FEL 2005

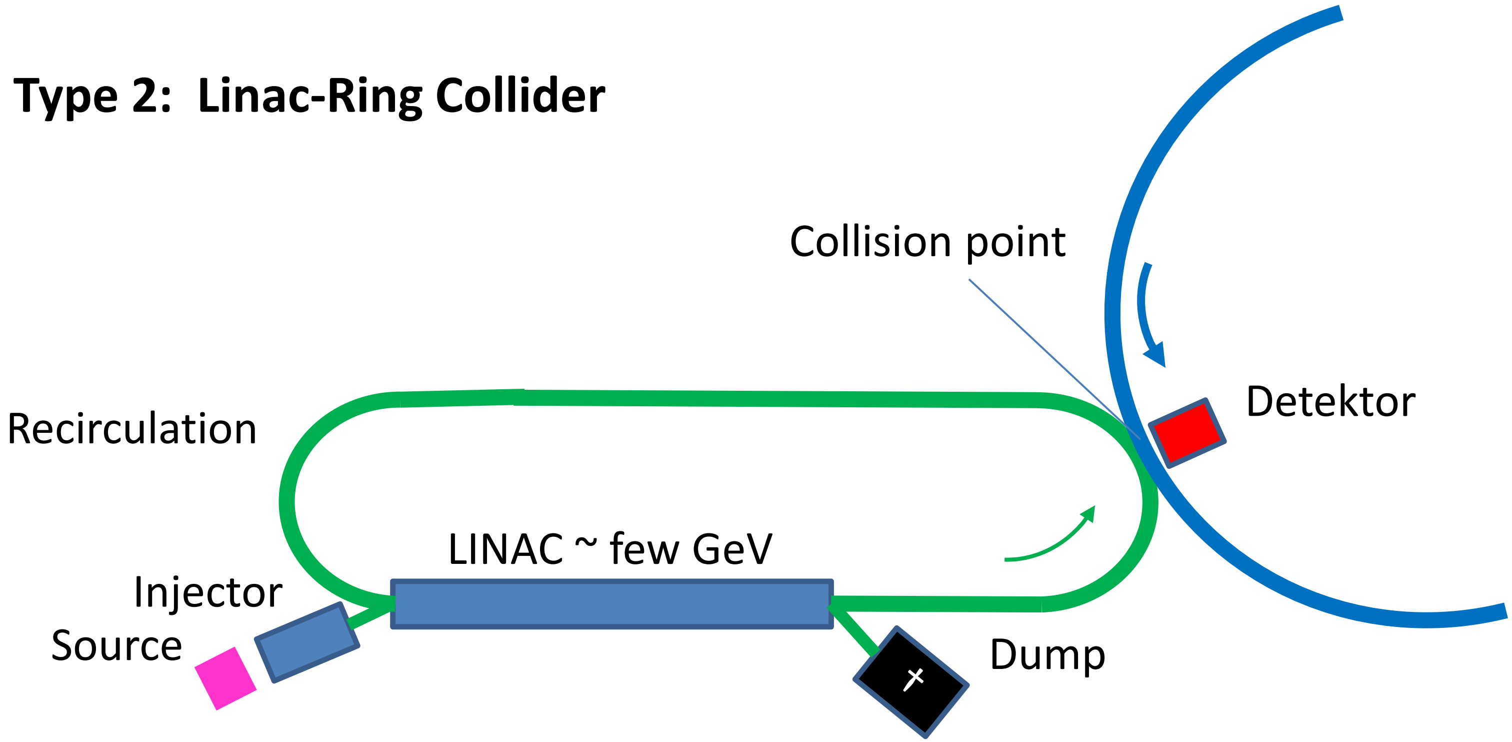
Type 1: Fixed target experiment:



<u>Promises</u>:
- Stationary beam conditions even at very low energies due to Pseudo internal target (PIT)
- Reasonable reaction rates even without **any** target enclosure
- Superior for reactions searching for rare events („Dark particles“)
- All types of reactions investigating **low** momentum transfer

Planned Experiments: Dark light (JLAB) / MAGIX (MESA)

Type 2: Linac-Ring Collider



Promises: - strong beam beam tuneshift for lepton beam possible
- spin polarization of electron beam easier to manage than in ring/ring designs
- multiturn designs feasible (typically 3-6 turns)

Planned set-ups: LHeC (CERN) eRHIC (Brookhaven National Loboratory ;BNL)

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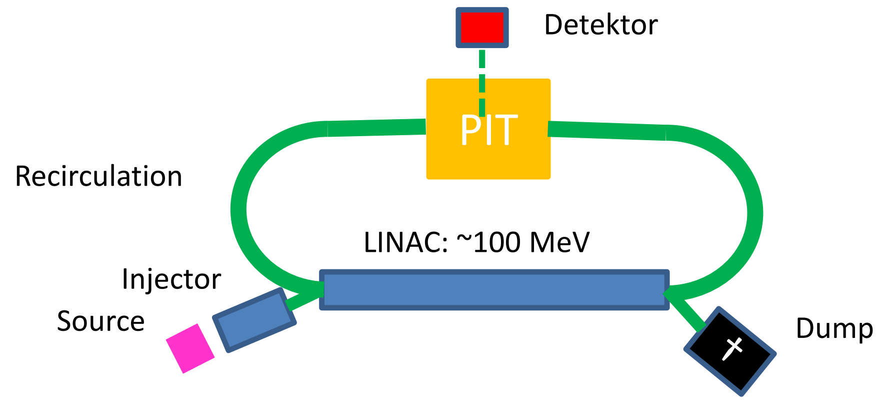
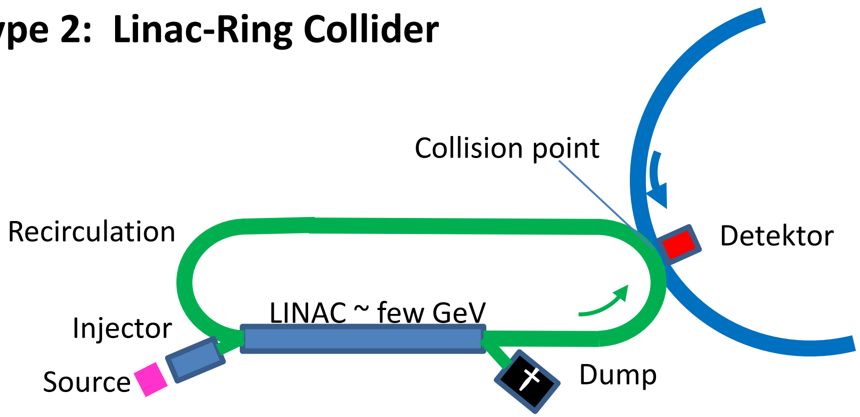


Type 2: Linac-Ring Collider



- The requirements are somewhat relaxed wrt to radiation generation: in general longer bunches
  → less coherent radiation problems
  → less problems with instabilities
- Additional tasks/challenges Type 1
  - Target/Detector design
  - small energy spread required
  - Halo Control/Collimation
- Additional tasks/challenges Type 2
  - multiturn desirable (→beam dynamics, rf control)
  - spin polarisaton/spin orientation required

Possible ERL applications

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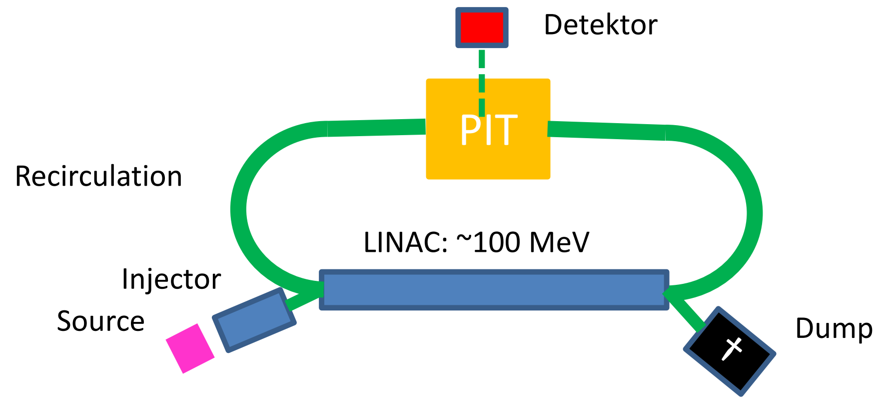
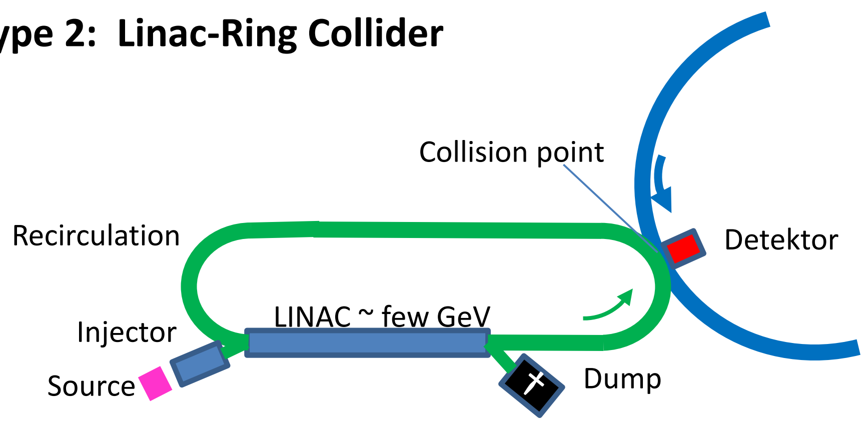


Type 2: Linac-Ring Collider



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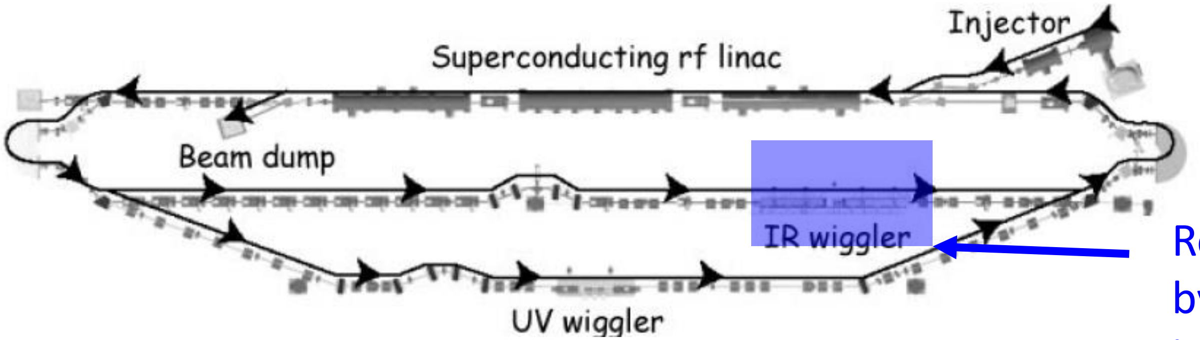


Replace wiggler by „Pseudo“ internal target

Parameter	IR FEL Upgrade	UV FEL
Beam energy at wiggler	80–210 MeV	200 MeV
Average beam current	10 mA	5 mA
Bunch charge	135 pC	135 pC
Bunch repetition rate	74.85 MHz	74.85 MHz
Normalized emittance (rms)	13 mm-mrad	5–10 mm-mrad
Bunch length at wiggler (rms)	200 fs	200 fs
Peak current	270 A	270 A
FEL extraction efficiency	1%	0.25%
$\delta p/p$ before wiggler (rms)	0.5%	0.125%
$\delta p/p$ after wiggler (full)	10%	5%
CW FEL power	>10 kW	>1 kW

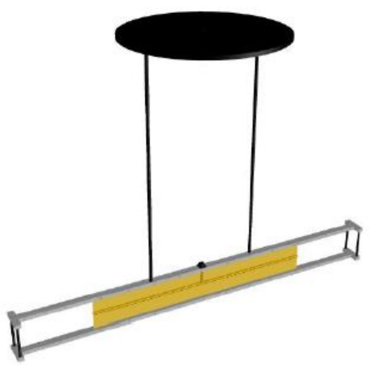
L Merminga et al. Ann. Rev. Part. Sci 53 387 (2003)

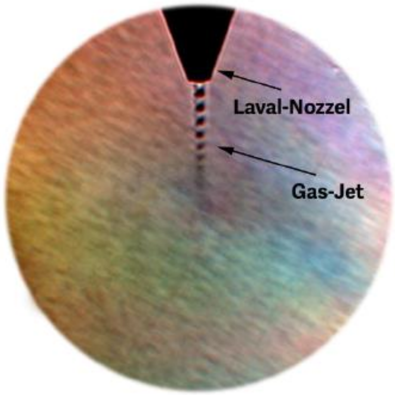
JLAB ERL Laser output: 10kW
Beam Power in Wiggler: ~1MW
R.F power needed: ~100kW

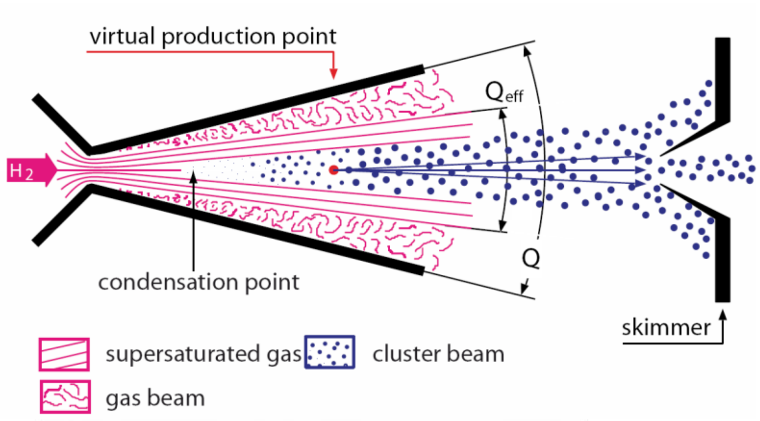
The energy taken away by scattered particles in one passage of the target can be much smaller than the one extracted in the FEL
→ Experiments with „Pseudo“ internal targets could be attractive.
(Proposed for dark matter search by Heinemayer et al. (2007): arXiv:0705.4056v2)

Internal targets: state of the art

Tube Target	Jet Target	Cluster-Jet Target
• Molecular Flow inside of a tube	• Gas Jet flows through the Chamber perpendicular to the beam	• Formation of clusters in the Jet







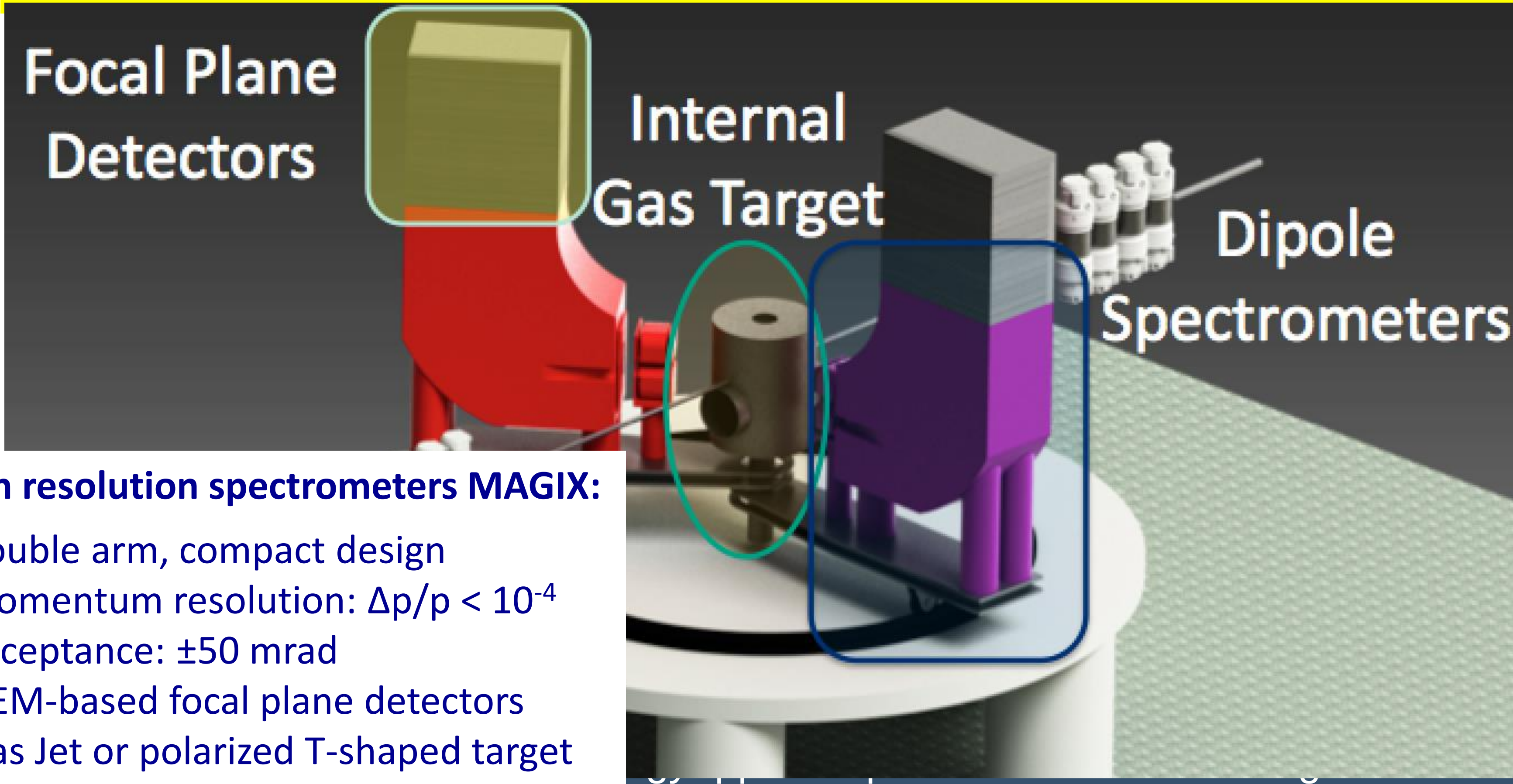
This is needed for POLARIZED Target (a la HERMES at HERA)!

S. Aulenbacher
https://indico.mitp.uni-mainz.de/event/66/session/5/contribution/48/material/slides/0.pdf

MAGIX @ MESA (JGU Mainz)

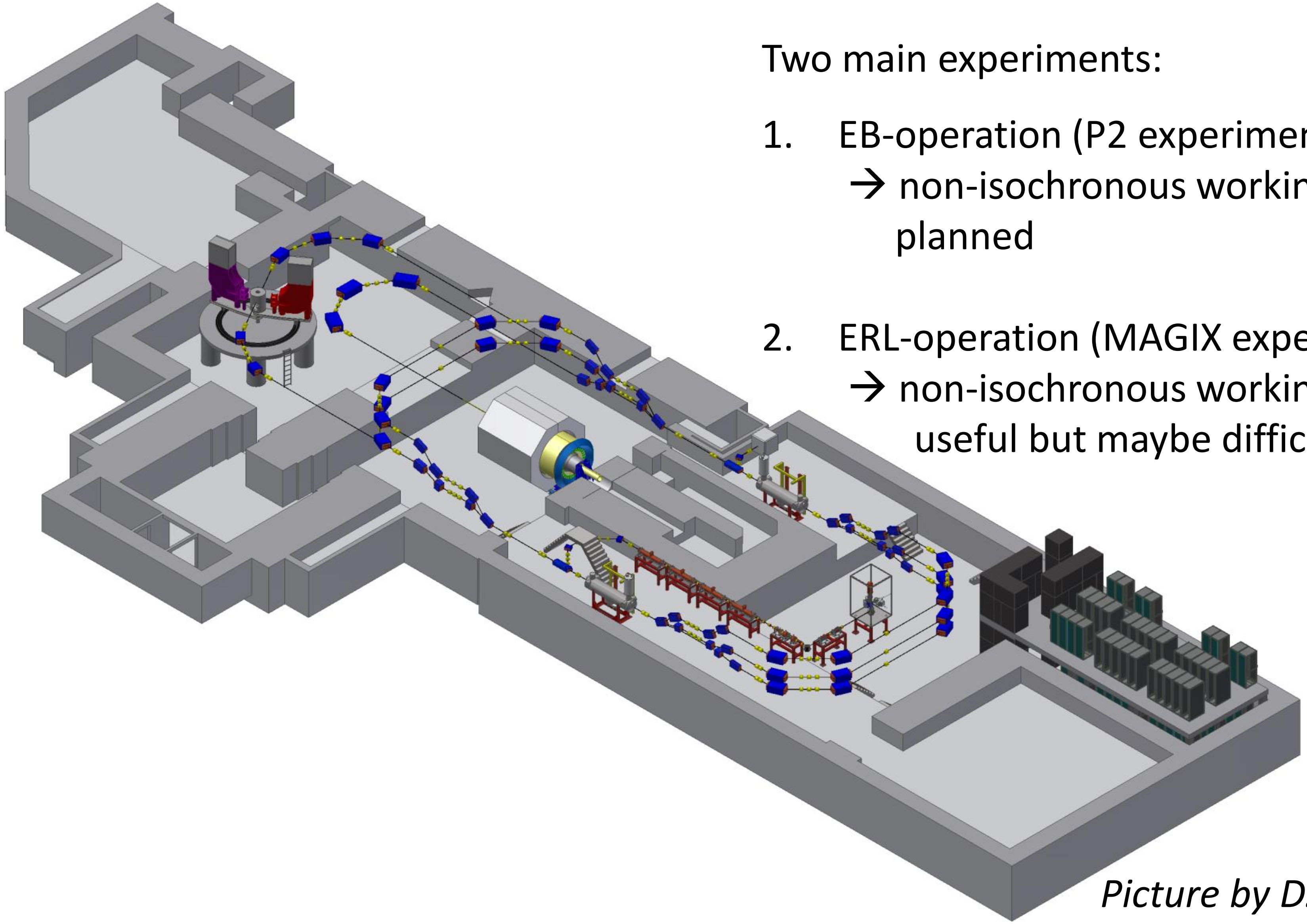
Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target

→ **a novel technique in nuclear and particle physics**
→ **measurement of low momenta tracks with high accuracy**
→ **competitive luminosities**
→ **Small device if compared to GeV scale spectrometer set ups!**



High resolution spectrometers MAGIX:

- double arm, compact design
- momentum resolution: $\Delta p/p < 10^{-4}$
- acceptance: ±50 mrad
- GEM-based focal plane detectors
- Gas Jet or polarized T-shaped target



Two main experiments:

1. EB-operation (P2 experiment)
   → non-isochronous working point planned

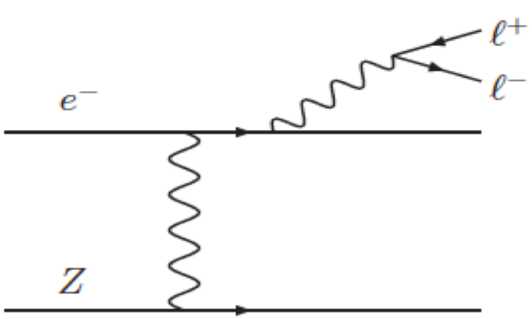
2. ERL-operation (MAGIX experiment)
   → non-isochronous working point useful but maybe difficult

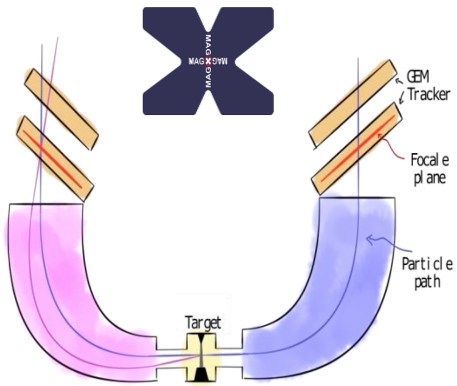
Picture by D. Simon

Dark Matter Experiments

- Presently, there is no clear evidence if dark matter particles exist
- Searches for WIMPS so far not succesful
- Other possibility New forces and force carriers: „ Dark Photons“ „ Dark Z“ „A'“
- These are detectable by the so-called kinetic mixing effect

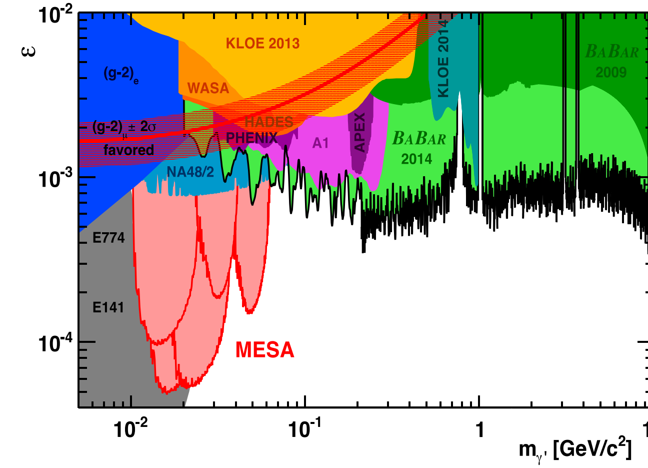
→ Pseudo internal target experiment: Initially foreseen for dark photon search



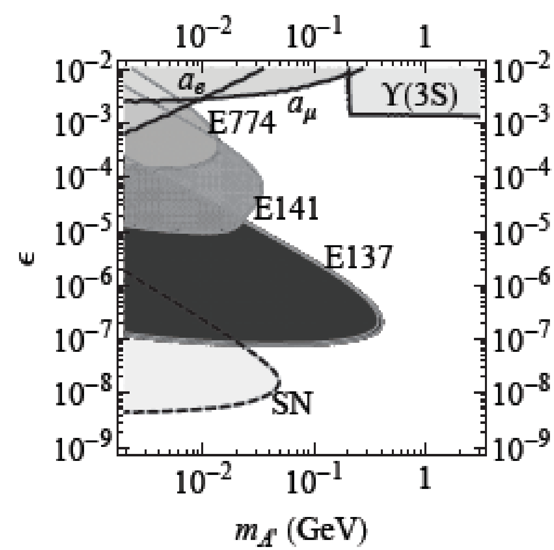


The strong suggestion that it would be possible to discover the partice has covered the „red line“ (without finding the dark photon…)

Status in 2016



Status in 2013



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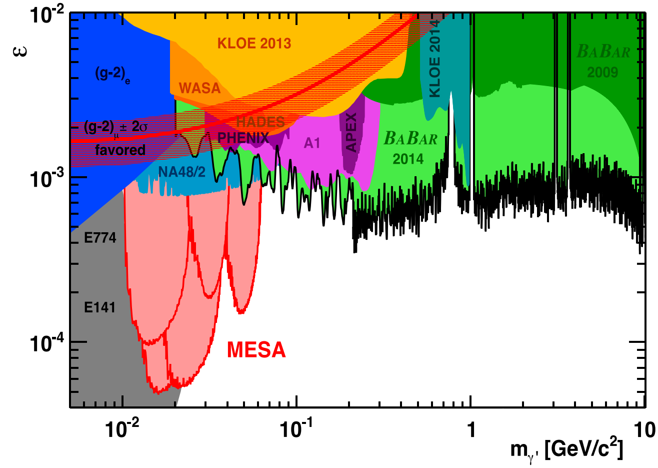
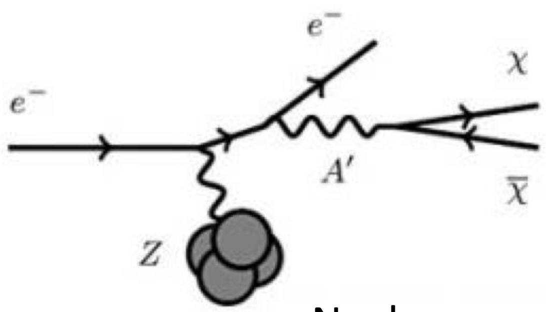


- g-2 band could as well be motivated by „invisible“ decay into dark matter…



Nucleus

$$m_{A'}^2 = (p_e + P_{nucleus} - p_{e'} - P_{nucleus})^2$$

By measuring the (very small) recoil of the Nucleus (proton) One reconstract if particles of the A‘ type have been Produced – very good conditions for this in the PIT regime

ERL‘s in the LINAC ring configuration

Physics motivation is mainly **deep inelastic** lepton/hadron scattering

Collider mode: Luminosity given by

- Beam beam tune shift

- The large tune shift for the electrons can be tolerated because of ERL operation!

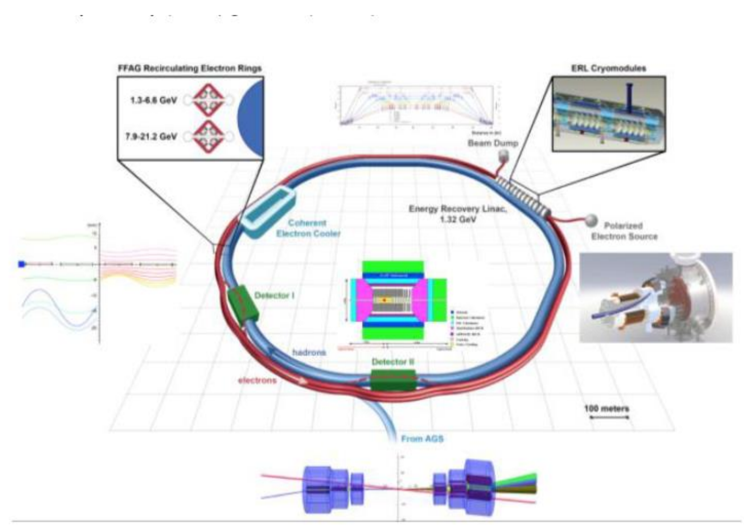
- Spin polarization is mandatory, at least for the ERL beam, better for both (Double polarized collider)

ERL's in the LINAC ring configuration: eRHIC

- 16 recirculations in two beamlines!
- Only on 1,3 GeV Linac required
- FFAG test set up presently being designed at Cornell University

Table 1: BNL eRHIC Beam Parameters and Luminosities

	e	P	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy (GeV)	15.9	250	167	100
CM energy (GeV)		122.5	81.7	63.2
Bunch freq. (MHz)	9.4	9.4	9.4	9.4
Bunch Int. (nucl.), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge (nC)	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron *rms* ε_N (μm)		0.27	0.20	0.20
Electron *rms* ε_N (μm)		31.6	34.7	57.9
β^* (cm) (both planes)	5	5	5	5
Hadron beam-beam ξ		0.015	0.014	0.008
Electr. Beam disruption		2.8	5.2	1.9
Space charge par. ξ		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak L, 10^{33} cm^{-2}s^{-1}		1.5	2.8	1.7
Improve L, 10^{34} cm^{-2}s^{-1}		1.5	2.8	1.7
Ultimate L, 10^{35} cm^{-2}s^{-1}		1.5	2.8	1.7



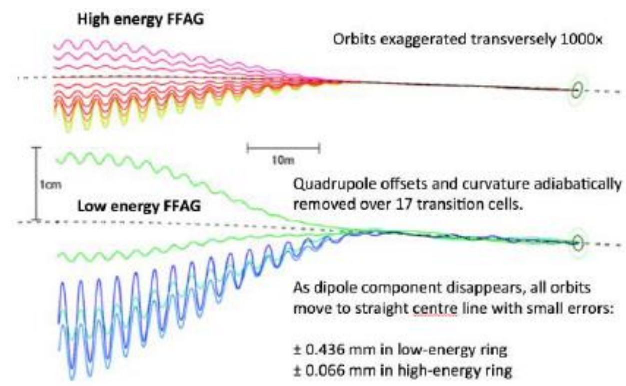
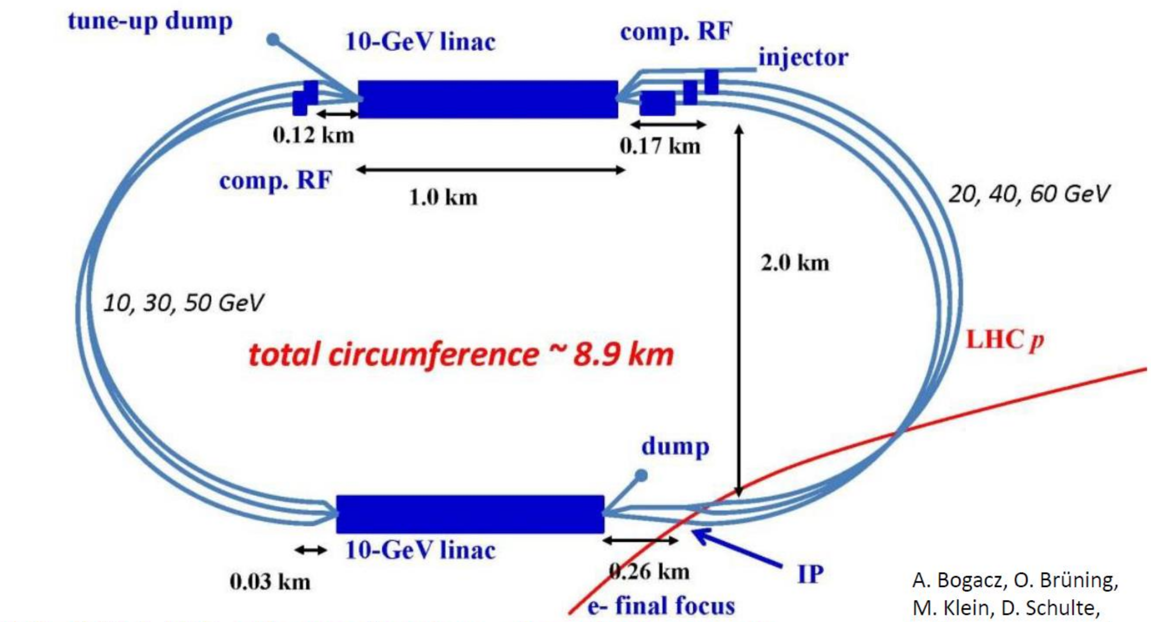


Figure 6: Straight section design for the eRHIC NS-FFAG beam lines.

V. Litvinenko et al.
TUPTY047 Proceedings of IPAC2015, Richmond, VA, USA

LHeC Linac-Ring ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-’s collide w. LHC protons/ions



(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al

- „Single“ polarised collider
- Higher CM energy than eRHIC
- Luminosity ~10^33
- Seperate recirculation orbits

Frank Zimmermann, LHeC workshop 2014
https://indico.cern.ch/event/278903/contributions/631178/attachments/510300/704305/LHeC_overview.pdf

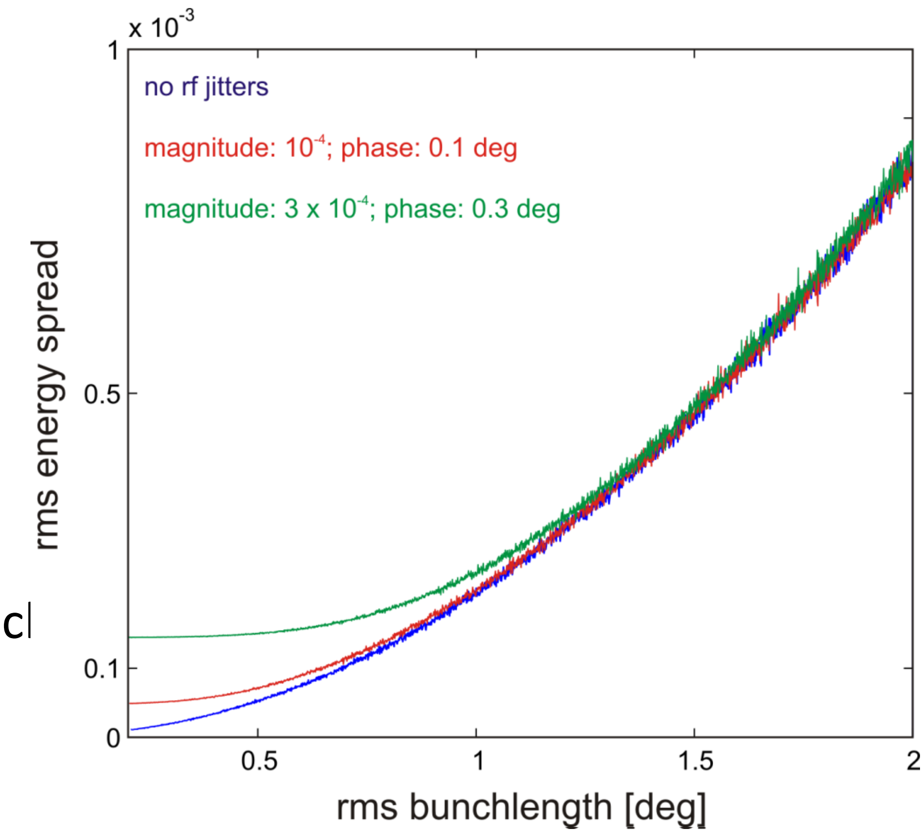
Energy spread in electron linacs

For relativistic electrons (v≈c):
almost no changes
in longitudinal position within bunch

Acceleration on crest of the rf-wave:

→ Short bunches needed because bunchlength causes energy spread!

→ Particles stay "frozen" at their longitudinal position within the bunch



→ + additional errors from phase and amplitude jitters of the rf-system:

$$\sqrt{\left(\frac{\Delta E_{max}}{E_{max}}\right)^2 + (1 - cos\Delta\varphi)^2} < \left(\frac{\Delta E}{E_{max}}\right)_{cavity,rms} < \left|\frac{\Delta E_{max}}{E_{max}}\right| + |1 - cos\Delta\varphi|$$

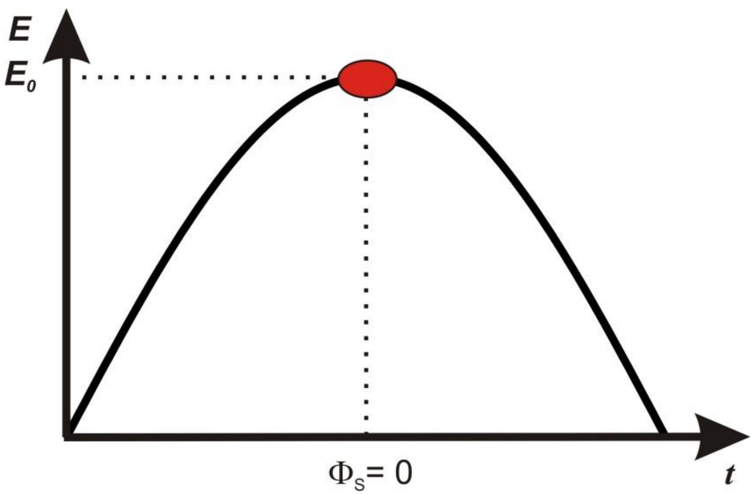
(M. Konrad, PhD thesis, TU Darmstadt 2013)

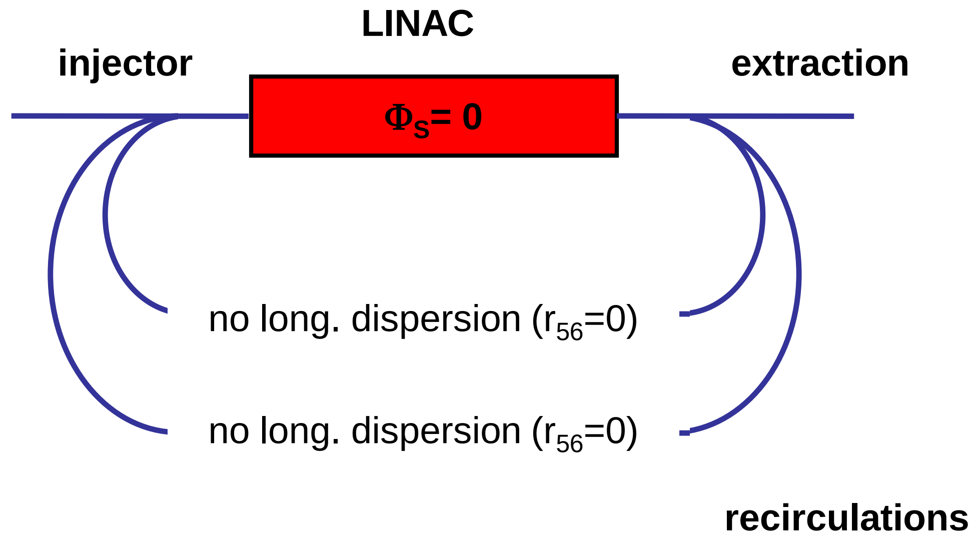
Isochronous recirculation scheme

Convenient for long linacs with many cavities:

Acceleration on crest of rf field with shortest possible bunches

→ Errors scale with $\sqrt{N}$ (N = number of cavities)





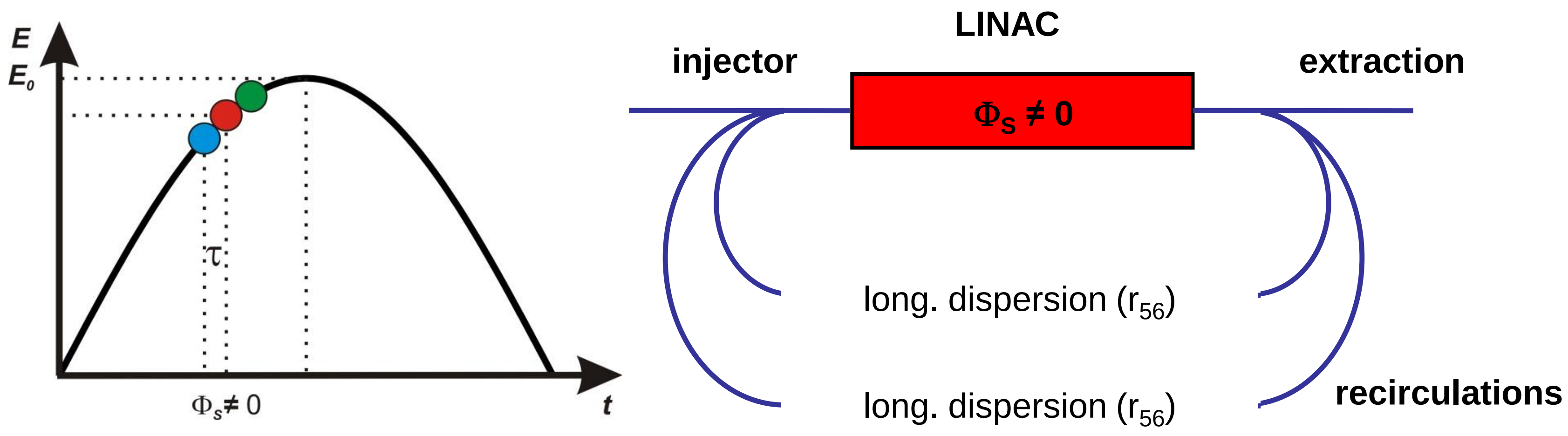
In (short) few turn recirculators:

Amplitude errors of accelerating cavities can add up coherently over all turns → no averaging of errors when $t_{linac} << \tau_{cavity}$

→ Energy spread can exceed experimental requirements

Non-isochronous recirculation scheme

- Common operation mode for microtrons and synchrotrons
- Acceleration on edge of rf field
- Different time of flight for particles having different energies

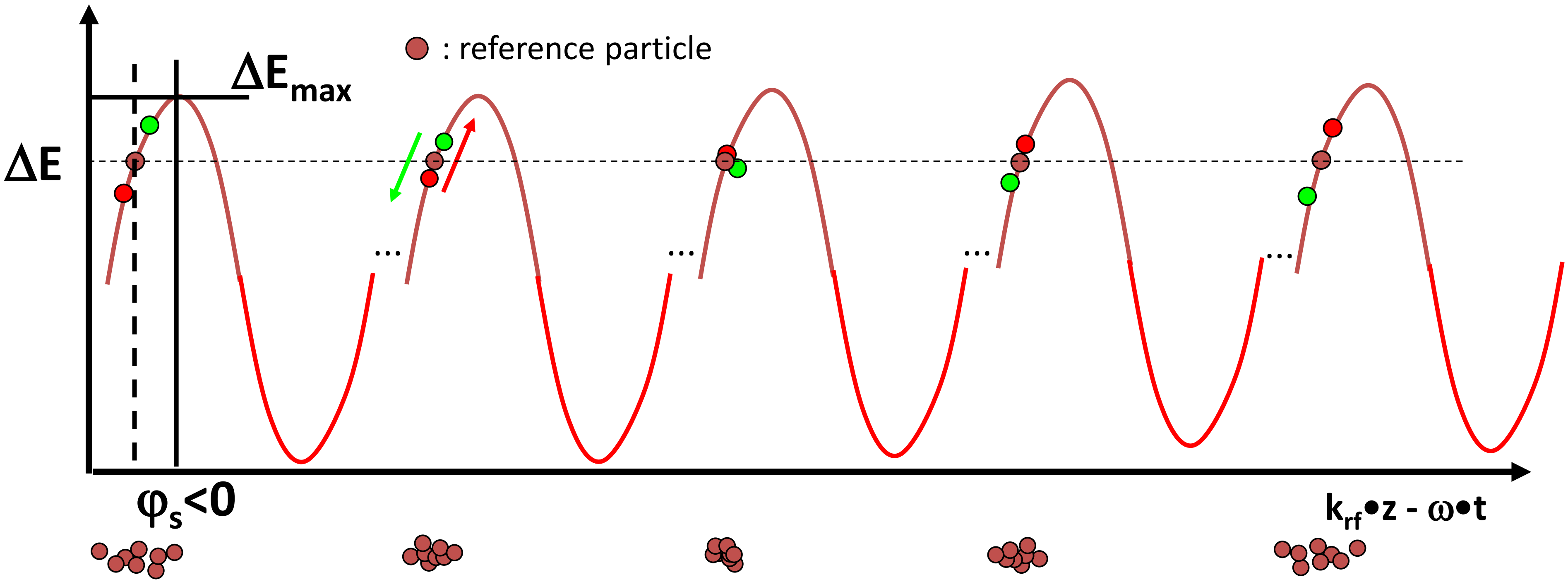


→ Particles perform synchrotron oscillations in longitudinal phase space

Half- or full integer oscillations lead to reproduction of the longitudinal phase space at injection [*Herminghaus, NIM A 305 (1991) 1*].

→ complete compensation of rf phase- and amplitude jitters possible

Non-isochronous recirculation scheme



(Jankowiak/Aulenbacher, lecture on accelerator physics)

Example: MESA External Beam Operation

Simulations for a new longitudinal working point

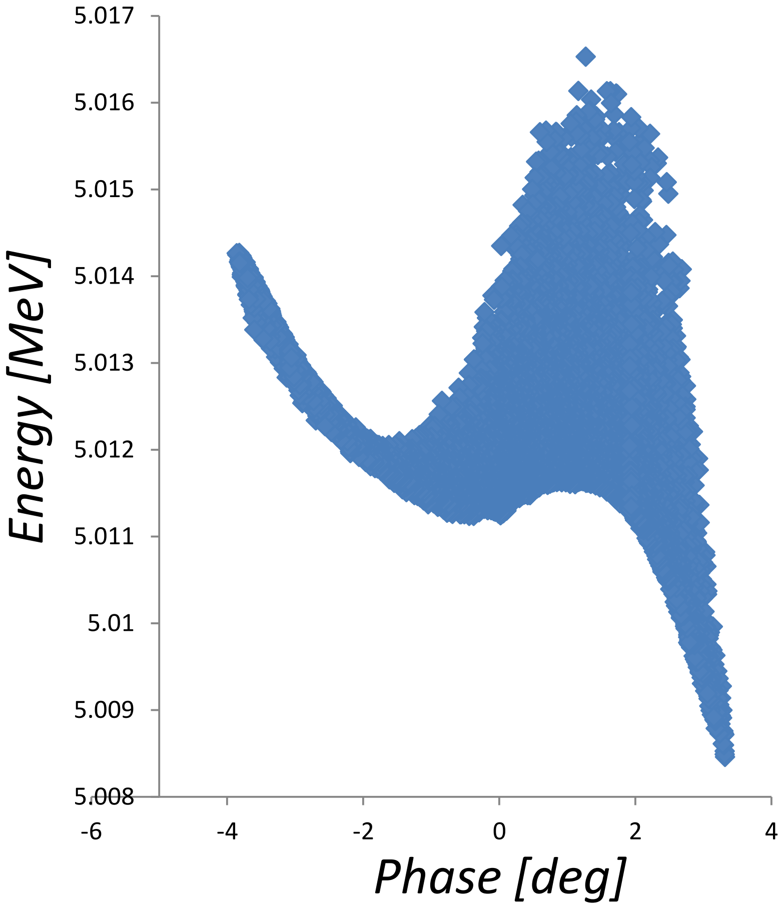
Goal: Find optimal combination of r_{56} and Φ_S for MESA 6-pass external beam mode

1. Import longitudinal phase space from MAMBO 150 µA simulation
2. Create randomized cavity parameters (4 cavities, $\Delta A_{rms} = 1 \cdot 10^{-4}$, $\Delta\phi_{rms} = 0.1°$)
3. For each pair of r_{56} and Φ_S track each particle through the accelerator

$$E_{i+1} = E_i + (A + \Delta A)\cos(\phi_S + \delta\varphi + \Delta\phi)$$

$$\varphi_{i+1} = \varphi_i + r_{56} \cdot \delta E / E_{ref} \cdot 156°$$

4. Calculate rms energy spread for each pair of r_{56} and Φ_S



Example: MESA External Beam Operation

Results for 6-pass external beam mode:

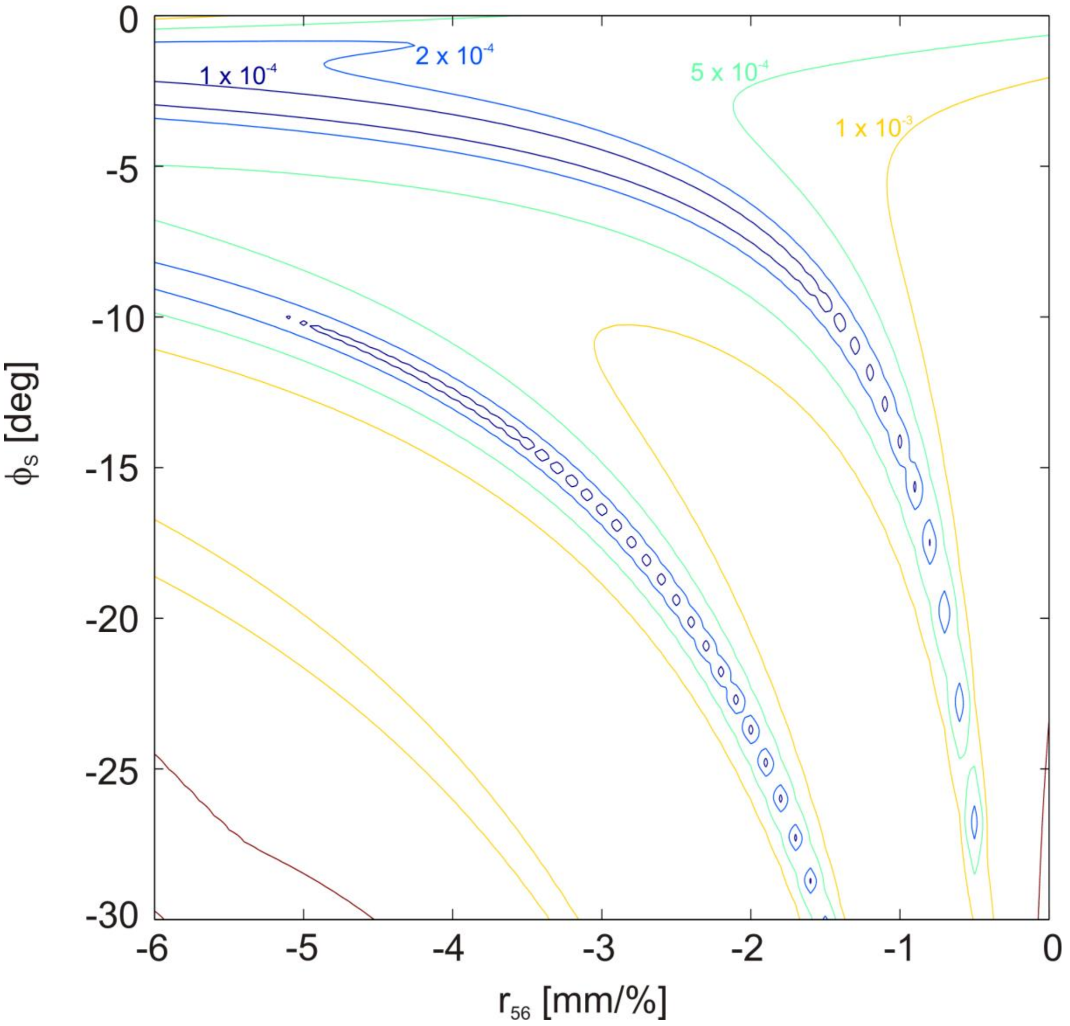
→ best energy spread at:

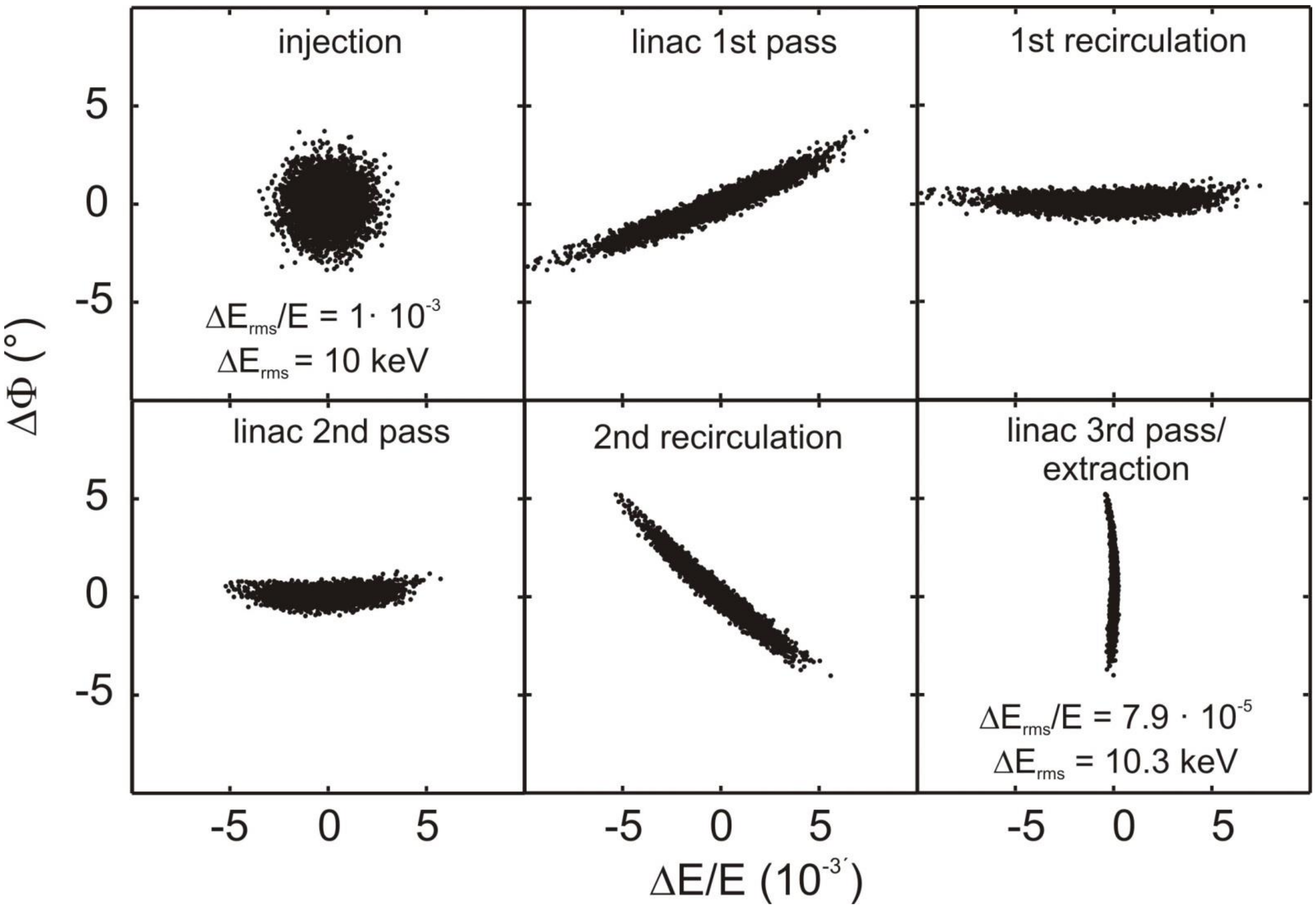
r_{56} = -2.6 mm/% and

Φ_S = -5.8°

$\Delta E_{rms}/E = 5.5 \cdot 10^{-5}$

isochronous: $\Delta E_{rms}/E = 3.4 \cdot 10^{-4}$





Compare with assumption (no additiona errors from linac):

Energy spread at

Injection (10 MeV):

$\Delta E_{I;rms}/E_I = 1 \cdot 10^{-3}$

$\Delta E_{I;rms} = 10$ keV

After acceleration to full energy (130 MeV):

$\Delta E_{rms}/E =$

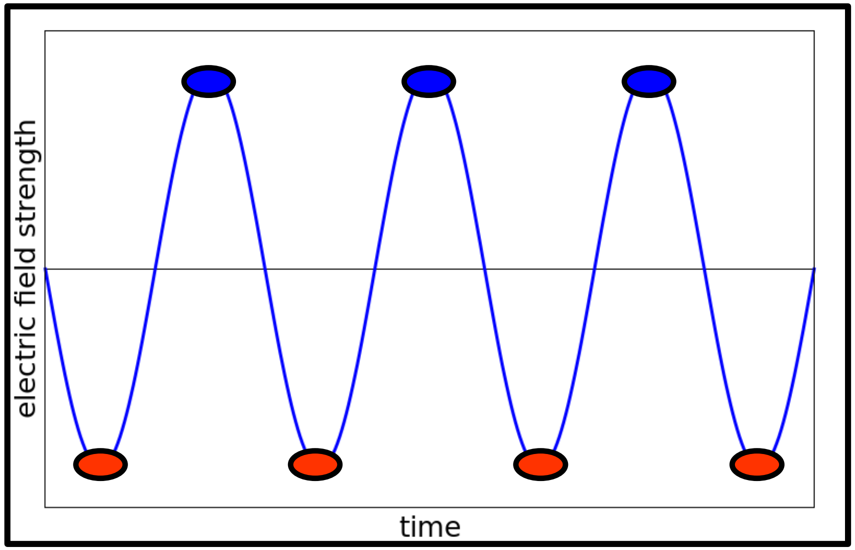
10 keV/130 MeV =

$7.7 \cdot 10^{-5}$

Compare the two different ERL operation modes:

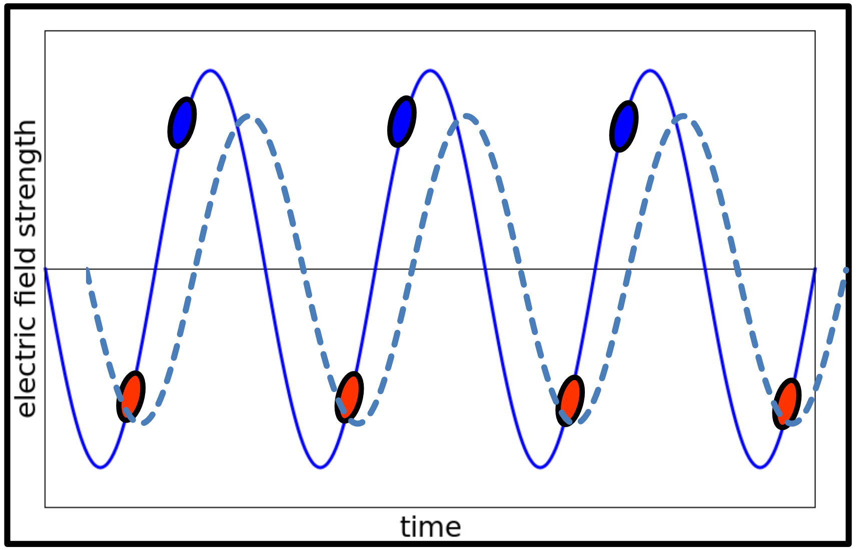
isochronous operation

Accelerating and decelerating bunches in phase with maximum/minimum of rf-field



non-isochronous operation

Decelerating bunches re-enter cavities at a different phase
→ possible disturbance on accelerating phase as well

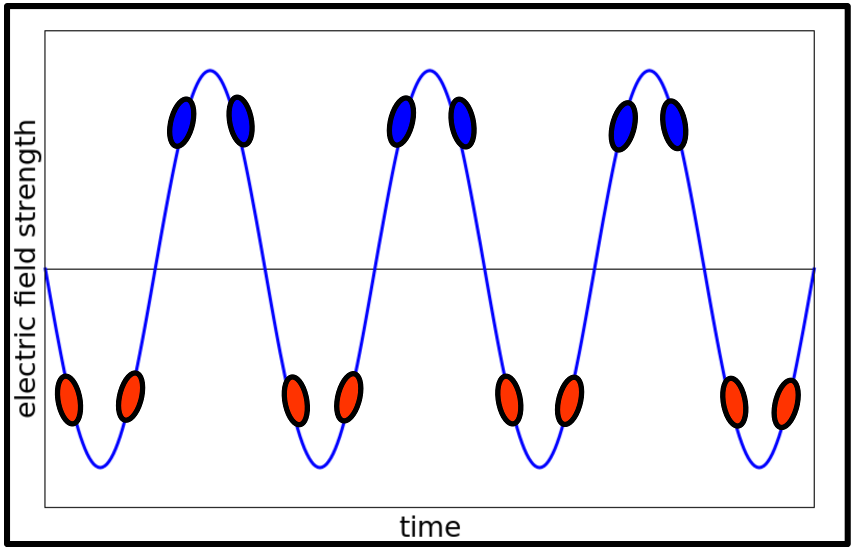


→ On the non-isochronous working efficiency of energy recovery decreases
→ Challenging/Impossible for rf-control system to sustain desired accelerating field

Non-Isochronous ERL Operation

Maybe a different non-isochronous scheme in ERL operation possible?

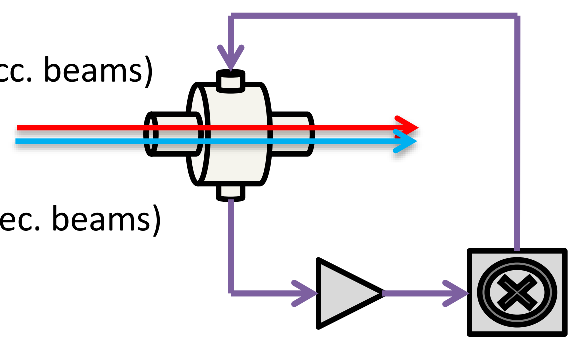
- Use the double sided design of MESA
- First two passes acceleration on edge
- Use r_{56} for a half turn in phase space
- Second two passes acceleration on **opposite** edge
- Use r_{56} for a half turn in phase space (other direction)
- end up with better energy spread
- Deceleration vice-versa



Main challenges controlling SC-ERL cavities :

- RF power for accelerated beam comes from decelerated beam
  → the decelerated beam is the main power source
- Microphonics cause mismatch between beam frequency and cavity frequency
- „usual“ RF control loop is weak compared to the power demand

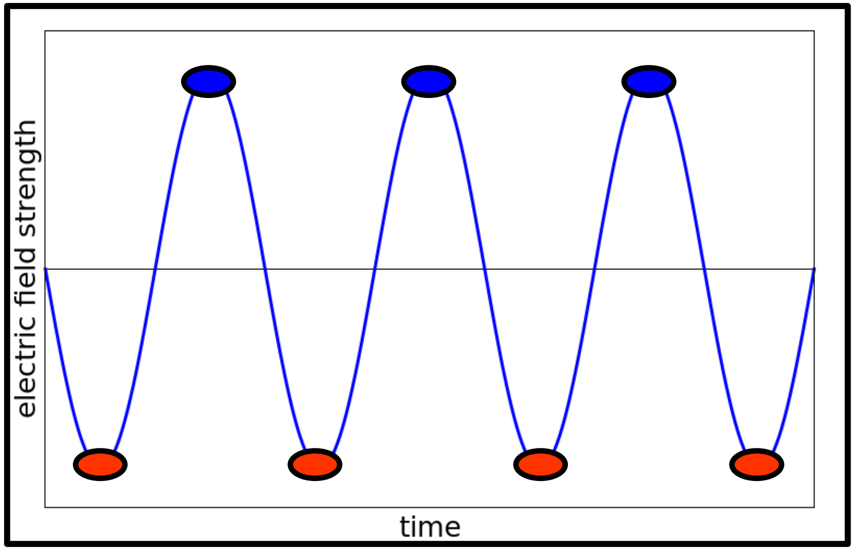
ERL mode (100 mA, 12.5 MV/m, 2 recirculations):



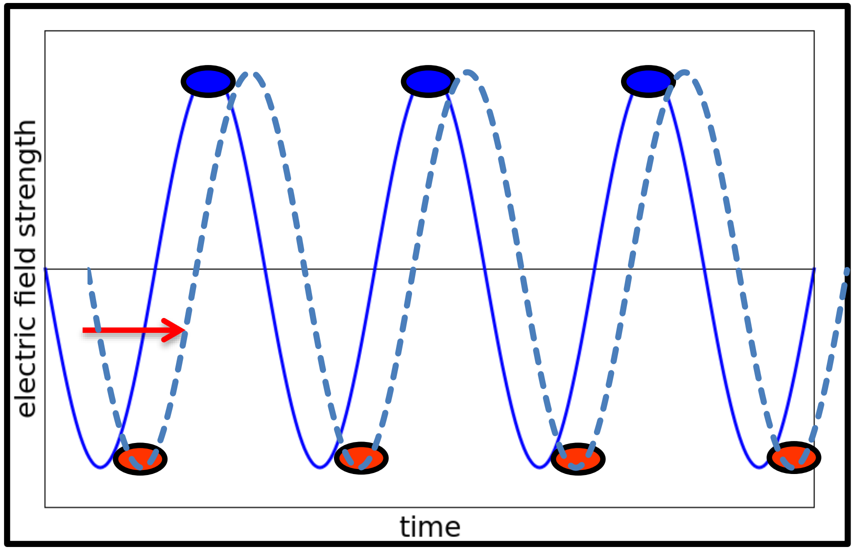
LLRF for cold systems: challenges in ERL mode

Phase and magnitude stability in ERL mode:

Accelerating and decelerating bunches need to be in phase with maximum/minimum of rf-field



What if the decelerating bunches arrive at the wrong phase wrt to the accelerating ones?



Decelerating bunches force rf-field to different phase, this needs to be compensated by LLRF-control system

→ Maybe active Feedback needed to stabilize reentering phase of the decelerated beam

LLRF for cold systems: challenges in ERL mode

Example for Cornell demonstrator (by Ralf Eichhorn):

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Titel hinzufügen

$$P_{forw} = \frac{V_{acc}^2}{4 \cdot R/Q \cdot Q_L} \cdot \frac{\beta + 1}{\beta} \left\{ 1 + \left(2Q_L \cdot \frac{\Delta\omega}{\omega_e} + \frac{I_b R/Q \cdot Q_L}{V_{acc}} \cdot \Delta\phi \right)^2 \right\}$$

Power coupler design choice

microphonics

Energy recovery efficiency

- Let's take the best cavity:

	Microp./ Hz	Q0	Qext
Cavity #2	15	1.98e10	5.38e7

Δϕ	Pfor
0°	4.4 kW
1°	65 kW
2°	200 kW

So to stay below 5 kW,
phase has to stay below 0,05 deg
(this is 30 μm in path length!)

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Summary & Outlook

- ERLs can provide huge beam power in cw operation at moderate costs
- recently ERL-based light sources have become somehow unpopular, but ERLs for particle physics remain very interesting
- demonstrators and small ERLs exist and/or are under construction → the next step: SC high current ***multiturn*** ERLs
- beam energy spread optimization through non-isochronous beam dynamics and rf control can be very challenging and need to be investigated further
- but there are much more challenges in operation of ERLs than presented here like e.g. BBU, high power diagnostics, FFAG lattices, machine protection, sources, injectors…