JLEIC and Electron Cooling: An Introduction

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Collider Luminosity

- Luminosity formula $L = (f/2\pi)\, N_e N_p / \Sigma_x \Sigma_y$, $\Sigma_x = (\sigma_{xe}^2 + \sigma_{xp}^2)^{1/2}$, $\Sigma_y = (\sigma_{ye}^2 + \sigma_{yp}^2)^{1/2}$
- General design rule: $\sigma_{xe} = \sigma_{xp}$ $\sigma_{ye} = \sigma_{yp}$ (for beam-beam effect)
- Beam spot size at a collision point $\sigma_x = (\varepsilon_x \beta^*_x)^{1/2}$
- β-function characterizes the beam optics
  - It describes focusing/defocusing of the beam in the beam transport system (a ring),
  - It is determined by distribution and strength of quadrupoles (dipoles guide particle motion)
  - β^* is the value of β-function at a collision point
- ε_x is called beam emittance, it characterizes the volume a particle beam (bunch) occupies in the phase space.
- Luminosity optimization: making the beam spot size at IP as small as possible

  ➔ small β^* ➔ better optics design ➔ limited by many factors (magnet imperfection, etc)

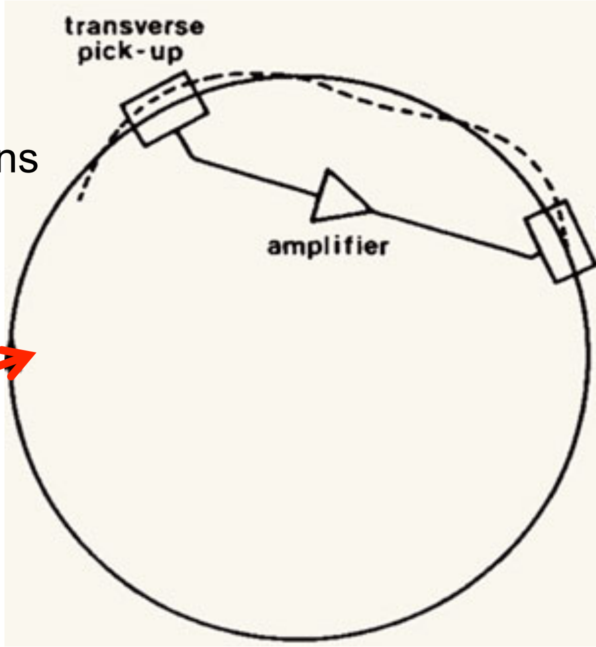
  ➔ small beam emittance ε_x ➔ damping by cooling

Reduction of Emittance

- There are many different definitions:
  - geometry (RMS) emittance
  - normalized emittance: geometric emittance multiplied by $\beta\gamma$ (a relativistic invariant)
  - 95% emittance: 4 sigma phase space volume for a Gaussian distribution
- According to Liouville's theorem, the phase space volume in a classical Hamiltonian system is an invariant; The magnet system (dipoles and quads) is a Hamiltonian system
- To achieve a reduction of beam emittance (phase space volume), one must introduce a dissipative force such that the extended system is no longer a Hamiltonian system
- This process of emittance reduction is called beam cooling
- The JLEIC electron beam has synchrotron radiation damping (strong and rapid)
- For the JLEIC proton/ion beams, energy is too low so there is no radiation damping
- Typical values of proton normalized emittance: no cooling ~ 2 to 3 mm mrad
  after cooling ~ 0.1 to 0.5 mm mrad

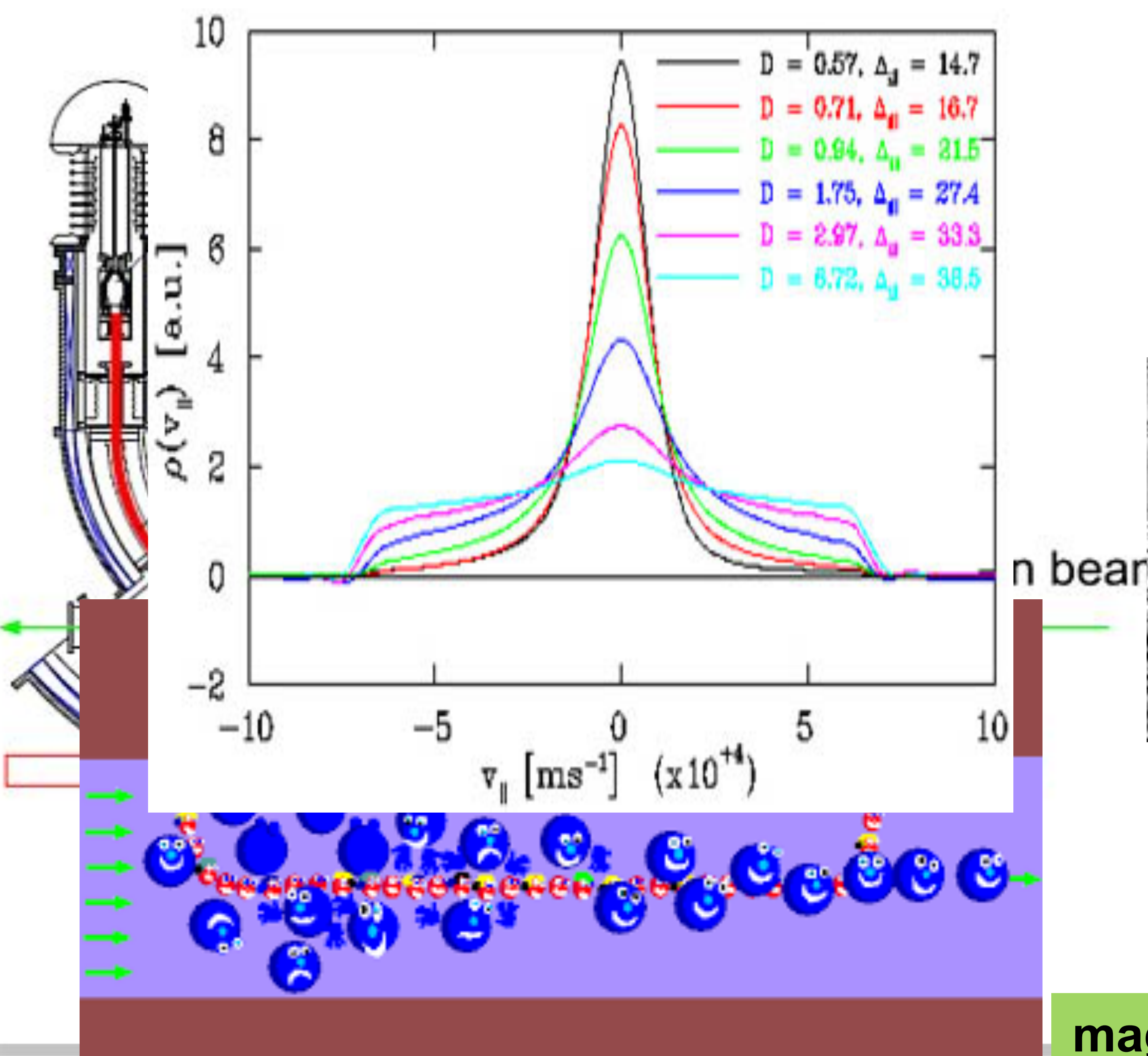
Beam Cooling

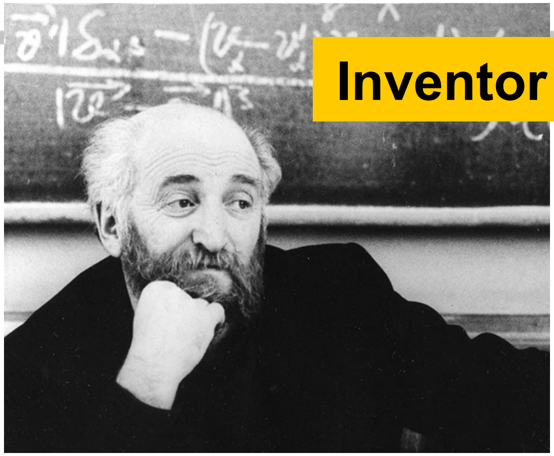
- Two types of beam cooling
  - Through feedback ➔ stochastic cooling
  - Through particle-particle (including photons) interactions/collisions
    - ➔ electron cooling, laser cooling and muon cooling
- One important parameter is cooling time
- Stochastic cooling (pickup-kicker)
  - Cooling time ~ number or particles / signal amplifier bandwidth
  - Good for heavy ions (for RHIC, and likely JLEIC Pb)
  - Not good for protons (p vs. $^{208}Pb^{+82}$, 82 times more particles)
  - Coherent Electron Cooling: increasing bandwidth through SASE FEL



- Electron cooling
  - Arrange co-moving of cold electron and hot proton/ions
  - Like cold water cools hot water, cold gas cools hot gas
  - Heat diffusive motion through particle-particle interaction (Coulomb collisions)
  - Highly efficient (especially if the beam emittance is not very large, ~ a few mm mrad)

Electron Cooling: An Illustration





Inventor

Pioneers

Theorist

magnetized cooling

Multi-Step Cooling for High Performance

- **Cooling of the JLEIC protons/ions**
  - achieves a small emittance
  - achieves a short bunch length of 1 to 2 cm (with strong SRF)
  - enables ultra strong final focusing and crab crossing
  - suppresses intra-beam scatterings (IBS), maintaining beam emittance
  - expands luminosity lifetime

- **Cooling time**

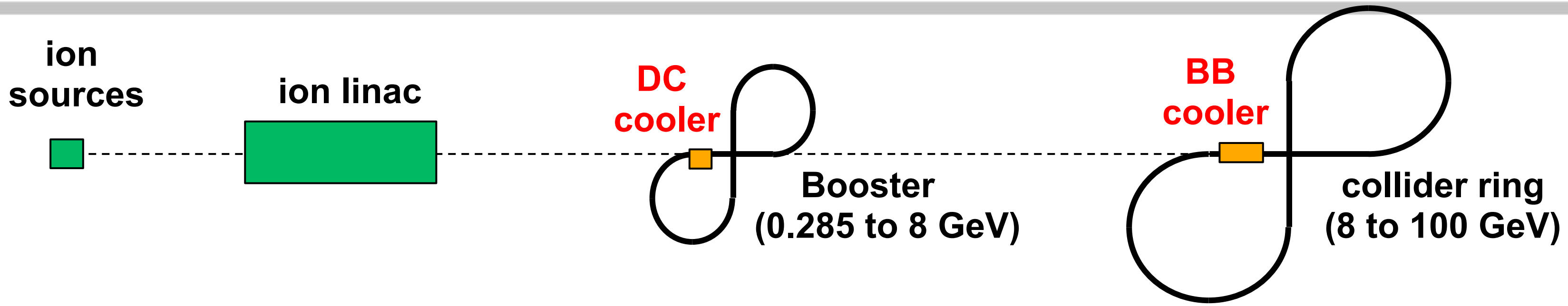
It is advantage to cool at

- Low energy
- When emittance is not big

$$\tau_{cool} \sim \gamma^2 \frac{\Delta\gamma}{\gamma} \sigma_z \varepsilon_{4d}$$

- **Multi-step scheme**
  - taking advantages of high cooling efficiency at low energy or/and with small emittance

JLEIC Multi-Step Cooling Scheme



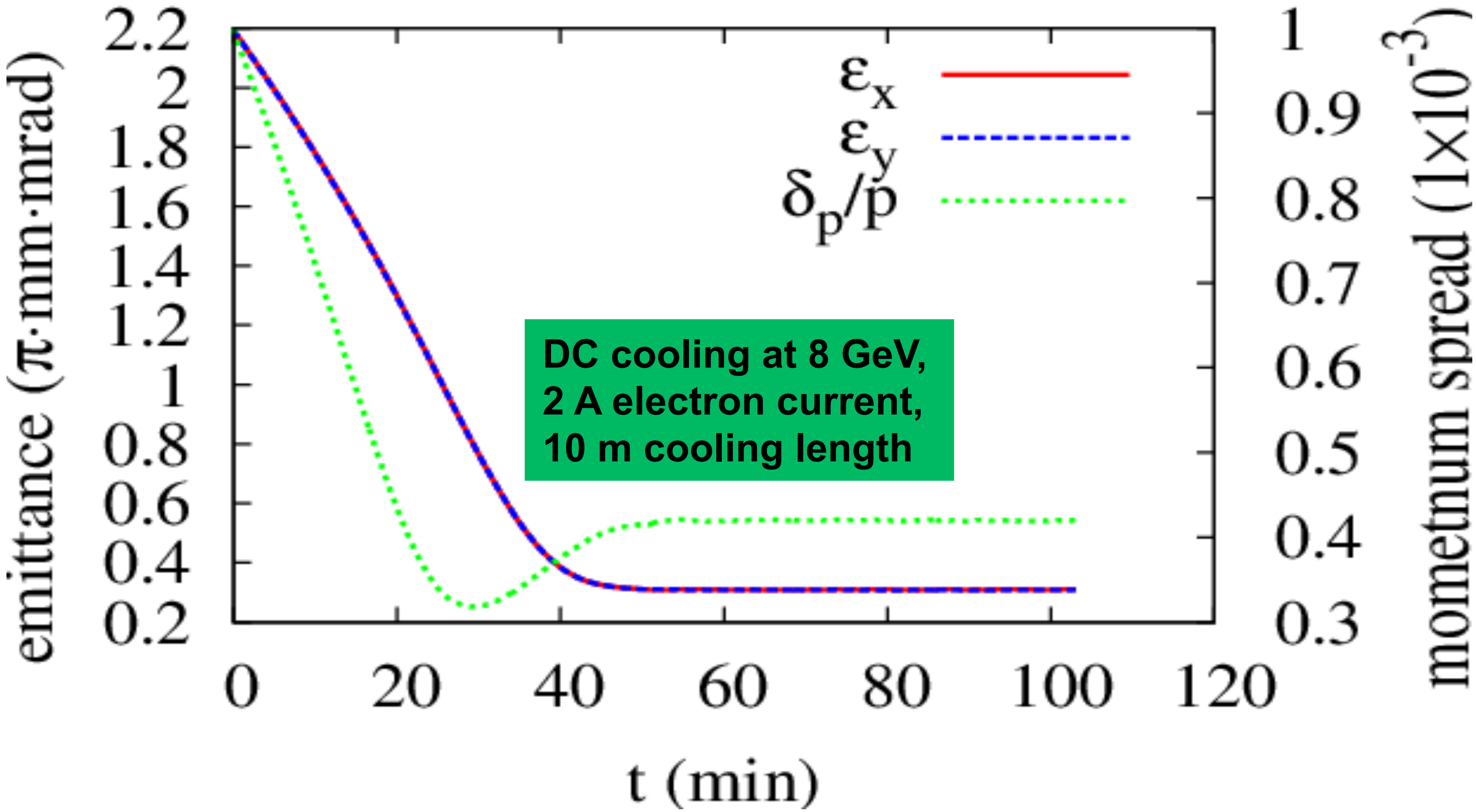
Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	MeV
Booster ring	DC	Injection/accumulation of positive ions	0.11 ~ 0.19 (injection)	0.062 ~ 0.1
		Emittance reduction	2	1.1
Collider ring	Bunched Beam (BB)	Maintain emittance during stacking	7.9 (injection)	4.3
		Maintain emittance	Up to 100	Up to 55

- **DC cooling for emittance reduction**
- **BB (bunched beam) cooling for emittance preservation**
- **We anticipate up to 2 orders of magnitude increase of combined cooling rate**

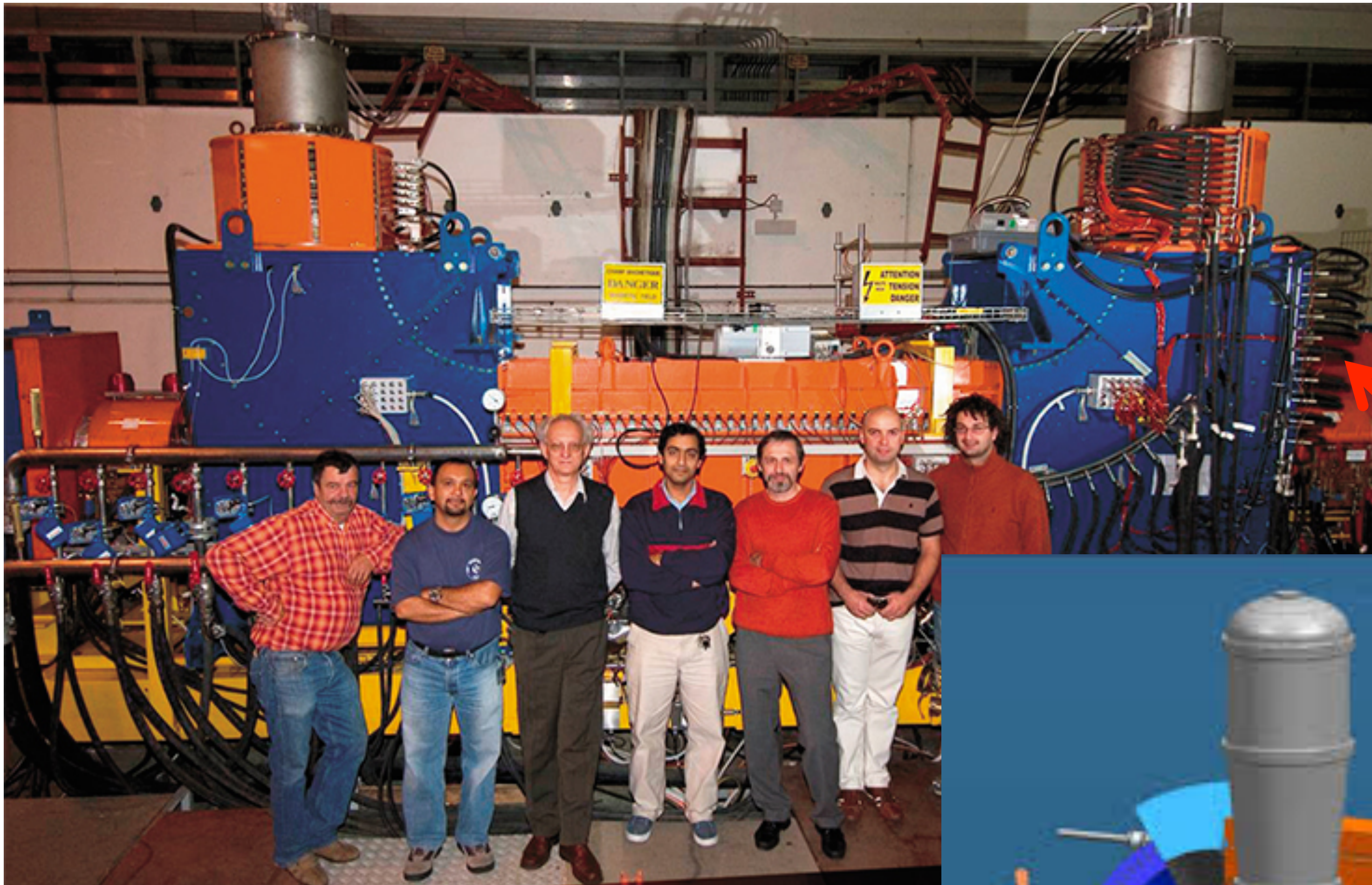
DC Cooling at 2 GeV

Simulation:

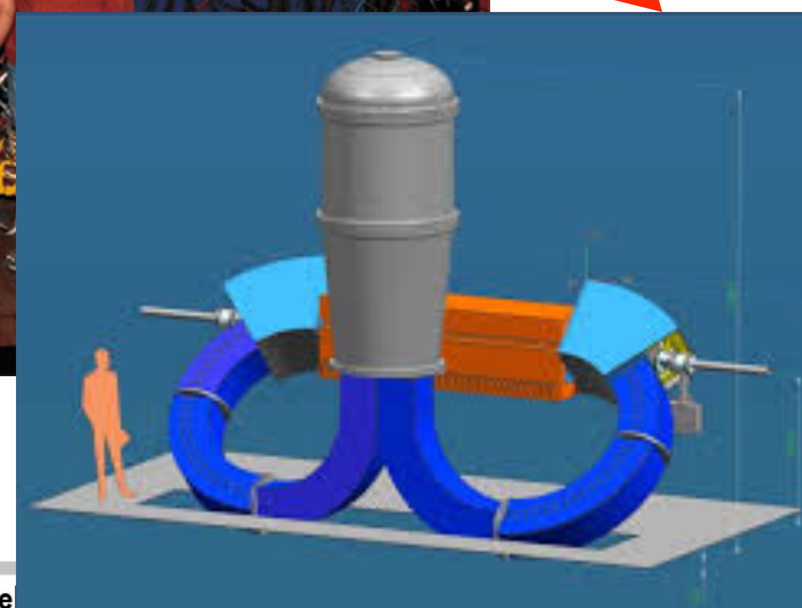
- Cooling time: ~30 min at 8 GeV (from 2 μm rad to 0.5 μm rad)
- DC cooler: 10 m and 2 A



Such DC Cooler is Available

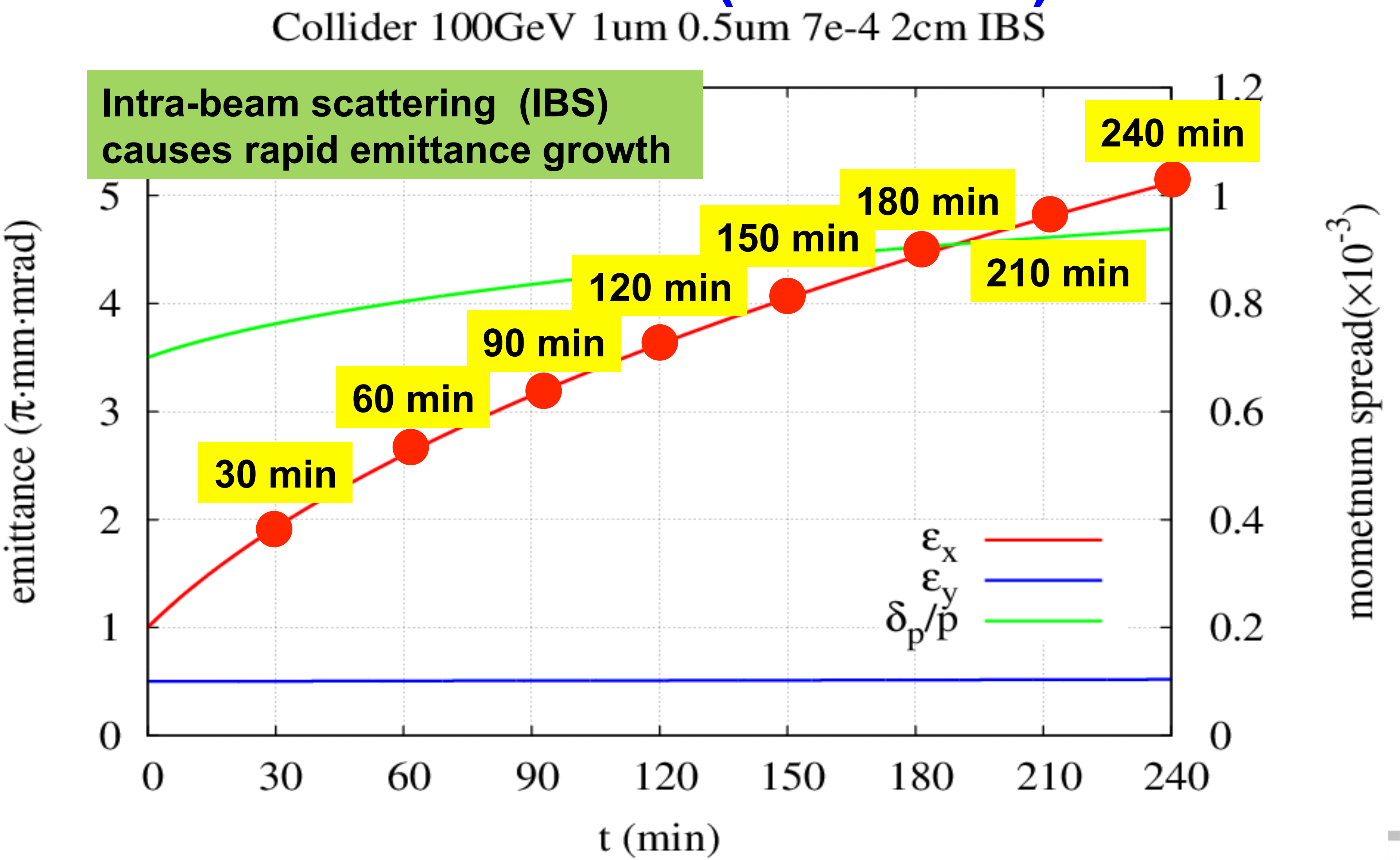


flip-over



2 MeV DC Cooler at
COSY, Juelich, Germany

What Happens if No Cooling During Beam Store (Collision)?



JLEIC Bunched Beam ERL e-Cooler

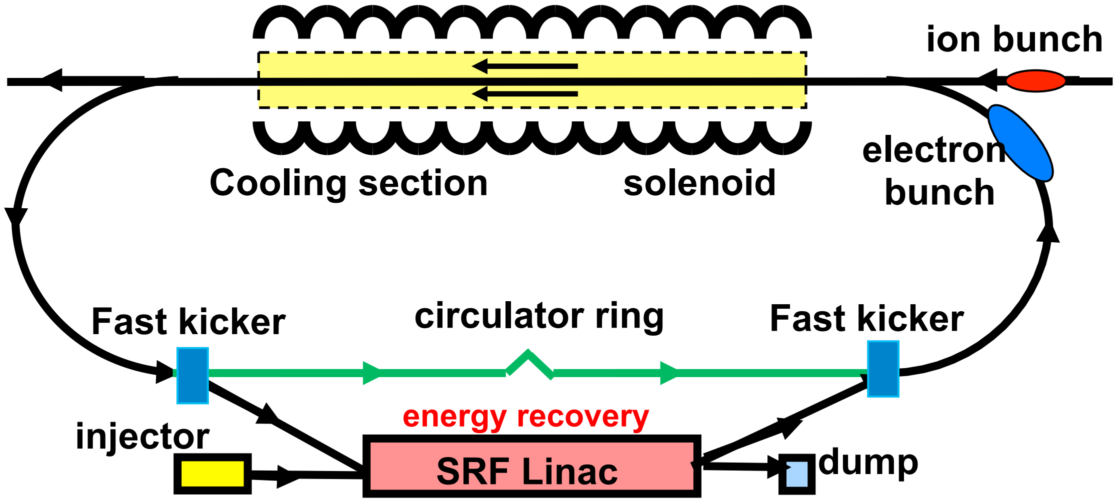
Requirement and technology challenges

- Proton collision energy up to 100 GeV
  - ➔ energy of the cooling electron beam is up to 55 MeV (for meeting the condition of co-moving with same velocity)
  - ➔ can not be a DC cooler, must use a SRF linac
  - ➔ Both proton and cooling electron beams are bunched with very short RMS length
- Need several ampere current (orders of magnitude beyond state-of-art)
- High beam power: ~100 MW

Technology choices

- Energy-recovery-linac (ERL)
- Magnetized beam/photo-gun
- Circulator cooler ring

Bunch revolutions in CCR		~25
Current in CCR/ERL	A	1.5/0.06
Electrons/bunch	10^{10}	1.25
Bunch repetition in CCR/ERL	MHz	476/30



Accelerator R&D

- High energy bunched beam electron cooling is essential for achieving ultra high luminosity for JLEIC, without it we loss about 3 to 5 times luminosity
- This is the No. 1 technology risk of JLEIC, hence the highest priority R&D
- We are conducting aggressive R&D on high energy electron cooling
  - Conceptual/analytic and simulation studies: design optimization and accurate production of cooling rate
  - Design of a bunched beam ERL based e-cooler (by a working group)
  - Development of key technology for this cooler: magnetized photo-cathode electron gun (LDRD), fast kicker
  - Experiment to demonstrate cooling of ions by a bunched electron beam
  - Development of a test facility using JLab LERF (formally ERL FEL) for testing a circulator electron cooler
- We have engaged in collaborations with other US lab and international institutions, and are making efforts to expend this collaborations