Luminosity Concepts and Issues of the Electron-Light Ion Collider

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Center for Advanced Studies of Accelerators

Beam Physics Seminar
Jefferson Lab
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OVERWIEW

We will discuss the constraints and possible solutions for luminosity level up to $10^{35}/cm^2s$ of the proposed Electron-Light Ion Collider at CEBAF (ELIC) based on use of 5-7 GeV multi-turn ERL (linac with circulator-collider ring, kicker operated) and 30-150 GeV ion storage ring with electron cooling (EC). The currently composed

for colliders with EC as a way to diminish the IB Simpact on luminosity. These considerations and other advances and issues have been addressed to the developing of the *luminosity calculator* and formulating the *minimum requirements* to the polarized electron sources and low energy part of ion accelerator complex.

OUTLINES

- Generalities
- ELIC draft layout
- Luminosity factors
- Electron cooling
- Short ion bunches
- Low beta-star
- Crab crossing
- Traveling ion focus
- Intra-beam scattering, cooling and flat beams
- Luminosity lifetime and calculator
- Beam-beam characterization of ELIC
- Forming the ion beam
- Forming the electron beam
- Conclusions and outlook

The CEBAF II/ELIC Upgrade at JLab

Highly likely to be "Absolutely Central" to Advancing Nuclear Science

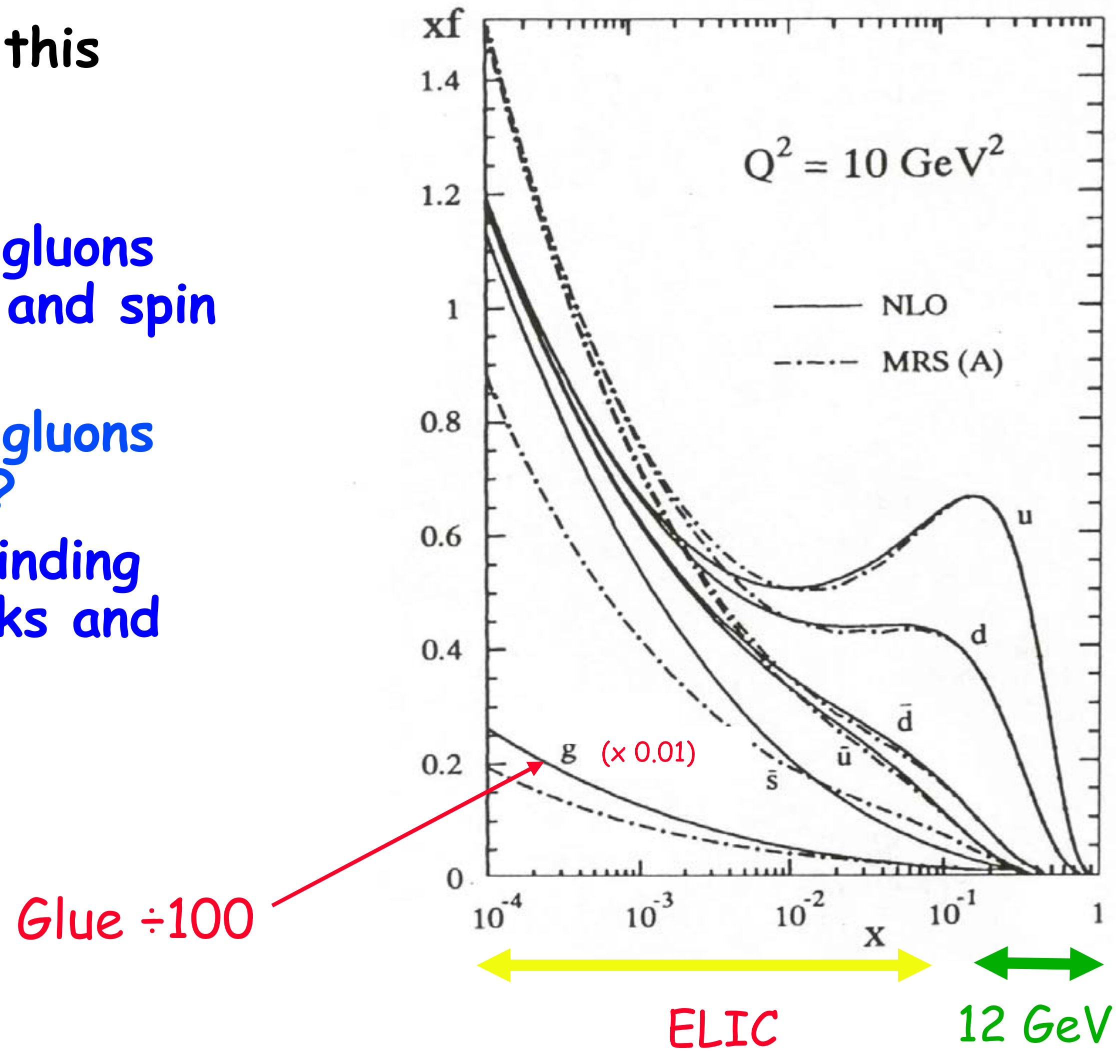
"Scientific /Engineering Challenges to Resolve"

Courtesy of Rolf Ent
2/15/03

CEBAF II/ELIC Upgrade - Science

Science addressed by this Upgrade:

- How do quarks and gluons provide the binding and spin of the nucleons?
- How do quarks and gluons evolve into hadrons?
- How does nuclear binding originate from quarks and gluons?



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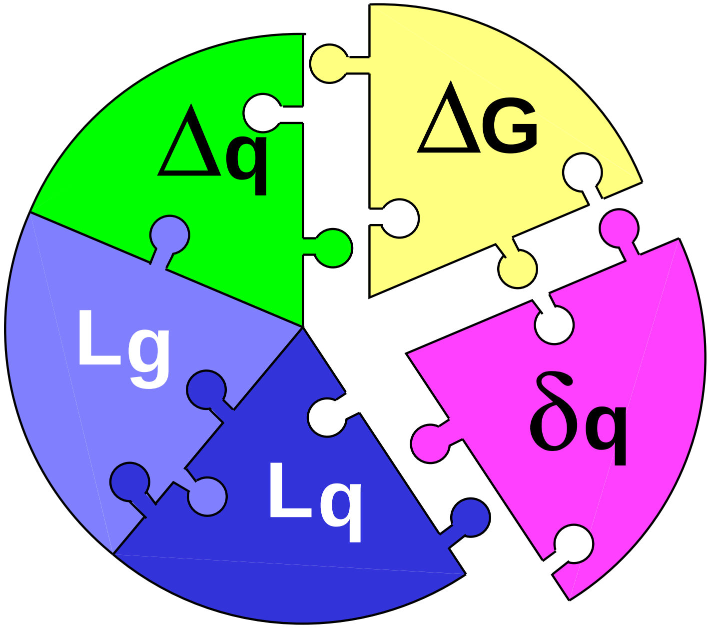
The Spin Structure of the Proton

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- From NLO-QCD analysis of DIS measurements … (SMC analysis)
  $\Delta\Sigma = 0.38$ (in AB scheme)
  $\Delta G = 1.0^{+1.9}_{-0.6}$,,
- quark polarization $\Delta q(x)$
  →first 5-flavor separation from HERMES (see later)
- transversity $\delta q(x)$
  →a new window on quark spin
  →azimuthal asymmetries from HERMES and JLab-6
- gluon polarization $\Delta G(x)$
  →RHIC-spin and COMPASS will provide some answers!
- orbital angular momentum L
  →how to determine? → GPD's



CEBAF II/ELIC Upgrade can solve this puzzle due to large range in x and Q^2 and precision due to high luminosity

Courtesy of Rolf Ent 2/15/03

CEBAF II/ELIC Upgrade - Science

- At present, uncertain what range of Q^2 really required to determine complete structure of the nucleon. Most likely Q^2 ~ 10 GeV^2?
  - Upcoming years wealth of data from RHIC-Spin, COMPASS, HERMES, JHF, JLab, etc.
  - DVCS (JLab-12!) and single-spin asymmetries possible at lower Q^2
  - Range of Q^2 directly linked to required luminosity
- What energy and luminosity, fixed-target facility or collider (or both)?
- JLab Science Policy Advisory Group: "The goal must be to find the best match to the science needs on the time scale of the next NSAC long range plan."

Upgrade is highly likely to be "Absolutely Central" to Field

Courtesy of Rolf Ent

CEBAF Beyond 12 GeV

- Clear scientific case by 12-GeV JLab Upgrade, addressing outstanding issues in Hadron Physics:
  - Unprecedented measurements to region in x (> 0.1) where basic three-quark structure of nucleons dominates.
  - Measurements of correlations between quarks, mainly through Deep-Virtual Compton Scattering (DVCS) and constraints by nucleon form factors, in pursuit of the Generalized Parton Distributions.
  - Finishing the job on the transition from hadronic to quark-gluon degrees of freedom.

- Over the next 5-10 years, data from facilities worldwide concurrent with vigorous accelerator R&D and design will clarify the key physics and machine issues, revealing the relative advantages and technical feasibility of these accelerator designs and permitting an informed choice of design approaches.
  - 25 GeV Fixed-Target Facility?
  - Electron-Light Ion Collider, center-of-mass energy of 20-65 GeV?

Courtesy of Rolf Ent

CEBAF II/ELIC Upgrade - Readiness

- Electron-Light Ion Collider (ELIC)
  - R&D needed on
    - High Charge per Bunch and High Average Current Polarized Electron Source
    - High Energy Electron Cooling of Protons/Ions
    - High Current and High Energy demonstration of Energy Recovery
    - Integration of Interaction Region design with Detector Geometry
  - NSAC Report: "Strong consensus among nuclear scientists to pursue R&D over the next three years to address a number of design issues"

- 25-GeV Fixed-Target Facility
  - Use existing CEBAF footprint
  - Upgrade Cryo modules to 12-GeV design (7-cell design, 18 MV/m)
  - Change ARC magnets, Switchyard, Hall Equipment

Significant "Scientific/Engineering Challenges to Resolve"

Courtesy of Rolf Ent

ELIC: A High Luminosity and Efficient Spin Manipulation Electron-Light Ion Collider at CEBAF

Lia Merminga, Ya. Derbenev

Center for Advanced Studies of Accelerators

Jefferson Lab

CIPANP 2003

Conference on the Intersections of Particle and Nuclear Physics

Grand Hyatt Hotel - New York City

May 19-24, 2003

Nuclear Physics Requirements

- The features of the facility necessary to address these issues:
  - Center-of-mass energy between 20 GeV and 45 GeV
    with energy asymmetry of ~10, which yields
    $E_e \sim 3$ GeV on $E_i \sim 30$ GeV up to $E_e \sim 5$ GeV on $E_i \sim 100$ GeV
  - CW Luminosity from 10^{33} to 10^{35} cm^{-2} sec^{-1}
  - Ion species of interest: protons, deuterons, ^3He
  - Longitudinal polarization of both beams in the interaction region $\geq$ 50% –80% required for the study of generalized parton distributions and transversity
  - Transverse polarization of ions extremely desirable
  - Spin-flip of both beams extremely desirable

Courtesy of Lia Merminga

Two Design Scenarios

- Two accelerator design scenarios have been proposed:
  - ring – ring*
  - linac – ring
- Linac – ring option presents advantages with respect to
  - spin manipulations
  - reduction of synchrotron radiation load on the detectors
  - wide range of continuous energy variability
- Feasibility studies were conducted at BNL† (based on RHIC) and Jefferson Lab‡ to determine whether the linac-ring option is viable

* Y. Shatunov et al., 2nd EPIC Workshop, 2000

† I. Ben-Zvi, J. Kewisch, J. Murphy, S. Peggs, NIM A Vol. 463 (2001)

‡ L. Merminga, G. Krafft, V. Lebedev, Proc. of HEACC 2001

Courtesy of Lia Merminga

Conclusions of Generic Linac-Ring Studies

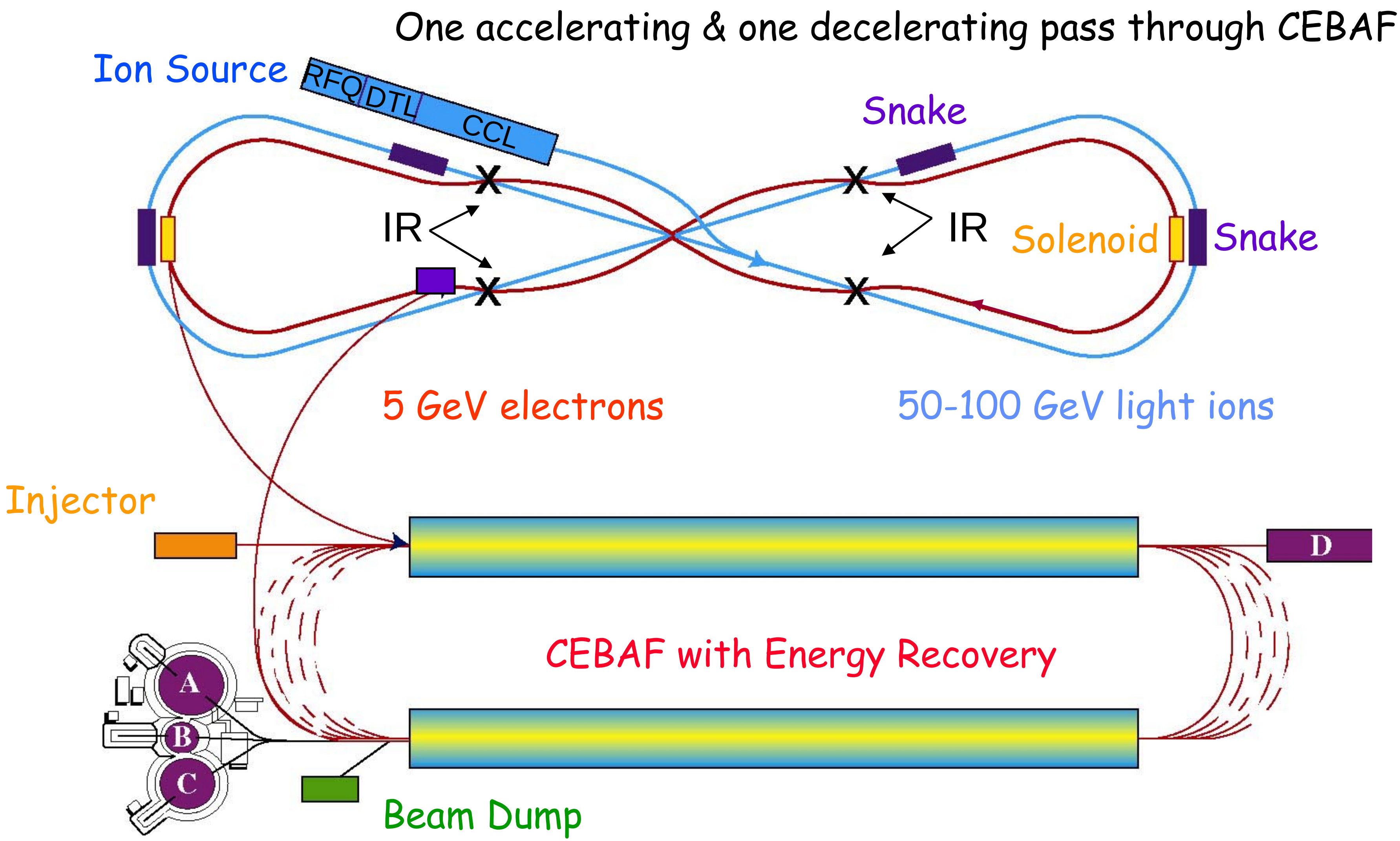
- Luminosities at or greater than 10^{33} cm^{-2} sec^{-1} appear attainable with an electron linac-on-proton ring design

- RF power and beam dump considerations require that the electron linac is an Energy Recovering Linac (ERL)

- Electron cooling of the protons is required for luminosity at or above 10^{33} cm^{-2} sec^{-1}

Courtesy of Lia Merminga

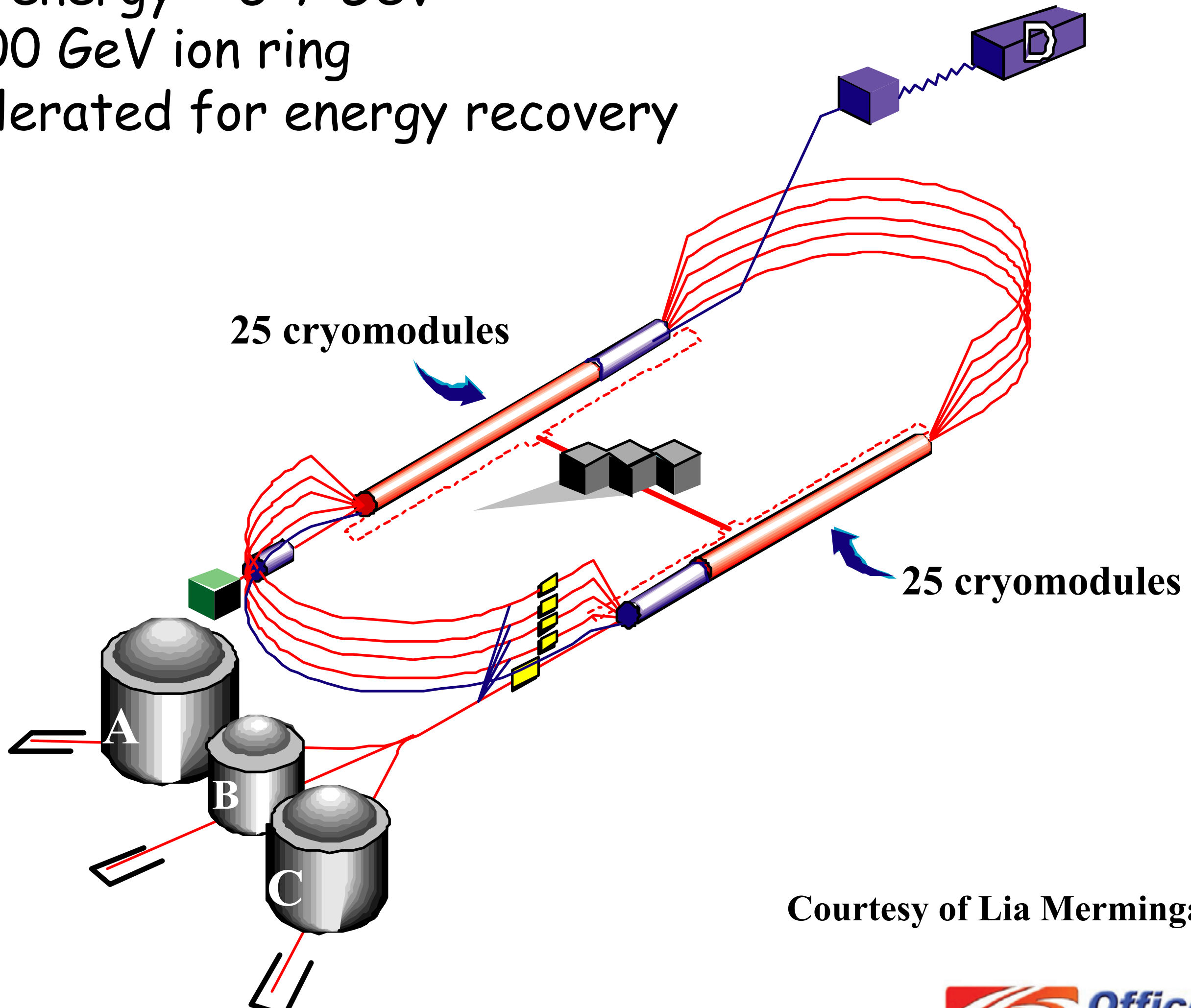
ELIC Layout



One accelerating & one decelerating pass through CEBAF
Ion Source
RFQ
DTL
CCL
Snake
IR
IR
Solenoid
Snake
5 GeV electrons
50-100 GeV light ions
Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

CEBAF with Energy Recovery

- Install 50 Upgrade CEBAF cryomodules at ~20 MV/m in both linacs
- Single-pass CEBAF energy ~ 5-7 GeV
- Collision with 50-100 GeV ion ring
- Electrons are decelerated for energy recovery



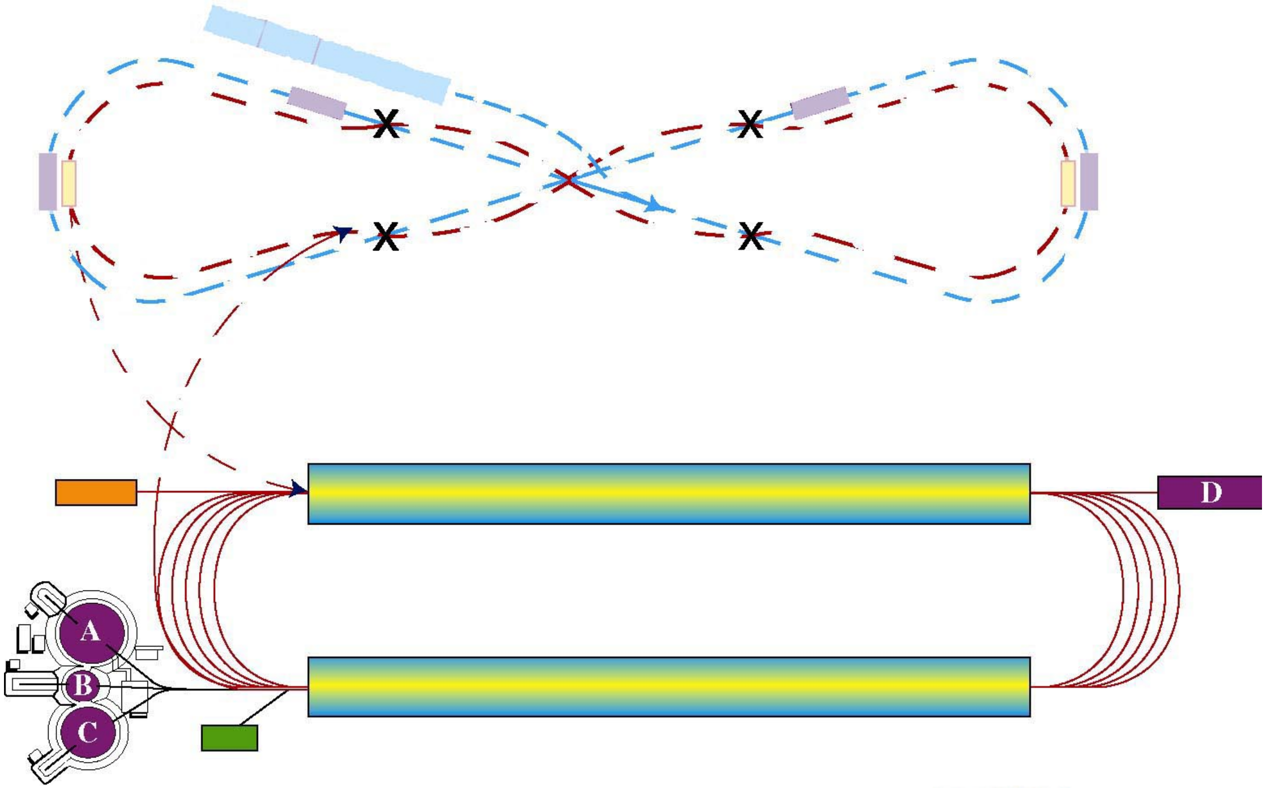
Courtesy of Lia Merminga

The same electron accelerator can also provide 25 GeV electrons for fixed target experiments for physics

- Implement 5-pass recirculator, at 5 GeV/pass, as in present CEBAF

(One accelerating & one decelerating pass through CEBAF ⇒ 20-45 GeV CM Collider Program)

- Exploring whether collider and fixed target modes can run simultaneously



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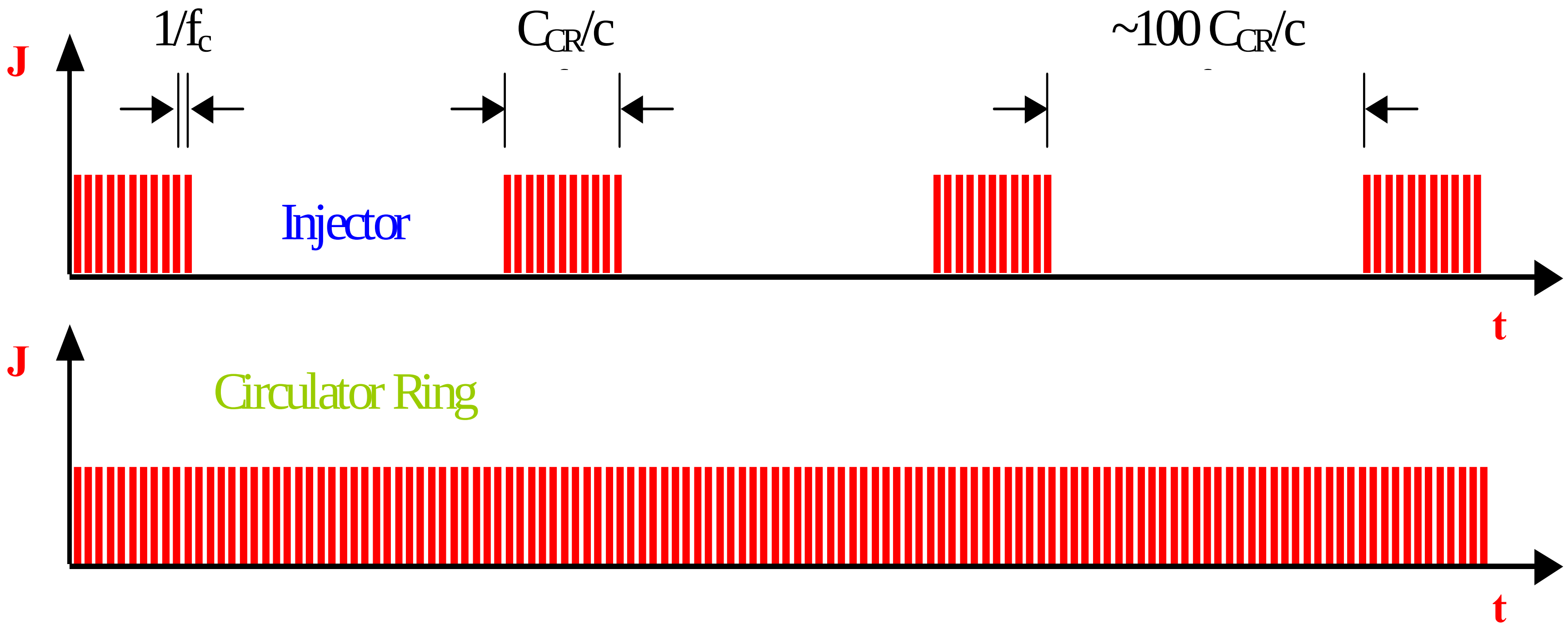
Circulator Ring



Different filling patterns are being explored
(Derbenev, Hutton, Litvinenko)

LCR features

Respectively the RR option:

- Easy spin (no crossing resonances, no quantum depolarization)
- Emittance determined by the photoinjector (CR regime)
- Easily variable energy
- Easier interaction point (no depolarization of bends to appear)
- Larger admissible beam-beam tune shift (higher lumi)
- Larger accessible circulating current

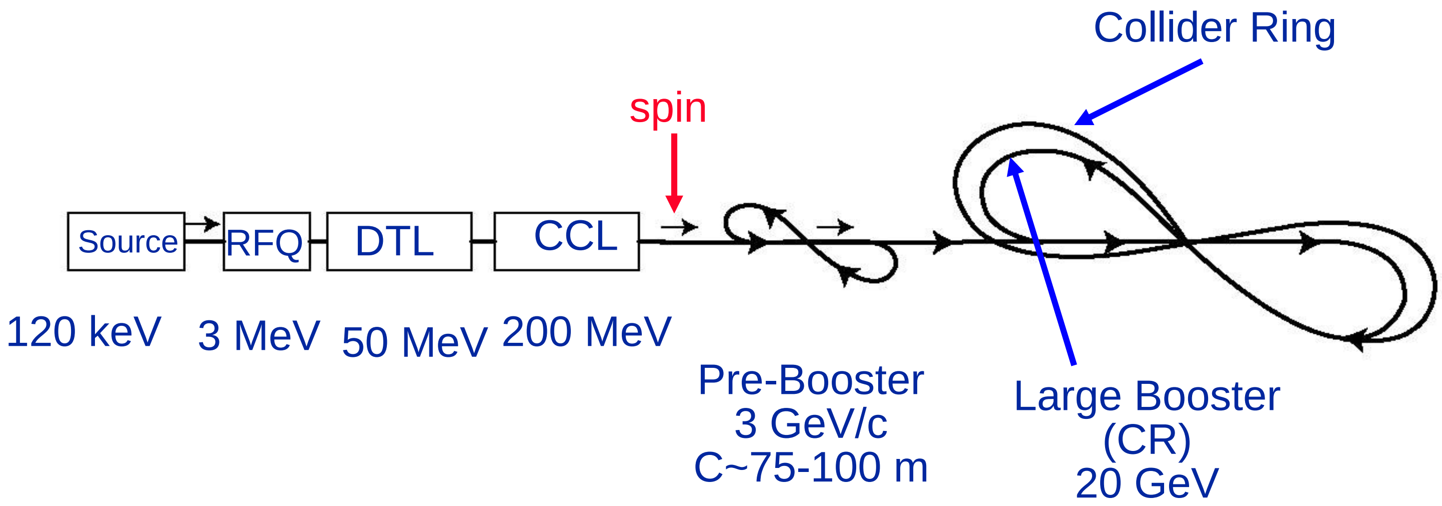
Respectively the LR option:

- Photoinjector released of high average current
- Reduction of BBU in SRF linac
- Reduction of HOM

Issues:

- Fast ejection-injection (develop best kickers)
- Microwave stability of short bunches in CR
- CSR effect
- SRF in CR to maintain short bunches

Ion Complex


Collider Ring
spin
Source
RFQ
DTL
CCL
120 keV
3 MeV
50 MeV
200 MeV
Pre-Booster
3 GeV/c
C~75-100 m
Large Booster
(CR)
20 GeV

A Version of Ion Linac: From Protons to Ar

Courtesy of P.N. Ostroumov, Physics Division, ANL
September 18, 2003

The linac includes room temperature RFQ and interdigital IH structure operating at fixed velocity profile. These two structures are very effective up to ~4 MeV/u especially for pulsed machines. At 7.5 MeV/u the argon beam must be stripped to charge state 17+. ECR source can provide charge state 9+ with pulsed current up to several milliamps.

After stripping some dog leg system should clean unwanted charge states. Based on the RIA the cost of such linac will be ~$50M. Should be some difference in the cost due to the pulsed mode of operation – the cryogenic load should be much smaller than for the RIA cavities.

Total length	120 m
Output energy for $^{36}Ar^{17+}$	95 MeV/u
Output energy for protons (H-minus)	200 MeV/u
Fundamental frequency	115 MHz
Number of 115 MHz QWR (RIA type) E_{peak} Voltage β_G	68 20 MV/m 1.58 MV 0.15
Number of 345 MHz DSR (RIA type) E_{peak} Voltage β_G	63 20 MV/m 2.28MV 0.394

Element	Ar beam charge	Ar beam energy, MeV/u	Proton energy, MeV	Length, m	# of cryostats
115 MHz RFQ	$^{36}Ar^{9+}$	1.0	1.0	3.0	-
115 MHz Room Temperature IH structure	$^{36}Ar^{9+}$	4.0	4.0	6.0	-
115 MHz QWR	$^{36}Ar^{9+}$	7.5	20.7	10.0	2
115 MHz QWR	$^{36}Ar^{17+}$	40.4	78.3	40.6	7
345 MHz DSR	$^{36}Ar^{17+}$	94.5	199.8	51.3	9

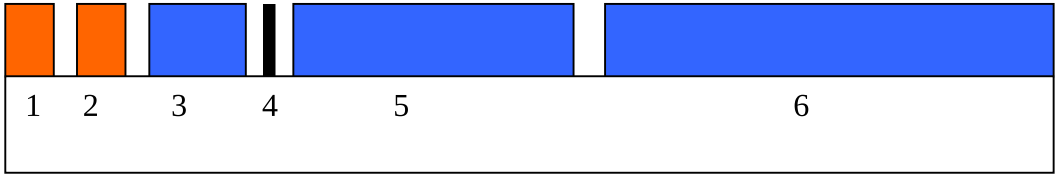


Fig.1. Layout of the linac. 1-RFQ, 2- RT IH structure
3 and 5 - QWR, 115 MHz
4 – stripper for Argon beam,
6 – 345 MHz double-spoke resonators.

A Version of Ion Linac: From Protons to Ar

Courtesy of P.N. Ostroumov, Physics Division, ANL
September 18, 2003

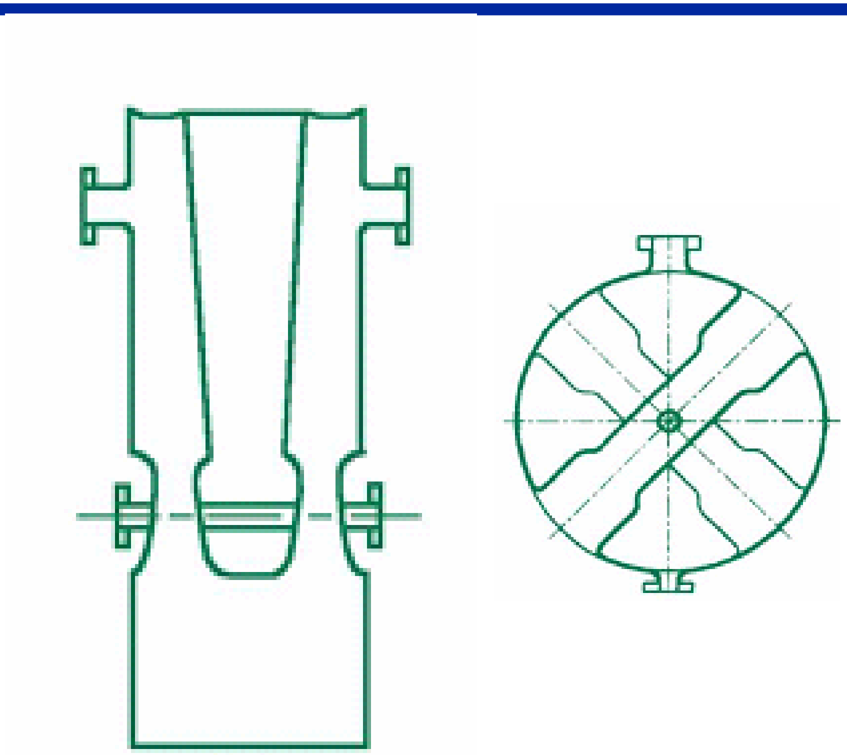


Fig. 2. 115 MHz QWR, beta=0.15 and 2-spoke cavity, 345 MHz, beta=0.4

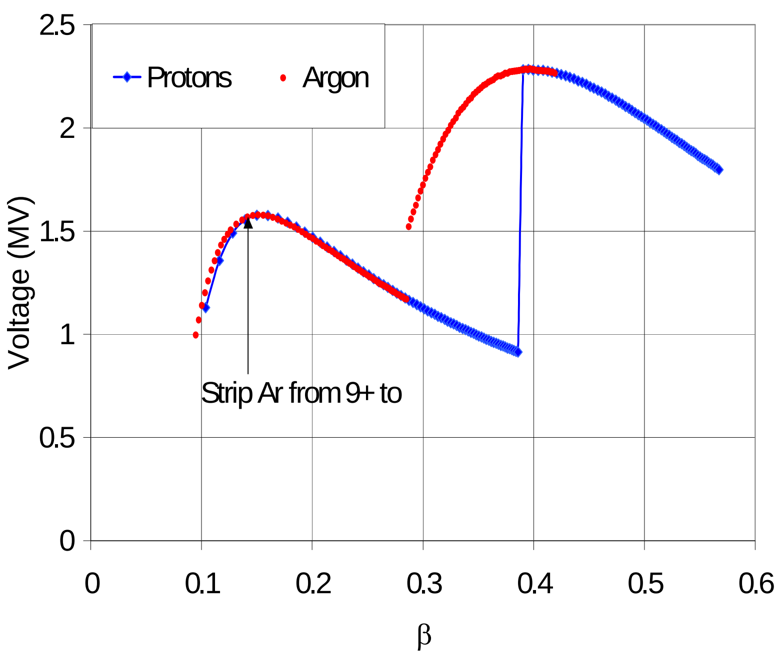


Fig. 3. Voltage gain per resonator as a function of ion velocity.

Accelerated beam parameters:
Transverse emittance (5·rms) ~ 1 π·mm·mrad
Longitudinal emittance (5·rms) <10 π·keV/u·nsec
Momentum spread can be controlled by the rebuncher and can be as low as ~0.05%.

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Luminosity factors

$$L = f \times N_e N_i / (4\pi\sigma_x\sigma_y)^*$$

Dynamical parameterization:

$$L e^2 = (JE\xi/\beta^*)_e = (JE\xi/\beta^*)_i$$

e – *particle charge*
J – *beam current*
$E = \gamma mc^2$ – *energy*
$\xi_e = N_i r_e / 4\pi\sqrt{(\varepsilon_x \varepsilon_y)_e}$ - *beam-beam tune shift of e-beam*
$\xi_i = N_e r_i / 4\pi\sqrt{(\varepsilon_x \varepsilon_y)_i}$ --------------------------- *of i-beam*
$\varepsilon = \gamma\,\theta^*\sigma^*$ - *normalized emittance*
$\beta^* = \sigma^*/\theta^*$ - *"beta-star"*

Conventional demand: $\beta^* \geq \sigma_z^*$ *(bunch length)*

Luminosity degradation

- Multiple IBS (intra-beam scattering)
- Long term beam-beam stochastic particle escape
- Noise
- Residual gas
- Background collision scattering

ELIC Parameter Table

Parameter	Units	Point Design 1		Point Design 2		Point Design 3	
		e^-	Protons	e^-	Protons	e^-	Protons
Energy	GeV	5	50	5	50	5	50/100
Cooling	-	-	Yes	-	Yes	-	Yes
CR			No		Yes		Yes
Lumi	cm^{-2} sec^{-1}	1×10^{33}		1×10^{34}		6×10^{34} / 1×10^{35}	
N_{bunch}	ppb	1×10^{10}	2.5×10^{10}	2×10^{10}	5×10^{9}	1×10^{10}	1×10^{10}
f_c	MHz	150		500		1500	
I_{ave}	A	0.24	0.6	1.6	0.4	2.5	2.5
σ^*	μm	14	14	6	6	4.5/3.2	4.5/3.2
ε_n	μm	10	0.2	10	0.2	10	0.1
β^*	cm	20	5	4	1	2/1	1
σ_z	cm	0.1	5	0.1	1	0.1	1
ξ_e / ξ_i	-	0.5	0.006	0.1	0.01	0.2	0.01
$\Delta\nu_L$	-	-	0.05	-	0.05	-	0.09

Electron Cooling and Luminosity

Optimizing the Electron Cooling

Measures to undertake:

- Equalize cooling rates using the *dispersive mechanism*
- This allows one to avoid beam extension, hence, relax of the *alignment demands*
- *Reduce x-y coupling outside the cooling section to a minimum*

Then, one gets a minimum critical electron current and ion equilibrium (flat beam) against IBS

Very Short Ion Bunches

- *Electron cooling in cooperation with a strong SRF allows to obtain very short ion bunches (1cm or even shorter)*

Circulators for Electron Cooling

- Cooling of intense ion beams (up to a few Amps) requires a high electron current (hundreds of mA), in order to defeat the IBS

This request can be satisfied at ERL incorporated with Circulator

Luminosity potentials in colliders with cooling

Decrease the bunch length ⇒ design a low beta-star

Decrease the transverse emittances

Raise the tune shift limit: large Q_s + damping

Diminish the IBS using flat beams (non-coupled optics)

Raise the bunch repetion rate (with current) by an arrangement for crab crossing

Design the Traveling Ion Focus (at $\sigma_{zi} \gg \sigma_{ze}$)

p/e colliding beams at proton beam under cooling (ELIC)

Parameter	Unit	Value
Beam energy	**GeV**	**150/7**
Cooling beam energy	**MeV**	**75**
Bunch collision rate	**GHz**	**1.5**
Number of particles/bunch	**10^{10}**	**.2/1**
Beam current	**A**	**.5/2.5**
Cooling beam current	**A**	**2.5**
Energy spread	**10^{-4}**	**3**
Bunch length	**mm**	**5**
Beta-star	**mm**	**5**
Focal length	**m**	**4**
Large beta	**km**	**3.2**
Horizontal emittance, norm	**μm**	**1/100**
Horizontal beam size at large beta	**mm**	**5**
Vertical emittance, norm	**μm**	**.01/1**
Number of interaction points		**4**
Total beam-beam tune shift		**.04/.16**
Space charge tune shift in p-beam		**.02**
Luminosity over 4 IP	**10^{35}/cm^2.s**	**2***
Cooling/IBS time in p-beam core	**min**	**5**
Core & lumi lifetime	**h**	**20**
Lifetime due to background scattering at collisions	**h**	**100**

***With e-bunches about 1 – 2 mm as short, the luminosity might be increased by a factor of 3 by the arrangement of the Traveling Ion Focus**

Short ion Bunches and Low β^*

Table 1: Cooled p-bunches in a ring with SRF resonators

Parameter	Unit	Value
Beam energy	GeV	150
Resonators frequency	GHz	1.5
Voltage amplitude	MV	100
Ring circumference	Km	1.2
Compaction factor	10^{-3}	4
Synchrotron tune		.06
Energy acceptance	%	.3
Energy spread, rms	10^{-4}	3
Bunch length, rms	mm	5

Table 2: Final focus of EIC with short bunches (p/e)

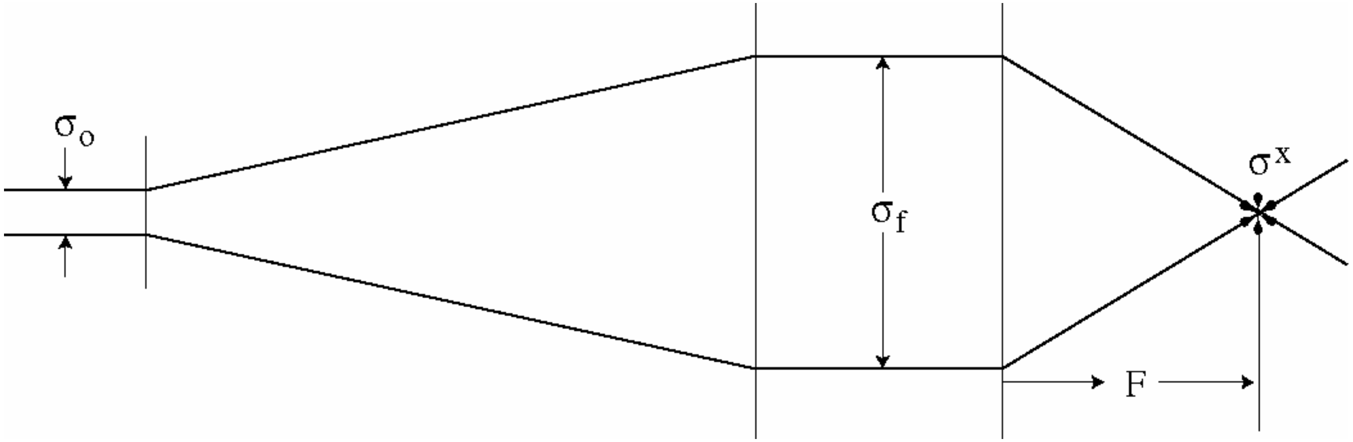
Beam energy	GeV	150/7
Bunch length, rms	mm	5/5
Focal length	m	4/4
Large beta	Km	3.2/3.2
Beta-star	mm	5/5
Transverse emittance, norm, rms	μm	1/100
Beam size at large beta, rms	mm	5/5
Beam size at star point, rms	μm	6/6

Low Beta-star for Ion Beam

Small transverse and longitudinal beam size (both after cooling) allow one to design quite a strong final focus:

β^* about 1 cm or even shorter

- **Chromaticity seems not an obstacle, and it can be compensated if needed**



$$\beta^* = \frac{F^2}{\beta_f} = \frac{F^2}{\beta_0}\left(\frac{\sigma_0}{\sigma_f}\right)^2 = \frac{F^2}{\gamma\sigma_f^2}\varepsilon_n$$

Parameter	Units	Value
γ		100
F	m	3
σ_f	mm	2
ε_n	4×10^{-5} cm	1

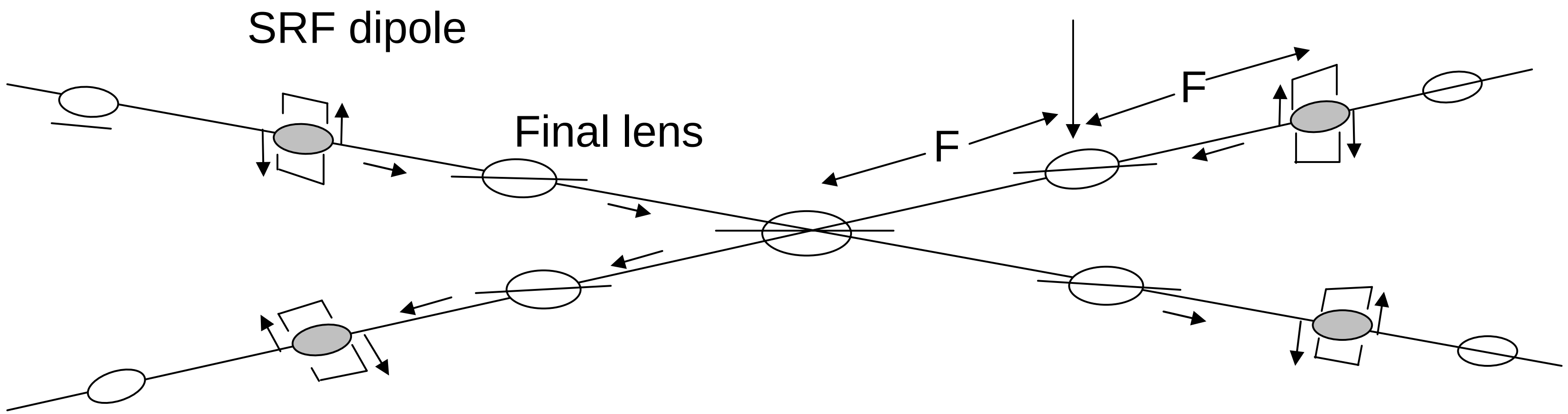
→ β^*=1 cm

Crab Crossing

R. Palmer 1988, general idea

Short bunches make feasible the Crab Crossing

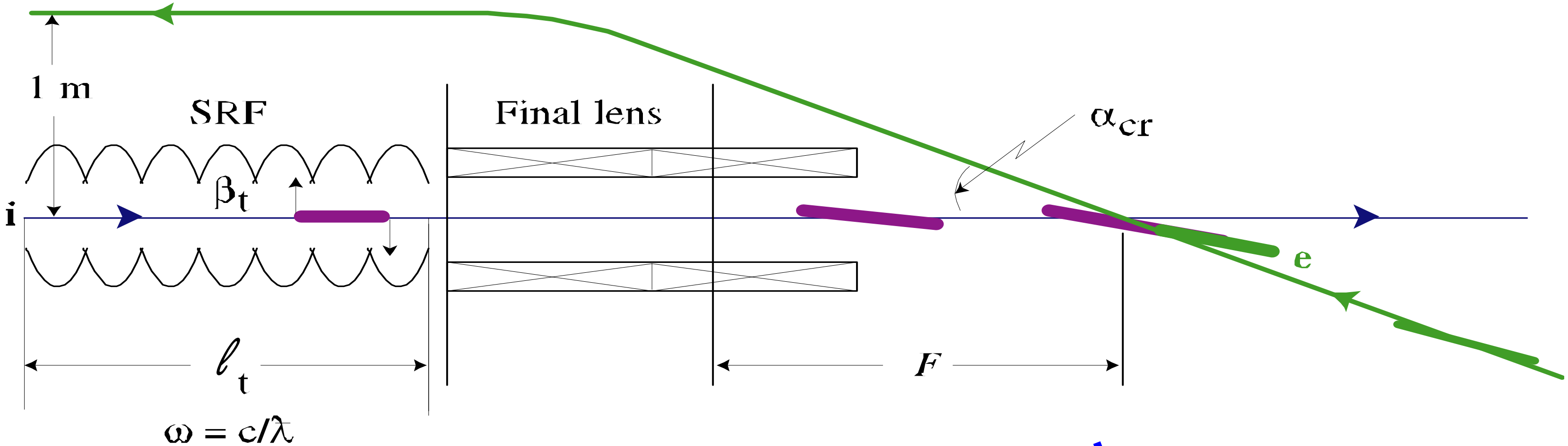
SRF deflectors 1.5 GHz can be used to create a proper bunch tilt



Parasitic collisions are avoided without loss of luminosity

Crab Crossing for ELIC

- Short bunches also make feasible the Crab Crossing:
- SRF deflectors 1.5 GHz can be used to create a proper bunch tilt



$$\alpha_{cr} = 2\alpha_f = 2\theta_t \frac{F}{\lambda} 2\pi$$

$$\theta_t = \frac{eB_t l_t}{E}$$

$E = 100\ GeV$

$F = 3\ m$

$\lambda = 20\ cm \quad (1.5\ GHz$

$B_t = 600\ G \quad (= 20\ MV/m)$

$l_t = 4\ m$

$\sigma_f = 1\ mm$

$$\alpha_{cr} = 0.1$$

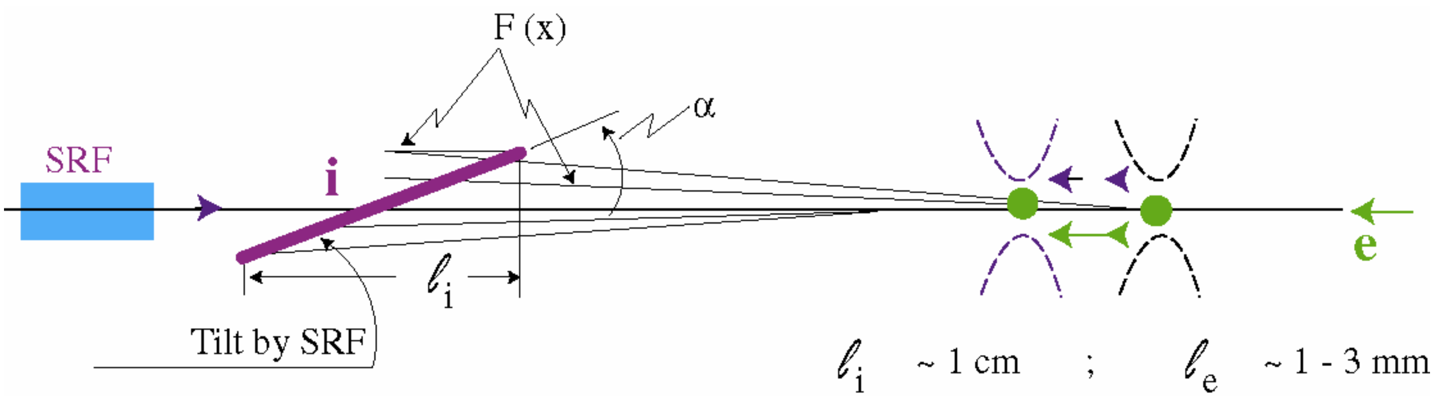
$$\theta_t = 5 \cdot 10^{-4}$$

Traveling Ion Focus

R. Brinkmann, 1995, general idea

SRF deflectors (the same as for crab crossing) also can be used for arrangement of Traveling Focus (at *li >> le*), in cooperation with sextupole non-linearity introduced in the final focusing magnets

- Traveling Focus allows one to decrease *Ni* or use bunches of a larger εi



$$\varphi = \frac{\omega}{c} s \qquad \alpha = \frac{dx}{ds} \qquad \beta_i^* << l_i$$

Matching condition: $\frac{dF}{ds} = \frac{1}{2}$ **hence,** $\frac{dF}{dx} = \frac{1}{2\alpha}$

$\Delta F_b \sim \frac{1}{2} l_i$ **(over the bunch)**

ΔF **over the aperture:**

$$\Delta F_A = \frac{A}{2\alpha}$$

The feasibility condition:

$$\Delta F_A << F \quad \Rightarrow \quad \alpha >> \frac{A}{2F}$$

Ease to satisfy

Characterization of beam-beam limitations

Coherent space charge effects

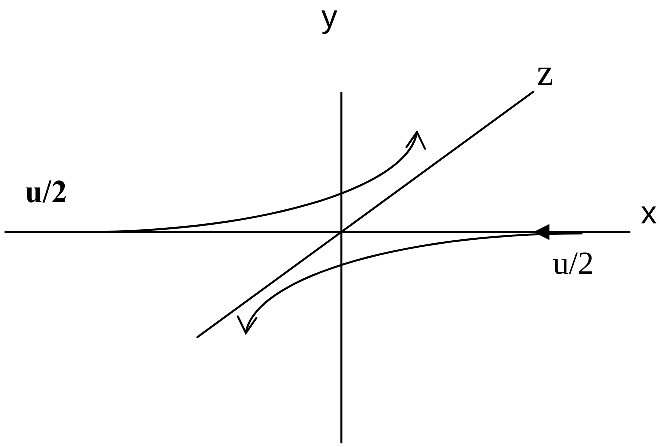
- The active electron impedance is reduced at CR regime (compare one loop regime)
- Linac noise effect is reduced, as will
- What is important, generally: Landau damping due to the non-linear tune shift spread
- Large synchrotron tune raises the head-tail effects threshold

Incoherent interaction

- Tune shifts are modest in value
- Large synchrotron tune (.06 of ions, up to .3 of electrons) prevents Chirikov's stochasticity
- The Arnold's diffusion is rarified and weakened, as well
- E-beam "lifetime" is short (compare a storage ring)

IBS, beam-beam, EC and luminosity

IBS heating mechanism: energy exchange at intra-beam collisions increases the energy spread and excites the transverse oscillators via orbit dispersion



IBS rate:

$$\frac{d}{dt}\left(\frac{\Delta\gamma}{\gamma}\right)^2 \succ \frac{n}{u}$$

density

velocity spread

IBS, beam-beam, EC and luminosity (con't)

Multiple IBS time:

$$\tau_i = \frac{8\gamma\varepsilon_x\varepsilon_y\Delta\gamma\sigma_z}{N_p r_p^2 c\cdot\log_i}\cdot\frac{\Delta\gamma/\gamma}{\gamma\theta_y}$$

Flat beams are profitable, since the velocity spread grows with flatness. To gain this, one has to reduce the x-y coupling in the ring to an optimum.

Cooling time (optimized):

6-D emittance, norm

$$\tau_c = \frac{8\gamma\varepsilon_6}{\eta N_e r_e r_p c \quad \log_c}\bullet\frac{S_e}{S_i}$$

Beam area

$$N_e > N_e^{cr} = N_p \frac{m}{\eta M}\frac{\gamma\theta_y}{\Delta\gamma/\gamma}\frac{\log_i}{\log_c}\ ;\ \eta = \frac{L_c}{C}$$

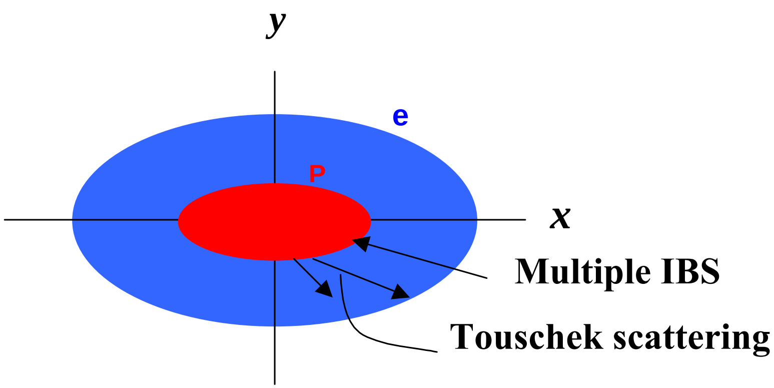
; $\log_c \sim 2 - 5$

Flat colliding beams equilibrium

At low coupling, cooling results in flat beams

x – emittance is determined by the IBS

y – emittance is limited by the beam-beam interaction



- Luminosity is determined by the beam area
- IBS effect is reduced by a factor of the aspect ratio
- Cooling effect at equilibrium can be enhanced by flattening the electron beam in cooling section solenoid

Flip-flop dance is eliminated under the condition

$$\frac{\gamma\theta_y}{\Delta\gamma/\gamma} \approx \frac{\gamma}{Q}æ$$

æ — x-y coupling parameter

Q — betatron Q-value

Core & Luminosity lifetime

Touschek' lifetime, T

IBS at large momentum transfer *(single scattering*) drives the particles out of the beam core, limiting the luminosity lifetime.

The *optimum equilibrium* is found by equating between time of *single scattering cooling time* for the scattered particles and *beam cycle* time of the collider. It results in the relationships:

$$T = (\tau_i)_{eq} \bullet (\log_i)^2 = \frac{\gamma^2 N_i \left(\frac{\Delta\gamma}{\gamma} \sigma_z\right)_{eq}}{2\pi^2 c \xi_i^2} \bullet \log_i$$

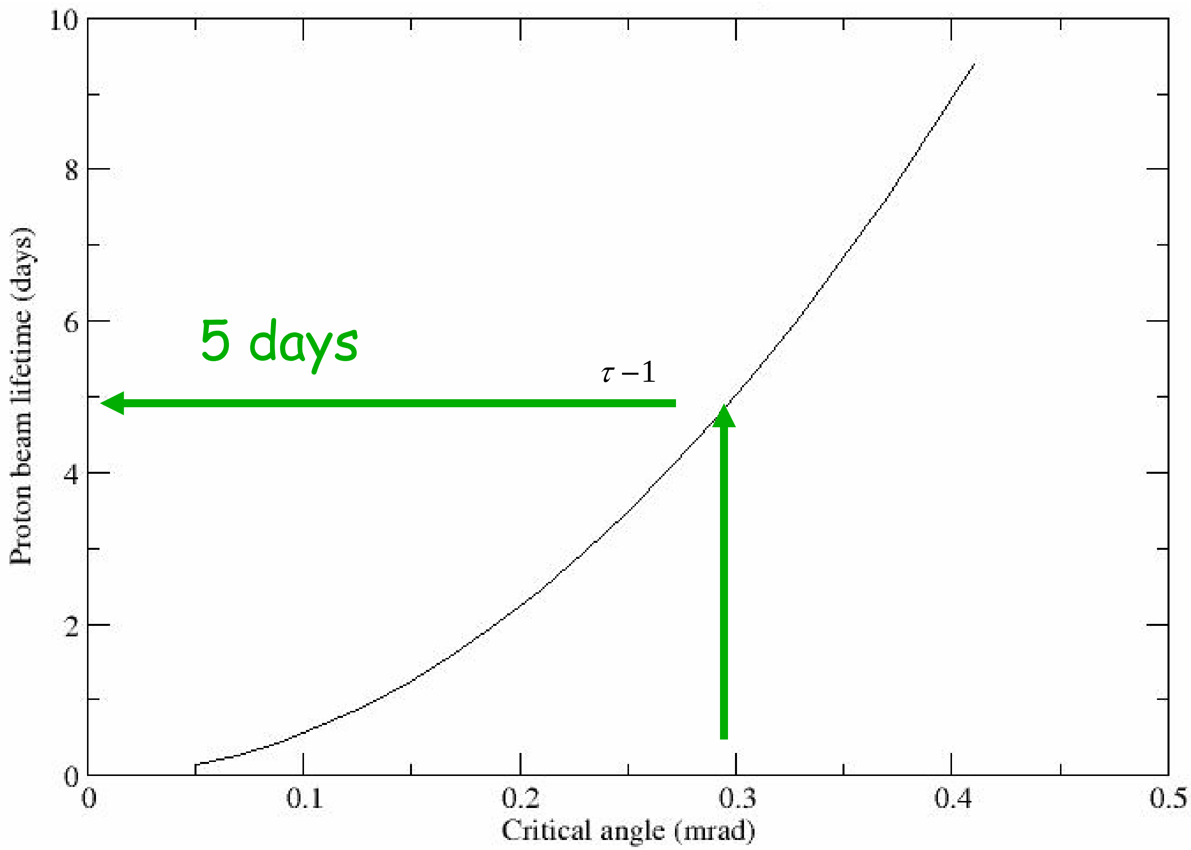
$$\frac{S_e}{S_i} = \frac{N_e}{N_e^{cr}} = \log_i$$

Lifetime due to Intrabeam Scattering

- IBS heating mechanism: Energy exchange at intra-beam collisions leads to x-emittance increase due to energy-orbit coupling, and y-emittance increase due to x-y coupling
- Electron cooling is introduced to suppress beam blow up due to IBS, and maintain emittances near limits determined by beam-beam interaction.
- Since $L \propto 1/\sigma_x\sigma_y$, reduction of transverse coupling while conserving beam area, would result in decrease of impact of IBS on luminosity
- Electron cooling then leads to a flat equilibrium with aspect ratio of 100:1.
- Touschek effect: IBS at large momentum transfer (single scattering) drives particles out of the core, limiting luminosity lifetime.
- A phenomenological model which includes single scattering and cooling time of the scattered particles has been used to estimate an optimum set of parameters for maximum luminosity, at a *given* luminosity lifetime.

Lifetime due to Background Processes

Proton beam lifetime from small-angle elastic ep-scattering



Contributions from inelastic processes have smaller effect by factor of ~10

Courtesy: A. Afanasev, et al.

ERL-based EC with Circulator Ring

Parameter	Unit	Value
Max/min energy of e-beam	MeV	75/10
Electrons/bunch	10^{10}	1
Number of bunch revolutions in CR	100	1
Current in CR/current in ERL	A	2.5/0.025
Bunch rep. rate in CR	GHz	1.5
CR circumference	m	60
Cooling section length	m	15
Circulation duration	μs	20
Bunch length	cm	1
Energy spread	10^{-4}	3-5
Solenoid field in cooling section	T	2
Beam radius in solenoid	mm	1
Cyclotron beta-function	m	0.6
Thermal cyclotron radius	μm	2
Beam radius at cathode	mm	3
Solenoid field at cathode	KG	2
Laslett's tune shift in CR at 10 MeV		0.03
Time of longitudinal inter/intra beam heating	μs	200

Feasibility of High Energy Electron Cooling

Advances on electron beam

SRF energy recovering linac (ERL)

- Removes the linac power show-stopper
- Allows for two stages cooling or even cooling while accelerating
- Allows for fast varying the e-beam parameters and optics when optimizing the cooling in real time
- Delivers a low longitudinal emittance of e-beam

Electron circulator-cooling ring

- Eases drastically the high current issues of electron source and ERL

Beam transport with discontinuous solenoid

- Solves the problem of combining the magnetized beam transport with effective acceleration

Beam adapters

- Allows one to flatten the e-beam area in order to reach the optimum cooling effect

Advances and Issues on hadron beam

Advances

Dispersive cooling

- Raises the transverse cooling rates up to the value of the longitudinal one
- Allows one to avoid large beam extension in cooling section
- Eases the beam alignment

Non-coupled beam optics of hadron ring

- Diminishes the IBS effect

Issues

Electron beam alignment

- Control of the relative dipole moment seems an effective method for bunched beams

High electron charge per bunch

- Use beam coalescence technique

Forming the ion beam

Main issues:
- Initial cooling time
- Bunch charge & spacing

General recommendations:
- Prevent the emittance increase at beam transport (introducing a fast feedback)
- Use staged cooling
- Start cooling at possibly lowest energy
- Use the continuous cooling during acceleration in collider ring, if necessary

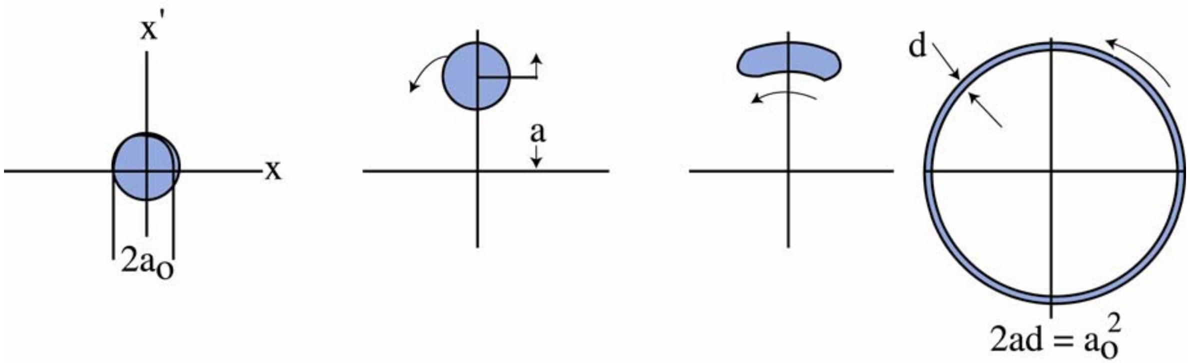
Possible advanced technique to form high quality intense proton and ion beams:
- *hollow beam gymnastics* to overcome the space charge limit in booster

Beam bunching, cooling and ramp agenda:
- After stacking in collider ring, the beam under cooling can be re-bunched by high frequency SC resonators, then re-injected for coalescence (if needed), more cooling and final acceleration & cooling
- The final focus could be switched on during the energy ramp, keeping the Q-values constant

How to stack ion beam in booster over space charge limit maintaining beam emittance

Halo transformation of ion beam in phase space after linac /before injection in booster/

/process similar to beam debunching in a ring: after beam kick, an introduced resonance dipole field (static) drops adiabatically along the beam path /



/Similar gymnastics in y-plane/

Beam stacking:
•Focus the smoky beam to stripping foil
•beam raster applying an RF dipole field (compensated)
Turning the smoky beam back to the true size:
•After beam longitudinal bunching/acceleration to a large gamma in booster, make the reverse halo gymnastics in phase space by resonance RF dipoles

FORMING E-BEAM FOR COLLIDER

1. Injector version

Polarized source

e-gun	500 KeV
Laser pulse	0.33 ns
Bunch charge	80 pC
Peak current	240 mA
e-bunch transverse emittance, norm	10 mm.mrad
Rep.rate	25 - 250 MHz
Average current	2 – 20 mA

1st accelerator cavity

Voltage	2 MV
Frequency	500 MHz
Beam energy	2.5 MeV

1st compressor

Prebuncher frequency	500 MHz
Voltage	0.2 MV
Energy gradient after prebuncher	2x 10%
1st drift	2 m
Bunch length after 1st compression	1 cm
Beam radius (assumed value)	2 mm
Coulomb defocusing length	30 cm

2nd compressor

Buncher frequency	1.5 GHz
Energy gradient	2x 10%
2nd drift	1.8 m
Bunch length, final	0.5mm
Beam radius	2 mm
Coulomb defocusing length	35 cm

FORMING THE E-BEAM FOR COLLIDER (con't)

2. 50 MeV, 1.5 GHz SRF accelerator

/ should be operated as ERL, accepting 5 GeV bunches from Circulator/

Bunch rep.rate from injector	25 – 250 MHz
Bunch rep.rate from Circulator	1.25 – 12.5 MHz

FORMING THE E-BEAM FOR COLLIDER (con't)

3. Coalescer ring /longitudinal coalescence/

Circumference	24 m
Beam energy	50 MeV
Bend field	2 KG
Number of bunch revolutions	0 - 19
Bunch spacing	1.2 – 12 m
Injection/ejection rep.rate	(25 / 1.25) – (250/12,5) MHz
Injection/ejection bunch charge	80pC/1.6nC
Injection/ejection momentum spread in bunch	(0.1 /4)%
Betatron phase advance over turn	90 degree
Dispersion at injection kick area	2 m
Bunch length after coalescence	1 cm
Beam width in the dispersion plane	8 cm
Laslett's tune shift, max	0.05

4.Chicane compressor

Complemented with SRF compensator for energy spread introduced by the coalescer if needed

R&D Topics

Several important R&D topics have been identified:

- High charge per bunch and high average current polarized electron source
- High energy electron cooling of protons/ions
  - Electron cooling of 100 GeV protons requires 50 MeV electrons. Practical only if based on SRF-ERL technology, demonstrated and routinely used at the JLab IRFEL
  - BNL/BINP, in collaboration with JLab, pursuing an ERL-based electron cooling device for heavy ions at RHIC
- Integration of interaction region design with detector geometry
- High current and high energy demonstration of energy recovery

Courtesy of Lia Merminga

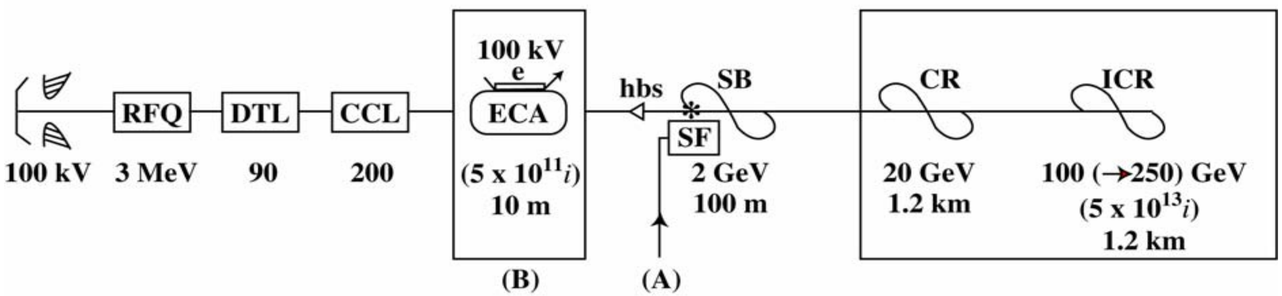
R&D Strategy

Our R&D strategy is multi-pronged:

- Conceptual development
  - "Circulator Ring" concept promises to ease high current polarized photoinjector and ERL requirements significantly
  - Additional concepts for luminosity improvements are being explored
- Analysis/Simulations
  - Electron cooling and short bunches
  - Beam-beam physics
  - Circulator ring dynamics
  - ERL physics
- Experiments
  - JLab FEL (10mA), Cornell/JLab ERL Prototype (100mA), BNL Cooling Prototype (100mA) to address high current ERL issues
  - CEBAF-ER: The Energy Recovery experiment at CEBAF to address ERL issues in large scale systems

Courtesy of Lia Merminga

ELIC Ion Complex

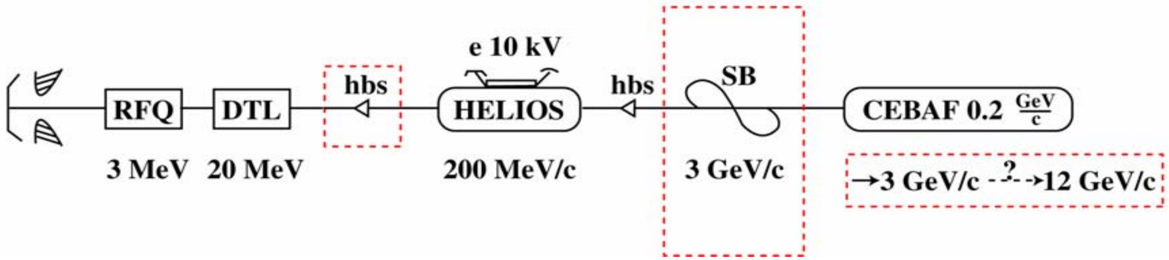


Option B: ● Positive source (p, d, He^3), = 20 m A
● Electron cooling accumulator (ECA)

hbs: Hollow beam stretcher

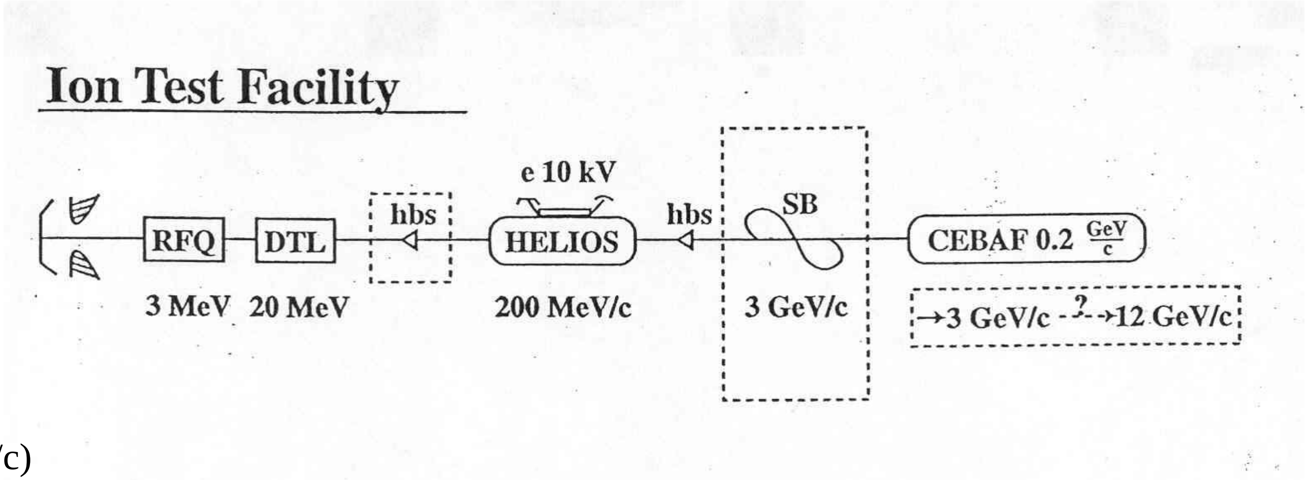
Option A: ● Negative source (H^-, D^-), ? = 10 m A
● Stripping foil (SF) in SB (small booster)

Ion Test Facility



200 MeV Accumulator Ring (20 MeV in ITF) could be used as an ion accumulator in both ways, electron cooling or stripping accumulation (stripping foil can be installed in AR bombardment by a factor of ~ 10

ION Test Facility



First stage constituents:

- Ion source (unpolarized)
- RFQ 3 MeV
- DTl 20 MeV (=200 MeV/c)
- Electron Cooling Accumulator (ECA, 10 KeV e-beam)

/HELIOS ring? – with EC of IUCF/

Second stage:

- Small Booster (SB): injection momentum 200 MeV/c, maximum momentum 3 GeV/c
- CEBAF ring (with or without acceleration)

Test studies at ITF:

- High ion current accumulation with EC
- Hollow beams: obtaining/dynamics/cooling
- Stacking over space charge limit
- Stripping injection/accumulation
- High ion current stability in boosters and at start energy of ICR
- ?

Conclusions

- The considered high luminosity and efficient spin manipulation concepts of ELIC are essentially based on exploiting the advanced accelerator technologies: SRF, ERL, Polarized Electron and Ion Sources and High Energy Electron Cooling

- On this base, some novel approaches to utilizing the polarized electron and ion beams and organizing the Interaction Points have been proposed (electron circulators for collider and electron cooling, crab crossing, twisted spin synchrotrons and other)

- Basic factors limiting the luminosity have been taken into account, and an approach to the luminosity calculator has been developed

- Approaches to forming the intense, high quality ion and electron beams for collider and efficient electron cooling to be intensively explored

- For further development and examination of ELIC concepts, one needs a serious extension of the analytical and, especially, the computational efforts