Conceptual Studies for an Electron-Ion Collider at CEBAF

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Abstract

I will report on conceptual development of the proposed spin-polarized Electron-Light Ion Collider at CEBAF based on use of 5-7 GeV recovering electron linac (ERL) with multi-turn circulator-collider ring (kicker operated) and 30-150 GeV ion storage ring with electron cooling (EC). An ultra-high luminosity (up to $10^{35}/cm^2s$) is envisioned to be achievable with very short ion bunches under EC and high bunch collision rate (1.5 GHz). Crab crossing is used to eliminate beam-beam parasitic interactions. An efficient spin manipulation and maintenance for all ion species (p, d, He and Li) and electrons is provided by use of figure 8 boosters and collider rings. Such 4 interaction points (IP) collider is considered absolutely central to advancing nuclear science following the 12 GeV CEBAF fixed target program.

Our recent studies concentrated on schematic IP design, optimized EC agenda, luminosity lifetime due to Touscheck scattering in ion beam and stacking the intense low emittance ion beams. The last issue, in particular, will be lightened up in association with related ideas and studies of the SNS project.

Jefferson Lab

Complexes:

CEBAF (Continuous 6 GeV Electron Beam Accelerator Facility for NP)

FEL on ~ 200 MeV ERL (1→10→100→...KWt)

Essential Science:

Nuclear Physics Dept: 3+1 halls + Theory

Accelerator Dept:
SRF Institute (core of competence)
CASA (Center for Advanced Studies of Accelerators):
- CEBAF and FEL operation support
- ERL development
- CEBAF upgrades and Future Projects
- Beam Physics - any

FEL applications (basic science)

Future NP Projects:

12 GeV CEBAF upgrade (has approved by DoE – funding to start…)

Next under study:
24 GeV CEBAF upgrade
Electron-Ion Collider up to 65 GeV in c.m., based on 5-7 GeV ERL and 30-150 GeV/n ion beam

OUTLINE

ELIC general layout and basic parameters

Motivations

Electron complex

Ion complex

Spin

Electron cooling

Interaction points

Crab crossing

ERL-ring synchronization

Electron cooling, IBS, beam-beam and luminosity

- **Stacking ion beams**

Issues

Conclusions

Nuclear Physics Requirements

- **The features of the facility necessary to address these issues:**
  - Center-of-mass energy between 20 GeV and ~~45~~ GeV ~~(60)~~ 65 **with energy asymmetry of ~10, which yields**

    √ $E_e \sim 3$ GeV on $E_i \sim 30$ GeV **up to** $E_e \sim$ ~~5~~ 7 GeV on $E_i \sim$ ~~100~~ 150 GeV
  - **CW Luminosity from** 10^{33} to 10^{35} cm^{-2} sec^{-1}
  - √ **Ion species of interest:** protons, deuterons, ^3He, Li
  - Longitudinal polarization of both beams in the interaction region ≥ 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**

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

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}

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

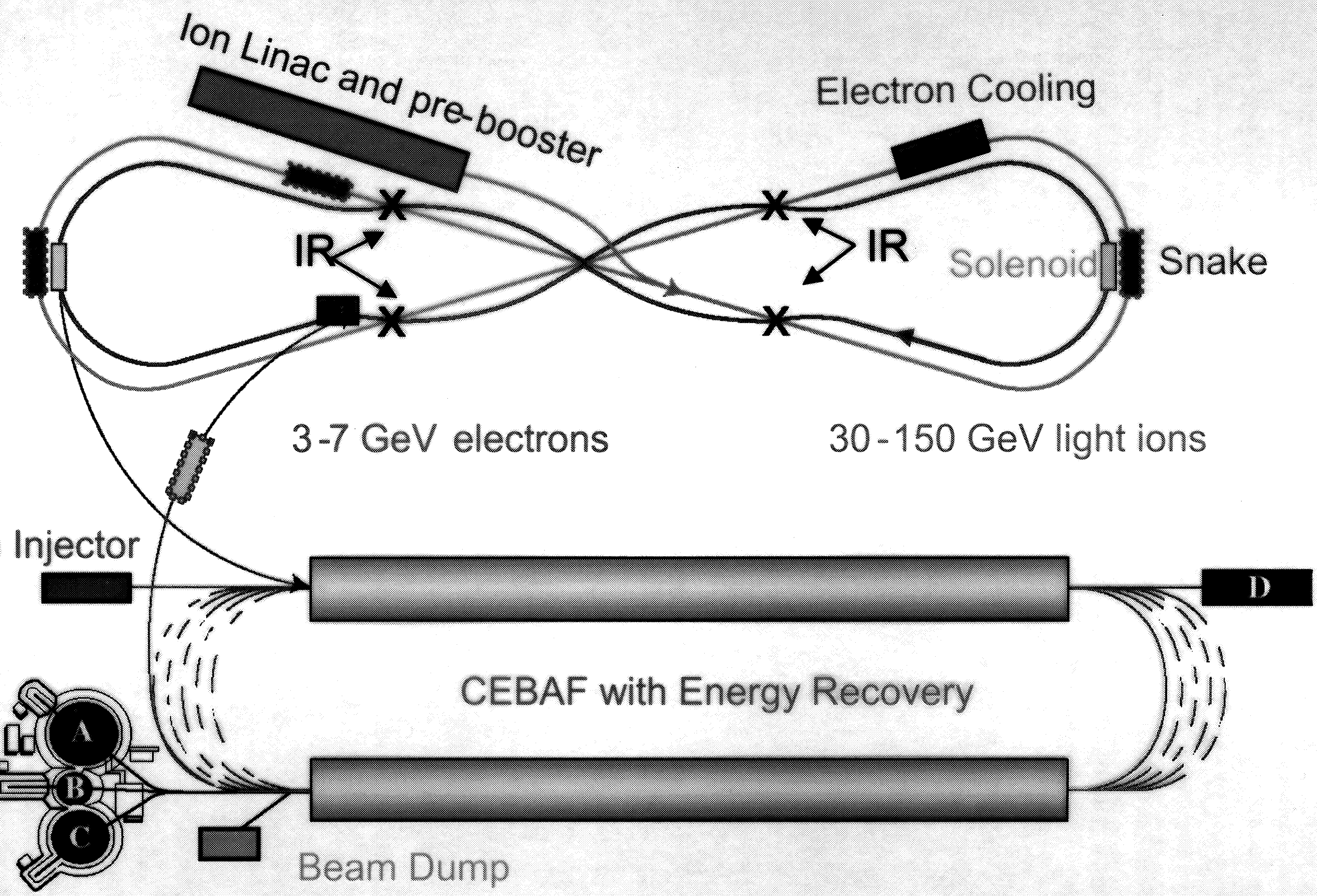
CIPANP 2003

Conference on the Intersections of Particle and Nuclear Physics

Grand Hyatt Hotel - New York City

May 19-24, 2003

ELIC Layout


Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

ELIC Table of Parameters

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**	**100/5**	**30/3**
Cooling beam energy	**MeV**	**75**	**50**	**15**
Bunch collision rate	**GHz**	**1.5**		
Number of particles/bunch	**10^{10}**	**.4/1.0**	**.4/1.1**	**.12/1.7**
Beam current	**A**	**1/2.4**	**1/2.7**	**.3/4.1**
Cooling beam current	**A**	**2**	**2**	**.6**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**5**		
Beta-star	**mm**	**5**		
Horizontal emittance, norm	**µm**	**1/100**	**.7/70**	**.2/43**
Vertical emittance, norm	**µm**	**.04/4**	**.6/6**	**.2/43**
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.073**	**.01/.007**
Space charge tune shift in p-beam		**.015**	**.03**	**.06**
Luminosity per IP*, 10^{34}	$cm^{-2} s^{-1}$	7.7	5.6	.8
Core & luminosity IBS lifetime	**h**	**24**	**24**	**> 24**
Lifetime due to background scattering	**h**	**200**	**> 200**	**> 200**

The CEBAF II/ELIC Upgrade at JLab

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

"Scientific/Engineering Challenges to Resolve"

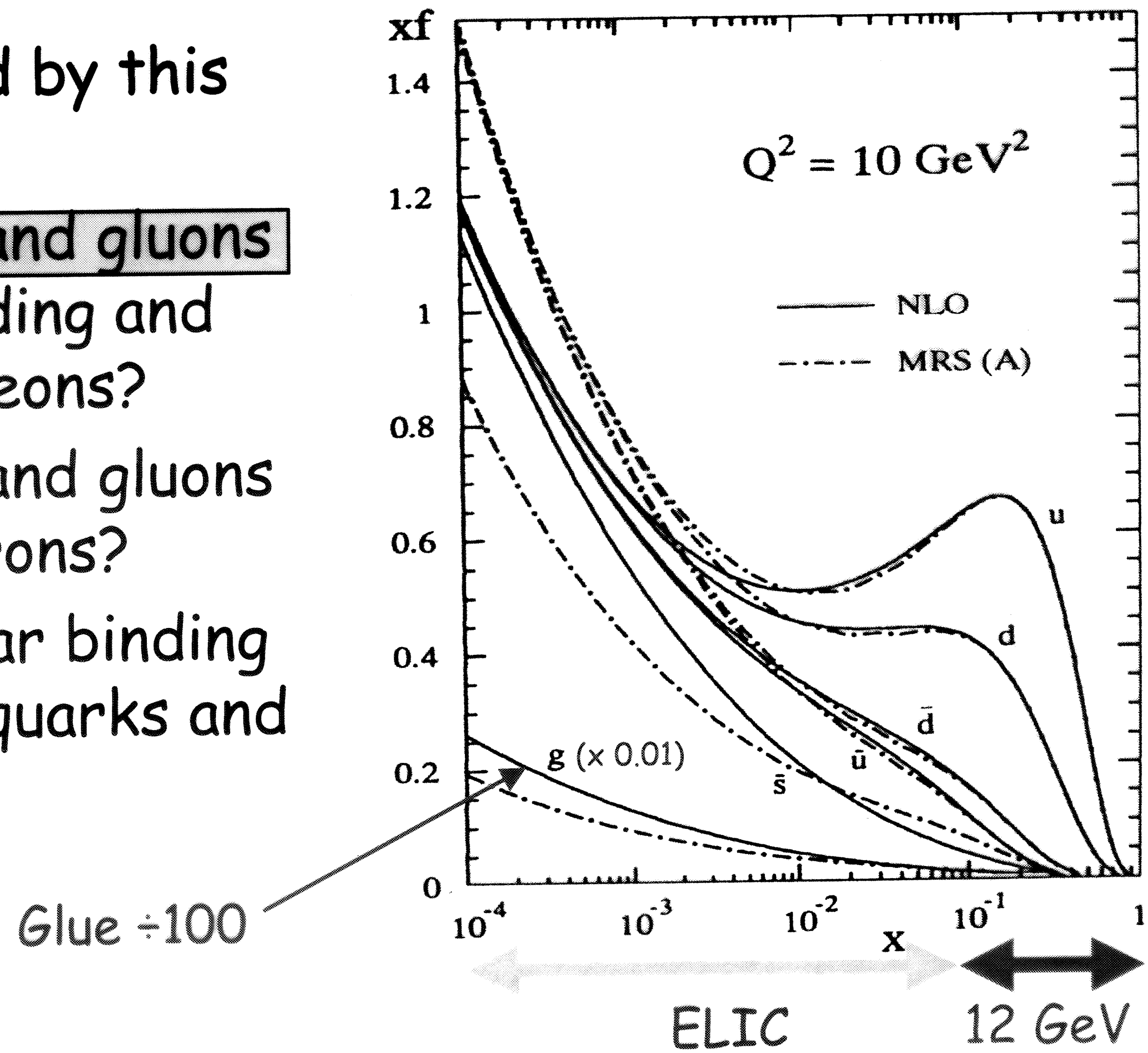
Rolf Ent

02/15/2003

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?

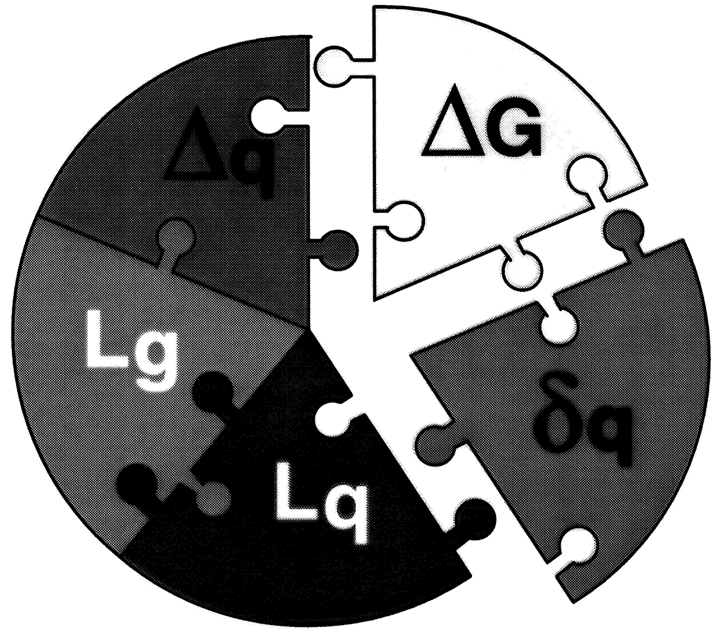


Thomas Jefferson National Accelerator Facility

The Spin Structure of the Proton

- 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

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

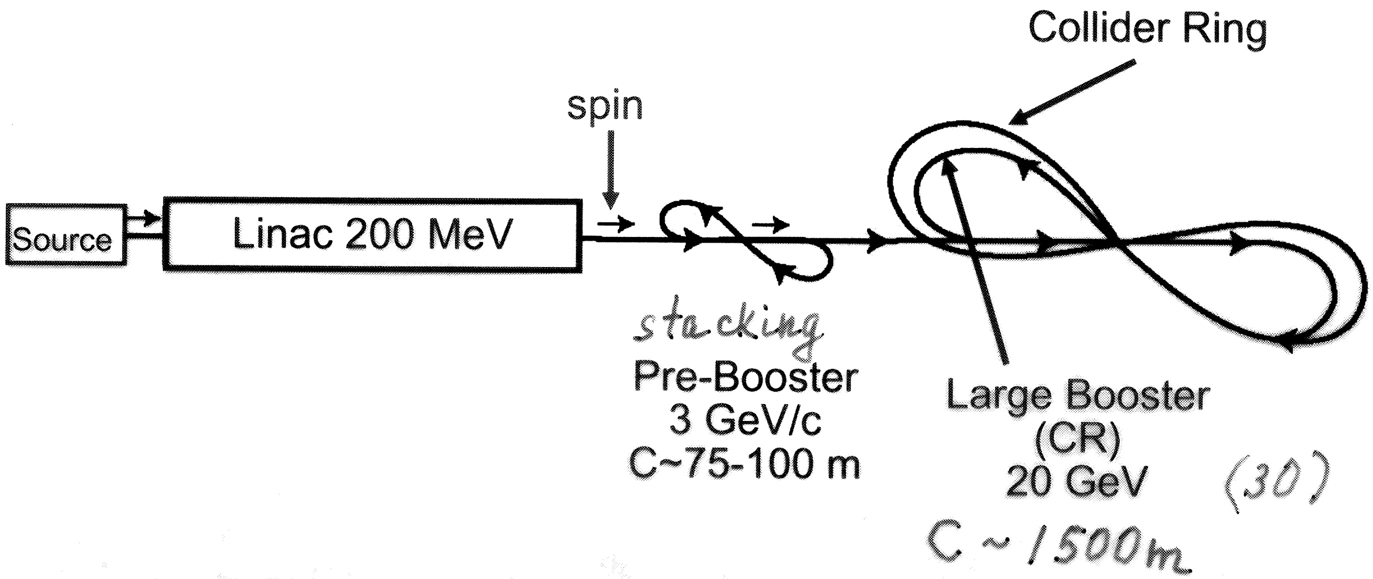


ELIC@JLab can solve this puzzle due to large range in x and Q^2 and precision due to high luminosity

Ion Complex

"Figure-8" rings:

- Zero spin tune avoids intrinsic spin resonances
- No spin rotators required



Talk by Derbenev on Ion Polarization in ELIC

Ion ring basic parameters

Parameter	Unit	Value
Proton energy, min/max	GeV	150/20
Circumference	M	1532
Arcs radius	M	100
Arcs angle	grad	240 x 2
Arcs length	M	470 x 2
Crossing straights length	M	346 x 2
Straights crossing angle	grad	60
Bend field in arcs, max	T	9
Bend radius in dipoles	M	75
Beta in arcs (combined magnets?)	M	6
Dispersion function in arcs	M	.36
Number of oscillations in arcs		23
Revolution frequency	KHz	200
Frequency change at acceleration	%	.1

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

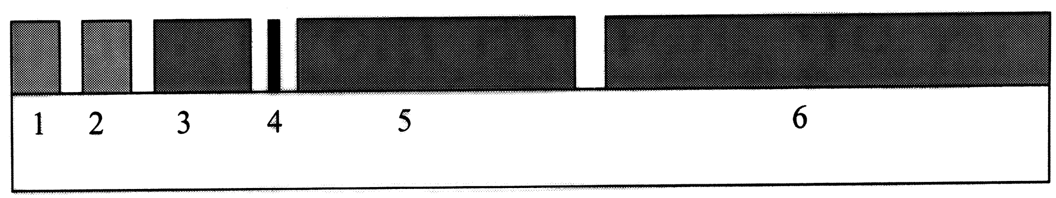


Fig.1. Layout of the linac. 1-RFQ, 2- RT IH structure
3 and 5 - QWR, 115 MHz
4 – stripper for Argon beam,
6 – 345 MHz double-spoke resonators.

A Version of Ion Linac: From Protons to Ar

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September 18, 2003

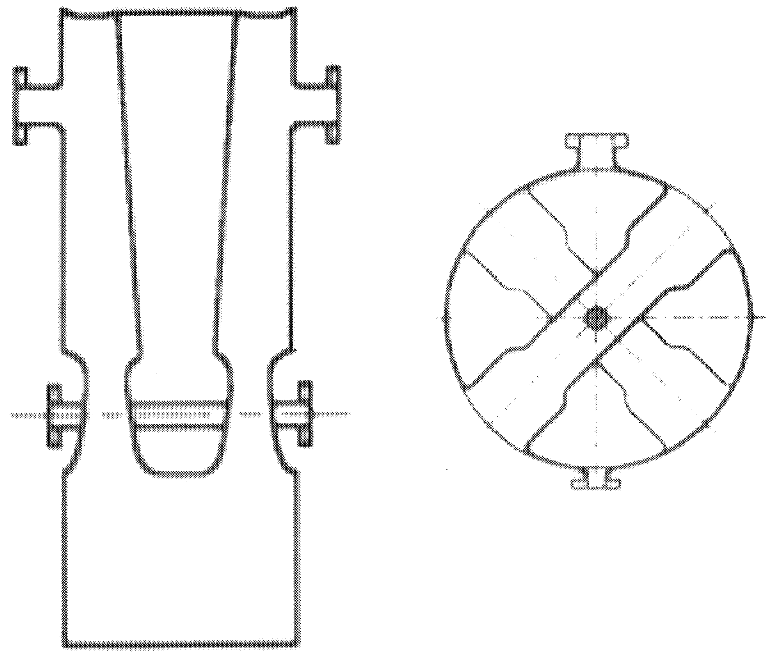

Fig. 2. 115 MHz QWR, beta=0.15 and 2-spoke cavity, 345 MHz, beta=0.4

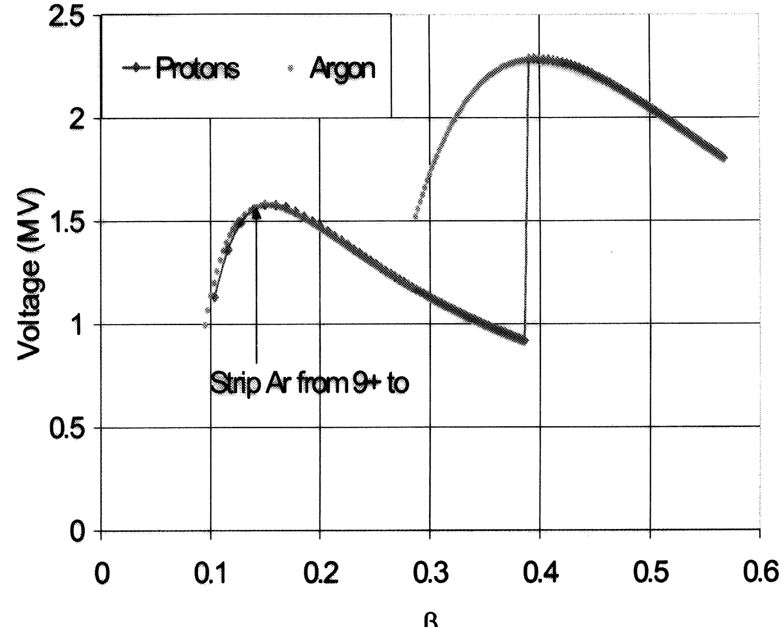

Fig. 3. Voltage gain per resonator as a function of ion velocity.

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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Accelerated beam parameters:

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- **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%.**

Accelerator Physics of the Ion Ring

Instability mechanisms have been examined for the top luminosity parameters:

- Longitudinal Microwave Instability ok
- Transverse Microwave Instability ok
- Longitudinal Coupled Bunch Instability
- Transverse Mode Coupling Instability

→ Would require feedback

- Electron Cloud Instability ok

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

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	1.5
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)

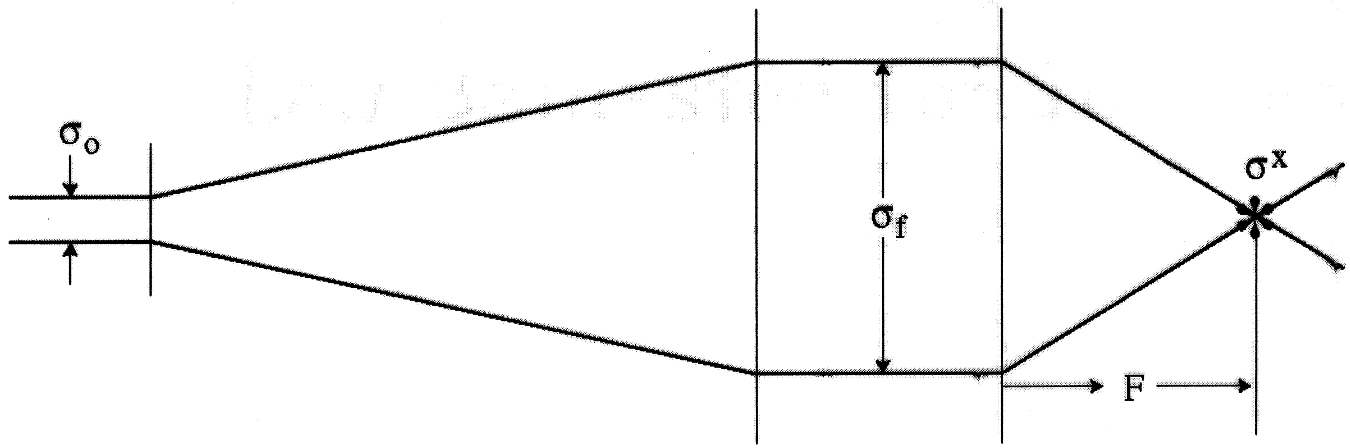
Beam energy	GeV	150/7
Bunch length, rms	mm	5/5
Focal length	m	4/4
Large beta	Km	3.2/3.2
Beta-star	mm	5/5
Transverse emittance, norm, rms	μm	1/100
Beam size at large beta, rms	mm	5/5
Beam size at star point, rms	μm	6/6

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

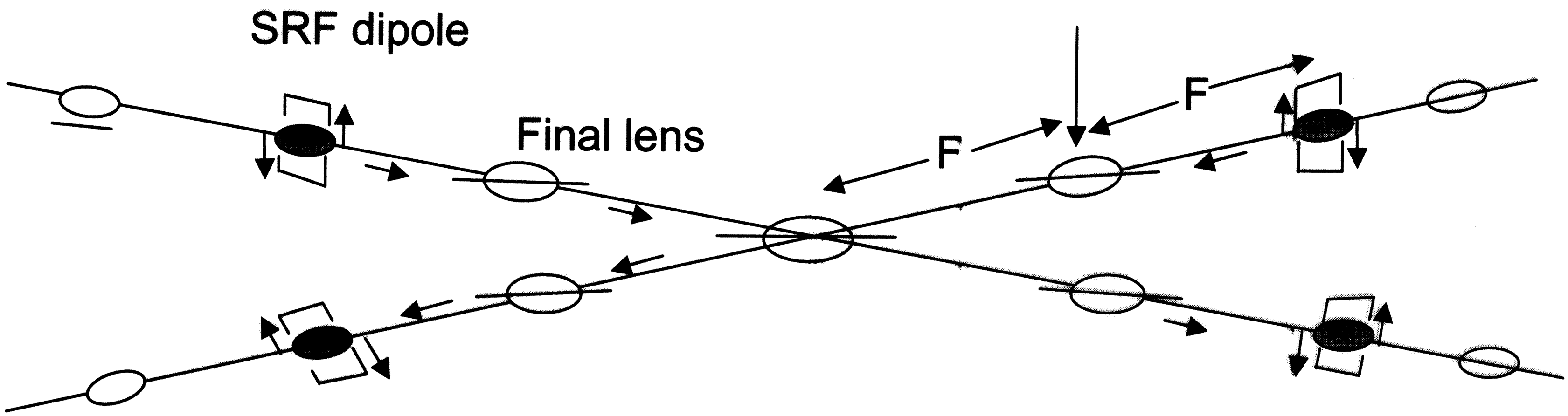
→ β^*=1 cm

Crab Crossing

R. Palmer 1988, general idea

Short bunches make feasible the Crab Crossing

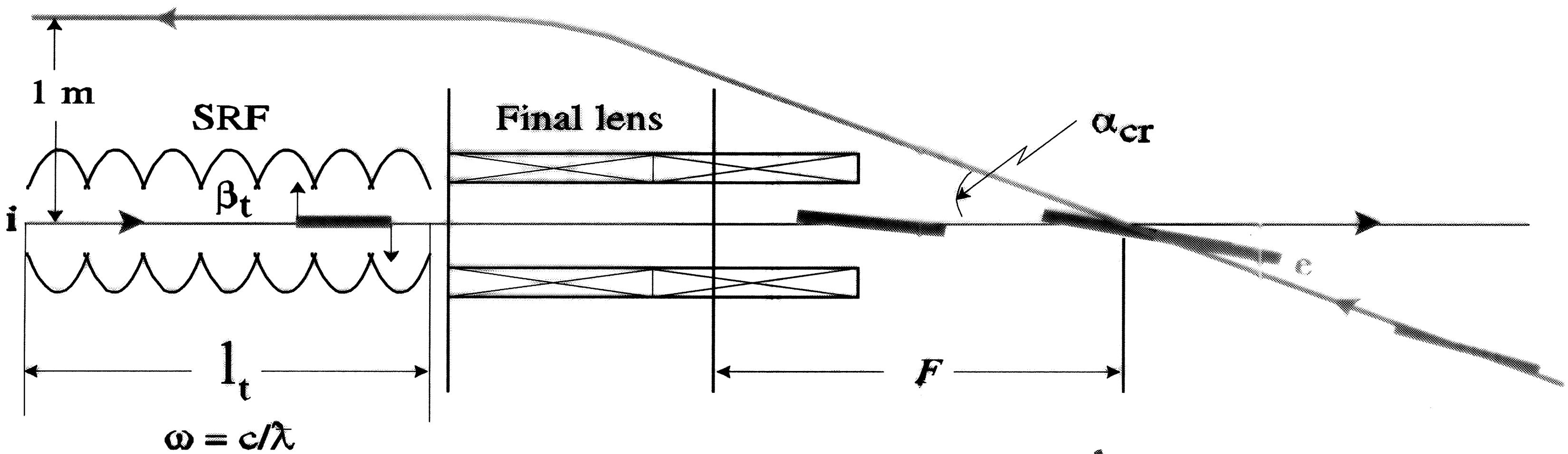
SRF deflectors 1.5 GHz can be used to create a proper bunch tilt



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



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

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

$E = 100\ GeV$

$F = 3\ m$

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

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

$l_t = 4\ m$

$\sigma_f = 1\ mm$

→

$\alpha_{cr} = 0.1$

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

Short Ion Bunches and Low β*

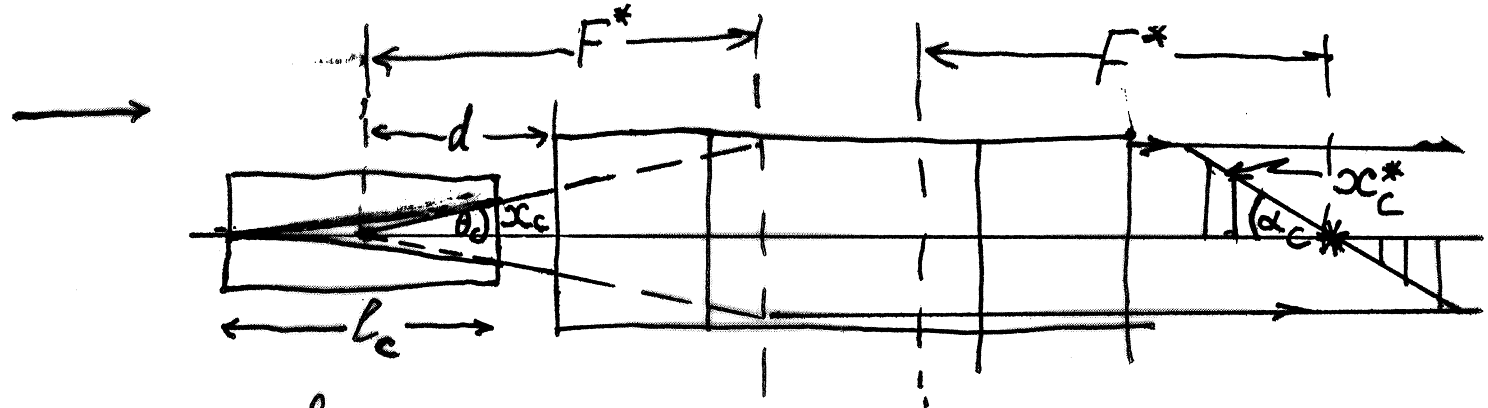
Cooled p-bunches in a ring with SRF cavities

Parameter	Unit	Value
Beam energy	GeV	150
RF 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

Final focus of ELIC 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

Strong SRF -> high synchrotron tune (0.06) which helps stabilize short ion bunches against microwave instabilities and beam-beam interaction.



$$x_c = \frac{l_c}{2}\cdot\theta_c\,; \qquad \theta_c = \theta_0\varphi = \theta_0\frac{s}{\lambda}\,; \qquad \lambda = \frac{c}{\omega} = \frac{c}{2\pi f}\,; \quad f = 1.5\ \text{GHz}$$

$$\alpha_c = \frac{dx_c^*}{ds} = \theta_0\cdot\frac{F^*}{\lambda} \qquad \theta_0 = \frac{b_0 l_c}{pc} = \frac{0.3\,(b_0 l_c)(\text{TM})}{p(\text{GeV/c})}$$

$$x_c^* = \theta_c\cdot F^*$$

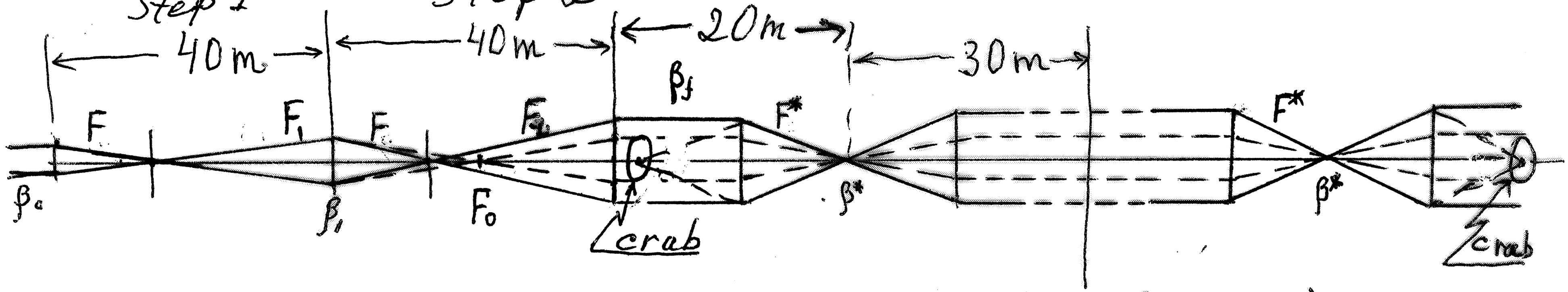
an example: $\alpha_c = 5\cdot10^{-2}$ rad (0.1 rad crossing angle)

$F^* = 5$ m ; $cp = 150$ GeV

↓

$\theta_0 = 3\cdot10^{-4}$ rad ; → $b_0 l_c = 0.15$ TM ≡ 45 MV; → $l_c \approx 3$m

- Two steps of beam extension
- Step 2 is off at injection/acceleration/cooling



$\frac{\beta_1}{\beta_0} = \left(\frac{F_1}{F_0}\right)^2 \sim 25; = \frac{\beta_f}{\beta_1};$

$\beta_0 \sim 10\,m$
$F \sim 7\,m$
$F_2 \sim F_1 \sim 35\,m$
$F_0 = 20\,m$
$F^* \sim 5\,m$
$\beta^* \sim 5\,mm$

$\beta_1 = 250\,m$ ($\longrightarrow 100$) by reducing F_1 (while increasing F_0)

$\beta_f = 5000\,m$

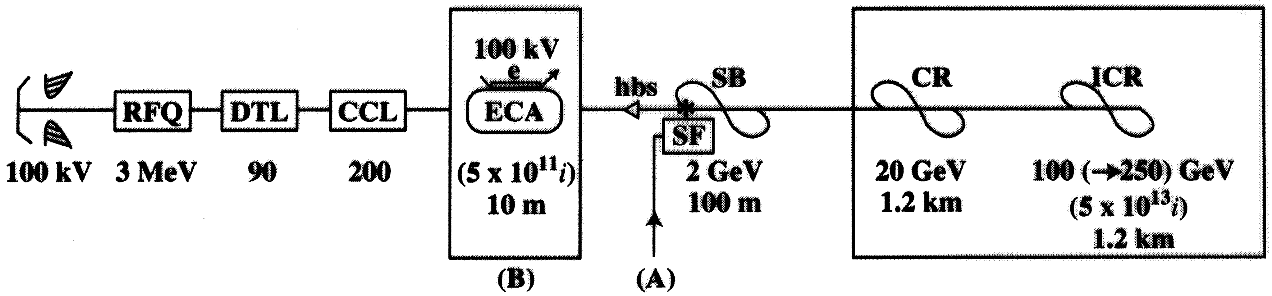
$(\sigma_x)_f \approx \sqrt{\frac{\varepsilon_x}{\gamma}(\beta_1 \to \beta_f)} \lesssim 6\,mm$

(IR length/detector): $40+40+20+30 = 130\,m$

"Free" space: $170 - 130 = 40\,m$

- Global phase advance is controlled by regular optics in arcs

ELIC Ion Complex

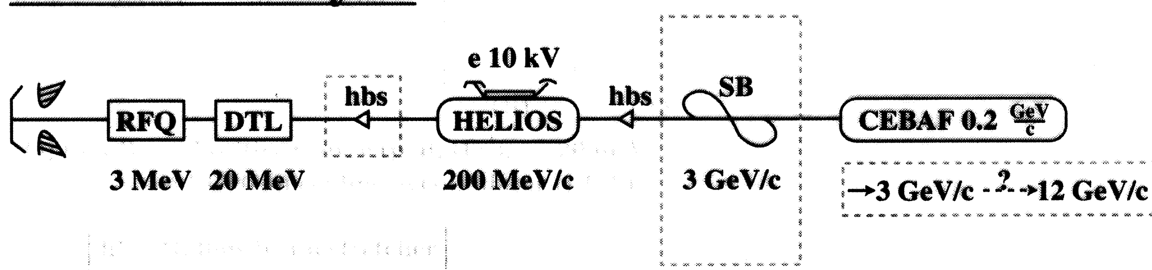


Option B:
- Positive source (p, d, [redacted]), = 20 m A ; $^3He^{++}$ ~ 1 mA ; Li^{+++} ~ ? (low)
- Electron cooling accumulator (ECA)

hbs: Hollow beam stretcher

Option A:
- Negative source (H^-, D^-), ? = 10 m A (1 mA now)
- Stripping foil (SF) in SB (small booster)

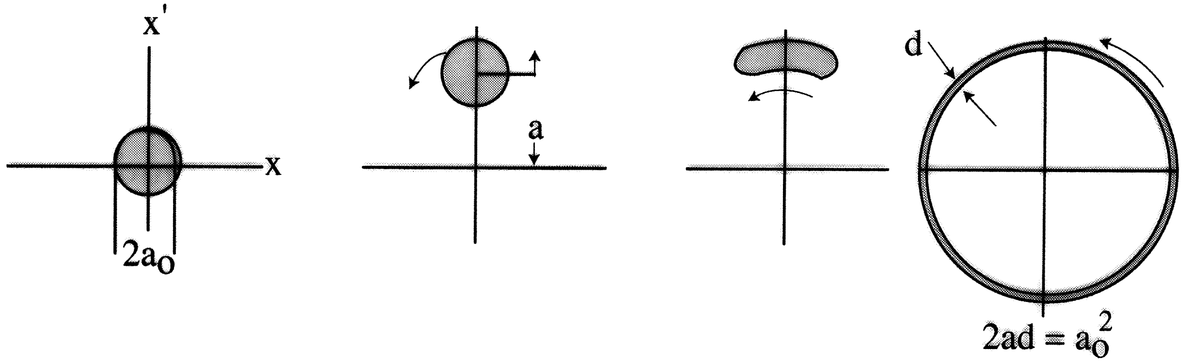
Ion Test Facility



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/

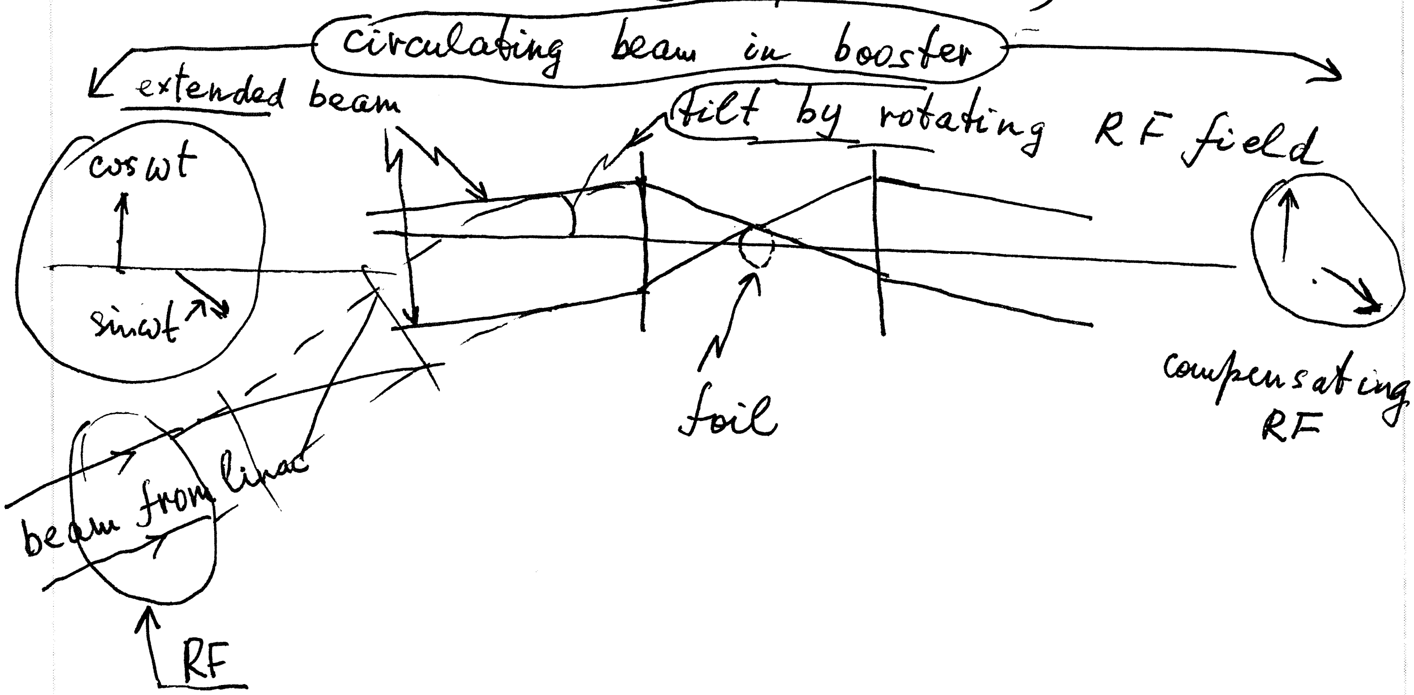
Beam stacking:
- **Focus the smoky beam to stripping foil**
- **beam raster applying an RF dipole field (compensated)**

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**

Possible advances (but also constraints)

1. Use hollow beam transformations
   - scattering becomes more critical
   - heating less intense

2. Make strong focus at foil
   +
   beam raster (compensated)



- possibility for beam extension before focus is limited for hollow beam

3. Use resonance focus + beam raster (?)

Beam stacking in pre-booster

1st issue: space charge

$N \to (1 \div 5) \times 10^{12}$ ($\to \times 15$ in collider)

$\varepsilon_n \leq 3\mu m$

$\gamma = 1.2 \xrightarrow{acc} 3 \div 4$

$J_{linac} = (2 \div 10)\, mA$

$J_b \to (0.25 \div 1.25)\, A$

$$\Delta\nu \to \frac{N r_0}{4\pi \varepsilon_n \gamma^2 \beta} \quad \text{(coasting beam)}$$

$$\parallel$$

5×10^{-2} ($\to$ at $N = 10^{12}$, $\varepsilon_n = 3\mu m$)

($\to \gtrsim 0.1$ for a bunched beam)

$\downarrow$

0.5 at $N = 5 \times 10^{12}$

2nd issue: scattering in foil

Number of turns in booster:

$$\frac{J_b}{J_{linac}} \sim (1 \div 5) \times 100 \quad \text{or more}$$

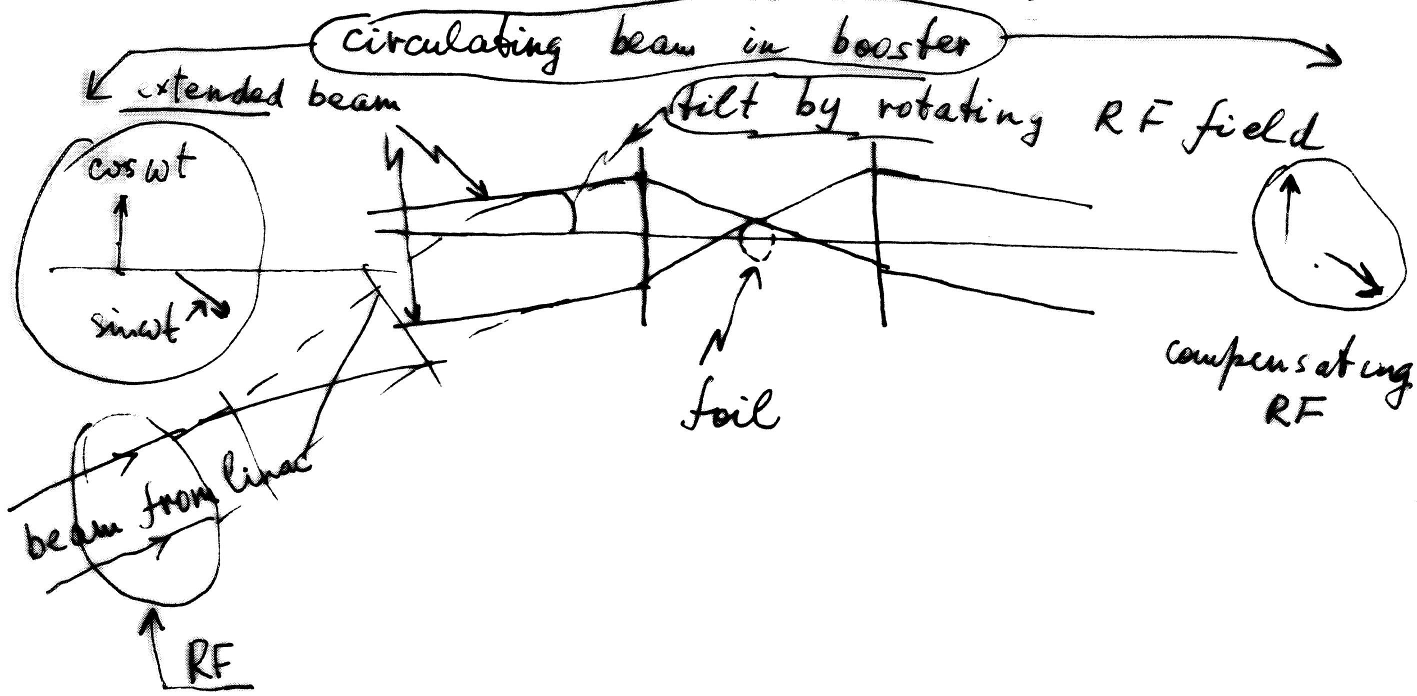
3-d issue: heating the foil

Possible advances / but also constraints /

1. Use hollow beam transformations

- scattering becomes more critical
- heating less intense

2. Make strong focus at foil
+
beam raster (compensated)



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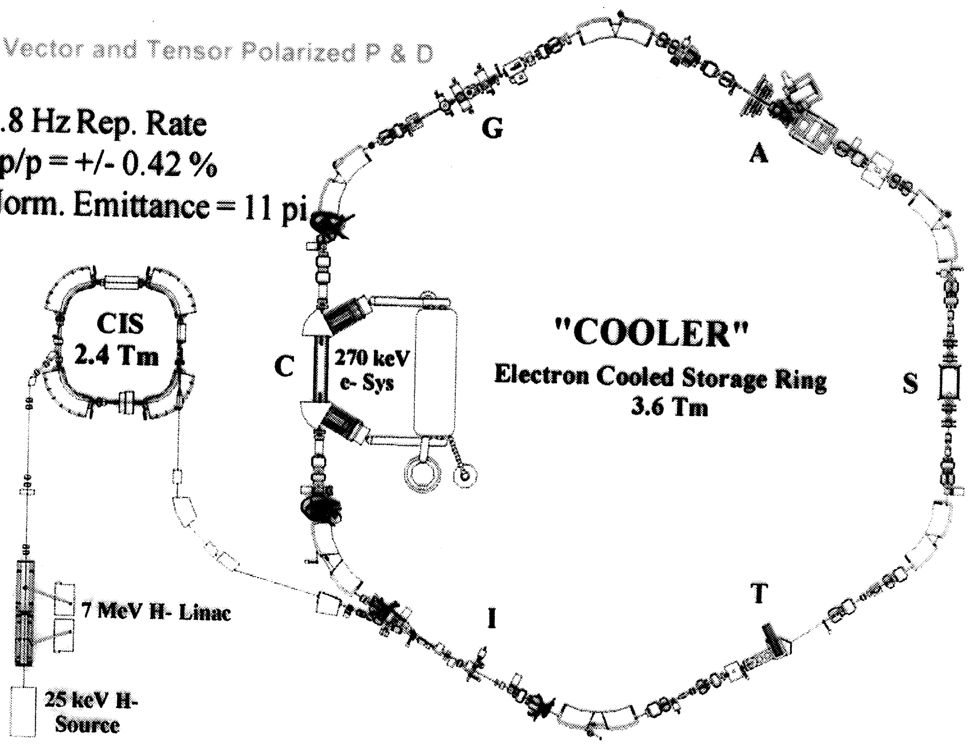
3-d issue: heating the foil

IUCF Kick Injection with e-Cooling

~85%-90% Vector and Tensor Polarized P & D

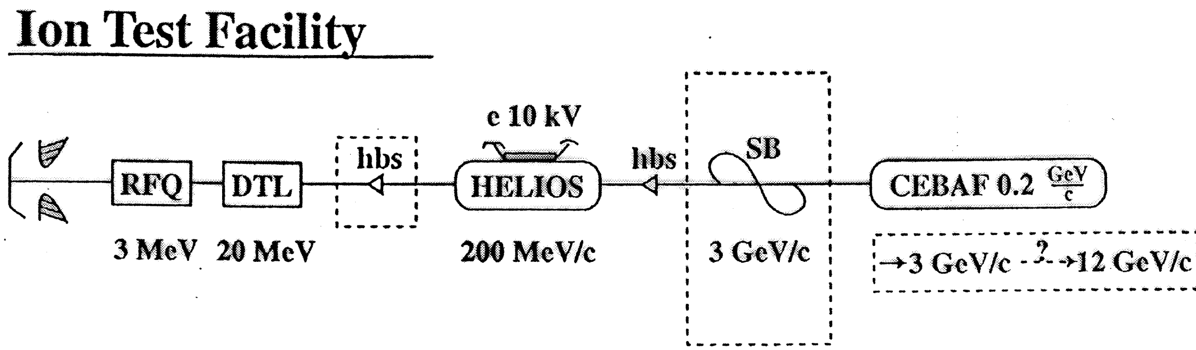
0.8 Hz Rep. Rate
dp/p = +/- 0.42 %
Norm. Emittance = 11 pi



II. COOLER INJECT PERFORMANCE:

4×10^9 unpol p/pulse Injected at 202 MeV }
1×10^9 pol p/pulse Injected at 202 MeV } 50% Injection Efficiency
3.5×10^{10} p Accumulated in 120 seconds at 202 MeV (cooled accum)
0.99×10^{10} pol p Accumulated in 120 sec at 202 MeV "
0.7×10^{10} unpol d Accumulated in 60 sec & ramped to 240 MeV "
0.7×10^{10} pol d accumulated and ramped to 230 MeV
~85%-90% Vector and Tensor Polarized P & D
Goal: 2.5×10^{10} p/p Injected, 1-5 Hz, 80 % Vector Polarized

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
- ?

Electron Cooling, Intrabeam Scattering and Luminosity Lifetime

Talk by Derbenev on Electron Cooling and Luminosity of EIC

- IBS heating mechanism: Energy exchange at intra-beam collisions increases the energy spread and excites horizontal oscillations via dispersion, and vertical oscillations via 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.
- For low transverse coupling, electron cooling leads to flat beams (with emittance aspect ratio of 25:1 for ELIC).
- Therefore, reducing the transverse coupling while conserving beam area (which determines the luminosity), decreases the impact of IBS on luminosity
- Touschek effect: IBS at large momentum transfer (single scattering) drives particles out of the beam 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.

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**

ELIC Beam Physics and design issues

Polarized e-source (cathode, gun, laser)

ERL – CR fast kickers

Electron cloud

Stacking ion beam

Beam-beam limits and optimization

Detectors requirements, demands and design

Optimum clocking

Achromatic IP

Conclusions

- An excellent scientific case starts developing for a high luminosity, polarized electron-light ion collider, to address fundamental questions in Hadron Physics
- JLab design studies have led to an approach that promises luminosities from 10^{33} cm^{-2} sec^{-1} up to nearly 10^{35} cm^{-2} sec^{-1}, for electron-light ion collisions at a center-of-mass energy between 20 and 65 GeV
- This design can be realized using energy recovery on the JLab site and can be integrated with a 25 GeV fixed target program for physics
- Planned R&D will address open readiness issues