

Ion Programme of LHC

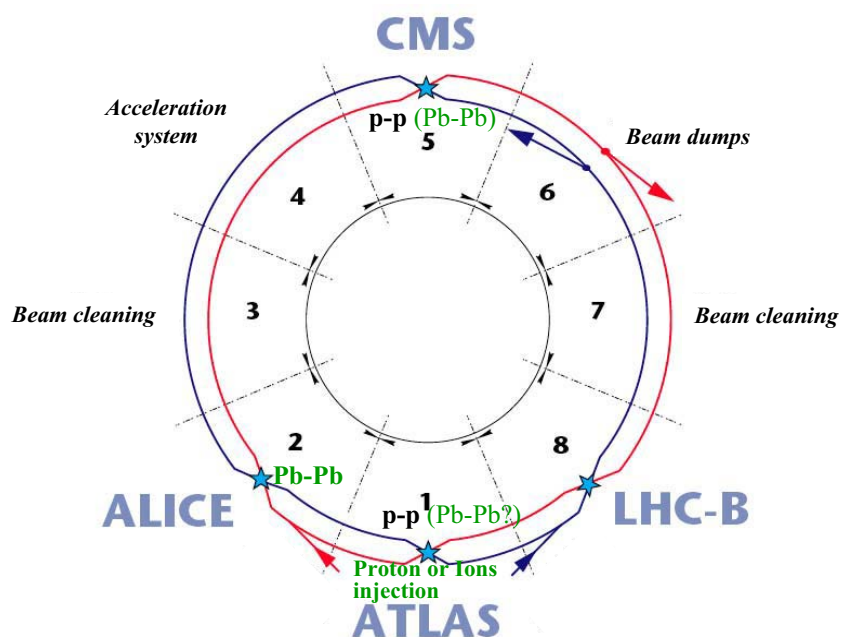
Hans-H. Braun

- I-LHC layout and planning
- Limitations on LHC ion beams
- Other projects for e-ion collider

Miniworkshop on Machine and Physics Aspects
of CLIC based future Collider Option, 30.8.2004

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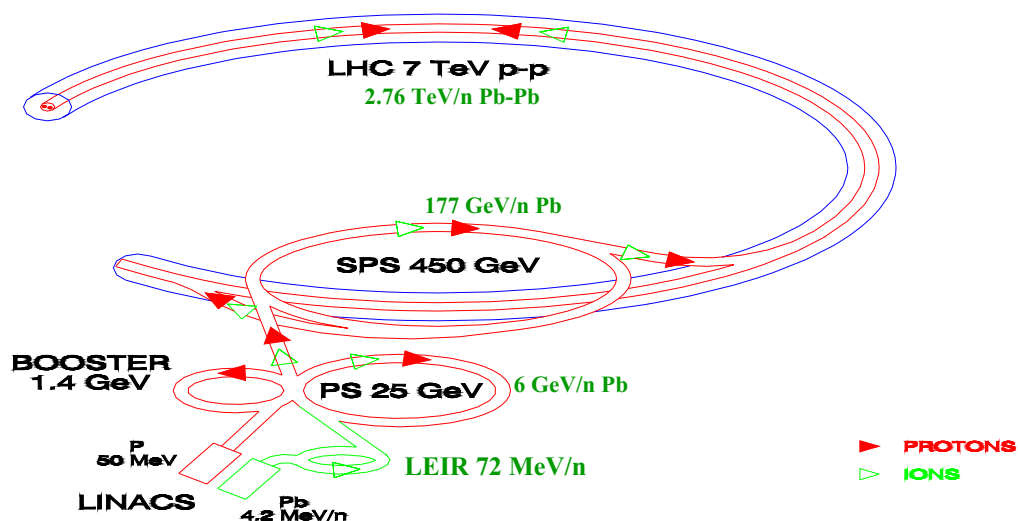
LHC: Layout



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The LHC Injector Chain - Overview



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Pb Collisions in LHC: Nominal + Early

Parameter	Units	Nominal	Early Scheme
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$\text{cm}^{-2} \text{s}^{-1}$	$1 \cdot 10^{27}$	$5 \cdot 10^{25}$
# bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
Number of Pb ions/bunch		$7 \cdot 10^7$	$7 \cdot 10^7$
Transv. norm. rms emittance ¹	μm	1.5	1.5
r.m.s. beam radius at IP	μm	16 (same as p)	16
Longitudinal emittance	eVs/charge	2.5	2.5
bunch length (r.m.s.)	cm	7.5	7.5
Lumi initial decay time (2 exp.)	h	5.5	11

$$^1 \varepsilon_{\text{rms}}^* = (\beta\gamma)_{\text{rel}} \sigma^2 / \beta_{\text{Twiss}}$$

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Tentative I-LHC Schedule (Early Beam)

	LEIR injection line	LEIR ring	PS	SPS	LHC
Start hardware commissioning	January 2005	April 2005 ¹	February 2006		
Start beam commissioning	May 2005	August 2005 ¹	May 2006	(late 2006?) spring 2007	from April 2008
Problems	New source available? Hardware installed? Little time for hardware commissioning	LEIR conversion completed? Maybe running-in through winter 2005/6?	Start-up after an 18-months shutdown with new beams	SPS experts are busy commissioning LHC ring in 2007	ALICE wants beam "at the end of 1 st proton period" (Nov. 2007?)

¹SPS and PS stopped in 2005 → "ideal" year for LEIR commissioning (more help available)

I-LHC (Ions for LHC) vs. ALICE Planning

ALICE (CMS, + ATLAS?) Planning

- Running-in detector in 2007 with p-p, followed by p-p physics run
- Year 1: Pb-Pb pilot run "at the end of first p-p run", normally in April 2008, ~1 week, L a few $10^{25} \text{ cm}^{-2}\text{s}^{-1}$ (corresponds to "Early Scheme")
- Years 2 (2009?) and 4: Pb-Pb @ L $\sim 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ (Nominal Pb beam) for rare observables
- Year 3: p-Pb @ L $\sim 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ for nuclear modifications of structure functions
- Year 5 (2012?): Ar-Ar @ L $\sim 10^{27} - 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ for energy density dependence

I-LHC Planning

- Deal exclusively with Pb ions
- "Early Pb Scheme" - much easier to achieve - for 2008 (and 2009?)
- Nominal Pb Scheme by 2009 (2010?)
- Other ion-ion collisions (typically In, Kr, Ar, O) by ~2012 → improvement programme albeit without major hardware changes

Some remarks about ion beams in LHC

I-LHC beam emittances are chosen to give for the same magnetic field strength of the ring magnets the same beam sizes as for protons beams

The beam energy per nucleon for ions are lower by a factor Z/A compared with protons.

The separated RF systems for the two rings allow to have different ions species in the two rings (*problems with instabilities due to parasitic crossings as observed in RHIC need further studies*) .

Presently the injector machines foresee only the acceleration of ^{208}Pb ions. Other ions are certainly possible with moderate upgrades of injector. But very little studies have been done so far. Presently other ion species are not part of the LHC baseline program.

Intensity limitations for Ion beams in LHC

Single bunch intensity

Intra Beam Scattering

balanced by Synchrotron radiation

$$\tau_{\text{Growth}} \sim Z^2/A^3 \sim N_B/A$$

$$\tau_{\text{Damping}} \sim A^4/Z^5 \sim 1/Z$$

Space charge limit in injector chain

Intra Beam Scattering limits in injector chain

$$\Delta Q_{\text{SC}} \sim N_B Z^2/A$$

Total beam current

Residual gas scattering $\sigma \sim A^{2/3}$

Particle loss induced gas desorption from vacuum chamber walls can lead to vacuum run-away

Particle losses in IP's proportional to Luminosity

Total beam intensity is limited by permissible loss rate given by $T \cdot N_B \cdot n / \tau$.

This loss rate is given by the power the collimation system can handle and the collimation efficiency, i.e. the fraction of particles lost on the S.C.-magnets relative to the losses on the collimators.

Collimation efficiency for ions is considerably worse than for protons, because of the different interaction mechanism of the ions in the collimators.

SPS

Bunchlets - Yes or No?

- ❑ Injection plateau lasting 43.2 s at 57.1 Tm, accumulating up to 13 PS batches à 4 bunches (4 pairs of bunchlets) each. Very little transverse blow-up/losses allowed
- ❑ Pb ions suffer from incoherent space charge detuning and Intra-Beam Scattering (IBS) Halving the number of ions/bunch (= making bunchlet pairs) halves these effects as well.
- ❑ Bunchlet pairs can be recombined by a 100 RF system before extraction to the LHC
- ❑ Space charge detuning ΔQ (about the same in either plane) for nominal Pb ion bunches:
 - 0.082 calculated
 - P-Pbar experience: SPS can stand not more than $\Delta Q = 0.07$.
 - Recent measurements (with p): ΔQ up to 0.18 acceptable on the injection plateau
- ❑ IBS growth times (nominal bunches): ~ 300 s (to be confirmed) which is acceptable
- ❑ ΔQ and IBS the same for Nominal and Early schemes (bunch properties identical)
- ❑ No bunchlets in the early scheme ("calculated risk")
 - No installation of 100 MHz RF systems now (intended to check their impact on p beams)



Synchrotron Radiation

- Scaling with respect to protons
in same ring, same magnetic field

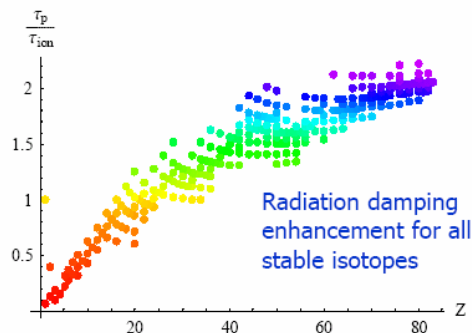
$$\frac{U_{\text{ion}}}{U_p} \simeq \frac{Z^6}{A^4} \simeq 162,$$

$$\frac{u_{\text{ion}}^c}{u_p^c} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

$$\frac{N_{\text{ion}}}{N_p} \simeq \frac{Z^3}{A} \simeq 2651,$$

$$\frac{\tau_{\text{ion}}}{\tau_p} \simeq \frac{A^4}{Z^5} \simeq 0.5$$

- Radiation damping for Pb is twice as fast as for protons
 - Many very soft photons
 - Critical energy in visible spectrum





Required gas pressures

Protons with lifetime 100h

Gas	σ_{in}	n/m^{-3}	$P(300K)/nTorr$	$P(5K)/Pa$	$P_{bg}/(W/m)$
H2	0.09	1.03×10^{15}	32.	7.11×10^{-8}	0.0377
He	0.113	8.2×10^{14}	25.5	5.66×10^{-8}	0.0377
CH4	0.433	2.14×10^{14}	6.65	1.48×10^{-8}	0.0377
H2O	0.397	2.33×10^{14}	7.24	1.61×10^{-8}	0.0377
CO	0.56	1.65×10^{14}	5.14	1.14×10^{-8}	0.0377
CO2	0.86	1.07×10^{14}	3.32	7.37×10^{-9}	0.0377

Lead ions with pressure that gave proton lifetime 100h

Gas	σ_{in}	n/m^{-3}	v_{bg}/h	$P_{bg}/(W/m)$
H2	3.75	1.03×10^{15}	2.4	0.0165
He	2.48	8.2×10^{14}	4.55	0.00872
CH4	10.9	2.14×10^{14}	3.96	0.01
H2O	7.52	2.33×10^{14}	5.28	0.00752
CO	7.22	1.65×10^{14}	7.76	0.00512
CO2	11.	1.07×10^{14}	7.89	0.00503

Lead ions with lifetime 100h

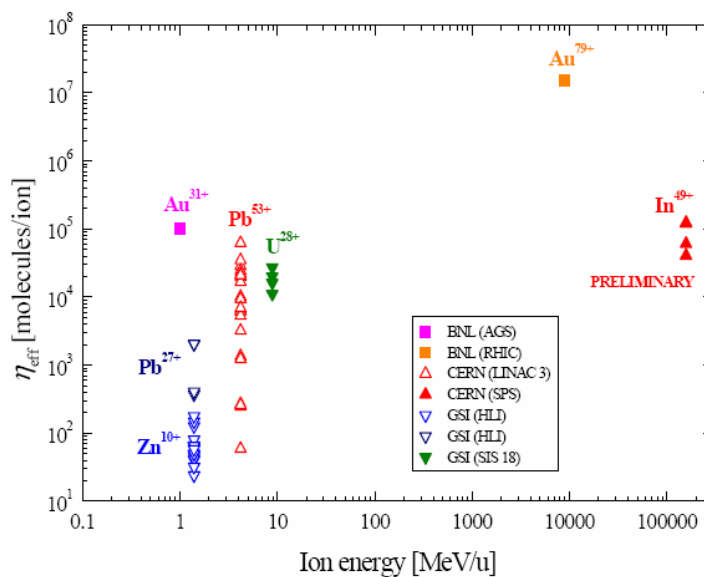
Gas	σ_{in}	n/m^{-3}	$P(300K)/nTorr$	$P(5K)/Pa$	$P_{bg}/(W/m)$
H2	3.75	2.47×10^{13}	0.768	1.71×10^{-9}	0.000397
He	2.48	3.73×10^{13}	1.16	2.58×10^{-9}	0.000397
CH4	10.9	8.47×10^{12}	0.263	5.85×10^{-10}	0.000397
H2O	7.52	1.23×10^{13}	0.383	8.5×10^{-10}	0.000397
CO	7.22	1.28×10^{13}	0.399	8.86×10^{-10}	0.000397
CO2	11.	8.43×10^{12}	0.262	5.82×10^{-10}	0.000397

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Heavy-ion induced desorption data: New Overview



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From Edgar Mahner



Nominal scheme, lifetime parameters (again)

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam) ^a	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	[10 ⁻⁴]	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time ^b	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	[Wm ⁻¹]	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^6
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number ^c		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering) ^d	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime ^e	[hour]	-	< 5.6

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Preliminary study for other ions than ²⁰⁸Pb has been done in
LHC project report 450, "Review of the LHC ion program," Daniel Brandt, 2000

Ion	Limit	N_0^{max}	τ_{IBS} [h]	\mathcal{L}_0 [cm ⁻² s ⁻¹]
Pb ₂₀₈ ⁸²	Quench	6.8×10^7	15	1.0×10^{27}
Sn ₁₂₀ ⁵⁰	Quench	2.8×10^8	10	1.7×10^{28}
Kr ₈₄ ³⁶	IBS/Source	5.5×10^8	10	6.6×10^{28}
Ar ₄₀ ¹⁸	IBS/Source	2.2×10^9	10	1.0×10^{30}
O ₁₆ ⁸	IBS/Source	1.2×10^{10}	10	3.1×10^{31}

Maximum bunch intensities and ultimate initial luminosities for ions in the LHC

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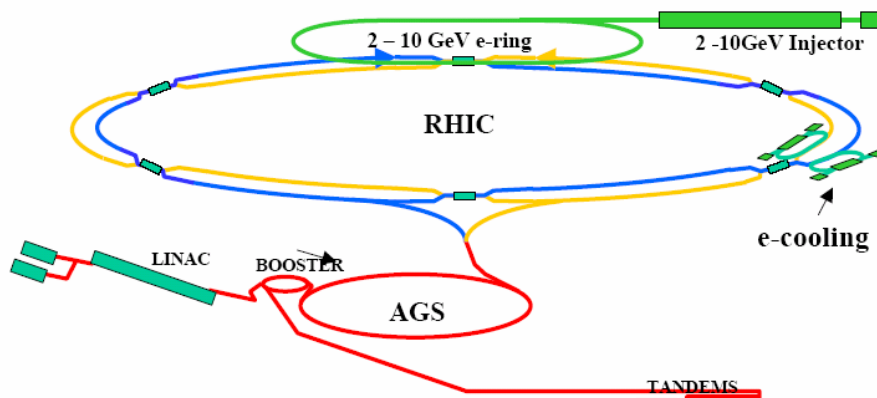
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eRHIC ZDR Base Line Design

- 5- 10 GeV electrons and positron beams
- 250 GeV p, 100 GeV/nucleon heavy ions
- Maximum Luminosity 10^{33} nucleons $\text{cm}^{-2}\text{s}^{-1}$
- High integrated luminosity, up to $90 \text{ pb}^{-1}/\text{day}$
- Longitudinal polarization 70% for e^- @ 5 - 10 GeV, e^+ @ 10 GeV
- Polarized protons > 70%, polarized neutrons (^3He) > 70%
- One interaction region
- Operational flexibility for collisions with various ion species of different energies

Possible eRHIC layout

- Collisions at 12 o'clock interaction region
- 10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference
- Inject at full energy 5 - 10 GeV
- Existing RHIC interaction region allows for typical asymmetric detector (similar to HERA or PEP II detectors)



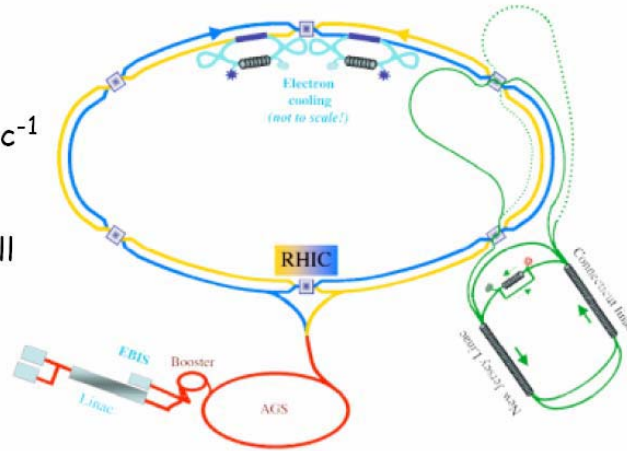
Linac-Ring eRHIC example: Stand-alone ERL with two IPs

Features:

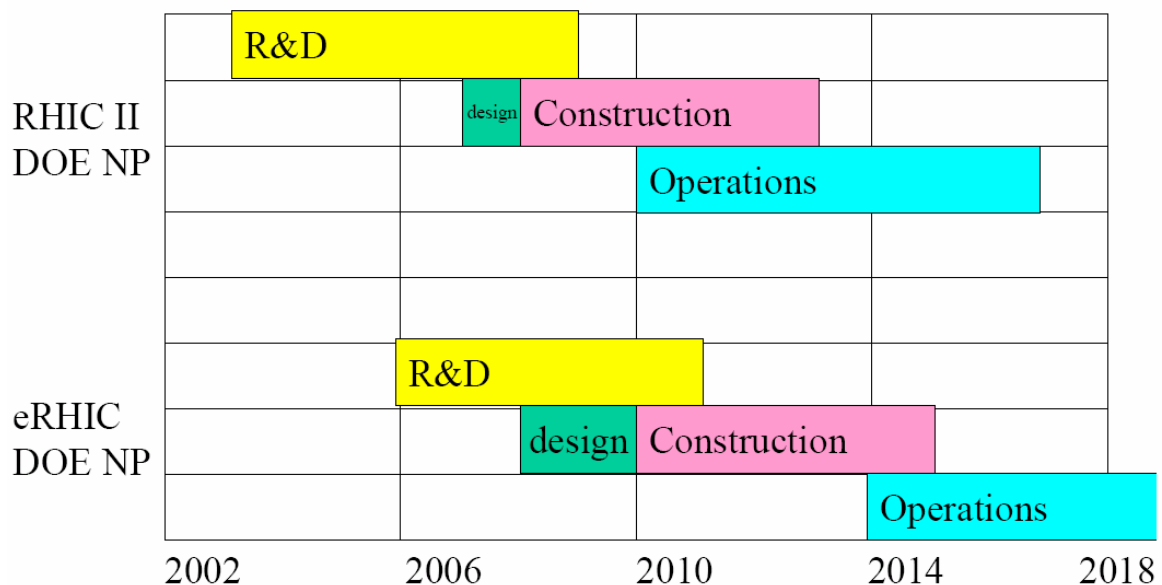
- $L_{\max} \sim 1.2 \text{ to } 2.5 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
- Full range of CM energies
- Polarization transparency at all energies
- STAR & PHENIX still run

Limitations:

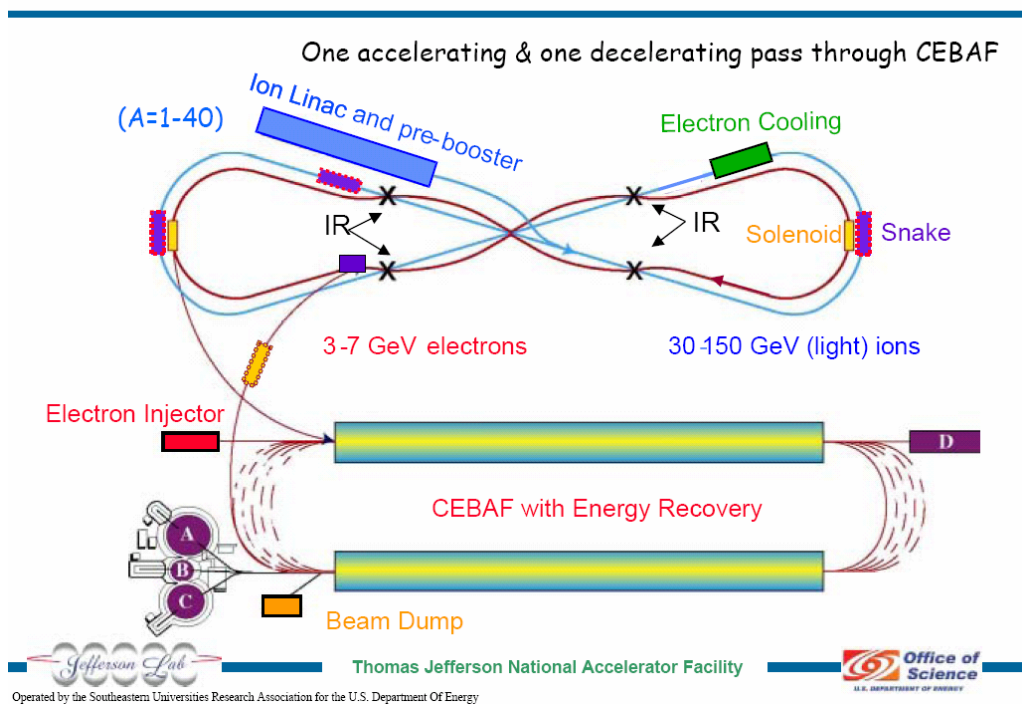
- No e^+ beam



Technically driven schedule



ELIC Layout



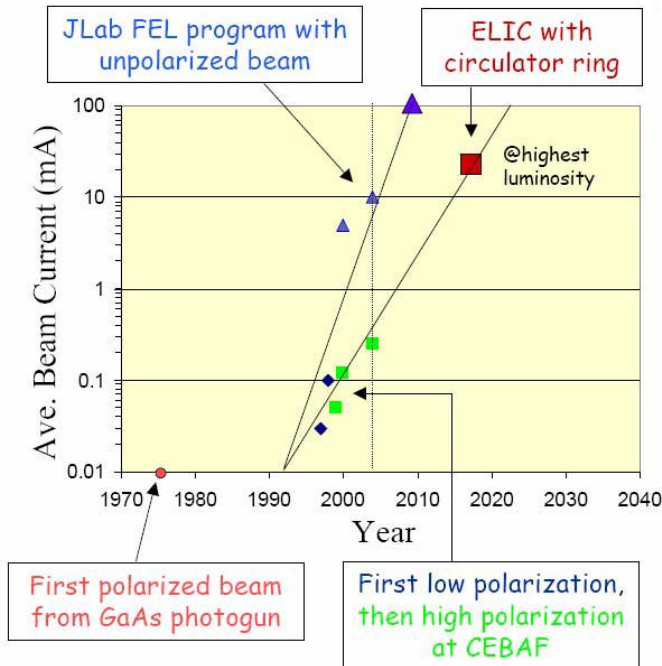
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ELIC Physics Specifications

- Flexible Center-of-mass energy between 20 and 65 GeV
 - $E_e \sim 3 \text{ GeV}$ on $E_i \sim 30 \text{ GeV}$ up to $E_e \sim 7 \text{ GeV}$ on $E_i \sim 150 \text{ GeV}$
worked out in detail (gives E_{cm} up to 65 GeV)
- CW Luminosity up to $8 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ per Interaction Point
- Ion species of interest: protons, deuterons, ^3He , light-medium ions
 - Proton and neutron
 - Light-medium ions not necessarily polarized
 - Up to Calcium
- Longitudinal polarization of both beams in the interaction region
(+Transverse polarization of ions +Spin-flip of both beams)

Towards Higher Electron Beam Current



Source requirements for ELIC less demanding with circulator ring! Few mA's versus $\gg 100$ mA of highly polarized beam.

Lifetime Estimate @ 25 mA:

CEBAF enjoys **excellent** gun lifetime:
 ~200 C charge lifetime
 (until QE reaches 1/e of initial value)
 ~100,000 C/cm² charge density lifetime
 (we use a ~0.5 mm dia. spot)

If Charge-Lifetime assumption valid:
 With ~1 cm dia. spot size lifetime
 of 36 weeks at 25 mA!

Need to test the scalability of charge lifetime with laser spot diameter \rightarrow
Measure charge lifetime versus laser spot diameter in lab. (Poelker, Grames)



Thomas Jefferson National Accelerator Facility



Operated by the Southeastern Universities Research Association for the U.S. Department Of Energy
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U.S. DEPARTMENT OF ENERGY

NESR (RIB)

magnetic bending power	13 Tm
transverse ring acceptance	150 (h)/50 (v) mm mrad
with momentum acceptance	$\pm 2 \times 10^{-2}$
injector	CR
beam emittance at injection	0.5(h)/0.5(v) mm mrad
momentum spread at injection	$\pm 5 \times 10^{-4}$
electron cooling:	
number of fragments per cycle	$< 5 \times 10^9$
reference ion energy (A/Z=2.7)	740 MeV/u
cooling time (10 ⁸ U-like ions)	0.3 s
beam emittance after cooling	0.1 (h)/ 0.1 (v) mm mrad
momentum spread after cooling	$\pm 1 \times 10^{-4}$
min. energy after deceleration	100 MeV/u

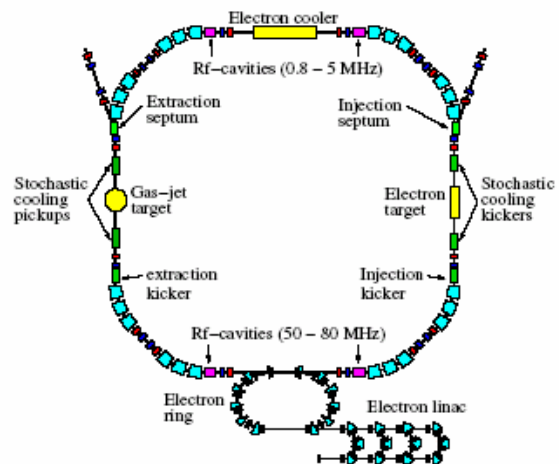
GSI / FAIR project

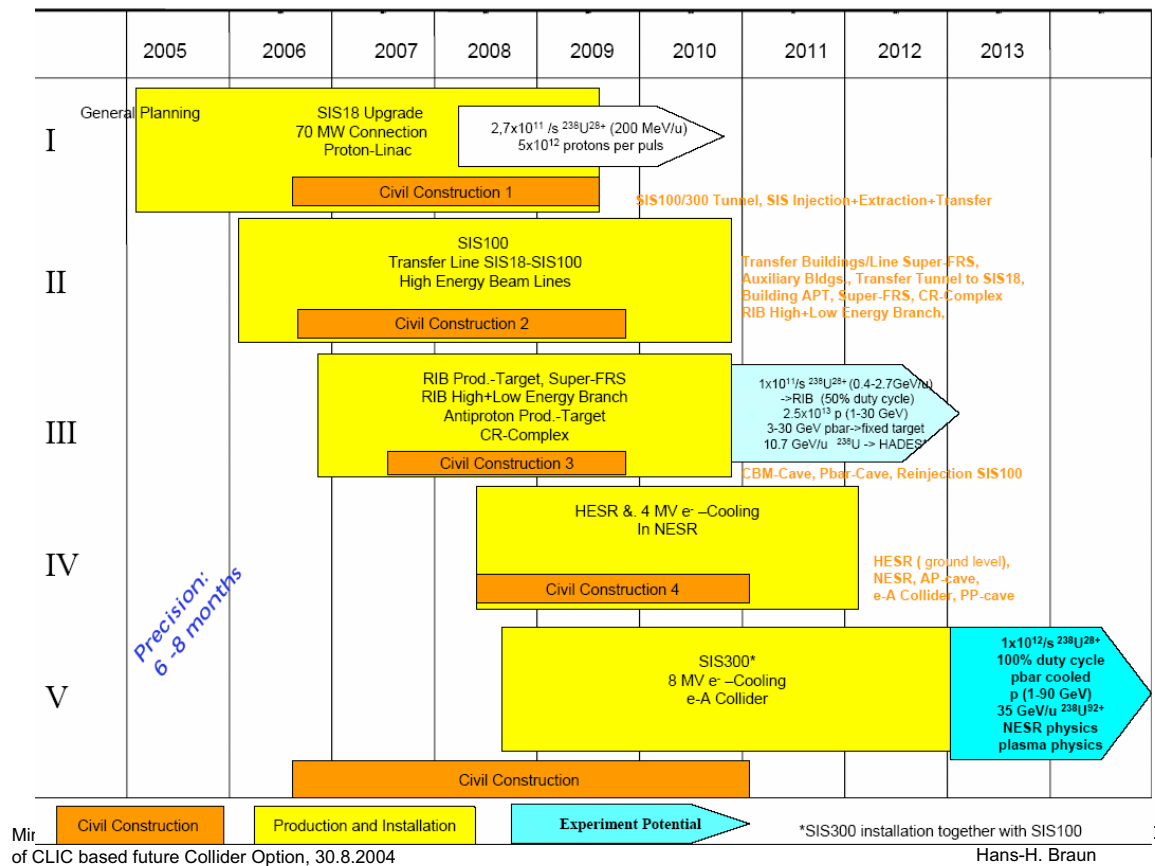
option e-A collisions:

electron energy	200 - 500 MeV
number of ion bunches	40 - 64
number of electron bunches	6 - 8
ion bunch population	$\leq 5.6 \times 10^6$
electron bunch population	$\leq 5 \times 10^{10}$
luminosity	$1 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$

SIS100/200 for fixed target experiments:

expected beam parameters for slow extraction from SIS200	
duty cycle	$\approx 100\%$
maximum beam current	$1 \times 10^{12} \text{ ions / s}$
beam emittance	2(h)/5(v) mm mrad
momentum spread	$\pm 2.5 \times 10^{-4}$





Informations on LHC ion program

<http://ab-div.web.cern.ch/ab-div/Conferences/Chamonix/2004/default.html>
<http://ab-div.web.cern.ch/ab-div/Publications/LHC-DesignReport.html>

Slides and references for FAIR, eRHIC and e-LIC

<http://nsac2004.bnl.gov/>
[Overview-Electron Ion Collisions](#)
[Realization at e-RHIC](#)
[Realization at e-LIC](#)
[HI Physics Opportunity at GSI](#)
[HI Physics and Experiments](#)

Raju Venugopalan
 Richard Milner
 Rolf Ent
 Bengt Friman
 Peter Braun-Munzinger

<http://www-new.gsi.de/GSI-Future/cdr/PDF/S3.pdf>

A. Koop et. al., Conceptual Design of an Electron-Nucleus Scattering Facility at GSI, Final Report, BINP 2001.

<http://www.agsrhichome.bnl.gov/eRHIC/>

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