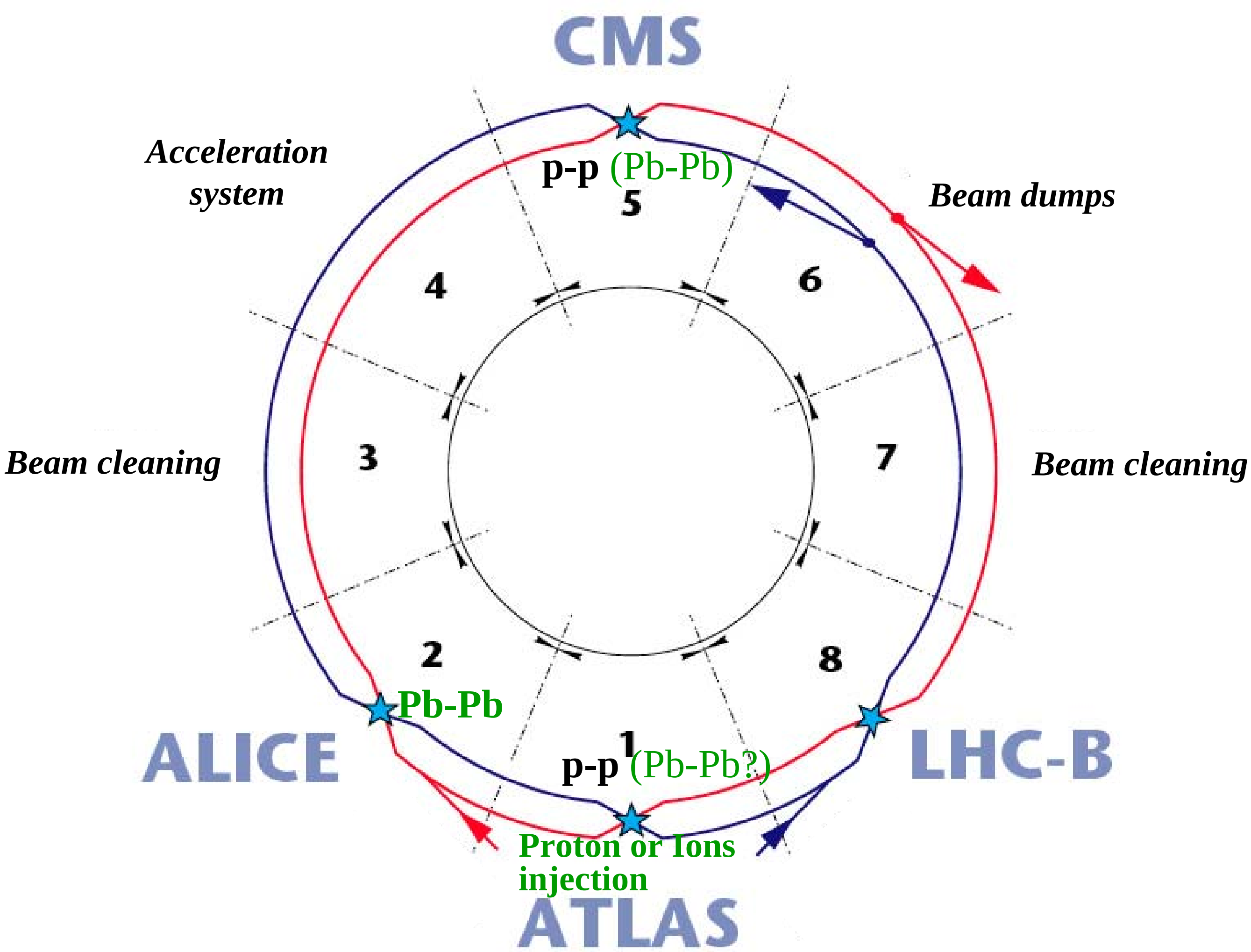
Ion Programme of LHC

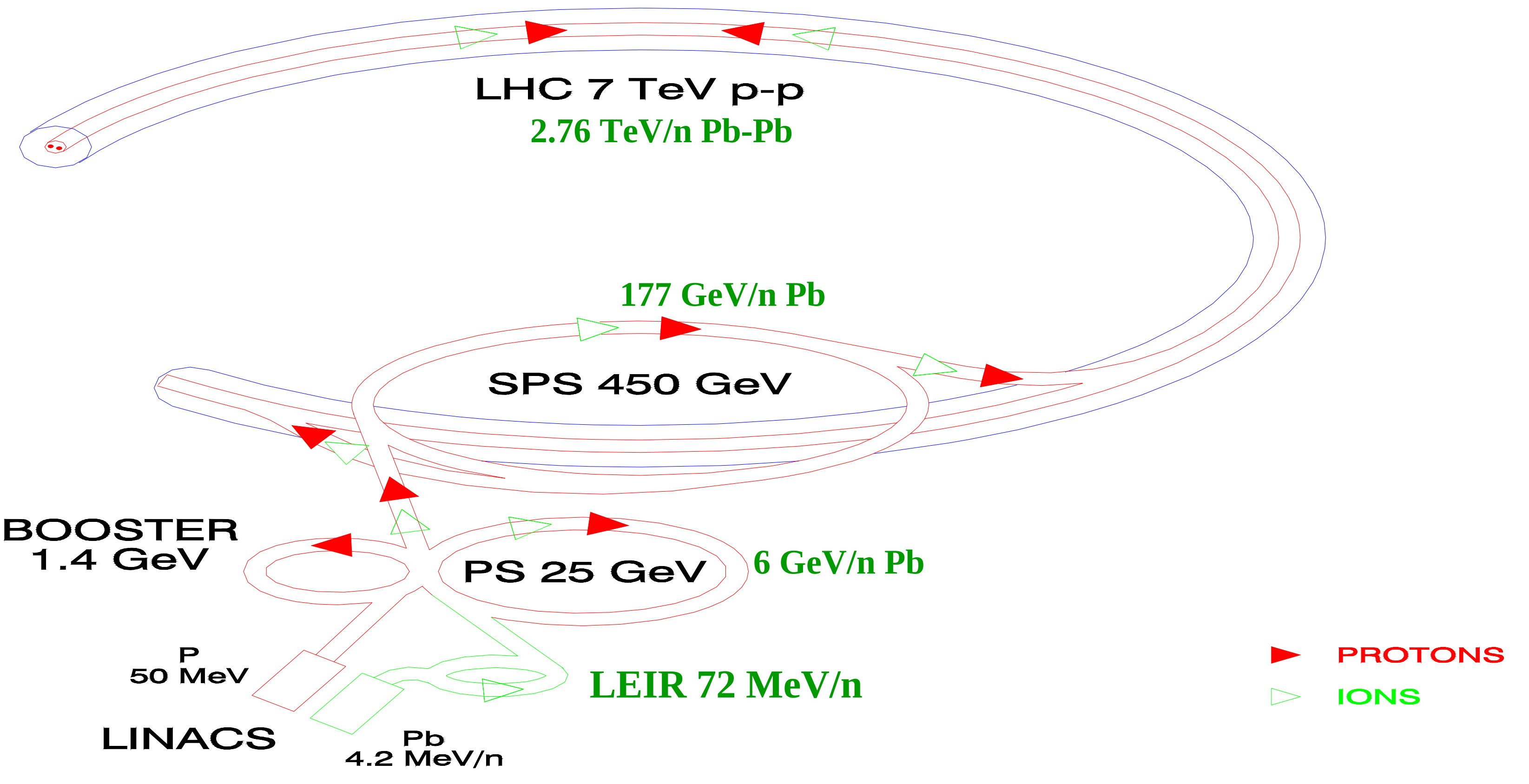
Hans-H. Braun

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

LHC: Layout


CMS
Acceleration system
p-p (Pb-Pb)
5
Beam dumps
4
6
Beam cleaning
3
7
Beam cleaning
2
8
Pb-Pb
ALICE
1
p-p (Pb-Pb?)
LHC-B
Proton or Ions injection
ATLAS

The LHC Injector Chain - Overview



Pb Collisions in LHC: Nominal + Early

Parameter	**Units**	**Nominal**	**Early Scheme**
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	cm^{-2} s^{-1}	$1\ 10^{27}$	$5\ 10^{25}$
# 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		**$7\ 10^7$**	**$7\ 10^7$**
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] $\varepsilon^*_{\mathbf{rms}} = (\beta\gamma)_{\mathbf{rel}}\ \sigma^2/\beta_{\mathbf{Twiss}}$

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 1st proton period" (Nov. 2007?)**

[1] SPS 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} $cm^{-2}s^{-1}$ (corresponds to "Early Scheme")
- Years 2 (**2009**?) and 4: Pb-Pb @ L ~ 10^{27} $cm^{-2}s^{-1}$ (Nominal Pb beam) for rare observables
- Year 3: p-Pb @ L ~ 10^{29} $cm^{-2}s^{-1}$ for nuclear modifications of structure functions
- Year 5 (**2012**?): Ar-Ar @ L ~ 10^{27} - 10^{29} $cm^{-2}s^{-1}$ 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 $\tau_{Growth} \sim Z^2/A^3 \sim N_B/A$

balanced by Synchrotron radiation $\tau_{Damping} \sim A^4/Z^5 \sim 1/Z$

Space charge limit in injector chain $\Delta Q_{SC} \sim N_B\, Z^2/A$

Intra Beam Scattering limits in injector chain

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)

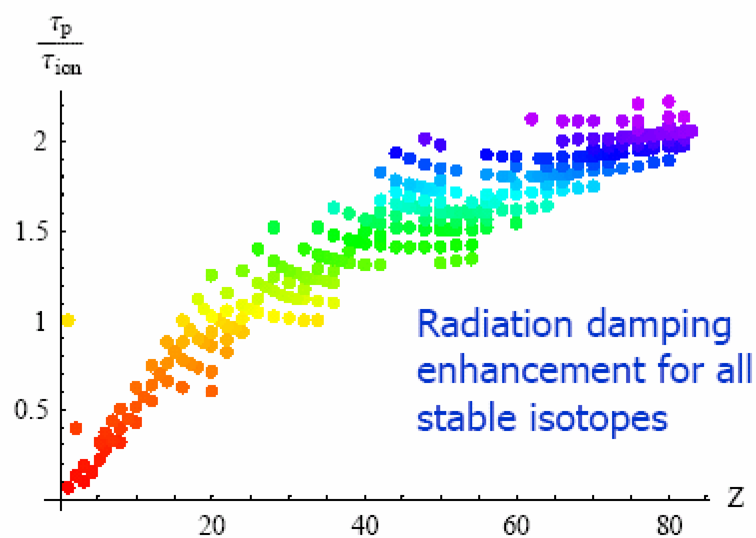
Synchrotron Radiation

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

$$\frac{U_{\rm ion}}{U_{\rm p}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\rm ion}}{u^c_{\rm p}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

$$\frac{N_{\rm ion}}{N_{\rm p}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\rm ion}}{\tau_{\rm p}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$

– 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	0.8[illegible]	1.07×10^{14}	3.32	7.37×10^{-9}	0.0377

Lead ions with pressure that gave proton lifetime 100h

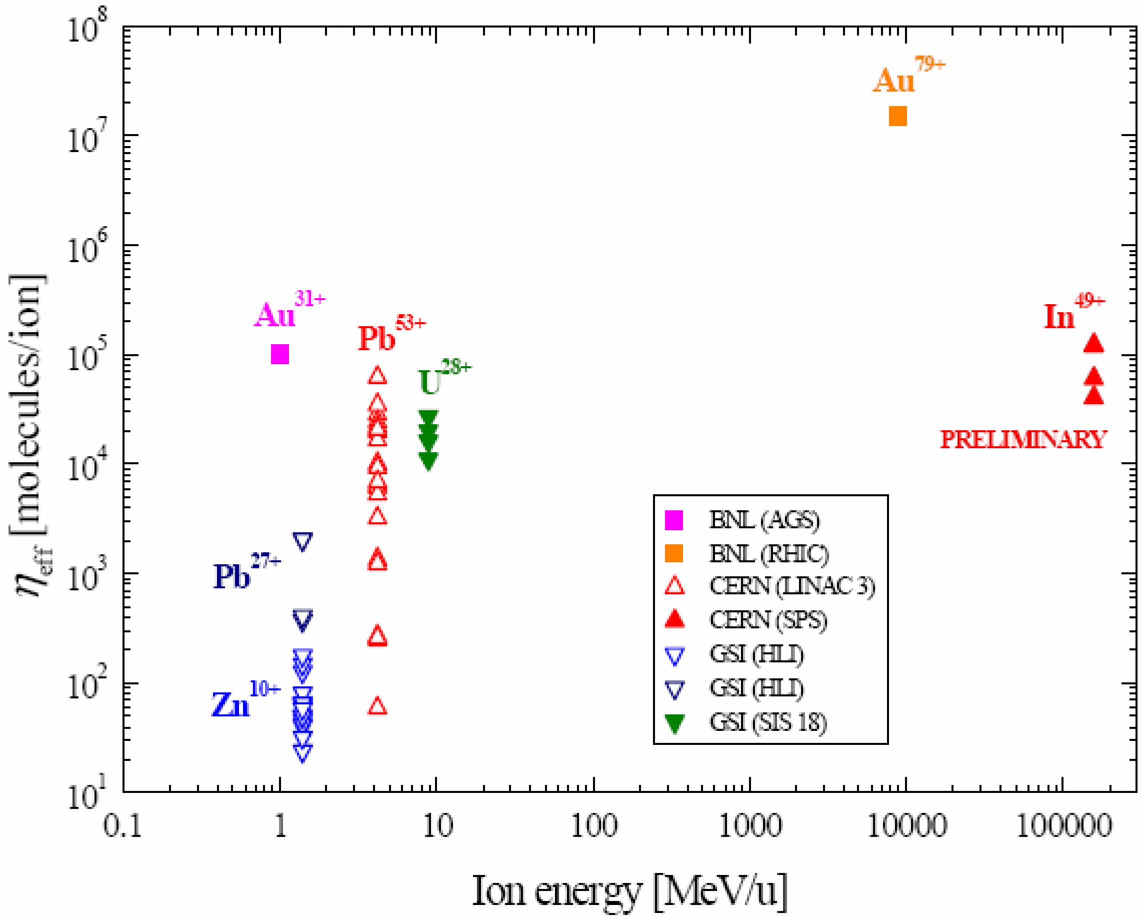
Gas	σ_{in}	n/m^{-3}	τ_{bg}/h	$P_{bg}/(W/m)$
H2	3.75	1.03×10^{15}	2.4	0.0165
He	2.48	8.2×10^{14}	4.55	0.00872
CH4	10.9	2.14×10^{14}	3.96	0.01
H2O	7.52	2.33×10^{14}	5.28	0.00752
CO	7.22	1.65×10^{14}	7.76	0.00512
CO2	11.	1.07×10^{14}	7.89	0.00503

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

J.M. Jowett, LHC Performance Workshop, Chamonix, 19/1/2004

Heavy-ion induced desorption data: New Overview



J.M. Jowett, LHC Performance Workshop, Chamonix, 19/1/2004

15

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	$[\mathrm{Wm}^{-1}]$	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

J.M. Jowett, LHC Performance Workshop, Chamonix, 19/1/2004

Preliminary study for other ions than ^{208}Pb 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^{82}_{208}	Quench	6.8×10^{7}	15	1.0×10^{27}
Sn^{50}_{120}	Quench	2.8×10^{8}	10	1.7×10^{28}
Kr^{36}_{84}	IBS/Source	5.5×10^{8}	10	6.6×10^{28}
Ar^{18}_{40}	IBS/Source	2.2×10^{9}	10	1.0×10^{30}
O^{8}_{16}	IBS/Source	1.2×10^{10}	10	3.1×10^{31}

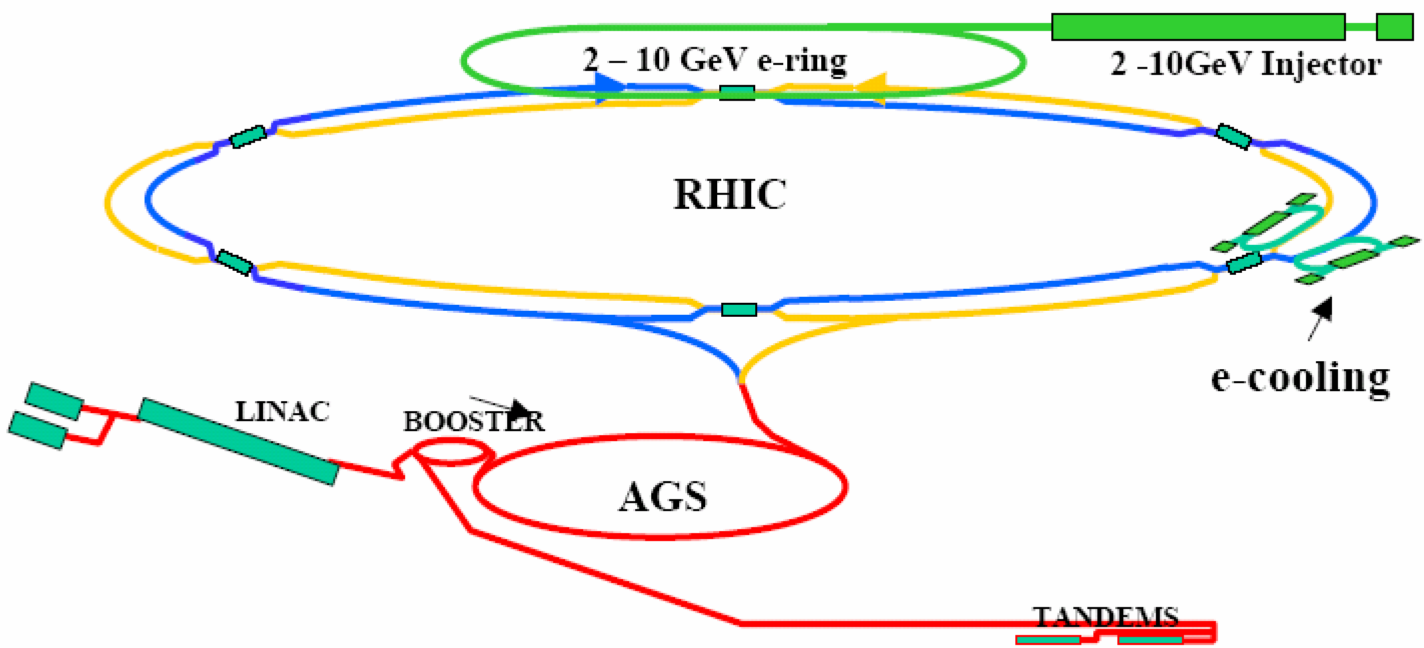
Maximum bunch intensities and ultimate initial luminosities for ions in the LHC

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 $cm^{-2}s^{-1}$
- High integrated luminosity, up to 90 pb^{-1}/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)



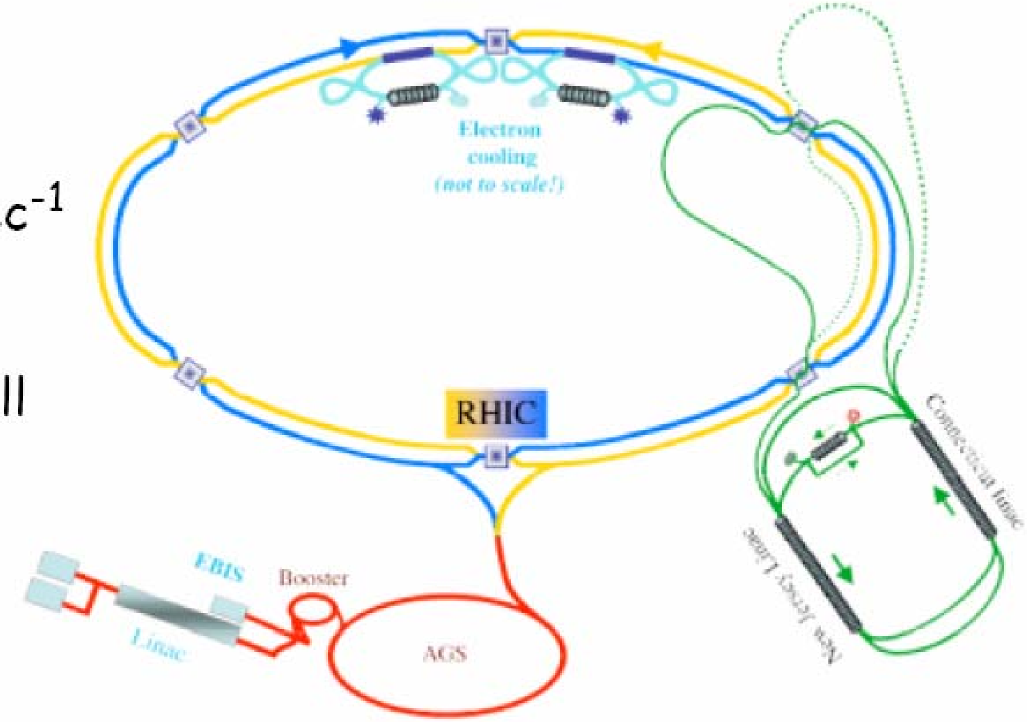
Linac-Ring eRHIC example: Stand-alone ERL with two IPs

Features:

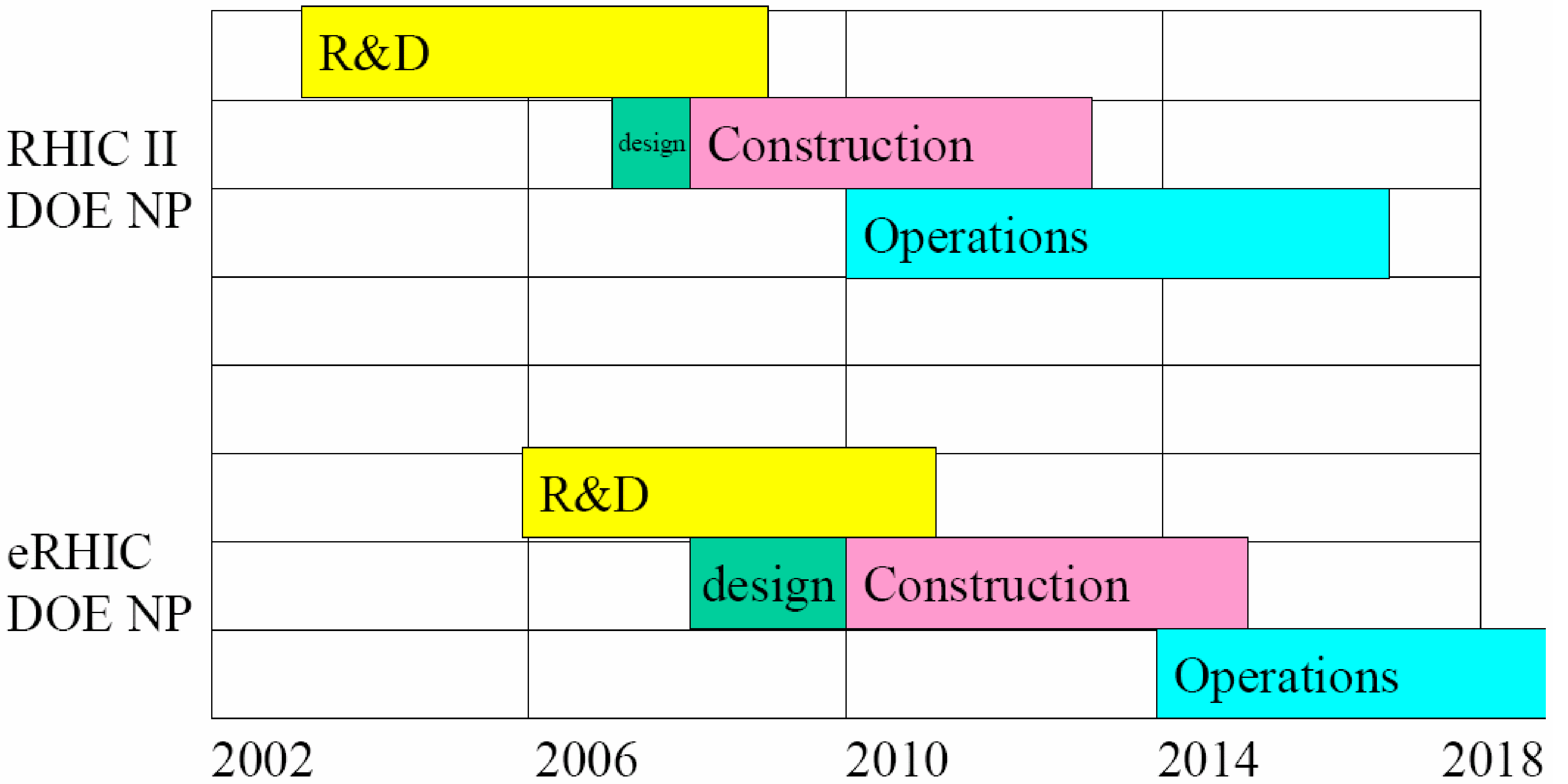
- L_{max} ~ 1.2 to 2.5 x $10^{33}cm^{-2}sec^{-1}$
- Full range of CM energies
- Polarization transparency at all energies
- STAR & PHENIX still run

Limitations:

- No e^{+} beam

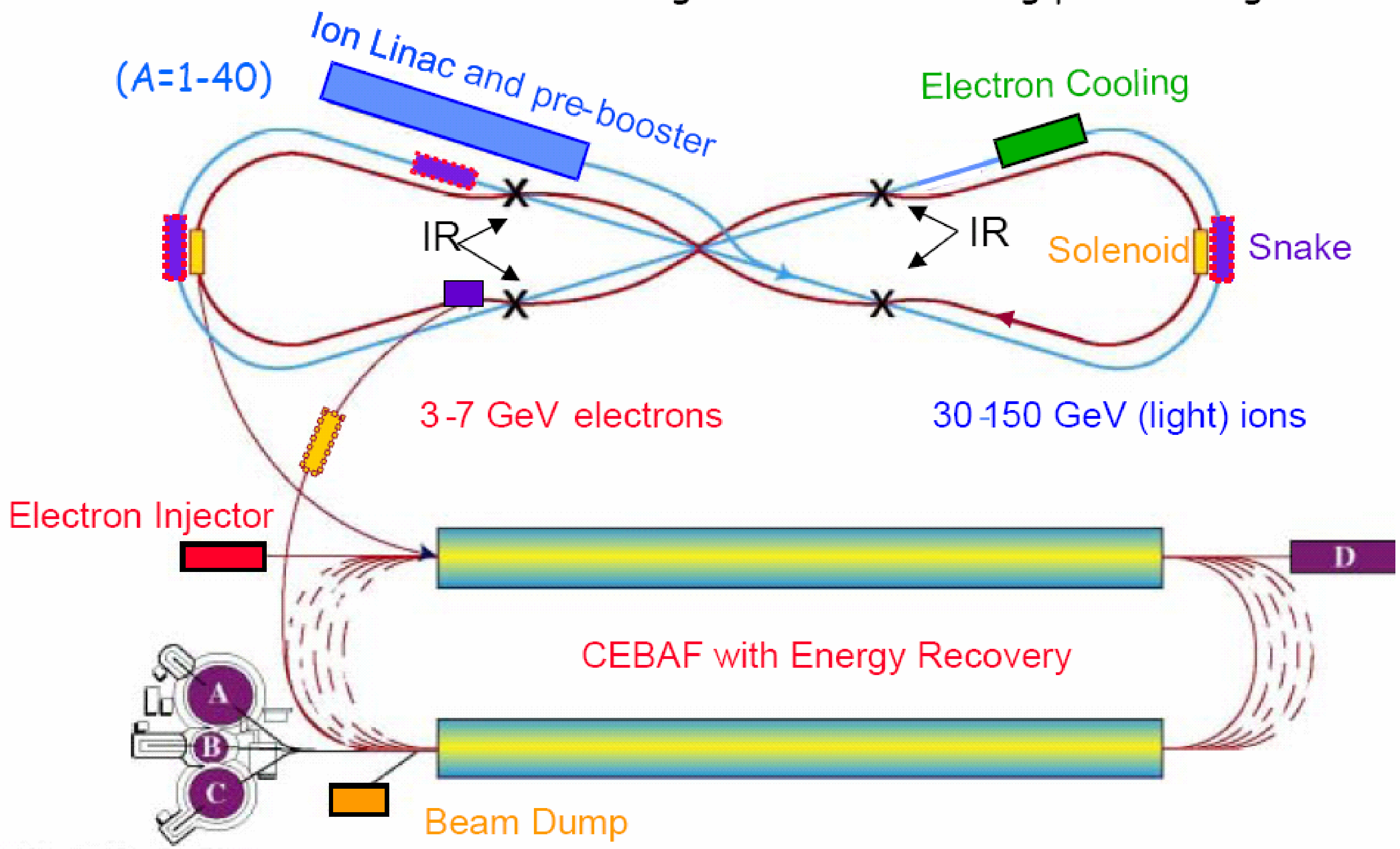


Technically driven schedule



ELIC Layout

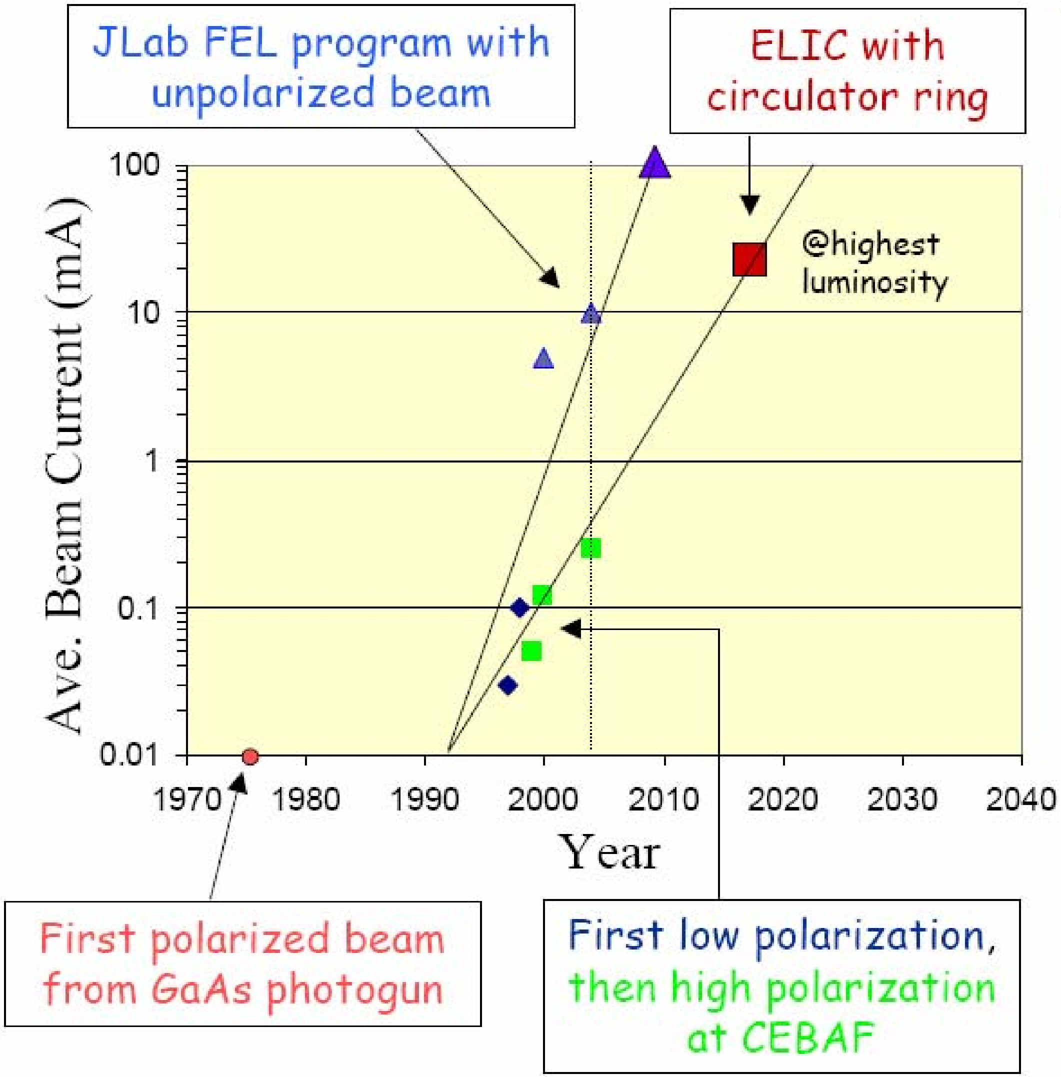
One accelerating & one decelerating pass through CEBAF



ELIC Physics Specifications

- Flexible Center-of-mass energy between 20 and 65 GeV
  - $E_e \sim 3$ GeV on $E_i \sim 30$ GeV up to $E_e \sim 7$ GeV on $E_i \sim 150$ GeV worked out in detail (gives E_{cm} up to 65 GeV)
- CW Luminosity up to 8×10^{34} cm^{-2} sec^{-1} per Interaction Point
- Ion species of interest: protons, deuterons, ^{3}He, 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 >> 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/cm^2 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 → Measure charge lifetime versus laser spot diameter in lab. *(Poelker, Grames)*

GSI / FAIR project

NESR (RIB)

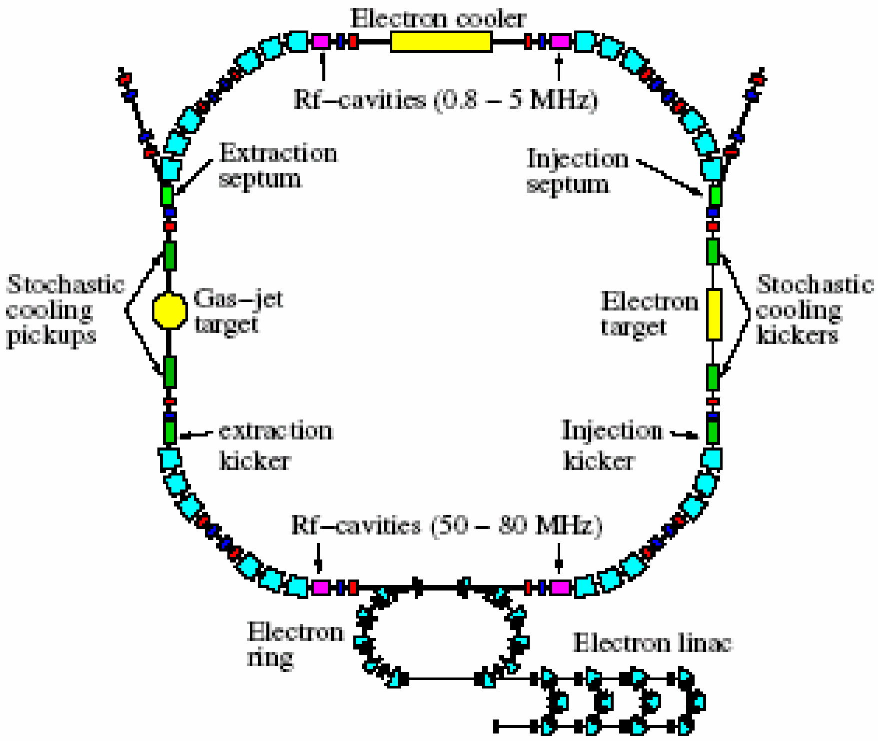
magnetic bending power	13 Tm
transverse ring acceptance	150 (h)/50 (v) mm mrad
with momentum acceptance	$\pm 2\times10^{-2}$
injector	CR
beam emittance at injection	0.5(h)/0.5(v) mm mrad
momentum spread at injection	$\pm 5\times10^{-4}$
electron cooling:	
number of fragments per cycle	$<5\times10^{9}$
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	$\pm 1\times10^{-4}$
min. energy after deceleration	100 MeV/u

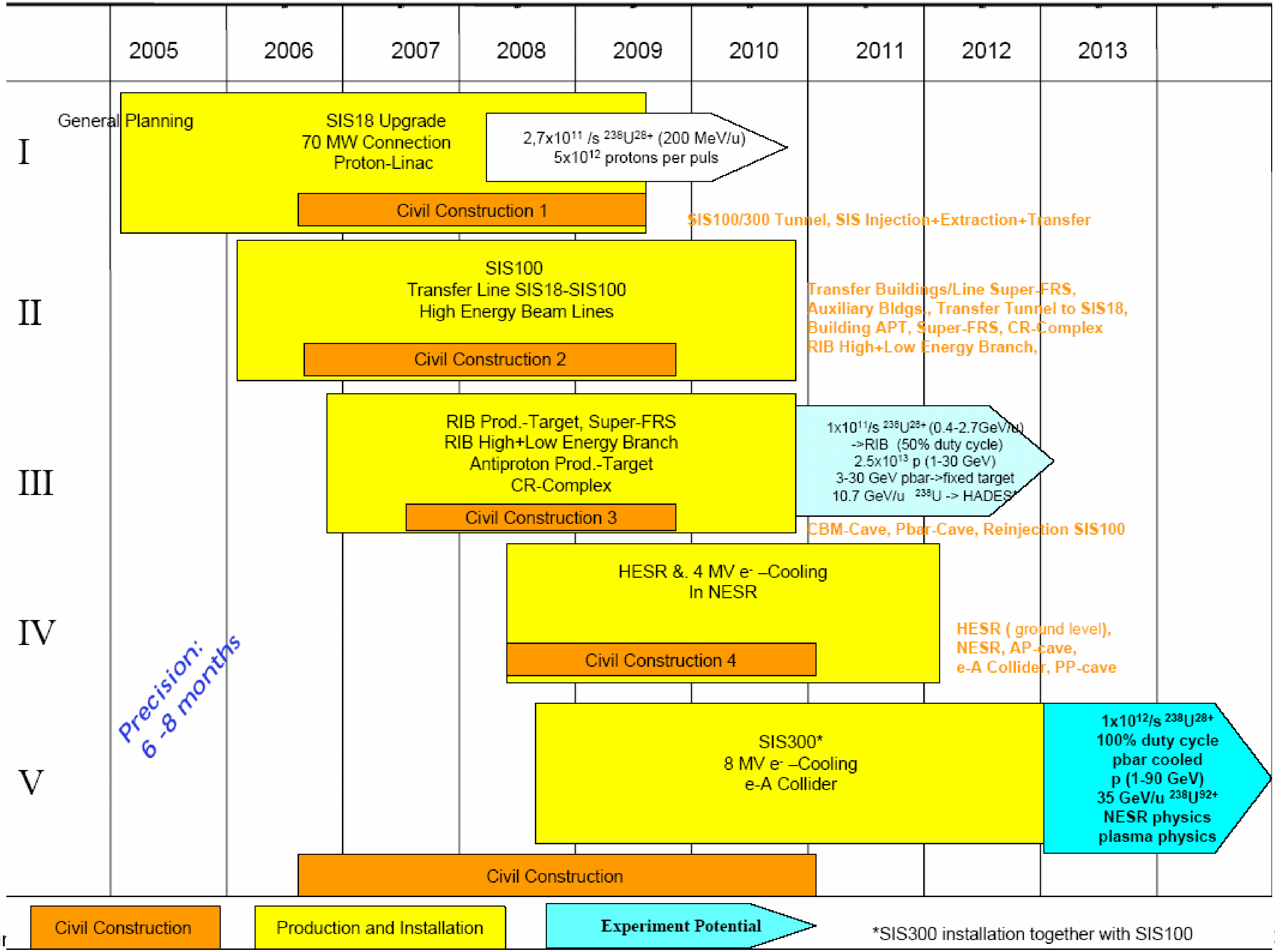
option e-A collisions:

electron energy	200 – 500 MeV
number of ion bunches	40 – 54
number of electron bunches	6 – 8
ion bunch population	$\leq 8.6\times10^{6}$
electron bunch population	$\leq 5\times10^{10}$
luminosity	1×10^{28} cm^{-2} s^{-1}

SIS100/200 for fixed target experiments:

expected beam parameters for **slow** extraction from SIS200	
duty cycle	≈ 100 %
maximum beam current	1×10^{12} ions / s
beam emittance	2(h)/5(v) mm mrad
momentum spread	$\pm 2.5\times10^{-4}$




2005
2006
2007
2008
2009
2010
2011
2012
2013
I
General Planning
SIS18 Upgrade
70 MW Connection
Proton-Linac
2,7x10^11 /s 238U28+ (200 MeV/u)
5x10^12 protons per puls
Civil Construction 1
SIS100/300 Tunnel, SIS Injection+Extraction+Transfer
II
SIS100
Transfer Line SIS18-SIS100
High Energy Beam Lines
Civil Construction 2
Transfer Buildings/Line Super-FRS,
Auxiliary Bldgs., Transfer Tunnel to SIS18,
Building APT, Super-FRS, CR-Complex
RIB High+Low Energy Branch,
III
RIB Prod.-Target, Super-FRS
RIB High+Low Energy Branch
Antiproton Prod.-Target
CR-Complex
Civil Construction 3
1x10^11/s 238U28+ (0.4-2.7GeV/u)
->RIB (50% duty cycle)
2.5x10^13 p (1-30 GeV)
3-30 GeV pbar->fixed target
10.7 GeV/u 238U -> HADES
CBM-Cave, Pbar-Cave, Reinjection SIS100
IV
HESR &. 4 MV e- –Cooling
In NESR
Civil Construction 4
HESR (ground level),
NESR, AP-cave,
e-A Collider, PP-cave
Precision:
6 -8 months
V
SIS300*
8 MV e- –Cooling
e-A Collider
1x10^12/s 238U28+
100% duty cycle
pbar cooled
p (1-90 GeV)
35 GeV/u 238U92+
NESR physics
plasma physics
Civil Construction
Civil Construction
Production and Installation
Experiment Potential
*SIS300 installation together with SIS100

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	Raju Venugopalan
Realization at e-RHIC	Richard Milner
Realization at e-LIC	Rolf Ent
HI Physics Opportunity at GSI	Bengt Friman
HI Physics and Experiments	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/

Thanks to John Jowett and Karlheinz Schindl for providing slides, information and helpful discussions for this presentation