RHIC Luminosity Upgrade (Electron Cooler and EBIS)

C-AD Accelerator Complex

EBIS (Linac-based pre-injector)

RHIC performance

RHIC II luminosity upgrade (electron cooling)

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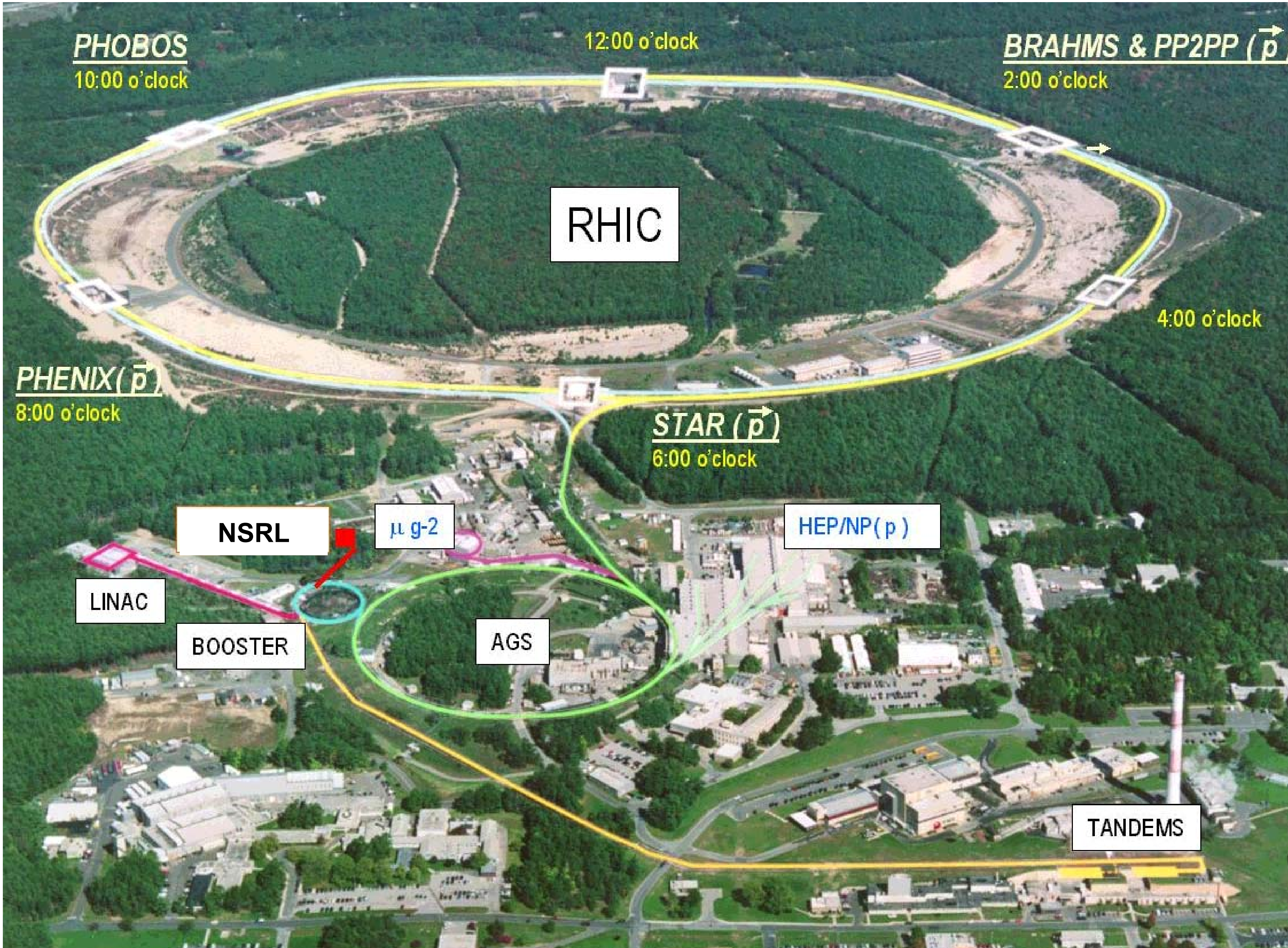
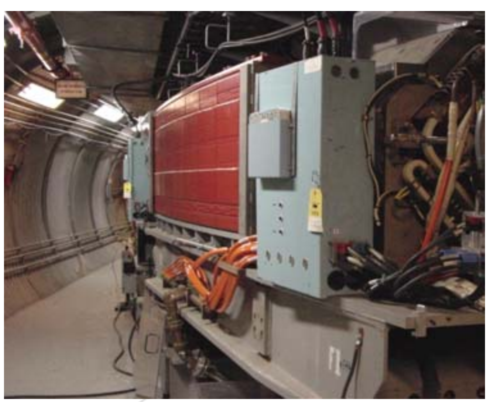
Thomas Roser
NSAC subcommittee meeting
June 2, 2004

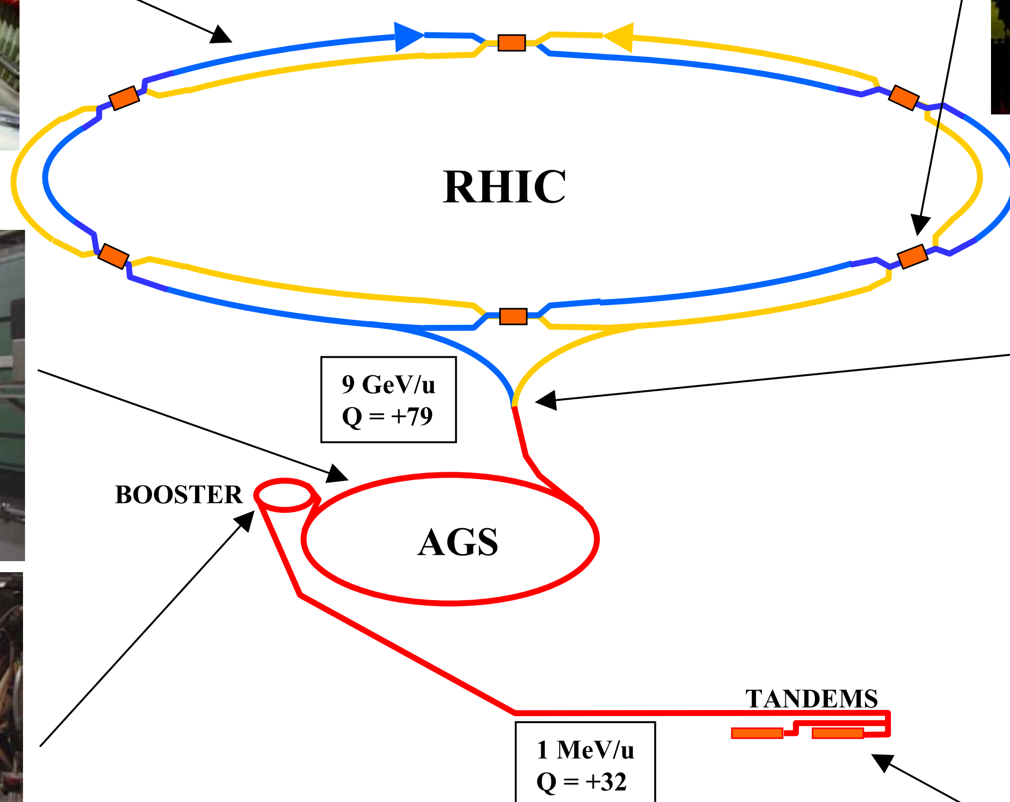

PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
NSRL
μ g-2
HEP/NP(p)
LINAC
BOOSTER
AGS
TANDEMS

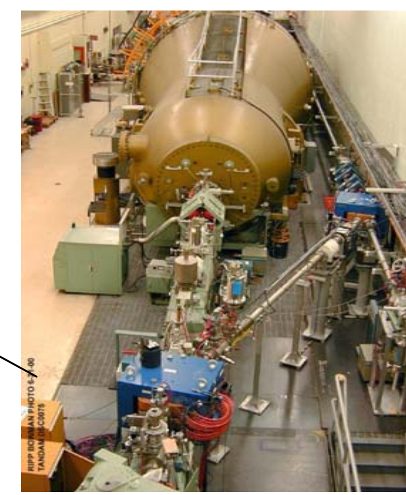
Relativistic Heavy Ion Collider

High luminosity collider of all ion species:

Au-Au:	100 GeV/n x 100 GeV/n
p-Au, d-Au:	100 GeV/n x 100 GeV/n
p↑ - p↑:	250 GeV x 250 GeV



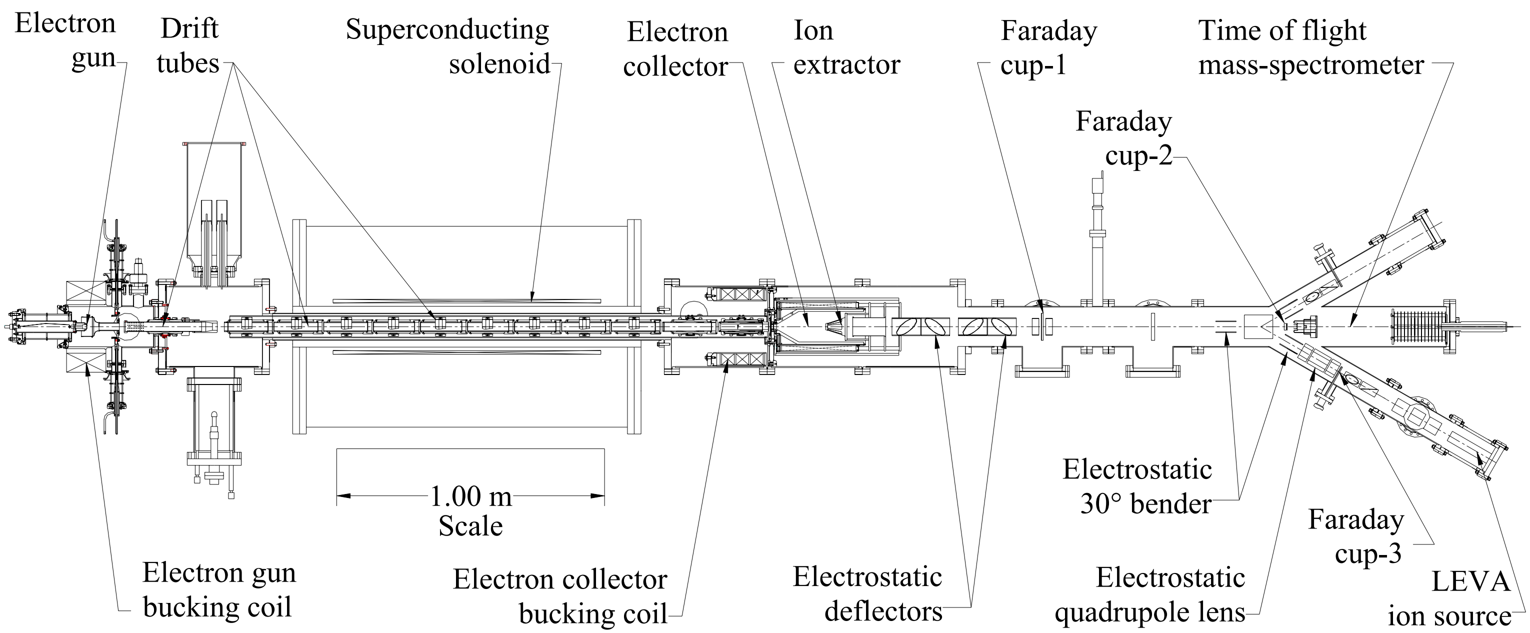




EBIS/Linac-based RHIC Pre-Injector

- Highly successful development of Electron Beam Ion Source (EBIS) at BNL: achieved ½ of required RHIC performance with ½ of EBIS trap length.
- EBIS allows for a reliable, low maintenance Linac-based pre-injector replacing the Tandem Van de Graaffs
- Greatly reduced operating costs, and avoidance of ~ 6 M$ in reliability-driven investments in the tandems
- Highly flexible to handle the multiple simultaneous needs of RHIC, NSRL, and AGS
- Produces beams of ALL ion species including noble gas ions (NSRL), Uranium (RHIC) and polarized He^3 (eRHIC)
- Ready to start construction; Cost: 18 M$;
  Technically driven construction schedule: FY2005 – 07
  NASA participation under discussion (~ 25 %)

Results from Test EBIS (½ of RHIC EBIS)



	RHIC Requirements	Achieved
E-beam current	10 A	10 A
Pulse length	≤ 40 μs	20 μs
Yield of Au^{33+}	3.4×10^9 (10 A, 1.5 m)	1.7×10^9 (8 A, 0.7m)
Yield of U^{45+}	2.4×10^9	

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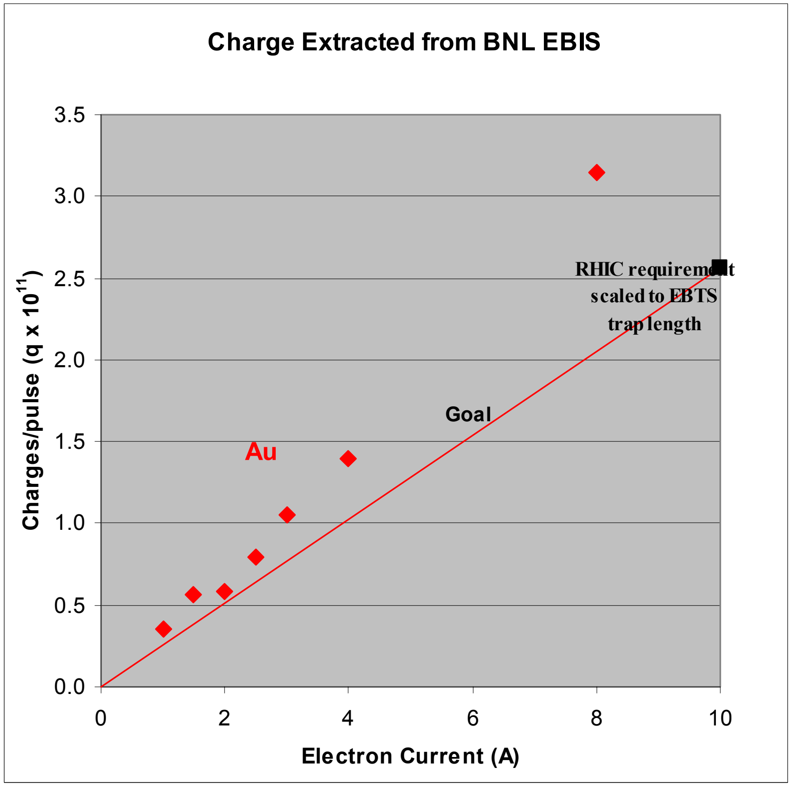
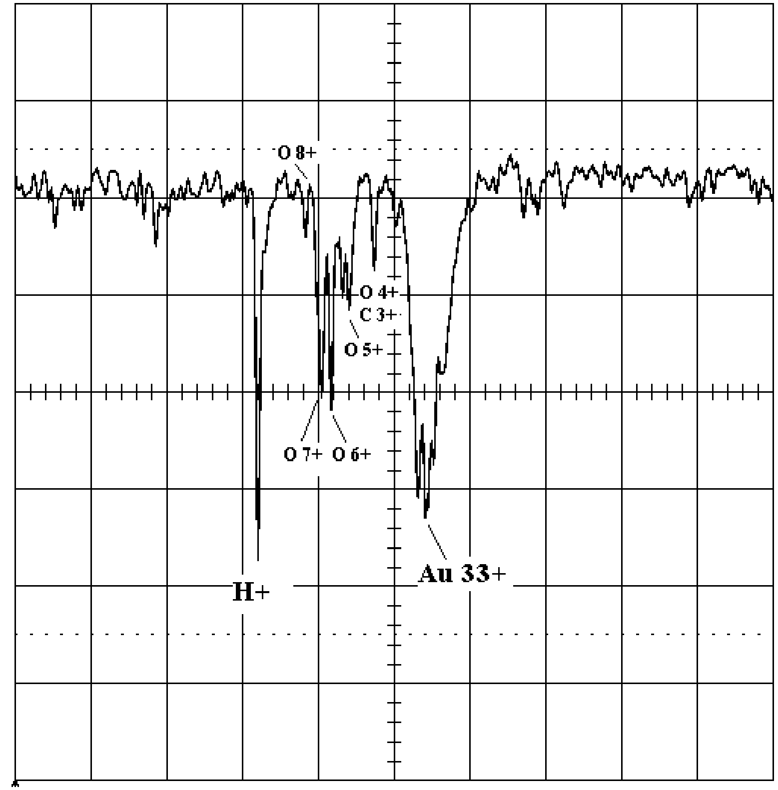
Results from Test EBIS (½ of RHIC EBIS)





Extracted gold ion yield shows more than 50% neutralization

Gold charge state with only 40 ms confinement time.

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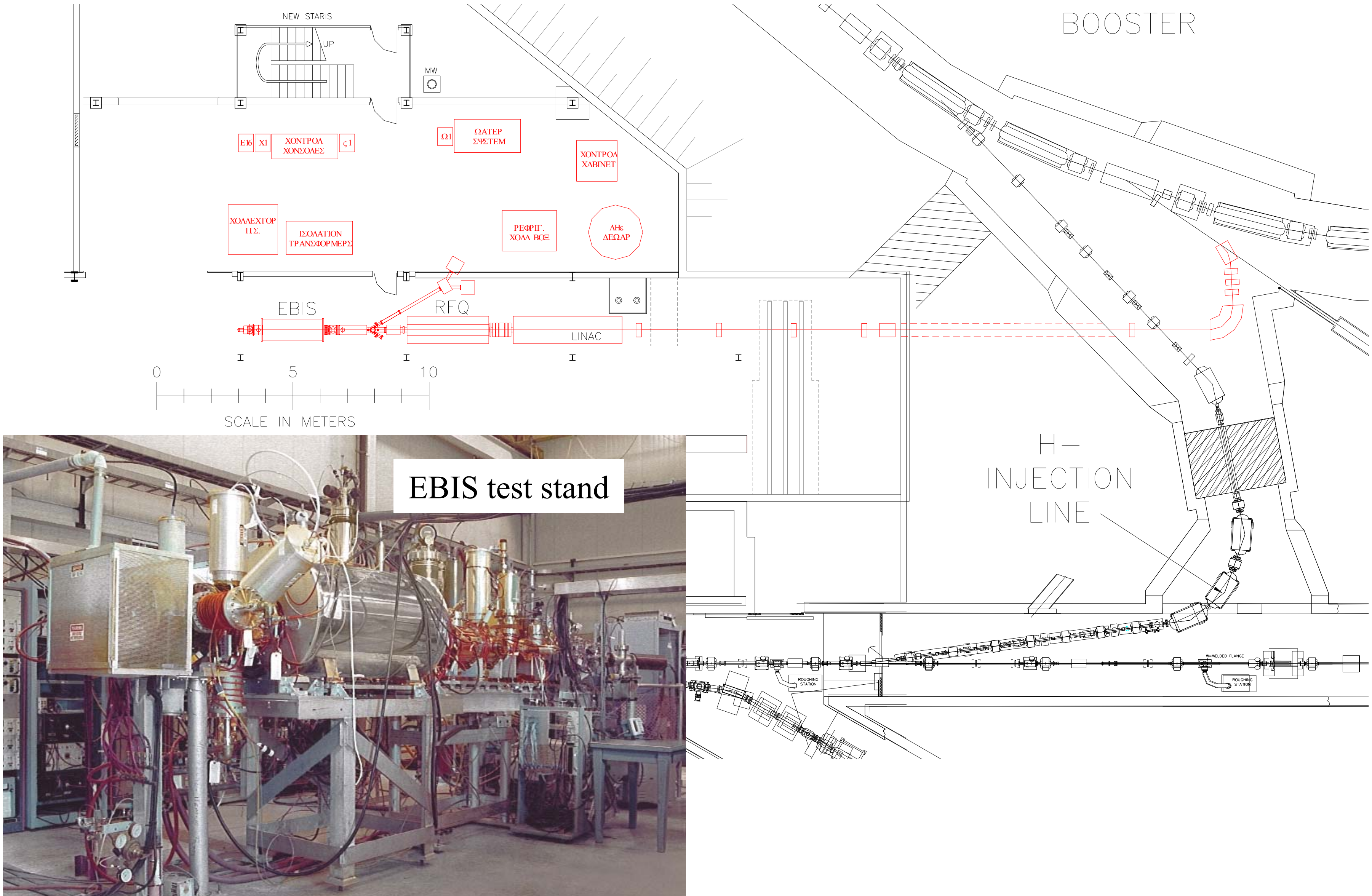
EBIS layout


NEW STARIS
UP
MW
BOOSTER
EBIS
RFQ
LINAC
0
5
10
SCALE IN METERS
H–
INJECTION
LINE
EBIS test stand

5-Year Construction Schedule (AY$)

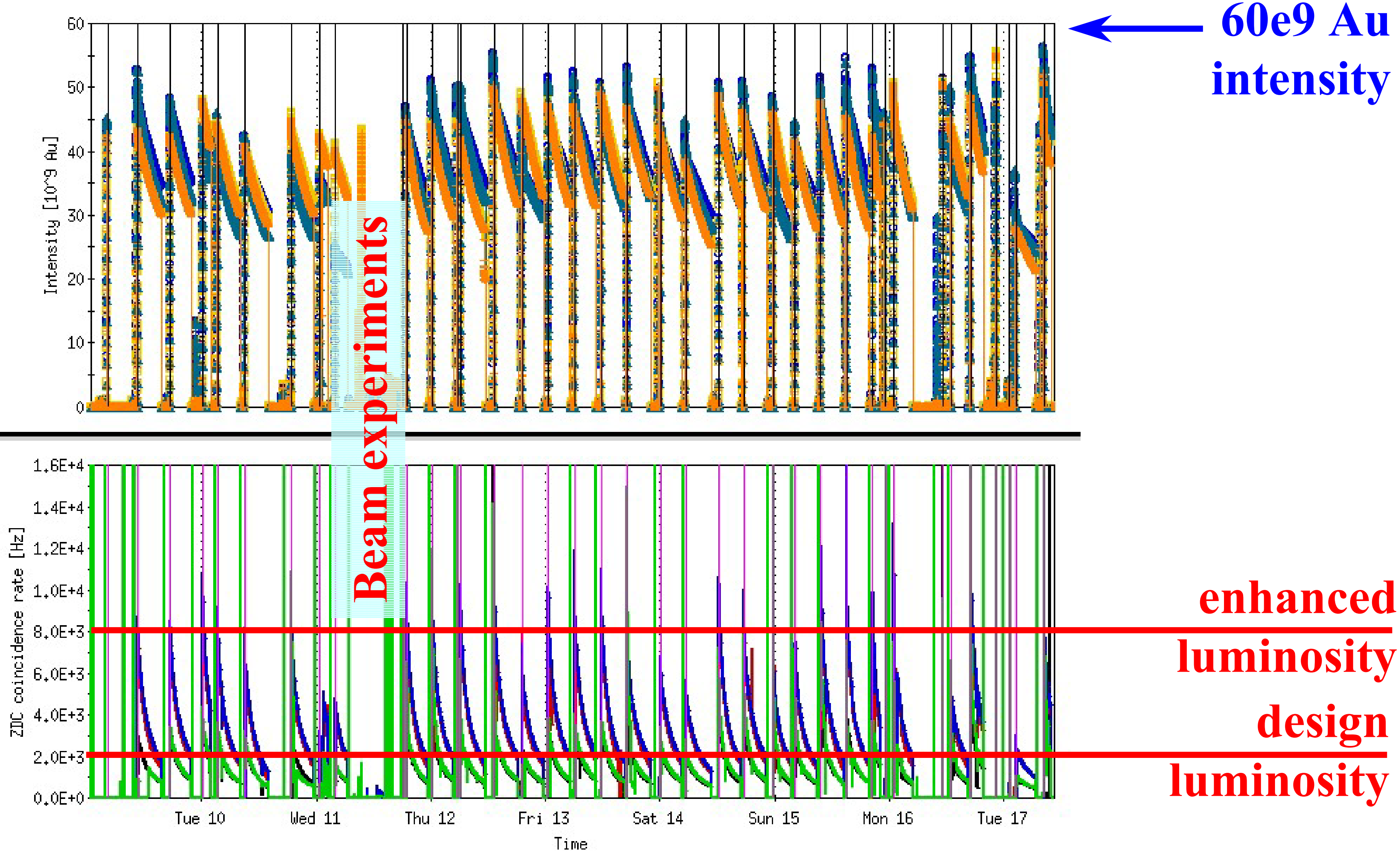
Scheduling of Project Funding

	Prior Years	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009	Total
Project Cost								
Facility Cost								
Total Line Item TEC	0	0	0	2,100	6,000	6,000	2,200	16,300
Other Project Costs								
R&D	0	0	925	430	0	0		1,355
Conceptual Design	0	200	0	0	0	0		200
Other Project Related Costs*	0				30	290	300	620
Total, Other Projects Costs	0	200	925	430	30	290	300	2,175
Total Project Cost (TPC)	0	200	925	2,530	6,030	6,290	2,500	18,475

*The Linac-Based Pre-Injector was granted a categorical exclusion from NEPA Review.

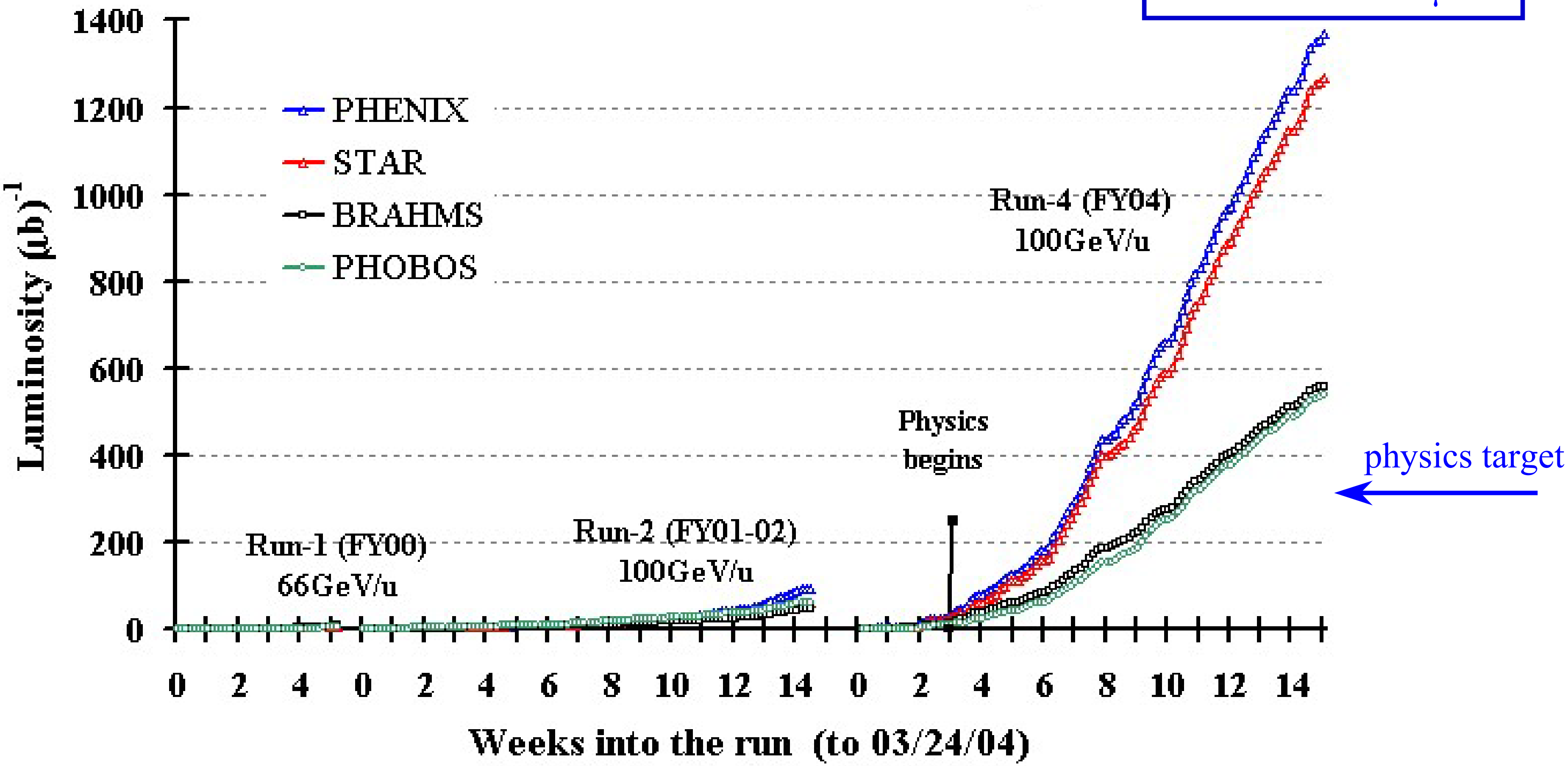
RHIC Run-4 – one week of physics stores

Week 9 Feb to 17 Feb [66% of calendar time in store]



RHIC Run-4 – luminosity evolution

Phenix	1370 μb^{-1}
Star	1270 μb^{-1}
Phobos	560 μb^{-1}
Brahms	540 μb^{-1}



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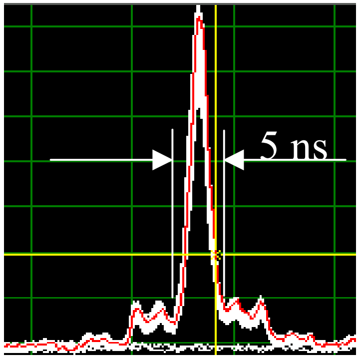
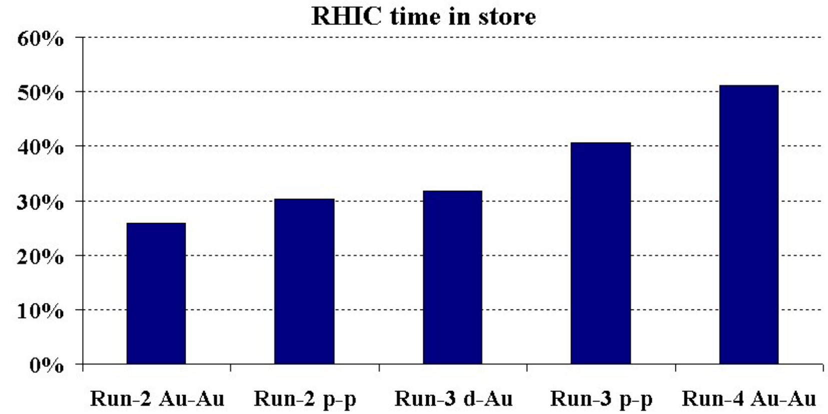
Performance summary



- Energy/beam: 100 GeV/nucl.
- Diamond length: σ = 20 cm

RHIC bunch profile



Mode	# bunches	Ions/bunch $[10^9]$	β^* [m]	Emittance [$\pi\mu$m]	L_{peak} $[cm^{-2}s^{-1}]$	L_{ave}(store) $[cm^{-2}s^{-1}]$	L_{ave} (week) $[week^{-1}]$
Au-Au [Run-4]	45	1.1	1	15 - 40	15×10^{26}	4×10^{26}	160 $(\mu b)^{-1}$
d-Au [Run-3]	55	110(d), 0.7(Au)	2	15	7×10^{28}	2×10^{28}	4.5 $(nb)^{-1}$
p↑-p↑ [Run-4]	28	170 (*)	1	20 - 30	15×10^{30}	10×10^{30}	(**)
Au-Au RHIC design	56	1	2	15 - 40	9×10^{26}	2×10^{26}	50 $(\mu b)^{-1}$
p-p RHIC design	56	100	2	20	5×10^{30}	4×10^{30}	1.2 $(pb)^{-1}$

Best store or week
(*) Unpolarized source
(**) No data run

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Machine goals for next 4 years (pre-RHICII)

- **Enhanced RHIC luminosity (112 bunches, $\beta^* = 1$m):**
- **Au – Au: 8×10^{26} cm^{-2} s^{-1} (100 GeV/nucleon)**
- **For protons also 2×10^{11} protons/bunch (no IBS):**
- **p↑ – p↑: 60×10^{30} cm^{-2} s^{-1}; 70 % polarization (100 GeV)**
  150×10^{30} cm^{-2} s^{-1}; 70 % polarization (250 GeV)

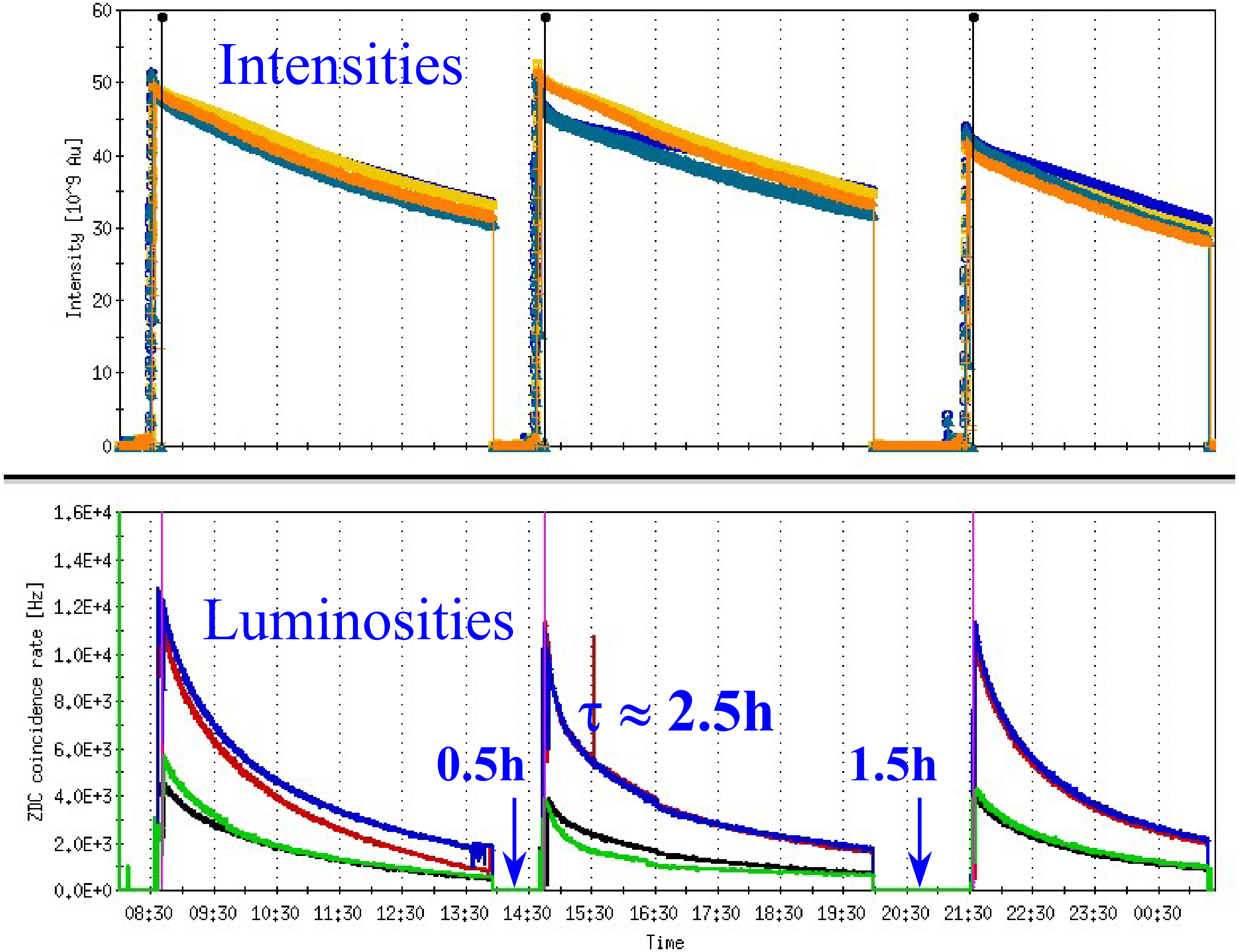
  (luminosity averaged over store delivered to 2 IRs)

4× design 2× achieved

16× design 6× achieved

Main luminosity limitation at present is pressure rise due to electron cloud formation. This is being addressed by surface treatment (NEG, baking) of all room temperature beam vacuum chambers.

Luminosity Limit – Intra-Beam Scattering (IBS)



- Debunching requires continuous gap cleaning (tune meter)
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

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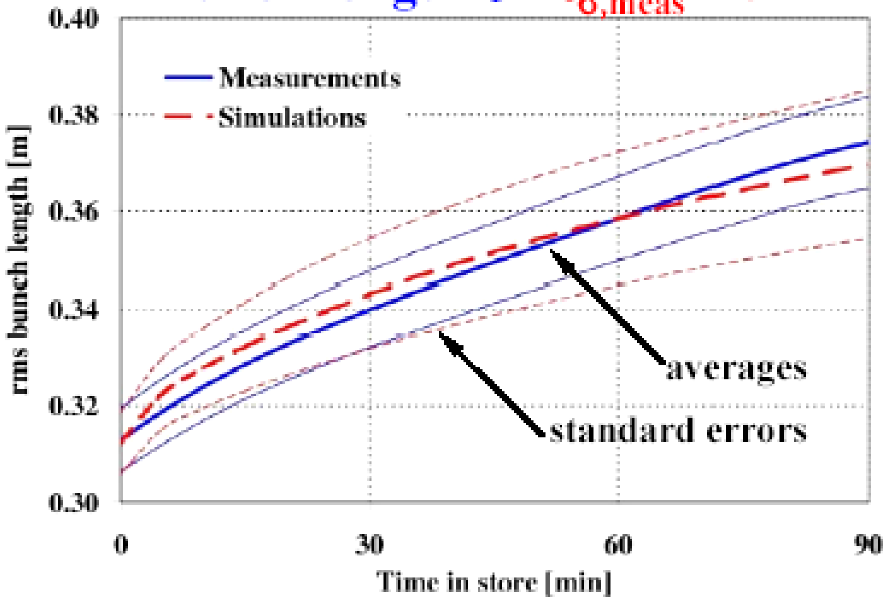
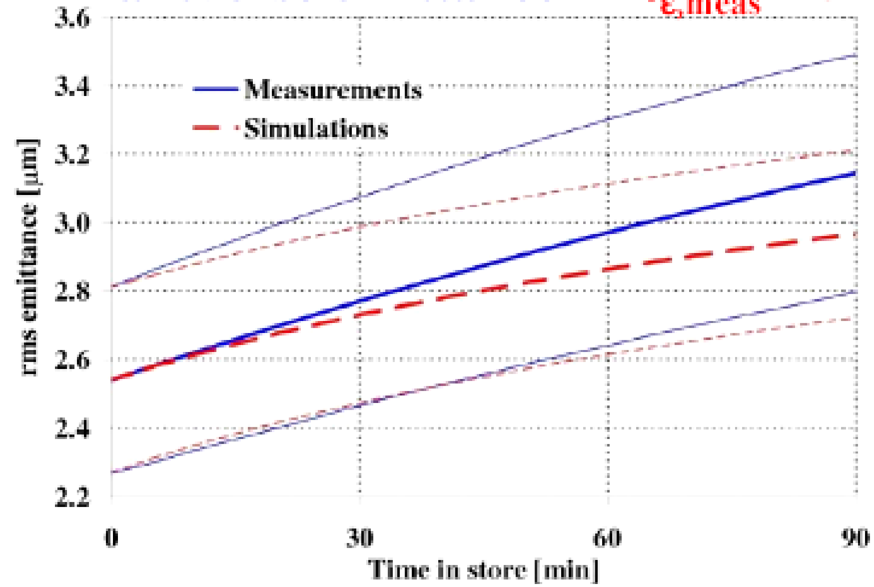
Intra-Beam Scattering (IBS) in RHIC

Bunch length σ $\tau_{\sigma,meas} \approx 8h$



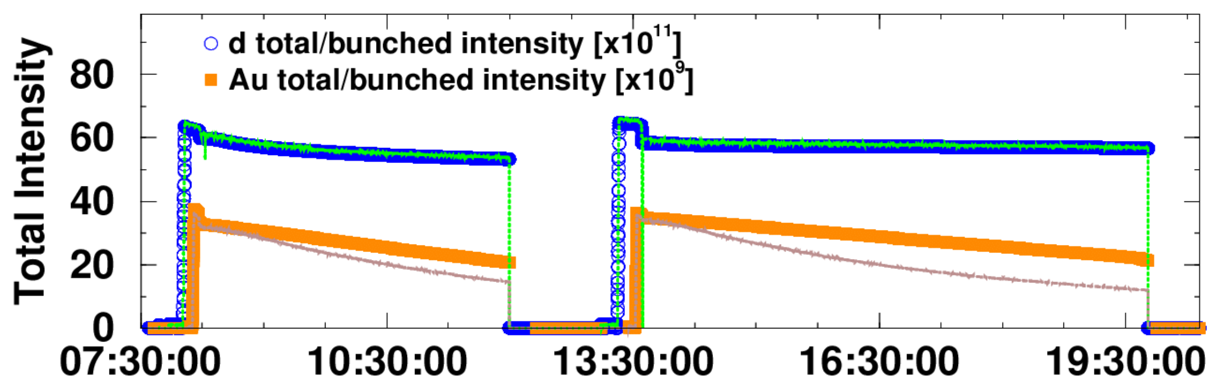
Transverse emittance ε $\tau_{\varepsilon,meas} \approx 6h$



Longitudinal and transverse emittance growth agrees well with model

Some additional source of transverse emittance growth

Deuteron and gold beams are different because of IBS



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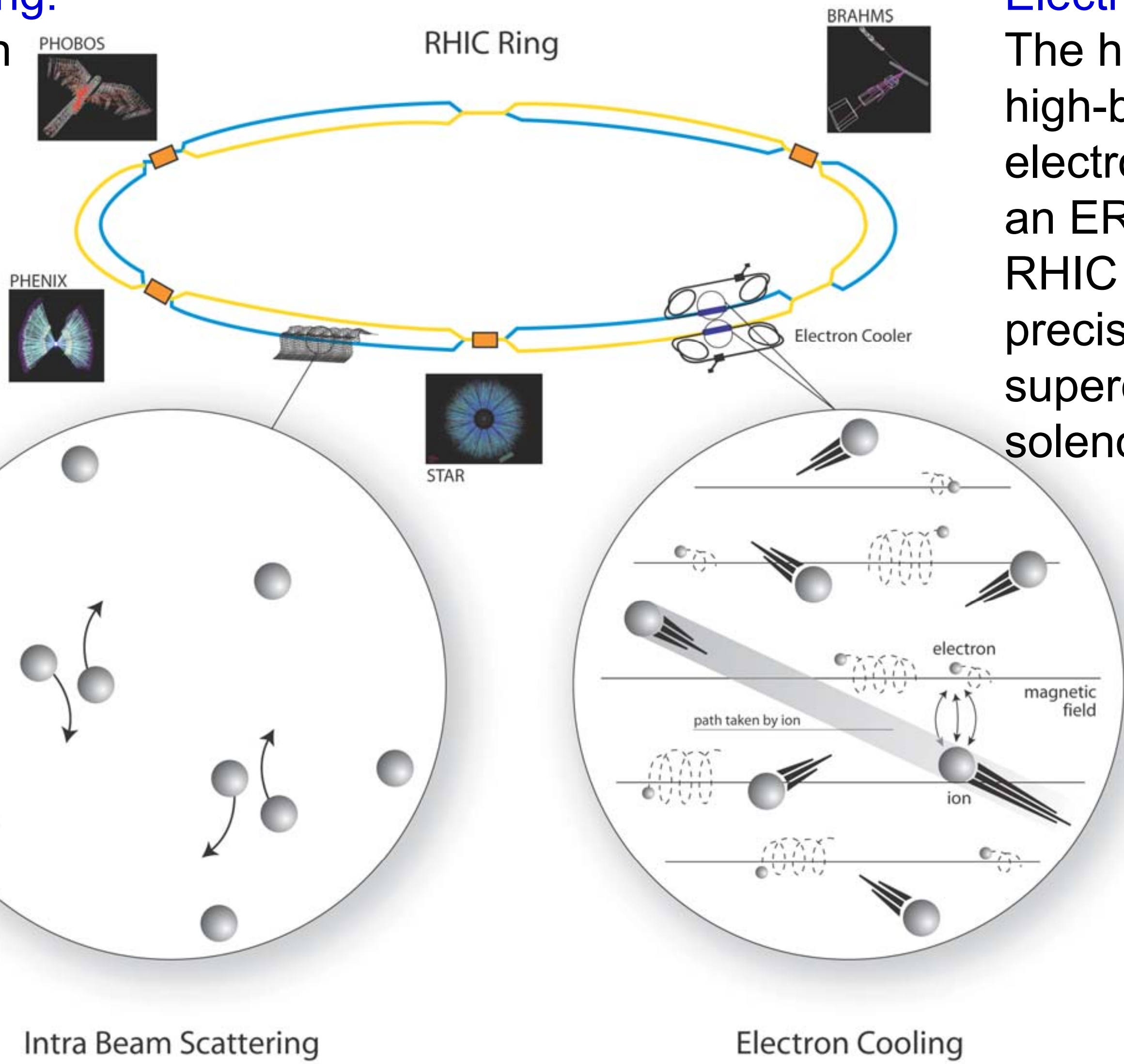
Electron cooling and IBS

Intra-Beam Scattering:
The ions collide with each other, leading to accumulation of random energy (heat) derived from the guide fields and the beam's energy.



Electron cooling:
The high-current high-brightness electron beam from an ERL will cool the RHIC ions in a high-precision, 26 m long superconducting solenoid.

RHIC II luminosity upgrade

Eliminate beam blow-up from intra-beam scattering with electron beam cooling at full energy!

What will remain the same:

- 120 bunch pattern
  - 100 ns collision spacing (~ same data acquisition system)
  - Only one beam collision between DX magnets
- 20 m magnet-free space for detectors
  - No "mini-beta" quadrupoles
- Approx. the same bunch intensity
  - No new vacuum or instability issues
  - Background similar as before upgrade

What changes:

- 3 x peak luminosity and no luminosity decay
- Smaller transverse and longitudinal emittance
  - Smaller vertex region
- Store length is limited to ~ 4 hours by "burn-off" due to Au-Au interactions (~ 200 b)

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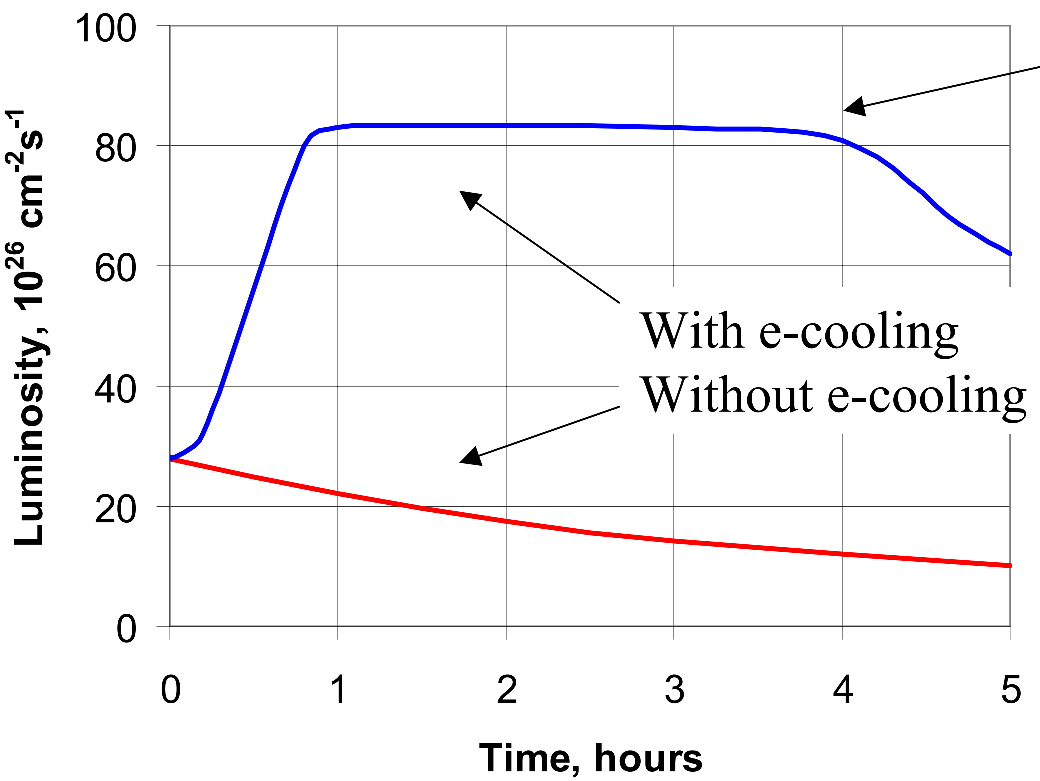
RHIC electron cooling

- Au ions in RHIC are 100 times more energetic than in a typical cooler ring. Relativistic factors slow the cooling by a factor of γ^2. Cooling power needs to be a factor of γ^2 higher than typical.
- Bunched electron beam requirements for 100 GeV/u gold beams:
  E = 54 MeV, <I>=100-200 mA, electron beam power: ~ 5-10 MW!
- Requires high brightness, high power, energy recovering superconducting linac, as demonstrated by JLab for IR FEL. (100 MeV, 10 mA)
- First linac based, bunched electron beam cooling system used at a collider
- Cost: ~ 55 M$ (FY03$, updated design study underway)
  Technically driven schedule: 2008 – 2012
  Construction mainly independent of ongoing RHIC operations. Installation possible during ~ 3 months yearly shut-down periods
- Reviewed by C-AD MAC in March 2004 [O. Boine-Frankenheim (GSI), A. Chao (SLAC), J.-P. Delahaye (CERN), D. McGinnes (FNAL), L. Merminga (JLAB), F. Willeke (DESY, Chair)]

RHIC Luminosity with and without Cooling

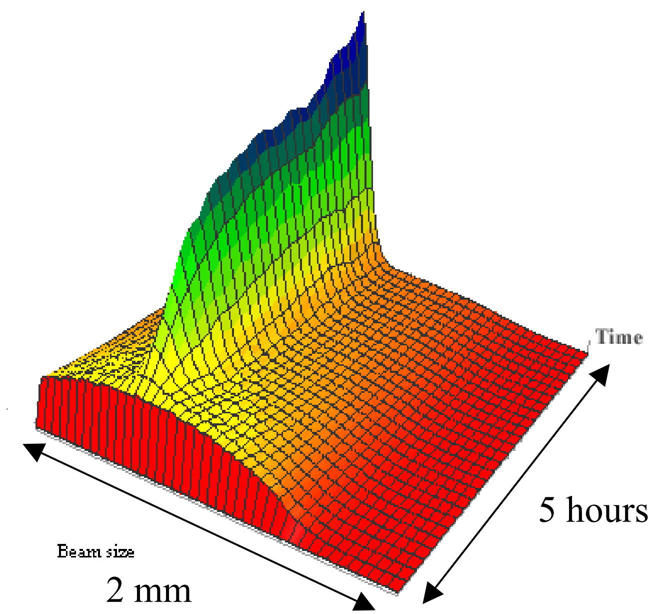


Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

Four IRs with two at high luminosity

Transverse beam profile during store



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RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n × 100 GeV/n):	**w/o e-cooling**	**with e-cooling**
Emittance (95%) πμm	15 → 40	15 → 10
Beta function at IR [m]	1.0	1.0
Number of bunches	112	112
Bunch population [10^9]	1	1 → 0.3
Beam-beam parameter per IR	0.0016	0.004
Peak luminosity [10^{26} cm^{-2} s^{-1}]	32	90
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8	70

Pol. Proton Collision (250 GeV × 250 GeV):		
Emittance (95%) πμm	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	112	112
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Ave. store luminosity [10^{30} cm^{-2} s^{-1}]	150	500

Other species and energies with electron cooling

Polarized proton collisions:

- Pre-cooling at injection energy possible (no IBS)
- Effect of electron beam on proton polarization needs to be studied

Lower energy gold-gold collisions:

- Luminosity still scales with energy^2 (beam-beam limited)
- Strong longitudinal cooling gives as small a vertex distribution as at 100 GeV
- Store length not limited by “burn off”

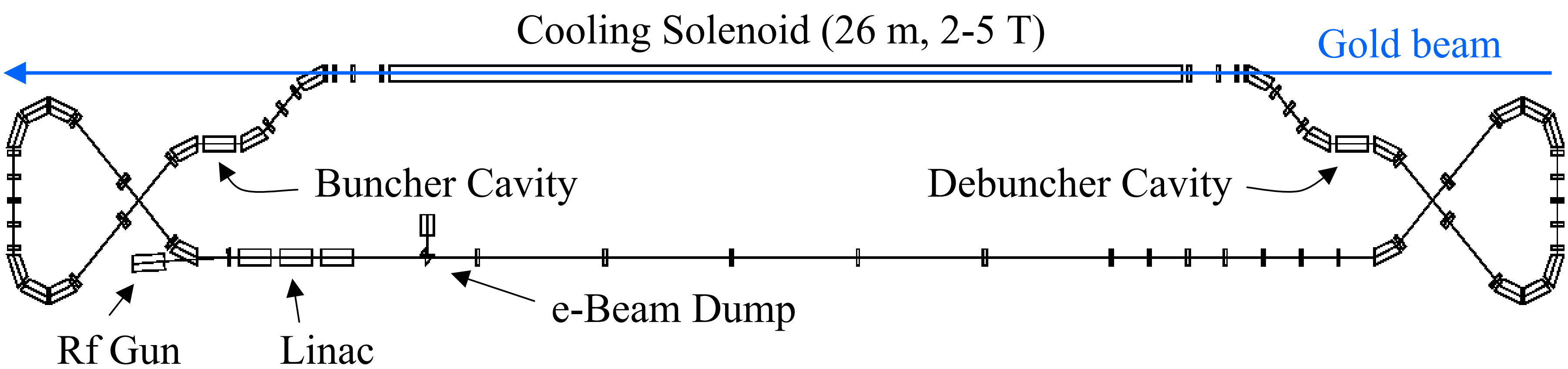
Lighter ions:

- Pre-cooling allows operation at beam-beam limit

pA and dA:

- Cooling of gold beam is limited by beam-beam effect of gold beam on p or d
- Beam-beam limit for dA is twice as large as for pA

RHIC Electron Cooler R&D



- Simulation and experimental benchmarking of cooling force in RHIC high energy regime (using SIMCOOL, BETACOOL, direct numerical calculations [Vorpal, Tech-X, Colorado], e-coolers at GSI, COSY, CELSIUS)
- Demonstrate high precision (<10 ppm) solenoid
- Demonstrate 20 nC, 100 – 200 mA 700 MHz CW superconducting rf photo-cathode electron gun (collab. with AES)
- Develop 700 MHz CW superconducting cavity for high intensity beams (collab. with Jlab, AES)
- Build R&D Energy Recovering Linac

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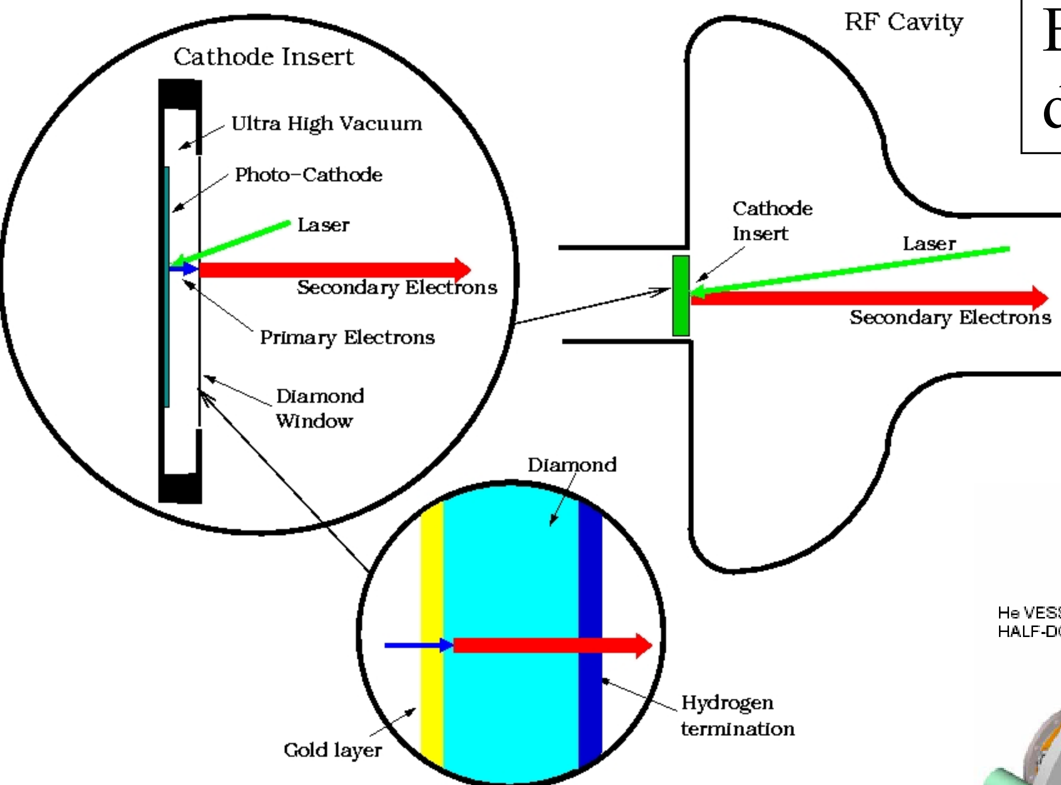
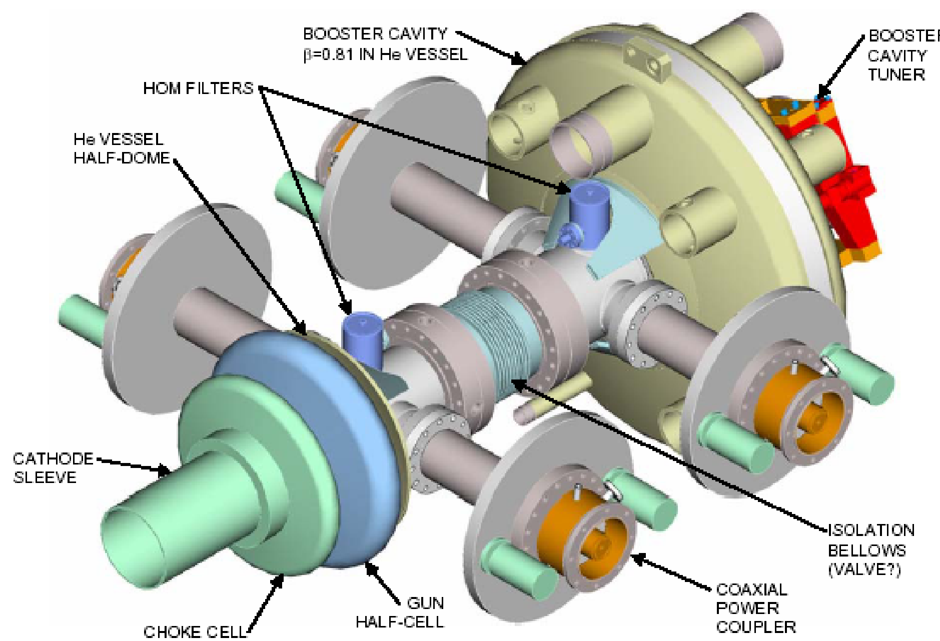
CW Photo-cathode and Superconducting rf Gun R&D

Emission enhancement using a diamond window



Initial conceptual design for a superconducting gun with high quantum efficiency cathode.



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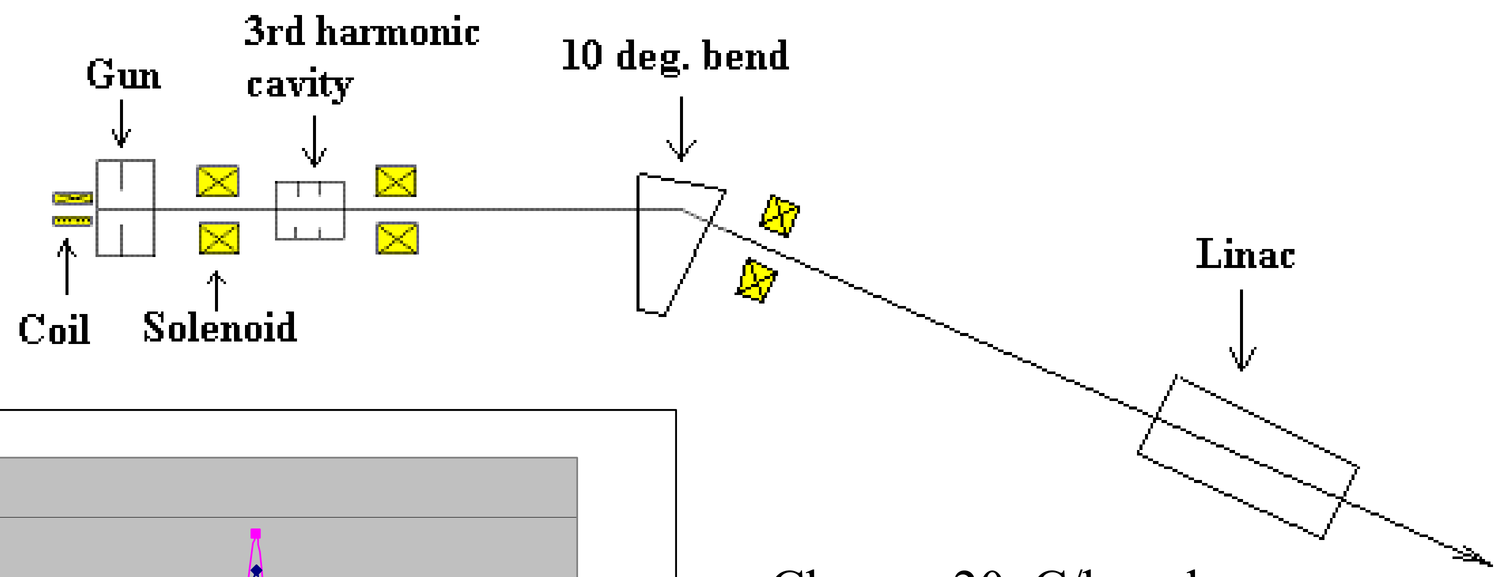
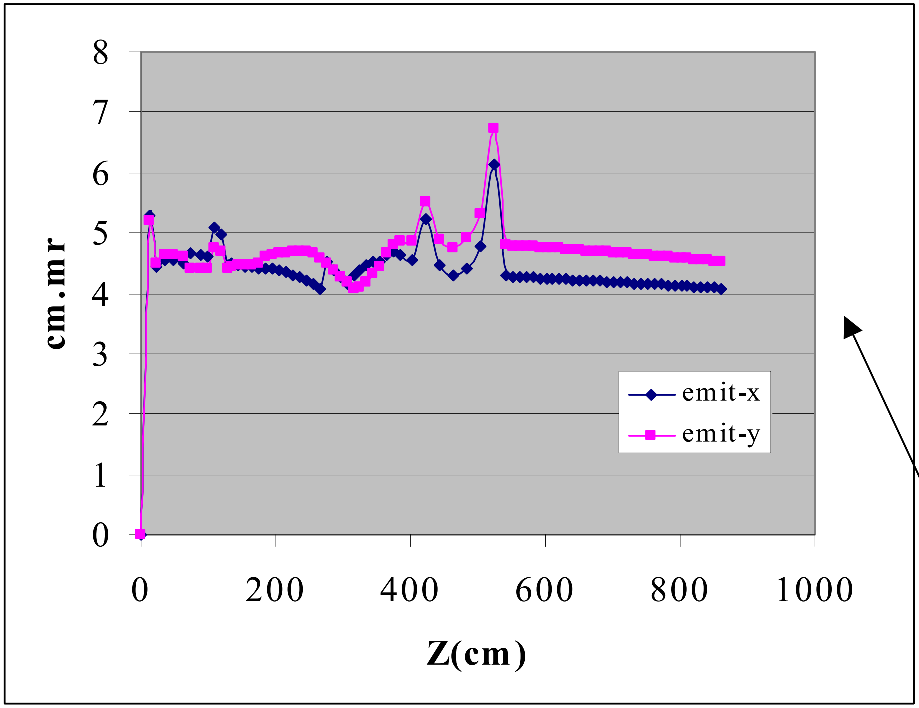
Magnetized Beam Dynamics for Gun and Linac

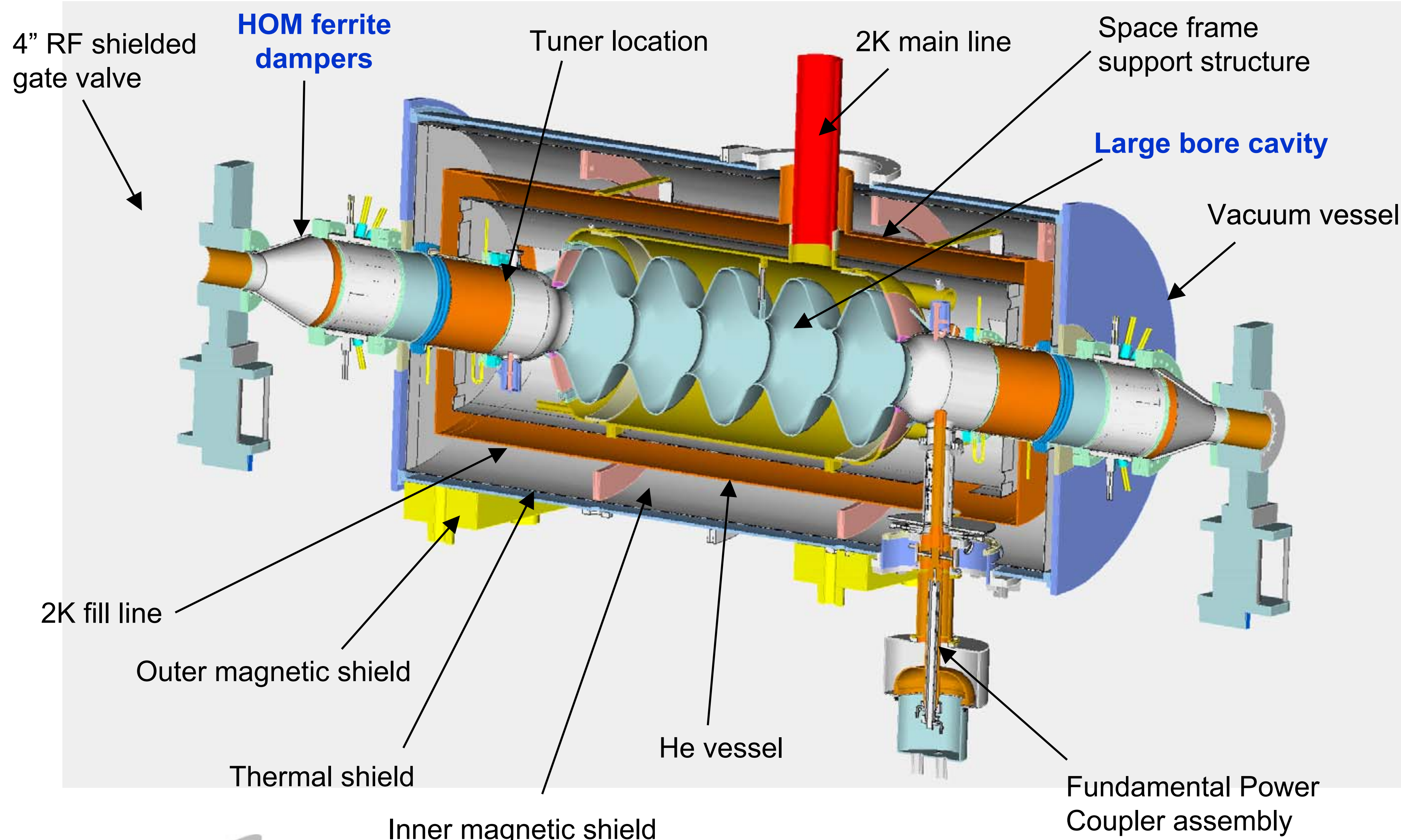




Charge: 20nC/bunch
Spot radius on cathode: 10mm
Magnet field on cathode: 200G
Energy at gun exit: 4.9MeV

Emittance (calculated in a rotating frame) as a function of path length.

700 MHz CW Superconducting Cavity for High Intensity Beams



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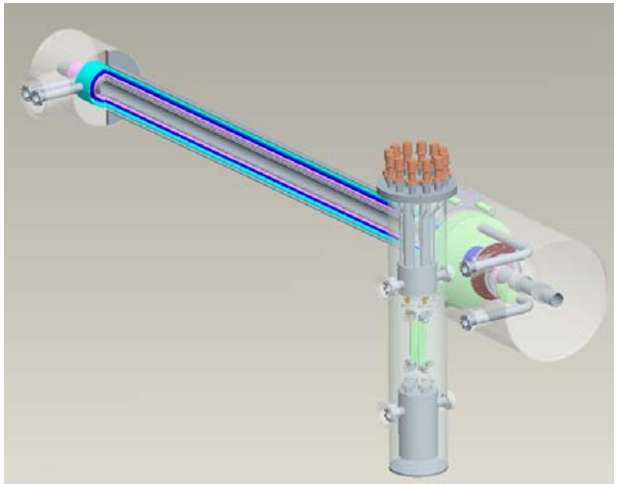
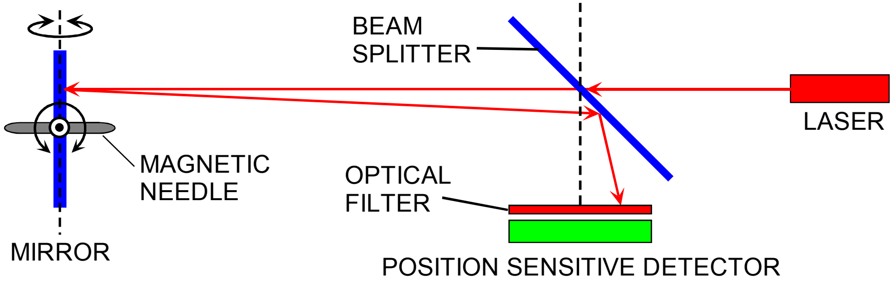
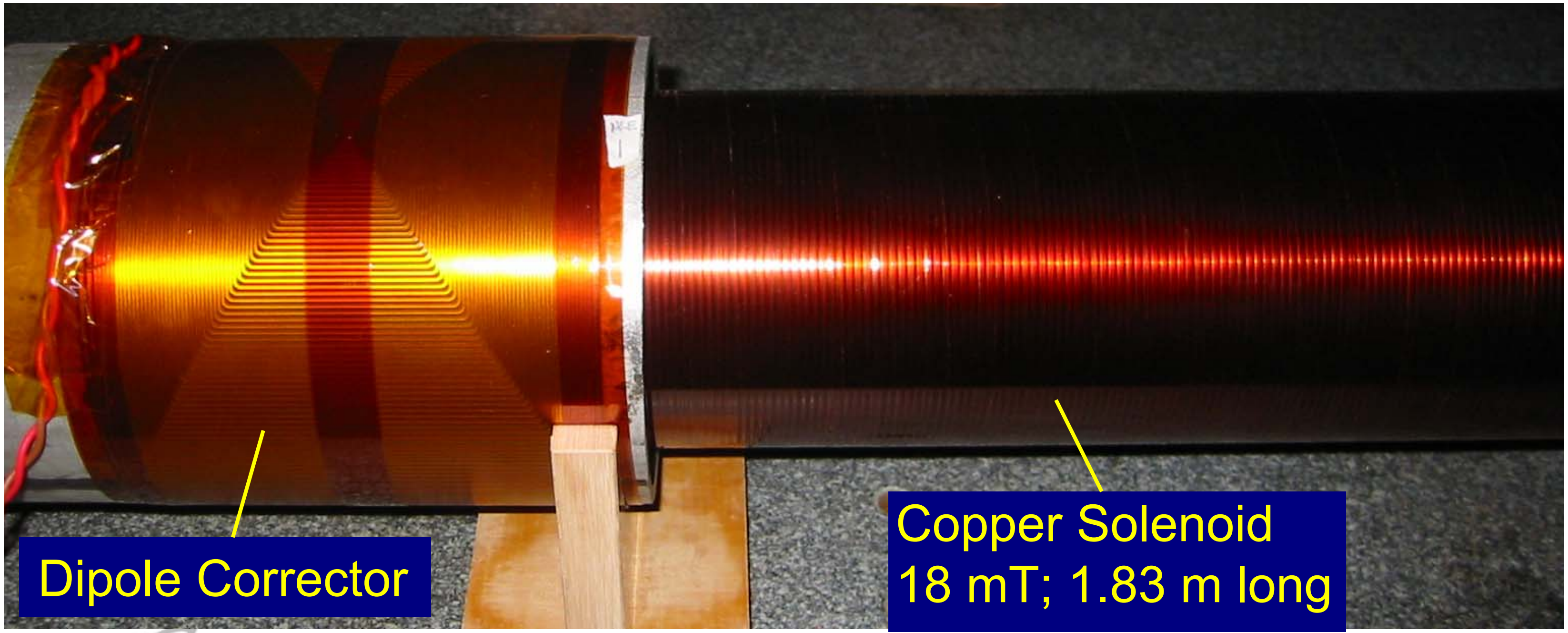
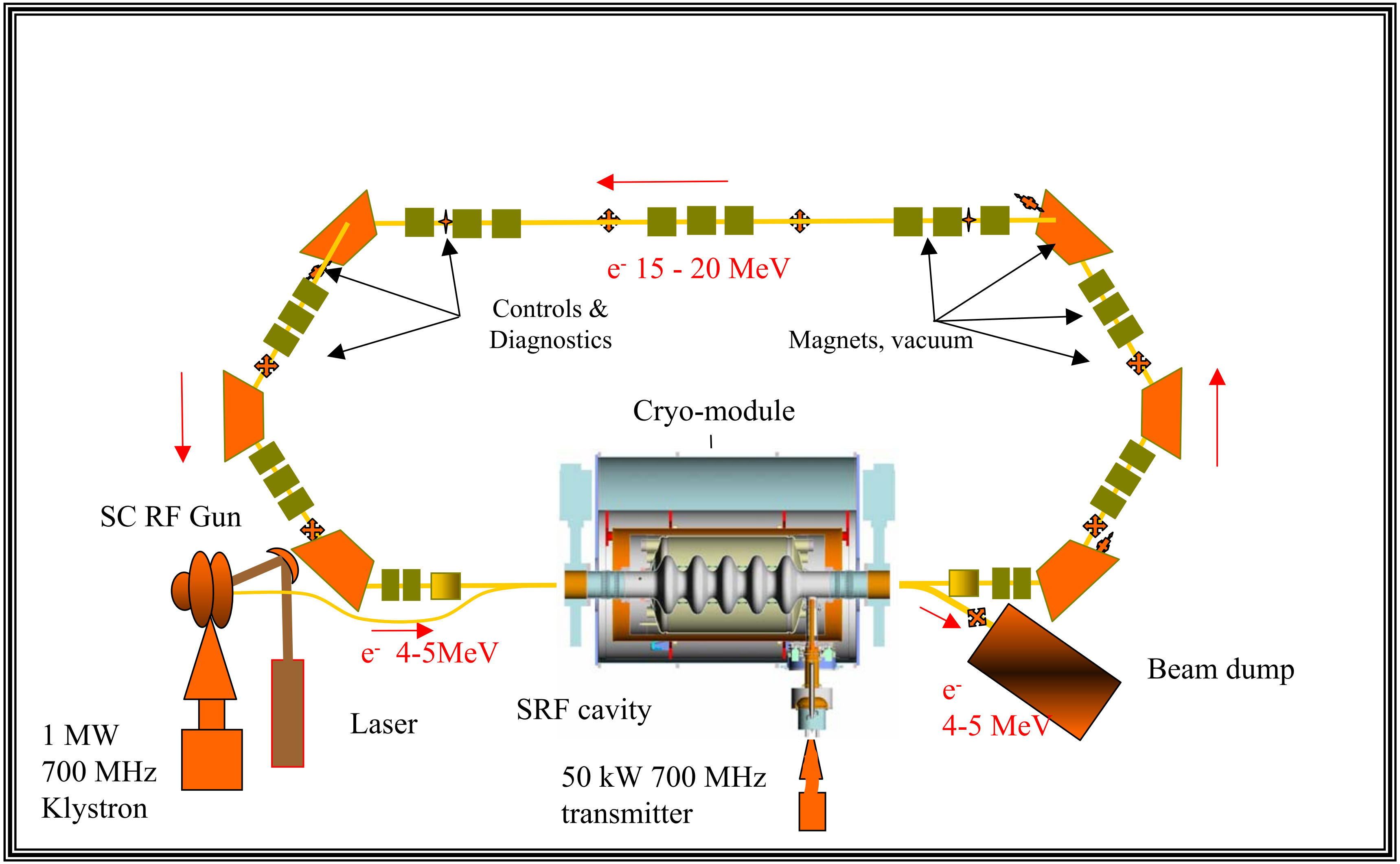
Solenoid R&D: <10 ppm Directional Uniformity







R&D Energy Recovery Linac *in Bldg. 912*



ERL beam parameters

ERL	e-Cooler	Prototype
ERL circumference [m]	~ 120	~ 20
Number of passes	1	1 to 2
Beam rep-rate [MHz]	9.38 -28.15	9.38 - ?
for tuning		1 Hz – 1 kHz
Beam energy [MeV]	54.677	20 - 40
Electrons per bunch (max)	10^{11}	10^{11}
Normalized emittance [µm rad]	~ 50	~ 50
RMS Bunch length [m]	0.03 – 0.2	0.05
Charge per bunch [nC]	10+	10+
Average e-beam current [A]	0.1+	0.01 – 0.1+
Efficiency of energy recovery	99.9…%	> 99.95%
Efficiency of current recovery	99.999….%	> 99.9995%

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Electron Cooling R&D Timeline

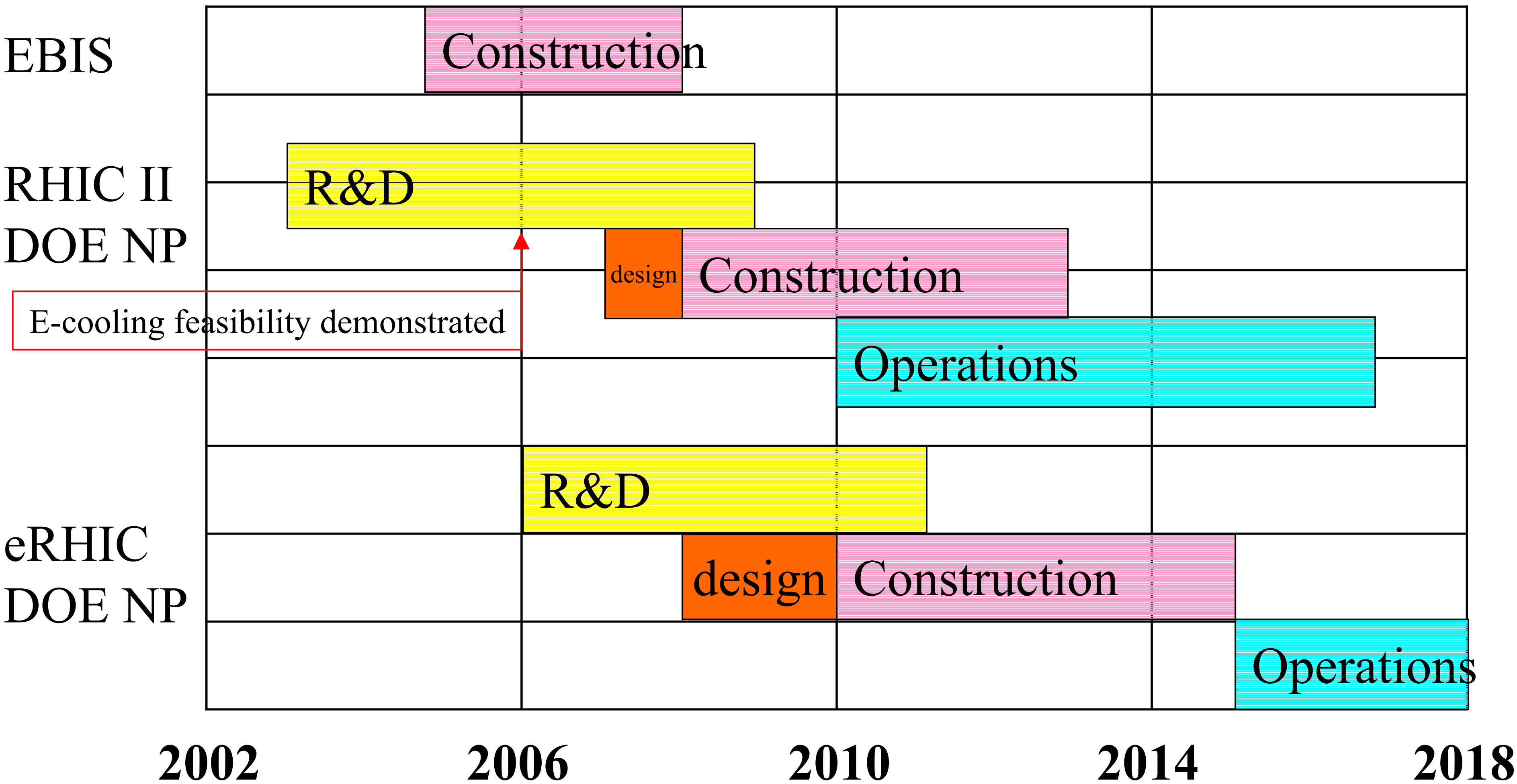
Theory, simulations and benchmarking experiments	
• Codes completed,	
▪ initial cooling calculations	June 2004
▪ Definition of cooler parameters	July 2004
• Start-to-end beam dynamics of e-beam	March 2005
• Initial benchmarking experiments	December 2005 *
• Simulations of cooler and RHIC dynamics	December 2005 *
• Final simulations and adjustments	September 2006
Electron source	
• Photocathode	
▪ R&D complete	July 2005
▪ System ready for ERL	March 2006
• Superconducting gun	
▪ Design complete	September 2005
▪ Gun ready for testing	September 2006
Superconducting 5-cell cavity	
• Copper prototype	June 2004
• Cavity and cryostat ready for processing at JLAB	January 2005
• Test of cavity at BNL complete	June 2005
Solenoid	
• Measurement system ready	October 2005
• Prototype ready	March 2006
• Prototype testing complete	September 2006
Energy Recovery Linac	
• Infrastructure ready	September 2005
• Commissioning	March 2007

* e-cooling feasibility demonstration

Sources of Funding, k$

	FY03	FY04	FY05(Exp./Req.)	FY06 (Exp./Req.)
DOE Nuclear Physics	900	2000	2000	2000
BNL Prog. Dev/GPP	600	1200	1200	600
SBIR Tech-X	100	750	500	
JTO Cryo-module	350	300	100	
ONR Photo-cathode		490	490	
JTO ERL			300	300
JTO Photoinj.			600	600
Total	1950	4740	5190	3500

Technically Driven Schedule (in Fiscal Years)



Summary

- Successful operation of RHIC with 100 GeV/n beams in three modes:
  - Gold – gold collisions, peak luminosity = 15×10^{26} cm^{-2} s^{-1}
  - Deuteron – gold collisions, peak luminosity = 7×10^{28} cm^{-2} s^{-1}
  - Polarized proton collisions, peak luminosity = 15×10^{30} cm^{-2} s^{-1}
- Plan for "enhanced luminosity" (x 4 design) over next 4 years
- RHIC II luminosity upgrade (x 40 design) using full energy electron cooling
- Linac-based RHIC pre-injector (EBIS) is ready for construction.

Questions from John Jowett

1. A basic message of the CAD-MAC report is that the status of the EBIS and the Electron Cooler are very different. The EBIS is essentially ready to be implemented. On the other hand there are substantial beam physics and engineering uncertainties related to the Electron Cooler. Please clarify the relative levels of technical risk.

EBIS is ready for construction start. Electron cooler needs R&D to establish feasibility (end of 2005) and technology R&D (by ~ 2007)

2. In his presentation at the CAD-MAC, Ilan Ben-Zvi said he expected that all outstanding R&D issues related to the Electron Cooler would be settled in about 3 years. Is this expectation maintained in the light of the CAD-MAC's report? Could it accommodate, for example, the recommended proof-of-principle demonstration of the novel beam transport scheme on an existing facility ? Similarly for other recommendations. At what point could construction be proposed?

We still expect to complete electron cooling R&D in about three years (see above). The response to the recommendations of the MAC report are addressed in separate document. High space charge magnetized beam transport could be tested at ATF (BNL), A0 (FNAL), or test ERL over the next three years. Construction could start in 2008.

Questions from John Jowett

3. If the EBIS project is launched, are resources - particularly expert manpower - sufficient to maintain the R&D effort on the Electron Cooler at the necessary level ? Please summarize the overall picture including other activities and the other smaller components of the RHIC upgrade.

Expert personnel involved in EBIS and electron cooling don't overlap. For overall schedule see "technically driven schedule".

4. The purpose of the Electron Cooler is to overcome the strong intra-beam scattering (IBS) that would blow up the emittances of the RHIC-II beams. How good is the quantitative understanding of IBS in the present RHIC? Does the assessment of required electron cooling power include a prudently pessimistic extrapolation of present uncertainties ? As the CAD-MAC point out, there are further uncertainties in the prediction of magnetized cooling rates, the interplay of cooling with IBS and other effects.

Longitudinal IBS in RHIC is well understood. Transverse emittance growth is about twice IBS calculations. There is an ongoing effort to improve IBS calculations and identify additional sources of emittance growth. The present cooler design includes this level of cooling power contingency. There is good simulation progress to fully understand high energy, magnetized cooling. Experimental bench marking is planned for next year. We expect a positive impact of electron cooling on the beam-beam limit but this is not included in our performance projections.

Questions from John Jowett

5. Please summarize additional benefits of the EBIS to other programs.

- Improvements in reliability, setup time, and stability should lead to increased integrated luminosity in RHIC.
- Reduced operating costs, and avoidance of ~ 6 M$ in reliability-driven investments in the tandems.
- Elimination of two stripping stages and an 860 m long transport line, leading to improved performance.
- Simplification of Booster injection (few turn vs. present 40 turn)
- Increased flexibility to handle the multiple simultaneous needs of RHIC, NSRL, and AGS.
- Capability to provide ions not presently available, such as noble gas ions (for NSRL), uranium (RHIC), or, with additional enhancements, polarized 3He (eRHIC).
- Simpler technology, robust, more modern (Tandem replacement parts are becoming difficult to get).