ASAC 2009 Presentation

Accelerator R&D Activities

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SNS AP group

Talk outline

- Instabilities + Space Charge
- Laser stripping
- Sequence of developments as SNS ring intensity increases
- Nonlinear accelerator lattices with regular motion and large tune spread to kill instabilities and mitigate space charge effects

Instability-related Features of Ring Design

Common high intensity design features:

High energy spread design and broadband feedback provision +

For eP instability mitigation:

a) Electron collection near stripper foil;

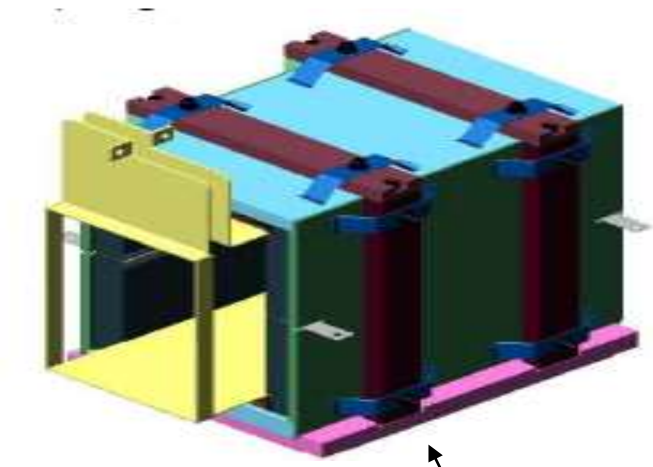
b) Experiments of 1999 showed significant reduction of electrons in a coated spool piece of PSR vacuum chamber. This led to a decision to coat all pieces of VC with TiN;

c) Solenoids near the regions with high loss;

d) Clearing electrode near the stripper foil;

e) Electron detectors for electron accumulation study.

Instability-related Ring Design Features (cont...)



Extraction kicker:

- First estimations show thresholds around 1E10^14 protons.
- BNL team redesigned and re-measured kickers, lowered transverse impedance by factor 2.

14 units

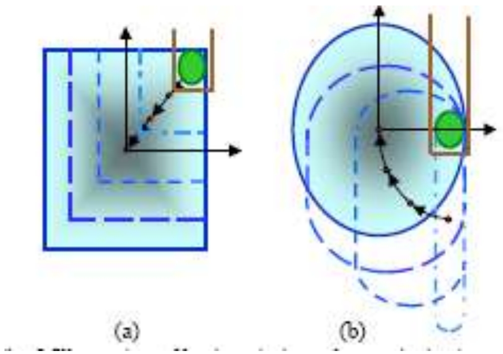
Injection kicker and resistive wall:

- Impedances are dangerous below the integer tune, may cause closed orbit instability.
- Chamber coated with Cu (~0.7 um), and TiN (~0.1 um), to mitigated resistive wall and e-p instability.
- Advanced estimation of transverse impedance was done.

coated ceramic inside

8 units

Choice of correlated painting for SNS



a) correlated
b) Anti correlated

Upper plots –correlated,
Lower for plots – anti correlated.
Conclusion – anti correlated is much worse because of distributions with tails

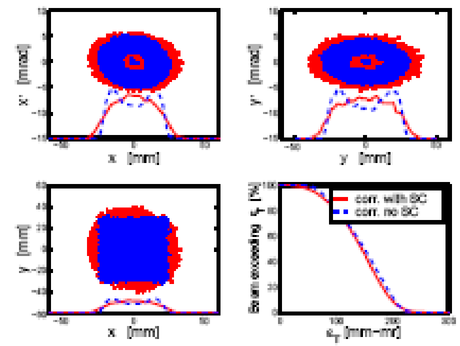


Fig. 2 Particle distribution and emittance distribution resulting from an example of correlated painting.

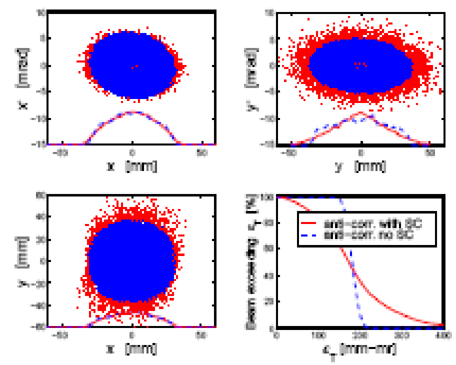
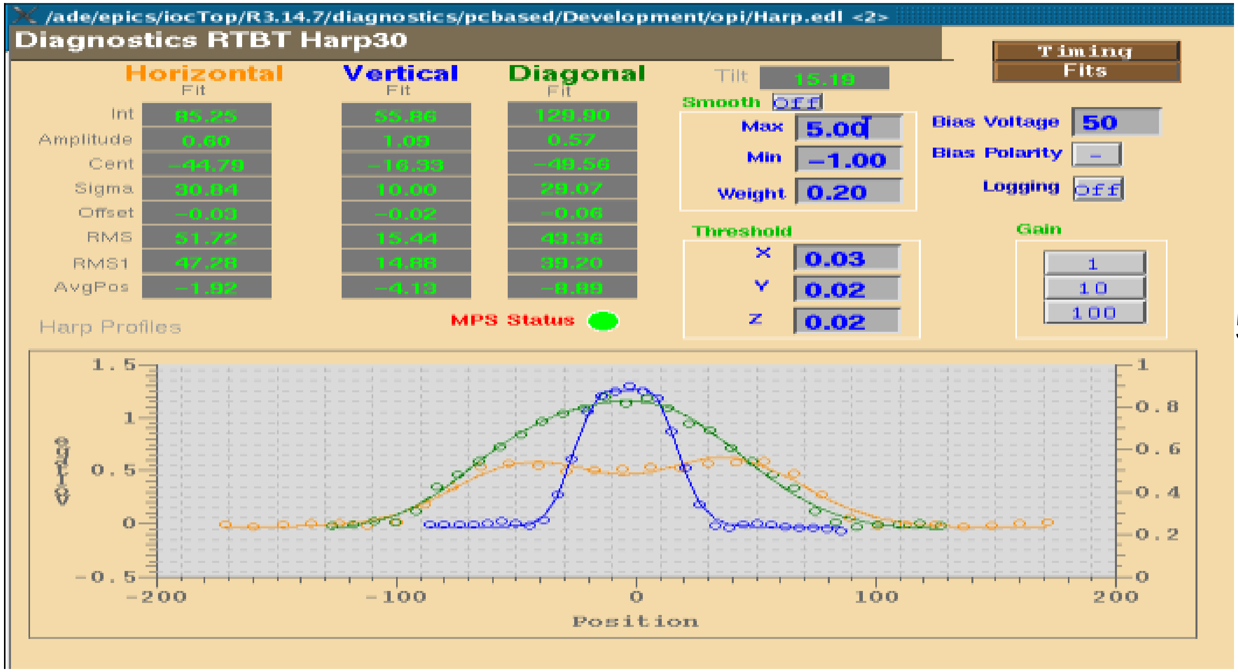


Fig. 3 Particle distribution and emittance distribution resulting from an example of anti-correlated painting.

J. Beebe-Wang, et al, EPAC2000

Painted beam (correlated painting)



RTBT profile –
500 turns painting

Not an ideal profile – we need constant density elliptical beam for target.

Correlated painting creates not self-consistent beams
Anti correlated painting – not self-consistent during all moments of injection. Is there any injection that creates space charge self consistent distributions at all moments of injection?

Yes (see next slide)

3D self-consistent distribution painting

Linear longitudinal focusing 3D ellipsoid with constant density

3 types of 3D self-consistent distributions found (see Danilov et al, PRSTAB 6, 094202 (2003), one of them below

$$f=\frac{C}{\sqrt{H_b-H}}\delta(X_0'-Y_0\ldots)\delta(Y_0'+X_0\ldots),\, H<H_b\,(0\ otherwise)\ \{3,2\}\ case,$$

Transformation

$$x \longrightarrow x + D\delta$$

should preserve constant density

$$H=a(\delta^2+\Omega_s^2(s/\Pi)^2)+bR^2,\ circular\ transverse\ motion,\ linear\ longitudinal\ well;$$

$$H=a\delta^2+bR^2,\ circular\ transverse\ motion,\ barrier\ cavity.$$

$$F(\delta)=\frac{C}{\sqrt{A^2-\delta^2}},$$

$A-normalized\ cavity\ voltage$

From spreader cavity

$$F(\delta,R)=\frac{C}{\sqrt{A_0^2(1-bR^2)-\delta^2}}$$

$$R^2\propto t,\ const\ current$$

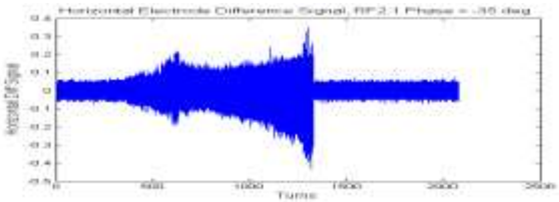
$$A^2\propto(1-t/t_{full})$$

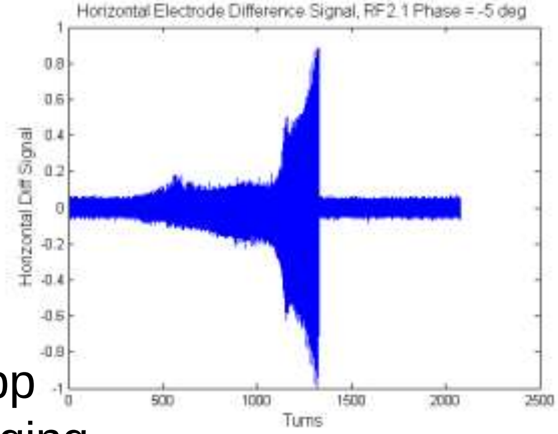
Excellent coincidence!!!

Barrier cavity distribution - the most optimal case for SNS and Project X

Details in Holmes, et al, “Barrier Cavity option for SNS”, ICFA2006, Tsukuba

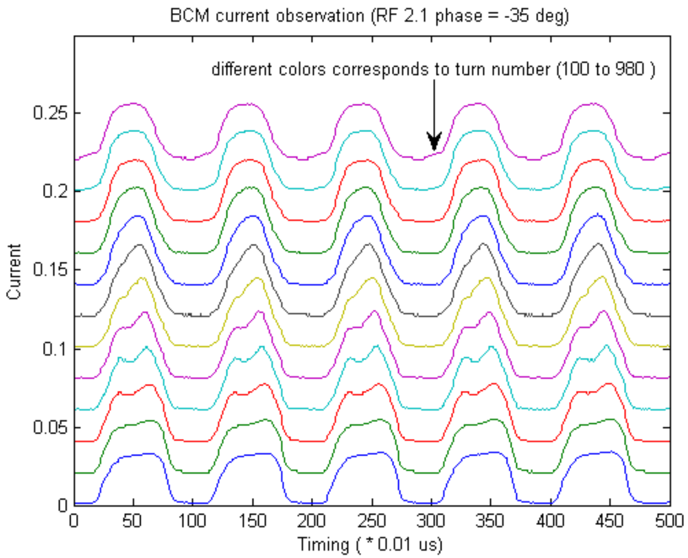
Bunch shape scanning (courtesy Z. Liu)

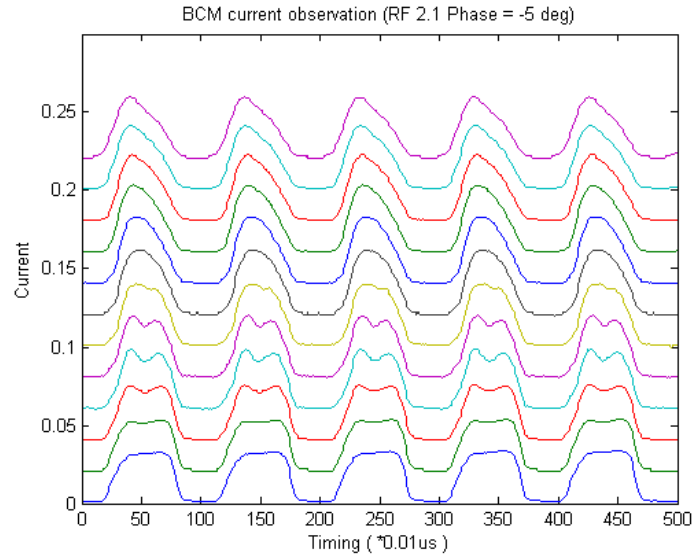




Longitudinal shape of the bunch drastically affects the ep instability.

We were able to cleanly extract $1.13*10^{14}$ ppp after making the trailing edge steep by changing the phase of 2nd harmonic RF



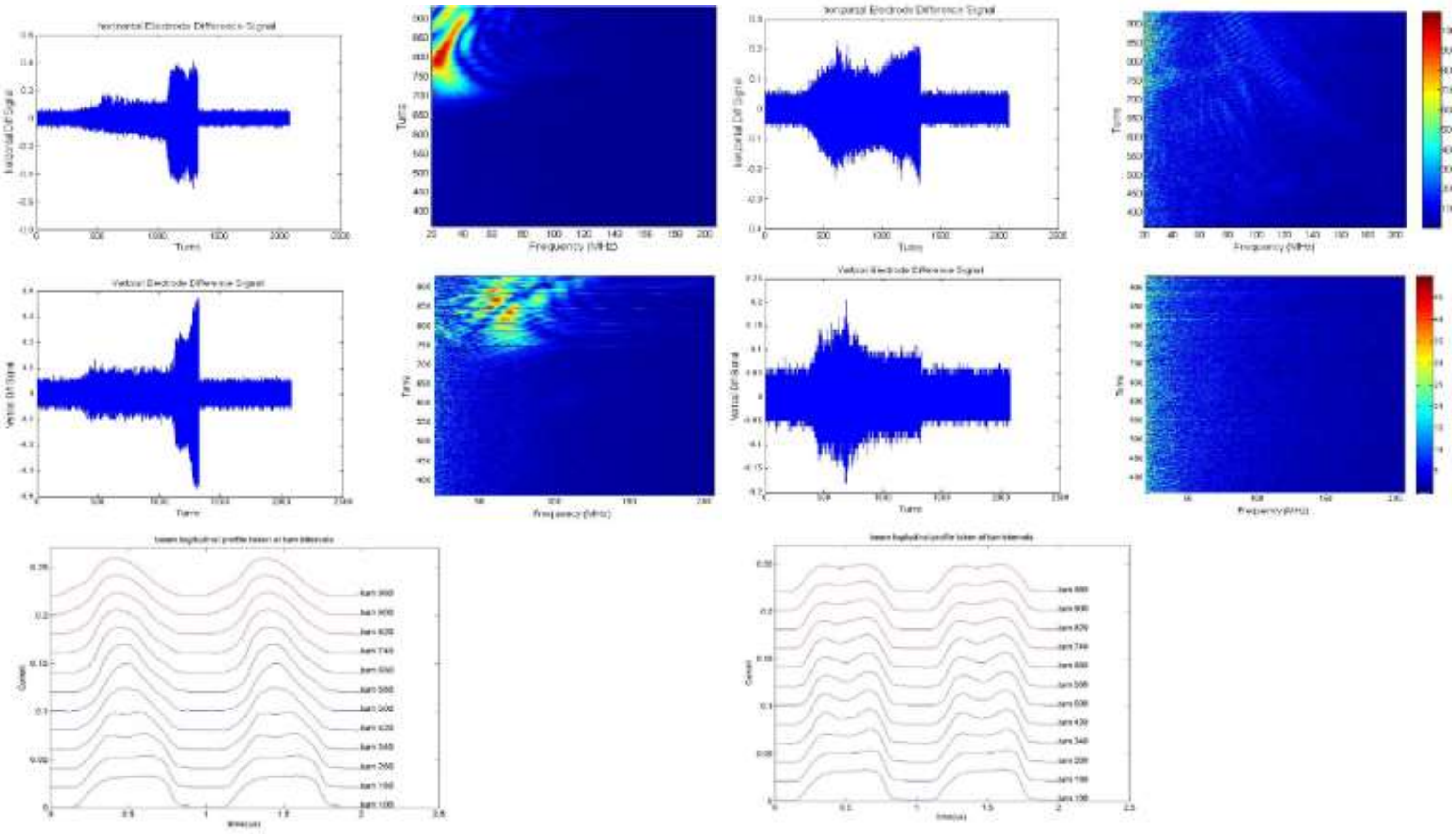


Maximal charge extracted was $1.3*10^{14}$, but with large loss

Oak Ridge National Laboratory

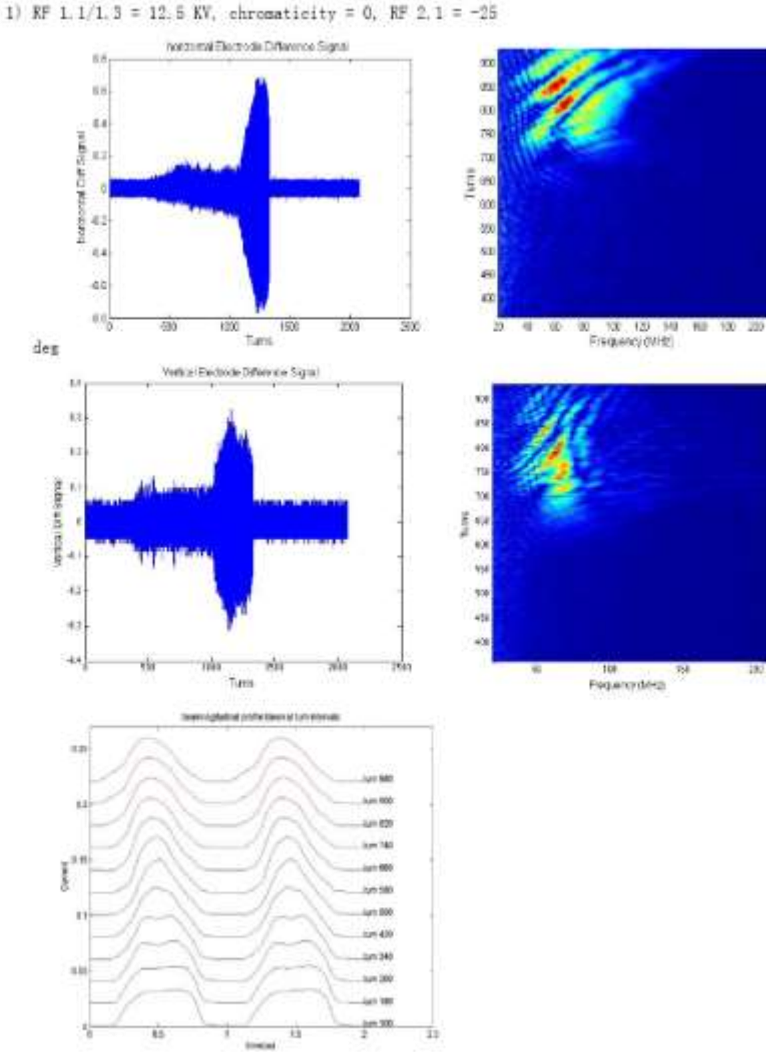
Bunch length scanning 18μC

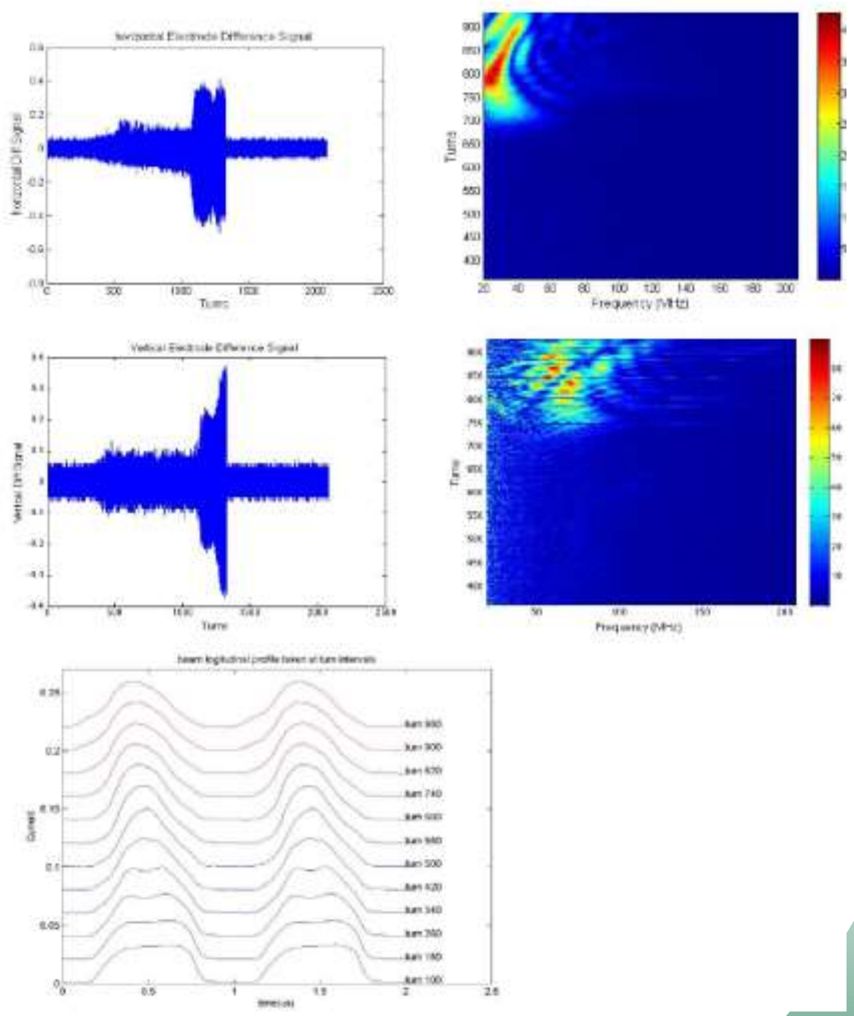
12.5 kV main 2 RF stations (left), and 5.5 kV (right) for flat beam the e-p instability disappears



E-p Instability with and w/o Chromaticity

Zero chromaticity (left), and the natural one (right).
One can see a dramatic change of the instability spectrum

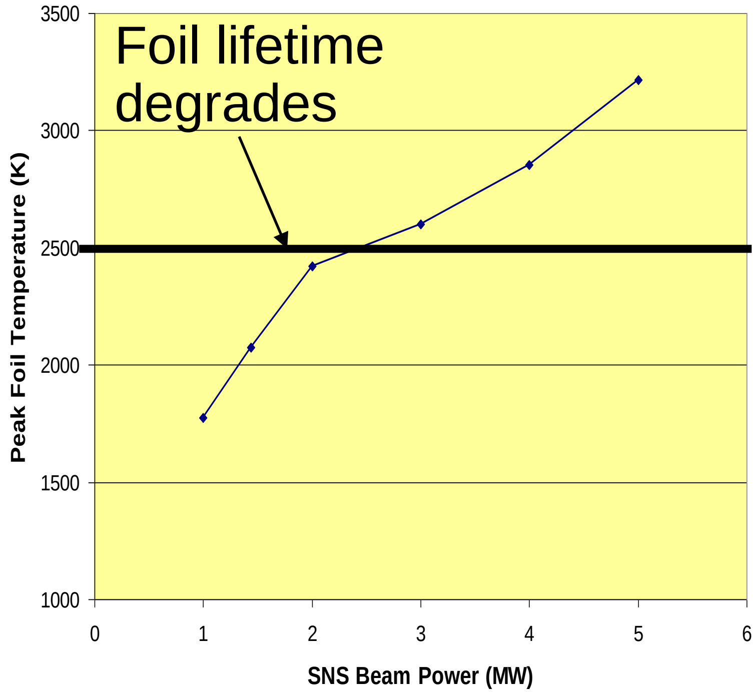




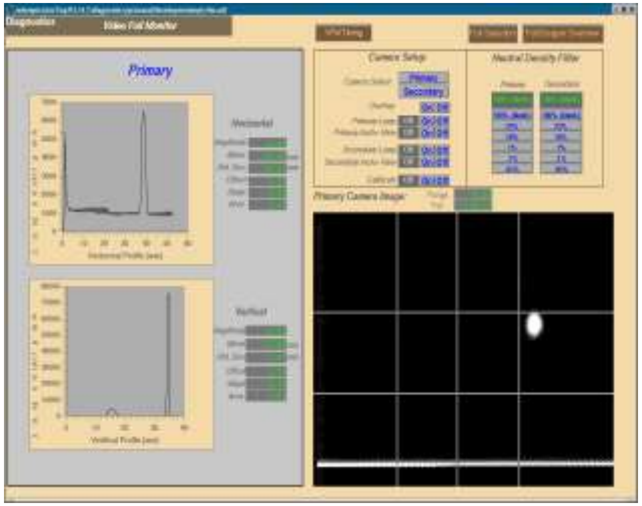
Stripping Foil Limitations

- The SNS will use 300-400 $\mu g/cm^2$ Carbon or Diamond foils
- Two important limitations:
  1. Foil Lifetime: tests show rapid degradation of carbon foil lifetime above 2500 K, yet we require lifetime > 100 hours
  2. Uncontrolled beam loss: Each proton captured in the ring passes through foil 6-10 times: leads to uncontrolled loss of protons

Presently, injection area is the most activated at SNS



SNS Foil Glowing 160 kW

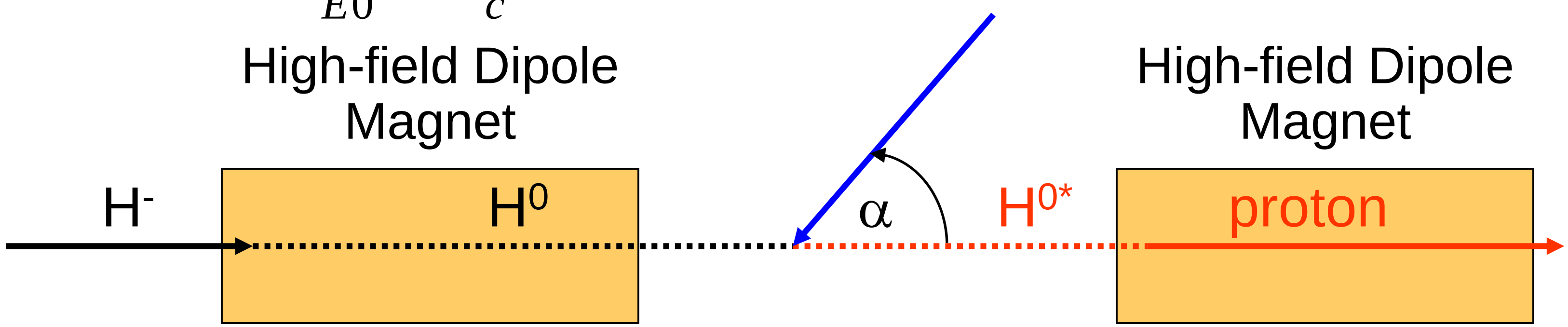


Damaged PSR Foil

Three-Step Stripping Scheme

- **Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser [V. Danilov et. al., Physical Review Special topics – Accelerators and Beams 6, 053501]**

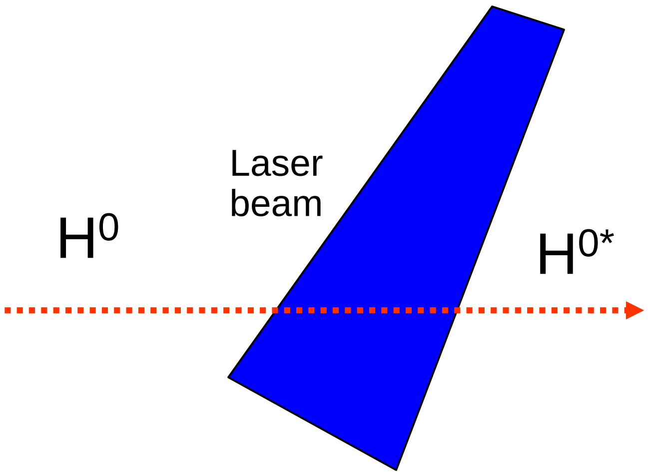
$$f(1->3) = f_{laser}\frac{E}{E0}(1+\frac{v_{beam}}{c}\cos(\alpha))$$

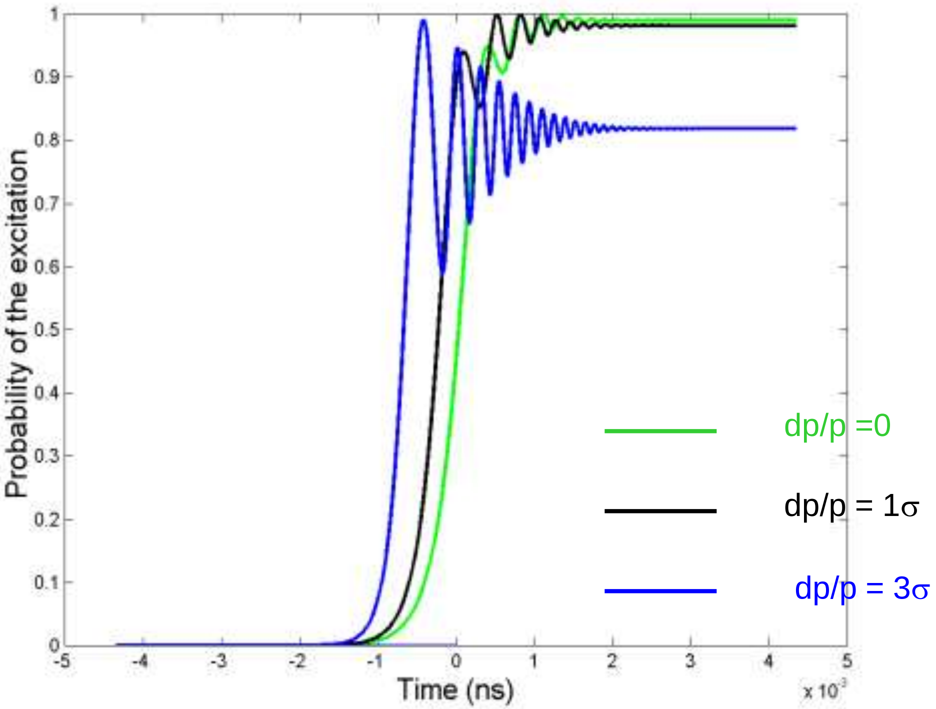


Step 1: Lorentz Stripping	Step 2: Laser Excitation	Step 3: Lorentz Stripping
$H^- \rightarrow H^0 + e^-$	H^0 (n=1) + $\gamma \rightarrow H^{0*}$ (n=3)	$H^{0*} \rightarrow p + e^-$

Approach that Overcomes the Doppler Broadening

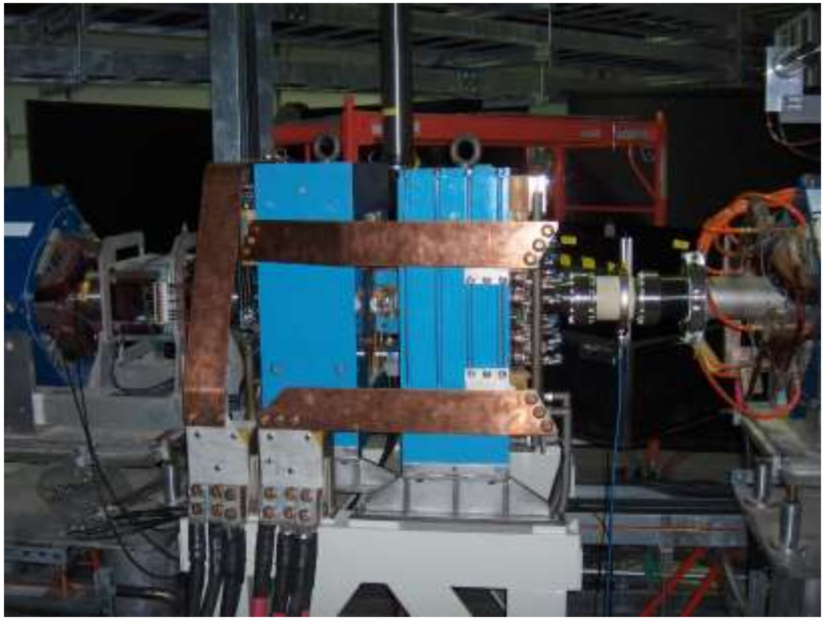
- **By intersecting the H^0 beam with a *diverging* laser beam, a frequency sweep is introduced:**

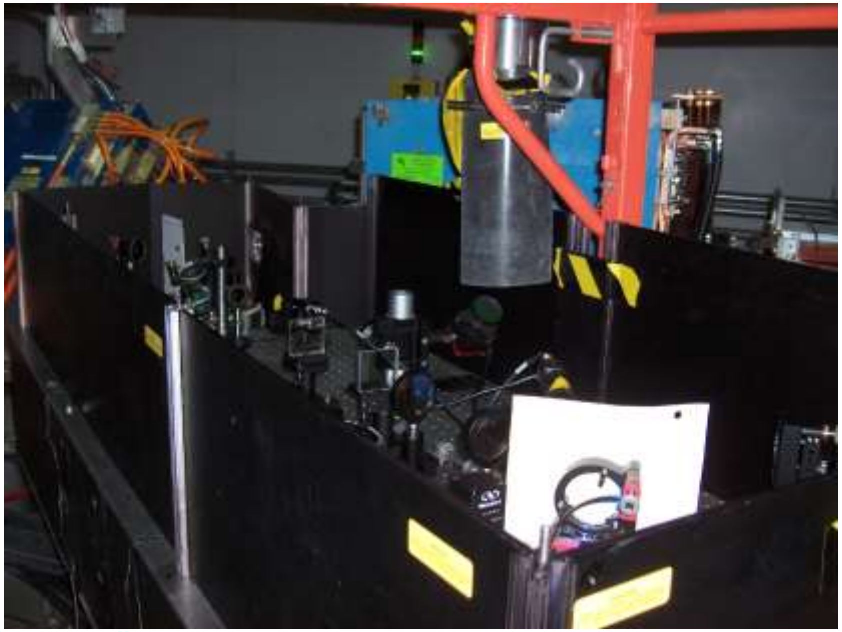




- The quantum-mechanical two-state problem with linearly ramped excitation frequency shows that the excited state is populated with high efficiency
- Estimations for existing SNS laser (10 MW 7 ns) gave 90% efficiency

Laser Stripping Assembly





Magnets
(BINP production)

Optics table (1^{st} experiment)
1^{st} experiment – failed
2^{nd} 50% efficiency achieved
(v. chamber failure afterwards)
3^{rd} – 85% achieved
4^{th} – 90 % achieved

Straightforward use is costly – laser power needed I s 10 MW*0.06=.6 MW

Laser power reduction – intermediate experiment

- Matching laser pulse time pattern to ion beam one by using mode-locked laser instead of Q-switched

  ~ x25 gain

- Using dispersion derivative to eliminate the Doppler broadening due to the energy spread

  ~ x10 gain

- Recycling laser pulse

  ~ x10 gain

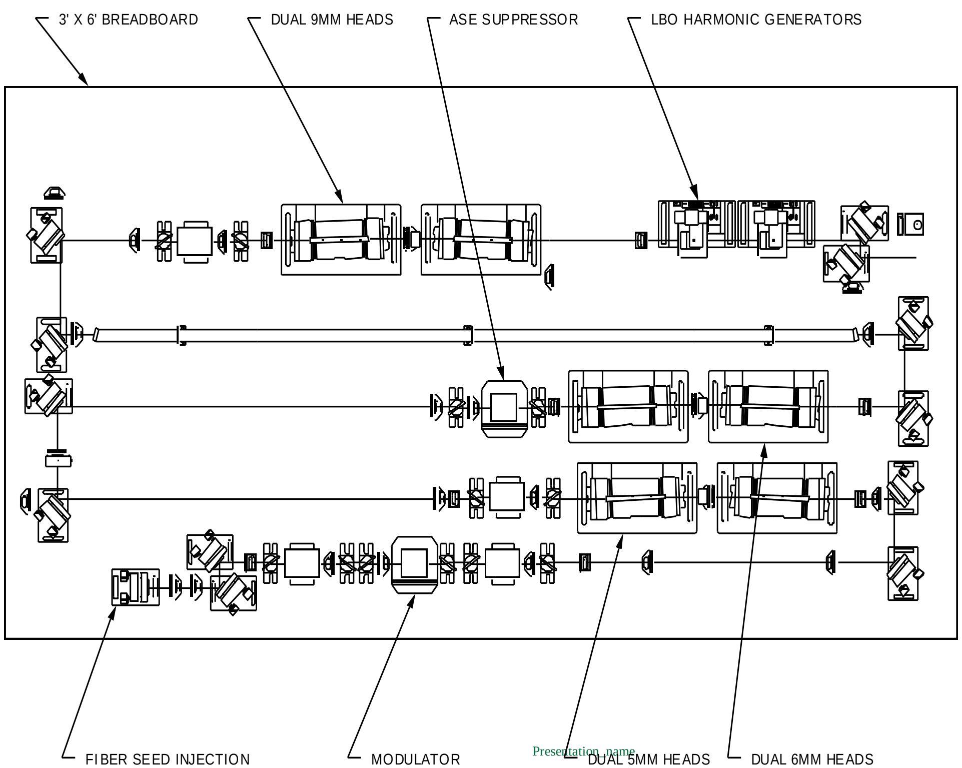
- Vertical size and horizontal angular spread reduction

  ~ x2-5 gain

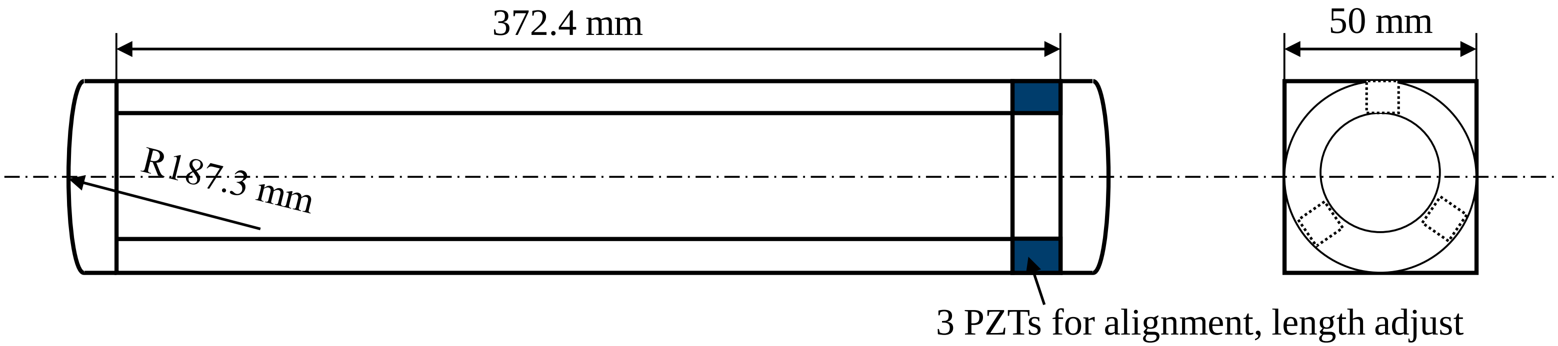
By combining all factors the required average laser power can be reduced to 50 – 120W, which is within reach for modern commercial lasers.

Mode locked laser parameters

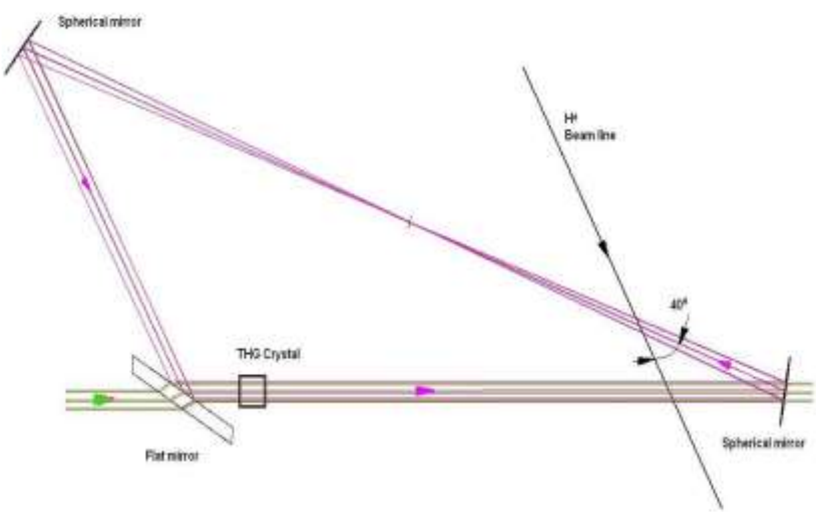
Parameter	Offered	Comment
Wavelength	355nm	
Energy	30 uJ	
Pulse Duration	10 µs	>10µs possible with programmable waveforms
SLM Oscillator	mode locked	
Temporal Profile	flat envelope	
Beam Diameter	~5mm	
Spatial Profile	Like Powerlite	Harmonics at laser
Beam Divergence	Like Powerlite	
Repetition Rate	10 Hz/402.5 MHz	Macropulse rate / micropulse rate
Shot to Shot Stability	3% RMS	for pulse envelope
Polarization	Vert	
Jitter	<50ns	Macropulse envelope
Interface	GUI	
Laser Head size	3' x 6' x 13"	Larger table available for upgrades
Cabinets	CAB35	
Electrical Requirements	30A 1 phase 220V	
Water Requirements	2 X Powerlite	



Fabri-Perot and Inside Crystal Conversion Schemes



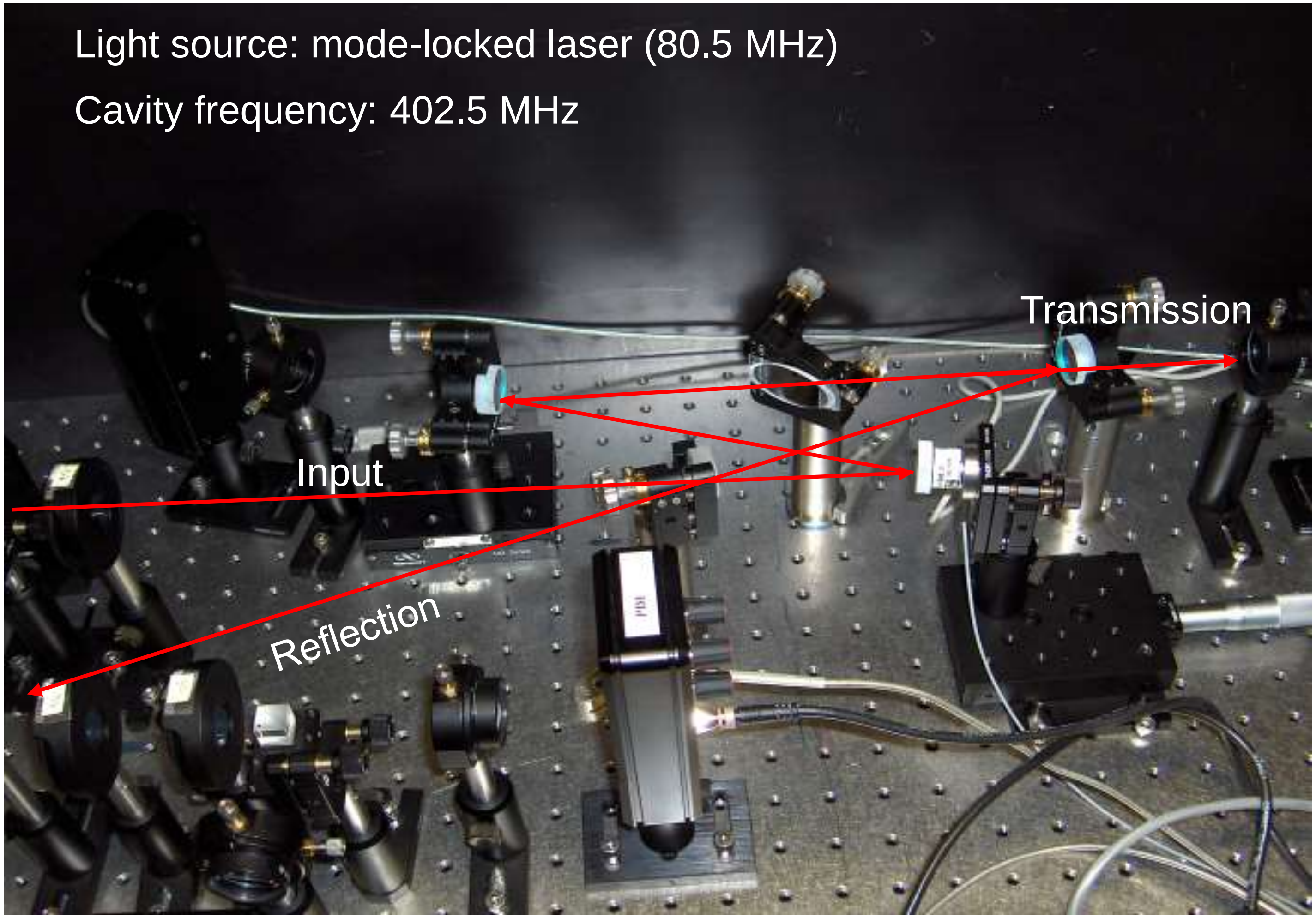
Design and production: Light Machinery
Finesse: ~ 37
Designed power amplification factor: ~ 10
R > 92% at 355 nm



Inside Crystal Conversion
Flat mirror is transparent to fundamental harmonics and reflects 355 nm light

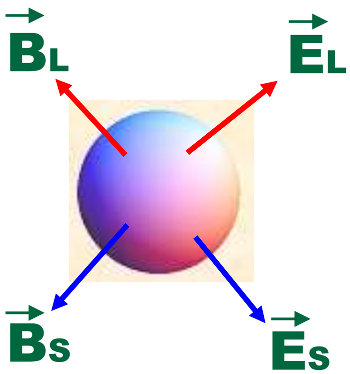
Optical Setup of Ring Cavity (Z. Zhao, Y. Liu)

Power amplification factor 13 (low rep rate)≈100 in typical setup obtained in red light with the test 80 MHz laser



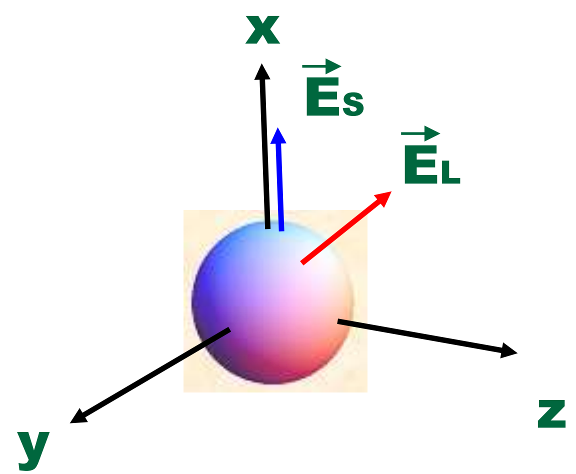
Approach to the solution of the problem

Laboratory frame



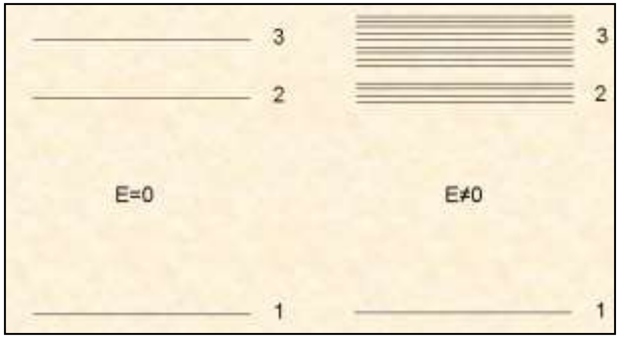
Lorentz Transformation of EM fields

Particle rest frame



Wave function has the following form

$$\Psi(\vec{r},t)=\sum_{j=1}^{14} c_j(t)\psi_j(\vec{r}) \qquad \Psi(\vec{r},0)=\psi_1(\vec{r})$$



Probability to find electron in atom

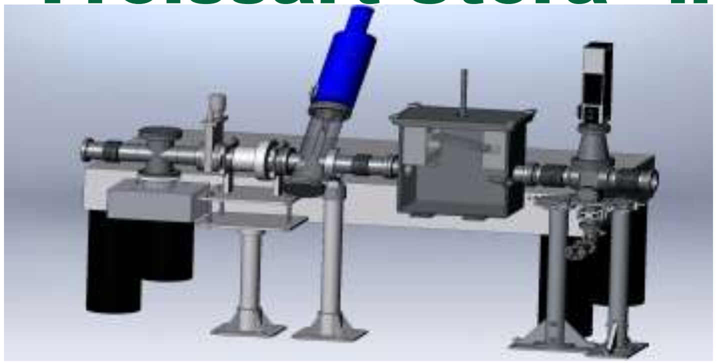
Number of levels

$$c_j^2(t) - \textit{population of } j \textit{ level}$$

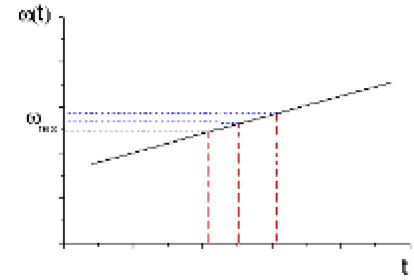
$$p_{in}(t)=\sum_{i=1}^{14} c_j^2(t) \qquad 1^2+2^2+3^2=14$$

$$p_{autoionization}(t)=1-p_{in}(t)$$

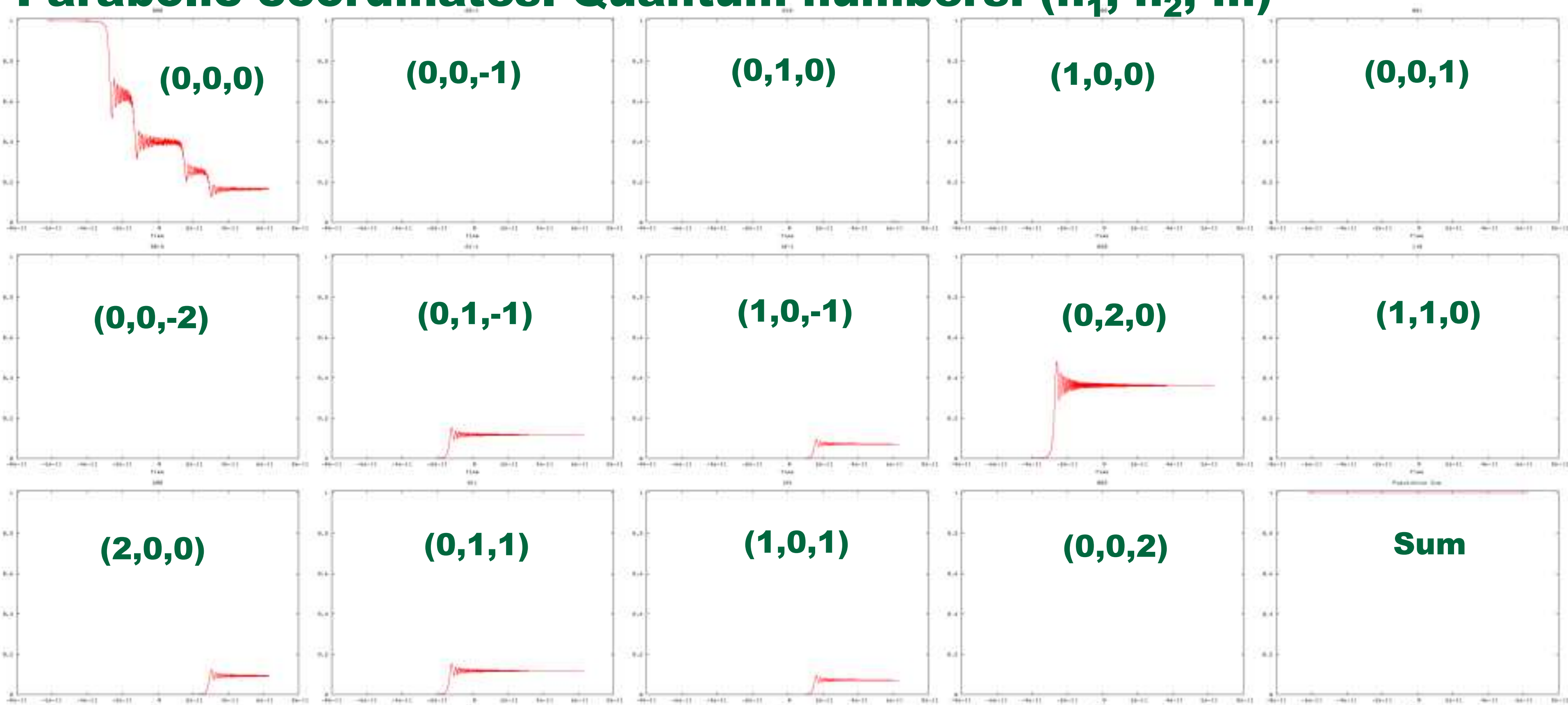
“Froissart-Stora” in presence of field



$\vec{E} \neq 0$



Parabolic coordinates. Quantum numbers: (n_1, n_2, m)



2008 Progress in Laser Stripping

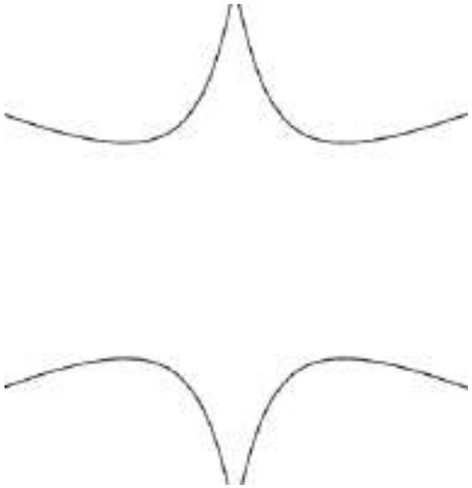
- **Laser room is under preparation for experiments – the new laser and other equipment is about to be installed there;**
- **Test Fabri-Perot cavity produced amplification about 30 for red light;**
- **Crystal scheme was developed, crystals ordered for experiments;**
- **A code (ORBIT module) was developed to calculate and optimize the stripping efficiency in arbitrary magnetic and electric field (an important step for final injection design)**

Large Picture of Ring Developments

Physics	Technology	
Minimization of impedances	TiN coating	
	$1*10^{14}$ ppp	
		SNS ring is here now
Feedback system	Laser stripping Diamond foils	ongoing development
Self-consistent space charge injection	$2*10^{14}$ ppp Barrier cavity	theory development
	$3*10^{14}$ ppp	

Introducing very large tune spread without resonances –
“Integrable” Accelerator Lattices

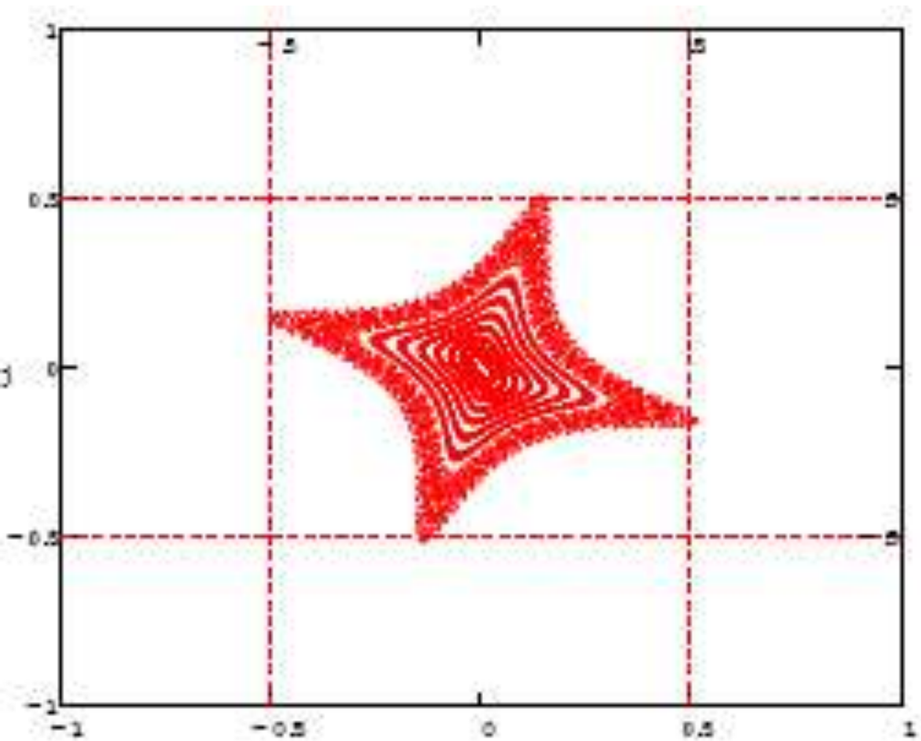
How solutions look like?

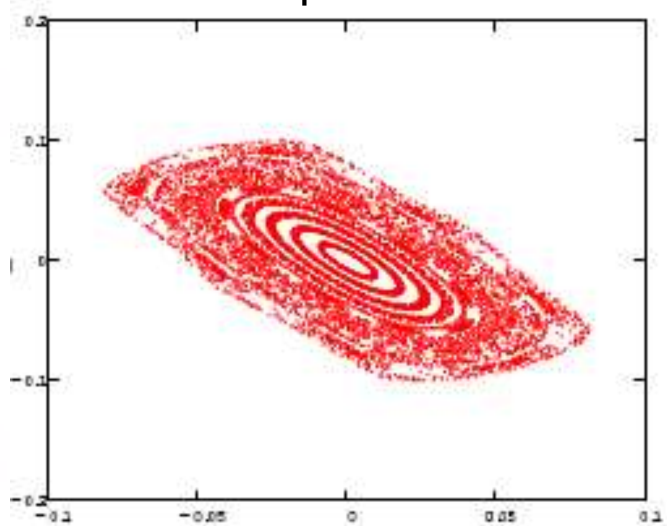


Special lens profiles (on the left)
Special betatron phase advances (1/4) between the lengths

The kicks – octupole x^3,
This lens – $x/(1+x^2)$ (and many other Integrable forms)

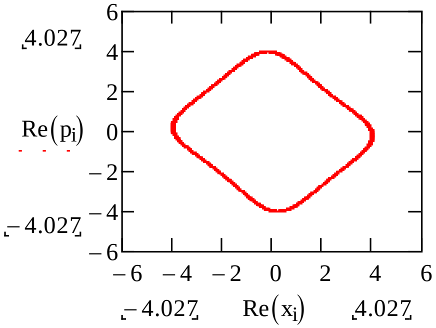
Phase space integrable (left), and octupole (right), the scale 5 times less for octupoles

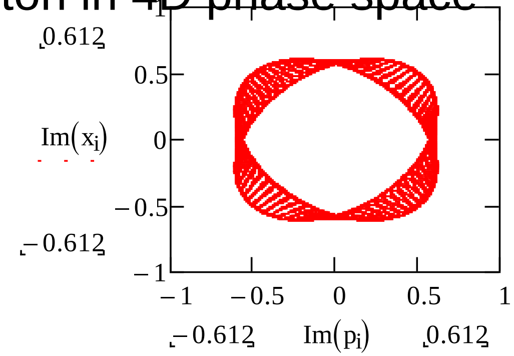




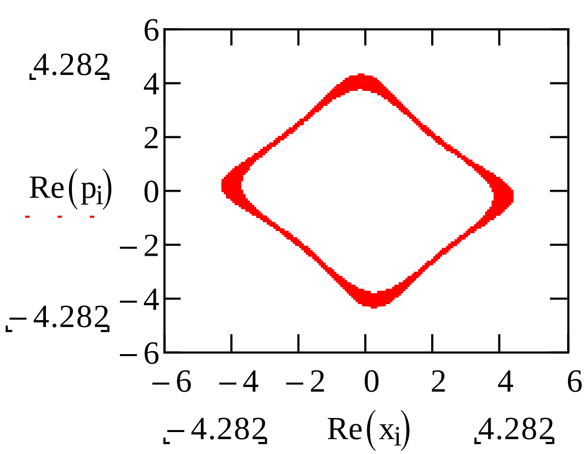
Examples of 2D integrable systems with strongly coupled motion

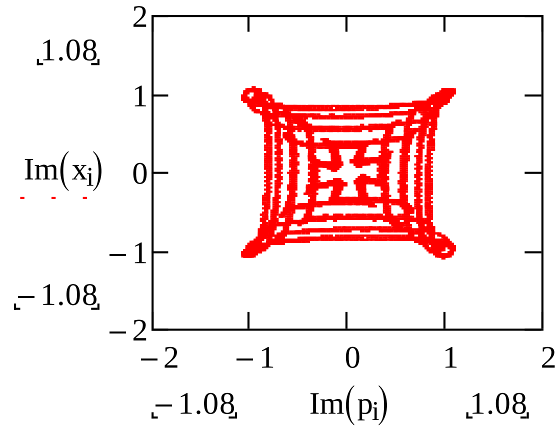
Resonance free 2D integrable accelerator phase space –
The motion is on Liouville tori in 4D phase space





Family of solutions is very rich –
one can create finite number of resonances.
Phase space near resonance below





Benefits from “Integrable” optics use

- Extreme tune spread – 30-50% of betatron tune
- No resonances, no particle loss
- Suppression of instabilities and space charge effects
- Order of magnitude jump in beam brightness
- Reduction of vacuum chamber and magnet size – order of magnitude money savings for future projects for future projects

Conclusion

- SNS developed a successful approach for the ring to get above 10^{14} ppp (or 1 MW)
- New physics and technology is under development to go to 3 MW
- Nonlinear "integrable" accelerator optics is advanced to possible practical implementation to introduce large spread without resonances